The 6th workshop on the XYZ particles,
Fudan University, 11-13 Jan, 2020

Recent pentaquark results at LHCb

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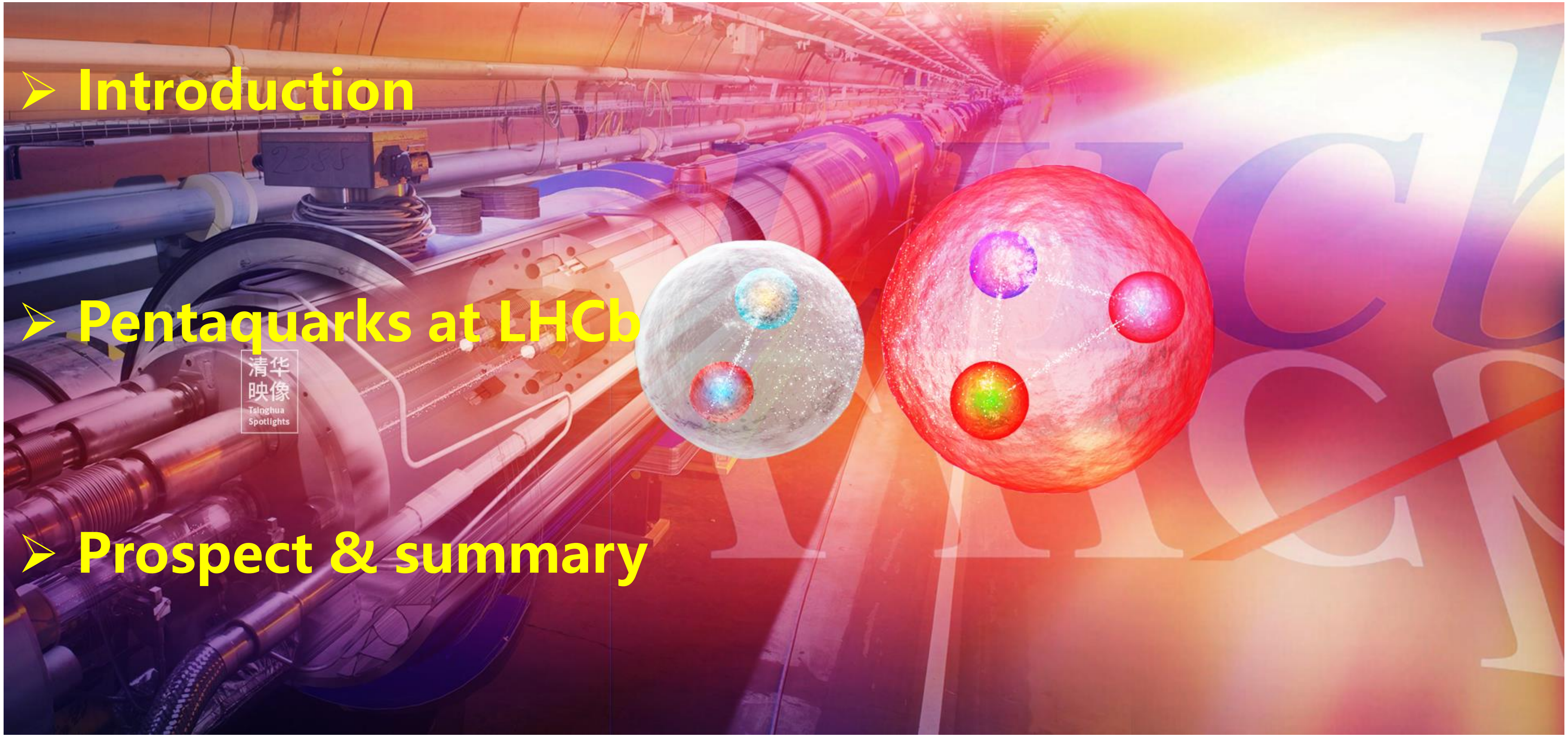
清华大学

2020.01.11

Outline



- Introduction
- Pentaquarks at LHCb
- Prospect & summary

The year 1995

The Nobel Prize in Physics 1995

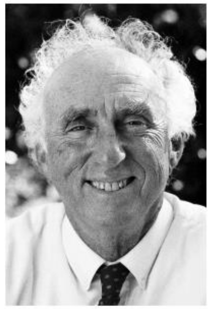
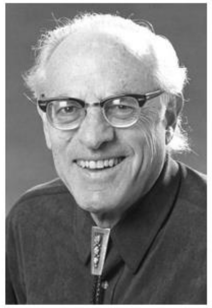


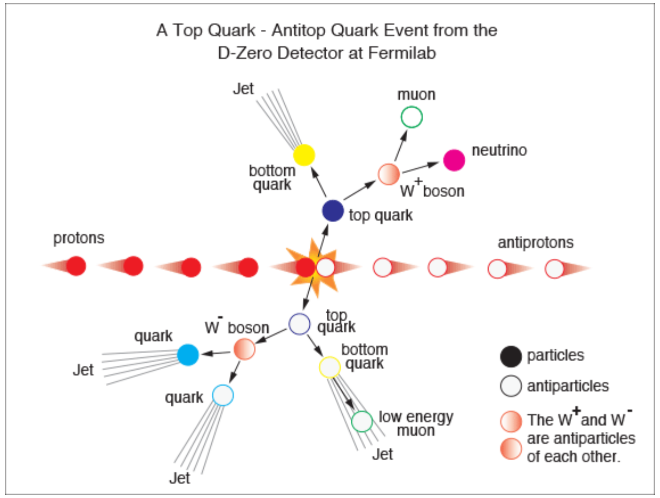
Photo from the Nobel Foundation archive.
Martin L. Perl
Prize share: 1/2



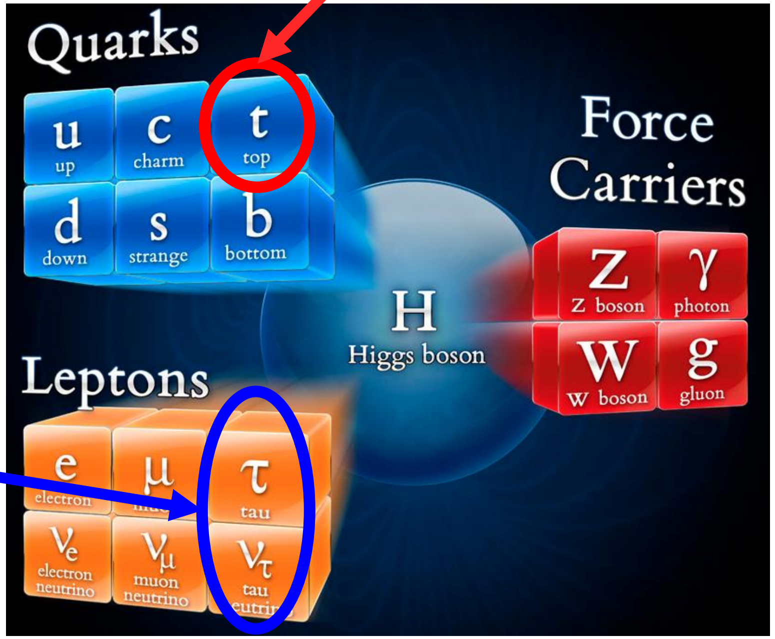
© University of California Regents
Frederick Reines
Prize share: 1/2

The Nobel Prize in Physics 1995 was awarded "for pioneering experimental contributions to lepton physics" jointly with one half to Martin L. Perl "for the discovery of the tau lepton" and with one half to Frederick Reines "for the detection of the neutrino."

For the discovery of two fundamental particles τ and ν_τ



The 6th quark discovered at Fermilab



51 Pegasi b · Discovered

Oct 06, 1995

Discovery of an exoplanet orbiting a solar-type star

The 2019 Physics Laureates

This year's Physics Laureates are awarded "for contributions to our understanding of the evolution of the universe and Earth's place in the cosmos", with one half to James Peebles "for theoretical discoveries in physical cosmology" and the other half jointly to Michel Mayor and Didier Queloz "for the discovery of an exoplanet orbiting a solar-type star."

Ill. Niklas Elmehed. © Nobel Media.

The year 1995

WORLD TRADE ORGANIZATION

Microsoft Windows 95

ebay

launch (original logo)

Important Events

Apr 19 Oklahoma City bombing - a truck bomb at Alfred P. Murrah Federal Building kills 168 & injures 500

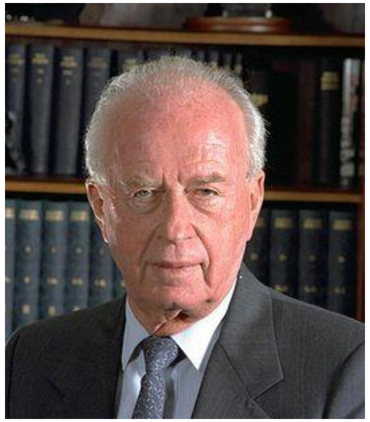
May 11 In New York City, more than 170 countries decide to extend the Nuclear Nonproliferation Treaty indefinitely and without conditions.

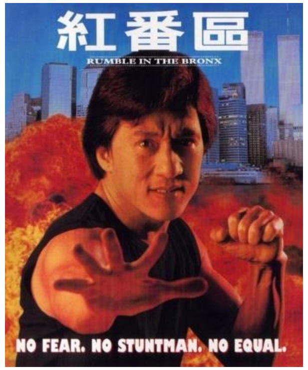
Bombs, massacres, wars and efforts to cease them

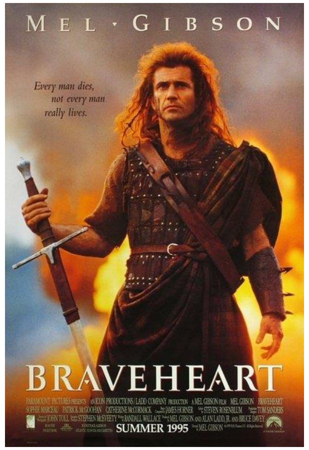
Jul 11 7,000 Bosnian Muslim men are massacred when Bosnian Serbs overrun the 'haven' of Srebrenica

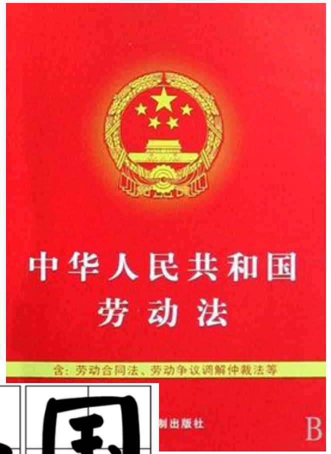
Jul 23 Comet Hale-Bopp is discovered and becomes visible to the naked eye nearl later

Dec 14 Yugoslav Wars: The Dayton Agreement is signed in Paris by leaders of vari governments ending the conflict in former Yugoslavia









瀛海威时空

双休日 编辑 讨论

双休日是指一般都是在周六以及周日放假休息的时间，包括大人工作休息以及小孩学习休息。

我国自1995年5月1日起实行双休日。2015年5月1日，是我国双休日制度实行的第20年。

科教兴国

The year 1995

Possible effects of color screening and large string tension in heavy quarkonium spectra

Yi-Bing Ding, Kuang-Ta Chao, and Dan-Hua Qin
Phys. Rev. D **51**, 5064 – Published 1 May 1995

Origin of LHCb: 1995

CKM matrix (quark-mixing matrix) & the unitarity triangles

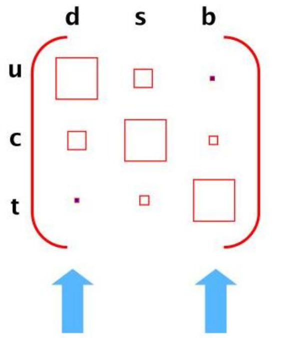
LHC-B

CERN/LHCC 95-5
LHCC/ I 8
25 August 1995

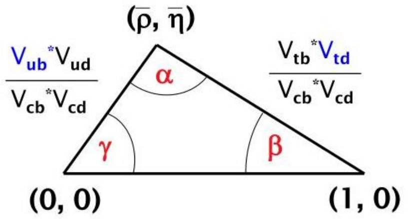
Last update
28 March 1996

LETTER OF INTENT

A Dedicated LHC Collider Beauty Experiment for Precision Measurements of CP-Violation



Apply unitarity constraint to these two columns



Abstract

The LHC-B Collaboration proposes to build a forward collider detector dedicated to the study of CP violation and other rare phenomena in the decays of Beauty particles. The forward geometry results in an average 80 GeV momentum of reconstructed B-mesons and, with multiple, efficient and redundant triggers, yields large event samples. B-hadron decay products are efficiently identified by Ring-Imaging Cerenkov Counters, rendering a wide range of multi-particle final states accessible and providing precise measurements of all angles, α, β and γ of the unitarity triangle. The LHC-B microvertex detector capabilities facilitate multi-vertex event reconstruction and proper-time measurements with an expected few-percent uncertainty, permitting measurements of B_s-mixing well beyond the largest conceivable values of x_s. LHC-B would be fully operational at the startup of LHC and requires only a modest luminosity to reveal its full performance potential.

… dedicated to the study of CPV and other rare phenomena in the decays of Beauty particles.

… precise measurements of the CKM angles …

Physics at LHCb (now)

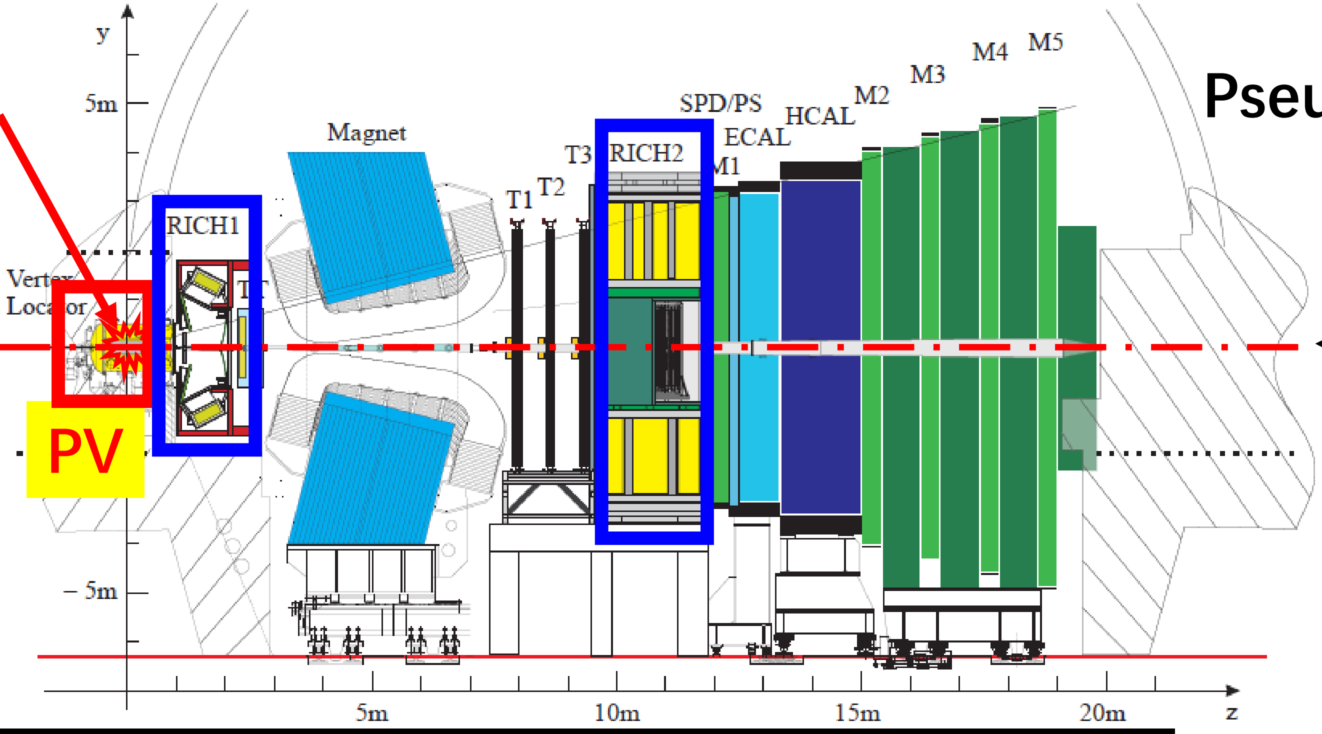
- **Indirect search of BSM via precision measurements**
  - CKM, CPV and rare decays in b and c hadrons
- Precise measurements of QCD + EW at large rapidity
- Hadron spectroscopy
- Direct searches of New Physics
- Heavy-ion and fixed-target physics

The LHCb detector

JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30 (2015) 1530022

Collision point

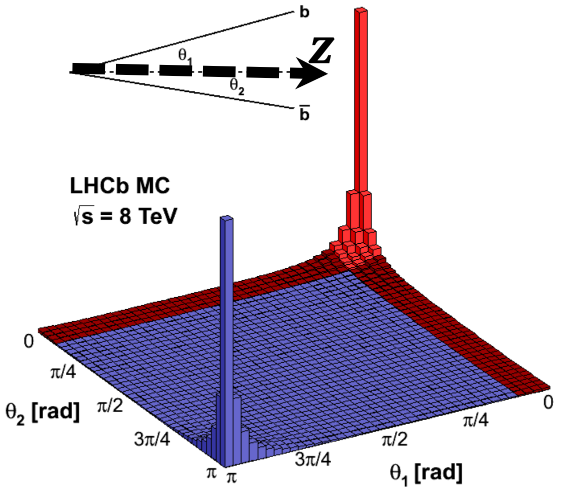
Beam1



Beam2

Pseudorapidity coverage
$2 < \eta < 5$

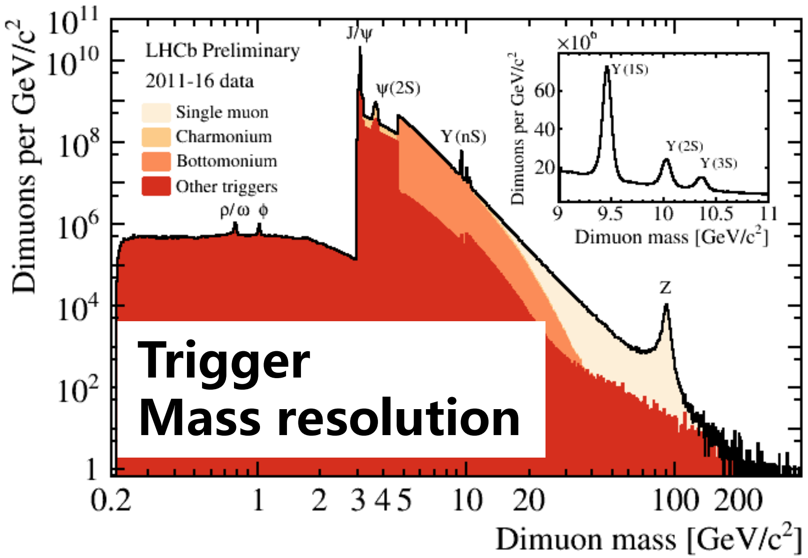
VELO silicon strips

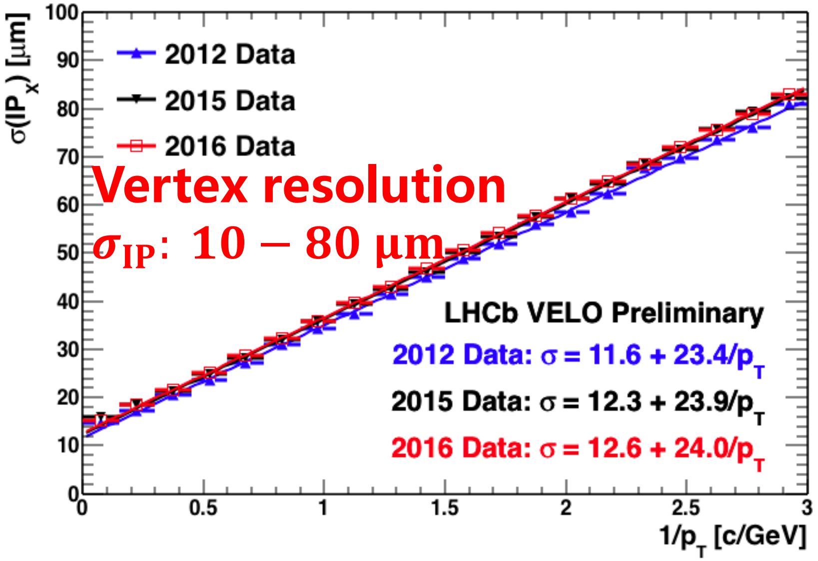


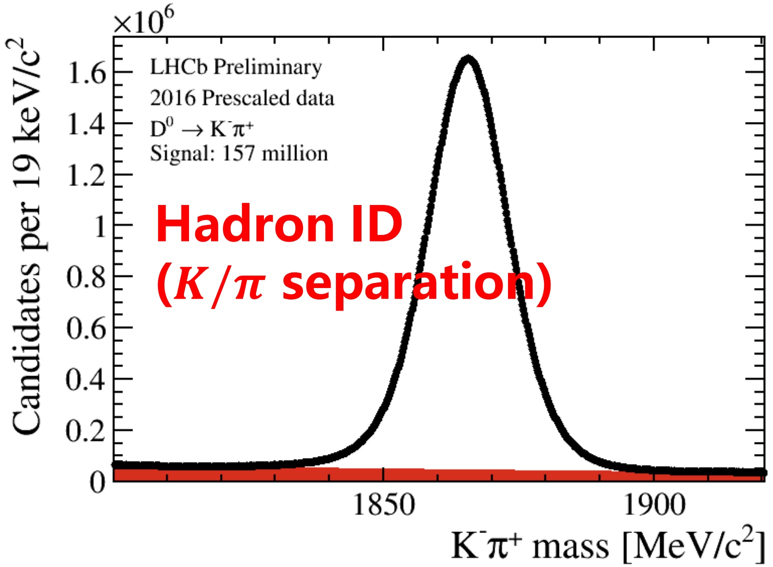
Vertex:	$\sigma_{\mathrm{IP}} = 20\ \mu\mathrm{m}$
Time:	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%$ $(5 - 100\ \mathrm{GeV}/c)$
Mass :	$\sigma_m = 8\ \mathrm{MeV}/c^2$ for $B \to J/\psi X$ (constrained $m_{J/\psi}$)
Hadron ID:	$\varepsilon(K \to K) \sim 95\%$ mis-ID $\varepsilon(\pi \to K) \sim 5\%$
Muon ID:	$\varepsilon(\mu \to \mu) \sim 97\%$ mis-ID $\varepsilon(\pi \to \mu) \sim 1 - 3\%$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E\ (\mathrm{GeV})}$

