LHCb Heavy Flavour Production and Spectroscopy (Conventional)

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Introduction

The LHCb detector

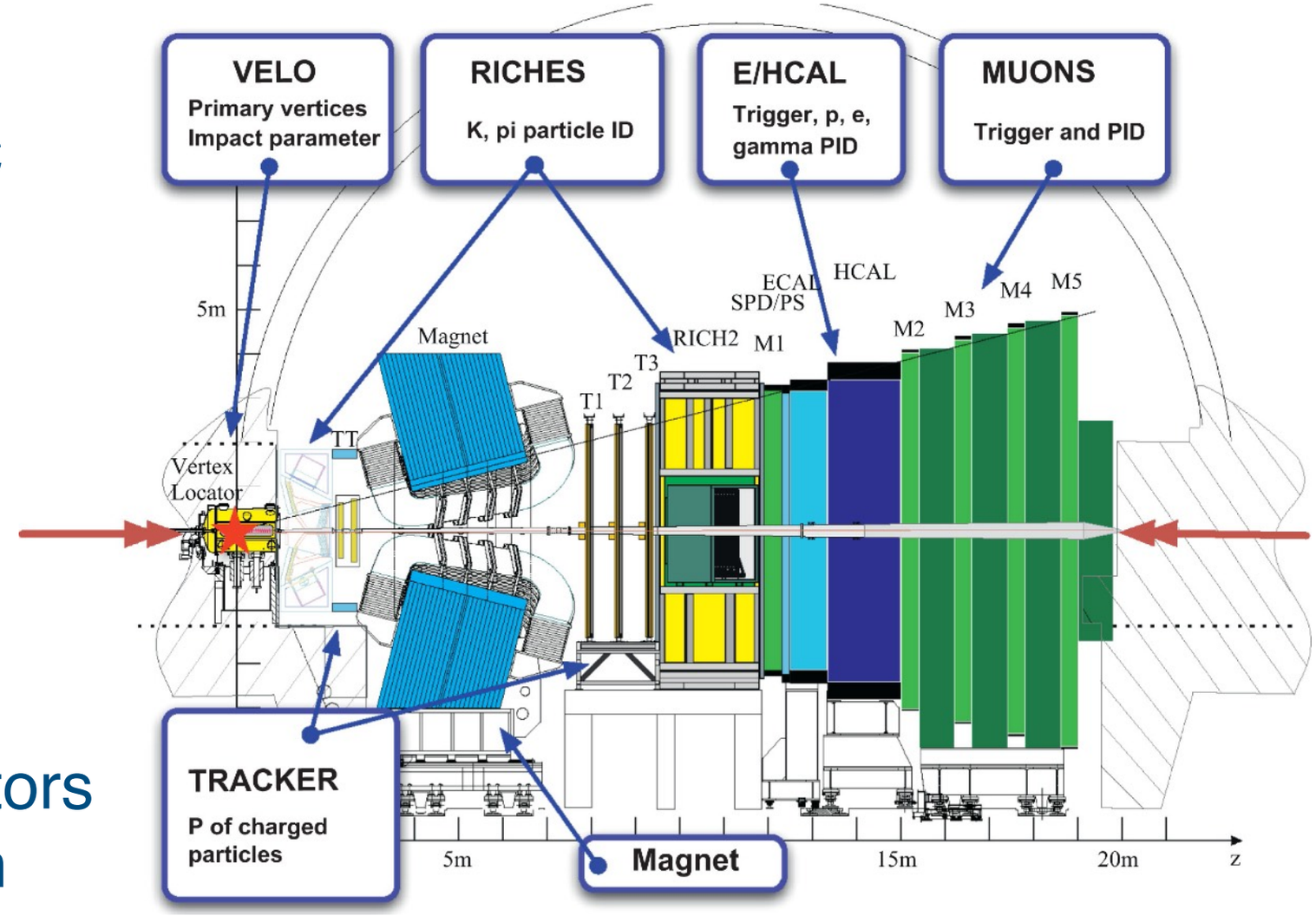
LHCb

LHCb - single arm forward spectrometer, located at LHC

Acceptance: $2 < \eta < 5$

Proton-proton interaction at up to 13 TeV

Physics goals:
- CP violation in b and c sectors
- General purpose physics in forward region



Introduction

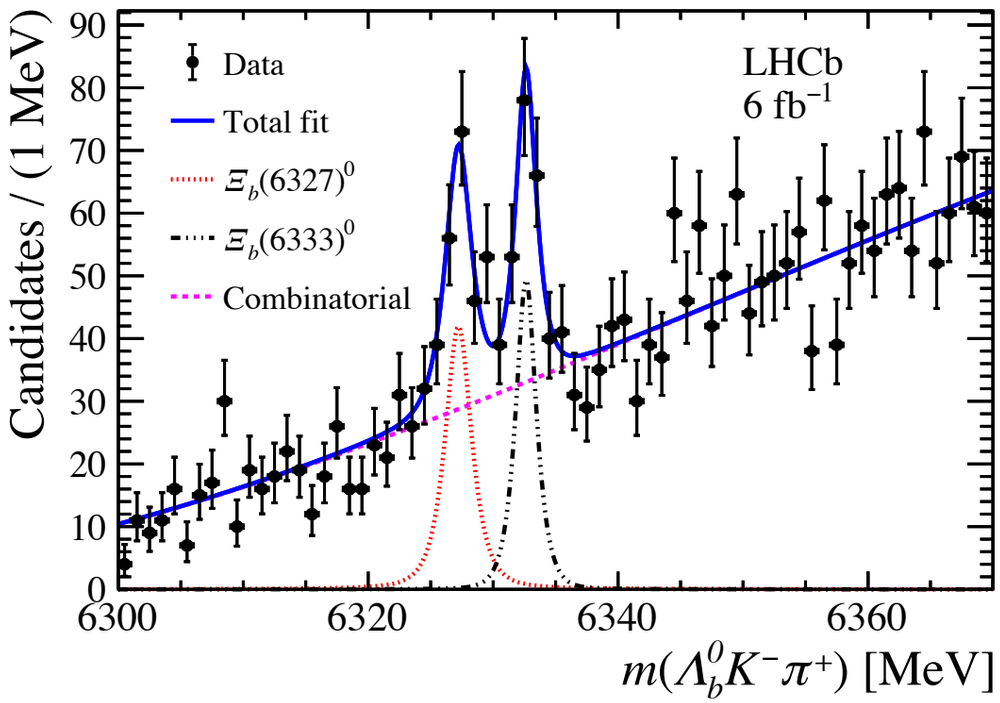
- Strong interaction and QCD less known than EW in the Standard Model
  - Critical in precision SM test and searching for new physics
- Studies of QCD properties
  - Hadron spectroscopy: quark-quark/gluon interaction in confinement regime
  - Heavy flavour production: perturbative and non-perturbative, factorisation

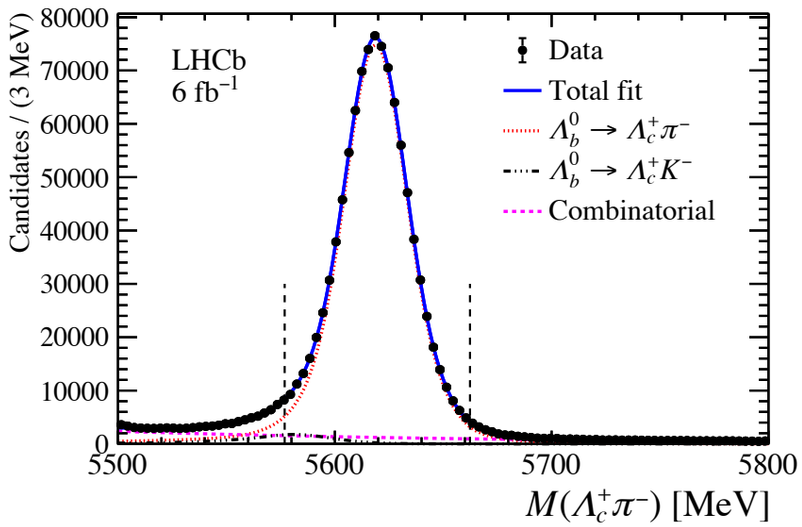
Conventional spectroscopy

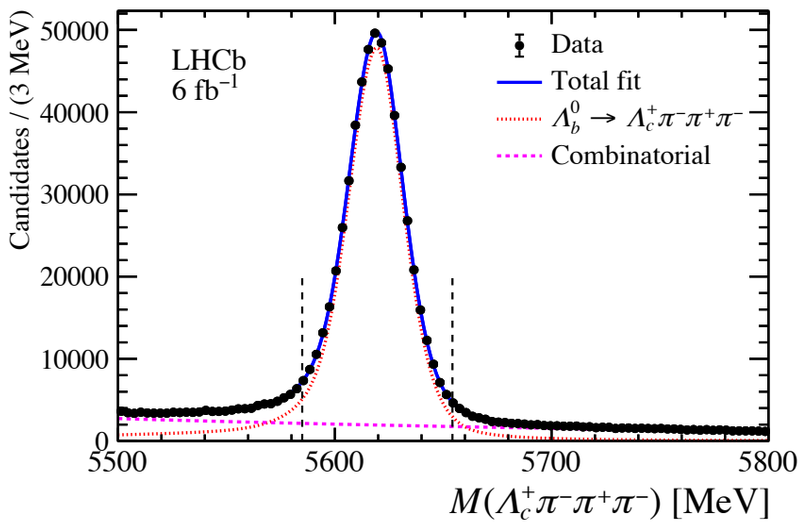
Observation of $\Xi_b(6327)^0$ and $\Xi_b(6333)^0$ states

[arXiv:2110.04497]

- L = 5.7 fb^{-1}, collected in 2015-2018
  - 1M $\Lambda_b^0(\to \Lambda_c^+\pi^-)$ and 0.5M $\Lambda_b^0(\to \Lambda_c^+3\pi)$
- Decay: $\Xi_b(6327)^0$ or $\Xi_b(6333)^0 \to \Lambda_b^0 K^-\pi^+$
  - 9σ significance vs background-only hypothesis
  - 5σ significance vs one-peak hypothesis



