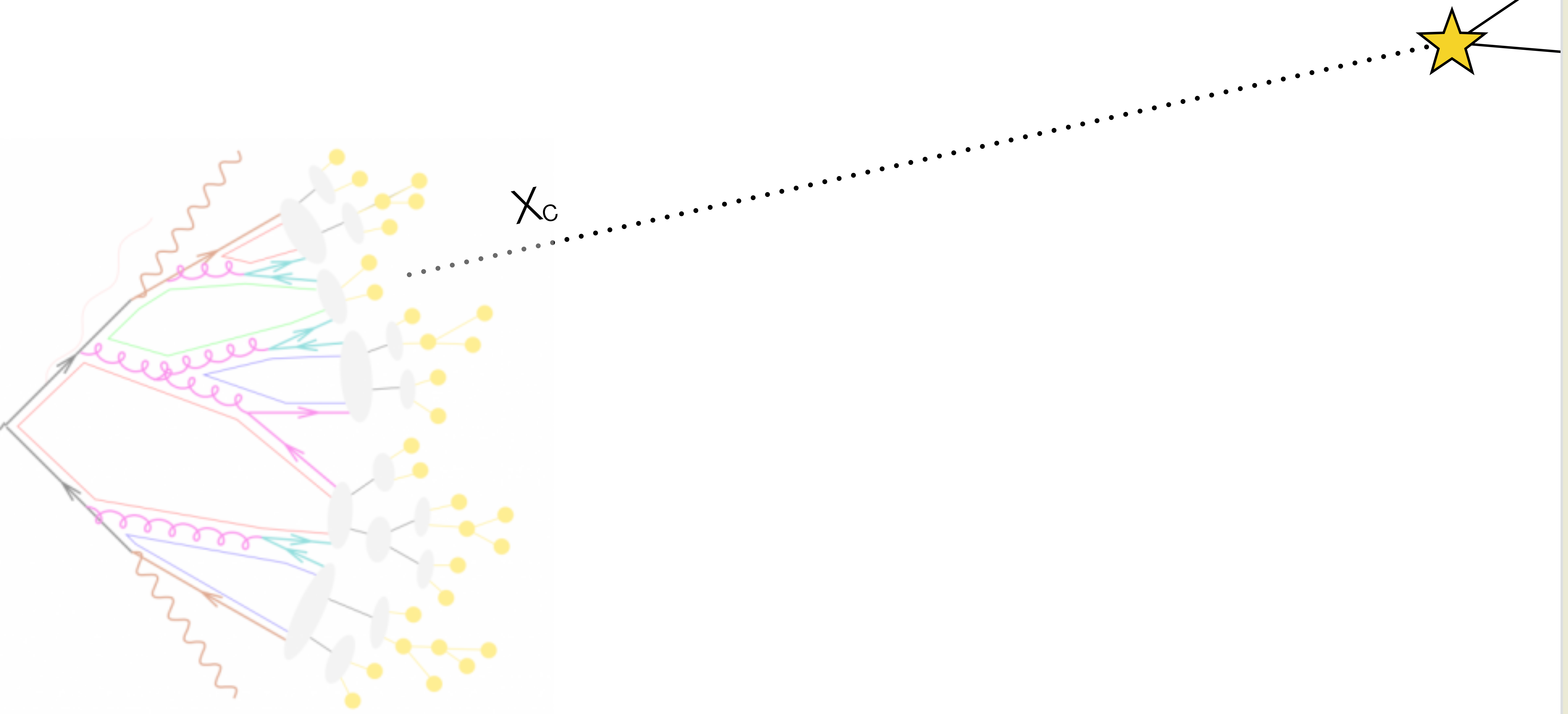
LHCb results on charmed hadrons

Production, properties, and decay

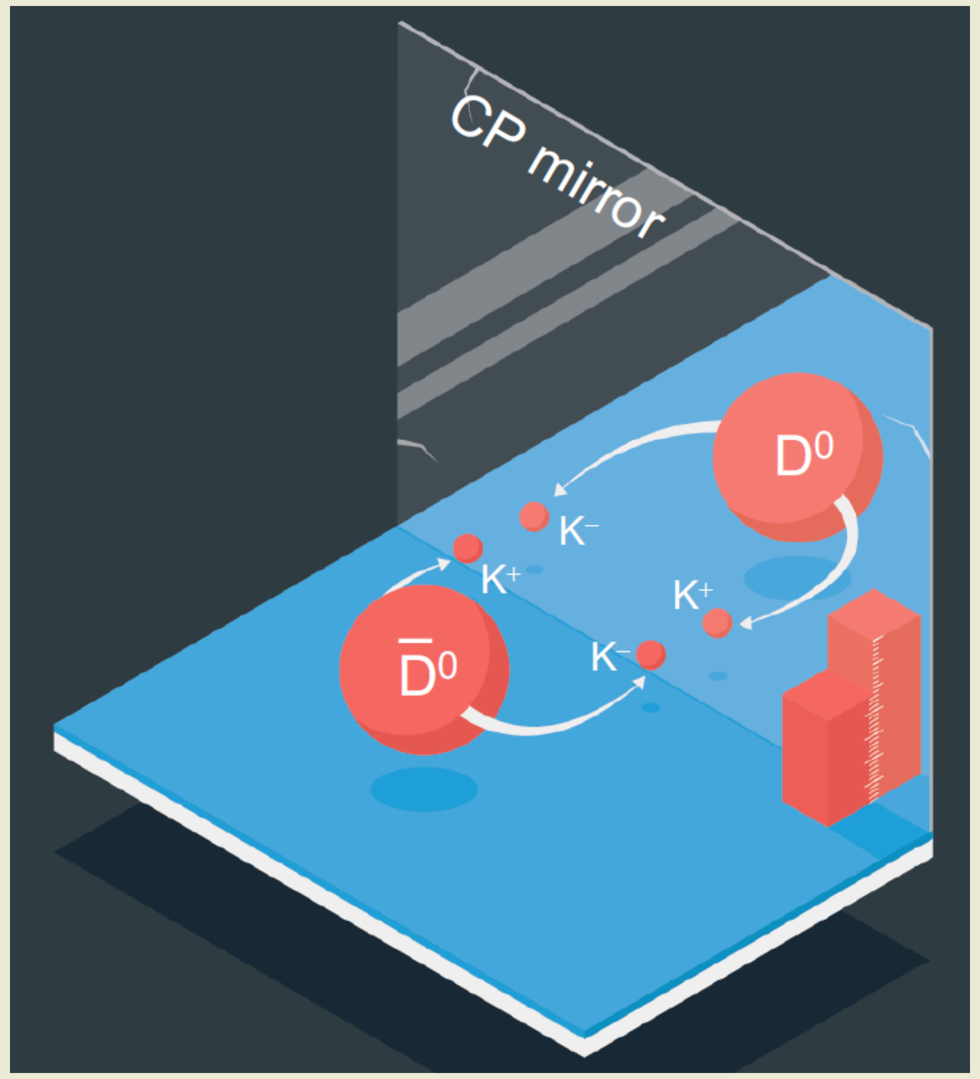
EPS-HEP | QCD & Hadronic physics July 8, 2025
Laurent Dufour, on behalf of the LHCb collaboration

The charm as probe for QCD



Decay

- Form factors & CKM
- Spectroscopy (intermediate new states)
- CP-violation & final-state interactions



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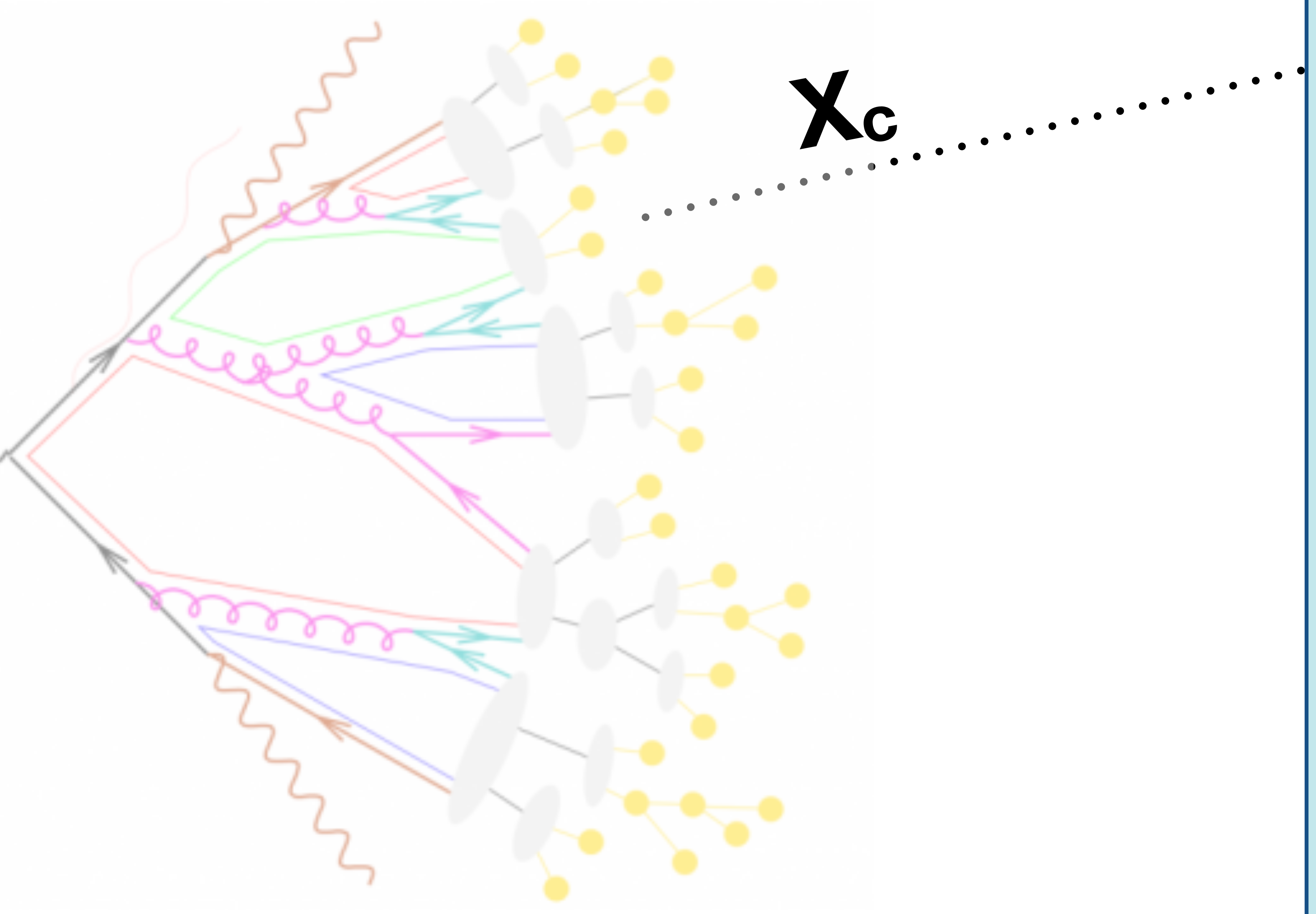
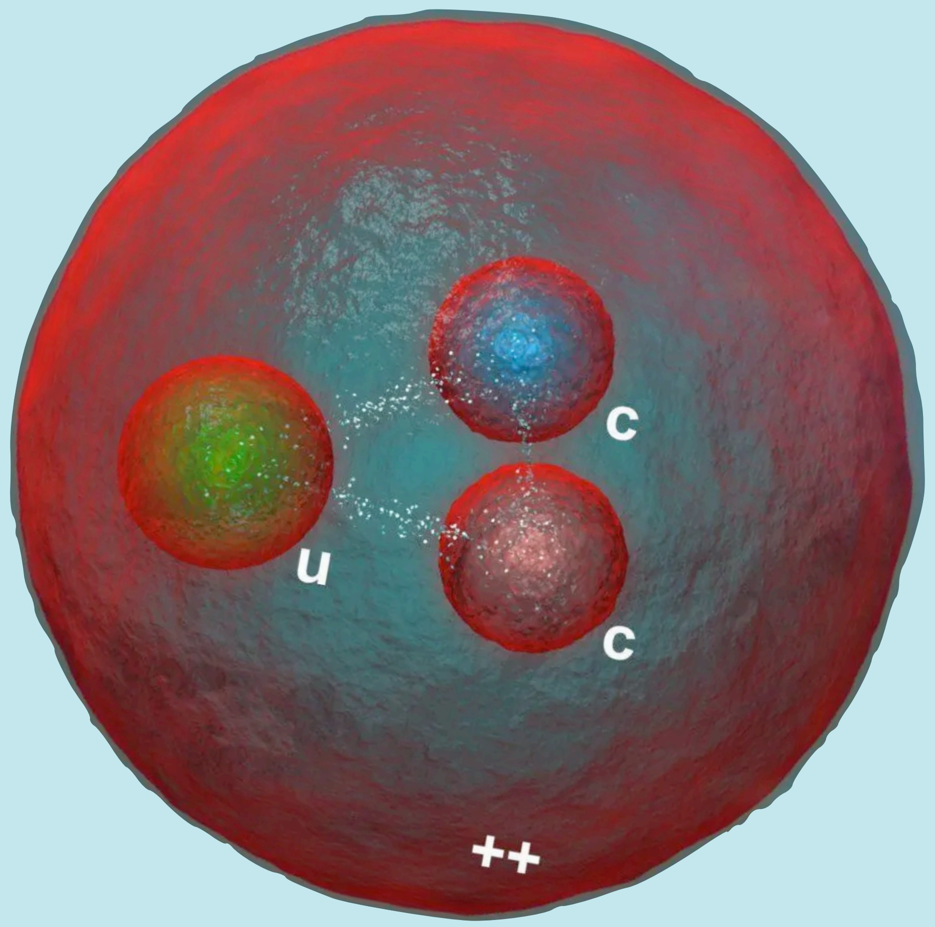


