QCD and hadronic final state (heavy quarks and flavours) from LHC and RHIC

Charlotte Van Hulse, on behalf of ALICE, ATLAS, CMS, LHCb
IJCLab, Paris-Saclay University

EIC Center at Jefferson Lab

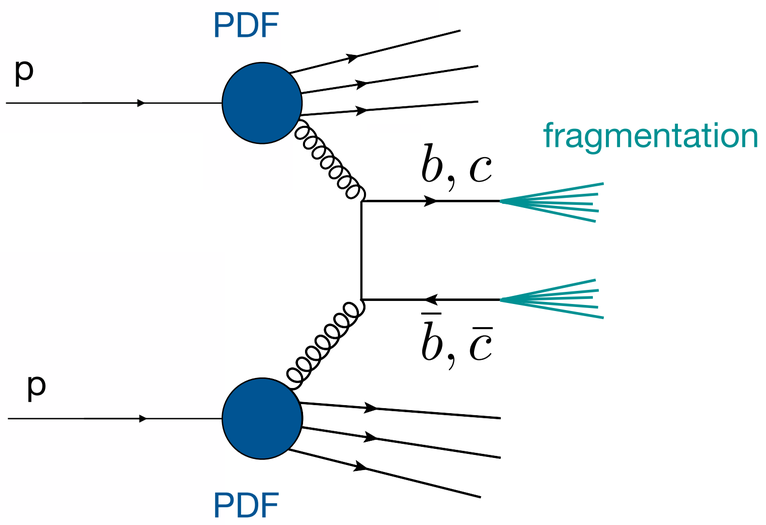
DIS 2021
12-16 April, 2021
Virtual@Stony Brook University

Overview

- Open-flavour production
- Inclusive quarkonium production
- Exclusive quarkonium production in ultra-peripheral collisions
- Spectroscopy

Open-flavour production

Charm and beauty production



large mass:

→ provides hard scale: (test) perturbative QCD

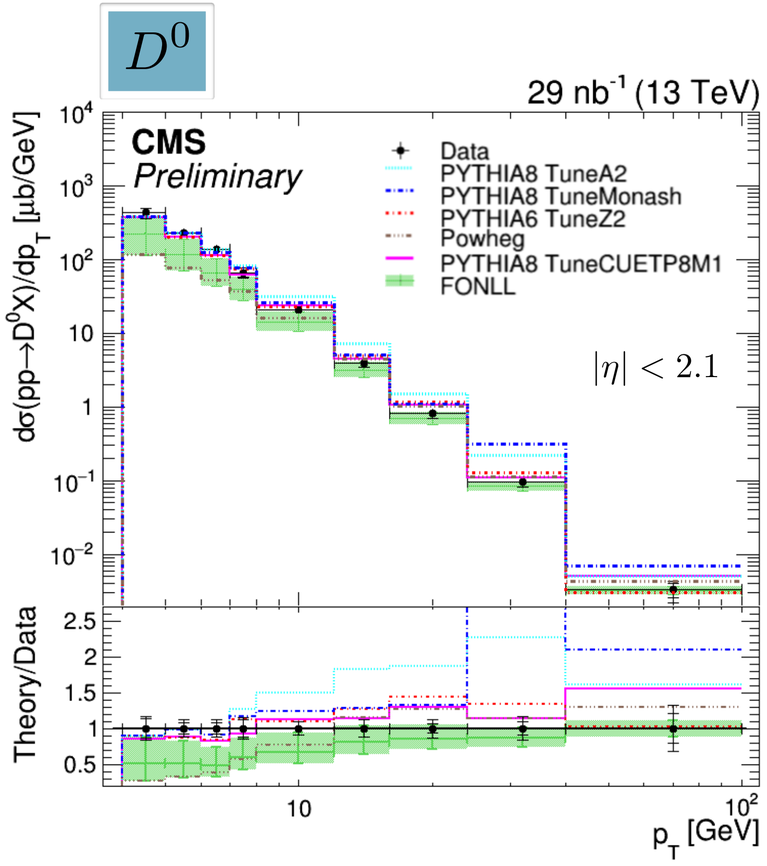
→ probe nucleon/nucleus

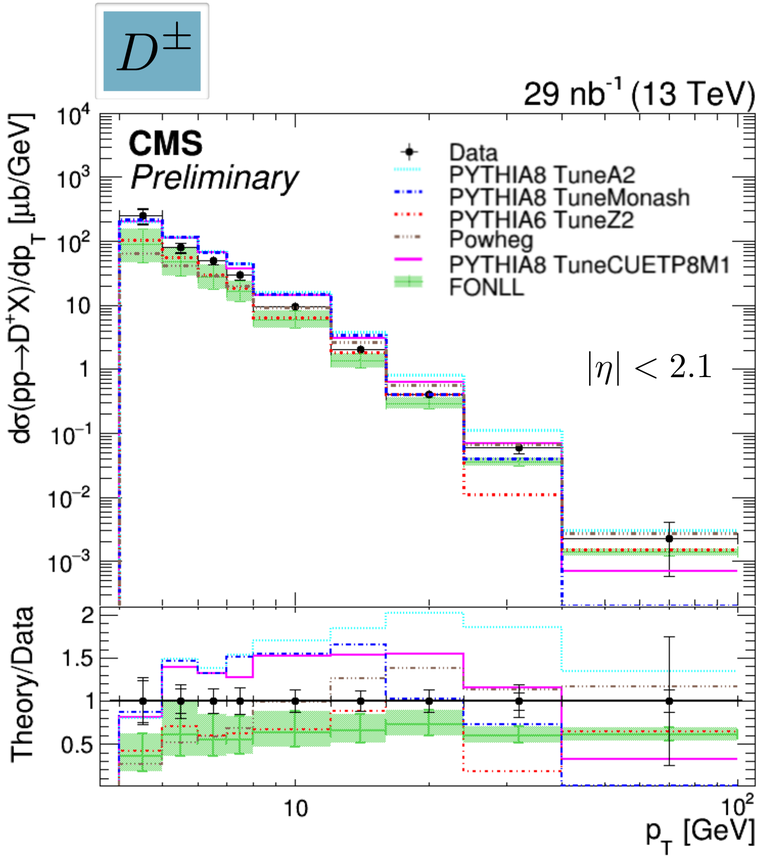
→ created at beginning of interaction

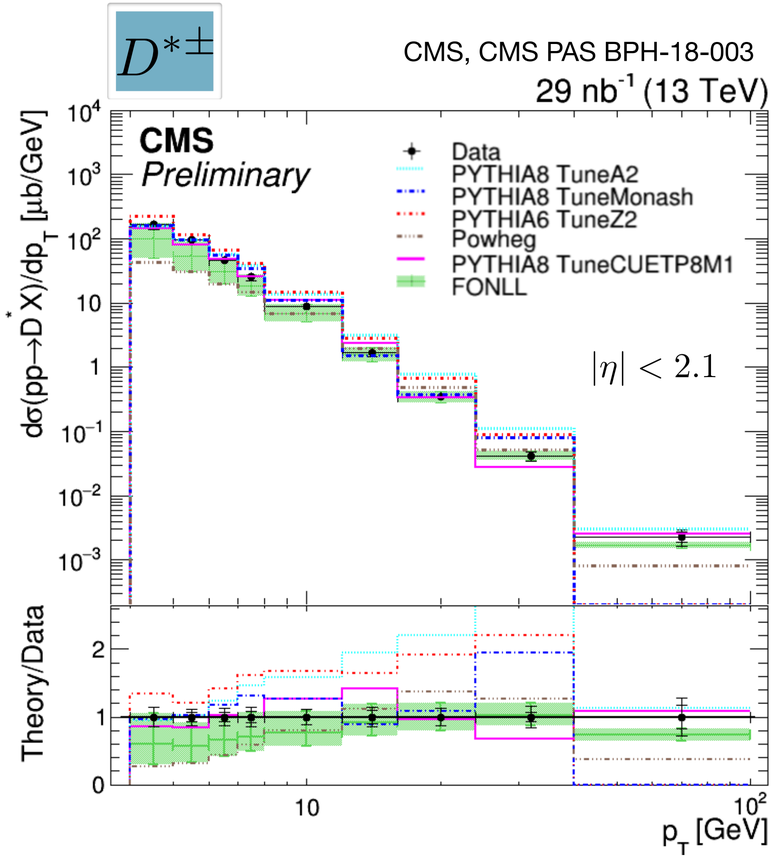
→ investigate parton interaction with medium

D meson production

Prompt D*±, D±, D0 production in pp at $\sqrt{s}$ = 13 TeV



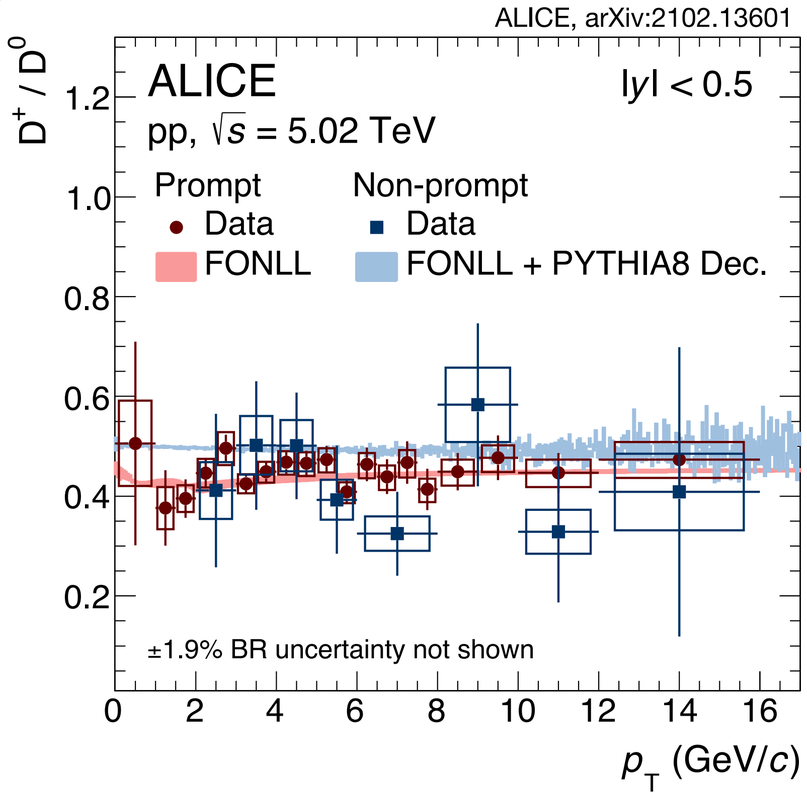




overall, fair agreement data and Monte Carlo, but no full description of kinematic dependence

Fragmentation of c quarks

D^+/D^0



- Updated (EPJC79(2019)388) and new measurement
- Ratio is constant with p_T

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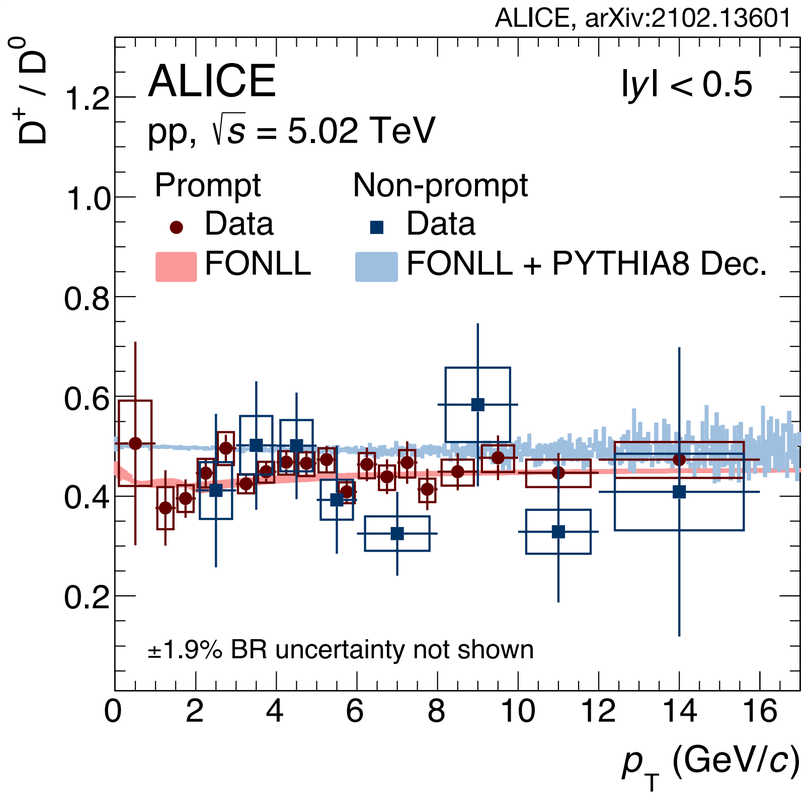

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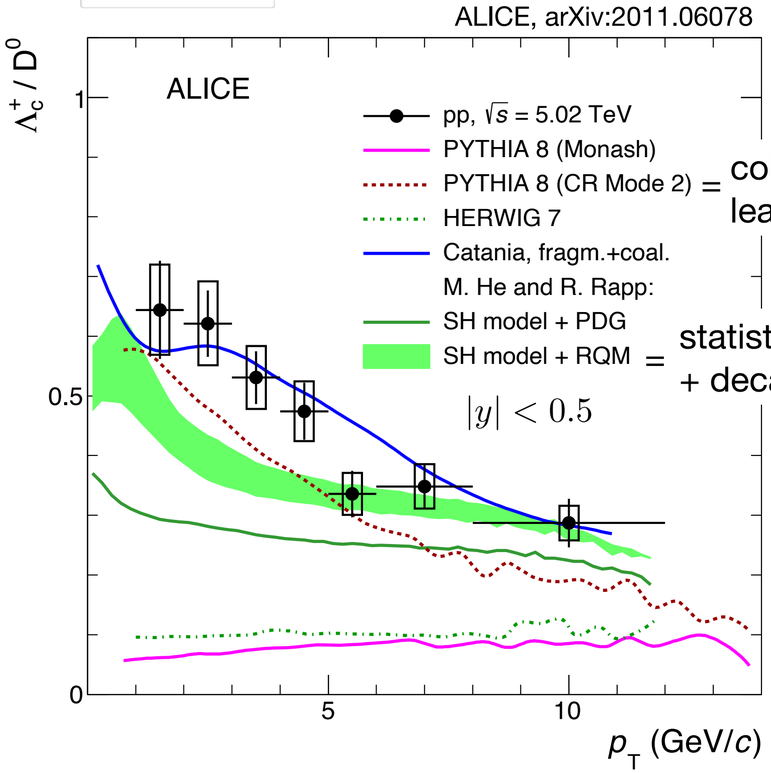
Λ_c^+/D^0



PYTHIA 8 (CR Mode 2) = colour reconnection beyond the leading-colour approximation

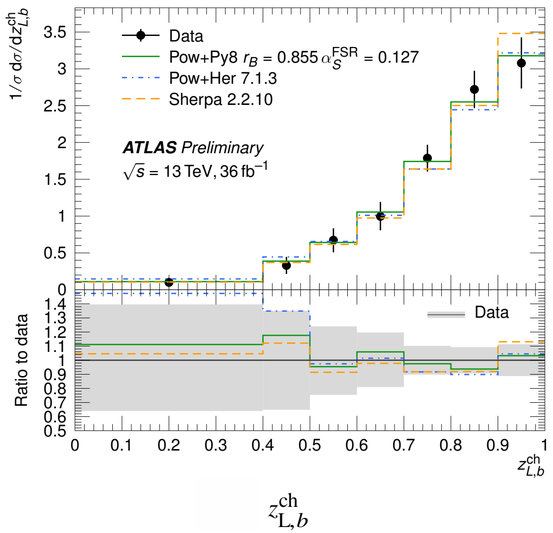
SH model + RQM = statistical hadronisation model + decaying excited states

- Improved precision wrt. $\sqrt{s}$ =7 TeV measurement (JHEP04(2018)108)
- Decrease with p_T

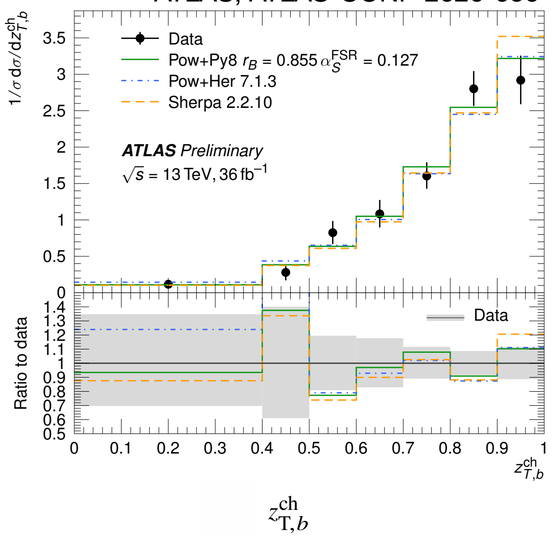
  → suggests difference for meson and baryon fragmentation
- Larger than for e^+e^- and ep measurements

  → suggests non-universality

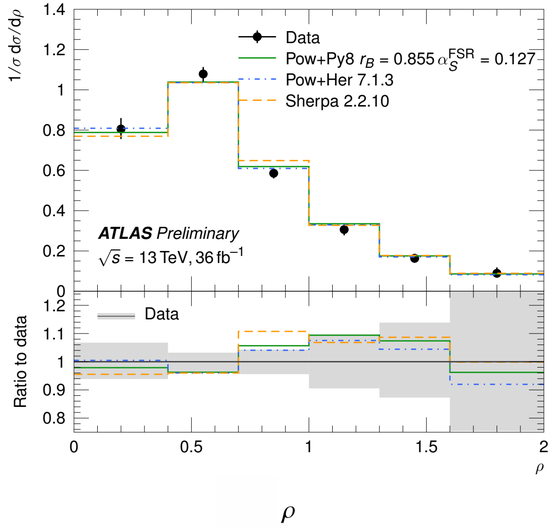
Fragmentation of b quarks



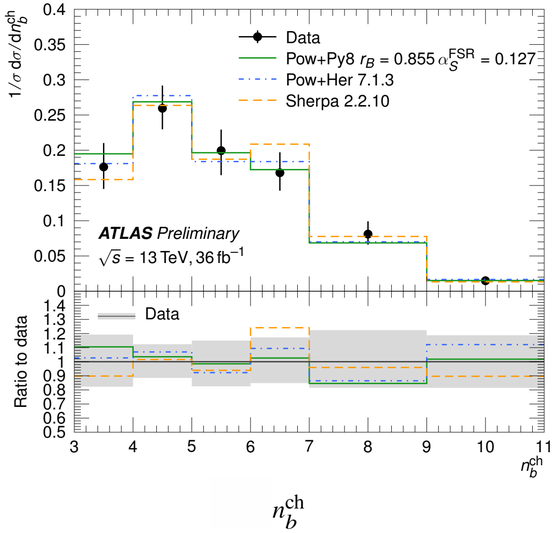
$z^{\mathrm{ch}}_{\mathrm{L},b}$



$z^{\mathrm{ch}}_{\mathrm{T},b}$



ρ



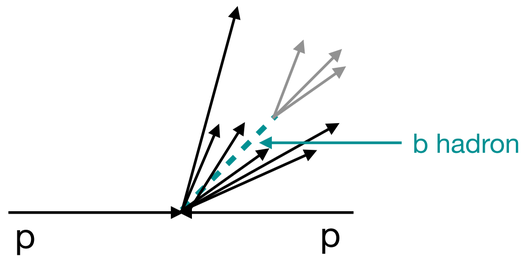
n_b^{ch}

overall good agreement between data and Monte Carlo

- b hadrons in jets from $t\bar{t}$ event sample
- Complement data from e^+e^- annihilation
- Probe effect of QCD ISR, multiple partonic interactions on fragmentation in more complex environment of hadron colliders
- Comparison of charged momentum of b hadron to
  - charged jet components

$$z^{\mathrm{ch}}_{T,b} = \frac{p^{\mathrm{ch}}_{T,b}}{p^{\mathrm{ch}}_{T,\mathrm{jet}}}$$

