Heavy-flavour production and spectroscopy

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on behalf of the
ALICE, ATLAS, CMS and LHCb Collaborations

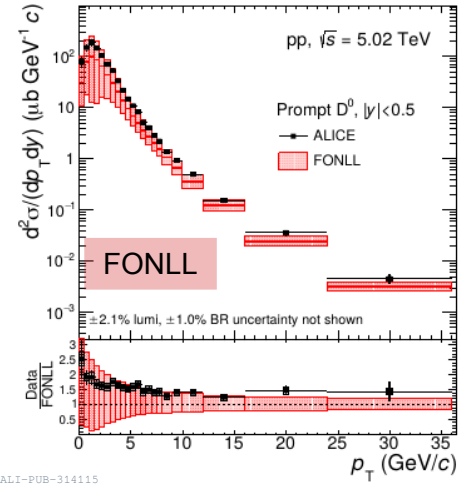
Open-heavy flavour production

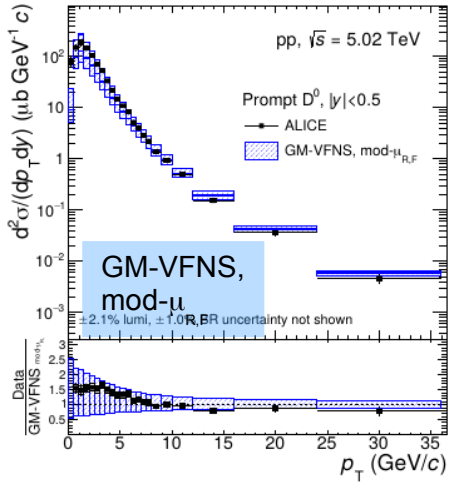
D-meson production in pp collisions

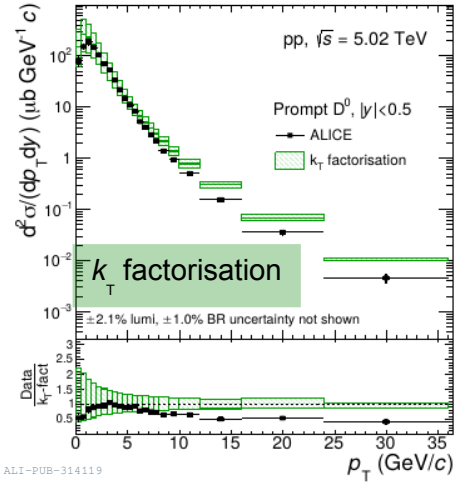
- pp collisions at √s = 5.02 TeV
  $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, $D_s^+ \rightarrow K^+K^-\pi^+$, $D^{*+} \rightarrow D^0\pi^+$

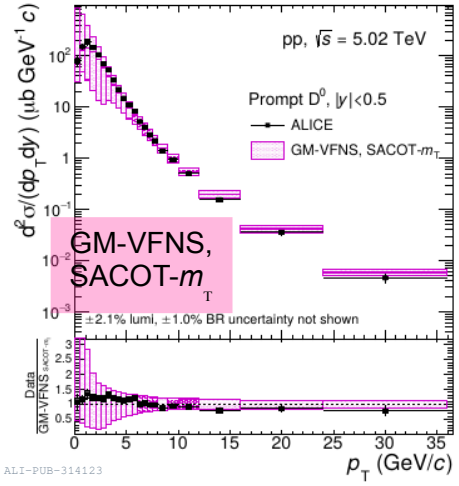
ALICE Collaboration, arXiv: 1901.07979

$$\mathrm{d}\sigma_{\mathrm{pp}\rightarrow\mathrm{HX}} = \mathrm{PDF}_{\mathrm{a}}(x_{\mathrm{a}}, \mu_{\mathrm{f}}^2) \otimes \mathrm{PDF}_{\mathrm{b}}(x_{\mathrm{b}}, \mu_{\mathrm{f}}^2) \otimes \mathrm{d}\sigma_{\mathrm{ab}\rightarrow\mathrm{Q\overline{Q}}}(x_{\mathrm{a}}, x_{\mathrm{b}}, \mu_{\mathrm{f}}^2) \otimes \mathrm{D}_{\mathrm{Q}\rightarrow\mathrm{H}}(z_{\mathrm{Q}}, \mu_{\mathrm{f}}^2)$$









- Systematic comparison with several pQCD calculations with different schemes - agreement within uncertainties
  - non-strange D mesons overestimated or underestimated in different p_T ranges
  - D_s production tends to be underestimated by all pQCD calculations
- Data: smaller uncertainties than theoretical ones
  - larger uncertainties at low p_T, dominated by factorisation and renormalisation scales of the perturbative calculations

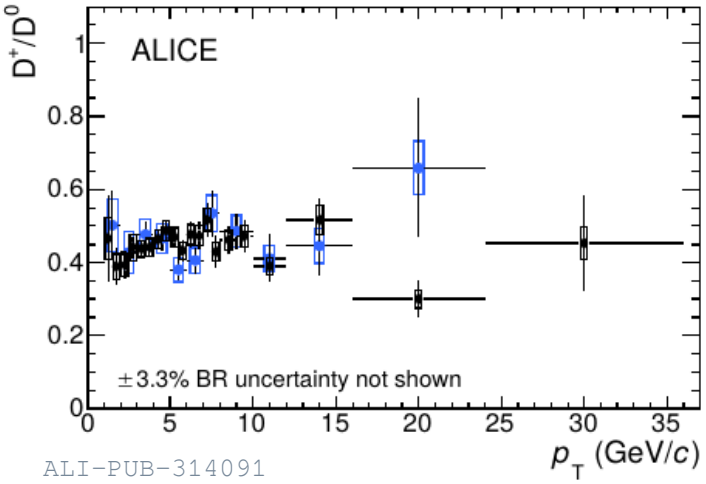
D-meson production in pp collisions

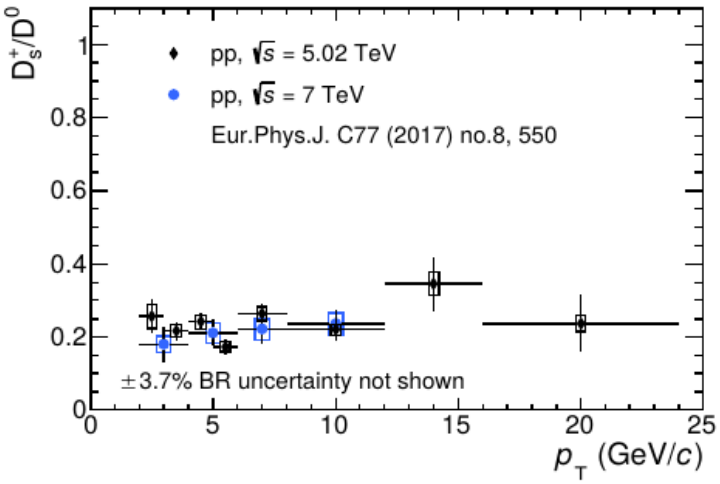
Particle ratios

- Particle species ratios at different energies: √s = 5.02, 7 TeV

ALICE Collaboration, arXiv: 1901.07979

$$\mathrm{d}\sigma_{\mathrm{pp}\to\mathrm{HX}} = \mathrm{PDF}_{\mathrm{a}}(x_{\mathrm{a}},\mu_{\mathrm{f}}^2) \otimes \mathrm{PDF}_{\mathrm{b}}(x_{\mathrm{b}},\mu_{\mathrm{f}}^2) \otimes \mathrm{d}\sigma_{\mathrm{ab}\to\mathrm{Q\overline{Q}}}(x_{\mathrm{a}},x_{\mathrm{b}},\mu_{\mathrm{f}}^2) \otimes \mathrm{D}_{\mathrm{Q}\to\mathrm{H}}(z_{\mathrm{Q}},\mu_{\mathrm{f}}^2)$$





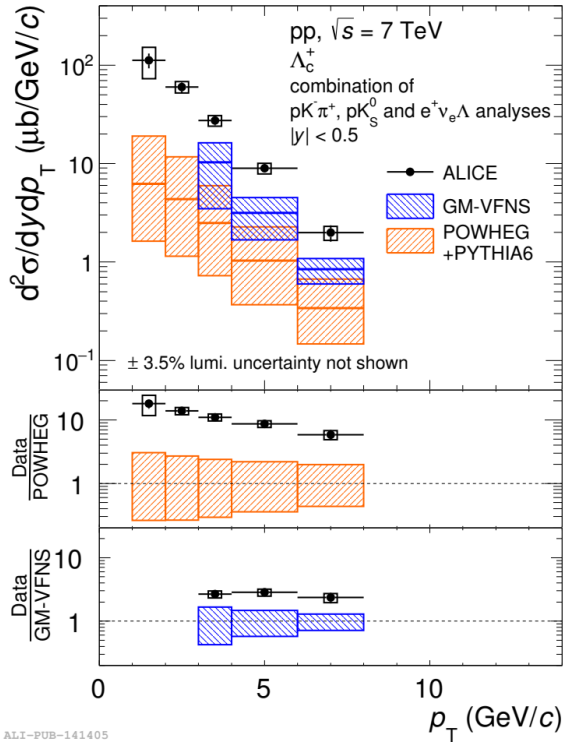
- Sensitivity to fragmentation functions for different hadronisations of charm
  - No differences between D-meson ratios for different collision energies
  - Compatible with ratios measured in e^+e^- and ep collisions
    → No dependence on collision systems
  - Agreement with models

