UNIVERSITÀ DEGLI STUDI DI FERRARA
- EX LABORE FRUCTUS -

LHCb Heavy-ion results in collider and fixed-target mode

L. L. Pappalardo
(on behalf of the LHCb Collaboration)

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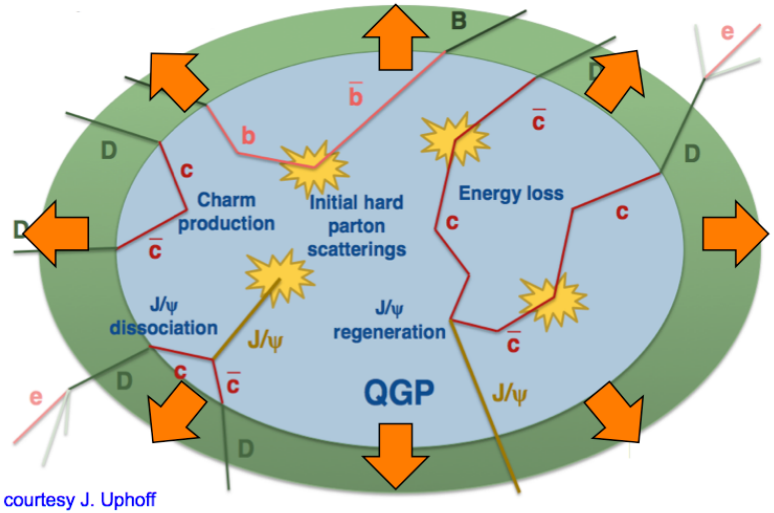
Outline

- Physics motivations
- The LHCb detector and its fixed-target system
- Prompt charm production in pPb collisions in collider mode
- Prompt charm production in pHe and pAr fixed-target collisions
- Conclusions

Physics motivations

Heavy quarks are effective probes to study the properties of the deconfined medium created in **ultra-relativistic heavy-ion collisions:**

- Their masses are significantly higher than the QGP critical temperature ($T_c \sim 156$ MeV)
- They are **produced in the early stages of the collision** in a time scale that is shorter than that of the QGP formation
- Their overall yields are not modified by the medium



graphics courtesy J. Uphoff

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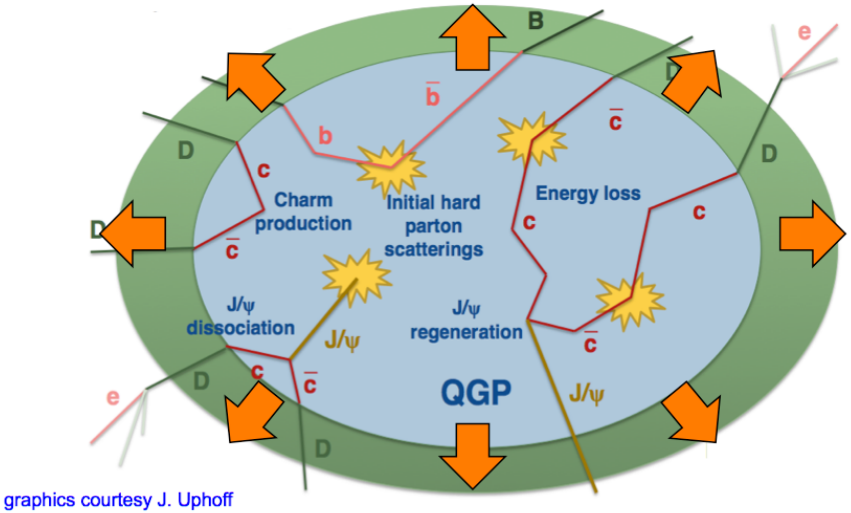
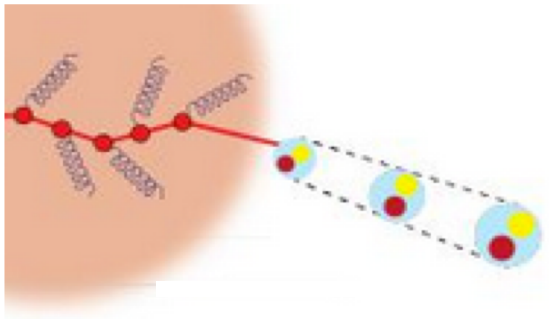


graphics courtesy J. Uphoff

Extracted from arXiv:1212,1701



Quarks loose energy via **radiative gluonic emissions** and **collisions** with the medium constituents.

Studying these **re-scatterings and energy loss processes** is of outmost importance for understanding the properties of the formed QGP and its space-time evolution!

Physics motivations

A correct interpretation of these processes in terms of QGP formation, requires a full understanding of the **cold-nuclear-matter effects:**

- Initial-state radiation or energy-loss
- Final-state hadronic rescattering and absorption
- **Modification of the nucleon PDFs in nuclear matter**

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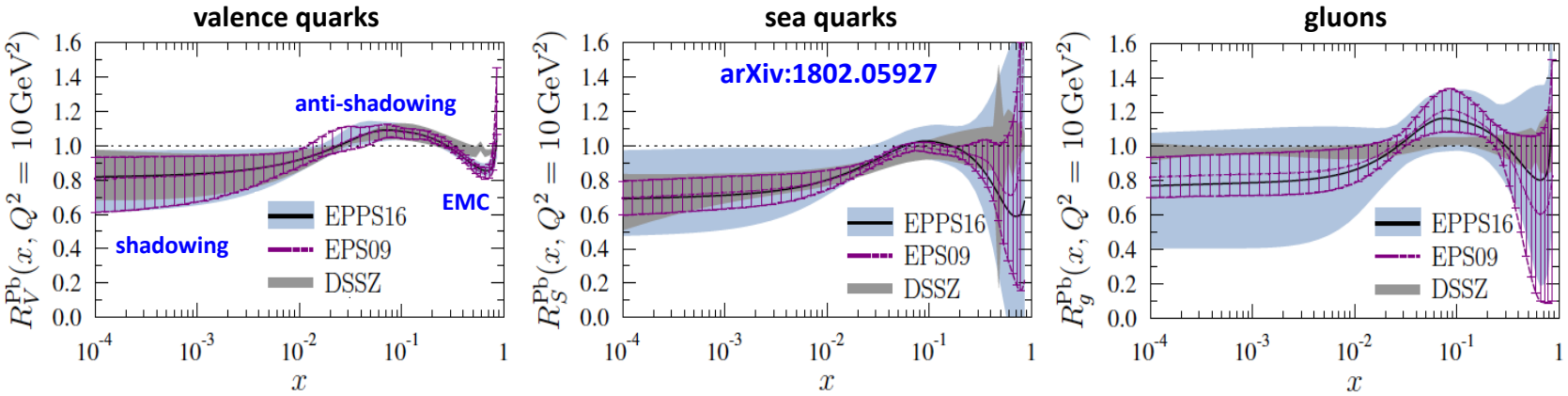

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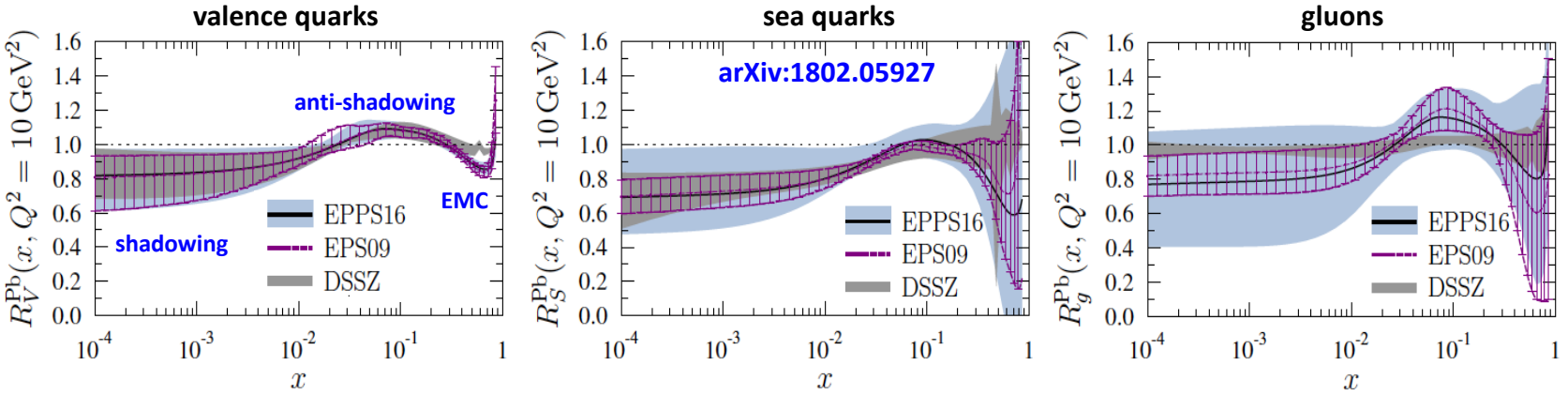


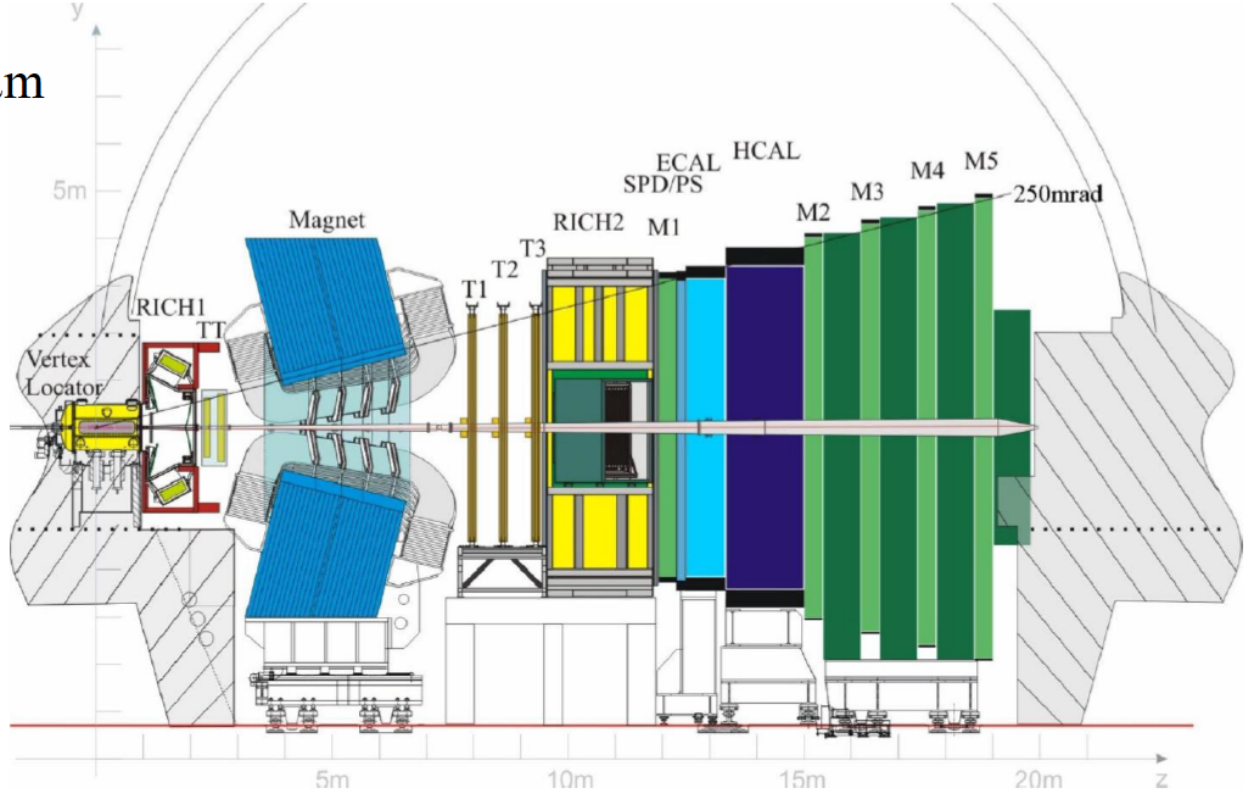
➢ **Measurements of prompt heavy-quark production in pPb collisions at LHC** allow to constrain nPDFs at Bjorken-x $\sim 10^{-5} - 10^{-6}$ (under the assumption that it is the dominant effect)

➢ Thanks to its high performances in heavy-flavour measurement and the possibility to measure prompt heavy flavours at low p_T and forward rapidity, **LHCb can play a crucial role in these studies!**

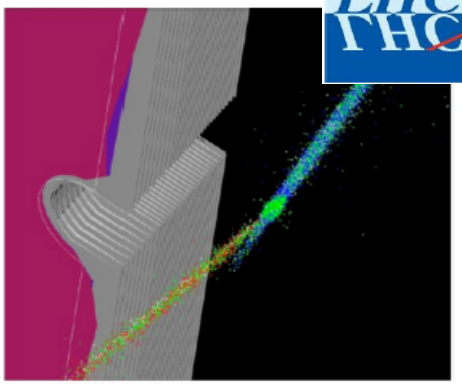
The LHCb detector

A single-arm forward spectrometer designed for the study of particles containing c or b quarks

- Acceptance: $2 < \eta < 5$
- Vertex detector
  - IP resolution ~ 20 μm
- Tracking system
  - $\frac{\Delta p}{p} = 0.5\% - 1\%$ (5-200 GeV/c)
- RICH
  - K/π/p separation
- Electromagnetic + hadronic Calorimeters
- Muon systems



Fixed-target measurements @ LHCb



SMOG: System for Measuring Overlap with Gas:

- Low density noble gas injected in the VELO ($\sim 10^{-7} mbar$)
- Gas pressure 2 orders of magnitude larger than LHC vacuum
- **Beam-gas collision rate increased by 2 orders of magnitude**
- Conceived for **precise luminosity determination** (beam-gas imaging)

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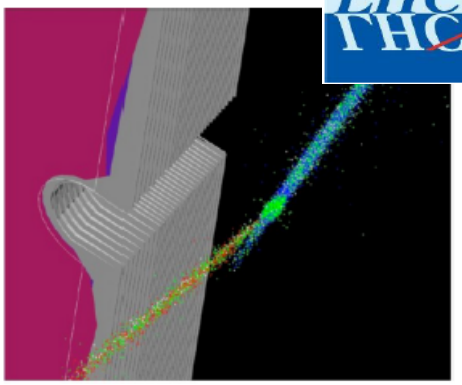

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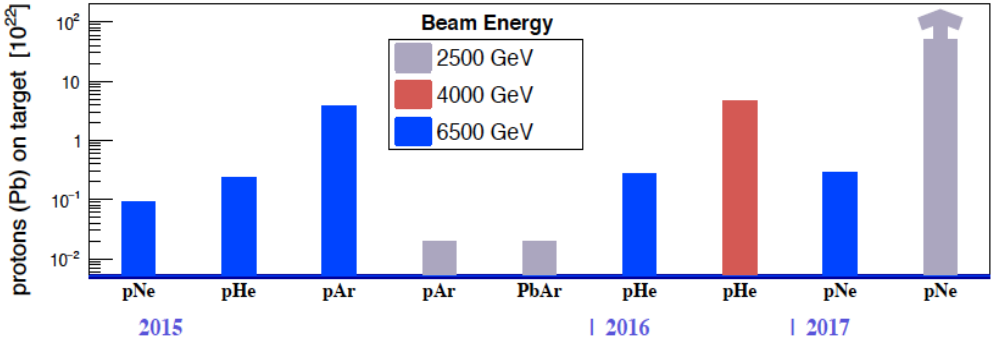

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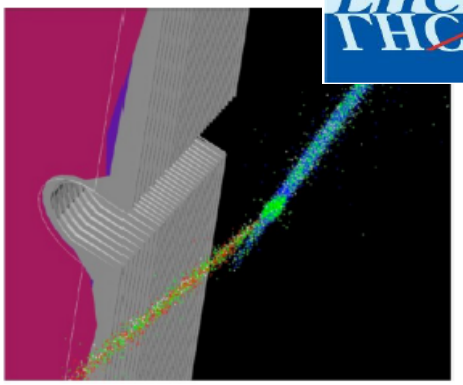

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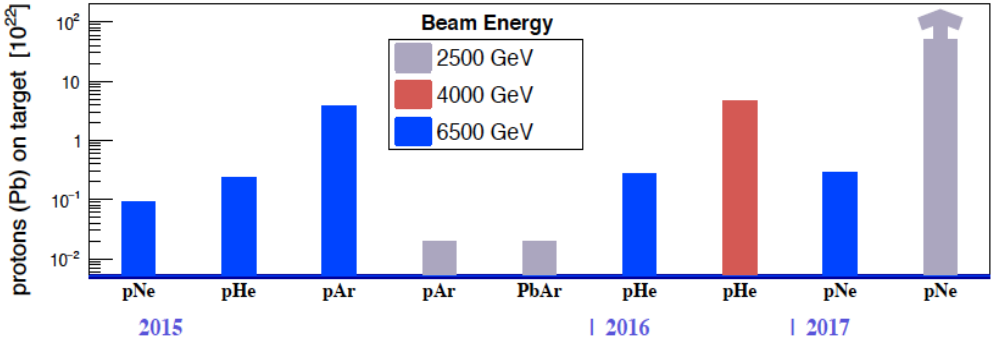
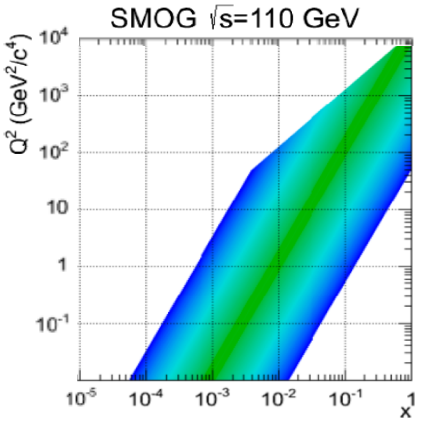
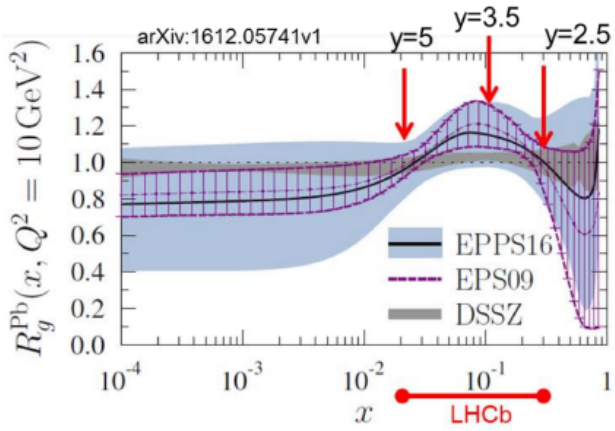
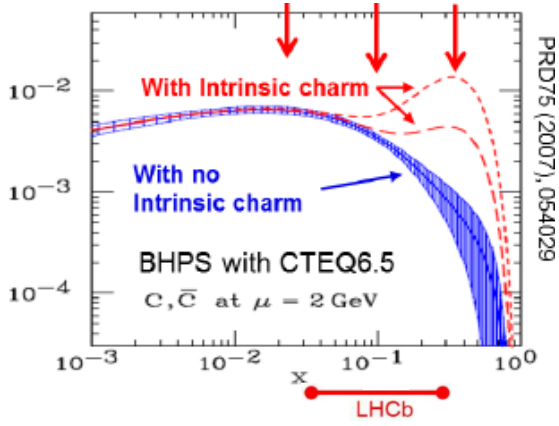
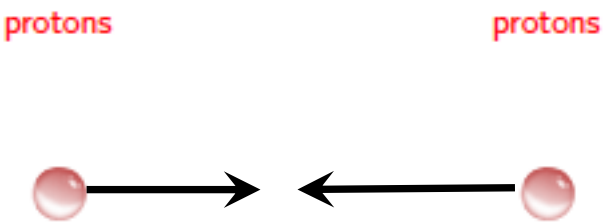