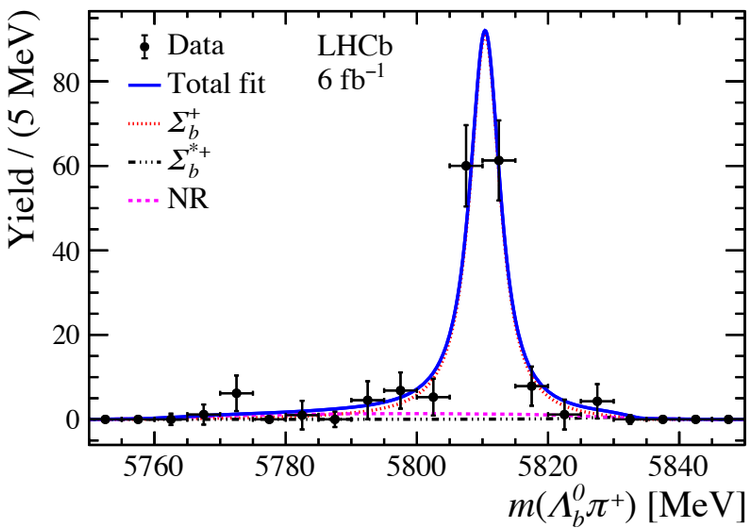


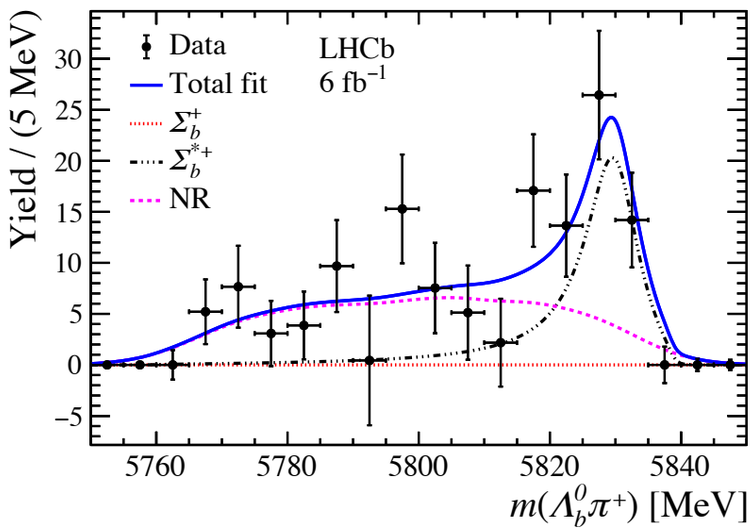


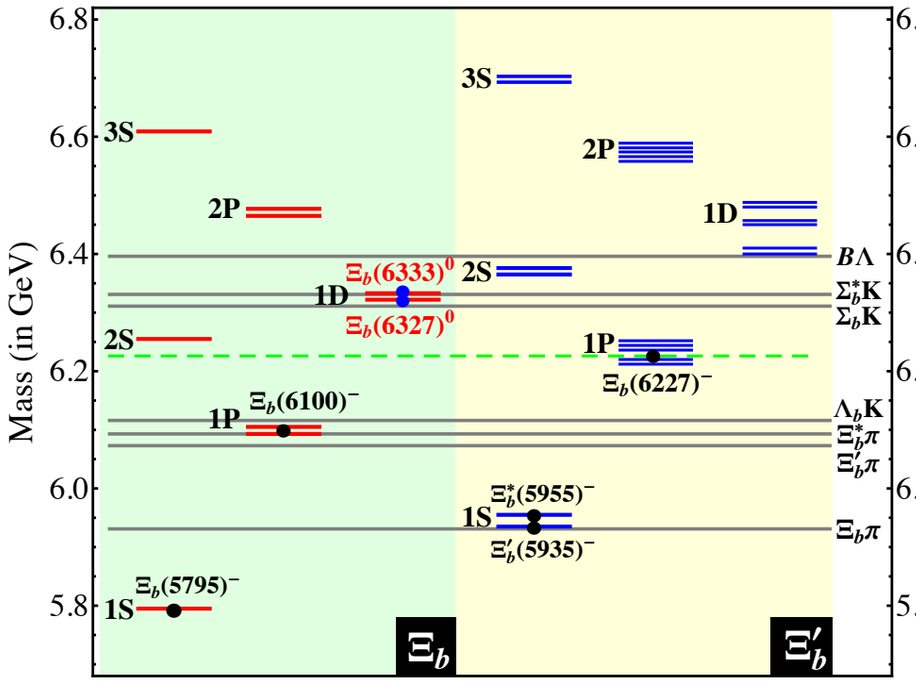
Observation of $\Xi_b(6327)^0$ and $\Xi_b(6333)^0$ states

[arXiv:2110.04497]

- Mass measurements
  - $m(\Xi_b(6327)^0)$: $6327.28^{+0.23}_{-0.21}$(stat) ± 0.08(syst) ± 0.24($m(\Lambda_b^0)$) MeV
  - $m(\Xi_b(6333)^0)$: $6332.69^{+0.17}_{-0.18}$(stat) ± 0.03(syst) ± 0.22($mm(\Lambda_b^0)$) MeV
- Background subtracted $m(\Lambda_b^0\pi^+)$ spectra
  - $\Xi_b(6327)^0$: predominantly to $\Sigma_b^+K^-$
  - $\Xi_b(6333)^0$: half $\Sigma_b^{*+}K^-$ and half NR
- Strong candidates of 1D Ξ_b states





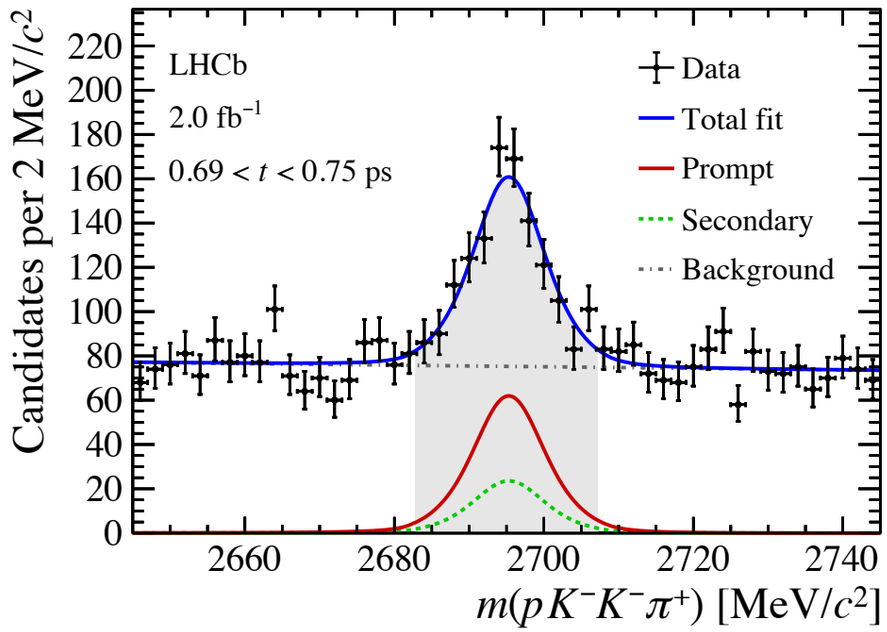


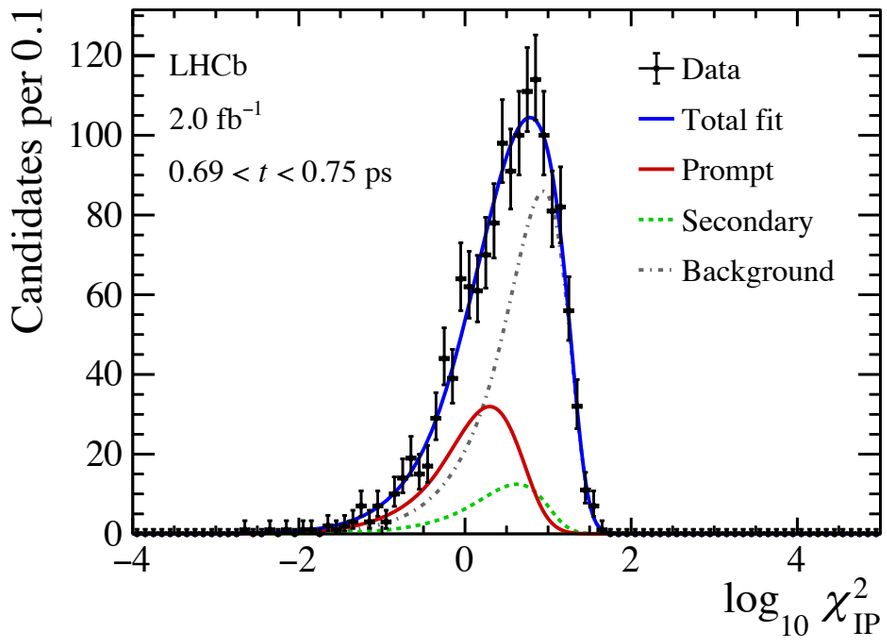
See Hongjie's talk

Measurement of Ξ_c^0 and Ω_c^0 lifetimes

[arXiv:2109.01334]

- L = 5.7 fb^{-1}, collected in 2016-2018
- Prompt $\Omega_c^0/\Xi_c^0 \to pK^-K^-\pi^+$ decays
- 12K Ω_c^0 and 36K Ξ_c^0 signals produced directly from pp collisions
- Larger signal yields than samples from b-hadron decays used in previous study
- Higher background level
- Selection efficiency varies with decay time
- Prompt signal yields determined in decay-time intervals with
  - $m(pK^-K^-\pi^+)$: invariant mass
  - χ^2_{IP}: significance of the impact parameter

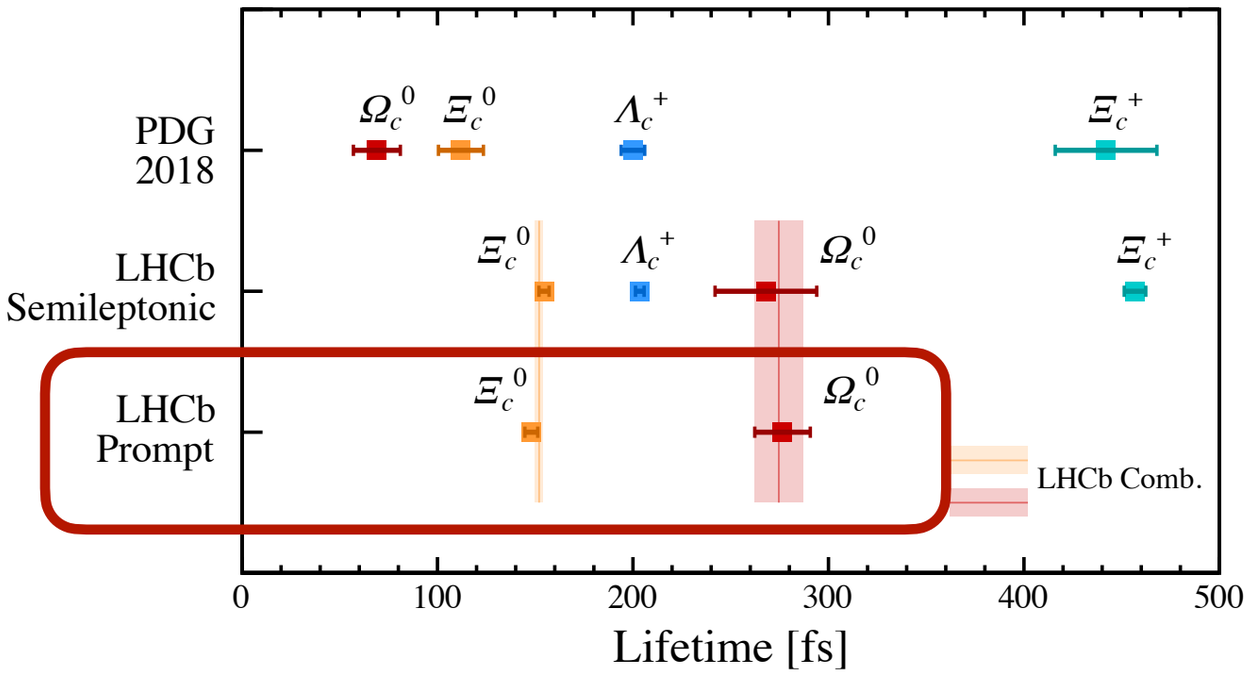


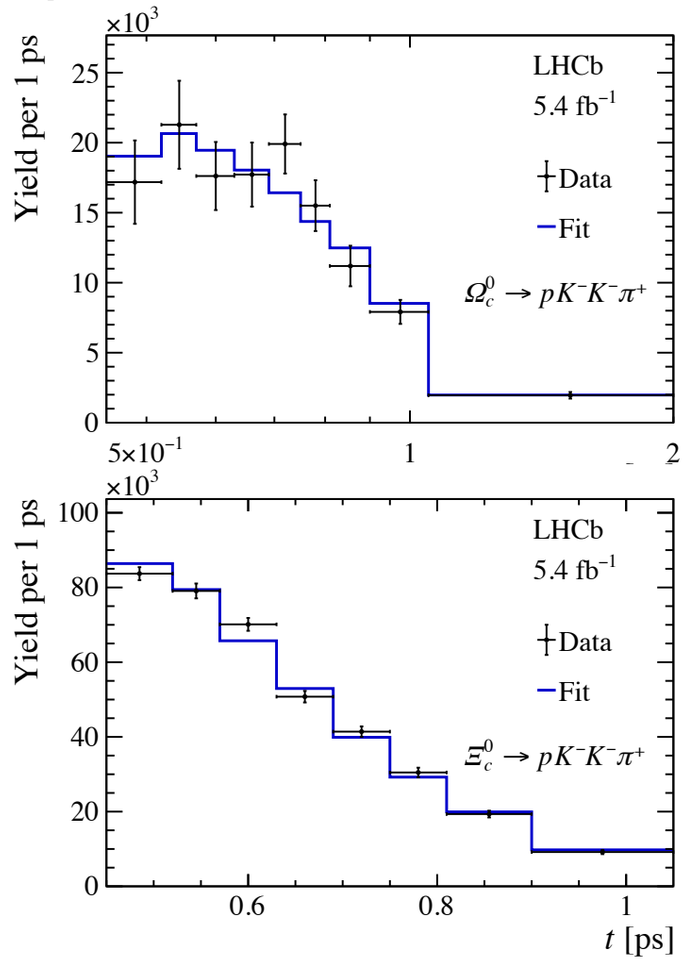


Measurement of Ξ_c^0 and Ω_c^0 lifetimes

[arXiv:2109.01334]

