GDR-InF annual workshop
4-6 Nov. 2019, Sommières France

LHCb heavy flavor measurements and opportunities

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4 Nov. 2019

Introduction

- Unique probes of heavy-ion collisions
  - $m_Q \gg \Lambda_{QCD}$, production calculable with perturbative-QCD
  - $t_{\mathrm{prod}} \sim 1/m_T$, information about initial and final state
- Information from heavy flavor
  - Initial state

    nPDF [PRL121(2018)052004, arXiv:1906.02512]

    saturation [Nucl.Phys.A735(2004)248…]

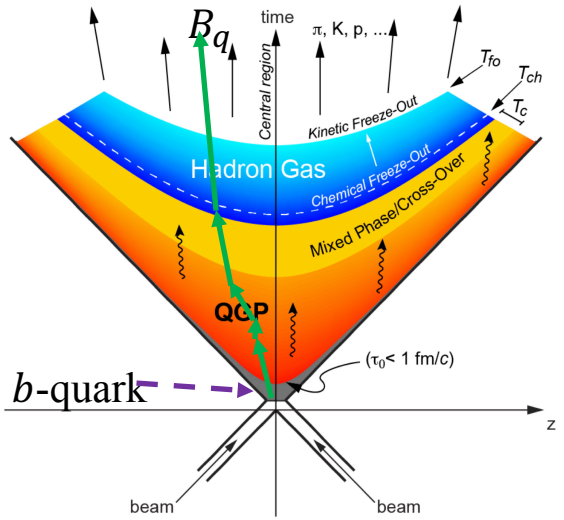
    …
  - Final state, medium properties

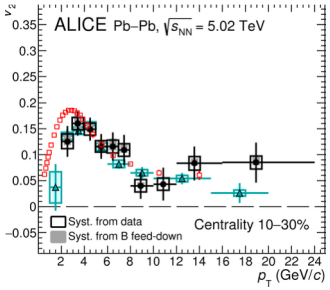
    Elliptic flow [Nucl.Phys.A735(2004)248…]

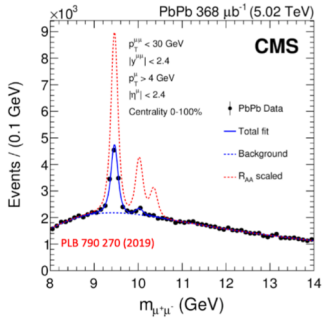
    Energy loss [Eur.Phys.J.A53(2017)5…]

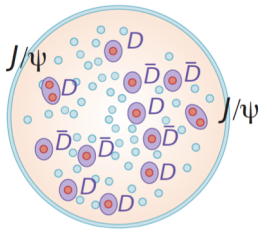
    Quarkonium dissociation/sequential suppression [Int.J.ofMod.Phys.A 28(2013)1340012…]

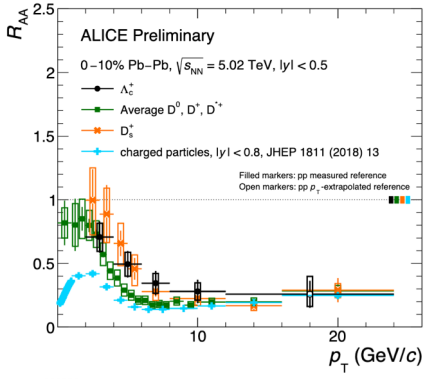
    Coalescence hadronization [PLB595(2004)202…]











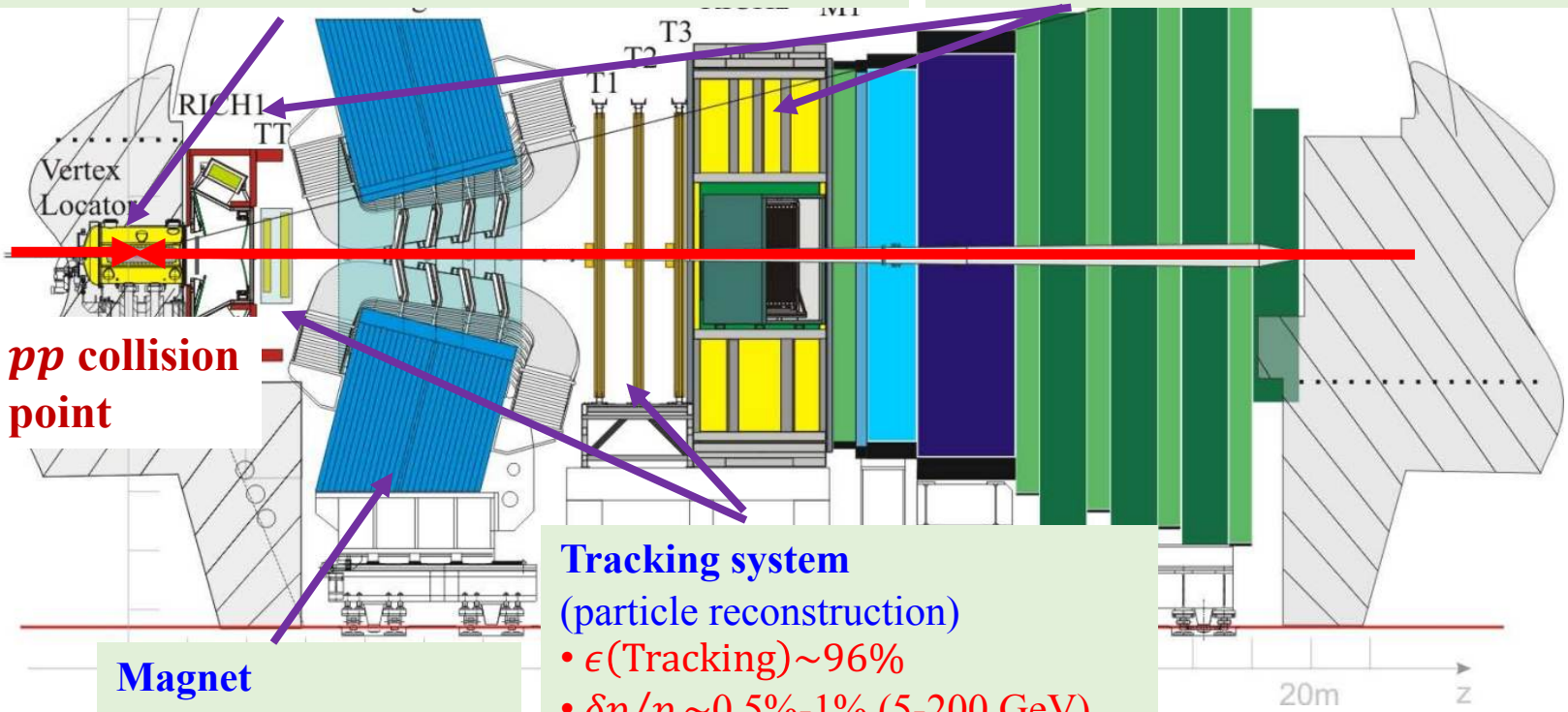
LHCb experiment

Precision measurements in b, c flavor sectors

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

$\tau(H_b)$~1.5 ps, $\tau(H_c)$~0.1 − 1 ps
Vertex Locator (vertex reconstruction)
• Impact parameter resolution: $(15 + 29/p_T)\mu m$
• Time resolution: 45 fs, resolving HF decay vertex

Decays: $b \to c \to s$ $(K^{\pm})$;
Baryon → proton
RICH detectors (K/π /p separation)
• $\epsilon(K \to K)$~95% for $r(\pi \to K)$~5%

