Overview of heavy-flavour production in heavy-ion collisions with LHCb

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on behalf of the LHCb collaboration

LHCb Implications Workshop

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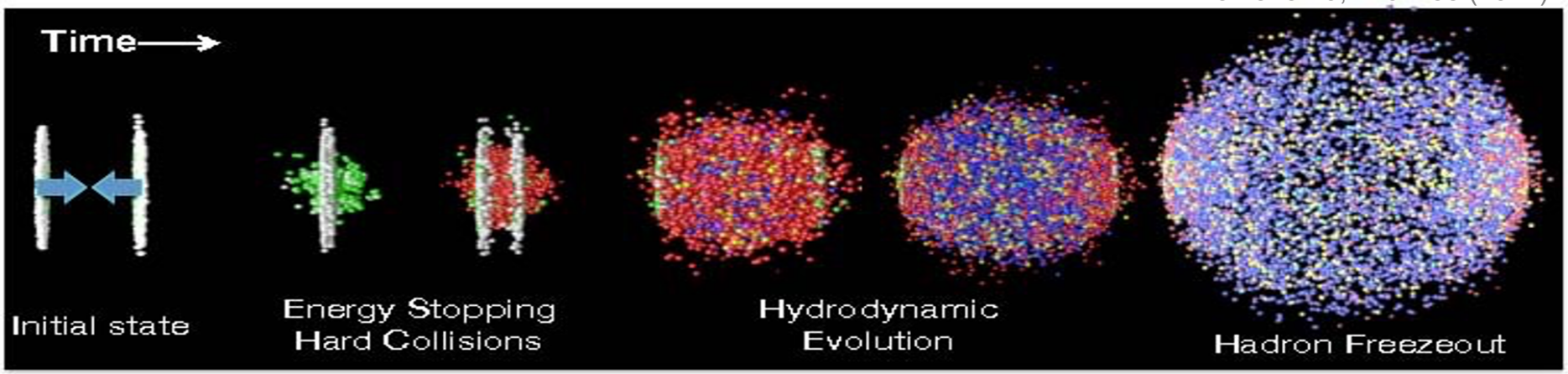
Heavy quarks in heavy-ion collisions

- Heavy quarks are excellent probes of the cold and hot nuclear matter effects.
  - Produced in initial hard scatterings
  - $m_Q \gg \Lambda_{\mathrm{QCD}}$: allow perturbative calculations on cross-sections
  - $t_{\mathrm{prod}} \ll t_{\mathrm{QGP}}$: experience whole time evolution of collisions

Pramana 79, 719–735 (2012)



- Modification of nPDFs: $R_{p\mathrm{A}}$
- Initial-state and final-state energy loss
- Heavy quarkonium suppression
- Parton QCD energy loss: R_{AA}
- Collective behaviour: v_2
- Strangeness enhancement: D_s^+/D^+ ratio *etc.*
- Hadronisation: baryon/meson ratio

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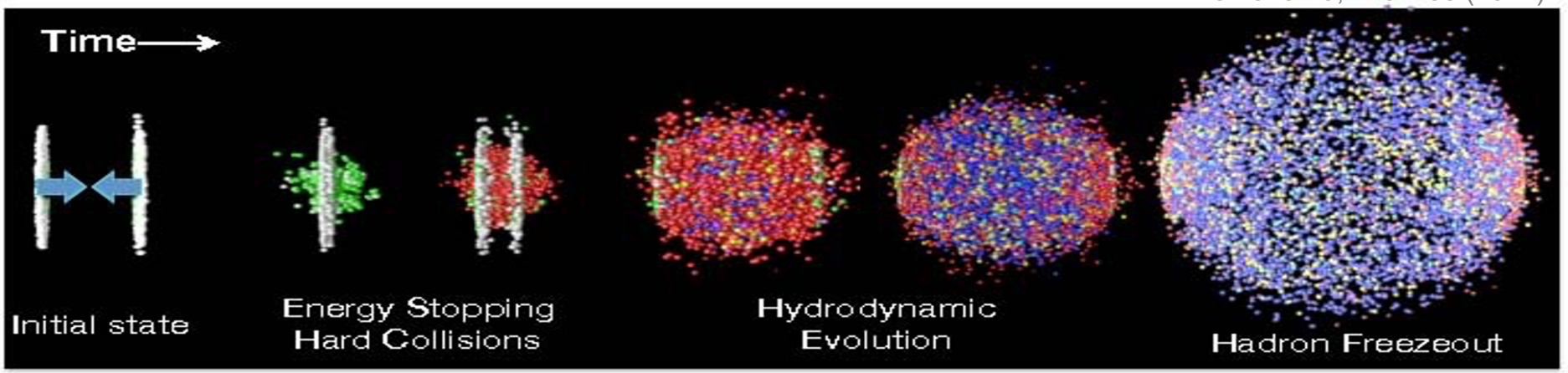

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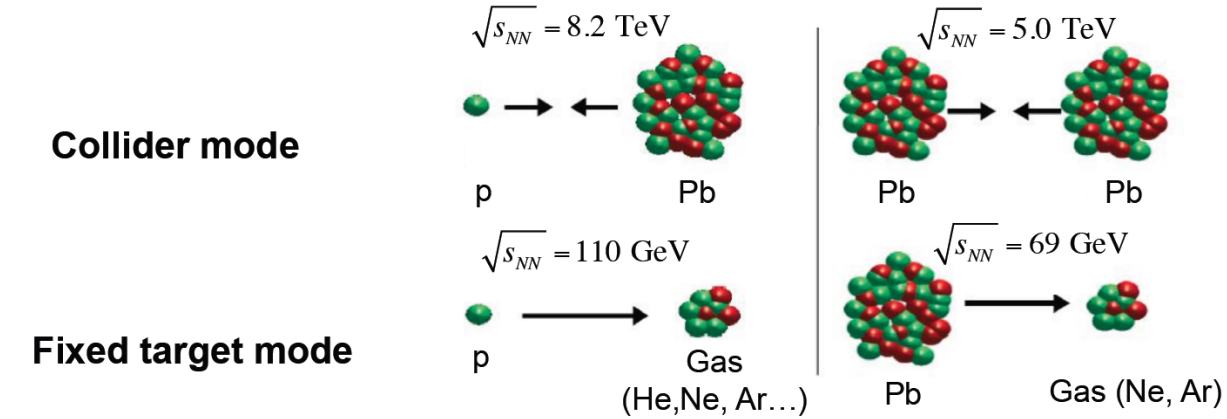
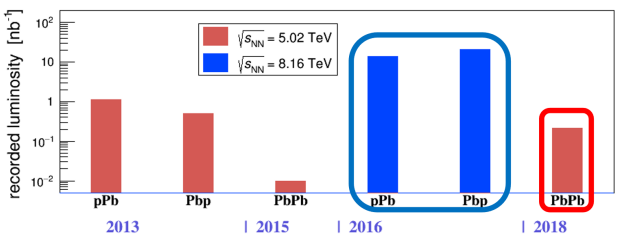
Heavy-ion data sets

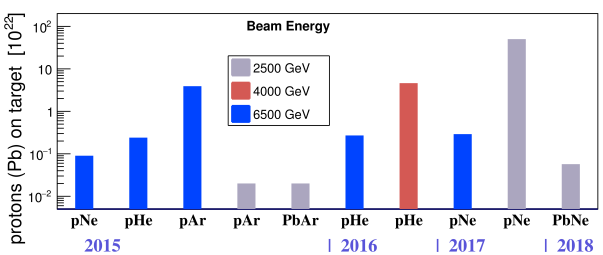
- LHCb beam configurations



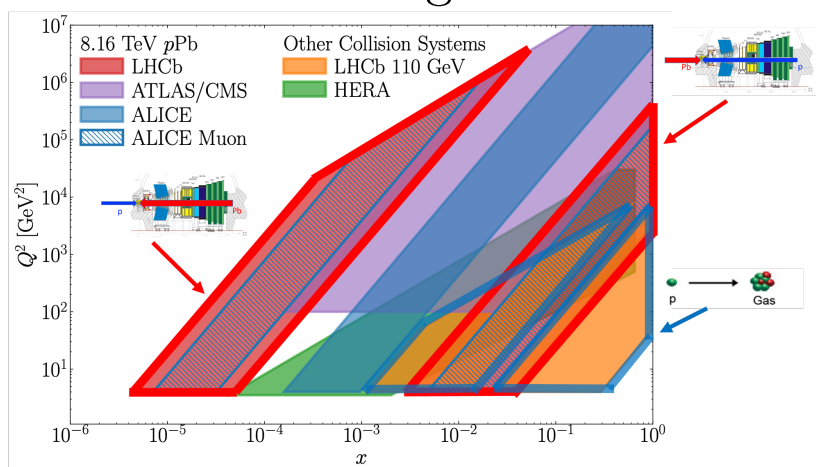
- Data sets
  - Collider mode



  - Fix-target mode



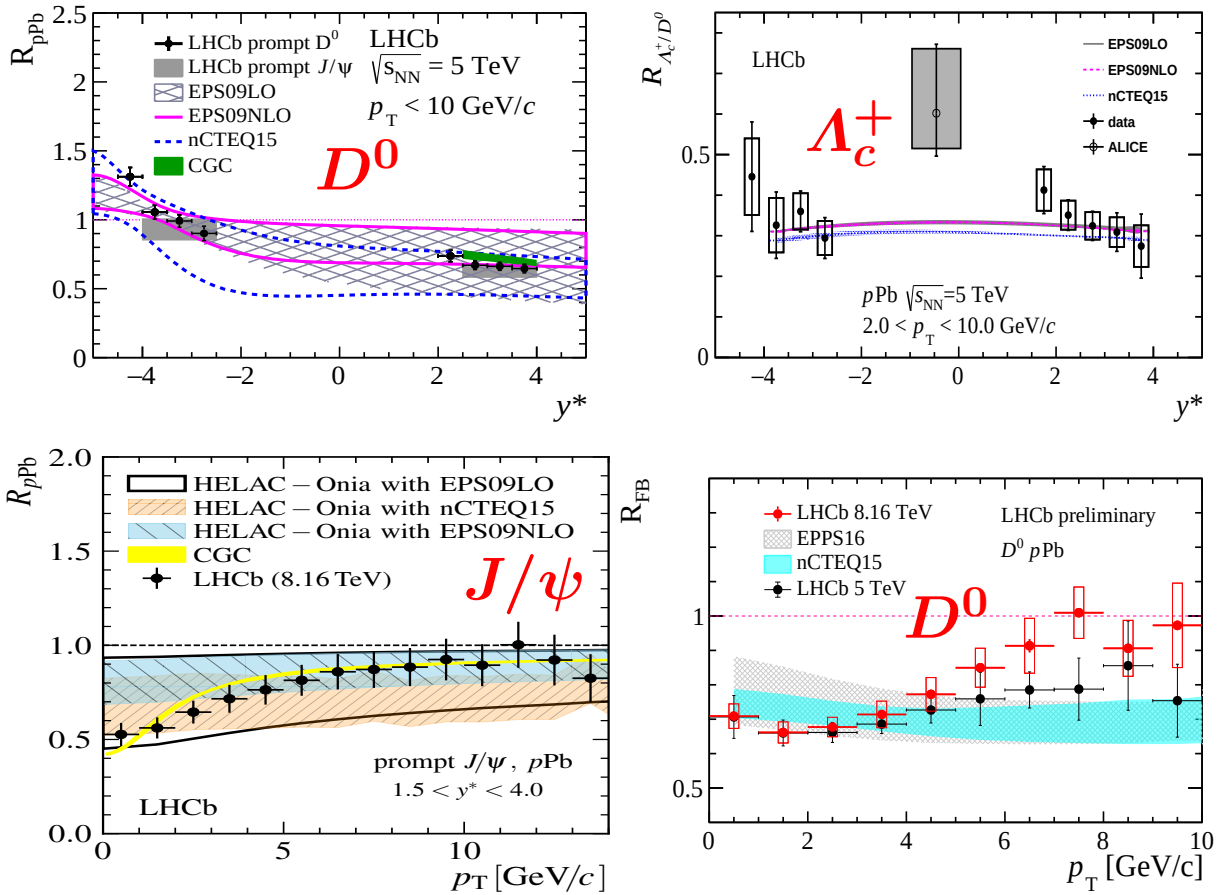
- Kinematic coverage



Summary of past results

Heavy-flavour production in pPb (charm)