Charm hadron

- Hadron spectrum of heavy quarks

  including doubly heavy

- Lifetime & mixing



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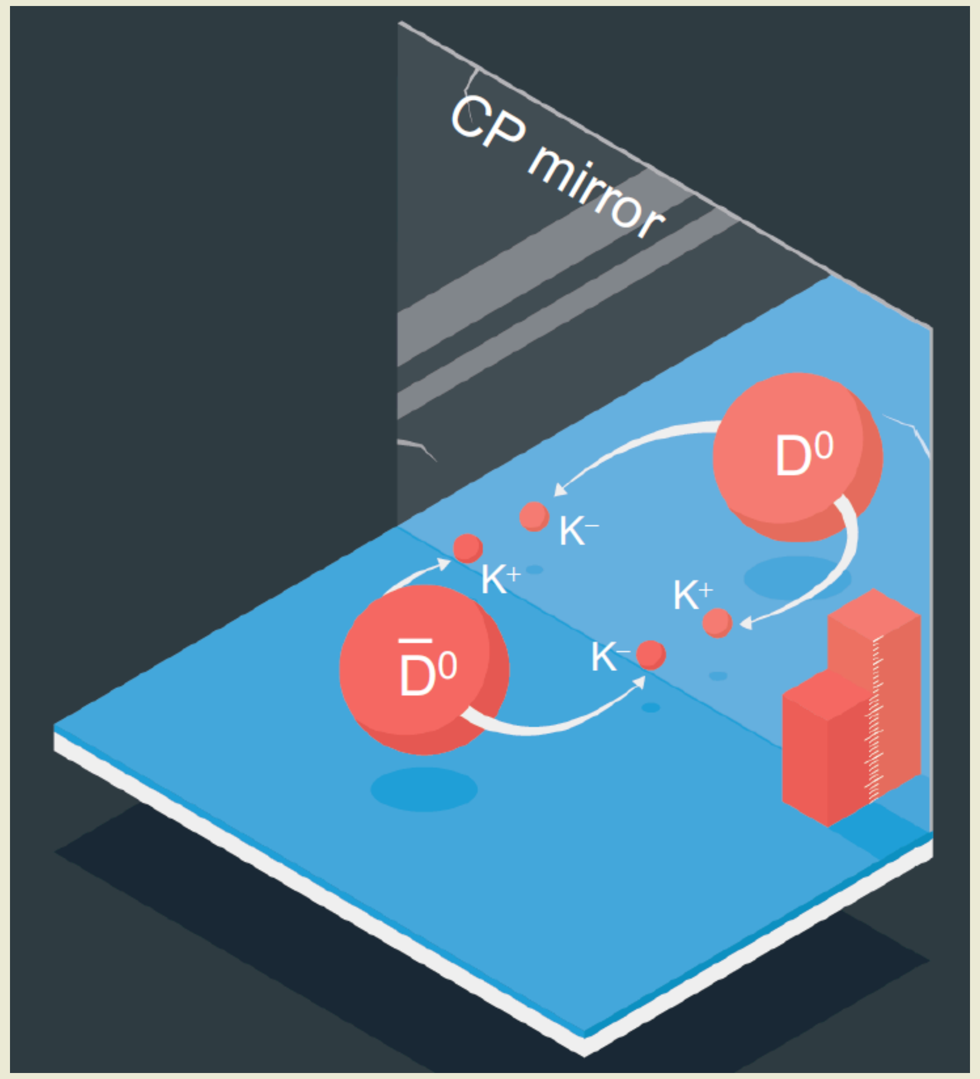
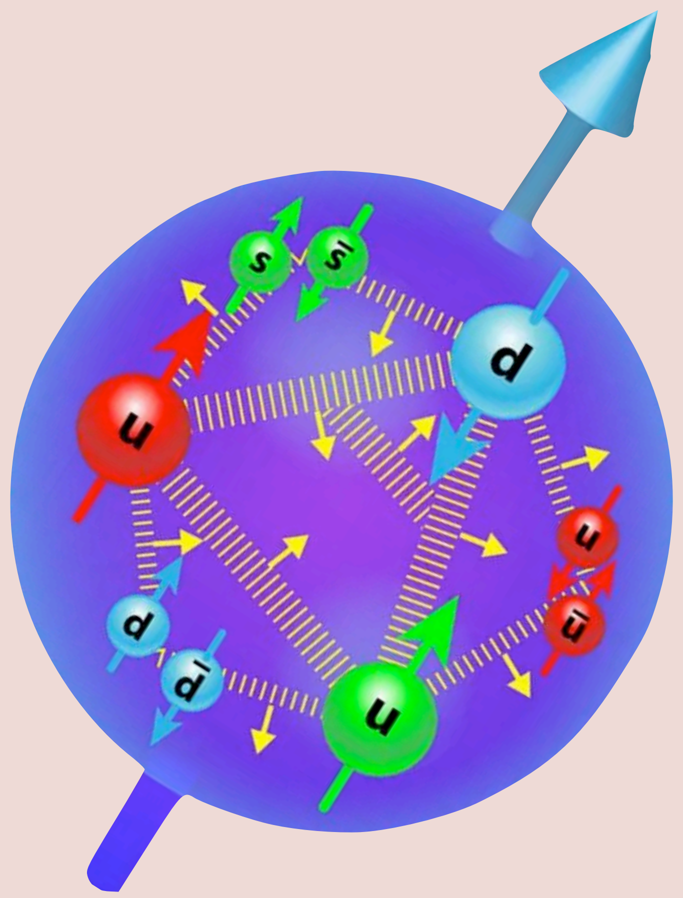


The charm as probe for QCD

Production

- Primary hard probe in heavy nuclei collisions
- Hadronisation in all systems
- Contents of the proton



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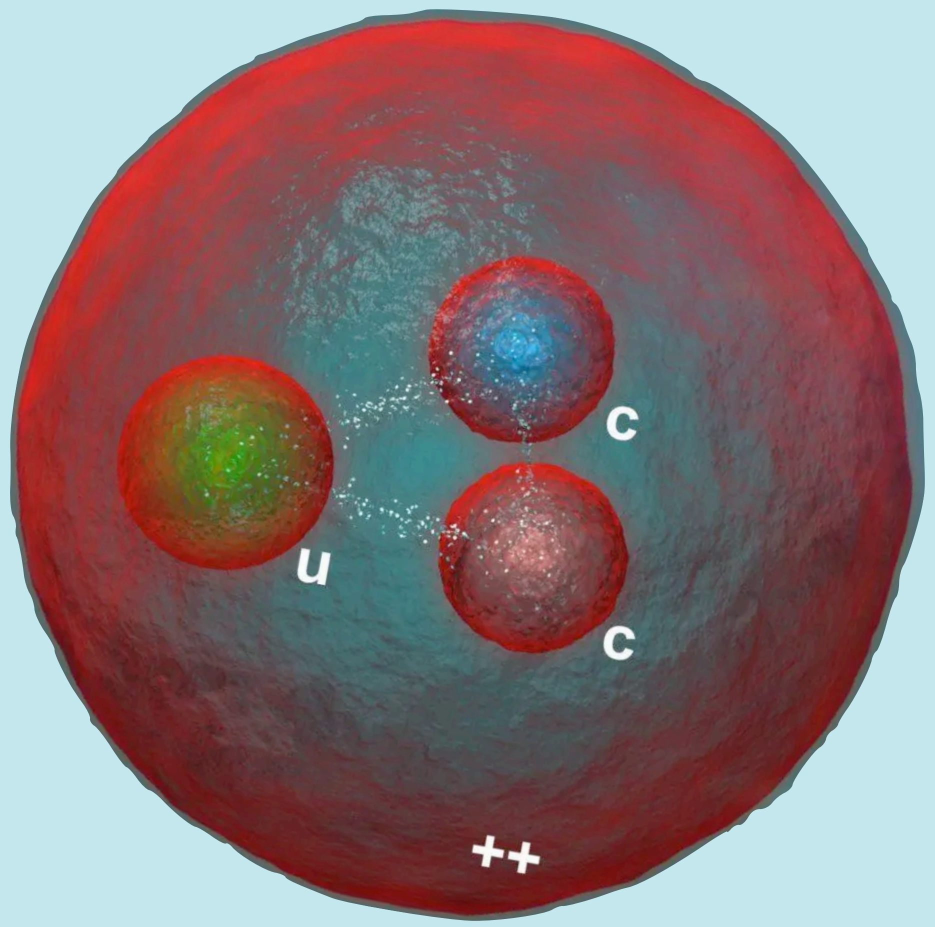

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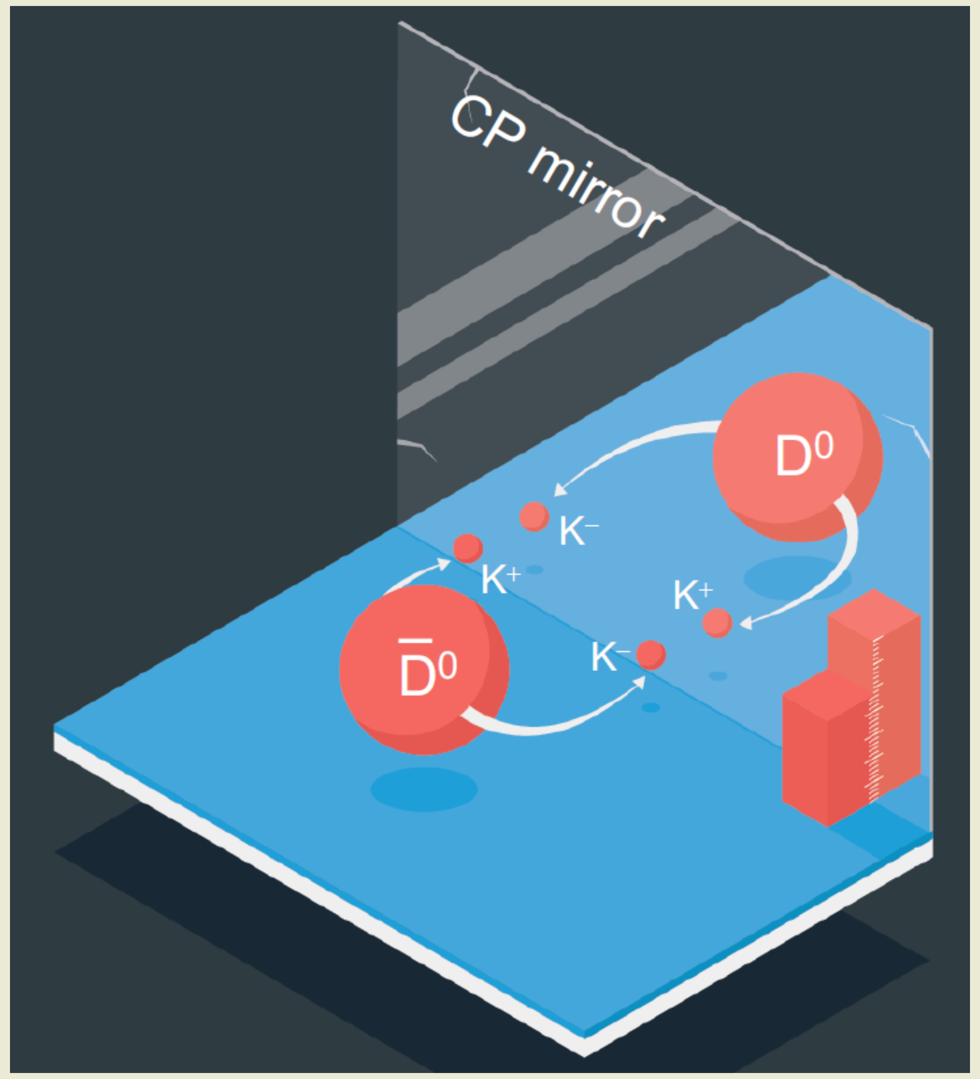
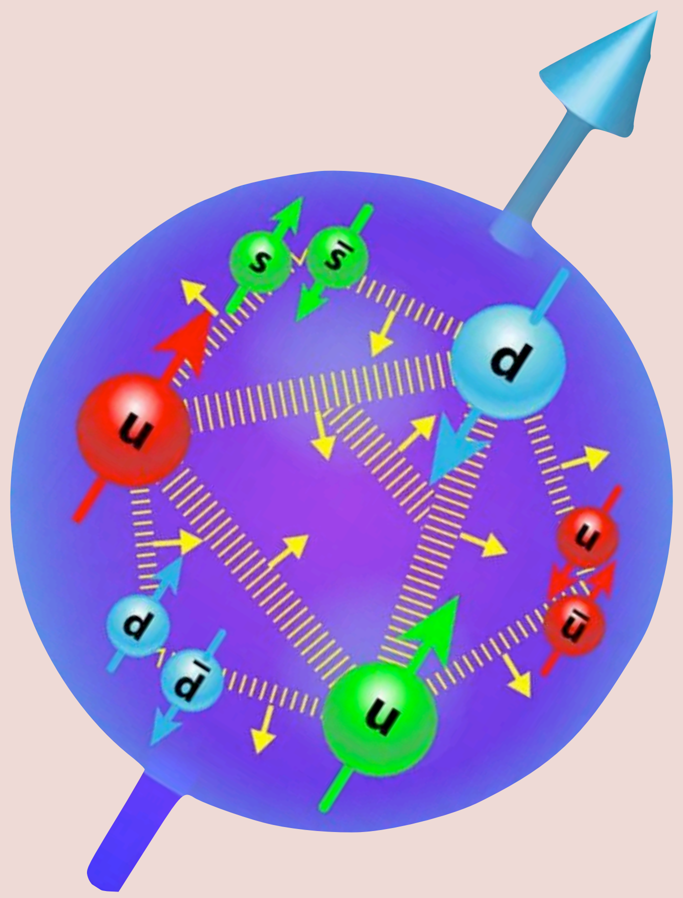


The charm as probe for QCD

See talk from
G. Punzi & others in T07

Production

- Primary hard probe in heavy nuclei collisions
- **Hadronisation in all systems**
- Contents of the proton

