Recent results on quarkonium production

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Disclaimer: only a selection of the results could be shown (time limit)

QNP, 10 July 2024, Barcelona (Spain)

Why heavy flavours?

- Heavy quarks are produced in initial hard scatterings with **large Q^2 → calculable with pQCD.**
- Large masses $m_b > m_c \gg \Lambda_{QCD}$ → short formation time (<QGP lifetime) → **experience whole medium evolution**
- Interactions with the medium don't change the flavour, but can modify the phase-space distribution.
  Thermal production rate in the QGP is expected to be 'small'.
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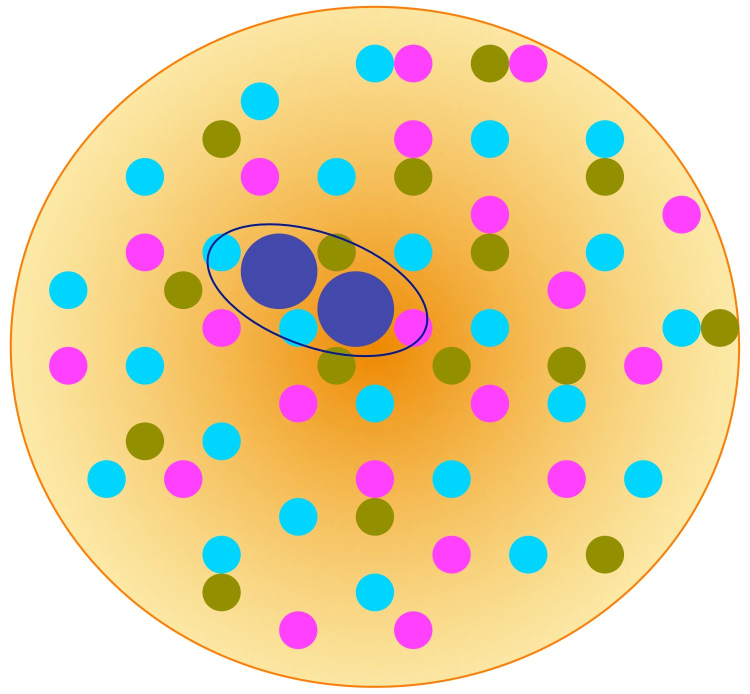
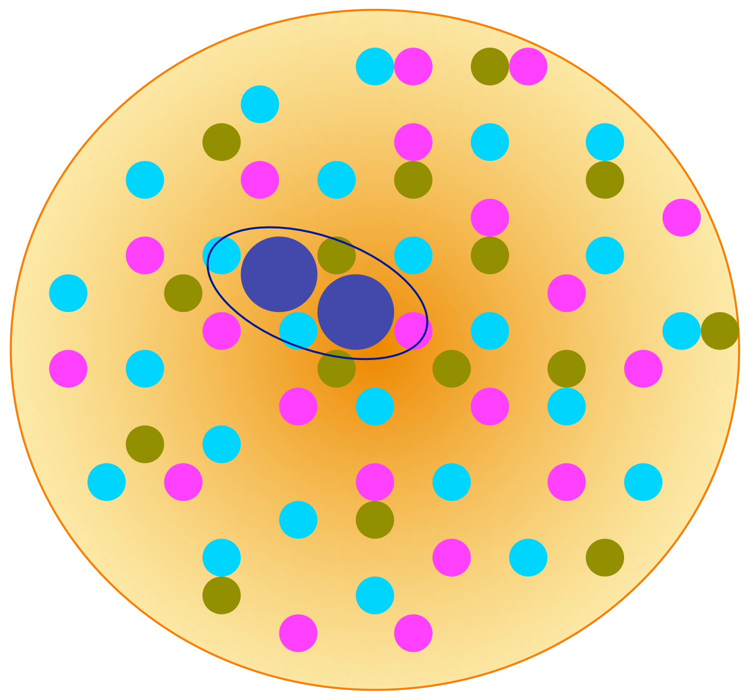
Quarkonia in medium



vacuum like

Quarkonia in medium

- Quarkonia are bound states of heavy quarks



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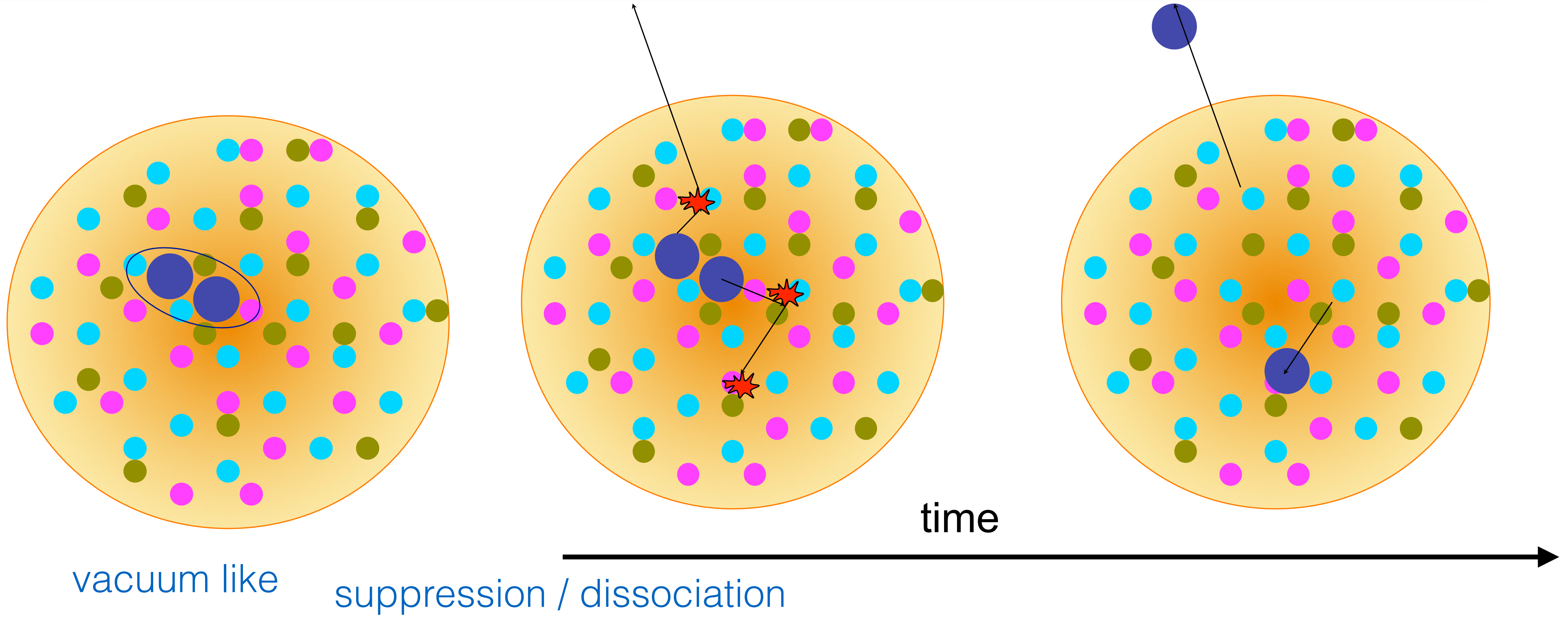

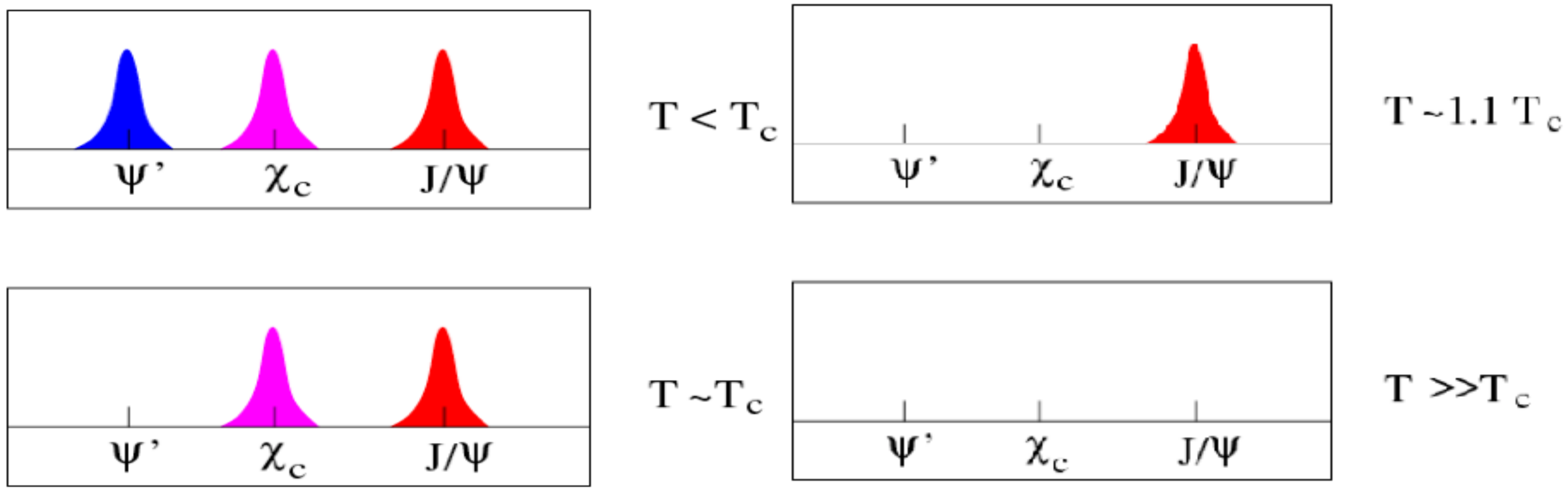

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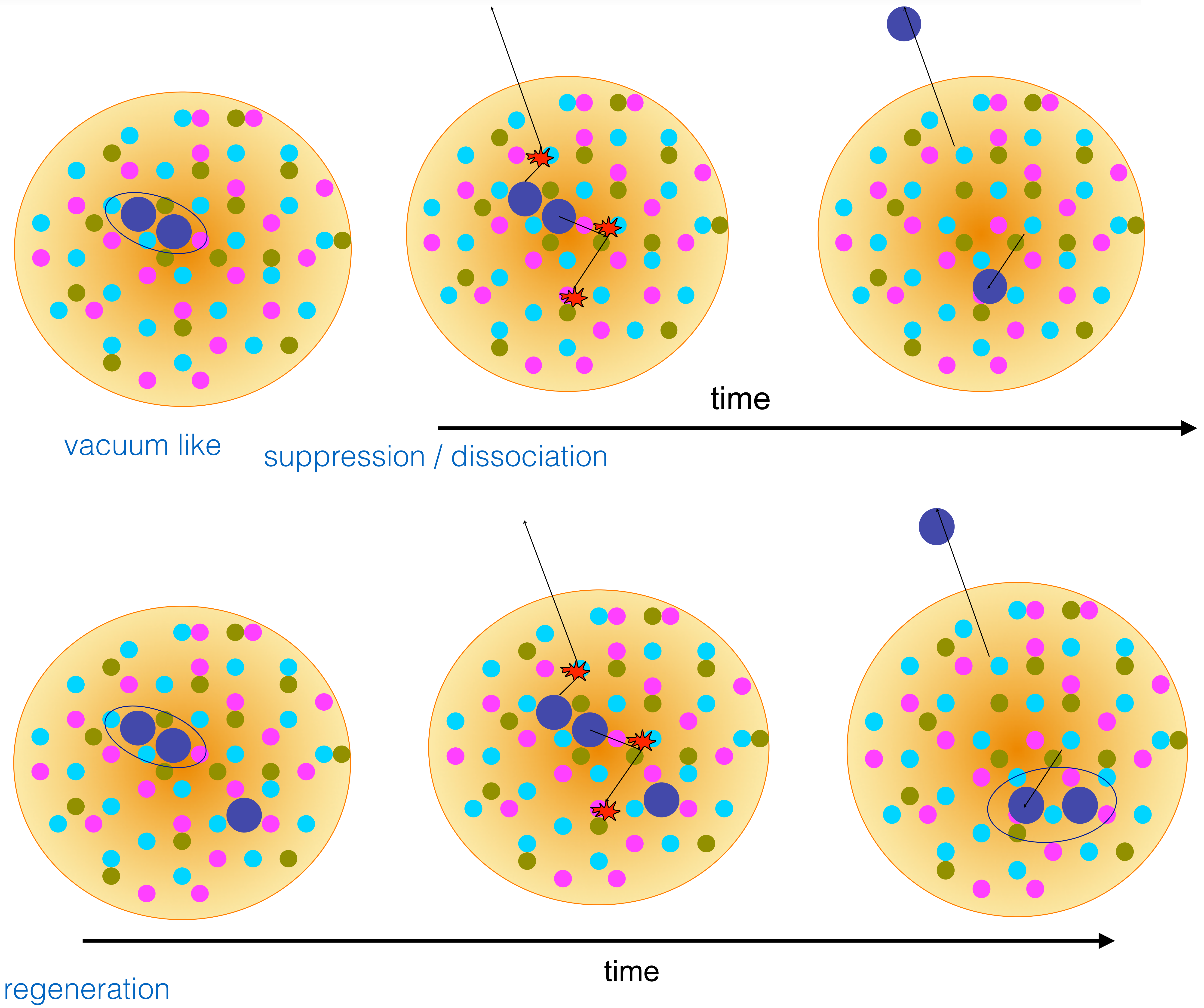

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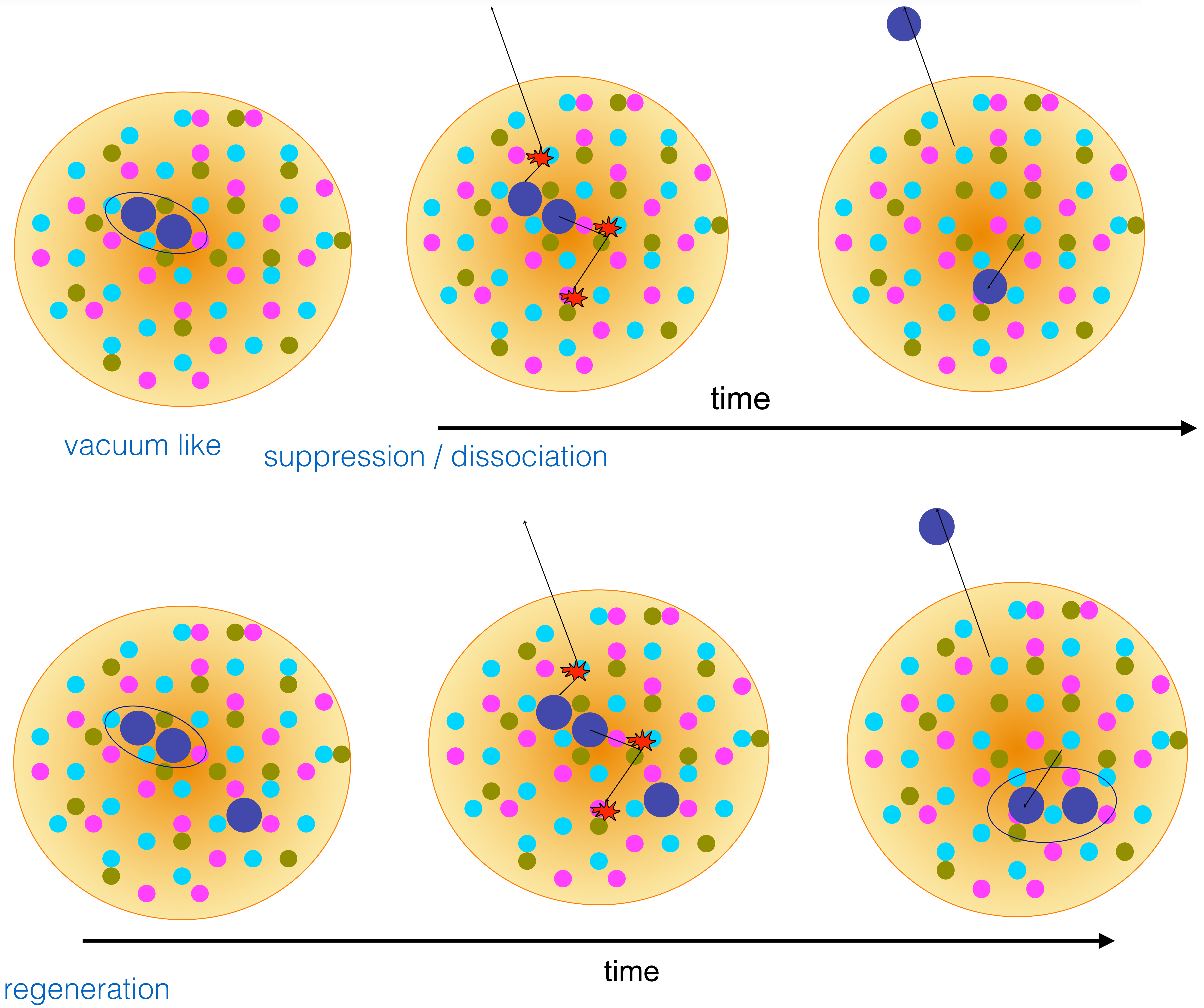

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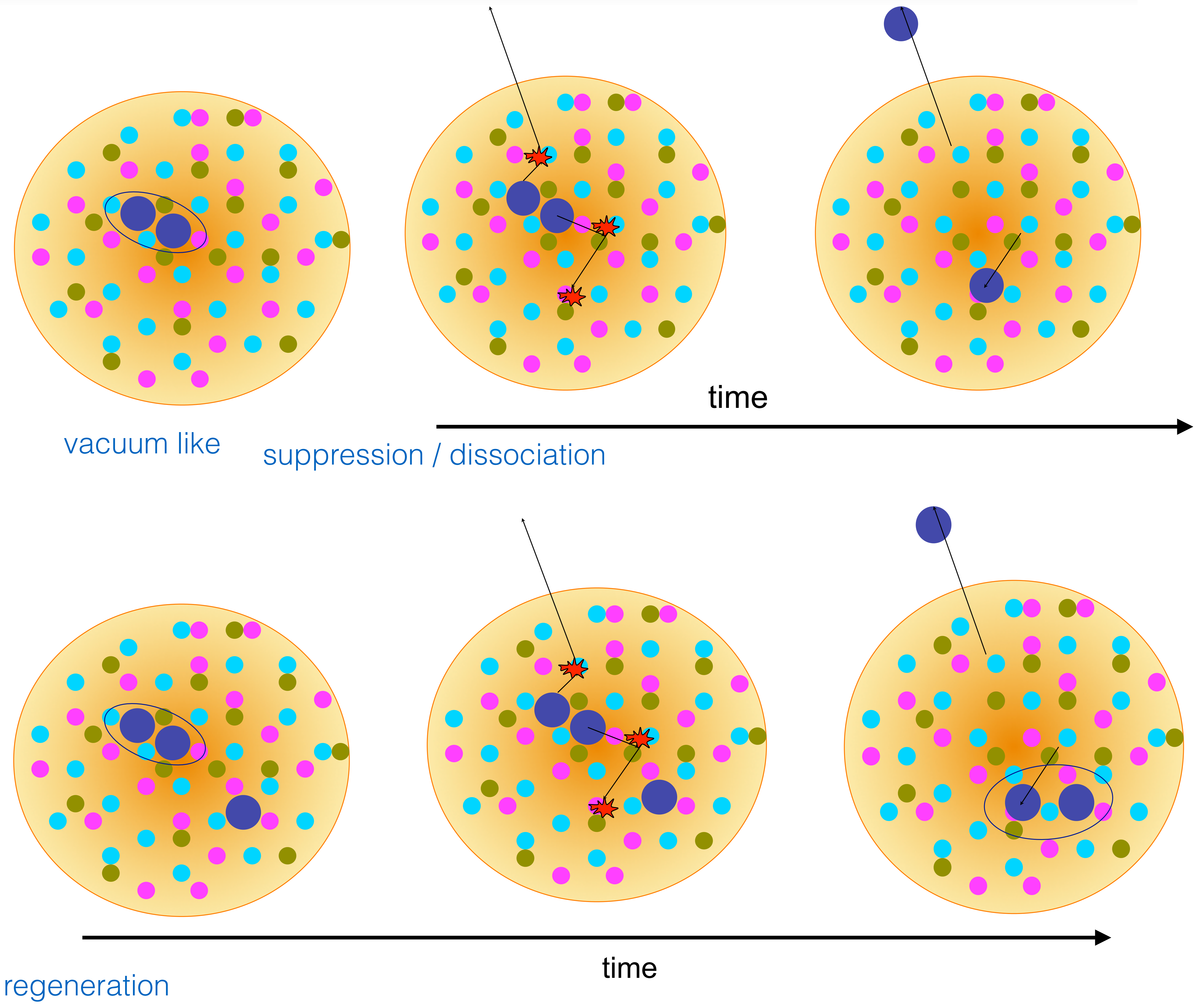
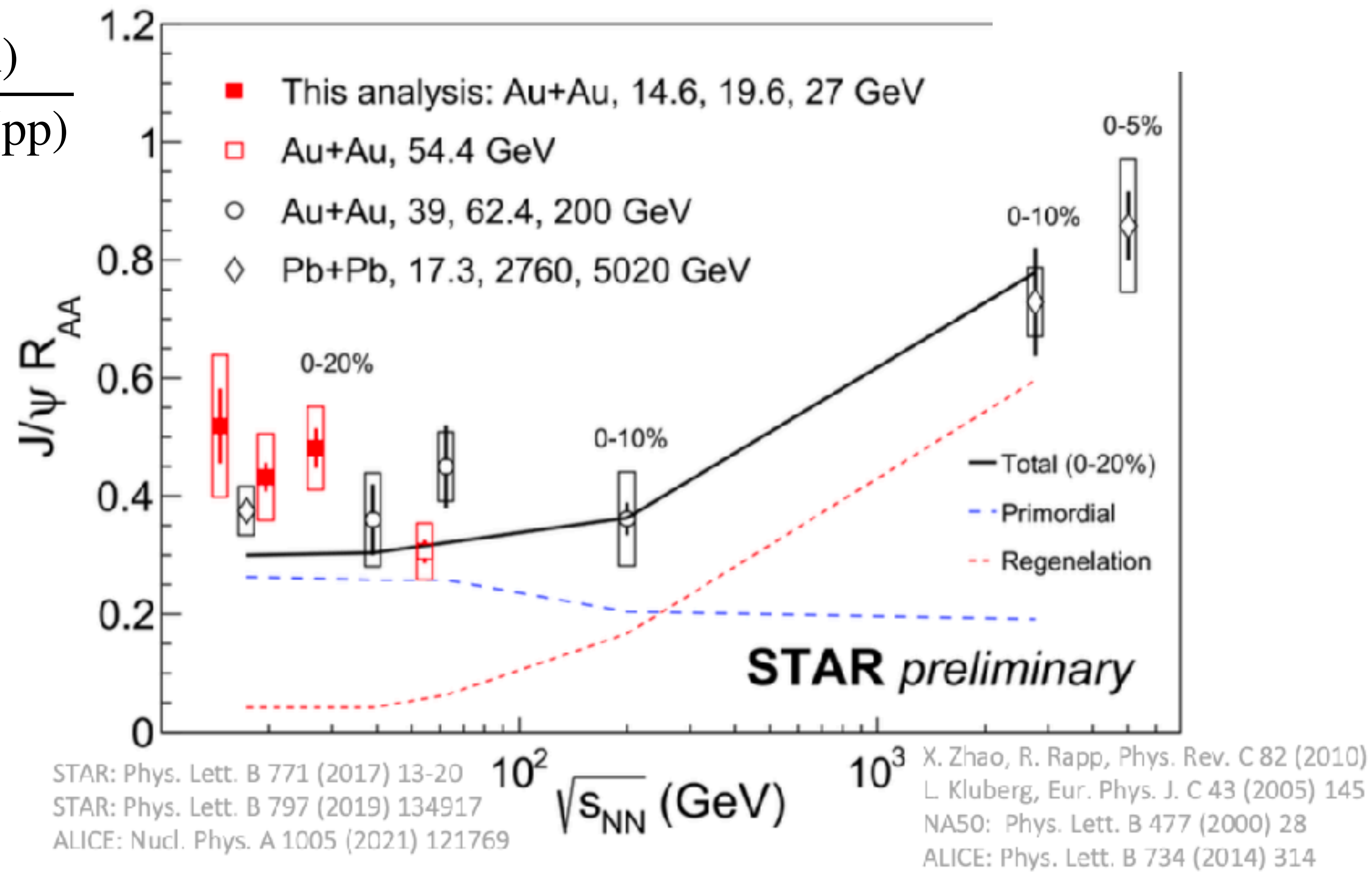
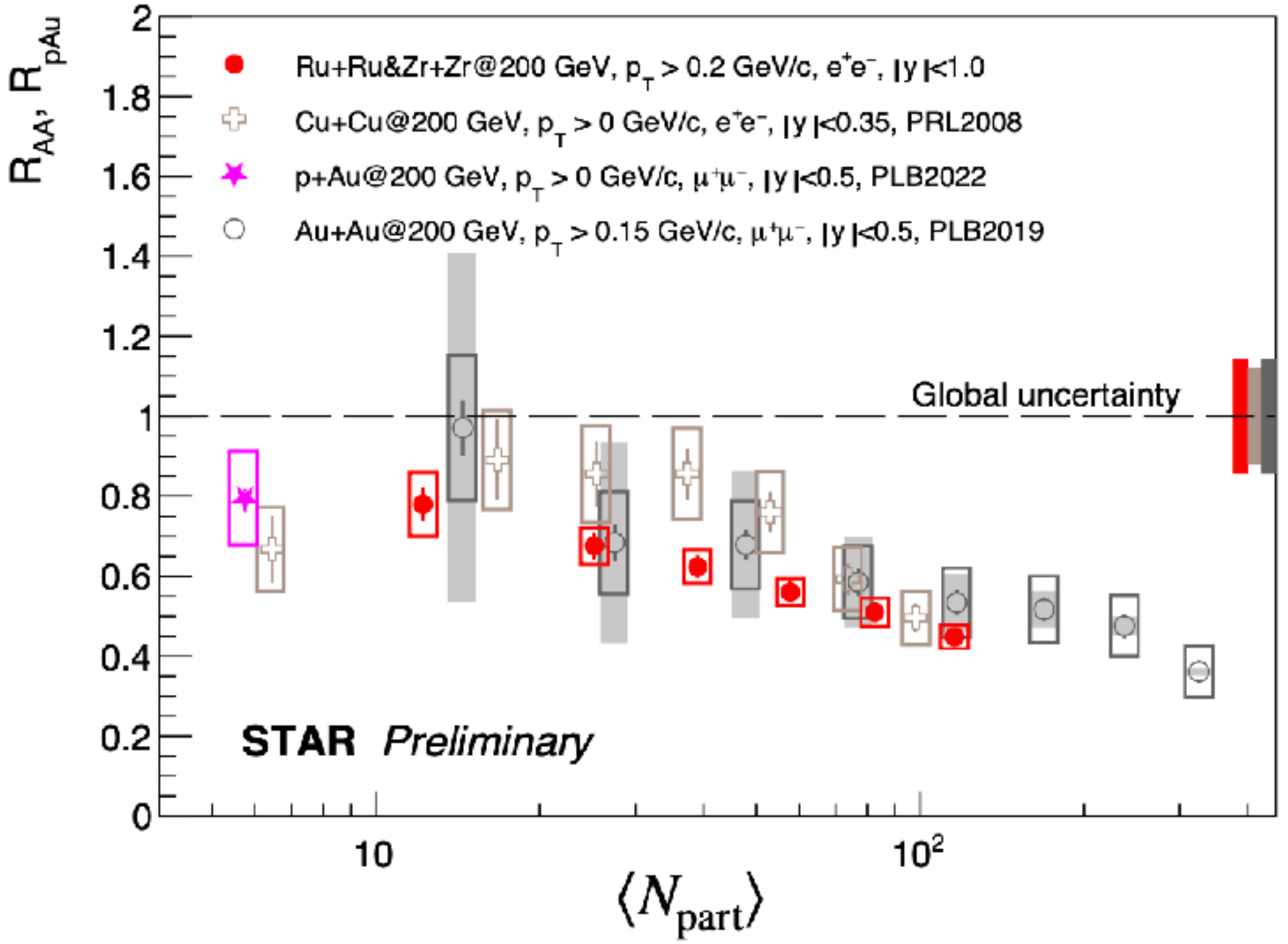
- Modern dynamical picture [Phys.Rept. 858 (2020) 1-117]



