第六届中国LHC物理会议

清华大学 2020.11.6-9

LHCb Heavy Flavor Production and Spectroscopy (conventional)

张艳席

北京大学

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  - Observation of a new excited D_s^+ state
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- Heavy flavor production
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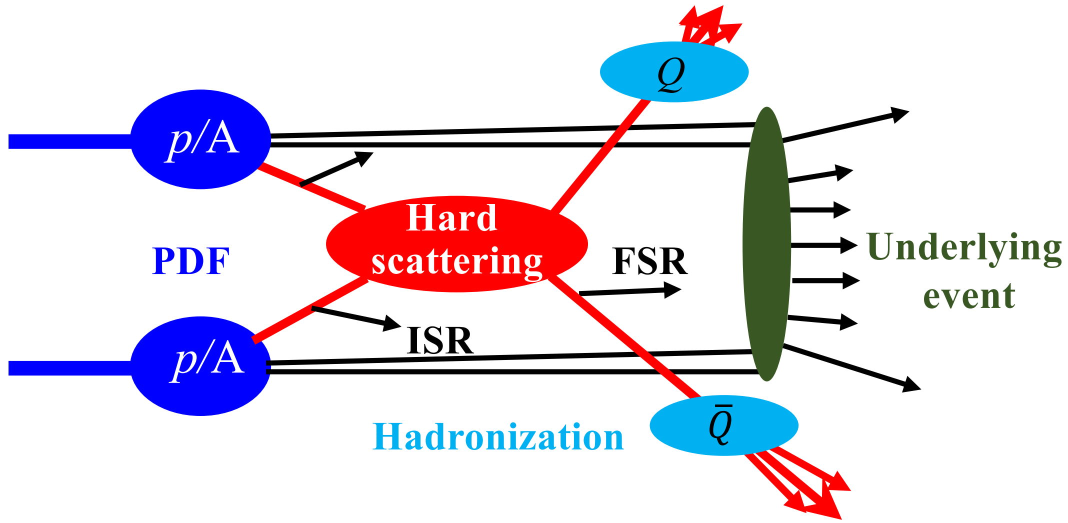
  - Associated production of two heavy flavor

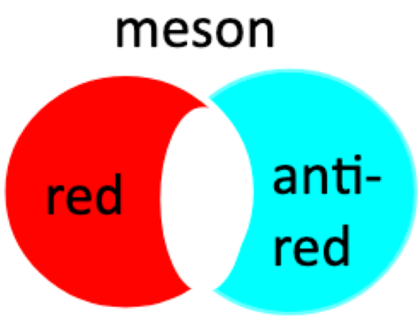
The strong interaction

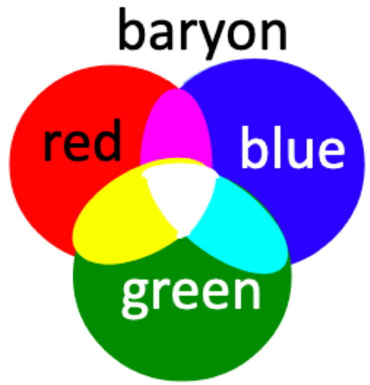
- Strong interaction and QCD less known than EW in the Standard Model
  Critical in precision SM test and searching for new physics
- Studies of QCD properties
  - Hadron spectroscopy: quark-quark/gluon interaction in confinement regime
  - Heavy flavor production: perturbative and non-perturbative,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



  - Nuclear matter: multiple particle system

Conventional spectroscopy



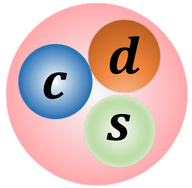


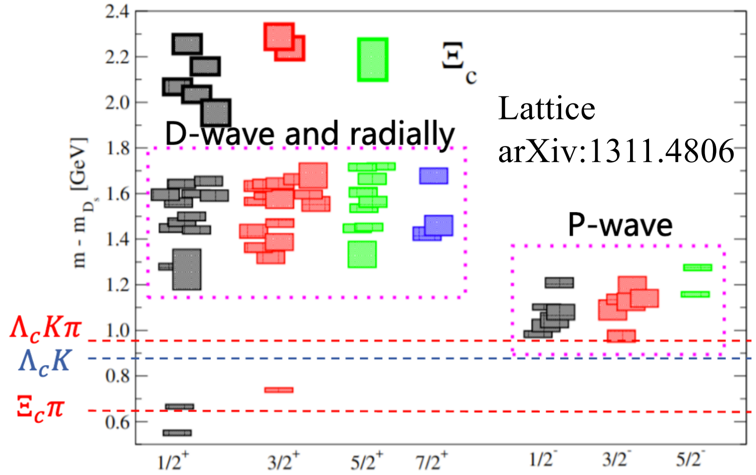
Observation of new Ξ_c^{**0} states

Zhihao Xu (Nov.6)

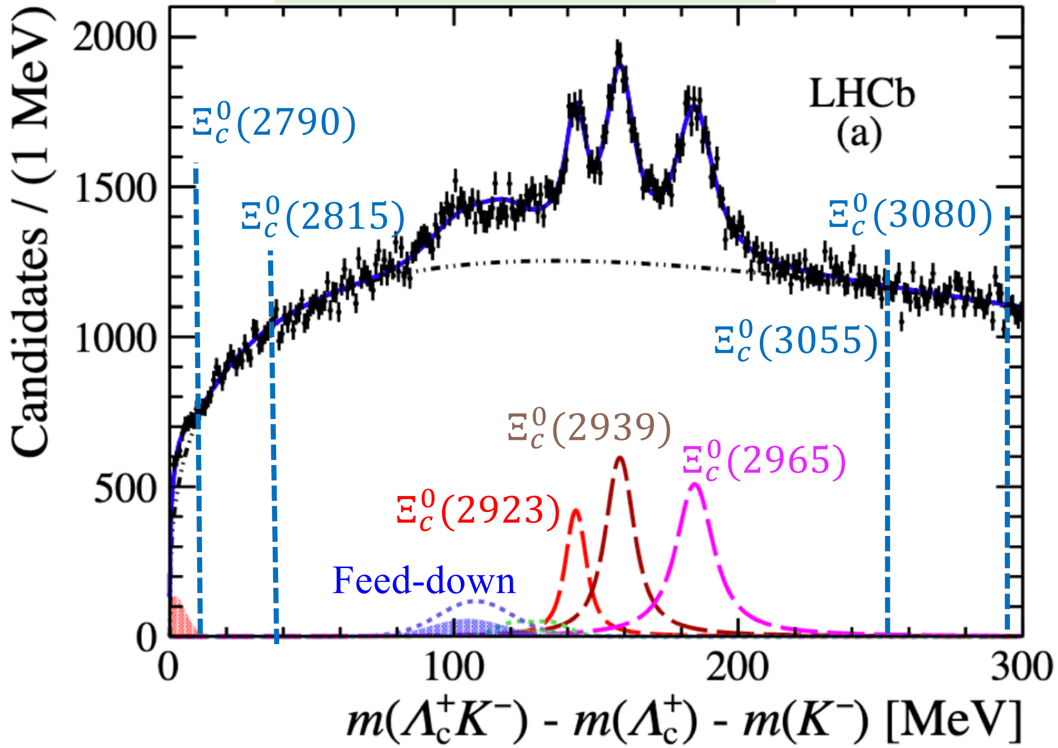
- Rich excited Ξ_c spectroscopy, only ≈10 states identified experimentally
- All states possible in prompt *pp* collisions
- LHCb studied the $\Xi_c^{**0} \to \Lambda_c^+ K^-$

PRL124(2020)222001





$\Lambda_c^+ K^-$ mass spectrum



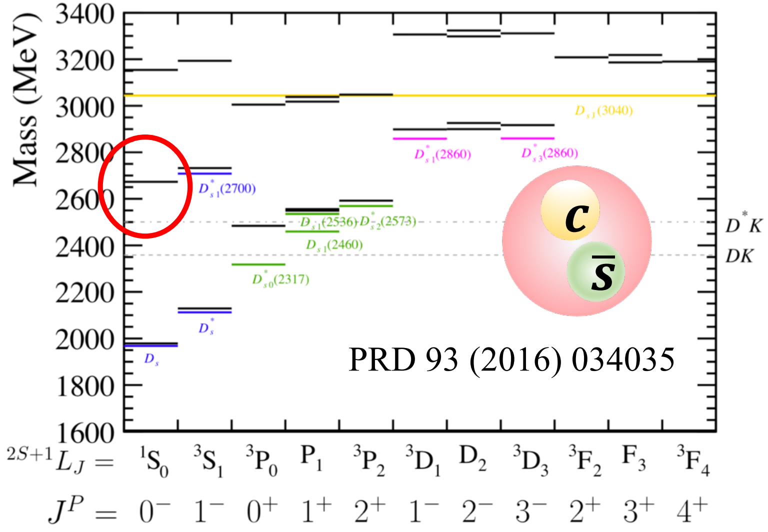
- Observed three new states
  - ➢ $\Xi_c^0(2930)$ previously observed in $B \to \Lambda_c^+ \Lambda_c^- K$ decays resolved as $\Xi_c^0(2923)$, $\Xi_c^0(2939)$
  - ➢ $\Xi_c^0(2970)$ observed in $\Lambda_c^+ K\pi$ decay not seen but $\Xi_c^0(2965)$
- Other known states not obvious, higher states seen by feed-down

Were observed in $\Xi_c^{(\prime)}\pi$, ΛD, $\Lambda_c^+ K\pi$

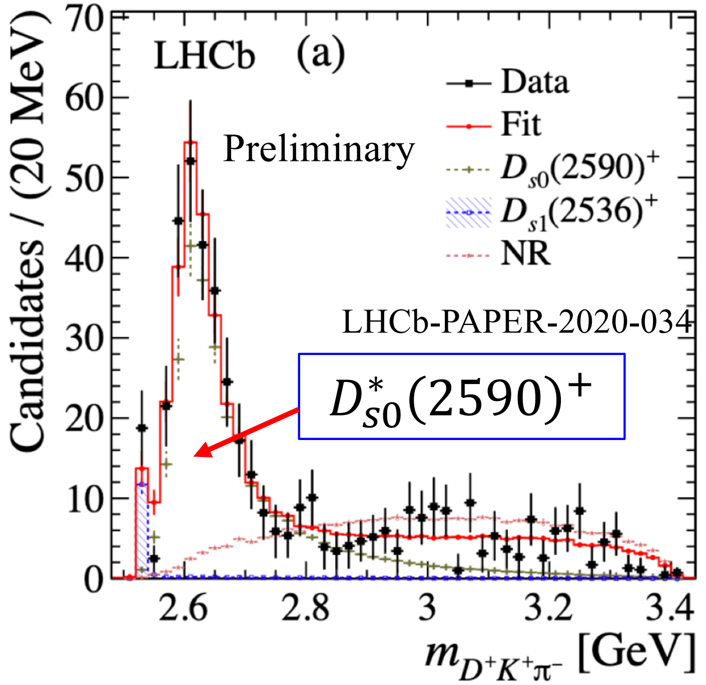
Observation of new excited D_s^+

Chen Chen (Nov.6)

- Spectrum known better than baryons
- But still hard to establish SU(3) for D_s^{**+}, D^{**}
  - ➢ Large discrepancy with predicted masses
- Missing states accessible in beauty decays: clean and allows to determine J^{PC}



LHCb studied $B^0 \to D^- D^+ K^+ \pi^-$, looking for excited D_s^+ in $D^+ K^+ \pi^-$ 3-body final states



Amplitude fit for $m(K^+\pi^-) < 0.75$ GeV region, dominated by $K_0^*(700)^0$ s-wave

➢ $J^P = 0^-$ preferred, $1^+, 2^-$ rejected by >15σ

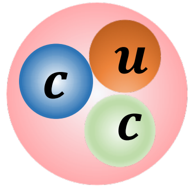
➢ $m_R = 2591 \pm 6 \pm 7$ MeV
$\Gamma_R = 89 \pm 16 \pm 12$ MeV

Consistent with the $D_s(2^1S_0)^+$ state.
But mass 80 MeV lower than prediction, though width is compatible!

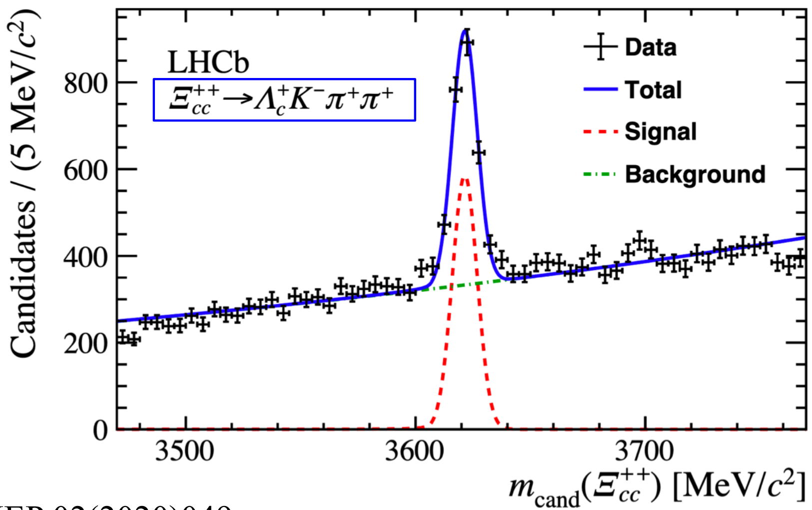
Precision Ξ_{cc}^{++} mass

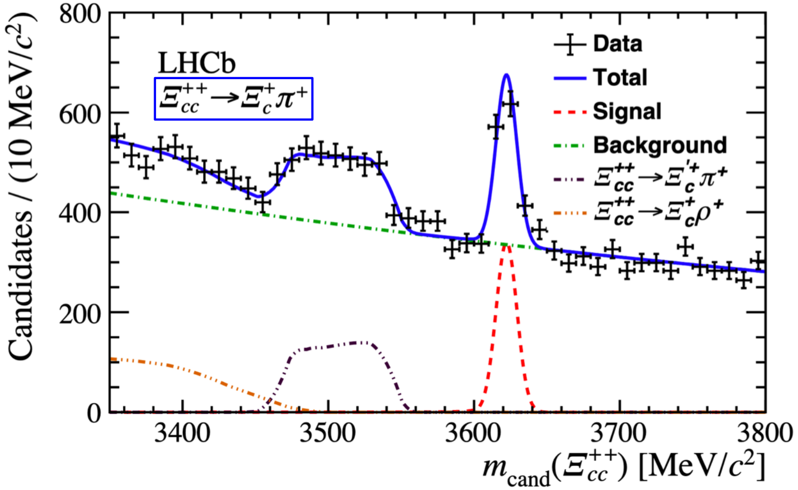
Yixiong Zhou (Nov.6)

- Ξ_{cc}^{++} the only established doubly charmed baryon by experiment
  - ➢ Observed in $\Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$ decays
  - ➢ Weak decay: $\tau = 0.256^{+0.024}_{-0.022} \pm 0.014$ ps
  - ➢ Mass: $m(\Xi_{cc}^{++}) = 3621.40 \pm 0.80$ MeV, consistent with models and LQCD

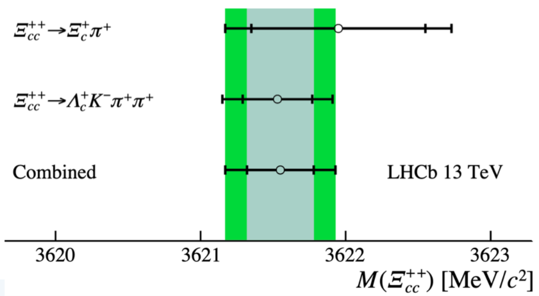


- $m(\Xi_{cc}^{++})$ updated using almost full Run II data, combining both known modes





