LHCb heavy flavor measurements

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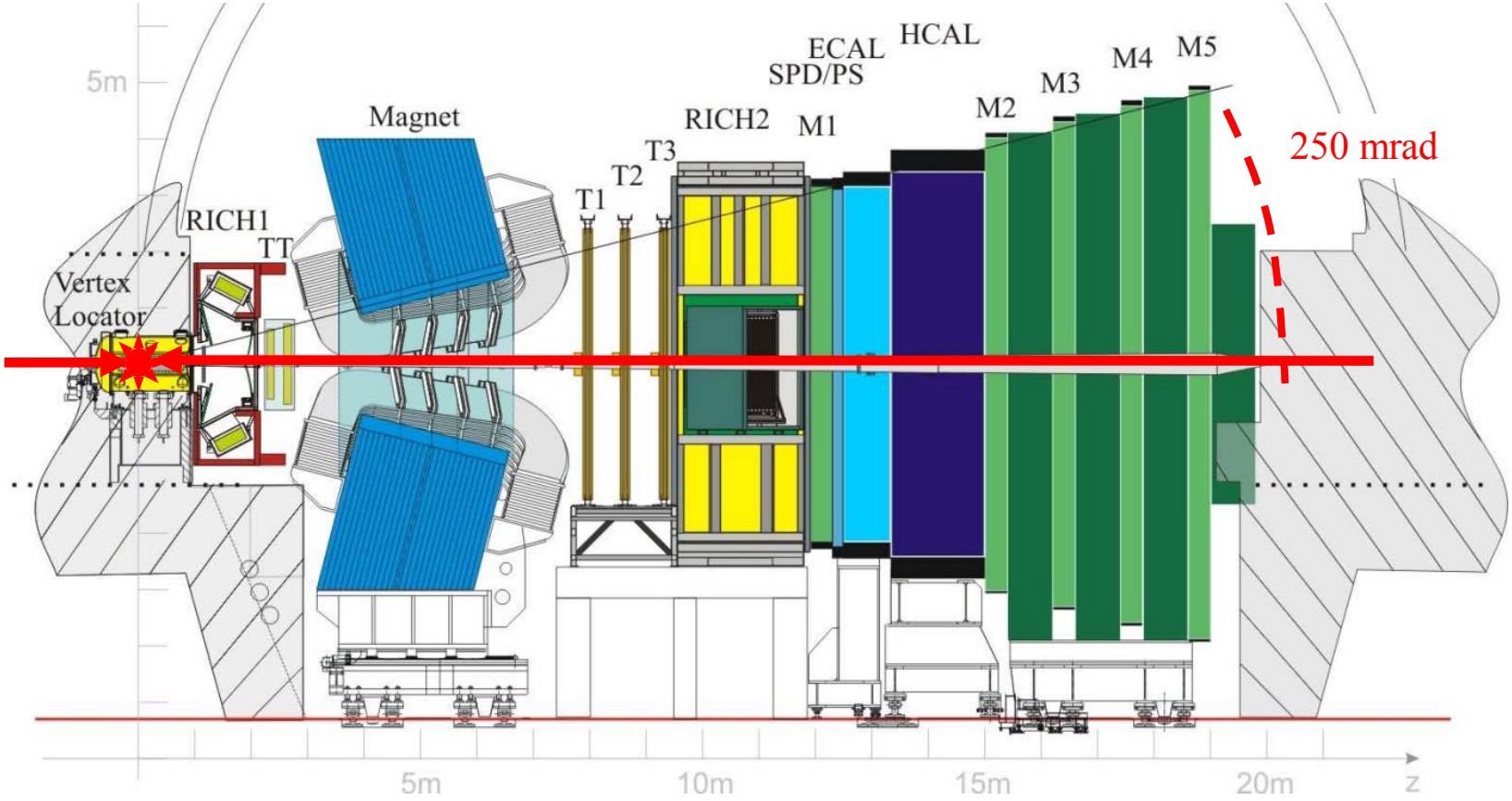
Outline

- The LHCb experiment
- Open charm in pPb collisions
- J/ψ in pPb collisions
- Fixed-target program
- Studies of PbPb collisions
- Prospects
- Summary

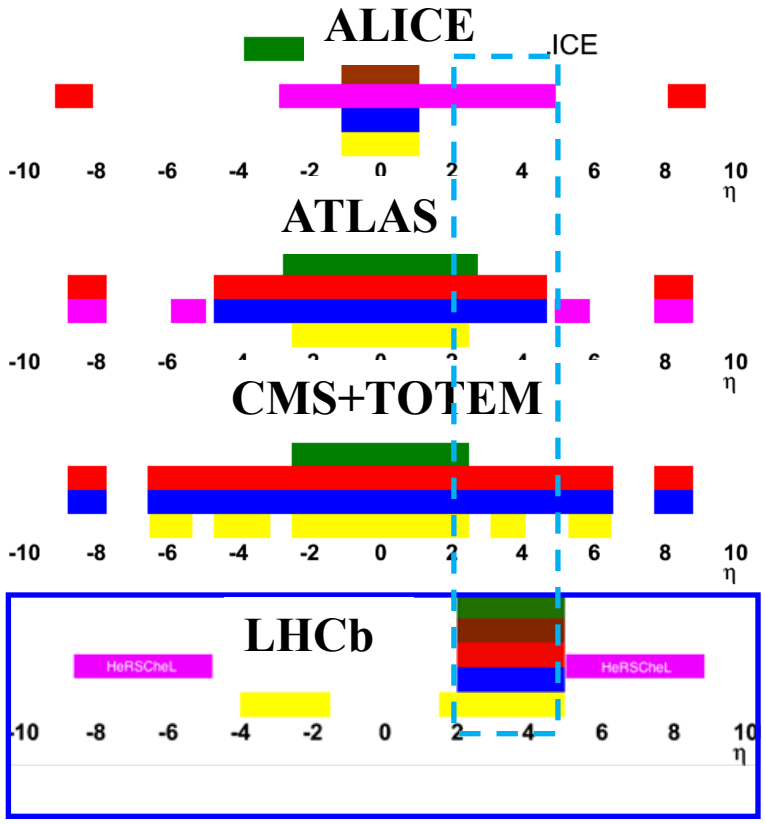
LHCb experiment

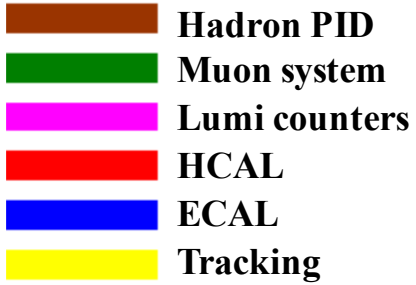
JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

Aiming for precision measurements in b, c flavor sectors
Acceptance: $2 < \eta < 5$

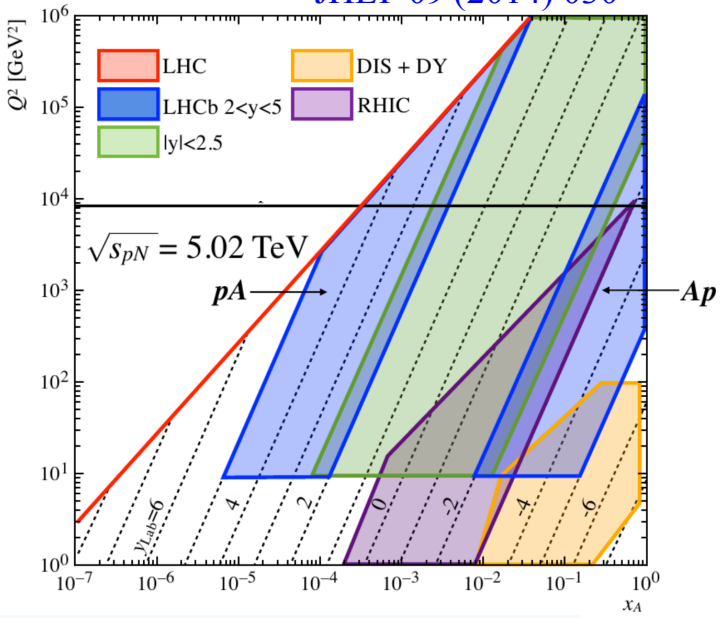


LHCb experiment





JHEP 09 (2014) 030



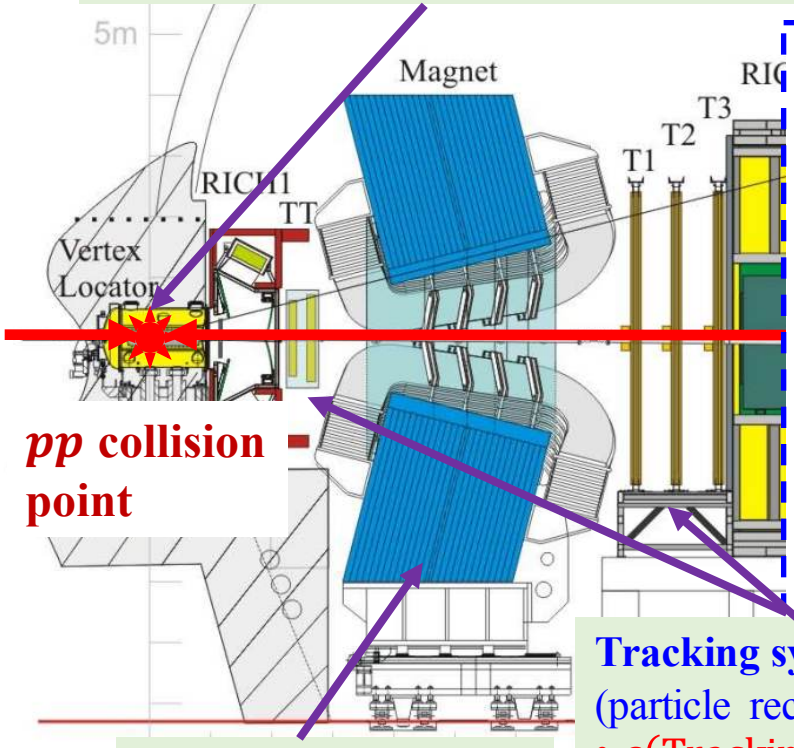
LHCb fully instrumented in the forward region $(2 < \eta < 5)$

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

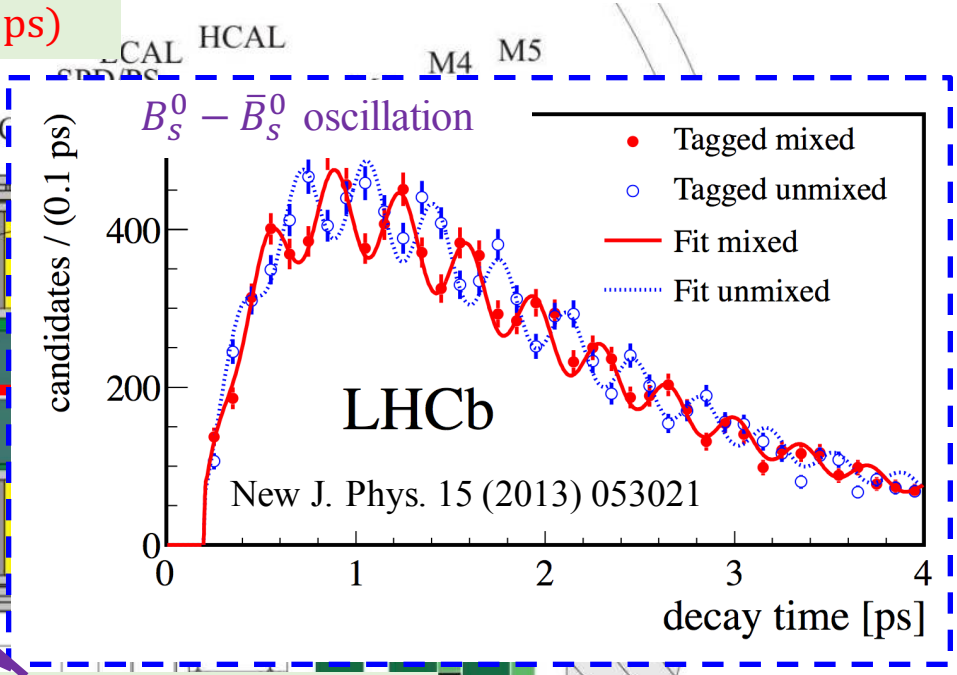
LHCb experiment

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

Vertex Locator (vertex reconstruction)
- Impact parameter resolution: 20μm
- Decay time resolution: 45 fs (τ_B~1.5 ps)



***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

RICH detectors ($K/\pi/p$ separation)

- $\epsilon(K \to K)$~95%
- Mis-ID r$(\pi \to K)$~5%
- $\epsilon(\mu \to \mu)$ ~97% with r$(\pi \to \mu)$~3%

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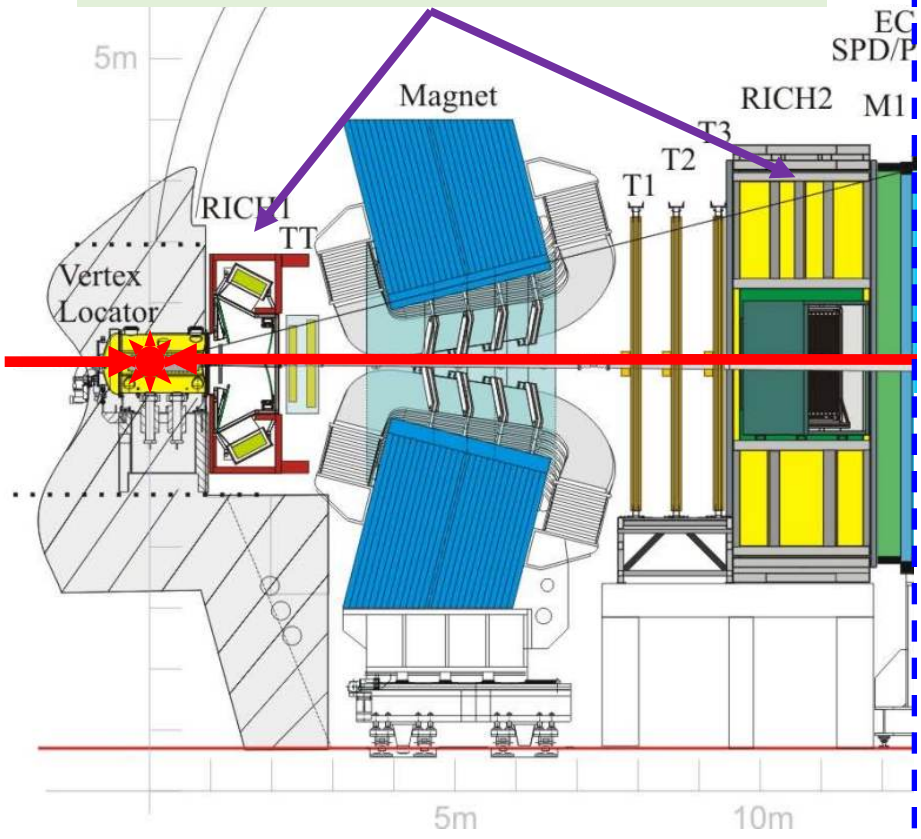
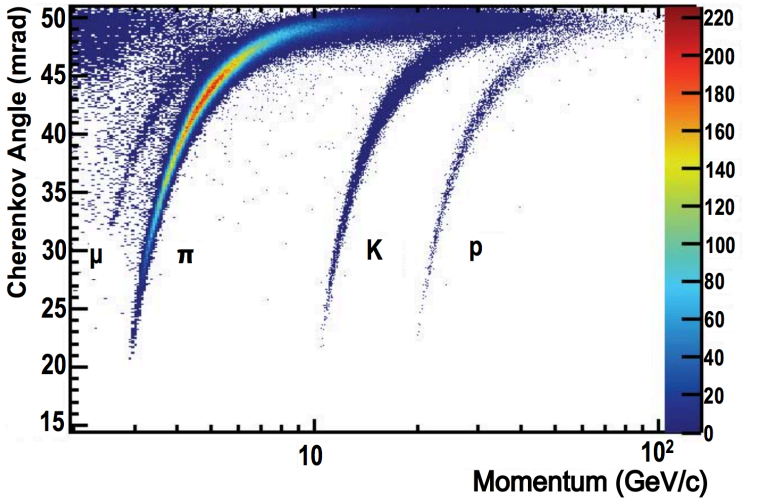
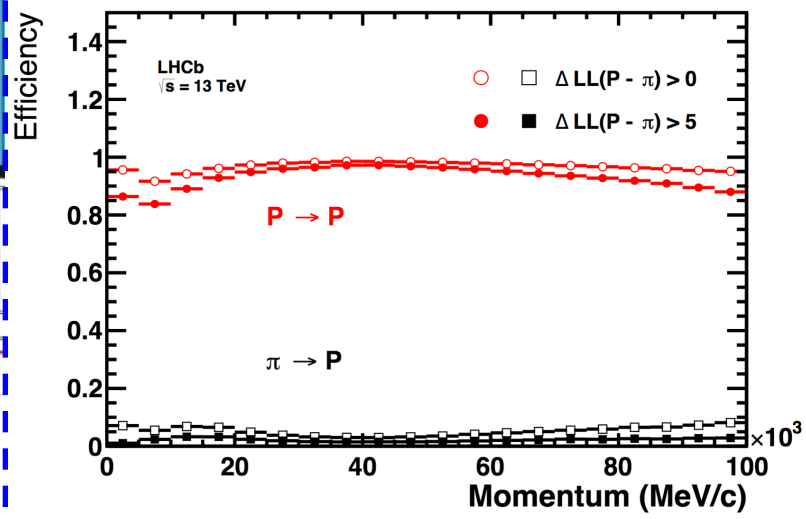


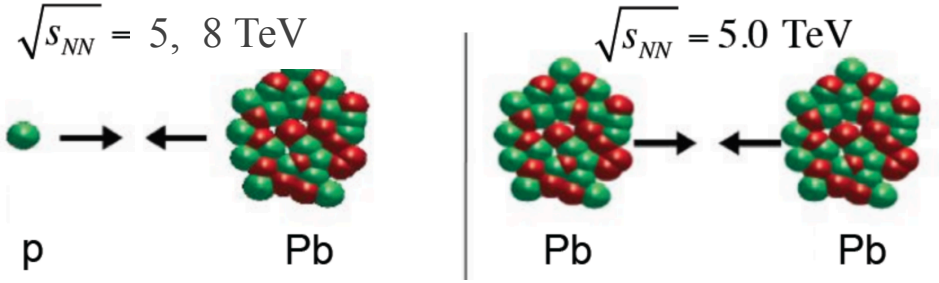




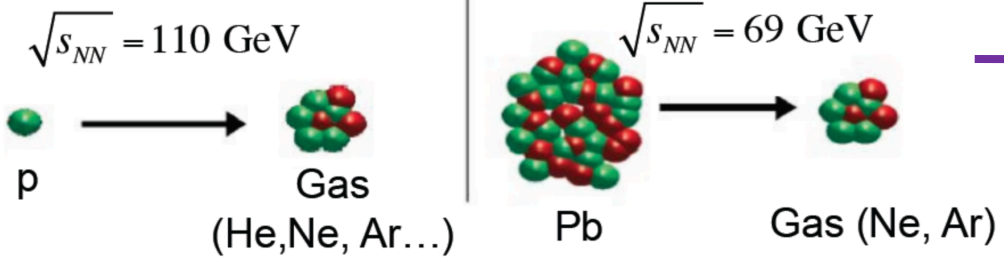
LHCb heavy ion data

- LHCb collected pp, pPb, PbPb/XeXe, and p- or Pb- gas collisions
  - ➢ At different center-of-mass energy ($\sqrt{s_{NN}}$) and rapidity coverage

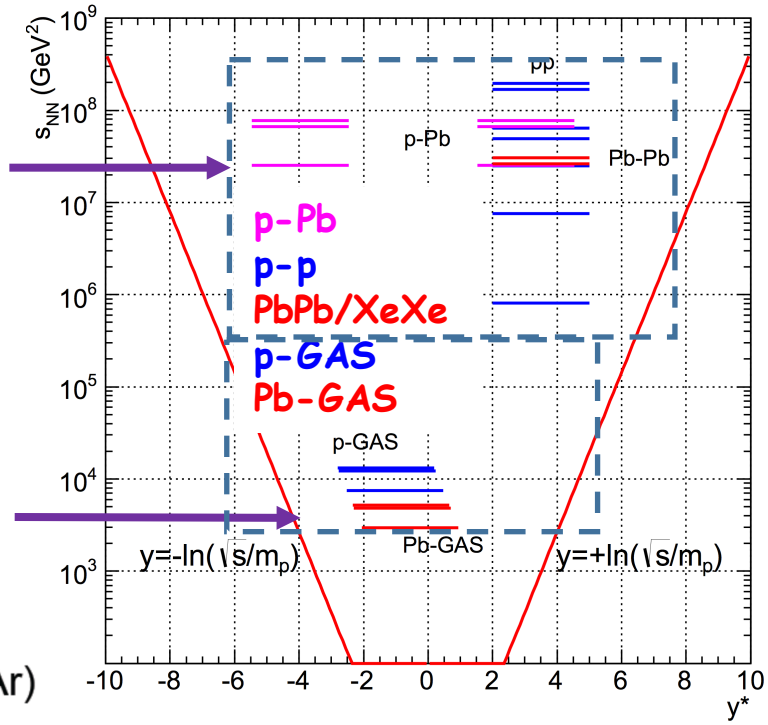
Collider mode: forward/backward rapidity



Fixed target mode: mid or backward rapidity, energies between SPS and RHIC



LHCb rapidity coverage in rest frame



GAS targets: He, Ne, Ar, Kr, Xe → Different sizes of colliding system

→ Data already available

Open charm production in pPb collisions

Data:

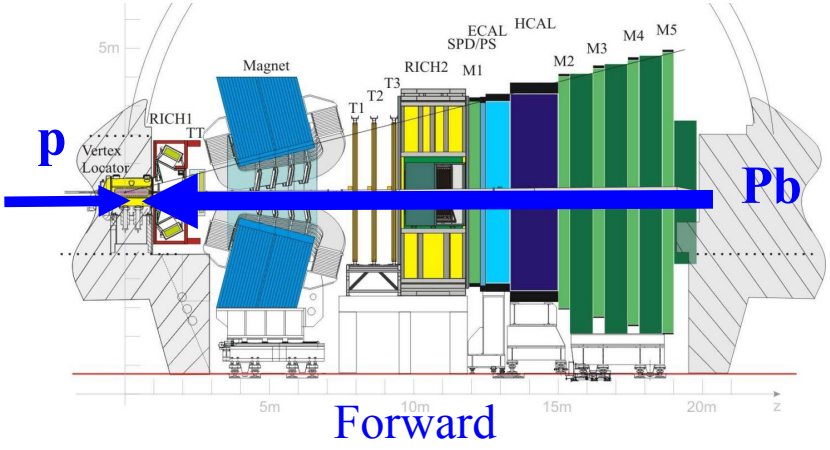
$\sqrt{s_{NN}} = 5$ TeV (2013)

