Hadron Physics at LHCb

钱文斌
中国科学院大学
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2025年强子物理和有效场论暑期学校，郑州大学

Outline of the talk

- Introduction
- LHCb experiment
- Amplitude analysis
- Spectroscopy results
- More than spectroscopy
- Prospects and conclusion

Hadrons

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Hadron

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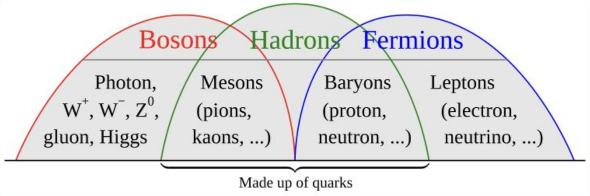
From Wikipedia, the free encyclopedia

In particle physics, a **hadron** is a composite subatomic particle made of two or more quarks held together by the strong nuclear force. Pronounced /ˈhædrɒn/, the name is derived from Ancient Greek ἁδρός *(hadrós)* 'stout, thick'. They are analogous to molecules, which are held together by the electric force. Most of the mass of ordinary matter comes from two hadrons: the proton and the neutron, while most of the mass of the protons and neutrons is in turn due to the binding energy of their constituent quarks, due to the strong force.

Can force mediator or leptons form a composite particle?

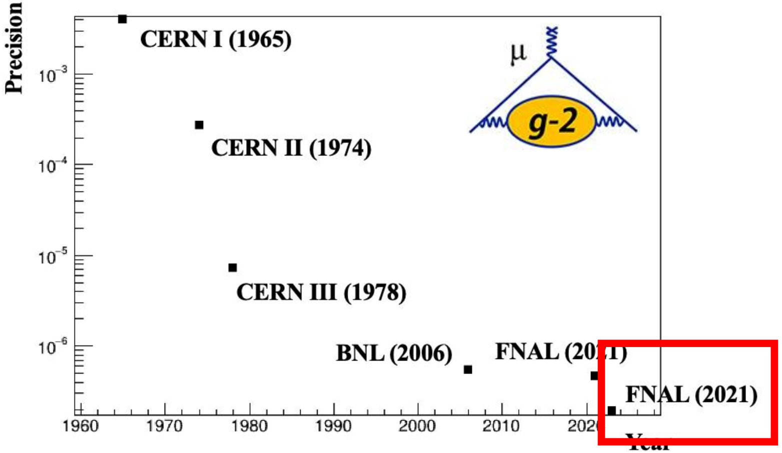


A hadron is a composite subatomic particle. Every hadron must fall into one of the two fundamental classes of particle, bosons and fermions.

- **Made by two or more quarks; held together by the strong nuclear force**
- **Most of the ordinary matter are proton and neutron; most of the mass of hadron from the strong force (Higgs only generate a small amount)**

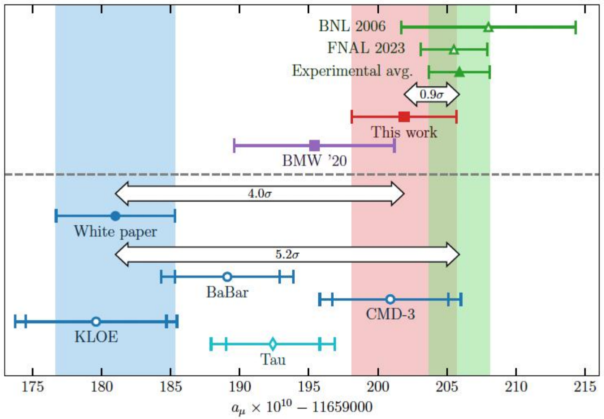
Hadron physics

- **Almost all high energy physics are related to hadron physics**



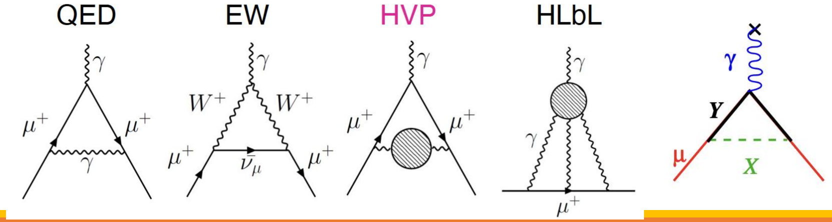
$\mathcal{O}(0.2\ \text{ppm})$

$a_\mu(\text{FNAL}) = 116\,592\,055(24) \times 10^{-11}$



2025.06： $a_\mu(\text{AVE}) = 116\,592\,0715(145) \times 10^{-11}$, 124 ppb

$$a_\mu^{\text{SM}} = \frac{g_\mu - 2}{2} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{HVP}} + a_\mu^{\text{HLbL}} + a_\mu^{\text{NP}}$$



- **Lepton properties, however, QCD still important (Hadronic Vacuum Polarization, Hadronic Light-by-Light etc.)**
- **Method developed to understand QCD (lattice, dispersive relationship)**

BESIII input

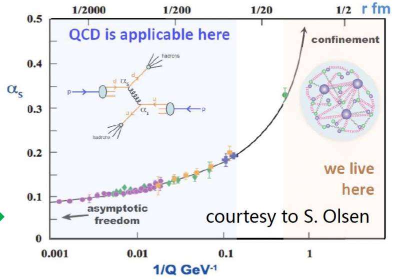
Tasks of flavor and hadron physics

- SM model very successful;
- Still an effective theory, many unexplained phenomena;
- Most related to flavor and hadron physics

Understanding QCD at low energy

- Properties of QCD confinement
- Structures of hadrons

Non-perturbative!



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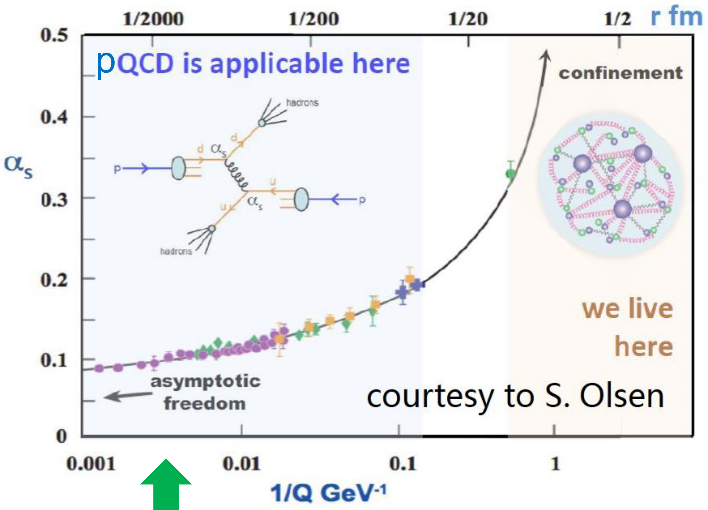
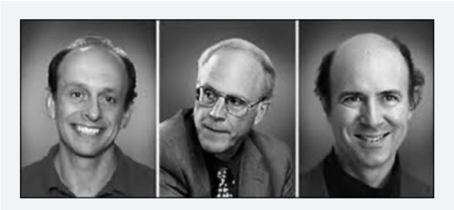
New Physics hunting

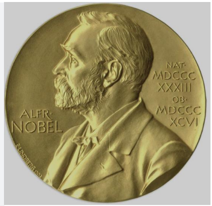
- Matter and antimatter asymmetry observed in the Universe
- Origin of dark matter? New particles or new forces? Flavor hierarchy

Hadron physics: colorful and tasty

QCD at low energy





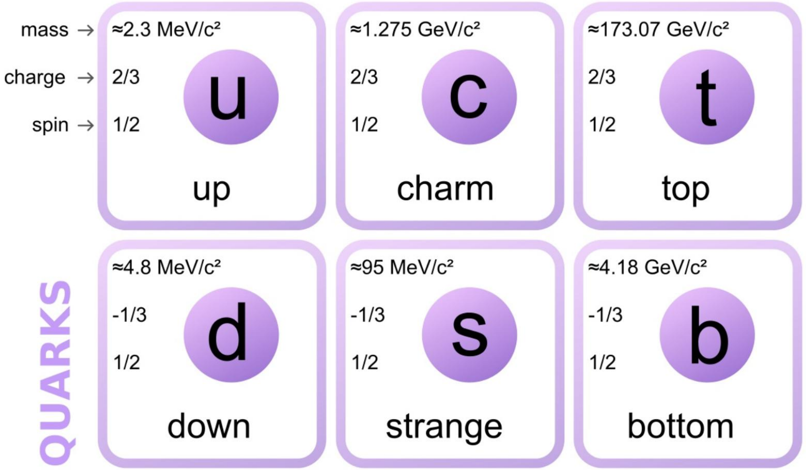


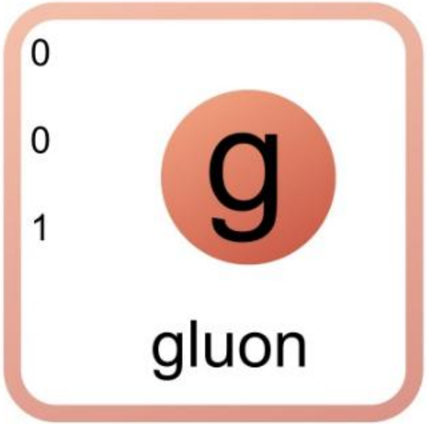
- Spectroscopy studies
- Structure of hadrons
- Hadron interaction with matter
- Production and decay of hadrons
- Fragmentation process into hadron
- Everything related to matter

Questions related to hadron structures

- **How quarks are combined into hadrons? How many types of matter?**
- **What are the properties of strong force at low energy?**
- **How does the strong force generate mass of proton and neutron?**
- **……**

Quarks and gluon





- **In total, 6 (flavor) x 3 (color) x 2 (antimatter) = 36 quarks**
- **How many different types of hadrons can they make? (if not counting excited states): 36 for meson ($q\overline{q}'$) and 112 for baryons ($qq'q''$ or $\overline{q}\overline{q}'\overline{q}''$);**
- **hadron does not show color property**
- **Can gluon itself form a hadron?**

Top quark

- Top quark a bit special, no resonance seen until recently
- Lifetime of top quark: 7×10^{-25} s

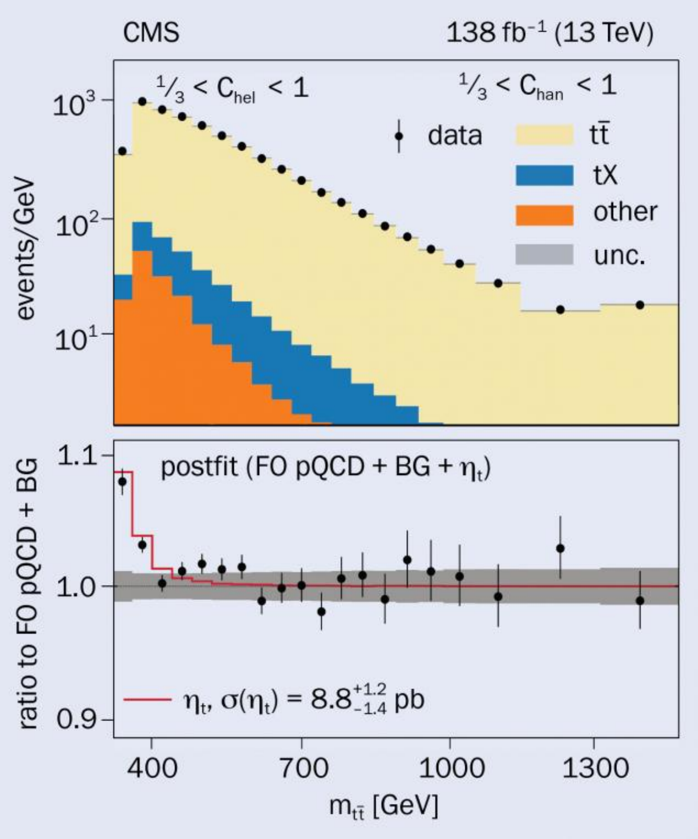
1 fm ~ 3×10^{-24} s

	强相互作用	电磁相互作用	弱相互作用	引力相互作用
源	色荷	电荷	弱超荷	质量
作用常数	$\alpha_s = \frac{g_s^2}{4\pi\hbar c}$ $\cong 1\sim 10$	$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c}$ $\cong 1/137$	$\frac{G_F(M_p c^2)^2}{(\hbar c)^3}$ $\cong 1\times 10^{-5}$	$\frac{G_N M^2}{4\pi\hbar c}$ $\cong 5\times 10^{-40}$
力的传递者	胶子（g）	光子（γ）	中间玻色子（$W^{\pm}$，Z^0）	——
典型作用时间	10^{-23} 秒	10^{-16} 秒	10^{-10} 秒	——
力程	1fm	∞	1/400 fm	∞

Long distance
Slower interaction

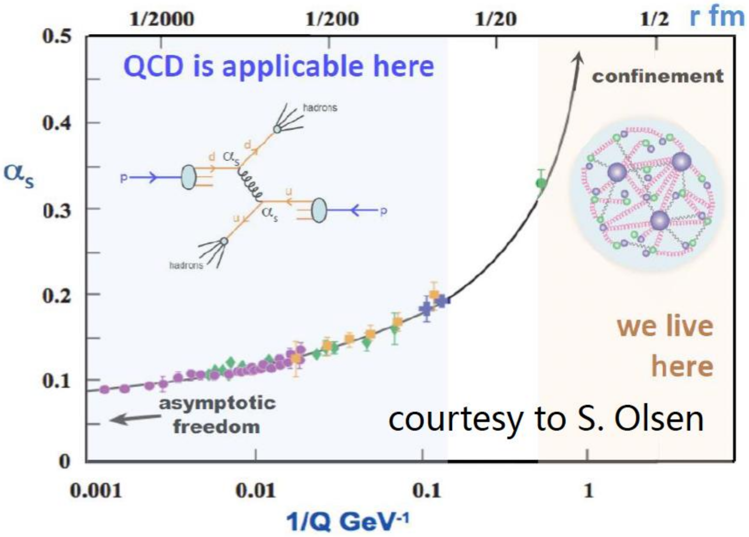
Short distance
Quicker interaction

Toponium (1)



- Both CMS and ATLAS seen excess of events near threshold of $m(t\bar{t})$
- New physics or the smallest composite particle yet observed in nature: toponium
- Text book claim: top quark lifetime too short to form any bound states
- Cross section: $8.8^{+1.2}_{-1.4}$ pb
- Total $t\bar{t}$ cross section: ~830 pb
- Could it really be toponium?

Toponium (2)



- In Bohr model: (m_t/m_e ~ 340000, charge +2e/3)
  - $v_1 = 4\alpha c/9$
  - $r_1 = 9\hbar/4\alpha mc$ ~ 0.7 fm
  - $E_1 = 8mc^2\alpha^2/81$ ~ 0.5 keV
- $\alpha_s \sim 0.2 > \alpha \sim 0.01$: QCD dominant
  - $v_1 = \alpha c$ ~ 0.2c
  - $r_1 = \hbar/\alpha_s mc$ ~ 0.01 fm
  - $E_1 = mc^2\alpha^2/2$ ~ 2.0 MeV

$$\frac{2\pi r_1}{v_1} = 2\tau$$

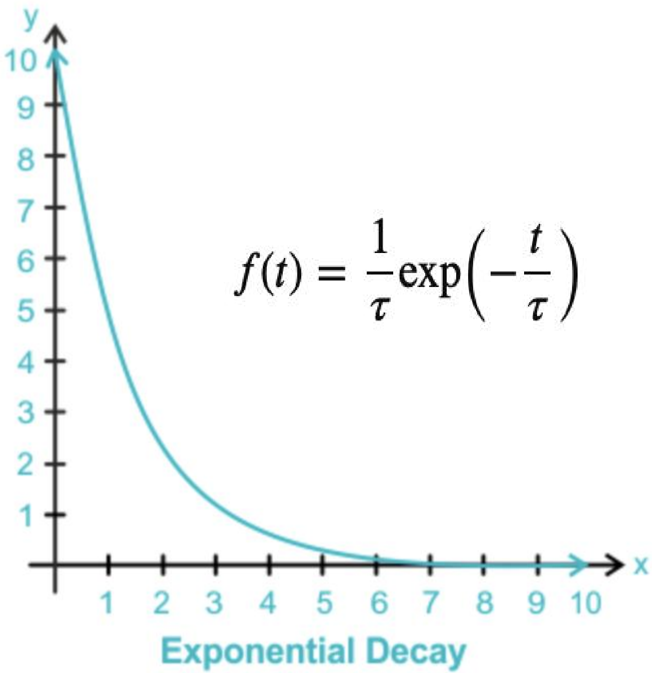
QED potential:

$$V(r) = -\frac{\alpha}{r},$$

QCD potential:

$$V(r) = -C_F\frac{\alpha_S(1/r)}{r} + \sigma r \qquad C_F = 4/3 \quad \sigma = 0.18\,\mathrm{GeV}^2$$

Toponium (3)

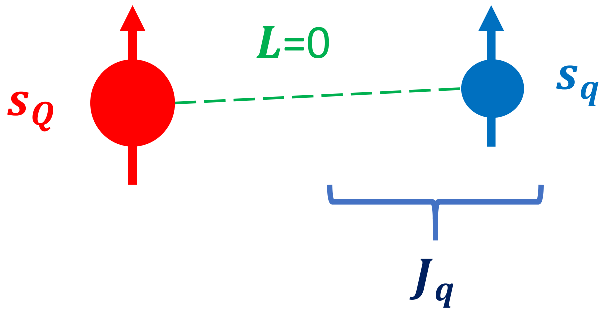


$$f(t) = \frac{1}{\tau}\exp\left(-\frac{t}{\tau}\right)$$

- Lifetime of top quark: ~ 7×10^{-24} s
- Average interaction length between $t\bar{t}$
  - 1 fm: around 6τ, probability around 6×10^{-4}
  - 0.5 fm: around 3τ, probability around 3×10^{-3}
  - 0.25 fm: around 2τ, probability around 2×10^{-2}
- Estimation varies from 2% to 0.01%
- Measured: ~1%
- There could be toponium formed before top decays

Godfrey-Isgur model

- Ignor multi-quark or gluonic excitations
- QCD-inspired potential:
  - Confining part (long range): $\propto r$
  - Coulomb-like part (short range): $\propto -\alpha_s/r$
  - Spin-dependent part: hyperfine splitting
  - Mainly depends on r
- Wave function solutions from Schrodinger equation
- Spin-parity
  - Nature: 0^+, 1^-, 2^+, 3^-, 4^+...
  - Un-nature: 0^-, 1^+, 2^-, 3^+, 4^-...
- Decaying into two pseudo-scalar particle: nature spin-parity

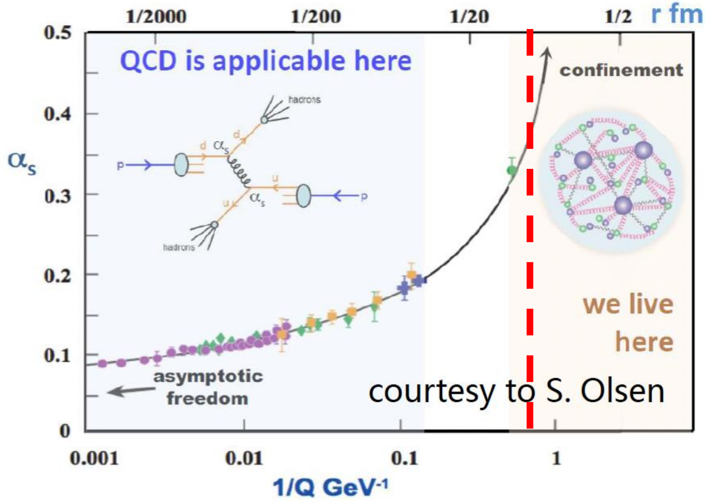


Quark mass

- All other quarks except top decays after formation of hadrons
- Mass very different from each other

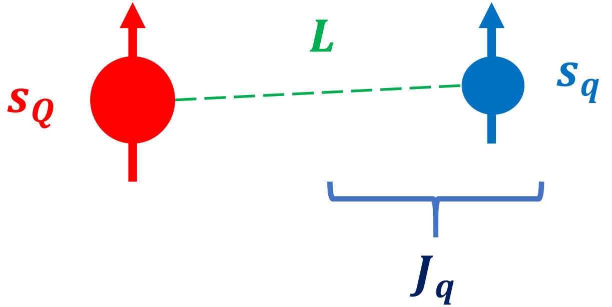
Quark	u	d	c	s	t	b
Mass (MeV)	2.3	4.8	1275	95	173070	4180

- $\Lambda_{QCD} \sim 200$ MeV
- Perturbative calculations
  - α_s (large momentum transfer)
  - Λ_{QCD}/m_Q
- Heavy quarks: b, c play a special role



Heavy quark spin symmetry (HQSS)

- When $m_Q \gg \Lambda_{\mathrm{QCD}}$, spin of heavy quark decouples with other freedom or $m_Q \to \infty$, all spin interaction vanishes ($\mathcal{O}(1/m_Q)$)
  - Heavy quark can be considered to be static ($\lambda_Q \sim 1/m_Q$)
  - Spin of heavy quark (s_Q) and total angular momentum (J_q) conserved
  - Splitting between different s_Q approaches 0 when $m_Q \to \infty$
  - System very similar for different heavy quarks

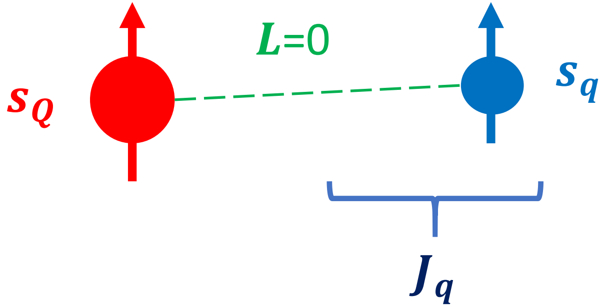


Application

- **Mass splitting between doublet of ground state (spin related)**

$M_{D^*} - M_D \sim 140$ MeV
$M_{D_s^*} - M_{D_s} \sim 142$ MeV
$M_{B^*} - M_B \sim 45$ MeV
$M_{B_s^*} - M_{B_s} \sim 45$ MeV

$M_{D^*}^2 - M_D^2 \sim 0.54$ GeV²
$M_{B^*}^2 - M_B^2 \sim 0.48$ GeV²
$M_{D_s^*}^2 - M_{D_s}^2 \sim 0.57$ MeV
$M_{B_s^*} - M_{B_s} \sim 0.52$ MeV



- **Mass splitting decreases as $1/m_Q$**
- **Also works when the light part is changed to s quark**
- **One may also expect**

$M_{B_s} - M_B \sim M_{D_s} - M_D$

Light freedom

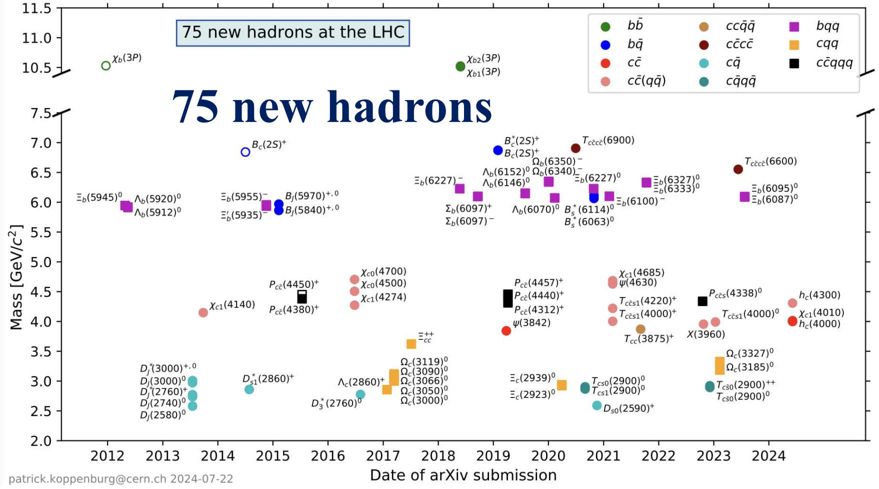
$M_{B_1^*} - M_B \sim M_{D_1^*} - M_D$

$M_{B_2^*} - M_B \sim M_{D_2^*} - M_D$

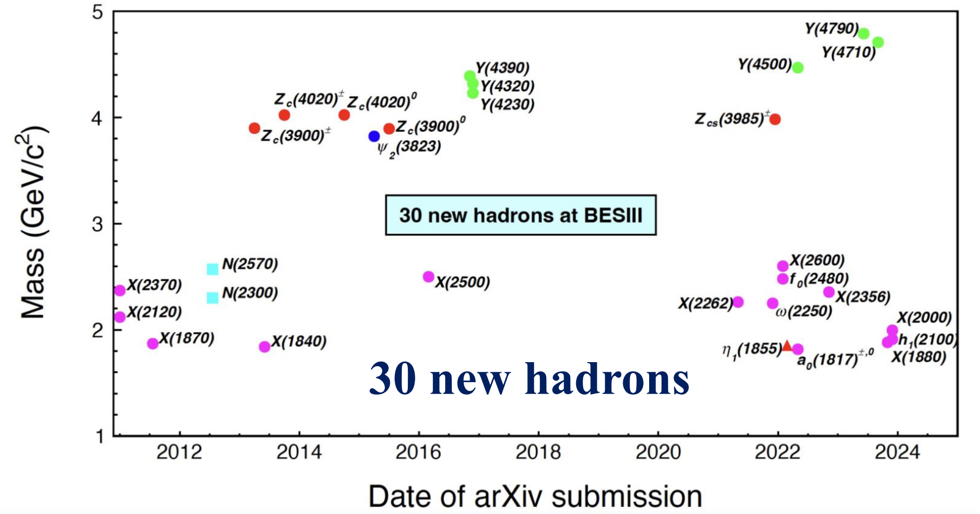
Angular momentum

Particle zoo 2.0

- **Many new hadrons discovered since the discovery of $\chi_{c1}(3872)$ in 2003: renaissance and revolution?**



LHC (mainly LHCb)



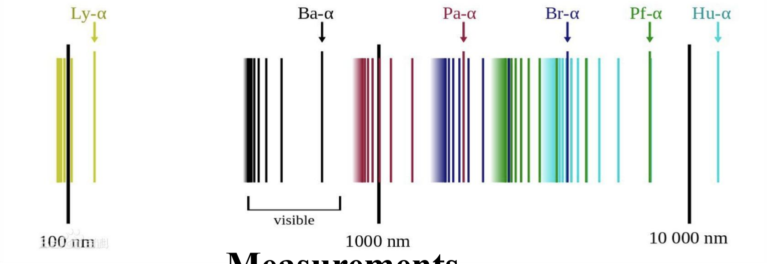
BESIII

- **+ 17 new hadrons from Belle (>35 from its start)**
- **> 20 new hadrons since 2022 (only selected ones are shown)**
- **Many can not be explained by conventional quark model**

More than 140 new hadrons

Spectroscopy studies

Complicated



Measurements

Empirical summary to Balmer's equation:

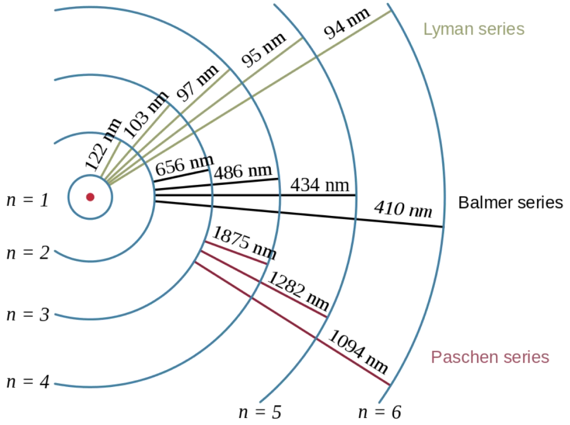
$$\lambda = 365.46\frac{n^2}{n^2 - 2^2}\,\text{nm}, \quad n = 3,4,5,\cdots$$

Rydberg's equation:

$$\sigma = \frac{1}{\lambda} = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) \qquad R = 1.0973731534\times10^7\,\text{m}^{-1}$$ 里德伯常量

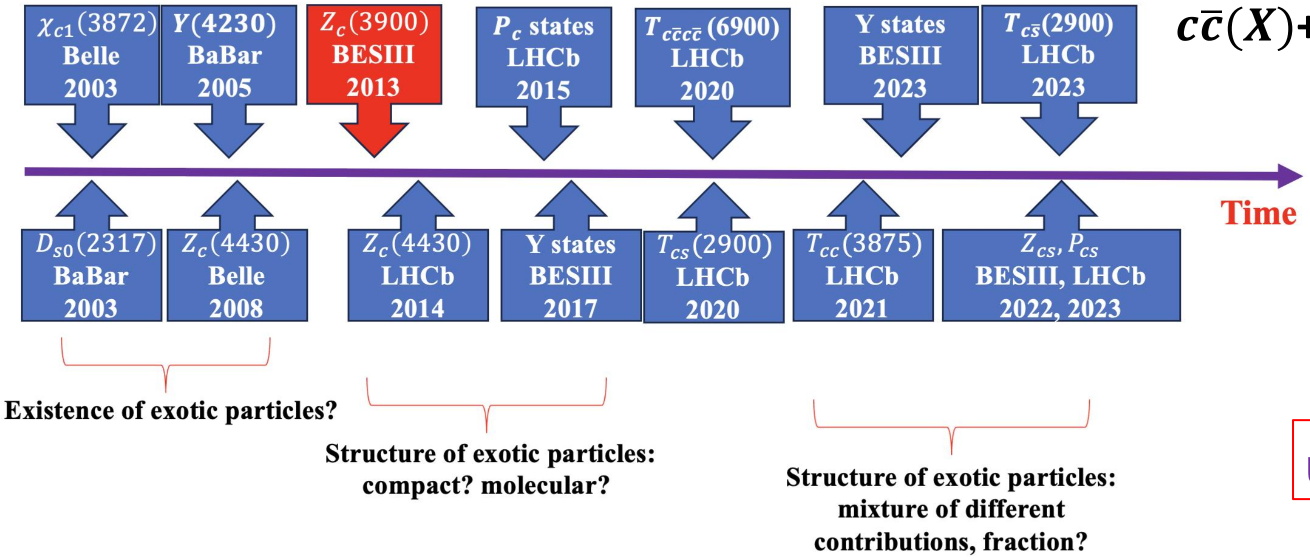
$$n_f = 1,2,3,4,\cdots, \quad n_i = n_f + 1, n_f + 2, n_f + 3, \cdots$$

Bohr model



Force

A history of understanding



$c\bar{c}(X)$+ $c\bar{s}$ (X)

More states

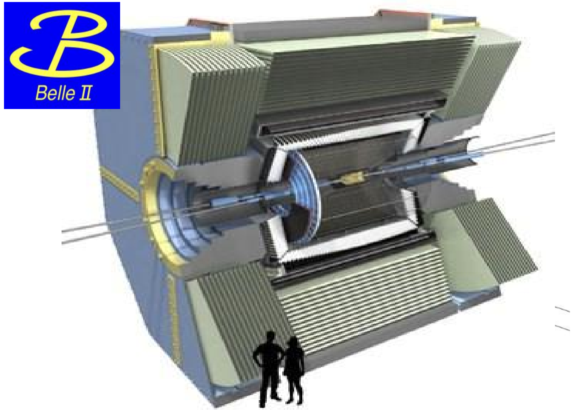
Better understanding

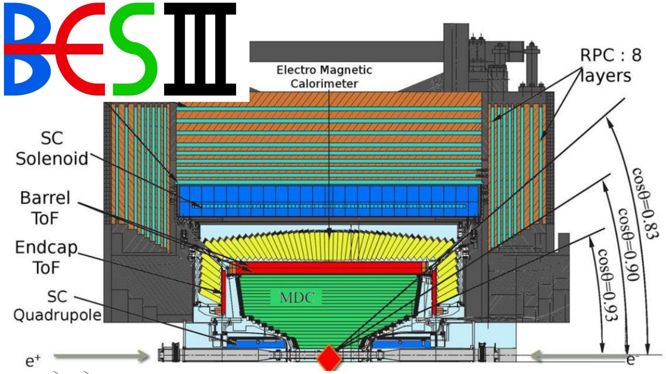
Unified model for all hadrons?

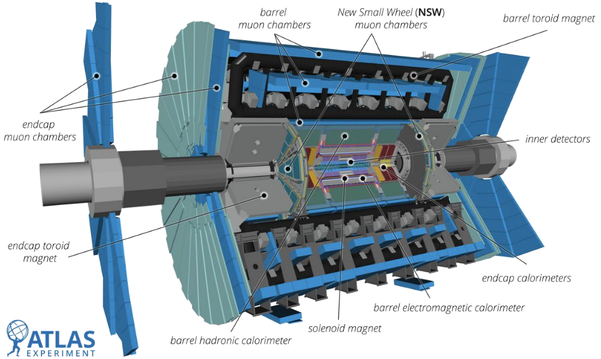
Particle X = $c\bar{c}$ + $c\bar{c}qq$ + cq $\bar{c}q$ + $c\bar{c}$ qq + $c\bar{c}g$ …

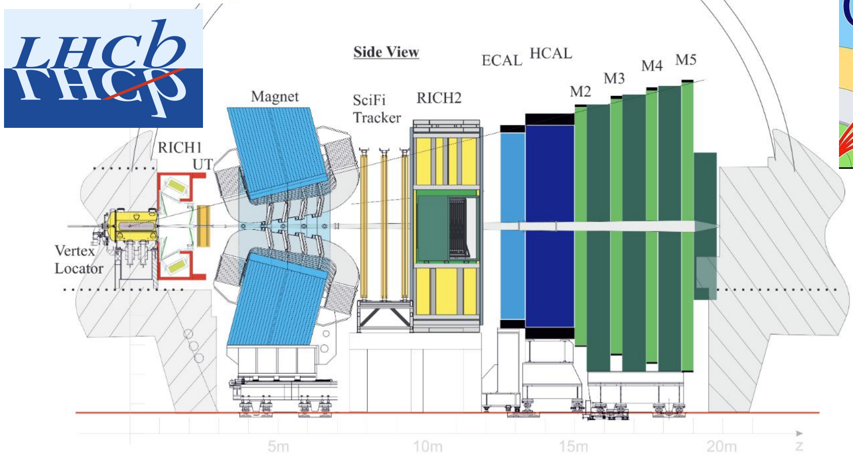
LHCb experiment

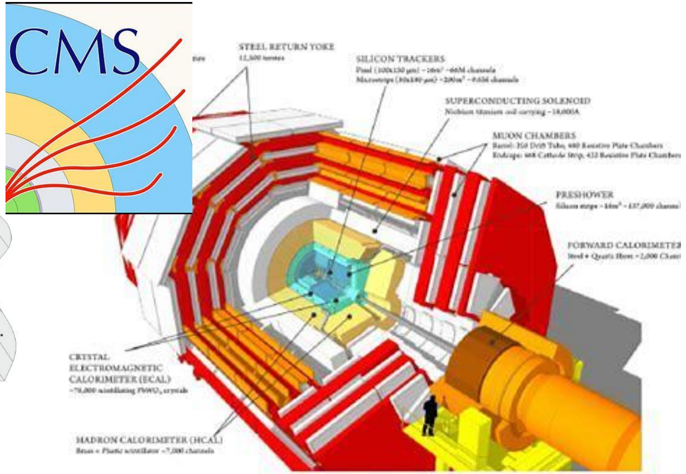
Experiments in the world





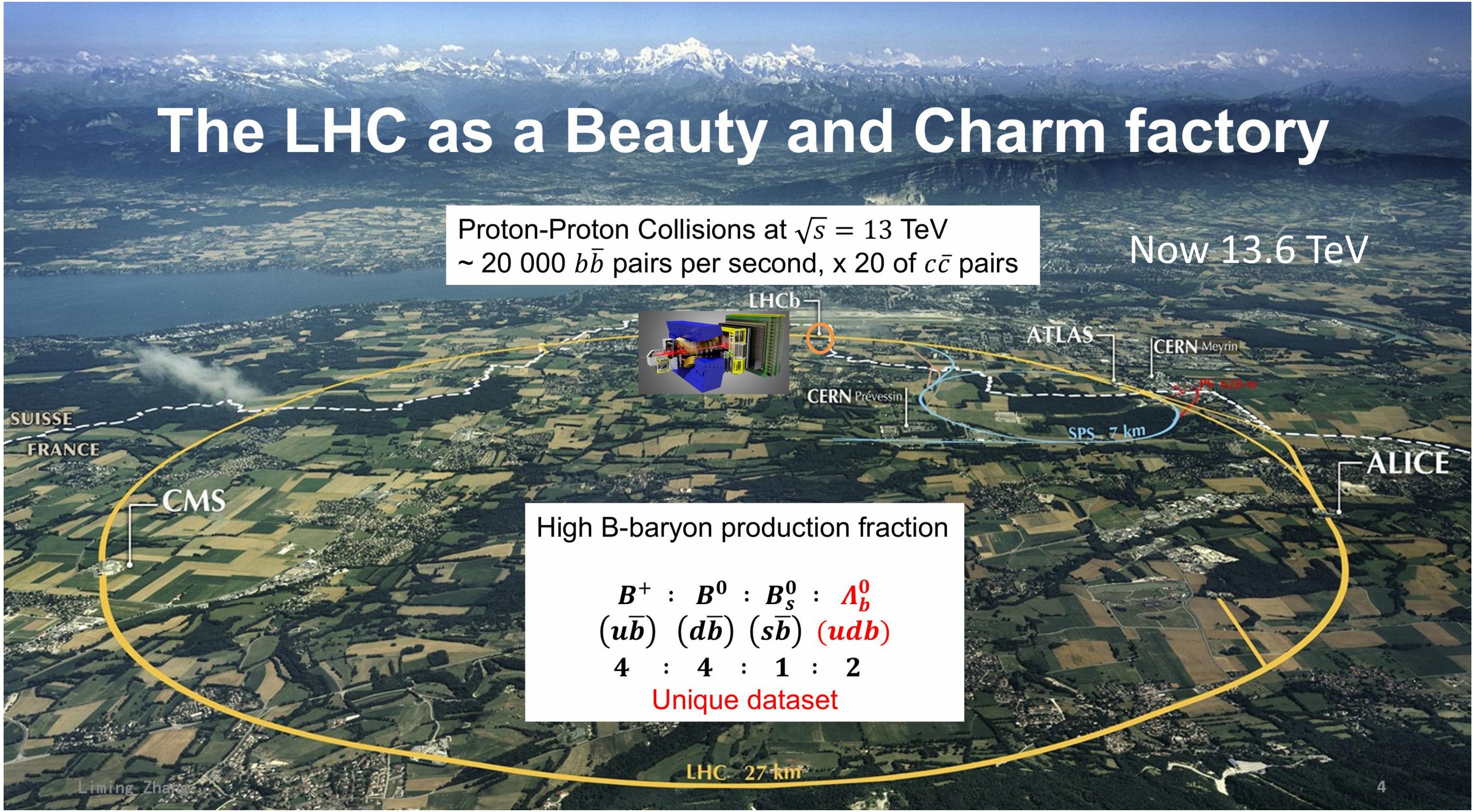






+ many dedicated experiments

LHC: a new energy and luminosity frontier



Production of b hadrons

Experiments	Production	Efficiency
LHCb (50 fb^{-1})	$\sim10^{13}$	~0.1%
Belle II (5 ab^{-1})	$\sim10^{10}$	few%
CEPC	$\sim10^{12}$	few%

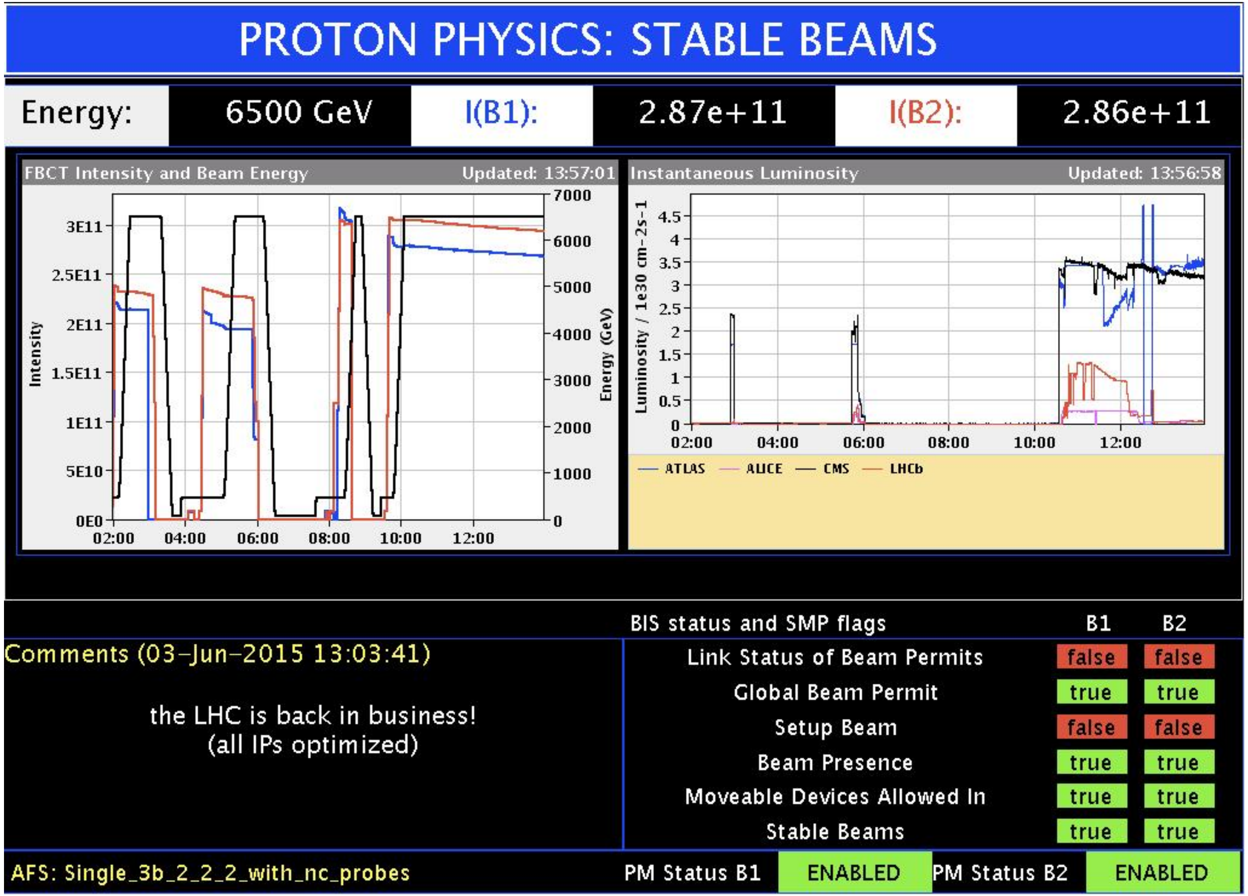
- Beauty in LHCb more than 1 order of magnitudes larger than other experiments; CPV and time-dependent studies
- Production not only $B^{0,+}$ mesons, but also B_s^0 + b baryons
- e^+e^- experiments: final states with neutral particles; absolute branching fraction measurements etc.

Charm production at LHCb

Experiments	Production	Efficiency
LHCb (50 fb^{-1})	~200 x 10^{12}	<0.1%
BelleII	~0.1 x 10^{12}	few%
CEPC	~0.26 x 10^{12}	few%
BESIII	~0.25 x 10^{8}	> 10%
Super tau-charm	~25 x 10^{8}	> 10%

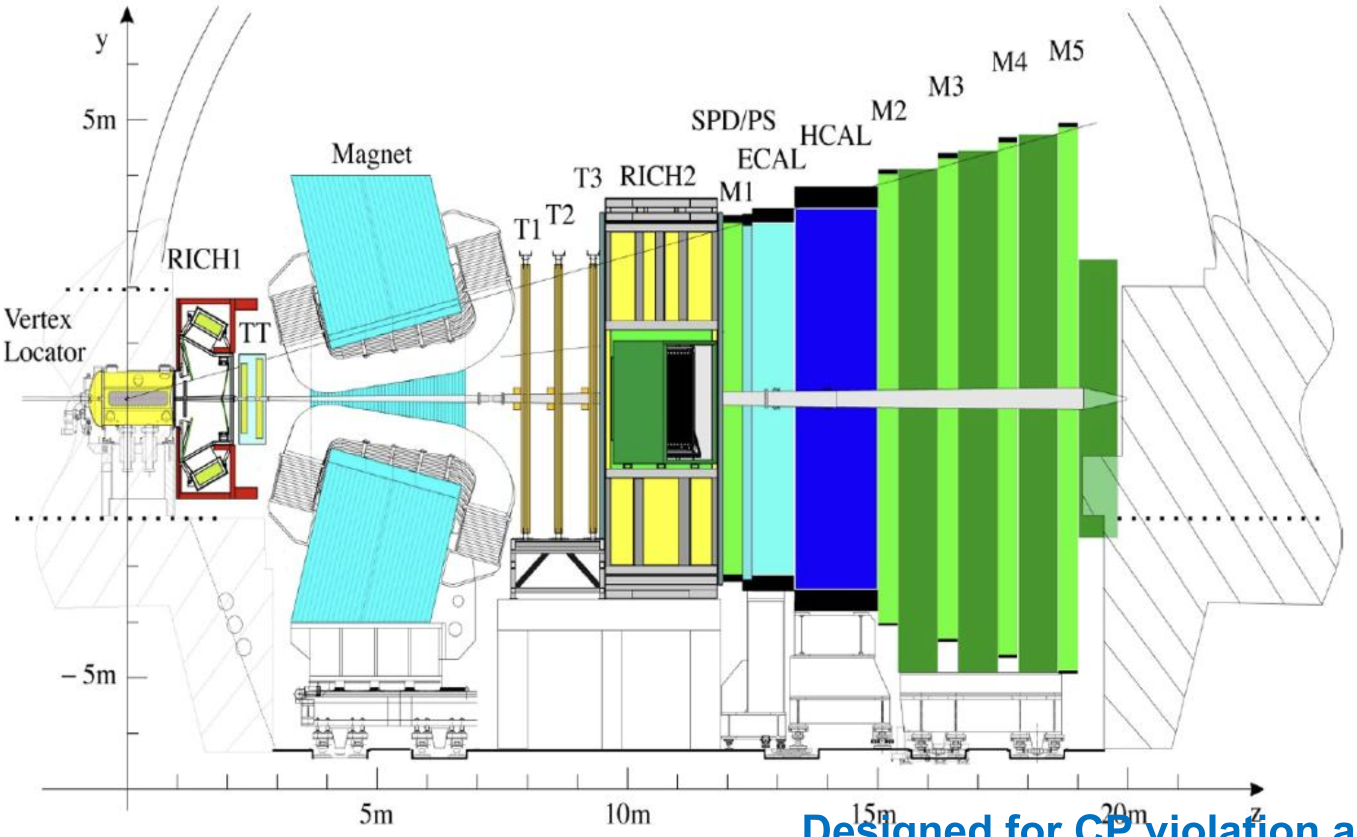
- **Charm in LHCb more than 2 orders of magnitudes larger than other experiments; CPV and time-dependent studies**
- **BESIII: quantum-correlated production**
- e^+e^- **experiments: final states with neutral particles; absolute branching fraction measurements etc.**

What we eat in canting



The LHCb detector (before 2019)

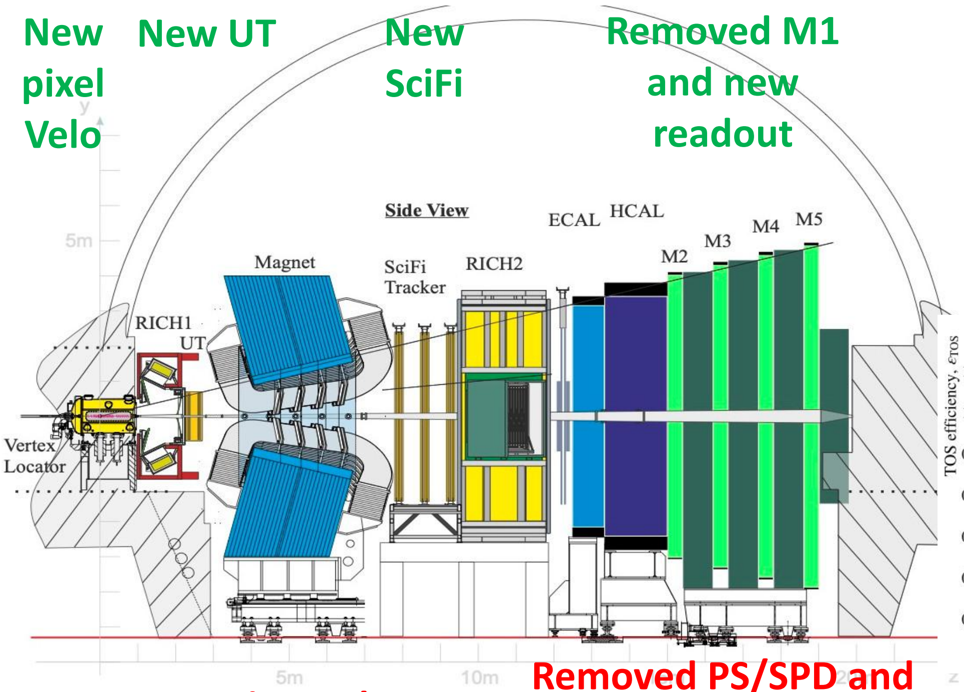
2008 JINST 3 S08005



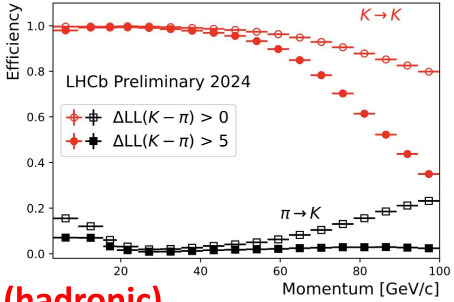
Designed for CP violation and heavy flavor studies

A new LHCb detector

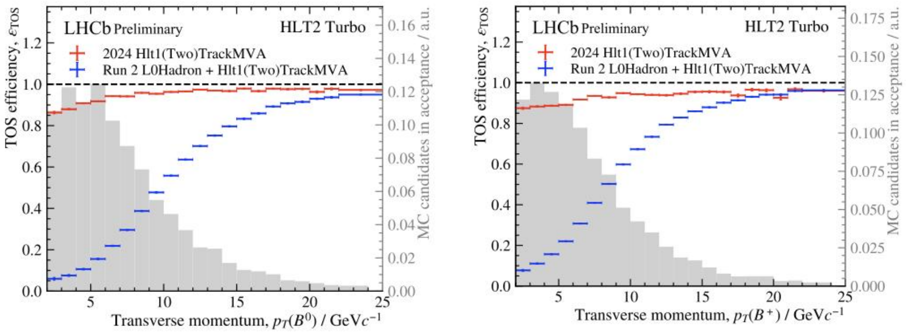
- With our new LHCb detector, already collected more data than Run1+2
- More importantly, full software trigger ➜ better performance on hadronic final states



Similar PID performance



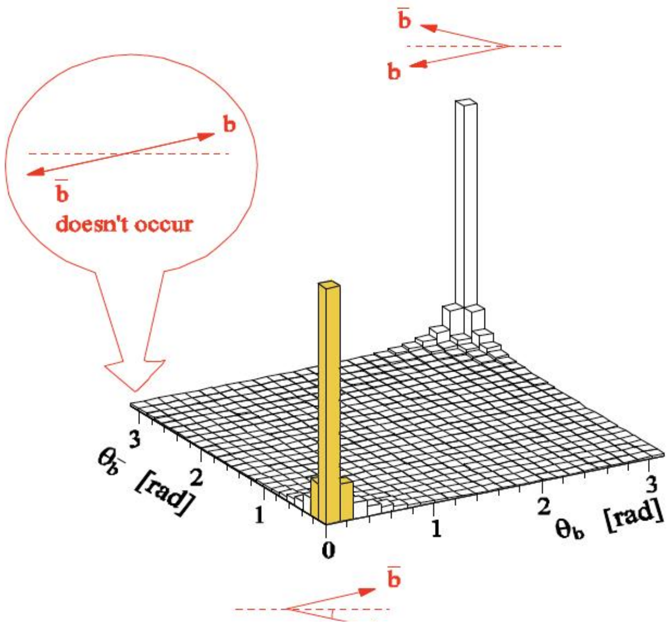
Twice trigger efficiencies (hadronic)

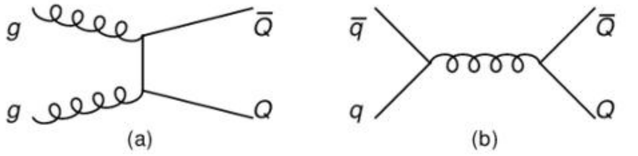


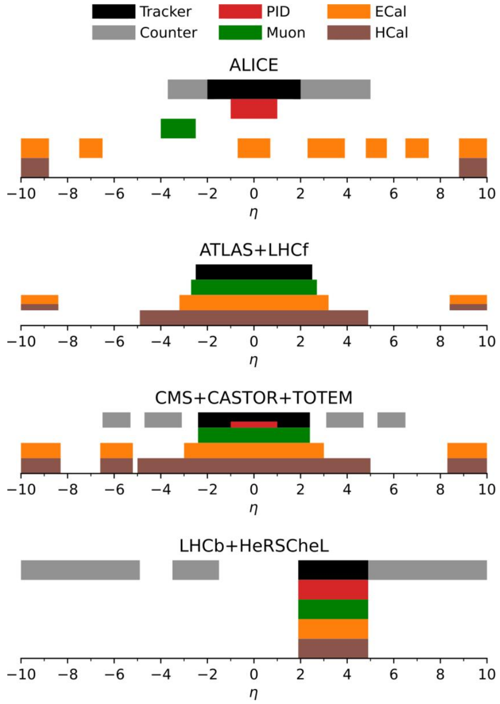
$B^0 \to D^- \pi^+$ $\quad$ $B^+ \to \bar{D}^0 \pi^+$

The LHCb Coverage

2008 JINST 3 S08005

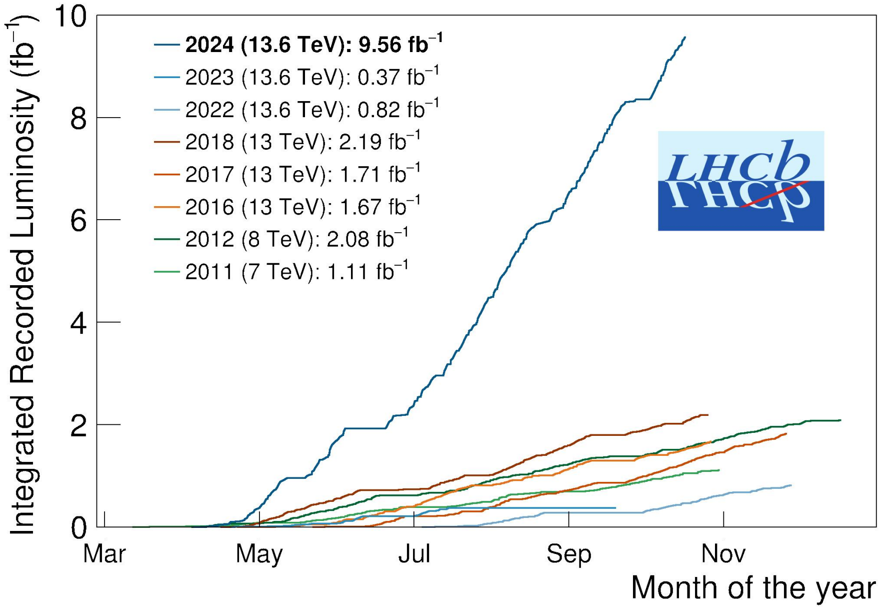






- **Very different from other collision experiments**
- **However, not a fixed-tag experiment**

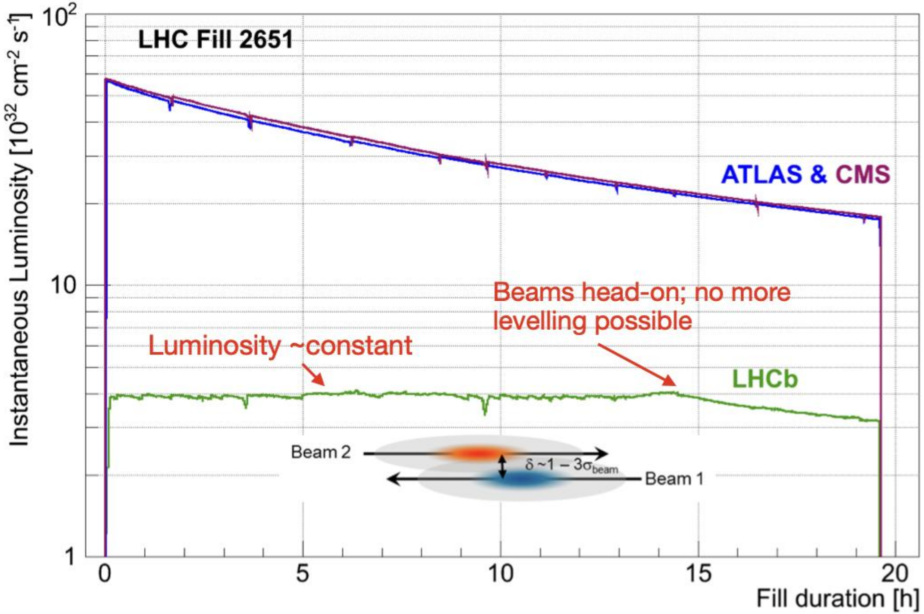
The LHCb status



- **Run 1:**
  - **2011 (7 TeV): 1 fb^{-1}**
  - **2012 (8 TeV): 2 fb^{-1}**
- **Run 2:**
  - **2015-2018 (13 TeV): 6 fb^{-1}**
- **Run 3:**
  - **2024 alone (13.6 TeV): 9.56 fb^{-1}**

- **A new LHCb detector for Run 3 operates at $\times$ 5 higher instantaneous luminosity**
- **Similar performance, while efficiency for hadron final states increased by a factor of 2**