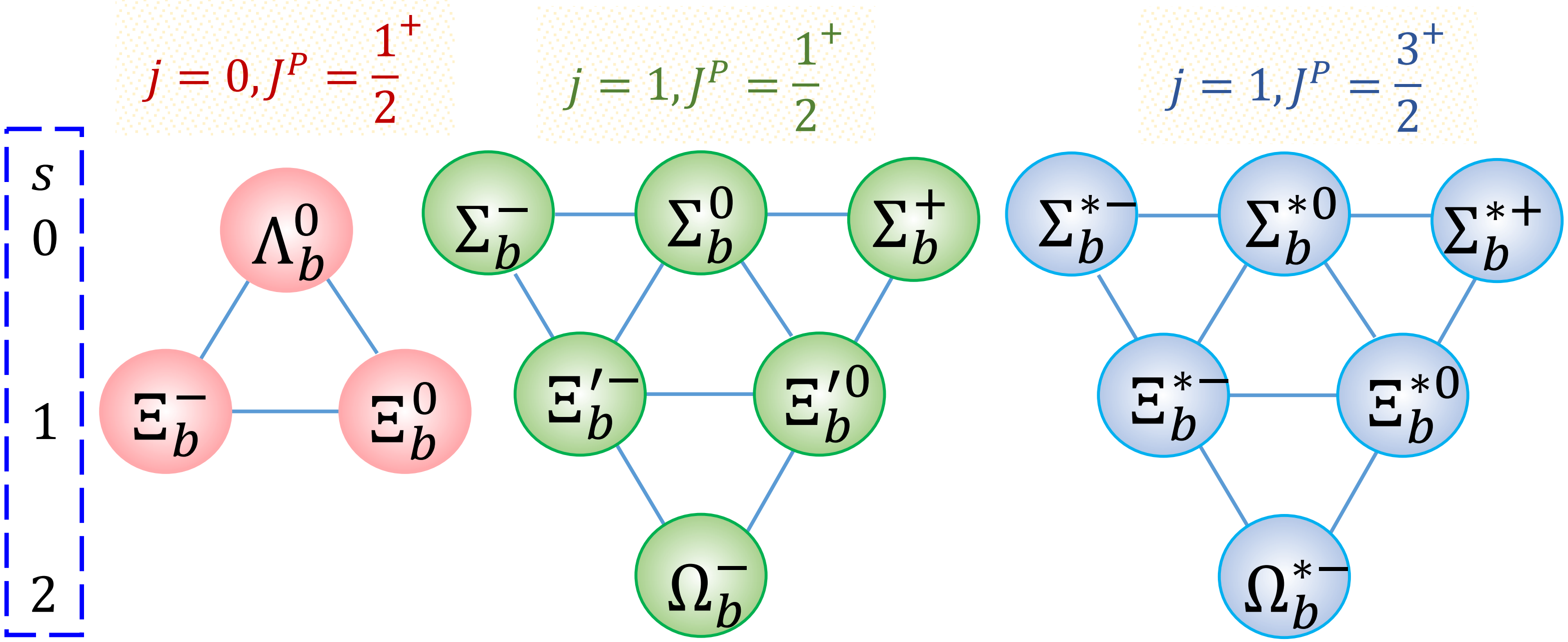
JHEP 02(2020)049

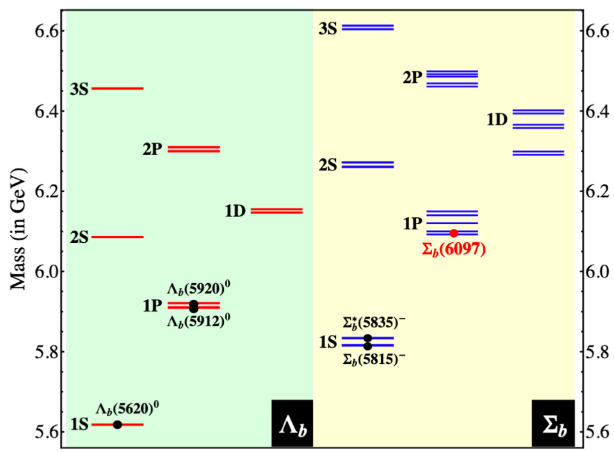


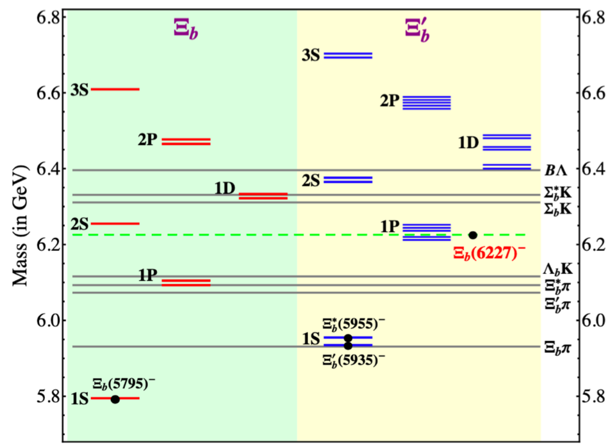
$$m(\Xi_{cc}^{++}) = 3621.55 \pm 0.23 \pm 0.30 \text{ MeV}$$

Beauty baryons

- Ground states







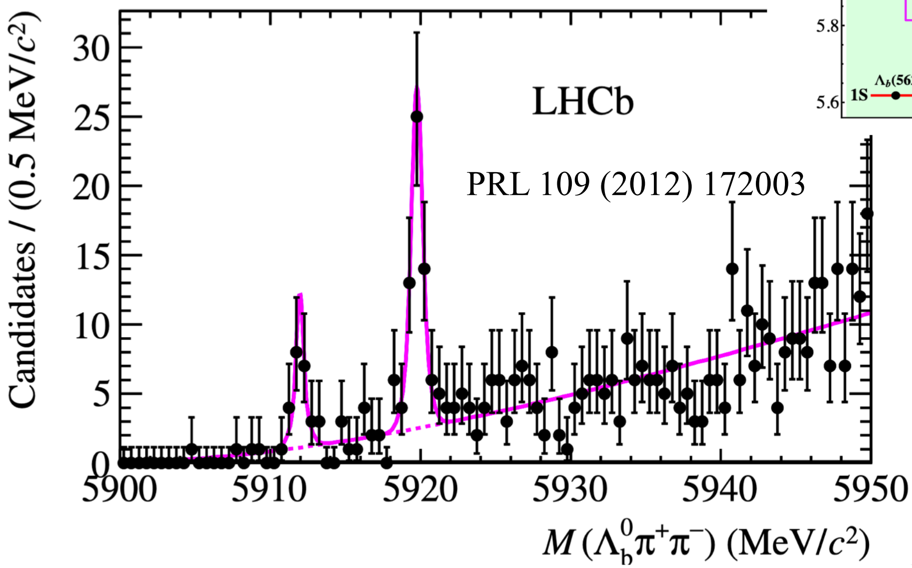
PRD 98 (2018) 031502
PRD 98 (2018) 074032

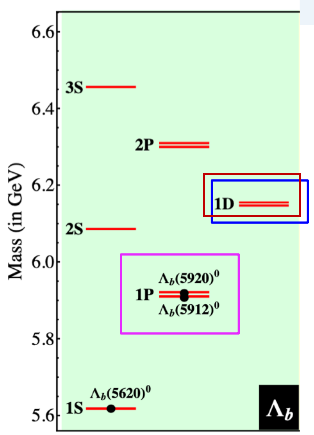
Spectrum poorly established

Excited Λ_b^0 baryons

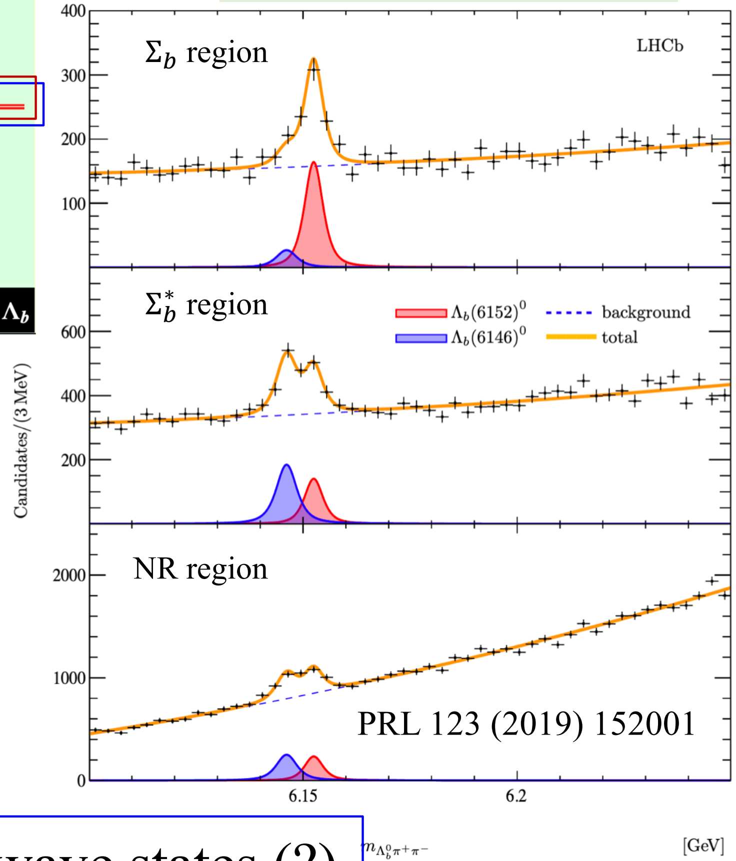
- $\Lambda_b^0\pi^+\pi^-$ mass spectrum

Low mass region





High mass region



P-wave states

State	Mass (MeV)	Width (MeV)
$\Lambda_b^0(5912)$	5912.21 ± 0.21	< 0.25
$\Lambda_b^0(5920)$	5920.11 ± 0.21	< 0.19

D-wave states (?)

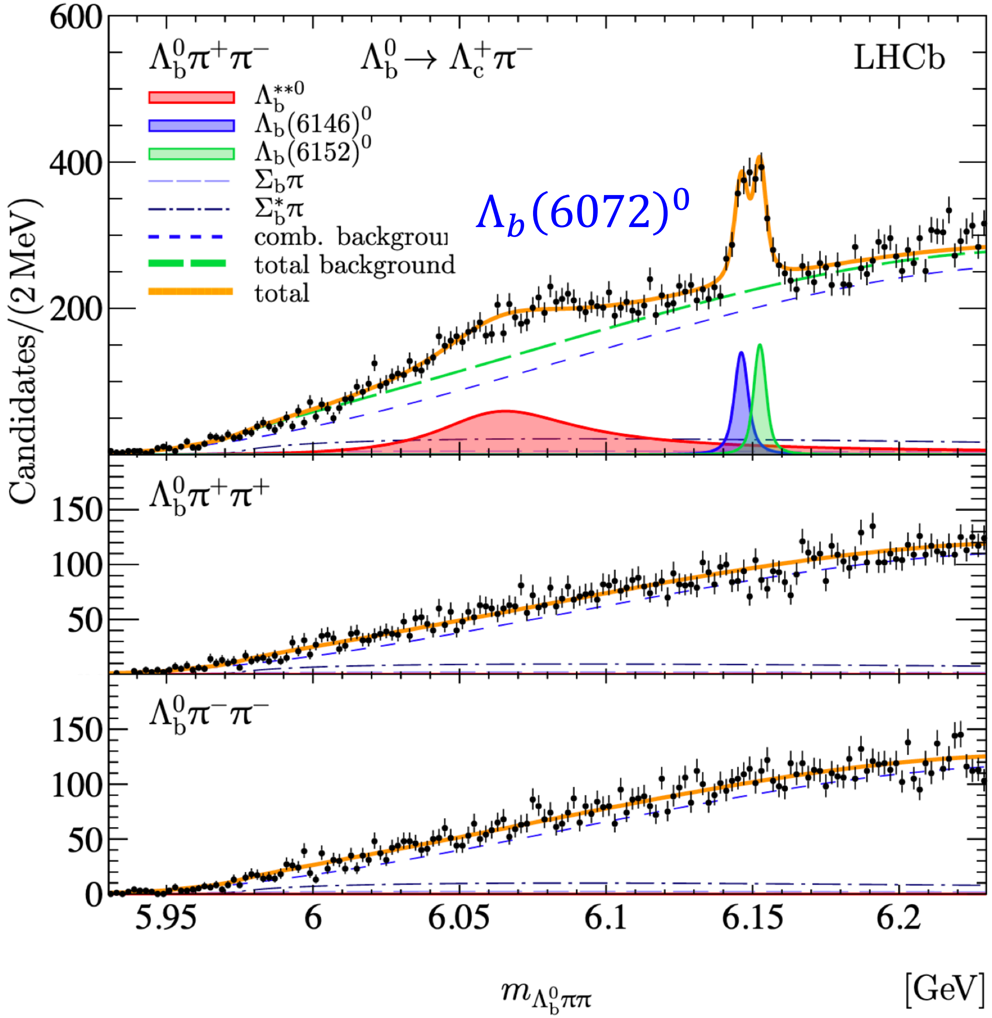
State	Mass (MeV)	Width (MeV)
$\Lambda_b^0(6146)$	6146.2 ± 0.4	2.9 ± 1.3
$\Lambda_b^0(6152)$	6152.5 ± 0.4	2.1 ± 0.9

Excited Λ_b^0 baryons

- $\Lambda_b^0\pi^+\pi^-$ mass spectrum

Intermediate mass region

JHEP 06 (2020) 136



Mass and width agree with 2S state

All known Λ_b^0 states

State	Mass (MeV)	Width (MeV)
$\Lambda_b^0(5620)$	5620.60 ± 0.17	–
$\Lambda_b^0(5912)$	5912.20 ± 0.21	< 0.66
$\Lambda_b^0(5920)$	5919.92 ± 0.19	< 0.83
$\Lambda_b^0(6072)$	6072.3 ± 3.0	72 ± 11
$\Lambda_b^0(6146)$	6146.2 ± 0.4	2.9 ± 1.3
$\Lambda_b^0(6152)$	6152.5 ± 0.4	2.1 ± 0.9