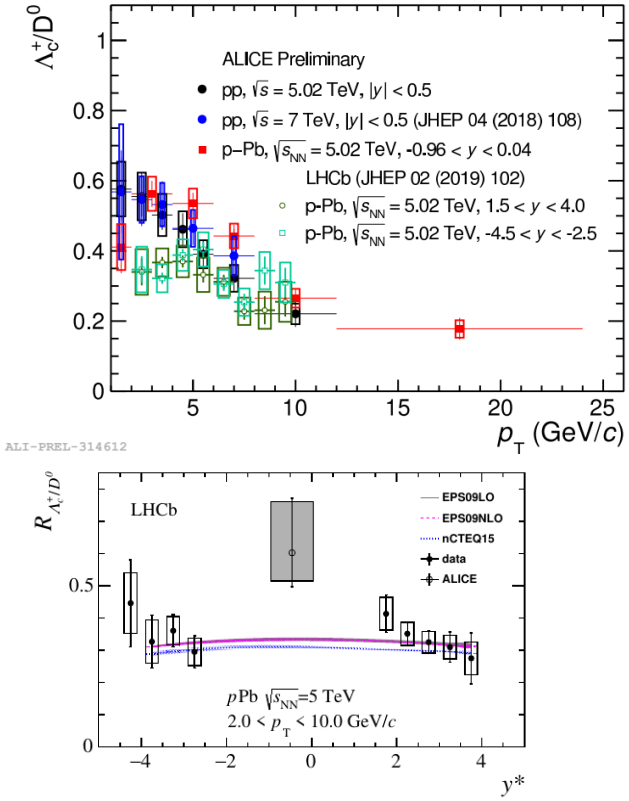
→ Universality of D-meson fragmentation functions

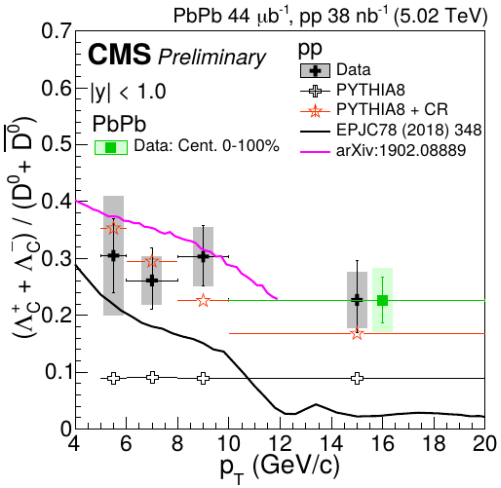
Λ_c production in pp and p-Pb collisions

- p_T-differential result significantly underestimated by models
  - Fragmentation to heavy-flavour baryons not well understood
- Λ_c/D ratios
  - Possible p_T dependence and slight rapidity dependence
  - Higher than previous measurements in e^+e^- and ep collisions (R ≈ 0.11-0.22 depending on p_T of hadron etc.)

ALICE Collaboration, JHEP04(2018)108
LHCb Collaboration, Nucl.Phys.B871(2013)1
JHEP02(2019)102
CMS Collaboration, CMS-PAS-HIN-18-009







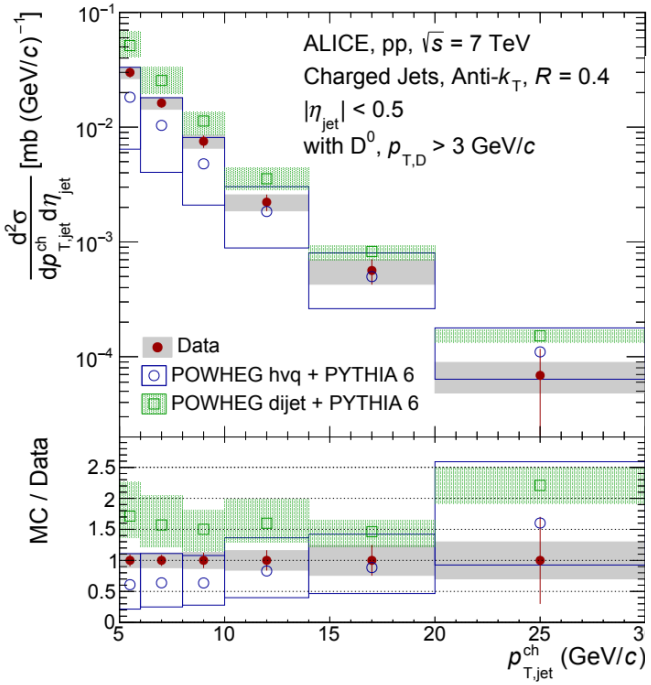
→ Hint of a violation of the universality of the fragmentation functions

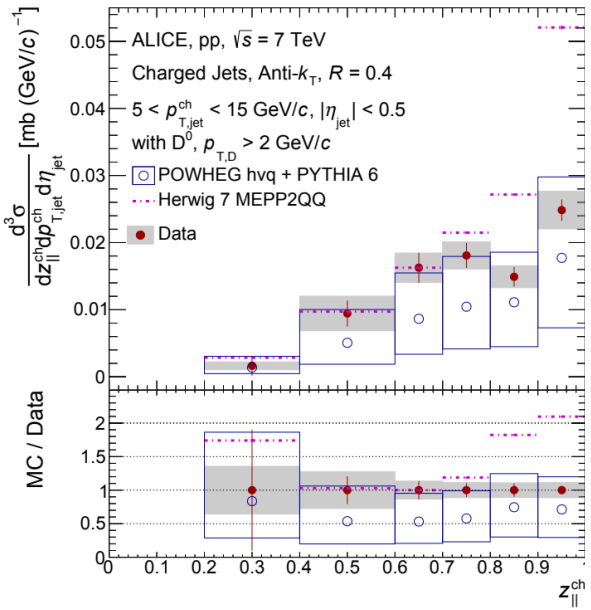
D-meson tagged jets
Fragmentation Functions

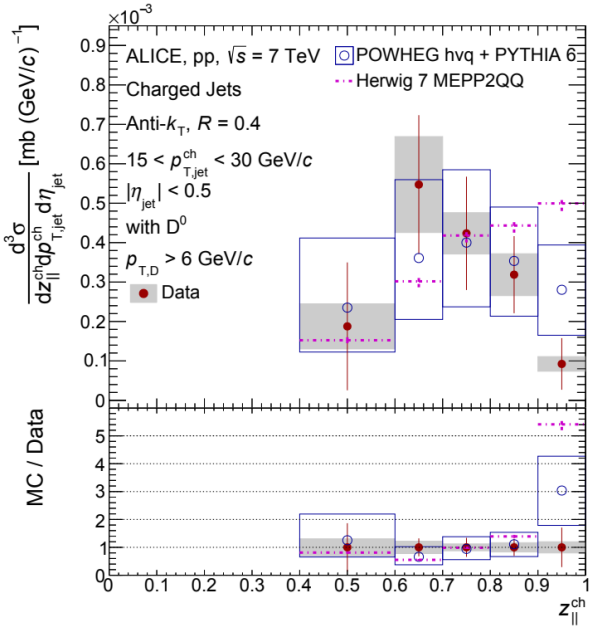
- Cross-section measurement in agreement with POWHEG hvq+PYTHIA6 calculations

ALICE Collaboration, arXiv: 1905.02510
ATLAS Collaboration, Phys.Rev. D85(2012)052005
CMS Collaboration, CMS-PAS-HIN-18-007

$$z_{\parallel} = \frac{\overrightarrow{p_{\mathrm{jet}}} \cdot \overrightarrow{p_{\mathrm{D}}}}{\overrightarrow{p_{\mathrm{jet}}} \cdot \overrightarrow{p_{\mathrm{jet}}}}$$





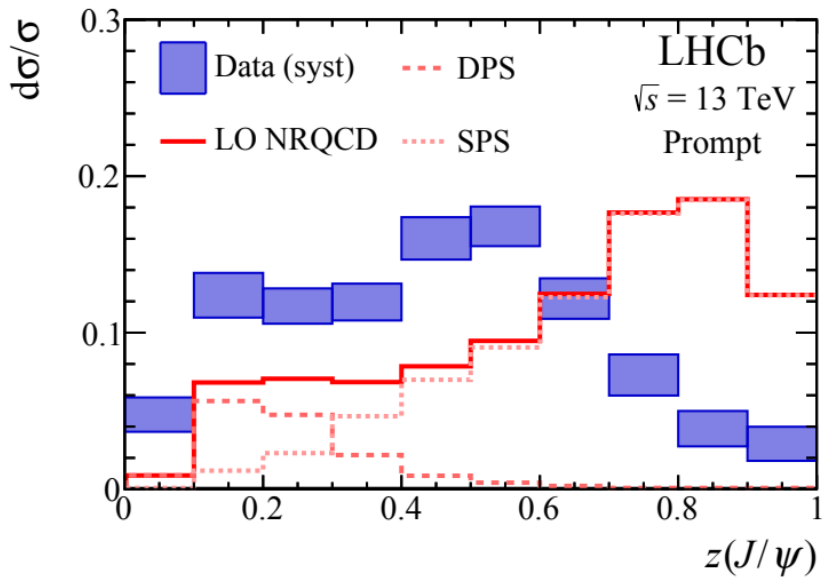


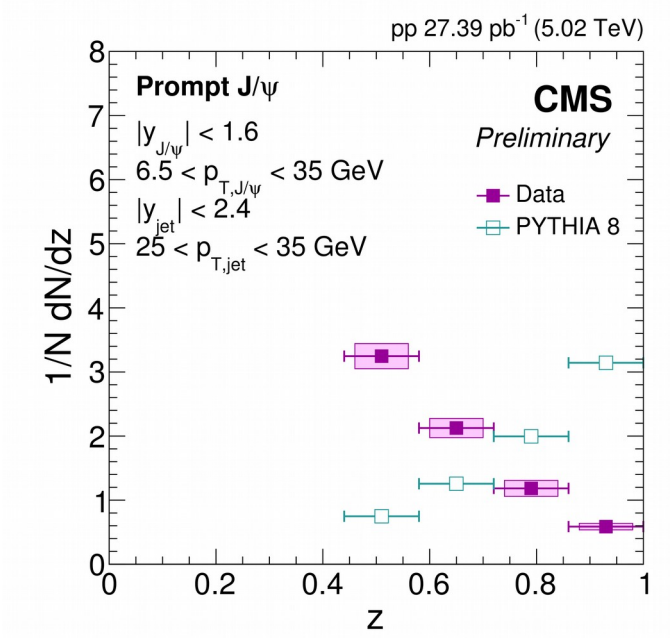
- $z_{\parallel}$: momentum fraction carried by the D meson
  - Good agreement between data and models for jets < 15 GeV/c
  - Hint of a softer fragmentation function in data wrt theory in particular for higher p_T jets