- χ^2 fits to the decay-time distributions
- $\tau(\Omega_c^0) = 276.5 \pm 13.4(\text{stat}) \pm 4.4(\text{syst}) \pm 0.7(D^0)$ fs
- $\tau(\Xi_c^0) = 148.0 \pm 2.3(\text{stat}) \pm 2.2(\text{syst}) \pm 0.2(D^0)$ fs



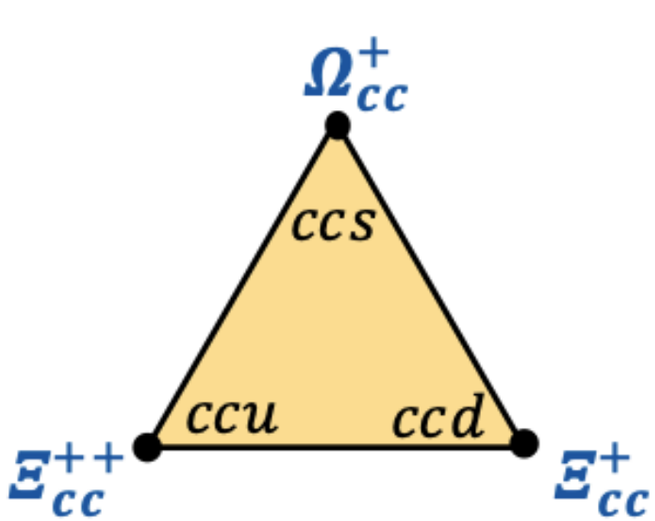


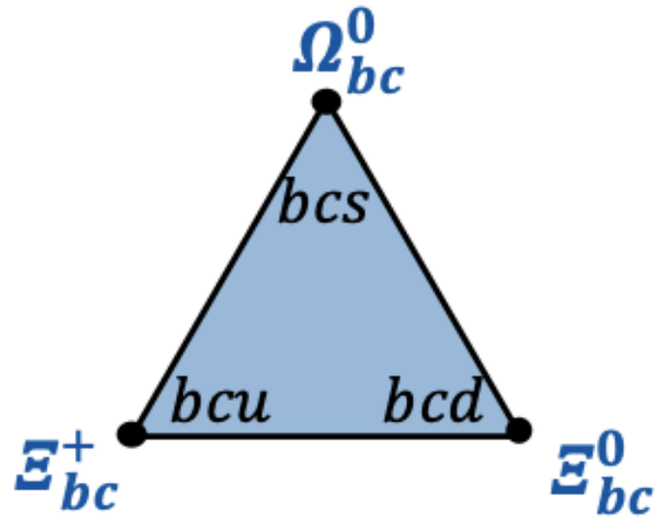
Confirmed the lifetime hierarchy observed previously
$\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$

See Ao's talk

Doubly heavy baryon

- Ground states ($J^P=1/2^+$) in the constituent quark model



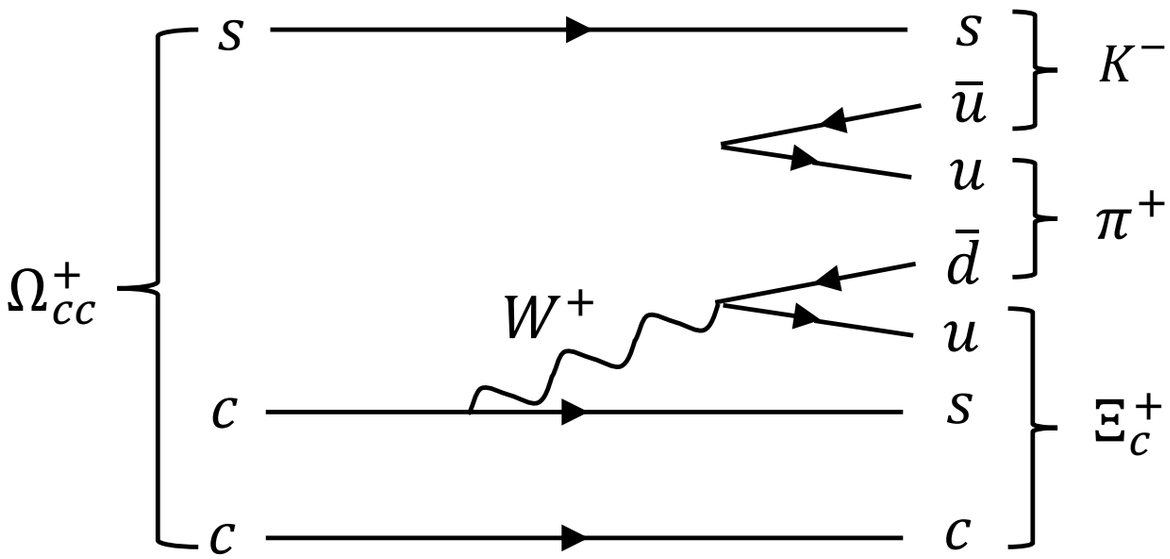


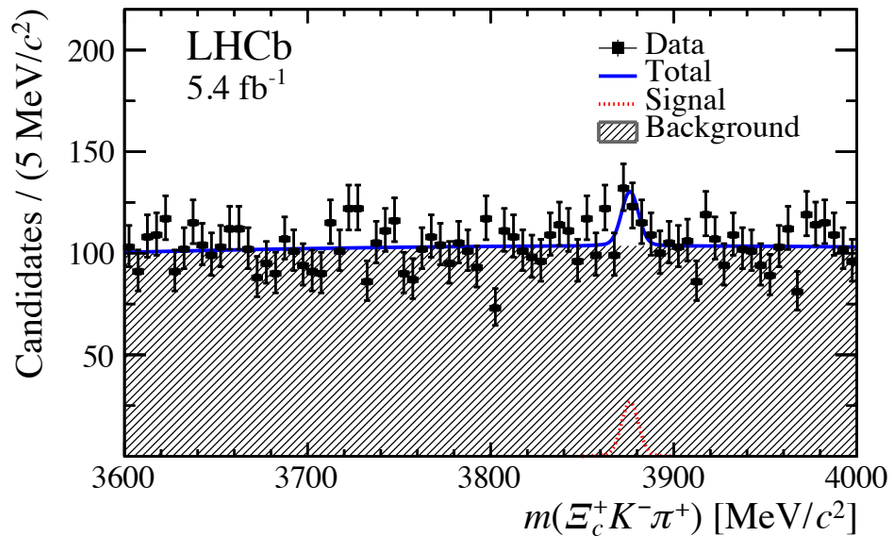
- Ξ_{cc}^{++} observation and subsequent studies led by LHCb Chinese groups
  Observation: arXiv:1707.01621,
  Lifetime: arXiv:1806.02744,
  New decay channel: arXiv:1807.01919,
  Production: arXiv:1910.11316,
  Mass: arXiv:1911.08594.
- Recent efforts on searches of Ξ_{cc}^{+}, Ω_{cc}^{+}, Ξ_{bc}^{0}, Ω_{bc}^{0}

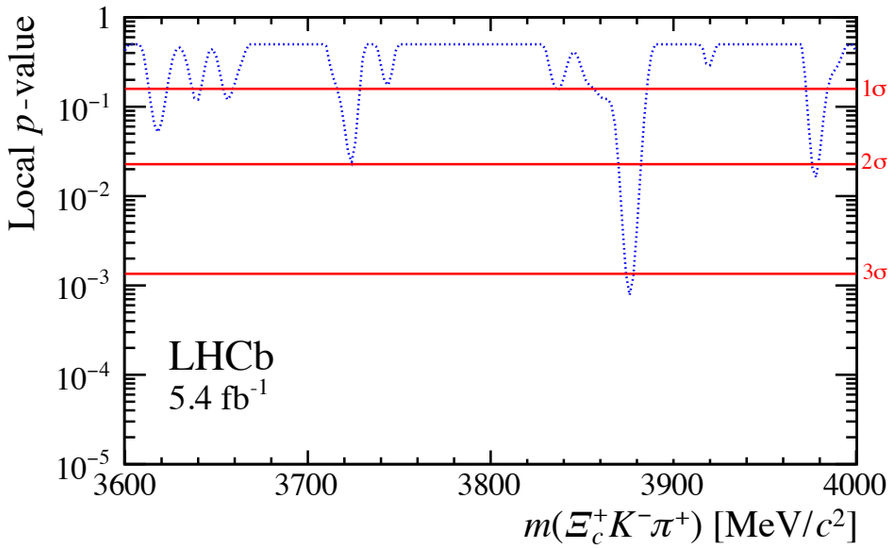
Search for Ω_{cc}^+

[SCPMA 64 (2021) 101062]

- L = 5.4 fb^{-1}, collected in 2016–2018
- Searches for $\Omega_{cc}^+ \to \Xi_c^+\pi^+K^-$
- First search for Ω_{cc}^+







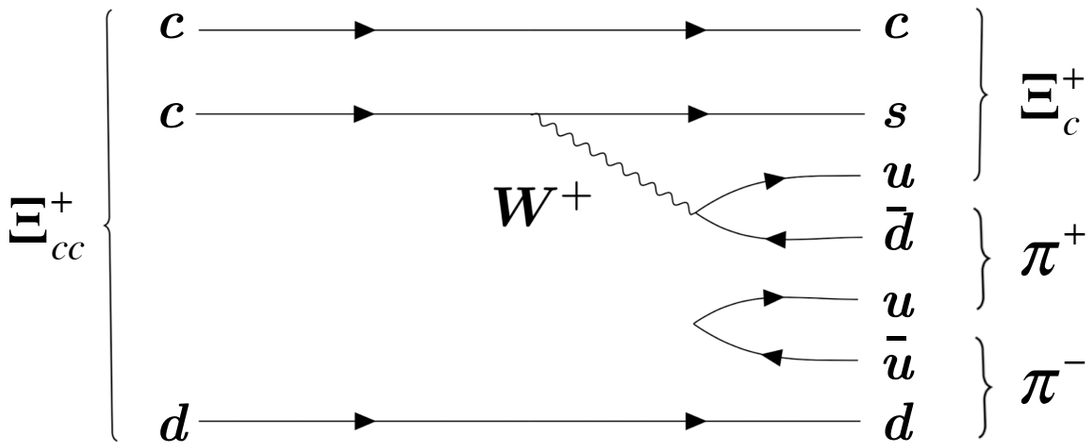
global (local) significance is 1.8σ (3.2σ)