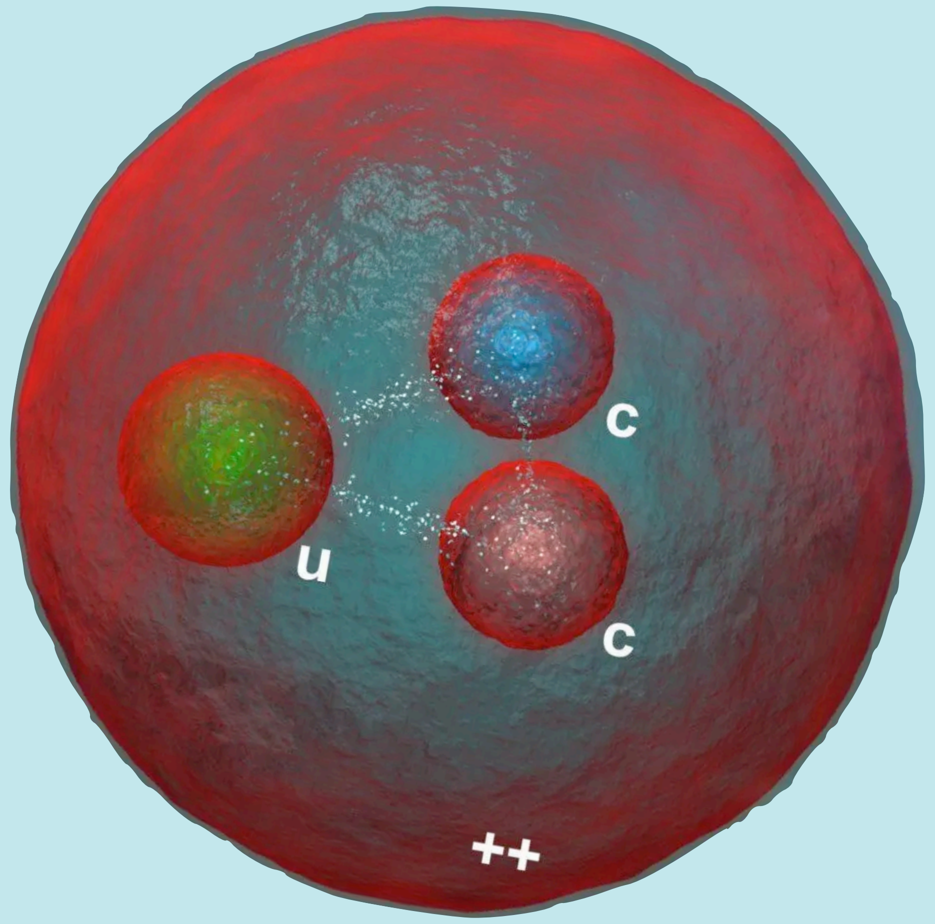


Charm hadron

- **Hadron spectrum of heavy quarks**

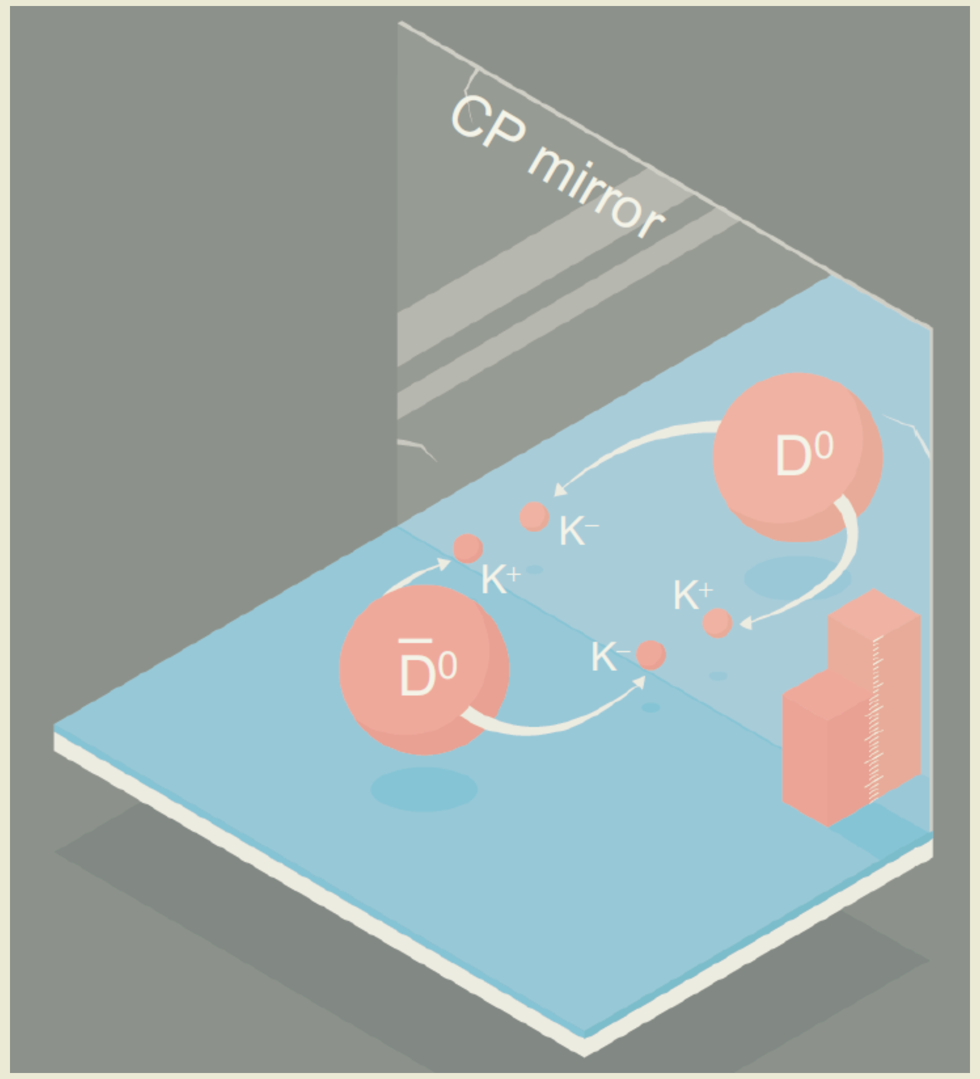
  including doubly heavy

- Lifetime & mixing

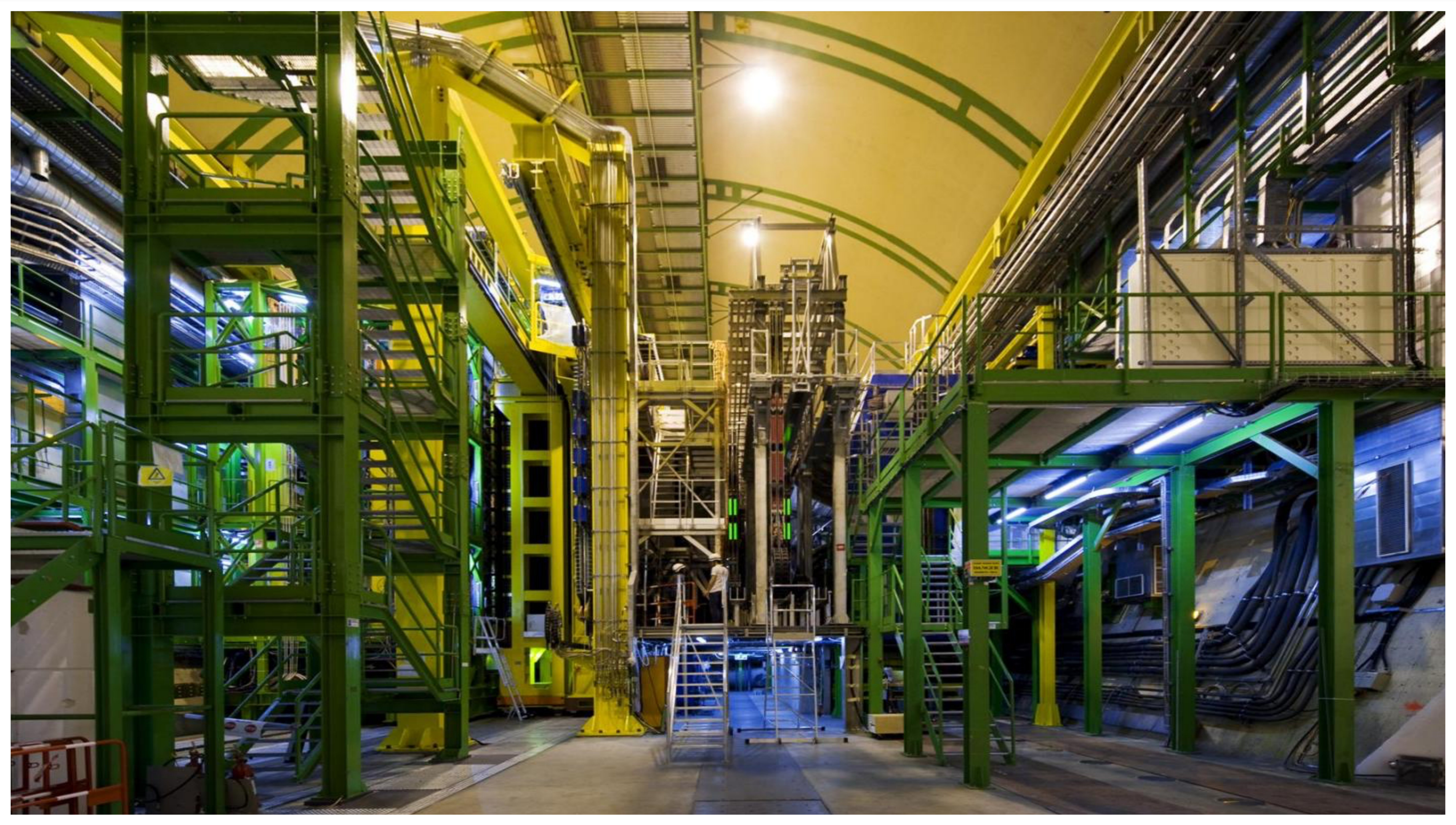


Decay

- Form factors & CKM
- Spectroscopy (intermediate new states)
- *CP-violation & final-state interactions*



The LHCb experiment at the LHC



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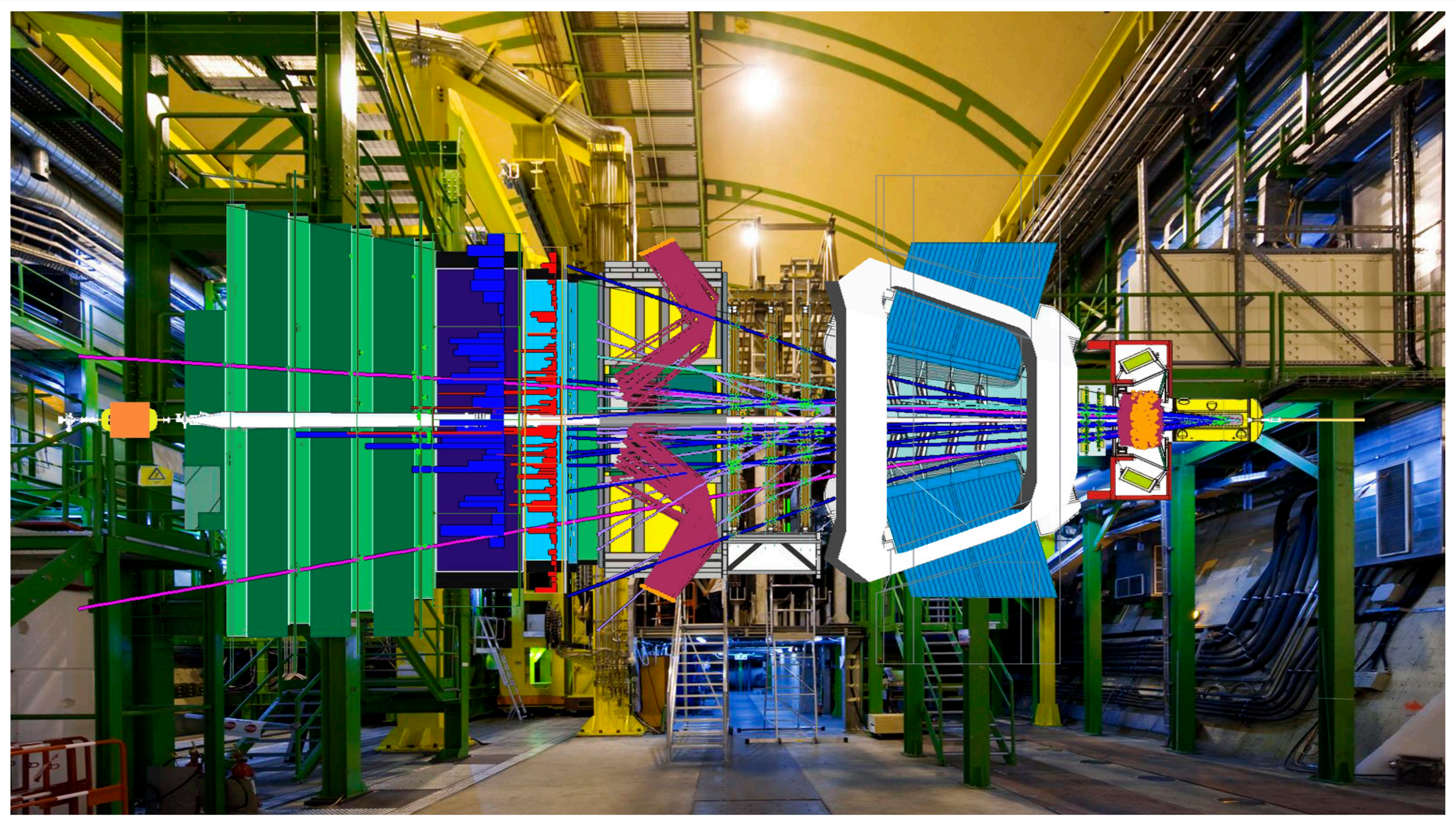

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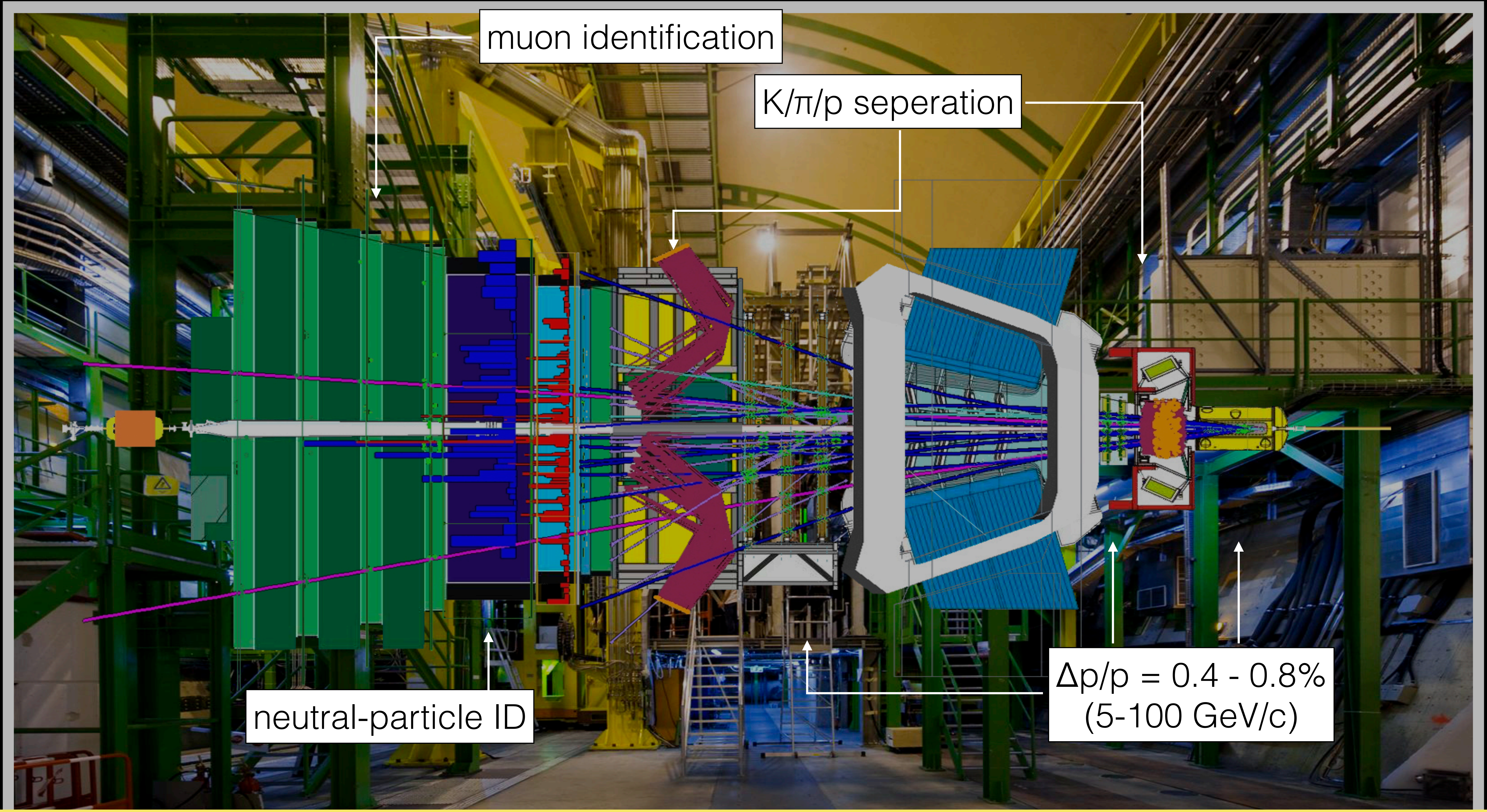
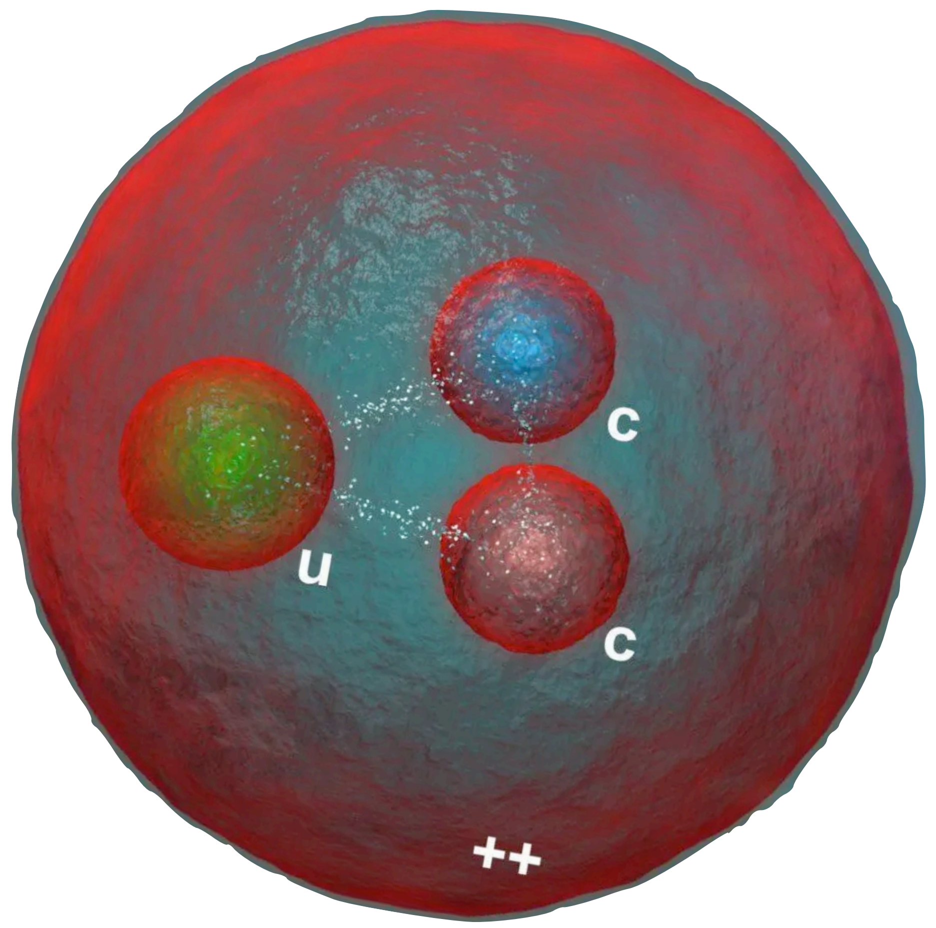
Int. J. Mod. Phys. A 30, 1530022 (2015)



Experiment with **excellent PID & resolution** situated at the LHC (**abundant charm-hadron production**)

Charmed states as probe for QCD



[Rep. Prog. Phys. 80 (2017) 076201]

c s u or c s d

Completing the puzzle of Ξ_c states

- Expecting a rich spectrum of *c*-baryon states, including S/P/D-wave excitations; yet many states not observed yet

- **Experimentalist's task** a proper estimation of the masses, widths, and quantum numbers (spin & parity) of the different states, testing expected patterns (including isospin partners)

- Risk of overlapping/ambiguous signals make detector resolution & sufficient data critical… **LHCb well suited for this**

Many blanks:
expected, yet not observed (in '17)