J/ψ production in jets
Fragmentation Functions

LHCb Collaboration, Phys.Rev.Lett.118(2018)192001
CMS Collaboration, CMS-PAS-HIN-18-012,
CMS-PAS-BPH-15-003

- Softer fragmentation function in data wrt to theory
  - Similar observations for J/ψ by LHCb and CMS





b-hadron production fractions in pp collisions

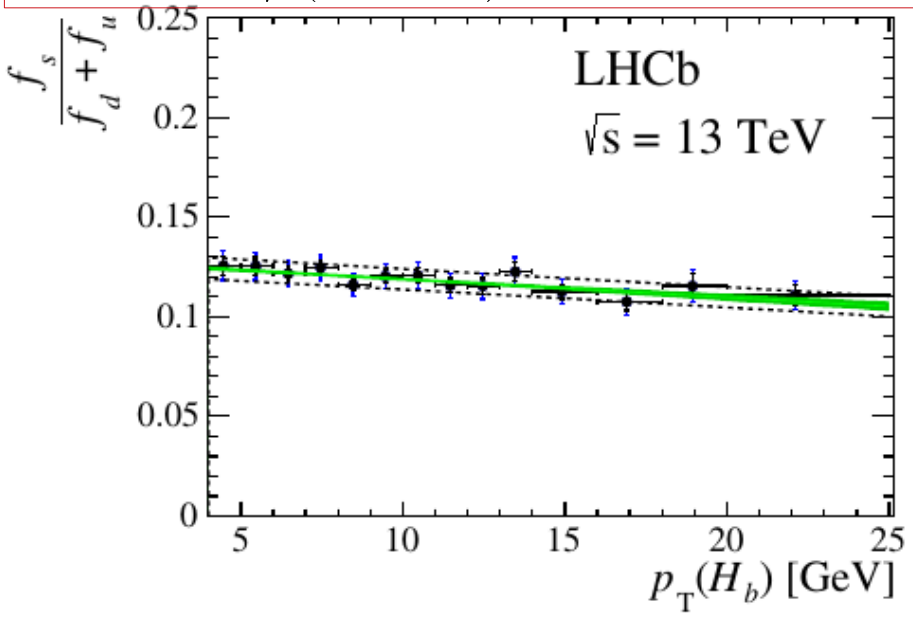
LHCb Collaboration, arXiv:1902.06794

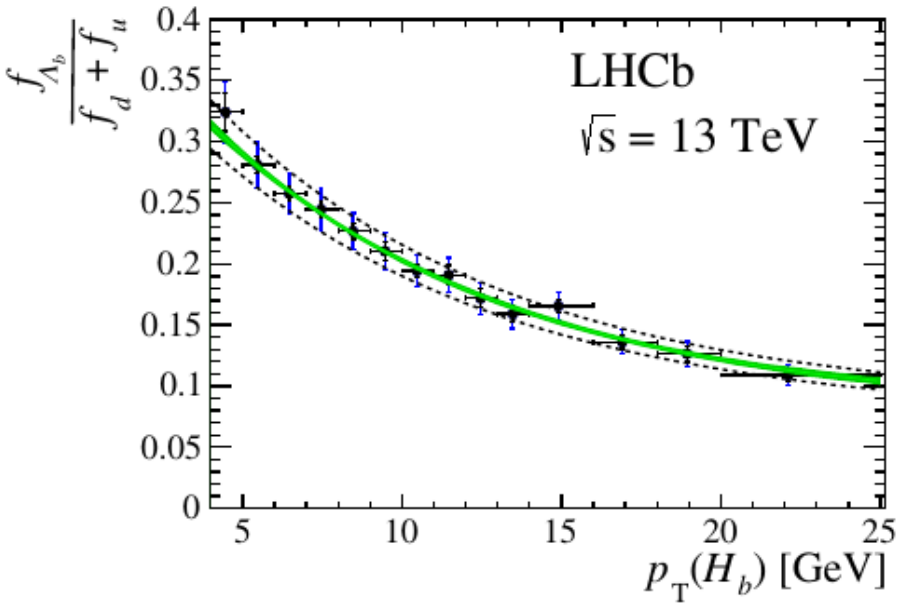
- Production fractions of $\overline{B}_s^0$ and Λ_b^0 hadrons normalised to B^- and $\overline{B}^0$ in pp at 13 TeV
  - Measurement via inclusive semileptonic decays $H_b \to H_c\, \mu^- \overline{\nu}_\mu X$
  - $f_s/(f_u + f_d)$ slightly and $f_{\Lambda_b^0}/(f_u + f_d)$ strongly depends on p_T
  - No rapidity dependence

Average values:

$$f_s/(f_u + f_d) = 0.122 \pm 0.006$$

$$f_{\Lambda_b^0}/(f_u + f_d) = 0.259 \pm 0.018$$

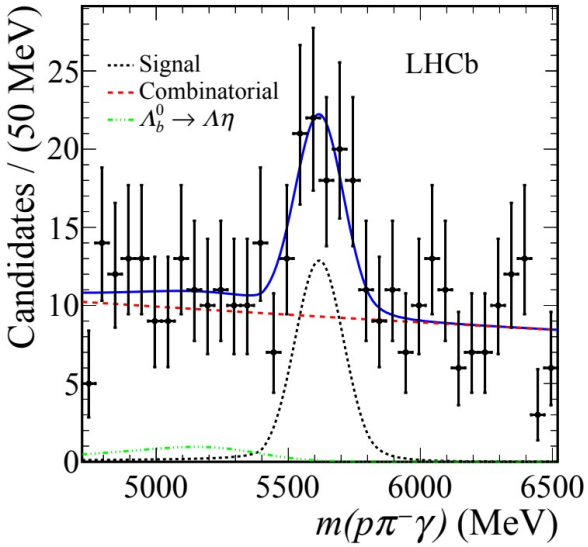


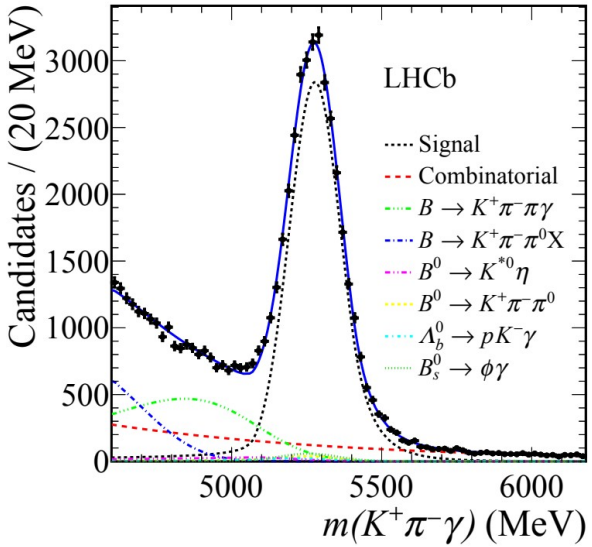


Radiative decay $\Lambda_b^0 \to \Lambda\gamma$

- $\Lambda_b^0 \to \Lambda\gamma$ measured in 1.7 fb^{-1} of pp collisions at 13 TeV with significance 5.6σ LHCb Collaboration, arXiv:1904.06697
  - Proceeds via b $\to$ sγ flavour-changing neutral-current transition
  - Forbidden at tree level in Standard Model (SM)
    $\to$ sensitive to new particles entering the loop-level transition
  - Polarisation of photon predicted to be predominantly left-handed in SM
  - Helicity of Λ measurable $\to$ acess to helicity structure of b $\to$ sγ
- $B^0 \to K^{*0}\gamma$ decay as normalisation mode $\to$ Branching fraction

$$\mathcal{B}(\Lambda_b^0 \to \Lambda\gamma) = (7.1 \pm 1.5 \pm 0.6 \pm 0.7) \cdot 10^{-6}$$





$\to$ First observation of radiative decay of beauty baryon

Heavy-flavour production and PDFs

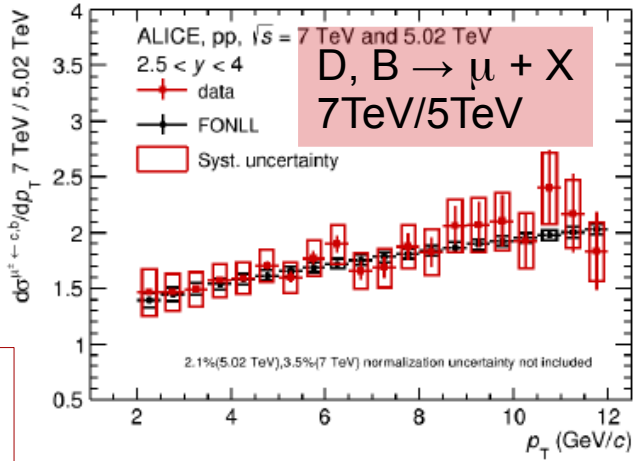
- Ratios of measurements at different energies and rapidities
  → constrain gluon PDF at small values of Bjorken-x (10^{-4}-10^{-5})

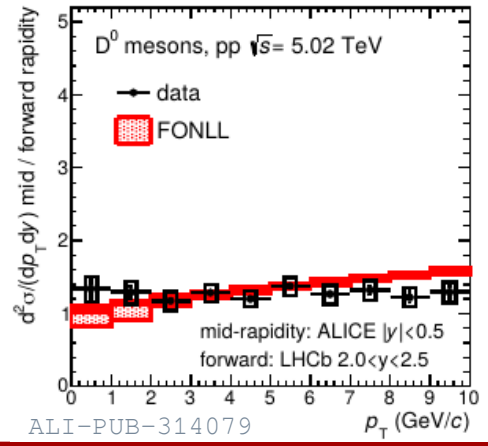
ALICE Collaboration, arXiv: 1901.07979
arXiv: 1905.07207
LHCb Collaboration, JHEP09(2016)13

