

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

Charlotte Van Hulse,
IJCLab, Paris-Saclay University



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Joint workshop "GDR-QCD/QCD@short distances and
STRONG2020/PARTONS/FTE@LHCE/NLOACCESS"

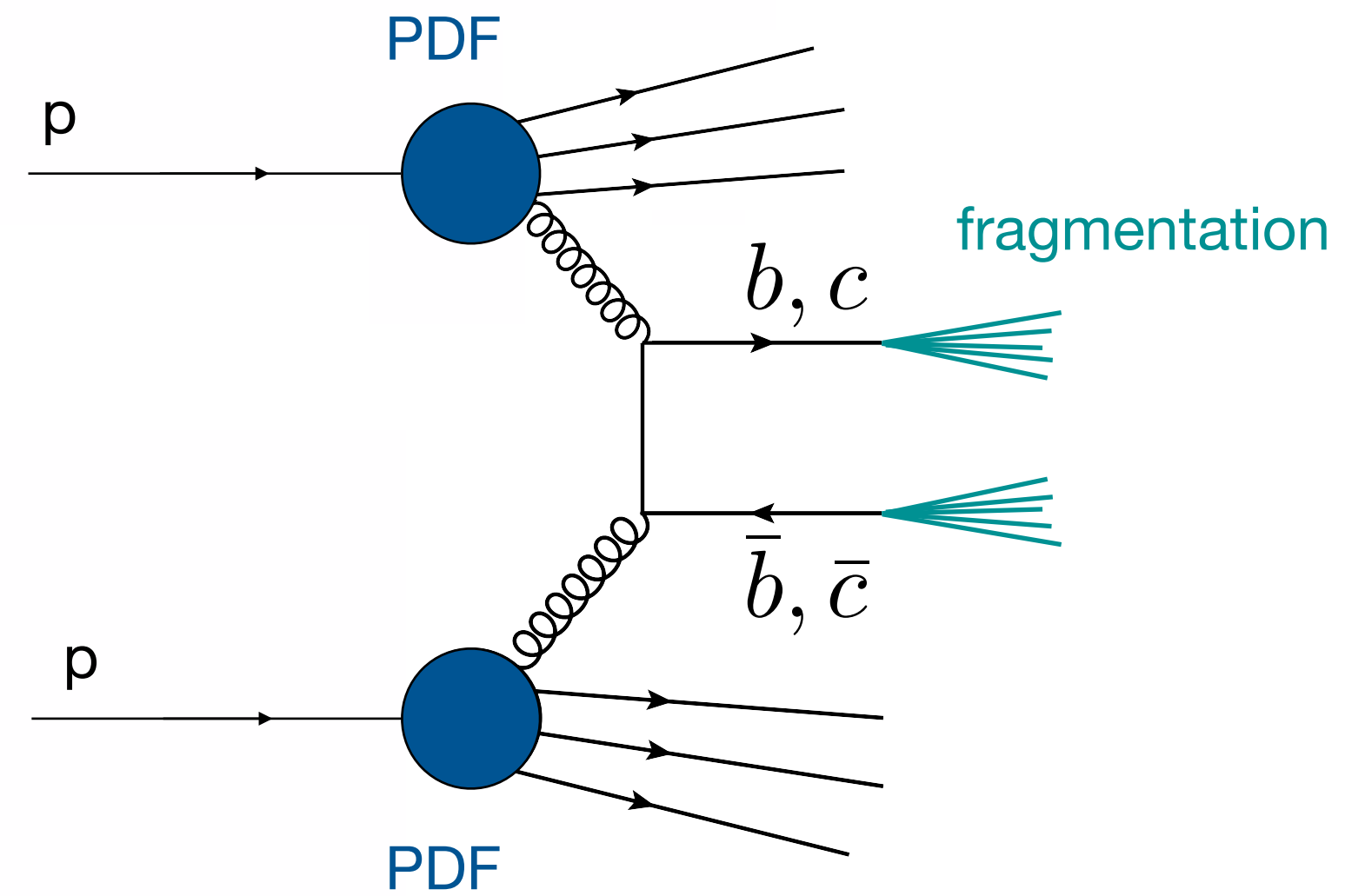
31 May — 4 June 2021

Overview

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

Open-flavour production

Charm and beauty production

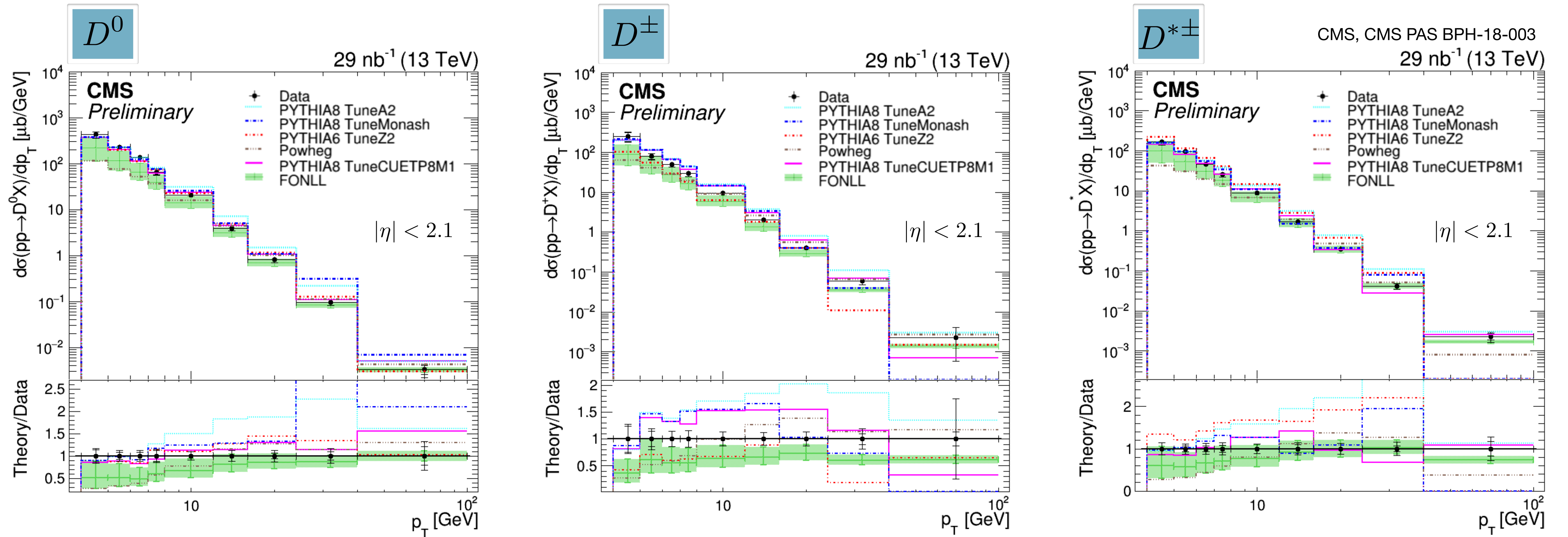


large mass:

- provides hard scale: (test) perturbative QCD
- probe nucleon/nucleus
- created at beginning of interaction
- investigate parton interaction with medium

D meson production

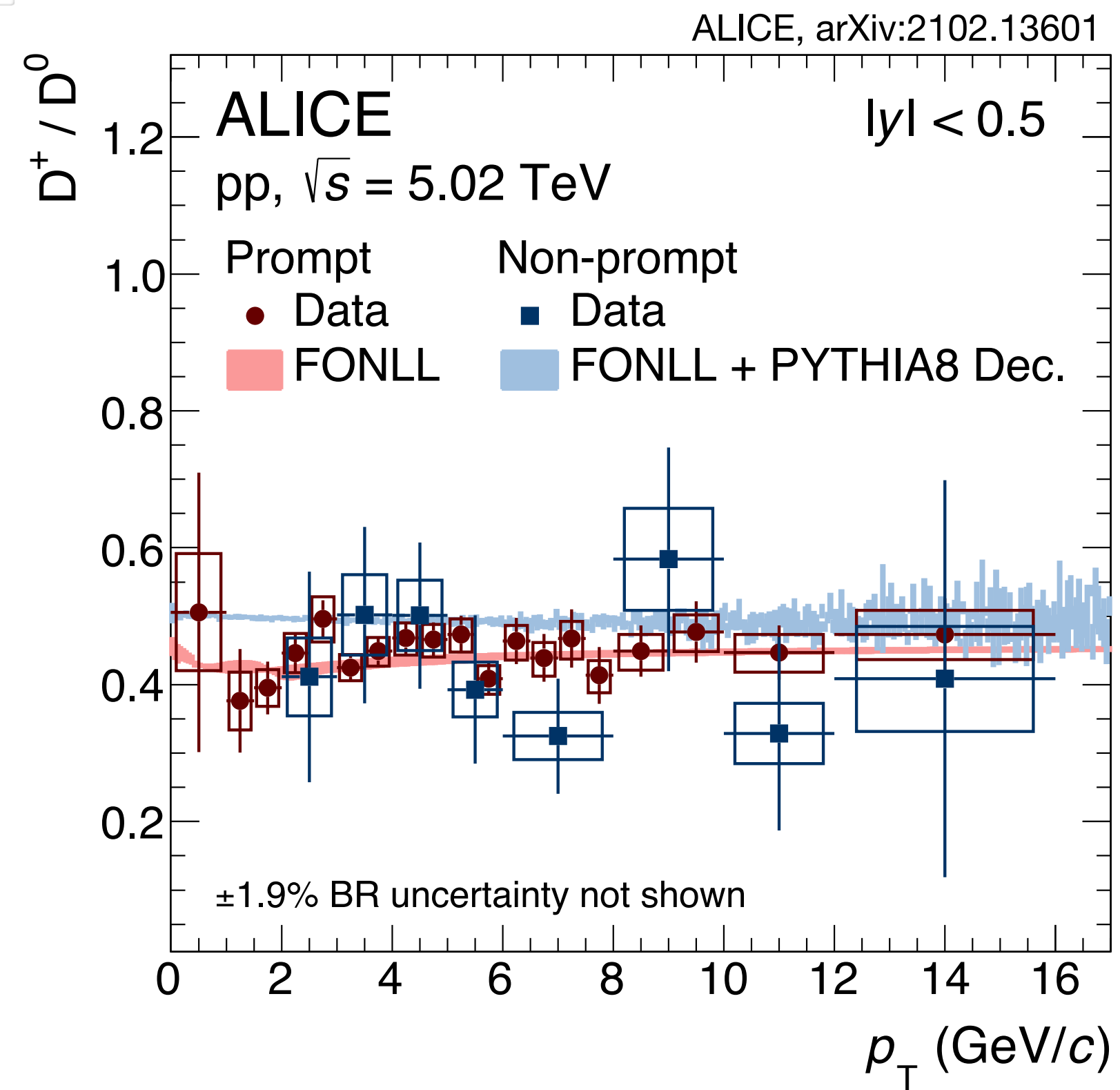
Prompt $D^{*\pm}$, D^\pm , D^0 production in pp at $\sqrt{s} = 13$ TeV



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

Fragmentation of c quarks

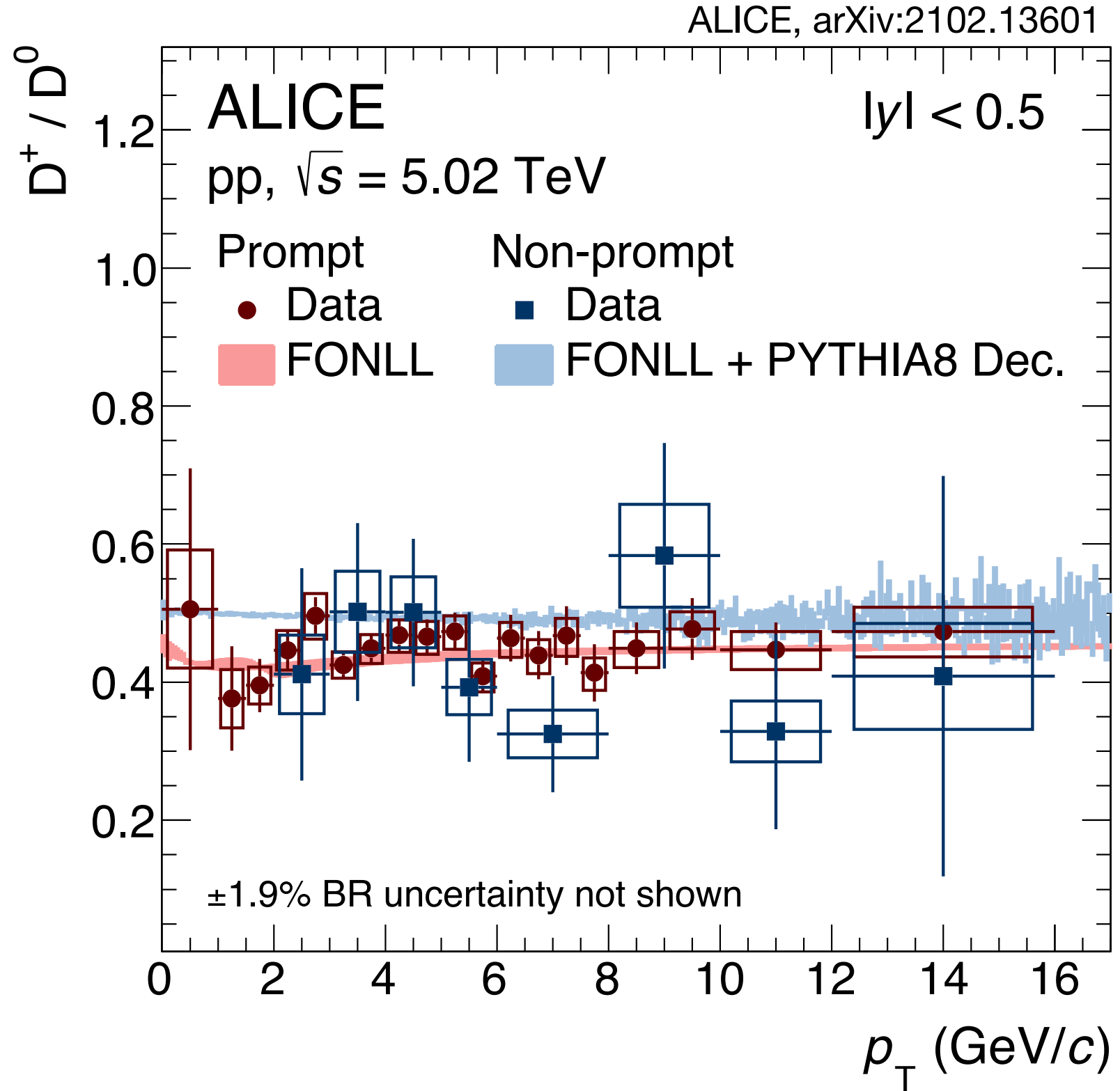
$$D^+ / D^0$$



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

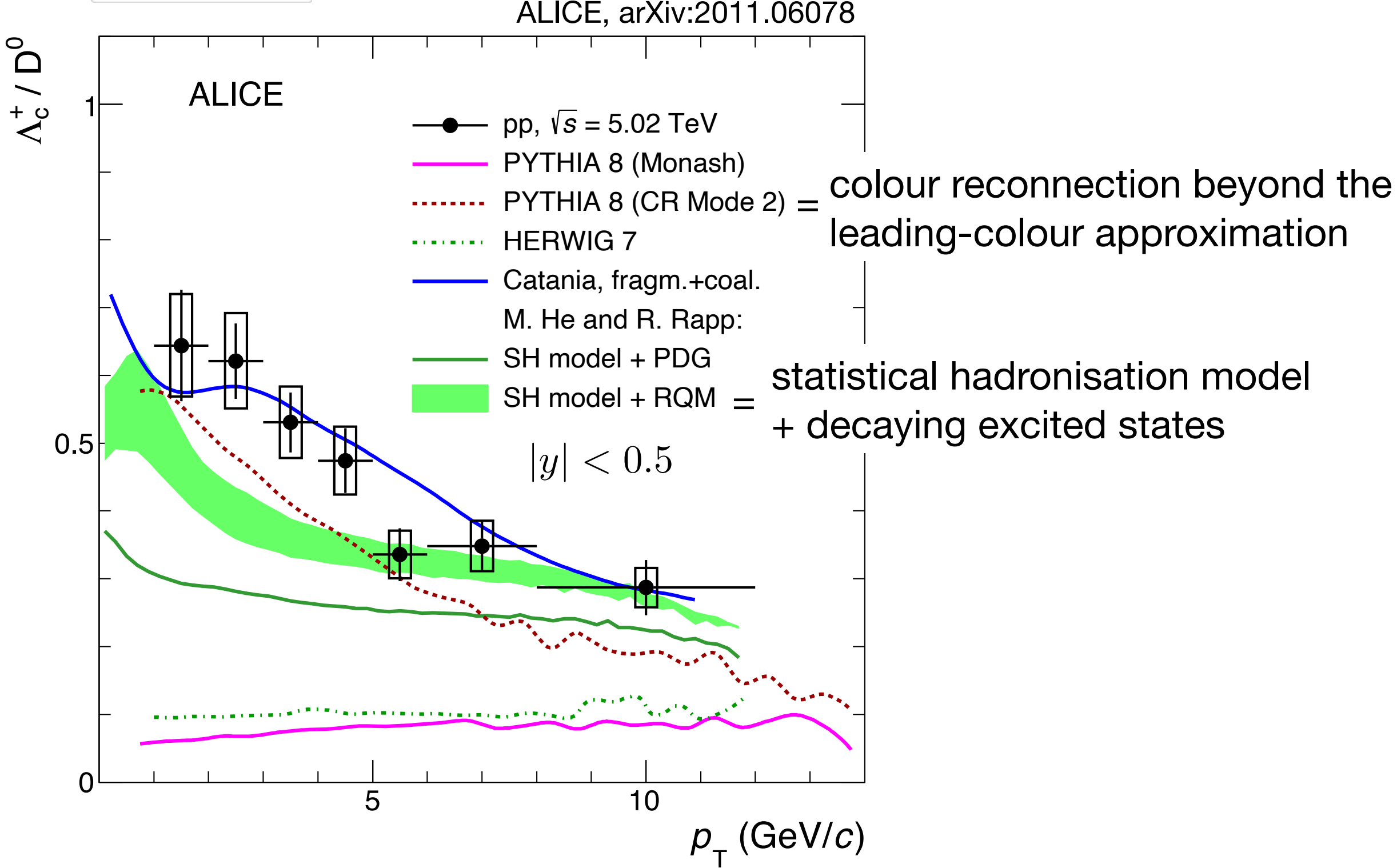
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$$\Lambda_c^+ / D^0$$

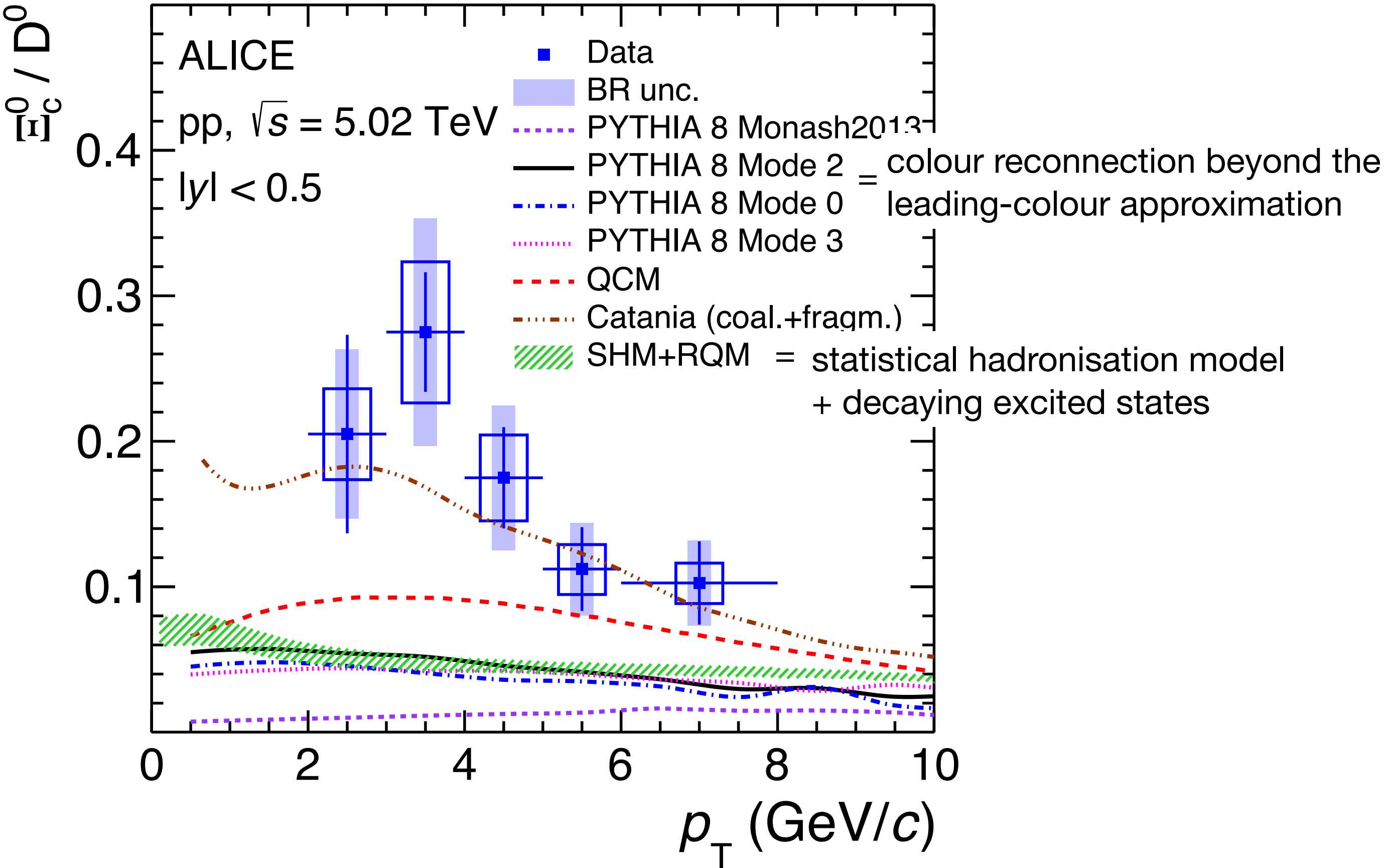


- Improved precision wrt. $\sqrt{s} = 7$ TeV measurement (JHEP04(2018)108)
- Decrease with p_T
 → suggests difference for meson and baryon fragmentation
- Larger than for e^+e^- and ep measurements
 → suggests non-universality