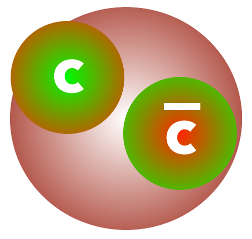
Energy and system size dependence of J/ψ R_{AA}

$$R_{AA} = \frac{\sigma(AA)}{N_{coll} \cdot \sigma(pp)}$$

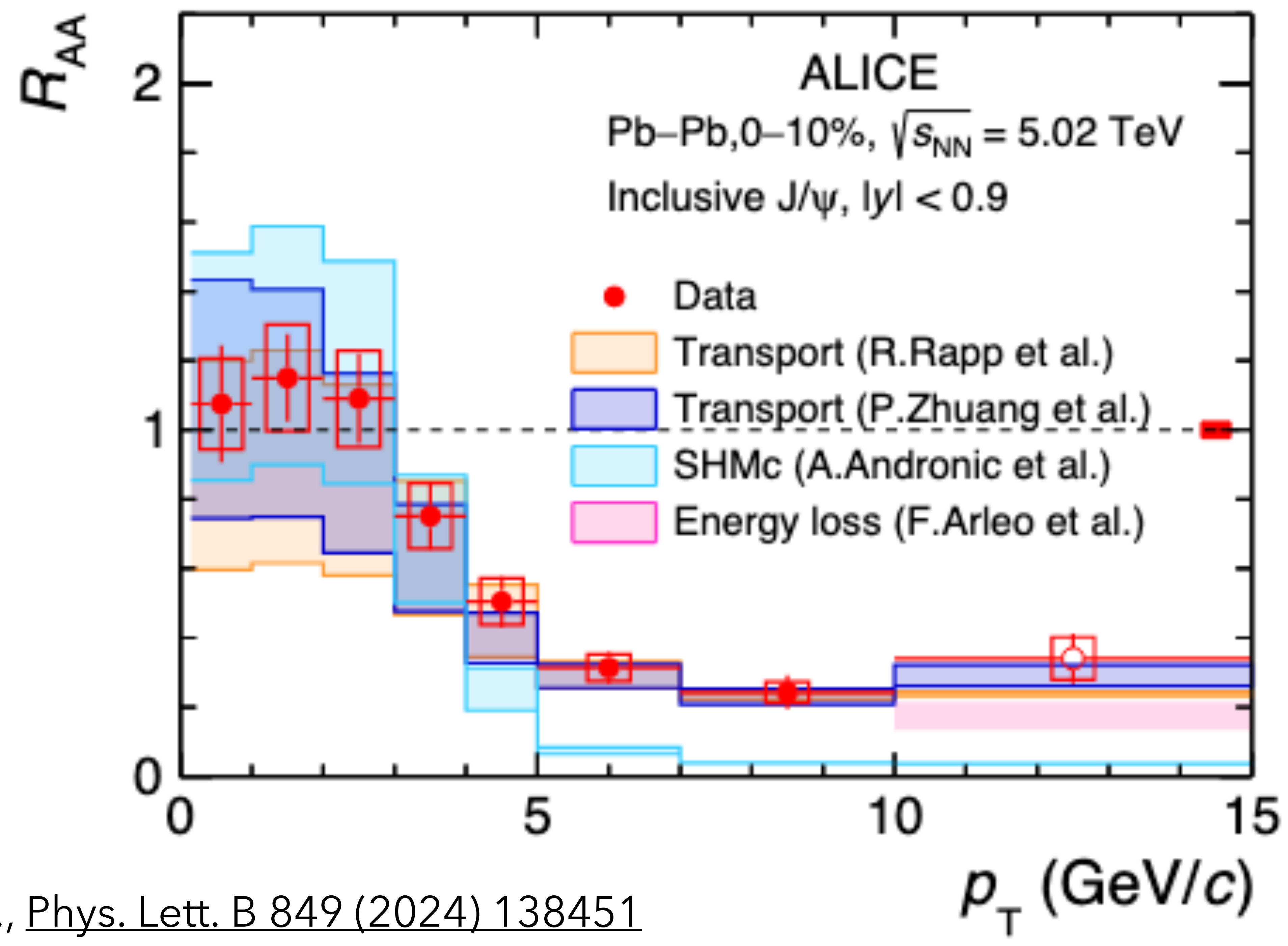




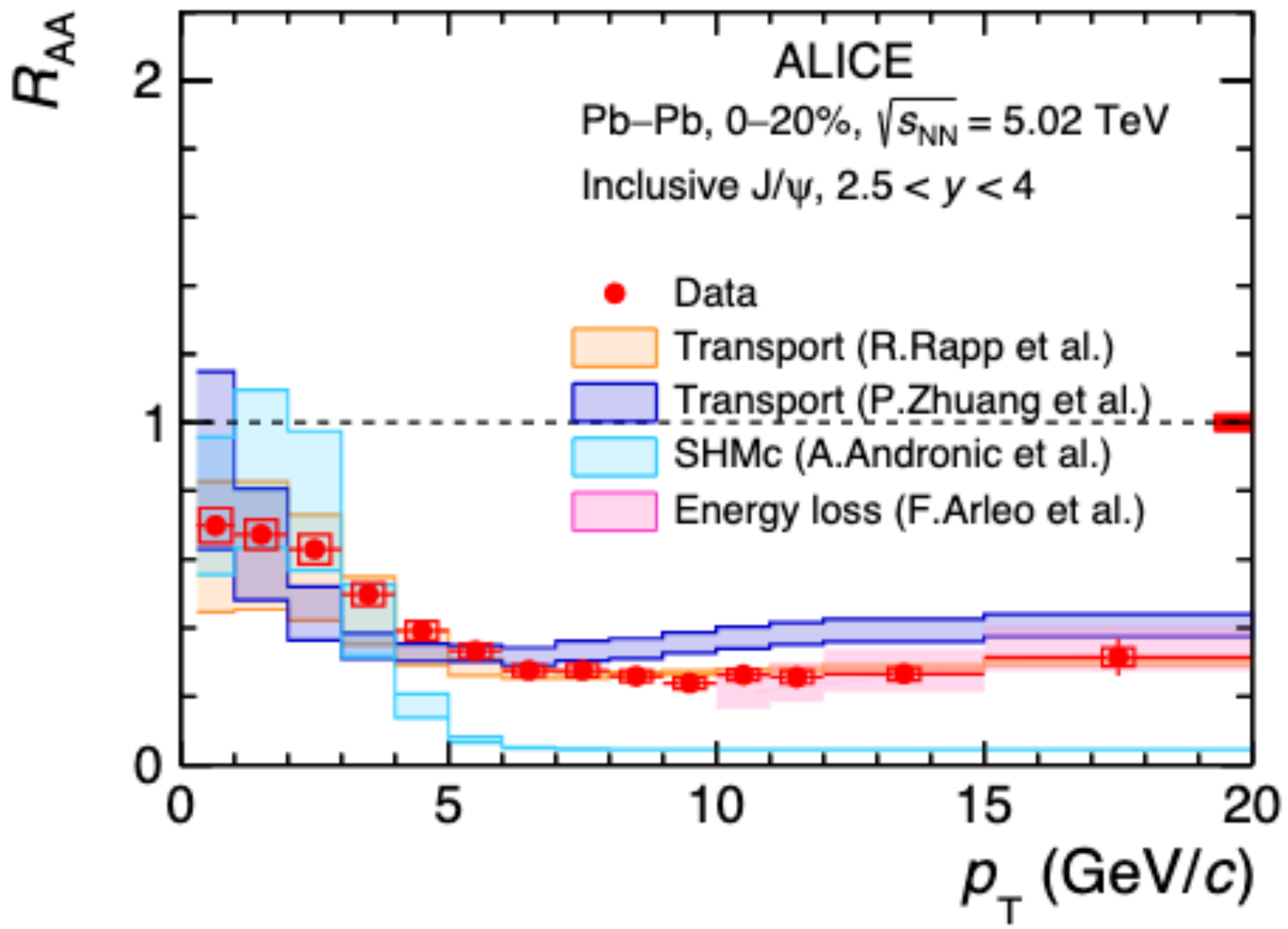
- J//ψ **suppression** (R_{AA} <1) in central heavy-ion collisions observed at RHIC and LHC energies
- Strong rise of the J/ψ R_{AA} from RHIC to LHC energies → evidence for **charmonium regeneration** at the LHC
- STAR: No strong collision system size dependence of the J/ψ R_{AA}
- Suppression at $\sqrt{s_{NN}}$ = 200 GeV in AuAu beyond expectation from CNM



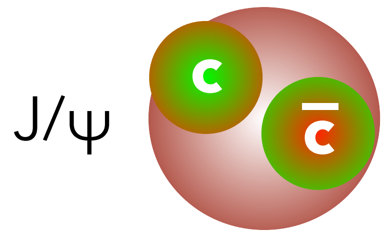
J/ψ R_{AA} at the LHC



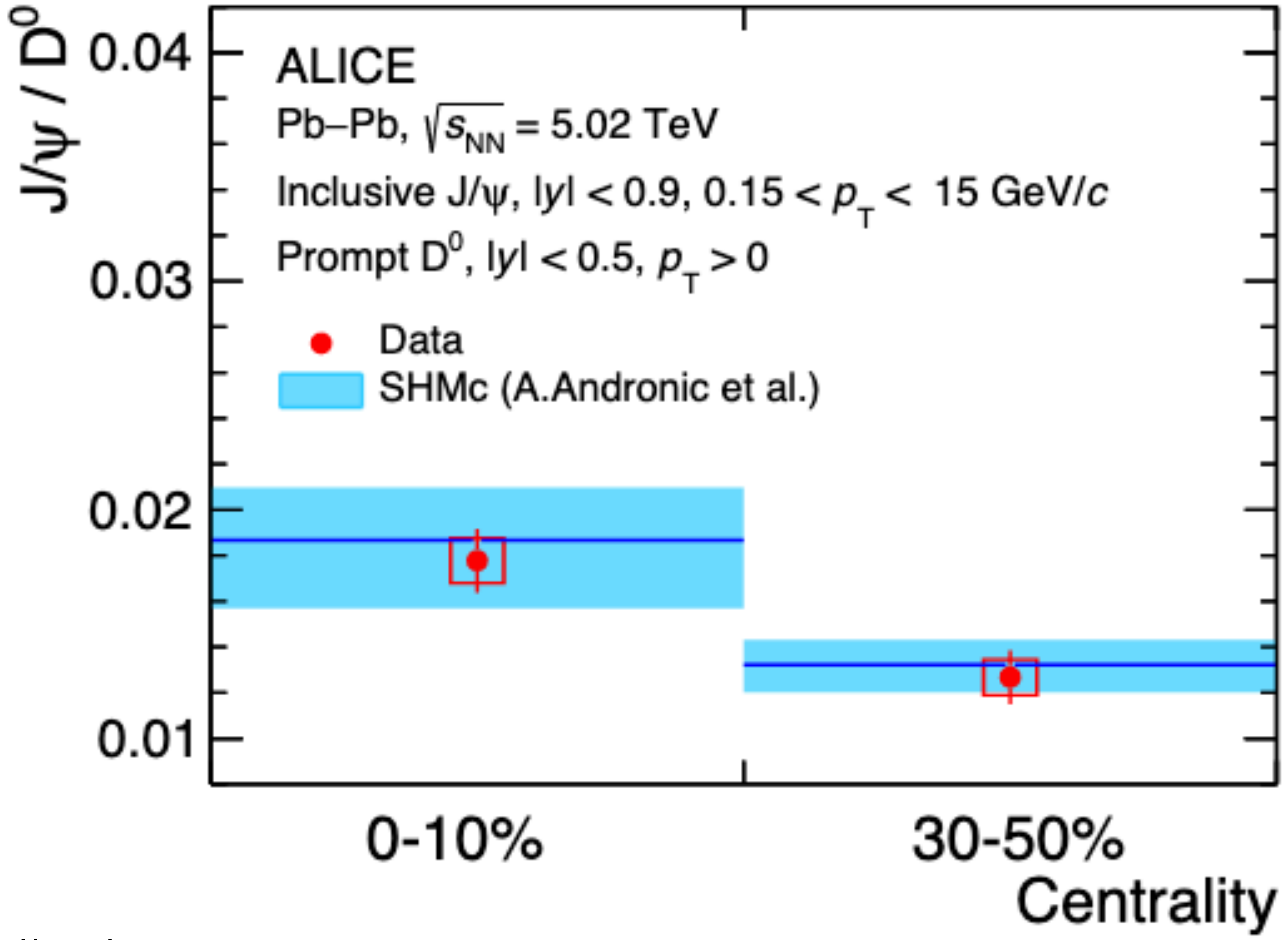
ALICE Coll., Phys. Lett. B 849 (2024) 138451



- J/ψ production in central PbPb collisions described by an **interplay between dissociation, regeneration and energy loss**
- Stronger regeneration at midrapidity w.r.t forward rapidity



J/ψ / D^0 yield ratio



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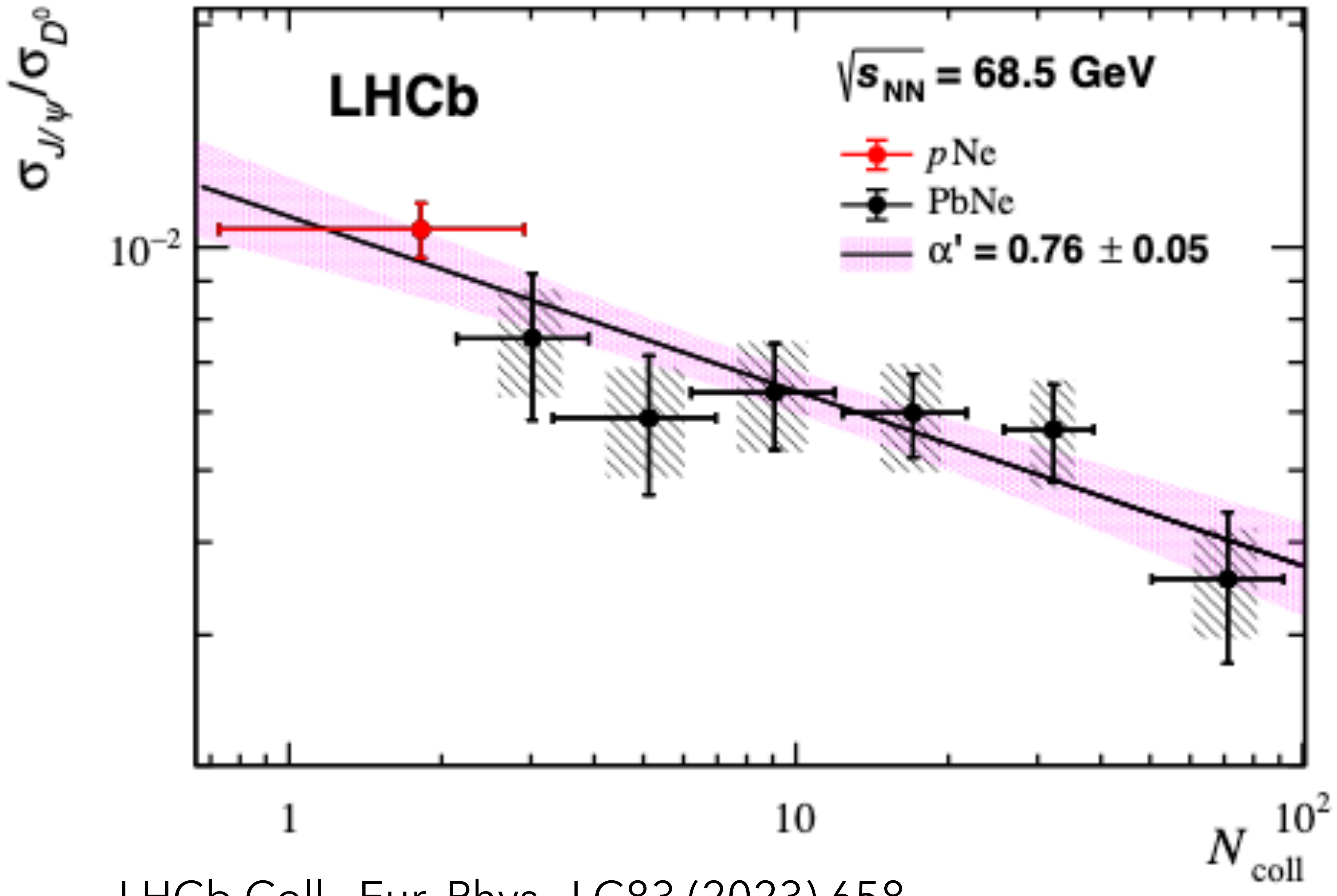
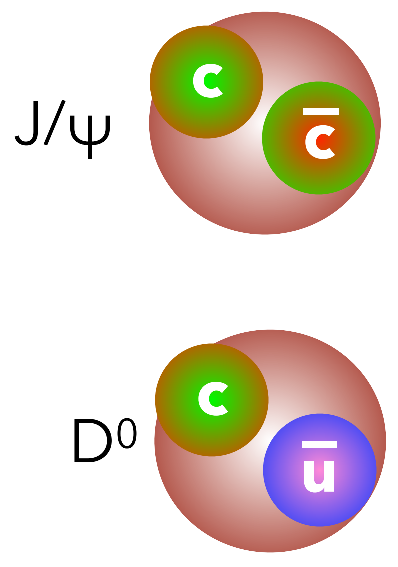
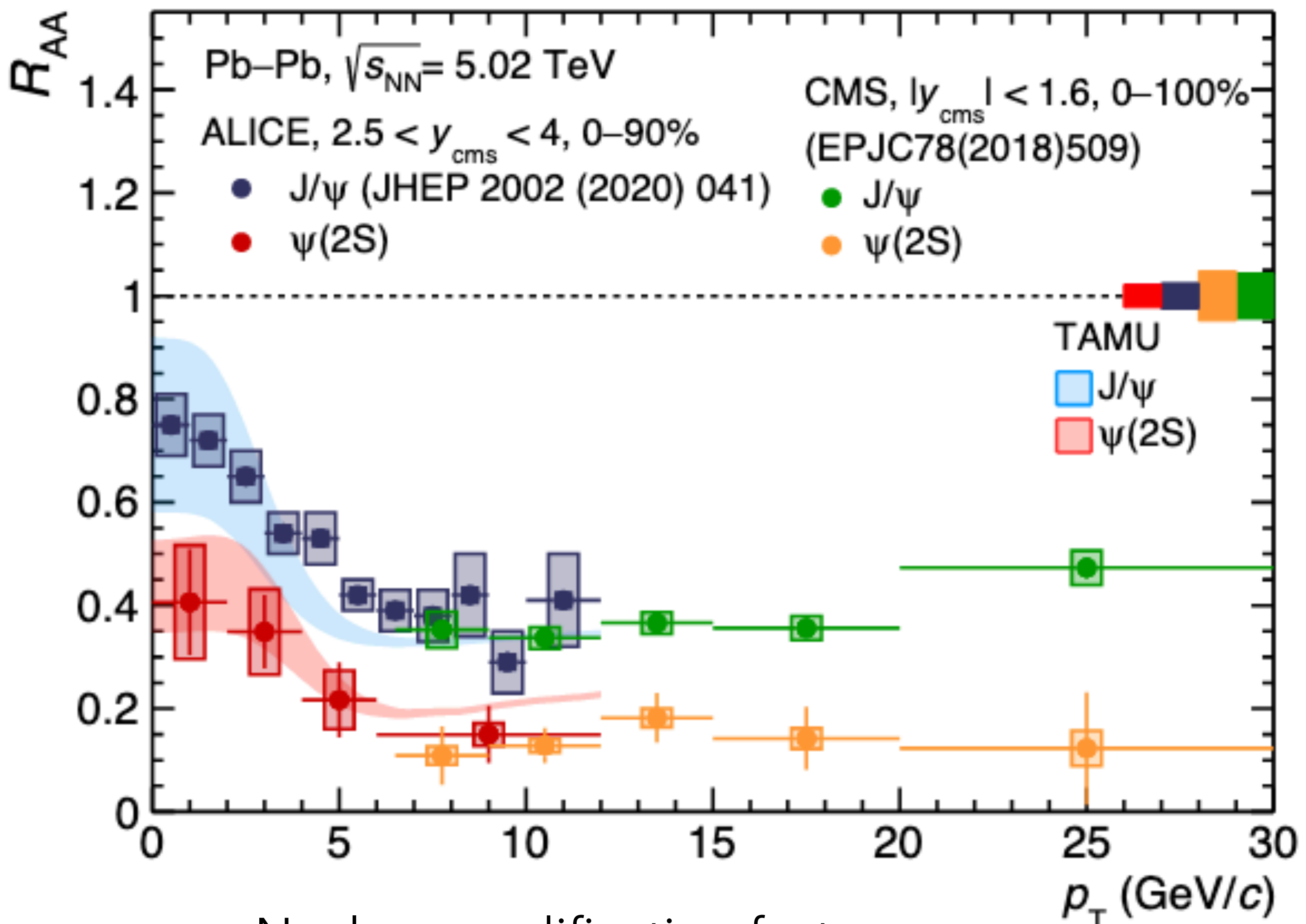


