Charm-Hadron Production at Hadron Colliders

Miriam Watson
University of Birmingham

ICHEP 2016

38th International Conference on High Energy Physics

Chicago

3rd - 10th August 2016

UNIVERSITY OF BIRMINGHAM

THE ROYAL SOCIETY

Introduction: Charm hadrons

- More than 15 papers or conference notes on charm hadrons since last summer
- A brief tour through these recent results
- Many previous papers not covered here

- Hidden charm production
  - Charmonium in pp collisions at 7, 8 and 13 TeV

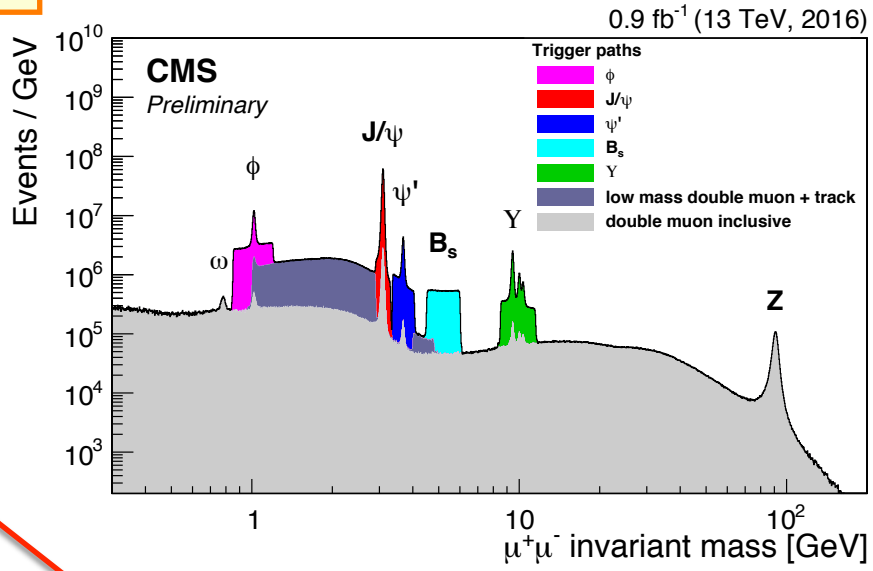
- Open charm
  - D meson production in pp and $p\bar{p}$ collisions
  - D meson production in pPb and PbPb collisions
  - Multiplicity dependence and azimuthal correlations

- Associated production
  - Υ and open charm
  - $J/\psi+\Upsilon$, $J/\psi+J/\psi$

- More results in “X(3872) and its bottomonium counterpart” (Konstantin Toms) and in the Heavy Ion sessions

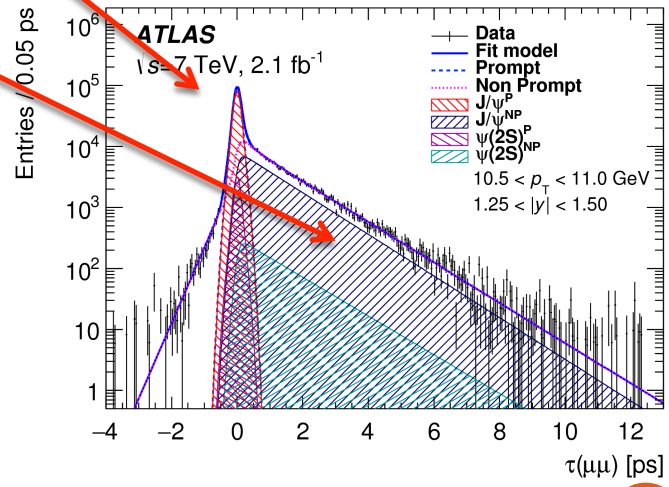
Overview of charmonium analyses

- Use di-muon decays J/ψ, ψ(2S) → μμ:
  - Easy for reconstruction and triggering
  - Di-muon triggers with invariant mass windows

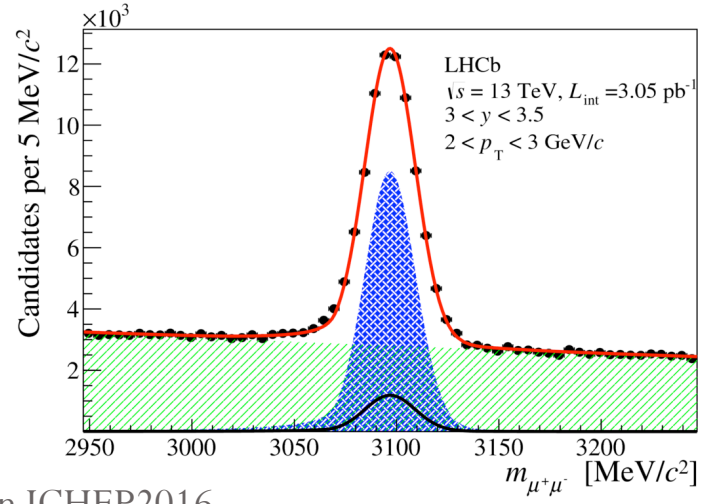


- Prompt: Produced directly in the pp interaction or through feed-down decays from higher charmonium states
- Non-prompt: Produced in decay chain of B-hadrons (decay vertex can be displaced from primary pp vertex)

μμ pseudo-proper time



μμ invariant mass



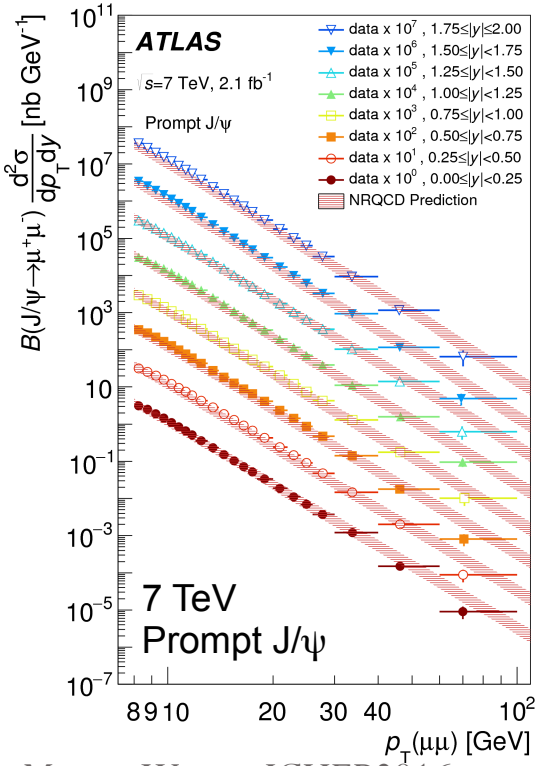
Differential J/ψ, ψ(2S) cross sections, 7+8 TeV (pp)

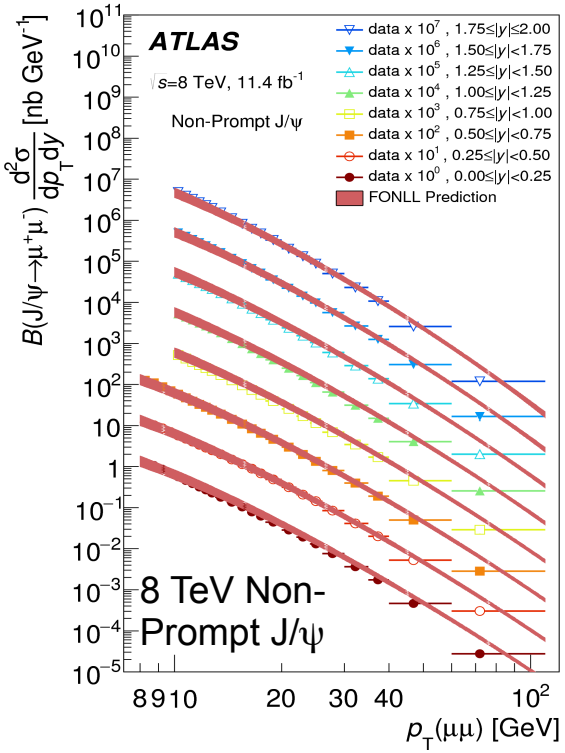
arXiv:1512.03657, Eur. Phys.J. C76 (2016) 5, 283

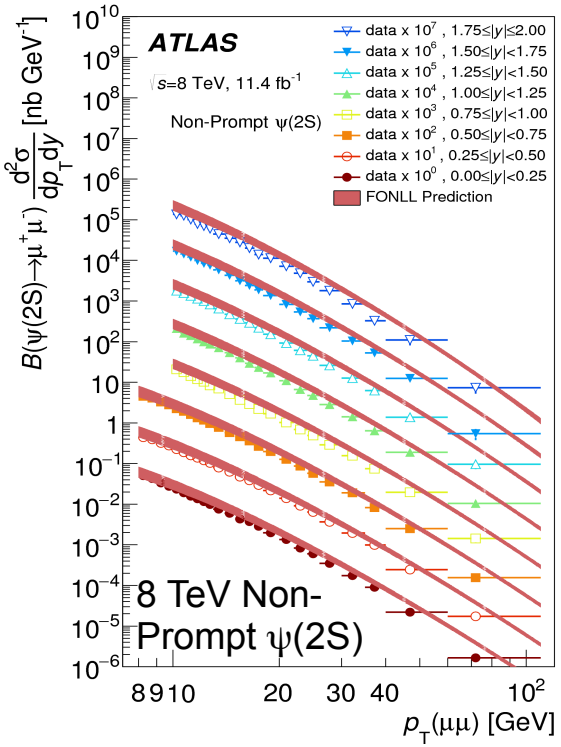
- Prompt and non-prompt production:
  - J/ψ, ψ(2S) at 7 TeV (2.1 fb^{-1}), 8 TeV (11.4 fb^{-1})
  - Double-differential: range $8 < p_T \leq 110$ GeV and $|y| < 2$

- Prompt compared to NLO NRQCD theory calculations
- Fair agreement between calculation and data

- Non-prompt compared to fixed-order-next-to-leading-log (FONLL) calculations
- J/ψ: FONLL predicts slightly harder p_T
- ψ(2S): Shapes agree, but yields higher in FONLL



