Theorie LHC France workshop – GDR QCD 2016
IPNO, Nov. 2016

Heavy flavor production at LHC

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ALICE ATLAS EXPERIMENT CMS Compact Muon Solenoid LHCb

8 Nov. 2016

Outline

- Introduction
- Production cross-sections
- Associated production
- Heavy quarkonia polarization
- Production in pA
- Summary

Personal biased selections

Introduction

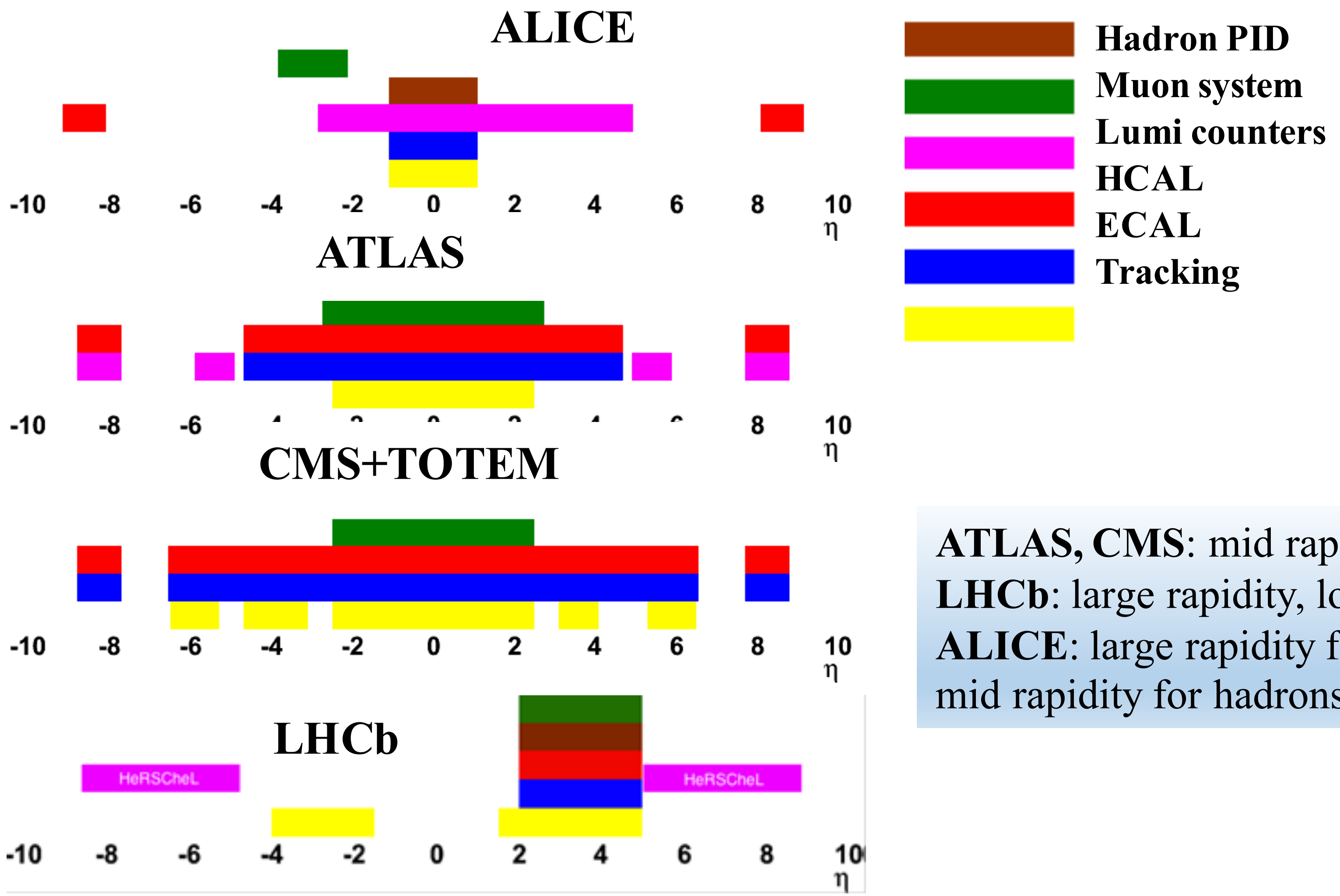
- Heavy flavor productions are tools to understand QCD
  - ➢ Heavy quark (pair) production can be calculated perturbatively within QCD
  - ➢ Many ways to deal with non perturbative effects, ideas tested with data
    - ✓ Quarkonia production: CEM, CSM, NRQCD

$$\sigma(pp \to \mathcal{Q} + X) = \sum_n \boxed{\hat{\sigma}(pp \to Q\bar{Q}[n] + X)} \times \boxed{\langle \mathcal{O}^{\mathcal{Q}}(n) \rangle}$$

- Better understanding of QCD is fundamental and essential for new physics searches
  - ➢ Important inputs for precision measurements of SM EW physics
  - ➢ Anomalies observed in beauty/charm decays: new physics or QCD effects?

- Heavy flavor productions also probe nuclear matter effects
  - ➢ Produced in early stage of collisions, then interact with medium
  - ➢ Production in pA collisions is reference for AA collisions for cold nuclear effects
    - ✓ Shadowing, anti-shadowing, energy loss, CGC…

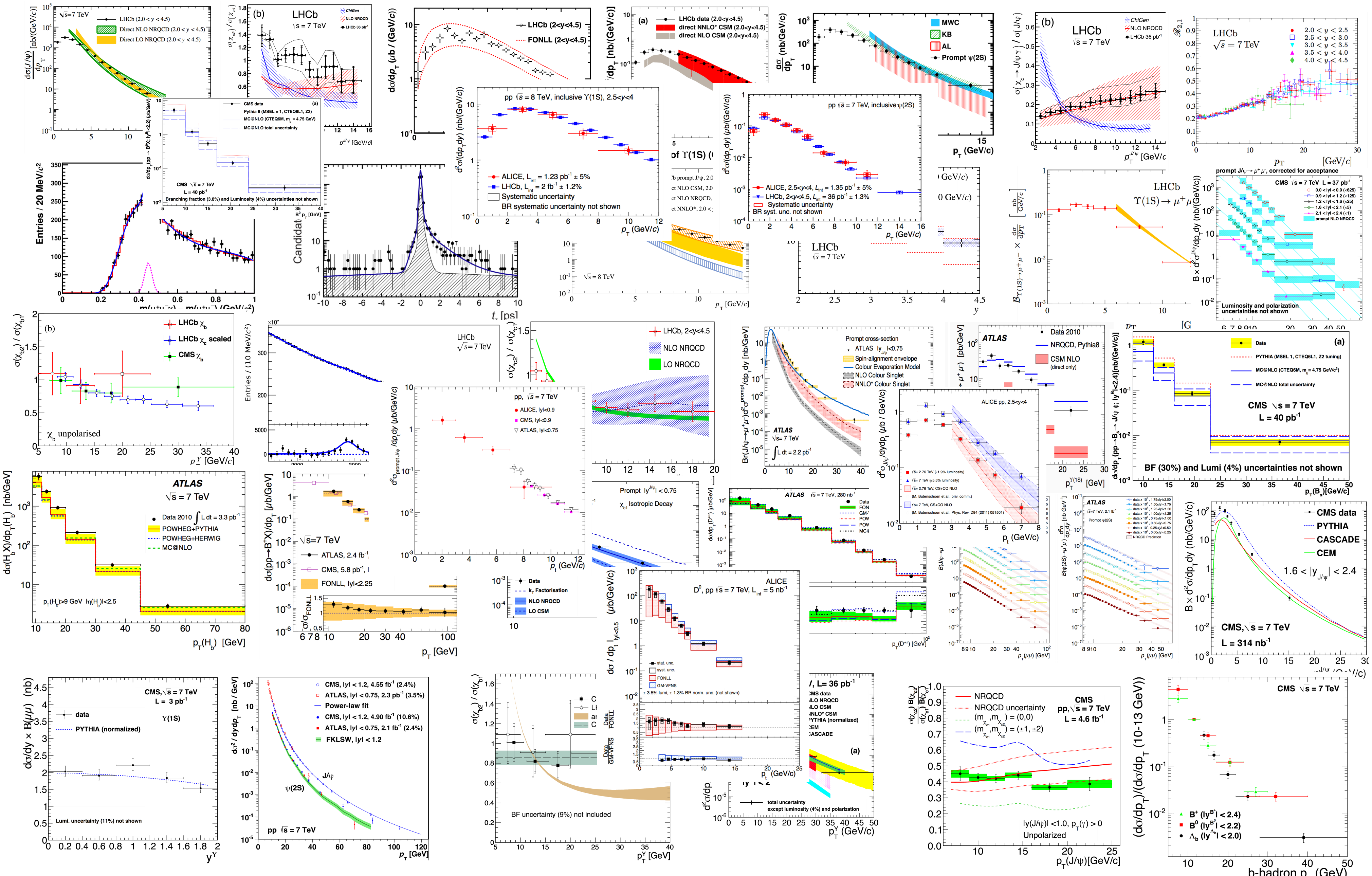
LHC experiments



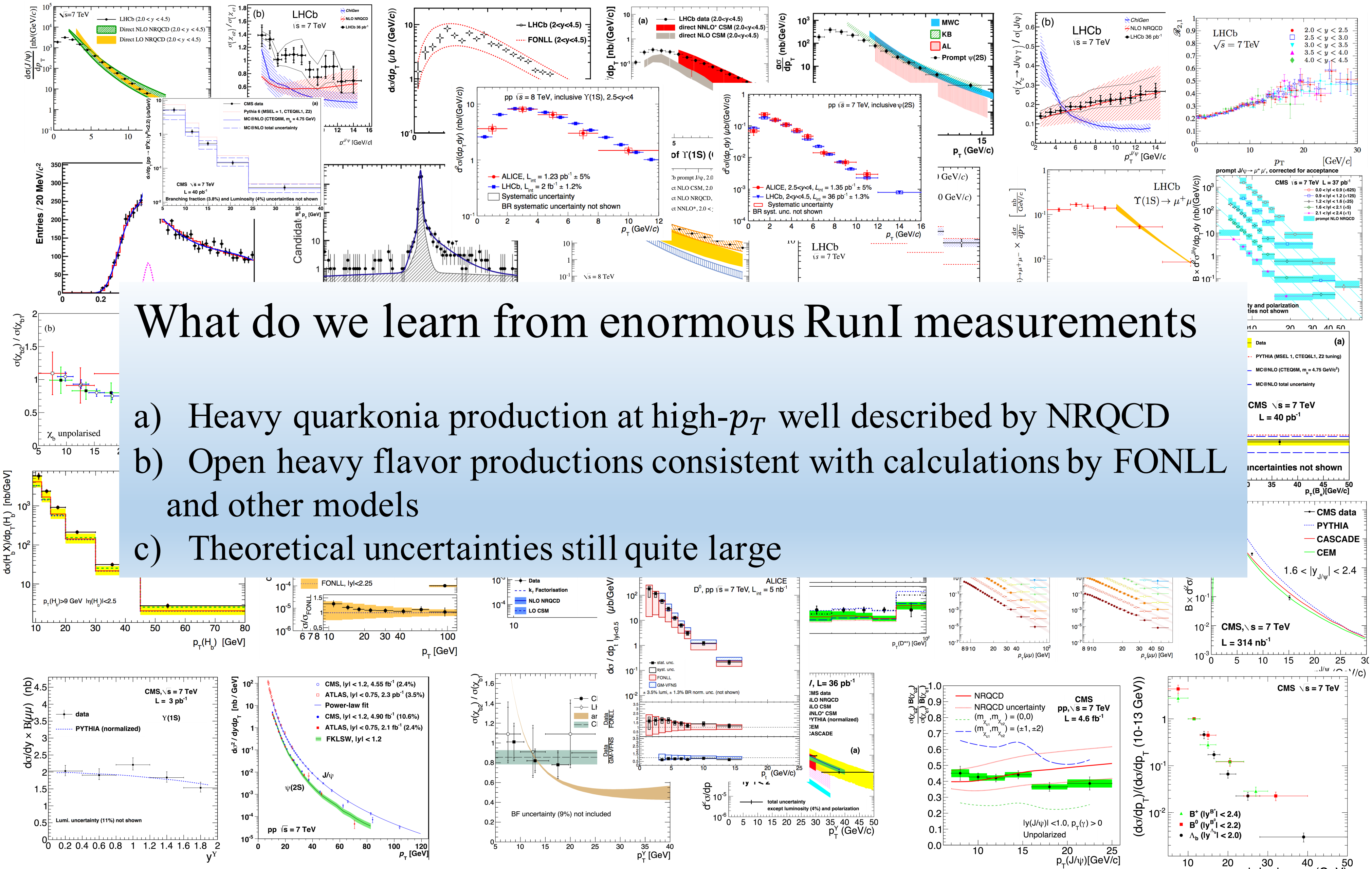
ATLAS, CMS: mid rapidity, high p_T
LHCb: large rapidity, low p_T
ALICE: large rapidity for muons, mid rapidity for hadrons

Productions in pp collisions in LHC run I

Heavy flavor production at LHC RunI



Heavy flavor production at LHC RunI



What do we learn from enormous RunI measurements

a) Heavy quarkonia production at high-p_T well described by NRQCD

b) Open heavy flavor productions consistent with calculations by FONLL and other models

c) Theoretical uncertainties still quite large

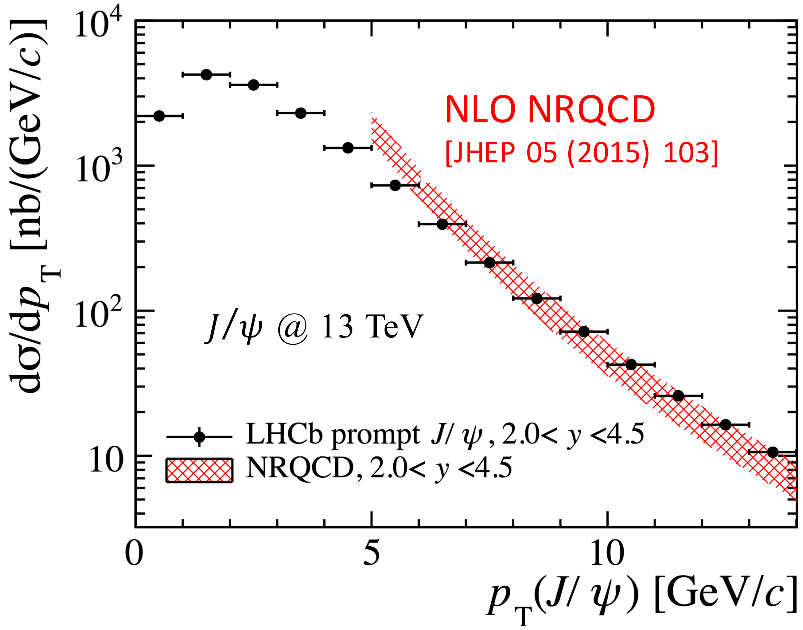
Productions in pp collisions (LHC run II data)