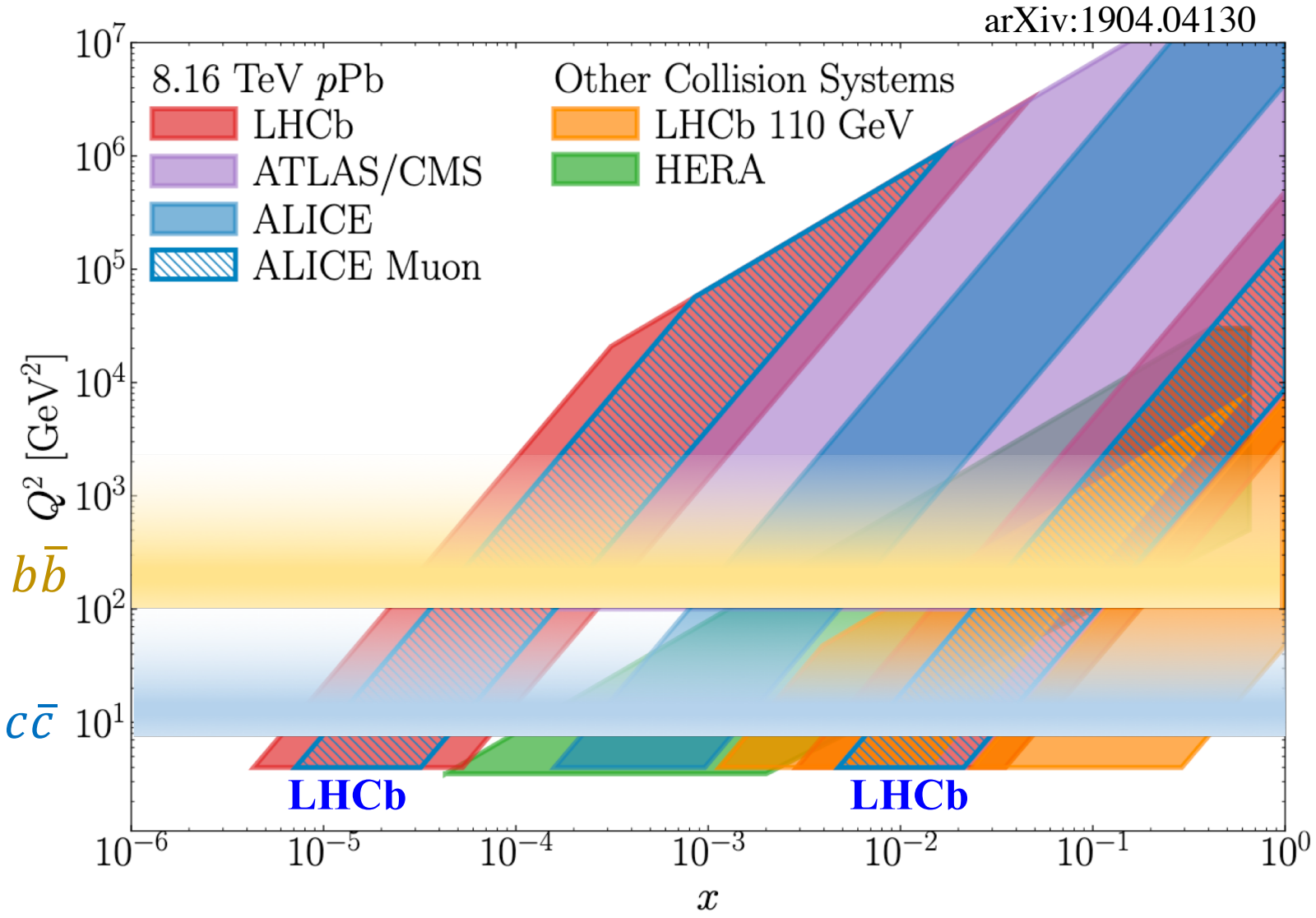


***pp* collision point**

Tracking system
(particle reconstruction)
• ϵ(Tracking)~96%
• $\delta p/p$ ~0.5%-1% (5-200 GeV)
• $\sigma(m_{B\to hh}) \approx 22$ MeV

Magnet
Bending power: 4 Tm

LHCb experiment



LHCb measurements of heavy flavor production in pp collisions

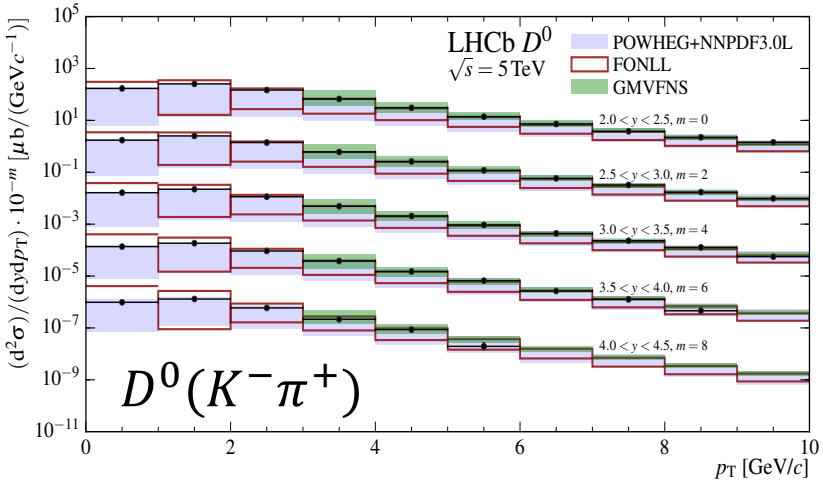
- Open heavy flavor
- Double heavy production
  - Quarkonia
  - Quarkonium –like ($B_c^+, \Xi_{cc}, \ldots$)

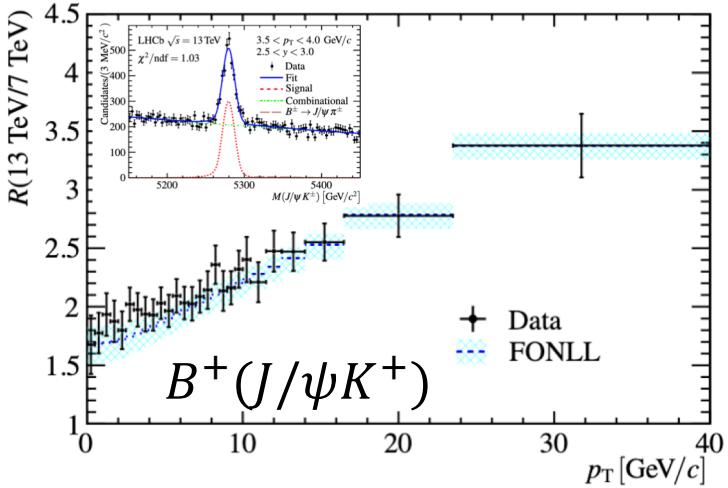
http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_all.html

Open heavy flavor production

JHEP 06 (2017) 147
JHEP 12 (2017) 026

- Exclusive decays, very clean. Subjected to (very) small branching fraction

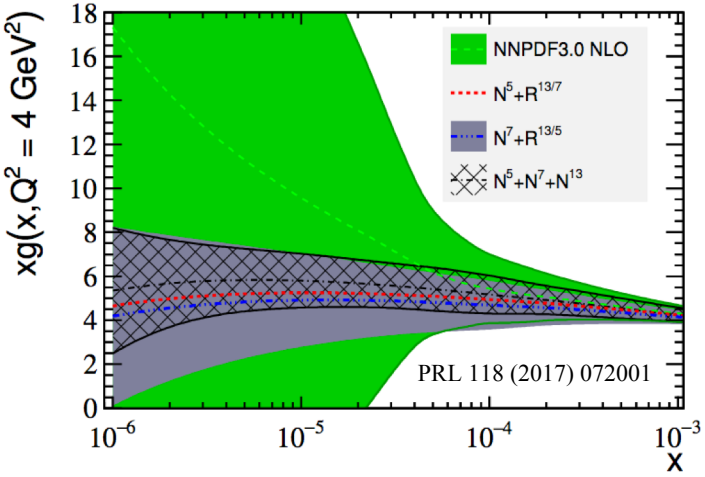




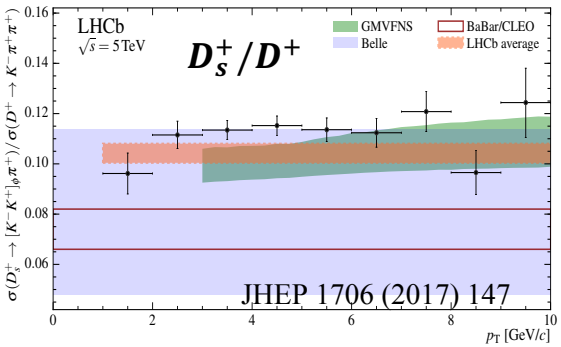
Cross-section and ratios at different energies good agreement with theory predictions in p_T, y intervals in all LHCb acceptance.

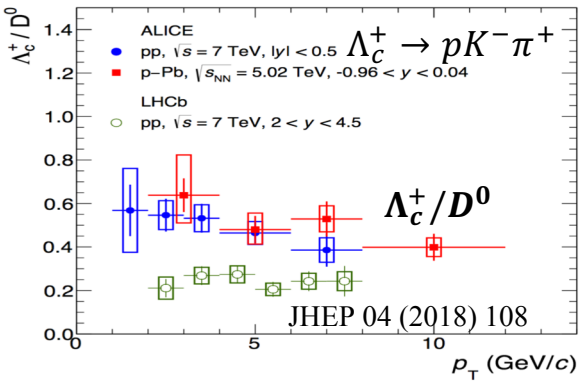
Strong constrains to gluon PDF at small-x.

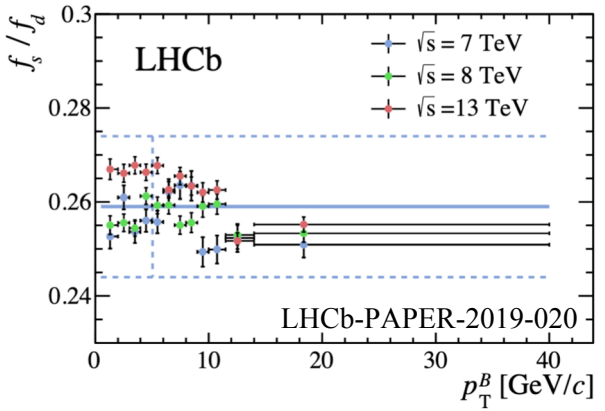
Reference for production in heavy-ion data.