But other assignments exist

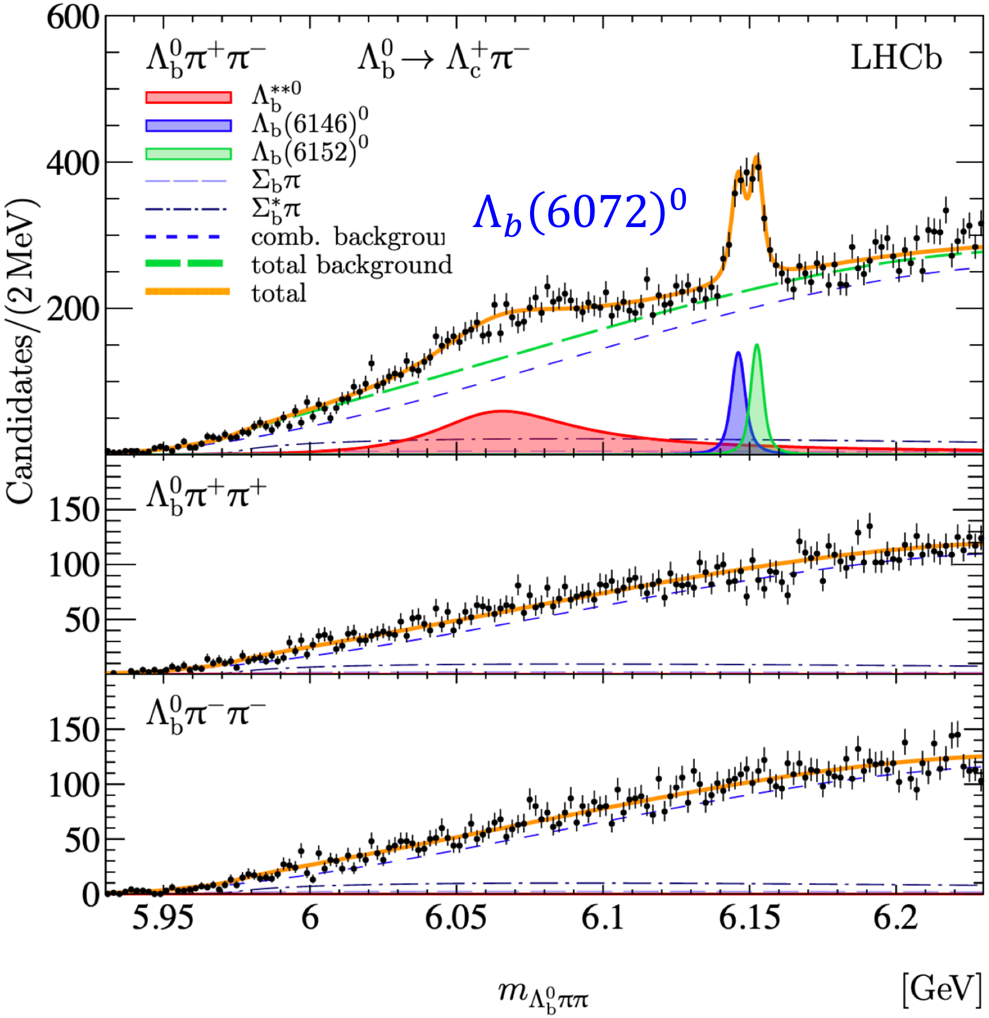
PRD 102 (2020) 014009

Excited Λ_b^0 baryons

- $\Lambda_b^0\pi^+\pi^-$ mass spectrum

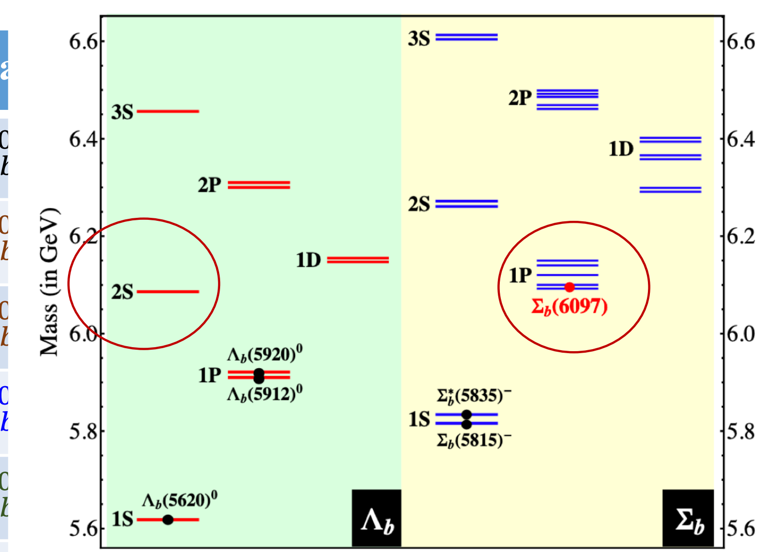
Intermediate mass region

JHEP 06 (2020) 136



Mass and width agree with 2S state

All known Λ_b^0 states



$\Lambda_b^0(6152)$ 6152.5 ± 0.4 2.1 ± 0.9

But other assignments exist

PRD 102 (2020) 014009

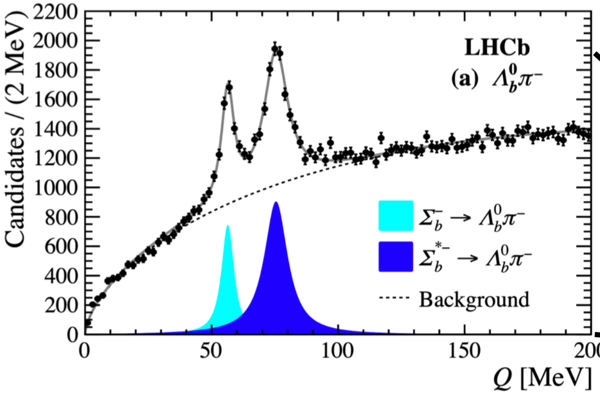
Excited $\Sigma_b^{+/-}$ baryons

- $\Lambda_b^0\pi^{\pm}$mass spectrum

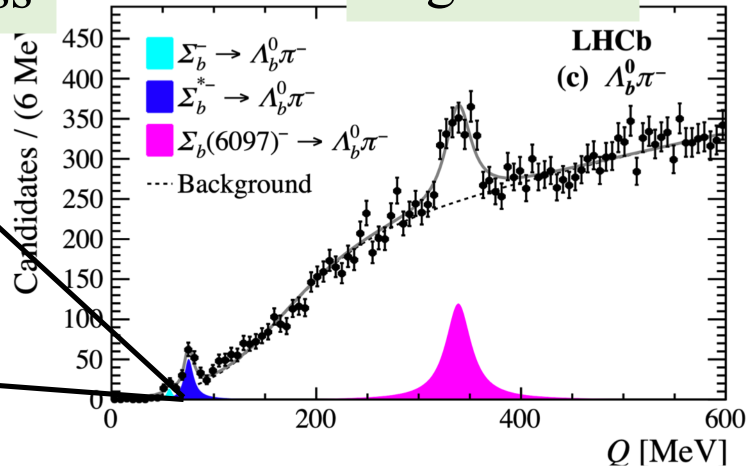
Low mass

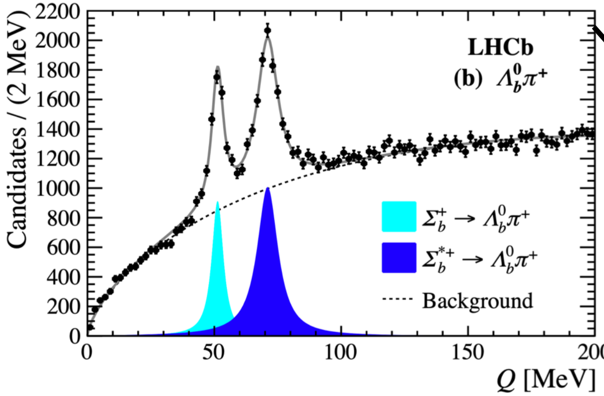
High mass

PRL 122 (2019) 012001

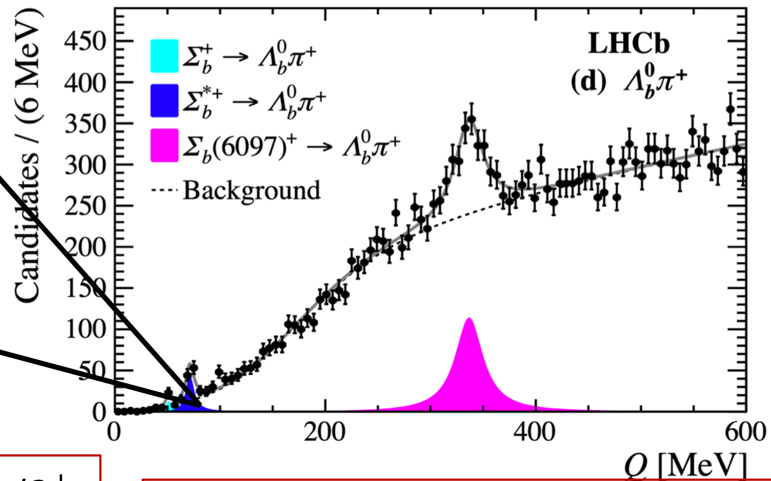


Zoom





Zoom



State	Mass (MeV)	Width (MeV)	
$\Sigma_b^{+/-}$	5810/5815	5	$1/2^+$
$\Sigma_b^{*+/-}$	5830/5835	19	$3/2^+$
$\Sigma_b^{**+/-}$	6098/6096	30	

$$m(\Sigma_b^{**}) - m(\Sigma_b) \approx m(\Lambda_b(5920)^0) - m(\Lambda_b^0)$$

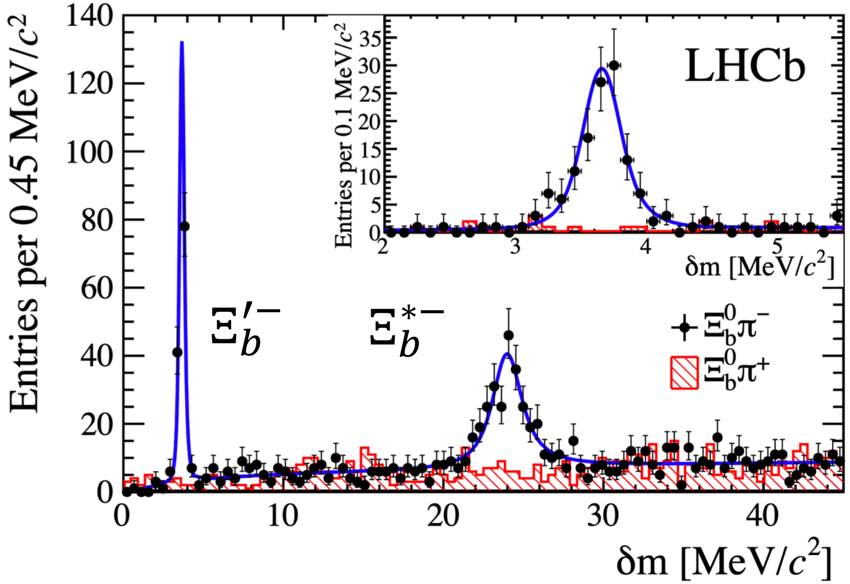
Consistent with P-wave. Five states expected. Many states overlaid?

Spin triplet Ξ_b baryons

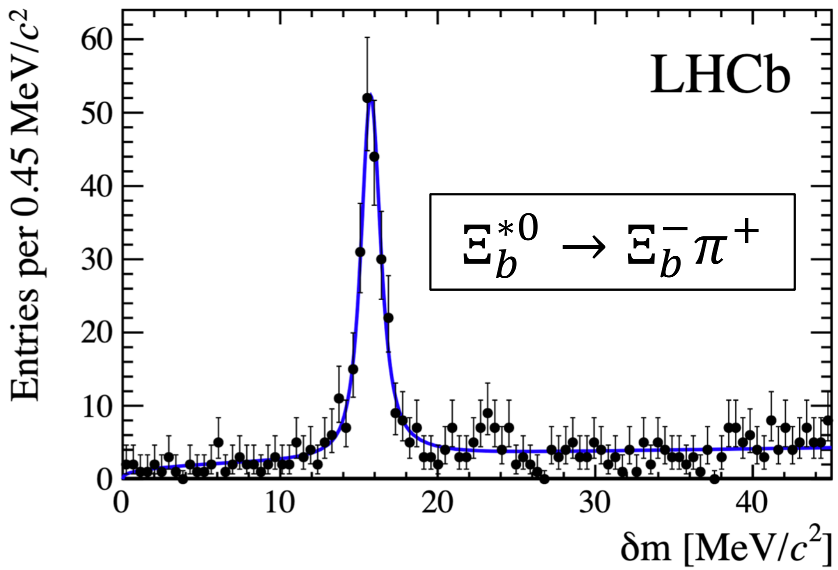
- $\Xi_b \pi$ mass spectrum

Low mass

PRL 114 (2015) 062004

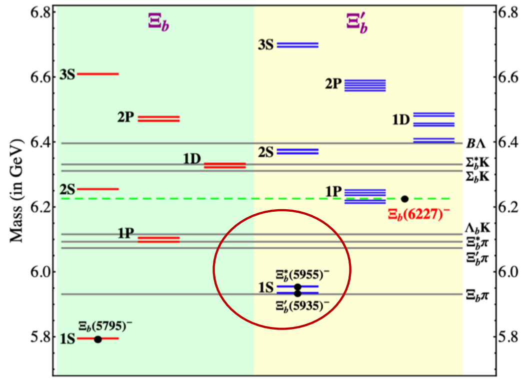


JHEP 05 (2016) 161



Ξ_b^{*0} first seen by CMS [PRL 108 (2012) 252002]

State	Mass (MeV)	Width (MeV)	
Ξ_b^-	5797.0 ± 0.6	–	
Ξ_b^0	5791.9 ± 0.5	–	
$\Xi_b'(5935)^-$	5935.01 ± 0.05	< 0.05	$1/2^+$
$\Xi_b^*(5955)^-$	5955.33 ± 0.13	1.65 ± 0.33	$3/2^+$
$\Xi_b^*(5952)^0$	5952.3 ± 0.6	0.90 ± 0.18	$3/2^+$

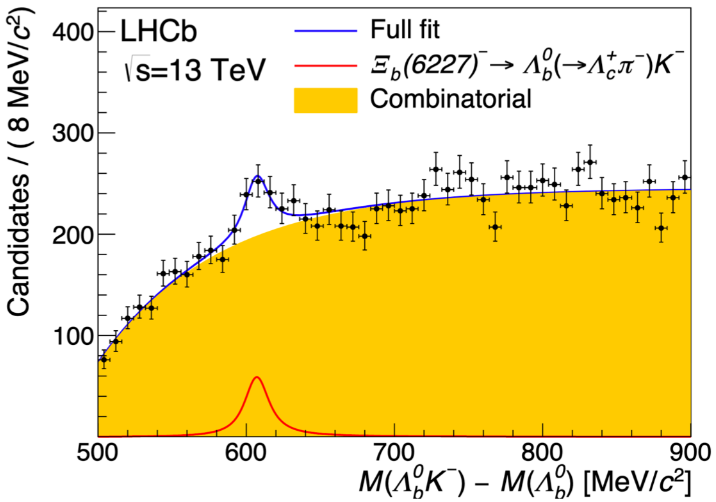


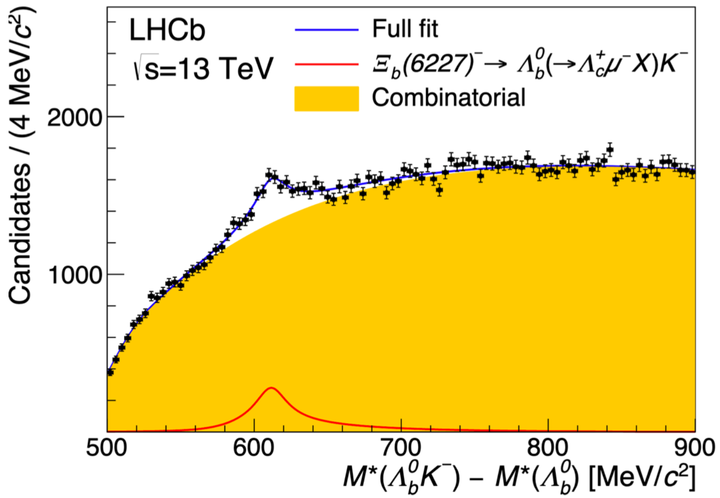
$\Xi_b^{\prime 0}$ below $\Xi_b^- \pi^+$ threshold

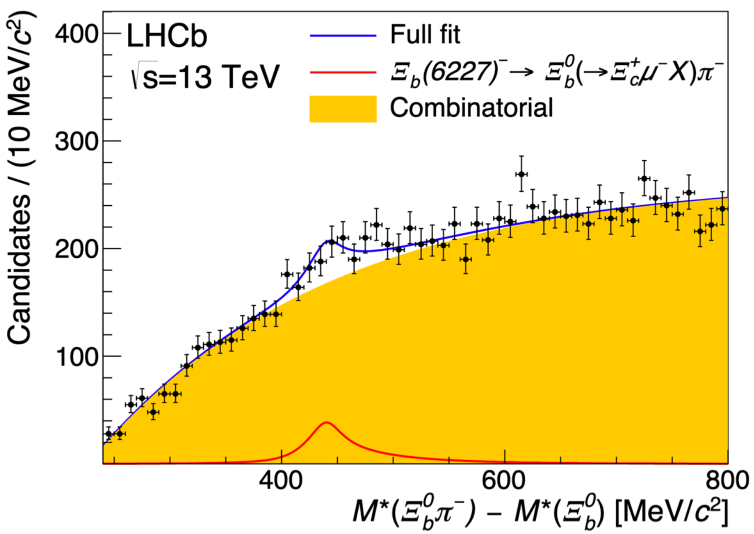
Excited Ξ_b^- baryons

- $\Xi_b^0\pi^-$ and $\Lambda_b^0 K^-$ mass spectra

PRL 121 (2018) 072002







State	Mass (MeV)	Width (MeV)
$\Xi_b(6227)^-$	6226.9 ± 2.0	18 ± 6

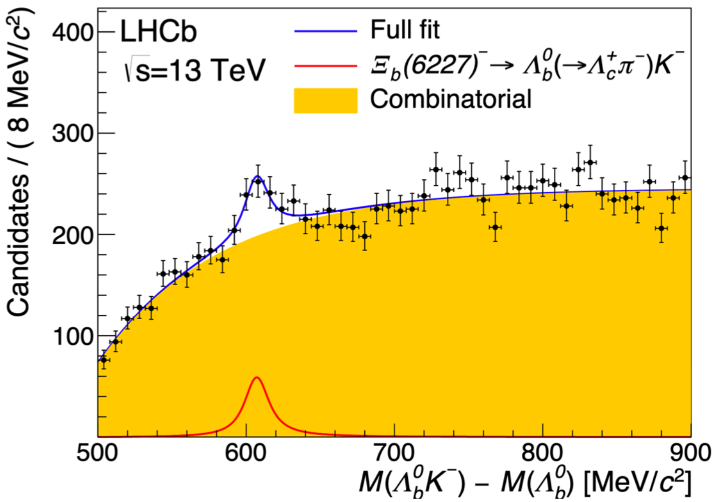
$$\frac{B(\Xi_b(6227)^- \to \Lambda_b^0 K^-)}{B(\Xi_b(6227)^- \to \Xi_b^0 \pi^-)} \sim 1$$

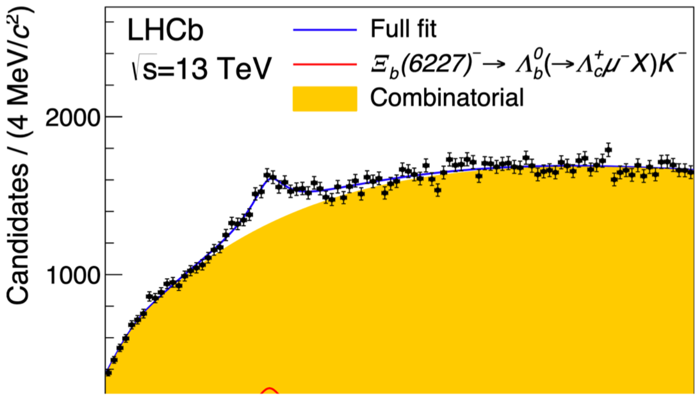
A P-wave state of Ξ_b^- or many states overlaid of P-wave $\Xi_b^{*\prime -}$ (?)