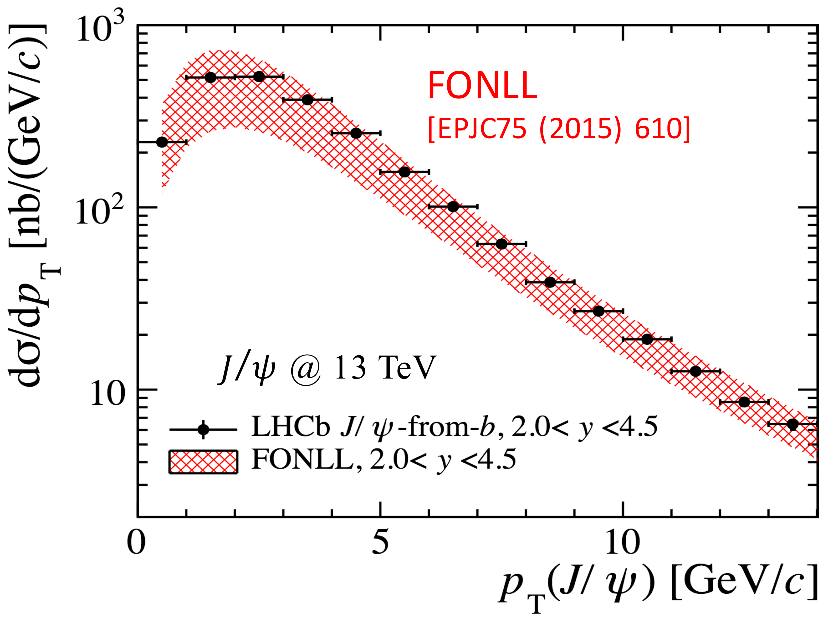
- J/ψ @ 13 TeV (LHCb)
- Prompt charm @ 5, 13 TeV (LHCb)
- B^+ @ 13 TeV (CMS)

JHEP 10 (2015) 172
JHEP 03 (2016) 159
arXiv:1610.02230
arXiv:1609.00873

$J/\psi : p_T$ distributions

LHCb: JHEP 10 (2015) 172



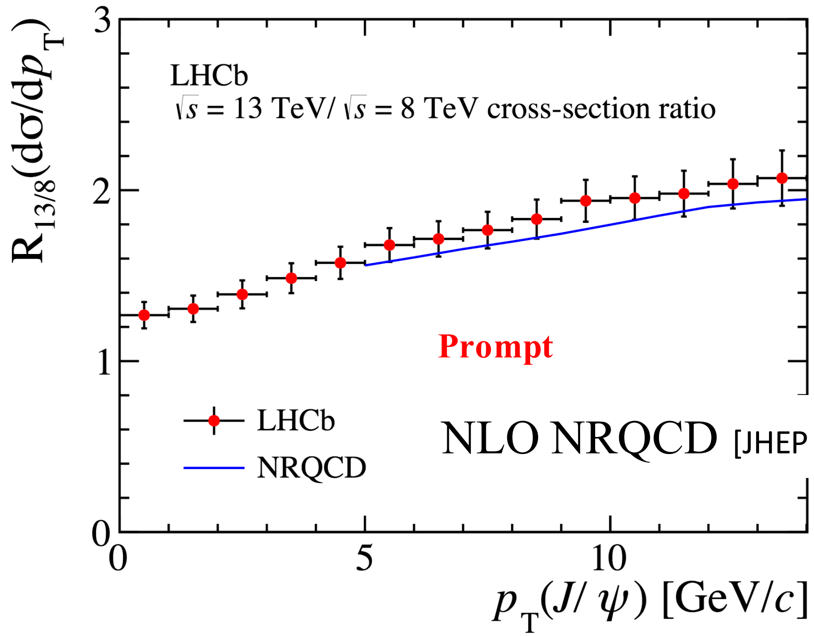


- Prompt: in good agreement with NLO NRQCD predictions
- From *b*: consistent with FONLL calculations

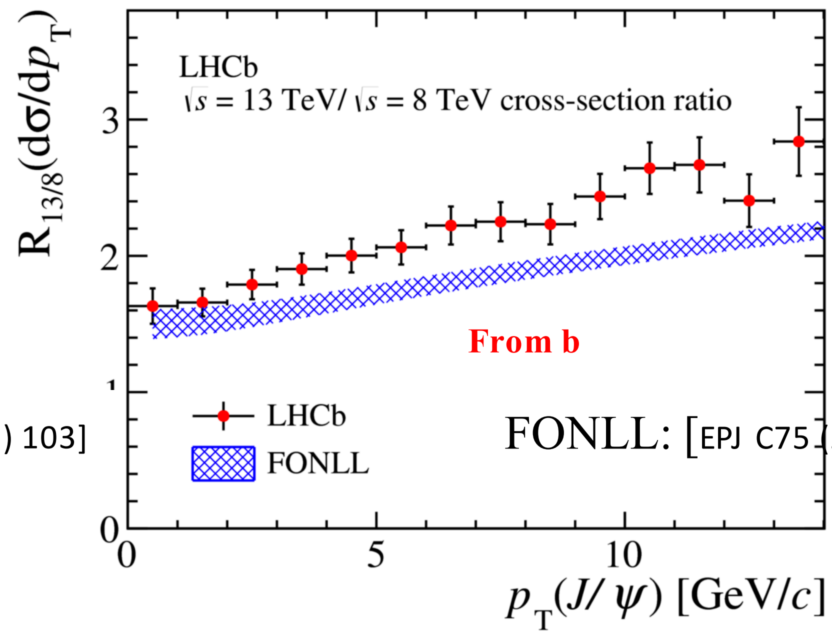
Ratio of $\sigma(J/\psi)$ at 13, 8 TeV

Uncertainties largely cancel

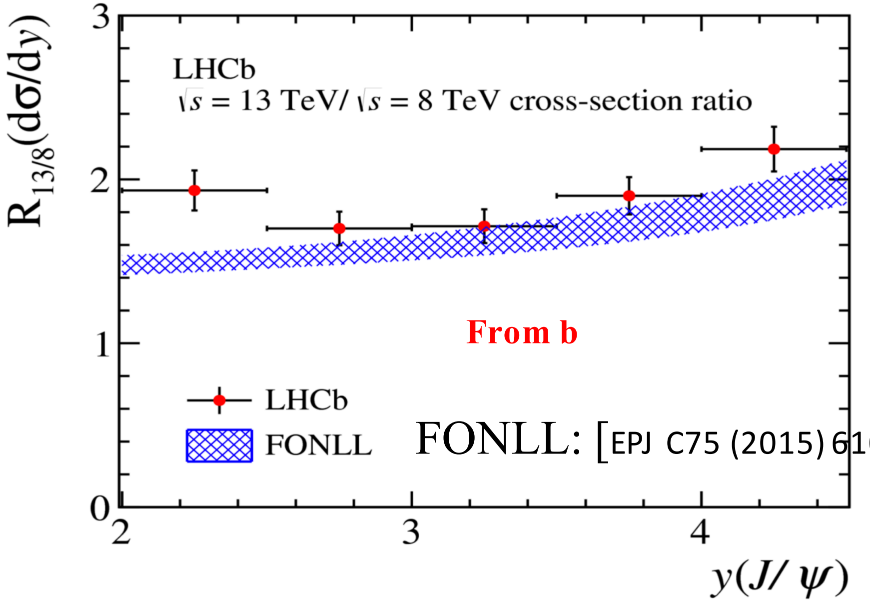
LHCb: JHEP 10 (2015) 172



NLO NRQCD [JHEP 05 (2015) 103]



FONLL: [EPJ C75 (2015) 610]

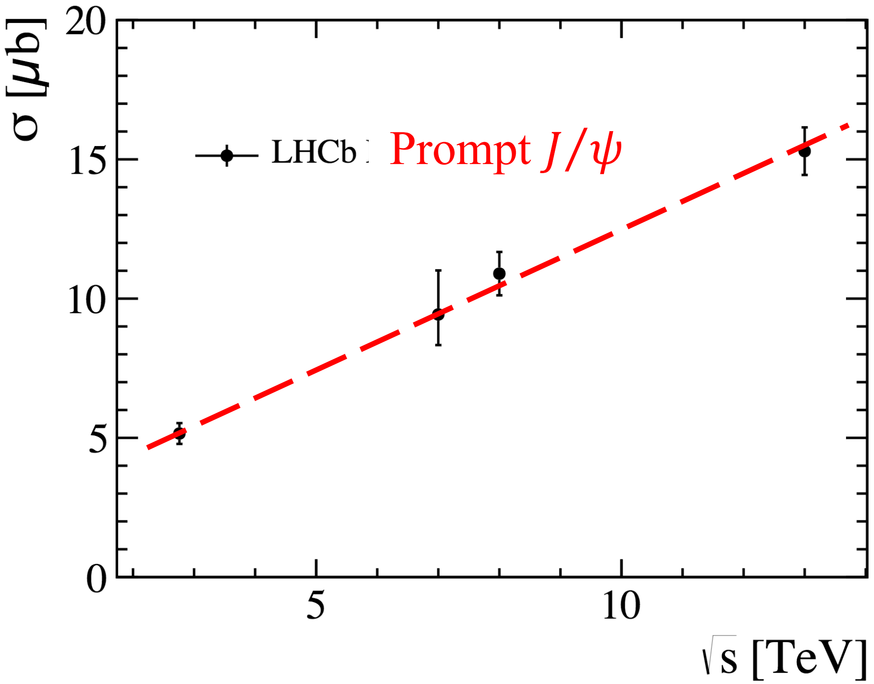


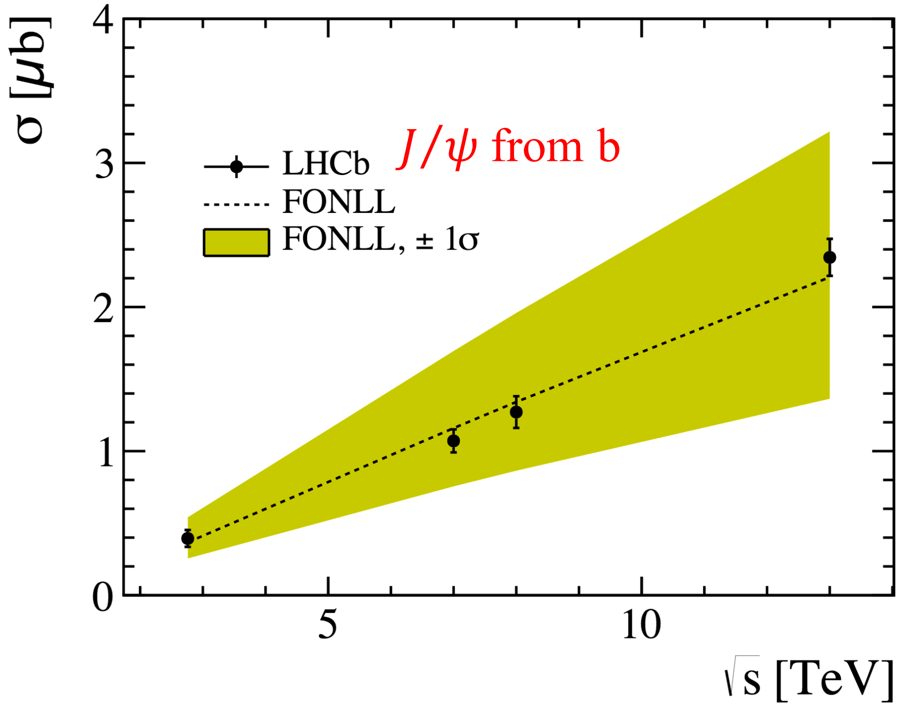
FONLL: [EPJ C75 (2015) 610]

- Cross-section ratio between 13 and 8 TeV increases with p_T
- Ratio for prompt J/ψ is consistent with NLO NRQCD predictions
- Agreement with FONLL also not bad