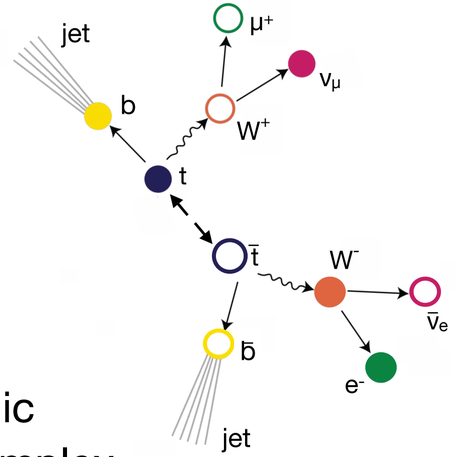
$$z^{\mathrm{ch}}_{L,b} = \frac{\vec{p}^{\,\mathrm{ch}}_{b} \cdot \vec{p}^{\,\mathrm{ch}}_{\mathrm{jet}}}{|p^{\mathrm{ch}}_{\mathrm{jet}}|^2}$$



  - $t\bar{t} \to e\mu b\bar{b}$

$$\rho = \frac{2p^{\mathrm{ch}}_{T,b}}{p^{e}_{T} + p^{\mu}_{T}}$$

  - number of stable, charged decay products n_b^{ch}



Inclusive quarkonium production

Quarkonium production

- Production mechanism of quarkonia not understood
- Usual assumption: factorisation between $Q\overline{Q}$ formation and $Q\overline{Q}$ hadronisation
- Different approaches for hadronisation: colour-evaporation model, colour-singlet model, non-relativistic QCD (NRQCD)

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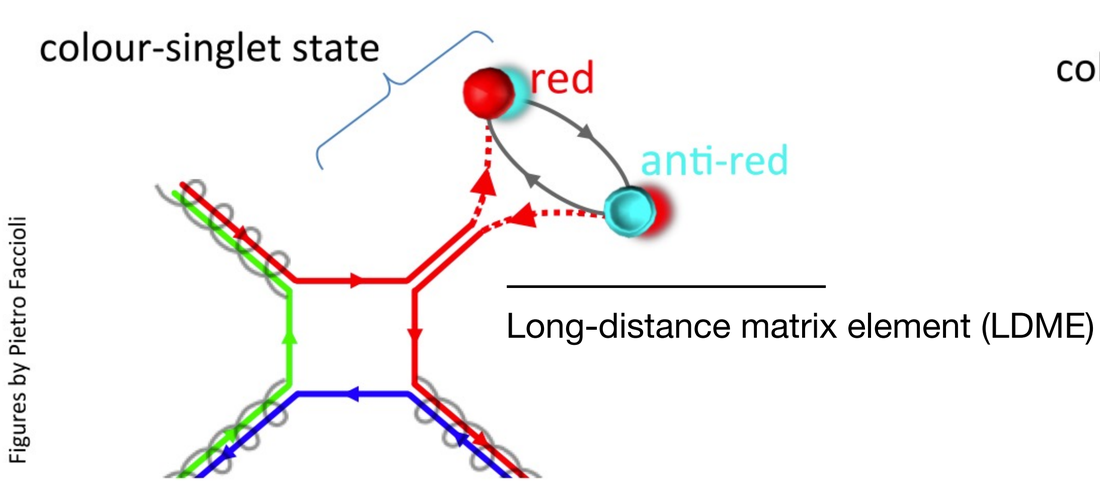

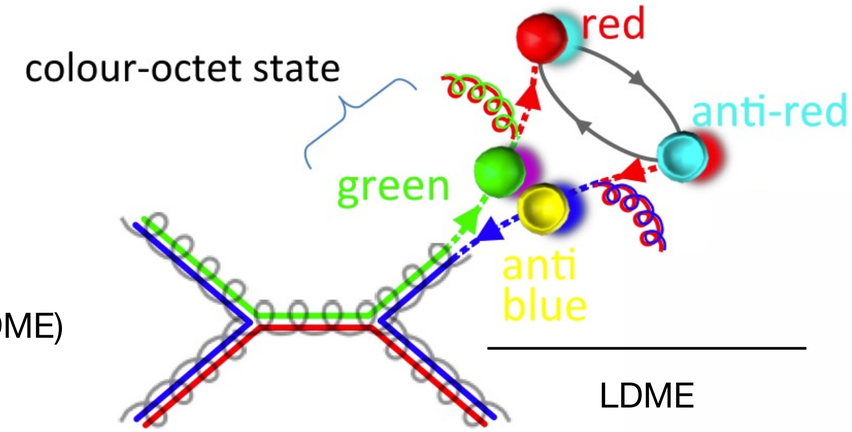

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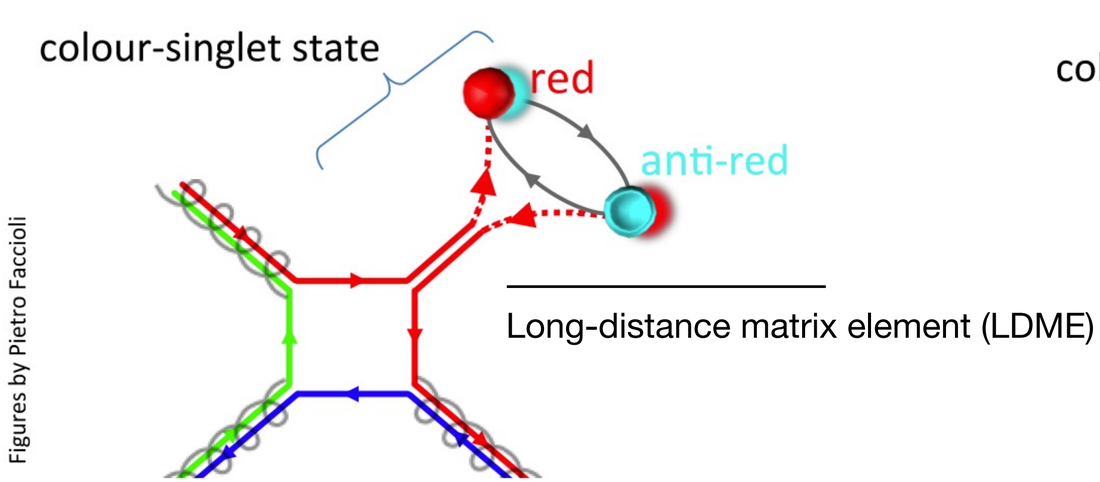

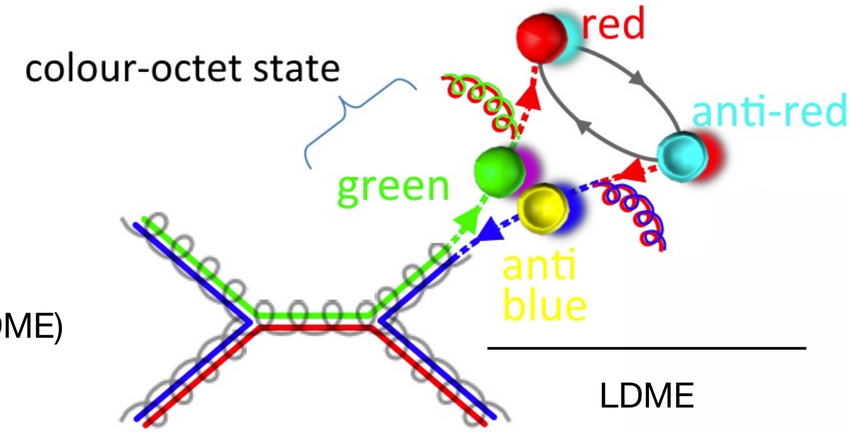

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NRQCD

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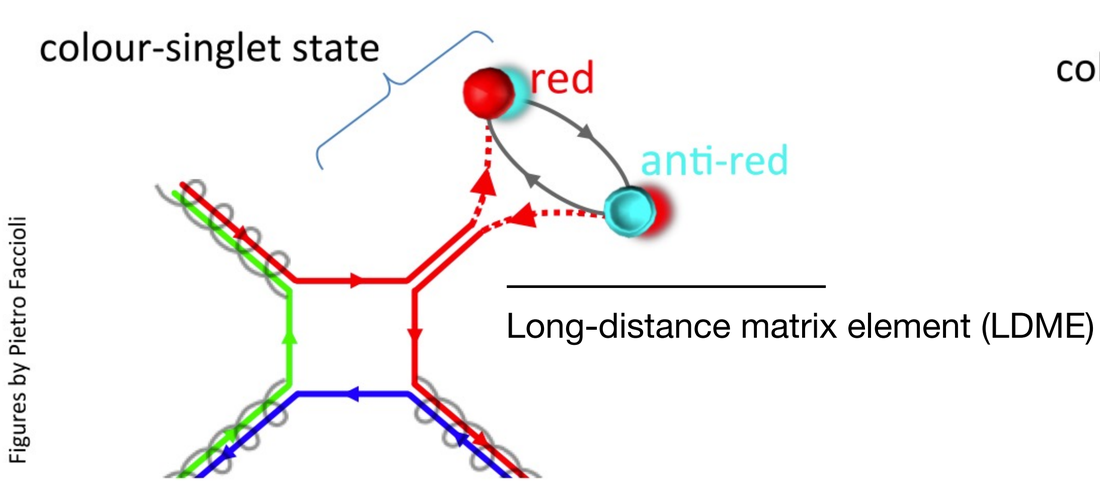

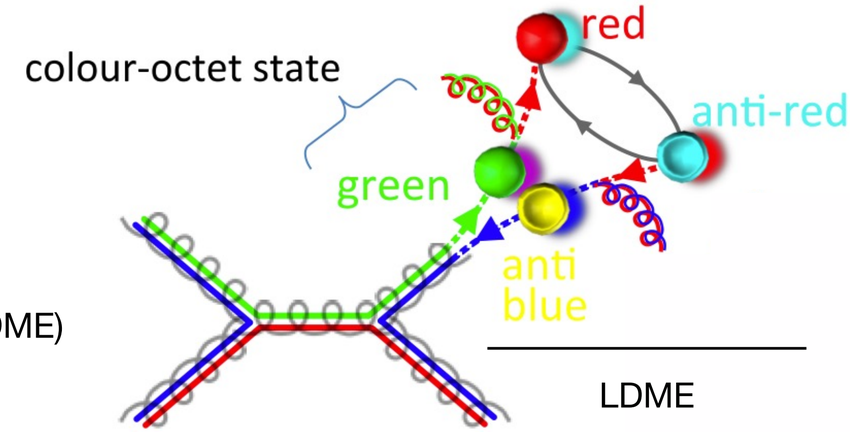

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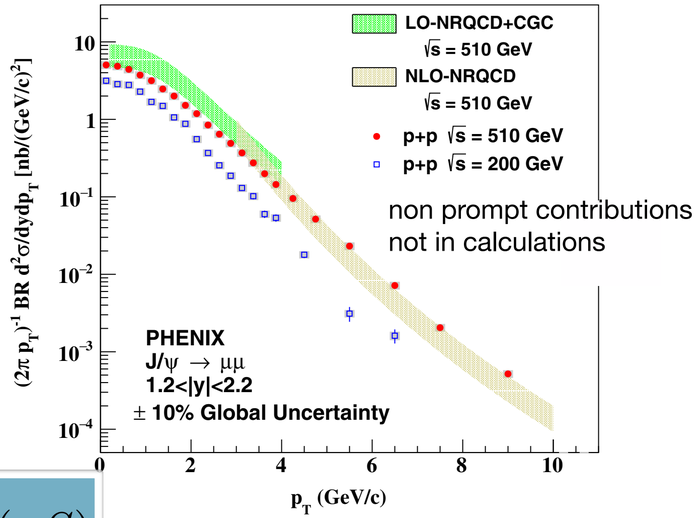
Measurements to probe quarkonium production:
- different COM energies
- large range in p_T and rapidity
- various types of quarkonium states
- polarisation

Quarkonium production in pp

J/ψ

1.2<|y|<2.2

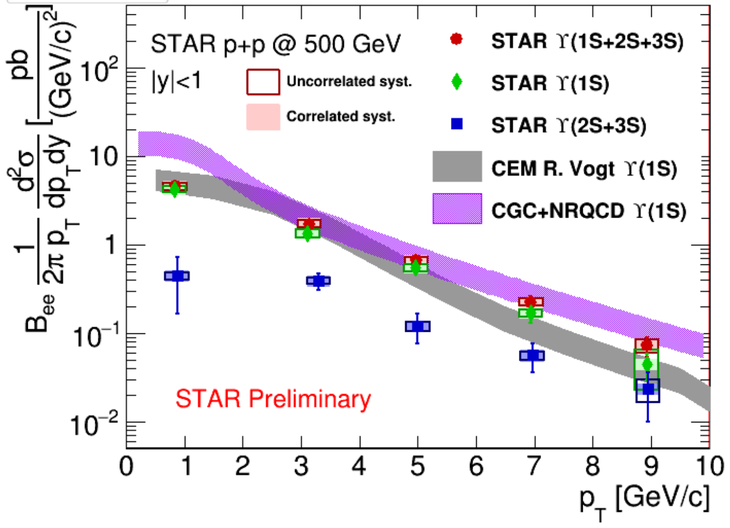
PHENIX, Phys. Rev. D **101** (2020) 052006



non prompt contributions not in calculations

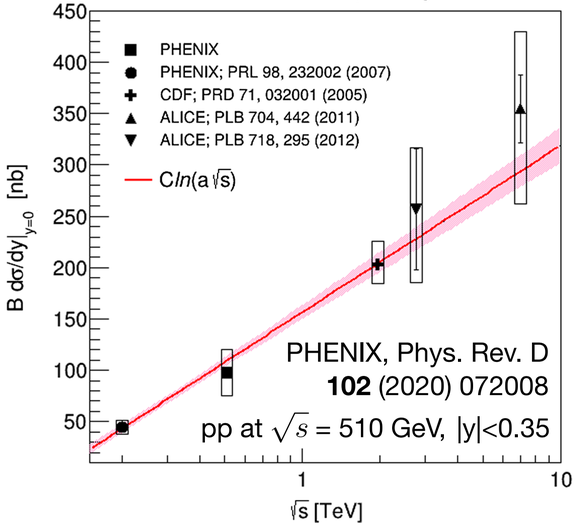
$\Upsilon(nS)$

STAR, pp at $\sqrt{s}$ = 500 GeV

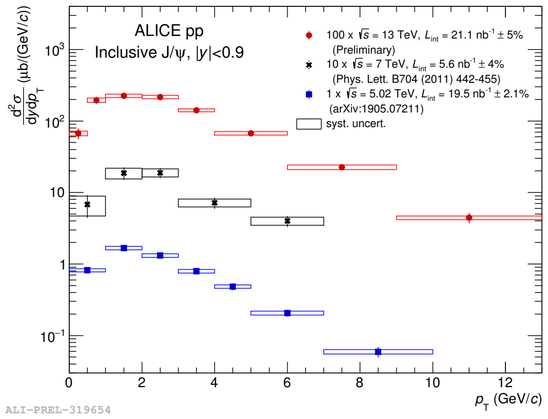


J/ψ

COM E dependence mid-rapidity



- ALICE, J/ψ in pp at $\sqrt{s}$ = 13 TeV



- ATLAS, J/ψ and ψ(2S) in pp at $\sqrt{s}$ = 13 TeV (ATLAS-CONF-2019-047)
- ATLAS, Υ in pp at $\sqrt{s}$ = 5 TeV (ATLAS, ATLAS-CONF-2019-054)

Quarkonium production in pp

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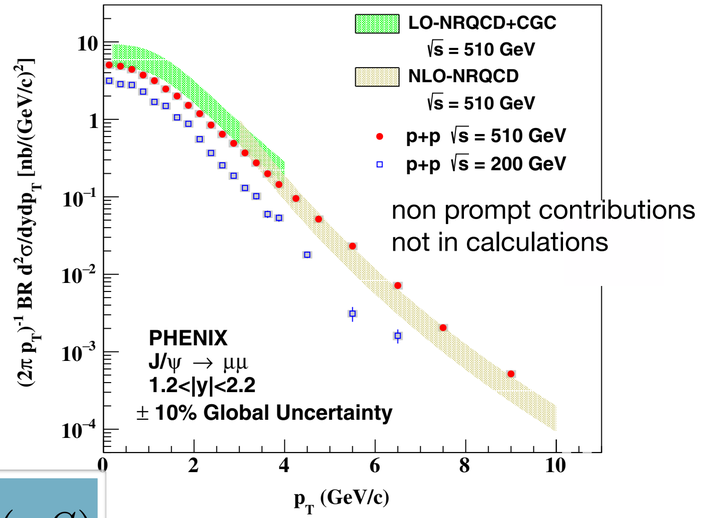
1.2<|y|<2.2

PHENIX, Phys. Rev. D **101** (2020) 052006



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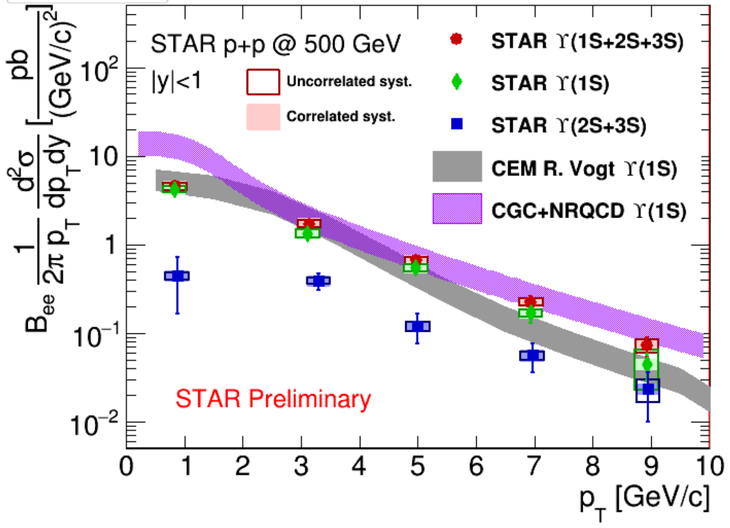

