Observation of several new tetra-quark states at the LHCb experiment

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Outline

- **Introduction**
- **A general amplitude analysis tool: TF-PWA**
- **First observation of a double charged tetraquark state and its neutral partner**
- **First observation of a resonant structure near $D_s^+ D_s^-$ threshold**
- **Conclusion**

Composition of nature

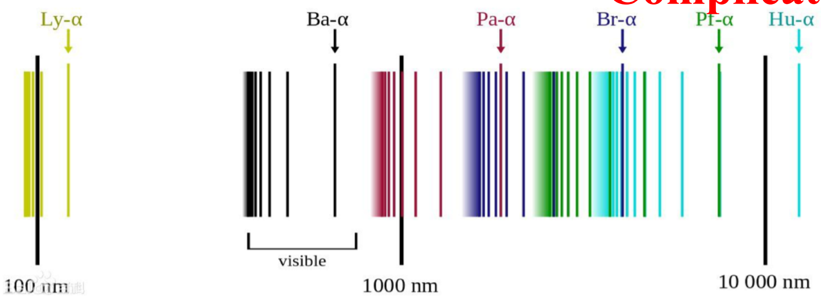
古代哲学

网络图片

Atomic spectrum

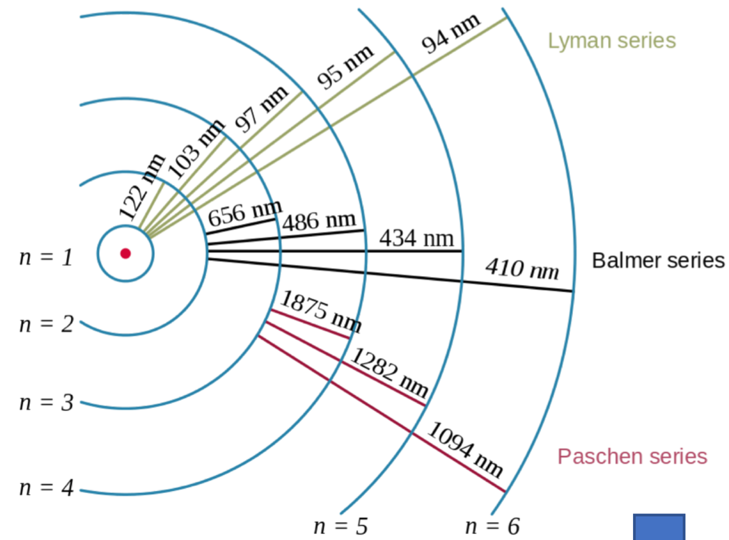
赛先生

Complicated



Measurements

Bohr model



Empirical summary

Balmer's equation:

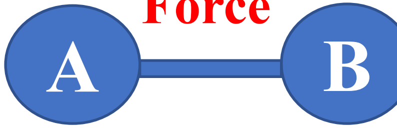
$$\lambda = 365.46 \frac{n^2}{n^2 - 2^2} \mathrm{nm}, \quad n = 3,4,5,\cdots$$

Rydberg's equation:

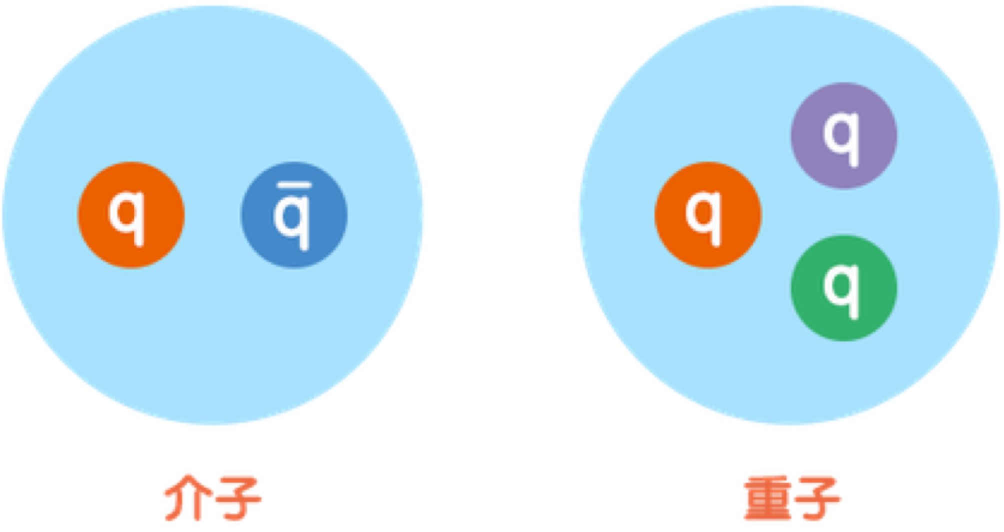
$$\sigma = \frac{1}{\lambda} = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) \qquad R = 1.0973731534 \times 10^{7}\,\mathrm{m}^{-1}$$

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

Force



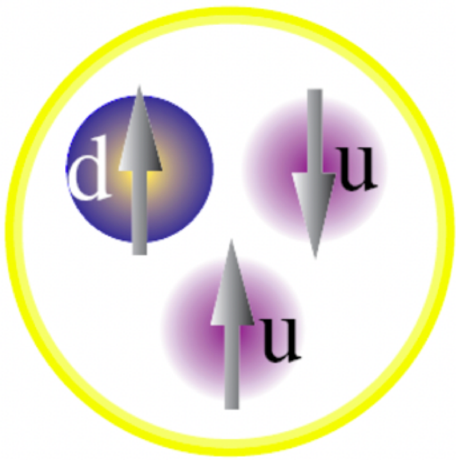
Surprisingly successful model



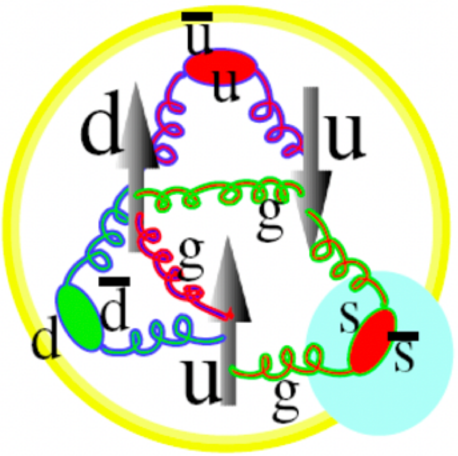
- **Most of particles can be explained by a picture of two partons or three partons**
- **Very simple picture to explain very complicated QCD**
- **Not even understand why this picture is successful**

Our understanding of proton

Constituent quarks



Parton distributions



$\bar{d}(x) = \bar{u}(x)$

$\bar{s}(x) = s(x)$

Garvey & Peng, Prog. Part. Nucl. Phys. 47, 203 (2001)

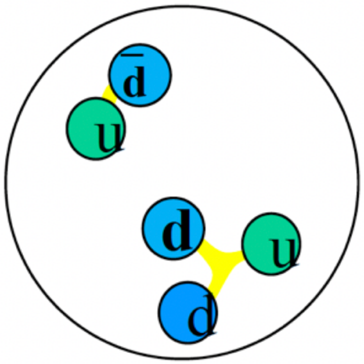
- **Deep inelastic scattering and Drell-Yan process tell us:** $\int (\overline{d(x)} - \overline{u(x)})dx \sim 0.12$
- **Spin crisis of proton**

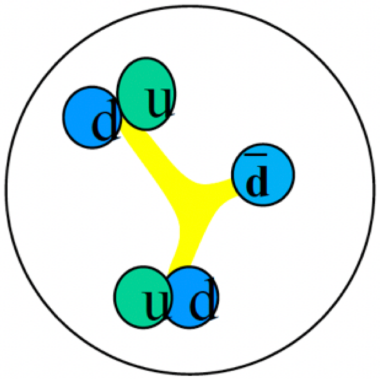
expt.: $\Delta u \in [0.82, 0.85]$, $\Delta d \in [-0.45, -0.42]$, and $\Delta s \in [-0.11, -0.08]$

$$\Delta q \equiv \int_0^1 [q(x) \uparrow + \bar{q}(x) \uparrow - q(x) \downarrow - \bar{q}(x) \downarrow] dx.$$

A different picture of proton

Current picture





30% of 5-quark component in proton

Meson cloud picture: Thomas, Speth, Henley, Meissner, Miller, Weise, Oset, Brodsky, Ma, …

$$| p \rangle \sim | uud \rangle + \varepsilon_1 \, | n\,(udd)\, \pi^+(\bar{d}u) \rangle + \varepsilon_2 \, | \Delta^{++}(uuu)\, \pi^-(\bar{u}d) \rangle + \varepsilon' \, | \Lambda\,(uds)\, K^+(\bar{s}u) \rangle \ldots$$

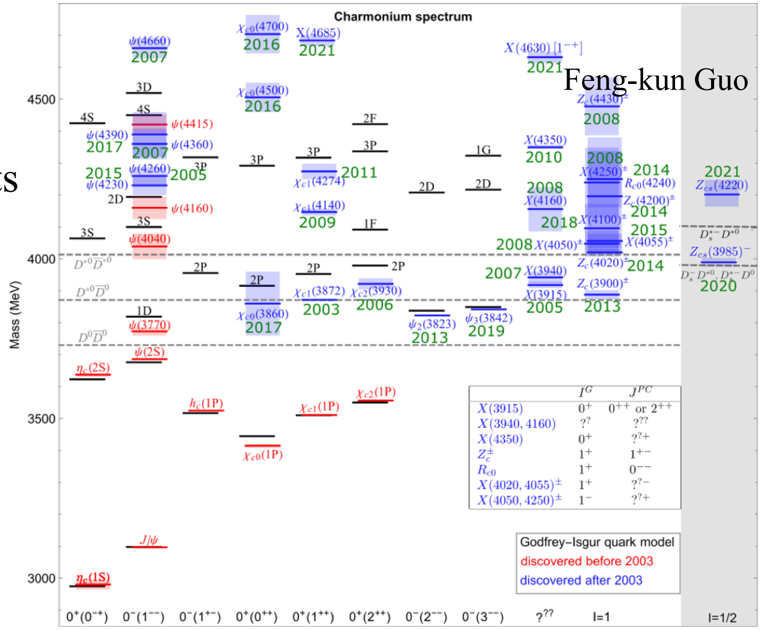
Penta-quark picture : Riska, Zou, Zhu, …

$$| p \rangle \sim | uud \rangle + \varepsilon_1 \, | [ud][ud]\,\bar{d} \rangle + \varepsilon' \, | [ud][us]\,\bar{s} \rangle + \ldots$$

Slides borrowed from B. Zou

History

- $X(3872)$: **first tetraquark candidates, now called** $\chi_{c1}(3872)$
  - Main motivation for exotic: mass different from prediction
- $Z_c(3900), Z_c(4200),$ $Z_c(4430)$: **charged exotics**
  - Clearly not charmonia, smoking gun; though hidden charm
- P_c **states: pentaquarks!**
- $X(5568)$: **four different flavors!**
  - However, negative conclusions from other experiments
- $X_{0,1}(2900)$: **four different flavors, open charmed**
  - Needs confirmation from other decays
- T_{cc}^{+}: **not with hidden charm, but with** cc **quarks**
- $X(6900)$: **four charm quarks** $c\bar{c}c\bar{c}$

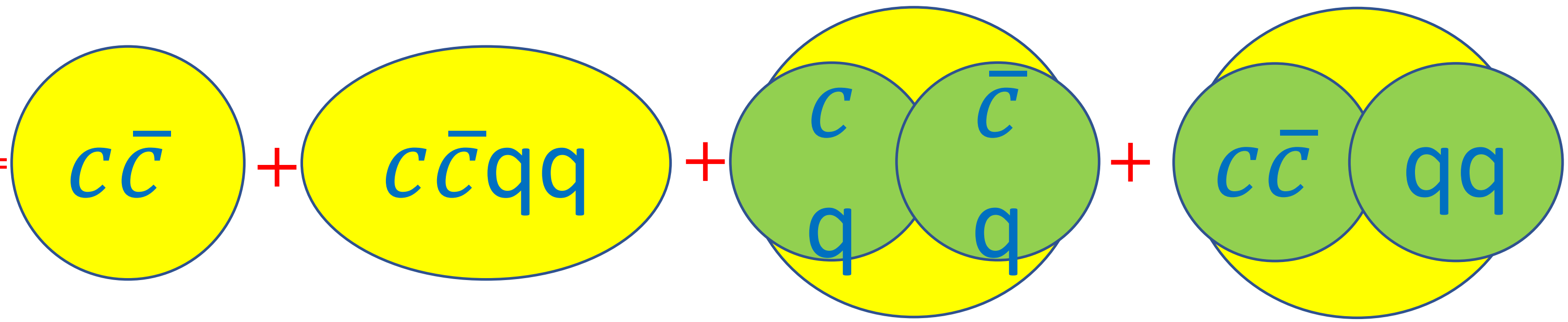


Feng-kun Guo

Current task: understanding inner structures of these exotic hadrons

Similar picture as proton

Particle X =



+ ...