$\sigma(J/\psi)$ as a function of $\sqrt{s}$

LHCb: JHEP 10 (2015) 172



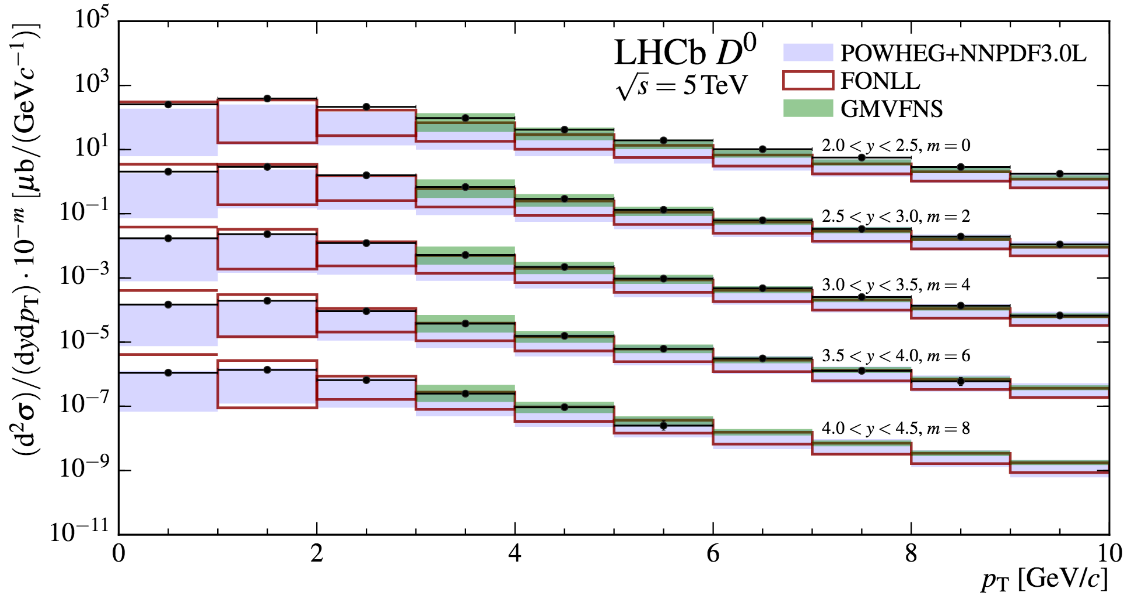


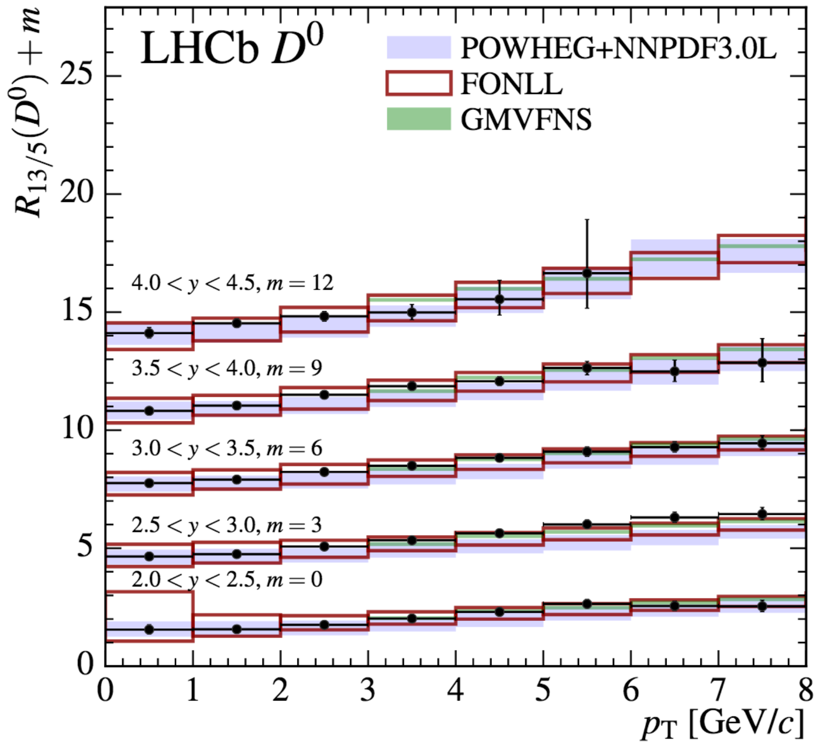
$\sigma(J/\psi\,,\text{prompt})$ scales almost linearly with $\sqrt{s}$ in range 2.76-13 TeV

$\sigma(J/\psi\,,\text{from } b)$ well described by FONLL prediction [JHEP 05 (1998) 007]

Open charm: p_T distributions

LHCb: JHEP 03 (2016) 159, arXiv:1610.02230
POWHEG+NNPDF2.0L: [JHEP 11 (2015) 009]
FONLL: [EPJ C75 (2015) 610]
GMVFNS: [EPJ C72 (2012) 2082]



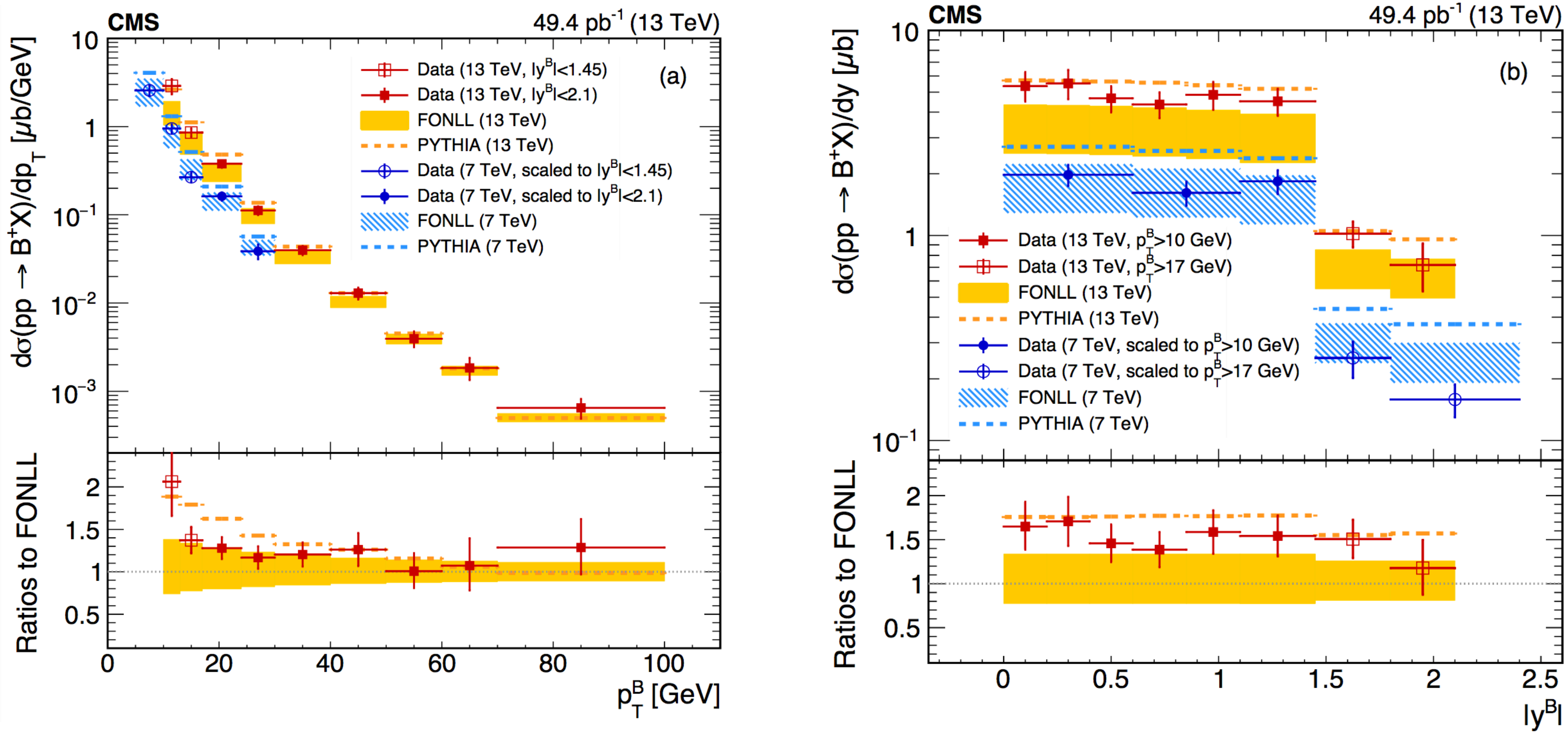


p_T distributions in good agreement with theoretical predictions, ratio cross-sections described surprisingly well.

B^+: differential cross-sections

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

CMS: arXiv:1609.00873, PRL 106 (2011) 112001
PYTHIA: 8.1
FONLL: [JHEP 05 (1998) 007] [JHEP 03 (2001) 006]



Distributions in good agreement with predictions from PYTHIA and FONLL in terms of shape and normalization

Associated production

- Double J/ψ @ LHCb, CMS, ATLAS
- J/ψ + open charm
- Υ + open charm

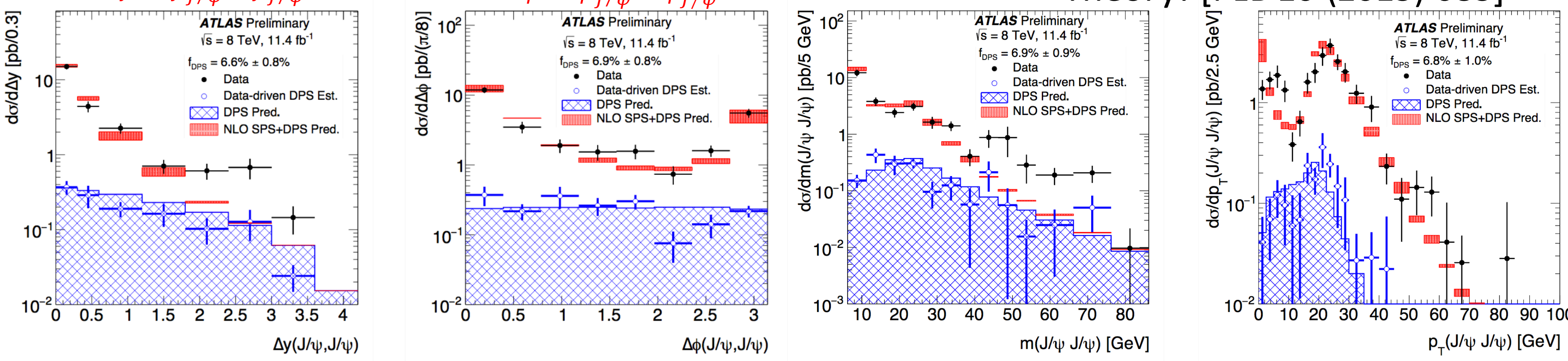
PLB707 (2012) 52
JHEP 06 (2012) 141
JHEP 09 (2014) 094
JHEP 07 (2016) 052
ATLAS-CONF-2016-047

Double J/ψ by ATLAS

ATLAS-CONF-2016-047

ATLAS: $p_T(J/\psi) > 8.5$ GeV, $|y(J/\psi)| < 2.1$, f_{DPS} determiend assuming DPS dominates for $|\Delta y| \geq 1.8$ and $|\Delta\phi| \leq \frac{\pi}{2}$, $f_{DPS} \approx (7 \pm 1)\%$, dominted by SPS in full phase space

$\Delta y = y_{J/\psi} - y_{J/\psi}$ $\Delta\phi = \phi_{J/\psi} - \phi_{J/\psi}$ Theory: [PLB 10 (2015) 083]



- DPS templates in data obtained using mixed events
- DPS distributions well described by data
- Peaking in $|\Delta y| = 0$, $|\Delta\phi| = 0, \pi$ and $|p_T| \approx 20$ GeV suggests SPS dominated
- Tensions between data and NLO SPS in large $m(J/\psi\, J/\psi)$ and large $|\Delta y|$

Effective cross sections:

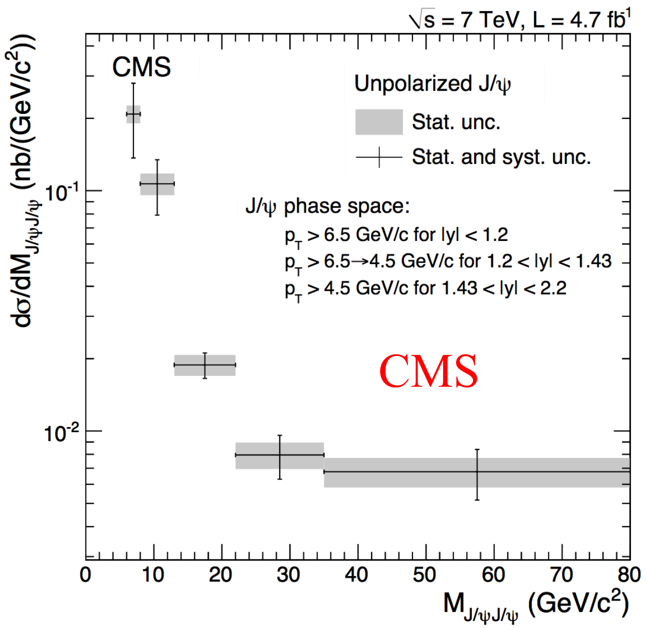
DPS (SPS): double (Single) parton scattering

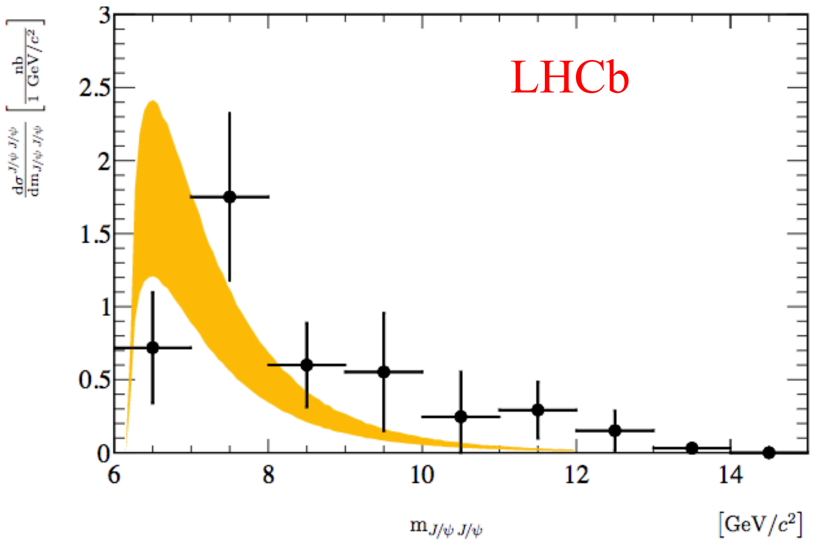
$$\sigma_{\rm eff} = \frac{1}{2}\frac{\sigma_{J/\psi}\sigma_{J/\psi}}{\sigma_{\rm DPS}^{J/\psi,J/\psi}} = \frac{1}{2}\frac{\sigma_{J/\psi}\sigma_{J/\psi}}{f_{\rm DPS}\times\sigma_{J/\psi J/\psi}} \approx 8.7 \pm 1.1({\rm stat}) \pm 1.4({\rm syst})\ {\rm mb}$$

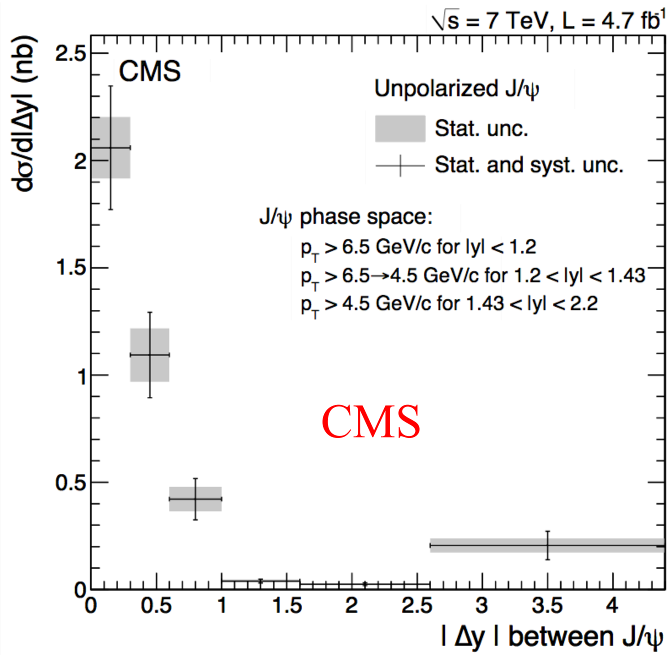
slightly lower than other measurements (15-20 mb)