Fragmentation of c quarks

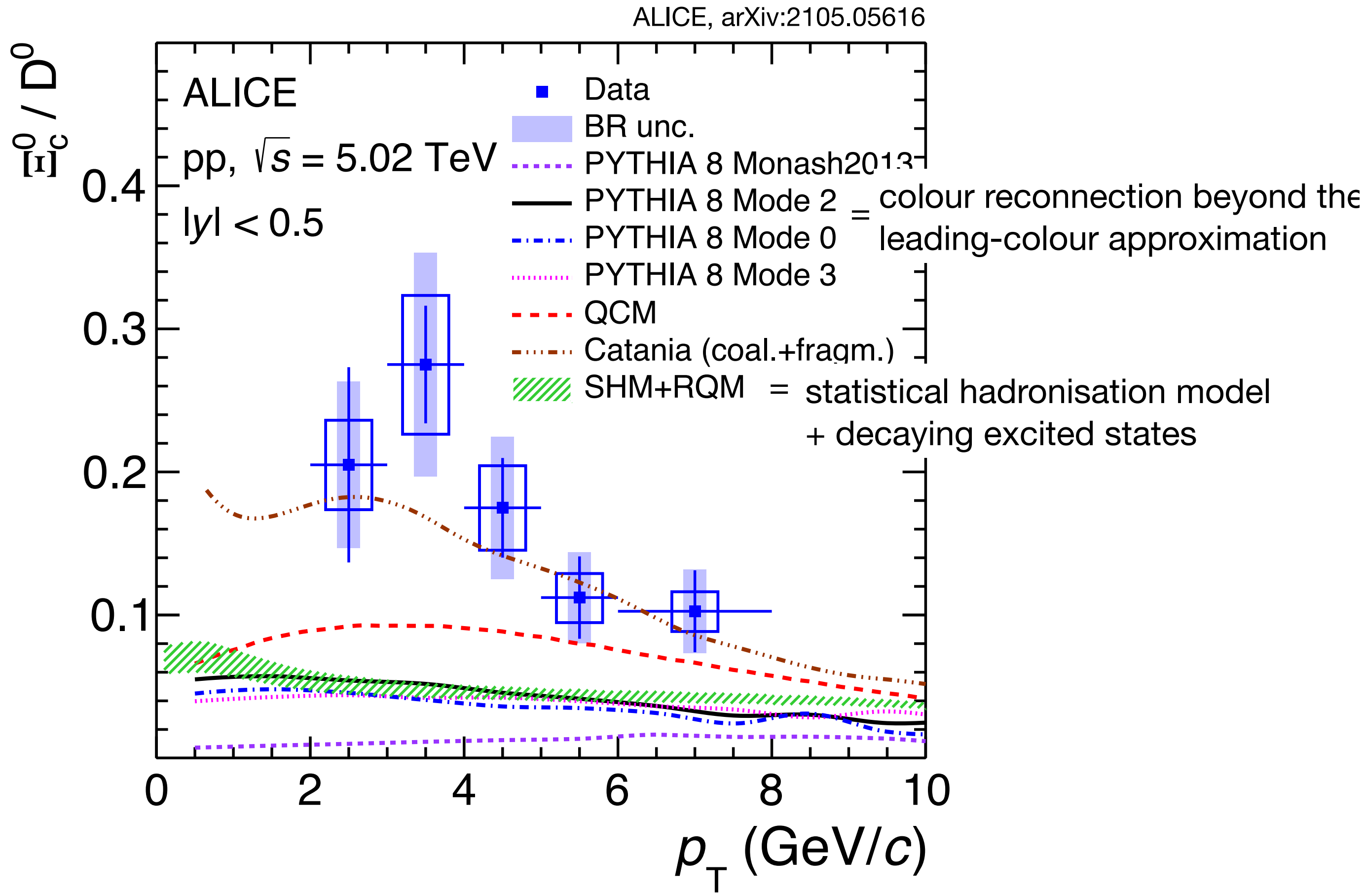
$$\Xi_c^0 / D^0$$

ALICE, arXiv:2105.05616

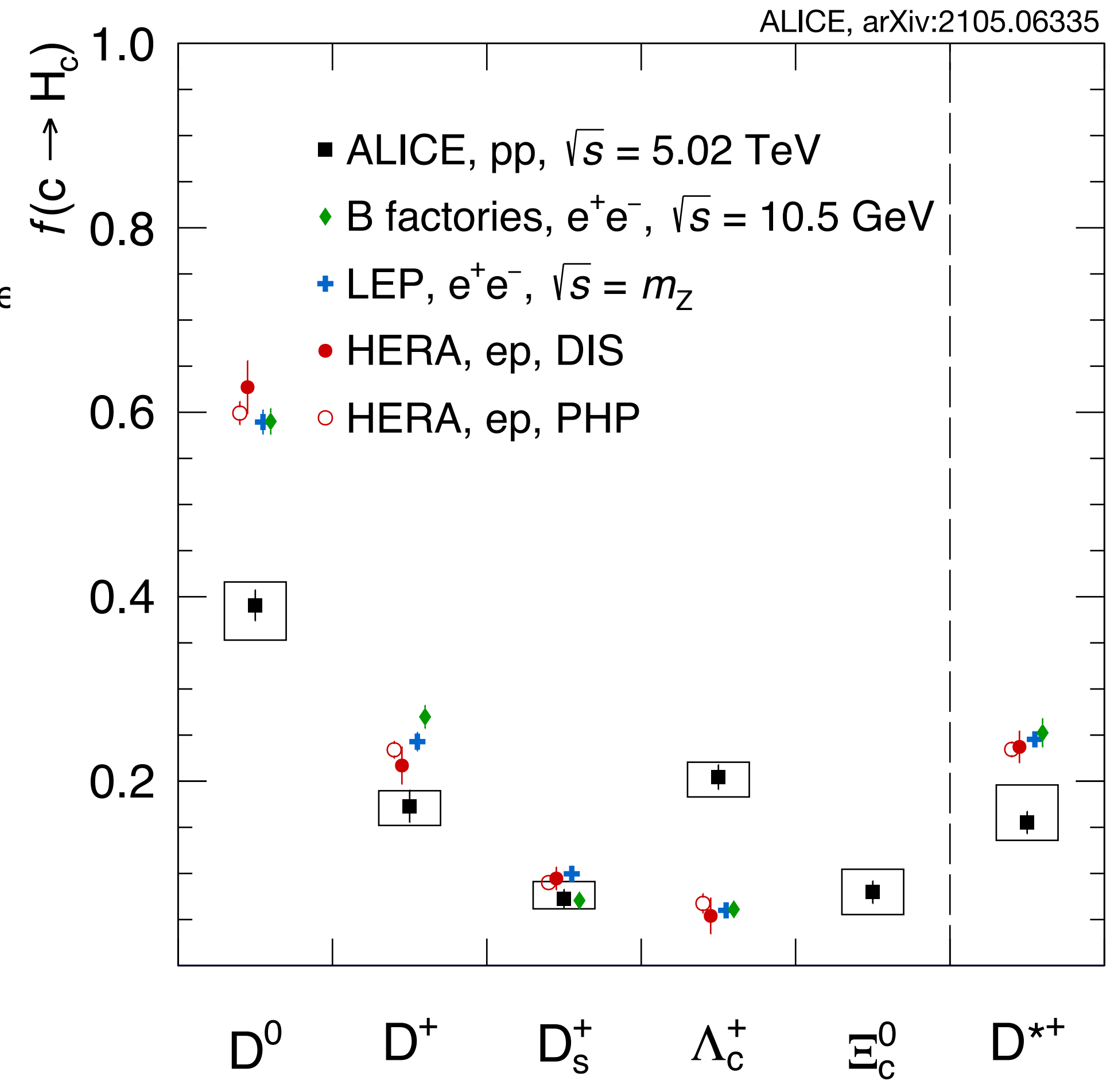


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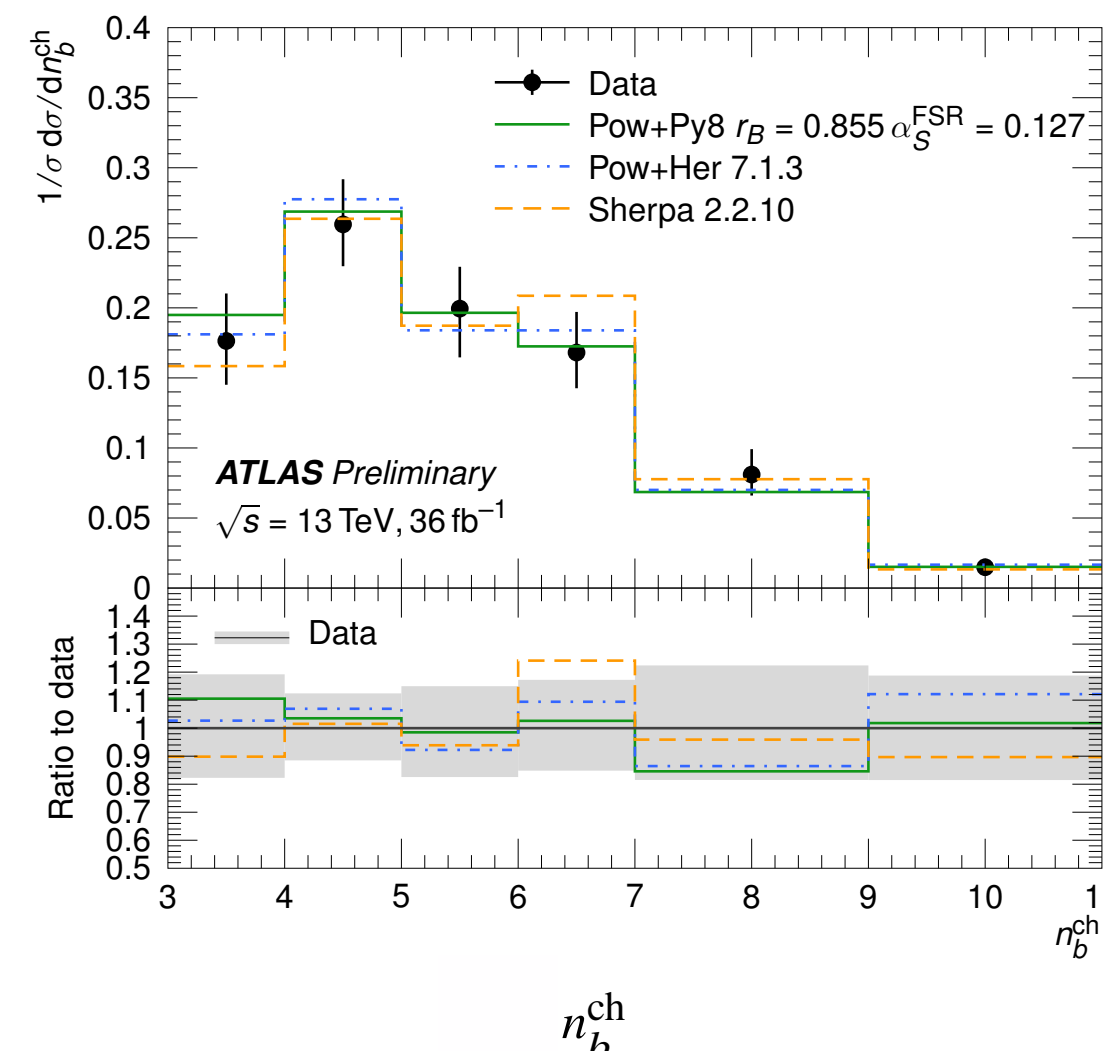
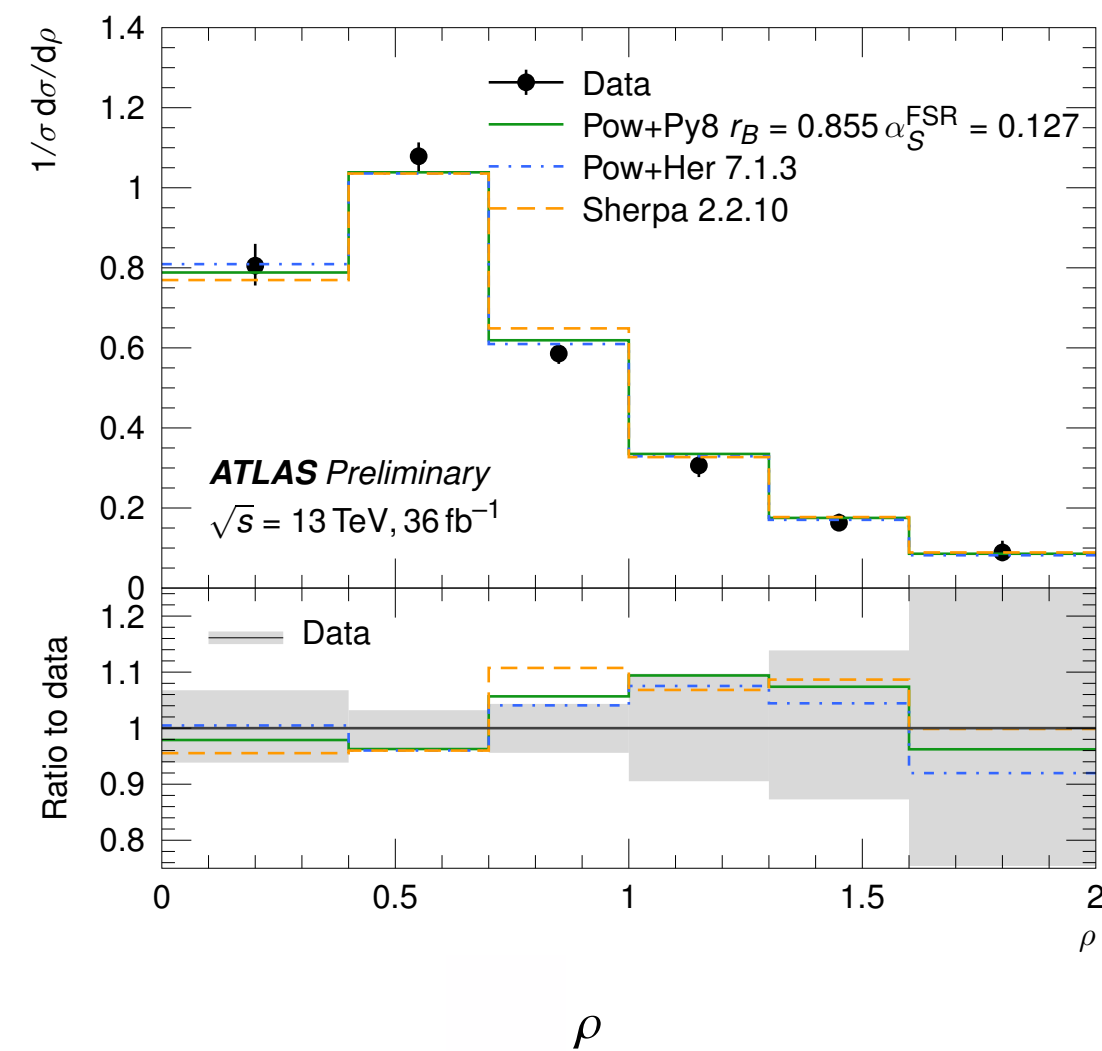
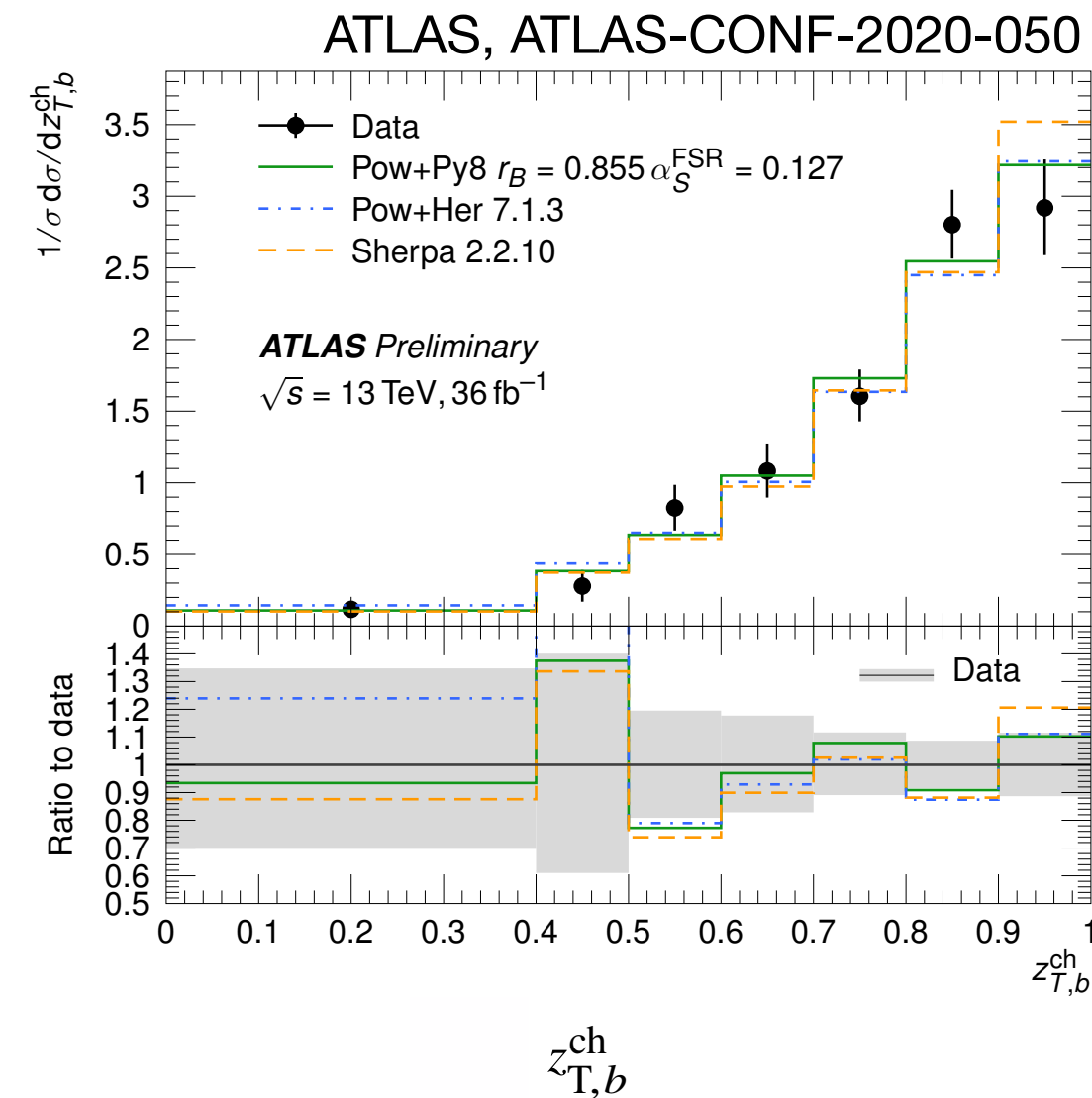
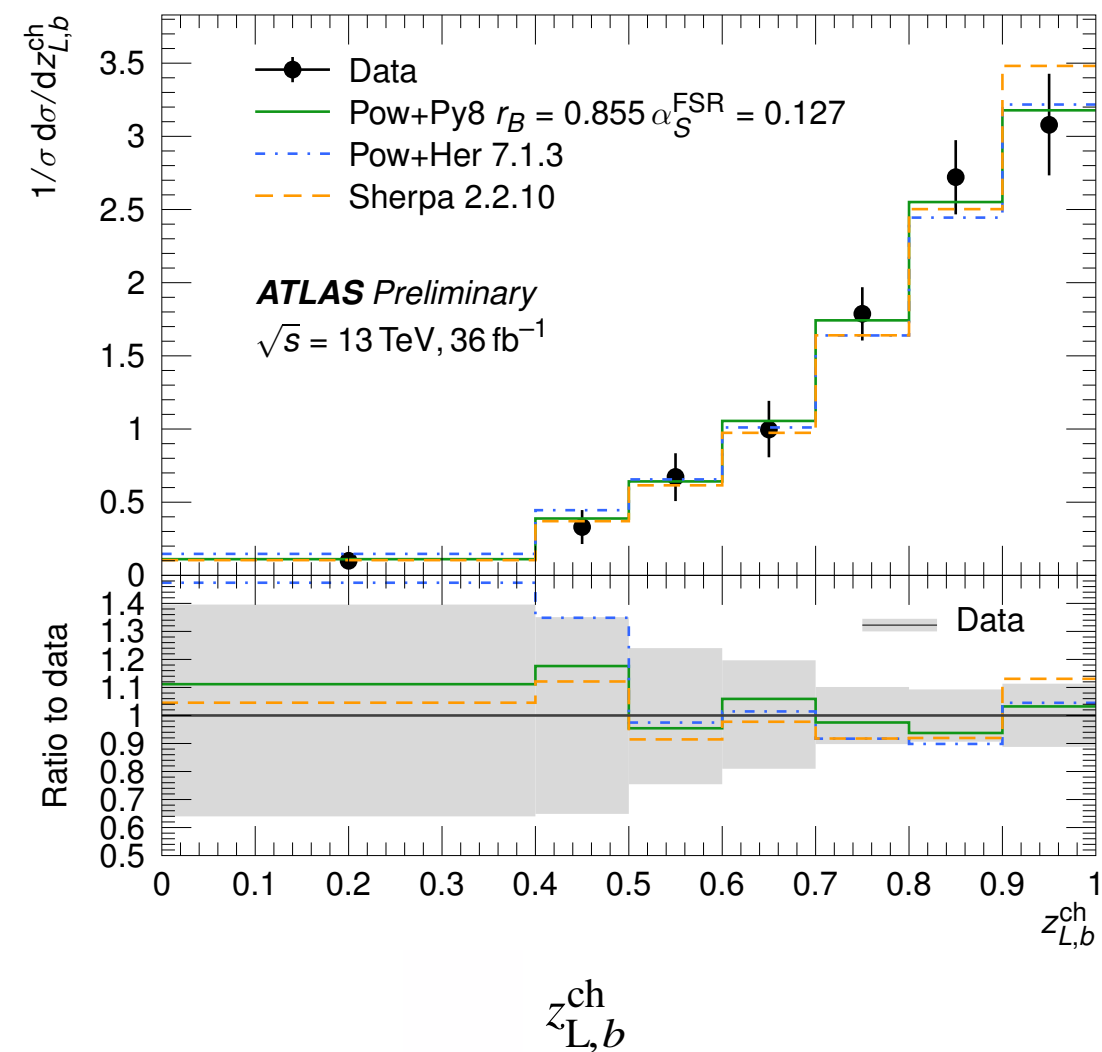
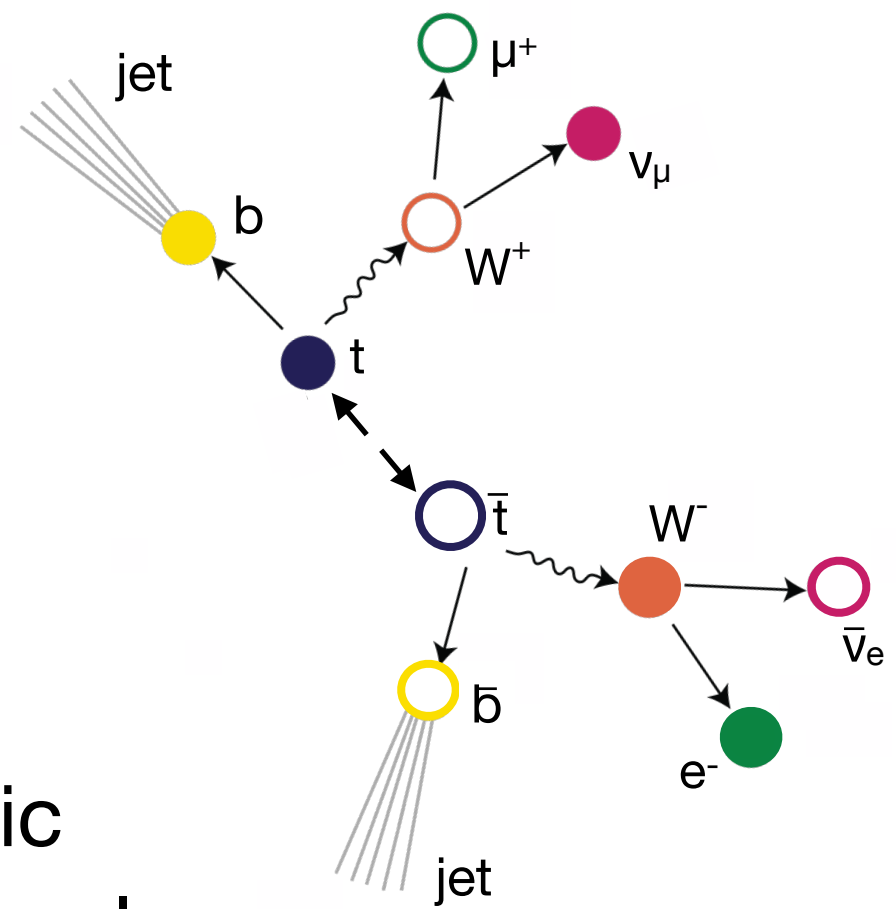


Fractions of charm quark fragmentation into charm hadrons



Additional indication of non-universal hadronisation

Fragmentation of b quarks

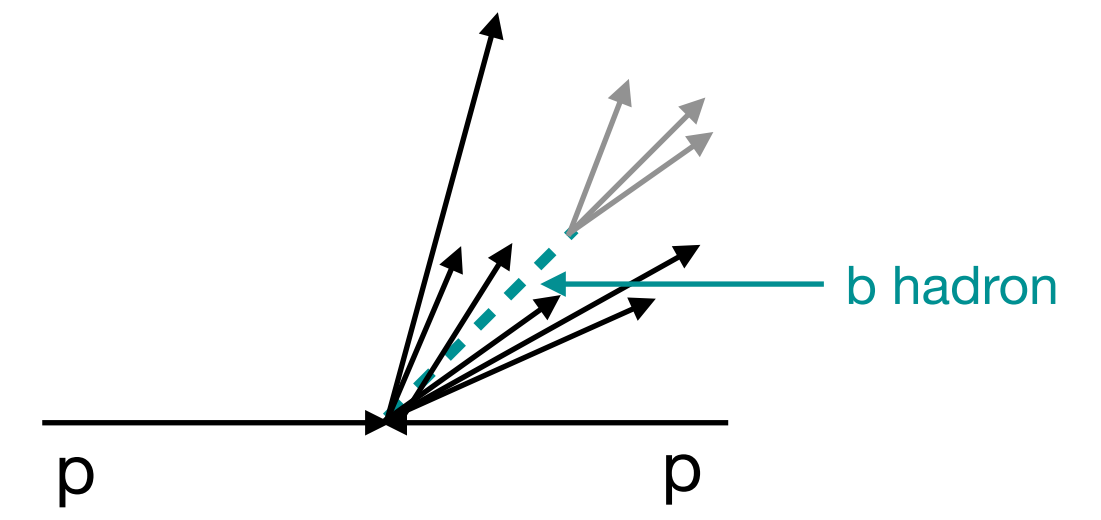


- b hadrons in jets from $t\bar{t}$ event sample
- Complement data from e^+e^- annihilation
- Probe effect of QCD ISR, multiple partonic interactions on fragmentation in more complex environment of hadron colliders
- Comparison of charged momentum of b hadron to

▶ charged jet components

$$z_{T,b}^{\text{ch}} = \frac{p_{T,b}^{\text{ch}}}{p_{T,\text{jet}}^{\text{ch}}}$$

$$z_{L,b}^{\text{ch}} = \frac{\vec{p}_b^{\text{ch}} \cdot \vec{p}_{\text{jet}}^{\text{ch}}}{|p_{\text{jet}}^{\text{ch}}|^2}$$