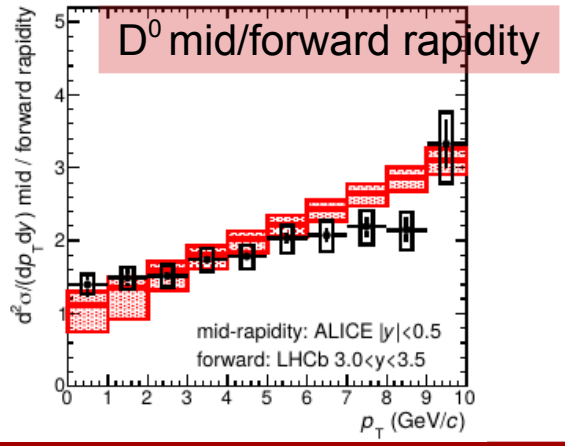
$$\mathrm{d}\sigma_{\mathrm{pp}\to\mathrm{HX}} = \mathrm{PDF}_{\mathrm{a}}(x_{\mathrm{a}},\mu_{\mathrm{f}}^2) \otimes \mathrm{PDF}_{\mathrm{b}}(x_{\mathrm{b}},\mu_{\mathrm{f}}^2) \otimes \mathrm{d}\sigma_{\mathrm{ab}\to\mathrm{Q}\overline{\mathrm{Q}}}(x_{\mathrm{a}},x_{\mathrm{b}},\mu_{\mathrm{f}}^2) \otimes \mathrm{D}_{\mathrm{Q}\to\mathrm{H}}(z_{\mathrm{Q}},\mu_{\mathrm{f}}^2)$$

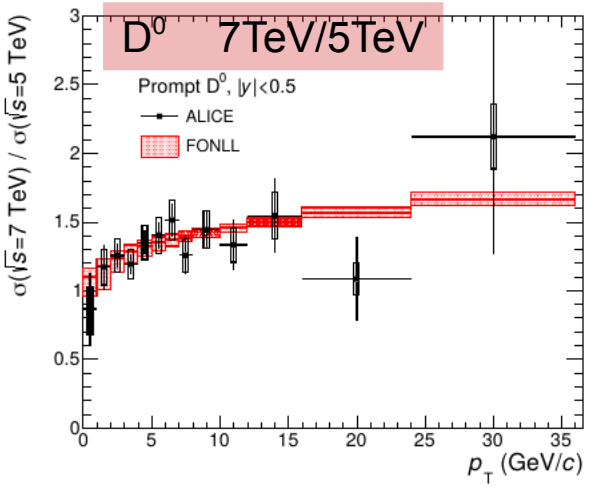
- Systematic uncertainties of pQCD calculations reduced in ratio, due to correlation of parameters used in calculations
  - Renormalisation and factorisation scales μ_F, μ_R, PDF partially cancel out
  - m_Q, Frag. Func., B.R. fully correlated

Comparison: data and theory
→ Consistent trend as a function of p_T at same y
→ Hint of different slopes for ratios for mid- to forward rapidity



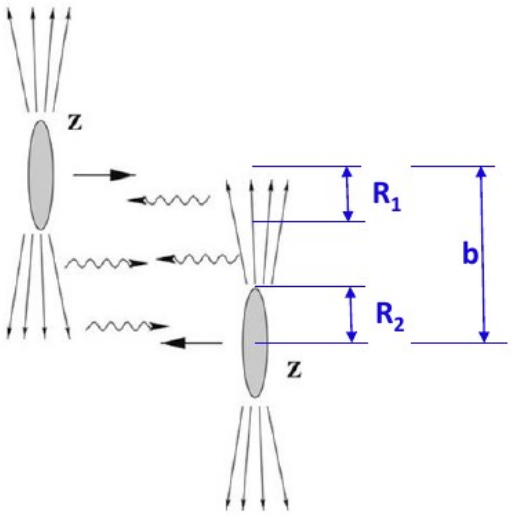


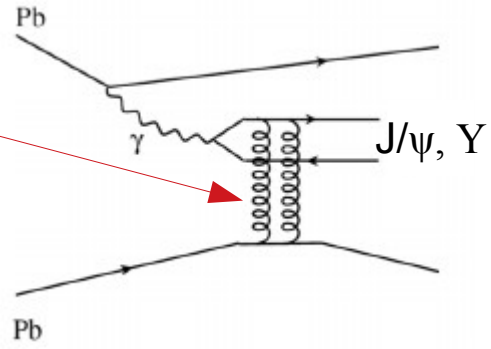




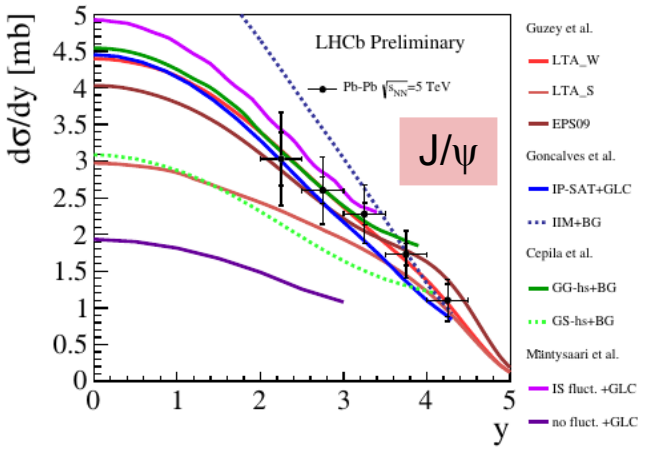
Pb-Pb UPC: LHC as a γPb collider

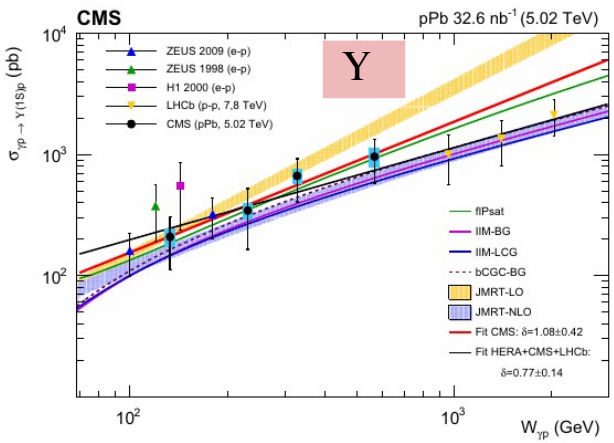
- Ultra-peripheral (UPC) collisions: $b > R_1 + R_2$
  - Hadronic interactions strongly suppressed
  - Akin to exclusive vector meson production in electron–proton collisions, at HERA
- High photon flux
  - Well described in Weizsäcker-Williams approximation (quasi-real photons)
  - flux proportional to Z^2
  - large cross section for γ-induced reactions
- Coherent J/ψ or Υ photoproduction cross section proportional to the square of the gluon density in the target
- Mass of quarkonium serves as hard scale
- Bjorken-x (10^{-2}-10^{-5})
- Quarkonium photoproduction in Pb-Pb UPC gives info on gluon shadowing in nuclei at low x



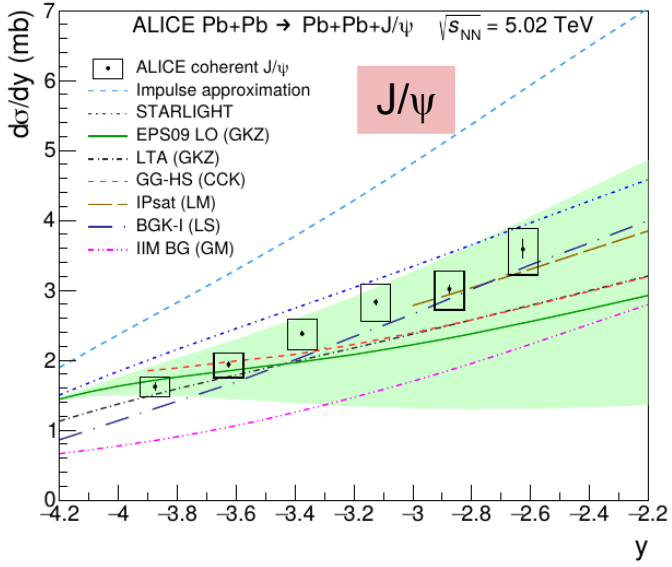


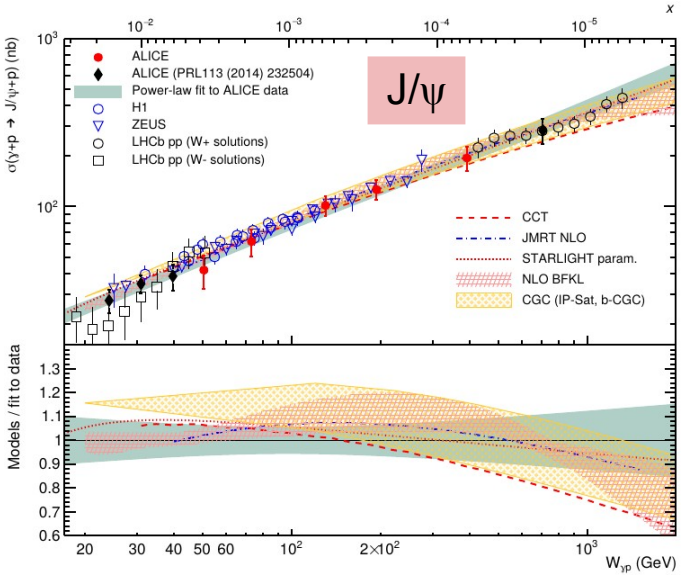
J/ψ and Υ photoproduction in Pb-Pb and p-Pb collisions