Forward: 1.06 ± 0.02 nb^{-1}

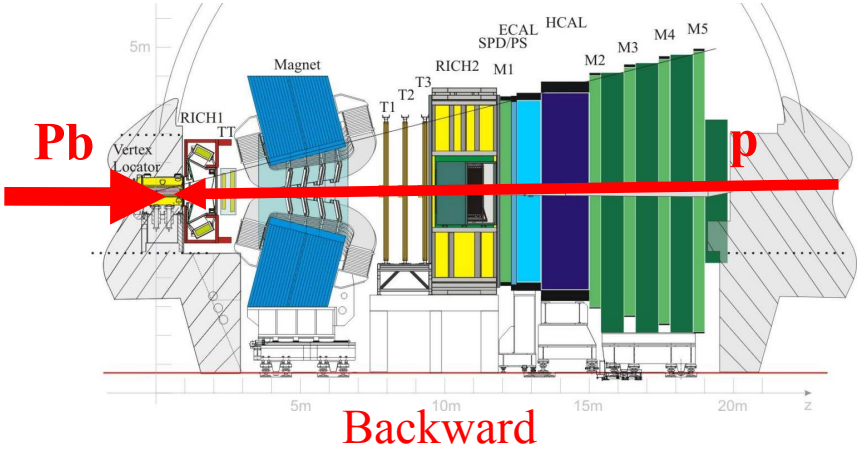
Backward: 0.52 ± 0.01 nb^{-1}

D^0: JHEP 1710 (2017) 090

Λ_c^+: LHCb-CONF-2017-005



Forward

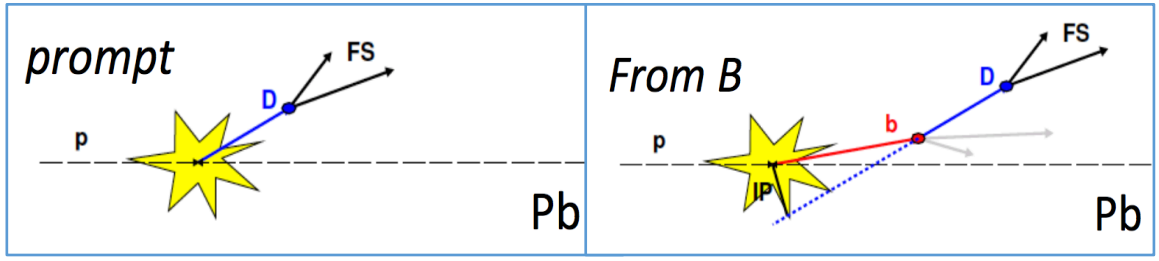


Backward

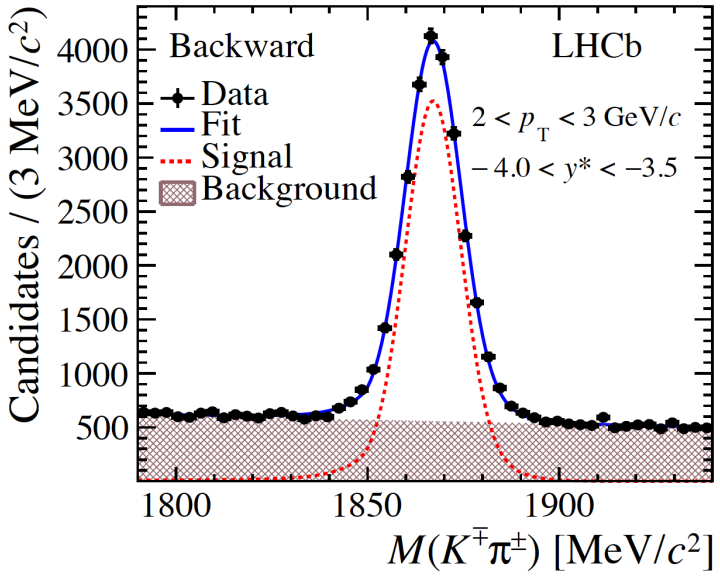
Prompt D^0 production

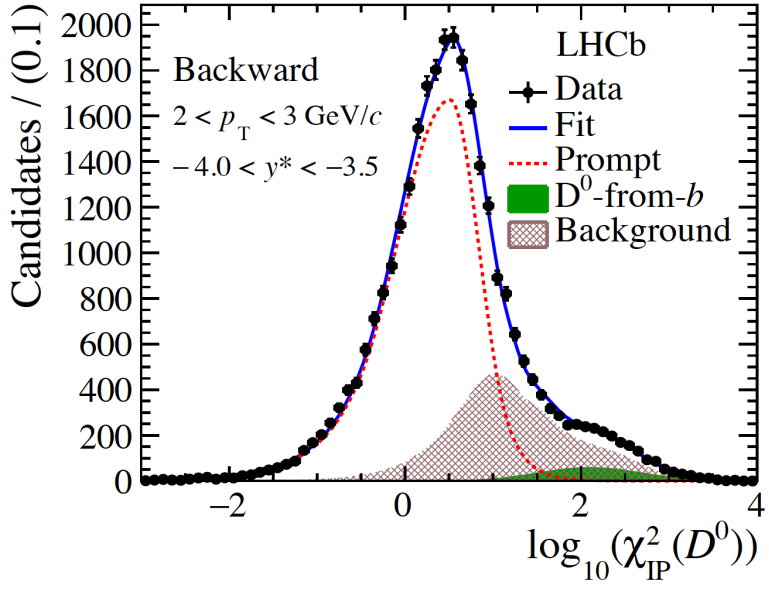
JHEP 1710 (2017) 090

- D^0 fully reconstructed through $D^0 \to K^{\pm}\pi^{\mp}$ decays
- Reconstruction and particle ID efficiency calibrated using data
- Prompt D^0 and D^0 from b hadrons separated with impact parameter (IP) w.r.t. primary vertex



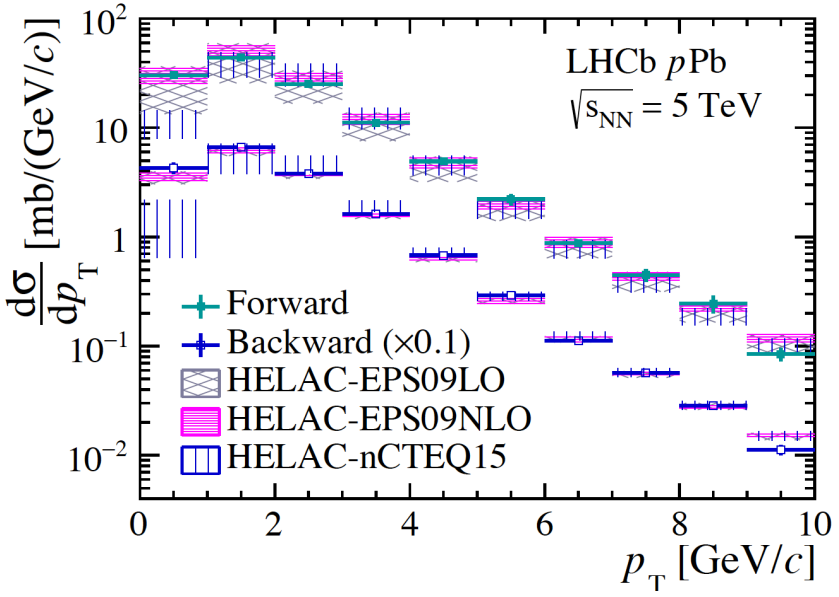
- Yield extraction fits

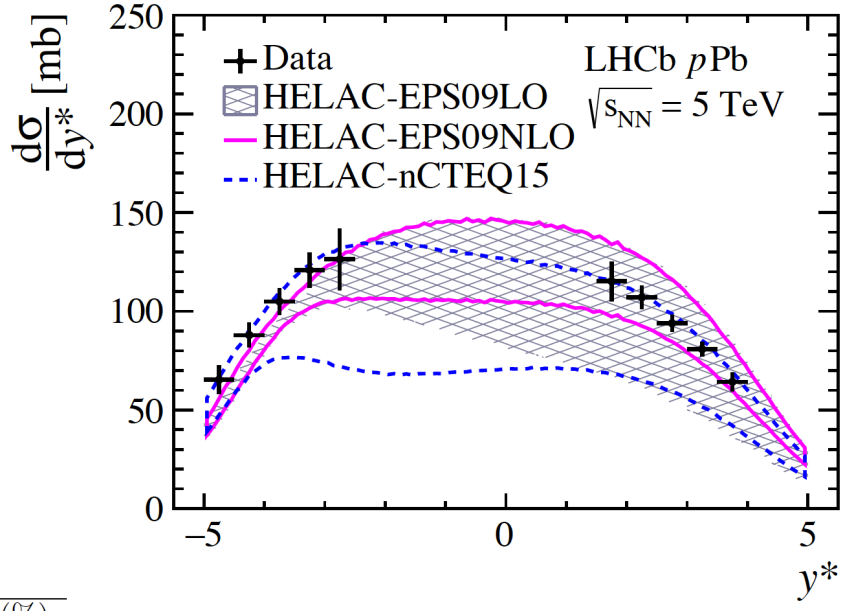




D^0 production

JHEP 1710 (2017) 090





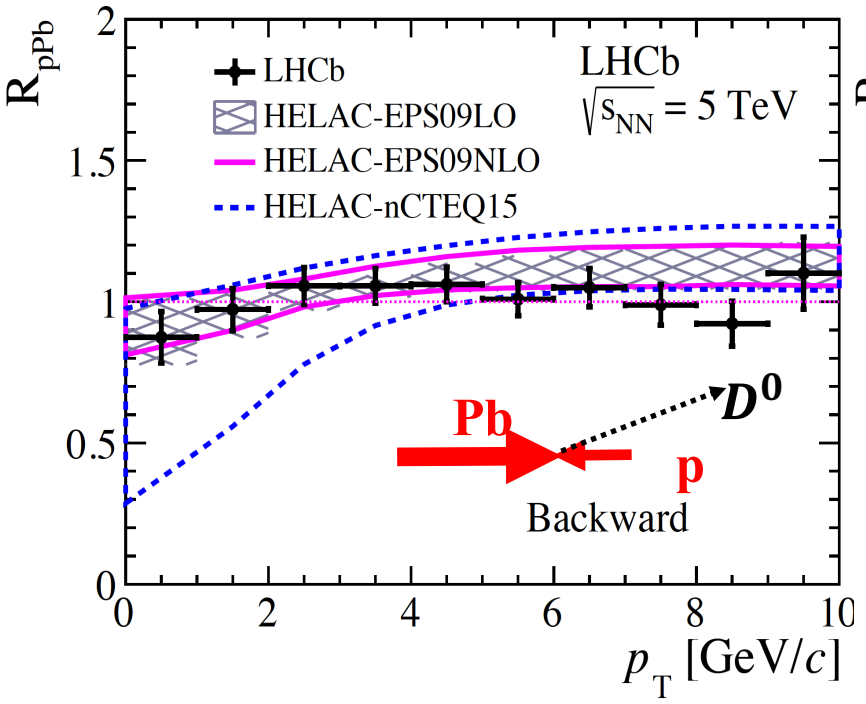
Source	Relative uncertainty (%)	
	Forward	Backward
Correlated between bins		
Invariant mass fits	0.0 – 5.0	0.0 – 5.0
$\log_{10}(\chi^2_{IP}(D^0))$ fits	0.0 – 5.0	0.0 – 5.0
Tracking efficiency	3.0	5.0
PID efficiency	0.6 – 17.0	0.6 – 30.0
Luminosity	1.9	2.1
$\mathcal{B}(D^0 \to K^{\mp}\pi^{\pm})$	1.0	1.0
Uncorrelated between bins		
Simulation sample size	1.0 – 4.0	1.0 – 5.0
Statistical uncertainty	0.5 – 20.0	1.0 – 20.0

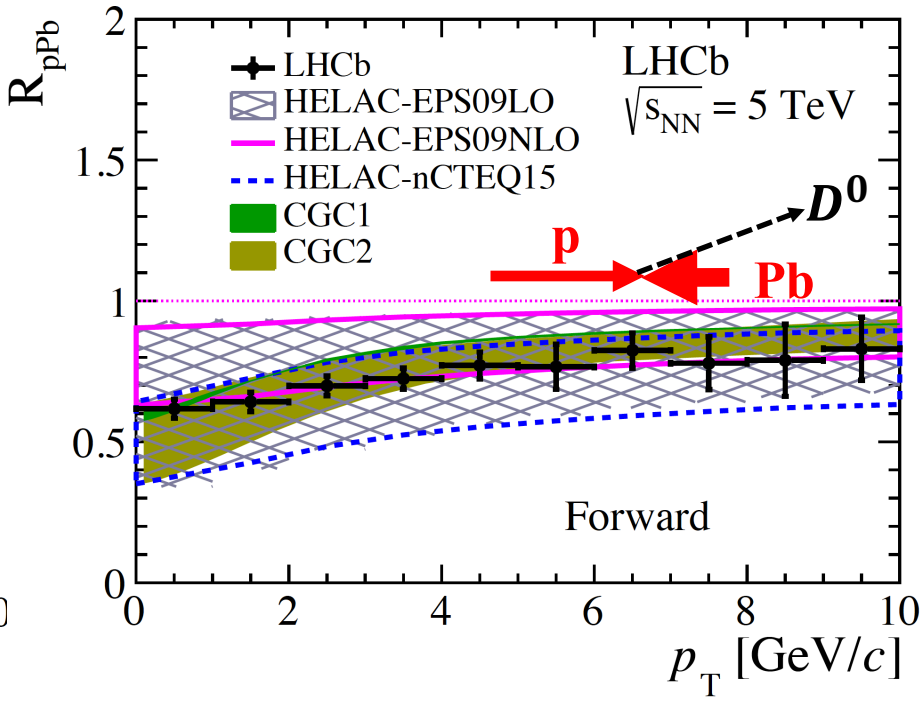
HELAC: EPJ C77 (2017) 1
Production using nPDF

Experimental uncertainties much smaller than theoretical ones, will be further improved with new data

Nuclear modification $R_{p\mathrm{Pb}}$

JHEP 1710 (2017) 090



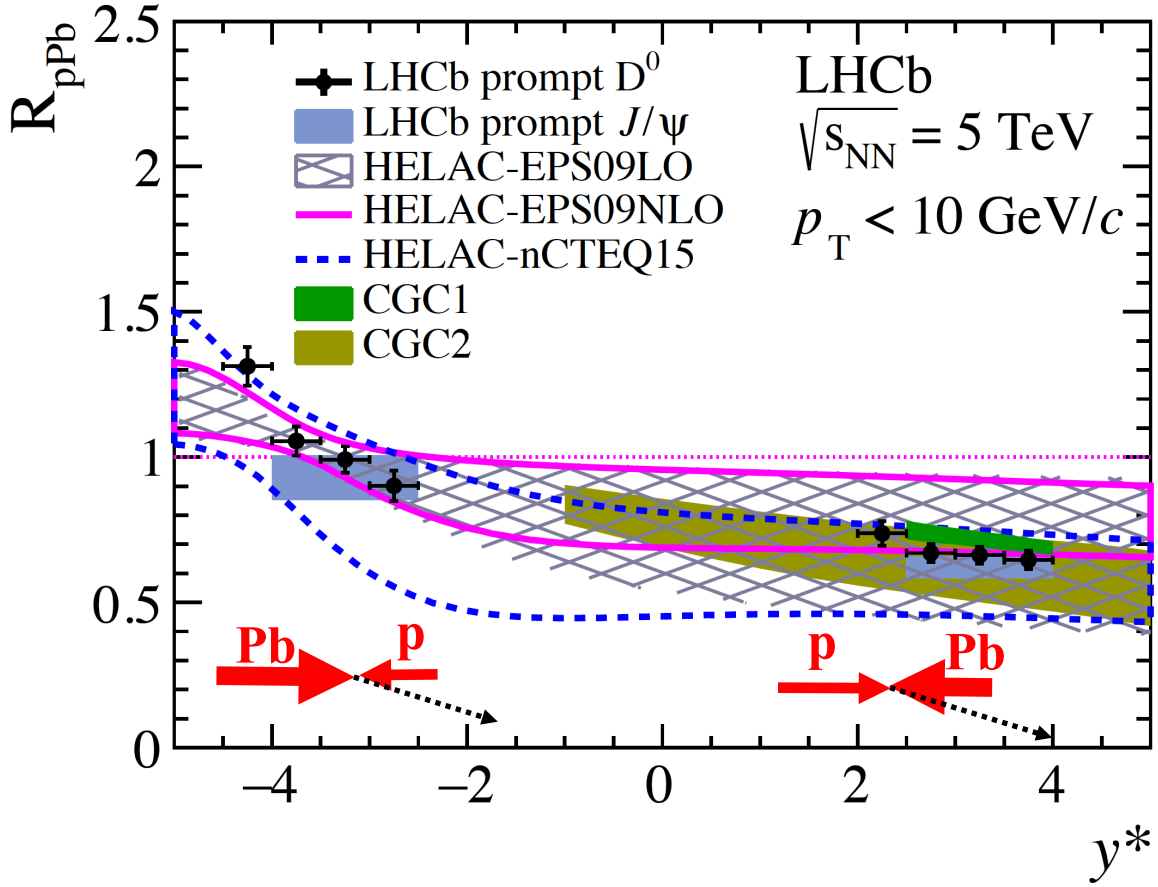


Data agree with theoretical calculations using nPDF or CGC

CGC1: Phys. Rev. D 91 (2015) 114005
CGC2: arXiv:1706.02728

Nuclear modification $R_{p\mathrm{Pb}}$

JHEP 1710 (2017) 090

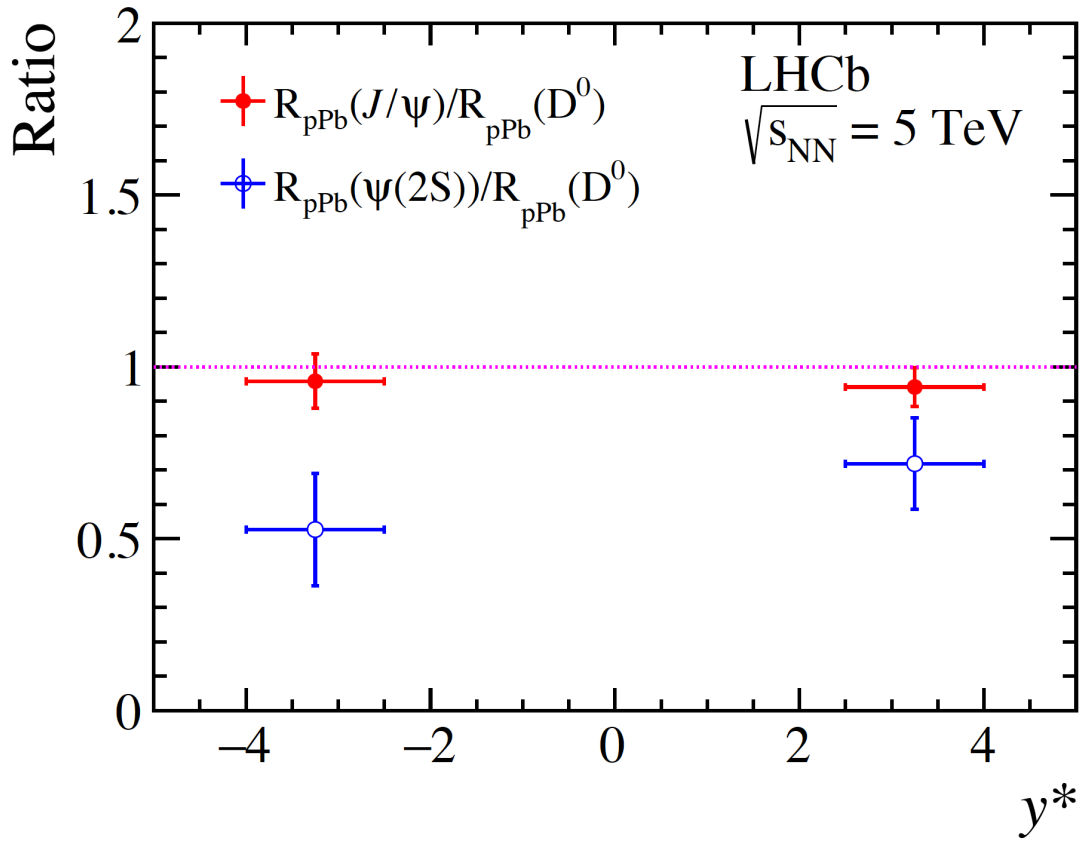


- Data agree with theoretical calculations using nPDF or CGC
- $R_{p\mathrm{Pb}}$ for D^0 and J/ψ are similar

J/ψ in pPb at 5 TeV: JHEP 02 (2014) 072
J/ψ in pPb at 8.16 TeV: PLB 774 (2017) 159

Nuclear modification $R_{p\mathrm{Pb}}$

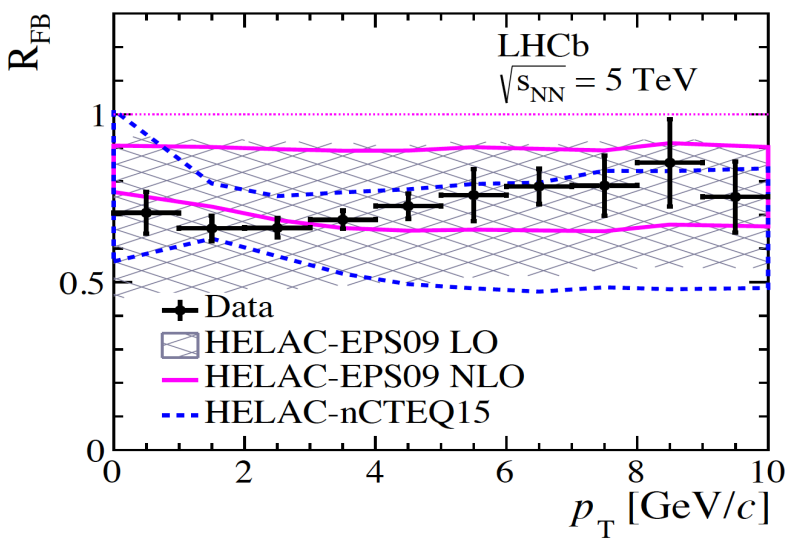
JHEP 1710 (2017) 090

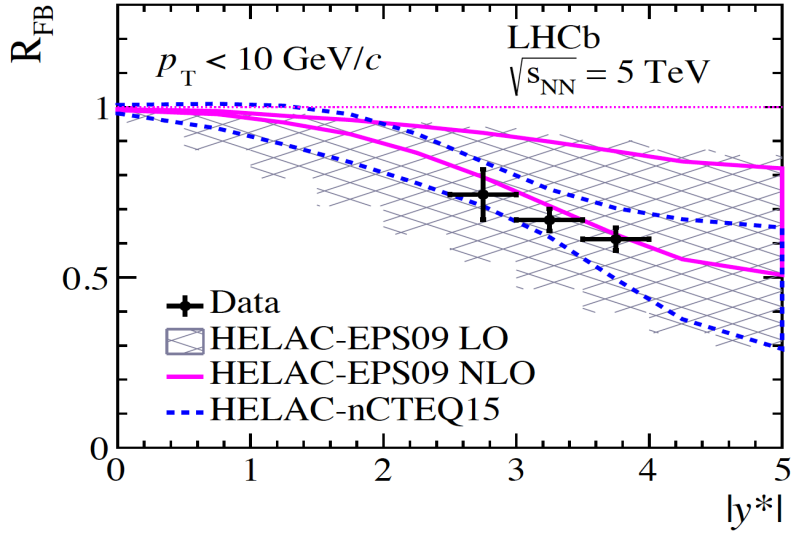


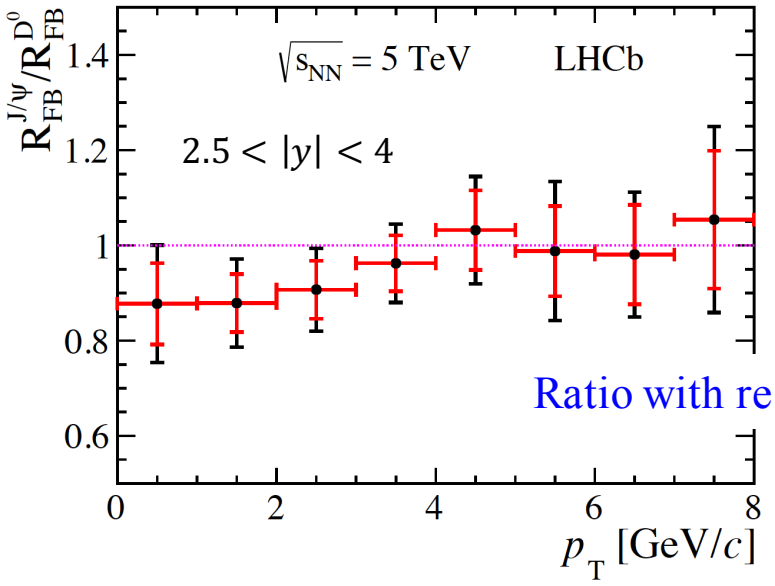
Nuclear modification for D^0 consistent with J/ψ, stronger effect for $\psi(2S)$