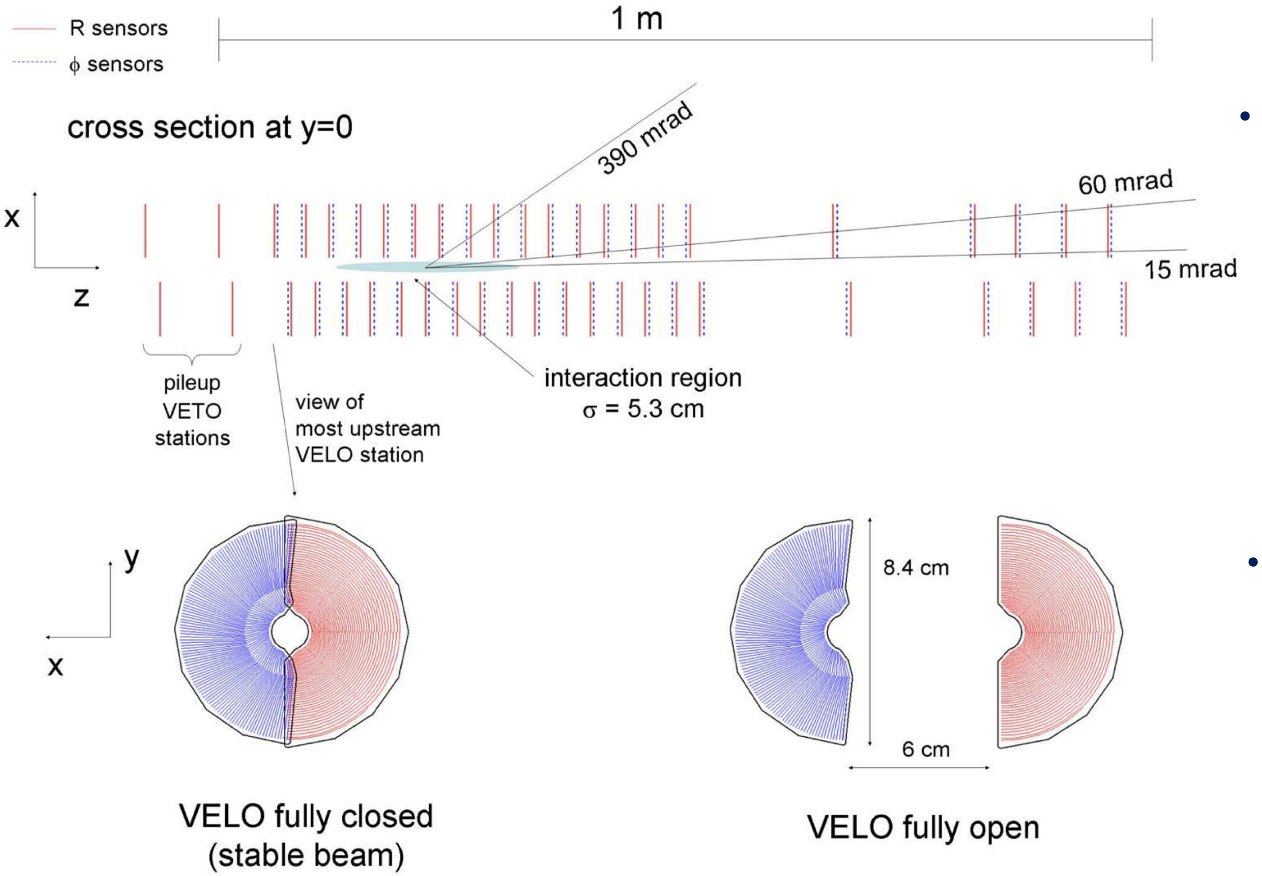
The LHCb luminosity



- Instantaneous luminosity for LHCb at Run 1 and 2 are $2{\sim}4.5 \times 10^{32}$ cm^{-2}s^{-1}
- While in Run 3, it is 20×10^{32} cm^{-2}s^{-1}
- Average number of visible pp collision $\mu \sim$ 1.1 (33% empty events) in Run1,2
- Low pp collisions important for flavor physics (lifetime related measurements)

- Instantaneous luminosity at ATLAS and CMS falls exponentially
- LHCb controls its luminosity by beam offset

The LHCb VELO detector

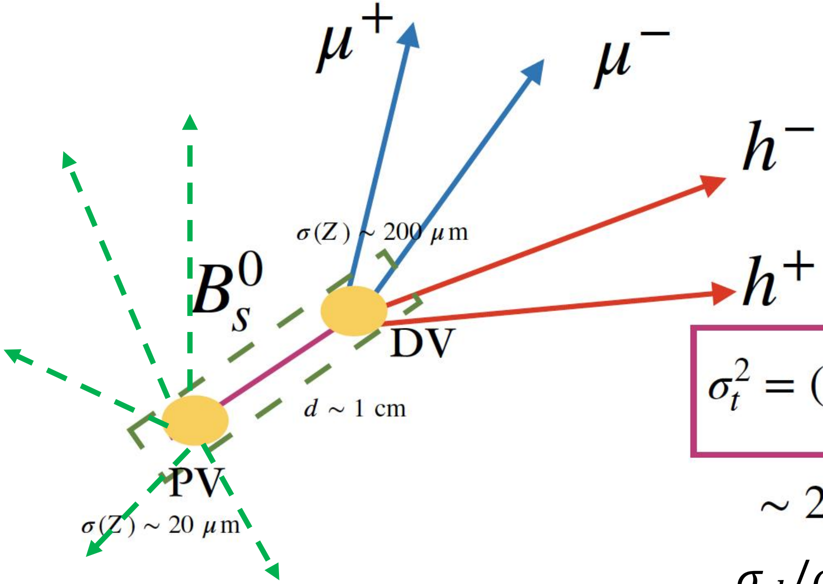


- **Designed to measure pp collision and secondary decays from beauty and charmed mesons**

- **VELO only closed when stable beam**

Why a silicon detector important

- **Lifetime of b and c hadrons: ~ 10^{-12} s; typical momentum ~ 60 GeV → flies around 0.5 cm**
- **Help in distinguish tracks from decays of b and c hadrons and tracks from pp collisions**



More than 100 tracks

- **Crucial for lifetime measurements**
  - **Lifetime resolution in LHCb ~ 44 fs**

$$t = \frac{d \times m}{p}$$

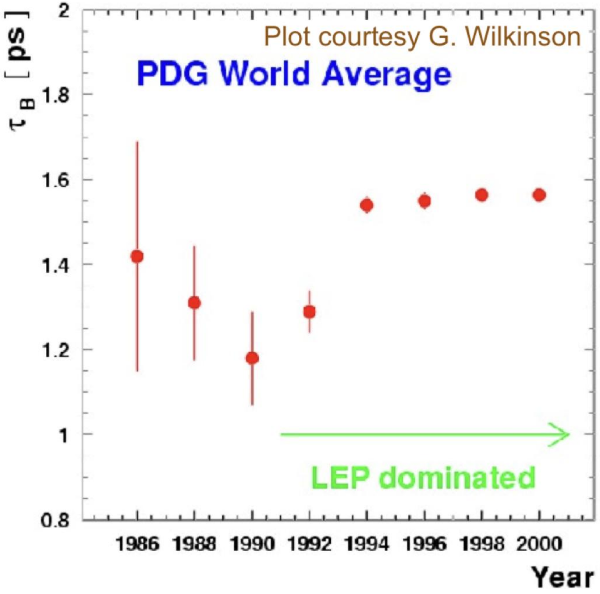
$$\sigma_t^2 = \left(\frac{m}{p}\right)^2 \sigma_d + \left(\frac{t}{p}\right)^2 \sigma_p^2$$

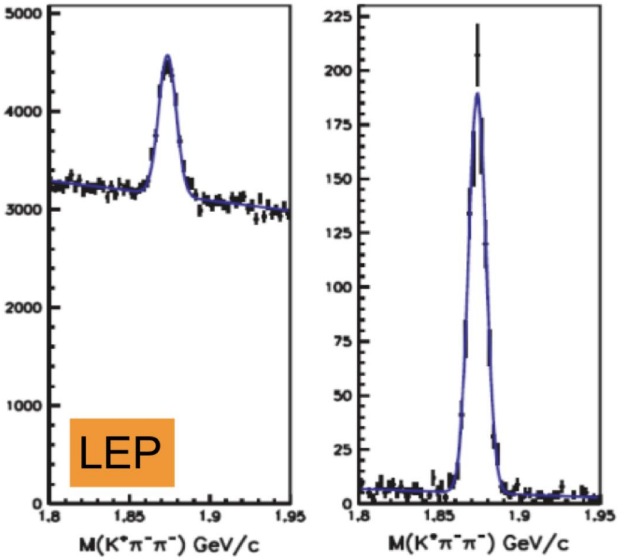
$\sim 200\ \mu m$ $\quad$ $\sigma_p/p \sim 0.4\,\%$

$\sigma_d/d \sim 4\%$

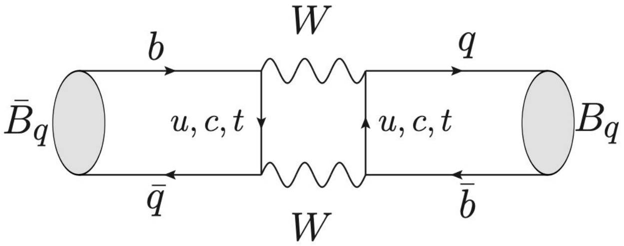
Impact of silicon detector

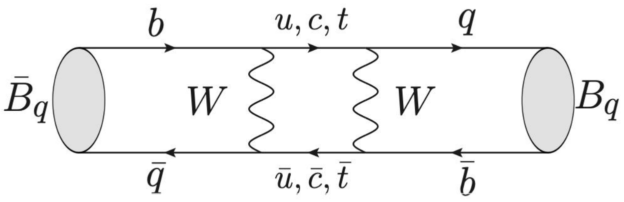
Dramatic effect on measurement precision!





Meson mixing





Meson	Δm(ps⁻¹)	ΔΓ/Γ	τ (ps)
B^0	~0.5	~0	~1.5
B_s^0	~17.8	~0.14	~1.5

$\cos \Delta m_q \tau \times t/\tau$

Not diagonalized

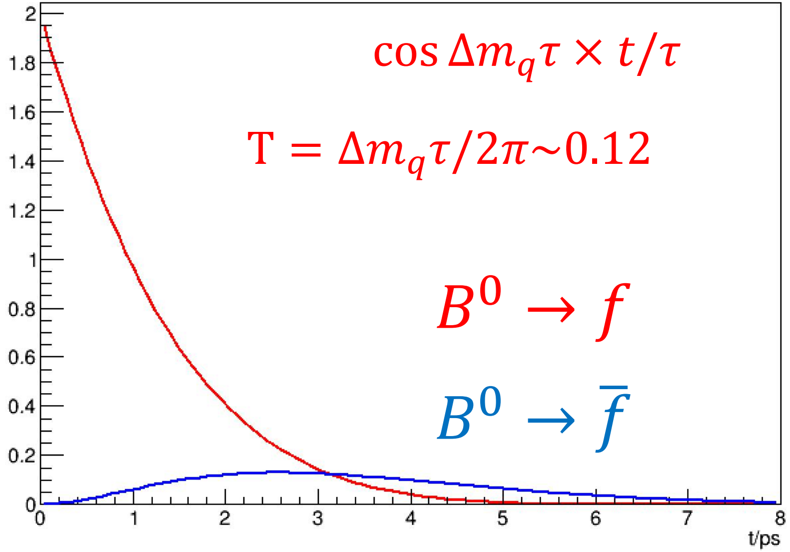
$$\frac{\partial}{\partial t}\begin{pmatrix} B_q \\ \overline{B_q} \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} B_q \\ \overline{B_q} \end{pmatrix}$$

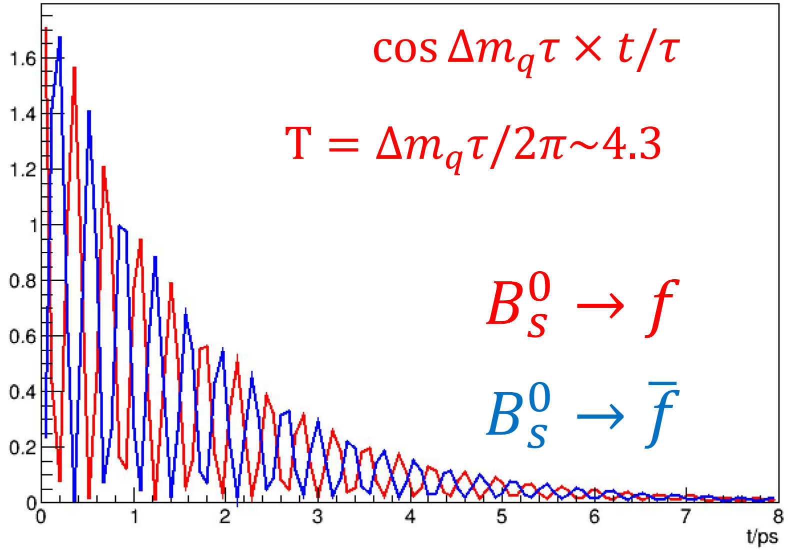
Mass eigenstates != flavor eigenstates

$$|B_{L,H}\rangle = p\,|B_q^0\rangle \pm q\,|\bar{B}_q^0\rangle$$

$$\Delta m_q \equiv m_H - m_L$$
$$\Delta\Gamma_q \equiv \Gamma_L - \Gamma_H$$
$$\Gamma_q \equiv (\Gamma_L + \Gamma_H)/2$$

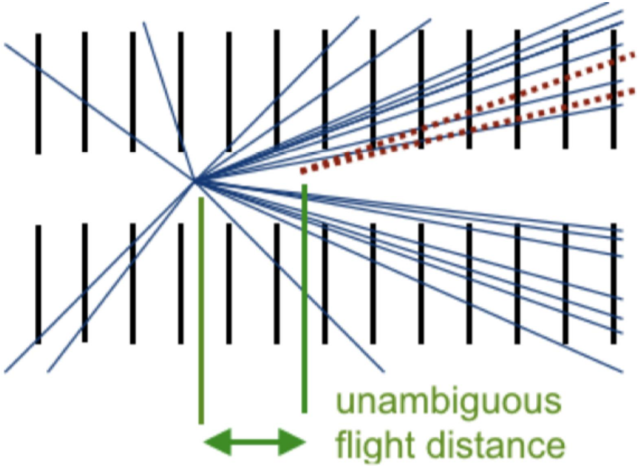
Oscillation

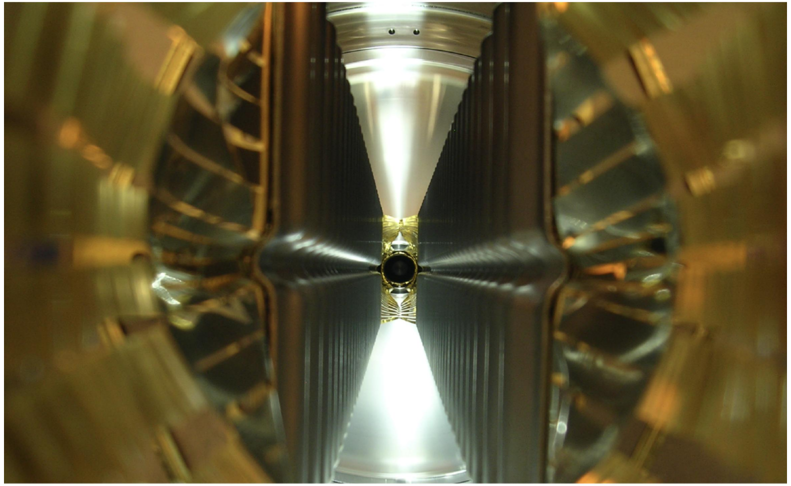




- **Flagship measurement when LHCb designed is to measure Δm_s**
- **To resolve oscillation, further constraints on lifetime resolution; 5σ separation between two oscillation peaks: ~ 50 fs**
- **CPV power $\propto e^{\Delta m_q \sigma_t^2/2}$, 0.73 @ 45 fs, 0.28 @ 90 fs**

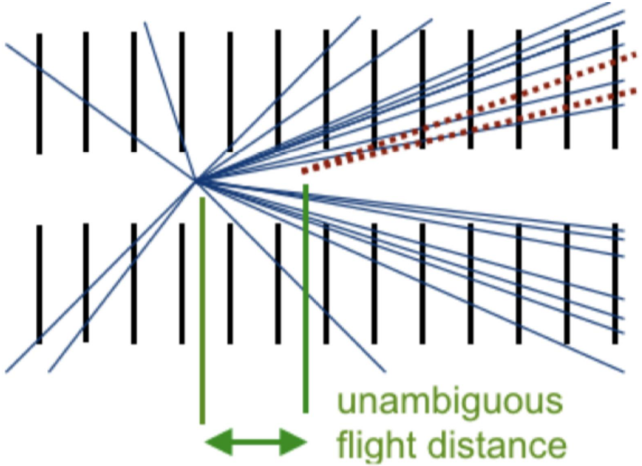
First hit point at the silicon detector

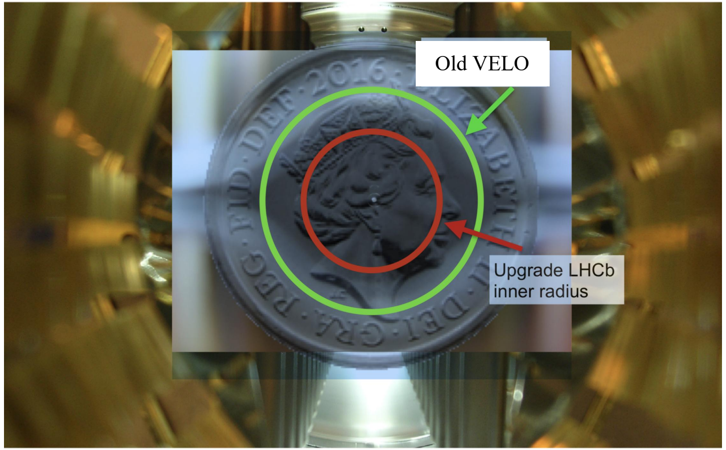




- Secondary vertex resolution depends on how close the first detection point to it
- Make it as close as possible to the beam pipe
- Now only 8mm!!!
- VELO closed only during stable beam

First hit point at the silicon detector

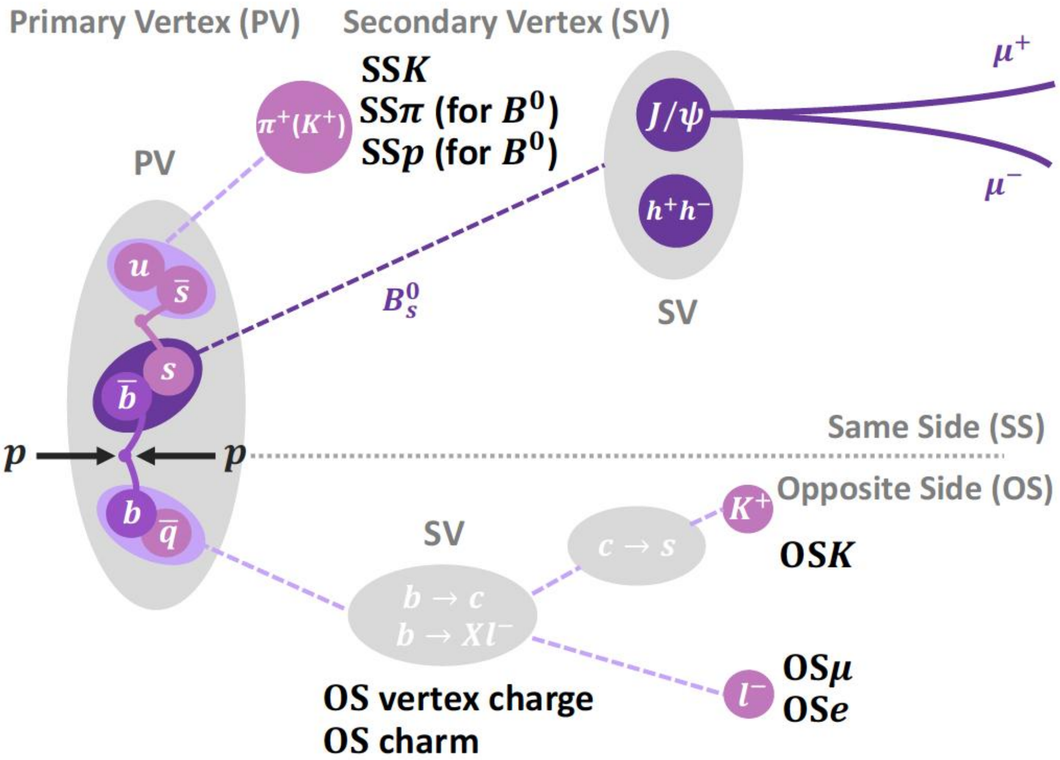




5p coin

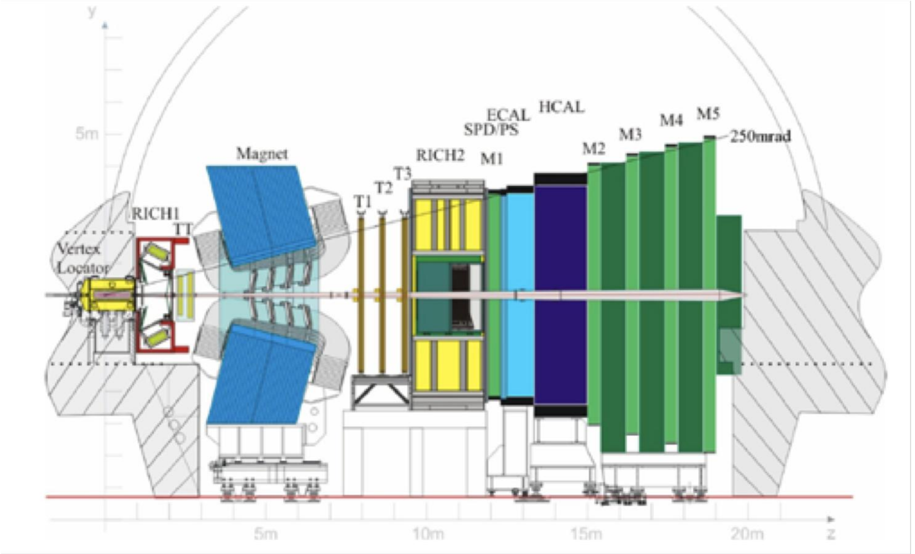
- Secondary vertex resolution depends on how close the first detection point to it
- Make it as close as possible to the beam pipe
- Now only 8mm!!!
- VELO closed only during stable beam

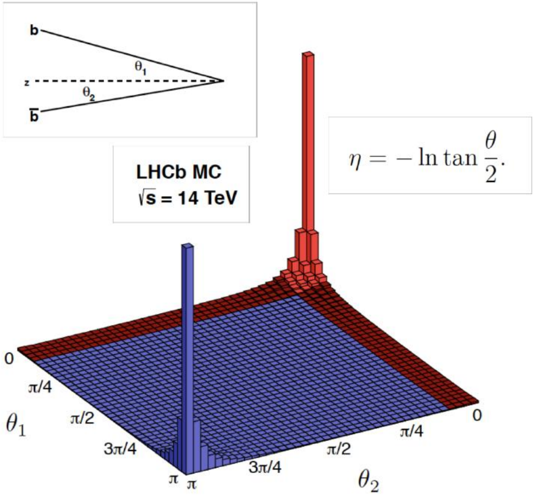
Flavor tagging



- Need to know flavor of B when it is produced
- Based on knowledge of the other B or s/d quark associated with B production
- Low effective tagging power/yields

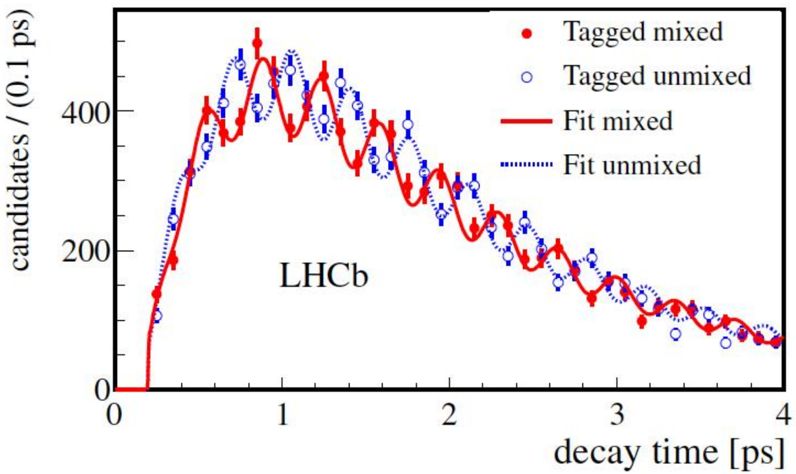
Where is the other B?





- b and $\bar{b}$ produced heavily boosted in one direction
- Single-armed detector designed to have 27% b and $\bar{b}$ produced inside LHCb acceptance

Measurement of Δm_q



- **Measured using $B_S^0 \to D_S^- \pi^+$, $B^0 \to D^{(*)} \mu \nu X$**

$$\Delta m_d = 0.5065(19)\text{ps}^{-1}$$

$$\Delta m_s = 17.757(21)\text{ps}^{-1}$$

Precision of 0.38% and 0.12%!!!

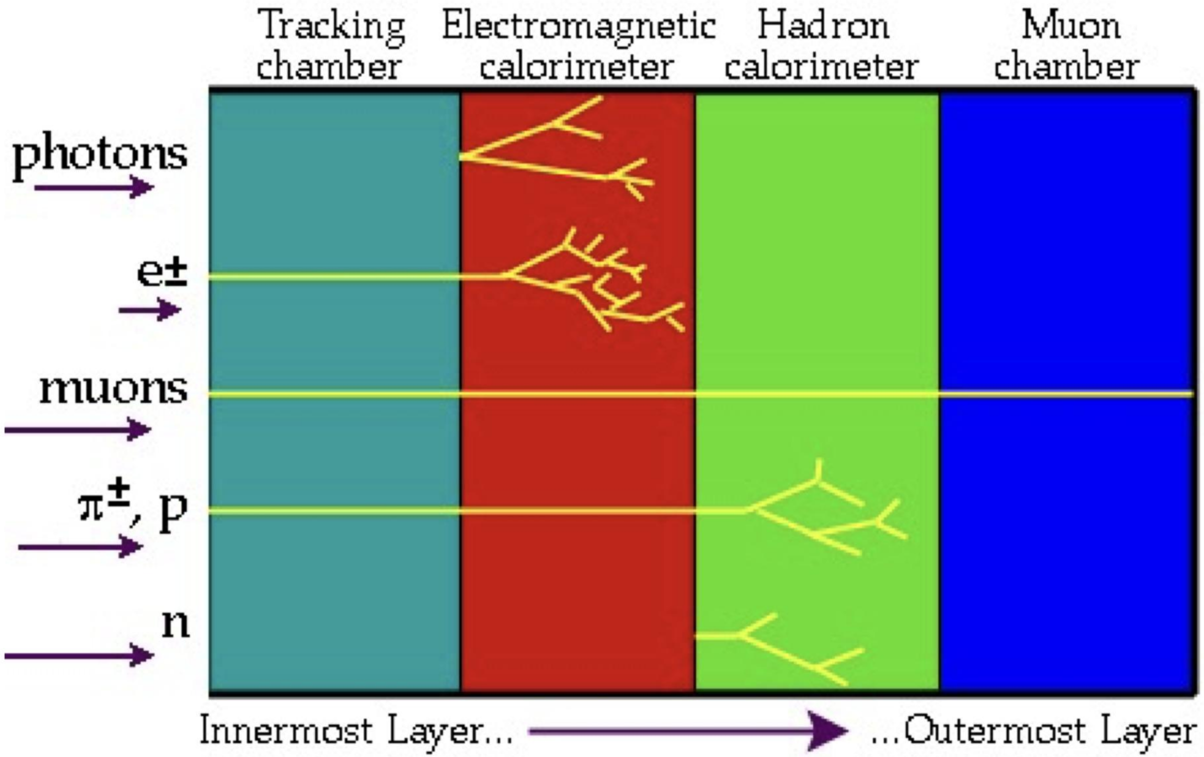
$$S_0(x) = x\left[\frac{1}{4} + \frac{9}{4}\frac{1}{1-x} - \frac{3}{2}\frac{1}{(1-x)^2}\right] - \frac{3}{2}\left[\frac{x}{1-x}\right]^3 \ln x$$

$$\Delta m_q = \frac{G_F^2}{6\pi^2}\left|V_{tq}^* V_{tb}\right|^2 M_W^2 S_0(x_t) B_q f_{Bq}^2 M_{Bq} \widehat{\eta_B}, \quad x_t = \frac{m_t^2}{M_W^2}$$

- **Uncertainties mainly from Bag parameters (3%) obtained from lattice**
- **Large reduction of uncertainties by making ratios of the two**

PID system

- **Key different in detector design for experiments dedicated to flavor physics**

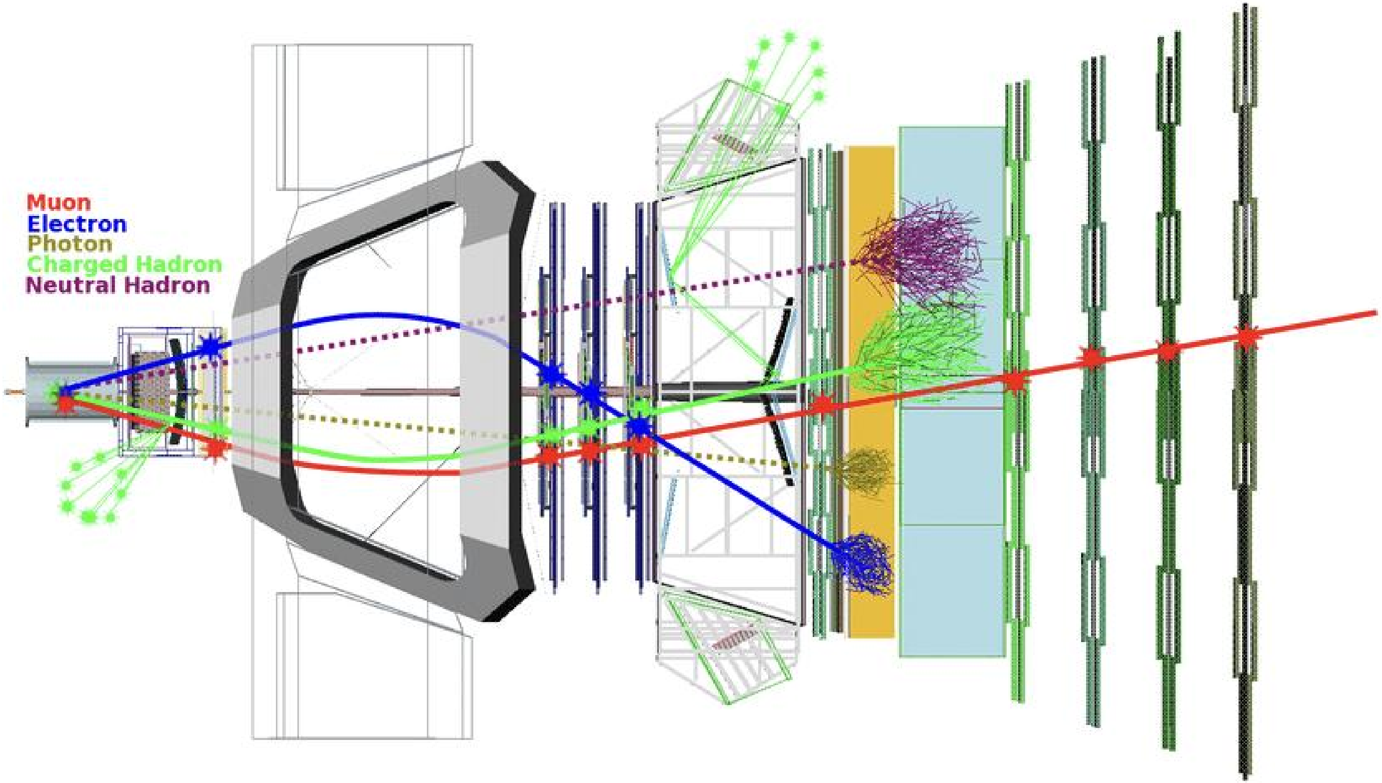


GPD

Flavor

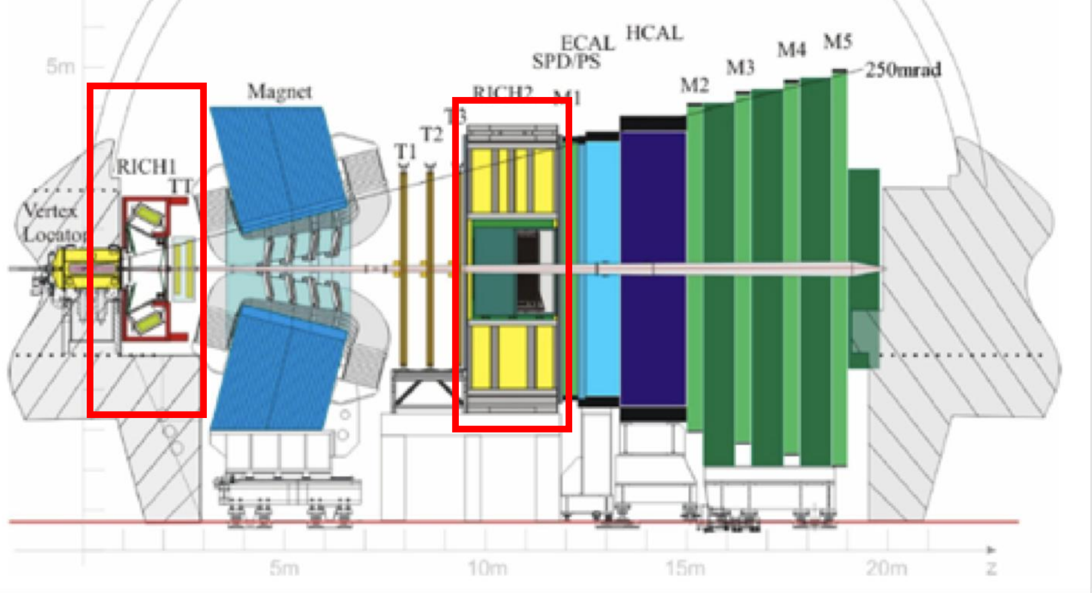
Needs to identify different hadrons

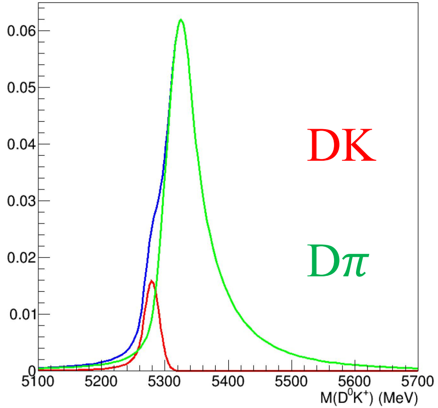
PID system in LHCb

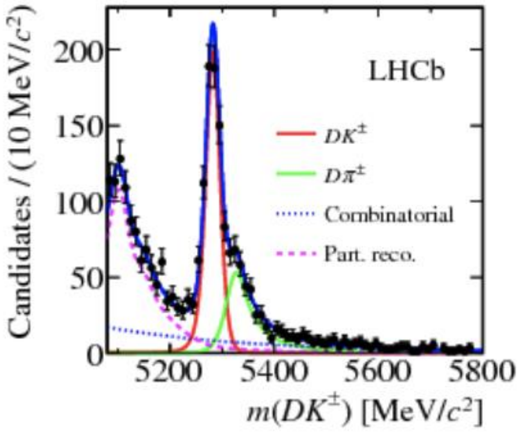


LHCb PID system

- Example: Sensitivities of CPV mainly come from $B^- \to DK$ decays ; Needs to remove large $B^- \to D\pi$ background
- Two RICH systems offer good PID performance around 10-100 GeV; (Muon system to distinguish muon from other particles)

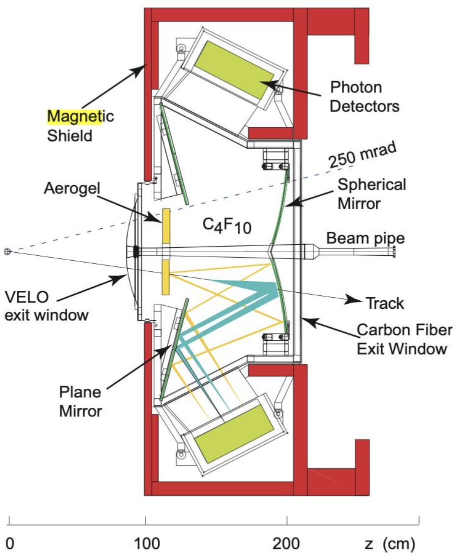


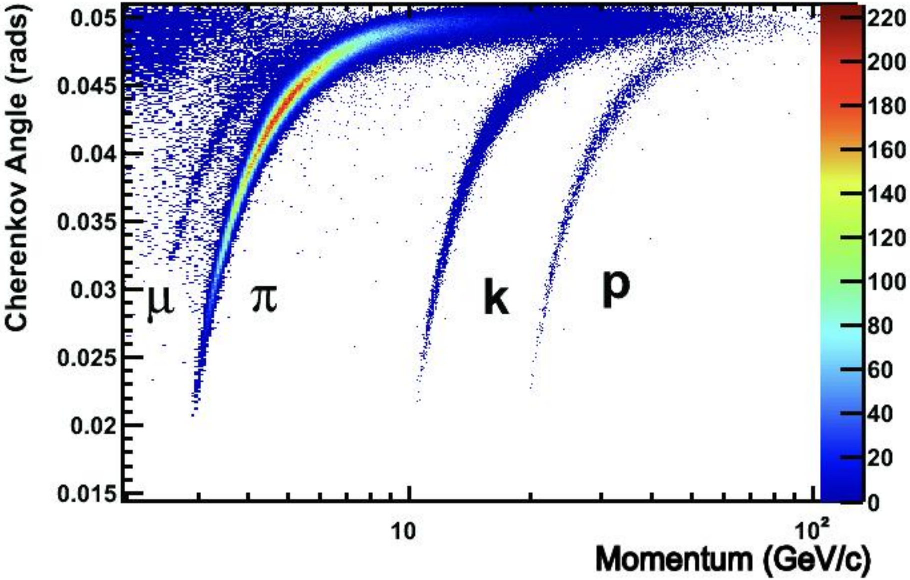




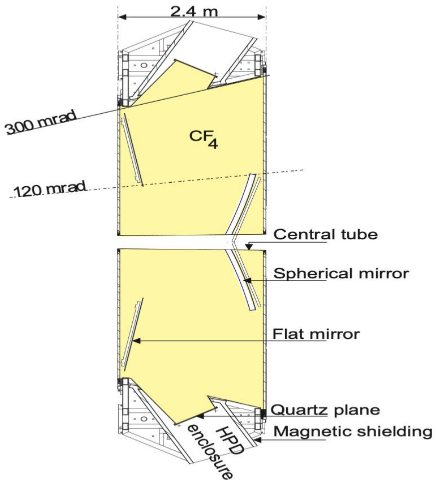
Cherenkov detector

RICH1





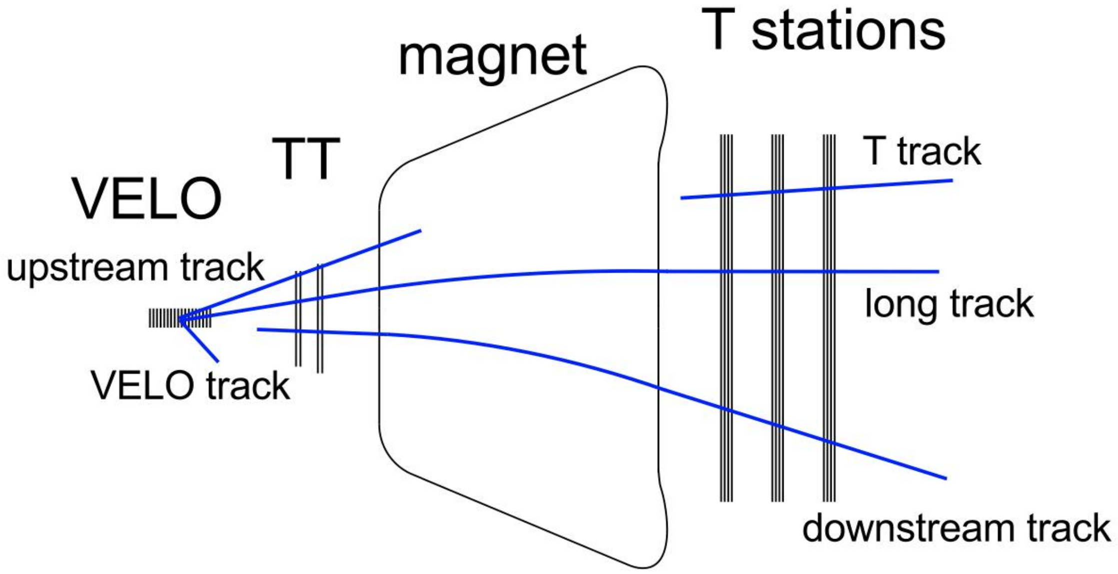
RICH2



- By knowing momentum and velocity, one can identify hadrons
- Velocity determined by $\cos\theta_c = \frac{1}{n\beta}$

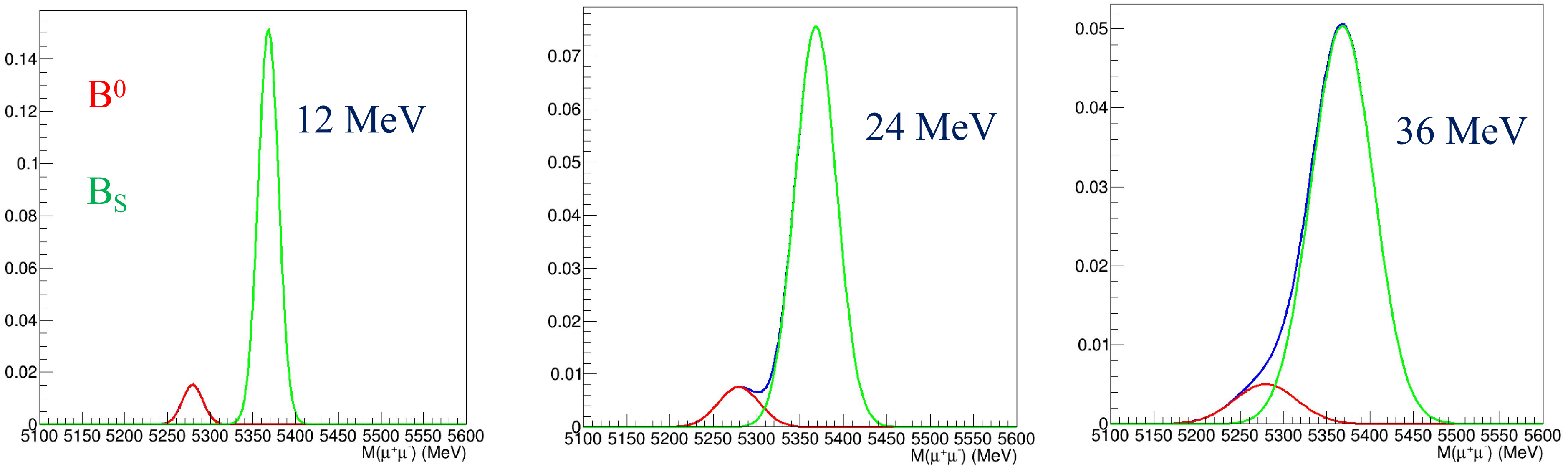
LHCb tracking system

- Tracking system consists of VELO, TT, T stations
- Offer momentum measurements together with magnet; ~0.5% momentum resolution
- Layout offers sensitivity to different track types: VELO tracks for vertex reconstruction; downstream tracks for long-lived particles (K_S etc.)

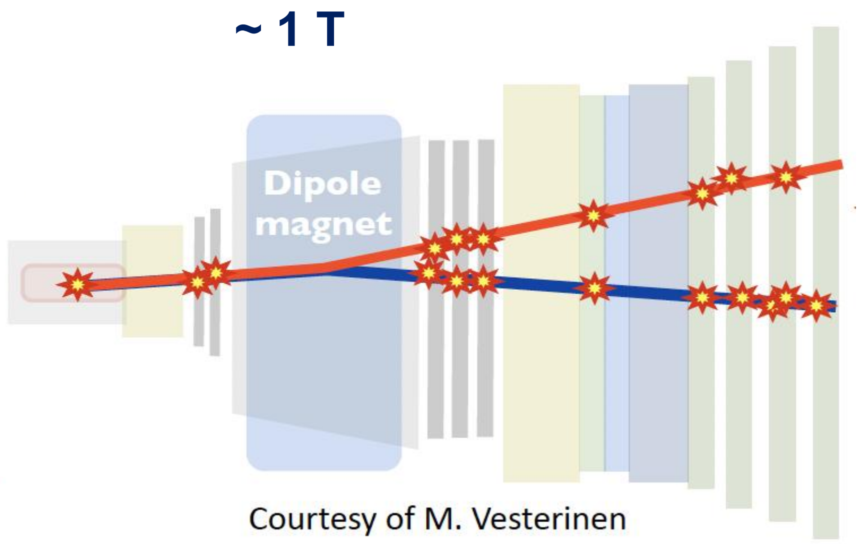


Why tracking is important

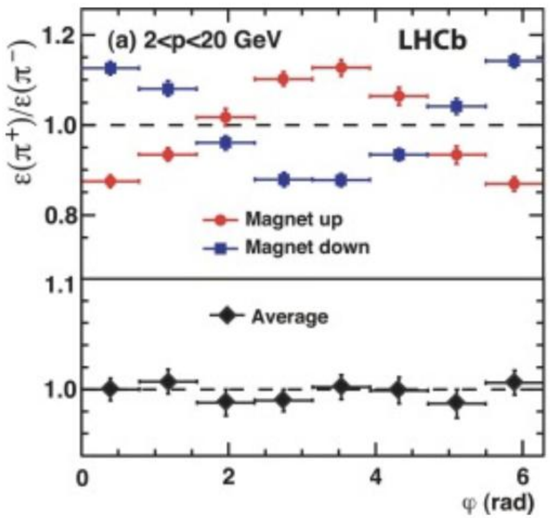
- **Good momentum resolution extremely important for distinguishing two resonances close to each other (famous pentaquarks)**
- **Also important to distinguish B^0 and B_S in hadron collider (LHCb vs CMS)**
- **Significance of rare decays also largely depending on mass resolution**



LHCb magnet

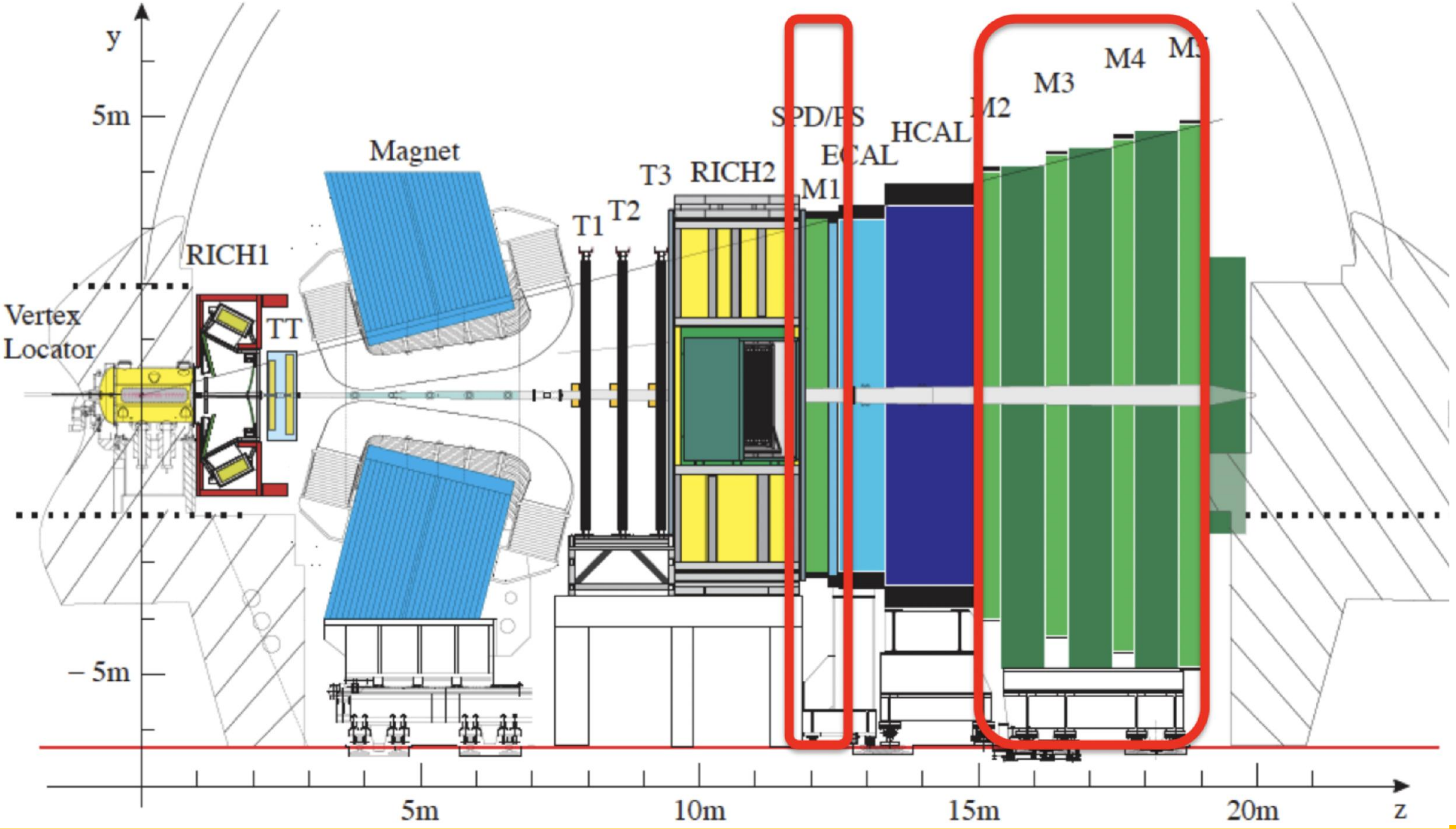


π asymmetries

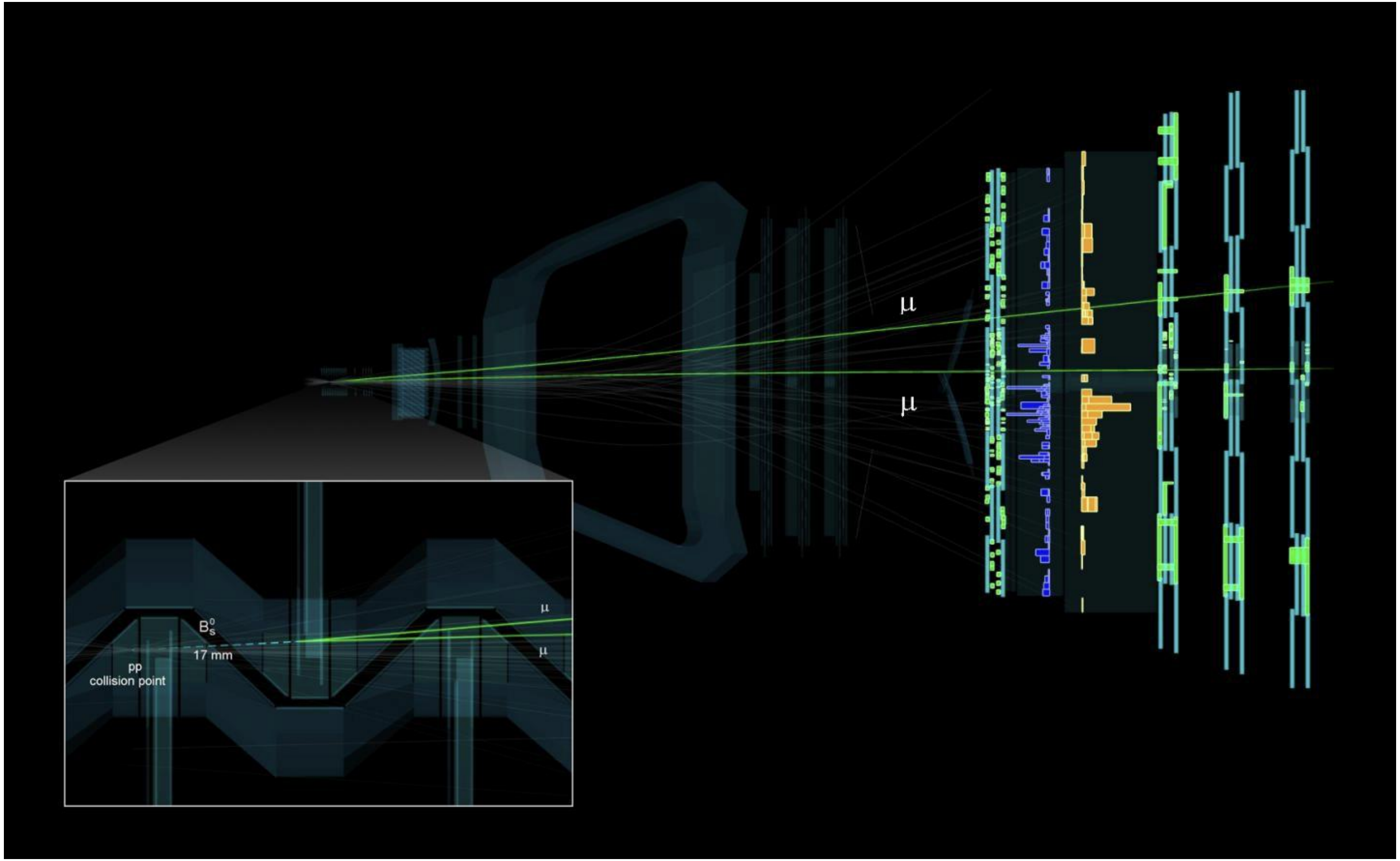


- LHCb magnet in y direction;
- Change magnet direction during operation (mag. down or mag. up)
- Detection asymmetry cancels largely in two scenarios