LHCb Coll., Eur. Phys. J C83 (2023) 658

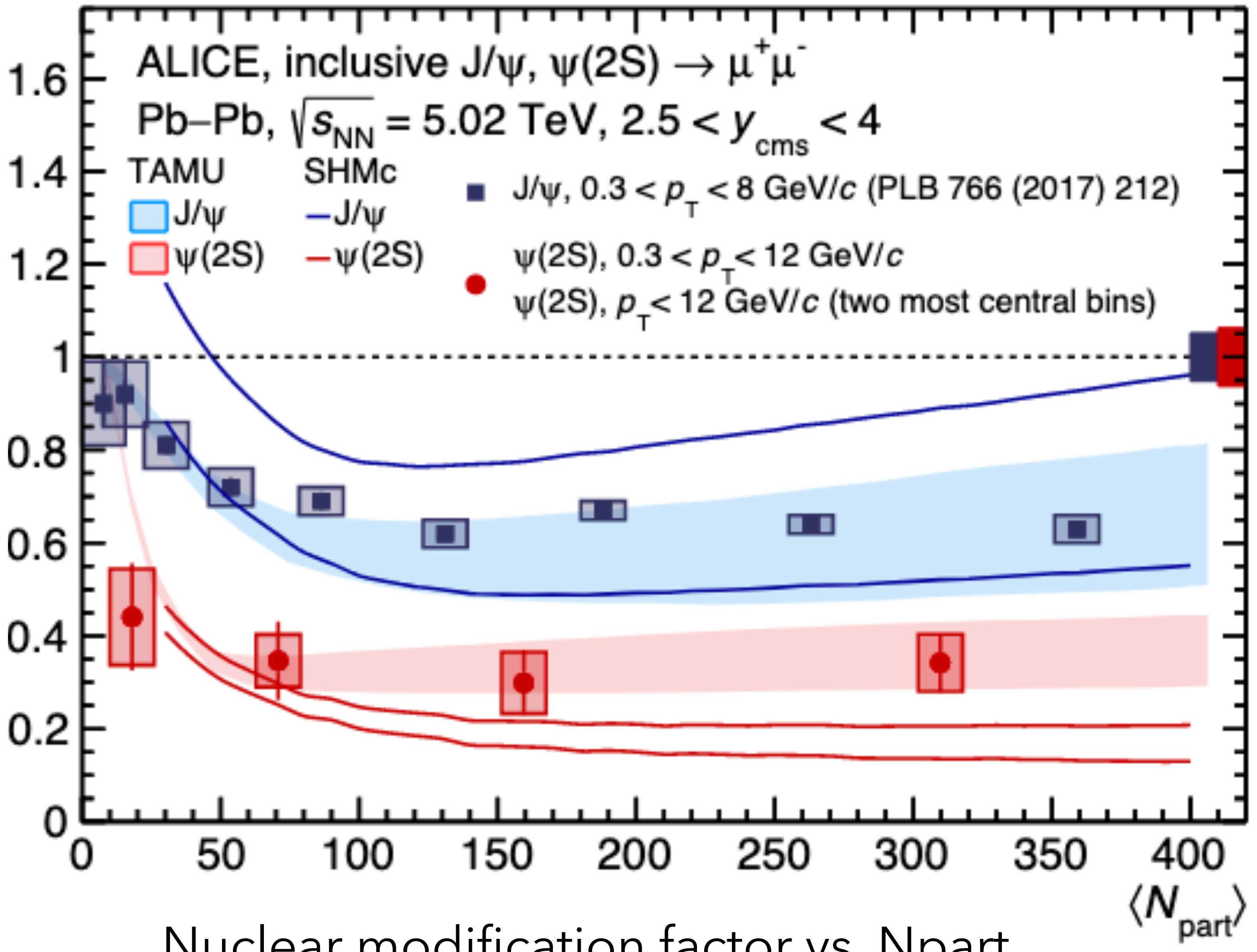


- $J/\psi/D^0$ ratio interesting to further constrain models (similar initial state). Increasing ratio with centrality well described by SHMc at $\sqrt{s_{NN}}$ = 5.02 TeV (ratio related to charm fugacity)
- Fixed Target@LHC: No evidence of anomalous J/ψ suppression in central PbNe collisions at $\sqrt{s_{NN}}$ = 68.5 GeV

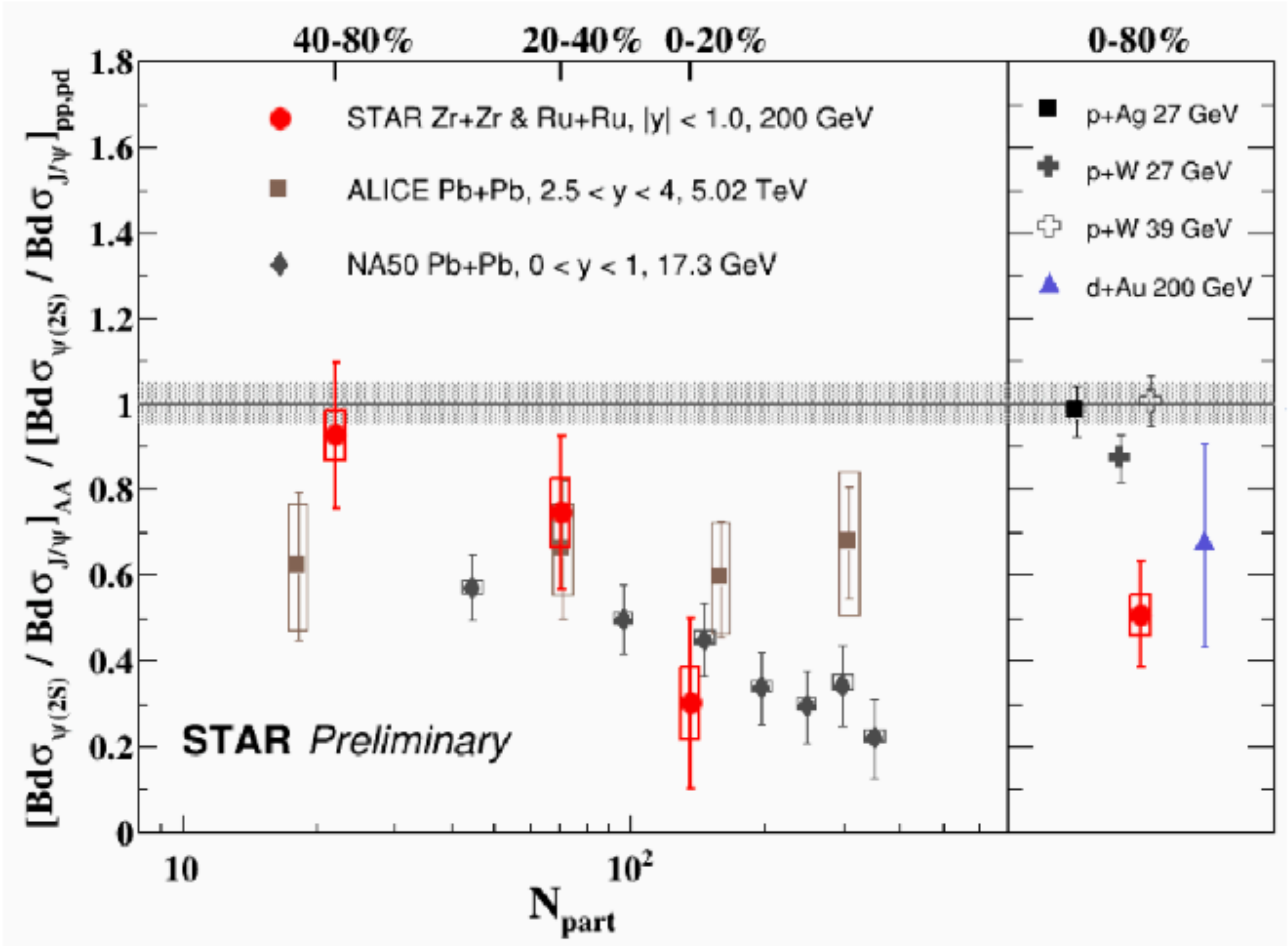
ψ(2S) and ψ(2S)/J/ψ ratio



Nuclear modification factor vs. p_T

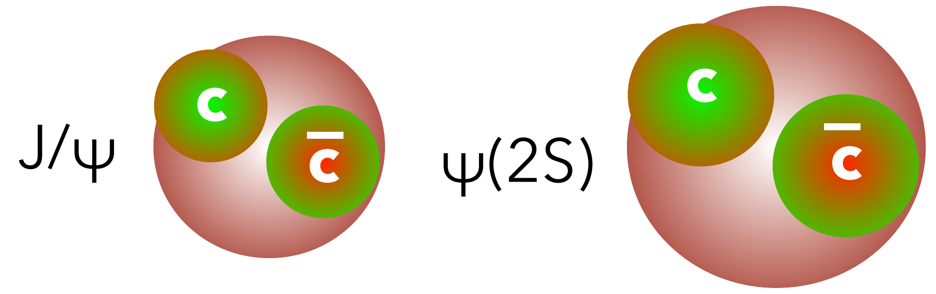


Nuclear modification factor vs. Npart



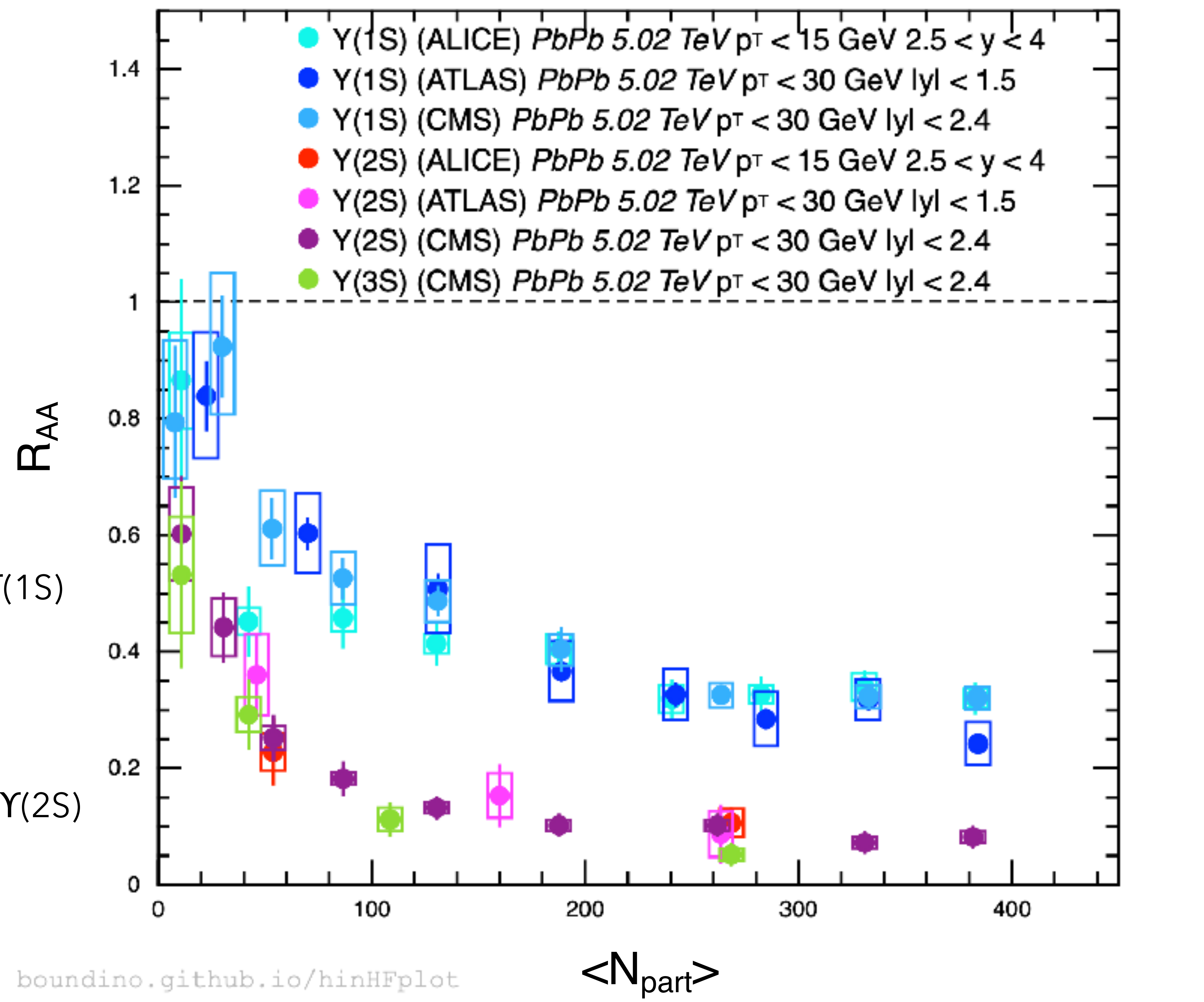
ψ(2S) /J/ψ double ratio AA/pp vs Npart

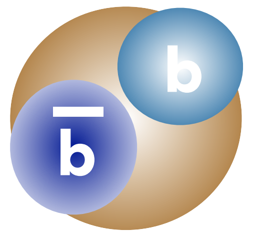
- Golden probe at low p_T to disentangle among regeneration models
- **Larger suppression of ψ(2S)** w.r.t. J/ψ in a wide p_T interval
- Transport model reproduces better the ψ(2S) R_{AA} in central PbPb events
- Suggesting **sequential suppression of charmonia**



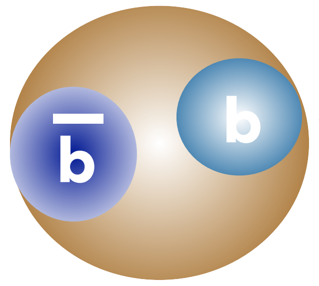
ALICE Coll., PRL 132 (2024) 042301; ALICE Coll., JHEP 2002 (2020) 041; CMS Coll., EPJC 78 (2018) 509; NA50 Coll., EPJC 49 (2007) 559

Υ(nS) R_{AA}





Υ(1S)



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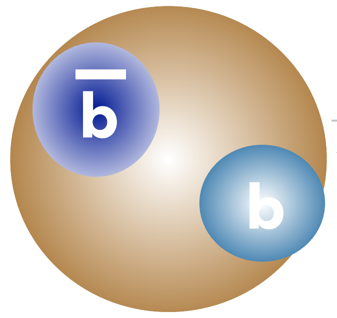
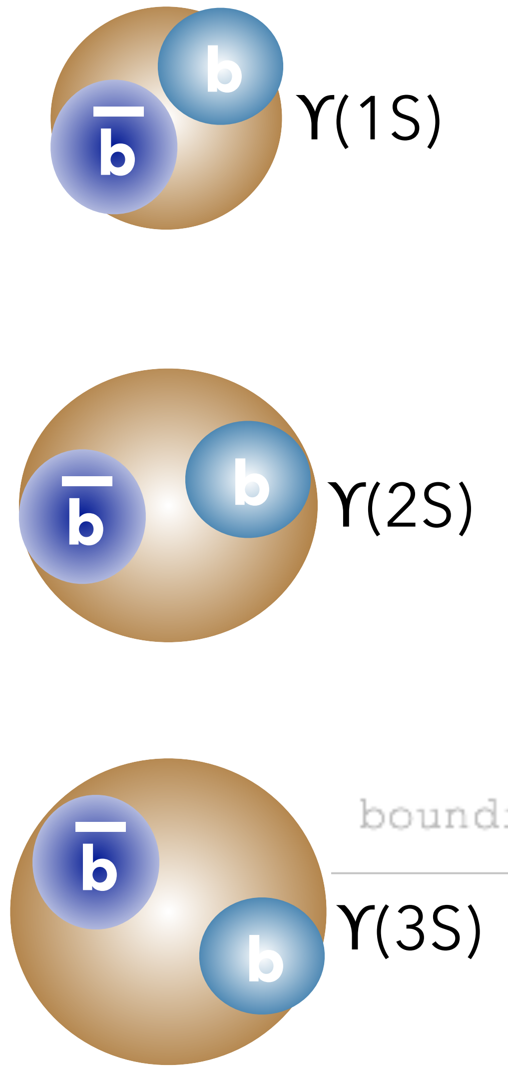
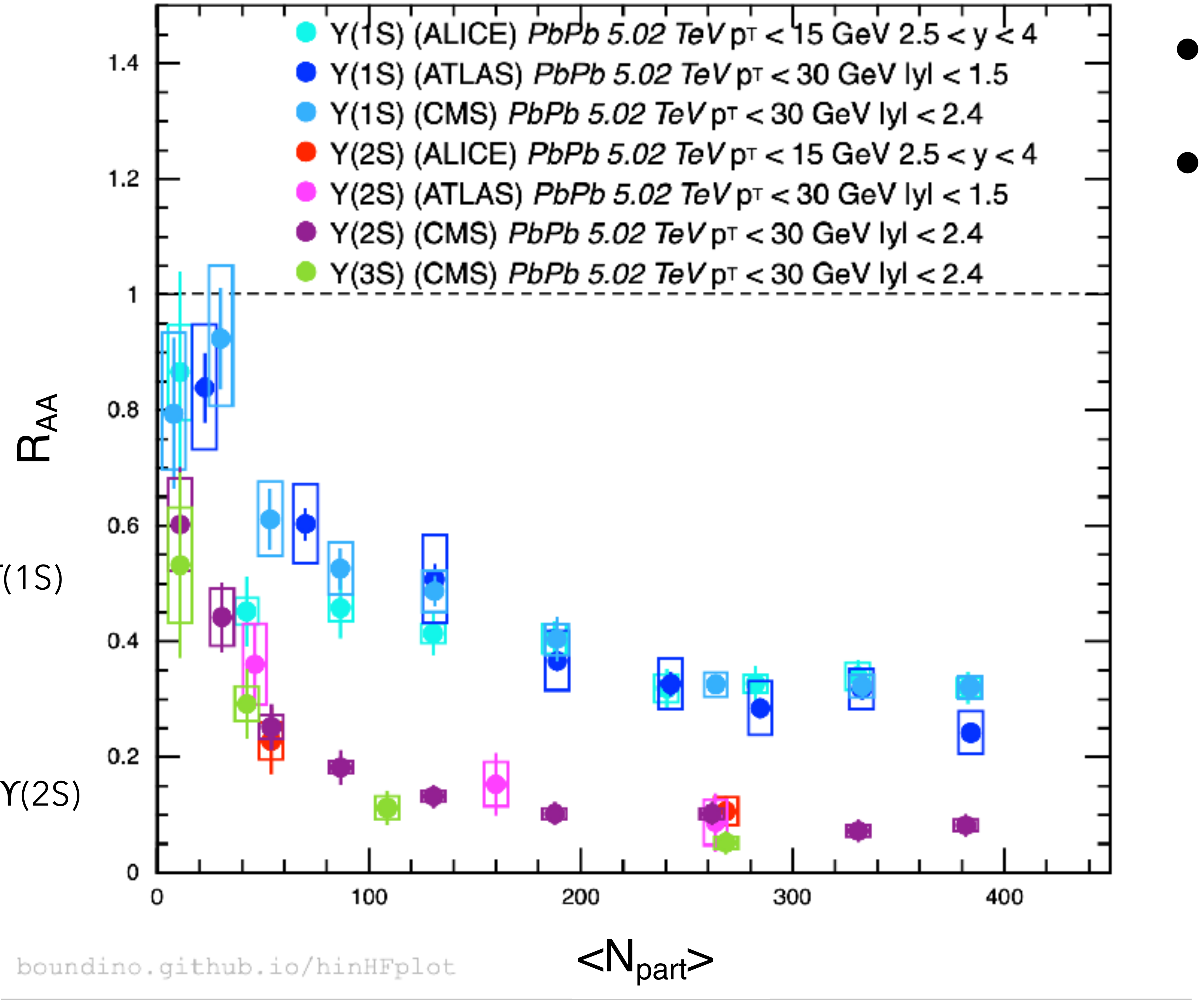


Υ(3S)

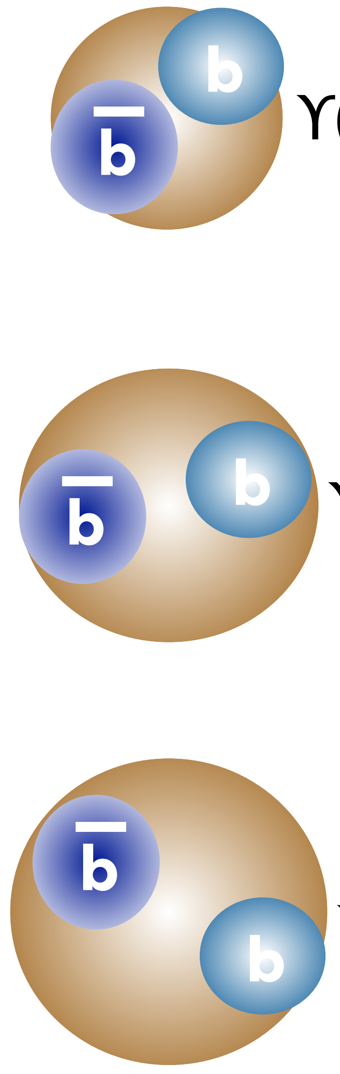
Υ(nS) R_{AA}





- Observation of Υ(3S) by CMS in PbPb collisions
- **Sequential suppression of Υ(nS)** states at the LHC energies
  R_{AA} (Υ(3S)) ≲ R_{AA} (Υ(2S)) < R_{AA} (Υ(1S))

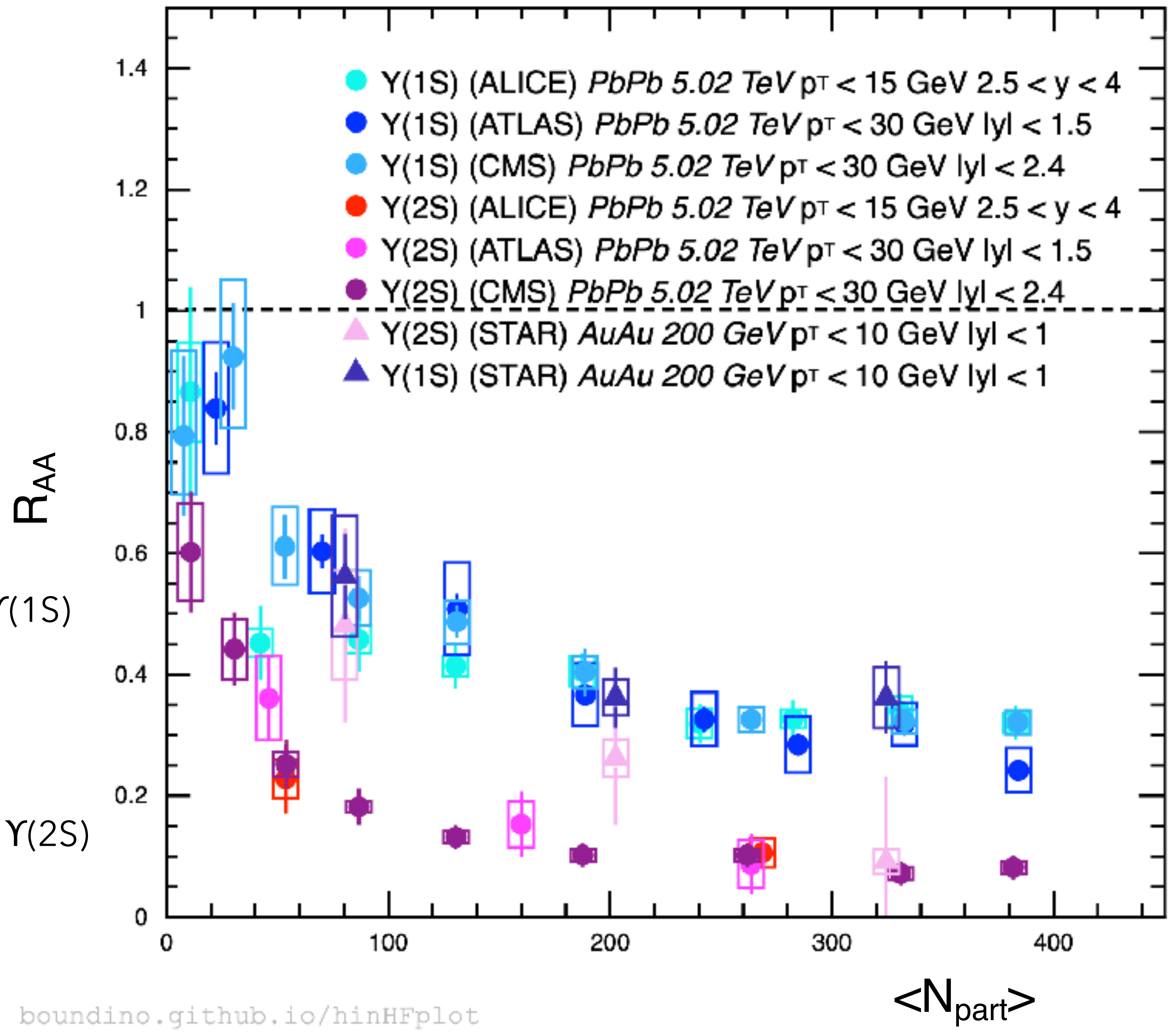
Υ(nS) R_{AA}



Υ(1S)

