b and *c* spectroscopy at LHCb

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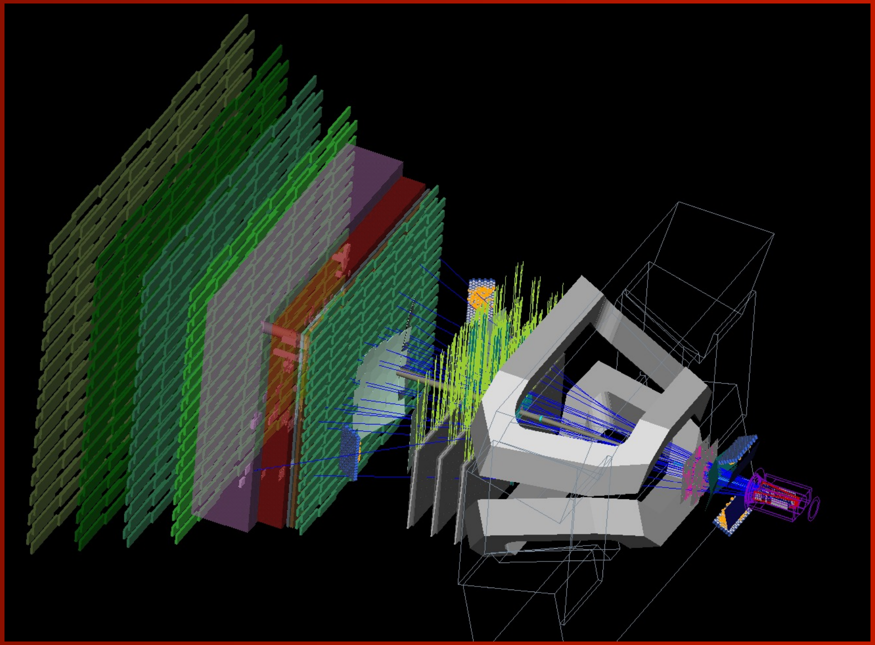
on behalf of the LHCb collaboration



Overview

- Spectroscopy is a highly active field at the LHC!
  All of the experiments are contributing!

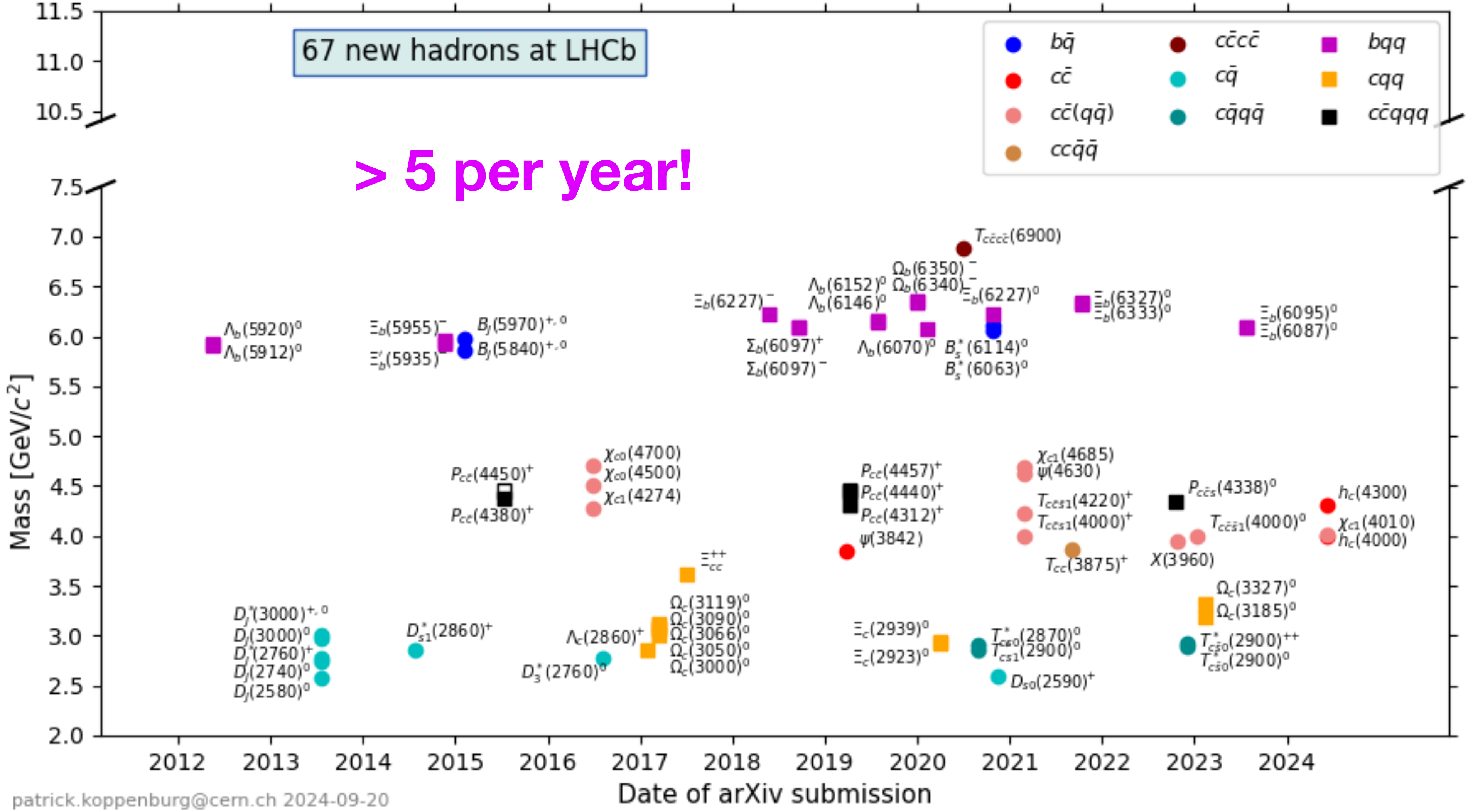
- LHCb benefits from its precision and the LHC's large *beauty* and *charm* production in the forward region

- To understand composite matter we study
  - **conventional** *and* **exotic** particles/resonances
  - **existing** *and* **new** particles/resonances

- Will focus on the most recent LHCb *b* and *c* spectroscopy results
  - Spanning across various LHCb physics specialties

- Link to all recent LHCb results

New hadrons



LHCb collaboration, P. Koppenburg, List of hadrons observed at the LHC, LHCb-FIGURE-2021-001 (2021) and updates (2024).

Today

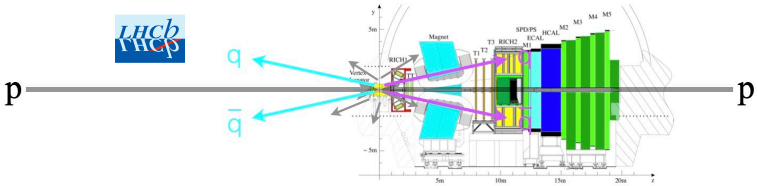
- Spin-parities of the $\Xi_c(3055)^{+(0)}$ baryons **arXiv:2409.05440** ***NEW!***

- Muonic Dalitz decays of χ_b mesons **arXiv:2408.05134, accepted to JHEP**
  Precise spectroscopy of hidden-beauty states ***NEW!***

- Exotic J/ψϕ resonances in diffractive processes **arXiv:2407.14301**

- Observation of new charmonium(-like) states **PRL 133 131902 (2024)** **PRL Editor's suggestion**

Run 1 (2011-2012) → 3/fb at 7-8 TeV
Run 2 (2015-2018) → 6/fb at 13 TeV



First determination of the

Spin-parities of the $\Xi_c(3055)^{+(0)}$ baryons

arXiv:2409.05440

NEW!

- $\Xi_c(3055)^{+(0)}$ observed for the first time by Babar (Belle) PhysRevD.77.012002 (2008) (PhysRevD.94.032002 (2016))

- Many proposed interpretations, including:
  - D-wave excitation with the spin-parity (J^P) assignments of $3/2^+$, $5/2^+$ or $7/2^+$ [PRD 78 (2008) 056005, Rept.Prog.Phys. 80 (2017), 076201]
  - Possible compatibility with the 2S excitation of the $\Xi_c(3F)$ or $\Xi_c(6F)$ states, with a possible J^P assignment of $1/2^+$ or $3/2^+$ [PRD 96 (2017) 114003]
  - Hadron molecular states are also proposed, favouring a J^P assignment of $1/2^-$ or $3/2^-$ [EPJC 79 (2019) 167]

- **Experimental determination of $\Xi c(3055)^{+(0)}$ J^P is important for charm baryon spectroscopy**

First determination of the

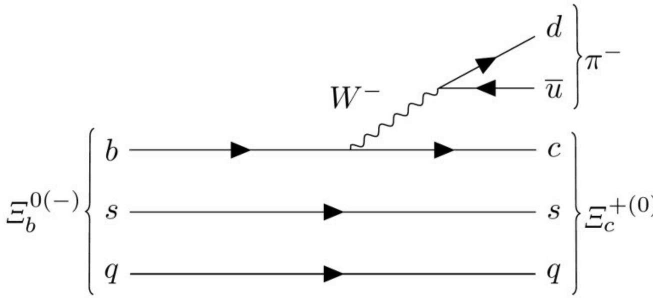
Spin-parities of the $\Xi_c(3055)^{+(0)}$ baryons

arXiv:2409.05440

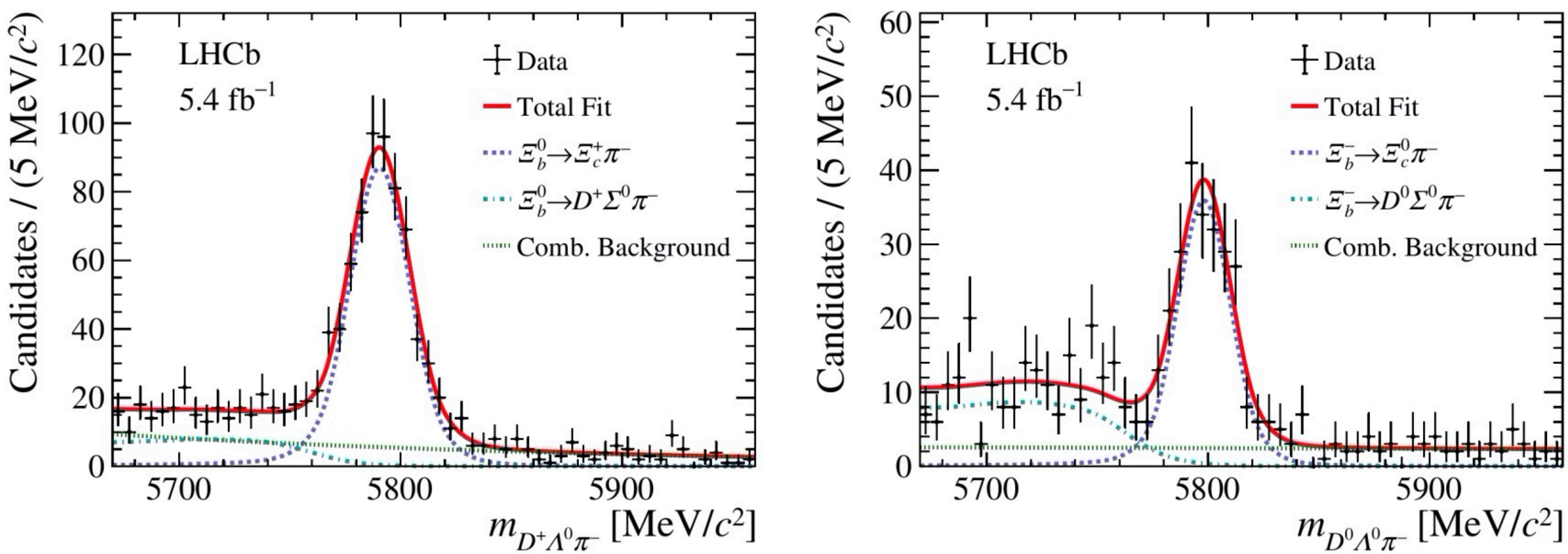
NEW!

- Study of $\Xi_c(3055)^{+(0)}$ based on 2016-2018 (Run 2) data (5.4 fb^{-1})

- $\Xi_c(3055)^{+(0)}$ studied in decay of $\Xi_b^{0(-)}$
  - $\Xi_b^{0(-)} \to \Xi_c^{**+(0)}\pi^-$
  - $\Xi_c^{**+(0)} \to D^{+(0)}\Lambda^0$, $D^{+(0)} \to K\pi\pi(K\pi)$, $\Lambda^0 \to p\pi^-$



- The total $\Xi_b^{0(-)}$ yields are 637 ± 31 (232 ± 19)



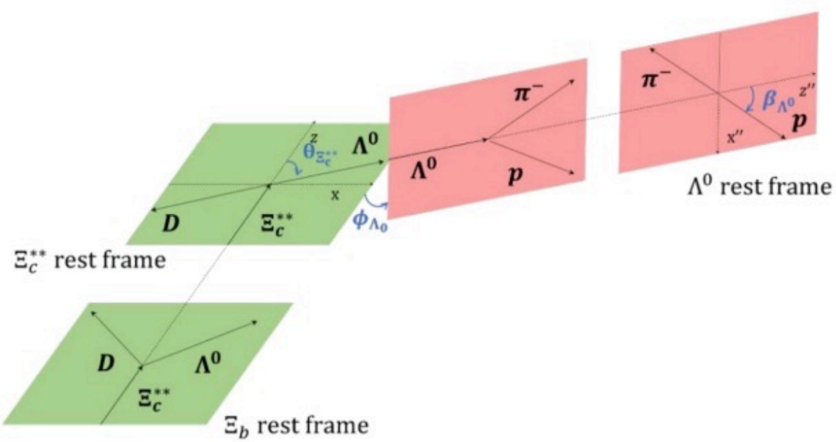
First determination of the

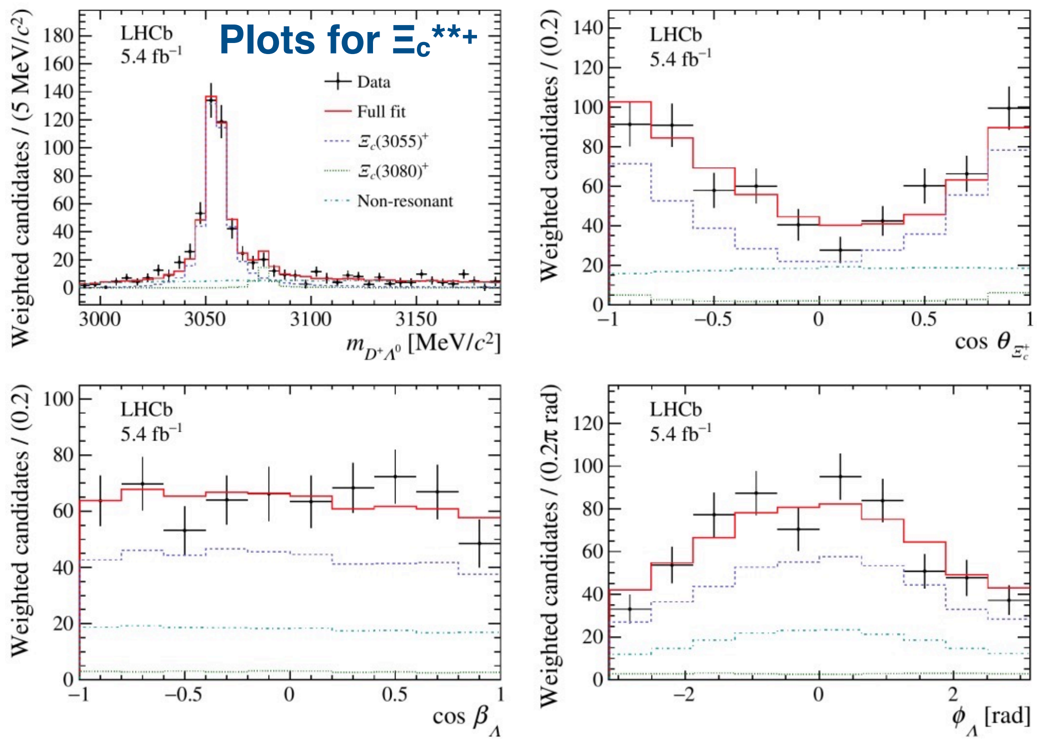
Spin-parities of the $\Xi_c(3055)^{+(0)}$ baryons

arXiv:2409.05440

NEW!