	J^P (nL)	Exp. Mass [3]
Λ_c	$1/2^+$ [illegible]	[illegible]
[illegible]	[illegible]	2578.4 ± 0.5
Ξ_c^*	$3/2^+$ $(1S)$	$2645.56^{+0.24}_{-0.30}$
Ω_c	$1/2^+$ $(1S)$	2695.2 ± 1.7
Ω_c^*	$3/2^+$ $(1S)$	2765.9 ± 2.0
Λ_c	$1/2^-$ $(1P)$	$\Lambda_c(2595)$: 2592.25 ± 0.28
Λ_c	$3/2^-$ $(1P)$	$\Lambda_c(2625)$: 2628.11 ± 0.19
Ξ_c	$1/2^-$ $(1P)$	$\Xi_c(2790)$: 2792.4 ± 0.5
Ξ_c	$3/2^-$ $(1P)$	$\Xi_c(2815)$: $2816.74^{+0.20}_{-0.23}$
Σ_c	$1/2^-$ $(1P)$	–
Σ_c	$1/2^-$ $(1P)$	
Σ_c	$3/2^-$ $(1P)$	$\Sigma_c(2800)$: 2792^{+14}_{-5}
Σ_c	$3/2^-$ $(1P)$	
Σ_c	$5/2^-$ $(1P)$	
Ξ_c'	$1/2^-$ $(1P)$	–
Ξ_c'	$1/2^-$ $(1P)$	$\Xi_c(2923)$: 2923.04 ± 0.35 [304]
Ξ_c'	$3/2^-$ $(1P)$	$\Xi_c(2939)$: 2938.55 ± 0.30 [304]
Ξ_c'	$3/2^-$ $(1P)$	$\Xi_c(2965)$: 2964.88 ± 0.33 [304]
Ξ_c'	$5/2^-$ $(1P)$	–
Ω_c	$1/2^-$ $(1P)$	–
Ω_c	$1/2^-$ $(1P)$	$\Omega_c(3000)$: 3000.41 ± 0.22
Ω_c	$3/2^-$ $(1P)$	$\Omega_c(3050)$: 3050.20 ± 0.13
Ω_c	$3/2^-$ $(1P)$	$\Omega_c(3066)$: 3065.46 ± 0.28
Ω_c	$5/2^-$ $(1P)$	$\Omega_c(3090)$: 3090.0 ± 0.5
Λ_c	$1/2^+$ $(2S)$	$\Lambda_c(2765)$: 2766.6 ± 2.4
Ξ_c	$1/2^+$ $(2S)$	$\Xi_c(2970)$: $2966.34^{+0.17}_{-1.00}$
Σ_c	$1/2^+$ $(2S)$	–
Σ_c	$3/2^+$ $(2S)$	–
Ξ_c'	$1/2^+$ $(2S)$	–
Ξ_c'	$3/2^+$ $(2S)$	–
Ω_c	$1/2^+$ $(2S)$	$\Omega_c(3119)$: 3119.1 ± 1.0
Ω_c	$3/2^+$ $(2S)$	
Λ_c	$3/2^+$ $(1D)$	$\Lambda_c(2860)$: $2856.1^{+2.3}_{-5.9}$
Λ_c	$5/2^+$ $(1D)$	$\Lambda_c(2880)$: 2881.63 ± 0.24
Ξ_c	$3/2^+$ $(1D)$	$\Xi_c(3055)$: 3055.9 ± 0.4
Ξ_c	$5/2^+$ $(1D)$	$\Xi_c(3080)$: 3077.2 ± 0.4
Σ_c	$1/2^+$ $(1D)$	–
Σ_c	$3/2^+$ $(1D)$	–
Σ_c	$3/2^+$ $(1D)$	–
Σ_c	$5/2^+$ $(1D)$	–
Σ_c	$5/2^+$ $(1D)$	–
Σ_c	$7/2^+$ $(1D)$	–
Ξ_c'	$1/2^+$ $(1D)$	–
Ξ_c'	$3/2^+$ $(1D)$	–
Ξ_c'	$3/2^+$ $(1D)$	–
Ξ_c'	$5/2^+$ $(1D)$	–
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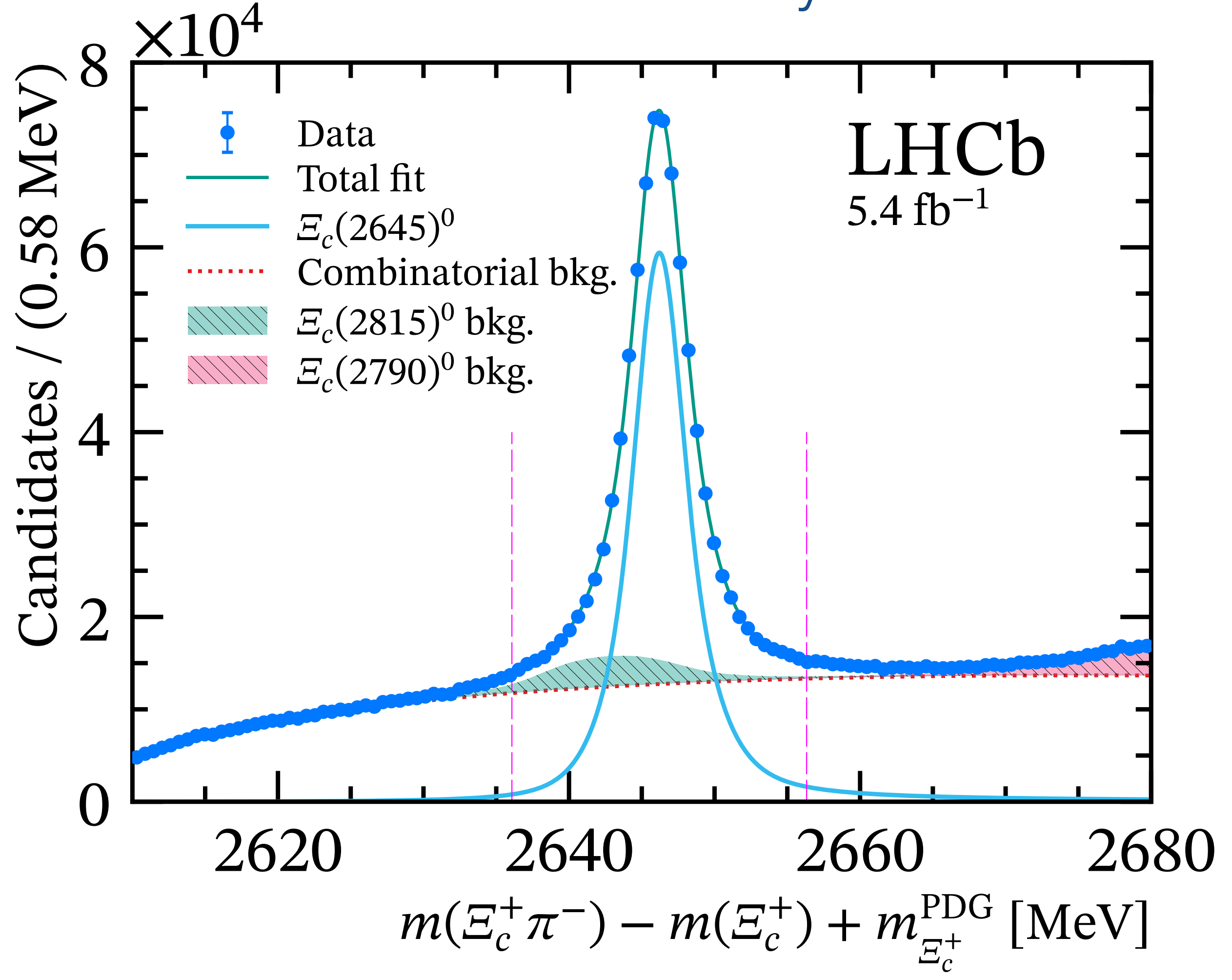
Ξ_c'	$7/2^+$ $(1D)$	–
Ω_c	$1/2^+$ $(1D)$	–
Ω_c	$3/2^+$ $(1D)$	–
Ω_c	$3/2^+$ $(1D)$	–
Ω_c	$5/2^+$ $(1D)$	–
Ω_c	$5/2^+$ $(1D)$	–
Ω_c	$7/2^+$ $(1D)$	–

Run 2

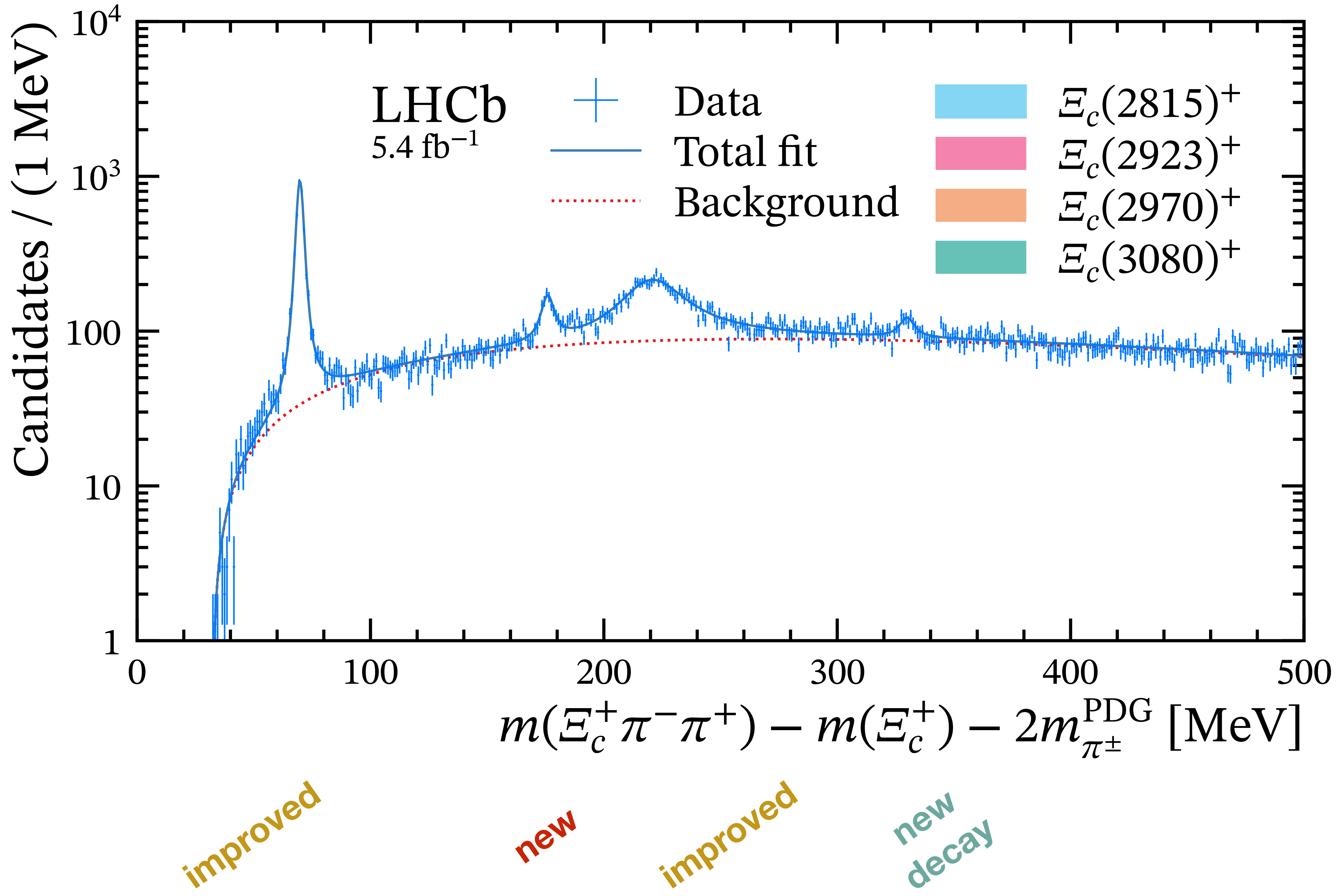
New Ξ_c state: $\Xi_c(2923)^+$

[arXiv:2502.18987]
Submitted to Phys. Rev. Letters



LHCb explored *prompt* $\Xi_c(2645)^0 \pi^+$ spectrum in Run 2 data of 5.4 fb^{-1}

★ $\Xi_c(2645)^0 \to \Xi_c^+ \pi^-$ with ~400K $\Xi_c^+ \to p K^- \pi^+$ decays



New state observed $\Xi_c(2923)^+$: isospin partner of $\Xi_c(2923)^0$

- $M = 2922.8 \pm 0.62$ MeV, $\Gamma = 5.3 \pm 1.7$ MeV

Observed new decay of $\Xi_c(3080)^+$

- $\Xi_c(3080)^+ \to \Xi_c(2645)^0\pi^+$

Improved the knowledge of $\Xi_c(2815)^+$ & $\Xi_c(2970)^+$

- $\Xi_c(2815)^+$ $M = 2816.65 \pm 0.23$ MeV, $\Gamma = 2.07 \pm 0.14$ MeV
- $\Xi_c(2970)^+$ $M = 2968.62 \pm 0.56$ MeV, $\Gamma = 31.7 \pm 2.3$ MeV

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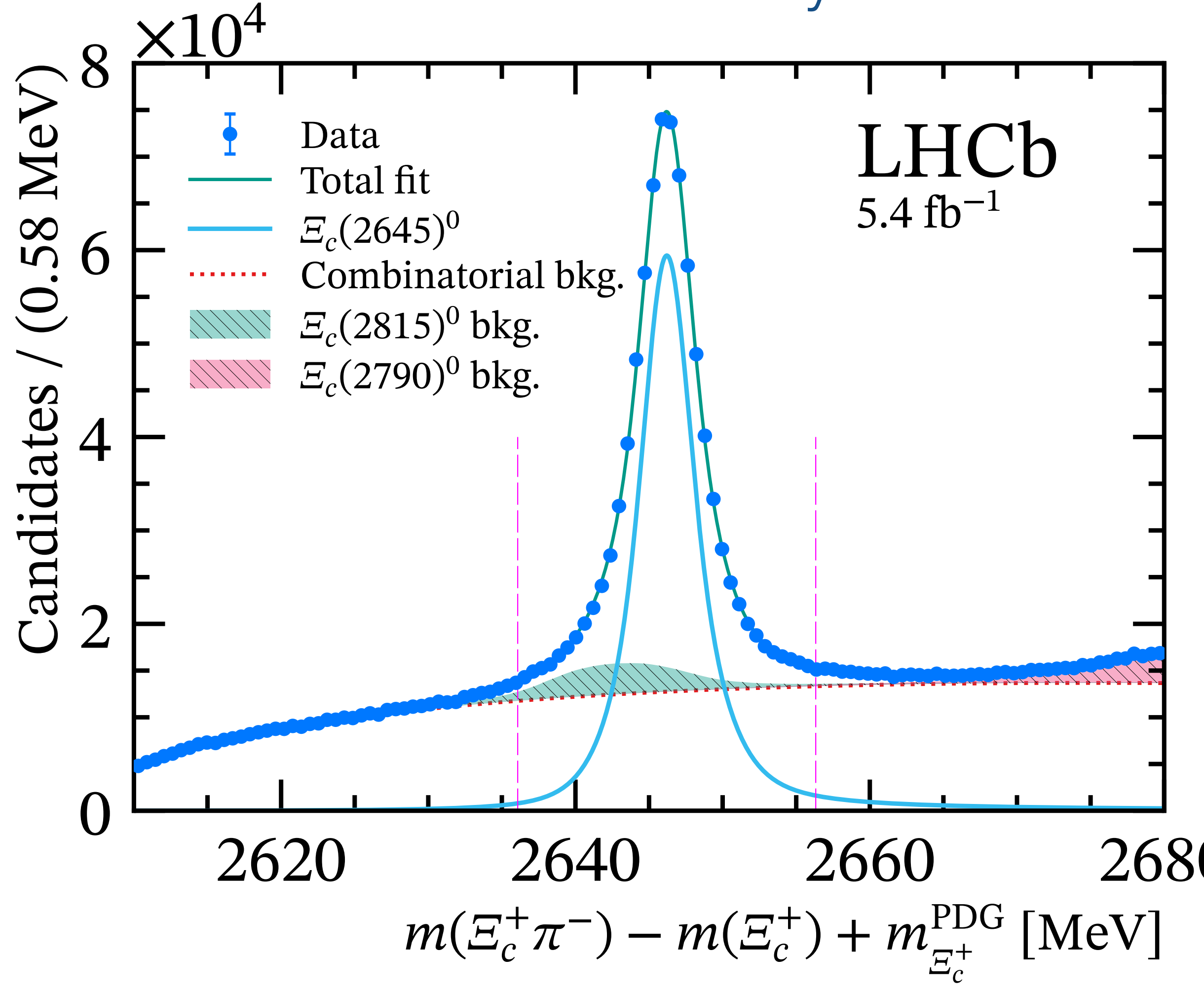