Υ(2S)

Υ(3S)



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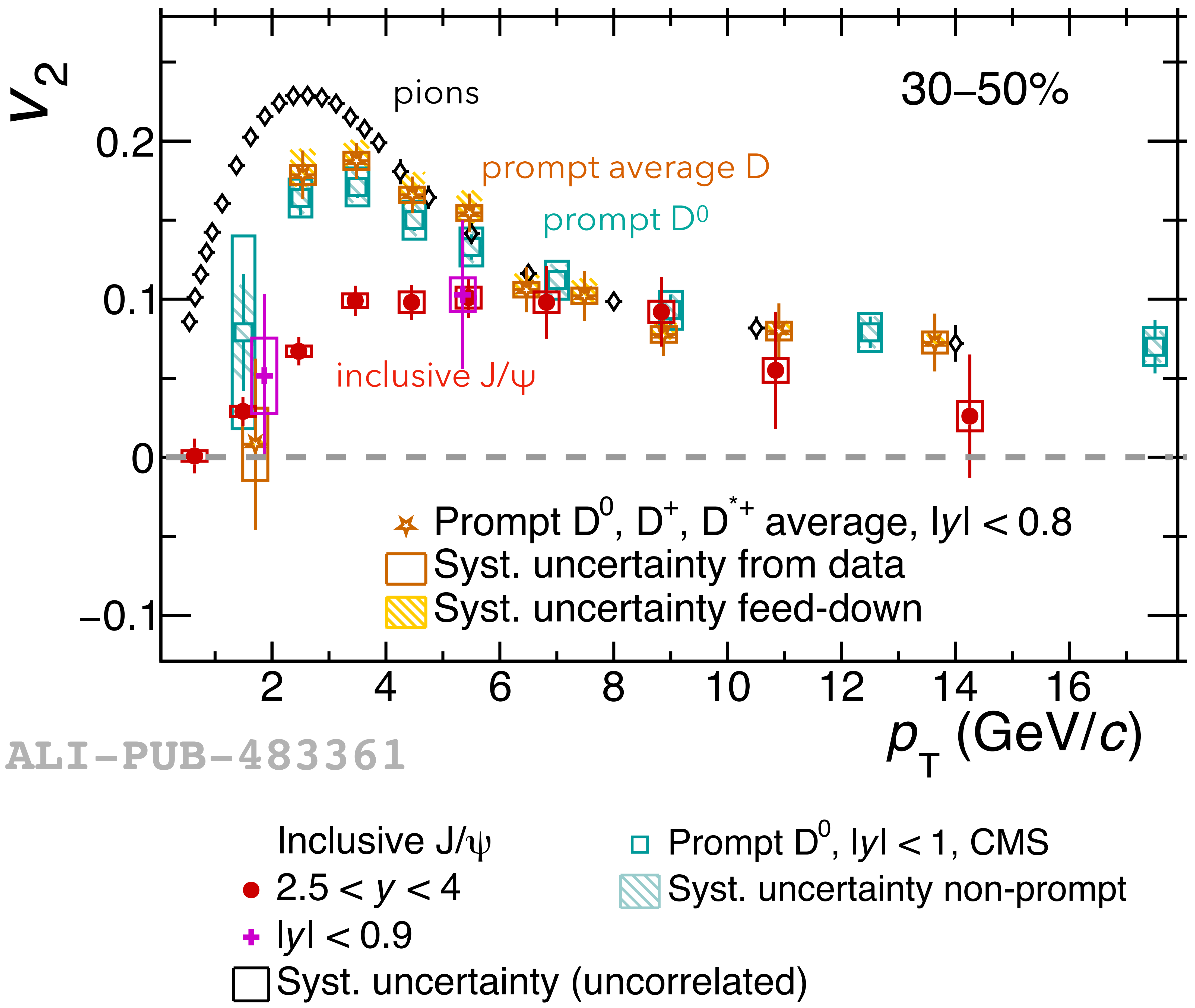
- Similar Υ(1S) suppression at RHIC(▲) and at the LHC(●): favouring a negligible melting of direct Υ(1S) production. Suppression of excited states only + CNM effects.
- Hint that Υ(2S) might be less suppressed at RHIC in peripheral events than at the LHC?

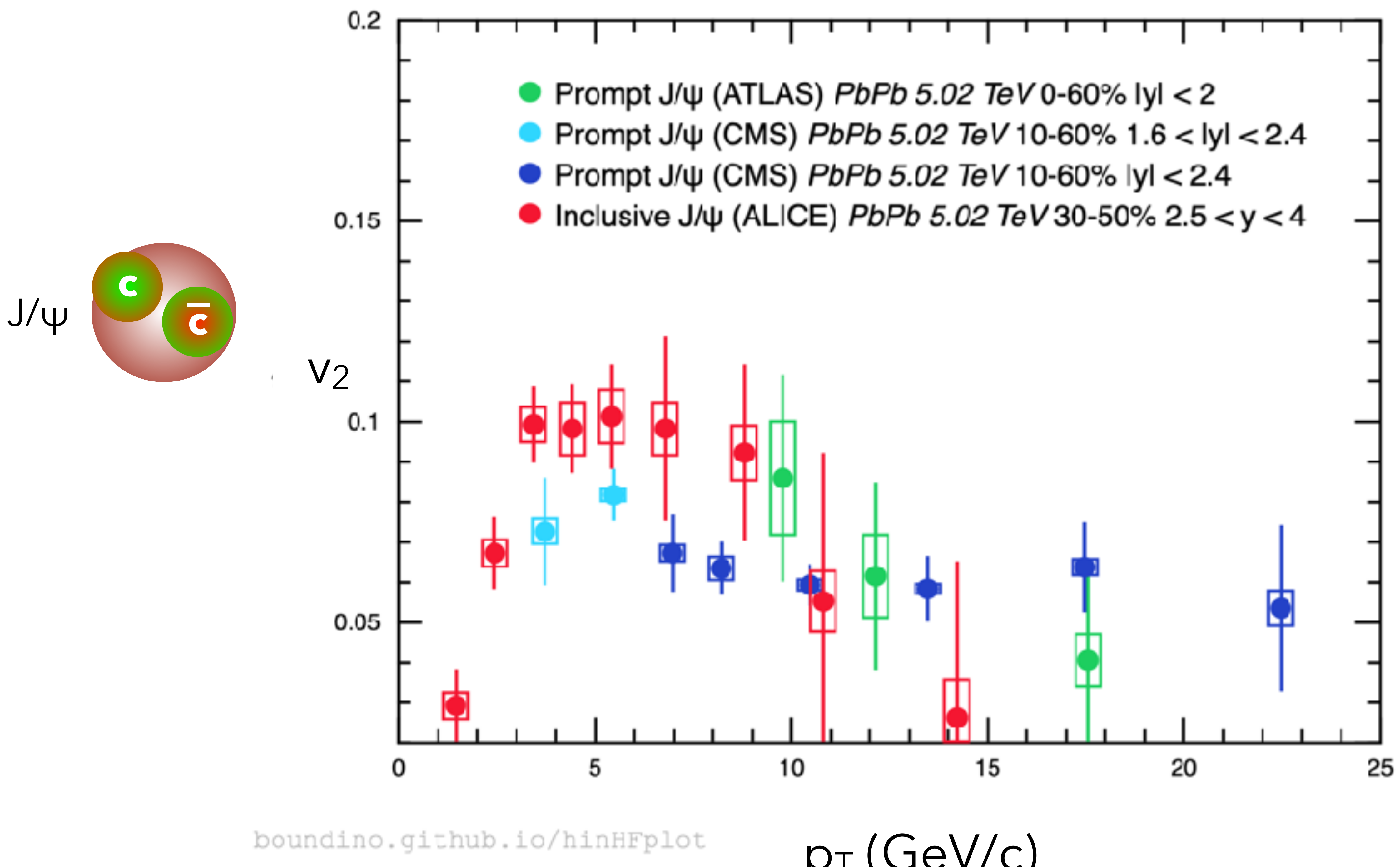
Picturing the PbPb v_2 results in a nutshell

- **Positive v_2** of heavy flavours in mid-central PbPb collisions
  → Evidence of **strong collective effects**
- Exhibit a **mass hierarchy** at low and intermediate p_T (≲8 GeV/c)
  v_2 (J/ψ) < v_2 (D) < v_2 (π)
  similar curve at high p_T.
  - Low/intermediate p_T :
    later thermalization of charm quarks (vs. light quarks) and/or
    recombination of charm quarks
  - High p_T :
    path-length dependent energy loss

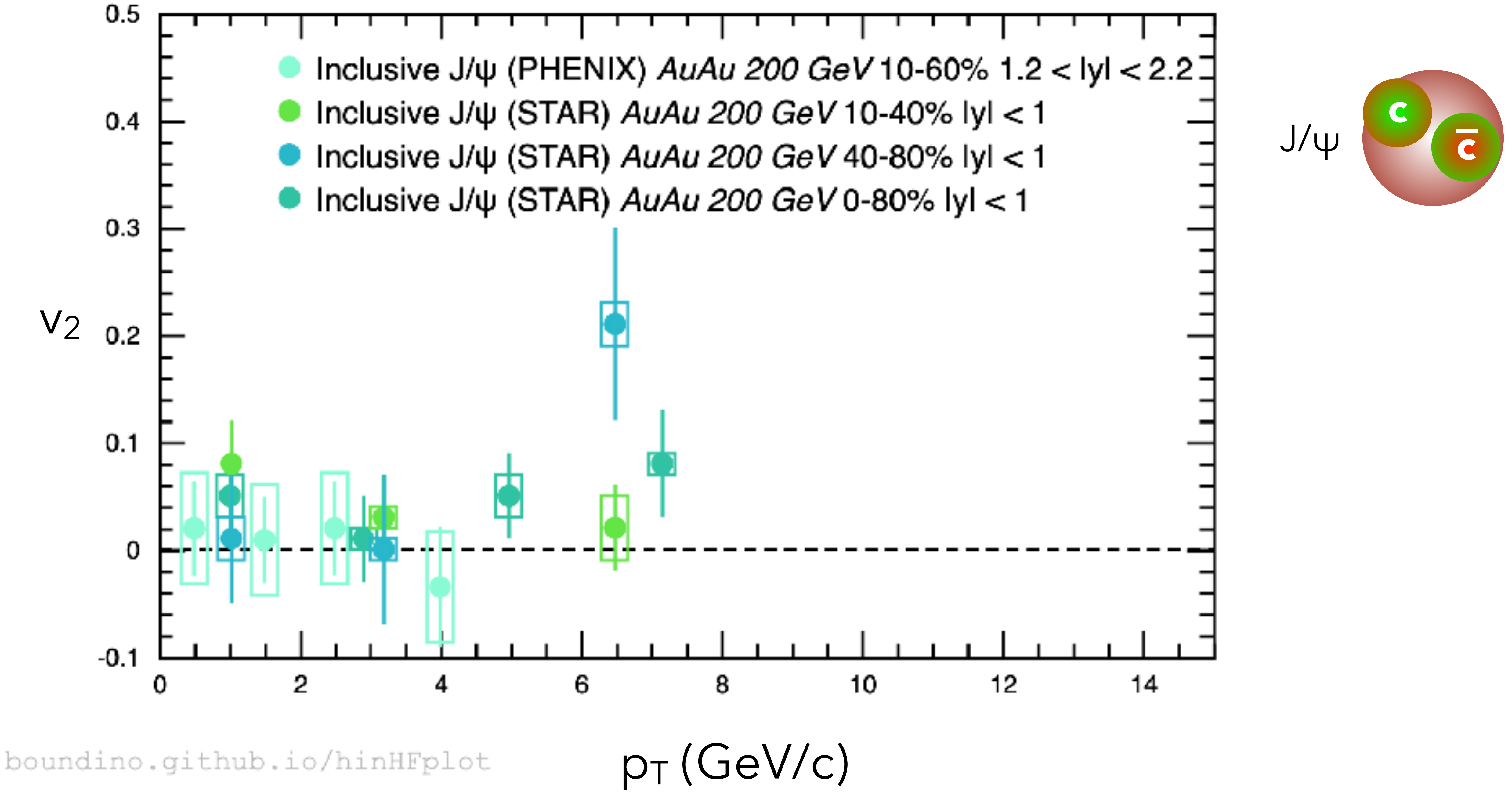


ALICE, JHEP 09 (2018) 006
CMS, Phys. Rev. Lett. 120, 202301 (2018)
ALICE, Phys. Lett. B 813 (2021) 136054
ALICE, JHEP 10 (2020) 141

Quarkonium collectivity in heavy-ion collisions



v_2 of J/ψ at the LHC



v_2 of J/ψ at RHIC

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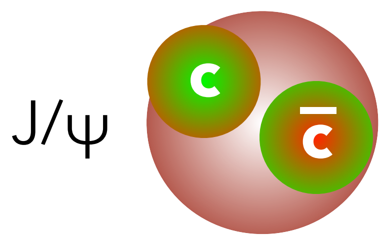

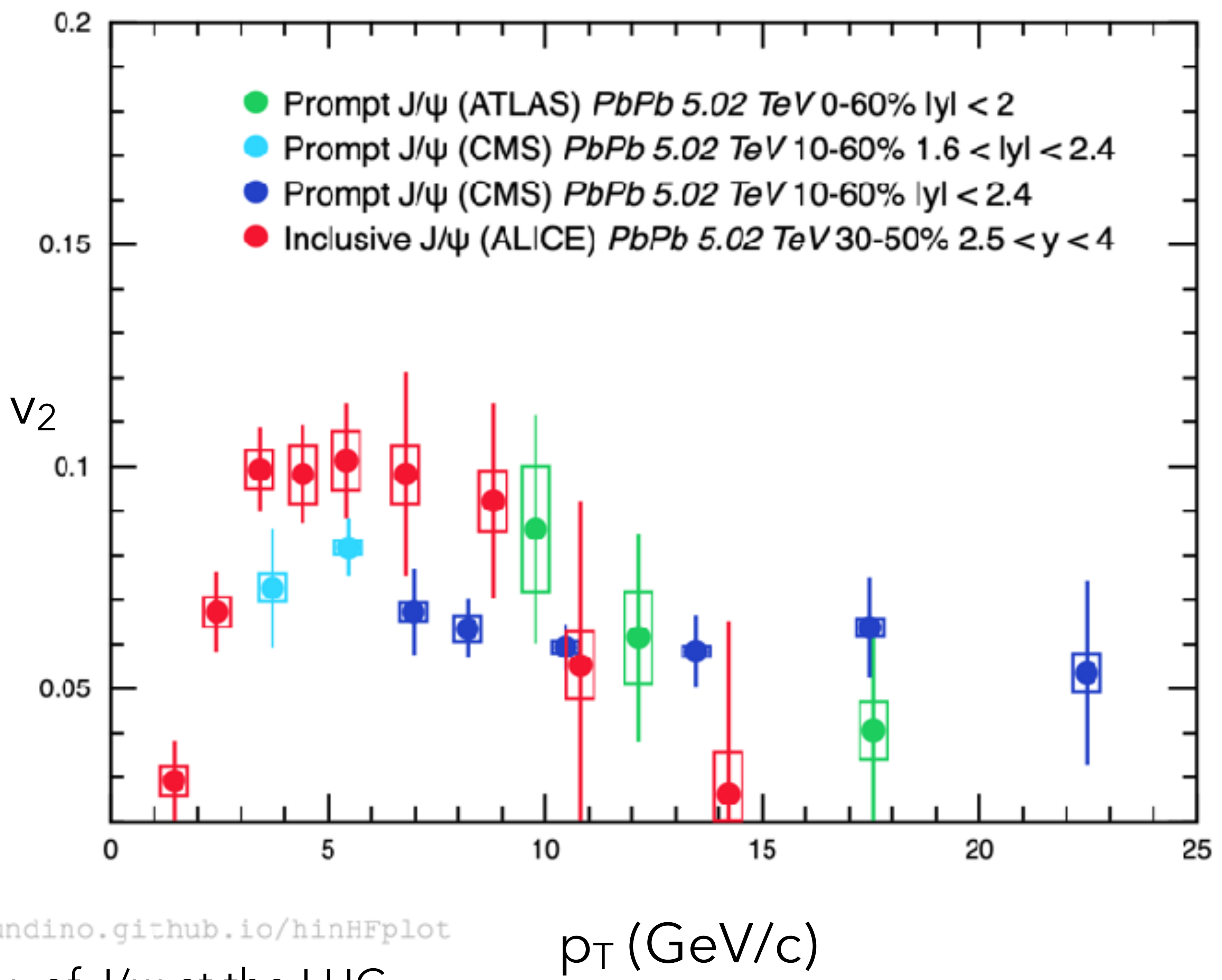

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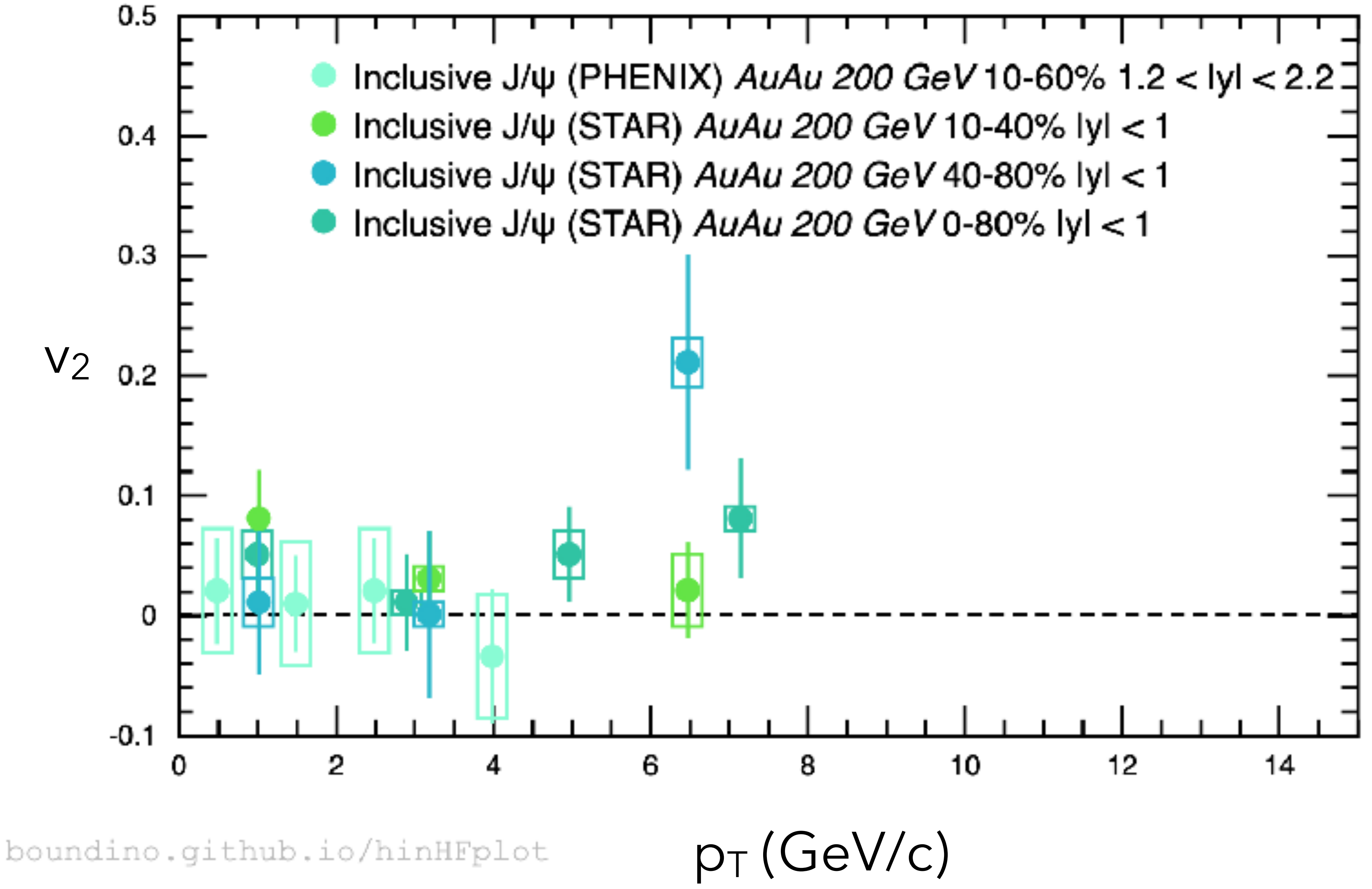

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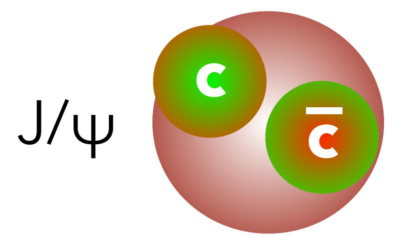

- Significant J/ψ v_2 at low p_T and the LHC energies → Sign of **charmonium regeneration**

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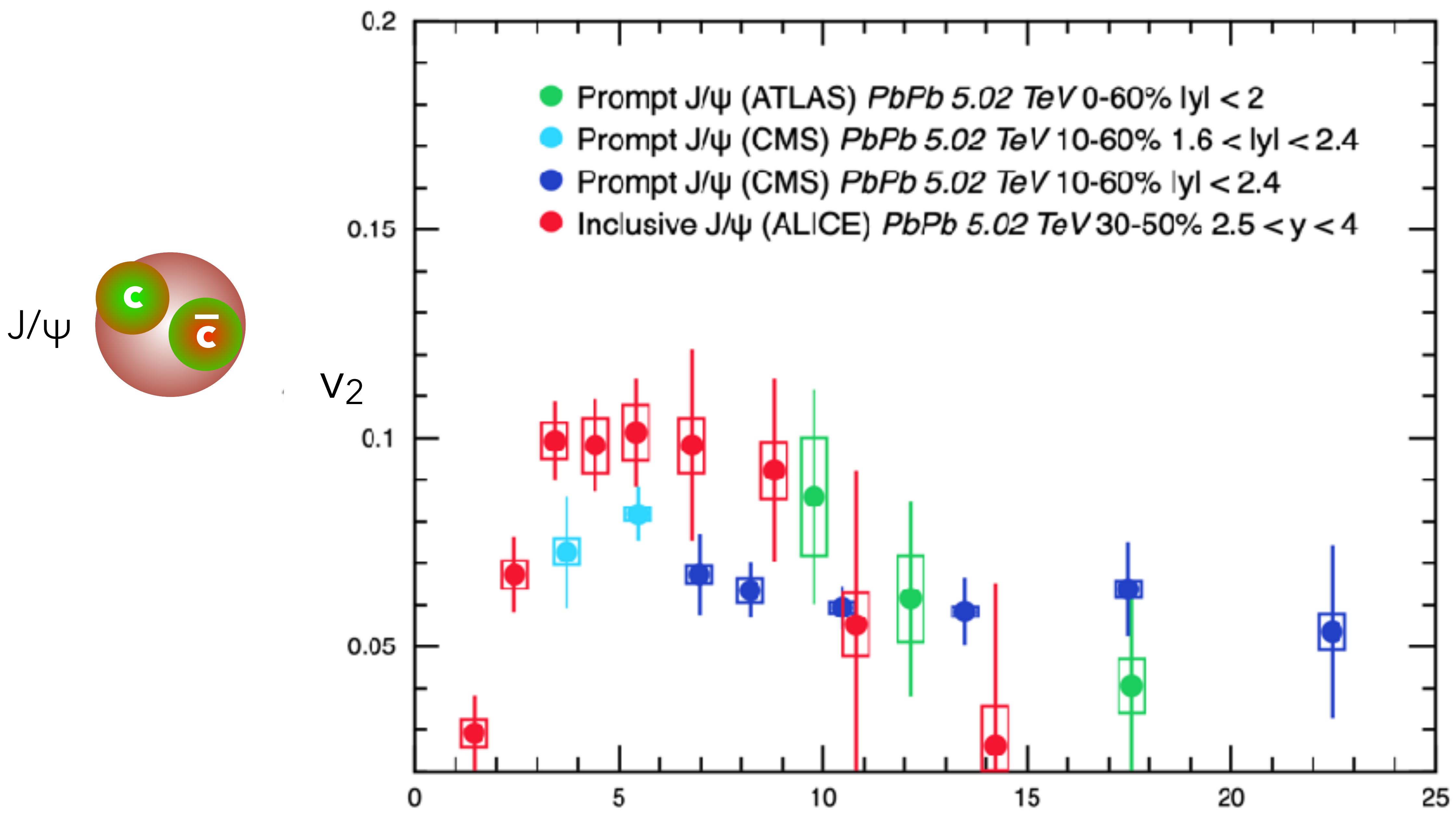