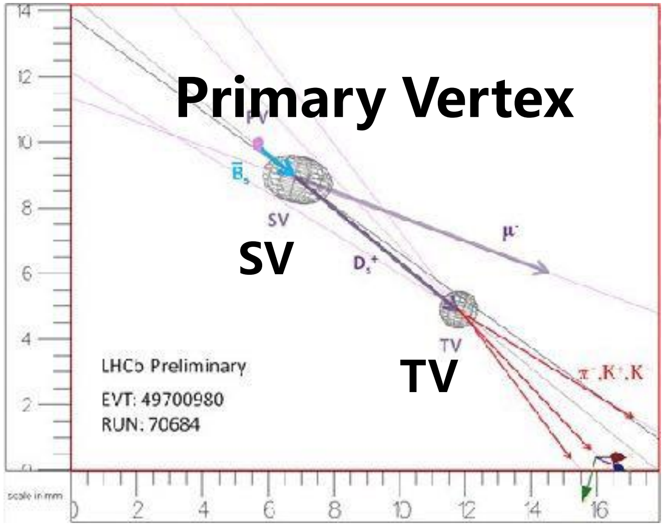
A detector at the collider which looks like one for fixed-target experiment

Pros of hadron spectroscopy at LHCb





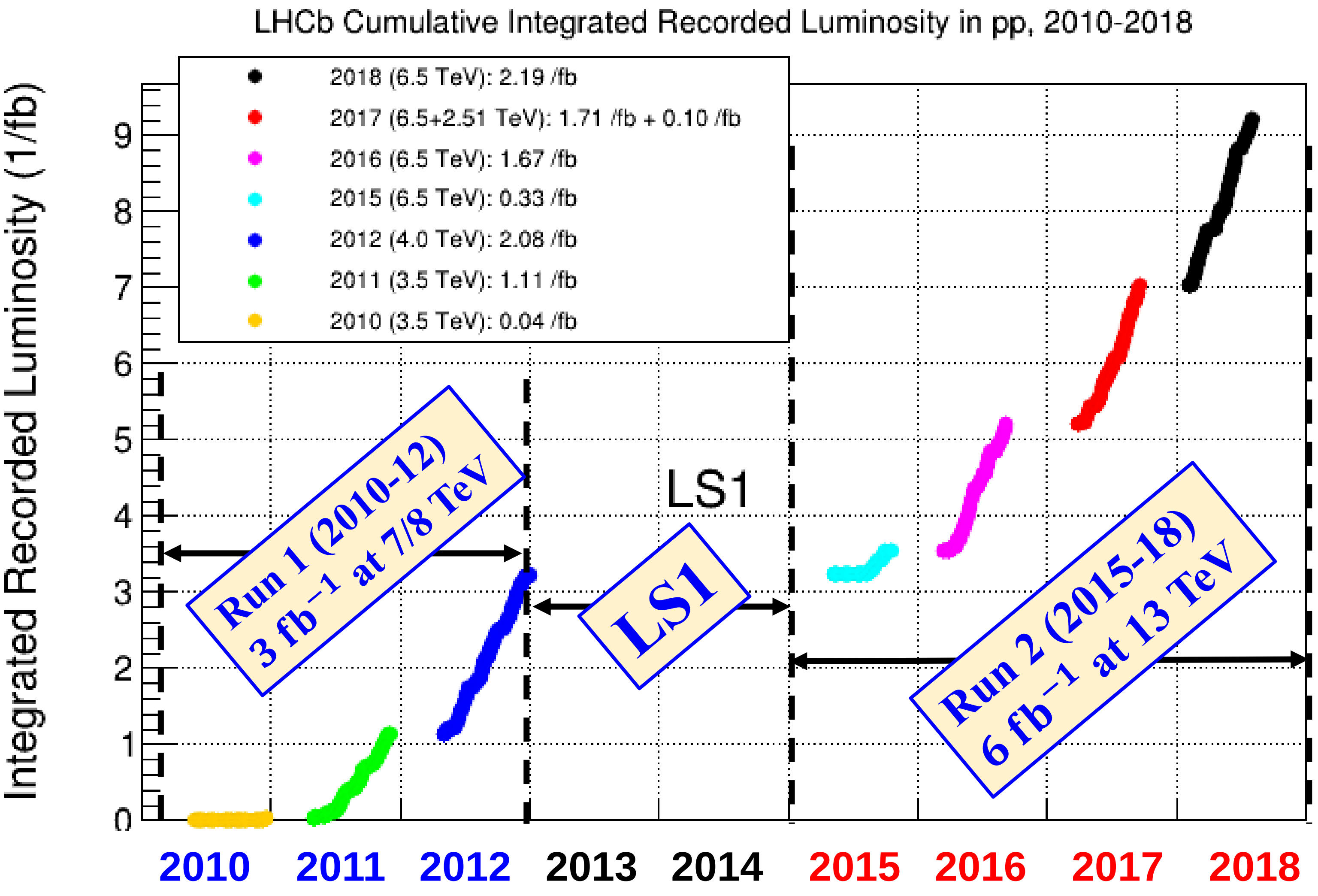




- **Large production cross-section**
- **Efficient trigger**
- **Vertex locator with high precision**
- **High precision tracking system**
- **Powerful hadron identification**
- **Efficient muon system**

https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2016
https://twiki.cern.ch/twiki/bin/view/LHCb/ConferencePlots

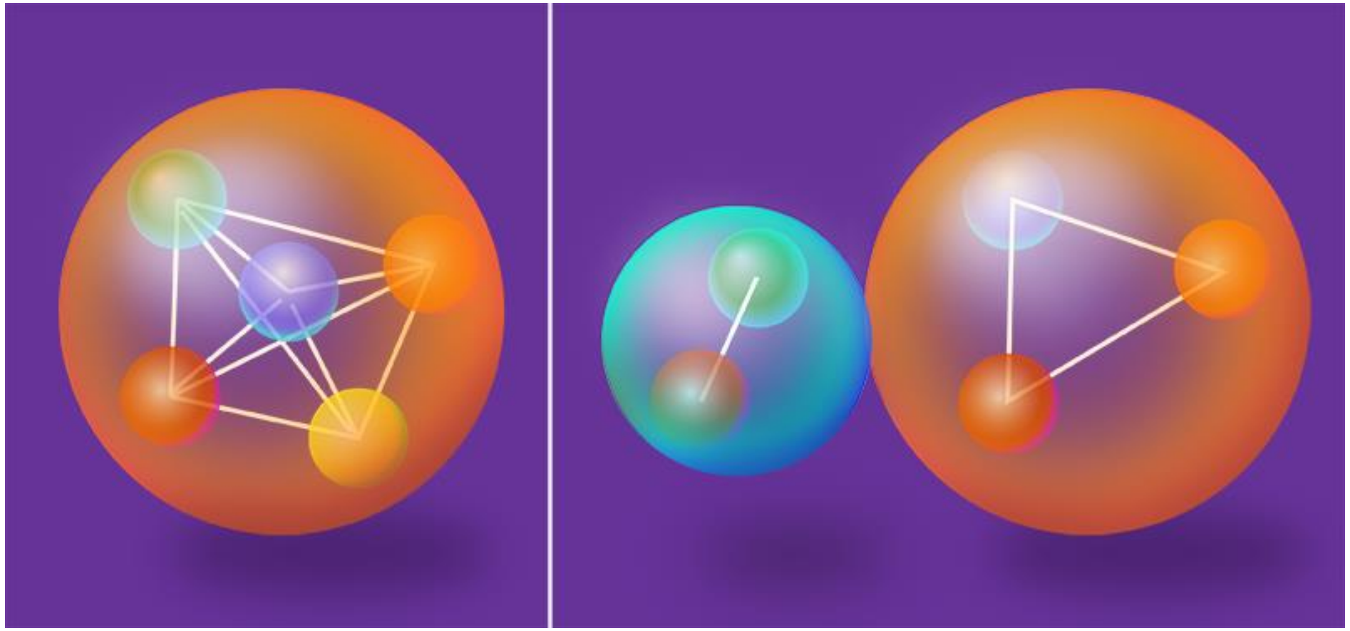
Data taking (run1+run2)



- A huge amount of $b\bar{b}$ and $c\bar{c}$ have been produced
  - $\sim 10^{12}\ b\bar{b}$
  - $\sim 10^{13}\ c\bar{c}$
- Many impressive results have been achieved

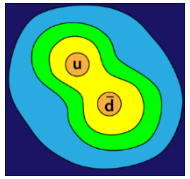
More than 9 $\mathbf{fb^{-1}}$ accumulated in Run1+Run2

Pentaquarks

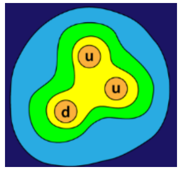


Normal hadrons and exotic hadrons

- Possible existence of **exotic hadrons** was proposed by Gell-Mann and Zweig at the birth of quark model
- Normal hadrons and exotic hadrons

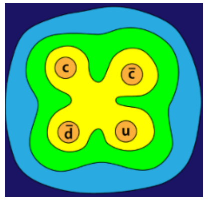


$q\bar{q}$

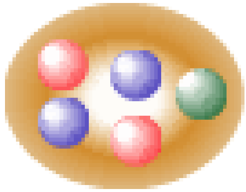


qqq

Normal hadrons



$qq\bar{q}\bar{q}$



$qqqq\bar{q}$

Exotic hadrons

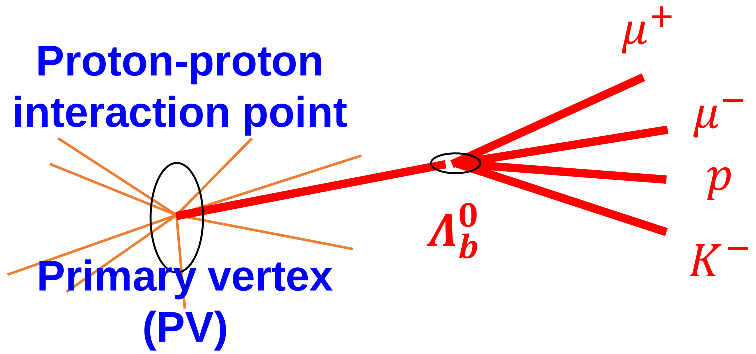
- Many searches for **pentaquarks** in the past 50 years, but no convincing experimental evidence before LHCb

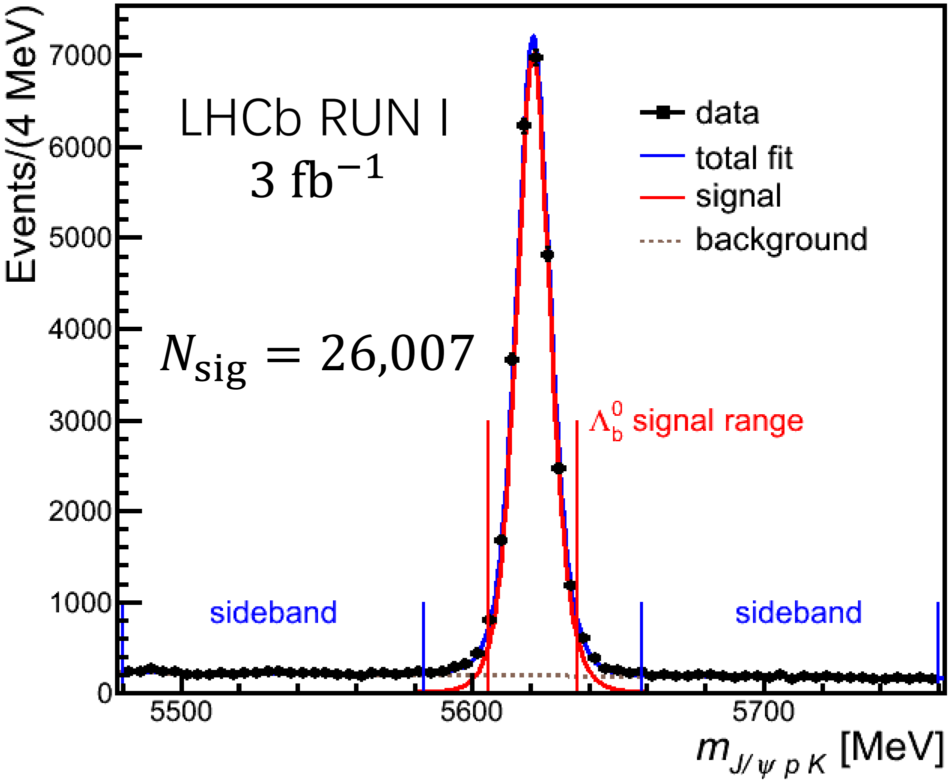
$\Lambda_b^0 \to J/\psi p K^-$ decays

➢First observed by LHCb as a potential background for $B_s^0 \to J/\psi K^+ K^-$

- Large signal yield found, used for Λ_b^0 lifetime measurement

PRL 111, 102003





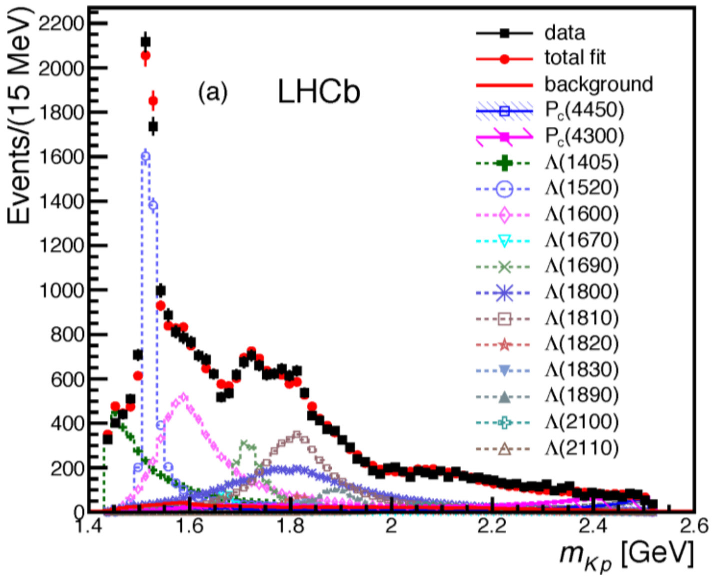
PRL 115 (2015) 072001

➢Tsinghua group then used this decay to measure Λ_b^0 production cross-sections

Observation of pentaquarks

PRL 115 (2015) 072001

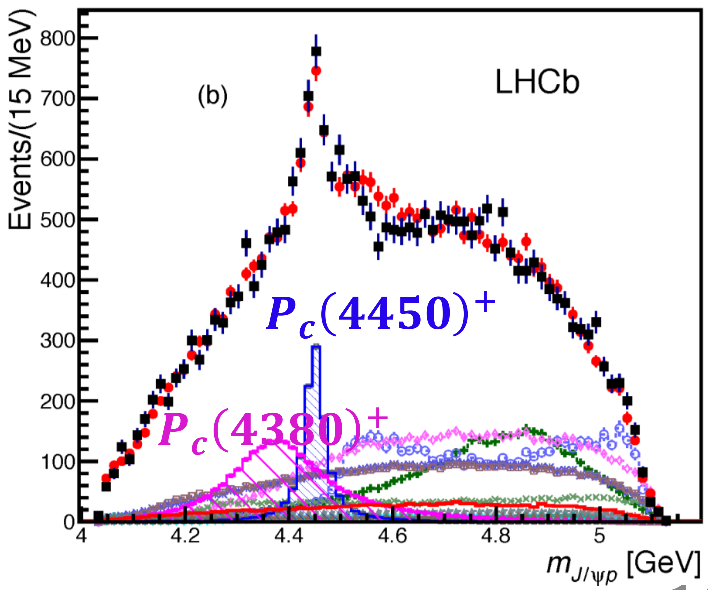
- **Two P_c^+ states observed in full amplitude analysis of $\Lambda_b^0 \to J/\psi p K^-$ decays**
- **Best fit gives $J^P = (\frac{3}{2}^-, \frac{5}{2}^+)$**
  - $J^P = (\frac{3}{2}^+, \frac{5}{2}^-)$ & $(\frac{5}{2}^+, \frac{3}{2}^-)$ **not excluded**



Resonance	Mass (MeV)	Width (MeV)	Fraction(%)
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$8.4 \pm 0.7 \pm 4.2$
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$4.1 \pm 0.5 \pm 1.1$

$$\mathcal{B}(\Lambda_b^0 \to P_c(4380)^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p) = (2.66 \pm 0.22 \pm 1.33^{+0.48}_{-0.38}) \times 10^{-5}$$
$$\mathcal{B}(\Lambda_b^0 \to P_c(4450)^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p) = (1.30 \pm 0.16 \pm 0.35^{+0.23}_{-0.18}) \times 10^{-5}$$

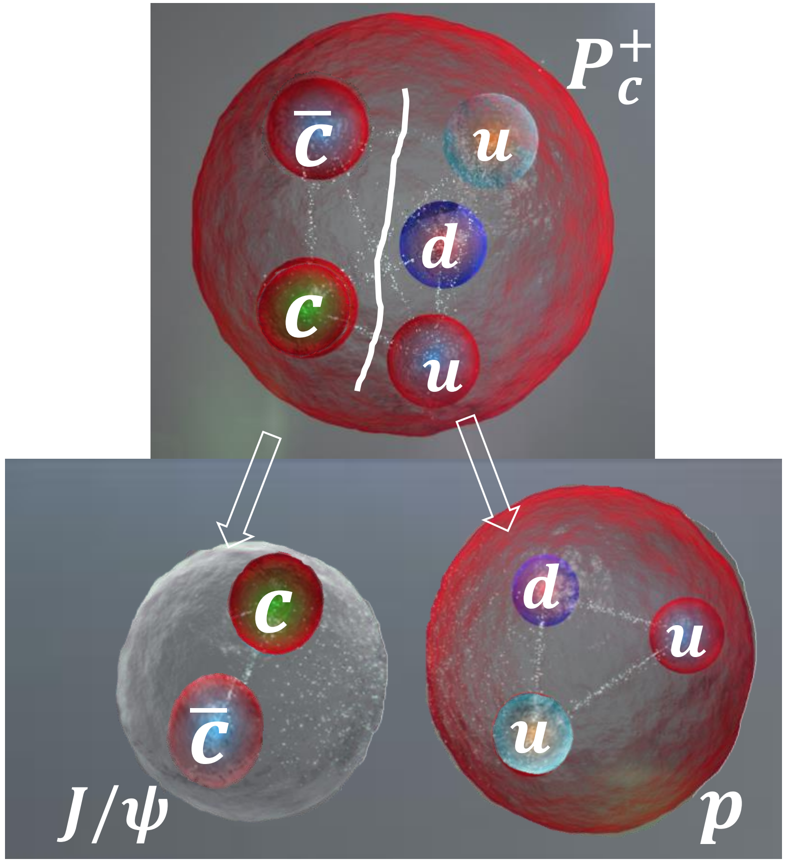
Chin. Phys. C40 (2016) 011001



Structure of the pentaquarks?

Tightly-bound

$$\boldsymbol{M_{P_c^+} = M_{J/\psi} + M_p + \sim 400\ \mathrm{MeV}}$$



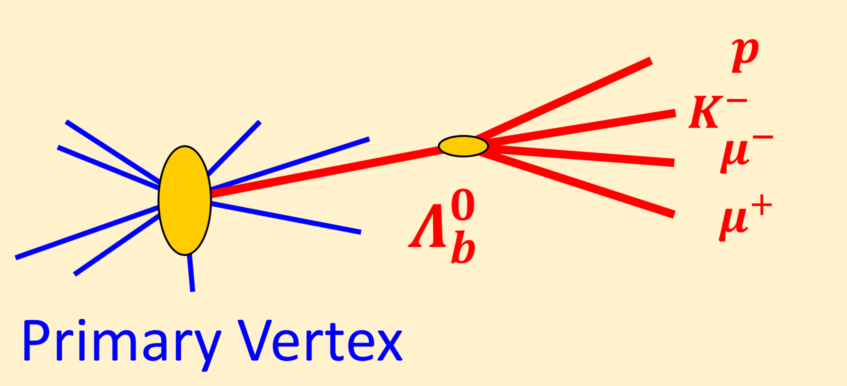
- Fall-apart decay:
  - **Wide states?**
  - What slows it down to make $P_c(4450)^+$ narrow? L between diquarks?
  - $\boldsymbol{P_c(4380)^+ \;\; S = 1,\; L = 0}$ **broad,** $\boldsymbol{P_c(4450)^+ \;\; S = 0,\; L = 1}$ **narrow**
- Spectrum
  - Many states expected (n, L, S)

Maiani et al, PLB749 (2015) 289
Lebed, PLB749 (2015) 454
Anisovich et al, PLB749 (2015) 454
and others

Update with full run1+run2 data

- We planned to update the results to using the full data sets
  - To determine the J^P quantum numbers
  - To better determine other properties

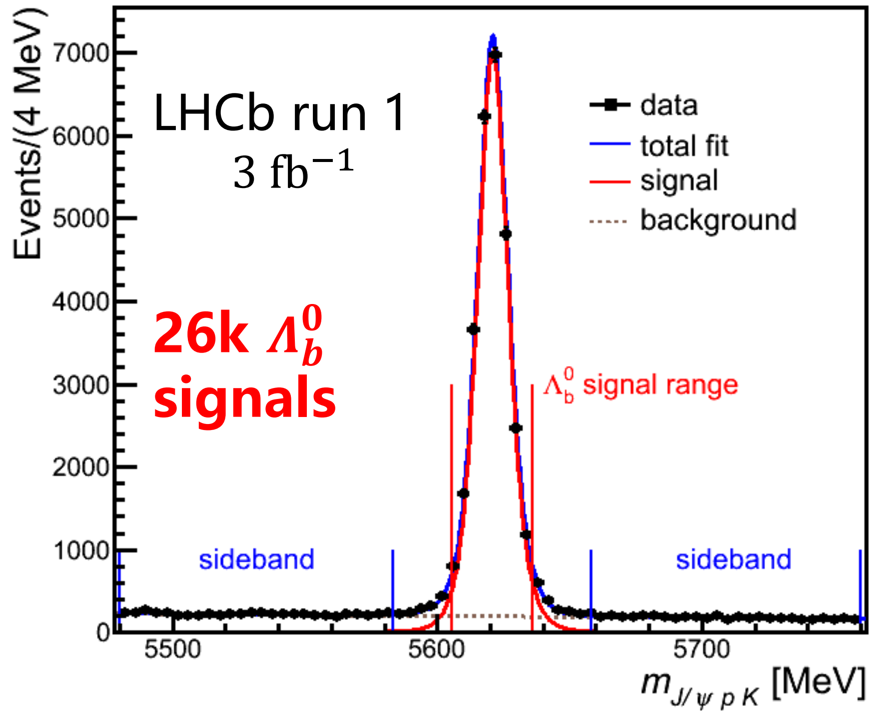
Improved selection



- Exploit features of B-hadron decays
  - High p_T
  - Detached from primary vertex
  - Hadron ID information
- Selection improved with better uses of hadron ID
  - Hadron ID information used as input variables of MVA
    - ✓ A much powerful MVA selector is achieved
  - Hadron ID used to help vetoing mis-ID backgrounds
    - ✓ $B^0 \to J/\psi K^-\pi^+$, $B_s^0 \to J/\psi K^+K^-$, et al.
- Efficiency increased by a factor of two
  - With a background fraction similar to the previous publication