Double J/ψ by LHCb, CMS

PLB707 (2012) 52
JHEP 09 (2014) 094







$$\sigma^{J/\psi J/\psi} = 5.1 \pm 1.5 \text{ nb}$$

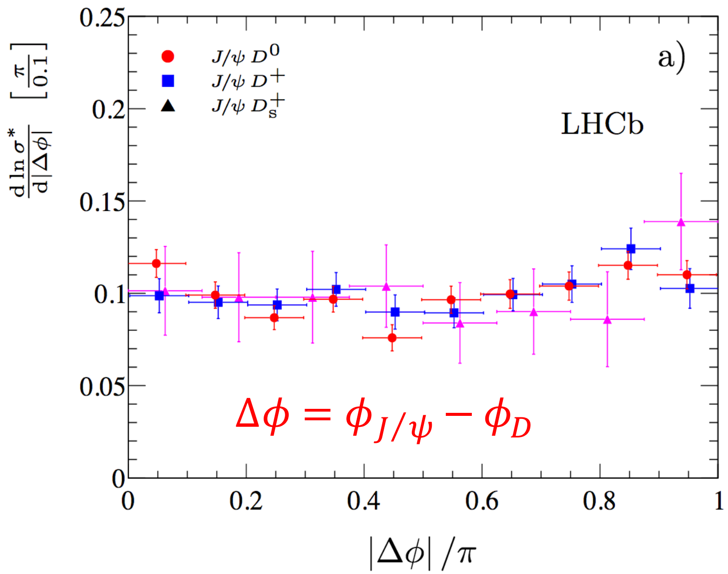
$$\frac{\sigma^{J/\psi J/\psi}}{\sigma^{J/\psi}} = (5.1 \pm 1.0 \pm 0.6^{+1.2}_{-1.0})\times 10^{-4}$$

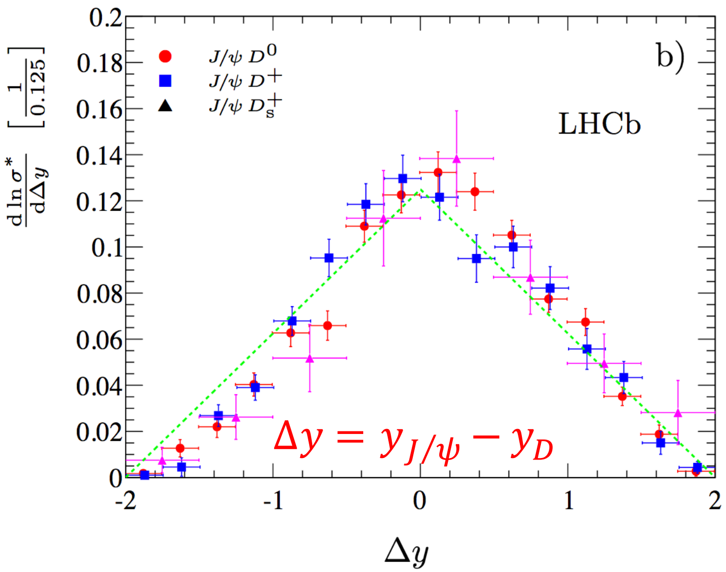
$$=> \ \sigma_{\text{eff}} \geq \frac{\sigma_{J/\psi J/\psi}}{2\sigma_{J/\psi J/\psi}} \approx 10 \text{ mb} \quad \text{large DPS?}$$

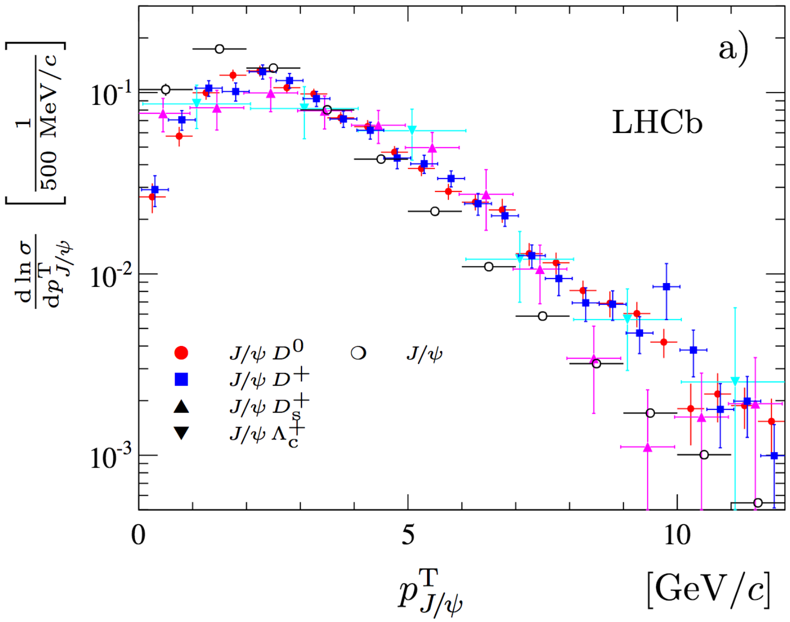
- $|\Delta y|$ and $m(J/\psi\, J/\psi)$ distributions at CMS agree with ATLAS
- LHCb result suggests a hint of large DPS contribution (at low p_T)

J/ψ + open charm

LHCb: JHEP 06 (2012) 141



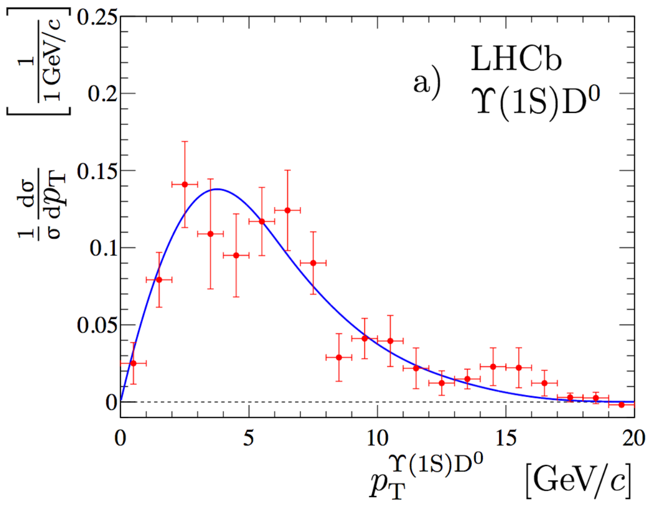


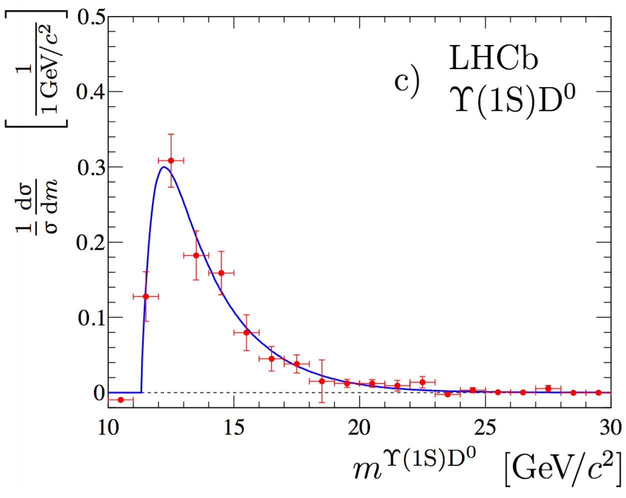


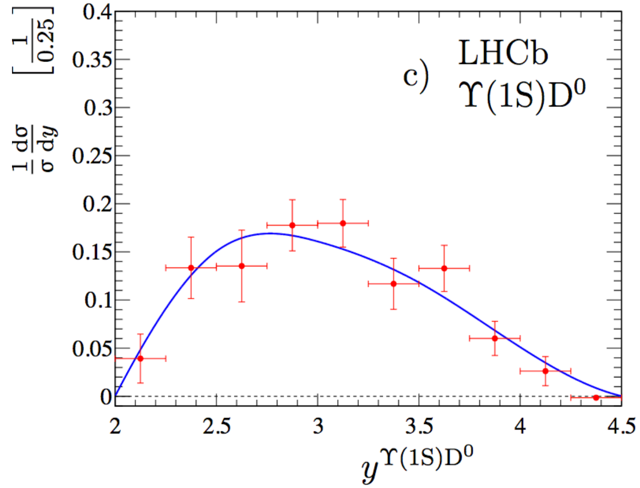
- Correlation between J/ψ and D^0 is small
- J/ψ p_T distribution is harder than inclusive

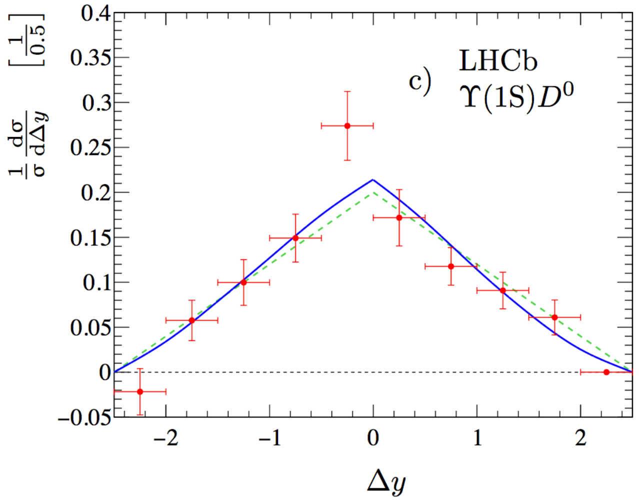
Υ + open charm

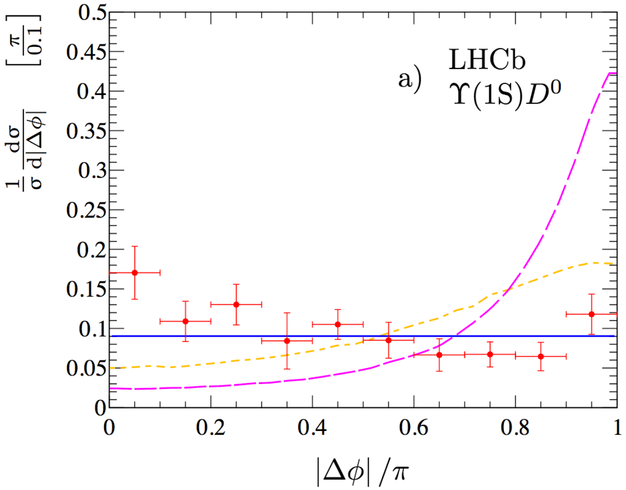
LHCb: JHEP 07 (2016) 052











Assume Υ and D produced independently (as DPS)

SPS: [S. P. Barano: k_T-factorization and collinear approximation]

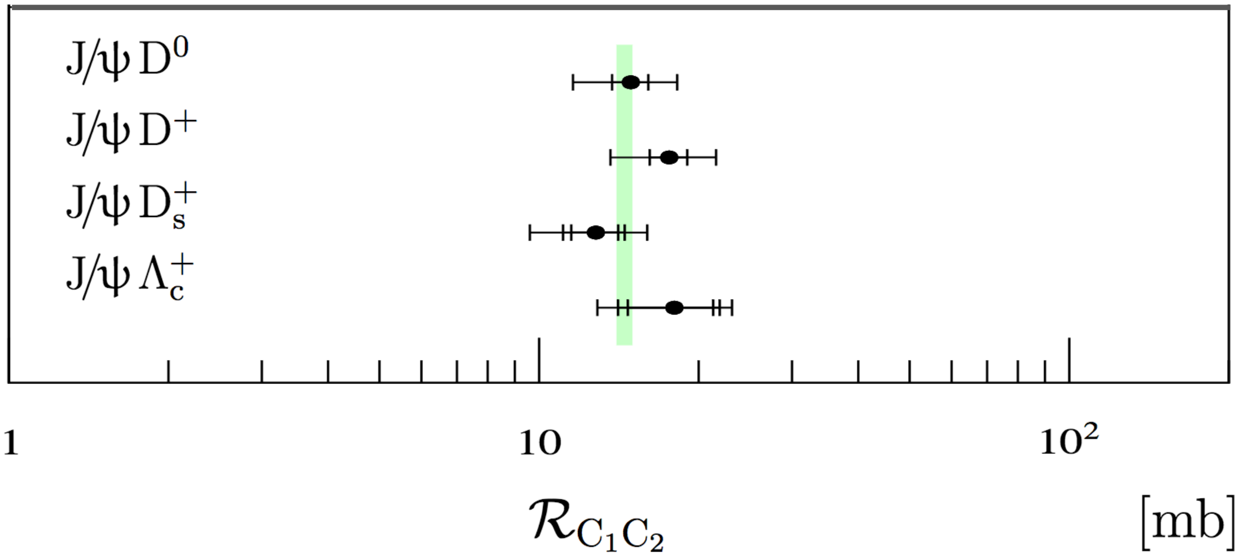
Data suggest Υ and D are not strongly correlated, favoring DPS production

Effective cross-section: σ_{eff}

- Assume associated production is purely from Double Parton Scattering:

LHCb: JHEP 06 (2012) 141
JHEP 07 (2016) 052

$$\sigma_{\text{eff}}^{\text{DPS}} = \alpha \frac{\sigma_{C_1} \times \sigma_{C_2}}{\sigma_{C_1 C_2}^{\text{DPS=asso.}}}$$



$$\sigma_{\text{eff}}|_{\Upsilon(1S)D^{0,+},\sqrt{s}=7\,\text{TeV}} = 18.0 \pm 2.1\,(\text{stat}) \pm 1.2\,(\text{syst}) = 18.0 \pm 2.4\,\text{mb}$$

$$\sigma_{\text{eff}}|_{\Upsilon(1S)D^{0,+},\sqrt{s}=8\,\text{TeV}} = 17.9 \pm 1.8\,(\text{stat}) \pm 1.2\,(\text{syst}) = 17.9 \pm 2.1\,\text{mb}$$

Consistent with other measurements, dominated by DPS?