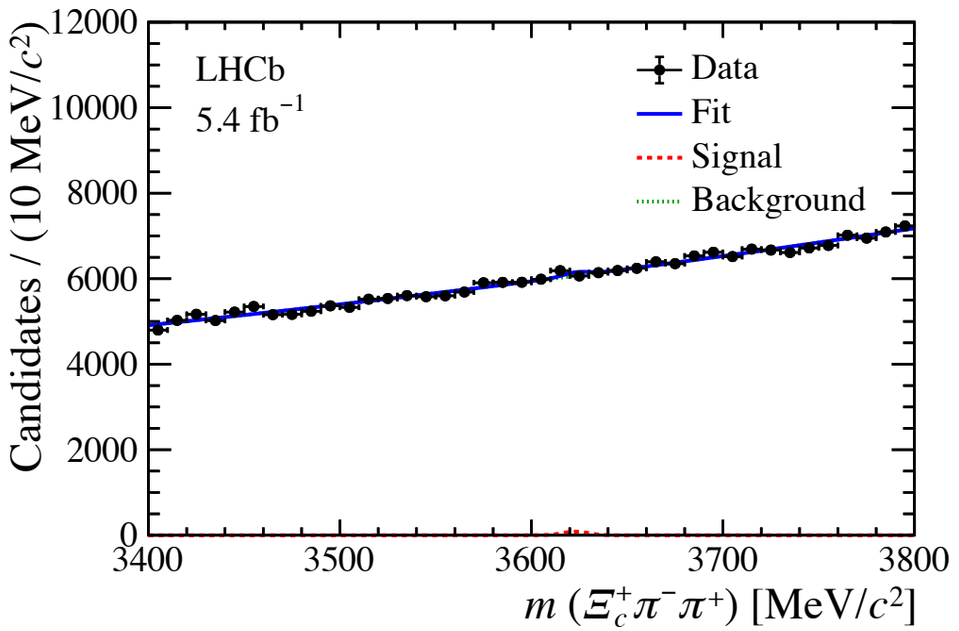
See Jingyi's talk

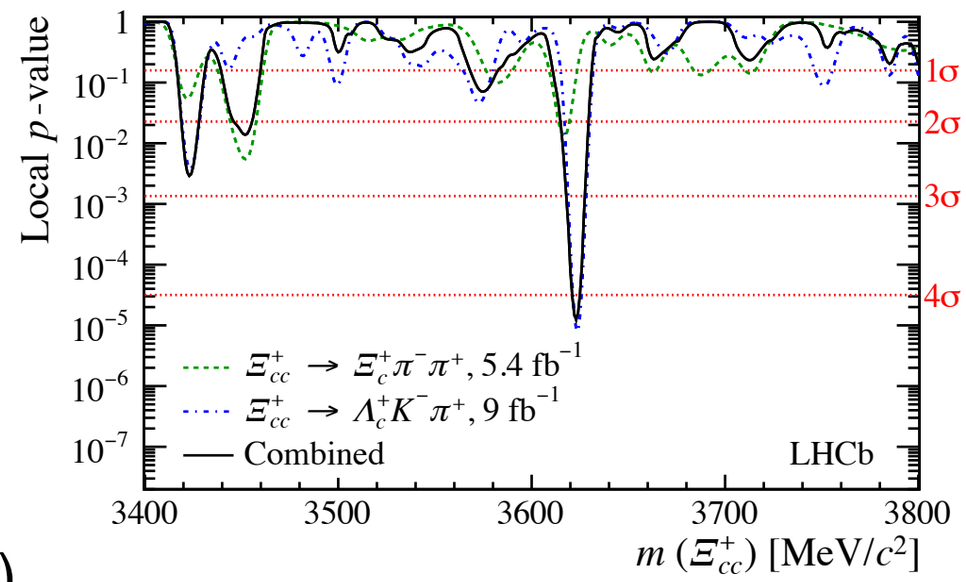
Search for Ξ_{cc}^+

[arXiv:2109.07292]

- L = 5.4 fb^{-1}, collected in 2016–2018
- Searches for $\Xi_{cc}^+ \to \Xi_c^+\pi^+\pi^-$
- Previously studied in $\Xi_{cc}^+ \to \Lambda_c^+K^-\pi^+$







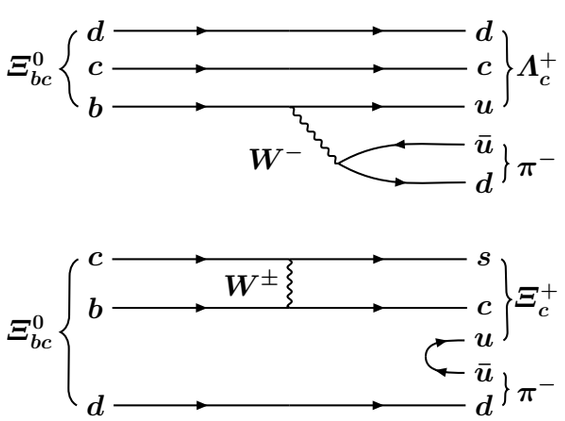
combined global (local) significance is 2.9σ (4.0σ)

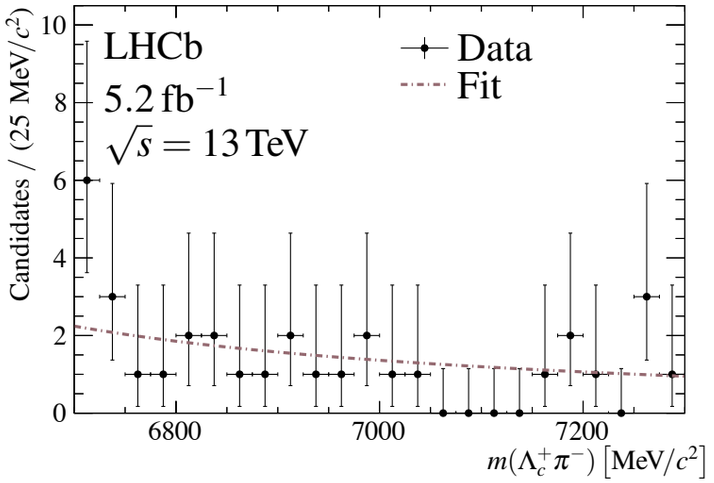
See Jiesheng's talk

Search for Ξ_{bc}^0 and Ω_{bc}^0

[CPC 45 (2021) 093002]

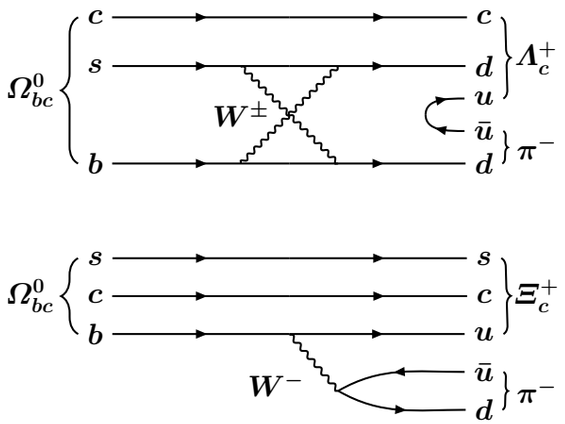
- L = 5.2 fb^{-1} data collected in 2016–2018
- Searches for $\Xi_{bc}^0/\Omega_{bc}^0 \to \Lambda_c^+\pi^-$ and $\Xi_{bc}^0/\Omega_{bc}^0 \to \Xi_c^+\pi^-$
- First search for Ω_{bc}^0

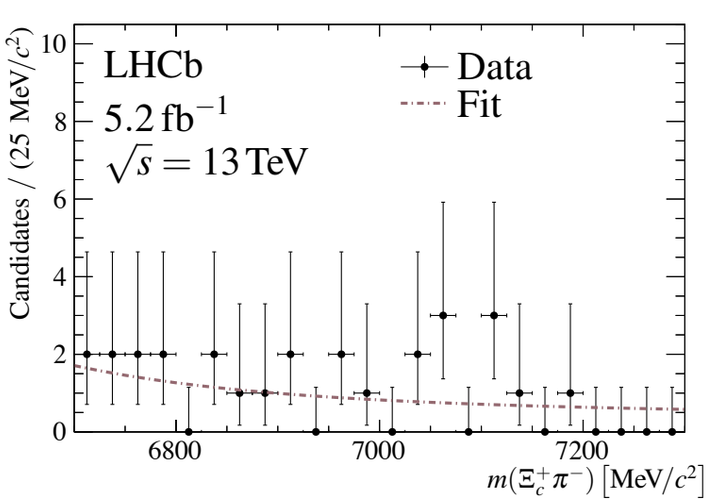




$$\frac{\sigma\left(pp\to H_{bc}^0 X\right)\times\mathcal{B}\left(H_{bc}^0\to\Lambda_c^+\pi^-\right)}{\sigma\left(pp\to\Lambda_b^0 X\right)\times\mathcal{B}\left(\Lambda_b^0\to\Lambda_c^+\pi^-\right)}$$

- $< (0.5 - 2.5) \times 10^{-4}$ @ 95% CL for considered masses and lifetimes





$$\frac{\sigma\left(pp\to H_{bc}^0 X\right)\times\mathcal{B}\left(H_{bc}^0\to\Xi_c^+\pi^-\right)}{\sigma\left(pp\to\Xi_b^0 X\right)\times\mathcal{B}\left(\Xi_b^0\to\Xi_c^+\pi^-\right)}$$

- $< (1.4 - 6.9) \times 10^{-3}$ @ 95% CL for considered masses and lifetimes

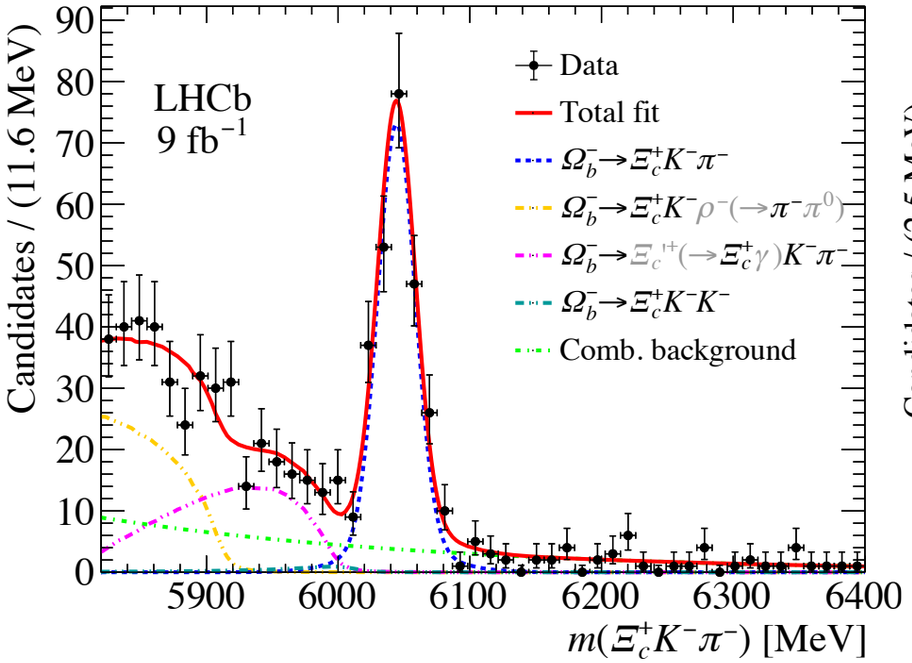
See Shiyang's talk

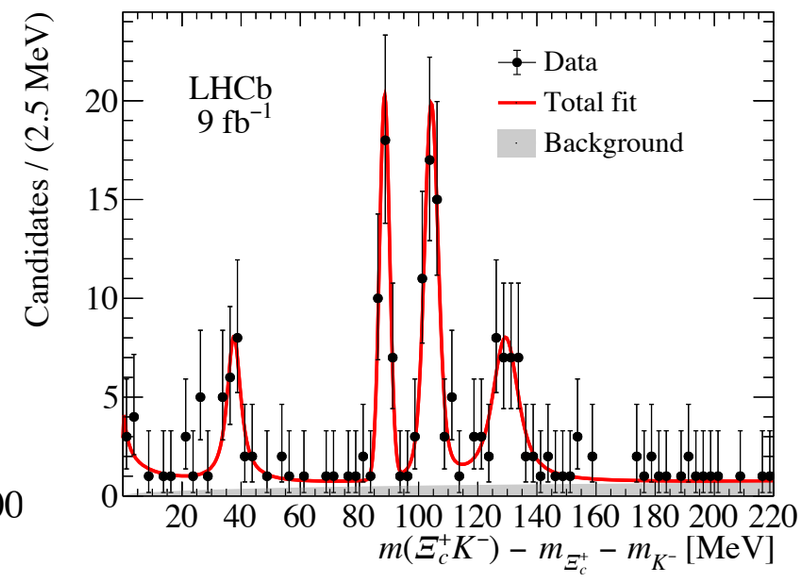
Observation of excited Ω_c^0 in exclusive Ω_b^- decays