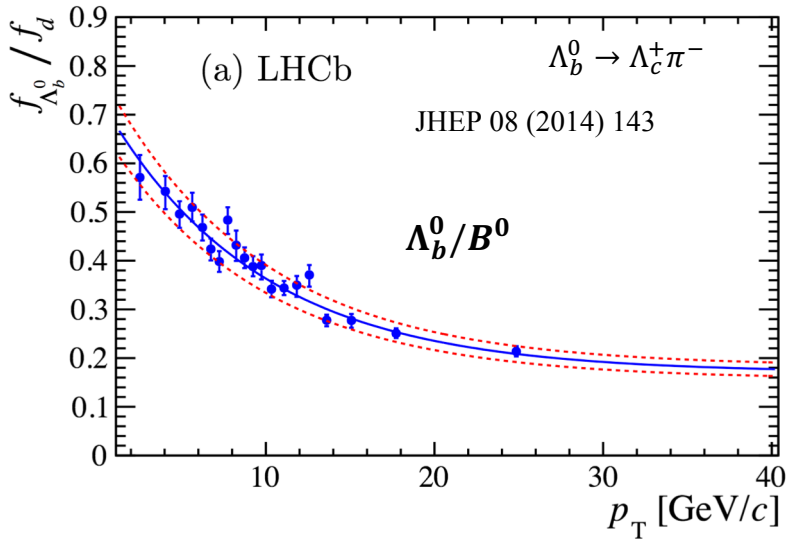


Fragmentation









Fragmentation fraction depends on collision energy and kinematics

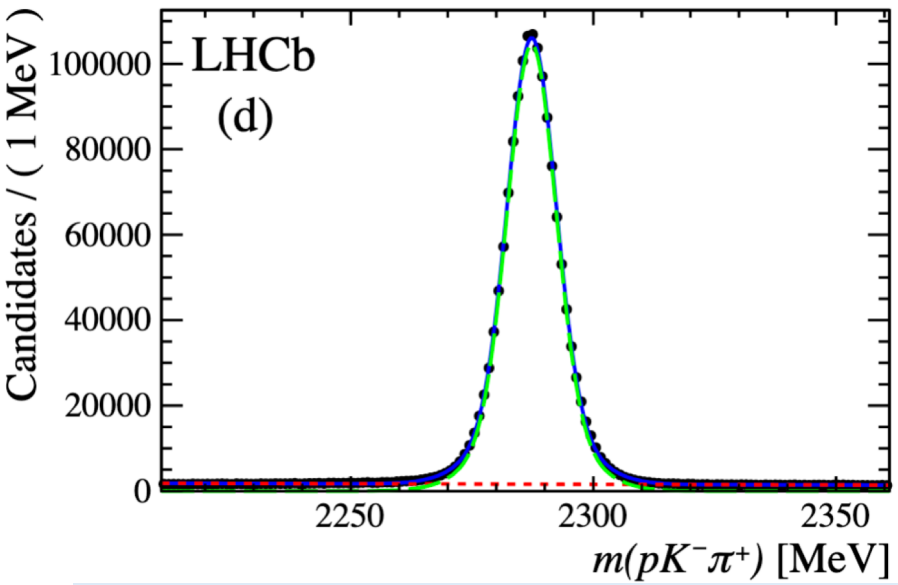
- ✓ $f_{\Lambda_b^0} \approx 8.9 \pm 1.2\%$ (PDG), $\approx 20\%$ (LHCb)
- ✓ Inconsistency for $f_{\Lambda_c^+}$ cross experiments

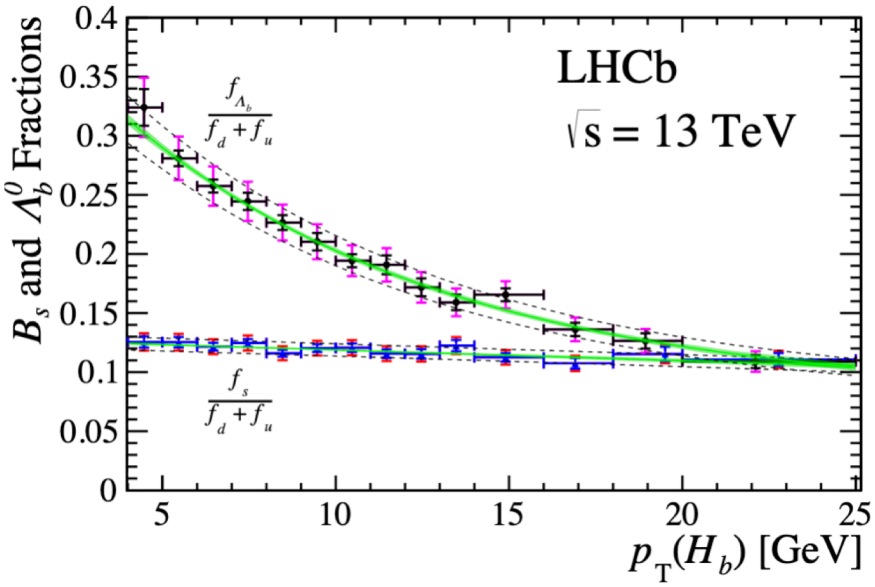
Measurements in pp collisions with the same condition is essential for heavy ion data.

Semi-leptonic decays

- Significant gain for beauty decays
  - $B(H_b \to H_c l^- X)/B(H_b \to H_c \pi^-) \sim 100$
  - Easy to trigger for $l^- = \mu^-$
- Disadvantage: signal extraction more difficult, cutting phase space and kinematics
- Signal yield about 10 times of exclusive decays, also very clean

PR D100 (2019) 031102

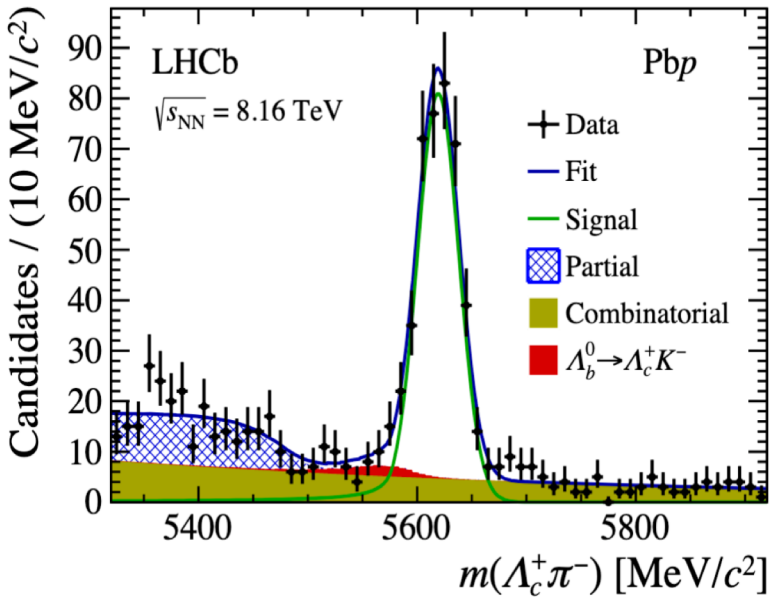


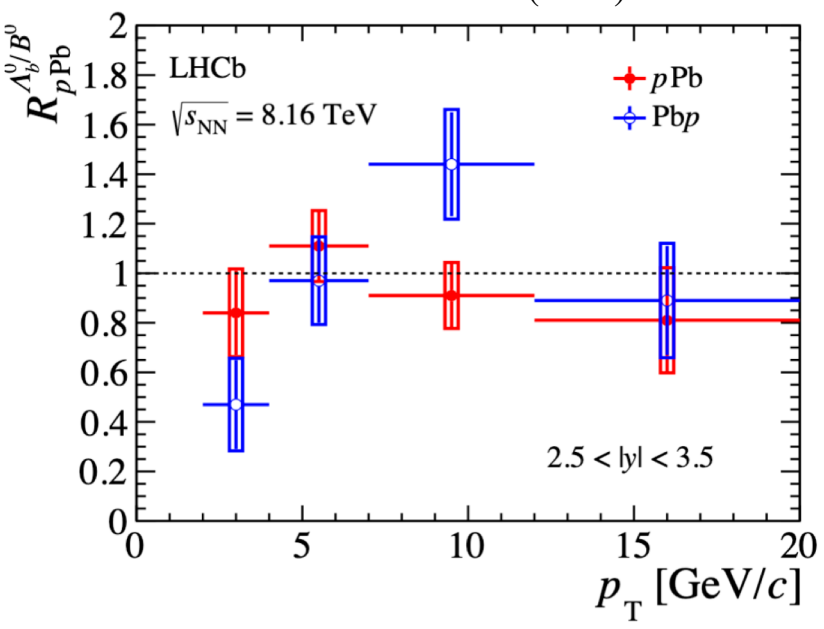


$\frac{f_{\Lambda_b^0}}{f_u+f_d}(p_T > 4\ \text{GeV}) = 0.259 \pm 0.018$, $\frac{f_s}{f_u+f_d}(p_T > 4\ \text{GeV}) = 0.122 \pm 0.006$,
Uncertainty dominated by branching fractions, otherwise <2%

Semi-leptonic decays

PR D99 (2019) 052011





Decay	pPb	Pbp
$B^+ \to \overline{D}^0\pi^+$	1958 ± 54	1806 ± 55
$B^+ \to J/\psi\, K^+$	883 ± 32	907 ± 33
$B^0 \to D^-\pi^+$	1151 ± 38	889 ± 34
$\Lambda_b^0 \to \Lambda_c^+\pi^-$	484 ± 24	399 ± 23

Yield will increase by ~10 using SL decays.