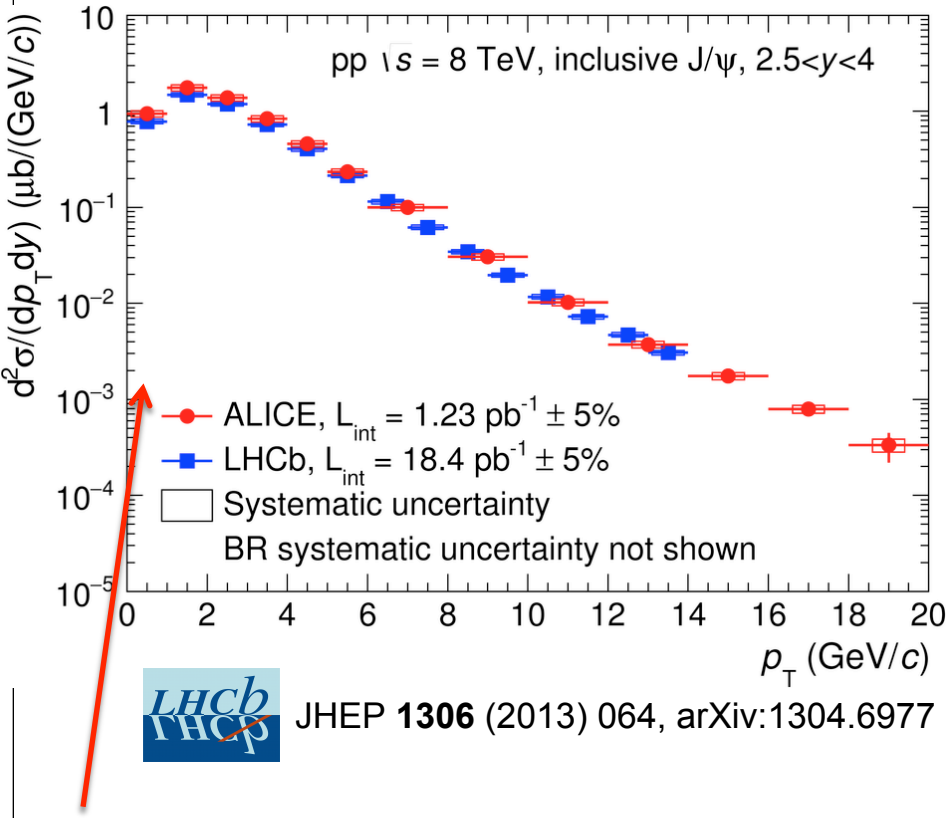




Forward quarkonium production at 8 TeV (pp)

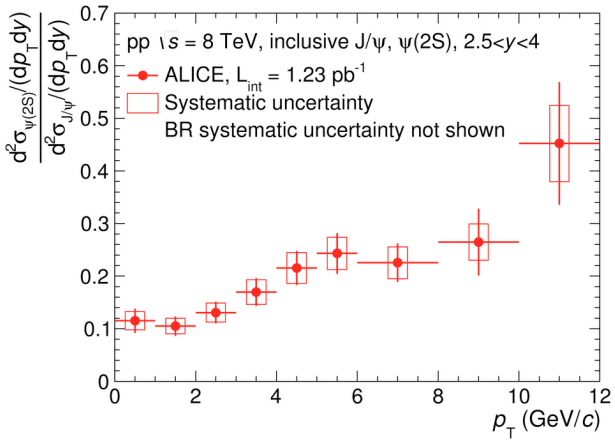
arXiv:1509.08258, Eur. Phys. J. C 76 (2016) 184

- Inclusive production:
  - J/ψ, ψ(2S) at 8 TeV (1.2 pb^{-1})
  - Differential: range $0 < p_T < 20$ (12) GeV and $2.5<y<4$



JHEP **1306** (2013) 064, arXiv:1304.6977

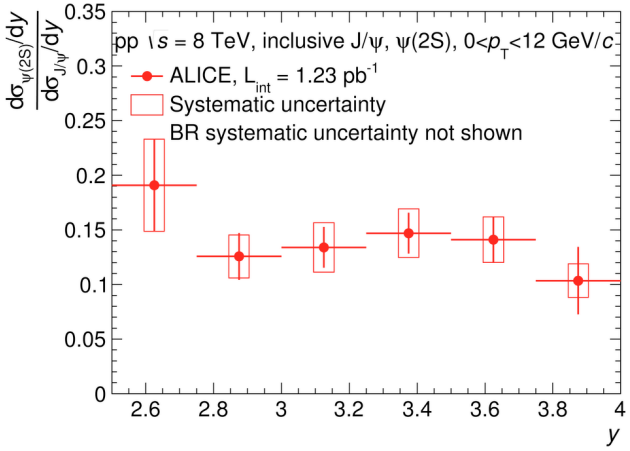
Measured down to p_T=0



ψ(2S) /J/ψ vs. p_T

$\sigma(\psi(2S)) / \sigma(J/\psi) = 0.14 \pm 0.01 \pm 0.02$ fiducial

Consistent with 7 TeV

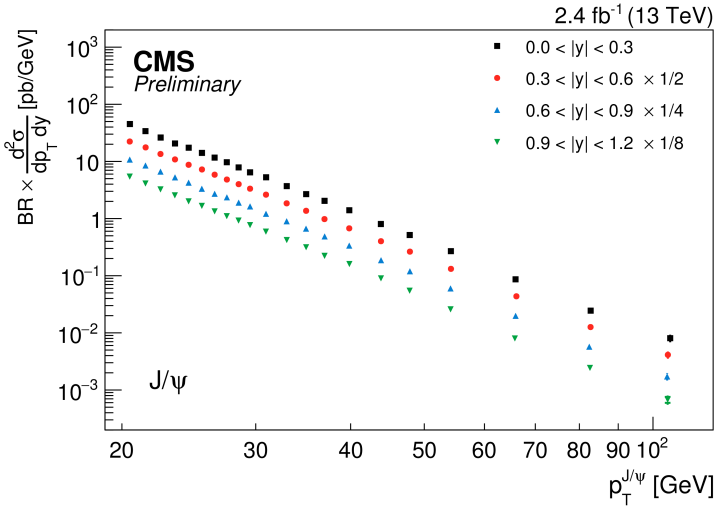


ψ(2S) /J/ψ vs. y

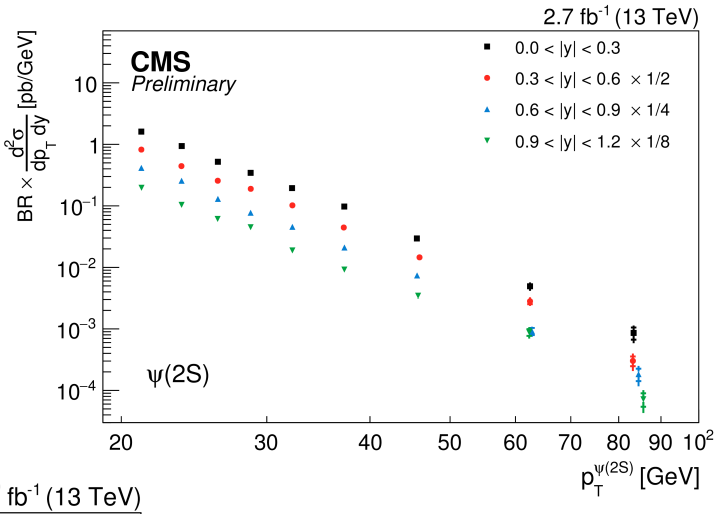
Quarkonium production at 13 TeV (pp)

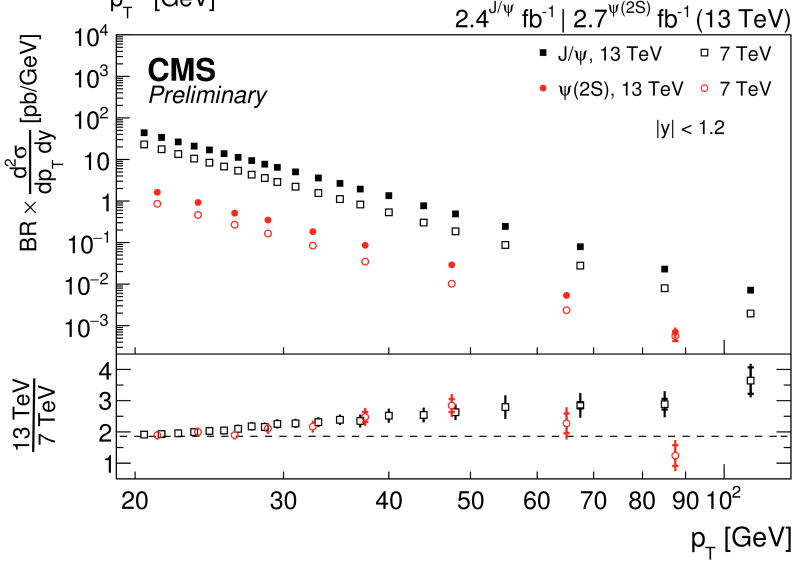
CMS-PAS-BPH-15-005
April 2016

- Prompt and non-prompt production:
  - J/ψ, ψ(2S) at 13 TeV (2.4-2.7 fb^{-1})
  - Double-differential: range $20<p_T<120$ (100) GeV and $|y| < 1.2$



Shapes consistent between rapidity slices





13 TeV / 7 TeV:

Factor 2-3 higher and increasing with p_T

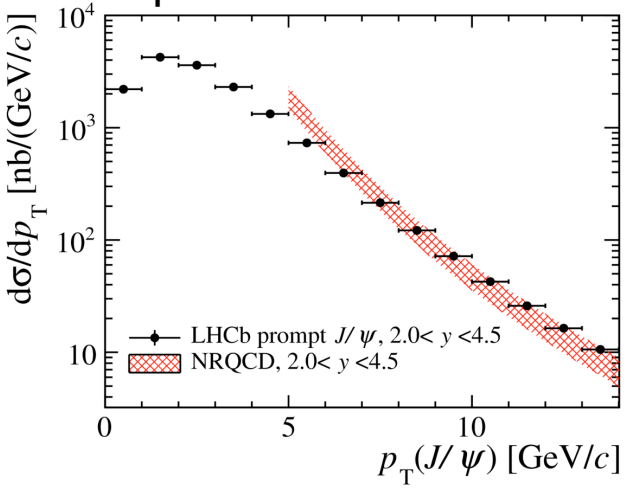
Increase expected from evolution of PDFs

