LHCP Conference, May 2023, Belgrade (Serbia)

Quarkonium production cross section and polarisation

Andry Rakotozafindrabe

cea irfu

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

Quarkonium production @ LHC : a vivid QCD laboratory

- Charmonium or bottomonium : a bound state of a heavy quark (c or b) and its antiquark
- Prompt production
  - ***direct*** (no feed-down at all) or from **higher resonance** (in family) **feed-down**
- Non-prompt production
  - charmonium produced via **b-hadron feed-down**
  - access to open beauty production, for e.g. study the elusive $B_c^{(*)}(2S)^+$ *CMS [PRD 102 (2020) 9, 092007]*

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2 scale problem: factorisation approach
- perturbative: initial $q\bar{q}$ production
- non-perturbative: binding into physical quarkonium (hadronisation)

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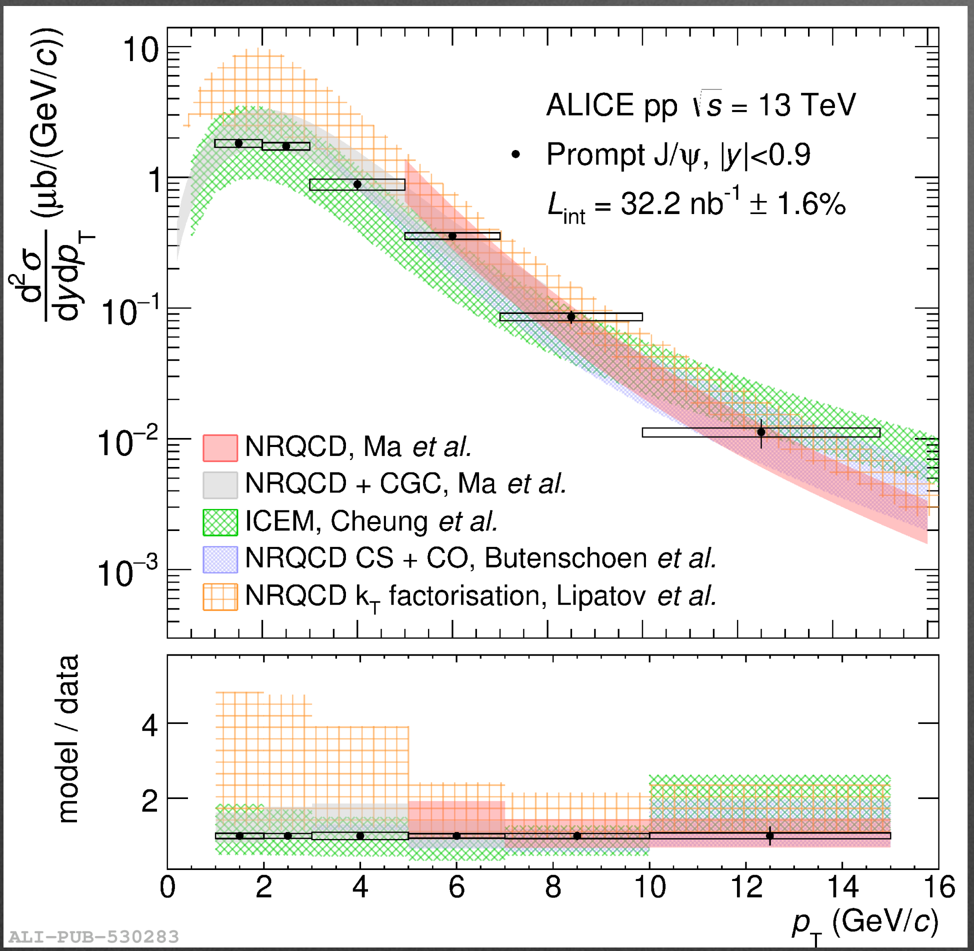
- Quarkonium production used as a tool to study: *[Prog.Part.Nucl.Phys. 122 (2022) 103906]*
  - gluon content of the proton/nucleus *[See talk by J. G. Contreras Nuno – Heavy Ion Physics session, 25/05 16:12]*
  - associated production of quarkonium pairs *[See talk by Y. Wei – QCD Physics session, 25/05 14:47]*
  - quark-gluon plasma *[See talks by P. Gossiaux and C. Hadjidakis – Joint Heavy Ion + Flavour session, 23/05 11:30]*
  - multiple-parton scattering interactions
  - spectroscopy (exotic quarkonium states) *[Rev.Mod.Phys. 90 (2018) 1, 015003]*

Prompt J/ψ, ψ(2S) p_T spectra : from low to high p_T

√s = 13 TeV , mid-y

ALICE [JHEP 03 (2022) 190]



NRQCD, Ma et al. [PRL 106 (2011) 042002]

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ICEM, Cheung et al. *[PRD 98 (2018) 11, 114029]*

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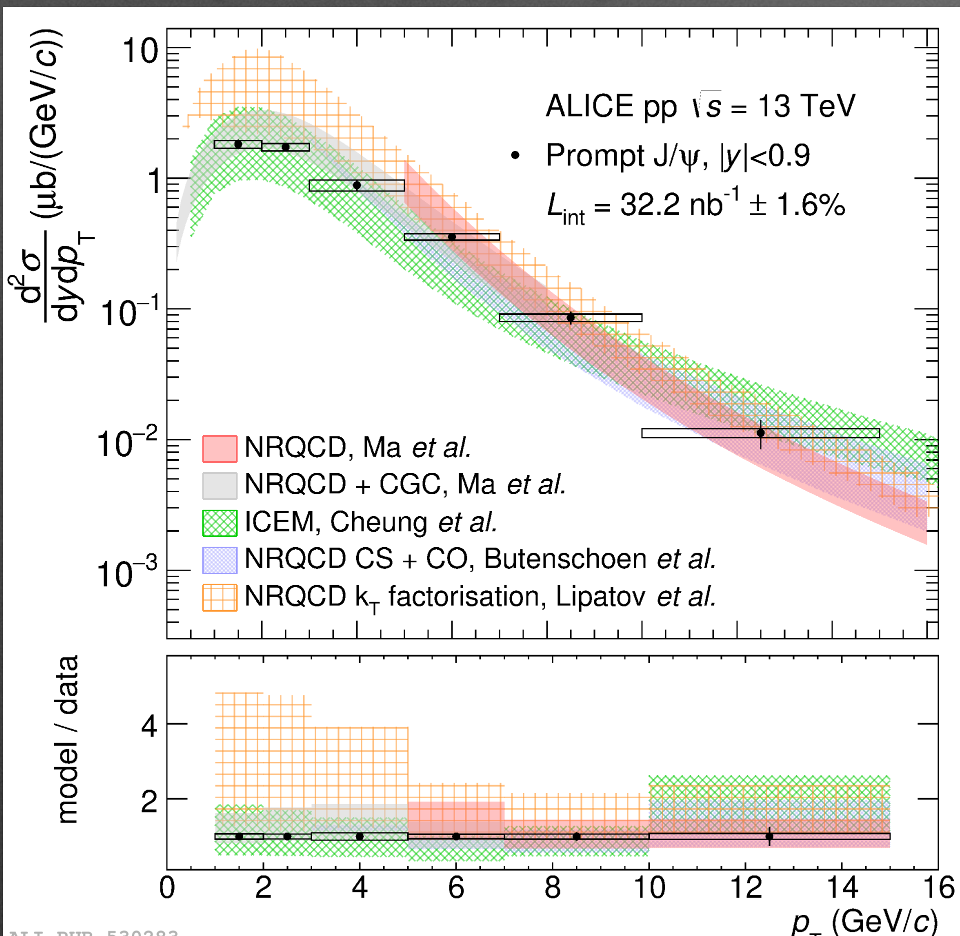
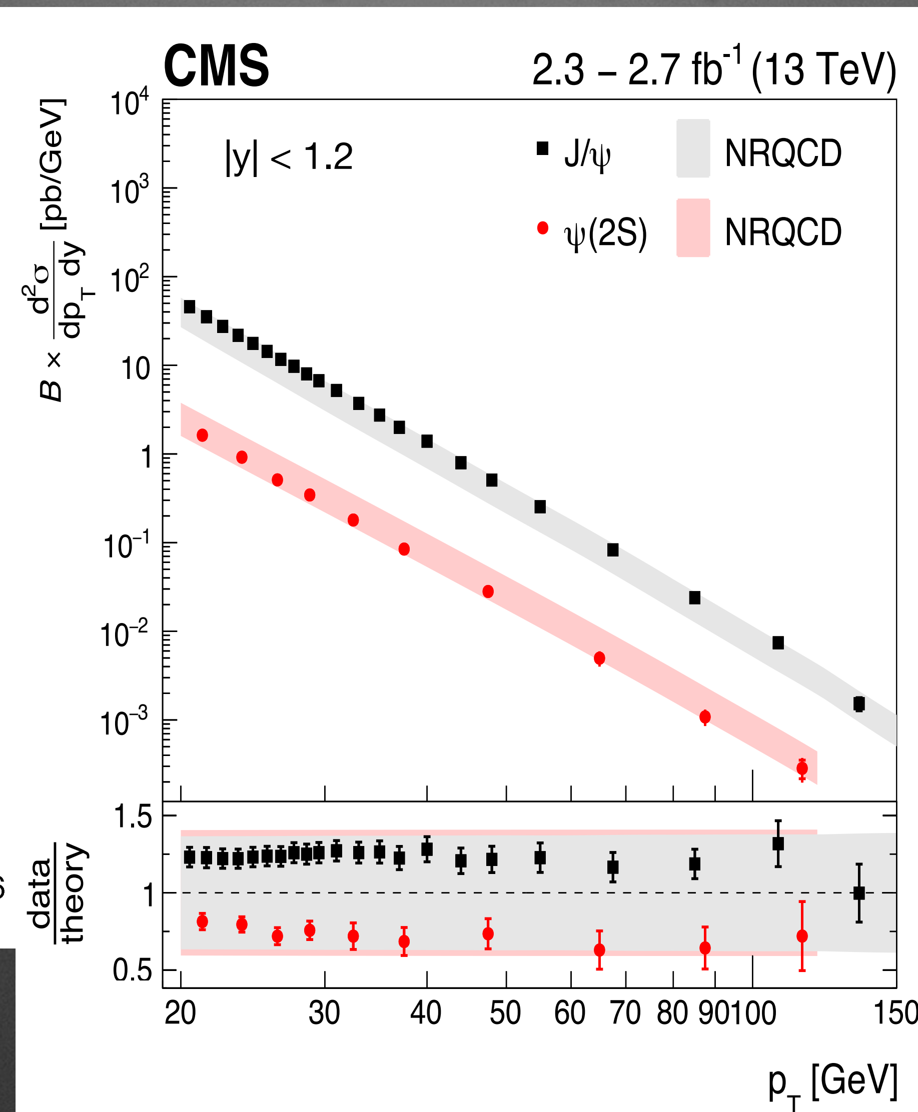


CMS [PLB 780 (2018) 251]



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Prompt J/ψ, ψ(2S) p_T spectra : from low to high p_T

- High precision measurements challenge models over a very wide p_T range

√s = 13 TeV , mid-y

ALICE [JHEP 03 (2022) 190]

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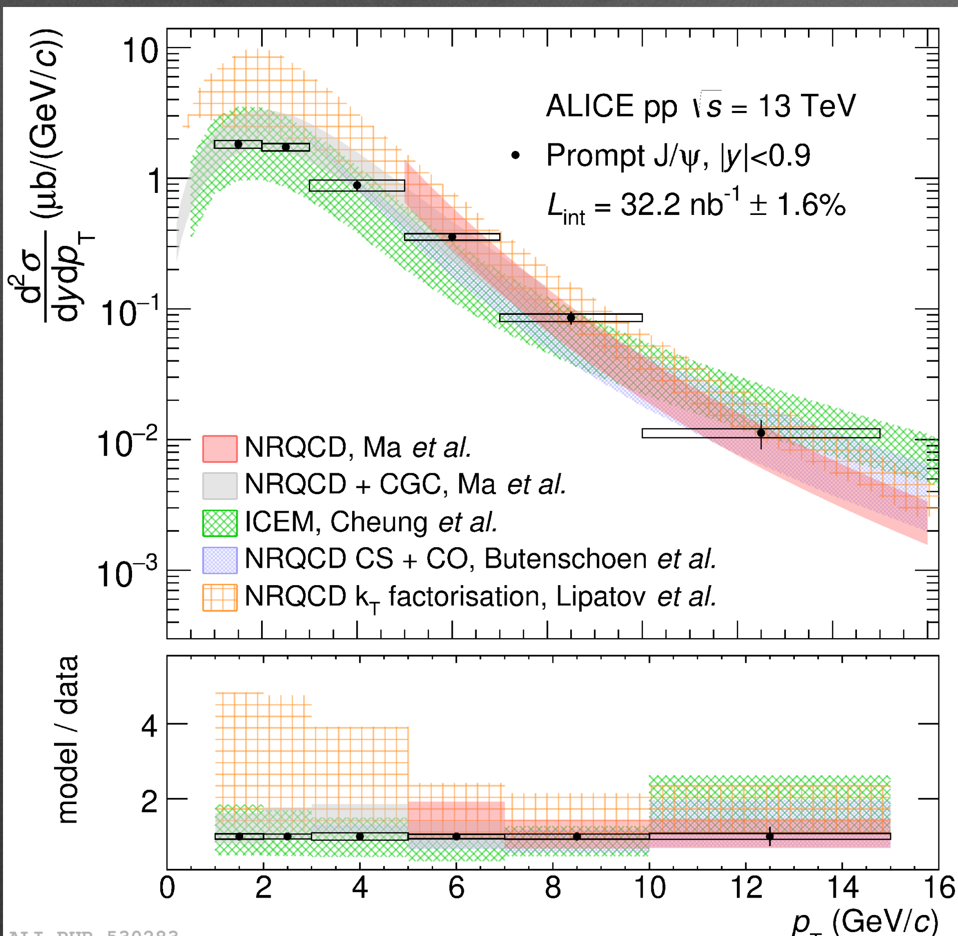
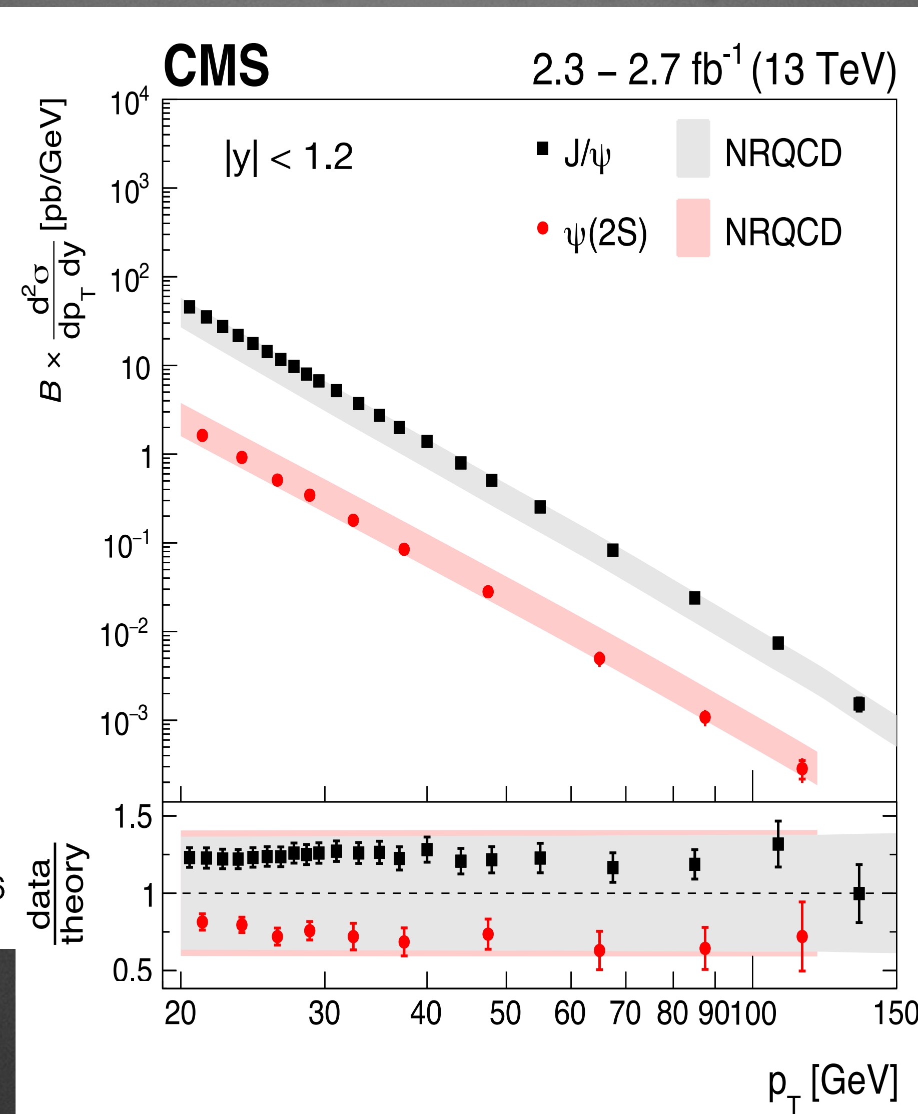
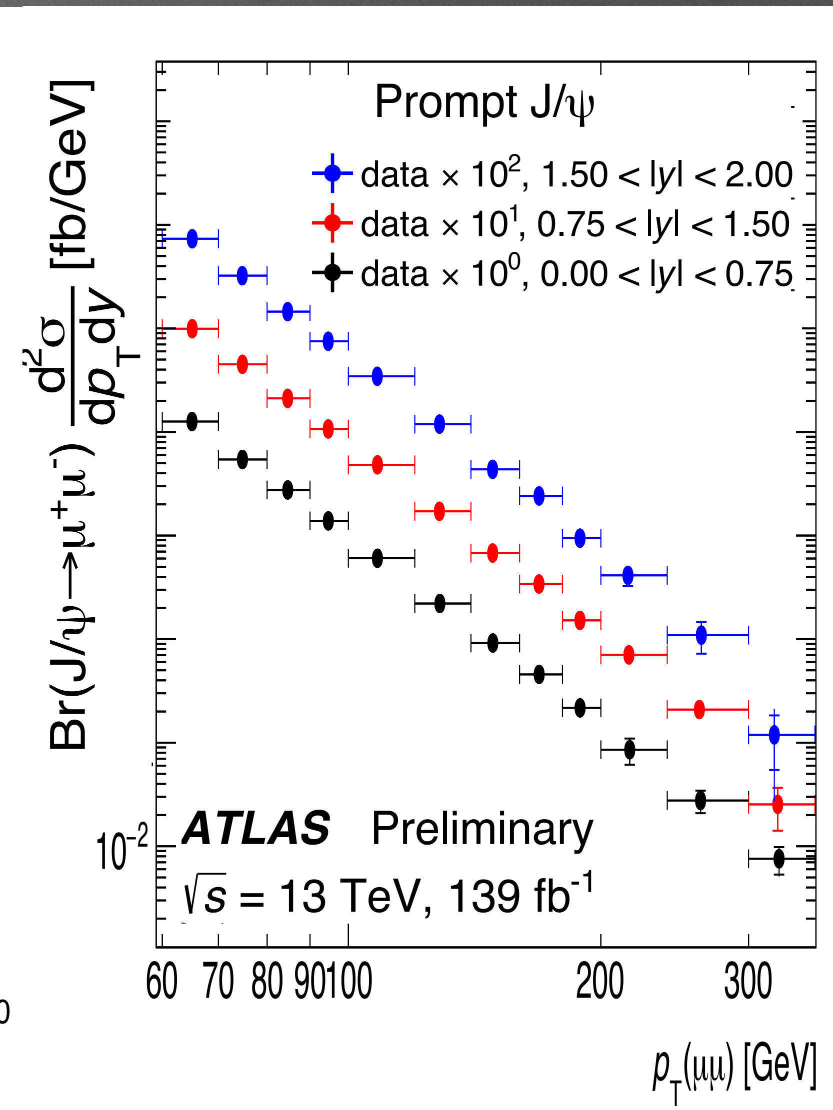
ATLAS : full Run 2 pp 13 TeV dataset [ATLAS-CONF-2019-047]







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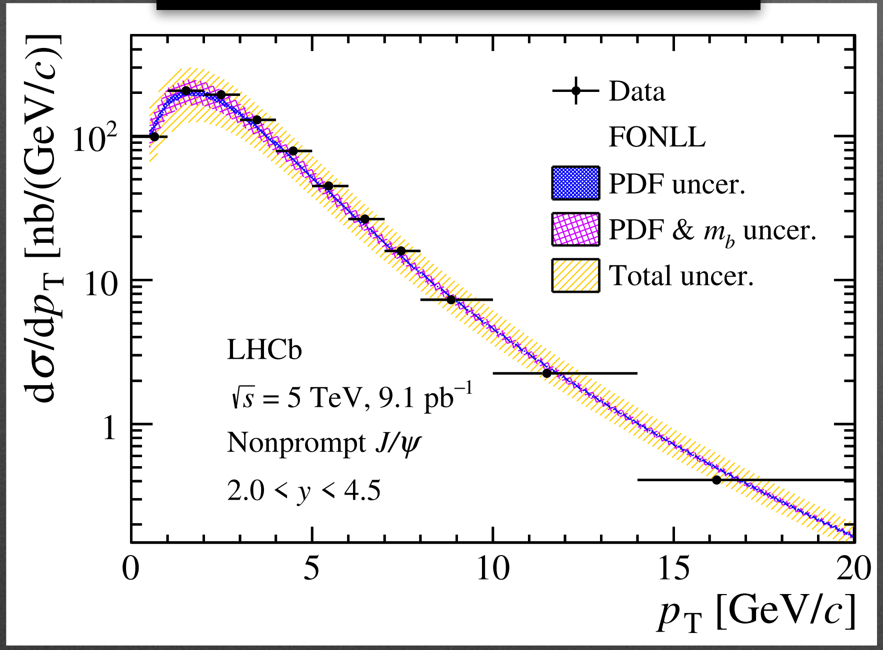
Non-prompt J/ψ p_T spectra

√s = 5 TeV, forward-y



LHCb [JHEP 11 (2021) 181]

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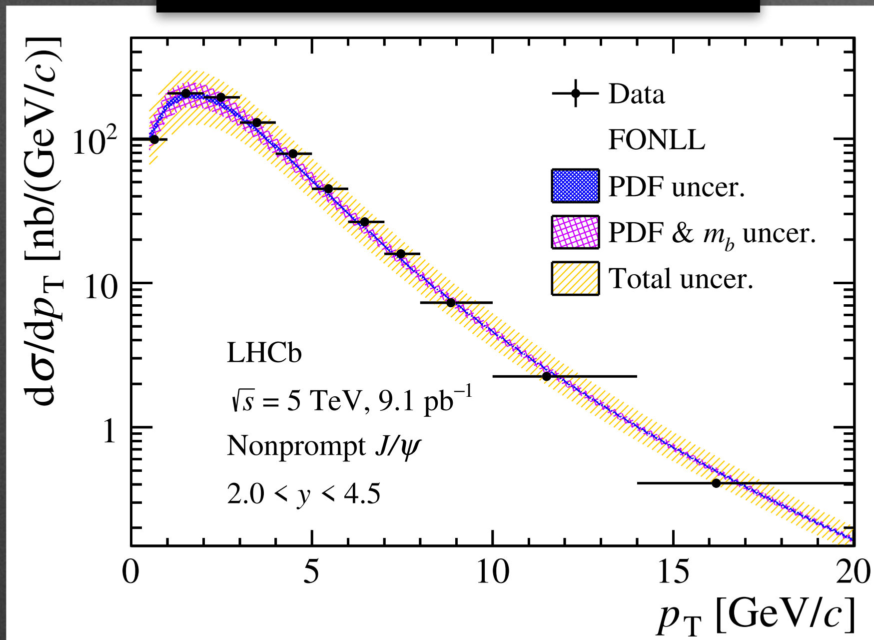

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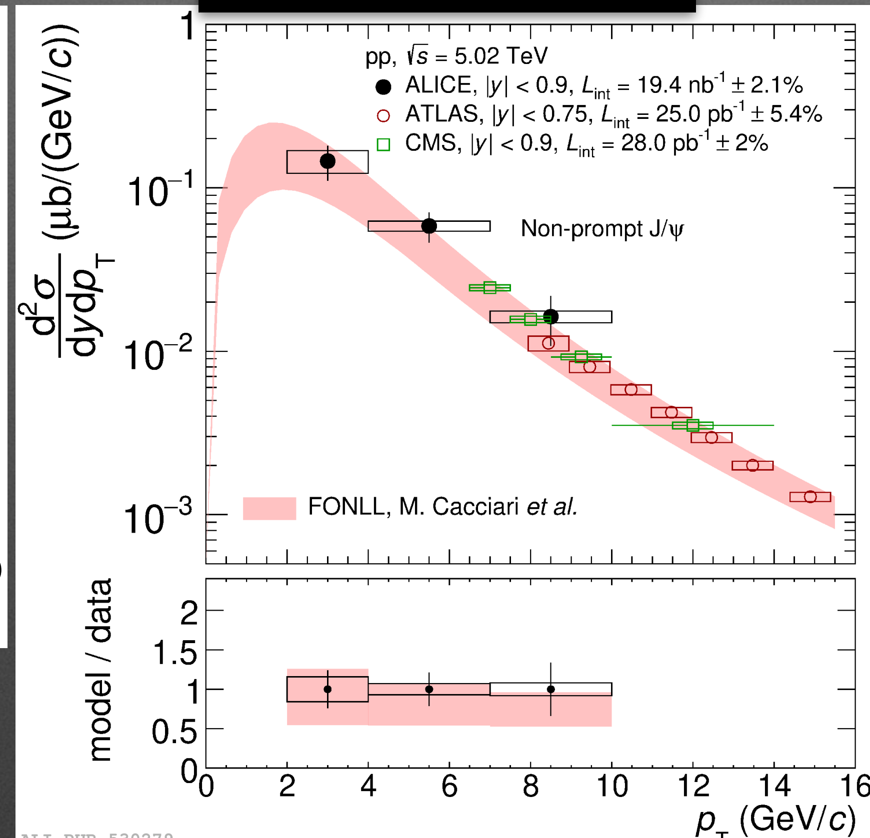
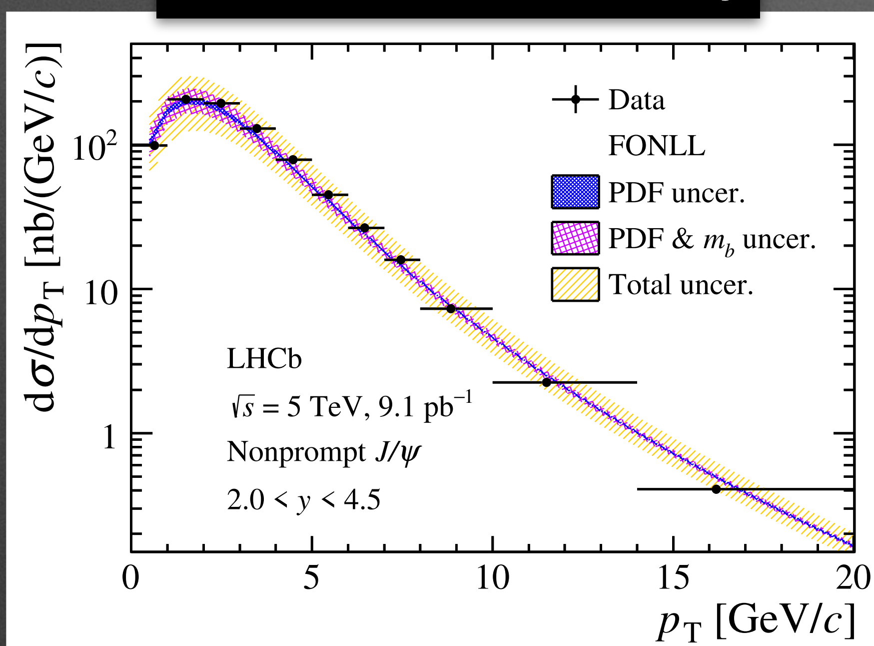