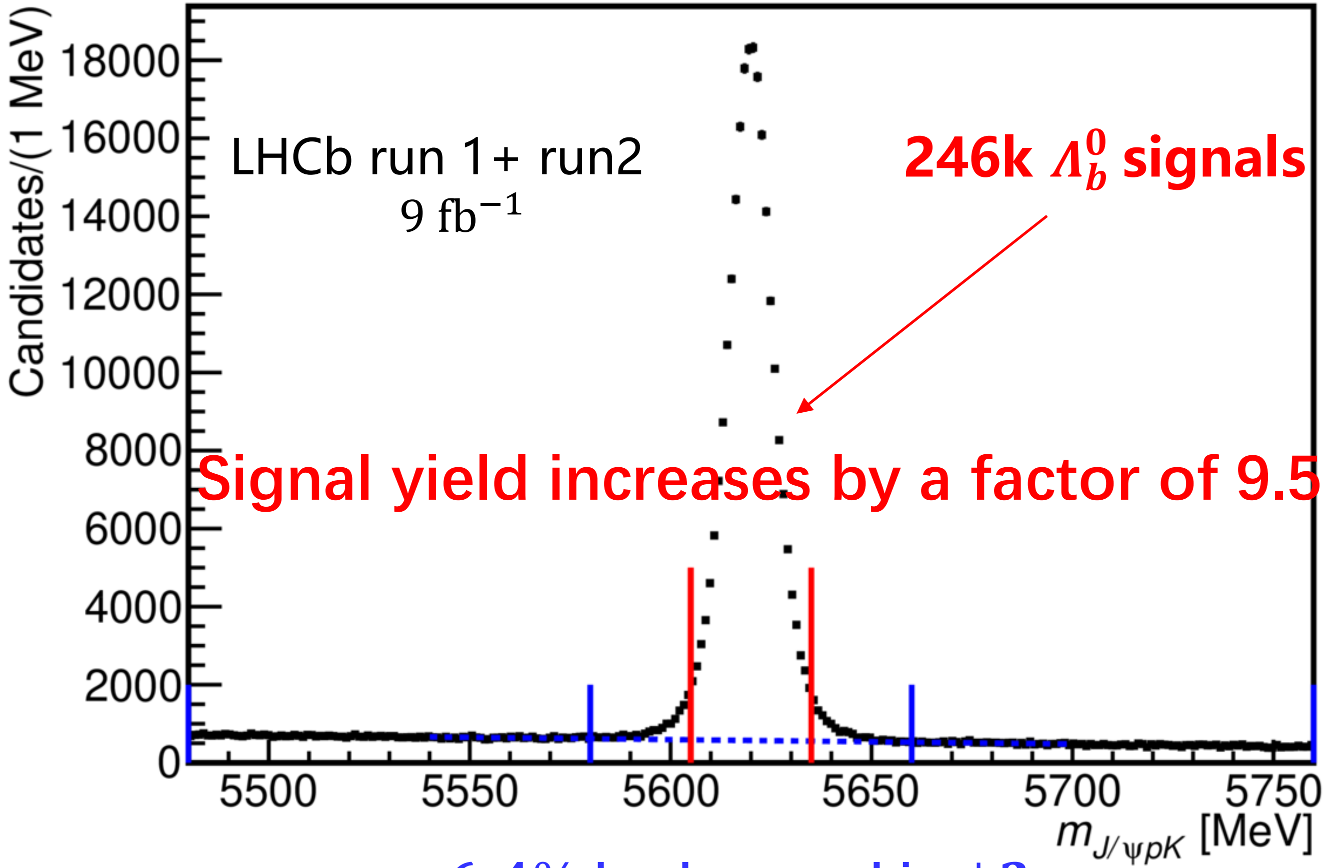
New $\Lambda_b^0 \to J/\psi p K^-$ sample

- ✓ Improved selections (~2x)
- ✓ Increased luminosity (~3x)
- ✓ Increased cross-sections (~1.5x)



5.4% background in $\pm 2\sigma$

PRL 115 (2015) 072001



6.4% background in $\pm 2\sigma$

PRL122 (2019) 222001

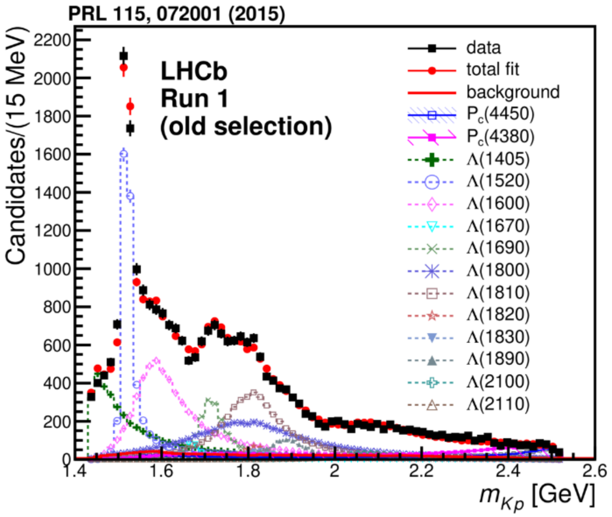
Data consistency check

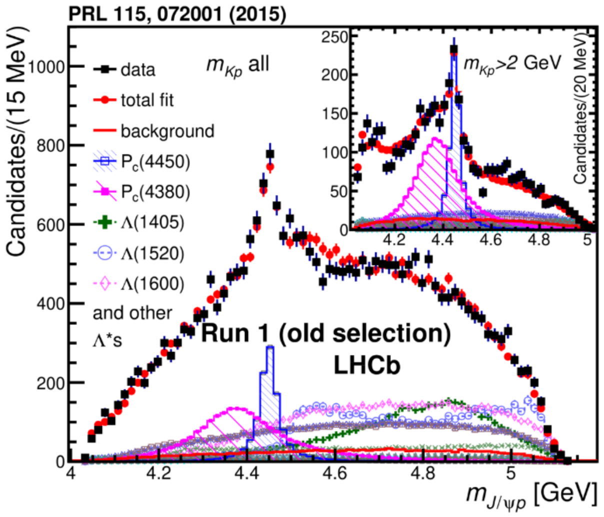
PRL 115 (2015) 072001

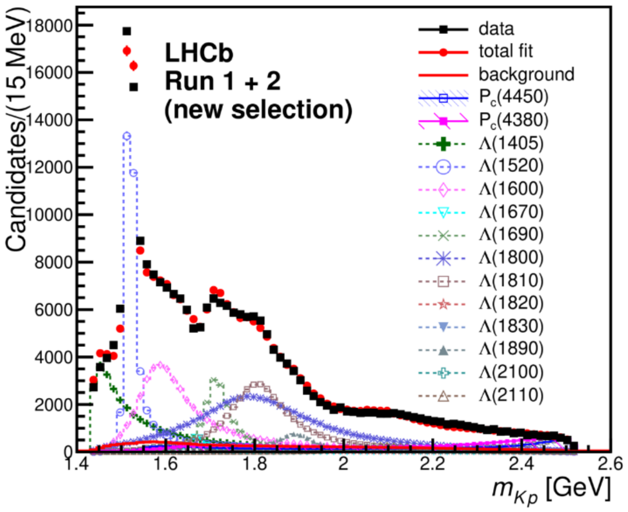
PRL122 (2019) 222001

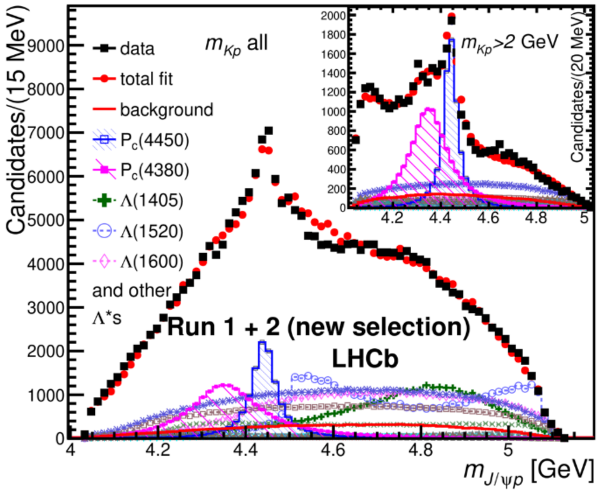
$\Lambda_b^0 \to J/\psi\Lambda^*(\to K^-p)$

$\Lambda_b^0 \to K^-P_c^+(\to J/\psi p)$









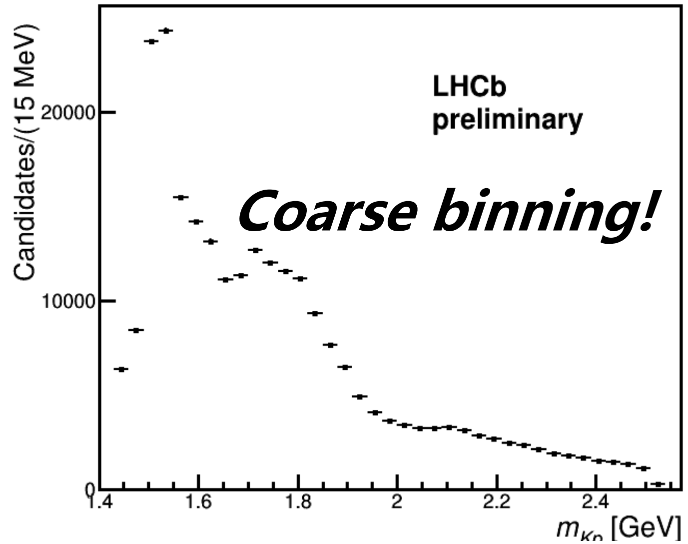
6D amplitude analysis fit to masses and decay angles

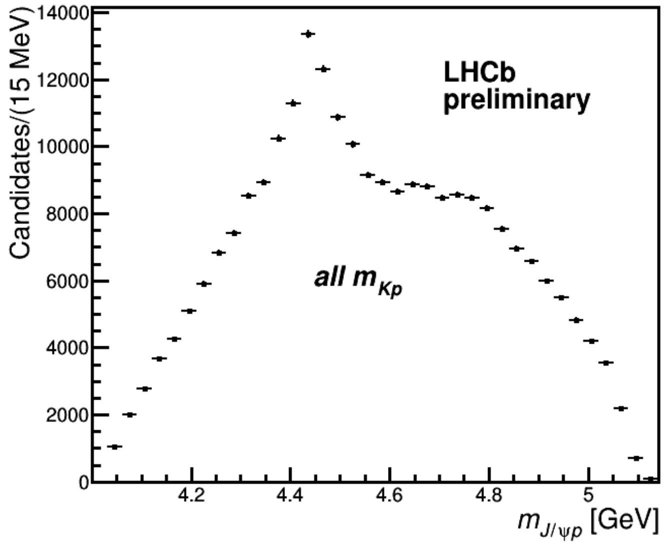
- **Fit with the same amplitude model to the full data sample**
  - It gives parameters of $P_c(4450)^+$ and $P_c(4380)^+$ that are **consistent** with the run1 results

- **However, more could be different …**

Binning from coarse to fine: new narrow peaks

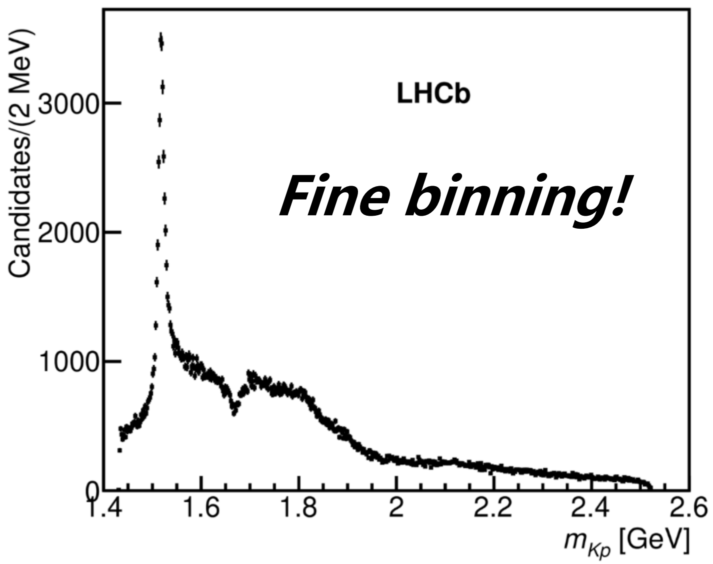
PRL122 (2019) 222001

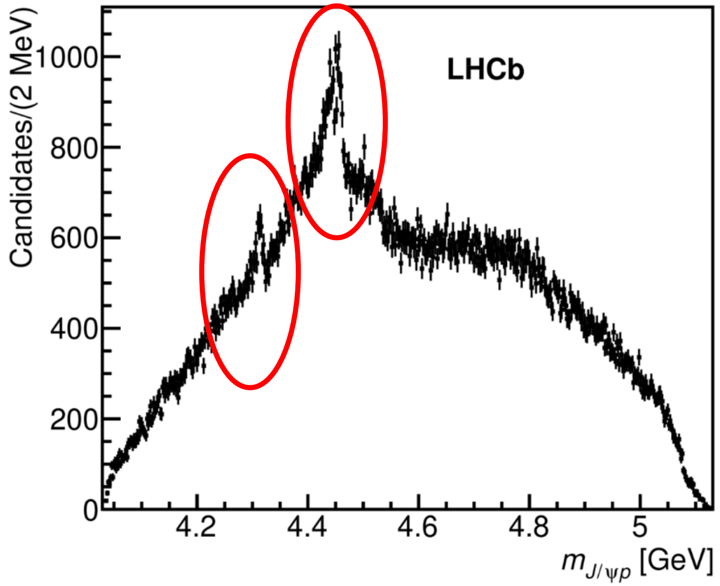


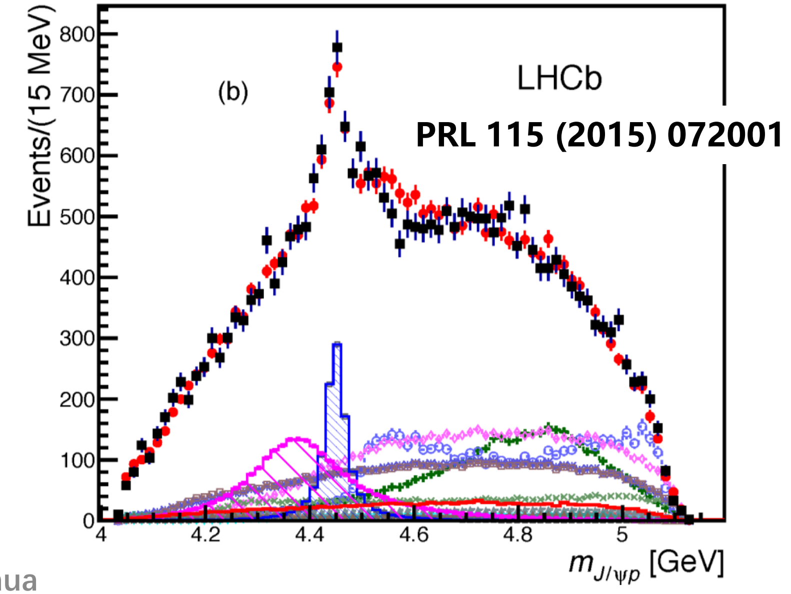


- Old bin width: 15 MeV
- Large statistics allows for finer binning of 2 MeV, comparable with $m(J/\psi p)$ resolution (2.3-2.7 MeV)

Fine $J/\psi p$ structures observed (insignificant in run1 sample)

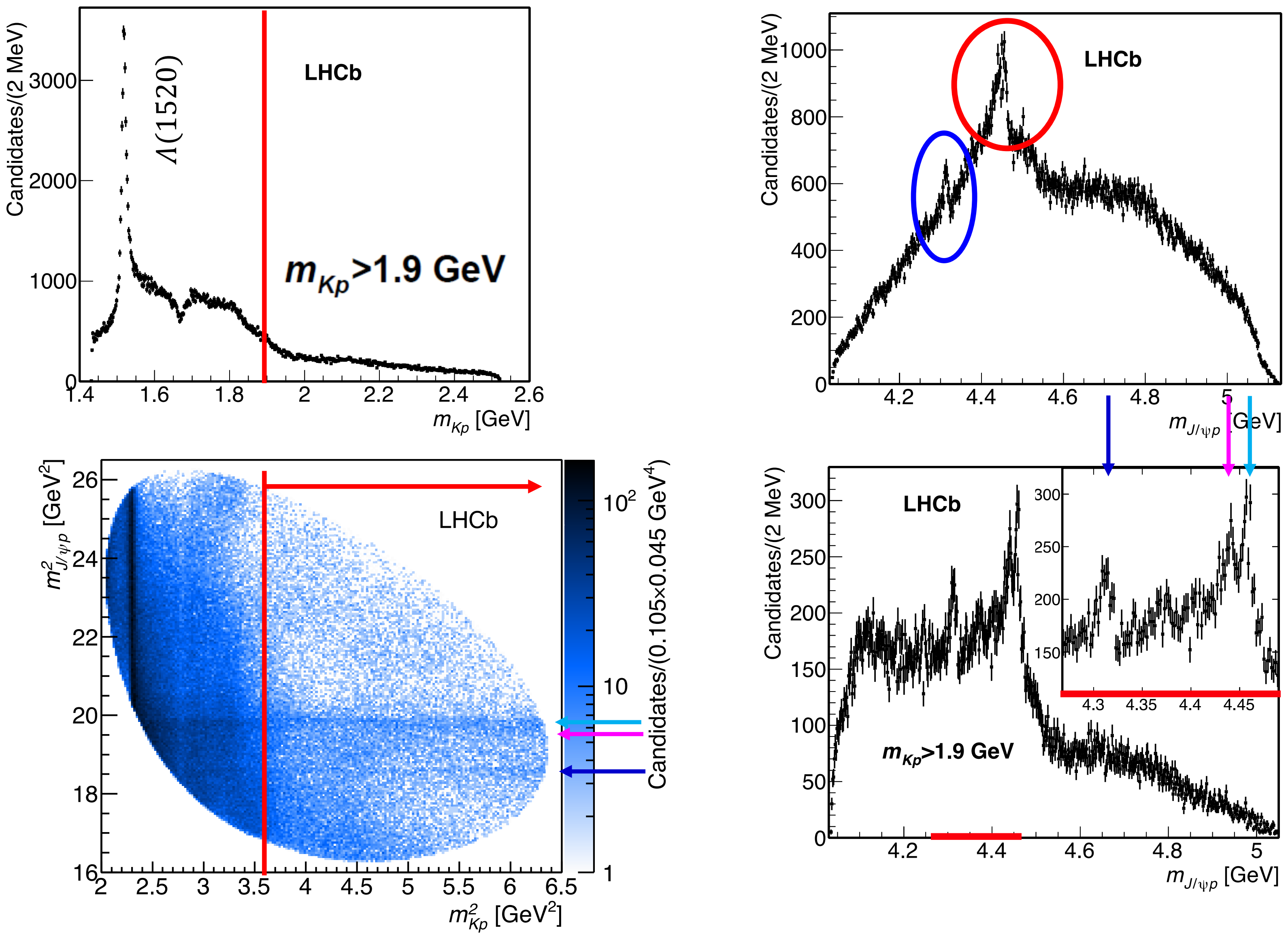






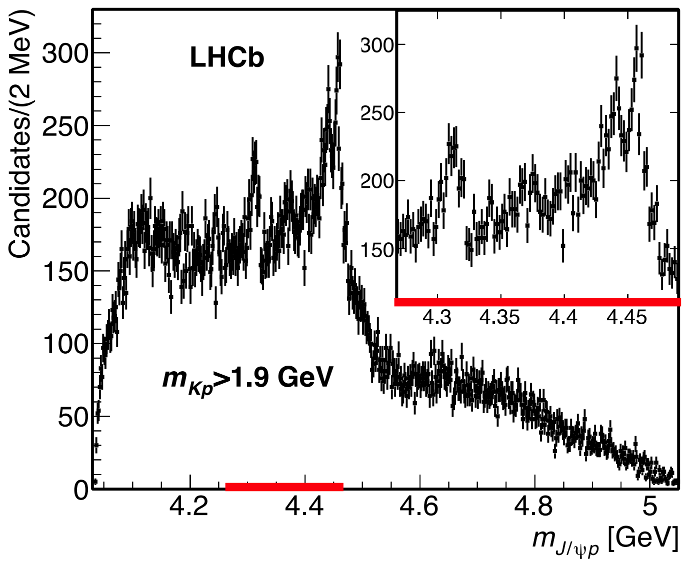
Display in smaller bin size

PRL 122, 222001 (2019)



What the new data tell: a first glance

- The peaking structure at around $4450\ \mathrm{MeV}$ confirmed
  - Resolved into two narrower peaks with nearly identical masses
  - Unable to resolve in earlier smaller data set
    - ✓ Mass split small and comparable to the natural widths
- A new narrow peak at lower mass discovered
  - Insignificant to be identified with earlier data set
- AmAn challenging & time-consuming
  - Must consider the resolution effect of $m_{J/\psi p}$
  - Data sample much larger
    - ✓ The amplitude model needs to be improved
  - Work in progress



How to fit the new data

- **Simplified approach:** 1D fit to the $m_{J/\psi p}$ distribution
  - Narrow signals
    - ✓Three Breit-Wigner (BW) functions $\otimes$ resolution (2-3 MeV)
  - Background of Λ^* + non-Λ_b^0 + possible broad P_c^+: two models compared
    - ✓Higher-order polynomial, or low-order polynomial + broad BW

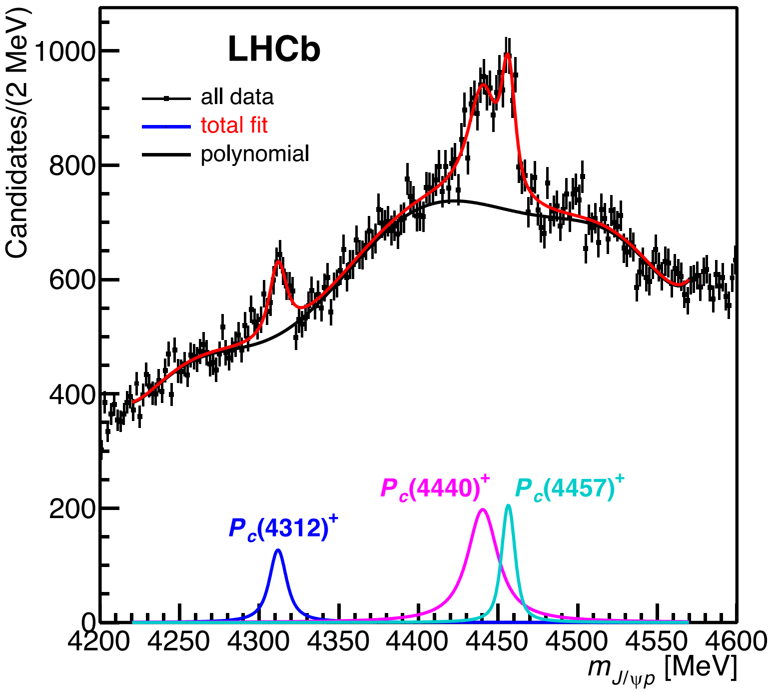
- Robust determination of M and Γ of **narrow** structures
- Neither sensitive to J^P nor to **broad** peaks, like $P_c(4380)^+$
- Several $m_{J/\psi p}$ distributions with different selections or weighting to estimate systematic uncertainties