ALICE Collaboration, arXiv: 1903.06272, Eur.Phys.J. C79 (2019) 402
LHCb Collaboration, Nucl.Phys.A982(2019)247
CMS Collaboration, EPJC79(2019)277

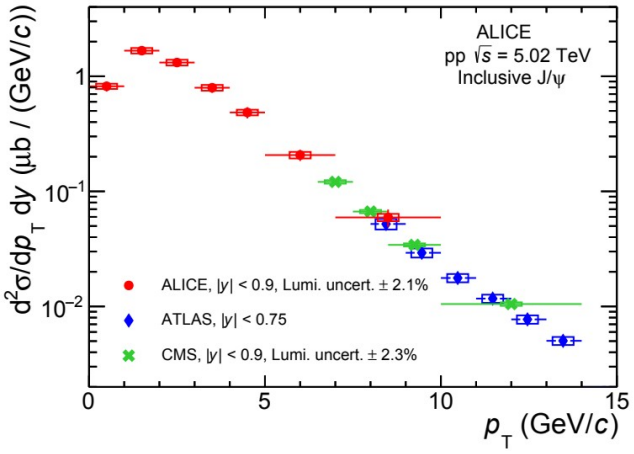


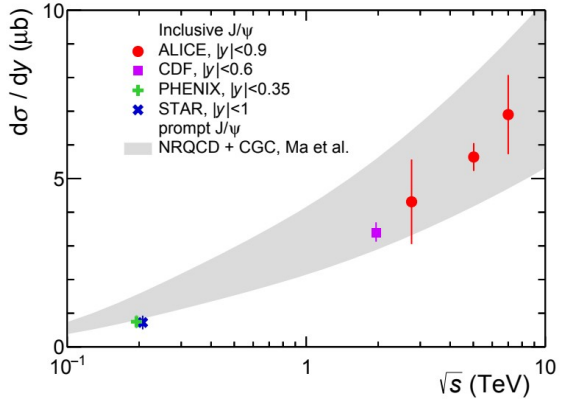


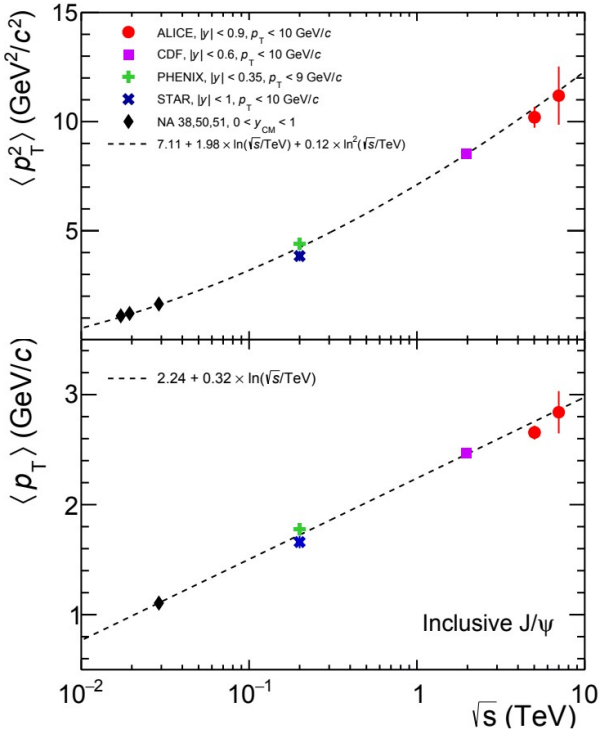
→ Models with moderate nuclear gluon shadowing in agreement with data
→ Constrain the gluon distributions at low values of Bjorken-x in global PDF fits

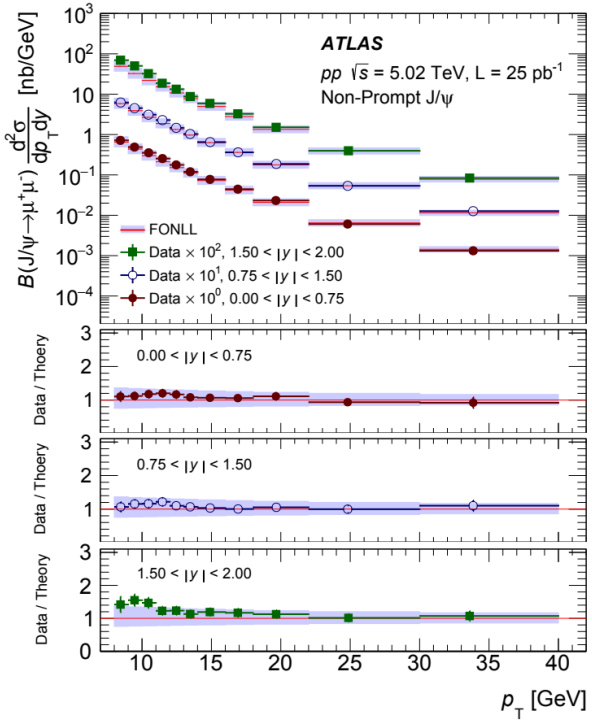
Quarkonium production

J/ψ in pp collisions at 5 TeV









ALICE Collaboration, arXiv: 1905.07211
ATLAS Collaboration, Eur.Phys.JC76(2016)1
Eur.Phys.JC78(2018)171
CMS Collaboration, Eur.Phys.JC77(2017)269

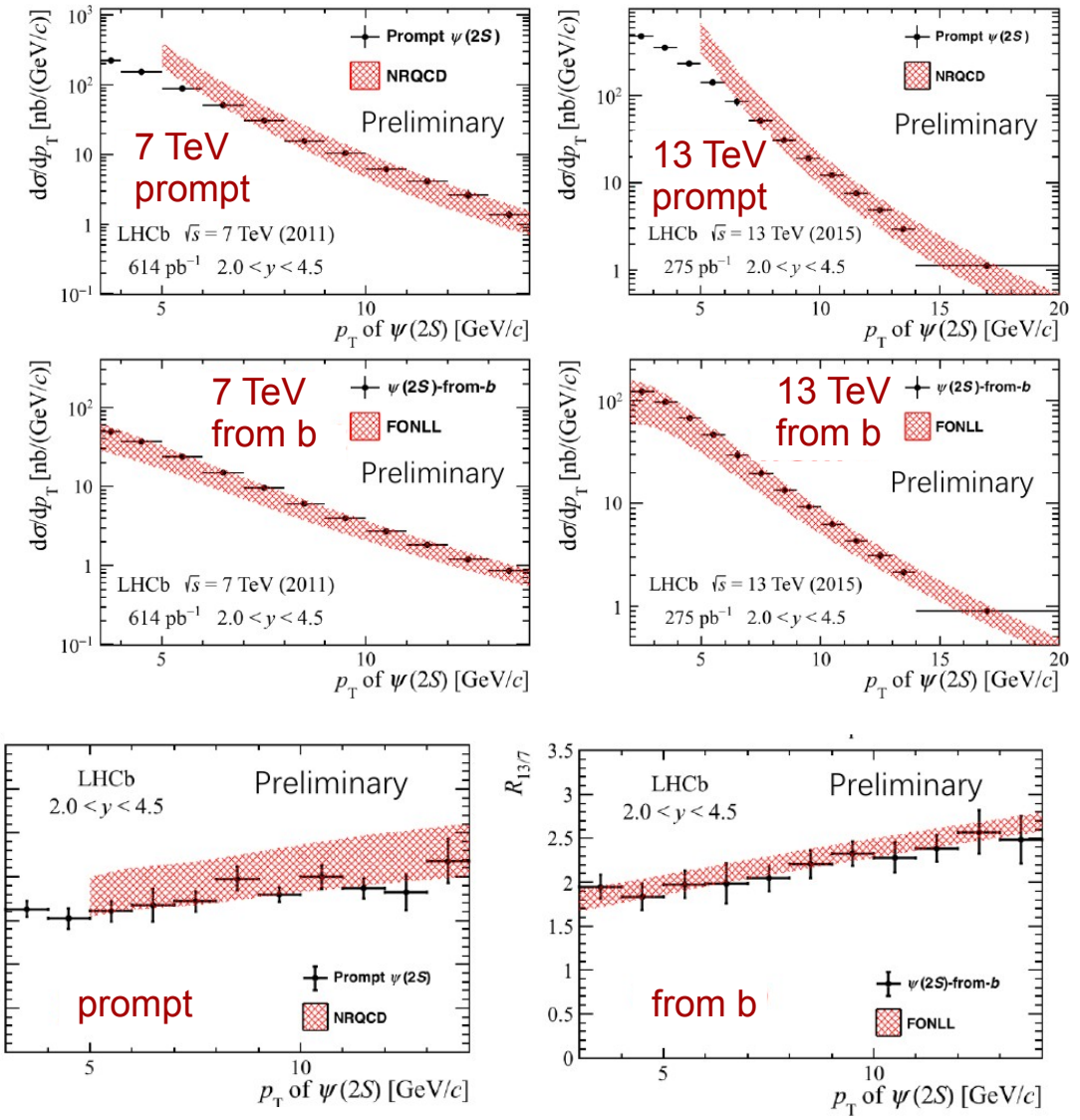
- Inclusive J/ψ production down to zero p_T
- Cross section approx. logarithmic increase in √s
- Large model uncertainties
- Steady increase of $\langle p_T \rangle$ and $\langle p_T^2 \rangle$ with energy
  - For fixed Bjorken-x p-exchange Q^2 grows with energy
  - Faster increase of $b\bar{b}$ compared to $c\bar{c}$ cross section