- Amplitude analyses of $\Xi_b^{0(-)} \to D^{+(0)}\Lambda^0\pi^-$ performed using helicity formalism
- $\Xi_c(3055)^{+(0)}$ [and $\Xi_c(3080)^{+(0)}$] resonances described by relativistic Breit-Wigner convoluted by Gaussian resolution functions
- Non-resonant component described by exponential functions
- Free parameters: $\Xi_c^{**+(0)}$ mass, $\Xi_c^{**+(0)}$ width, $\Xi_c^{**+(0)}$ helicity couplings
- Best fit for $\Xi_c(3055)^{+(0)}$ corresponds to **$J^P = 3/2^+$**
  - Other hypotheses for J^P rejected at >= 6.5σ(3.5σ)





First determination of the

Spin-parities of the $\Xi_c(3055)^{+(0)}$ baryons

arXiv:2409.05440

NEW!

- The masses and widths updated with a precision comparable to previous determinations

Quantity	$\Xi_c(3055)^+$	$\Xi_c(3055)^0$
$m\,[\mathrm{MeV}/c^2]$	$3054.52 \pm 0.36 \pm 0.17$	$3061.00 \pm 0.80 \pm 0.23$
$\Gamma\,[\mathrm{MeV}]$	$8.01 \pm 0.76 \pm 0.34$	$12.4 \pm 2.0 \pm 1.1$
α	$-0.92 \pm 0.10 \pm 0.05$	$-0.92 \pm 0.16 \pm 0.22$
$R_{\mathcal{B}}$	$0.045 \pm 0.023 \pm 0.006$	$0.14 \pm 0.06 \pm 0.04$

- First measurement of up-down asymmetries [α, relative difference between helicity state decay rates] in $\Xi_b^{0(-)} \to \Xi_c(3055)^{+(0)}\pi^-$ decays
    - Consistent with complete parity violation

- The first determination of the relative branching fractions [R_B] for $\Xi_c(3080)^{+(0)}$ and $\Xi_c(3055)^{+(0)}$

- Our measurement of $\Xi_c(3055)^{+(0)}$ $J^P=3/2^+$ rules out (disfavors) the hadron molecular state hypothesis

First observation of

Muonic Dalitz decays of χ_b mesons

arXiv:2408.05134, accepted to JHEP

NEW!

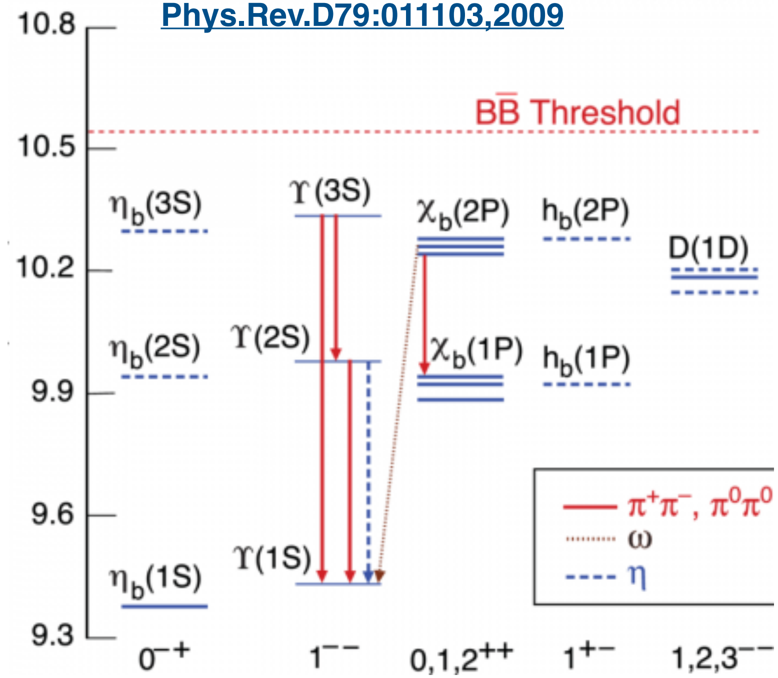
- Radiative transitions between different J^{PC} levels have been intensively studied in the past

- Previously, e^+e^- experiments relied on the photon energy of the Υ(2S) and Υ(3S) to χ_b state transitions

  BaBar, Phys. Rev. D90 (2014) 112010. arXiv:1410.3902
  CLEO, Phys. Rev. Lett. 94 (2005) 032001, arXiv:hep-ex/0411068.
  CUSB, Phys. Rev. D46 (1992) 1928
  Crystal Ball, Phys. Rev. D34 (1986) 2611
  ARGUS, Phys. Lett. B160 (1985) 331

- LHCb for the first time reports the muonic Dalitz decays from the χ_b levels to the Υ(1S)
  - These decays are used to measure the masses of these states.
    - Reduced systematics due to all-muon final state

Example $b\bar{b}$ transitions
Phys.Rev.D79:011103,2009

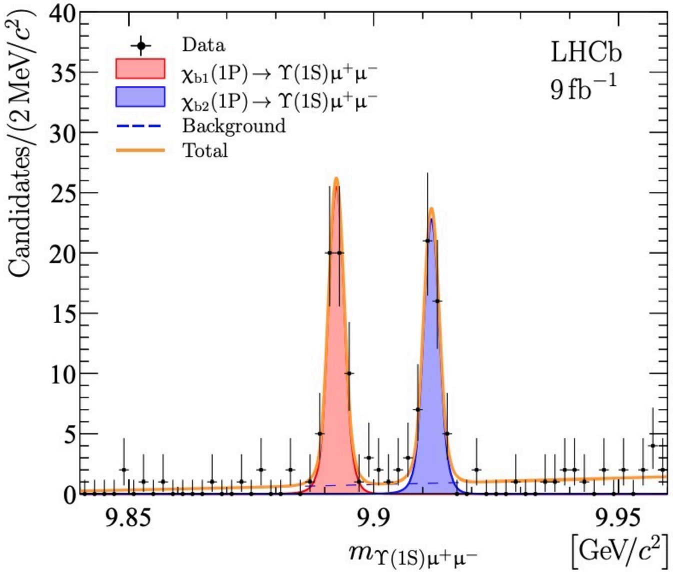


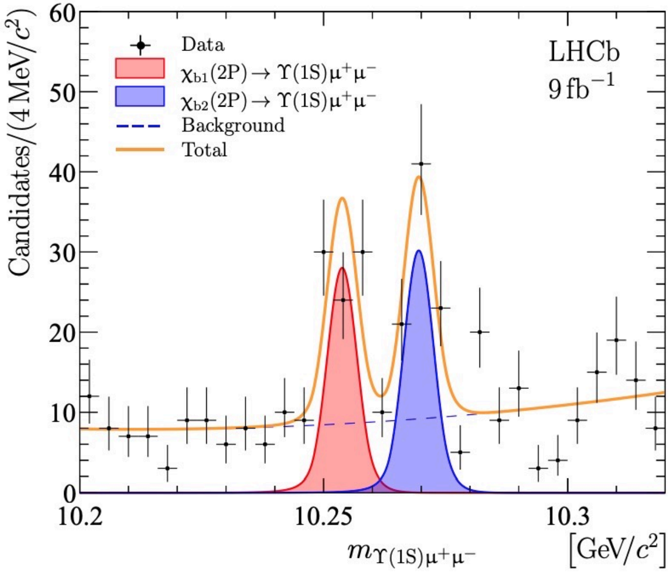
First observation of [arXiv:2408.05134](), accepted to JHEP

Muonic Dalitz decays of χ_b mesons

NEW!

- Full Run 1 & Run 2 datasets. The results are competitive.
  - world best for $\chi_b(1P)$ - and in agreement with the world averages.





$$m_{\chi_{b1}(1P)} = 9\,892.50 \pm 0.26 \pm 0.10 \pm 0.10\,\mathrm{MeV}/c^2$$
$$m_{\chi_{b2}(1P)} = 9\,911.92 \pm 0.29 \pm 0.11 \pm 0.10\,\mathrm{MeV}/c^2$$
$$m_{\chi_{b1}(2P)} = 10\,253.97 \pm 0.75 \pm 0.22 \pm 0.09\,\mathrm{MeV}/c^2$$
$$m_{\chi_{b2}(2P)} = 10\,269.67 \pm 0.67 \pm 0.22 \pm 0.09\,\mathrm{MeV}/c^2$$

systematics negligible

$$m_{\chi_{b2}(1P)} - m_{\chi_{b1}(1P)} = 19.4 \pm 0.4\,\mathrm{MeV}/c^2$$
$$m_{\chi_{b2}(2P)} - m_{\chi_{b1}(2P)} = 15.7 \pm 1.0\,\mathrm{MeV}/c^2$$

BaBar

$19.01 \pm 0.24\,\mathrm{MeV}/c^2$

$13.04 \pm 0.26\,\mathrm{MeV}/c^2$

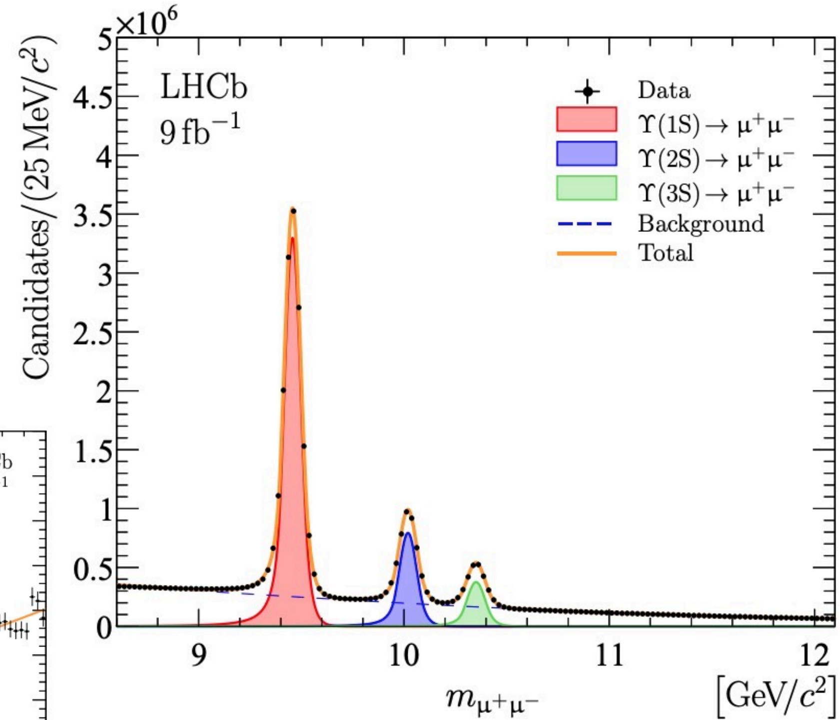
Phys. Rev. D90 (2014) 112010

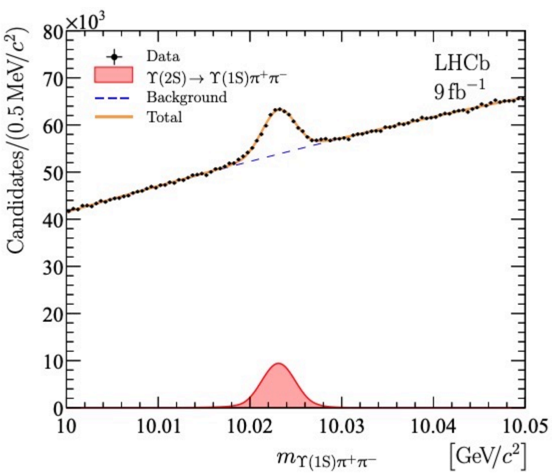
arXiv:2408.05134, accepted to JHEP

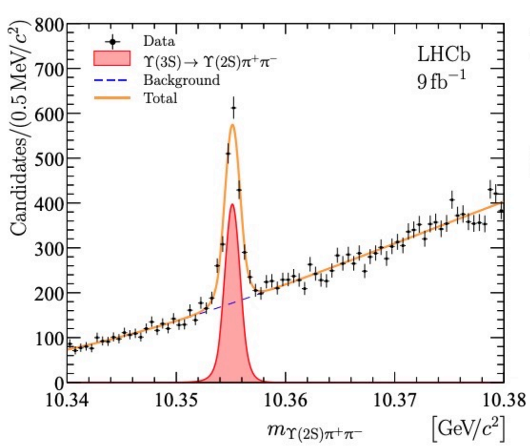
Precise spectroscopy of hidden-beauty states

NEW!