Types of collisions at LHCb



Taken from A. Bursche presentation @ ECT Trento, 02/2017

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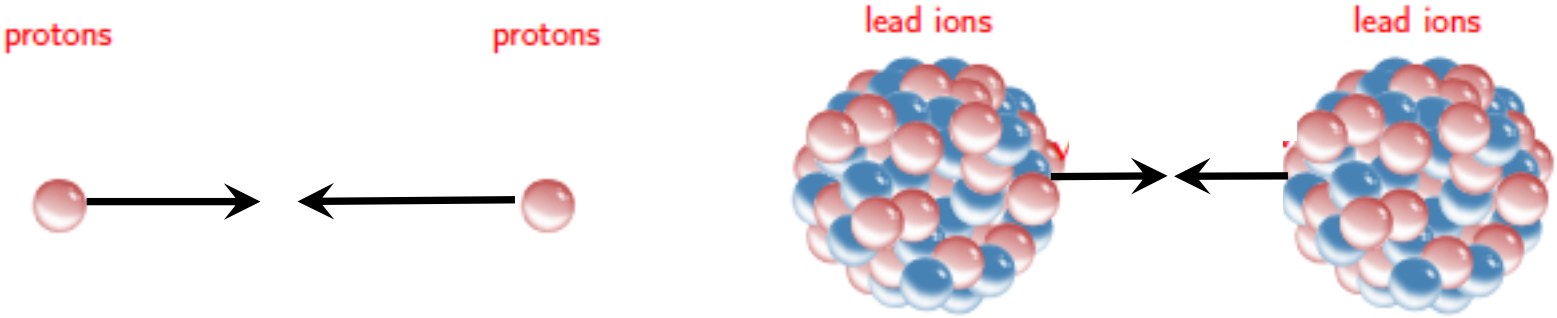

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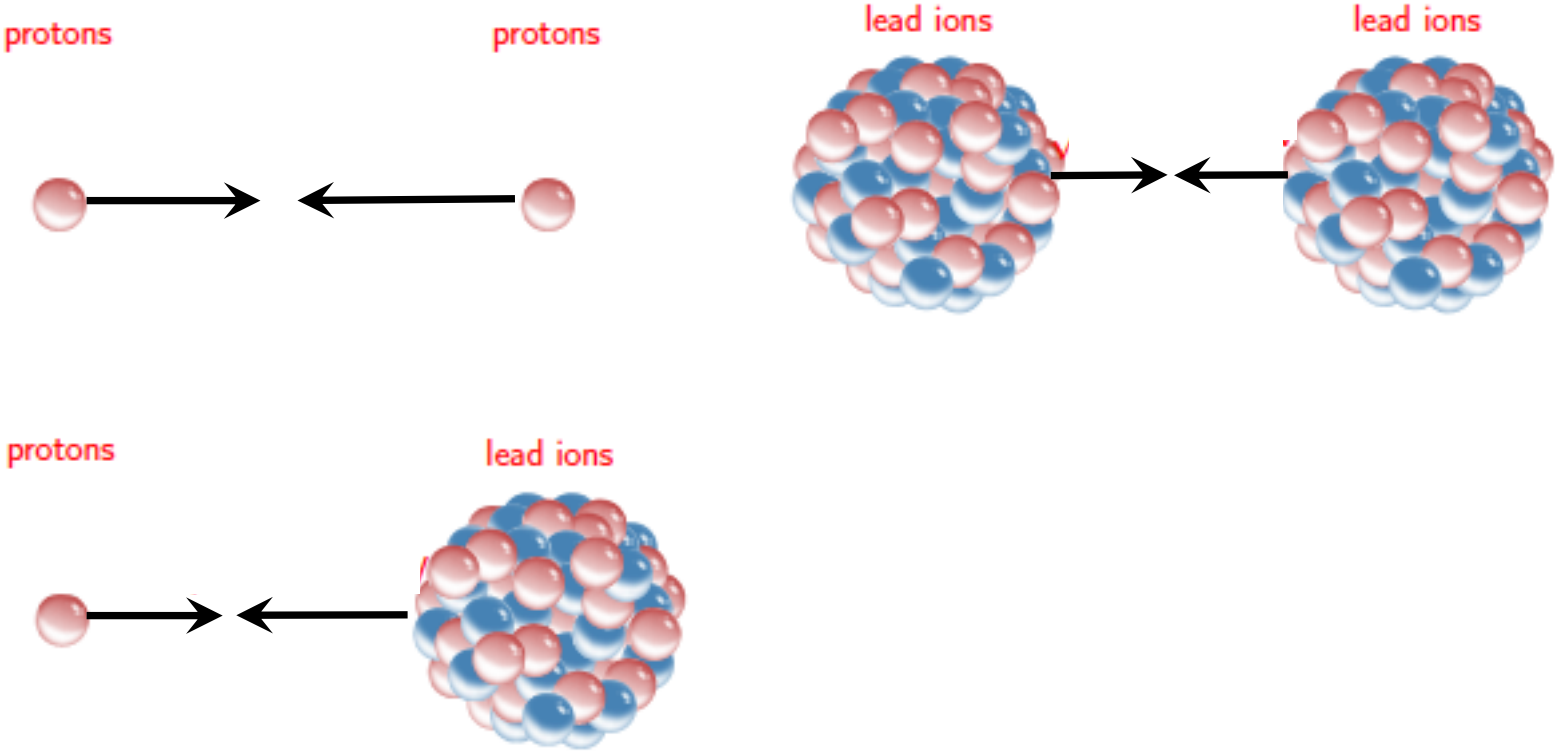

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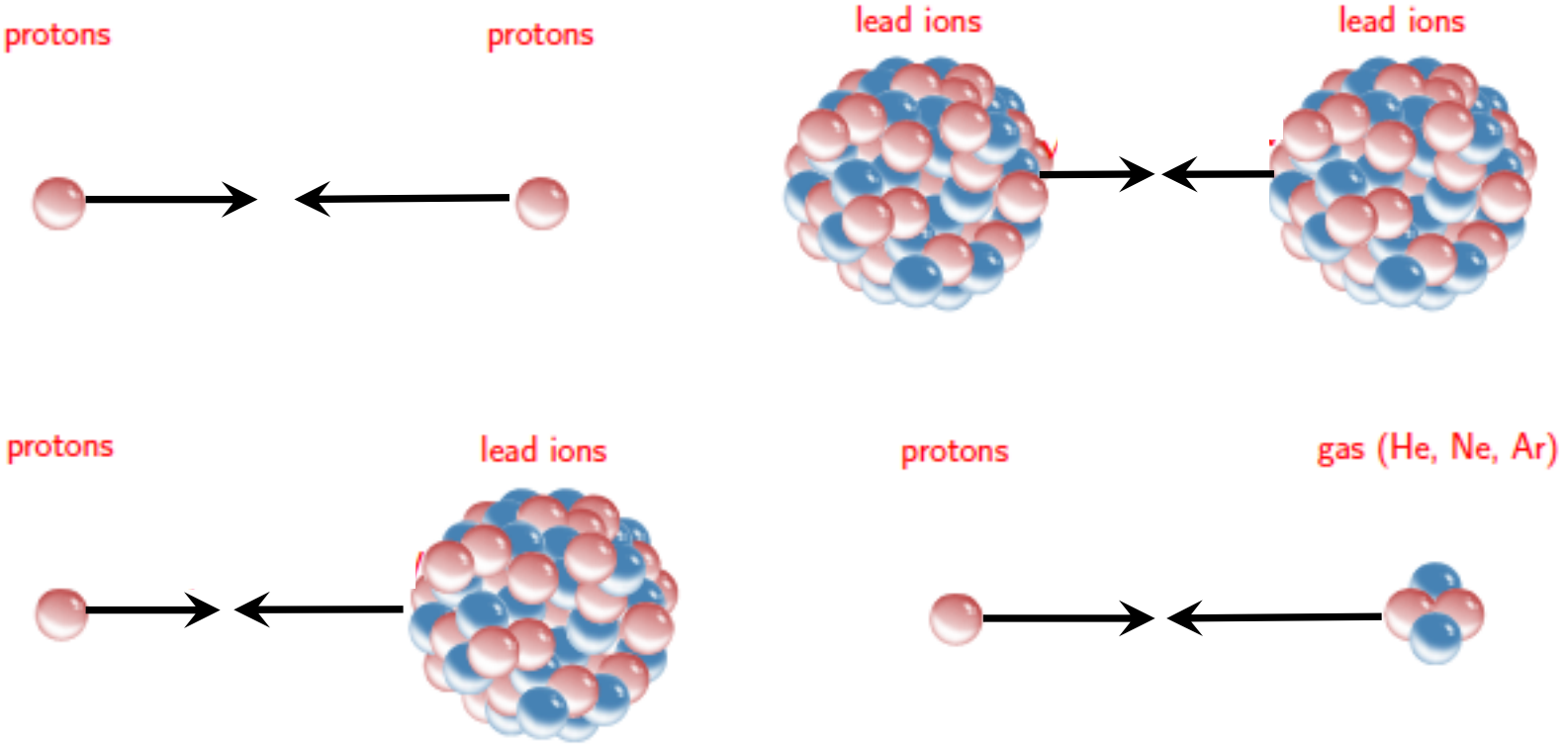

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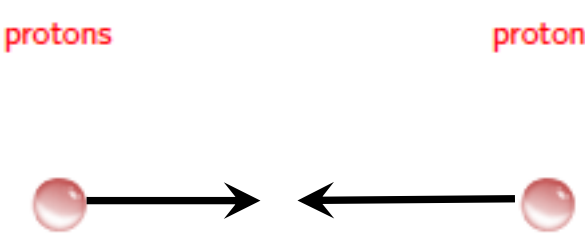

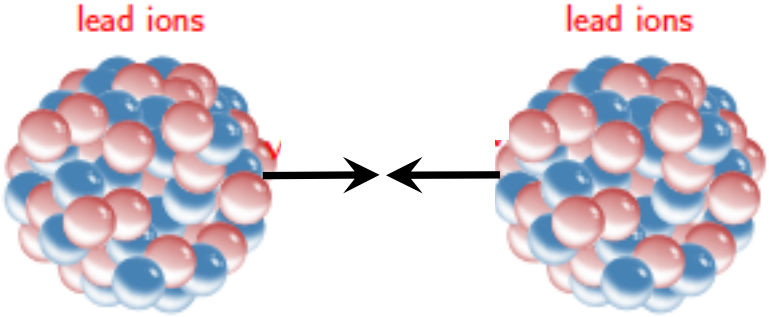

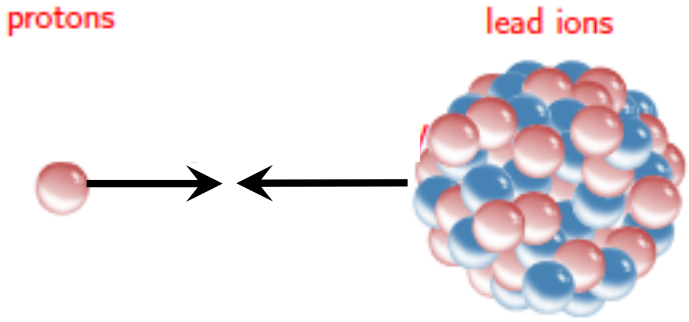

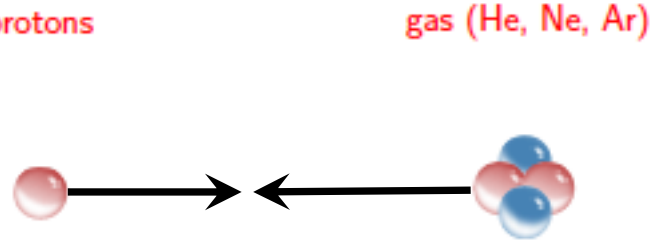

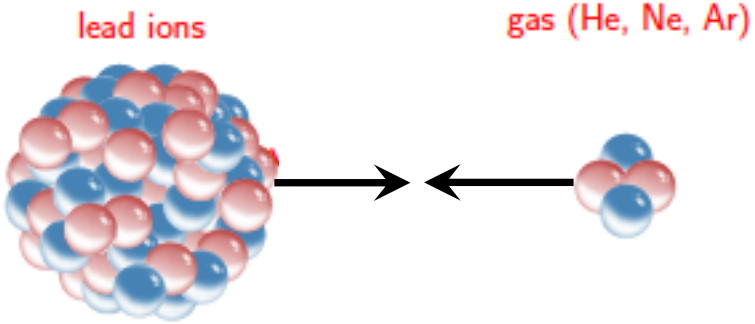

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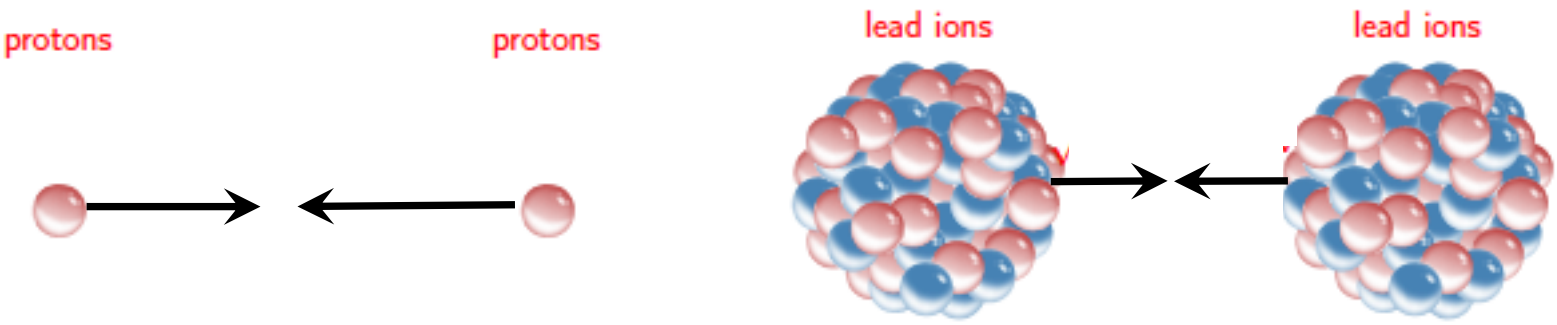
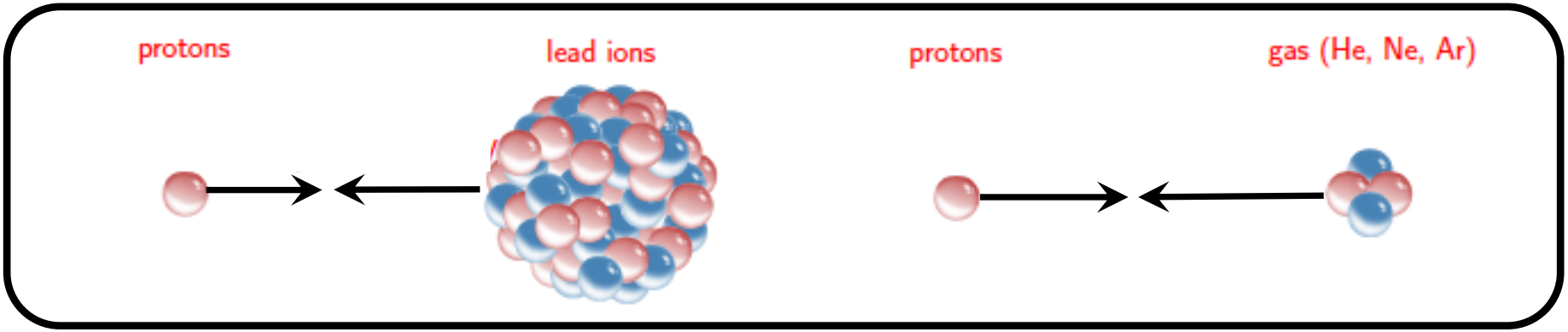
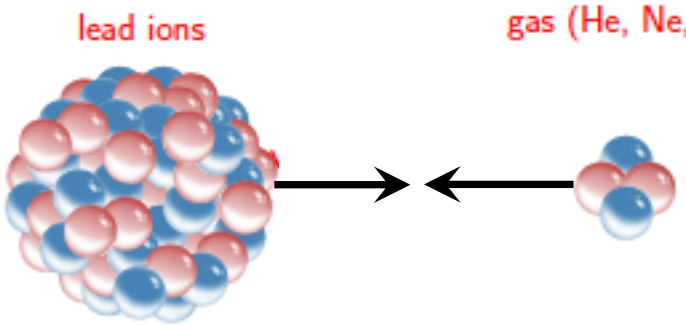


Today's selection





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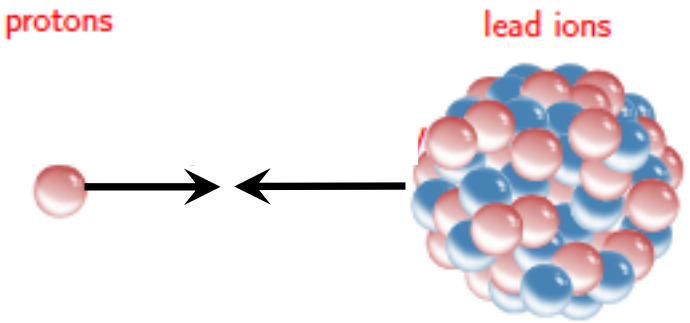
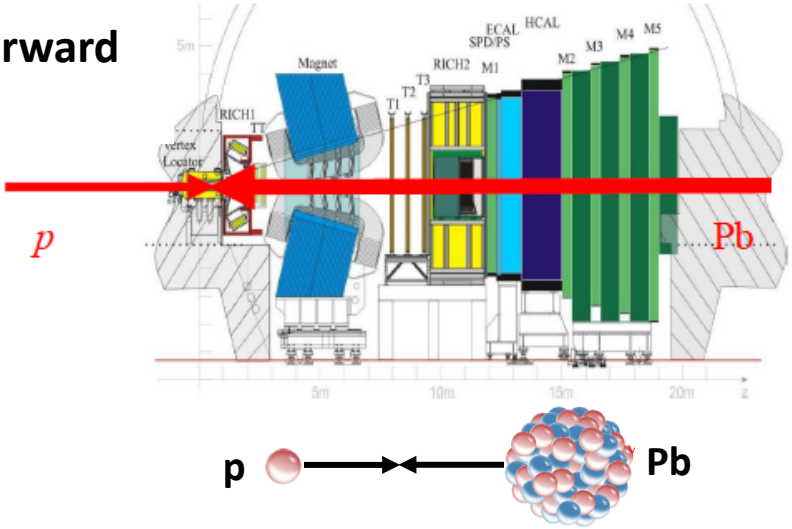
pPb collisions in collider mode