Example:

$c\bar{c}$ MESONS
(including possibly non- $q\bar{q}$ states)

$\chi_{c1}(3872)$ $I^G(J^{PC}) = 0^+(1^{++})$

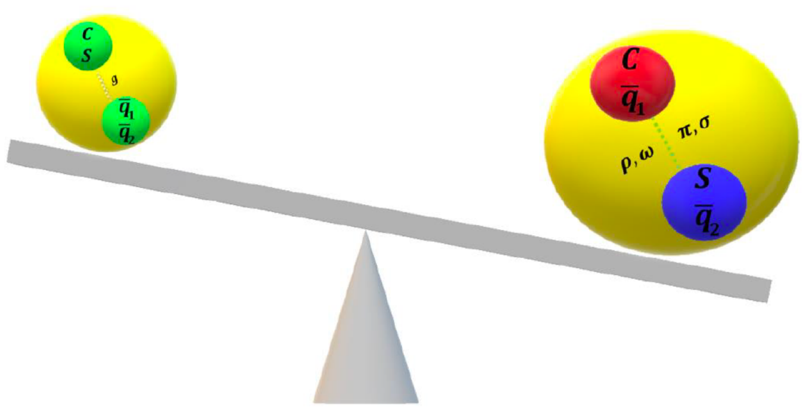
also known as $X(3872)$

Experimental tasks:

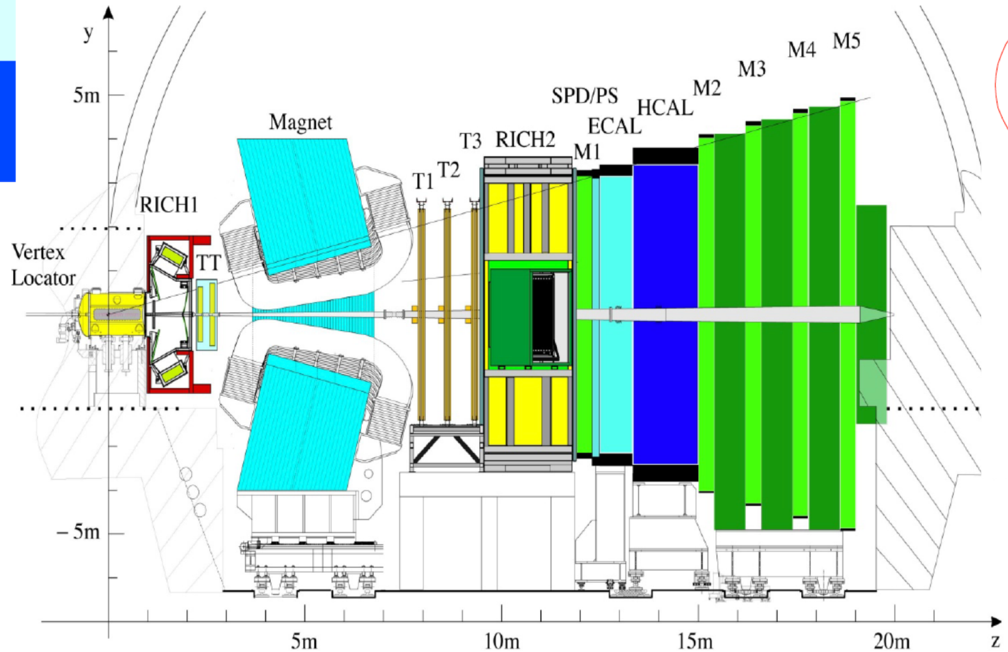
Discover more and understand them through production and decays

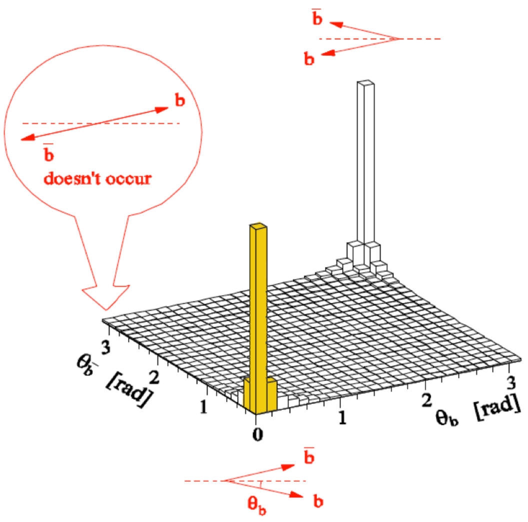
$$\frac{\Gamma(X(3872) \to \bar{D}D^*)}{\Gamma(X(3872) \to J/\psi\pi^+\pi^-)} = 9.1^{+3.4}_{-2.0}$$

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



The LHCb experiment





Excellent vertex and IP, decay time resolution:

- $\sigma(\text{IP}) \approx 20\ \mu\text{m}$ for high-p_{T} tracks
- $\sigma(\tau) \approx 45$ fs for $B_s^0 \to J/\psi\phi$ and $B_s^0 \to D_s^- \pi^+$ decays

Very good momentum resolution:

- $\delta p/p \approx 0.5\% - 1\%$ for $p \in (0{,}200)$ GeV
- $\sigma(m_B) \approx 24$ MeV for two-body decays

Hadron and Muon identification

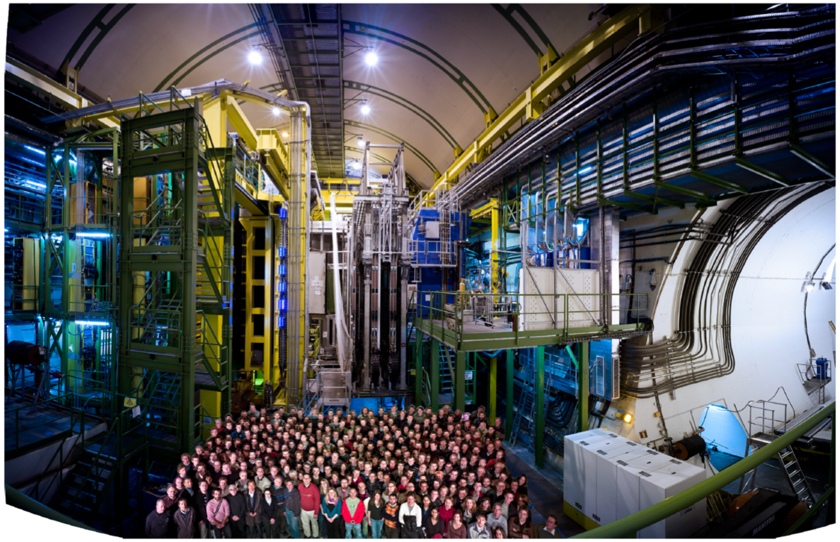
- $\epsilon_{K\to K} \approx 95\%$ for $\epsilon_{\pi\to K} \approx 5\%$ up to 100 GeV
- $\epsilon_{\mu\to\mu} \approx 97\%$ for $\epsilon_{\pi\to\mu} \approx 1 - 3\%$

Data good for analyses

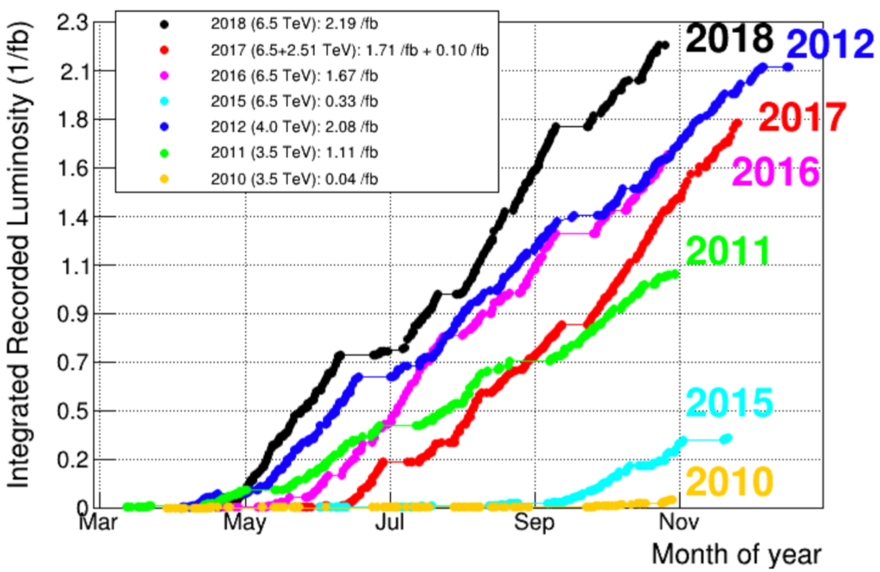
- $> 99\%$

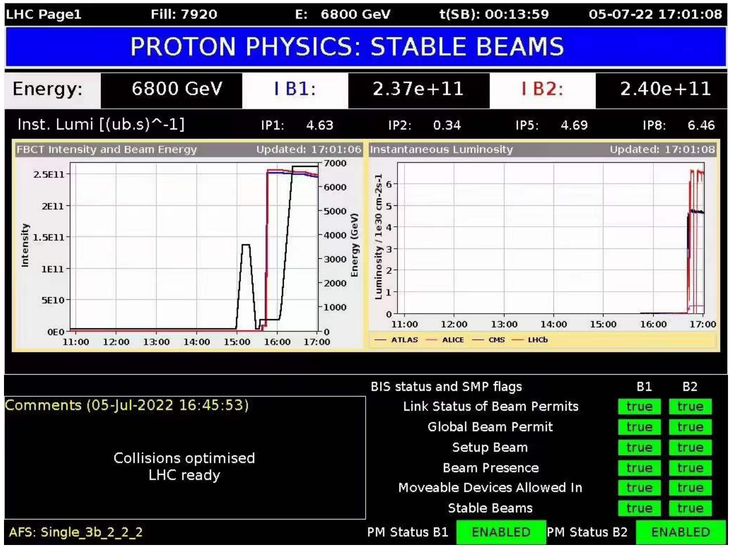
Designed for CP violation and heavy flavor studies