J/ψ

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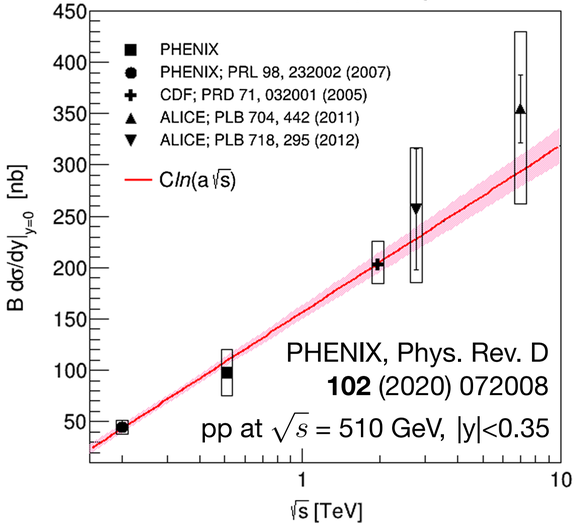

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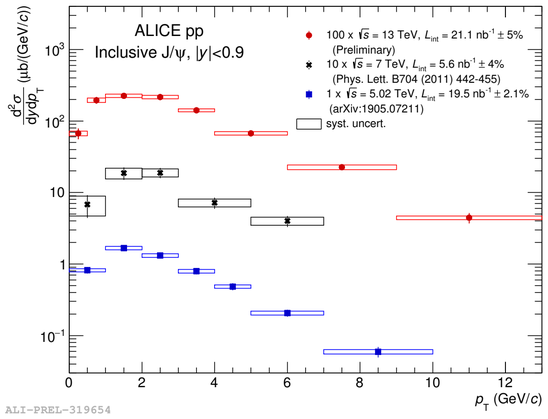

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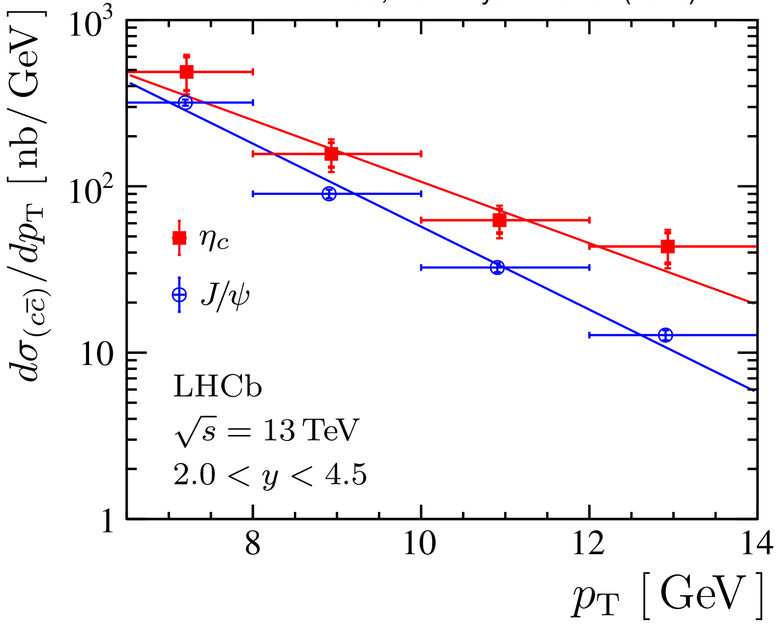
η_c

Prompt production

LHCb, Eur. Phys. J. C **80** (2020) 191



J/ψ : $J^{PC} = 1^{--}$ ground state

η_c : $J^{PC} = 0^{-+}$ ground state

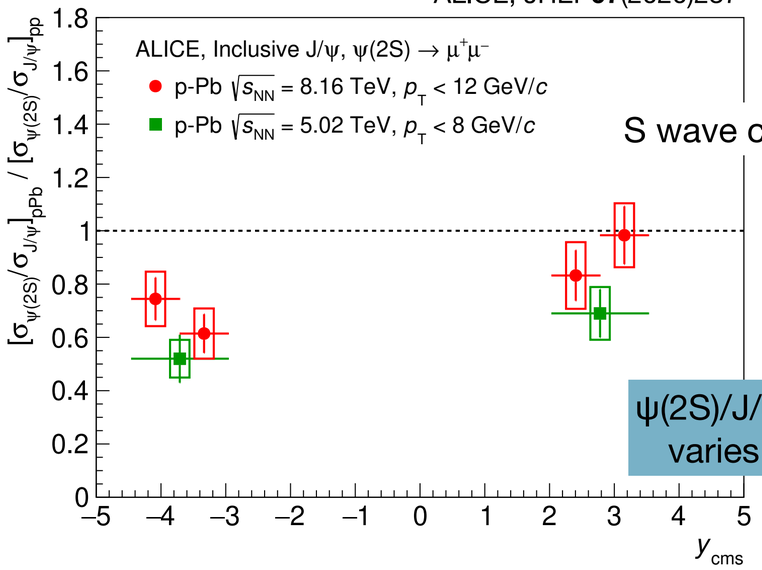
LDME(J/ψ) ⟷ (HQSS) LDME(η_c)

slope(J/ψ)<slope(η_c):
possible colour-octet contribution

Nuclear effects on quarkonium production

charmonium

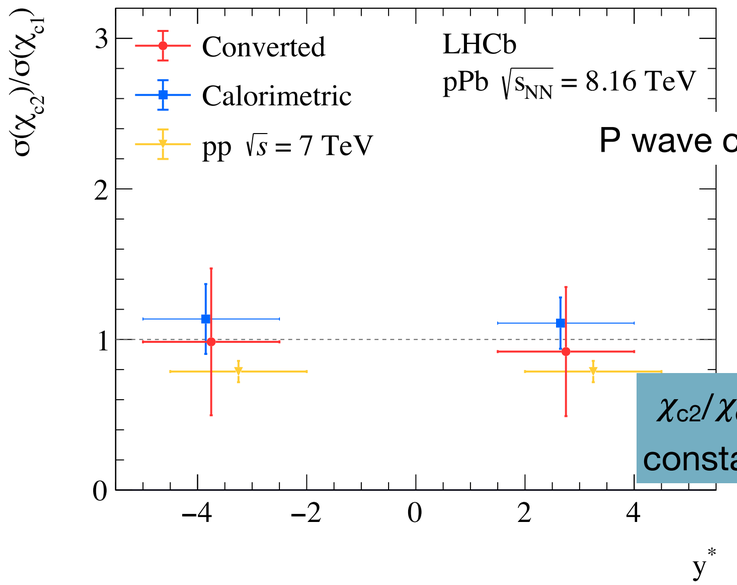
ALICE, JHEP**07**(2020)237



S wave charmonium

ψ(2S)/J/ψ pPb/pp ratio varies with rapidity

LHCb, arXiv:2103.07349

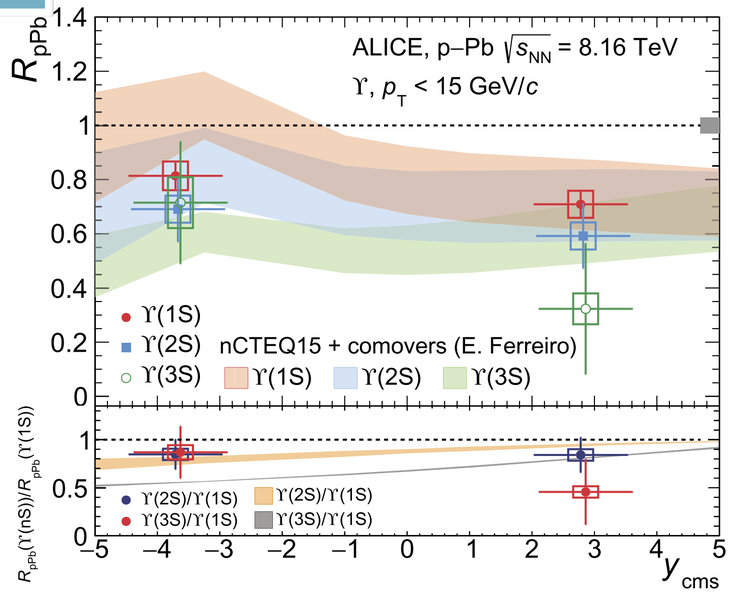


P wave charmonium

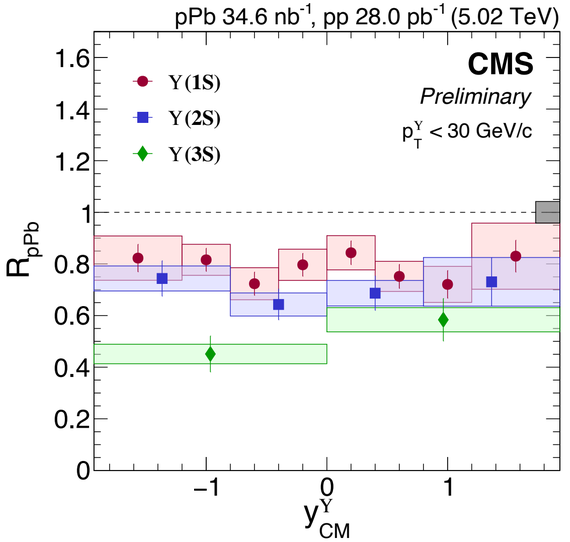
χ_{c2}/χ_{c1} pPb/pp ratio constant with rapidity

bottomonium

ALICE, Phys. Lett. B **806**(2020)135486



CMS, CMS PAS HIN-18-005



ϒ(2S)/ϒ(1S) pPb/pp ratio constant with rapidity

Polarisation

angular distribution of positive lepton:

$$\frac{d^2N}{d\cos\theta d\phi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\phi} \sin(2\theta)\cos\phi + \lambda_\phi \sin^2\theta \cos(2\phi)$$

frame independent variables(*)

$\tilde{\lambda}$ { 0: no net polarisation
-1: longitudinal polarisation
+1: transverse polarisation

$$\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi} \qquad F = \frac{1 + \lambda_\theta + 2\lambda_\phi}{3 + \lambda_\theta}$$

(*) EPJC **69** ('10) 657; PRD **83** ('11) 056008.
See also: arXiv:1703.04752; EPJ C **78** ('18) 5;
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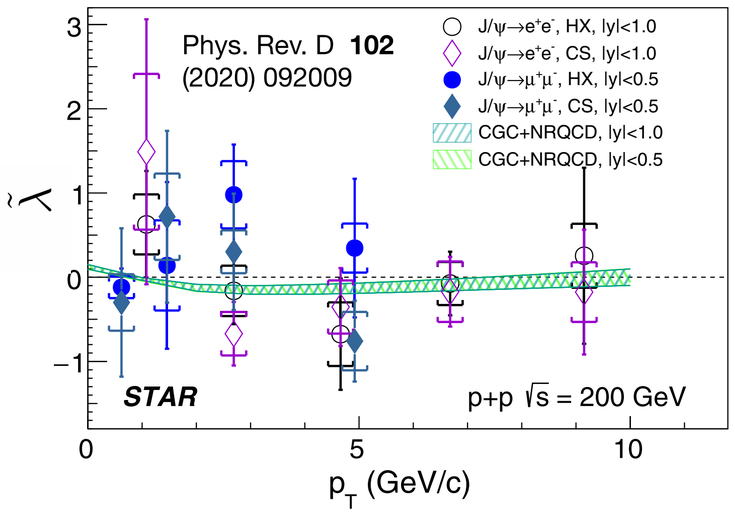
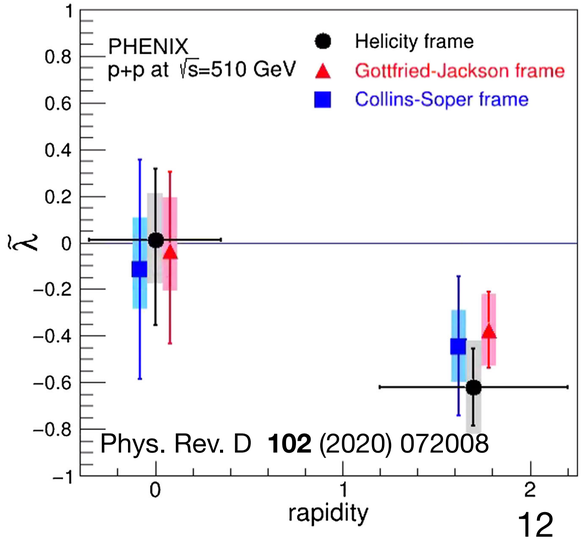
- Complement measurements from ALICE (PRL **108** ('12) 082001, EPJC **78** ('18) 562), CMS (PLB **727** ('13) 381), LHCb (EPJC **73** ('13) 2631)
- First measurement in PbPb by ALICE (arXiv:2005.11128)

J/ψ

STAR: pp at $\sqrt{s} = 200$ GeV



PHENIX: pp at $\sqrt{s} = 510$ GeV



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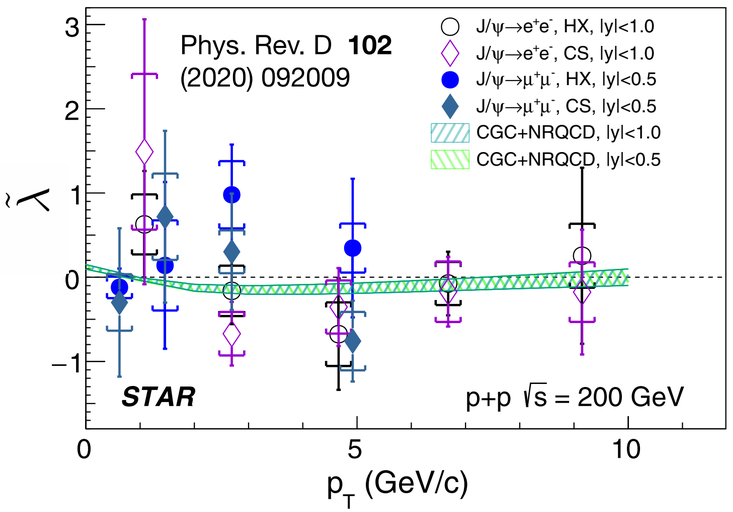

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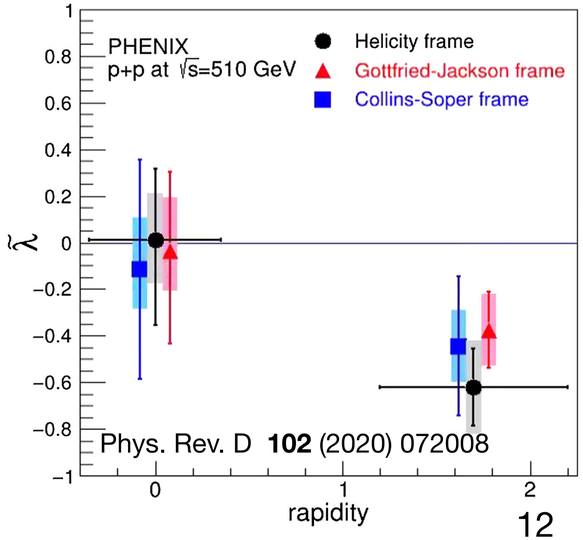
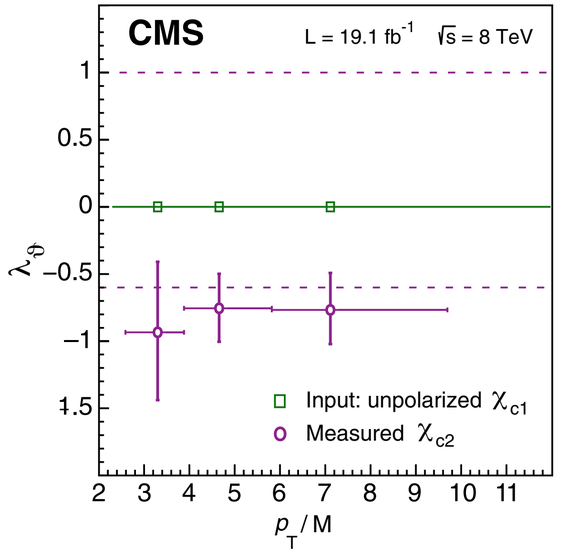
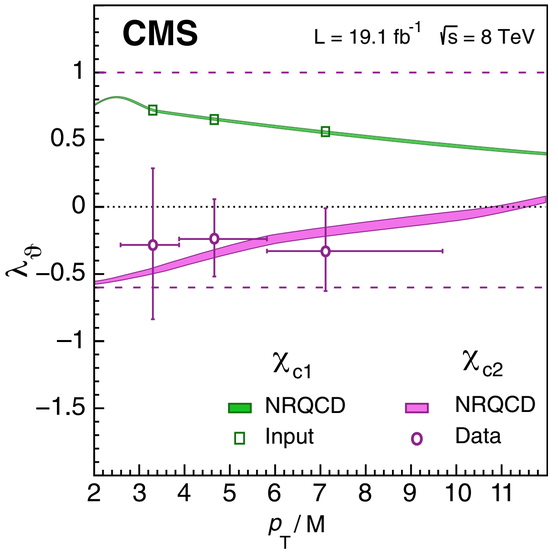