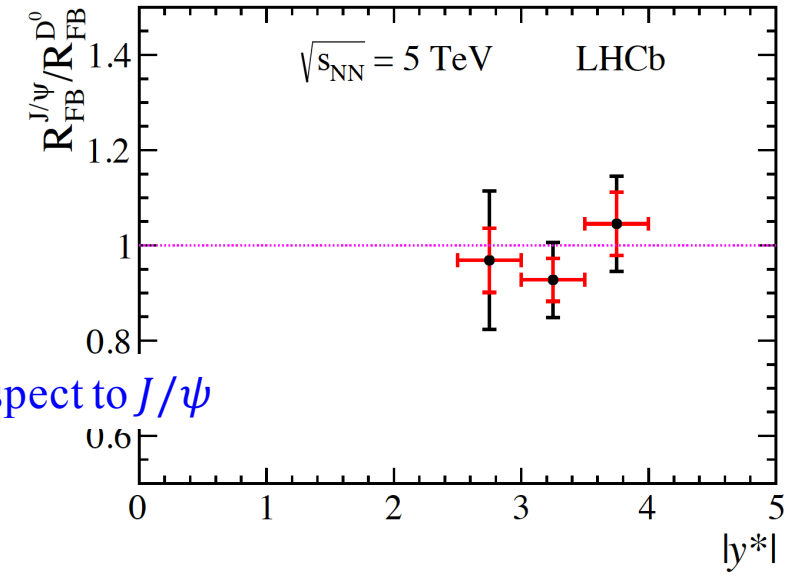
Forward-backward ratio R_{FB}

JHEP 1710 (2017) 090





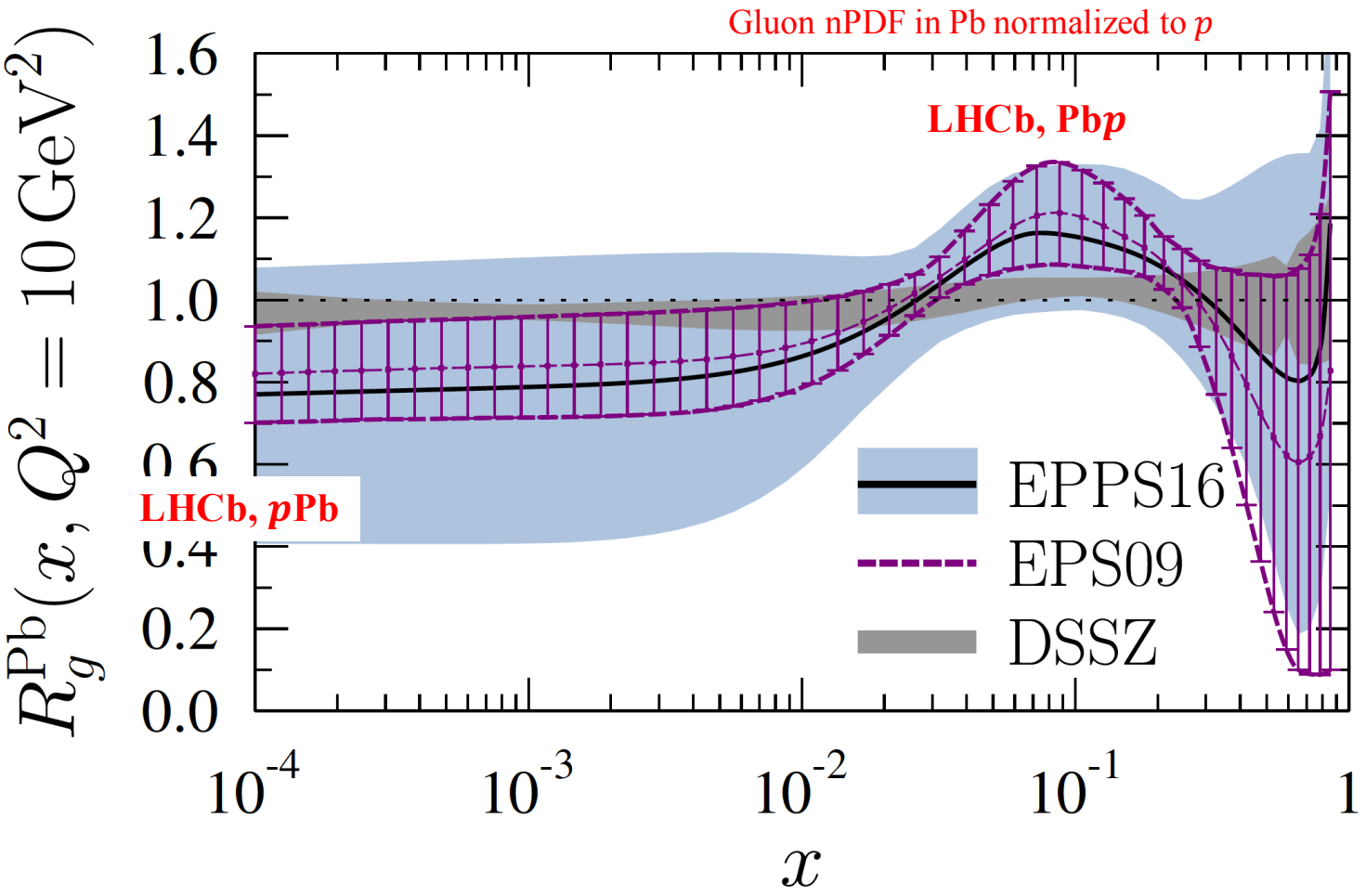




Ratio with respect to J/ψ

Nuclear parton distribution function

- LHCb results help to reduce uncertainty for $x \sim 10^{-5}, 10^{-1}$



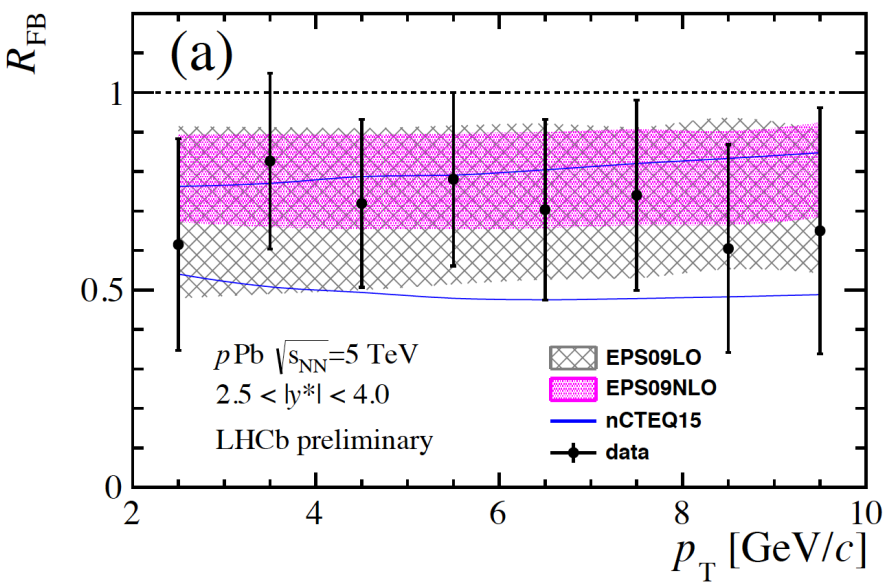
EPJC 77 (2017) 163

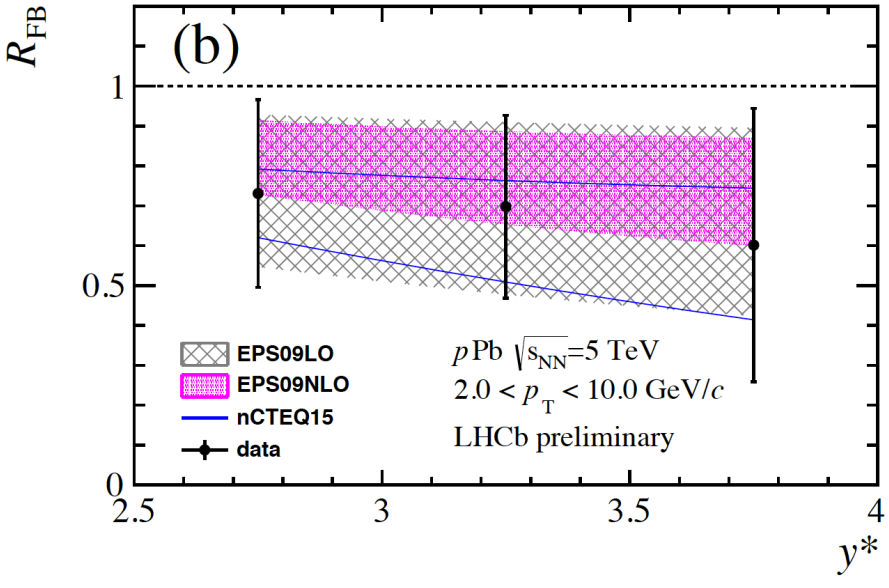
Λ_c^+ production in pPb collisions $\Lambda_c^+ \to pK^-\pi^+$

LHCb-CONF-2017-005

Forward-backward ratio

LHCb-CONF-2017-005

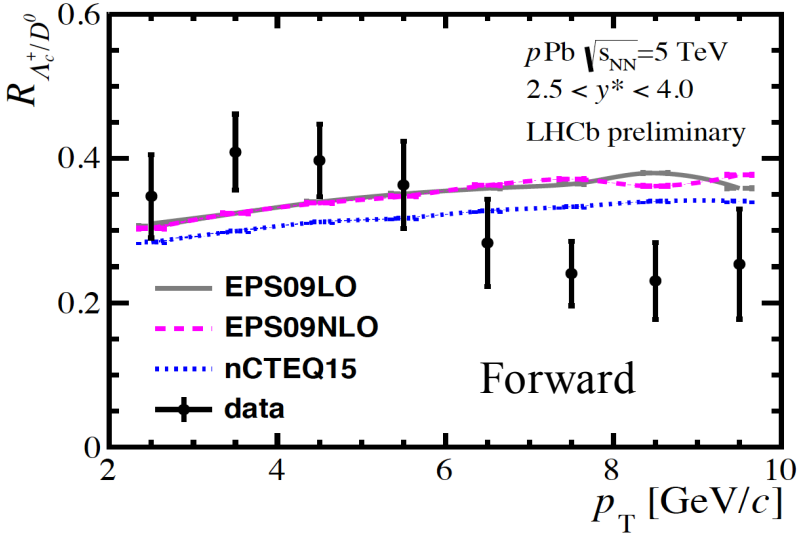


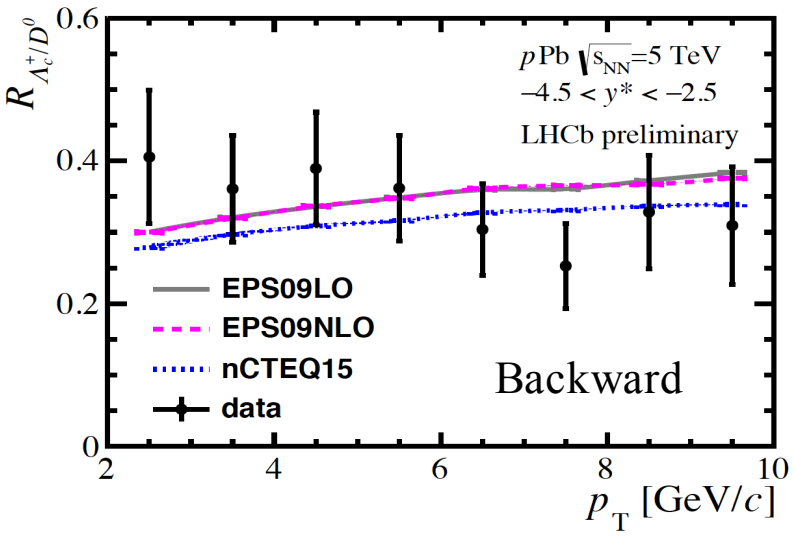


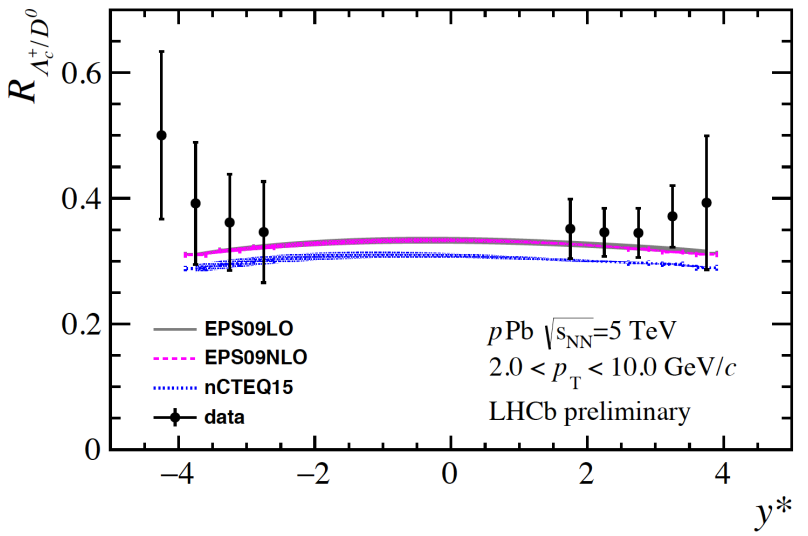
Consistently smaller than one, agree with calculations using nuclear PDF
Size of systematic uncertainties comparable with theory band

Comparison with D^0

LHCb-CONF-2017-005







- Different proton PDFs for HELAC-EPS09 (CT10NLO) and HELAC-nCTEQ15 (CT14NLO) calculations
- nPDF uncertainties ~1%

- Scale agrees with predictions considering nPDF, similar nuclear effects for Λ_c^+ and D^0
- p_T distributions may be different in forward, to be confirmed with more statistics

J/ψ production in pPb collisions

Data:

$\sqrt{s_{NN}} = 8.16$ TeV (2016)

Forward: 13.6 ± 0.3 nb^{-1}

Backward: 20.8 ± 0.5 nb^{-1}

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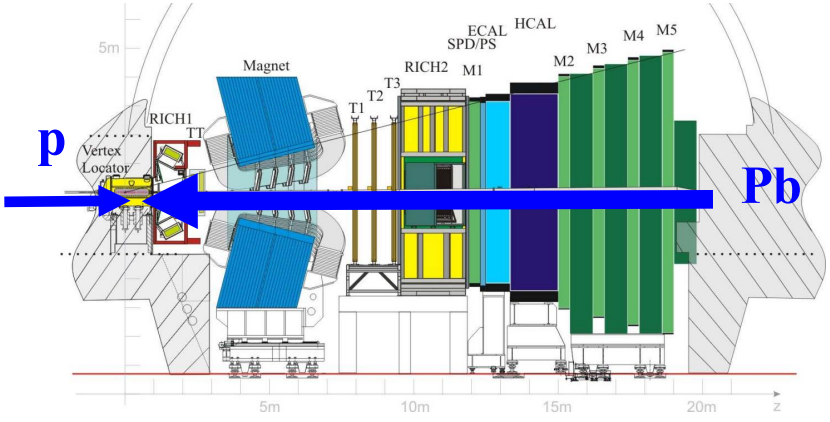

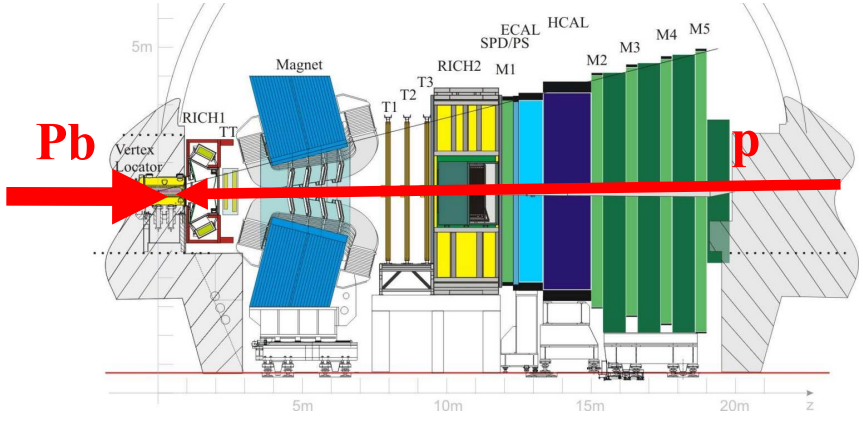

J/ψ production

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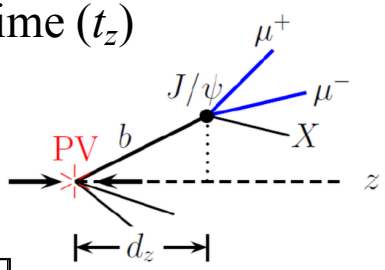
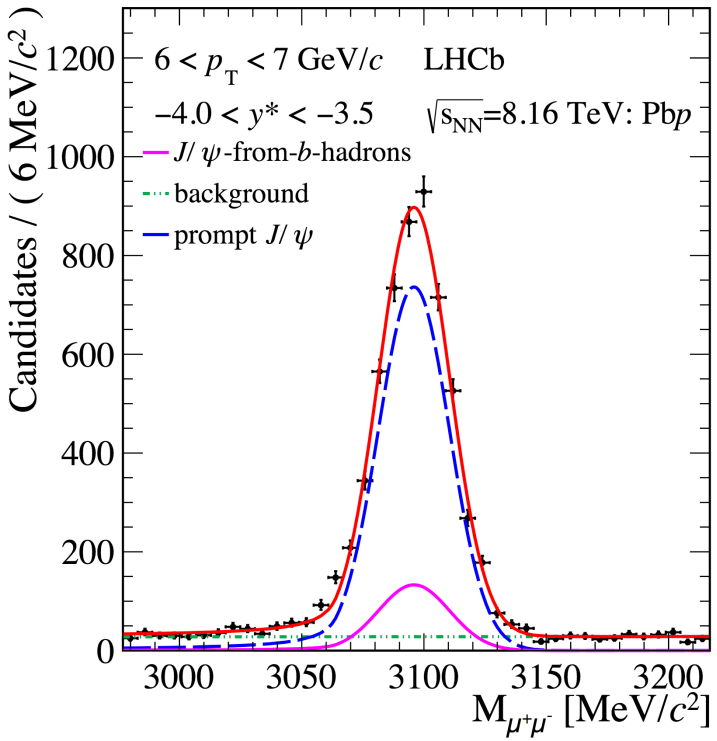
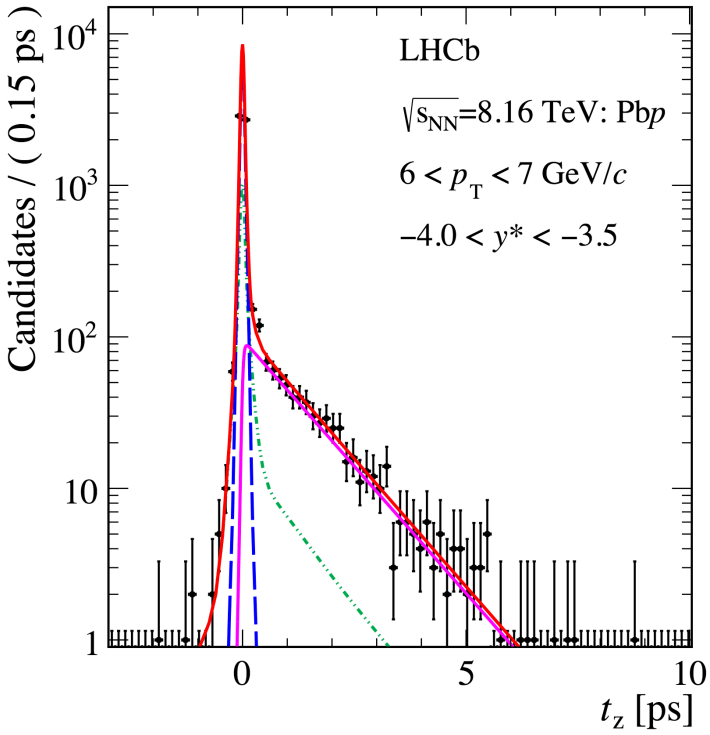
- Candidates fully reconstructed from well identified muons
- Prompt J/ψ and those from b decay separated using pseudo-decay time (t_z)







J/ψ-from-b fraction: f_b

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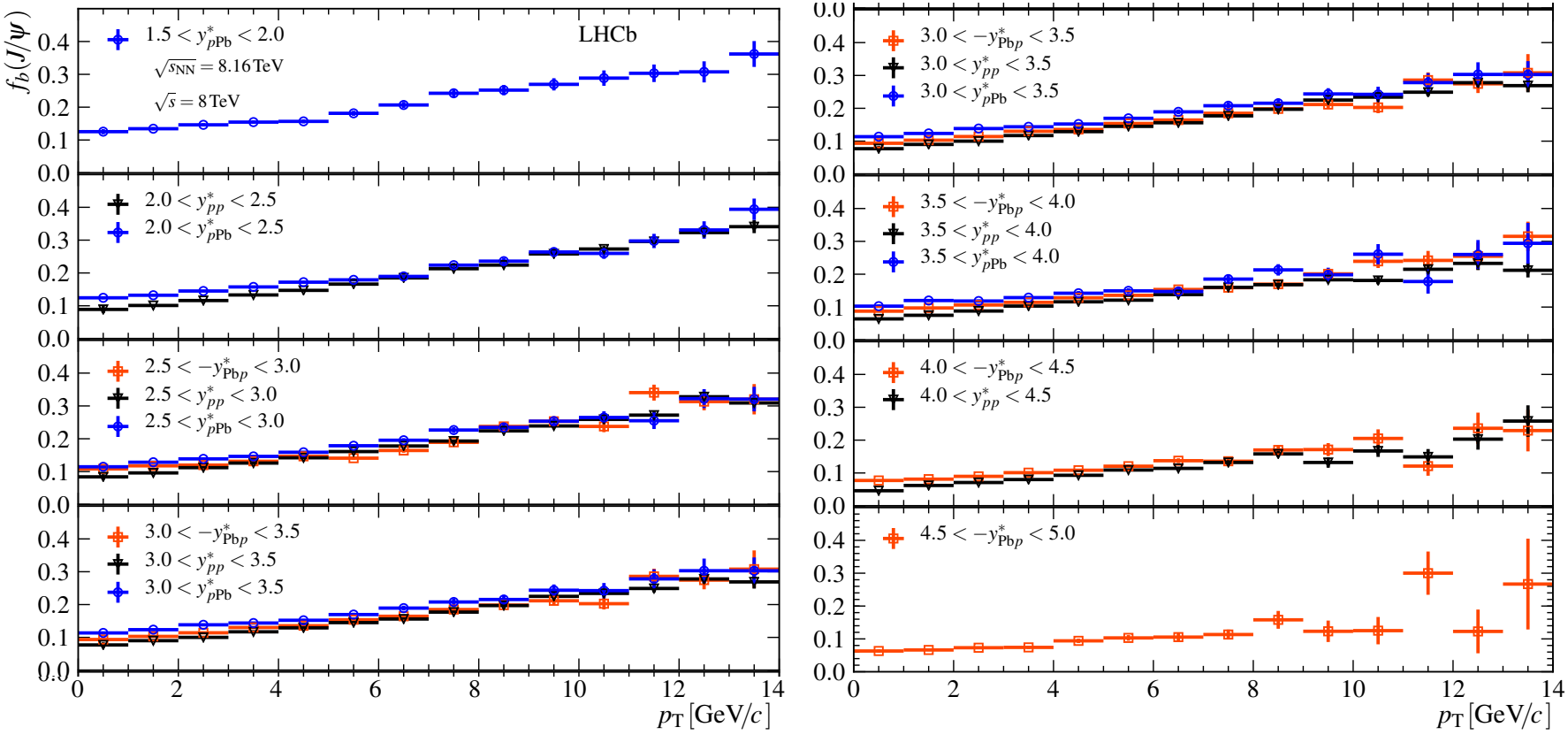
- f_b larger than in pp, prompt J/ψ more suppressed in pPb collisions compared to J/ψ-from-b