More on LHCb

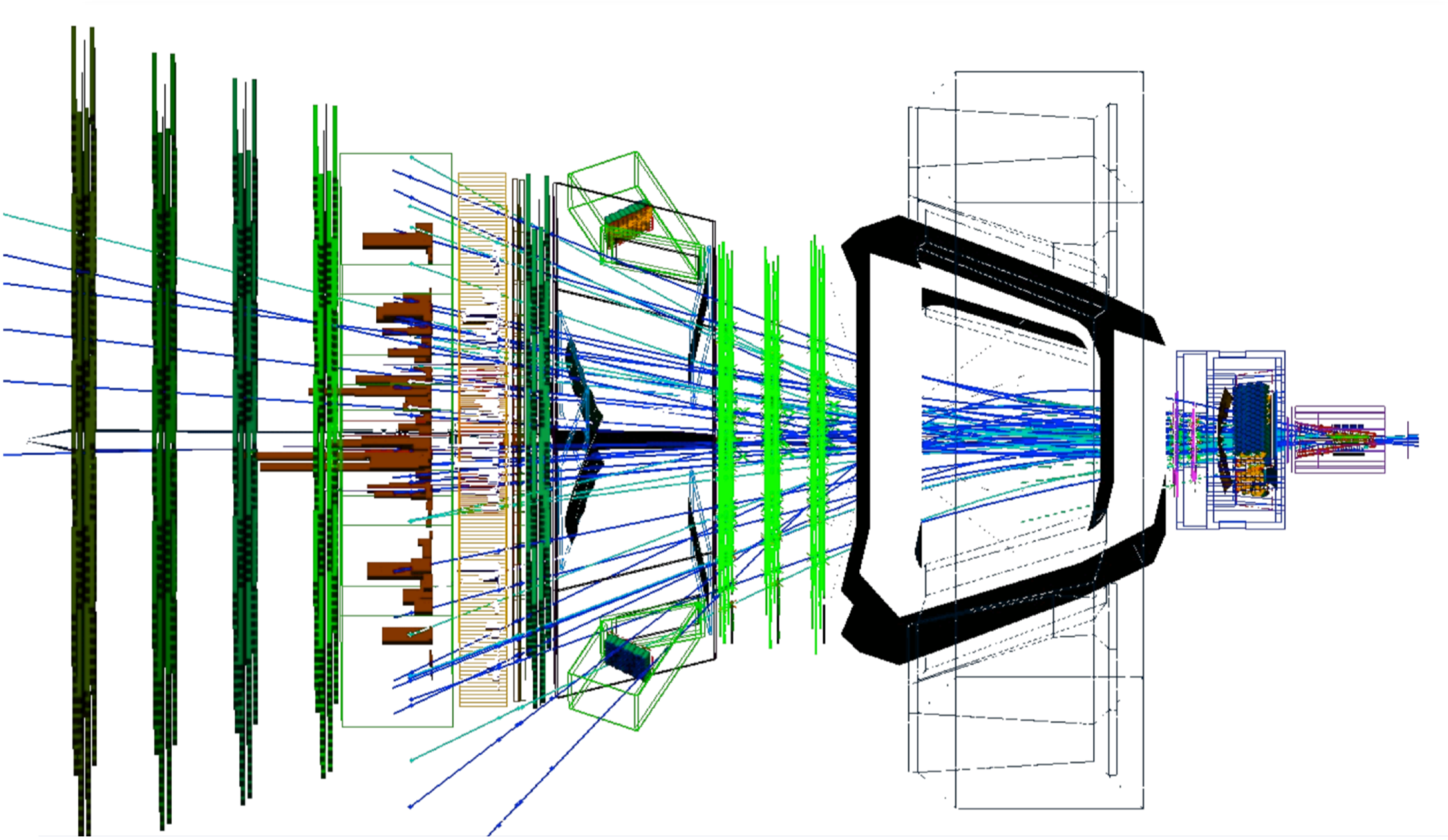


- Start to take data from 2010
- Run 1:
    - 2011 (7 TeV): 1 fb^{-1}
    - 2012 (8 TeV): 2 fb^{-1}
- Run 2:
    - 2015-2018 (13 TeV): 6 fb^{-1}
- A new LHCb starts this year



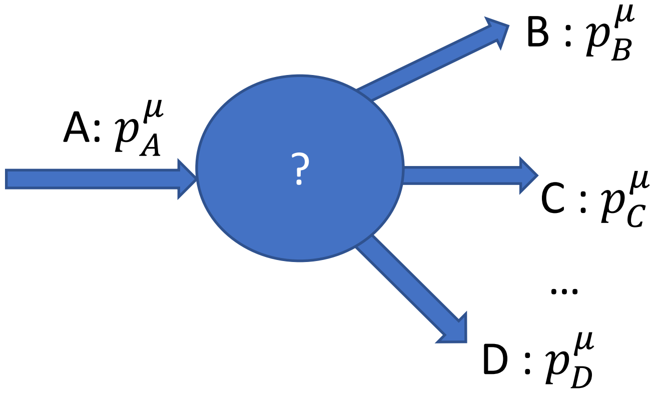


A collision in the LHCb detector



Extract resonant information

- **Most exotic states and their properties established in multi-body decays**
- **Amplitude analyses crucial**



$$\sim P(p_B^\mu, p_C^\mu, p_D^\mu; \vartheta)$$

- **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**
- **We have developed a new framework using TensorFlow**

TensorFlow

A general and user-friendly partial wave analysis framework

Hao Cai[1], Chen Chen[5], Yi Jiang[2], Pei-Rong Li[3], Yin-Rui Liu[2], Xiao-Rui Lyu[2], Rong-Gang Ping[4], Wenbin Qian[2], Mengzhen Wang[5], Zi-Yi Wang[2], Liming Zhang[5],Yang-Heng Zheng[2]

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

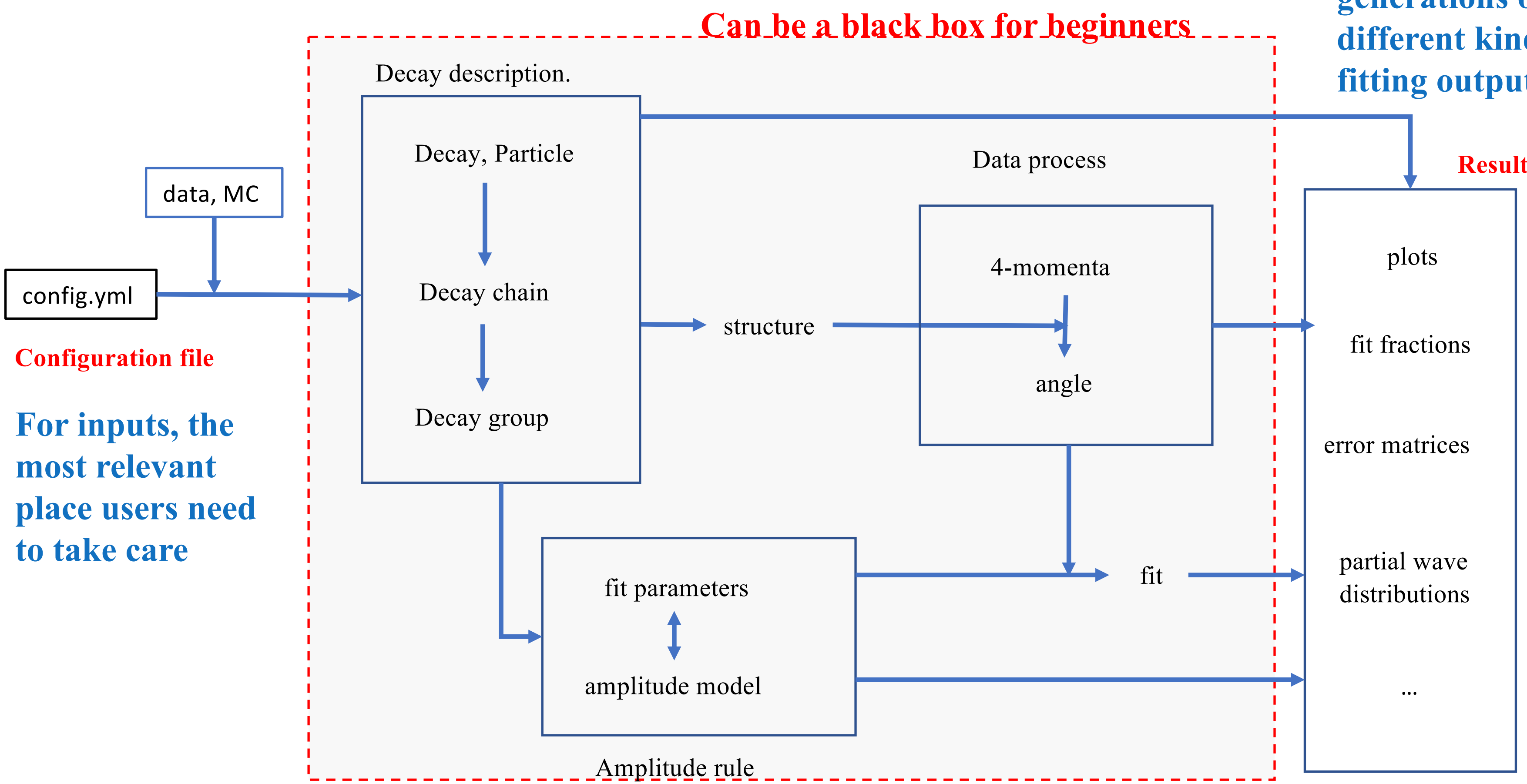
- **Joint efforts + experience on previous analyses + very good students**
- **Cross-checks performed with several independent fitters developed previously for dedicated analyses: e.g. $Z(4430)^+$ and pentaquark search, $B^0 \to \overline{D^0}\pi^+\pi^-$ analysis etc.**

Features

- Based on Tensor-Flow v2
- Fast
  - GPU based
  - Vectorized calculation
  - Automatic differentiation
- General
  - Custom model available
- Easy to use
  - Simple configuration file
  - Automatics process
  - All necessary functions implemented
- Open access and well supported

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

Framework



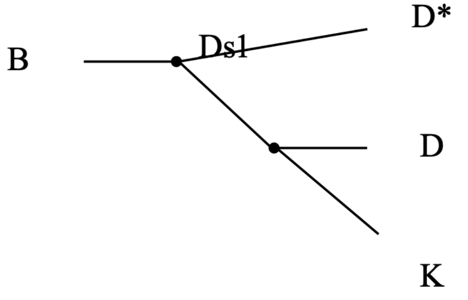
Automatic generations of different kinds of fitting outputs

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

Topology based algorithm

Decay group

…



…

$$\mathcal{A} = \tilde{A}_1 + \tilde{A}_2 + \cdots$$

Decay chain

$B^0 \to R(\to D^0 K^+)\, D^{*-}$

$B^0 \to R(\to D^0 D^{*-})\, K^+$

etc.

$$\tilde{A} = A_1 R A_2 + \cdots$$

Decays

$B^0 \to D_{s1}^*(2700)^+ D^{*-}$

$B^0 \to D_{s1}^*(2860)^+ D^{*-}$

etc.

Wigner D-matrix:

$$A = F D^{*J}\,(\phi, \theta, 0)$$

Particles

initial state (B^0),

final states (D^{*-}, D^0, K^+)

propagator ($D_{s1}^*(2700)$)

Breit-Wigner: $R(m)$, Other user defined function

$$A^R_{\lambda_A,\lambda_B',\lambda_C',\lambda_D'}$$

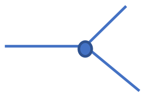
$$=$$

$$\sum_{\lambda} F_{\lambda_R \lambda_B} D^{j_A\star}_{\lambda_A,\lambda_R-\lambda_B}(\varphi_1,\theta_1,0) R(M) F_{\lambda_C,\lambda_D} D^{j_R\star}_{\lambda_R,\lambda_C-\lambda_D}(\varphi_2,\theta_2,0)$$

$$D^{j_B\star}_{\lambda_B,\lambda_B'}(\alpha_B,\beta_B,\gamma_B) D^{j_C\star}_{\lambda_C,\lambda_C'}(\alpha_C,\beta_C,\gamma_C) D^{j_D\star}_{\lambda_D,\lambda_D'}(\alpha_D,\beta_D,\gamma_D)$$

$$\frac{d\sigma}{d\Phi} \propto \sum_{\lambda_A} \sum_{\lambda_B,\lambda_C,\lambda_D} \left| \sum_R A^R_{\lambda_A,\lambda_B,\lambda_C,\lambda_D} \right|^2$$

Decay



$F_{\lambda_1,\lambda_2} D^{j_0\star}_{\lambda_0,\lambda_1-\lambda_2}(\varphi,\theta,0)$

Wigner-D matrix

Particle

$R(M) = \dfrac{1}{m_0^2 - M^2 - i m_0 \Gamma}, \cdots$

1

$D^{j_1\star}_{\lambda_1,\lambda_1'}(\alpha,\beta,\gamma)$

Benchmarks

CPU: i7-9750H@2.6 Hz with 12 cores
GPU: Nvidia 1660 Ti, a cheap GPU

Test based on simple MC (200000) sample of a simple amplitude model of $e^+e^- \to R_1(1^+)\pi, R_1 \to D^*D^*$

Both based on TF-PWA

process	CPU (ms)	GPU (ms)	Ratio
$N = \int \|A\|^2 d\Phi$	573	53	~11 X 12 = 132
N with $\frac{\partial N}{\partial \vartheta}$	1122	117	~9.5 X 12 = 114

Almost a factor of 100 times faster for GPU than single CPU core.

