

Study of prompt D⁰ meson production and cold nuclear matter effects in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5 \text{ TeV}$ in the forward region with LHCb

A. Dosil Suárez
on behalf of the LHCb Collaboration

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Outline

Introduction

- Physics motivation for proton-nucleus studies
- LHCb experiment
- Proton-Lead data taking

Results

- Prompt D^0 cross-section in pPb collisions
- D^0 production cross-section in pp at 5 TeV
- Nuclear modification factor R_{pPb} and forward-backward ratio R_{FB}

Summary and prospects

Physics motivation for proton-nucleus studies

- Proton-nucleus collisions allow QCD studies at low x and high gluon densities but also provide reference for heavy ion studies
- The study of pA collisions provides important input to:
 - Disentangle the Quark Gluon Plasma (QGP) effects from Cold Nuclear Matter (CNM) effects
 - Probe nuclear parton distribution functions (which are poorly constrained)
 - Provide a reference sample for nucleus-nucleus collisions

Initial state effects:

- Gluon shadowing¹
- Gluon saturation²
- Radiative energy loss³
- Cronin effects⁴

Final state effects:

- Nuclear absorption⁵
- Radiative energy loss⁶
- Comovers⁷

Neither initial nor final:

- Coherent energy loss⁸

¹JHEP 0904 (2009) 065

²Nucl. Phys. A770 (2006) 40

³Lett. 68 (1992) 1834

⁴Phys. Rev. D, 11:3105, 1975

⁵Phys. A700 (2002) 539

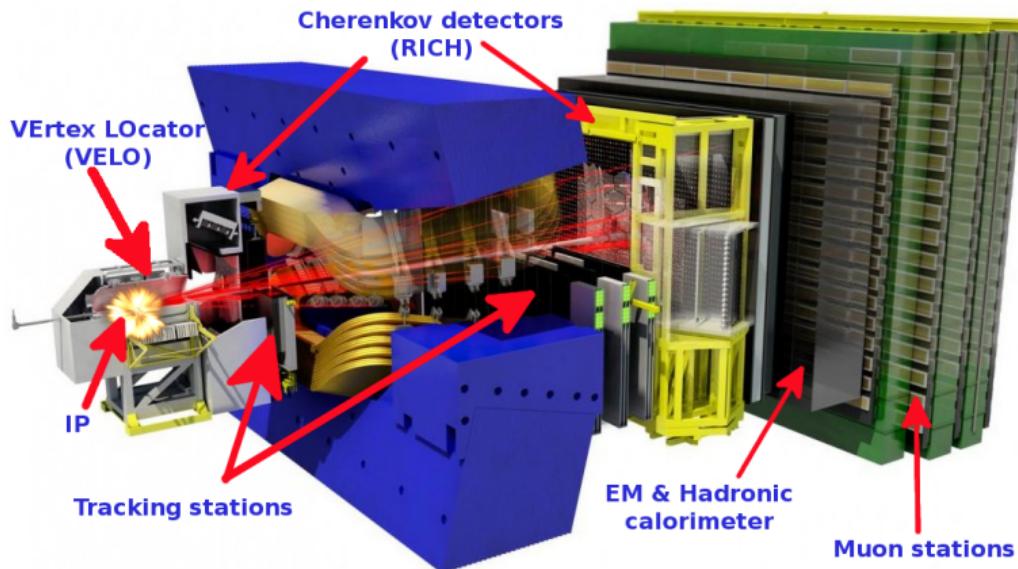
⁶Phys. Rev. C61 (2000) 035203

⁷arXiv:1411.0549v2

⁸Phys. Rev. Lett. 109 (2012) 122301

The LHCb experiment

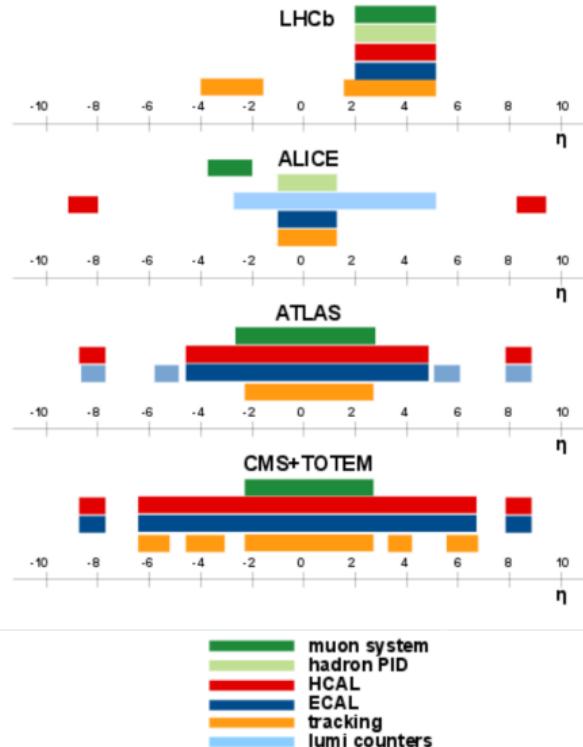
LHCb is a forward spectrometer designed to study flavour physics but actually it is a general purpose detector, capable to do also heavy ion and fixed target physics