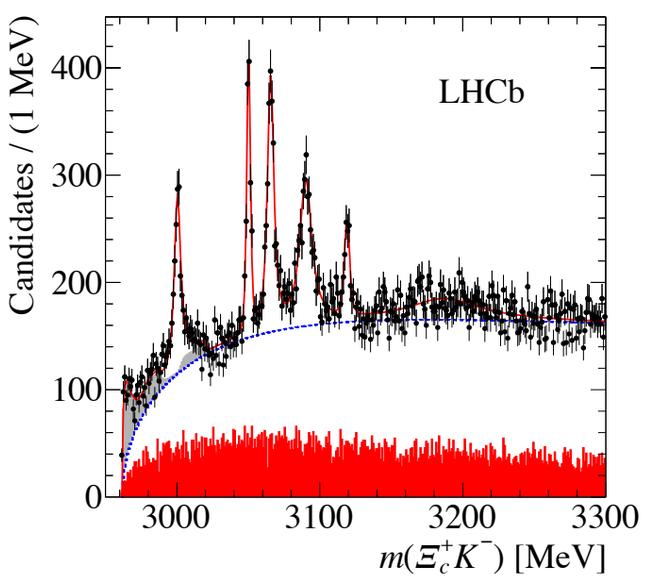
[arXiv:2107.03419]

- L = 9 fb^{-1}, collected in Run 1&2
- Study m($\Xi_c^+K^-$) spectrum in $\Omega_b^- \to \Xi_c^+K^-\pi^-$ decay
- Select m($\Xi_c^+K^-\pi^-$) within m(Ω_b^-)$\pm 2\sigma$
- 4 narrow peaks observed in m($\Xi_c^+K^-$) spectrum
  - Consistent with $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3065)^0$, $\Omega_c(3090)^0$
  - Missing $\Omega_c(3120)^0$ compare to prompt study
  - Enhancement in the threshold seen

Reminder: Run 1 prompt study



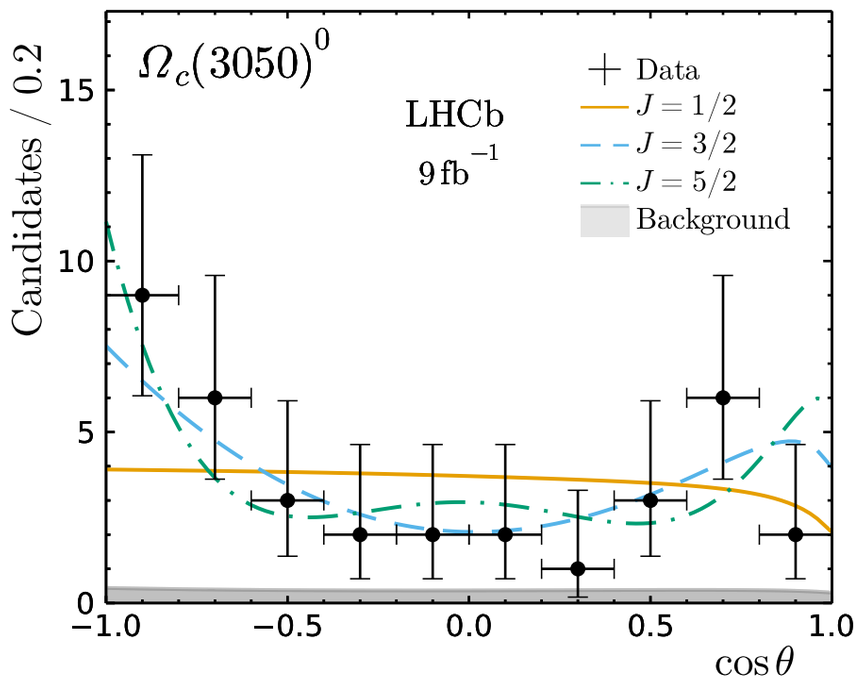


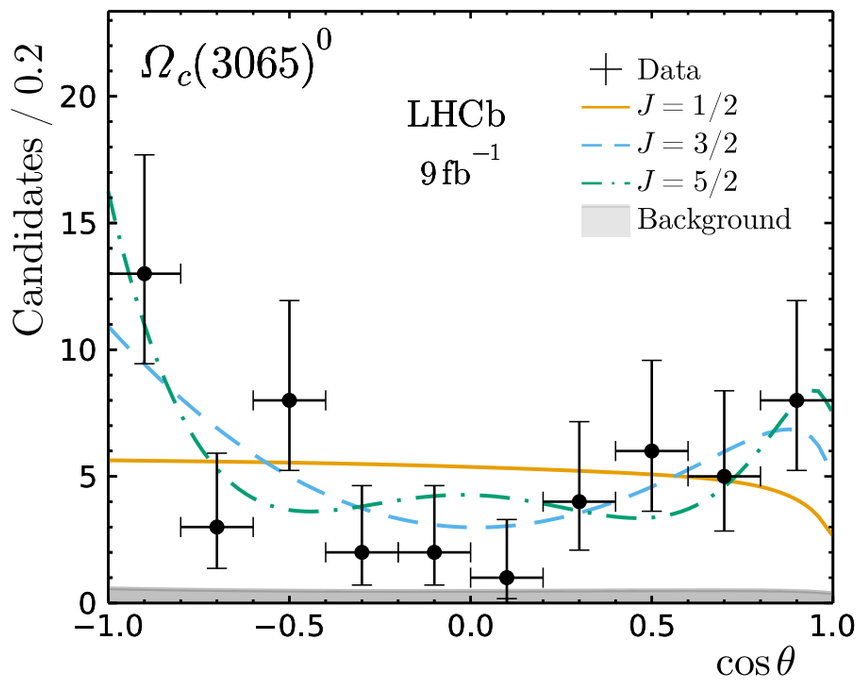


Spin test for the excited Ω_c^0 baryons

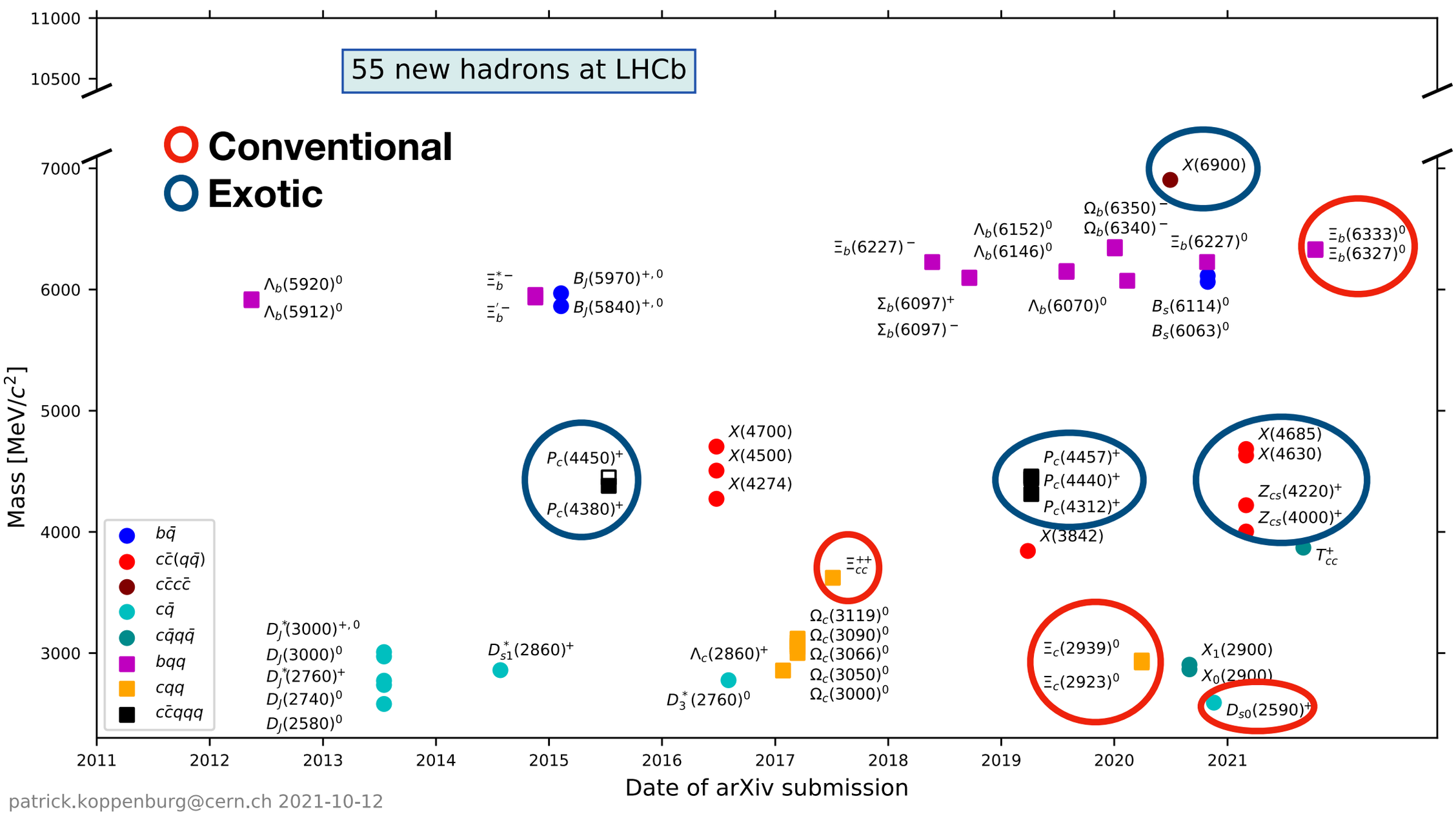
[arXiv:2107.03419]

- Spin tested using helicity angle distributions
- Rejected quantum numbers order of the four peaks
  J=1/2, 1/2, 3/2, 3/2 proposed in several works,
  by a p-value corresponding to 3.5 standard deviations
- J=1/2, 3/2, 3/2, and 5/2 favoured by this work
  - Threshold enhancement = missing 1/2 state?
  - Full LHCb Run 2 data being exploited to revisit excited Ω_c^0 in prompt





Hadrons observed at LHCb



patrick.koppenburg@cern.ch 2021-10-12

55 new hadrons observed at LHCb,
15 of them (27%) with efforts from LHCb Chinese groups