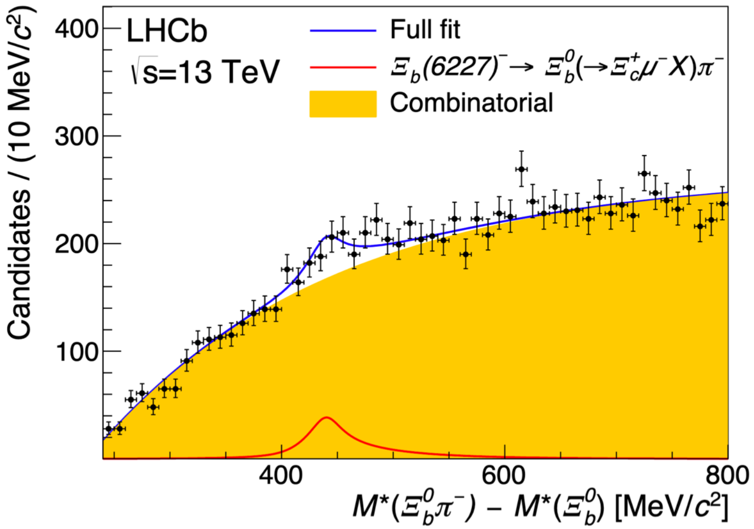
Excited Ξ_b^- baryons

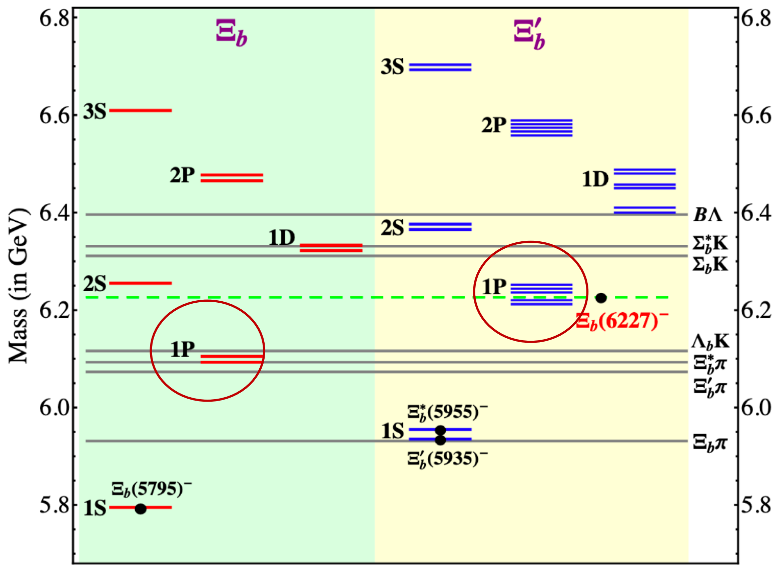
- $\Xi_b^0\pi^-$ and $\Lambda_b^0 K^-$ mass spectra

PRL 121 (2018) 072002







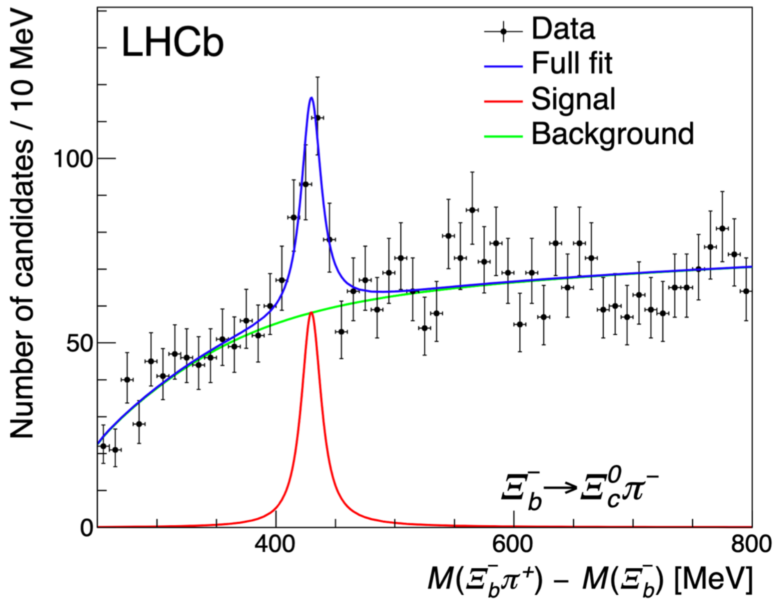


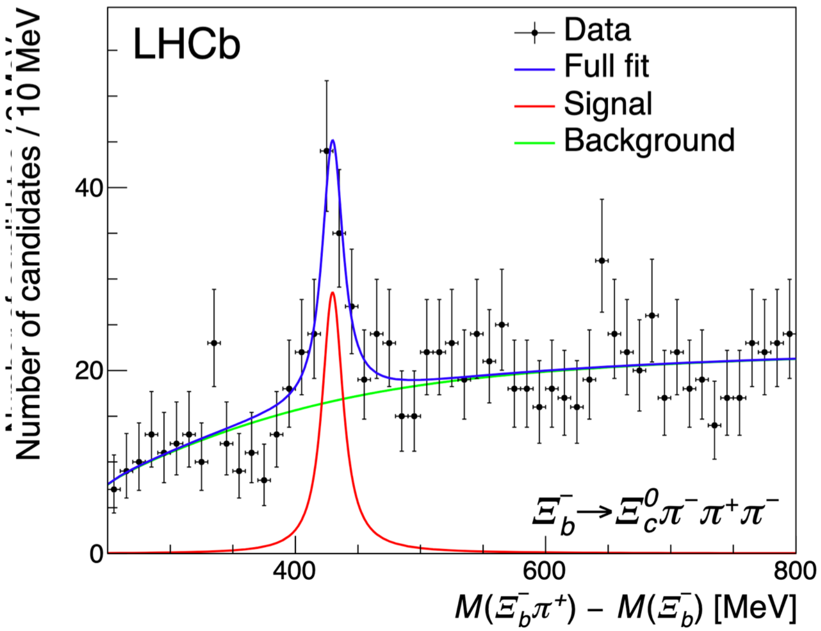
A P-wave state of Ξ_b^- or many states overlaid of P-wave $\Xi_b^{*\prime-}$ (?)

Excited Ξ_b^0 baryons

LHCb-PAPER-2020-019
arXiv:2010.14485

- $\Xi_b^- \pi^+$ mass spectrum





A new state $\Xi_b(6227)^0$ observed

State	Mass (MeV)	Width (MeV)
$\Xi_b(6227)^0$	6227.1 ± 1.5	18.6 ± 4.7

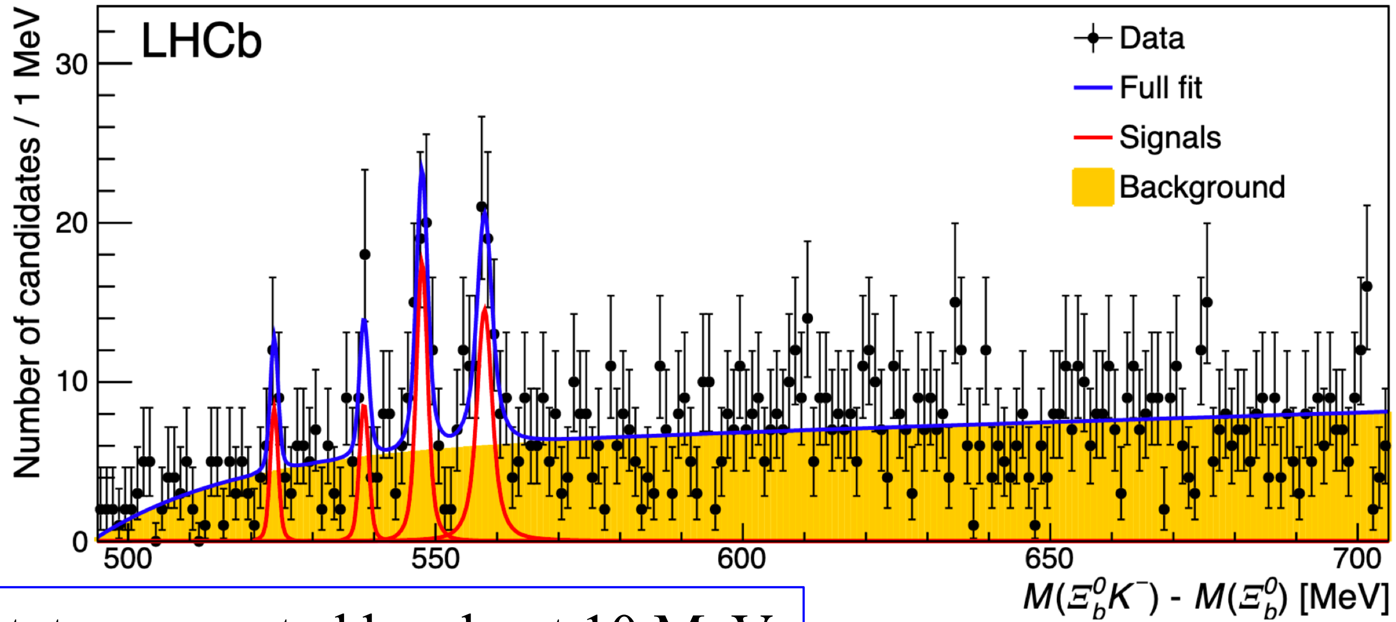
$$\frac{f_{\Xi_b(6227)^0}}{f_{\Xi_b^-}} \mathcal{B}(\Xi_b(6227)^0 \to \Xi_b^- \pi^+) = 0.045 \pm 0.008 \pm 0.004$$

Mass and width consistent with $\Xi_b(6227)^-$

Excited Ω_b^- baryons

- $\Omega_b^{**-} \to \Xi_b^0 K^-$ mass spectrum

PRL 124 (2020) 082002



Four states separated by about 10 MeV

$m(\Omega_b(6316)^-) = 6315.64 \pm 0.31 \pm 0.07 \pm 0.50\,\text{MeV}$ (2.1σ) $\Gamma < 2.8$ MeV

$m(\Omega_b(6330)^-) = 6330.30 \pm 0.28 \pm 0.07 \pm 0.50\,\text{MeV}$ (2.6σ) $\Gamma < 3.1$ MeV

$m(\Omega_b(6340)^-) = 6339.71 \pm 0.26 \pm 0.05 \pm 0.50\,\text{MeV}$ $(>5\sigma)$ $\Gamma < 1.5$ MeV

$m(\Omega_b(6350)^-) = 6349.88 \pm 0.35 \pm 0.05 \pm 0.50\,\text{MeV}$ $(>5\sigma)$ $\Gamma = 1.4^{+1.0}_{-0.8} \pm 0.1$ MeV

To compare $m(\Omega_b^-) = 6046.1 \pm 1.7$ MeV

Excited Ω_b^- baryons: matching

- Five 1P states with one state not detected $\left(\frac{1}{2}\right)^-, \left(\frac{1}{2}\right)^-, \left(\frac{3}{2}\right)^-, \left(\frac{3}{2}\right)^-, \left(\frac{5}{2}\right)^-$

States	Ref.1	Ref.2	Ref.3	Ref.4	Ref.5	Ref.6	Ref.7
$\Omega_b(6316)^-$	$\frac{1}{2}^-$	$\frac{1}{2}^-$ or $\frac{3}{2}^-$	$\frac{3}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{1}{2}^-$	$\frac{1}{2}^-$ or $\frac{3}{2}^-$
$\Omega_b(6330)^-$	$\frac{1}{2}^-$	$\frac{1}{2}^-$ or $\frac{3}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{1}{2}^-$
$\Omega_b(6340)^-$	$\frac{3}{2}^-$	$\frac{3}{2}^-$ or $\frac{5}{2}^-$	$\frac{3}{2}^-$	$\frac{1}{2}^-$	$\frac{5}{2}^-$	$\frac{3}{2}^-$	$\frac{3}{2}^-$
$\Omega_b(6350)^-$	$\frac{3}{2}^-$	$\frac{1}{2}^-$ or $\frac{5}{2}^-$	$\frac{3}{2}^-$	$\frac{3}{2}^-$	$\frac{3}{2}^-$	$\frac{5}{2}^-$	$\frac{3}{2}^-$

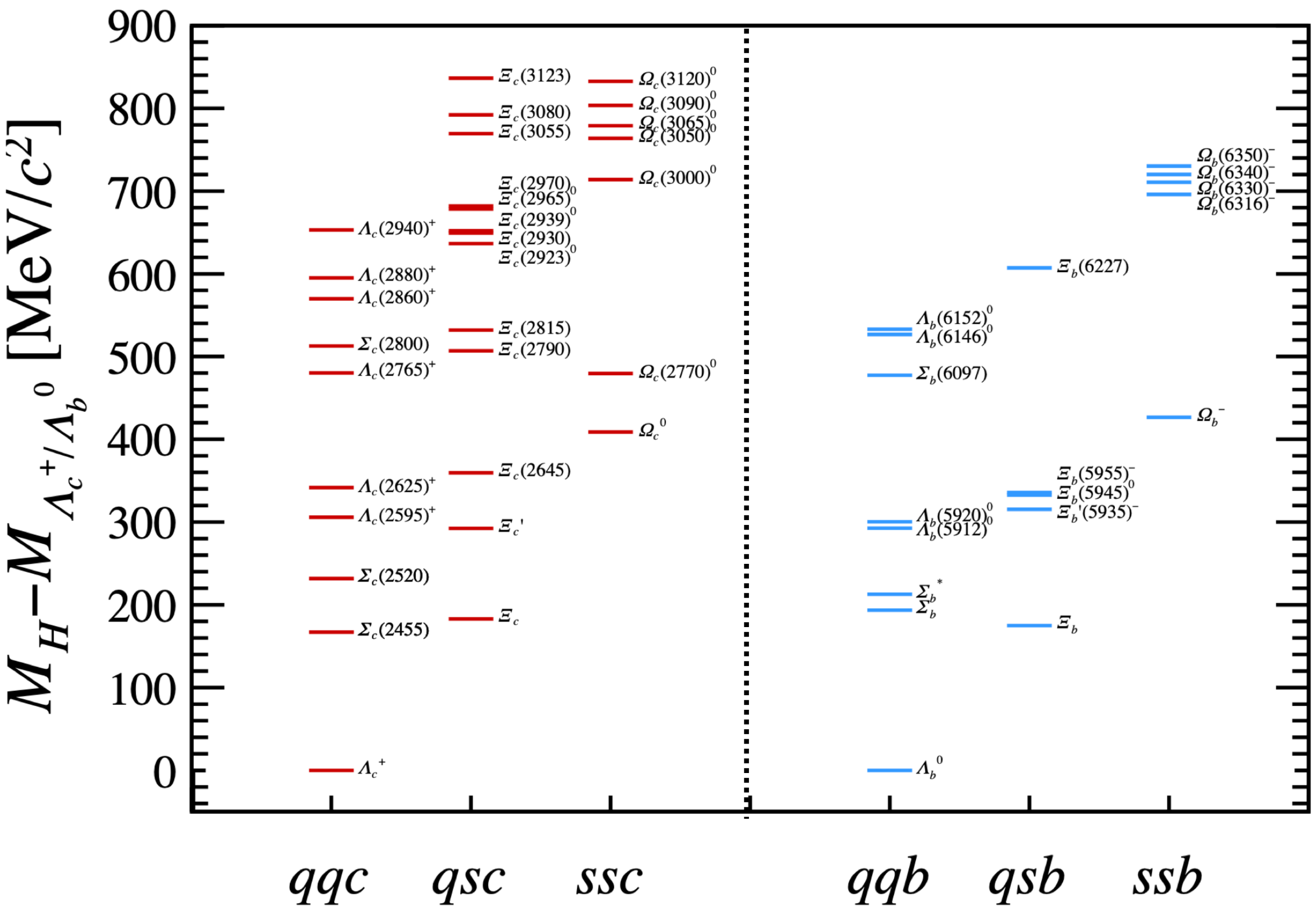
- Baryon-meson molecule? Thresholds far away.