ALICE [JHEP 03 (2022) 190]
ATLAS [EPJ C 78 (2018) 3, 171]
CMS [EPJ C 77 (2017) 4, 269]

Non-prompt J/ψ p_T spectra

- J/ψ ← b : FONLL expectations are compared to measured p_T spectra at different √s and y
  - Tend to overestimate the data at very high p_T

√s = 5 TeV, forward-y



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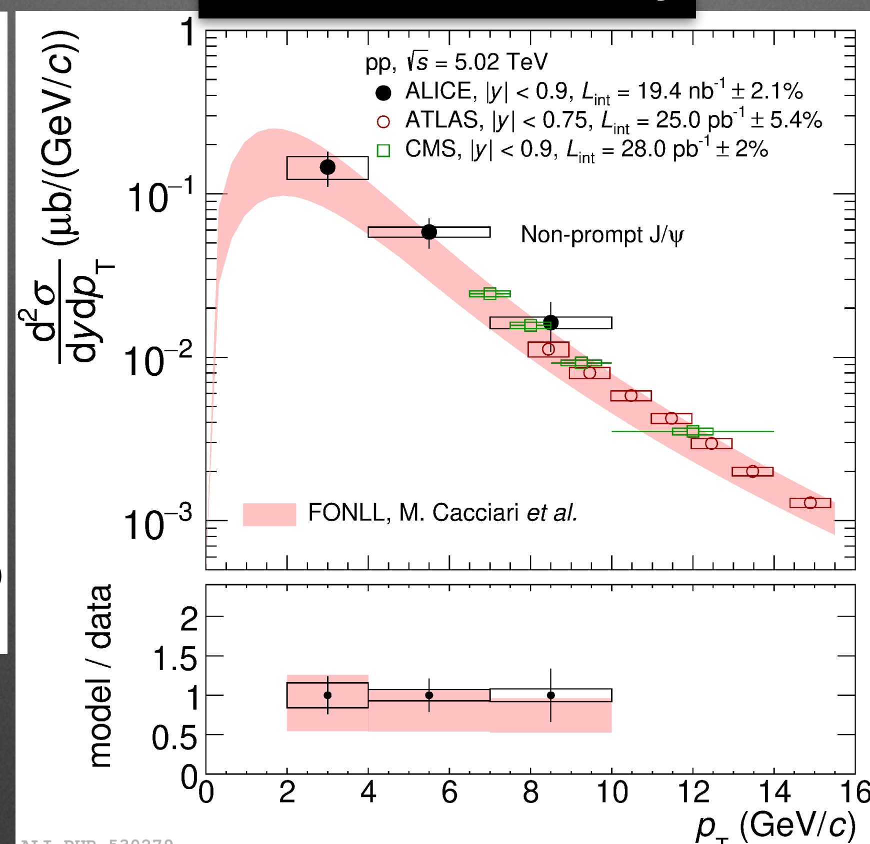

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FONLL, Cacciari et al. [JHEP 10 (2012) 137]

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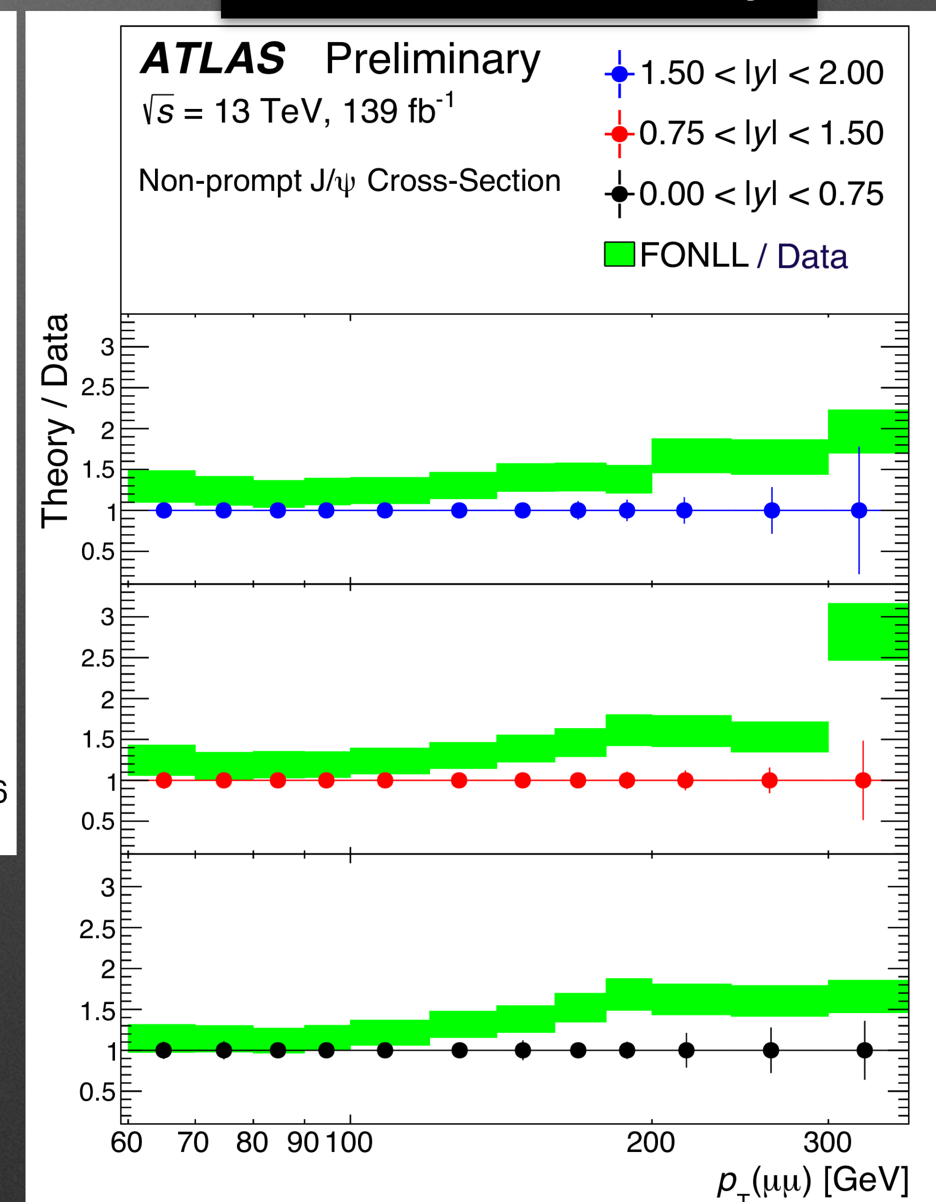

[ATLAS-CONF-2019-047]

Polarisation of P-wave charmonia $\sqrt{s}$ = 8 TeV

- Within NRQCD, χ_{c1} and χ_{c2} polarisations can be predicted with a single CO (color octet) parameter from χ_{c2}/χ_{c1} cross-section ratio *NRQCD prediction Faccioli et al. [EPJ C 78 (2018) 3, 268]*

- « Relative » polarisation study of χ_{c2} vs χ_{c1} *CMS [PRL 124 (2020) 16, 162002]*

angular dependences of the χ_{c2}/χ_{c1} yield ratio

$$\chi_c \to J/\psi\,\gamma$$

$\gamma \to e^+e^-$ conversions

$J/\psi \to \mu^+\mu^-$ angular distribution in the rest frame of the J/ψ

$$1 + \lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\varphi \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi$$

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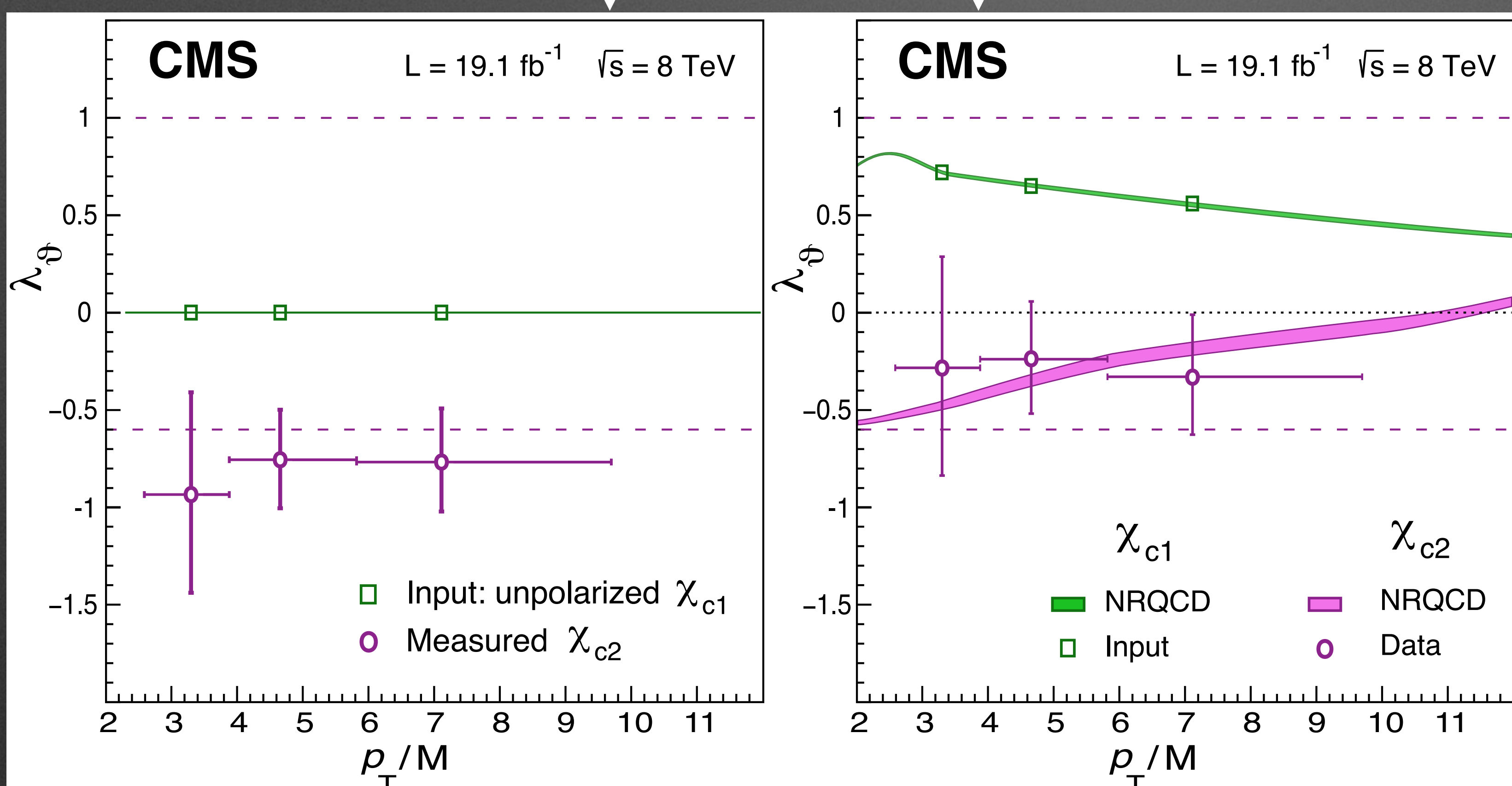
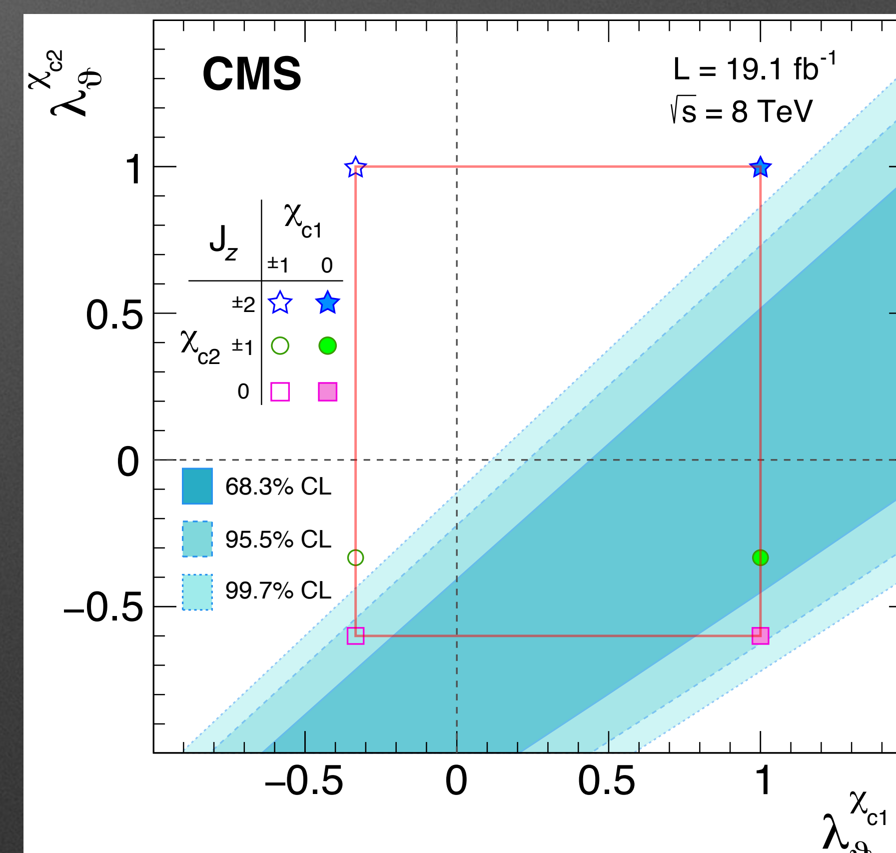
Measured $\lambda_\vartheta^{\chi c2}$ for $\lambda_\vartheta^{\chi c1}$ fixed to unpolarised or NRQCD scenarios

$\lambda_\vartheta^{\chi c2}$ vs $\lambda_\vartheta^{\chi c1}$ contours





Unpolarised scenario and a sizeable part of the physically allowed region (red rectangle) are excluded at 99.7% CL

Nature of the exotic $\chi_{c1}(3872)$?

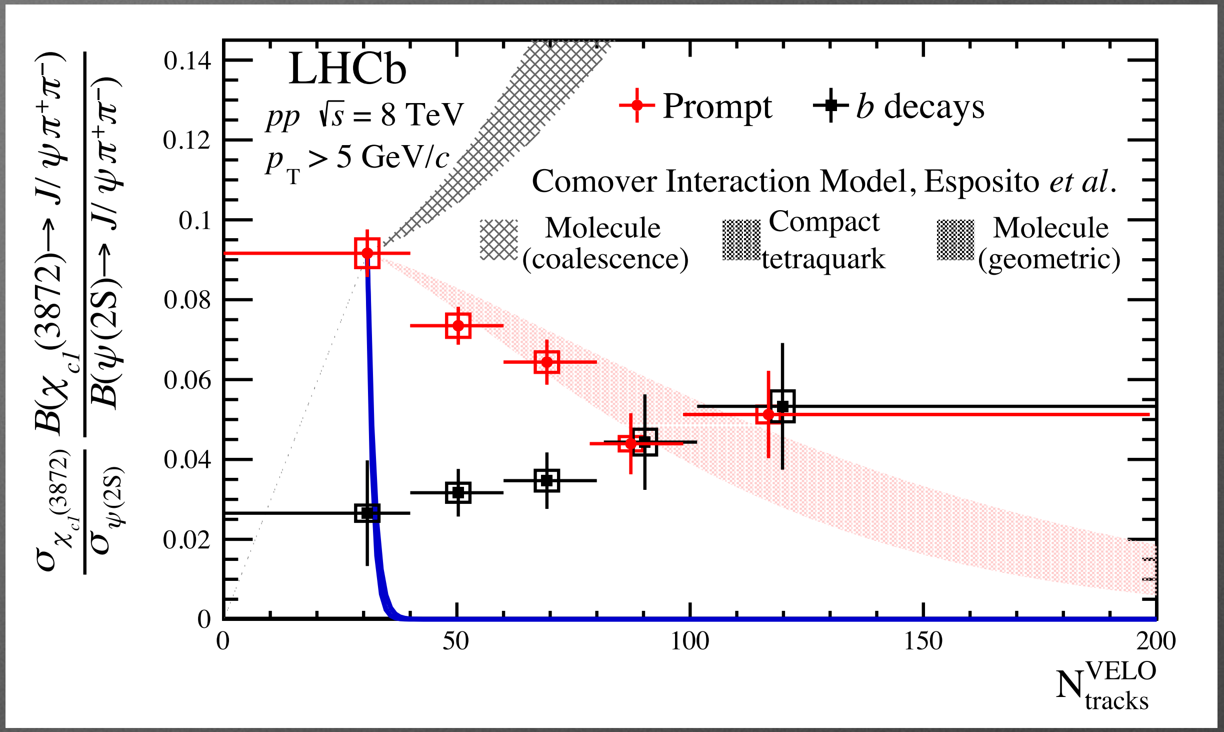
LHCb [PRL 126 (2021) 9, 092001]

(1) Esposito et al. [Eur.Phys.J.C 81 (2021) 7, 669]

(2) Braaten et al. [Phys.Rev.D 103 (2021) 7, L071901]

Test binding strength and radius via final state effects dependent on the hadronic environment (multiplicity) generated at the primary vertex

$\sqrt{s}$ = 8 TeV



- Prompt $\chi_{c1}(3872)$ / ψ(2S) ratio decreases with multiplicity. Under different assumptions, such behaviour would emerge from opposite scenarios:
  - a compact tetraquark in the model (1)
  - a large molecule of neutral charm mesons in the model (2)

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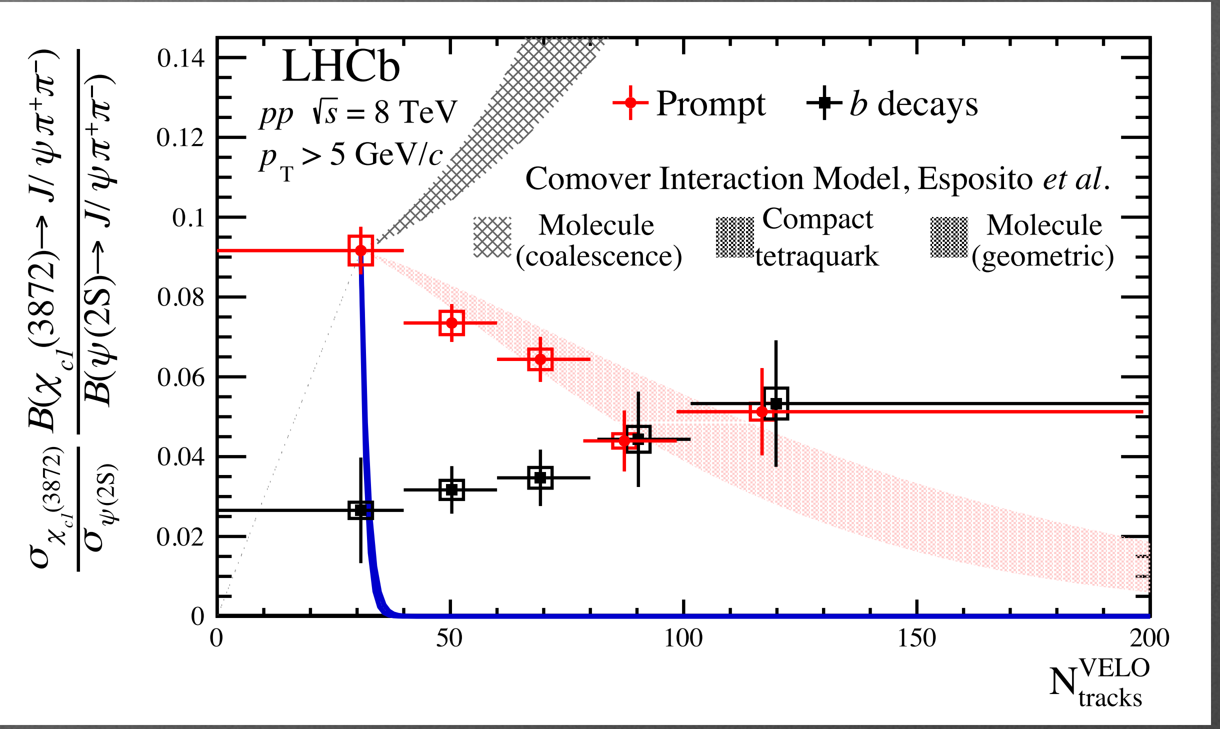

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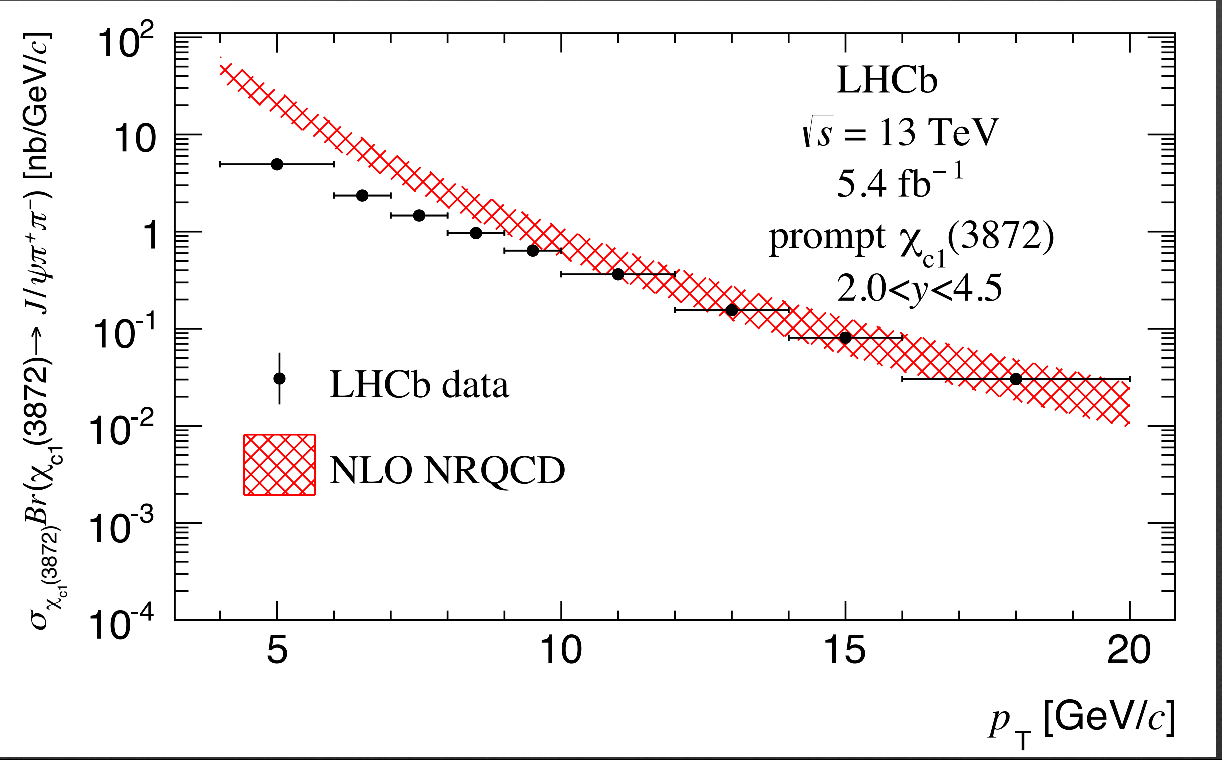
LHCb [JHEP 01 (2022) 131]
NLO NRQCD, Meng et al. [Phys.Rev.D 96 (2017) 7, 074014]

Prompt χ_{c1}(3872) production vs p_T

√s = 13 TeV



- For p_T > 10 GeV/c, agreement with NLO NRQCD predictions which model the χ_{c1}(3872) state as a mixture of χ_{c1}(2P) and $D^0\bar{D}^{*0}$ molecule states