Automatic differentiation cost the same time as normal evaluation, faster with increase of parameters

Functions implemented

- 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
- …

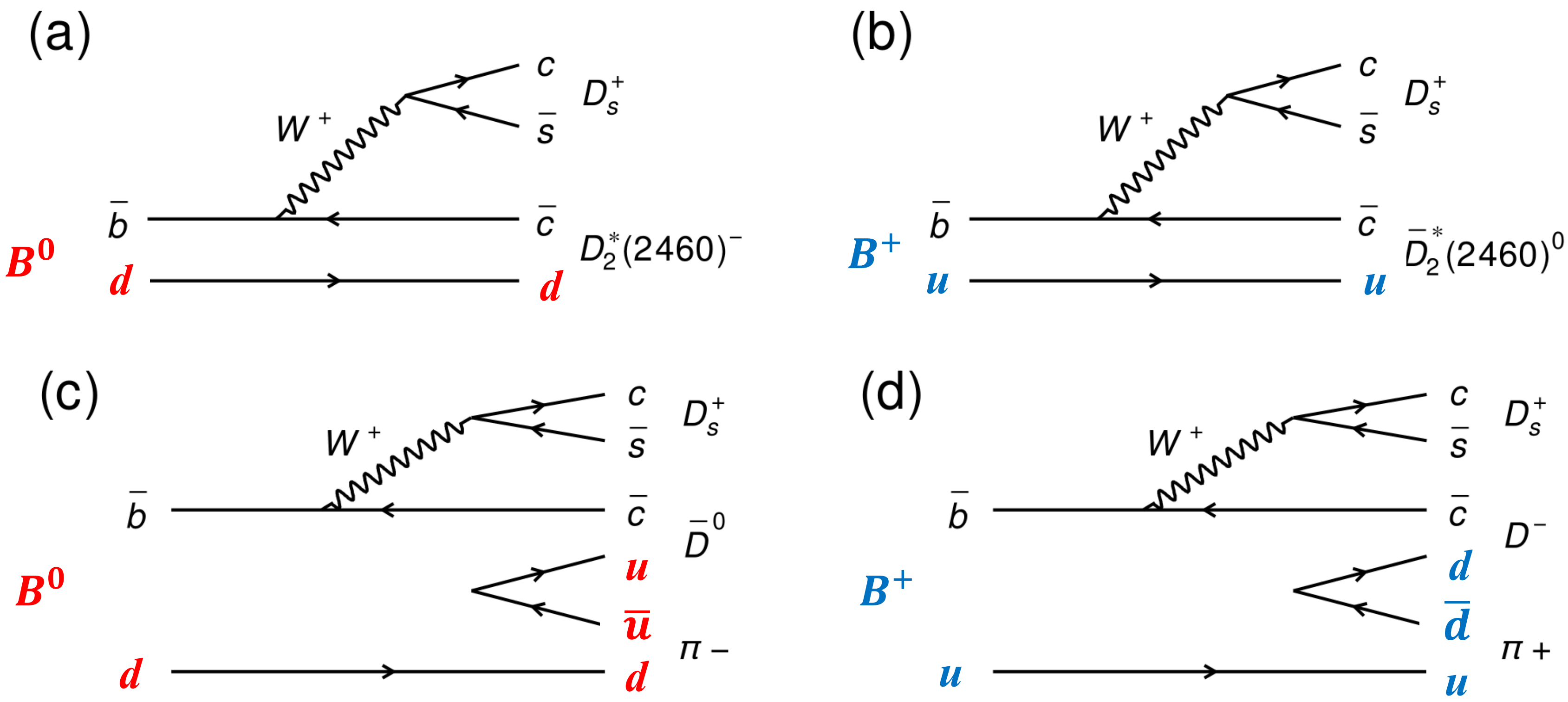
Used in many LHCb/BESIII analyses, including those discussed below

Observation of a double-charged tetra-quark states and its isospin partner

LHCb-PAPER-2022-026
LHCb-PAPER-2022-027

Feynman diagrams

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

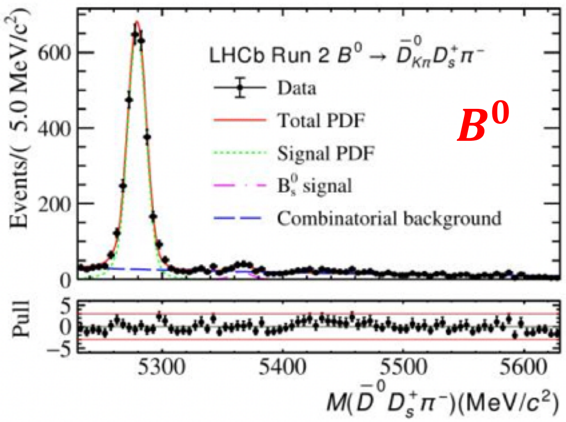


- **Connected by isospin relationship in all aspects**

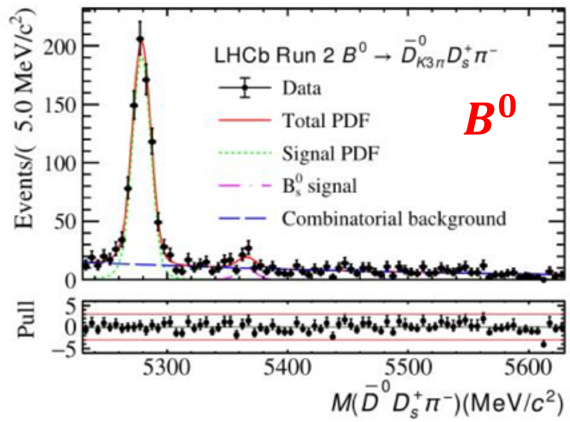
Signal yields

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

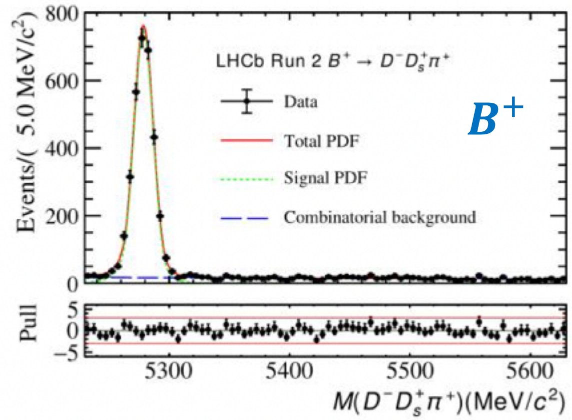
$D^0 \to K^- \pi^+$



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



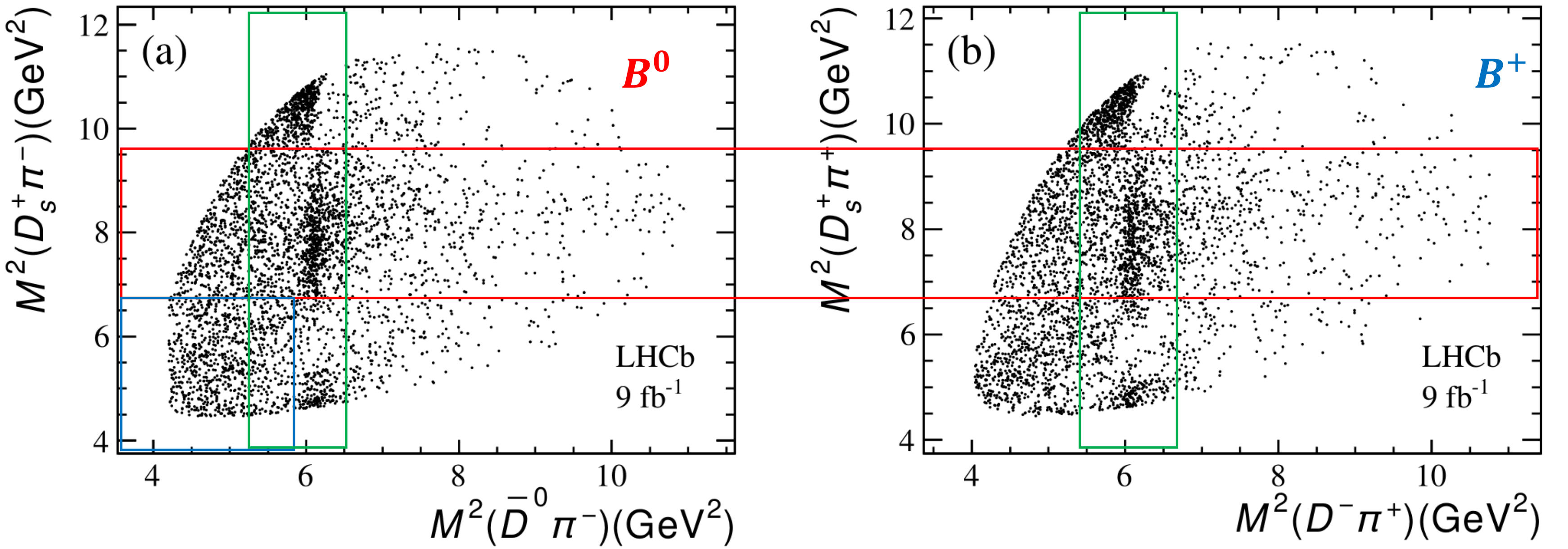
$D^- \to K^- \pi^+ \pi^+$



- **Very pure samples, ideal for amplitude analysis**
- **~4000 B^0 signals with a purity of ~90%;**
- **~3750 B^+ signals with a purity of ~95%**

Preliminary

First impression on Dalitz plot



Preliminary

- **Very similar distributions over Dalitz plot**
- **Clear accumulation of events on both channels around 2.9 GeV of $m(D_s^+\pi^-)$ and $m(D_s^+\pi^+)$**
- **$D^{*-}(2010)$ cut-off in B^0 channel; small isospin breaking effects at threshold**
- **Very clear contributions from $D_2(2460)$**

Amplitude analysis

- **Unbinned maximum likelihood fits performed with TF-PWA**

$$P(x;\Theta) = f_{\text{sig}} \cdot P_{\text{sig}}^{\text{norm}}(x;\Theta) + f_{\text{bkg}} \cdot P_{\text{bkg}}^{\text{norm}}(x),$$

Fractions determined from mass fits

- **Background modelled from upper sideband with extrapolating into signal regions**
- **Signal PDF:** $$P_{\text{sig}}^{\text{norm}}(x;\Theta) = \frac{\epsilon(x)\,|\mathcal{A}(x;\Theta)|^2}{I_{\text{sig}}(\Theta)}.$$

Normalization factor

- **Efficiencies obtained from full simulation with corrections for data-simulation difference**
- **Amplitude model:** $\mathcal{A}(x;\Theta) = \sum c_i \cdot \mathcal{A}_i(x;\Theta_i),$

Angular distribution + line shape (RBW etc.)