χc

Polarisation in helicity frame through χ_{c2}/χ_{c1}

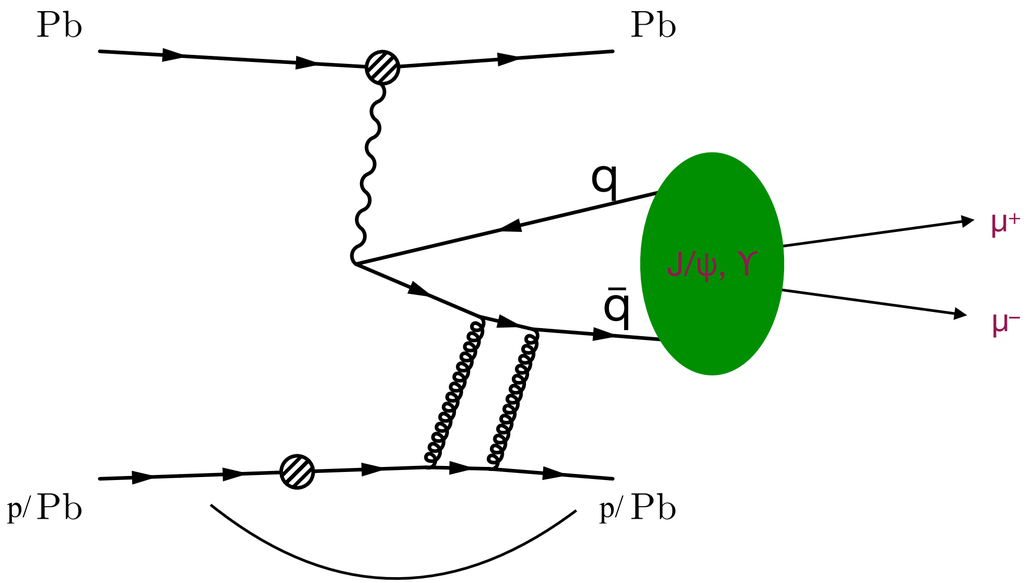
Phys. Rev. Lett. **124** (2020) 162002





Exclusive quarkonium production

Exclusive vector-meson production in ultra-peripheral hadron-hadron collisions



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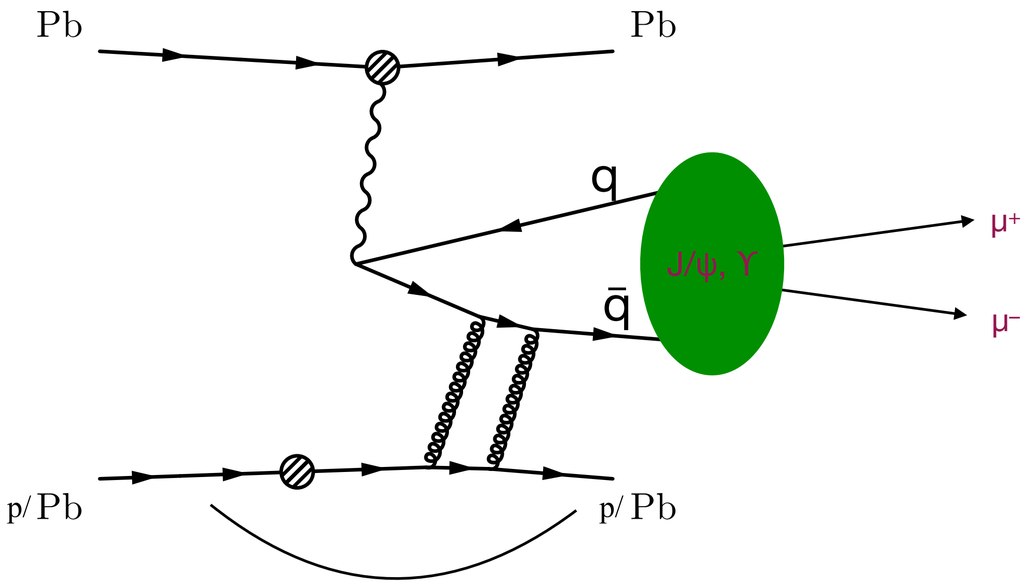


photon flux $\propto Z^2$

pPb collisions

Z(p)=1

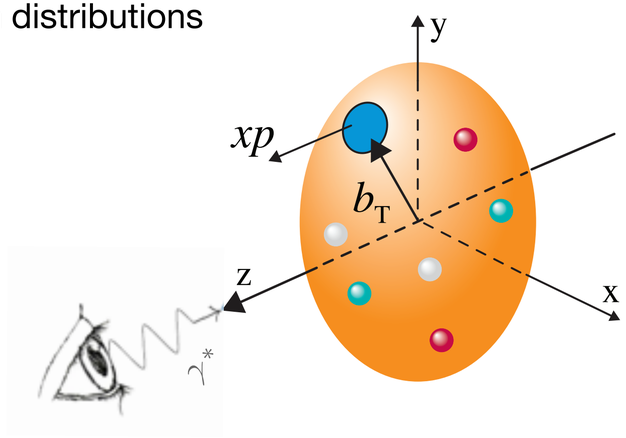
Z(Pb)=82

⟶ Pb ion dominant photon emitter

no ambiguity in identity of photon emitter

Study of exclusive quarkonium production

3D parton distributions



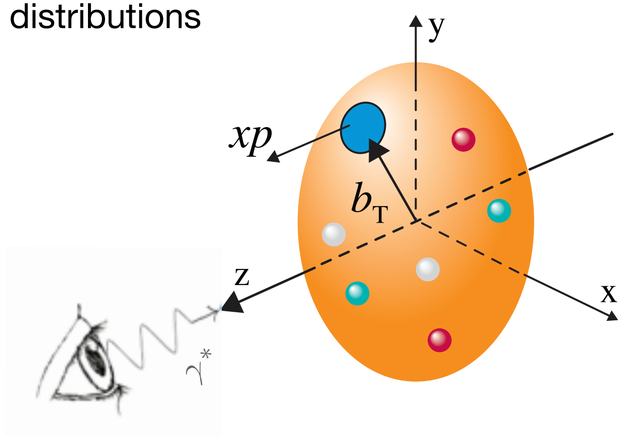
Generalised parton distributions

↓ M. Burkardt, PRD **92** ('00) 071503
Int. J. Mod Phys. A **18** ('03) 173

3D distribution in x and transverse position b_T

Study of exclusive quarkonium production

3D parton distributions



Generalised parton distributions

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Int. J. Mod Phys. A **18** ('03) 173

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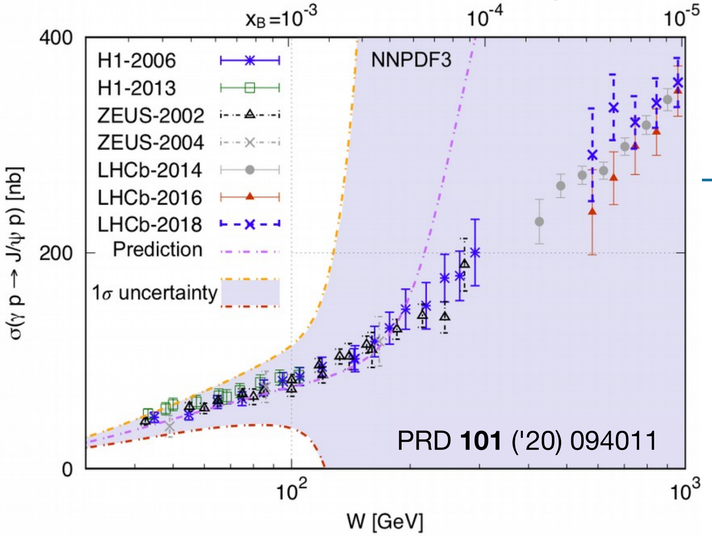
At low x



Approximate access to gluon PDF

$$\left.\frac{d\sigma}{dt}\right|_{t=0} \propto [g(x_B)]^2$$

M. G. Ryskin, Z. Phys. C57 (1993) 89–92;
S. P. Jones et al., arXiv:1609.09738

Study of exclusive quarkonium production

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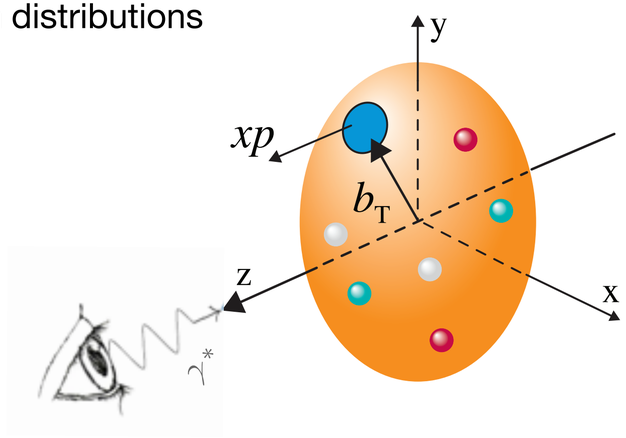

Generalised parton distributions

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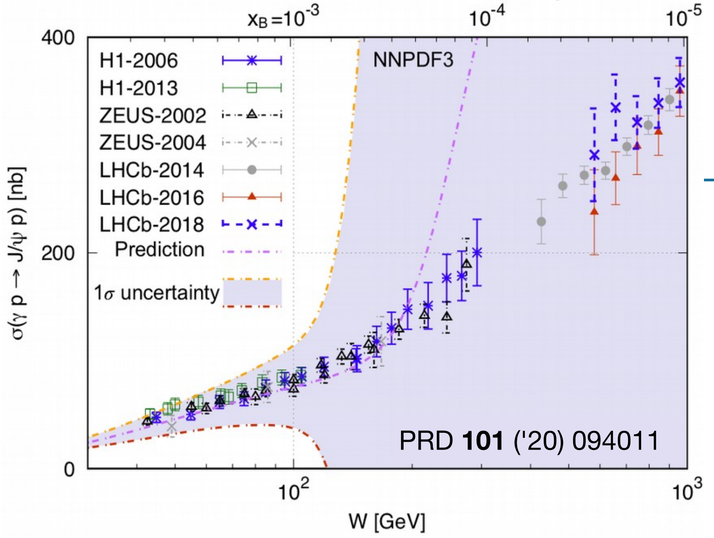

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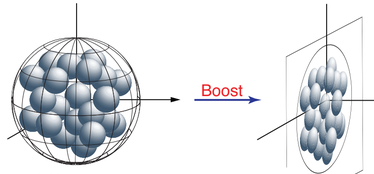
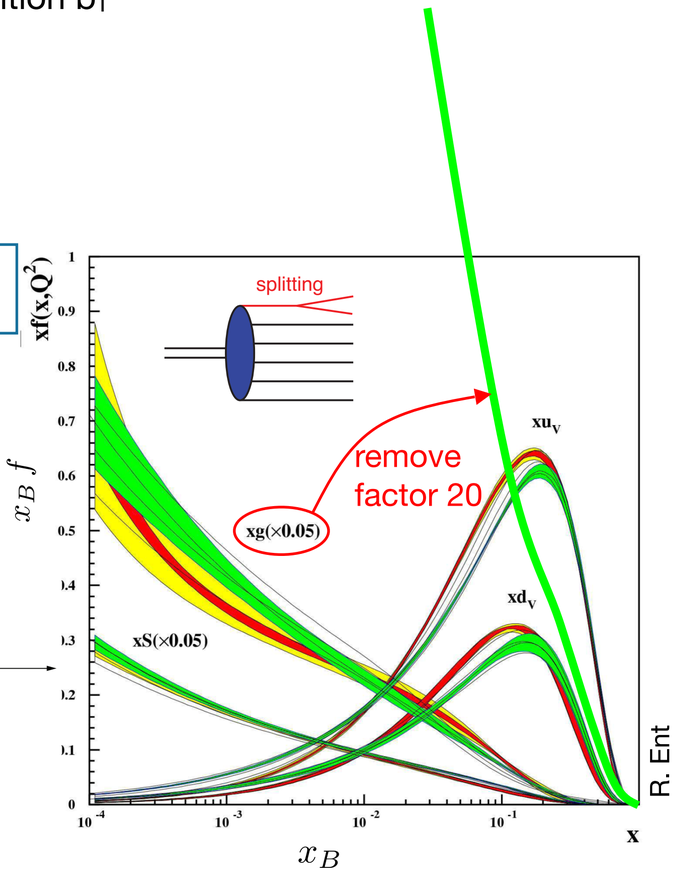
Test saturation

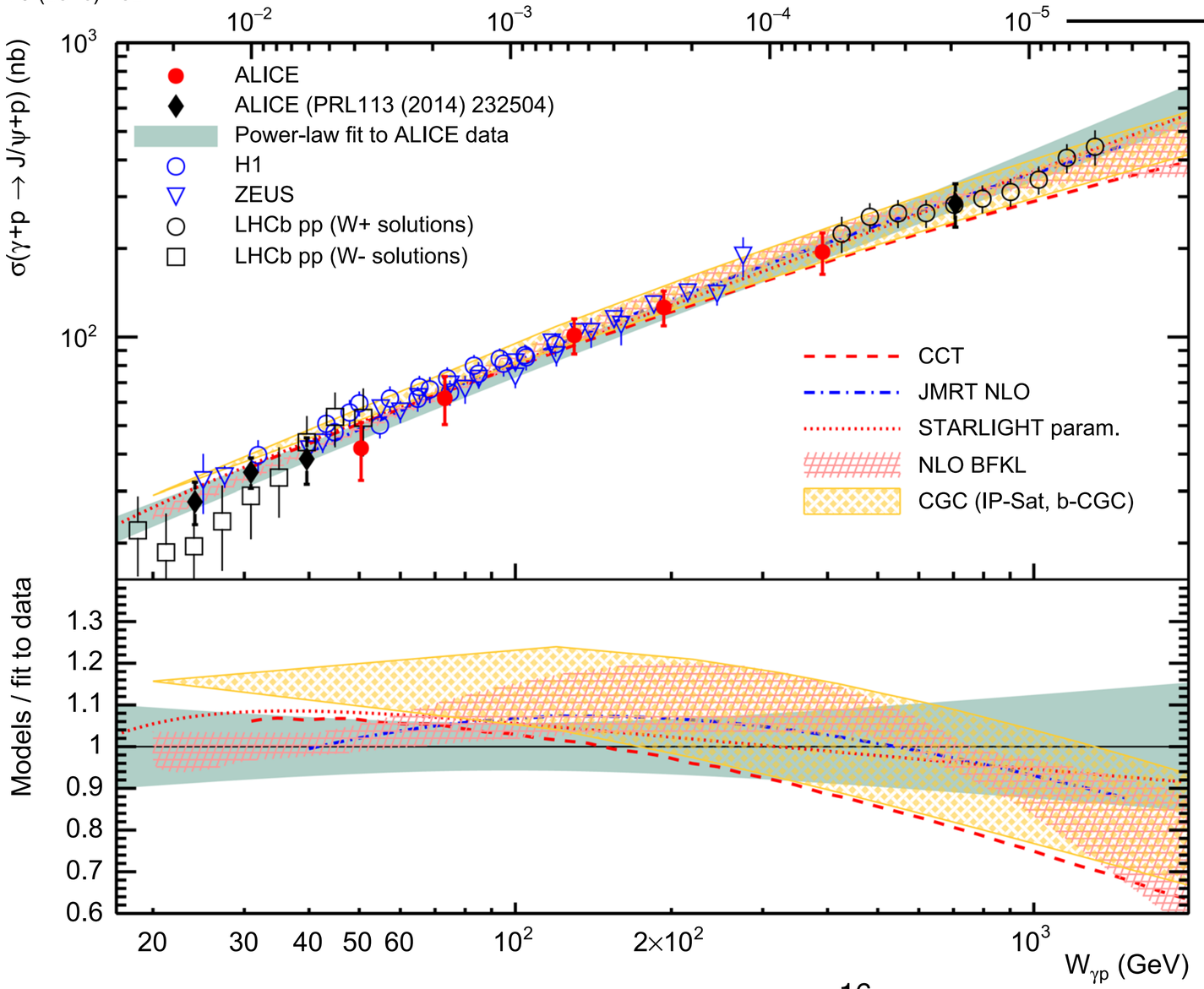


$A^{1/3}$ enhancement of saturation effect



J/ψ photoproduction on nucleon

ALICE, Eur. Phys. J. C **79** (2019) 402



→ access to low-x_B gluon GPDs

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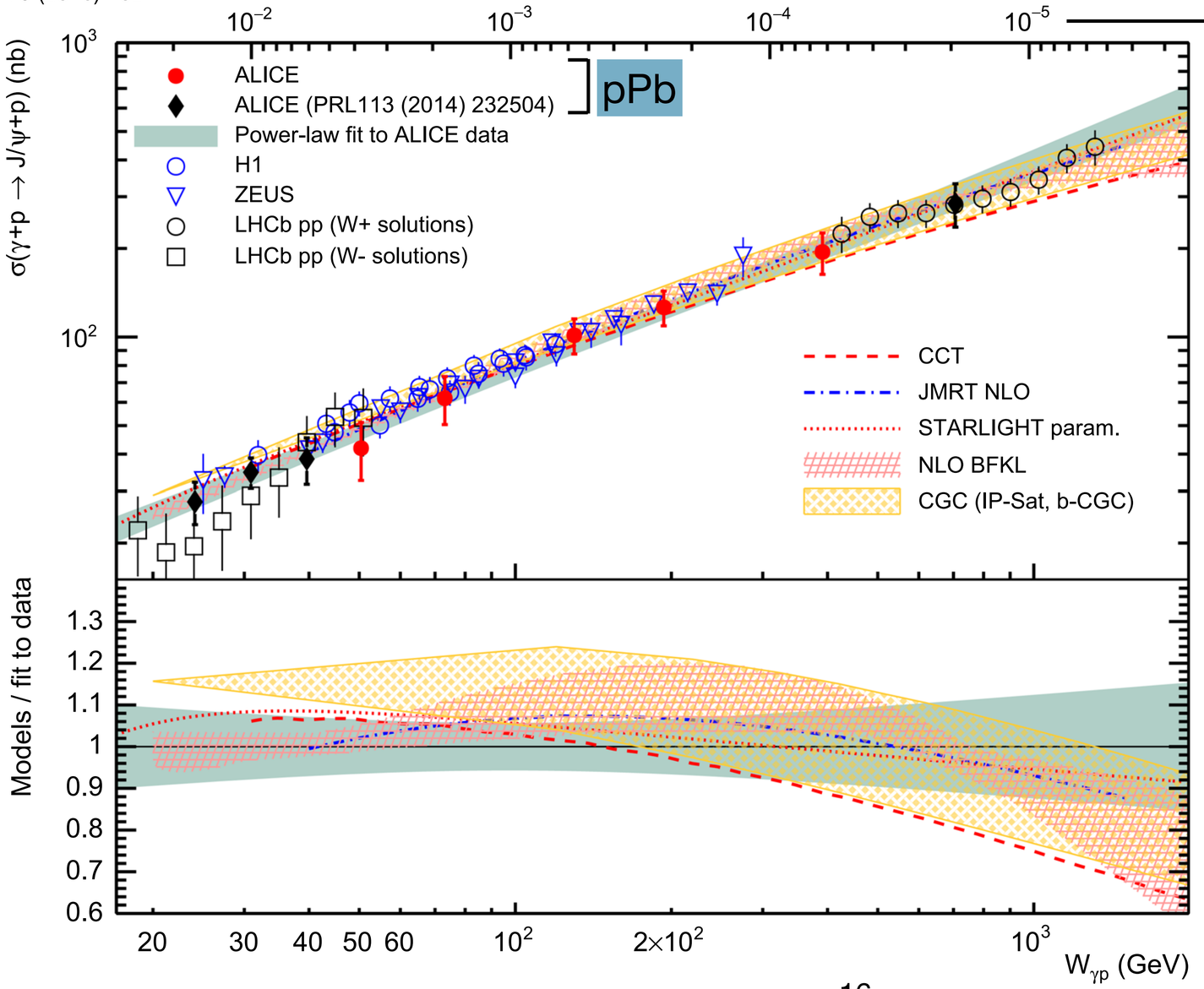
ALICE, Eur. Phys. J. C **79** (2019) 402