B_s^0 will also be possible (about 3% statistical uncertainty).

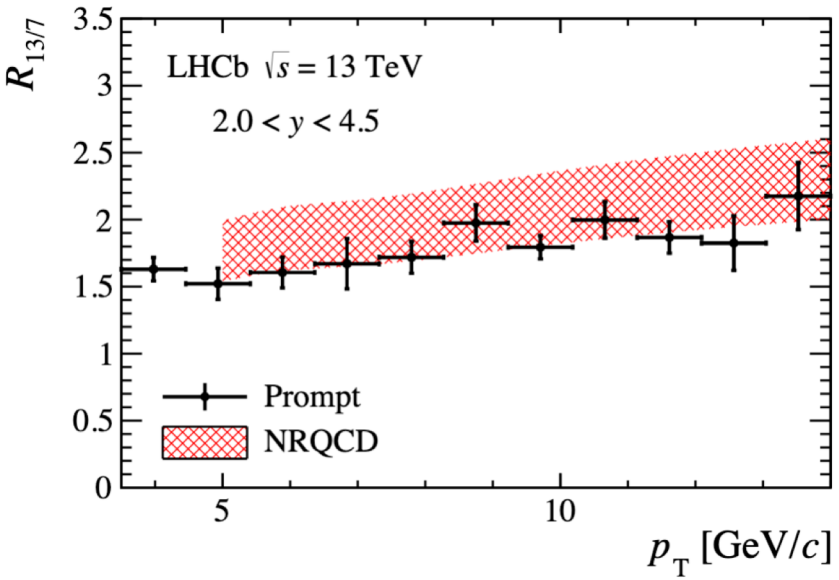
Alice studied non-prompt D^0, extended to B_s^0, Λ_b^0?

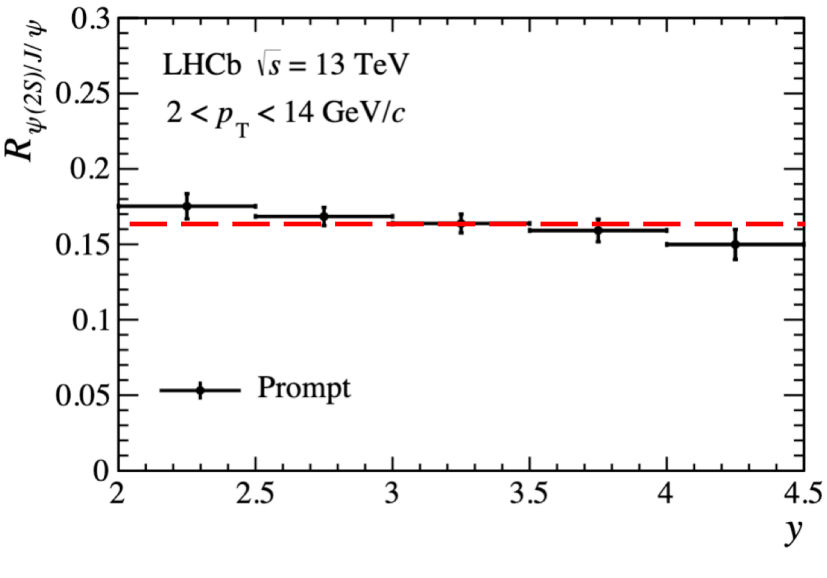
Towards precise fragmentation data in heavy ion collisions

Quarkonia

- Lucky for vector states, $J/\psi, \psi', \Upsilon(nS)\ldots$ using $\mu^+\mu^-/e^+e^-$ decays
- Recent measurement of $\psi(2S)$ in pp collisions

LHCb-PAPER-2018-049



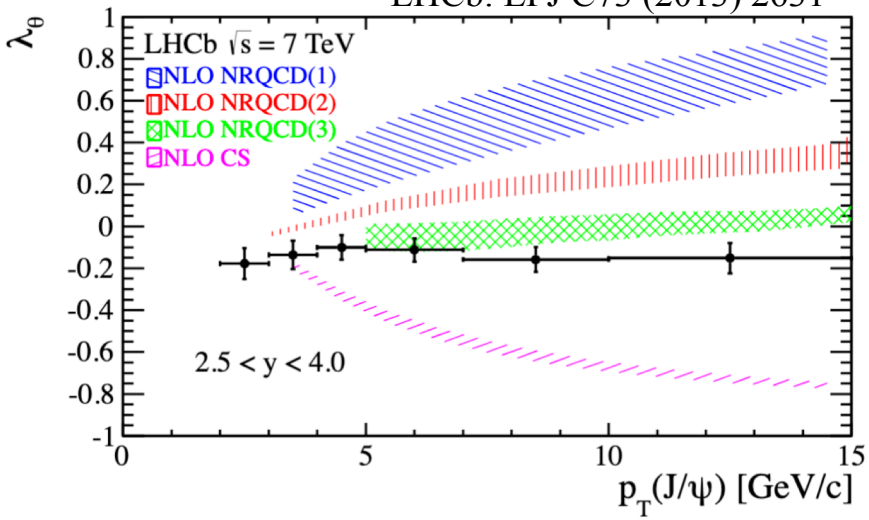


$\sigma(\psi')$ energy dependence described by NRQCD
$\sigma(\psi')/\sigma(J/\psi)$ slight rapidity dependence, real or detection/kinematic effect?

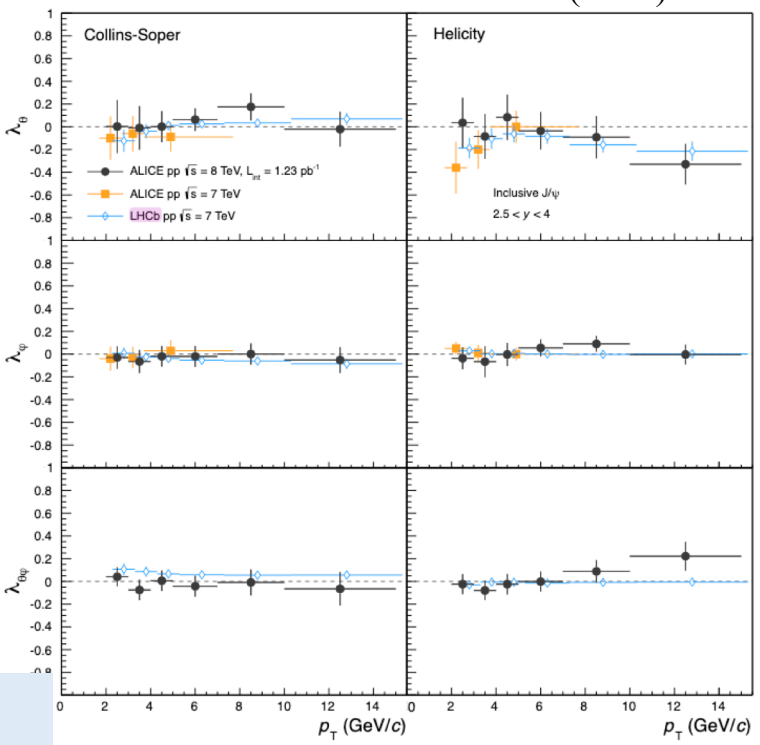
Quarkonia polarization

- Polarization of $J/\psi, \psi', \Upsilon(\mathrm{nS})$ in pp collisions measured only in Run I data

LHCb: EPJ C73 (2013) 2631



ALICE: EPJ C78 (2018) 562

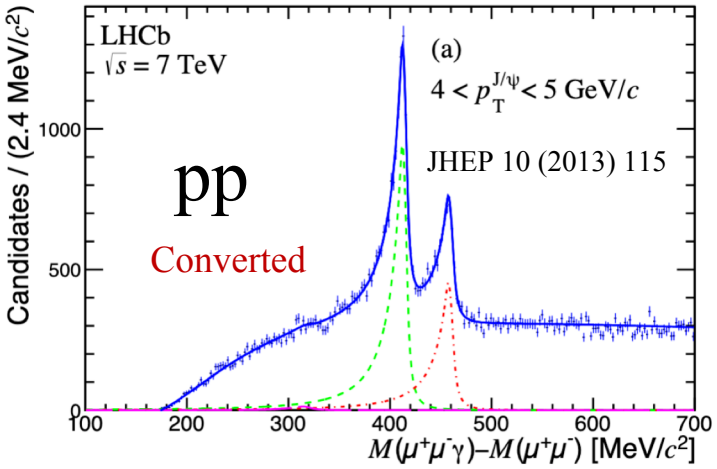


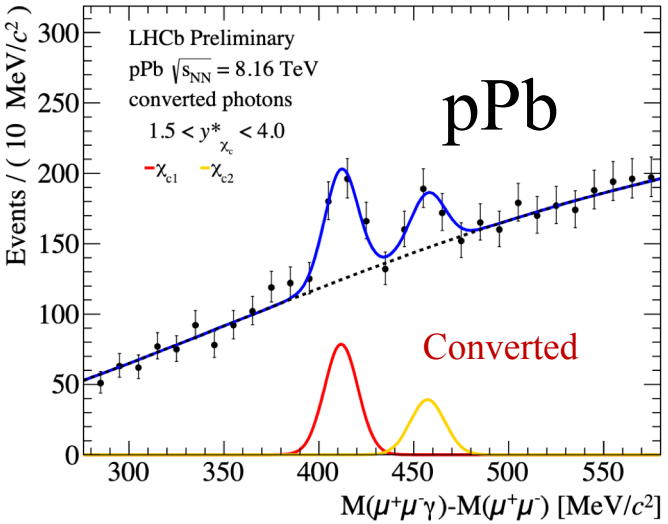
Surprisingly small polarization in contrast to NRQCD/CSM predictions.