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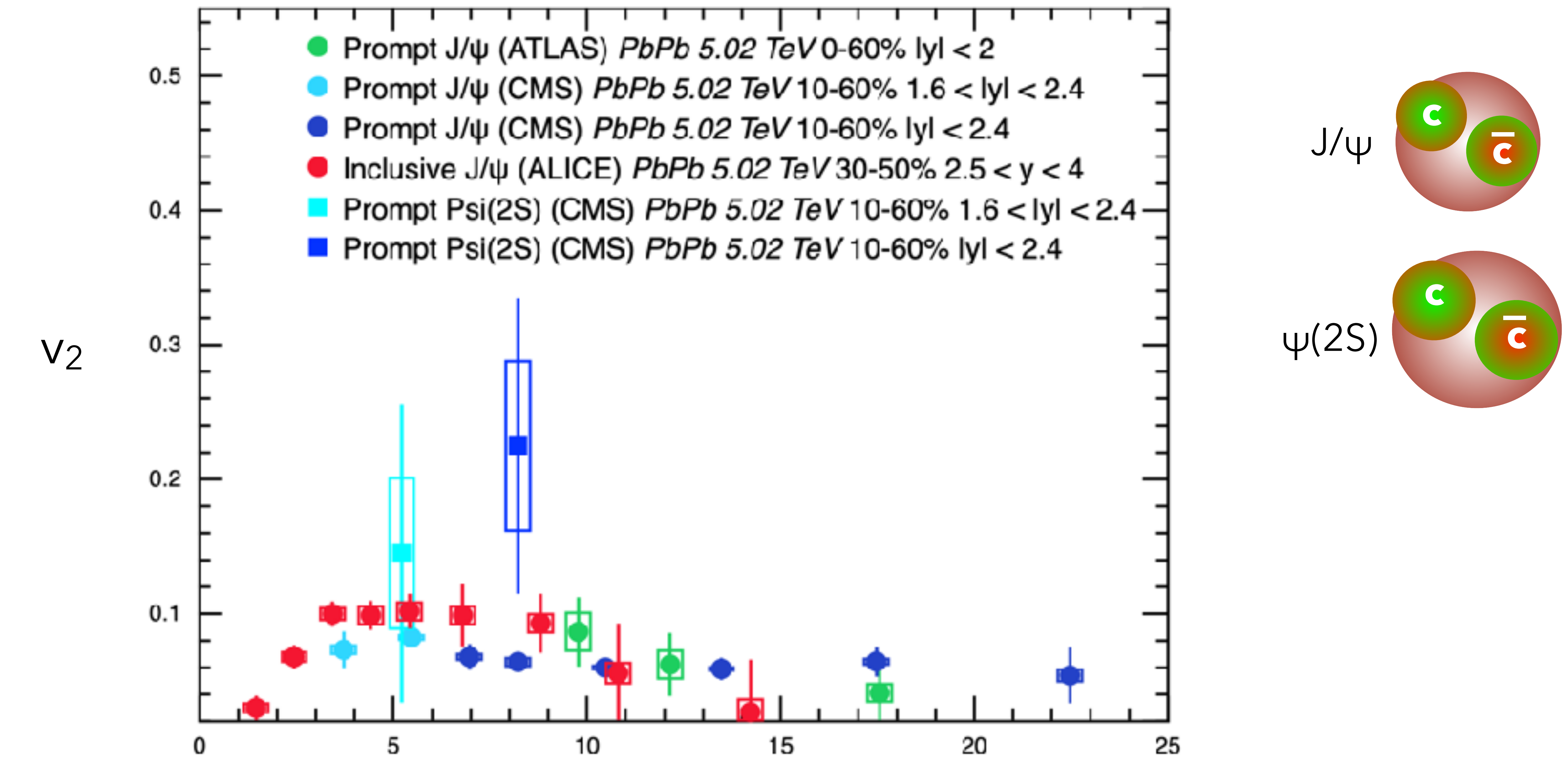

v_2 of J/ψ and ψ(2S) at the LHC

- Significant J/ψ v_2 at low p_T and the LHC energies → Sign of **charmonium regeneration**
- Hint for ψ(2S) v_2 larger than J/ψ v_2 for p_T > 6.5 GeV/c?
  Larger contribution from recombination for ψ(2S)? Interesting to extend with Run 3 and down to lower p_T

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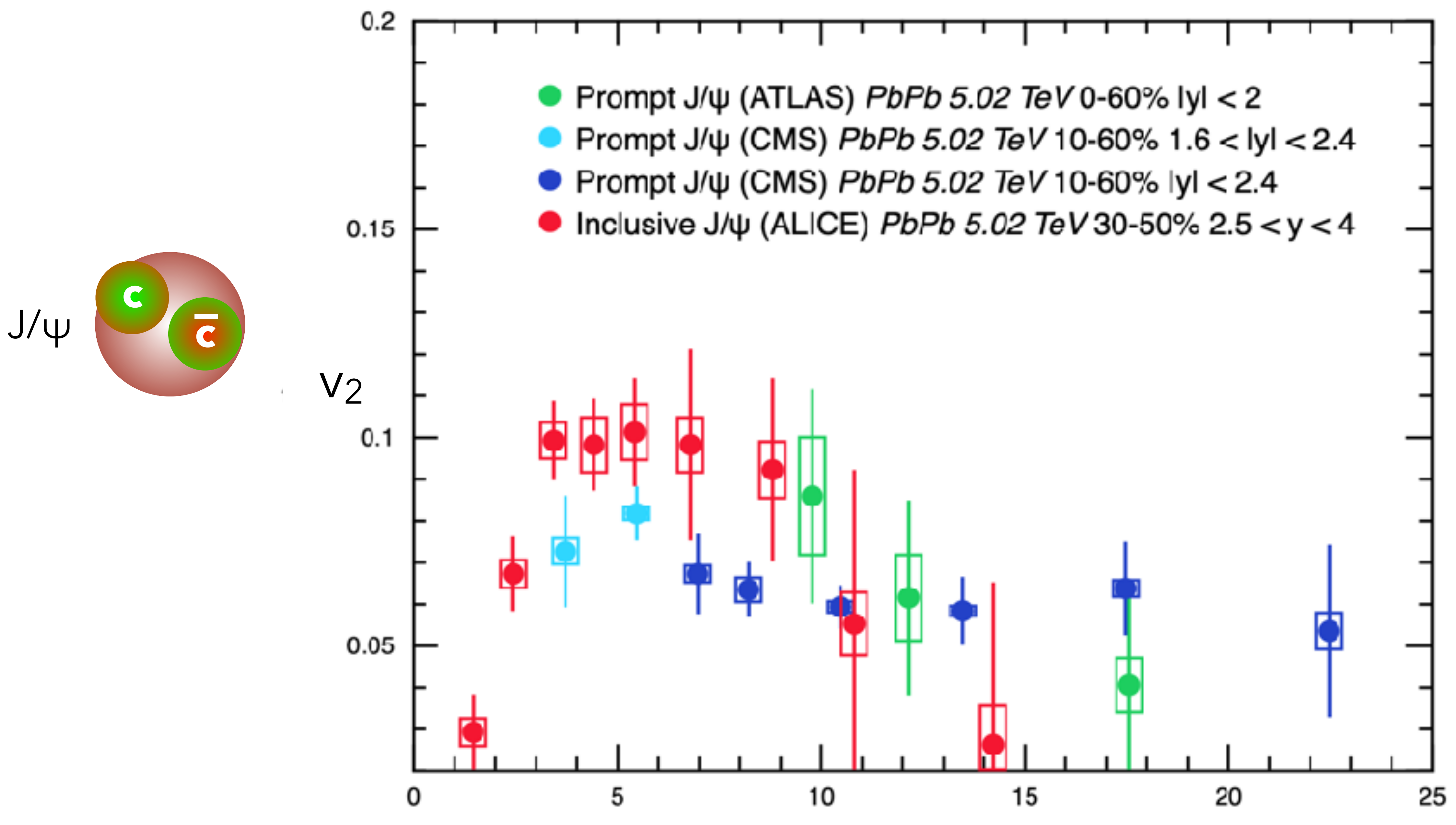
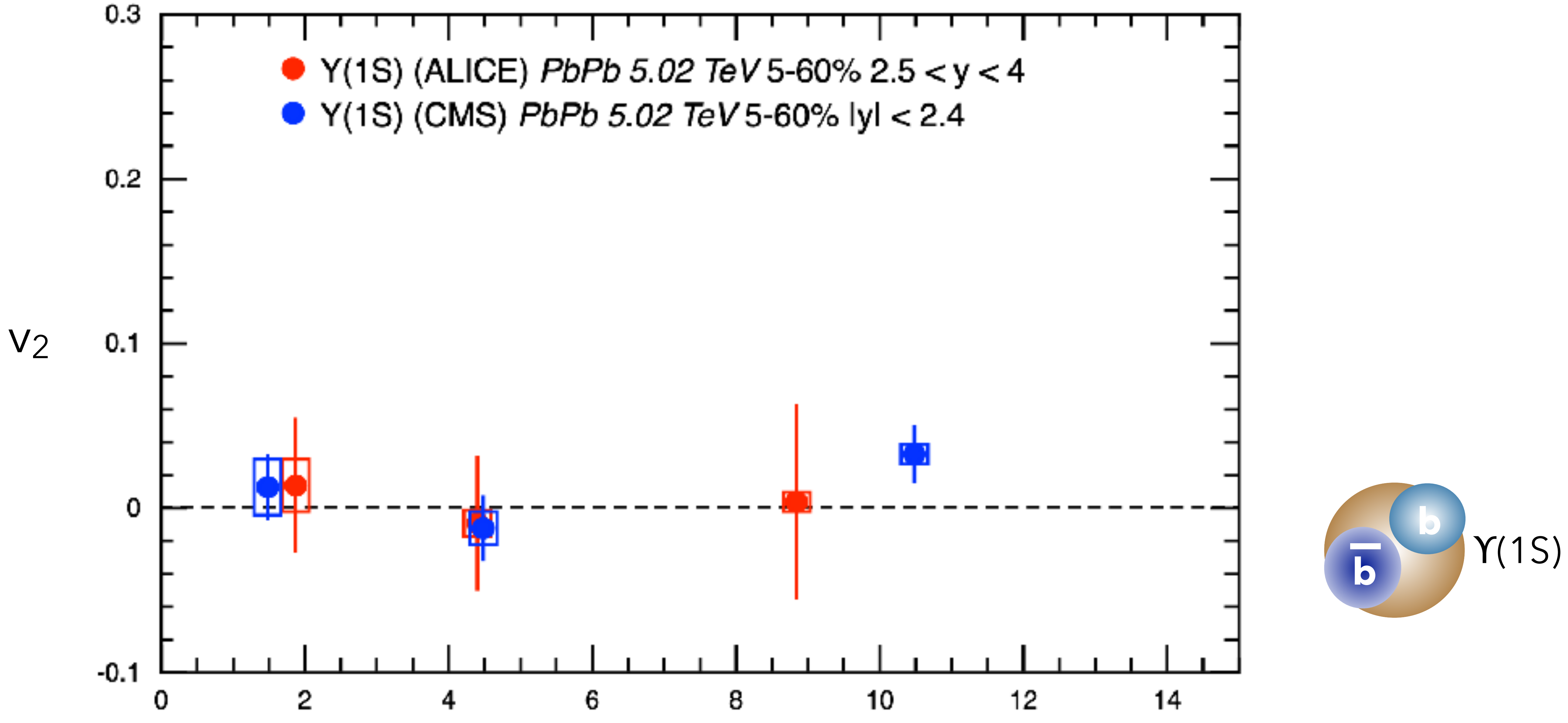


v₂ of J/ψ at the LHC

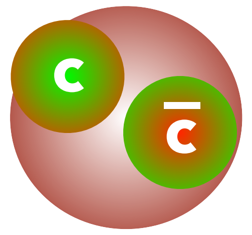


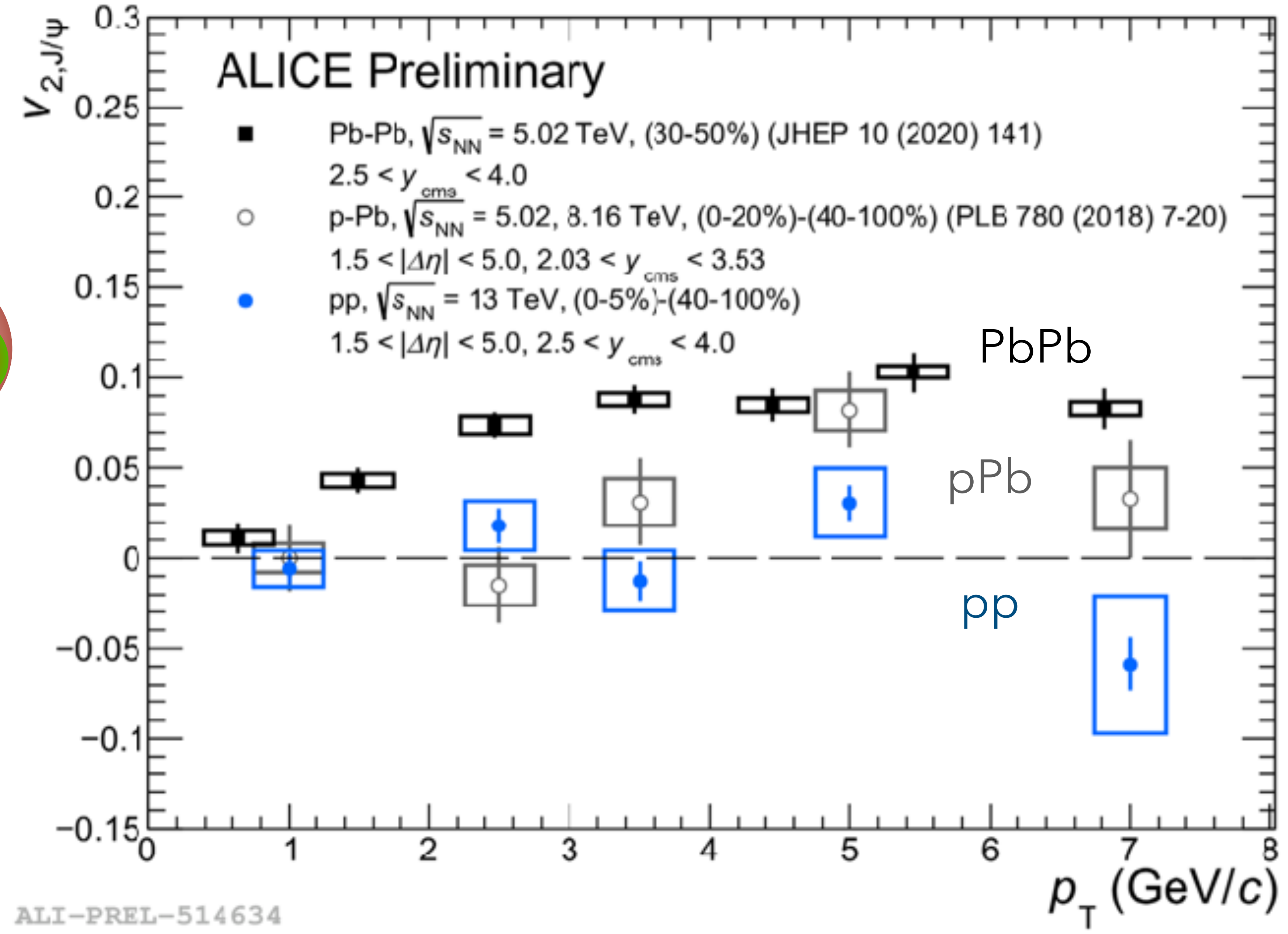
v_2 oϒ(1S) at the LHC

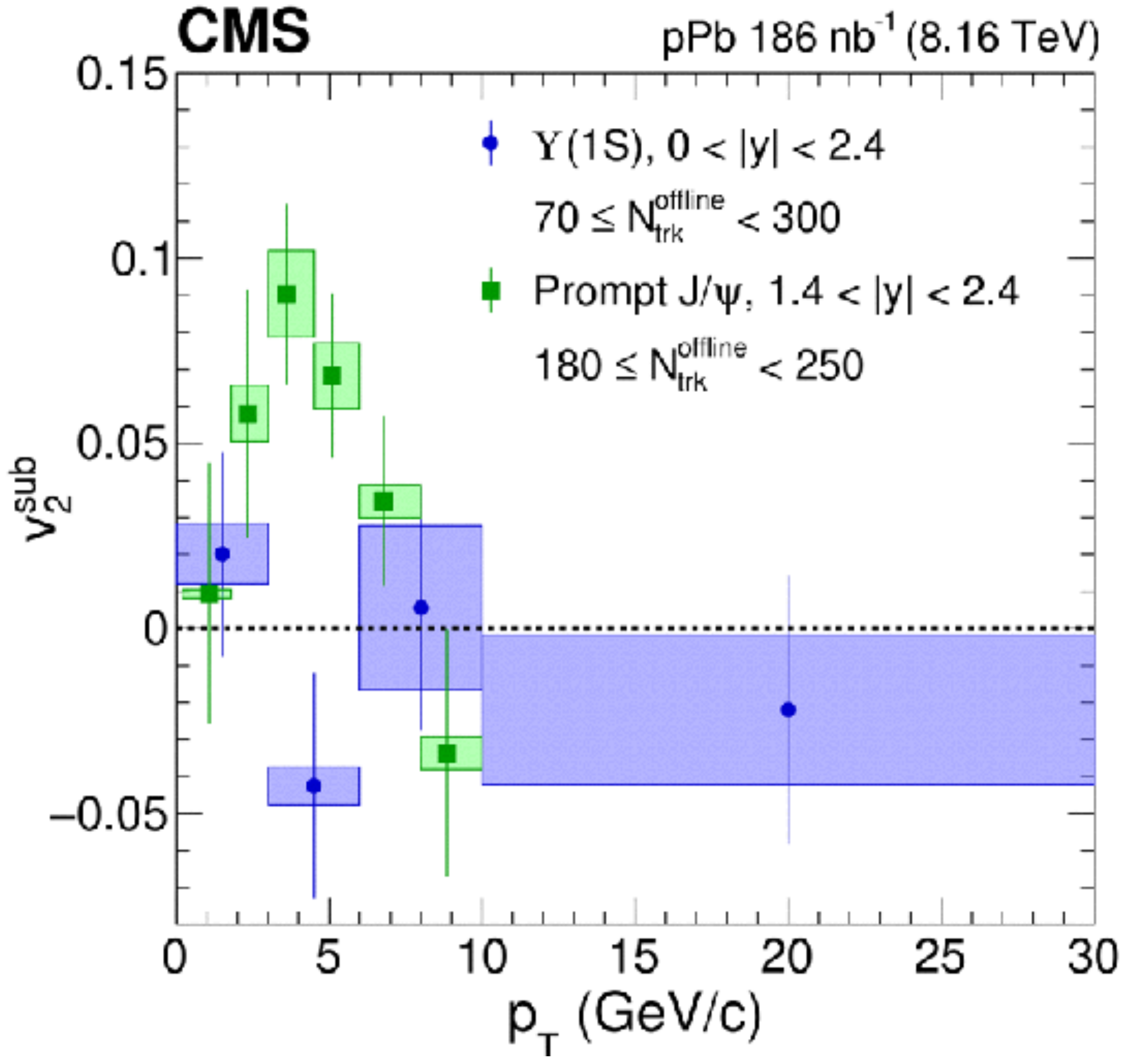
- Significant J/ψ v_2 at low p_T and the LHC energies → Sign of **charmonium regeneration**
- Hint for ψ(2S) v_2 larger than J/ψ v_2 for p_T > 6.5 GeV/c?
  Larger contribution from recombination for ψ(2S)? Interesting to extend with Run 3 and down to lower p_T
- **ϒ(1S) v_2 compatible with zero** → no evidence for regeneration within uncertainties
  Would be interesting to look at v_2 of excited states if doable

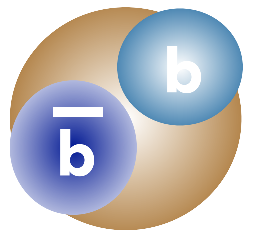
Quarkonium collectivity in smaller systems

J/ψ







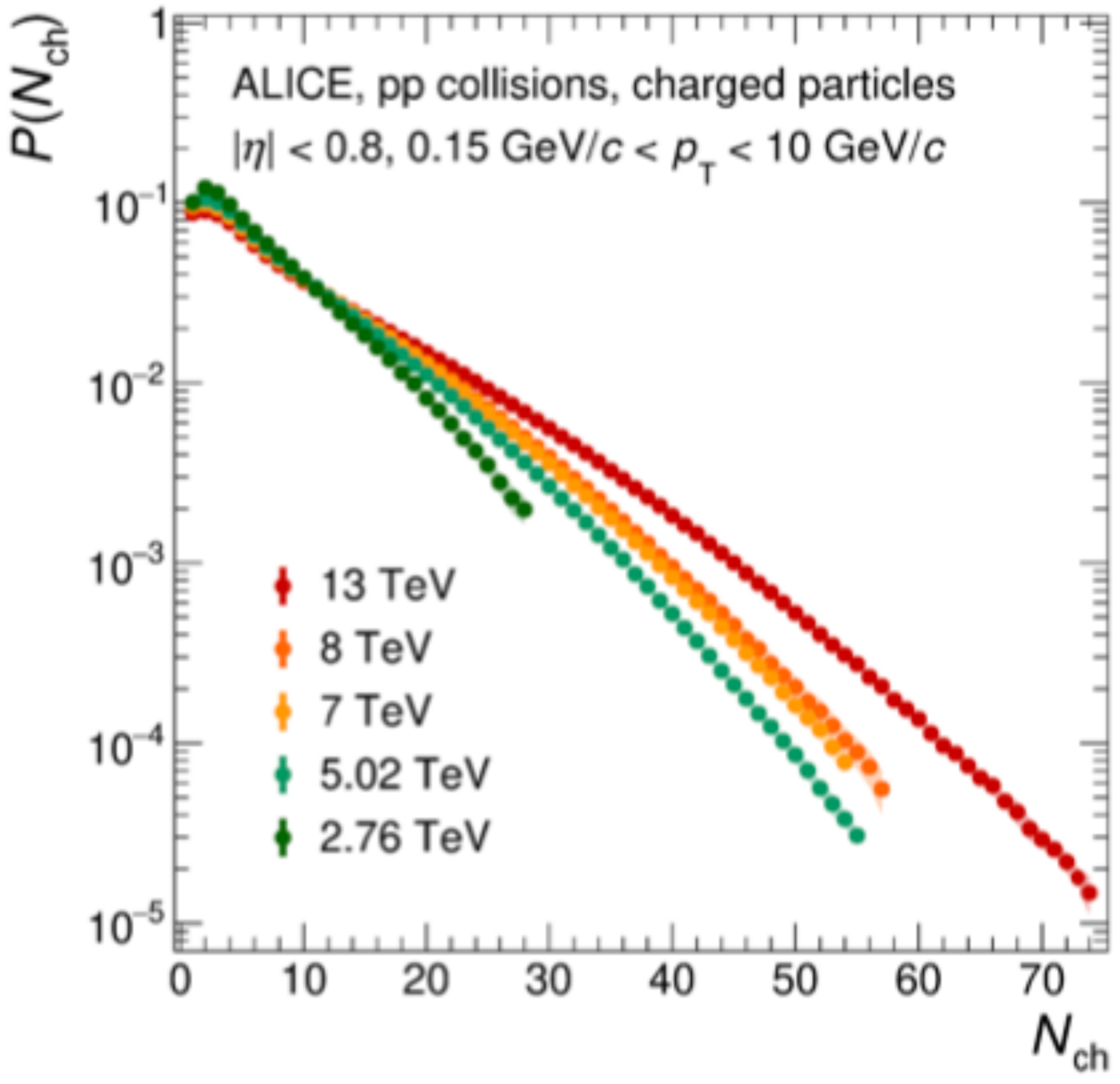


ϒ(1S)

CMS Coll., Phys. Lett. B 850 (2024) 138518
CMS Coll., Phys. Lett. B 791 (2019) 172
X. Du et al, High Energy Phys. (2019) 2019:15
ALICE, JHEP 10 (2020) 141 (Pb-Pb)
ALICE, PLB 780 (2018) 7-20 (p-Pb)

- **Significant J/ψ v_2 at intermediate p_T in pPb collisions at high multiplicity**, not explained by transport models (negligible path-length dependence and regeneration).
- No hint of collective behaviour observed for J/ψ in pp data at high multiplicity.
- Possibly a common mechanism at the origin of collective behaviour in both pPb and PbPb?
- ϒ(1S) v_2 consistent with zero → No significant dependence of b-quark modification on in-medium path length.