Nuclear modification

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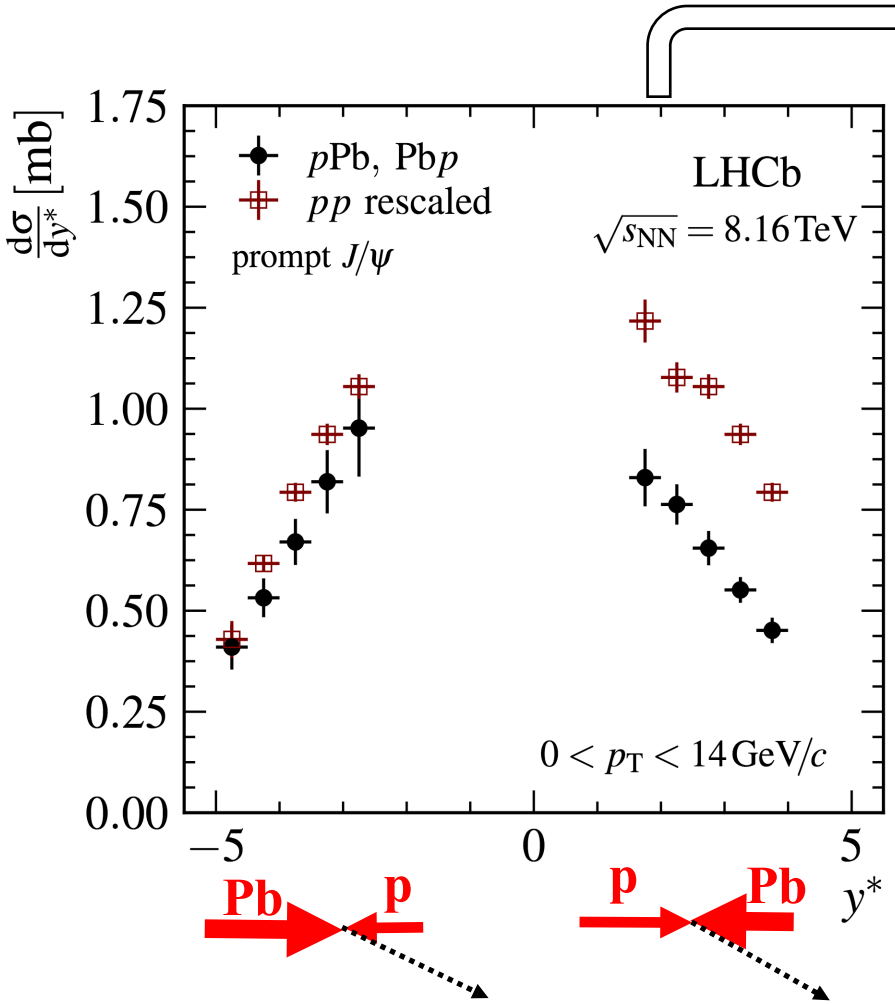
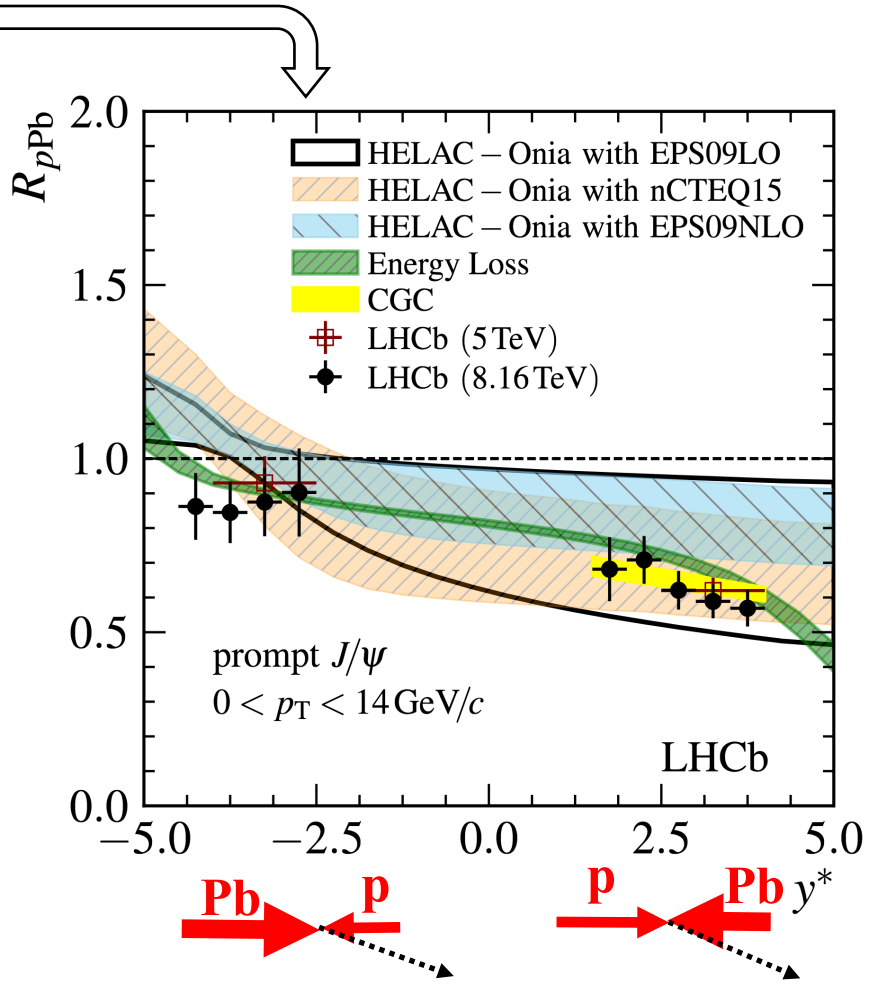
- Prompt J/ψ: modest suppression in backward, strong suppression in forward





Nuclear modification

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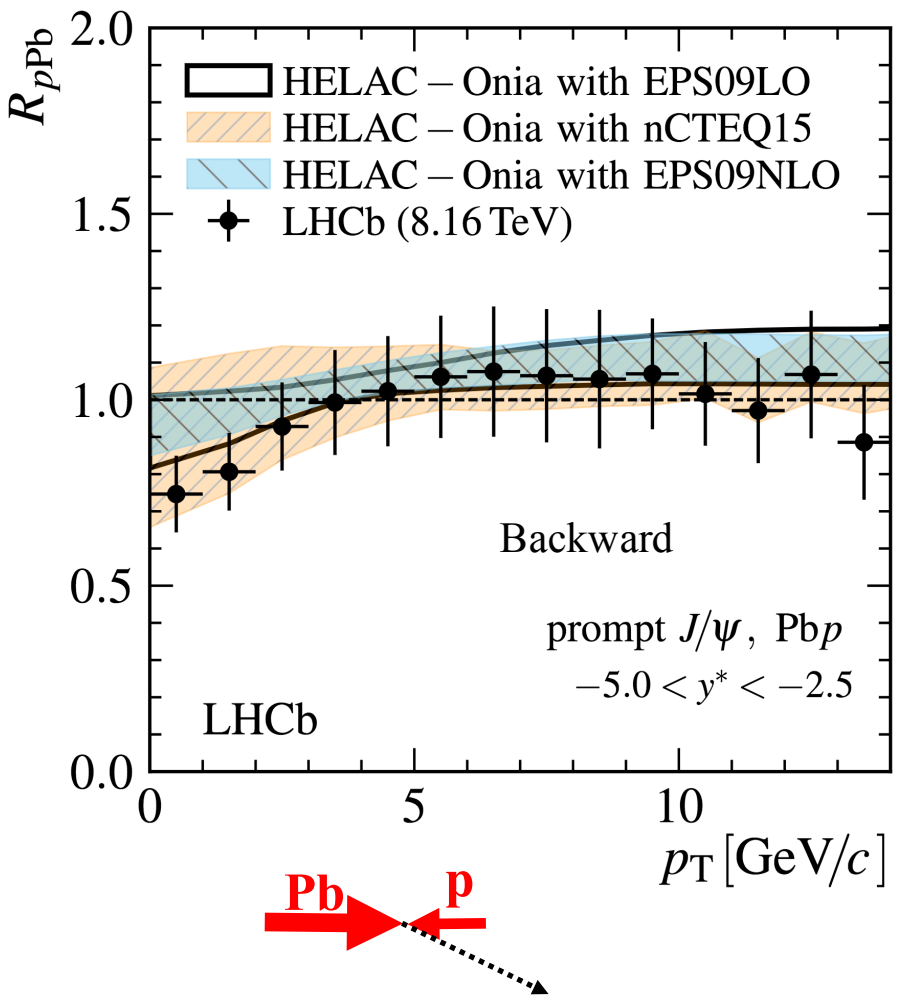
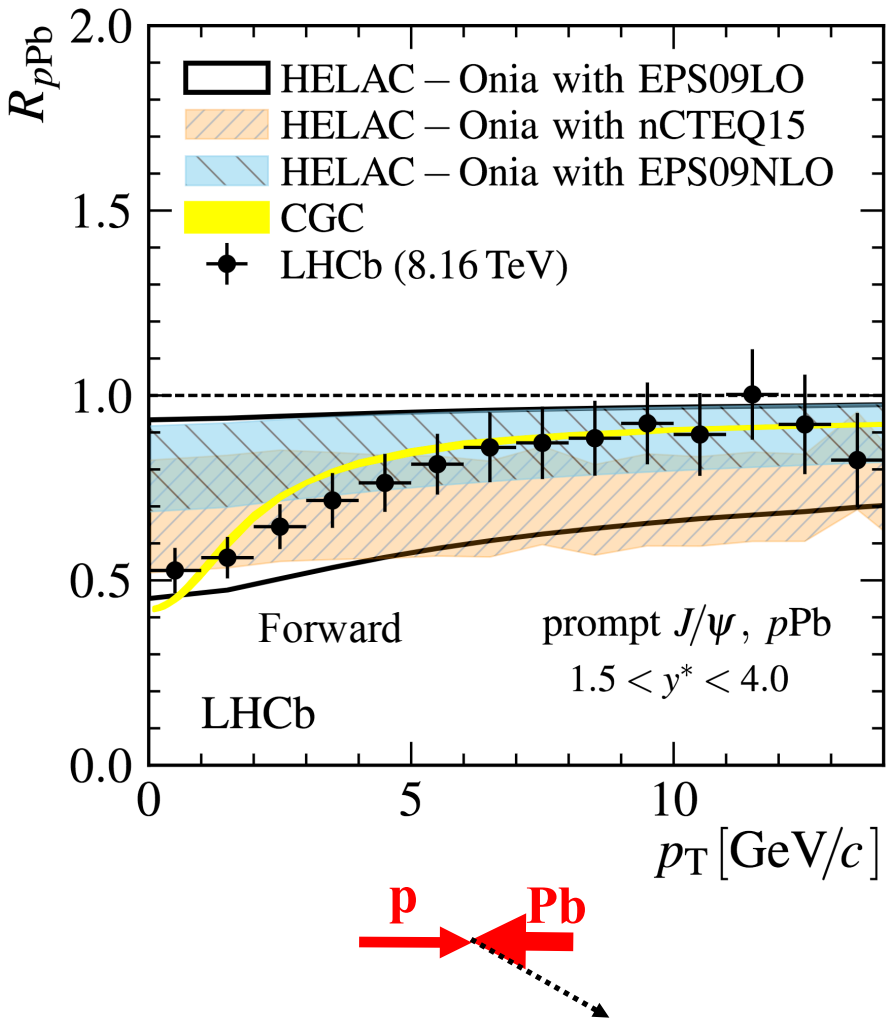
- Prompt J/ψ: $R_{p\mathrm{Pb}}$ increases with p_{T}, strong suppression at low p_{T}

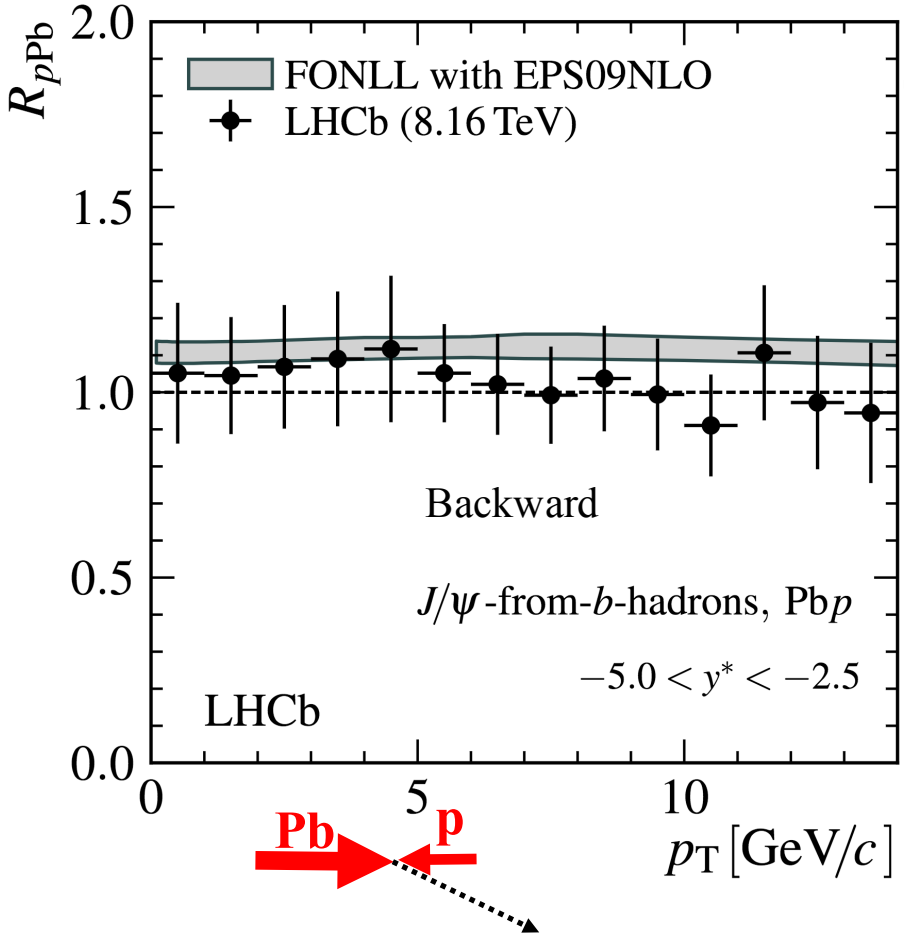


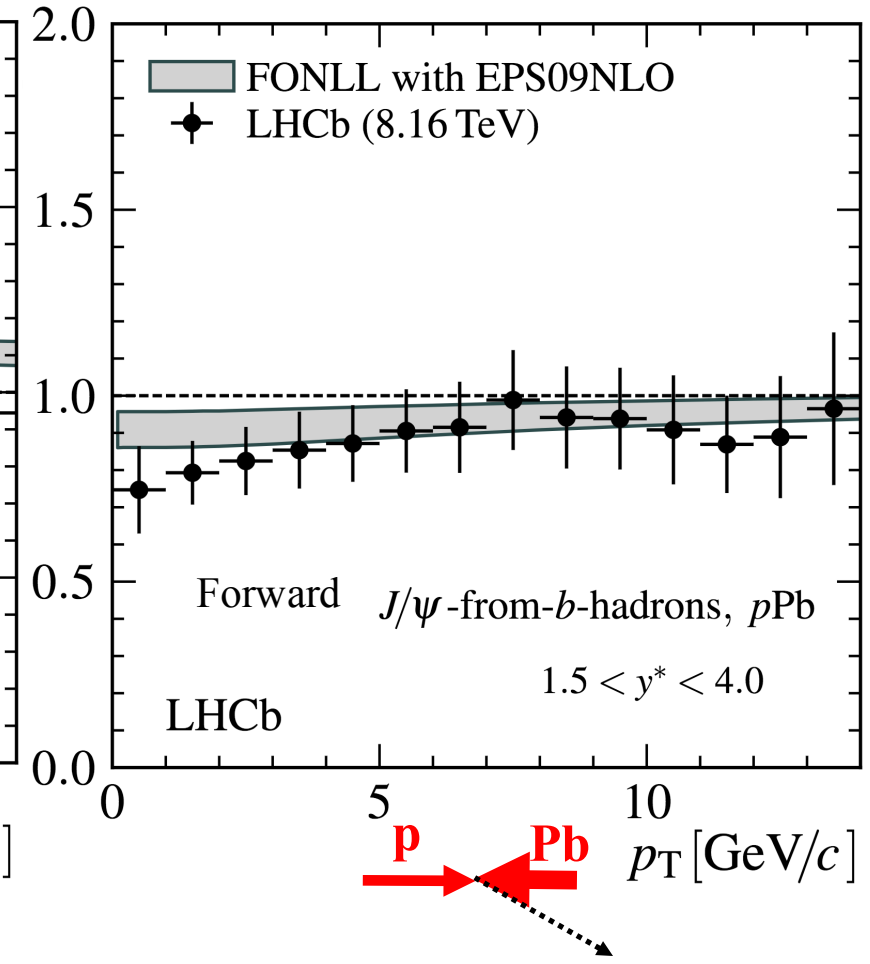


Nuclear modification

PLB 774 (2017) 159

- J/ψ from b: $R_{p\mathrm{Pb}}$ slight increases with p_T in forward, consistent with being flat in backward. Suppressed in forward especially at low p_{T}





Forward-backward ratio

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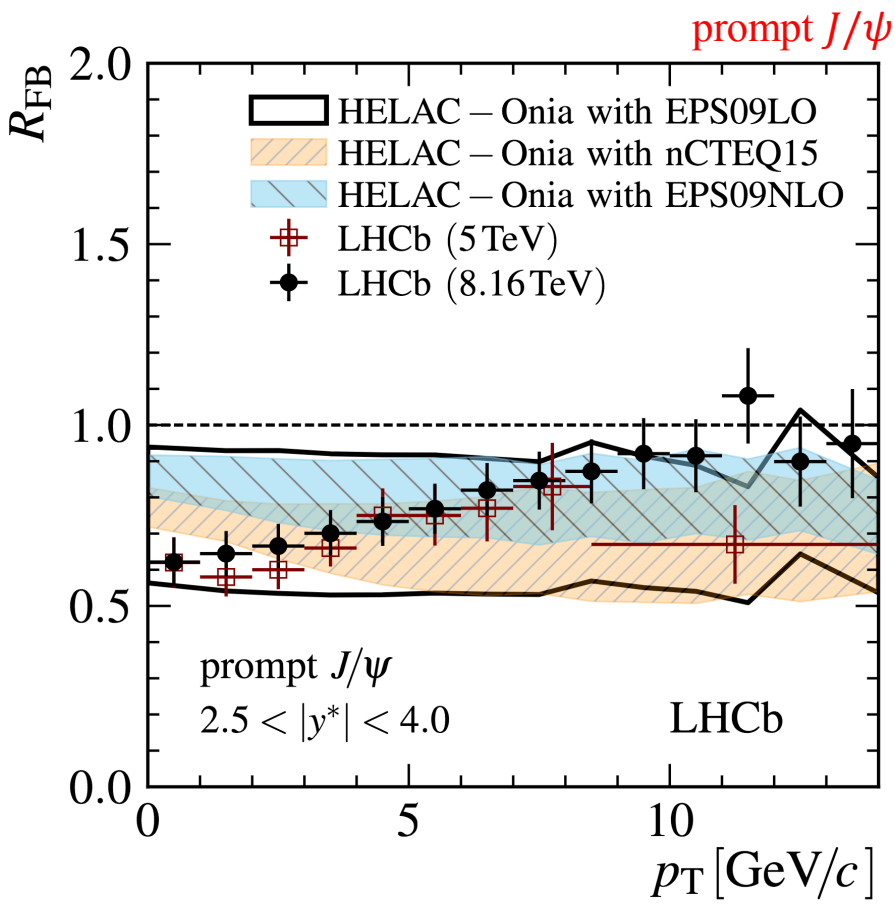
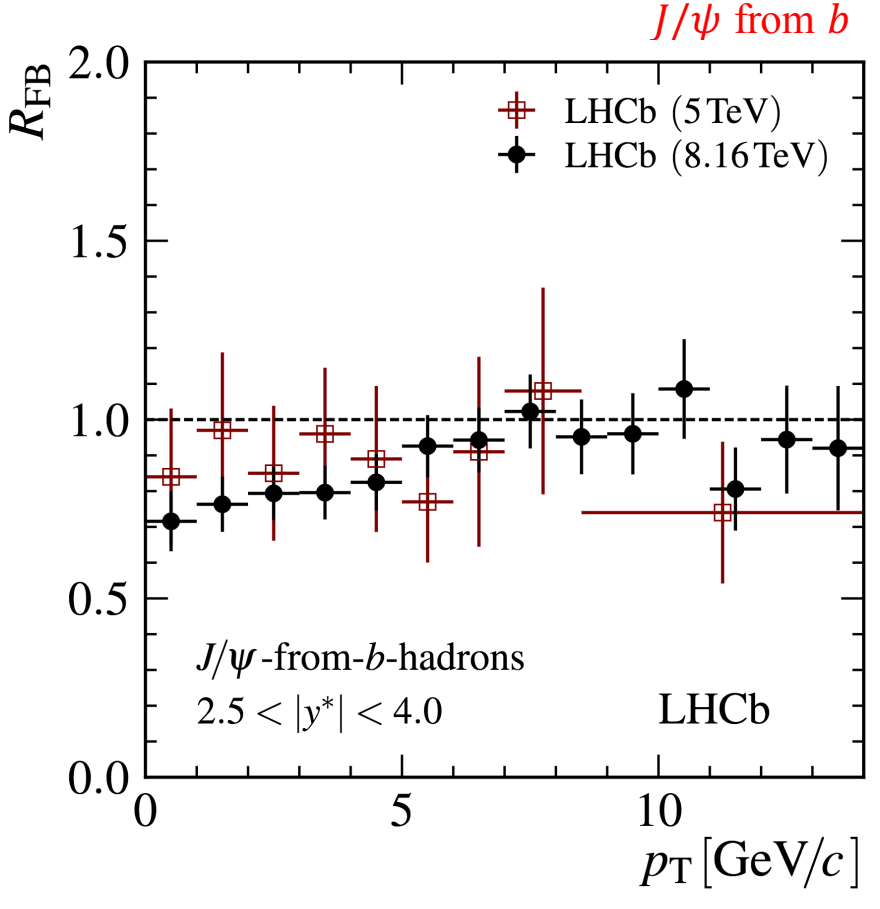
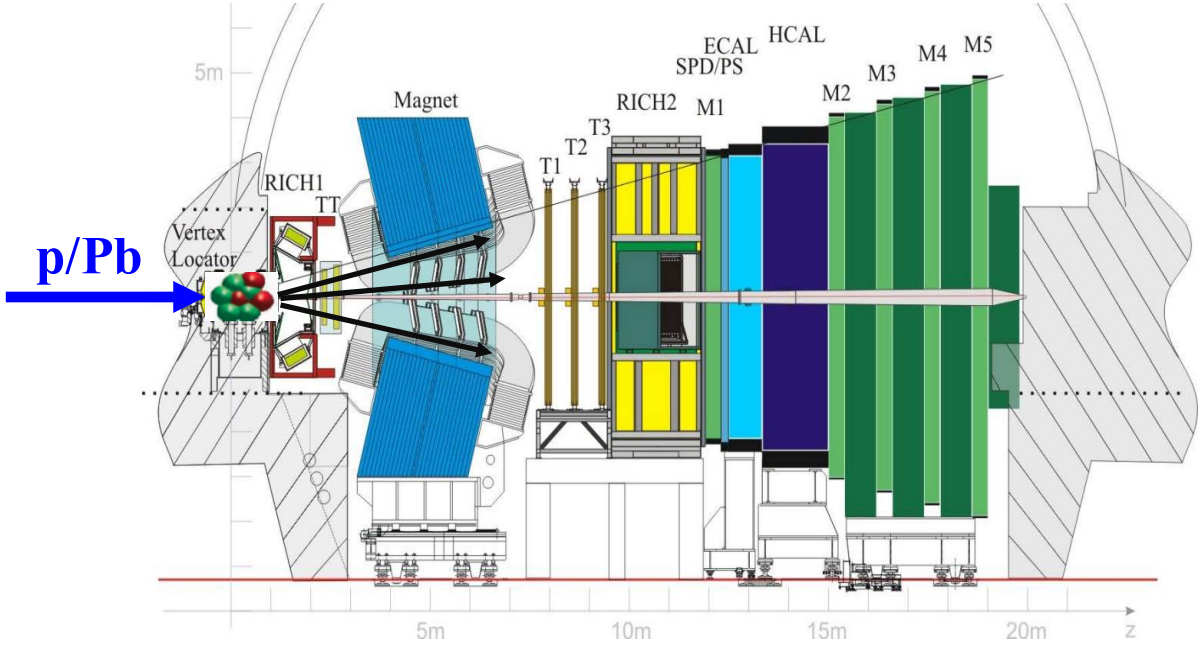
- $R_{\rm FB}$ smaller than unity especially at low $p_{\rm T}$, increasing with $p_{\rm T}$
- No evidence of energy dependence