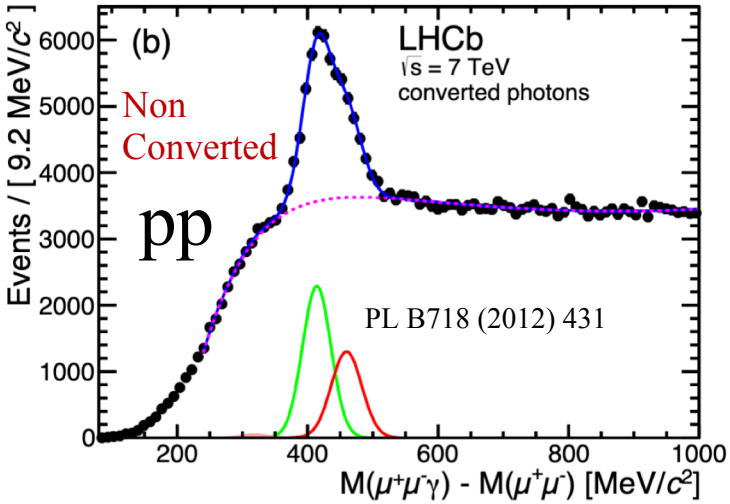
What about in pPb and PbPb collisions?
Zero polarization for J/ψ recombined in medium?

Demanding a lot of statistics, > 100 pb^{-1} pp equivalent.
May be achievable in Run3 (YR WG5: 2.3 nb-1 PbPb)

Non vector quarkonia



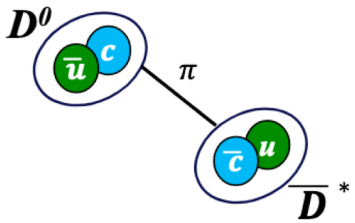




χ_{cJ} measured with both converted ($\gamma \to e^+e^-$) and non-converted photon in pp data. Reduced statistics but χ_{c1} and χ_{c2} peaks better resolved.

X(3872)

$M_{\chi_{c1}(3872)} - (M_{D^0} + M_{\bar{D}^{*0}}) = 0.01 \pm 0.27$ MeV



Hadronic molecular?

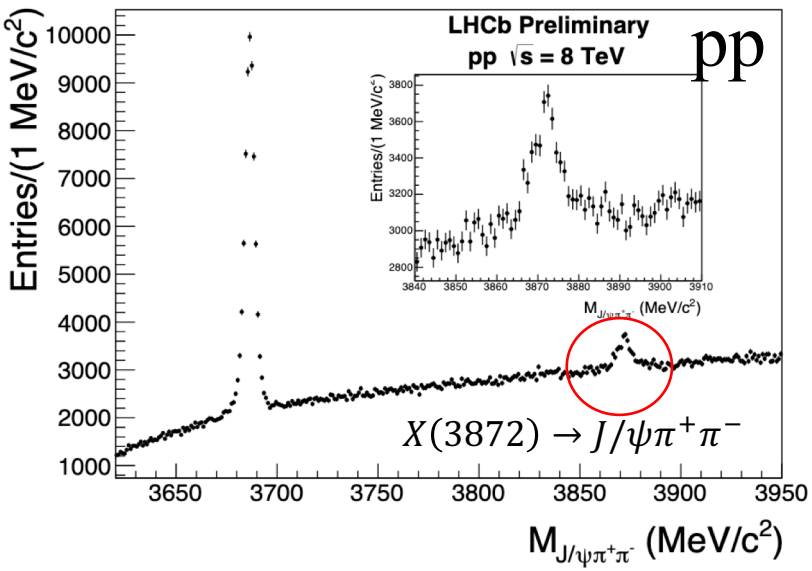
$D\bar{D}^*$ Molecule

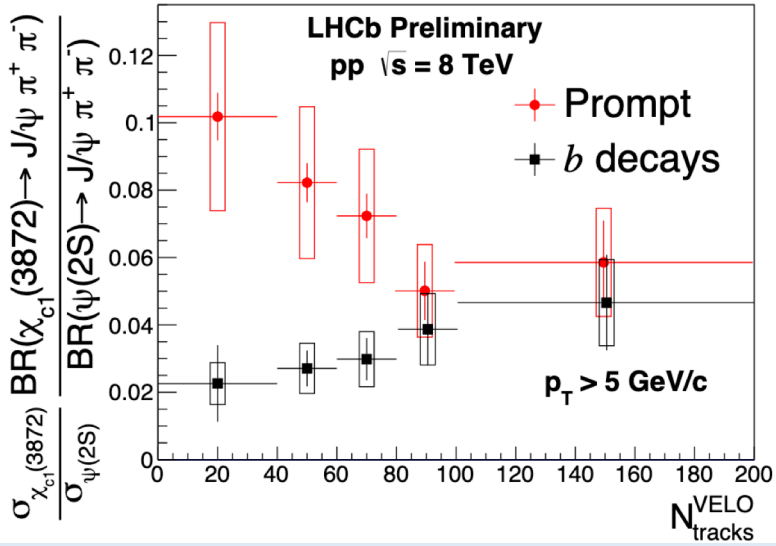
state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'	X(3872)
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69	3.872
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05	0.00001± 0.00027

Satz, J. Phys. G 32 (3) 2006

Another system to test sequential suppression/comover?

LHCb-CONF-2019-005



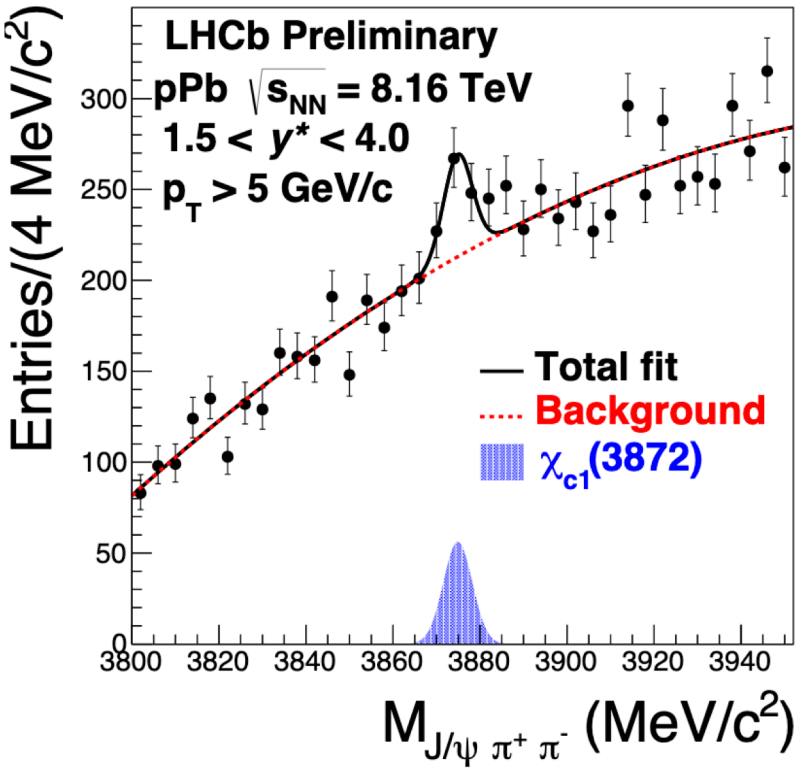


Production relative to $\psi(2S)$ decreases as event activity increases in pp data.