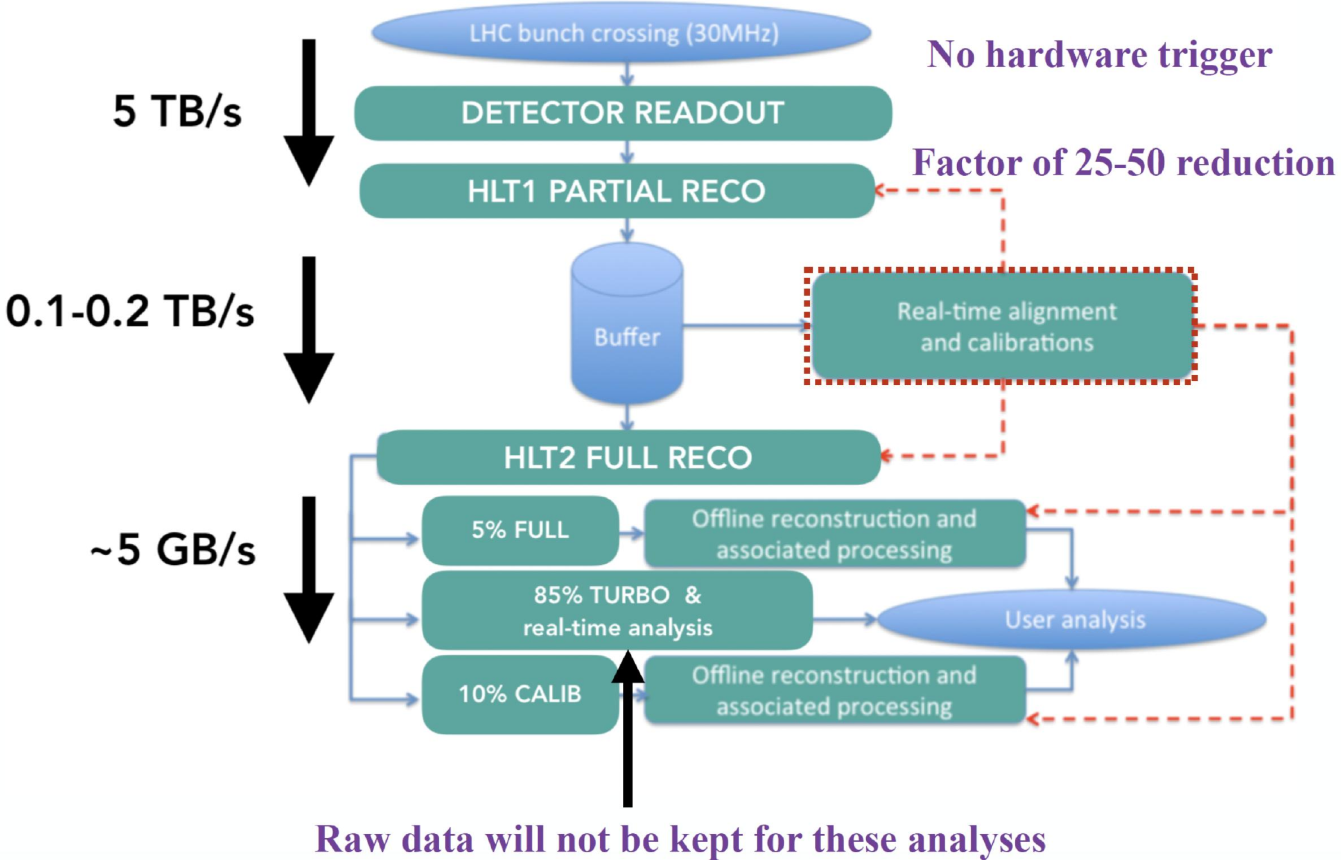
LHCb muon system



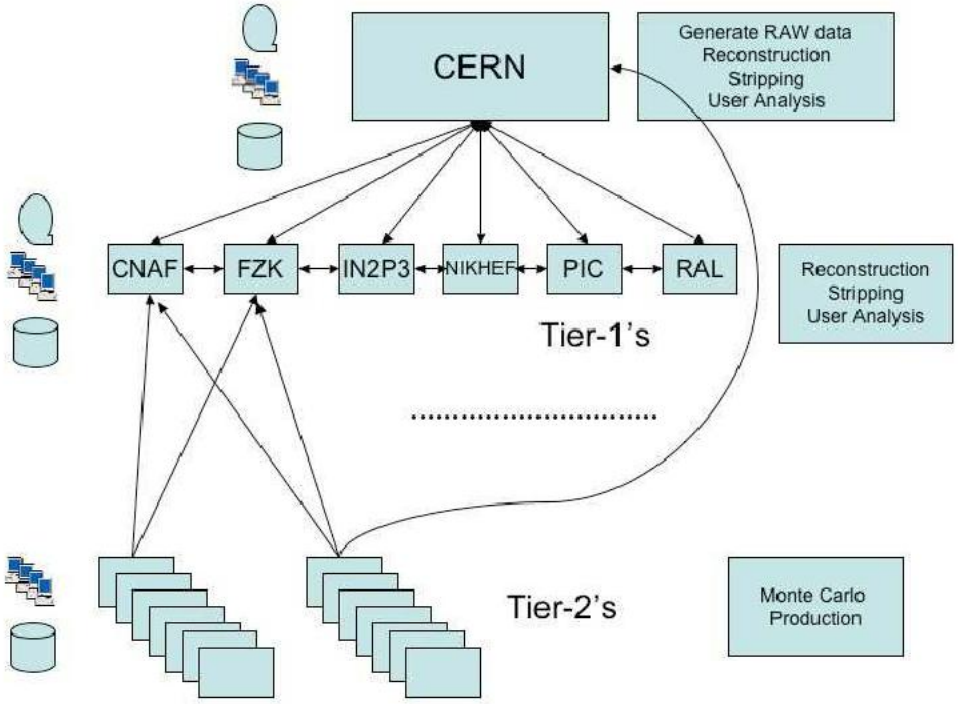
$B_s^0 \to \mu^+\mu^-$ in LHCb



How data is collected



Impression of LHCb

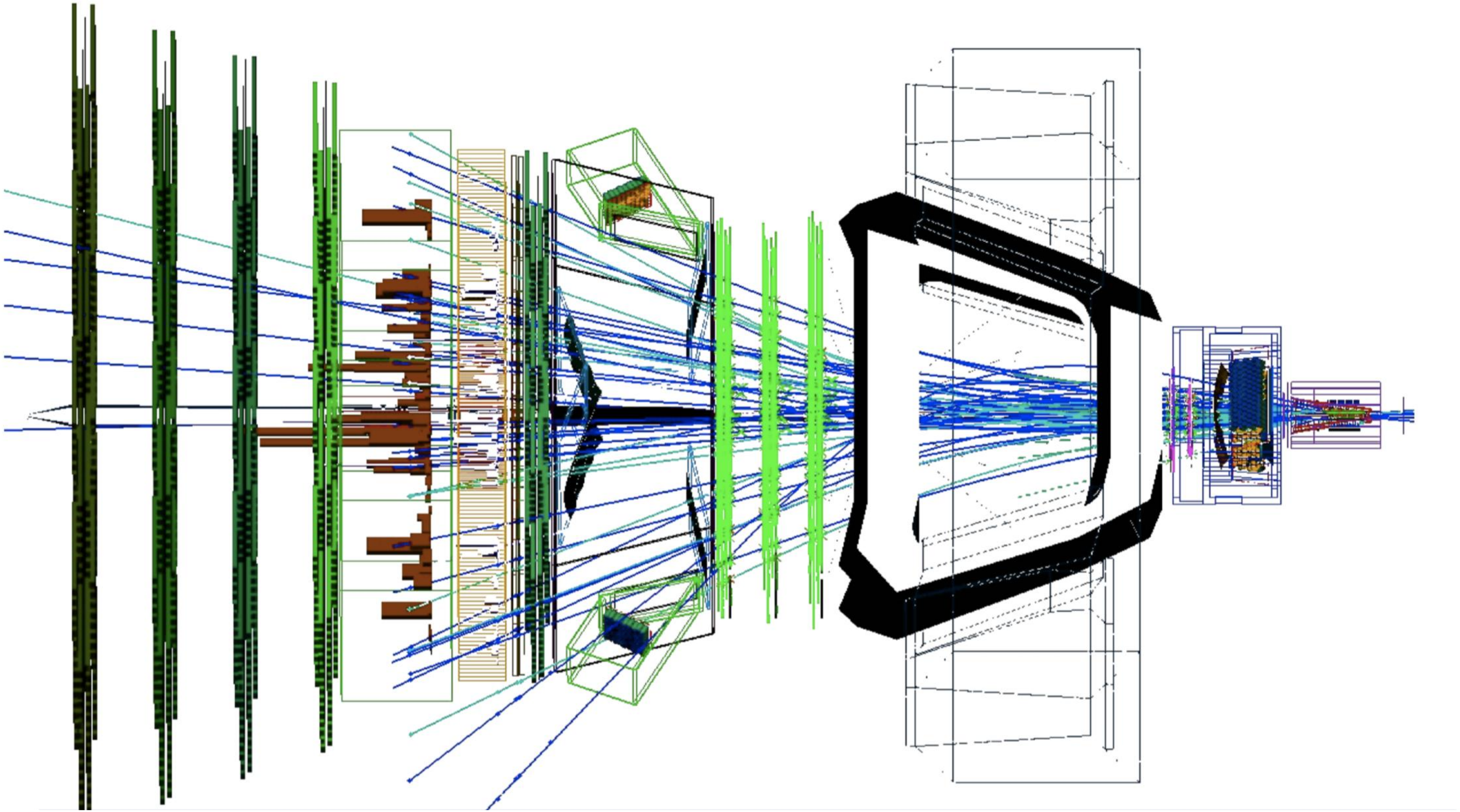


40 Tb/s of data to the detector
1% of global internet traffic

Distributed analysis framework: grid

Tier1: Beijing IHEP; Tier2: Lanzhou
All Chinese group contributes

A collision in the LHCb detector



LHCb Physics and LHCb China

主要研究内容

- 重味物理与CP破坏
- 稀有衰变与新物理
- 强子产生与谱学，QCD
- 电弱物理与Higgs物理
- 重离子物理，…

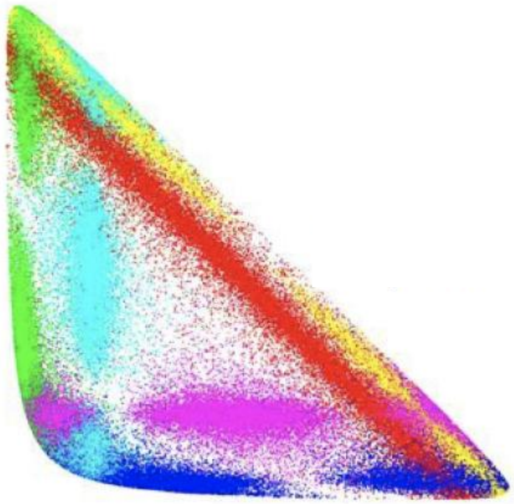
LHCb合作组：24个国家，100多家单位，近1800名成员

LHCb中国组：清华大学、华中师范大学、高能物理研究所、中国科学院大学、武汉大学、湖南大学、华南师范大学、北京大学、兰州大学、河南师范大学、中国科学技术大学、西北工业大学

Amplitude analysis

Dalitz plot

- Amplitude analysis widely used in flavor physics
- Simplest case: Dalitz plot, a spin 0 particle decays to three spin 0 particles



$D \rightarrow K_S\pi^+\pi^-$ as an example:

green & blue: $K^*(892)$ vector

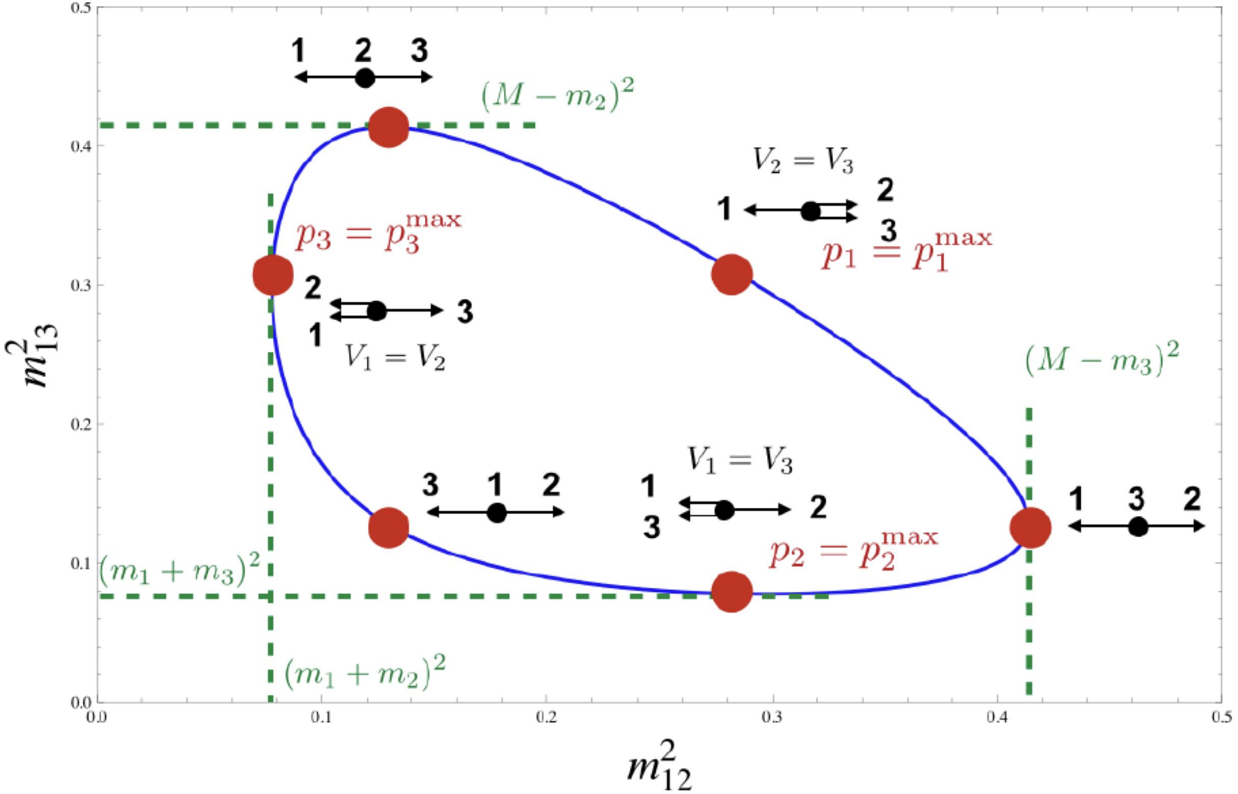
cyan & magenta: $K_2^*(1430)$ tensor

yellow: $\rho(770)$ vector

red: $f_0(980)$ scalar

- Resonances with different spins behave differently
- Separate them and extract information according to interference between them

Dalitz plot（1）



$$m_{13}^2 + m_{12}^2 + m_{23}^2 = M^2 + m_1^2 + m_2^2 + m_3^2$$

- **Named after R. Dalitz**
- **Kinematic and freedom**

Constraints	Degree of freedom
3 four-vectors	12
4-momentum conservation	-4
3 masses	-3
3 Euler angles	-3
TOT	2

Decay rate

- **Decay rate of a particle M into n body final state**

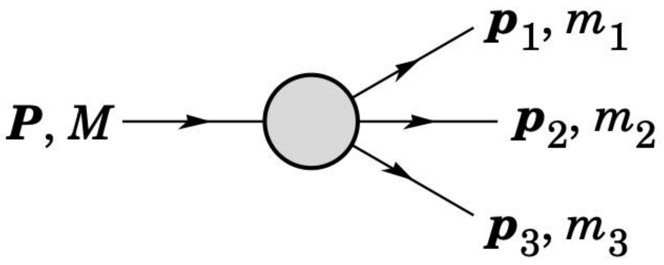
$$d\Gamma = \frac{(2\pi)^4}{2M} |\mathscr{M}|^2 \, d\Phi_n\,(P;\, p_1, \ldots, p_n),$$

$$d\Phi_n(P;\, p_1, \ldots, p_n) = \delta^4\left(P - \sum_{i=1}^{n} p_i\right) \prod_{i=1}^{n} \frac{d^3 p_i}{(2\pi)^3 2E_i}$$

- **Two-body decay** $d\Gamma = \frac{1}{32\pi^2} |\mathscr{M}|^2 \frac{|\boldsymbol{p}_1|}{M^2} \, d\Omega\ ,$

- **Three-body decay**

$$d\Gamma = \frac{1}{(2\pi)^5} \frac{1}{16M} |\mathscr{M}|^2 \, dE_1 \, dE_3 \, d\alpha \, d(\cos\beta) \, d\gamma$$



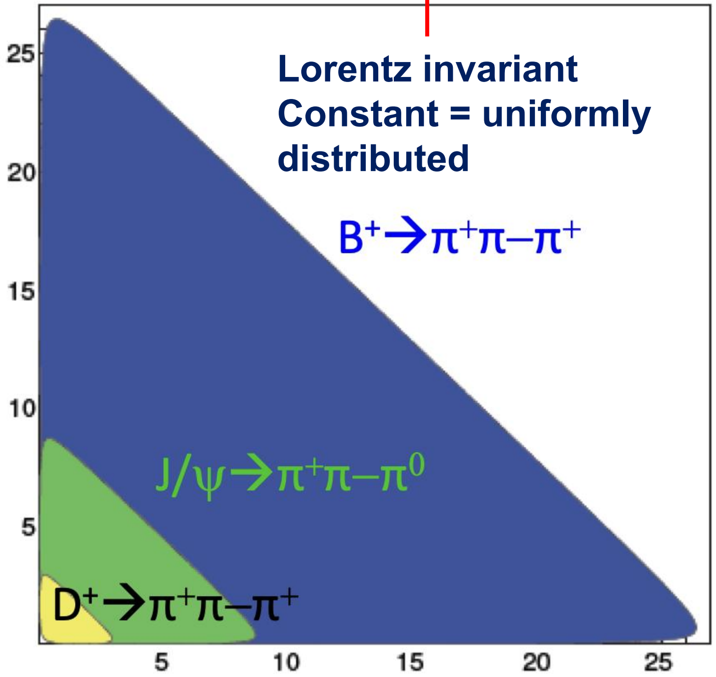
Integrated over angle freedom

$$d\Gamma = \frac{1}{(2\pi)^3} \frac{1}{32M^3} \overline{|\mathscr{M}|^2} \, dm_{12}^2 \, dm_{23}^2$$

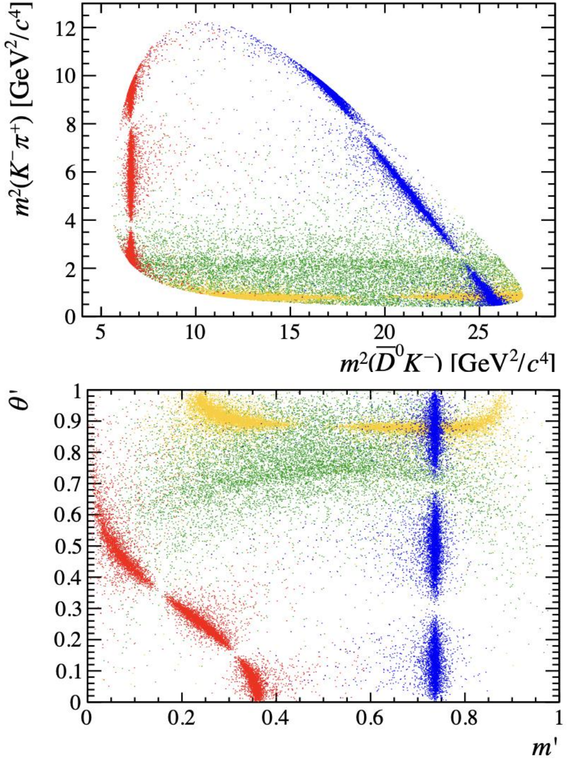
Phase space and square Dalitz

$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}\overline{|\mathscr{M}|^2}\,dm_{12}^2\,dm_{23}^2$$

Lorentz invariant
Constant = uniformly distributed

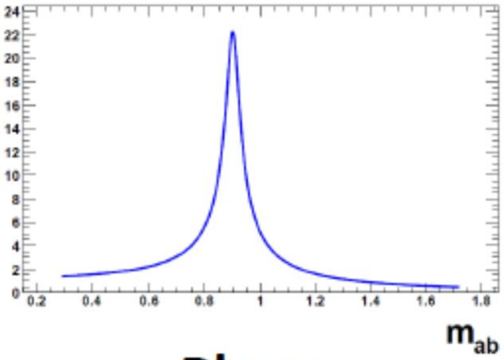


$$m' \equiv \frac{1}{\pi}\cos^{-1}\left(2\frac{m_{12}-m_{12}^{\min}}{m_{12}^{\max}-m_{12}^{\min}}-1\right) \quad \text{and} \quad \theta' \equiv \frac{1}{\pi}\theta_{12},$$

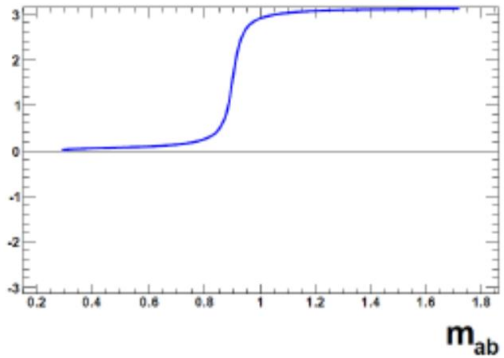


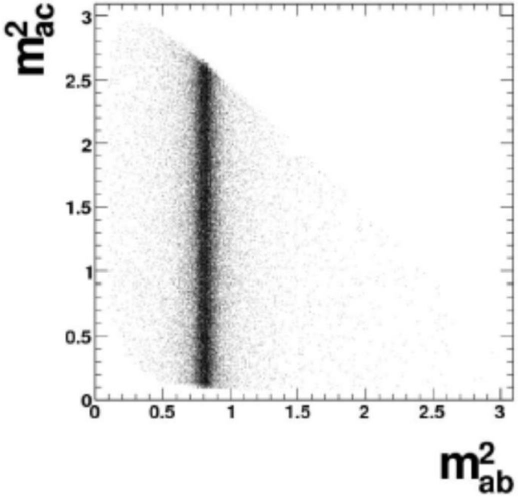
Resonance

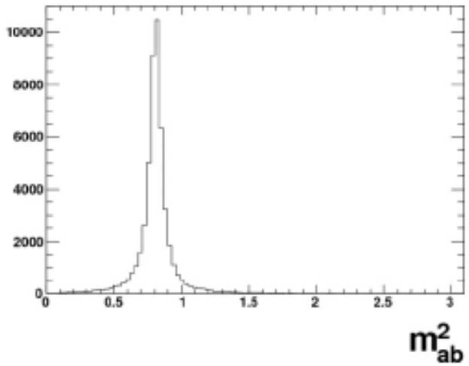
Magnitude



Phase

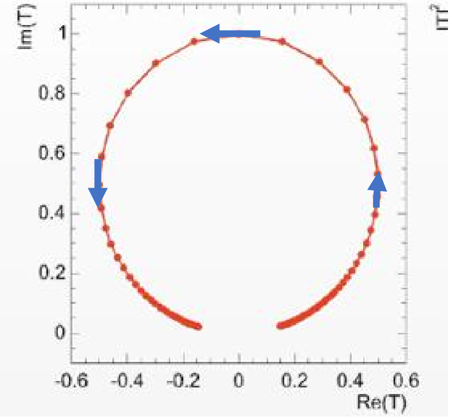




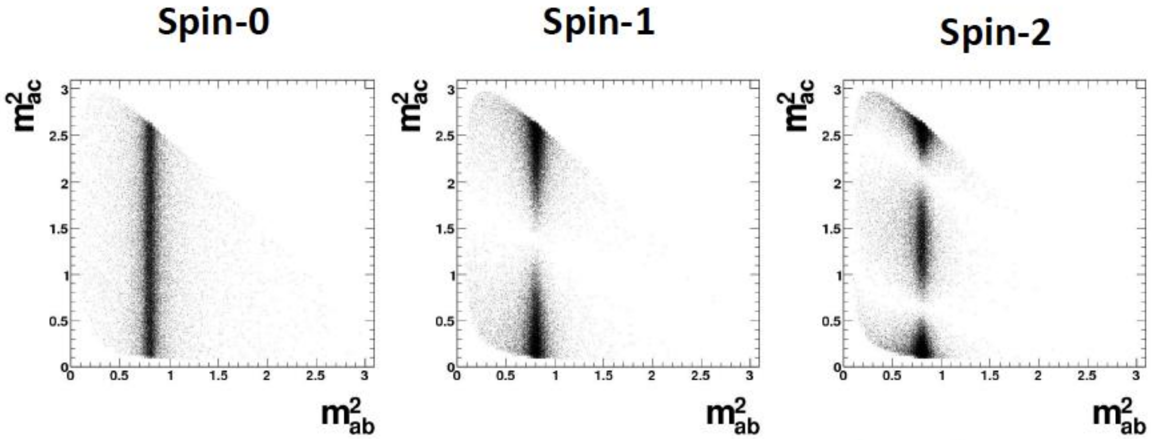


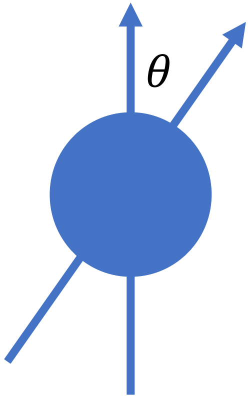
$$\frac{1}{(m_0^2 - m^2) - i\, m_0 \Gamma(m)}\,,$$

$$\Gamma(m) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2L+1} \left(\frac{m_0}{m}\right) X^2(q\, r_{\rm BW}^R)\,,$$

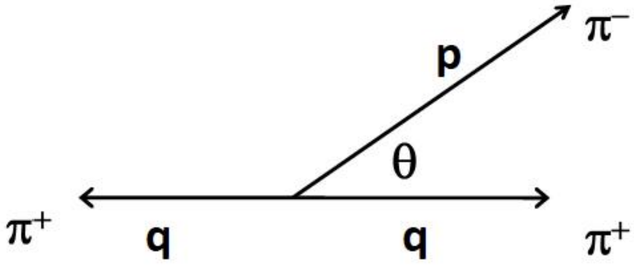


Angular distribution



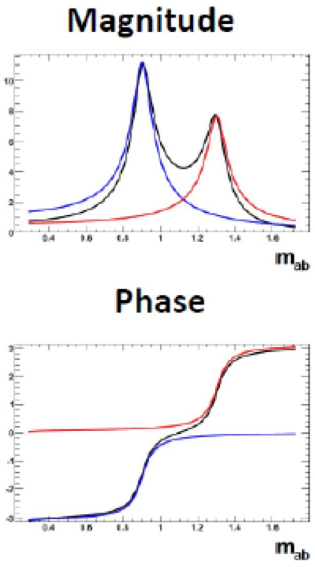


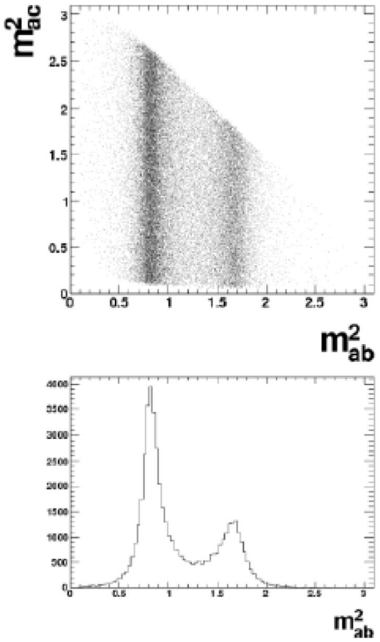
$P_0(\cos\theta) = 1$ $\quad$ $P_1(\cos\theta) = \cos\theta$ $\quad$ $P_2(\cos\theta) = \frac{1}{2}(3\cos^2\theta - 1)$



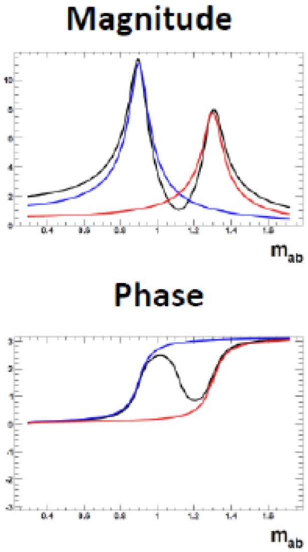
Interference

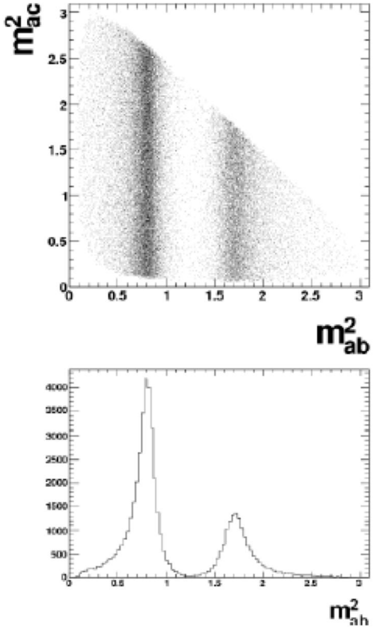
Constructive





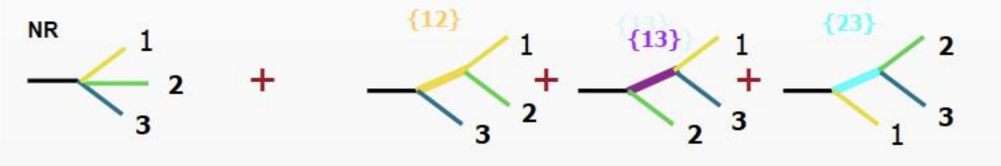
Destructive





Modeling

- **Isobar model: coherent sum of quasi-two-body contributions**



$$A(s_{12}, s_{23}) = \sum_j A_j = \sum_j a_j F_j(s_{12}, s_{23}), \qquad \bar{A}(s_{12}, s_{23}) = \sum_j \bar{A}_j = \sum_j \bar{a}_j \bar{F}_j(s12, s23)$$

Contain both strong and weak contributions

weak phase δ → (CP) -δ, strong phase: θ → (CP) θ ➡ CPV if δ are different for different resonances

Strong dynamics: resonant line-shape, angular distributions
Invariant under CP transform

TF-PWA

- **Amplitude analyses very complicated: main limitations to start an analysis**
- **Enormous data from BESIII, LHCb and other flavor physics experiments: massive CPU time needed to perform analyses**
- **A general PWA framework using modern acceleration technology (such as GPU, AD,…) eagerly needed**

A general and user-friendly partial wave analysis framework

Hao Cai[1], Chen Chen[5], Shuangshi Fang[4], Haojie Jing[2], Yi Jiang[2], Pei-Rong Li[3], Beijiang Liu[4], Yin-Rui Liu[2], Xiao-Rui Lyu[2], Runqiu Ma[4], Rong-Gang Ping[4], Wenbin Qian[2], Rongsheng Shi[3], Mengzhen Wang[5], Shi Wang[4], Zi-Yi Wang[2], Jiajun Wu[2], Shuming Wu[2], Liming Zhang[5],Yang-Heng Zheng[2]

[1]WHU, [2]UCAS, [3]LZU, [4]IHEP, [5]THU

Features

- Fast
  - GPU based
  - Vectorized calculation
  - Automatic differentiation
- General
  - Custom model available
- Easy to use
  - Simple configuration file
  - Automatics process
  - All necessary functions implemented

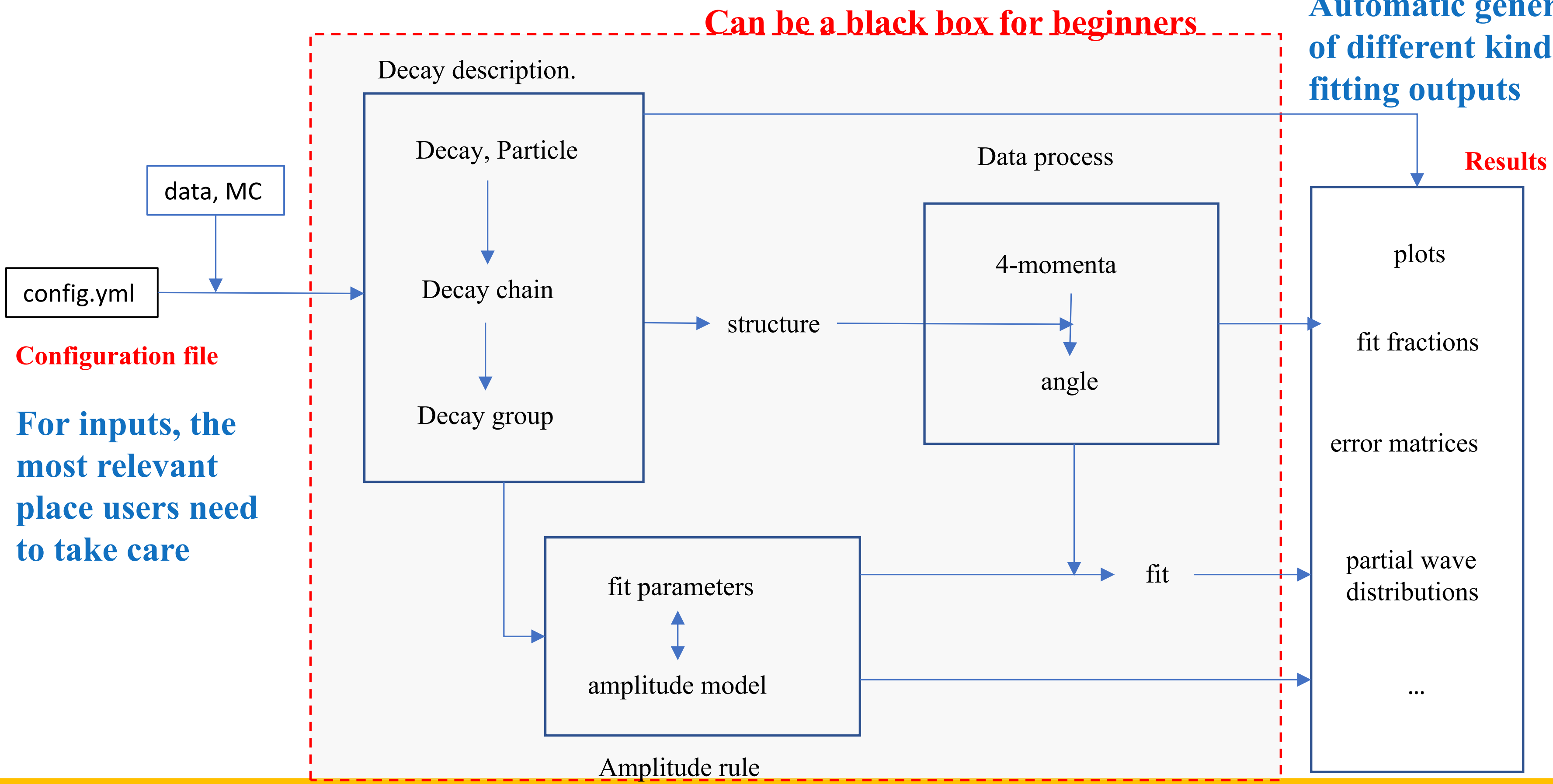
TensorFlow

https://gitlab.com/jiangyi15/tf-pwa

Open access and well supported

Framework

Automatic generations of different kinds of fitting outputs



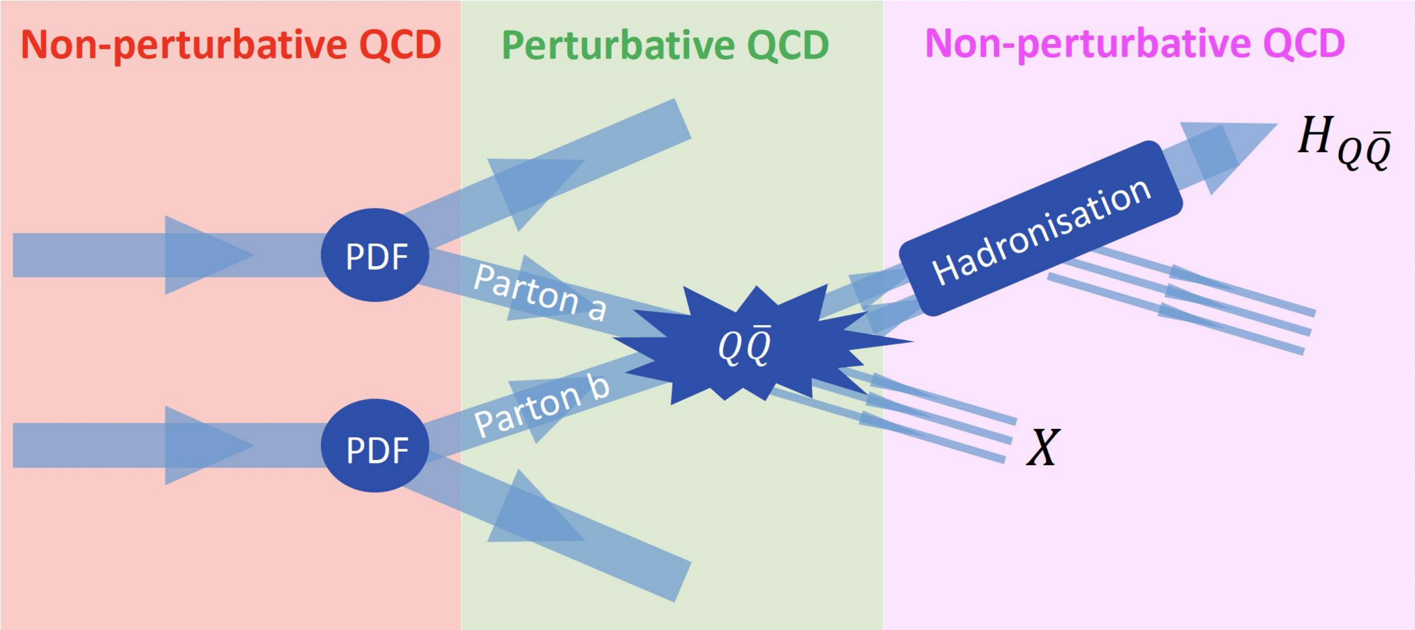
For inputs, the most relevant place users need to take care

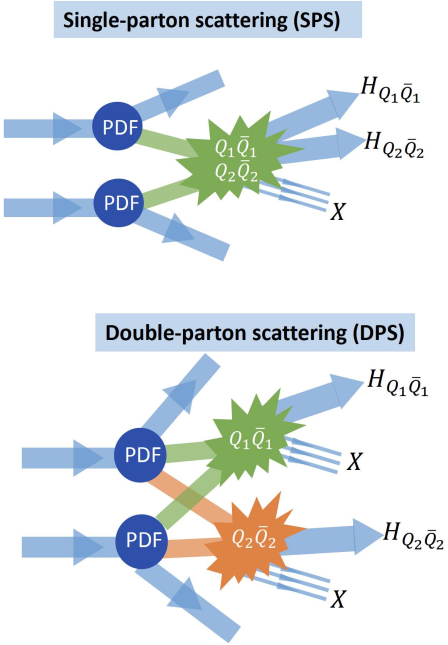
Key functions

- All functions needed for amplitude analysis:
  - Toy studies
  - Plotting
  - Fit fractions, interference fractions
  - Simultaneous fit between different datasets
  - Parity conversation
  - Gaussian constraints on parameters
  - 2D chi2 test
  - CP violation fit
  - Final states with identical particles
  - Amplitude factorization
  - Resolution
  - Simple symbolic formula
  - Model independent fit
  - Error propagation
- Different ways of modeling: helicity formalism, covariant tensor, irreducible tensor formalism
- Capability to form time-dependent Dalitz analysis
- Used by more than 100 analyses in LHCb and BESIII collaborations

Spectroscopy studies

Quarkonium production

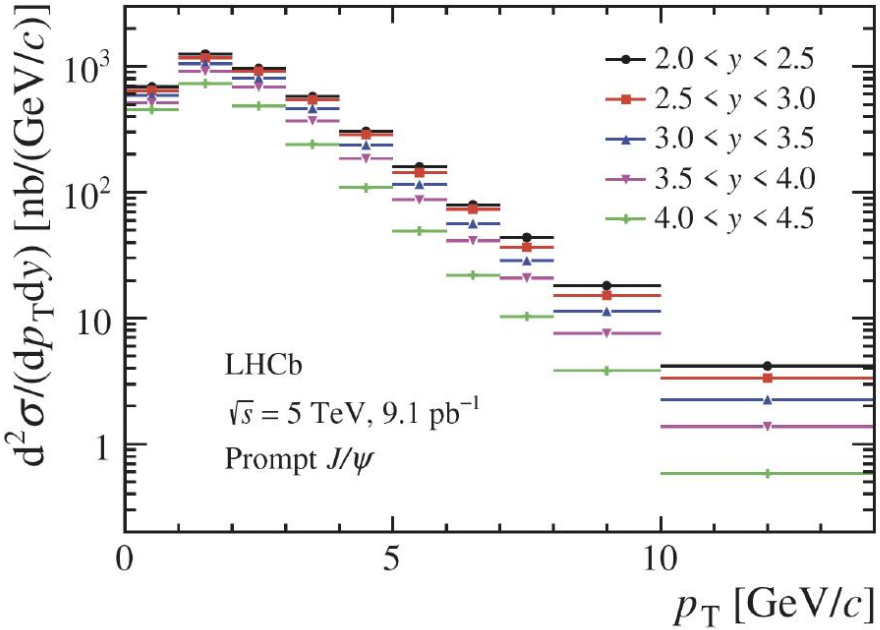


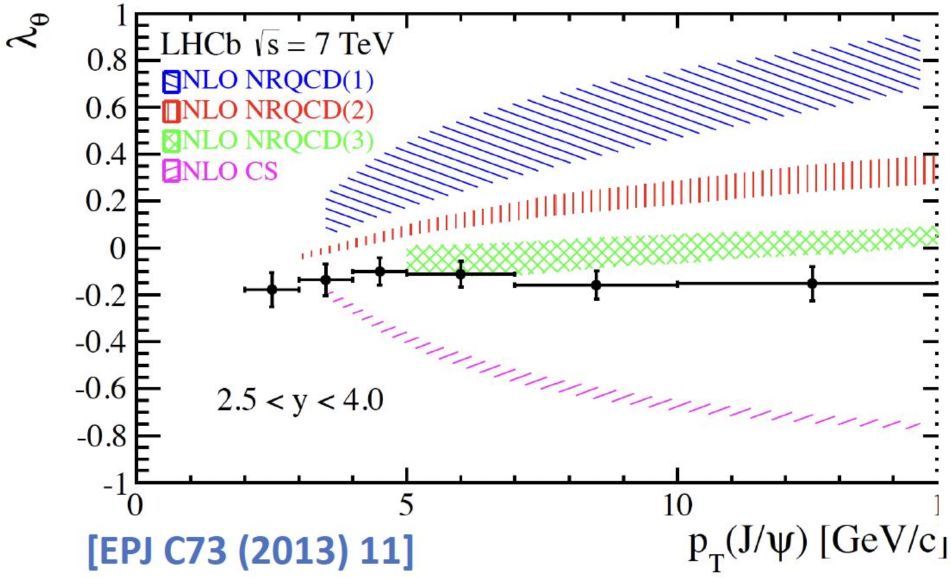


$$\sigma(H_{Q\bar{Q}}) = \sum_{a,b,n} \int \mathrm{d}x_1 \mathrm{d}x_2 f_{a/p}(x_1) f_{b/p}(x_2) |\mathcal{A}(ab \to Q\bar{Q}[n] + X)|^2 \times \langle \mathcal{O}^H(n) \rangle$$

LDMEs: extracted from measurements
& process independent

Cross section and polarization

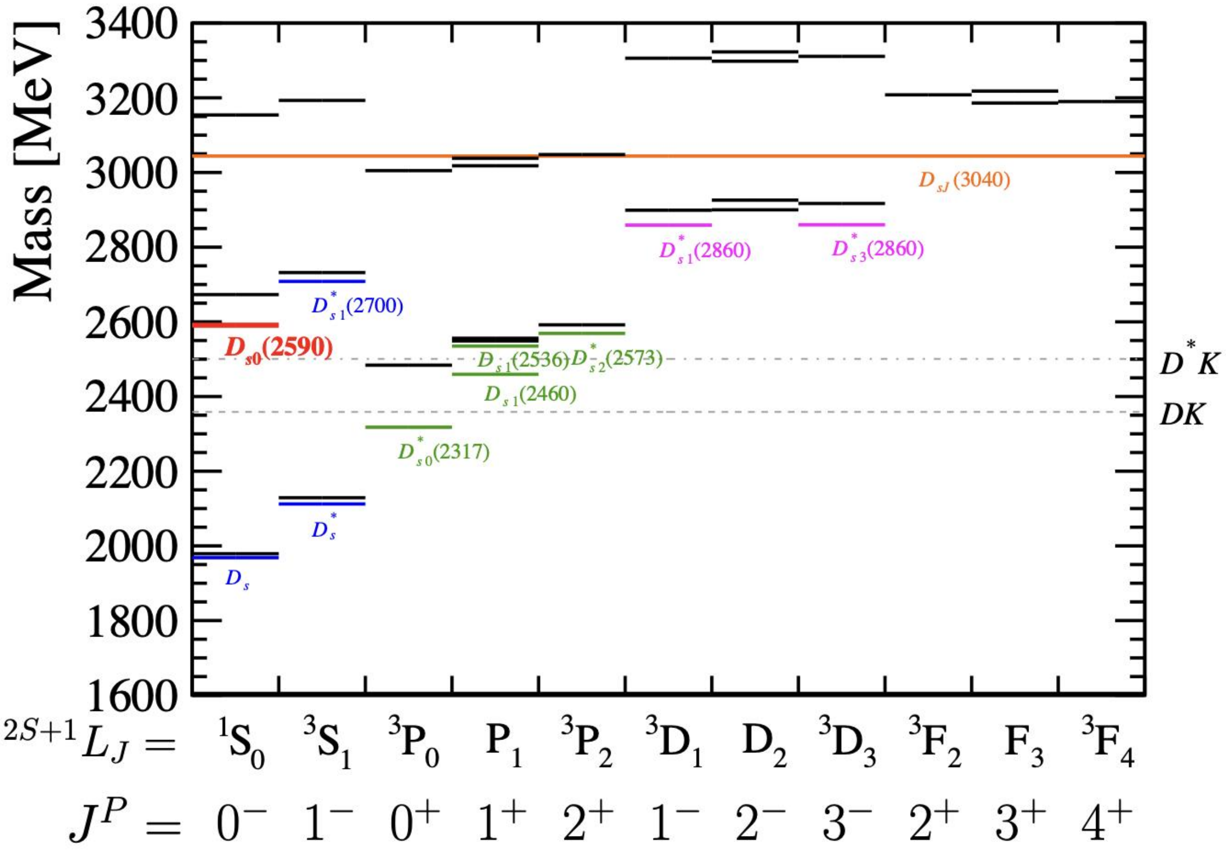




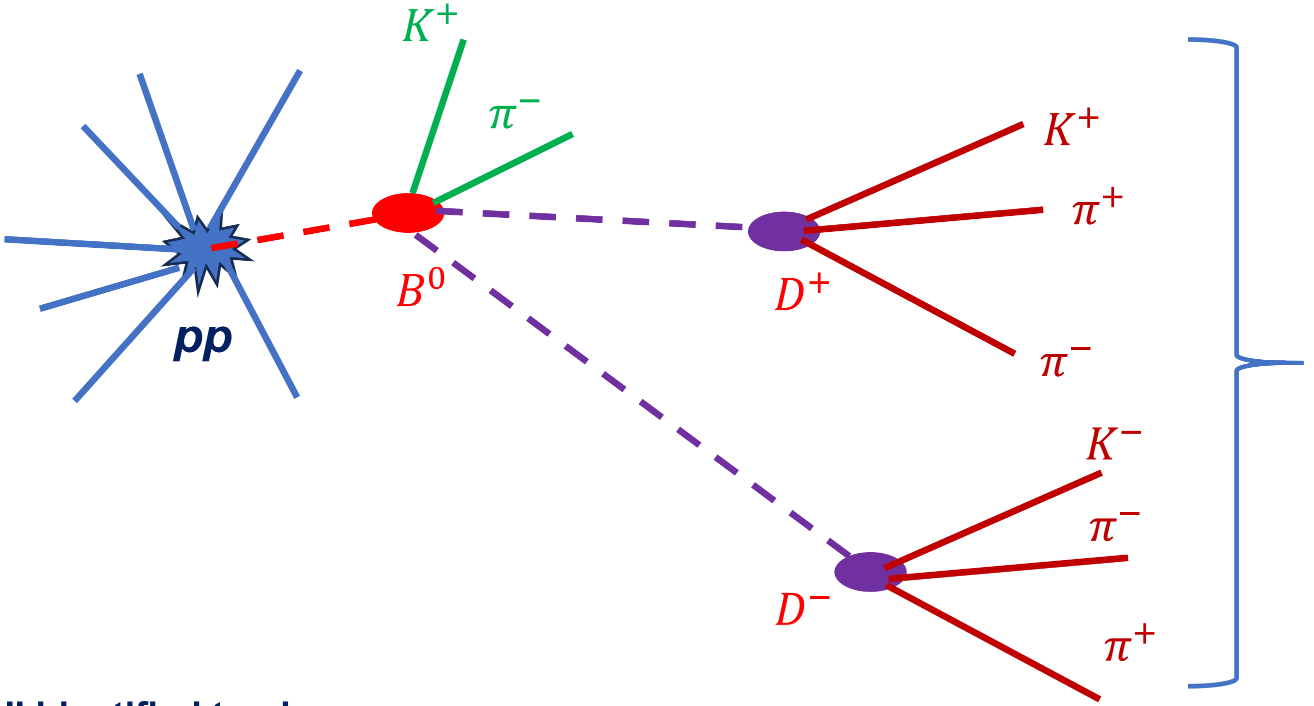
[EPJ C73 (2013) 11]

- **Many models to explain measured cross section and polarization from different experiments**
- **However, not yet one which can explain all the results**
- **Crucial point: matrix elements extraction**

Excited D_s spectrum



How to reconstruct a *b* candidate



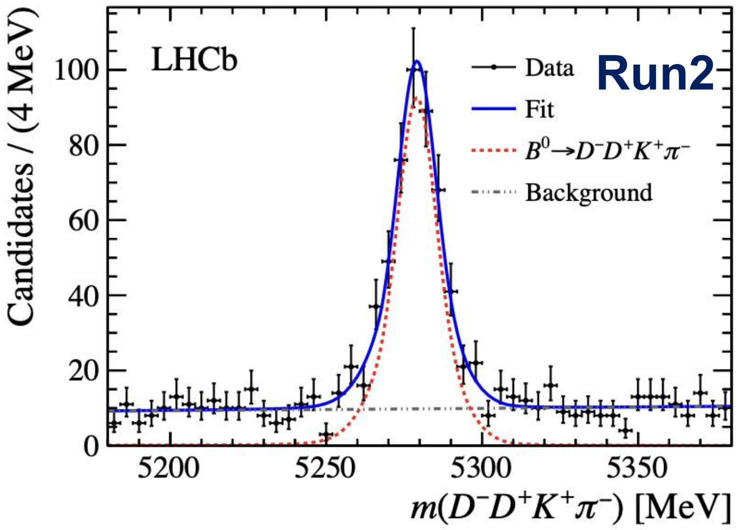
$B^0 \to D^+ D^- K^+ \pi^-$

Tracks and its properties are reconstructed from hits in detector

- **Well identified tracks**
- **Relatively large p_T**
- **Large impact parameter**
- **Good vertex**

Discovery of $D_{s0}(2590)$

$B^0 \to D^+ D^- K^+ \pi^-$

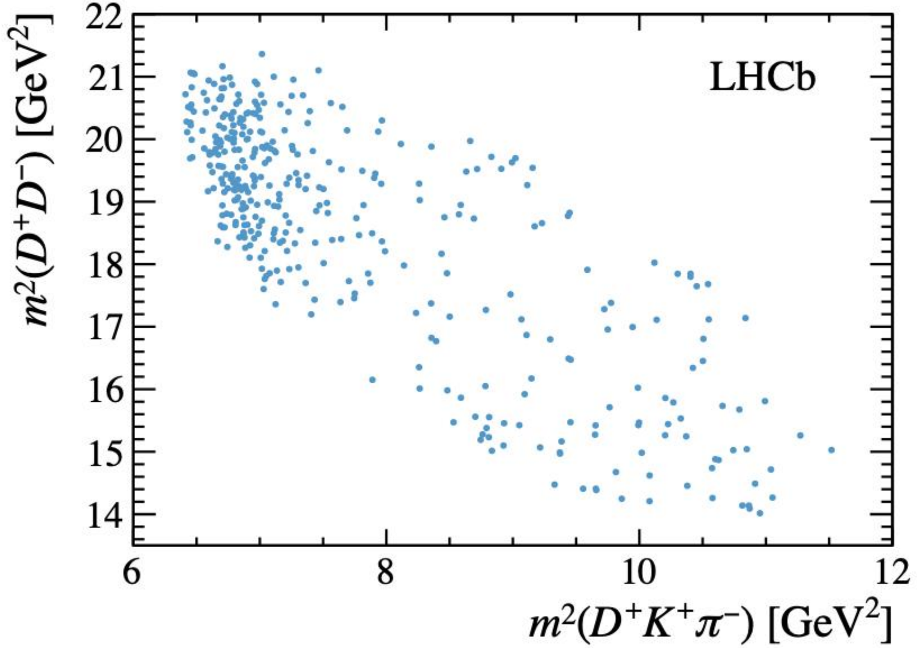


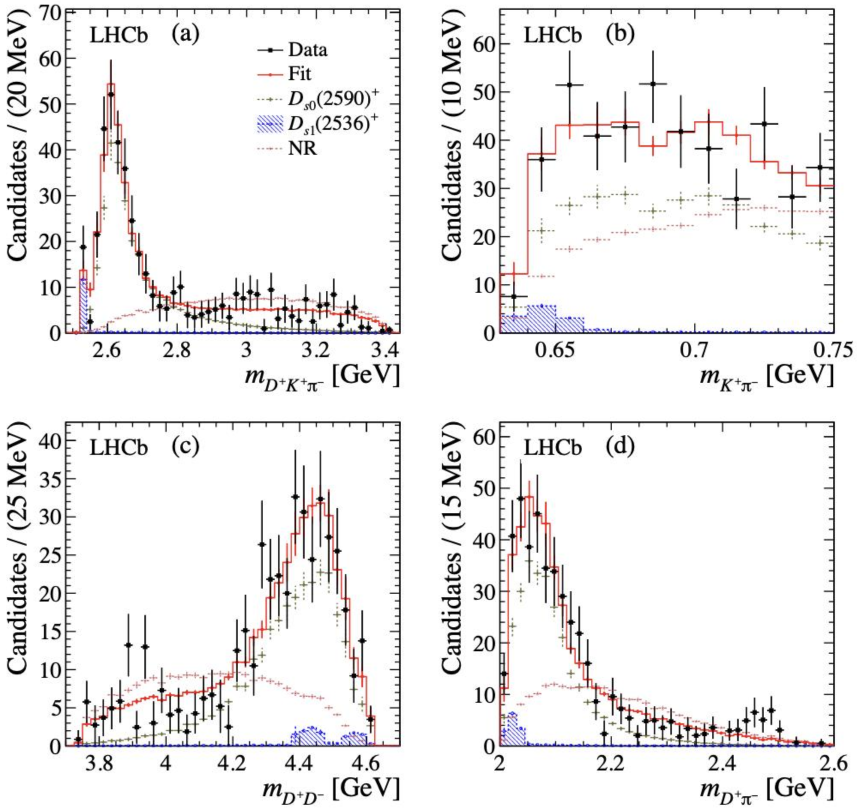
- **Signal modeling: resolution smearing + FSR**
- **Background: random combination of tracks**
- **Mis-identified background (not in this plot)**
- **Partially reconstructed background (not in this plot)**
- **Non doubly charmed background (not shown in this plot)**

- **Kinematic fit to improve resolution**
- **Unbinned maximum likelihood to extract out signal yields (444 ± 27)**

Discovery of $D_{s0}(2590)$

$B^0 \to D^+ D^- K^+ \pi^-$





$0^- \to 0^- + 0^+$

$1^+ \to 0^- + 0^+$

Significance test and look-elsewhere effect

- **Wilks' Theorem, a statistical model parameterized by $\boldsymbol{\theta} \in \boldsymbol{\Theta}$**
  - **Null hypothesis H_0, no signal, restricted $\boldsymbol{\theta}$ to a subset $\boldsymbol{\Theta}_0 \in \boldsymbol{\Theta}$**
  - **Alternative hypothesis H_1, having considered resonance**
- **Test statistic based on likelihood ratio,**

$$\boldsymbol{\Delta = 2\log(LL(H_1)/LL(H_0))}$$

- **Δ follows a χ^2 distribution with ndof = dim($\boldsymbol{\Theta}$) − dim($\boldsymbol{\Theta}_0$)**

Example:

$$H_1: \quad |M|^2 = \left|\sum_i r_i e^{i\phi_i} F_i + r_0 e^{i\phi_0} F_0\right|^2$$

$$H_0: \quad |M|^2 = \left|\sum_i r_i e^{i\phi_i} F_i\right|^2$$

Significance test and look elsewhere effect

- **Regularity conditions**
  - θ_0 **lies in the interior of** Θ
  - **Likelihood function sufficiently smooth (twice differentiable)**
  - **Parameters are identifiable: different parameter values lead to different probability distributions**

Example:

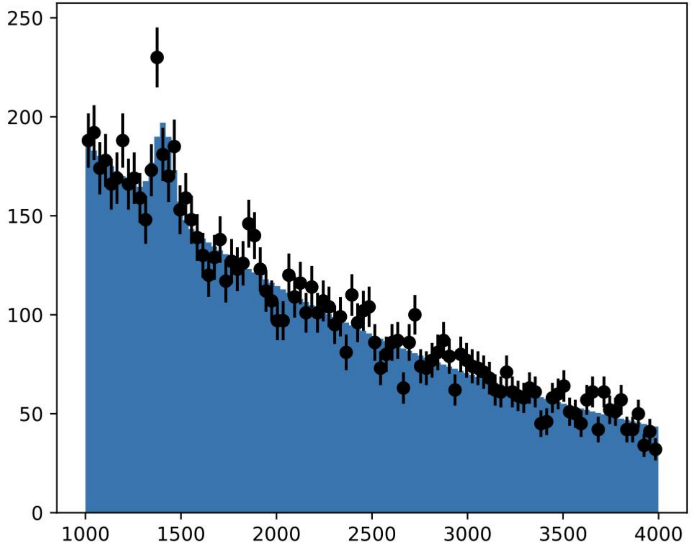
$$H_1: \quad |M|^2 = \left|\sum_i r_i e^{i\phi_i} F_i + r_0 e^{i\phi_0} F_0\right|^2$$

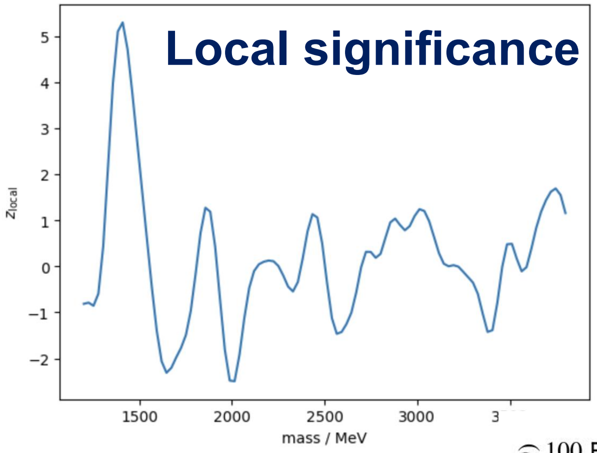
$$H_0: \quad |M|^2 = \left|\sum_i r_i e^{i\phi_i} F_i\right|^2$$

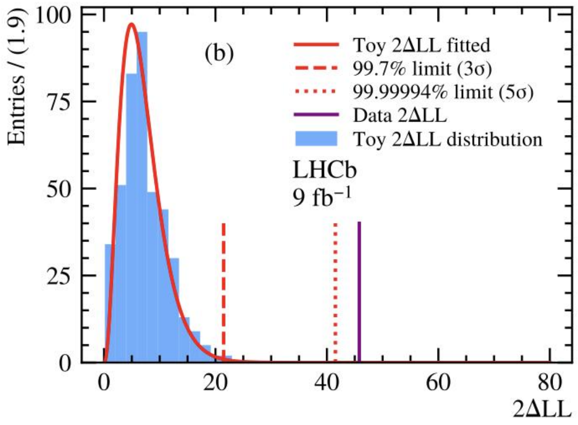
What if F_0 contains fit parameters?