Main channel	$\Xi_b'\bar{K}$	$\Xi_b^*\bar{K}$	$\Xi\bar{B}$	$\Xi\bar{B}^*$
Threshold mass	6431	6451	6598	6643

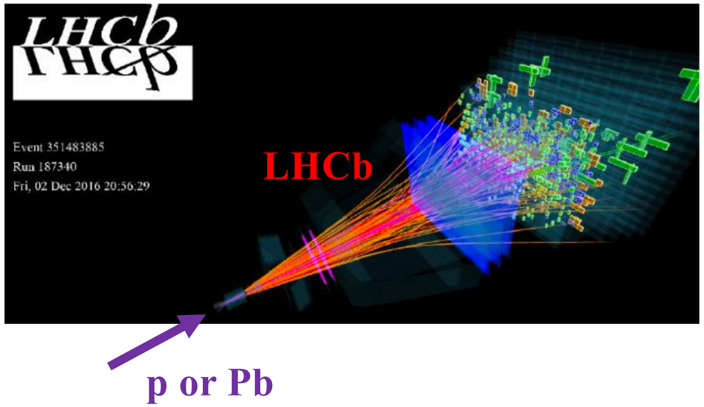
1. PRD 102 (2020) 014207
2. EPJC 80 (2020) 279
3. arXiv:2010.10697
4. J. Phys. Conf. Ser. 1610 (2020) 012011
5. IJMPA 35 (2020) 2050043
6. EPJC 80 (2020) 198
7. PRD 101 (2020) 114013

Beauty vs charm baryons

- Still many nearby states missing

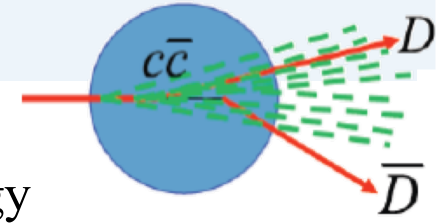


Production in nuclear environment



Quarkonia nuclear break-up

- Quarkonia break up by co-moving particles
  - ➢ Excited state easier to disassociate due to smaller binding energy
  - ➢ Disassociation increases with event activity



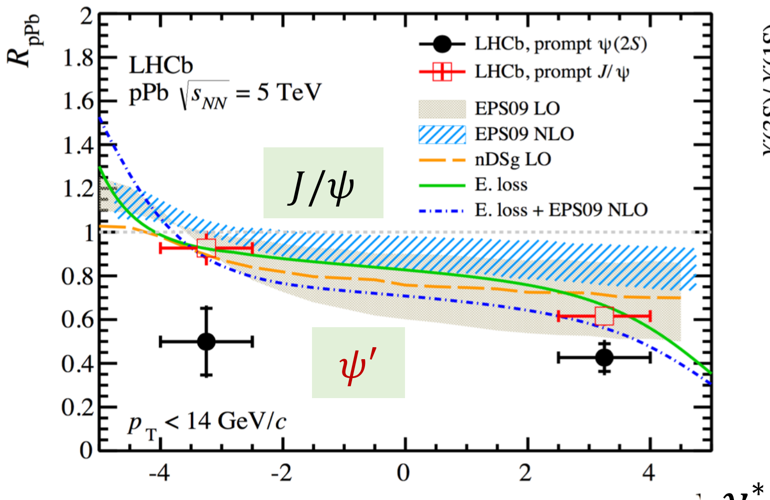
Hadronic comovers

PLB 749 (2015) 98

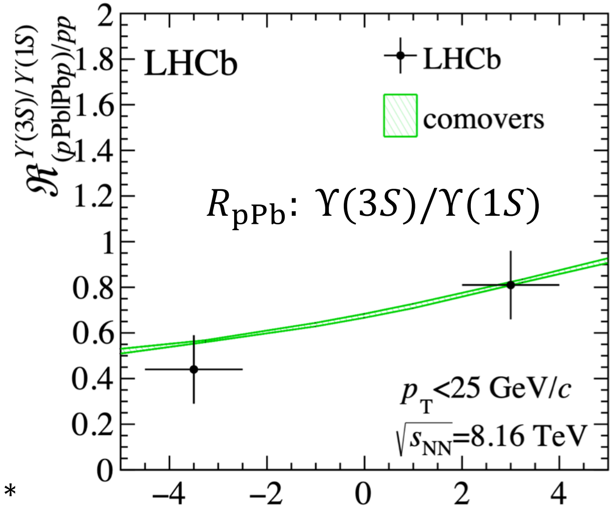
Charmonium binding energies ($2m_D - m_H$)

$D\bar{D}^*$ ***Molecule***

state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'	X(3872)
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69	3.872
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05	0.00001± 0.00027



JHEP 03 (2016) 133



JHEP 11 (2018) 194 y^*

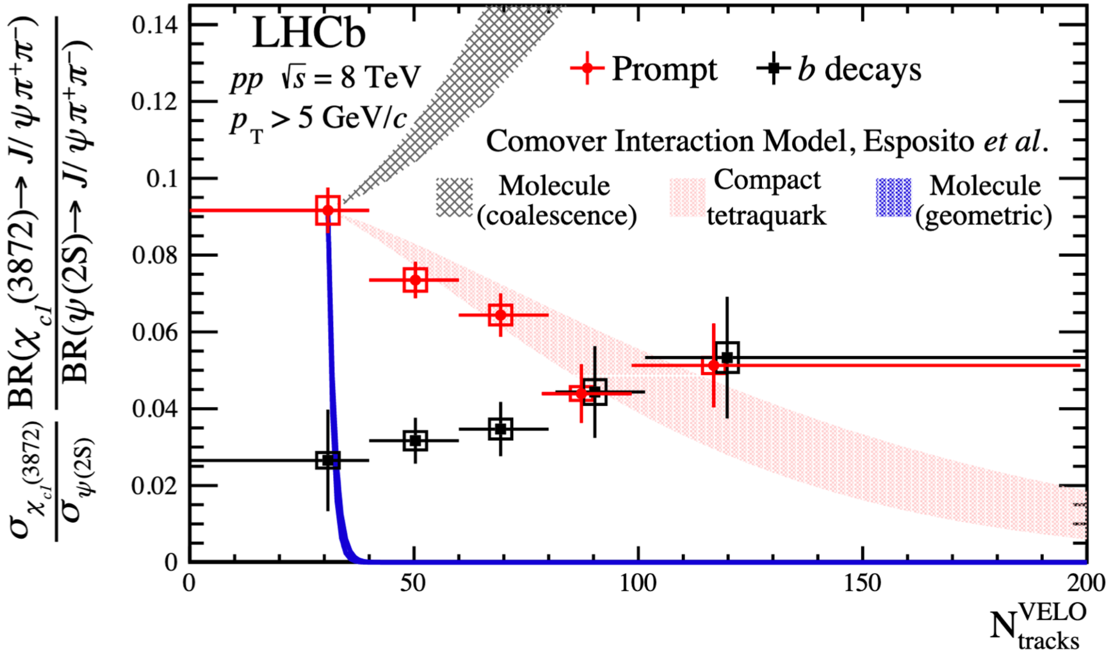
$$R_{pPb} = \frac{\sigma_{pPb}}{208\sigma_{pp}}$$

ψ' more suppressed than J/ψ, similarly for $\Upsilon(3S)$ over $\Upsilon(1S)$, comovers?

$X(3872)$ break-up

LHCb-PAPER-2020-023
arXiv: 2009.06619

- $X(3872)$ production relative to $\psi(2S)$ as a function of event activity
  - From b-decay: no significant change. Produced out of collision environment
  - Prompt: increasing suppression relative to $\psi(2S)$



Binding energy $(2m_D - m_H)$

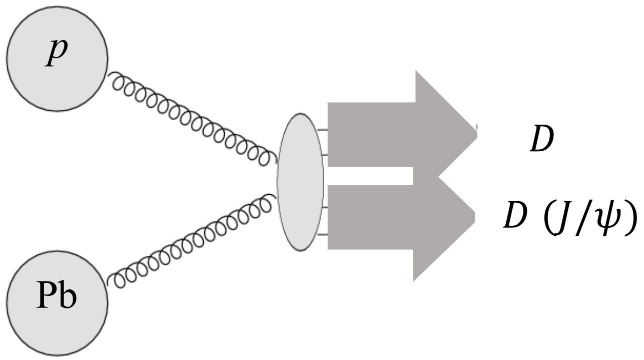
state	ψ'	X(3872)
mass [GeV]	3.69	3.872
ΔE [GeV]	0.05	0.00001± 0.00027

$D\overline{D}^*$ ***Molecule***

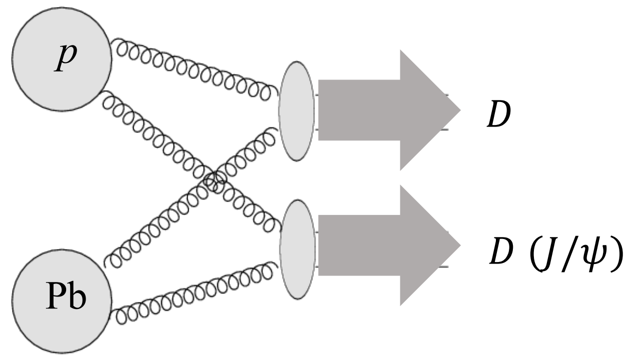
- Explanation using comover model [arXiv:2006.15044]
  - Break-up rate too small compared to expectation in molecule picture
  - Consistent with tightly bound state → large component of $|c\bar{c}>$ (?)

Enhancement of double parton scattering

Single-parton scattering (SPS)



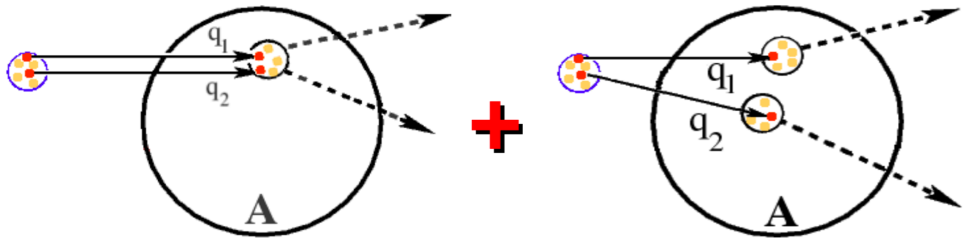
Double-parton scattering (DPS)



- DPS sensitive to parton distribution function (PDF)
- If two collisions uncorrelated: DPS cross-section $\sigma^{H_{Q1}H_{Q2}} = \kappa \frac{\sigma^{H_{Q1}}\sigma^{H_{Q2}}}{\sigma_{\text{eff}}}$

  σ_{eff}: related to geometry, final state independent, universal

- DPS production enhanced in heavy ion collisions, compared to AB scaling



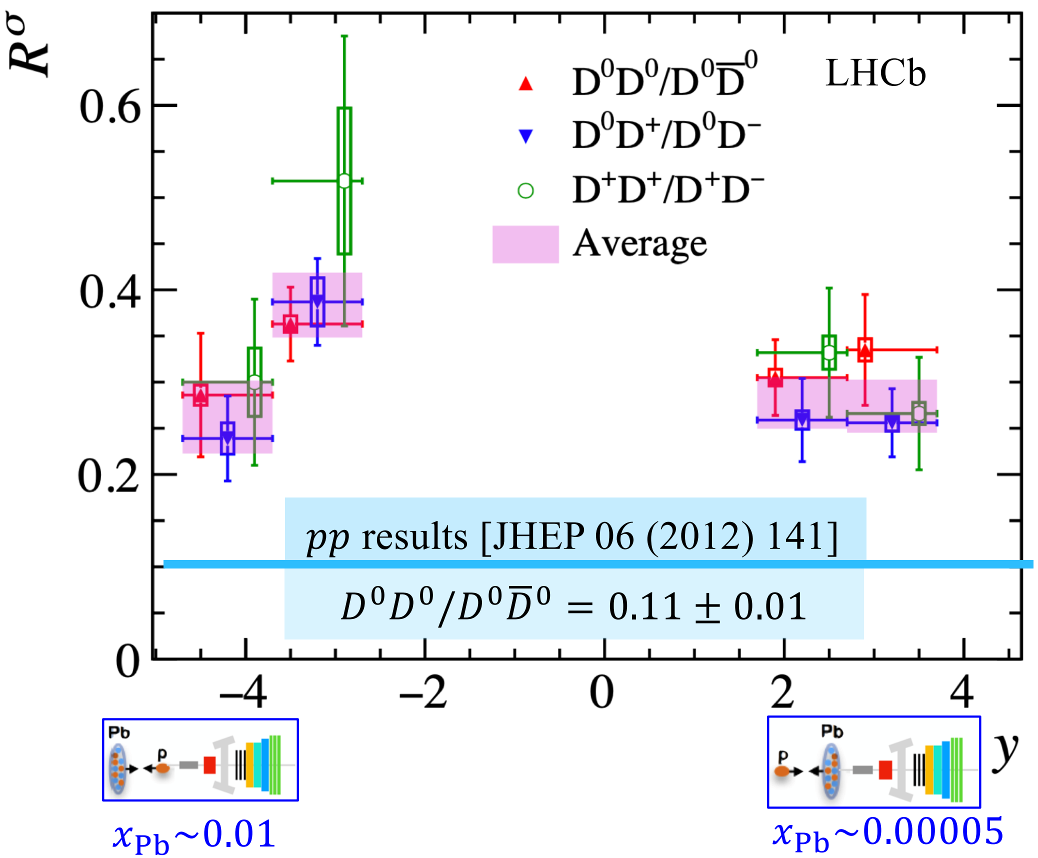
$$\sigma^{\text{DPS}}_{(pA)} = \sigma^{\text{DPS},1}_{(pA)} + \sigma^{\text{DPS},2}_{(pA)}$$

PRL 118 (2017) 122001

Enhancement factor is about three in *p*Pb collisions

Associated charm production in pPb data

- Like-sign DD, opposite-sign $D\bar{D}$ and $J/\psi D$ in pPb collisions
- Like-sign over opposite-sign ratio about 3 times of that in pp data



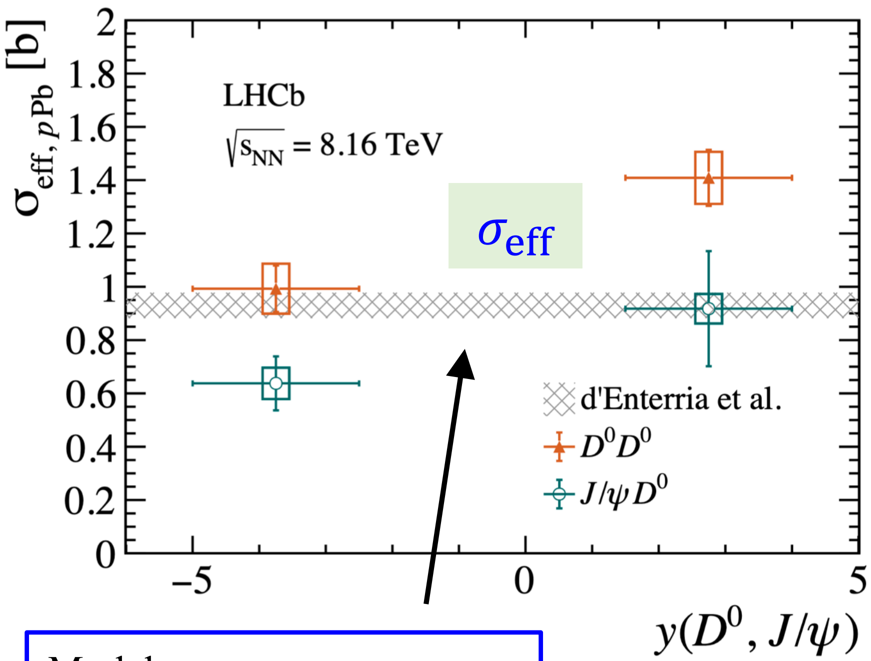
LHCb-PAPER-2020-010
arXiv: 2007.06945, accepted by PRL

- Opposite-sign production by SPS ($c\bar{c}$): scaled with A = 208
- Like-sign production dominated by DPS, scaled by ≈ 3A

Nuclear enhancement

LHCb-PAPER-2020-010
arXiv: 2007.06945, accepted by PRL

- σ_{eff} extracted using D^0D^0 and $J/\psi D^0$ production, assuming solely DPS



Model [PLB 718 (2013) 1395]
$\sigma_{\text{eff},pPb} = 0.93 \pm 0.05$ b

PDF: $x_{\text{Pb}} \sim \frac{m_T}{\sqrt{s}} e^{-y}$

Nuclear modification factor

$$R_{\text{pPb}} = \frac{\sigma_{\text{pPb}}}{208\sigma_{pp}}$$

Pair	$+\lvert y\rvert$	$-\lvert y\rvert$
D^0D^0	1.3 ± 0.2	4.2 ± 0.8
$J/\psi D^0$	1.5 ± 0.5	4.6 ± 1.3

- ➢ Consistent with factor 3 enhancement
- ➢ Value for $J/\psi D^0$ smaller than D^0D^0: → SPS contamination for $J/\psi D^0$?
- ➢ Proton direction ($+\lvert y\rvert$) larger than lead direction ($-\lvert y\rvert$))
  → hint of position dependent nuclear PDF modification

PRD 101 (2020) 054036

Summary

- LHCb progresses establishing heavy hadron spectroscopy
  - **Three new excited Ξ_c^0 states**
  - **New excited D_s^+ state (2^1S_0?)**
  - **Precision measurement of Ξ_{cc}^{++} mass**
  - **New beauty baryons**