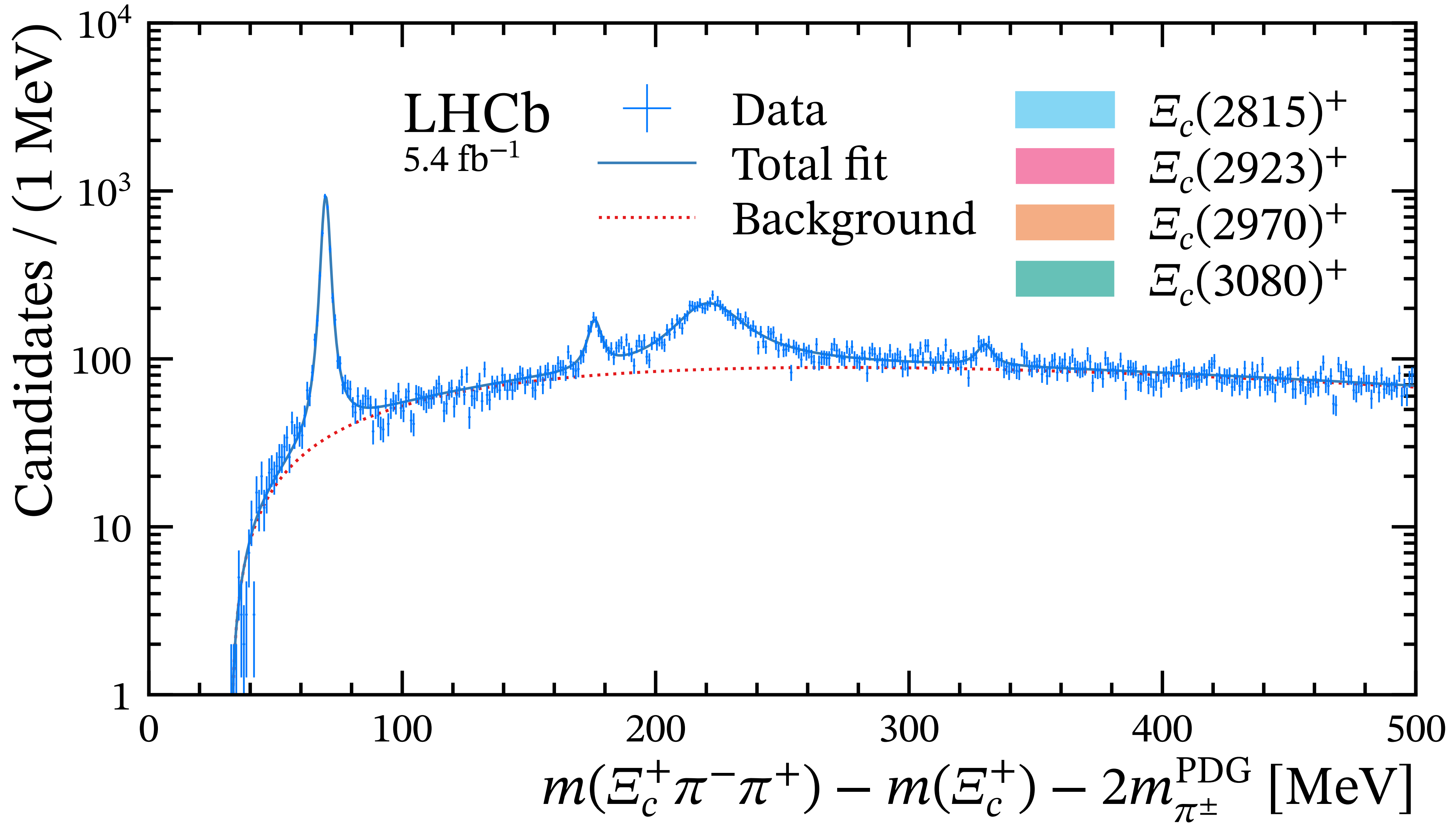

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Much wider than $\Xi_c(2965)^0$ - not an isospin partner?

Run 2

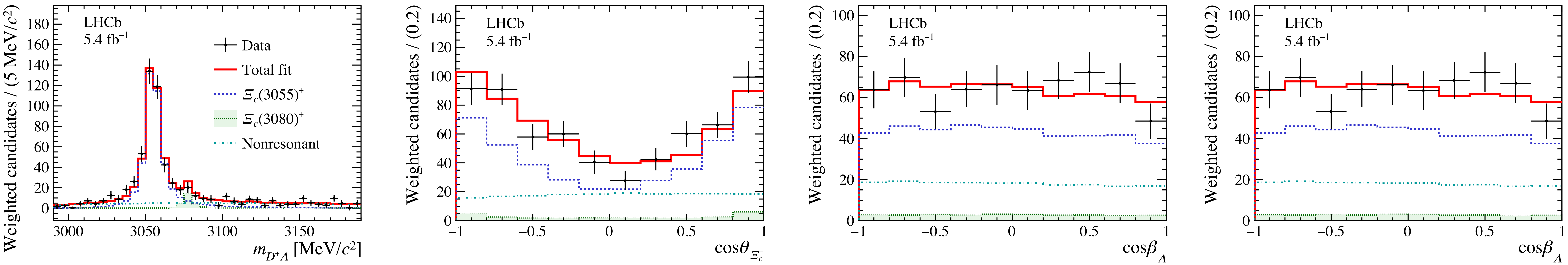
Spin & parity of $\Xi_c(3055)^{+/0}$

[Phys.Rev.Lett. 134 (2025) 8, 081901]

Marginalised too many details in my talk, please read

- Exploit the weak decay $\Xi_b^{0(-)} \to \Xi_c(3055)^{+(0)}(\to D^{+(0)}\Lambda)\pi^-$ (Ξ_b produced in the pp collision)
- Use $m(D^{+(0)}\Lambda)$ and 3 angles to test different J^P hypotheses for the Xic (3/2) using the helicity formalism. Hypotheses: 1/2, 3/2, 5/3, 7/2, all with either parity

$J^P = 3/2^+$ hypothesis favoured over others: 6.5 (3.5) σ for charged (neutral) $\Xi_c(3055)$



[arXiv:2504.05063]
Submitted to JHEP

New Ξ_{cc}^{++} decay: Ξ_c π π

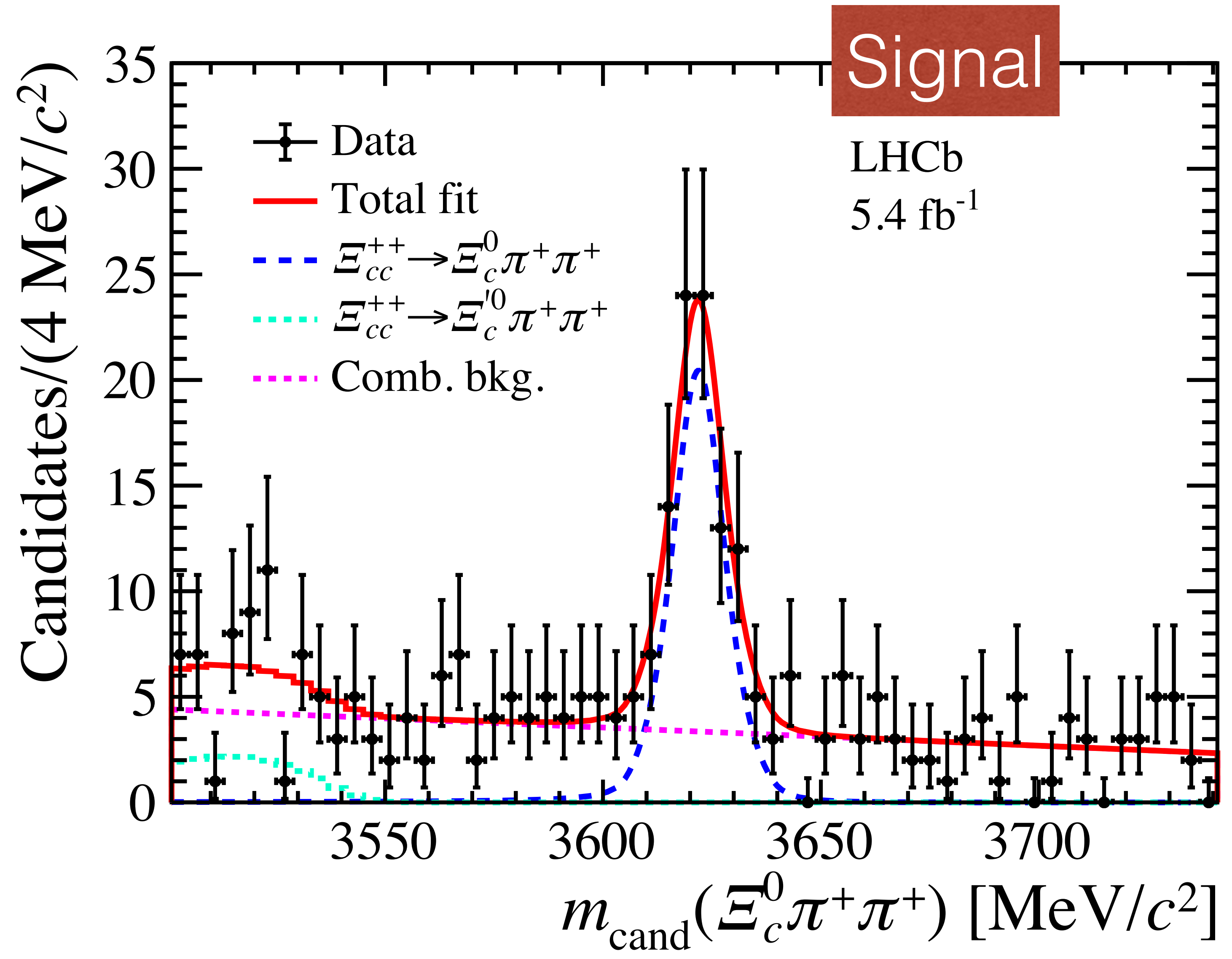
- Doubly charmed baryons can give an insight in hadronic systems with 2 ‘heavy’ quarks, relatively unexplored

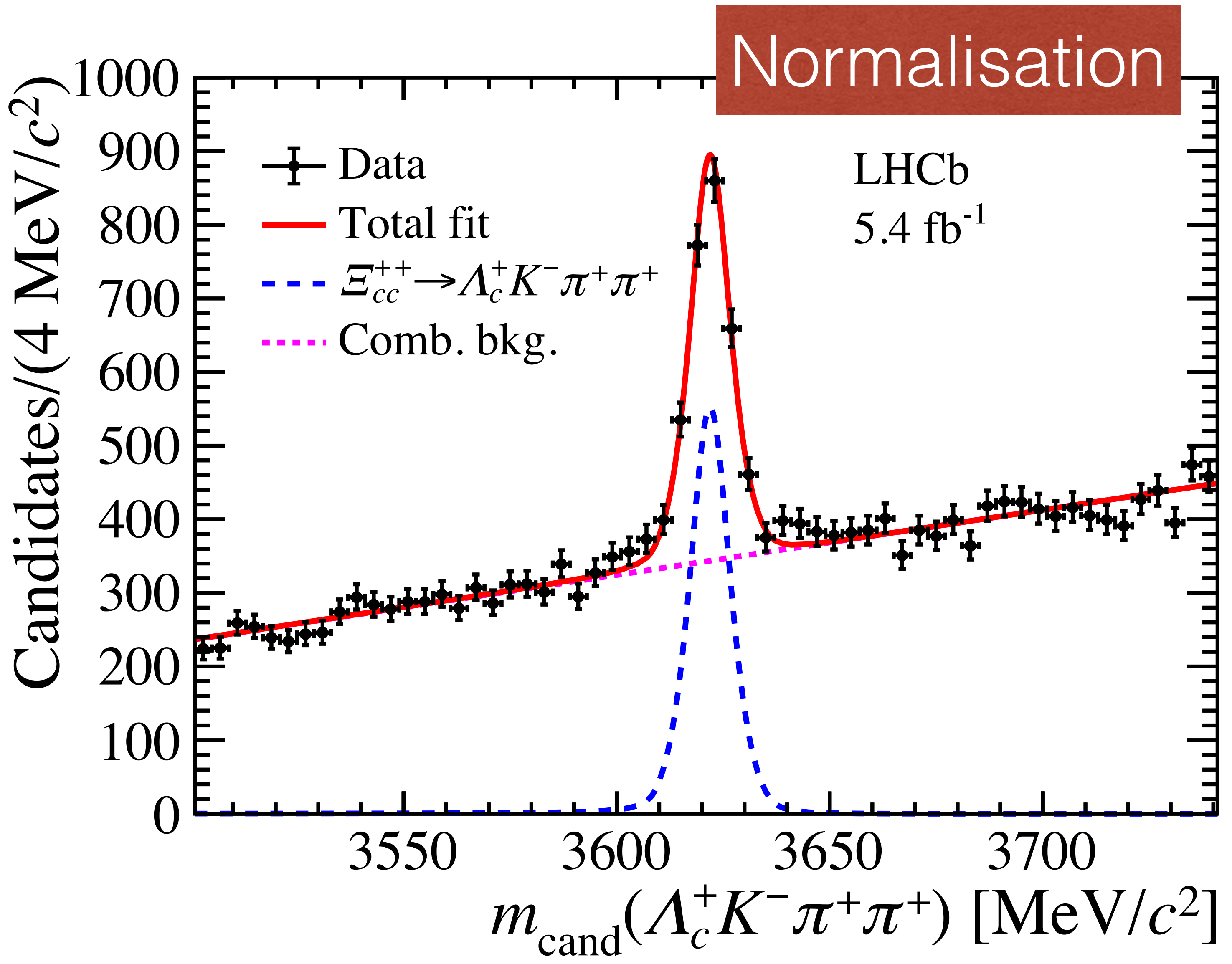
- $\Xi_{cc}^{++}(ccu)$ only one observed so far, and only via 3 decay modes
(searches for $\Xi_{cc}^{+}(ccd)$ and $\Omega_{cc}^{+}(ccs)$ continue, but more challenging…)

- New: using the Run-2 data, observed a clear signal of
$\Xi_{cc}^{++}(ccu) \to \Xi_c^0 \pi^+ \pi^+$