The LHCb pPb beam configurations

Forward



Center-of-mass rapidity coverage:

- y^*: rapidity in nucleon-nucleon cms
- **Forward** (beam): $1.5 < y^* < 4.0$

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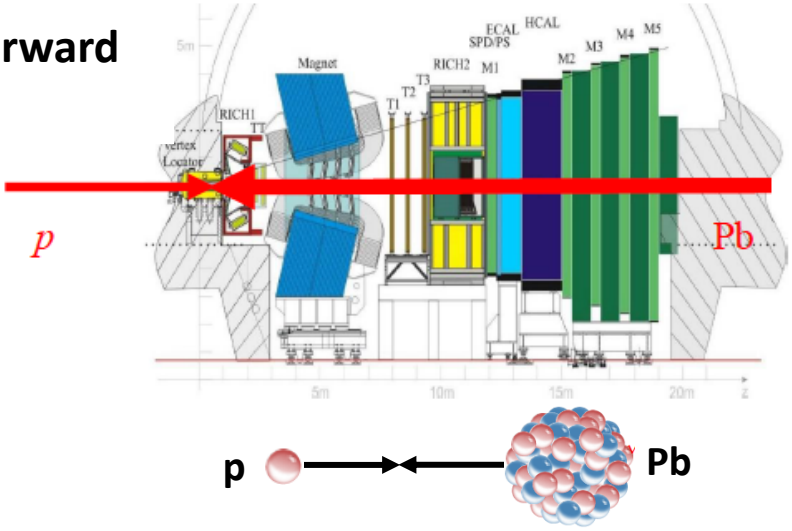
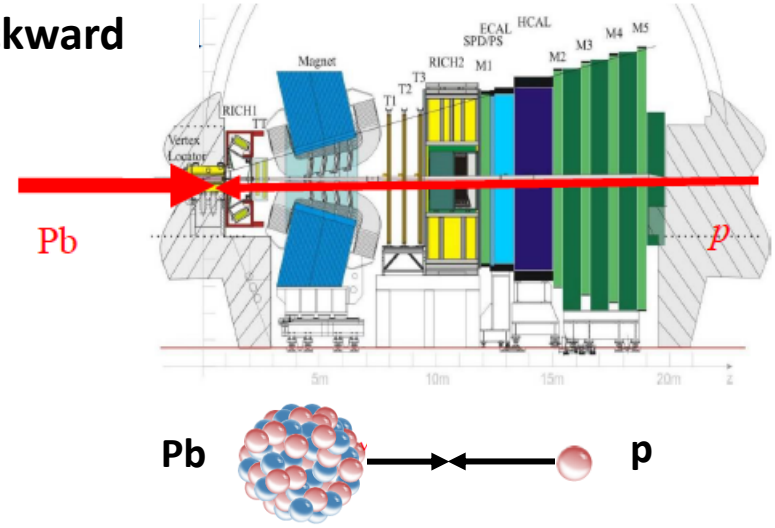


Backward



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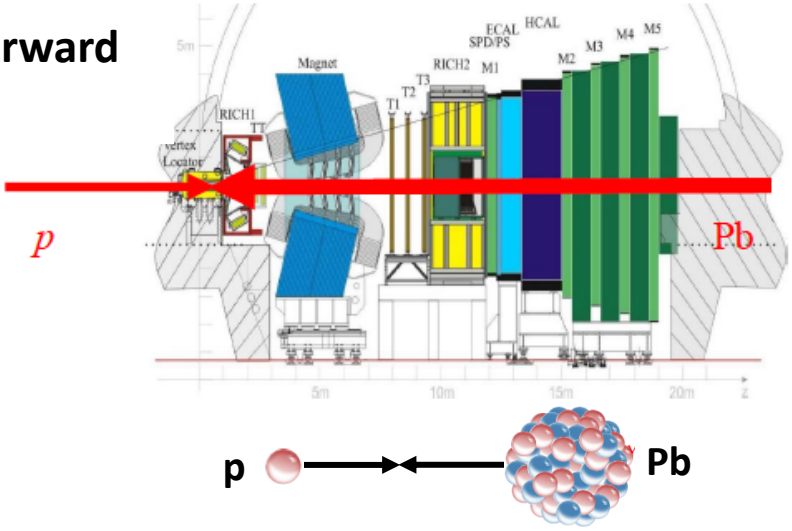

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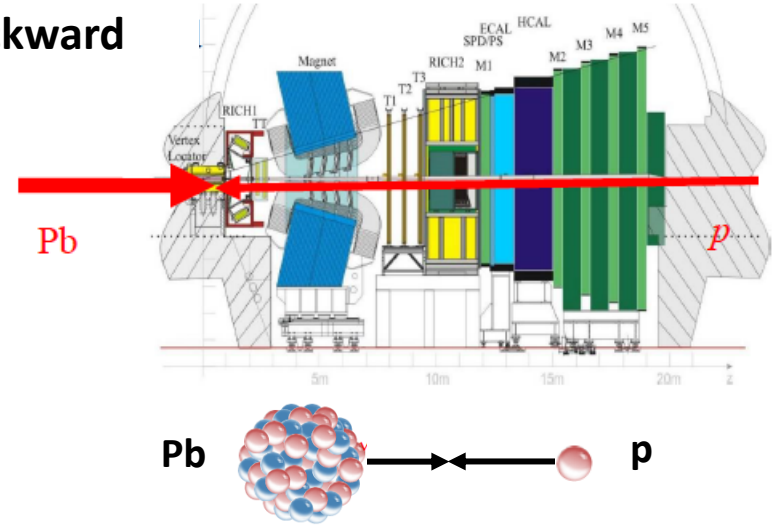

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Center-of-mass energy and int. lumi

- $\sqrt{s_{NN}} = 5.02$ TeV (2013)
  - pPb (1.06 nb^{-1}) + Pbp (0.52 nb^{-1})
- $\sqrt{s_{NN}} = 8.16$ TeV (2016)
  - pPb (13.6 nb^{-1}) + Pbp (21.8 nb^{-1})

Prompt charm production in pPb collisions

Prompt D^0 measurement in pPb at $\sqrt{s_{NN}} \simeq 5\ TeV$

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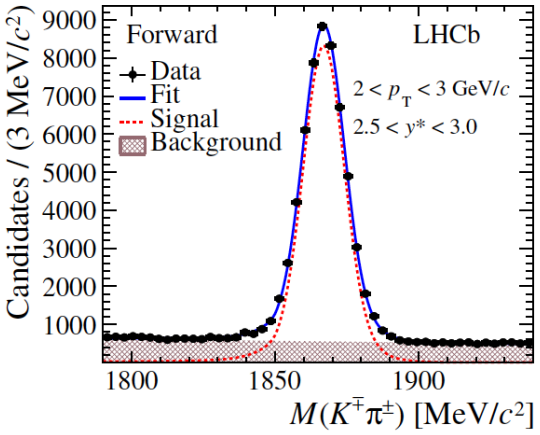

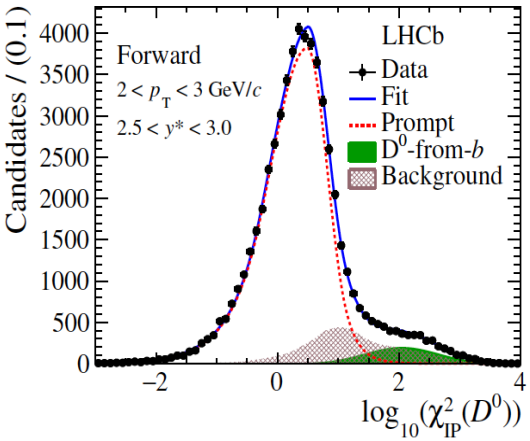

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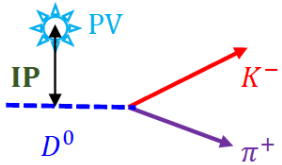
- Inclusive yield of D^0 candidates extracted through fit of inv. mass:
- Prompt D^0 selected from D^0-from-b through fit of IP distance distribution



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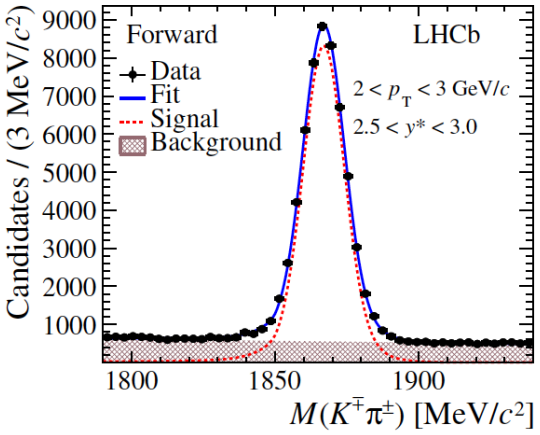

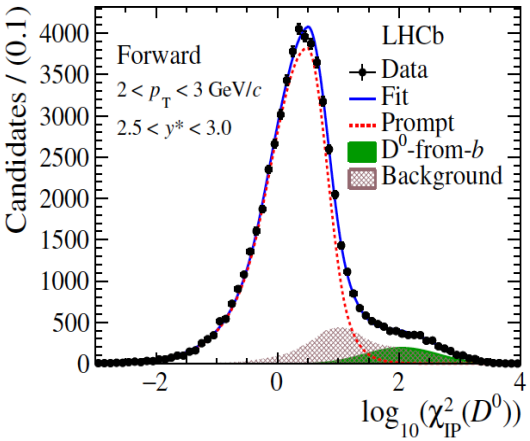

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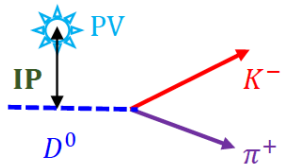
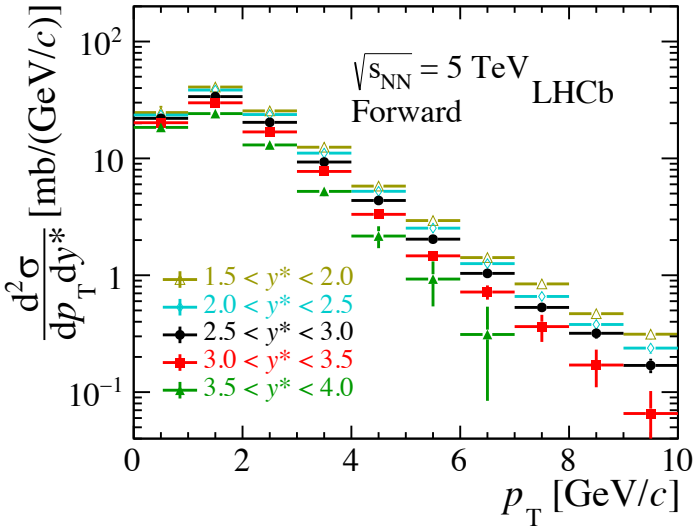
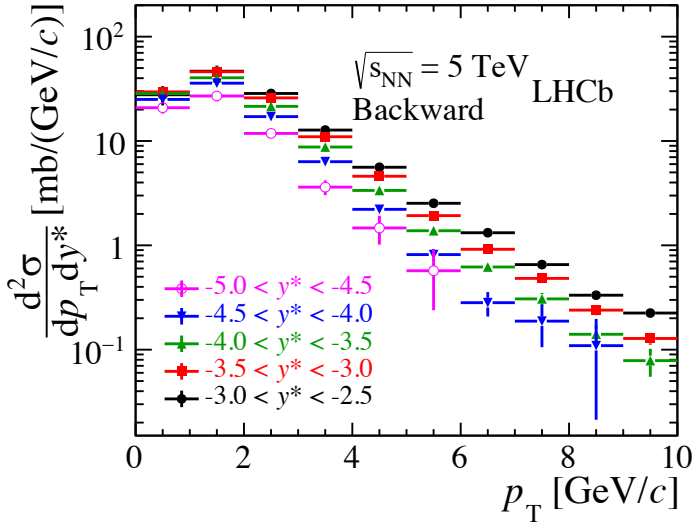




$\sigma_{forward} = 230.6 \pm 0.5 \pm 13.0$ mb



$\sigma_{backward} = 252.7 \pm 1.0 \pm 20.0$ mb

Prompt D^0 diff. cross section in pPb at $\sqrt{s_{NN}} \simeq 5\,TeV$

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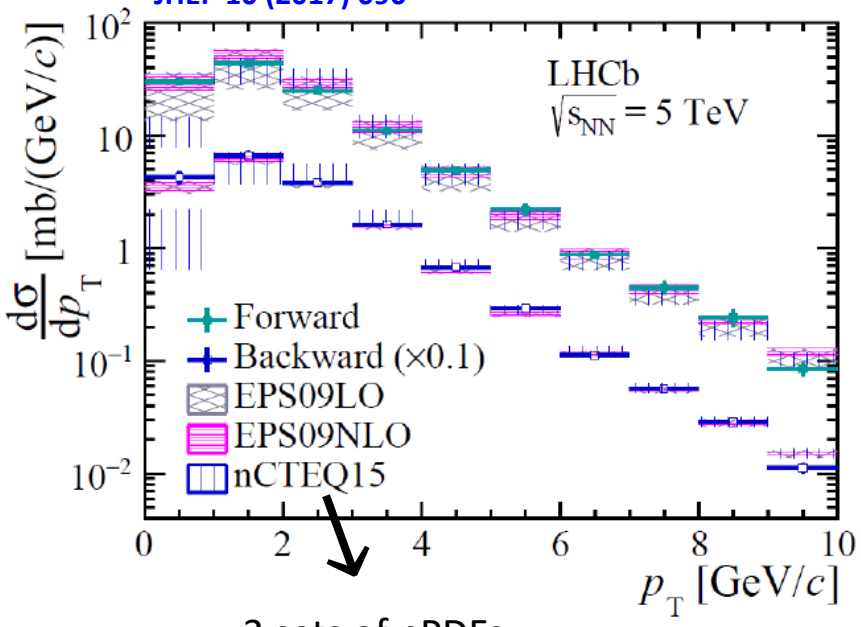
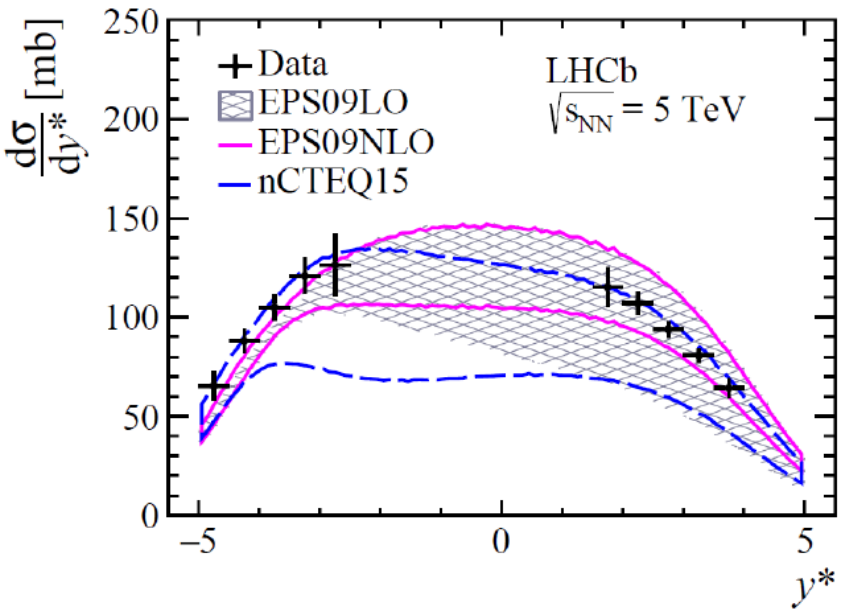


3 sets of nPDFs

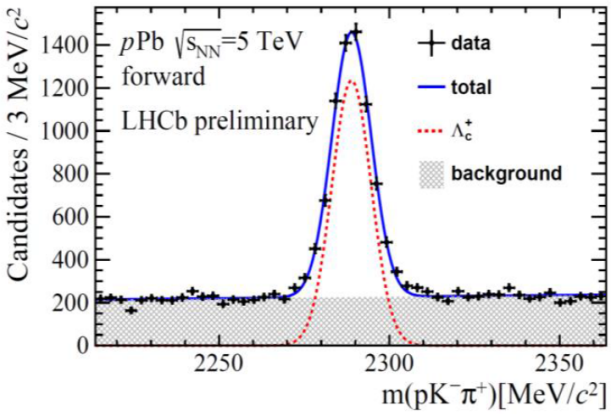


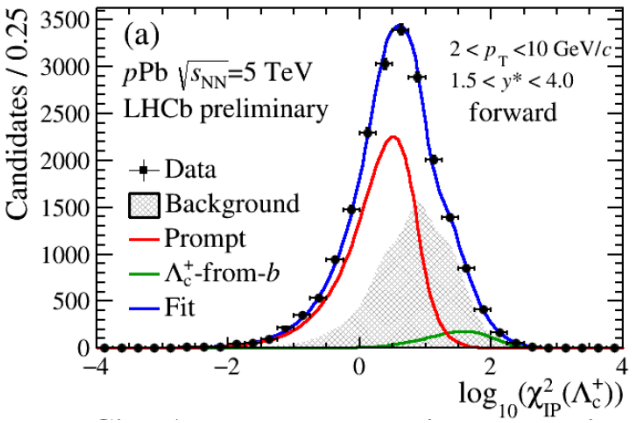
Eur. Phys. J. C77 (2017) 1
Comput. Phys. Commun. 184 (2013) 2562
Comput. Phys. Commun. 198 (2016) 238

- Data consistent with HELAC-Onia calculation including different nPDFs parametrizations
- Models constrained by existing LHC pp cross section measurements
- **Experimental uncertainties smaller than theoretical uncertainties!**

