New measurements in the quarkonium sector with focus on new discriminatory observables

Minjung Kim for the ALICE, ATLAS, CMS and LHCb Collaborations
Physikalisches Institut, Universität Heidelberg

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Quarkonium production in heavy-ion collisions

Matsui and Satz, PLB 178 (1986) 416 Karsch et al., PLB 637 (2006) 75

- Initial idea: quarkonium production suppressed via colour screening in QGP

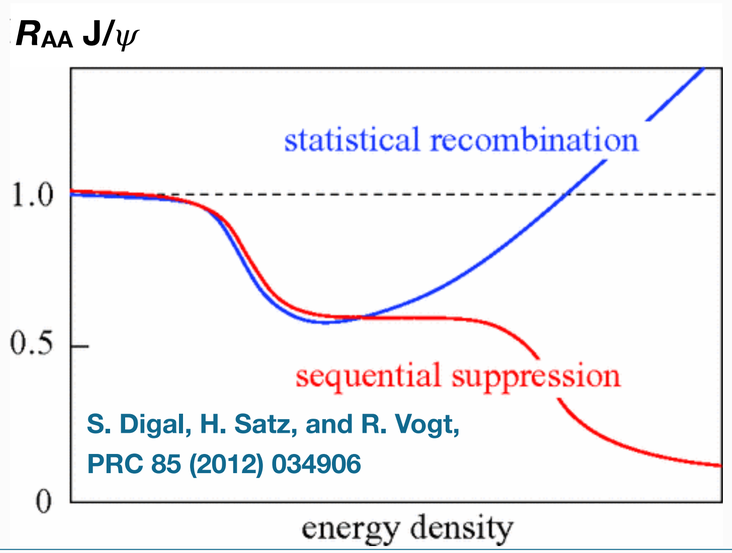
P. Braun-Muzinger, J. Stachel, PLB 490(2000)196 R. L. Thews, M. Schroedter, J. Rafelski, PRC 63 (2001) 054905

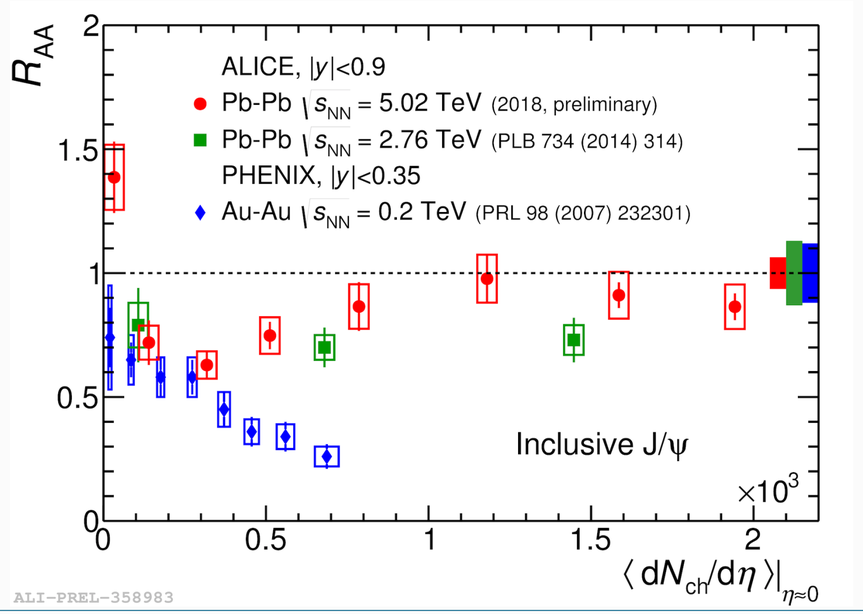
➡ **J/ψ** at LHC energies: with larger $c\bar{c}$ cross section, (re)generation of charmonium and charmed hadron production take place at the phase boundary or in QGP

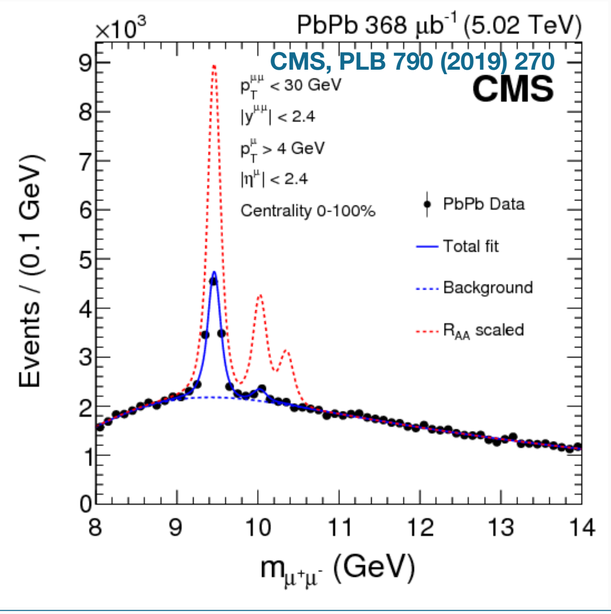
A. Rothkopf, Phys.Rept. 858 (2020) 1

➡ **Bottomonium** at LHC energies: limited recombination effect w.r.t. charmonium, probe the full time evolution of QGP

- Measurements of ground states production are insufficient for understanding quarkonia in presence of QGP

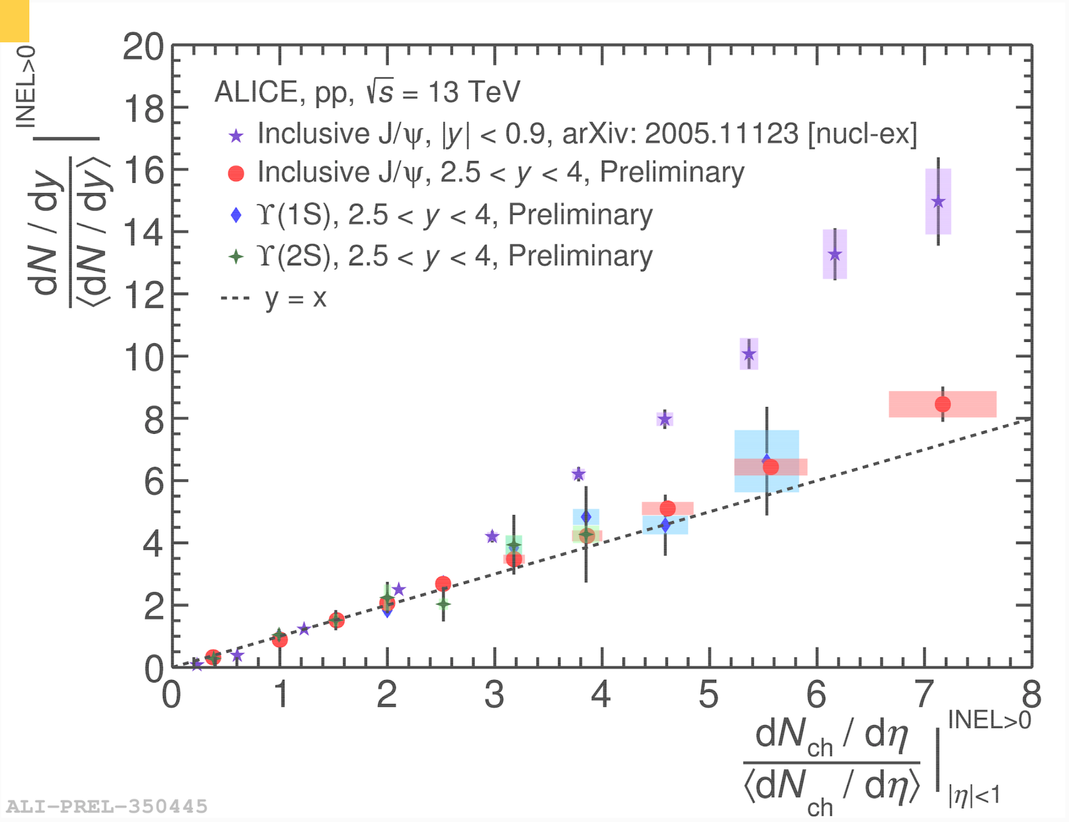


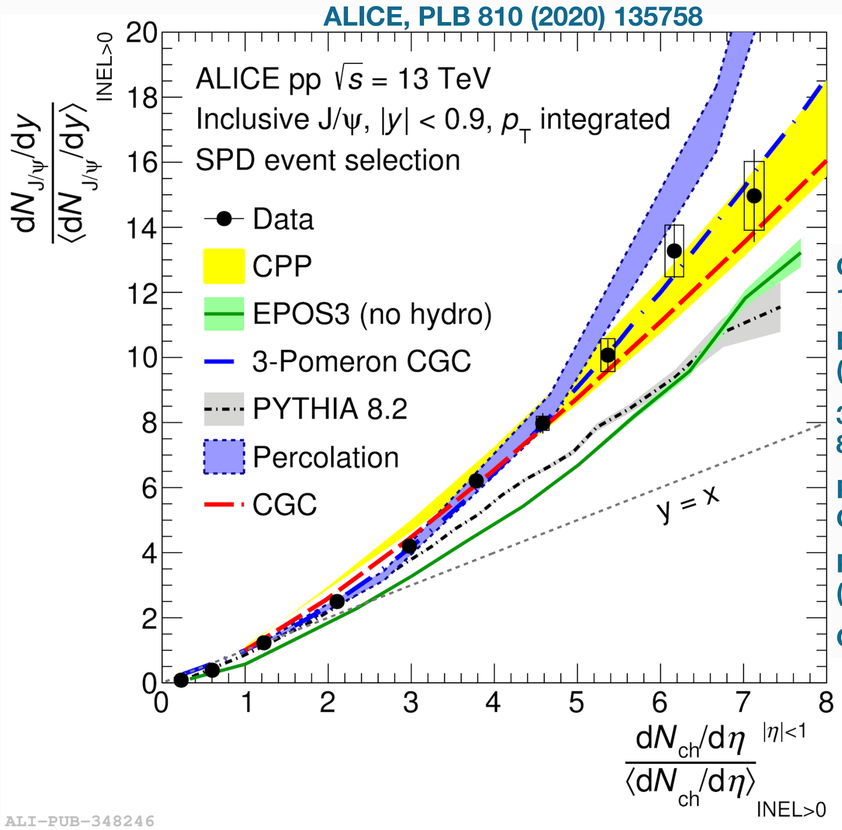




Quarkonium production vs. event activity

pp





CPP: Kopeliovich et al., PRD 88 (2013) 116002

EPOS3: Werner et al., Phys.Rept.350 (2001) 93

3-Pomeron CGC: Siddikov. et al., EPJC 80 (2020), 560

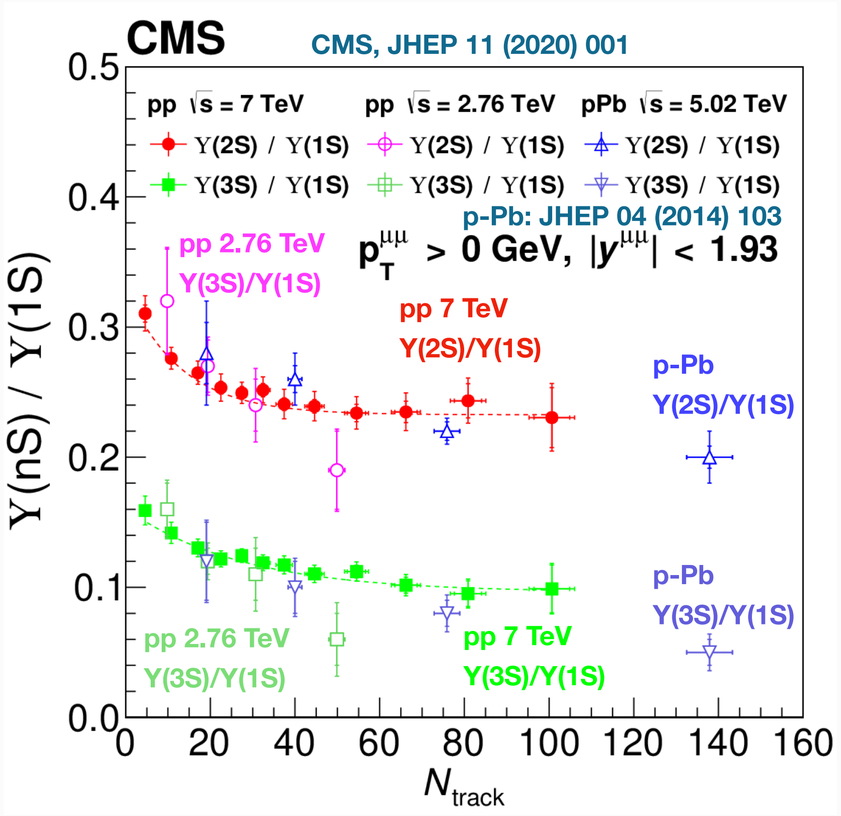
PYTHIA8. Sjostrand et al., Comput.Phys.Comm.178 (2008)

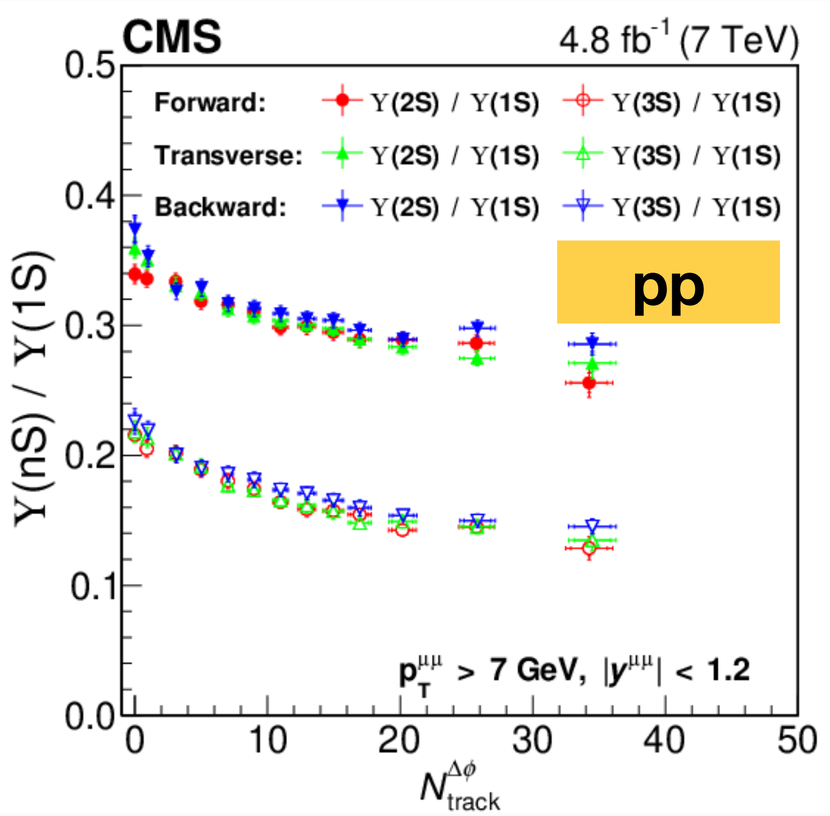
Percolation: Ferreiro, Pajares, PRC 86 (2012) 034903