See Johan's talk: *Summary and news from LHCb*

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

The LHCb experiment



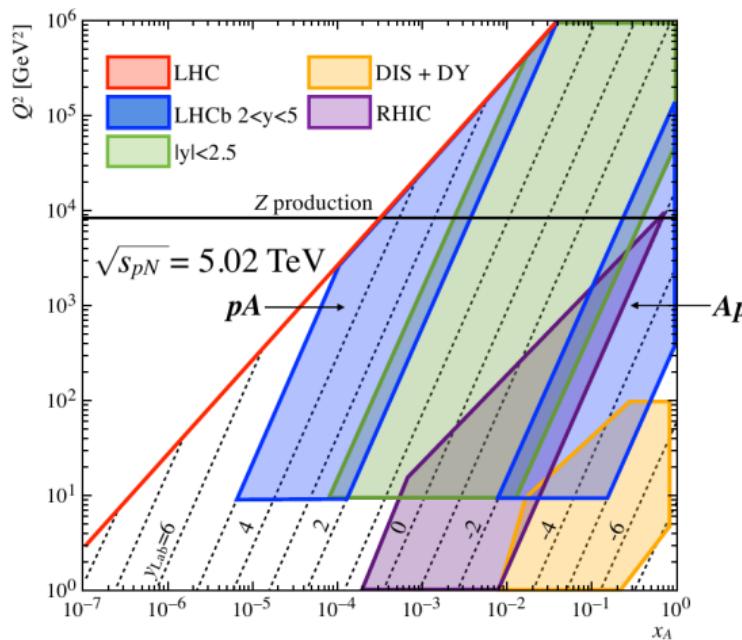
Characteristics

- Impact parameter: $\sigma_{\text{IP}} = 20 \mu\text{m}$
- Momentum resolution: $\Delta p/p = 0.5 \sim 0.8\%$ ($5 - 100 \text{ GeV}/c$)
- RICH K – π separation: $\epsilon(K \rightarrow K) \sim 95\%$ mis-ID $\epsilon(\pi \rightarrow K) \sim 5\%$
- Muon: $\epsilon(\mu \rightarrow \mu) \sim 97\%$ mis-ID $\epsilon(\pi \rightarrow \mu) \sim 1 - 3\%$
- Acceptance $2 < \eta < 5$
- Fully instrumented in the forward region
 - Heavy Ion physics studies in a unique kinematic range
 - Complementary measurements to other LHC experiments
- Forward and backward coverage using p-Pb and Pb-p beams

See Johan's talk: *Summary and news from LHCb*

Accessible range in p-Pb collisions

Accessible $x - Q^2$ range in p-Pb collisions



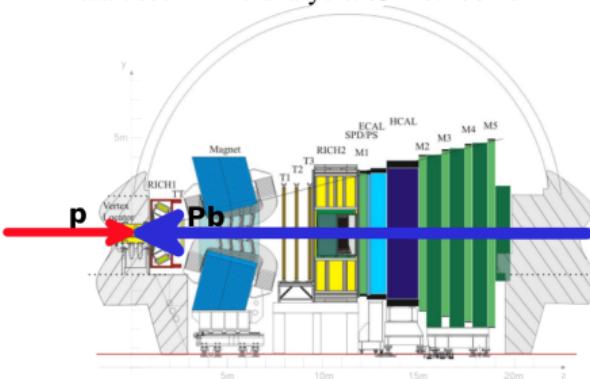
- LHCb probes two different regions in x - Q^2 plane: $x_{1,2} = \frac{Q}{\sqrt{s}} e^{\pm y}$
 - Complementary to ATLAS and CMS
 - Sensitivity to nuclear PDF at large x_A and low $x_A \approx 2 \times 10^{-4}$
 - x_A : Momentum fraction carried by a parton inside the nucleon bound in the lead ion



Proton-Lead data taking

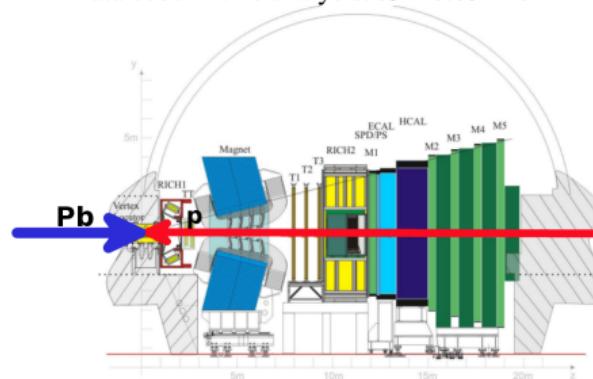
p-Pb configuration (Forward)

- Beam 1 energy: $E_p = 4 \text{ TeV}$
- Beam 2 energy: $E_{\text{Pb}} = 1.58 \text{ TeV}$
- $y - y^* = +0.47$ in lab system
- Rapidity coverage: $1.5 < y^* < 4.4$
- Data used in this analysis: $\mathcal{L} = 0.106 \text{ nb}^{-1}$



Pb-p configuration (Backward)

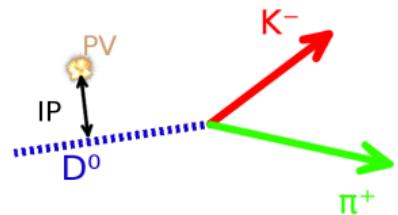
- Beam 1 energy: $E_{\text{Pb}} = 1.58 \text{ TeV}$
- Beam 2 energy: $E_p = 4 \text{ TeV}$
- $y - y^* = -0.47$ in lab system
- Rapidity coverage: $-5.4 < y^* < -2.5$
- Data used in this analysis: $\mathcal{L} = 0.052 \text{ nb}^{-1}$



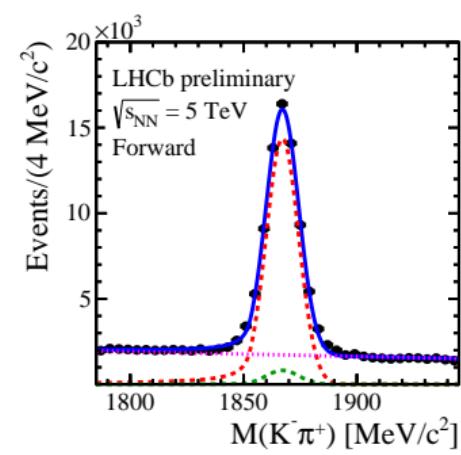
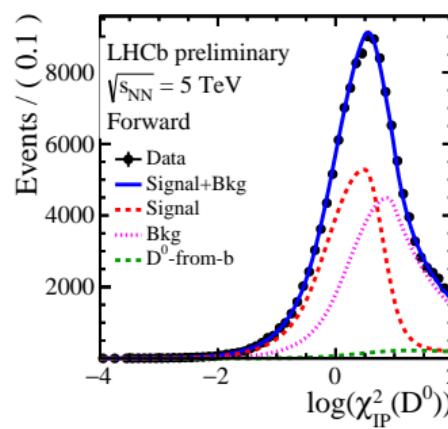
- Common range for measurements: $2.5 < |y^*| < 4.4$
- Center-of-mass energy : $\sqrt{s_{\text{NN}}} = 5 \text{ TeV}$
- Data collected in the proton-ion runs in 2013 (Using here 10% of the total \mathcal{L})