- **When $r_0 = 0$, it violates condition 1 and 3, however, if changing $r_0 e^{i\phi_0} \to x_0 + i y_0$, the two conditions restored**

Example

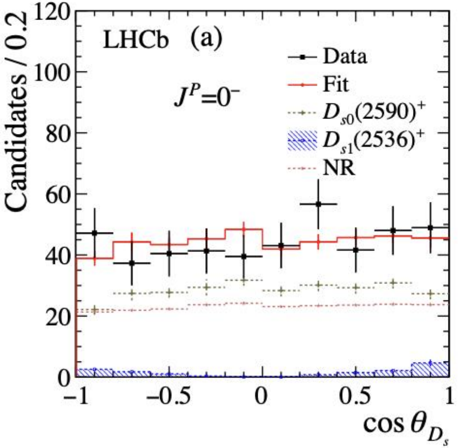




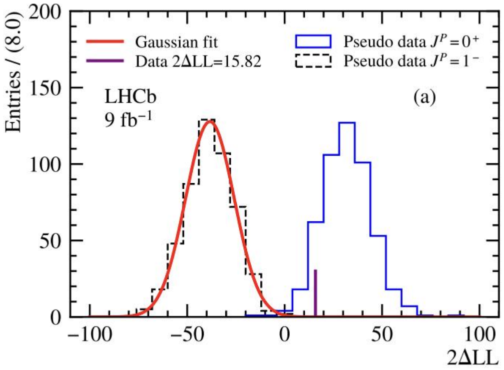


- **Case 1: to search for a resonance at 1400 with width 10**
- **Case 2: to search for a resonance in the range between 1000-4000**

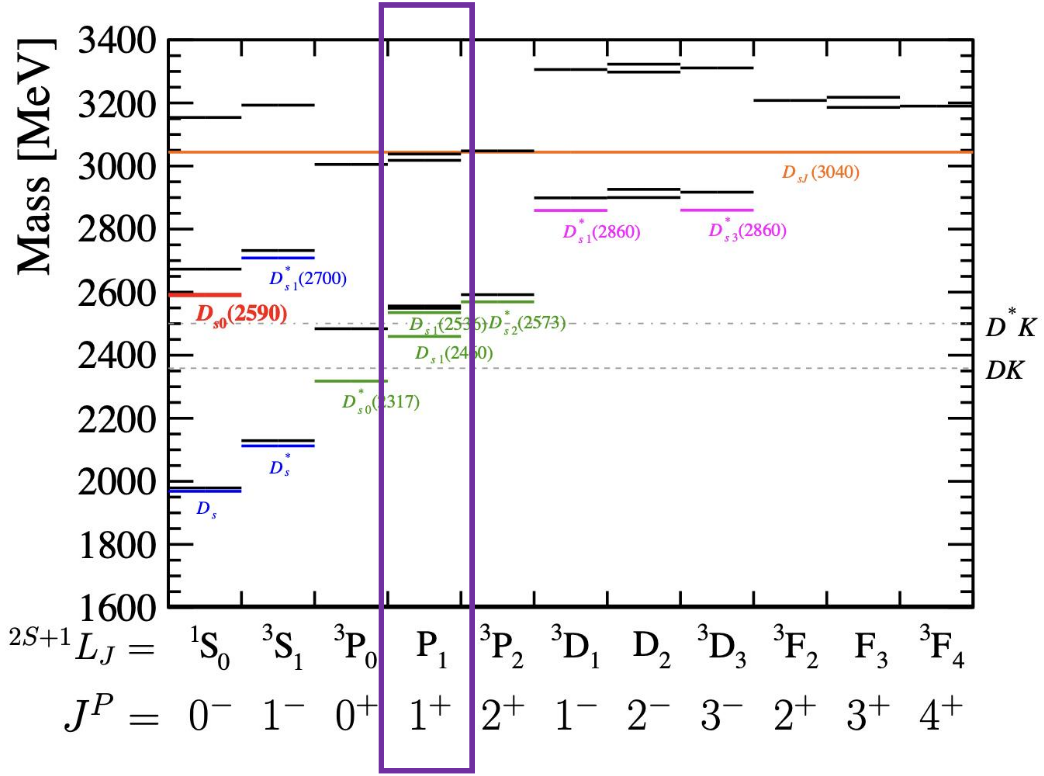
Spin parity determination



- **Different spin gives different angular distributions over helicity angle**
- **Hypothesis test (based on toys)**
  - **Toy 1: generated with spin A and ΔLL = LL(spin A) − LL(spin B)**
  - **Toy 2: generated with spin B and ΔLL = LL(spin A) − LL(spin B)**

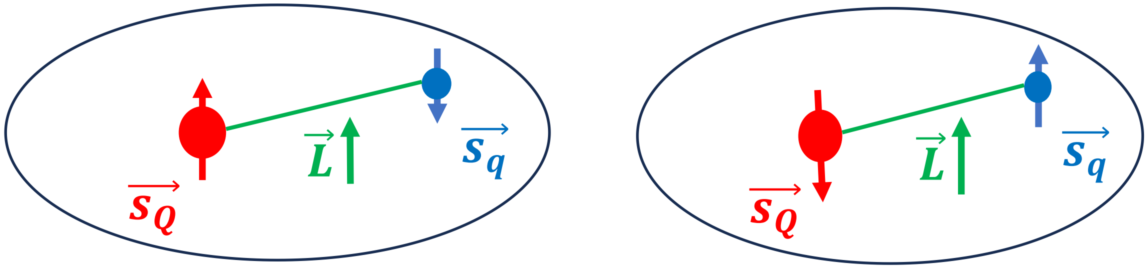


$D_s(2536)^+$ and $D_s(2460)^+$



- $J^P = 1^+$
- L = 1, S=0 or 1
- Mass of $D_s(2536)^+$ very close to predicted value
- Mass of $D_s(2460)^+$ significantly lower than predicted value (nature not clear)
- Same J^P allows mixing between two

$D_s(2536)^+$ and $D_s(2460)^+$



$D_{s1}^+ \to D^{*0}K^+$:

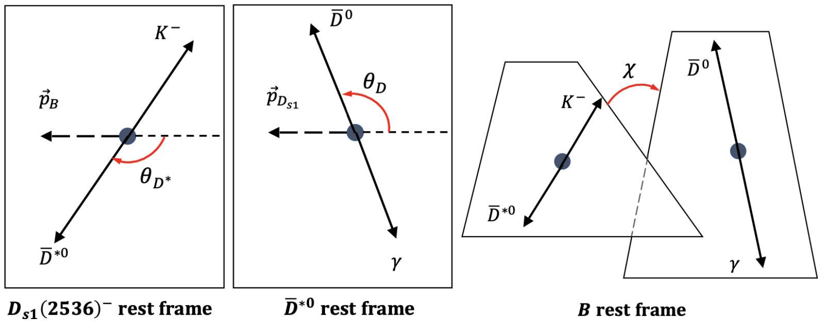
$|^{1/2}E_1>$: **S wave**

$|^{3/2}E_1>$: **D wave**

P-wave forbidden by parity

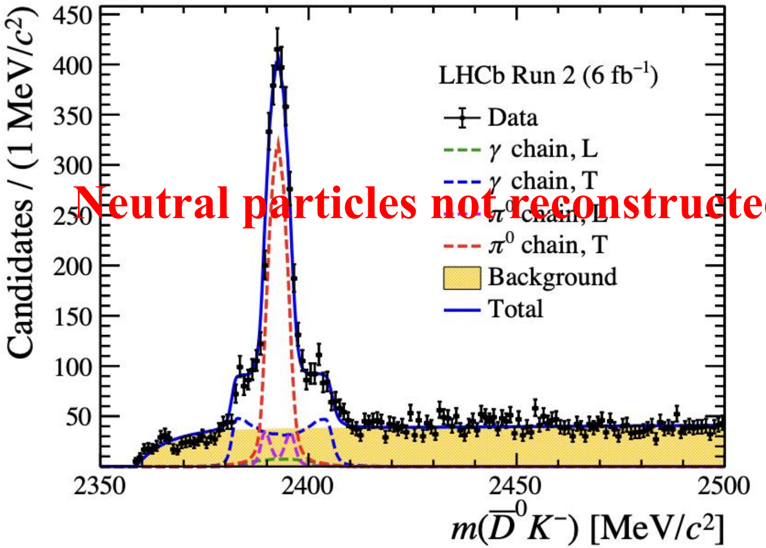
$$|D_{s1}(2460)^+\rangle = \cos\theta\,|^{1/2}E_1\rangle + \sin\theta\,|^{3/2}E_1\rangle,$$
$$|D_{s1}(2536)^+\rangle = -\sin\theta\,|^{1/2}E_1\rangle + \cos\theta\,|^{3/2}E_1\rangle,$$

- **Different wave gives different angular distributions**

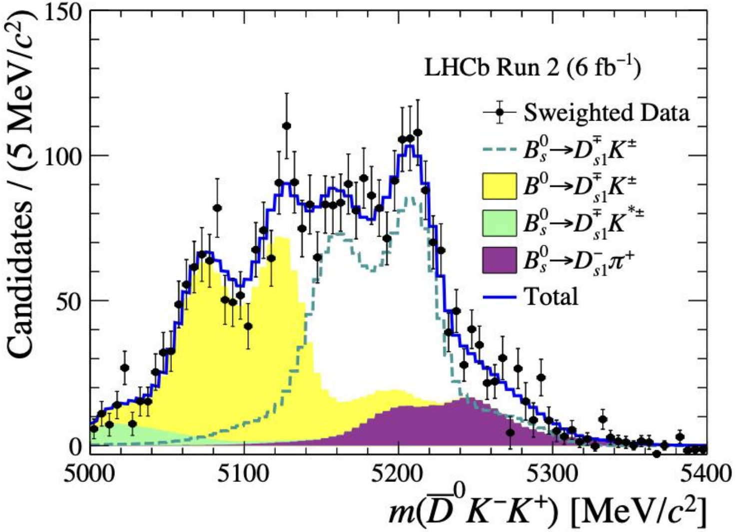


$$\frac{d^3\Gamma}{d\cos\theta_{D^*}\,d\cos\theta_D\,d\chi} \propto \omega_{\rm long}(\theta_{D^*},\theta_D)|H_0|^2 + \omega_{\rm tran}(\chi,\theta_{D^*},\theta_D)|H_+|^2 + \omega_{\rm int}(\chi,\theta_{D^*},\theta_D)\Re(H_0^*H_+),$$

$D_s(2536)^+$ and $D_s(2460)^+$



Neutral particles not reconstructed



$D_{s1}(2536)^+ \to D^{*0}K^+,\ D^{*0} \to D^0\pi^0/D^0\gamma$

$$k = 1.89 \pm 0.24 \pm 0.06, \quad |\phi| = 1.81 \pm 0.20 \pm 0.11 \ \text{rad},$$

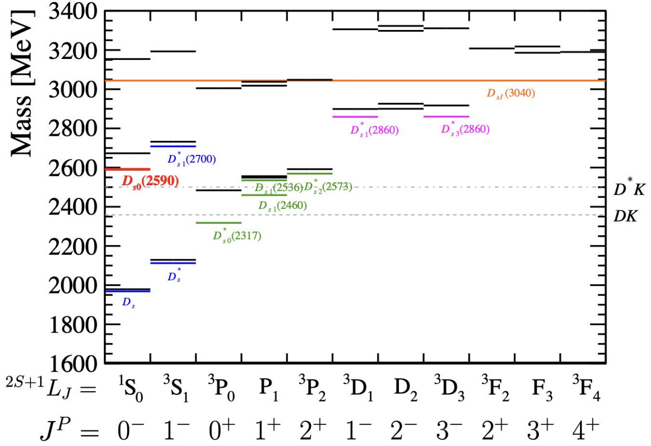
- **S-wave fraction: $(55 \pm 7 \pm 3)\%$， allows to calculate mixing angle and understand the nature of these orbitally excited states**

$D_s(2460)^+$ and $D_s(2317)^+$

$\vec{s}_l$	J^P	Charm meson	Mass (MeV)	Charm strange meson	Mass (MeV)	Difference (MeV)
1/2	0^-	$D^{0(\pm)}$	1864.83 (1869.58)	$D_s^{\pm}$	1968.27	103.44 (98.69)
	1^-	$D^{*0(\pm)}$	2006.85 (2010.26)	$D_s^{*\pm}$	2112.1	105.25 (101.84)
1/2	0^+	$D_0^*(2400)^{0(\pm)}$	2318 (2351)	$D_{s0}^*(2317)^{\pm}$	2317.7	-0.3 (-33.3)
	1^+	$D_1(2430)^0$	2427	$D_{s1}(2460)^{\pm}$	2459.5	32.5
3/2	1^+	$D_1(2420)^{0(\pm)}$	2420.8 (2423.2)	$D_{s1}(2536)^{\pm}$	2535.10	114.3 (111.9)
	2^+	$D_2^*(2460)^{0(\pm)}$	2460.57 (2465.4)	$D_{s2}^*(2573)^{\pm}$	2569.1	108.53 (103.7)

What causes these difference?

Mass very close to DK and D^*K threshold, molecules of DK or D^*K instead of proposed in quark model? Or a compact four quark state?



$D_s(2460)^+$ and $D_s(2317)^+$

$D_s(2317)^+$

- Mass below DK threshold
- Width very narrow (<3.8 MeV @ 95% CL)
- Dominant decay channel: $D_s^+\pi^0$, Isospin breaking?
- Neutral and doubly charged partner not found previously

$D_{s1}(2460)^+$

- Mass above DK threshold
- Width very narrow (<3.5 MeV @ 95% CL)
- Dominant decay channel: $D_s^+\pi^0$, Isospin breaking?

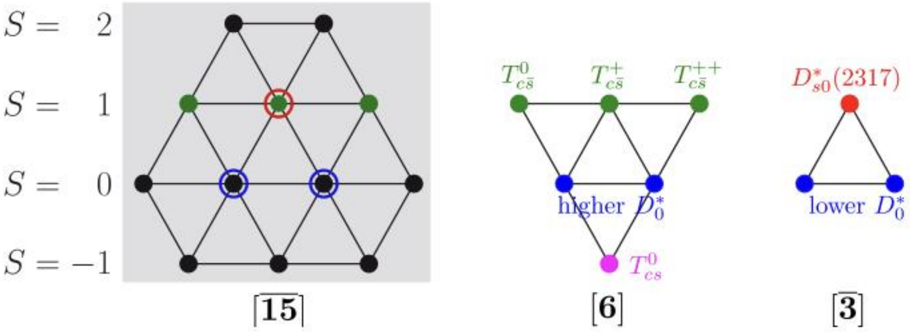
Γ_1	$D_s^{*+}\pi^0$	$(48 \pm 11)\%$
Γ_2	$D_{s+}\gamma$	$(18 \pm 4)\%$
Γ_3	$D_{s+}\pi^+\pi^-$	$(4.3 \pm 1.3)\%$

Why doubly charged?

- **For a four quark state containing a charm quark: $cq\bar{q}'\bar{q}''$**

$$\bar{3} \otimes 3 \otimes \bar{3} = \bar{3} \oplus 3 \oplus \bar{6} \oplus 15$$

Models	SU(3) flavor multiplets
$c\bar{q}$ (w/ or w/o unquenching effects)	$[\bar{\mathbf{3}}]$
Hadronic molecules	$[\bar{\mathbf{3}}] \oplus [\mathbf{6}]$
Diquark-antidiquark tetraquarks	$[\bar{\mathbf{3}}] \oplus [\mathbf{6}] \oplus [\overline{\mathbf{15}}]$

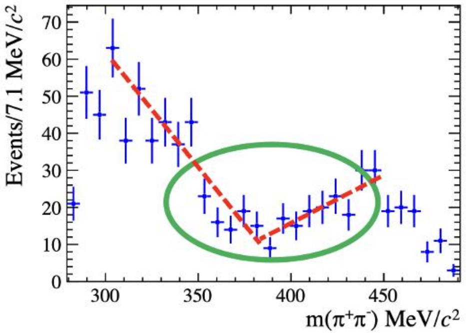


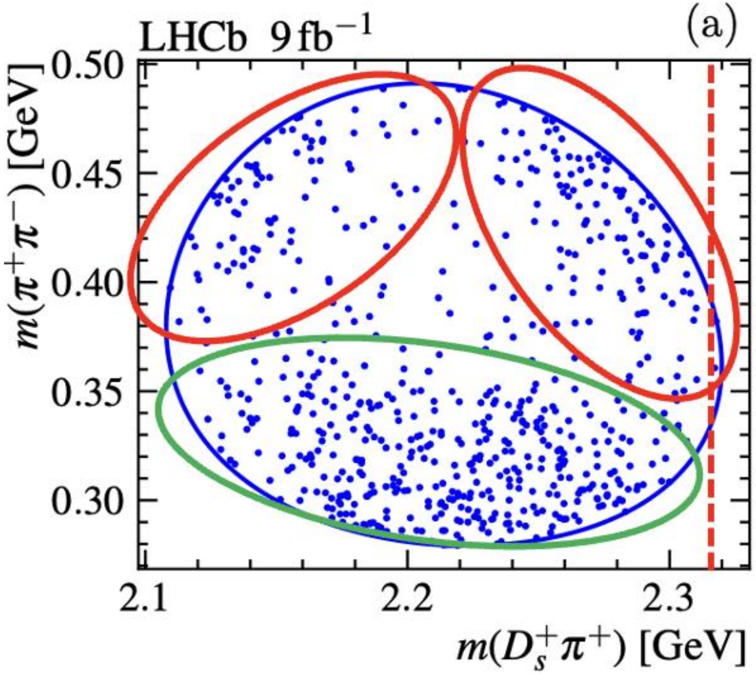
- **If I = 1 $T_{c\bar{s}}$ state found, indicating $D^*_{s0}(2317)$ also multiquark state**
- **What about D_0^*?**
- **If 15 also found, distinguishable between hadronic molecules and Diquark-antidiquark tetraquarks**

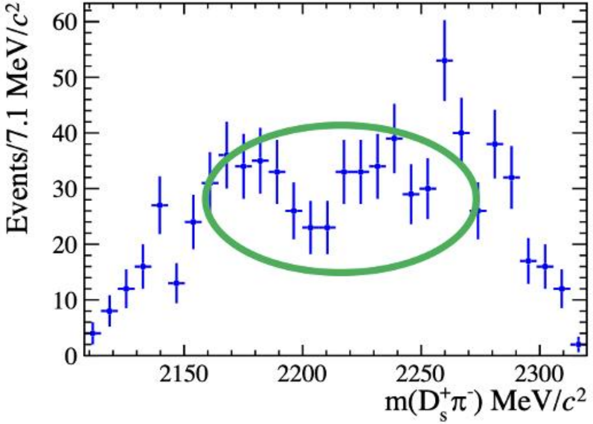
Search for neutral and doubly charged $D_s(2317)$

- BaBar, 2006, searched in $e^+e^- \to c\bar{c} + X$ @10.6 GeV, not found
- Belle, 2015, searched in $B \to DD_s^+\pi$, not found
- LHCb, 2023, searched in $B \to DD_s^+\pi$, found neutral and doubly charged $T_{c\bar{s}}(2900)$
- $2900 - 2317 = 583$ MeV similar as $M(\psi(2S)) - M(\psi(1S))$: radial excitation of $D_s(2317)^+$
- Many other theoretical discussions
- We look into $B \to D^{(*)}D_s^+\pi^+\pi^-$, where $D_s(2460)^+ \to D_s^+\pi^+\pi^-$

Dalitz plot



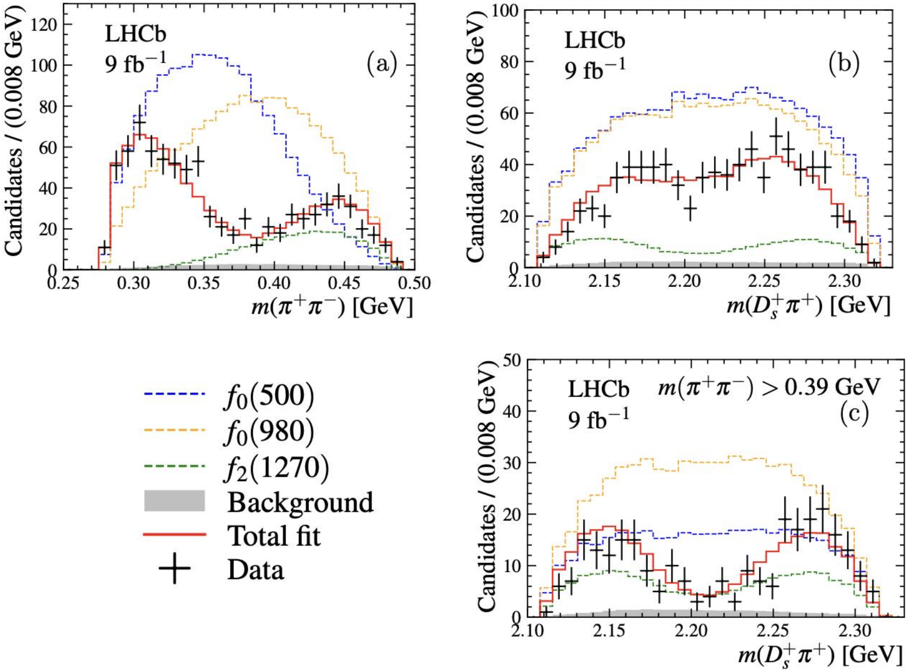




- **Clear gathering of events in three different regions, possible contributions from $T_{c\bar{s}}$?**
- **Double peak structures in $m(\pi^+\pi^-)$, quite interesting**

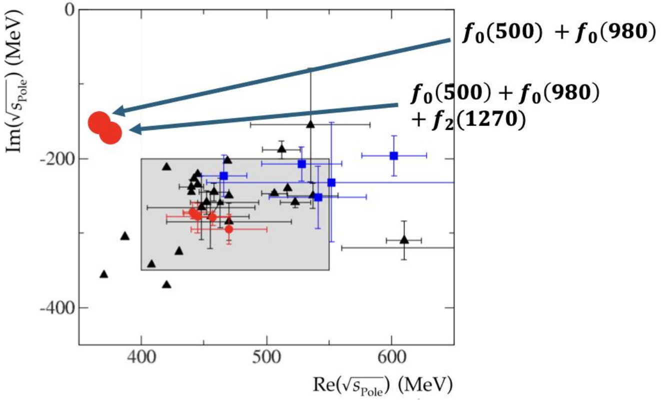
Fit results with $\pi\pi$ only models

$m(\pi^+\pi^-) \in [279.2,\ 491.2]$ MeV



Model	Resonance	Mass (MeV)	Width (MeV)	FF (%)
$f_0(500) + f_0(980) + f_2(1270)$	$f_0(500)$	$376 \pm 9 \pm 16$	$175 \pm 23 \pm 16$	$197 \pm 35 \pm 23$
	$f_0(980)$	945.5	167	$187 \pm 38 \pm 43$
	$f_2(1270)$	1275.4	186.6	$29 \pm 2 \pm 1$

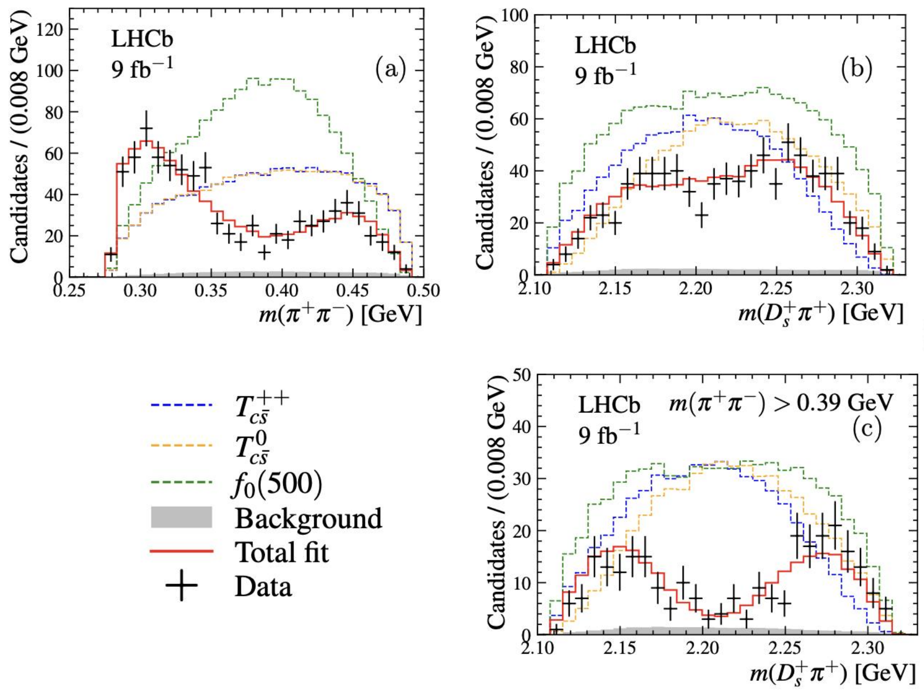
- Both $f_0(980)$ and $f_2(1270)$ far away from threshold (492 MeV)
- Very puzzling $f_0(500)$ parameters



- $\pi\pi$ S-wave line shapes quite different from other processes

Fit results for models with $T_{c\bar{s}}$

$m(\pi^+\pi^-) \in [279.2,\ 491.2]$ MeV



- **$f_0(500)$ mass and width agree with other measurements**
- **Scattering length in K-Matrix determined to be**

$$a = [-0.862(\pm 0.070) + 0.443(\pm 0.067)i]\ \text{fm}$$

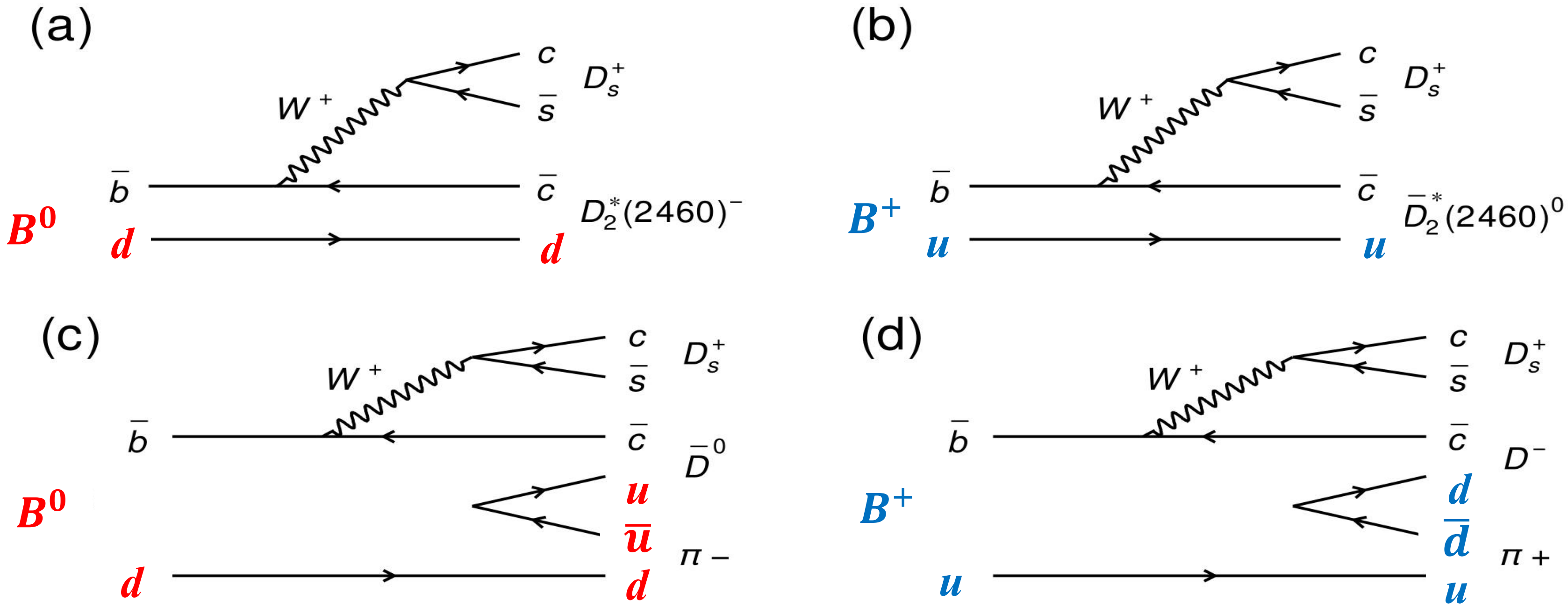
- **Significance of $T_{c\bar{s}} > 10\sigma$**
- **Coupling, masses and widths of $T_{c\bar{s}}^{0}$ and $T_{c\bar{s}}^{++}$ fixed to be the same; if free, consistent with each other**

Discussion

- Both models with and without $T_{c\bar{s}}(2327)$ states can describe data
- However, models without $T_{c\bar{s}}(2327)$ states have some deficiencies and implausible
- Model with $T_{c\bar{s}}(2327)$ states:
  - Mass consistent with $D_s(2317)^+$
  - Width significantly larger than $D_s(2317)^+$
  - Spin 0^+
- Relationship with $D_s(2317)^+$?
- Indication of exotic structures in $D_s(2460)^+$?
- How about $D_s(2536)^+$

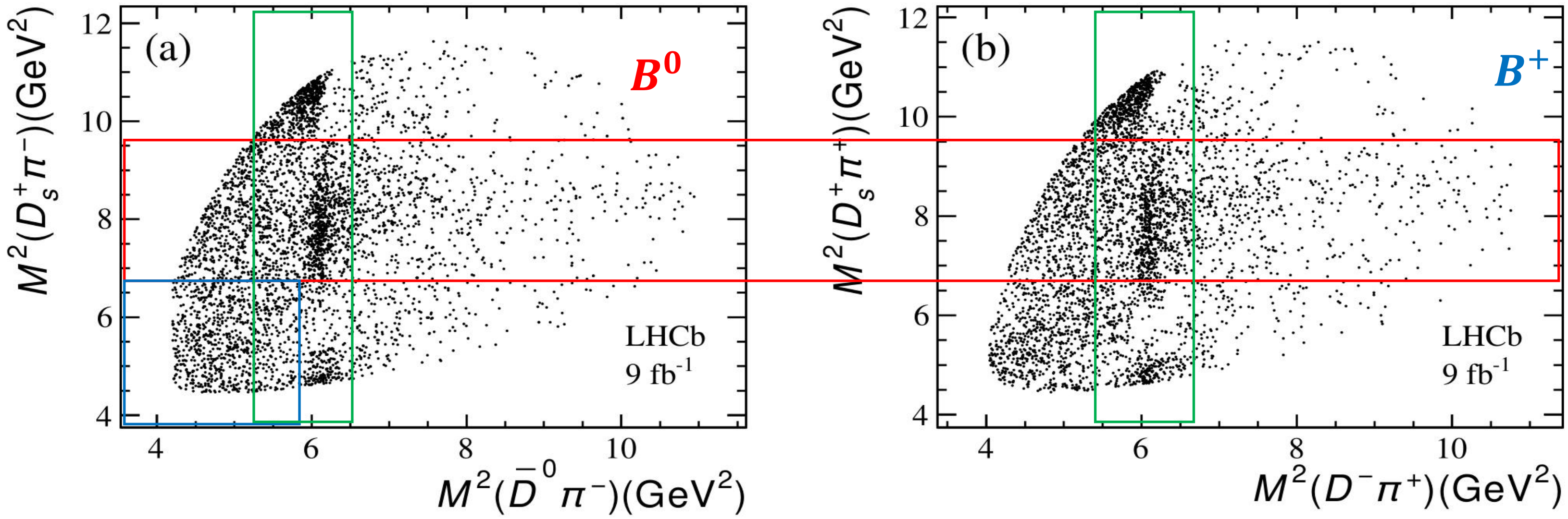
Other doubly charged state?

- Two decays considered: $B^0 \to \overline{D^0} D_s^+ \pi^-$, $B^+ \to D^- D_s^+ \pi^+$



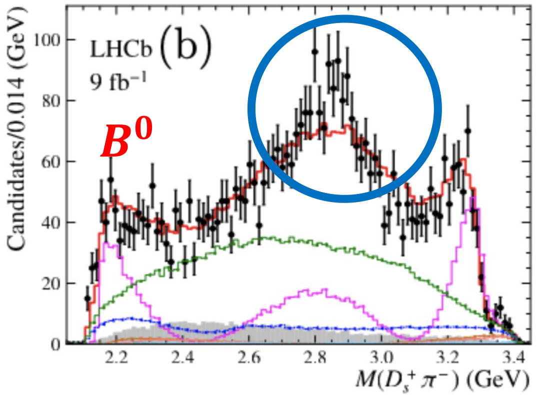
- Connected by isospin relationship in all aspects

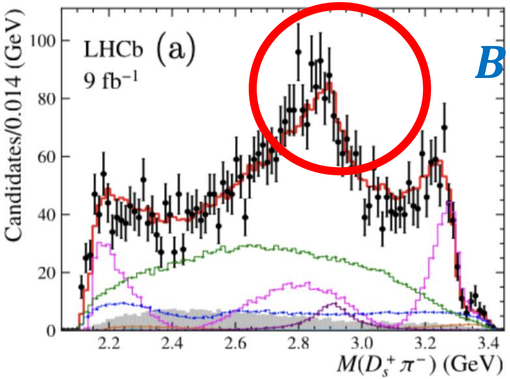
Dalitz plot



- **Very similar distributions over Dalitz plot**
- **Clear accumulation of events on both channels around 2.9 GeV of $m(D_s^+\pi^-)$ and $m(D_s^+\pi^+)$**

Amplitude analysis

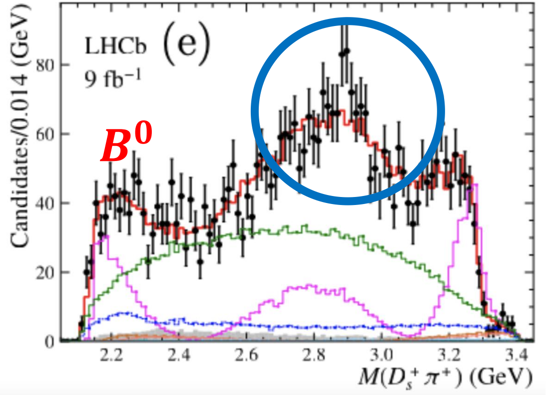


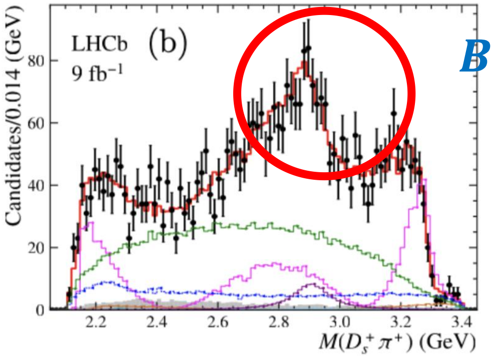


B^+

$T^a_{c\bar{s}}(2900)^0$

$m = 2.908 \pm 0.011 \pm 0.020$ GeV
$\Gamma = 0.136 \pm 0.023 \pm 0.011$ GeV
$J^P = 0^+$





B^+

$T^a_{c\bar{s}}(2900)^{++}$

$T_{c\bar{s}}(2900) - T_{c\bar{s}}(2327)$

$\sim \psi(2S) - \psi(1S)$

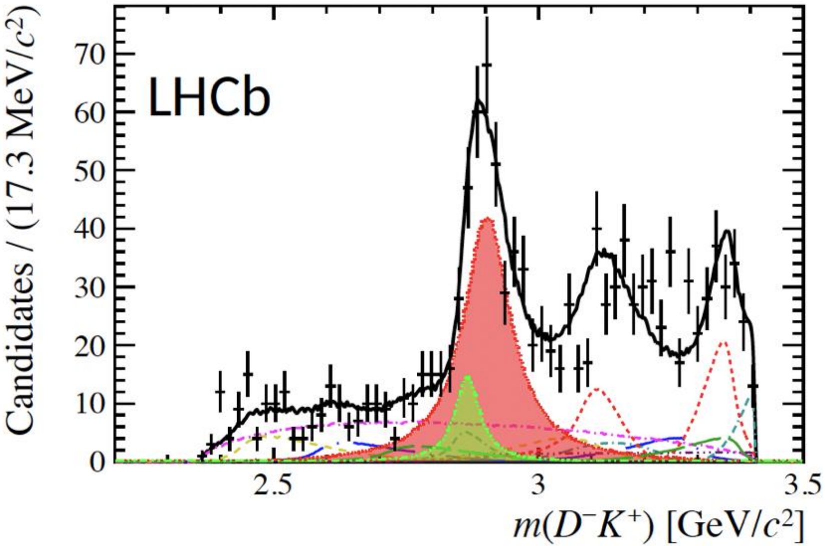
Without new states

With new states

$T_{c\bar{s}}(2900)$ radial excitation of $T_{c\bar{s}}(2327)$?

Further tetraquark states with c and s?

- $T^a_{c\bar{s}}(2900)$ have quark content $c\bar{s}\bar{u}d$ and $c\bar{s}u\bar{d}$
- Any states with quark content $cs\bar{u}\bar{d}$?



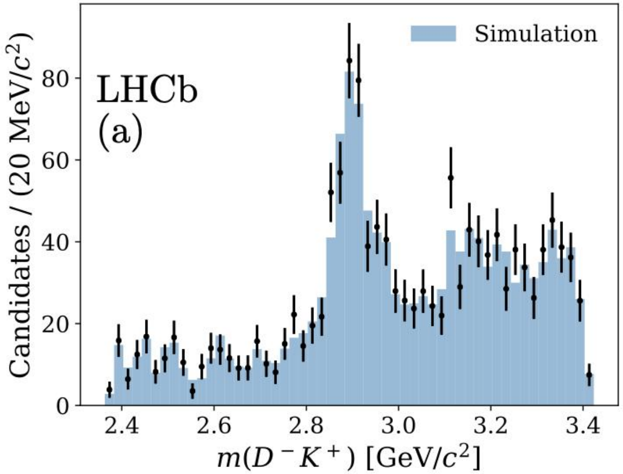
In $B^+ \to D^+D^-K^+$ decays, two states observed

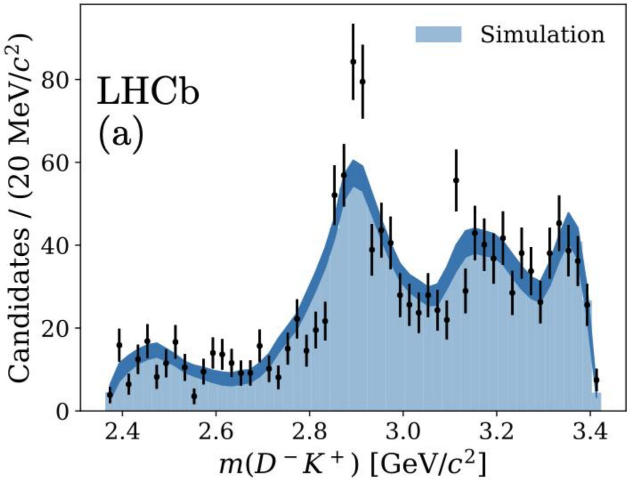
Exotic	Mass (MeV)	Width (MeV)	Spin-parity
$X_0(2900)$	$2866 \pm 7 \pm 2$	$57 \pm 12 \pm 4$	0^+
$X_1(2900)$	$2904 \pm 5 \pm 1$	$110 \pm 11 \pm 4$	1^-
$T^a_{c\bar{s}}(2900)^0$	$2892 \pm 14 \pm 15$	$119 \pm 26 \pm 12$	0^+
$T^a_{c\bar{s}}(2900)^{++}$	$2921 \pm 17 \pm 19$	$137 \pm 32 \pm 14$	0^+

- Very similar mass
- Spin 1 state has larger yields and larger width

A model-independent technique

- First used by Babar to search for $Z_c(4430)^+$, however, not fully correct
- Further developed by LHCb to search for $Z_c(4430)^+$
- Applied when normal resonances in m_{12}^2 while considered new resonance in m_{13}^2
- In each $m(D^+D^-)$ slices, perform Legendre expansion to certain order





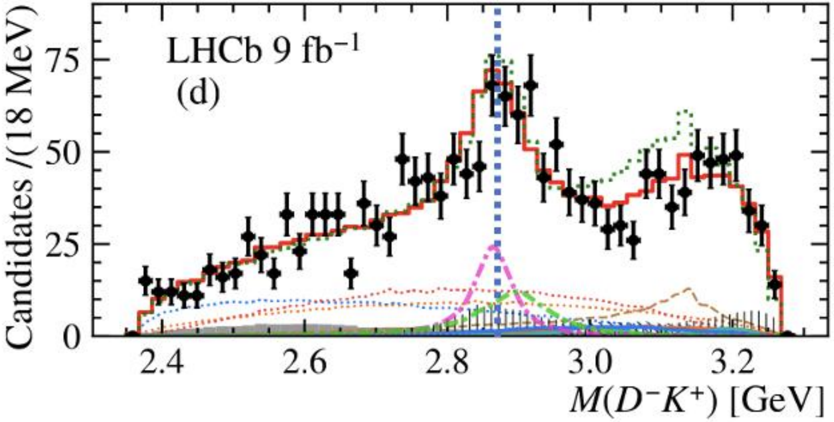
Uniform Dalitz distribution weighted according to

$$\sum_{k=0}^{k_{\max}} \langle Y_k^j \rangle P_k \left(h_i(D^+D^-) \right)$$

Comparison with $m(D^-K^+)$ offers information on new resonance

Confirmation of $X_{0,1}(2900)$

- $X_{0,1}(2900)$ found in $B^+ \to D^+D^-K^+$ decays, a nature idea is to search in $B^+ \to D^{*+}D^-K^+$ decays



- Confirming $T^*_{\bar{c}\bar{s}0}(2870)^0$ and $T^*_{\bar{c}\bar{s}1}(2900)^0$ in a new decay channel $B^+ \to D^{*+}T^*_{\bar{c}\bar{s}}$

	$T^*_{\bar{c}\bar{s}0}(2870)^0$			$T^*_{\bar{c}\bar{s}1}(2900)^0$	
m_0	2914 ± 19	2866 ± 7	m_0	2887 ± 10	2904 ± 5
Γ_0	128 ± 32	57 ± 13	Γ_0	92 ± 23	110 ± 12

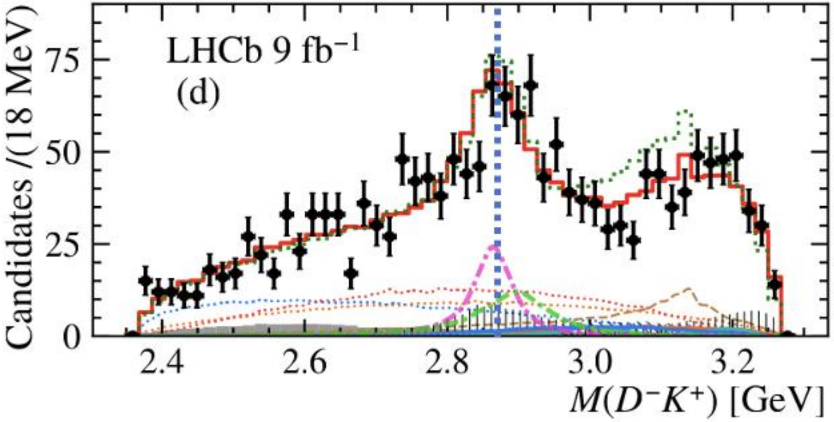
This work

Mass and width agree within 2σ

Previous work

Branching fractions

- $X_{0,1}(2900)$ found in $B^+ \to D^+D^-K^+$ decays, a nature idea is to search in $B^+ \to D^{*+}D^-K^+$ decays



- However, branching fraction ratios between spin 0 and 1 particles show tension

$$\frac{\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0 D^{(*)+})}{\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+})}$$

$$1.17 \pm 0.31 \pm 0.48$$

This work

$$0.18 \pm 0.05$$

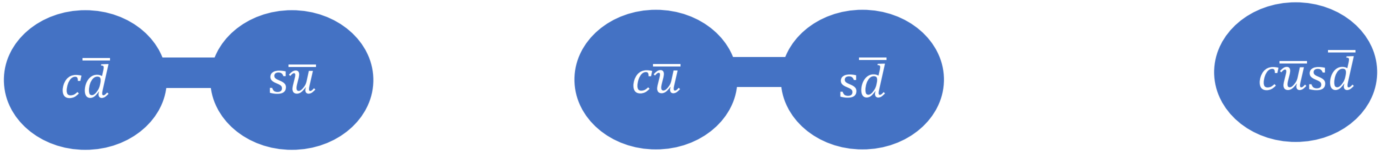
Previous work

- Large difference on branching fraction ratio, further hints on structures?

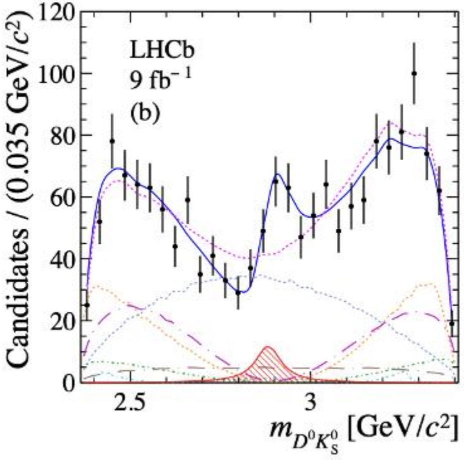
Isospin relationship

$c\bar{d}\quad s\bar{u}$

- $X_{0,1}(2900)$ found in $B^+ \to D^+D^-K^+$ decays, with $X_{0,1}(2900) \to D^+K^-$



- Search in $B^+ \to D^+\bar{D}^0K_S^0$: finding $T^*_{\bar{c}\bar{s}0}(2870)^0$, but not $T^*_{\bar{c}\bar{s}1}(2900)^0$ to $D^0K_S^0$



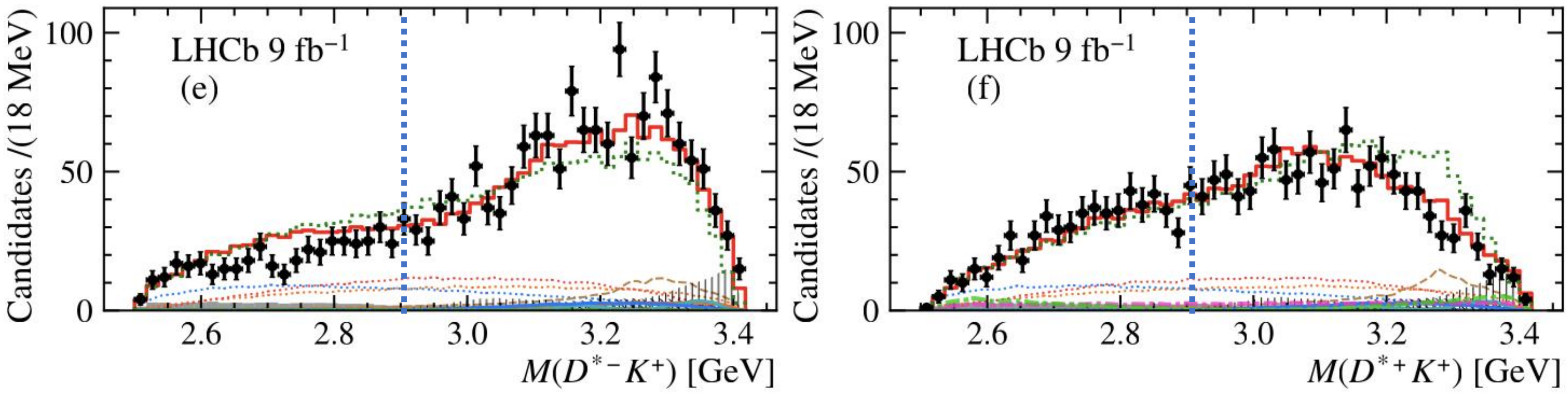
$$\frac{T^*_{cs0}(2870)^0 \to D^0K_S^0}{T^*_{cs0}(2870)^0 \to D^+K^-} = 3.3 \pm 1.9$$

$$\frac{T^*_{cs1}(2870)^0 \to D^0K_S^0}{T^*_{cs1}(2870)^0 \to D^+K^-} = 0.15 \pm 0.17$$

While 1 from Isospin symmetry?

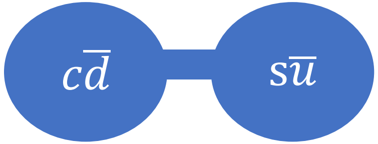
- Similar as $B \to D^*T_{cs}$, more spin 0 contributions than spin 1

$X_{0,1}(2900) \to D^*K$?



- 0^+ can not decay into D^*K
- 1^- not found in $D^{*-}K^+$ decays

D^+? D^{*+}

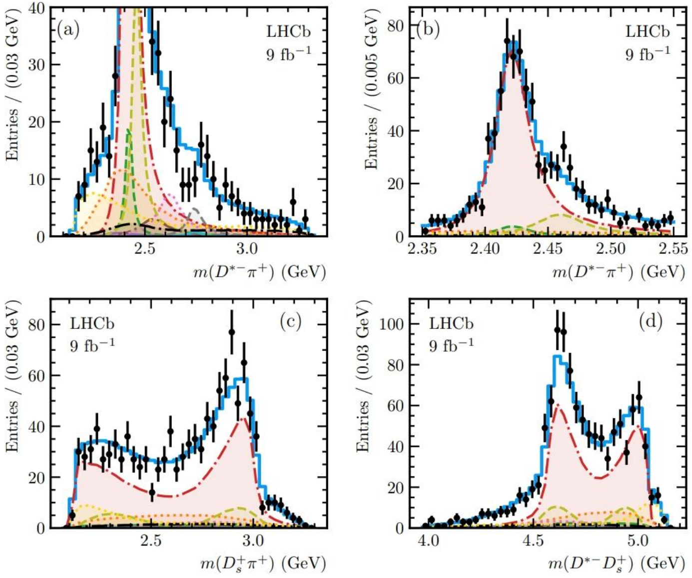


$$\mathbf{FF}(B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^+, T^*_{\bar{c}\bar{s}1}(2900)^0 \to D^{*-}K^+) < 1.5\% \text{ @ } 95\% \text{ C.L.}$$

$$\frac{Br(T^*_{\bar{c}\bar{s}1}(2900)^0 \to D^{*-}K^+)}{Br(T^*_{\bar{c}\bar{s}1}(2900)^0 \to D^-K^+)} < 0.21 \text{ @ } 95\%$$

How about doubly charged $T_{c\bar{s}}(2900)^{++}$

- $T_{c\bar{s}}(2900)^{++}$ found in $B^+ \to D^- D_s^+ \pi^+$ decays, a nature idea is to search in $B^+ \to D^{*-} D_s^+ \pi^+$ decays



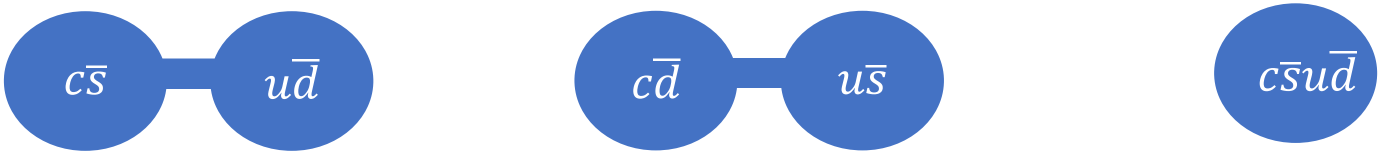
Around 1K signal events (4K in previous work)

- **Main contributions from D^* states including $D_1(2420)$, $D_1(2430)$, $D_2(2460)$, $D_0(2550)$, $D_1^*(2600)$ and $D_2(2740)$ etc.**
- **No strong evidence of $T^a_{c\bar{s}0}(2900)^{++}$, upper limits set on fit fractions to be smaller than 2.5% @ 90% CL**
- **Statistic matters**
- **Could we search in $B^0 \to \bar{D}^{*0} D_s^+ \pi^-$ decays for $T_{c\bar{s}}(2900)^0$?**

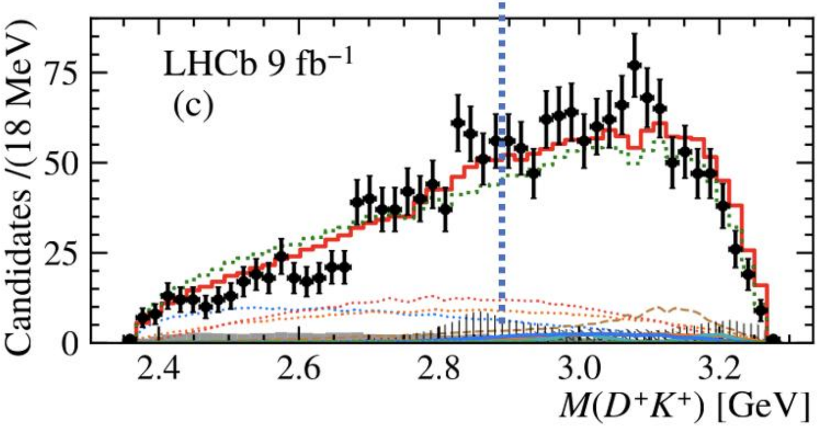
How about doubly charged $T_{c\bar{s}}(2900)^{++}$

$c\bar{s}$ $u\bar{d}$

- $T_{c\bar{s}}(2900)^{++}$ found in $B^+ \to D^- D_s^+ \pi^+$ decays, with $T_{c\bar{s}}(2900)^{++} \to D_s^+ \pi^+$



- Search in $B^+ \to D^- D^+ K^+$ or $B^+ \to D^{*-} D^+ K^+$



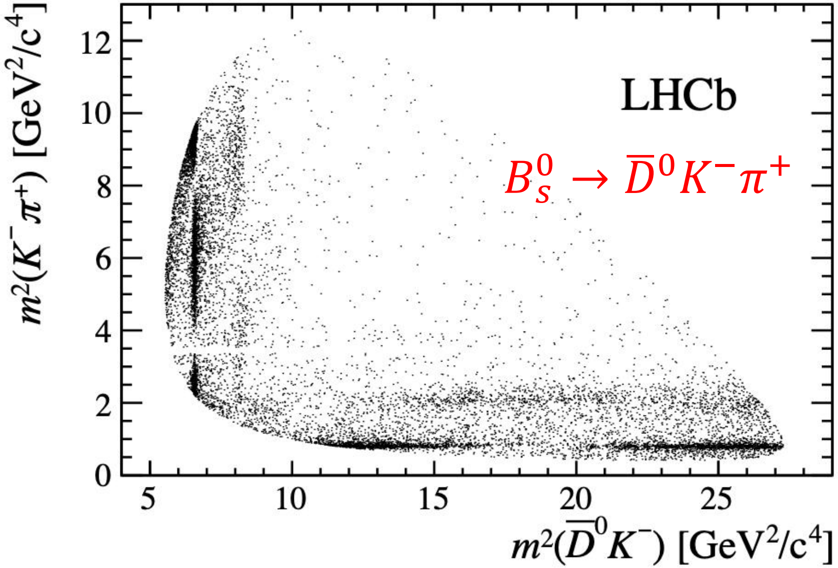
- Negative in search $T_{c\bar{s}0}(2900)^{++}$

$\mathrm{FF}(B^+ \to T_{c\bar{s}0}(2900)^{++} D^{*-}, T_{c\bar{s}0}(2900)^{++} \to D^+ K^+) < 3.3\%$ @ 95% C.L.