Productions in fixed-target collisions

LHCb-CONF-2017-001

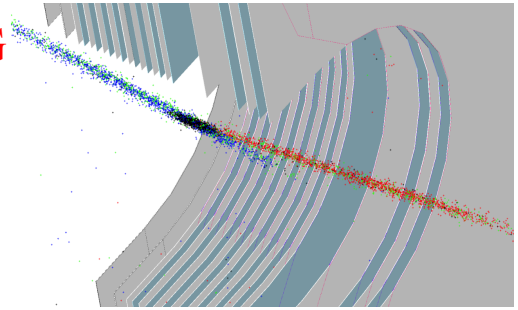


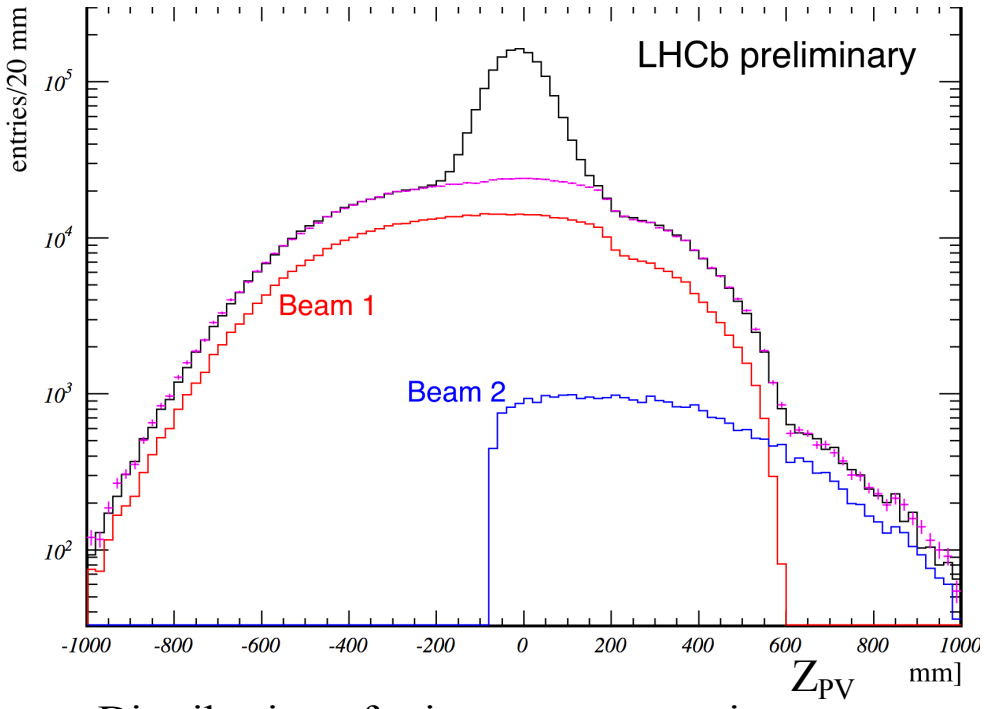
Fixed targets setup

JINST 9 P12005

- Fixed-target beam configuration implements the SMOG

  System for Measuring the Overlap with Gas
  - ➢ Primarily for high precision luminosity measurements
  - ➢ Injection of noble gas into interaction region
  - ➢ Allows to study p or Pb-Gas collisions at different $\sqrt{s_{NN}}$





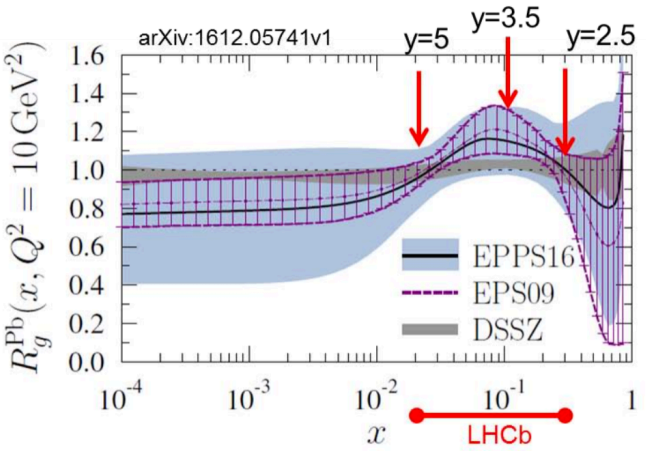
Distribution of primary vertex positon

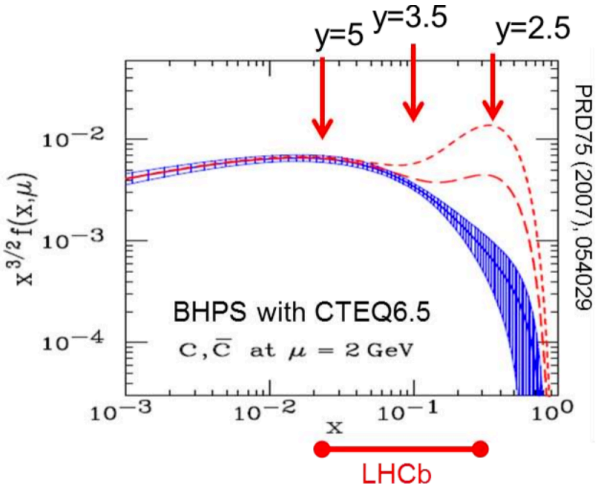
LHCb-CONF-2012-034

Beam 1 only
Beam 2 only
Weighted sum
All collisions

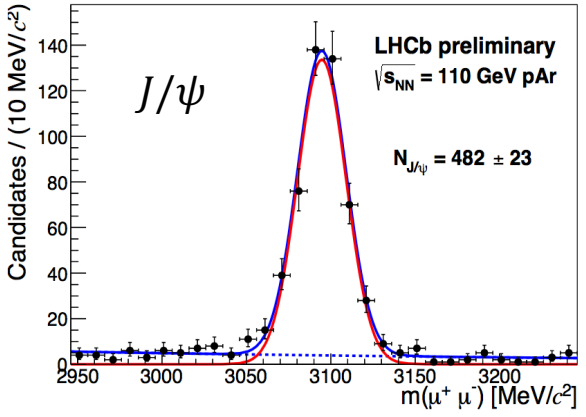
J/ψ and D^0 production in pAr LHCb-CONF-2017-001

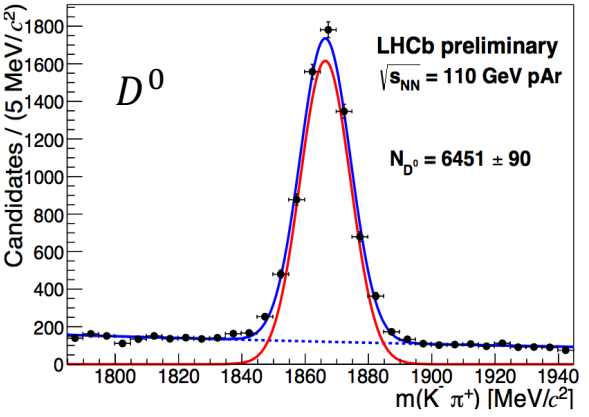
- Productions in SMOG at LHCb probe nuclear PDF especially the anti-shadowing region (large x), also sensitive to intrinsic charm





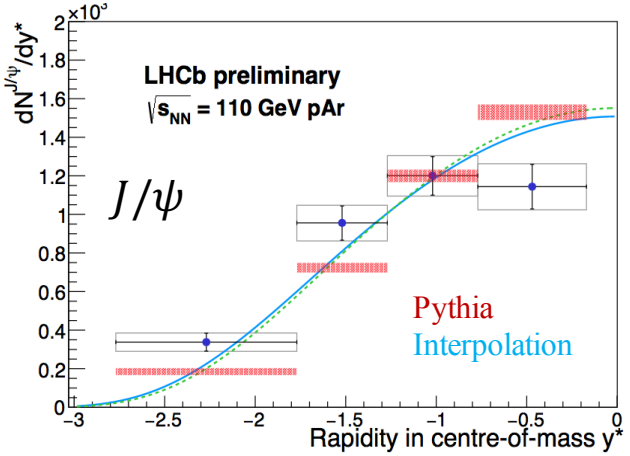
- Clean signal peaks

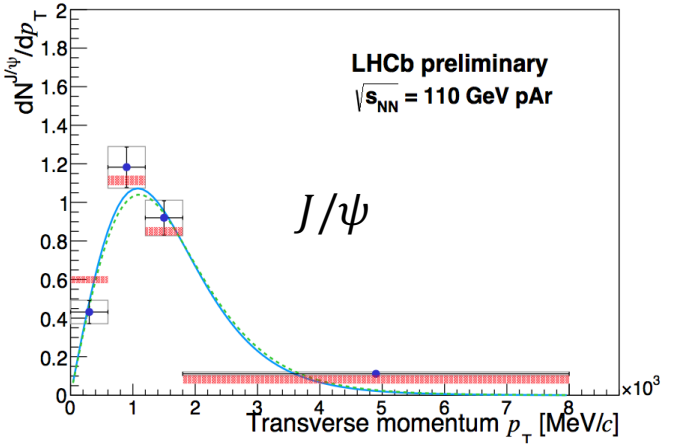




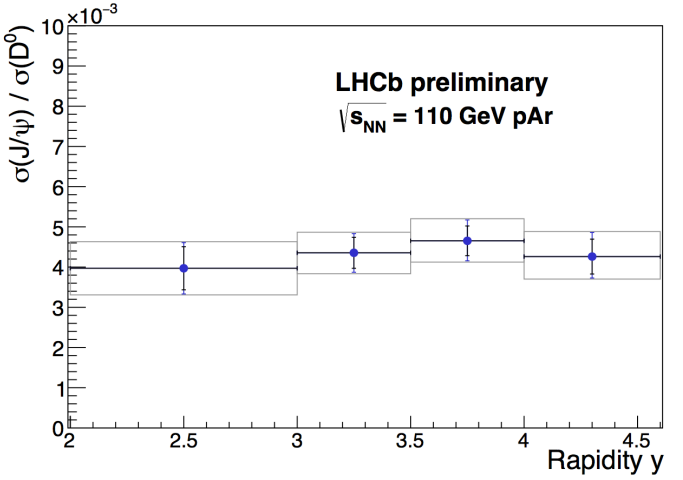
J/ψ and D^0 production in pAr LHCb-CONF-2017-001

- Luminosity not available yet, only kinematic distributions and cross-section ratios
- p_T and rapidity distributions compatible with Pythia 8 and interpolations from pC (HERA-B 41.5 GeV) and pp (PHENIX, 200 GeV)

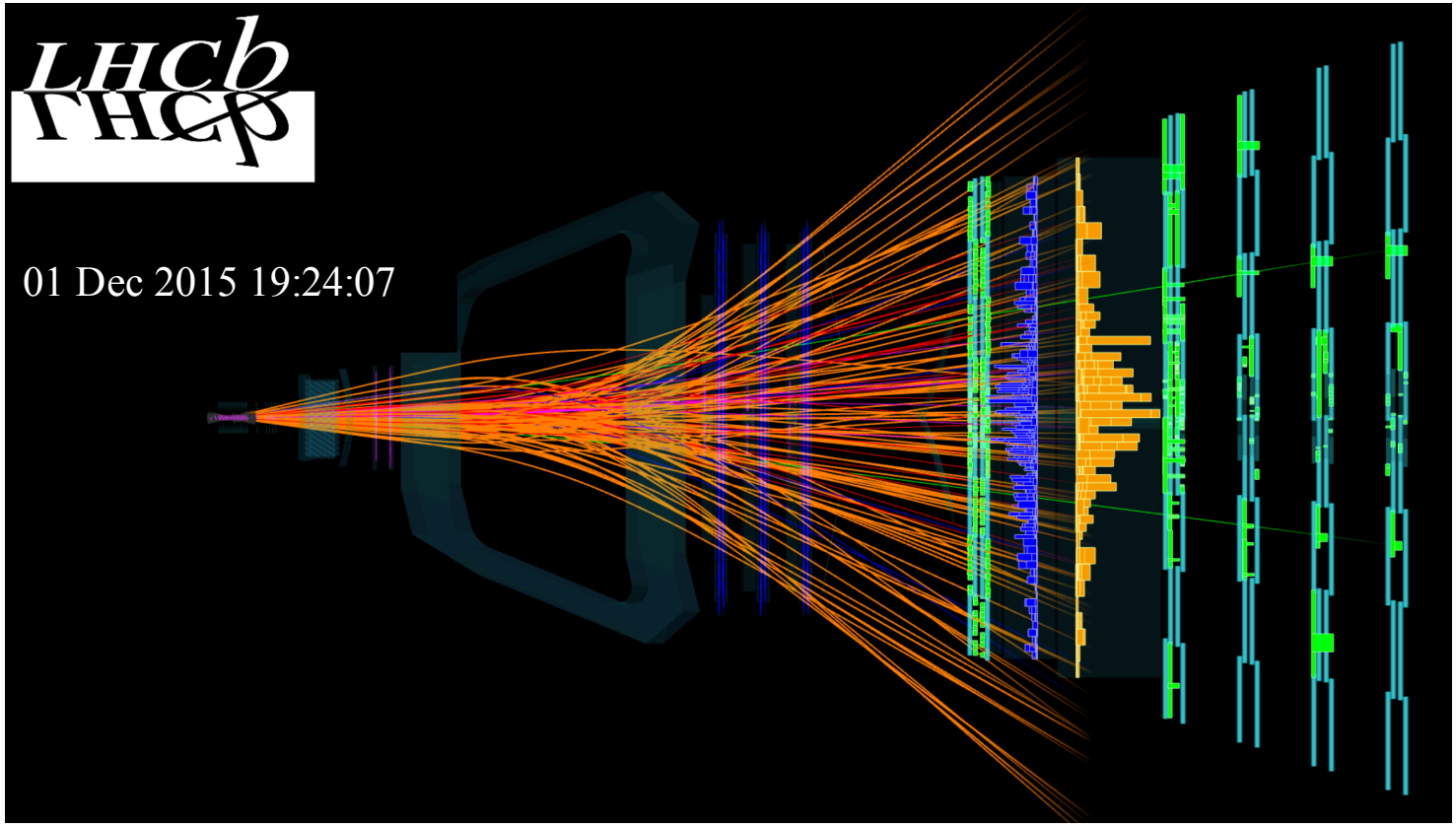




- $J/\psi, D^0$ cross-section ratio flat with rapidity



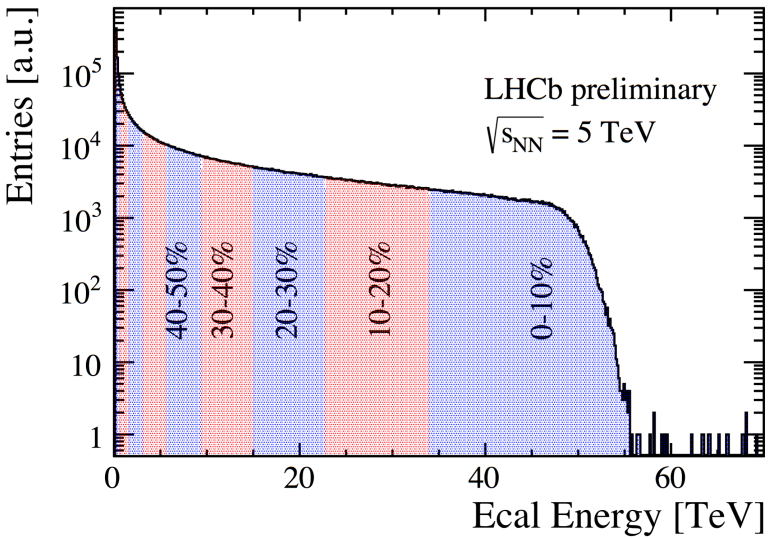
PbPb collisions at LHCb

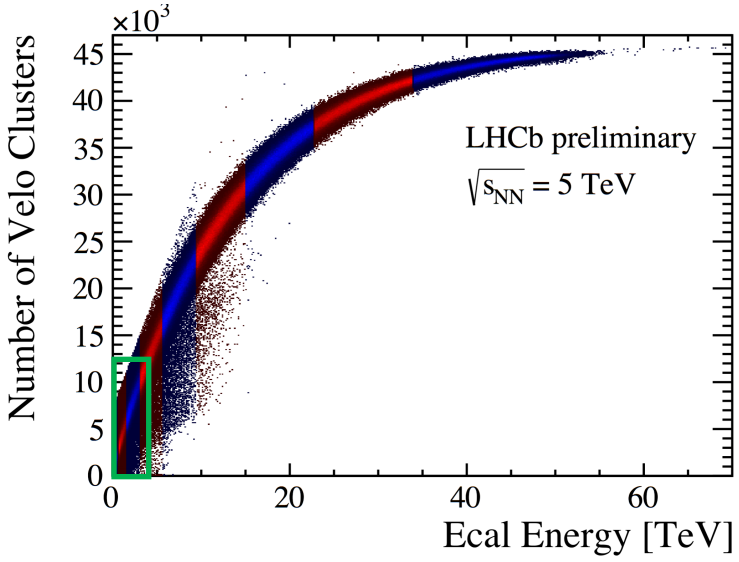


Display of one reconstructed PbPb event

Centrality coverage at LHCb

- LHCb is optimized for low multiplicity events, challenging for high occupancy
- Event activity measurements: counting energy deposited in calorimeters, not saturated even at large multiplicities



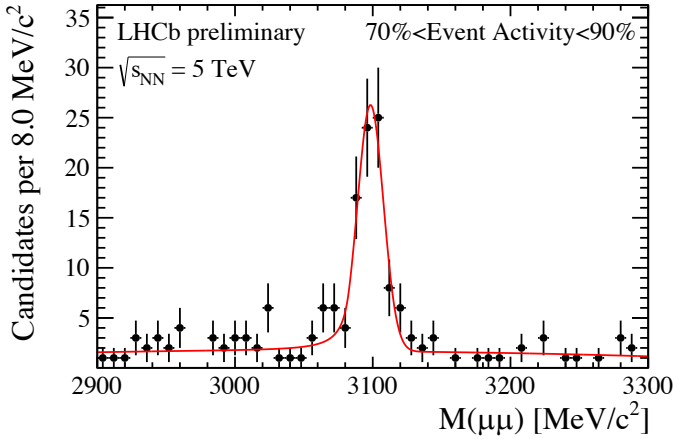


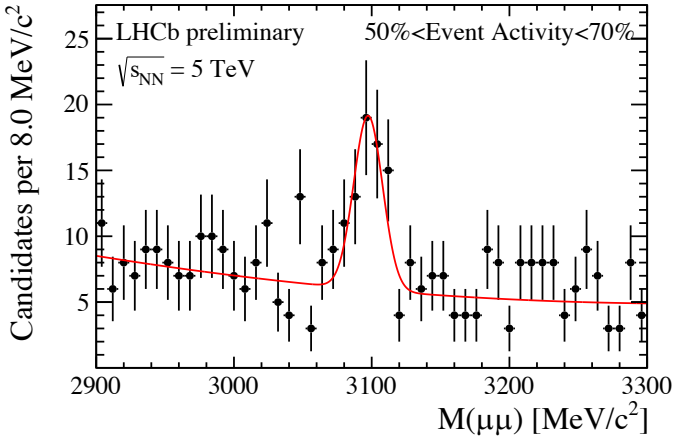
- VELO detector (tracking) saturates at ~10K hits → 50% event activity class

J/ψ and D^0 signals in PbPb collisions

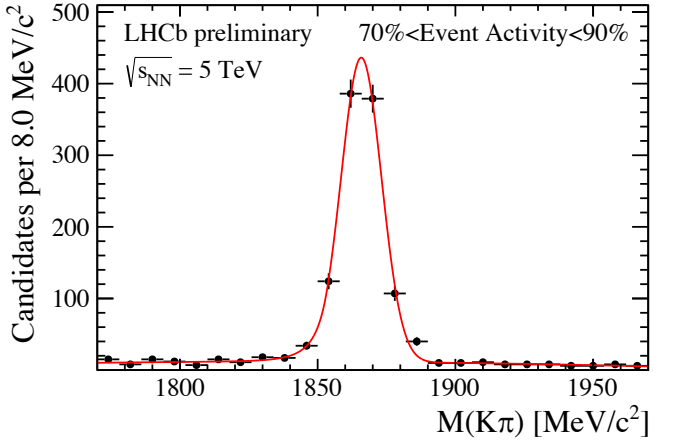
$J/\psi \to \mu^+\mu^-$

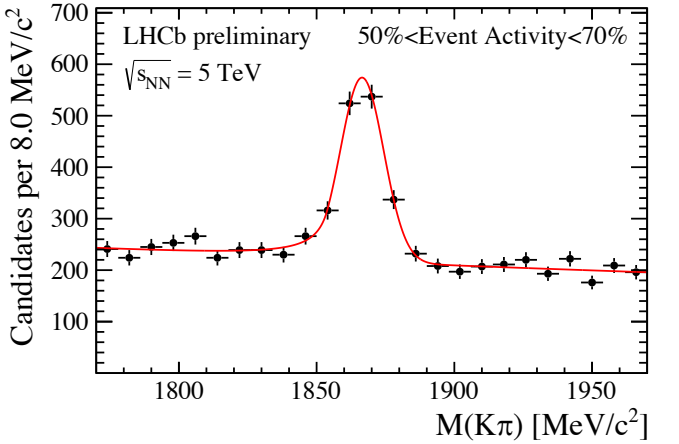
Full statistics





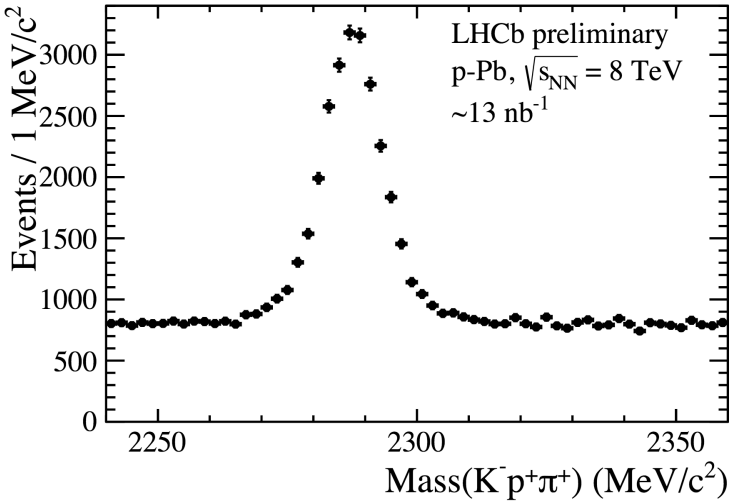
$D^0 \to K^-\pi^+$

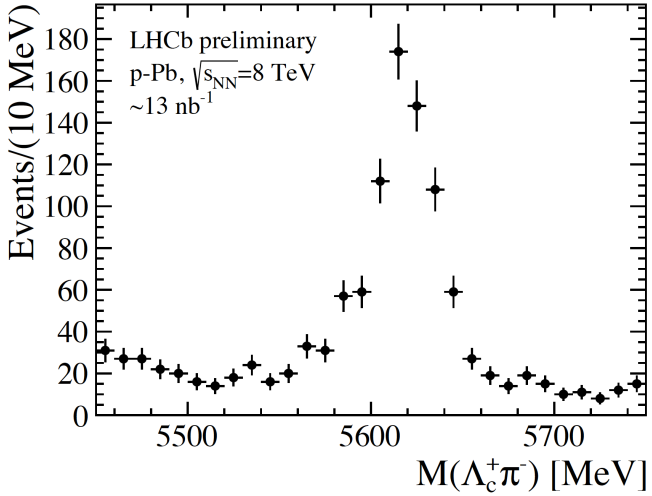


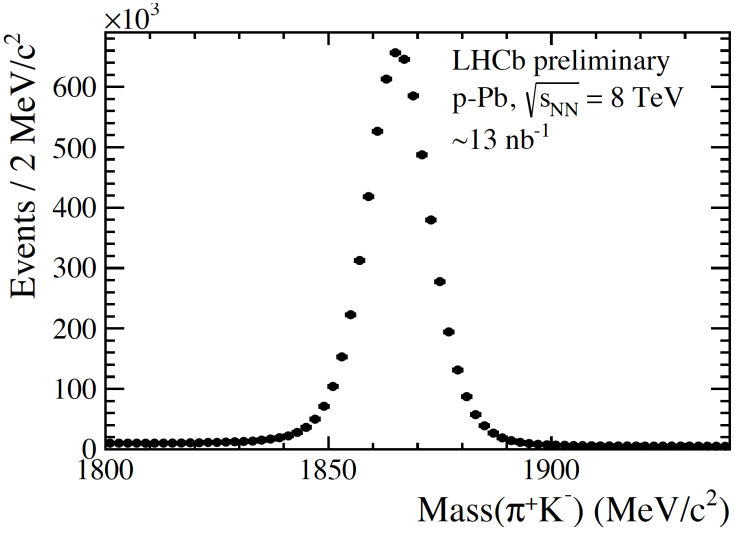


Prospects

*p*Pb 2016 ($\mathcal{L}$~13/21 nb^{-1})







Charm, Double-charm, Beauty, $\psi(2S)$, χ_c, $\Upsilon(n\mathrm{S})$, DY, W/Z ...