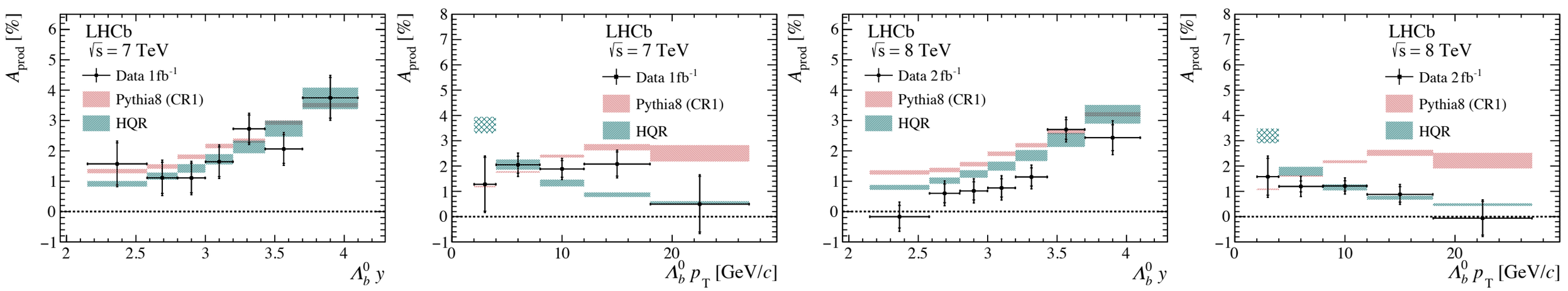
Heavy flavour production

Λ_b^0 production asymmetry at 7 and 8 TeV

[arXiv:2107.09593]

- L = 3 fb^{-1}, Decay mode: $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\mu^-\overline{\nu}X$
- Production asymmetry: $A_P(\Lambda_b^0) = \dfrac{\sigma(pp \to \Lambda_b^0 X) - \sigma(pp \to \overline{\Lambda}_b^0 X)}{\sigma(pp \to \Lambda_b^0 X) + \sigma(pp \to \overline{\Lambda}_b^0 X)}$
- Raw asymmetry: $A_{raw}(\Lambda_b^0) = \dfrac{N(\Lambda_b^0 \to \Lambda_c^+\mu^- X) - N(\overline{\Lambda}_b^0 \to \Lambda_c^-\mu^+ X)}{N(\Lambda_b^0 \to \Lambda_c^+\mu^- X) + N(\overline{\Lambda}_b^0 \to \Lambda_c^-\mu^+ X)}$
  - Assume no CP violation in Λ_b^0 and Λ_c^+ decays

    $A_P(\Lambda_b^0) = A_{raw}(\Lambda_b^0) - A_D(pK^-\pi^+\mu^-)$

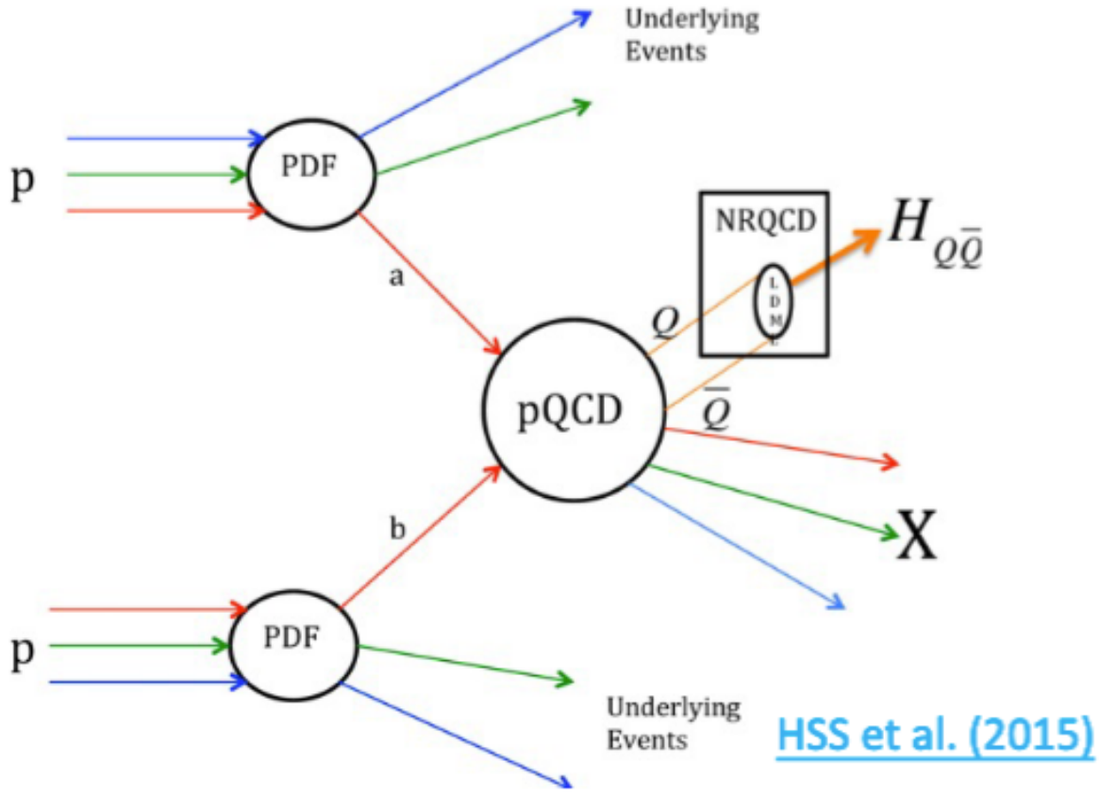


Measured production asymmetry compared with models
Lai & Leibovich: Phys. Rev. D91, 054022
Pythia8 (CR1): JHEP 11 (2014) 043, JHEP 08 (2015) 003

Measurement of J/ψ production in *pp* at 5 TeV

[arXiv:2109.00220]

- Prompt J/ψ
  - Probe J/ψ production mechanism
  - $c\bar{c}$ pair production: perturbative QCD
  - Hadronisation: non-perturbative QCD
- J/ψ-from-b
  - Probe b-hadron production mechanism
  - Theory model: Fixed Order plus Next-to-Leading Logarithms (FONLL).

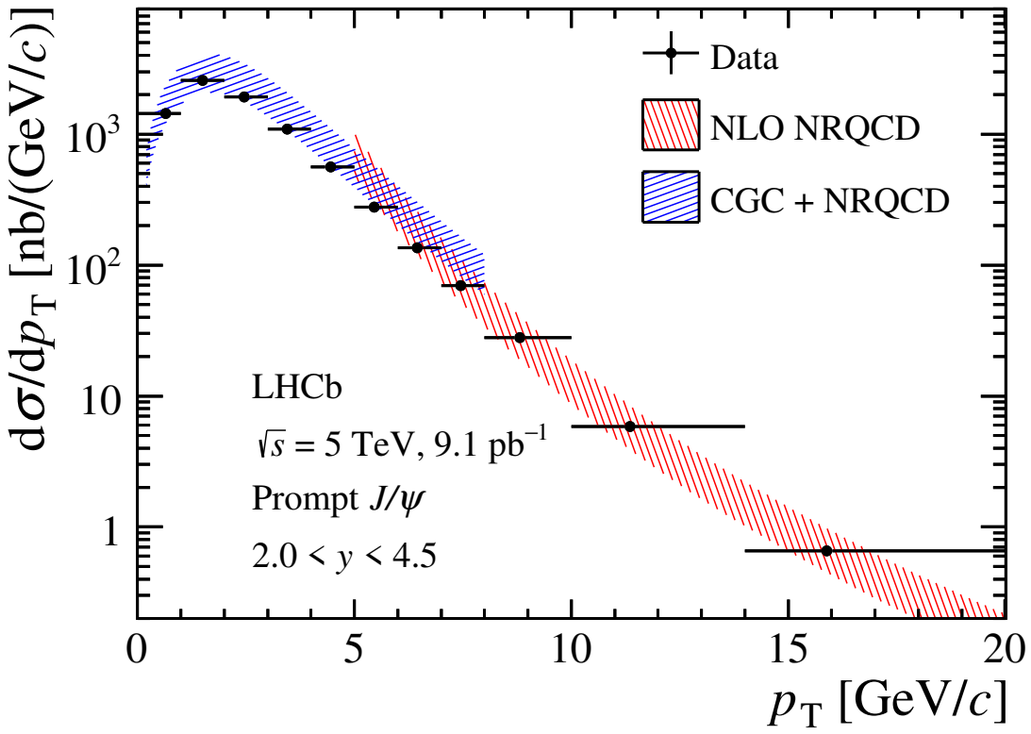


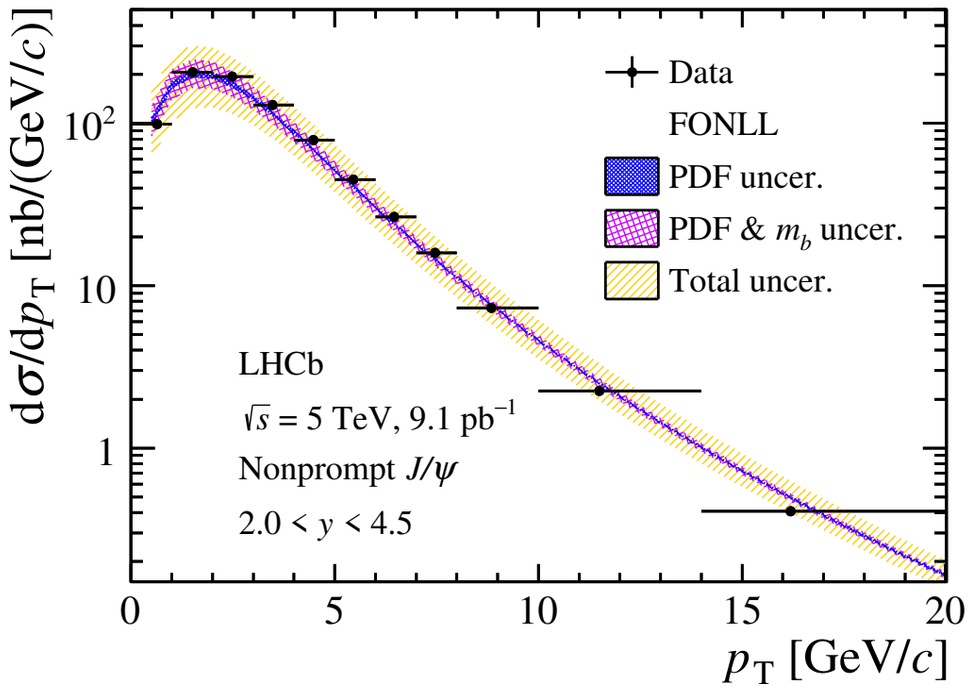
HSS et al. (2015)

Measurement of J/ψ production in *pp* at 5 TeV

[arXiv:2109.00220]

- L = 9.13 pb^{-1}, data collected in 2015
- Integrated cross-sections (p_T < 20 GeV/c, 2.0 < y < 4.5)
  - σ_{prompt}= 8.154 ± 0.010(stat) ±0.283(syst) μb
  - $\sigma_{from\text{-}b}$= 0.820 ± 0.002(stat) ±0.034(syst) μb





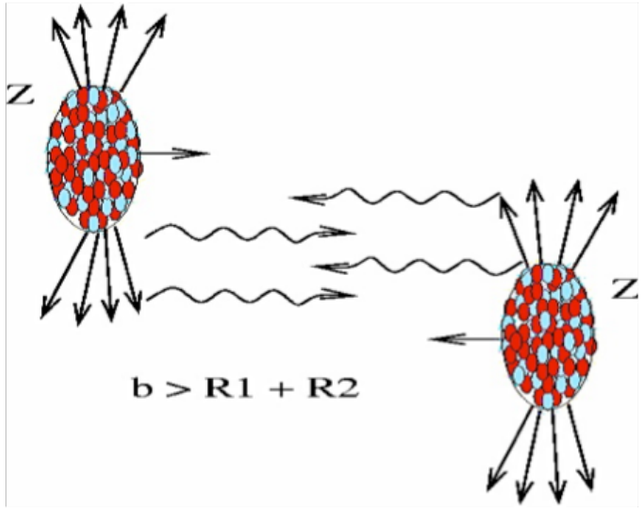
Good agreement with predictions both for prompt J/ψ and J/ψ-from-b
Important reference for ion collision studies