Υ(1S), (2S), (3S) : p_T spectra

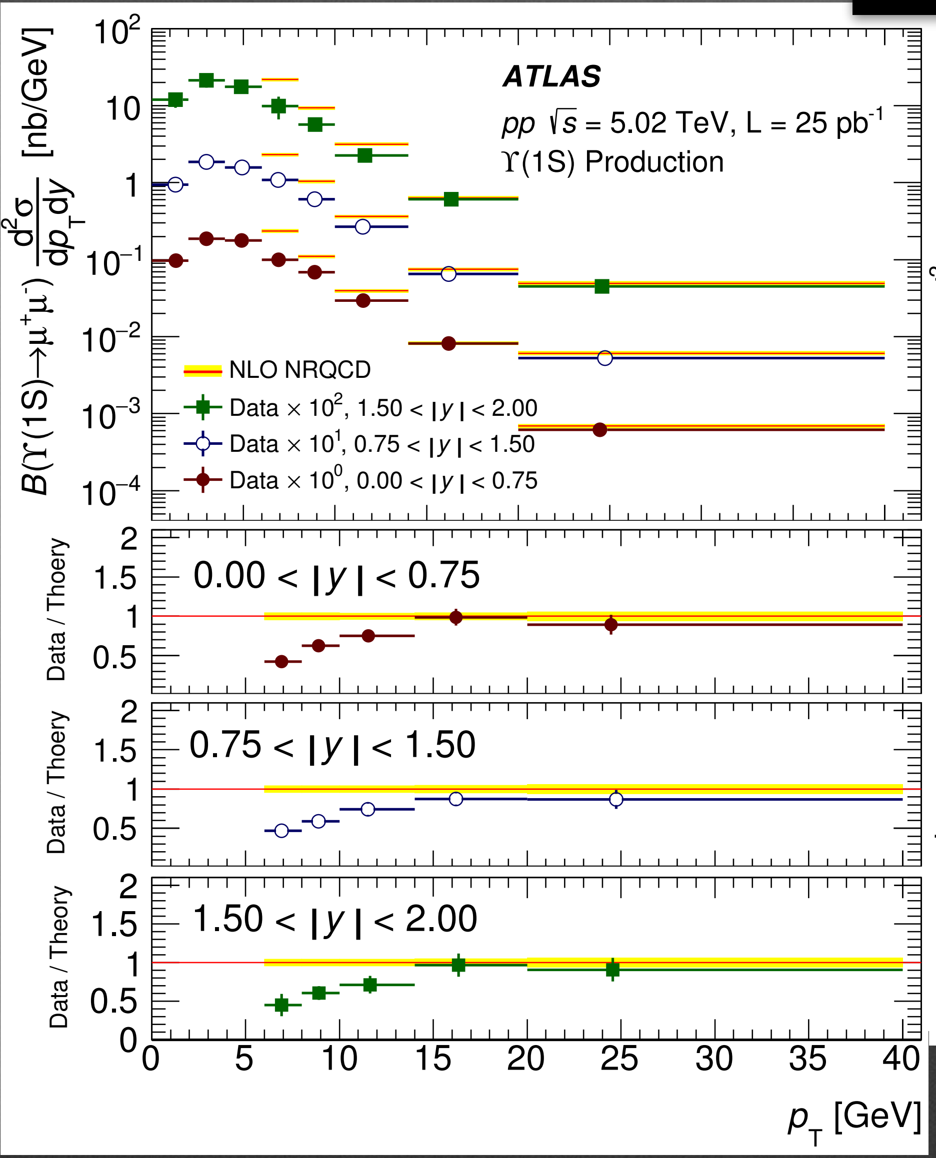
√s = 5, 13 TeV

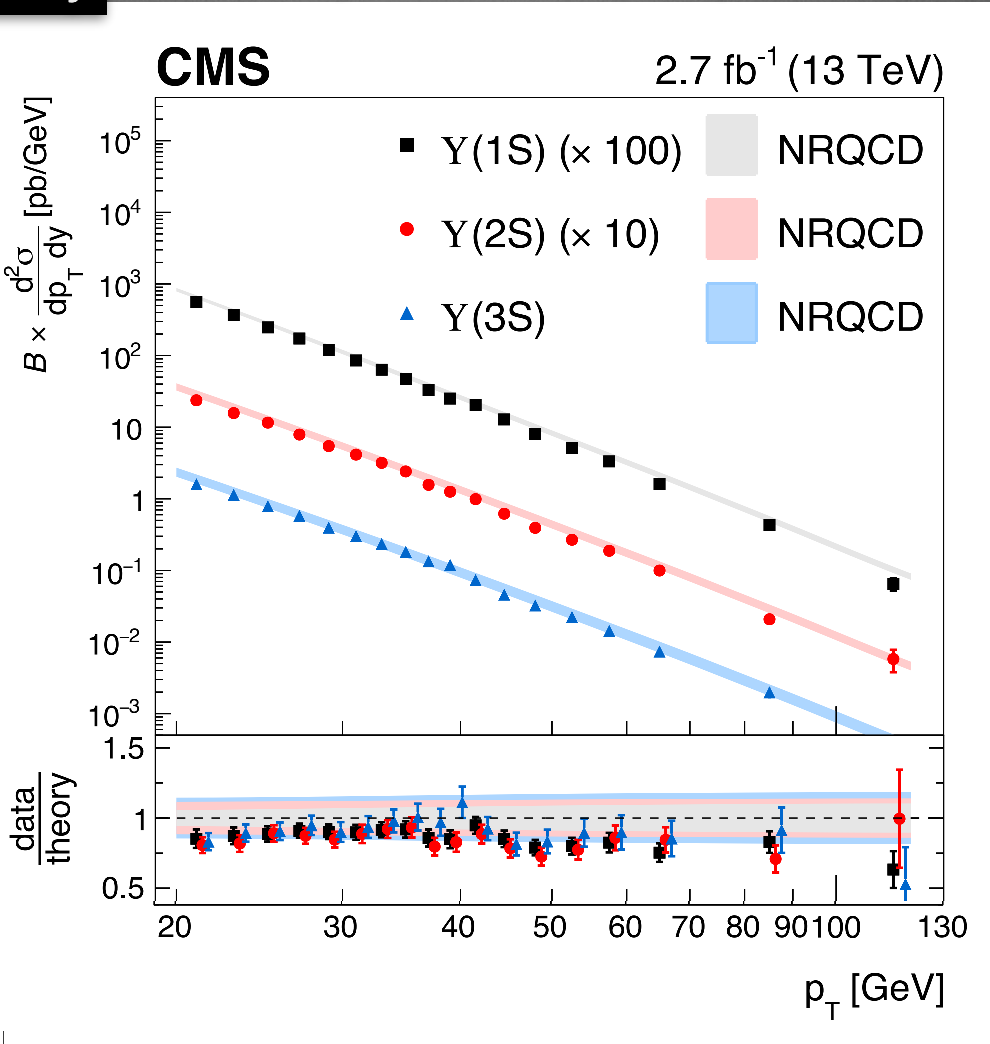
- Experimental data can constrain the choice of non-perturbative inputs (LDMEs) to NRQCD predictions

ATLAS [EPJ C 78 (2018) 3, 171]

mid-y

CMS [PLB 780 (2018) 251]





NRQCD predictions Han et al. [PRD 94 (2016) 1, 014028]

NRQCD predictions Han et al. [PRD 94 (2016) 1, 014028] obtained with LDMEs extracted from fitting data at p_T > 15 GeV/c were also found to overestimate LHCb measurements.

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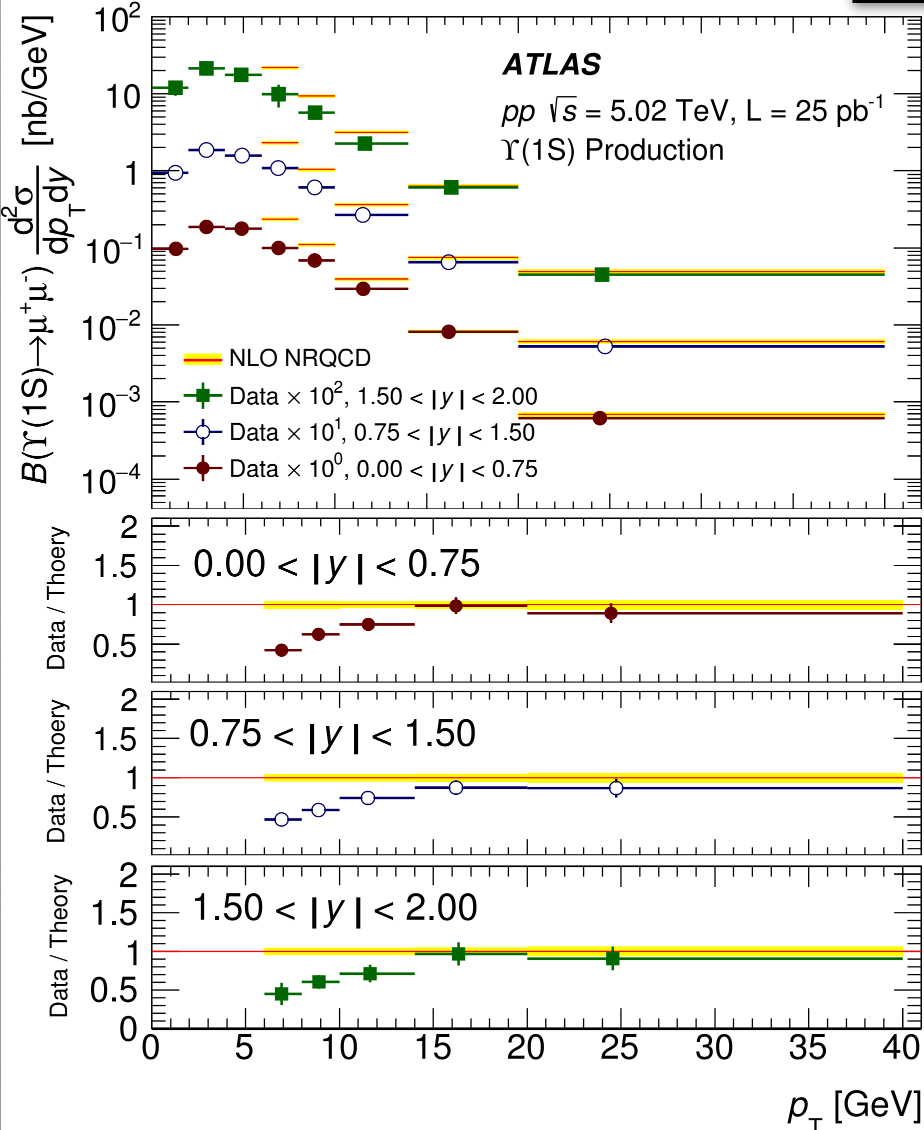

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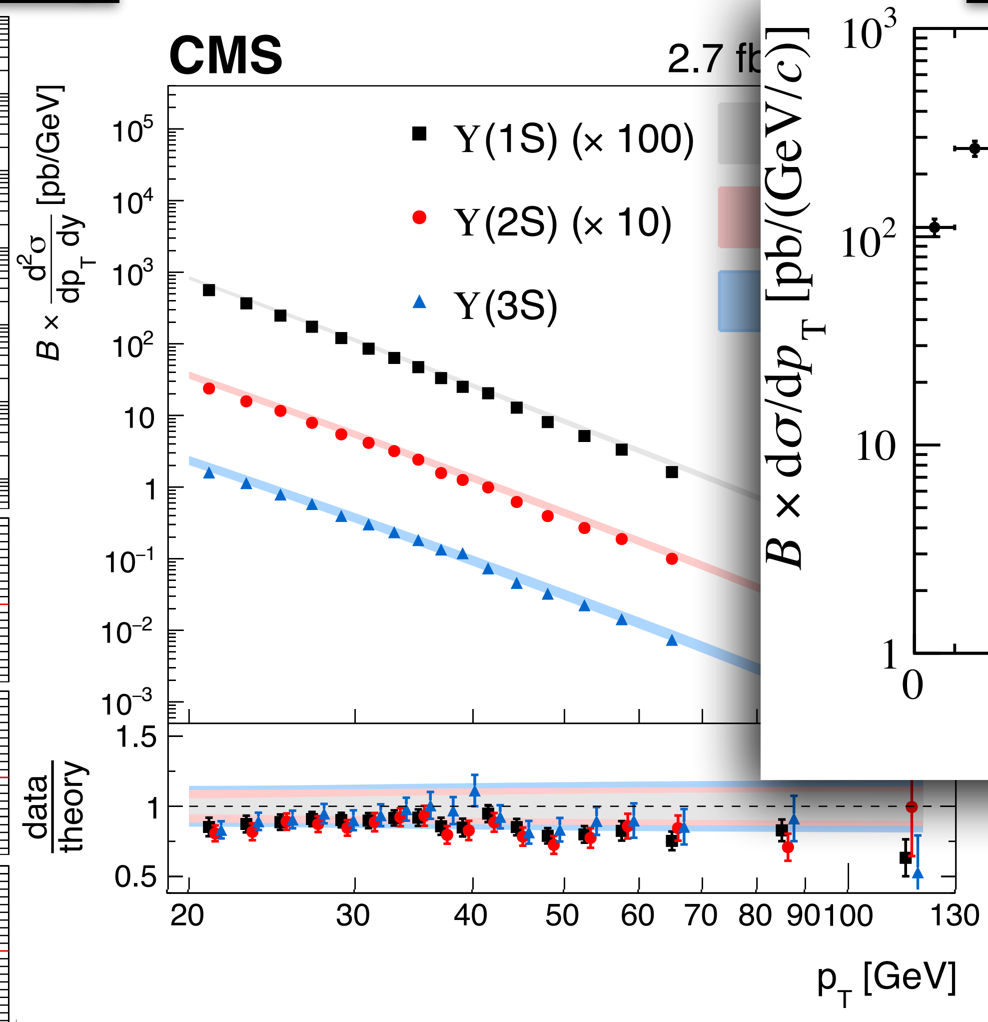
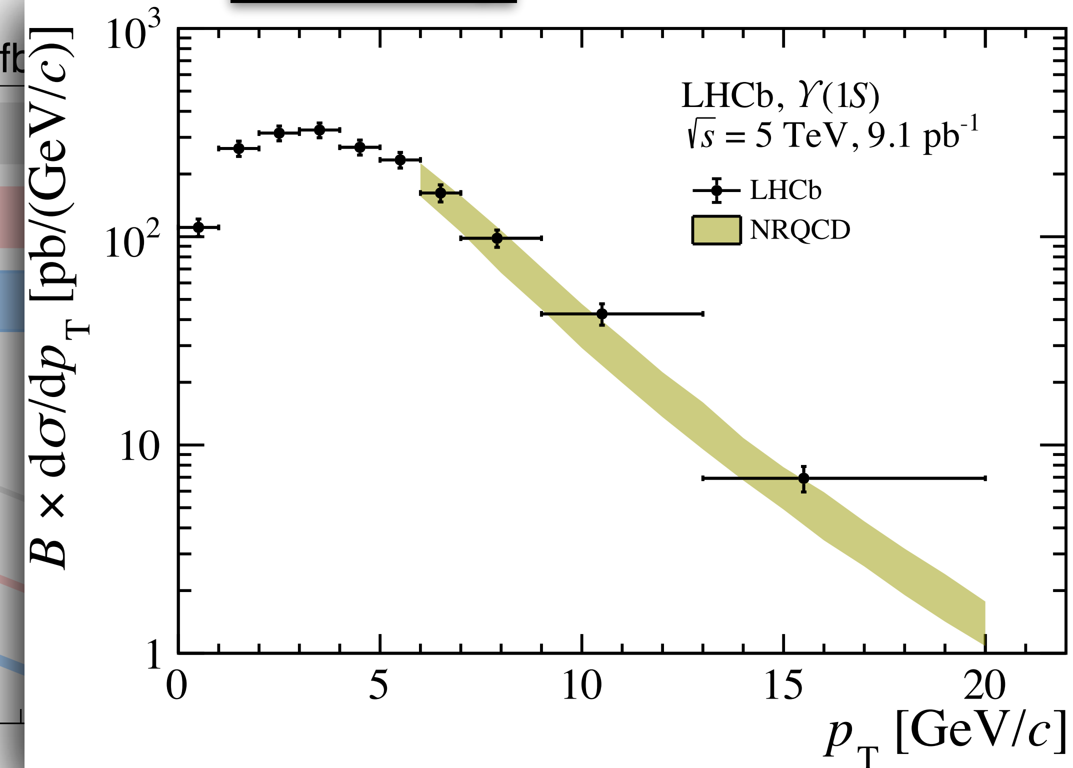


forward-y

LHCb [arXiv: 2212.12664]



NRQCD predictions Feng et al. [Chin.Phys.C 39 (2015) 12, 123102] obtained with different LDMEs.

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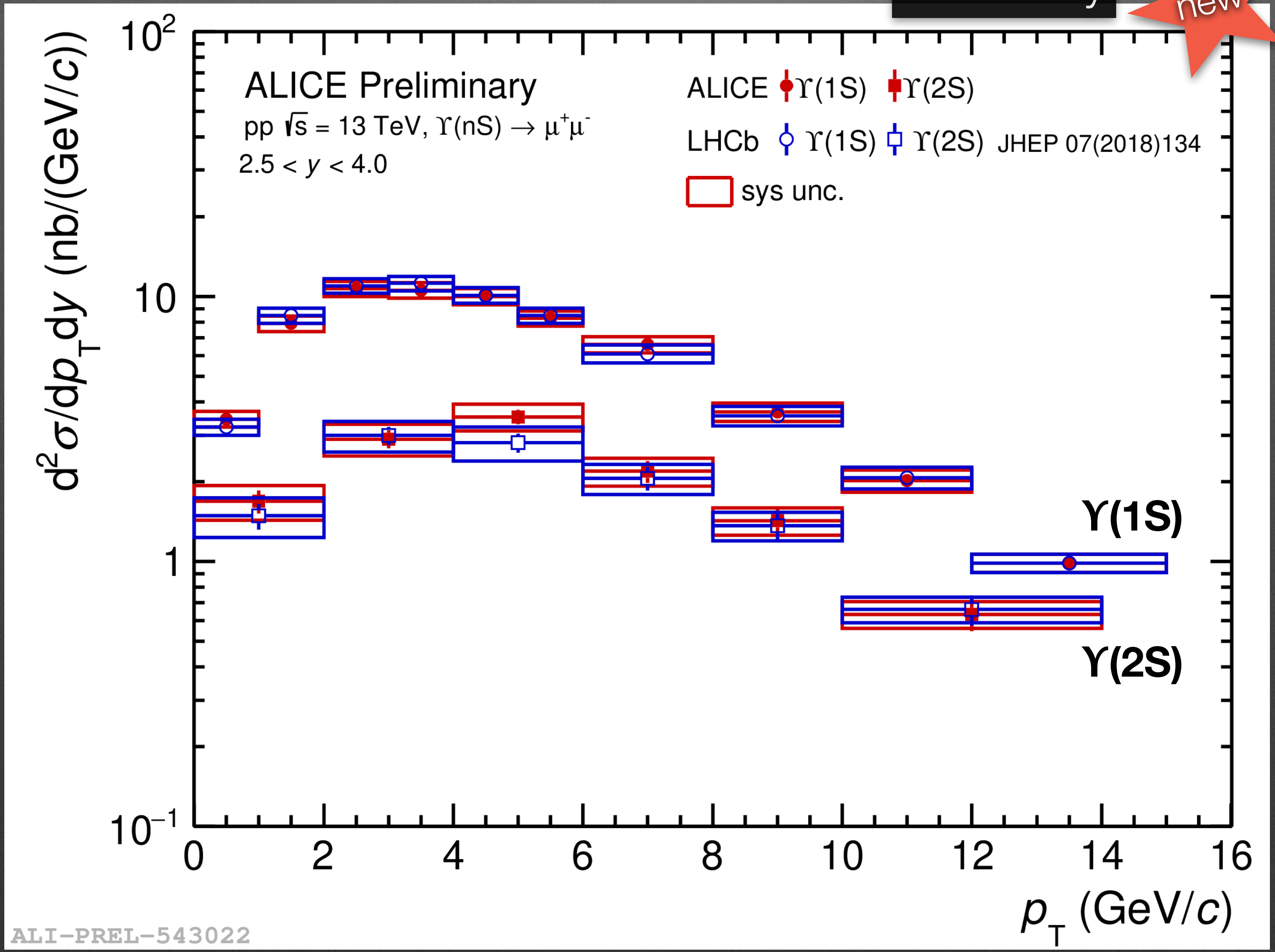
Υ(1S), (2S), (3S) : p_T spectra

√s = 13 TeV

- New preliminary results released by ALICE, compatible with LHCb measurements

forward-y

new

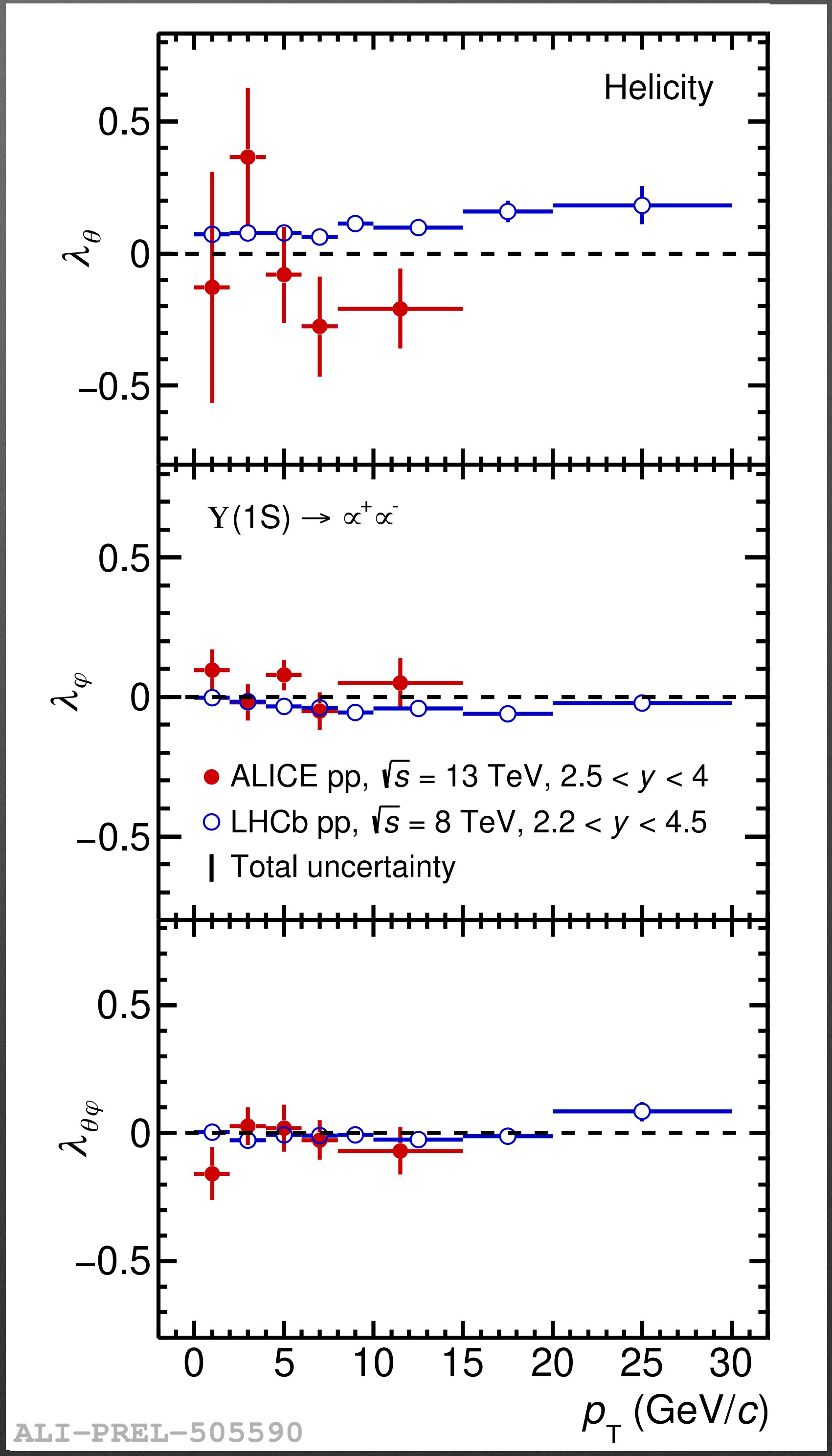


ALICE preliminary
LHCb [JHEP 07 (2018) 134]

Υ(1S) polarisation

$\sqrt{s}$ = 8, 13 TeV, forward-y

ALICE preliminary
LHCb [JHEP 12 (2017) 110]

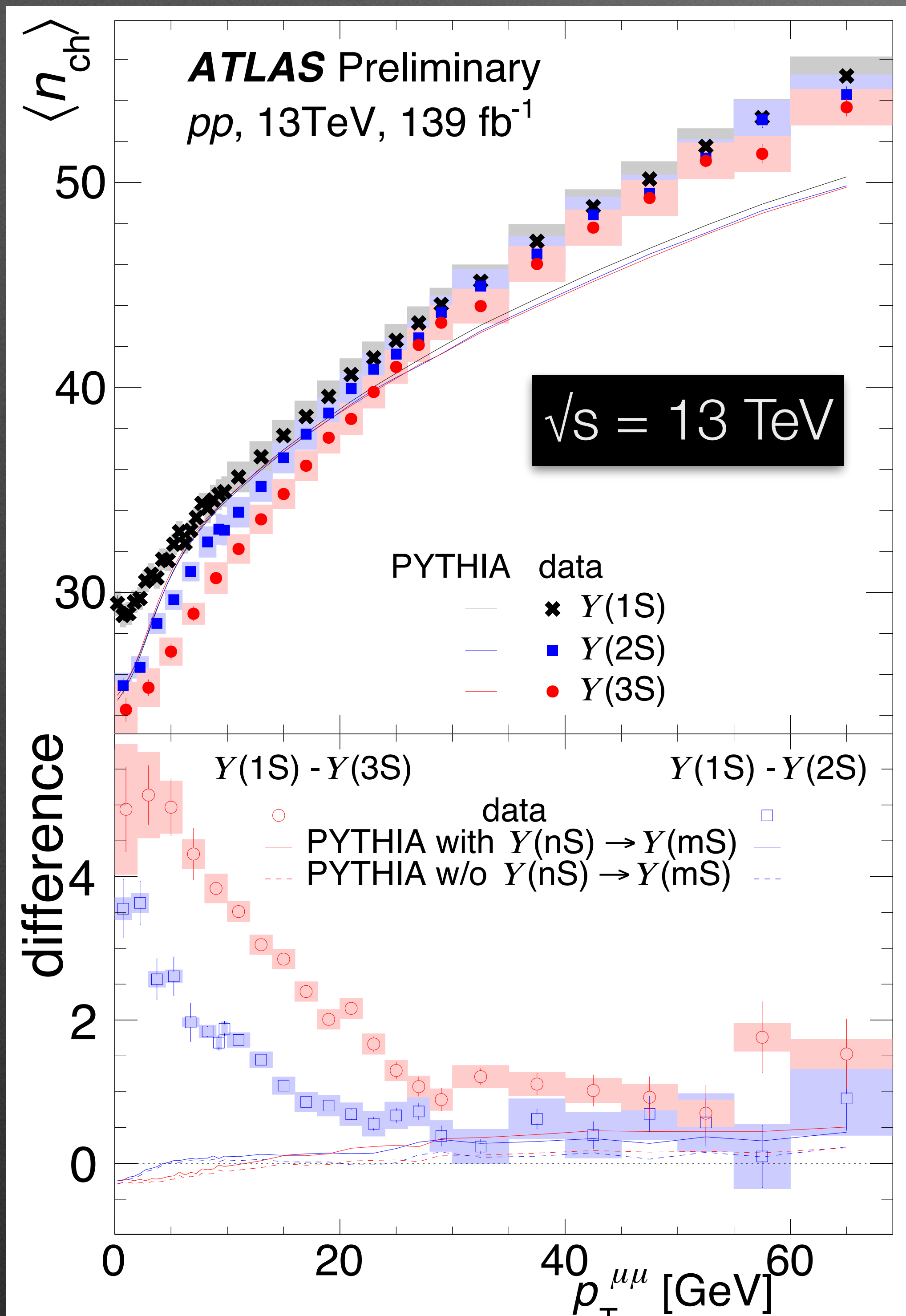


- LHCb results: close to an isotropic decay
  - $\lambda_{\theta\varphi}$ and λ_φ parameters are very close to zero, λ_θ parameter is slightly above zero
- Recent preliminary results released by ALICE aggregates pp dataset collected in 2016, 2017 and 2018
  - Compatible with LHCb measurements
  - Evaluated down to ~zero p_T
  - Limited by the statistical precision