▶ $t\bar{t} \rightarrow e\mu b\bar{b}$

$$\rho = \frac{2p_{T,b}^{\text{ch}}}{p_T^e + p_T^\mu}$$

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

overall good agreement between data and Monte Carlo

Inclusive quarkonium production

Quarkonium production

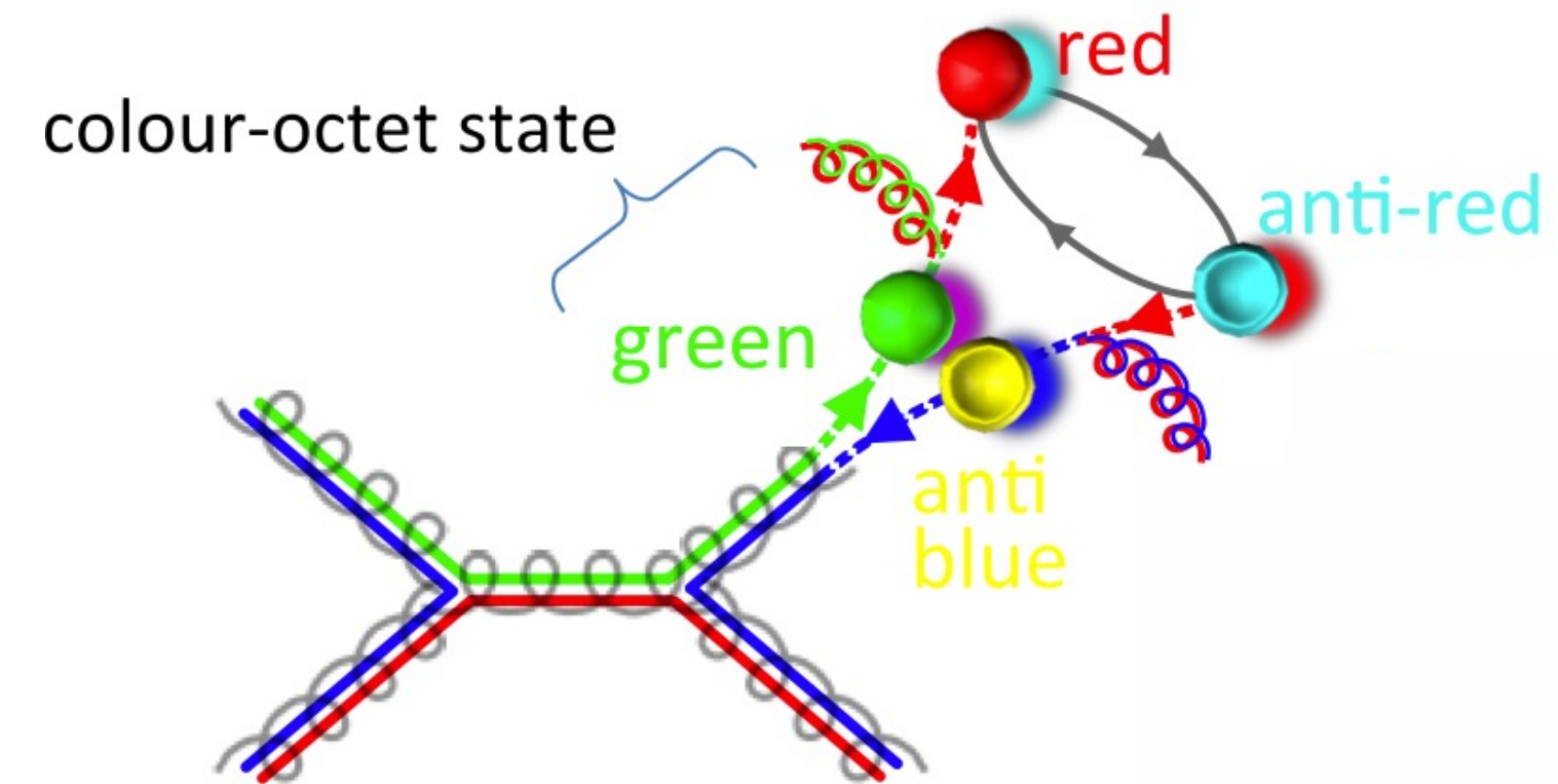
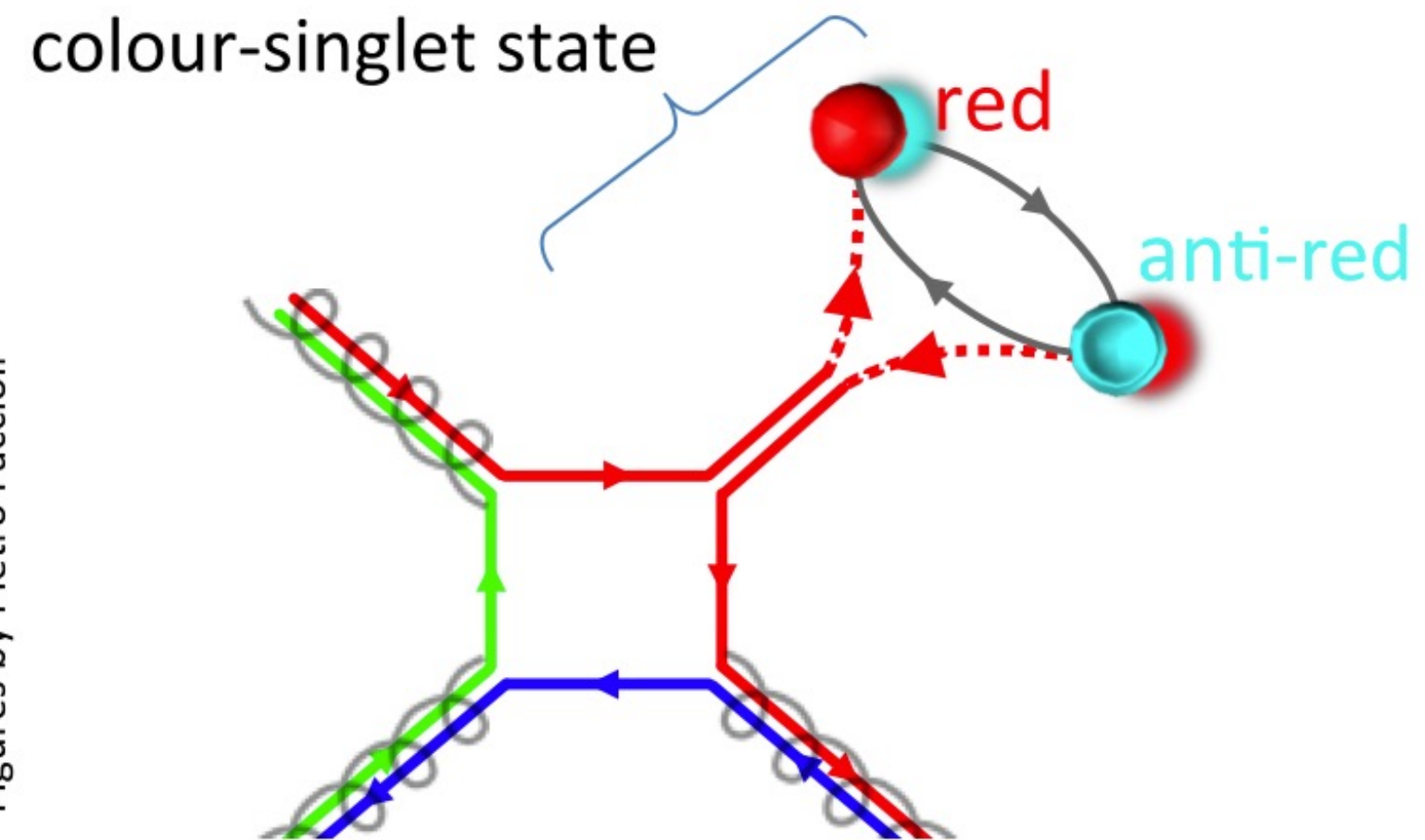
- Production mechanism of quarkonia not understood
- Usual assumption: factorisation between $Q\bar{Q}$ formation and $Q\bar{Q}$ hadronisation
- Different approaches for hadronisation: colour-evaporation model, colour-singlet model, non-relativistic QCD (NRQCD)

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NRQCD

Figures by Pietro Faccioli



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NRQCD



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NRQCD



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Measurements to probe quarkonium production:

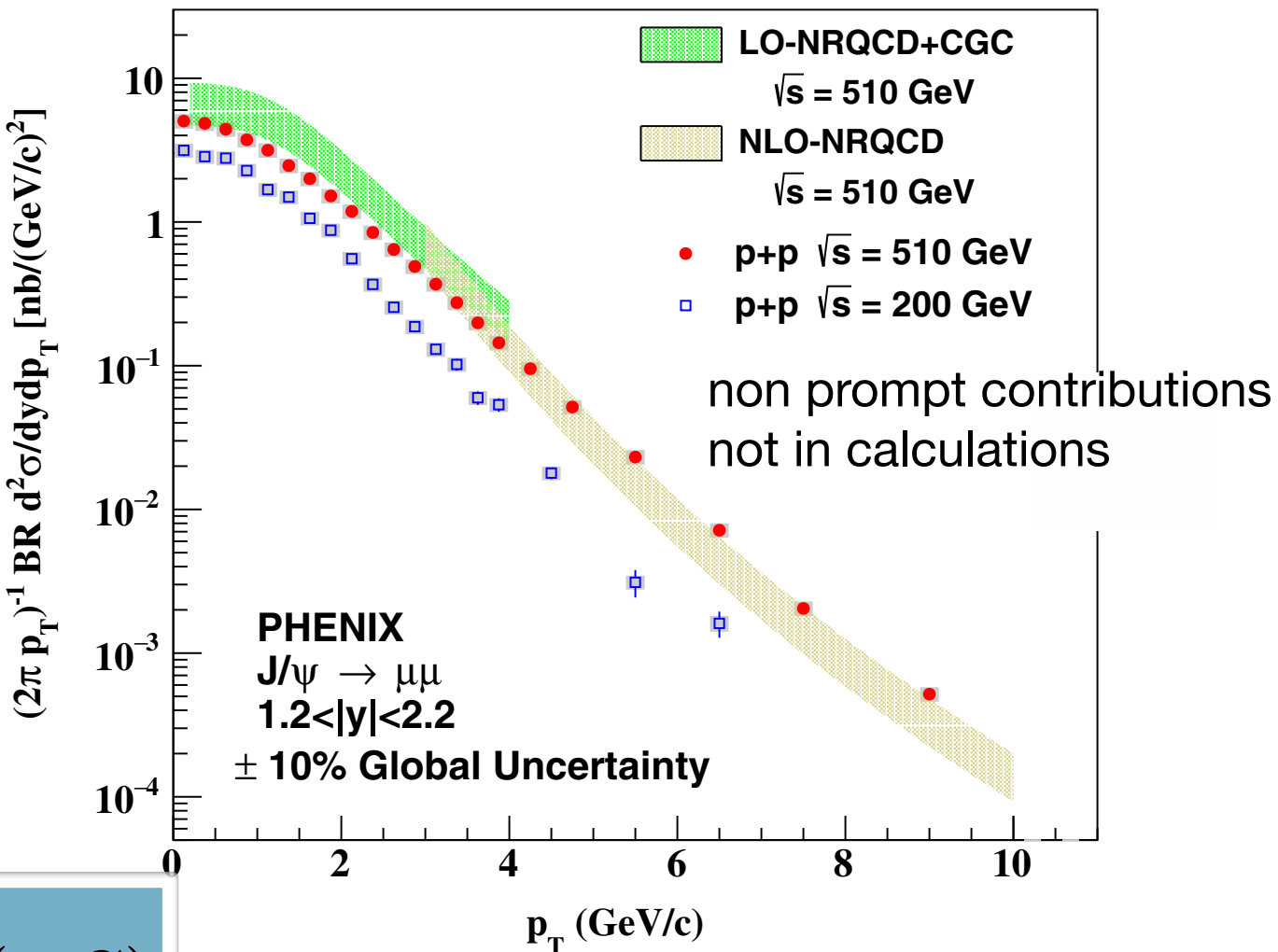
- different COM energies
- large range in p_T and rapidity
- various types of quarkonium states
- polarisation

Quarkonium production in pp

J/ψ

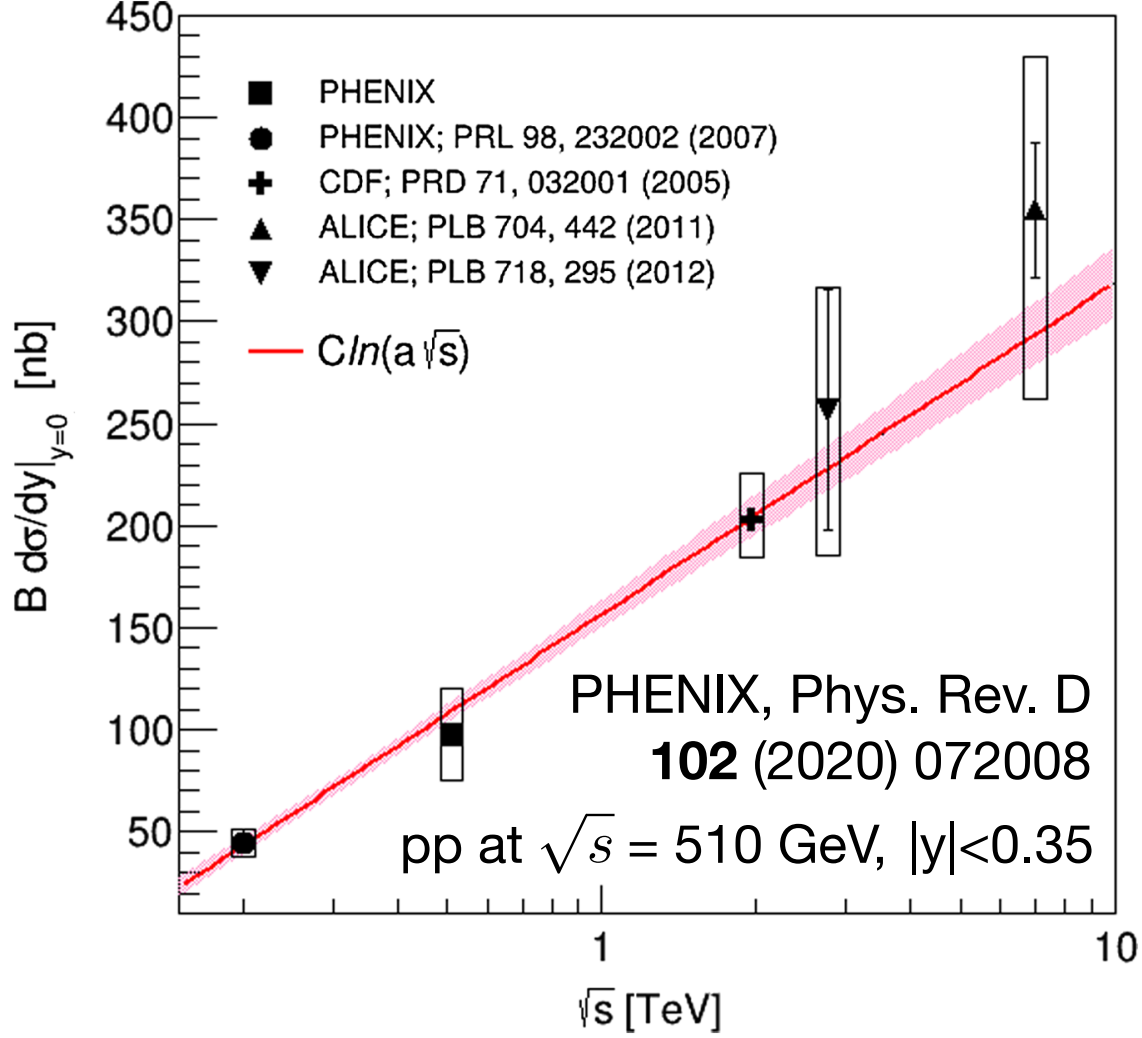
$1.2 < |y| < 2.2$

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



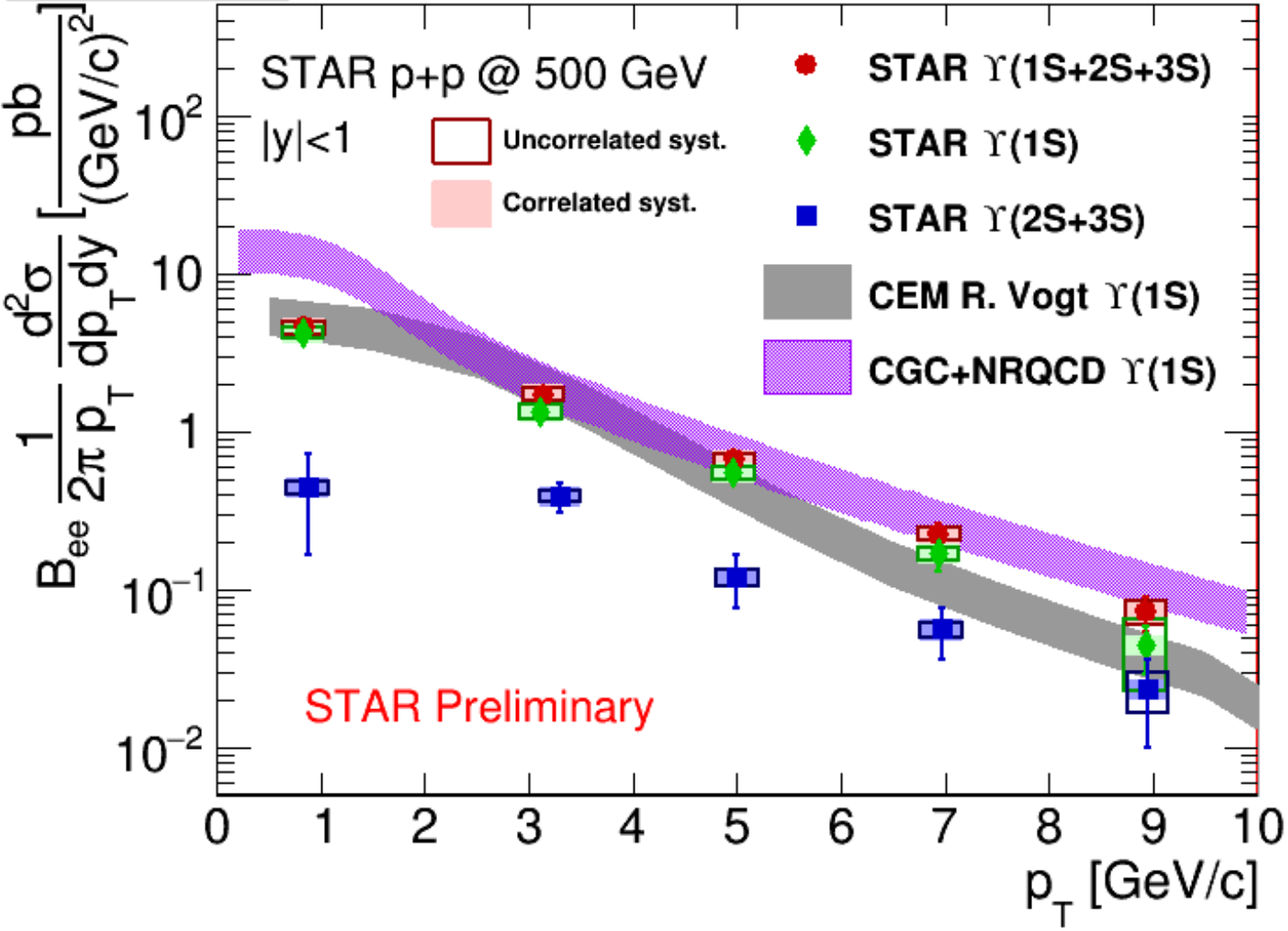
J/ψ

COM E dependence
mid-rapidity

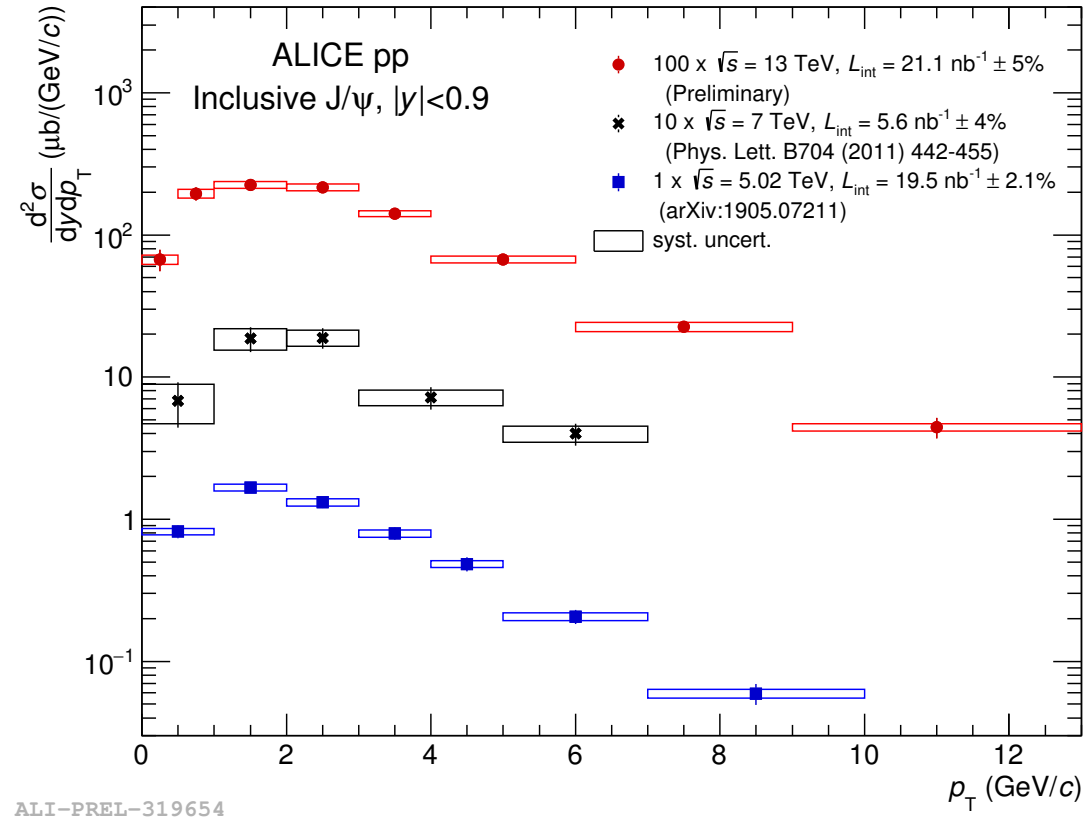


$\Upsilon(nS)$

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



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



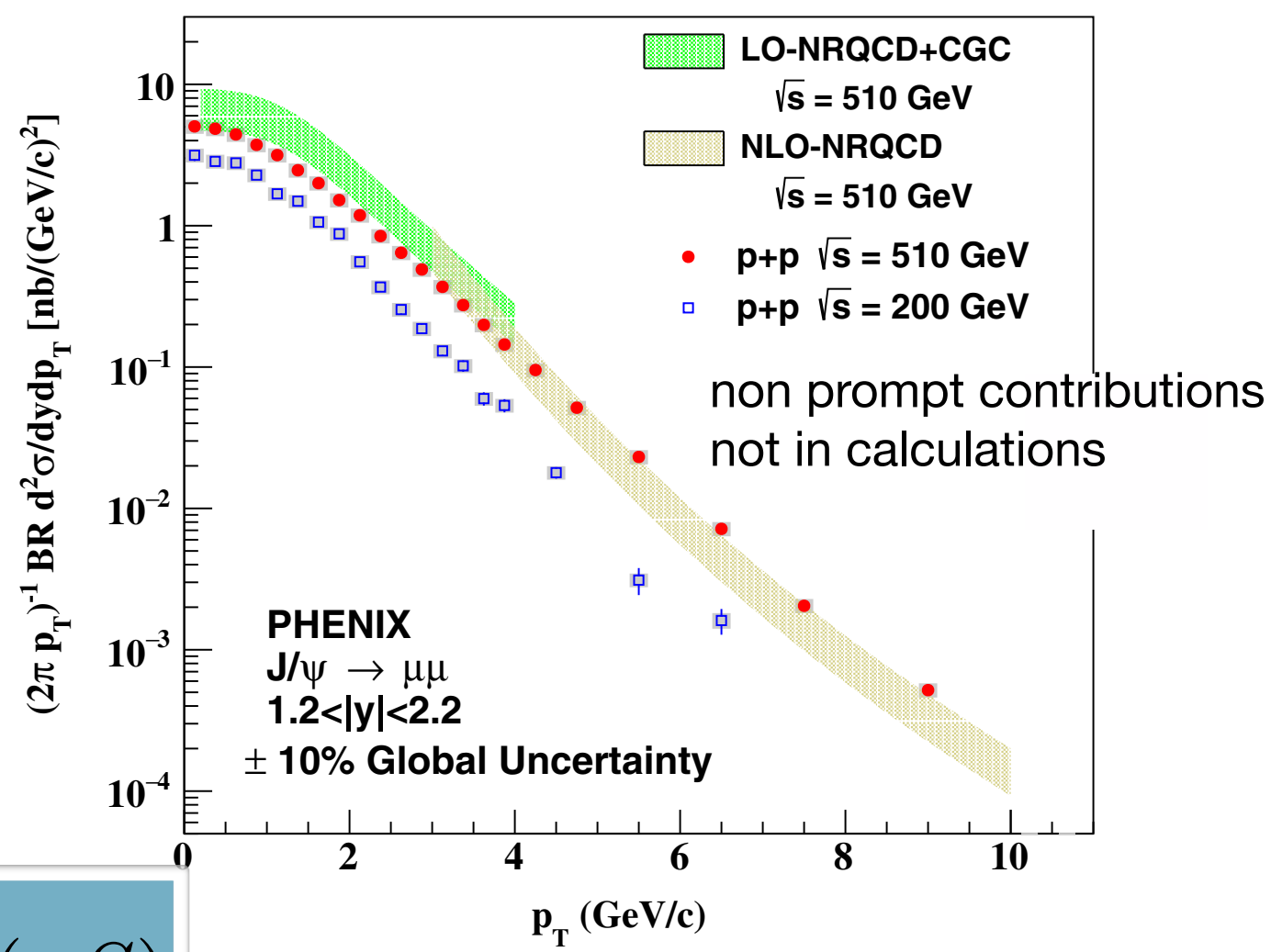
- ATLAS, J/ψ and $\psi(2S)$ in pp at $\sqrt{s} = 13$ TeV (ATLAS-CONF-2019-047)
- ATLAS, Υ in pp at $\sqrt{s} = 5$ TeV (ATLAS, ATLAS-CONF-2019-054)