More SMOG data are being analyzed

Summary

- LHCb contributes to heavy ion studies, unique (forward) kinematic range
- Precise measurements of charm cross-sections in pPb collisions at 5 TeV
  - Strong cold nuclear effects observed
  - Helping to constrain nPDF
- Precise measurement of J/ψ productios in pPb collisions at 8.16 TeV
  - For both prompt J/ψ and J/ψ from b decay
- More analyses with pPb data being performed, results coming out soon
- LHCb unique for SMOG fixed-target collisions

Thank you for your attention

Additional material

LHCb experiment

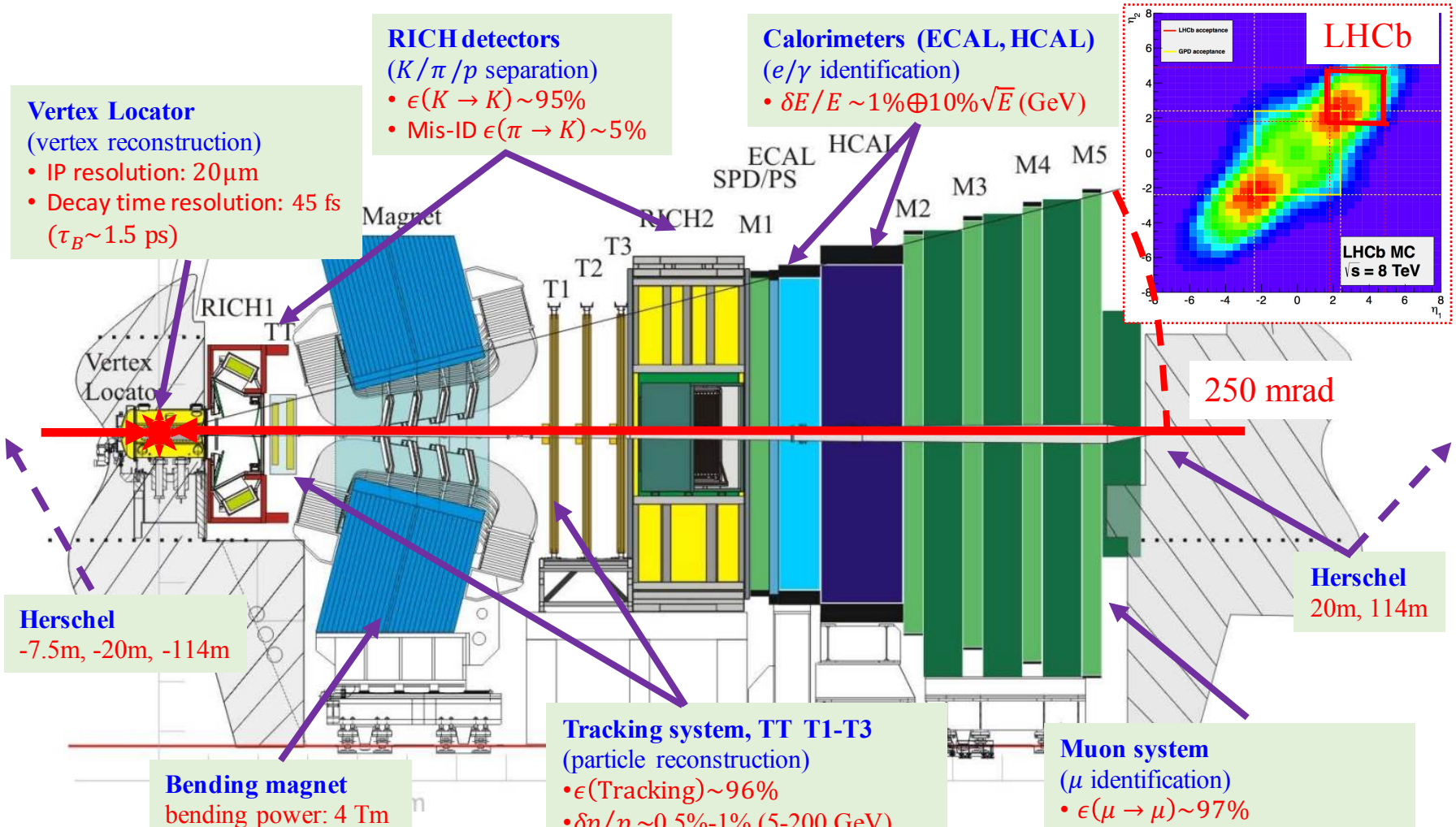
Aiming for precision measurements in b, c sectors

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

Vertex Locator
(vertex reconstruction)
- IP resolution: 20μm
- Decay time resolution: 45 fs (τ_B~1.5 ps)

RICH detectors
($K/\pi/p$ separation)
- $\epsilon(K \to K)$~95%
- Mis-ID $\epsilon(\pi \to K)$~5%

Calorimeters (ECAL, HCAL)
(e/γ identification)
- $\delta E/E$ ~1%⊕10%$\sqrt{E}$ (GeV)



Herschel
-7.5m, -20m, -114m

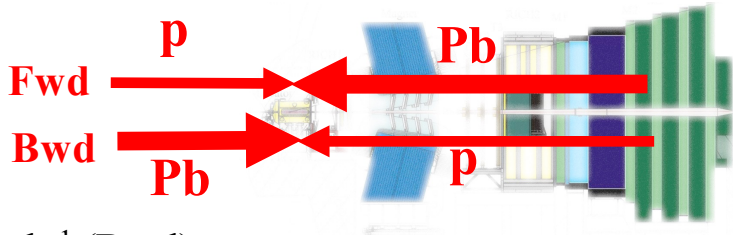
Herschel
20m, 114m

Bending magnet
bending power: 4 Tm

Tracking system, TT T1-T3
(particle reconstruction)
- ϵ(Tracking)~96%
- $\delta p/p$ ~0.5%-1% (5-200 GeV)
- $\sigma(m_{B\to hh}) \approx 22$ MeV

Muon system
(μ identification)
- $\epsilon(\mu \to \mu)$~97%
- Mis-ID $\epsilon(\mu \to \mu)$~1 − 3%

The data samples



- p-Pb collisions
  - $\sqrt{s_{NN}}$ = 5 .02TeV (2013): 1.06 nb^{-1} (Fwd) + 0.52 nb^{-1} (Bwd), MB trigger
  - $\sqrt{s_{NN}}$ = 5 .02TeV (2016): 0.6 nb^{-1} (Fwd), charm hadron/muon triggers
  - $\sqrt{s_{NN}}$ = 8.16 TeV (2016): 13.6 nb^{-1} (Fwd) + 20.8 nb^{-1} (Bwd), 10^{9} MB + physics triggers
- PbPb collisions
  - $\sqrt{s_{NN}}$ = 5 TeV (2015): 0.4 μb^{-1}, MB trigger
- SMOG (fixed target) runs

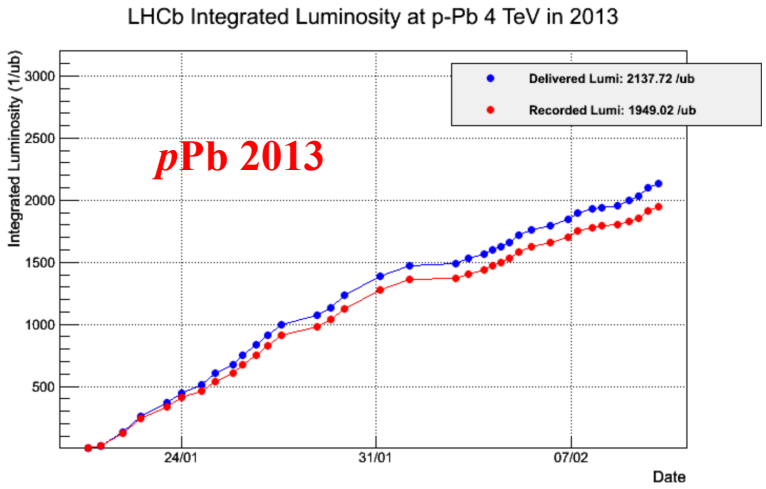
Projectile	Target	$\sqrt{s_{NN}}$ /GeV (p/Pb on target, E21)
p	He	110 (2.4x), 110 (2.7x), 87 (40x)
	Ne	87 (pilot), 110 (0.9x)
	Ar	110 (39X), 69 (0.2x)
Pb	Ne	55 (pilot)
	Ar	69 (0.2x)

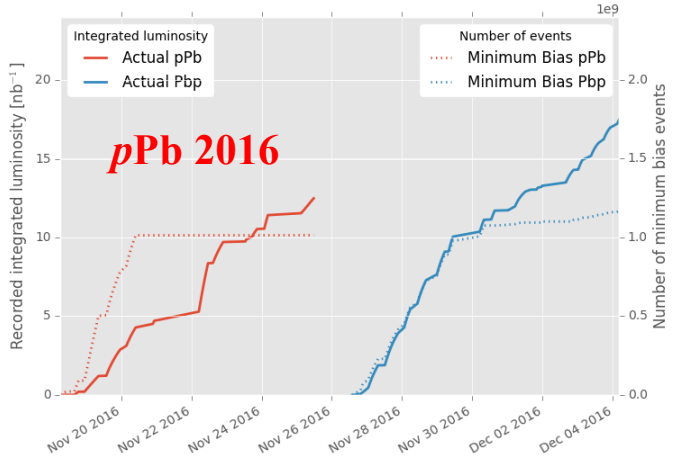
* Heavily analyzed

- And pp collisions for comparisons

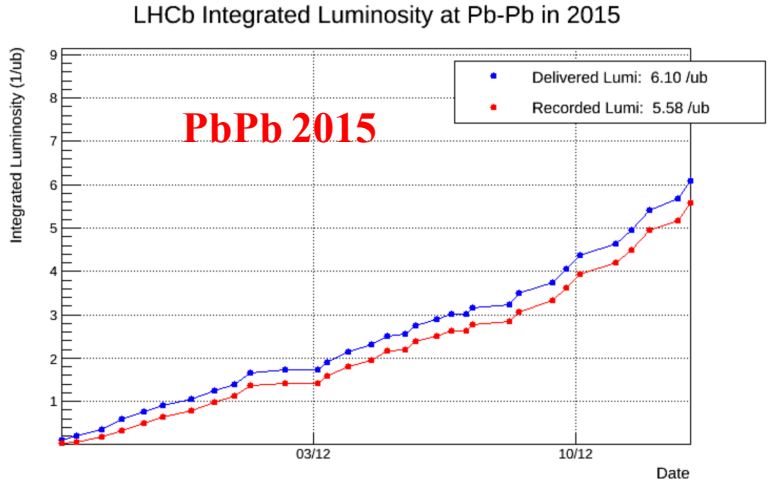
LHCb heavy ion data taking

- pPb runs: 2 nb^{-1} at $\sqrt{s_{NN}} = 5$ TeV (2013), 30 nb^{-1} at $\sqrt{s_{NN}} = 8.16$ TeV (2016)





- 2015/2016/2017
  - ➢ Several fixed target data taking periods (p-He, p-Ne, p-Ar, Pb-Ar with $E_p = 6.5$ TeV)
  - ➢ First participation in PbPb data taking successfully at $\sqrt{s_{NN}} = 5$ TeV, ~150 h

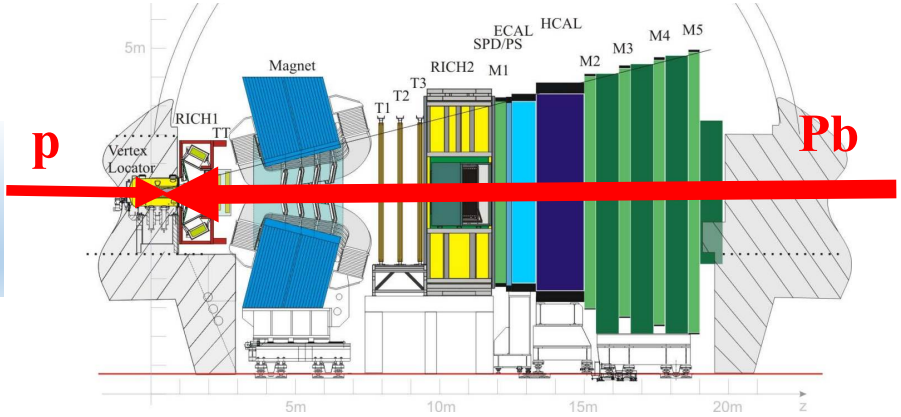


pPb data taking (2013/2016)

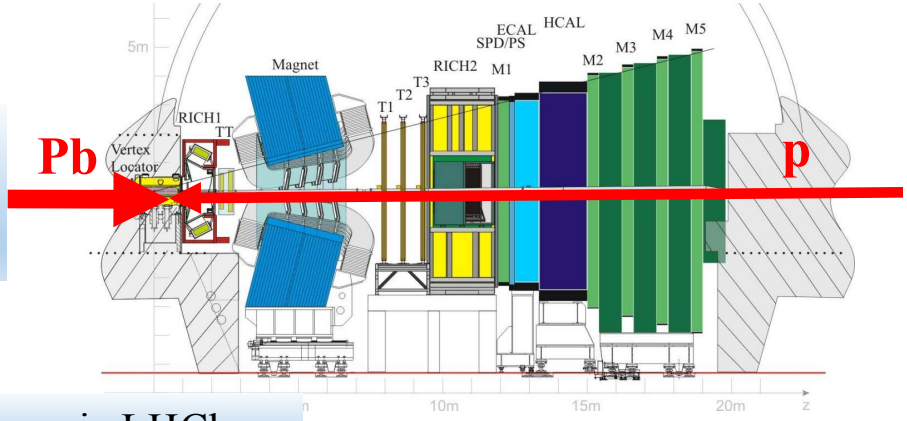
- pPb data collected at nucleon-nucleon (NN) center-of-mass energy $\sqrt{s_{NN}} = 5/8$ TeV
- NN center-of-mass system shifted by $\Delta y = 0.47$ in proton beam direction

Two beam configurations:

p+Pb collisions (forward)
Rapidity coverage: $(1.5 < y^* < 4)$
data analyzed: L_{int}~1.1/13.6 nb^{-1}



Pb+p collisions (backward)
Rapidity coverage: $(-5 < y^* < -2.5)$
data analyzed: L_{int}~0.5/20.8 nb^{-1}

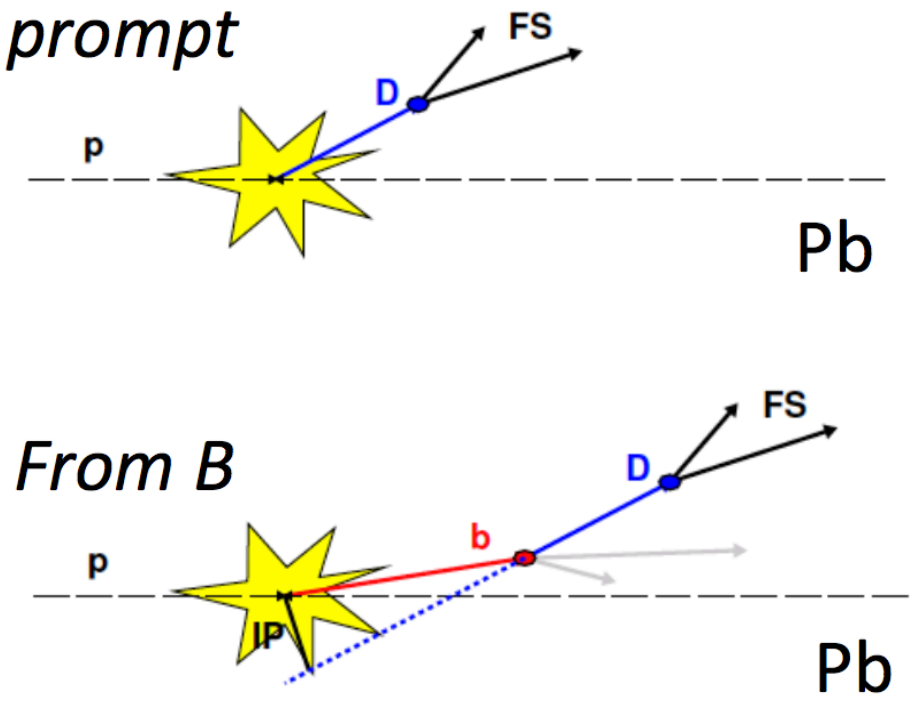


On average, multiplicity higher for Pb+p collisions in LHCb

y^*: rapidity defined in NN center-of-mass frame

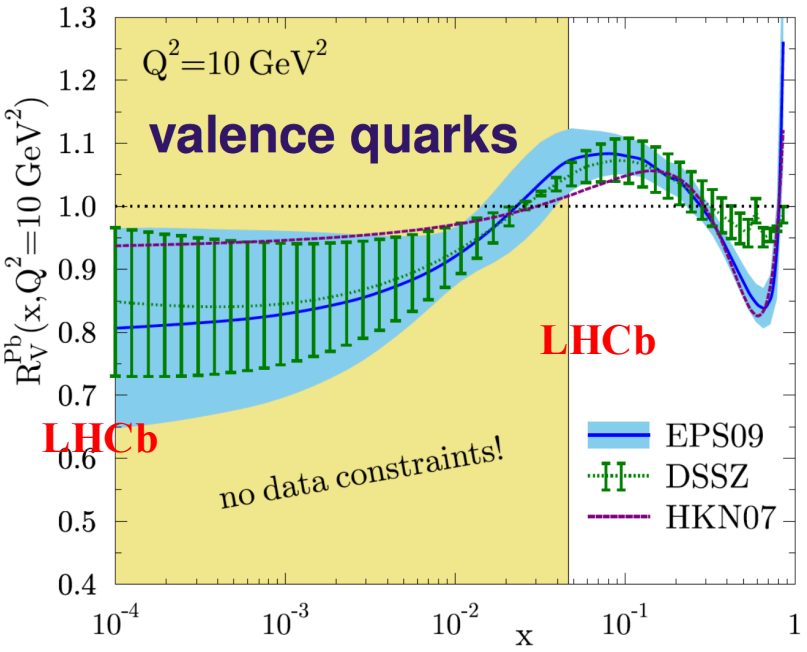
Open charm tagging

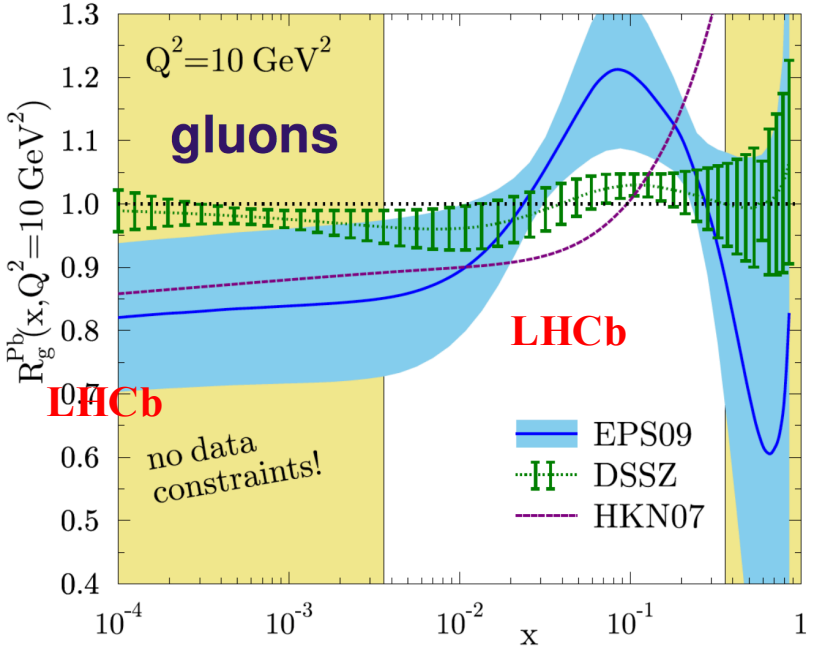
- Suppression of hadronic backgrounds
  - Displaced tracks and vertex
  - Particle identification for kaons and protons
- Separation from non-prompt production using impact parameter