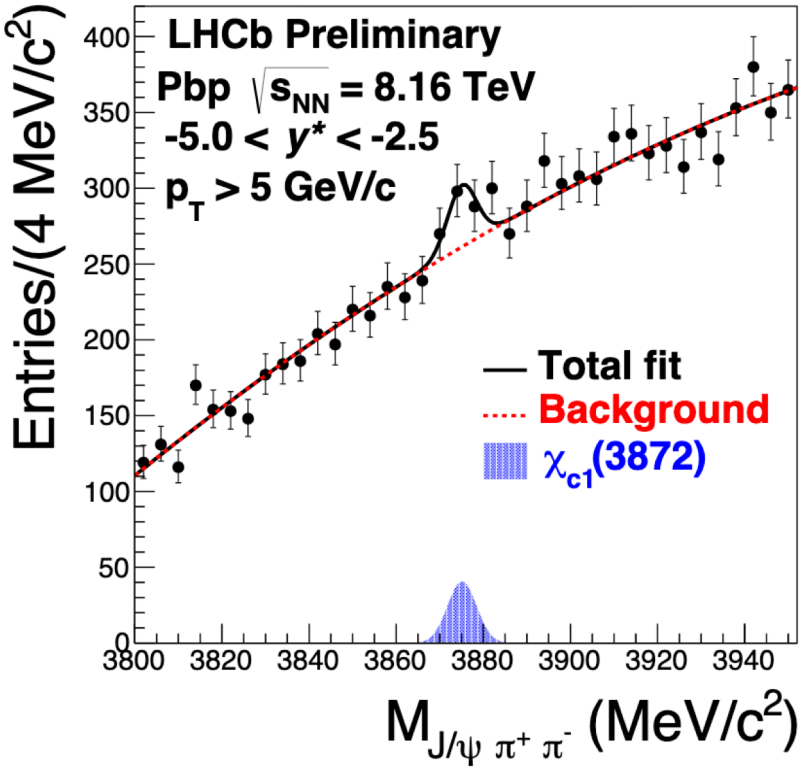
X(3872)

Accessible in proton-Pb collision, more suppressed in Pbp data?

$L \approx 12\ \mathrm{nb}^{-1}$

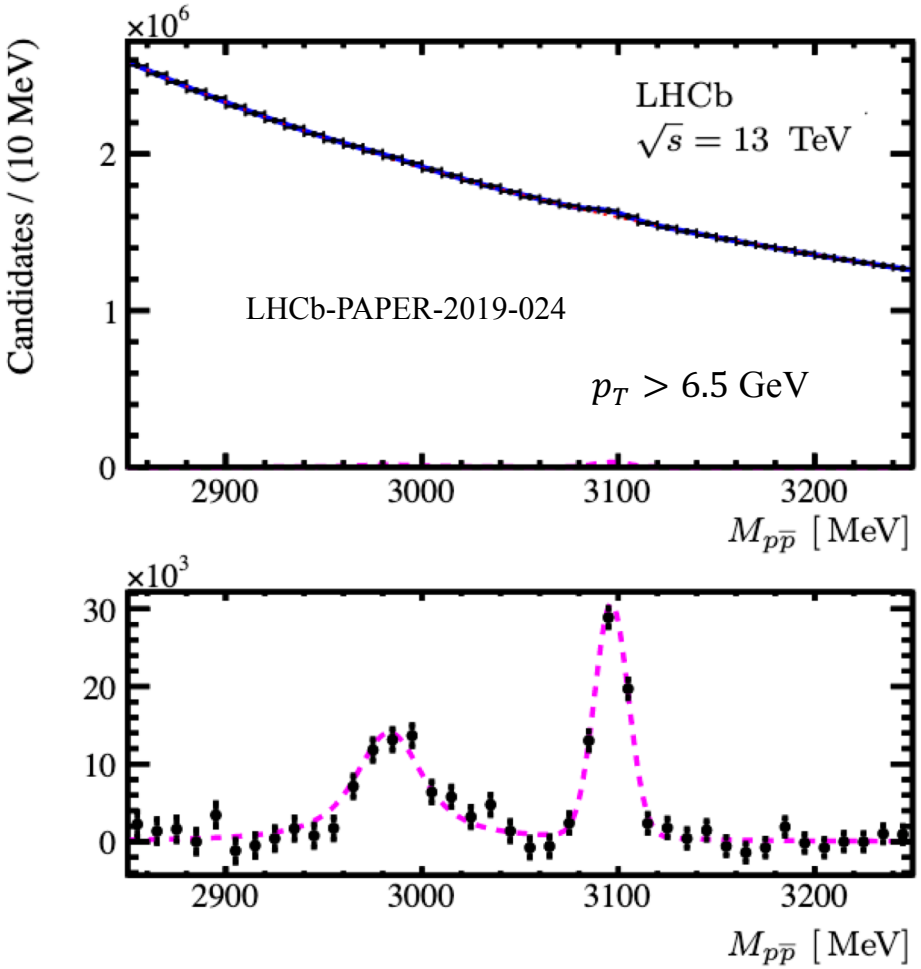


$L \approx 19\ \mathrm{nb}^{-1}$



$\eta_c(1S)$

- Abundantly produced, slightly higher binding energy compared to J/ψ



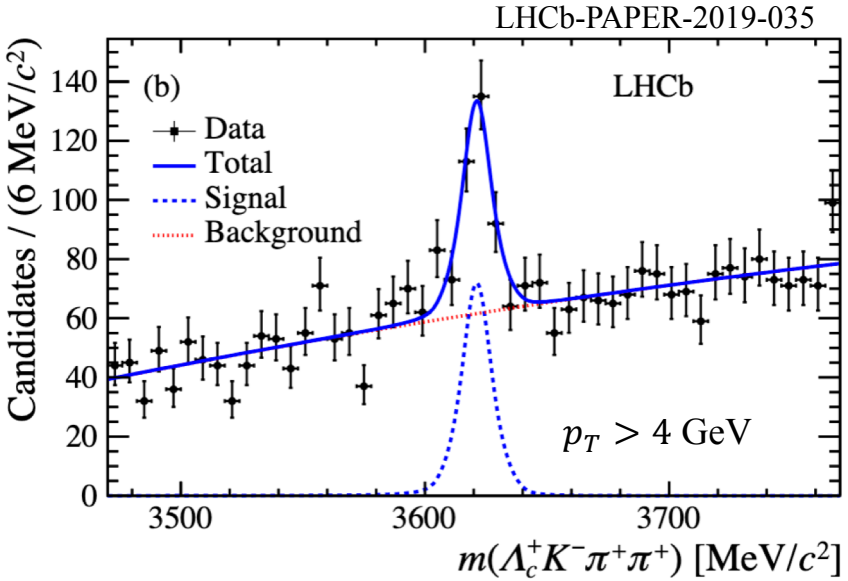
Detection of prompt η_c already challenging in pp data, pushing to high-p_{T}.

May be improved with $\eta_c \to \Lambda\bar{\Lambda}$:
$B(\eta_c \to \Lambda\bar{\Lambda}) \approx B(\eta_c \to p\bar{p})$

Does it probe a different nuclear effect compared to J/ψ?

Ξ_{cc}^{++} production

- Difficult due to low production rate and small detection efficiency



$\epsilon(\Xi_{cc}^{++}) \approx 1\%$ for $p_{\mathrm{T}} > 4$ GeV

$\sigma(\Xi_{cc}^{++} \to \Lambda_c^+ K^- 2\pi^+)/\sigma(\Lambda_c^+)$

$=(2.22 \pm 0.27 \pm 0.29)\times 10^{-4}$

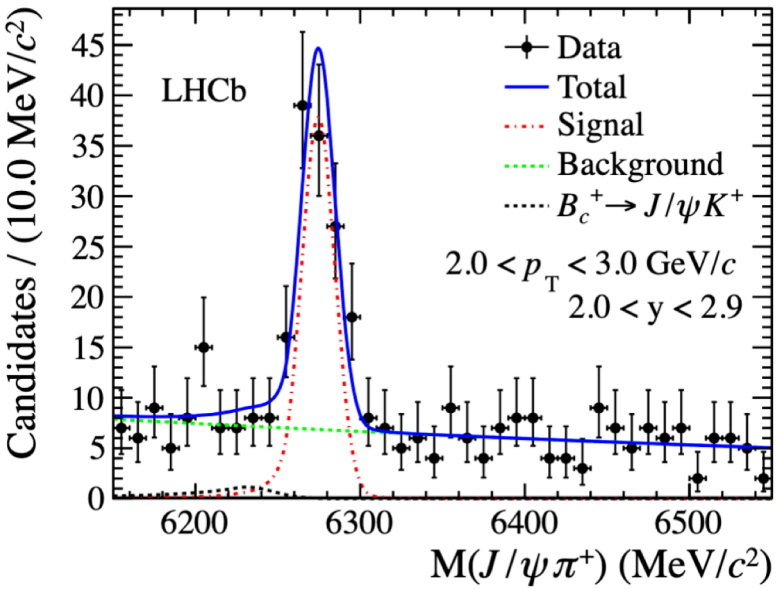
- Production mechanism similar to J/ψ in PbPb collisions
  - Dissociation of primary production + medium recombination at low p_{T}
  - $E_b(ccq) = 1/2 E_b(c\bar{c})$, may be comparable rate of recombination as J/ψ
  - $N(\Xi_{cc}^{++}) \approx 0.02$/PbPb at mid y for 0-10% centrality, enhanced by $\times 10$ ($R_{AA} \gg 1$), however yield is strongly reduced at $p_{\mathrm{T}} > 4$ GeV

Hope to reach low p_{T} in the future!