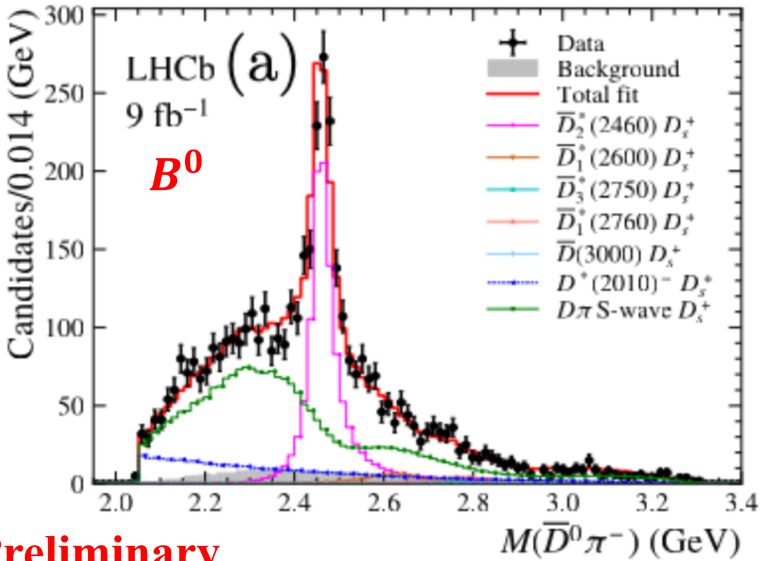
D^* resonances

- D^* main contributors for the Dalitz distribution,;
- Current observed D^* states

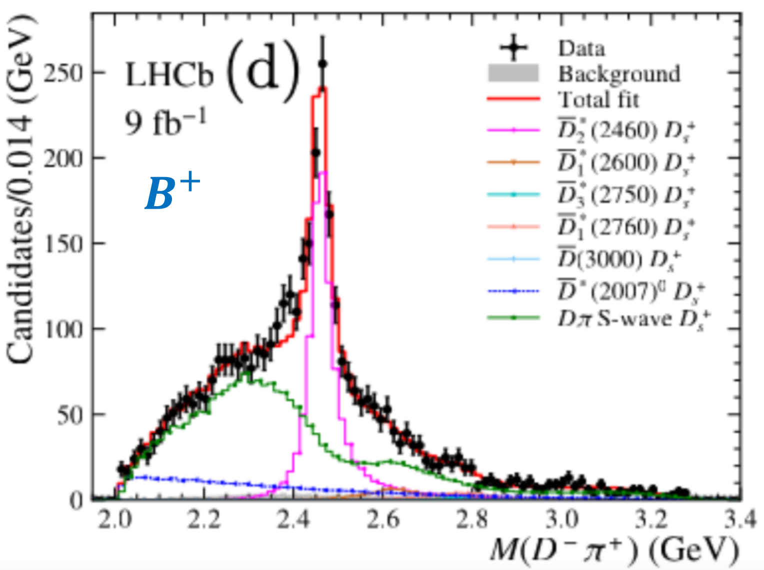
Resonance	J^P	Mass (GeV)	Width (GeV)
$D^*(2007)^0$	1^-	2.00685 ± 0.00005	$< 2.1 \times 10^{-3}$
$D^*(2010)^-$	1^-	2.01026 ± 0.00005	$(8.34 \pm 0.18) \times 10^{-5}$
$D_0^*(2300)$	0^+	2.343 ± 0.010	0.229 ± 0.016
$D_2^*(2460)$	2^+	2.4611 ± 0.0007	0.0473 ± 0.0008
$D_1^*(2600)^0$	1^-	2.627 ± 0.010	0.141 ± 0.023
$D_3^*(2750)$	3^-	2.7631 ± 0.0032	0.066 ± 0.005
$D_1^*(2760)^0$	1^-	2.781 ± 0.022	0.177 ± 0.040
$D(3000)^0$	$?^?$	3.214 ± 0.060	0.186 ± 0.080

- $D^*(2007)^0$ and $D^*(2010)^-$ close to threshold, small isospin violation effects seen
- PDG currently gives average masses and widths for D^{**} states
- $D_1^*(2600)^-, D_1^*(2760)^-, D(3000)^-$ not observed yet
- Spin-parity of $D(3000)^0$ not established yet

D^* contributions



Preliminary

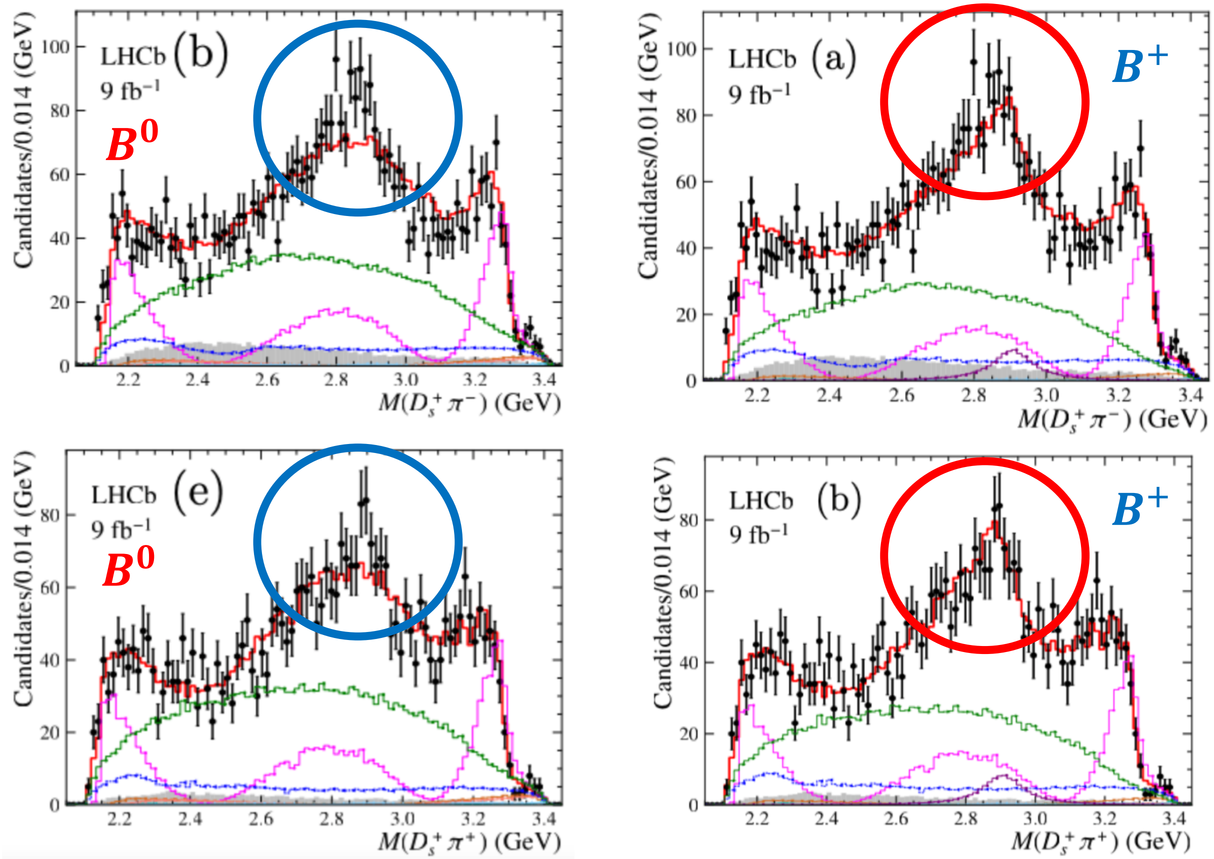


- **Different models for $D^*(2007)^0$ and $D^*(2010)^-$, though shapes turn out to be similar**
- **S-wave can be described by RBW + NR, however, to avoid unitarity problem, a spline function used, offering better and conservative description**
- **$D_1^*(2600), D_1^*(2760), D(3000)$ not significant, however, still included conservatively**
- **Generally very good description of $m(D\pi)$ spectrum**

Exotics

Preliminary

Without new states



With new states

- **Not very good description on $m(D_s\pi)$ around 2.9 GeV**
- **Further $m(D\pi)$ or $m(DD_s)$ contributions not help**
- **Add new states on $m(D_s\pi)$, $T^a_{c\bar{s}}(2900)^0$ and $T^a_{c\bar{s}}(2900)^{++}$ help a lot**

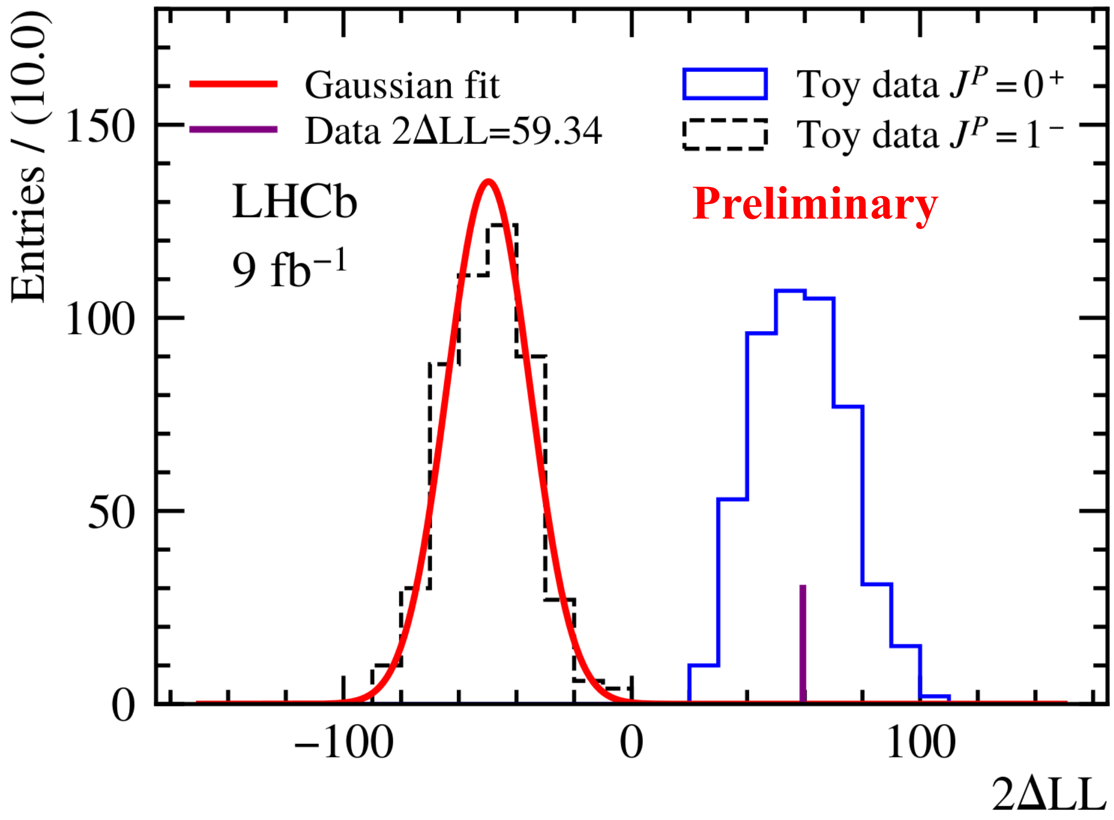
More on exotics

- **Isospin relationship imposed on $m(D\pi)$, apart from $D^*(2010)$ and $D^*(2007)$, confirmed by separate fits**
- **Two scenarios considered for $T^a_{c\bar{s}}(2900)^0$ and $T^a_{c\bar{s}}(2900)^{++}$: with and without isospin relationship**

Scenarios	Exotics	Mass (GeV)	Width (GeV)	Significance
No isospin relationship	$T^a_{c\bar{s}}(2900)^0$	$2892 \pm 14 \pm 15$	$119 \pm 26 \pm 12$	8.0σ
	$T^a_{c\bar{s}}(2900)^{++}$	$2921 \pm 17 \pm 19$	$137 \pm 32 \pm 14$	6.5σ
With isospin relationship	Both	$2908 \pm 11 \pm 20$	$136 \pm 23 \pm 11$	9.0σ