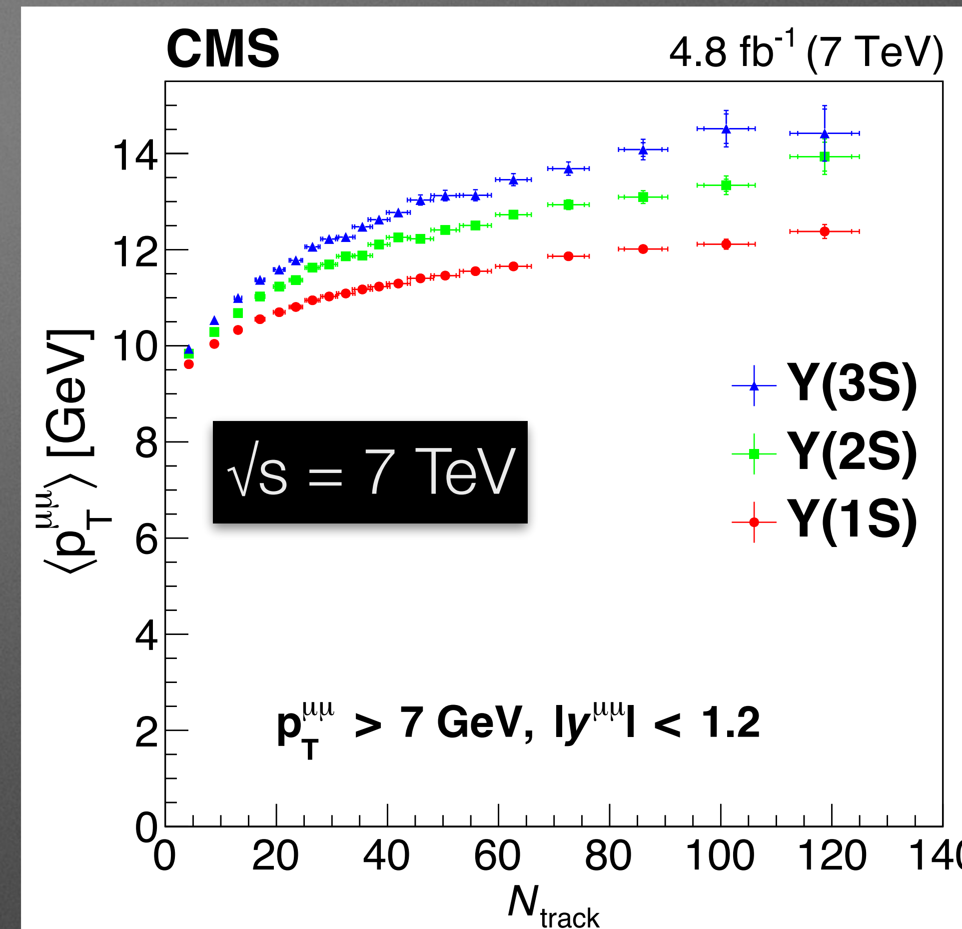
(λ_θ , λ_φ , $\lambda_{\theta\varphi}$) = (0, 0, 0) isotropic decay
(1, 0, 0) fully transverse polarisation
(-1, 0, 0) fully longitudinal polarisation

Υ(nS) production : dynamics in the underlying event

Mean number of charged particles with $0.5 < p_T < 10$ GeV/c and $|\eta| < 2.5$ in events with Υ(nS)



ATLAS [ATLAS-CONF-2022-023]



CMS [JHEP 11 (2020) 001]

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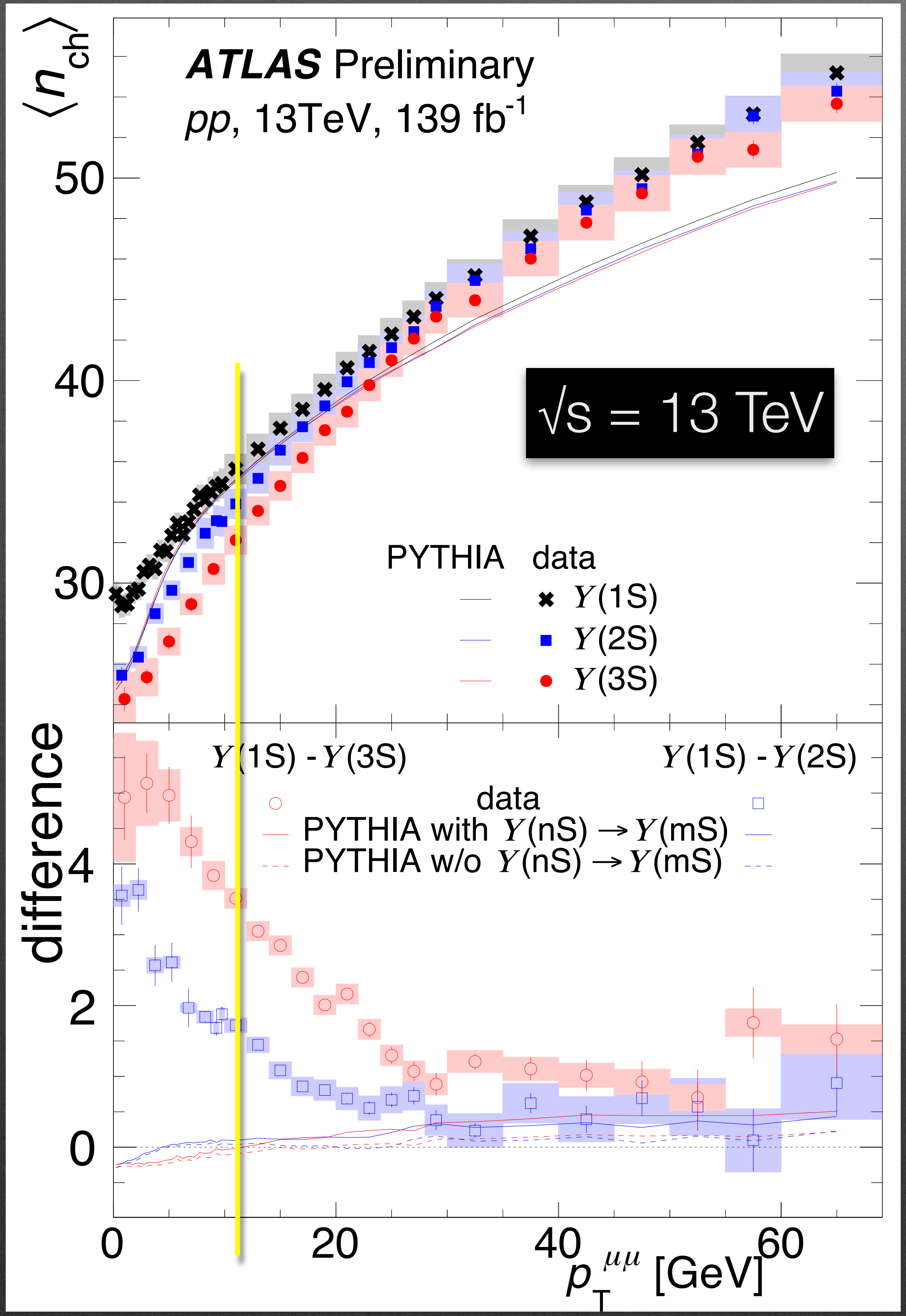

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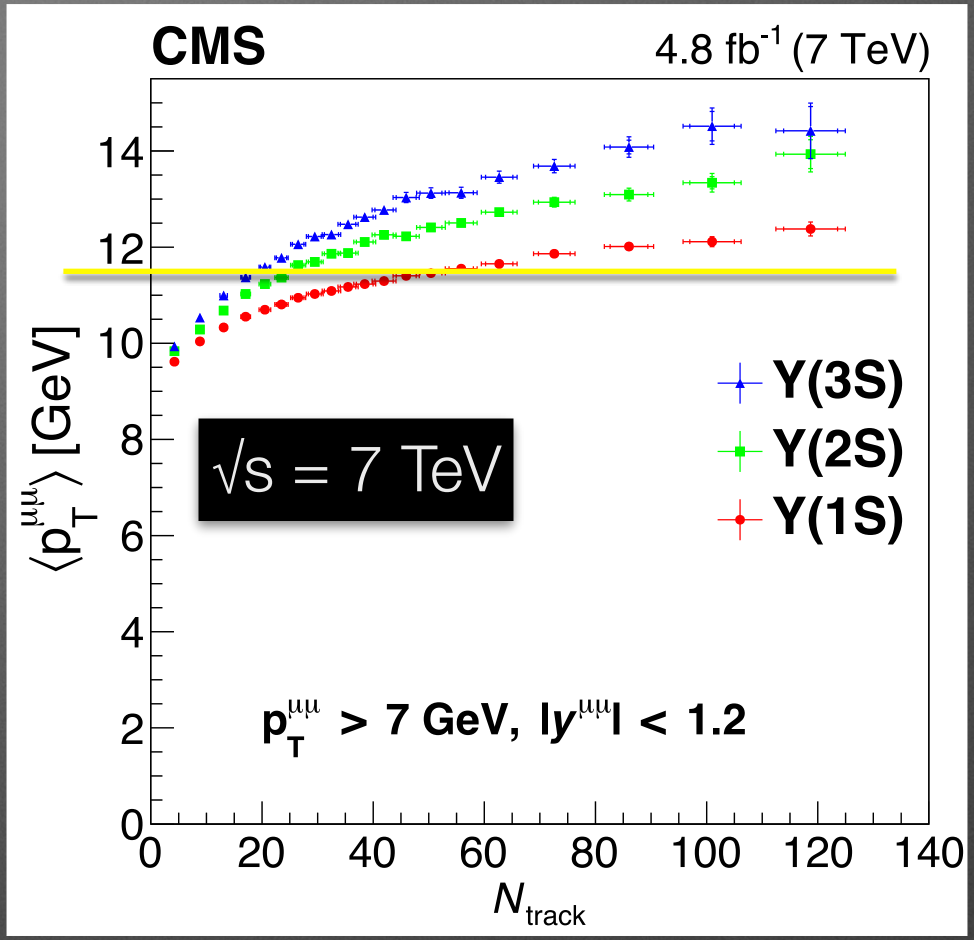

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- At a given $p_T^{\mu\mu}$, there is a deficit of charged particles in the events with excited states

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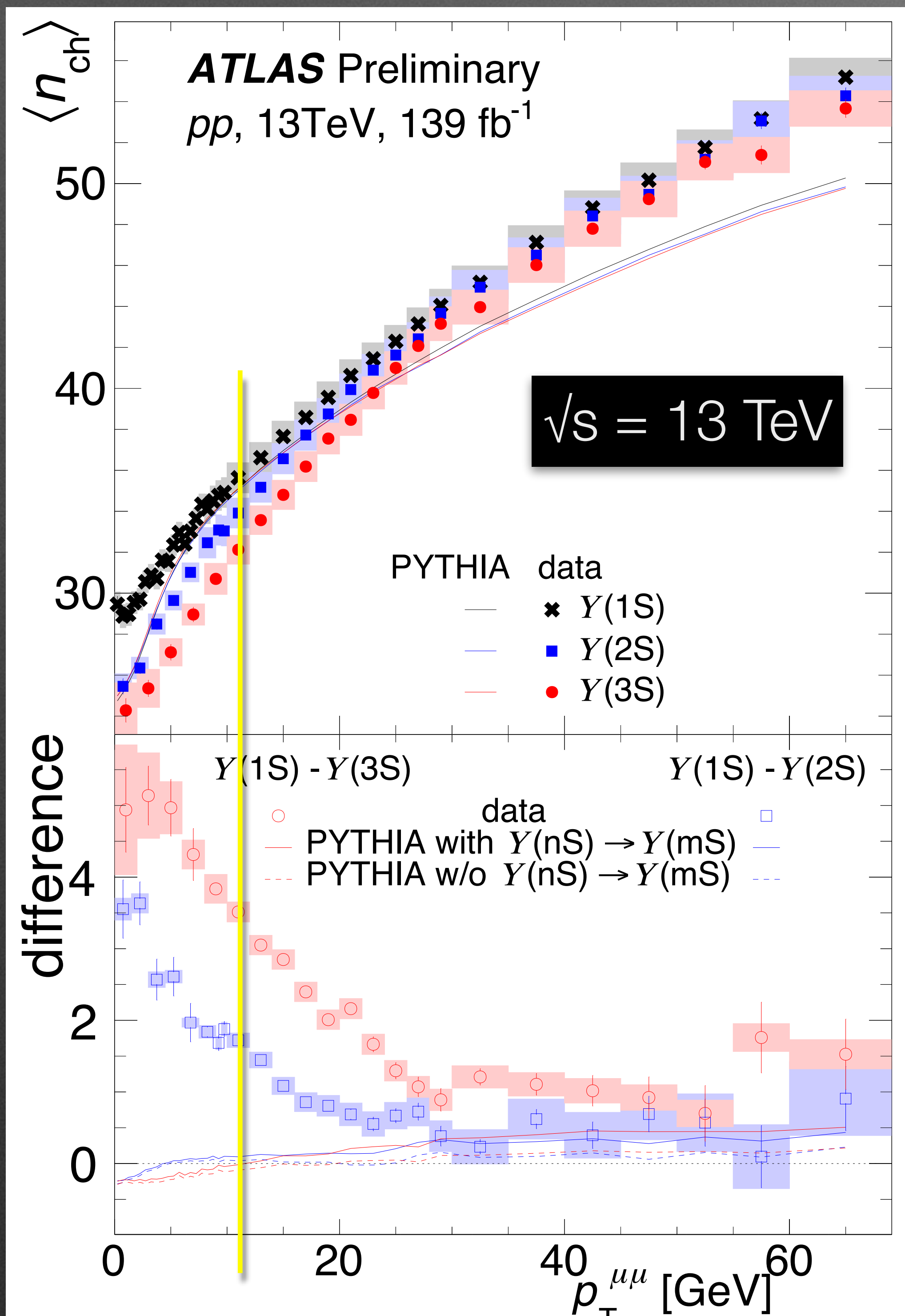

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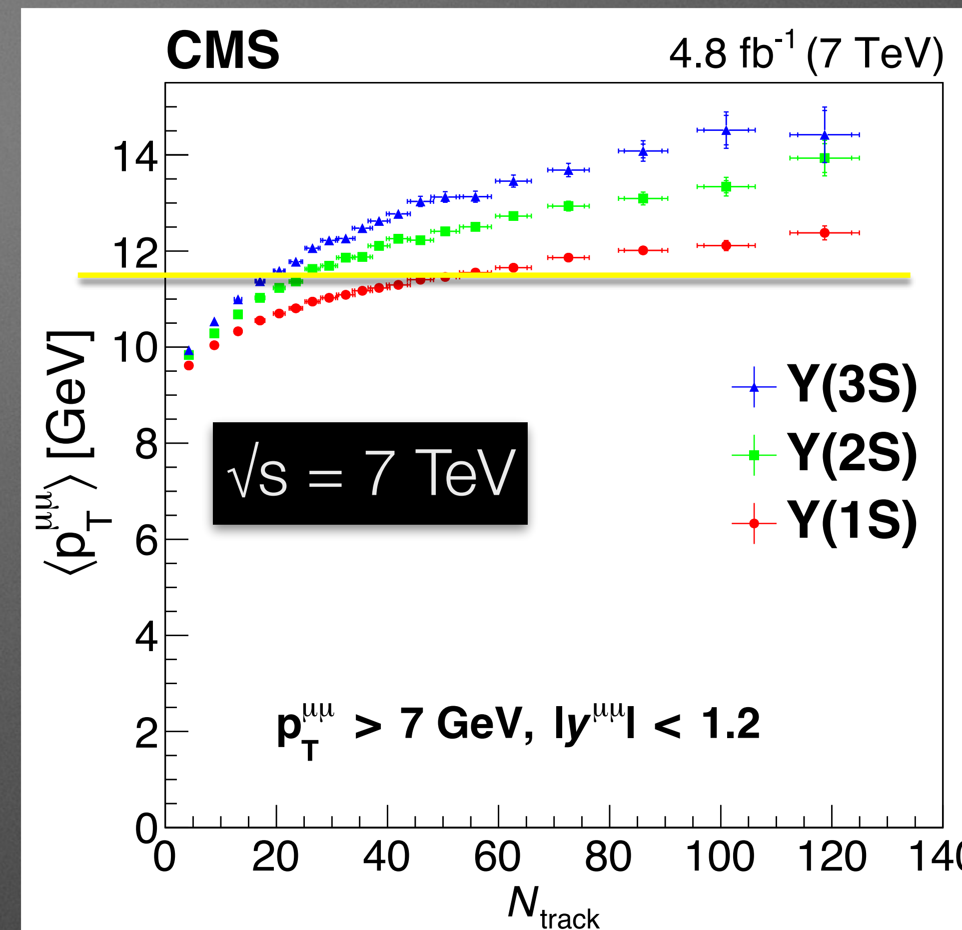


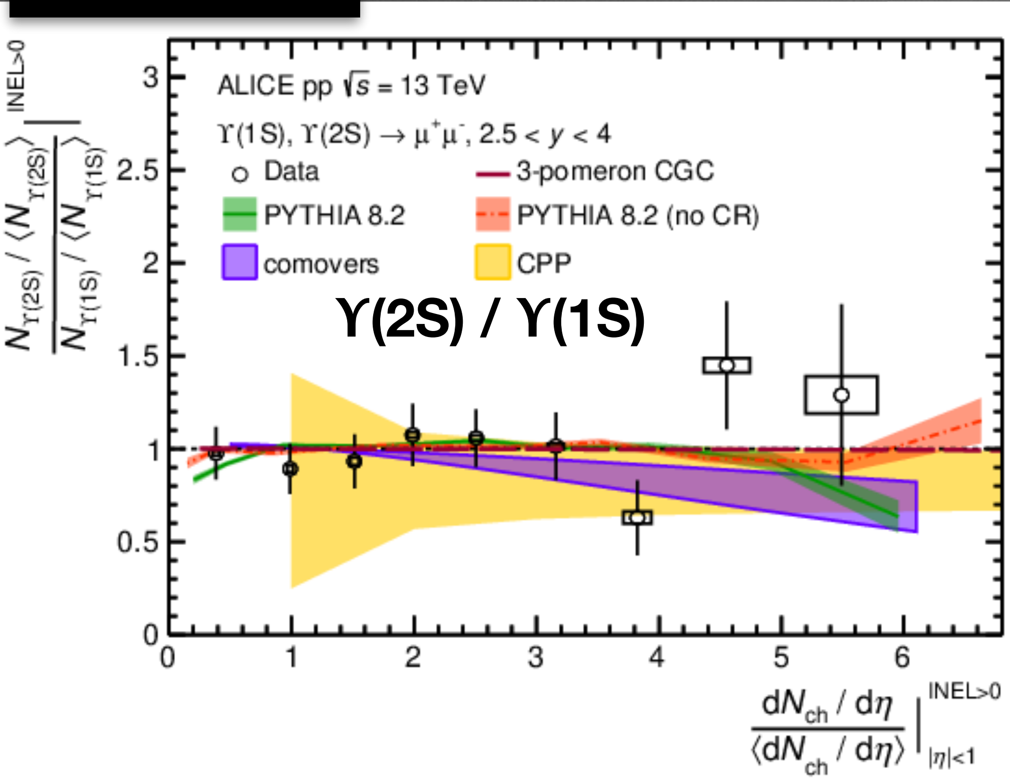
CMS [JHEP 11 (2020) 001]

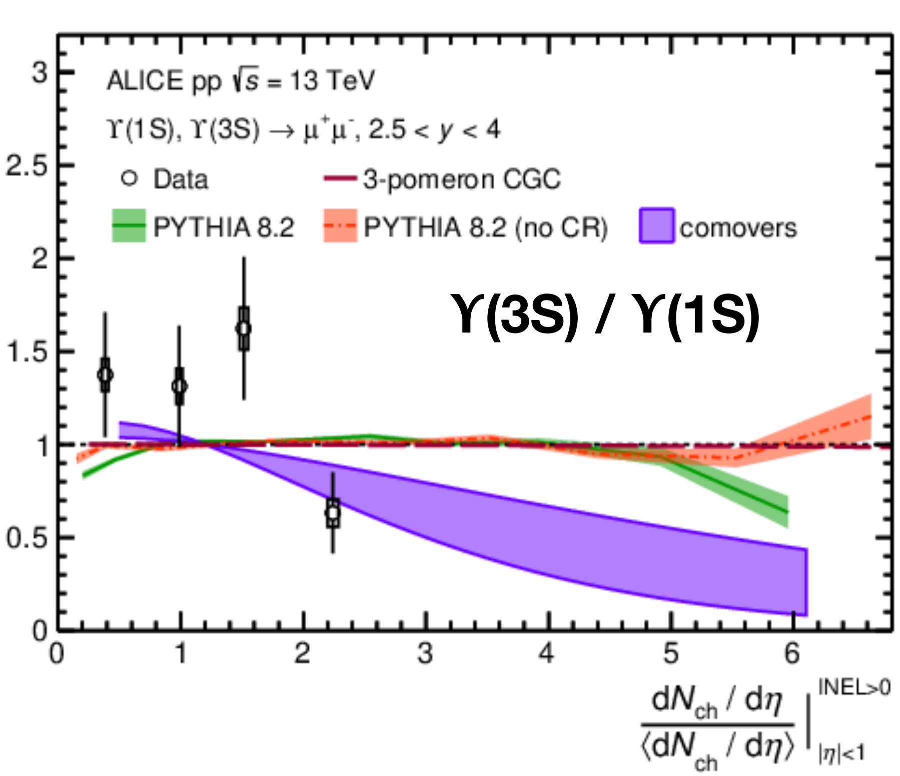
- At a given $p_T^{\mu\mu}$, there is a deficit of charged particles in the events with excited states
- Large differences across Υ(nS) states at low p_T are:
  - reduced at high p_T
  - unexpected with PYTHIA event generator

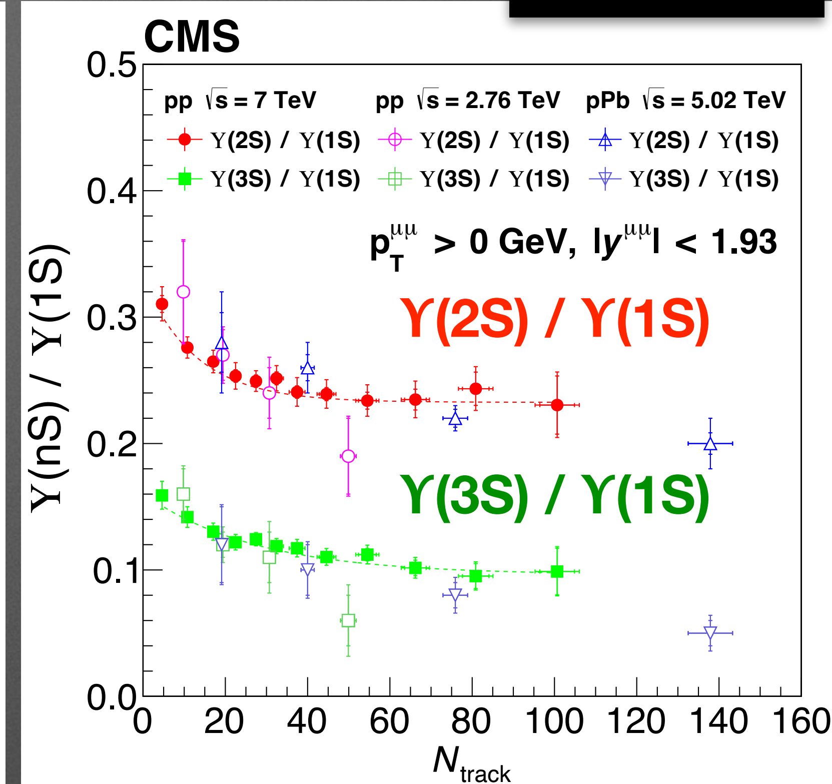
Υ(nS) / Υ(1S) ratios vs multiplicity

√s = 13 TeV

√s = 7 TeV







Comovers, Ferreiro [PLB 749 (2015) 98]
3-pomeron CGC, Levin et al. [EPJ C 80 (2020) 6, 560]
CPP, Kopeliovich et al. [PRD 101 (2020) 5, 054023]

ALICE [arXiv:2209.04241]

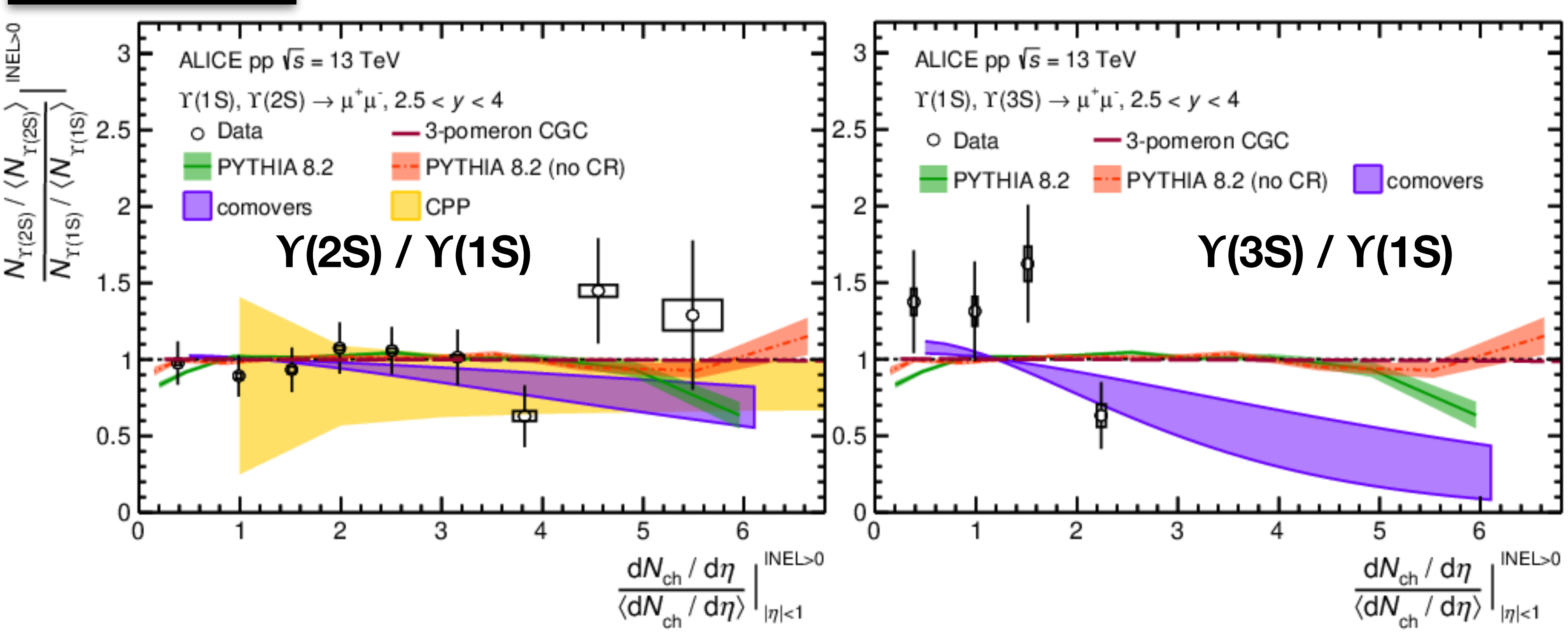
CMS [JHEP 11 (2020) 001]