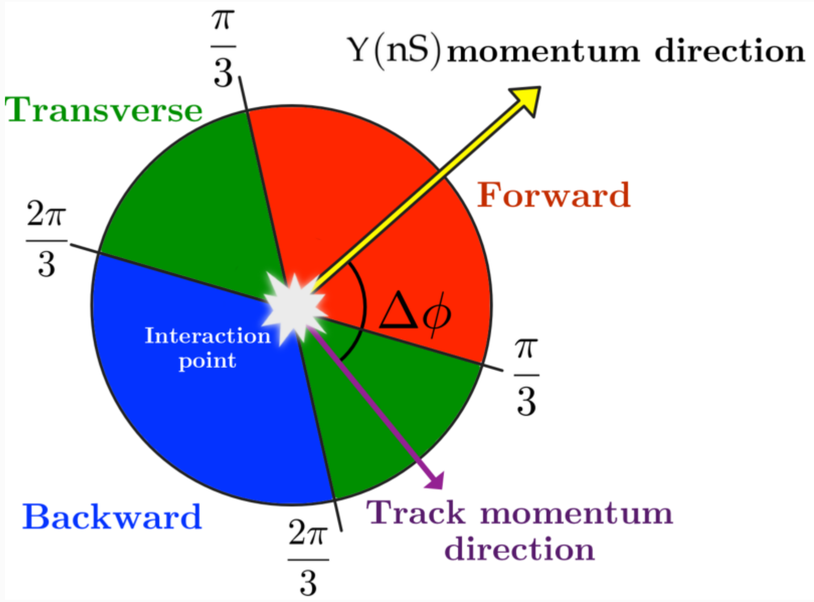
CGC: Ma et al., PRD 98 (2018) 074025

- Linear increase of J/ψ, Υ(1S) and Υ(2S) yields with multiplicity at forward rapidity while midrapidity J/ψ increases stronger than linear
- Most predictions qualitatively describe data

Quarkonium production vs. event activity





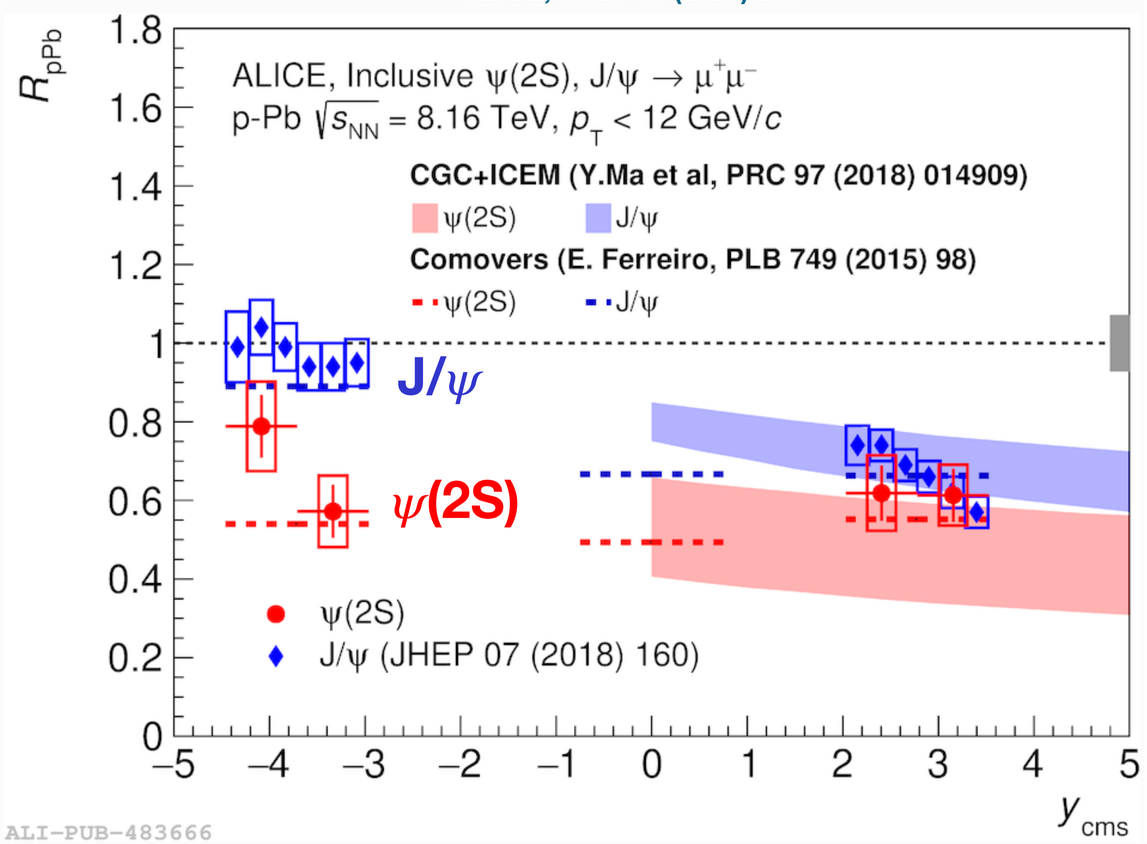


- Y(2S)/Y(1S) and Y(3S)/Y(1S) decreases with multiplicity in pp as well as in p-Pb collisions
- Decreasing trend with multiplicity seen for all azimuthal angles at high p_T
  → Connection to underlying event (UE)

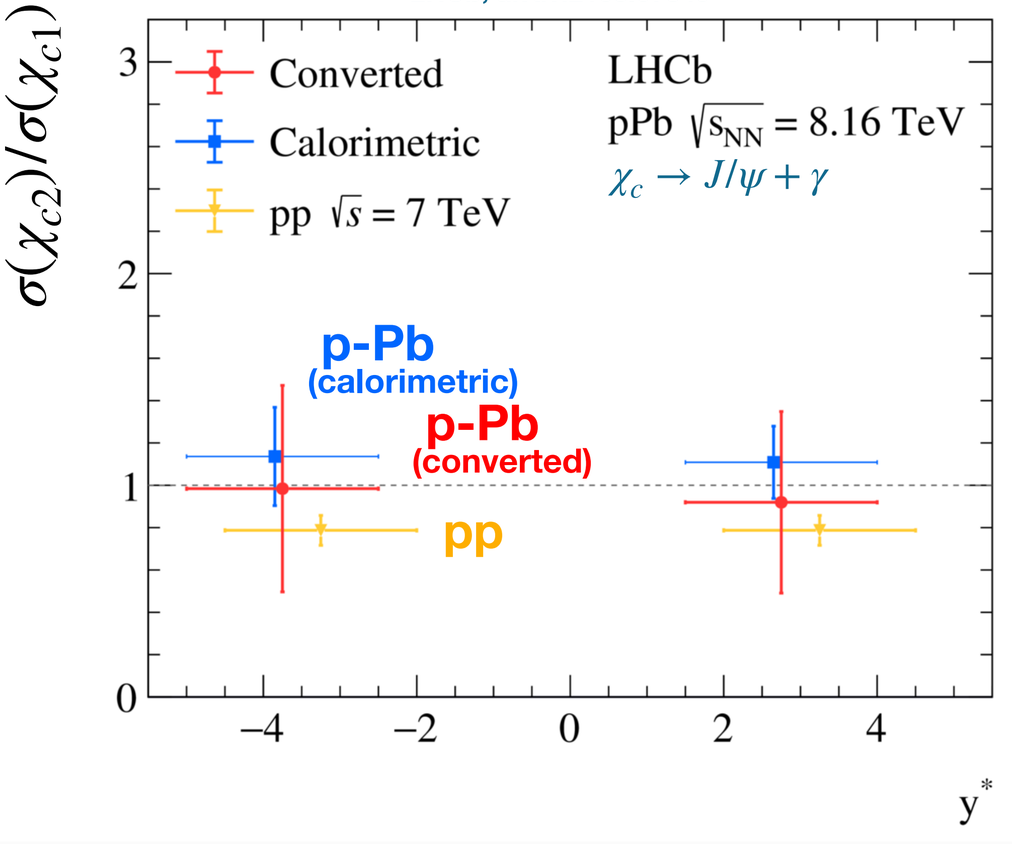
Excited charmonium states in p-Pb collisions

p-Pb

ALICE, JHEP 07 (2020) 237

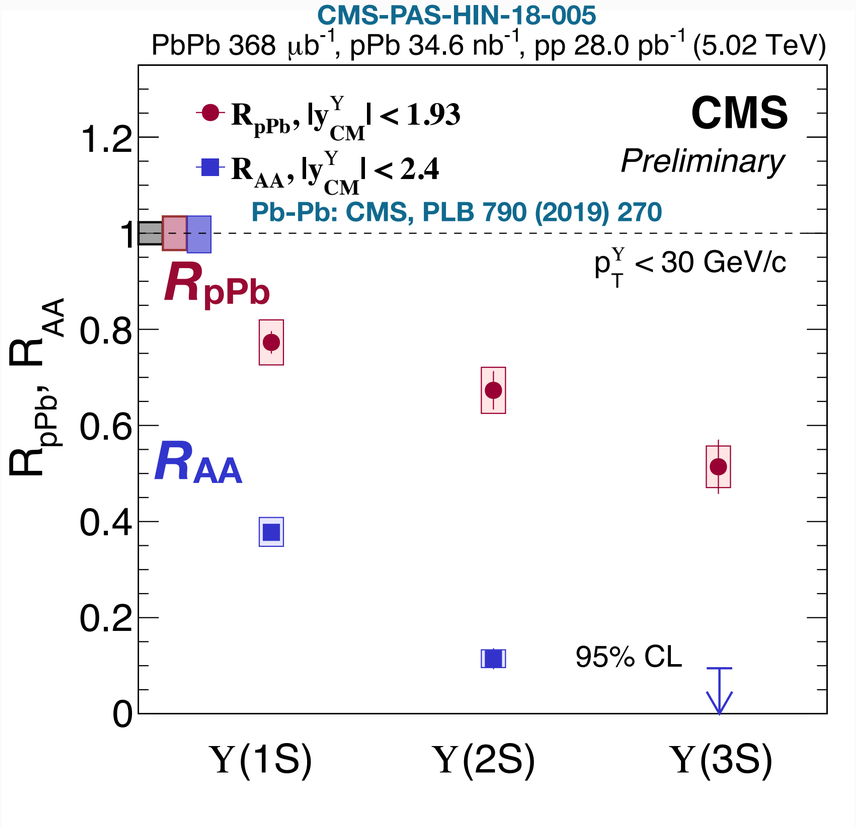


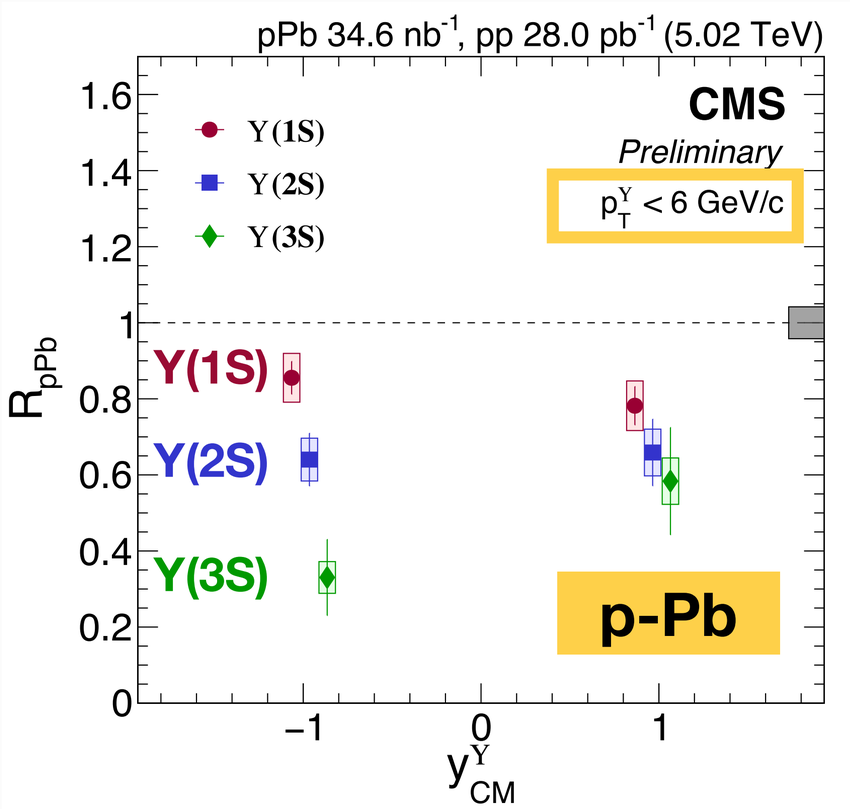
LHCb, arXiv:2103.07349



- Stronger suppression of the ψ(2S) w.r.t. J/ψ at backward rapidity while similar suppression shown at forward rapidity
- Within uncertainties, same cold nuclear matter effects seen on χ_{c1} and χ_{c2} at forward and backward rapidity

Excited bottomonium states in p-Pb collisions





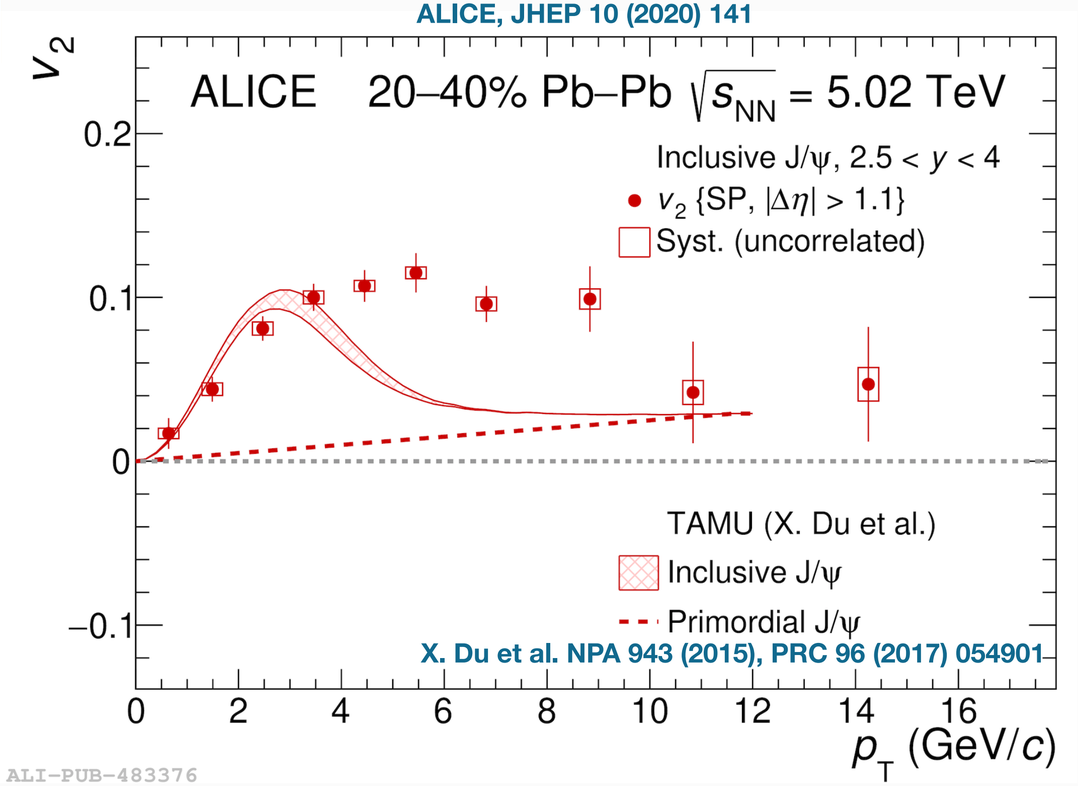
previous measurements: ALICE PLB 806 (2020) 135486 LHCb, JHEP 11 (2018)194 ATLAS, EPJC 78 (2018) 171 CMS, JHEP 04 (2014) 103

- Sequential suppression observed in p-Pb collisions with improved precision; yet much less than in Pb-Pb collisions
- Not much rapidity and p_T dependence except for Υ(3S) at backward rapidity and at low p_T

