Charm and charmonium production in pp collisions at the LHC

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Outline of the Talk

- Charm: motivation
- Results:
  - Inclusive HF production via electrons and muons
  - Charm hadron production and total cross section

- Charmonium: motivation
- Results:
  - J/ψ production: inclusive, prompt and non-prompt
  - Other charmonium states
  - J/ψ polarization

- Double charm(onium) production and charm(onium) production vs. multiplicity

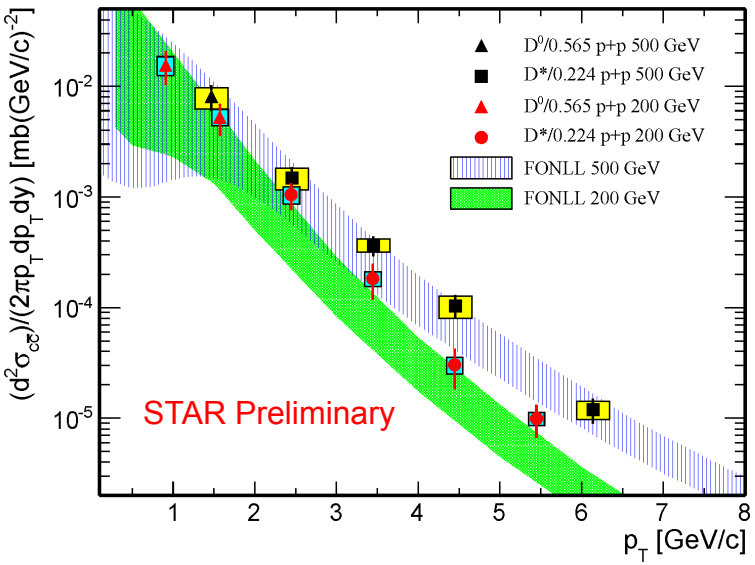
Charm production: Motivation (I)

- Important test of pQCD in a new energy domain ($3.5\times\sqrt{s}_{TEVATRON}$)
- State-of-the-art calculations: FONLL, POWHEG, GM-VFNS…

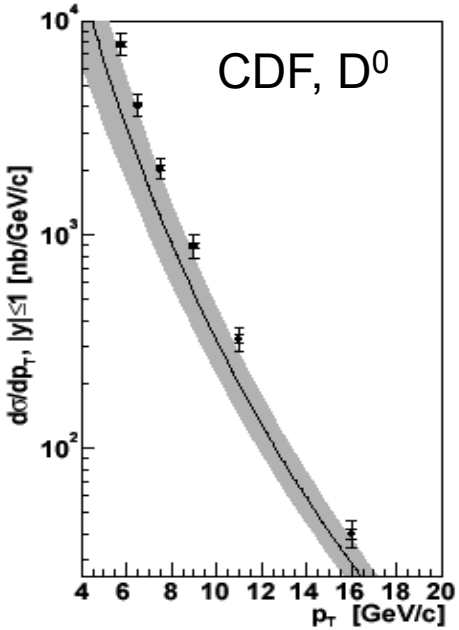
FONLL: Cacciari, Frixione, Mangano, Nason and Ridolfi, JHEP0407 (2004) 033

$$\frac{d\sigma}{dp_T} = A(m)\alpha_s^2 + B(m)\alpha_s^3 + G(m,p_T)\left[\alpha_s^2 \sum_{i=2}^{\infty} a_i [\alpha_s \log(\mu/m)]^i + \alpha_s^3 \sum_{i=1}^{\infty} b_i [\alpha_s \log(\mu/m)]^i\right]$$

- D production on the upper edge of prediction, at 0.2 and 2 TeV:



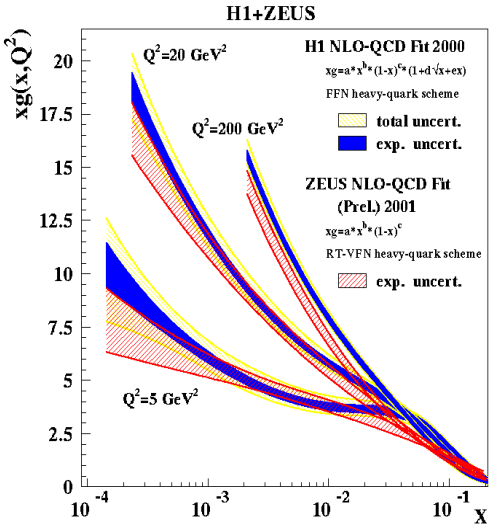
STAR, PRD 86 (2012) 72013 (200 GeV)
J. Bielcik (Moriond2013)

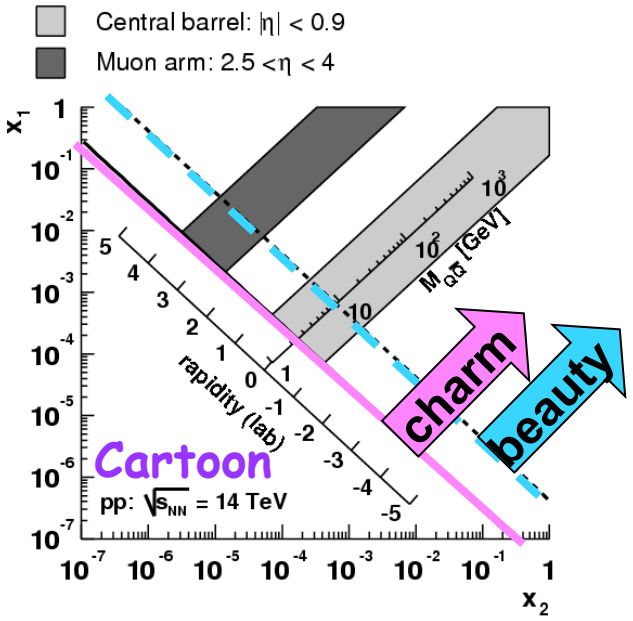


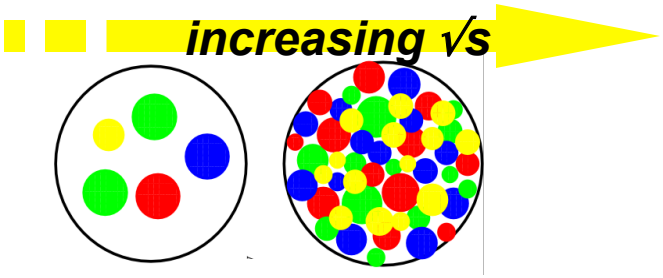
CDF, PRL91 (2003) 241804

Charm production: Motivation (2)

- Probe unexplored small-x region with HQs at low p_T and/or forward y
  - down to x~10^{-4} with charm already at y=0



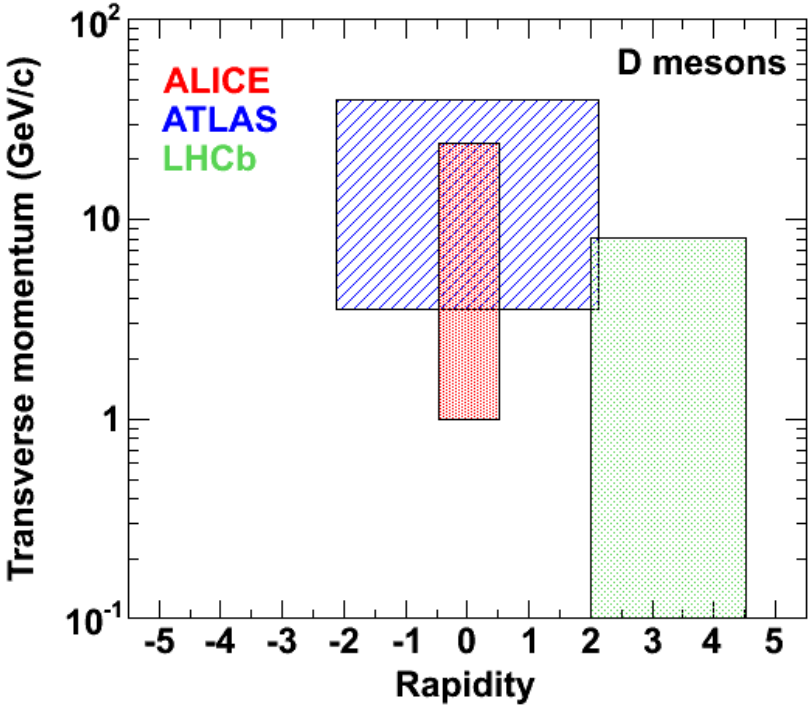


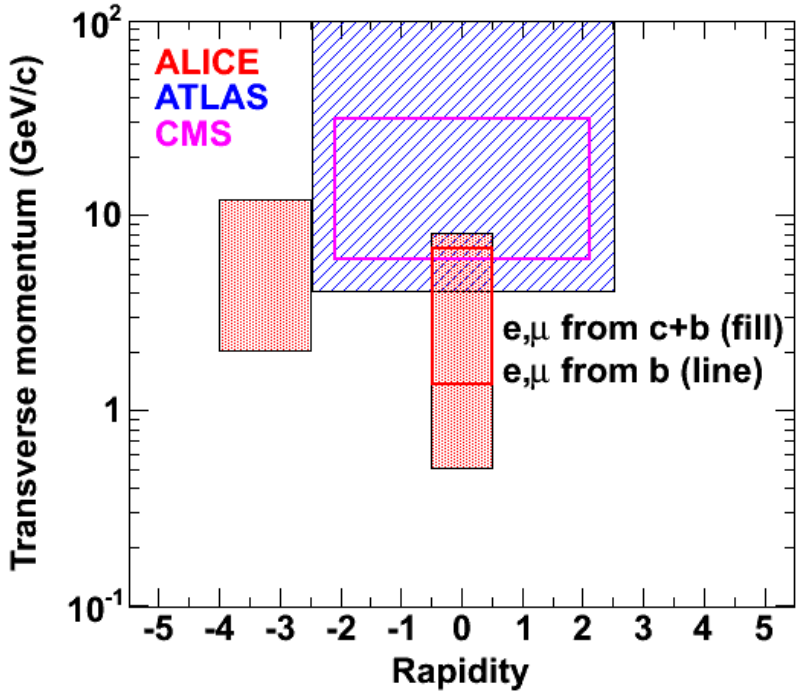


- What happens at such small x?
  - Saturation of gluon PDFs? (non-linear evolution/recombination)
  - Does the factorization approach still hold?

See “HERA and the LHC” proceedings (CERN-2005-014, hep-ph/0601012-3) for a review

Charm production measurements: complementarity of LHC experiments

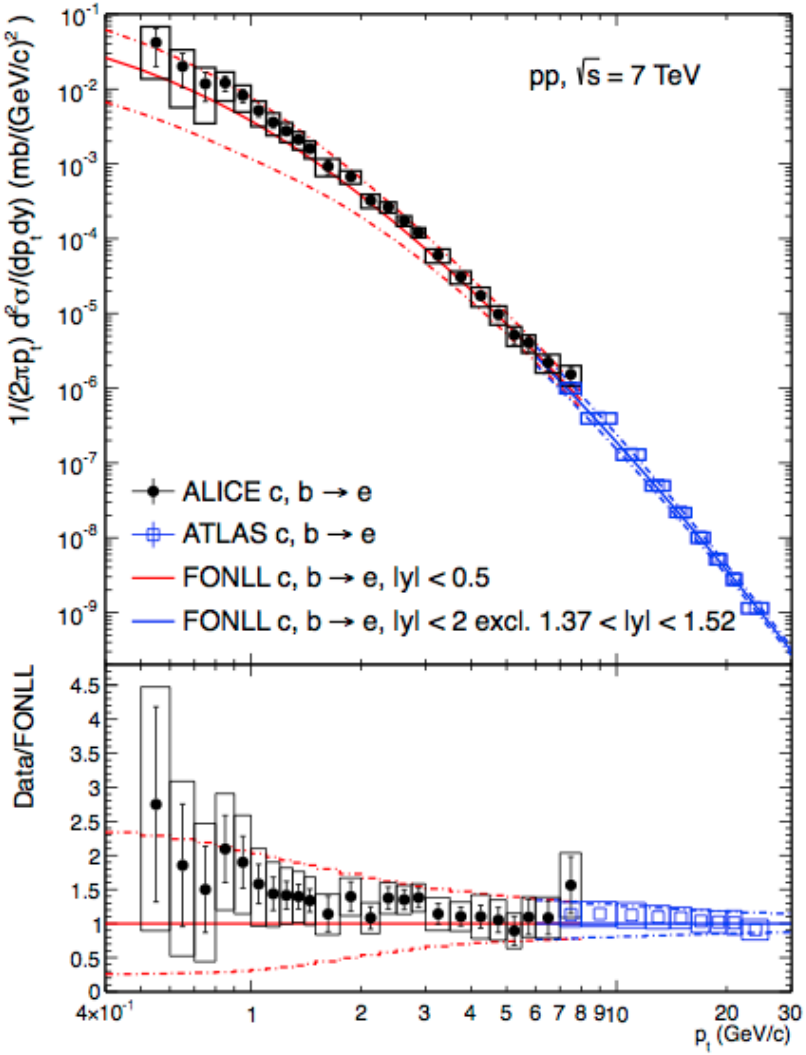




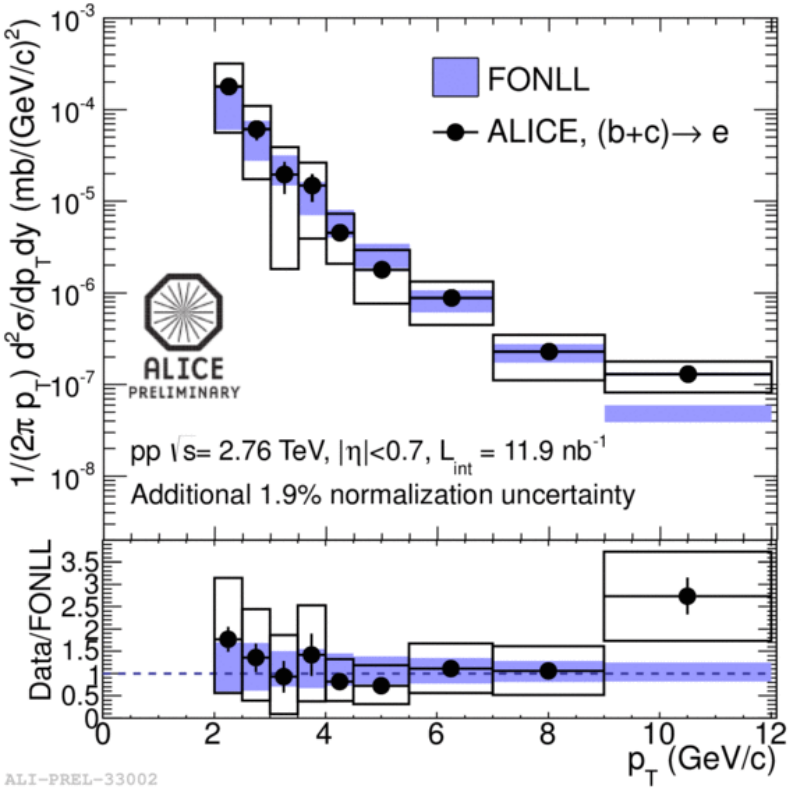
ALICE, JHEP 1201 (2012) 128
ATLAS-CONF-2011-017
LHCb, arXiv:1302.2864