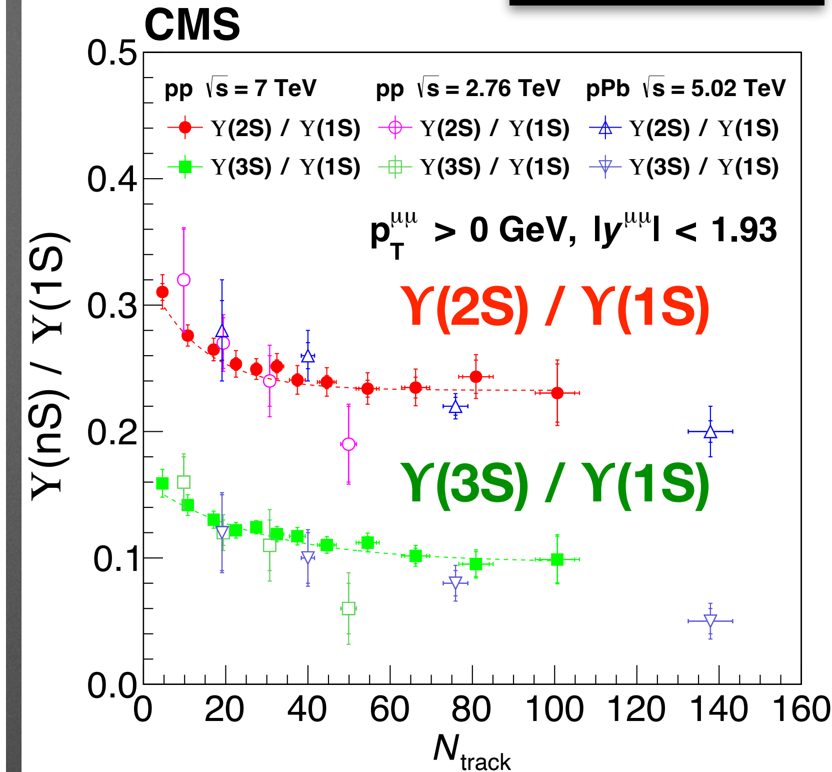
- Test any final state (break-up ?) effect dependent on the multiplicity by removing most initial state effects in the ratios
  - Higher mass states have a lower binding energy w.r.t. the ground state

Υ(nS) / Υ(1S) ratios vs multiplicity

√s = 13 TeV

√s = 7 TeV





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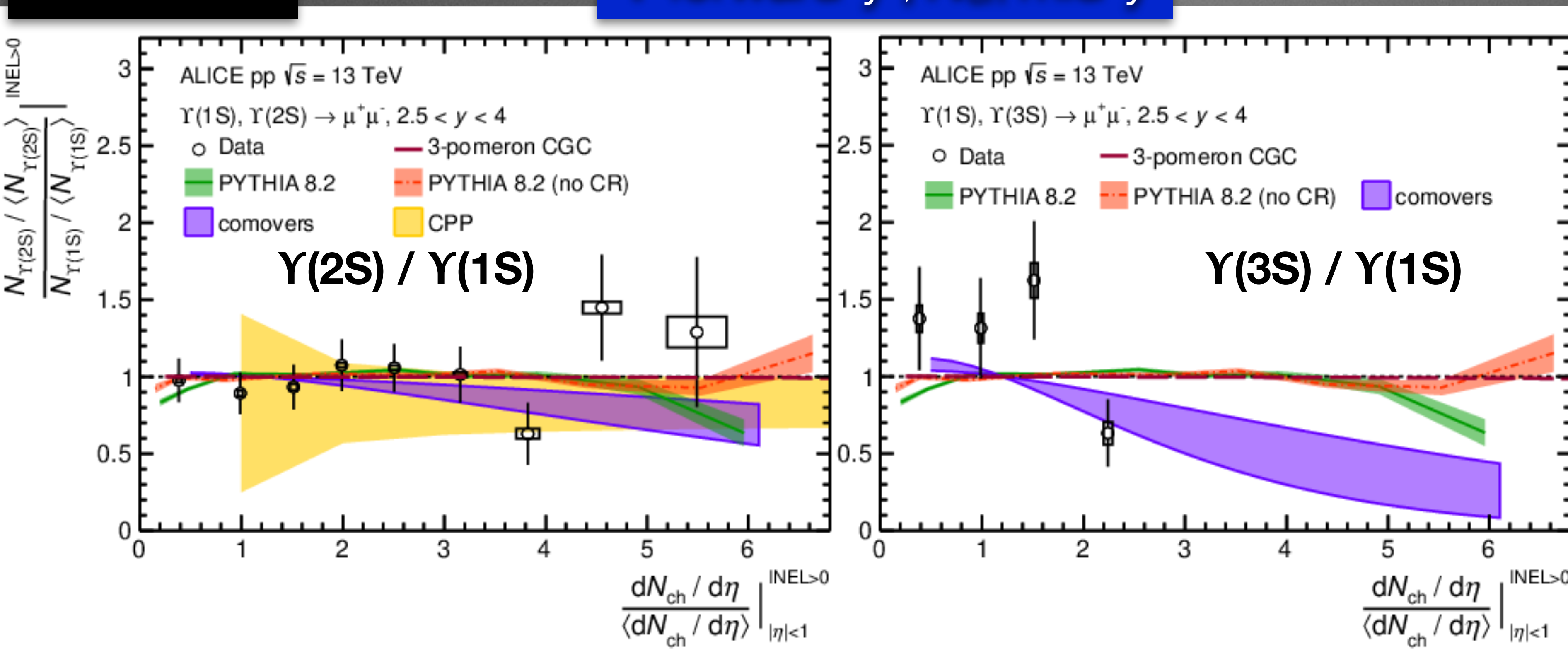
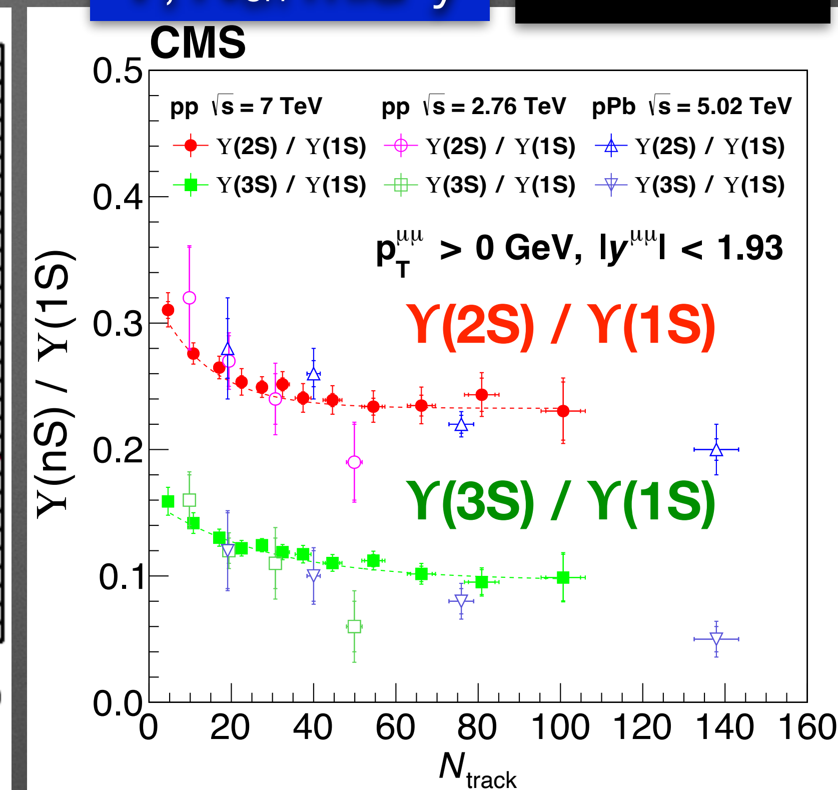
- Challenge soft particle production (underlying event, multiple-parton scatterings, small system hydrodynamics, …) and its simultaneous interplay with hard process (quarkonium production) in the models

Υ(nS) / Υ(1S) ratios vs multiplicity

$\sqrt{s}$ = 13 TeV | Υ forward-y , N_{ch} mid-y

Υ, N_{ch} mid-y | $\sqrt{s}$ = 7 TeV





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- Challenge soft particle production (underlying event, multiple-parton scatterings, small system hydrodynamics, …) and its simultaneous interplay with hard process (quarkonium production) in the models
  - Υ(nS) , N_{ch} : what if there is a rapidity gap ?

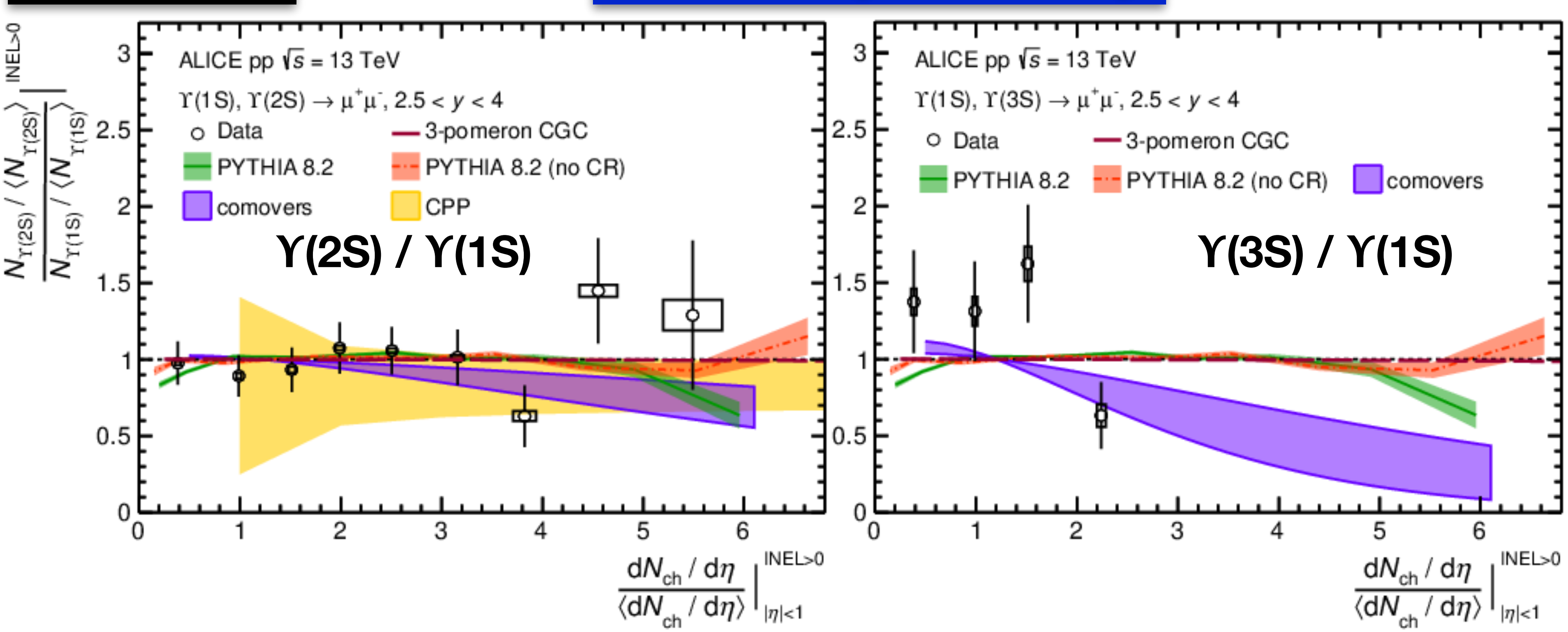
Υ(nS) / Υ(1S) ratios vs multiplicity

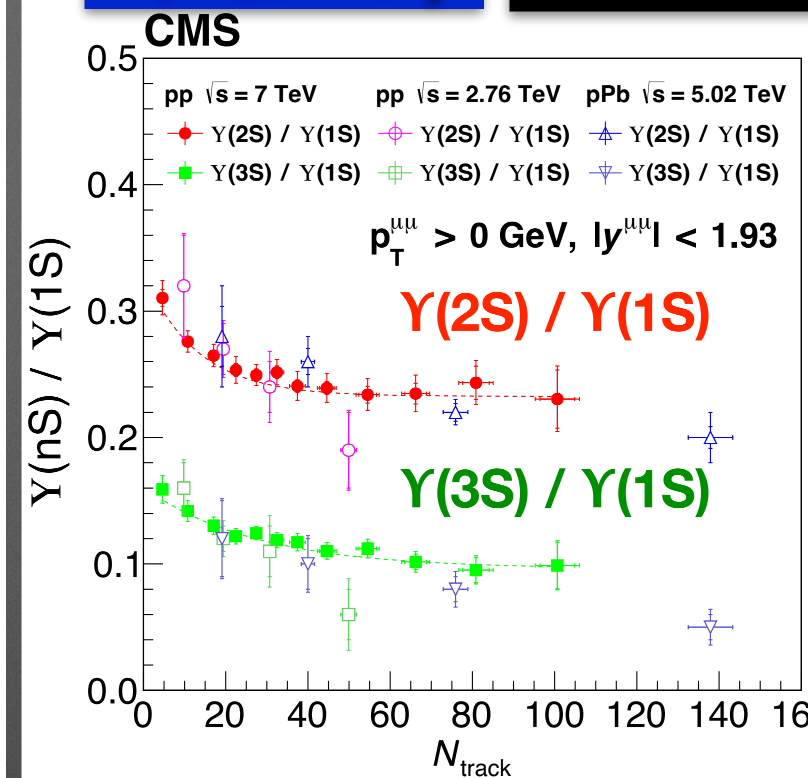
$\sqrt{s}$ = 13 TeV

Υ forward-y , N_{ch} mid-y

Υ, N_{ch} mid-y

$\sqrt{s}$ = 7 TeV





Comovers, Ferreiro [PLB 749 (2015) 98]
3-pomeron CGC, Levin et al. [EPJ C 80 (2020) 6, 560]
CPP, Kopeliovich et al. [PRD 101 (2020) 5, 054023]

ALICE [arXiv:2209.04241]

CMS [JHEP 11 (2020) 001]

- Challenge soft particle production (underlying event, multiple-parton scatterings, small system hydrodynamics, …) and its simultaneous interplay with hard process (quarkonium production) in the models
  - Υ(nS) , N_{ch} : what if there is a rapidity gap ?
- ALICE to CMS comparison: dataset collected during Run 2
  - ➡ Very interesting prospects in Run 3 !

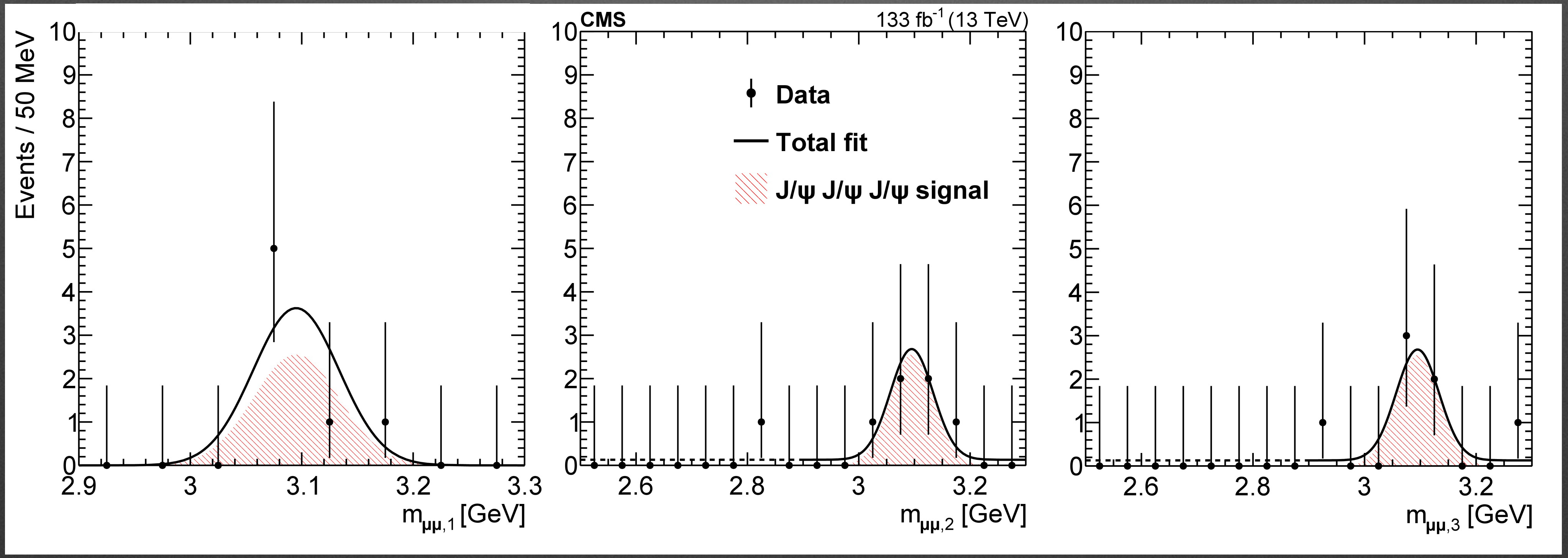
Associated production : triple J/ψ

√s = 13 TeV

- Observation of simultaneous production of three J/ψ in pp collisions with stat. significance > 5σ
- Cross-section $272^{+141}_{-101}(\text{stat}) \pm 17(\text{syst})\,\text{fb}, |y_{J/\psi}| < 2.4$

CMS [NP 19 (2023) 3, 338]

triple J/ψ ⟼ 6μ



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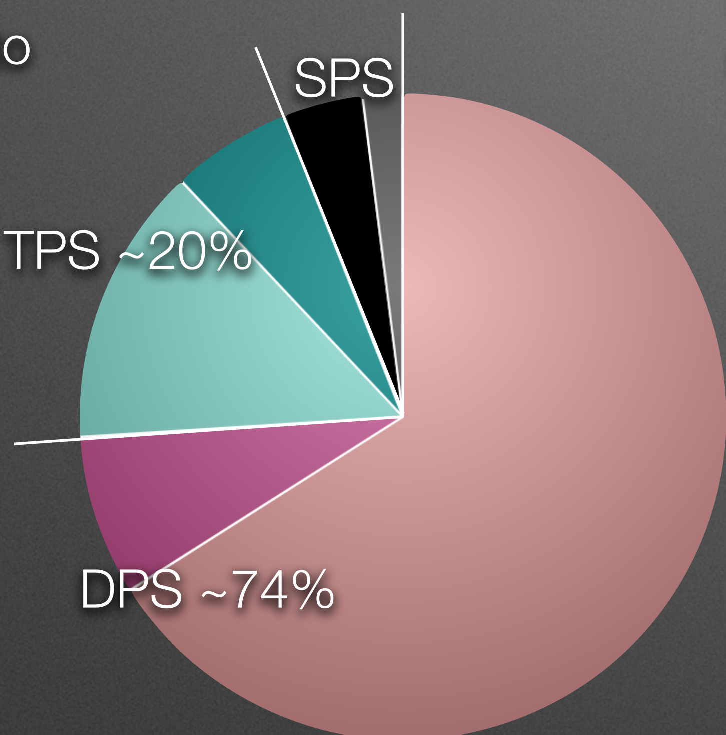
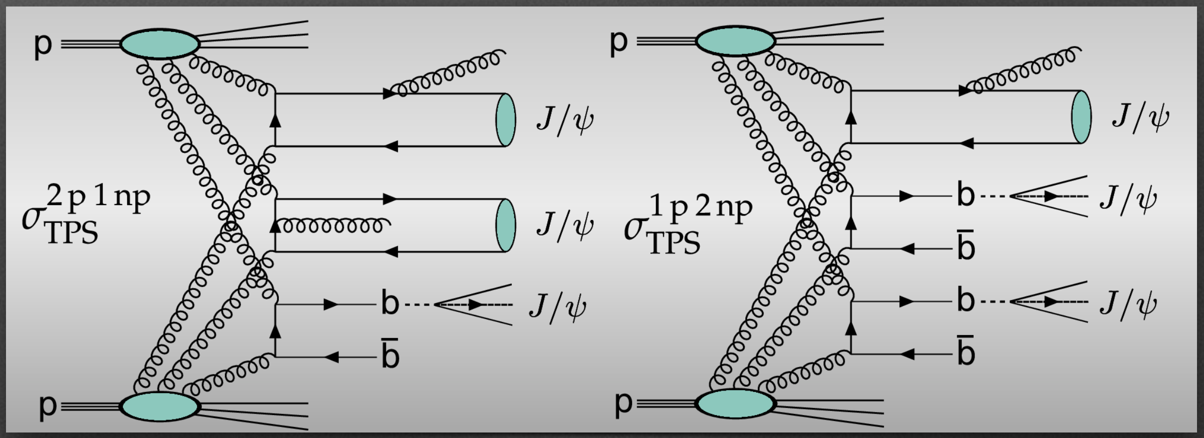
- Cross-section $272^{+141}_{-101}(\mathrm{stat}) \pm 17(\mathrm{syst})\,\mathrm{fb},\ |y_{J/\psi}| < 2.4$
- Process dominated by double (DPS) and triple (TPS) parton scatterings, minimal « contamination » from single (SPS) parton scattering
    - efficient probe of the gluon density in the proton and its fast evolution with √s

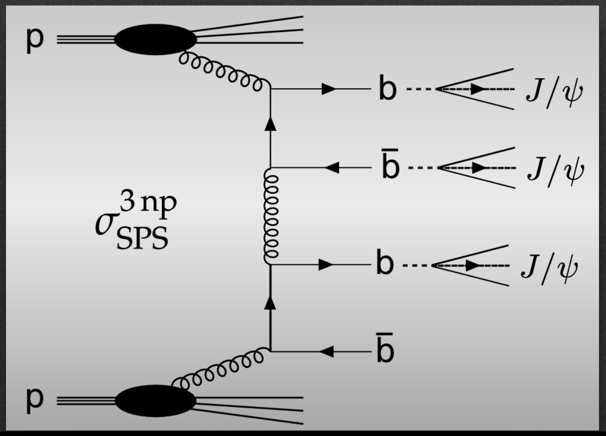
Contributions to cross-section



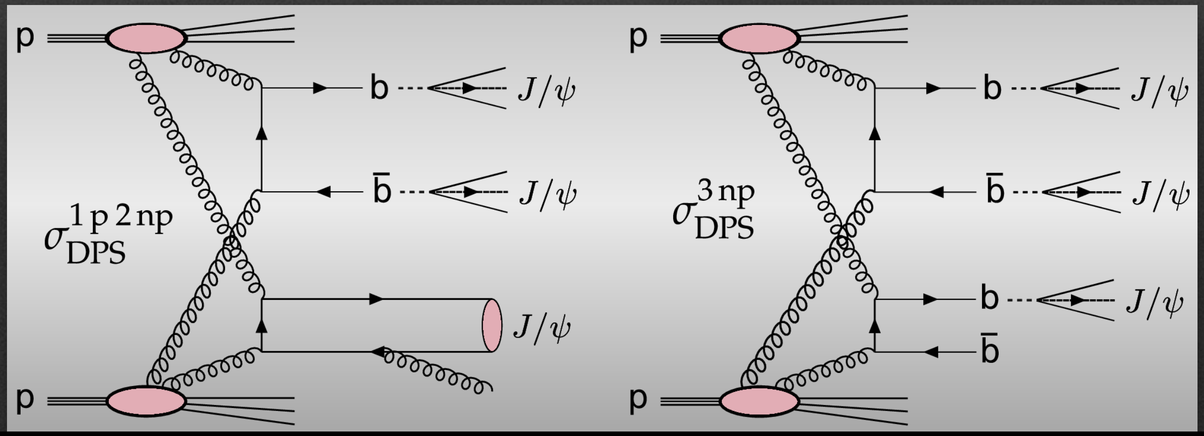
TPS : dominant processes



SPS : dominant process



DPS : dominant processes



Associated production : triple J/ψ

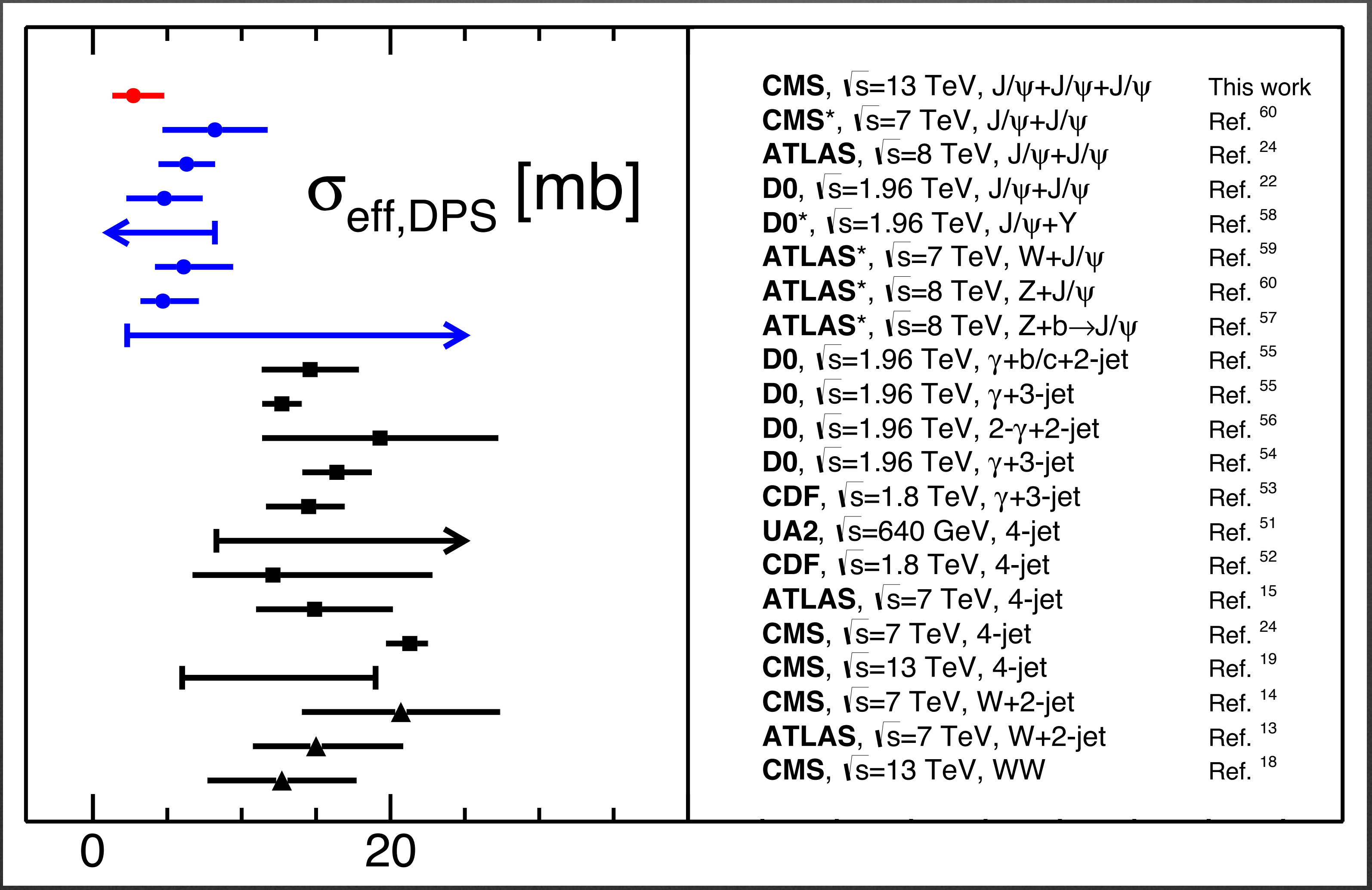
√s = 13 TeV

- Extracted $\sigma_{\text{eff,DPS}}$ ∝ average (squared) transverse separation of the partons involved in the DPS

$$\sigma_{\text{DPS}}^{\text{pp}\to ab} = \left(\frac{m}{2}\right) \frac{\sigma_{\text{SPS}}^{\text{pp}\to a} \cdot \sigma_{\text{SPS}}^{\text{pp}\to b}}{\sigma_{\text{eff,DPS}}}$$