Polarization of quarkonia in pp collisions

- J/ψ and $\psi(2S)$ polarisation at LHCb
- J/ψ polarisation at ALICE
- J/ψ , $\psi(2S)$ and $\Upsilon(1S)$ polarisation at CMS

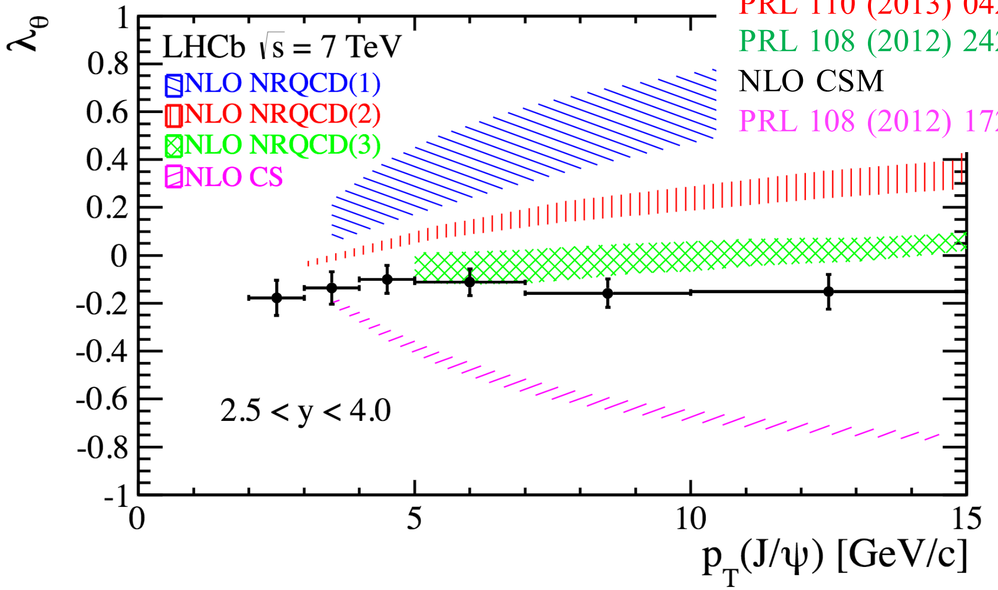
EPJC73 (2013) 2631
EPJC74 (2014) 2872
PRL 108 (2012) 082001
PLB 727 (2013) 381
PRL 110 (2013) 081802
PLB 761(2016) 31

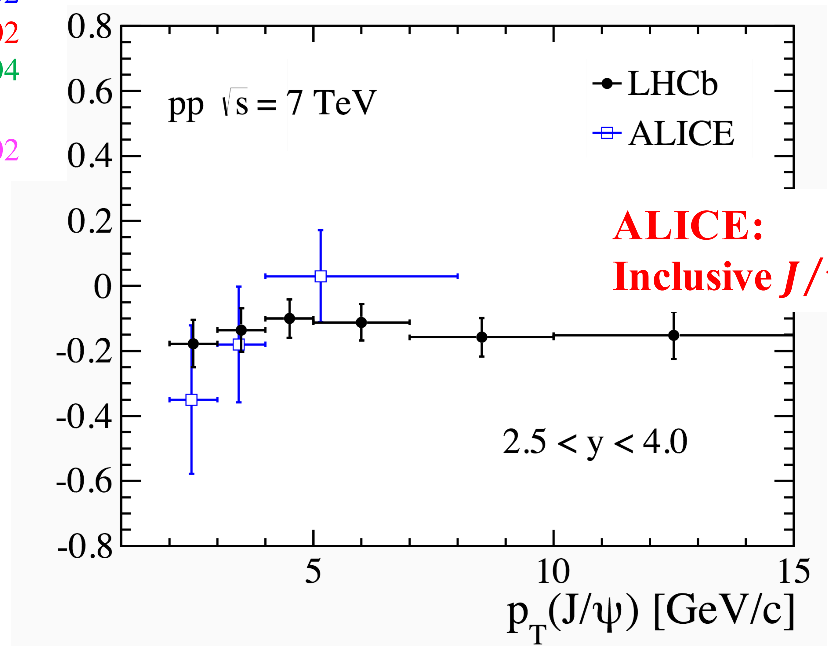
J/ψ polarisation

EPJC73 (2013) 2631
PRL 108 (2012) 082001
PLB 727 (2013) 381

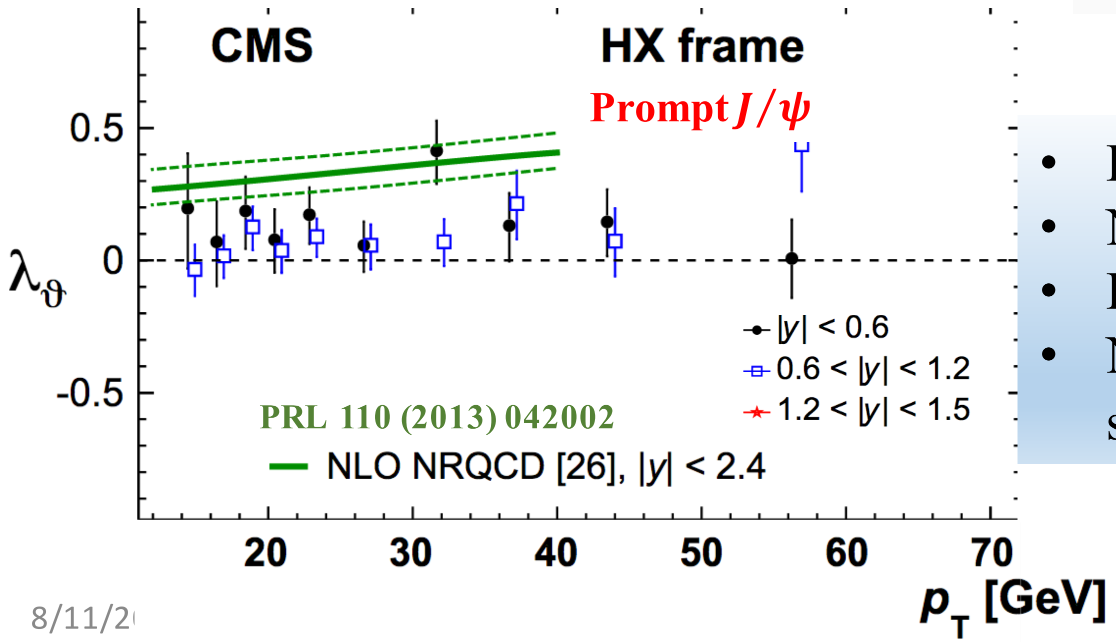
Prompt J/ψ

NLO NRQCD
PRL 108 (2012) 172002
PRL 110 (2013) 042002
PRL 108 (2012) 242004
NLO CSM
PRL 108 (2012) 172002





ALICE: Inclusive J/ψ



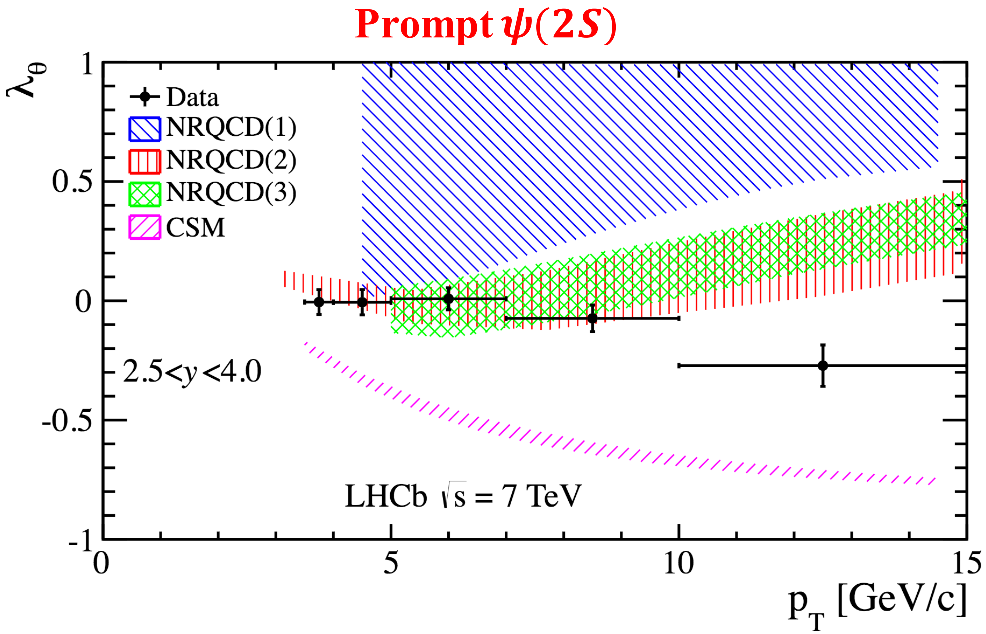
Prompt J/ψ

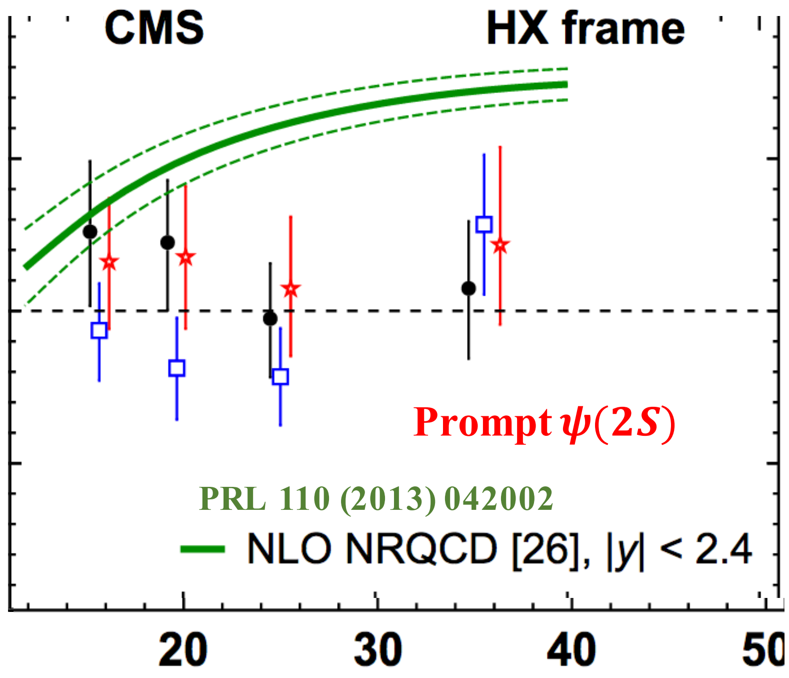
PRL 110 (2013) 042002

- Data consistent with no/small polarization
- No strong p_T dependence
- Rule out NLO CSM predictions
- NLO NRQCD calculations also not satisfactory

$\psi(2S)$ polarisation

EPJC74 (2014) 2872
PLB 727 (2013) 381





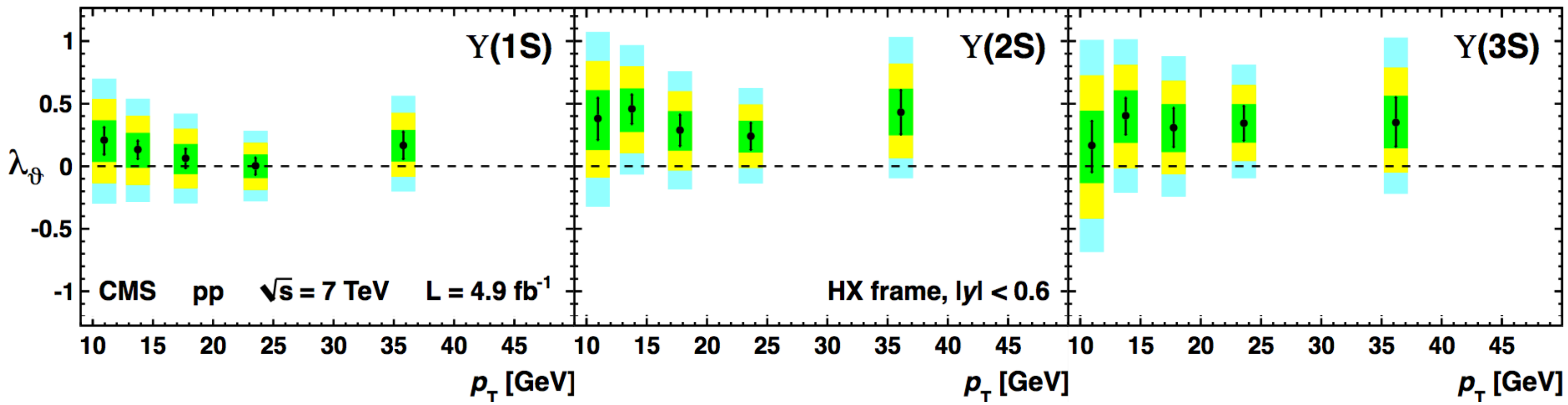
NLO NRQCD
PRL 108 (2012) 172002
PRL 110 (2013) 042002
PRL 108 (2012) 242004
NLO CSM
PRL 108 (2012) 172002

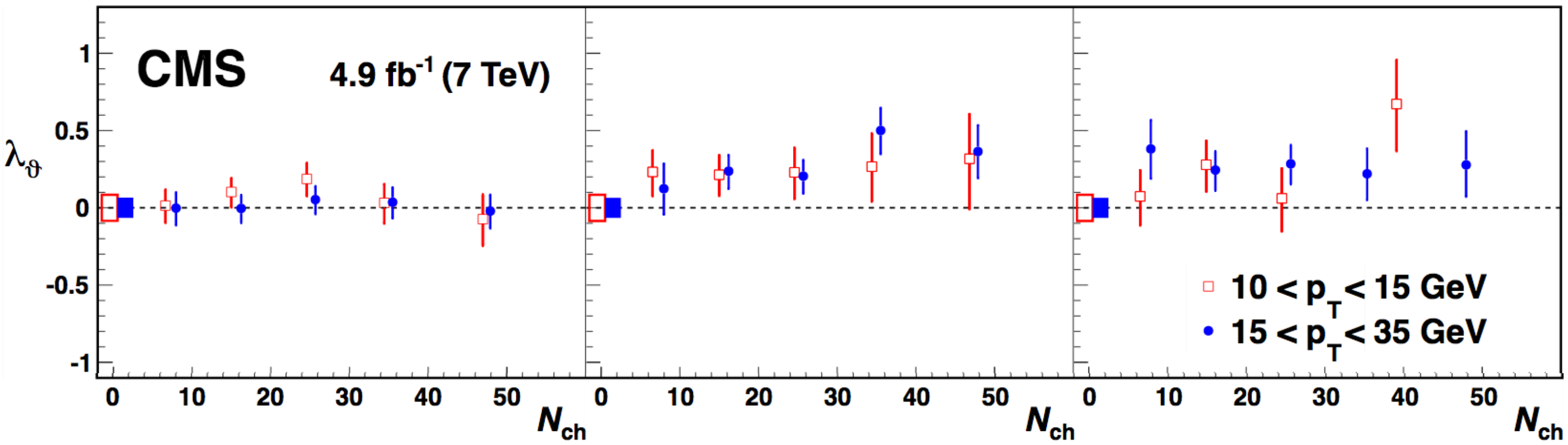
Feed down is negligible

- Data consistent with no/small polarization
- No strong p_T dependence
- Rule out NLO CSM predictions
- NLO NRQCD calculations also not satisfactory