Fit-1: all candidates

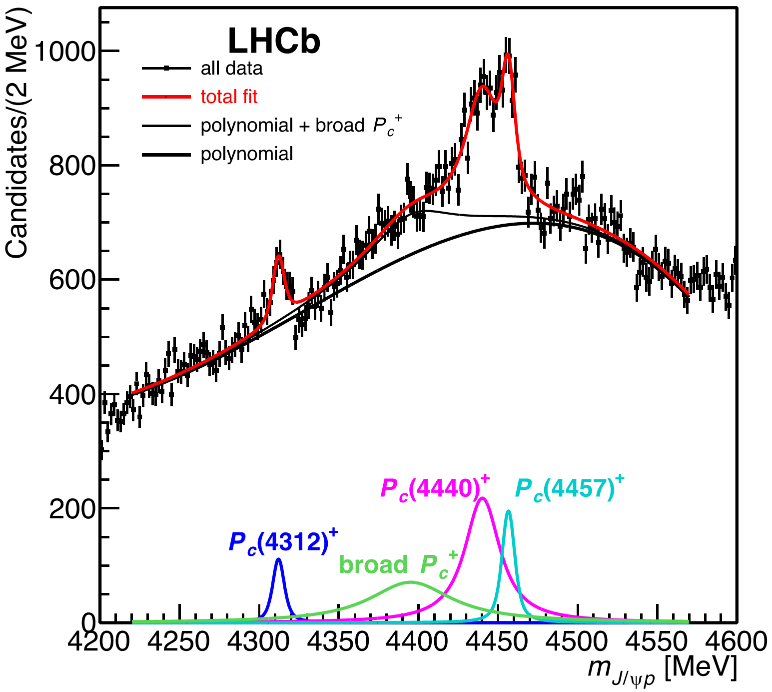
PRL 122, 222001 (2019)

- Fit the full $m_{J/\psi p}$ distribution
- Clear narrow structures, but background is high

high-order polynomial



low-order polynomial + broad P_c^+ as bkg



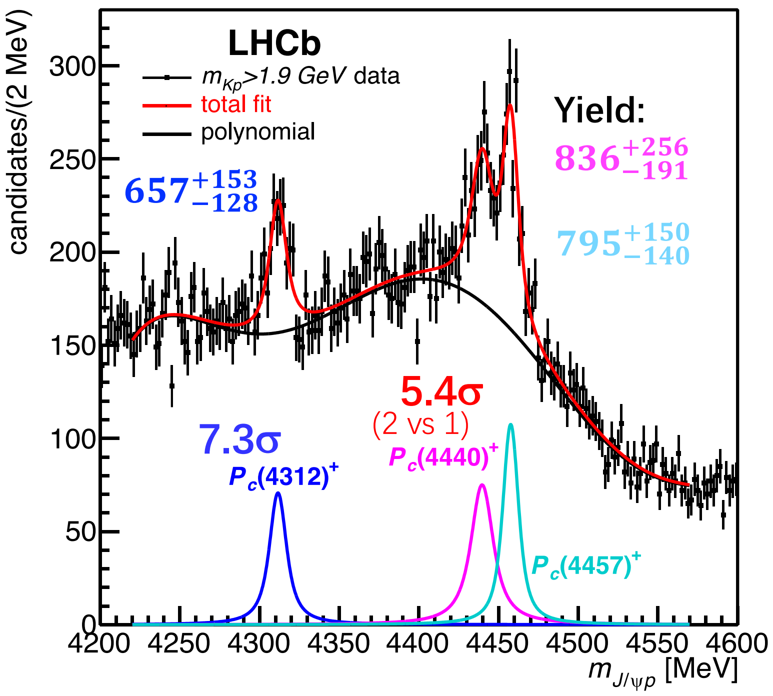
Fit-2: P_c^+ dominating region

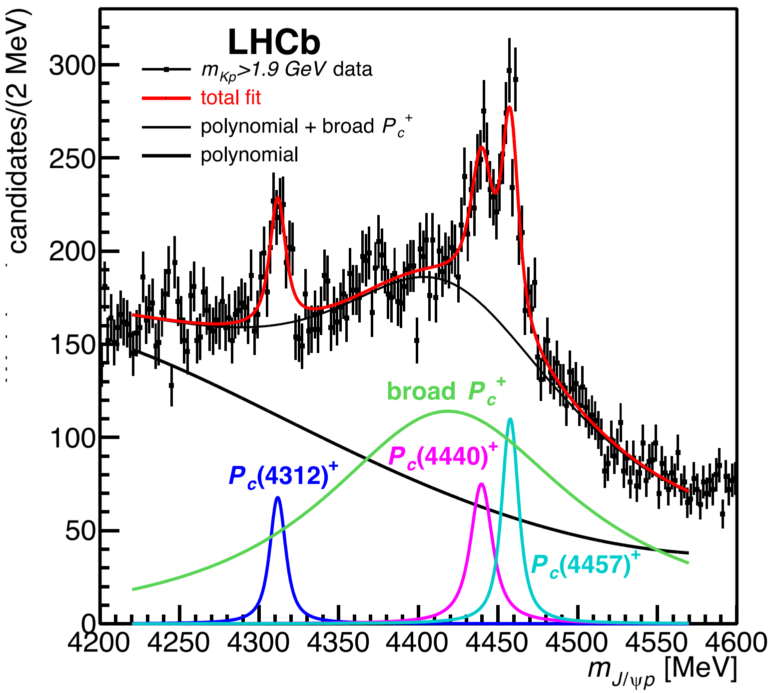
PRL 122, 222001 (2019)

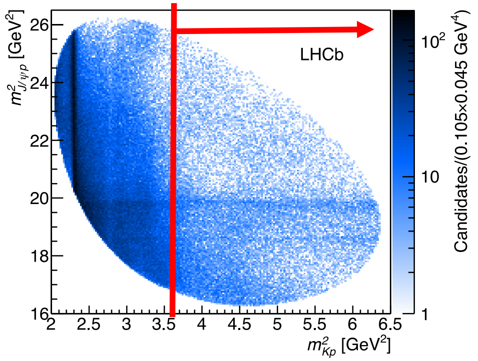
- Fit candidates with $m_{pK} > 1.9$ GeV
  - 80% Λ^* bkg removed
- Significance:
  - Evaluated with toy simulations from the 6D amplitude model
  - Look Elsewhere Effect

$P_c(4312)^+$: 7.3σ

2 peaks over 1 (~ 4450 MeV): 5.4σ



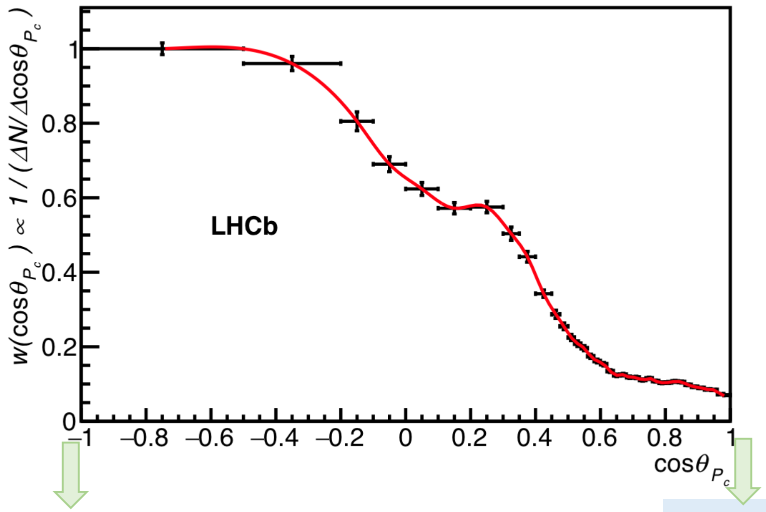




Fit-3: Novel method

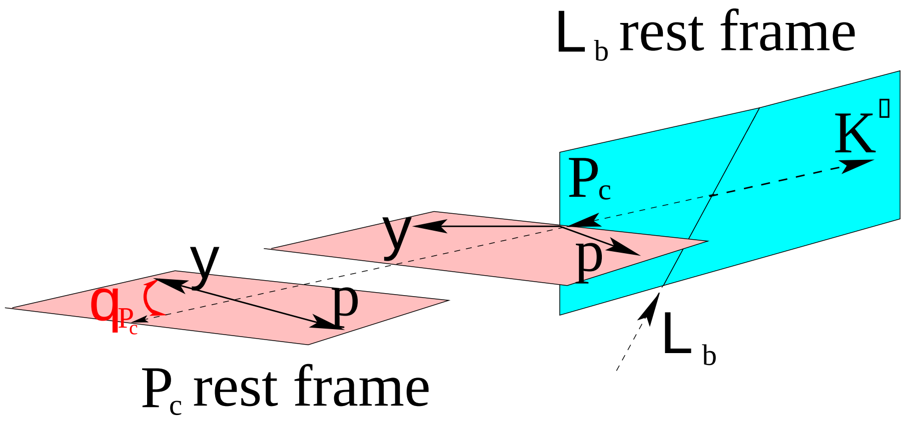
PRL 122, 222001 (2019)

- Candidates weighted by $w(\cos\theta_{P_c}) = \frac{1}{\sigma^2_{\text{stat.}}} \approx \frac{1}{S+B}$
  - w is inverse of $\cos\theta_{P_c}$ distribution of Λ_b^0 candidates with $m_{J/\psi p} \in [4.2, 4.6]$ GeV
- θ_{P_c} is P_c helicity angle : angle between $\vec{p}_{J/\psi}$ and $-\vec{p}_K$ in the $J/\psi p$ rest frame



high m_{pK}
less Λ^*
high w

low m_{pK}
more Λ^*
low w

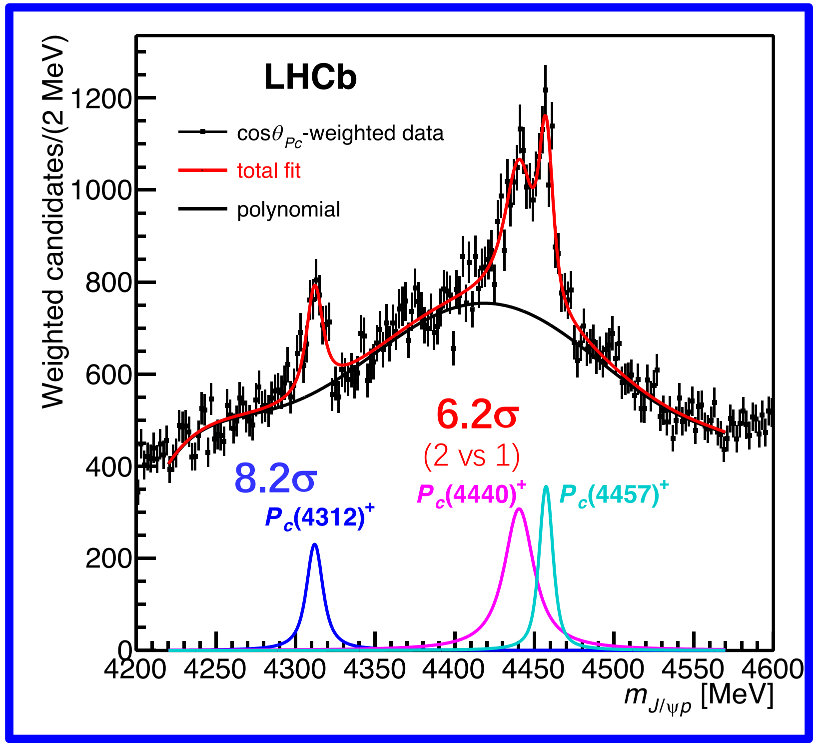


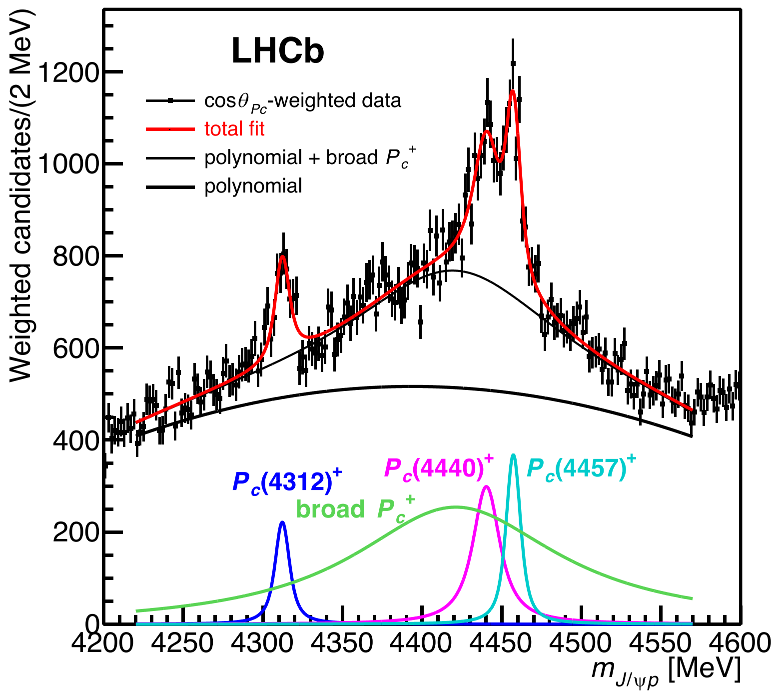
Fit-3: Novel method

PRL 122, 222001 (2019)

- Candidates weighted by $w(\cos\theta_{P_c}) = \frac{1}{\sigma^2_{\text{stat.}}} \approx \frac{1}{S+B}$
  - w is inverse of $\cos\theta_{P_c}$ distribution of Λ_b^0 candidates with $m_{J/\psi p} \in [4.2, 4.6]$ GeV
- Most statistically sensitive method

the nominal $\boldsymbol{M}$&$\boldsymbol{\Gamma}$ measurements





PRL122 (2019) 222001

Results

To determine the relative P_c^+ production rates, fit inclusive $m(J/\psi p)$ obtained with $1/\varepsilon$ event-weights, where ε is the efficiency parameterization in 6D Λ_b^0 decay phase-space (masses and angles)

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}$$

State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

Further information needs the amplitude analysis of the $\Lambda^0 \to J/\psi p K^-$ decay

Other studies

- Ongoing work to understand the P_c's nature
  - J^P determination from amplitude analysis of $\Lambda_b^0 \to J/\psi pK$
  - Other decay channels suggested

PHYSICAL REVIEW D **100,** 056005 (2019)

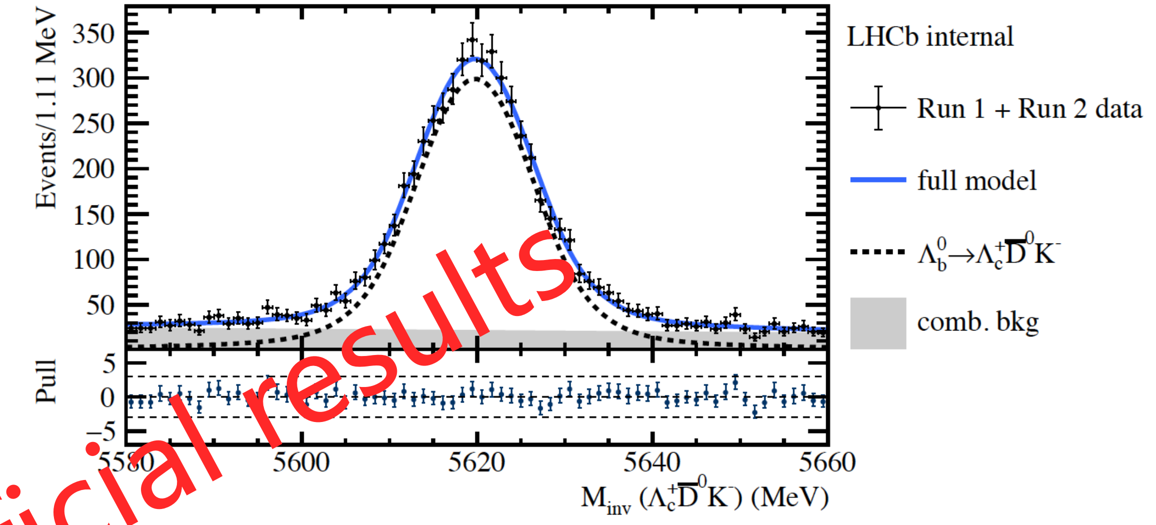
Strong decays of the latest LHCb pentaquark candidates in hadronic molecule pictures

Yong-Hui Lin[1,2,*] and Bing-Song Zou[1,2,3,†]

Mode	Widths (MeV) with (f_2, f_3)				
	$\bar{D}\Sigma_c$	$\bar{D}^*\Sigma_c$			
	$P_c(4312)$	$P_c(4440)$		$P_c(4457)$	
	$\frac{1}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$
$\bar{D}^*\Lambda_c$	10.7	12.5	6.8	10.8	6.9
$J/\psi p$	0.1	0.6	1.8	0.2	0.6
$\bar{D}\Lambda_c$	0.3	2.7	1.2	2.0	1.2
πN	1.7	0.2	1.9	0.07	0.6
$\chi_{c0}p$	-	0.1	0.009	0.05	0.003
$\eta_c p$	0.4	0.07	0.008	0.02	0.003
ρN	0.0008	0.4	0.3	0.1	0.1
ωp	0.003	1.5	1.2	0.5	0.4
$\bar{D}\Sigma_c$	-	3.4	0.6	2.8	0.9
$\bar{D}\Sigma_c^*$	-	0.9	7.3	2.3	7.2
Total	13.2	22.4	21.0	18.8	17.9

$\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-$ (LHCb unofficial results)

- Two LHCb PHD theses in public
  - https://doi.org/10.11588/heidok.00025126
  - https://doi.org/10.11588/heidok.00027350



LHCb unofficial measurement

$$\frac{\mathscr{B}(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-)}{\mathscr{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = (14.04 \pm 0.58 \pm 0.33 \pm 0.45)\,\%$$

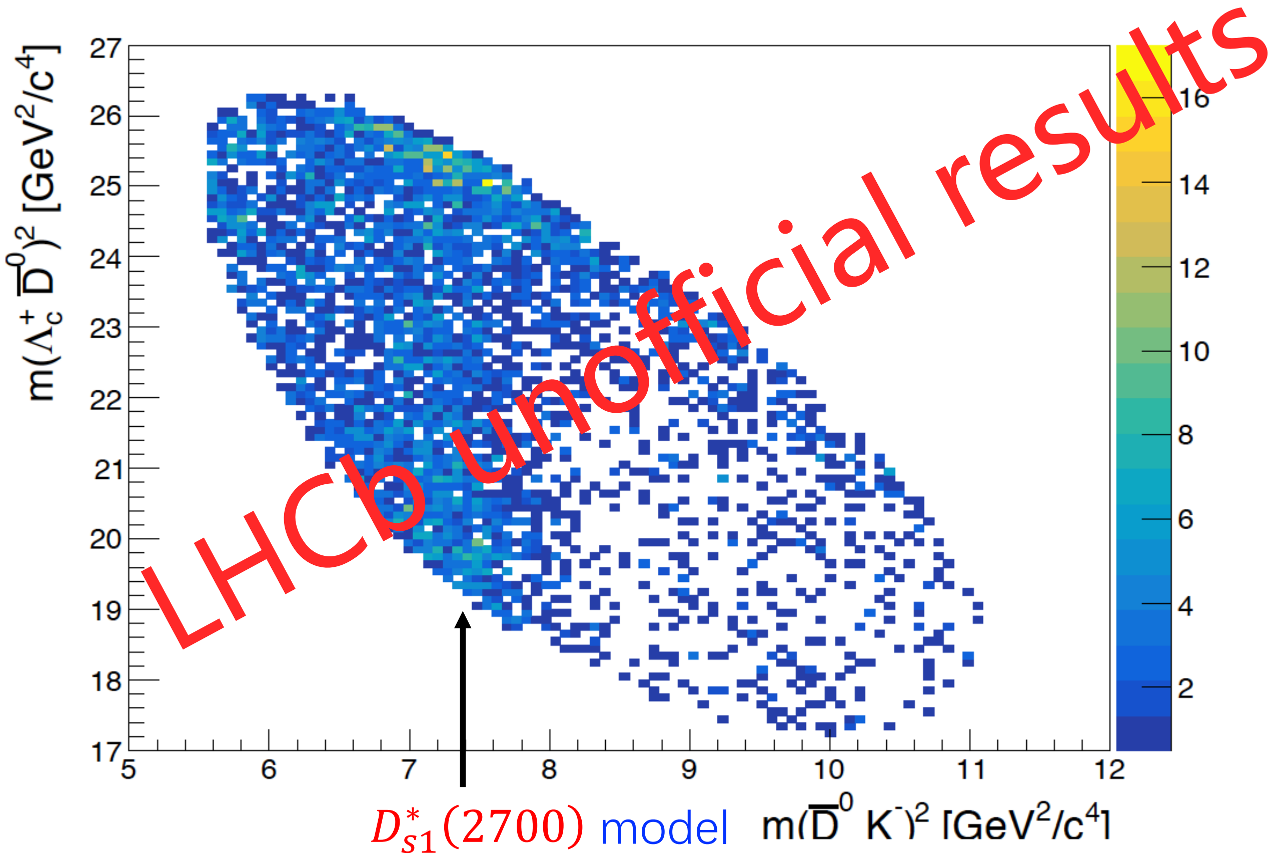
Using PDG values for $\mathcal{B}$ of $\Lambda_b^0 \to \Lambda_c^+ D_s^-$ and $\Lambda_b^0 \to J/\psi p K^-$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 4.8 \pm 1.0(\text{stat.} + \text{syst.})$$

LHCb unofficial results

Amplitude result

- Dominated by $D_s^{*-} \to \bar{D}^0 K^-$
- No sign of P_c signal at 4.312^2=18.6GeV^2 4.452=19.8GeV^2

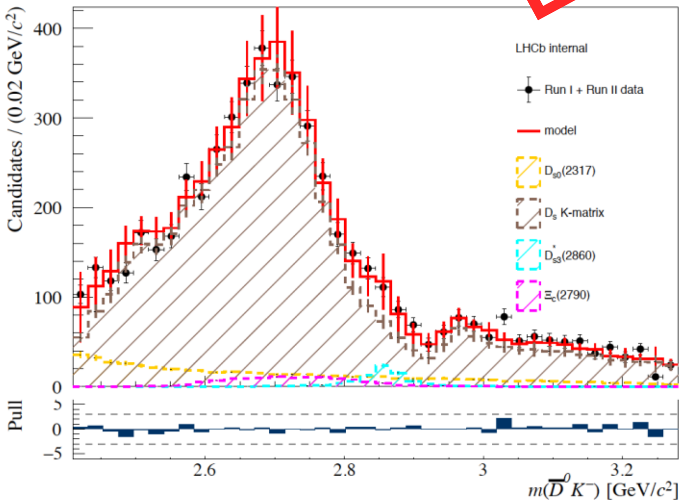


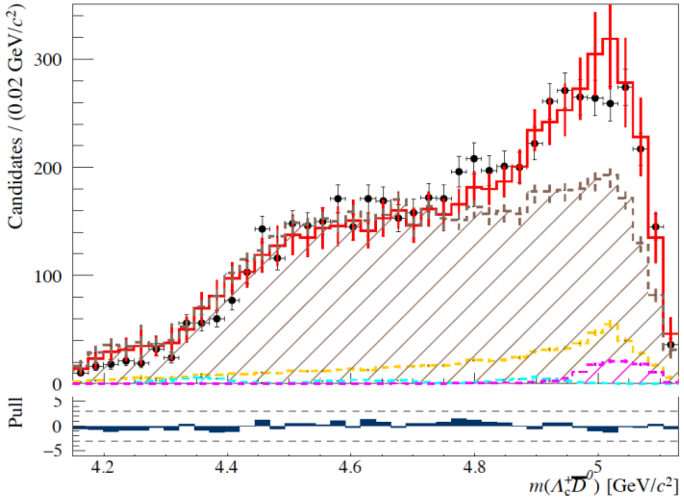
$D_{s1}^*(2700)$ model
$D_{s1}^*(2860)$ by K-matrix