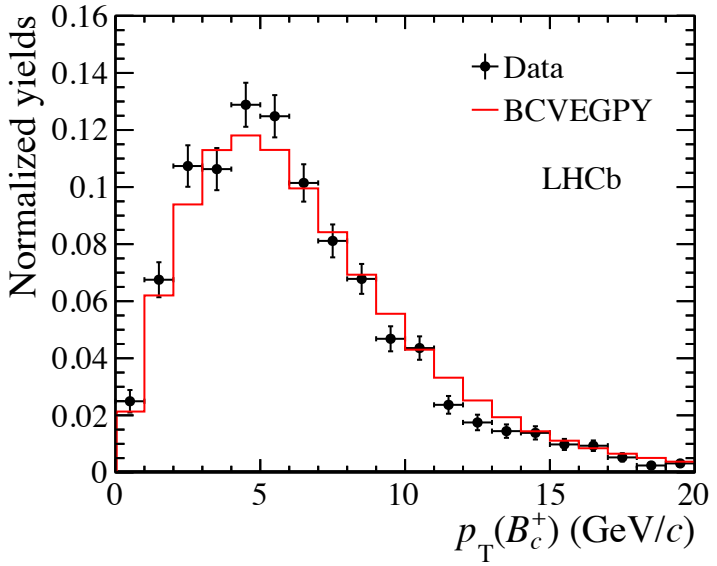
PR D97 (2018) 074003

B_c^+ production

- Subjected to dissociation and recombination in medium
  - recombination dominate production in central collisions, enhanced by ~10
- LHCb measurement with $B_c^+ \to J/\psi\pi^+$ PR C62 (2000) 024905
  - 2 fb^{-1} pp data at 8 TeV



PRL 114(2015) 132001



Reasonably clean signal, $N_{sig} \approx 3100$.

p_T distribution well modelled by BCVEGPY[hep-ph/0504017]

$$\frac{R(B_c^+ \to J/\psi\pi^+)}{R(B^+ \to J/\psi K^+)} = (0.68 \pm 0.02)\%$$

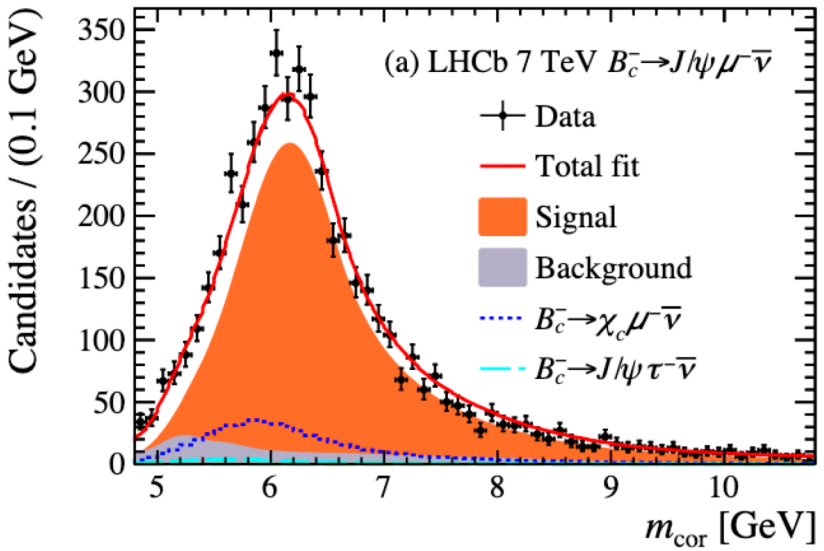
B_c^+ production with SL decays

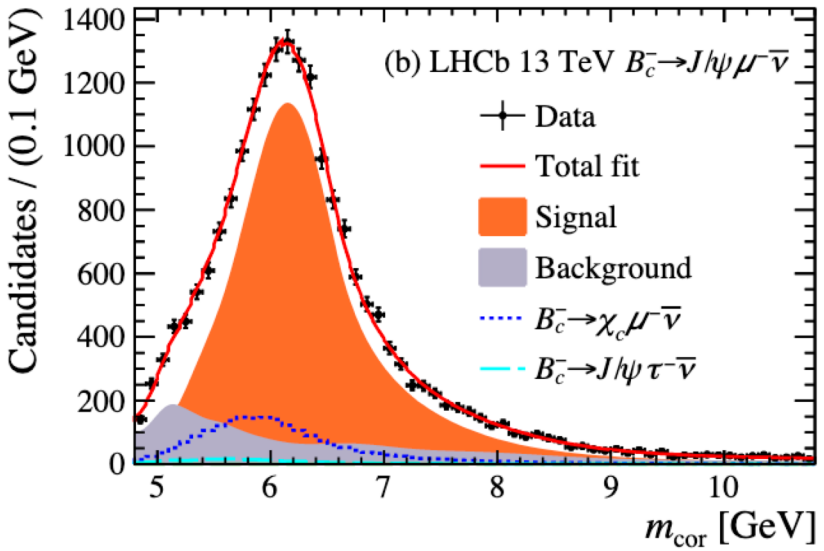
- $B(B_c^+ \to J/\psi\mu^+\nu) = 1 - 8\%$, about $15\times B(B_c^+ \to J/\psi\pi^+)$
- LHCb measurement at 7 (1 fb^{-1}) and 13 TeV (1.7 fb^{-1})

Phys.Atom.Nucl. 67 (2004) 1559

LHCb-PAPER-2019-033

  - $p_T(B_c^+) > 4$ GeV to reject background
  - Signal obtained from $m_{\rm cor} = \sqrt{m(J/\psi\mu^+)^2 + p_\perp^2} + p_\perp$ using templates
    - ✓ Signal, feed-down: simulated $B_c^+ \to J/\psi\mu^+\nu,\ \psi', \chi_c\,\mu^+\nu, J/\psi\tau^+\nu$ decay
    - ✓ Background: inclusive $b \to J/\psi$ decay from simulation



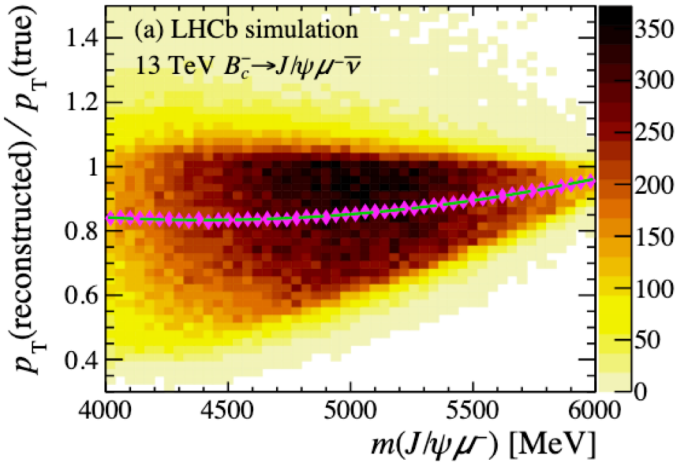


Almost background free. Total yields: 4K at 7 TeV and 15K at 13 TeV, about ×3 larger compared to $B_c^+ \to J/\psi\pi^+$. Losses due to p_T and other selection criteria.

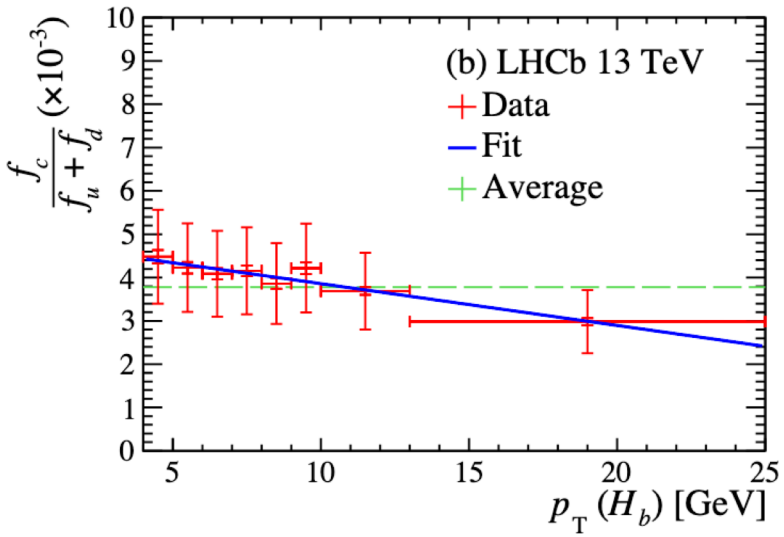
B_c^+ production with SL decays

- $p_T(B_c^+)$ estimated from $p_T(J/\psi\mu^+)$ using simulation

LHCb-PAPER-2019-033



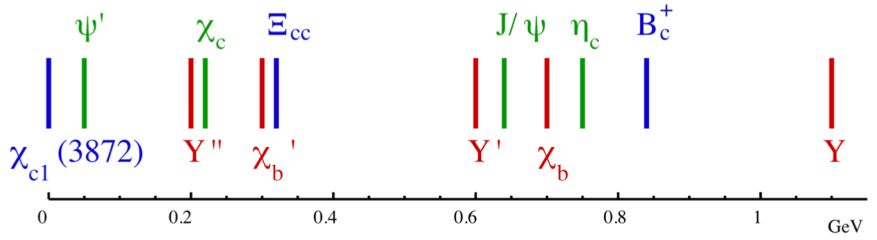
A good B_c^+ decay model is required. Both Ebert [PRD82(2010)034019] and Kiselev [arXiv:0211021] models studied and found to agree with data.