- Simplified picture…



Measurements vs. charged-particle multiplicity

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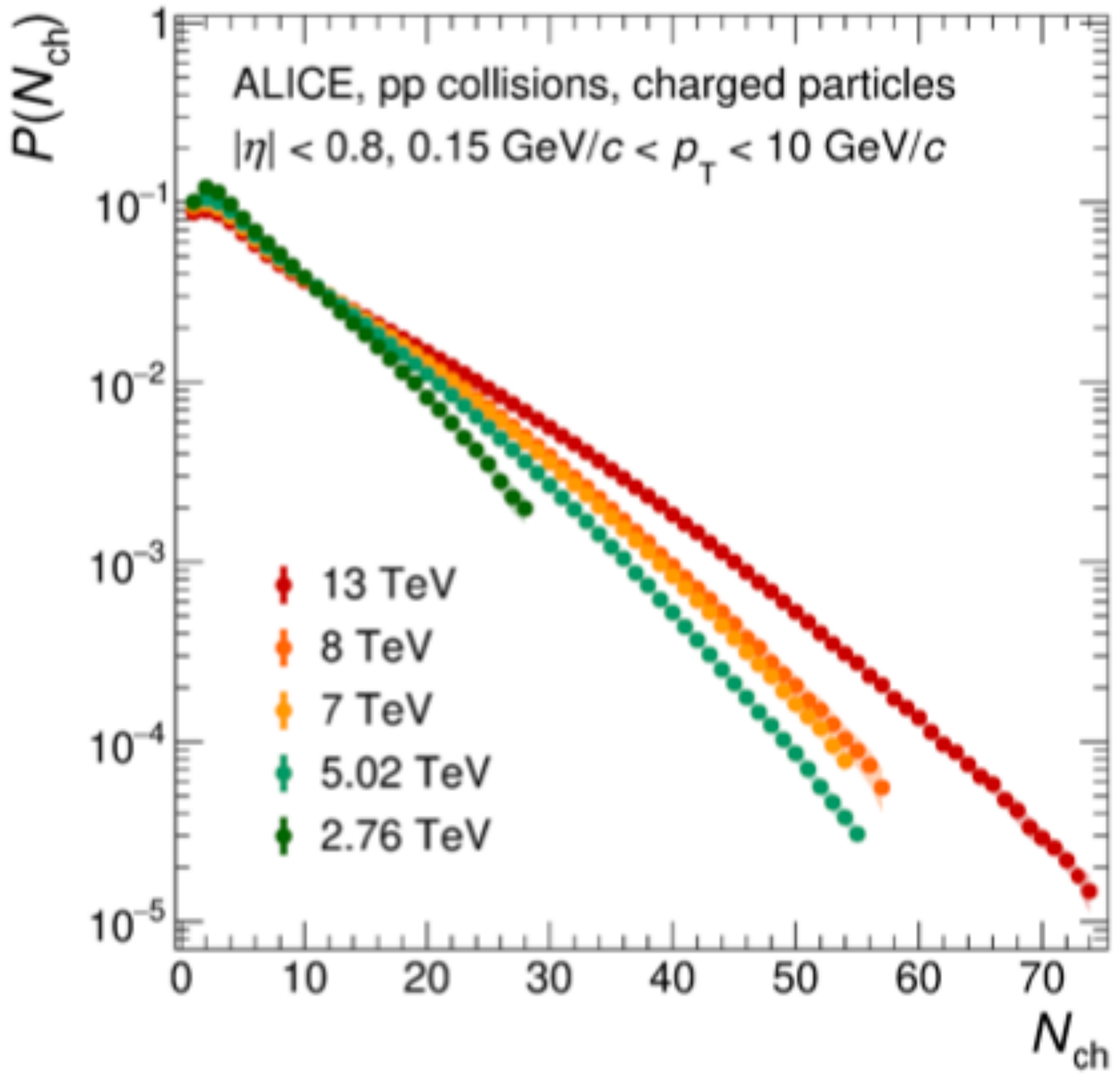

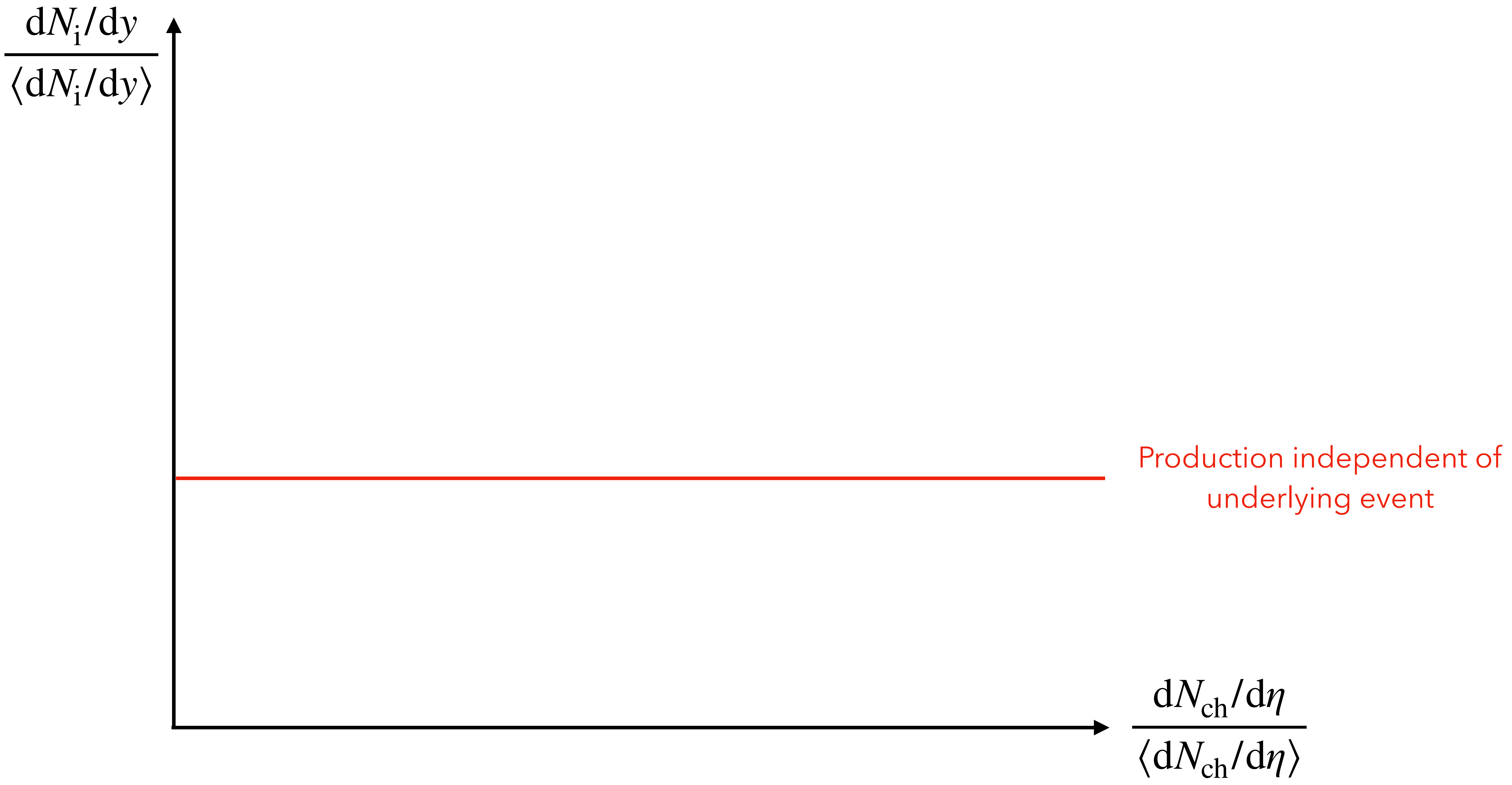

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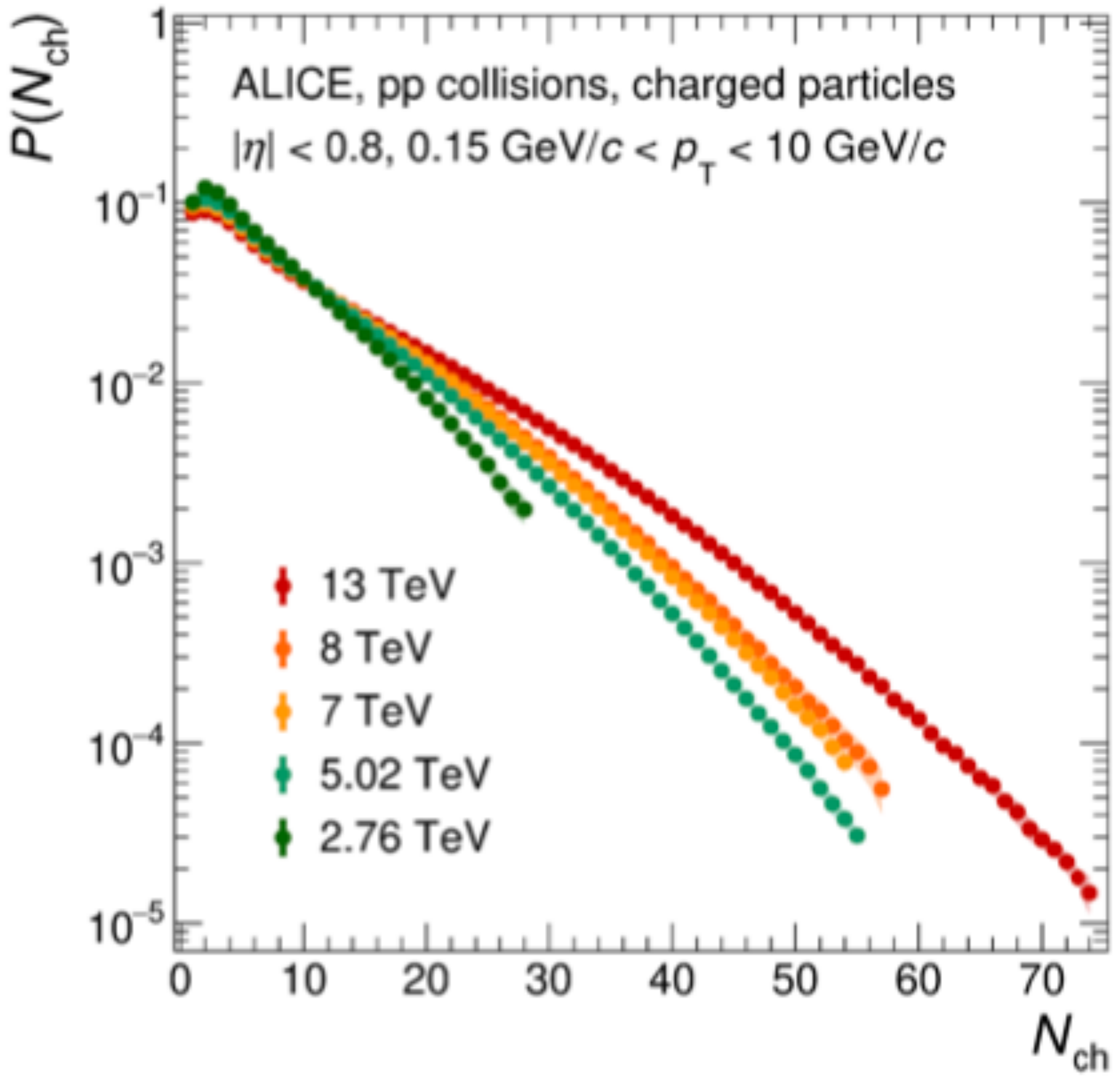

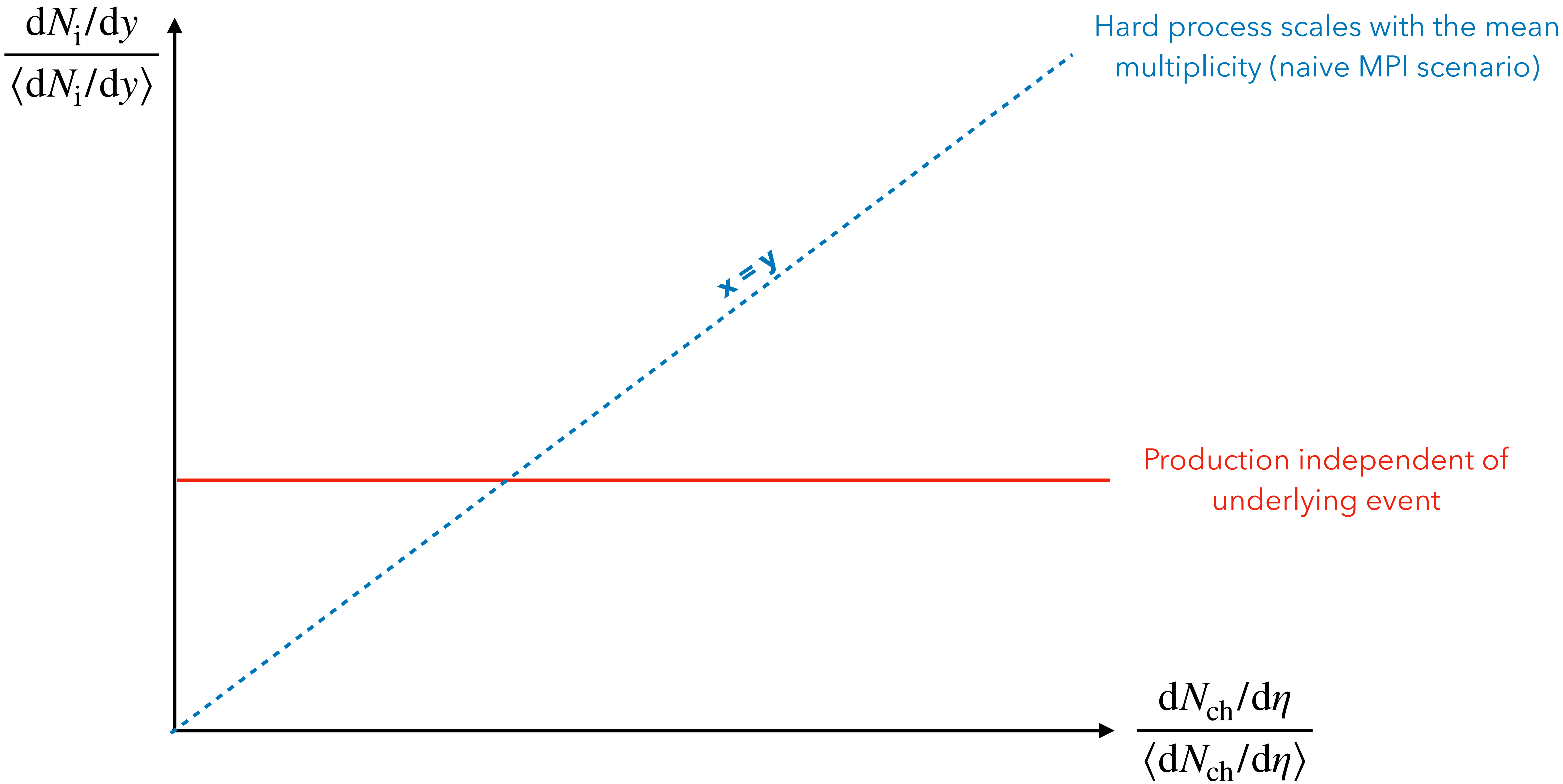

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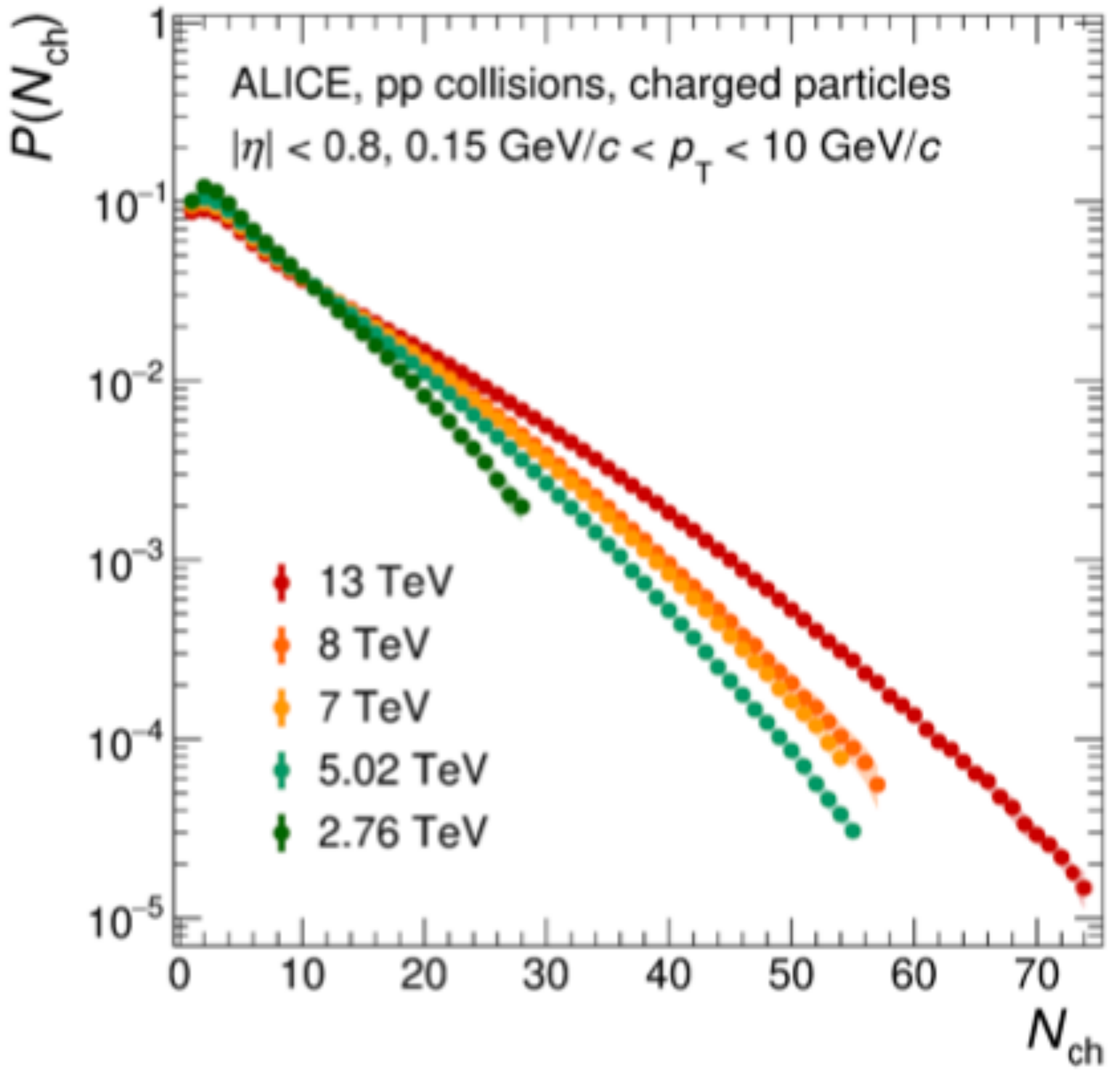