Fits without P_c states

Fit fractions

Component	Baseline model	Model with all possible partial waves
$D^*_{s0}(2317)$	0.099 ± 0.013	0.094 ± 0.046
D_s K-matrix	0.862 ± 0.029	0.844 ± 0.067
$D^*_{s3}(2860)$	0.0181 ± 0.0077	0.030 ± 0.023
$\Xi_c^0(2790)$	0.0257 ± 0.0051	0.026 ± 0.013
Sum	1.0029 ± 0.0041	0.9942 ± 0.0059





Search for $P_c^+ \to \Lambda_c^+ \bar{D}^0$

- Fit fraction (stat. only)

Hypothesis	$P_c(4312)^+$ fit fraction	$P_c(4440)^+$ fit fraction	$P_c(4457)^+$ fit fraction
$P_c(4312)^+$ only	$0.0009^{+0.0013}_{-0.0009}$	/	/
$P_c(4440)^+$ $(J^P = \frac{1}{2}^-)$ only	/	$0.0015^{+0.0021}_{-0.0015}$	/
$P_c(4440)^+$ $(J^P = \frac{3}{2}^-)$ only	/	$0.000024^{+0.000025}_{-0.000024}$	/
$P_c(4457)^+$ $(J^P = \frac{1}{2}^-)$ only	/	/	0.0015 ± 0.00015
$P_c(4457)^+$ $(J^P = \frac{3}{2}^-)$ only	/	/	0.00026 ± 0.0021
$P_c(4312)^+$, $P_c(4440)^+$ $(J^P = \frac{1}{2}^-)$, $P_c(4457)^+$ $(J^P = \frac{1}{2}^-)$	0.0023 ± 0.0018	0.00034 ± 0.00027	0.000090 ± 0.000071
$P_c(4312)^+$, $P_c(4440)^+$ $(J^P = \frac{3}{2}^-)$, $P_c(4457)^+$ $(J^P = \frac{3}{2}^-)$	$0.0024^{+0.0025}_{-0.0024}$	0.0019 ± 0.0019	$0.00010^{+0.00011}_{-0.00010}$

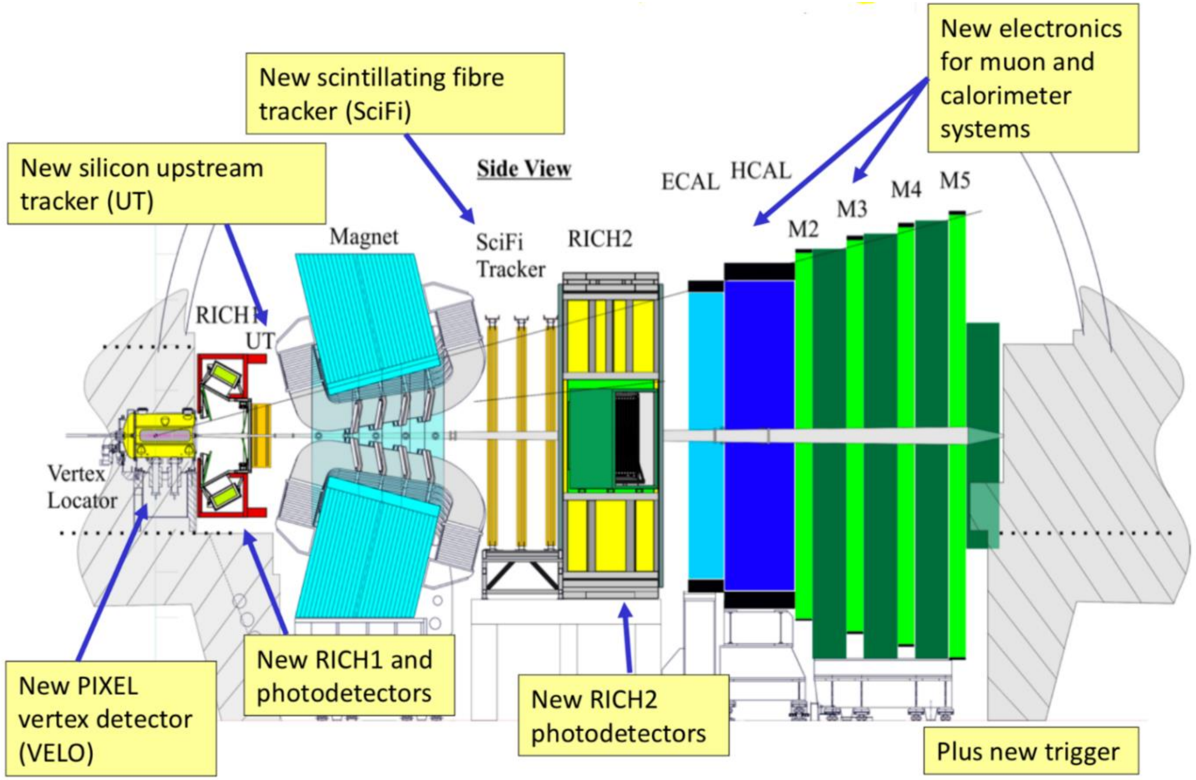
$\frac{\mathcal{B}(P_c \to \Lambda_c^+ \bar{D}^0)}{\mathcal{B}(P_c \to J/\psi p)}$	4312	4440	4457
Central value	1.5 ± 2.5	0.7 ± 1.0	0.2 ± 3.6
95% CL	< 6.4	< 2.5	< 7.5

Data have not contradicted molecular model predictions yet, more data needed

Prospects

LHCb Upgrade (2019-2020)

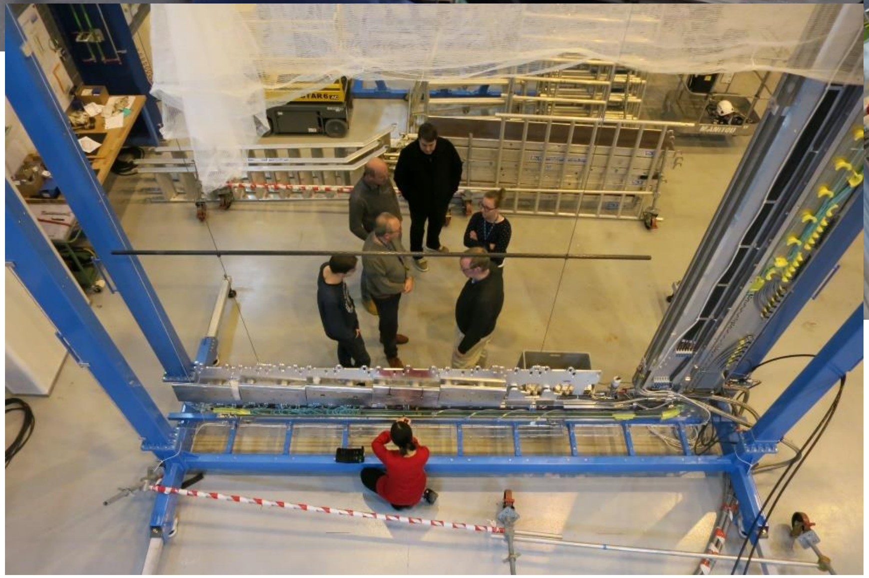
[LHCB-TDR-017]



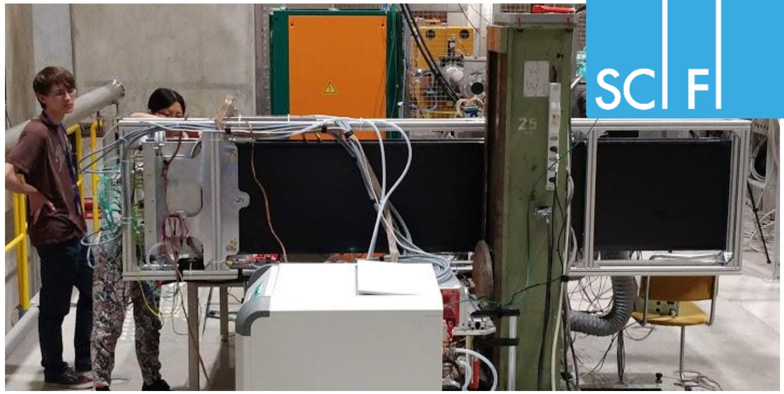
CERN-LHCC-2012-007

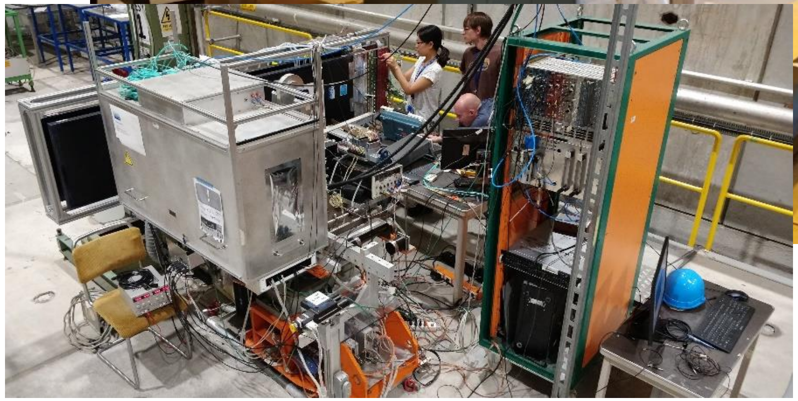
- **Increase luminosity to $2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$**
  - 5 times larger than current maximum instantaneous luminosity
- **All sub-detectors read out at 40 MHz for a full software trigger**
  - Record with 10 GB/s
- **All subdetector apart from muon and calorimeter systems will be fully replaced**

Scintillating Fibre (SciFi) tracker installation



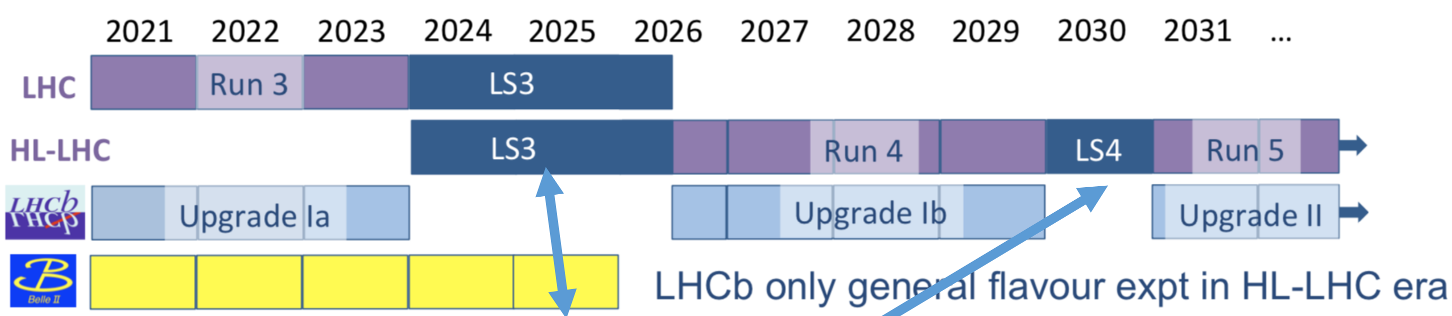
Scintillating Fibre (SciFi) tracker installation





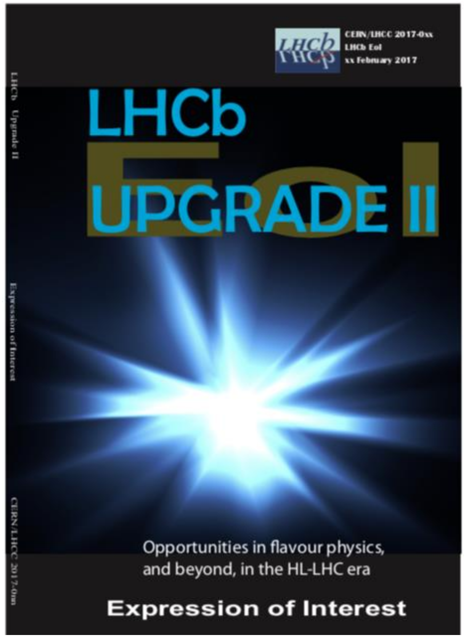
LHCb Upgrade 2

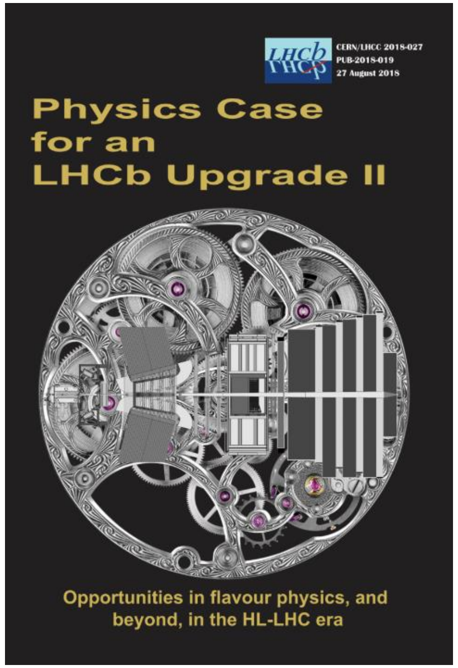
- Upgrade 2 proposed to take full profit of HL-LHC
  - $\mathcal{L} = 1 - 2 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, 10 times larger than Upgrade 1
  - Aiming at $300\ \mathrm{fb}^{-1}$ after Run5



- Consolidate in LS3
- Major upgrade in LS4

- EOI submitted in 2017 (CERN-LHCC-2017-003)
- Physics document submitted in 2018 (arXiv:1808.08865)



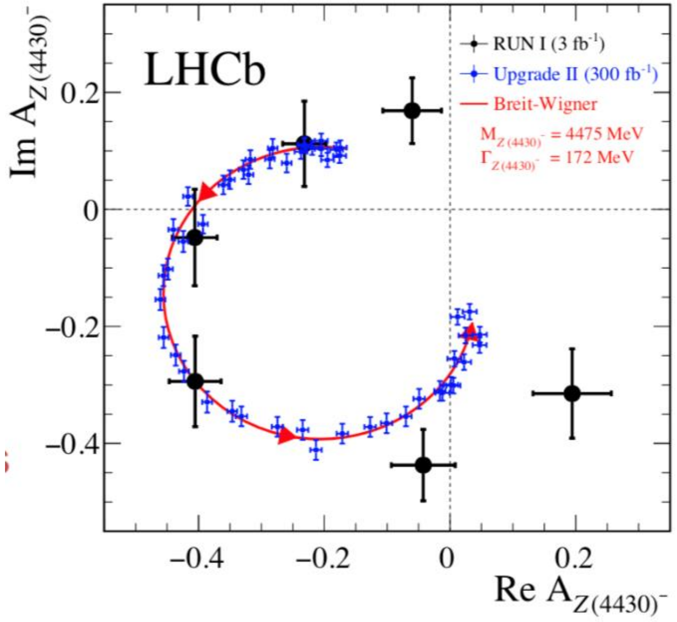


Physics case: hadron spectroscopy

arXiv:1808.08865

- Much more b- and c-hadrons would be produced with the Upgrade
- A gold mine of hadron spectroscopy studies
  - Observation of new states
  - Precision determination of the characteristics of observed hadrons
  - Understand the nature of these states and strong interactions

	LHCb			Belle II
Decay mode	$23\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$	$50\,\mathrm{ab}^{-1}$
$B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$	14k	30k	180k	11k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k	4k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M	140k
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100	—
$\Lambda_b^0 \to J/\psi pK^-$	340k	700k	4M	—
$\Xi_b^- \to J/\psi \Lambda K^-$	4k	10k	55k	—
$\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$	7k	15k	90k	<6k
$\Xi_{bc}^+ \to J/\psi\, \Xi_c^+$	50	100	600	—



Summary

- LHCb operated well in run1+run2 and produced nice results
  - Confirmed the $P_c(4450)^+$ peak structure, which is resolved into two narrower states, $P_c(4440)^+$ and $P_c(4457)^+$
  - Observed a new narrow state $P_c(4312)^+$
- 1D fit to narrow peaks with naïve background model used
  - More accurate result has to wait for detailed amplitude analysis
- LHCb Upgrade is under construction
  - Expect to accumulate data of $50\ \mathrm{fb}^{-1}$ after Run4 (2029)
- LHCb Upgrade2 proposed and R&D started
  - Expect to accumulate data of $300\ \mathrm{fb}^{-1}$ after Run5 (around 2035)
- Stay tuned for new results from LHCb

细推物理须行乐
何用浮名绊此身。

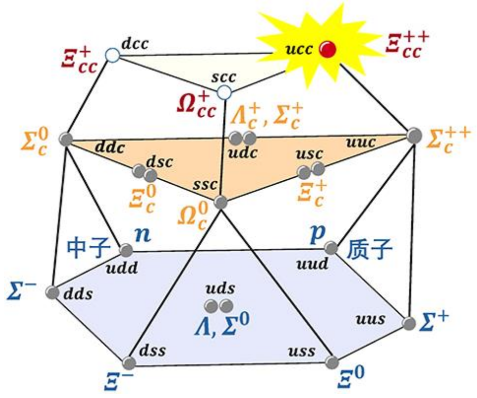
杜工部

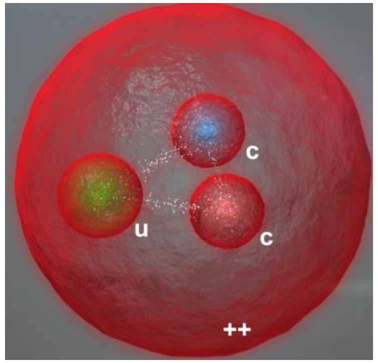
相逢意气为君饮
系马高楼垂柳边。

王右丞

谢谢！

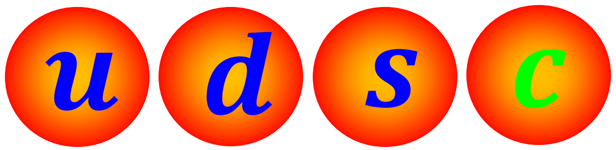
Doubly charmed baryons

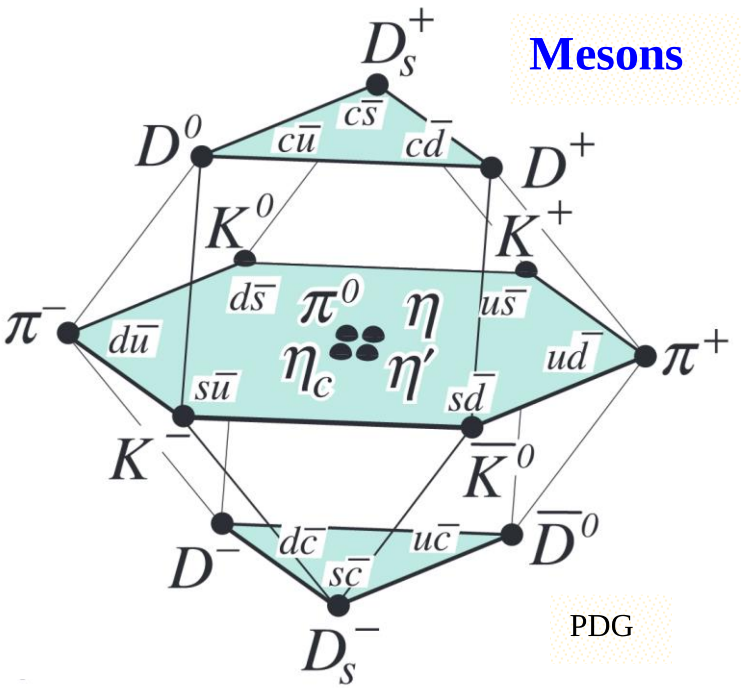




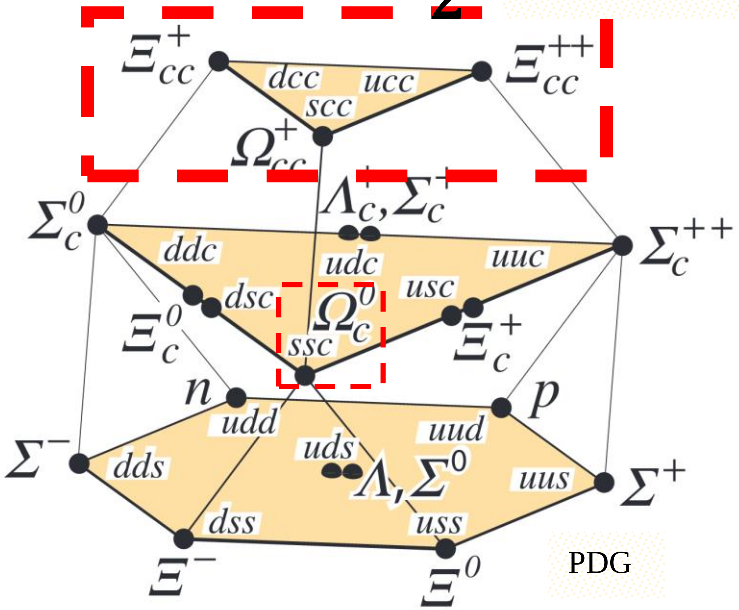
SU(4) quark model

- When extended to (u, d, s, c), hadrons form SU(4) multiplets
- Our knowledge of charmed baryons is limited
  - $C = 2$ baryons: $\Xi_{cc}^{+}(ccd)$, $\Xi_{cc}^{++}(ccu)$ and $\Omega_{cc}^{+}(ccs)$
  - Excited charmed baryons