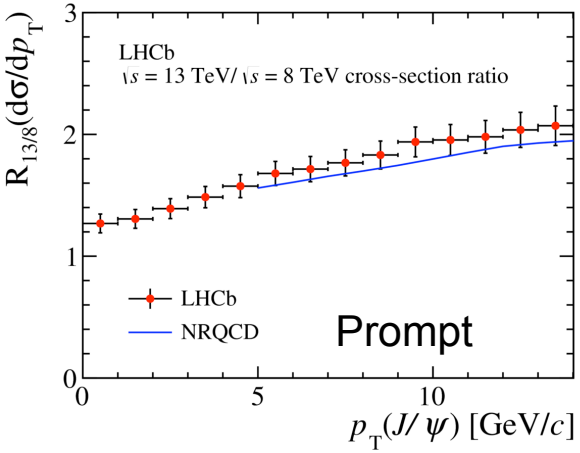
Forward J/ψ production at 13 TeV (pp)

arXiv:1509.00771,
JHEP10(2015)172

- Prompt and non-prompt production:
  - J/ψ at 13 TeV (3.05 pb^{-1})
  - Double-differential: range p_T<14 GeV and 2.0<y<4.5

- Prompt cross-sections compared to NLO NRQCD

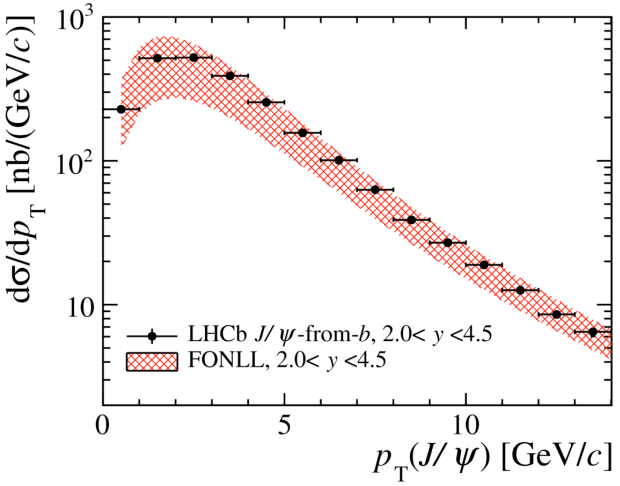


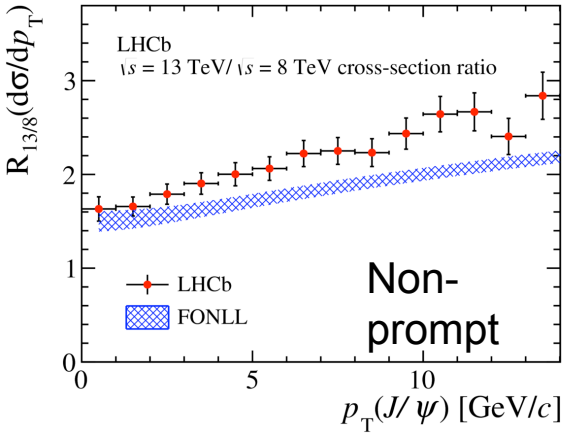


Models agree well within uncertainties

13 TeV / 8 TeV: NRQCD reasonable agreement, FONLL below data

- Non-prompt compared to fixed-order-next-to-leading-log (FONLL) calculations

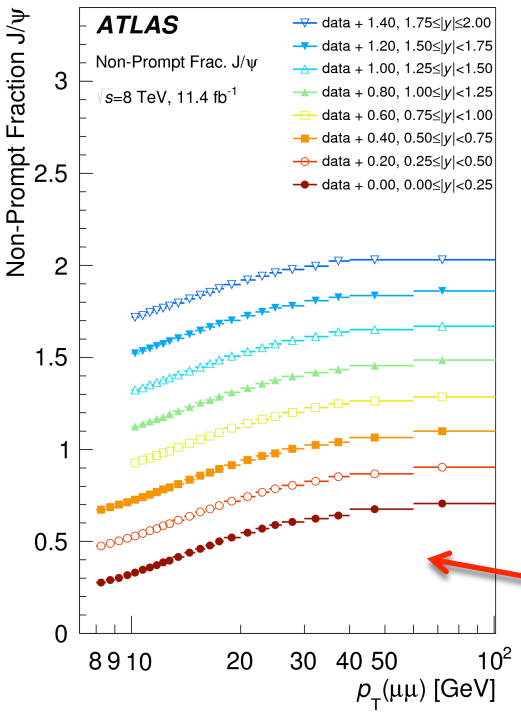


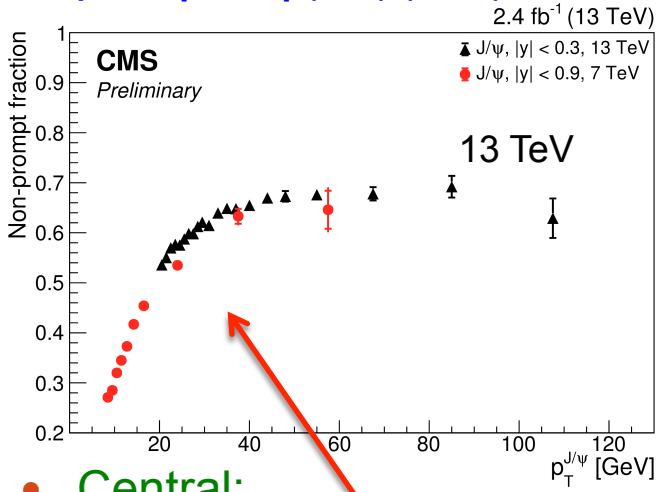


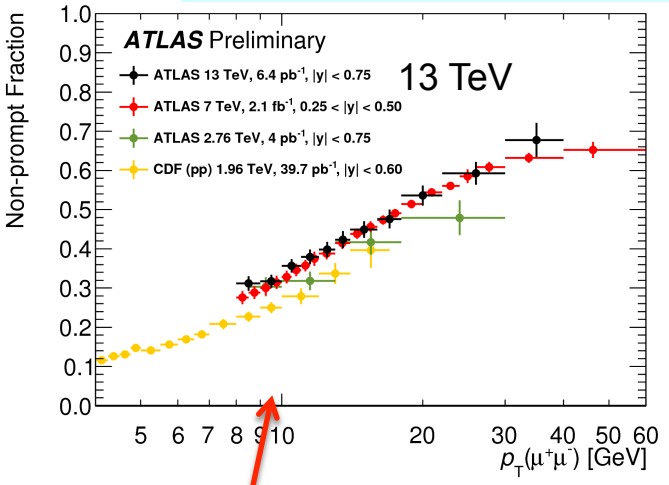
Non-prompt fractions at 7, 8 and 13 TeV (pp)

arXiv:1509.00771,
CMS-PAS-BPH-15-005,
arXiv:1512.03657,
ATLAS-CONF-2015-030

- Fraction = N(non-prompt J/ψ or ψ(2S))/ N(inclusive)

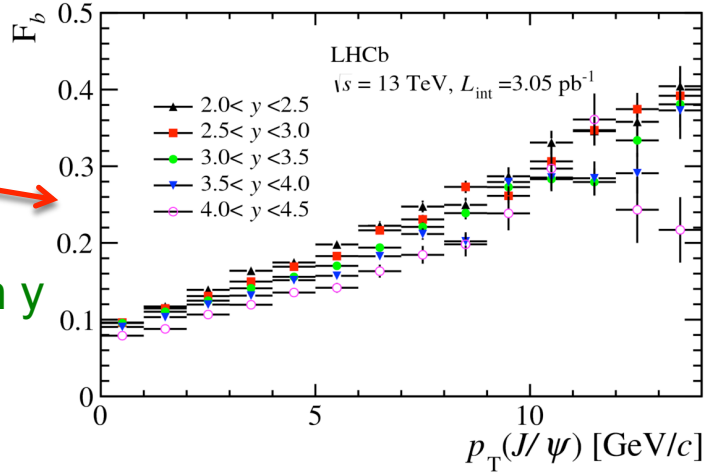






- Central:
  - increases with p_T
  - no strong dependence on y
  - some change from lower c.m. energies

- Forward:
  - increases with p_T
  - tends to decrease with y



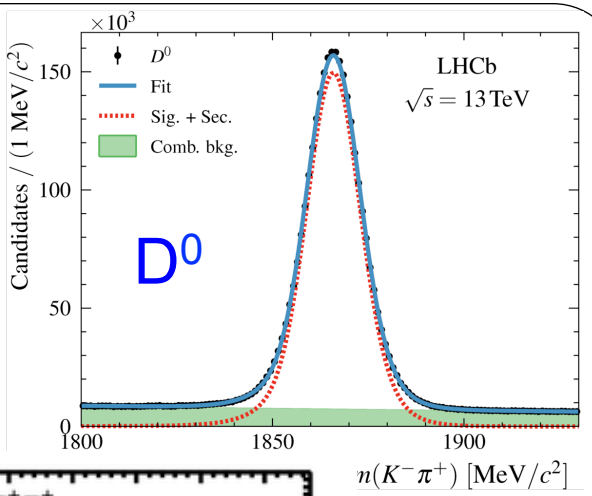
Open charm production: D mesons

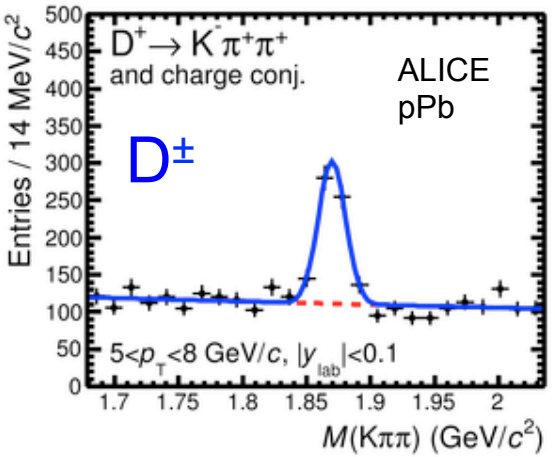
- D mesons produced in c and b fragmentation
- Theoretical calculations to NLO and NLL
- Still large theoretical uncertainties (scales, multiple interactions)