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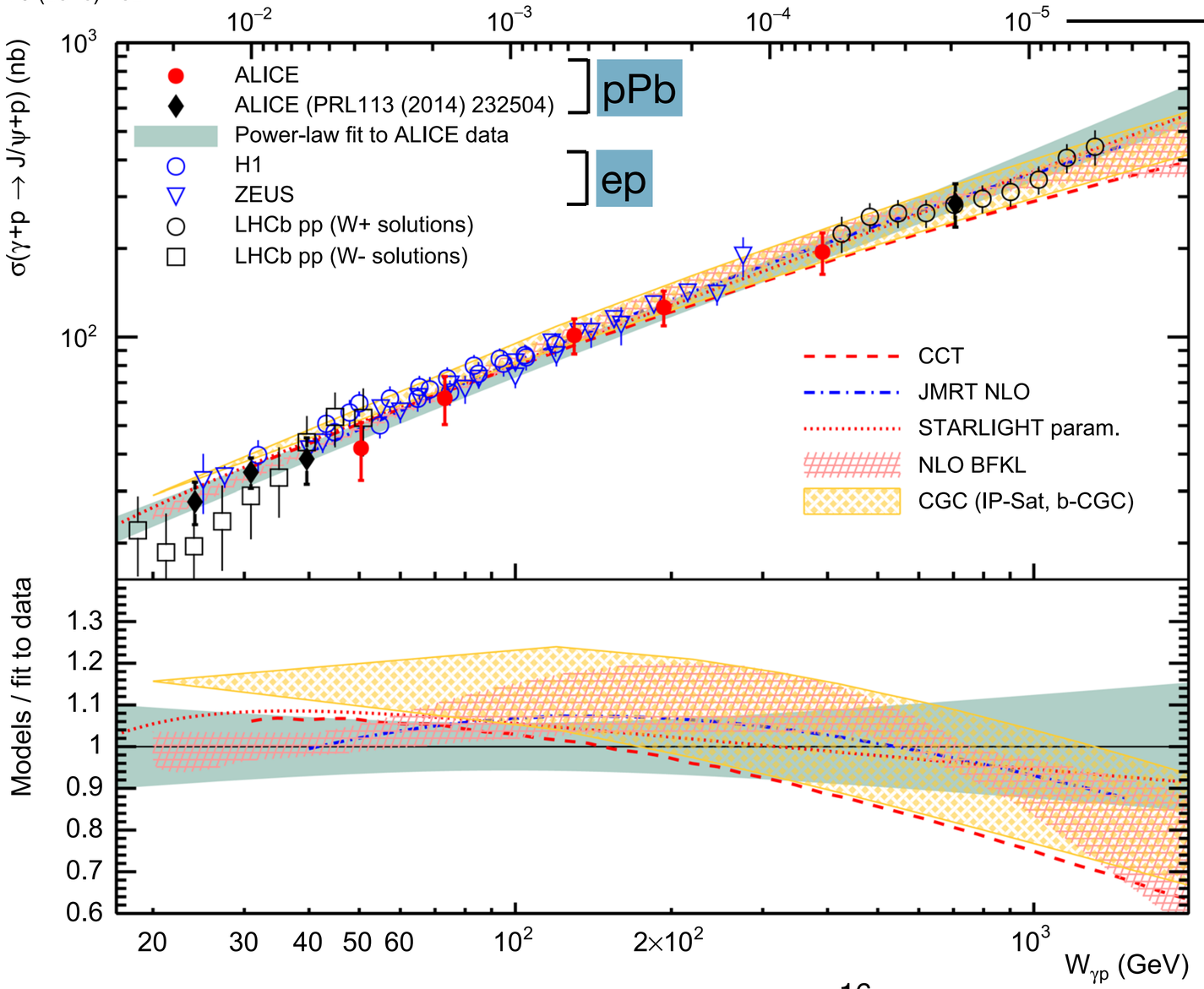

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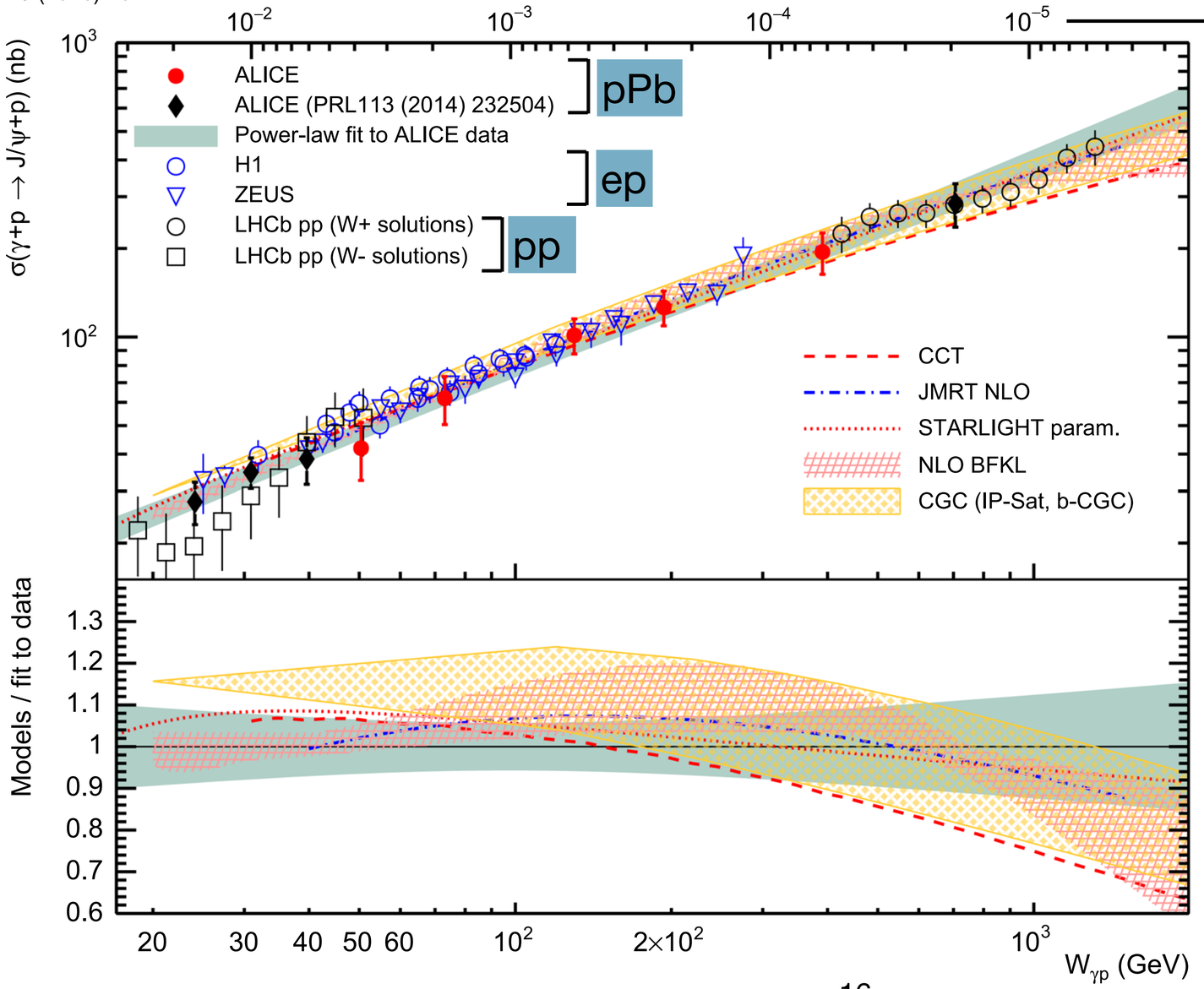

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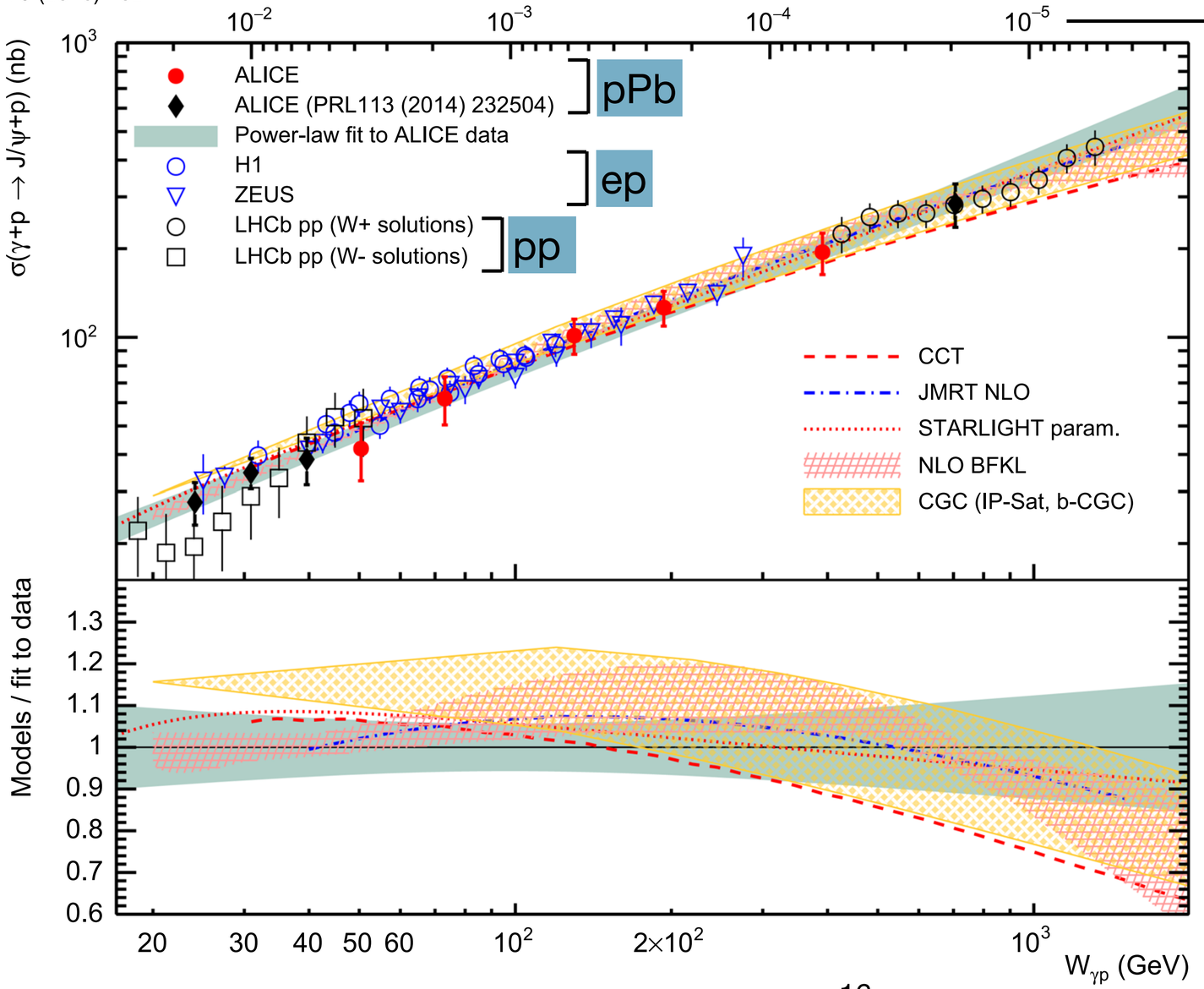


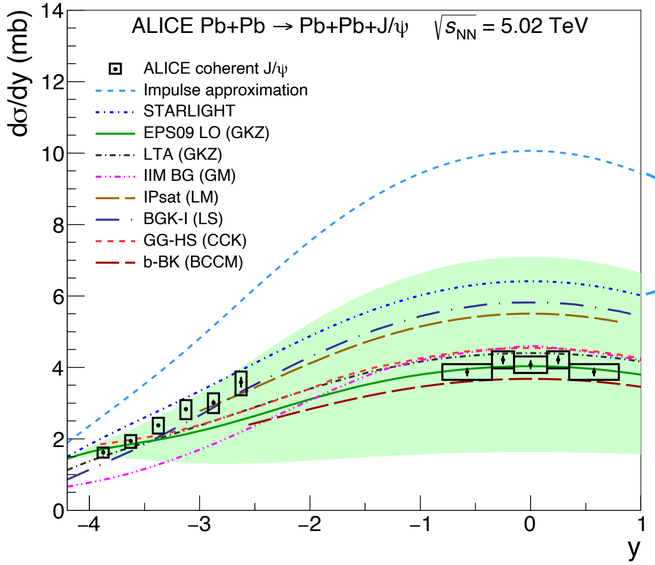
→ access to low-x_B gluon GPDs

overall compatibility between pp, Pbp and ep data: hint of universality of underlying physics

Coherent photoproduction in PbPb

J/ψ

ALICE, 2101.04577



-4.0<y<-2.5

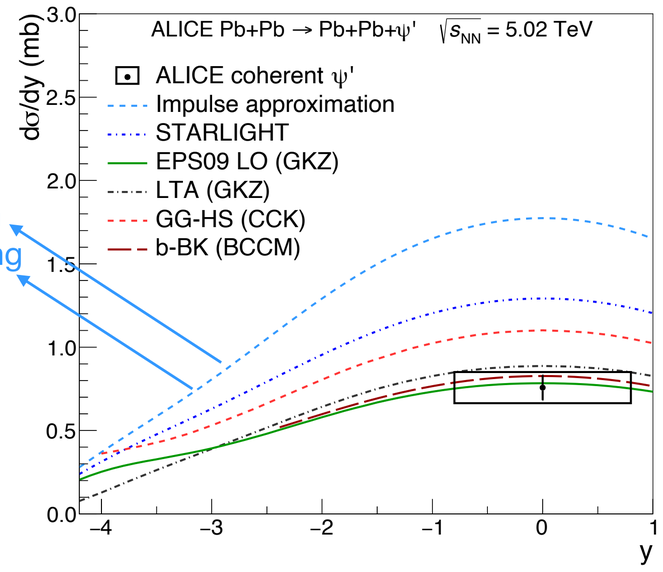
0.7 x 10^{-2} < x_B < 3.3 x10^{-2} (dominant)

1.1 x 10^{-5} < x_B < 5.1 x10^{-5}

no gluon shadowing

$\psi(2S)$

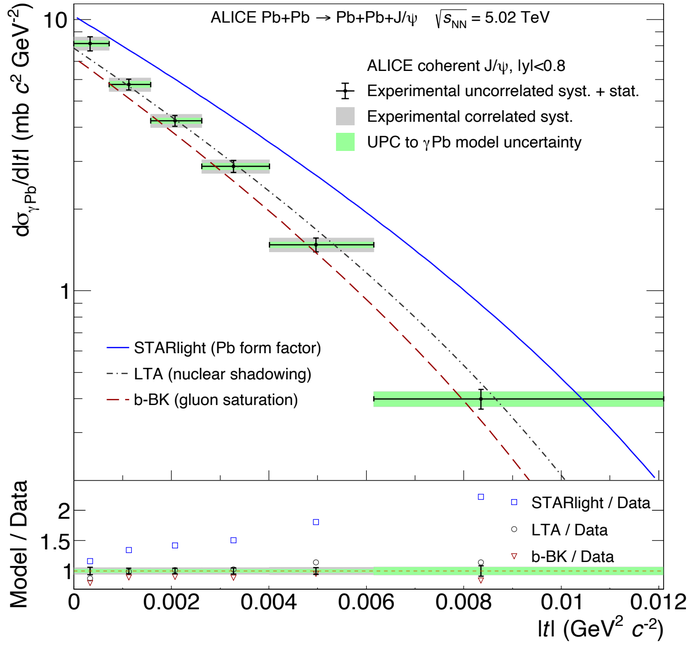
ALICE, 2101.04577



|y|<0.8 ⟷ 0.3 x 10^{-3} < x_B < 1.4 x10^{-3}

J/ψ

ALICE, 2101.04623



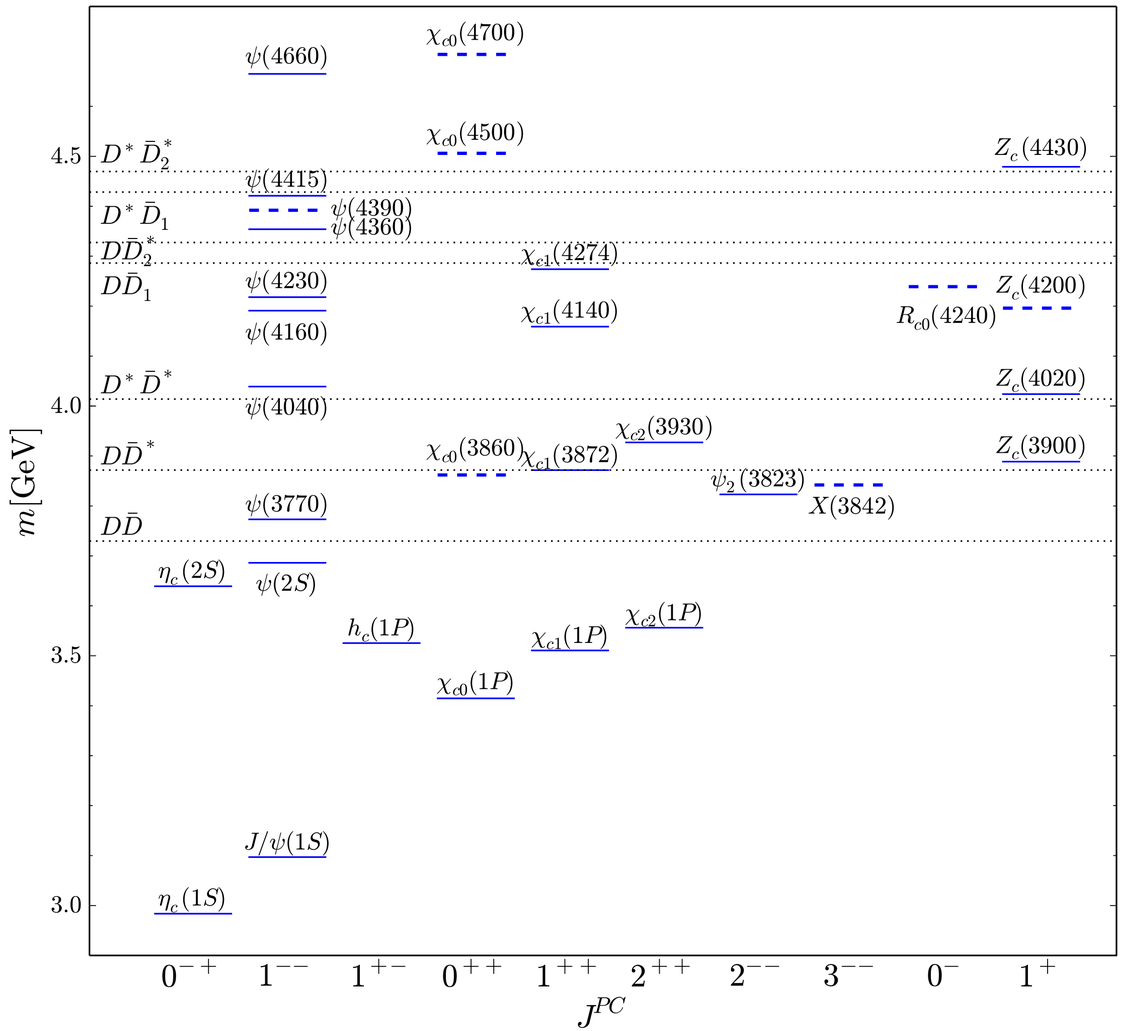
Results indicate shadowing in gluon PDF:

$$R_g = \frac{g^{Pb}}{A\, g^{p}} \approx 0.65 \text{ at } x \approx 10^{-3}$$

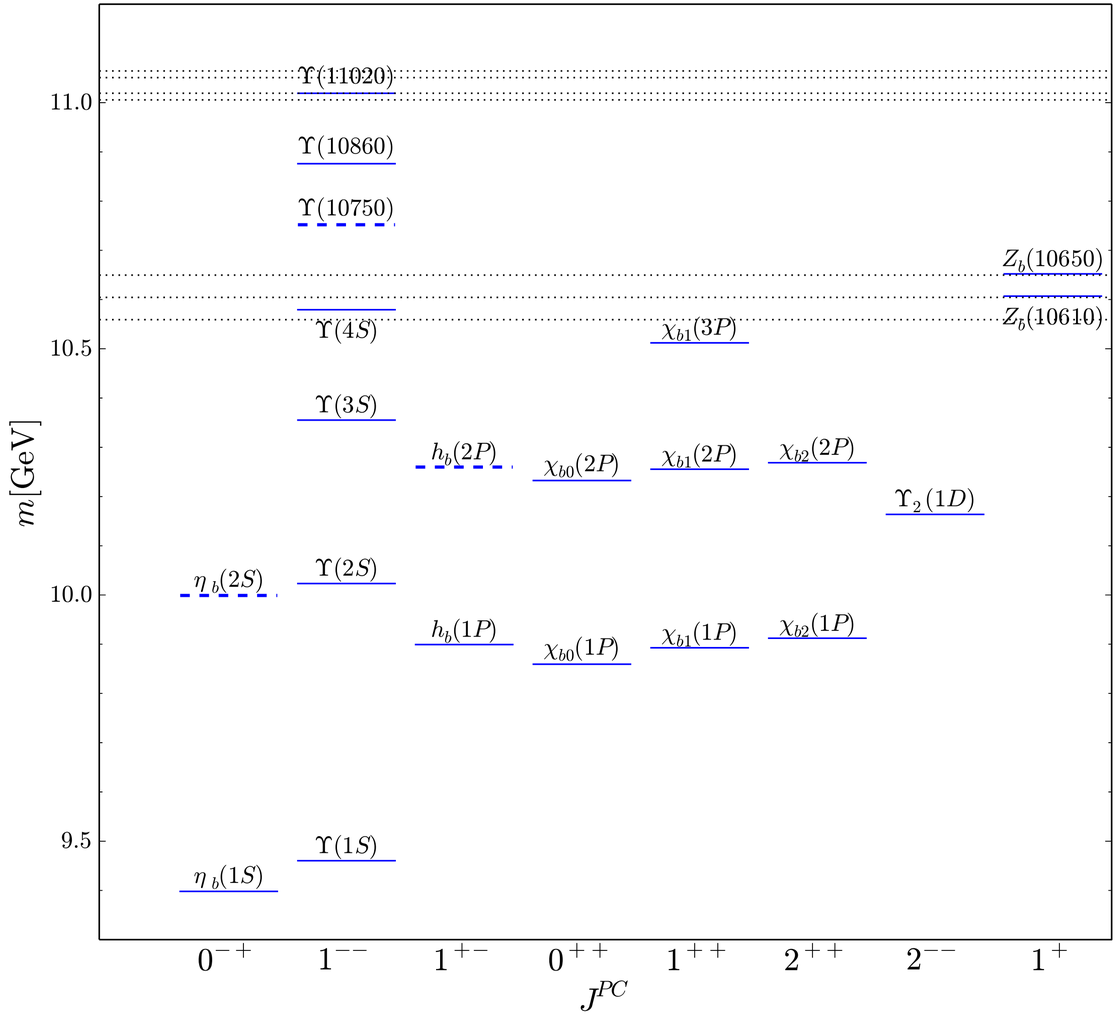
Spectroscopy

Spectrum of $c\bar{c}$ and $b\bar{b}$ states

charmonium spectrum



bottomonium spectrum



established experimentally

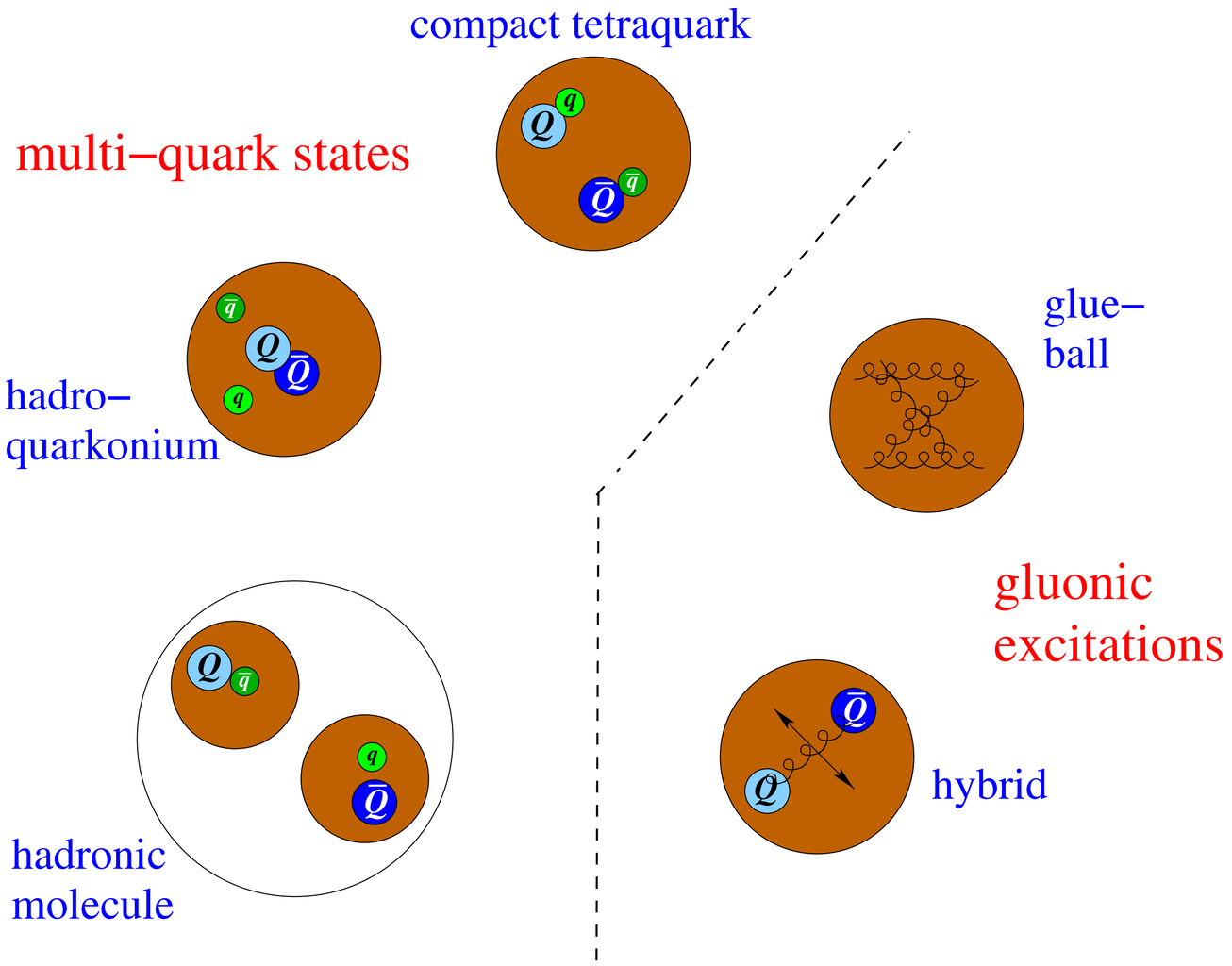
claimed experimentally

open charm/bottom thresholds

N. Brambilla et al., Phys. Rep. 873 (2020) 1–154

situation in July 2019

Exotic states

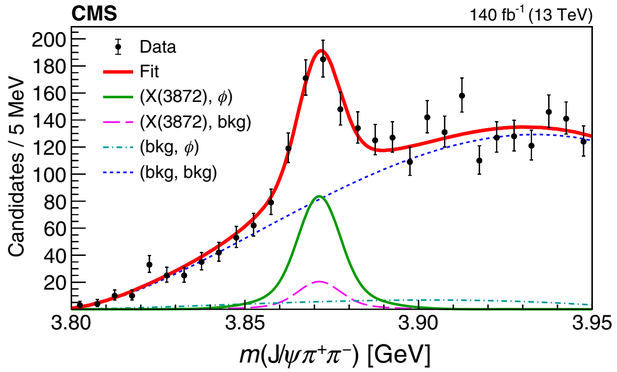


N. Brambilla et al., Phys. Rep. 873 (2020) 1–154

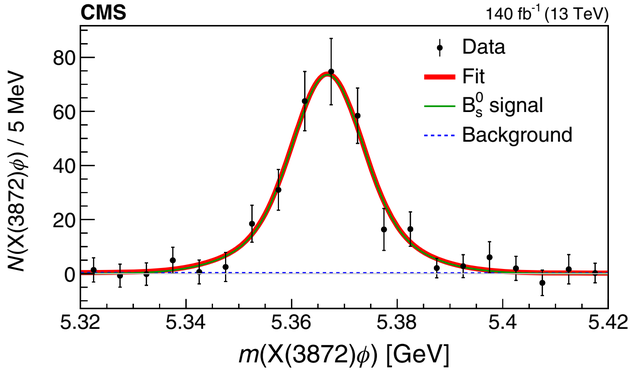
$\chi_{c1}(3872)$ from B_s^0 decay

CMS: first observation of $B_s^0 \to \chi_{c1}(3872)\,\phi$

$\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$



Phys. Rev. Lett. **125** (2020) 152001



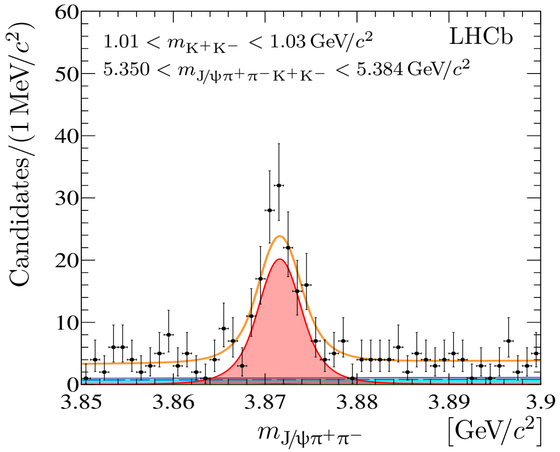
$$\frac{\mathcal{B}[B_s^0 \to \chi_{c1}(3872)\phi]\;\mathcal{B}[\chi_{c1}(3872) \to J/\psi\pi^+\pi^-]}{\mathcal{B}[B_s^0 \to \psi(2S)\phi]\;\mathcal{B}[\psi(2S) \to J/\psi\pi^+\pi^-]}$$

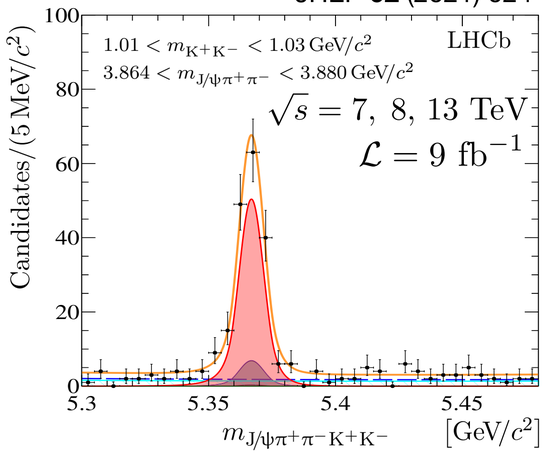
$$= [2.21 \pm 0.29(\text{stat}) \pm 0.17(\text{syst})]\%$$

LHCb: $B_s^0 \to \chi_{c1}(3872)\,\phi$

$\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$

JHEP **02** (2021) 024





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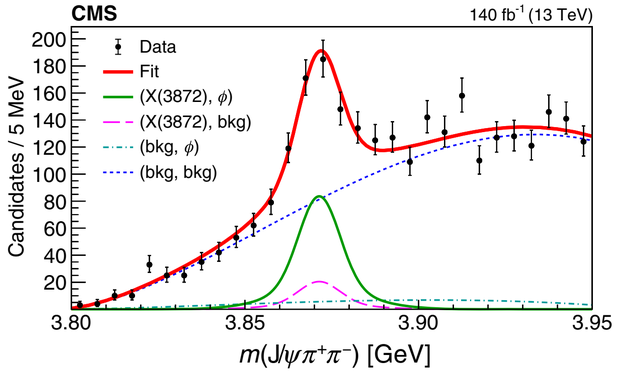
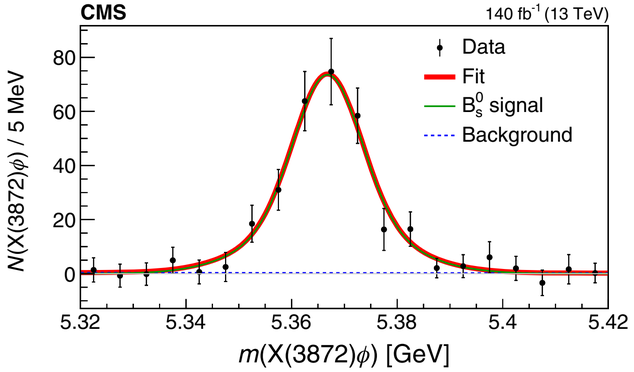


Phys. Rev. Lett. **125** (2020) 152001



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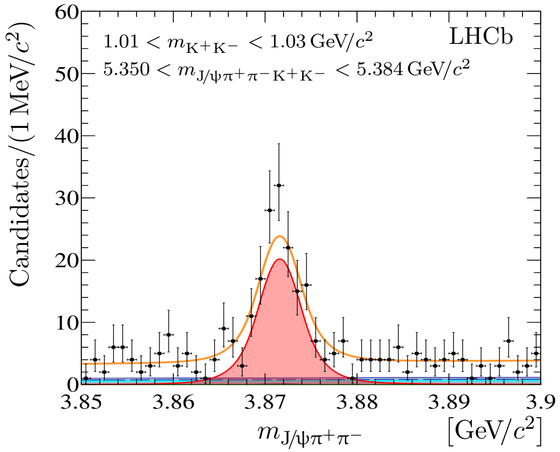
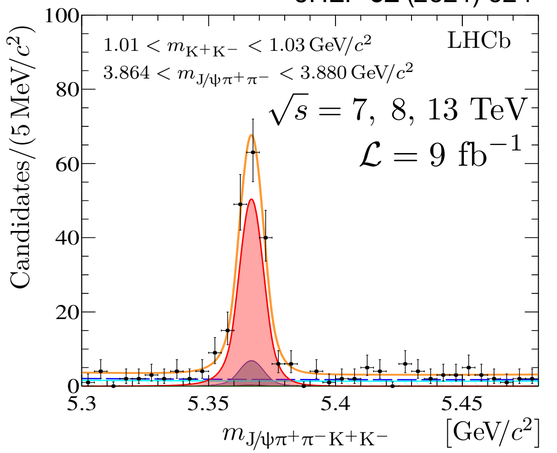
JHEP **02** (2021) 024





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Comparison to other decays: information on nature of $\chi_{c1}(3872)$

$$\frac{\mathcal{B}[B_s^0 \to \chi_{c1}(3872)\phi]}{\mathcal{B}[B^0 \to \chi_{c1}(3872)K^0]} \approx 1$$

$$\frac{\mathcal{B}[B_s^0 \to \chi_{c1}(3872)\phi]}{\mathcal{B}[B^+ \to \chi_{c1}(3872)K^+]} \approx 0.5 \qquad \frac{\mathcal{B}[B_s^0 \to \psi(2S)\phi]}{\mathcal{B}[B^+ \to \psi(2S)K^+]} = 0.87 \pm 0.10$$

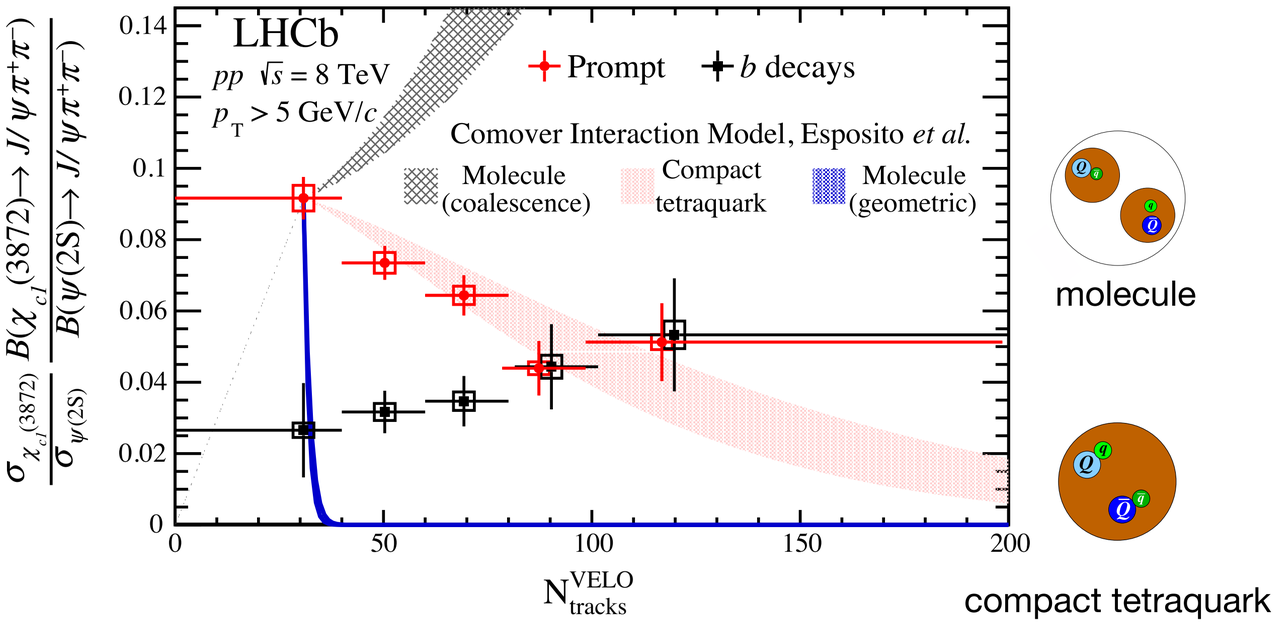
Prompt $\chi_{c1}(3872)$ production

LHCb: pp at $\sqrt{s} = 8$ TeV; $\mathcal{L} = 2$ fb^{-1}

$$\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$$

Multiplicity dependence in pp collisions

LHCb, Phys. Rev. Lett. **126** (2021) 092001



molecule

compact tetraquark

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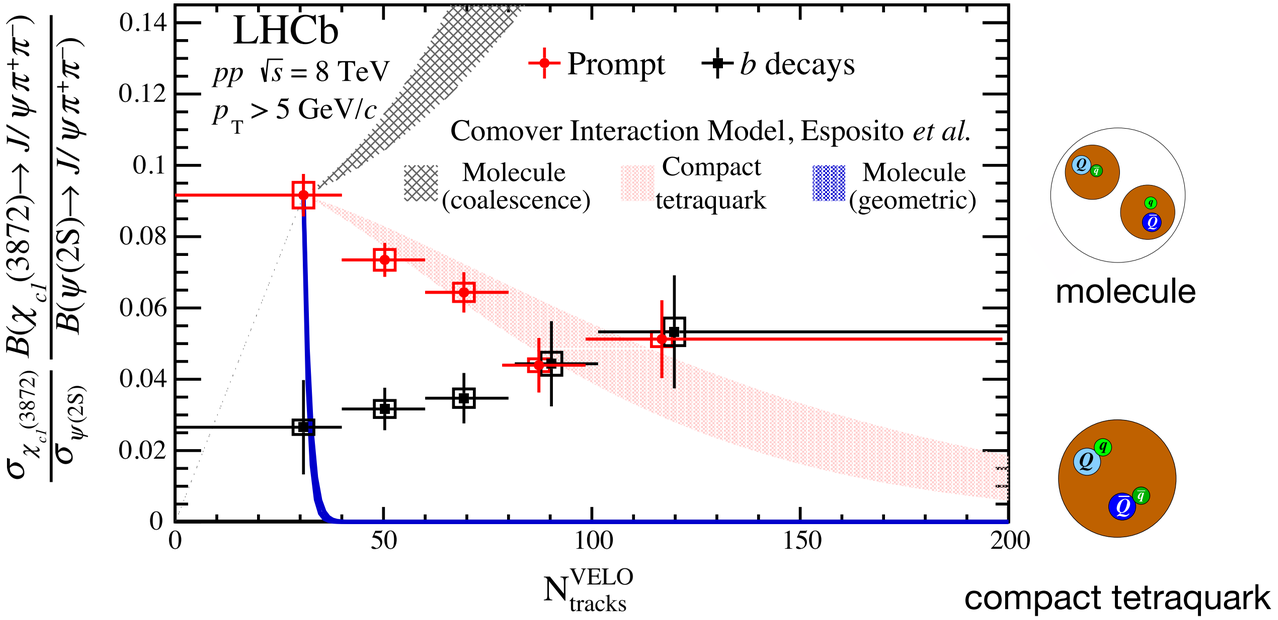
LHCb, Phys. Rev. Lett. **126** (2021) 092001