Quarkonium production in pp

J/ψ

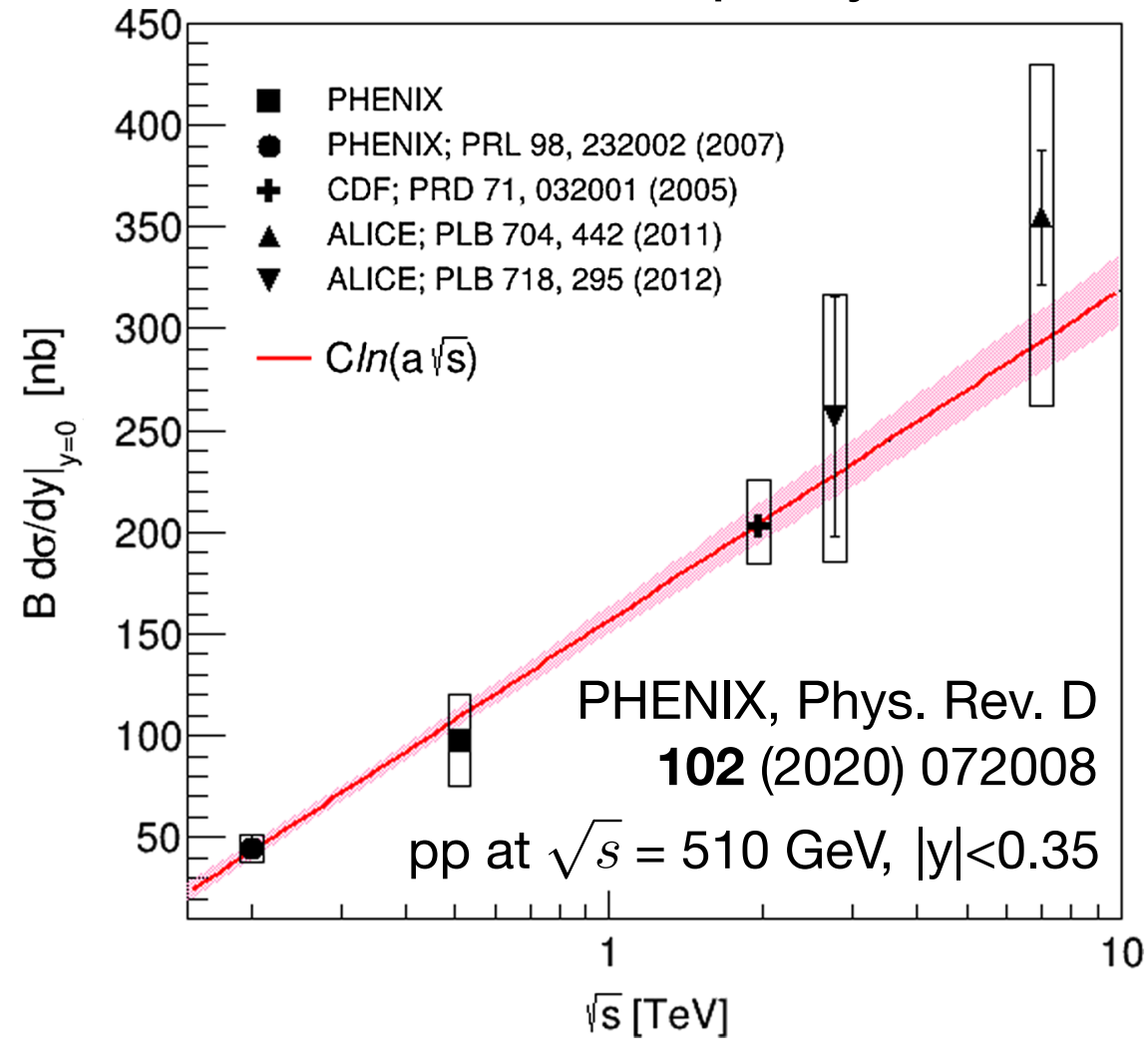
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PHENIX, Phys. Rev. D **101** (2020) 052006



J/ψ

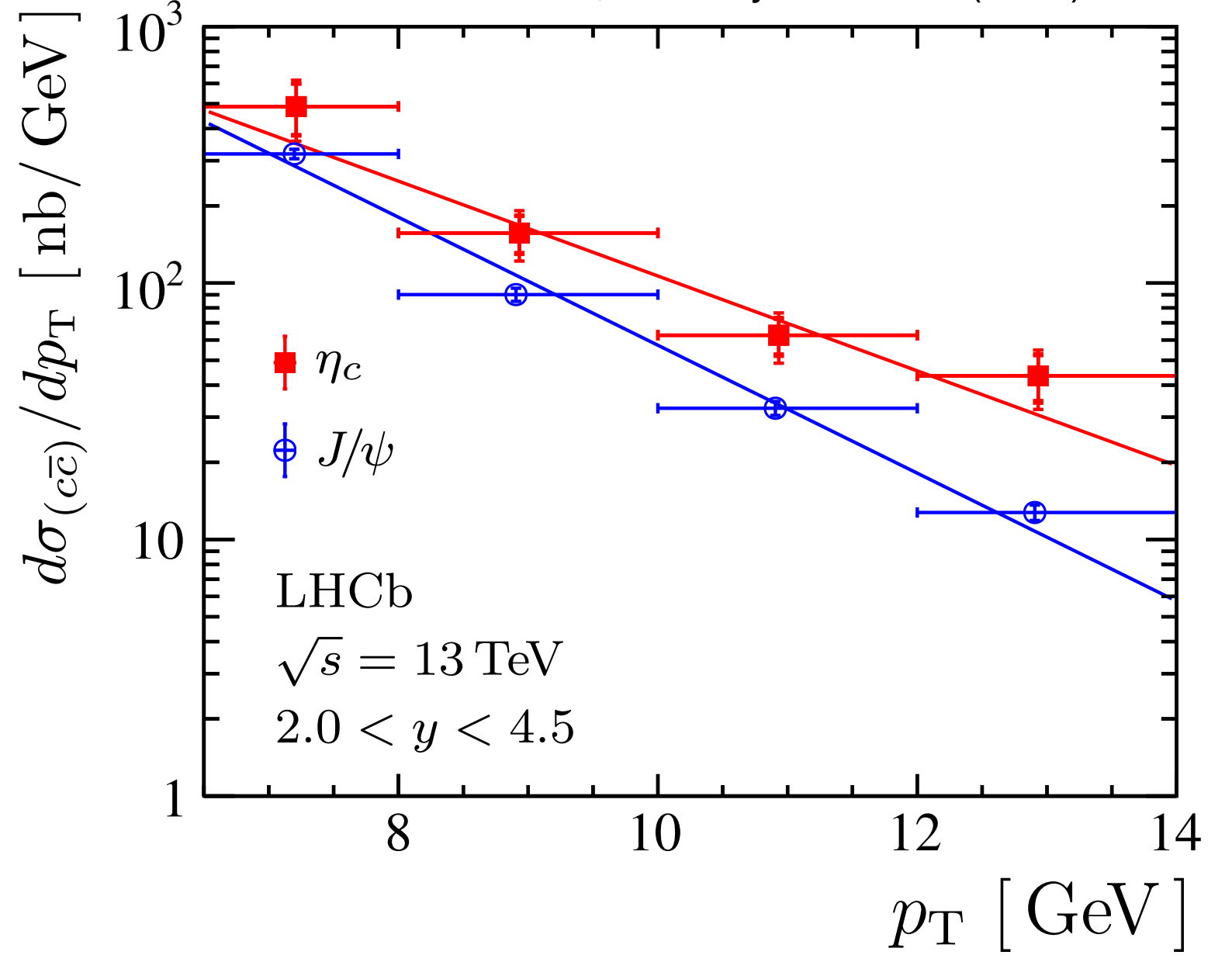
COM E dependence
mid-rapidity



η_c

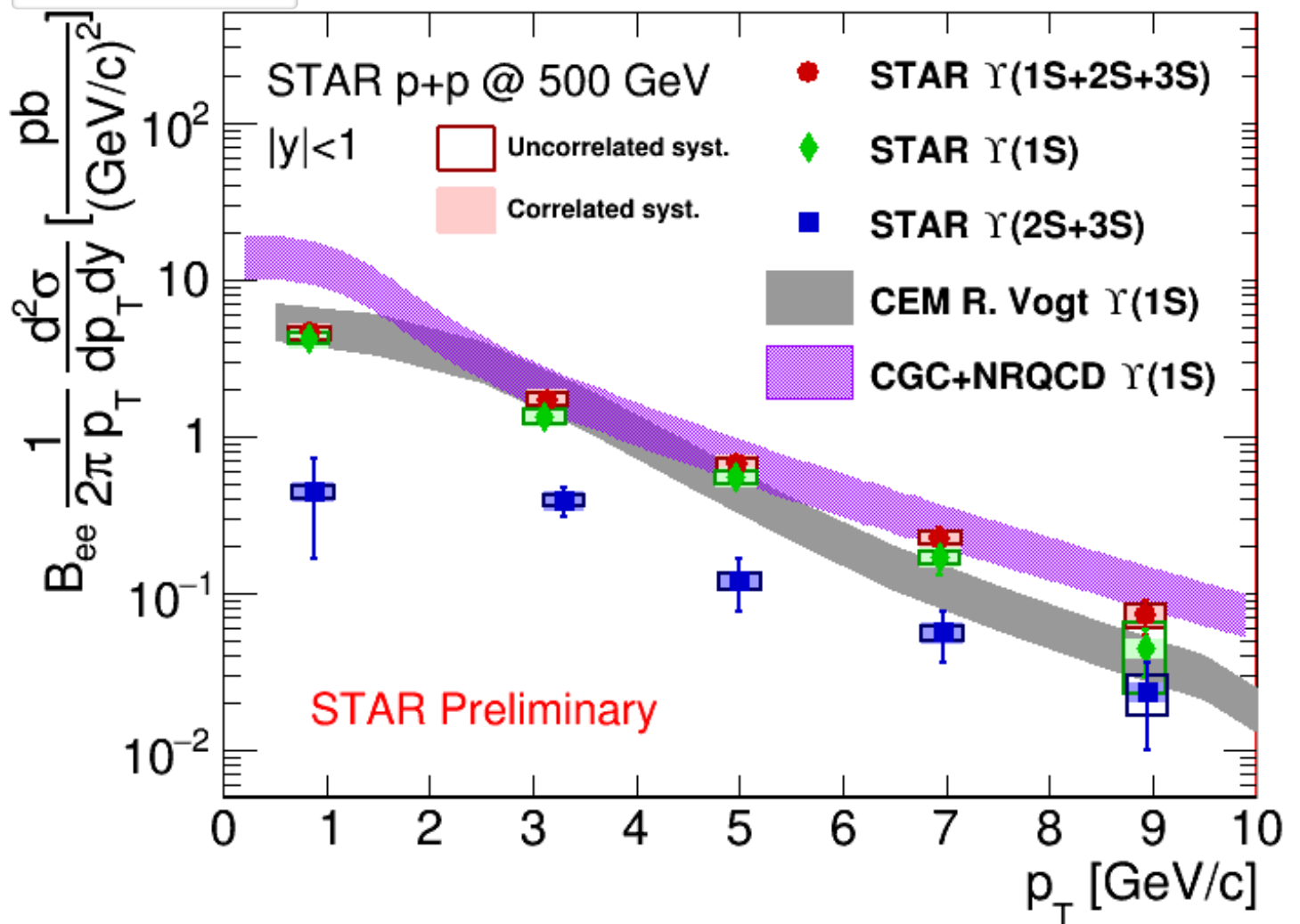
Prompt production

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

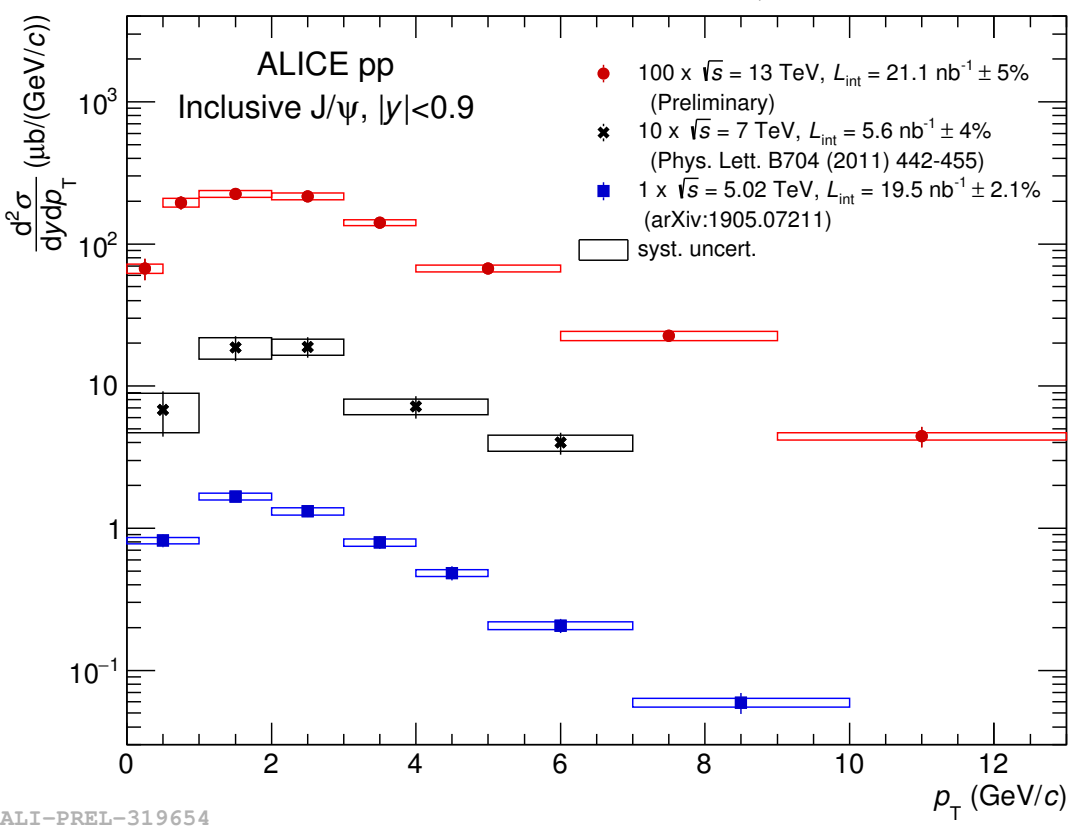


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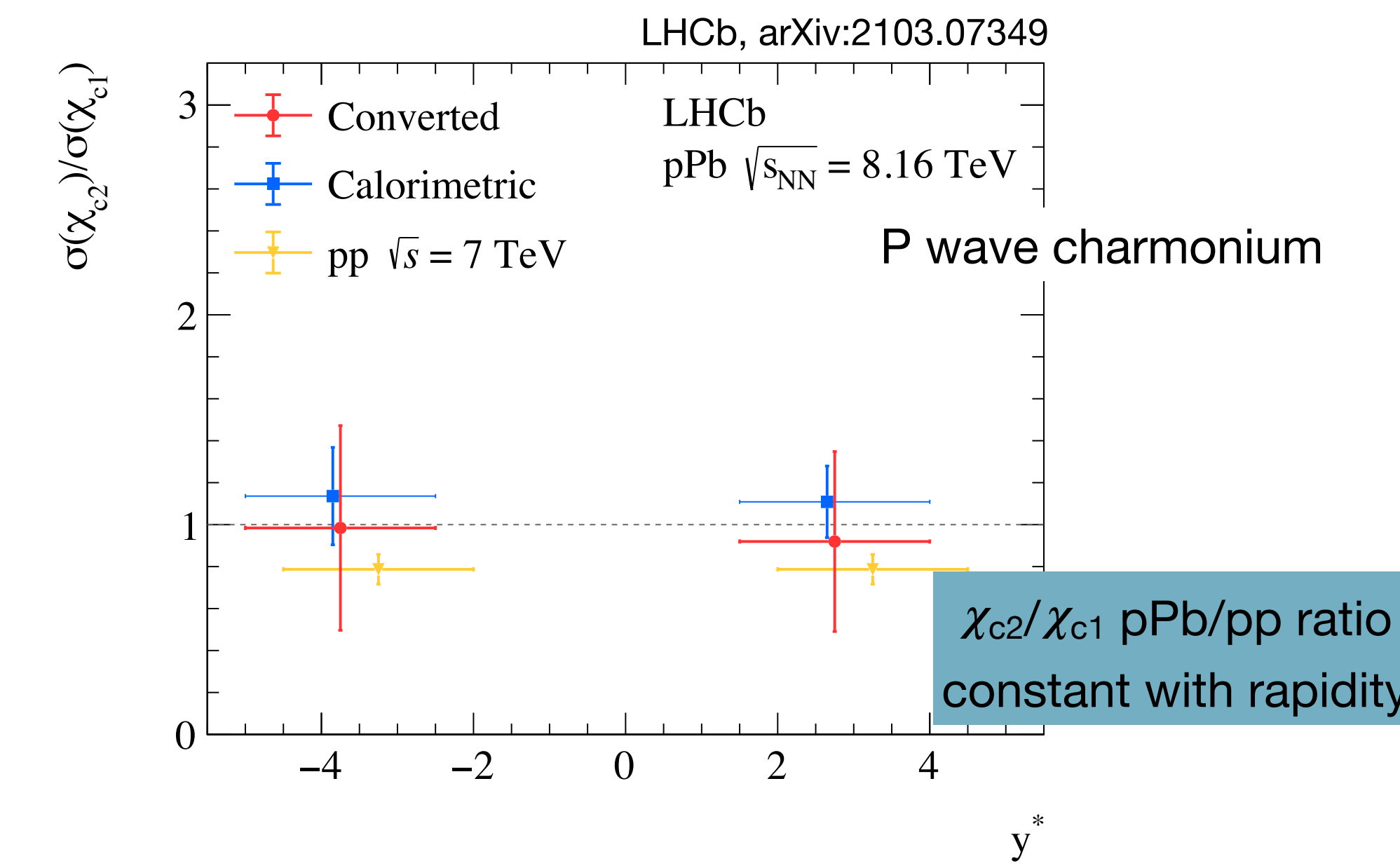
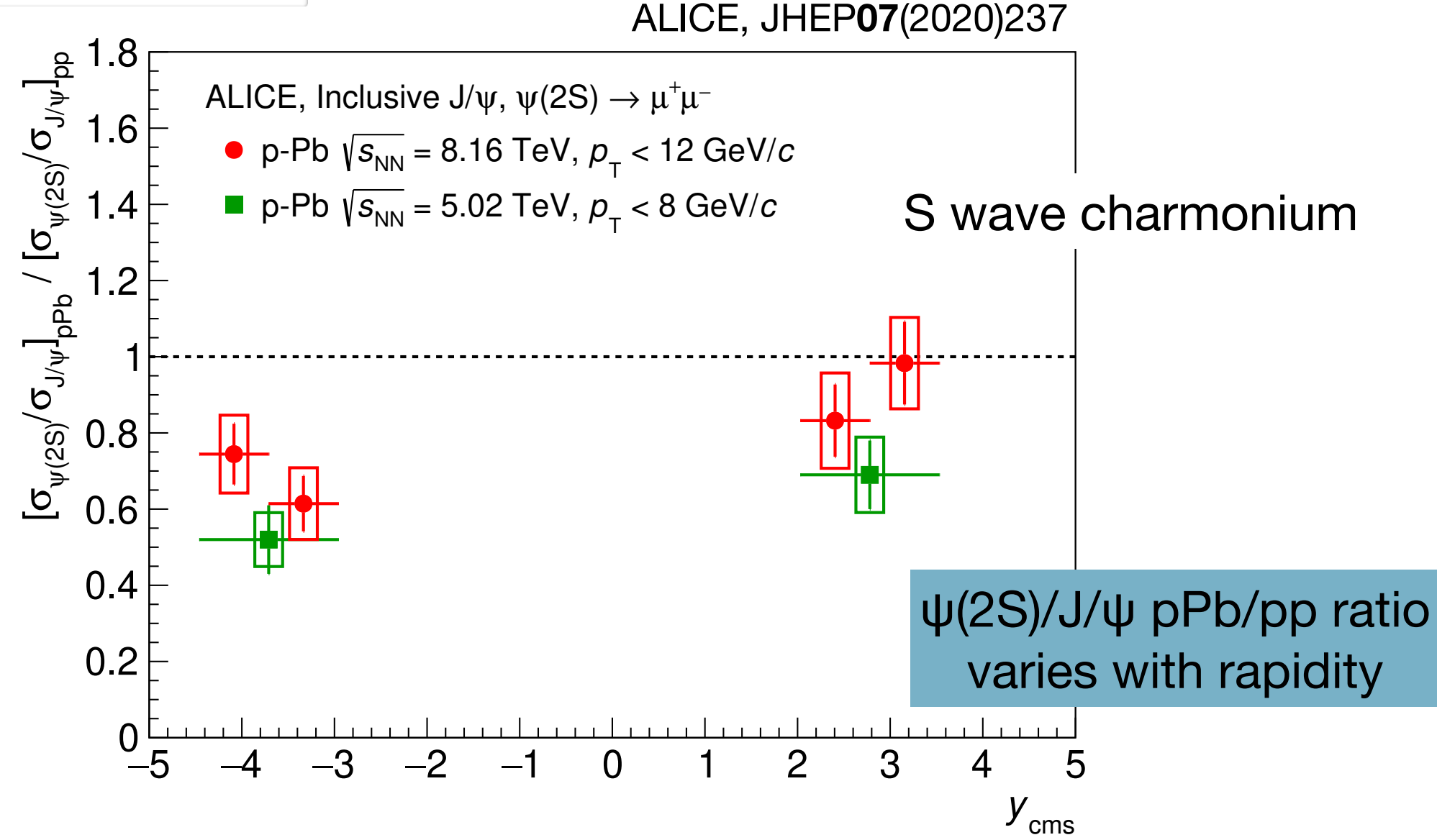
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$J/\psi : J^{PC} = 1^{--}$ ground state
 $\eta_c : J^{PC} = 0^{-+}$ ground state

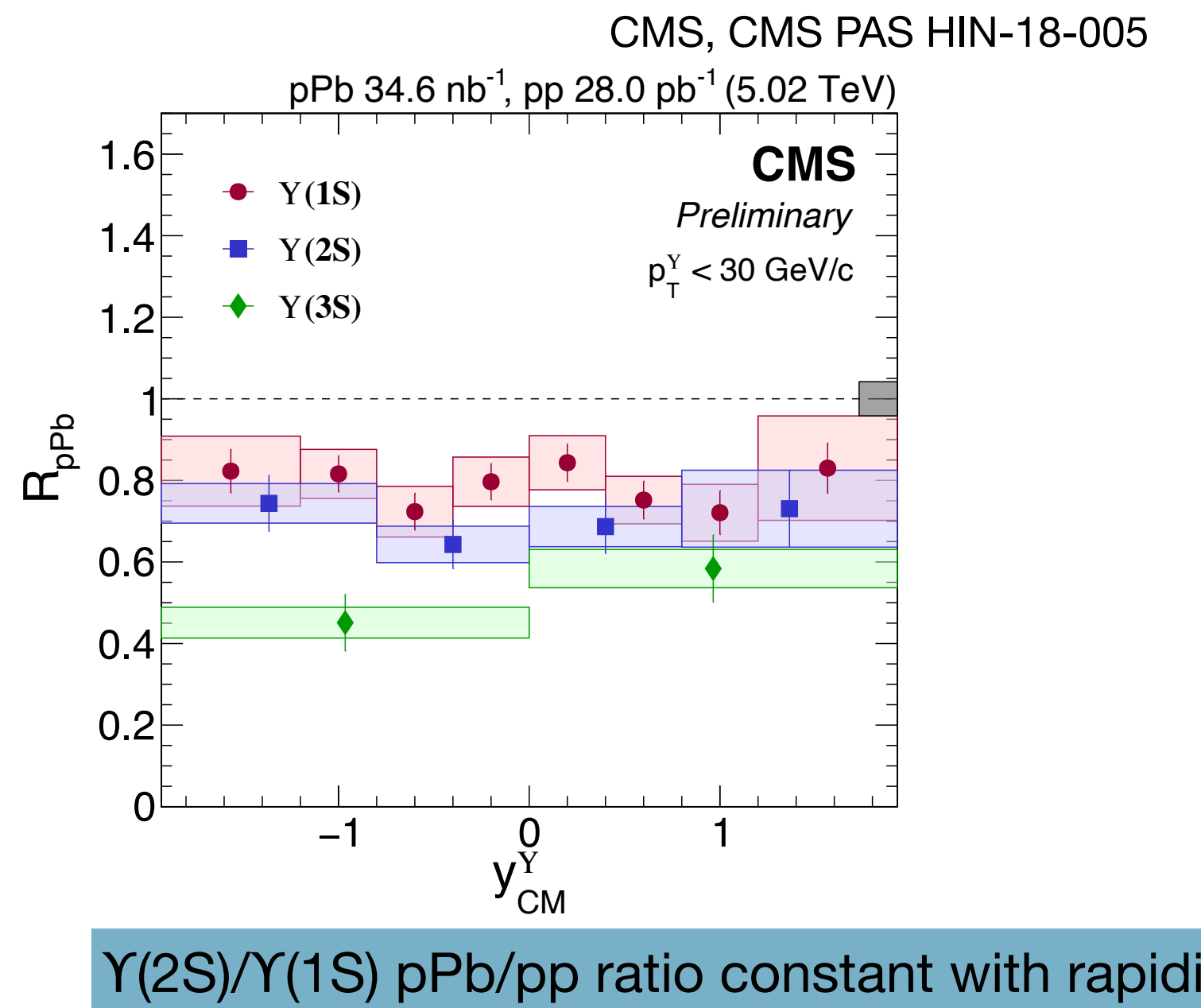
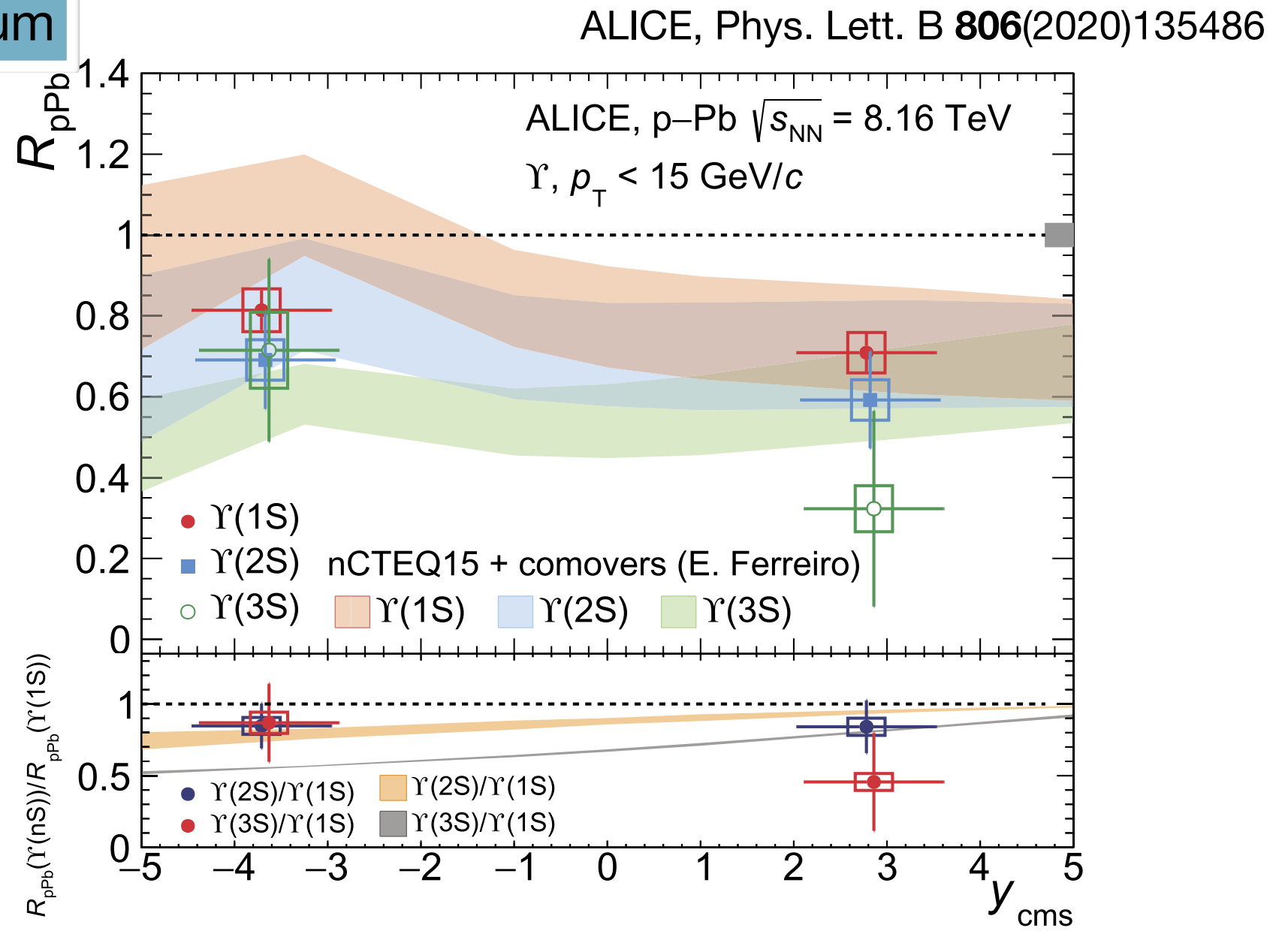