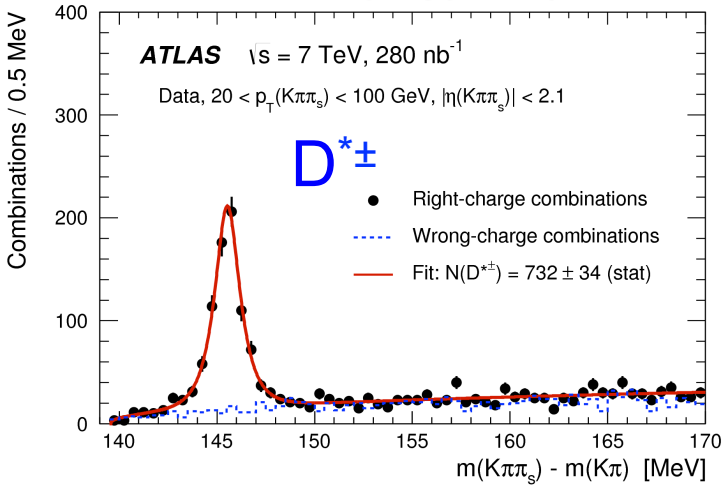
- Aim:
  - Test QCD
  - Understand backgrounds to new physics
  - Baseline for heavy ion collisions

- Decay modes:
  - $D^0 \rightarrow K^- \pi^+$
  - $D^+ \rightarrow K^- \pi^+ \pi^+$
  - $D_s^+ \rightarrow \phi \pi^+ \rightarrow (K^- K^+) \pi^+$
  - $D^{*+} \rightarrow D^0 + \pi^+ \rightarrow (K^- \pi^+) + \pi^+$

  (+charge conjugates)

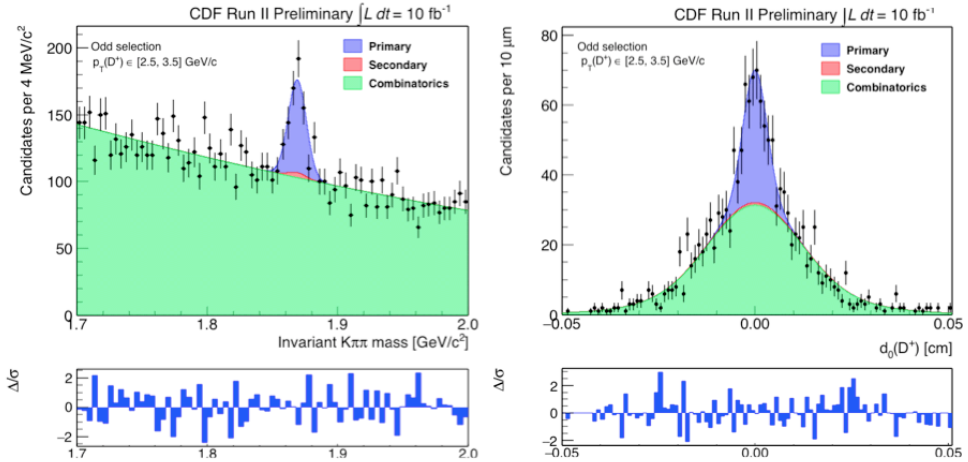






D^+ meson production at low p_T, $\sqrt{s}$=1.96 TeV ($p\bar{p}$)

CDF note 11199, June 2016

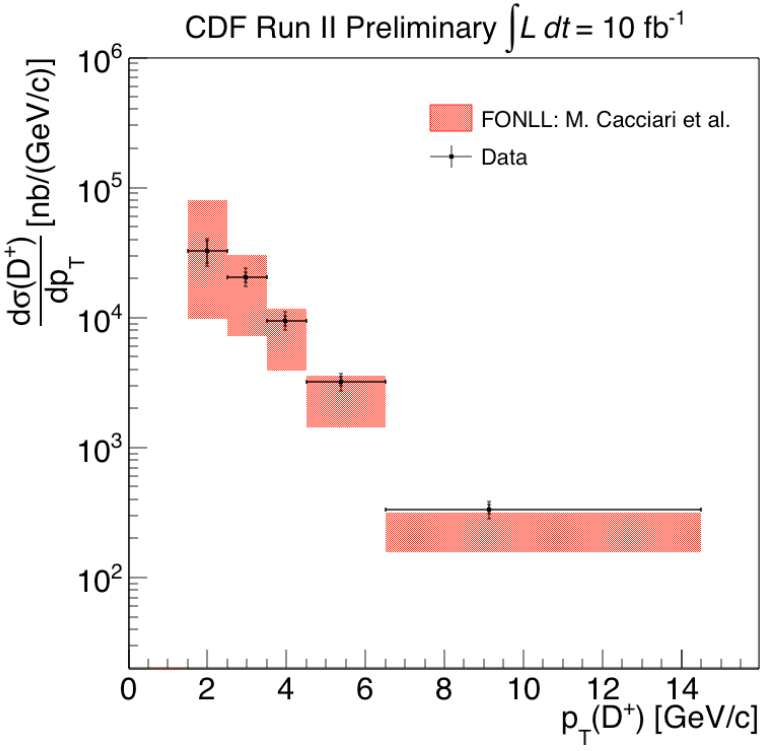


m(Kππ) $d_0(D^+)$

- $D^+ \rightarrow K^- \pi^+ \pi^+$ in full Run II dataset (10 fb^{-1})
- p_T>1.5 GeV and |y|<1
- Simultaneous fit to mass and transverse impact parameter

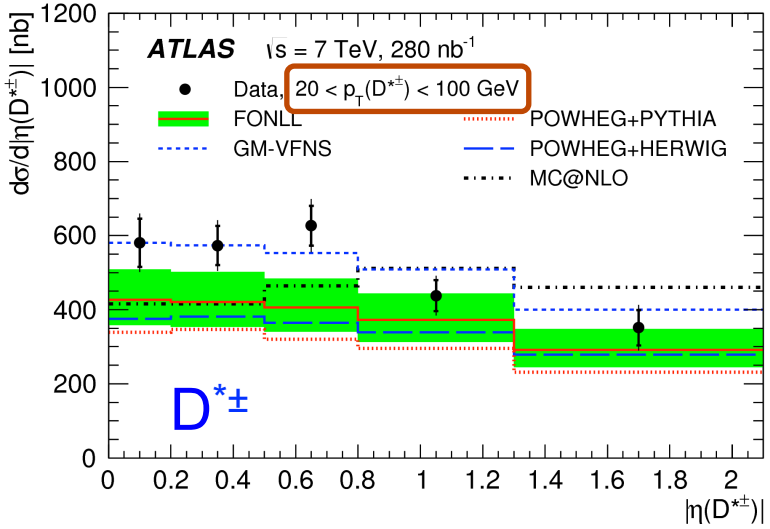
$$\sigma(D^+, p_T > 1.5\ \mathrm{GeV}/c, |y| < 1)$$
$$= 71.9 \pm 6.8(\mathrm{stat}) \pm 9.3(\mathrm{syst})\ \mu\mathrm{b}$$

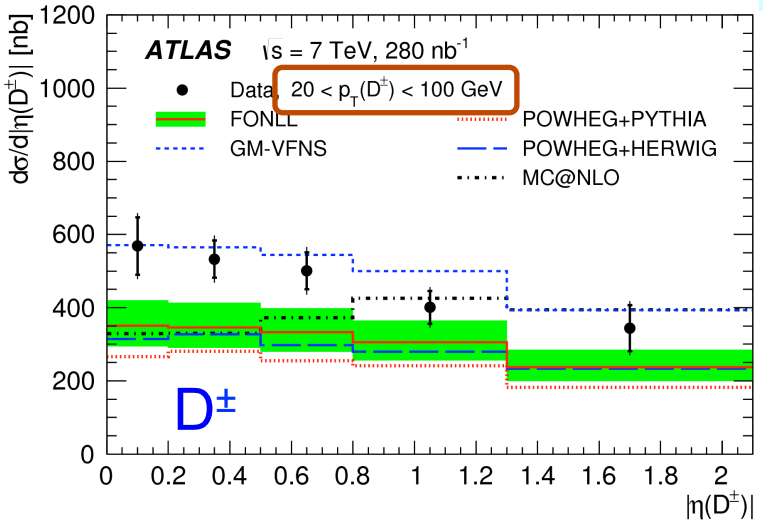
Measurements lie in FONLL uncertainty band, but some shape difference



$D^{*\pm}$, $D^{\pm}$ and $D_s^{\pm}$ meson production at 7 TeV (pp)

arXiv:1512.02913, Nucl. Phys. B907 (2016) 717



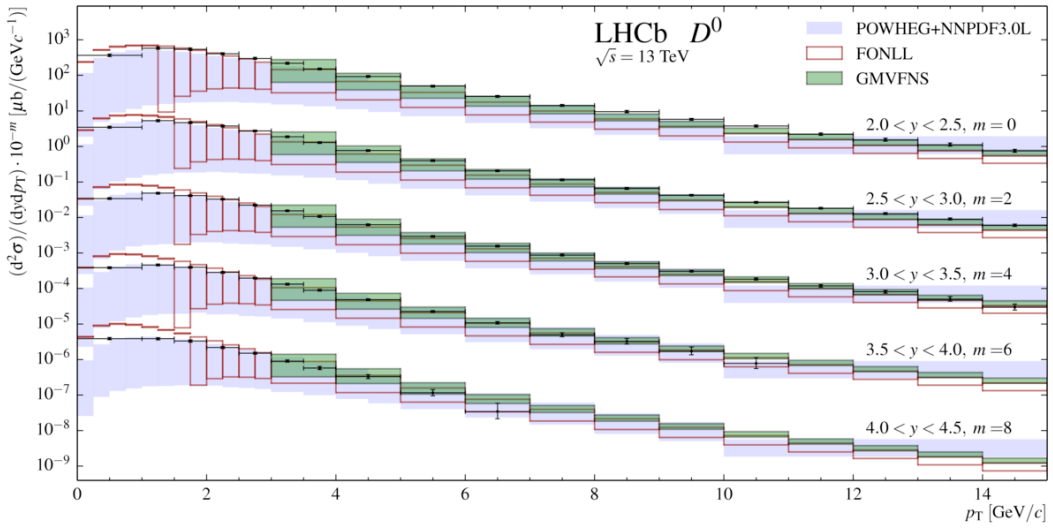


- Fiducial cross-sections for D^{*+}, D^{+}, D_s^{+}: $3.5<p_T<100$ GeV, $|\eta|<2.1$
- Differential cross-sections for D^{*+}, D^{+} compared to NLO predictions:
  - GM-VFNS - agrees both in shape and normalization
  - FONLL, POWHEG, MC@NLO ~agree within large theoretical uncertainties
  - MC@NLO - shape differs from data in $|\eta|$ at higher p_T
- Extrapolated to give total $c\bar{c}$ cross-section and charm fragmentation ratios