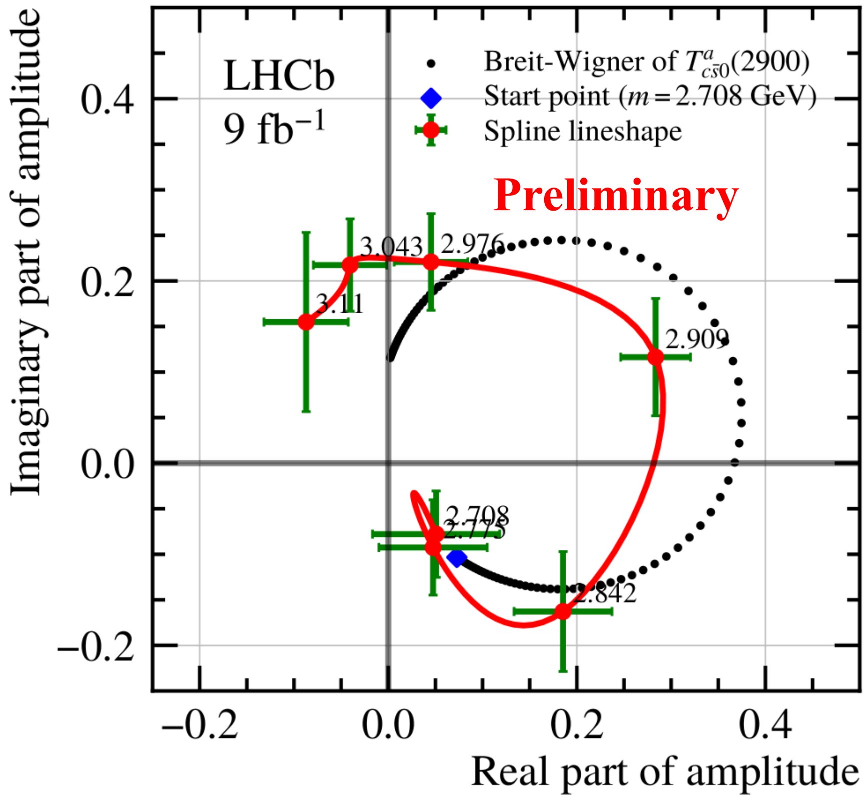
- **Significance estimated considering look-else-where effects**
- **Two states consist with each other: isospin triplet**
- **$J^P = 0^+$ preferred for both cases**

Spin analysis



- **Toys generated for spin analysis: 0^+ preferred over 1^- (second best solution) by 7.6σ**
- **0^+ is also significantly preferred when exotics not constrained by isospin**

Argand diagram



- **Replacing RBW description of exotic states with splines (no model assumption)**
- **Spline description consist with RBW behavior**

Discussion

- In $B^+ \to D^+ D^- K^+$ decays, two states observed with quark content $cs\bar{u}\bar{d}$
- $T_{cs}^{a}(2900)$ have quark content $c\bar{s}\bar{u}d$ and $c\bar{s}u\bar{d}$
- Very similar mass, $T_{cs}^{a}(2900)$ has larger width
- Only 0^+ $T_{cs}^{a}(2900)$ states found

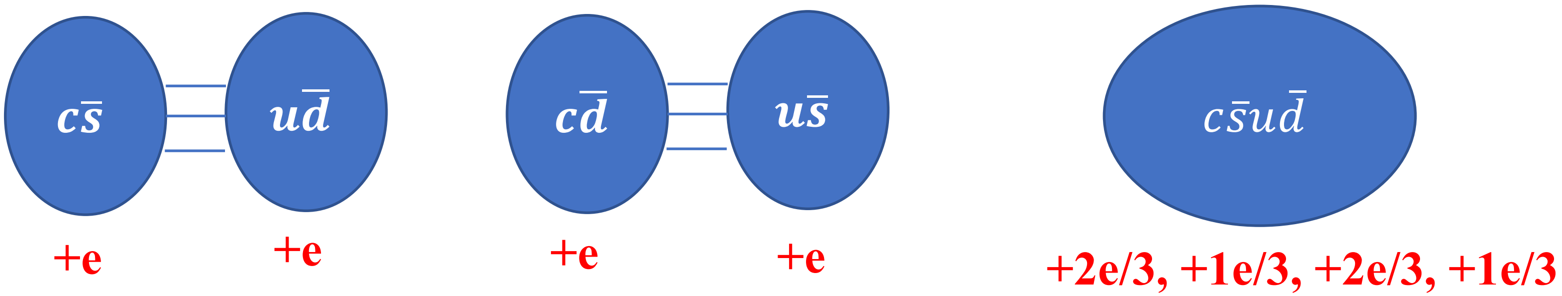
Preliminary

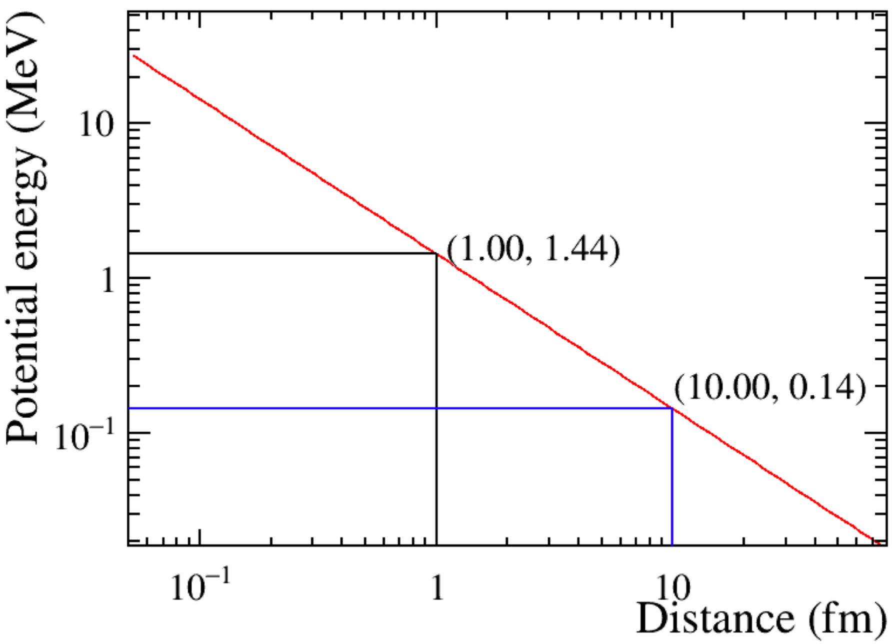
Exotic	Mass (MeV)	Width (MeV)	Spin-parity
$X_0(2900)$	$2866 \pm 7 \pm 2$	$57 \pm 12 \pm 4$	0^+
$X_1(2900)$	$2904 \pm 5 \pm 1$	$110 \pm 11 \pm 4$	1^-
$T_{c\bar{s}}^{a}(2900)^0$	$2892 \pm 14 \pm 15$	$119 \pm 26 \pm 12$	0^+
$T_{c\bar{s}}^{a}(2900)^{++}$	$2921 \pm 17 \pm 19$	$137 \pm 32 \pm 14$	0^+

- $X(5568)$ claimed by D0 collaboration in $B_s^0\pi^\pm$ final states, with quark flavor $b\bar{s}\bar{u}d$, however, negative results from other experiments
- Some suggestions for $T_{cs}^{a}(2900)$ (1705.10088, 2204.02649, 2008.07145, 2008.07340 et al.)

Charge

- **For double charged tetraquark candidates, if molecular, replusion potential around 1.44 MeV @ 1 fm!**

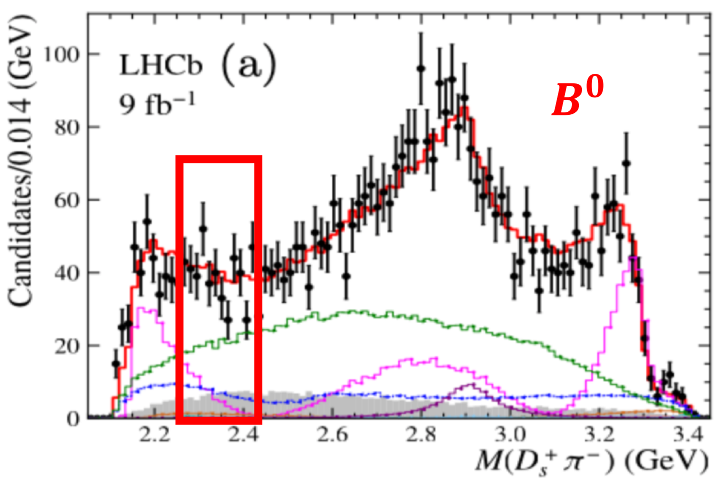




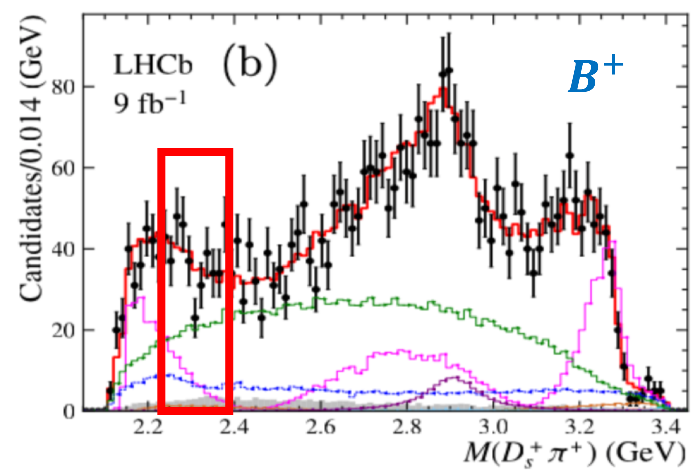
- **If compact states, all four quarks have positive charge**
- **Or may be just cusp**

Isospin

- $T^{a}_{c\bar{s}}(2900)^0$ and $T^{a}_{c\bar{s}}(2900)^{++}$ are two of the isospin triplet;
- Missing one $(D_s^+\pi^0)$, hard for LHCb, though not entirely impossible;
- Some suggests $D_s^+(2317)$ (decaying into $D_s^+\pi^0$) to be a tetraquark state; though no clue from current charged pion modes (contamination from $D_2(2460)$)
- I = 0 considered to have strong attraction while I = 1 to have weak attraction or even repulsion;