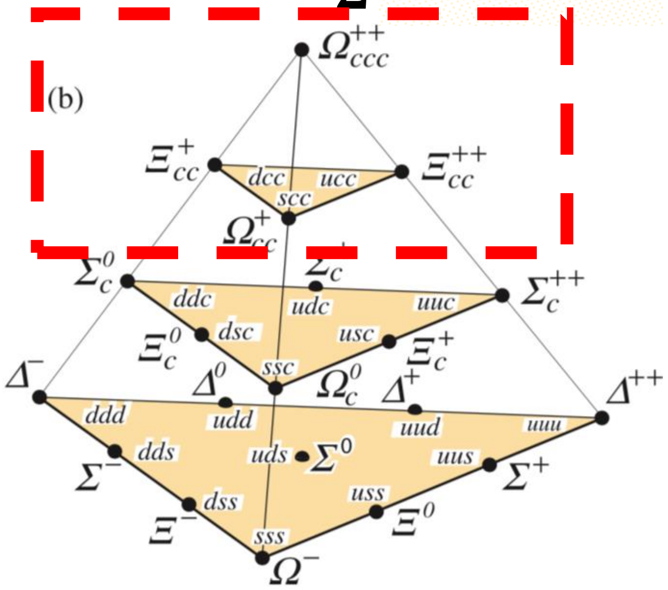




$J^P = \frac{1}{2}^+$ Baryons



$J^P = \frac{3}{2}^+$ Baryons

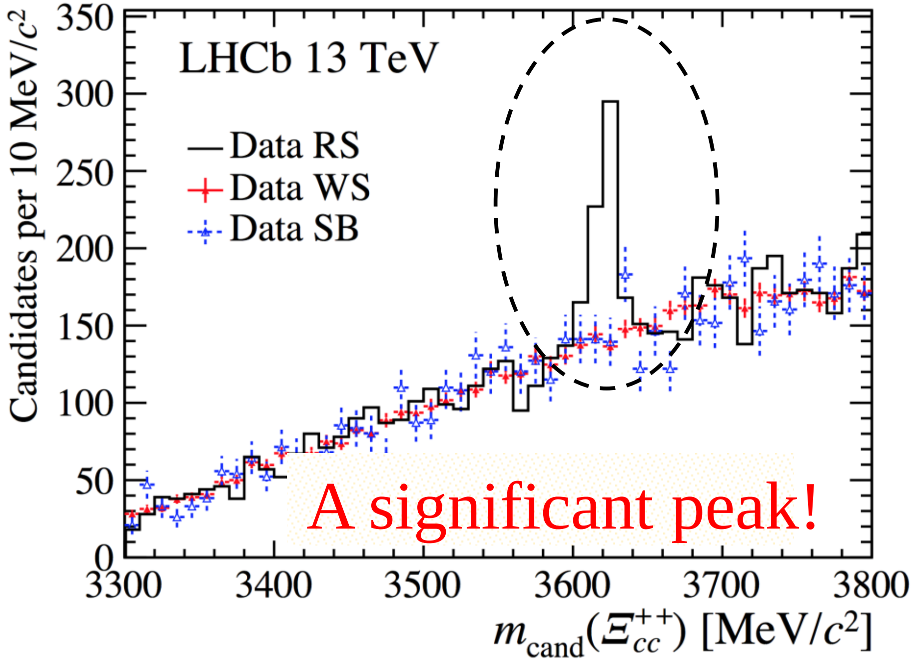


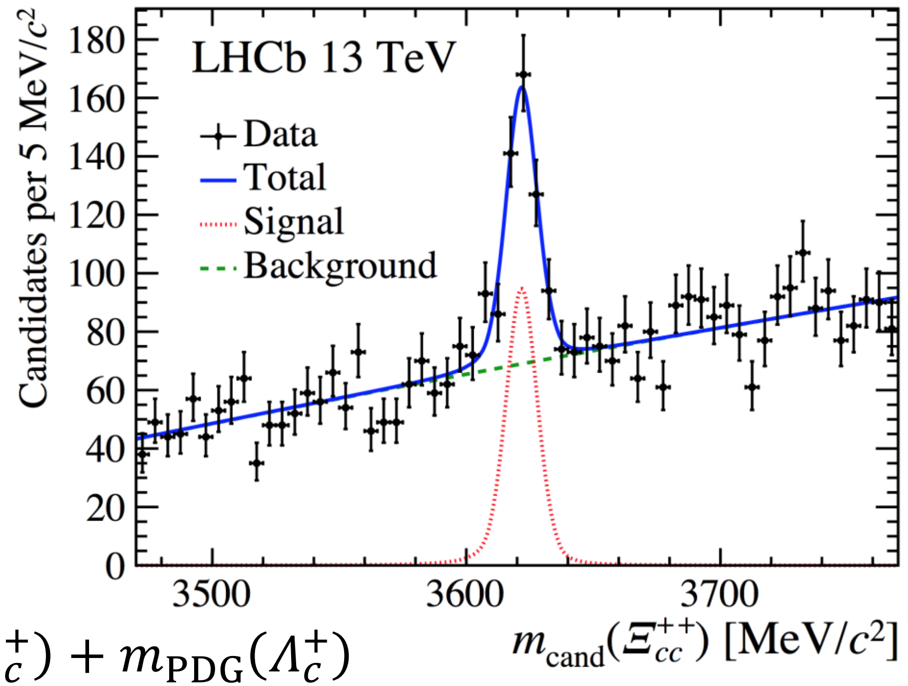
Observation of Ξ_{cc}^{++} at 13 TeV

PRL119 (2017) 112001

- Significant structure at around $\mathbf{3620\ MeV}/c^2$ in 2016 data
  - Local stat. significance $> \mathbf{12\sigma}$
  - Confirmed in 2012 data ($> \mathbf{7\sigma}$)

$N_{\rm sig} = 313 \pm 33$
$m = 3621.80 \pm 0.72\ \mathrm{MeV}/c^2$
$\sigma = 6.63 \pm 0.82\ \mathrm{MeV}/c^2$





$$m_{\rm cand}(\Xi_{cc}^{++}) = m(\Lambda_c^+ K^- \pi^+ \pi^+) - m_{\rm cand}(\Lambda_c^+) + m_{\rm PDG}(\Lambda_c^+)$$

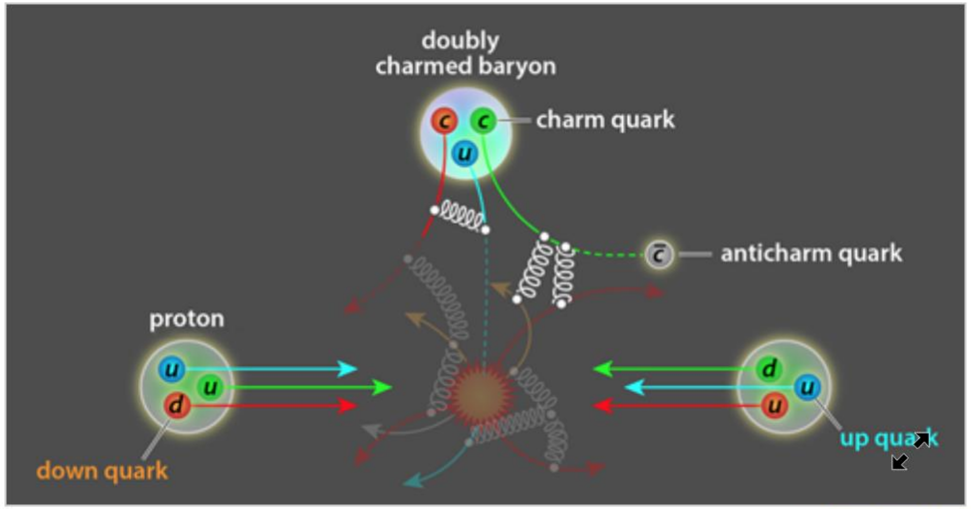
Highlighted by PRL editors as *"Editors' suggestion"*

Viewpoint: A Doubly Charming Particle

Raúl A. Briceño, Department of Physics, Old Dominion University, Norfolk, VA 23529, USA and Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

September 11, 2017 • *Physics* 10, 100

High-precision experiments at CERN find a new baryon containing two charm quarks.



APS/Alan Stonebraker

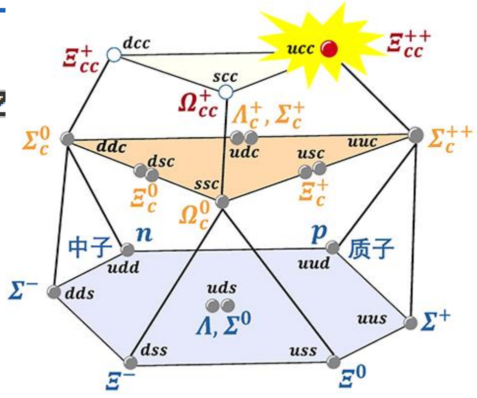
Figure 1: The LHCb Collaboration has provided evidence for a doubly charmed baryon called Ξ_{cc}^{++} [1]. The baryon is formed when two charm quarks, produced in high-energy proton-proton collisions, join a light quark.

CCTV and others

CCTV 央视网 com 新闻

国内 | 国际 | 图片 | 视频

我国科学家牵头首次发现新型重子

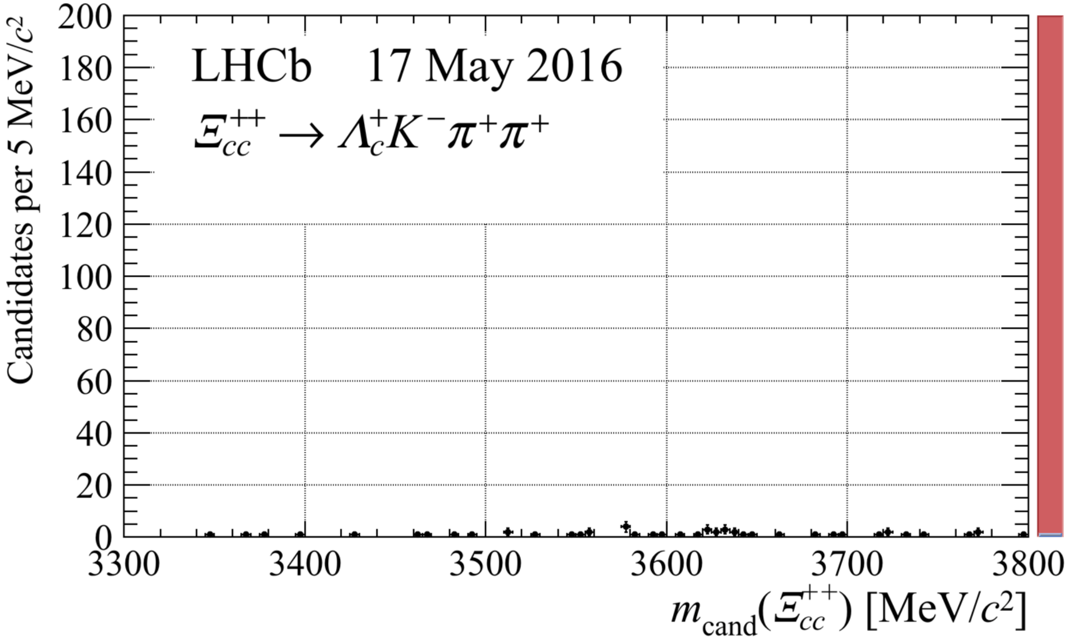


科技频道 来源：科技日报 2017年07月07日 09:22

原标题：我国科学家牵头发现新型重子

科技日报北京7月6日电（记者操秀英）北京时间7月6日，欧洲核子研究中心大型强子对撞机（LHC）上的实验组宣布首次发现双粲重子。该发现由中国科学家主导。国际合作组已将研究论文提交至《物理评论快报》。

LHCb中国组负责人，清华大学高原宁教授介绍道，按照夸克模型的分类，重子由三克组成，熟知的质子和中子是最常见的重子。自然界中存在六种不同夸克：u, d, s, c, b 三种较轻，后三种较重。理论预期存在很多种具有不同组分的重子。此前发现的重子最一个重夸克，但此次发现的重子含有两个重夸克。这次发现的重子含有两个c夸克（粲和一个u夸克（上夸克），带两个单位电荷。



SCIENCE

Demystifying Science: What is Xicc++ ?

JULY 09, 2017 04:02 IST
UPDATED: JULY 09, 2017 00:42 IST

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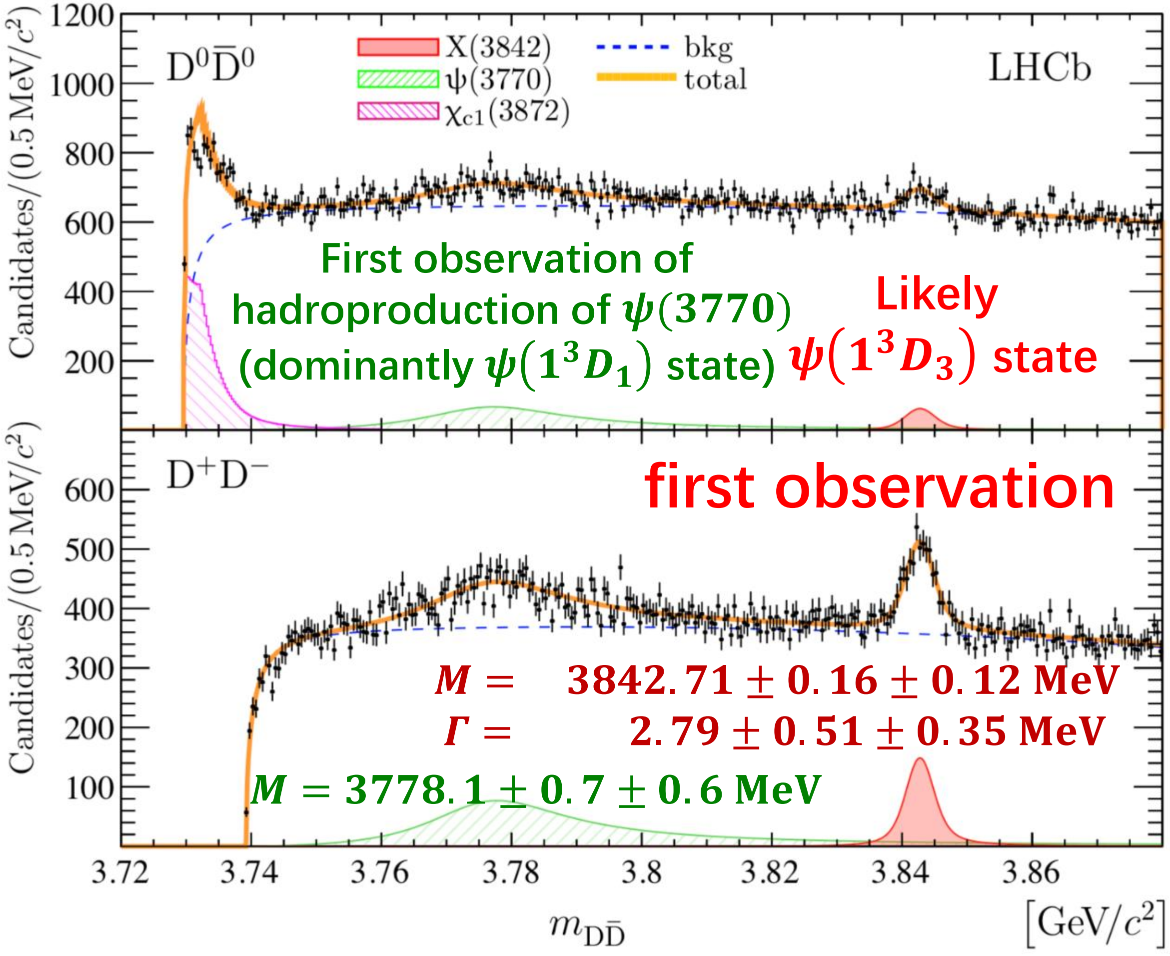
MORE-IN

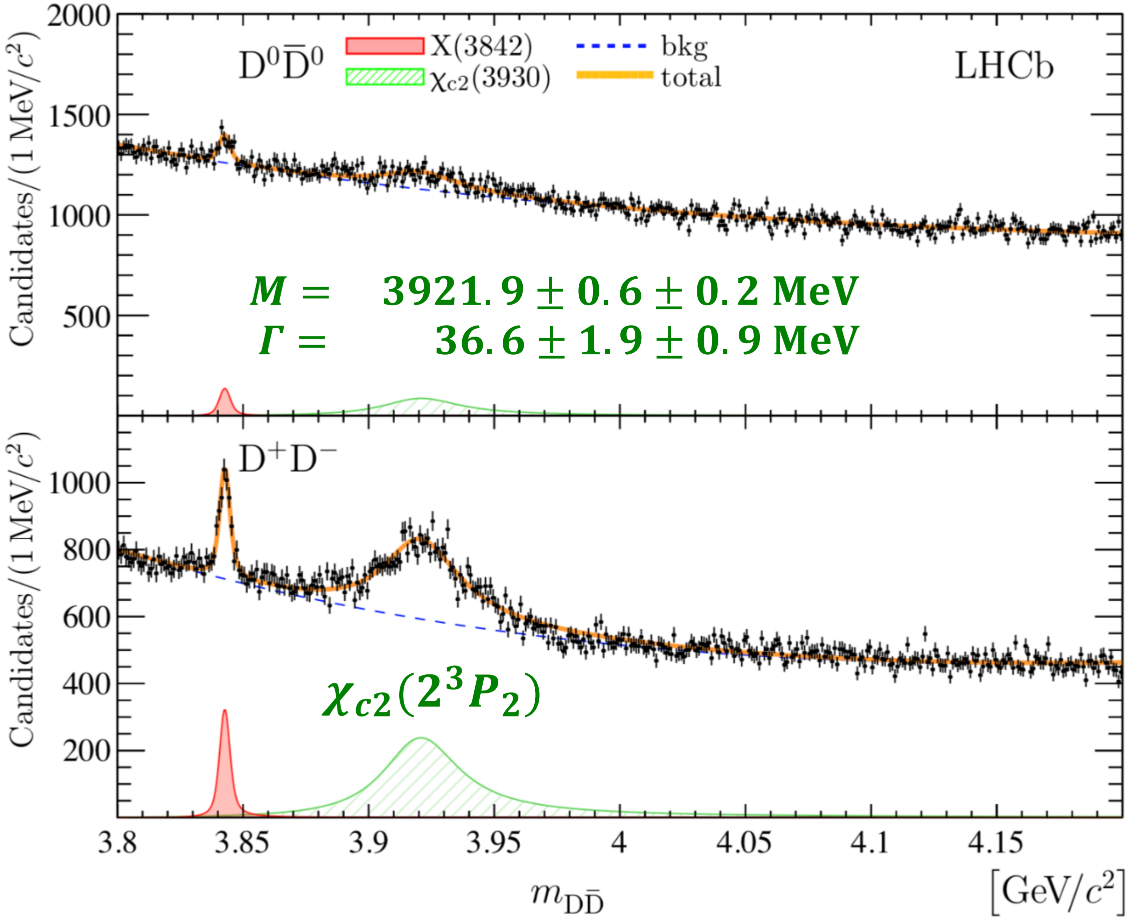
It's a new kind of quark, or a subatomic particle, that is a

Observation of $X(3842)$ in $m(D\bar{D})$

arXiv:1903.12240

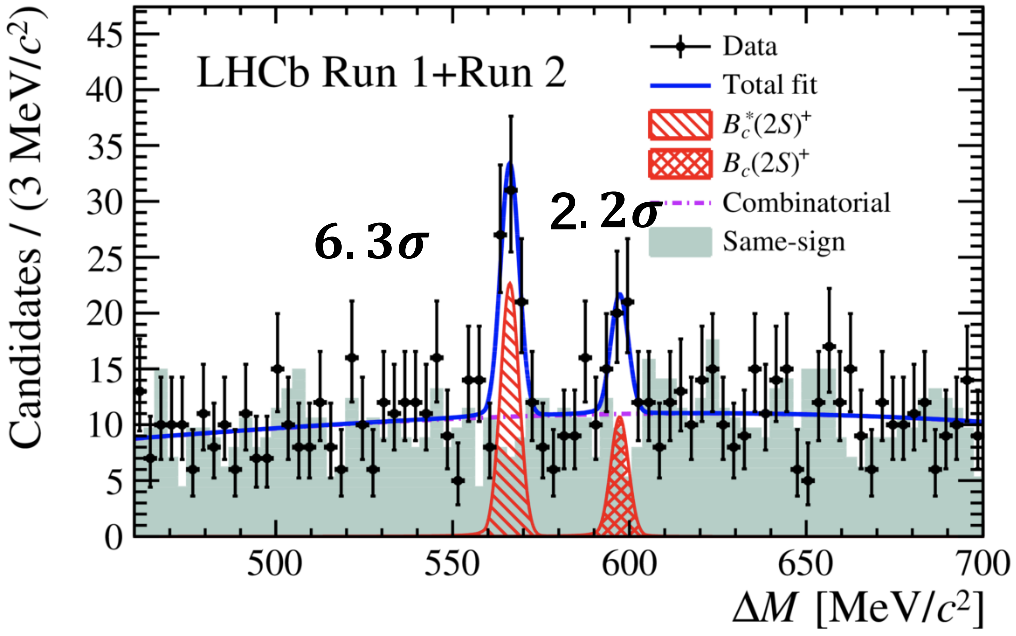
- First observation of $X(3842)$, probably $\psi(1^3D_3)$
- First observation of hadroproduced $\psi(3770)$ and $\chi_{c2}(3930)$





Observation of excited B_c^+

LHCb: arXiv:1904.00081

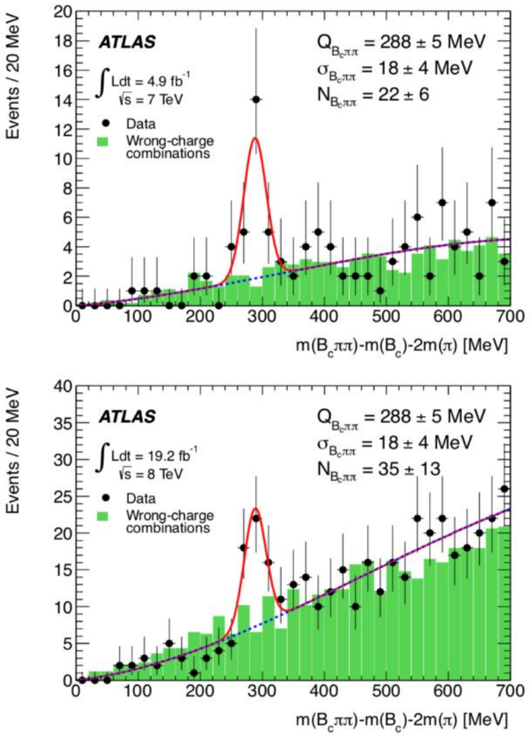


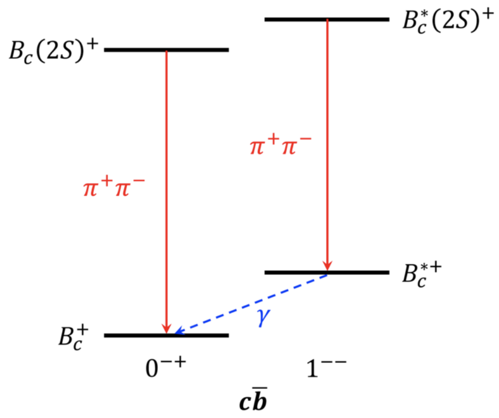
$$M = 6841.2 \pm 0.6\,(\mathrm{stat}) \pm 0.1\,(\mathrm{syst}) \pm 0.8\,(B_c^+)\ \mathrm{MeV}/c^2$$

$$M = 6872.1 \pm 1.3\,(\mathrm{stat}) \pm 0.1\,(\mathrm{syst}) \pm 0.8\,(B_c^+)\ \mathrm{MeV}/c^2$$