Prompt Λ_c^+ measurement in pPb at $\sqrt{s_{NN}} \simeq 5\,TeV$

LHCb-PAPER-2018-021 in preparation





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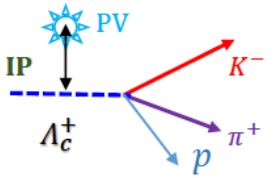
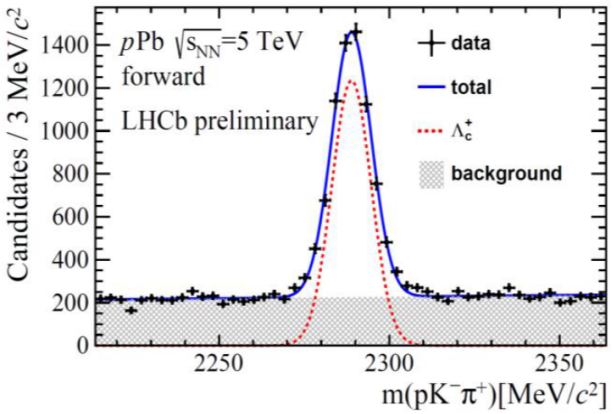
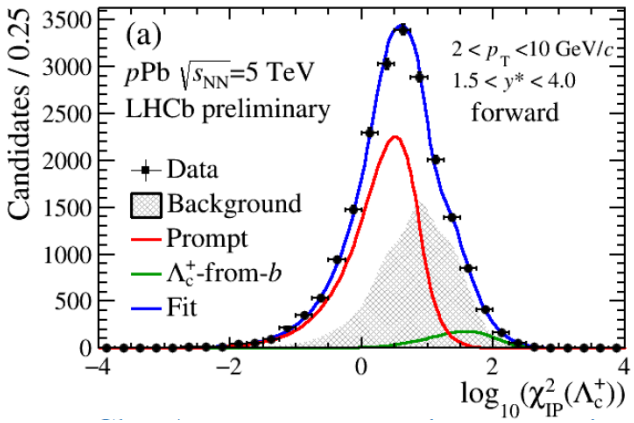


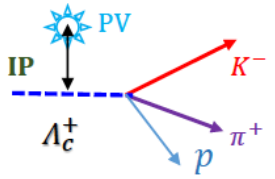
Prompt Λ_c^+ measurement in pPb at $\sqrt{s_{NN}} \simeq 5\ TeV$

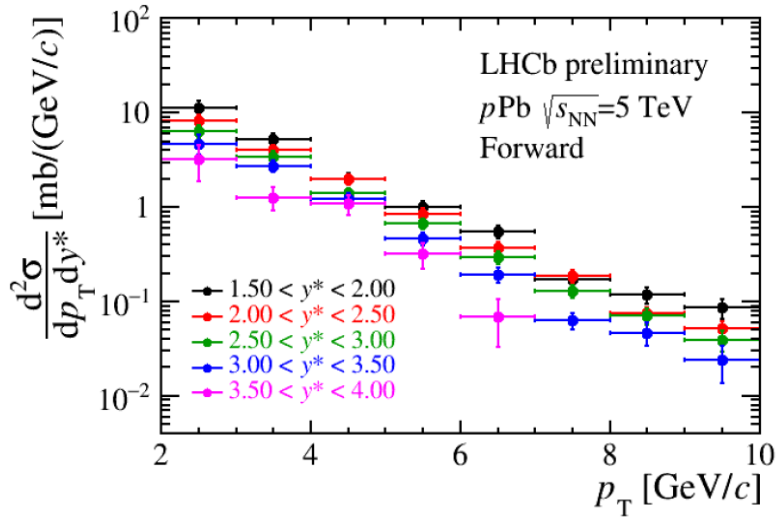
LHCb-PAPER-2018-021 in preparation

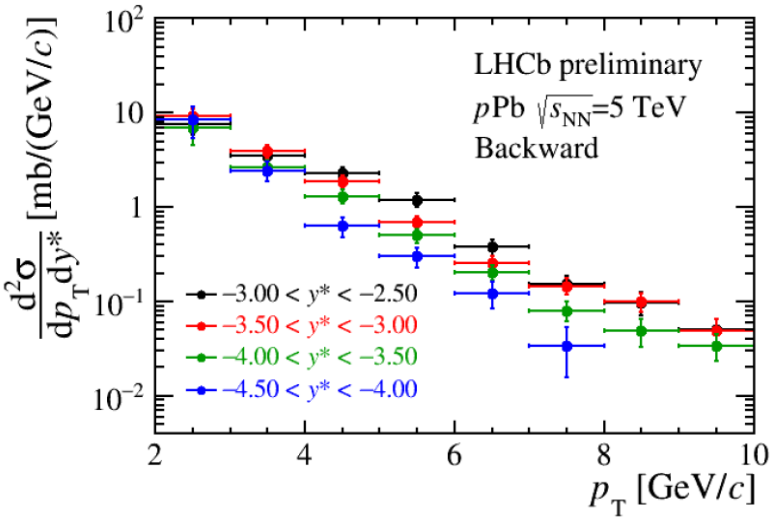




- Reconstr. via $\boldsymbol{\Lambda_c^+ \to pK^-\pi^+}$
- Inclusive yield of Λ_c^+ candidates through fit of inv. mass:
- Prompt Λ_c^+ selected from Λ_c^+-from-b through fit to IP distance distrib.







$\boldsymbol{\sigma_{Fwd} = 32.1 \pm 1.0 \pm 4.1\ mb}$

$\boldsymbol{\sigma_{Bwd} = 27.7 \pm 1.5 \pm 4.5\ mb}$

Prompt J/ψ production in pPb at $\sqrt{s_{NN}} = 8.16\,TeV$

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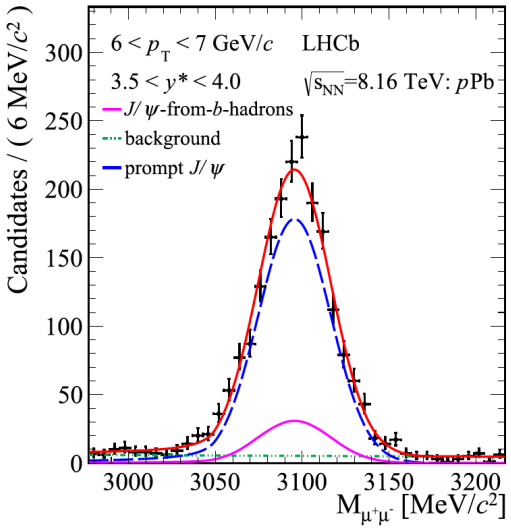
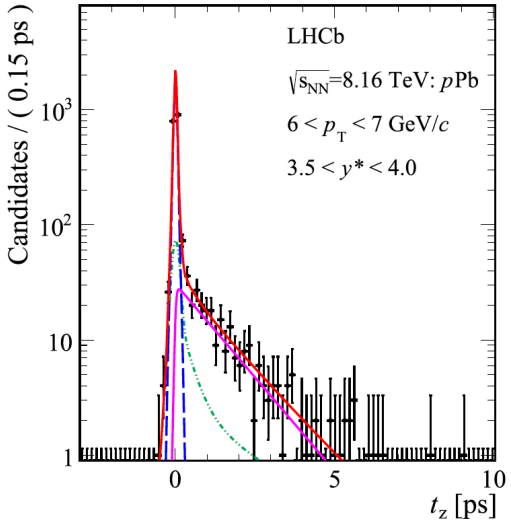


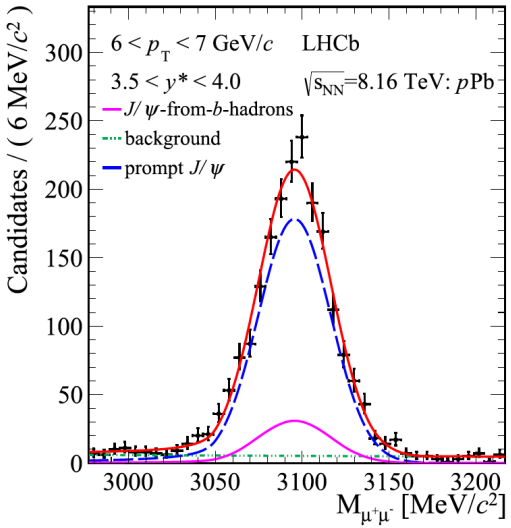


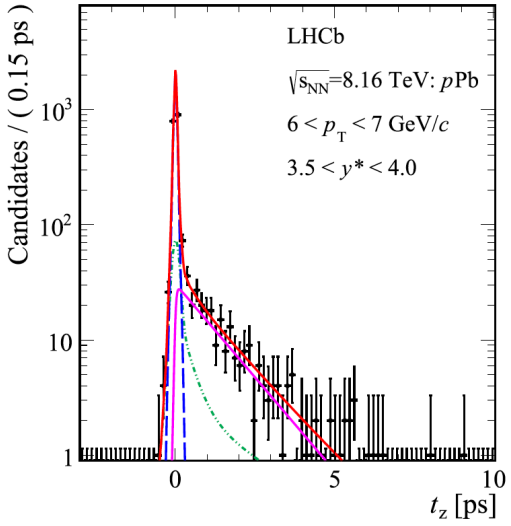
- Reconstruction via $\boldsymbol{J/\psi \to \mu^-\mu^+}$
- Inclusive yield of J/ψ candidates extracted through fit of inv. mass:
- Prompt J/ψ selected from J/ψ -from-b through fit of **pseudo-proper time** distrib.:

$$t_Z = (Z_{J/\psi} - Z_{PV}) \times M_{J/\psi}/p_Z$$

Prompt J/ψ production in pPb at $\sqrt{s_{NN}} = 8.16\,TeV$

PLB 774 (2017) 159





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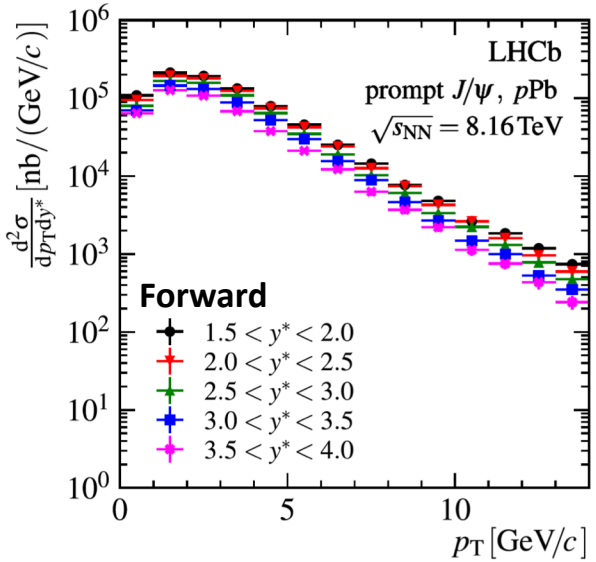

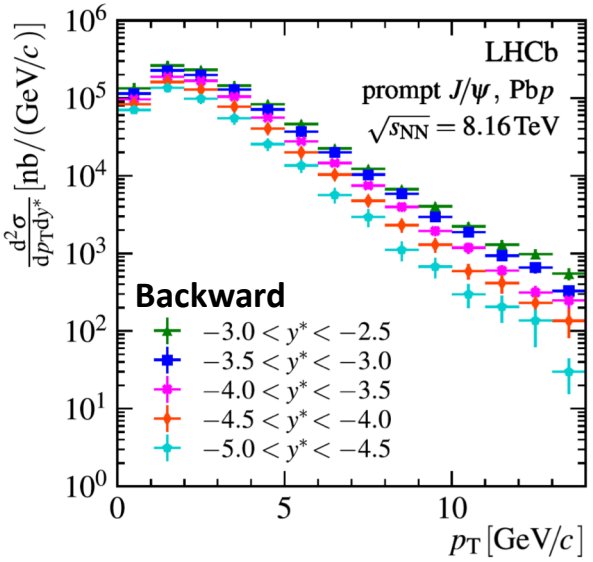

$$\boldsymbol{\sigma_{Fwd} = 1625 \pm 4 \pm 117\ \mu b}$$

$$\boldsymbol{\sigma_{Bwd} = 1692 \pm 4 \pm 182\ \mu b}$$

Nuclear Modification Factor (NMF)

$$R_{p\mathrm{Pb}}(p_{\mathrm{T}}, y^*) \equiv \frac{1}{A} \frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_{\mathrm{T}}, y^*)/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{pp}(p_{\mathrm{T}}, y^*)/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*} \qquad (A = 208)$$

NMF for D^0 (5 TeV) and J/ψ (8 TeV) production in pPb

Forward (y^* integrated) **Backward (y^* integrated)**

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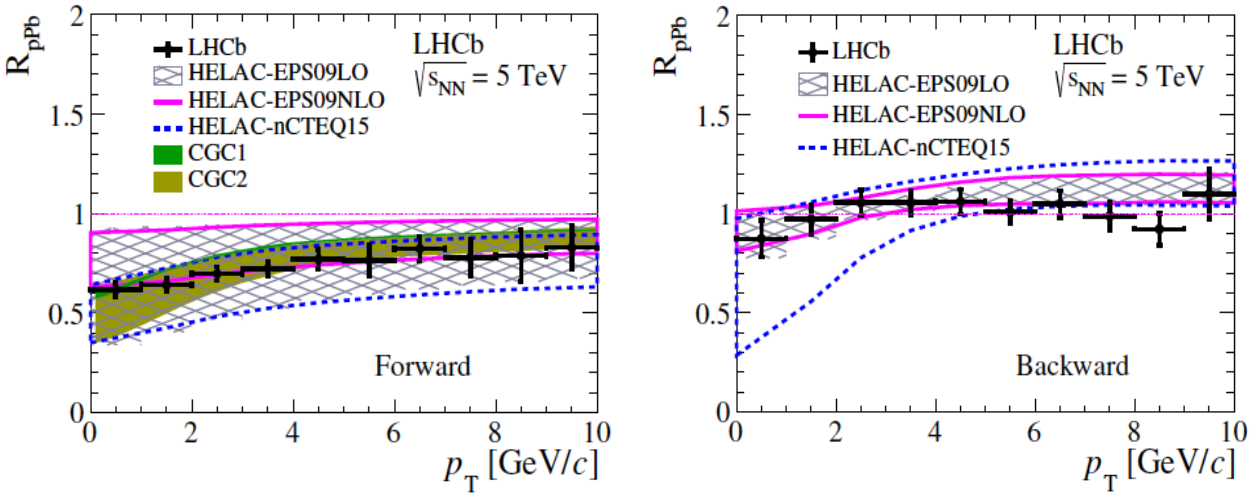
Prompt D^0



- **Fwd**: R_{pPb} significantly suppressed at small p_T
- **Bwd**: $R_{pPb} \approx 1$
- consistent with models (nPDFs, CGC)

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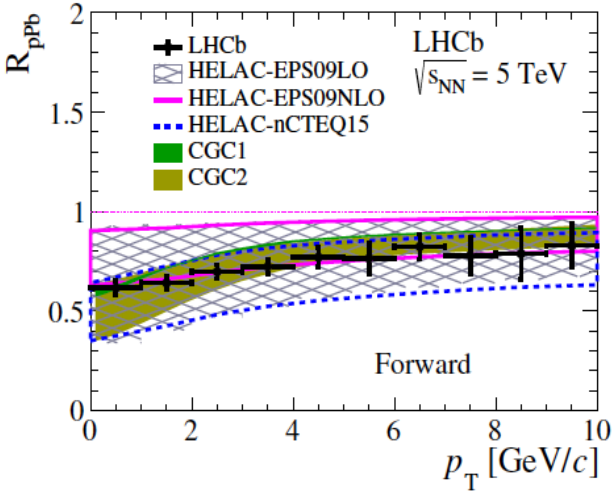
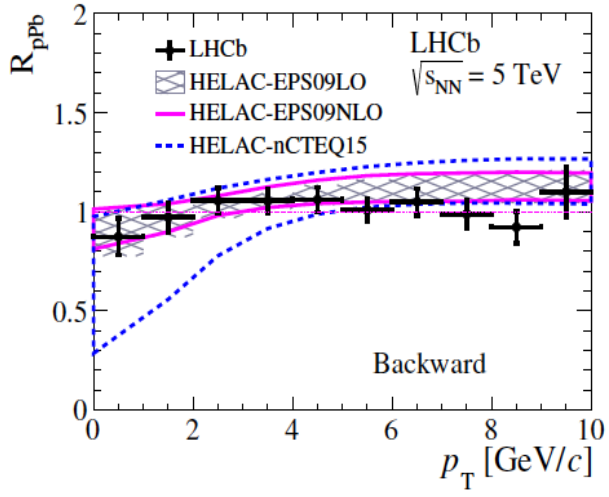
NMF for D^0 (5 TeV) and J/ψ (8 TeV) production in pPb

Forward (y^* integrated) **Backward (y^* integrated)**

JHEP 10 (2017) 090

Prompt D^0





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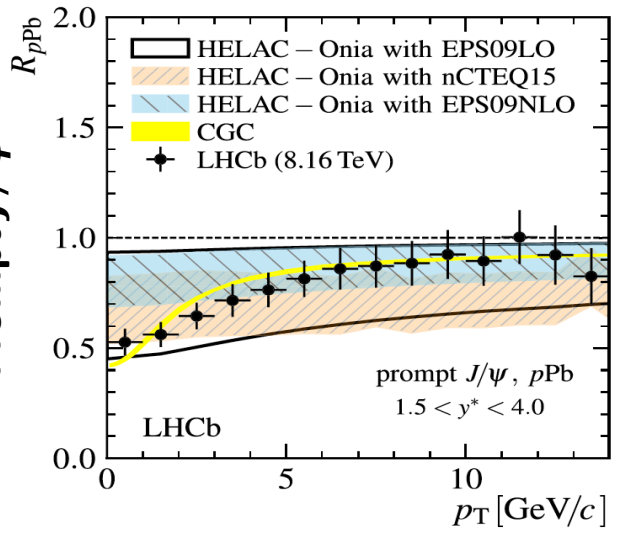
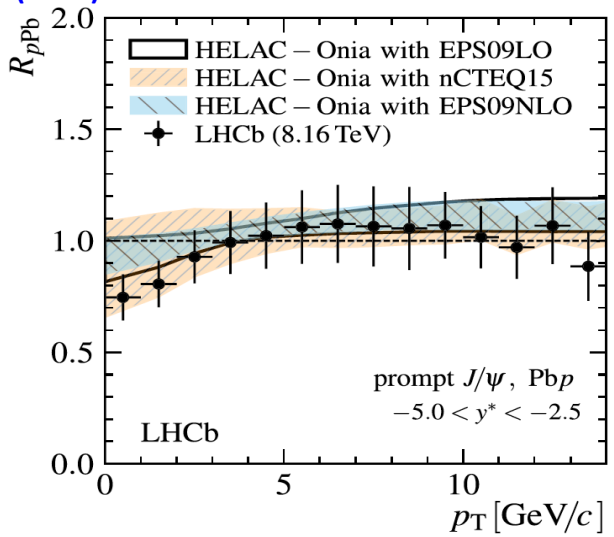
Prompt J/ψ





- Compatible with previously published 5 TeV data

NMF for D^0 (5 TeV) and J/ψ (8 TeV) production in pPb

Forward (y^* integrated) **Backward (y^* integrated)**

Prompt D^0

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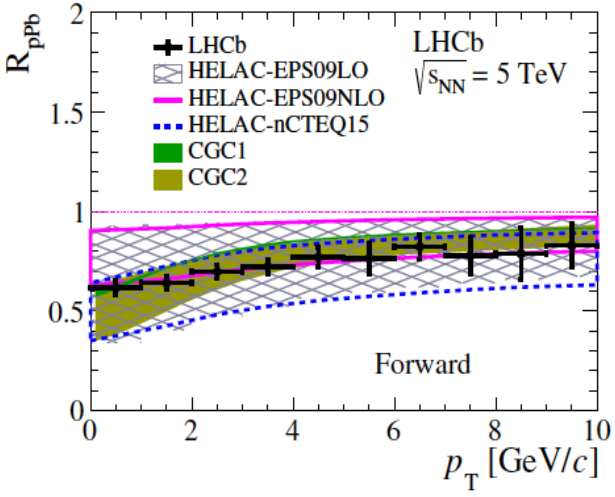