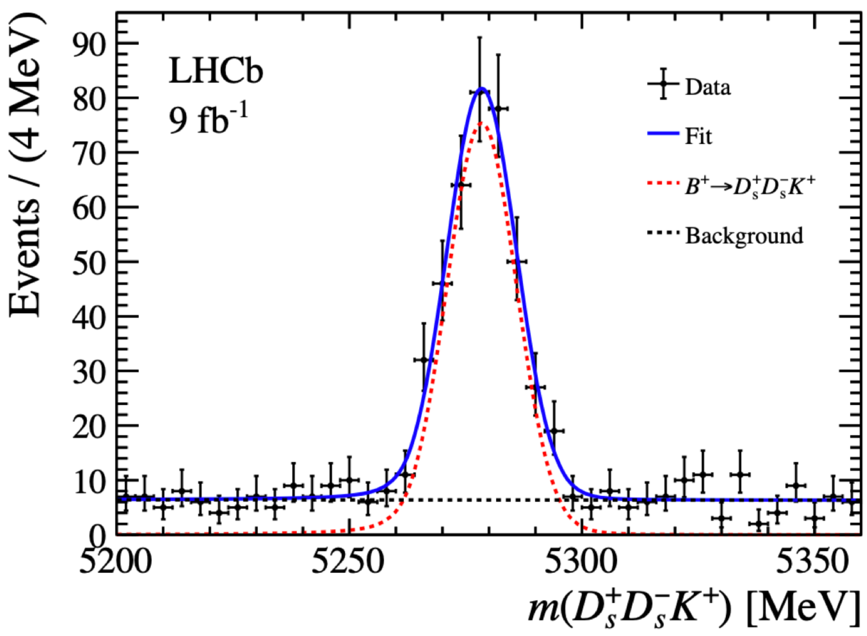
Preliminary

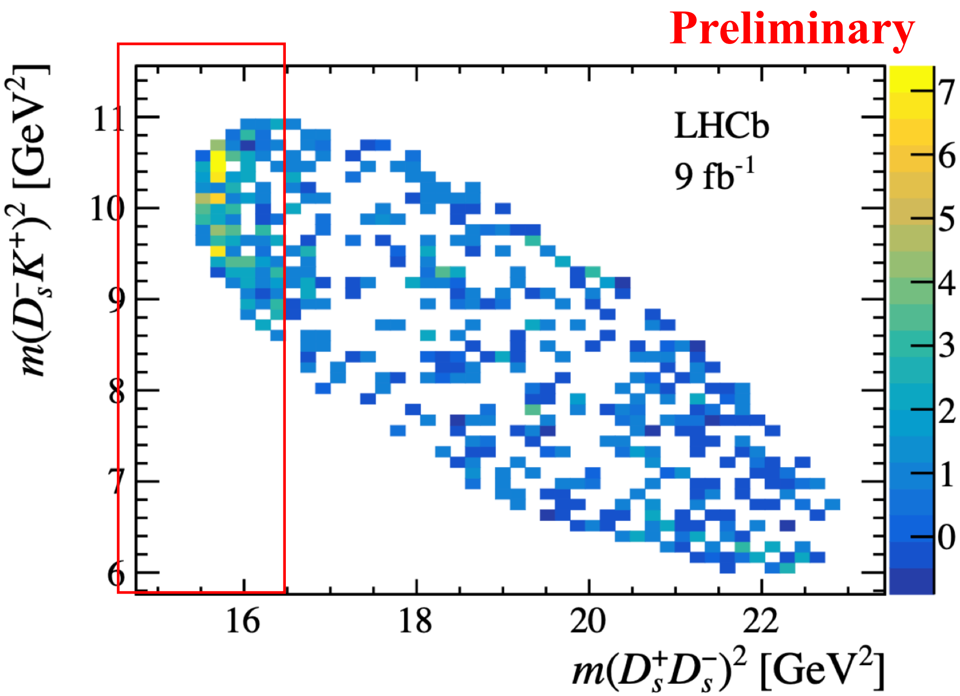


Observation of a resonant structure near the $D_s^+ D_s^-$ threshold

LHCb-PAPER-2022-018
LHCb-PAPER-2022-019

Yields and Dalitz plot distribution

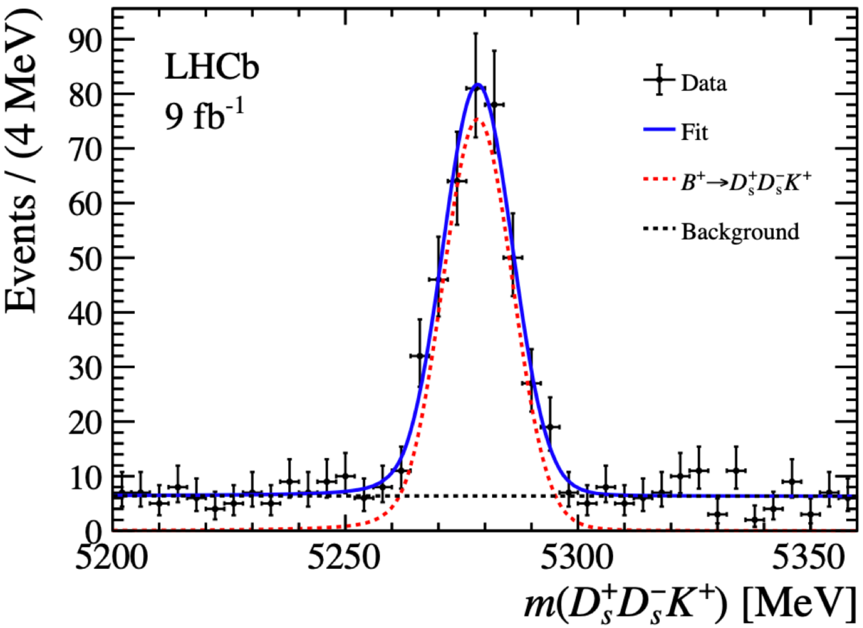


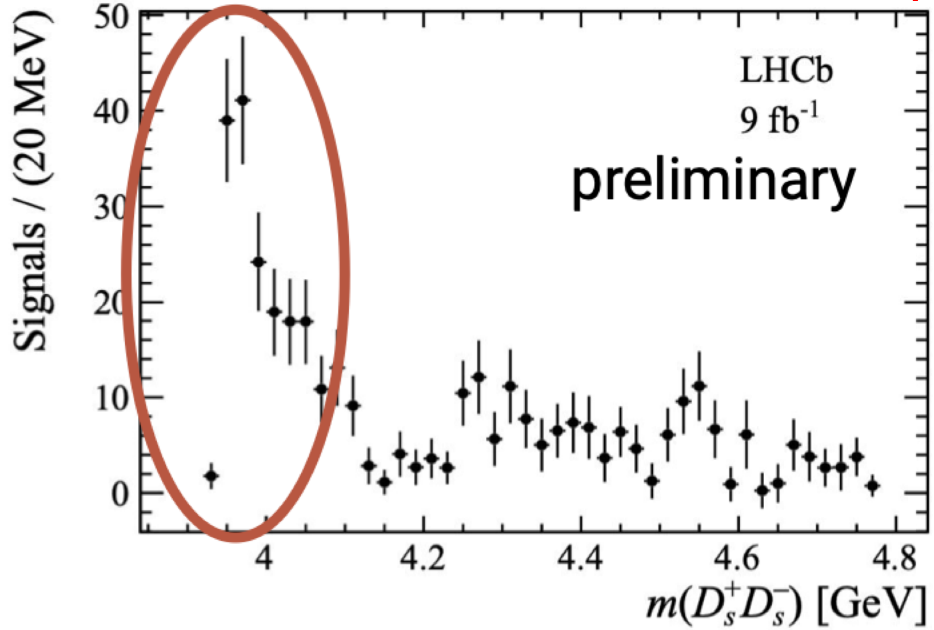


- $B^{+} \to D_{s}^{+} D_{s}^{-} K^{+}$: ~360 signal candidates with a purity of ~85%
- No clear structures over Dalitz plot except accumulations at the $m(D_{s}^{+} D_{s}^{-})$ threshold around 3.9 GeV

Yields and Dalitz plot distribution

Preliminary

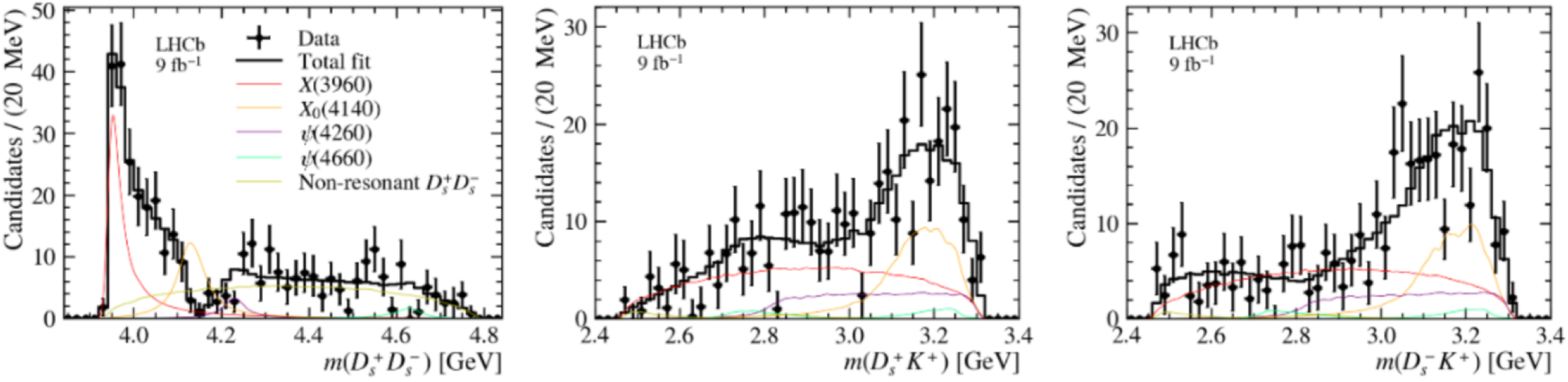




- $B^+ \to D_s^+ D_s^- K^+$: ~360 signal candidates with a purity of ~85%
- No clear structures over Dalitz plot except accumulations at the $m(D_s^+ D_s^-)$ threshold around 3.9 GeV

Amplitude fit results

Preliminary



- **Only resonances on $m(D_s^+ D_s^-)$ contribute**
- **Dominant contribution from NR (~46.6%) and a near threshold state $X(3960)$ (~24.2%, more than 12.6 σ)**
- **Evidence of contributions from $\psi(4260)$, $\psi(4660)$ and $X(4140)$**
- **Other states ($\chi_{c0}(4500)$, $\chi_{c0}(4700)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$ and $\chi_{c2}(3930)$) also tested, though not significant**

Puzzles around 3930 MeV

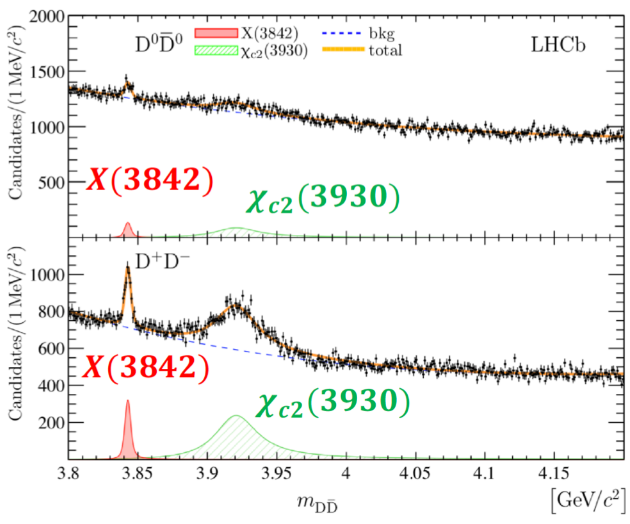
Summary of current PDG

$D_s^+ D_s^-$ 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 $B^+ \to D^+D^-K^+$).