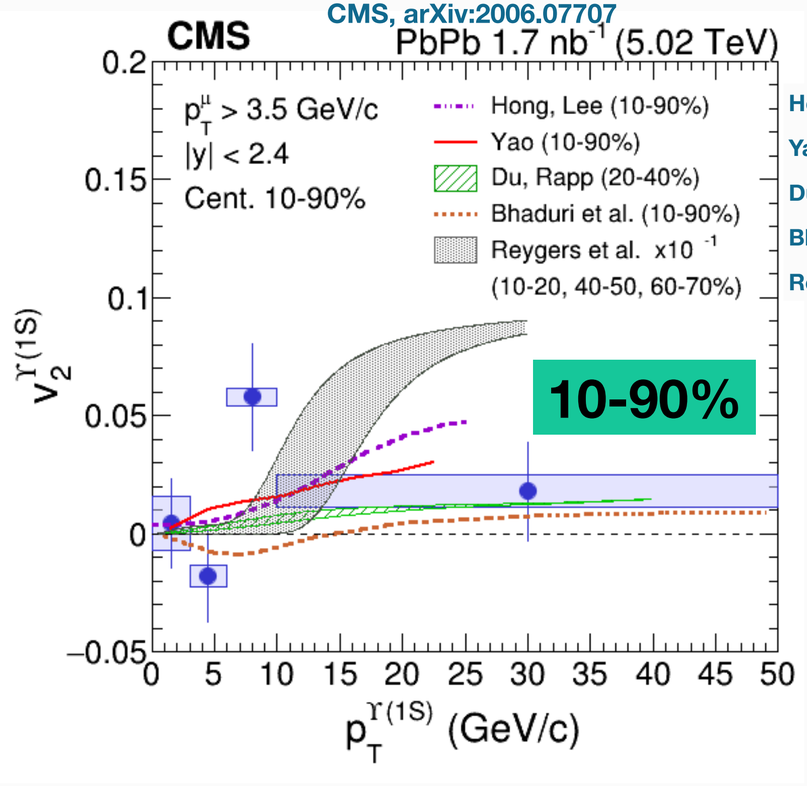
Quarkonium elliptic flow in Pb-Pb collisions

Pb-Pb

ALICE, JHEP 10 (2020) 141



CMS, arXiv:2006.07707



Hong, Lee, PLB 801 (2020) 135147

Yao et al., JHEP01 (2021) 046

Du, Rapp, PRC 96 (2017) 054901

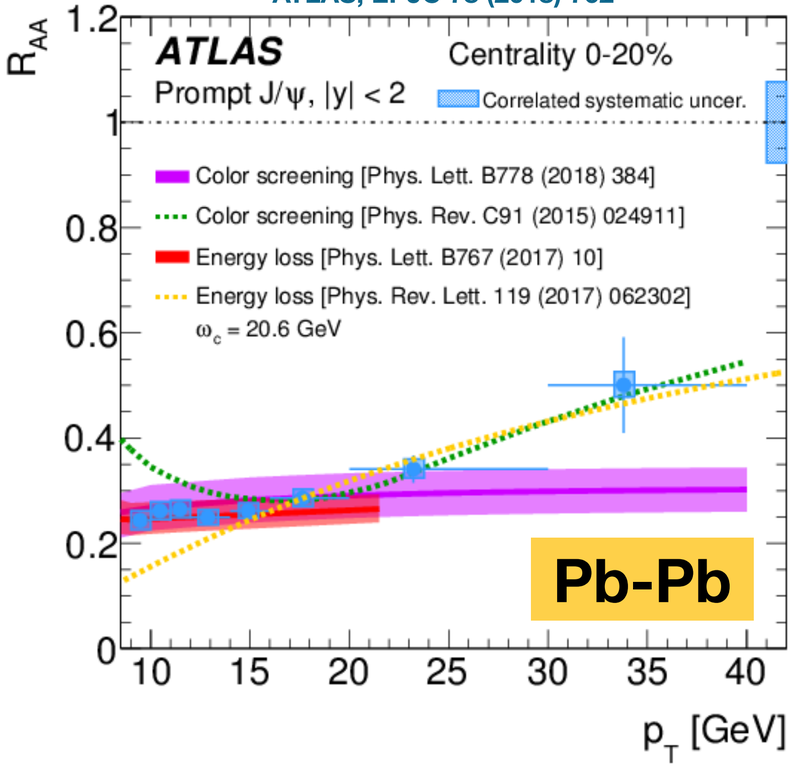
Bhaduri et al., PRC 100 (2019) 051901

Reygers et al., PRC 101 (2020) 064905

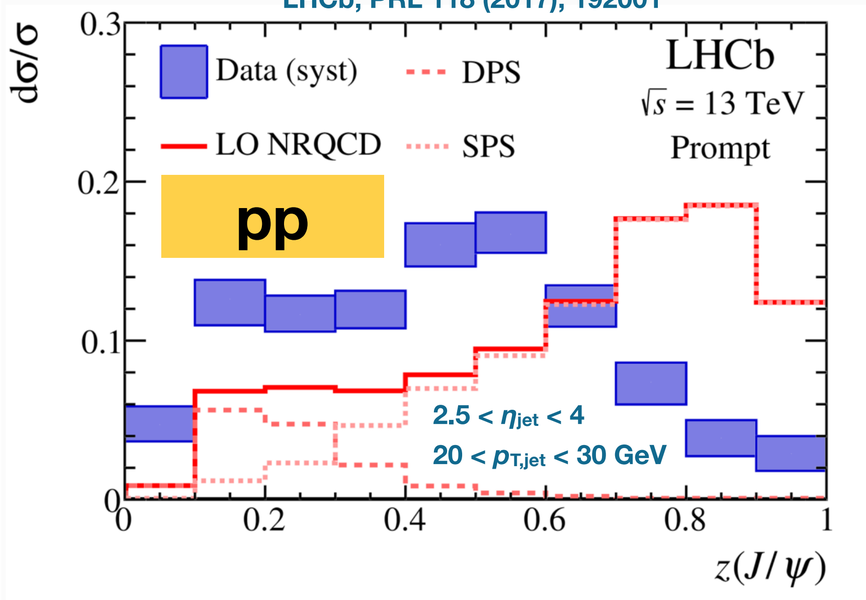
- J/ψ v_2 at low p_T in Pb-Pb collisions from flow of deconfined (thermalised) charm quark; while v_2 for p_T > 4 GeV/c not described by transport model
- No evidence for finite Υ(1S) v_2 over measured p_T range as in previous measurement ALICE, PRL 123 (2019) 192301
- Measurements consistent with the different model predictions; but tension at high p_T

J/ψ in jets in pp and Pb-Pb collisions

ATLAS, EPJC 78 (2018) 762

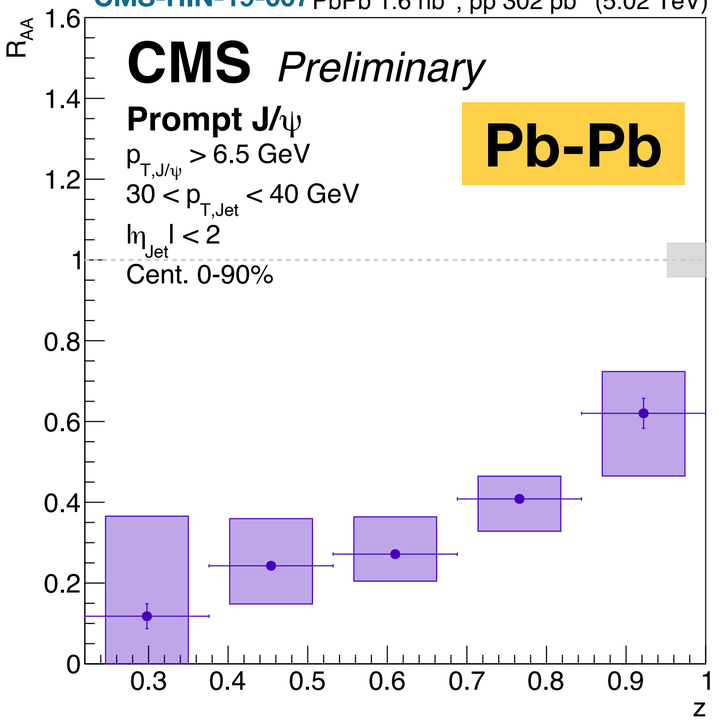


LHCb, PRL 118 (2017), 192001



$$z = \frac{p_{\mathrm{T,J/}\psi}}{p_{\mathrm{T,jet}}}$$

CMS-HIN-19-007 PbPb 1.6 nb^{-1}, pp 302 pb^{-1} (5.02 TeV)

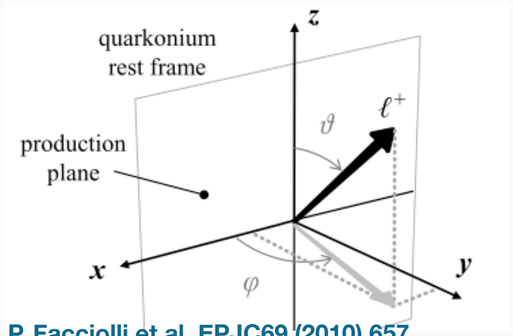


- Prompt J/ψ produced with far more jet activity (softer fragmentation) than in PYTHIA (LO NRQCD) in pp collisions
- Less suppression for isolated J/ψ (large *z*) than for J/ψ with larger jet activity seen in Pb-Pb collisions
- J/ψ as a tool for studying in medium energy loss mechanism?

J/ψ polarisation in Pb-Pb collisions

Pb-Pb

$$W(cos\theta, \phi) \propto \frac{1}{3+\lambda_\theta} \cdot (\lambda_\theta cos^2\theta + \lambda_\phi sin^2\theta cos2\phi + \lambda_{\theta\phi} sin2\theta cos\phi)$$



P. Facciolli et al. EPJC69 (2010) 657

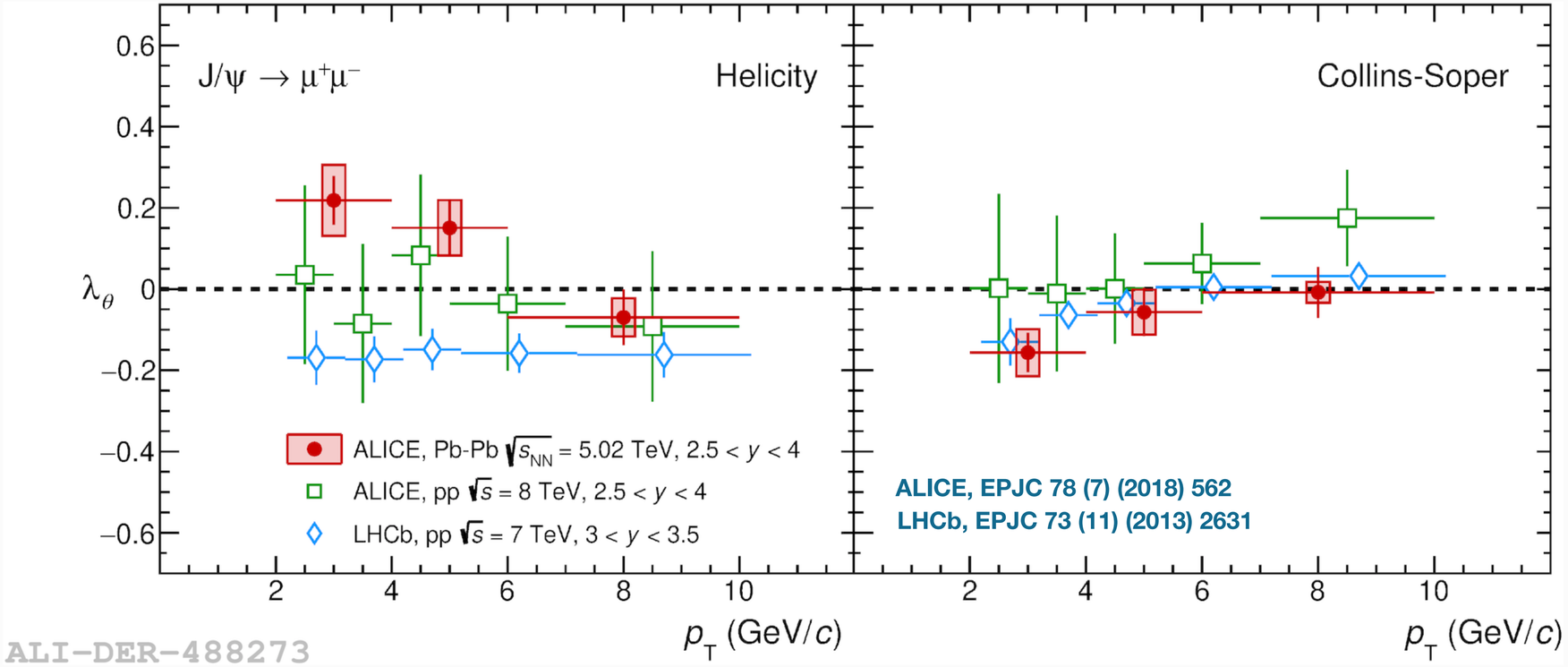
$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (0, 0, 0)$