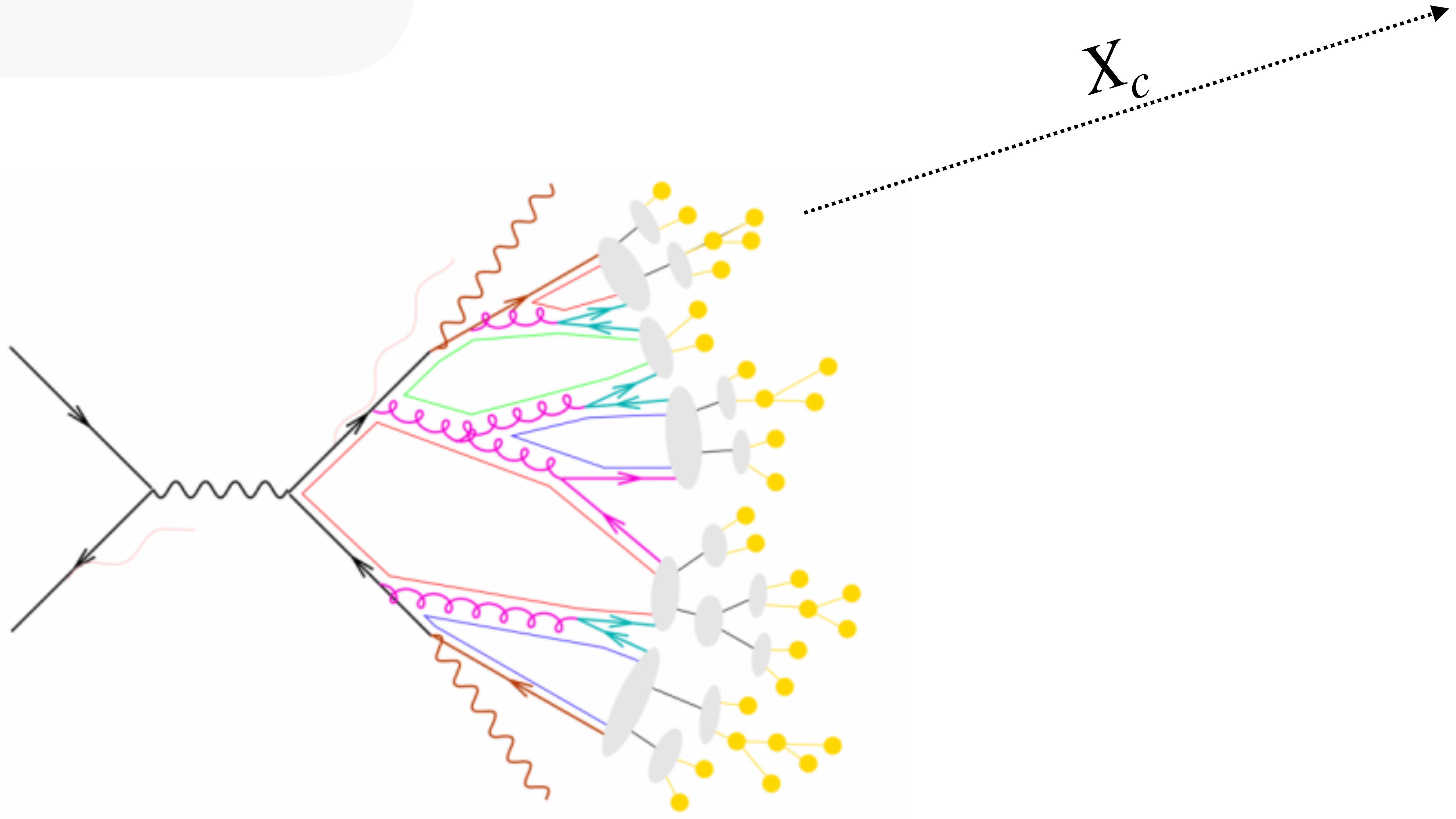
Measured branching fraction:

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^0 \pi^+ \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)} = 1.37 \pm 0.18(\text{stat}) \pm 0.09(\text{syst}) \pm 0.35(\text{ext})$$





Charmed production as probe for QCD



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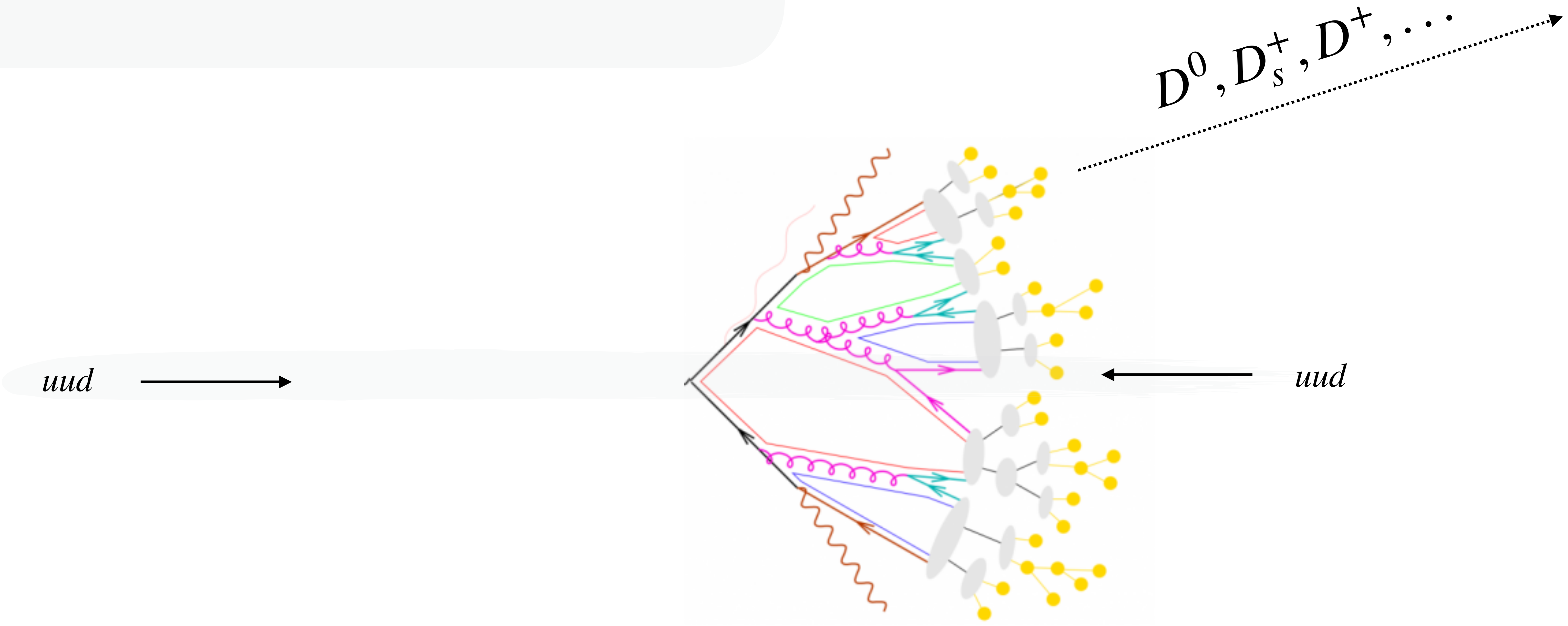
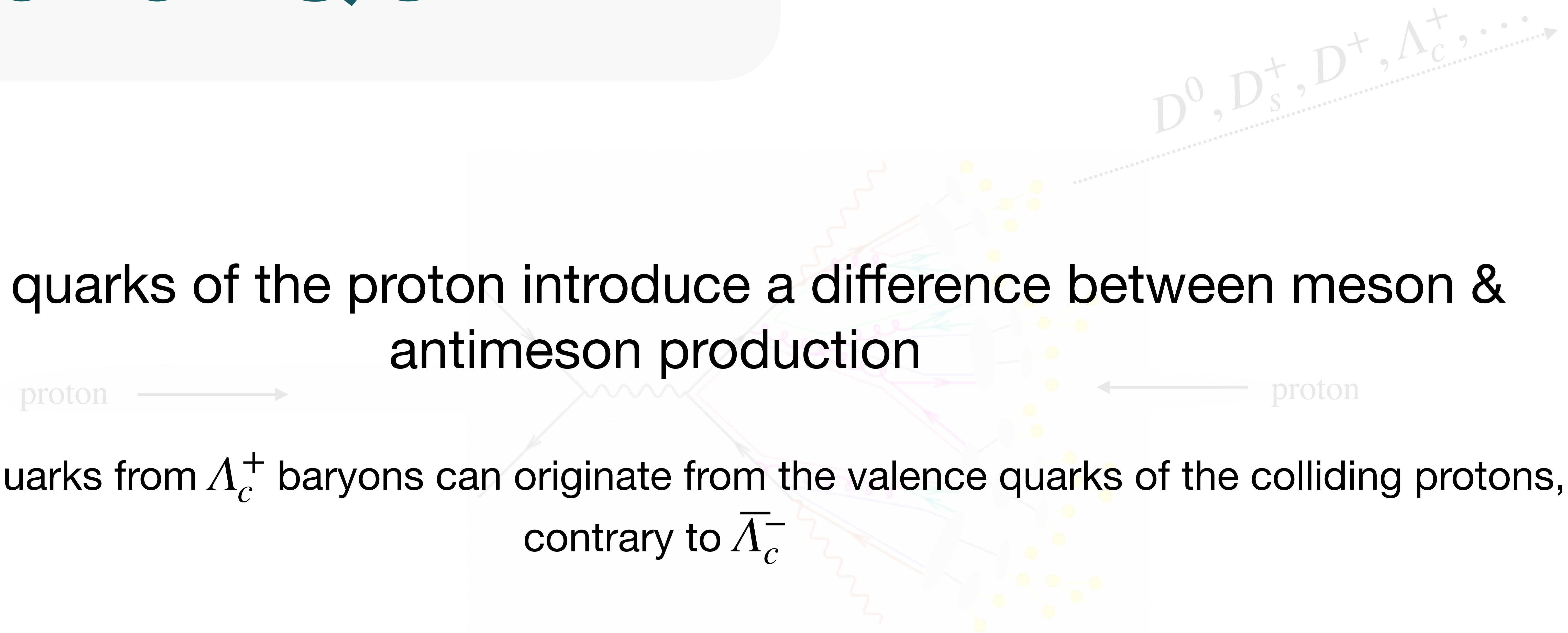


Asymmetries between charm and anticharm production
a probe for hadronisation in *pp* collisions

Charmed production as probe for QCD



Valence quarks of the proton introduce a difference between meson & antimeson production

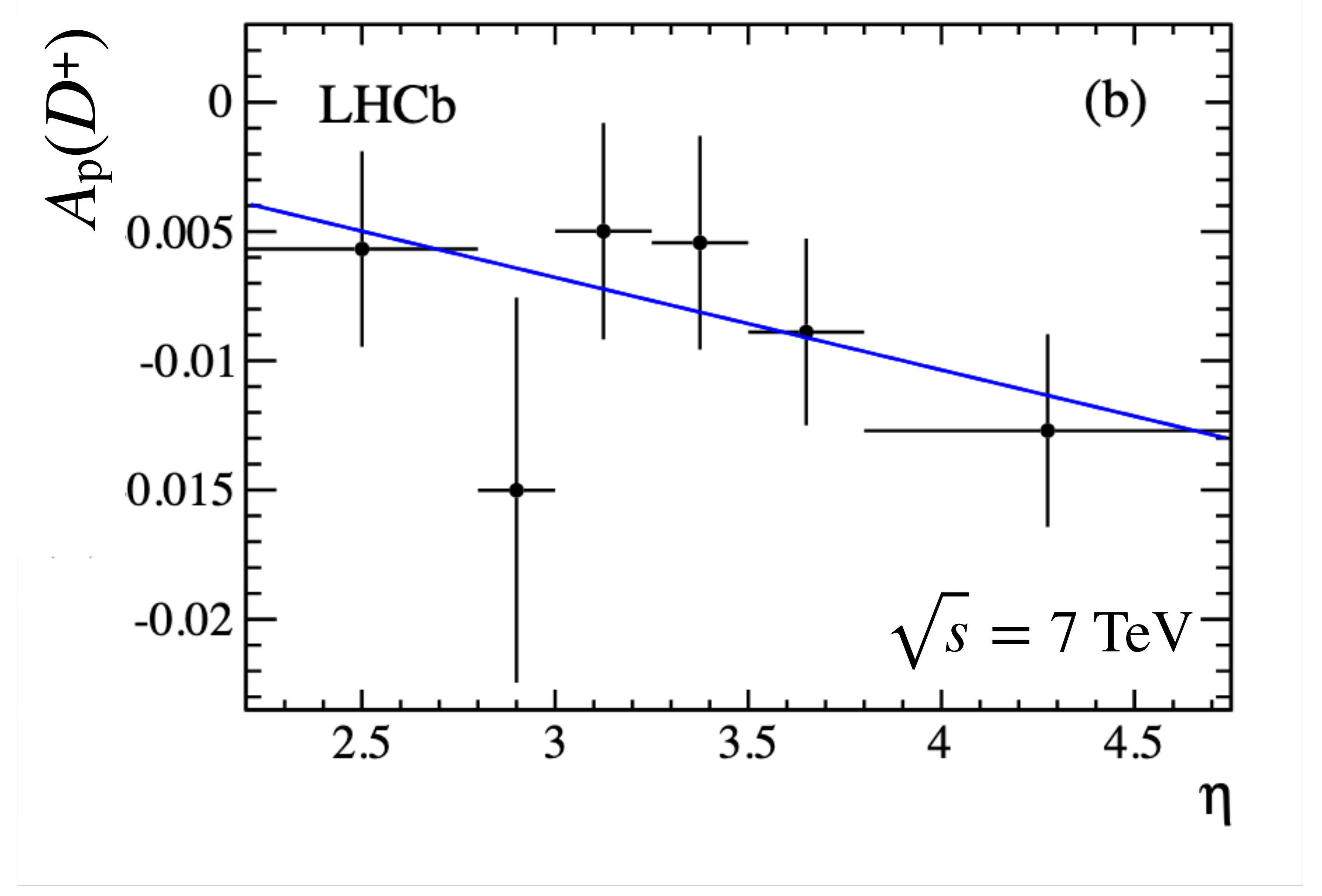
e.g. Valence quarks from Λ_c^+ baryons can originate from the valence quarks of the colliding protons, contrary to $\overline{\Lambda}_c^-$

Test of hadronisation models & non-perturbative QCD, sensitive to intrinsic charm of proton

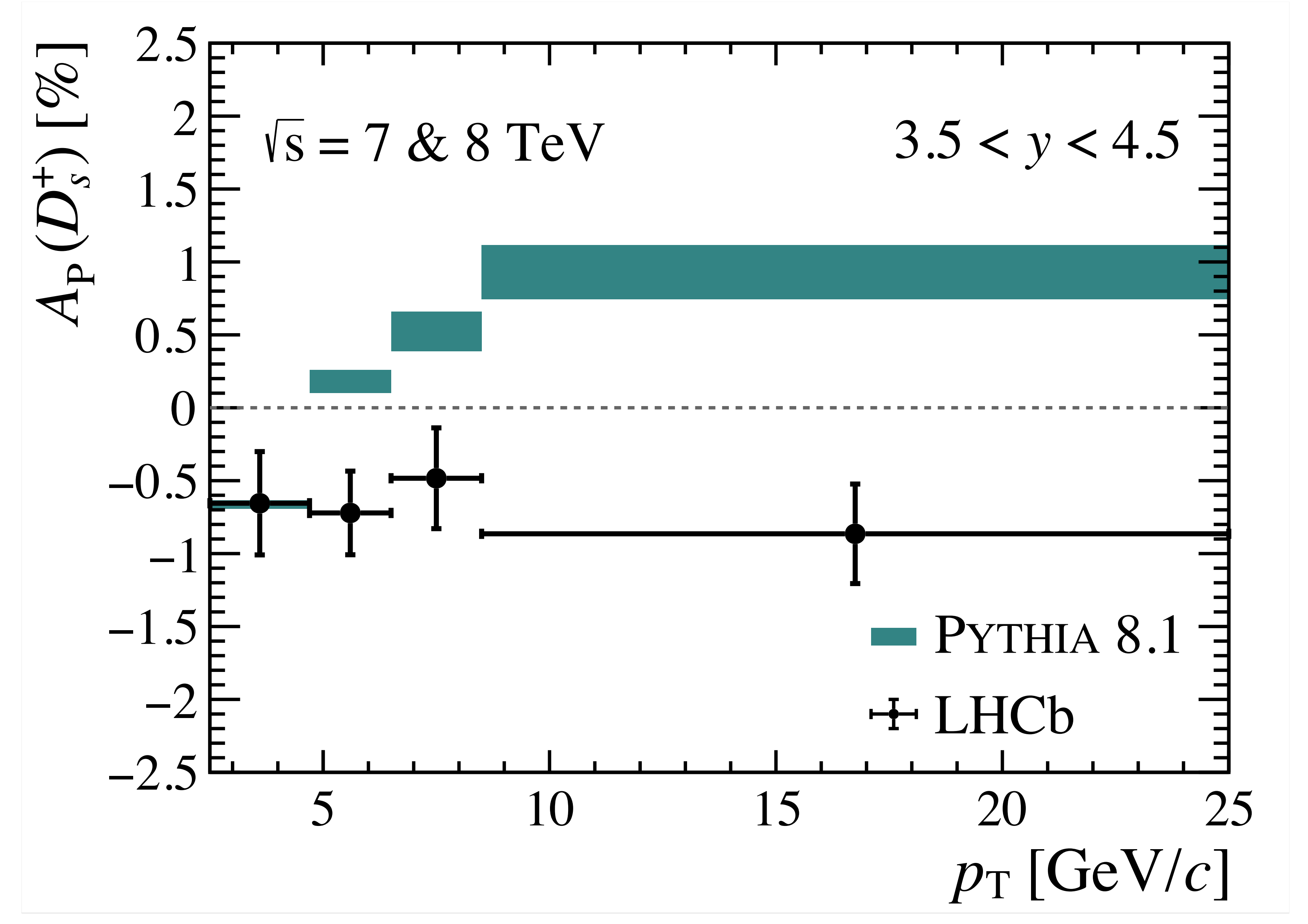
Measuring these asymmetries valuable for measurements of charm-anticharm differences (CPV)