ALICE, PRD86 (2012) 112007
ALICE, PLB708(2012)265
ATLAS, PLB707 (2012) 438
CMS, JHEP 6 (2012) 110

Heavy-flavour decay electrons



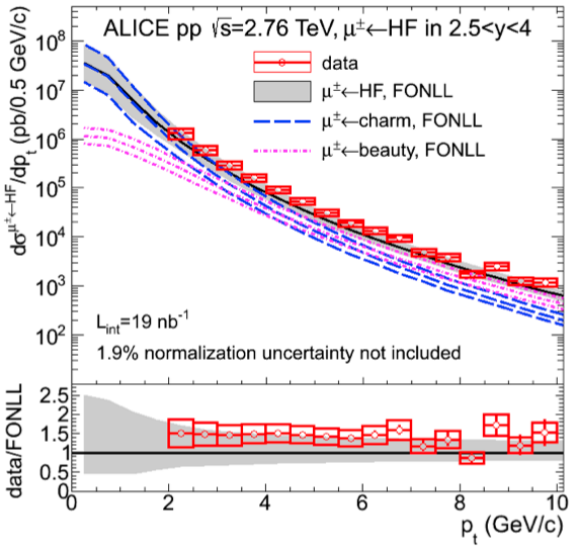
- ALICE & ATLAS complementarity
- FONLL describes data from 0.5 to 30 GeV/*c*



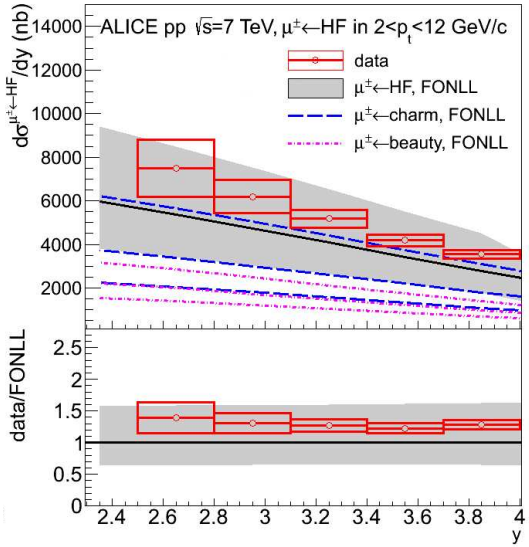
ALICE, PRD86 (2012) 112007
ATLAS, PLB707 (2012) 438

Heavy-flavour decay muons

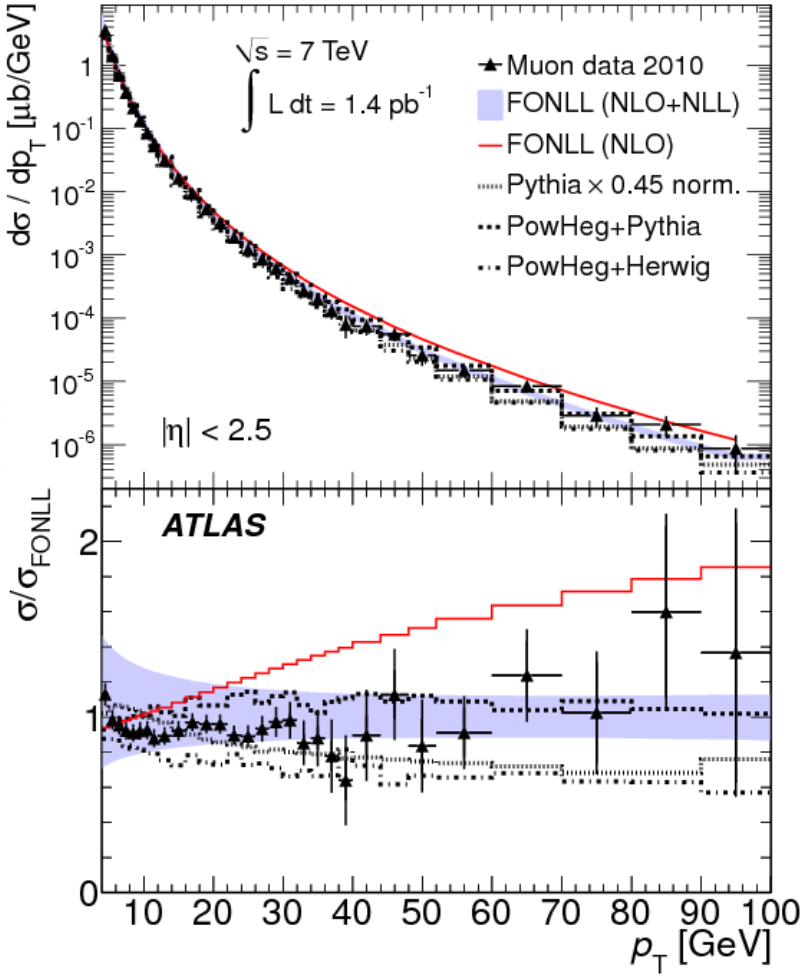
- ALICE: 2-10 GeV/*c*, 2.5<y<4
- ATLAS: 4-100 GeV/*c*, |y|<2.5



ALICE, PRL 109 (2012) 112301



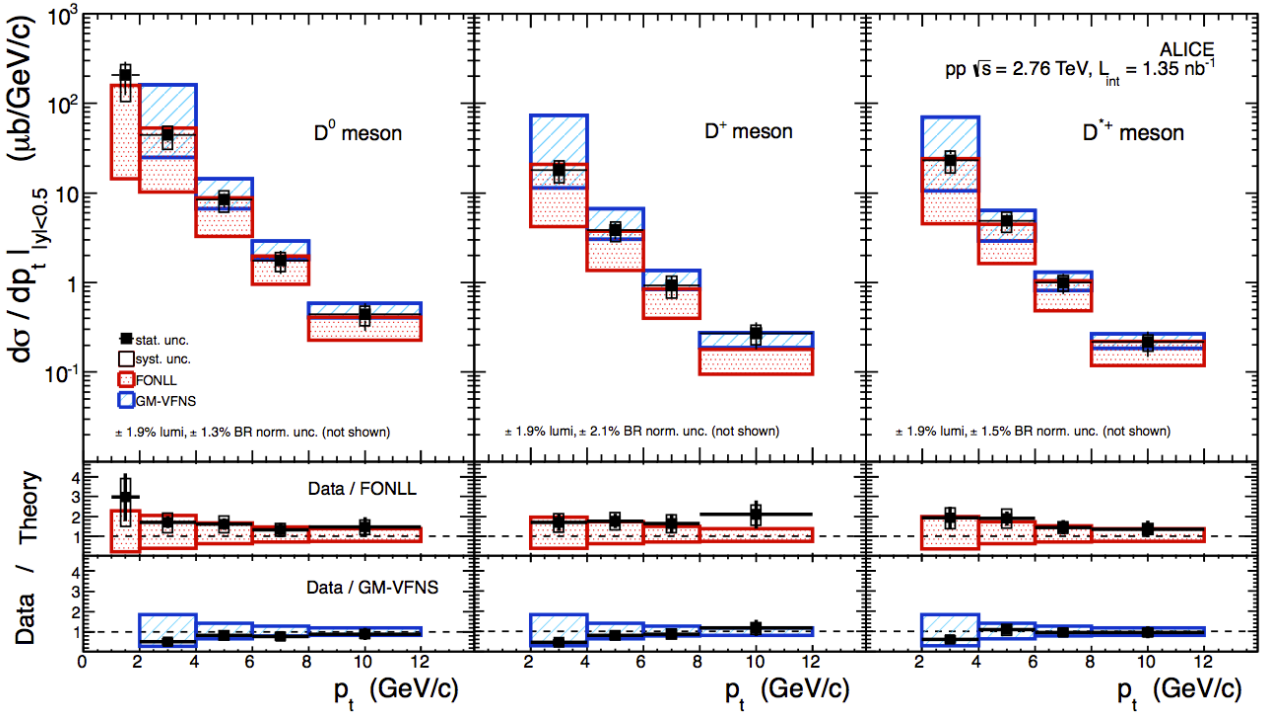
ALICE, PLB708(2012)265



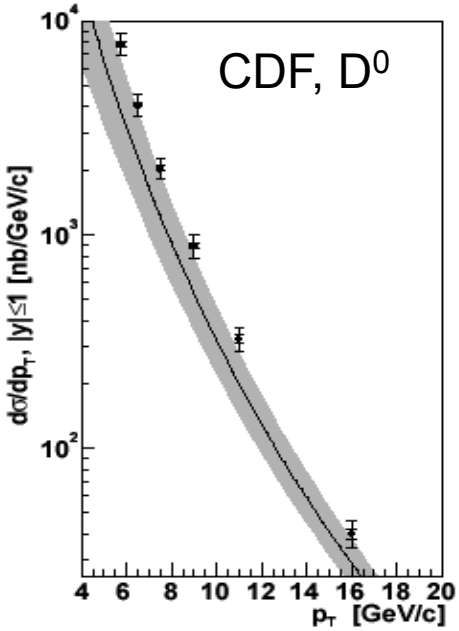
ATLAS, PLB707 (2012) 438

- FONLL and POWHEG describe the data consistently

pp 2.76 TeV, D^0, D^+, D^*, $|y|<0.5$



ALICE, JHEP 1207 (2012) 191

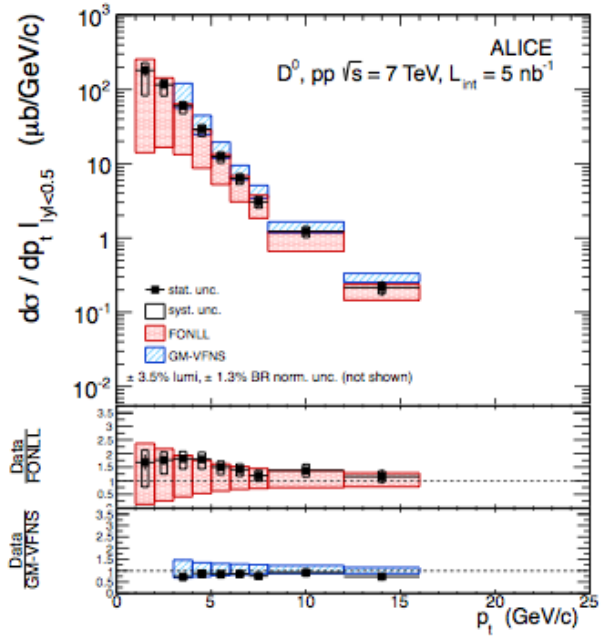


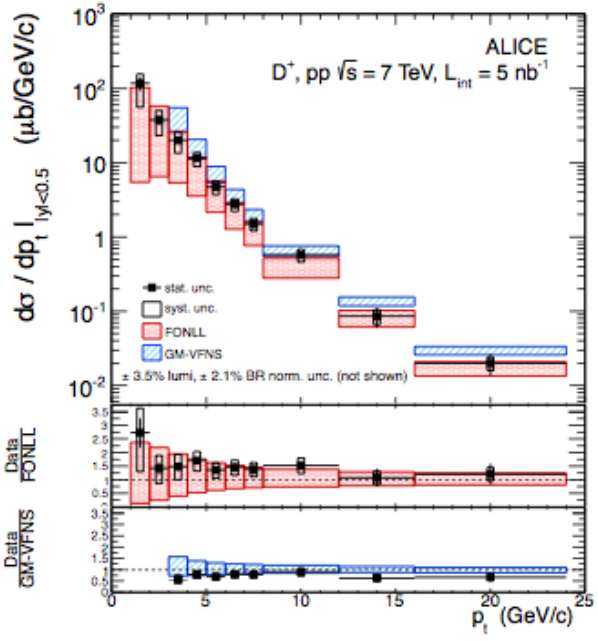
CDF, PRL91 (2003) 241804

- Theory-based feed-down correction (B→D)
- Fair description by pQCD within uncertainties
  - On upper side of FONLL
  - On lower side of GM-VFNS