➡ no polarisation

$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (\pm 1, 0, 0)$

➡ pure transverse (+) or longitudinal (-) polarisation

ALICE, PLB 815 (2021) 136146

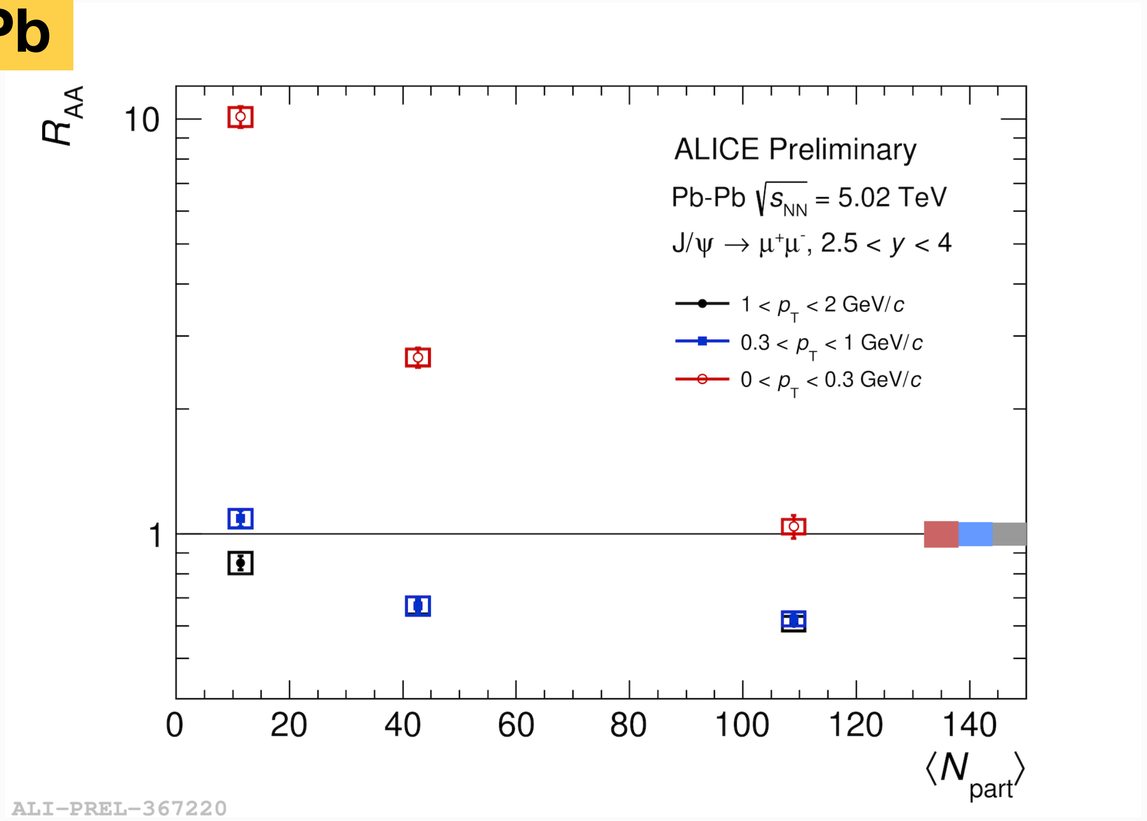


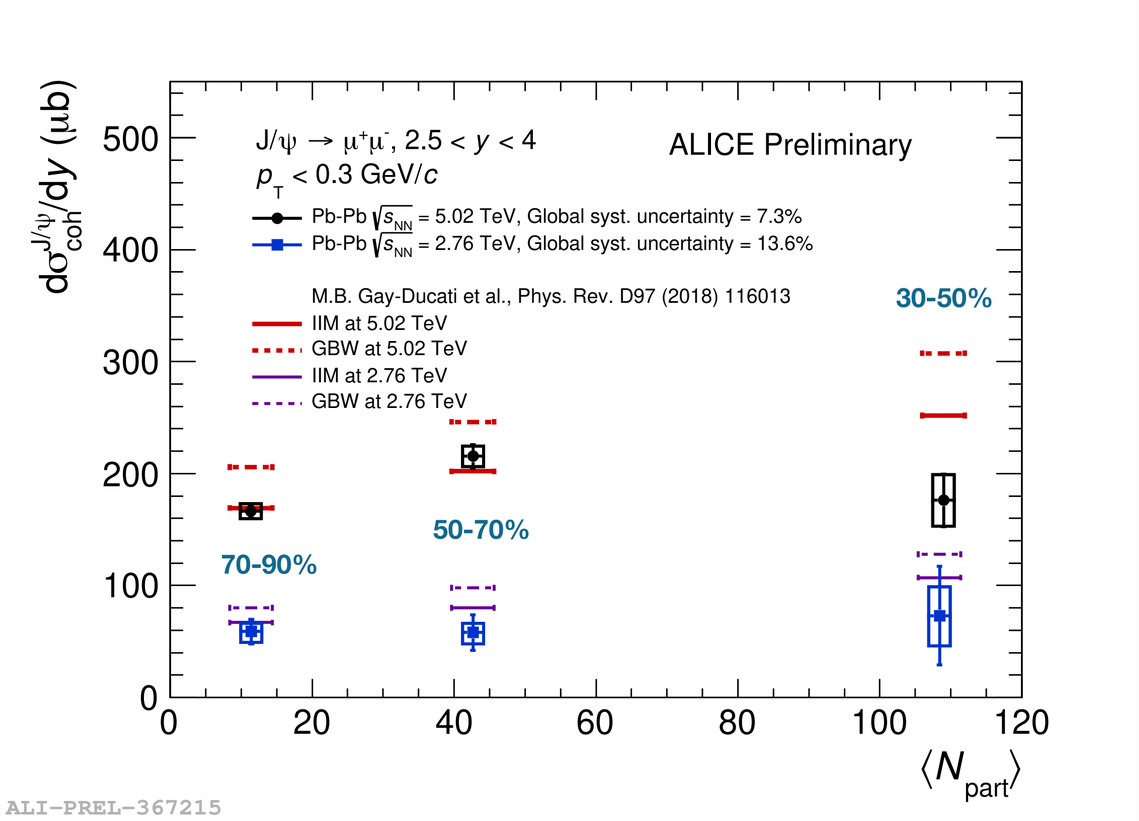
- Polarization parameters compatible with 0 except $\lambda_\theta^{\mathrm{HE}}$ 2.1σ deviation (transverse polarisation) and $\lambda_\theta^{\mathrm{CS}}$ 2.1σ deviation (longitudinal polarisation) at low p_T

  Compatible with pp measurements except for $\lambda_\theta^{\mathrm{HE}}$ at low p_T ($2 < p_T < 4$ GeV/c) shows significant difference (~3.3σ) w.r.t. LHCb pp measurements

Coherent J/ψ photoproduction in Pb-Pb collisions

Pb-Pb





first ALICE measurement: PRL 116 (2016) 222301

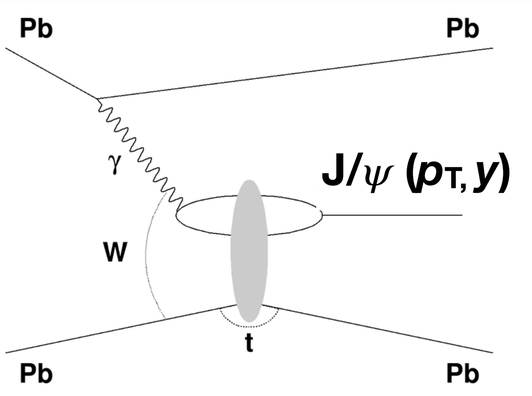
- Low p_T J/ψ (p_T < 0.3 GeV/c) large excess → coherent J/ψ photoproduction in Pb-Pb collisions
- Increase of the cross section at 5.02 TeV by a factor of ~3 w.r.t 2.76 TeV measurements at forward rapidity

UPC - S. Ragon' talk on 8 June

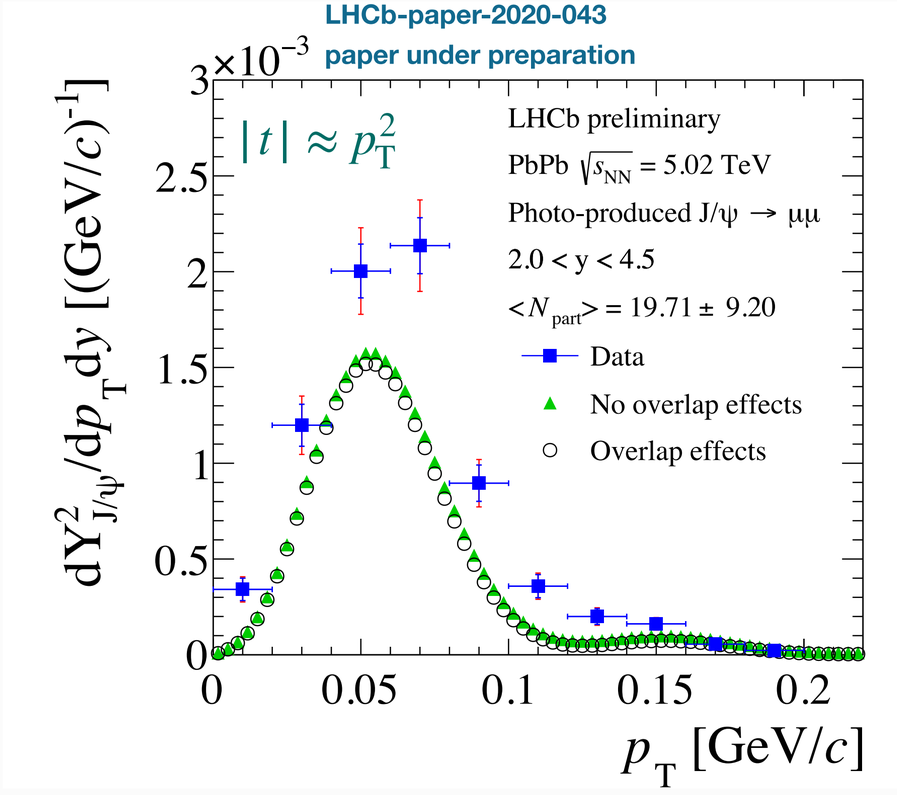
- UPC based model including overlap effect qualitatively describes the trend of data in peripheral collisions

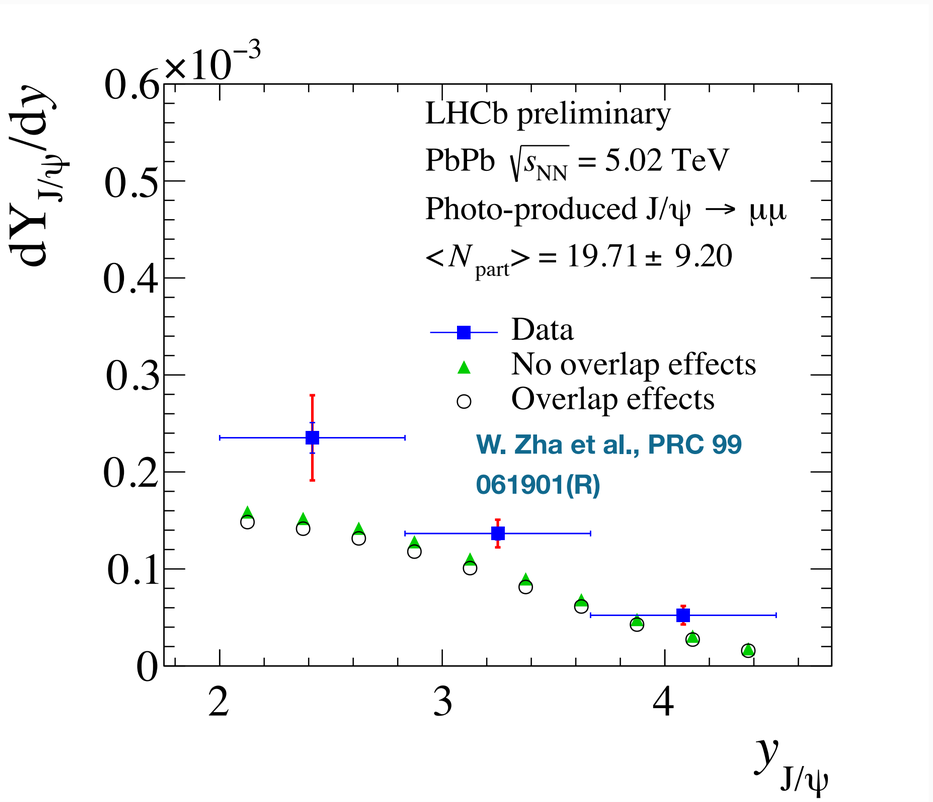
Coherent J/ψ photoproduction in Pb-Pb collisions

Pb-Pb



LHCb-paper-2020-043
paper under preparation





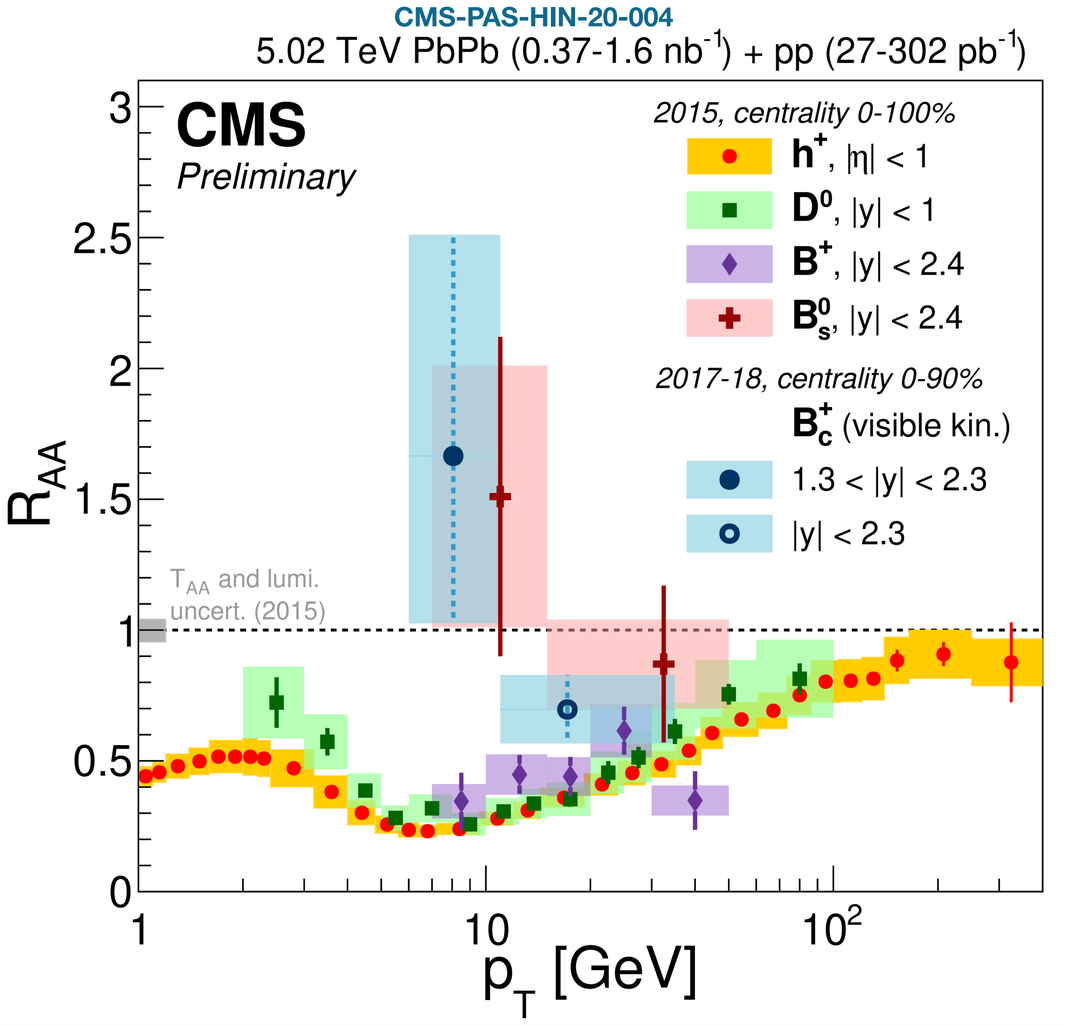
- Coherent J/ψ photoproduction measured as a function of p_T and of y
- Probe of gluon density and nuclear shadowing together with UPC measurement

J. G. Contreras, PRC 96 (2017) 015203

- Potential probe of QGP?

B_c mesons in Pb-Pb collisions

Pb-Pb



- First measurement of B_c ($B_c^+(c\bar{b})$ + $B_c^-(\bar{c}b)$) meson in Pb-Pb collisions via $B_c \rightarrow J/\psi(\rightarrow \mu\mu) + \mu + \nu_\mu$

- Less suppression than light hadrons and open heavy flavour hadrons with light quarks seen for B_c as B_s at low p_T
  → significant regeneration?