→ Hardening of J/ψ p_T spectrum

ψ(2S) in pp collisions at 7 and 13 TeV

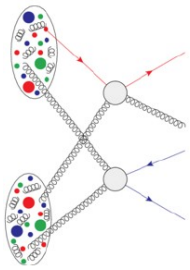
- ψ (2S) → $\mu^+\mu^-$ in pp collisions: 275 pb^{-1} at 13 TeV (2015) and 614 pb^{-1} at 7 TeV (2011)
- Comparison w models
  - Prompt result vs NRQCD
  - Non-prompt vs FONLL
  - Good agreement for high-p_T
  - Ratios more precise test of theories (most uncertainties cancel out)

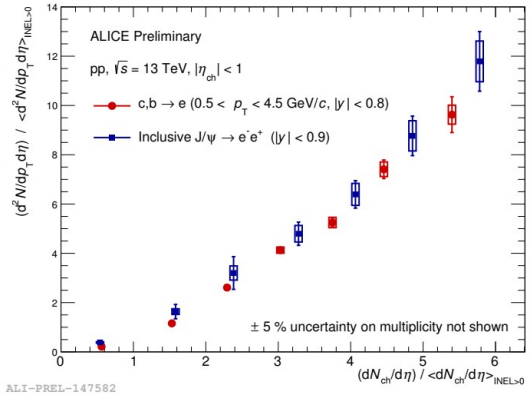
LHCb Collaboration, LHCb-PAPER-2018-049 in preparation

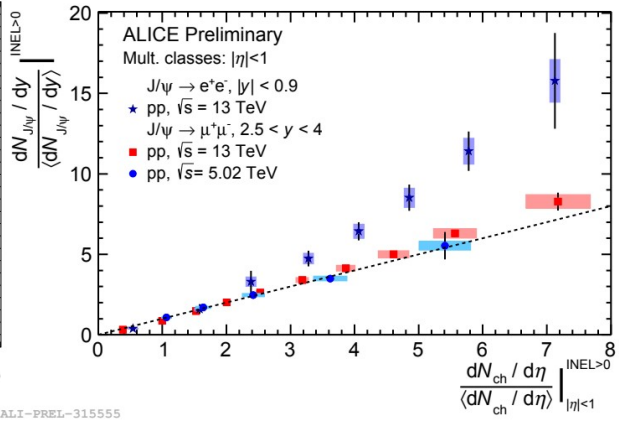


NRQCD: H.-S. Shao et al, JHEP 05 (2015) 103
FONLL: M. Cacciari et al, EPJC75 (2015) 610

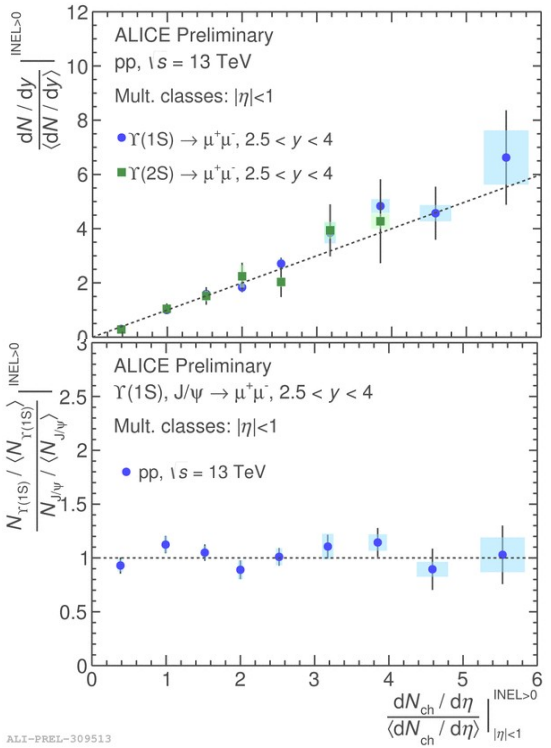
Quarkonium production vs. charged-particle multiplicity



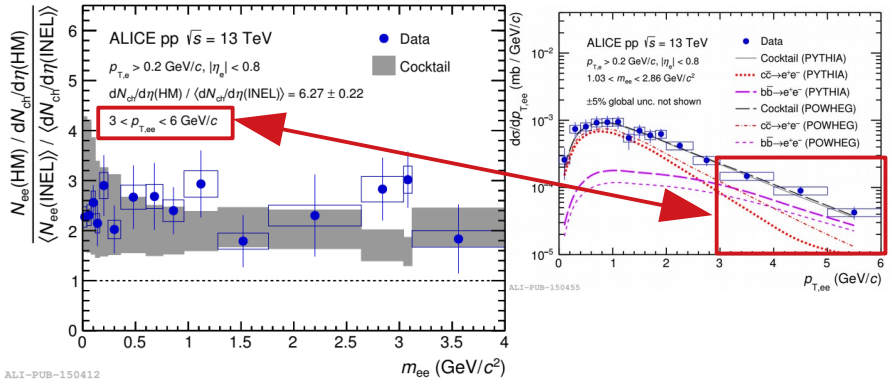




ALICE Collaboration, PLB788(2019)505



- Study: Interplay between soft and hard processes; role of multiple parton interactions (MPIs)
- Results show
  - Behaviour most likely related to $c\bar{c}$ and $b\bar{b}$ production processes
  - Not significantly influenced by hadronisation
  - No strong energy dependence
  - Strong rapidity dependence → auto-correlations



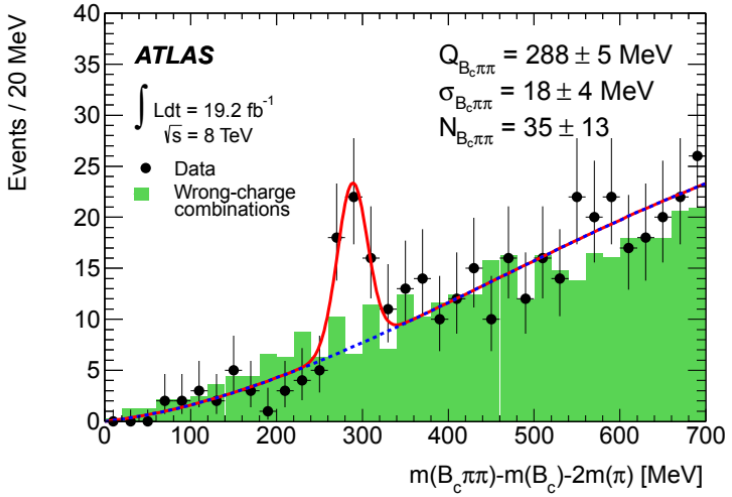
Spectroscopy

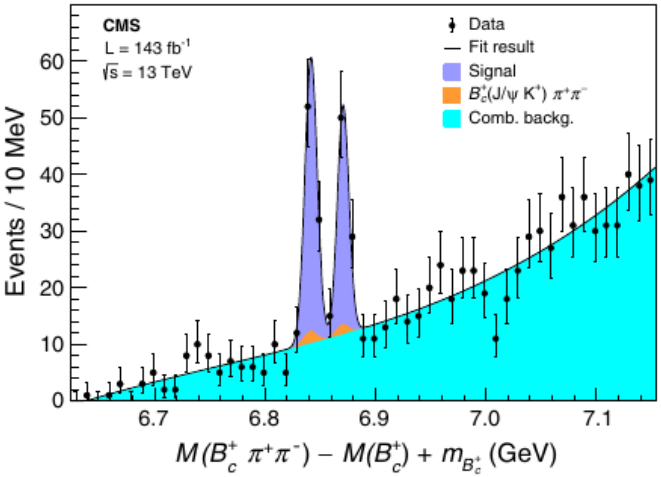
Observations of excited B_c^+ states

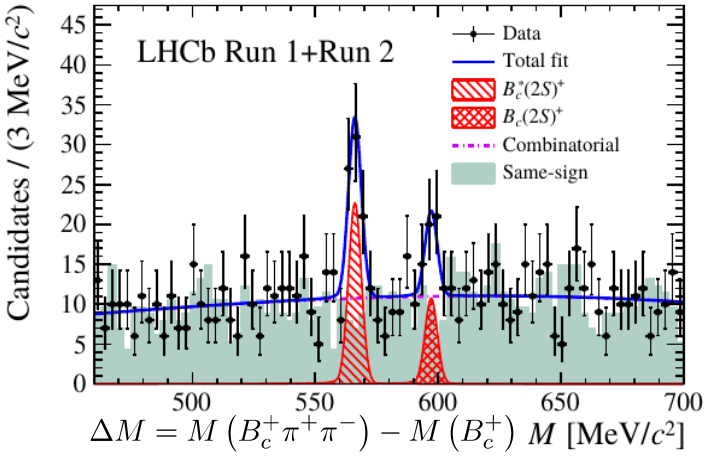
- ATLAS
  - Observed a state consistent with both $B_c^+(2S)$ and $B_c^{*+}(2S)$ in 24 fb^{-1} of pp collisions at $\sqrt{s}$ = 7 and 8TeV
- CMS:
  - Run 2: in 143 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV
  - B_c^+ candidates from $J/\psi(\rightarrow\mu^+\mu^-)\pi^+$ combinations
  - $B_c^+(2S)$ and $B_c^{*+}(2S)$ observed (combined significance of 6.5 standard deviations)
- LHCb
  - Run 1 and 2: in 8.5 fb^{-1} of pp collisions at $\sqrt{s}$ = 7, 8, 13 TeV

→ $B_c^+(2S)$ and $B_c^{*+}(2S)$ for the first time separatly observed

ATLAS Collaboration, PRL113(2014)212004
CMS Collaboration, PRL122(2019)132001
LHCb Collaboration, arXiv: 1904.00081