- Combine Υ(nS) → $\mu^+\mu^-$ and Υ([n]S) → Υ([n-1]S) $\pi^+\pi^-$ w/ Υ([n-1]S) mass constraint to get precise, competitive measurements of mass and mass splittings







$$m_{\Upsilon(1S)} = 9\,460.37 \pm 0.01 \pm 2.85\,\mathrm{MeV}/c^2$$

$\mu^+\mu^-$ only

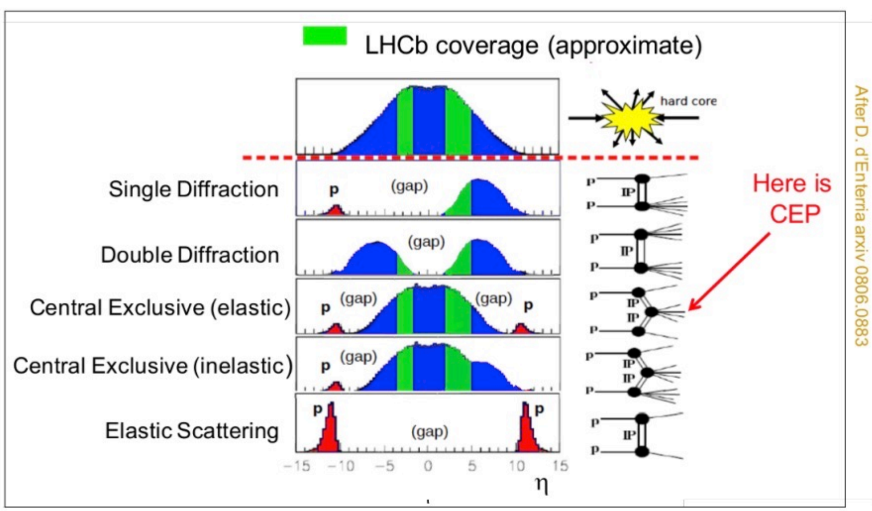
$$m_{\Upsilon(2S)} - m_{\Upsilon(1S)} = 562.84 \pm 0.02 \pm 0.13\,\mathrm{MeV}/c^2$$
$$m_{\Upsilon(3S)} - m_{\Upsilon(2S)} = 331.86 \pm 0.03 \pm 0.05\,\mathrm{MeV}/c^2$$

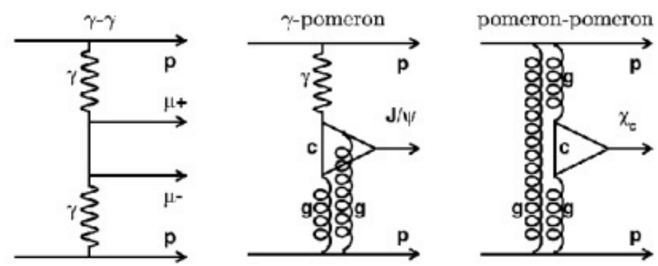
$\mu^+\mu^-$ and Υ([n-1]S) $\pi^+\pi^-$

arXiv:2407.14301

Exotic J/ψϕ resonances in diffractive processes

- Central (Exclusive) Diffractive Production can be studied at LHCb
- Colourless objects in QCD, Very low p_T objects, Clean expt. environment
- What do we look for?
  - $pp \rightarrow p + X + p$ (rapidity gaps and protons intact)
  - X in this case is J/ψϕ, look for this and no additional detected activity
  - HeRSCheL (JINST 13 (2018) P04017) gives *p* dissociation information
- Rich Physics: Photon-Pomeron, Double-Pomeron, Photoproduction, Glueballs, Exotica





✓Experimentally clean even @LHC

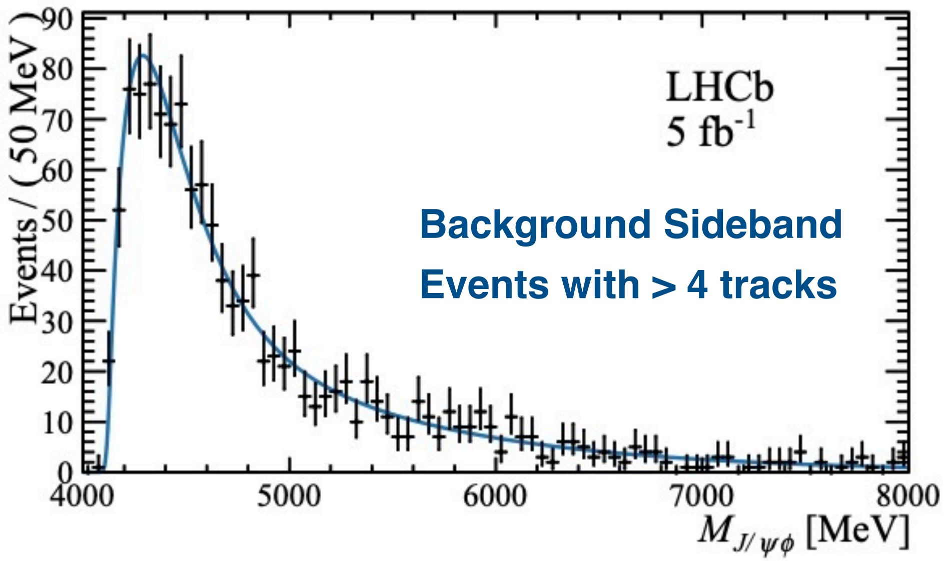
✓Spin-parity option narrowed down

✘Much smaller rate

arXiv:2407.14301

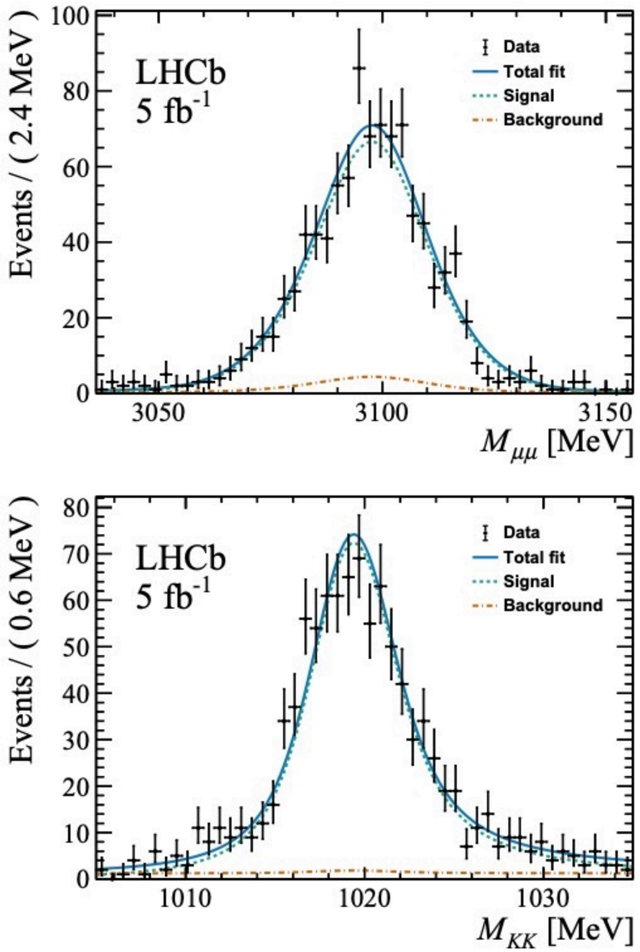
Exotic J/ψϕ resonances in diffractive processes

- Analysis performed with Run 2 data



- HeRSCheL high-rapidity shower counters help us determine if there is any proton dissociation (despite LHCb not seeing it); determines at least 69% of events have at least one proton dissociating (so at most 31% are elastic CEP)

Signal

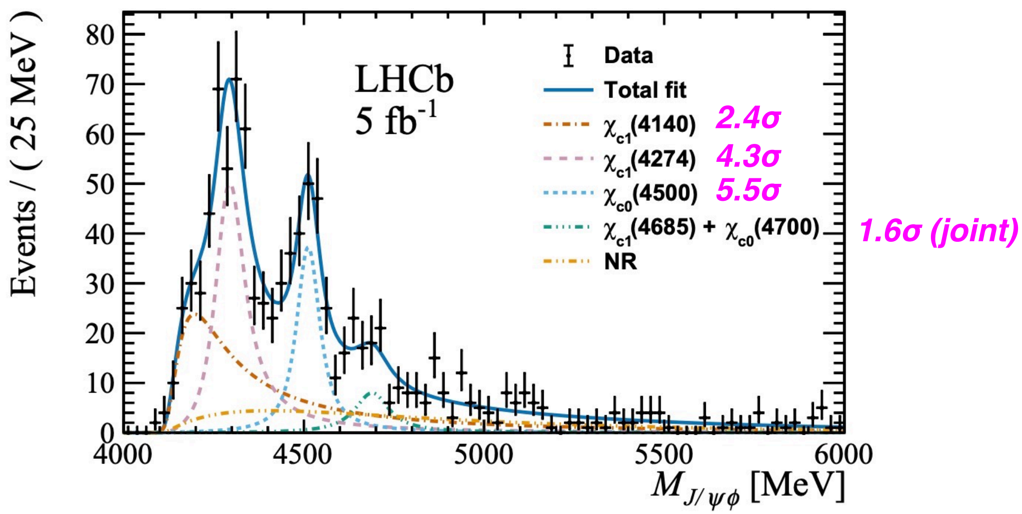


After all vetos (4 tracks only)

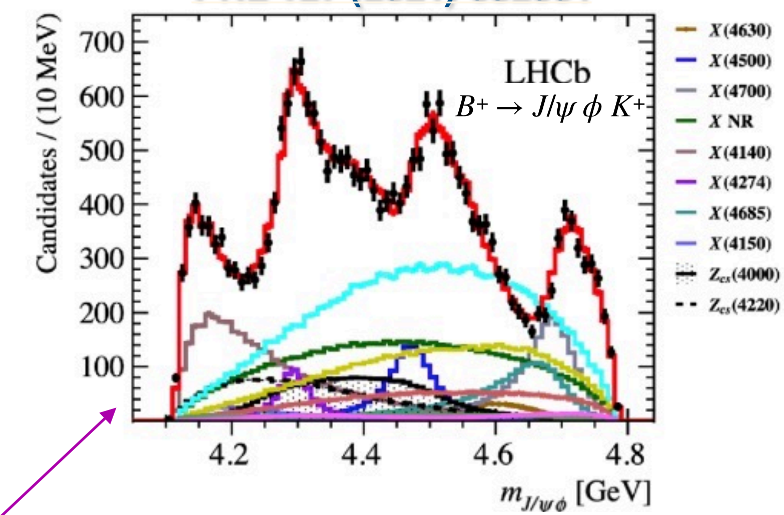
arXiv:2407.14301

Exotic J/ψϕ resonances in diffractive processes

- First exotic measurement in Central Exclusive Production



PRL 127 (2021) 082001



Mass & width measurement

Now find slightly higher mass of X(4500)

Parameter [MeV]	Current analysis	Ref. [13]
$M_{\chi_{c1}(4274)}$	$4298 \pm 6 \pm 9$	$4294 \pm 4^{+3}_{-6}$
$\Gamma_{\chi_{c1}(4274)}$	$92^{+22}_{-18} \pm 57$	$53 \pm 5 \pm 5$
$M_{\chi_{c0}(4500)}$	$4512.5^{+6.0}_{-6.2} \pm 3.0$	$4474 \pm 3 \pm 3$
$\Gamma_{\chi_{c0}(4500)}$	$65^{+20}_{-16} \pm 32$	$77 \pm 6^{+10}_{-8}$

Cross sections also measured

$$\sigma_{\chi_{c1}(4140)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4140)} = (0.80 \pm 0.15 \pm 0.28)\ \text{pb},$$
$$\sigma_{\chi_{c1}(4274)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4274)} = (0.73 \pm 0.08 \pm 0.17)\ \text{pb},$$
$$\sigma_{\chi_{c0}(4500)} \times \mathcal{B}_{\rm eff}^{\chi_{c0}(4500)} = (0.42^{+0.09}_{-0.08} \pm 0.06)\ \text{pb},$$
$$\sigma_{\chi_{c1}(4685)+\chi_{c0}(4700)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4685)+\chi_{c0}(4700)} = (0.14^{+0.07}_{-0.06} \pm 0.06)\ \text{pb},$$
$$\sigma_{\rm NR} \times \mathcal{B}_{\rm eff}^{\rm NR} = (0.43^{+0.24}_{-0.18} \pm 0.20)\ \text{pb},$$

PRL 133 131902 (2024)

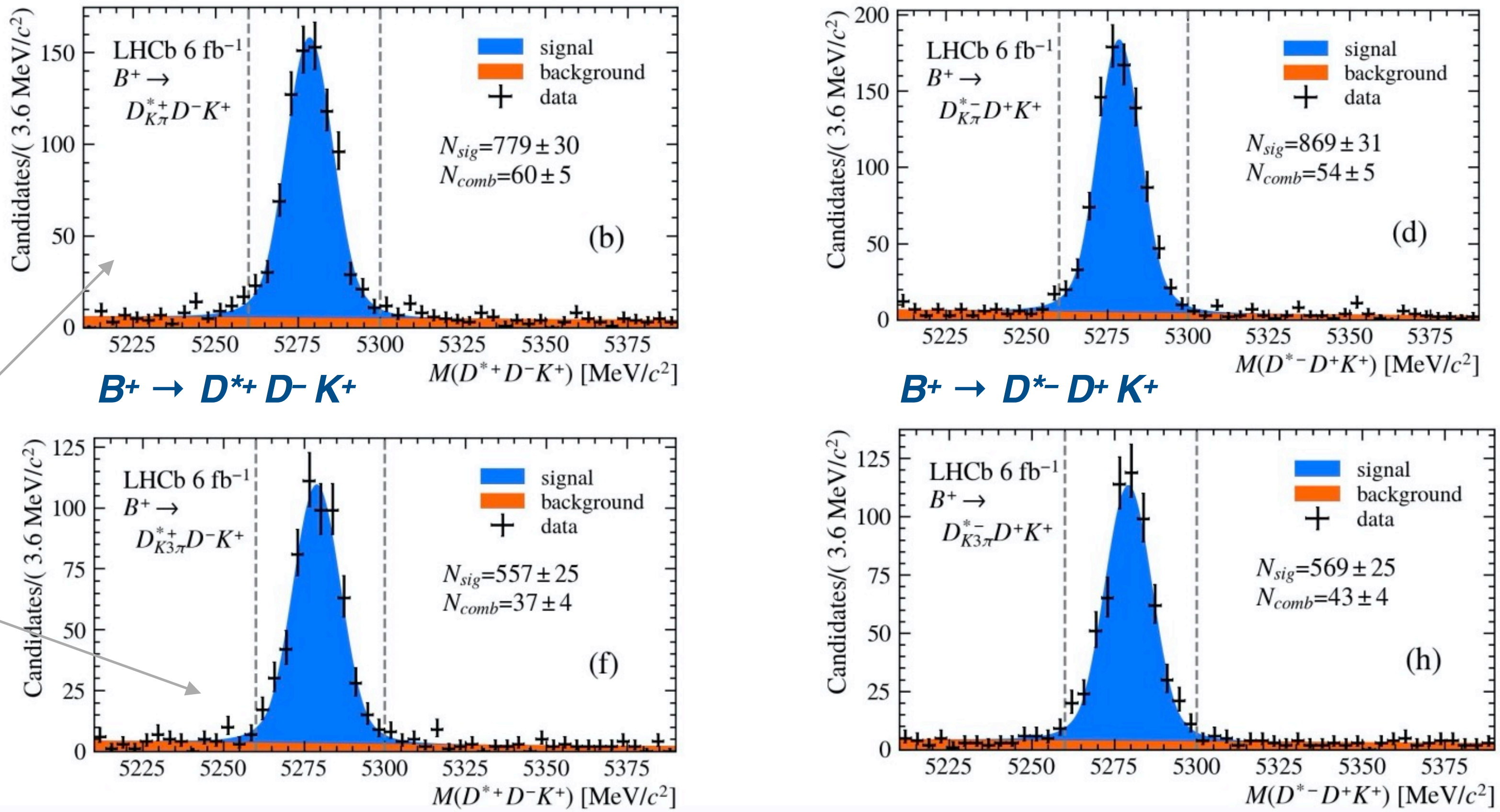
Observation of new charmonium(-like) states

- Simultaneous analysis of the $B^+ \to D^{*+} D^- K^+$ and $B^+ \to D^{*-} D^+ K^+$ decays
- Amplitudes for $B^+ \to (D^{*+}D^-)_R K^+$ and $B^+ \to (D^{*-}D^+)_R K^+$ linked by C-parity.
  - Allows determination of the C-parities of the R resonances.