Previous measurements (Run 1)

LHCb collaboration | Phys. Lett. B. 718 (2013) 902-907



LHCb collaboration | JHEP 08 (2018) 008



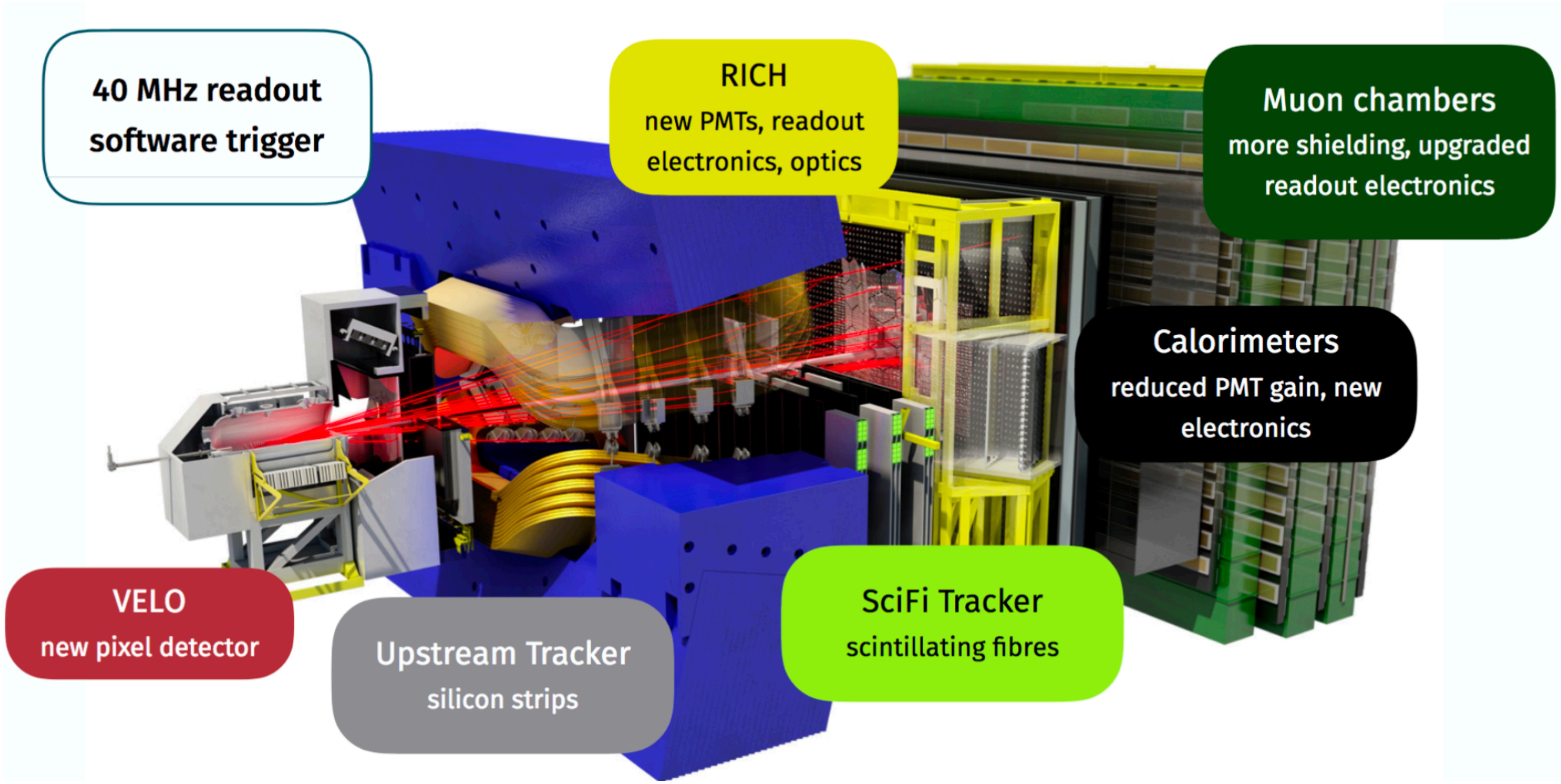
$$A_{\text{prod}}(D_s^+) = \frac{\sigma(pp \to D_s^+ X) - \sigma(pp \to D_s^- X)}{\sigma(pp \to D_s^+ X) + \sigma(pp \to D_s^- X)}$$

Expect (different) asymmetries present for all charm mesons & baryons, and depending on $\sqrt{s}$, p_T, η

LHC Run 3: 13.6 TeV

See also: V. V. Gligorov (plenary), D. Vom Bruch, G. Cavallero, M. Diaz, …

The LHCb Run 3 detector *the king is decommissioned, long live the king*



To good approximation: **a brand new detector**, operating since 2022

Paradigm shift significant (~5) simultaneous interactions per crossing, with a real-time full-software trigger

Run 3

[arXiv:2505.14494]
Submitted to JHEP

Charm-anticharm production asymmetries

First measurements of production asymmetries of the D^0, D_s^+ and D^+ at $\sqrt{s} = 13.6$ TeV, in 2D intervals of (pT, eta)

(first measurements of the D^0 production asymmetry in *pp* collisions at LHC energies)

Strategies(*)

$D_{(s)}^+$

$$A_{\rm prod}(D_{(s)}^+) = A(D_{(s)}^+ \to \phi(1020)\pi^+) - A_{\rm det}(\pi^+)$$

Asymmetry in yield (counting) — Corrections due to instrumental biases

D^0

$$A_{\rm prod}(D^0) = A(D^0 \to K^-\pi^+) - A_{\rm det}(K^-\pi^+)$$

Asymmetry in yield (counting) — Corrections due to instrumental biases

First measurements with the new detector: using very first datasets (2022 & 2023)

Excellent test of the techniques for future measurements of CP-violating asymmetries

*: CPV in Cabibbo-favoured decays assumed to be negligible, measurements of CP asymmetries used for other decays

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Strategies(*)

$D_{(s)}^+$	**D^0**
$A_{\text{prod}}(D^+_{(s)}) = A(D^+_{(s)} \to \phi(1020)\pi^+) - A_{\text{det}}(\pi^+)$	$A_{\text{prod}}(D^0) = A(D^0 \to K^-\pi^+) - A_{\text{det}}(K^-\pi^+)$
Controlled using tag-and-probe method (partially reconstructed tracks from K^0_S decays)	$A_{\text{det}}(K^-\pi^+) = A\left(D^{*+} \to (D^0 \to K^-\pi^+)\pi^+\right) - A\left(D^{*+} \to (D^0 \to K^-K^+)\pi^+\right)$

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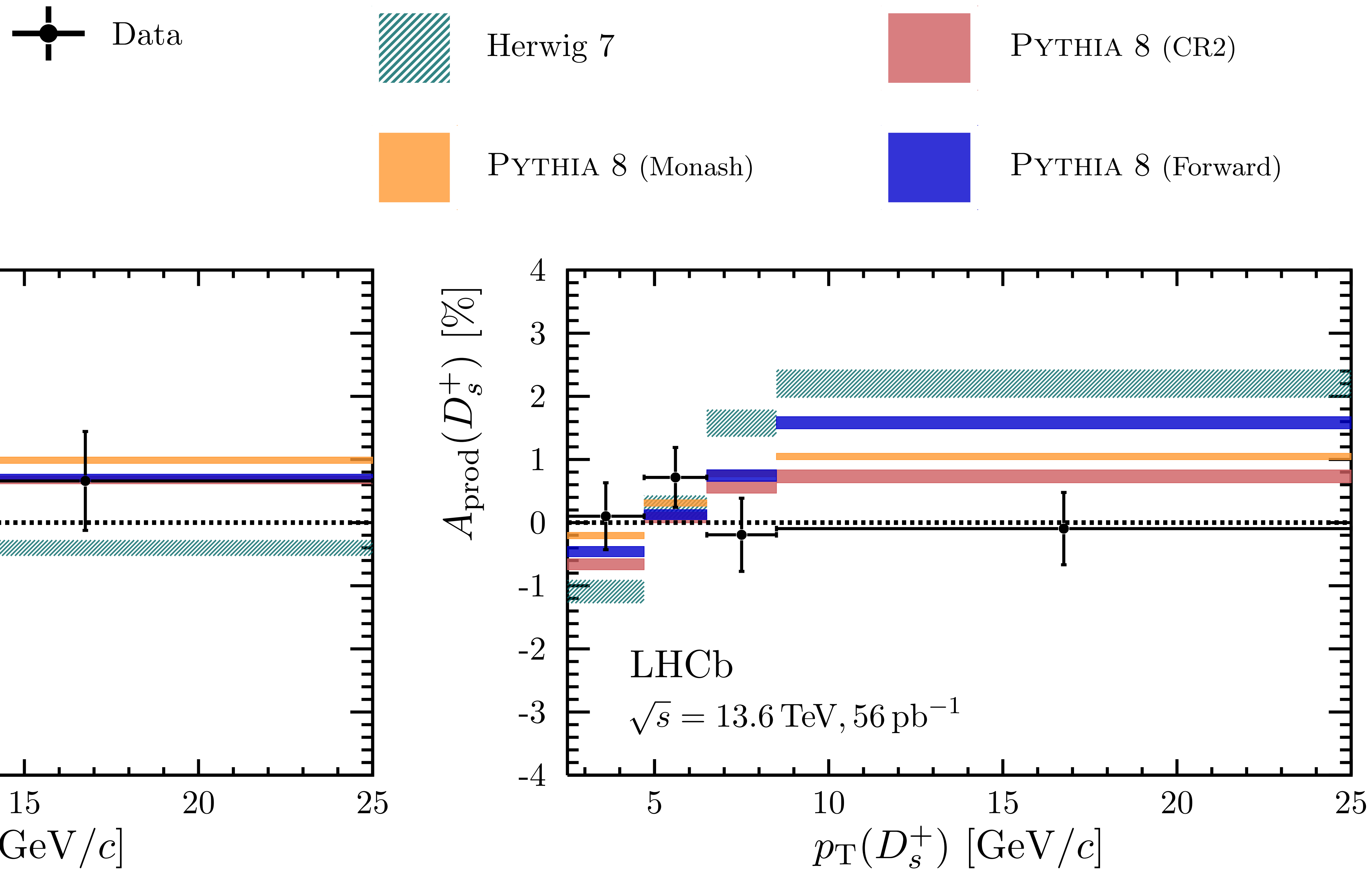
Production asymmetries: results (p_T)

- 2D measurements reported in the paper, along with exact measured distributions.

- 1D projections used to compare with common event generators: Herwig7 (cluster hadronisation), Pythia 8.3 (string)

Pythia8 Monash standard, based on e+ e- data
Pythia8 CR2 "QCD inspired" beam remnant+colour reconnection
Pythia8 Forward Recent tuning using LHCf data



Overall scale OK; high & low p_T behaviour most difficult to replicate

Run 3

[arXiv:2505.14494]
Submitted to JHEP

[2]: JHEP 10 (2021) 060

Production asymmetries: results (η)

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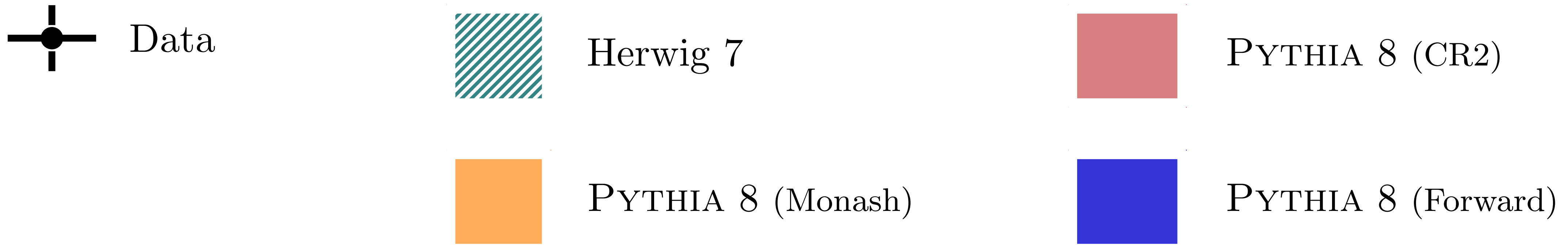
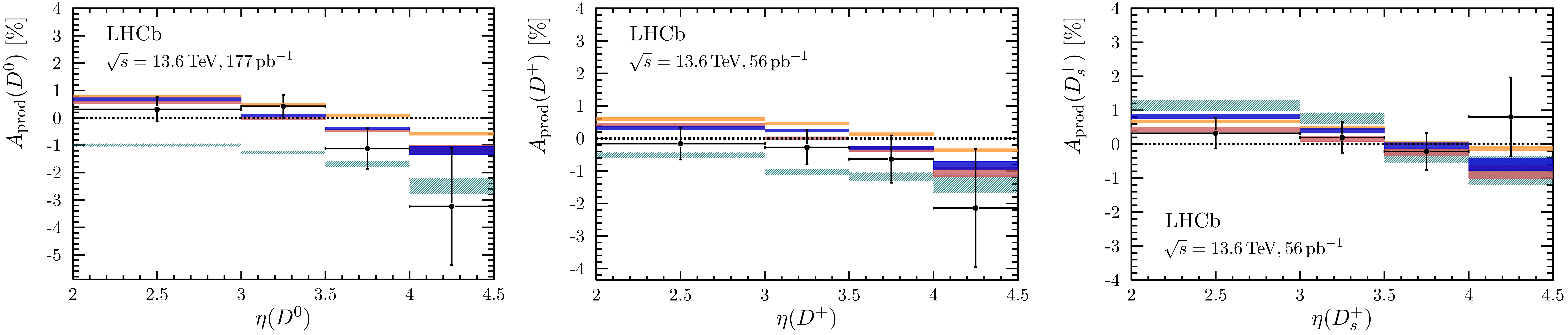




Reasonable agreement with Pythia. Best agreement with Pythia8 CR2 model (also observed for *b*-baryons[2])

Run 3

[arXiv:2505.14494]
Submitted to JHEP

Production asymmetries: integrated results

Integrating over LHCb phase-space, indication for typical size in LHCb analyses:

$$A_{\mathrm{prod}}(D^0) = \big(0.07 \pm 0.26\ (\mathrm{stat}) \pm 0.10\ (\mathrm{syst})\big)\%$$

$$A_{\mathrm{prod}}(D^+) = \big(-0.33 \pm 0.29\ (\mathrm{stat}) \pm 0.14\ (\mathrm{syst})\big)\%$$

$$A_{\mathrm{prod}}(D_s^+) = \big(0.18 \pm 0.26\ (\mathrm{stat}) \pm 0.08\ (\mathrm{syst})\big)\%$$

Comparing the statistical precision…

in Run 3 with 0.056 fb^{-1}

$$\sigma_{\mathrm{stat}}(A_{\mathrm{P}}(D^+)) = 0.29\,\%$$

in Run 1 with 1fb^{-1}

$$\sigma_{\mathrm{stat}}(A_{\mathrm{P}}(D^+)) = 0.26\,\%$$

Reached the same precision as Run-1 measurements that used 1 fb^{-1}, using only 1/10th of luminosity
demonstrates the potential of the Run-3 experiment for charm