Gluon-Quark PDFs

➜ *ratios of nucleon PDFs:* $F_N(\mathrm{Pb})/F_N(\mathrm{free})$



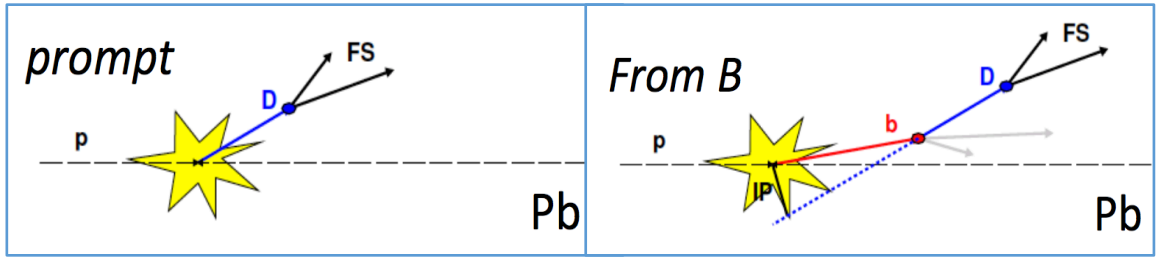


arXiv:1401.2345

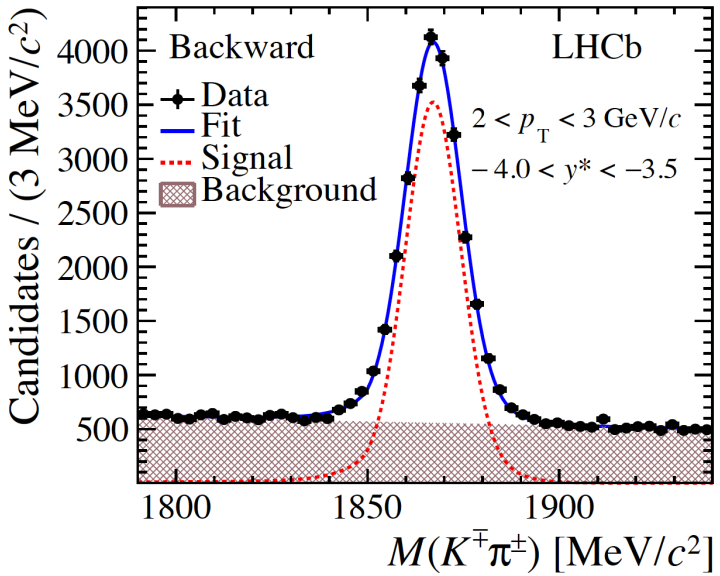
Prompt D^0 production

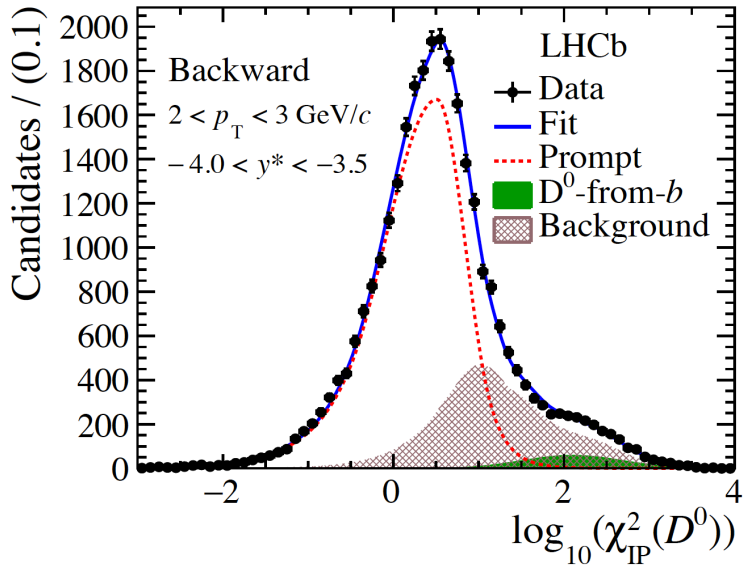
JHEP 1710 (2017) 090

- D^0 fully reconstructed through $D^0 \to K^{\pm}\pi^{\mp}$ decays
- Reconstruction and particle ID efficiency calibrated using data
- Prompt D^0 and D^0 from b hadrons separated with impact parameter (IP) w.r.t. primary vertex



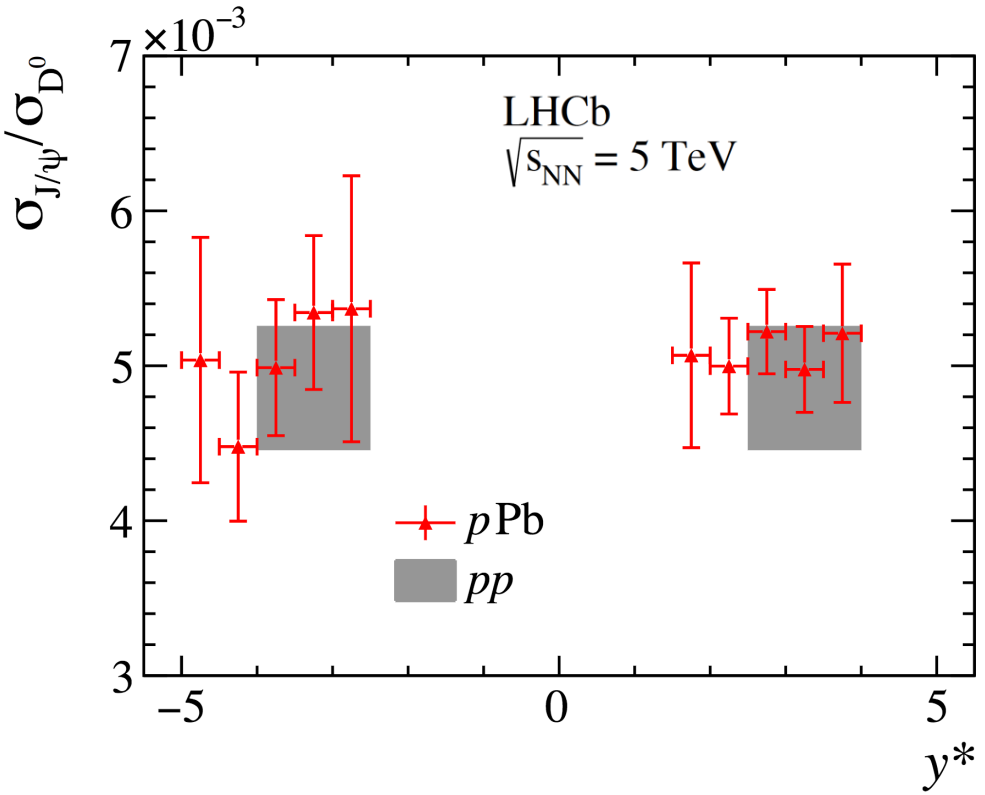
- Yield extraction fits





Nuclear modification $R_{p\mathrm{Pb}}$

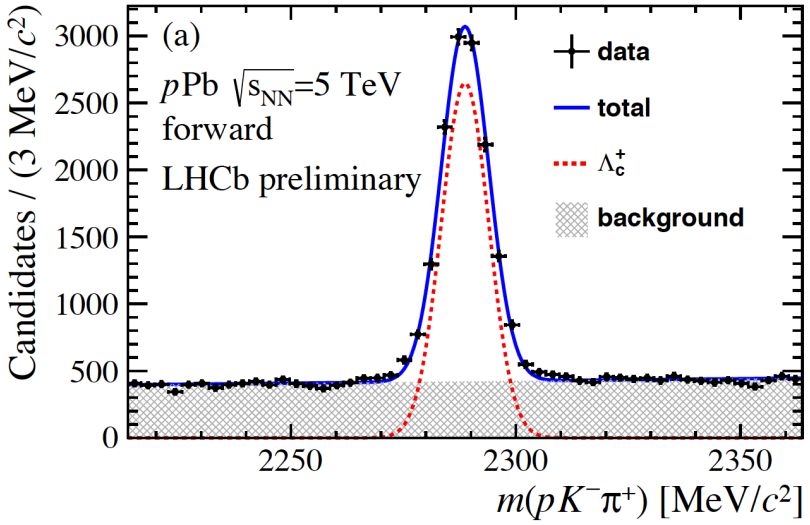
JHEP 1710 (2017) 090

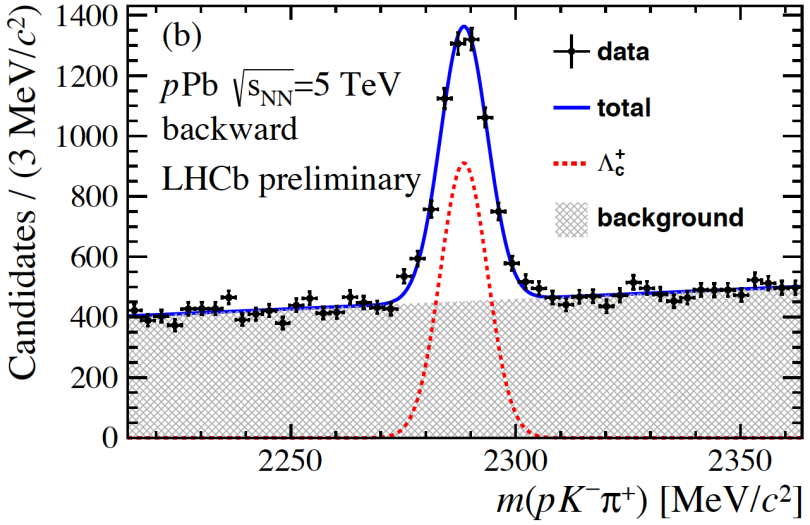


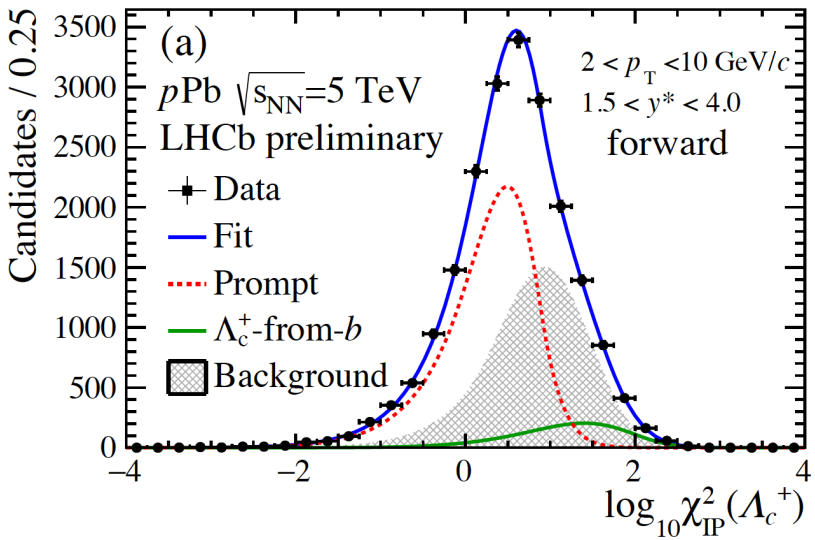
Nuclear modification for D^0 consistent with J/ψ, stronger effect for $\psi(2S)$

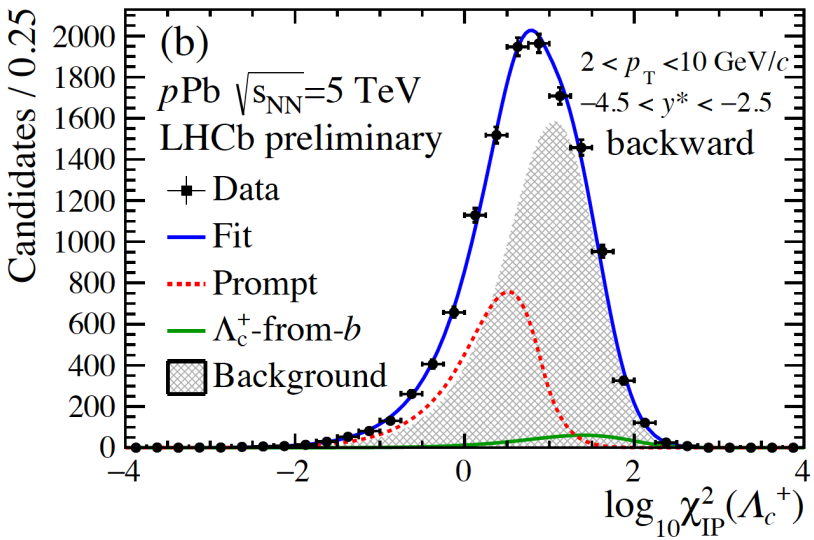
Λ_c^+ production

LHCb-CONF-2017-005



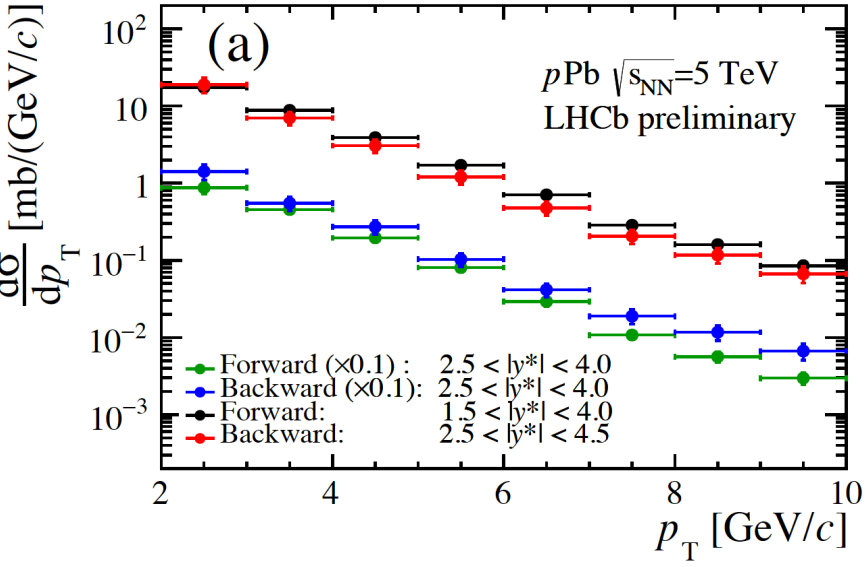


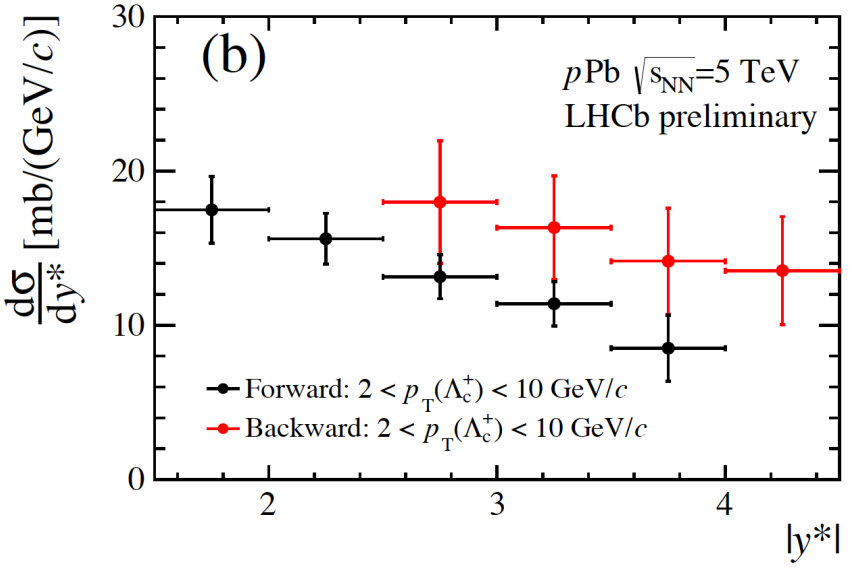




Λ_c^+ production

LHCb-CONF-2017-005





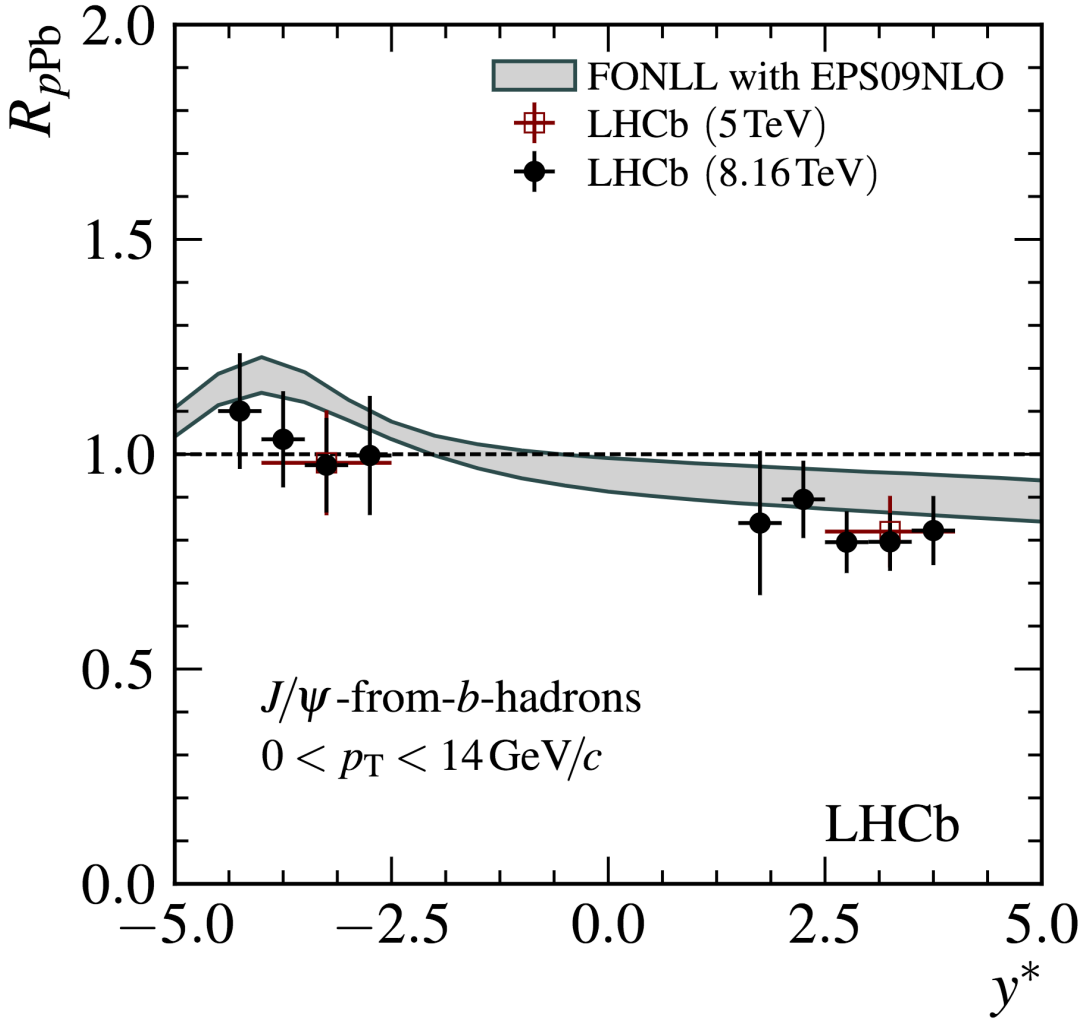
Source	Relative uncertainty (%)	
Correlated between bins	Forward	Backward
Invariant mass fit	0-12	0-14
$\log_{10}\chi^2_{IP}(\Lambda_c^+)$ fit	2-3	4-5
Efficiency	7-8	16-17
Luminosity	1.9	2.1
$\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$	5.2	5.2
Uncorrelated between bins		
Simulation sample size	2-13	2-14
Statistical uncertainty	3-33	6-44

Production more suppressed in forward sample

Nuclear modification

PLB 774 (2017) 159

- J/ψ from b: consistent with model prodection



Forward-backward ratio

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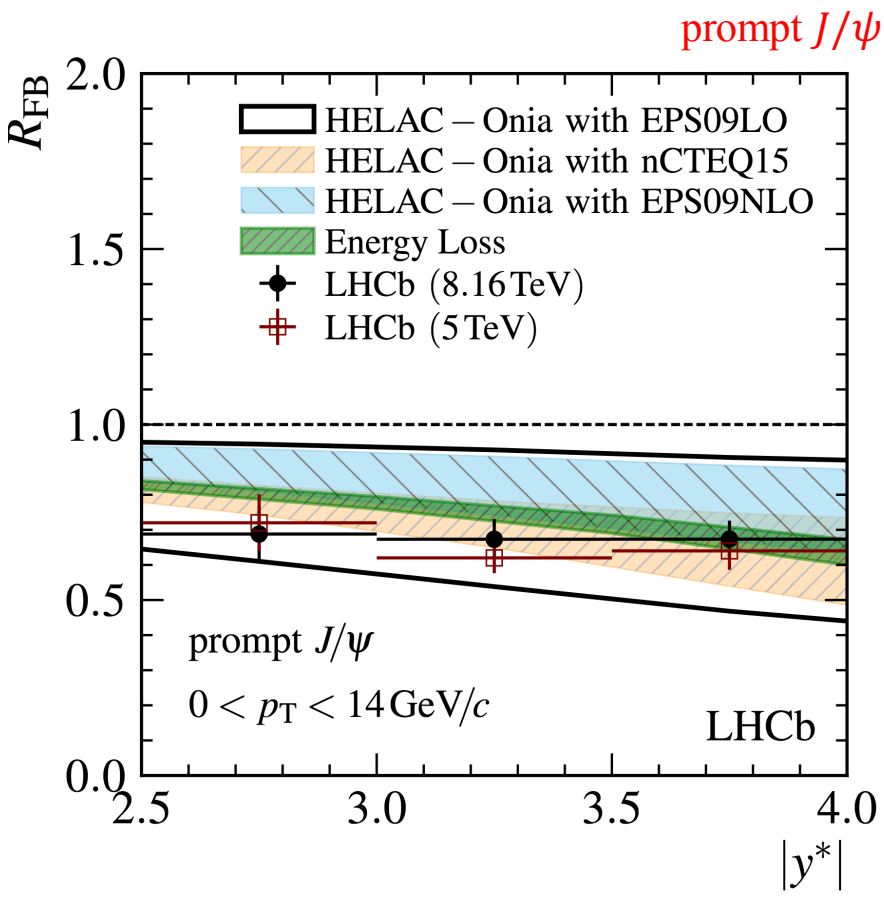
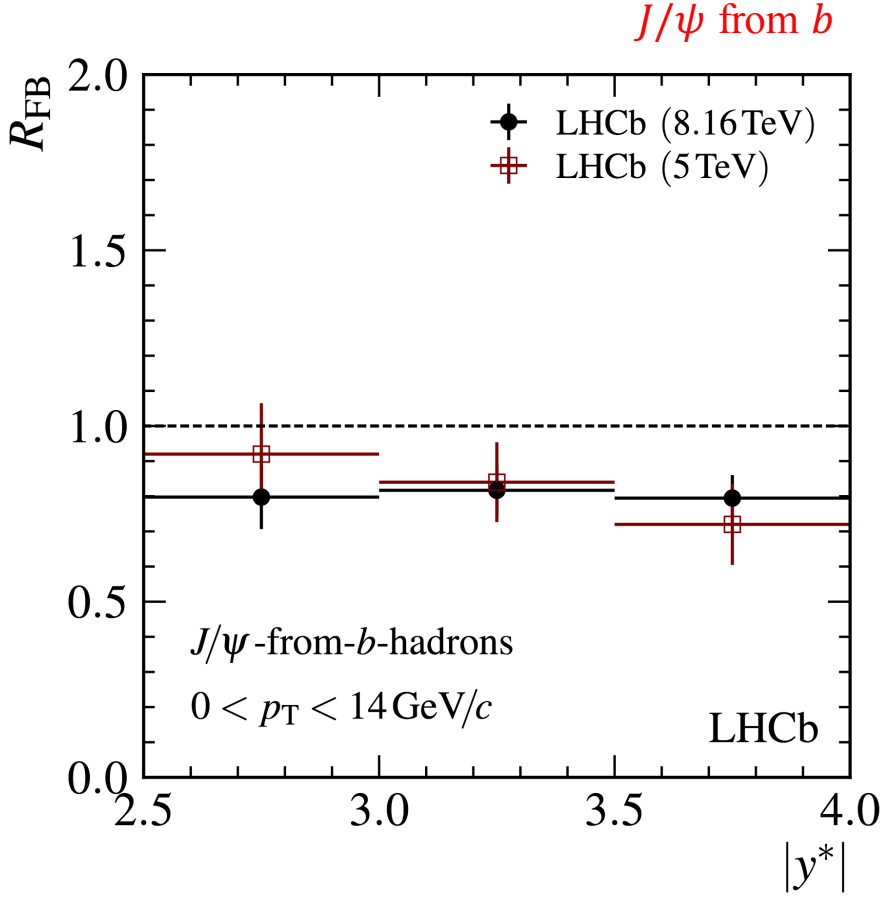
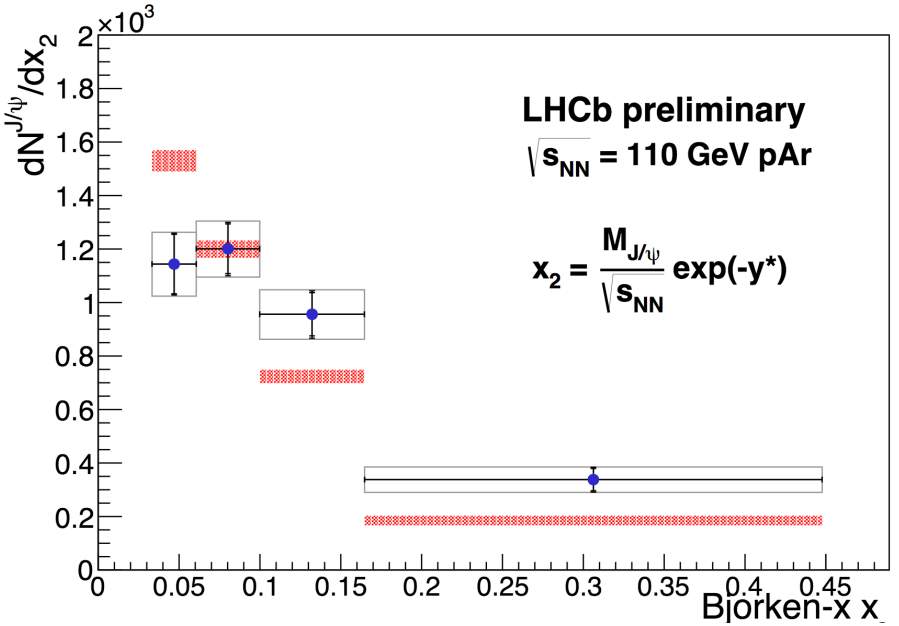
- R_{FB} smaller than unity especially at low p_T, increasing with p_T
- No evidence of energy dependence