Run 1&2 data (only Run 2 shown here)

$D^{*+} \to D^0 \pi^+$

D^0 reconstructed in $K\pi$ and $K\pi\pi\pi$ modes



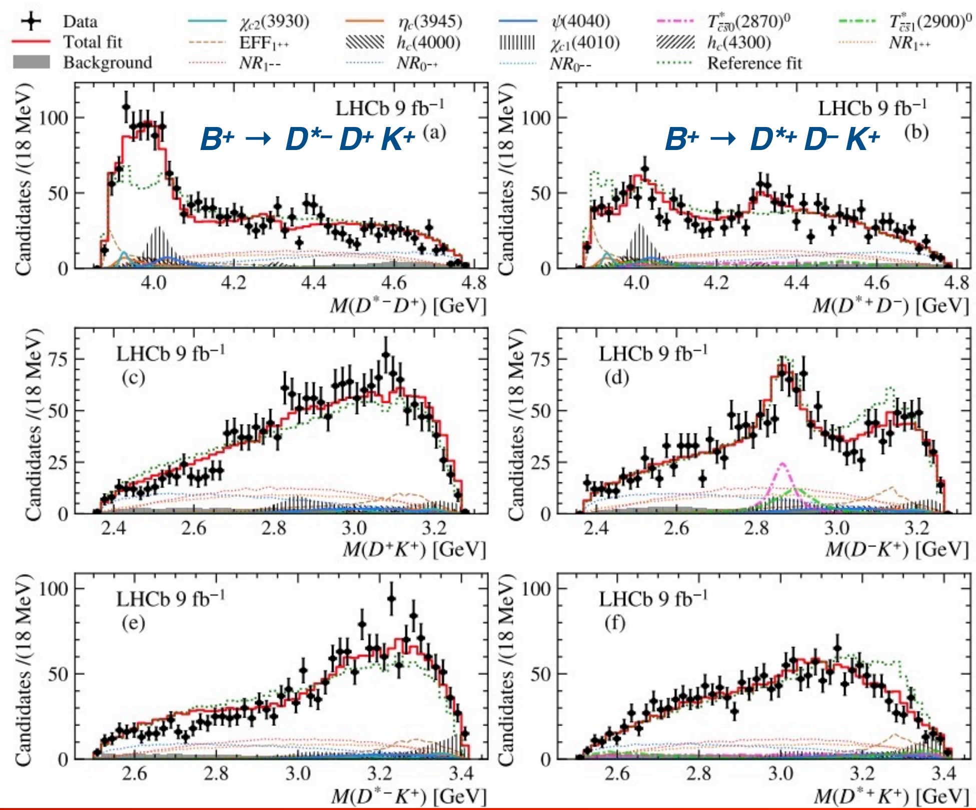
PRL 133 131902 (2024)

Observation of new charmonium(-like) states

- Multiple contributions needed in the $D^{*\pm} D^{\mp}$ spectra to describe the data:
  - Four non-resonant: 1^{++}, 0^{++}, 1^{--}, 0^{--},
  - $\chi_{c2}(3930)$, $\psi(4040)$ with fixed parameters,
  - $\eta_c(3945)$, $h_c(4000)$, $\chi_c(4010)$, $h_c(4300)$, with statistical significances of 10σ, 9.1σ, 16σ and 6.4σ.

$\eta_c(3945)$ compatible with X(3940)
PhysRevLett.98.082001
PhysRevLett.100.202001

- Fit includes the $T^{*}_{cs0}(2870)^0$, $T^{*}_{cs1}(2900)^0$ states
  - first found in $B^+ \to D^+ D^- K^+$ decays
    PhysRevLett.125.242001
    PhysRevD.102.112003
  - Resonances confirmed with statistical significances of 11σ, 9.2σ, respectively



PRL 133 131902 (2024)

Observation of new charmonium(-like) states

- $J^P = 1^+$ states are the main contribution in the $D^{*\pm} D^{\mp}$ mass spectra
- J^{PC} values for $\eta_c(3945)$, $h_c(4000)$, $\chi_c(4010)$, $h_c(4300)$: 0^{-+}, 1^{+-}, 1^{++}, 1^{+-}
  - Interferences due to different C-parities among states of same J^P result in different patterns in $M(D^{*+} D^{-})$ and $M(D^{*-} D^{+})$.

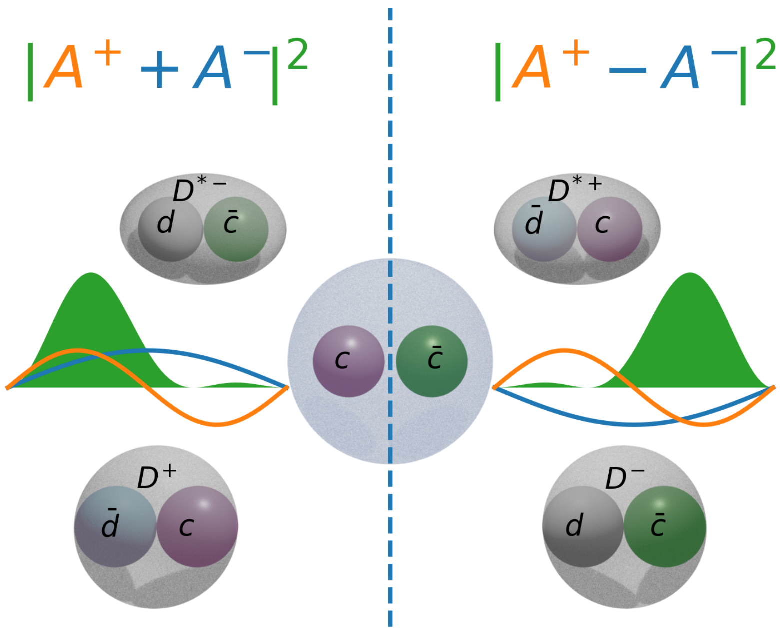
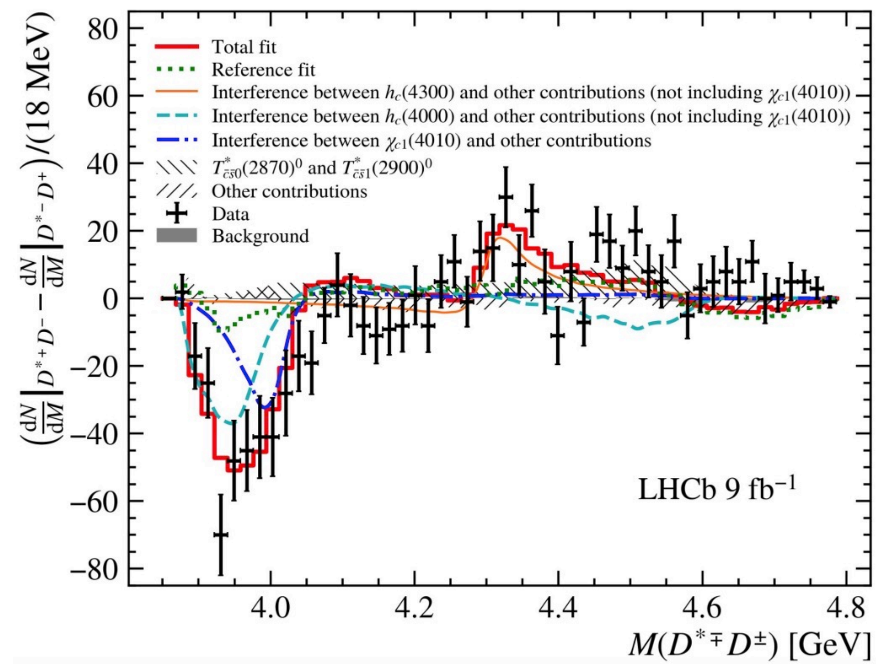


diagram for PRL Editor's suggestion



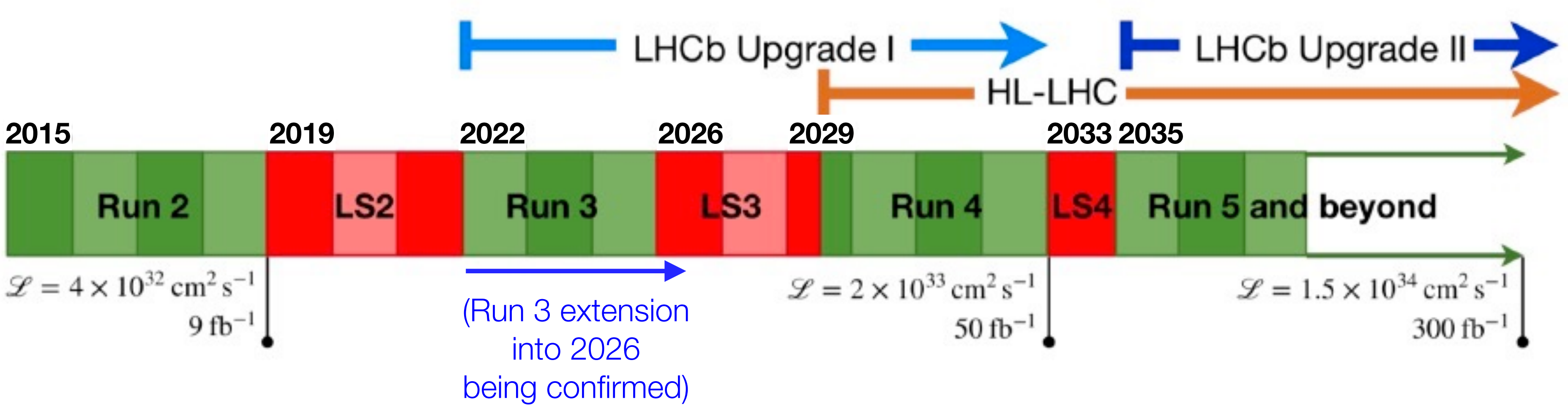
PRL 133 131902 (2024)

Observation of new charmonium(-like) states

- $J^P = 1^+$ states are the main contribution in the $D^{*\pm} D^{\mp}$ mass spectra
- J^{PC} values for $\eta_c(3945)$, $h_c(4000)$, $\chi_c(4010)$, $h_c(4300)$: 0^{-+}, 1^{+-}, 1^{++}, 1^{+-}

New creatures found for the (composite) particle zoo!

Spectroscopy Future Prospects

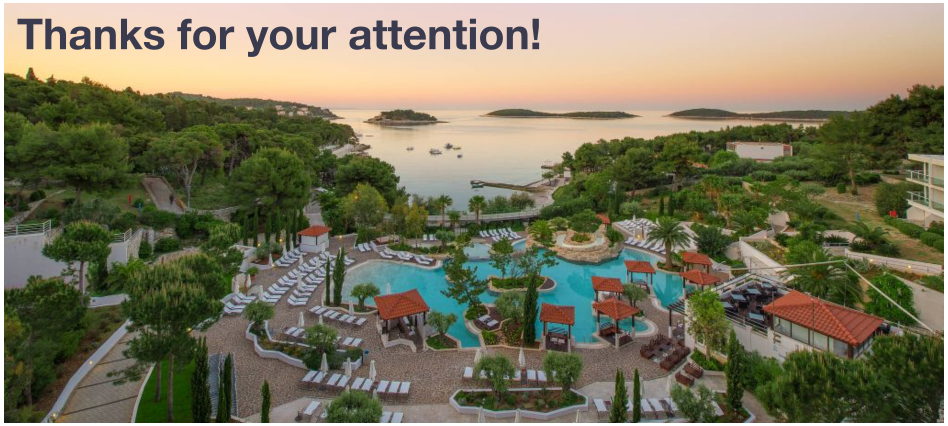


- All analyses shown so far use Run 1 and/or Run 2 data (9 fb^{-1} total)
- LHCb on target for > 7 fb^{-1} in Run 3 (expect > 23 fb^{-1} Run 1-3)
- Expectations:
  - Upgrade I (Run 1-4, 50 fb^{-1})
  - Upgrade II (Run 1-6, 300 fb^{-1})
- Much more data coming… increased precisions
  Pace of 5 more new particles per year squarely in realm of possibility…

Conclusion

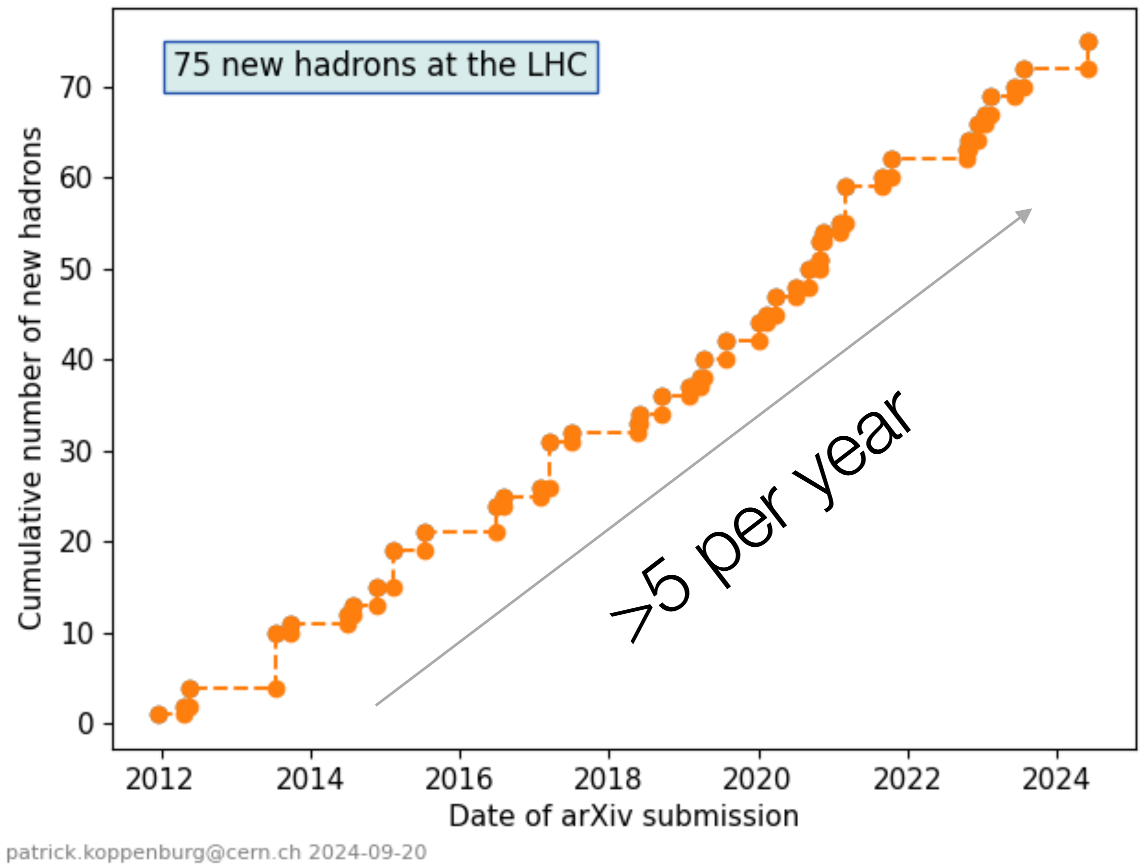
- Our detector has worked “like a charm” and seen many “beautiful things”
  - LHCb in its first two runs has published many beauty and charm spectroscopy results, often providing unexpected results.
  - LHCb is continuing to exploit its unique data set to investigate hadron decays. Several Run 1 & Run 2 analyses have approached final stages.

- New analyses are on the horizon; datasets at LHCb are becoming vast.
  - Expect LHCb spectroscopy results from Run 3(+) in the near(+) future!