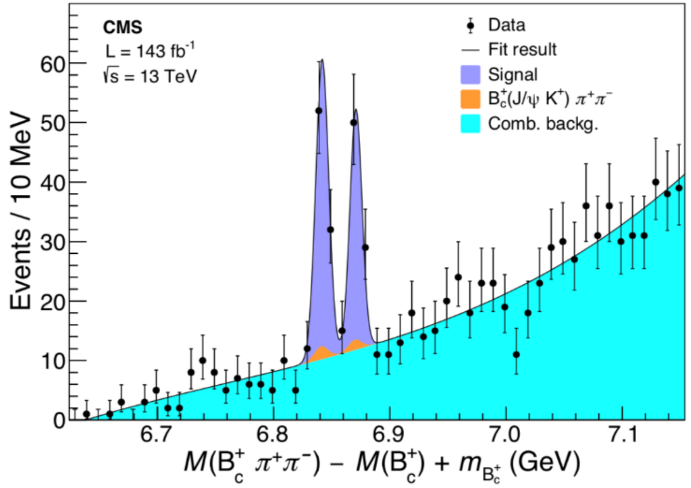
ATLAS: Phys.Rev.Lett.113(2014)212004

$$6842 \pm 4 \pm 5\ \mathrm{MeV}$$





CMS: Phys.Rev.Lett.122(2019)132001



$$6871.0 \pm 1.2\,(\mathrm{stat}) \pm 0.8\,(\mathrm{syst}) \pm 0.8\,(\mathrm{B_c^+})\ \mathrm{MeV}$$

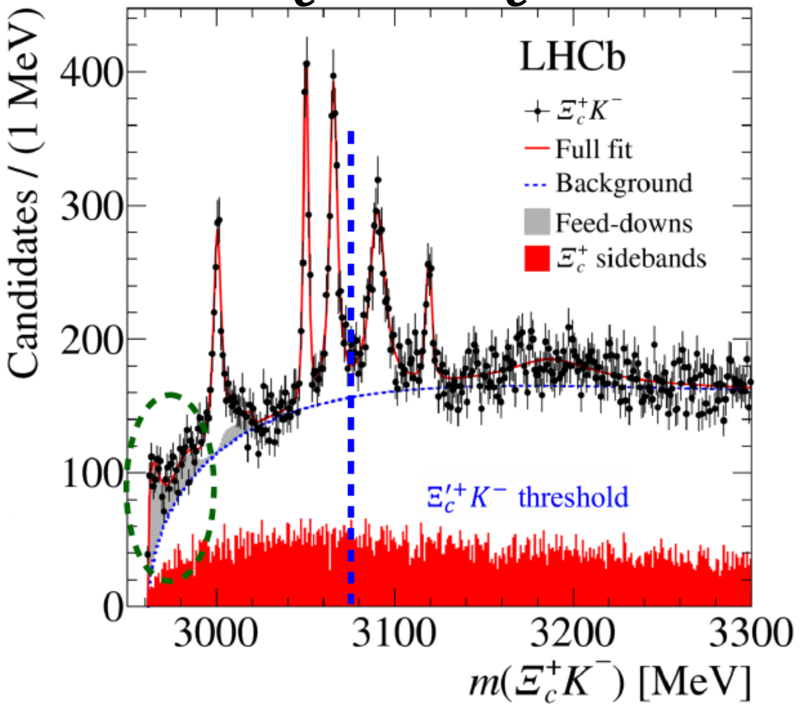
Jibo and Liupan are made the major contribution

Propellants provided by LHCb: conventional

➢ **Examples of conventional hadrons**

- Discovery of five narrow excited Ω_c^0 states all at once

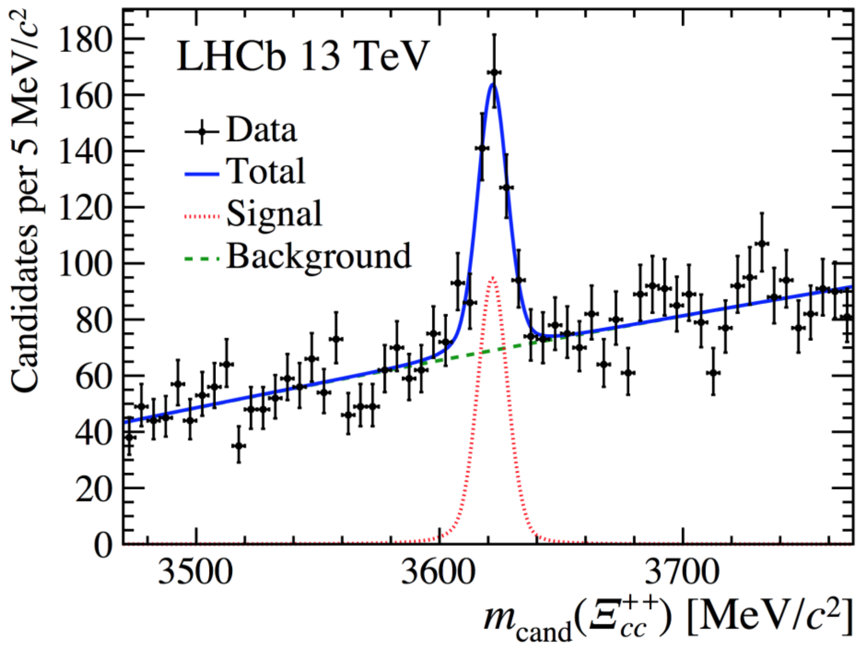
$$\Omega_c^{*0} \rightarrow \Xi_c^+ K^-$$



Phys. Rev. Lett. 118 (2017) 182001

- Observation of the doubly charmed baryon Ξ_{cc}^{++}

$$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$$

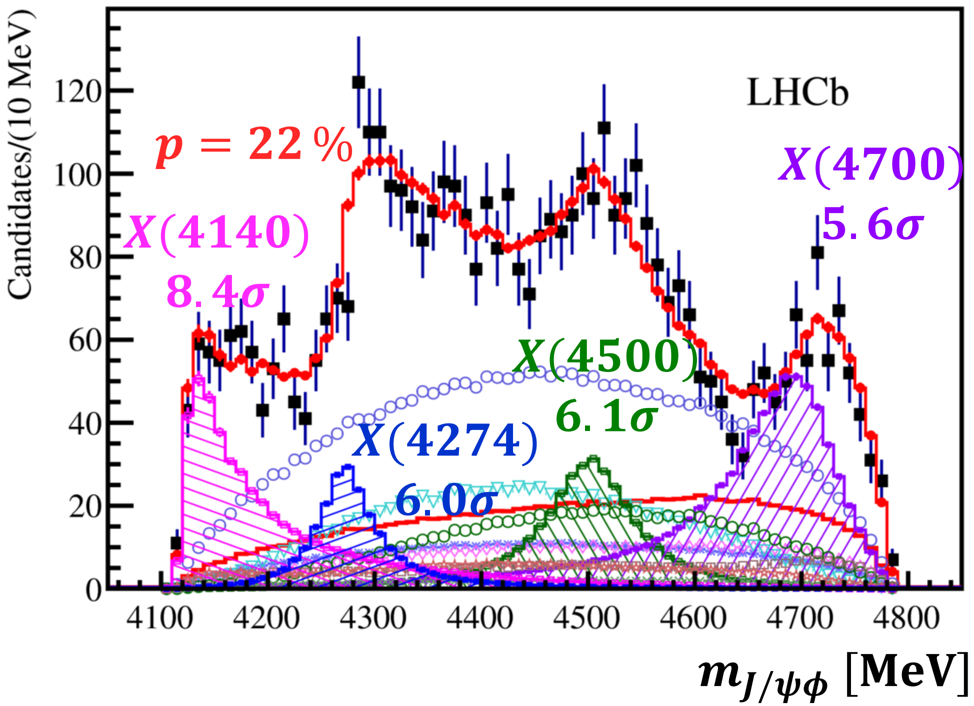


Phys. Rev. Lett. 119 (2017) 112001

Propellants provided by LHCb: exotic

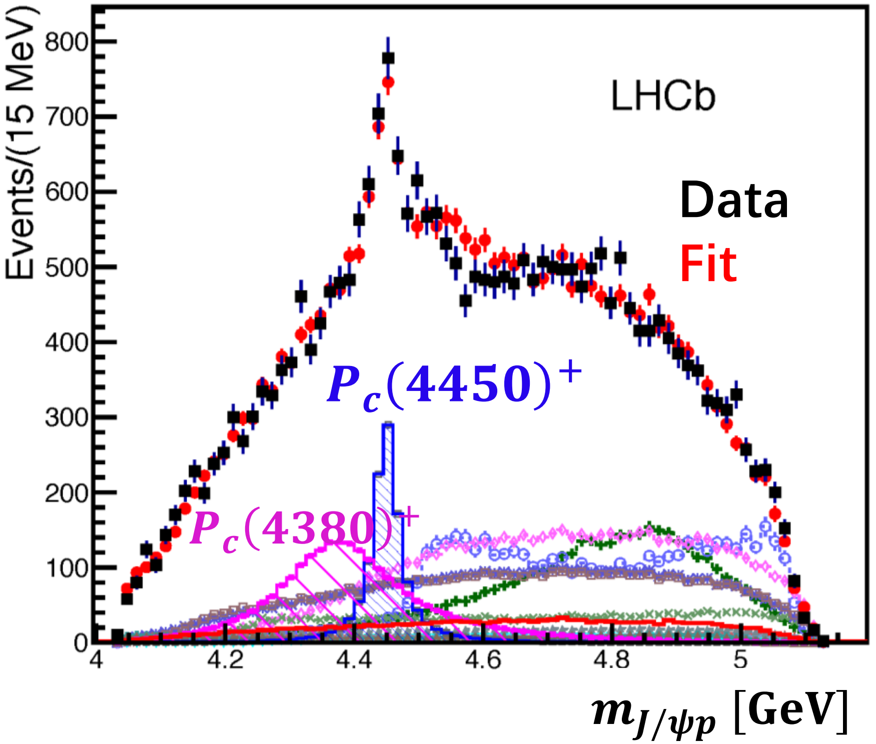
➢ **Examples of exotic hadrons**

- **Tetraquark candidates in the $J/\psi\phi$ system of $B^+ \to J/\psi\phi K^+$ decays**



Phys. Rev. Lett. 118 (2017) 022003

- **Pentaquark candidates in the $J/\psi p$ system of $\Lambda_b^0 \to J/\psi p K^-$ decays**

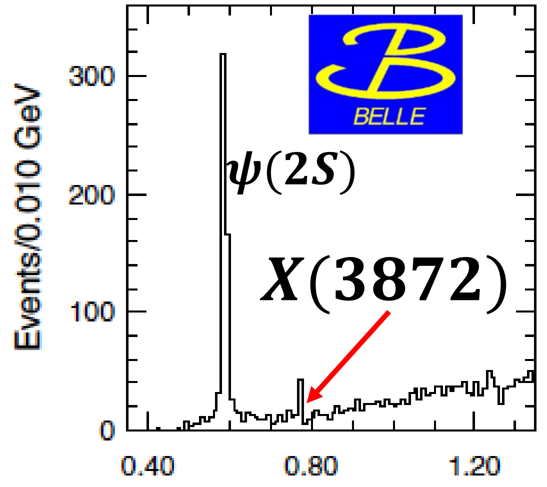


Phys. Rev. Lett. 115 (2015) 072001

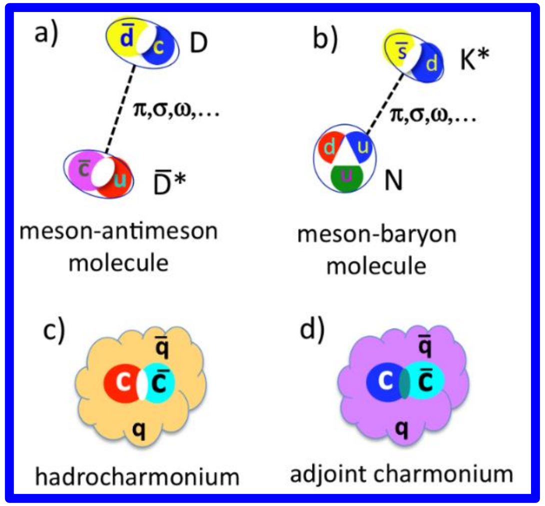
Renaissance of spectroscopy in heavy flavour

- The $X(3872)$ [$\chi_{c1}(3872)$] state observed by Belle in 2003 in the $J/\psi\pi^+\pi^-$ spectrum
  - The harbinger of a new direction in hadron spectroscopy
- More exotic hadrons, mostly containing $c\bar{c}$ or $b\bar{b}$, have been observed soon later
  - Various models proposed for quark composition and binding mechanisms of these states
- Great progress achieved with combined efforts from both theory and experiments
  - LHCb has been providing propellant to boost our understanding since the start of the LHC

PRL91 (2003) 262001



$m(J/\psi\pi^+\pi^-) - m(J/\psi)$ GeV



Rev. Mod. Phys. 90 (2018) 015003

Recently discovered exotic hadron candidates

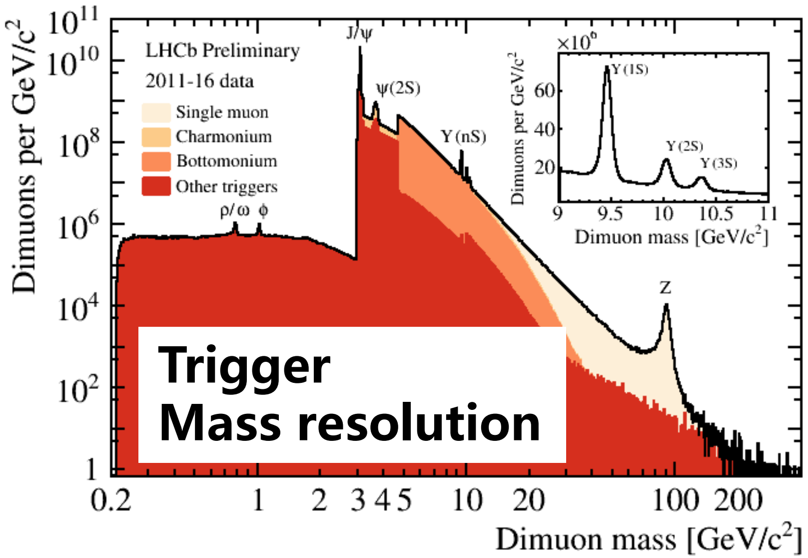
➢ A list of those containing hidden charm or beauty Rev. Mod. Phys. 90 (2018) 015003

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment
$Z_c^{+,0}(3900)$	3886.6 ± 2.4	28.1 ± 2.6	1^{+-}	$e^+e^- \to \pi^{-,0}(J/\psi\pi^{+,0})$ $e^+e^- \to \pi^{-,0}(D\bar{D}^*)^{+,0}$	BESIII (Ablikim *et al.*, 2013a, 2015f), Belle (Liu *et al.*, 2013) BESIII (Ablikim *et al.*, 2014b, 2015e)
$Z_c^{+,0}(4020)$	4024.1 ± 1.9	13 ± 5	$1^{+-}(?)$	$e^+e- \to \pi^{-,0}(h_c\pi^{+,0})$ $e^+e^- \to \pi^{-,0}(D^*\bar{D}^*)^{+,0}$	BESIII (Ablikim *et al.*, 2013b, 2014c) BESIII (Ablikim *et al.*, 2014a, 2015d)
$Z^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$B \to K(\chi_{c1}\pi^+)$	Belle (Mizuk *et al.*, 2008), *BABAR* (Lees *et al.*, 2012a)
$Z^+(4200)$	4196^{+35}_{-32}	370^{+99}_{-149}	1^+	$B \to K(J/\psi\pi^+)$ $B \to K(\psi'\pi^+)$	Belle (Chilikin *et al.*, 2014) LHCb (Aaij *et al.*, 2014b)
$Z^+(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$B \to K(\chi_{c1}\pi^+)$	Belle (Mizuk *et al.*, 2008), *BABAR* (Lees *et al.*, 2012a)
$Z^+(4430)$	4477 ± 20	181 ± 31	1^+	$B \to K(\psi'\pi^+)$ $B \to K(J\psi\pi^+)$	Belle (Choi *et al.*, 2008; Mizuk *et al.*, 2009), Belle (Chilikin *et al.*, 2013), LHCb (Aaij *et al.*, 2014b, 2015b) Belle (Chilikin *et al.*, 2014)
$P_c^+(4380)$	4380 ± 30	205 ± 88	$(\frac{3}{2}/\frac{5}{2})^{\mp}$	$\Lambda_b^0 \to K(J/\psi p)$	LHCb (Aaij *et al.*, 2015c)
$P_c^+(4450)$	4450 ± 3	39 ± 20	$(\frac{5}{2}/\frac{3}{2})^{\pm}$	$\Lambda_b^0 \to K(J/\psi p)$	LHCb (Aaij *et al.*, 2015c)
$Y_b(10860)$	$10891.1^{+3.4}_{-3.8}$	$53.7^{+7.2}_{-7.8}$	1^{--}	$e^+e^- \to (\Upsilon(nS)\pi^+\pi^-)$	Belle (Chen *et al.*, 2008; Santel *et al.*, 2016)
$Z_b^{+,0}(10610)$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$Y_b(10860) \to \pi^{-,0}(\Upsilon(nS)\pi^{+,0})$ $Y_b(10860) \to \pi^-(h_b(nP)\pi^+)$ $Y_b(10860) \to \pi^-(B\bar{B}^*)^+$	Belle (Bondar *et al.*, 2012; Garmash *et al.*, 2015), Belle (Krokovny *et al.*, 2013) Belle (Bondar *et al.*, 2012) Belle (Garmash *et al.*, 2016)
$Z_b^+(10650)$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$Y_b(10860) \to \pi^-(\Upsilon(nS)\pi^+)$ $Y_b(10860) \to \pi^-(h_b(nP)\pi^+)$ $Y_b(10860) \to \pi^-(B^*\bar{B}^*)^+$	Belle (Bondar *et al.*, 2012; Garmash *et al.*, 2015) Belle (Bondar *et al.*, 2012) Belle (Garmash *et al.*, 2016)

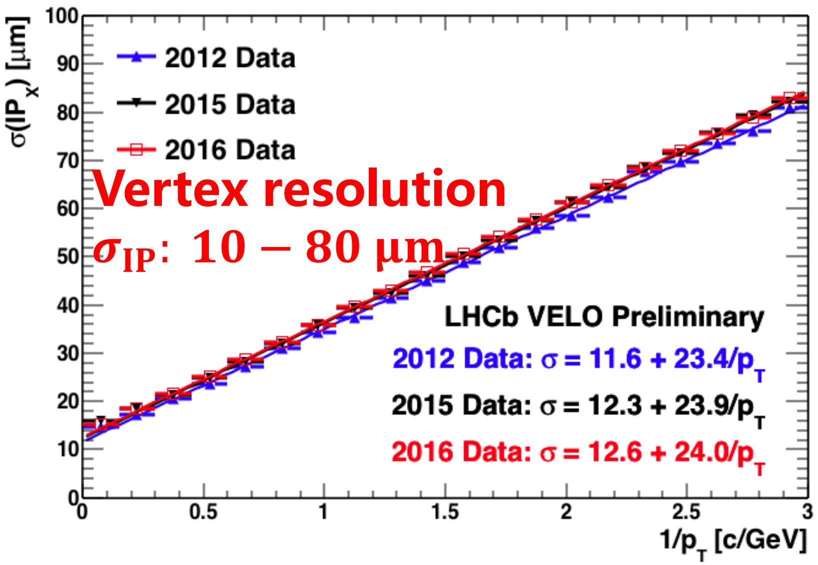
State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment
$X(3872)$	3871.69 ± 0.17	< 1.2	1^{++}	$B \to K(J/\psi\pi^+\pi^-)$ $p\bar{p} \to (J/\psi\pi^+\pi^-) + \cdots$ $B \to K(J/\psi\pi^+\pi^-\pi^0)$ $B \to K(D^0\bar{D}^0\pi^0)$ $B \to K(J/\psi\gamma)$ $B \to K(\psi'\gamma)$ $pp \to (J/\psi\pi^+\pi^-) + \cdots$ $e^+e^- \to \gamma(J/\psi\pi^+\pi^-)$	Belle (Choi *et al.*, 2003, 2011), *BABAR* (Aubert *et al.*, 2005c), LHCb (Aaij *et al.*, 2013a, 2015d) CDF (Acosta *et al.*, 2004; Abulencia *et al.*, 2006; Aaltonen *et al.*, 2009b), D0 (Abazov *et al.*, 2004) Belle (Abe *et al.*, 2005), *BABAR* (del Amo Sanchez *et al.*, 2010a) Belle (Gokhroo *et al.*, 2006; Aushev *et al.*, 2010b), *BABAR* (Aubert *et al.*, 2008c) *BABAR* (del Amo Sanchez *et al.*, 2010a), Belle (Bhardwaj *et al.*, 2011), LHCb (Aaij *et al.*, 2012a) *BABAR* (Aubert *et al.*, 2009b), Belle (Bhardwaj *et al.*, 2011), LHCb (Aaij *et al.*, 2014a) LHCb (Aaij *et al.*, 2012a), CMS (Chatrchyan *et al.*, 2013a), ATLAS (Aaboud *et al.*, 2017) BESIII (Ablikim *et al.*, 2014d)
$X(3915)$	3918.4 ± 1.9	20 ± 5	0^{++}	$B \to K(J/\psi\omega)$ $e^+e^- \to e^+e^-(J/\psi\omega)$	Belle (Choi *et al.*, 2005), *BABAR* (Aubert *et al.*, 2008b; del Amo Sanchez *et al.*, 2010a) Belle (Uehara *et al.*, 2010), *BABAR* (Lees *et al.*, 2012c)
$X(3940)$	[illegible]	37^{+27}_{-17}	$0^{-+}(?)$	$e^+e^- \to J/\psi(D^*\bar{D})$ $e^+e^- \to J/\psi(\cdots)$	Belle (Pakhlov *et al.*, 2008) Belle (Abe *et al.*, 2007)
$X(4140)$	[illegible]	83^{+27}_{-25}	1^{++}	$B \to K(J/\psi\phi)$ $p\bar{p} \to (J/\psi\phi) + \cdots$	CDF (Aaltonen *et al.*, 2009a), CMS (Chatrchyan *et al.*, 2014), D0 (Abazov *et al.*, 2014), LHCb (Aaij *et al.*, 2017a, 2017d) D0 (Abazov *et al.*, 2015)
[illegible]	[illegible]	[illegible]	[illegible]	$e^+e^- \to J/\psi(D^*\bar{D}^*)$	Belle (Pakhlov *et al.*, 2008)
$Y(4260)$	See $Y(4220)$ entry		1^{--}	$e^+e^- \to \gamma(J/\psi\pi^+\pi^-)$	*BABAR* (Aubert *et al.*, 2005a; Lees *et al.*, 2012b), CLEO (He *et al.*, 2006), Belle (Yuan *et al.*, 2007; Liu *et al.*, 2013)
$Y(4220)$	4222 ± 3	48 ± 7	1^{--}	$e^+e^- \to (J/\psi\pi^+\pi^-)$ $e^+e^- \to (h_c\pi^+\pi^-)$ $e^+e^- \to (\chi_{c0}\omega)$ $e^+e^- \to (J/\psi\eta)$ $e^+e^- \to (\gamma X(3872))$ $e^+e^- \to (\pi^-Z_c^+(3900))$ $e^+e^- \to (\pi^-Z_c^+(4020))$	BESIII (Ablikim *et al.*, 2017c) BESIII (Ablikim *et al.*, 2017a) BESIII (Ablikim *et al.*, 2015g) BESIII (Ablikim *et al.*, 2015c) BESIII (Ablikim *et al.*, 2014d) BESIII (Ablikim *et al.*, 2013a), Belle (Liu *et al.*, 2013) BESIII (Ablikim *et al.*, 2013b)
$X(4274)$	4273^{+19}_{-9}	56^{+14}_{-16}	1^{++}	$B \to K(J/\psi\phi)$	CDF (Aaltonen *et al.*, 2017), CMS (Chatrchyan *et al.*, 2014), LHCb (Aaij *et al.*, 2017a, 2017d)
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$(0/2)^{++}$	$e^+e^- \to e^+e^-(J/\psi\phi)$	Belle (Shen *et al.*, 2010)
$Y(4360)$	4341 ± 8	102 ± 9	1^{--}	$e^+e^- \to \gamma(\psi'\pi^+\pi^-)$ $e^+e^- \to (J/\psi\pi^+\pi^-)$	*BABAR* (Aubert *et al.*, 2007; Lees *et al.*, 2014), Belle (Wang *et al.*, 2007, 2015) BESIII (Ablikim *et al.*, 2017c)
$Y(4390)$	4392 ± 6	140 ± 16	1^{--}	$e^+e^- \to (h_c\pi^+\pi^-)$	BESIII (Ablikim *et al.*, 2017a)
$X(4500)$	4506^{+16}_{-19}	92^{+30}_{-21}	0^{++}	$B \to K(J/\psi\phi)$	LHCb (Aaij *et al.*, 2017a, 2017d)
$X(4700)$	4704^{+17}_{-26}	120^{+52}_{-45}	0^{++}	$B \to K(J/\psi\phi)$	LHCb (Aaij *et al.*, 2017a, 2017d)
$Y(4660)$	4643 ± 9	72 ± 11	1^{--}	$e^+e^- \to \gamma(\psi'\pi^+\pi^-)$ $e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle (Wang *et al.*, 2007, 2015), *BABAR* (Aubert *et al.*, 2007; Lees *et al.*, 2014) Belle (Pakhlova *et al.*, 2008)