Prompt D⁰ signal yield

- D⁰ reconstructed through D⁰ → K[±]π[∓] decays:
 - 0 GeV/c < p_T(D⁰) < 8 GeV/c
 - Tight requirements on Particle ID and vertex displacement
 - Reconstruction and Particle ID efficiency calibrated using data
- D⁰ yields obtained from two fits:
 - D⁰ yield determined from a fit to the M(Kπ) distribution
 - Fraction of D⁰-from-b determined from log₁₀(χ_{IP}²(D⁰)) distribution



- Full distribution: modified Gaussian
- Prompt D⁰ and D⁰-from-b signal shape from simulation
- Background shape from data

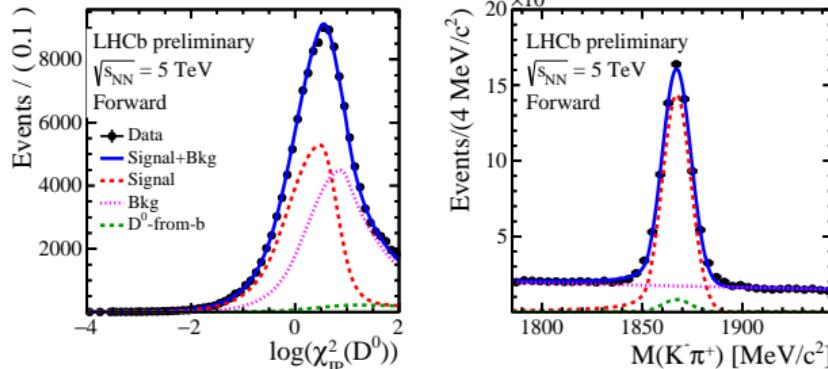


- Signal: Crystal Ball
- Background: Linear function

LHCb-CONF-2016-003

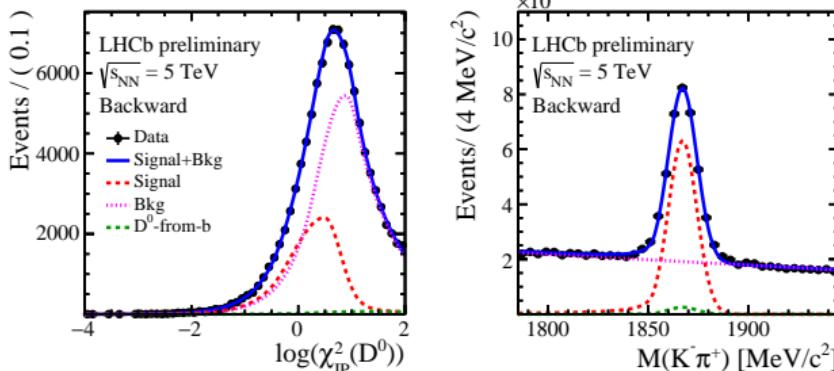
Prompt D^0 signal yield

Forward:



- $f_{D^0-\text{from}-b} = 2.8 \pm 0.1\%$

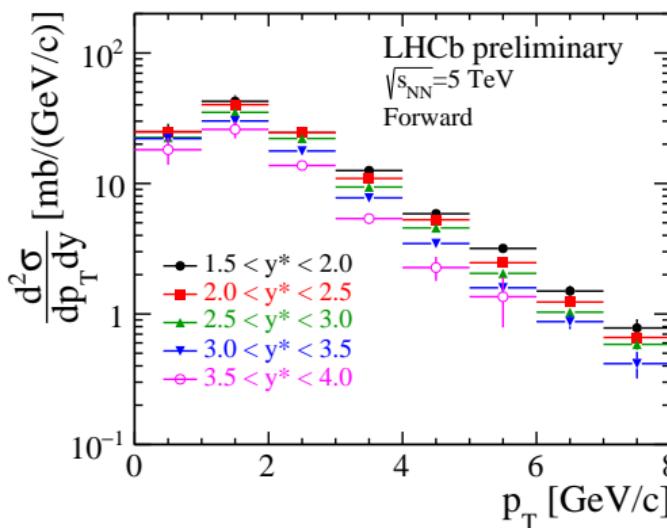
Backward:



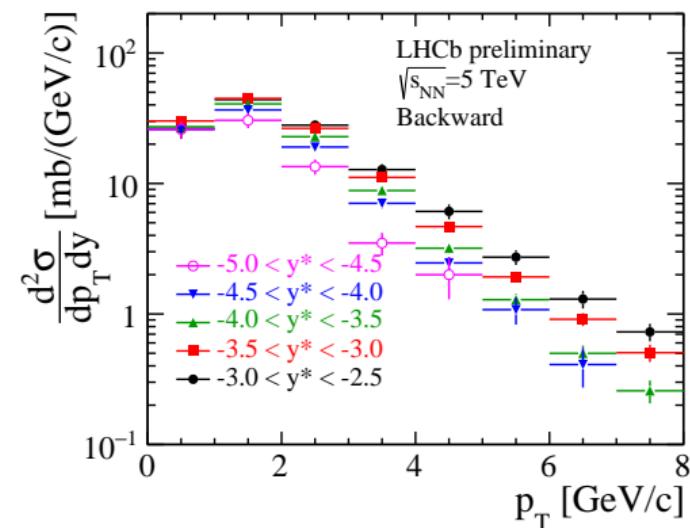
- $f_{D^0-\text{from}-b} = 1.9 \pm 0.3\%$

Prompt D⁰ double differential cross-section

Forward:



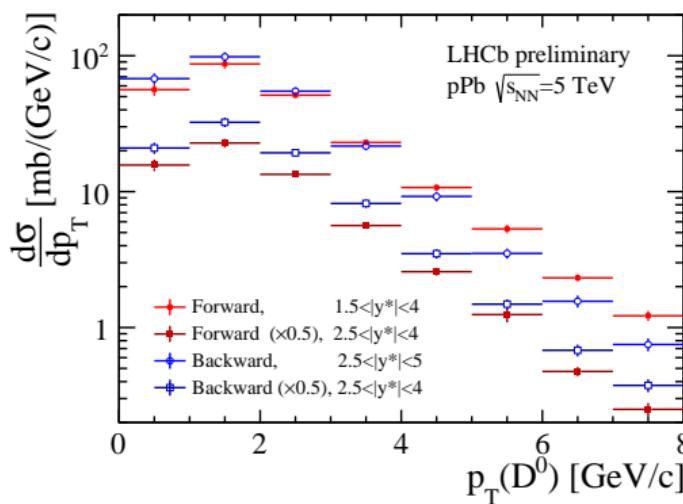
Backward:



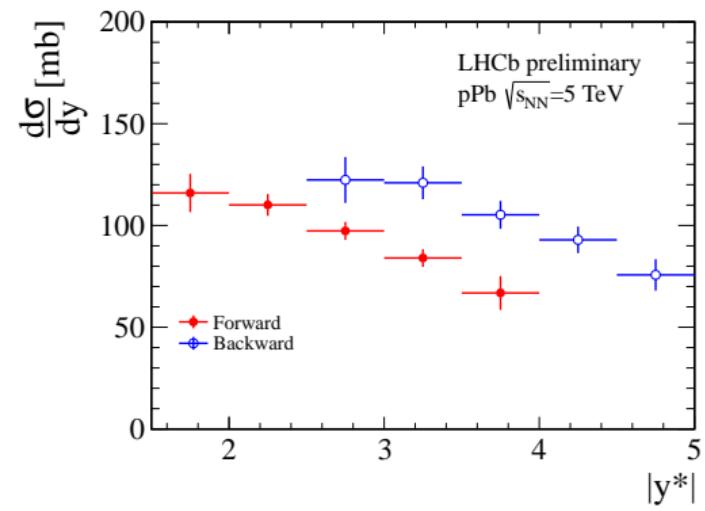
- $\sigma_{\text{Fwd}}(p_T < 8 \text{ GeV}/c, 1.5 < |y^*| < 4.0) = 237 \pm 1 \pm 15 \text{ mb}$
- $\sigma_{\text{Bwd}}(p_T < 8 \text{ GeV}/c, 2.5 < |y^*| < 5.0) = 259 \pm 3 \pm 19 \text{ mb}$

Prompt D⁰ one dimensional differential cross-sections

$\frac{d\sigma}{dp_T}$ vs p_T :

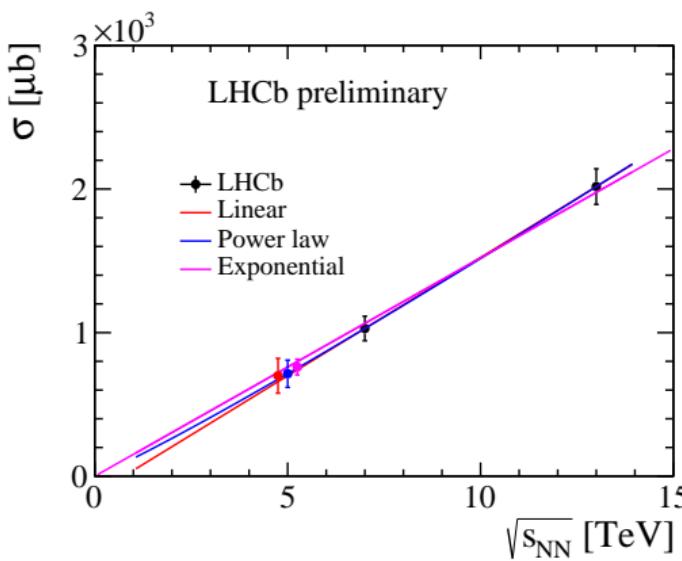


$\frac{d\sigma}{dy}$ vs $|y^*|$:



D⁰ production cross-section in pp@5 TeV

- LHCb measurement of $\sigma_{pp}(D^0)$ at $\sqrt{s_{NN}} = 5$ TeV is not available yet
 - Extrapolation from previous measurements at $\sqrt{s_{NN}} = 7$ TeV and $\sqrt{s_{NN}} = 13$ TeV



$$\sigma \sqrt{s} = \begin{cases} p_1(\sqrt{s})^{p_0} & \text{power law} \\ p_1 + p_0 \sqrt{s} & \text{linear} \\ p_1(1 - \exp(-\sqrt{s}/p_0)) & \text{exponential} \end{cases}$$

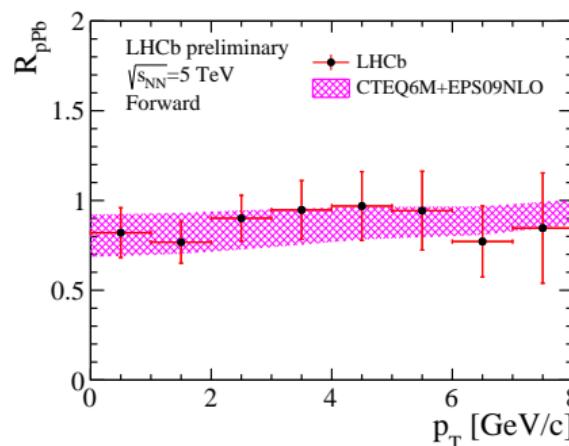
- $\sigma_{pp}^{\text{power law}}(5 \text{ TeV}, p_T < 8 \text{ GeV}/c, 2.5 < |y^*| < 4.0) = 713 \pm 95 (\text{LHCb}) \pm 47 (\text{fit model}) \mu\text{b}$