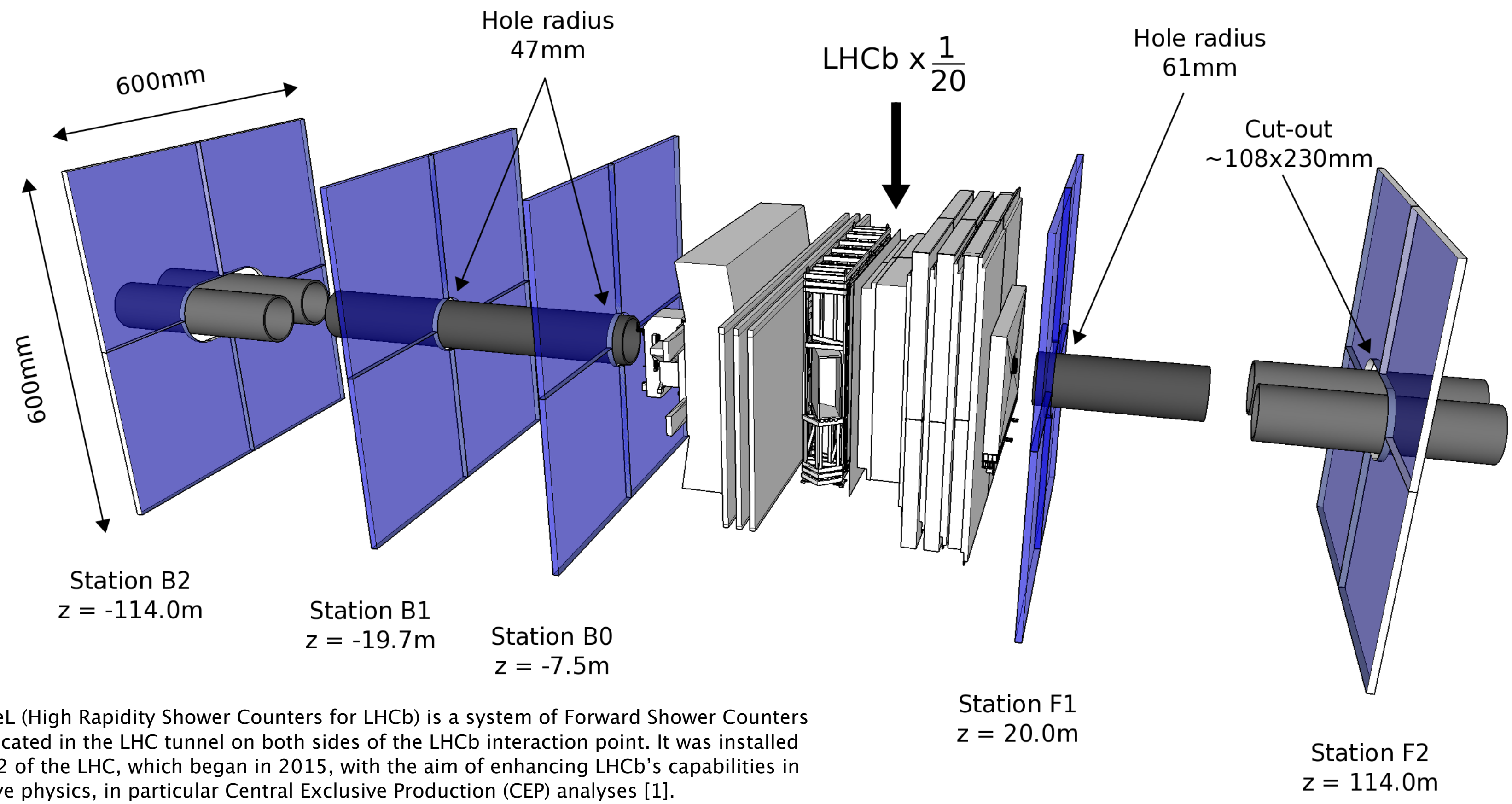
Additional Slides

Overview



LHCb collaboration, P. Koppenburg, List of hadrons observed at the LHC, LHCb-FIGURE-2021-001 (2021) and updates (2024).

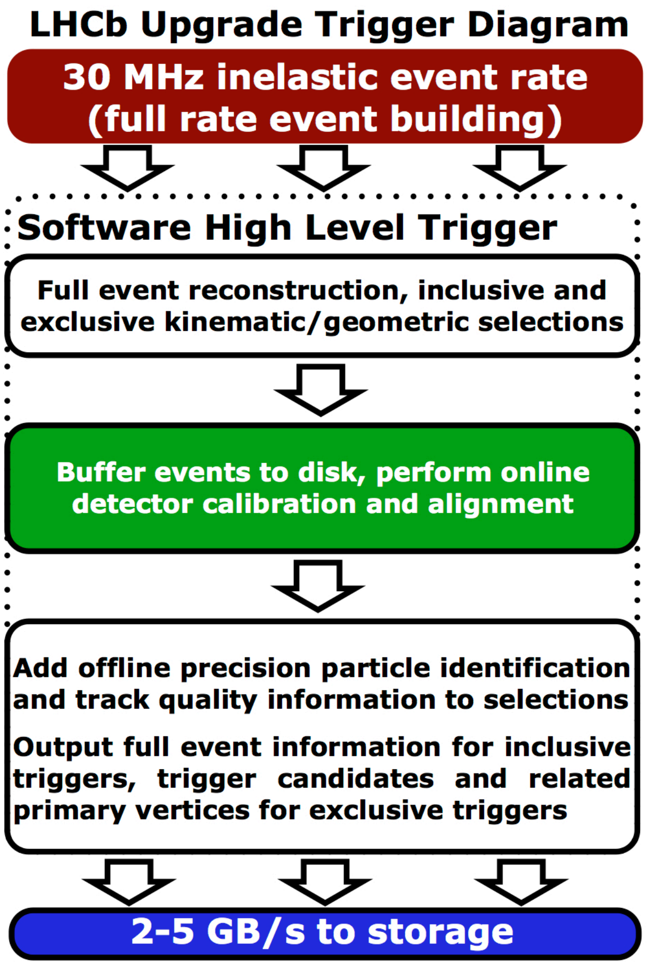
HeRSChEL



HeRSCheL (High Rapidity Shower Counters for LHCb) is a system of Forward Shower Counters (FSCs) located in the LHC tunnel on both sides of the LHCb interaction point. It was installed for Run 2 of the LHC, which began in 2015, with the aim of enhancing LHCb's capabilities in diffractive physics, in particular Central Exclusive Production (CEP) analyses [1].
Each FSC comprises a quadrant of scintillator planes equipped with PMTs, which are read out synchronously with the sub-detectors of the LHCb spectrometer. The planes are situated close to the beampipe and detect showers induced by very forward particles interacting in the beampipe or other machine elements [2, 3]. In this manner HeRSCheL provides sensitivity to activity at higher rapidities than is available from the other sub-detectors of the experiment. This increased acceptance will be valuable in the classification of different production processes in LHC collisions, for example the isolation of CEP candidates.

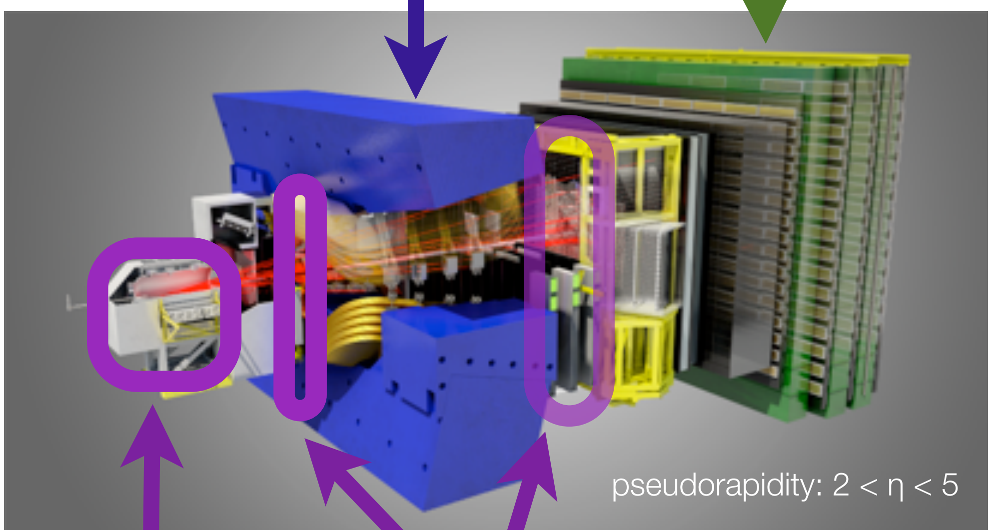
Trigger evolution for Run 3

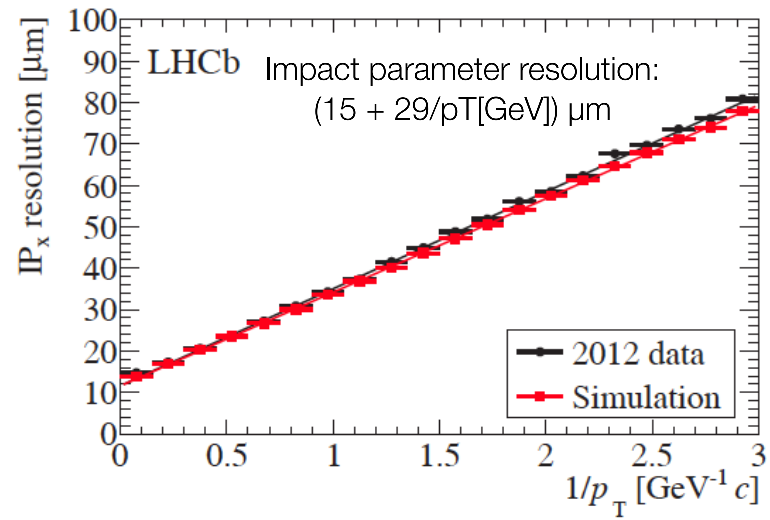
- LHCb has removed the Level-0 Hardware Trigger. In Run 3 we readout the full detector in every event (30 MHz).
- Run 1 + 2 hardware approach was based on simple detector signals to reduce rate to 1 MHz before events reach software trigger.
- Software trigger approach enables efficiency gain – typically factor between 3 and 10 for Heavy Flavour channels.
- First stage of software trigger is GPU based.
- With relatively little additional integrated luminosity, can get very large samples compared to existing datasets.



LHCb Experiment: Tracking

- Accurate decay time resolution from our vertex locator (VELO)
- High muon reconstruction efficiency from muon stations
- Good momentum resolution from tracking stations, $\Delta p/p$ = 0.5% — 1.0%

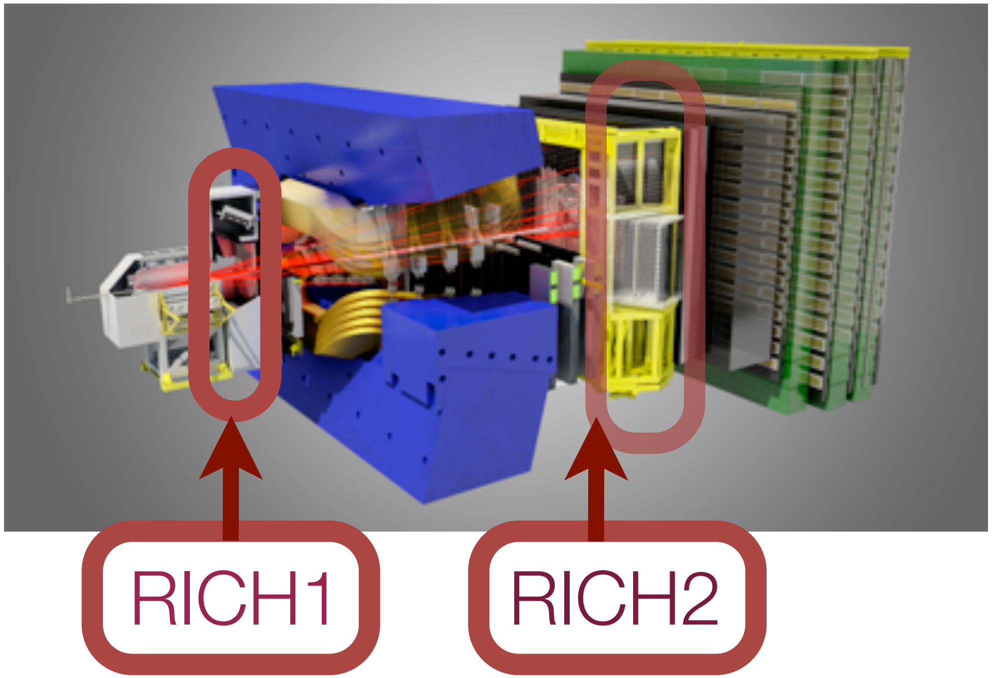


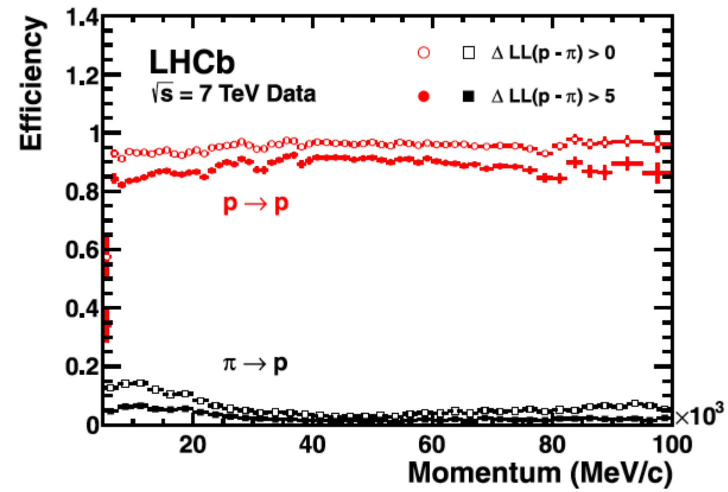


Int. J. of Mod. Phys A**30** 1530022 (2015)

LHCb Experiment: Particle ID and Trigger

- p/K/π separation provided by Ring Imaging Cherenkov (**RICH**) detectors





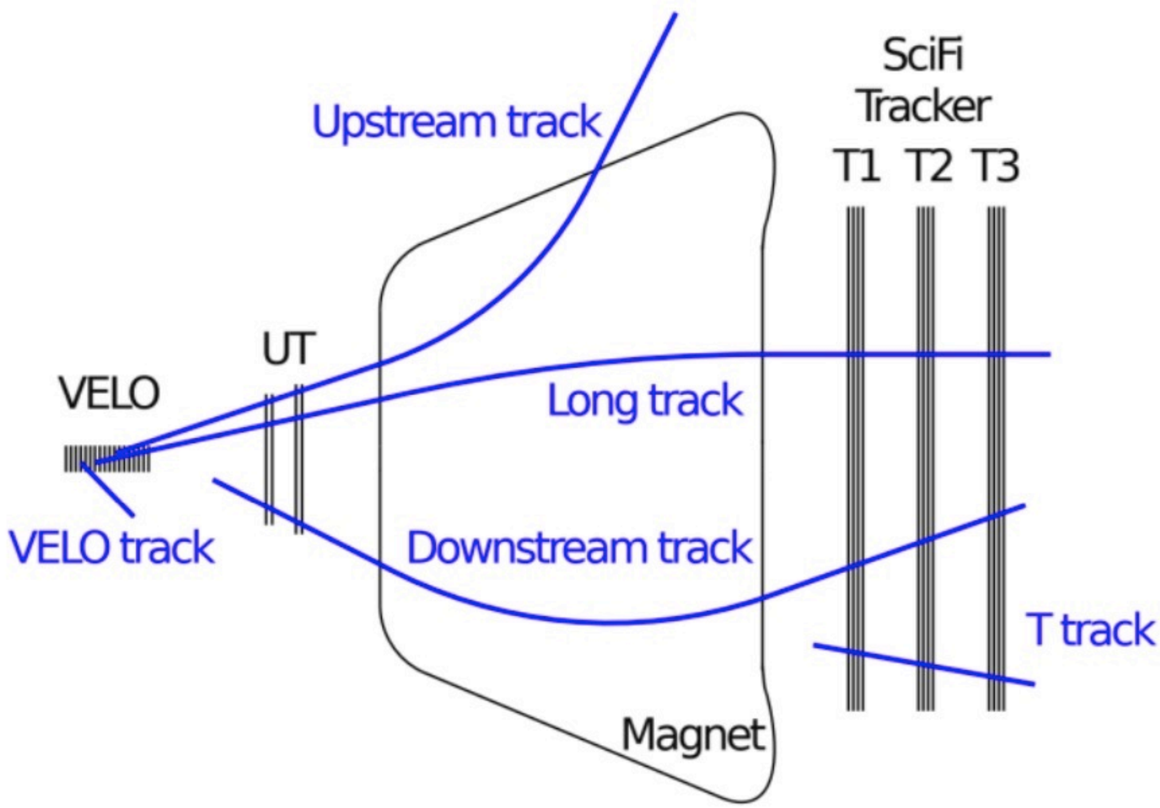
Eur. Phys. J. C**73** 2431 (2013)

- The ability to identify particles at LHCb is crucial to many of our analyses.
- Excellent trigger allows us to trigger on tracks with lower pT

First determination of the

Spin-parities of the $\Xi_c(3055)^{+(0)}$ baryons

arXiv:2409.05440
NEW!