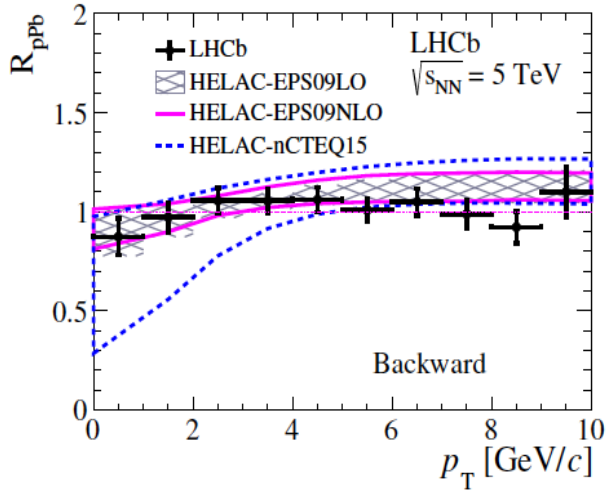

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Prompt J/ψ

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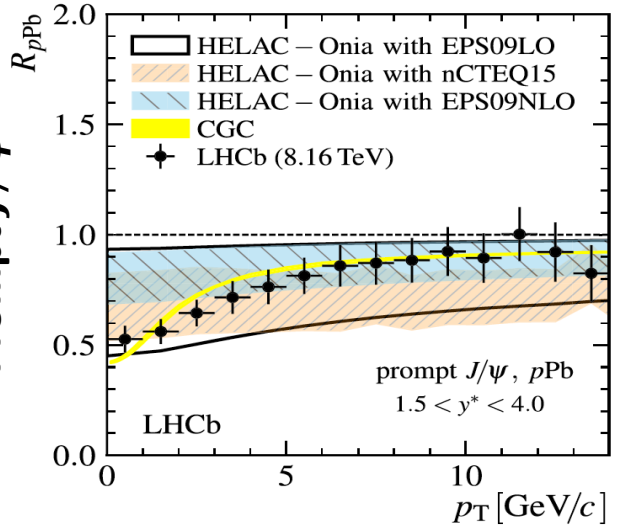
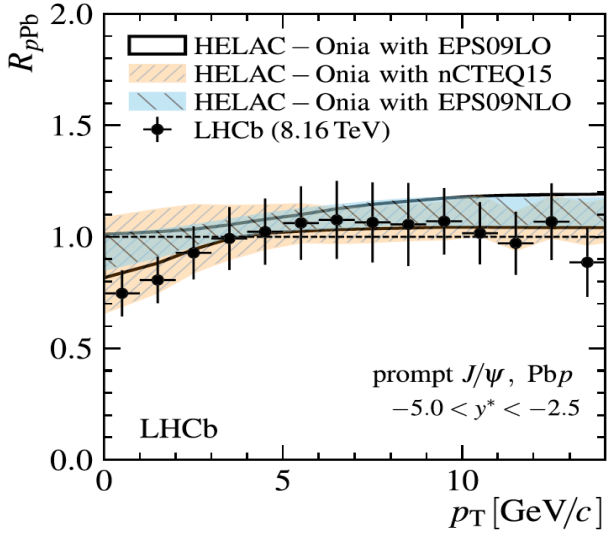
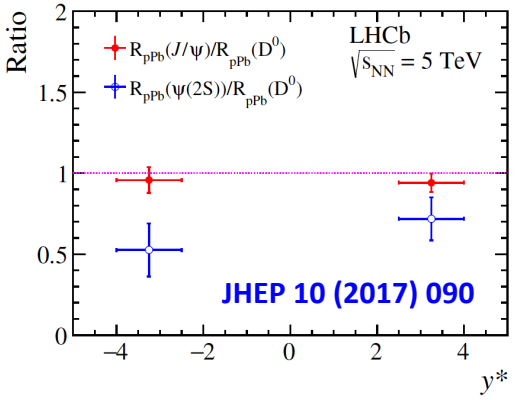




- Compatible with previously published 5 TeV data
- Similar behavior of D^0



Forward-Backward ratios

$$R_{\mathrm{FB}}(p_{\mathrm{T}}, y^*) \equiv \frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_{\mathrm{T}}, +|y^*|)/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{\mathrm{Pb}p}(p_{\mathrm{T}}, -|y^*|)/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*}$$

Constitutes another excellent probe to constrain the nPDF uncertainties!

FB ratios for prompt D^0, Λ_c^+ and J/ψ production in pPb

Prompt D^0 (5 TeV)

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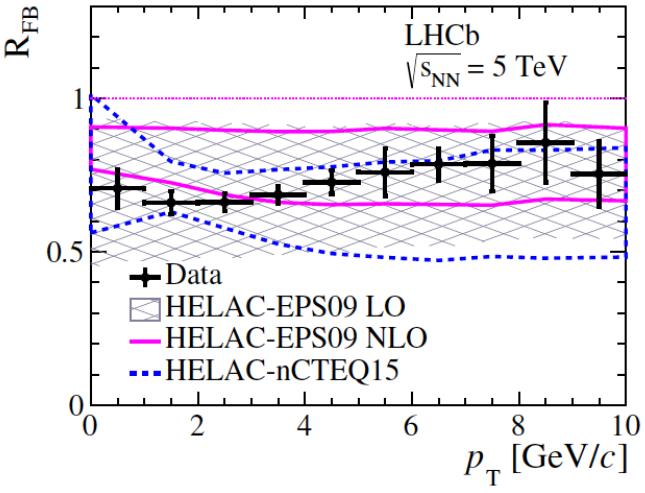

Prompt Λ_c^+ (5 TeV)

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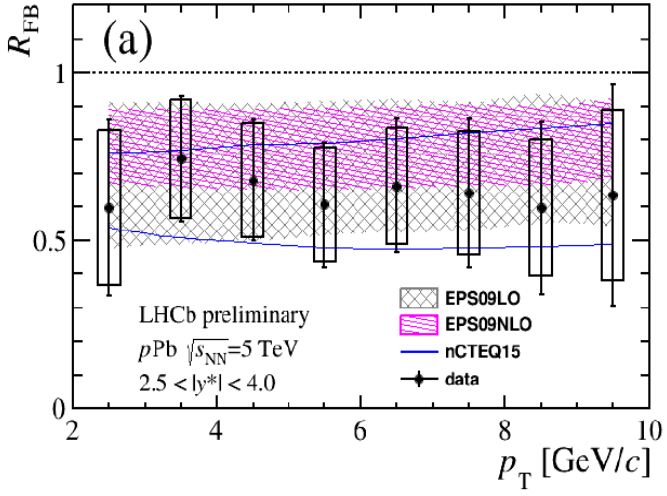

Prompt J/ψ (8 TeV)

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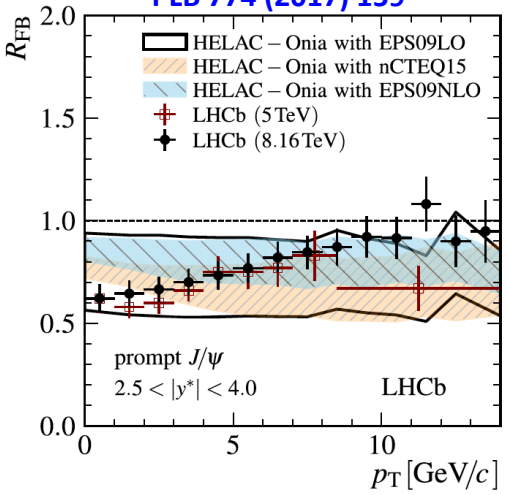
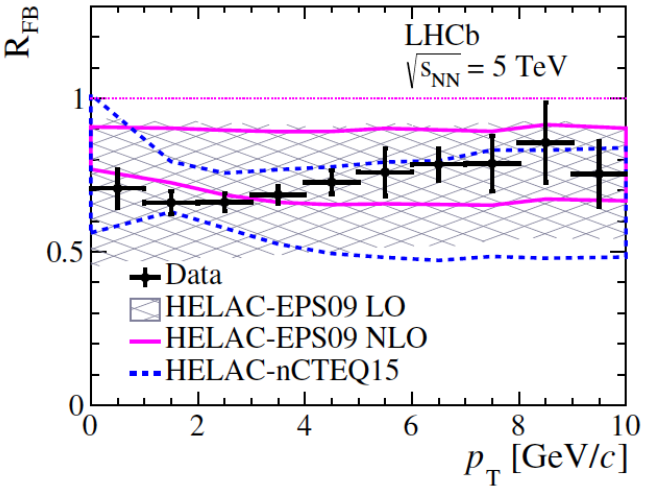


- **Large FB asymmetry are observed → larger production rate in the backward region compared to the forward region**

FB ratios for prompt D^0, Λ_c^+ and J/ψ production in pPb

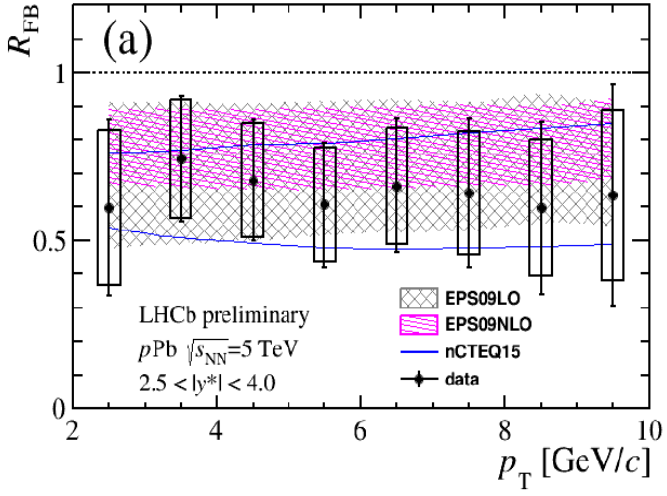
Prompt D^0 (5 TeV)

JHEP 10 (2017) 090



Prompt Λ_c^+ (5 TeV)

LHCb-PAPER-2018-021 in preparation



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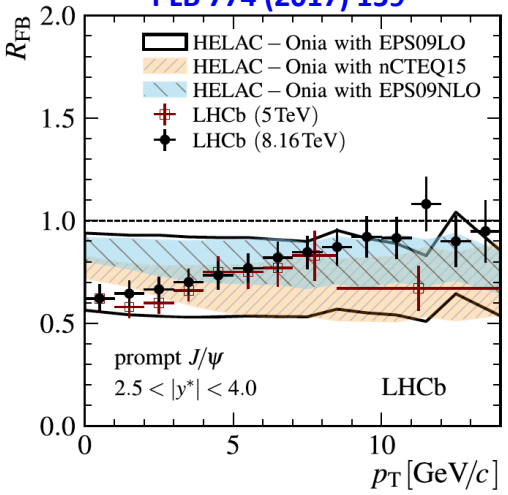

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Comput. Phys. Commun. 184 (2013) 2562
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- **Large FB asymmetry are observed → larger production rate in the backward region compared to the forward region**
- Compared to HELAC-Onia calculations (including different nPDFs parametrizations)
- Data are consistent with theory predictions within uncertainties

Charmed baryon/meson ratios

$$R_{\Lambda_c^+/D^0} = \frac{\sigma_{\Lambda_c^+}(y^*, p_{\mathrm{T}})}{\sigma_{D^0}(y^*, p_{\mathrm{T}})}$$

- Provides information on hadronization mechanisms in charm sector
- Sensitive to the FF of a c-quark into Λ_c^+ and D^0 hadrons
- Uncertainties in nPDFs mostly cancel out in the ratio

Charmed baryon/meson production ratio in pPb at 5 TeV

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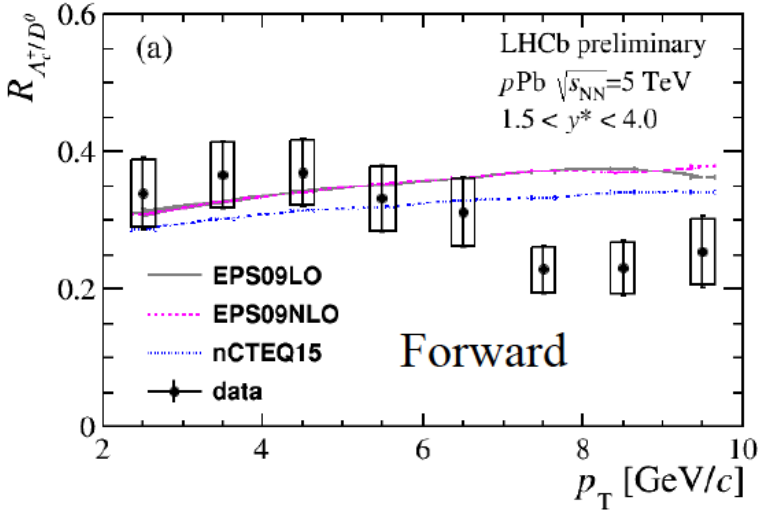
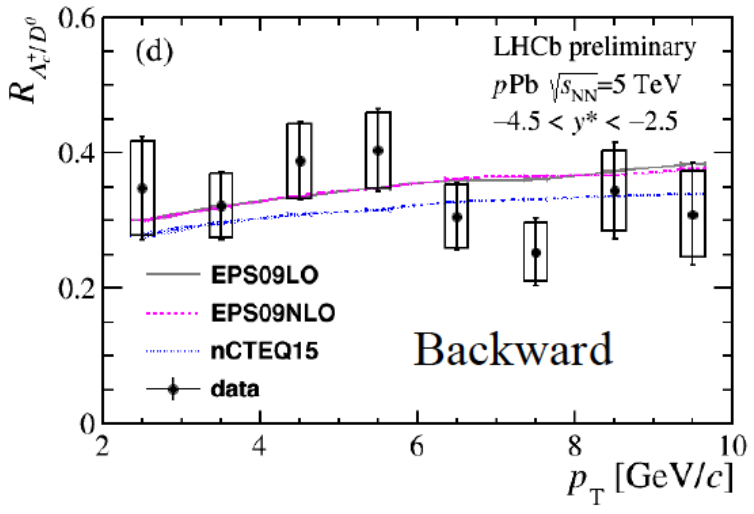
Forward

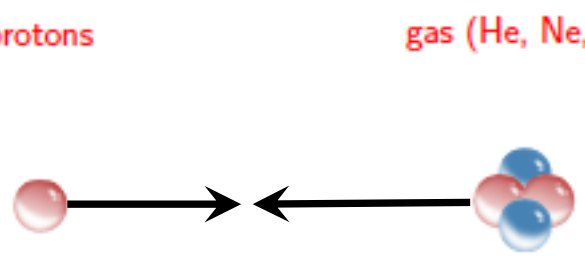


Backward



- Models constrained by existing LHC pp cross section measurements
- All predictions slightly increase with p_T
- Data consistent with calculations within uncertainty except for high-p_T in forward region

pA collisions in fixed-target mode



Fixed-target measurements @ LHCb

- The study of $c\bar{c}$ production in pA collisions on different nuclear targets is needed for a correct interpretation of the **charmonium suppression** observed in heavy-ion collisions

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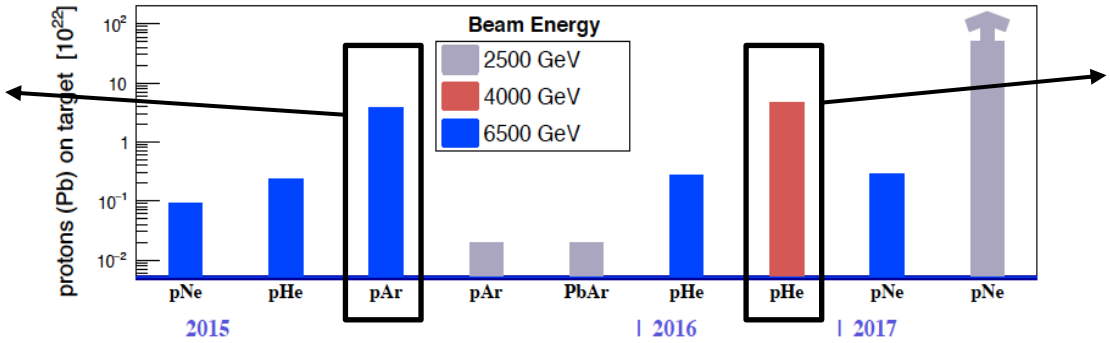
$\sqrt{s_{NN}} = 110.4$ GeV



$\sqrt{s_{NN}} = 86.6$ GeV

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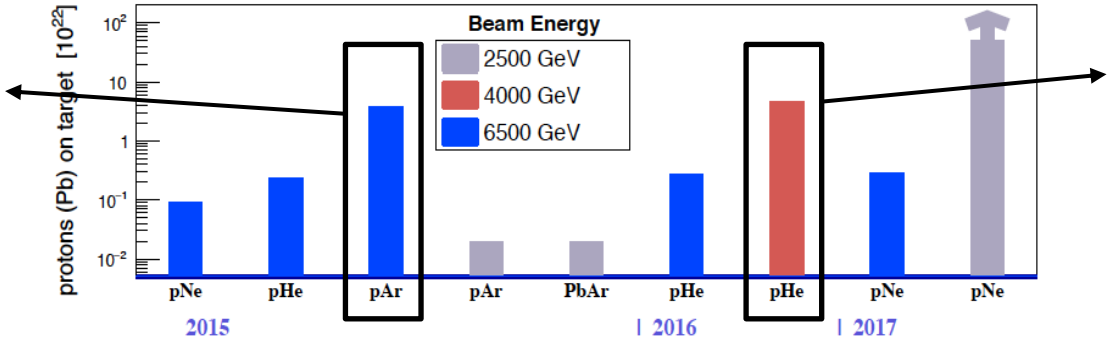
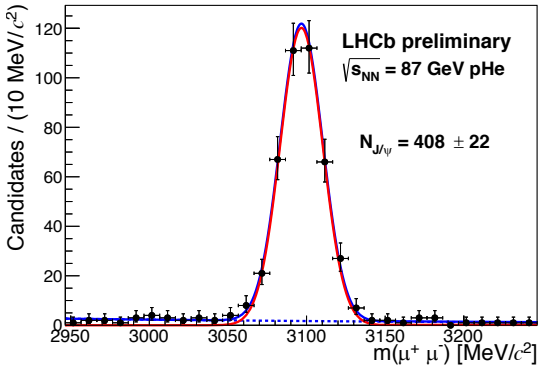
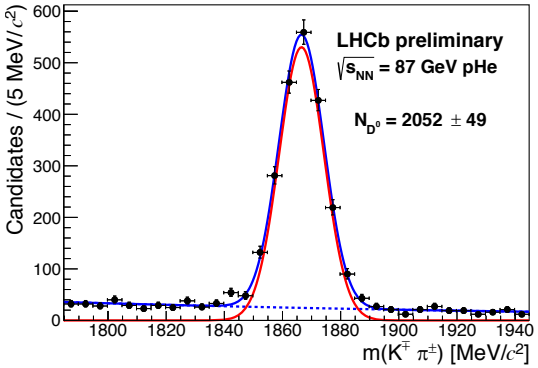