LHCb contributes

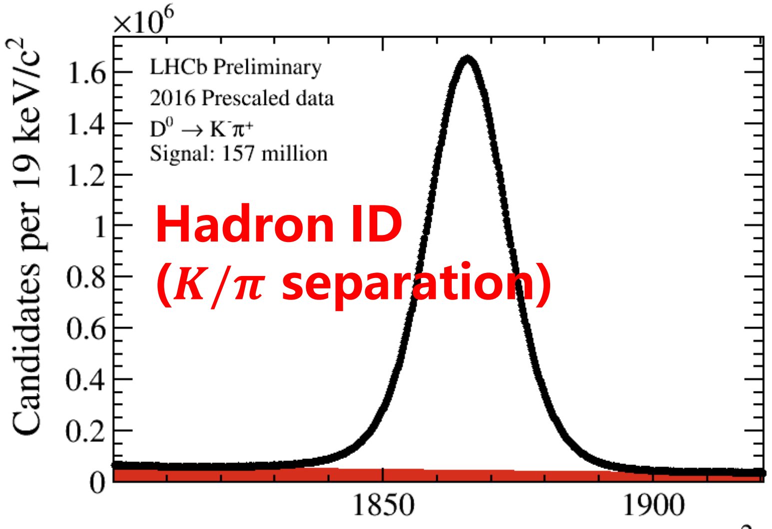
Pros of hadron spectroscopy at LHCb



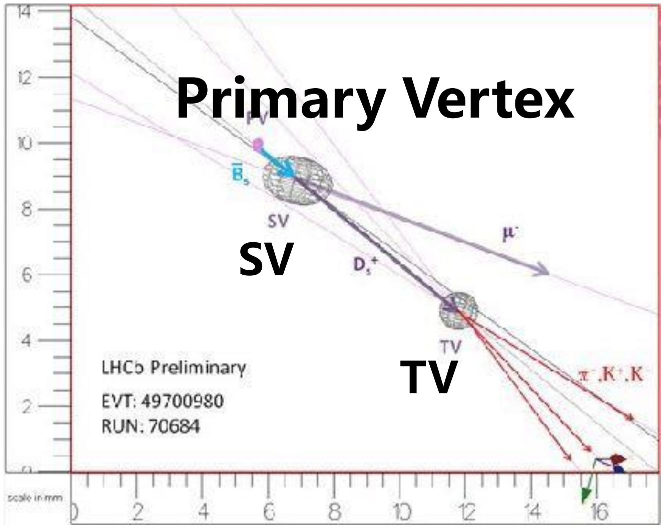
Trigger
Mass resolution



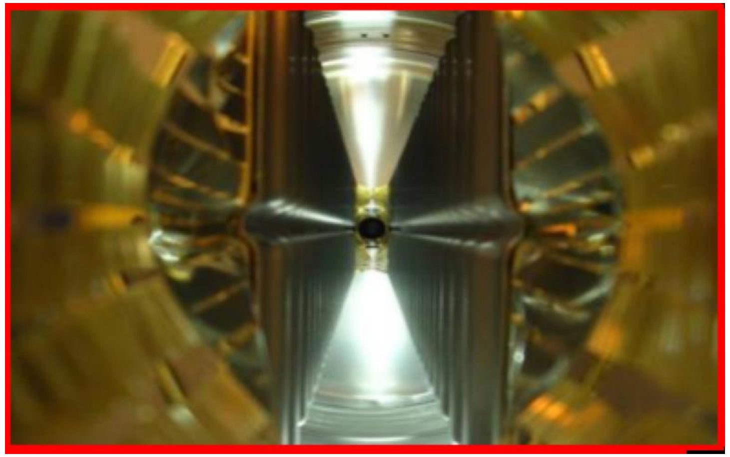
Vertex resolution
σ_{IP}: $10-80\ \mu\mathrm{m}$



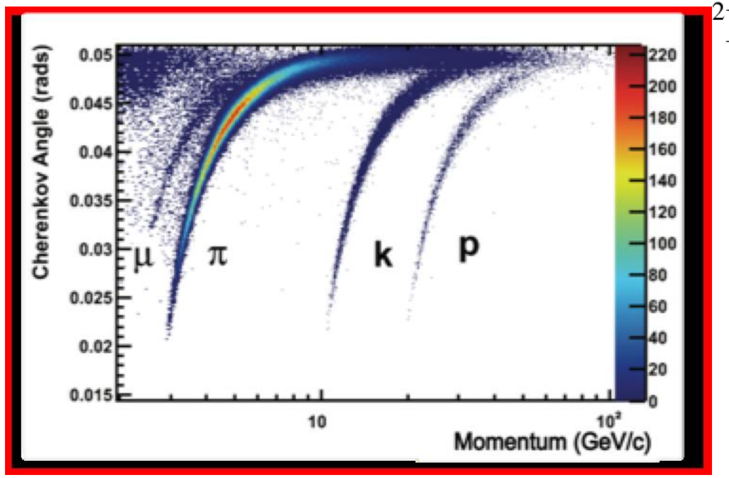
Hadron ID
(K/π separation)



Primary Vertex
SV
TV



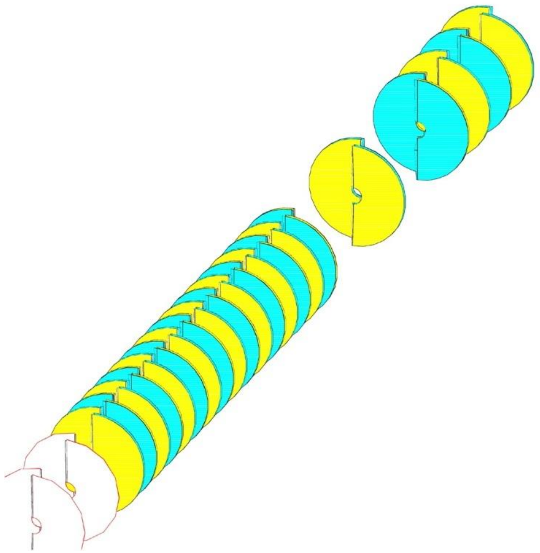
Closest distance between the beam and the VELO is around 0.5 cm

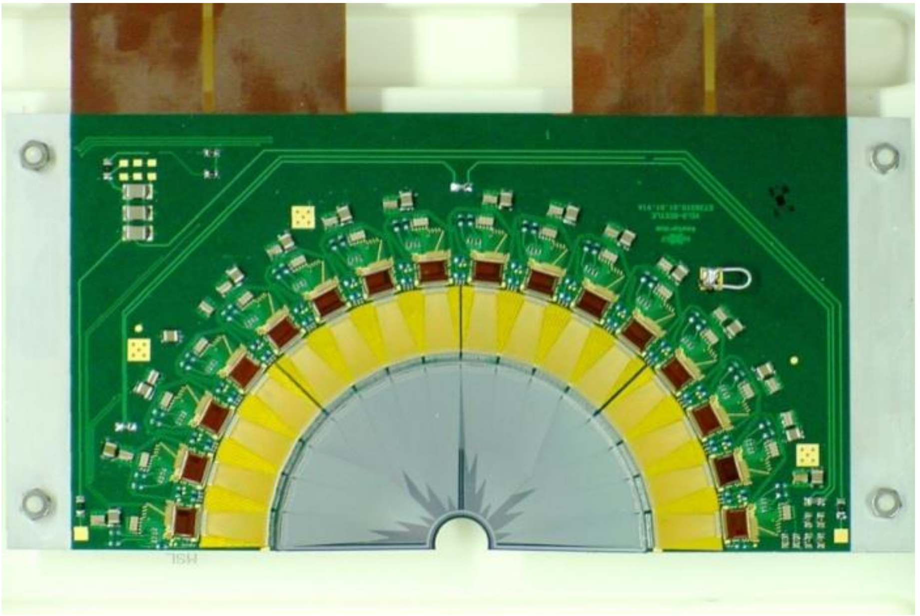


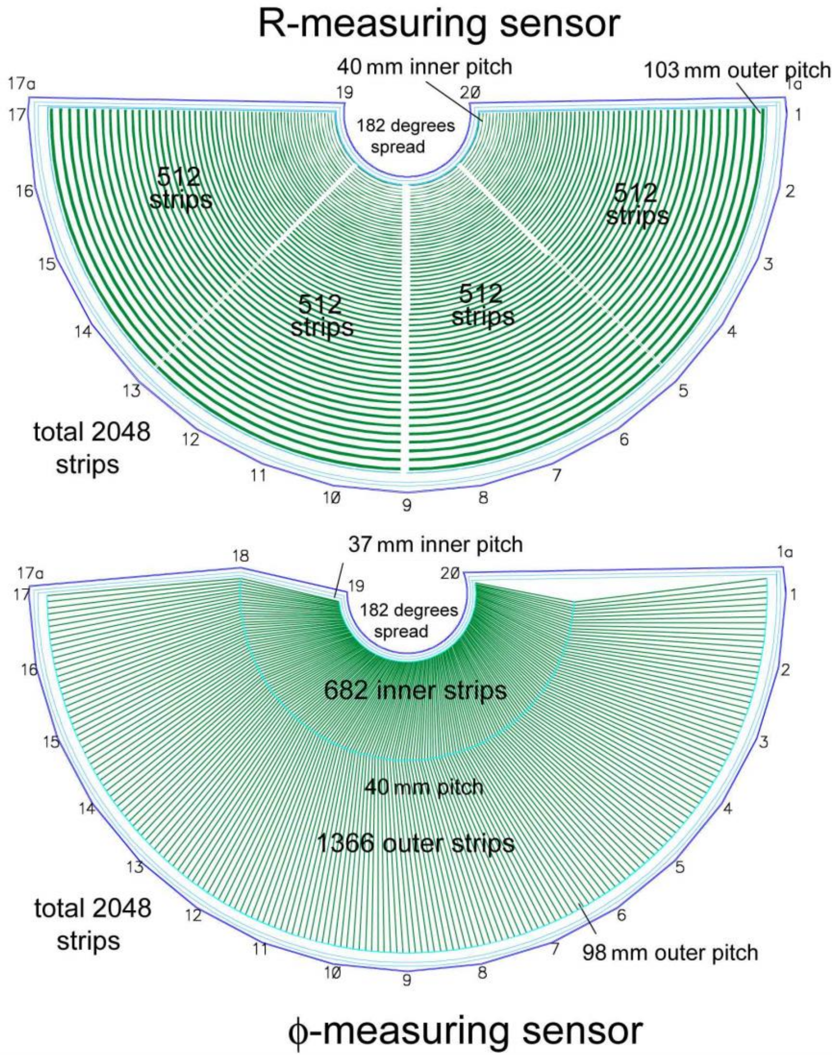
Well identified with $p \in 2-100\ \mathrm{GeV}/c$

https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2016
https://twiki.cern.ch/twiki/bin/view/LHCb/ConferencePlots

Vertex Locator





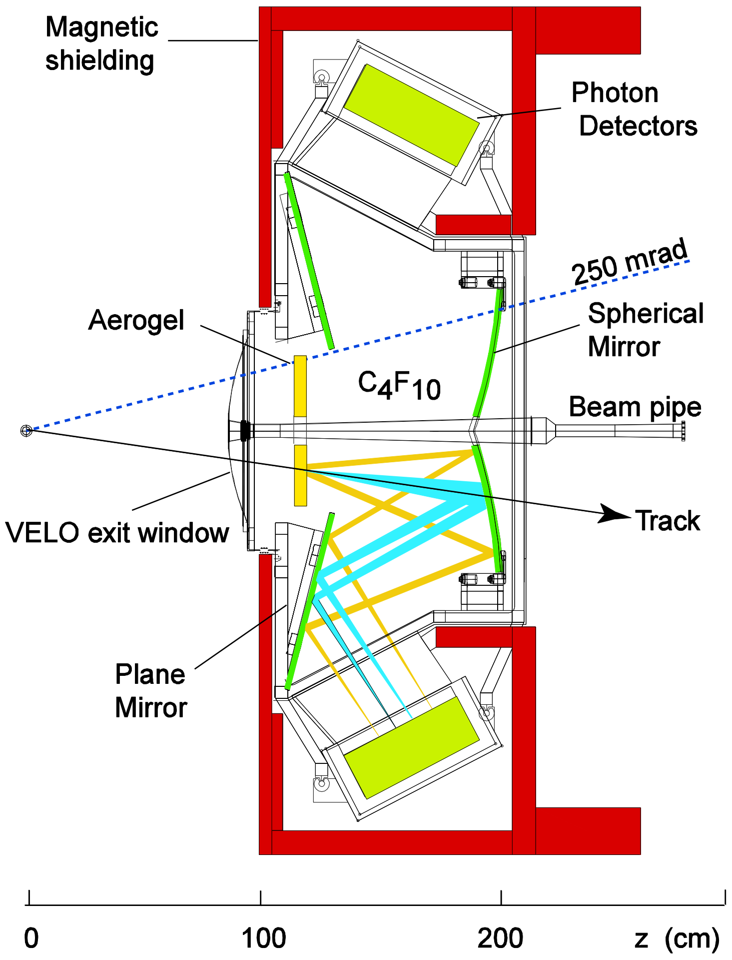


200 μm n-on-n Si short strips
double metal layer for readout
with Beetle chip (1/4 μm CMOS)

total 172 k channels
occupancy < 1%

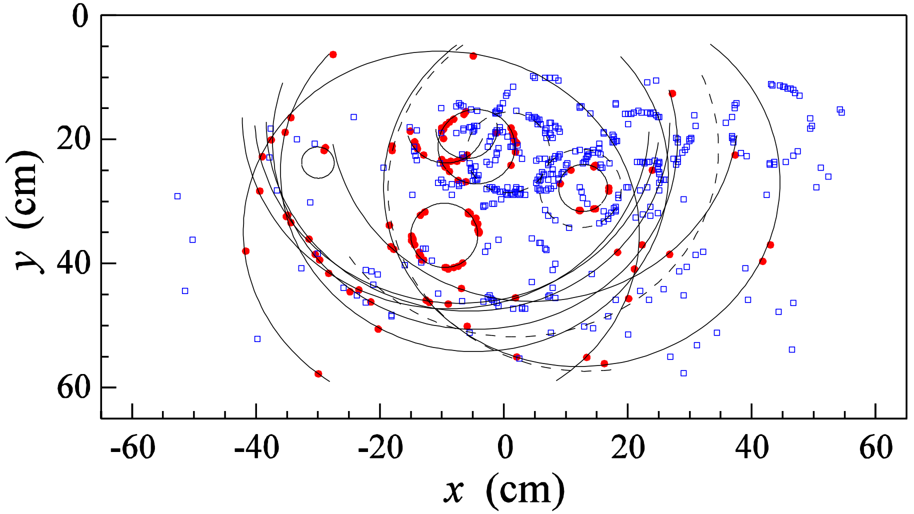
They have to be placed in secondary vacuum → complex mechanics

RICH detector

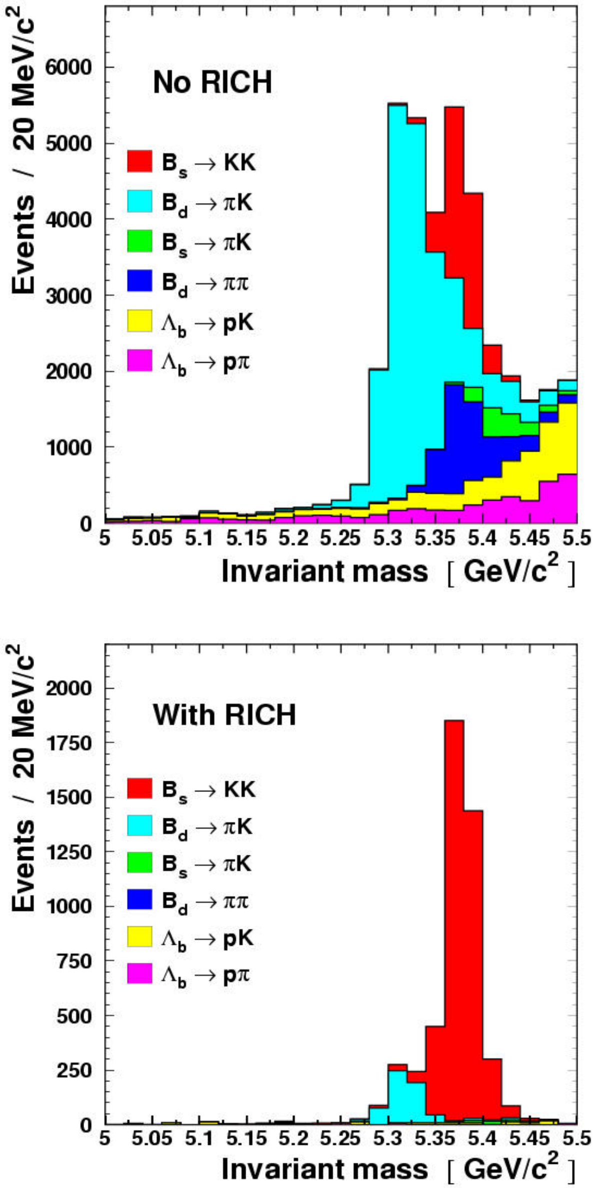


Use Cherenkov rings to identify charged particles, especially hadrons and muons

Typical event in the RICH1 photon detectors

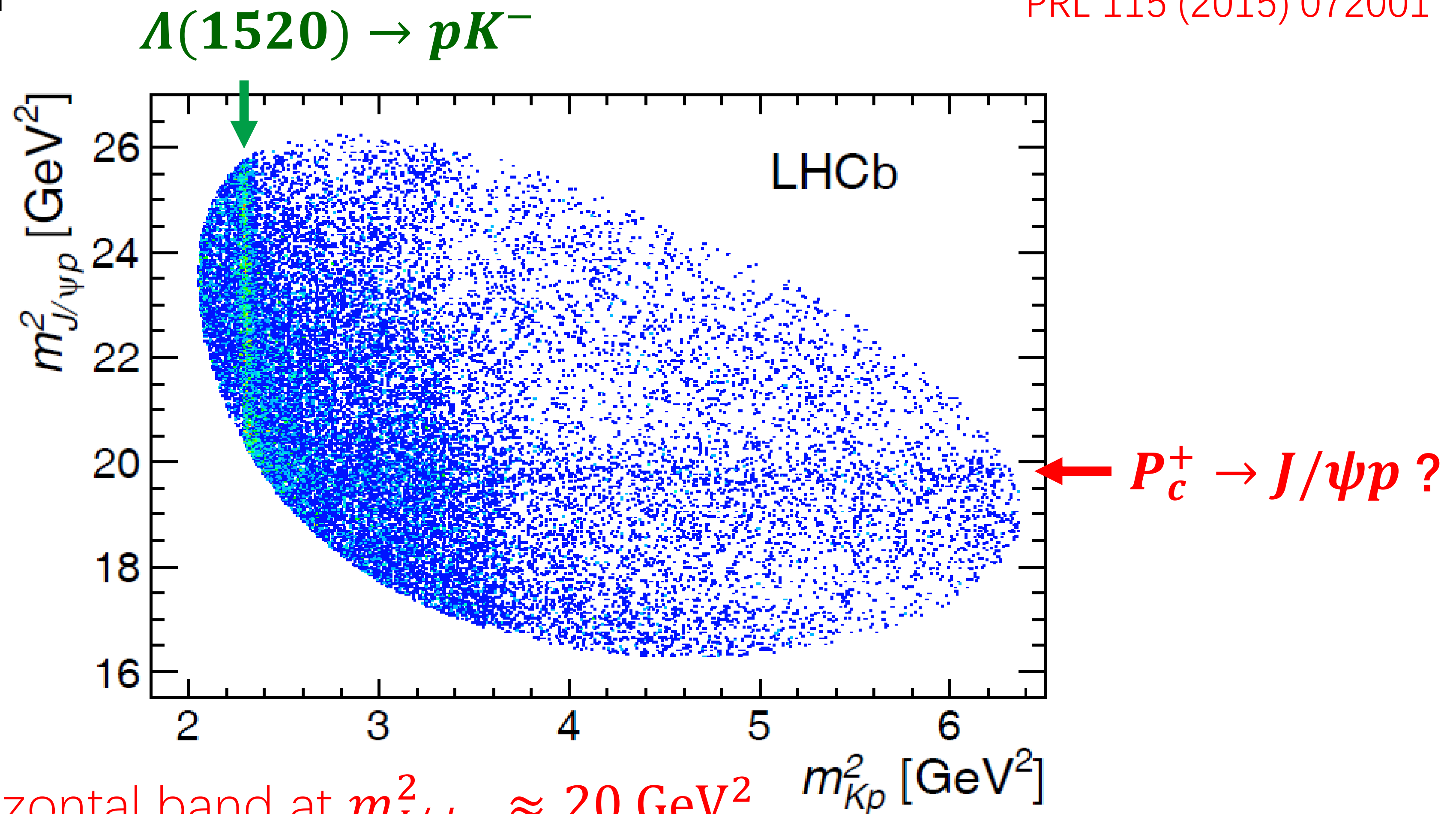


Performance of particle ID



"Dalitz plot"

PRL 115 (2015) 072001



- Clear horizontal band at $m^2_{J/\psi p} \approx 20$ GeV^2
- Λ^* structures dominate low m^2_{Kp} region, interferences unlikely generate the horizontal band at high m^2_{Kp} region

Fits with interferences

PRL122 (2019) 222001

- No interferences considered for nominal fits
- Fits with coherent sum between various BW amplitudes, including the broad P_c^+ state with the same J^P are also tried
- No significant evidence for interferences
  - but it provides the source of the largest systematic uncertainty on the mass and width determinations.

Example of the fit with interference:
$P_c(4312)^+$ interfering with the broad P_c^+