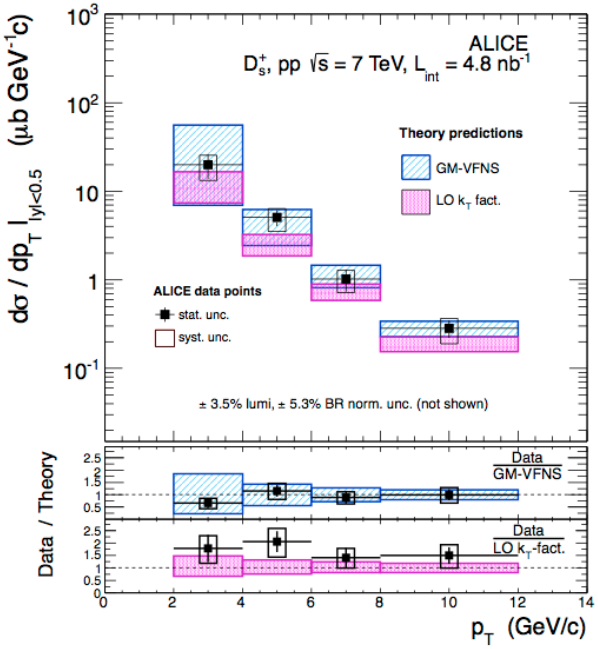
FONLL: Cacciari et al., arXiv:1205.6344
GM-VFNS: Kniehl et al., arXiv:1202.0439

pp 7 TeV, D^0, D^+, (D^*), D_s, |y|<0.5





ALICE, JHEP 1201 (2012) 128



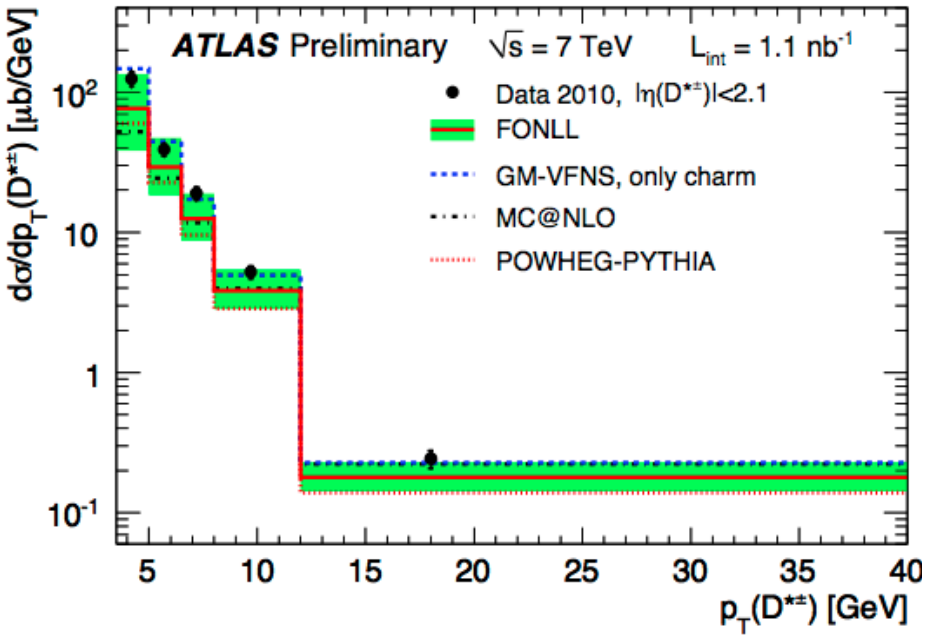
ALICE, PLB718 (2012) 279

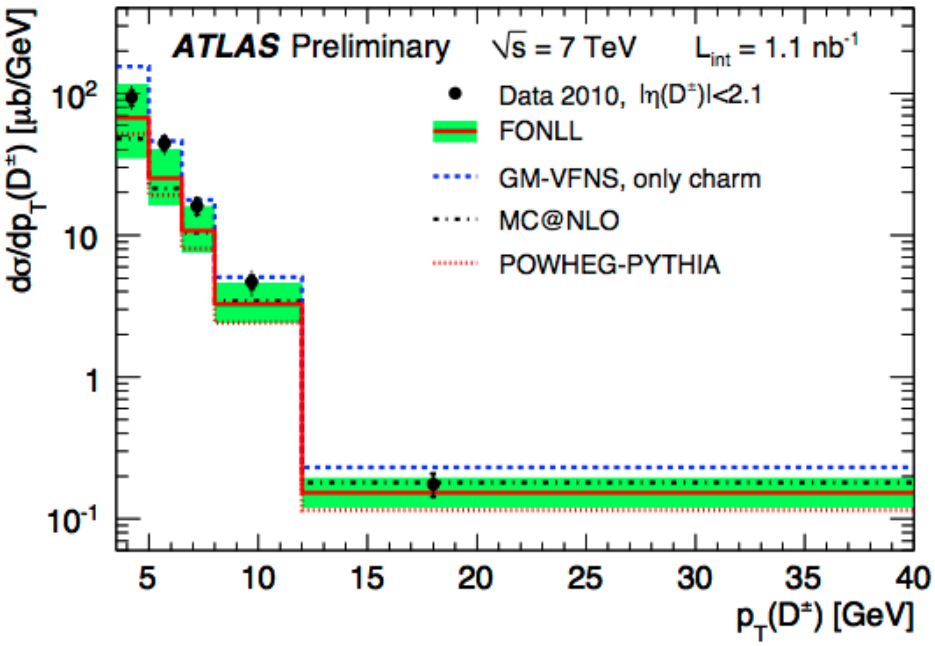
- Theory-based feed-down correction (B→D)
- Fair description by pQCD within uncertainties
  - On upper side of FONLL (D^0, D^+)
  - On lower side of GM-VFNS (D^0, D^+, D_s)

FONLL: Cacciari et al., arXiv:1205.6344
GM-VFNS: Kniehl et al., arXiv:1202.0439

k_T fact: Maciula, et al, arXiv:1208.6126

pp 7 TeV, D^+, D^*, $|\eta|<2.1$

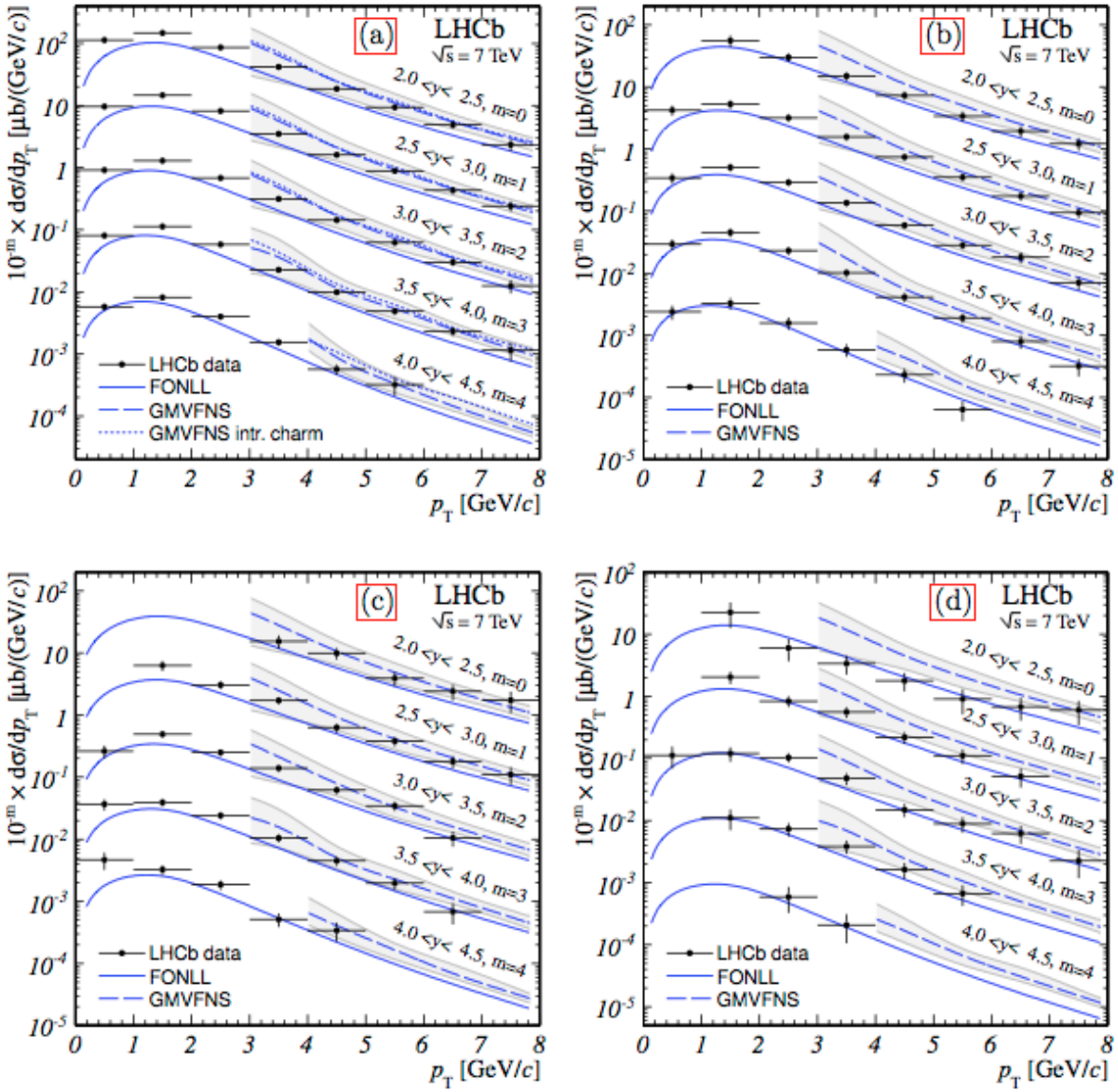




- Inclusive D mesons (no feed-down correction)
- Data/theory (FONLL and GM-VFNS) consistent with ALICE results
- Fair description with POWHEG and FONLL

ATLAS-CONF-2011-017
ATL-PHYS-PUB-2011-012

pp 7 TeV, D^0, D^+, D^*, D_s, 2<y<4.5

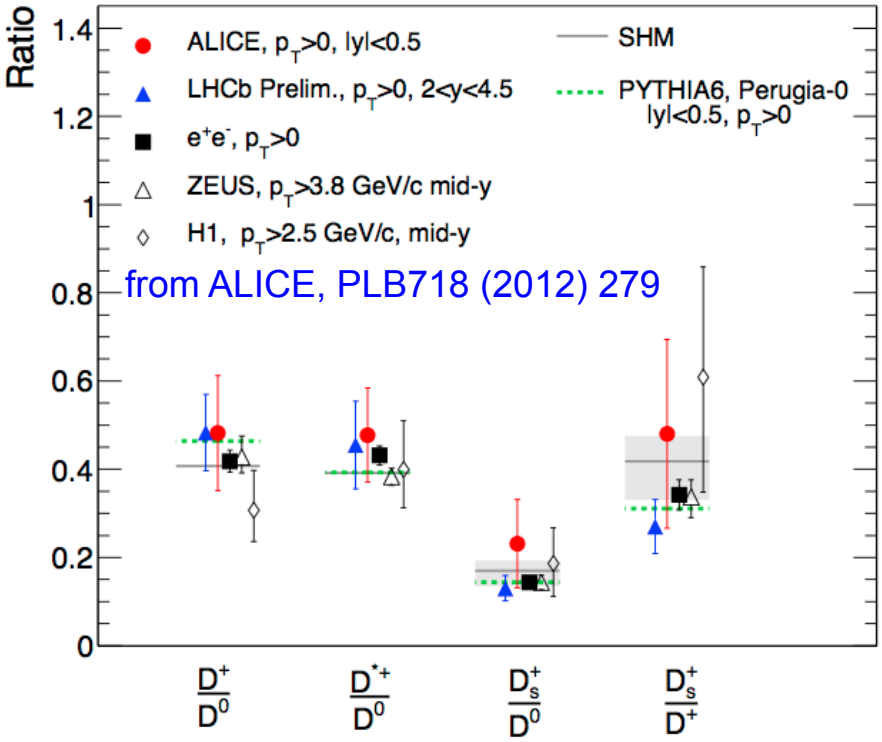


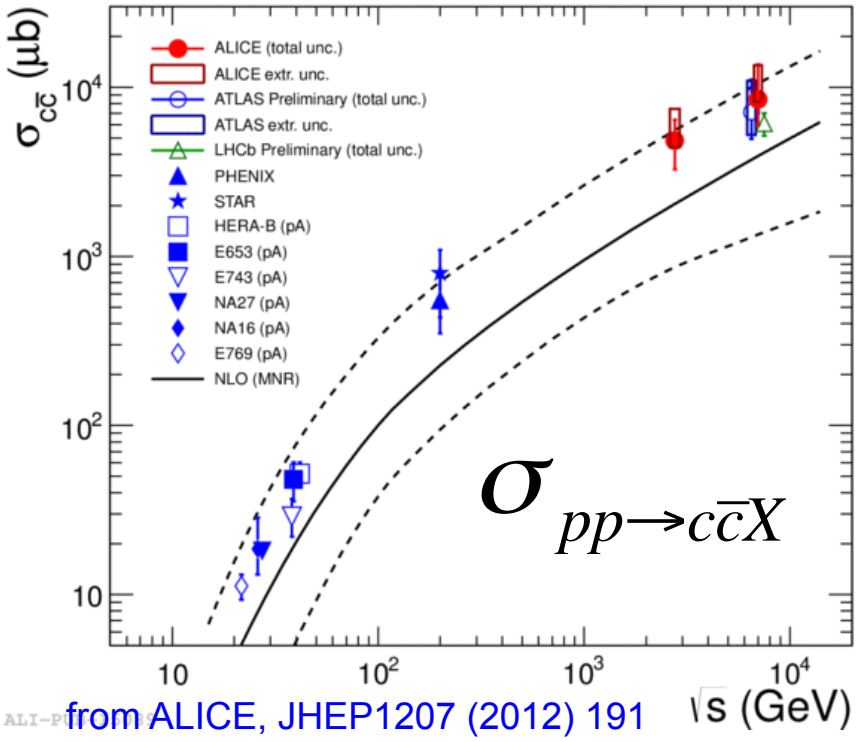
- 5 y intervals from p_T=0
- Data/Theory looks the same as at |y|<0.5, for both FONLL and GM-VFNS

LHCb, arXiv:1302.2864

FONLL: Cacciari et al., arXiv:1205.6344
GM-VFNS: Kniehl et al., arXiv:1202.0439

D-ratios and total charm cross section





- D meson ratios consistent when changing system and √s

ATLAS, ATLAS-PHYS-PUB-2011-012
LHCb, LHCb-CONF-2010-013

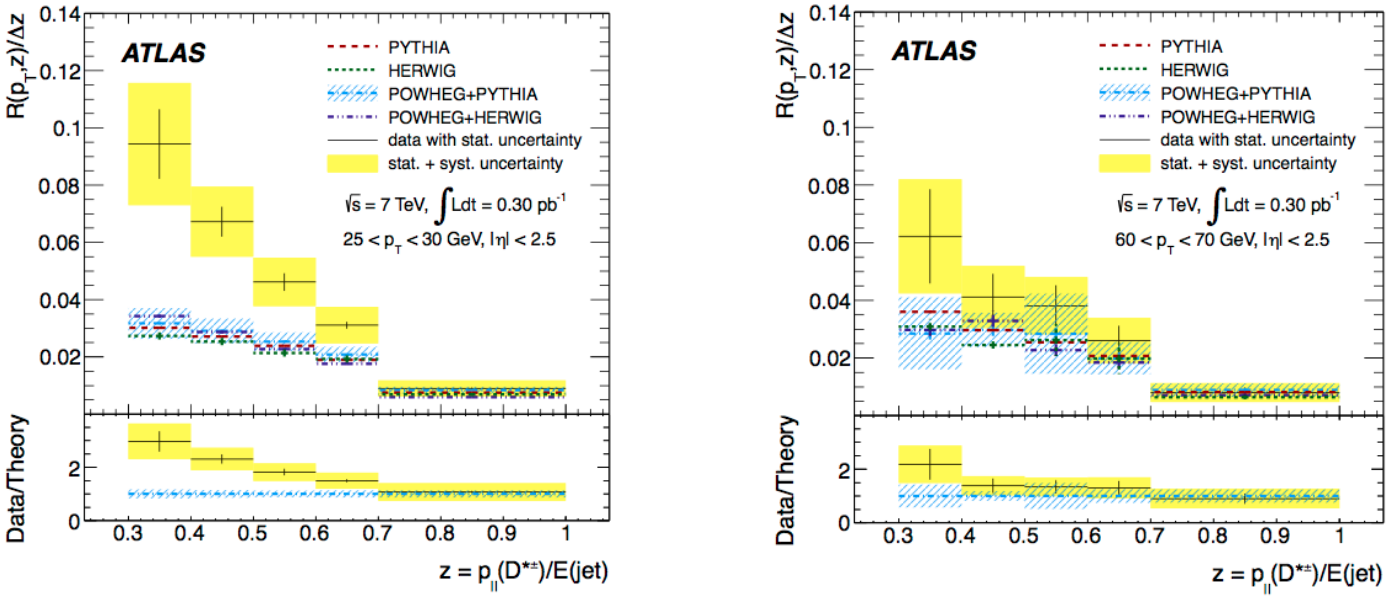
NLO pQCD: Mangano, Nason, Ridolfi, NPB373 (1992) 295.