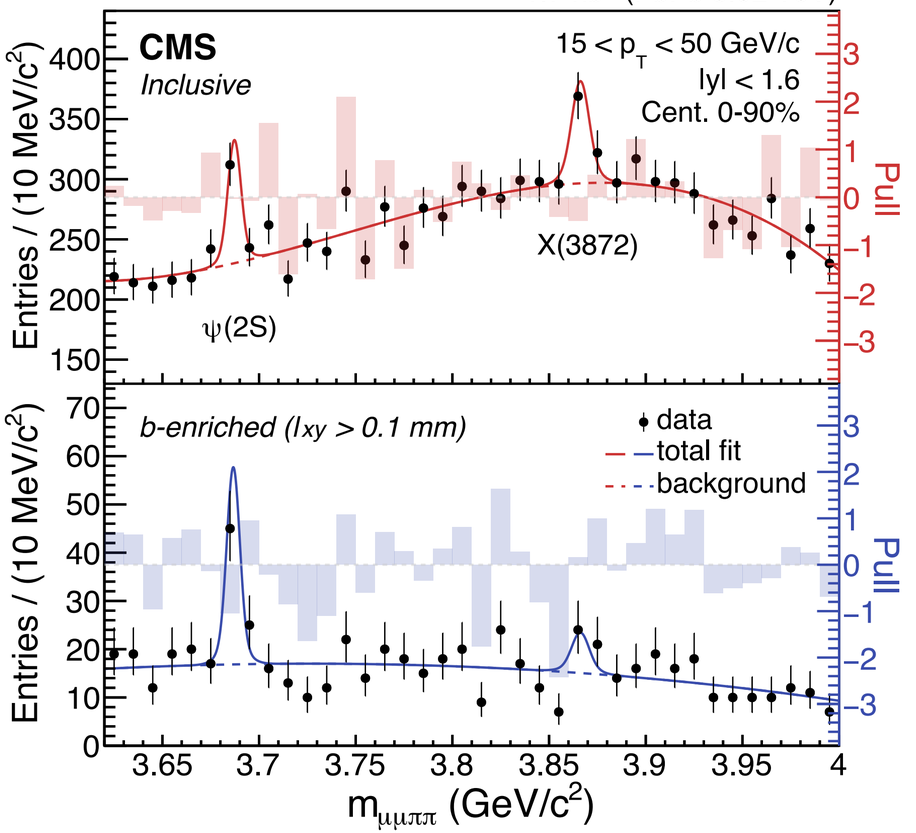
molecule

compact tetraquark

First evidence of production in PbPb

CMS, arXiv: 2102.13048

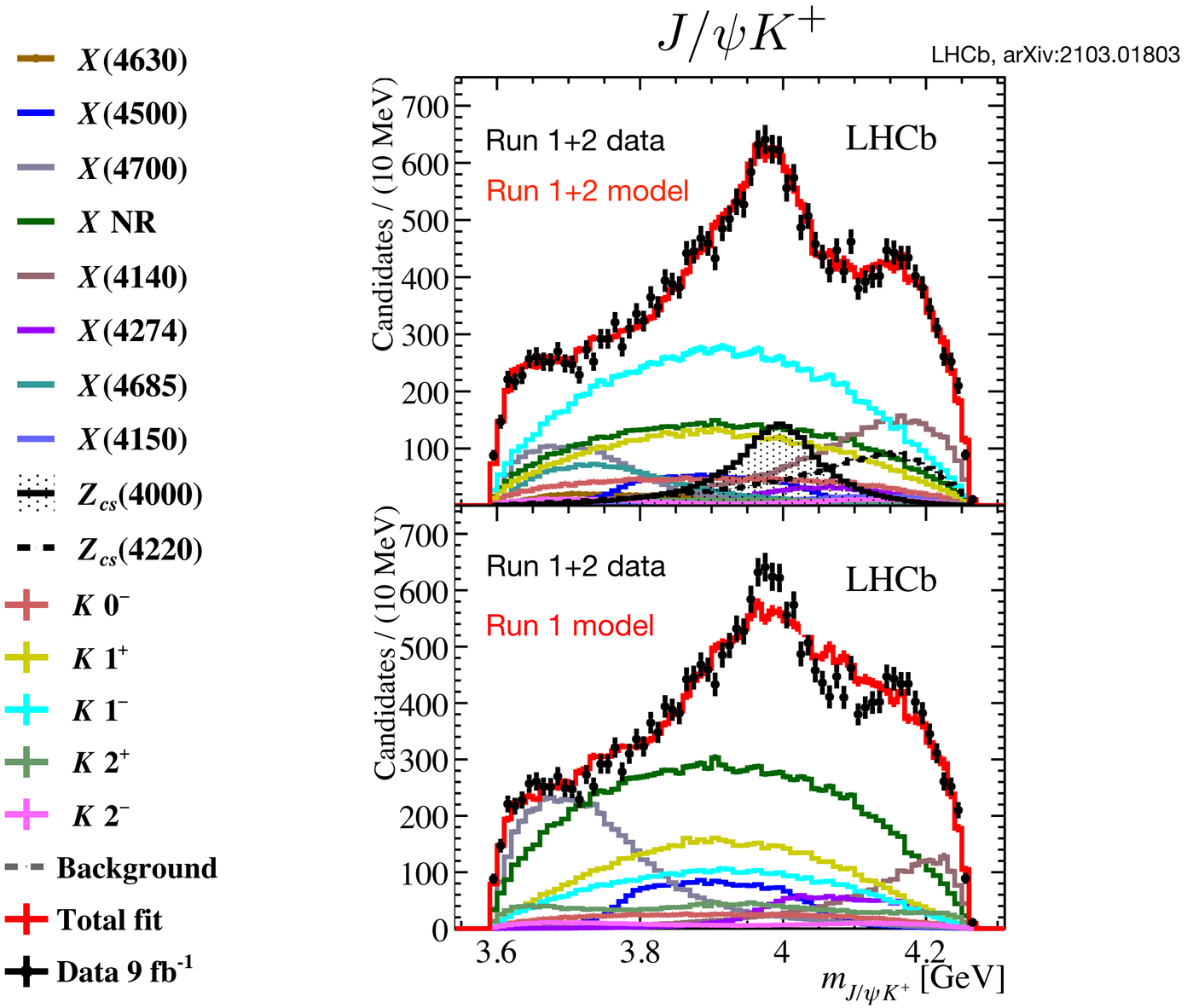
1.7 nb^{-1} (PbPb 5.02 TeV)



Prompt production (in pp and PbPb): complementary information to study structure of $\chi_{c1}(3872)$

Charged exotic states from $B^+ \to J/\psi\phi K^+$ decay

LHCb: pp at $\sqrt{s} = 7,\ 8,\ 13$ TeV; $\mathcal{L} = 9$ fb^{-1}



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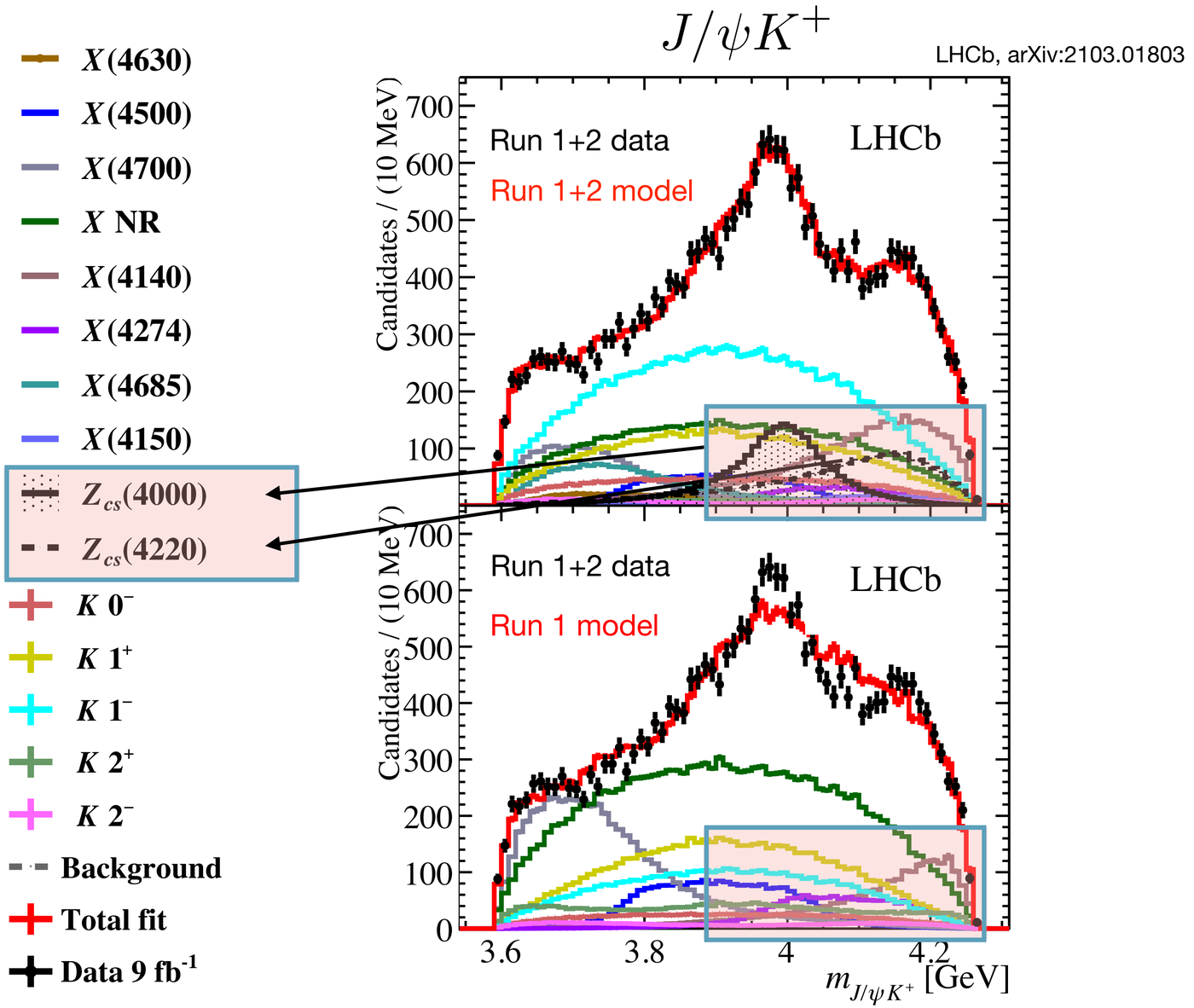

First observation of exotic state with $c\bar{c}u\bar{s}$!

- $Z_{cs}(4000)$: significance: 15 σ $J^P=1^+$
- $Z_{cs}(4220)$: significance: 5.9 σ $J^P=1^+$ or 1^-

Pentaquarks

- First observation for pentaquark states: $\Lambda_b^0 \to J/\psi p K^-$

Pentaquarks

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see also ATLAS ‘19

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- Search for pentaquark with strangeness: $\Xi_b^- \to \underbrace{J/\psi \Lambda K^-}_{udsc\bar{c}}$

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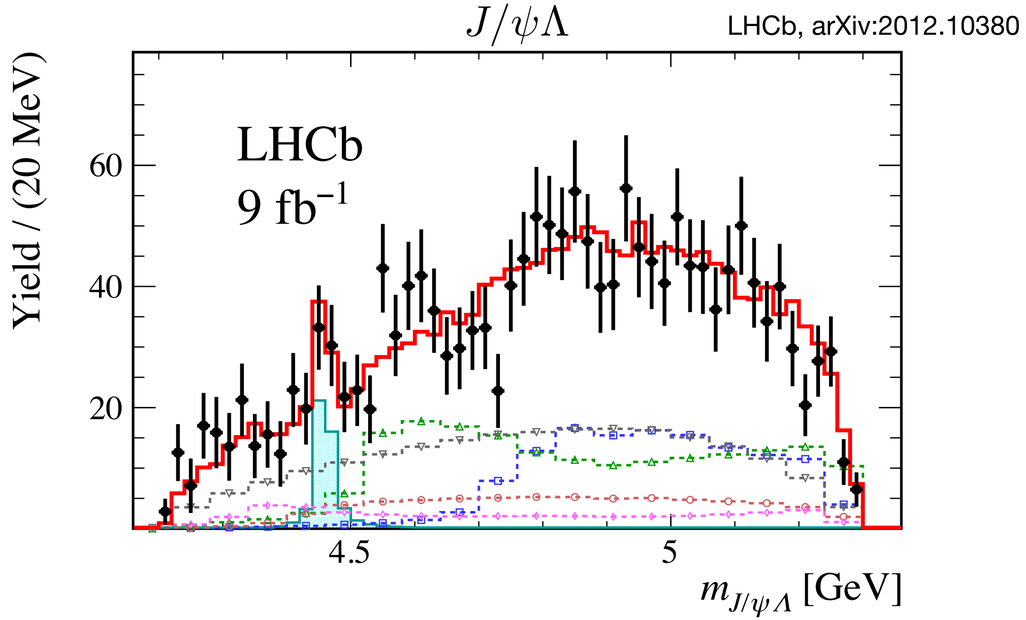

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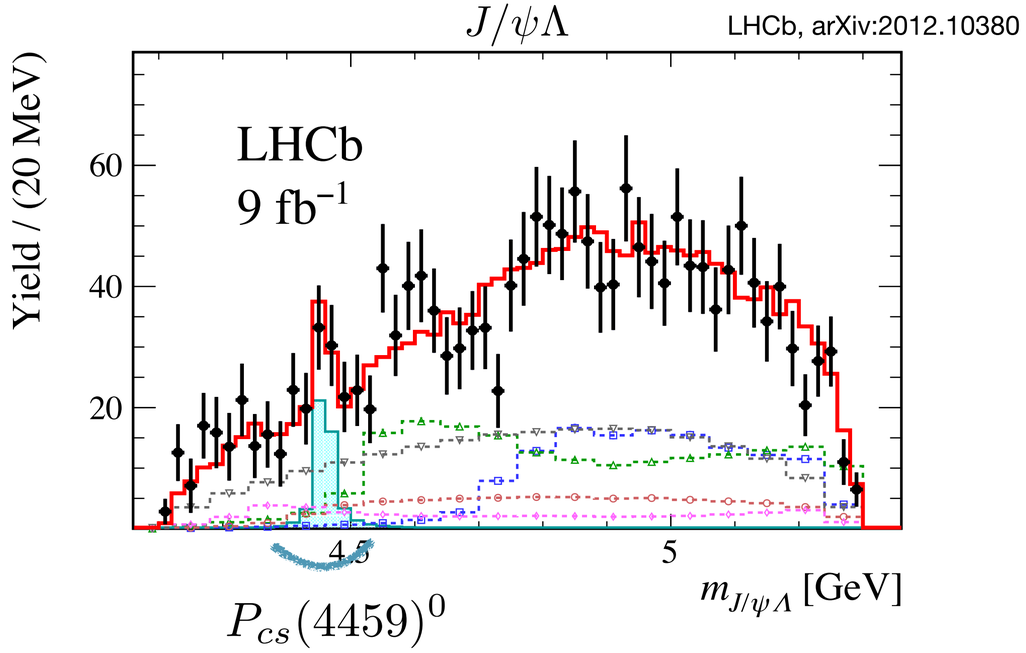

significance: 3.1 σ

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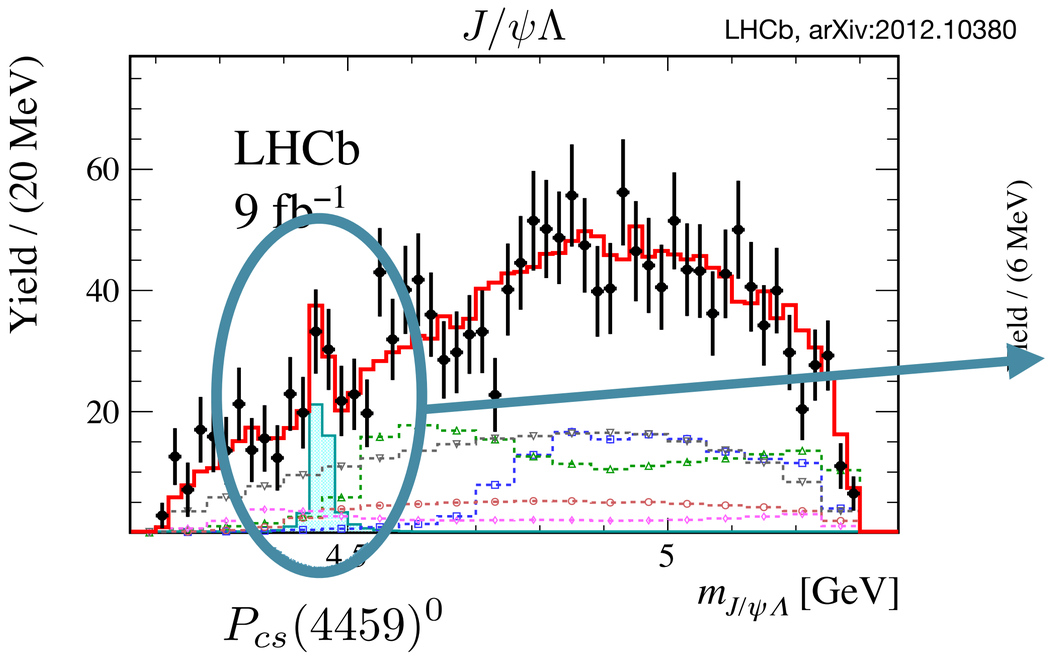