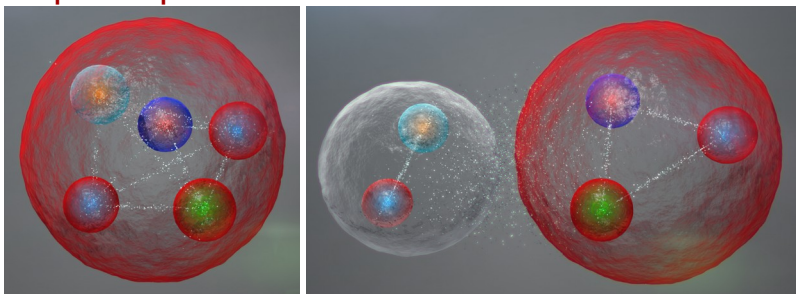
Pentaquarks in $\Lambda_b^0 \rightarrow J/\psi p K^-$

- Latest LHCb results on pentaquark searches
- Run 1 + Run 2 data (integrated luminosity 9 fb^{-1}), better data selection, increase in production cross section (13 TeV instead of 7 and 8 TeV)
- 9 times larger data sample
  → improved resolution on mass spectra
- Masses of narrow peaks just below $\Sigma^+_c \overline{D}^{(*)0}$ masses

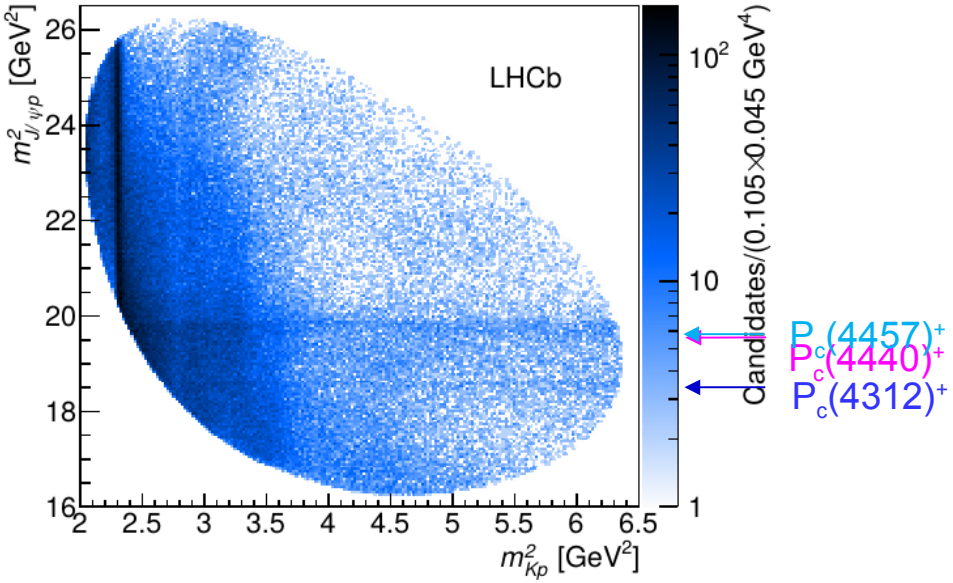
LHCb Collaboration, arXiv: 1904.03947

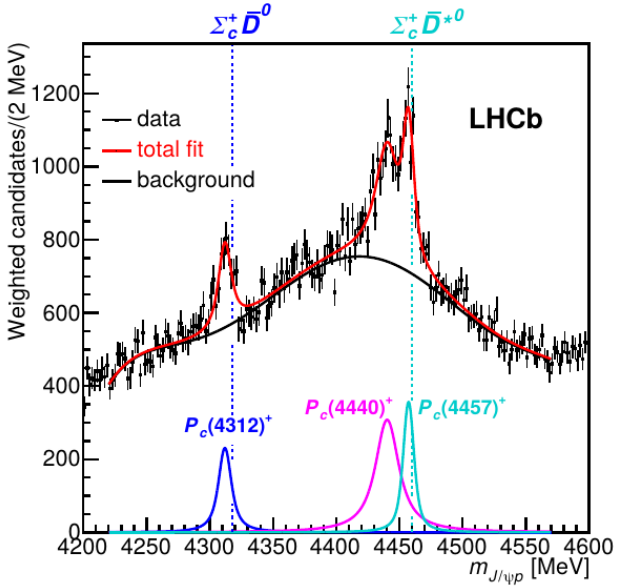
Tightly-bound pentaquark

Loosely-bound pentaquark



- Although compact pentaquark model not ruled out, these features favour the molecular interpretation → measure quantum numbers and find isospin partners for definitive answer

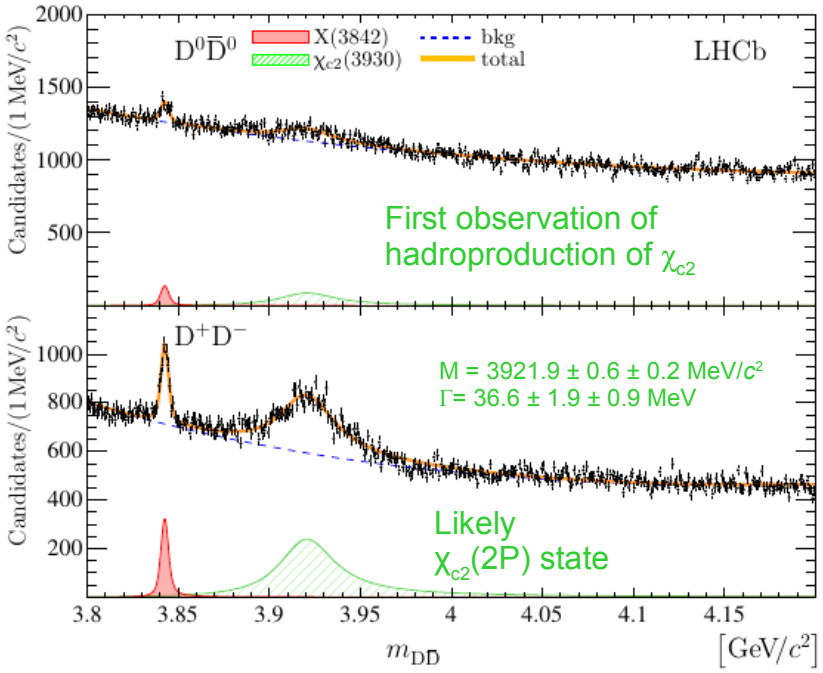


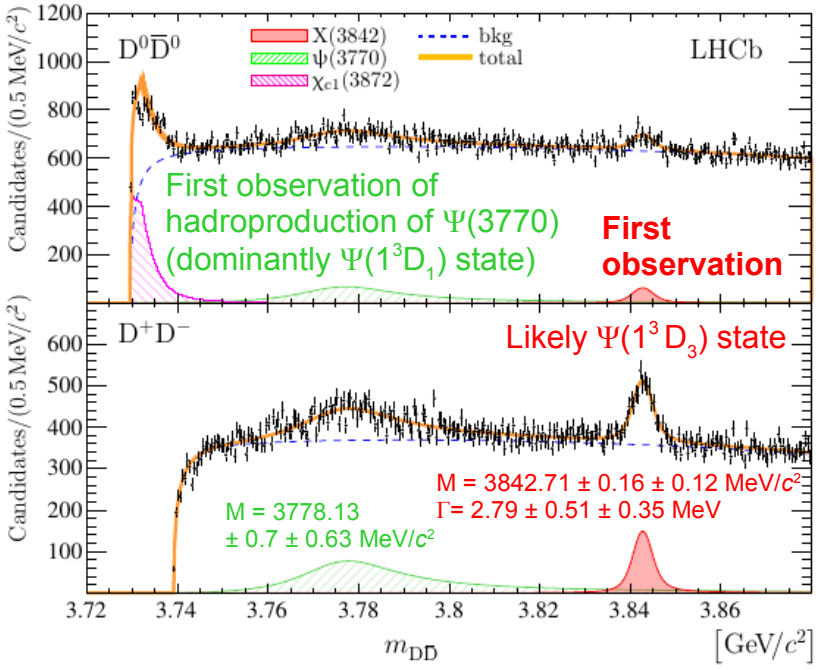


Near-threshold $D\bar{D}$ spectroscopy

LHCb Collaboration, arXiv: 1903.12240

- Charmonium spectroscopy
- Run 1 + Run 2 data (integrated luminosity 9 fb^{-1})
- Promptly produced $D\bar{D}$ candidates selected
- Fit performed in 3 overlapping mass regions to better parameterise the background





Summary

- Wealth of beautiful experimental results due to large data samples and improved analysis techniques
  - Heavy-flavour production, properties and spectroscopy

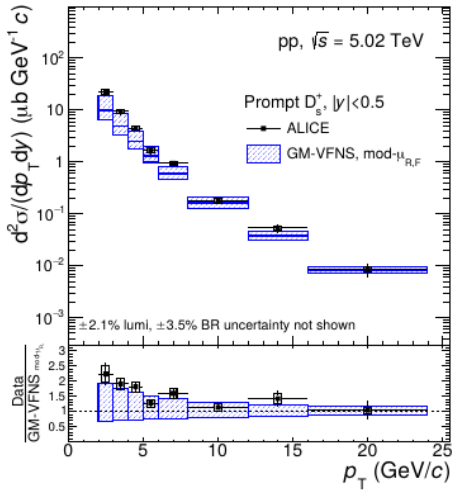
    → Precision measurements
    → First observations

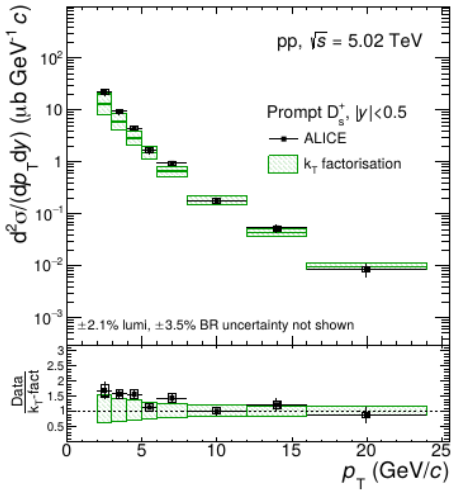
- Experimental results provide important contraints for theoretical models
  - Theoretical calculations with smaller uncertainties needed