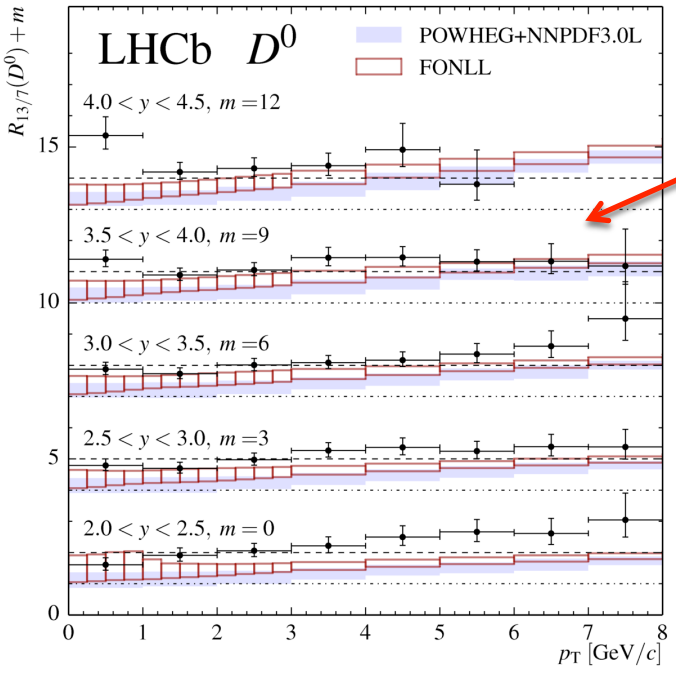
$$\sigma_{c\bar{c}}^{\mathrm{tot}} = 8.6 \pm 0.3\,(\mathrm{stat}) \pm 0.7\,(\mathrm{syst}) \pm 0.3\,(\mathrm{lum}) \pm 0.2\,(\mathrm{ff})^{+3.8}_{-3.4}\,(\mathrm{extr})\ \mathrm{mb}$$

Prompt charm production at 13 TeV (pp)

arXiv:1510.01707, JHEP 03 (2016) 159

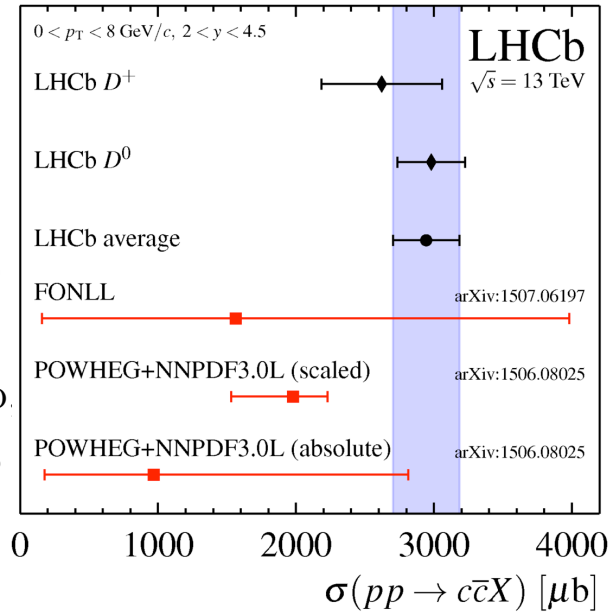


- Double-differential cross-sections for D^0,D^+,D_s^+,D^{*+}: $0<p_T<15$ GeV, $2.0<y<4.5$
- Data generally lie above NLO predictions but agree within uncertainties:
  - POWHEG+NNPDF3.0L
  - FONLL
  - GMVFNS



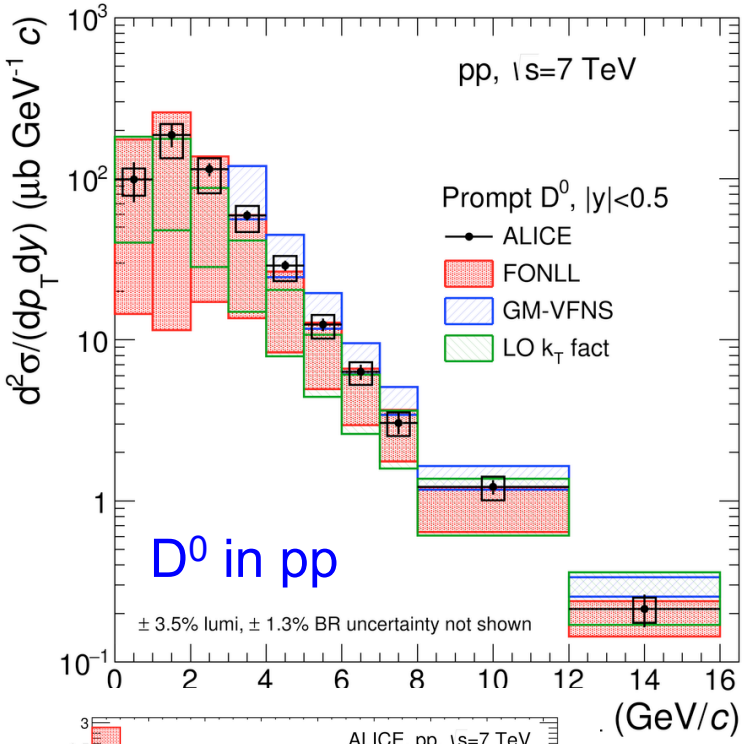
Ratio 13 TeV / 7 TeV: data consistently above predictions

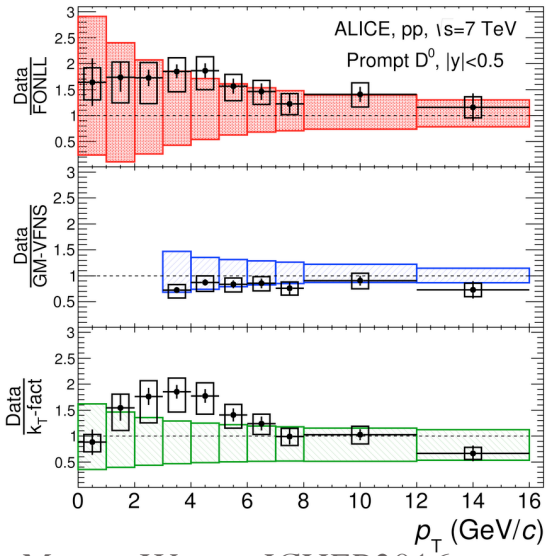
$$\sigma(pp \to c\bar{c}X) = 2940 \pm 3 \pm 180 \pm 160\ \mu\text{b}$$
$$p_T < 8\ \text{GeV}/c, 2.0 < y < 4.5$$



D meson production in pp (and pPb)

arXiv:1605.07569, sub. to JHEP



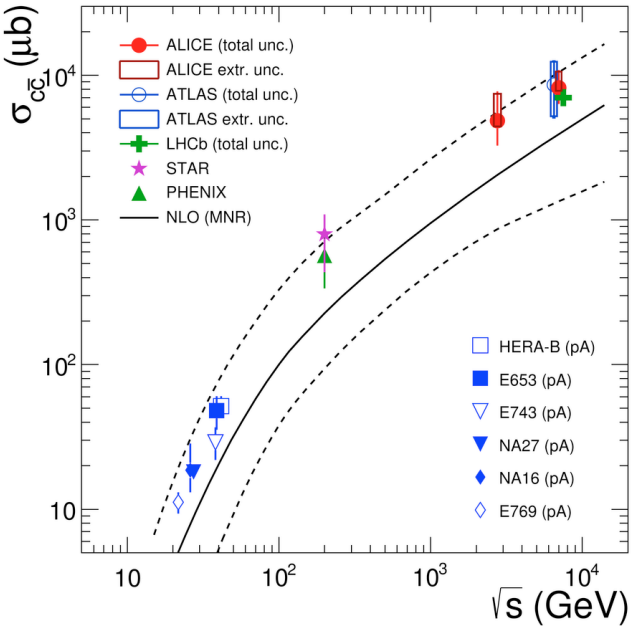


- Cross-sections for D^0,D^+,D_s^+,D^{*+}: pp at 7 TeV, pPb at 5 TeV
- D^0 production down to p_T=0 without vertexing: background estimates from 4 methods
- Combine with vertexing results for highest precision

$$\sigma^{c\bar{c}}_{pp,7\,TeV} = 8.18 \pm 0.67\,(stat.)\,^{+0.90}_{-1.62}\,(syst.)\,^{+2.40}_{-0.36}\,(extr.) \pm 0.29\,(lumi.) \pm 0.36\,(FF)\ mb$$

Data are described by theory within uncertainties

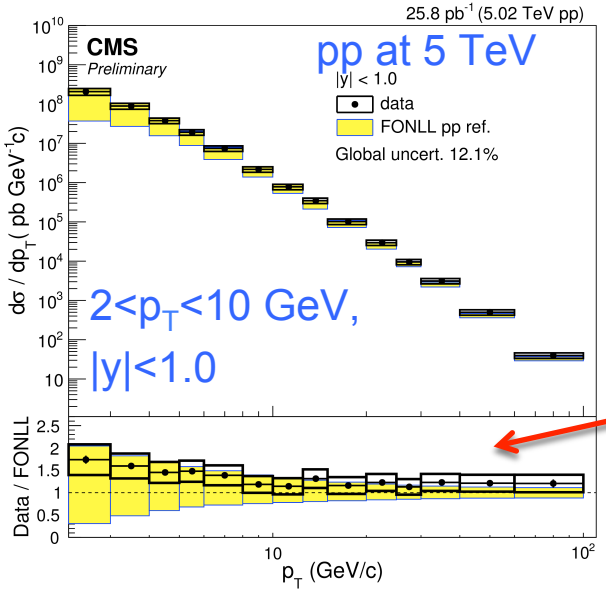
Central values:
Data/FONLL~1.5
Data/GM-VFNS~0.75
Data/k_T factorisation varies with p_T