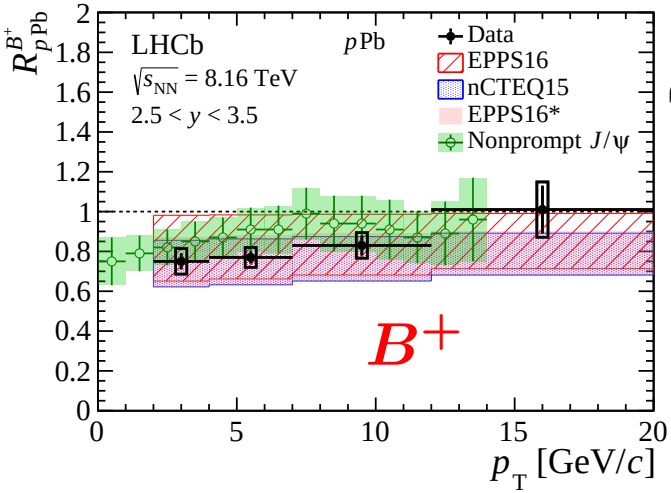
JHEP 10 (2017) 090, JHEP 02 (2019) 102
PLB 774 (2017) 159, LHCb-CONF-2019-004

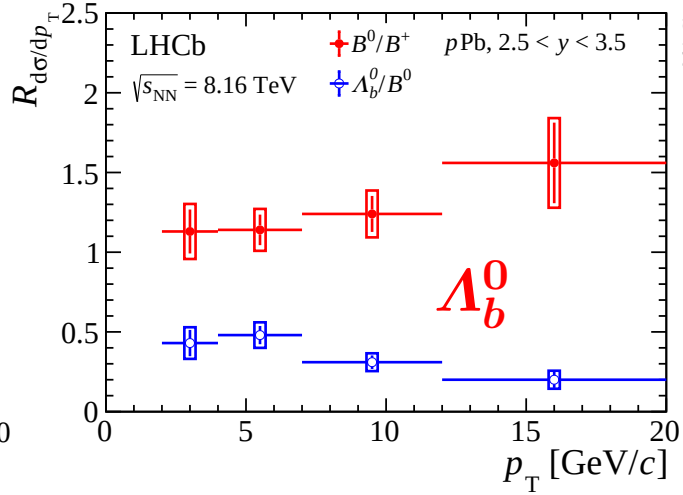


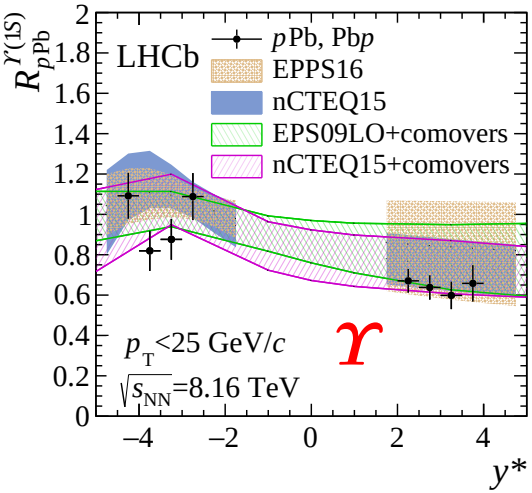
- The $R_{p\mathrm{Pb}}$ and $R_{\Lambda_c^+/D^0}$ results in good agreement with theories.
- D^0 R_{FB} in high p_{T} regions above theoretical calculations with large uncertainties.

Heavy-flavour production in pPb (beauty)

PRD 99, 052011 (2019)
JHEP 11 (2018) 194



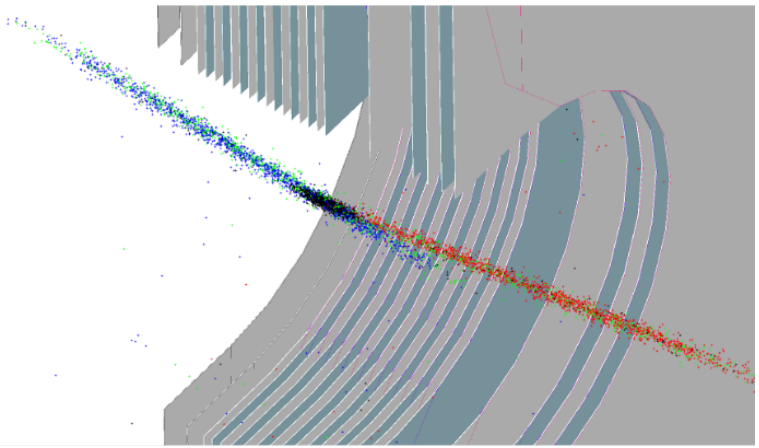




- Significant suppression is observed in forward rapidity regions for both B^+ and Υ $R_{p\mathrm{Pb}}$, consistent with theories.
- $R_{\Lambda_b^0/B^0}$ points show a decreasing trend as a function of p_{T}.

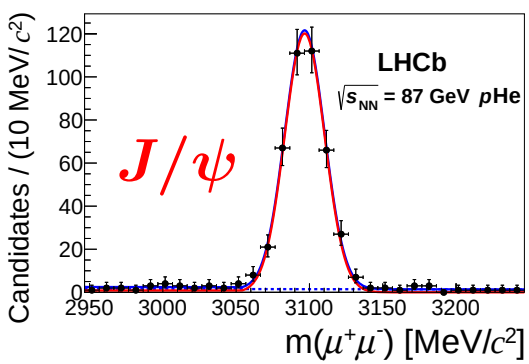
Charm production in the fixed-target configuration

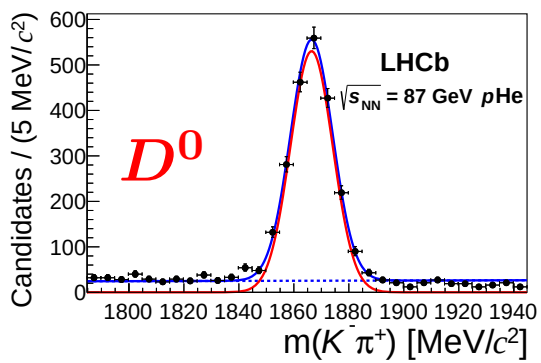
PRL 122 (2019) 132002

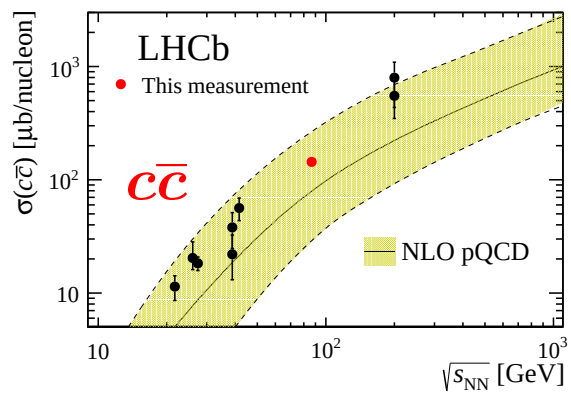


- Cover the backward rapidity region $y_{\mathrm{cms}} \sim [-2.5, 0]$
- Give access to large Bjorken-x region in heavy-quark production (up to $x \sim 0.37$ for D^0 mesons)

- The first measurement of heavy-flavor production in the fixed-target configuration at the LHC
  - pHe : $\sqrt{s_{\mathrm{NN}}} = 86.6\,\mathrm{GeV}$, $\mathcal{L} = 7.58 \pm 0.47\,\mathrm{nb}^{-1}$
  - pAr : $\sqrt{s_{\mathrm{NN}}} = 110.4\,\mathrm{GeV}$







Overview of recent results

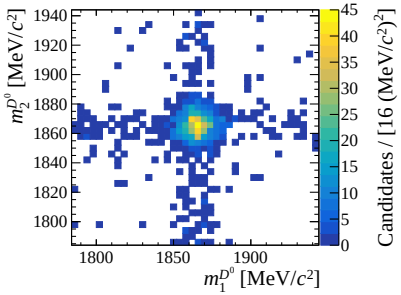
Recent results from heavy-ion collisions at LHCb

- pPb collisions
  - Double-charm production at $\sqrt{s_{\rm NN}} = 8.16$ TeV. PRL 125 (2020) 212001
  - Prompt cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ at $\sqrt{s_{\rm NN}} = 8.16$ TeV. PRC 103 (2021) 064905
- pp collisions
  - Multiplicity-dependent prompt cross-section ratio $\sigma(\chi_{c1}(3872))/\sigma(\psi(2S))$ at $\sqrt{s}$ =8 TeV. PRL 126 (2021) 092001
- PbPb collisions
  - Coherent J/ψ production in ultra-peripheral PbPb collisions at $\sqrt{s_{\rm NN}} = 5$ TeV. arXiv:2107.03223
  - Coherent J/ψ in peripheral PbPb collisions at $\sqrt{s_{\rm NN}} = 5$ TeV. arXiv:2108.02681

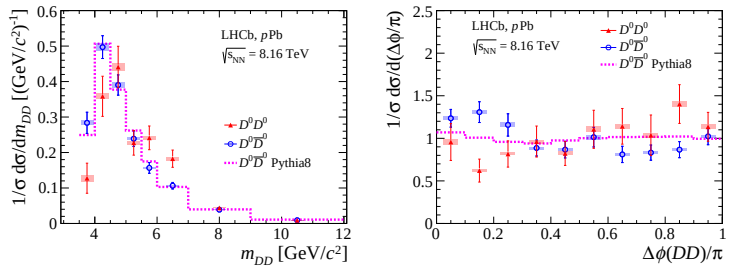
Double-charm production in pPb

PRL 125 (2020) 212001

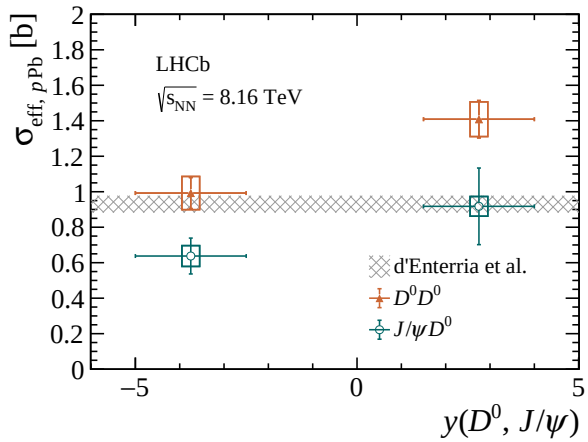
- Single parton scattering (SPS) and double parton scattering (DPS) are studied in the measurement.
- Pairs of charm hadrons measured.
  - Opposite-sign (OS), *e.g.* $D^0\overline{D}^0$, SPS enhanced
  - Like-sign (LS), *e.g.* D^0D^0, DPS enhanced



- OS charm pairs expected to be correlated.
- Good agreement between data and PYTHIA simulation.



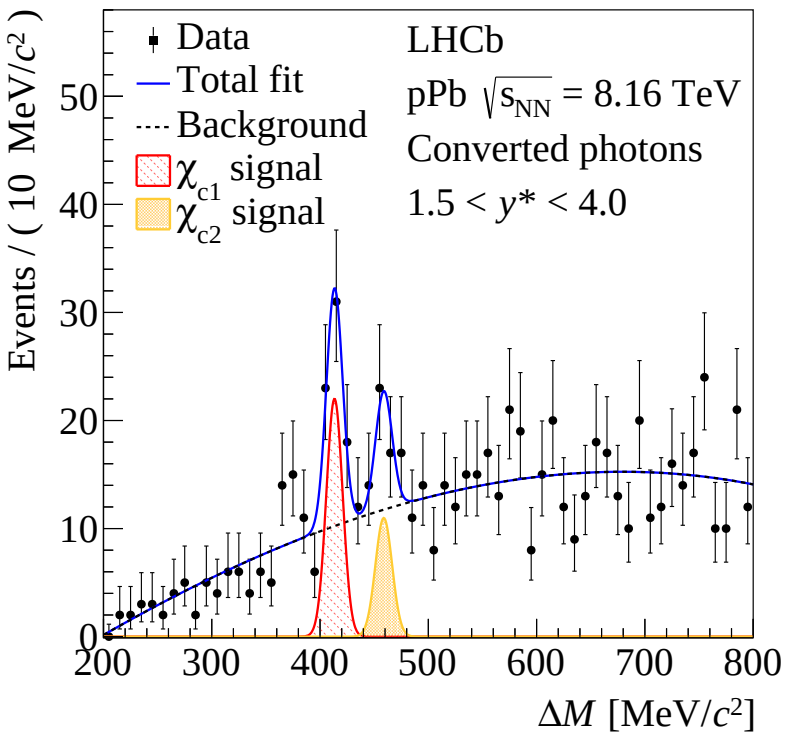
- The $\sigma_{\text{eff}} = (\sigma^A\sigma^B)/\sigma^{AB}_{\text{DPS}}$ defined to describe the DPS process.
- DPS/SPS enhanced by a factor of ~ 3 in pPb compared to pp.
- A suppression of DPS observed in forward rapidity compared to backward.