  - consistent with values derived from processes mostly induced by gluon-gluon scatterings

CMS [NP 19 (2023) 3, 338]



Associated production : ϒ(1S) pair production and search for resonances √s = 13 TeV

CMS [PLB 808 (2020) 135578]

- ϒ(1S) pair production observed in 4μ
- Measured ross-section (for unpolarised mesons) :

$$79 \pm 11(\mathrm{stat}) \pm 6(\mathrm{syst}) \pm 3(\mathcal{B})\ \mathrm{pb}$$

- First measurement of DPS contribution to di-ϒ(1S) production :

$$f_{\mathrm{DPS}} = (39 \pm 14)\%$$

Associated production : Υ(1S) pair production and search for resonances

√s = 13 TeV

CMS [PLB 808 (2020) 135578]

- Search for unknown resonance X, considering di-Υ(1S) production as background

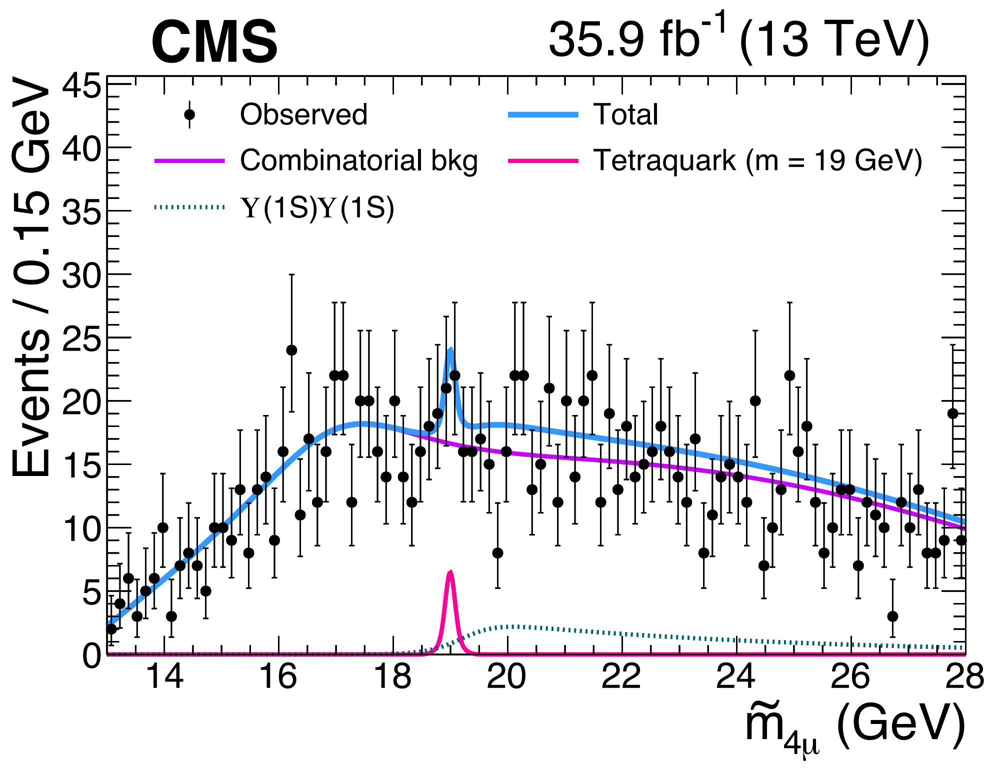
$$X \to \Upsilon(1S)\mu\mu$$
$$\hookrightarrow \mu\mu$$

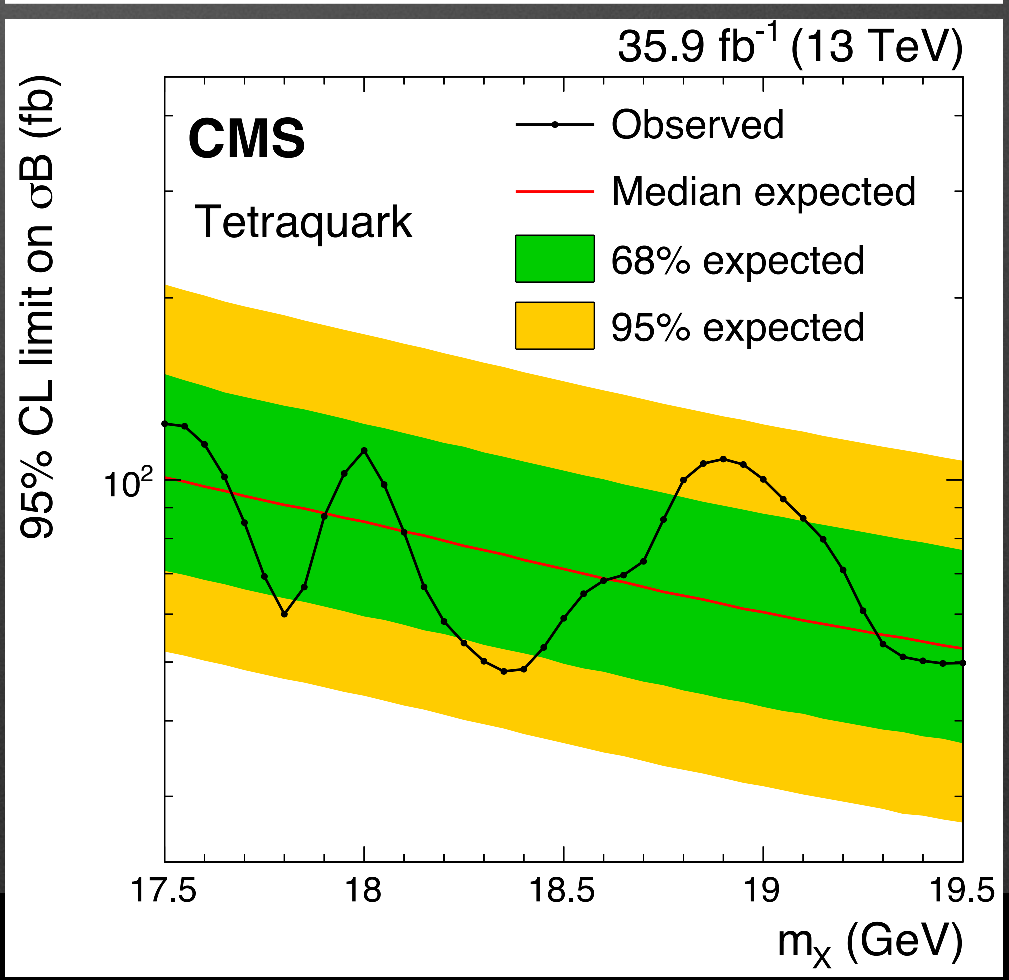
X : tetraquark, scalar, pseudoscalar, or spin-2 state

- With an estimated mass :

$$\widetilde{m}_{4\mu} = m_{4\mu} - m_{\mu\mu} + m_{\Upsilon(1S)}$$

- No excess of events compatible with signal is observed in the $\widetilde{m}_{4\mu}$ distribution

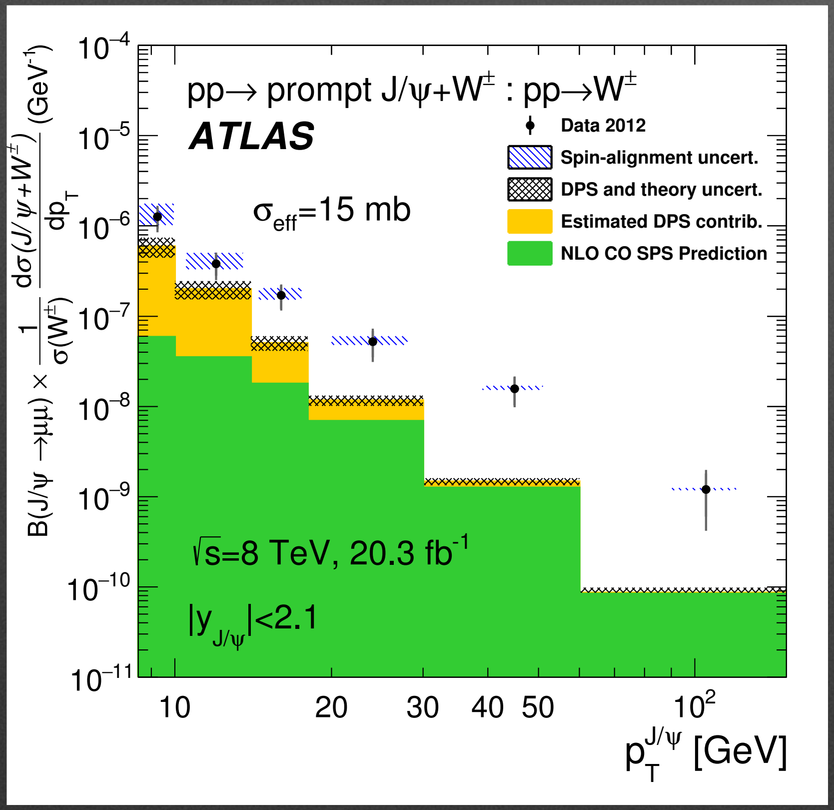




Associated production : prompt J/ψ + W

$\sqrt{s}$ = 8 TeV

- Test CO LDMEs when the associated production proceeds via SPS
- The measured p_T spectra, which cumulate SPS and DPS, steered many questions :



ATLAS [JHEP 01 (2020) 095]

NLO NRQCD SPS prediction, Song et al. [Chin.Phys.Lett. 30 (2013) 091201]
using *LDMEs* from *Chao et al. [PRL 108 (2012) 242004]* extracted from simultaneous fit of differential cross section and polarisation of prompt J/ψ at the Tevatron

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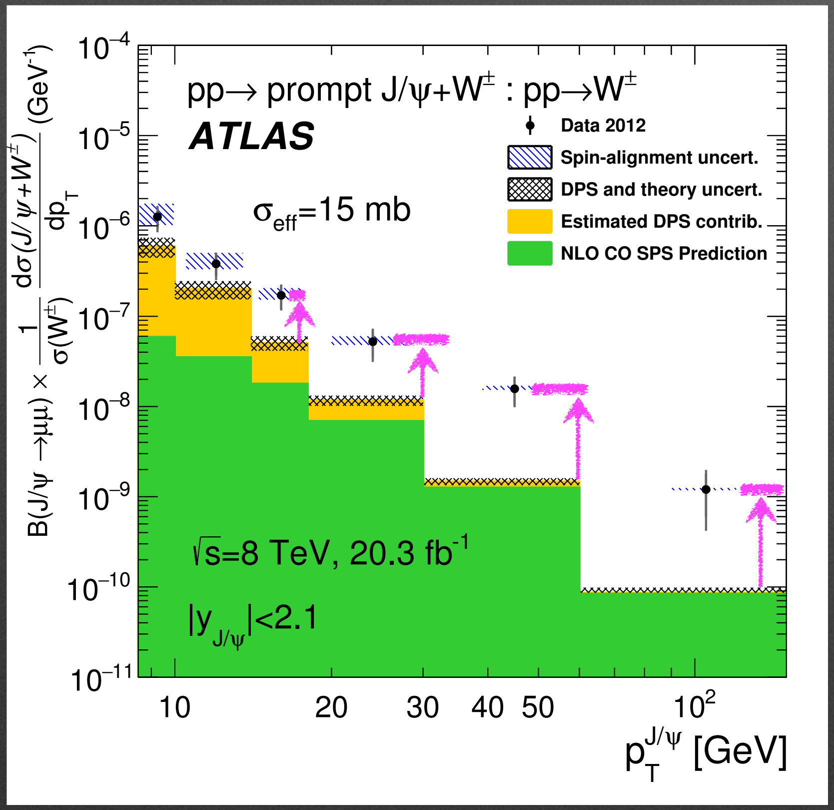

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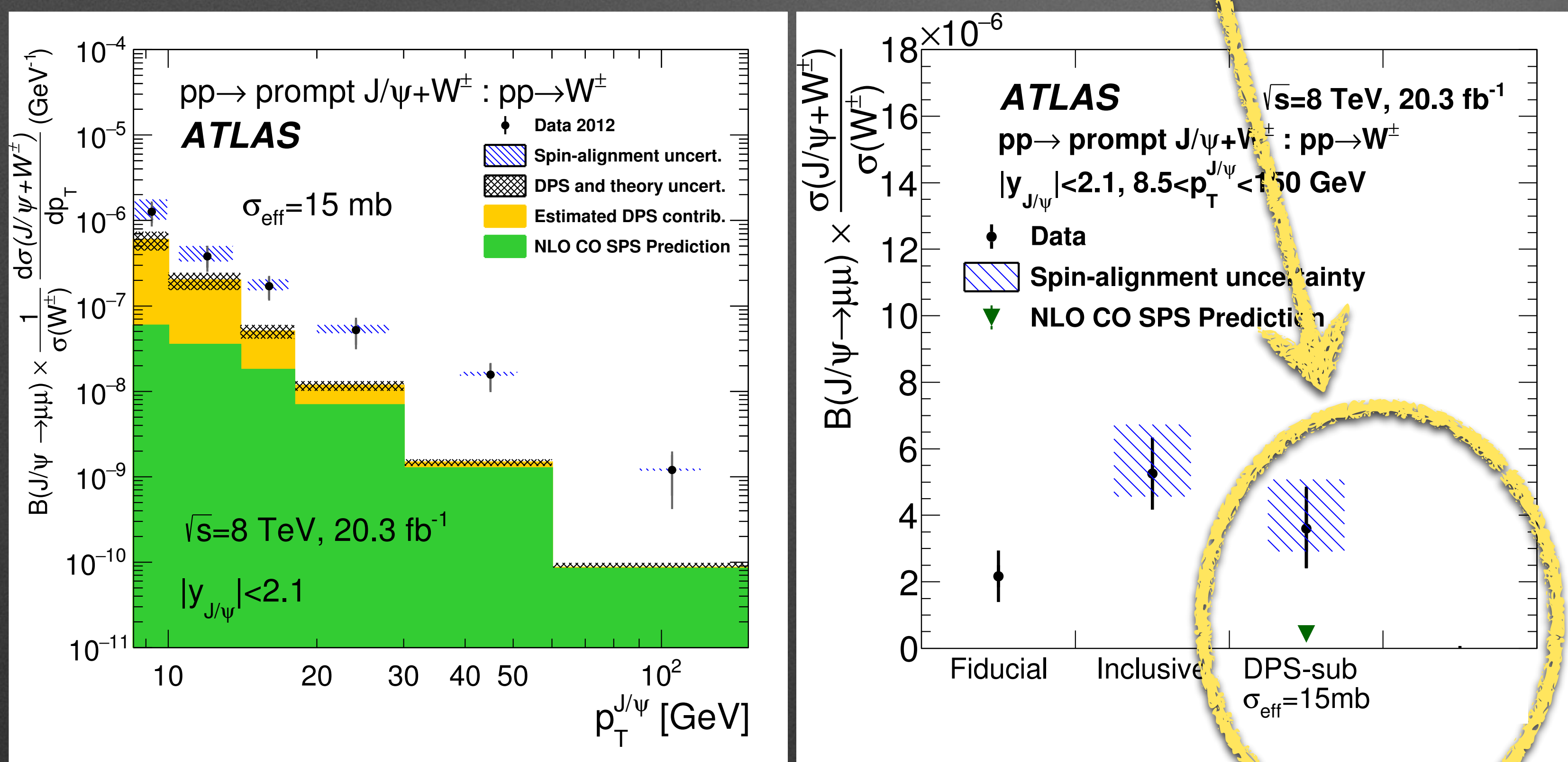

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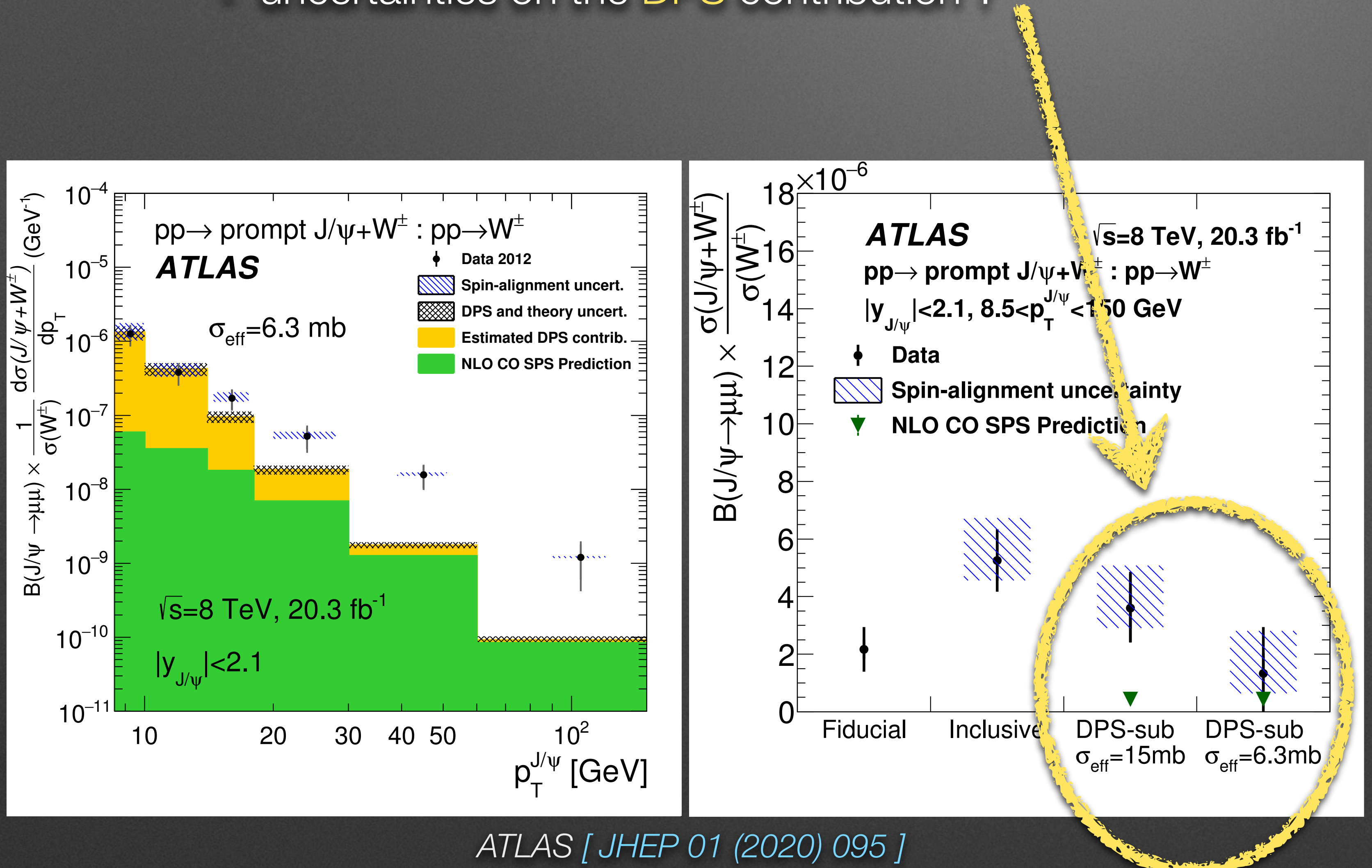

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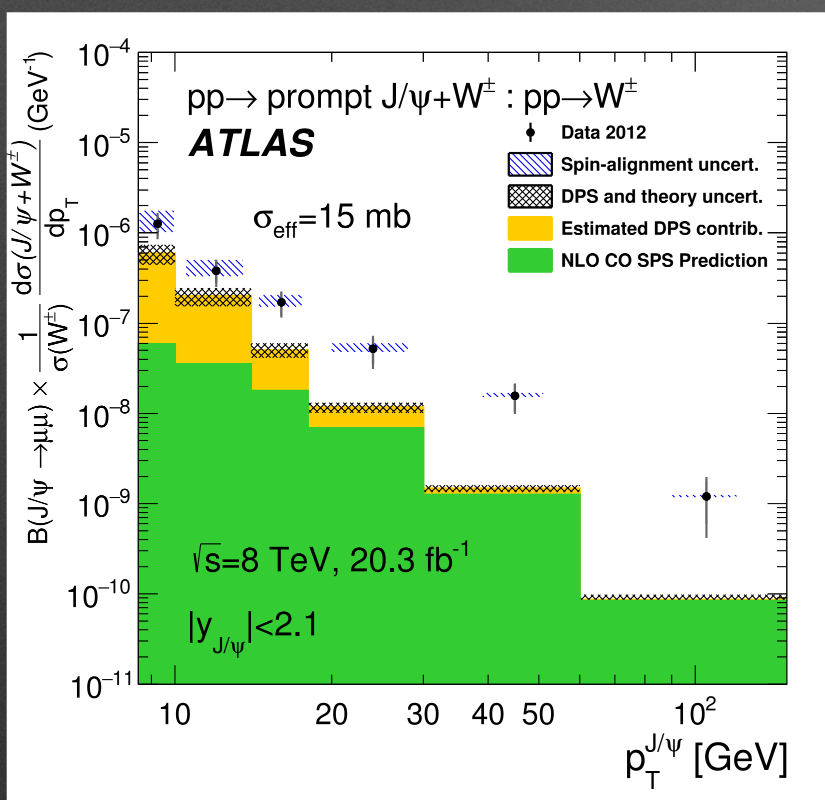
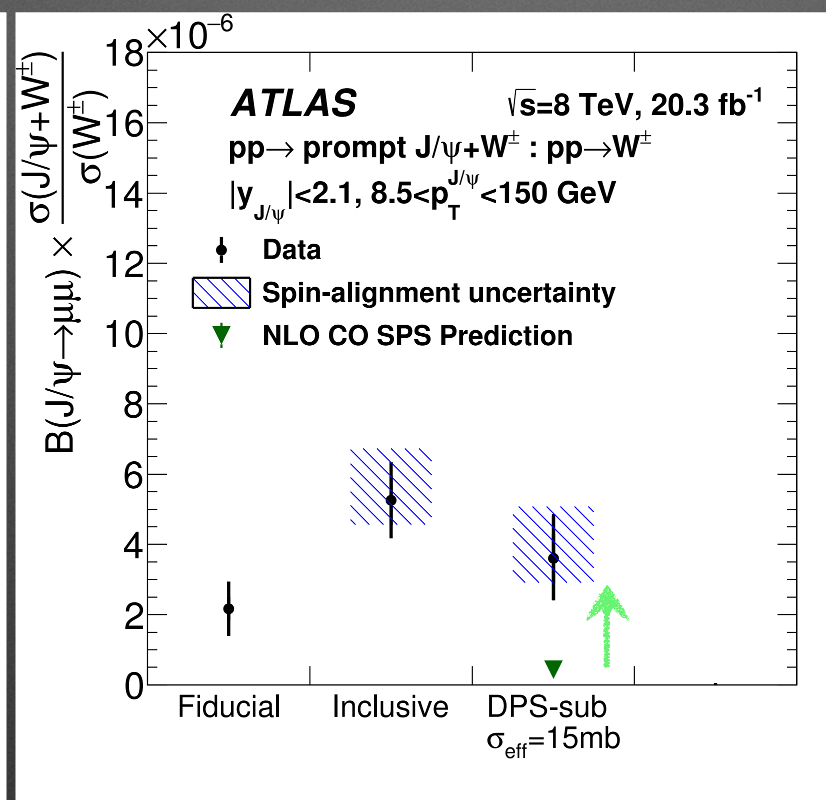
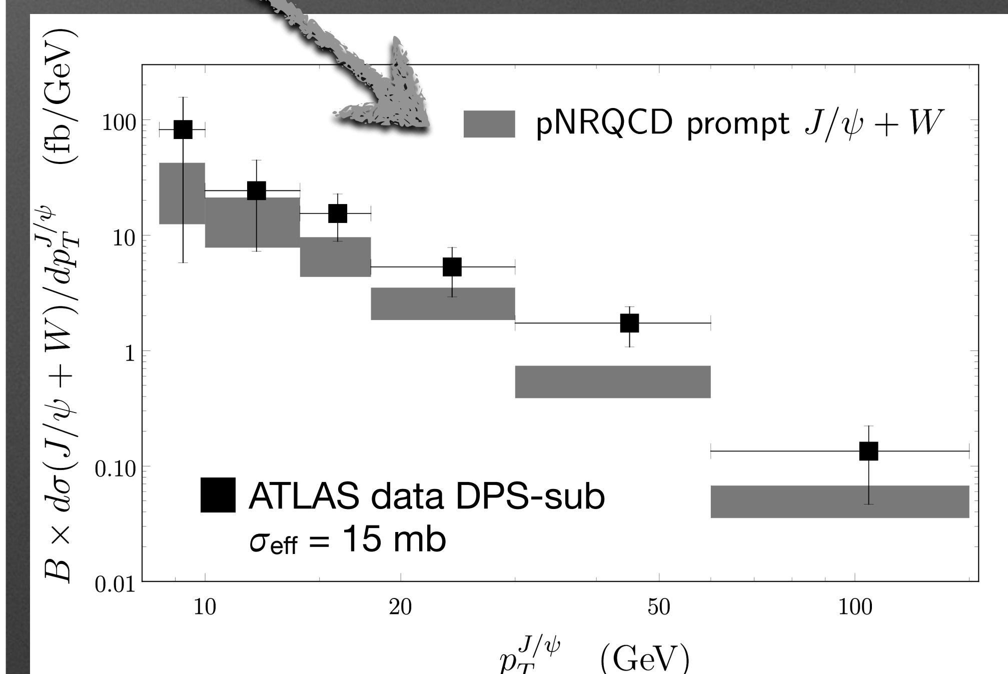
  - uncertainties on the DPS contribution ?
  - improve NRQCD framework ? improve LDME extraction ?