$\sqrt{s_{NN}} = 86.6$ GeV

- The yields of prompt J/ψ and D^0 are obtained in an unbinned ML fit of the invariant mass distributions using $J/\psi \to \mu^+\mu^-$ and $D^0 \to K\pi$



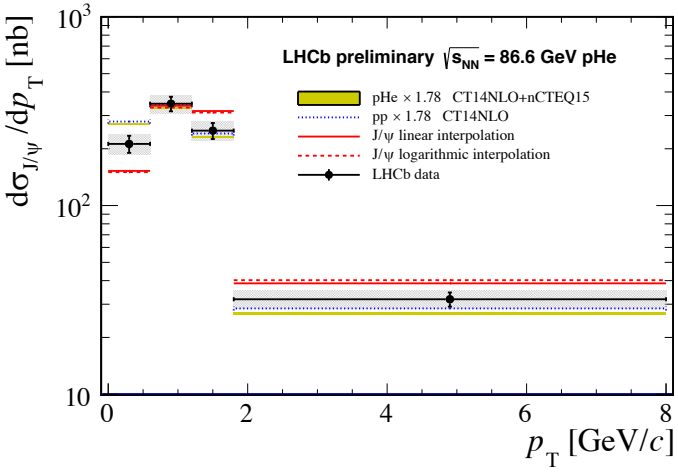


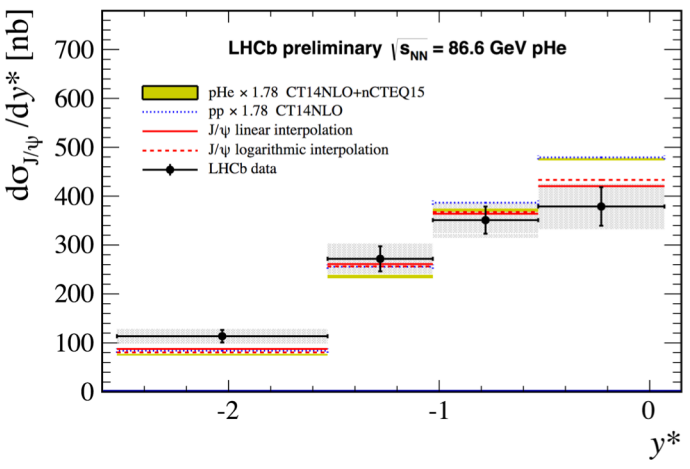
LHCb-PAPER-2018-023
(in preparation)

J/ψ and D^0 production cross section on He target at 87 GeV

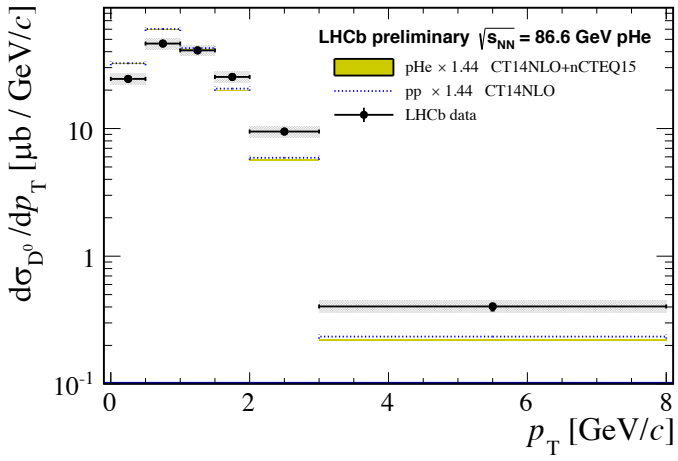
LHCb-PAPER-2018-023 (in preparation)

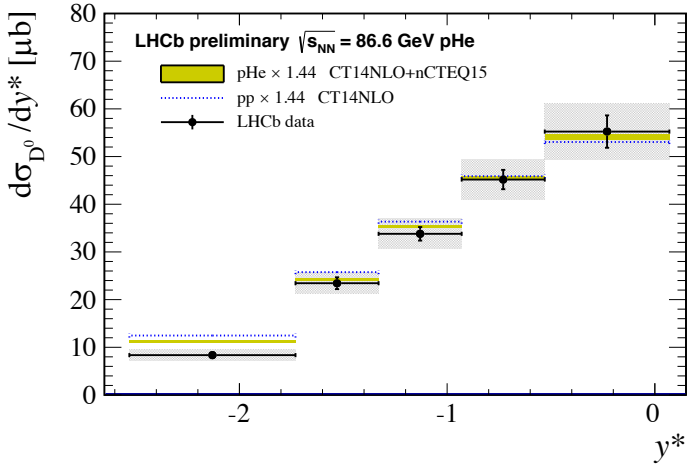
J/ψ





D^0



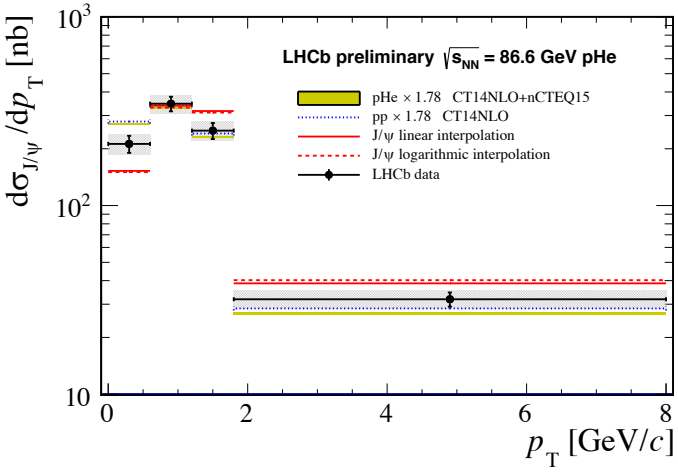


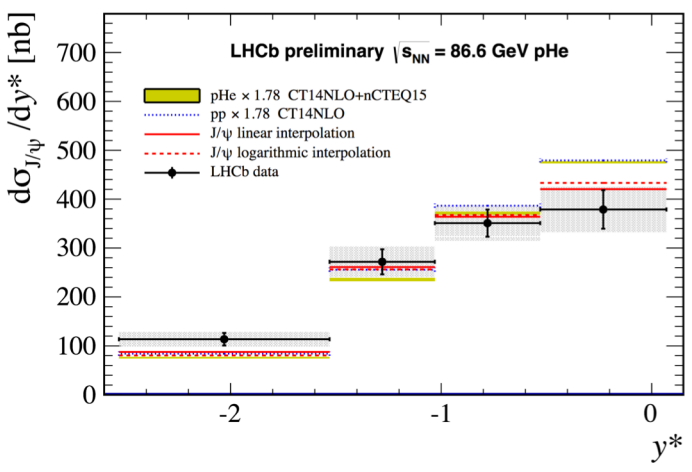
J/ψ and D^0 production cross section on He target at 87 GeV

LHCb-PAPER-2018-023 (in preparation)

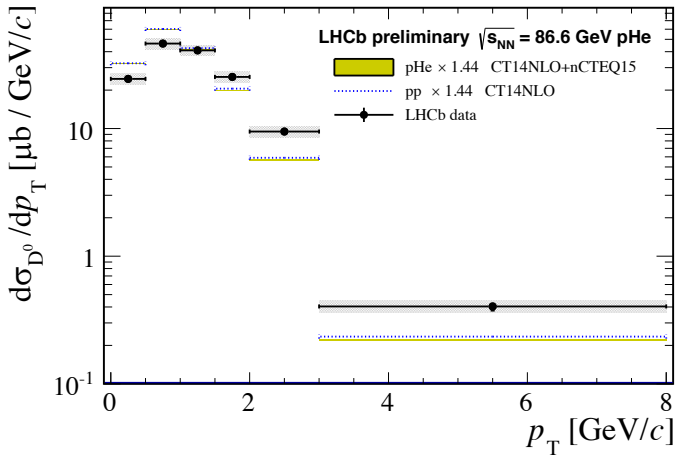
(models from JHEP 1303 (2013) 122)

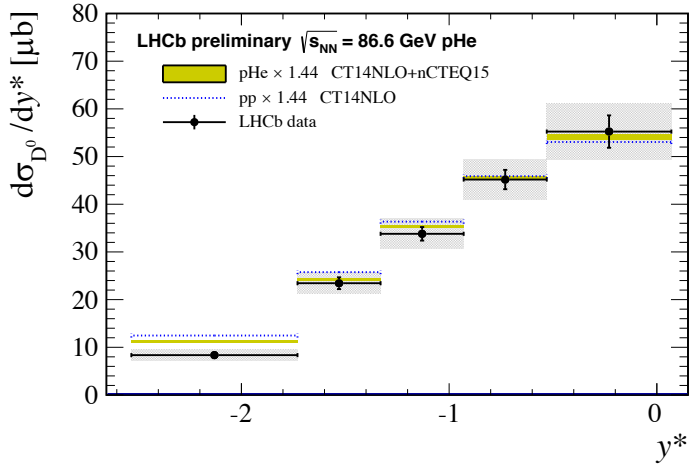
J/ψ





D^0





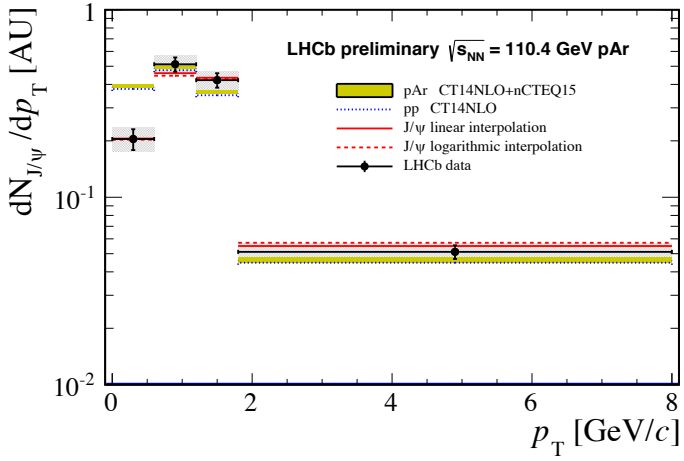
- HELAC-Onia calculations underestimate data (need scale factors)
- y^* dependence pretty well described by models, but p_T dependence not so well described
- Data are also compared with some phenomenological models

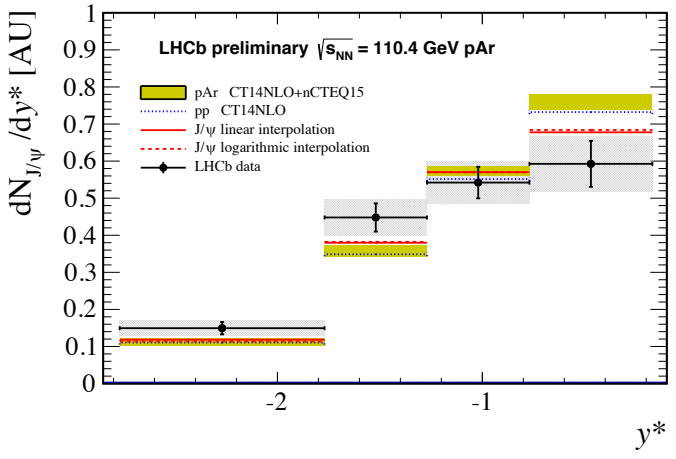
J/ψ and D^0 differential yields on Ar target at 110 GeV

LHCb-PAPER-2018-023 (in preparation)

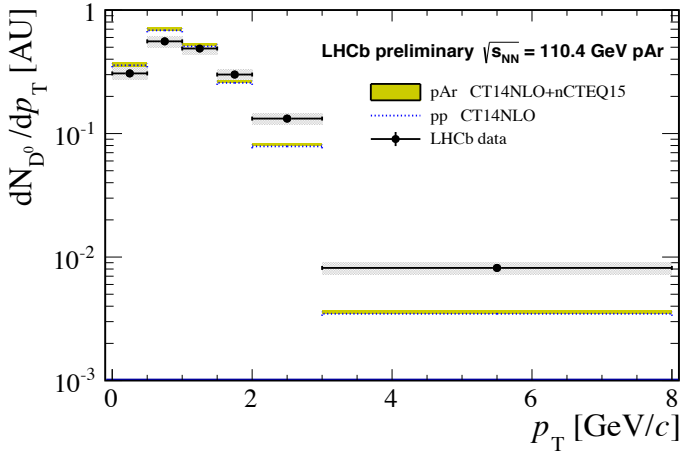
(models from JHEP 1303 (2013) 122)

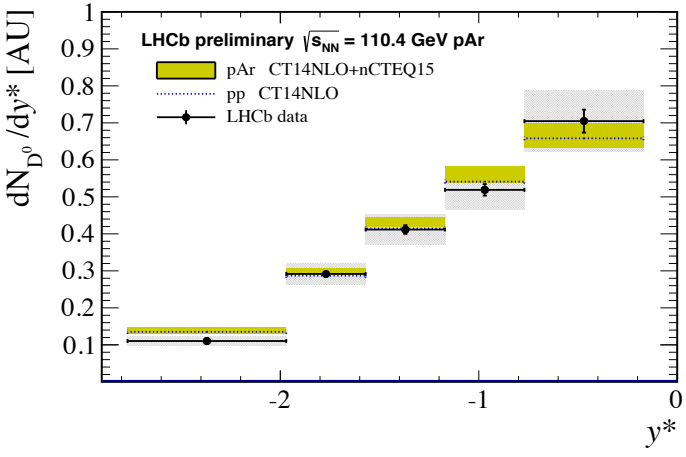
J/ψ





D^0





- HELAC-Onia calculations underestimate data (need scale factors)
- y^* dependence pretty well described by models, but p_T dependence not so well described
- Data are also compared with some phenomenological models

Conclusions

- **LHCb provided measurements of prompt D^0, Λ_c^+ and J/ψ production in pPb collisions**
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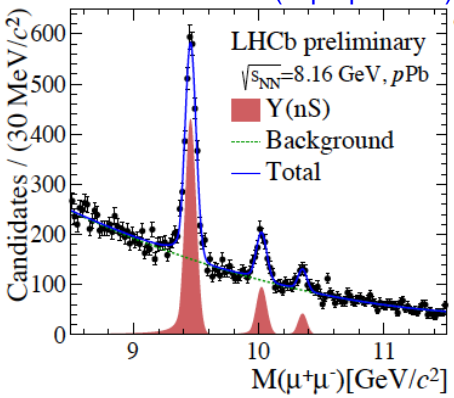
- **LHCb also provided first measurements of prompt D^0 and J/ψ production in pHe and pAr fixed-target collisions**
- **Upcoming results from high-statistics pPb data at 8 TeV:**
  - Precision measurement of prompt open-charm observables
  - Open-beauty production
  - Bottomonium production

LHCb-PAPER-2018-035 (in preparation)

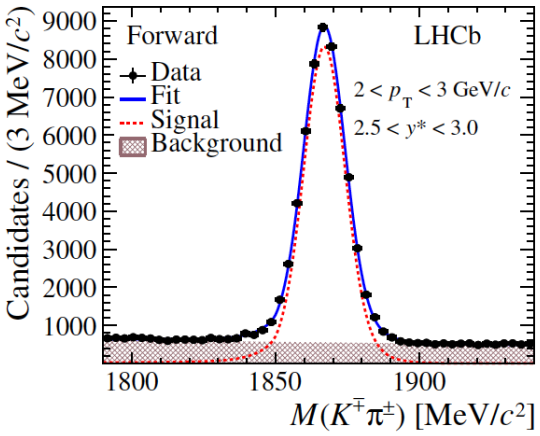


Backup

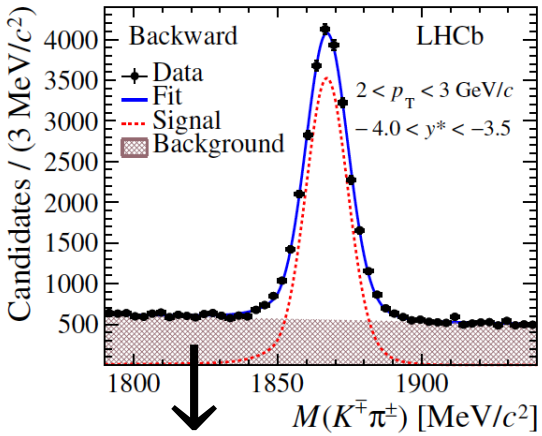
Prompt D^0 measurement in pPb at $\sqrt{S_{NN}} \simeq 5\ TeV$

JHEP 10 (2017) 090

Forward



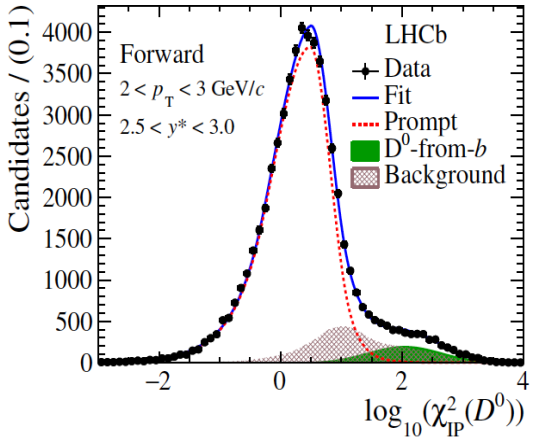
Backward



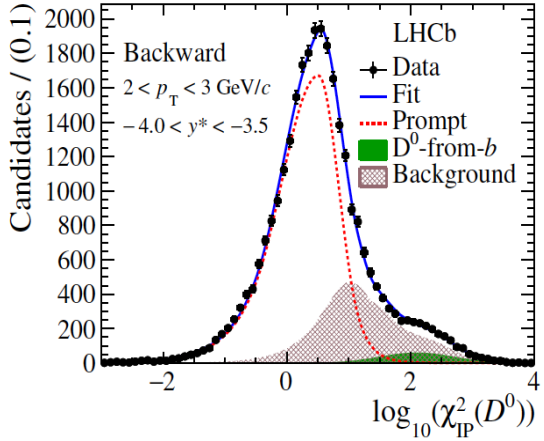
- Reconstr. via $D^0 \to K^-\pi^+$
- D^0 candidates selected through fit of inv. mass:
- **Signal**: CrystalBall + Gaussian
- **Background**: linear
- Obtain D^0 inclusive yield and number of background candidates

Larger bkg yield due to higher event multiplicity

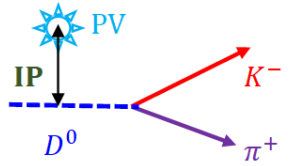
Forward



Backward



- Prompt D^0 selected from D^0-from-b through fit of IP distance distribution:



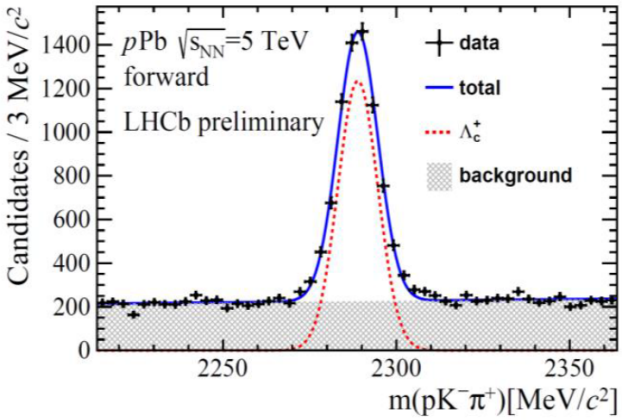
- **Prompt D^0 and D^0-from-b** shapes estimated from simulation
- **Prompt D^0**: modified gaussian
- **D^0-from-b**: gaussian
- **Bkg. shape** from sideband in data

➢ **Both fits are performed independently in each bin of (p_T, y^*)**

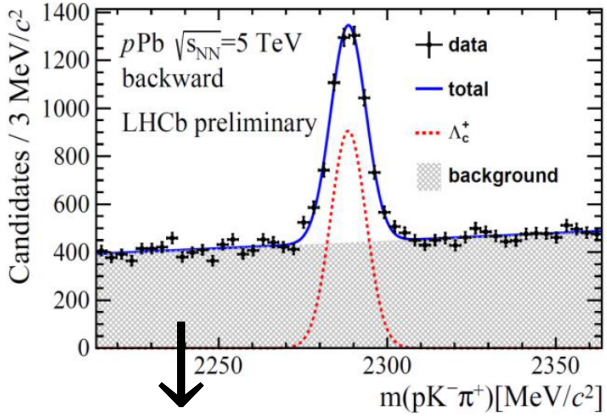
Prompt Λ_c^+ measurement in pPb at $\sqrt{S_{NN}} \simeq 5\ TeV$

LHCb-PAPER-2018-021 in preparation

Forward



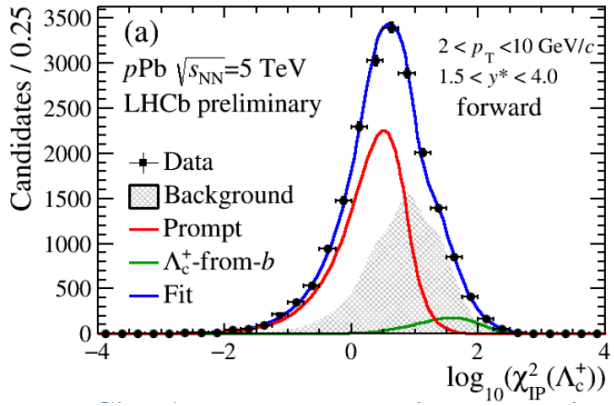
Backward



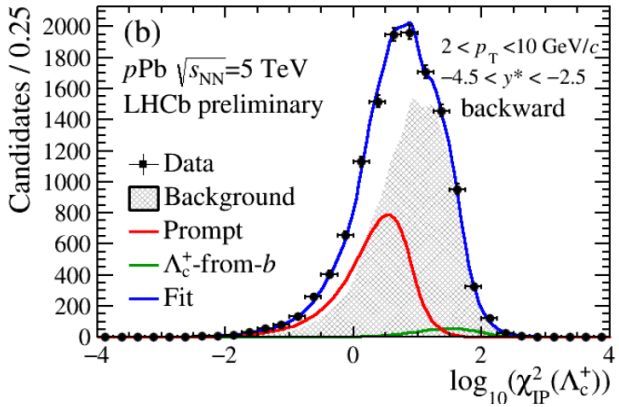
Larger bkg yield due to higher event multiplicity

- Reconstr. via $\Lambda_c^+ \to pK^-\pi^+$
- Λ_c^+ candidates through fit of inv. mass:
- **Signal**: Gaussian
- **Background**: linear
- Obtain Λ_c^+ inclusive yield and n. of background candidates

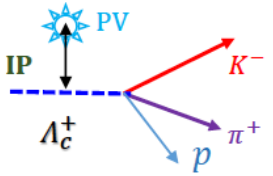
Forward



Backward



- Prompt Λ_c^+ selected from Λ_c^+-from-b through fit to IP distance distribution:

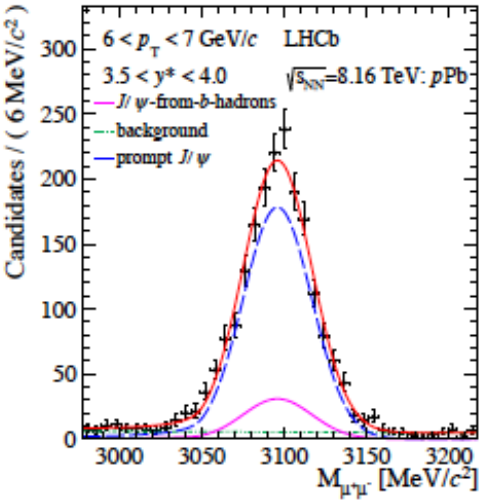


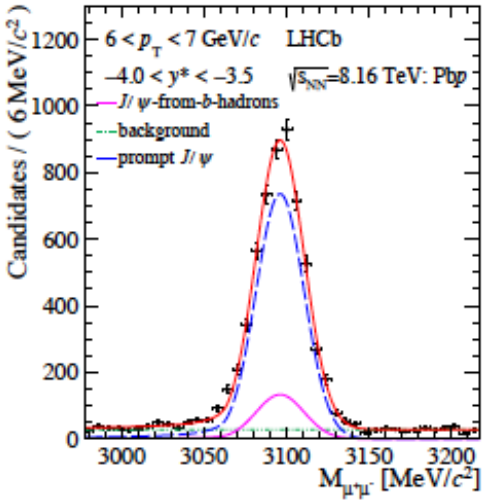
- **Prompt Λ_c^+ and Λ_c^+-from-b** shapes estimated from simulation and modelled with 2 Bukin functions
- **Bkg. shape** from sideband in data

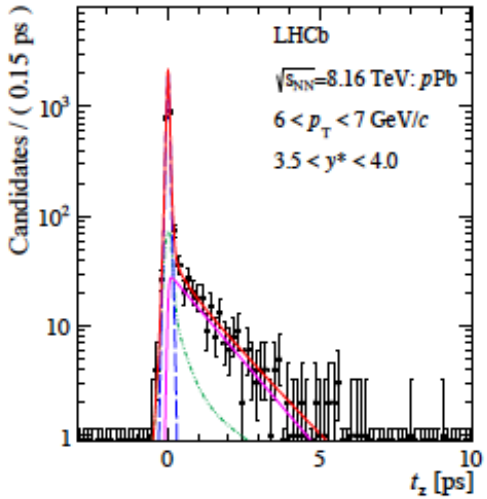
➢ **Both fits are performed independently in each bin of (p_T, y^*)**

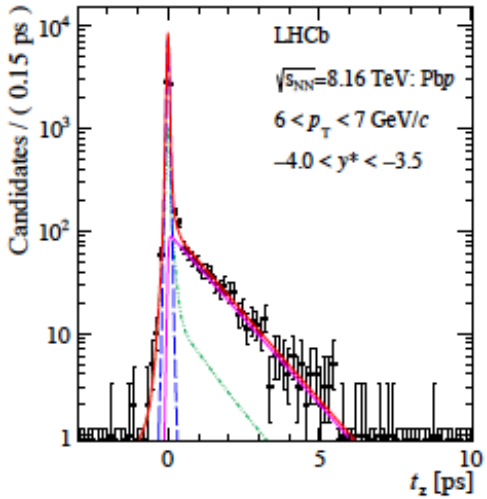
Prompt J/ψ production in pPb at $\sqrt{S_{NN}} \simeq 8.16\ TeV$

[PLB 774(2017) 159-178]









Mass distribution:
Signal: Crystal Ball
Background: exponential

Pseudo-proper time:

$t_Z = (Z_{J/\psi} - Z_{PV}) \times M_{J/\psi}/p_Z$

Signal: $\delta\ (t_Z)$ for prompt J/ψ;
Exponential for J/ψ-from-b.
Background: empirical function from sideband

Total yields:

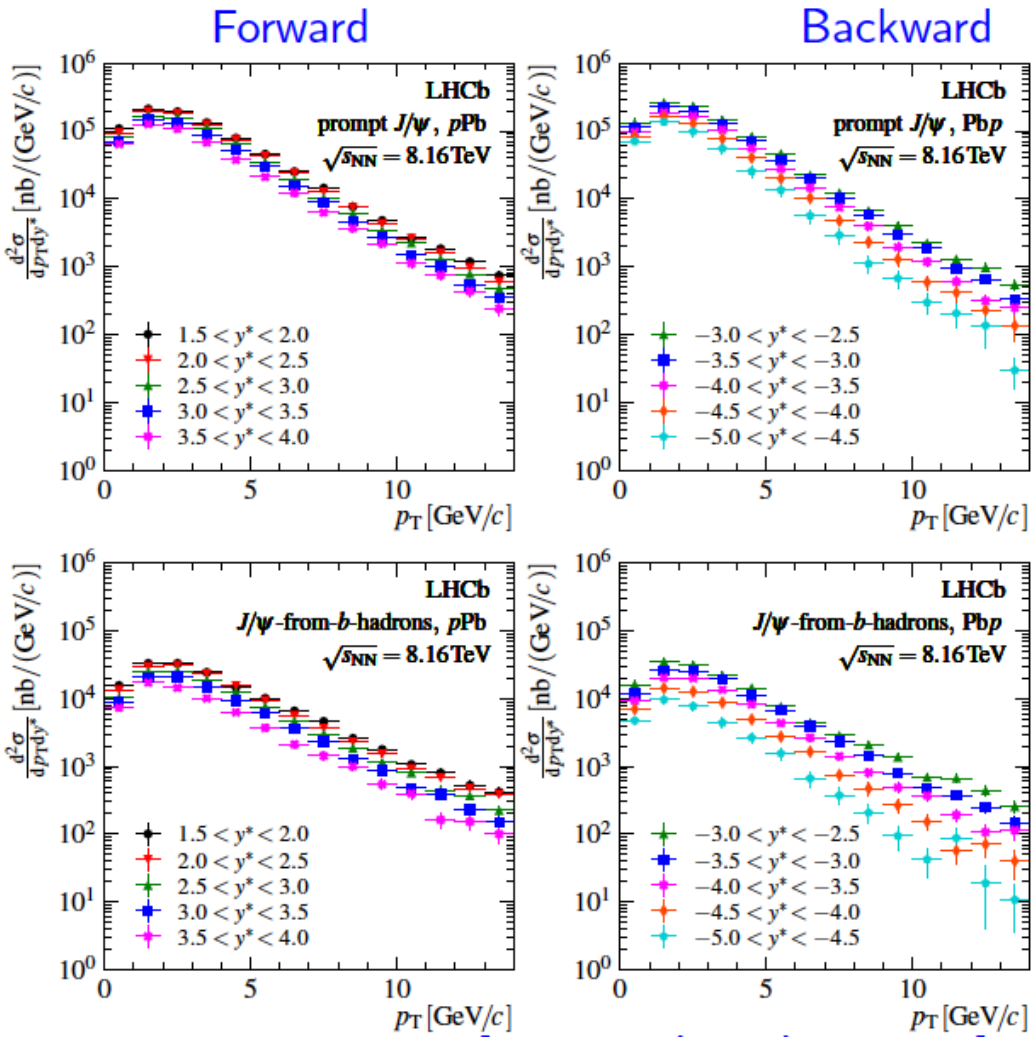
	prompt	from-b
Forward:	$\sim 3.8 \times 10^5$;	$\sim 6.7 \times 10^4$
Backward:	$\sim 5.6 \times 10^5$;	$\sim 7.1 \times 10^4$

J/ψ production in pPb at $8.16\,TeV$

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_\mathrm{T}\mathrm{d}y^*} = \frac{N(\mathrm{J}/\psi \to \mu^+\mu^-)}{\mathcal{L}\cdot\epsilon_{tot}\cdot\mathcal{B}\cdot\Delta p_\mathrm{T}\cdot\Delta y^*}$$

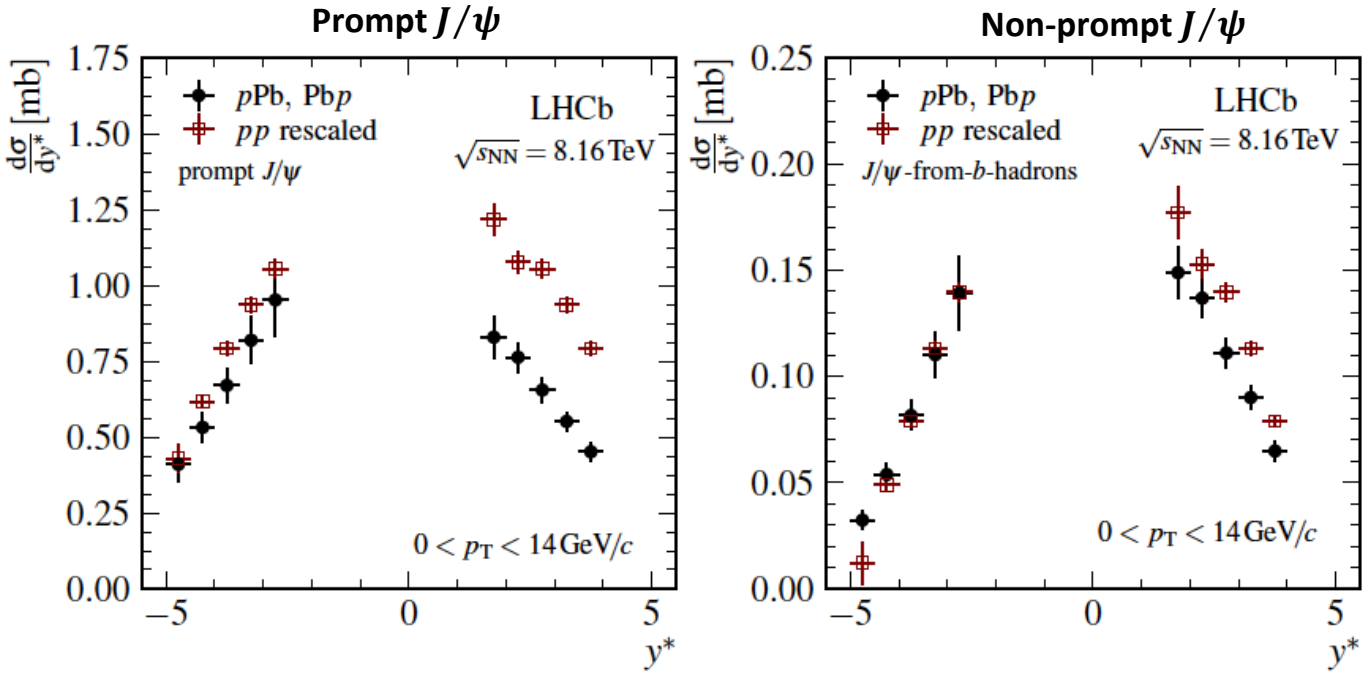
- N: number of reconstructed prompt J/ψ or J/ψ-from-b;
- $\mathcal{B}$: branching fraction of $J/\psi \to \mu^+\mu^-$ decay ($\sim 6\%$) [PDG];

[PLB 774(2017) 159-178]



J/ψ production in pPb at $8.16\ TeV$

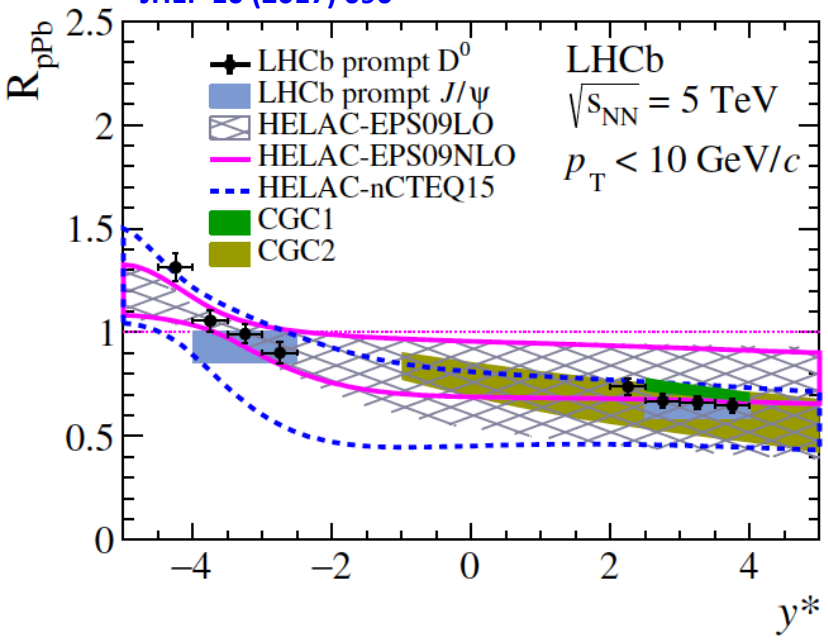
PLB 774 (2017) 159



- Sizeable Fwd-Bwd asymmetry observed for both pp and pPb collisions!