- Total charm in agreement ALICE, ATLAS, LHCb
- Charm is on upper side of NLO, at all energies

D meson production in jets

- Probability to have a D* in jets with $25<p_T<70$ GeV/c, as a function of $z=p_{||}(D^*)/E(\text{jet})$:

$$\mathcal{R}(p_T, z) = \frac{N_{D^{*\pm}}(p_T, z)}{N_{\text{jet}}(p_T)}$$



- All predictions fail to describe the data at low-z, especially for low jet p_T
  - Much more "soft" charm production than expected
  - Additional charm production in multi-parton interactions?

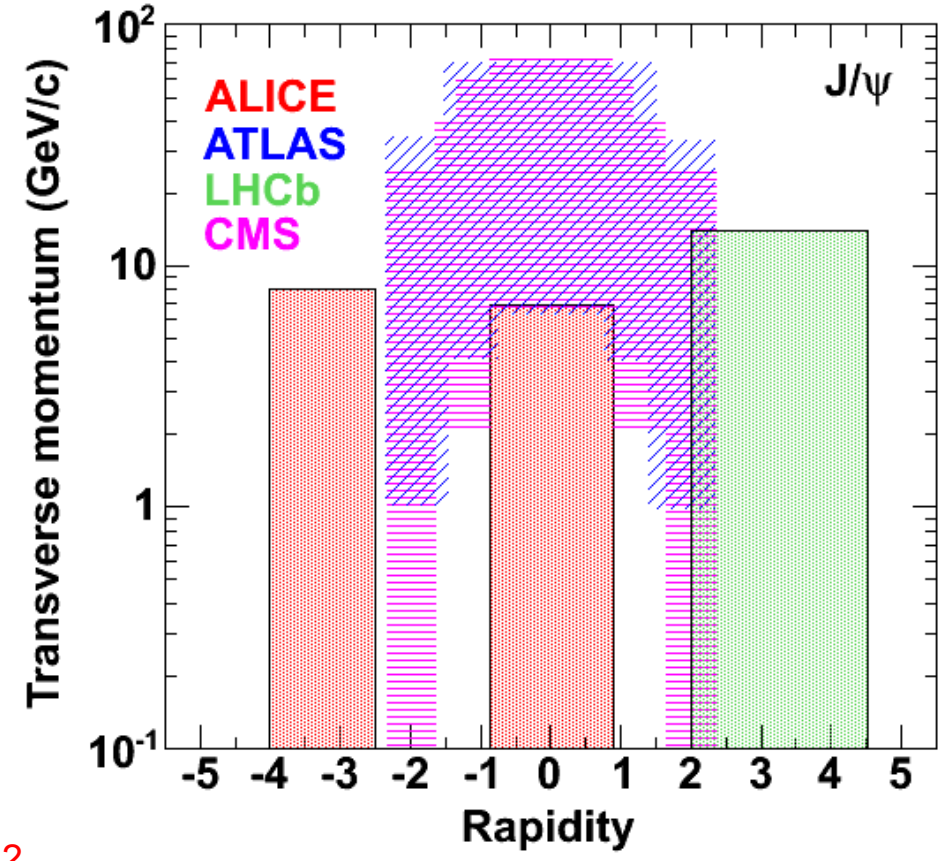
ATLAS, PRD85 (2012) 052005

Charmonia: Motivation

- Quarkonia production tests also non-perturbative aspects of QCD
  - Perturbative: short distance process (hard scattering)
  - Non-perturbative: long distance process (formation of bound state and colour neutralization)
- Theory calculations:
  - Colour singlet (CS) terms: colour neutralizes in the hard scattering
  - NRQCD Colour octet (CO) terms: colour neutralizes in the long distance process
    - However, weight of CO terms has to be derived from data

      → limited predictivity
- Models of production cannot describe both the kinematics and polarization at the Tevatron

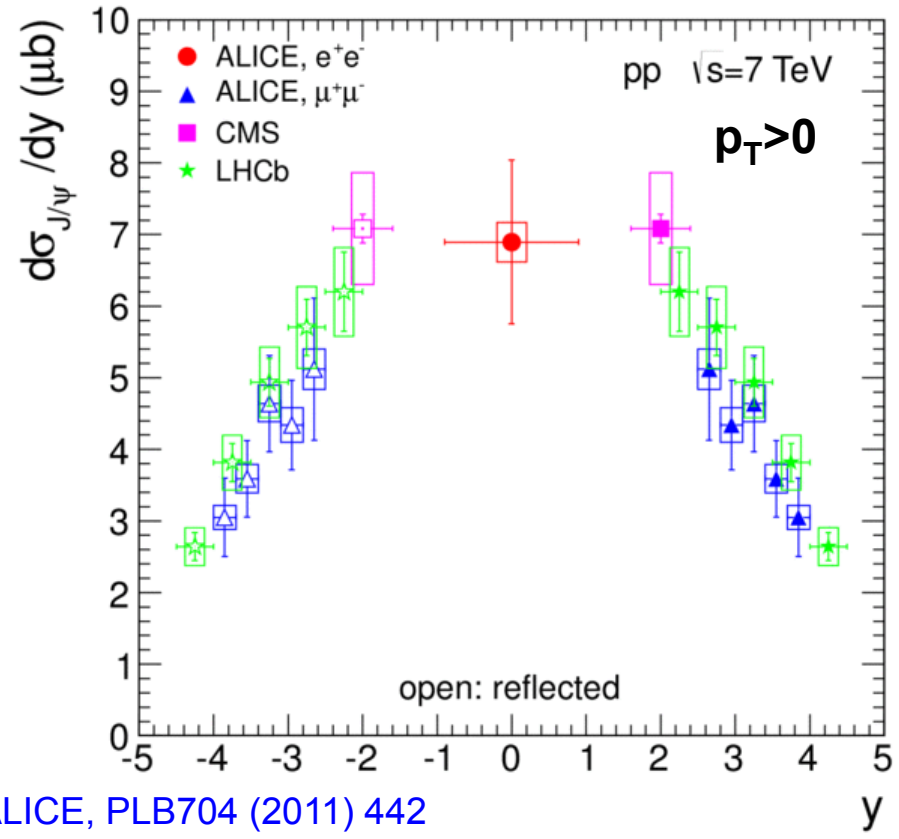
Charmonium production measurements: complementarity of LHC experiments

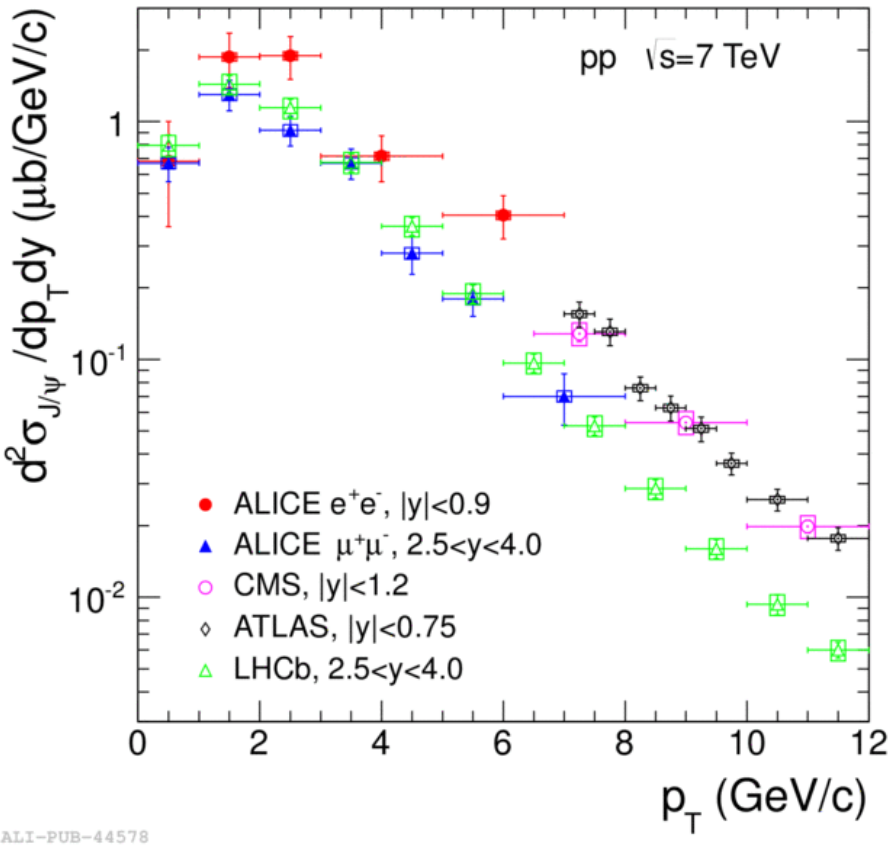


ALICE, PLB704 (2011) 442
ATLAS, NPB850 (2011) 387
CMS, EPJC71 (2011) 1575
LHCb, EPJC71 (2011) 1645

Inclusive J/ψ production, low p_T

- Inclusive = direct + feed-down from B + feed-down from excited c-cbar states (χ_c, …)





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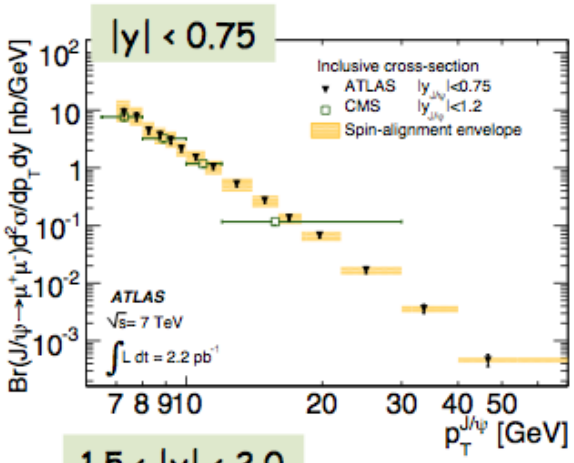
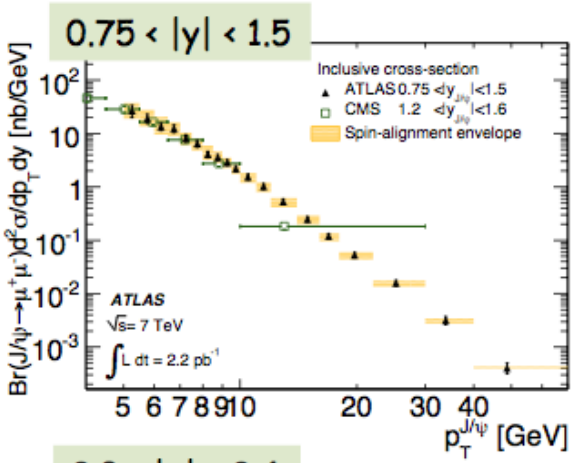
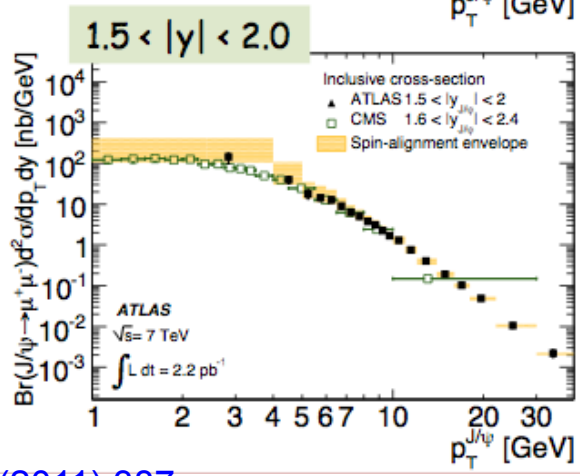
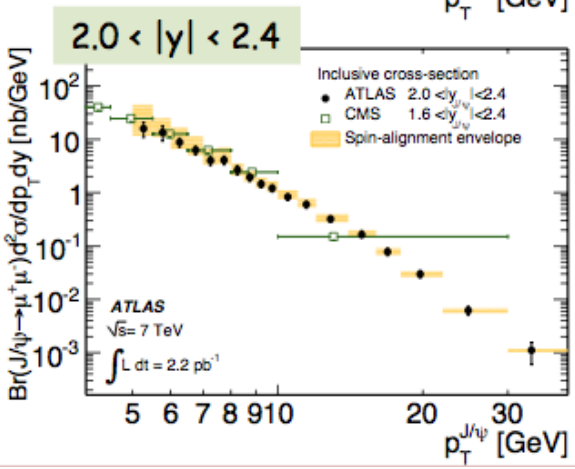