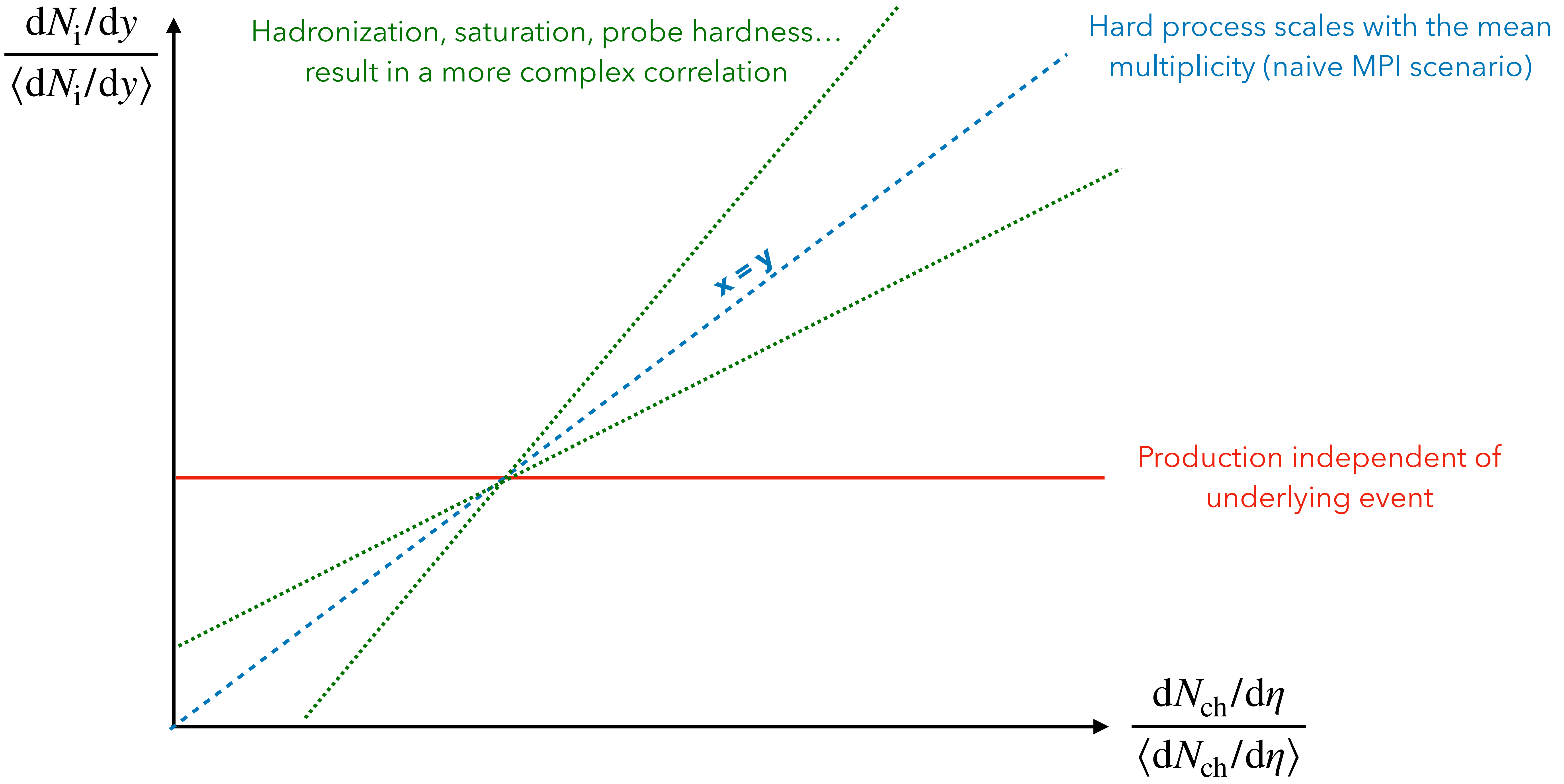

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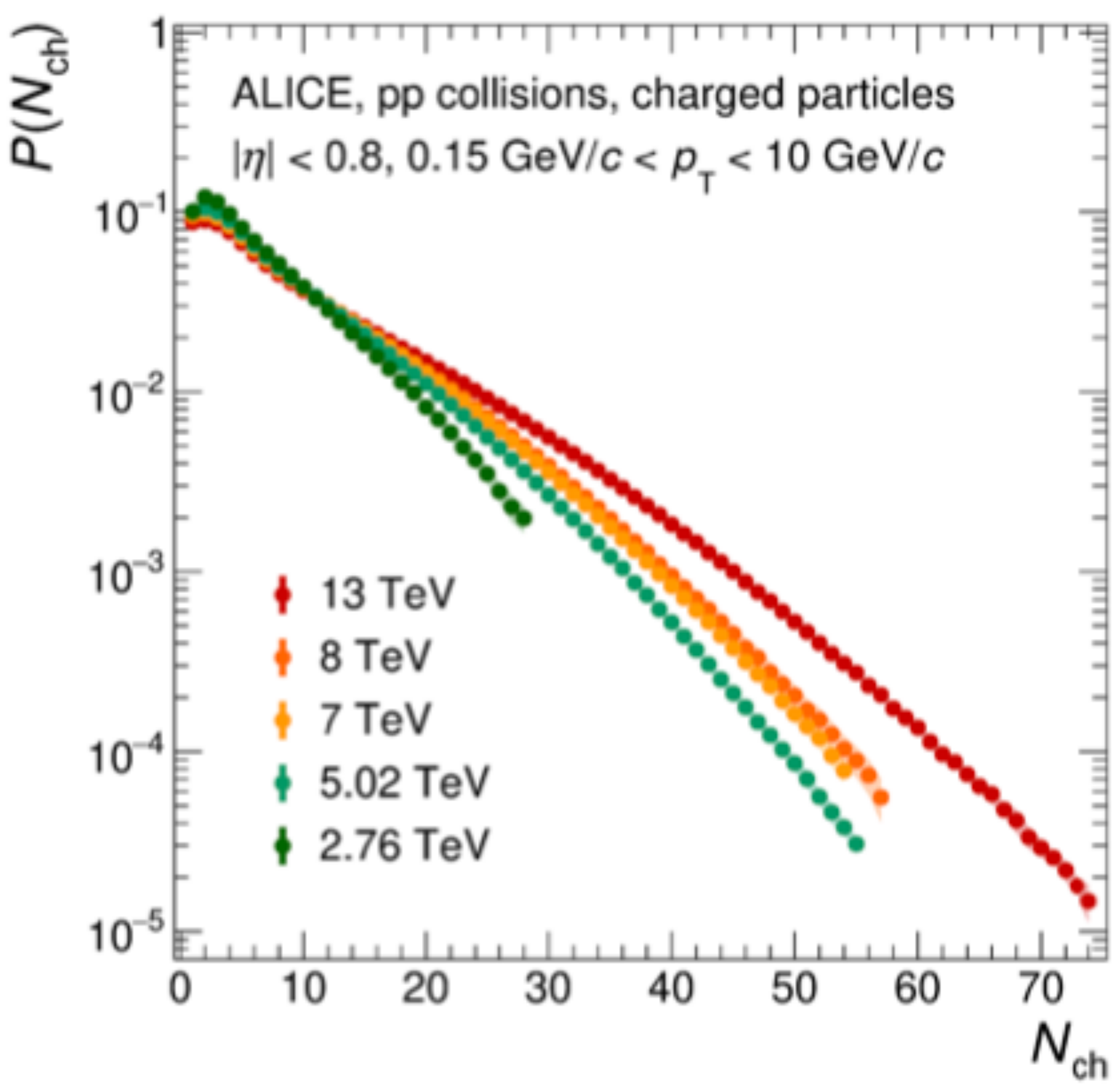
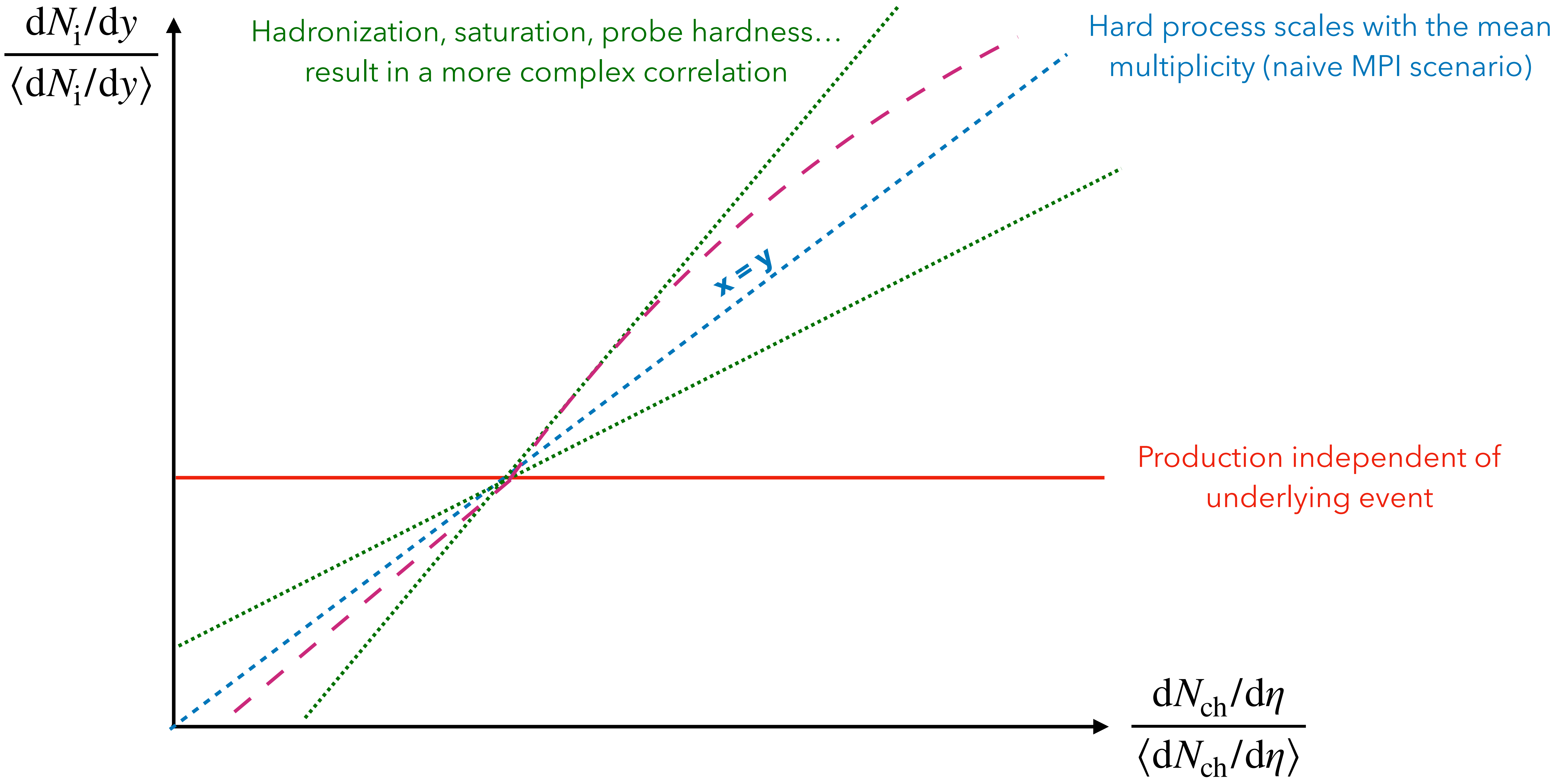
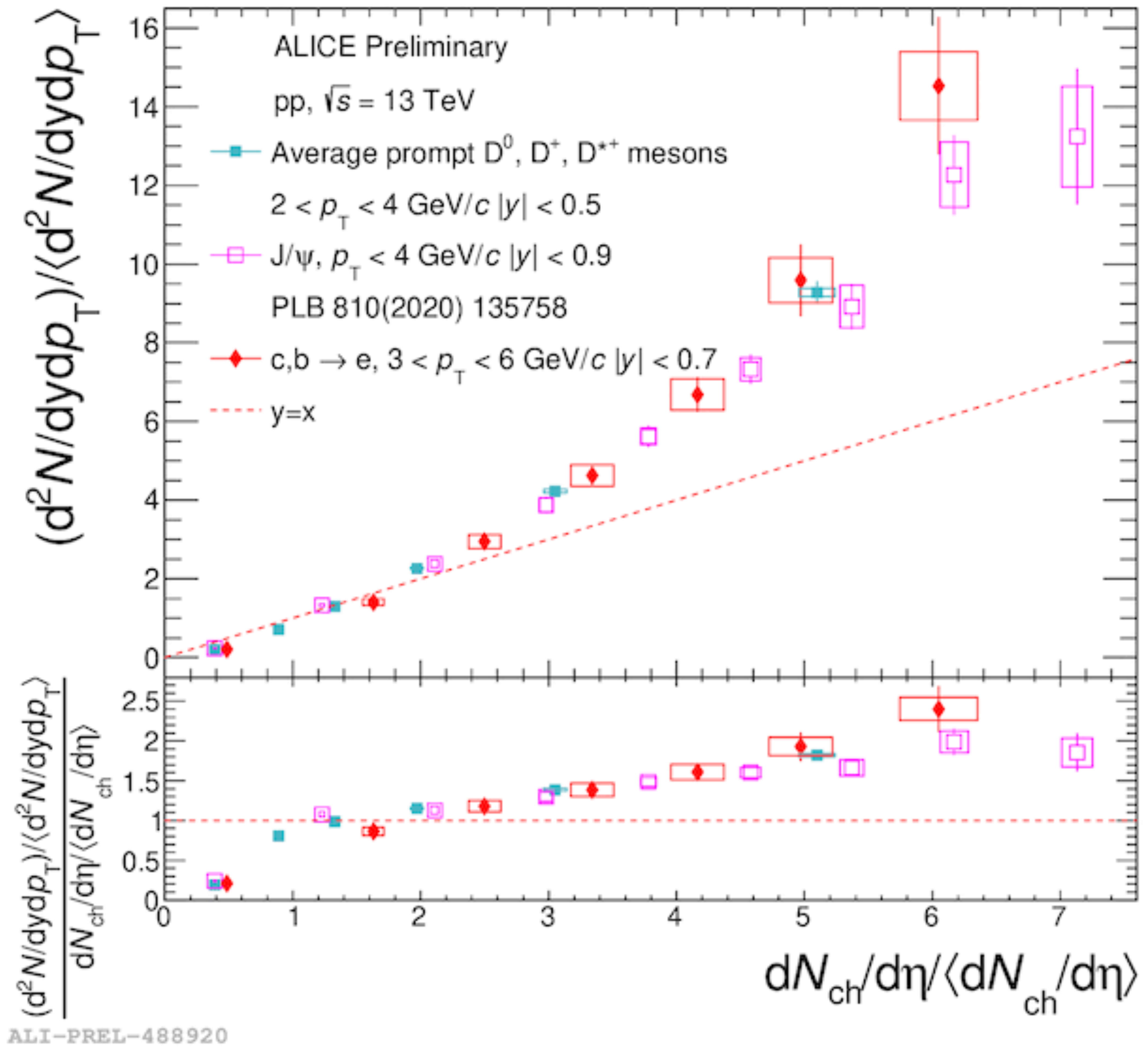


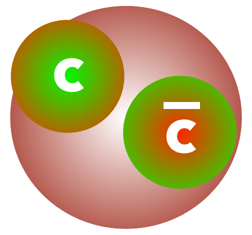


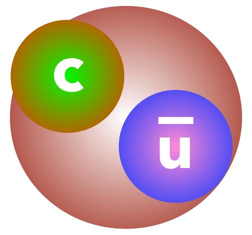
Charm yields vs. charged-particle multiplicity in pp

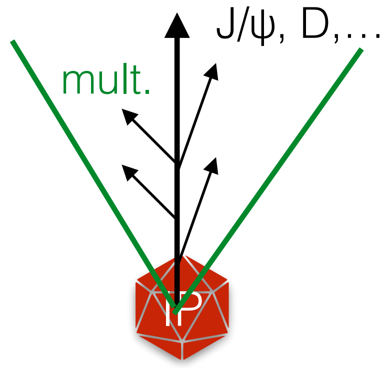
ALICE, PLB 810 (2020) 135758

- **Rapid increase with charged-particle multiplicity at mid-rapidity** (D, D_s, J/Ψ, non-prompt J/Ψ, c/b→l)
  - suggesting common origin,
  - trend described by models including some 'sort of' **multiple-parton interactions**
    - all models show a departure from linearity;
    - described by initial state model with modified gluon distribution or percolation models;
    - PYTHIA and EPOS do not reproduce quantitatively the trend.



J/ψ 

D0 



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ALICE, PLB 810 (2020) 135758

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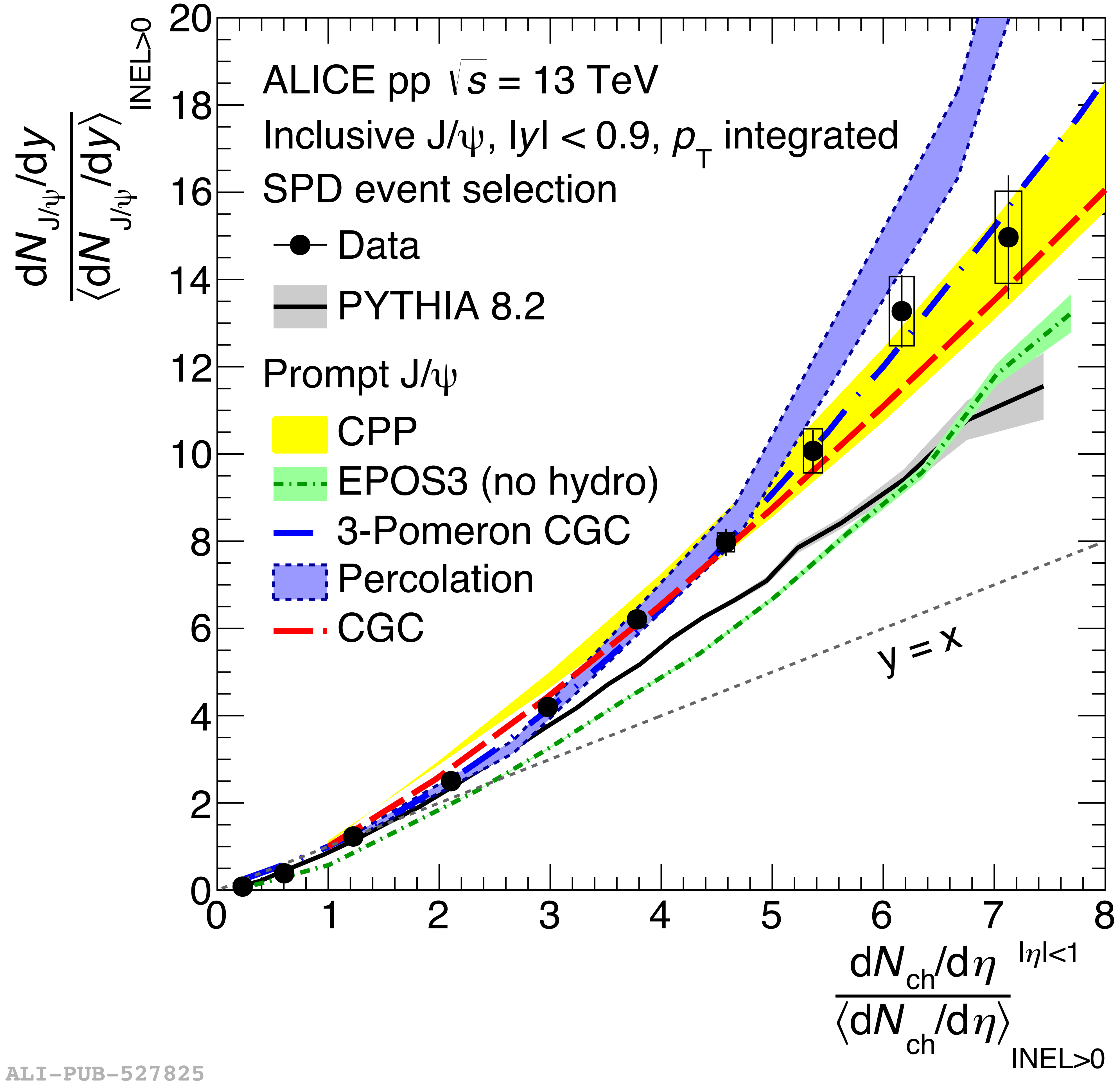
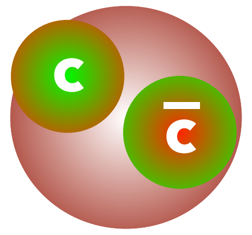
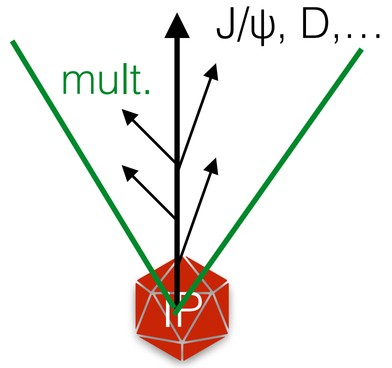


J/ψ



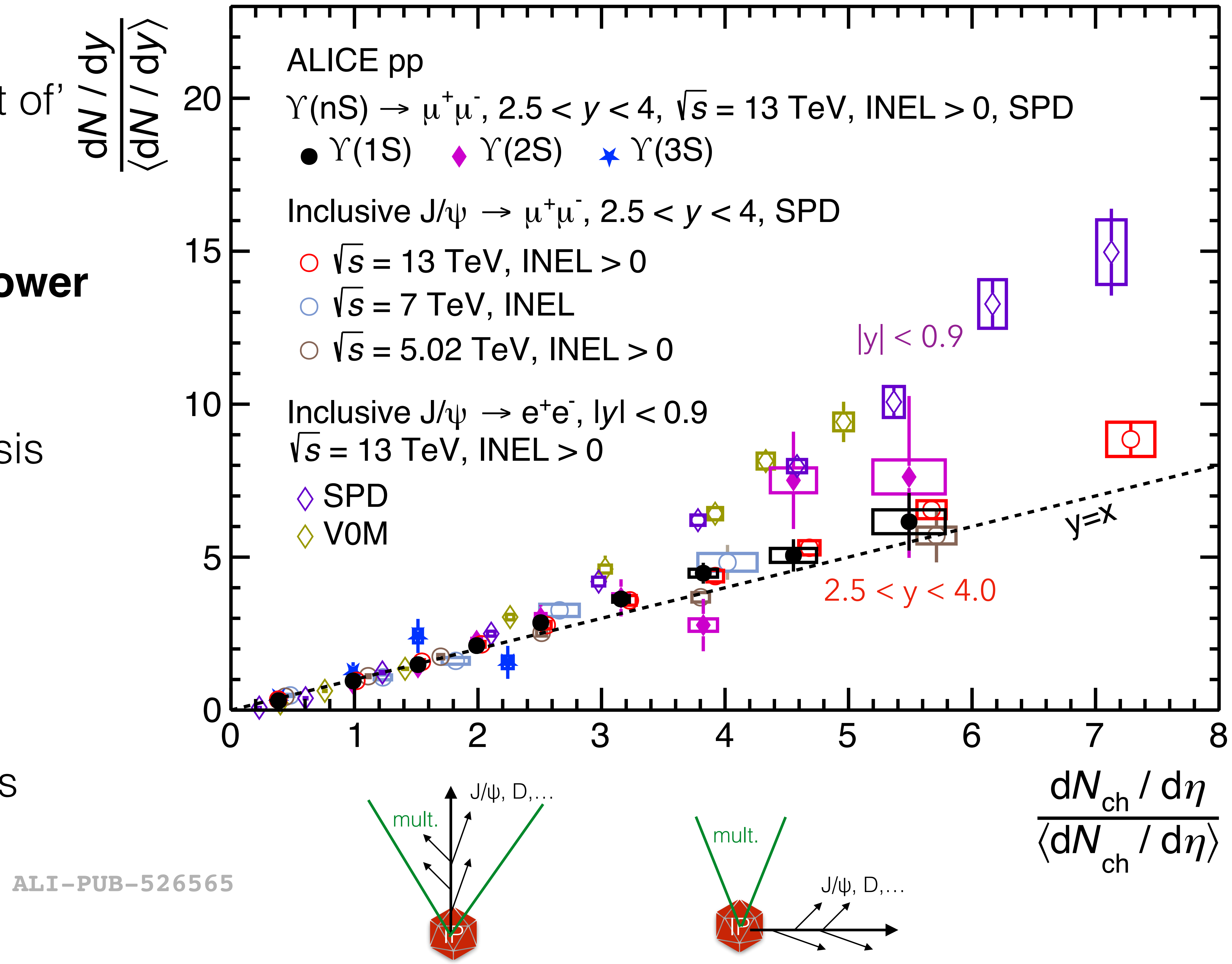


Quarkonium yields vs. charged-particle multiplicity in pp

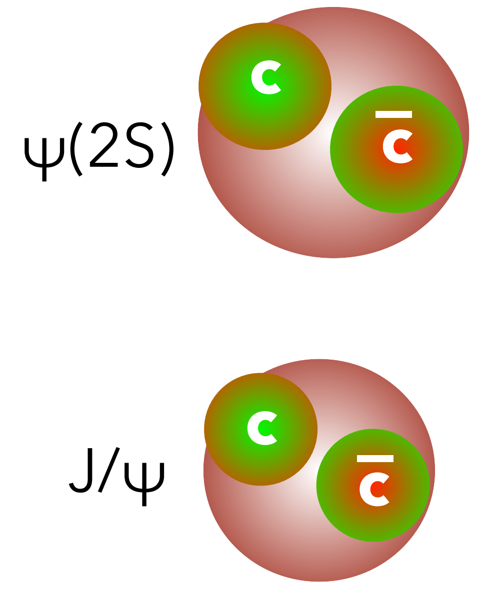
- Rapid increase with charged-particle multiplicity at midrapidity (D, D_s, J/Ψ, non-prompt J/Ψ)
  - suggesting common origin,
  - trend described by models including some 'sort of' multiple-parton interactions
- But **J/Ψ and ϒ results at forward-y suggest a slower increase** (than midrapidity ones)
  - **hadronisation?**
    D-meson measurements disfavour this hypothesis
  - **fragmentation?**
    Study particle species (kinematic dep.), also particle production in jets / isolated.
  - **associated production? underlying event?**
    Multi-differential studies: yields at different y, vs multiplicity at different y, in sphericity intervals or vs angle (event classifier).
  - **final state effects?**