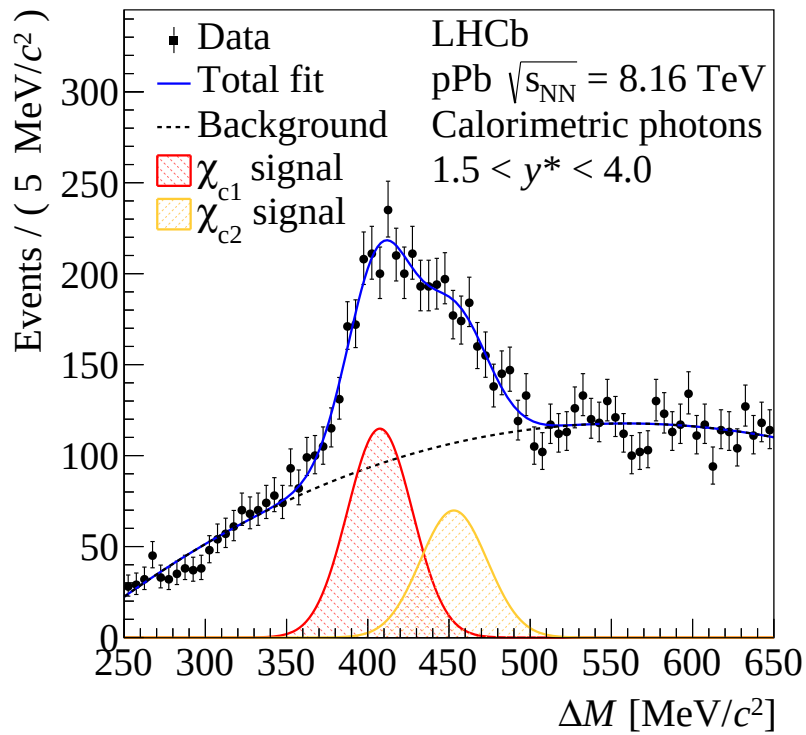


Prompt cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ in pPb

PRC 103 (2021) 064905

- 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.





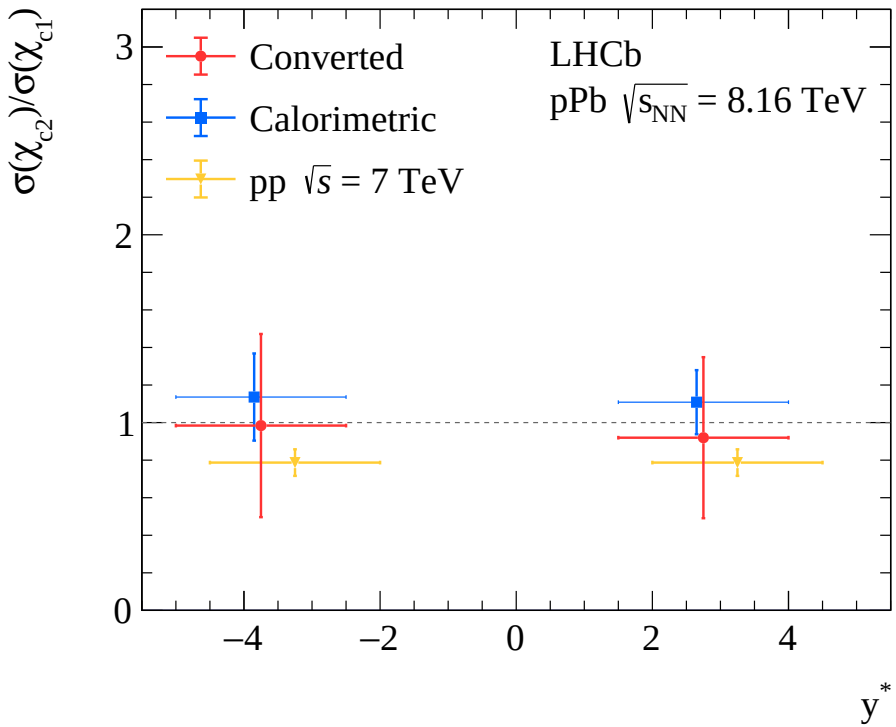
Results

PRC 103 (2021) 064905

- Prompt χ_c mesons selected using the pseudo-decay time t_z, where

$$t_z = \frac{(z_{\text{decay}} - z_{\text{PV}}) \times M_{\chi_{c1}}}{p_z} \ .$$

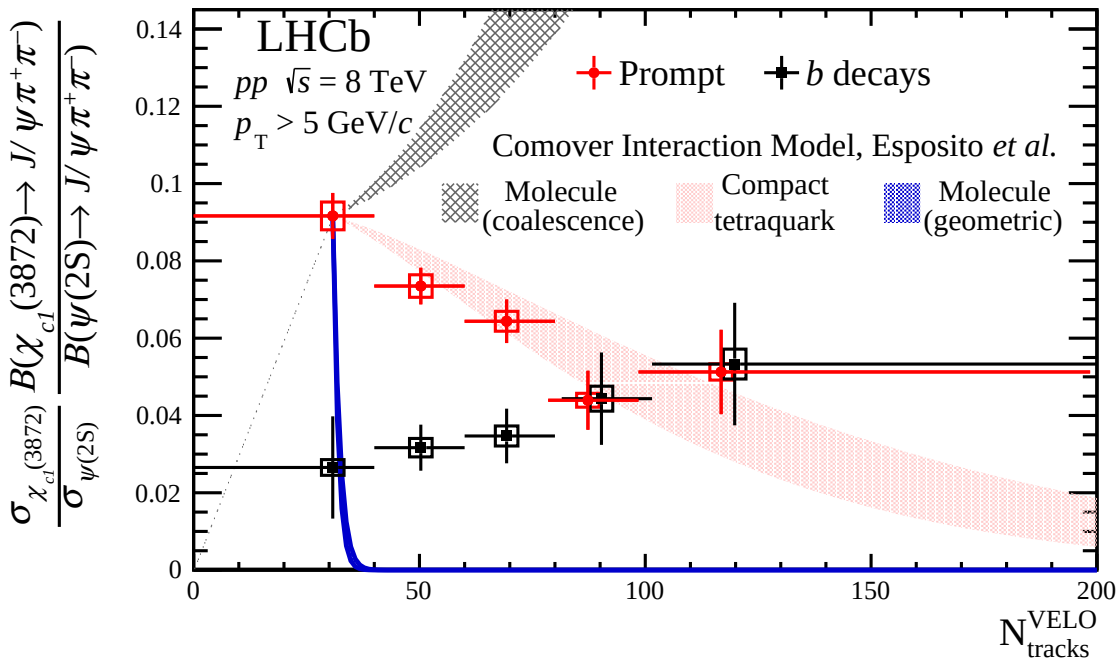
- The cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ is sensitive to final-state nuclear effects.
- Consistent with unity for both forward and backward rapidity regions.
- Consistent with results from pp.
- Suggest that the final-state nuclear effects impact the χ_{c1} and χ_{c2} states similarly.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



Multiplicity-dependent $\sigma(\chi_{c1}(3872))/\sigma(\psi(2S))$

PRL 126 (2021) 092001

- The prompt and nonprompt ratio shows different behaviours due to interactions with co-moving particles.

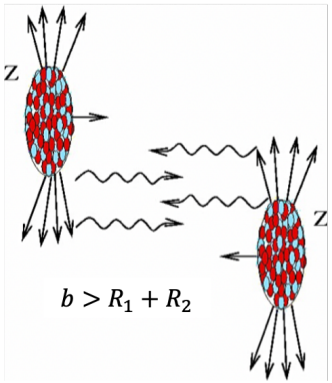


- Stronger suppression observed for $\chi_{c1}(3872)$ than $\psi(2S)$ hadrons.
- Comover calculations favour the $\chi_{c1}(3872)$ state being a compact tetraquark.

Coherent J/ψ production in UPCs

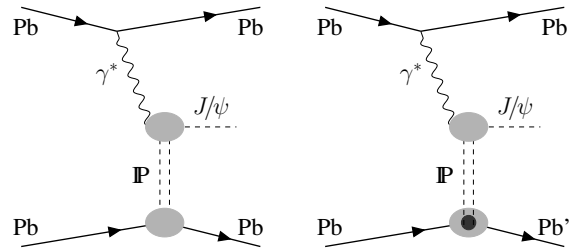
arXiv:2107.03223

- Ultra-peripheral collison (UPC)

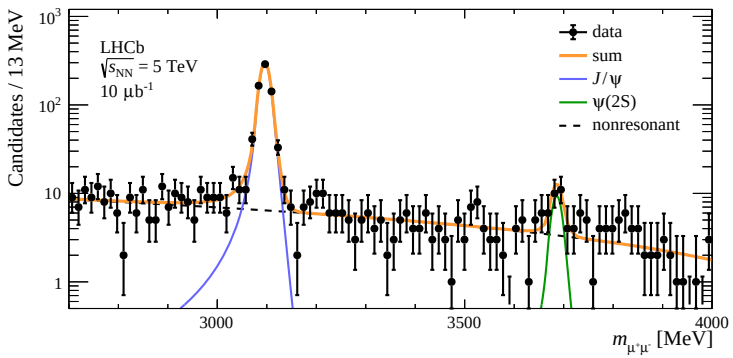


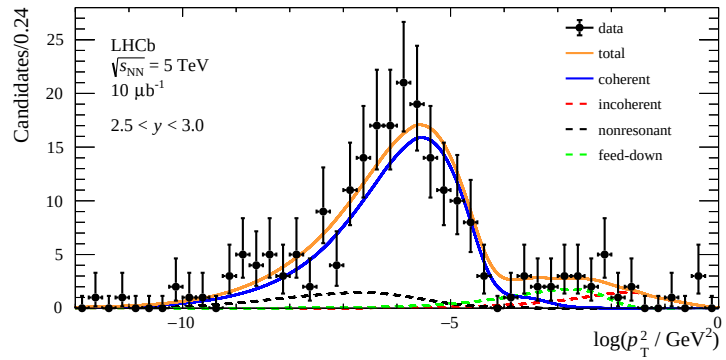
- The J/ψ production in UPCs

coherent incoherent



- Constrain gluon distribution function in Bjorken-x region of $\sim 10^{-5} - 10^{-2}$.
- Perform $M_{\mu^+\mu^-}$ fits and p_{T} fits to extract coherent J/ψ yields.