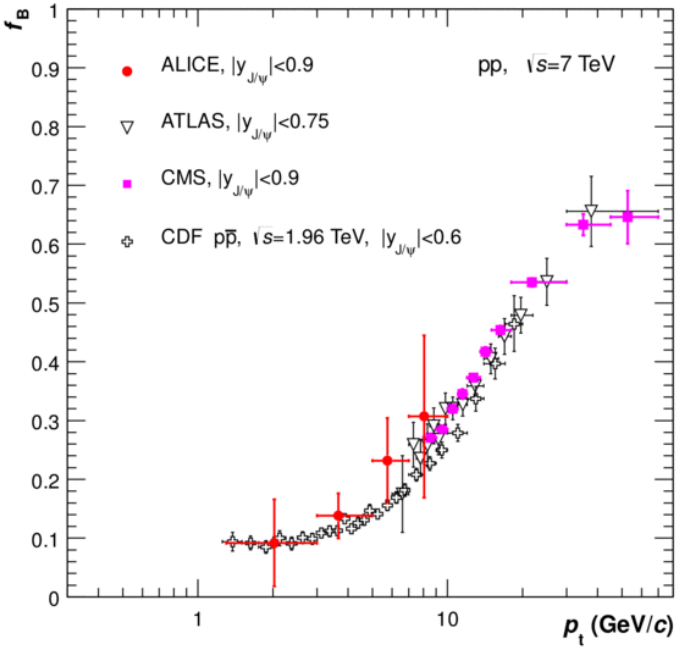


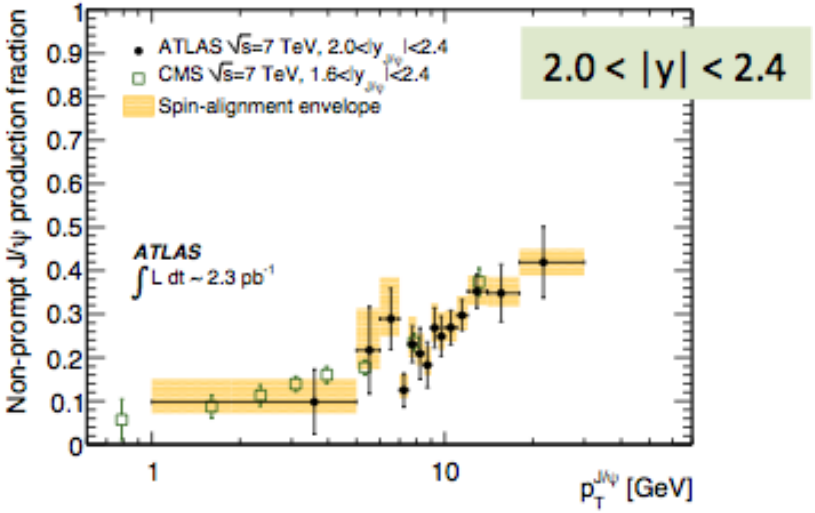


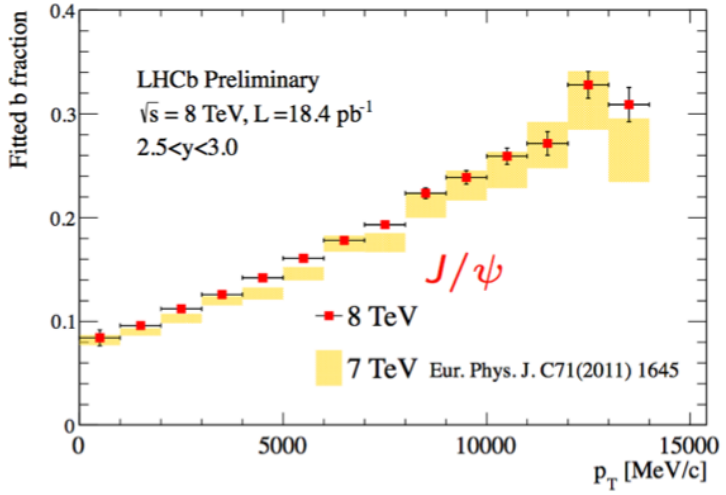
ATLAS, NPB850 (2011) 387
CMS, EPJC71 (2011) 1575

Prompt J/ψ fraction

- Consistent results at LHC (7,8 TeV) and Tevatron (2 TeV)



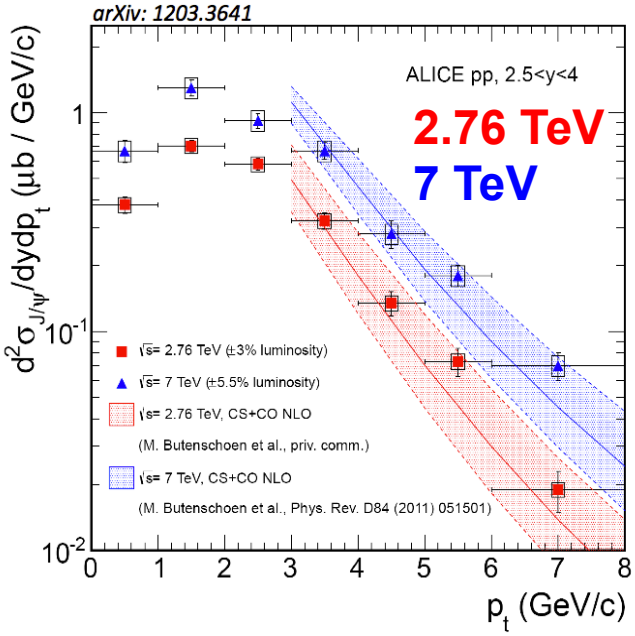




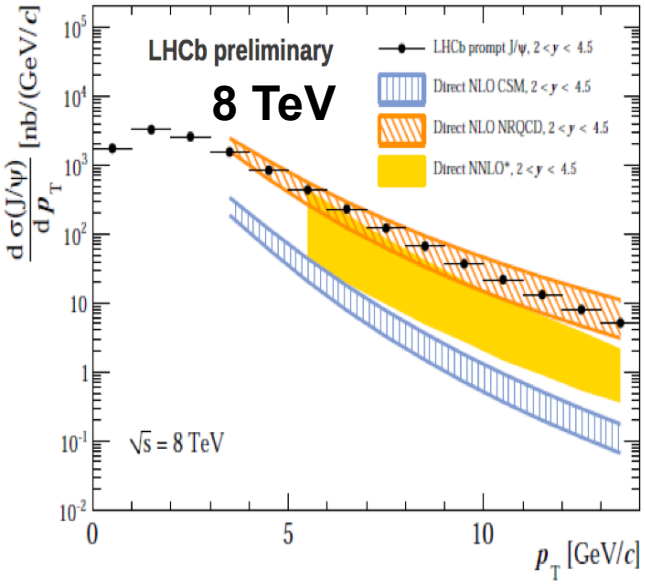
ALICE, JHEP1211 (2012) 065
ATLAS, NPB850 (2011) 387
CDF, PRD71 (2005) 032001
CMS, EPJC71 (2011) 1575
LHCb-CONF-2012-025

Comparison with theory: low p_T

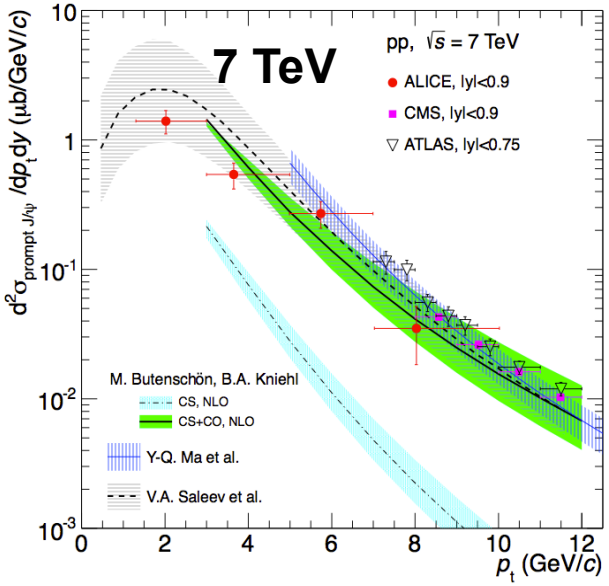
forward y **central y**



ALICE, PLB718 (2012) 295



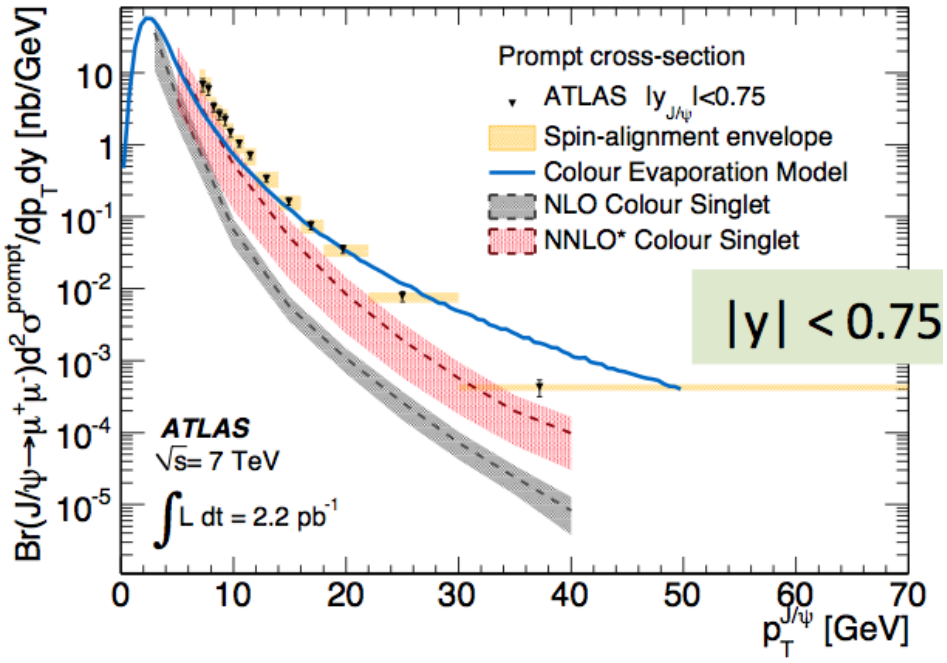
LHCb, LHCb-PAPER-2013-016



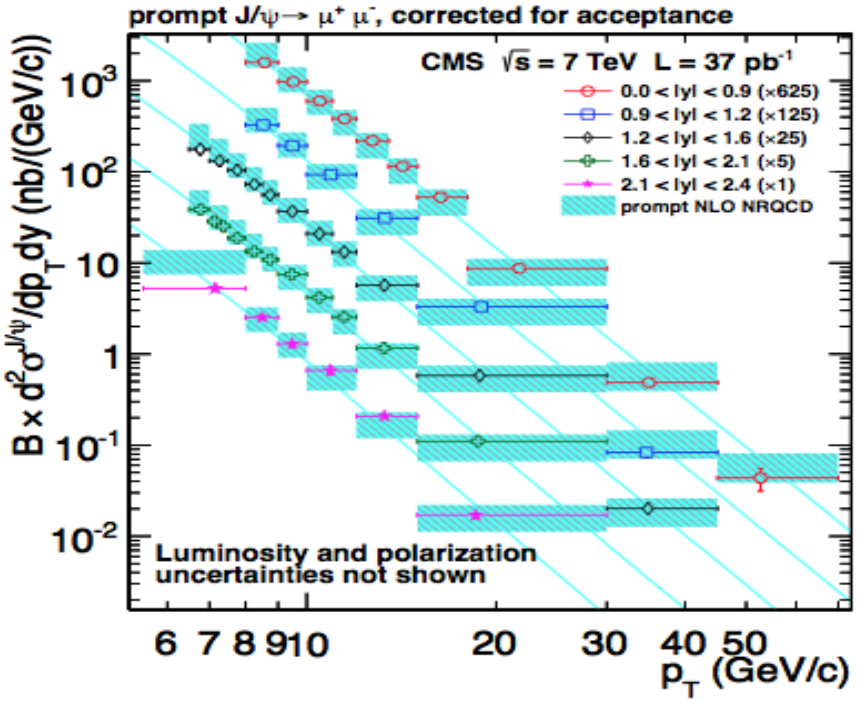
ALICE, JHEP1211 (2012) 065
ATLAS, NPB850 (2011) 387
CMS, JHEP02 (2012) 011

- Cross section described by NRQCD at NLO (CO+CS)
- Not by CS alone

Comparison with theory: high p_T



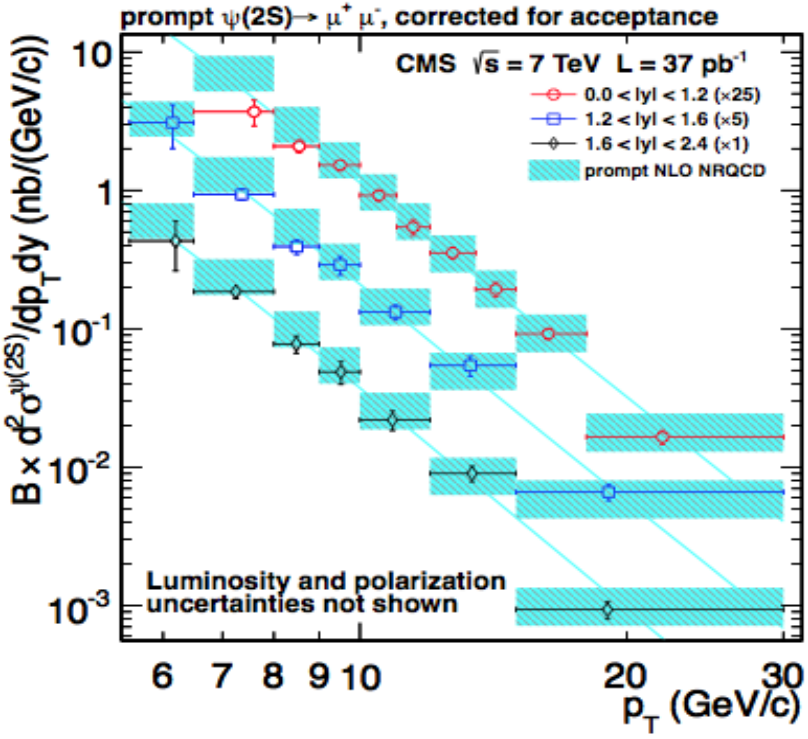
ATLAS, NPB850 (2011) 387



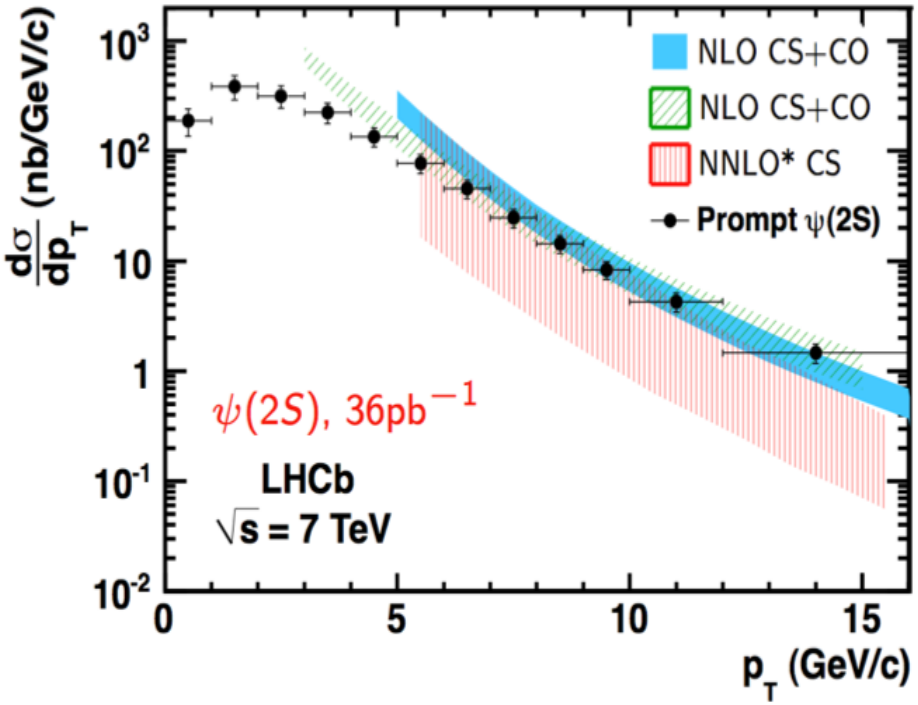
CMS, JHEP02 (2012) 011

- Cross section described by NRQCD at NLO (CO+CS)
- Not by CS alone, even with NNLO