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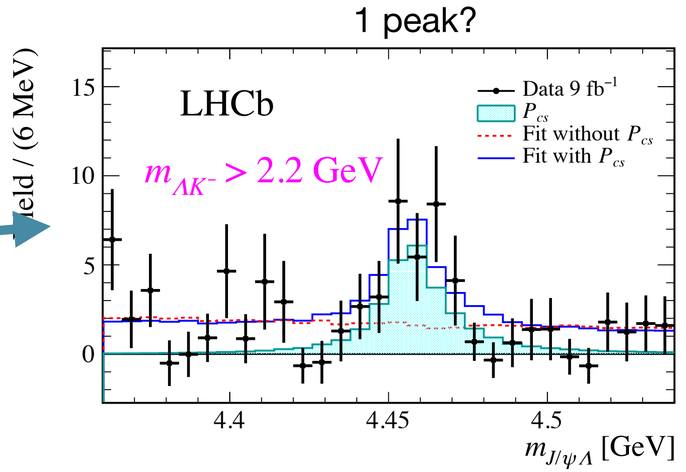
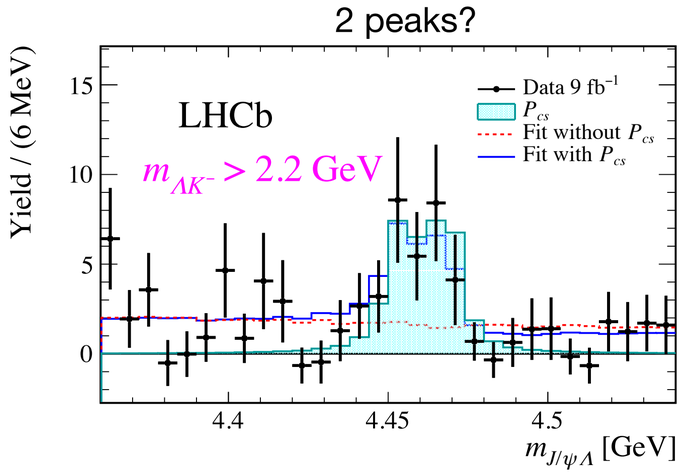
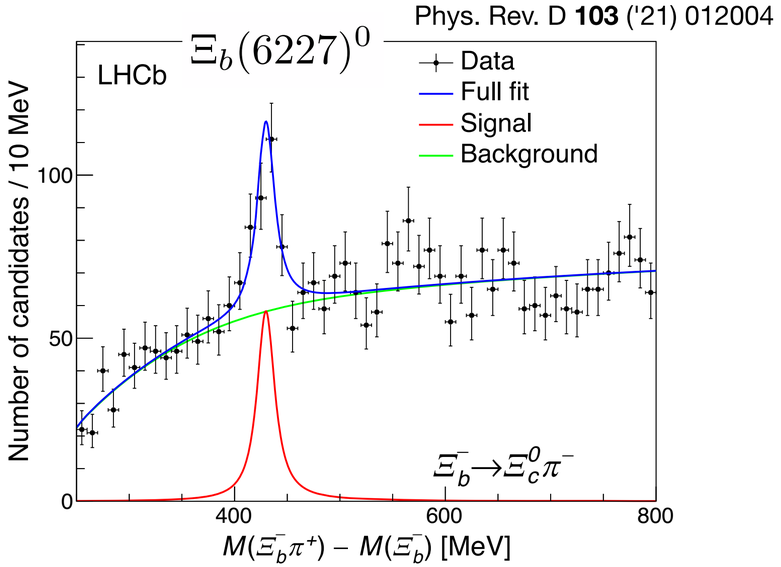




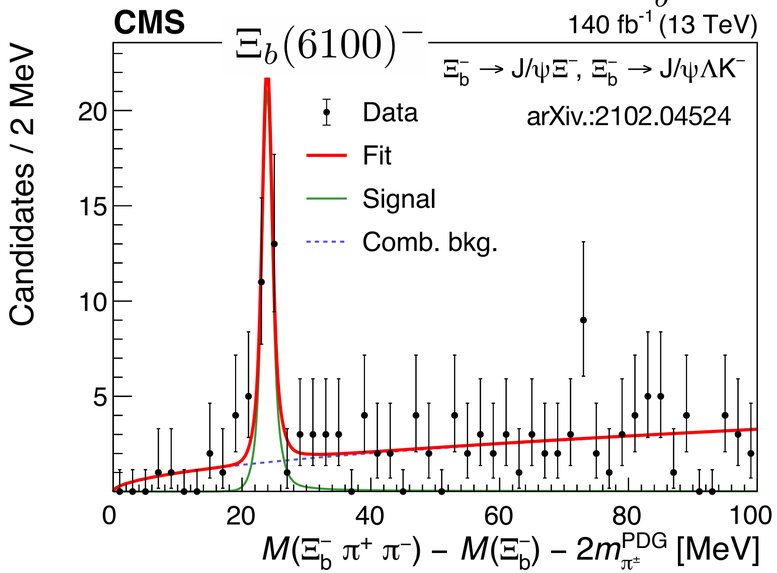
Excited states of conventional baryons

Observation of new excited Ξ_b^0 state

Phys. Rev. D **103** ('21) 012004

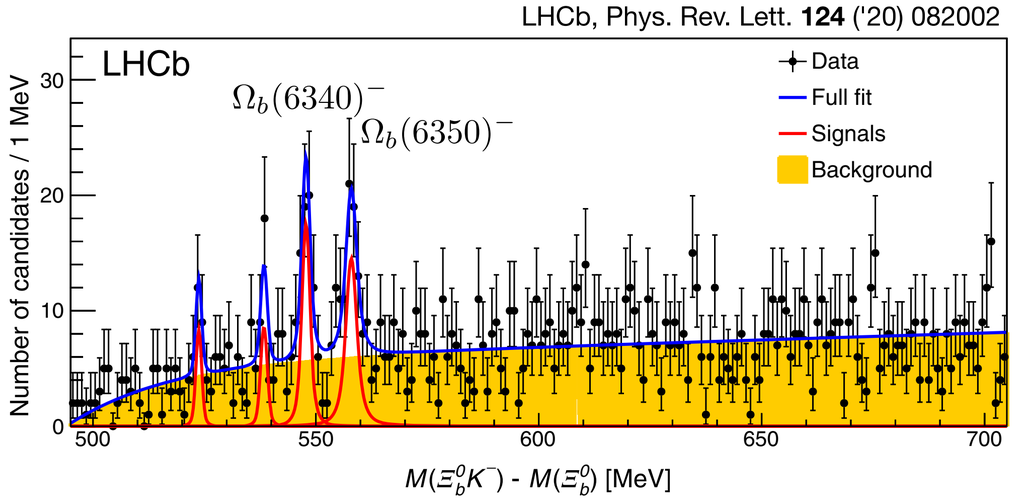


Observation of new excited Ξ_b^- state



First observation of excited Ω_b^- states

LHCb, Phys. Rev. Lett. **124** ('20) 082002



Summary

- The study of heavy quarks and flavours covers a wide spectrum.

- Meson production better under control than baryon production.
  Influence of medium on hadron production?

- Inclusive quarkonium production: complementary tool to open-flavour production to study nucleon/nucleus. Yet, no consensus on production mechanism.

- Exclusive quarkonium production in ultra-peripheral collisions:
  - complementary probe to ep studies, with additional complication, but higher energy.
  - can help to understand quarkonium production.

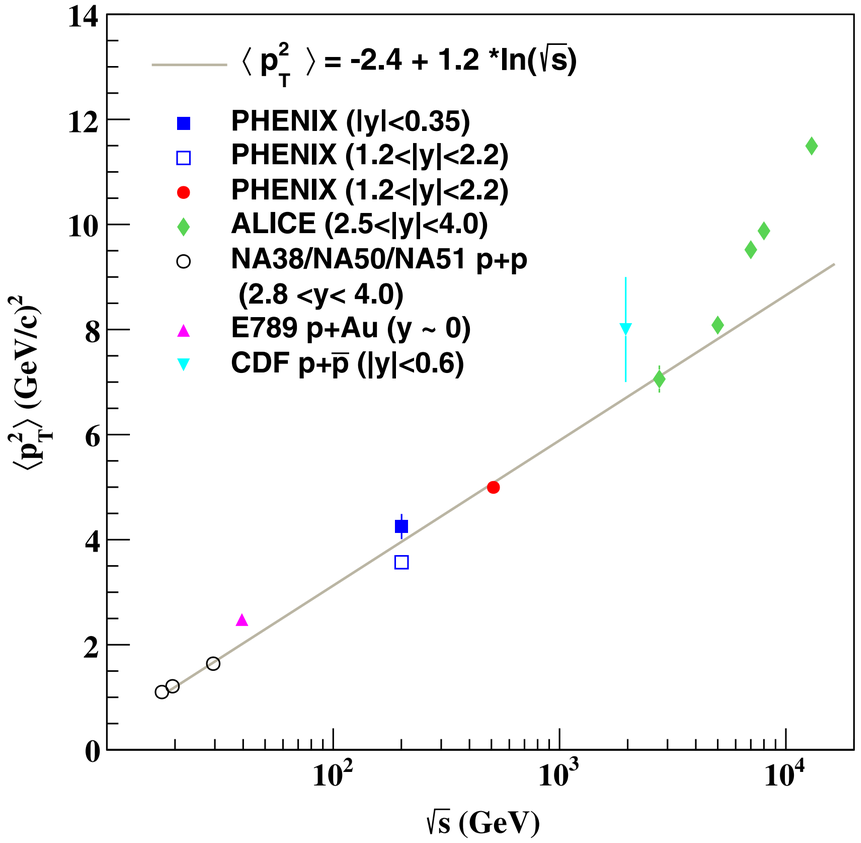
- Spectroscopy: wide spectrum of (new) states, without understanding of their nature.

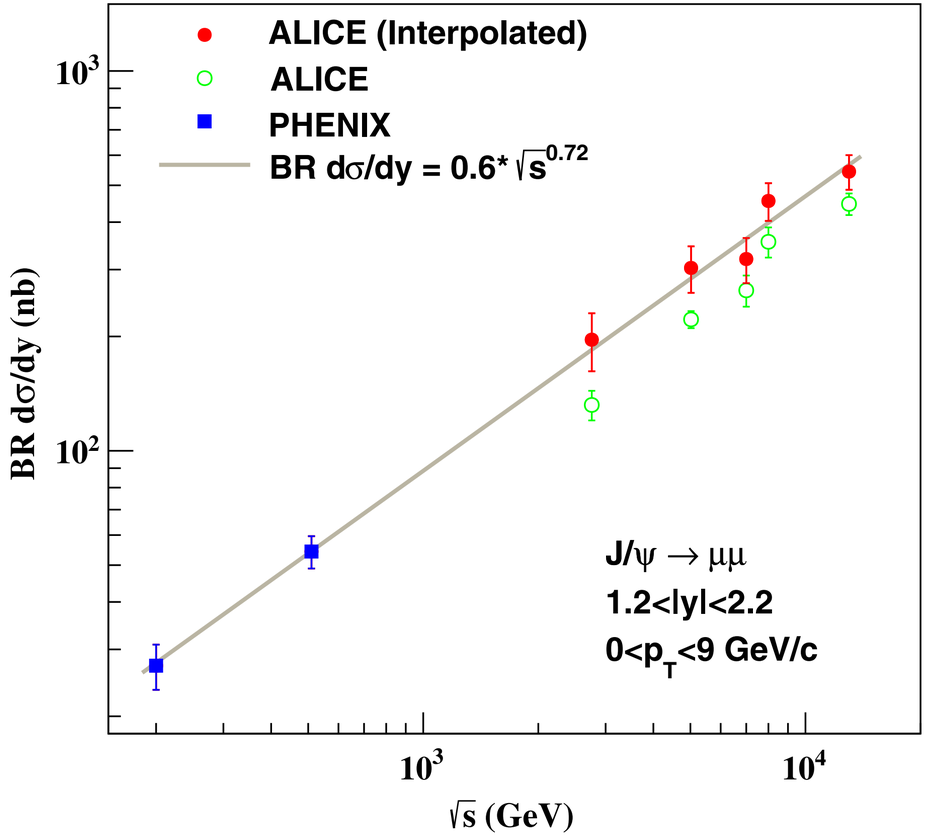
Back up

Inclusive J/ψ production at PHENIX

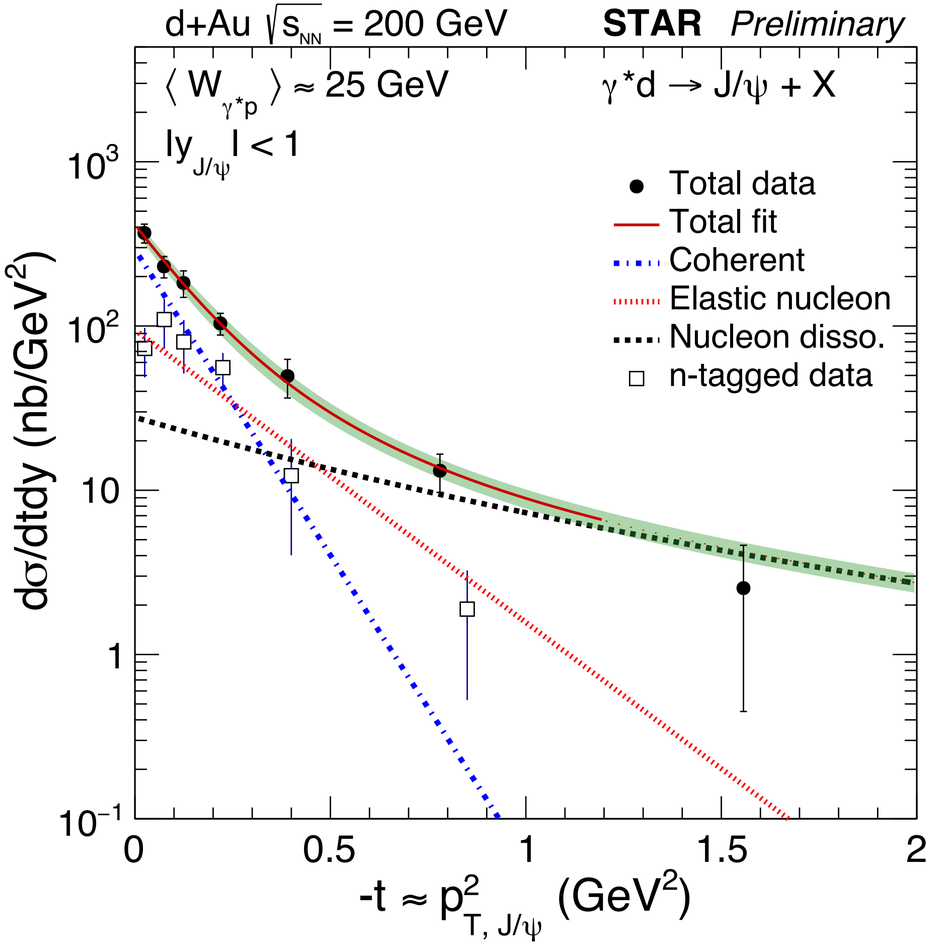
PHENIX: pp at $\sqrt{s} = 510$ GeV; $\mathcal{L} = 94.4$ pb^{-1}

PHENIX, Phys. Rev. D **101** (2020) 052006

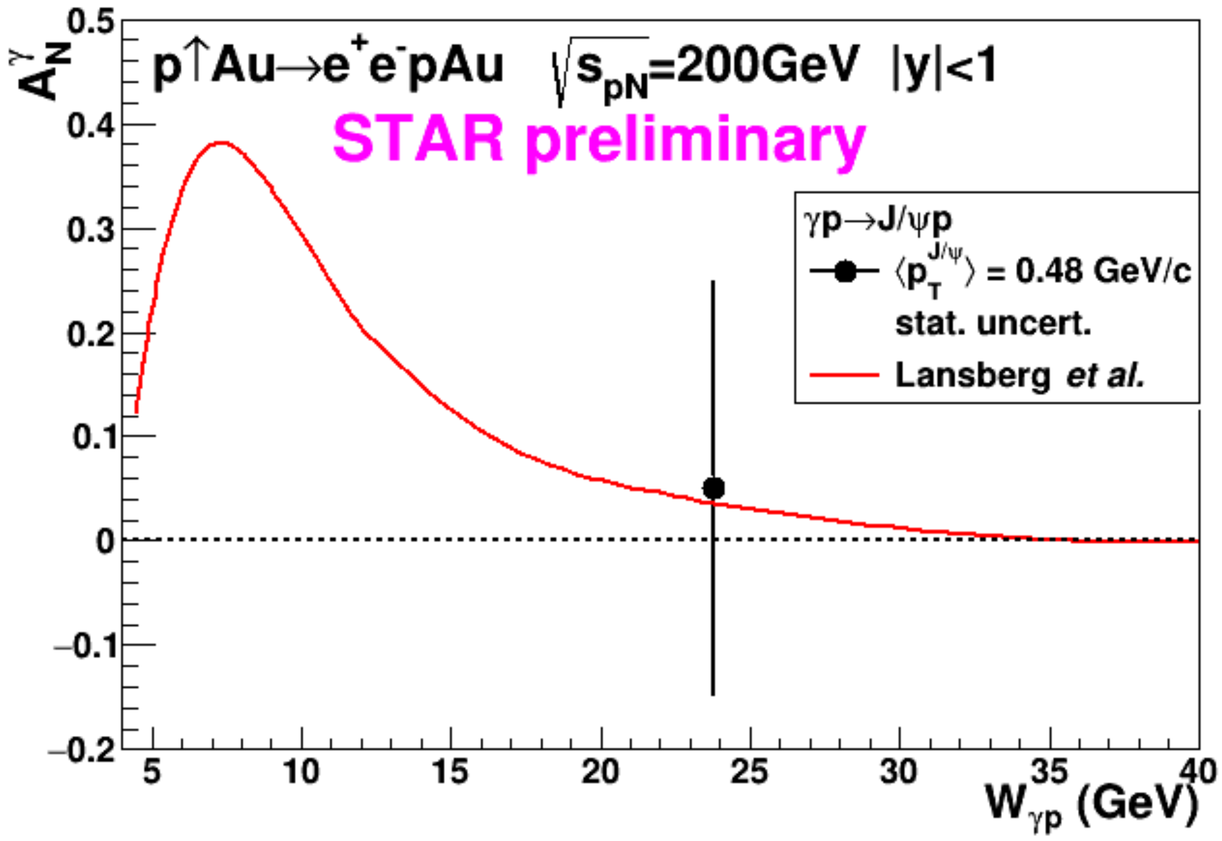




J/ψ production in d Au UPCs at STAR



Coherent Quarkonium photoproduction on transversely polarised proton



Transverse spin asymmetry in ultra-peripheral collisions

→ first low-x_B channel to complement transversely polarised fixed-target measurements