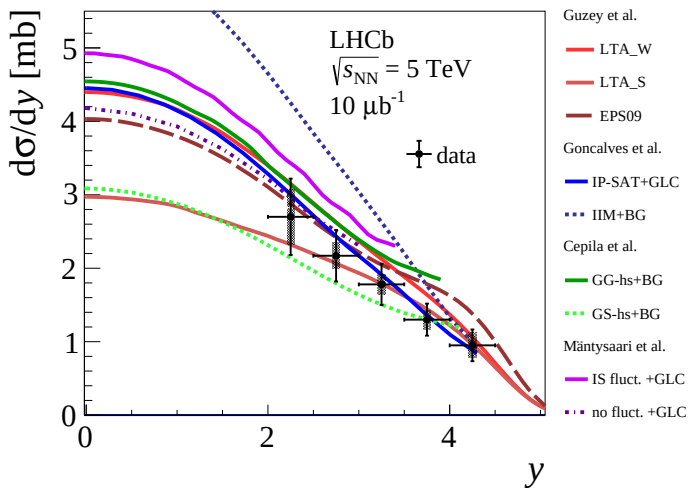




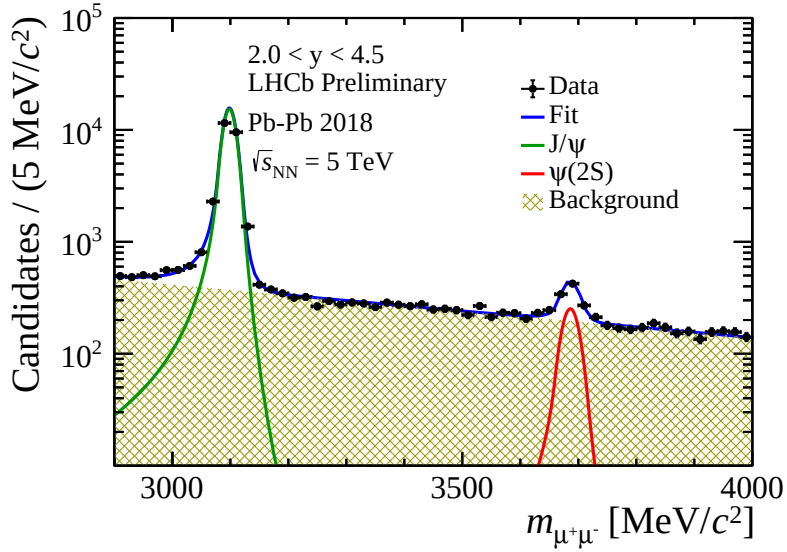
Coherent J/ψ cross-sections

arXiv:2107.03223

- Rapidity-dependent cross-sections obtained, compared to calculations from different nPDFs



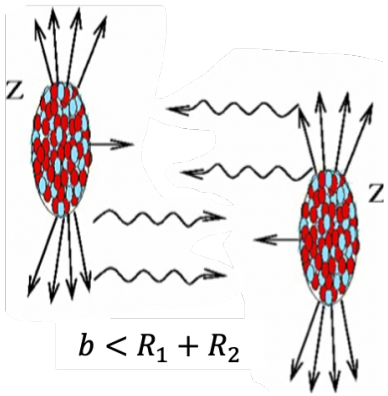
- Further measurements with larger data samples in process



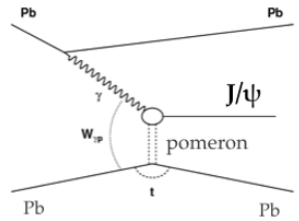
Coherent J/ψ production in peripheral PbPb collision

arXiv:2108.02681

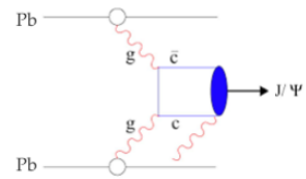
- Peripheral collision



- Excess of hadronic-producted J/ψ mesons observed by Alice [PRL 116 (2016) 222301]
- Suggest the presence of J/ψ photo-production

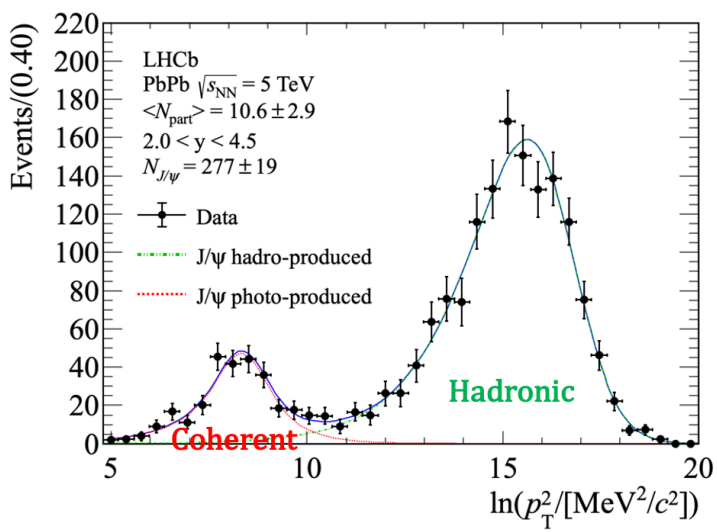


$\gamma(pomeron) \rightarrow J/\psi$



$gg \rightarrow J/\psi$

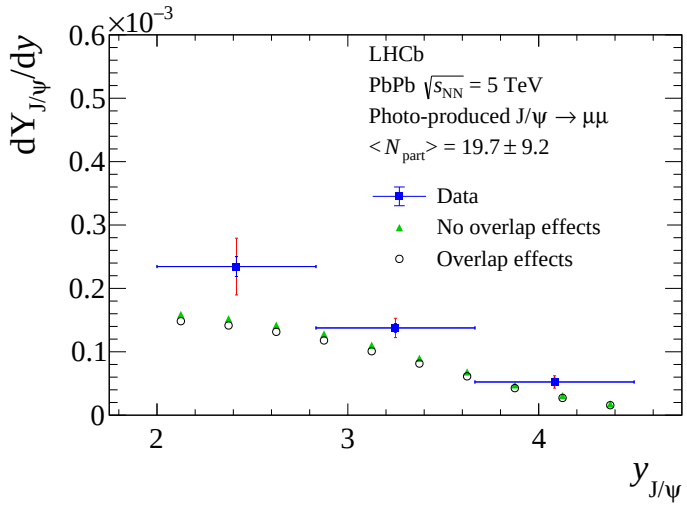
- Fit p_{T} distributions for coherent J/ψ yields

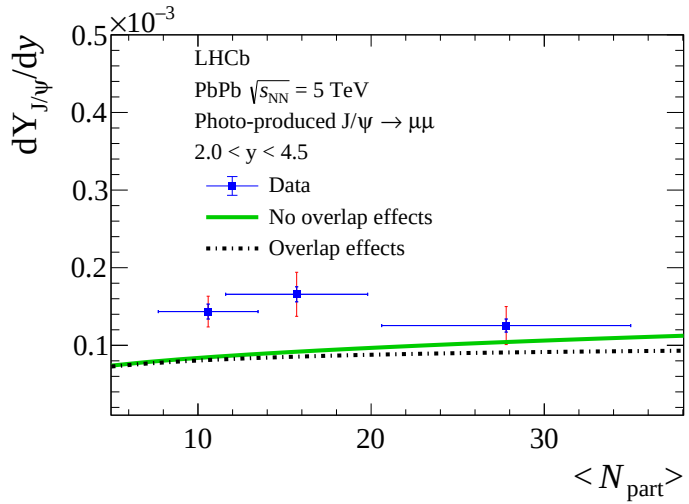


Coherent J/ψ yields

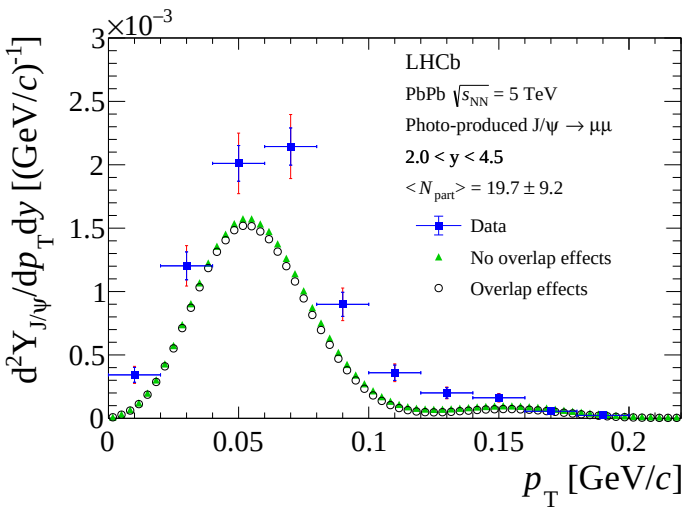
arXiv:2108.02681

- $\mathrm{d}Y_{J/\psi}/\mathrm{d}y$ as functions of rapidity and $\langle N_{\mathrm{part}} \rangle$ obtained





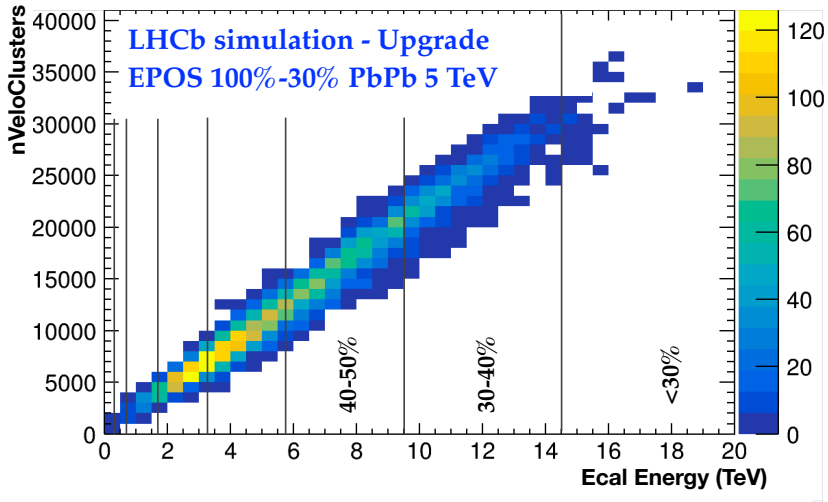
- The most precise p_{T} distributions to date, with an average of $\langle p_{\mathrm{T}} \rangle = 64.9 \pm 2.4\,\mathrm{MeV}/c$
- Shape consistent with theories

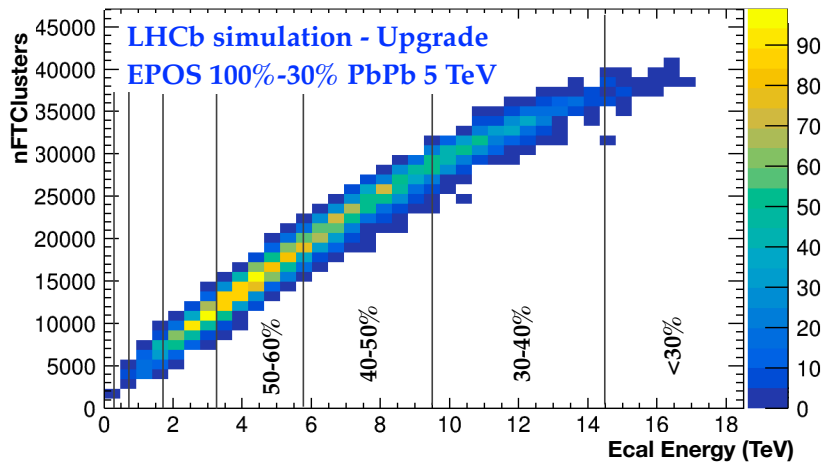


Future prospects and summary

Upgrade plan at Run3 (PbPb)

- Reconstruction for PbPb data limited to peripheral events (>60% in centrality) at Run2.
- Expect to reach more central PbPb events (up to $\sim 30\%$) with the help of the new tracking system.

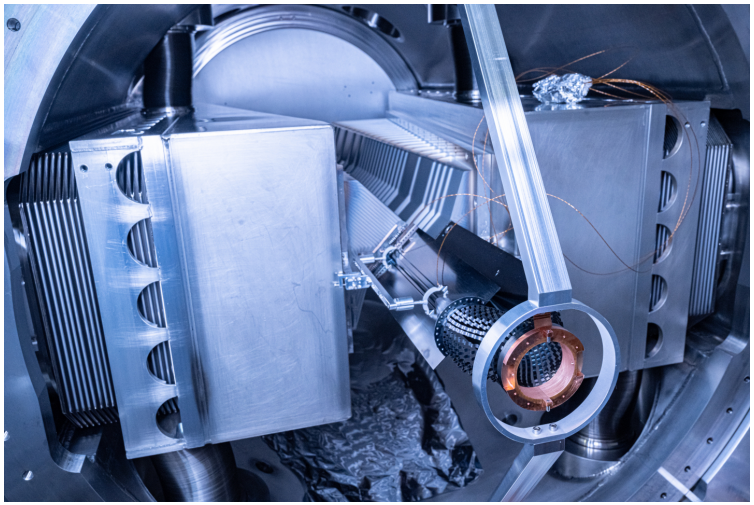




- More measurements accessible: R_{AA}, collective flow in PbPb *etc.*

Upgrade plan at Run3 (SMOG2)

LHCb-PUB-2018-015



- Newly designed **storage cell** adopted
- Wider choice in usable gas species
- 100× effective target areal density
- Already installed and able to run simultaneously with pp collisions

- More statistics expected

	SMOG published result pHe@87 GeV	SMOG largest sample pNe@69 GeV	SMOG2 example pAr@115 GeV
Integrated luminosity	7.6 nb^{-1}	$\sim$ 100 nb^{-1}	$\sim$ 45 pb^{-1}
syst. error on J/ψ x-sec.	7%	6 - 7%	2 - 3 %
J/ψ yield	400	15k	15M
D^0 yield	2000	100k	150M
Λ_c^+ yield	20	1k	1.5M
$\psi(2S)$ yield	negl.	150	150k
$\Upsilon(1S)$ yield	negl.	4	7k
Low-mass Drell-Yan yield	negl.	5	9k

Summary

- LHCb has strong capabilities to study heavy flavor in heavy-ion collisions.
  - Observe an enhancement on DPS in pPb collisions from the measurement of double-charm production.
  - Measure the χ_c states in heavy-ion collisions for the first time.
  - Study the structure of the $\chi_{c1}(3872)$ state from the multiplicity-dependent $\sigma(\chi_{c1}(3872)/\sigma(\psi(2S))$.
  - Constrain gluon distribution function by studying the coherent J/ψ production in UPC PbPb events.
  - Obtain a precise coherent J/ψ p_{T} distribution in peripheral PbPb collisions.
- Stay tuned for more results from Run2 data.
- More opportunities for heavy-ion physics at Run3 and beyond.