Prompt ψ' production



CMS, JHEP02 (2012) 011

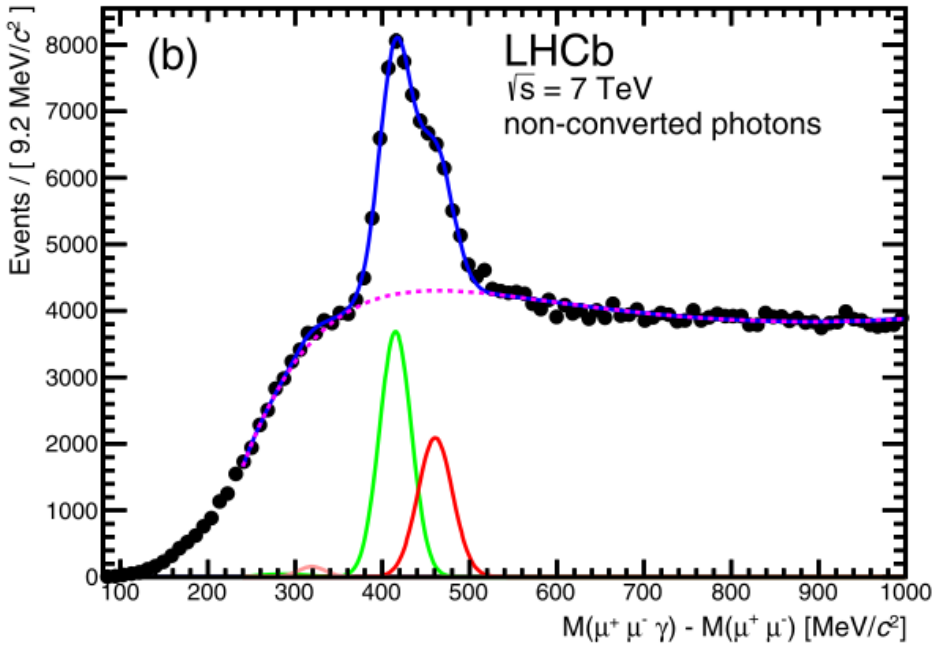


LHCb, EPJ C72(2012) 2100

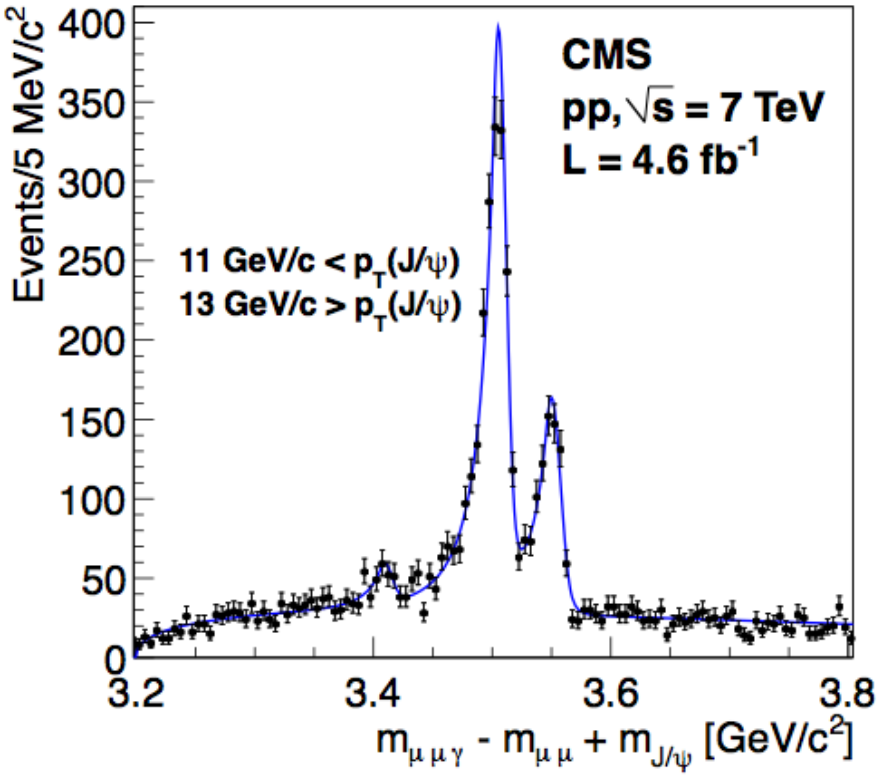
- Also ψ' production is described well by NRQCD calculation

Excited c-cbar states: ratio χ_{c1}/χ_{c2}

- Challenging analysis: $\chi_c \rightarrow J/\psi+\gamma$



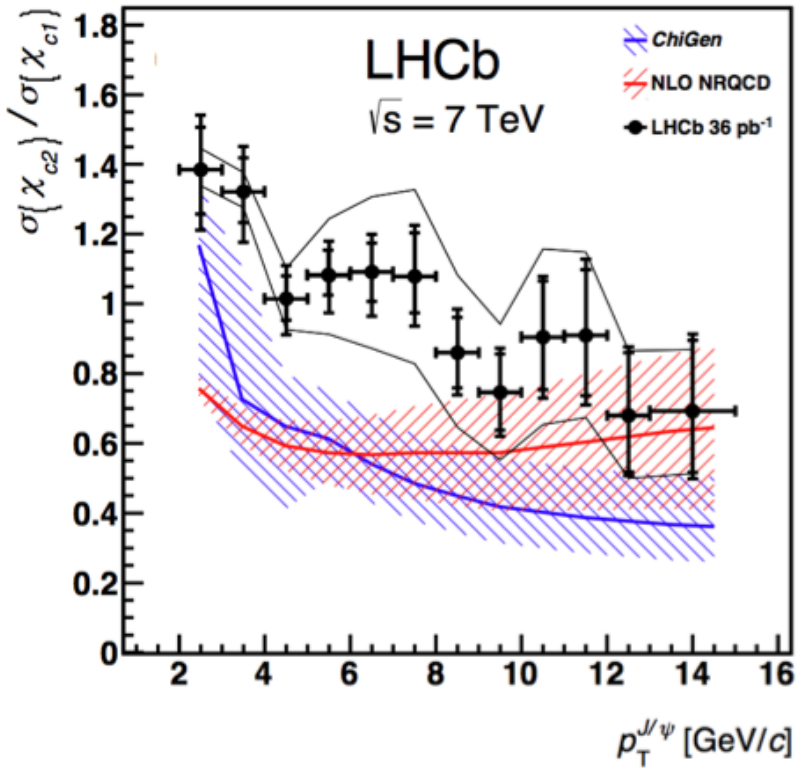
LHCb, PLB714 (2012) 215



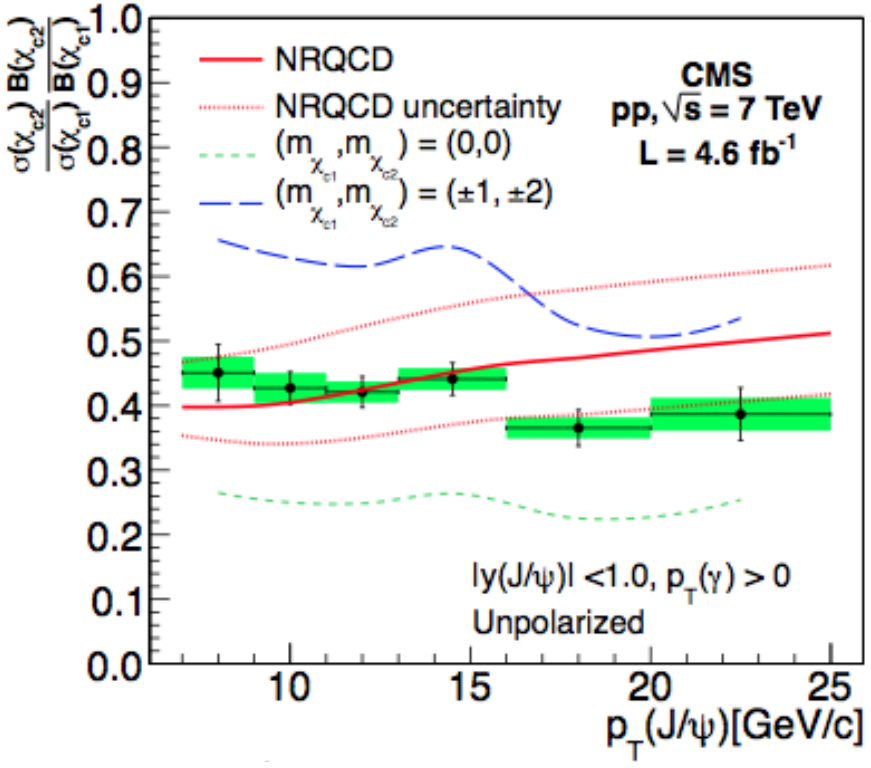
CMS, arXiv:1210.0875

Excited c-cbar states: ratio χ_{c1}/χ_{c2}

- Challenging analysis: $\chi_c \rightarrow J/\psi+\gamma$



LHCb, PLB714 (2012) 215

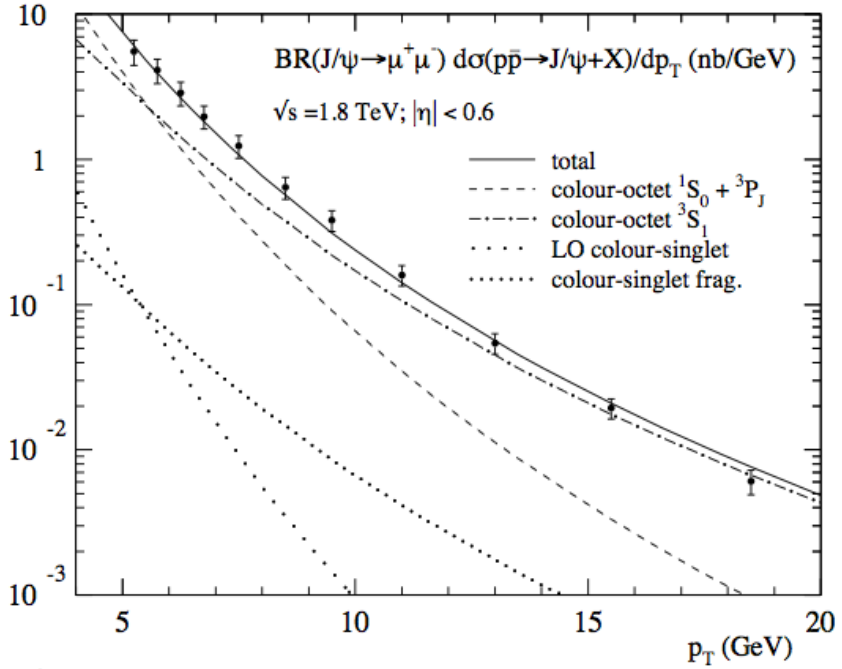


CMS, arXiv:1210.0875

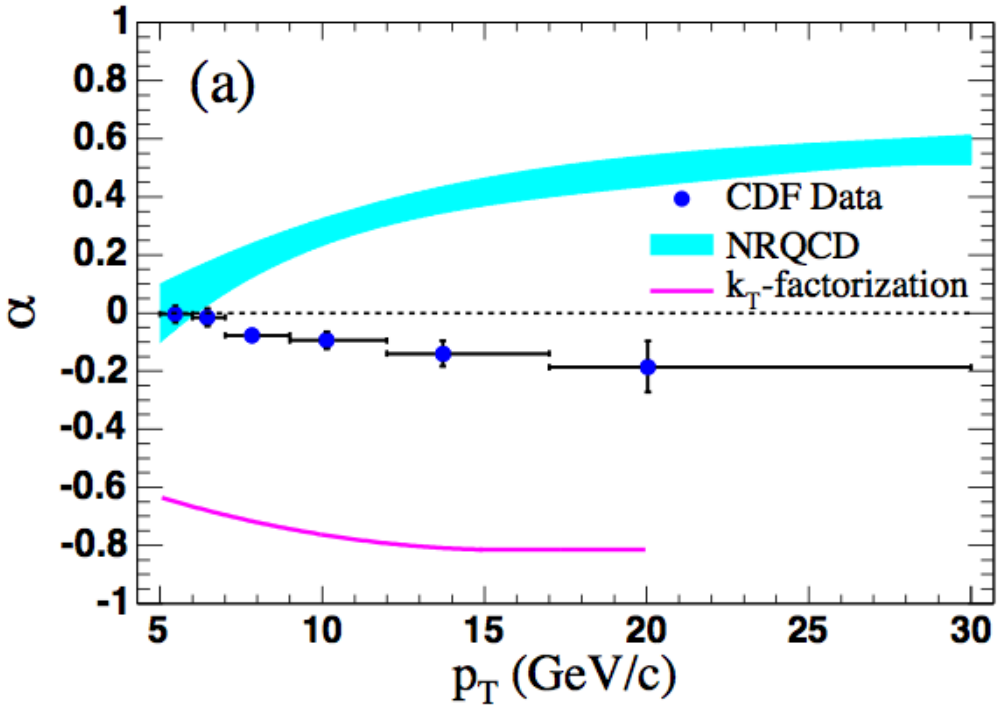
- Well described by NRQCD for p_T>8 GeV/c