Lambda candidates constructed from two Long tracks or two Downstream tracks

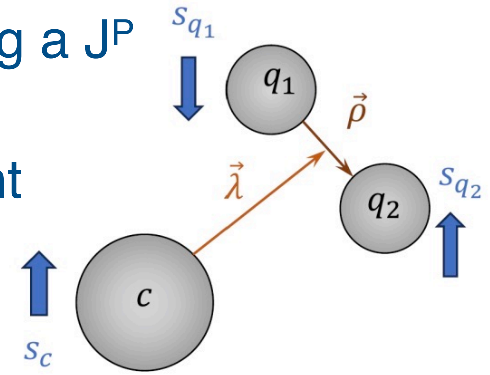
First determination of the

Spin-parities of the $\Xi_c(3055)^{+(0)}$ baryons

arXiv:2409.05440

NEW!

- $\Xi_c(3055)^{+(0)}$ observed for the first time by Babar (Belle) Phys.Rev.D77:012002,2008 (PhysRevD.94.032002)
- Excitation modes of $\Xi_c(3055)^{+(0)}$ extensively studied in literature
  - Excitation can happen between heavy quark and diquark (λ-mode) or between two light quarks (ρ-mode)
- Many proposed interpretations, including:
  - D-wave excitation with the spin-parity (J^P) assignments of $3/2^+$, $5/2^+$ or $7/2^+$ [PRD 78 (2008) 056005]
  - Possible compatibility with the 2S excitation of the Ξ_c(3F) or Ξ_c(6F) states, with a possible J^P assignment of $1/2^+$ or $3/2^+$ [PRD 96 (2017) 114003]
  - Hadron molecular states are also proposed, favouring a J^P assignment of $1/2^-$ or $3/2^-$ [EPJC 79 (2019) 167]
- Experimental determination of $\Xi_c(3055)^{+(0)}$ J^P is important for charm baryon spectroscopy



First determination of the

Spin-parities of the $\Xi_c(3055)^{+(0)}$ baryons

arXiv:2409.05440

NEW!

- Amplitude analysis performed using helicity formalism
- Resonances described by relativistic Breit-Wigner convoluted by Gaussian resolution functions
- Non-resonant component described by exponential functions
- Free parameters:
  - $\Xi_c^{**+(0)}$ mass
  - $\Xi_c^{**+(0)}$ width
  - $\Xi_c^{**+(0)}$ helicity couplings
- Best fit corresponds to **J^P = 3/2$^+$**
  - Other hypotheses rejected at levels shown in the table.

$J^P_{\Xi_c(3055)^{+(0)}}$	n_σ
$1/2^-$	12.9 (6.5)
$1/2^+$	11.0 (5.5)
$3/2^-$	7.3 (3.5)
$5/2^-$	6.5 (4.8)
$5/2^+$	9.8 (4.8)
$7/2^-$	10.7 (6.2)
$7/2^+$	10.9 (6.0)

First determination of the

Spin-parities of the $\Xi_c(3055)^{+(0)}$ baryons

arXiv:2409.05440

NEW!

$\Xi_c(3055)^{+(0)}$ measurement: helicity angles

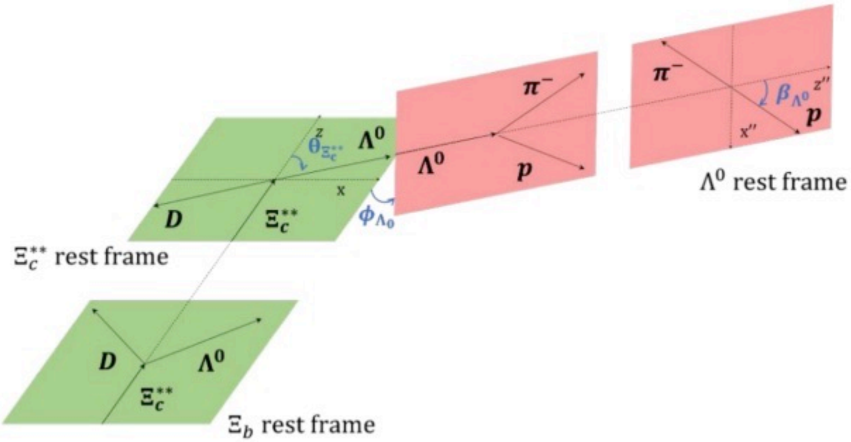
- $\Xi_b \to \Xi_c^{**}\pi^-$ $\quad A^{\Xi_b\to\Xi_c\pi^-}_{\lambda_{\Xi_b},\lambda_{\Xi_c},\lambda_\pi} = H^{\Xi_b\to\Xi_c\pi^-}_{\lambda_{\Xi_c}}\,\delta_{\lambda_{\Xi_b},\lambda_{\Xi_c}}$
- $\Xi_c^{**} \to D\Lambda$ $\quad A^{\Xi_c\to D\Lambda}_{\lambda_{\Xi_c},\lambda_D,\lambda_\Lambda} = H^{\Xi_c\to D\Lambda}_{\lambda_\Lambda}\,d^{J_{\Xi_c}}_{\lambda_{\Xi_c},\lambda_\Lambda}(\theta)$
- $\Lambda \to p\pi^-$ $\quad A^{\Lambda\to p\pi^-}_{\lambda_\Lambda,\lambda_p,\lambda_\pi} = H^{\Lambda\to p\pi^-}_{\lambda_p}\,D^{j_\Lambda}_{\lambda_\Lambda,\lambda_p}(\phi,\beta,0)$

Floated for each resonance

Strong decay, only phase term:

$\eta^{P_{\Xi_c}}(-1)^{J_{\Xi_c}+1/2}$

Fixed from input



First determination of the

Spin-parities of the $\Xi_c(3055)^{+(0)}$ baryons

arXiv:2409.05440

NEW!

$\Xi_c(3055)^{+(0)}$ measurement: systematic unc.

Source	σ_m [MeV/c^2]	σ_Γ [MeV]	σ_α	$\sigma_{R_\mathcal{B}}$
Mass input	±0.05	–	–	–
Momentum scale	±0.01	–	–	–
Detector resolution	±0.00	±0.07	±0.00	±0.000
MC sample size	±0.15	±0.30	±0.02	±0.002
Trigger efficiency	±0.01	±0.03	±0.02	±0.000
Λ categories	±0.03	±0.04	±0.01	±0.002
Ξ_b^0 Mass fit	±0.03	±0.13	±0.01	±0.001
Angular momentum	±0.00	±0.00	±0.04	±0.002
$\Gamma_{\Xi_c(3080)}$	±0.01	±0.01	±0.00	±0.003
$m_{\Xi_c(3080)}$	±0.00	±0.02	±0.00	±0.000
Clone tracks	±0.02	±0.03	±0.01	±0.003
Total	±0.17	±0.34	±0.05	±0.006

PRL 133 131902 (2024)

Observation of new charmonium(-like) states

- Amplitudes for $B^+ \to R(D^{*+} D^-) K^+$ and $B^+ \to R(D^{*-} D^+) K^+$ linked by *C*-parity.
- Total amplitude: coherent sum of resonant and non-resonant components in all channels.

$$\mathcal{A}(x) = \frac{1+d}{2}\left\{\sum_{j\in R(D^{*\pm}D^{\mp})} c_j A_j(x) + \sum_{k\in R(D^{*-}K^+,\ D^+K^+)} c_k A_k(x)\right\} + \frac{1-d}{2}\left\{\sum_{j\in R(D^{*\pm}D^{\mp})} C_j \times c_j A_j(x) + \sum_{l\in R(D^{*+}K^+,\ D^-K^+)} c_l A_l(x)\right\},$$

- Both S-wave and D-wave amplitudes contribute significantly to $R \to D^{*\pm} D^{\mp}$ decays for $J^P = 1^+$.
- Line shapes for these partial waves:

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

PRL 133 131902 (2024)

Observation of new charmonium(-like) states

Table 1: Resonant and nonresonant components included in the baseline fit and their spin parities, fit fractions and product branching fractions ($\mathcal{B}(B^+ \to RC) \times \mathcal{B}(R \to AB)$), where A, B, C are the three final-state particles. To obtain the branching fractions including both $R \to D^{*+}D^-$ and $R \to D^{*-}D^+$, the values in the table should be multiplied by a factor of two. The first uncertainties are statistical, estimated with a bootstrap method [32], the second are systematic and and the third are from the uncertainty of the $B^+ \to D^{*+}D^-K^+$ branching fraction. The masses and widths of the resonances marked with the † symbol are fixed to their PDG values [6].

Component	$J^{P(C)}$	Fit fraction [%] $B^+ \to D^{*+}D^-K^+$	Fit fraction [%] $B^+ \to D^{*-}D^+K^+$	Branching fraction [10^{-4}]
$\text{EFF}_{1^{++}}$	1^{++}	$10.9\,^{+2.3}_{-1.2}\,^{+1.6}_{-2.1}$	$9.9\,^{+2.1}_{-1.0}\,^{+1.4}_{-1.9}$	$0.74\,^{+0.16}_{-0.08}\,^{+0.11}_{-0.14} \pm 0.07$
$\eta_c(3945)$	0^{-+}	$3.4\,^{+0.5}_{-1.0}\,^{+1.9}_{-0.7}$	$3.1\,^{+0.5}_{-0.9}\,^{+1.7}_{-0.6}$	$0.23\,^{+0.04}_{-0.07}\,^{+0.13}_{-0.05} \pm 0.02$
$\chi_{c2}(3930)^\dagger$	2^{++}	$1.8\,^{+0.5}_{-0.4}\,^{+0.6}_{-1.2}$	$1.7\,^{+0.5}_{-0.4}\,^{+0.6}_{-1.1}$	$0.12\,^{+0.03}_{-0.03}\,^{+0.04}_{-0.08} \pm 0.01$
$h_c(4000)$	1^{+-}	$5.1\,^{+1.0}_{-0.8}\,^{+1.5}_{-0.8}$	$4.6\,^{+0.9}_{-0.7}\,^{+1.4}_{-0.7}$	$0.35\,^{+0.07}_{-0.05}\,^{+0.10}_{-0.05} \pm 0.03$
$\chi_{c1}(4010)$	1^{++}	$10.1\,^{+1.6}_{-0.9}\,^{+1.3}_{-1.6}$	$9.1\,^{+1.4}_{-0.8}\,^{+1.2}_{-1.4}$	$0.69\,^{+0.11}_{-0.06}\,^{+0.09}_{-0.11} \pm 0.06$
$\psi(4040)^\dagger$	1^{--}	$2.8\,^{+0.5}_{-0.4}\,^{+0.5}_{-0.5}$	$2.6\,^{+0.5}_{-0.4}\,^{+0.4}_{-0.5}$	$0.19\,^{+0.04}_{-0.03}\,^{+0.03}_{-0.03} \pm 0.02$
$h_c(4300)$	1^{+-}	$1.2\,^{+0.2}_{-0.5}\,^{+0.2}_{-0.2}$	$1.1\,^{+0.2}_{-0.5}\,^{+0.2}_{-0.2}$	$0.08\,^{+0.01}_{-0.03}\,^{+0.02}_{-0.01} \pm 0.01$
$T^*_{\bar{c}s0}(2870)^{0\,\dagger}$	0^+	$6.5\,^{+0.9}_{-1.2}\,^{+1.3}_{-1.6}$	–	$0.45\,^{+0.06}_{-0.08}\,^{+0.09}_{-0.10} \pm 0.04$
$T^*_{\bar{c}s1}(2900)^{0\,\dagger}$	1^-	$5.5\,^{+1.1}_{-1.5}\,^{+2.4}_{-1.6}$	–	$0.38\,^{+0.07}_{-0.10}\,^{+0.16}_{-0.11} \pm 0.03$
$\text{NR}_{1^{--}}(D^{*\mp}D^\pm)$	1^{--}	$20.4\,^{+2.3}_{-0.6}\,^{+2.1}_{-2.6}$	$18.5\,^{+2.1}_{-0.5}\,^{+1.9}_{-2.3}$	$1.39\,^{+0.16}_{-0.04}\,^{+0.14}_{-0.17} \pm 0.12$
$\text{NR}_{0^{--}}(D^{*\mp}D^\pm)$	0^{--}	$1.2\,^{+0.6}_{-0.1}\,^{+0.7}_{-0.6}$	$1.1\,^{+0.6}_{-0.1}\,^{+0.6}_{-0.5}$	$0.08\,^{+0.04}_{-0.01}\,^{+0.05}_{-0.04} \pm 0.01$
$\text{NR}_{1^{++}}(D^{*\mp}D^\pm)$	1^{++}	$17.8\,^{+1.9}_{-1.4}\,^{+3.6}_{-2.6}$	$16.1\,^{+1.7}_{-1.3}\,^{+3.3}_{-2.3}$	$1.21\,^{+0.13}_{-0.10}\,^{+0.24}_{-0.17} \pm 0.11$
$\text{NR}_{0^{-+}}(D^{*\mp}D^\pm)$	0^{-+}	$15.9\,^{+3.3}_{-1.2}\,^{+3.3}_{-3.3}$	$14.5\,^{+3.0}_{-1.1}\,^{+3.0}_{-3.0}$	$1.09\,^{+0.23}_{-0.08}\,^{+0.22}_{-0.23} \pm 0.09$

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Observation of new charmonium(-like) states

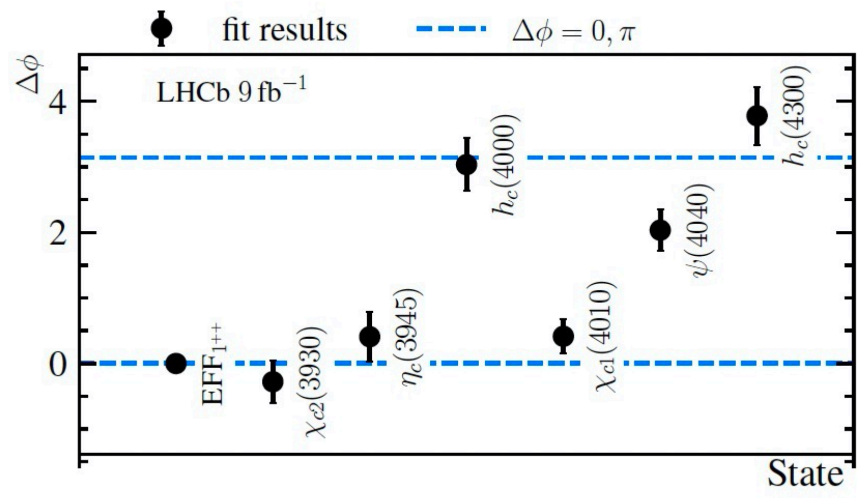

Figure 2: Results of the C-parity determination, where $C_j = \pm 1$ is replaced by $\exp(i\Delta\phi_j)$. Uncertainties are statistical only.