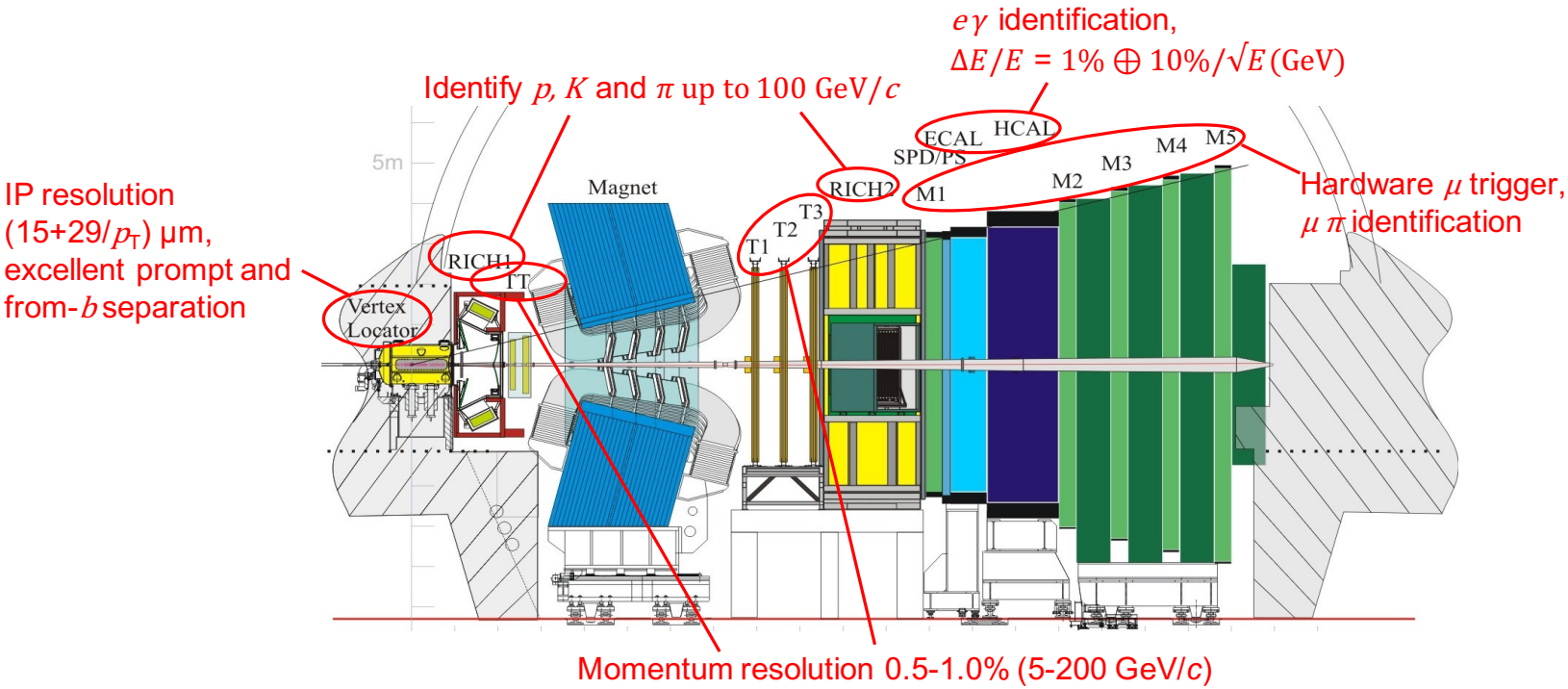
Thanks

Backups

LHCb detector at Run2

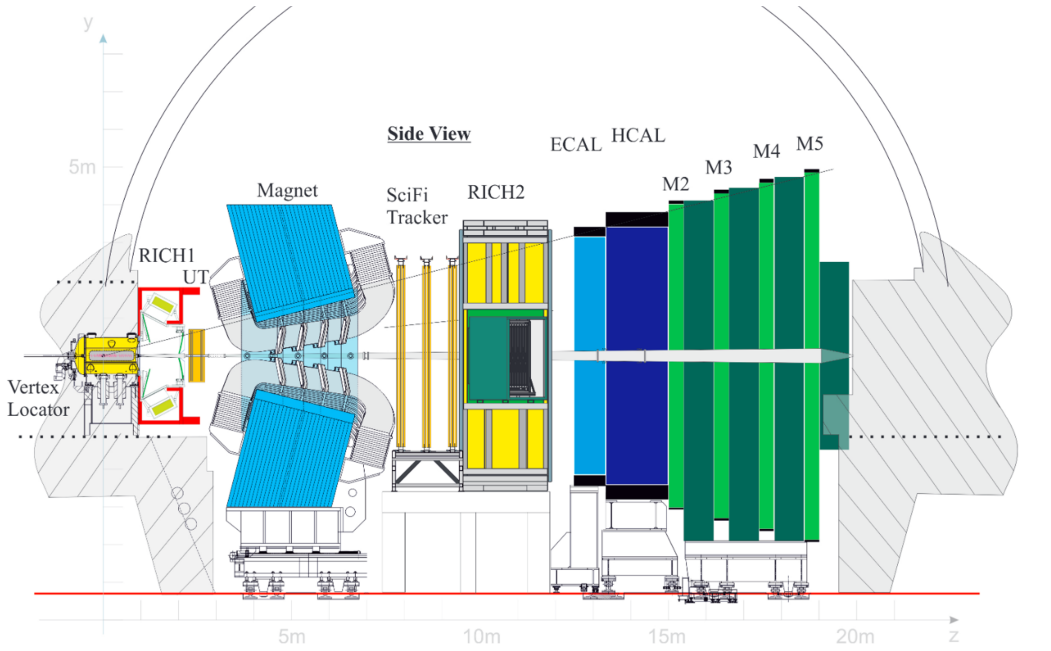
JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

- A single-arm forward spectrometer, covering the pseudo-rapidity range of $2 < \eta < 5$.
- Designed for studying particles containing b or c quarks.
- A general purpose detector measuring pp/pPb/PbPb and in fixed target mode.



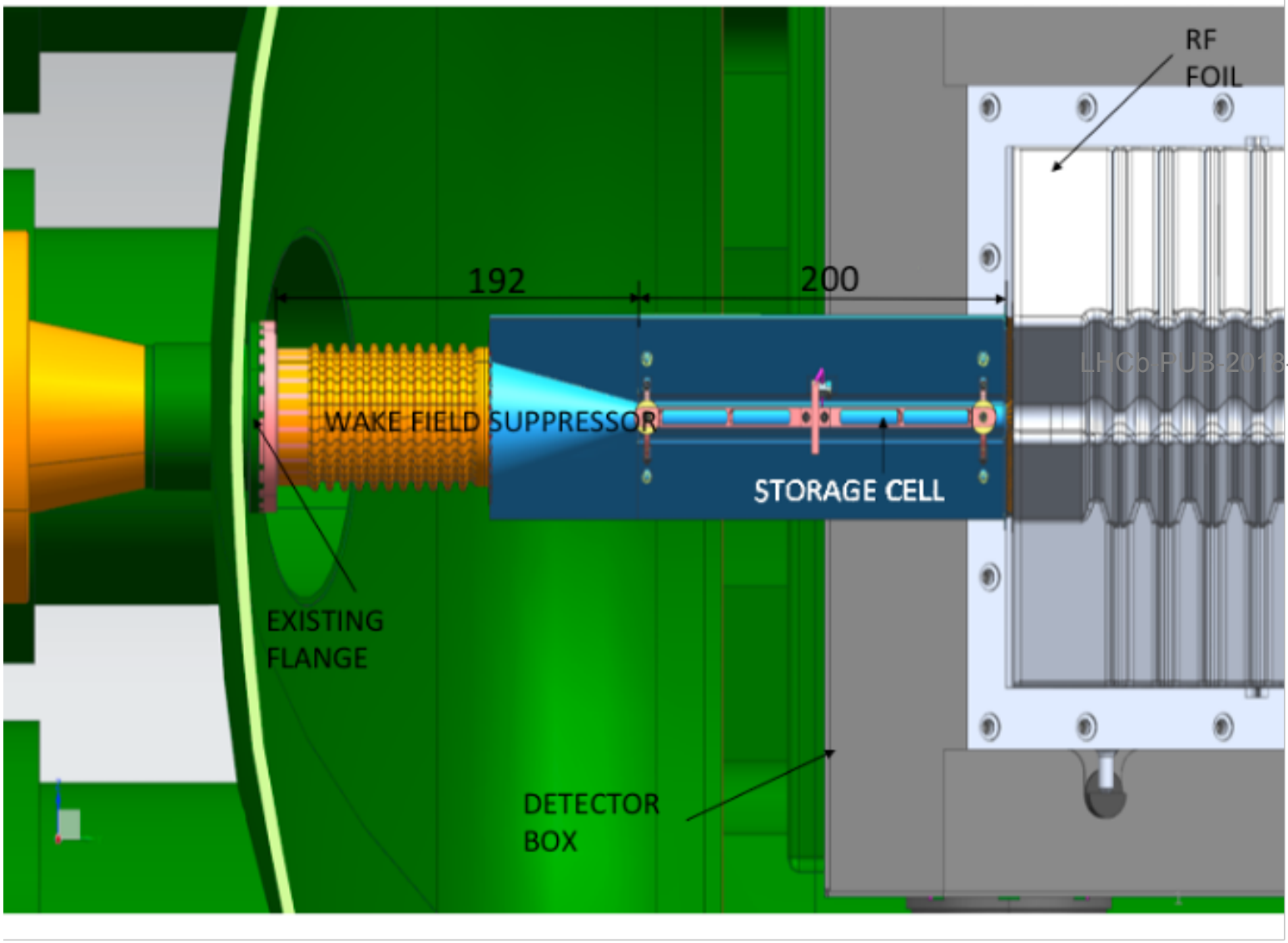
LHCb detector at Run3

CERN-LHCC-2012-007



- Collision rate at 40 MHz
- Pile-up factor $\mu \approx 5$
- New tracking system:
  - Silicon upstream detector (UT)
  - Scintillating tracking fibre (SciFi)
- Full software trigger:
  - Remove L0 triggers
  - Read out the full detector at 40 MHz