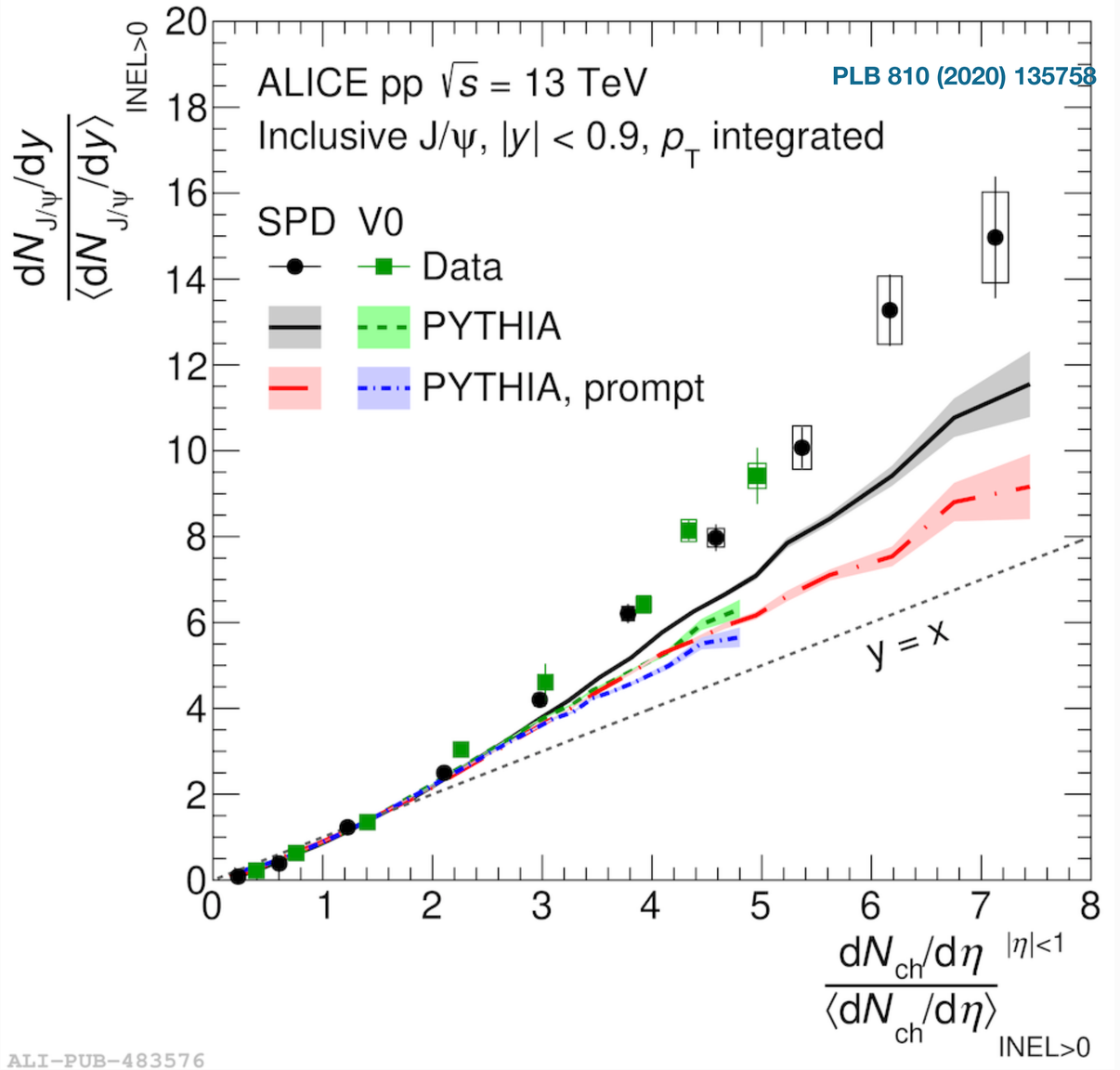
Summary and outlook

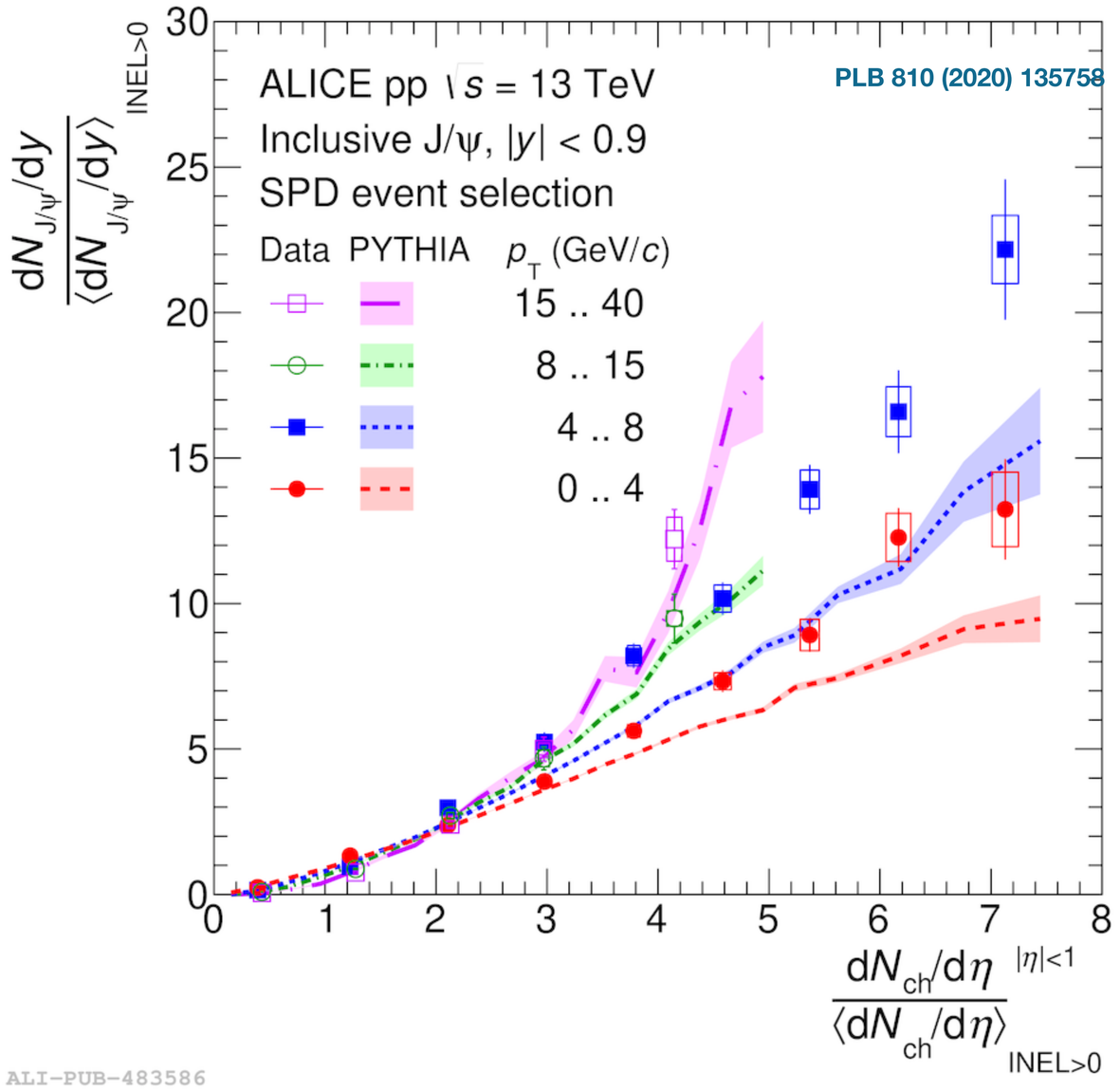
- Higher precision, more differential measurements achieved in all collision systems w.r.t. Run 1 and **new observables become accessible**
- pp collisions: deeper understanding of quarkonium production mechanism and effects of underlying event
- p-Pb collisions: more than initial state cold nuclear matter effects?
- Pb-Pb collisions:
  - interplay of suppression and regeneration
  - strong hints for charm quark thermalization in QGP, yet open questions left
- LHC Run 3 program starts soon - much larger data sample expected with upgrade detectors

STAY TUNED!

Backup

Quarkonium production vs. event activity





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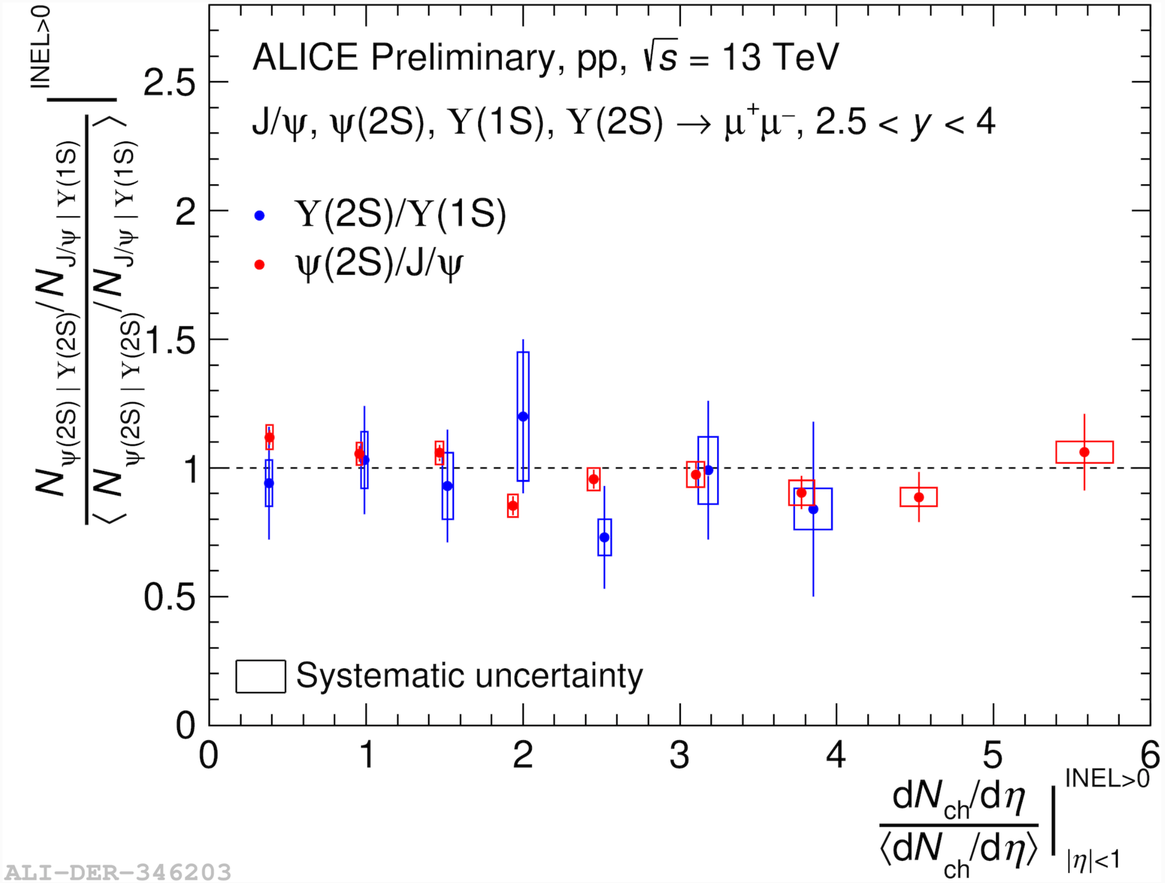
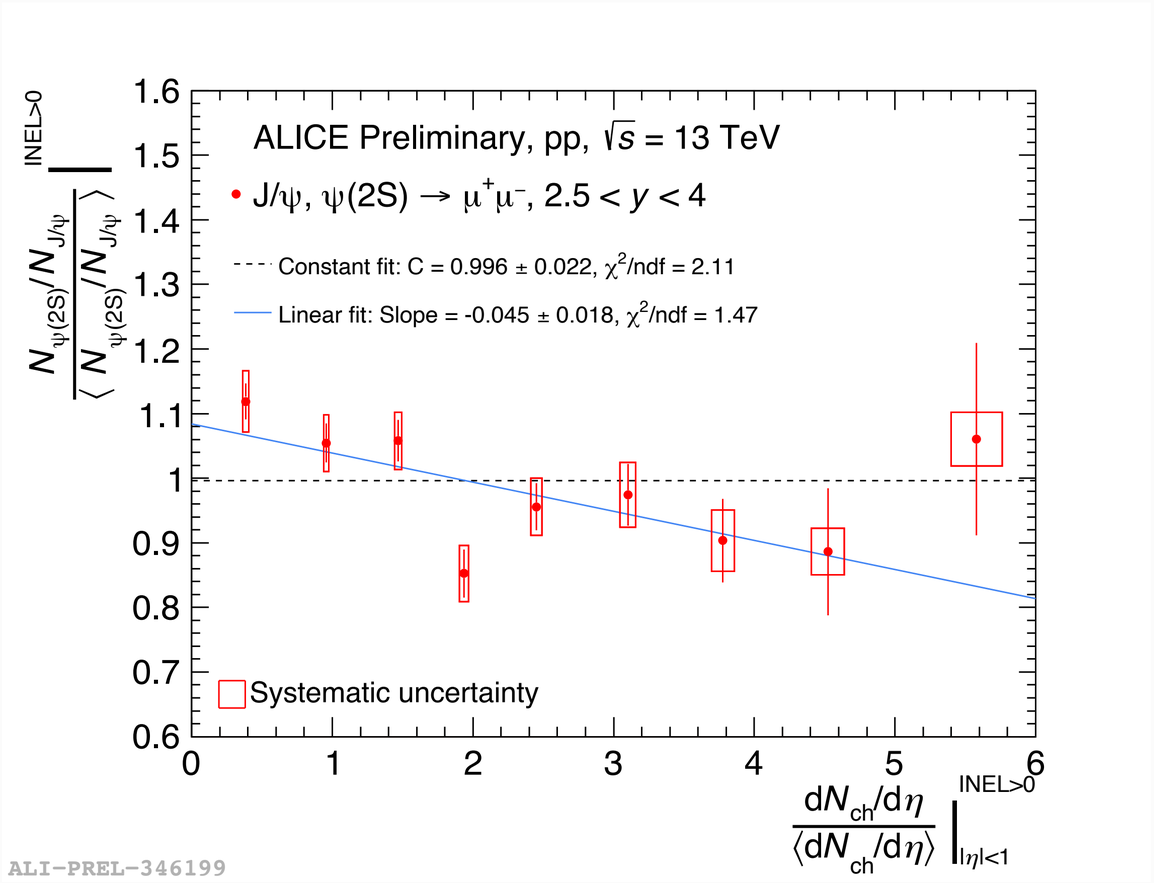
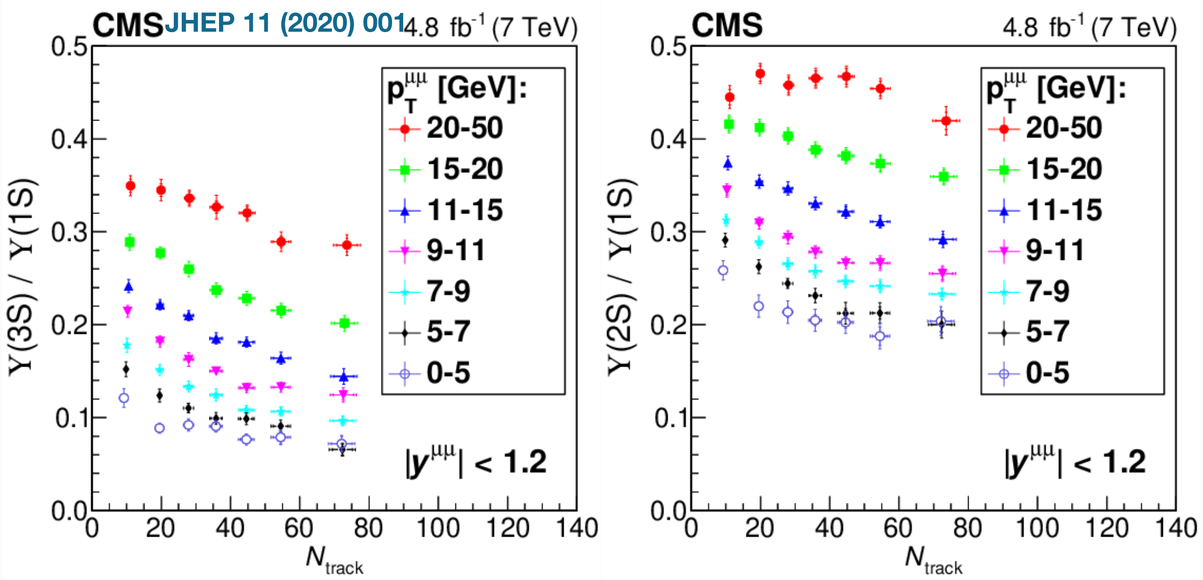
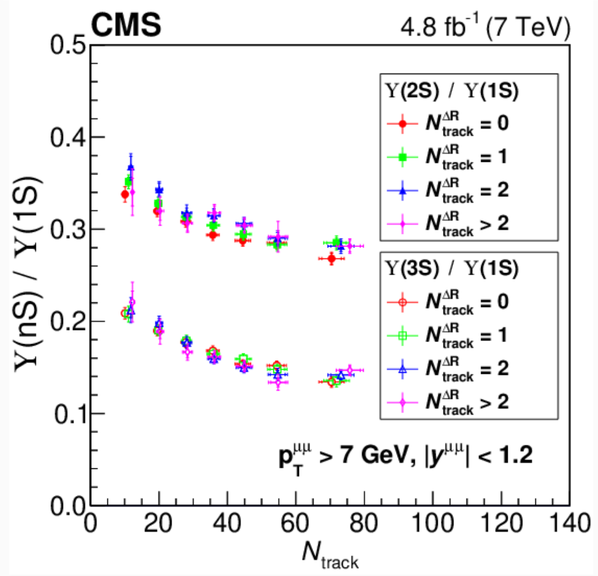
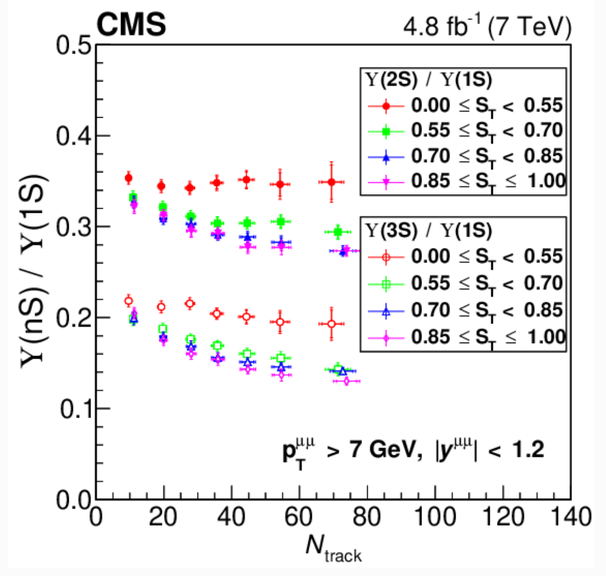