J/ψ polarization

- NRQCD needs colour octet terms to describe the high-p_T cross section
  - This should imply that high-p_T J/ψ's "recall" gluon polarization
- At Tevatron energy, NRQCD fails in describing the cross section and the polarization

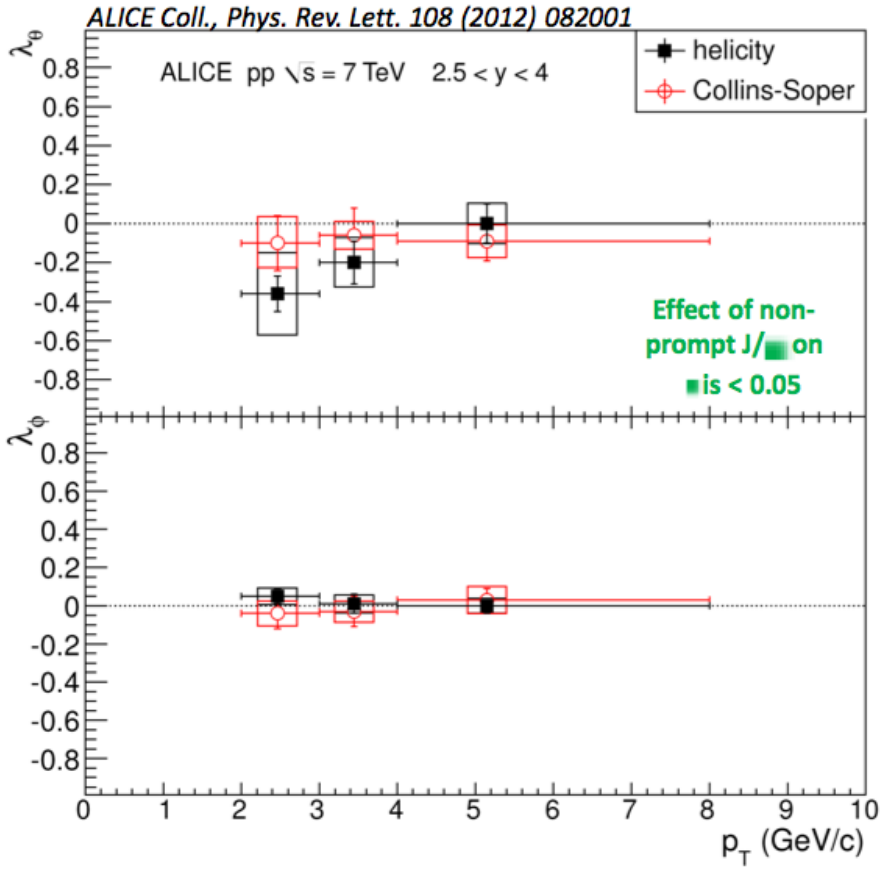


CERN-YELLOW-REPORT 2005-005



CDF, PRL99 (2007) 132001

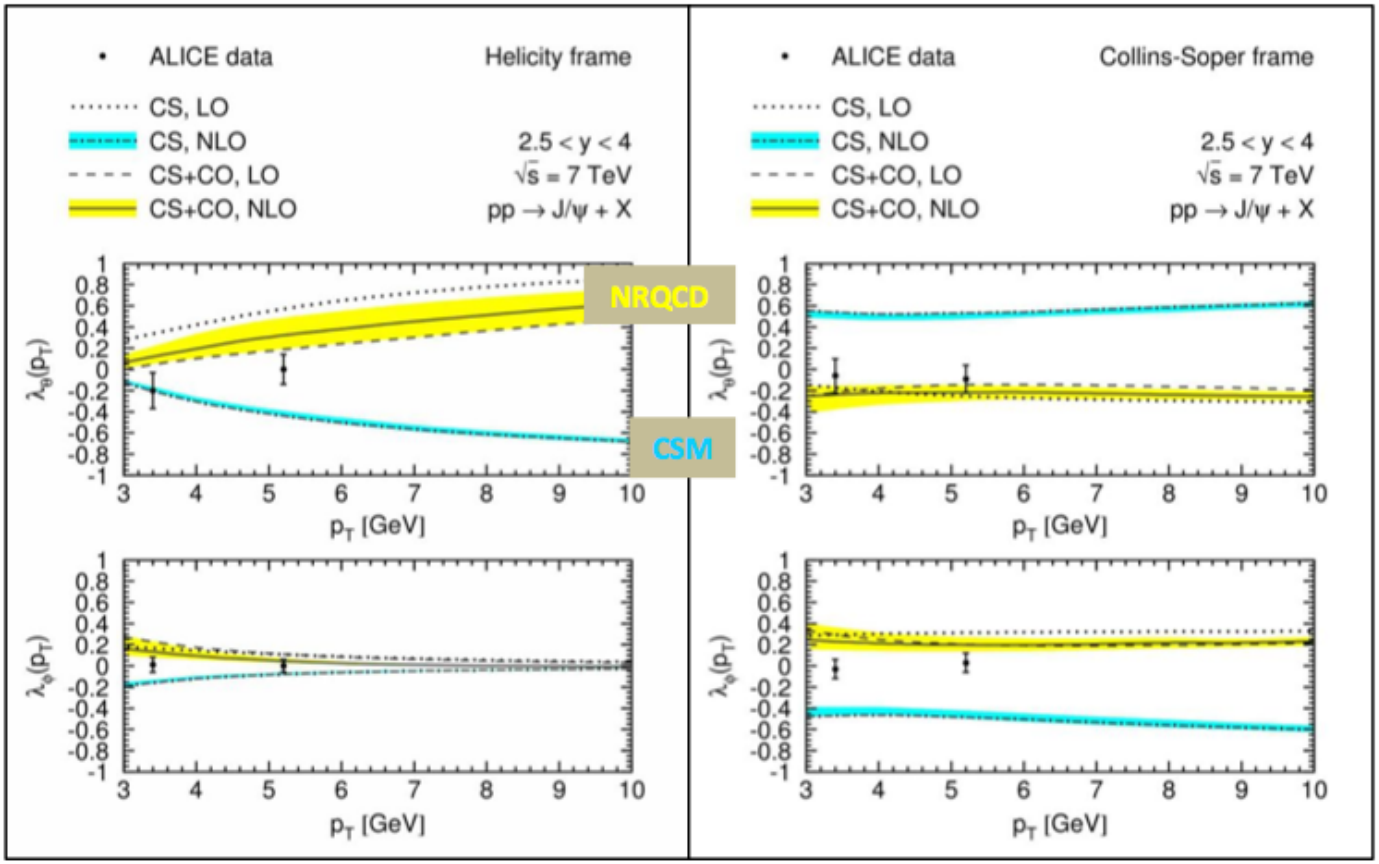
Inclusive J/ψ polarization at the LHC



- ALICE: no significant polarization in 2-8 GeV/*c*
  - Hint of longitudinal pol. (λ_θ) in helicity frame

ALICE, PRL108 (2012) 082001

Inclusive J/ψ polarization at the LHC

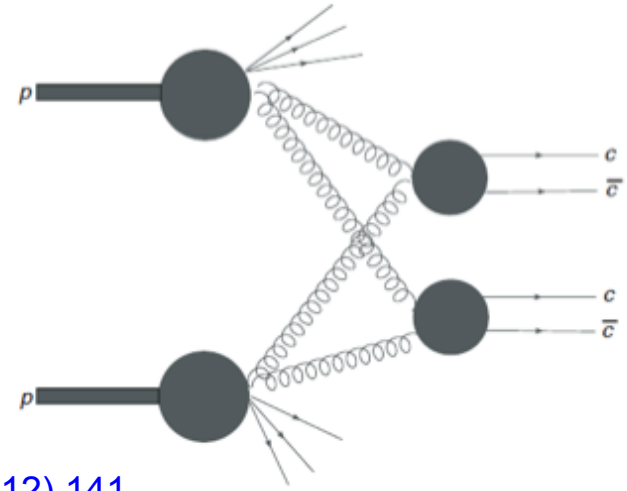


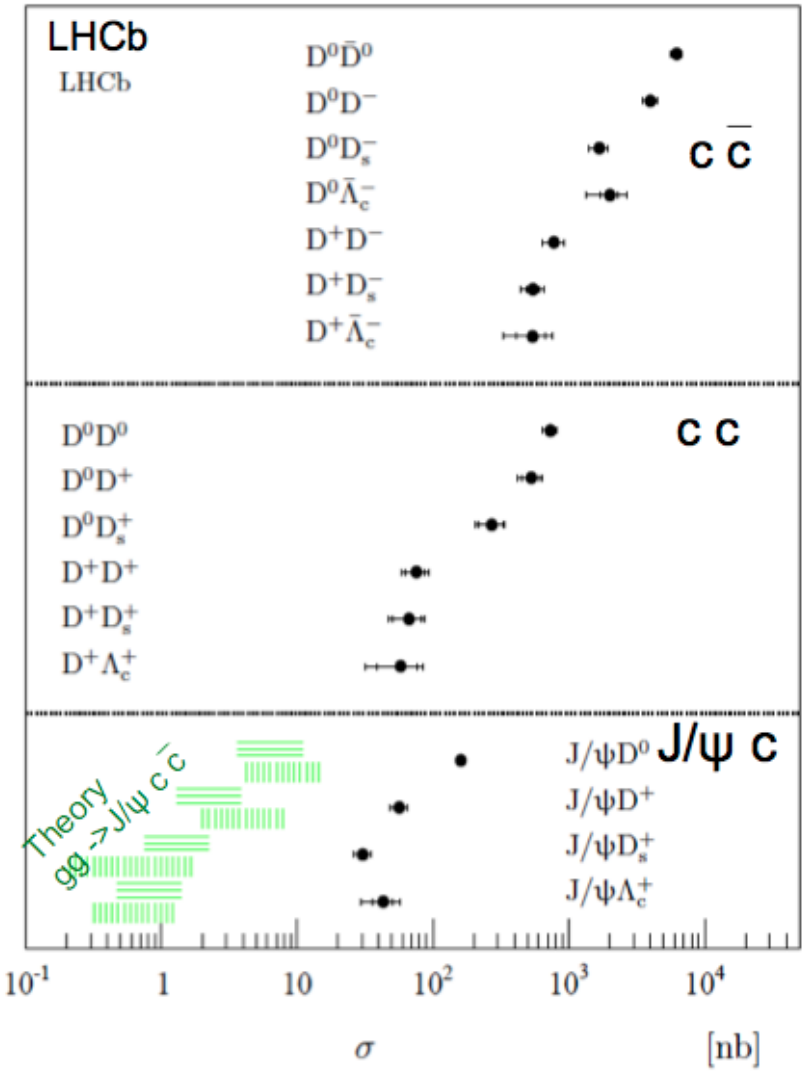
- NRQCD tends to overpredict polarization in helicity frame
- Higher-p_T results decisive for comparison

ALICE, PRL108 (2012) 082001
M. Butenschön B.A. Kniehl, PRL108 (2011) 172002

Double charm production (I)

- Large production cross section for D+D and D+J/ψ production
- σ(cc) ~ σ(c-cbar)/10
- Comparison with theory:
  - D+J/ψ under-predicted factor 50
  - No comparison for D+D
- Double-parton interactions?



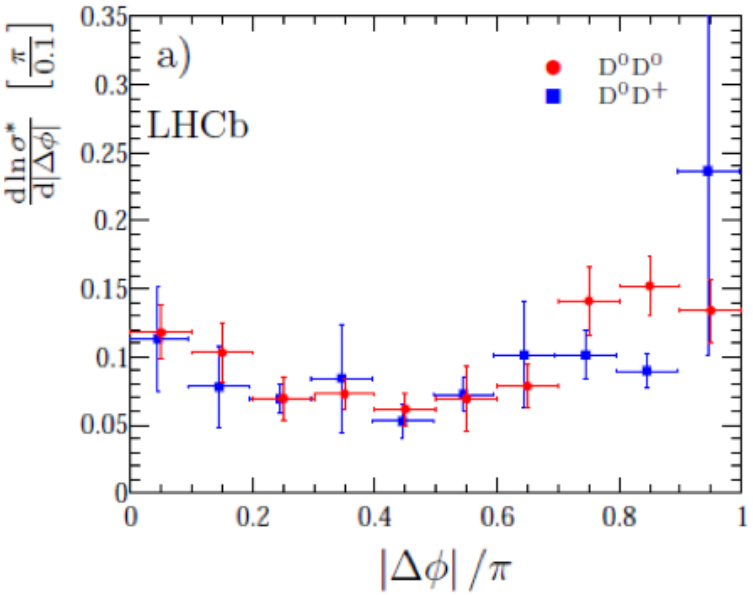


LHCb, JHEP 06 (2012) 141

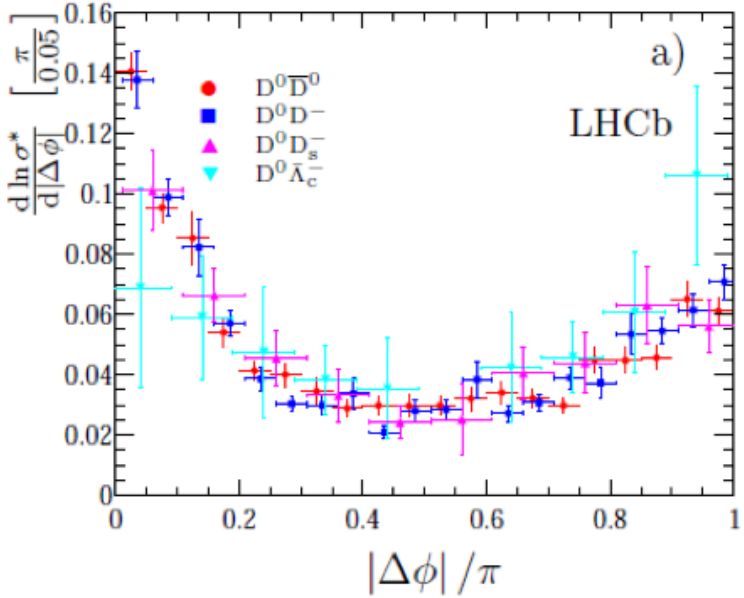
Double charm production (2)