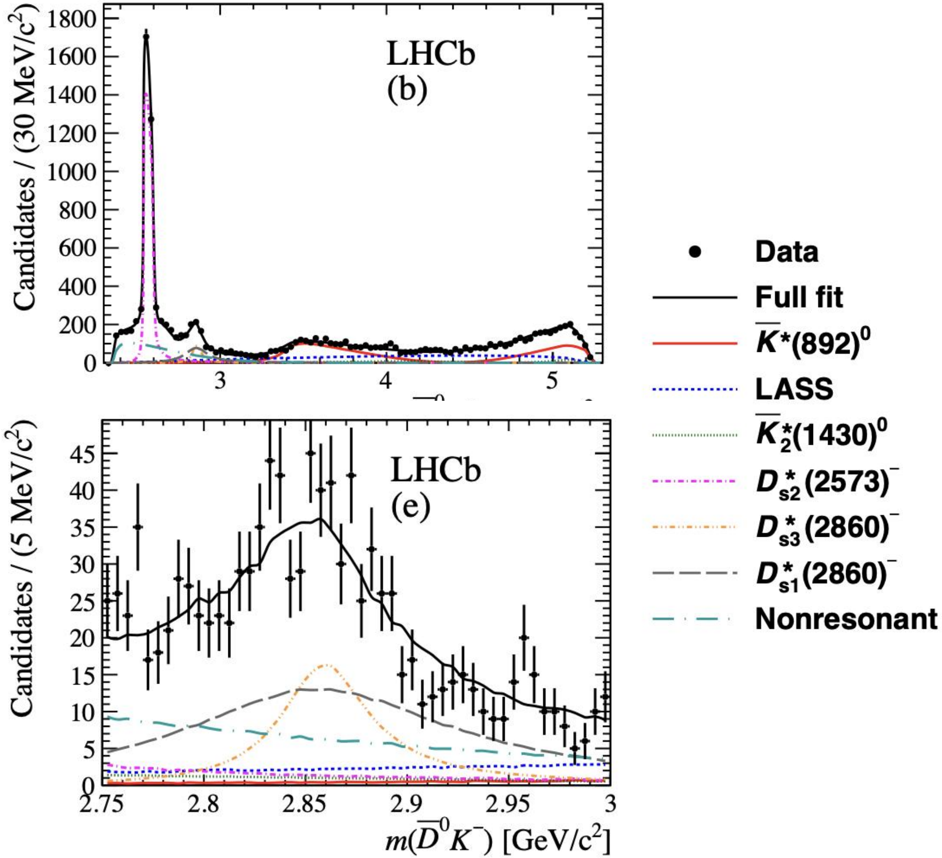
- Work ongoing in $B^+ \to D^- D^+ K^+$ decays
- Isospin: $B^0 \to \bar{D}^0 D^0 K_S^0$ decays

$D_{sJ}(2860)$

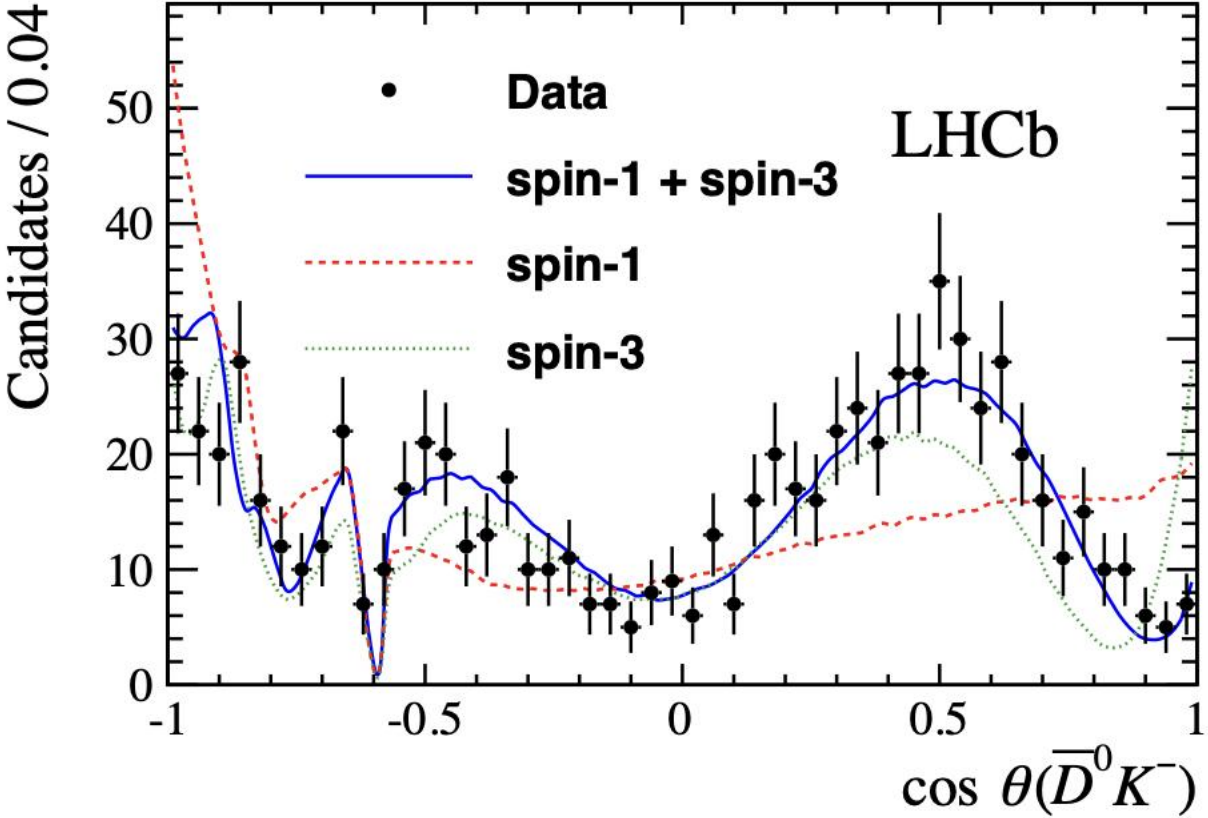
Around 11K signal events



$$m(D_{s1}^*(2860)^-) = 2859 \pm 12 \pm 6 \pm 23\,\mathrm{MeV}/c^2\,,$$
$$\Gamma(D_{s1}^*(2860)^-) = 159 \pm 23 \pm 27 \pm 72\,\mathrm{MeV}/c^2\,,$$
$$m(D_{s3}^*(2860)^-) = 2860.5 \pm 2.6 \pm 2.5 \pm 6.0\,\mathrm{MeV}/c^2\,,$$
$$\Gamma(D_{s3}^*(2860)^-) = 53 \pm 7 \pm 4 \pm 6\,\mathrm{MeV}/c^2\,,$$

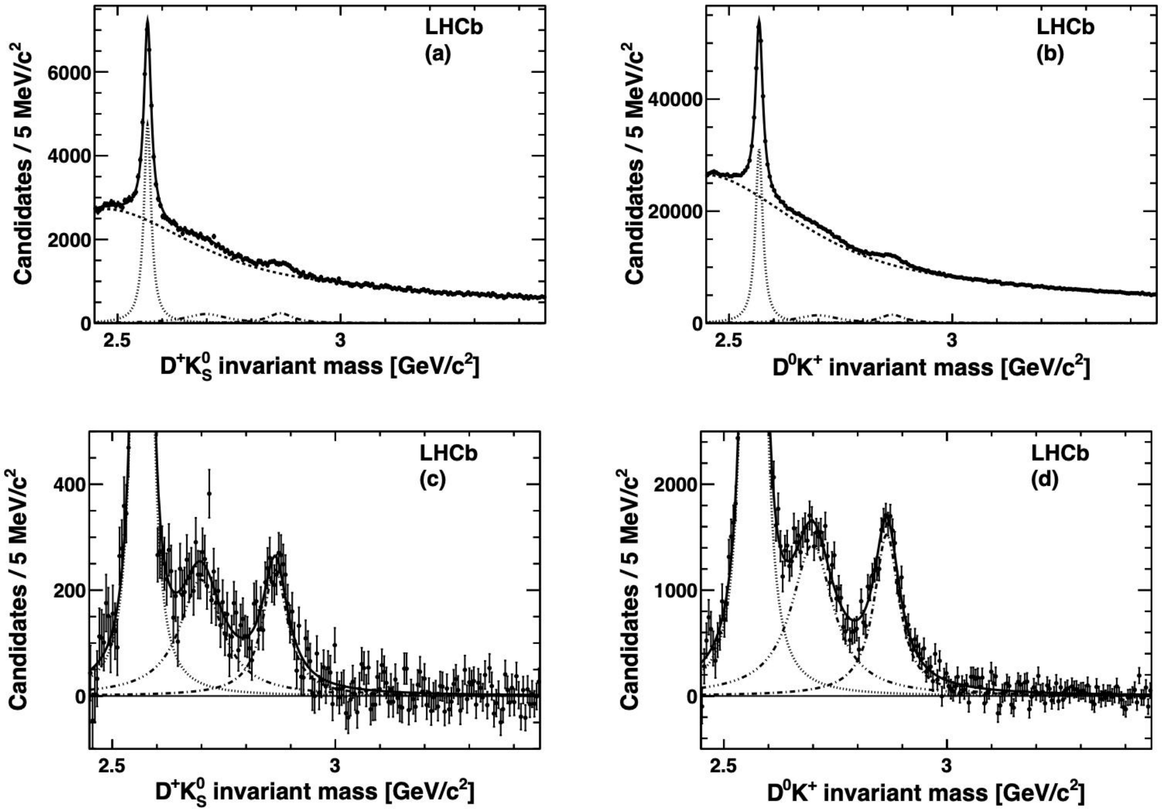


Spin-parity of $D_{sJ}(2860)^+$

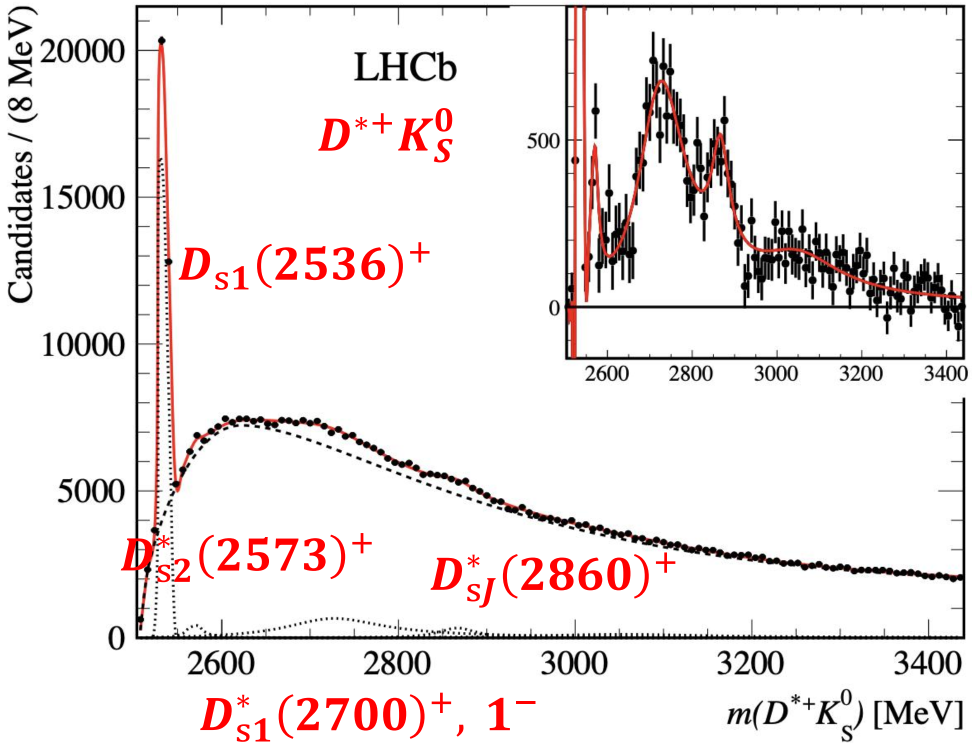


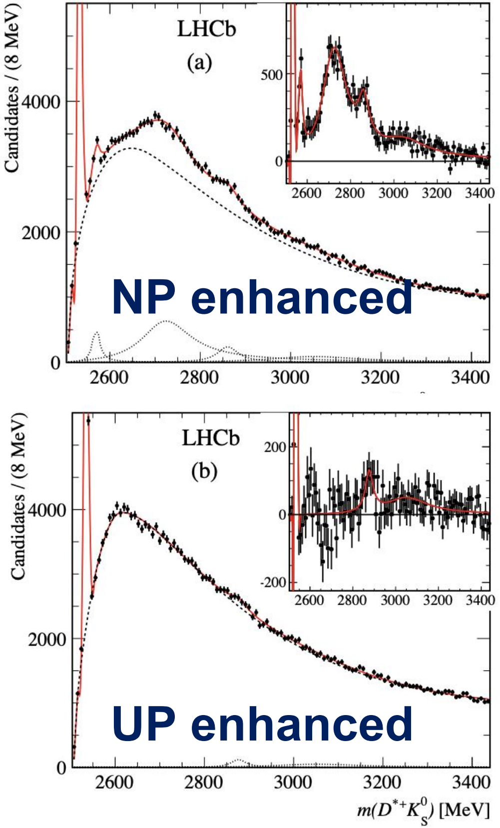
Alternative ways to search for resonances

- Spectroscopy not only can be studied via b decays, also from direct production through $pp \rightarrow X + D^0K^+,\ D^+K_S^0,\ D^{*+}K_S^0,\ D^{*0}K^+$
- Resonances of $D_{s2}^*(2573)^+$, $D_{s1}^*(2700)^+$, $D_{sJ}^*(2800)^+$
- Care needed when studying prompt production (feed down, reflection, experimental effects on parameter determination etc.)



Alternative ways to search for resonances





$\propto \sin^2\theta$

$\cos\theta < 0.5$

$\propto 1 + h\cos^2\theta$

$\cos\theta > 0.5$

Difference in two methods

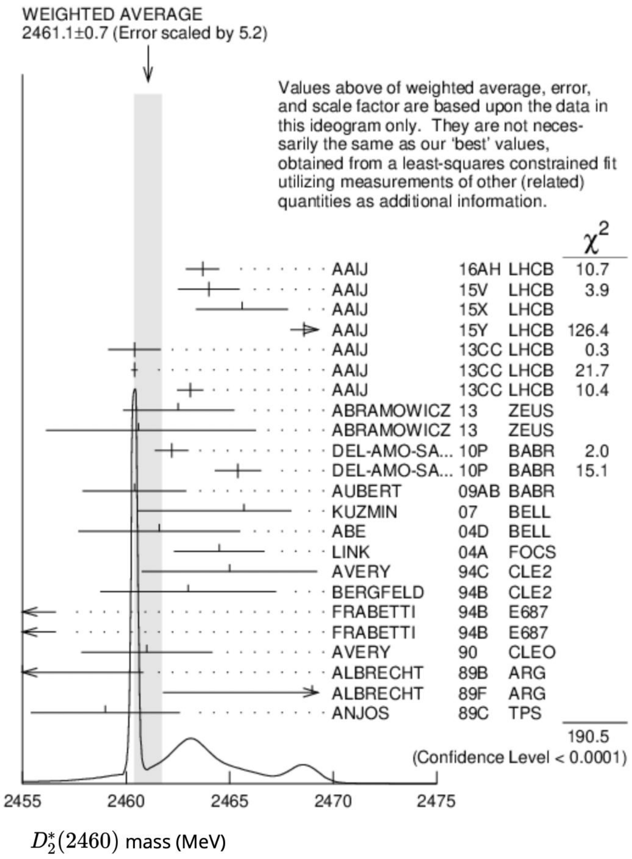
From b decays

- Less signals, but much lower background
- Full decay chain reconstructed
- Amplitude analysis to determine spin-parity
- Easy to separate overlap resonances
- More precise mass and width determination (well modelled background and efficiency)
- Interference properly considered

Inclusive searches

- Larger signals, but much higher background (feed down, reflection)
- Only considered part
- Spin-parity from helicity angle, however, quite limited sensitivity
- Hard to separate when resonances overlap
- Mass and width not as precise as expected
- Hard to include interference

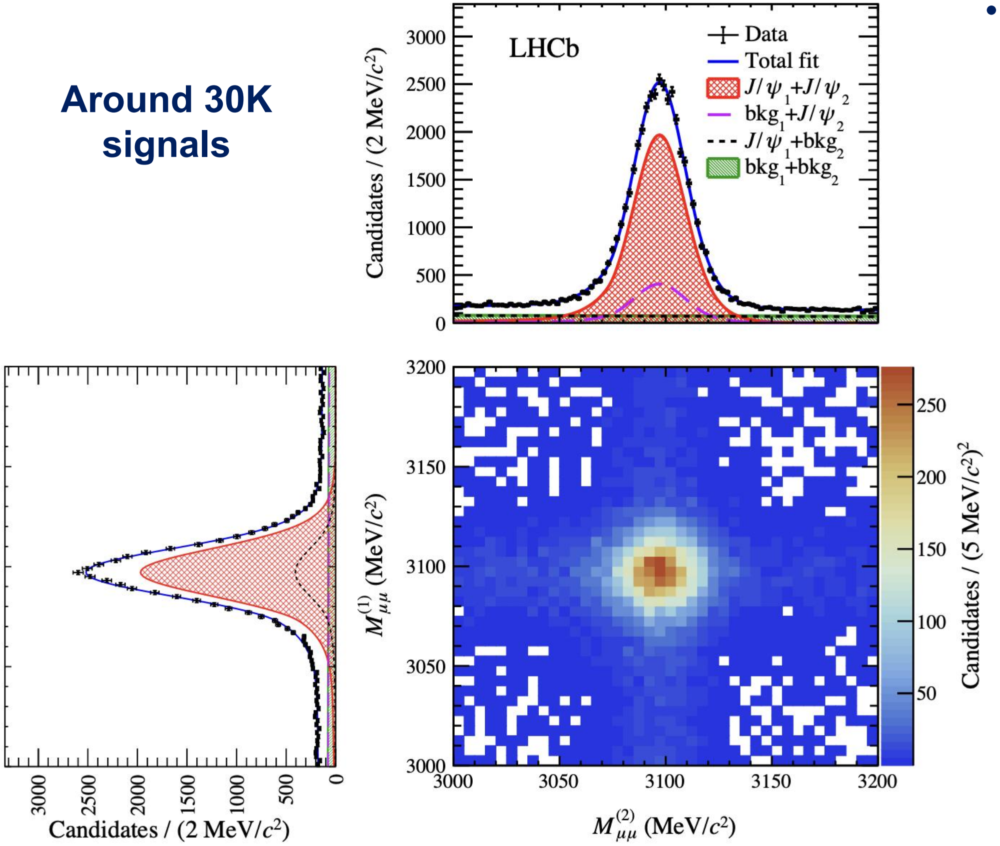
An example



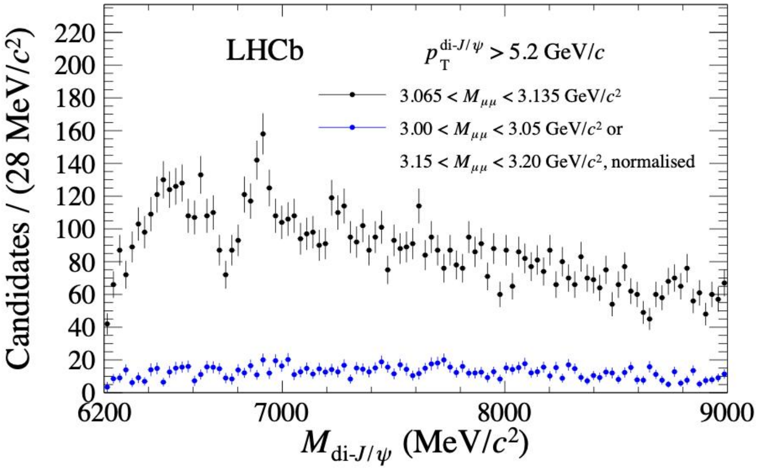
AAIJ	2016AH	PR D94 072001	Amplitude analysis of $B^- \to D^+\pi^-\pi^-$ Decays
AAIJ	2015X	PR D92 012012	Amplitude Analysis of $B^0 \to \overline{D}^0 K^+\pi^-$ Decays
AAIJ	2015Y	PR D92 032002	Dalitz Plot Analysis of $B^0 \to \overline{D}^0 \pi^+\pi^-$ Decays
AAIJ	2015V	PR D91 092002	First Observation and Amplitude Analysis of the $B^- \to D^+K^-\pi^-$ Decay
	Also	PR D93 119901 (errat.)	Erratum to AAIJ 2015V: First Observation and Amplitude Analysis of the $B^- \to D^+K^-\pi^-$ Decay
AAIJ	2013CC	JHEP 1309 145	Study of D_J Meson Decays to $D^+\pi^-$, $D^0\pi^+$ and $D^{*+}\pi^-$ Final States in pp Collisions
ABRAMOWICZ	2013	NP B866 229	Production of the Excited Charm Mesons D_1 and D_2^* at HERA
DEL-AMO-SANCHEZ	2010P	PR D82 111101	Observation of New Resonances Decaying to $D\pi$ and $D^*\pi$ in Inclusive e^+e^- Collisions near $\sqrt{s}$ = 10.58 GeV
AUBERT	2009AB	PR D79 112004	Dalitz Plot Analysis of
CHEKANOV	2009	EPJ C60 25	Production of Excited Charm and Charm-Strange Mesons at HERA
KUZMIN	2007	PR D76 012006	Study of $\overline{B}^0 \to D^0\pi^+\pi^-$ Decays
ABULENCIA	2006A	PR D73 051104	Measurement of Mass and Width of the Excited Charmed Meson States D_1^0 and D_2^{*0} at CDF
ABE	2004D	PR D69 112002	Study of $B^- \to D^{**0}\pi^-$ ($D^{**0} \to D^{(*)+}\pi^-$) Decays
LINK	2004A	PL B586 11	Measurement of Masses and Widths of Excited Charm Mesons D_2^* and Evidence for Broad States
ABREU	1998M	PL B426 231	First Evidence for a Charm Radial Excitation, $D^{*\prime}$
ASRATYAN	1995	ZPHY C68 43	Study of D^{*+} and Search for D^{**0} Production by Neutrinos in BEBC
AVERY	1994C	PL B331 236	Production and Decay of $D_1(2420)^0$ and $D_2^*(2460)^0$
BERGFELD	1994B	PL B340 194	Observation of $D_1(2420)^+$ and $D_2^*(2460)^+$
FRABETTI	1994B	PRL 72 324	Measurement of the Masses and Widths of $L = 1$ Charm Mesons
AVERY	1990	PR D41 774	P-wave Charmed Mesons in e^+e^- Annihilation
ALBRECHT	1989B	PL B221 422	Observation of $D^*(2459)^0$ in e^+e^- Annihilation
ALBRECHT	1989F	PL B231 208	Observation of the Charged Isospin Partner of the $D_2^*(2460)^0$
ANJOS	1989C	PRL 62 1717	Observation of Excited Charmed Mesons

$T_{c\bar{c}c\bar{c}}$

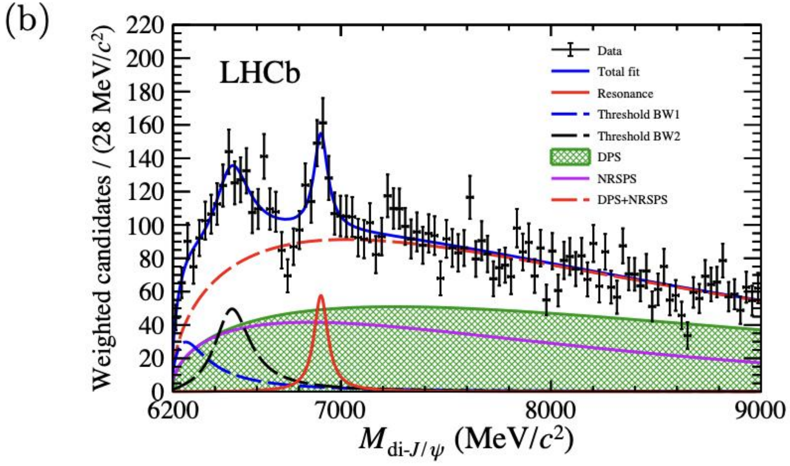
Around 30K signals

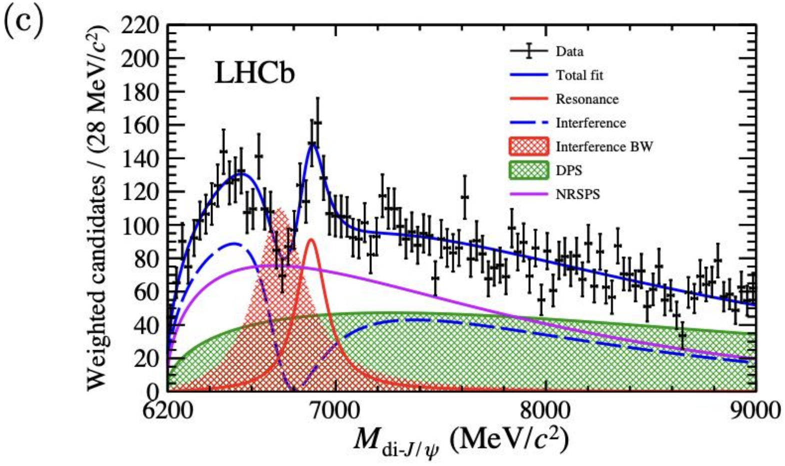


- **Only possible to be studied in hadron machines**



$T_{c\bar{c}c\bar{c}}$





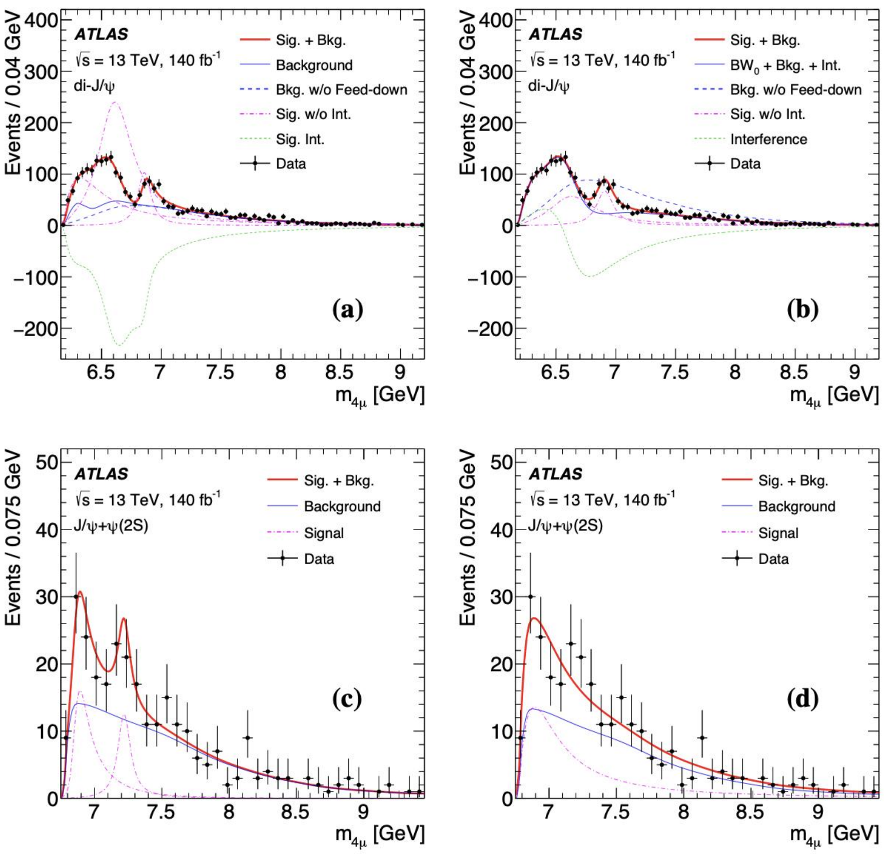
Model I: X(6900) + 2 RWB at threshold, tension around 6.75 GeV

$$m[X(6900)] = 6905 \pm 11 \pm 7\,\text{MeV}/c^2$$
$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\text{MeV},$$

Model II: X(6900) + RWB + interference with NRSPS

$$m[X(6900)] = 6886 \pm 11 \pm 11\,\text{MeV}/c^2$$
$$\Gamma[X(6900)] = 168 \pm 33 \pm 69\,\text{MeV}.$$

Follow ups by ATLAS and CMS



Model I: X(6900) + 2 RWB at threshold (with interference and feed down)

Model II: X(6900) + RWB at threshold (with interference of RWB to SPS)

Confirming X(6900) + broad structure at threshold

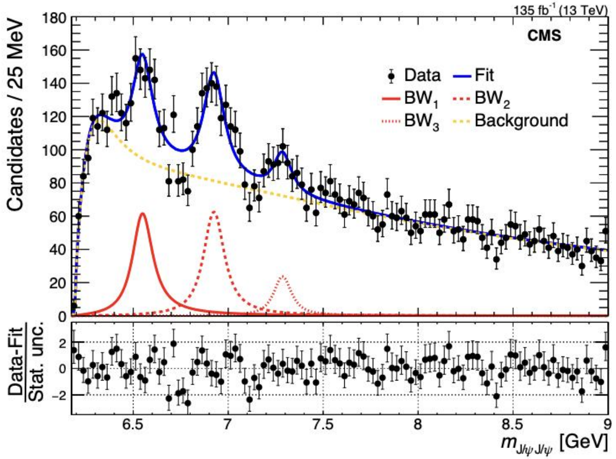
Also consider J/ψ + $\psi(2S)$:

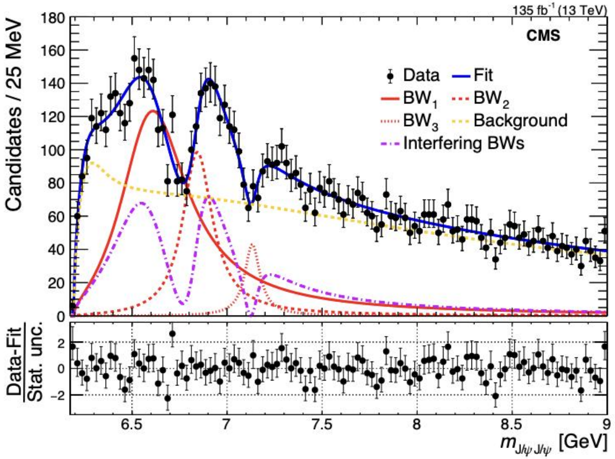
Model I: three resonances at di-J/ψ + additional one

Model II: only one RBW

Though statistically limited, not conclusive yet

Follow ups by ATLAS and CMS

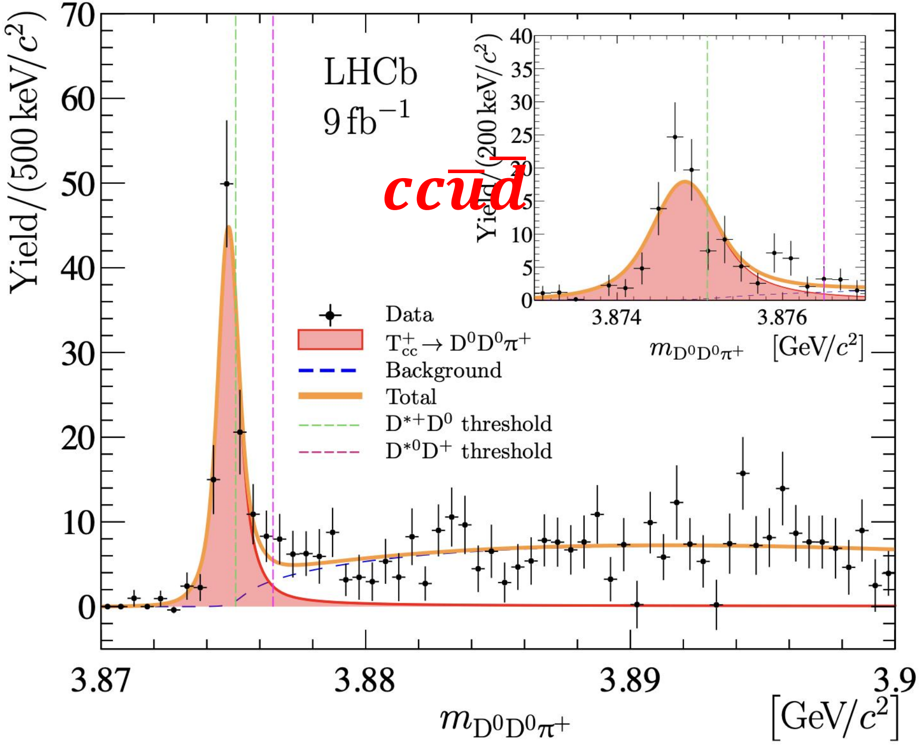




- **Two models considered, with and without interference between RBWs**
- **While confirming X(6900), two new resonances found (third one around 4.7σ, local)**
- **Also attempts for J^p (2^{++}?)**

		BW_1	BW_2	BW_3
No interference	m (MeV)	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 4$	$7287^{+20}_{-18} \pm 5$
	Γ (MeV)	$124^{+32}_{-26} \pm 33$	$122^{+24}_{-21} \pm 18$	$95^{+59}_{-40} \pm 19$
	N	470^{+120}_{-110}	492^{+78}_{-73}	156^{+64}_{-51}
Interference	m (MeV)	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
	Γ (MeV)	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

T_{cc}^{+}

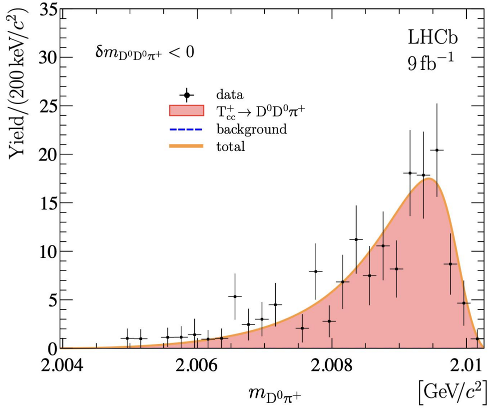


- **A new state below $D^{*+}D^0$ threshold found decaying into $D^0D^0\pi^+$**

$$\delta m \equiv m_{T_{cc}^+} - (m_{D^{*+}} + m_{D^0})$$

$$\delta m_{BW} = -273 \pm 61 \pm 5\,^{+11}_{-14}\ \text{keV}/c^2,$$
$$\Gamma_{BW} = 410 \pm 165 \pm 43\,^{+18}_{-38}\ \text{keV},$$

- **Mainly from D^0D^{*+}**
- **Decaying to $D^{*0}D^+$ also found**

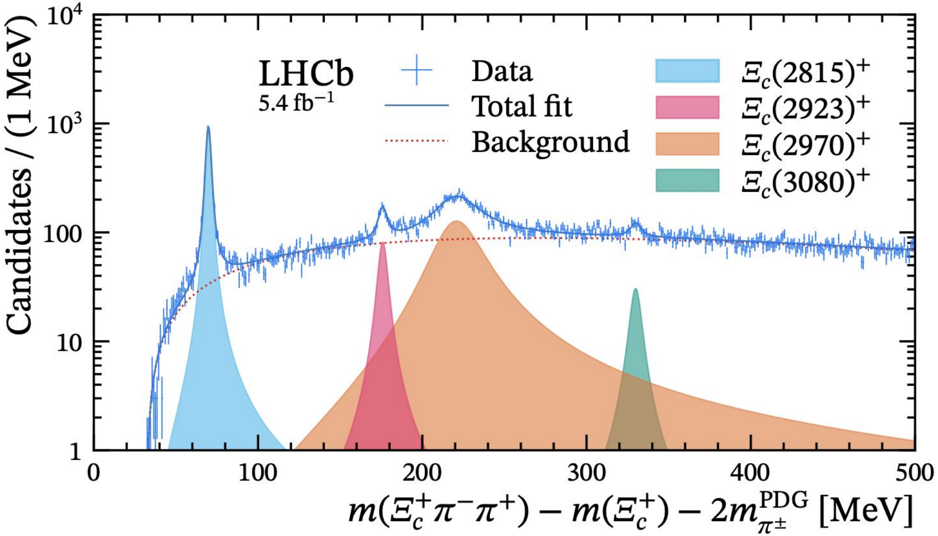


Baryons

arXiv:2502.18987

- **Singly charmed/beauty baryons with orbital angular momentum $L = 0$ have all been observed;**
- **However, very limited results on orbital radial excitations**

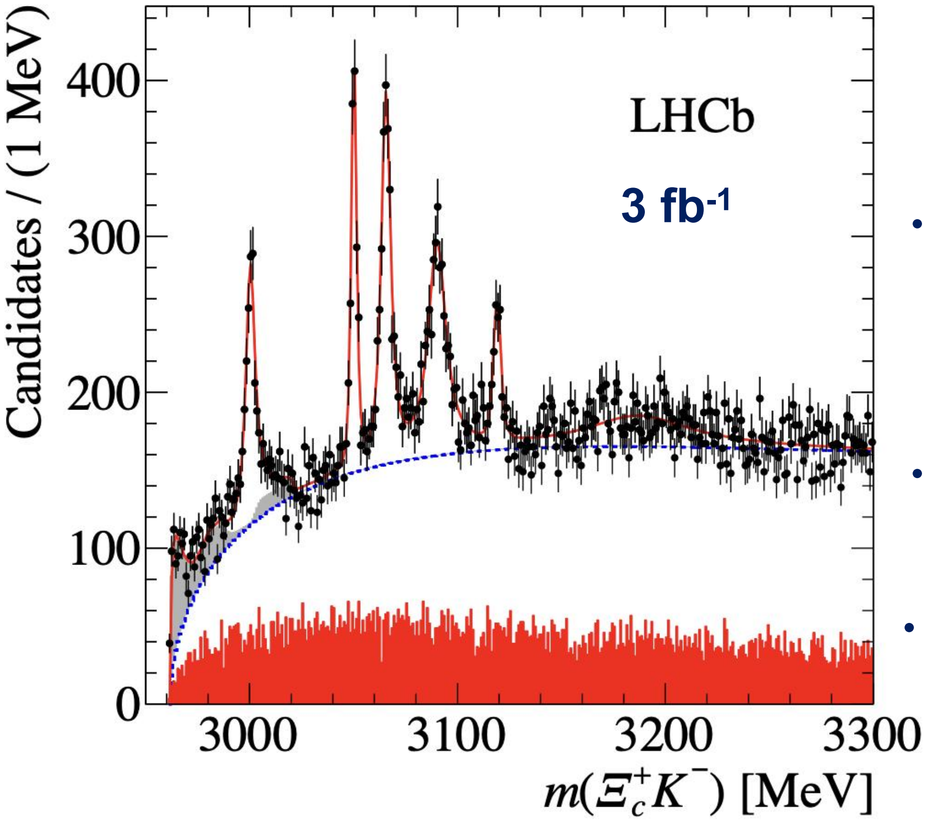
$\Xi_c^{**+} \to \Xi_c(2645)^0(\to \Xi_c^+\pi^-)\pi^+$



First observation

$$m[\Xi_c(2815)^+] = 2816.65 \pm 0.03 \pm 0.03 \pm 0.23\,\text{MeV},$$
$$\Gamma[\Xi_c(2815)^+] = 2.07 \pm 0.08 \pm 0.12\,\text{MeV},$$
$$m[\Xi_c(2923)^+] = 2922.8 \pm 0.3 \pm 0.5 \pm 0.2\,\text{MeV},$$
$$\Gamma[\Xi_c(2923)^+] = 5.3 \pm 0.9 \pm 1.4\,\text{MeV},$$
$$m[\Xi_c(2970)^+] = 2968.6 \pm 0.5 \pm 0.5 \pm 0.2\,\text{MeV},$$
$$\Gamma[\Xi_c(2970)^+] = 31.7 \pm 1.7 \pm 1.9\,\text{MeV},$$
$$m[\Xi_c(3080)^+] = 3076.8 \pm 0.7 \pm 1.3 \pm 0.2\,\text{MeV},$$
$$\Gamma[\Xi_c(3080)^+] = 6.8 \pm 2.3 \pm 0.9\,\text{MeV},$$

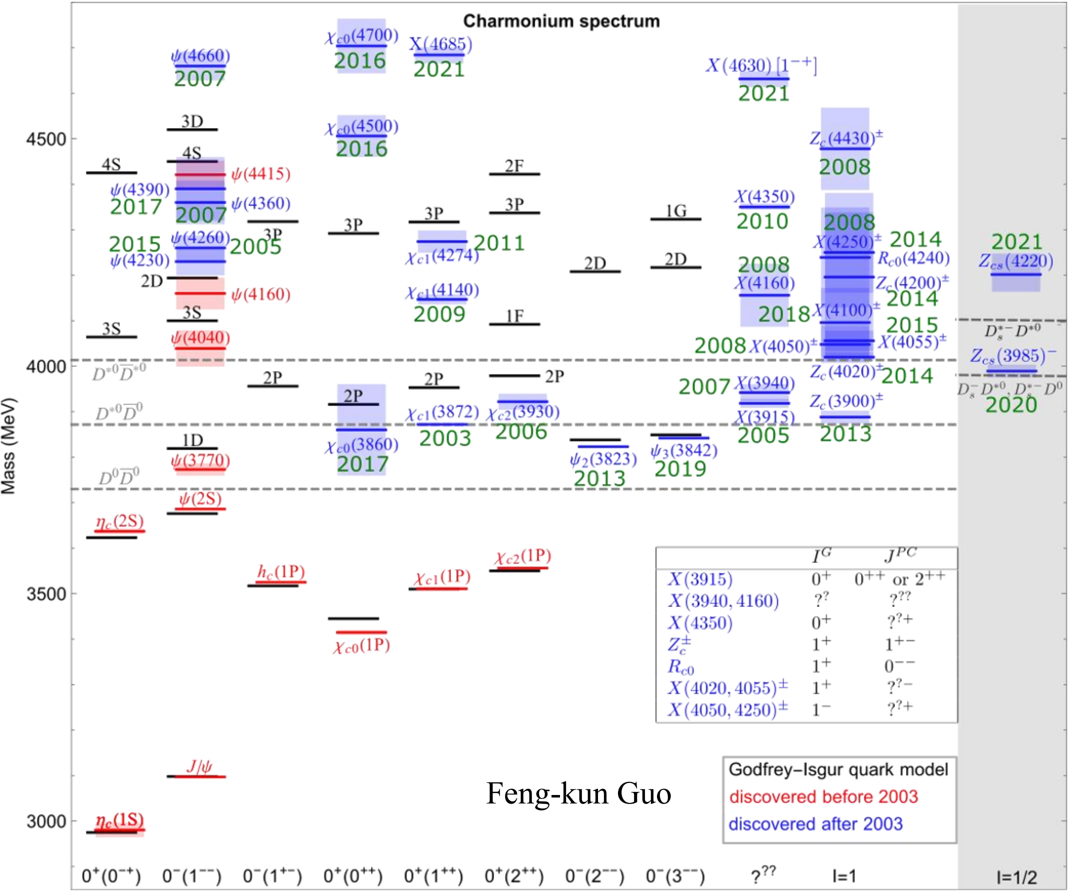
Sometimes you have surprise



$$\Lambda_c^+ = udc,\ \Sigma_c^{++} = uuc,\ \Sigma_c^+ = udc,\ \Sigma_c^0 = ddc,$$
$$\Xi_c^+ = usc,\ \Xi_c^0 = dsc,\ \Omega_c^0 = ssc$$

- **Five new, narrow excited Ω_c^0 states observed: $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, $\Omega_c(3119)^0$**
- **Feed down contributions from $\Omega_c(3066)^0 \to \Xi_c'^+ K^-$**
- **With more data, two broad resonances $\Omega_c(3185)^0$ and $\Omega_c(3327)^0$ are found**

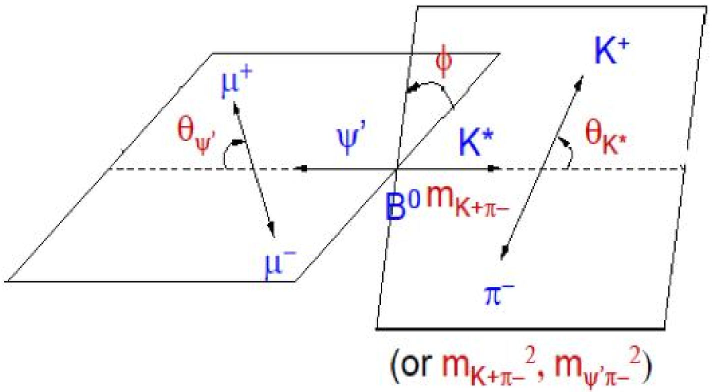
Charmonium-like particles

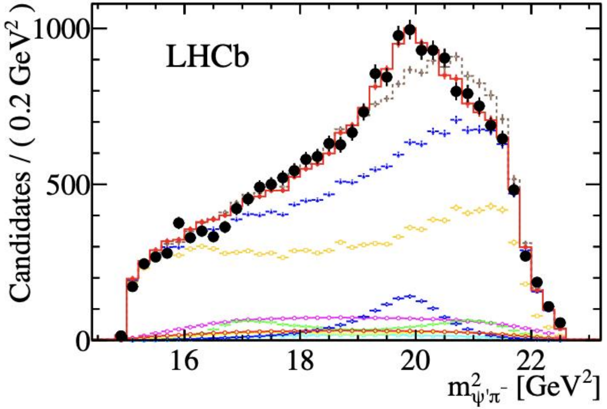


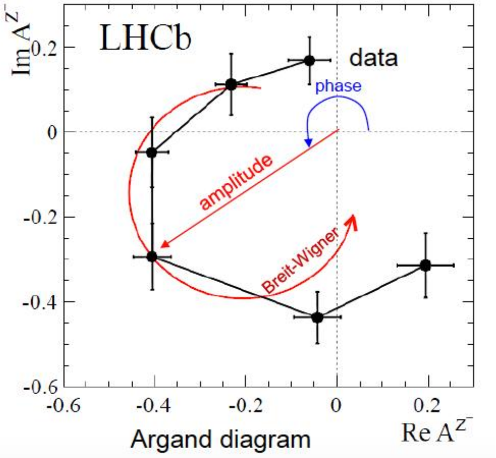
- Very crowd spectra above open-charm threshold, much more than predicted by $c\bar{c}$ model
- Many J^{PC} not determined
- Charged states (Z_c, Z_{cs}) can't be explained by $c\bar{c}$ model
- Little overlap between B decays and e^+e^- production
- …

$Z_c(4430)^+$

- First claimed by Belle in $B^0 \to \psi(2S)K^+\pi^-$ using 1D fit to $m(\psi(2S)K^+)$, later using 2D analysis
- However, Babar disfavors its existence using MI approach
- Smoking gun for multi-quark states
- LHCb performs a full 4D amplitude analysis, confirming its existence (several new methods widely used later developed here)
- Not only $Z_c(4430)^+$ but also gives a new resonance: $Z_c(4200)^+$

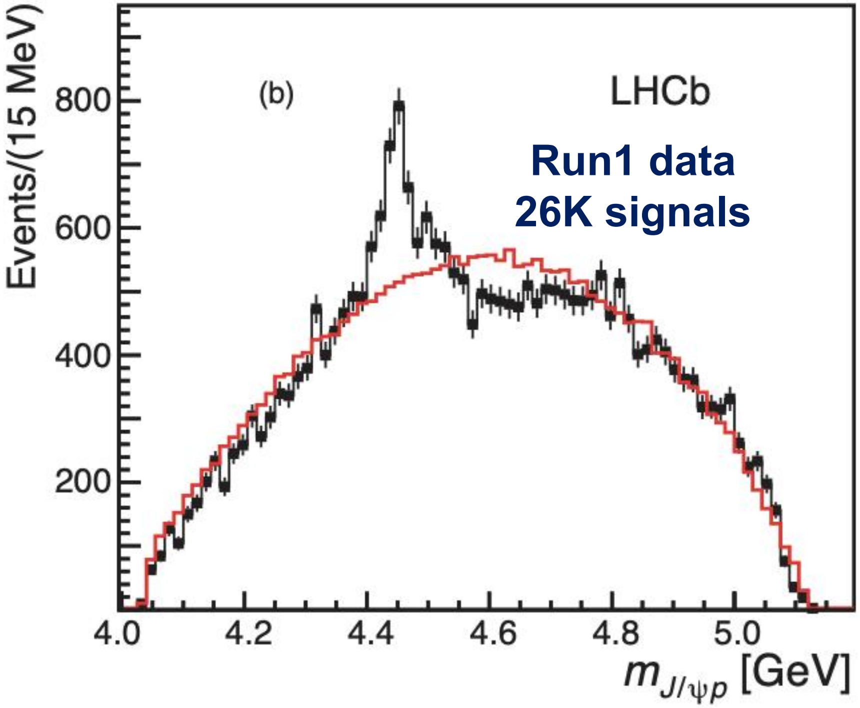


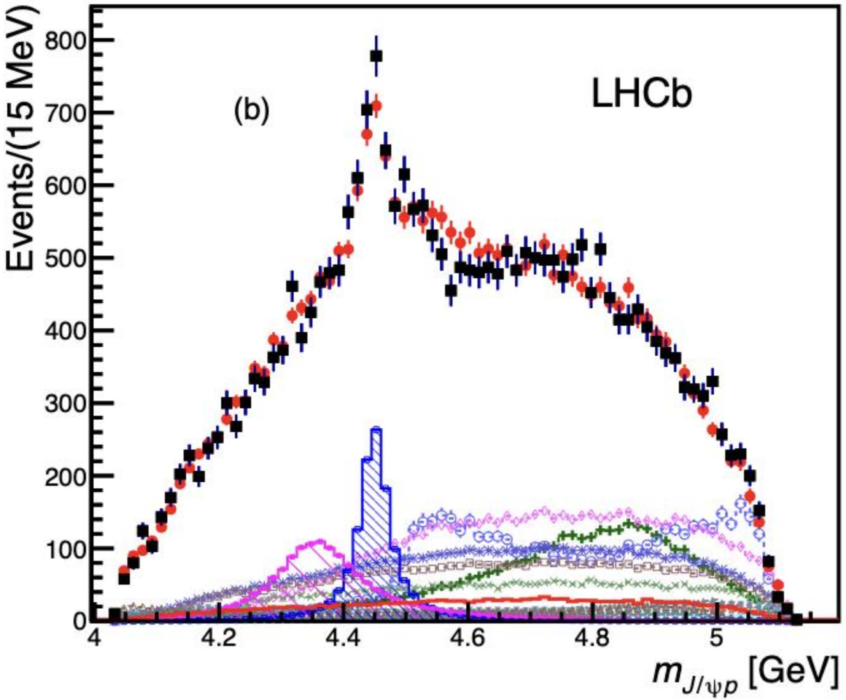




P_c

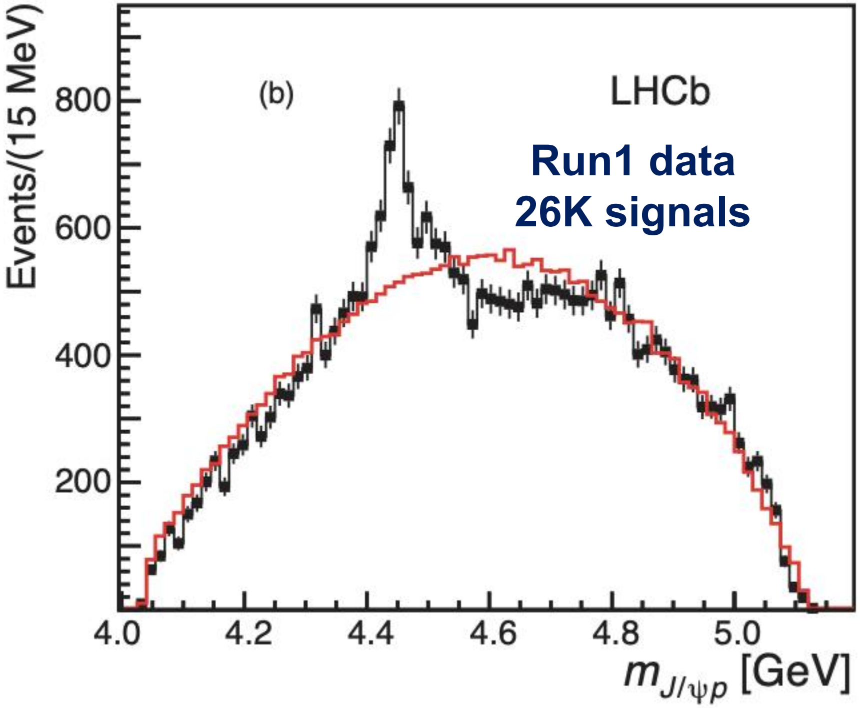
- **First analyzed by LHCb using Run1 data, discovering for states: $P_c(4380)$ and $P_c(4450)$ decaying to $J/\psi p$, first ever generally agreed pentaquark states**

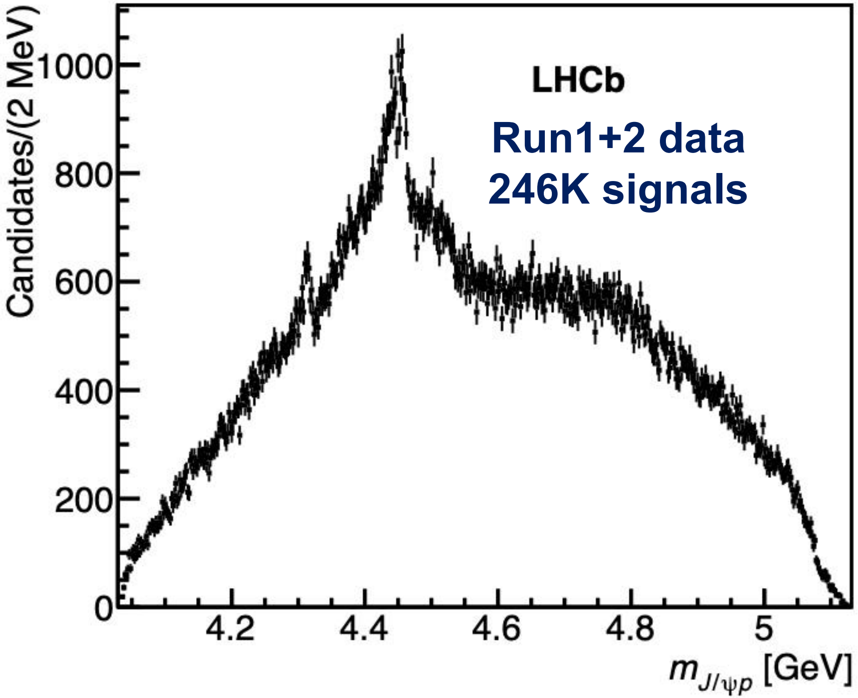




Statistic matters

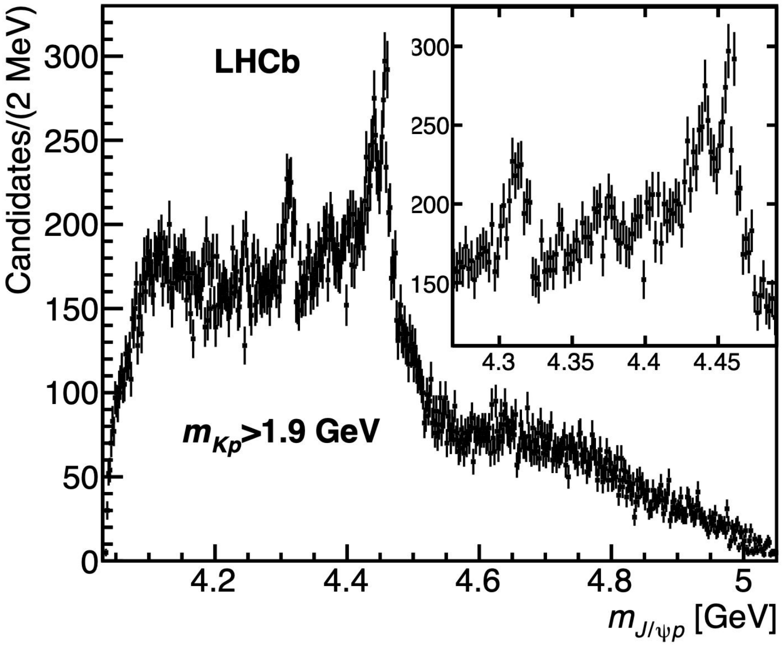
- Further analyzed by LHCb using Run1+2 data, more structures are seen
- More is different

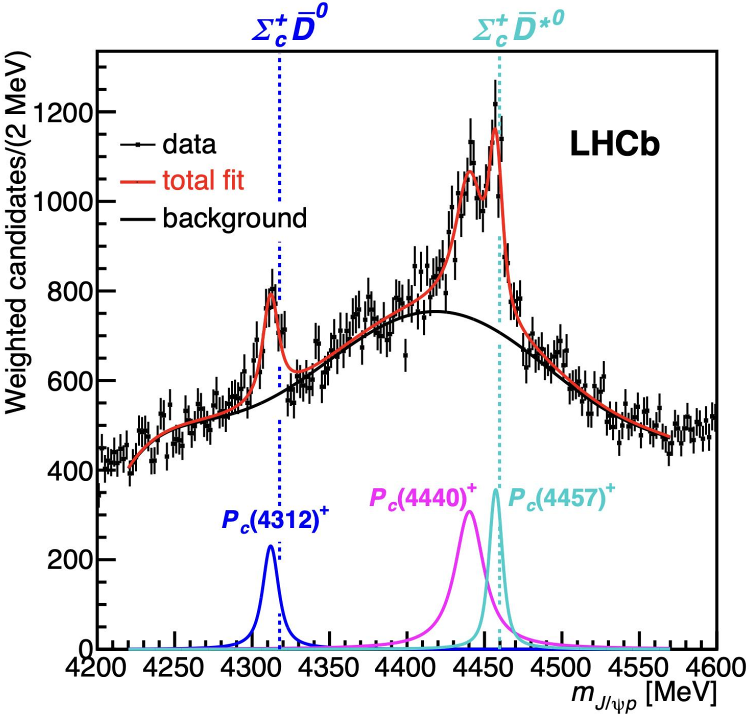




Statistic matters

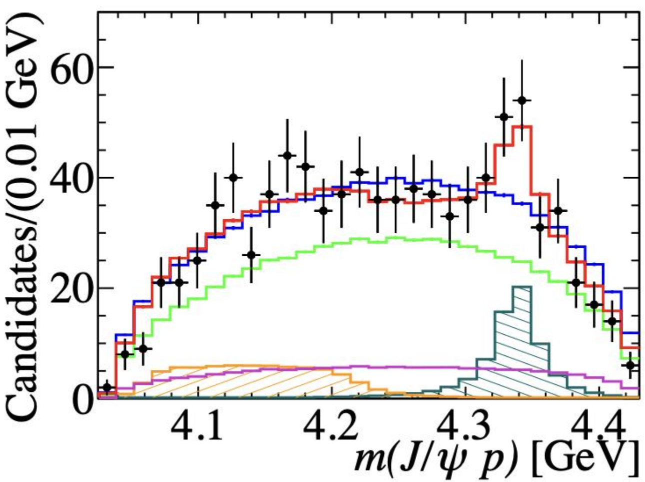
- **One more $P_c(4312)$ seen just below $\Sigma_c^+\bar{D}^0$ threshold**
- **Previously found $P_c(4450)$ becomes two narrow resonances, $P_c(4440)$ and $P_c(4457)$**