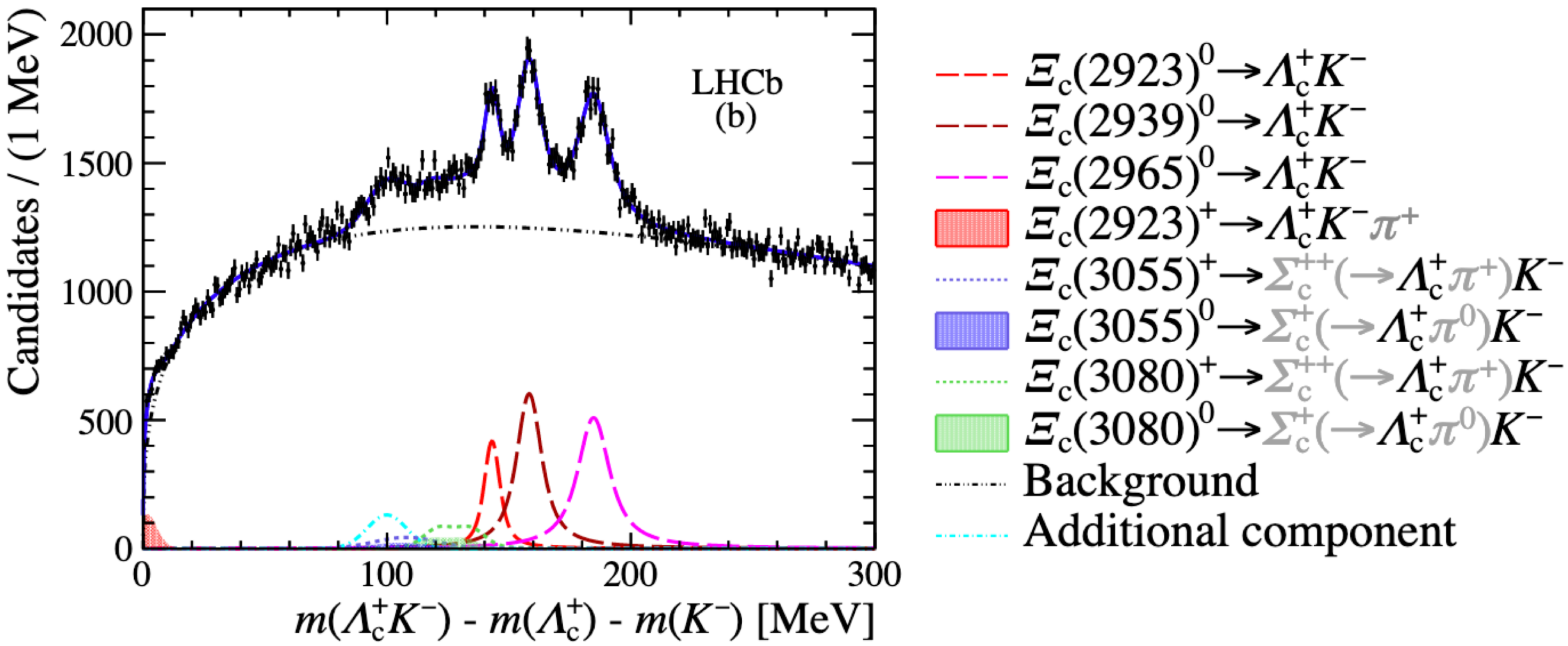
    Excited $\Lambda_b^0, \Sigma_b, \Xi_b, \Omega_b^-$ states
- Heavy flavor production to probe nuclear effect
  - **Comover interactions with quarkonium**
  - **Enhancement of double parton scattering**
- Run3: gain precision in hadronic final states: more lumi. + software trigger

Thank you for your attention

Backups

Observation of Ξ_c^{*0} states

Zhihao Xu (Nov.6)



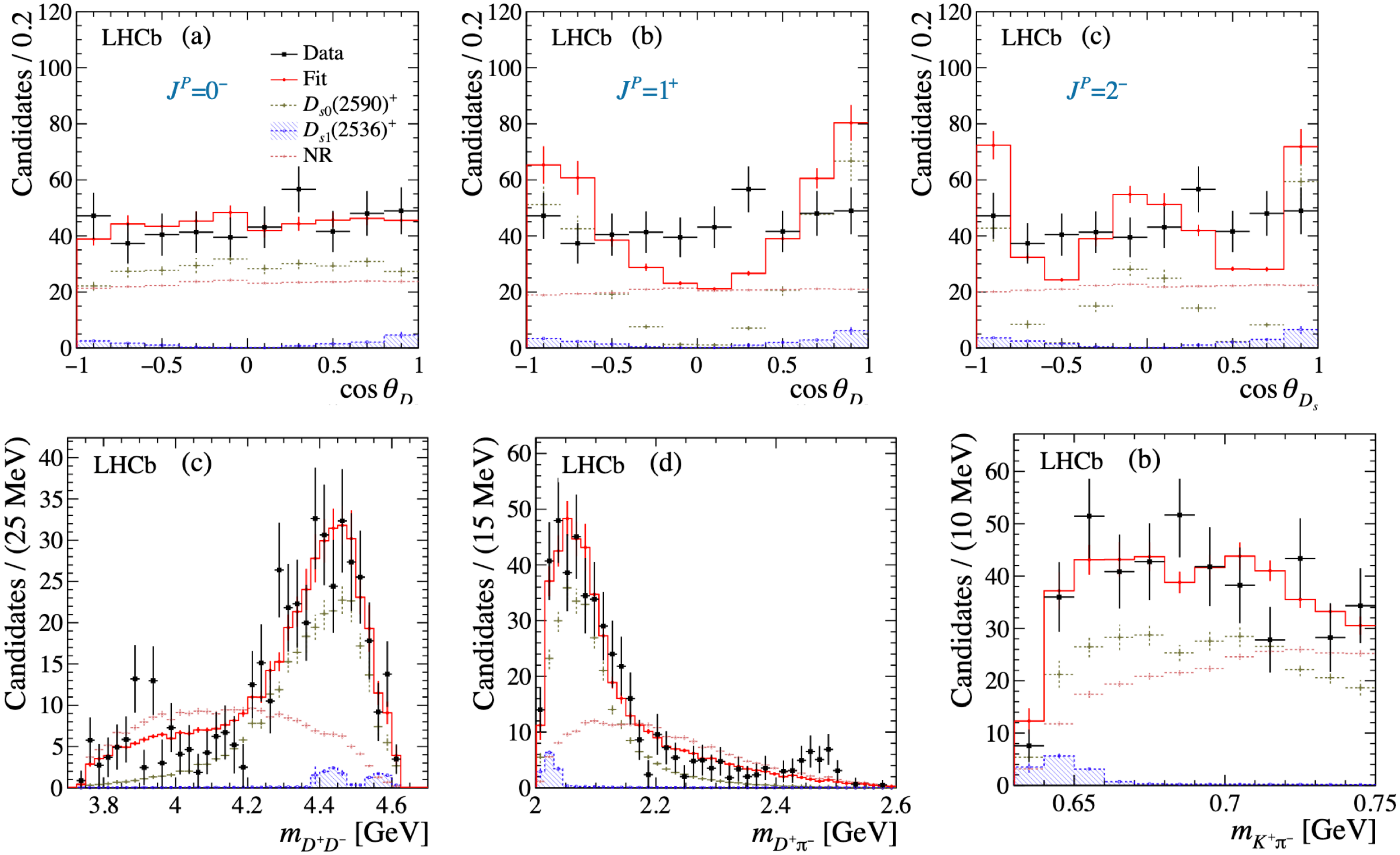
$$m(\Omega_c(3050)^0) - m(\Xi_c(2923)^0) \simeq m(\Xi_c(2923)^0) - m(\Sigma_c(2800)^0) \simeq 125\,\mathrm{MeV},$$

$$m(\Omega_c(3065)^0) - m(\Xi_c(2939)^0) \simeq 125\,\mathrm{MeV},$$

$$m(\Omega_c(3090)^0) - m(\Xi_c(2965)^0) \simeq 125\,\mathrm{MeV}.$$

Observation of new D_s^{*+} states

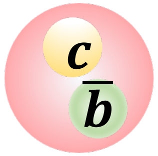
Chen Chen (Nov.6)



Precision B_c^+ mass measurement

Yanting Fan (Nov.6)

- B_c^+ has unique properties
  - Consists of two different heavy quarks
  - Excited spectroscopy similar to heavy quarkonia
  - Production and decay properties distinct from quarkonia



A special system to test QCD and effective models

JHEP 07 (2020) 123

- Mass measured combining almost all decay modes, mostly observed by LHCb

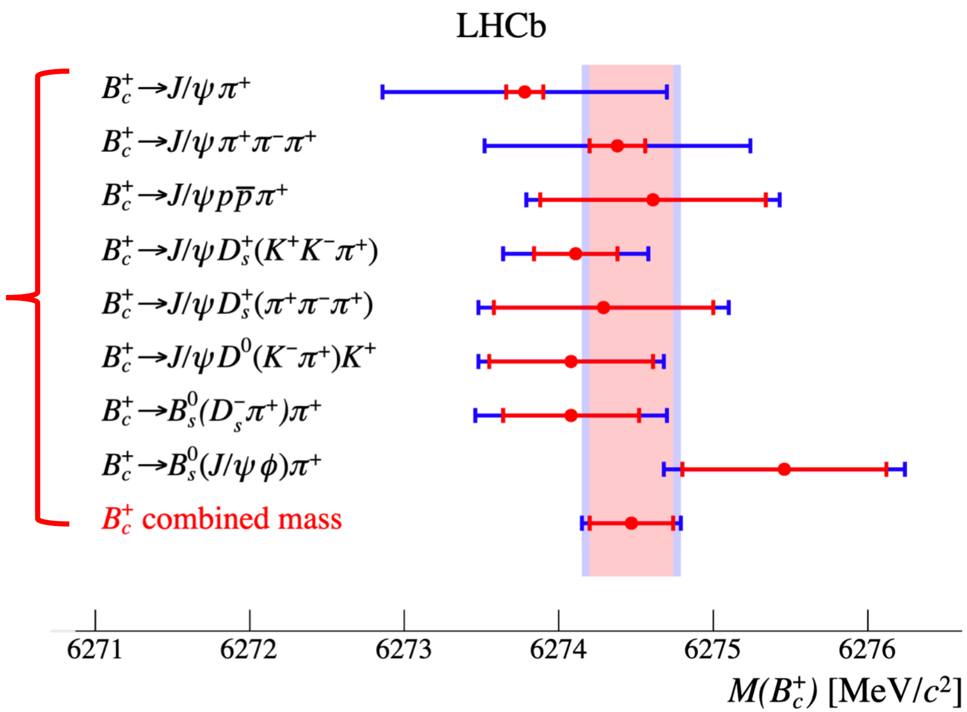
  Competing between statistical and systematic uncertainties

$$m(B_c^+) = 6274.47 \pm 0.32 \text{ MeV}$$

Compared with:

PDG: 6274.9 ± 0.8 MeV

LQCD: $6278 \pm 6 \pm 4$ MeV



LHCb detector

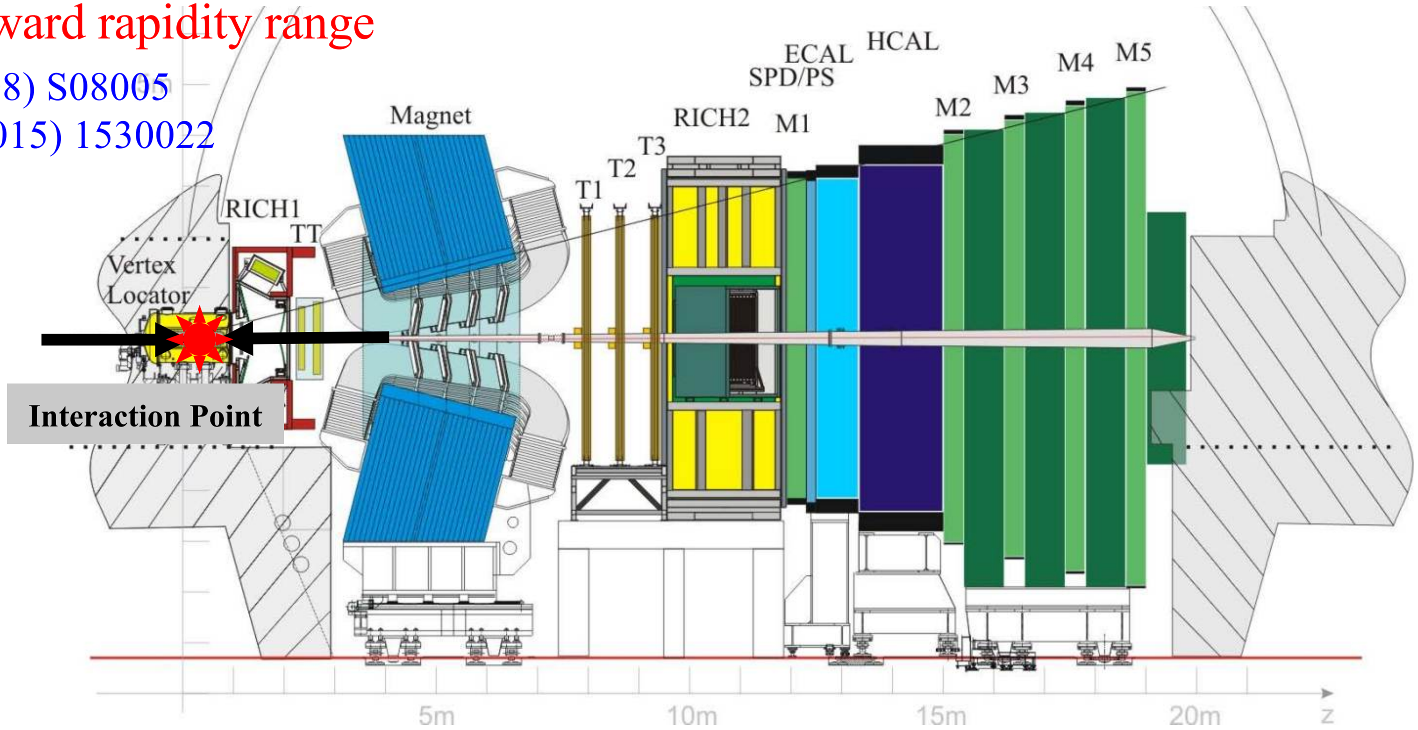
Aiming for precision measurements in b, c sectors

→ but becoming a General Purpose Detector

→ in forward rapidity range

JINST 3 (2008) S08005

IJMPA 30 (2015) 1530022



Excellent vertex and IP, decay time resolution:

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

Very good momentum resolution:

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

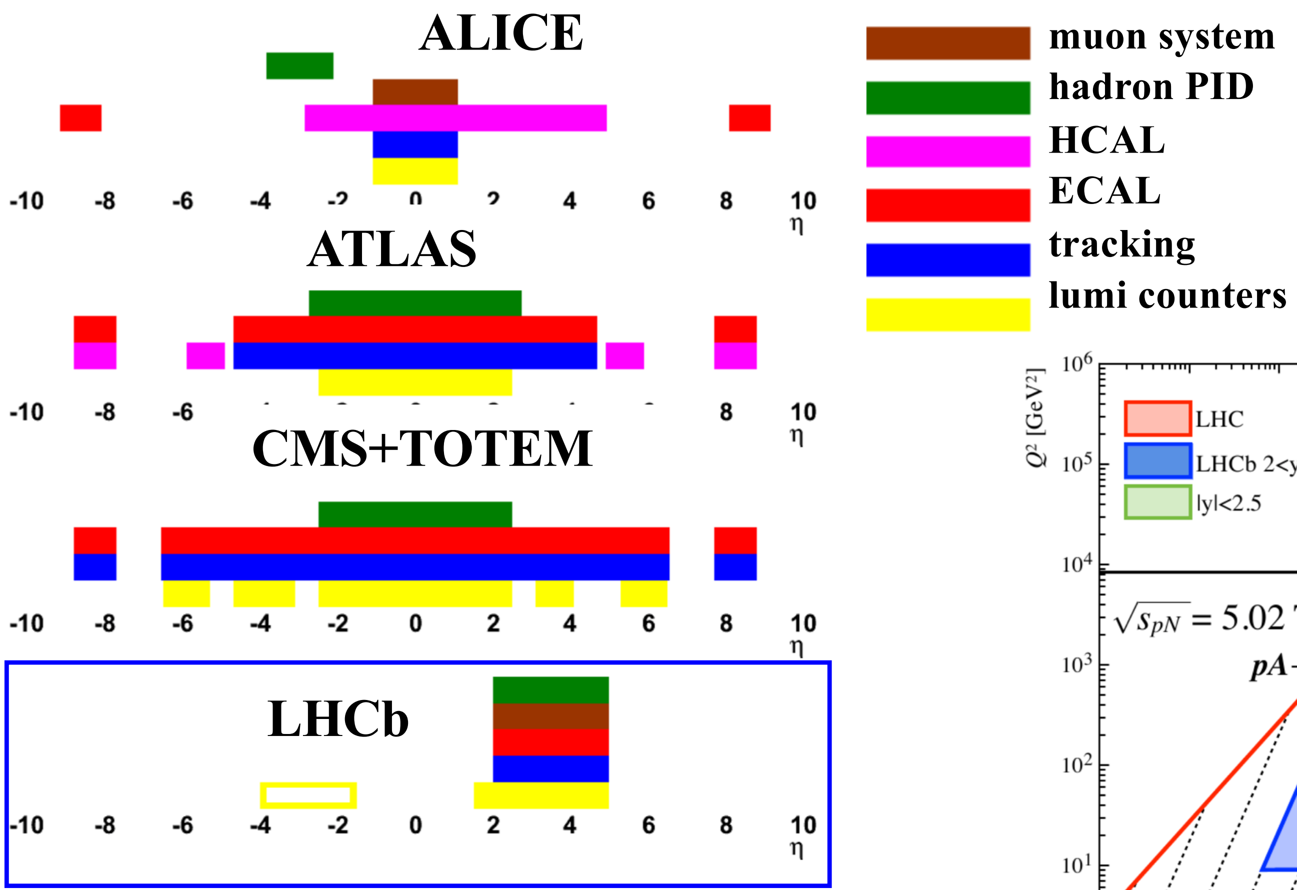
Hadron and Muon identification

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

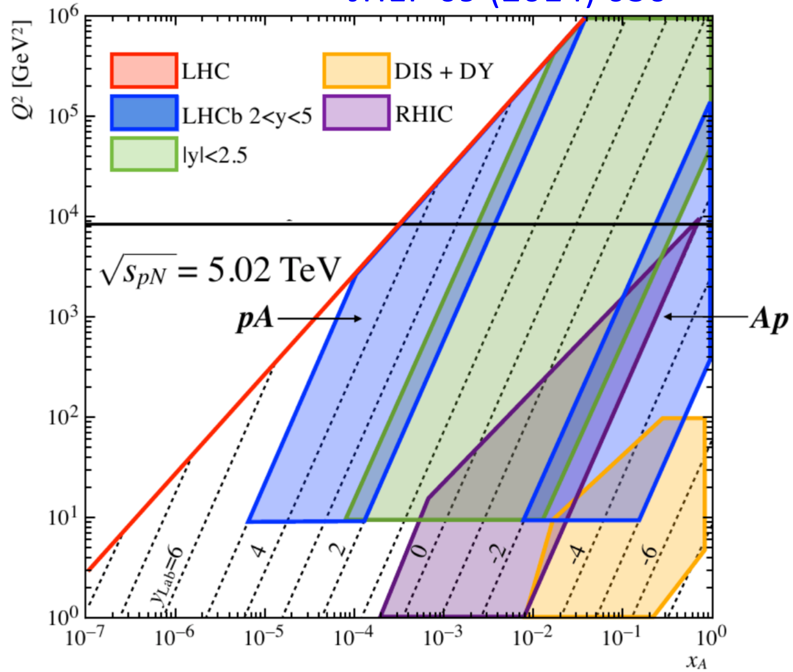
Data good for analyses

- $> 99\%$

LHCb experiment



JHEP 09 (2014) 030



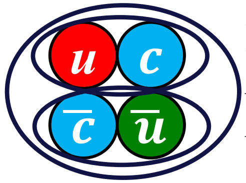
LHCb fully instrumented in the forward region ($2 < \eta < 5$)

- Heavy ion studies in a unique kinematic area: low p_T, large y, very small or large x
- Complementary to other LHC experiments

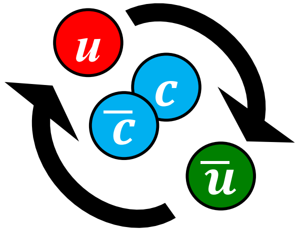
$X(3872)$

- Interpretation of X(3872) structure

Compact tetraquark/pentaquark



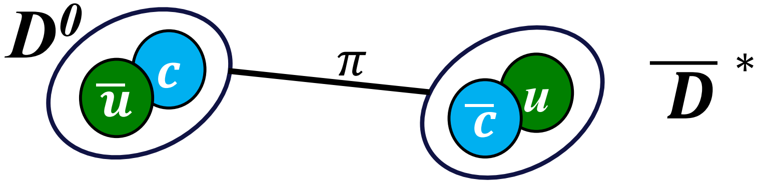
Diquark-diquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)



Hadrocharmonium/ adjoint charmonium
PLB 666 344 (2008)
PLB 671 82 (2009)

Hadronic Molecules

PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)



Mixtures of exotic +conventional states

$$X = a\,|c\bar{c}\rangle + b\,|c\bar{c}q\bar{q}\rangle$$

PLB 578 365 (2004)
PRD 96 074014 (2017)

- "Binding" energies E_b for disassociation $(2m_D - m_H)$

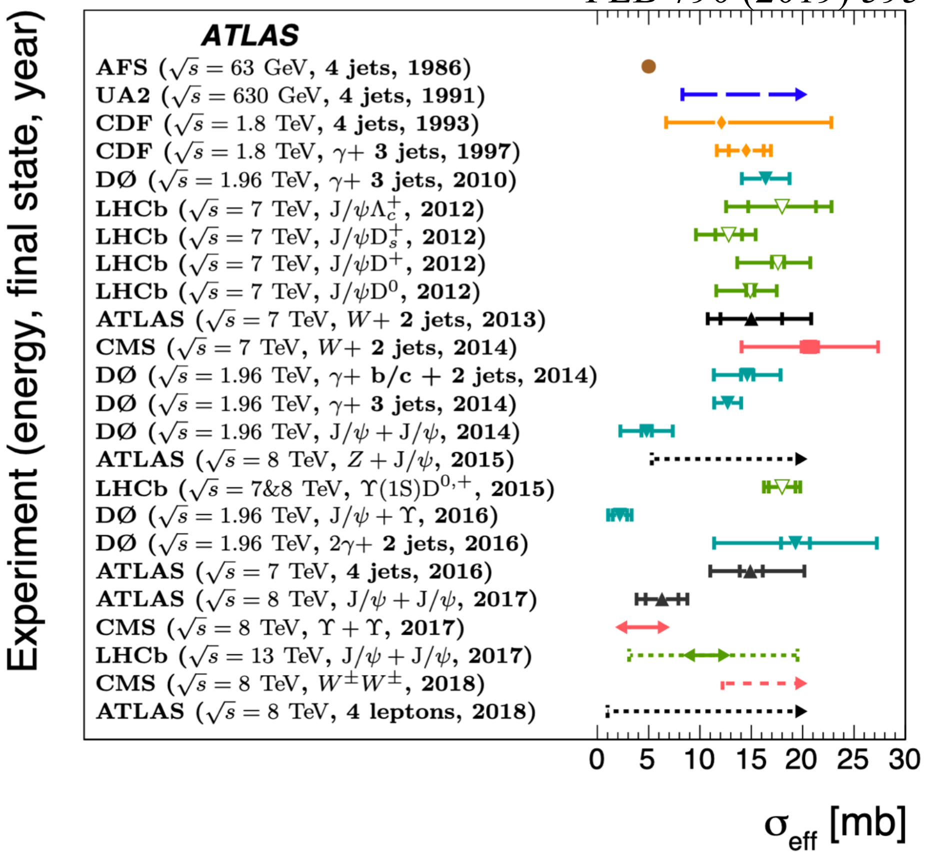
$D\bar{D}^*$ Molecule

state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'	X(3872)
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69	3.872
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05	0.00001± 0.00027

J. Phys. G 32 (3) 2006

Effective cross-section: σ_{eff}

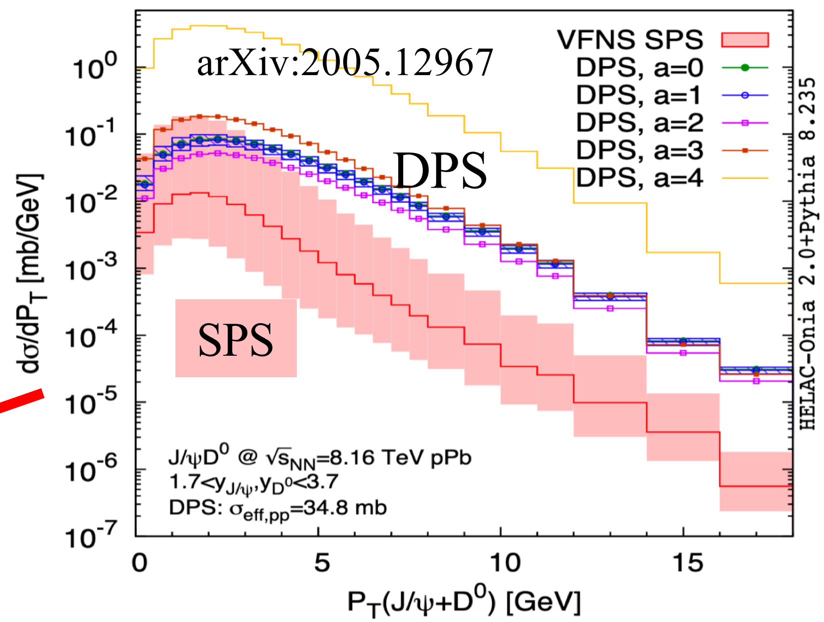
PLB 790 (2019) 595



$$\sigma_{eff} = \frac{1}{2}\frac{\sigma_{D^0}\sigma_{D^0}}{\sigma_{D^0D^0}(DPS)}$$

- $\sigma_{eff}\,(pp)$~ 15 mb
- Quarkonia data prefer lower value ~5 mb
  - → Flavor dependent ?
  - → Energy dependent ?
  - → Kinematic dependent ?
- (Some) assume associated production dominated by DPS → lower limit of σ_{eff}

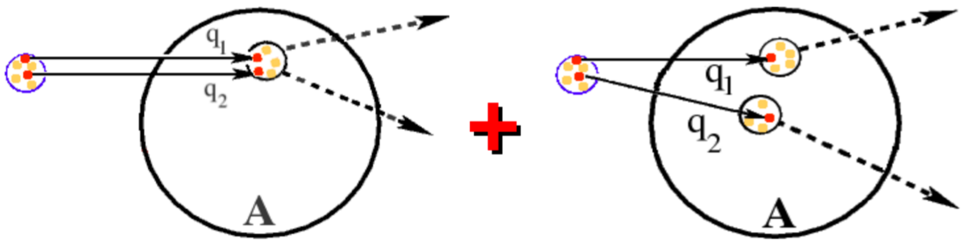
SPS may be comparable with DPS



DPS in heavy ion data

- DPS enhanced in proton-lead collisions

PRL 118 (2017) 122001



$$\sigma^{\mathrm{DPS}}_{(pA)} = \sigma^{\mathrm{DPS,1}}_{(pA)} + \sigma^{\mathrm{DPS,2}}_{(pA)}$$

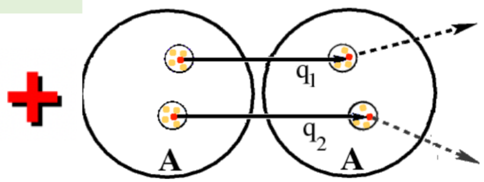
$\sigma^{\mathrm{SPS}}_{p\mathrm{Pb}} \sim A \times \sigma^{\mathrm{SPS}}_{pp}$, A=208, Glauber model [Ann.Rev.Nucl.Part.Sci. 57 (2007) 205]

$\sigma^{\mathrm{DPS}}_{p\mathrm{Pb}} \sim [A + A^{4/3}/\pi] \times \sigma^{\mathrm{DPS}}_{pp} \approx 3A \times \sigma^{\mathrm{DPS}}_{pp}$

$$\sigma_{\mathrm{eff},p\mathrm{Pb}} \approx \frac{A \times \sigma_{\mathrm{eff},pp}}{3} = 1\ \mathrm{b\ for}\ \sigma_{\mathrm{eff},pp} = 15\ \mathrm{mb}$$

$\approx$ 3 b without nuclear enhancement

- DPS enhancement even larger for AA collisions

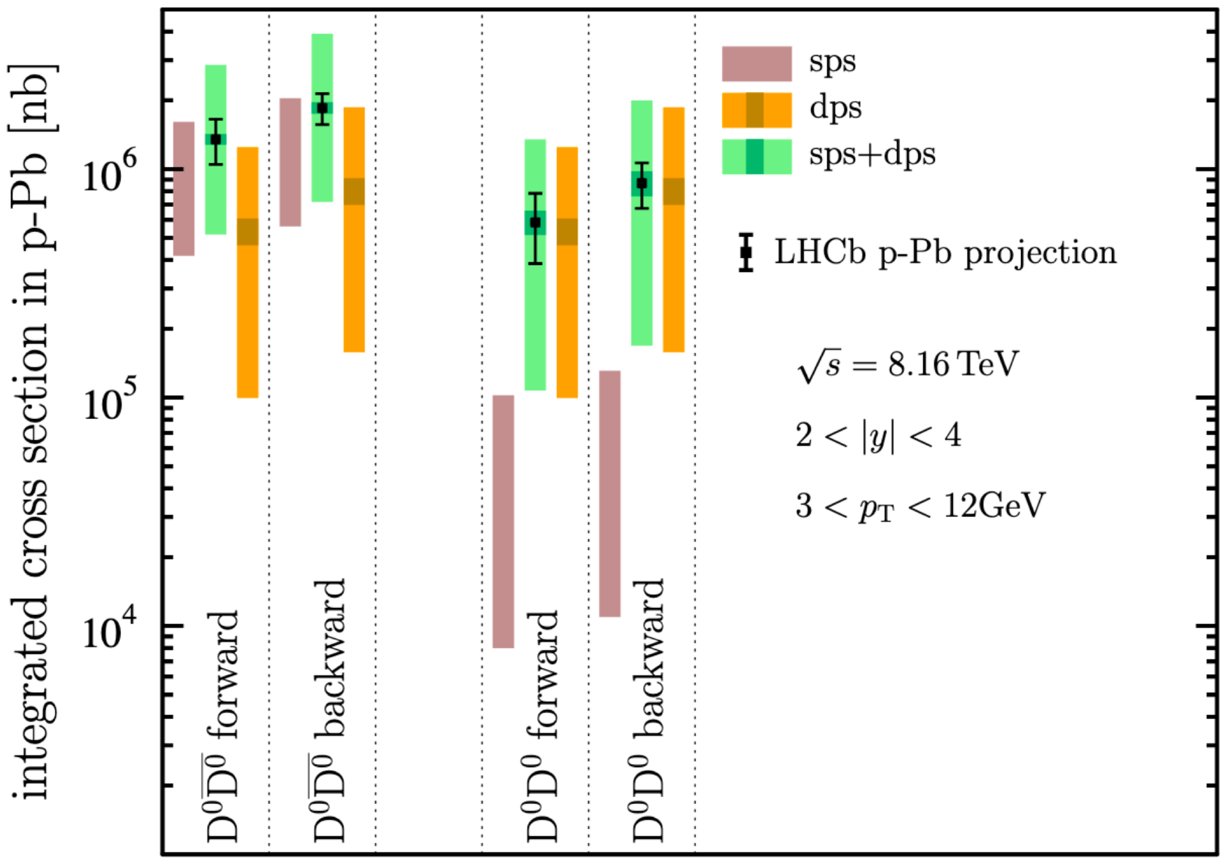


- Heavy ion data are cleaner environment to study DPS

Open charm pairs in *p*Pb

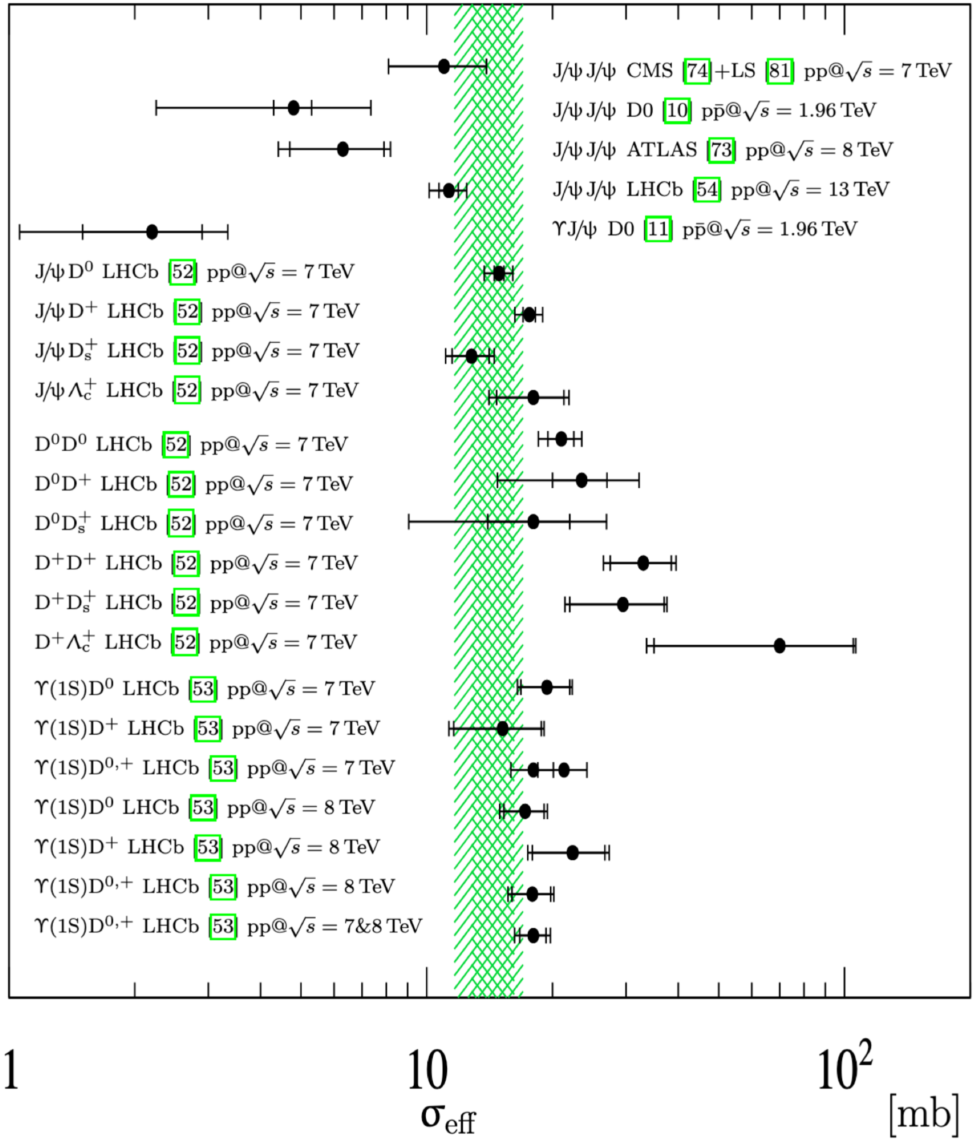
- LS production mostly DPS: DPS/SPS ~ 20
- OS production largely SPS: DPS/SPS ~ 0.5