Nuclear effects on quarkonium production

charmonium



bottomonium



Polarisation

angular distribution of positive lepton:

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

frame independent variables^(*)

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

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

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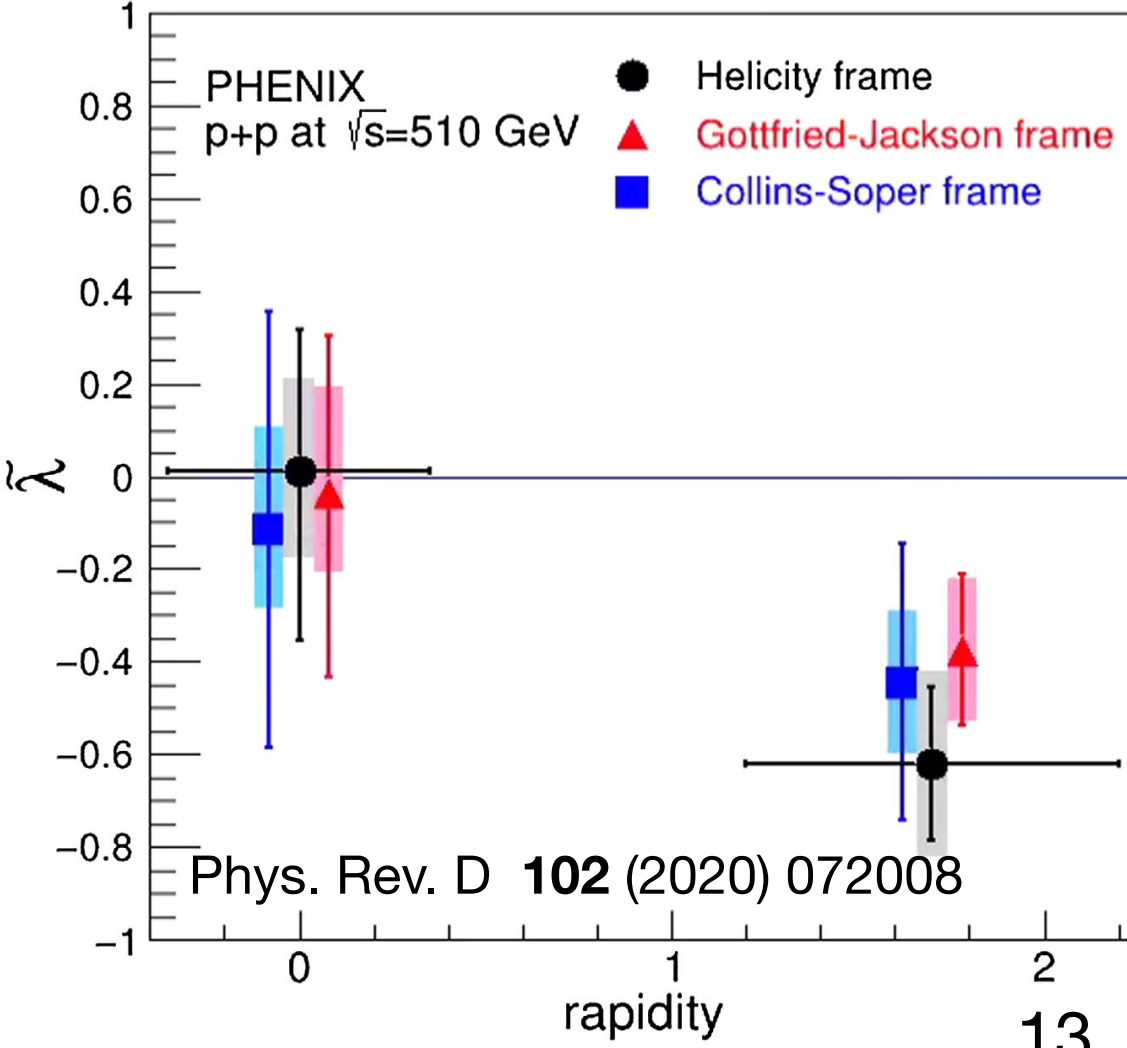
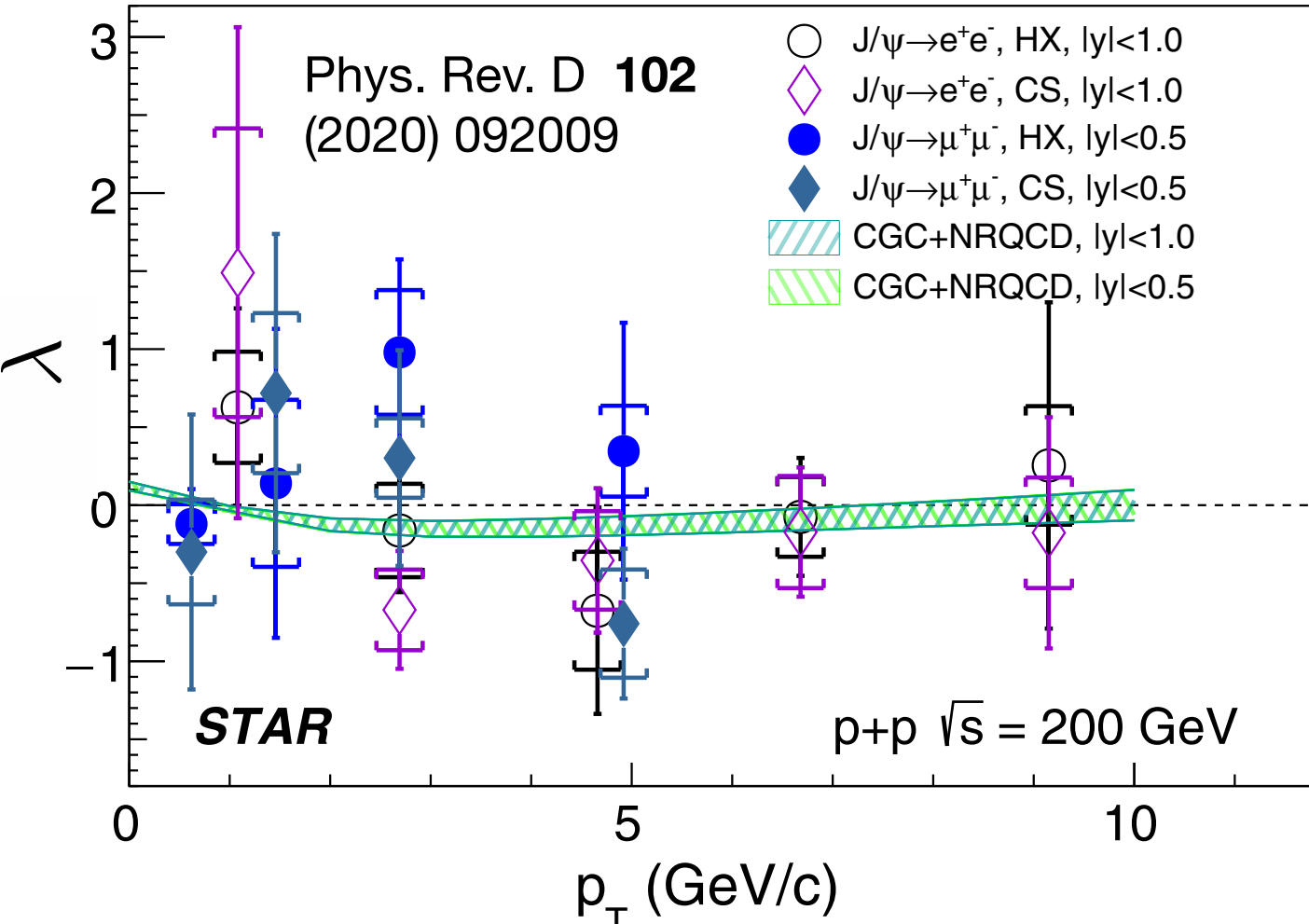
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- Complement measurements from ALICE (PRL **108** ('12) 082001, EPJC **78** ('18) 562), CMS (PLB **727** ('13) 381), LHCb (EPJC **73** ('13) 2631)
- First measurement in PbPb by ALICE (arXiv:2005.11128)

J/ψ

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

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



Polarisation

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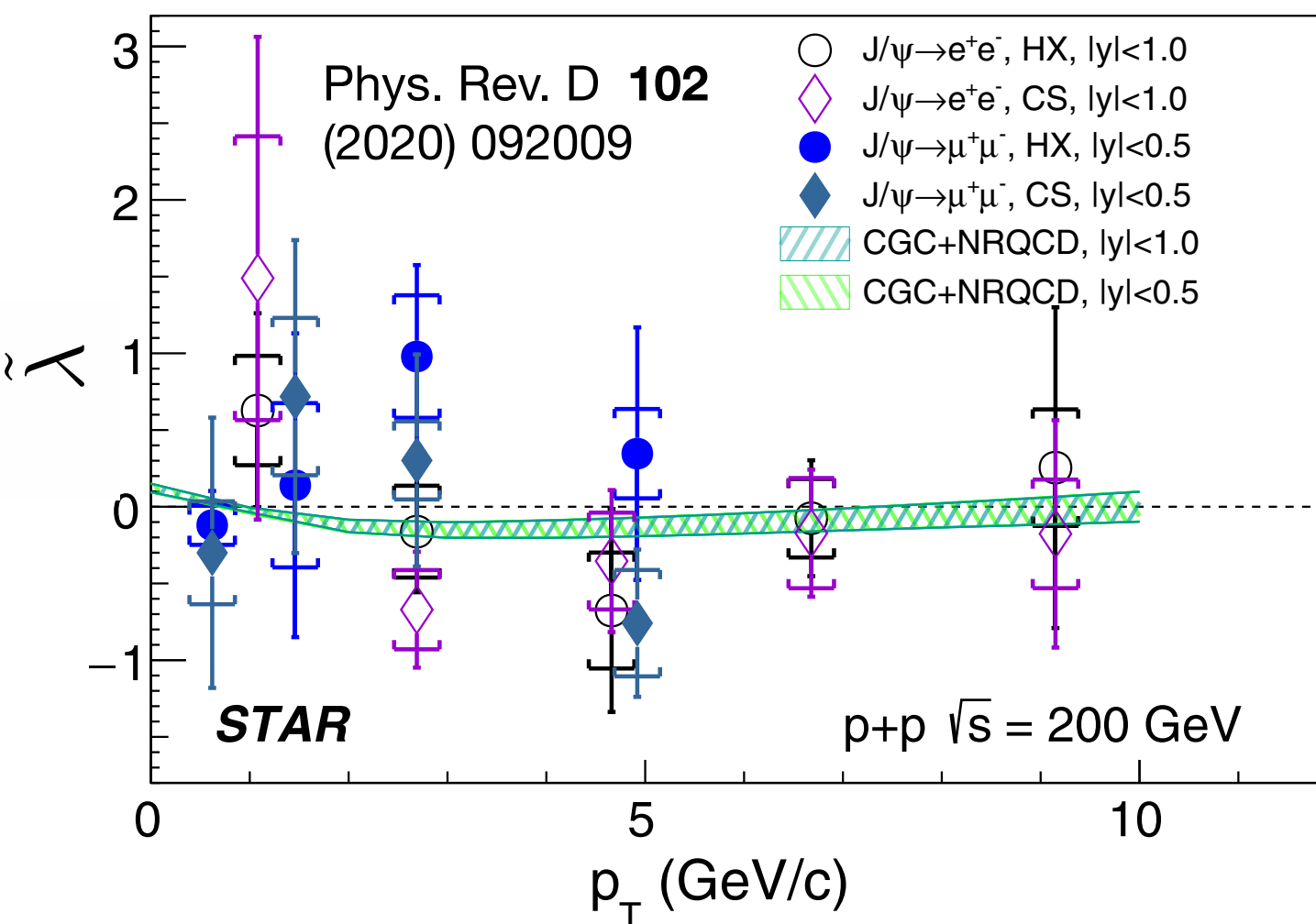
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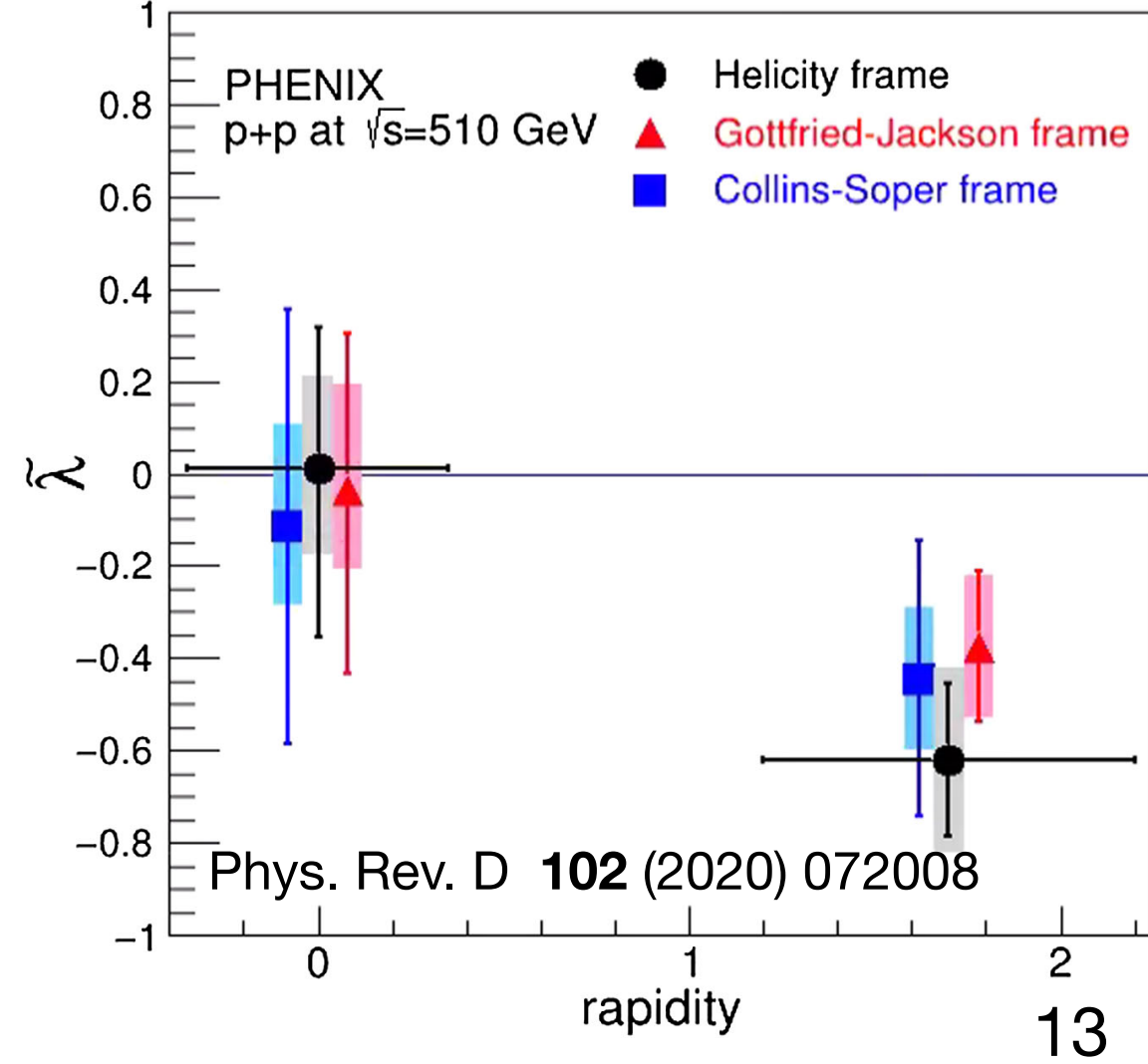
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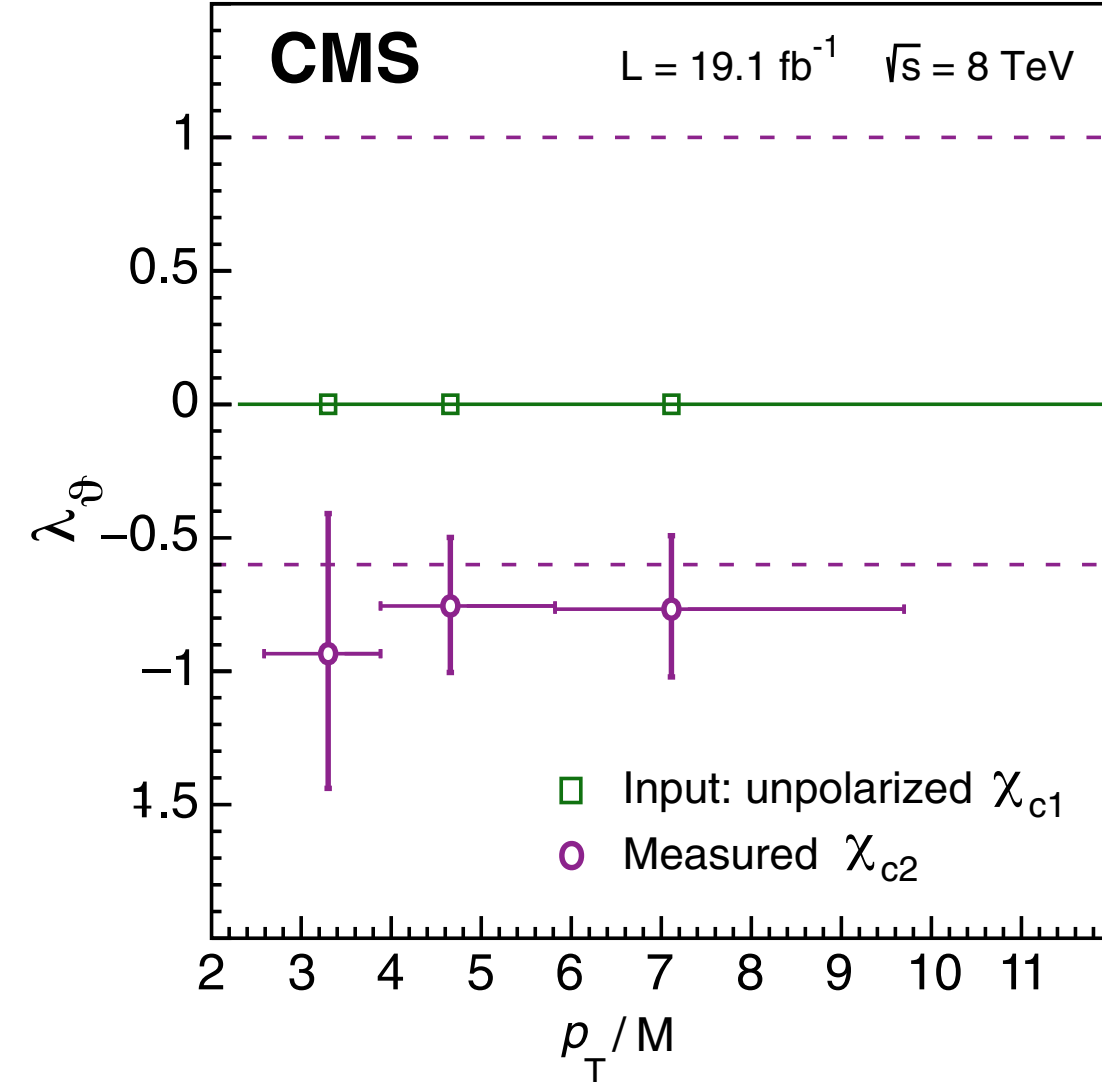