$\Upsilon(nS)$ polarisation

PRL 110 (2013) 081802
PLB 761(2016) 31





- Data consistent with no/small polarization
- No sign of p_T dependence
- No sign of event activity dependence

Note strong feed-down even for $\Upsilon(3S)$

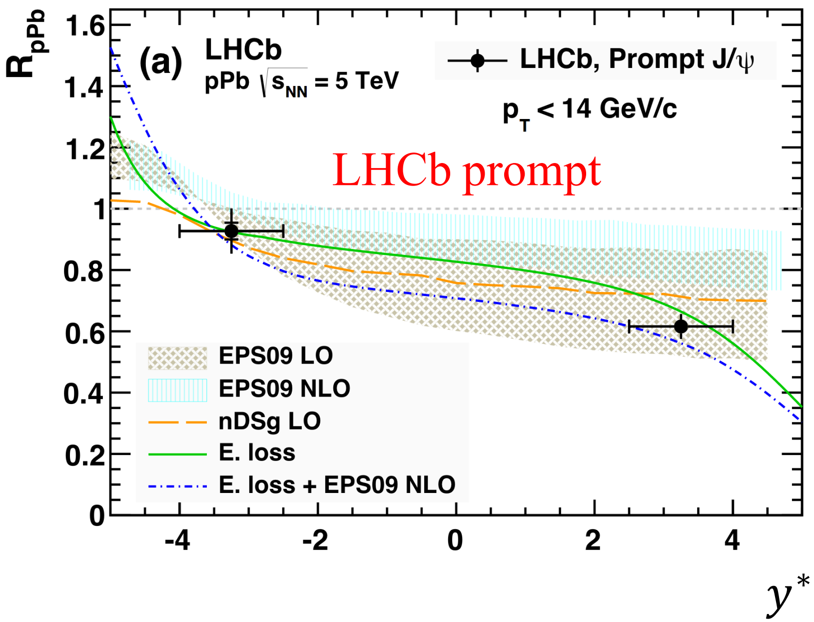
Heavy flavor production in pPb data

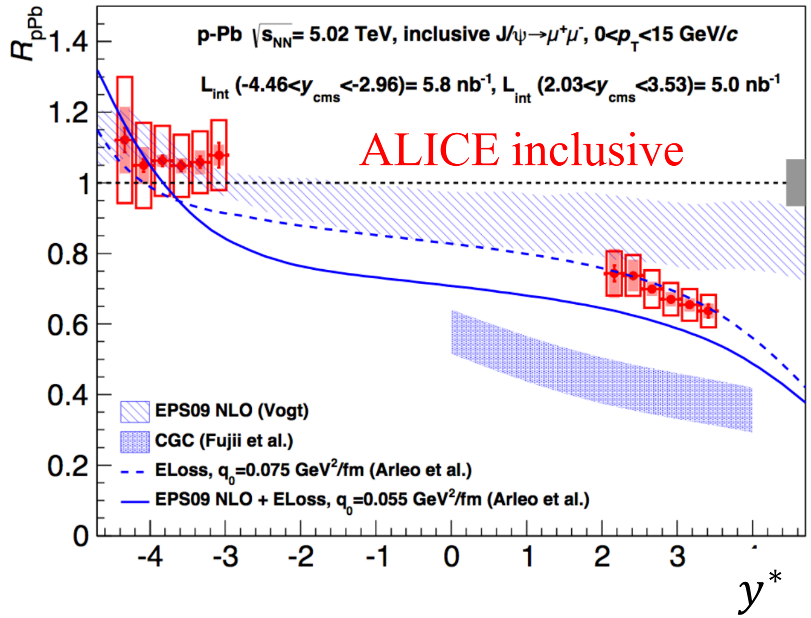
- J/ψ, $\psi(2S)$ at LHCb, ALICE
- Prompt D^0 at LHCb
- Prompt charm at ALICE

JHEP 02 (2014) 072
JHEP 02 (2014) 073
JHEP 12 (2014) 073
PRL 113 (2014) 232301
JHEP 06 (2015) 55
JHEP 03 (2016) 133
LHCb-CONF-2016-003

J/ψ in pPb

JHEP 02 (2014) 072
JHEP 02 (2014) 073





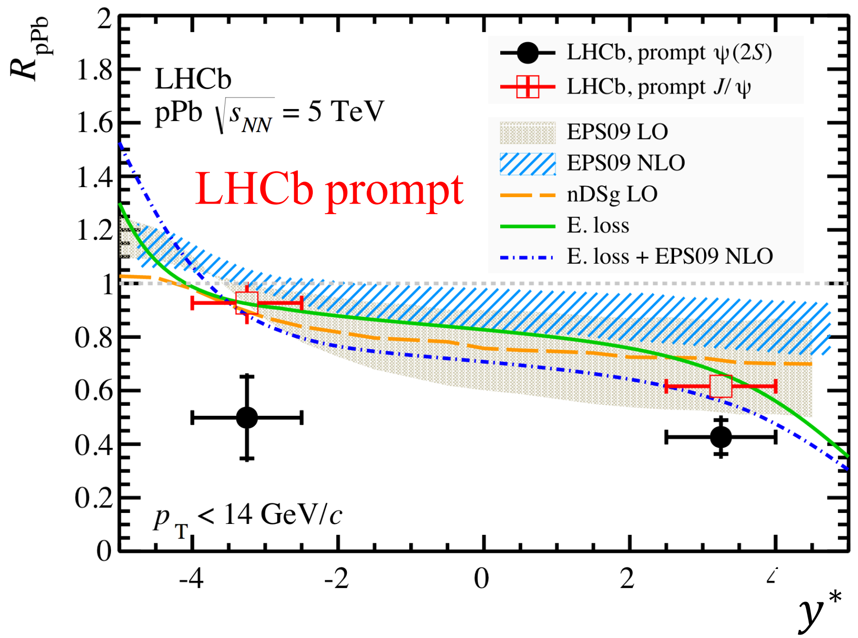
$$R_{pPb} = \frac{1}{A} \times \frac{d\sigma_{pPb}/dy}{d\sigma_{pp}/dy}$$

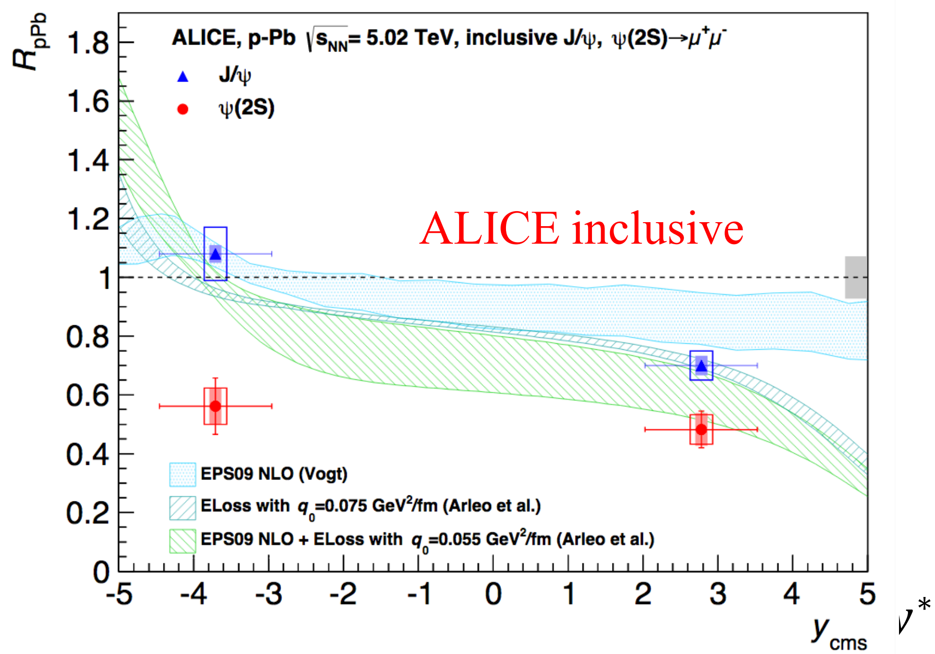
- **Forward rapidity:** strongly suppressed in forward region, significant signs of cold nuclear matter effects
  → Data well described by energy loss models w/ and w/o shadowing
- **Backward rapidity:** compatible with no suppression

Refer to papers for various models

$\psi(2S)$ in pPb

JHEP 03 (2016) 133
JHEP 12 (2014) 073



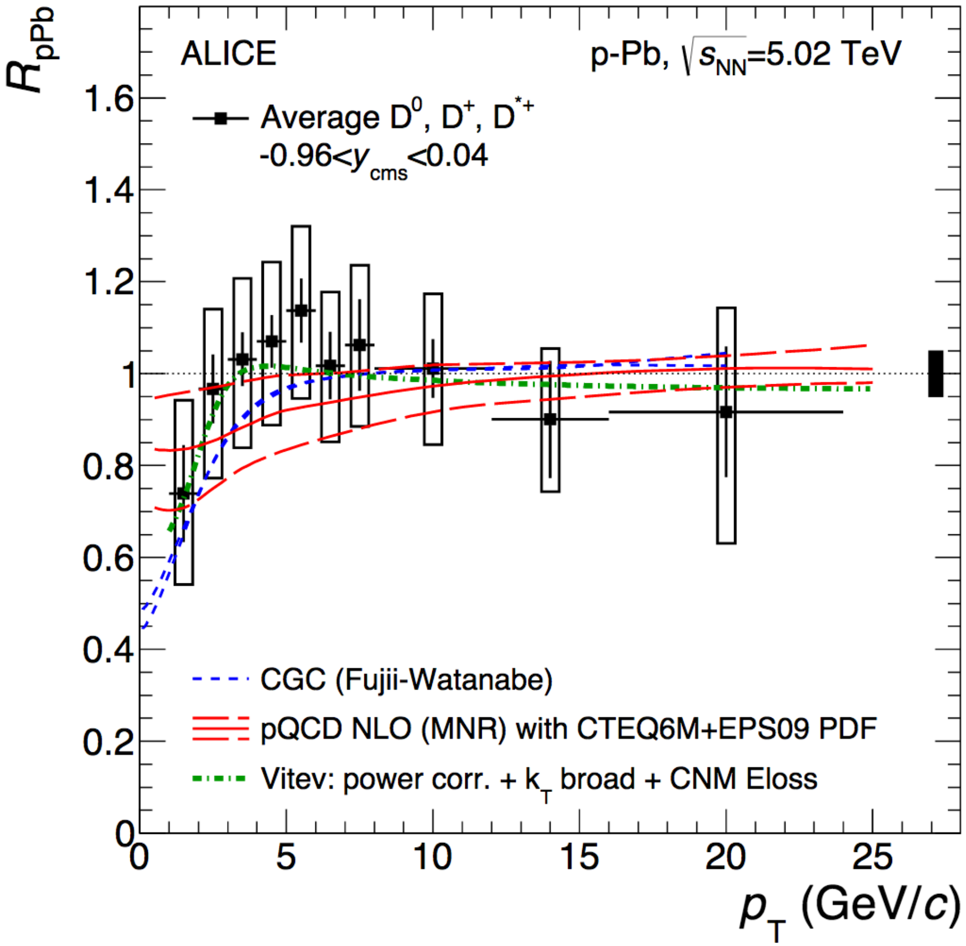


- $\psi(2S)$ suppressed than J/ψ, intriguing suppression in backward rapidity
  → Energy loss+shadowing don't explain $\psi(2S)$ suppression in backward rapidity
- LHCb and ALICE results are consistent

Refer to papers for various models

Open charm at ALICE

PRL 113 (2014) 232301

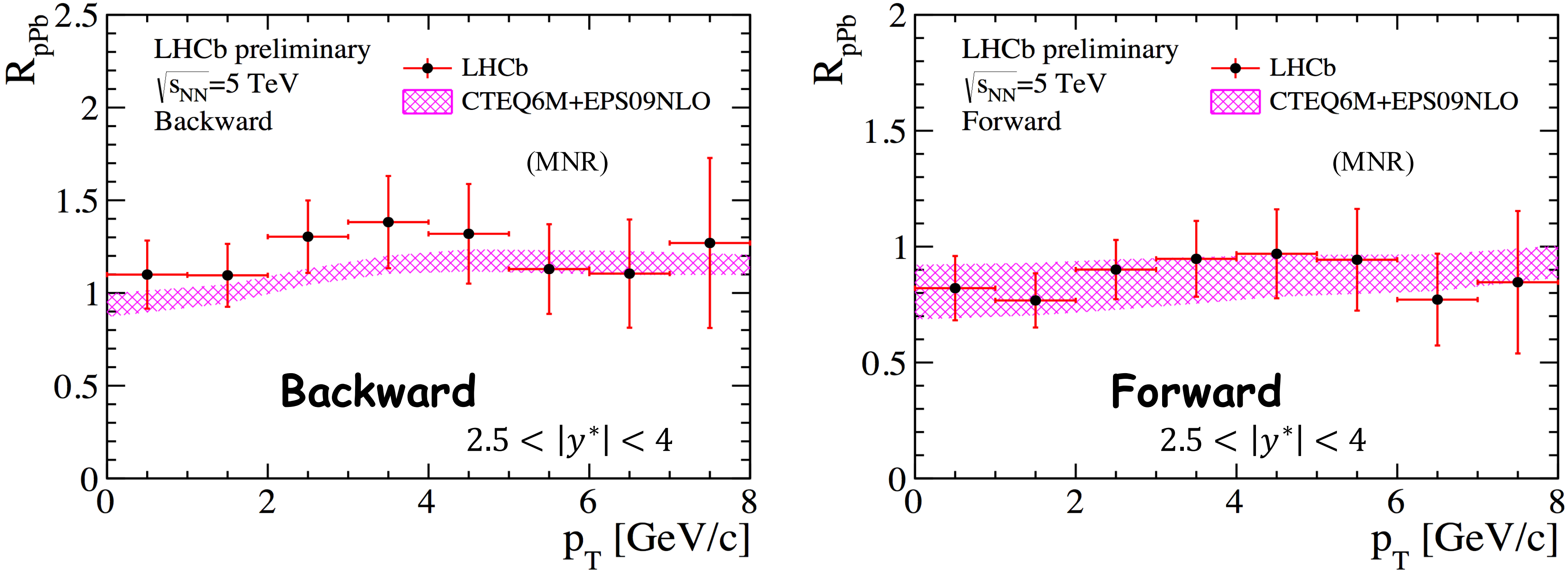


CGC: [Nucl.Phys. A920 (2013) 78-93]
MNR: [Nucl. Phys. B 373 (1992) 295]
Vitev: [Phys. Rev. C 80 (2009)054902]