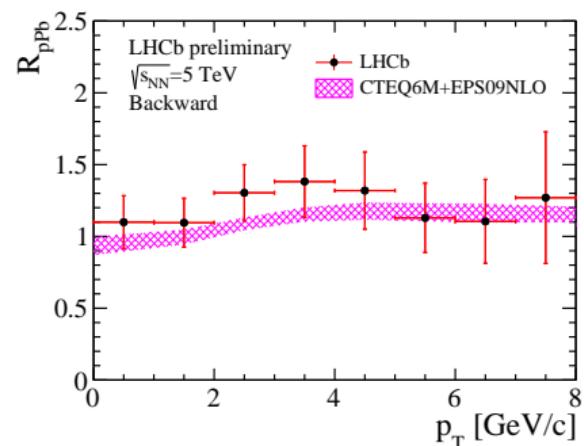
Prompt D⁰ nuclear modification factor

- Calculated using: $R_{pPb}(y^*, p_T, \sqrt{s_{NN}}) = \frac{1}{A} \frac{d^2\sigma_{pPb}(y^*, p_T, \sqrt{s_{NN}})/dy^* dp_T}{d^2\sigma_{pp}(y^*, p_T, \sqrt{s_{NN}})/dy^* dp_T}$
- Theoretical predictions from: NLO MNR computed using CTEQ6M and EPS09NLO

Forward:



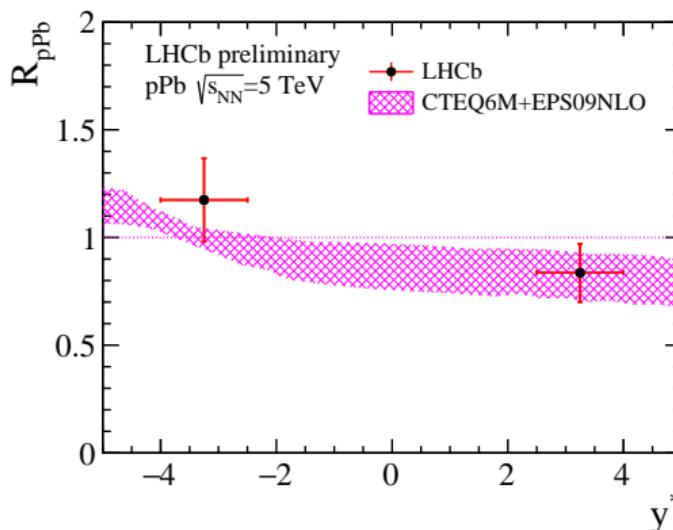
Backward:



- Results consistent with theoretical predictions
- Uncertainties dominated by σ_{pp} extrapolation

Prompt D⁰ nuclear modification factor

- Calculated using: $R_{pPb}(y^*, p_T, \sqrt{s_{NN}}) = \frac{1}{A} \frac{d^2\sigma_{pPb}(y^*, p_T, \sqrt{s_{NN}})/dy^* dp_T}{d^2\sigma_{pp}(y^*, p_T, \sqrt{s_{NN}})/dy^* dp_T}$
- Theoretical predictions from: NLO MNR computed using CTEQ6M and EPS09NLO



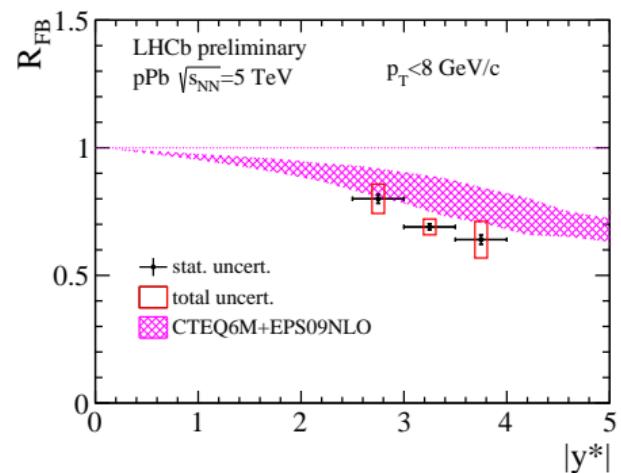
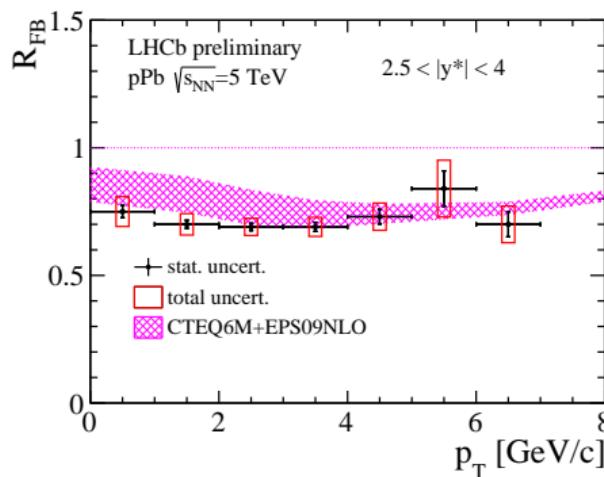
- Nuclear modification factor smaller in forward sample
- Results consistent with theoretical predictions
- Uncertainties dominated by σ_{pp} extrapolation



Results
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Prompt D⁰ forward-backward ratio

- Calculated using: $R_{FB}(y^*, p_T, \sqrt{s_{NN}}) = \frac{\sigma_{p\text{Pb}}(+|y^*|, p_T, \sqrt{s_{NN}})}{\sigma_{p\text{Pb}}(-|y^*|, p_T, \sqrt{s_{NN}})}$
- Results independent of σ_{pp}
- Many uncertainties cancel



- Significant forward-backward asymmetry
- Results agree with theoretical predictions

[Nucl. Phys. B373 \(1992\) 2959](#), [JHEP 10 \(2003\) 046](#), [JHEP 04 \(2009\) 065](#)
[LHCb-CONF-2016-003](#)

Summary and prospects

Summary

- We studied the D^0 production in proton-lead collisions using $0.106(\text{fwd}) + 0.052(\text{bwd}) \text{ nb}^{-1}$, 10% of the whole data collected by LHCb in 2013
- Calculated nuclear modification factor
- Calculated the forward-backward ratio
- Observed a strong cold nuclear matter effect
- Results are compatible with theoretical predictions