See Li's talk

Study of coherent J/ψ production in UPC

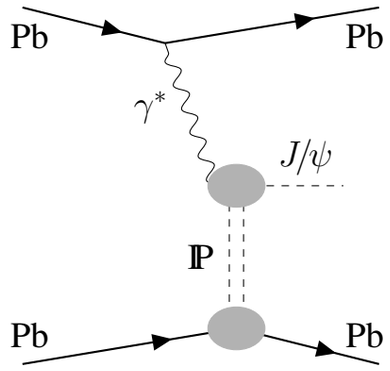
[arXiv:2107.03223]

- Ultra-peripheral collision (UPC)

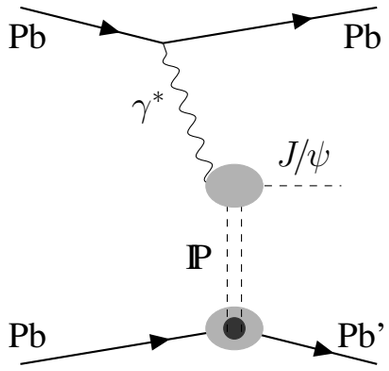


- The J/ψ production in UPC

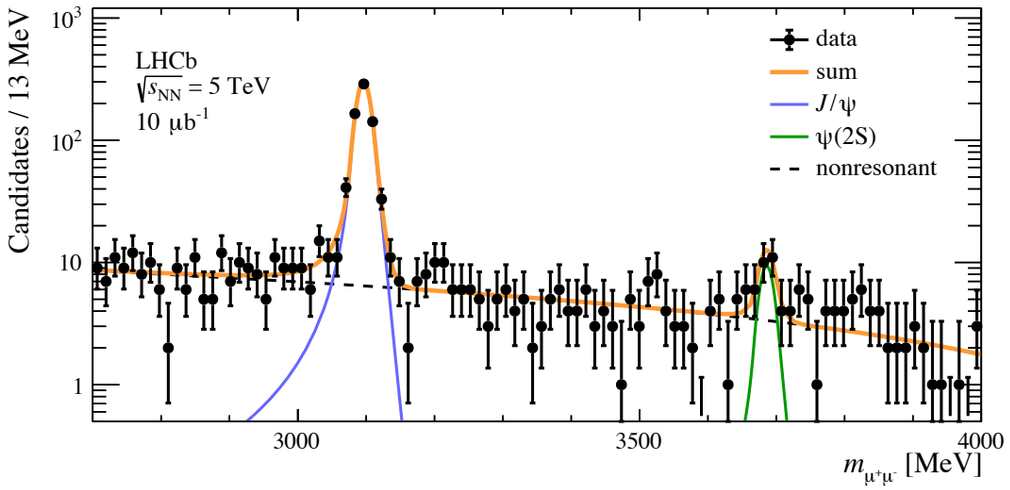
Coherent

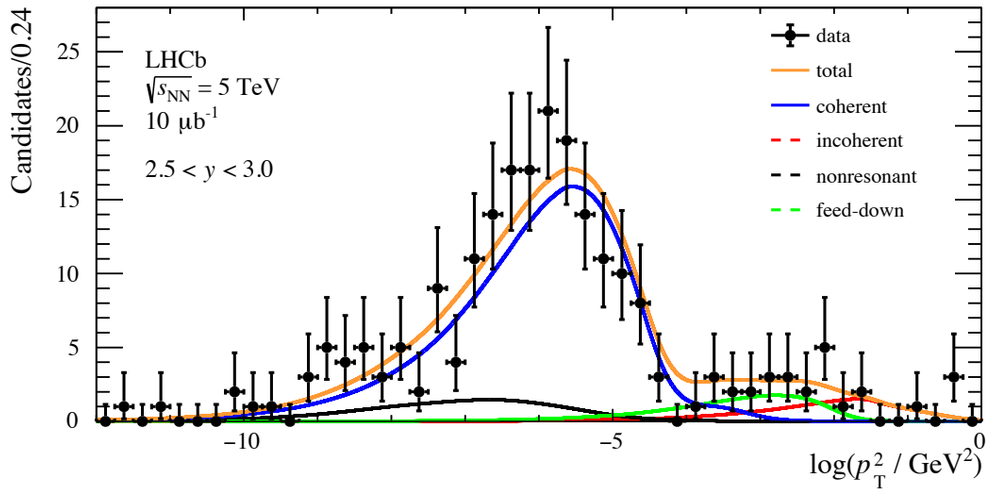


Incoherent



- L = 10 μb^{-1}, PbPb data collected in 2015
- Perform M(μ+μ-) fits and p_T fits to extract coherent J/ψ yields

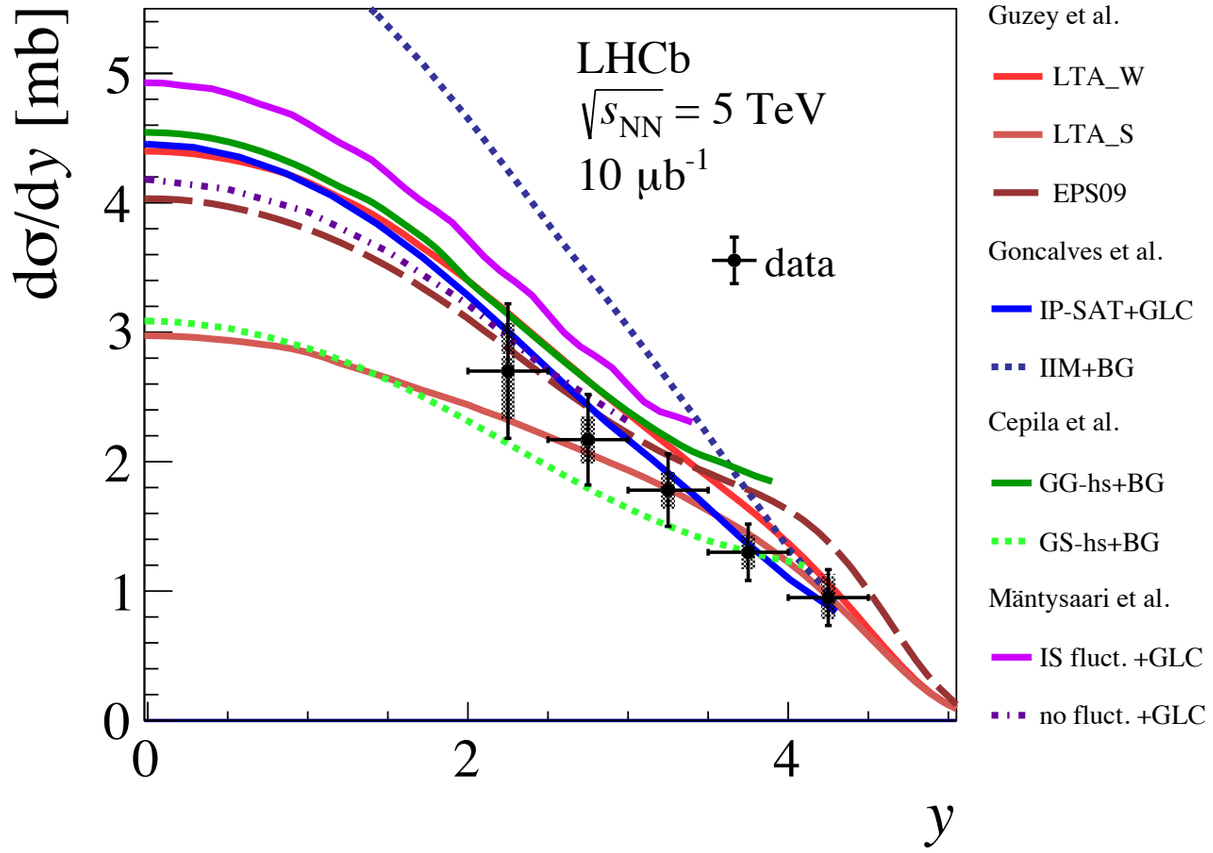




Study of coherent J/ψ production in UPC

[arXiv:2107.03223]

- Cross-section for coherent *J/ψ* production at 5 TeV:
  - σ= 4.45 ± 0.24 (stat) ± 0.18 (syst) ± 0.58 (lumi) mb,
- Constrain gluon distribution function in Bjorken-x region of ~10^{-5}-10^{-2}
- Coherent (photon couples to all nucleons) *J/ψ* production gives constraints to nPDF
- Uncertainty smaller than models spread

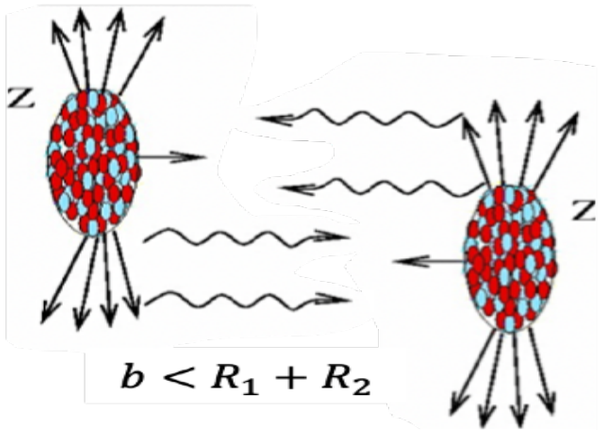


See Xiaolin's talk

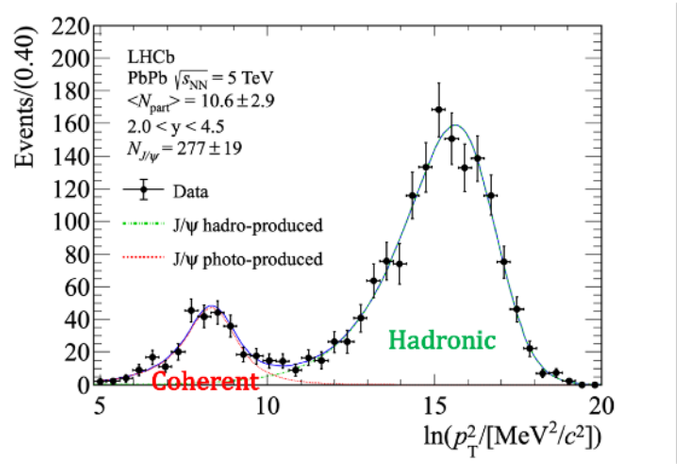
Study of coherent J/ψ production in PbPb collisions

[arXiv:2108.02681]