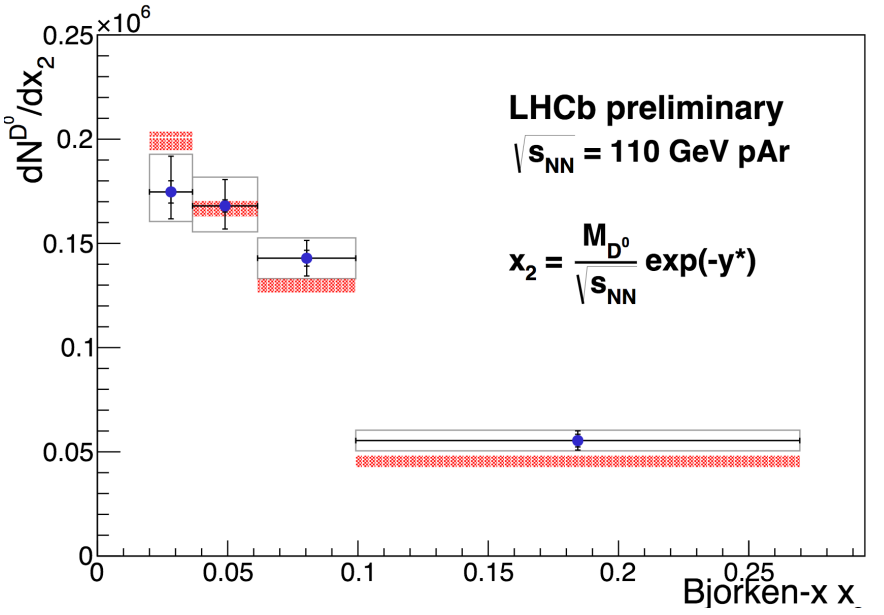




J/ψ and D^0 production in pAr LHCb-CONF-2017-001

Compared with Pythia

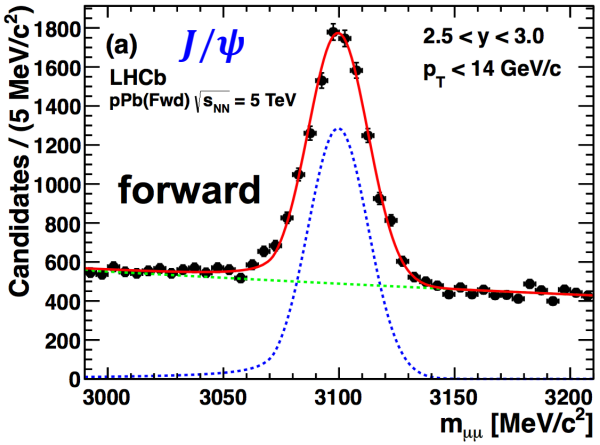


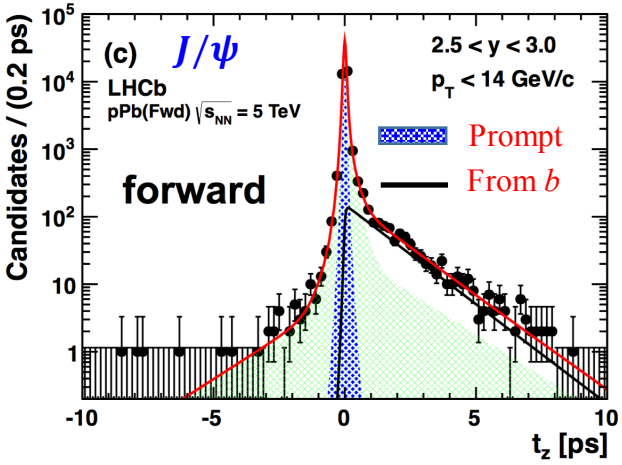


Heavy quarkonia production

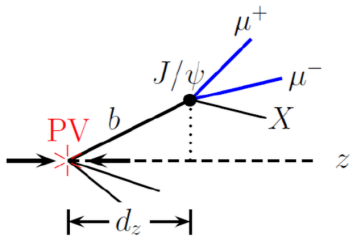
JHEP 02 (2014) 072
JHEP 07 (2014) 094
JHEP 03 (2016) 133

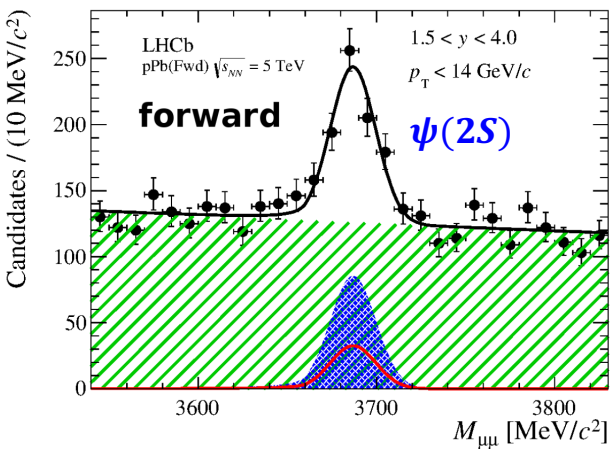
- Candidates fully reconstructed from well identified muons
- Prompt J/ψ, $\psi(2S)$ and those from b decay separated using pseudo-decay time (t_z)
  - ➢ LHCb is unique to separate the two components in the forward acceptance

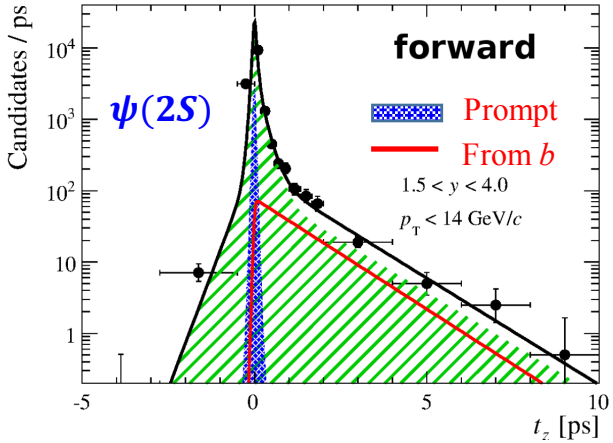




$$t_Z = \frac{(Z_{J/\Psi} - Z_{PV}) \times M_{J/\Psi}}{p_z}$$



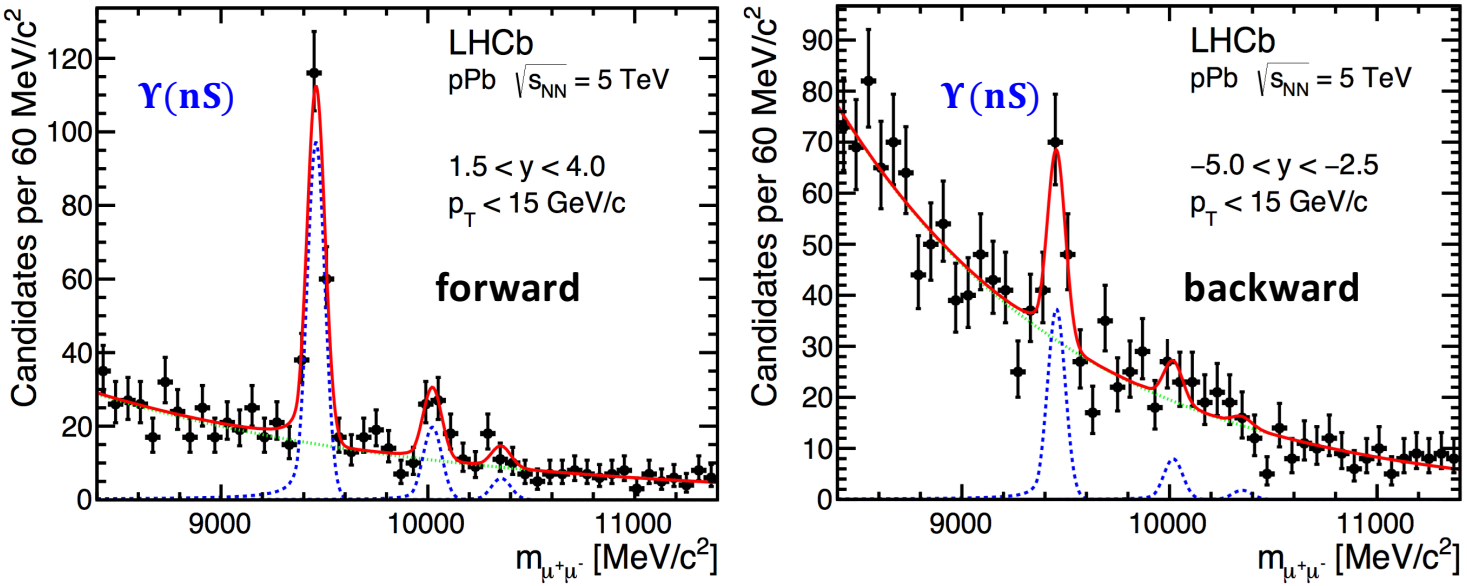




Heavy quarkonia production

JHEP 02 (2014) 072
JHEP 07 (2014) 094
JHEP 03 (2016) 133

- Candidates fully reconstructed from well identified muons
- Prompt J/ψ, $\psi(2S)$ and those from b decay separated using decay time

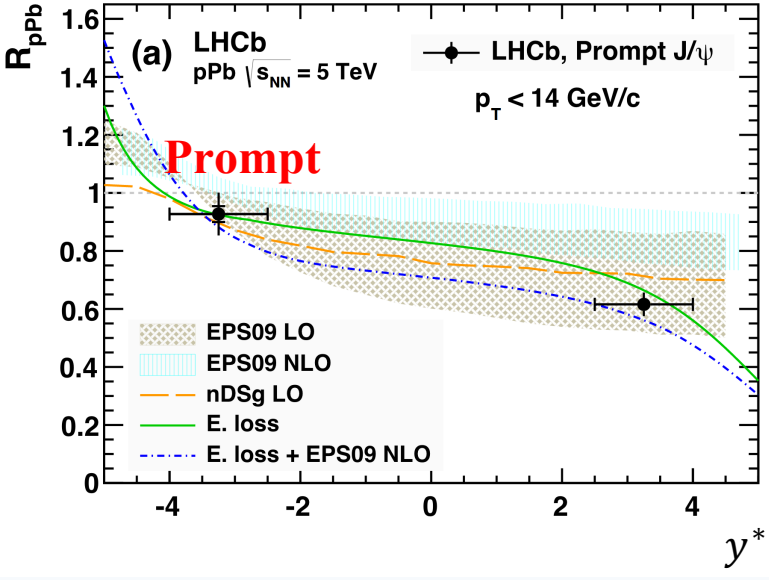


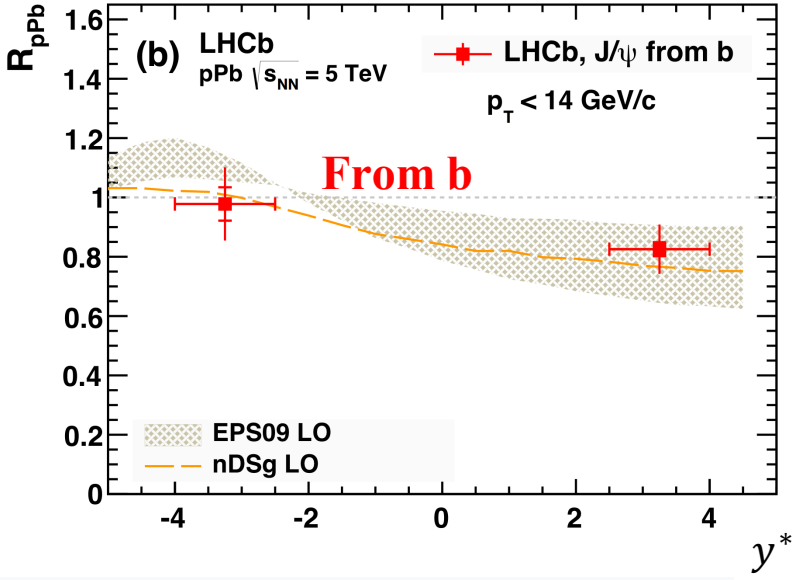
More data needed to study $\Upsilon(2S)$ and $\Upsilon(3S)$ productions

Nuclear modification factor (J/ψ)

JHEP 02 (2014) 072

$$R_{p\mathrm{Pb}} = \frac{1}{A} \times \frac{d\sigma_{p\mathrm{Pb}}/dy}{d\sigma_{pp}/dy}$$





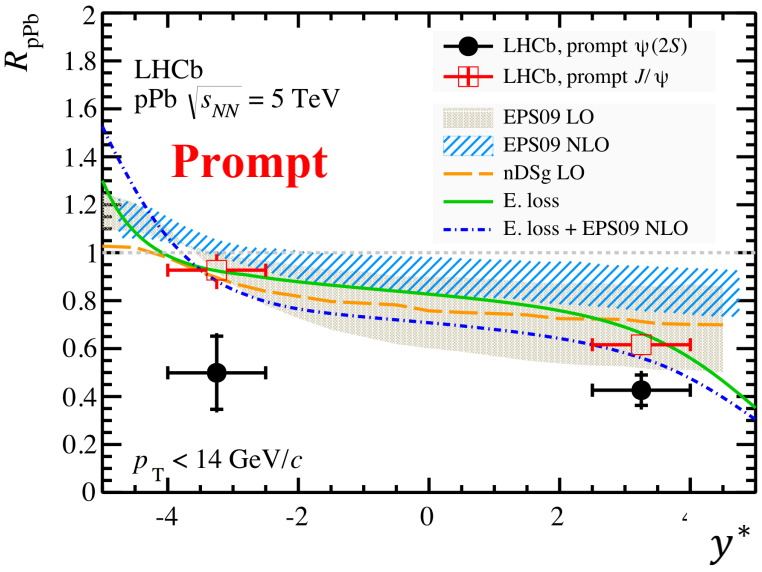
- **Prompt J/ψ**: strongly suppressed in forward region, significant signs of CNM effects
  → Data well described by energy loss models w/ and w/o shadowing
- **J/ψ from b**: modest suppression in forward region
  → Suggests suppression of b-hadron production
- **Backward rapidity:** compatible with no suppression

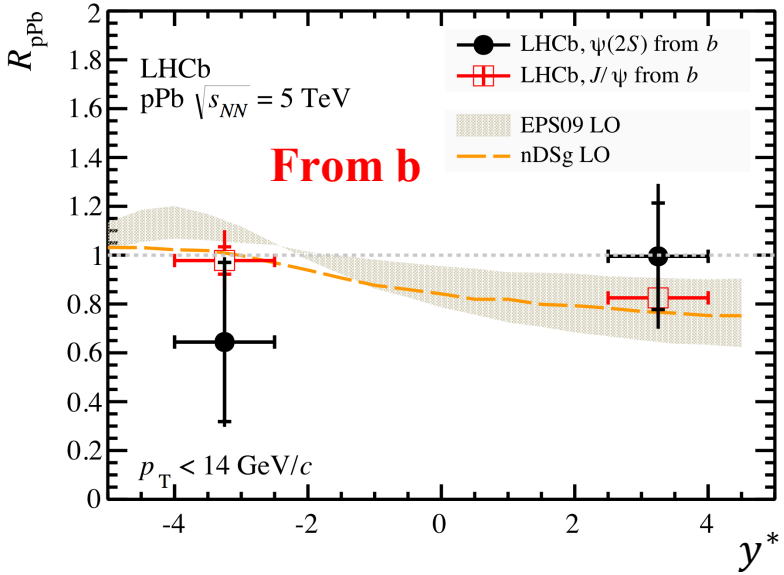
Models:
EPS09LO (CSM): PRC88 (2013) 047901, Nuclear Physics A 926 (2014) 236
EPS09LNO (shadowing + CEM): IJMP E 22 (2013) 1330007
Energy Loss: JHEP 03 (2013) 122, JHEP 05 (2013) 155
nDSg LO: PRC88 (2013) 047901

Nuclear modification factor ($\psi(2S)$)

JHEP 03 (2016) 133

$$R_{p\mathrm{Pb}} = \frac{1}{A} \times \frac{d\sigma_{p\mathrm{Pb}}/dy}{d\sigma_{pp}/dy}$$





- **Prompt $\psi(2S)$**: more suppressed than J/ψ, intriguing suppression in backward rapidity
  → Energy loss+shadowing don't explain $\psi(2S)$ suppression in backward rapidity, requiring other mechanism (Comovers?)
- **$\psi(2S)$ from b**: suppression consistent with that of J/ψ from b, as expected

Nuclear modification factor ($\Upsilon(1S)$)

$$R_{p\mathrm{Pb}} = \frac{1}{A} \times \frac{d\sigma_{p\mathrm{Pb}}/dy}{d\sigma_{pp}/dy}$$

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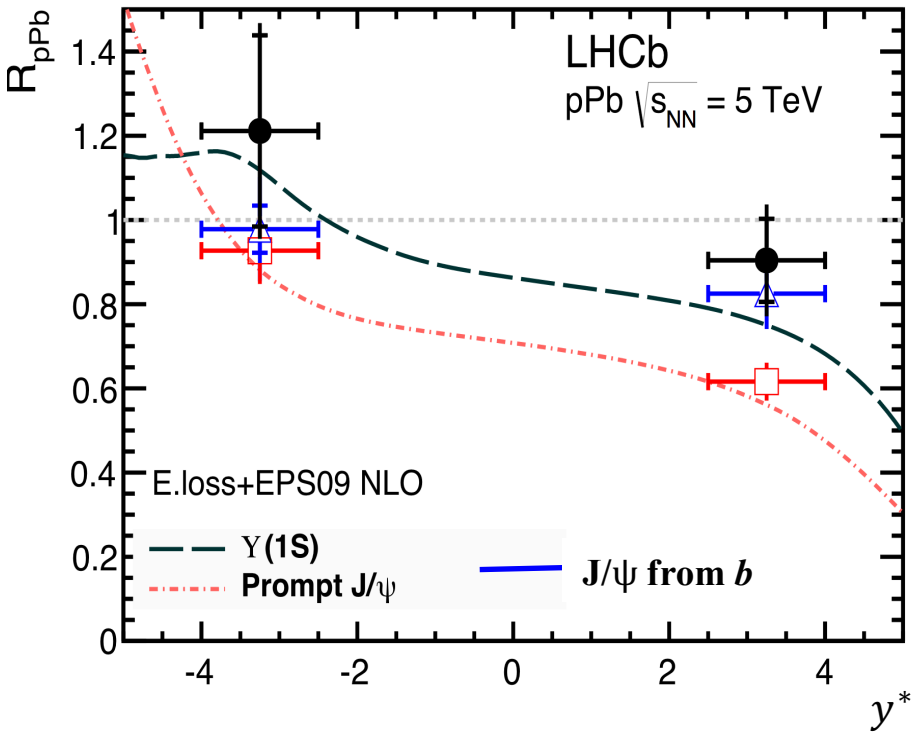
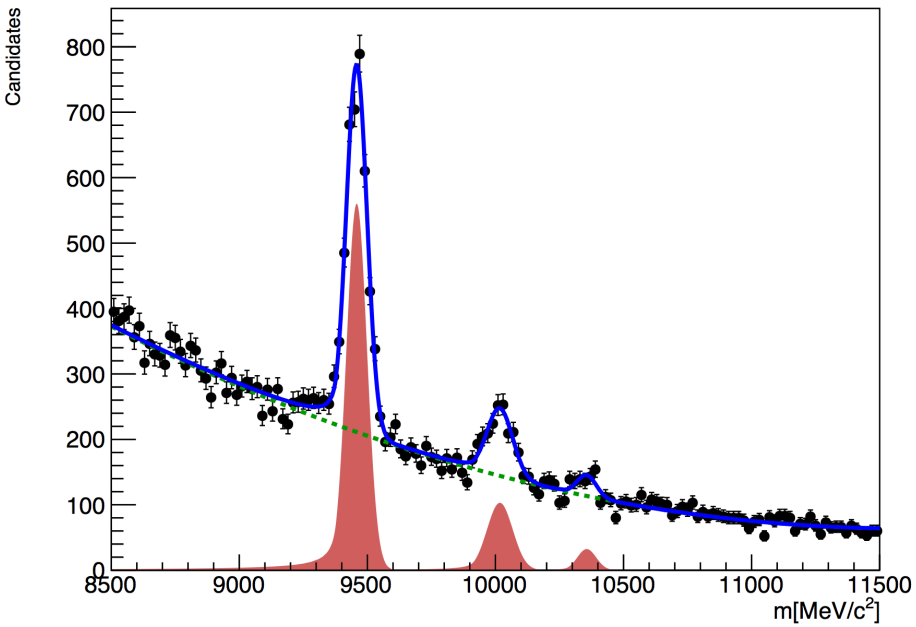
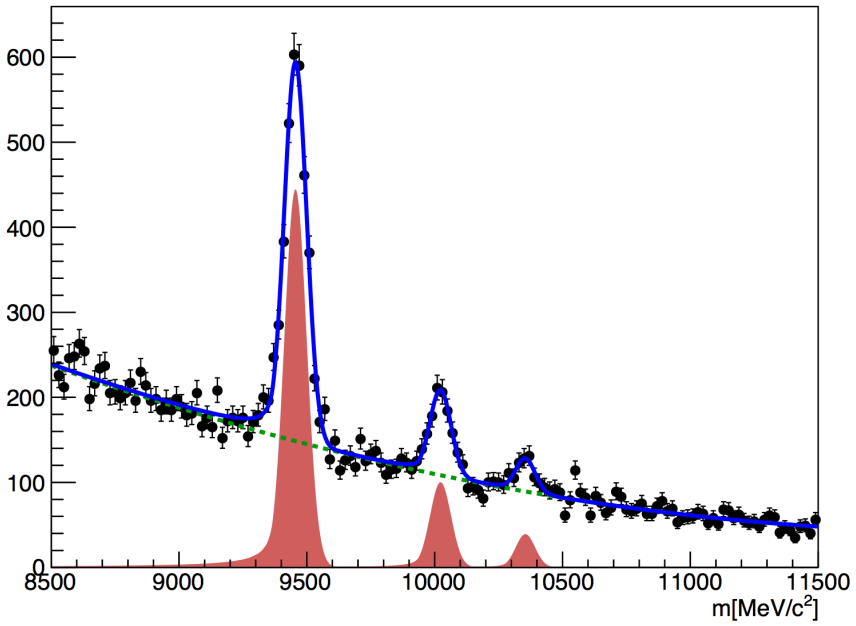


- Suppression in forward region is smaller than for J/ψ, but close to that of J/ψ from b → CNM effects on open b hadrons and bottomonia are not very different
- Hint of enhancement in the backward region → could be effect of anti-shadowing
- Data agree with prediction of energy loss + shadowing

Bottomonia in pPb 2016





yields	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	Integrated Lumi.
pPb	2619 ± 75	564 ± 58	204 ± 52	13.6nb^{-1}
Pbp	3029 ± 81	701 ± 60	164 ± 38	20.8nb^{-1}

Ultra-peripheral PbPb collisions: J/ψ

- Low multiplicity events: only two muons in the detector