Prospects

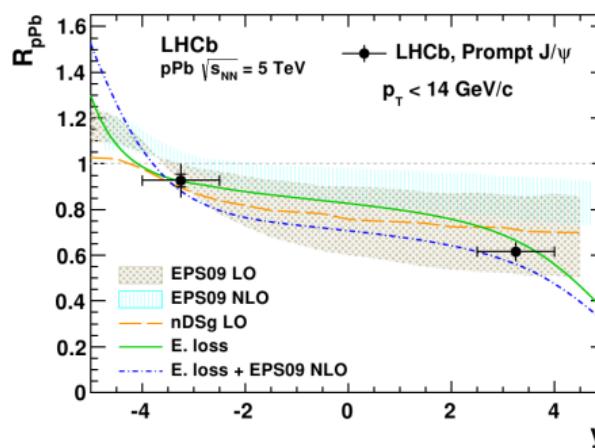
- Working on the measurement of $\sigma_{\text{pp}}(D^0)$ at $\sqrt{s_{\text{NN}}} = 5 \text{ TeV}$
 - Working on an update:
 - Analyse the whole pPb integrated luminosity available
 - Optimize selection cuts to improve the PID efficiency uncertainty
- ⇒ More precise measurements of R_{pPb} and R_{FB} will come up soon

Backup

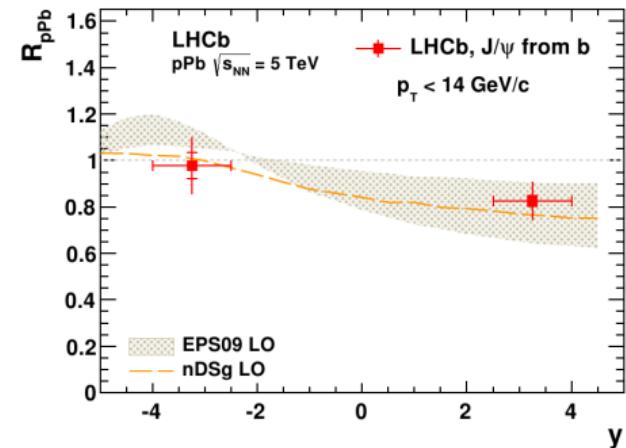
J/ ψ nuclear modification factor

- Calculated using: $R_{pPb}(y^*) = \frac{1}{A} \frac{d\sigma_{pPb}/dy^*}{d\sigma_{pp}/dy^*}$
- Results require interpolation of pp cross-section to $\sqrt{s_{NN}} = 5$ TeV

R_{pPb} of prompt J/ ψ



R_{pPb} of J/ ψ from b



EPS09LO (CSM): PRC88 (2013) 047901, Nuclear Physics A 926 (2014) 236

EPS09NLO (shadowing + CEM): IJMP E 22 (2013) 1330007

Energy Loss: JHEP 03 (2013) 122, JHEP 05 (2013) 155

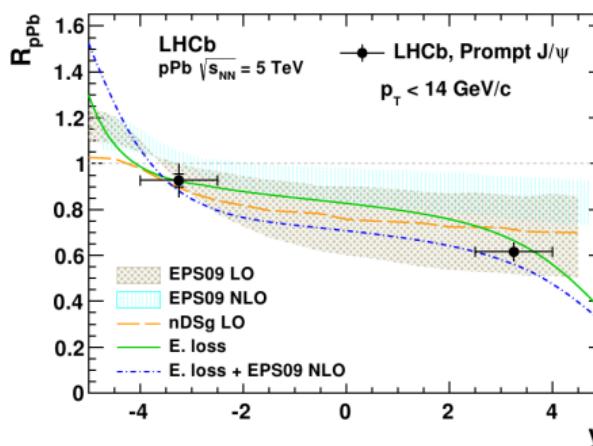
nDSg LO: PRC88 (2013) 047901

JHEP 02 (2014) 072

J/ ψ nuclear modification factor

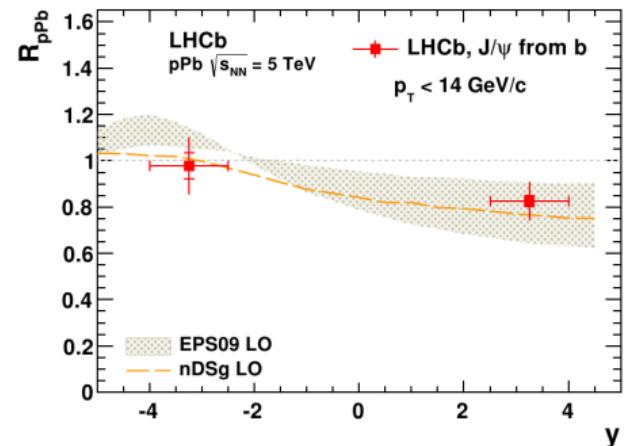
- Calculated using: $R_{pPb}(y^*) = \frac{1}{A} \frac{d\sigma_{pPb}/dy^*}{d\sigma_{pp}/dy^*}$
- Results require interpolation of pp cross-section to $\sqrt{s_{NN}} = 5$ TeV

R_{pPb} of prompt J/ ψ



- A suppression of $\sim 40\%$ at large rapidity is observed
- Measurements agree with most predictions

R_{pPb} of J/ ψ from b



- Modest suppression of J/ ψ from b in the forward region
- Theoretical predictions agree with the measurement within 1σ

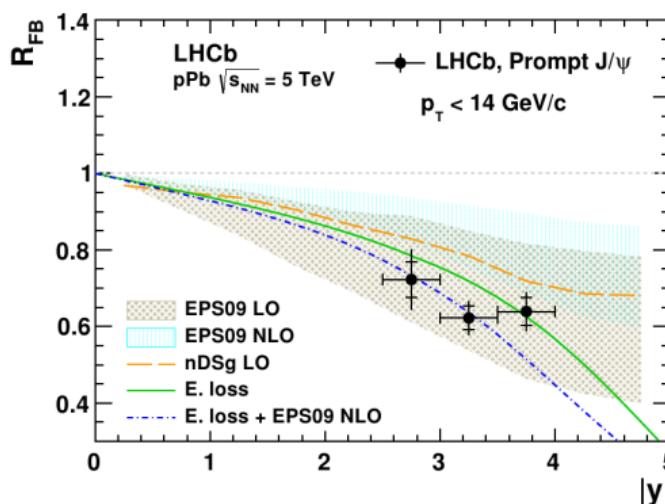


Results
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J/ ψ forward to backward ratio