Quarkonium production vs. event activity







$$S_{\mathrm{T}} \equiv \frac{2\lambda_2}{\lambda_1 + \lambda_2},$$

where $\lambda_1 > \lambda_2$ are the eigenvalues of the matrix constructed from the transverse momenta components of the charged particles (labelled with the index i), linearised by the additional term $1/p_{\mathrm{T}i}$ (following Ref. [49]):

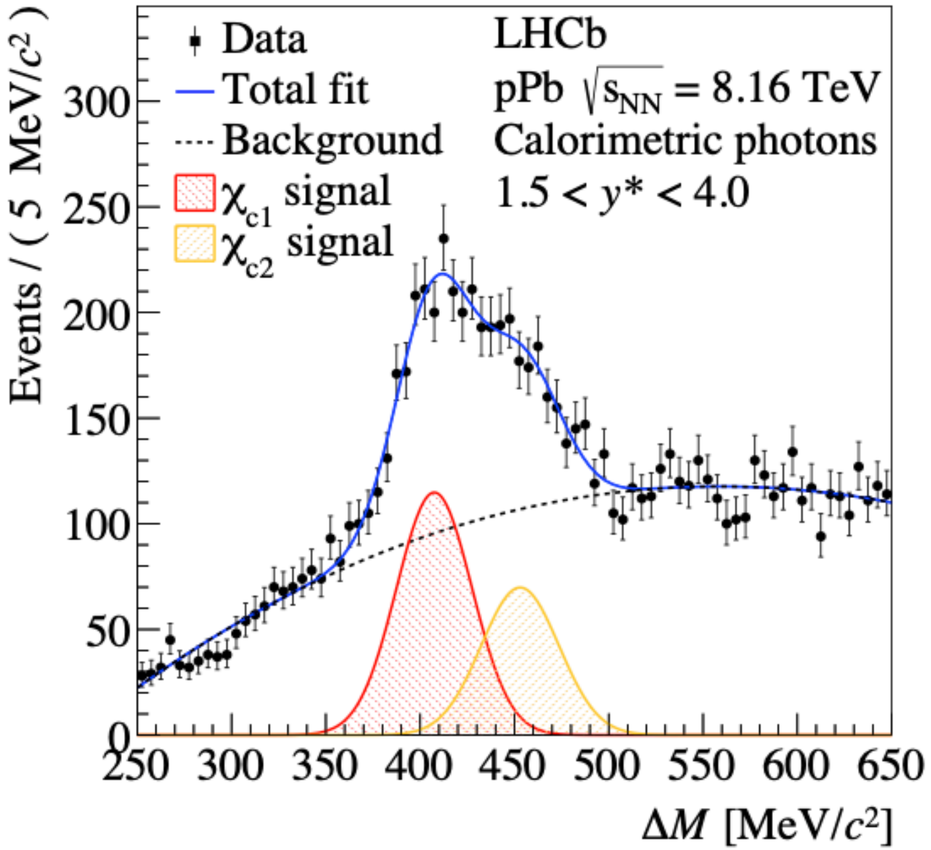
$$S_{xy}^{T} = \frac{1}{\sum_i p_{\mathrm{T}i}} \sum_i \frac{1}{p_{\mathrm{T}i}} \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} \\ p_{xi}p_{yi} & p_{yi}^2 \end{pmatrix}.$$

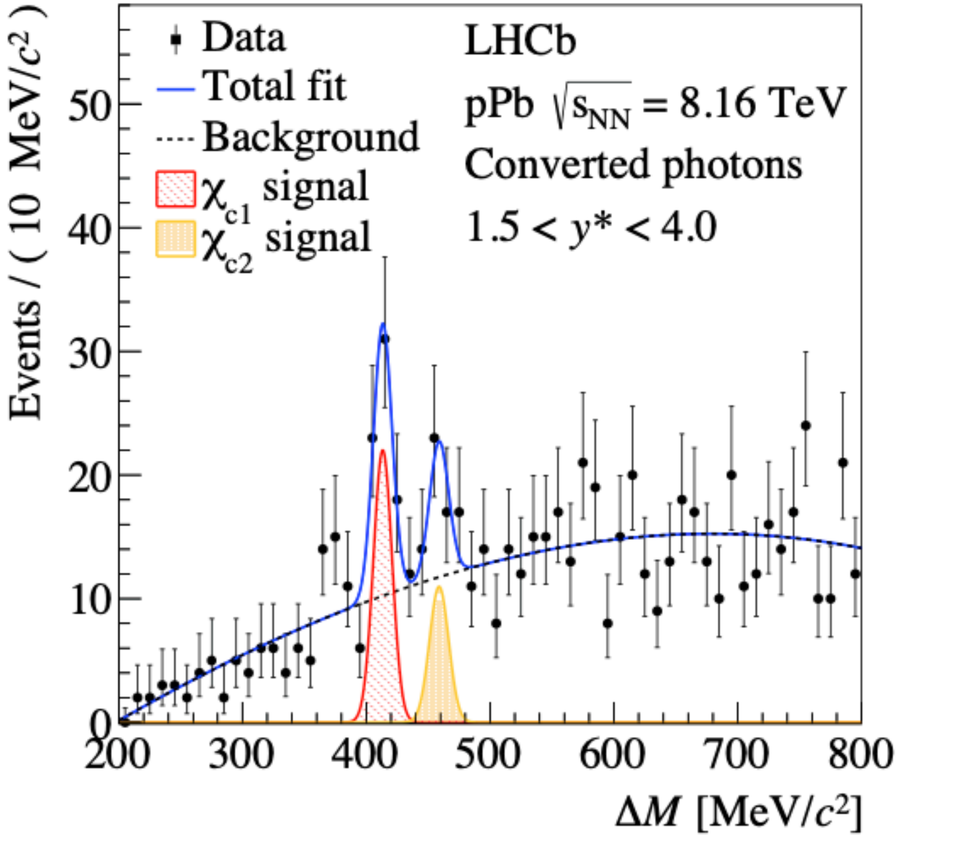
an isotropic event has sphericity close to 1 (”high” sphericity)

“jet- like” events have ST close to zero.

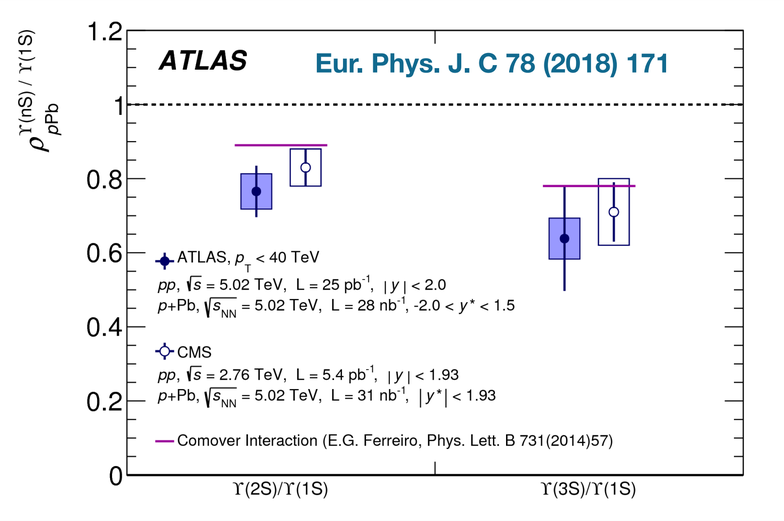
Prompt cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ in pPb 8.16 TeV