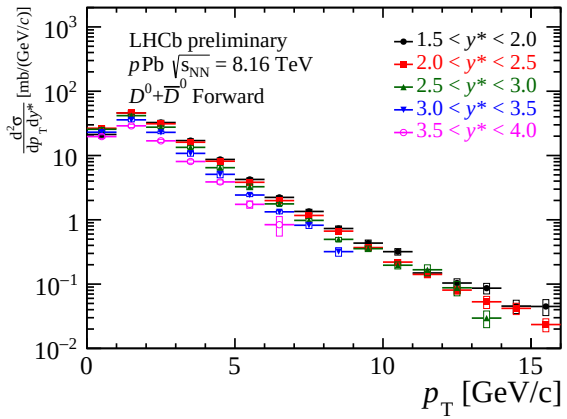
The sketch for SMOG2



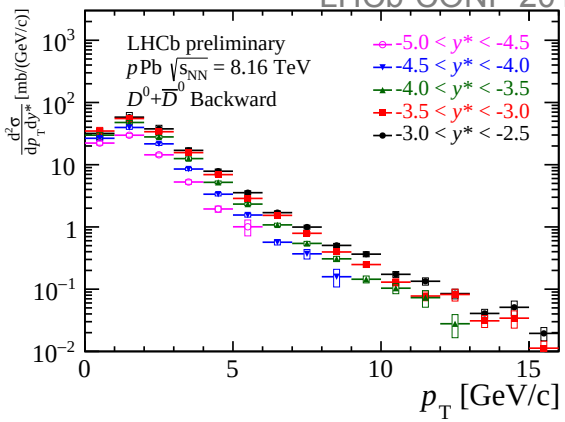
LHCb-PUB-2018-015

D^0 cross-sections at 8.16 TeV

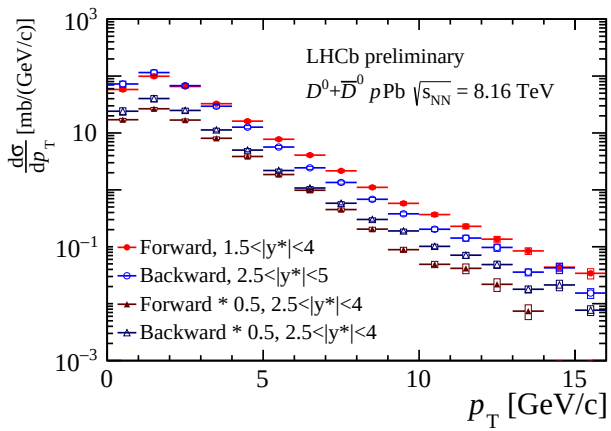
- Double-differential cross-sections:

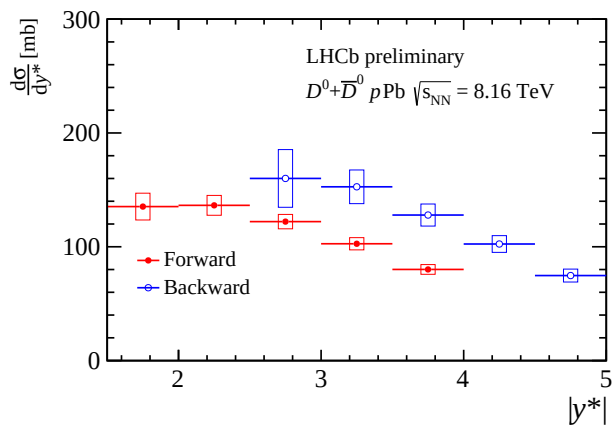


LHCb-CONF-2019-004



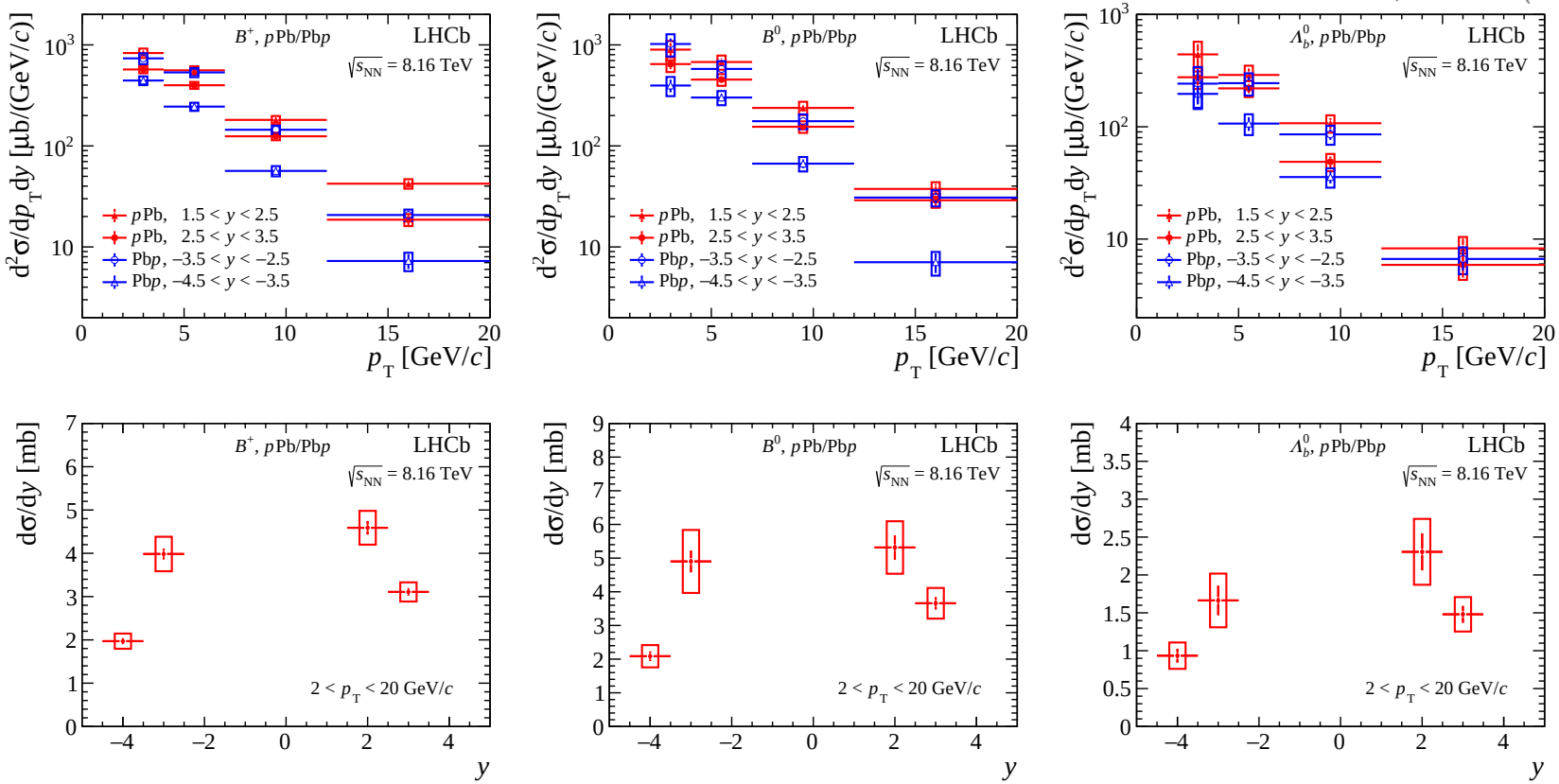
- One-dimensional cross-sections:





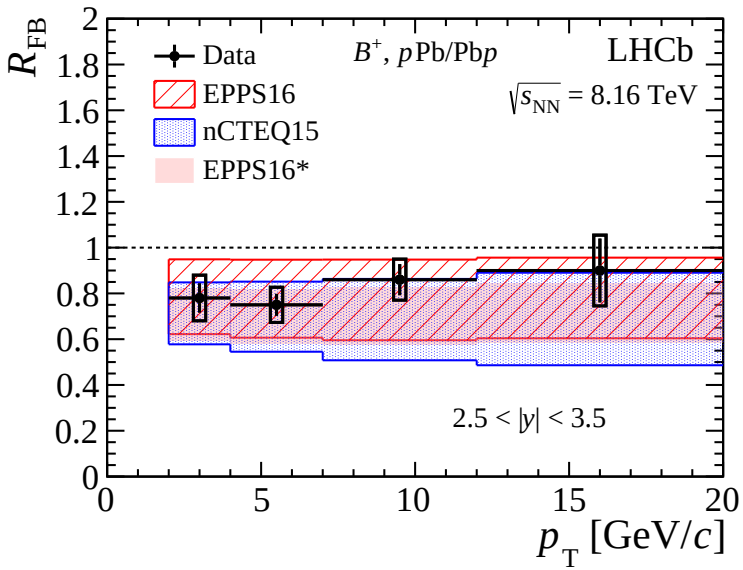
b-hadron cross-sections at 8.16 TeV

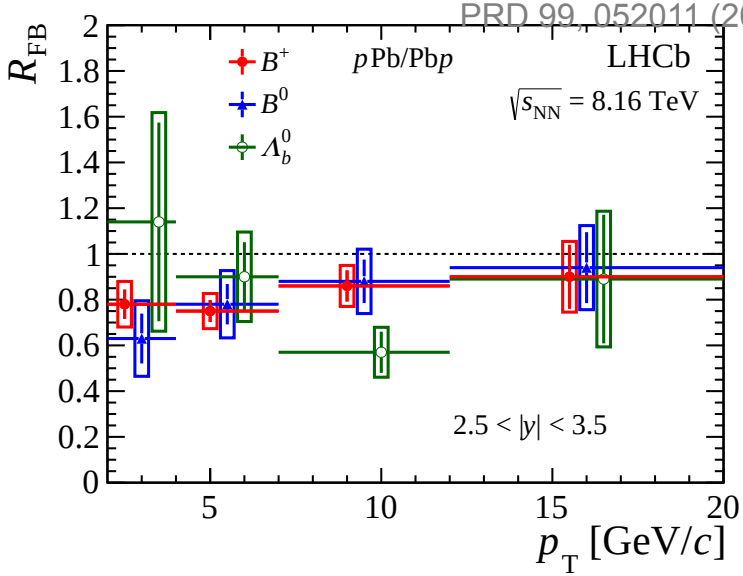
PRD 99, 052011 (2019)



- B^+ cross-sections calculated as average between $J/\psi K^+$ and $\overline{D}^0\pi^+$ modes.
- B^+, B^0 and Λ_b^0 cross-sections show similar p_{T} and y distributions.

b-hadron $R_{\rm FB}$





PRD 99, 052011 (2019)

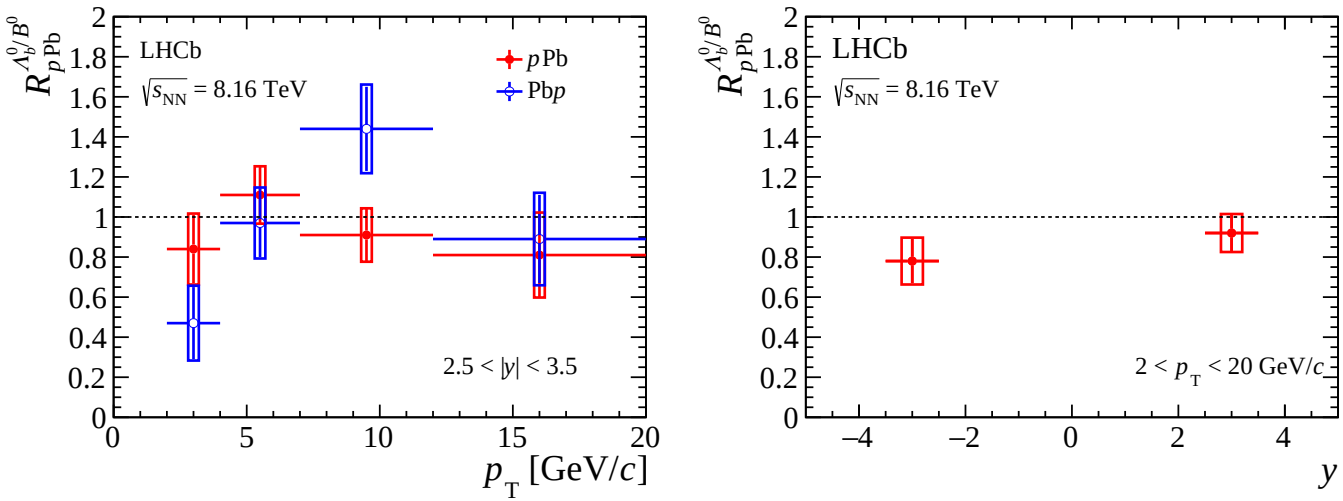
- A suppression of $\sim 25\%$ at positive rapidity is observed, without $p_{\rm T}$ dependence.
- The results are in good agreement with theories.
- The $R_{\rm FB}$ for B^+, B^0 and Λ_b^0 are compatible.