PHENIX: pp at $\sqrt{s} = 510$ GeV

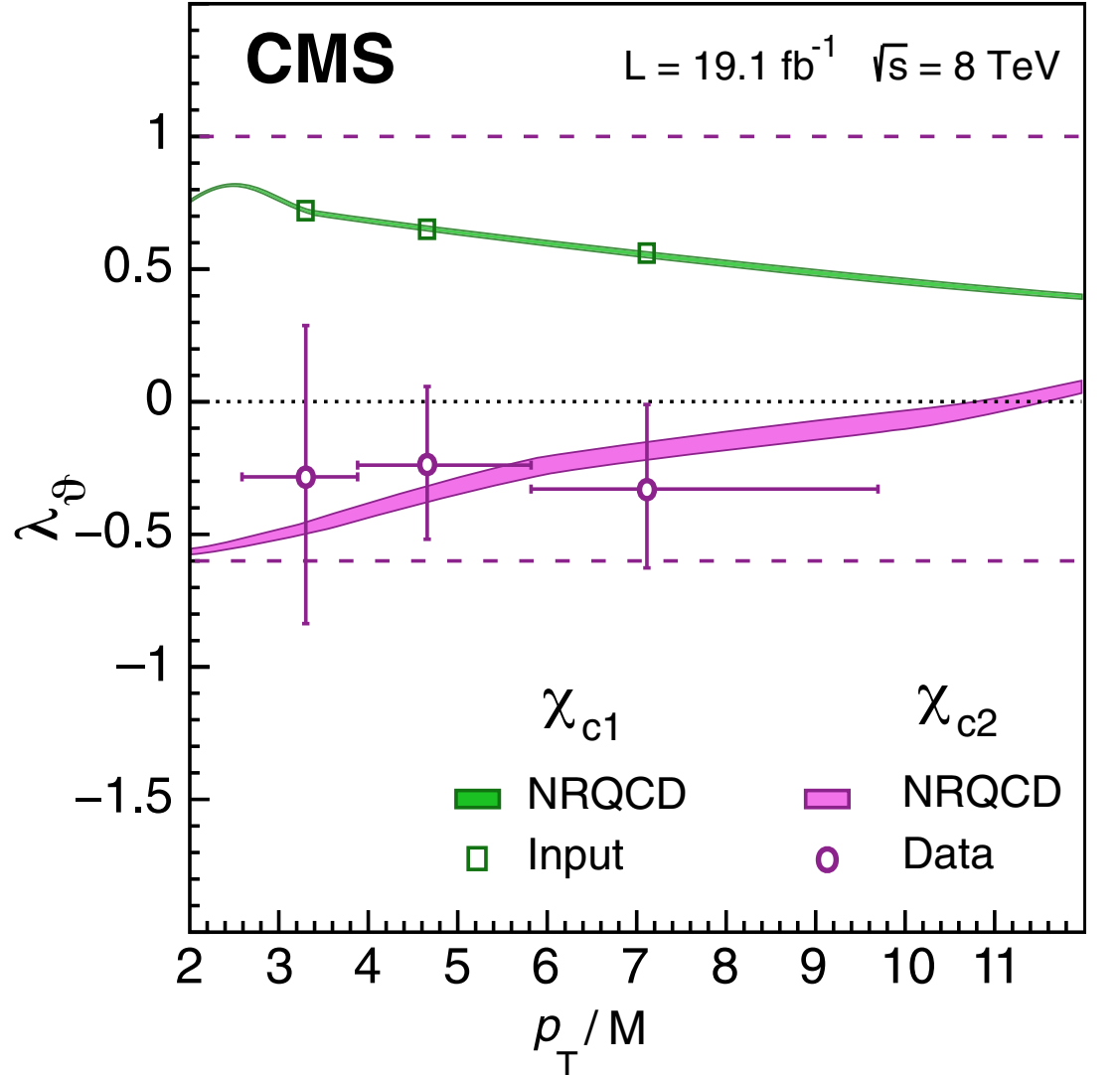


χ_c

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

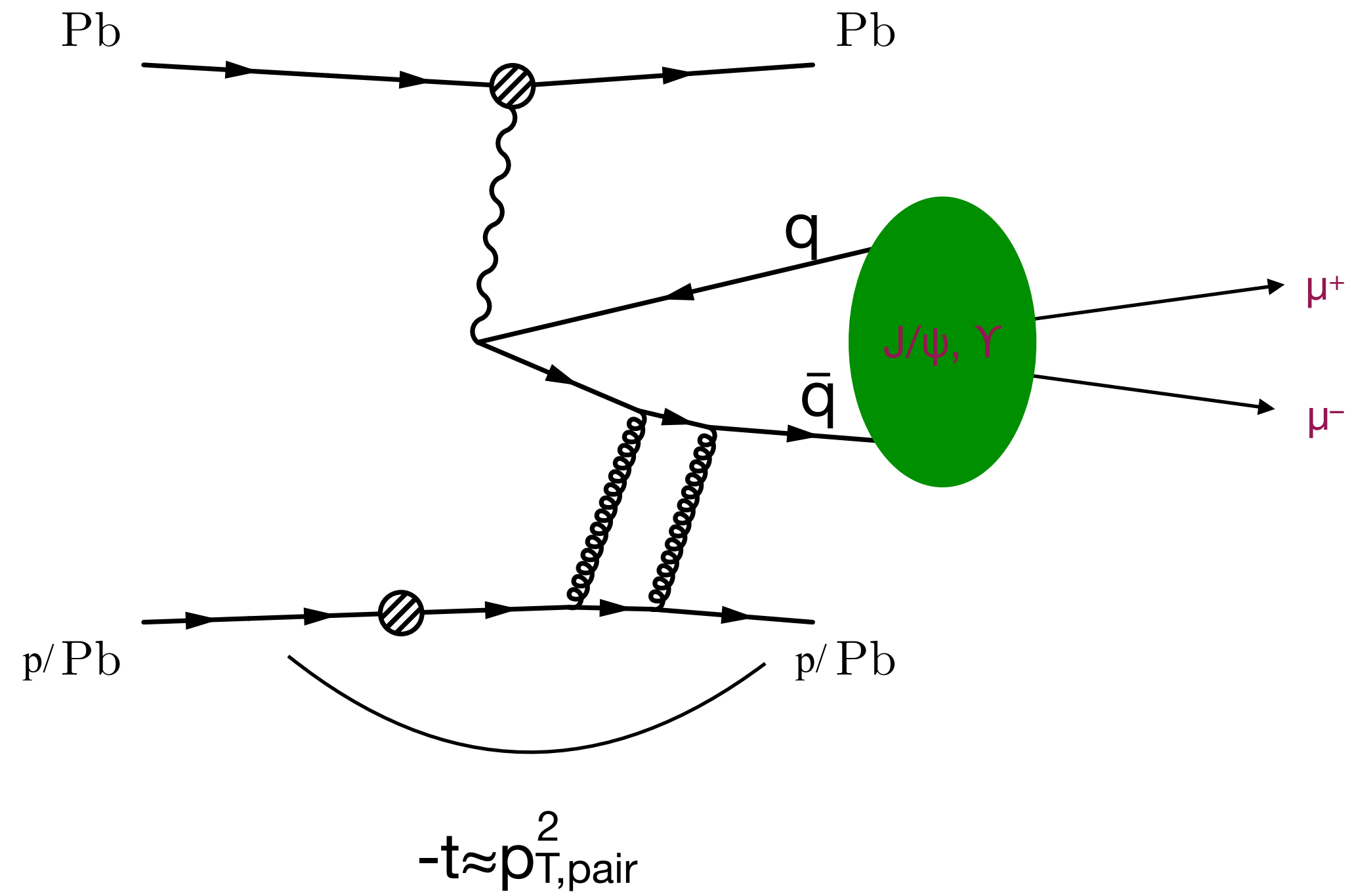


Phys. Rev. Lett. **124** (2020) 162002

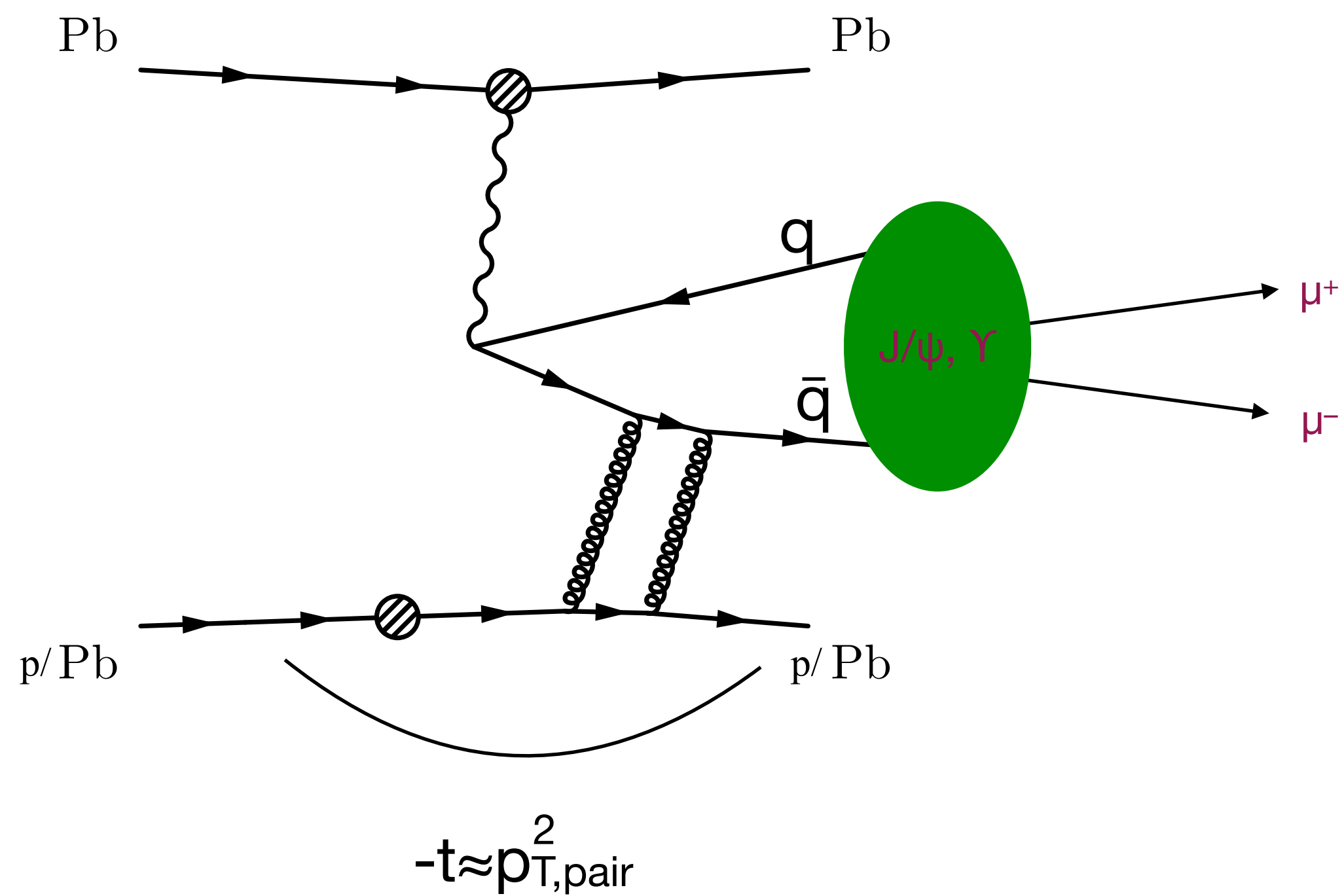


Exclusive quarkonium production

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



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



photon flux $\propto Z^2$

pPb collisions

$$Z(p)=1$$

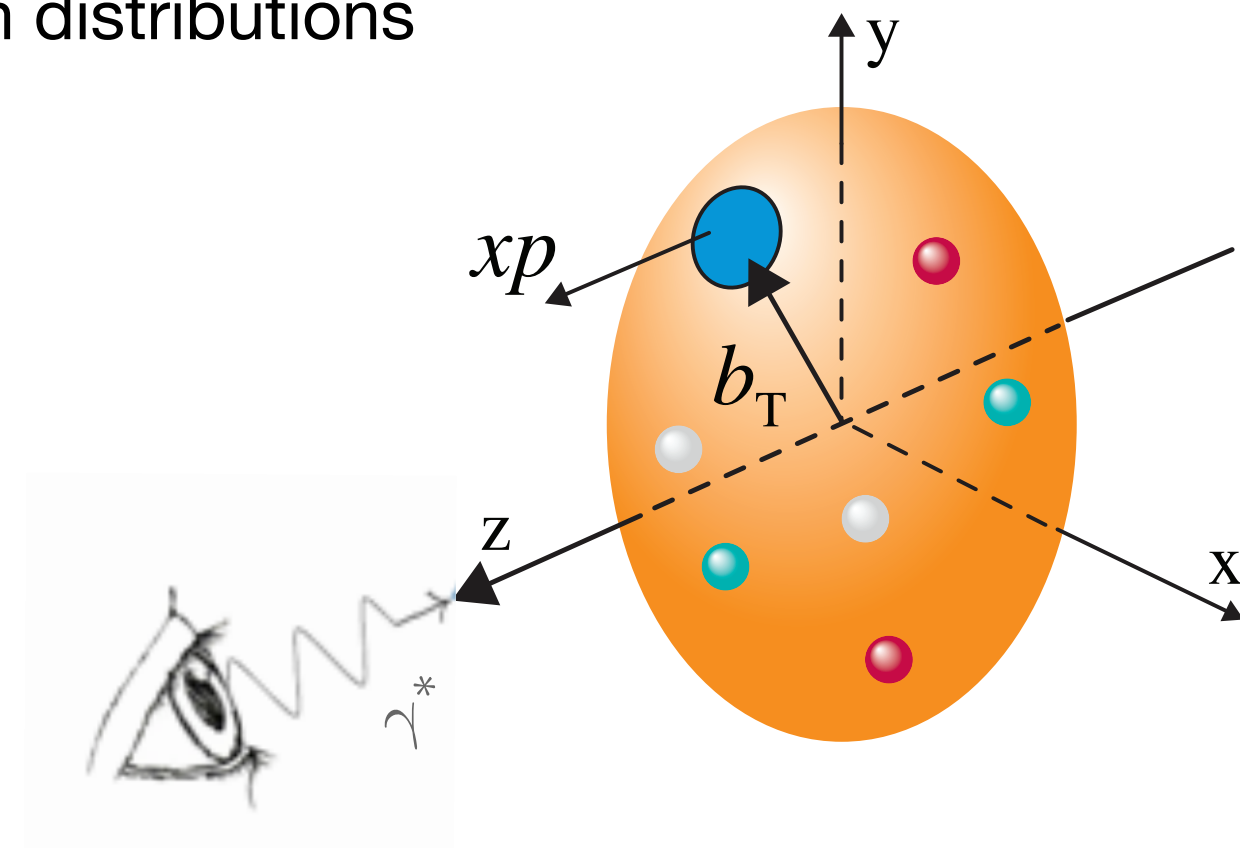
$$Z(\text{Pb})=82$$

→ Pb ion dominant photon emitter

no ambiguity in identity of photon emitter

Study of exclusive quarkonium production

3D parton distributions



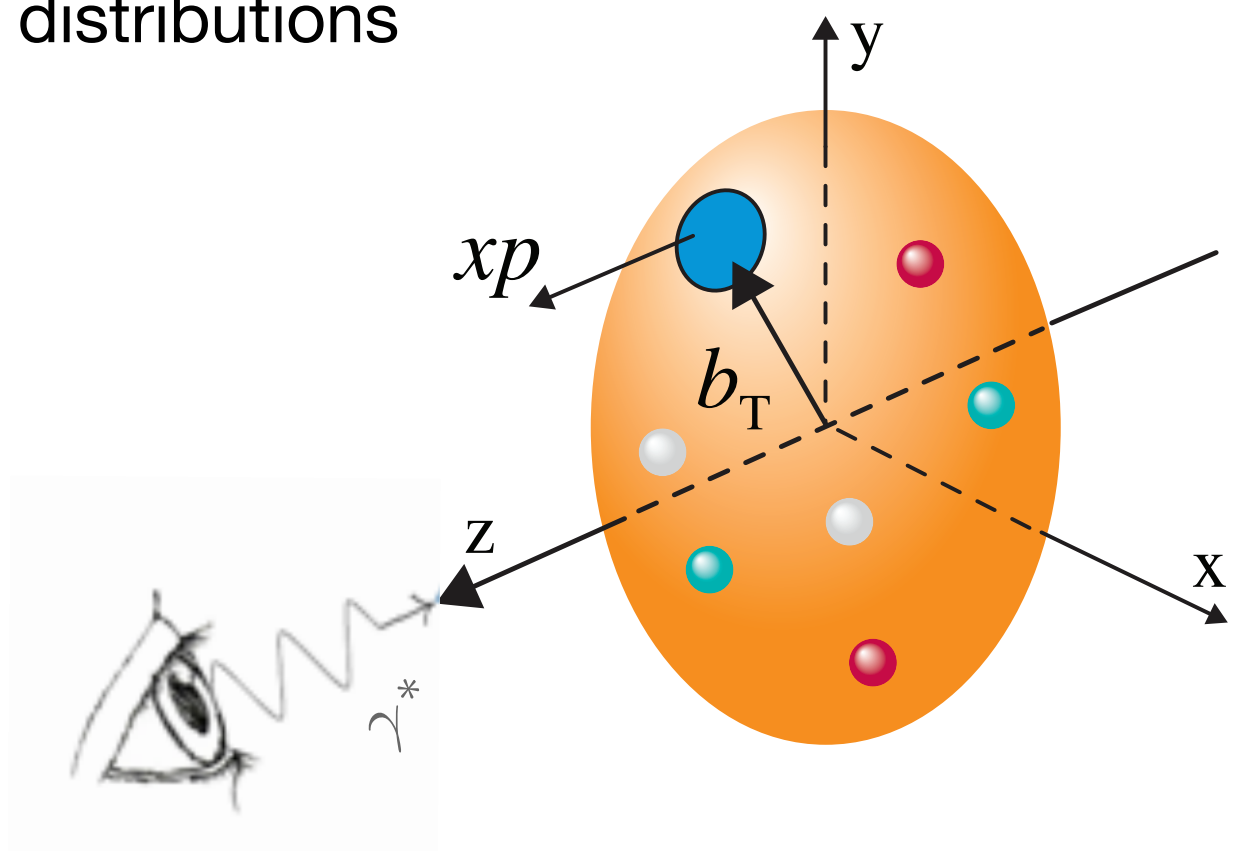
Generalised parton distributions

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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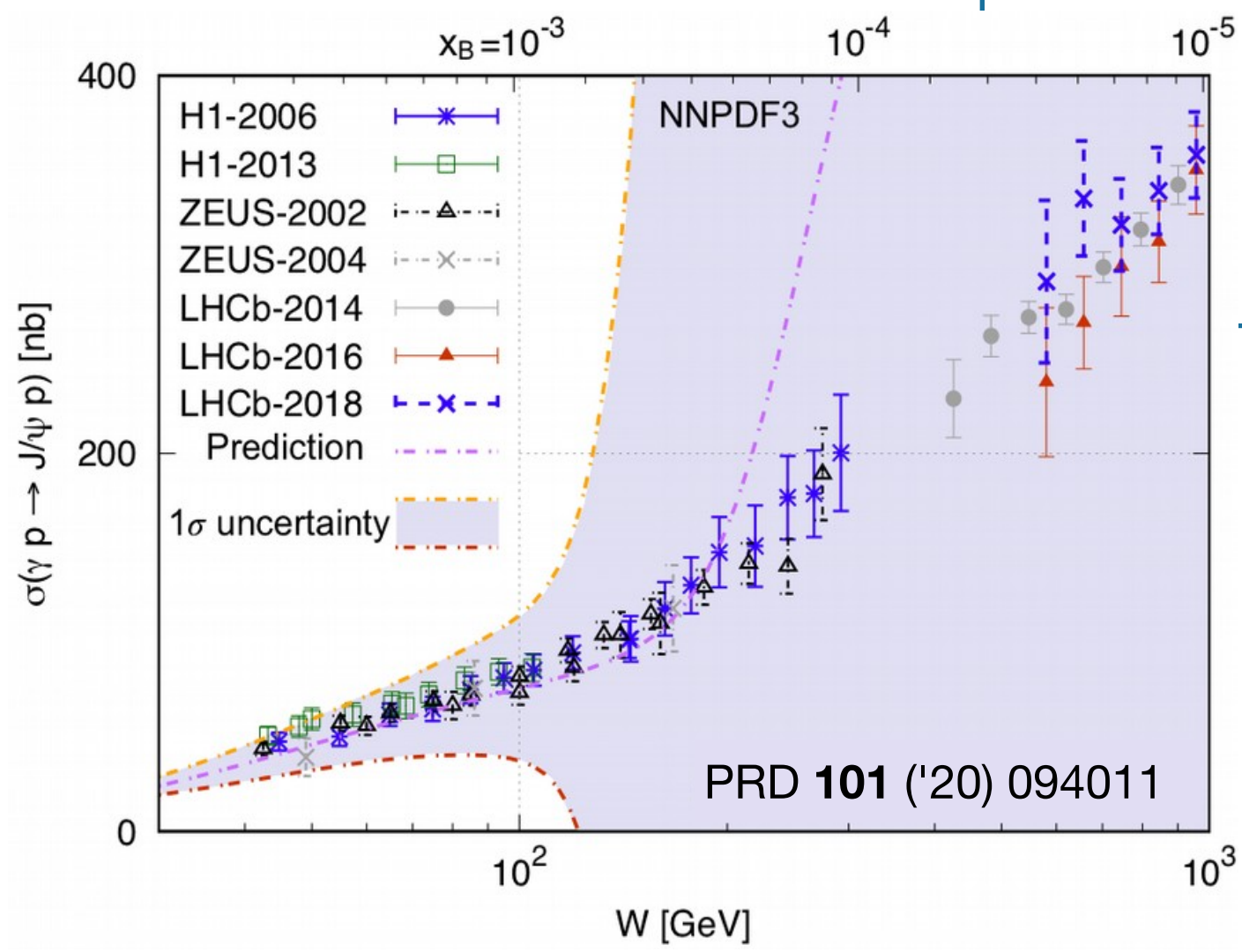
3D distribution in x and transverse position b_T

At low x

Approximate access to gluon PDF

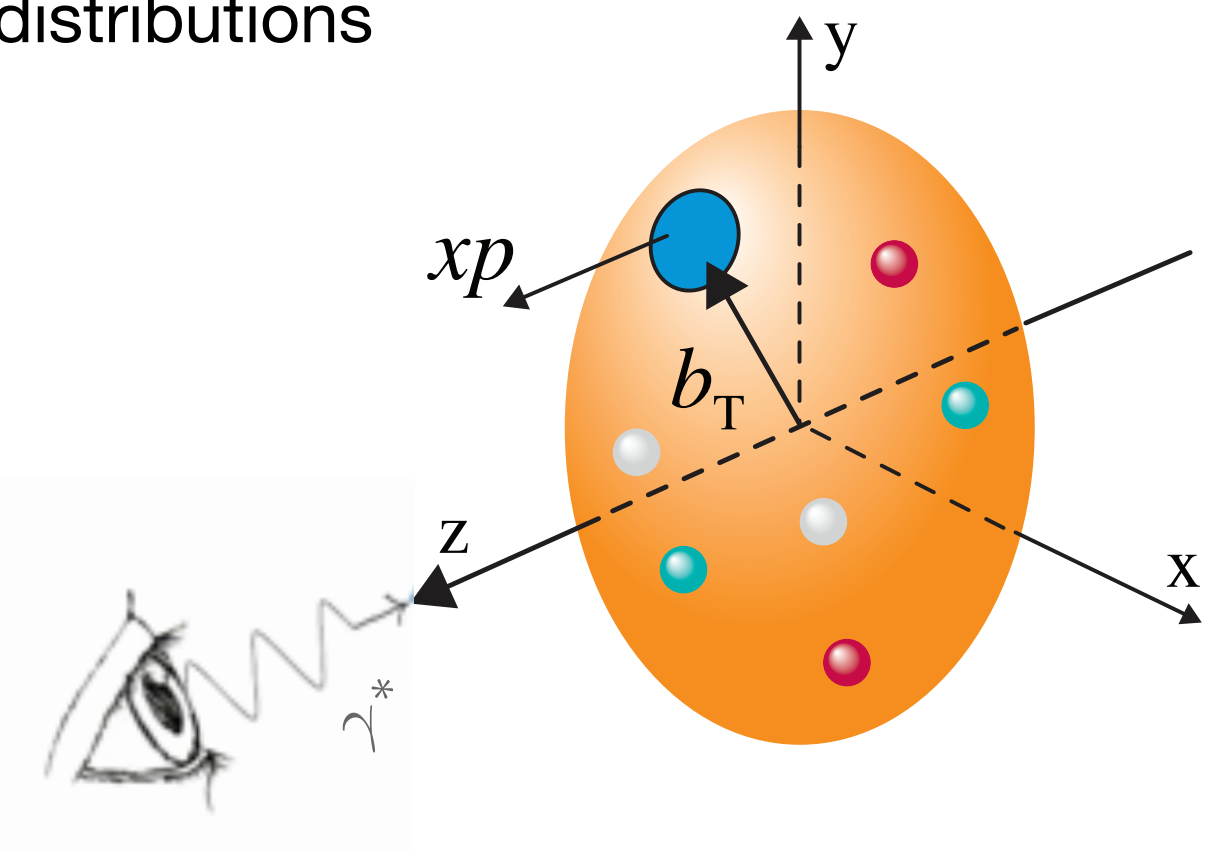
$$\left. \frac{d\sigma}{dt} \right|_{t=0} \propto [g(x_B)]^2$$

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



Study of exclusive quarkonium production

3D parton distributions

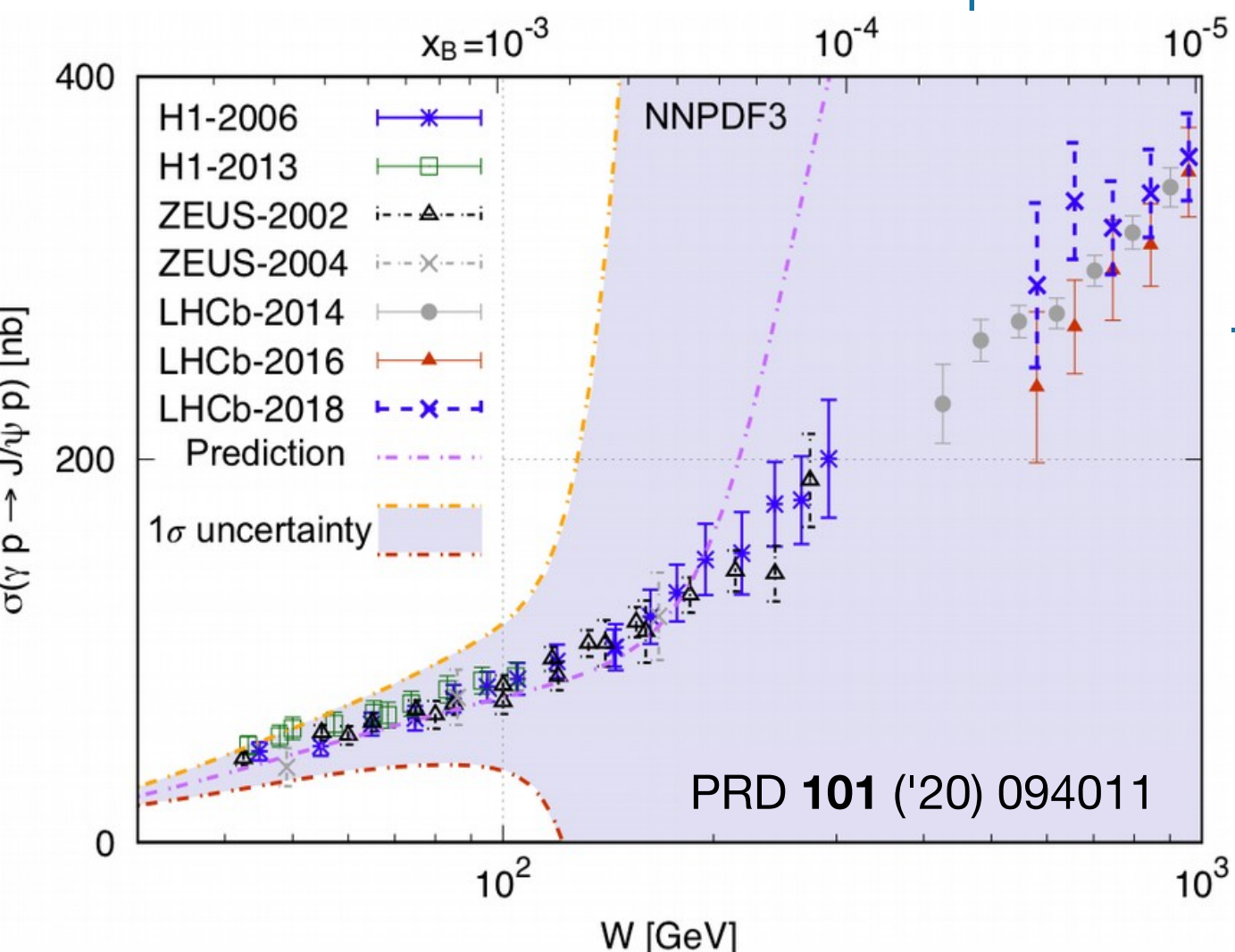


Generalised parton distributions

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3D distribution in x and transverse position bT