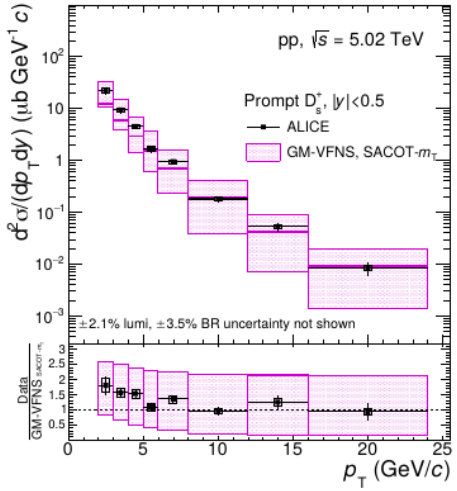
- Stay tuned for many more new results from Run 1 and Run 2

Back-Up

D_s^+-meson production in pp collisions at 5 TeV

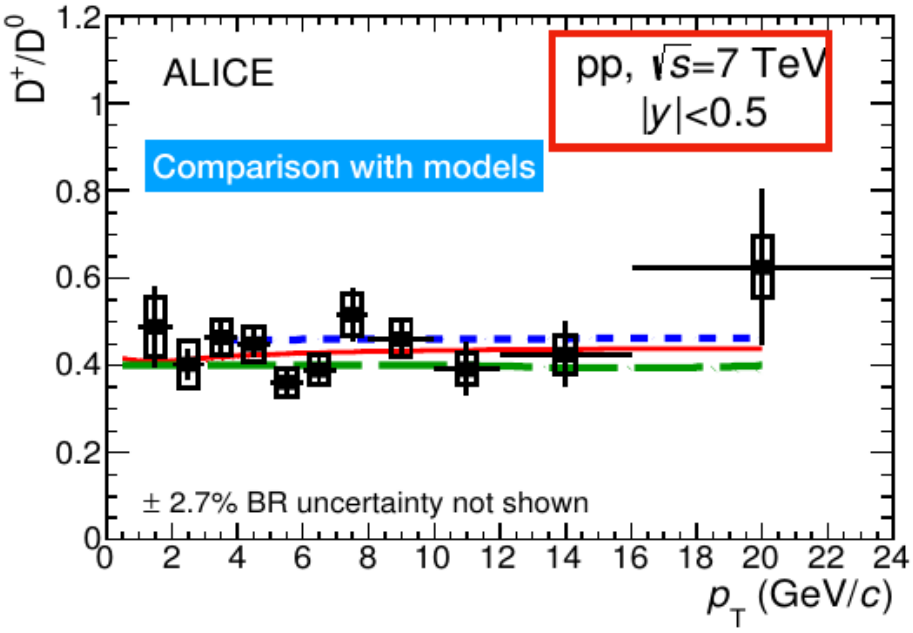


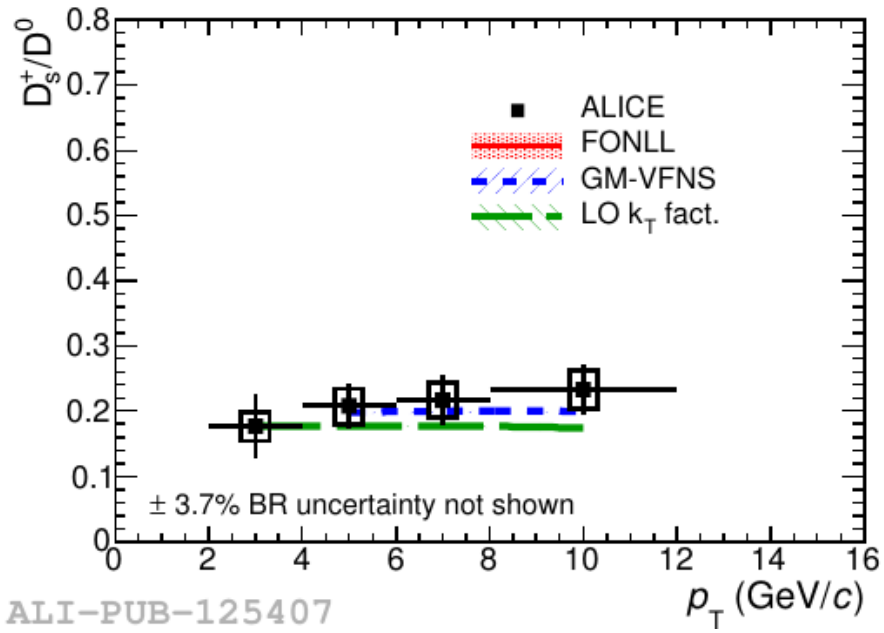




D-meson ratios w model comparisons: pp 7 TeV

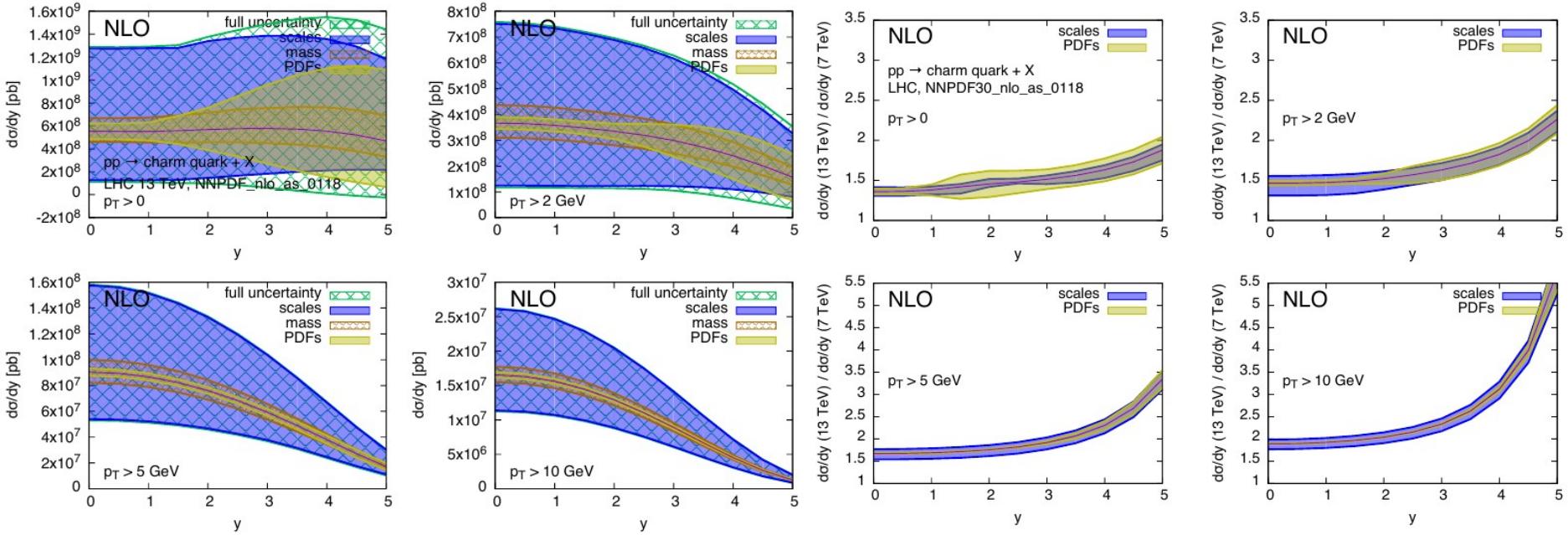
ALICE Collaboration, Eur.Phys.J. C77 (2017) 550





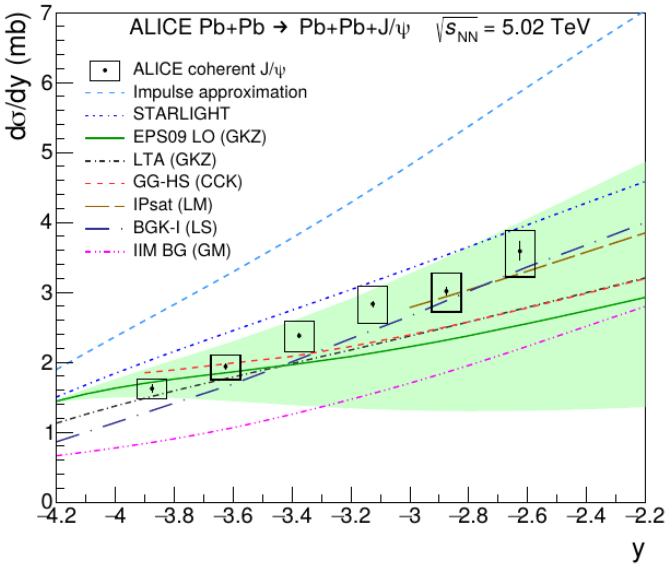
Gluon PDF constraints due to ratios

M. Cacciari, arXiv:1507.06197.pdf



Pb-Pb UPC: LHC as a γPb collider (II)

ALICE Collaboration, arXiv: 1903.06272,



- Impulse approximation: no nuclear effects
- STARLIGHT: VDM + Glauber
  Klein, Nystrand et al.,Comput. Phys. Commun. 212(2017)258
- EPS09 L0 (GKZ): EPS09 shadowing
  Guzey, Kryshen, Zhalov, PRC93(2016)055206
- LTA (GKZ): Leading Twist Approximation
  Guzey, Kryshen, Zhalov, PRC93 (2016) 055206
- GM: Colordipole model + IIM CGC
  Goncalves, Machado et al.:
  PRC90(2014)015203, JPG 42(2015)105001
- LM IPSat: Color dipole model + IPSat CGC
  T. Lappi, H. Mäntysaari, PRC83(2011)065202; 87(2013)032201
- CCK: hot-spot model + Glauber-Gribov
  Cepila, Contreras, Krelina, PRC97(2018)024901
- LS: Color dipole model + BGK-I CGC
  Luszczak, Schafer: arXiv:1901.07989