LHCb-PAPER-2019-005

		$m_{\chi_{c2}(3930)}$ [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
- Current PDG values driven by LHCb inclusive measurements

Inputs from $B \to DDh$

Summary of current PDG

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

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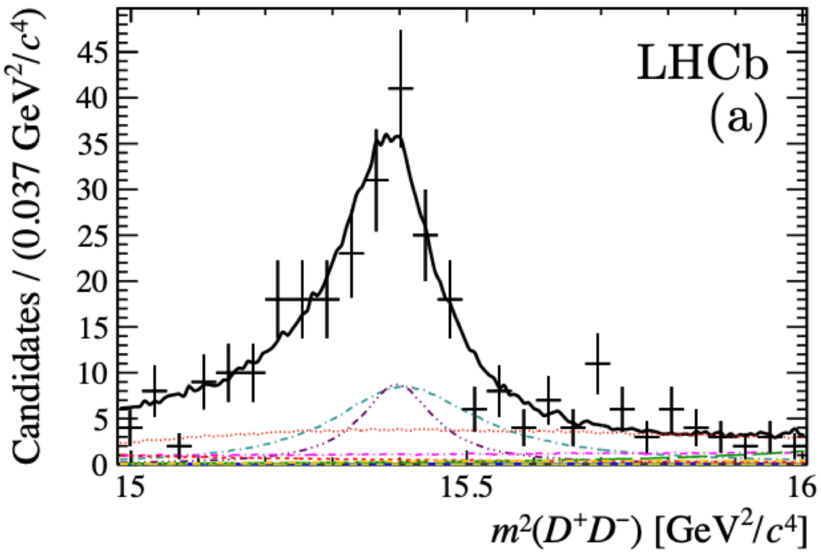
$\chi_{c2}(3930)$	2^{++}	3922.2 ± 1.0	35.3 ± 2.8	$\gamma\gamma$, $D\bar{D}$

- **Recent LHCb measurements with $B^+ \to D^+D^-K^+$ also gives interesting inspection on this area**



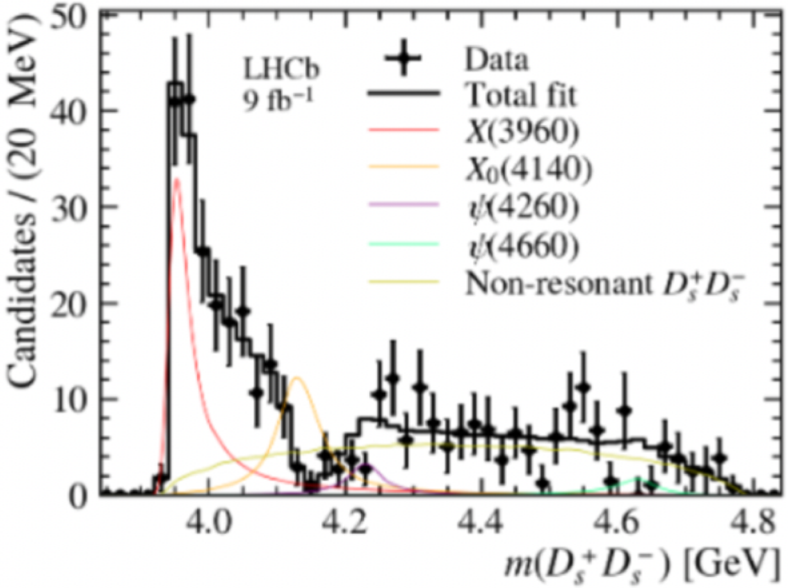
LHCb-PAPER-2020-025

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; lead to rethink of previous results**
- **It also puts the question whether this spin 0 particle = X(3915)?**
- **Hard to be in 2P triplets, thus may prefer exotic nature;**

$X(3960)$

Preliminary



- J^{PC} of 0^{++} is significantly preferred
- Mass and width determined to be

	M_0 (MeV)	Γ_0(MeV)
One channel	$3956 \pm 5 \pm 11$	$43 \pm 13 \pm 8$

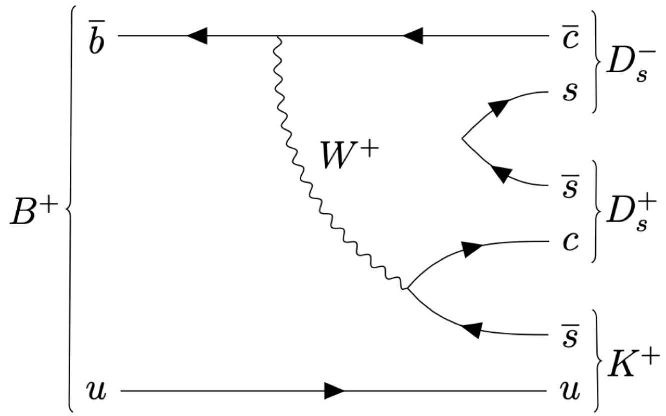
- $D_s^+ D_s^-$ threshold: ~3938 MeV

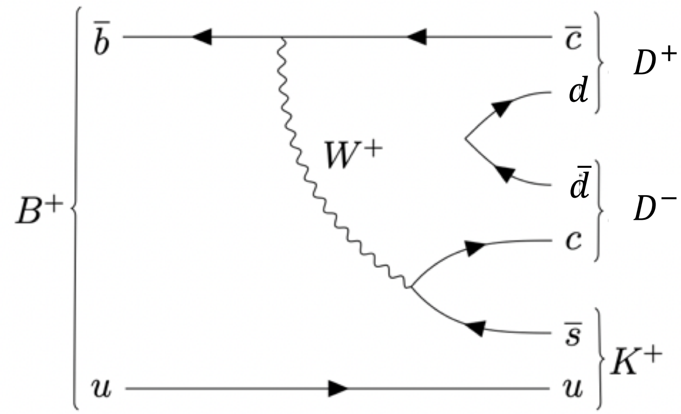
$$R(m \mid M_0, g_j) = \frac{1}{M_0^2 - m^2 - iM_0 \sum_j g_j \rho_j(m)},$$

Coupling constant   Phase space factor

- Default: only with one channel = RBW
- Two channels considered: $D_s^+ D_s^-$ $(D^+ D^-)$ with couplings: 0.33 ± 1.18 (0.15 ± 0.33) GeV, simultaneous fits with $B^+ \to D^+ D^- K^+$ decays needed

$X(3960)$





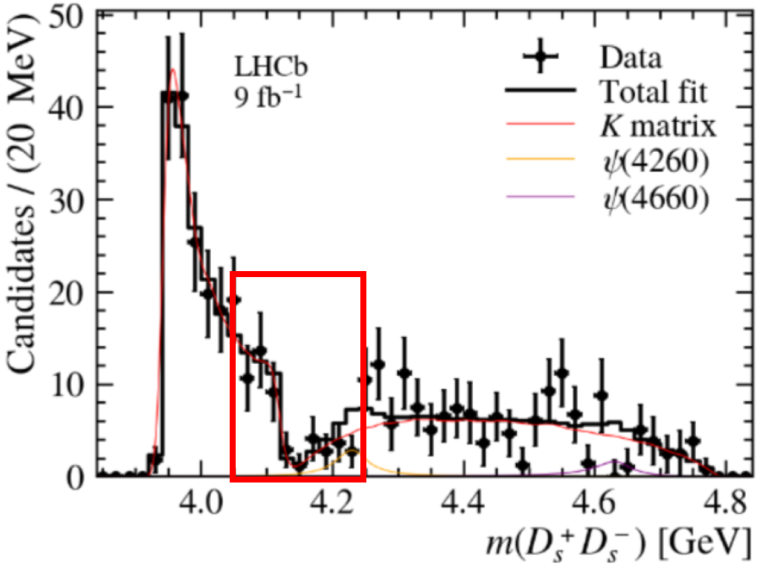
$$\frac{\mathcal{B}(B^+ \to D_s^+ D_s^- K^+)}{\mathcal{B}(B^+ \to D^+ D^- K^+)} = \frac{N_{\rm sig}^{\rm corr}}{N_{\rm con}^{\rm corr}} \left[\frac{\mathcal{B}(D^+ \to K^- \pi^+ \pi^+)}{\mathcal{B}(D_s^+ \to K^- K^+ \pi^+)}\right]^2 = 0.525 \pm 0.033,$$

Preliminary

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

- **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 $c\bar{c}s\bar{s}$**

$X(4140)$



- **Dip around 4140 MeV can be seen clearly**
- **Significance around 3.9σ; mass and width determined to be**

	M_0 (MeV)	Γ_0(MeV)
RBW	$4133 \pm 6 \pm 11$	$67 \pm 17 \pm 7$

- **$J/\psi\phi$ threshold: ~4116.4 MeV**

- **A KMatrix with single resonance with two decay channels**

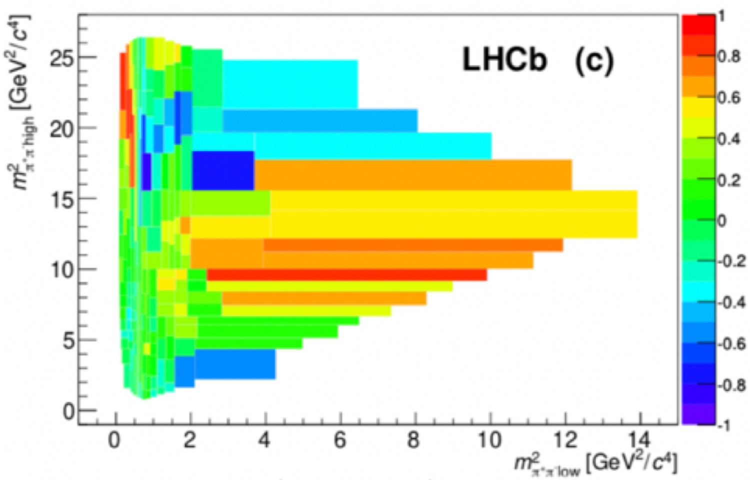
$$\begin{pmatrix} \mathcal{M}_{D_s^+ D_s^- \to D_s^+ D_s^-} & \mathcal{M}_{D_s^+ D_s^- \to J/\psi\phi} \\ \mathcal{M}_{J/\psi\phi \to D_s^+ D_s^-} & \mathcal{M}_{J/\psi\phi \to J/\psi\phi} \end{pmatrix} \equiv \begin{pmatrix} \mathcal{K}_{11} & \mathcal{K}_{12} \\ \mathcal{K}_{21} & \mathcal{K}_{22} \end{pmatrix}, \quad \mathcal{K}_{ab}(m) = \sum_R \frac{g_b^R g_a^R}{M_R^2 - m^2} + f_{ab},$$

- **Can't conclude whether the dip is due to resonances or due to opening of new decay channel**

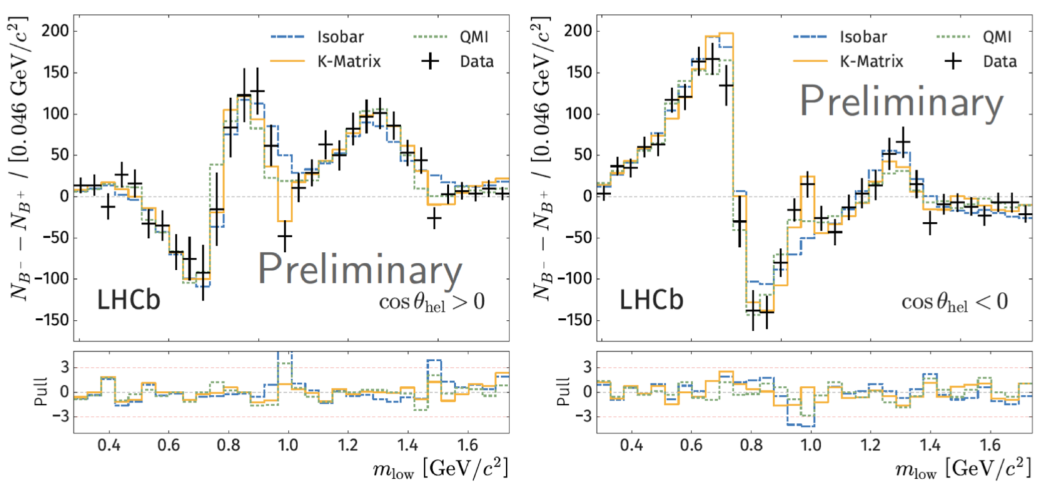
One slides for CP violation

LHCb-PAPER-2019-017
LHCb-PAPER-2019-018

- **Amplitude analysis also important for understanding contributions of CP violation in multi-body decays**
- **Hadronic dynamic can be described by amplitude mode and thus isolate weak information**



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



- **E.g in $B^+ \to \pi^+\pi^+\pi^-$ decays, one finds several new pattern of CP violation: CP violation due to S-P wave interference, CP violation in tensor particles etc.**

Conclusion

- **Understanding fundamental structures of hadrons is one of key topics in particle physics**
- **A general amplitude analysis tool, TF-PWA, has been developed to search for exotic hadrons, to understand their properties and also to study CP violation over phase space**
- **Using TF-PWA, three new tetra-quark states have been observed by the LHCb experiment, one with double charges ($T^a_{cs}(2900)^{++}$) together with its neutral isospin partner, $T^a_{cs}(2900)^0$, and the third $X(3960)$**
- **Stay tuned for more exotic states from LHCb**

Ruiting Ma, Ph. D student from UCAS, will present these results in ICHEP tomorrow

Thank You for Your Attention