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Observation of new charmonium(-like) states

- $J^P = 1^+$ states are the main contribution in the $D^{*\pm} D^{\mp}$ mass spectra
- Interferences due to different C-parities results in different patterns in M($D^{*+} D^-$) and M($D^{*-} D^+$).
- J^{PC} values for $\eta_c(3945)$, $h_c(4000)$, $\chi_c(4010)$, $h_c(4300)$: 0^{-+}, 1^{+-}, 1^{++}, 1^{+-}

This work		Known states [6]		$c\bar{c}$ prediction [34]	
$\eta_c(3945)$	$J^{PC} = 0^{-+}$	$X(3940)$ [9] [10]	$J^{PC} = ?^{??}$	$\eta_c(3S)$	$J^{PC} = 0^{-+}$
$m_0 = 3945\,^{+28}_{-17}\,^{+37}_{-28}$	$\Gamma_0 = 130\,^{+92}_{-49}\,^{+101}_{-70}$	$m_0 = 3942 \pm 9$	$\Gamma_0 = 37\,^{+27}_{-17}$	$m_0 = 4064$	$\Gamma_0 = 80$
$h_c(4000)$	$J^{PC} = 1^{+-}$	$T_{c\bar{c}}(4020)^0$ [35]	$J^{PC} = ?^{?-}$	$h_c(2P)$	$J^{PC} = 1^{+-}$
$m_0 = 4000\,^{+17}_{-14}\,^{+29}_{-22}$	$\Gamma_0 = 184\,^{+71}_{-45}\,^{+97}_{-61}$	$m_0 = 4025.5\,^{+2.0}_{-4.7} \pm 3.1$	$\Gamma_0 = 23.0 \pm 6.0 \pm 1.0$	$m_0 = 3956$	$\Gamma_0 = 87$
$\chi_{c1}(4010)$	$J^{PC} = 1^{++}$			$\chi_{c1}(2P)$	$J^{PC} = 1^{++}$
$m_0 = 4012.5\,^{+3.6}_{-3.9}\,^{+4.1}_{-3.7}$	$\Gamma_0 = 62.7\,^{+7.0}_{-6.4}\,^{+6.4}_{-6.6}$			$m_0 = 3953$	$\Gamma_0 = 165$
$h_c(4300)$	$J^{PC} = 1^{+-}$			$h_c(3P)$	$J^{PC} = 1^{+-}$
$m_0 = 4307.3\,^{+6.4}_{-6.6}\,^{+3.3}_{-4.1}$	$\Gamma_0 = 58\,^{+28}_{-16}\,^{+28}_{-25}$			$m_0 = 4318$	$\Gamma_0 = 75$
		$\chi_c(4274)$ [36]	$J^{PC} = 1^{++}$	$\chi_{c1}(3P)$	$J^{PC} = 1^{++}$
		$m_0 = 4294 \pm 4\,^{+6}_{-3}$	$\Gamma_0 = 53 \pm 5 \pm 5$	$m_0 = 4317$	$\Gamma_0 = 39$

[9] PRL 98, 082001
[10] PRL 100, 202001
[34] PRD 72, 054026
[35] PRL 115, 182002
[36] PRL 127, 082001

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Observation of new charmonium(-like) states

Table 2: Comparison of the $T^{*0}_{\bar{c}\bar{s}0,1}$ properties obtained in this work to those found previously in $B^+ \to D^+ D^- K^+$ decays [2]. In the branching fractions determined in this work, the $T^{*0}_{\bar{c}\bar{s}0,1}$ masses and widths are fixed to the previously measured values [2].

Property	This work	Previous work
$T^*_{\bar{c}\bar{s}0}(2870)^0$ mass [MeV]	$2914 \pm 11 \pm 15$	2866 ± 7
$T^*_{\bar{c}\bar{s}0}(2870)^0$ width [MeV]	$128 \pm 22 \pm 23$	57 ± 13
$T^*_{\bar{c}\bar{s}1}(2900)^0$ mass [MeV]	$2887 \pm 8 \pm 6$	2904 ± 5
$T^*_{\bar{c}\bar{s}1}(2900)^0$ width [MeV]	$92 \pm 16 \pm 16$	110 ± 12
$\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0 D^{(*)+})$	$(4.5\,^{+0.6}_{-0.8}\,^{+0.9}_{-1.0} \pm 0.4) \times 10^{-5}$	$(1.2 \pm 0.5) \times 10^{-5}$
$\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+})$	$(3.8\,^{+0.7}_{-1.0}\,^{+1.6}_{-1.1} \pm 0.3) \times 10^{-5}$	$(6.7 \pm 2.3) \times 10^{-5}$
$\frac{\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0 D^{(*)+})}{\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+})}$	$1.17 \pm 0.31 \pm 0.48$	0.18 ± 0.05

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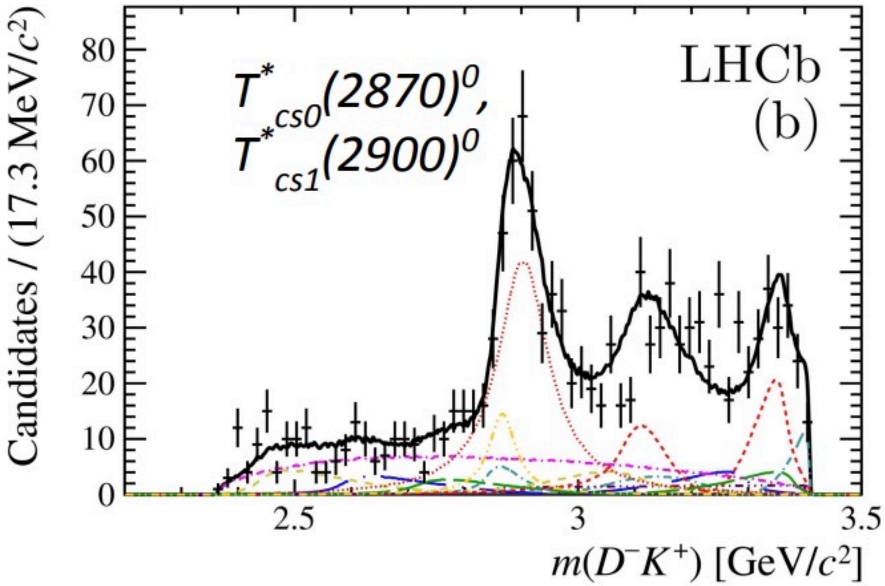
Observation of new charmonium(-like) states

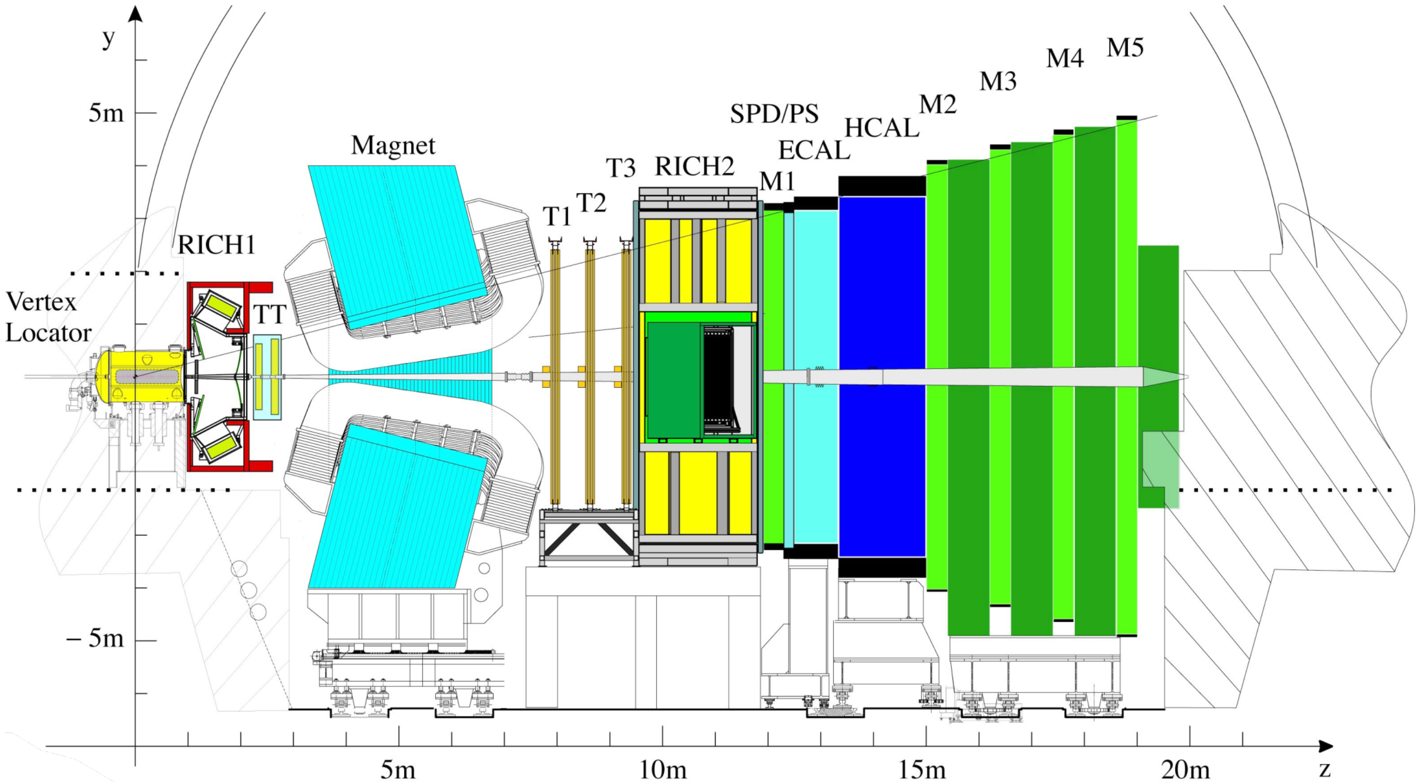


PhysRevLett.125.242001

PhysRevD.102.112003

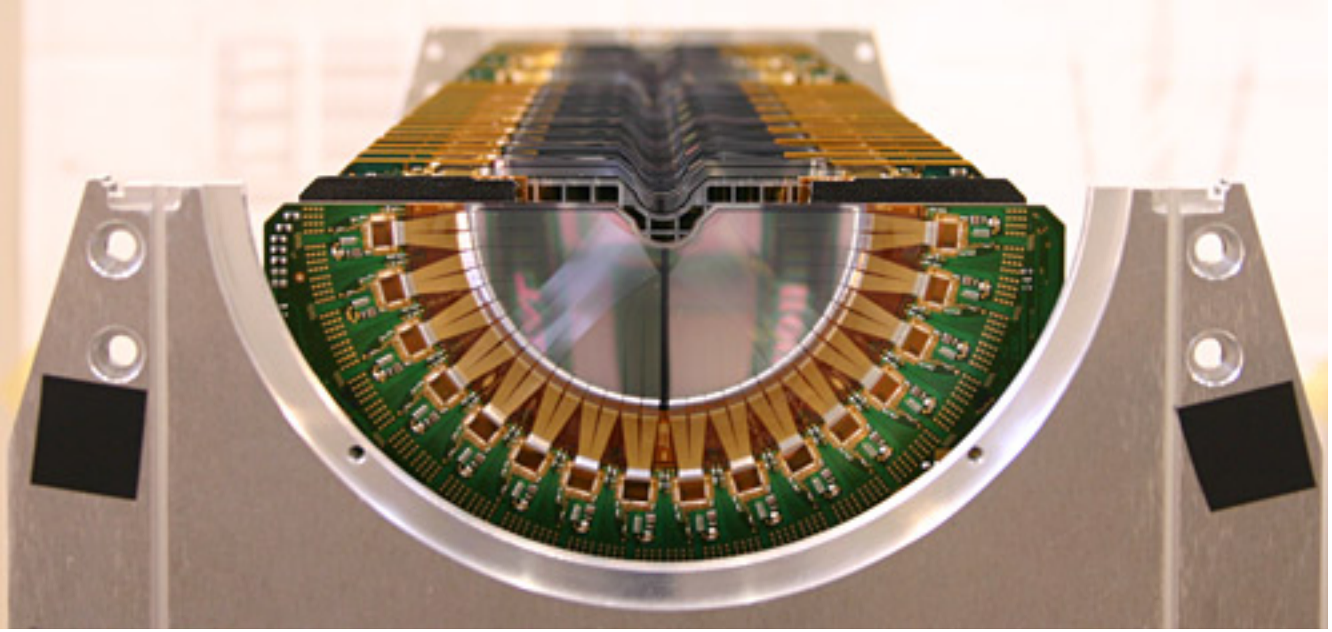
More Additional Slides

Experiment Overview



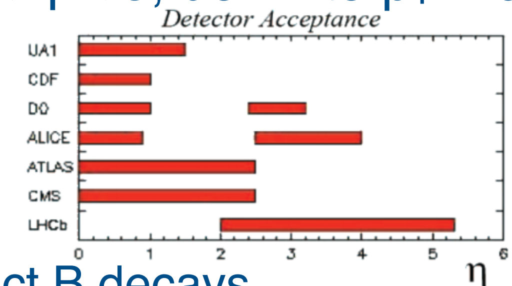
Vertex Locator (VELO)