Taking $B(B_c^+ \to J/\psi\mu^-\nu) = 1.95 \pm 0.46\%$
$f_c/(f_u + f_d)$ is determined, with average:
$\frac{f_c}{f_u+f_d} = (3.78 \pm 0.15 \pm 0.89(B))\times 10^{-3}$ at 13 TeV
Consistent result at 7 TeV

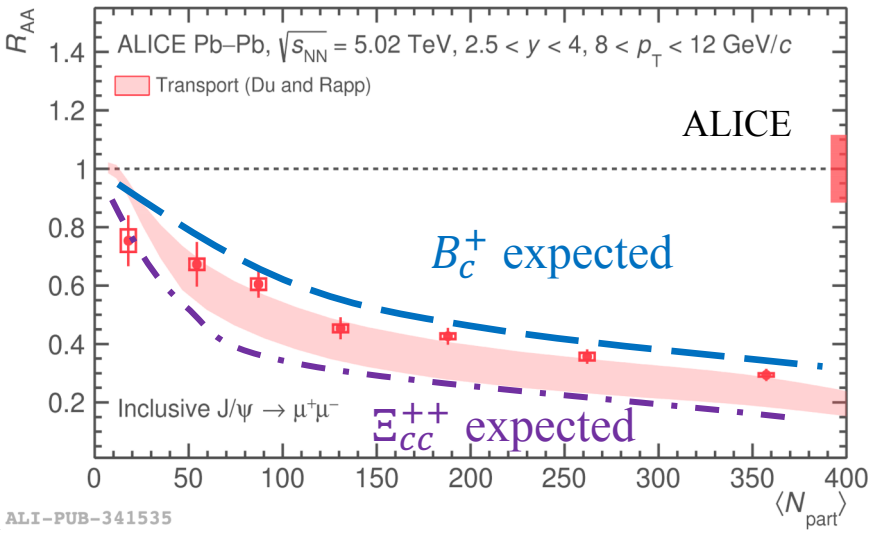
R_{AA} expectation

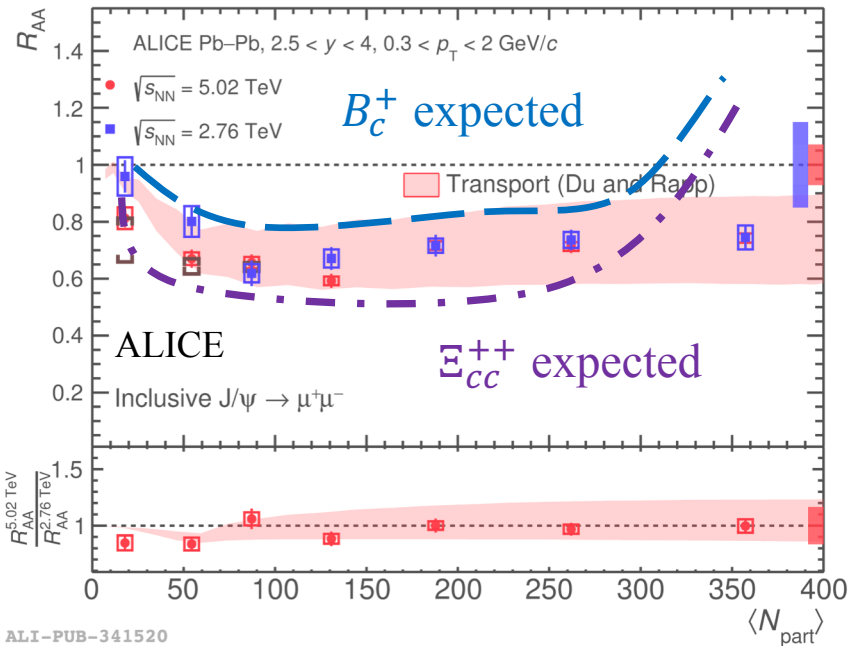
Example for forward rapidity



Low-p_T

High-p_T





Primary production of B_c^+/Ξ_{cc}^{++} is very tiny, $\leq 10\%$ of J/ψ

Enhanced production of B_c^+/B^+ and $\Xi_{cc}^{++}/\Lambda_c^+$, have we confirmed enhancement of B_s^0/B and D_s^+/D?

Summary

- LHCb, with excellent design for heavy flavor, measured almost all possible bottom/charm production in pp data
- Summarized

Those accessible in heavy ion data

- Open charm: abundantly produced, sensitive to PDF with $x \to 10^{-6}$. Reference for measurements in heavy ion data
- Open beauty: subjected to small branching fraction, not difficult in pp
- Fragmentation: reference to understand coalescence in medium
- Quarkonium: reference to relative suppression in nuclear matter

Those not deeply explored

- Quarkonia polarization: recombination
- $\eta_c, \chi_{cJ}, \chi_{c1}(3872)$: sequential suppression
- Ξ_{cc}^{++}
- B_c^+

Dissociation and enhancement from recombination

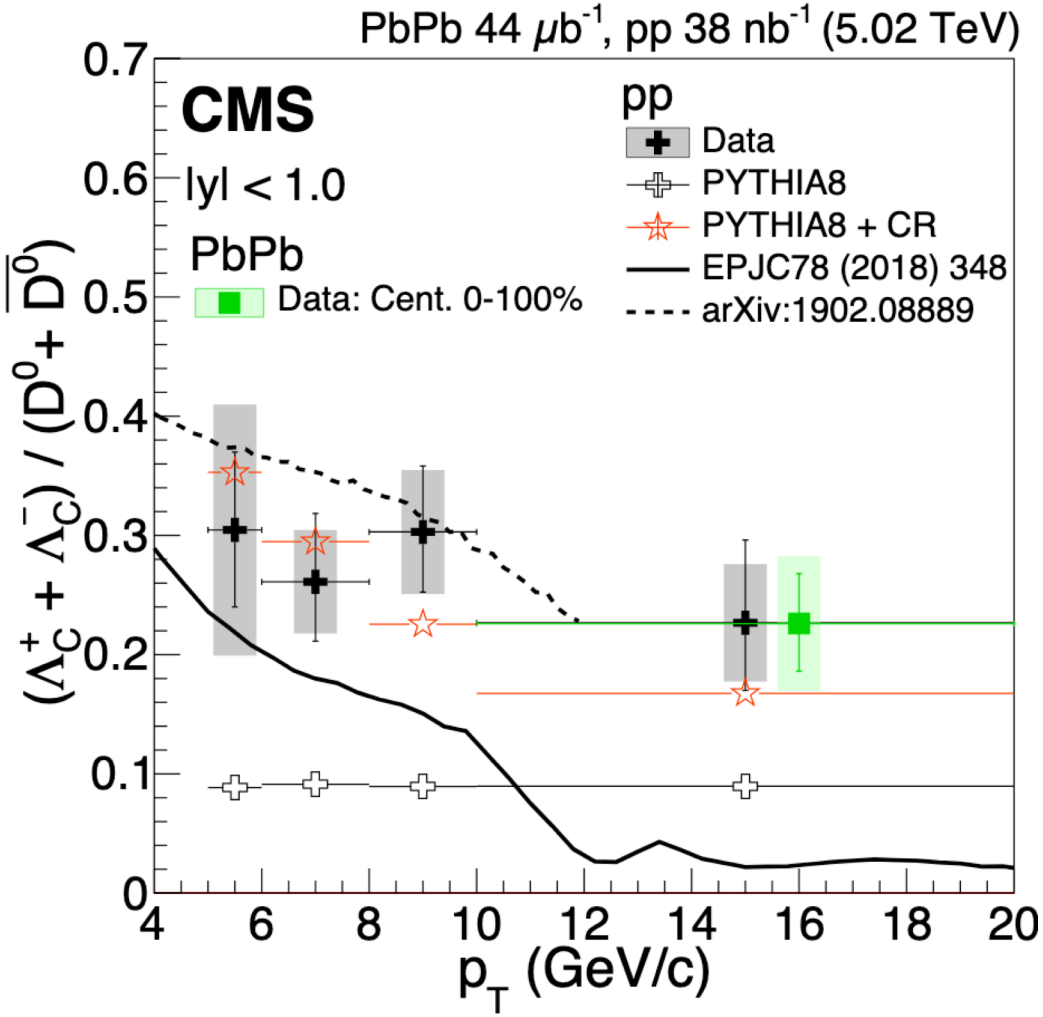
LHCb measurements using $\approx$ fb^{-1} data

May be able to see signals with PbPb collisions of ~10nb^{-1}, and pPb of ~1 pb^{-1}

Is the detector good enough to resolve these decays?

Many thanks to the organizers
Michael, Francesco, Yasmine…!

CMS measurement of Λ_c^+



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Non converted χ_c in pPb data