CPC 198 (2016) 23, JHEP 04 (2009) 065, EPJC 77 (2017) 163

Ratio of $R_{p\mathrm{Pb}}$ between Λ_b^0 and B^0

$$R_{p\mathrm{Pb}}^{\Lambda_c^+/D^0} = R_{p\mathrm{Pb}}^{\Lambda_c^+}/R_{p\mathrm{Pb}}^{B^0}$$

PRD 99, 052011 (2019)

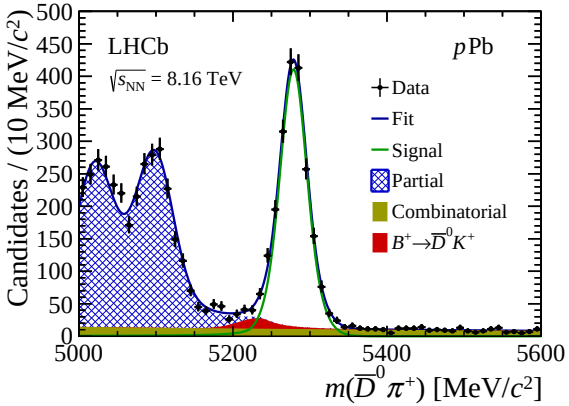


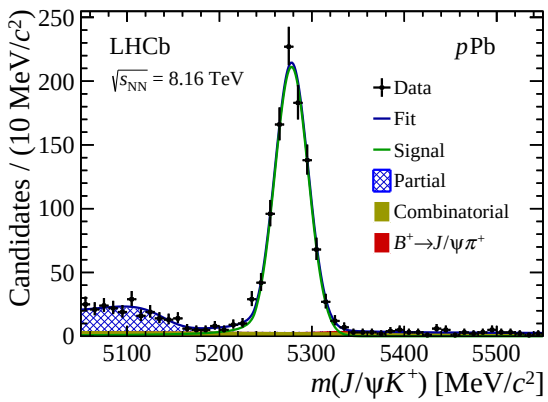
- Positive rapidity: consistent with unity in all kinematic bins $\Rightarrow$ b-quark fragmentation function in pPb similar to pp.
- Negative rapidity: hint of more suppression for Λ_b^0 compare with B^0. More data required to check whether there are different nuclear effects in beauty mesons and baryons.

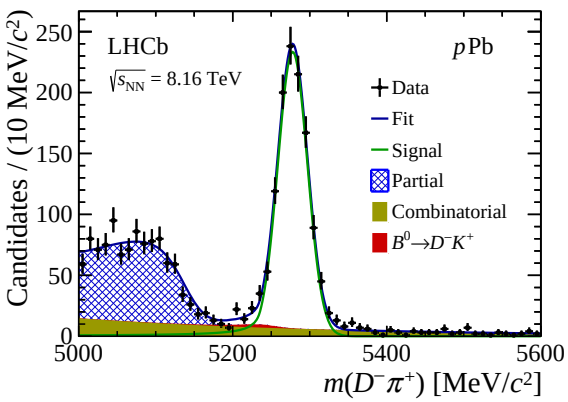
b-hadron mass distributions

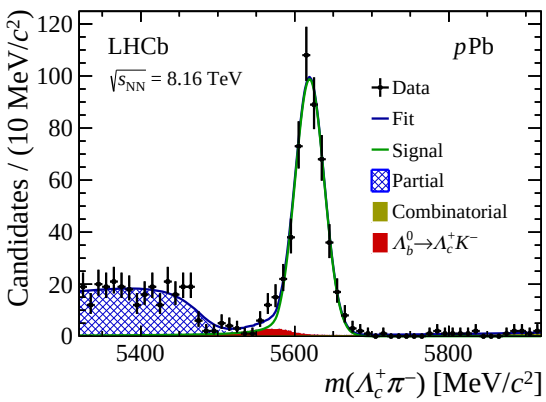
- b-hadron reconstruction using exclusive hadronic modes: $B^+ \to \overline{D}^0\pi^+$, $B^+ \to J/\psi\, K^+$, $B^0 \to D^-\pi^+$, $\Lambda_b^0 \to \Lambda_c^+\pi^-$.

PRD 99, 052011 (2019





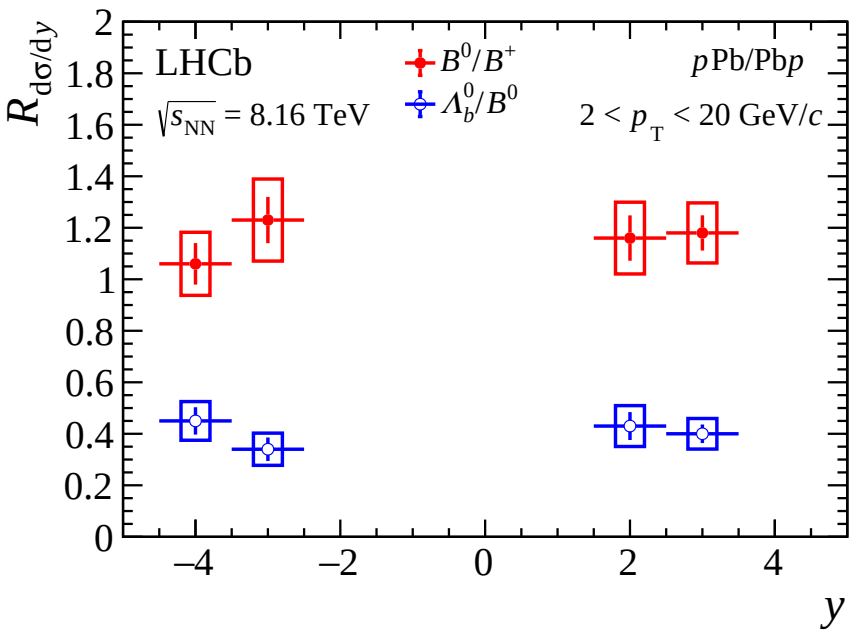


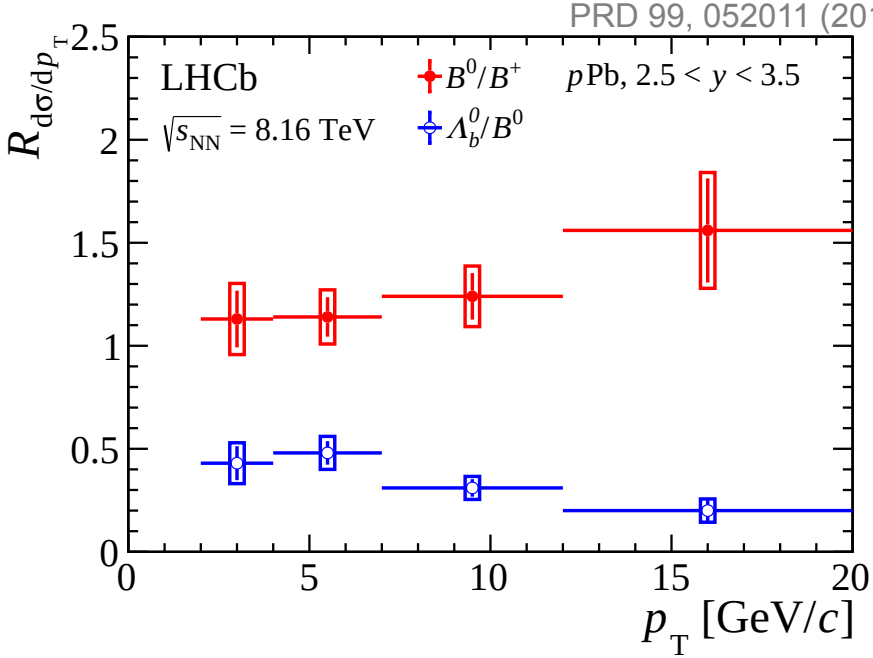


Decay	pPb	Pbp
$B^+ \to \overline{D}^0\pi^+$	1958 ± 54	1806 ± 55
$B^+ \to J/\psi\, K^+$	883 ± 32	907 ± 33
$B^0 \to D^-\pi^+$	1151 ± 38	889 ± 34
$\Lambda_b^0 \to \Lambda_c^+\pi^-$	484 ± 24	399 ± 23

b-hadron cross-sections ratios

PRD 99, 052011 (2019)



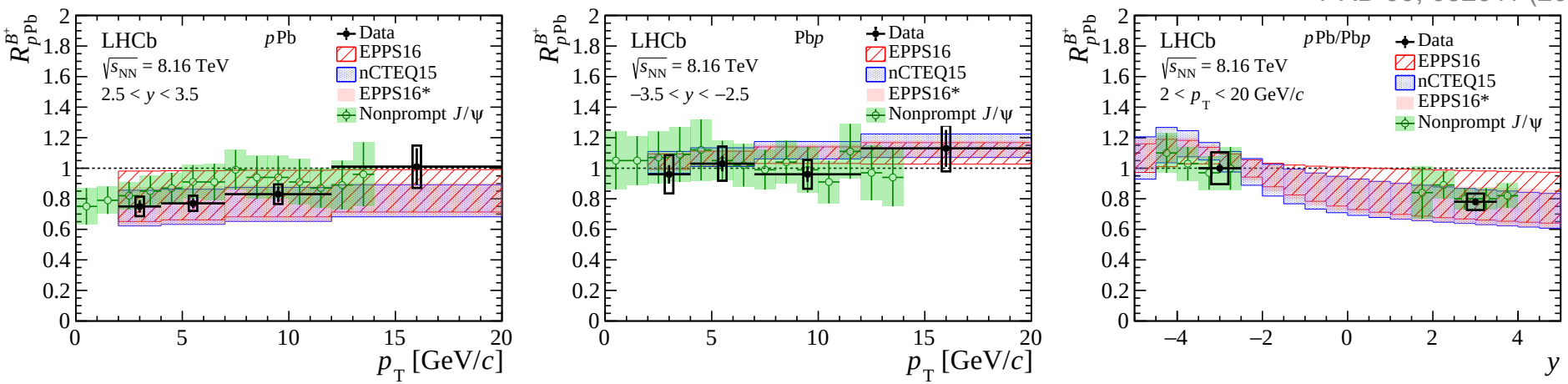


- B^0/B^+ ratio shows no significant p_{T} and y dependence within experimental uncertainties.
- $\Lambda_b^0/B^0 \approx 0.4$ similar to results in LHCb pp data.
- Λ_b^0/B^0 points show a decreasing trend as a function of p_{T}.

JHEP 08 (2014) 143

$R_{p\mathrm{Pb}}$ for B^+ meson

PRD 99, 052011 (2019)

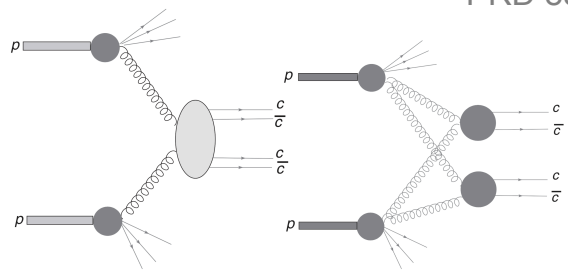


- σ_{pp} obtained from an interpolation of LHCb 7 TeV and 13 TeV results.
- Forward: significant suppression observed and $R_{p\mathrm{Pb}}$ increases with p_{T}.
- Backward : consistent with unity.
- The measurement in good agreement with calculations with nPDFs and J/ψ-from-b results.