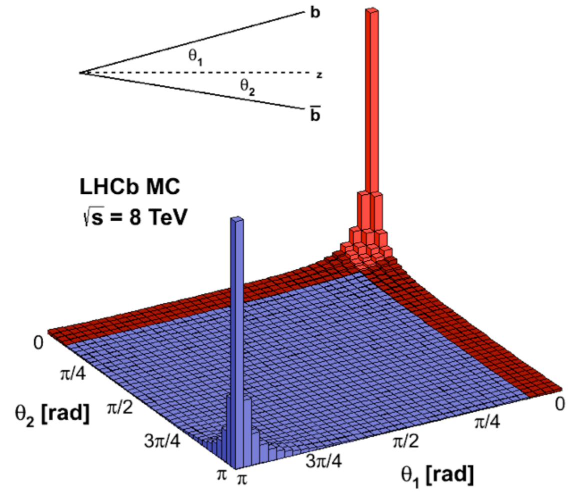
- Reconstruction of primary and (displaced) secondary vertices
- Excellent Impact Parameter resolution of ~ 20 μm
- Proper time resolution 30 to 50 fs



Experiment Overview

- The LHCb detector is a single arm forward spectrometer with a polar angular coverage from 10 to 300 mrad in the horizontal plane and 250 mrad in the vertical plane.
- Unique regime: $2 < \eta < 5$, down to $p_T \sim 0$

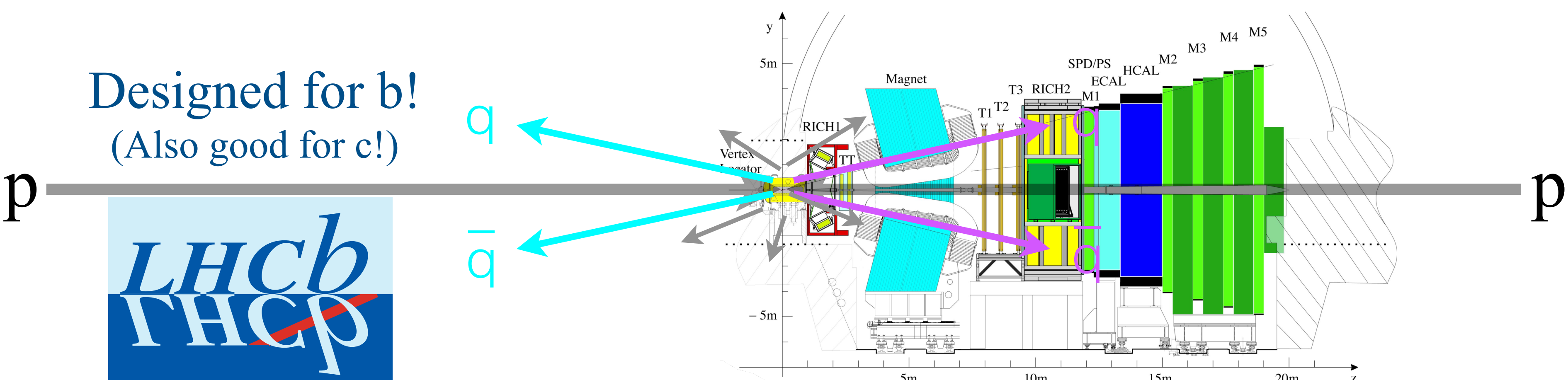




- Trigger
  - Designed to select B decays.
  - Also favors higher p_T secondary charm.

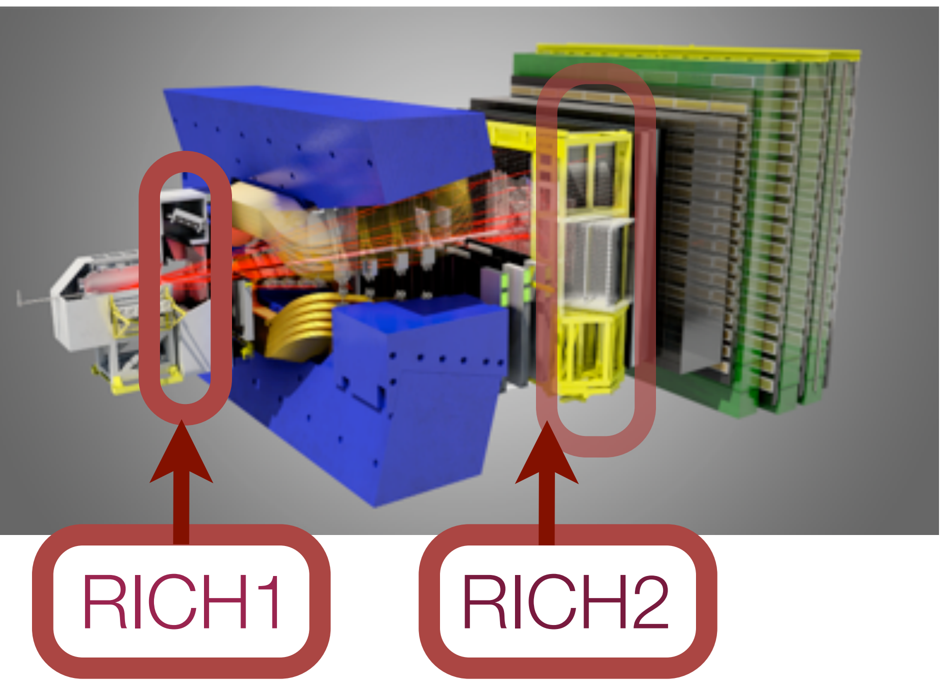
Designed for b!

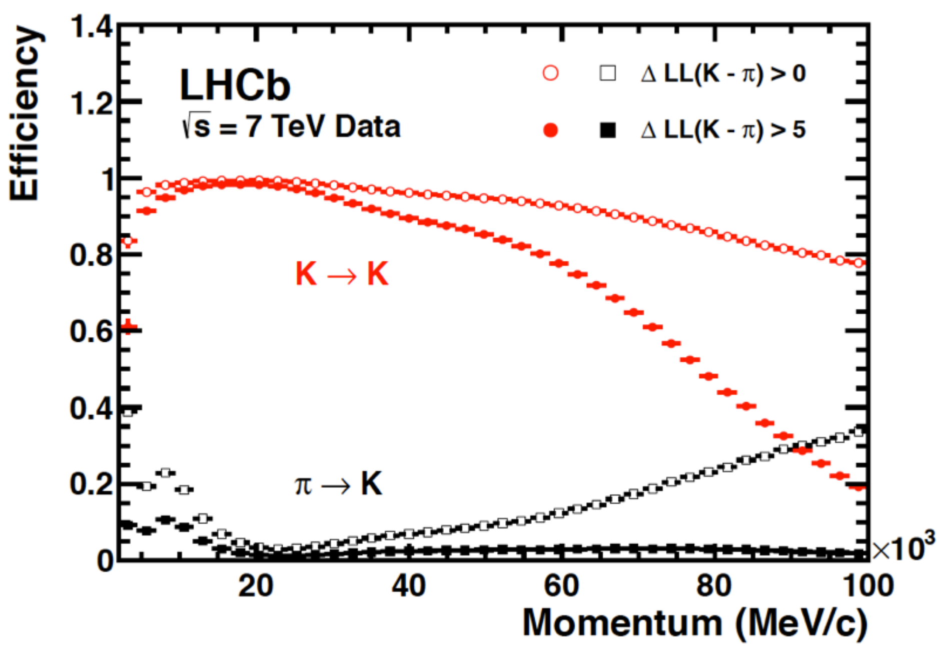
(Also good for c!)



LHCb Experiment: Particle ID

- Particle ID provided by <u>R</u>ing <u>I</u>maging <u>Ch</u>erenkov (RICH) detectors
  - Particles traveling faster than the speed of light through a medium of refractive index n will emit photons through Cherenkov radiation:
    - $\cos(\theta) = 1/n\beta$
- The Cherenkov angle and the momentum of the particle allows PID.

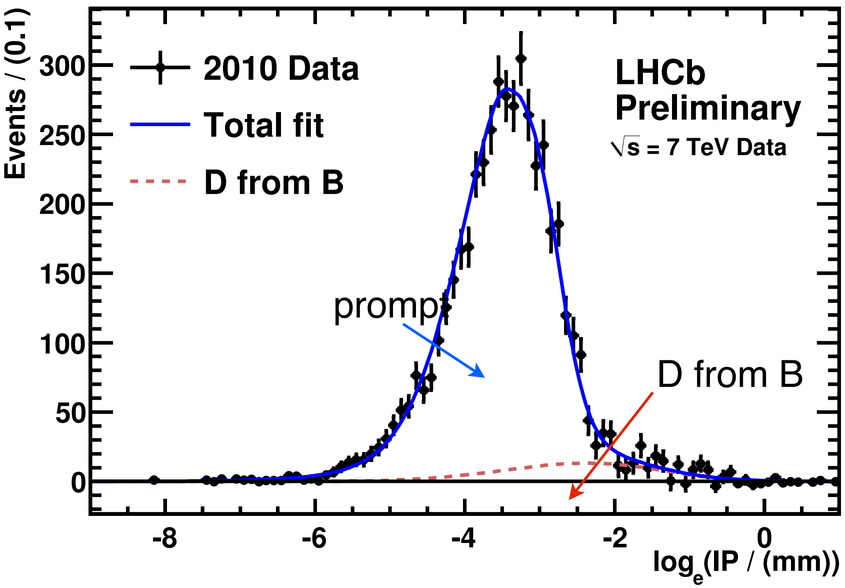




- The ability to identify particles at LHCb is critical to many of our analyses.

Prompt-Secondary Separation

- Separate prompt and secondary charm
  - Prompt charm
    - Defined as charm mesons produced at the primary interaction point.
    - This includes if they are from quickly decaying resonances
      - Examples: via D* decays, ψ(3770)
  - Secondary charm
    - Residual background from charm mesons decaying from long-lived particles.
- We can measure the prompt fraction
  - Look at impact parameter distribution of the charm meson



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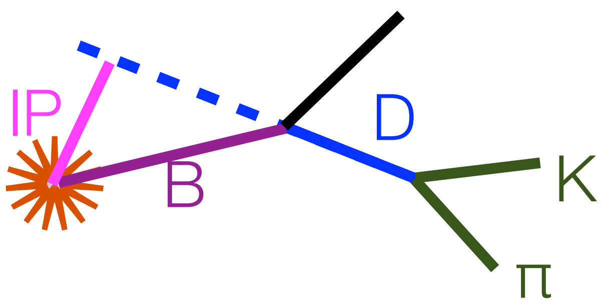
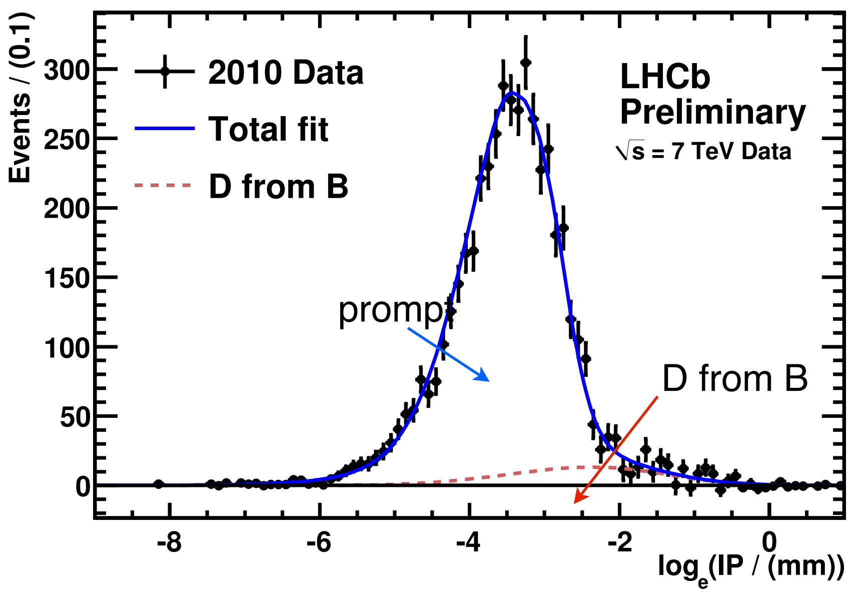
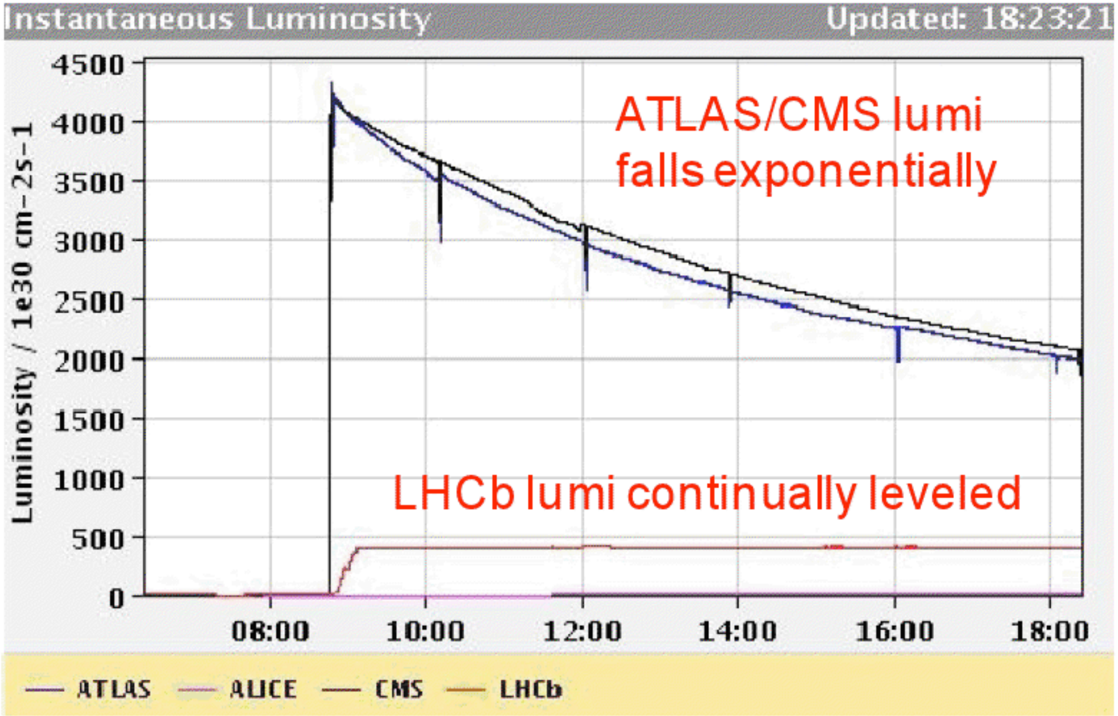




Luminosity

- Nominal instantaneous luminosity: $\mathscr{L} = 4 \times 10^{32}\ \mathrm{cm^{-2}s^{-1}}$
- LHCb instantaneous luminosity kept constant (luminosity leveling).



Charm at LHCb?

- We are most certainly a B physics experiment. However…
- The same properties that optimize LHCb for B physics also make LHCb **an excellent charm physics experiment**.

- The charm cross section is ~20 times larger than the b cross section.
  - **$\sigma(c\bar{c})_{LHCb}$ = 1419 ± 133 μb (Nucl. Phys. B 871 (2013), 1)** @ $\sqrt{s} = 7$ TeV
  - **$\sigma(b\bar{b})_{LHCb}$ = 75.3 ± 14.1 μb (Phys. Lett. B 694 (2010), 209)**
- ~5 trillion $c\bar{c}$ were produced during LHC Run 1, in our acceptance!

- LHCb can make precision measurements in charm with high sensitivity to New Physics hiding in quantum loops…
  - We have the world's best sensitivity to **CP violation** in charm.

- Boosted quarks, high rapidities: ideal for studying time-dependent effects