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

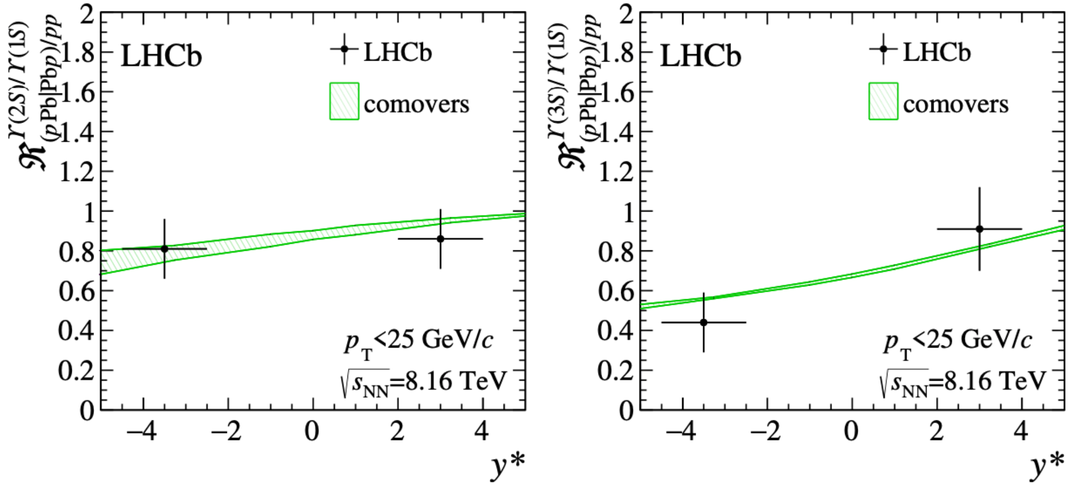


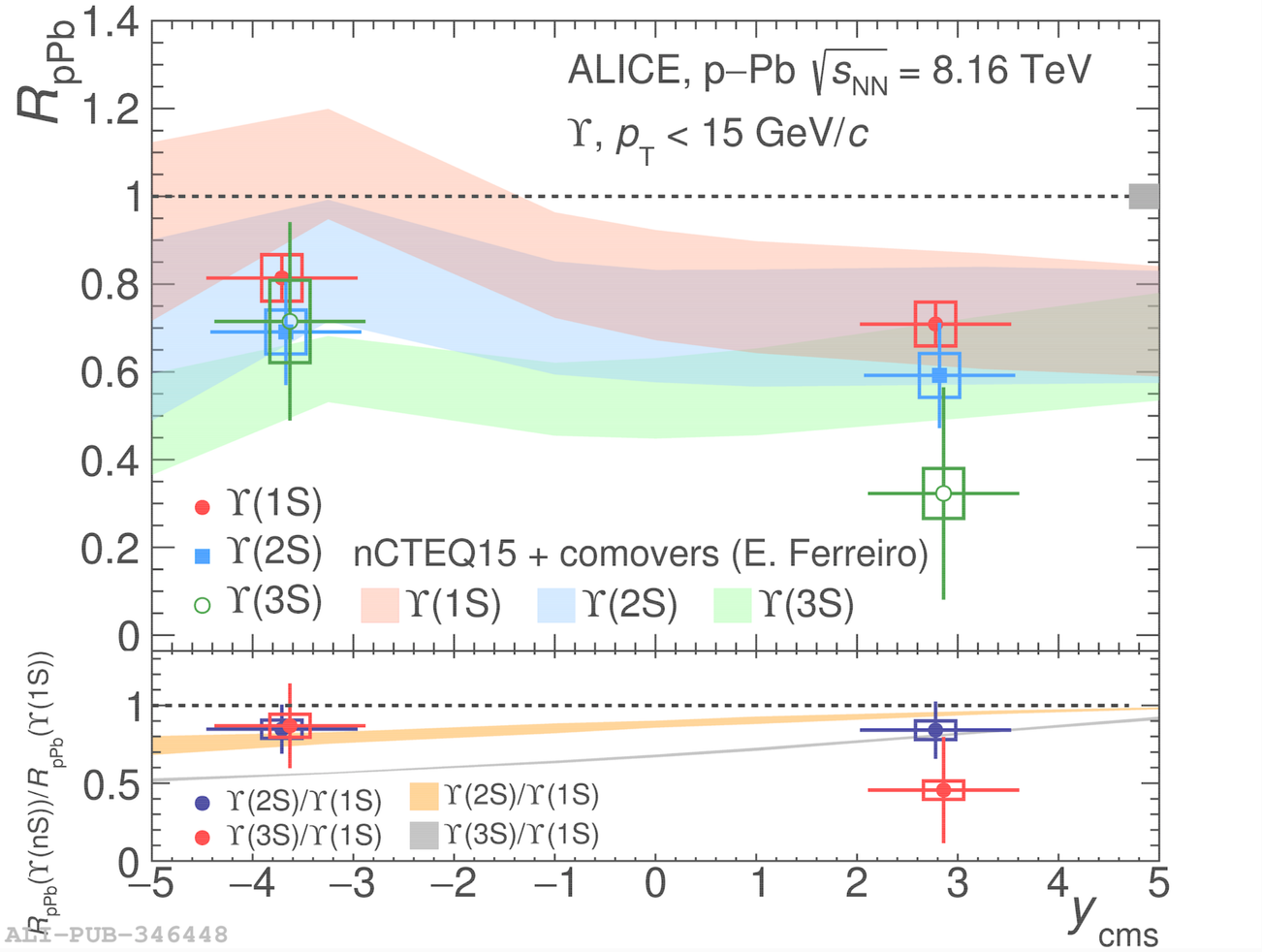


Excited bottomonium states in p-Pb collisions



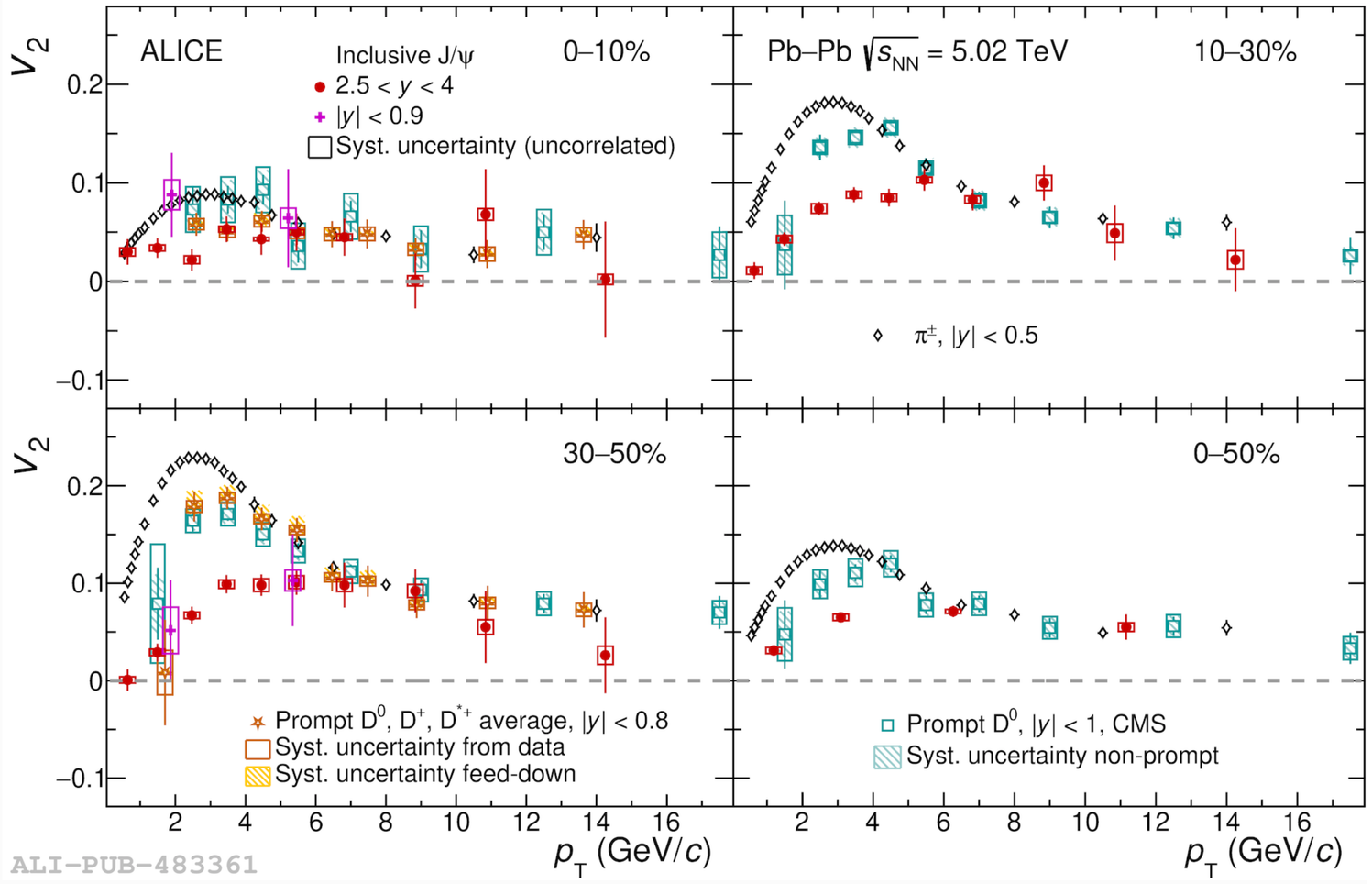
JHEP11(2018)194



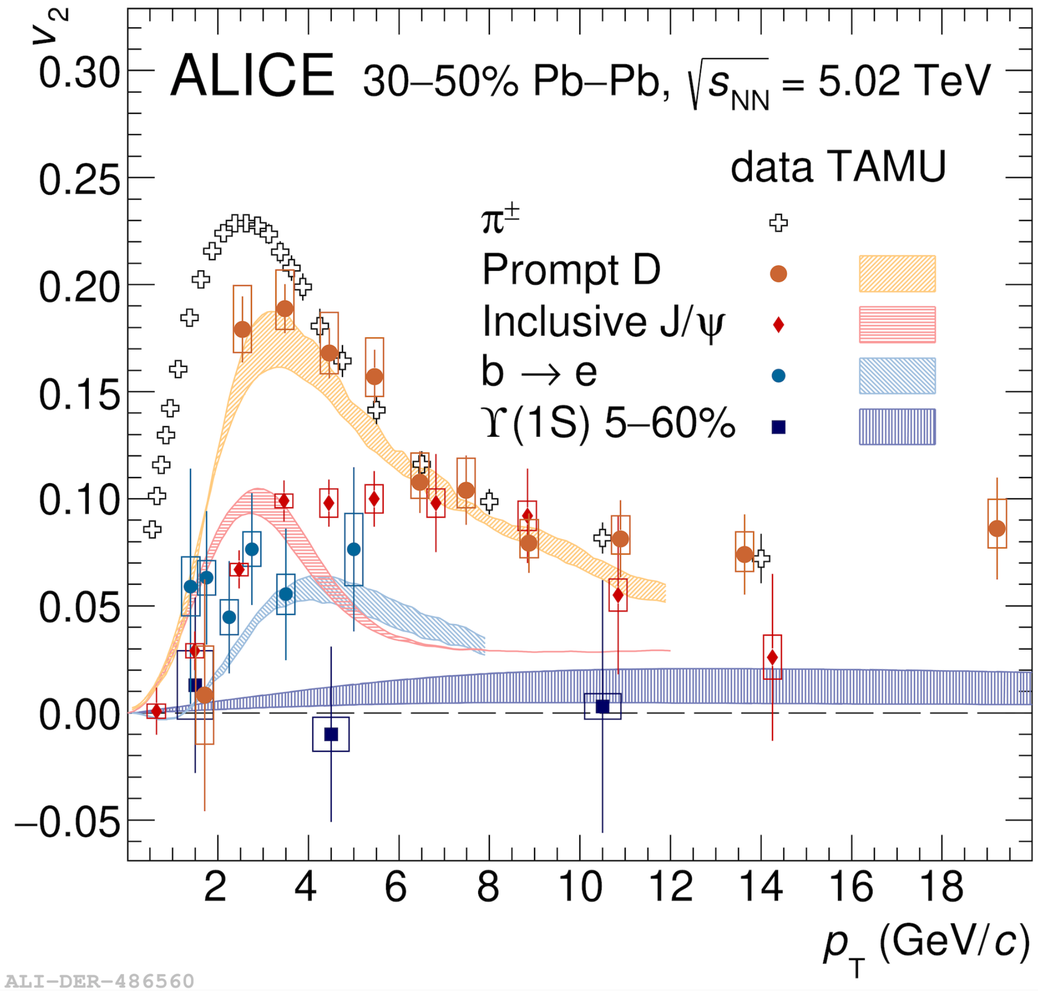


Quarkonium elliptic flow

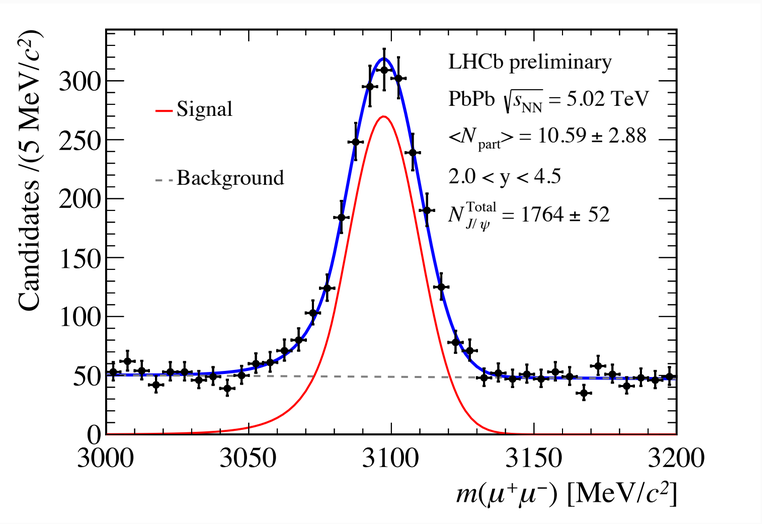
JHEP10 (2020) 141

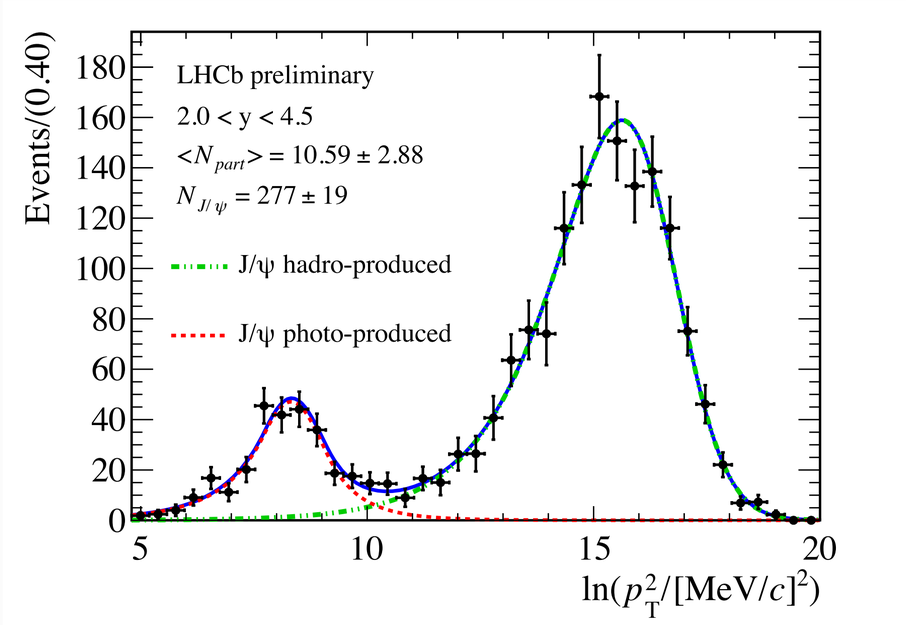


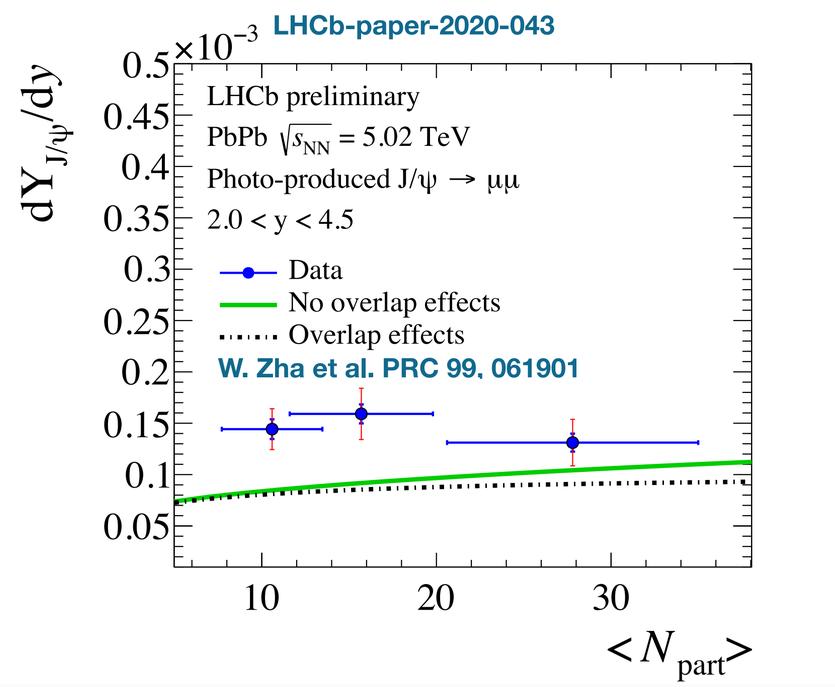
D: PLB 813 (2021) 136054
J/ψ: JHEP 10 (2020) 141
e←b: arXiv:2005.11130 (accepted by PRL)
Y(1S): PRL 123 (2019)192301
TAMU: PRL 124 (2020) 042301



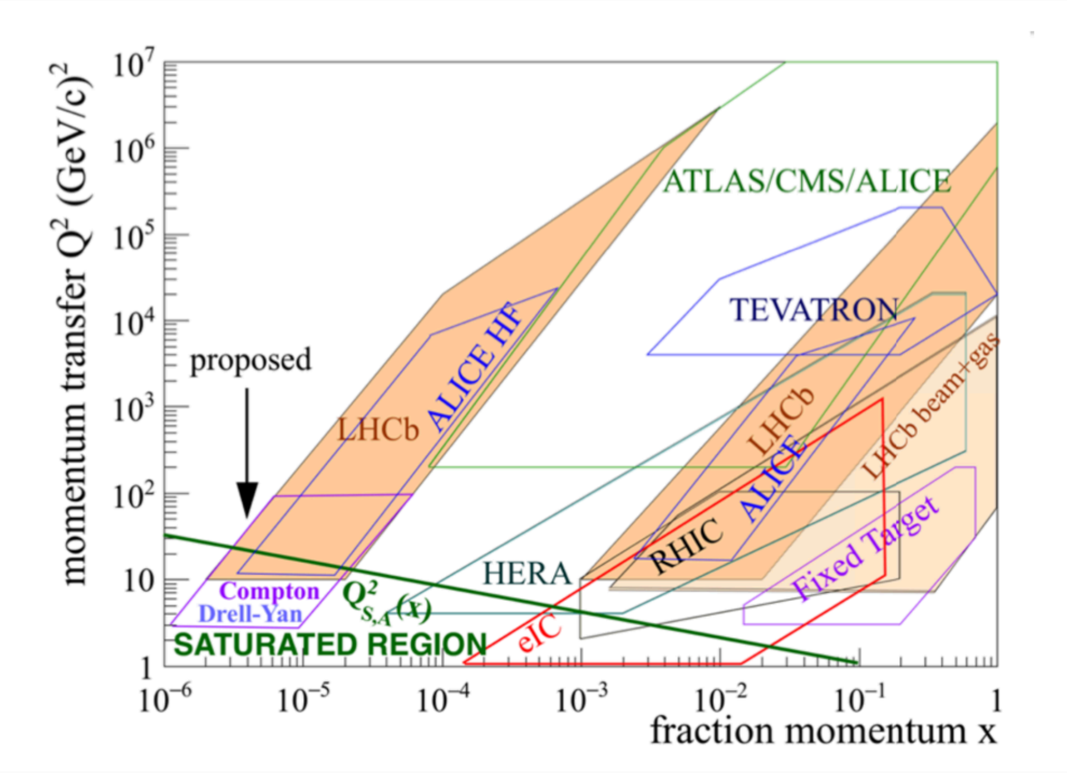
Coherent J/ψ photoproduction in hadronic Pb-Pb collisions

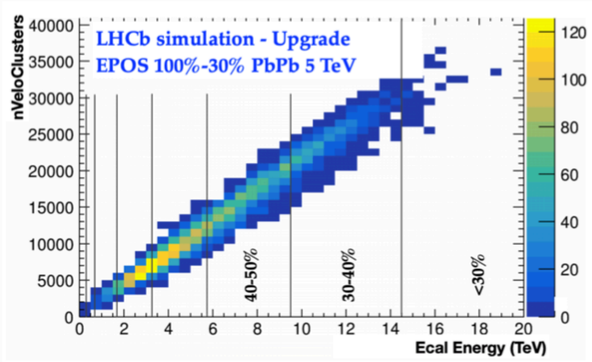


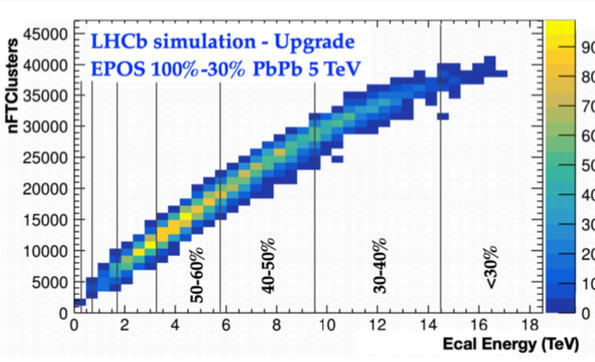




LHCb run 3


momentum transfer Q^2 (GeV/c)^2
fraction momentum x
ATLAS/CMS/ALICE
TEVATRON
LHCb ALICE HF
proposed
LHCb
ALICE
LHCb beam+gas
RHIC
Fixed Target
HERA
Compton
Drell-Yan
$Q^2_{s,A}(x)$
SATURATED REGION
eIC

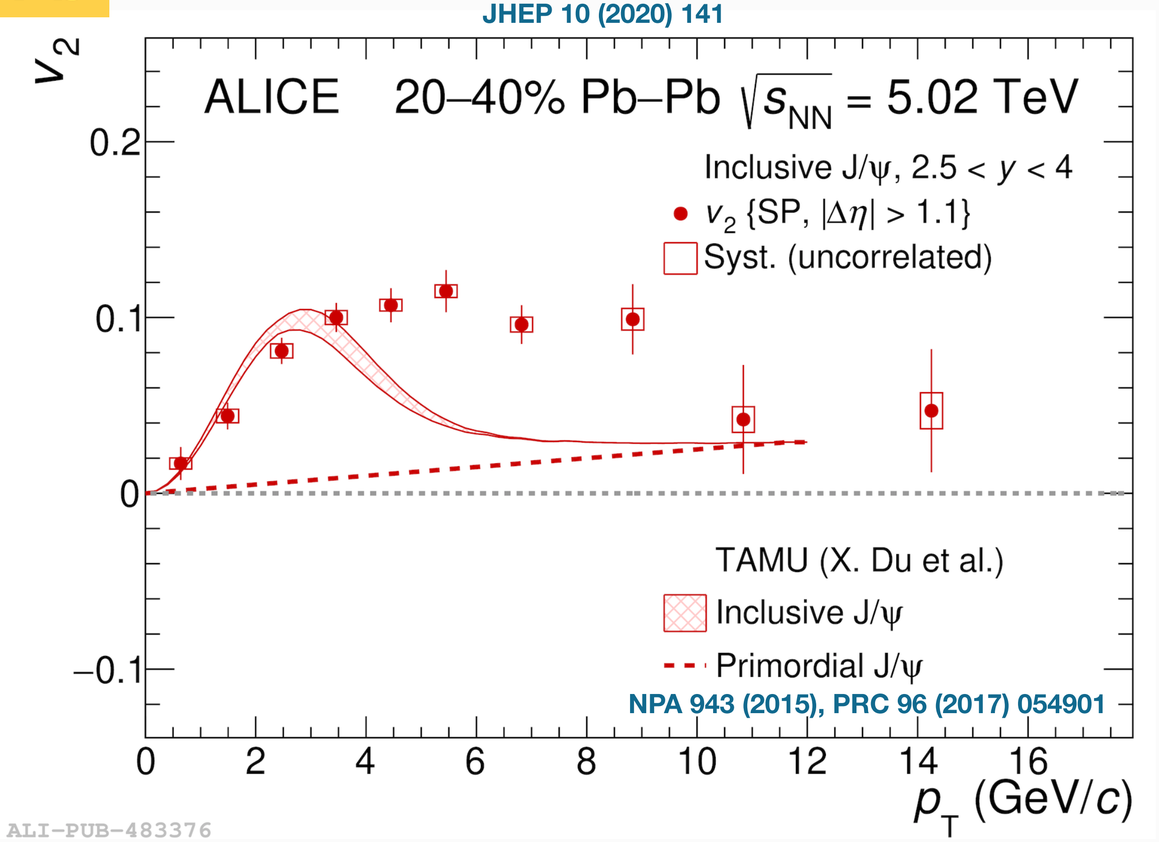

LHCb simulation - Upgrade
EPOS 100%-30% PbPb 5 TeV
nVeloClusters
Ecal Energy (TeV)
40-50%
30-40%
<30%