ATLAS [JHEP 01 (2020) 095]

pNRQCD, Brambilla et al. [JHEP 03 (2023) 242]

NLO NRQCD SPS prediction, Song et al. [Chin.Phys.Lett. 30 (2013) 091201] using *LDMEs* from *Chao et al. [PRL 108 (2012) 242004]* extracted from simultaneous fit of differential cross section and polarisation of prompt J/ψ at the Tevatron

- P-wave charmonia feed-down are included
- Computation of LDMEs in pNRQCD formalism takes advantage of some additional symmetries, reducing the number of non-perturbative unknowns.
- LDMEs extracted from joint fit of LHC data of prompt J/ψ, ψ(2S), ϒ(2S) and ϒ(3S)

Summary

- Today : a short selection of recent LHC results on hidden charm and beauty in the quarkonium system in pp collisions

- This QCD laboratory provides :
  - stringent contraints on the available models of the quarkonium production mechanism
  - harvest of results involving rare multi-parton scattering processes now accessible with LHC energy and luminosity
  - exploratory means to search for and study exotic resonances

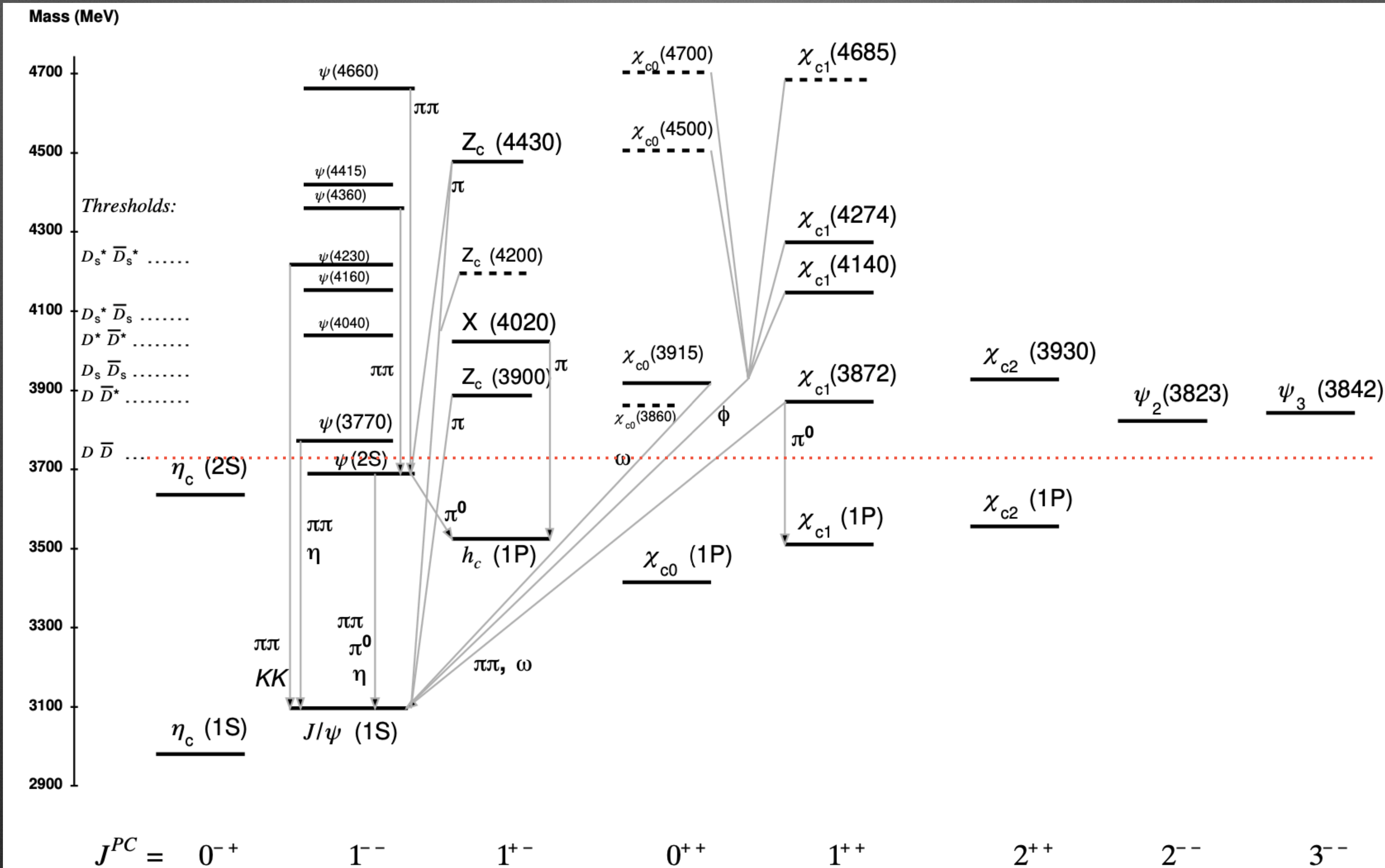
- Looking forward to upcoming results from LHC Run 3 !

Thanks for your attention

Spare slides

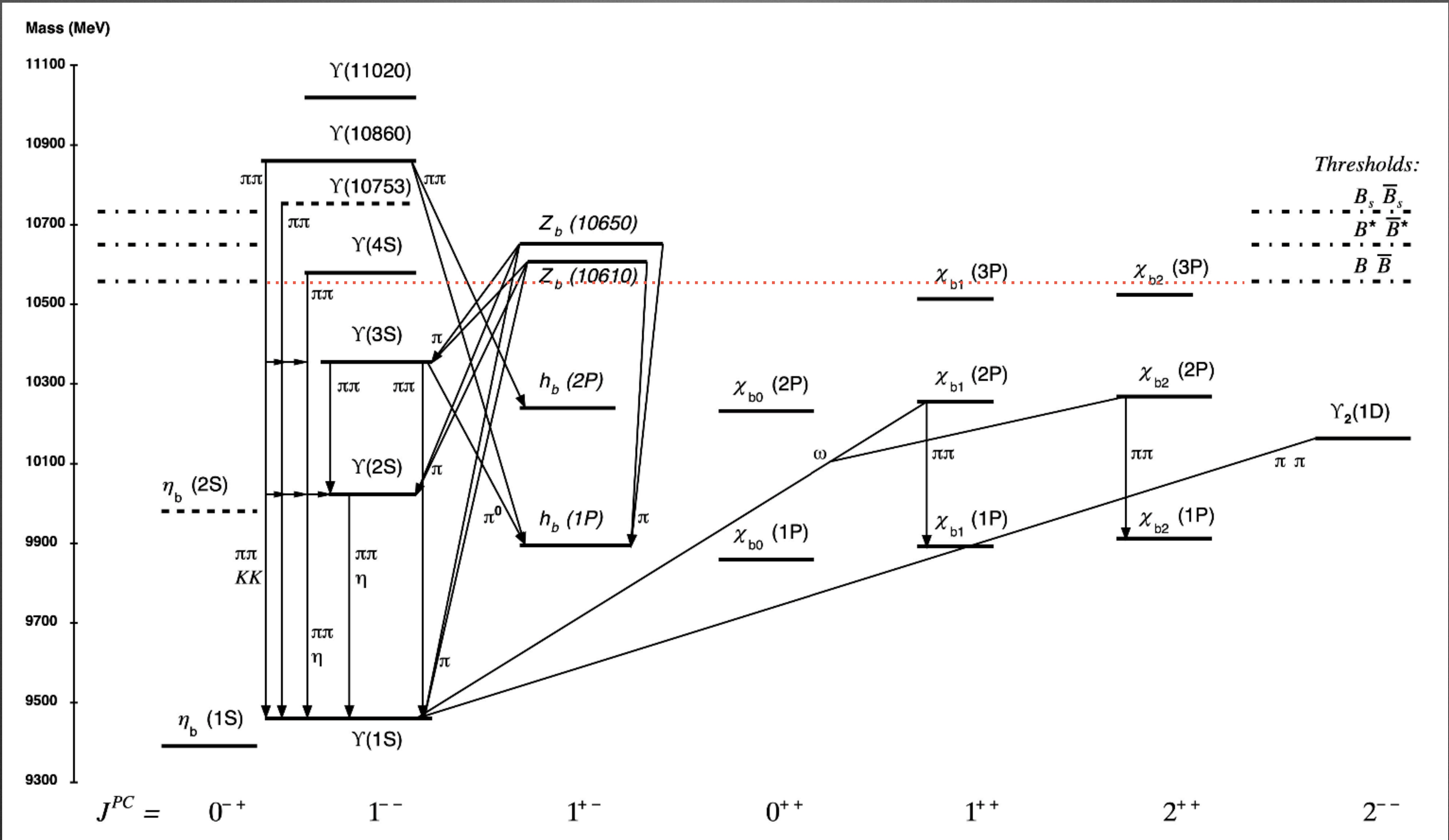
Charmonium system

PDG [Prog.Theor.Exp.Phys. 2022, 083C01]



Bottomonium system

PDG [Prog.Theor.Exp.Phys. 2022, 083C01]



Polarisation of P-wave charmonia

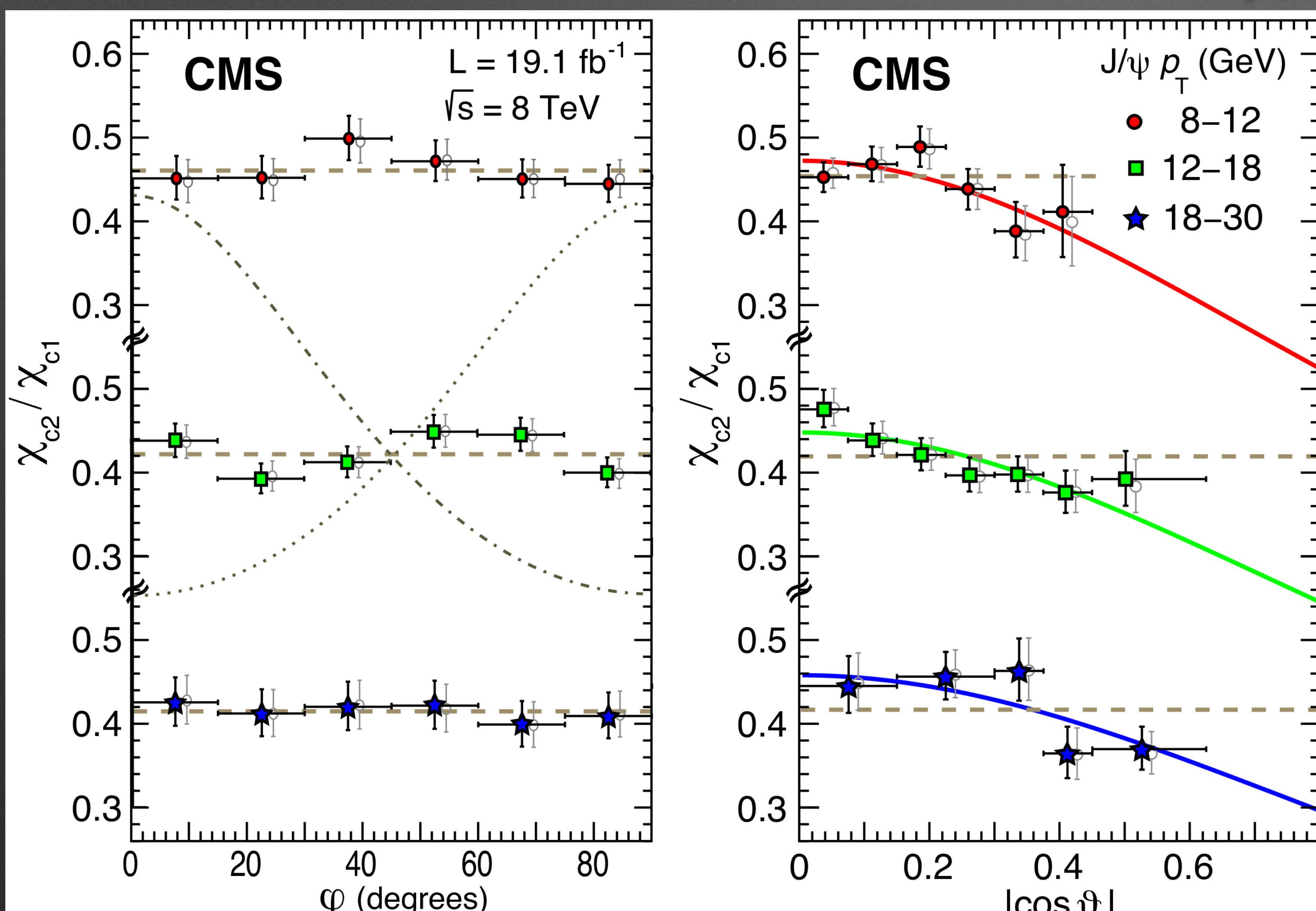
$\sqrt{s}$ = 8 TeV

- Within NRQCD, χ_{c1} and χ_{c2} polarisations can be predicted with a single CO (color octet) parameter from χ_{c2}/χ_{c1} cross-section ratio — *NRQCD prediction Faccioli et al. [EPJ C 78 (2018) 3, 268]*
- « Relative » polarisation study of χ_{c2} vs χ_{c1} — *CMS [PRL 124 (2020) 16, 162002]*

χ_{c2}/χ_{c1} yield ratios

— NRQCD scenario

- - - unpolarised scenario



conversions

$\chi_c \to J/\psi\,\gamma$, $\gamma \to e^+e^-$, $J/\psi \to \mu^+\mu^-$

angular distribution in the rest frame of the J/ψ

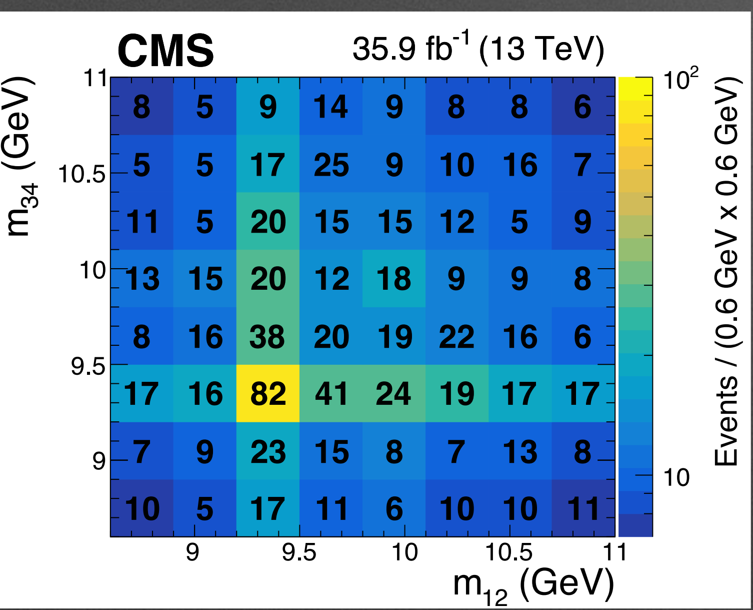
$$1 + \lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\varphi \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi$$

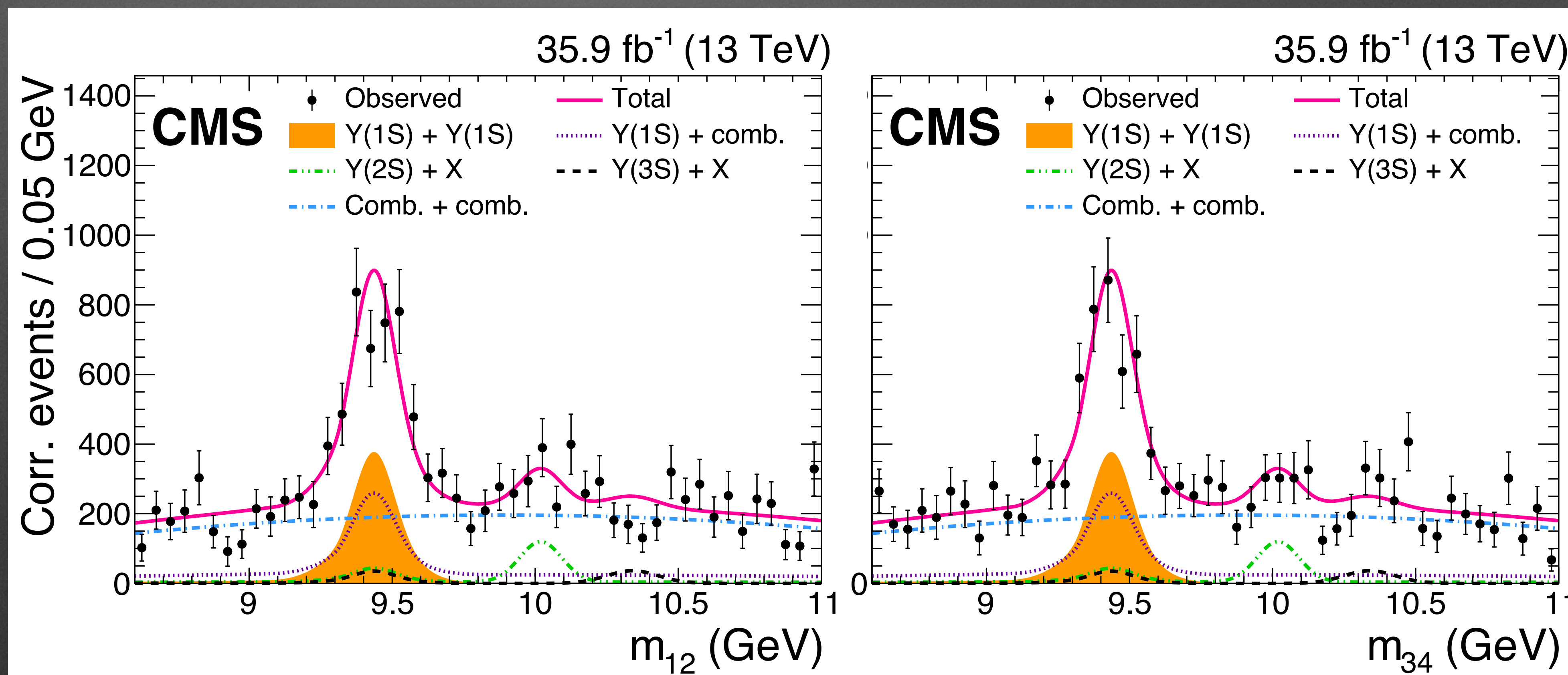
Associated production : ϒ(1S) pair production and search for resonances

√s = 13 TeV

- ϒ(1S) pair production cross-section (for unpolarised mesons) : $79 \pm 11(\mathrm{stat}) \pm 6(\mathrm{syst}) \pm 3(\mathcal{B})\ \mathrm{pb}$
- First measurement of DPS contribution to di-ϒ(1S) production : $f_{\mathrm{DPS}} = (39 \pm 14)\%$

ϒ(1S) pair production observed in 4μ





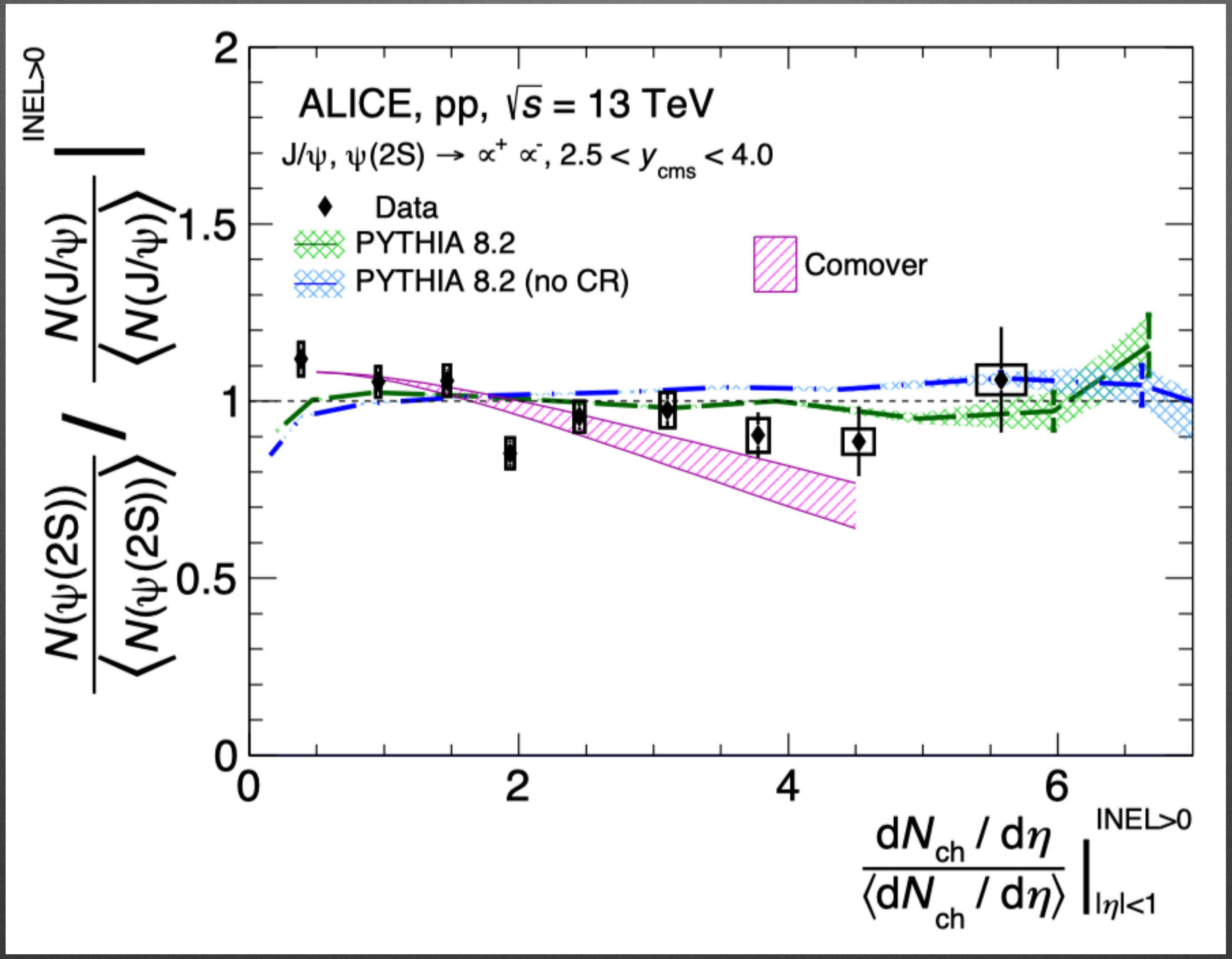
CMS [PLB 808 (2020) 135578]

ψ(2S) / J/ψ ratio vs multiplicity

$\sqrt{s}$ = 13 TeV

ALICE [arXiv:2204.10253]

Comovers, Ferreiro [PLB 749 (2015) 98]