PLB 800 (2020) 135084



$\sigma_{\rm eff}^{pp}$ by LHCb

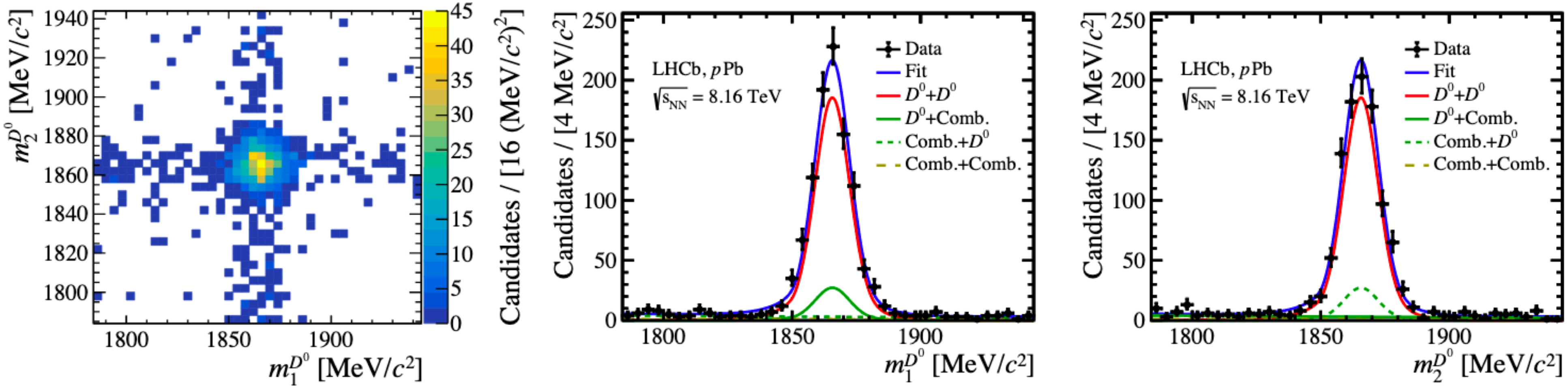
Adv.Ser.Direct.High Energy Phys. 29 (2018) 141



Hatched green:

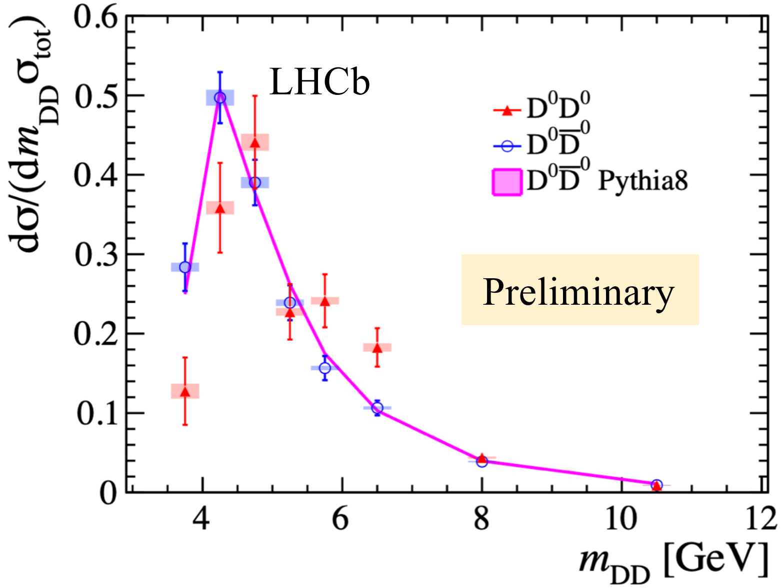
$\sigma_{\rm eff}^{pp} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb

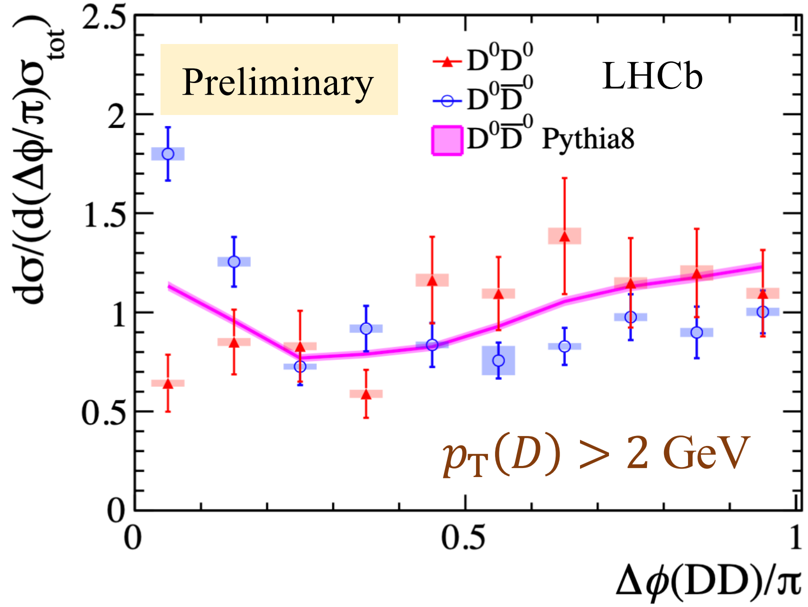
Pair mass distributions

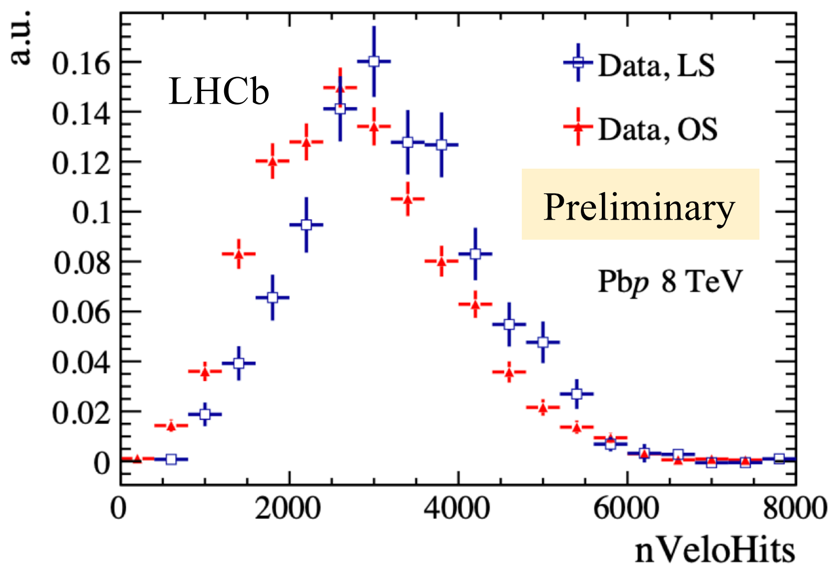


Charm pair production in pPb data

LHCb-PAPER-2020-010

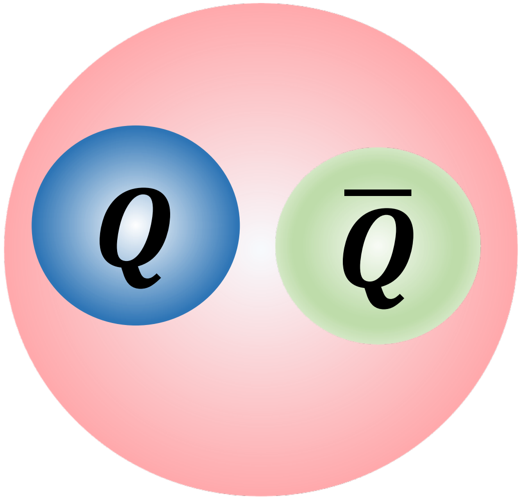






- Invariant mass
  - ➢ DD pair harder than $D\overline{D}$
  - ➢ $D\overline{D}$ well produced by Pythia8
- $\Delta\phi(DD)$
  - ➢ Flat for DD
  - ➢ Peaking at 0 for $D\overline{D}$, only qualitatively modeled by Pythia8
- DD events have larger event activity

Heavy quarkonium production



Heavy quarkonia production

- Factorization methods

$$\sigma(ij \to H + X) \Leftarrow \sum_n \underbrace{\sigma(ij \to Q\bar{Q}[n]X)}_{\text{Perturbative}} \underbrace{< Q\bar{Q}[n] \to H >}_{\text{Non-perturbative}}$$

n: spin, parity, color indices

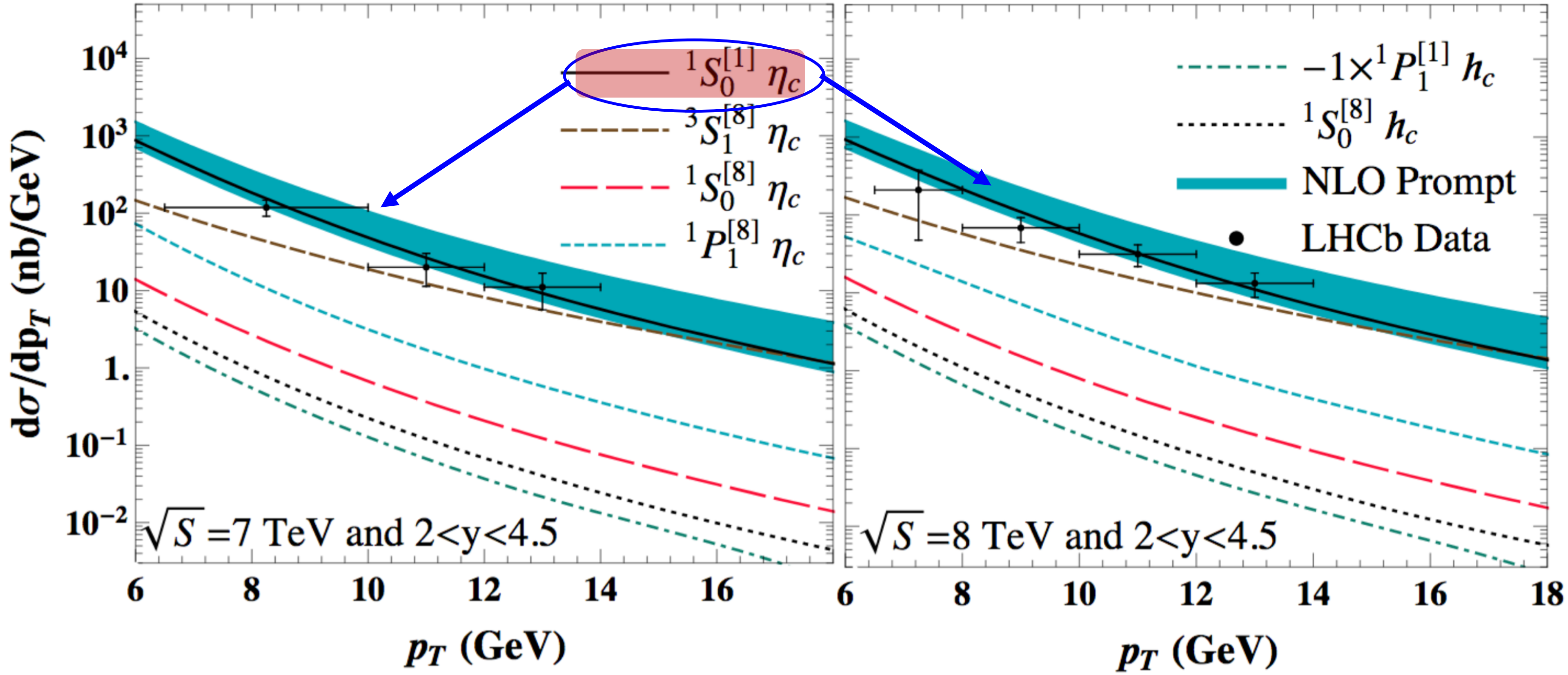
- **Color singlet mechanism (CSM):** $Q\bar{Q}[n]$ color singlet state, coincides with final state quarkonium J^{PC} quantum number
- **Non-relativistic QCD approach (NRQCD):** Both color singlet and octet, all viable J^{PC} states allowed with varying probabilities (long distance matrix elements, LDME)
  - LDME non perturbative, universal, obtained from data
  - Leading LDMEs for J/ψ production: ${}^3S_1^{[1]}$, ${}^3S_1^{[8]}$, ${}^1S_0^{[8]}$, ${}^3P_J^{[8]}$
- **Color evaporation model:** fixed rate for all $Q\bar{Q}$ pairs with $m_{Q\bar{Q}} < 2m_{H_Q}$
  - Improved version: $m_{H_{QQ}} < m_{Q\bar{Q}} < 2m_{H_Q}$

Different predications for p_T spectrum and polarization!

η_c production

Qingnian Xu (Nov.6)

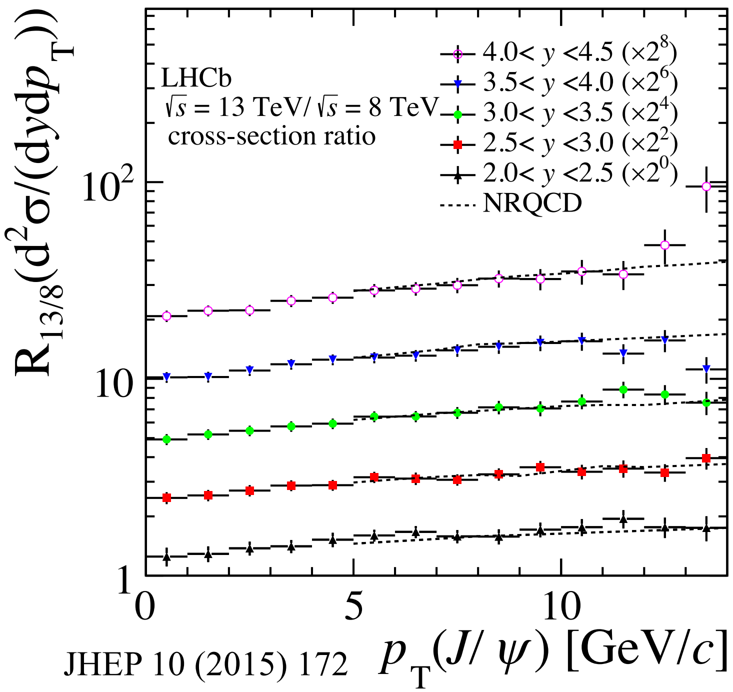
LHCb: EPJ C75 (2015) 7, EPJ C80 (2020) 191



- Data saturated by color singlet $O^{\eta_c}({}^1S_0^{[1]})$, relatively small CO contributions, different from J/ψ and ψ'.

Brief summary of quarkonia production

- NRQCD describes cross-section data at high p_T amazingly well
  - ➢ From Tevatron to LHC
  - ➢ Ratios between states
  - ➢ Ratios at different energies



JHEP 10 (2015) 172

- Polarization needs more work
  - ➢ Experiment: higher p_T range, better precision, more states
  - ➢ Theory: are LDMEs the only/right solution? Extending calculations at low p_T.

JHEP 12 (2018) 057, JHEP 01 (2014) 056