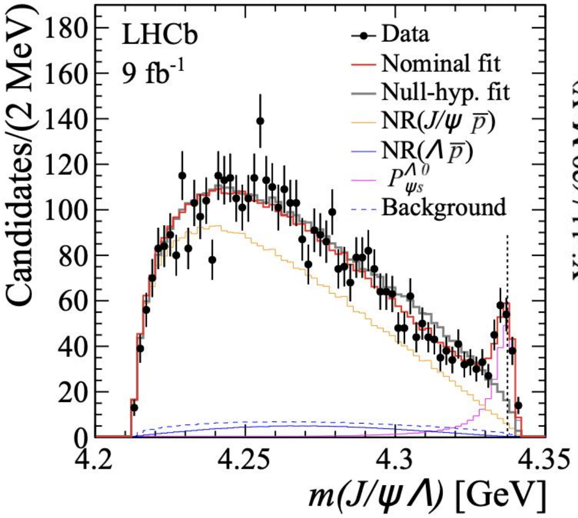
More pentaquark searches

$B^0 \to J/\psi p\bar{p}$



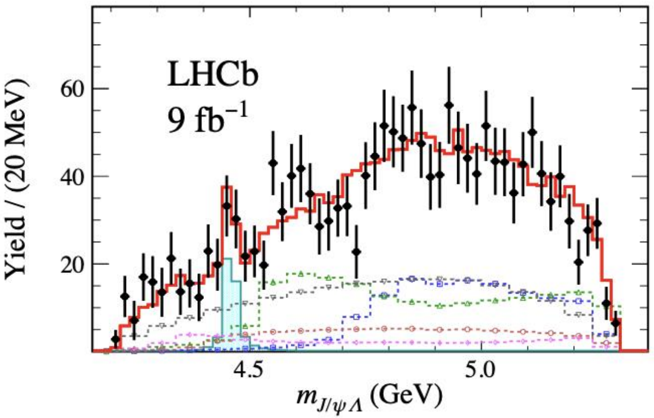
$m_0 \sim 4312$ MeV
$\sim 3.x\sigma$

$B^- \to J/\psi \Lambda \bar{p}$



$m_0 \sim 4338$ MeV
$\Gamma_0 \sim 7$ MeV
$J^P = 1/2^-$

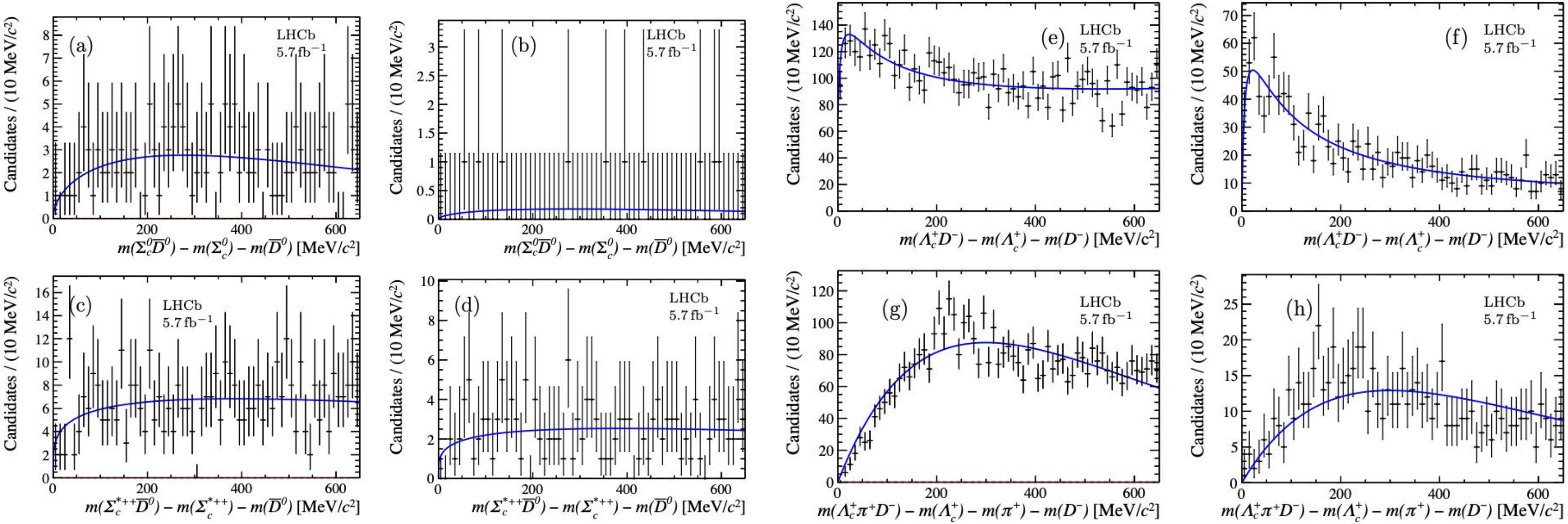
$\Xi_b^- \to J/\psi \Lambda K^-$



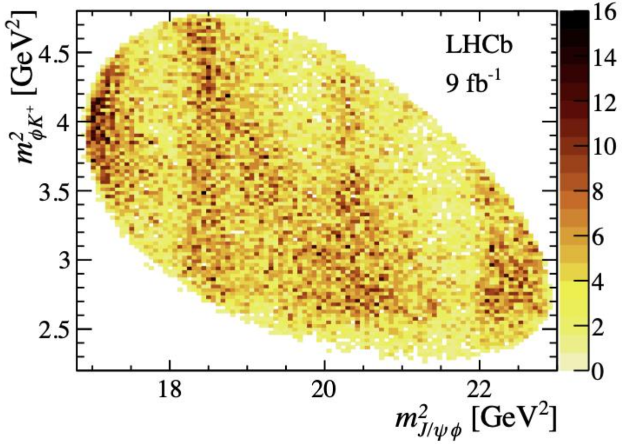
$m_0 \sim 4459$ MeV
$\sim 3.1\sigma$

Null results means

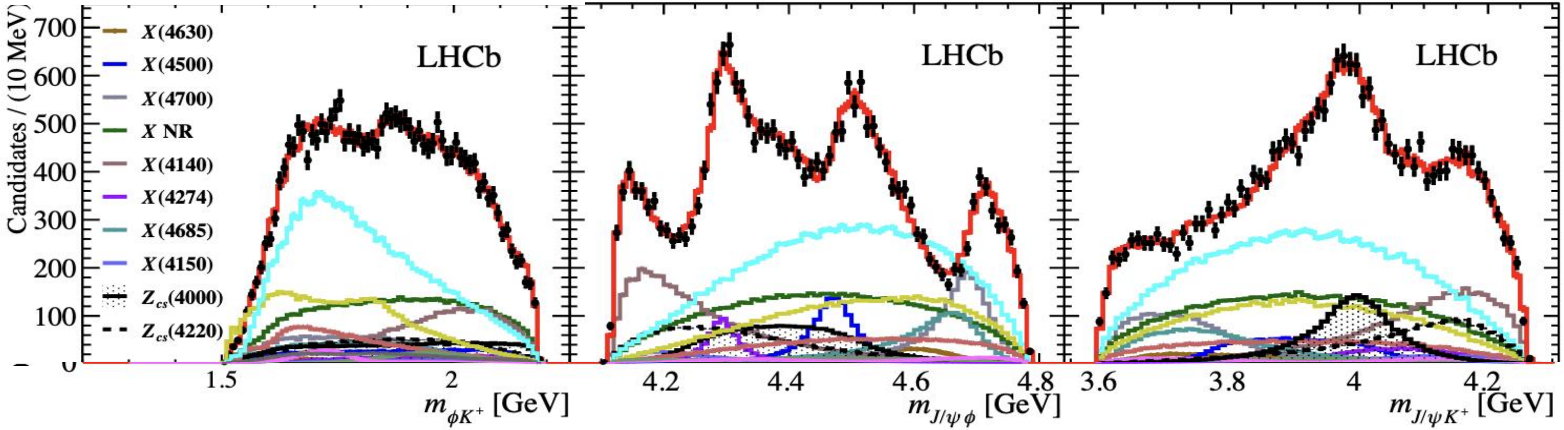
- **Many searches also performed in other channels, none found either due to non-P_c in the channel or small statistics**
- **However, these also provide important constraints on different models and help understand nature of hadrons**



A decay with many exotic states



- **First analyzed by LHCb using Run1 data, discovering for states: $X(4140)$, $X(4274)$, $X(4500)$, $X(4700)$ decaying to $J/\psi\phi$**
- **Later, using full Run1+2 data, two more states decaying into to $J/\psi\phi$, $X(4630)$, $X(4685)$ observed together with two states, $Z_{cs}(4000)^+$, $Z_{cs}(4220)^+$ decaying to $J/\psi K^+$**



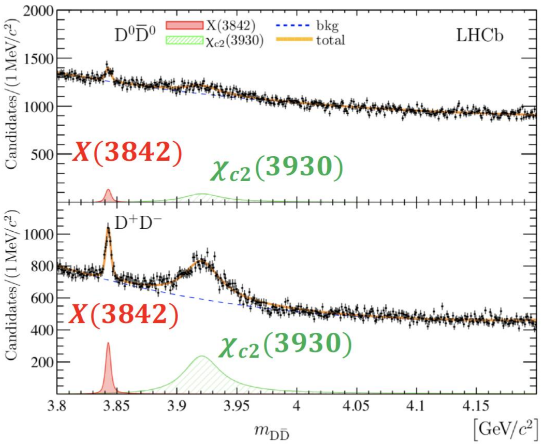
Puzzles around 3930 MeV

Summary of previous PDG $D_s^+ D_s^-$ threshold: 3936.68 MeV

	J^{PC}	Mass(MeV)	Width(MeV)	Decays
$X(3915)$	$0^{++}/2^{++}$	3918.4 ± 1.9	20 ± 5	$J/\psi\omega, \gamma\gamma$, ! $D\bar{D}$
$\chi_{c2}(3930)$	2^{++}	3922.2 ± 1.0	35.3 ± 2.8	$\gamma\gamma, D\bar{D}$

BaBar, Belle

- **$X(3915)$ less likely to be $\chi_{c0}(2P)$ [1208.1134, 1410.6534] due to its small width and mass close to $\chi_{c2}(3930)$, while now $\chi_{c0}(2P)$ is assigned to a state around 3860 MeV (not seen in $B^+ \to D^+D^-K^+$).**



		$m_{\chi_{c2}(3930)}$ [MeV/c^2]	$\Gamma_{\chi_{c2}(3930)}$ [MeV]
Belle	[17]	$3929 \pm 5 \pm 2$	$29 \pm 10 \pm 2$
BaBar	[18]	$3926.7 \pm 2.7 \pm 1.1$	$21.3 \pm 6.8 \pm 3.6$
This analysis		$3921.9 \pm 0.6 \pm 0.2$	$36.6 \pm 1.9 \pm 0.9$

- **LHCb measurements from inclusive DD channels show difference on the mass and width, 2σ lower mass and 2σ larger width (two states or one?)**
- **PDG values driven by LHCb inclusive measurements**

Puzzles around 3930 MeV

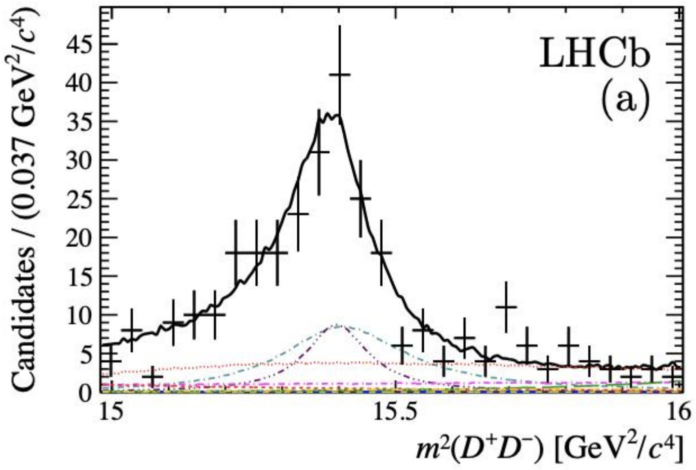
Summary of previous PDG

$D_s^+ D_s^-$ threshold: 3936.68 MeV

	J^{PC}	Mass(MeV)	Width(MeV)	Decays
$X(3915)$	$0^{++}/2^{++}$	3918.4 ± 1.9	20 ± 5	$J/\psi\omega, \gamma\gamma,$! $D\bar{D}$
$\chi_{c2}(3930)$	2^{++}	3922.2 ± 1.0	35.3 ± 2.8	$\gamma\gamma, D\bar{D}$

BaBar, Belle

- **LHCb measurements with $B^+ \to D^+D^-K^+$ also gives inputs**



Resonance	Mass (GeV/c^2)	Width (MeV)
$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$

- **Two resonances seen in DD decays, with J=0 and J=2; probably two in previous results**
- **It also puts the question whether this spin 0 particle = X(3915)? (PDG now said yes)**
- **Hard to be in 2P triplets, thus may prefer exotic nature;**

Another 0^{++}

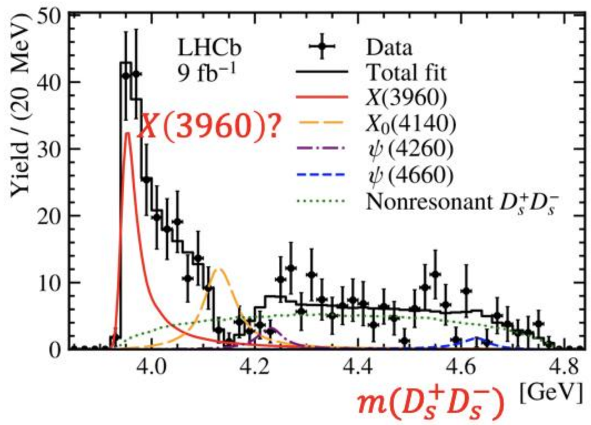
$D_s^+ D_s^-$ threshold: 3936.7 MeV

Nature of the three states?

Resonances	J^{PC}	M_0 (MeV)	Γ_0 (MeV)	Decays	References
$X(3960)$	0^{++}	$3956 \pm 5 \pm 11$	$43 \pm 13 \pm 8$	$D_s^+ D_s^-$	This work
$\chi_{c0}(3930)$	0^{++}	$3923.8 \pm 1.5 \pm 0.4$	$17.4 \pm 5.1 \pm 0.8$	$D^+ D^-$	PRD102.112003(2020)
$\chi_{c0}(3915)$	$0^{++}/2^{++}$	3921.7 ± 1.8	18.8 ± 3.5	$J/\psi\omega$, $\gamma\gamma$	PDG 2022

- A new state $X(3960)$ discovered in $D_s^+ D_s^-$ final state
- Mass and width differ by around 3σ and 2σ, respectively

$$\frac{\Gamma(X \to D^+ D^-)}{\Gamma(X \to D_s^+ D_s^-)} = \frac{\mathcal{B}^{(1)} \mathcal{F}_X^{(1)}}{\mathcal{B}^{(2)} \mathcal{F}_X^{(2)}} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08,$$



- Phase space of $D_s^+ D_s^-$ smaller than $D^+ D^-$
- Suspiciously smaller branching fraction into $D^+ D^-$ final states: different resonances or a tetraquark with $c\bar{c}s\bar{s}$

21 years ago

- First heavy exotic candidate containing $c\bar{c}$, opening a new field of research ($D_{s0}^*(2317)$ and $D_{s1}^*(2460)$ at the same year)


Observation of a narrow charmonium-like state in exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ decays

Belle Collaboration • S.K. Choi (Gyeongsang Natl. U.) Show All(174)

Sep, 2003 Sep, 2003

10 pages

Published in: *Phys.Rev.Lett.* 91 (2003) 262001

e-Print: hep-ex/0309032 [hep-ex]

DOI: 10.1103/PhysRevLett.91.262001

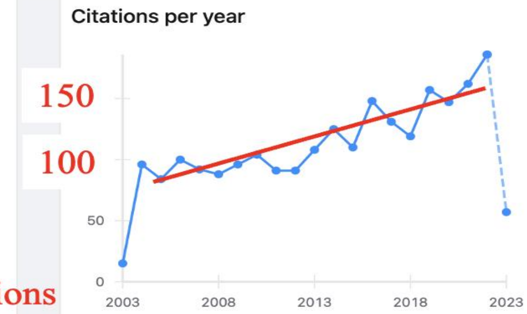
PDG: chi_c1(3872) --> pi+ pi- J/psi(1S) Show All(5)

Experiments: KEK-BF-BELLE

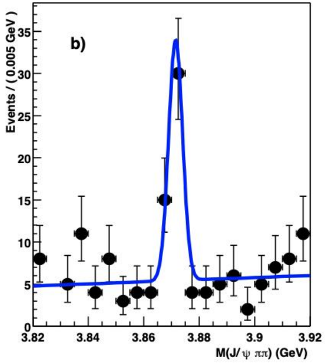
View in: ADS Abstract Service

pdf links cite claim reference search 2,307 citations

2307 citations



- Only around 36 signal $X(3872)$ events observed
- Aim: looking for 1^3D_2
- Surprise: find $X(3872)$ and it is not likely to be 1^3D_2
- Now: possible have 2^3P_1 component



Structure of $\chi_{c1}(3872)$

- **Important to discover new state, however, more importantly, to understand already discovered states**
- **Properties extensively studied, usually leading to different conclusions**

Mass: very close to $D^0\bar{D}^{*0}$, $m_{D^0} + m_{\bar{D}^{*0}} - m_{\chi_{c1}(3872)} = 0.01 \pm 0.14$ MeV

Width: narrow width (0.1~1 MeV)

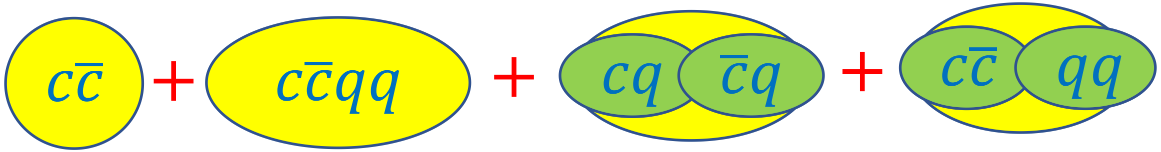
J^{PC}: 1^{++}

Decay: $D^0\bar{D}^{*0}$ (~35%), $J/\psi\omega$ (~4%), $J/\psi\rho$ (~3%)

Production: pp, $p\bar{p}$, B decays, pPb, PbPb

Molecular like
Charmonium like

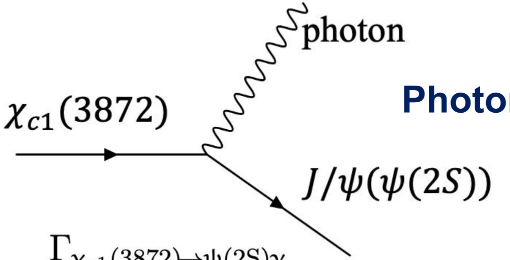
$\chi_{c1}(3872) =$



Can we determine contributions of different components?

Structure of $\chi_{c1}(3872)$

arXiv:2406.17006
PRL124(2020)242001



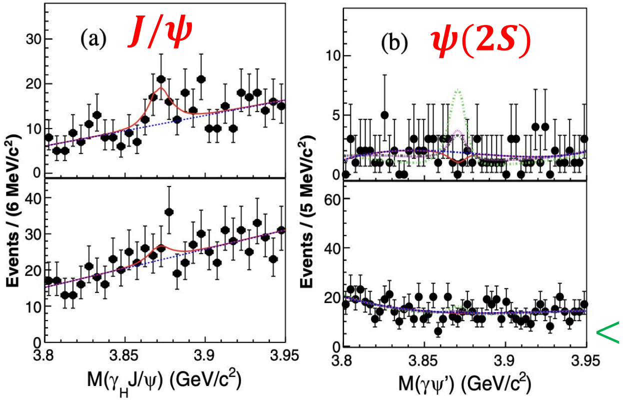
Photon to probe its structure

$$\mathscr{R}_{\psi\gamma} \equiv \frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}}$$

T. Barnes and S. Godfrey	[67]	5.8	$c\bar{c}$
T. Barnes, S. Godfrey and S. Swanson	[69]	2.6	$c\bar{c}$
F. De Fazio	[84]	(1.64 ± 0.25)	$c\bar{c}$
B.-Q. Li and K. T. Chao	[85]	1.3	$c\bar{c}$
Y. Dong *et al.*	[86]	$1.3 - 5.8$	$c\bar{c}$
A. M. Badalian *et al.*	[87]	(0.8 ± 0.2)	$c\bar{c}$
J. Ferretti, G. Galata and E. Santopinto	[88]	6.4	$c\bar{c}$
A. M. Badalian, Yu. A. Simonov and B. L. G. Bakker	[89]	2.4	$c\bar{c}$
W. J. Deng *et al.*	[90]	1.3	$c\bar{c}$
F. Giacosa, M. Piotrowska and S. Goito	[71]	5.4	$c\bar{c}$/vc
E. S. Swanson	[81]	0.38 %	$D\bar{D}^*$
Y. Dong *et al.*	[86]	0.33 %	$D\bar{D}^*$
D. P. Rathaud and A. K. Rai	[91]	0.25	$D\bar{D}^*$
R. F. Lebed and S. R. Martinez	[92]	0.33 %	$D\bar{D}^*$
B. Grinstein, L. Maiani and A. D. Polosa	[93]	3.6 %	$D\bar{D}^*$
F.-K. Guo *et al.*	[82]	$0.21(g_2'/g_2)^2$	$D\bar{D}^*$
D. A.-S. Molnar, R. F. Luiz and R. Higa	[83]	$2 - 10$	$D\bar{D}^*$
E. Cincioglu *et al.*	[94]	< 4	$D\bar{D}^*$
S. Takeuchi, M. Takizawa and K. Shimizu	[95]	$1.1 - 3.4$	$D\bar{D}^*$
B. Grinstein, L. Maiani and A. D. Polosa	[93]	$> (0.95^{+0.01}_{-0.07})$	$c\bar{c}q\bar{q}$

$c\bar{c}$

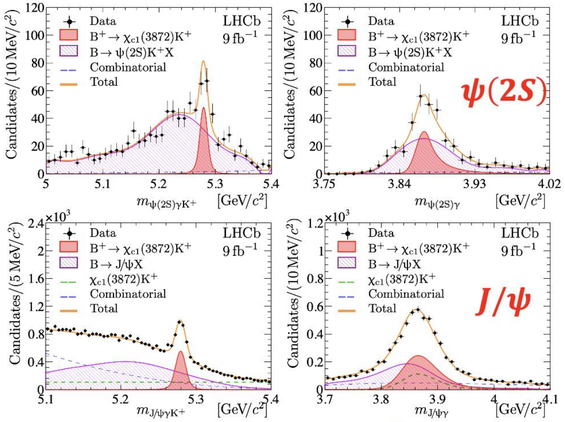
$D\bar{D}^*$



$\psi \to \mu^+\mu^-$

$\psi \to e^+e^-$

< 0.59 @ 90 C.L.



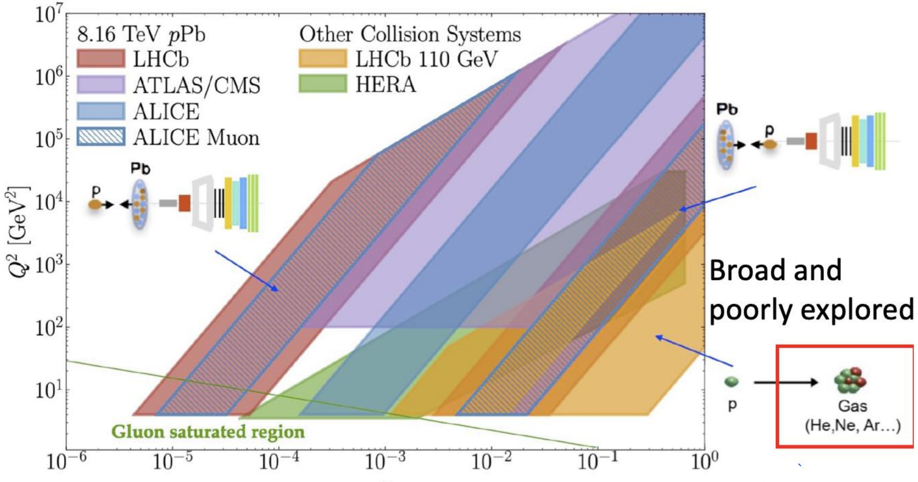
1.67 ± 0.25

***B* mass** **$\psi\gamma$ mass**

Fixed target experiment

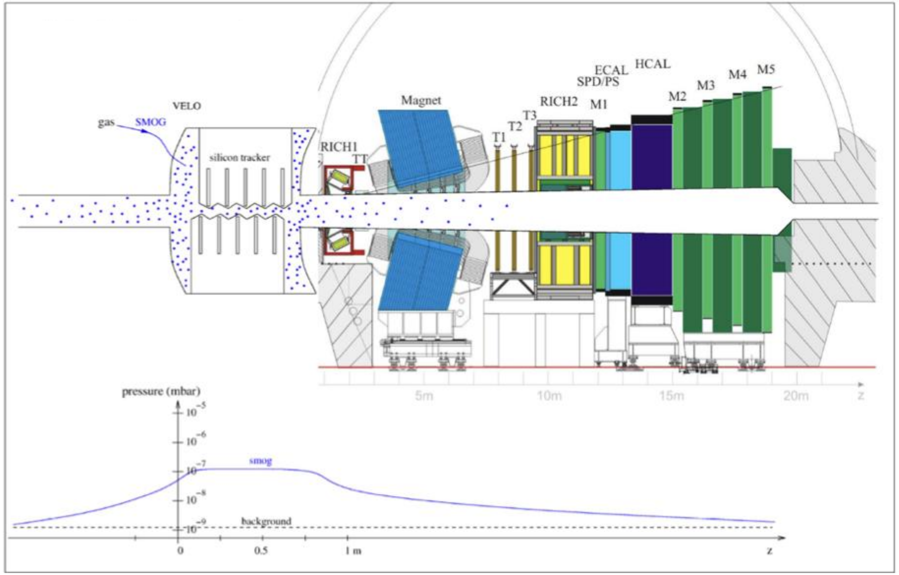
- **LHCb could also be a fixed target experiment to study properties of QGP; i.e. study suppression of quarkonium production in QGP vs pp collisions**
- **But it could also be used to understand properties of exotic particles**

$Q^2 \sim m^2 + p_T^2$



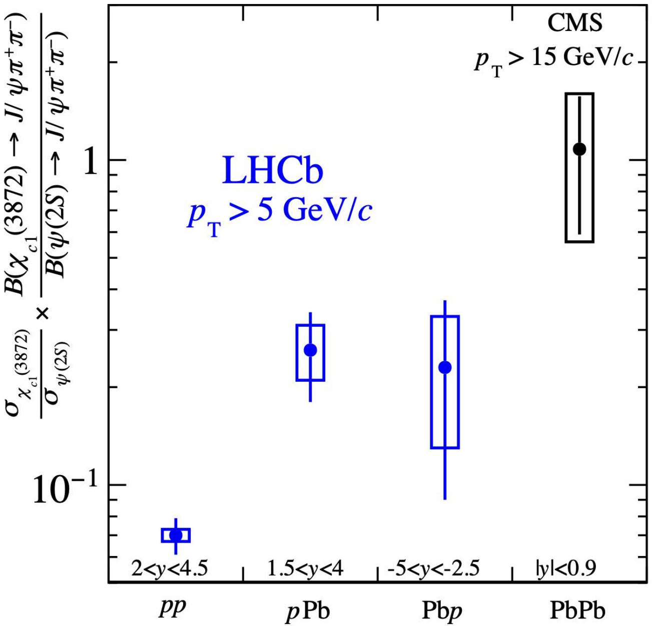
(QGP)

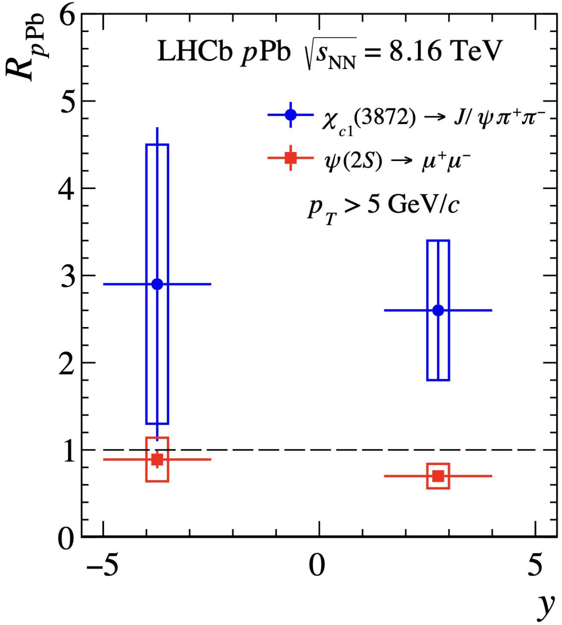
$x \sim \frac{Q}{\sqrt{s_{NN}}} e^{-\eta}$



$\chi_{c1}(3872)$ in heavy ion collision

- LHCb could also be a fixed target experiment to study properties of QGP; i.e. study suppression of quarkonium production in QGP vs pp collisions
- But it could also be used to understand properties of exotic particles

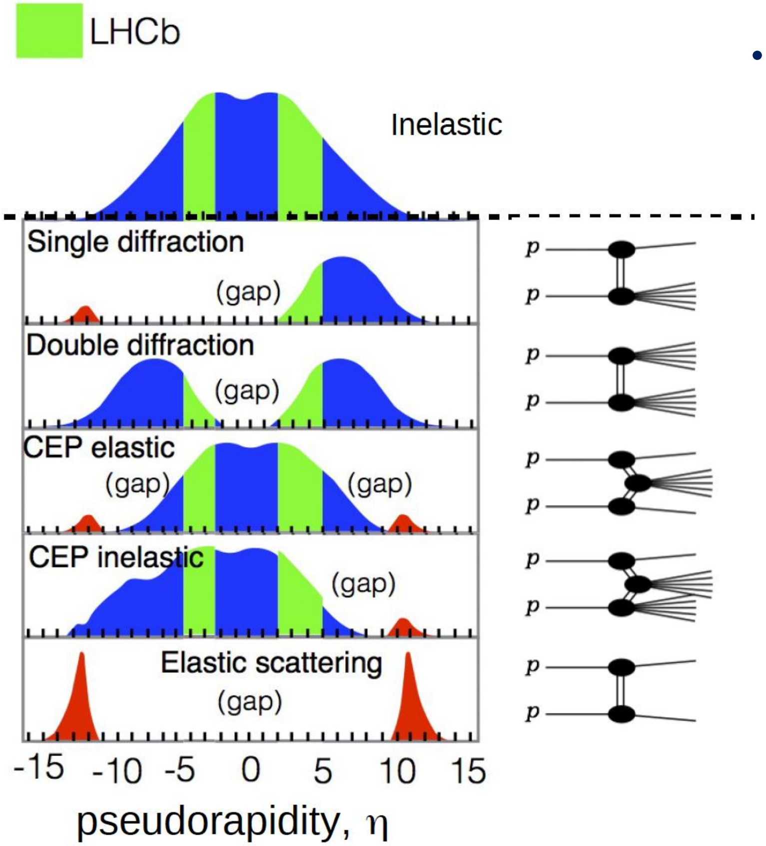




$$R_{pA}^{\chi_{c1}(3872)} = \frac{\sigma_{pA}^{\chi_{c1}(3872)}}{208 \times \sigma_{pp}^{\chi_{c1}(3872)}}$$

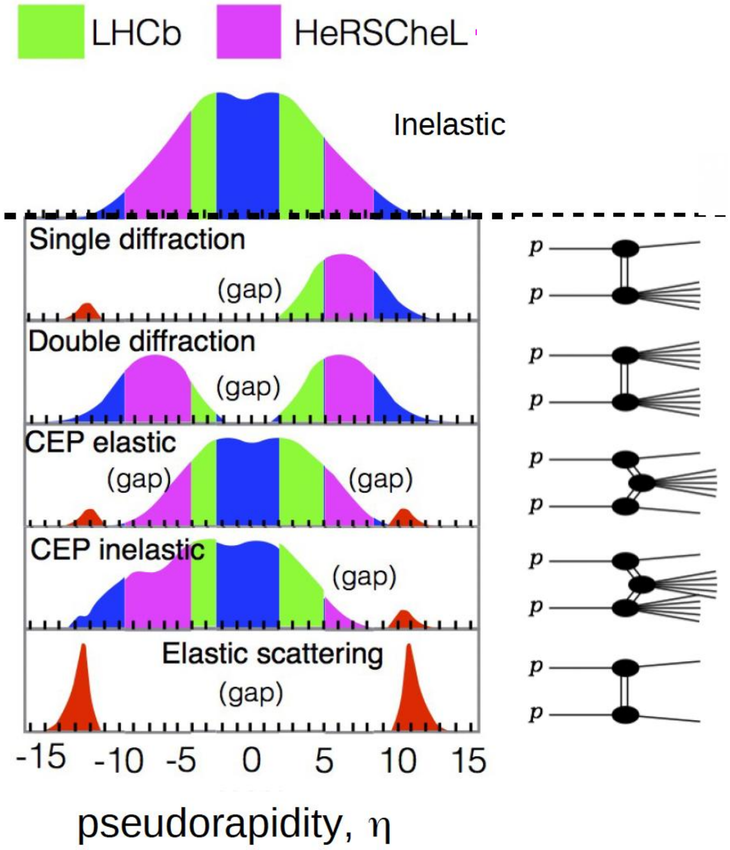
What does it mean if $\chi_{c1}(3872)$ larger than 1 while $\psi(2S)$ smaller than 1?

Central exclusive production

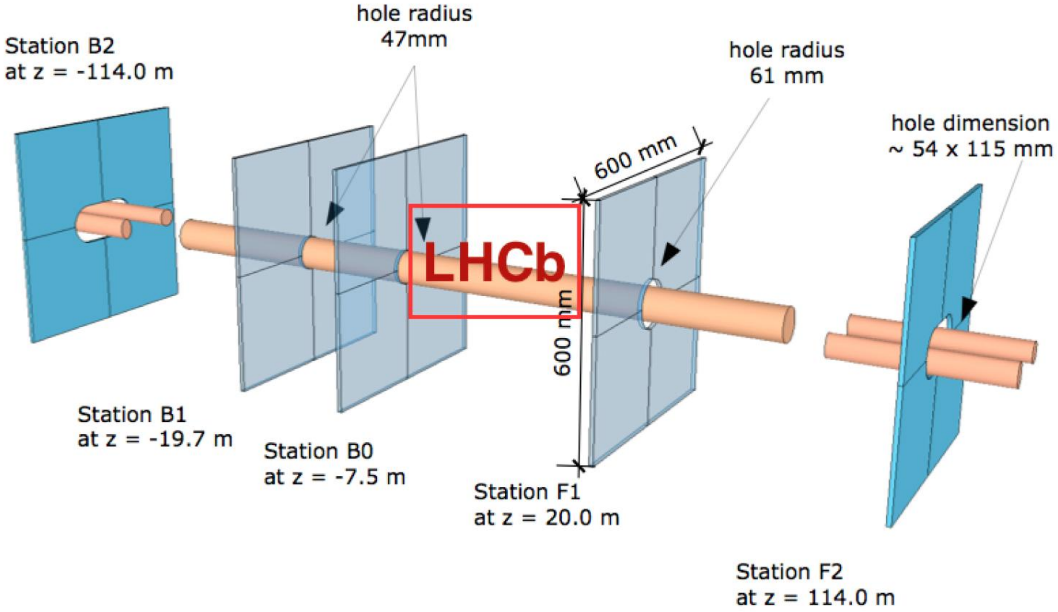


- **Collision events without any other activities except the studied one**

HeRSCheL

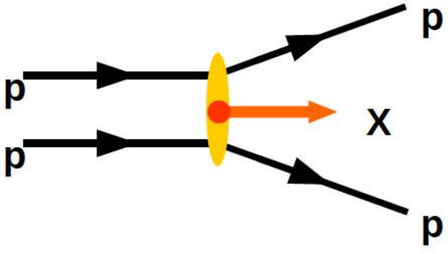


- **Scintillator with PMT (High Rapidity Shower Conter for LHCb)**

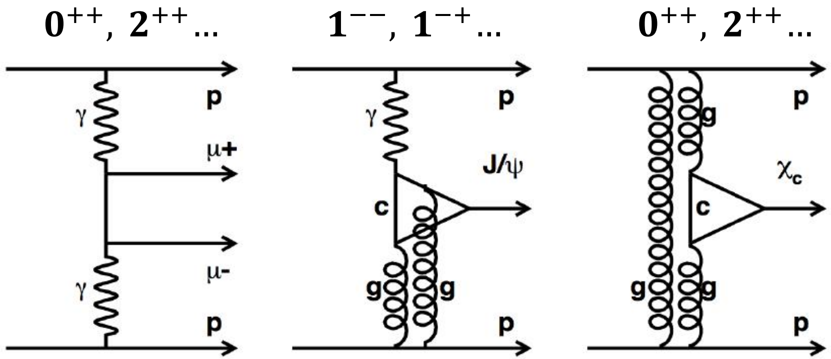


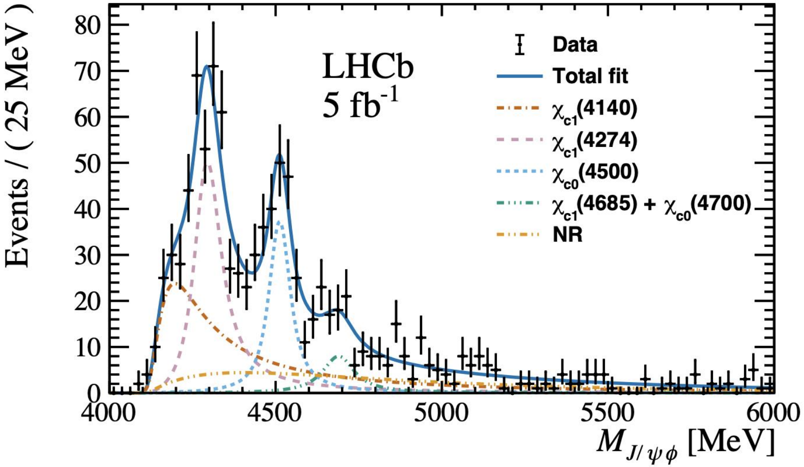
Exotic particle in CEP

- An unique environment to study QCD



, e.g.,





- Several states seen in $B^+ \to J/\psi\phi K$ also seen here
  - $\chi_{c1}(4140),\ 1^{--}$: 2.4σ
  - $\chi_{c1}(4274),\ 1^{--}$: 4.3σ
  - $\chi_{c0}(4500),\ 0^{++}$: 5.5σ
  - $\chi_{c1}(4685) + \chi_{c0}(4700)$: 1.6$\sigma$

Experimental inputs

Particle X = $c\bar{c}$ + $c\bar{c}qq$ + cq $\bar{c}q$ + $c\bar{c}$ qq + $c\bar{c}g$ ...

$cq\,\bar{c}q$ → **Charm + charm + X**

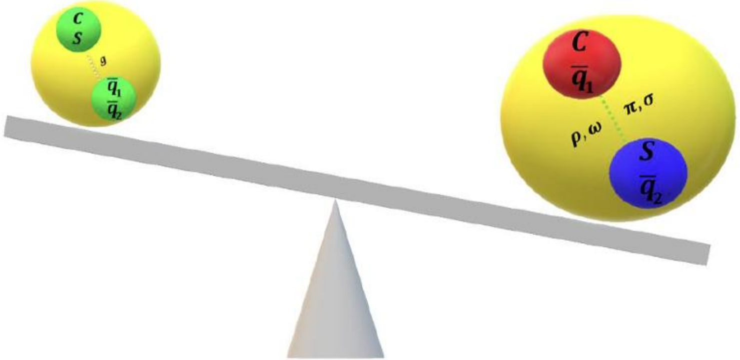
$c\bar{c}g$ → **charmonium + X**

Experimental tasks:

Discover more and understand them through production and decays

$$\frac{\Gamma(X(3872)\to \bar{D}D^*)}{\Gamma(X(3872)\to J/\psi\pi^+\pi^-)} = 9.1^{+3.4}_{-2.0}$$

$$\frac{\Gamma(Z_c(3885)\to \bar{D}D^*)}{\Gamma(Z_c(3885)\to J/\psi\pi)} = 6.2 \pm 1.1 \pm 2.7$$



However, studies with $B \to DDX$ decays rather limited

C parity

$$B^+ \to D^{*+} D^- K^+$$

$$B^+ \to D^{*-} D^+ K^+$$

$$B^+ \to X K^+,\ X \to \begin{cases} D^{*+} D^- \\ D^{*-} D^+ \end{cases}$$

- $B^+ \to XK^+$: weak decay, violate C and P
- $X \to D^* D$: strong decay, obey C and P symmetry

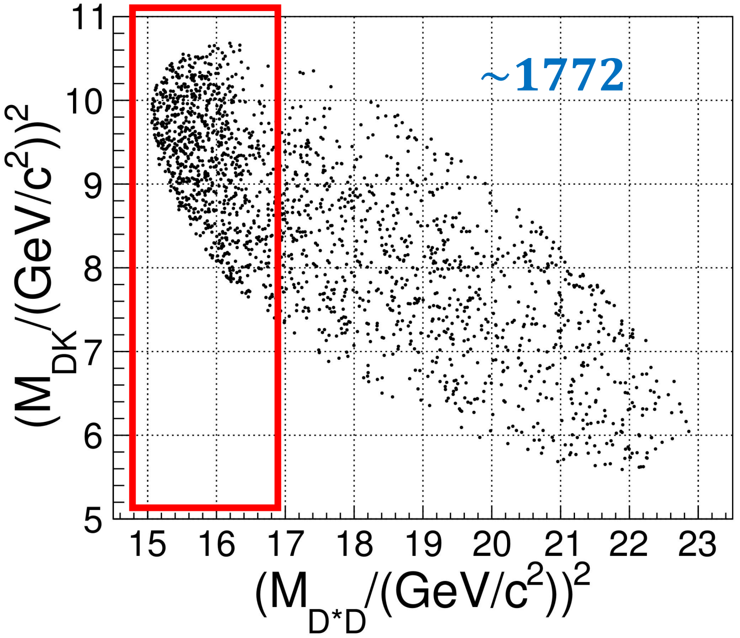
$\mathrm{C} = 1$: $|D^{*+} D^- > + |D^{*-} D^+ >$ → $A(X \to D^{*+} D^-) = A(X \to D^{*-} D^+)$

$\mathrm{C} = -1$: $|D^{*+} D^- > - |D^{*-} D^+ >$ → $A(X \to D^{*+} D^-) = -A(X \to D^{*-} D^+)$

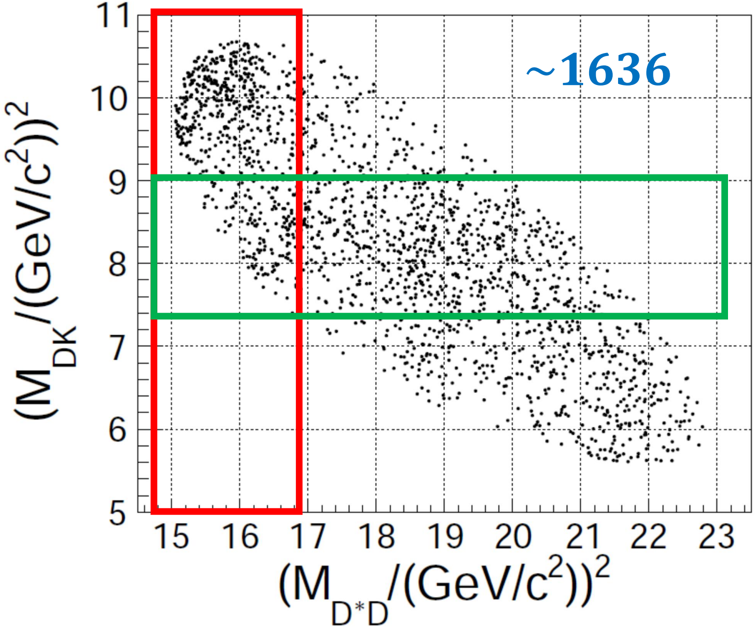
The first time, amplitude analysis can tell the C-parity of resonant particles, decaying not in the C eigenstates

Dalitz plot

$B^+ \to D^{*-} D^+ K^+$



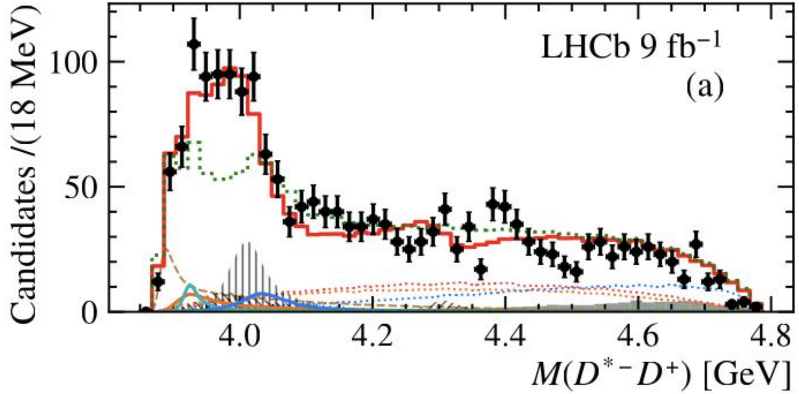
$B^+ \to D^{*+} D^- K^+$



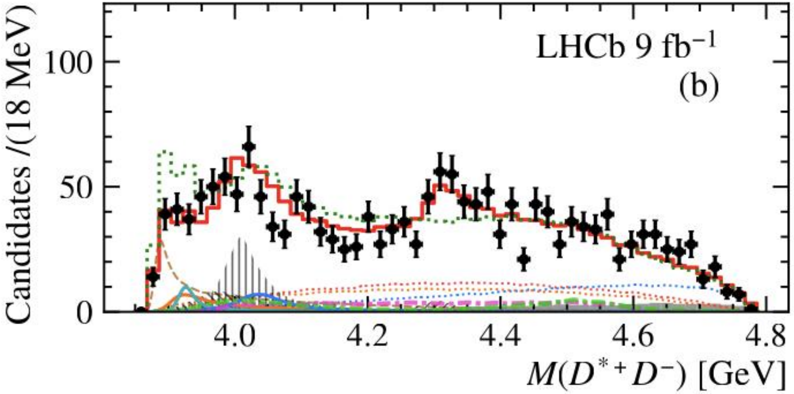
- Clear difference due to interference of different C parities
- Contributions from T^*_{cs} seen in one channel

Spectrum of $M(D^*D)$

$B^+ \to D^{*-}D^+K^+$



$B^+ \to D^{*+}D^-K^+$



$J^P = 0^-$
- $C = +1$: NR + $\eta_c(3945)$
- $C = -1$: NR

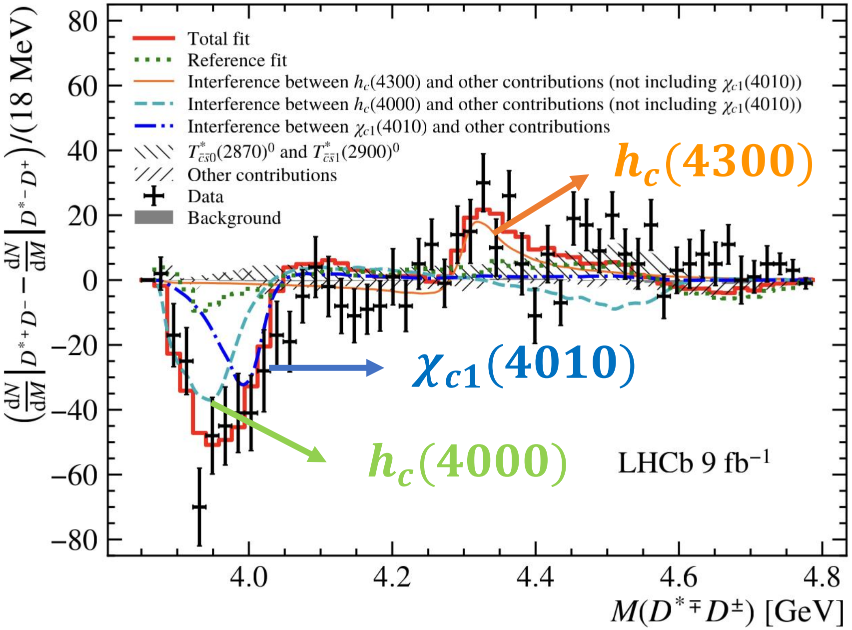
$J^P = 1^+$
- $C = +1$: NR + EFF + $\chi_{c1}(4010)$
- $C = -1$: $h_c(4000) + h_c(4300)$

$J^P = 2^{++}$: $\chi_{c2}(3930)$

$J^P = 1^{--}$: NR + $\psi(4040)$

Resonances well separated from each other except 1^{++}; more theoretically motivated model for future analysis

Three new states



Decay 1:

$$|A_1 + A_2|^2 = |A_1|^2 + |A_2|^2 + 2Re(A_1A_2^*)$$

Decay 2:

$$|A_1 + CA_2|^2 = |A_1|^2 + |A_2|^2 + 2CRe(A_1A_2^*)$$

Difference: C: relative C parity of A_2 to A_1

$$2(C-1)Re(A_1A_2^*)$$

Different J^P: $\int Re(A_1A_2^*) = 0$

$J^P = 1^+$
- $C = +1$: NR + EFF + $\chi_{c1}(4010)$
- $C = -1$: $h_c(4000) + h_c(4300)$

Only interference with same J^P but different C party remains

$h_c(4000)$

$h_c(4000): 1^{+-}$

$m_0 = 4000^{+17+29}_{-14-22}$ MeV

$\Gamma_0 = 184^{+71+97}_{-45-61}$ MeV

Significance: 9.1σ

$T_{c\bar{c}}(4020)^0: C = -1$

$m_0 = 4025.5^{+2.0}_{-4.7} \pm 3.1$ MeV

$\Gamma_0 = 23 \pm 6.0 \pm 1.0$ MeV

$e^+e^- \to (D^*\overline{D^*})^0\pi^0$

$h_c(2P): 1^{+-}$

$m_0 = 3956$ MeV

$\Gamma_0 = 87$ MeV

QM Predictions

Also prediction by wang et al.

Width much larger than $T_{c\bar{c}}(4020)^0$, potential candidate for $h_c(2P)$

1^+ resonance modeled by

$$f_{R,S/D}(m) = \frac{\gamma_{S/D}}{m_0^2 - m^2 - im_0[\gamma_S^2\Gamma_S(m) + \gamma_D^2\Gamma_D(m)]},$$

$$\Gamma(m) = \Gamma_0(m_0/m)\,(q/q_0)^{2l+1}\,B_l'^2(q, q_0, d) \qquad \gamma_S^2 + \gamma_D^2 = 1$$

$h_c(4300)$

$h_c(4300): 1^{+-}$

$m_0 = 4307.3^{+6.4+3.3}_{-6.6-4.1}$ MeV

$\Gamma_0 = 58^{+28+28}_{-16-25}$ MeV

$\chi_{c1}(4274): 1^{++}$

$m_0 = 4294 \pm 4^{+6}_{-3}$ MeV

$\Gamma_0 = 53 \pm 5 \pm 5$ MeV

$h_c(3P): 1^{+-}$

$m_0 = 4318$ MeV

$\Gamma_0 = 75$ MeV

Significance: 6.4σ

QM Predictions

$\chi_{c1}(3P): 1^{++}$

$m_0 = 4317$ MeV

$\Gamma_0 = 39$ MeV

Another state $\chi_{c1}(4274)$ at similar mass, however with different C parity; new state potentially $h_c(3P)$

$\chi_{c1}(4010)$

$\chi_{c1}(4010): 1^{++}$

$m_0 = 4012.5^{+3.6+4.1}_{-3.9-3.7}$ MeV

$\Gamma_0 = 62.7^{+7.0+6.4}_{-6.4-6.6}$ MeV

$\chi_{c1}(3872): 1^{++}$

$m_0 = 3871.64 \pm 0.06$ MeV

$\Gamma_0 = 1.19 \pm 0.21$ MeV

$\chi_{c1}(2P): 1^{++}$

$m_0 = 3953$ MeV

$\Gamma_0 = 165$ MeV

Significance: 16σ

QM Predictions

Lattice prediction

Puzzles with $\chi_c(2P)$

$\chi_{c0}(2P)$: current assigned to $\chi_{c0}(3860)$, however, not confirmed by other experiments; relationship with $X(3915)$ and $\chi_{c0}(3930)$ not clear

$\chi_{c1}(2P)$: mass (width) much smaller than QM predictions; relationship with $\chi_{c1}(4010)$ not clear

Prediction by wang et al. and Deng et al.

$\eta_c(3945)$

$\eta_c(3945)$: 0^{-+}

$m_0 = 3945^{+28+37}_{-17-28}$ MeV

$\Gamma_0 = 130^{+92+101}_{-49-70}$ MeV

$X(3940)$: $?^{??}$

$m_0 = 3942 \pm 9$ MeV

$\Gamma_0 = 37^{+27}_{-17}$ MeV

$\eta_c(3S)$: 0^{-+}

$m_0 = 4064$ MeV

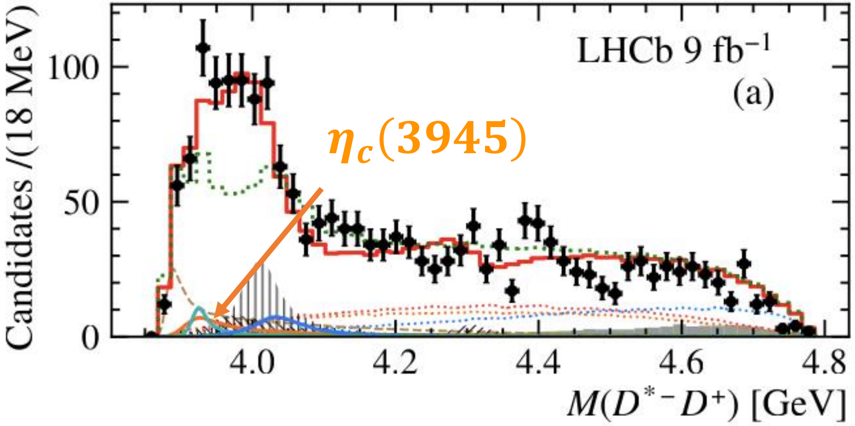
$\Gamma_0 = 80$ MeV

Significance: 10σ

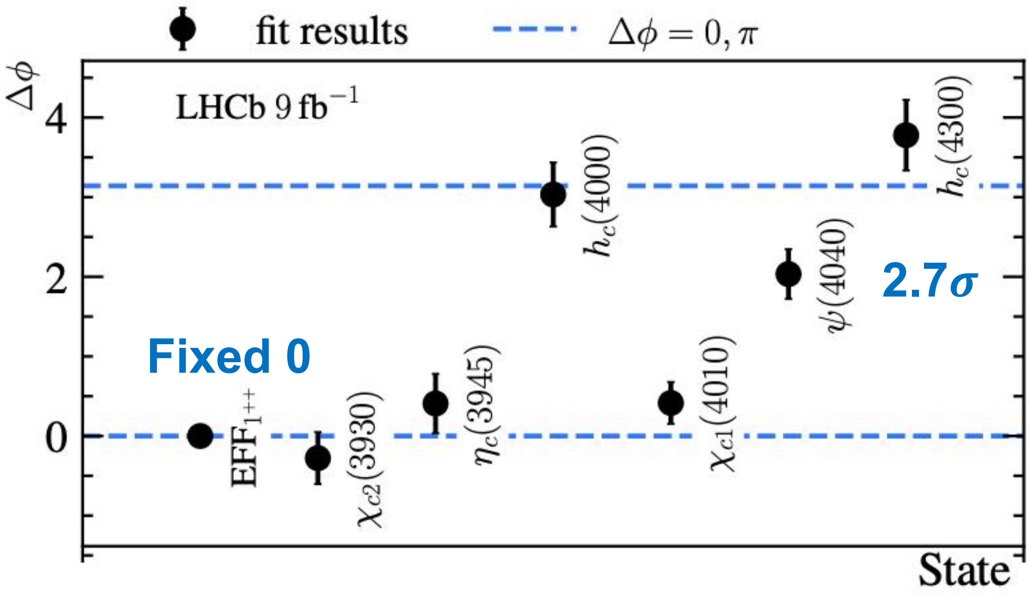
$e^+e^- \to \left(D^{(*)}\overline{D^{(*)}}\right)^0 J/\psi$

QM Predictions

Mass and width consistent with $X(3940)$, while J^{PC} now determined



Confirmation of C relationship



$$A^{R\to D^{*+}D^{-}}_{\lambda_R,\lambda_{D^{*+}},0} = C_R A^{R\to D^{*-}D^{+}}_{\lambda_R,\lambda_{D^{*-}},0} \Rightarrow A^{R\to D^{*+}D^{-}}_{\lambda_R,\lambda_{D^{*+}},0} = e^{i\Delta\phi} A^{R\to D^{*-}D^{+}}_{\lambda_R,\lambda_{D^{*-}},0}$$

$$C_R = 1 \Rightarrow \Delta\phi = 0, \quad C_R = -1 \Rightarrow \Delta\phi = \pi$$

More than spectroscopy

Flavor measurements

Understanding QCD at low energy

↓

Non-perturbative

↓

Short distance + long distance

New physics hunting

↓

Short distance

↓

$$\Gamma = (\text{Weak})\ (\text{EM})\ (\text{QCD})$$

Experimental measurements

Precisely calculated by QED

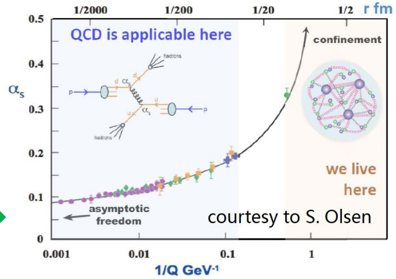
Tasks of flavor and hadron physics

- SM model very successful;
- Still an effective theory, many unexplained phenomena;
- Most related to flavor and hadron physics

Understanding QCD at low energy

- Properties of QCD confinement
- Structures of hadrons

Non-perturbative!

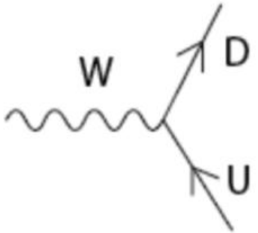


New Physics hunting

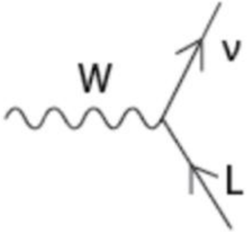
- Matter and antimatter asymmetry observed in the Universe
- Origin of dark matter? New particles or new forces? Flavor hierarchy

EW Standard Model

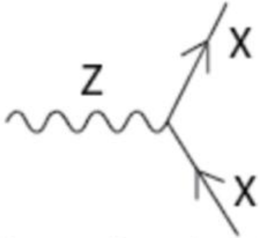
- **Interactions we see in EW SM**



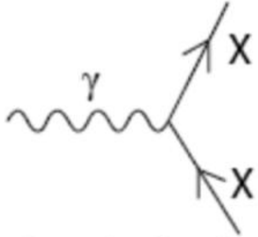
U is a up-type quark;
D is a down-type quark.



L is a lepton and v is the corresponding neutrino.



X is any fermion in the Standard Model.