Consistent with no suppression at mid rapidity within large uncertainties
Results well described by various theoretical models

Prompt D^0 at LHCb

LHCb-CONF-2016-003



Reference D^0 cross-section in pp collision at $\sqrt{s} = 5$ TeV extrapolated using LHCb measurements at 7 and 13 TeV, dominating uncertainties Nucl. Phys. B87 (2013), JHEP 03 (2016) 159

- Being updated with direct measurement in pp at $\sqrt{s} = 5$ TeV, $R_{p\text{Pb}}$ decreases by ~20%

arXiv:1610.02230

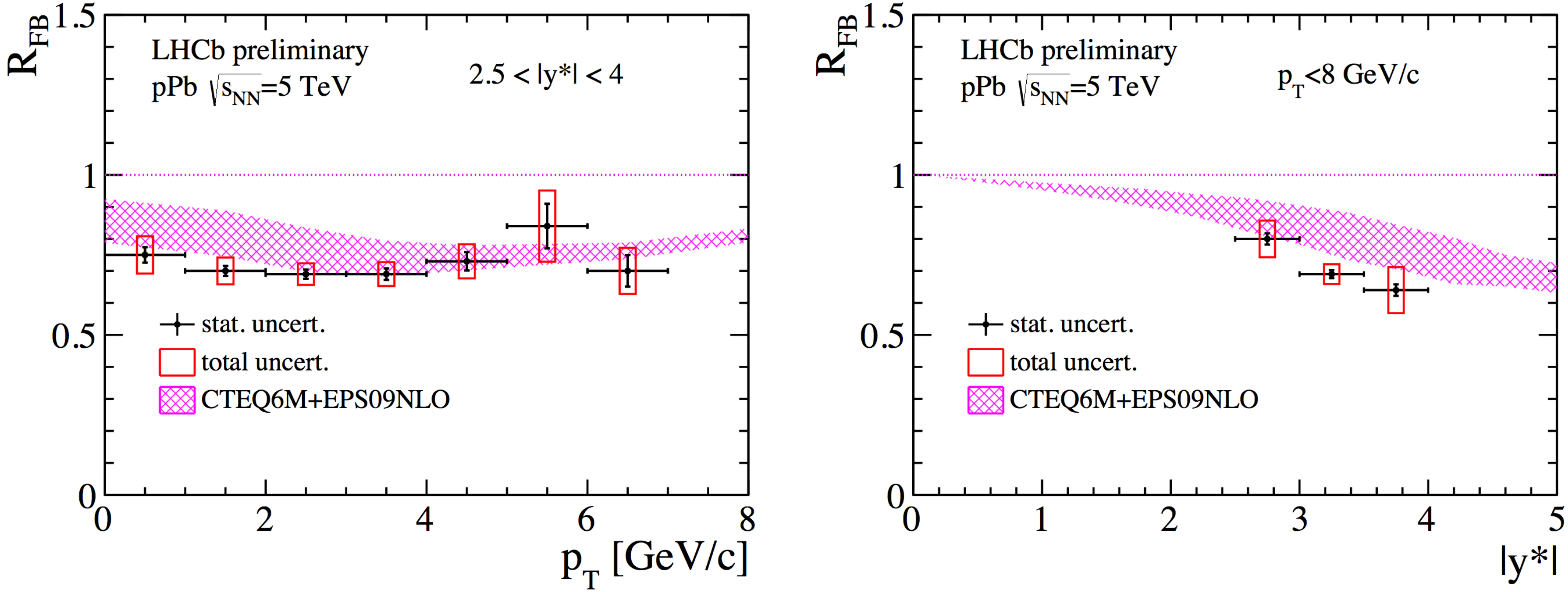
$R_{p\text{Pb}}$ for D^0 meson has no strong dependence on p_T
Measurements consistent with NLO MNR prediction using CTEQ6M+NLO EPS09 nPDF

MNR with CTEQ6M+EPS09NLO: Nucl. Phys. B373 (1992) 295, JHEP 10 (2003) 046, JHEP 04 (2009) 065

Prompt D^0 forward-backward ratio

LHCb-CONF-2016-003

- Calculated as $R_{\rm FB}(|y^*|, p_T) = \frac{\sigma_{p\rm Pb}(+|y^*|, p_T, \sqrt{s_{NN}})}{\sigma_{\rm Pb\mathit{p}}(-|y^*|, p_T, \sqrt{s_{NN}})}$, systematic uncertainty largely cancels



- R_{FB} for D^0 meson indicates significant production asymmetry in forward-backward rapidities (more important at large rapidity)
- Data consistent with NLO MNR prediction

MNR with CTEQ6M+EPS09NLO: Nucl. Phys. B373 (1992) 295, JHEP 10 (2003) 046, JHEP 04 (2009) 065

Summary

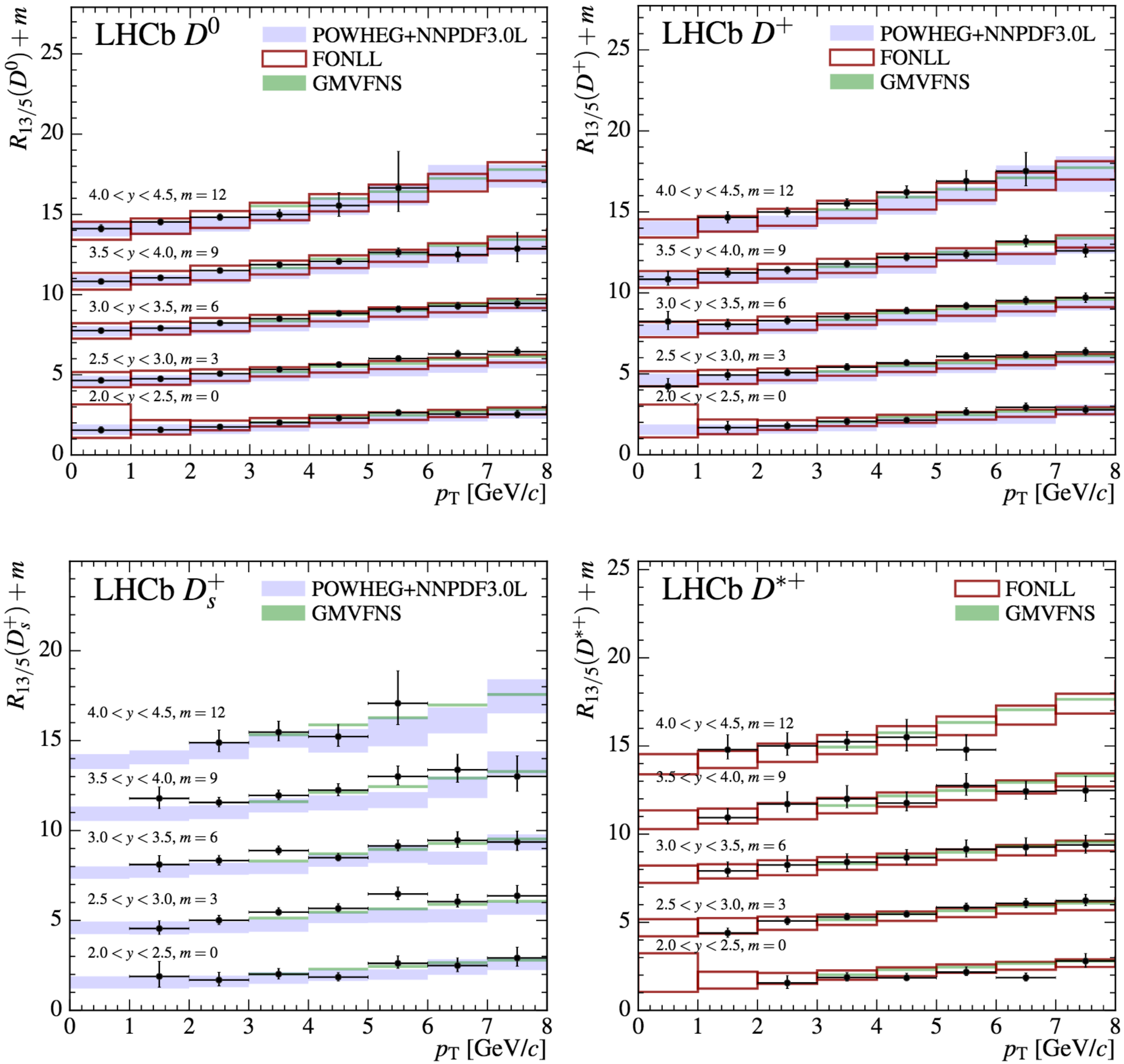
- Heavy flavor productions are important tools to understand QCD
- LHC made a lot of studies in heavy flavor productions in RunI and many new results in RunII coming out
- What we know:
  - Heavy quarkonia production by NRQCD
  - Open heavy flavor production by FONLL and other models
  - Cold nuclear effects exist in pPb, and described by models
- That need more efforts
  - Quarkonia polarisation
  - Double parton scattering?
  - All cold nuclear effects participate or only some of them, how to distinguish
  - Cold nuclear effects for $\psi(2S)$
- The good news is that LHC continues questing

Thank you for your attention

Backups

Ratio cross sections for charm at LHCb

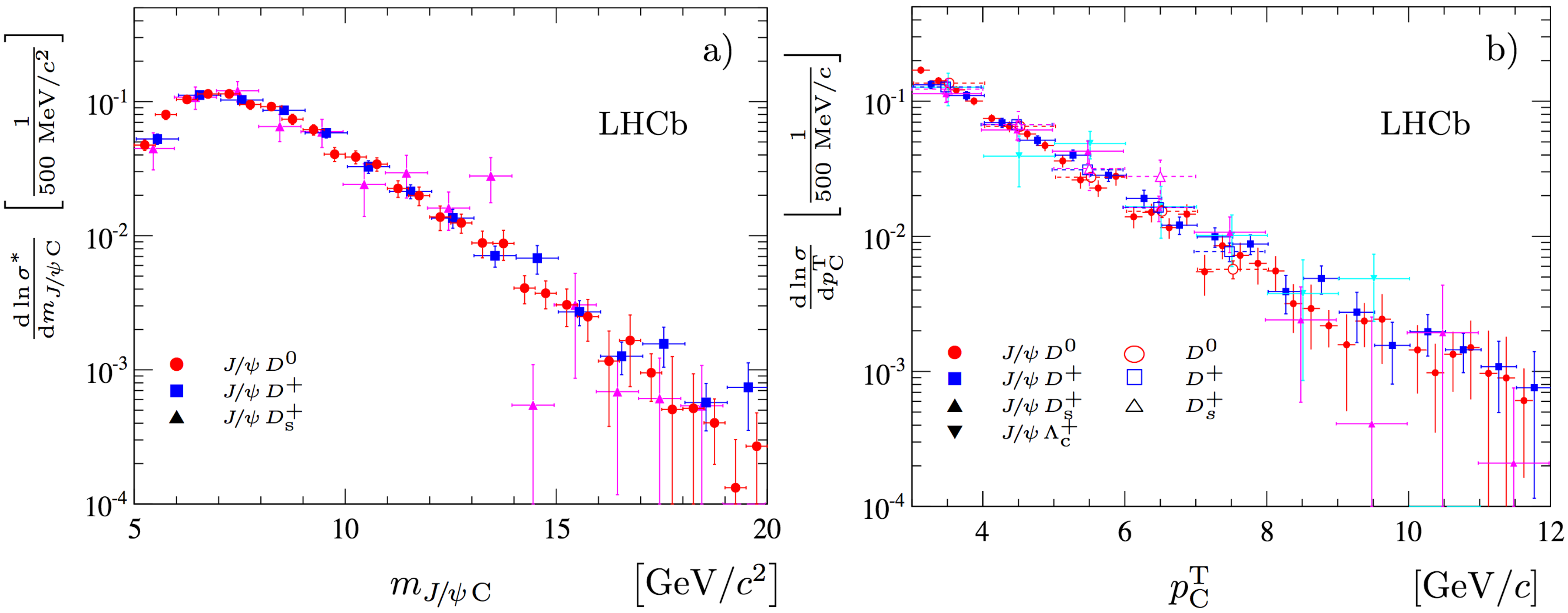
arXiv:1610.02230



J/ψ + open charm (LHCb)