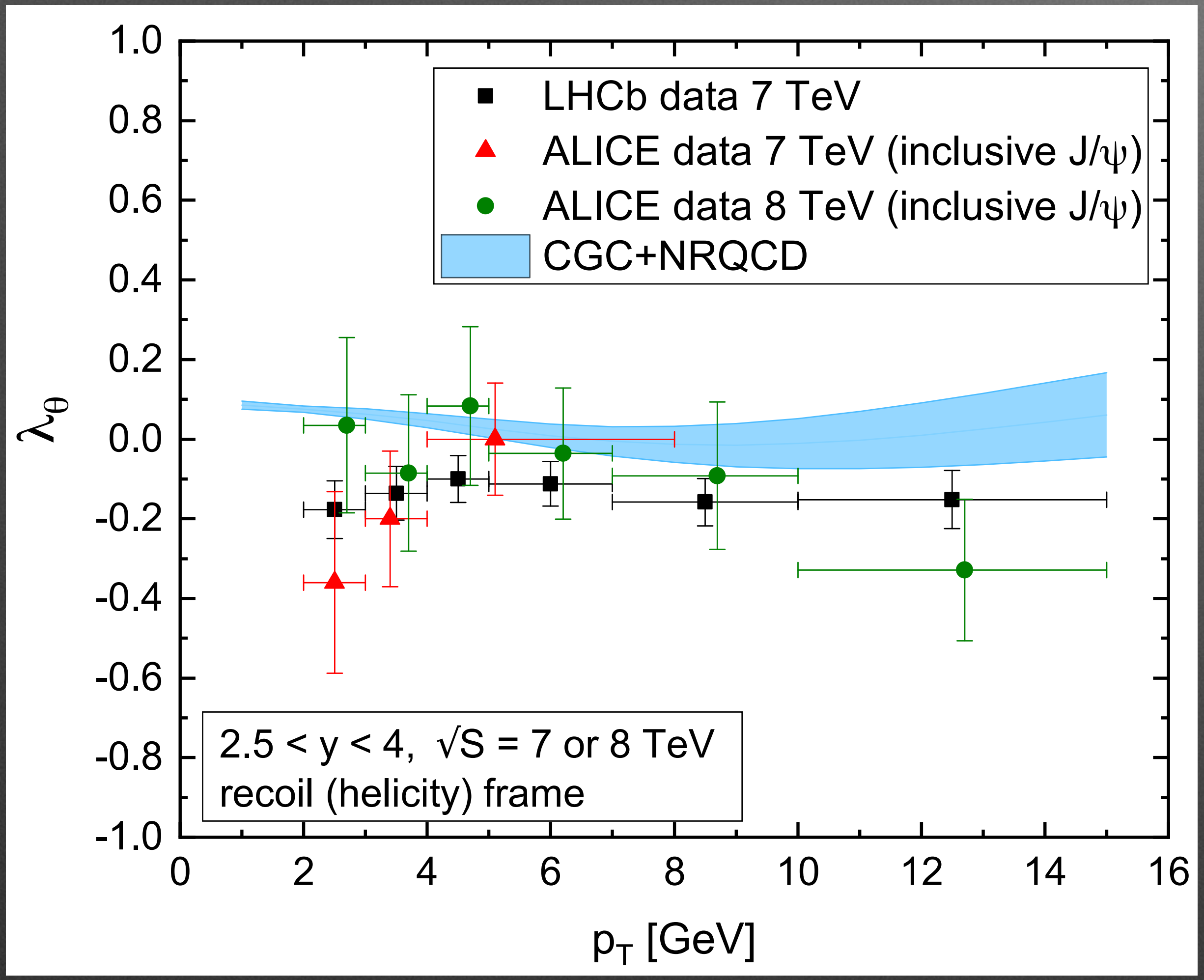


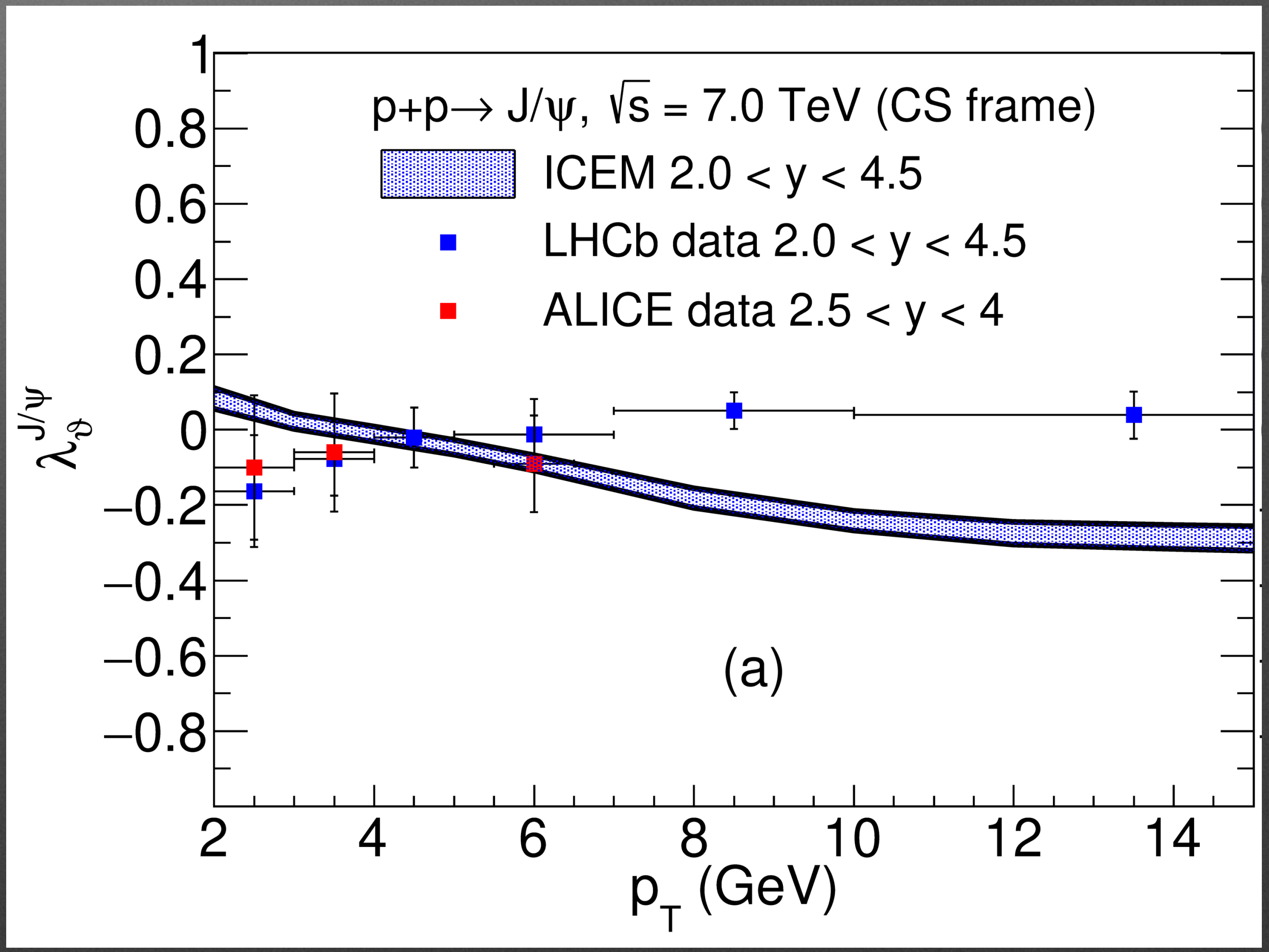
- Excited-to-ground state ratio is also measured in the charmonium sector
- Compatible with unity and model calculations

J/ψ polarisation

√s = 7, 8 TeV, forward-y

ALICE [PRL 108 (2012) 082001]
ALICE [EPJ C 78 (2018) 7, 562]
LHCb [EPJ C 73 (2013) 11, 2631]

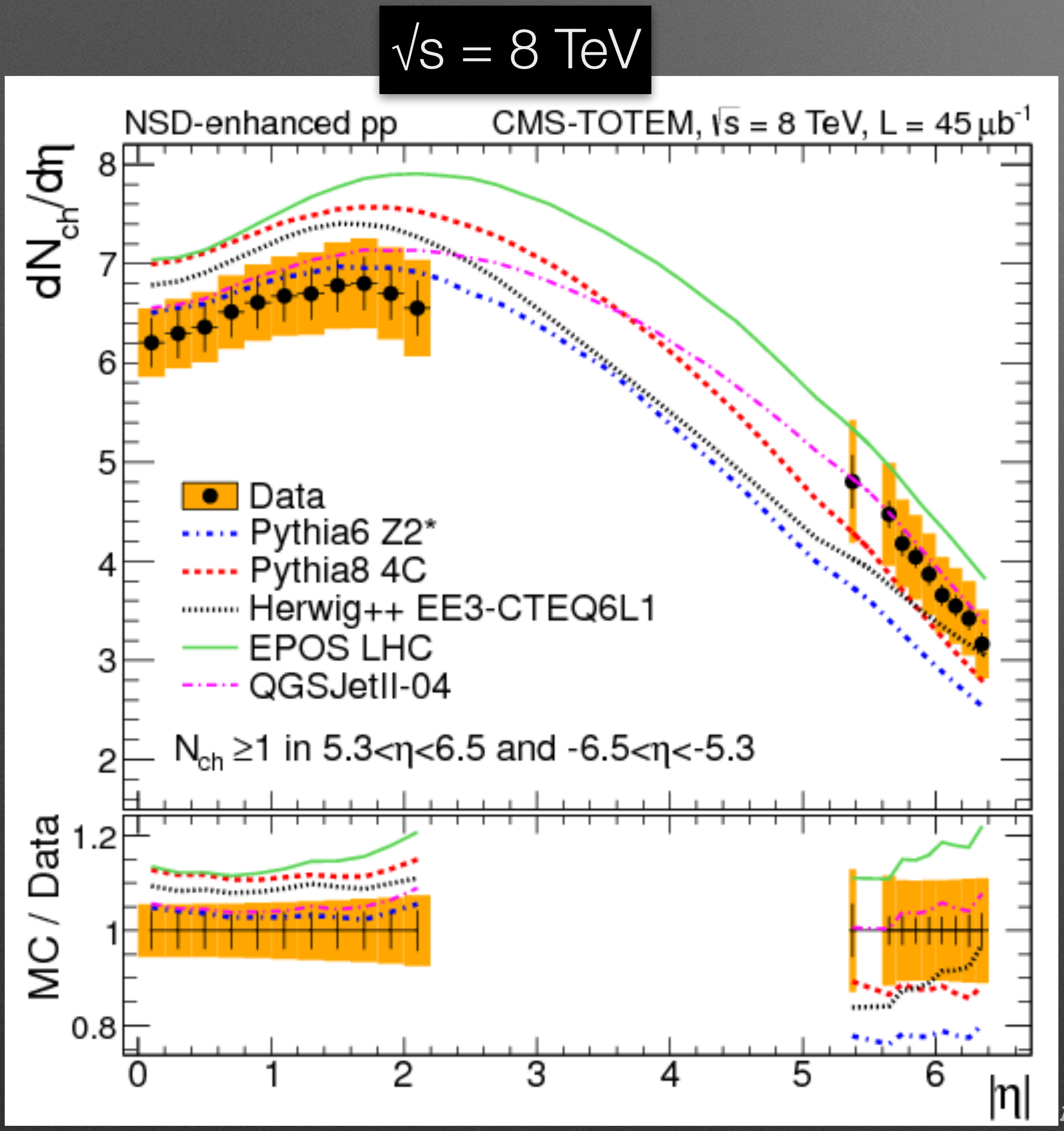




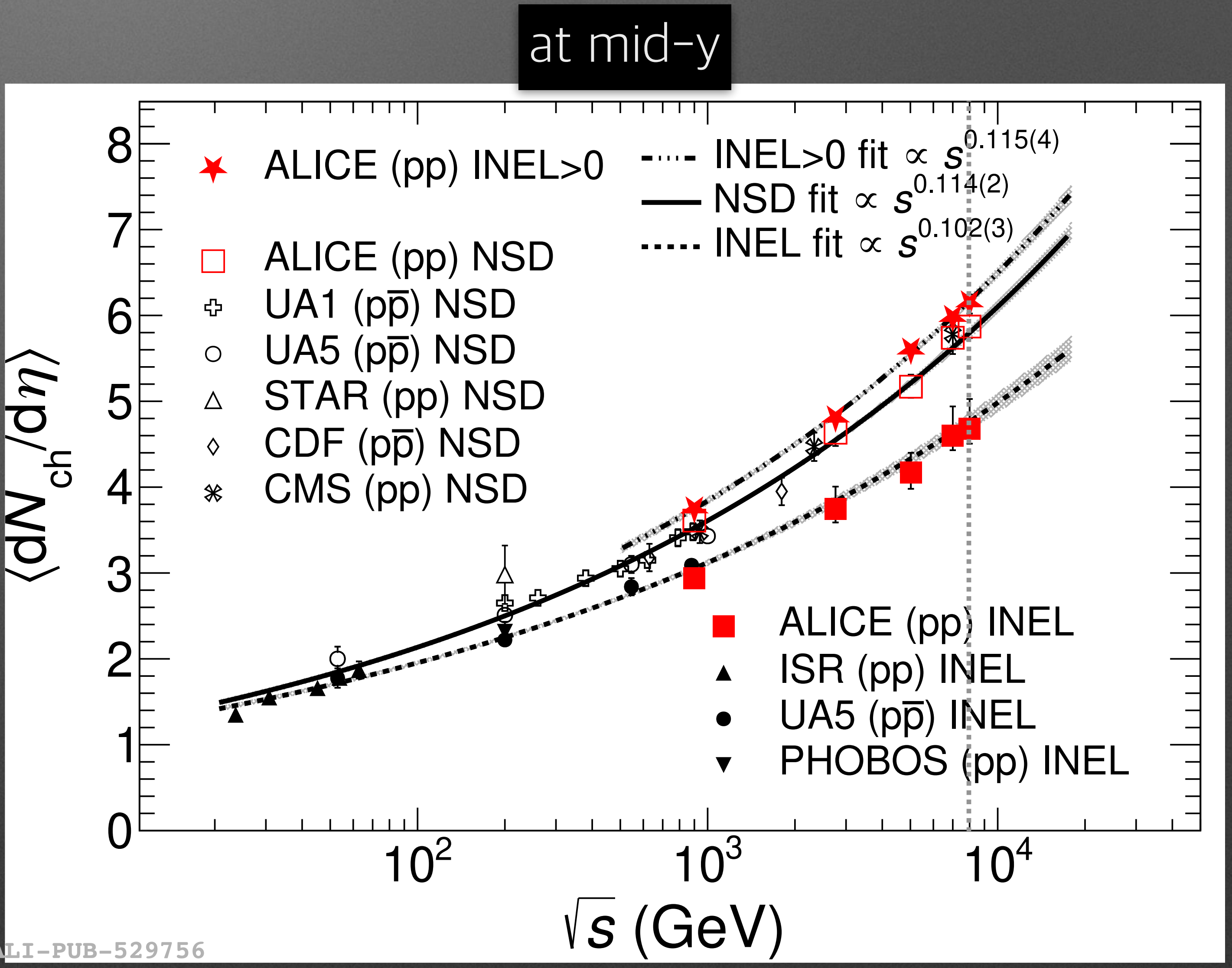
CGC + NRQCD, Ma et al. [JHEP 12 (2018) 057]

ICEM, Cheung, Vogt [PRD 104 (2021) 9, 094026]

Pseudorapidity densities of charged particles in pp collisions



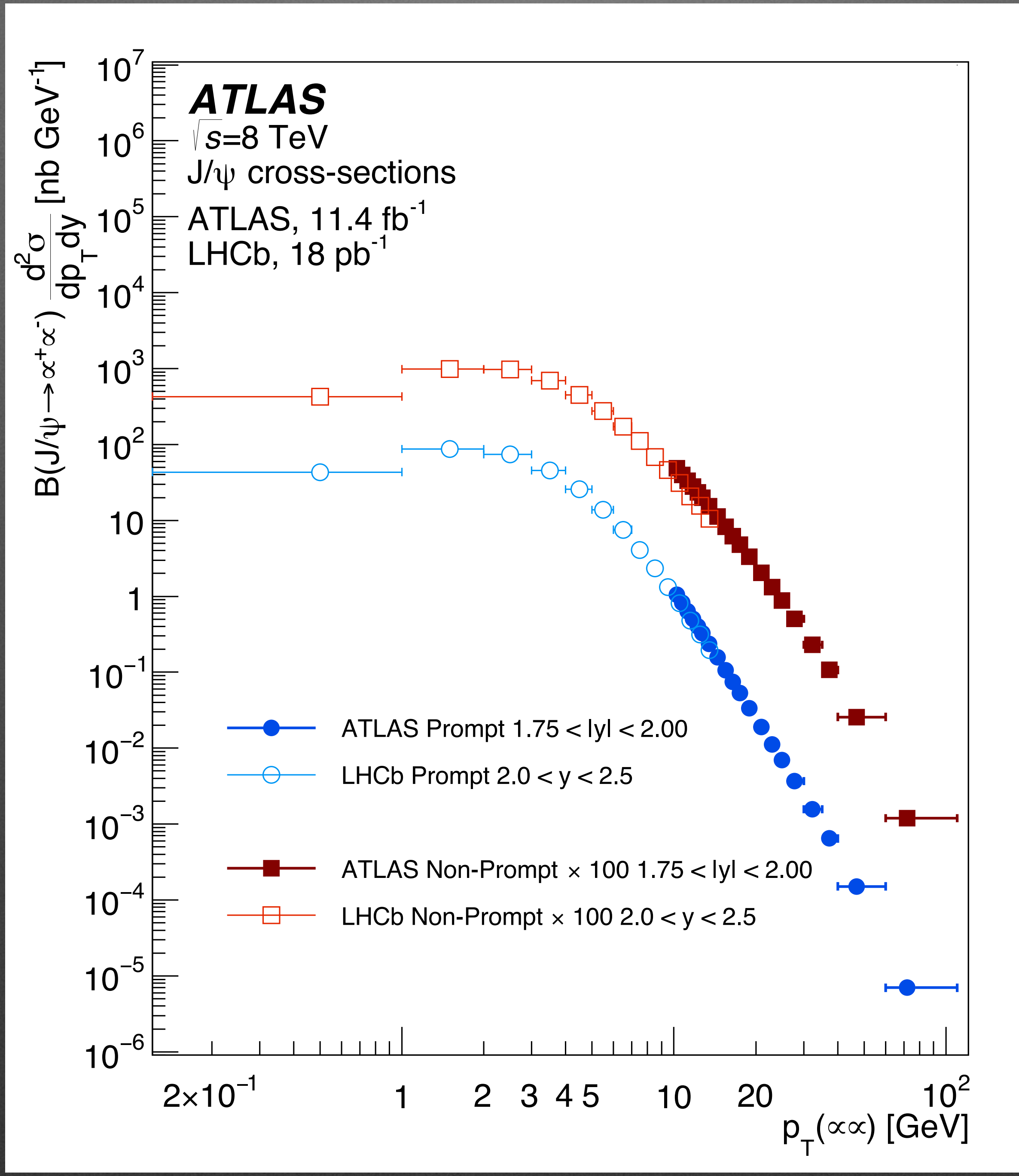
CMS-TOTEM [EPJ C 74 (2014) 10, 3053]



ALICE [arXiv:2211.15364]

J/ψ p_T spectra

√s = 8 TeV



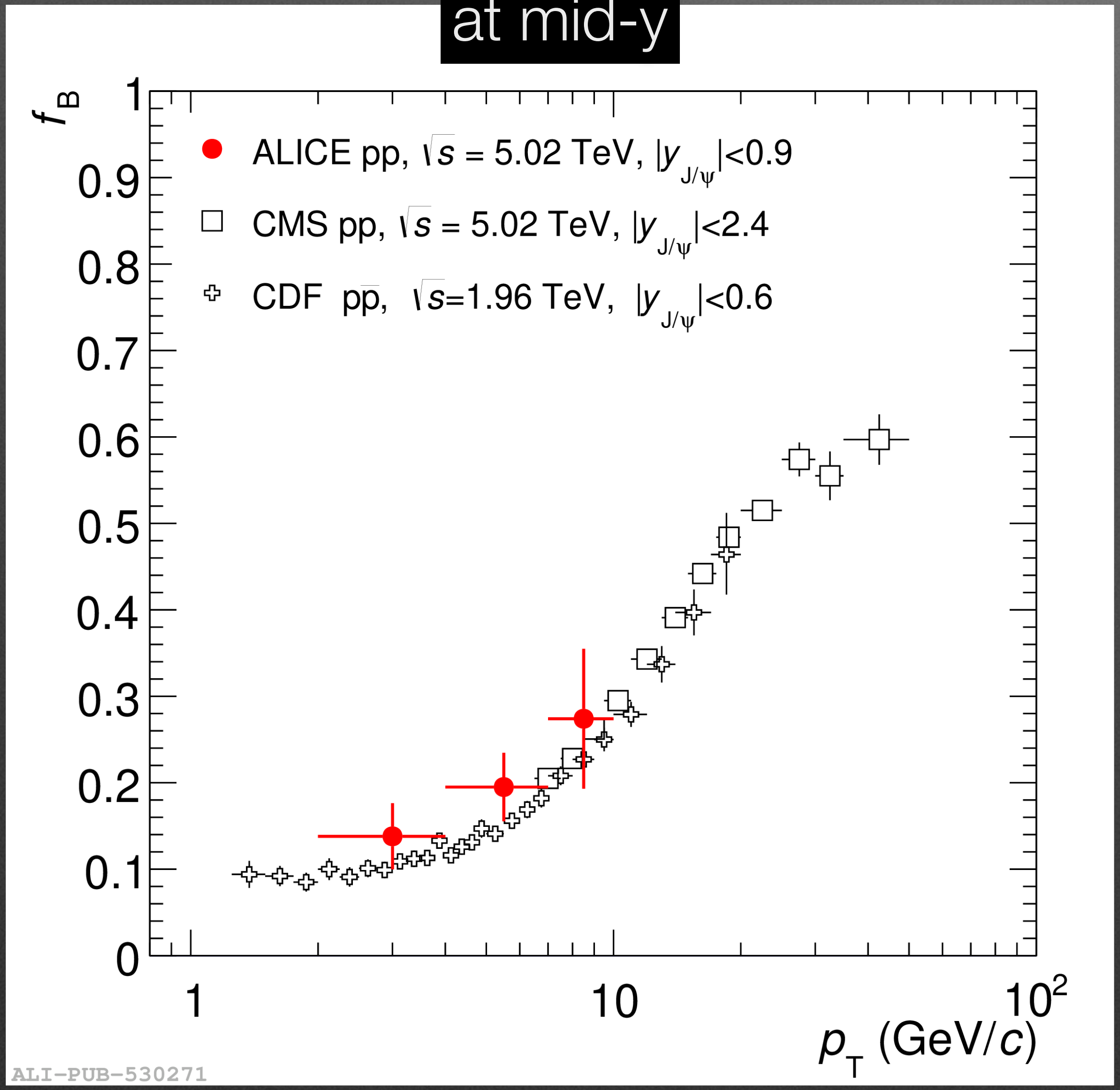
ATLAS [EPJ C 76 (2016) 5, 283] , [ATLAS-BPHY-2012-02]
LHCb [JHEP 06 (2013) 064]

Non-prompt J/ψ fraction vs p_T

$\sqrt{s}$ = 5 TeV

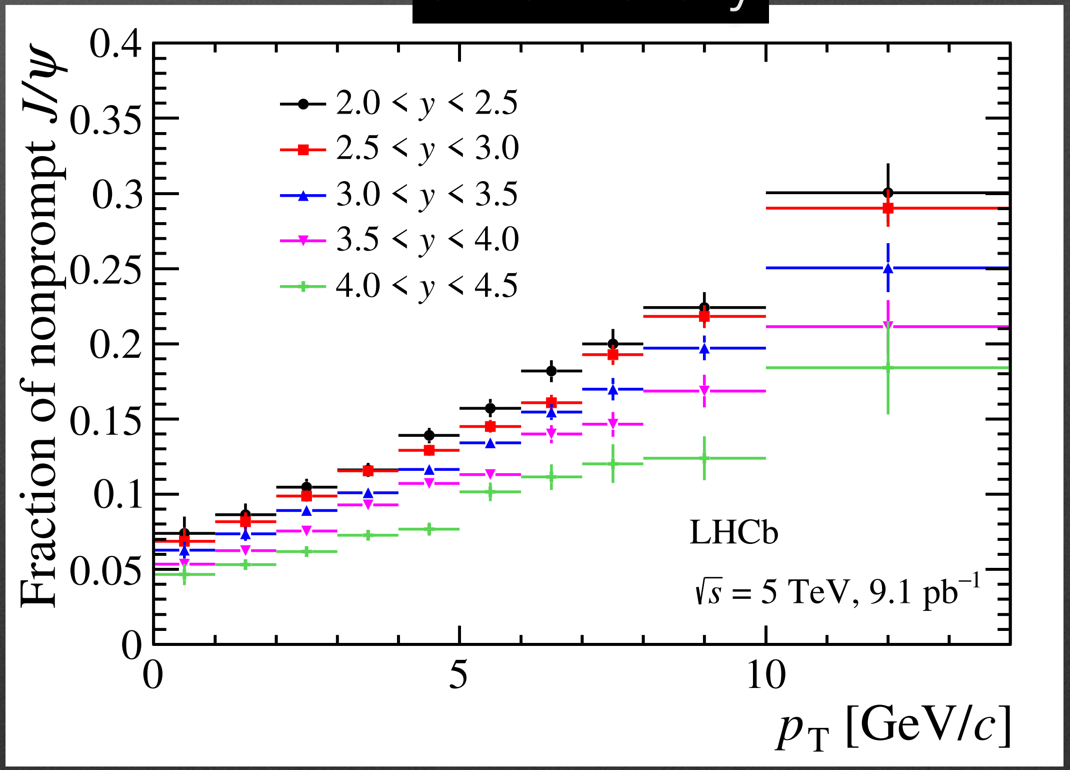
- Measurements available in different rapidity intervals (ALICE, CMS, LHCb)
- The fraction of J/ψ ← b increases with p_T

at mid-y



ALICE [JHEP 03 (2022) 190]

at forward-y



LHCb [JHEP 11 (2021) 181]

Three competing models (1/2)

How quarkonia are produced ? From initial $|q\bar{q}\rangle$ to the physical quarkonium $|Q\bar{Q}\rangle$:

- CSM (Colour-singlet model)
  - $|q\bar{q}\rangle \rightarrow |Q\bar{Q}\rangle$ allowed only if same quantum numbers (both colourless, same J^{PC})
  - transition probability determined by wavefunction at origin
- (Improved) CEM (Colour evaporation model)
  - initial pairs below open charm (beauty) threshold will hadronise to charmonium (bottomonium)
  - no requirements on initial quantum numbers
  - probability $|q\bar{q}\rangle \rightarrow |Q\bar{Q}\rangle$ only depends on the considered final state : universal constant $f_{Q\bar{Q}}$ for a given quarkonium
- both models : ordered only in increasing power of α_s (Feynman diagrams involved in hard creation of $|q\bar{q}\rangle$ pair)

Three competing models (2/2)

How quarkonia are produced ? From initial $|q\bar{q}\rangle$ to the physical quarkonium $\left|Q\bar{Q}\right\rangle$:

- NRQCD (non-relativistic QCD, based on an EFT) with
  - ordering in power of v (heavy quark velocity) and α_s
  - a physical quarkonium is a superposition of Fock states, e.g.

$$|J/\psi>= \mathcal{O}(1)\underbrace{\left|c\bar{c}\left[{}^3S_1^{(1)}\right]\right\rangle}_{\alpha_s^3}+\mathcal{O}(v)\underbrace{\left|c\bar{c}\left[{}^3P_J^{(8)}g\right]\right\rangle}_{\alpha_s^2}+\mathcal{O}(v^2)$$

  - the transition probability is determined by supposedly universal non-perturbative long-distance matrix elements (LDME) that are extracted from « fit » to experimental data

$$\left|q\bar{q}\left[{}^{2S+1}L_J^{(1,8)}\right]\right\rangle \rightarrow \left|Q\bar{Q}\right\rangle$$

  - NRQCD adds CO terms to the CSM
  - Heavy-quark spin-symmetry links CS and CO LDME of different quarkonium states

➡ stronger constraints on LDME from simultaneous study of several states