X is electrically charged.

$$\mathcal{L}_{CC} = \frac{g}{\sqrt{2}}\left(J_\mu^+ W^{+\mu} + J_\mu^- W^{-\mu}\right), \qquad \mathcal{L}_{NC} = eJ_\mu^{em}A^\mu + \frac{g}{\cos\theta_W}\left(J_\mu^3 - \sin^2\theta_W J_\mu^{em}\right)Z^\mu.$$

$$J_\mu^+ = \bar{U}_L^I \gamma_\mu D_L^I + \bar{\nu}_L^I \gamma_\mu \ell_L^I,$$

Only left handed

$$J_\mu^3 = \frac{1}{2}\left[\bar{U}_L^I\gamma_\mu U_L^I - \bar{D}_L^I\gamma_\mu D_L^I + \bar{\nu}_L^I\gamma_\mu\nu_L^I - \bar{\ell}_L^I\gamma_\mu\ell_L^I\right],$$

$$J_\mu^{em} = \frac{2}{3}\left(\bar{U}_L^I\gamma_\mu U_L^I + \bar{U}_R^I\gamma_\mu U_R^I\right) - \frac{1}{3}\left(\bar{D}_L^I\gamma_\mu D_L^I + \bar{D}_R^I\gamma_\mu D_R^I\right) - \left(\bar{\ell}_L^I\gamma_\mu\ell_L^I + \bar{\ell}_R^I\gamma_\mu\ell_R^I\right)$$

EM part couples to both left and right handed
J_μ^3 left handed, however, Z couples to both

Yukawa

- The mass matrix defined as

$$\mathcal{L}_{Yukawa} = -\sum_{i,j=1}^{n_g}\left[\lambda_{ij}^{D}\bar{D}_{Li}^{I}D_{Rj}^{I} + \lambda_{ij}^{U}\bar{U}_{Li}^{I}U_{Rj}^{I} + \lambda_{ij}^{\ell}\bar{\ell}_{Li}^{I}\ell_{Rj}^{I} + h.c.\right]\frac{v}{\sqrt{2}}\left(1+\frac{h}{v}\right)$$

$$M_{ij}^{D} \equiv \frac{v}{\sqrt{2}}\lambda_{ij}^{D}, \quad M_{ij}^{U} \equiv \frac{v}{\sqrt{2}}\lambda_{ij}^{U}, \quad M_{ij}^{\ell} \equiv \frac{v}{\sqrt{2}}\lambda_{ij}^{\ell}$$

- Diagonalize it:

$$V_L^U M^U V_R^{U\dagger} = M_{diag}^U \qquad V_L^D M^D V_R^{D\dagger} = M_{diag}^D$$

- We have two eigenstates: interaction and mass eigenstates

$$\begin{pmatrix} u_L \\ c_L \\ t_L \end{pmatrix} = V_L^U \begin{pmatrix} u_L^I \\ c_L^I \\ t_L^I \end{pmatrix} \qquad \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} = V_L^D \begin{pmatrix} d_L^I \\ s_L^I \\ b_L^I \end{pmatrix}$$

Unitary

Unitary

CKM matrix

- **The mass matrix defined as**

$$\mathcal{L}_{CC} = \frac{g}{\sqrt{2}}\left(J_\mu^+ W^{+\mu} + J_\mu^- W^{-\mu}\right), \qquad J_\mu^+ = \bar{U}_L^I \gamma_\mu D_L^I + \bar{\nu}_L^I \gamma_\mu \ell_L^I,$$

$$J_\mu^+ = \bar{U}_L \gamma_\mu V_{CKM} D_L + \bar{\nu}_L \gamma_\mu \ell_L,$$

=

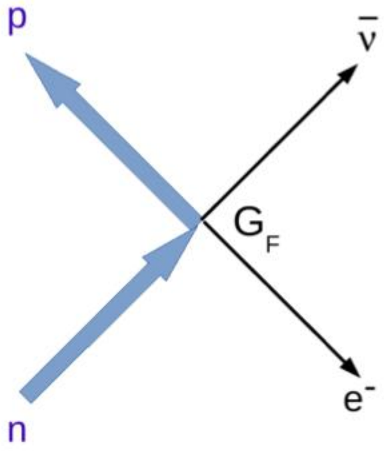
CKM closely related to Yukawa couplings

$$\begin{pmatrix} d^I \\ s^I \\ b^I \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Unitary

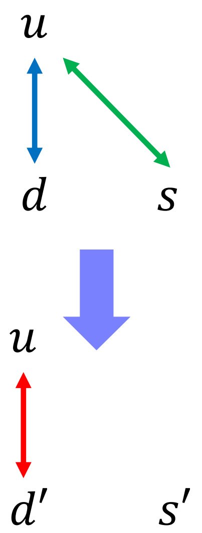
Cabibbo angle

- **1963, Cabibbo angle**



$$n \rightarrow p + e^- + \bar{\nu}_e \ (d \rightarrow u)$$
$$\Lambda \rightarrow p + e^- + \bar{\nu}_e (s \rightarrow u)$$

20 times smaller rate



$$\begin{bmatrix} d' \\ s' \end{bmatrix} = \begin{bmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{bmatrix} \begin{bmatrix} d \\ s \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{bmatrix} \begin{bmatrix} d \\ s \end{bmatrix}$$

Lepton-hadron same strength

$$\binom{\nu_e}{e} \quad \binom{p}{n} \quad \binom{p}{\Lambda}$$

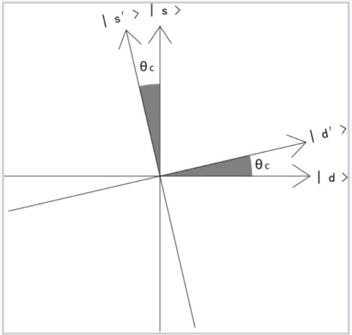
$G_F \quad G_F \cos\theta_c \quad G_F \sin\theta_c$

$\cos\theta_c \sim 0.2 \quad \cos^2\theta_c + \sin^2\theta_c = 1$

$$\binom{p}{N'}$$

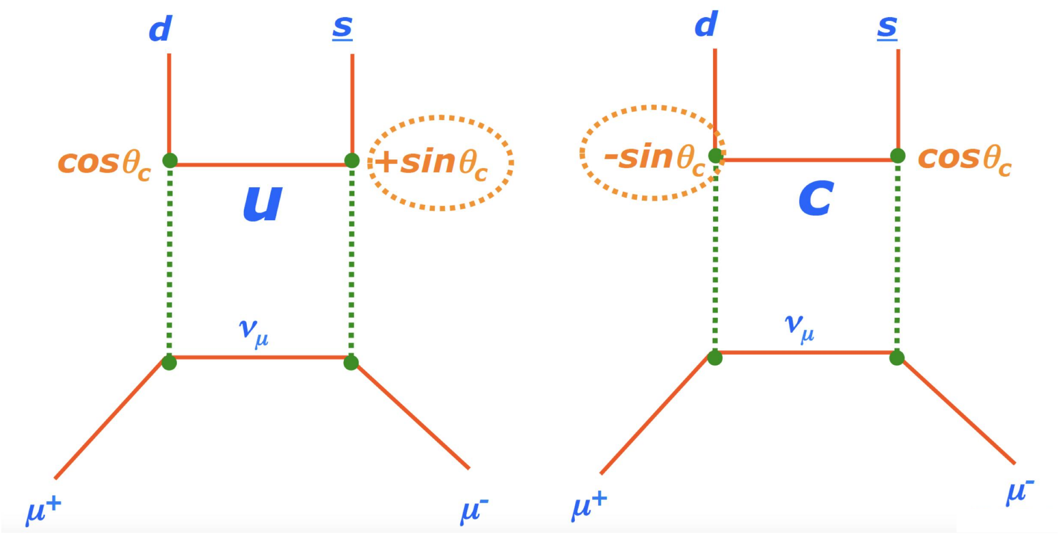
G_F

$$n = N' \cos\theta_c$$
$$\Lambda = N' \sin\theta_c$$

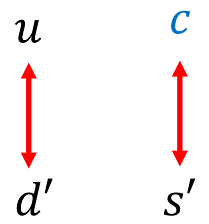


GIM mechanism

- Very small branching fraction of $K_L^0 \to \mu^+\mu^-$, $\sim 7 \times 10^{-9}$ much smaller than $K^+ \to \mu^+\nu_\mu$



$$\begin{bmatrix} d' \\ s' \end{bmatrix} = \begin{bmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{bmatrix} \begin{bmatrix} d \\ s \end{bmatrix},$$



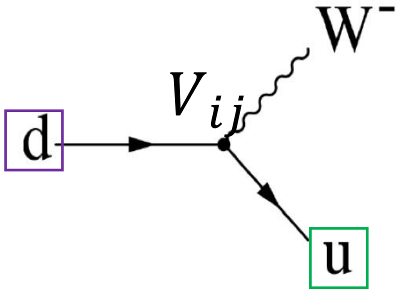
Prediction of charm quark

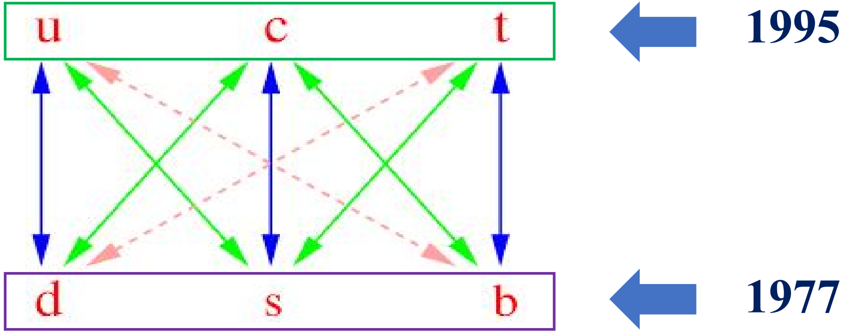
- Cancellation of amplitudes due to unitary condition of CKM matrix

CP violation mechanism

- 1974, discovery of charm quark (November revolution)

- 1973, Kobayashi and Maskawa propose third generation (needed to generate CPV, two not enough)





CKM $\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$

- An unitary matrix to indicate interacting strength between generations of quarks

- One weak phase offers CP violation in SM: $V_{ij} \neq V_{ij}^*$

How hadron physics is delt with

- **Extreme case: determine all the strong parameters + EW quantities by experimental measurements; example: CKM angle γ**

- **Middle scenario 1: constrain strong parameters using experimental measurements with theoretical assumptions; example: penguin pollution**

- **Middle scenario 2: strong parameters determined from Lattice calculations; example: determination of CKM matrix elements through semi-leptonic decays**

- **Worst case: strong parameters calculated based on models, pQCD, QCDf etc; example: charmless b decays**

What is angle γ: unitary condition

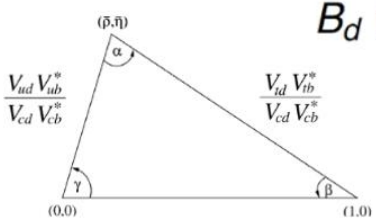
$$\begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\sum_i V_{ij}^* V_{ij} = 1 \quad \sum_j V_{ij}^* V_{ij} = 1$$

$$\sum_i V_{ij}^* V_{ik} = 0 \quad \sum_i V_{ji}^* V_{ki} = 0$$

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

B_d meson (bd)

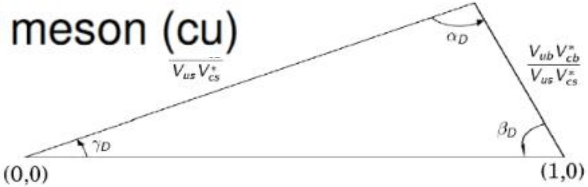


(small but non squashed)
B_D-meson triangle (bd)

$$\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} + \frac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*} + 1 = 0$$

$$V_{ud} V_{cd}^* + V_{us} V_{cs}^* + V_{ub} V_{cb}^* = 0$$

D meson (cu)



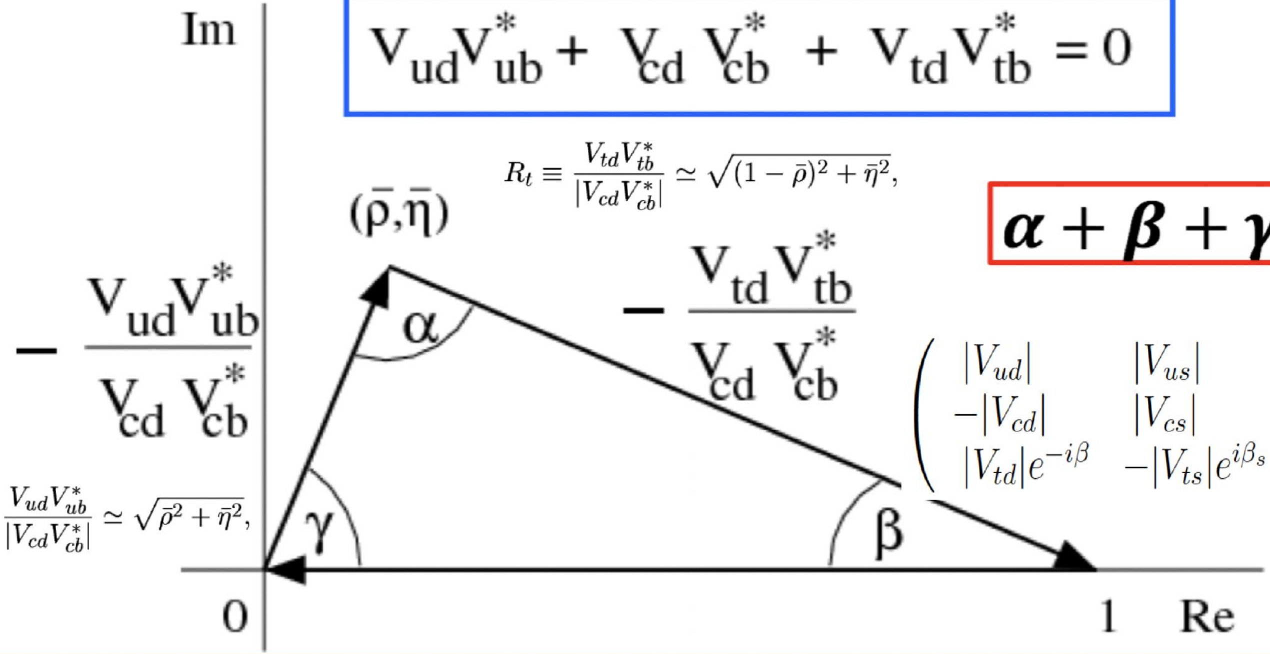
(large but squashed)
D-meson triangle (cu)

$$\frac{V_{ud} V_{cd}^*}{V_{us} V_{cs}^*} + \frac{V_{ub} V_{cb}^*}{V_{us} V_{cs}^*} + 1 = 0$$

The CKM triangle

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$\alpha + \beta + \gamma = \pi$$



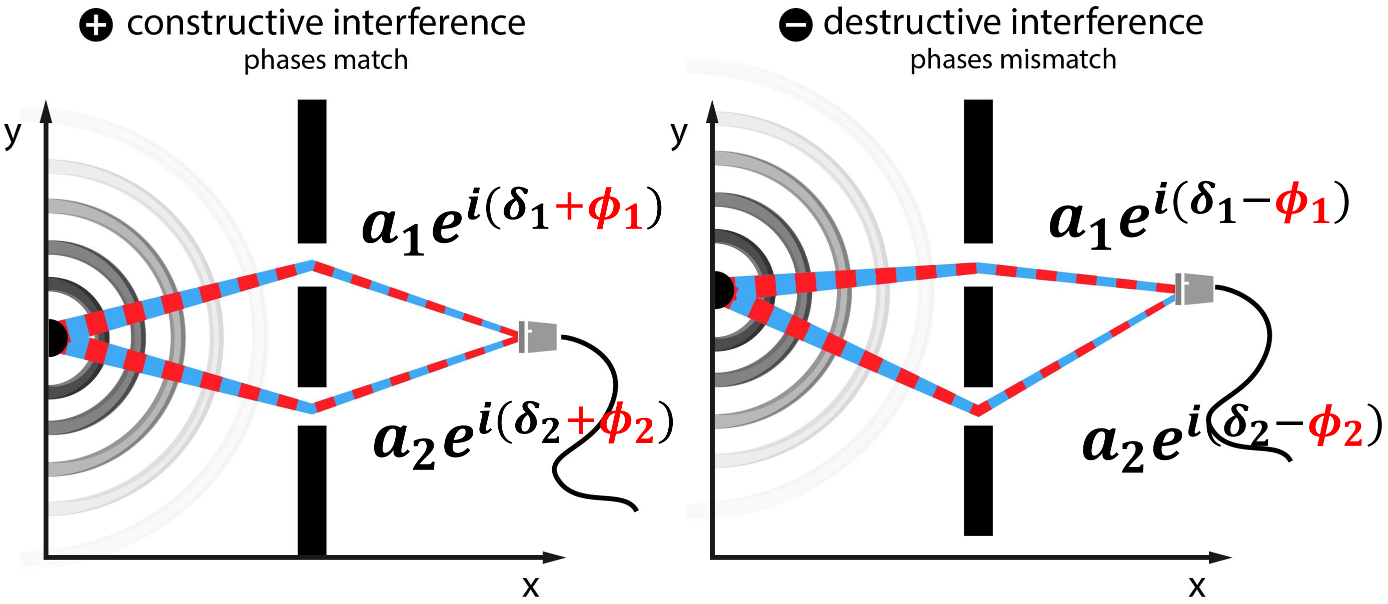
$$R_t \equiv \frac{V_{td}V_{tb}^*}{|V_{cd}V_{cb}^*|} \simeq \sqrt{(1-\bar{\rho})^2 + \bar{\eta}^2},$$

$$R_u \equiv \frac{V_{ud}V_{ub}^*}{|V_{cd}V_{cb}^*|} \simeq \sqrt{\bar{\rho}^2 + \bar{\eta}^2},$$

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] \qquad \beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right] \qquad \gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

How to generate CP violation



δ: strong phase; conserved under CP

ϕ: weak phase from CKM matrix; sign changed under CP

$$A_{CP} = \frac{|A|^2 - |\overline{A}|^2}{|A|^2 + |\overline{A}|^2} = \frac{2a_1 a_2 \sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2)}{a_1^2 + a_2^2 + 2a_1 a_2 \cos(\delta_1 - \delta_2)\cos(\phi_1 - \phi_2)}$$

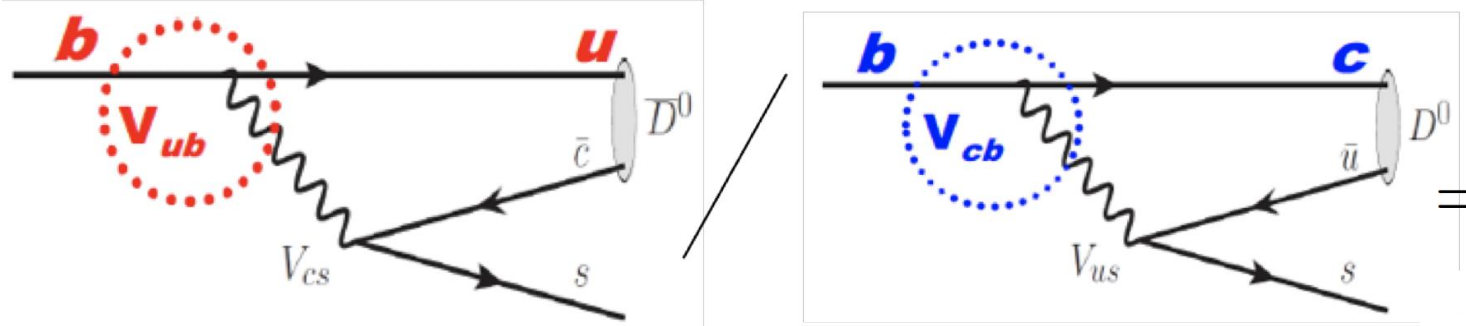
Strong and weak phases

- How CP violation is generated

$$A = a_1 e^{i(\delta_1+\phi_1)} + a_2 e^{i(\delta_2+\phi_2)} \qquad \bar{A} = a_1 e^{i(\delta_1-\phi_1)} + a_2 e^{i(\delta_2-\phi_2)}$$

$$A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} \propto \sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2)$$

- Weak phase changes sign under CP while strong does not
- However, to measure weak phase, one needs to know strong dynamics, a_1/a_2 , and $\delta_1 - \delta_2$

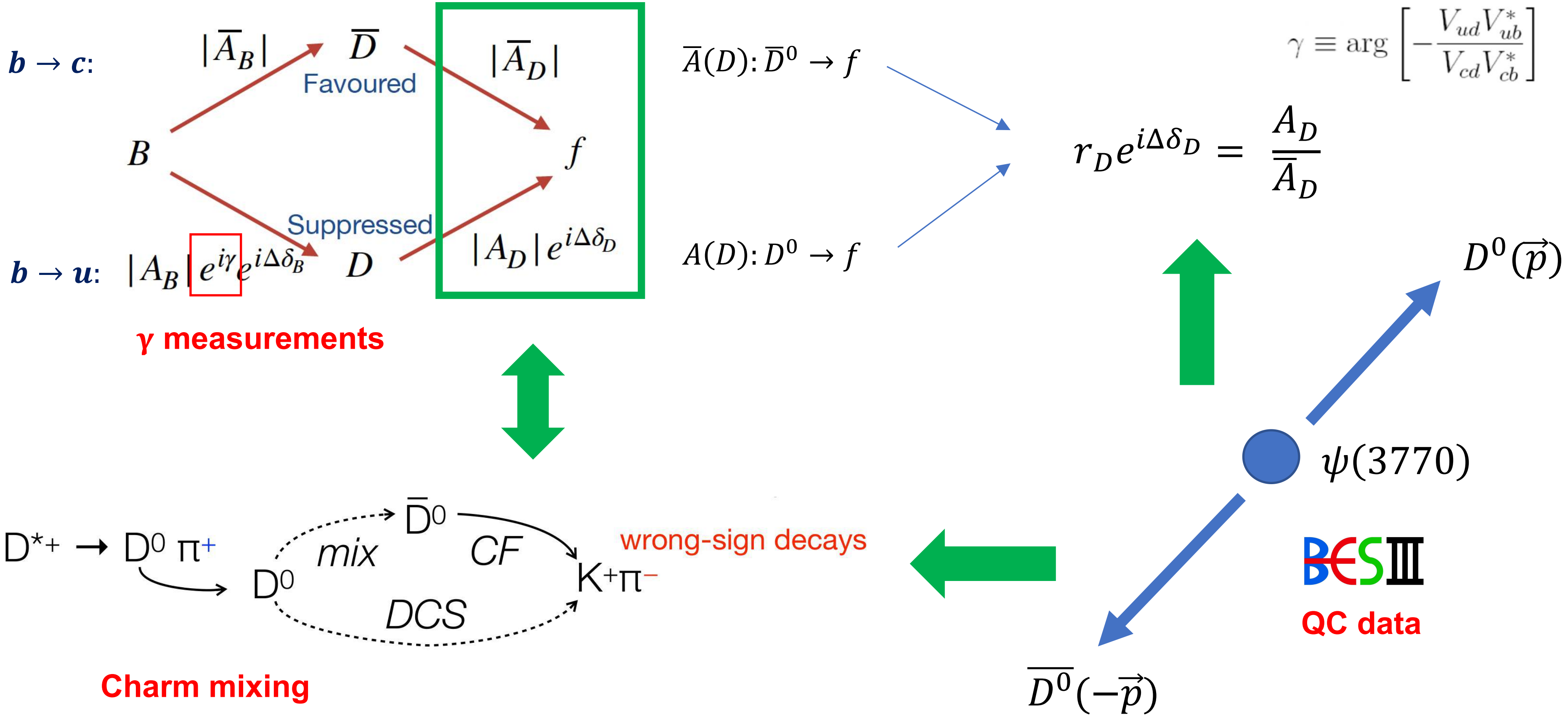


$$= r_B e^{i\delta_B}$$

$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

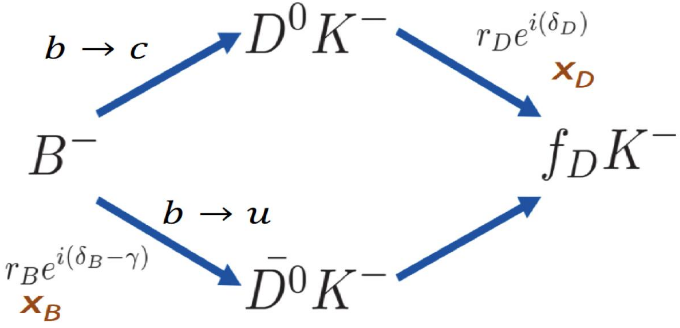
- Tree-level processes: SM candle, NP normally enters loop diagrams

CKM angle γ



Global fit

- **Measure CP violation in many different channels, with different strong phases and amplitude ratios in *D* decays**



GLW: D = CP eigenstates, e.g. KK, ππ

ADS: D = quasi-flavour-specific states e.g. Kπ

GGSZ: D = self-conjugate multi(3)-body states e.g. $K_s\pi\pi$

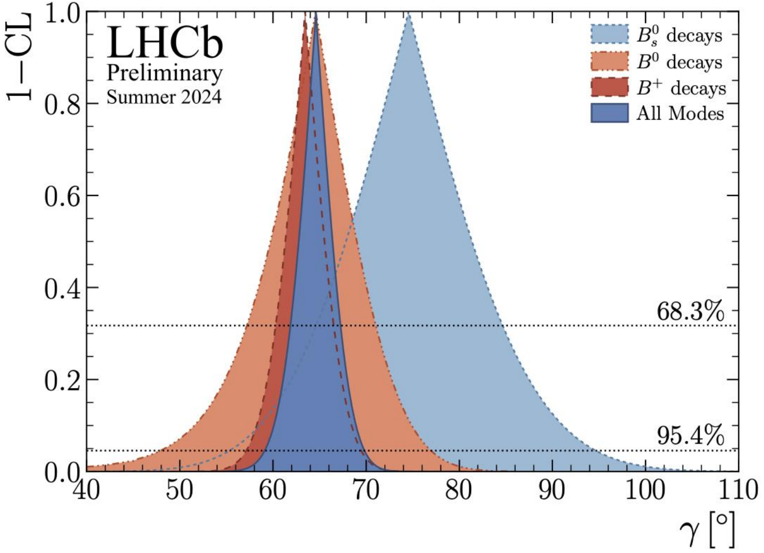
GLS: ADS variant with singly Cabbibo-suppressed decay $D \to K_s K\pi$

time-dependent $B_s \to D_s K$, $B^0 \to D\pi$ etc

Dalitz (GW) method: $B^0 \to DK\pi$

Global combination from LHCb

- 19 LHCb B decay measurements + 11 D decay measurements + 27 inputs from LHCb, HFLAV, BESIII and CLEO-c = 29 physics parameters of interest + additional nuisance parameters



$\gamma = (64.6 \pm 2.8)^\circ$ surpass LHCb design: 4°

Belle + Belle II: $\gamma = \left(78.6^{+7.2}_{-7.3}\right)^\circ$

- Previous tension between B_s^0 and other modes smaller, B_s^0 modes still with largest uncertainty
- Sensitivity dominated by B^+ modes
- Charm inputs crucial for γ measurements

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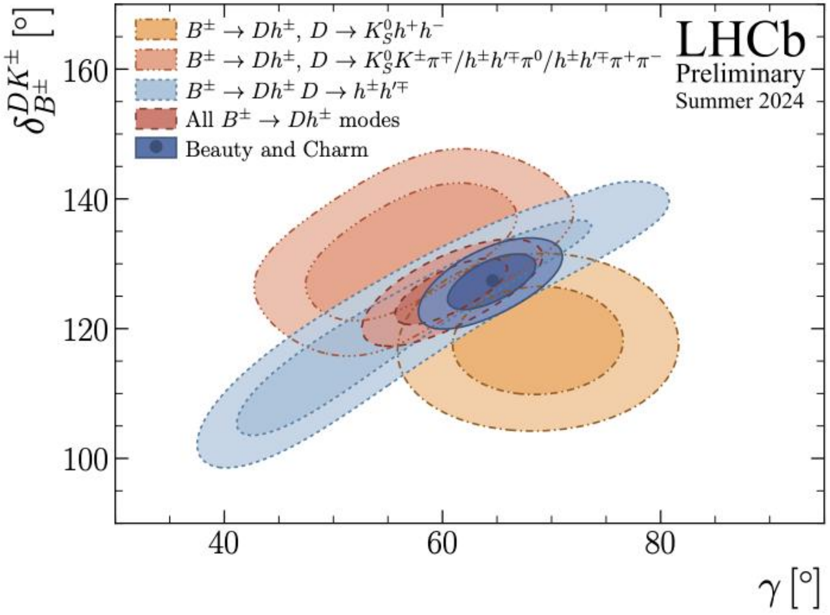

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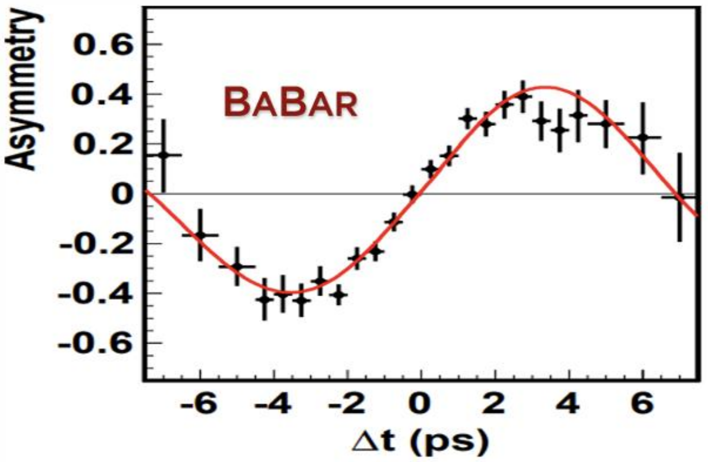
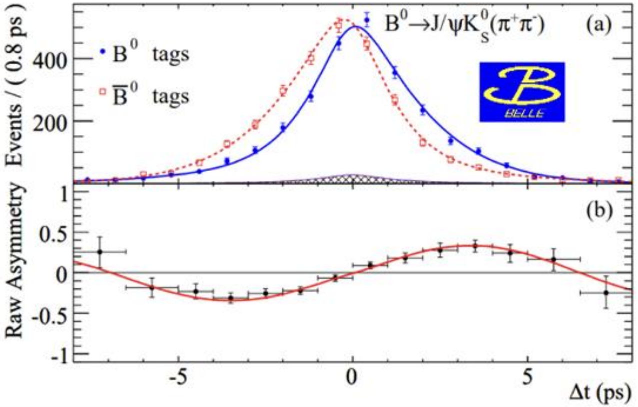
Observation of CP violation in B decays





2008诺贝尔物理学奖

$S \sim \sin 2\beta = 0.59 \pm 0.14 \pm 0.05$

$\sin 2\beta = 0.99 \pm 0.14 \pm 0.06$

Babar, PRL 87 (2001) 091801

Belle, PRL 87 (2001) 091802

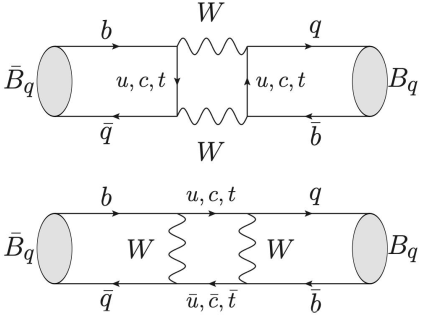
$$A_{CP}(t) = \frac{\Gamma(B^0 \to f_{CP}) - \Gamma(\overline{B}^0 \to f_{CP})}{\Gamma(B^0 \to f_{CP}) + \Gamma(\overline{B}^0 \to f_{CP})} \approx S\sin(\Delta m \cdot t)$$

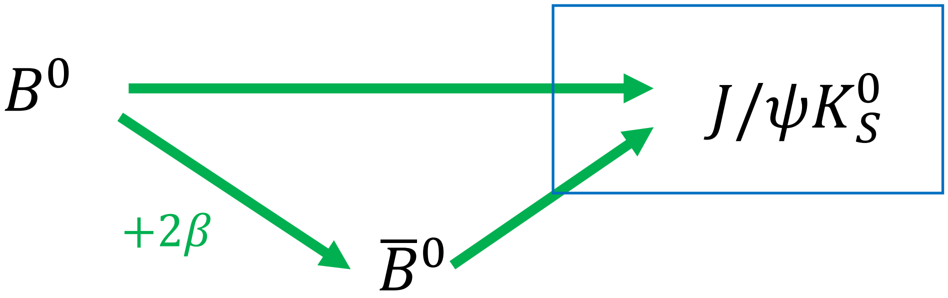
CKM mechanism of CP violation established

CKM angle β

- **Angle $\boldsymbol{\beta}$ enters through $\boldsymbol{B^0 \leftrightarrow \bar{B}^0}$ mixing**

$$\beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$





$$\frac{\partial}{\partial t}\begin{pmatrix} B_q \\ \overline{B_q} \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} B_q \\ \overline{B_q} \end{pmatrix}$$

$$A_{CP}(t) = \frac{\Gamma(B^0 \to f_{CP}) - \Gamma(\bar{B}^0 \to f_{CP})}{\Gamma(B^0 \to f_{CP}) + \Gamma(\bar{B}^0 \to f_{CP})}$$
$$\approx S\sin(\Delta m \cdot t)$$

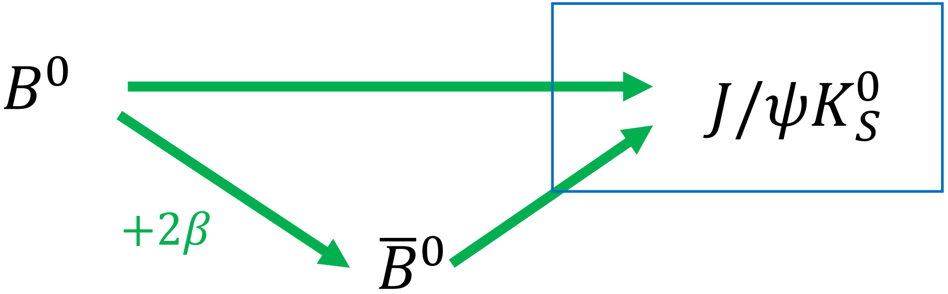
$$\frac{d\Gamma[B^0 \to f]/dt}{e^{-\Gamma t}} \propto (|A_f|^2 + |\bar{A}_f|^2) + (|A_f|^2 - |\bar{A}_f|^2)\cos(x\Gamma t) - 2\mathrm{Im}(\frac{q}{p}A_f^*\bar{A}_f)\sin(x\Gamma t)$$

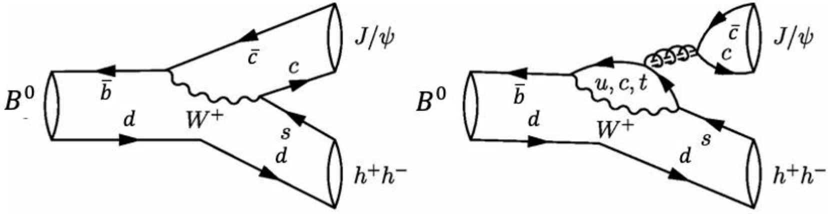
$$\frac{d\Gamma[B^0 \to f]/dt}{e^{-\Gamma t}} \propto (|A_f|^2 + |\bar{A}_f|^2) + (|A_f|^2 - |\bar{A}_f|^2)\cos(x\Gamma t) - 2\mathrm{Im}(\frac{q}{p}A_f^*\bar{A}_f)\sin(x\Gamma t)$$

CKM angle β

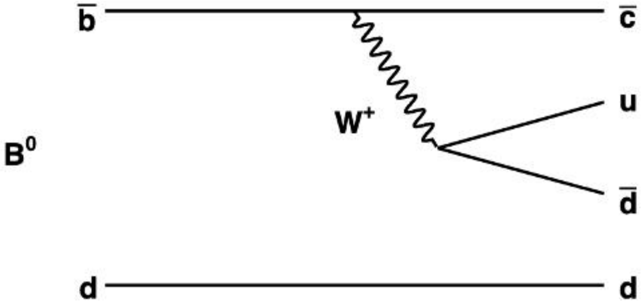
- **Angle β enters through $B^0 \leftrightarrow \bar{B}^0$ mixing**

$$\beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$



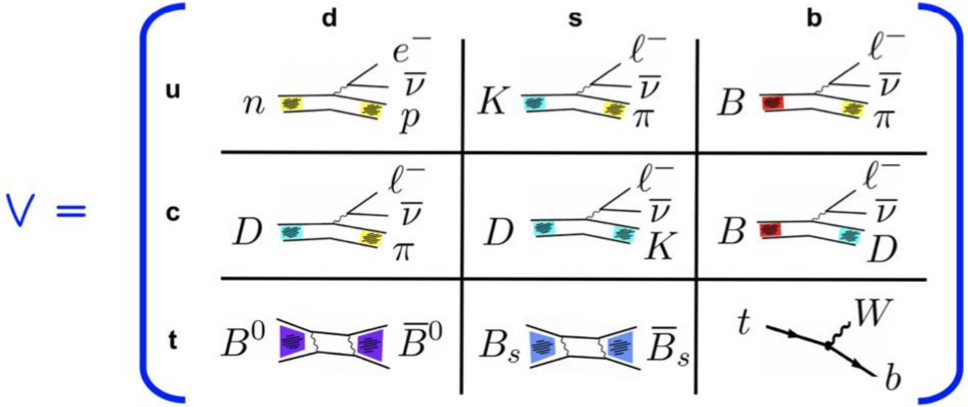


$$2\beta^{eff} = 2\beta + \delta\phi^{peng} + \delta\phi^{NP}$$



- **Use $B_s^0 \to J/\psi K_S^0$ to control penguin pollution (penguin enhanced progress)**
- **Alternative approach, penguin free decays**

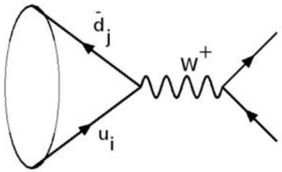
CKM matrix elements

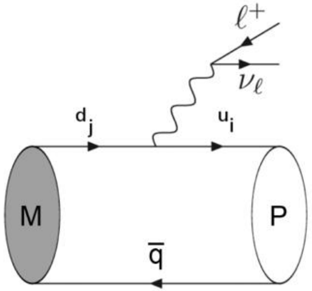


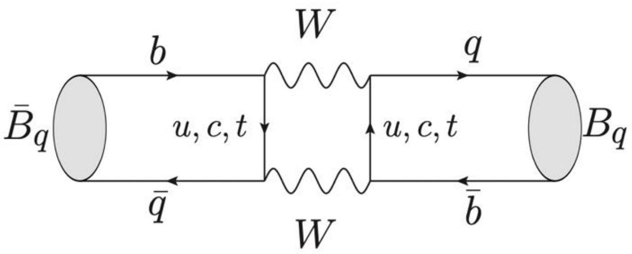
From S. Descotes-Genon

- $|V_{ud}|$: superallowed nuclear β decays
- $|V_{us}|$: $K \to \pi l \nu,\ K \to l\nu, \tau \to K\nu$ etc. + form factors, decay constants
- $|V_{cs}|$, $|V_{cd}|$: (semi-)leptonic charm decays + Lattice inputs
- $|V_{ub}|, |V_{cb}|$: (semi-)leptonic B decays + Lattice inputs
- $|V_{td}|$, $|V_{ts}|$: Δm_d, Δm_s + bag parameters, decay constants

General on magnitude measurements







- **Leptonic decays, only need decay constant of the decaying particle**

Precise BF measurements

$$B[M \to \ell\nu_\ell]_{SM} = \frac{G_F^2 m_M m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_M^2}\right)^2 |V_{q_u q_d}|^2 f_M^2 \tau_M (1 + \delta_{em}^{M\ell 2})$$

- **Semi-leptonic decays, form factor needed (2 when P is Pseudo-scalar, more for vector and fermions)**

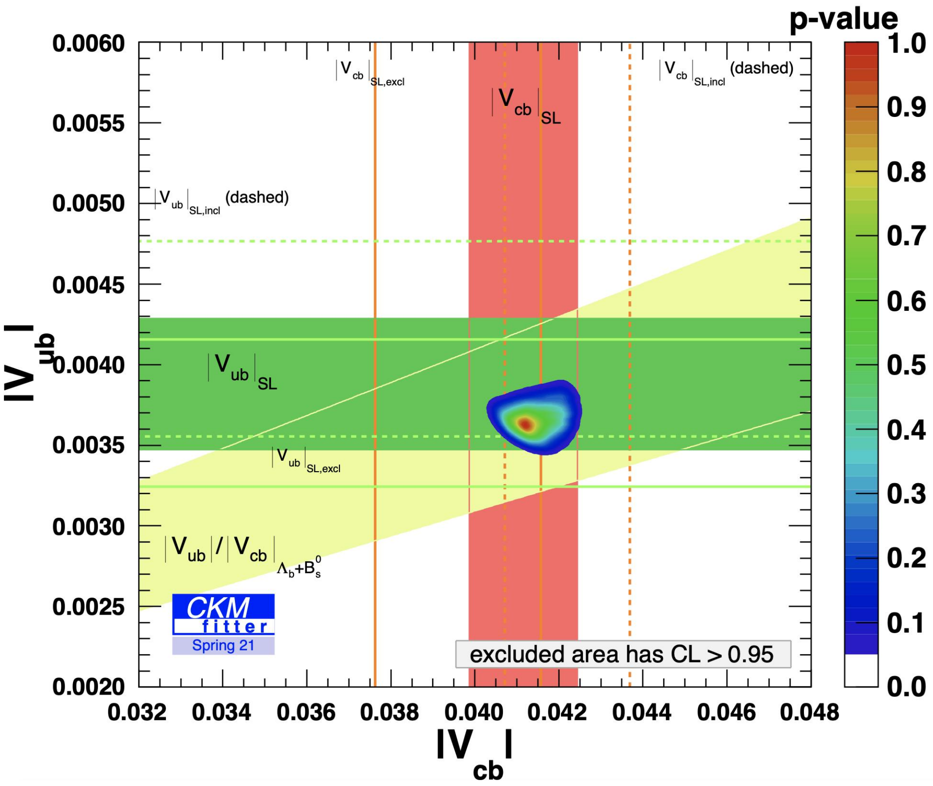
BF as function of q^2

$$\frac{d\Gamma(M \to P\ell\nu)}{dq^2} = \frac{G_F^2 |V_{q_u q_d}|^2}{24\pi^3} \frac{(q^2 - m_\ell^2)^2 \sqrt{E_P^2 - m_P^2}}{q^4 m_H^2} \times \left[\left(1 + \frac{m_\ell^2}{2q^2}\right) m_M^2 (E_P^2 - m_P^2) |f_+(q^2)|^2 + \frac{3m_\ell^2}{8q^2} (m_M^2 - m_P^2)^2 |f_0(q^2)|^2\right]$$

- **Meson mixing, decay constant and bag parameters**

$$\Delta m_q = \frac{G_F^2}{6\pi^2} \left|V_{tq}^* V_{tb}\right|^2 M_W^2 S_0(x_t) B_q f_{Bq}^2 M_{Bq} \widehat{\eta_B}$$

Puzzles on $|V_{ub}|$ and $|V_{cb}|$



- Long saga of V_{ub} and V_{cb} puzzles from inclusive and exclusive measurements
- Disaster for new physics searches if we don't understand CKM elements precisely

Changing $|V_{cb}|$: $39 \cdot 10^{-3} \Rightarrow 42 \cdot 10^{-3}$

changes $|V_{cb}|^2$: by 16% $(B_{s,d} \to \mu^+\mu^-,\ \Delta M_{s,d})$

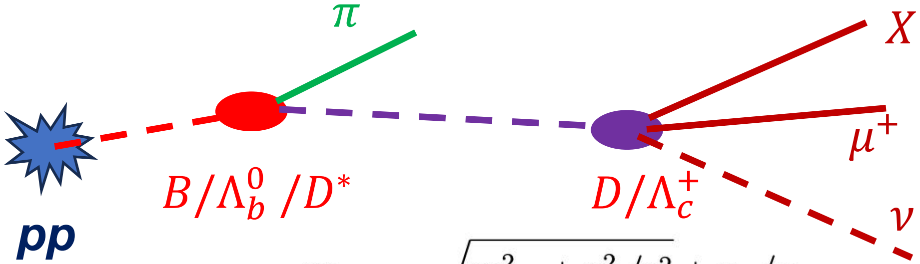
$|V_{cb}|^3$: by 25% $(K^+ \to \pi^+\nu\bar{\nu}, \varepsilon_K)$

$|V_{cb}|^4$: by 35% $(K_L \to \pi^0\nu\bar{\nu}, K_S \to \mu^+\mu^-)$

A. Buras

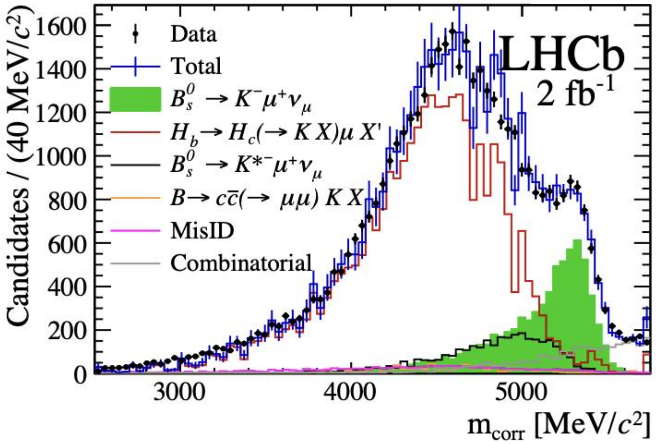
Semi-leptonic decays at LHCb

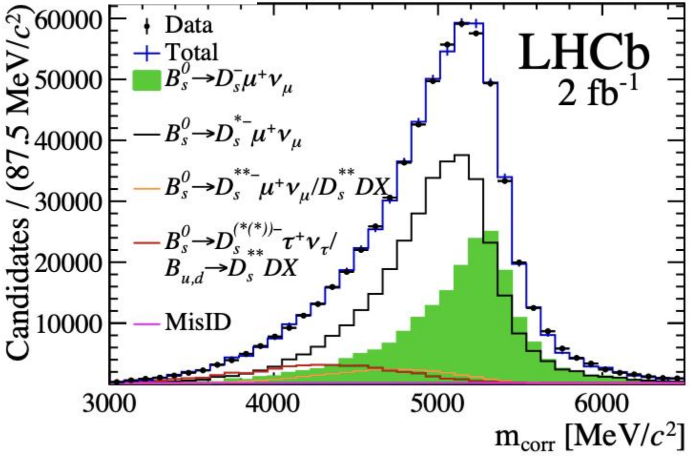
- **Not like e^+e^- machine, very complicated, however, not entirely impossible**



Two-fold ambiguity

$$m_{\rm corr} = \sqrt{m_{Y\mu}^2 + p_\perp^2/c^2} + p_\perp/c,$$



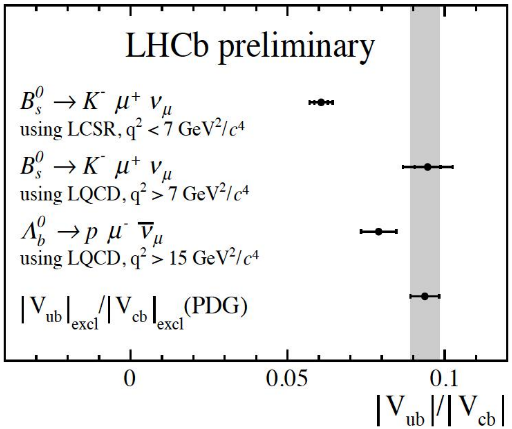


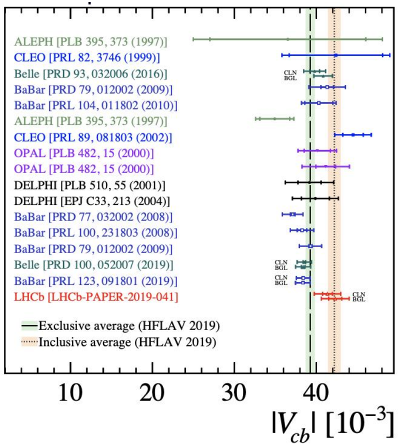
Results

- Two new measurements, one $|V_{ub}|/|V_{cb}|$ from $B_s \to K\mu\nu_\mu$ vs $B_s \to D_s^- \mu^+ \nu_\mu$

$$|V_{ub}|/|V_{cb}|(\text{low}) = 0.0607 \pm 0.0015(\text{stat}) \pm 0.0013(\text{syst}) \pm 0.0008(D_s) \pm 0.0030(FF) \quad \textbf{LQCD}$$

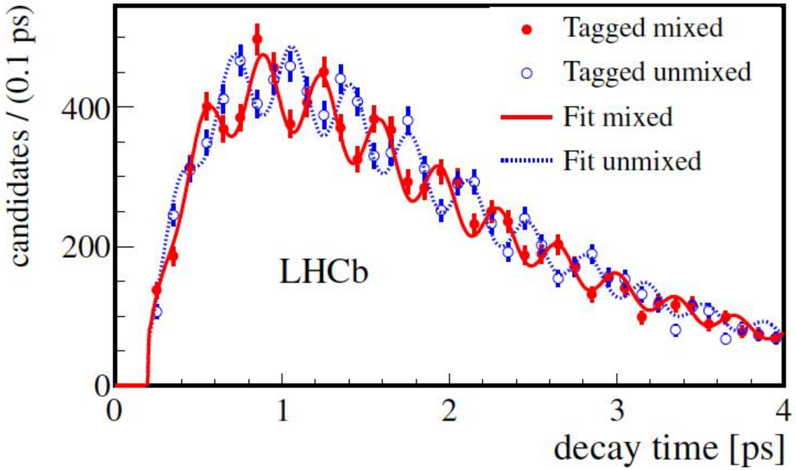
$$|V_{ub}|/|V_{cb}|(\text{high}) = 0.0946 \pm 0.0030(\text{stat})^{+0.0024}_{-0.0025}(\text{syst}) \pm 0.0013(D_s) \pm 0.0068(FF) \quad \textbf{LCSR}$$





- **Discrepancy** found in **high** and **low** q^2 region with different form factors, further investigation from both experimental and theoretical parts needed

Measurement of Δm_q



- **Measured using $B_S^0 \to D_S^- \pi^+$, $B^0 \to D^{(*)} \mu \nu X$**

$$\Delta m_d = 0.5065(19)\text{ps}^{-1}$$

$$\Delta m_s = 17.757(21)\text{ps}^{-1}$$

Precision of 0.38% and 0.12%!!!