At low x

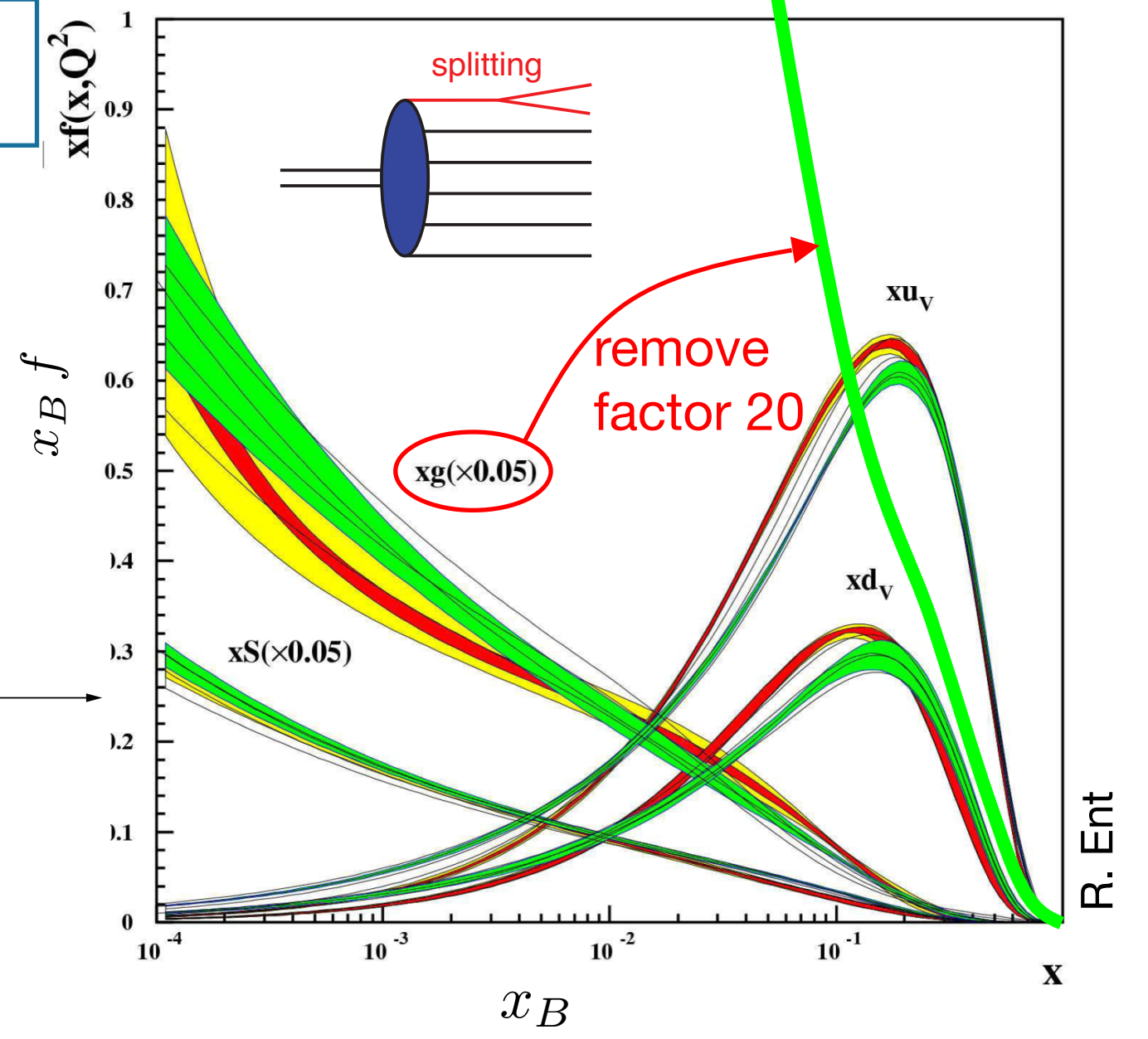
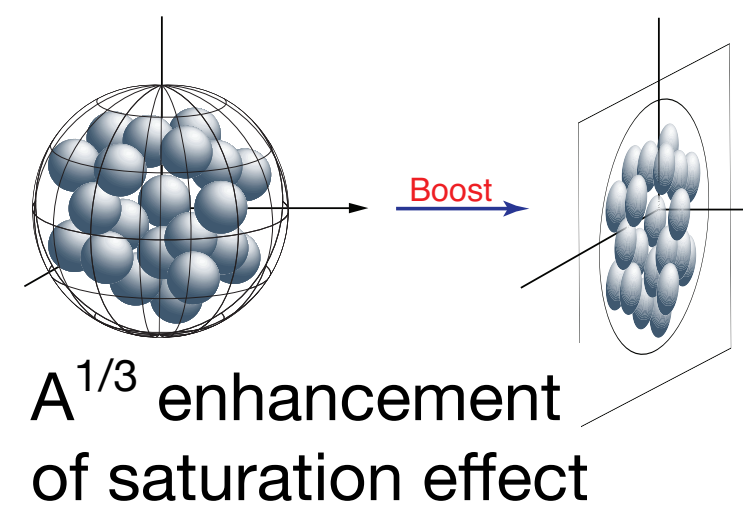


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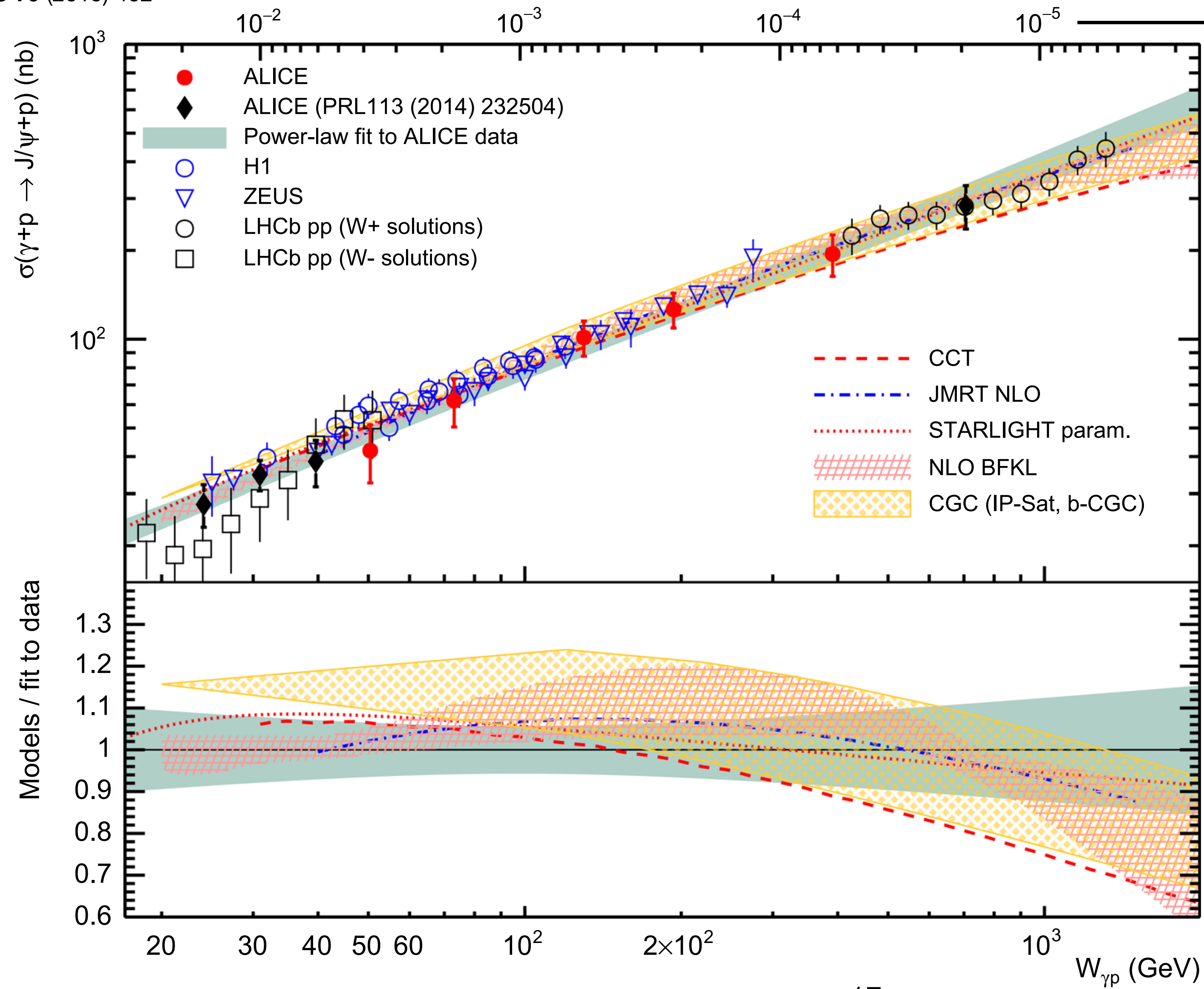
M. G. Ryskin, Z. Phys. C57 (1993) 89–92;
S. P. Jones et al., arXiv:1609.09738

Test saturation



J/ψ photoproduction on nucleon

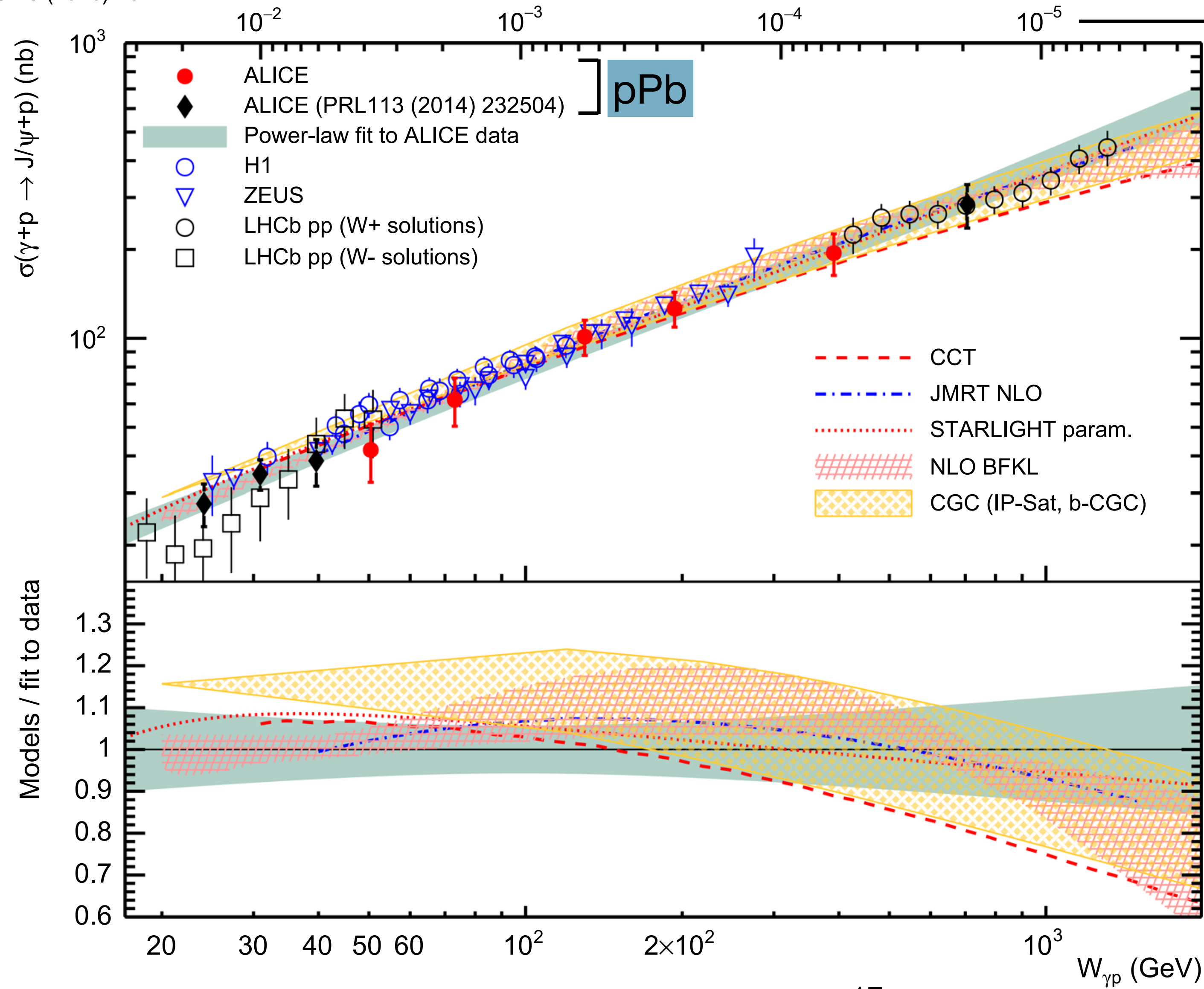
ALICE, Eur. Phys. J. C **79** (2019) 402



access to
low- x_B gluon GPDs

J/ψ photoproduction on nucleon

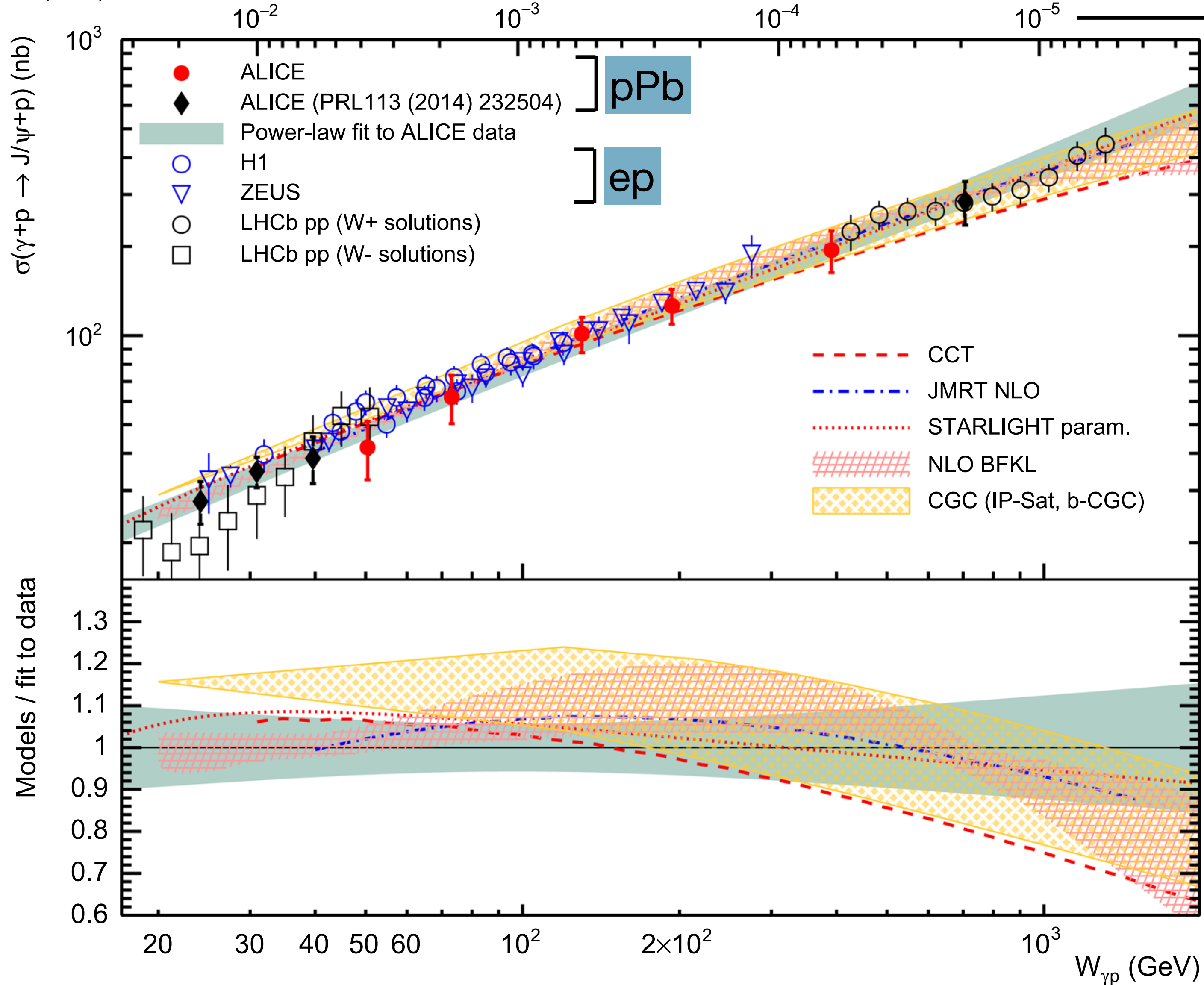
ALICE, Eur. Phys. J. C **79** (2019) 402



access to
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J/ψ photoproduction on nucleon

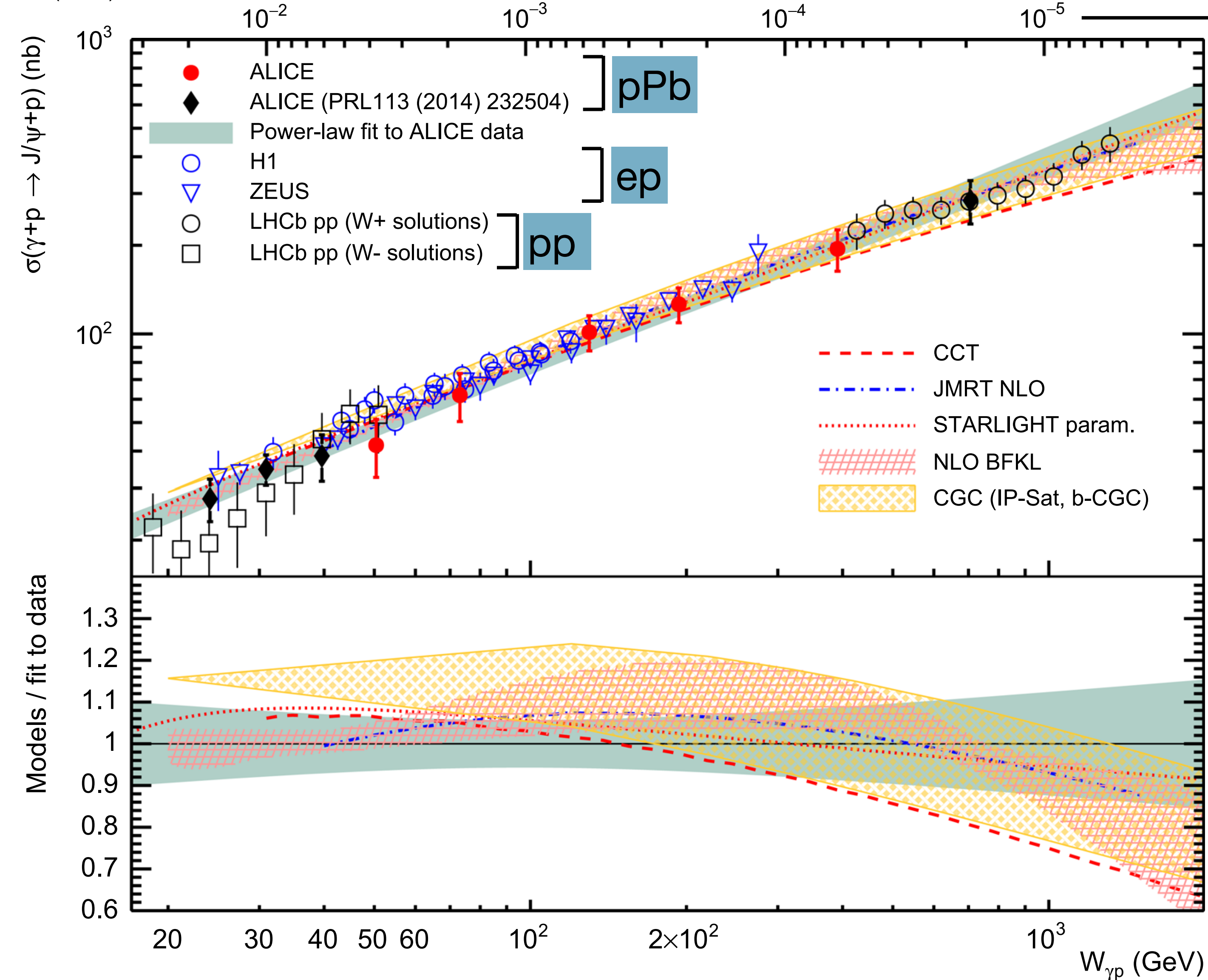
ALICE, Eur. Phys. J. C **79** (2019) 402



access to low- x_B gluon GPDs

J/ψ photoproduction on nucleon

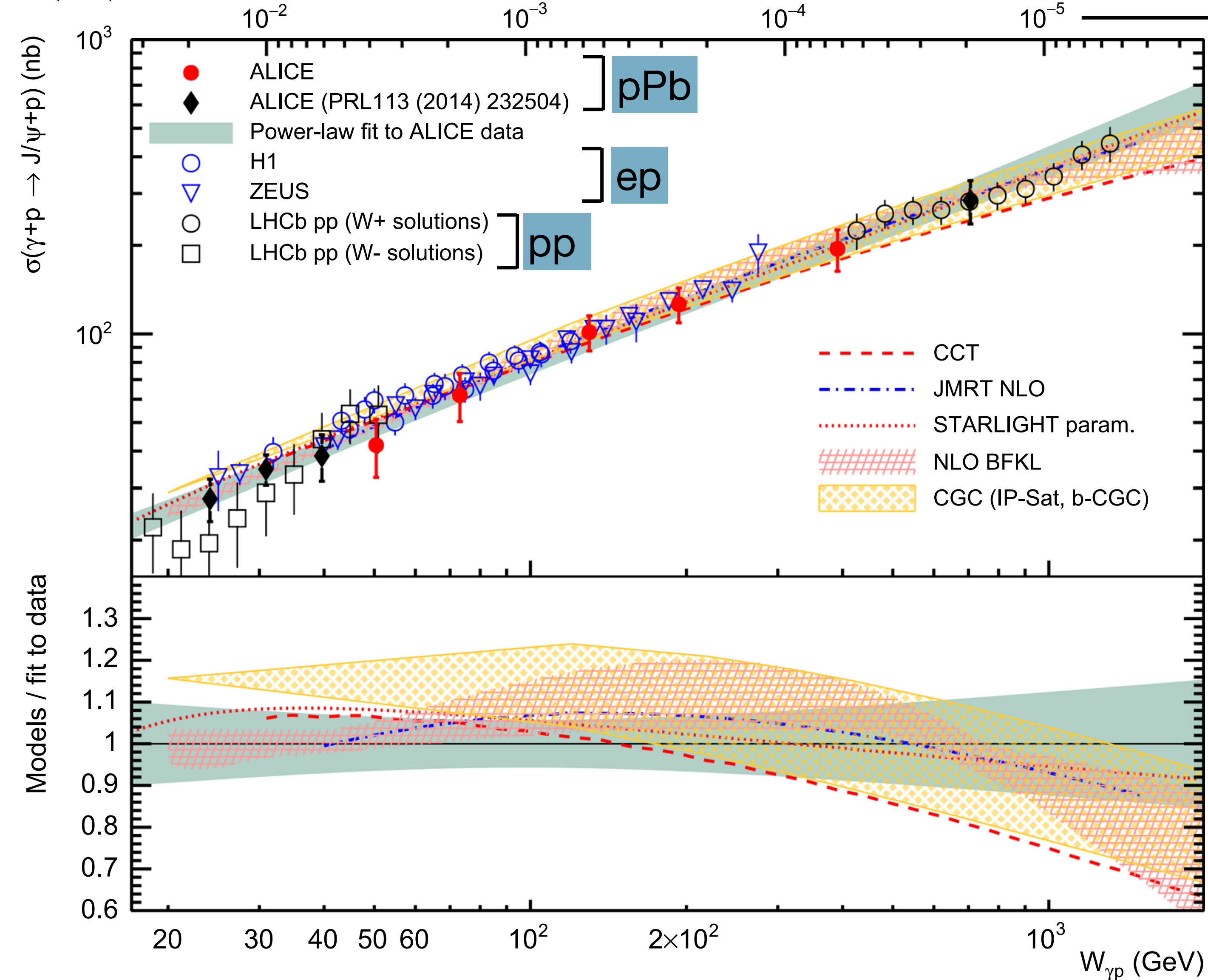
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access to low- x_B gluon GPDs