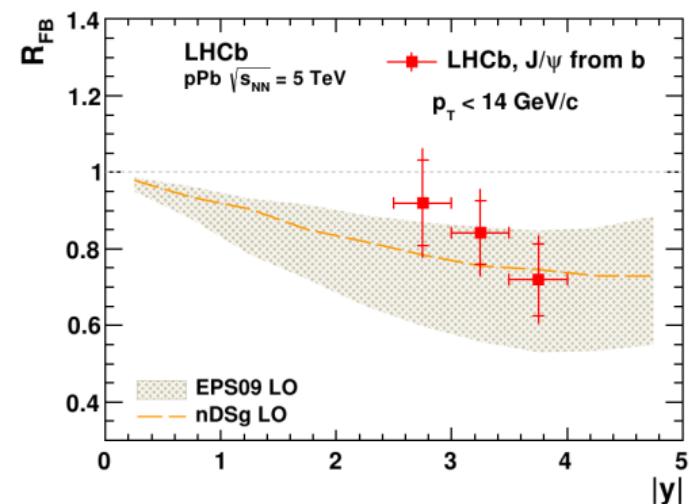
- Calculated using: $R_{FB}(y^*) = \frac{d\sigma_{pPb}/dy^*}{d\sigma_{pp}/dy^*}$
- Results does not require interpolation of pp cross-section
- Many uncertainties cancel

Prompt J/ ψ forward to backward ratio



- Significant forward-backward asymmetry
- Measurements agree with most predictions

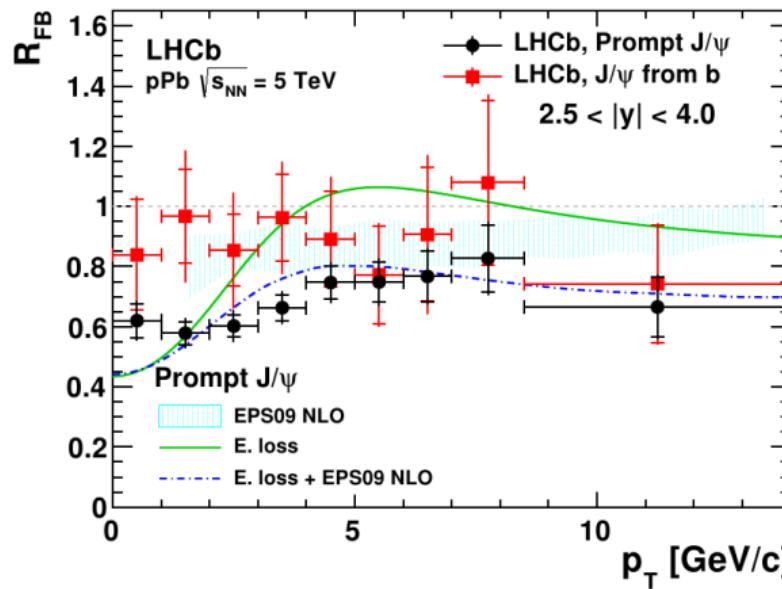
J/ ψ from b forward to backward ratio



- $R_{FB} \approx 1$

J/ ψ forward to backward ratio

J/ ψ and J/ ψ from b forward to backward ratio

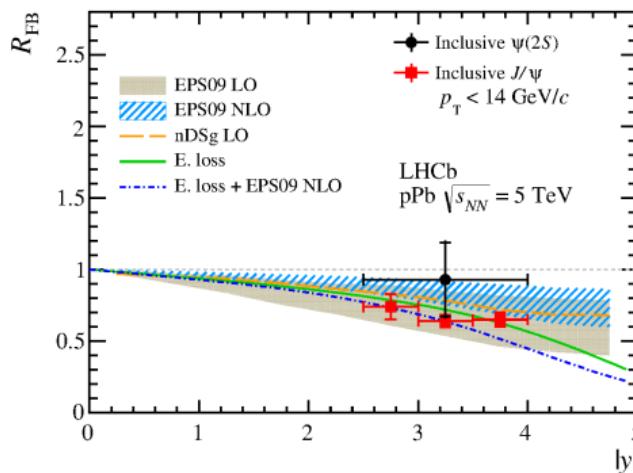


- Calculated using: $R_{FB}(p_T) = \frac{d\sigma_{pPb}/dp_T}{d\sigma_{pbp}/dp_T}$
- Results do not require interpolation of pp cross-section
- Theoretical predictions only available for prompt J/ ψ
- EPS09(NLO) + energy loss agrees with prompt J/ ψ data (except at low p_T)
- $R_{FB} \approx 1$ for J/ ψ from b

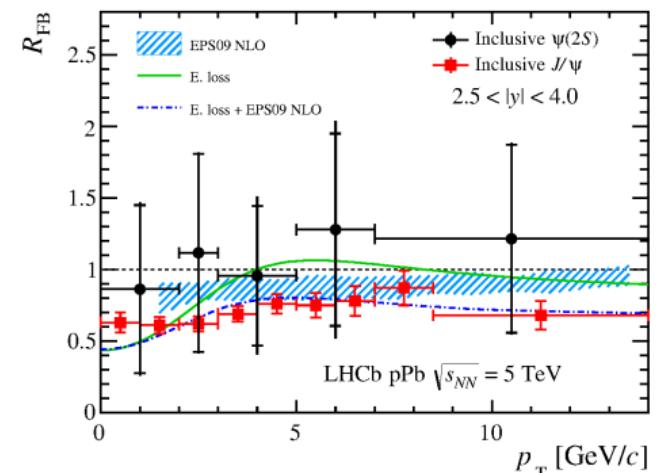
$\psi(2S)$ forward to backward ratio

- Calculated using: $R_{FB}(y^*) = \frac{d\sigma_{pPb}/dy^*}{d\sigma_{Pbp}/dy^*}$
- Results does not require interpolation of pp cross-section
- Part of experimental and theoretical uncertainties cancel

$R_{FB}(y^*)$



$R_{FB}(p_T)$



- Large experimental uncertainties
 - $\rightarrow R_{FB}$ of inclusive $\psi(2S)$ compatible both with unity and with suppression of inclusive J/ψ