- Invariant mass and charm p_T

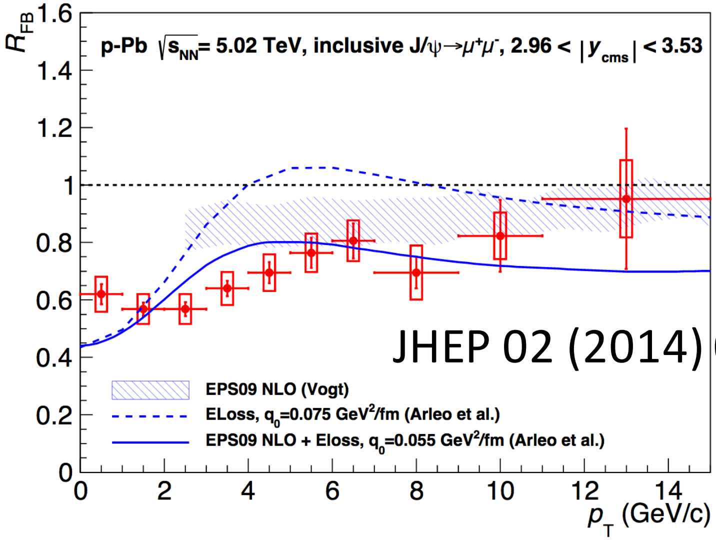
JHEP 07 (2016) 052



Charm p_T distributions similar to inclusive ones

$J/\psi(1S)$ in pPb

- R_{FB} as a function of p_T



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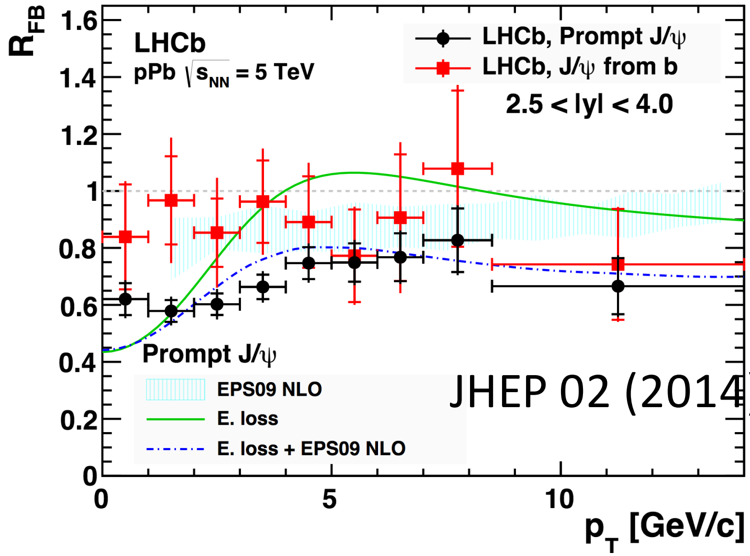
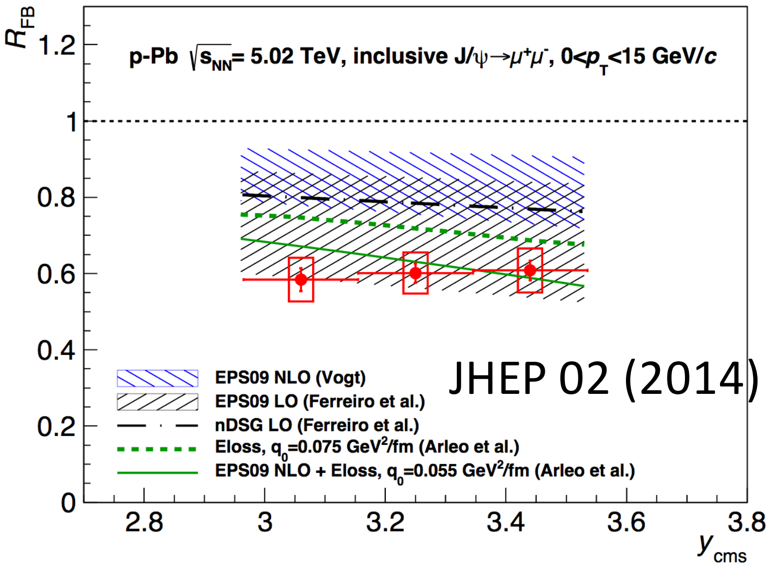


JHEP 02 (2014) 072



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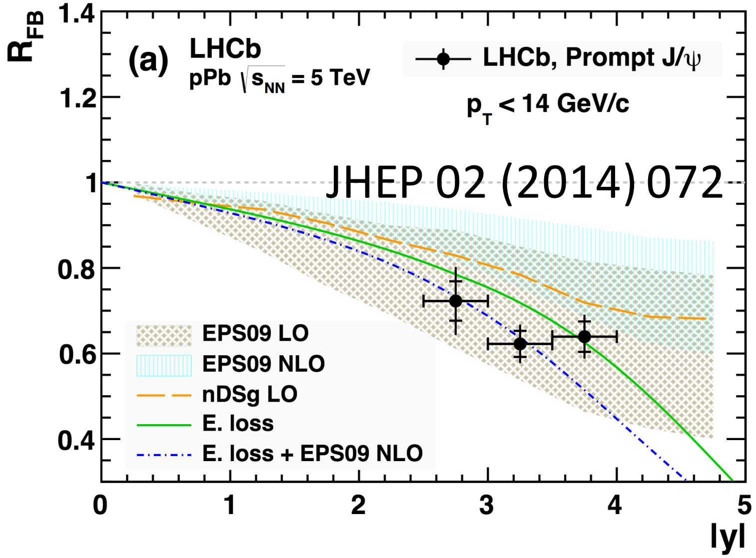

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Nuclear modification factor

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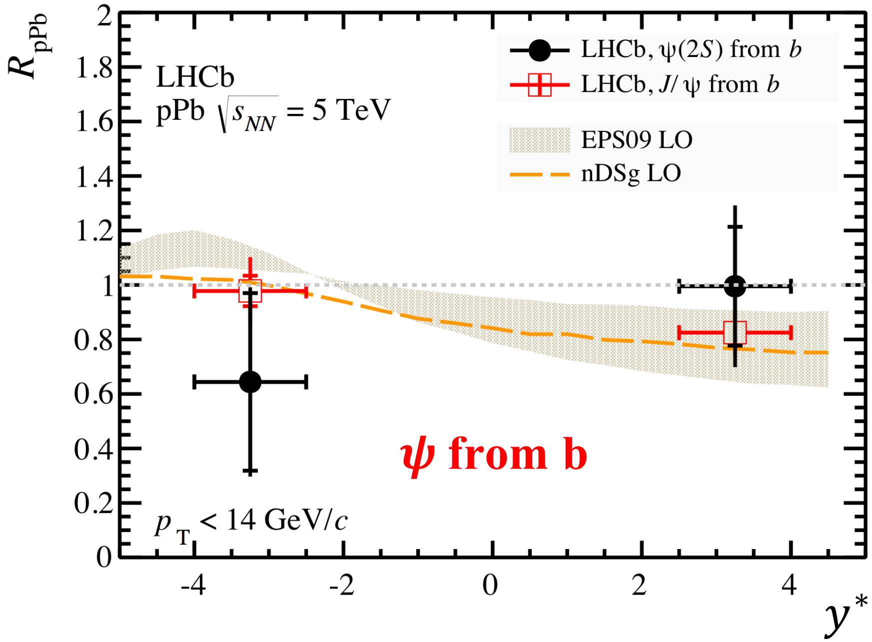

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- ***J/ψ* from *b***: modest suppression in forward region, signs of *b*-hadron production
- ***ψ*(2*S*) from *b***: nuclear modification factor consistent with that of *J/ψ*

J/ψ and $\psi(2S)$ in pPb

- $R_{p\mathrm{Pb}}$ as a function of p_T

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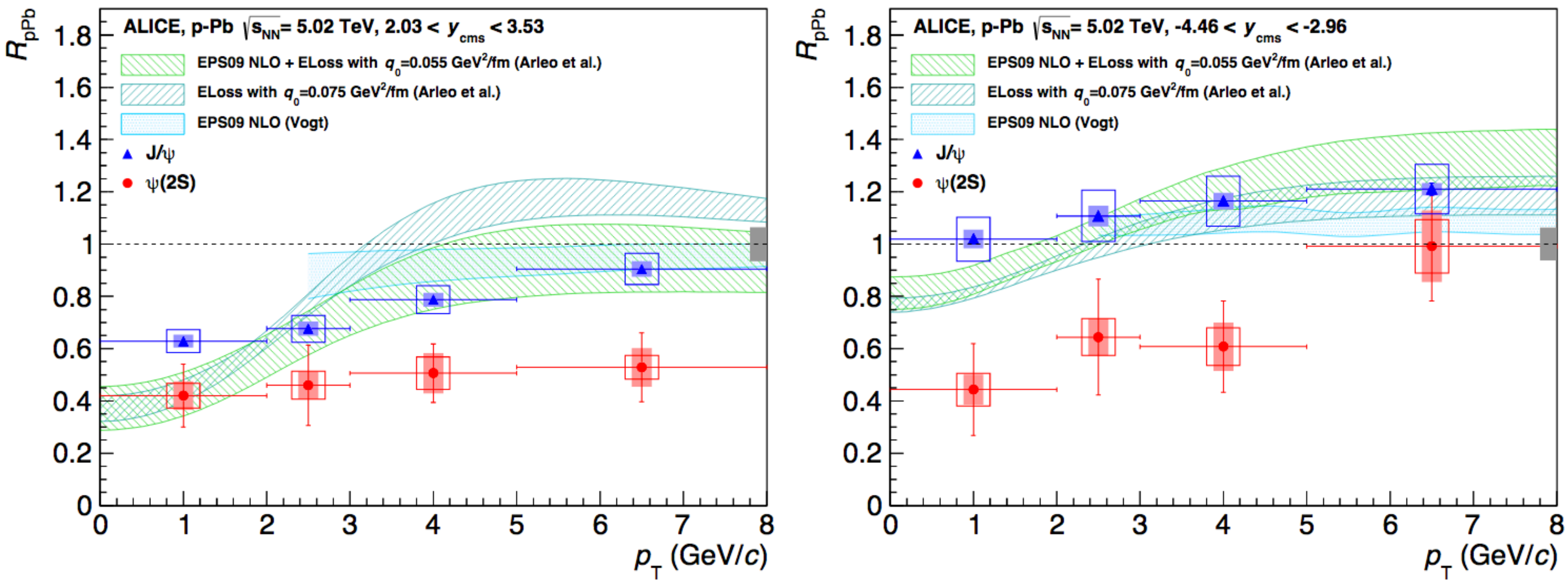

$\psi(2S)$ is more suppressed than J/ψ consistently in p_T bins

$\Upsilon(1S)$ in pPb

- $R_{p\mathrm{Pb}}$ as a function of rapidity

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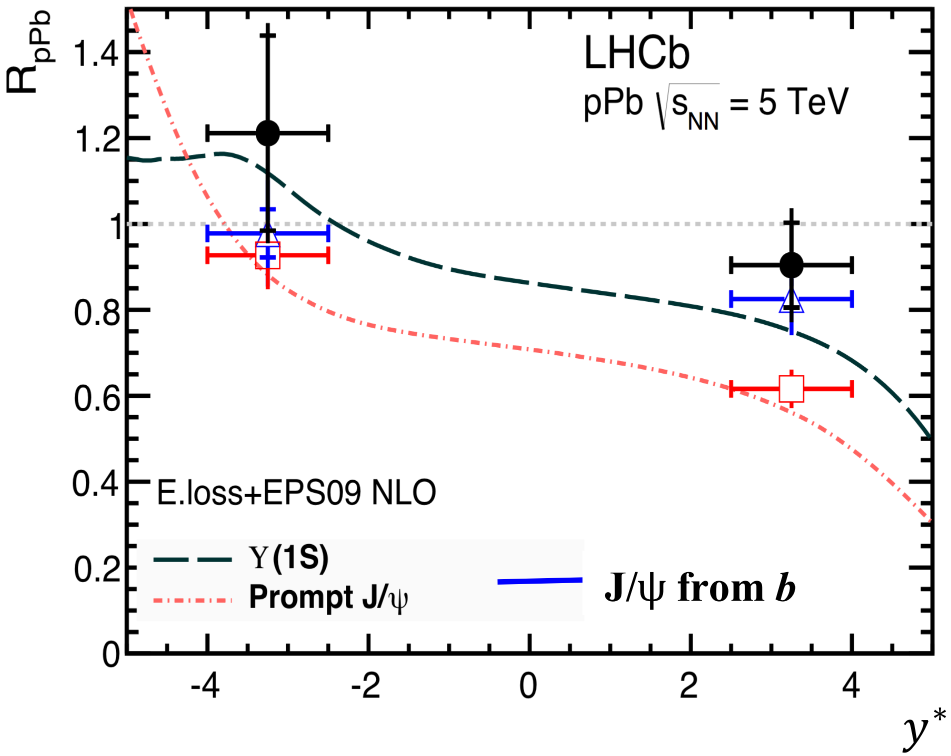

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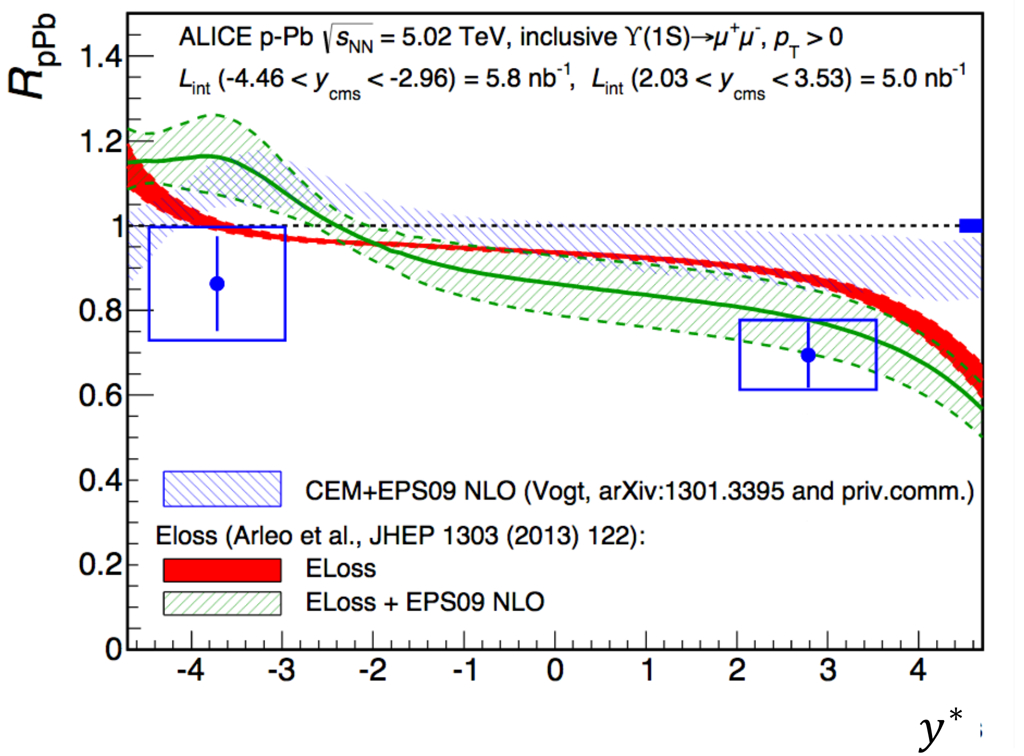

$\psi(2S)$ is more suppressed than J/ψ consistently in p_T bins