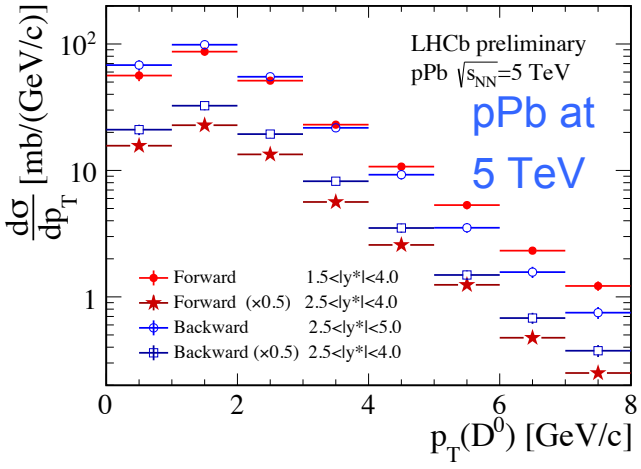
D^0 meson production in pp, pPb and PbPb

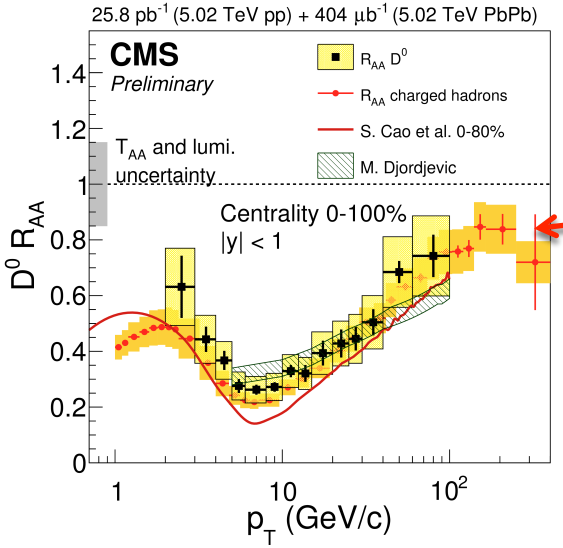
CMS-PAS-HIN-16-001, June 2016
LHCB-CONF-2016-003, May 2016

- More details in Heavy Ion session: a quick overview here

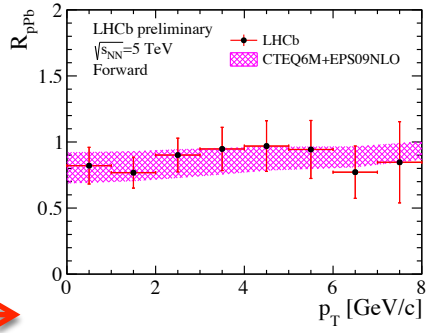


Data at top of FONLL band

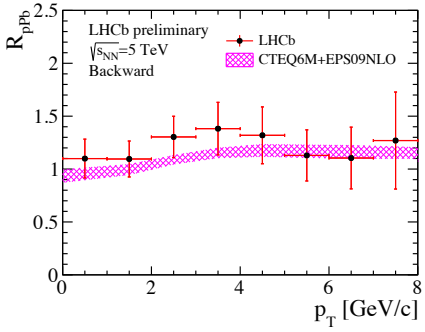




Nuclear modification factors are consistent with expectation

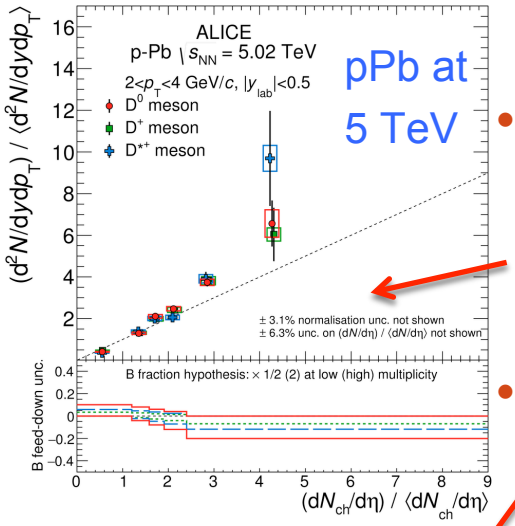


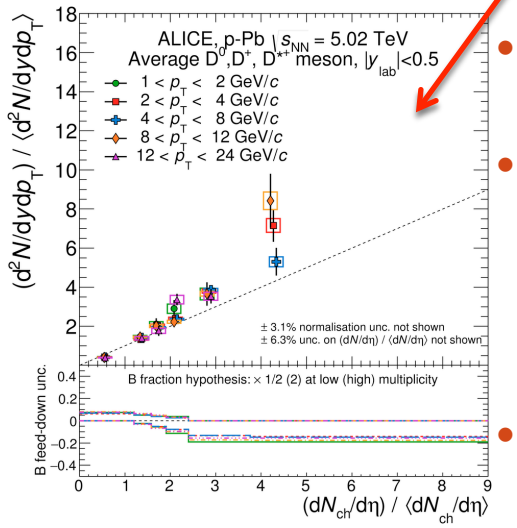
σ(pPb or PbPb) vs. σ(pp) with scaling factors



Multiplicity dependence and azimuthal correlations (pp, pPb)

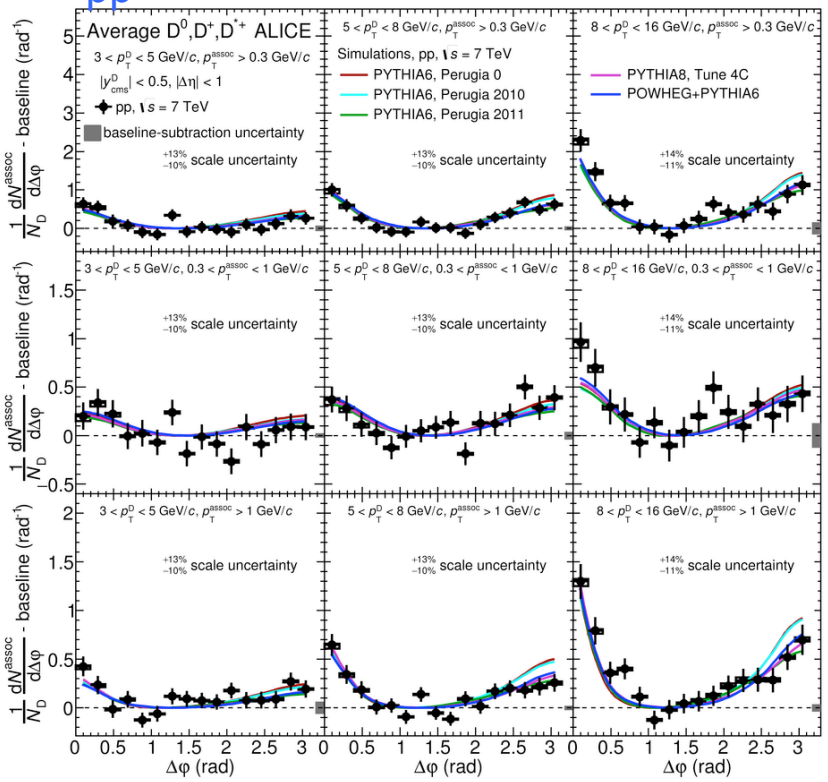
arXiv:1602.07240,
arXiv:1605.06963,
sub. to JHEP,EPJC



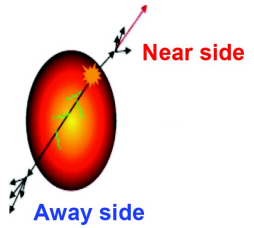


- Yields for D^0, D^+ and D^{*+} as a function of charged particle multiplicity
- Average D meson yields in p_T bins
- Yield increase independent of p_T
- Faster than linear increase with multiplicity at central rapidity
- Consistent with models which produce $c\bar{c}$ in multi-parton interactions

pp

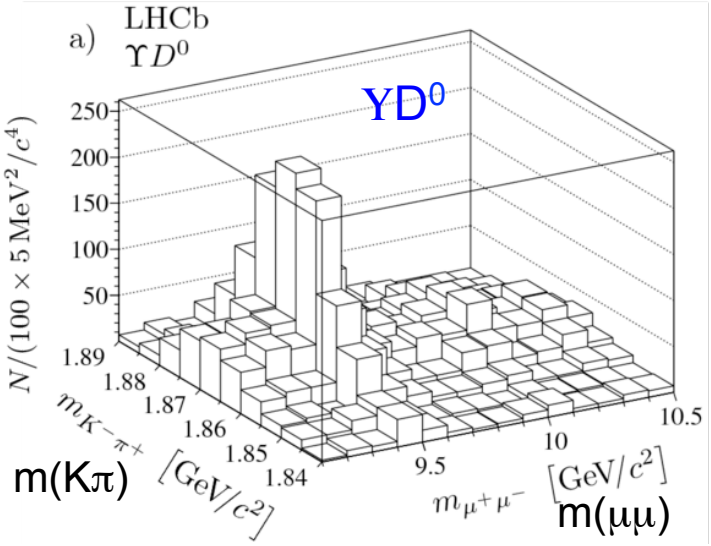


- Azimuthal correlations: hadronic activity near and away from D-meson momentum vector
- Very similar for pp, pPb
- Described by Pythia and Powheg MC