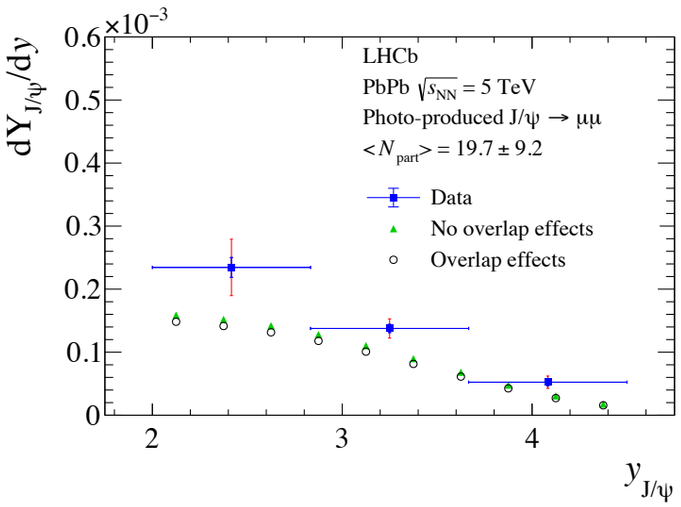
- Peripheral collision

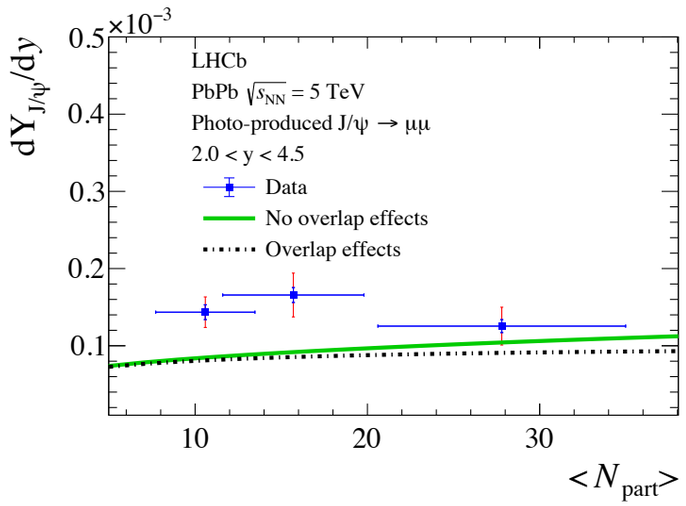


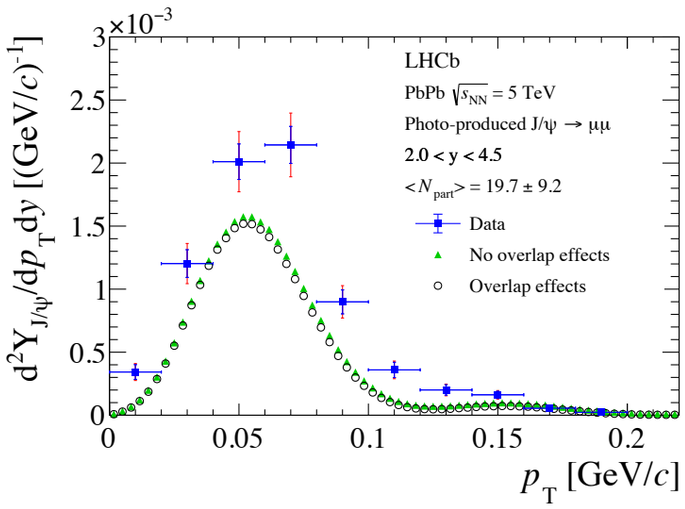
- L = 210 μb^{-1}, PbPb data collected in 2018
- p_T fits to extract coherent J/ψ yields



- Coherent J/ψ yields, compared with PhysRevC.97.044910, PhysRevC.99.061901:



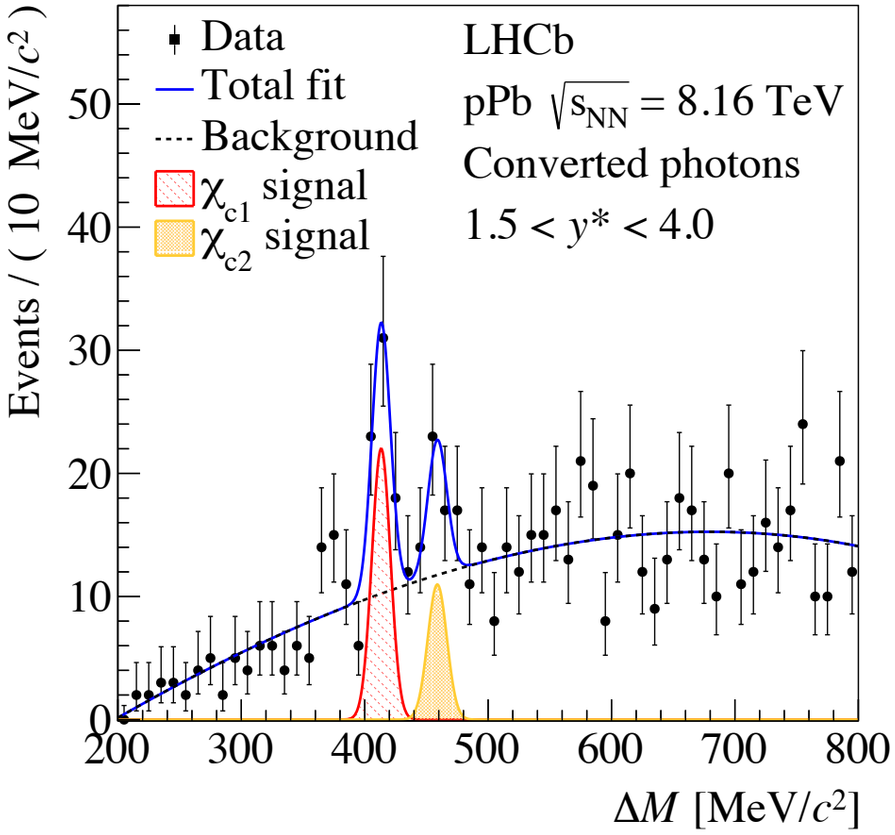


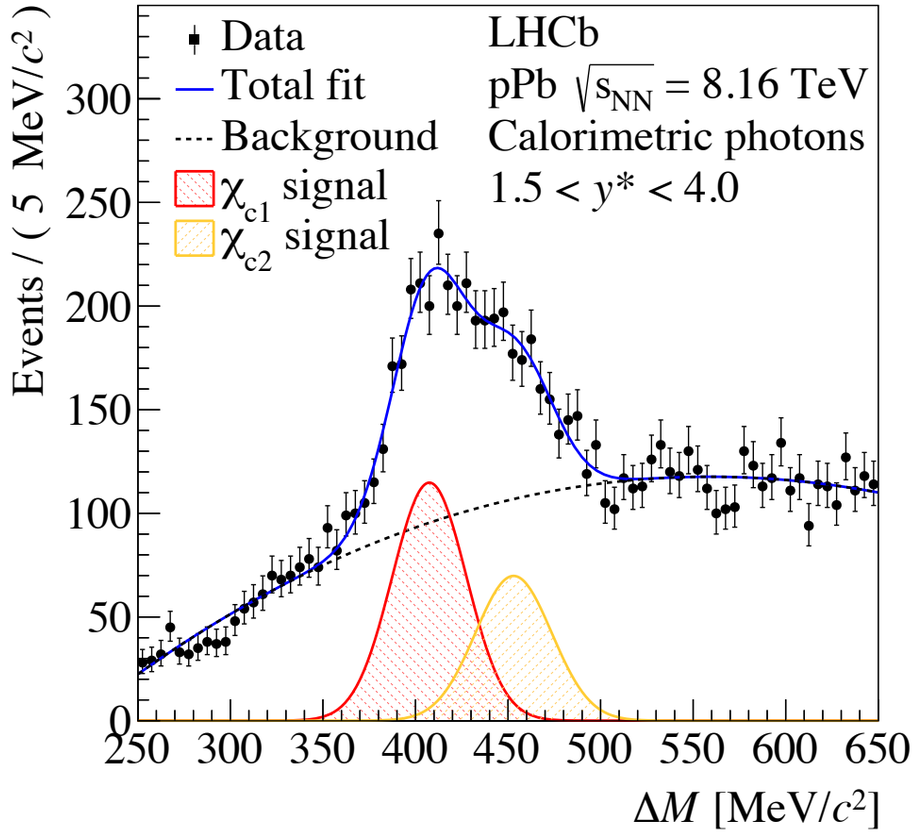


Prompt cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ in pPb

[arXiv:2103.07349]

- The first measurement of $\chi_{c1,2}$ charmonium production in nuclear collisions at the LHC.
- χ_{cJ} reconstructed via radiative decay $\chi_{cJ} \to (J/\psi \to \mu^+\mu^-)\gamma$, where photons are classified in two modes: converted photons, calorimetric photons.

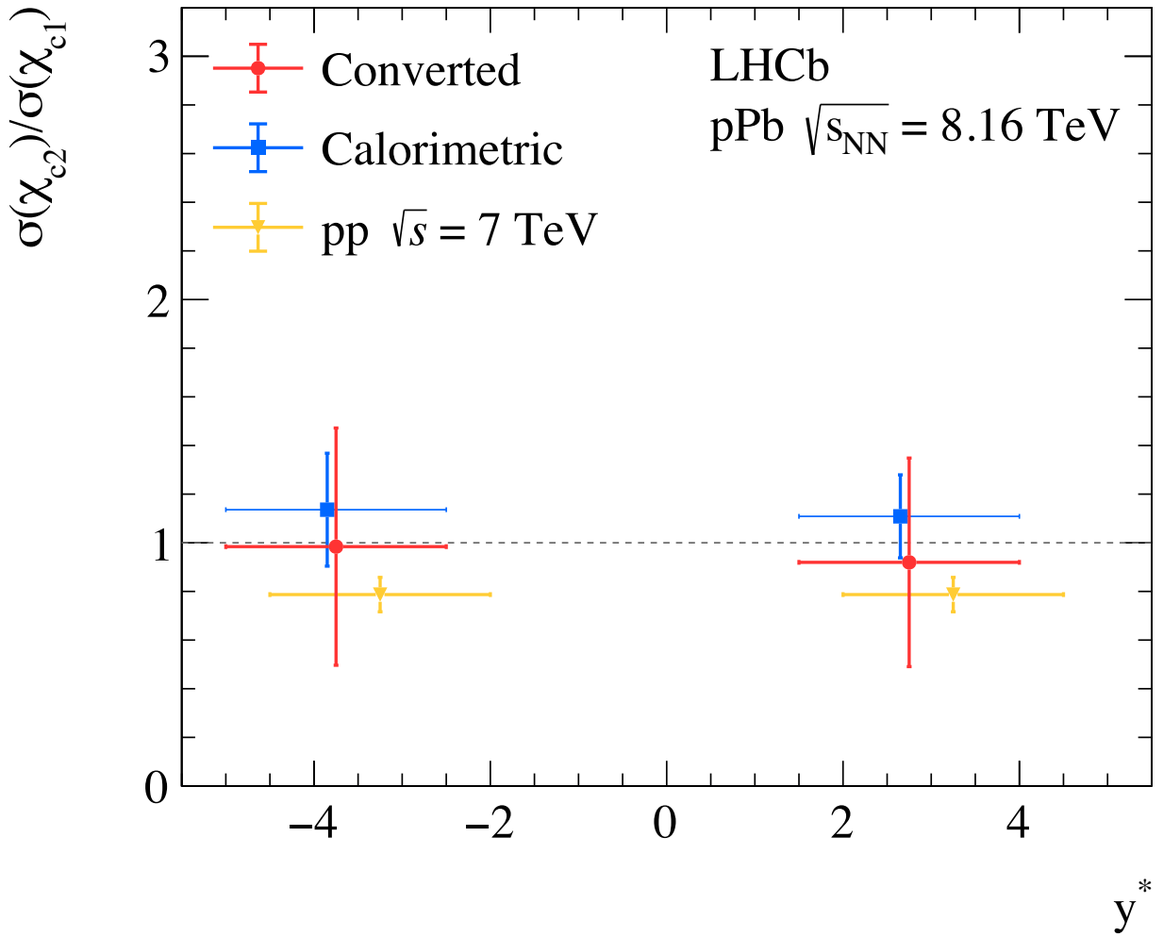




Prompt cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ in pPb

[arXiv:2103.07349]

- The cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ is sensitive to final-state nuclear effects.
- Consistent with unity for both forward and backward rapidity regions.
- Consistent with results from pp.
- Suggest that the final-state nuclear effects impact the χ_{c1} and χ_{c2} states similarly.
- Photon efficiencies under study for absolute χ_c cross-sections.



Summary

Summary

- LHCb progresses on establishing heavy hadron spectroscopy
  - Two excited Ξ_b^0 states observed
  - Ξ_c^0 and Ω_c^0 lifetimes measured
  - Searches for Ξ_{cc}^+, Ω_{cc}^+, Ξ_{bc}^0, Ω_{bc}^0 performed
  - Four excited Ω_c^0 states rediscovered
- LHCb progresses on heavy flavour production measurements
  - J/ψ production in pp/UPC/PbPb measured
  - Λ_b^0 production asymmetry measured
  - Prompt $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ ratio measured
- Tremendous efforts from LHCb Chinese groups
- Run3: gain precision in hadronic final states: more lumi. + fully software trigger