JHEP 08 (2013) 117, JHEP 12 (2017) 026
JHEP 04 (2009) 065, EPJC 77 (2017) 163, CPC 198 (2016) 38

- The first measurement of charm pair production in pPb at 8.16 TeV.
- The double parton scattering (DPS) are used to describe the charm pair production in heavy-ion collisions.
  - Simple parton scattering (SPS) vs DPS

PRD 85, 094034 (2012)



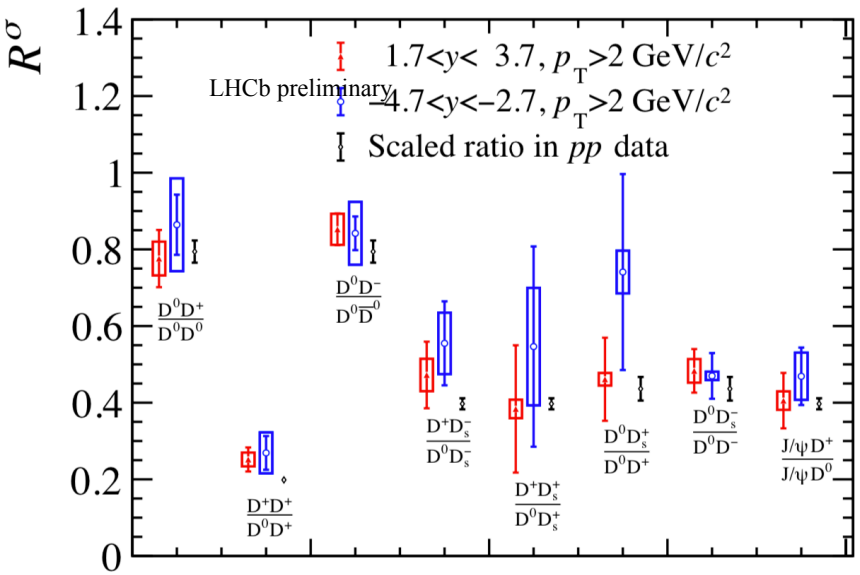
  - The cross-section of two final state particles in a DPS process:

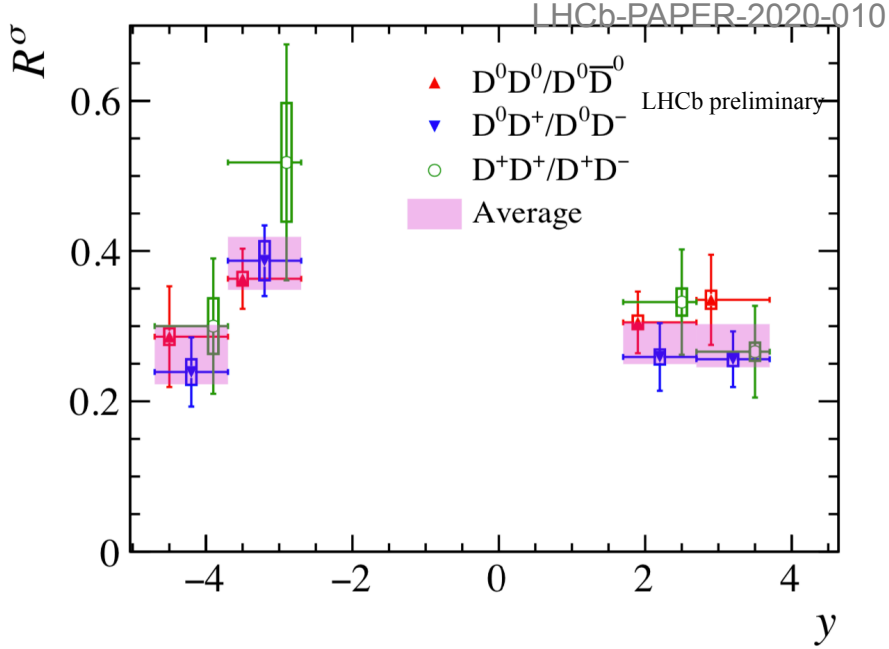
$$\sigma_{\mathrm{DPS}}^{AB} = \frac{1}{1+\delta_{AB}} \frac{\sigma_A \sigma_B}{\sigma_{\mathrm{eff}}} \ .$$

  - The effective cross-section σ_{eff} is expected independent of final states.
- Charm pairs from the same events included

	same-species	diff-species
like-sign (LS)	D^0-D^0, D^+-D^+, D_s^+-D_s^+,...	D^0-D^+, D^0-D_s^+, D^+-D_s^+, J/ψ-D, ...
opposite-sign (OS)	D^0-$\overline{D}^0$, D^+-D^-, D_s^+-D_s^-,...	D^0-D^-, D^0-D_s^-, D^+-D_s^-, ...

Charm pair cross-section ratios





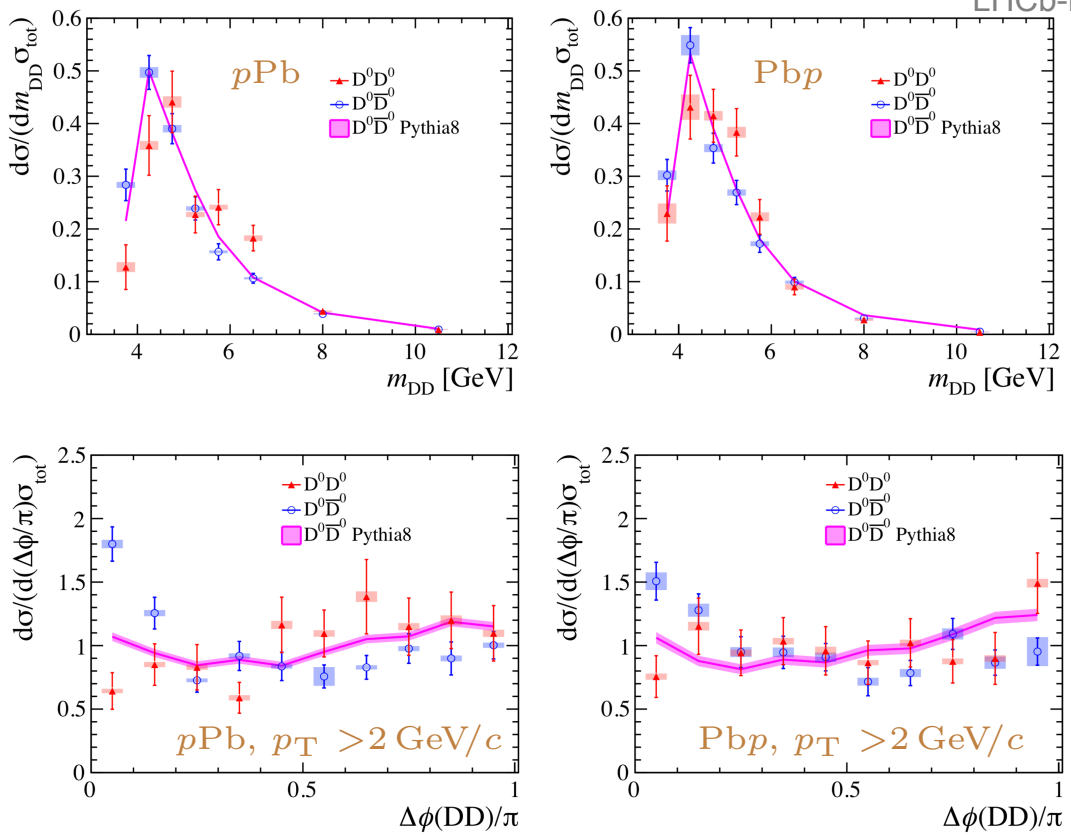
- Charm hadronisation not strongly modified in pPb compared to pp.
- Like-sign produced enhanced in pPb compared to pp, more enhanced for backward.

JHEP 06 141 (2012)

Correlations

- m_{DD} and $\Delta\phi$ distributions

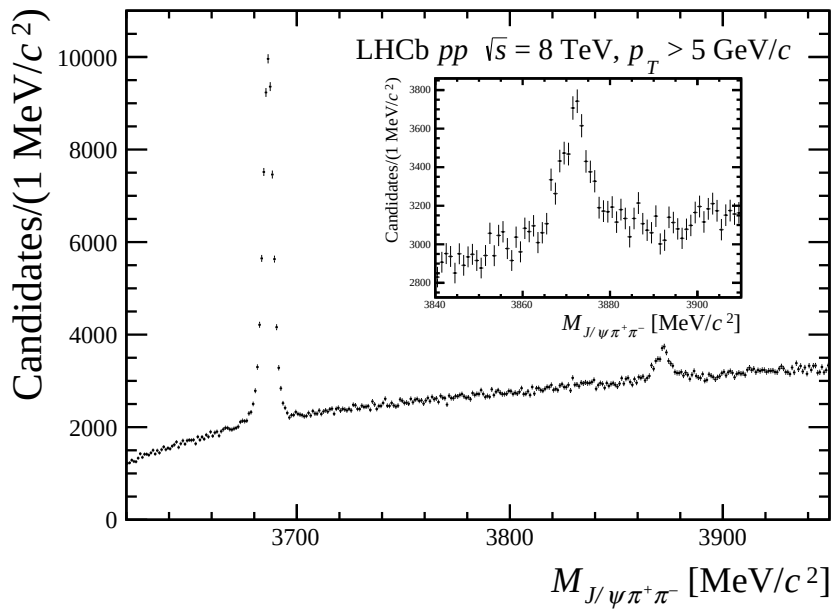
LHCb-PAPER-2020-010



- The results in good agreement with PYTHIA 8 generally.
- Discrepancy at low $\Delta\phi$ for p_{T} >2 GeV/c.

Multiplicity-dependent $\chi_{c1}(3872)/\psi(2S)$ in pp at 8 TeV

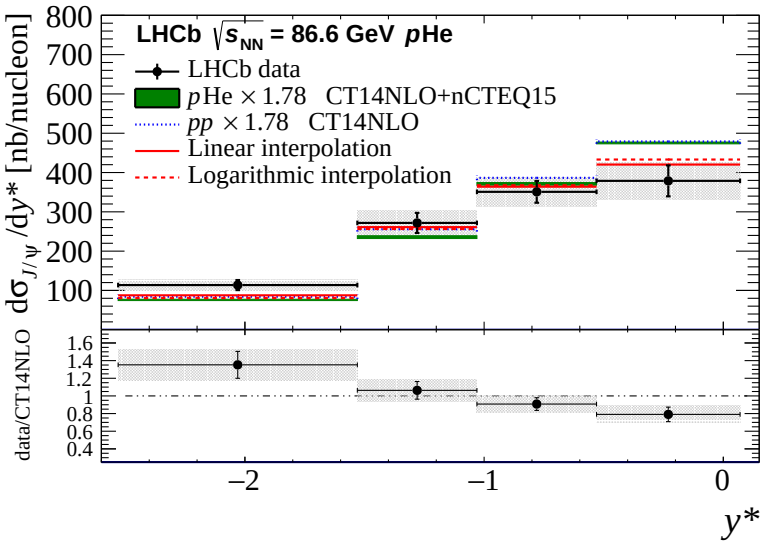
- The quantum numbers of $\chi_{c1}(3872)$ $J^{PC} = 1^{++}$ is incompatible with the conventional charmonia.
- The nature of $\chi_{c1}(3872)$ can be studied by studying its multiplicity-dependent relative suppression compared to a conventional charmonium state such as $\psi(2S)$.
- Both states are reconstructed via common final states $J/\psi\,\pi^+\pi^-$.
- The prompt and nonprompt are distinguished using t_z.

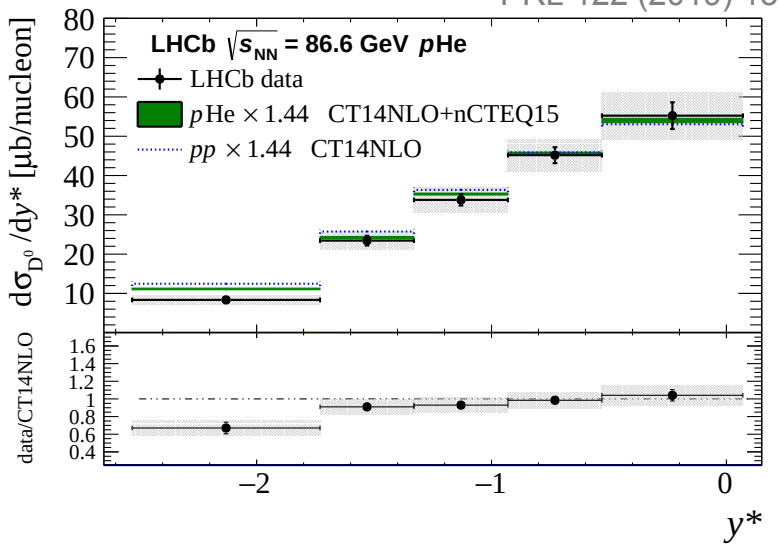


Charm production in fixed-target configuration

- Cover the large Bjorken-x region of the target nucleon.

PRL 122 (2019) 132002





- Consist with theories and no significant intrinsic charm contribution found.
- Looking forward to further measurements with larger statistics.

EPJC 77 (2017) 163, CPC 198 (2016) 38, CPC 184, 2562 (2013)
PRD 93, 033006 (2016), PRD 93, 085037 (2016)

Comparison with ALICE results on coherent J/ψ production

- $\sim 1.3\sigma$ with ALICE results (mid rapidity)