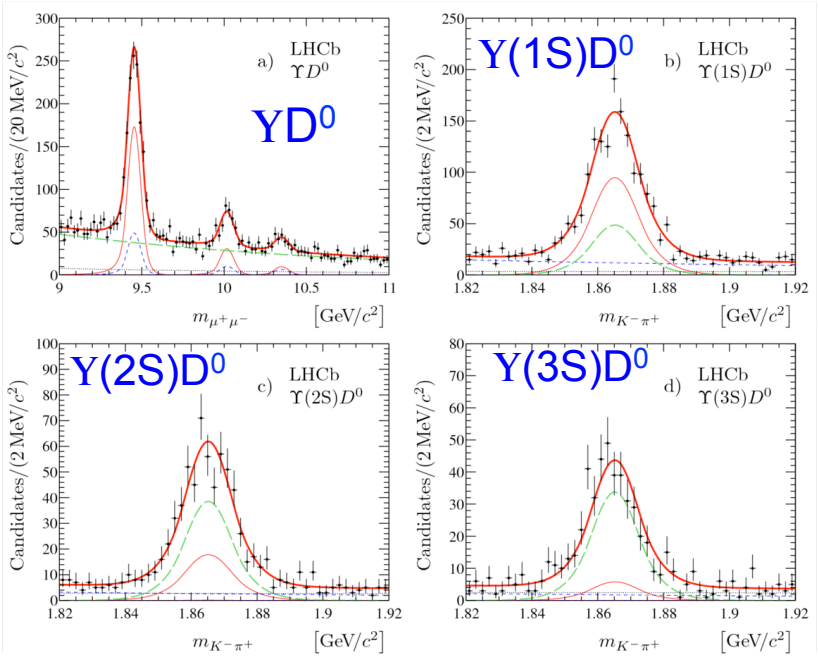
Associated production of Υ and open charm (pp)

arXiv:1510.05949,
JHEP 07(2016)052



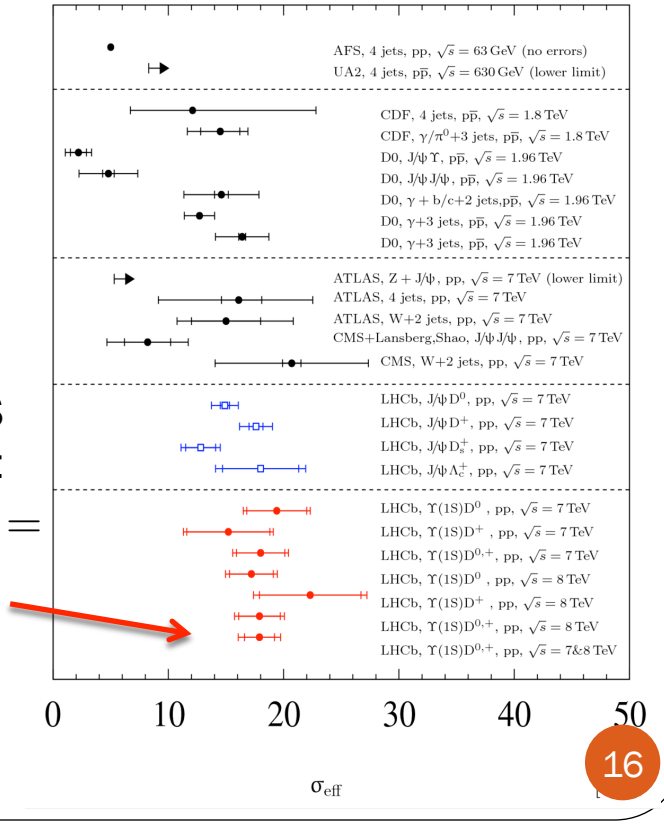
- Combine D^0, D^+, D_s^+, Λ_c^+ with Υ(1S,2S,3S) in 7, 8 TeV pp data
- Observe production of Υ(1S)D^0, Υ(2S)D^0, Υ(1S)D^+, Υ(2S)D^+, Υ(1S)D_s^+

Cross-sections and kinematic distributions consistent with double parton scattering (DPS) expectations



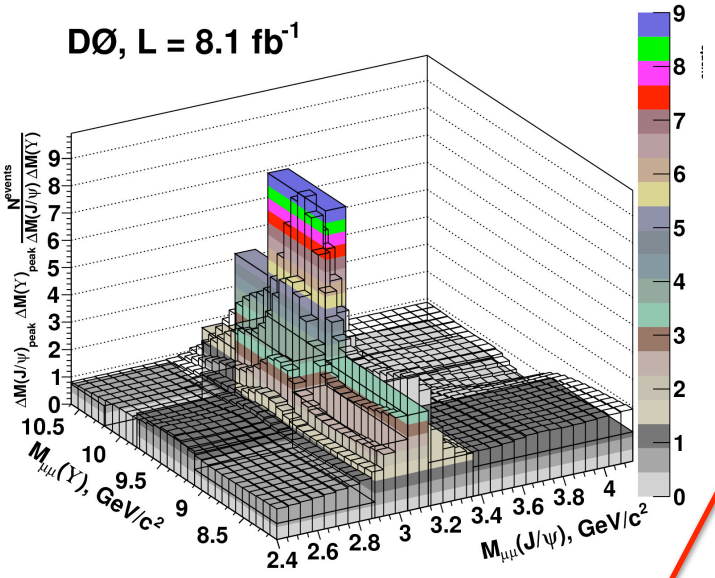
Effective DPS cross-section:

$\sigma_{\text{eff}}\big|_{\Upsilon(1S)D^{0,+}} = 18.0 \pm 1.8\,\text{mb}$



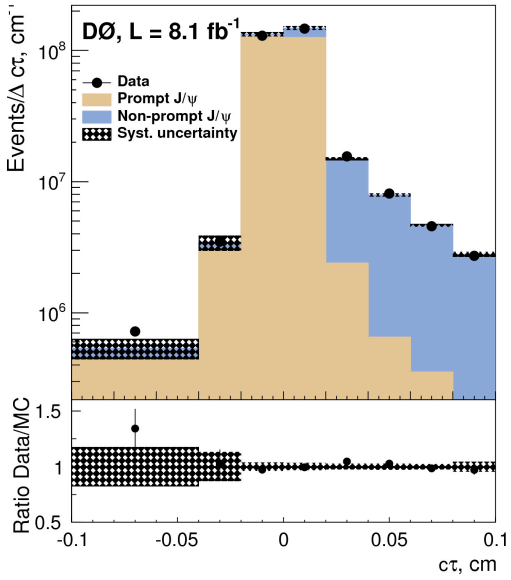
Simultaneous production of J/ψ and Υ ($p\bar{p}$)

arXiv:1511.02428,
Phys. Rev. Lett.
116, 082002 (2016)



- Measure J/ψ→μμ and Υ(1S,2S,3S)→μμ at √s=1.96 TeV
- Separate prompt and non-prompt J/ψ using decay length
- Prompt J/ψ+Υ signal:

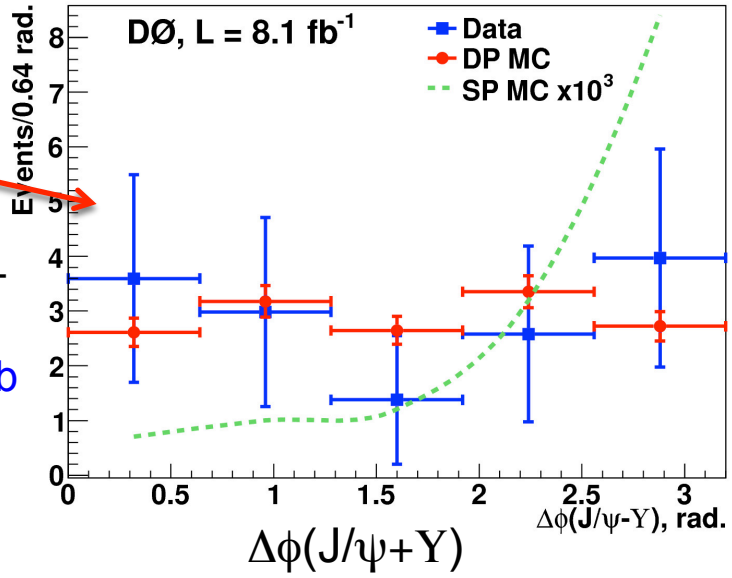
  12.0±3.8±2.8 events (3.2σ)



Data are consistent with DPS model

Effective DPS cross-section:

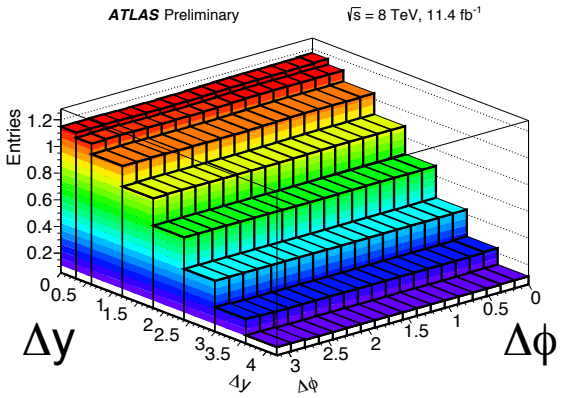
σ_{eff} = 2.2±0.7±0.9 mb



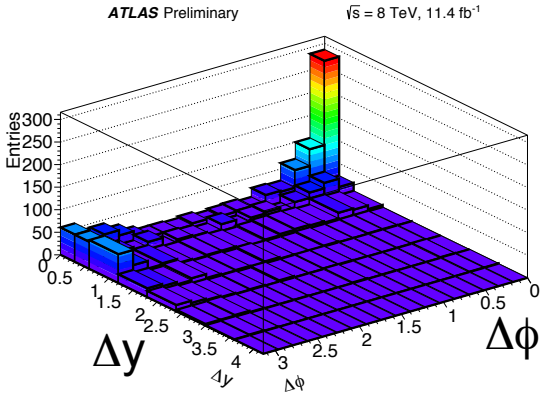
Prompt J/ψ pair production (pp)

ATLAS-CONF-2016-047, August 2016

- J/ψ pairs at 8 TeV (11.4 fb^{-1})
- p_T > 8.5 GeV and |y| < 2.1
- Fraction from DPS determined from kinematic correlations