NMF for prompt D^0 and J/ψ production in pPb

JHEP 10 (2017) 090



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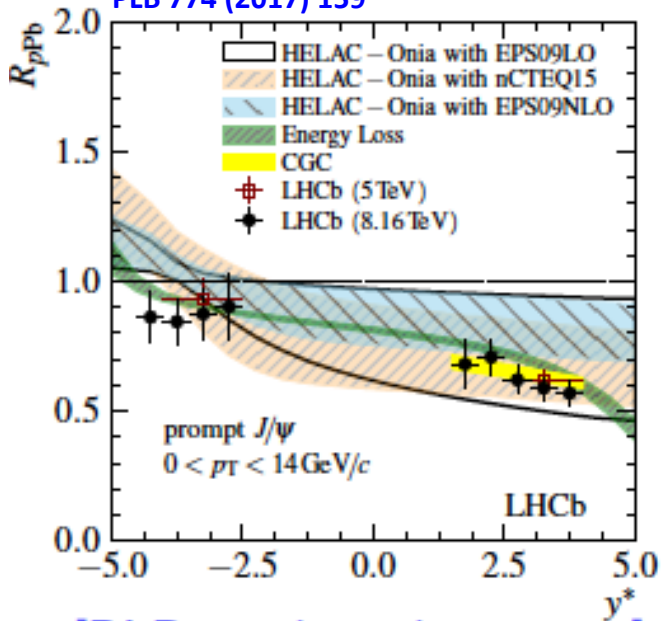
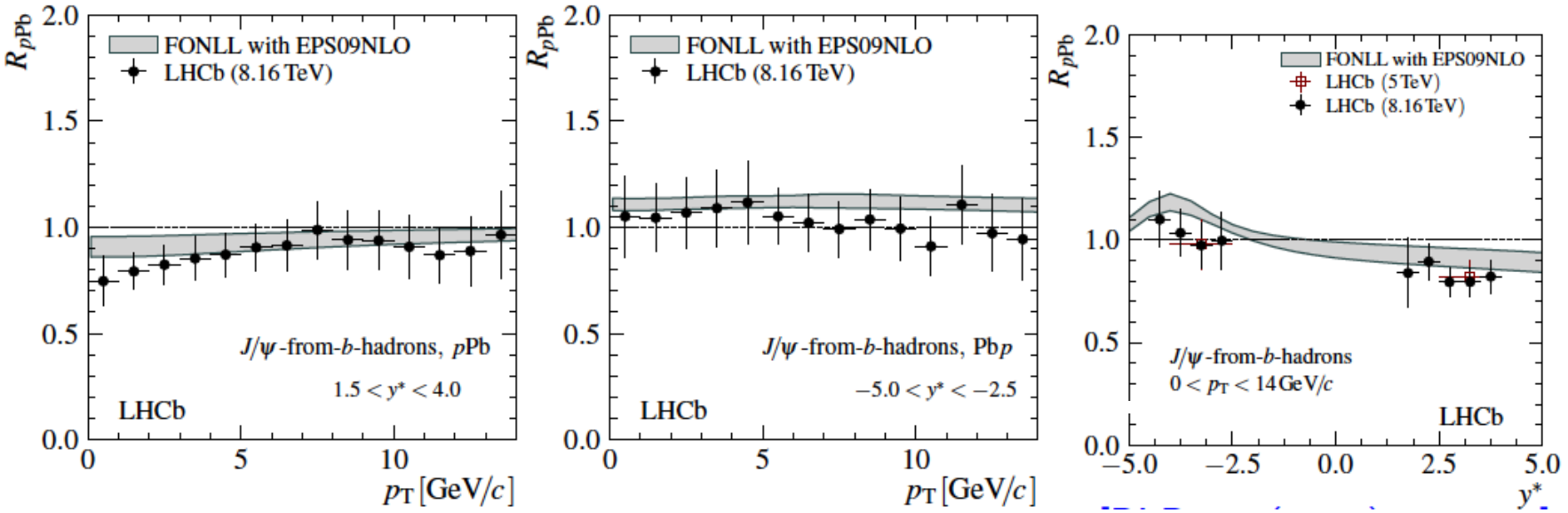


Eur. Phys. J. C77 (2017) 1
Comput. Phys. Commun. 184 (2013) 2562
Comput. Phys. Commun. 198 (2016) 238

- **Fwd**: R_{pPb} significantly suppressed (suppression decreases with p_T)
- **Bwd**: $R_{pPb} \approx 1$
- Measurements consistent with models (nPDFs and Color Glass Condensate)
- **Experimental uncertainties smaller than theoretical uncertainties**

NMF for non-prompt J/ψ production in pPb at 8.16 TeV

Forward (y^* integrated) **Backward (y^* integrated)** **p_T integrated**

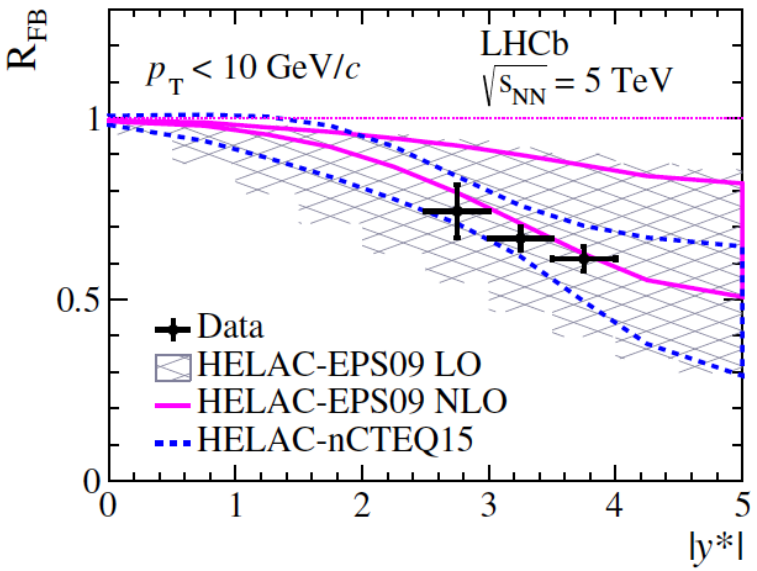


- In Fwd: suppression at low p_T up to 30%, converging to unity at high p_T
- In Bwd: R_{pPb} slightly above unity
- Overall agreement with theoretical model. Compatible with pPb 5 TeV results.

FB ratios for prompt D^0 and Λ_c^+ production in pPb at $5\ TeV$

Prompt D^0

JHEP 10 (2017) 090



Prompt Λ_c^+

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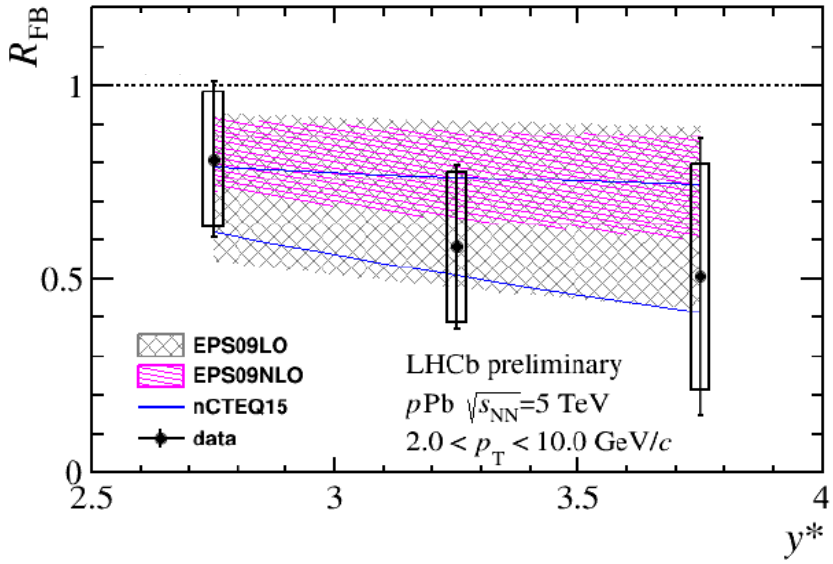
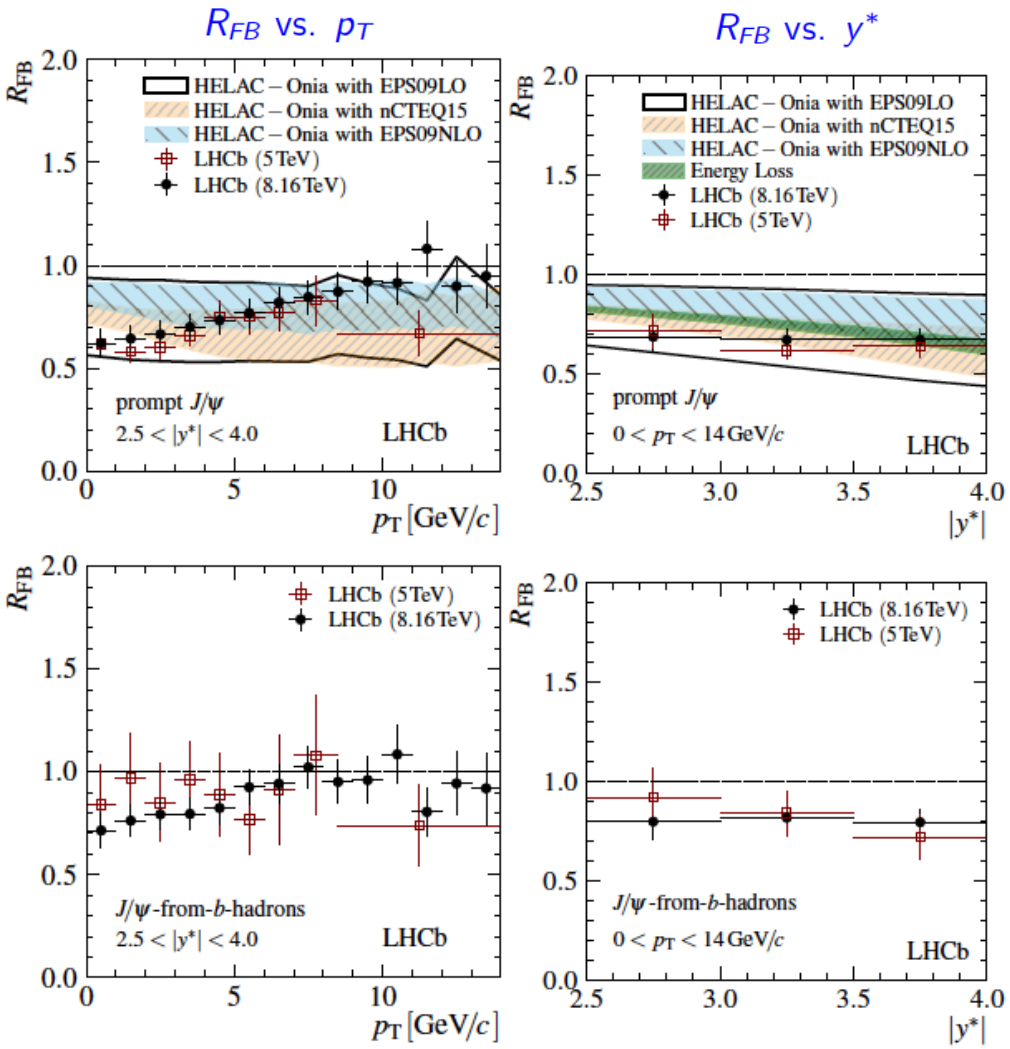


Eur. Phys. J. C77 (2017) 1
Comput. Phys. Commun. 184 (2013) 2562
Comput. Phys. Commun. 198 (2016) 238

- Compared to HELAC-Onia calculations (including different nPDFs parametrizations)
- Data are consistent with theory predictions within uncertainties
- **Experimental uncertainties are smaller than nPDFs calculation!**

FB asymmetry for J/ψ production in pPb at $8.16\,TeV$

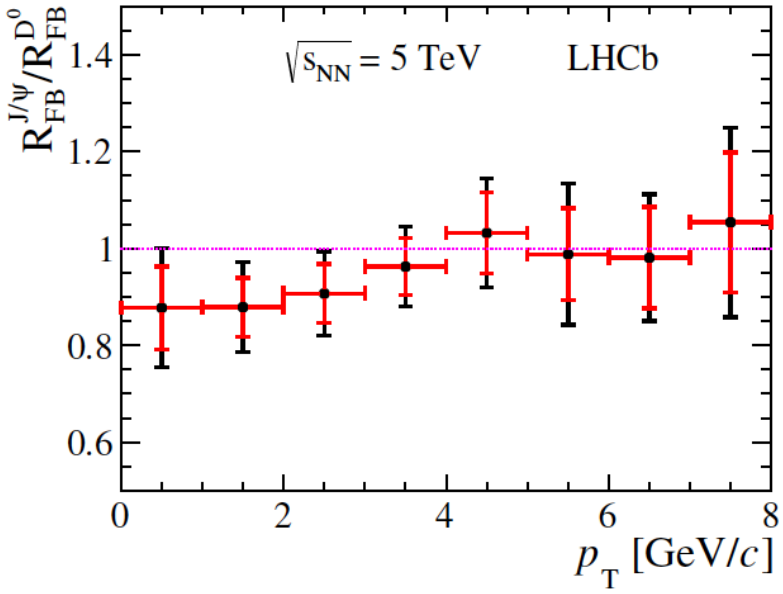


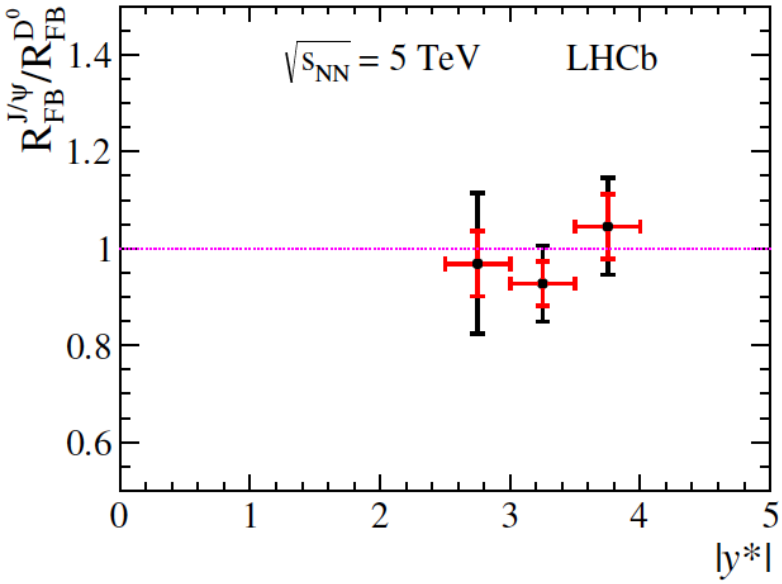
- Clear forward-backward asymmetry for prompt J/ψ, in particular at low p_T
- For J/ψ-from-b: R_{FB} is closer to unity
- Agreement with pPb 5 TeV data within uncertainties

[PLB 774(2017) 159-178]

Prompt J/ψ production in pPb at $\sqrt{s_{NN}} = 8.16\,TeV$

JHEP 10 (2017) 090 , JHEP 02 (2014) 072





R_{FB} of the same size for D^0 and J/ψ

Charmed baryon/meson production ratio in pPb at $5\ TeV$

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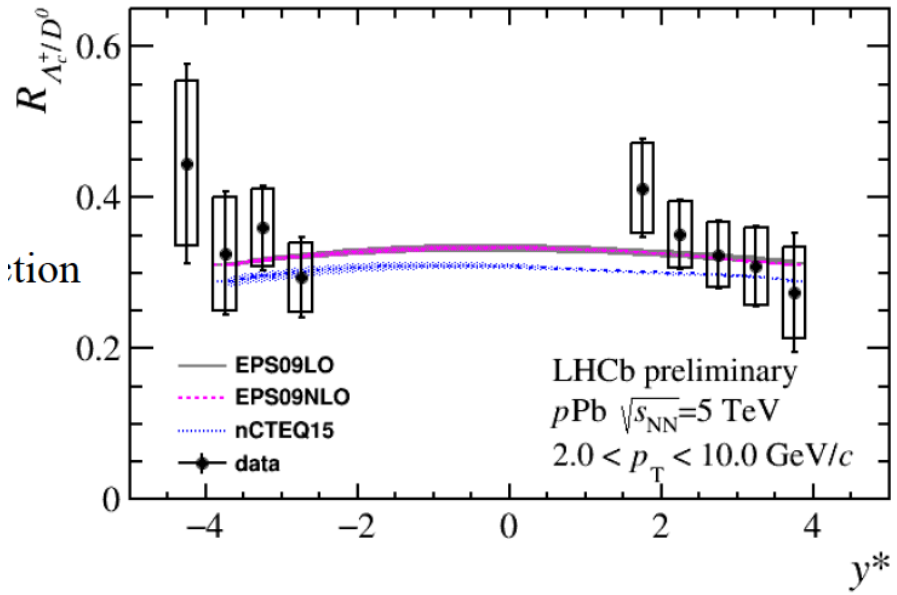
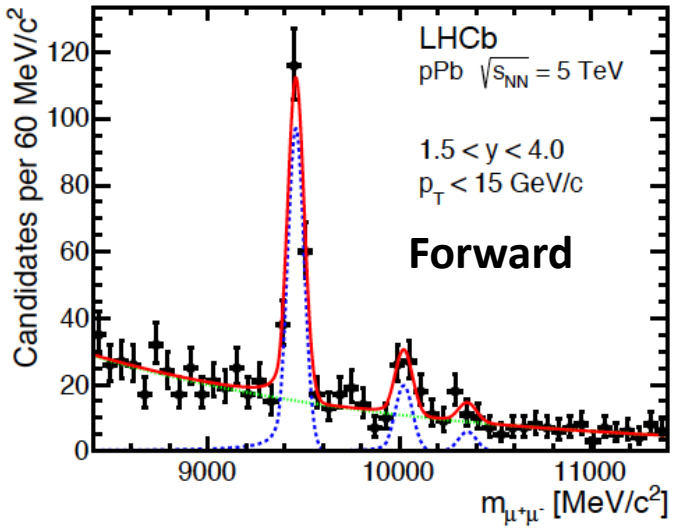
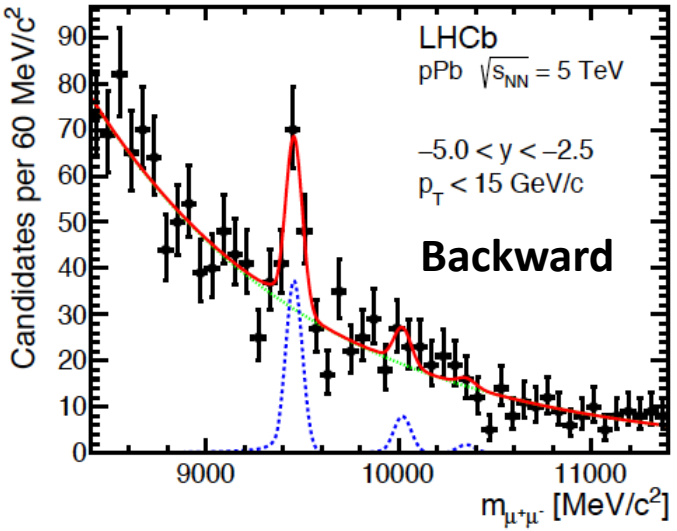


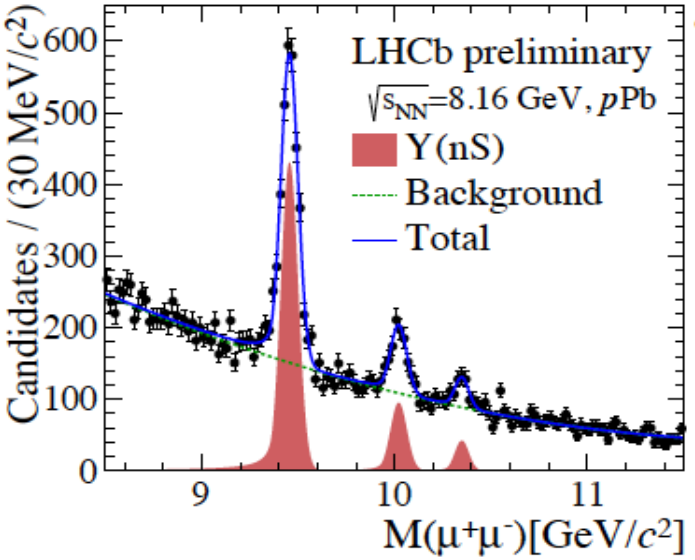
- Models constrained by existing LHC pp cross section measurements
- EPS09LO and EPS09NLO very similar, nCTEQ15 slightly lower
- All predictions basically flat across y^*
- Data consistent with calculations within uncertainty except for high-p_T in forward region

Bottomonium production in pPb at 5 TeV

JHEP 07 (2014) 094







LHCb-PAPER-2018-035
(in preparation)

Bottomonium production in pPb at $5\ TeV$

JHEP 07 (2014) 094