J/ψ photoproduction on nucleon

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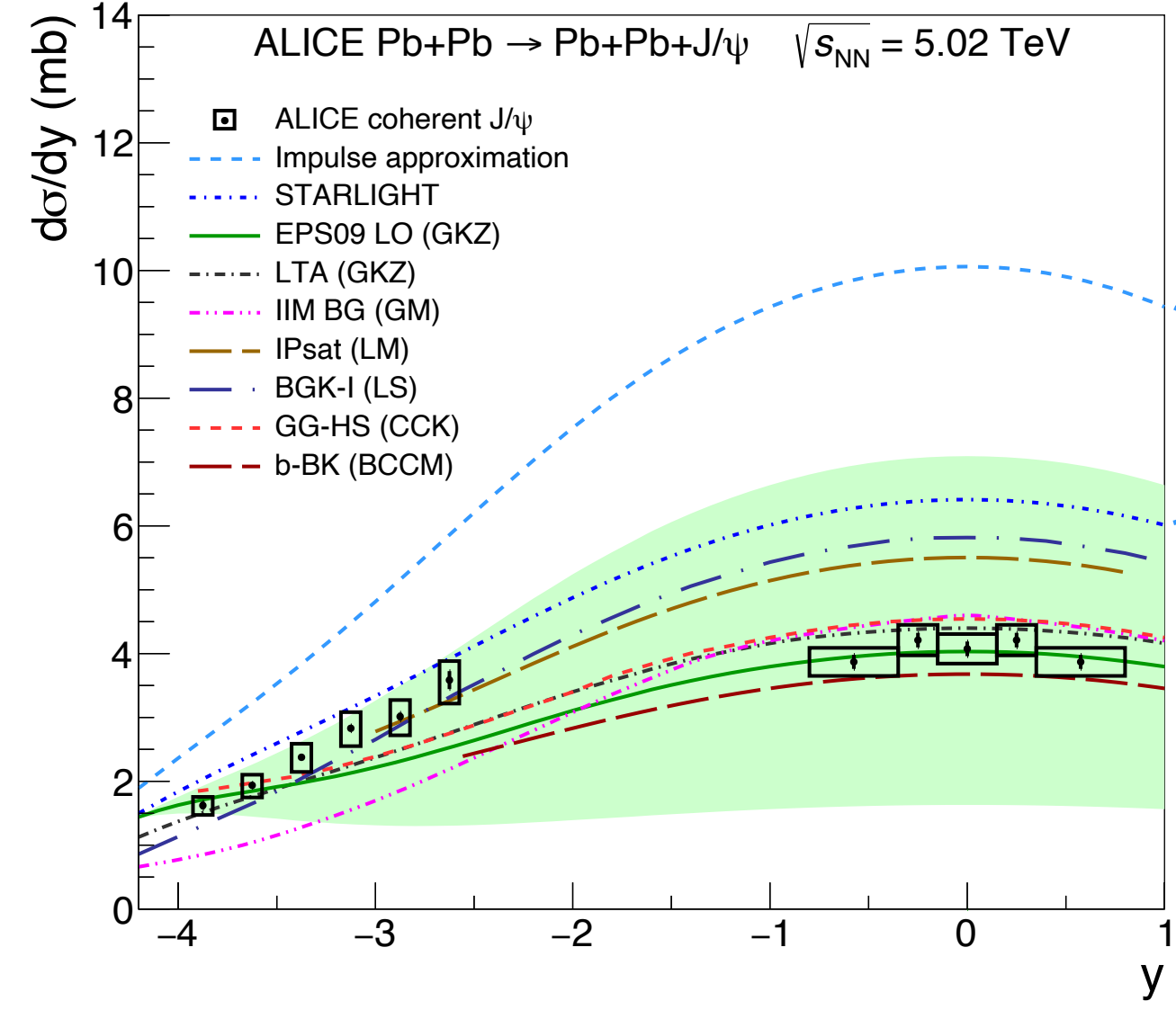


access to low- x_B gluon GPDs

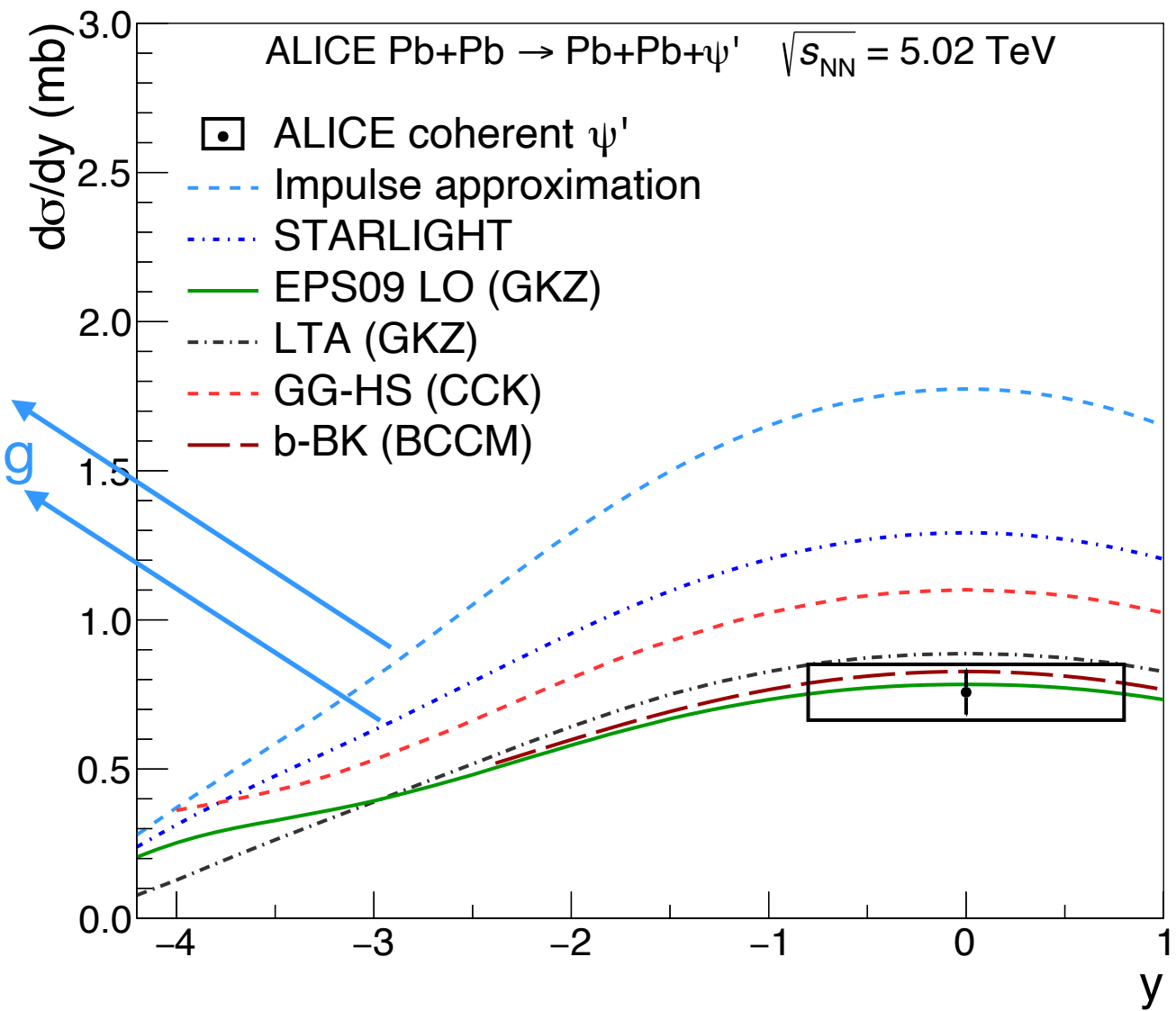
overall compatibility between pp, Pbp and ep data: hint of universality of underlying physics

Coherent photoproduction in PbPb

J/ψ
ALICE, 2101.04577



ψ(2S)
ALICE, 2101.04577



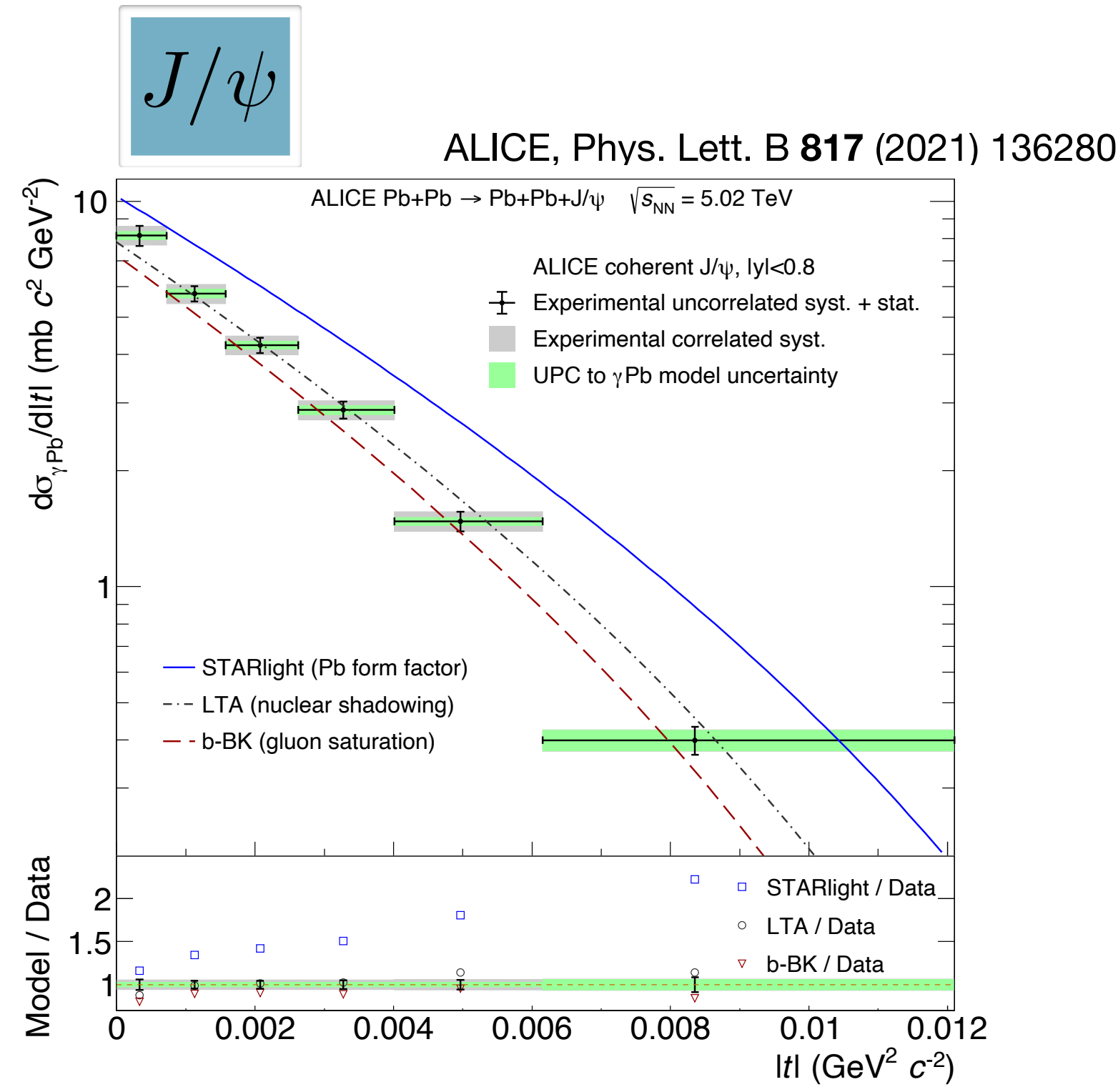
no gluon shadowing

$$|y| < 0.8 \iff 0.3 \times 10^{-3} < x_B < 1.4 \times 10^{-3}$$

$-4.0 < y < -2.5$
 \updownarrow
 $0.7 \times 10^{-2} < x_B < 3.3 \times 10^{-2}$ (dominant)
 $1.1 \times 10^{-5} < x_B < 5.1 \times 10^{-5}$

Results indicate shadowing in gluon PDF:

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



Summary

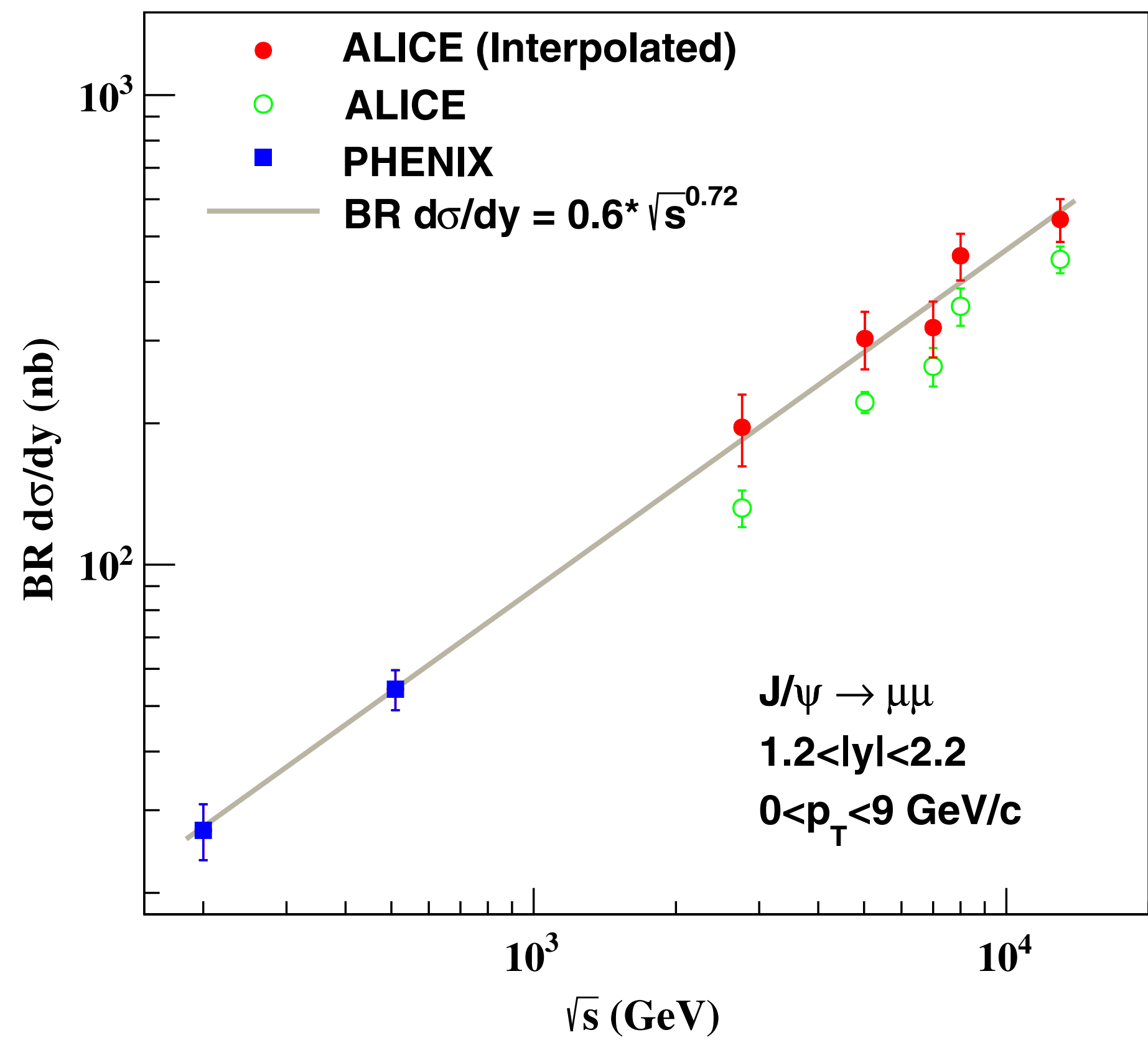
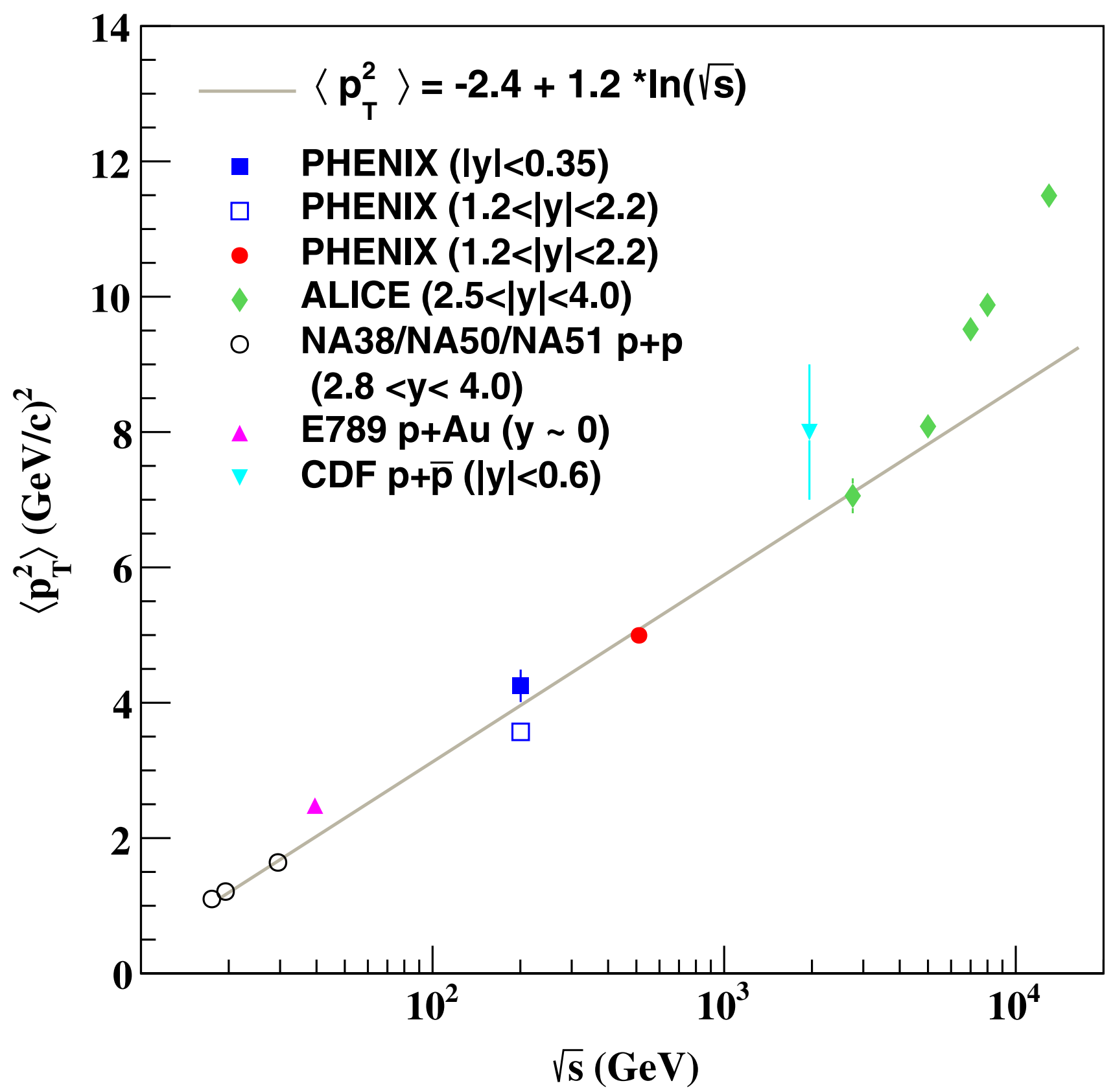
- The study of heavy quarks and flavours covers a wide spectrum.
- Meson production better under control than baryon production.
Influence of medium on hadron production?
- Inclusive quarkonium production: complementary tool to open-flavour production to study nucleon/nucleus. Yet, no consensus on production 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.

Back up

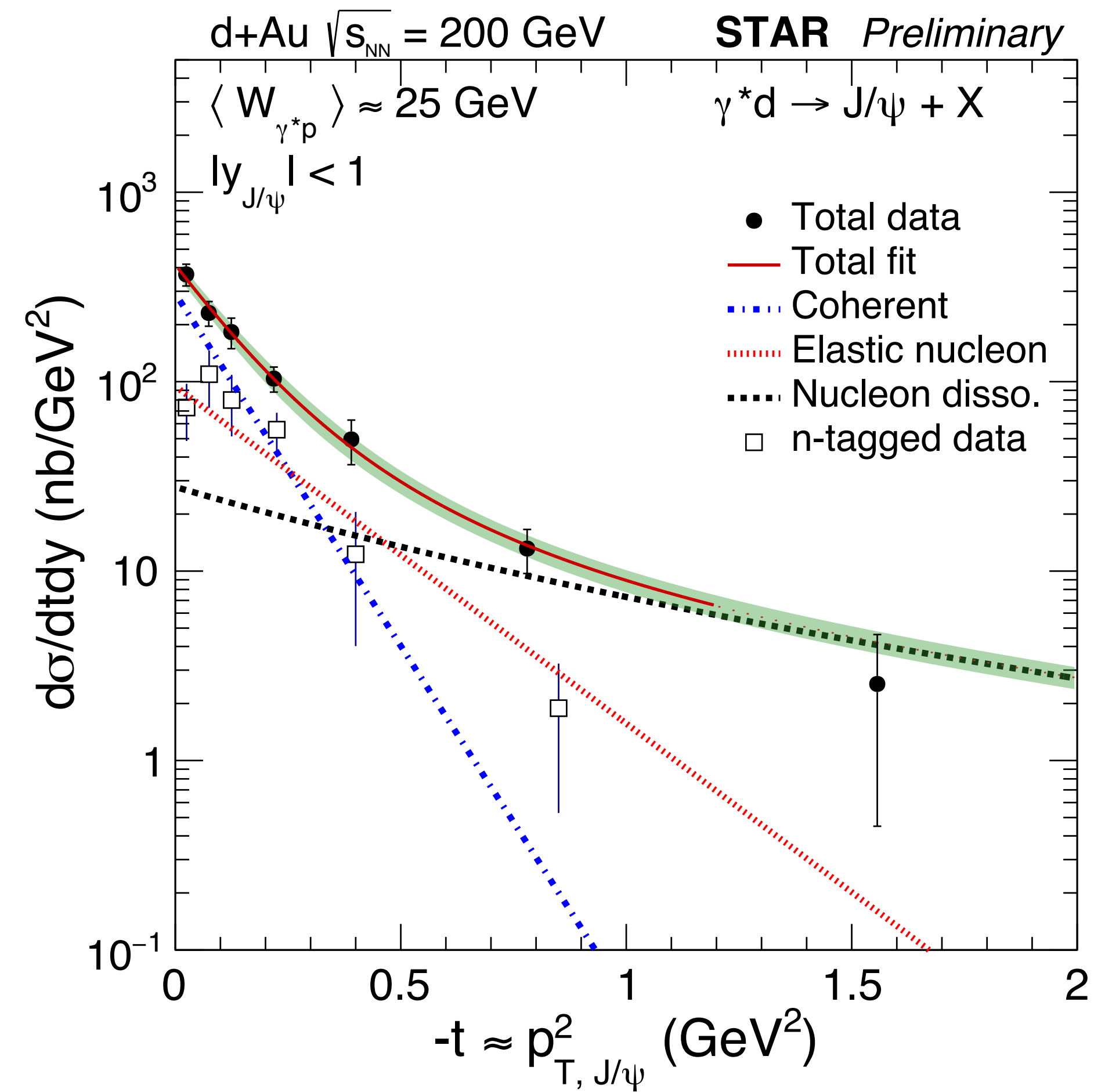
Inclusive J/ψ production at PHENIX

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

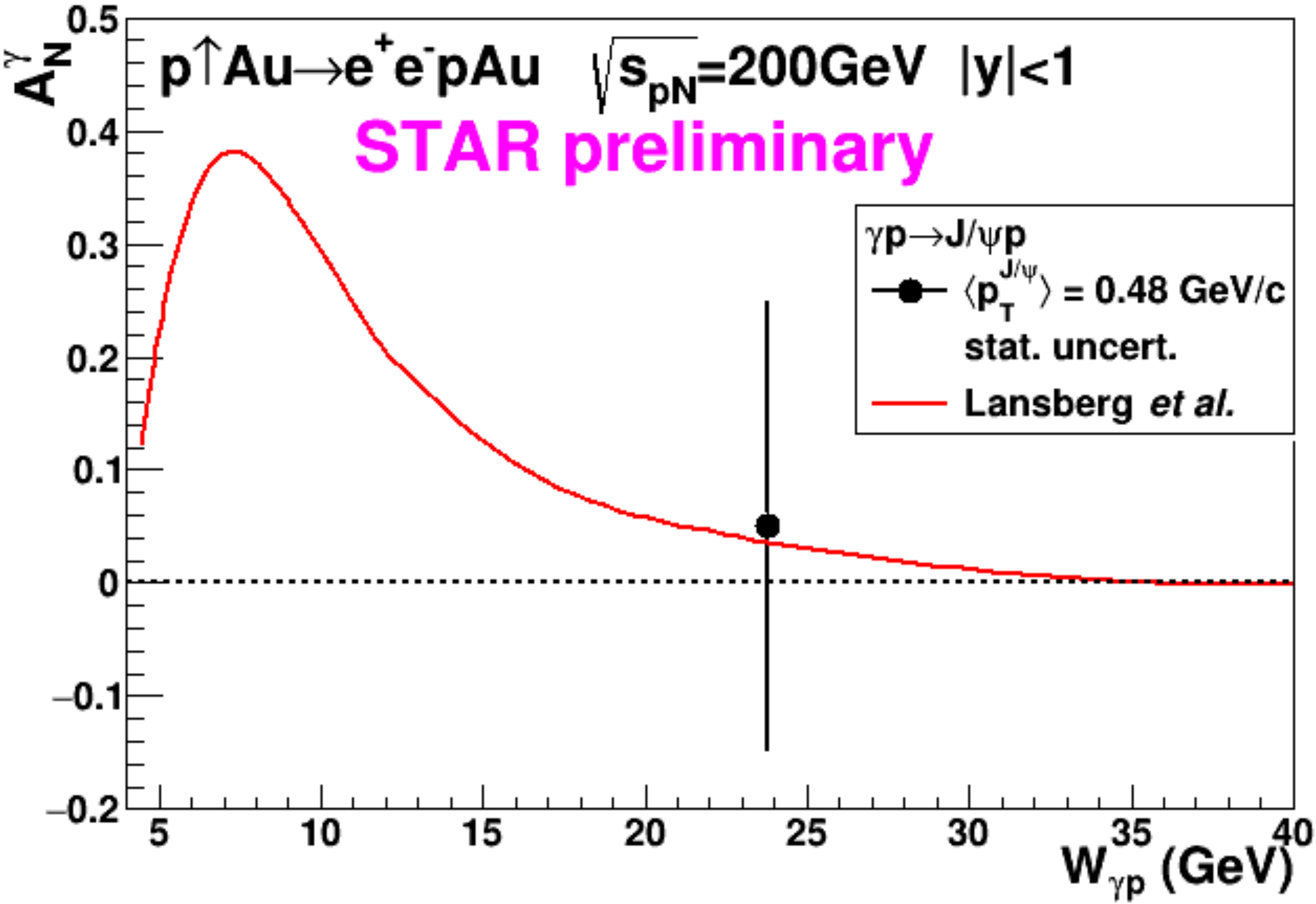
PHENIX, Phys. Rev. D **101** (2020) 052006



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