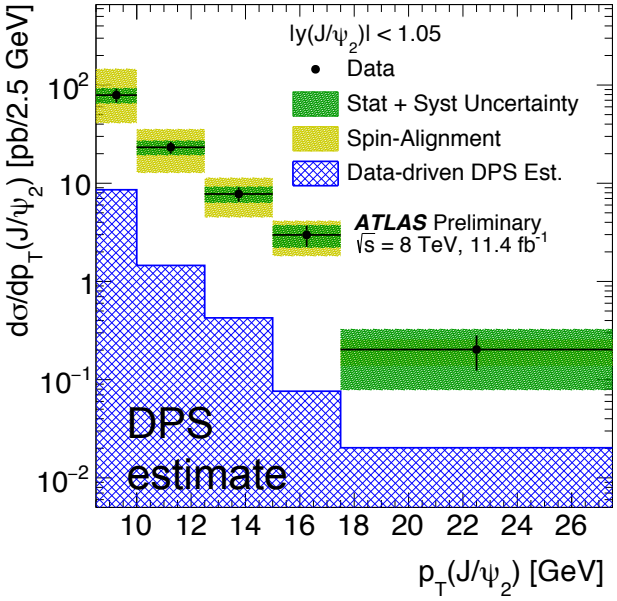


DPS template (mixed events)



SPS contribution in data

Differential cross-section vs. p_T of sub-leading J/ψ



Effective DPS cross-section:
σ_{eff} = 8.7±1.8 mb

Talk by Zdenek Dolezal tomorrow

Summary

- Many results from LHC Run1 and Tevatron Run II allow detailed tests of QCD
  - Quarkonium and open charm states
  - Comparison of pp, $p\bar{p}$, pPb and PbPb environments
  - Double-parton scattering estimates
- First results from LHC Run 2 have been presented, using 13 TeV collisions
- New data extend the reach to higher p_T and continue to probe our understanding of QCD phenomena

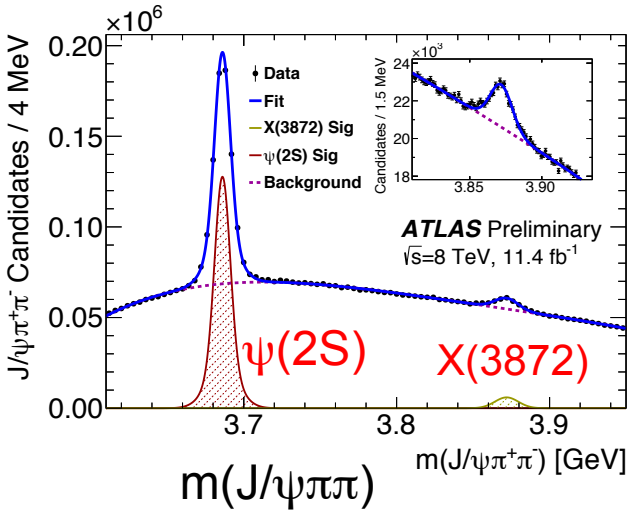
- Public results from LHC and Tevatron:
  - https://twiki.cern.ch/twiki/bin/view/ALICEpublic/ALICEPublicResults
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic
  - http://www-cdf.fnal.gov/physics/physics.html
  - http://cms-results.web.cern.ch/cms-results/public-results/publications/
  - http://www-d0.fnal.gov/Run2Physics/WWW/results.htm
  - https://lhcb.web.cern.ch/lhcb/Physics-Results/LHCb-Physics-Results.html

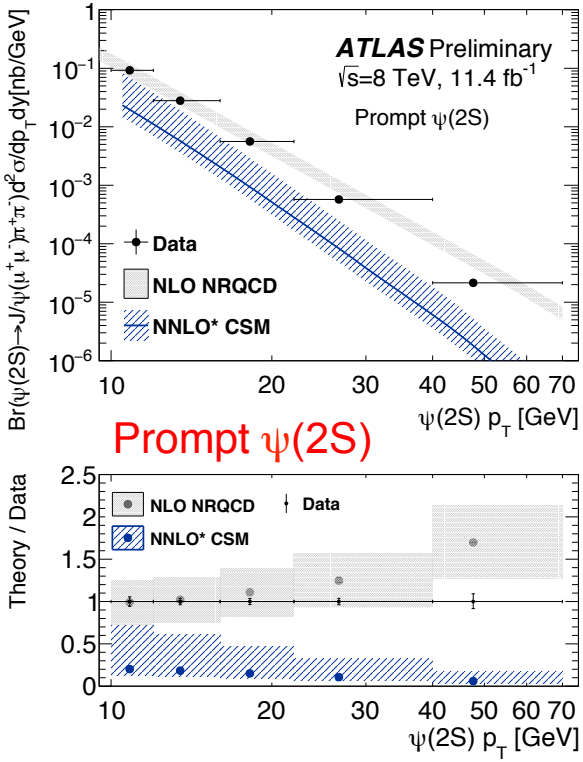
Backup slides

ψ(2S) and X(3872) → J/ψ π⁺π⁻ at 8 TeV

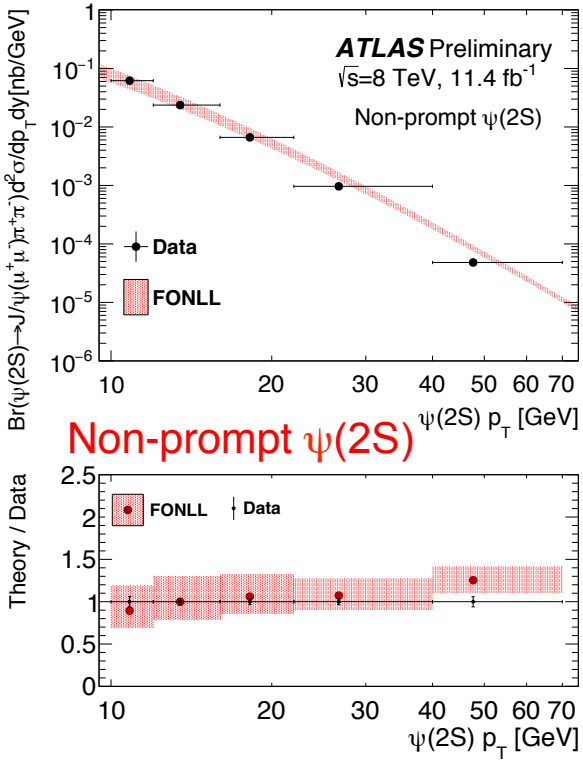
ATLAS-CONF-2016-028, June 2016

- See talk by Konstantin Toms
- X(3872): 'Exotic resonance' previously measured by Belle, BaBar, CDF, D0, CMS
- Mass of X(3872) close to $D^0\bar{D}^{*0}$ threshold
- J/ψ $\pi^+\pi^-$ decay channel
- 11.4 fb^{-1} at 8 TeV





Prompt ψ(2S)



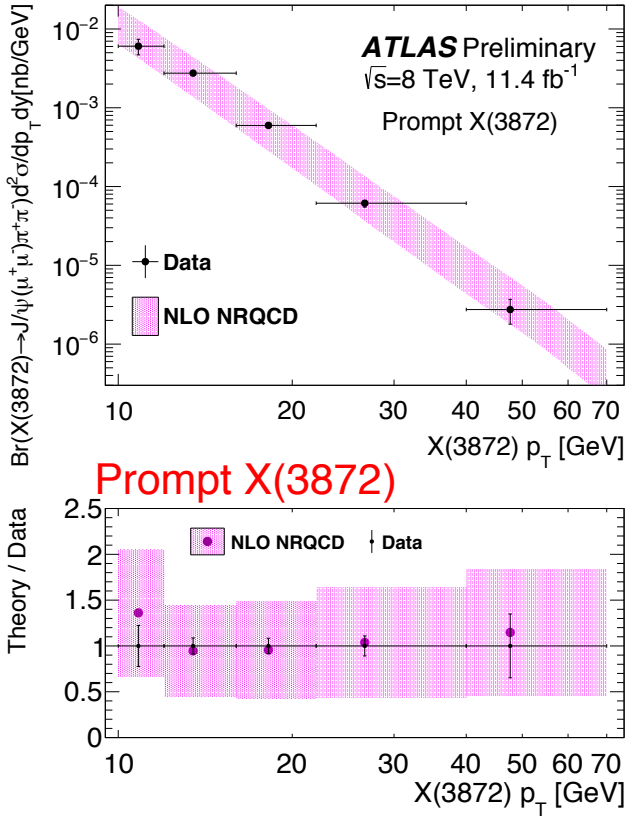
Non-prompt ψ(2S)

Prompt: NRQCD slightly overestimates at high p_T, Colour Singlet underestimates

Non-prompt: FONLL describes data well

ψ(2S) and X(3872) → J/ψ π⁺π⁻ at 8 TeV

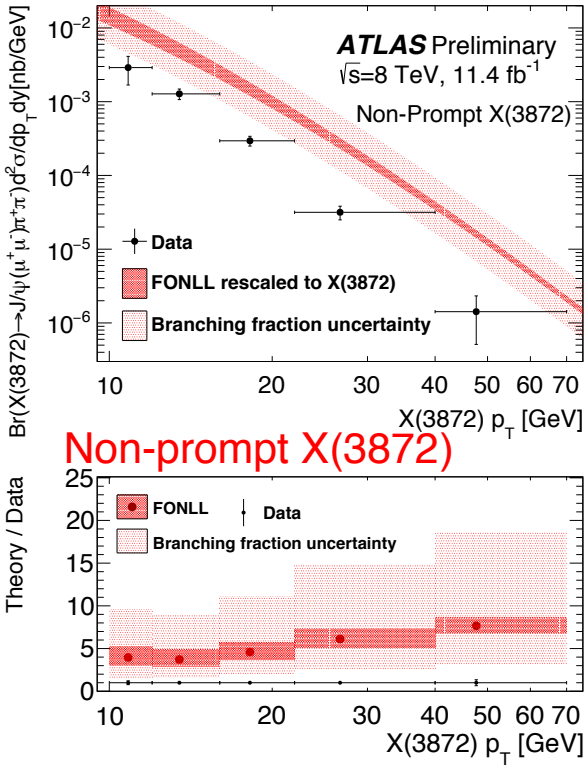
ATLAS-CONF-2016-028, June 2016



Prompt X(3872)

NRQCD agrees well: interprets X(3872) as a mixed $\chi_{c1}(2P)$-$D^0\bar{D}^{*0}$ state

FONLL recalculated for X(3872) overestimates data



Non-prompt X(3872)

Non-prompt fractions agree with JHEP 04 (2013) 154, Phys. Rev. Lett. 114 (2015) 191802 within uncertainties