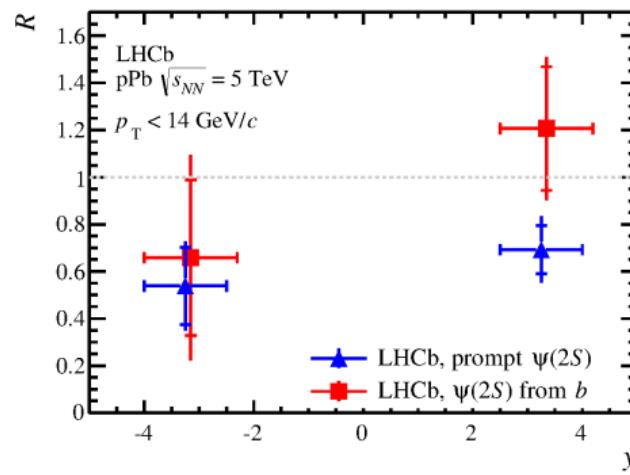
arXiv:1601.07878

Ratio between $R_{p\text{Pb}}$ of $\psi(2\text{s})$ and J/ψ

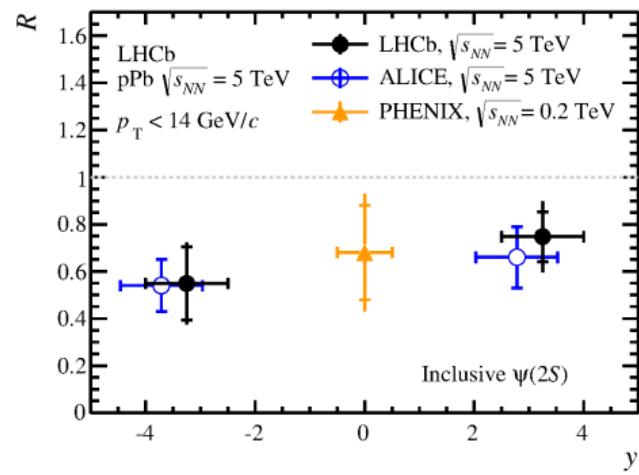
- Ratio is calculated as:

$$R = \frac{R_{p\text{Pb}}^{\psi(2\text{s})}}{R_{p\text{Pb}}^{J/\psi(2\text{s})}} \approx \frac{R_{p\text{Pb}}^{\psi(2\text{s})}(5 \text{ TeV})}{R_{p\text{Pb}}^{J/\psi(2\text{s})}(5 \text{ TeV})} \frac{R_{p\text{Pb}}^{J/\psi}(7 \text{ TeV})}{R_{p\text{Pb}}^{\psi(2\text{s})}(5 \text{ TeV})}, \quad \text{assuming } \frac{R_{p\text{Pb}}^{J/\psi}(5 \text{ TeV})}{R_{p\text{Pb}}^{\psi(2\text{s})}(5 \text{ TeV})} \approx \frac{R_{p\text{Pb}}^{J/\psi}(7 \text{ TeV})}{R_{p\text{Pb}}^{\psi(2\text{s})}(7 \text{ TeV})}$$

Ratio for prompt $\psi(2\text{s})$ and $\psi(2\text{s})$ from b



Comparison of ratios for prompt $\psi(2\text{s})$



- stronger suppression of prompt $\psi(2\text{s})$ than that of prompt J/ψ

ALICE: JHEP 12 (2014) 073, PHENIX: Phys. Rev. Lett. 111 (2013), no. 20 (202301), LHCb-PAPER-2015-058

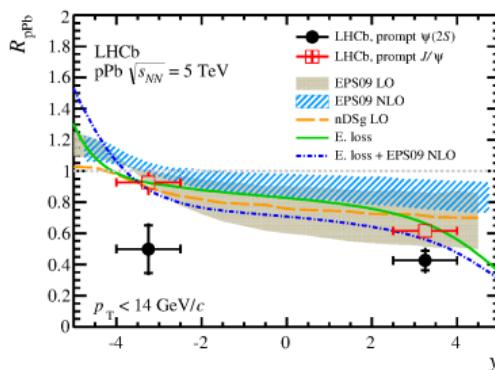
- Results for inclusive $\psi(2\text{s})$ compatible with ALICE

$\psi(2S)$ nuclear modification factor

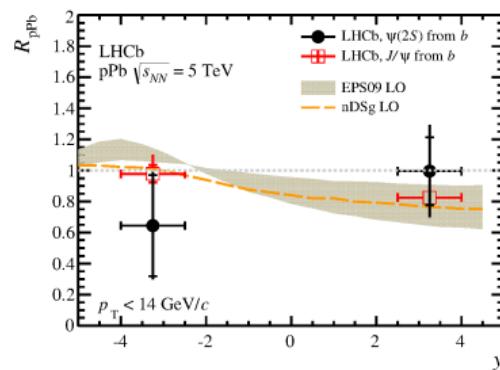
- Calculated from $R_{\text{pPb}}^{\text{J}/\psi}$:

$$R_{\text{pPb}}^{\psi(2S)} = R_{\text{pPb}}^{\text{J}/\psi} \times R$$

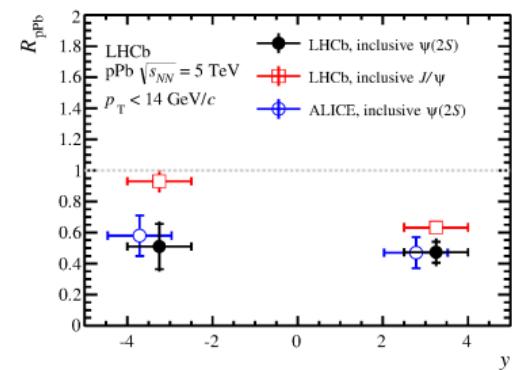
Prompt $\psi(2S)$



$\psi(2S)$ from b



Inclusive $\psi(2S)$



- Prompt $\psi(2S)$ more suppressed than prompt J/ψ
- EPS09 NLO+E.loss does not explain suppression in the backward region

- Suppression of $\psi(2S)$ from b and J/ψ from b consistent

- Suppression of inclusive $\psi(2S)$ consistent with ALICE results