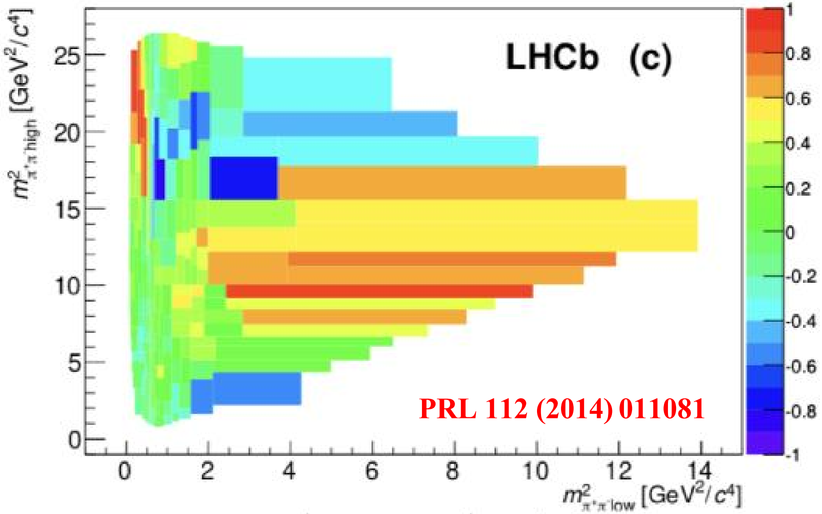
$$S_0(x) = x\left[\frac{1}{4} + \frac{9}{4}\frac{1}{1-x} - \frac{3}{2}\frac{1}{(1-x)^2}\right] - \frac{3}{2}\left[\frac{x}{1-x}\right]^3 \ln x$$

$$\Delta m_q = \frac{G_F^2}{6\pi^2}\left|V_{tq}^* V_{tb}\right|^2 M_W^2 S_0(x_t) B_q f_{Bq}^2 M_{Bq} \widehat{\eta_B}, \quad x_t = \frac{m_t^2}{M_W^2}$$

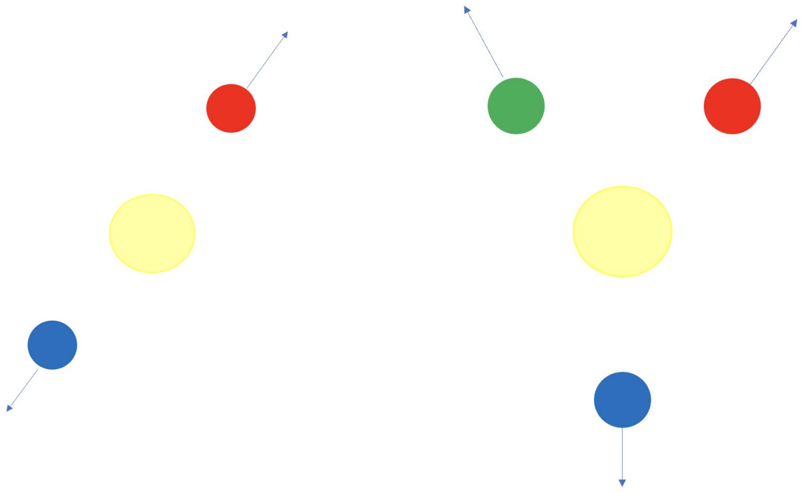
- **Uncertainties mainly from Bag parameters (3%) obtained from lattice**
- **Large reduction of uncertainties by making ratios of the two**

Beautiful CP violation pattern (direct CP violation)

CP violation as large as 80%



$$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$$



Two body decay

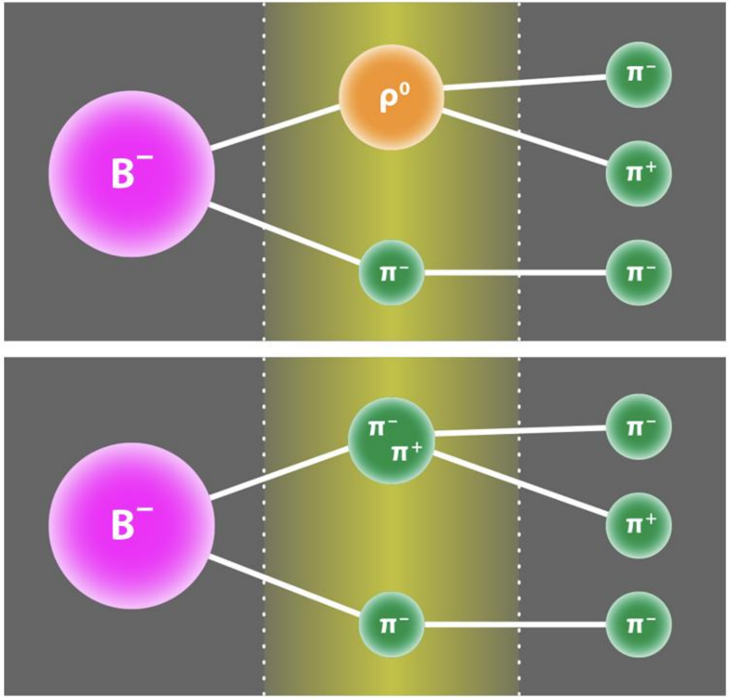
Three body decay

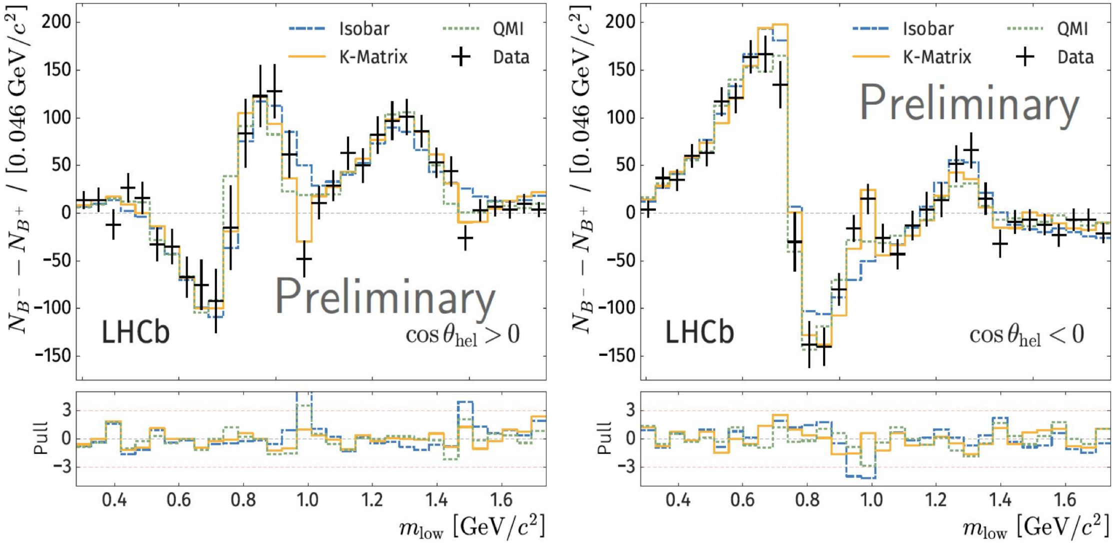
More freedom to study CP violation

Important to understand CP violation phenomena and search for new physics

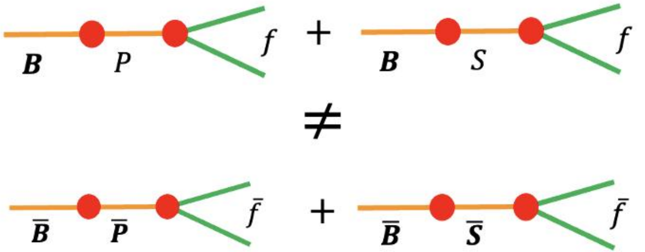
A new type of CP violation

PRL 124 (2020) 031801
PRD 101 (2020) 072006





CP violation from S- and P-wave interference



Methodology of A_{CP} measurements at LHCb

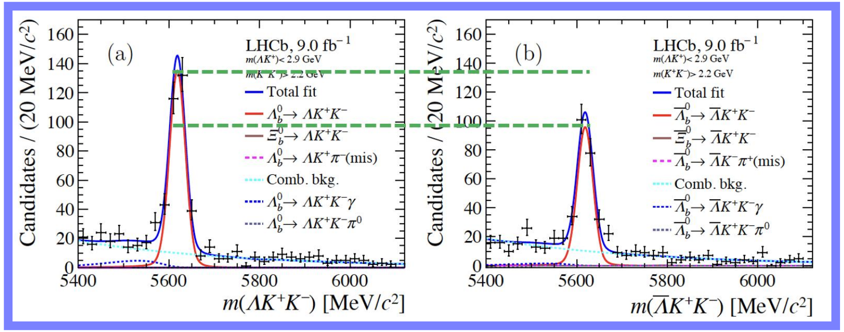
Physical quantity of interests

$$A_{CP}^{f} = \frac{\Gamma(\Lambda_b^0 \to f) - \Gamma(\overline{\Lambda}_b^0 \to \bar{f})}{\Gamma(\Lambda_b^0 \to f) + \Gamma(\overline{\Lambda}_b^0 \to \bar{f})}$$

Experimental effects

$$A_{\mathrm{Raw}}^{f} = \frac{N(\Lambda_b^0 \to f) - N(\overline{\Lambda}_b^0 \to \bar{f})}{N(\Lambda_b^0 \to f) + N(\overline{\Lambda}_b^0 \to \bar{f})}$$

What we see directly from mass plots



Preliminary

See later

Methodology of A_{CP} measurements at LHCb

Physical quantity of interests

$$A_{CP}^{f} = \frac{\Gamma(\Lambda_b^0 \to f) - \Gamma(\overline{\Lambda}_b^0 \to \overline{f})}{\Gamma(\Lambda_b^0 \to f) + \Gamma(\overline{\Lambda}_b^0 \to \overline{f})}$$

$$A_{CP}^{f} = A_{\mathrm{Raw}}^{f} - A_{\mathrm{P}}^{\Lambda_b^0} - A_{\mathrm{D}}^{f}$$

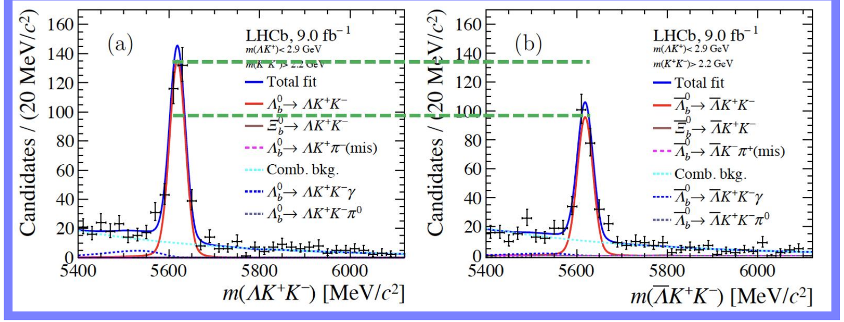
$$A_{\mathrm{P}}^{\Lambda_b^0} = \frac{\sigma(\Lambda_b^0) - \sigma(\overline{\Lambda}_b^0)}{\sigma(\Lambda_b^0) + \sigma(\overline{\Lambda}_b^0)} \qquad A_{\mathrm{D}}^{f} = \frac{\epsilon(f) - \epsilon(\overline{f})}{\epsilon(f) + \epsilon(\overline{f})}$$

Experimental effects

Production asymmetry

Detection asymmetry

$$A_{\mathrm{Raw}}^{f} = \frac{N(\Lambda_b^0 \to f) - N(\overline{\Lambda}_b^0 \to \overline{f})}{N(\Lambda_b^0 \to f) + N(\overline{\Lambda}_b^0 \to \overline{f})}$$



What we see directly from mass plots

Control channel for A_{CP} measurements

Signal channel

$$A_{CP}^{S} = A_{\mathrm{Raw}}^{S} - A_{\mathrm{P}}^{\Lambda_b^0} - A_{\mathrm{D}}^{S}$$

Control channel

$$A_{CP}^{C} = A_{\mathrm{Raw}}^{C} - A_{\mathrm{P}}^{\Lambda_b^0} - A_{\mathrm{D}}^{C}$$

$$\Delta A_{CP} = \Delta A_{\mathrm{Raw}} - \Delta A_{\mathrm{P}}^{\Lambda_b^0} - \Delta A_{\mathrm{D}}$$

$\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\pi^-$

$A_{CP}\sim 0$

Similar topology

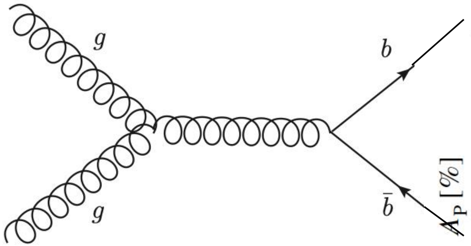
$\Delta A_P^{\Lambda_b^0}$: mostly canceled, small residual due to kinematic difference induced by selections

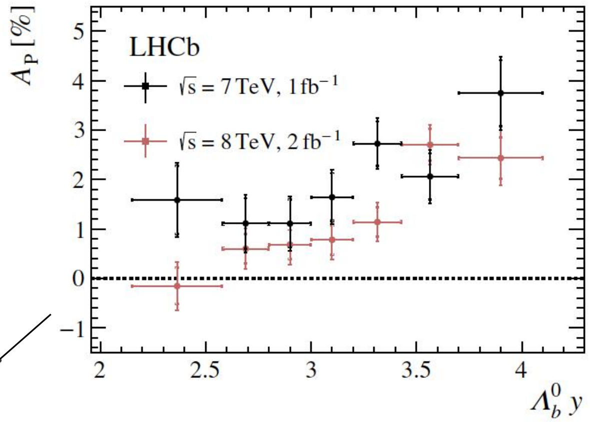
ΔA_D: mostly canceled, small residual due to kinematic difference induced by selections or particle type difference (K vs π)

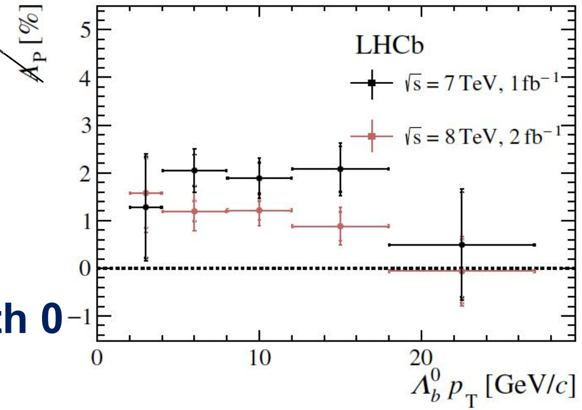
Production asymmetry

$$A_{\mathrm{P}}^{\Lambda_b^0} = \frac{\sigma(pp \to \Lambda_b^0) - \sigma(pp \to \overline{\Lambda}_b^0)}{\sigma(pp \to \Lambda_b^0) + \sigma(pp \to \overline{\Lambda}_b^0)}$$

- **Production asymmetry of $b\overline{b}$, dominated by gg fusion**
- **Hadronization asymmetry of Λ_b^0 and $\overline{\Lambda}_b^0$ in pp collisions**





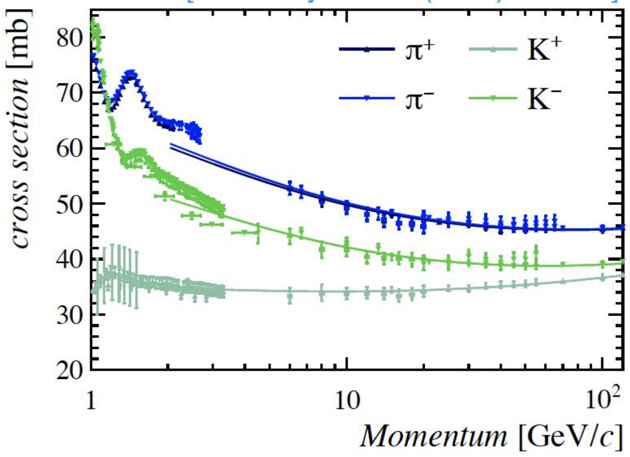


- **A_P : 1~2% , measured by LHCb as a function of y, p_T**
- **$\Delta A_P \sim 0.2\%$, with uncertainties around 0.2%: consistent with 0**

Detection asymmetry

$$A_{\mathrm{D}}^{f} = \frac{\epsilon(f) - \epsilon(\bar{f})}{\epsilon(f) + \epsilon(\bar{f})}$$

[Chin. Phys. C 40 (2016) 100001]



- Matter, antimatter interact with detector (made by matter) differently
- f: different combinations of p, K, π etc.
- Including effects from reconstruction of particles, PID, trigger effects; $A_D^h = A_{Rec}^h + A_{Tri}^h + A_{PID}^h$, $h = K, \pi, p$

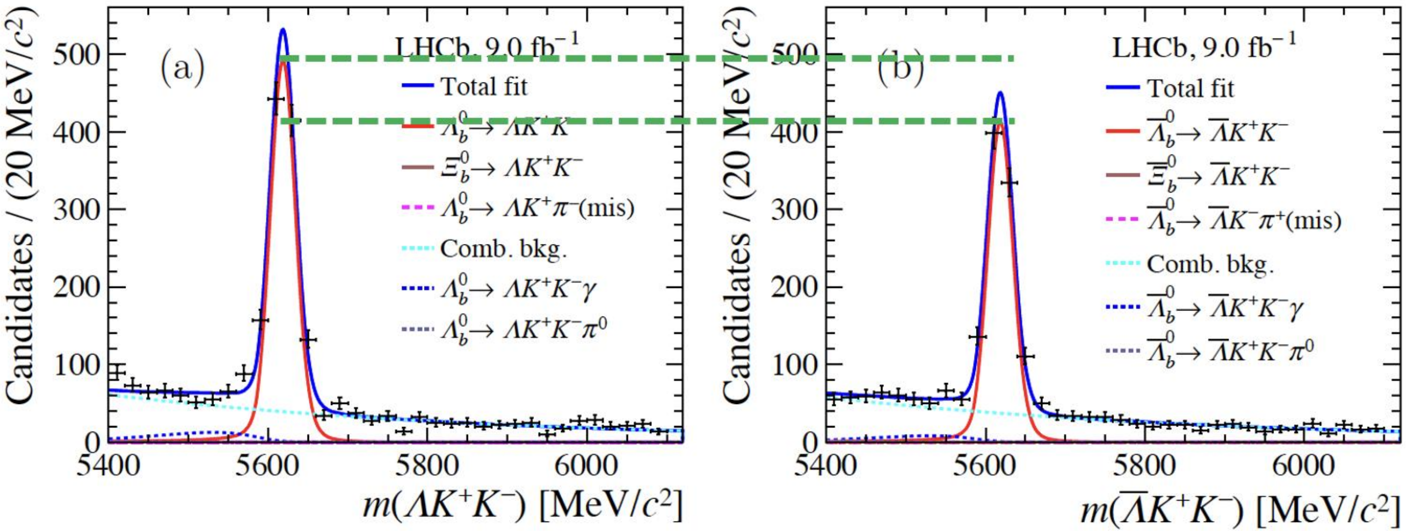
- Obtained using data-driven method with calibration channels

$A_D(\pi^{\pm}) \approx 0.1\%, A_D(K^{\pm}) \approx 1\%, A_D(p/\bar{p}) \approx 1-2\%$ → ΔA_D: ~1%

Significantly reduced using control channel

Evidence of CP violation

PRL 134 (2025) 101802



$$\Lambda_b^0 \to \Lambda K^+ K^-$$

$$\Delta A_{CP} = 0.083 \pm 0.023 \pm 0.016$$

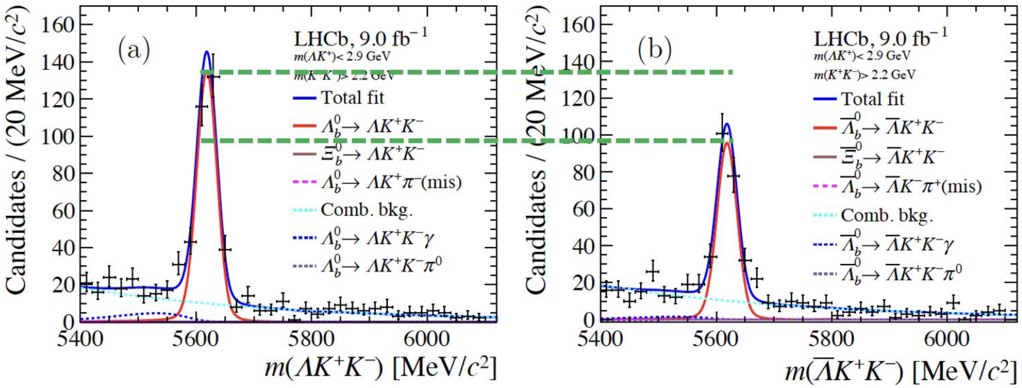
First evidence of CP violation, 3.1σ

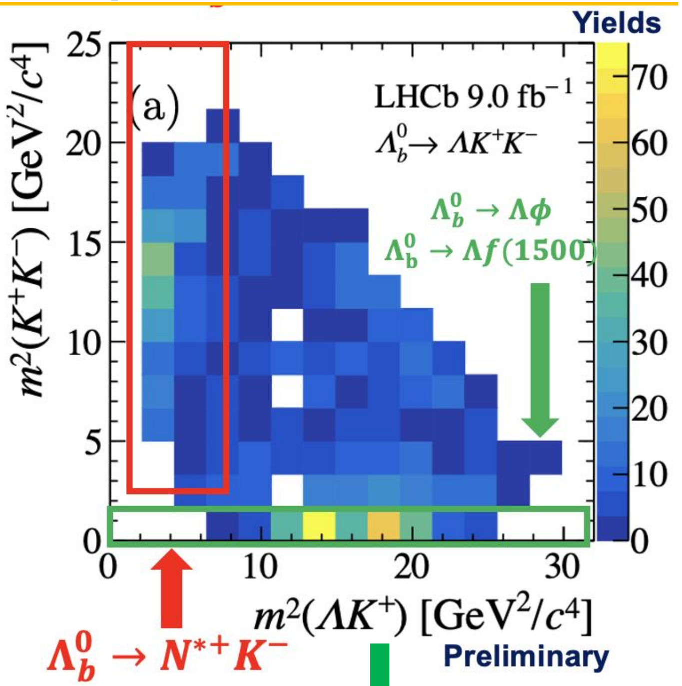
Three body decays, need to know which resonance contributes

Looking into Dalitz plot ($\Lambda_b^0 \to \Lambda K^+ K^-$)

PRL 134 (2025) 101802

Preliminary





$$\Delta A_{CP}(N^{*+}K^-) = 0.165 \pm 0.048 \pm 0.017$$

First evidence of CP violation in local resonant region, 3.2σ

region

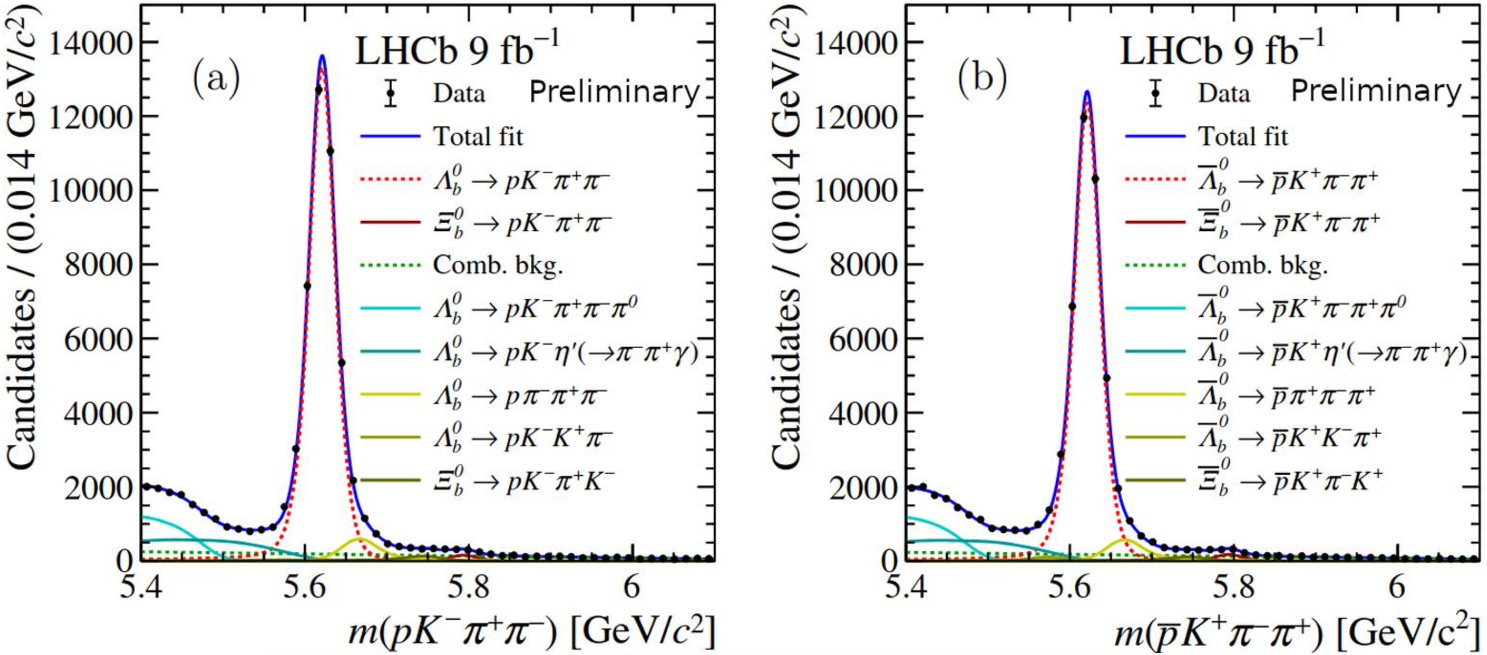
$$\Delta A_{CP}(\Lambda\phi) = 0.150 \pm 0.055 \pm 0.021$$

Consistent with 0 within 2.5σ

PRD107 (2023) 053009

Predicted CPV (resonant), ~1.5%

Observation of CP violation in baryon decays

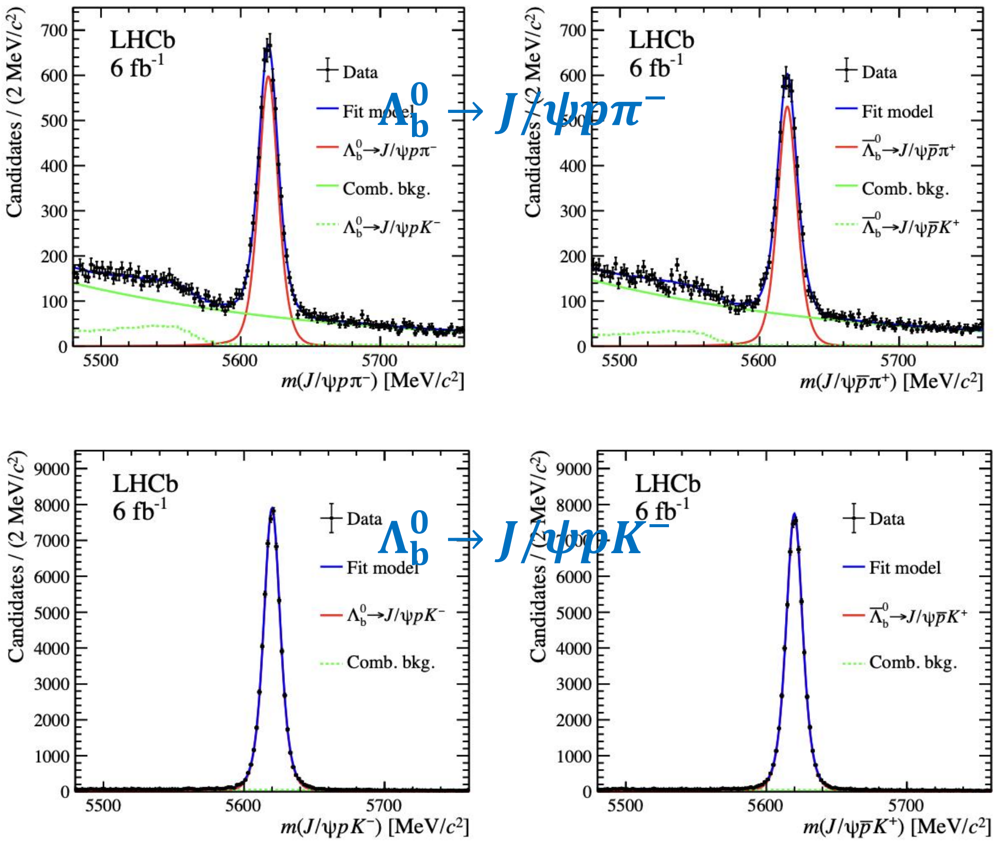


$$A_{CP} = (2.45 \pm 0.46 \pm 0.10)\%$$

LHCb-PAPER-2024-054

CP symmetry violated by more than 5σ

CP violation in $\Lambda_b^0 \to J/\psi ph$ decays



$$\Delta\mathcal{A}_{CP} = \mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi p\pi^-) - \mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi pK^-)$$
$$= (4.03 \pm 1.18 \pm 0.23)\%,$$

- **A significance of 3.3σ, when combining with Run 1 result, it reaches 3.9σ**

$$\Delta\mathcal{A}_{CP} = (4.31 \pm 1.06 \pm 0.28)\%.$$

- **CP violation seen in a channel where pentaquark is found!**

Global CKM fit results

- **With all these measurements and theoretical inputs from Lattice QCD, new updates on global fit performed**

$$A = 0.8215^{+0.0047}_{-0.0082} \text{ (0.8\% unc.)}$$

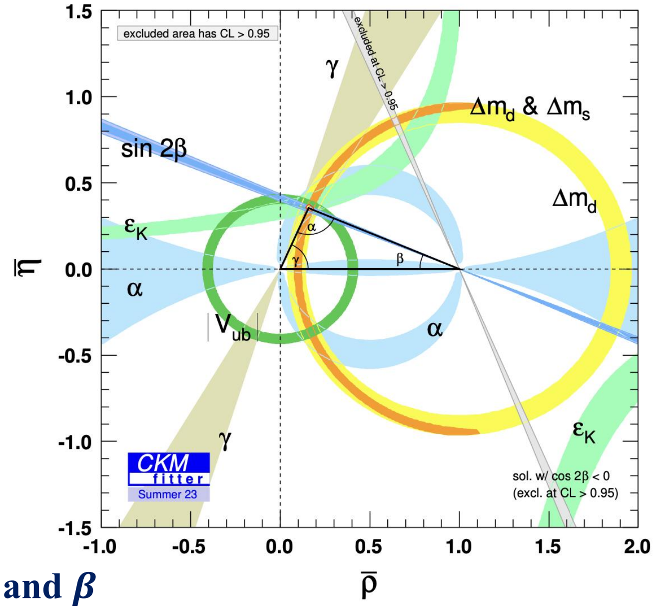
$$\lambda = 0.22498^{+0.00023}_{-0.00021} \text{ (0.1\% unc.)}$$

$$\bar{\rho} = 0.1562^{+0.0112}_{-0.0040} \text{ (4.9\% unc.)}$$

$$\bar{\eta} = 0.3551^{+0.0051}_{-0.0057} \text{ (1.5\% unc.)}$$

68% C.L. intervals

$\bar{\rho}, \bar{\eta}$: $\sim$ 20% more precise

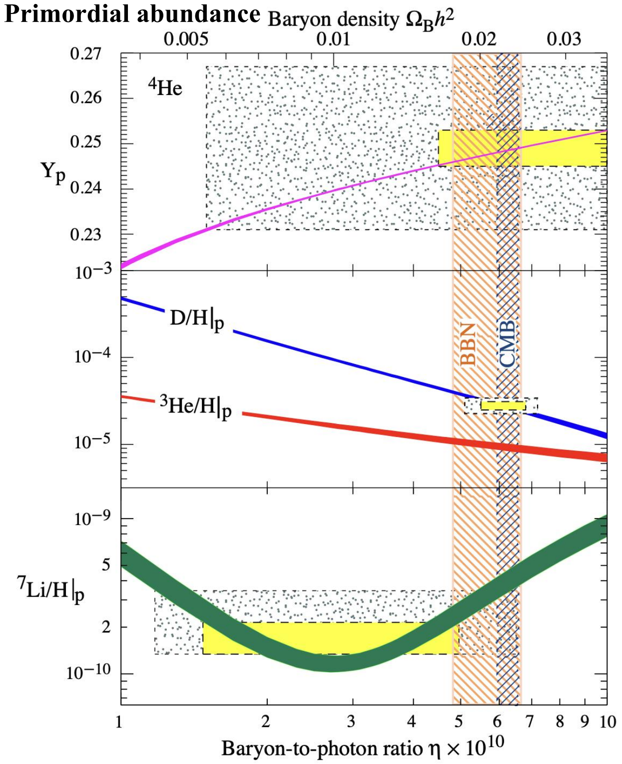


- **Better constrain due to improved measurements of CKM angle γ and β**
- **Global consistency looks good**

$$\text{CKM'21: p-value} \sim 29\% \ (1.1\sigma) \rightarrow \textbf{CKM'23}\text{: p-value} \sim 67\% \ (0.4\sigma)$$

- **Offers precise predictions on New Physics sensitive processes**

Matter and antimatter asymmetry



PLB667 (2008) 1

- "Visible" world dominated by matter
- Big-Bang Nucleosynthesis and Cosmic Microwave Background all indicate large matter-antimatter asymmetry in Universe:

$$\eta = \frac{n_B}{n_\gamma} \sim 10^{-10}$$

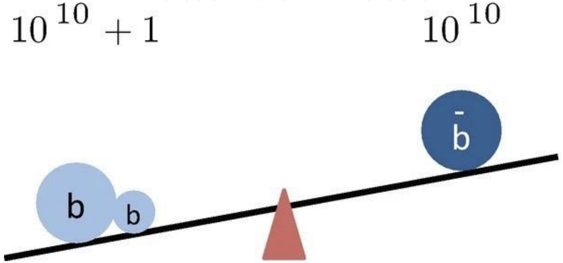
- No yet fully understood:

t

?

After inflation
Matter = Antimatter

Today
Matter dominated



Possible explanations

- Matter != Antimatter before big bang?
- Non-observed antimatter dominated regions?
  - Photons produced by annihilation at boundary not observed
  - Observed cosmic rays in space not supporting this scenario
  - Need explanations for separation

- Sakharov conditions for a baryon-generating interaction:
  - Baryon number violation (not yet observed)
  - C-symmetry and CP-symmetry violation
  - Interactions out of thermal equilibrium (condition 1, 2 may not be reversed)

EW Baryogenesis

PRL 55 (1985) 1039
CKMfitter

- Sakharov conditions: CP violation need
- In SM, offered by CKM matrix

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim \frac{n_B}{n_\gamma} \sim \frac{J \times P_u \times P_d}{M^{12}}$$

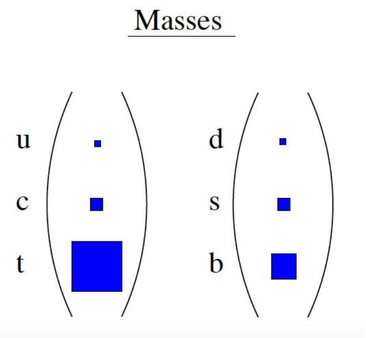
EW Scale:
M~100 GeV

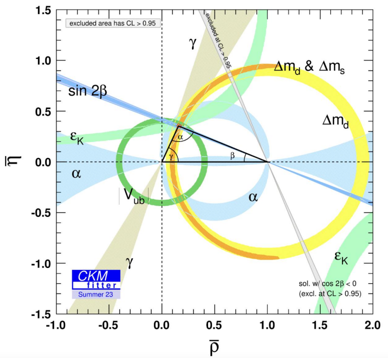
Jarlskog invariant:

$$P_u = (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)$$

$$P_d = (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)$$

$$J \sim 3 \times 10^{-5}$$





Far smaller than observed matter antimatter asymmetry in Universe

Need new mechanism

$$10^{-17} \ll 10^{-10}$$

EW Baryogenesis

PRL 55 (1985) 1039
CKMfitter

- Sakharov conditions: CP violation need
- In SM, offered by CKM matrix

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim \frac{n_B}{n_\gamma} \sim \frac{J \times P_u \times P_d}{M^{12}}$$

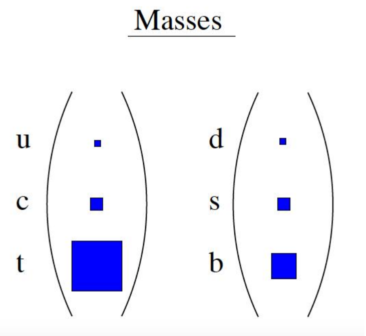
EW Scale:
M~100 GeV

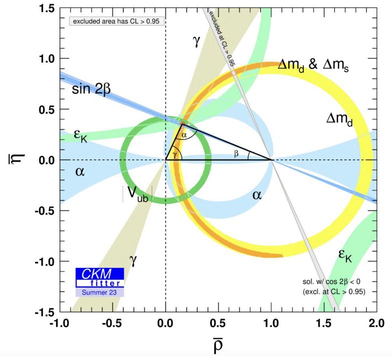
Jarlskog invariant:

$$P_u = (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)$$

$$P_d = (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)$$

$$J \sim 3 \times 10^{-5}$$





Far smaller than observed matter antimatter asymmetry in Universe

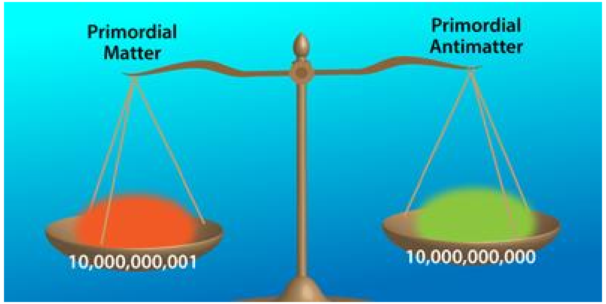
Need new mechanism

$$10^{-17} \ll 10^{-10}$$

More data needed to resolve the puzzle by over constraining CKM triangle

Why CKM precision test important

CKMfitter

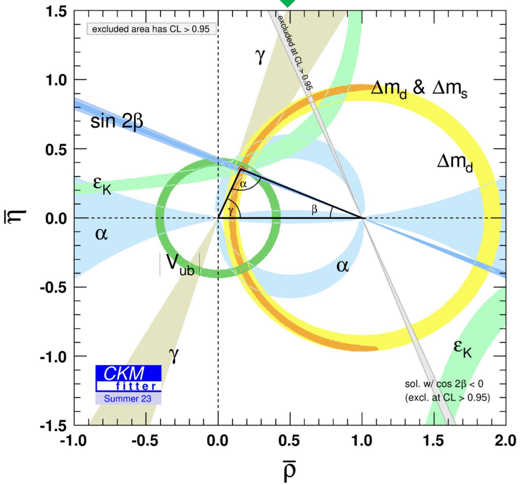


Unitarity: only requirement in SM

$$\sum_i V_{ij}^* V_{ij} = 1 \qquad \sum_i V_{ij}^* V_{ik} = 0$$

$$\begin{pmatrix} d^I \\ s^I \\ b^I \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Mass eigenstate vs interaction eigenstate



Is current precision enough? No

$$V_{ud}V_{ud}^* + V_{us}V_{us}^* + \overset{10^{-5}}{V_{ub}V_{ub}^*} - 1$$

$$= [0.00012, -0.00295]\ (3\sigma)$$

Cabbibo anomaly?

Disaster for new physics searches if CKM elements not precise

Changing $|V_{cb}|$: $39\cdot10^{-3} \Rightarrow 42\cdot10^{-3}$

changes $|V_{cb}|^2$: by 16% $(B_{s,d}\to\mu^+\mu^-,\ \Delta M_{s,d})$

$|V_{cb}|^3$: by 25% $(K^+\to\pi^+\nu\bar{\nu},\varepsilon_K)$

$|V_{cb}|^4$: by 35% $(K_L\to\pi^0\nu\bar{\nu},K_S\to\mu^+\mu^-)$

From A. Buras

Ways towards new physics

- Two main streams: direct search and indirect search through precision measurements
- Examples in history: many beyond "current" model new physics first found through indirect search

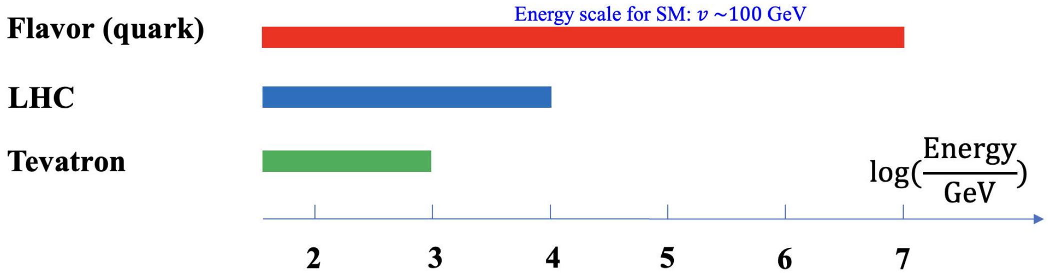
Precision measurements

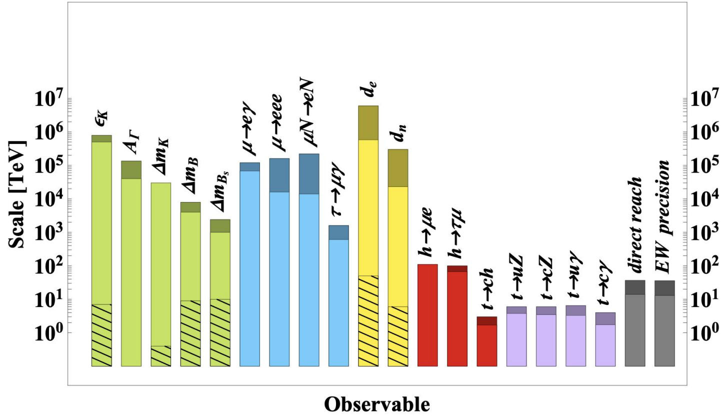
arXiv:1910.11775

- Sensitive to New Physics scale much higher than direct search: 1-10^4 TeV

$$\mathcal{A}(\psi_i \to \psi_j + X) = \mathcal{A}_0 \left(\frac{c_{\rm SM}}{v^2} + \frac{c_{\rm NP}}{\Lambda^2} \right)$$

NP scale: Λ





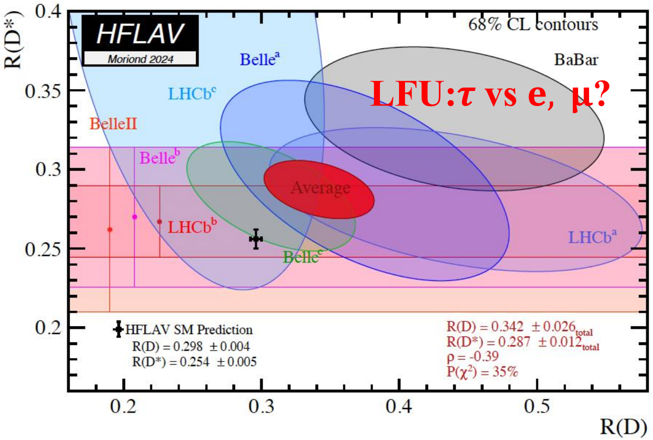
- Statistics or precision is key for flavor program: New Physics scale, i.e. Dim = 6, $\propto 1/\sqrt{\text{Uncertainty}}$

- Also "tasteful", not only can tell there is New Physics, but also tell properties of New Physics based on flavor it couples to

Flavor anomalies

$R(D) - R(D^*)$ anomaly: new physics at tree level?

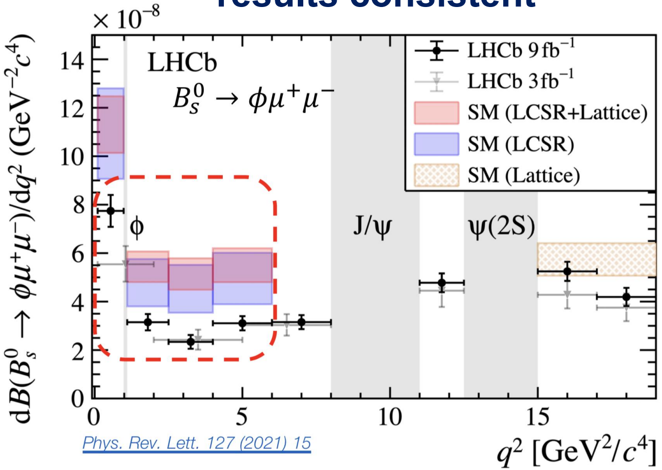
$$R\left(D^{(*)}\right) = \frac{\mathcal{B}(B \to D^{(*)-}\tau^+\nu_\tau)}{\mathcal{B}(B \to D^{(*)-}l^+\nu_l)}$$



Deviation significance: 3.3σ

Anomaly at $b \to s$ transitions

still 2-3σ deviation, new results consistent



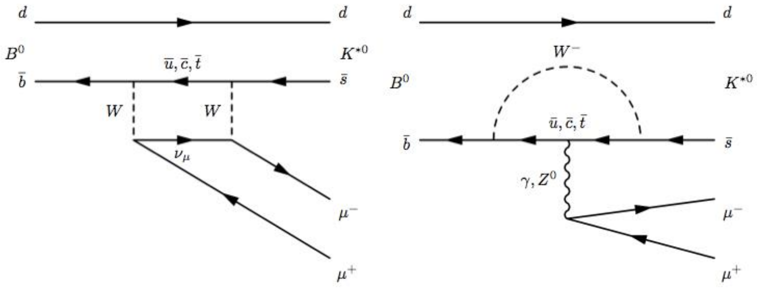
Phys. Rev. Lett. 127 (2021) 15

- **LFU test at $b \to s$ transitions between first and second generation (R_{K,K^*}) disappear**
- **Crucial: to understand charm loop contribution**

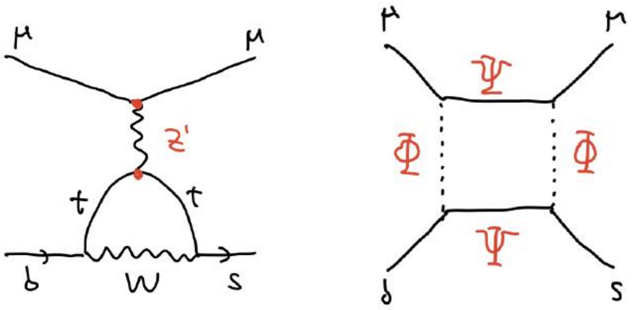
$$R(K, K^*) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

FCNC and charm loop

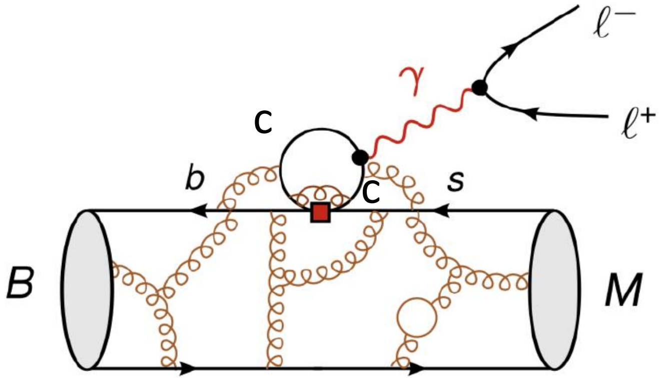
FCNC in Standard Model

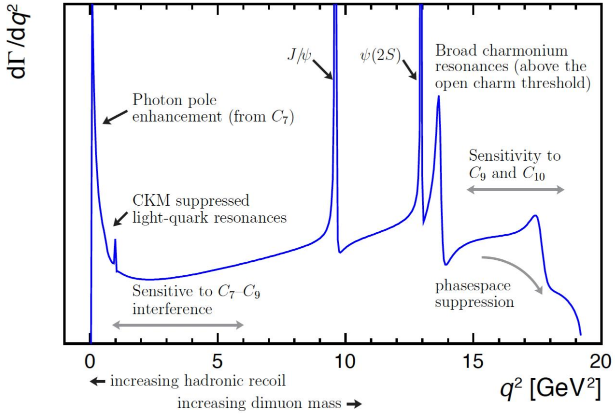


FCNC in new physics



Charm loop

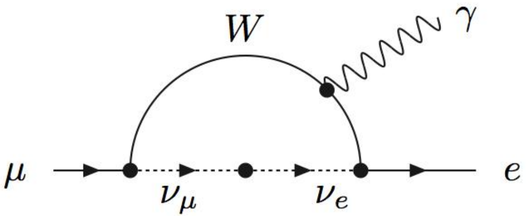




T.Blake, G.Lanfranchi, D.Straub, 1606.00916

LFV searches

- No matter the results from LFU, still extremely important to search for LFV



$\mathcal{B}(\mu^+ \to e^+\gamma) < 10^{-54}$

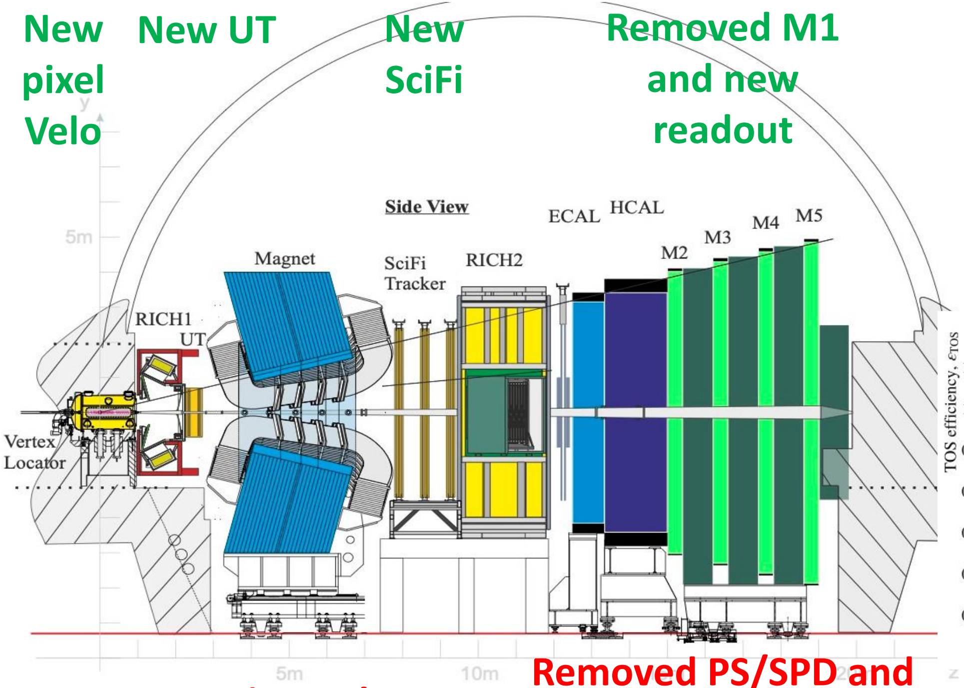
- SM contributions negligible
- Currently negative results
- Future experiments from COMET, Mu2e, Mu3e, Belle II, LHCb, ATLAS, CMS and BESIII will further improve their strength to NP

Decay	Best upper limit (90% C.L.)	Experiment
$\mu^+ \to e^+\gamma$	3.1×10^{-13}	MEGII
$\mu^- N \to e^- N$	7.0×10^{-13}	SINDRUM
$\tau^+ \to e^+\gamma$	3.3×10^{-8}	Babar
$\tau^+ \to \mu^+\gamma$	4.2×10^{-8}	Belle
$\tau^+ \to l^+ l^- l'^+$	$(1.8 \sim 2.7) \times 10^{-8}$	Belle (II)
$\mu^+ \to 3e^+$	1.0×10^{-12}	Mu3e
$Z^0 \to e^\pm \mu^\mp$	7.5×10^{-7}	ATLAS
$J/\psi \to e^\pm \tau^\mp$	7.5×10^{-8}	BESIII
$J/\psi \to e^\pm \mu^\mp$	4.5×10^{-9}	BESIII

Most important: more data coming

- **With our new LHCb detector, already collected more data than Run1+2**
- **More importantly, full software trigger ➜ better performance on hadronic final states**

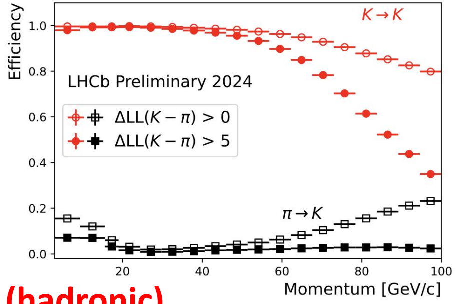
New pixel Velo **New UT** **New SciFi** **Removed M1 and new readout**



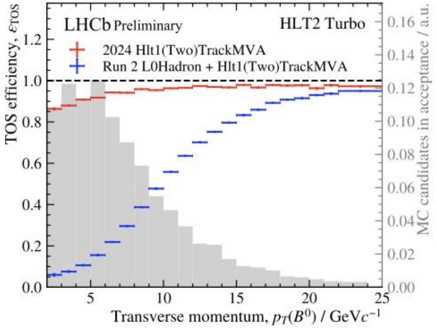
New RICH optics and PMS

Removed PS/SPD and new readout

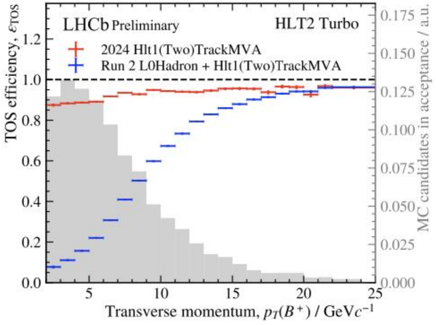
Similar PID performance



Twice trigger efficiencies (hadronic)

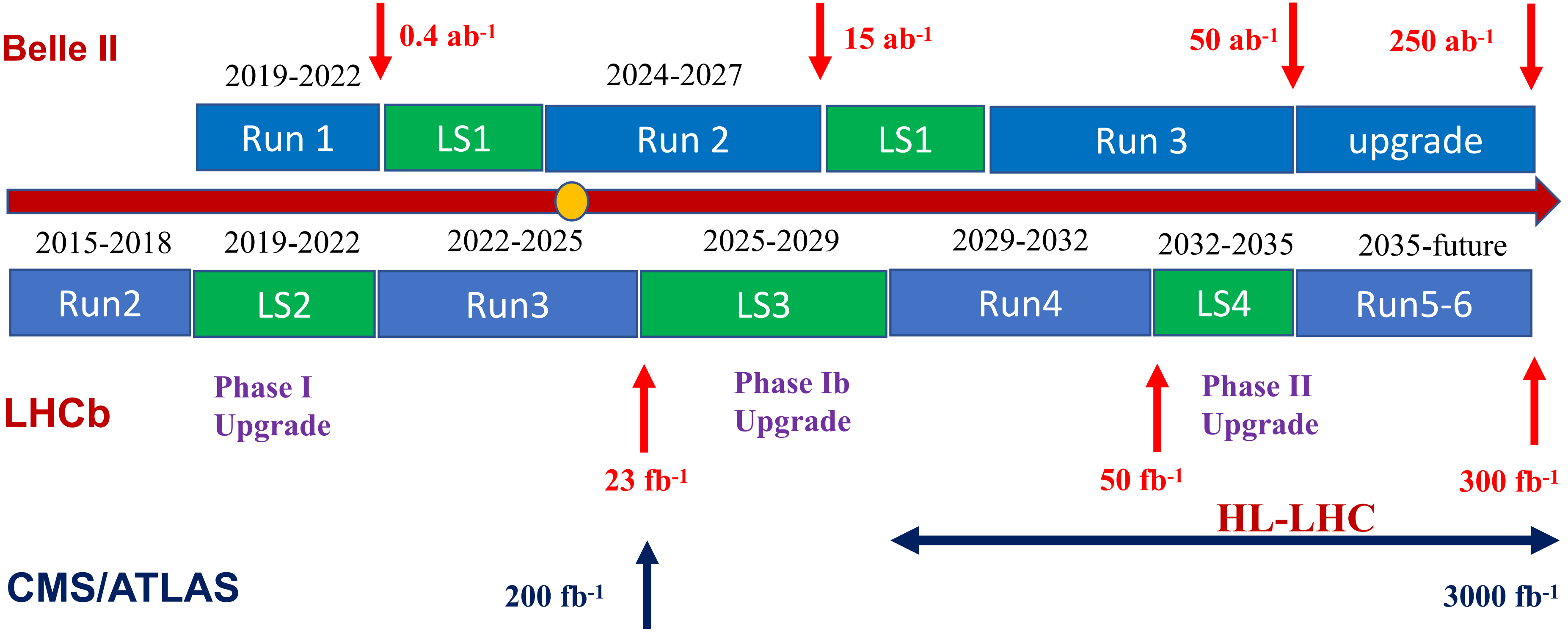


$B^0 \to D^- \pi^+$



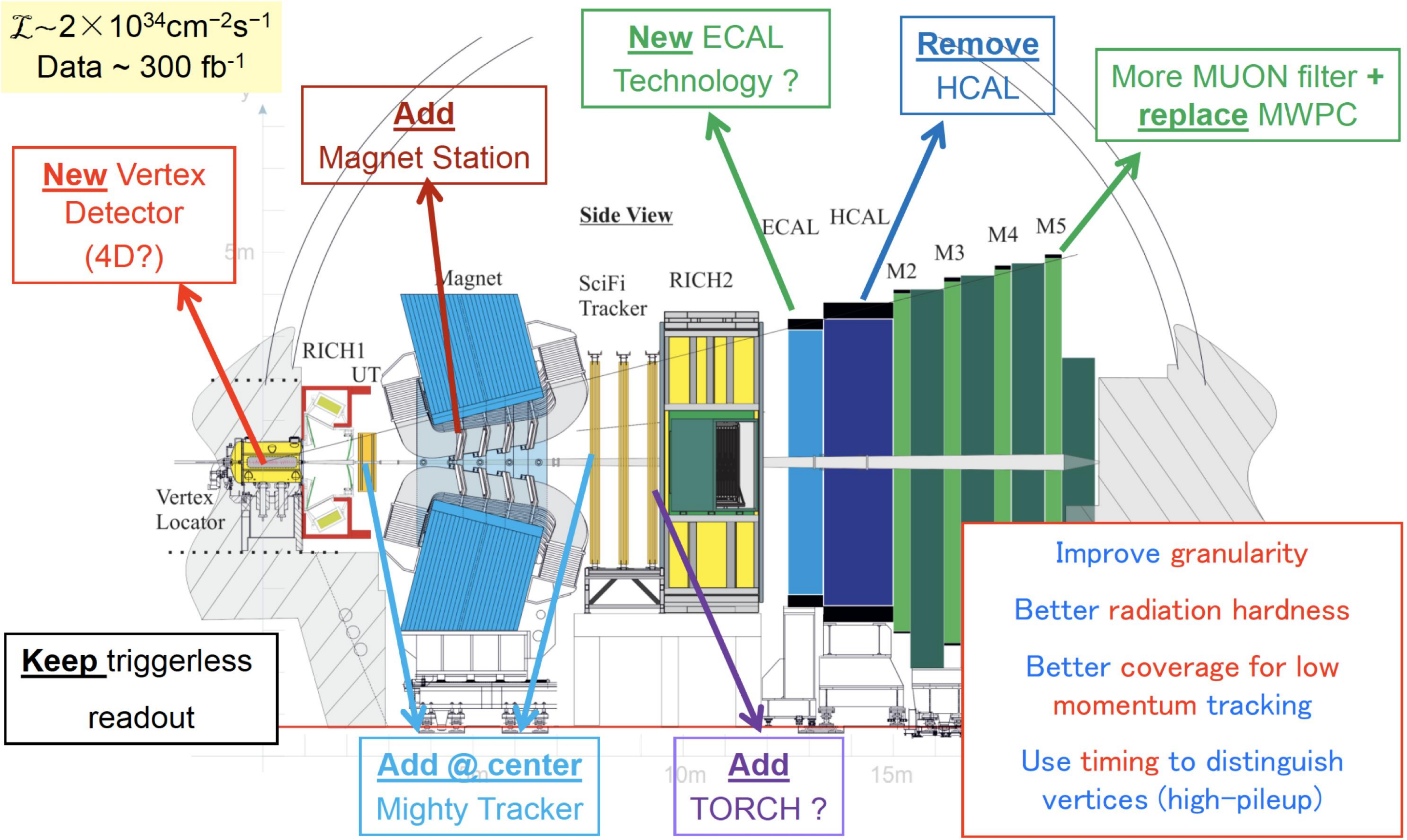
$B^+ \to \bar{D}^0 \pi^+$

Prospects

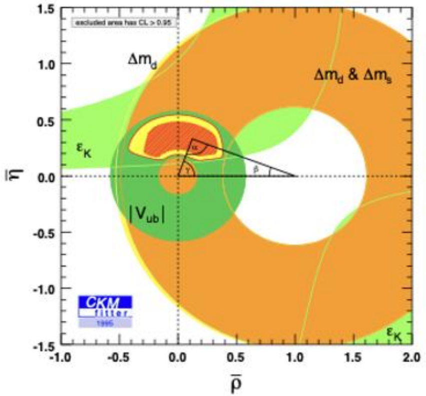


BESIII/super τ-charm/CEPC **BEPCII upgrade + running of super τ-charm/CEPC**

Next LHCb detector from 2030



Future of flavor and hadron physics



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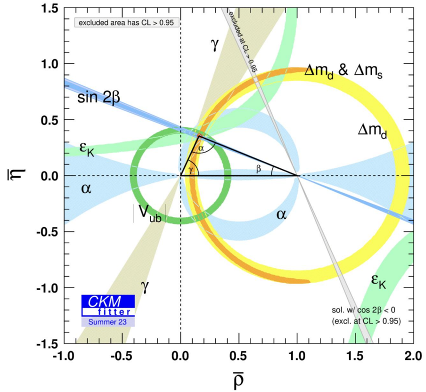
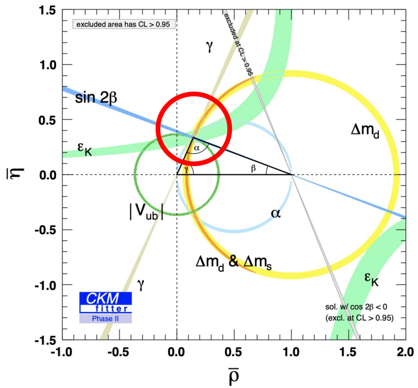
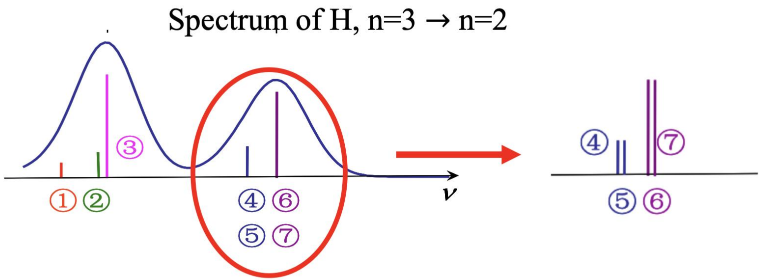


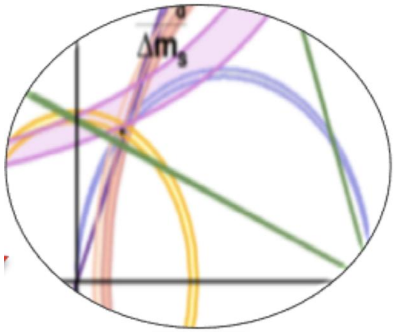
2023



2040?

Either we found New physics or we understand QCD at low energy

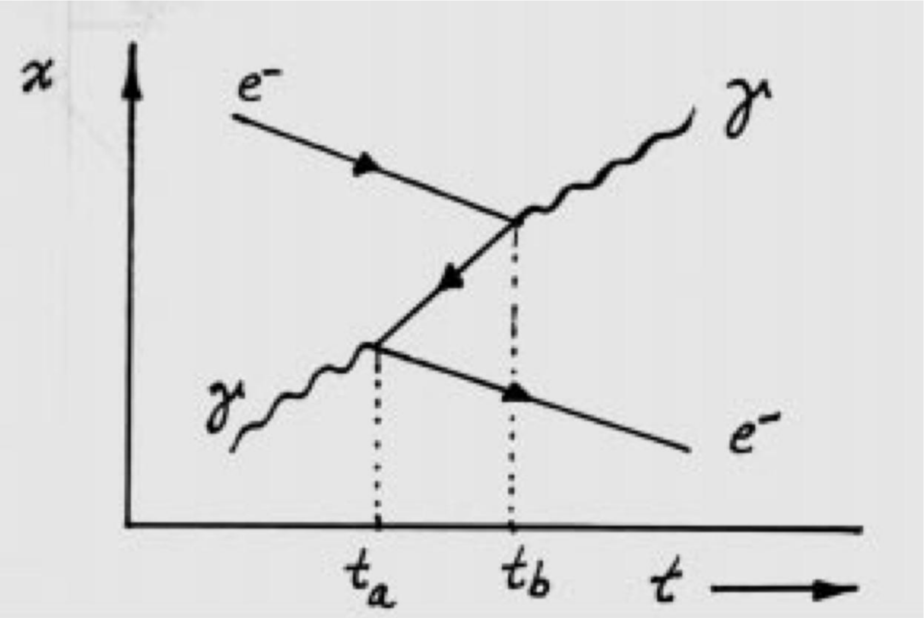




Thank you for your attention!

How to read antimatter?

Compton scattering



- $t < t_a$: $\gamma + e^-$ moving into each other
- $t = t_a$: $\gamma \to e^+ + e^-$
- $t_a < t < t_b$: e^+ coming from future time t_b, while e^- moving in the direction of time
- $t = t_b$: $e^+ + e^- \to \gamma$
- $t > t_b$: : $\gamma + e^-$ moving away from each other

Same particle, but travel backwards in time