Summary

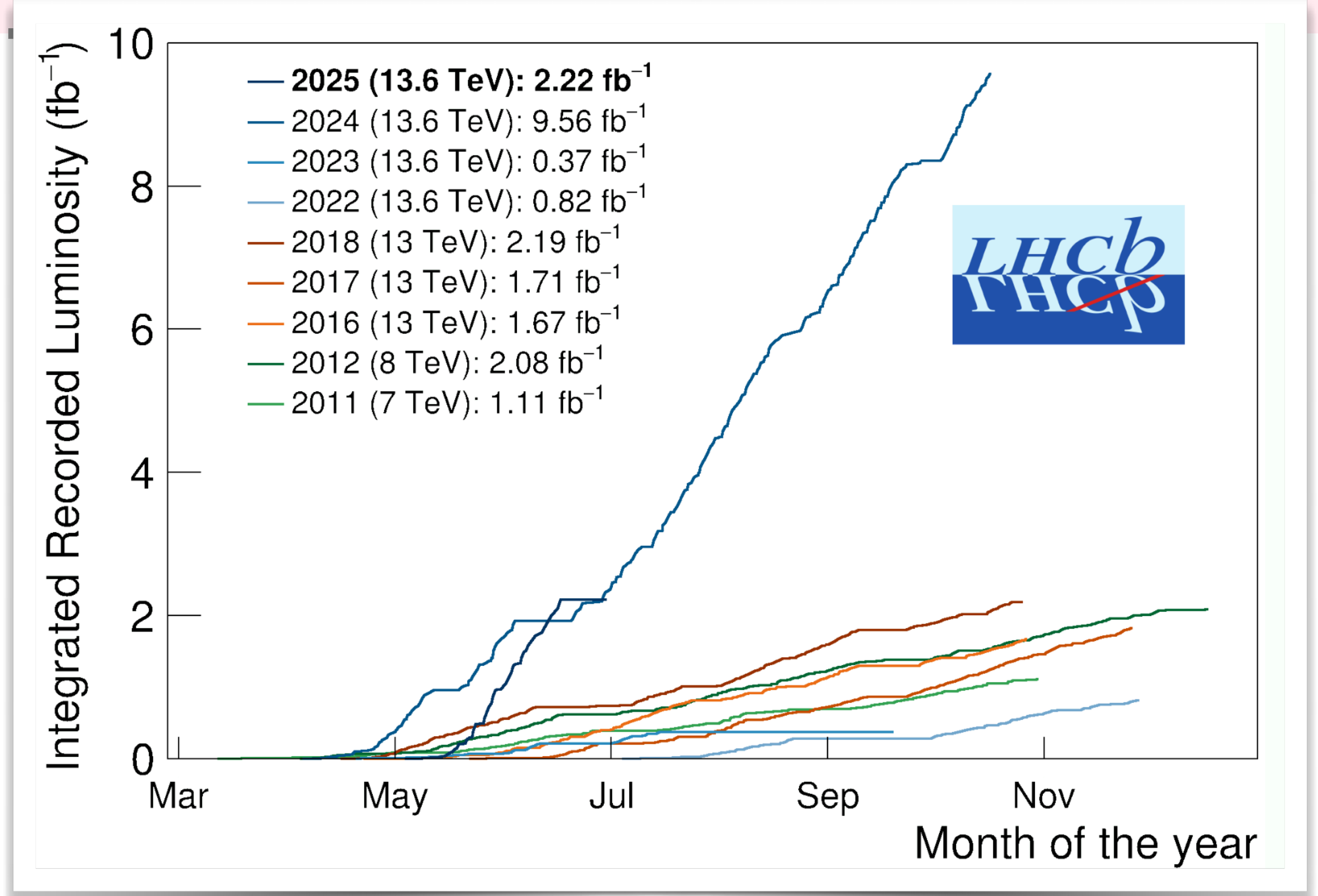
A snapshot of charmed hadron results from the LHCb collaboration

- New excited Ξ+c state $\Xi_c(2923)^+$
- Improved parameters for $\Xi_c(2815)^+$ and $\Xi_c(2970)^+$,
- A new decay of $\Xi_c(3080)^+$
- First observation of the $\Xi_{cc}^{++} \to \Xi_c^0 \pi^+ \pi^+$ decay
- First determination of the spin & parity of the $\Xi_c(3055)^{+,0}$ states

Charm hadrons & decays

- Production asymmetry of D^0, D^+ and D_s^+ mesons in pp collisions

Production



Run-3 LHCb on track to record an unprecedented data set
already more data than Run 1+2

First measurements confirm charm benefits massively from the new detector
Exciting times ahead!

LHCb results on charmed hadrons

Production, properties, and decay

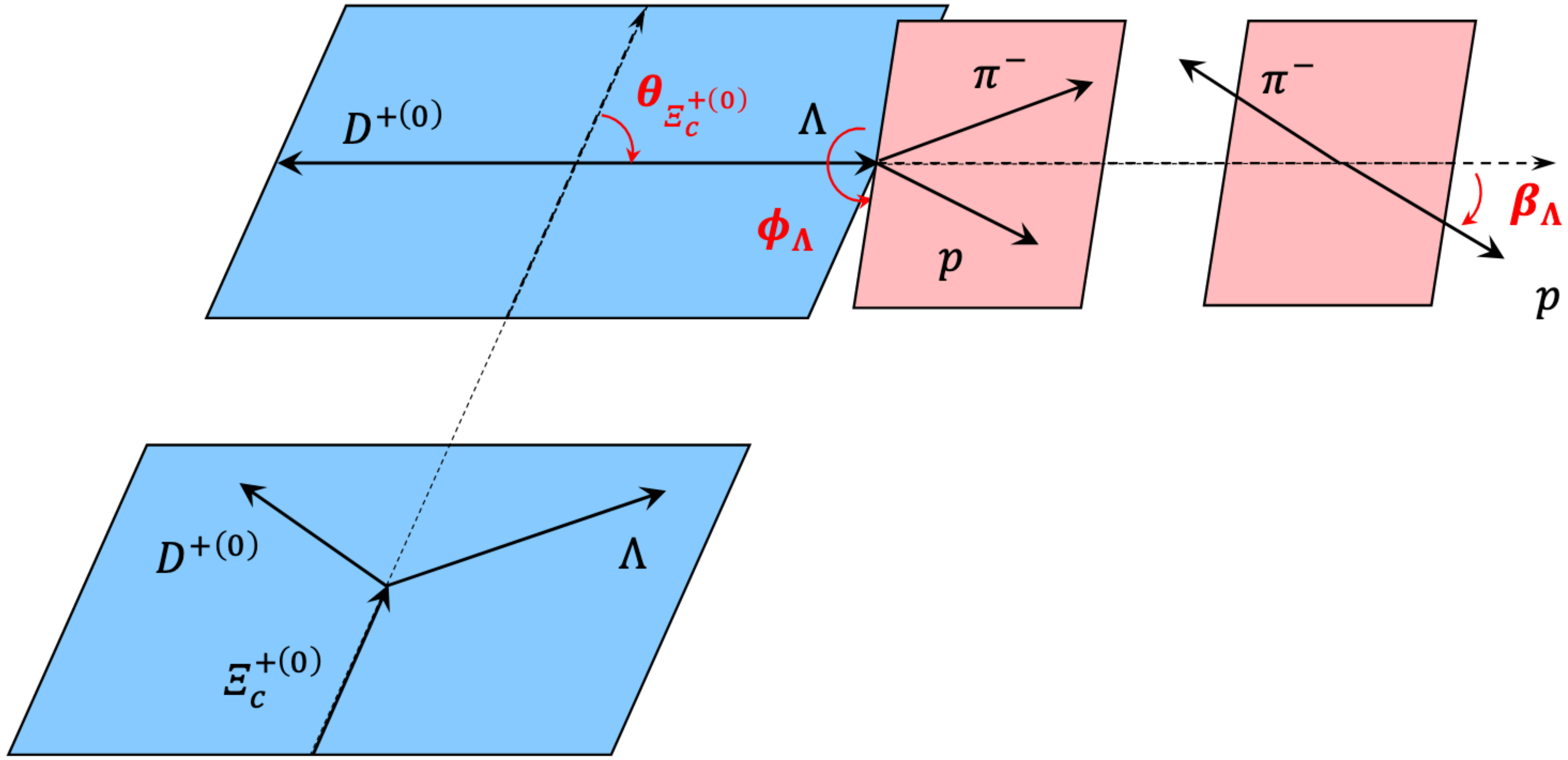
EPS-HEP | QCD & Hadronic physics July 8, 2025

Laurent Dufour, on behalf of the LHCb collaboration

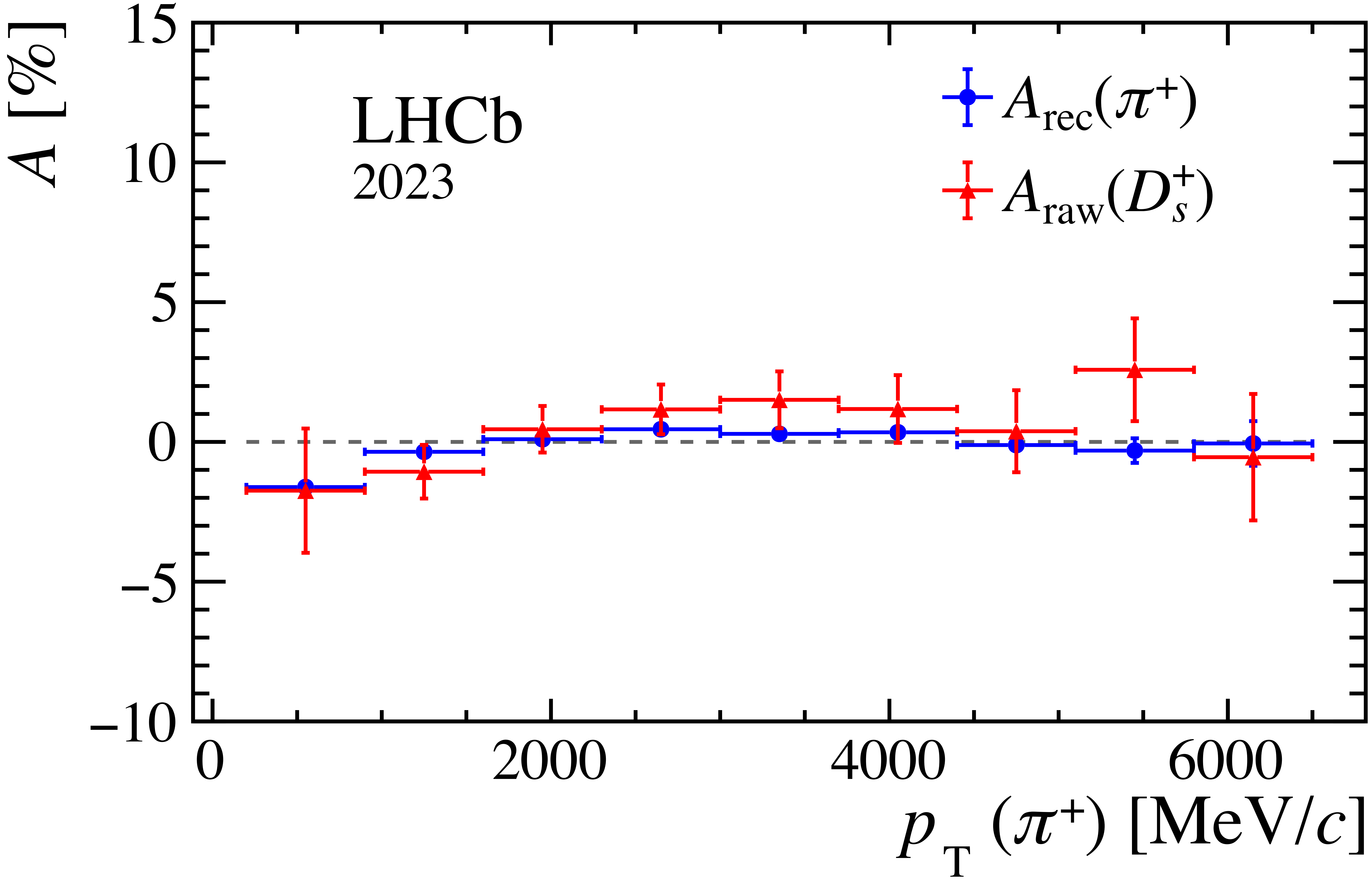
Helicity angles

Phys.Rev.Lett. 134 (2025) 8, 081901

$\Xi_b^{0(-)} \to D^{+(0)}\Lambda\pi^-$ decay kinematics are fully described by the invariant mass $m_{D^{+(0)}\Lambda}$ and three angular variables $\vec{\Omega} \equiv (\cos\theta_{\Xi_c^{+(0)}}, \phi_\Lambda, \cos\beta_\Lambda)$. The variable $\theta_{\Xi_c^{+(0)}}$ is the angle between the Λ momentum and the momentum of the pion from the $\Xi_b^{0(-)}$ decay, in the rest frame of the $D^{+(0)}\Lambda$ system (denoted as $\Xi_c^{+(0)}$), and is referred to as the $\Xi_c^{+(0)}$ helicity angle. Similarly, the Λ helicity angle β_Λ is defined by the momentum of the proton and that of the $D^{+(0)}$ meson in the Λ rest frame. The variable ϕ_Λ is the angle between the $\Xi_c^{+(0)} \to D^{+(0)}\Lambda$ and $\Lambda \to p\pi^-$ decay planes. These angles are illustrated in Fig. 5 in

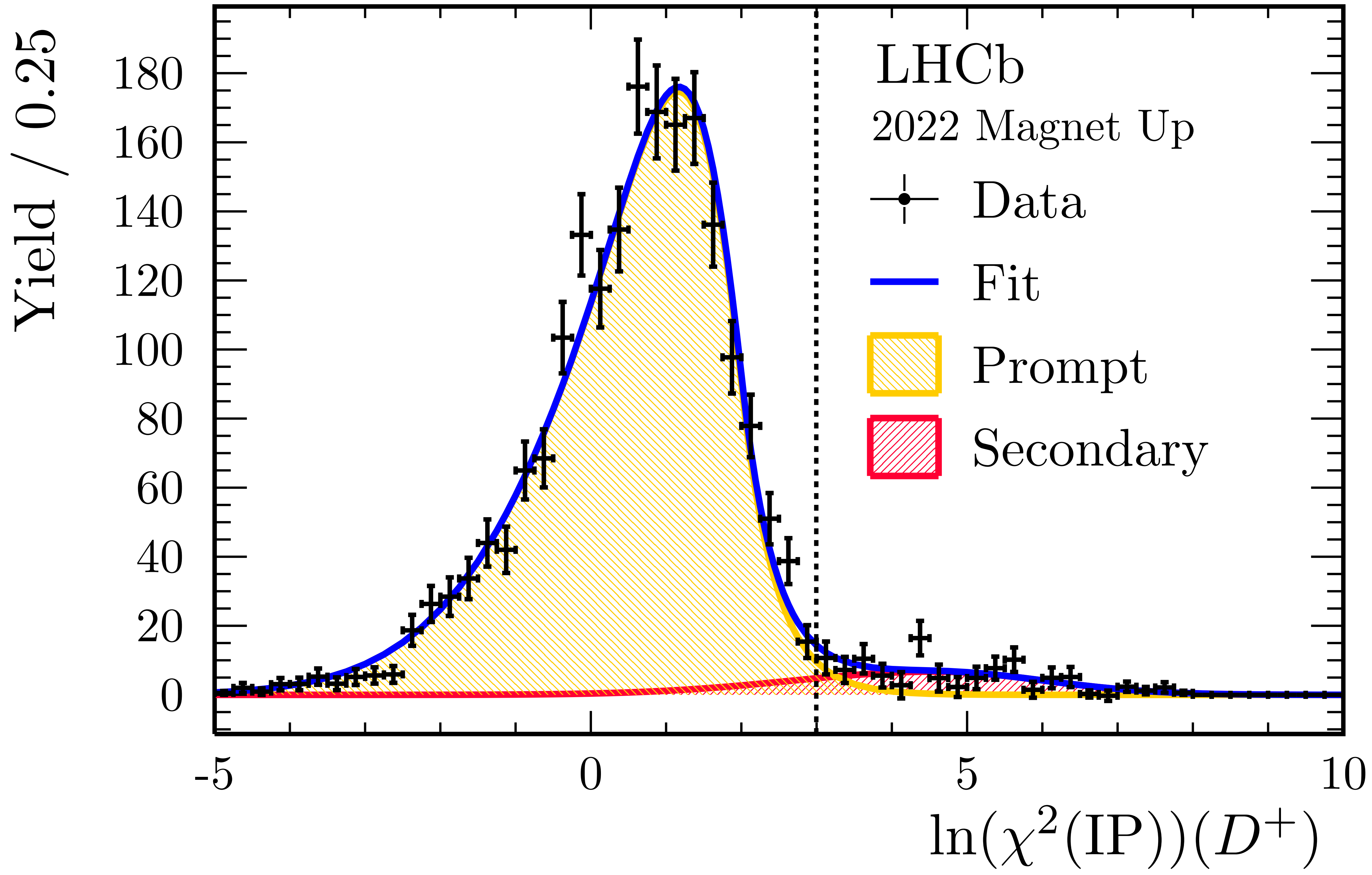


Pion asymmetries



Secondaries

Velo closed



Velo open