LHCb simulation - Upgrade
EPOS 100%-30% PbPb 5 TeV
nFTClusters
Ecal Energy (TeV)
50-60%
40-50%
30-40%
<30%

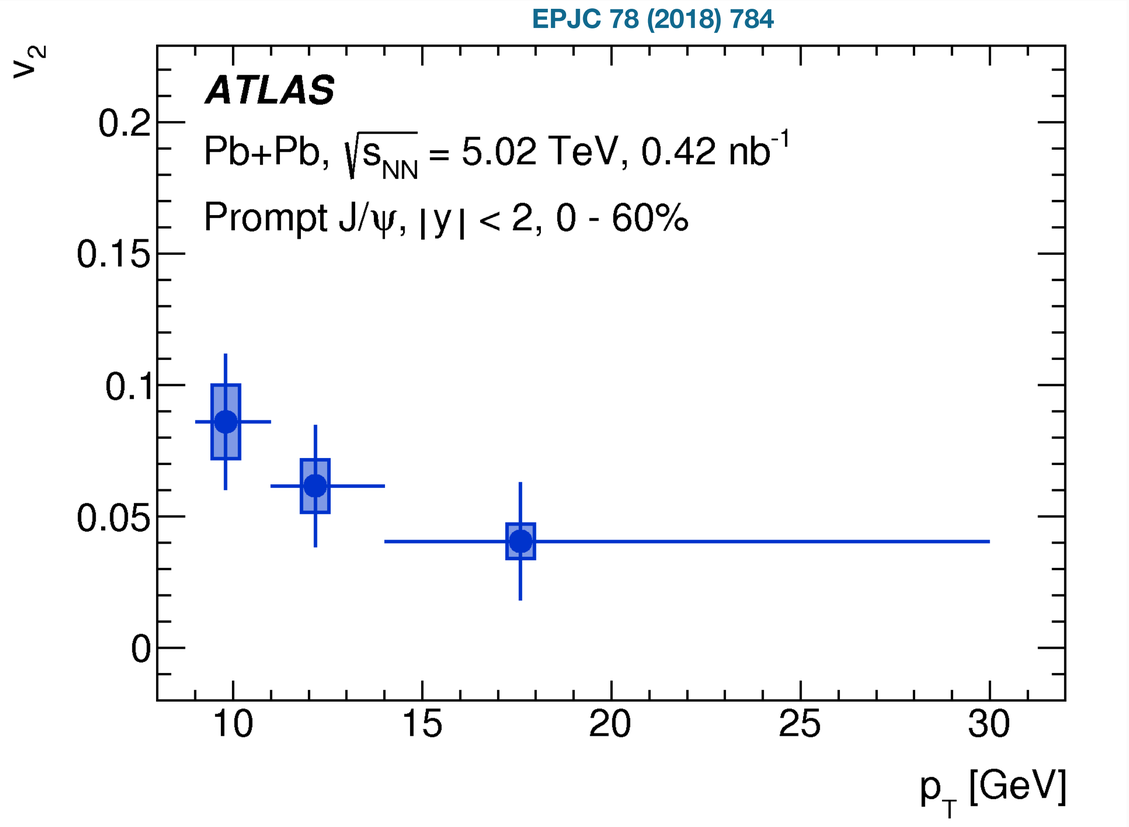
J/ψ elliptic flow in Pb-Pb collisions

Pb-Pb

JHEP 10 (2020) 141



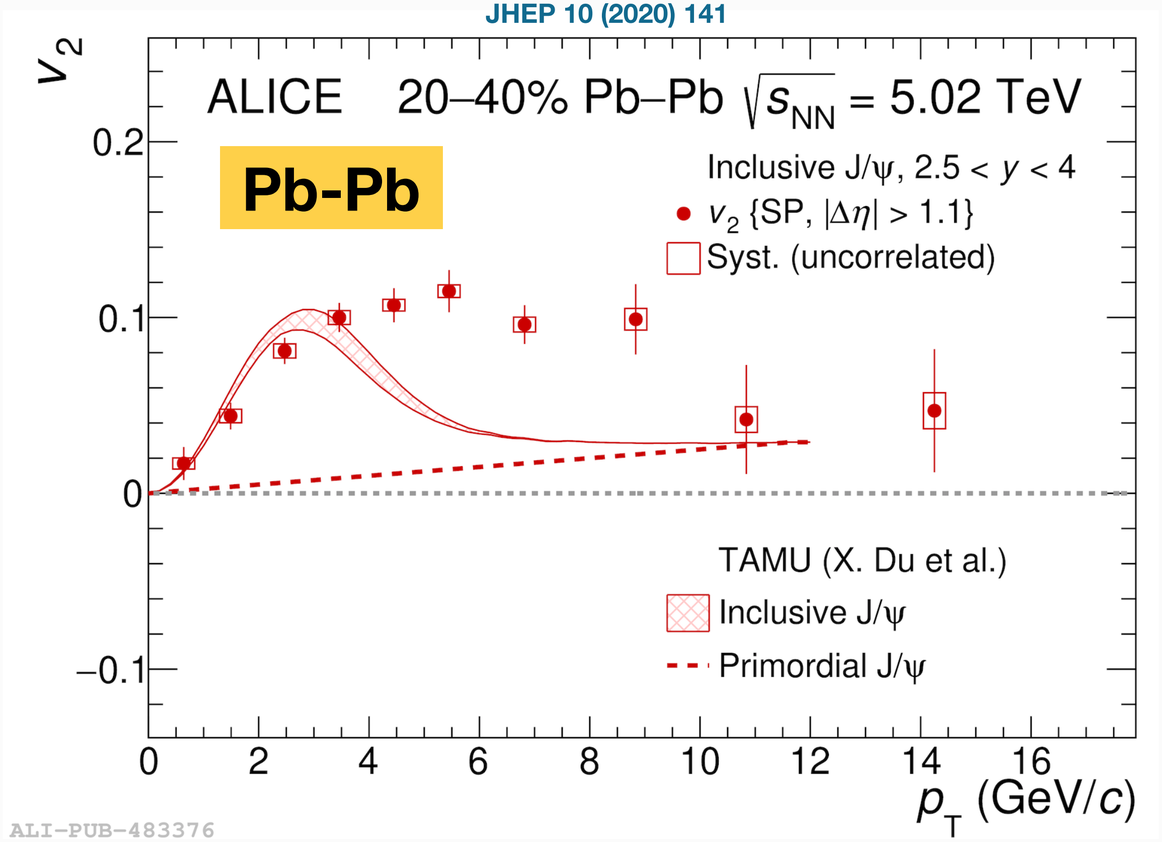
EPJC 78 (2018) 784



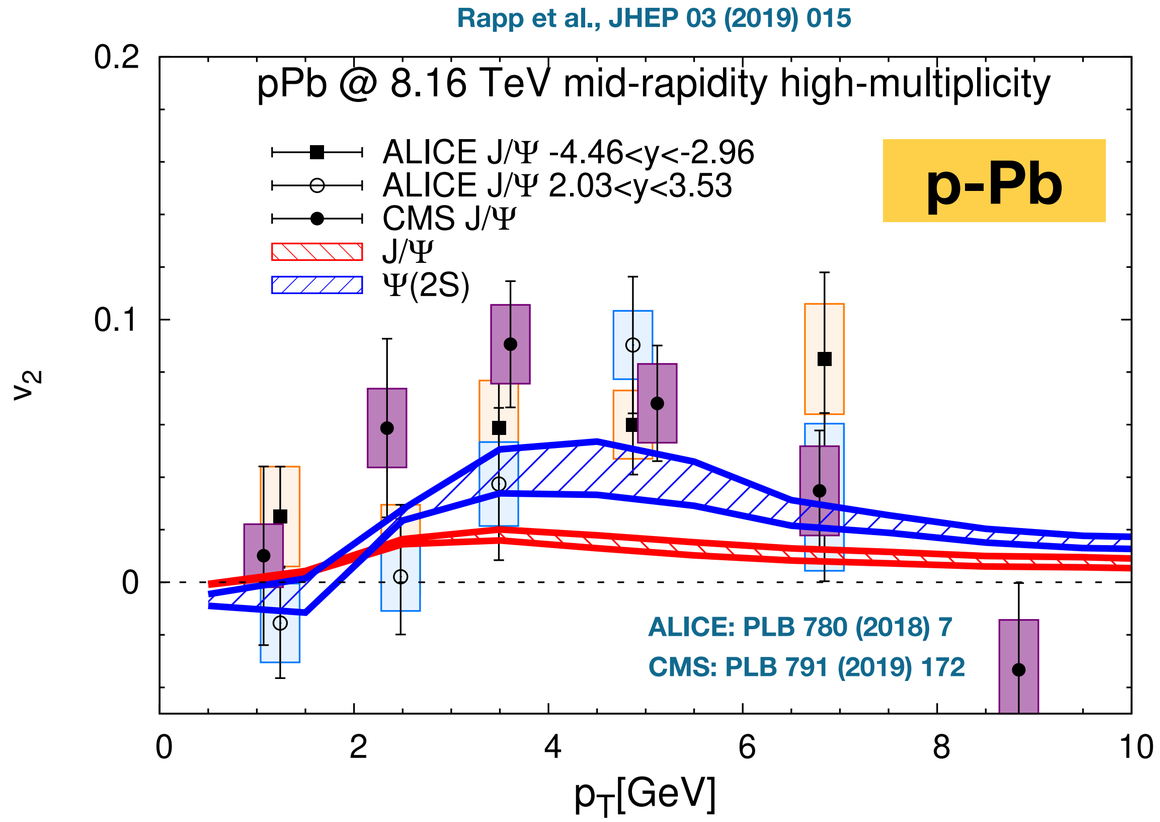
- J/ψ v_2 at low p_T in Pb-Pb collisions from flow of deconfined (thermalised) charm quark
- Sizeable positive J/ψ v_2 at high p_T not described by transport models
  → path-length dependence of energy loss?

J/ψ elliptic flow in p-Pb and Pb-Pb collisions

JHEP 10 (2020) 141



Rapp et al., JHEP 03 (2019) 015

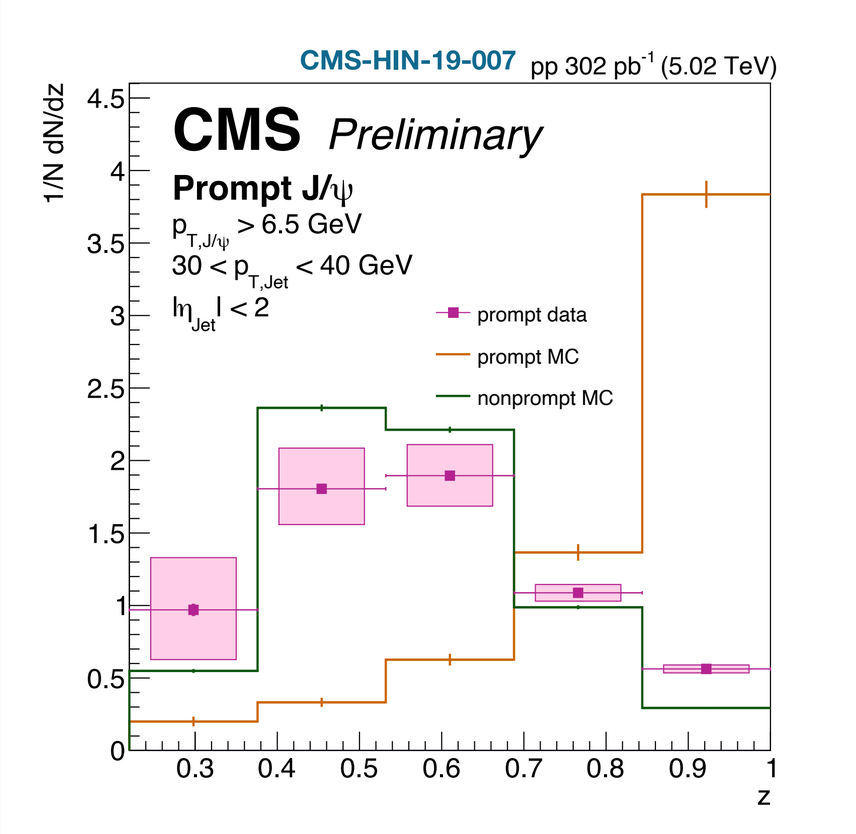


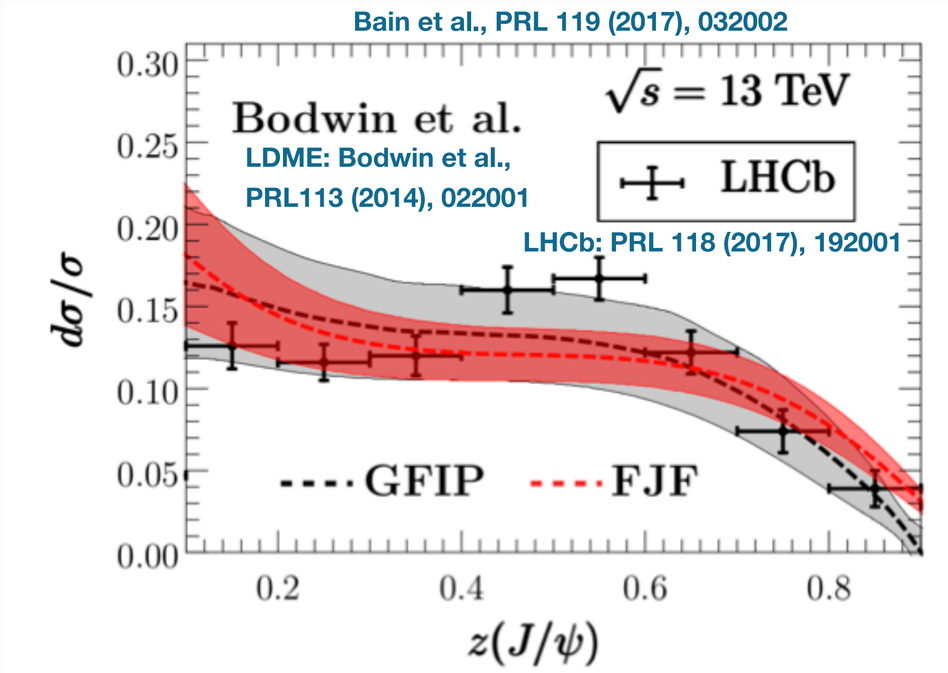
- J/ψ v_2 at low p_T in Pb-Pb collisions from flow of deconfined (thermalised) charm quark
- Non-zero J/ψ v_2 in high multiplicity p-Pb collisions, underpredicted by theory at intermediate p_T

J/ψ in jets in pp collisions

pp

$$z = \frac{p_{\mathrm{T,J/}\psi}}{p_{\mathrm{T,jet}}}$$





- Prompt J/ψ produced with far more jet activity (softer fragmentation) than in PYTHIA, closer to PYTHIA description of non-prompt J/ψ
- Theory including including NRQCD long-distance matrix elements (LDME) and leading order fragmentation functions successfully describes LHCb data