- Measurement of double D production & azimuthal correlation

Same signs: $c\bar{c}$



Opposite signs: $c\bar{c}$

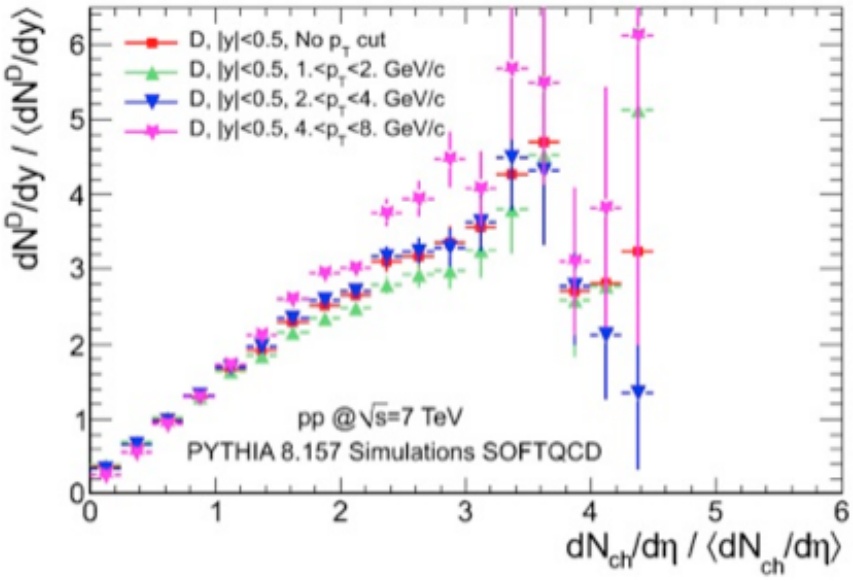


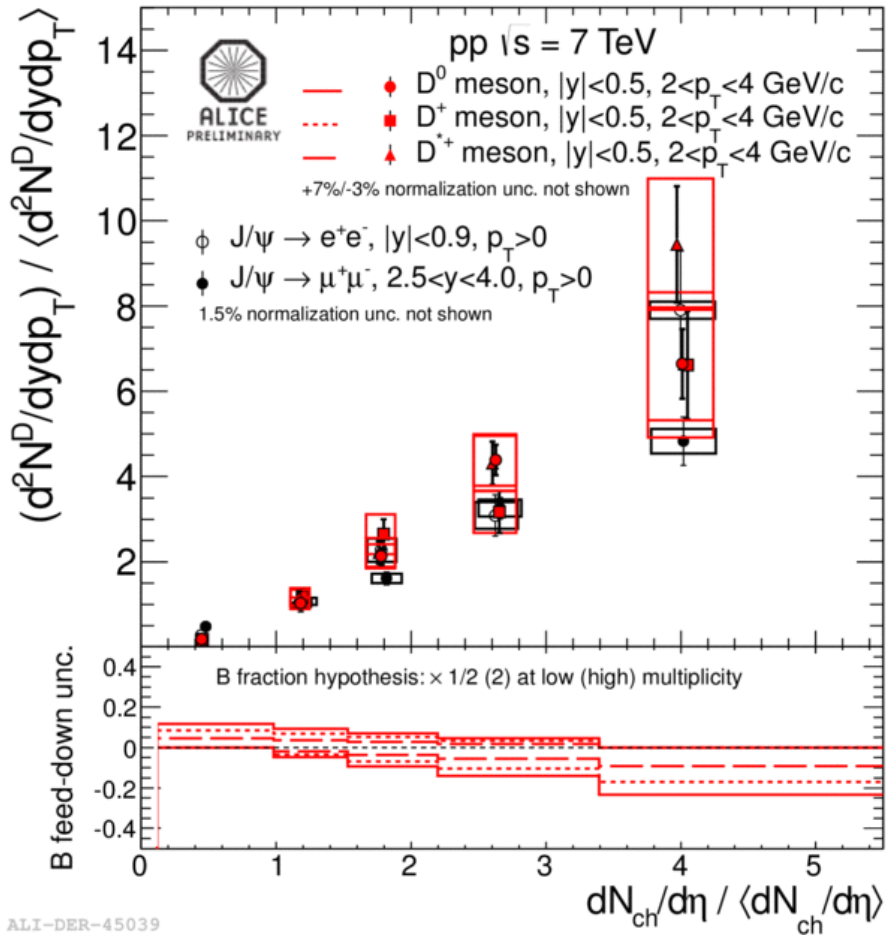
- Opposite signs: peak at $\Delta\varphi$~0 consistent with gluon splitting
- Same signs: almost flat → no production correlation
  - Is it another sign of multiple (double) hard partonic interactions?

LHCb, JHEP 06 (2012) 141

Charm production vs. multiplicity

- D meson and J/ψ production measured as a function of pp event multiplicity
- Indicates approx. linear increase
  - "Events with n-times the mean multiplicity show ~ n-times higher charm yield"
- Consistent with charm production in MPI? see e.g. PYTHIA8 with MPI:





ALICE, PLB712 (2012) 165
ALICE (MPI2012)

Summary

- Charm production at LHC energies is well described by factorized pQCD calculations
  - No large saturation effects at small *x* appear
  - However, large th. uncertainty prevents a precise study
- Charmonium production cross section described by NRQCD, but small polarisation observed in data is not understood
  - Similar puzzle as at the Tevatron?
- Several indications for multiple hard partonic interactions
  - Double c-cbar production
  - Increase of production yield with event multiplicity
  - Soft D meson fragmentation function

Discussion

Open charm and charmonium production:

- Are production cross sections and p_T spectra completely understood in the framework of FONLL (Powheg, MC@NLO) and NRQCD ?
- Are effective theories completely satisfactory ?

What is left to understand from the experimental point of view ?

Quarkonium polarisation:

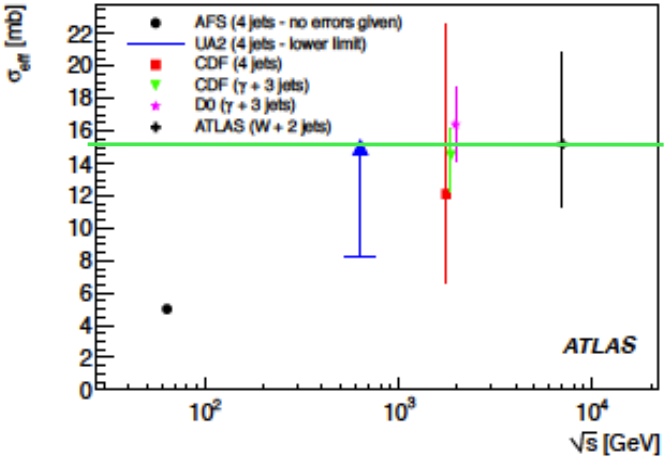
- Theories seem unable to describe production and polarization at the same time. Are we missing something fundamental ?

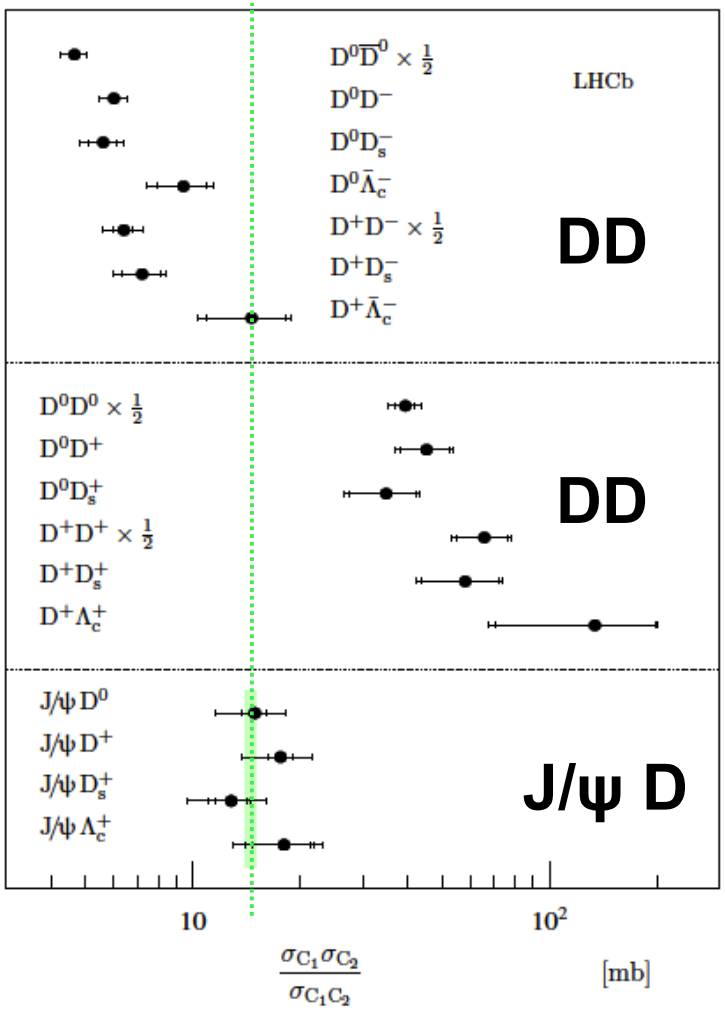
Can we do anything experimentally to sort out the puzzle ?

Discussion: double parton scattering

- Naïve approach to double-parton-scattering (DPS):

$$\sigma_{AB} = \frac{1}{\sigma_{\text{eff}}}\sigma_A \sigma_B \qquad \begin{cases} m=1 & \text{if } A=B \\ m=2 & \text{if } A\neq B \end{cases}$$





- J/ψ D: agreement with naive DPS
- DD: σ_{eff} is higher (=lower DD yield!) than naive DPS

- DD: large DPS cross section, still perturbative → access to parton-parton correlations in the proton ?

Discussion

Experiment:

- Which measurements are the experiments planning with the 8 TeV dataset ?
- What are the plans for the 14 TeV run ?

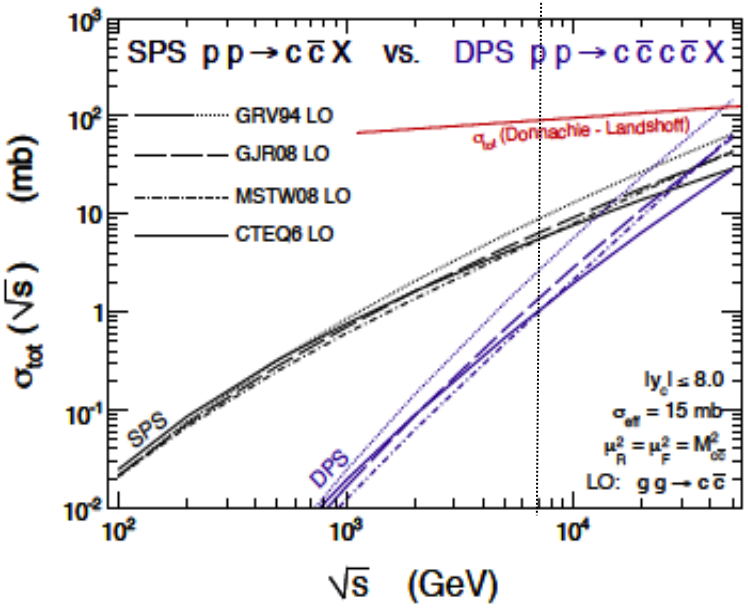
Exotic states:

what can LHC experiments do to shed light on their nature ?

Discussed Tomorrow.

EXTRA SLIDES

Luszczak, Maciula, Szczurek, arXiv:1111.3255,



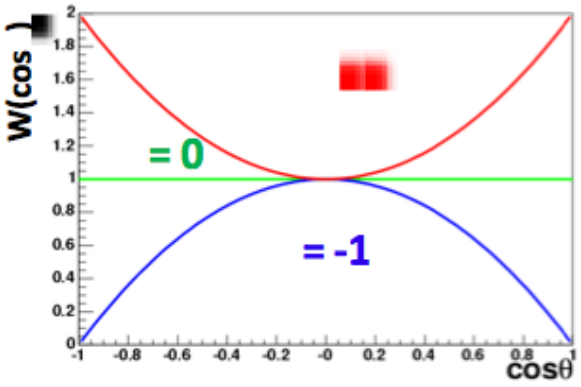
Polarization: ref. systems

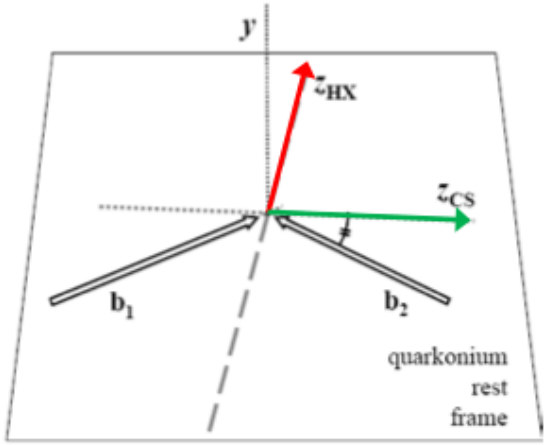
Inclusive J/ polarization measured through the extraction of the angular distribution of daughter muons (forward rapidity) in the quarkonium rest frame:

$$W(\cos\theta,\phi) \propto \frac{1}{3+\lambda_\theta} \cdot (1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi)$$

is the fundamental parameter:

- = +1 **transverse polarization**
- = 0 **no polarization**
- = -1 **longitudinal polarization**





Two different definitions of the *z*-axis considered:

- **helicity**: J/ momentum direction in the collision's reference frame;
- **Collins-Soper**: bisector of the angle between one beam and the opposite of the other beam in J/ rest frame;