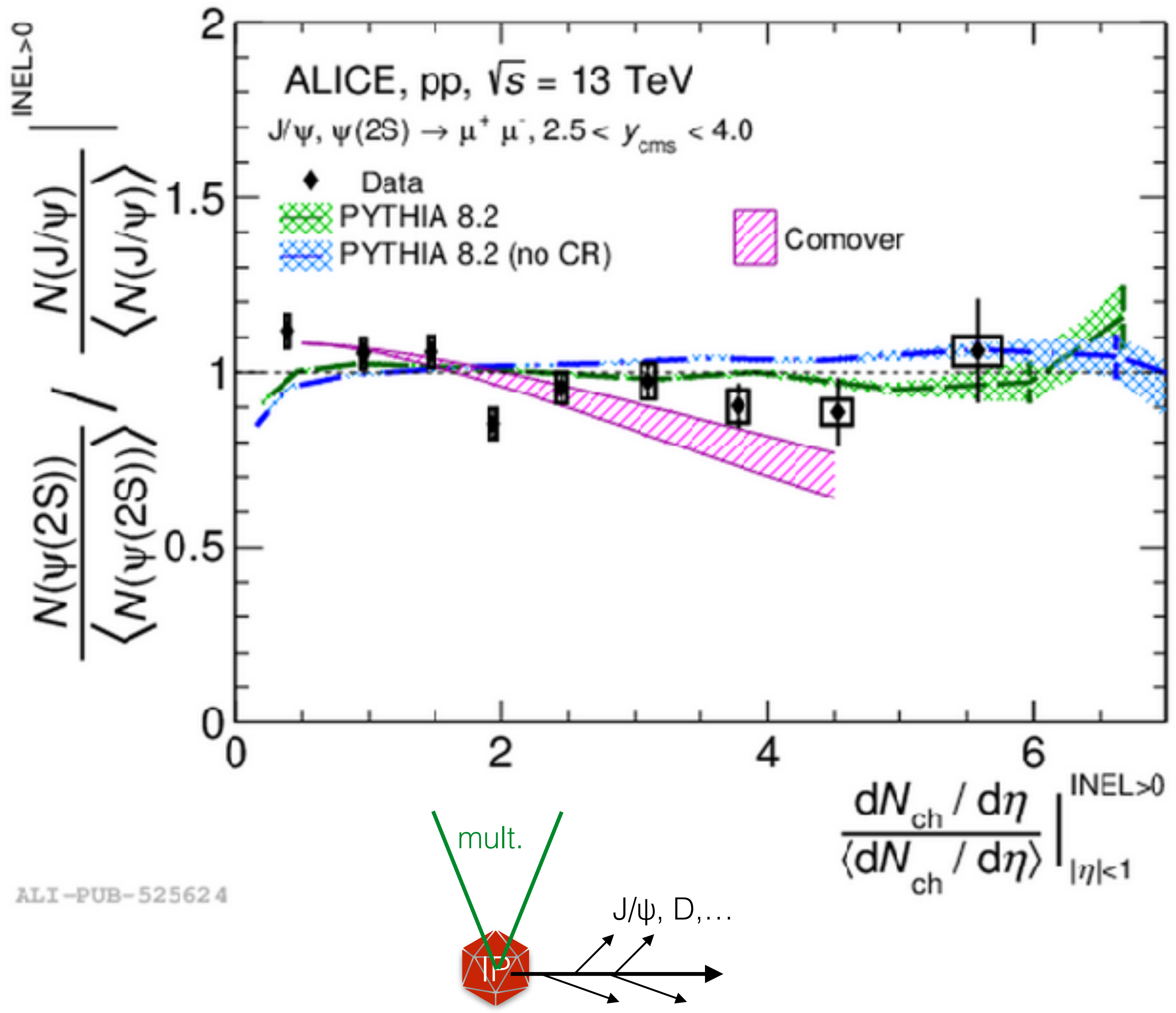
ALICE, JHEP 06 (2022) 015
ALICE, arXiv:2209.04241 (2022)

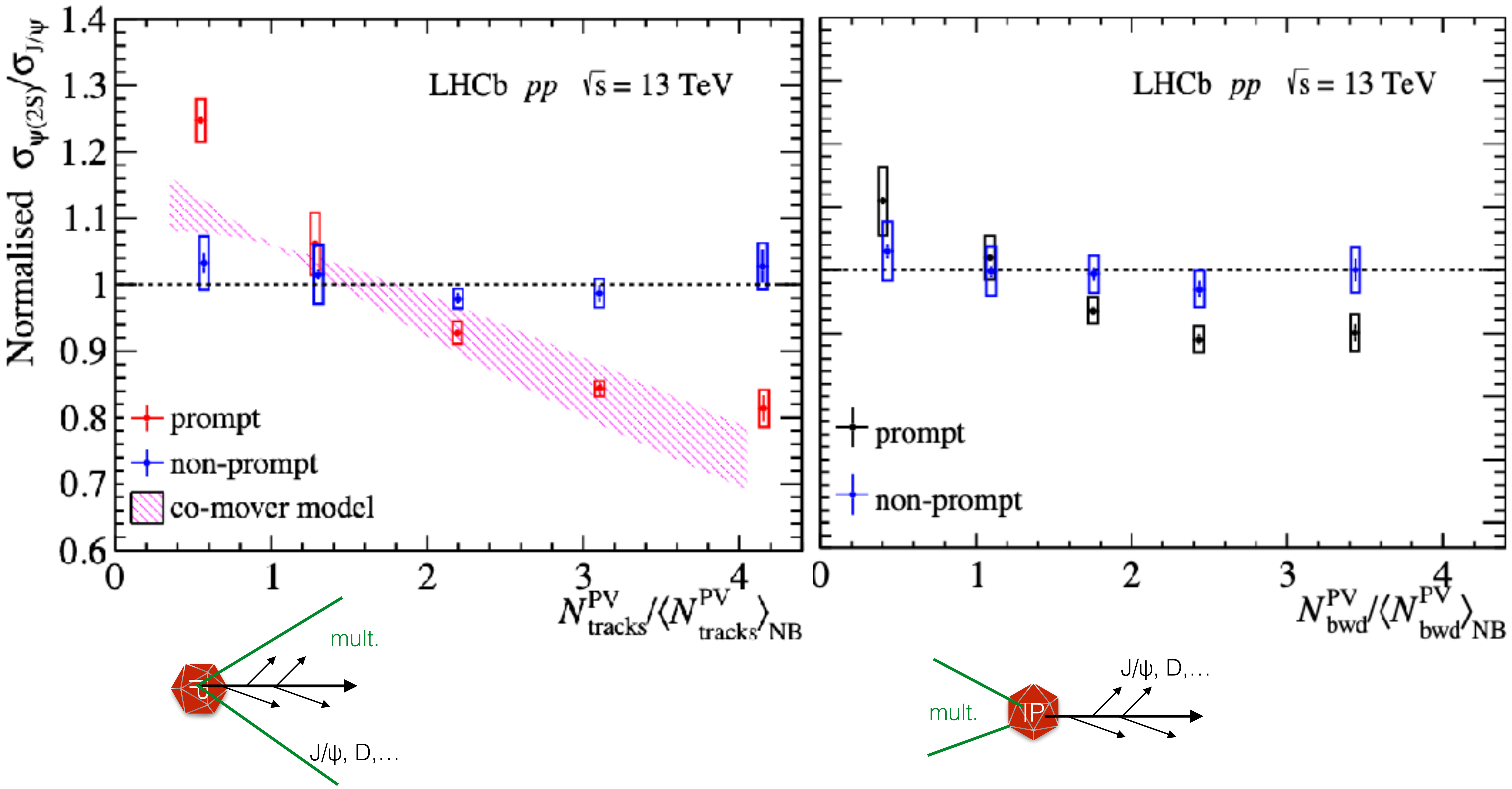
J/ψ ϒ(1S)



Excited-to-ground state ratios: possible final state effects?



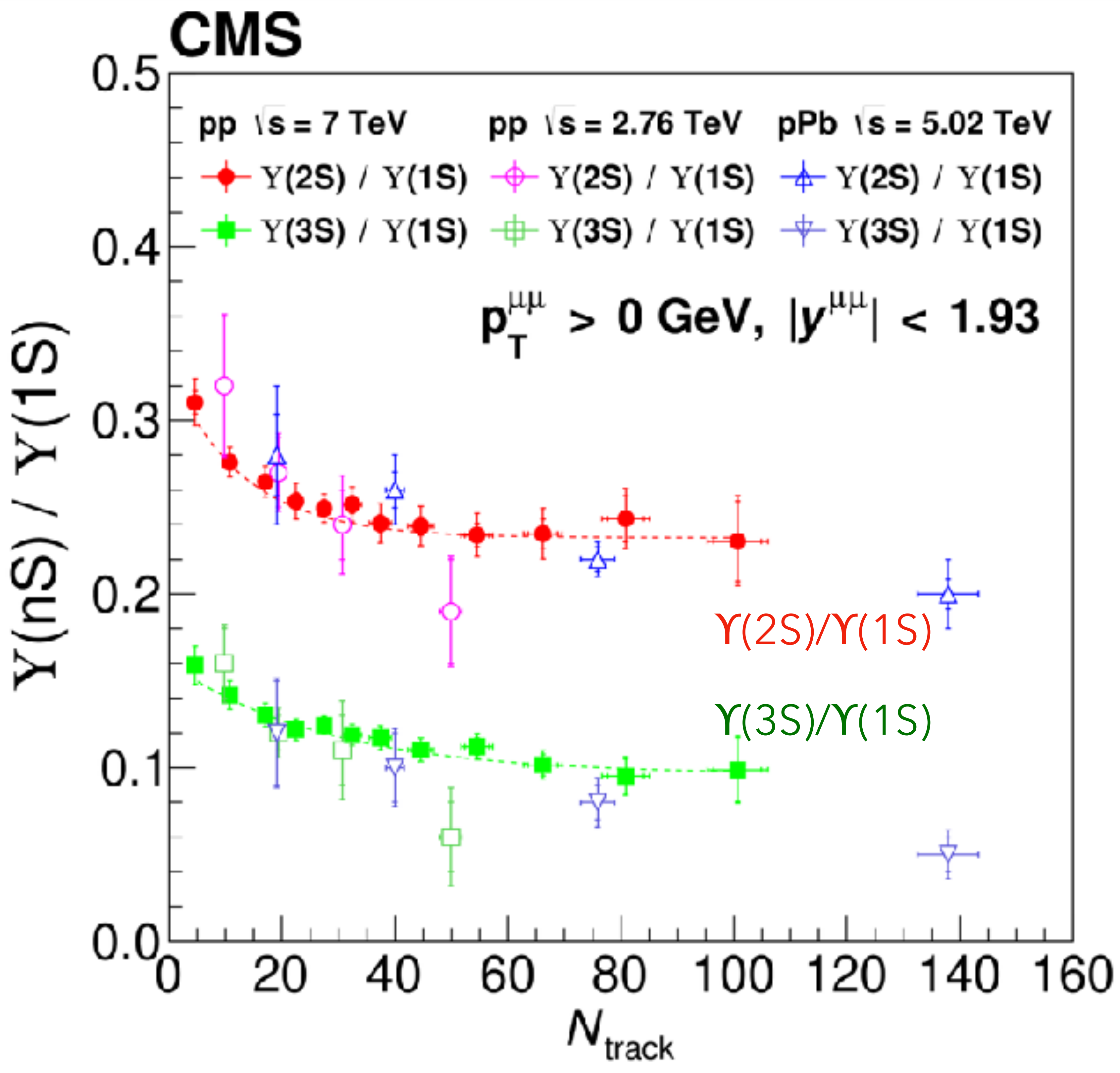


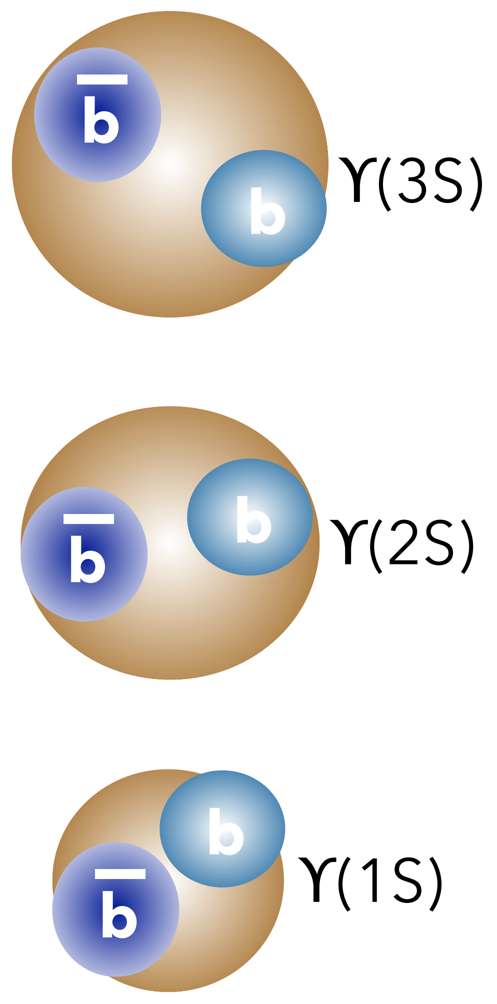


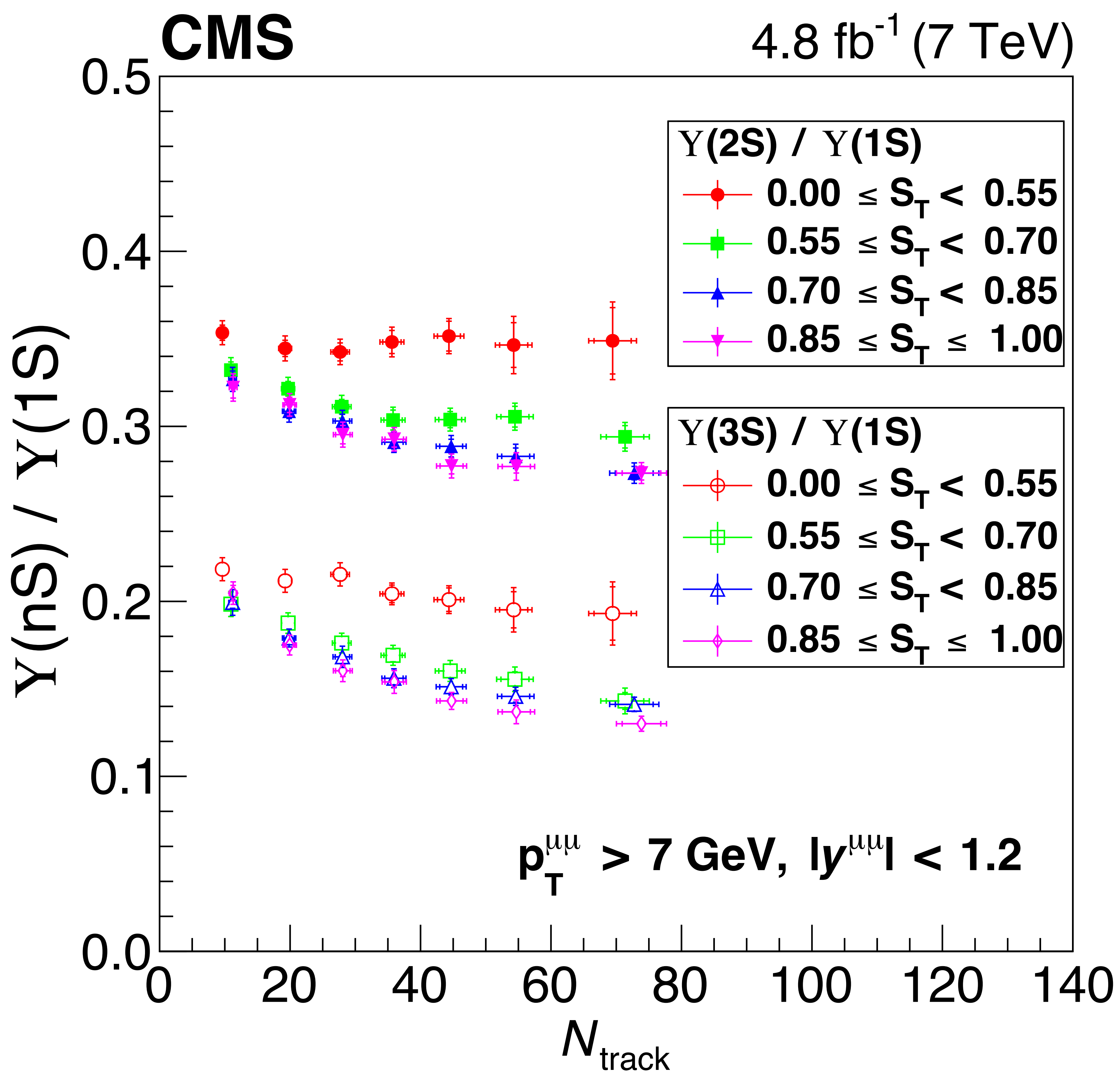
- **Excited-to-ground state ratios provide information on final state effects,** as most of the initial state effects cancel in the ratio, and the higher mass states are characterized by a lower binding energy.
- **ψ(2S)/J/ψ** ratio as a function of multiplicity in pp collisions:
  - inclusive ratio consistent with unity,
  - **decreasing trend of the prompt component,** consistent with model calculations.

ALICE, JHEP 06 (2023) 147
LHCb, JHEP 05 (2024) 243
CMS, CMS-PAS-HIN-24-001

Excited-to-ground state ratios: possible final state effects?







- **Decrease of Υ(nS)/Υ(1S) ratios as a function of multiplicity**, consistently across system size.
- The Υ(nS)/Υ(1S) ratios are **multiplicity independent for jet-like events**.

CMS, JHEP 04 (2014) 103
CMS, JHEP 11 (2020) 001

Associated production and double parton scattering in pp

- In the **collinear factorisation** approach, $\sigma^{DPS}_{1,2} = \dfrac{m}{2\,\sigma_{eff}}\,\sigma^{SPS}_1\,\sigma^{SPS}_2$

  m=1 if 1=2, and 2 otherwise. The **effective cross section** is a (universal) constant related to the transverse overlap function between the partons of the proton.
- **Double particle production exploited to study DPS.**
- Effective cross section results:
  - J/ψ+C in agreement with multi-jet and double W,
  - double quarkonium or quarkonium+W/Z are a bit lower.
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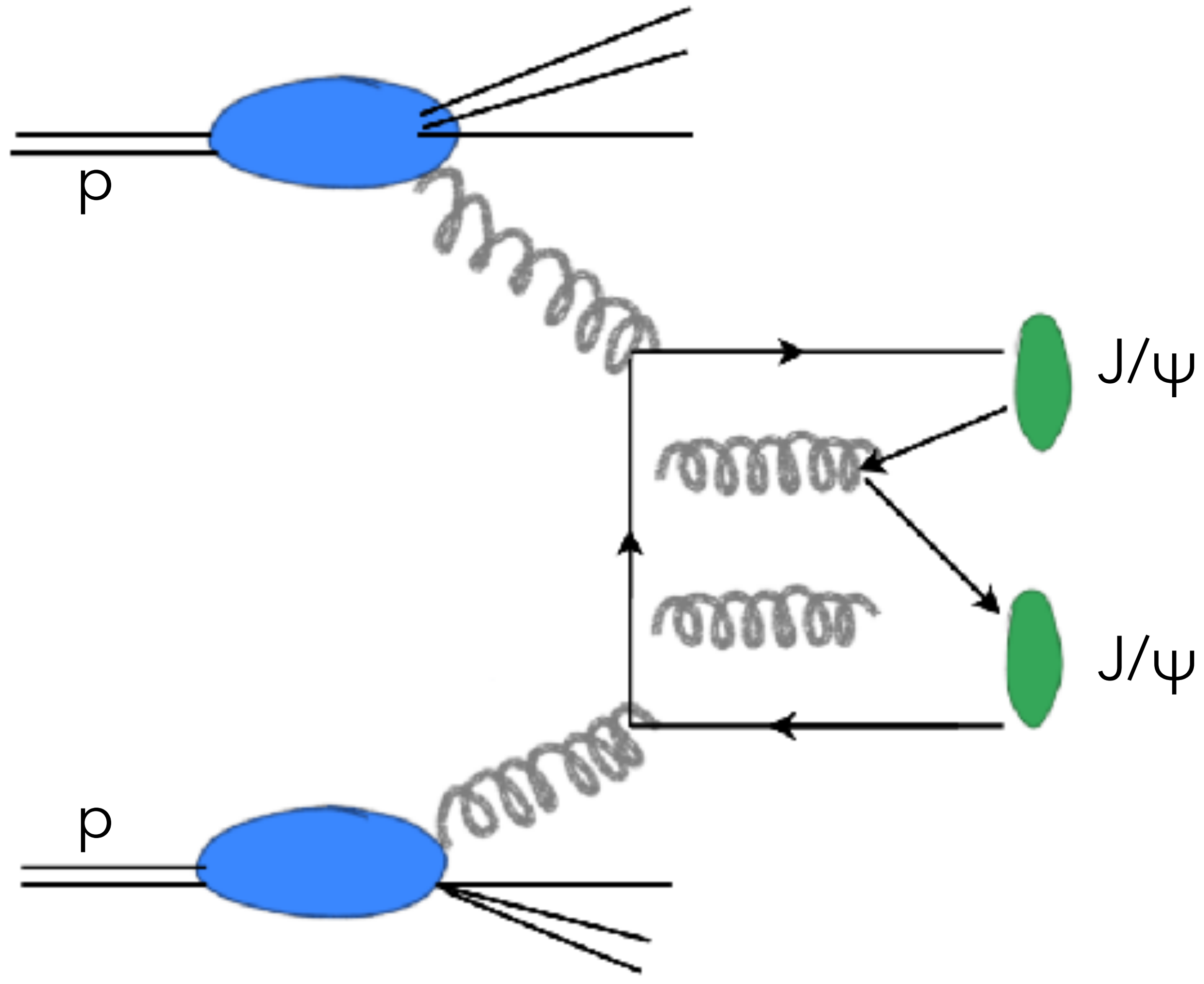
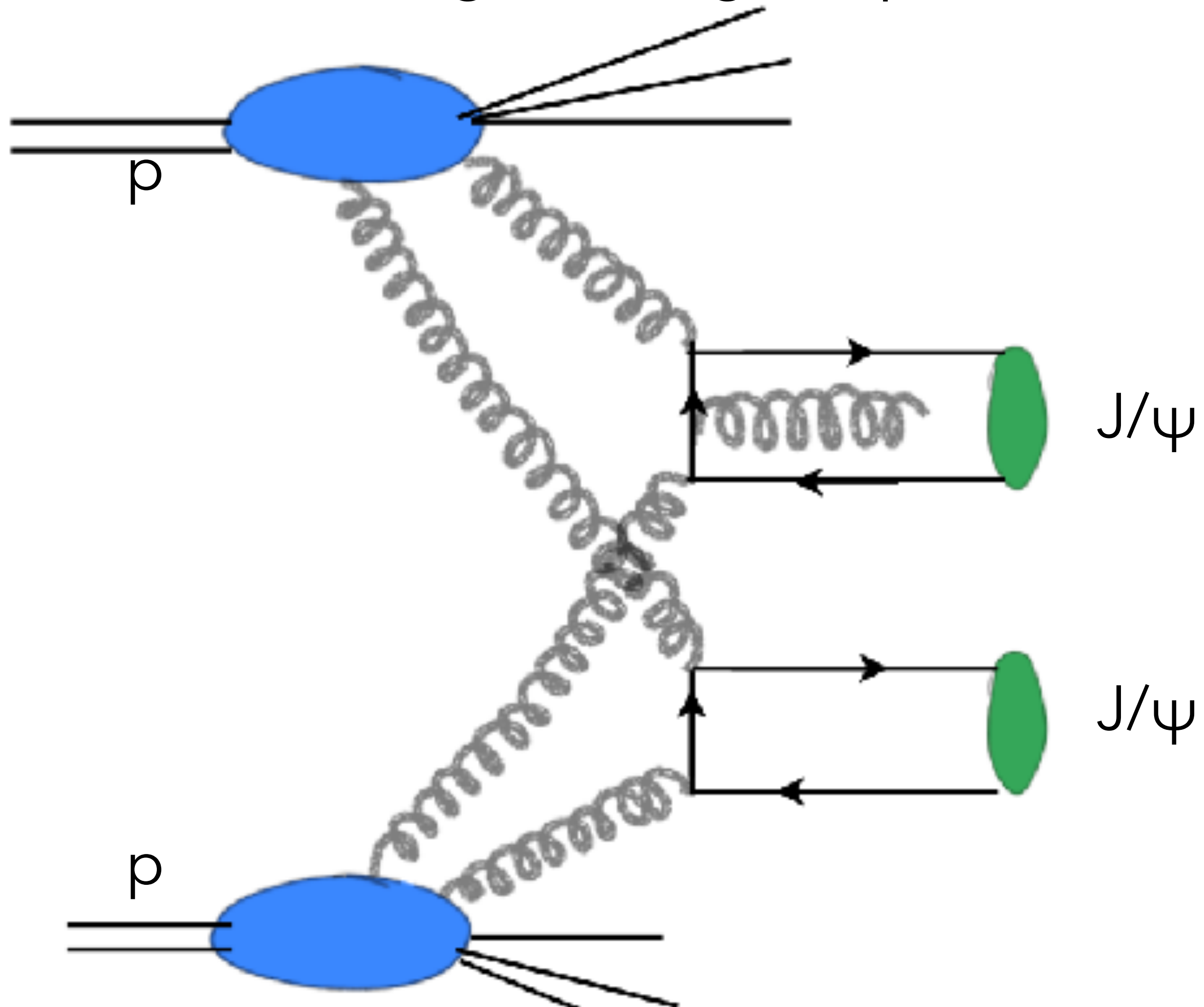
- Note: experimentally challenging to separate SPS-DPS (go to large Δη?)



Single Parton Scattering



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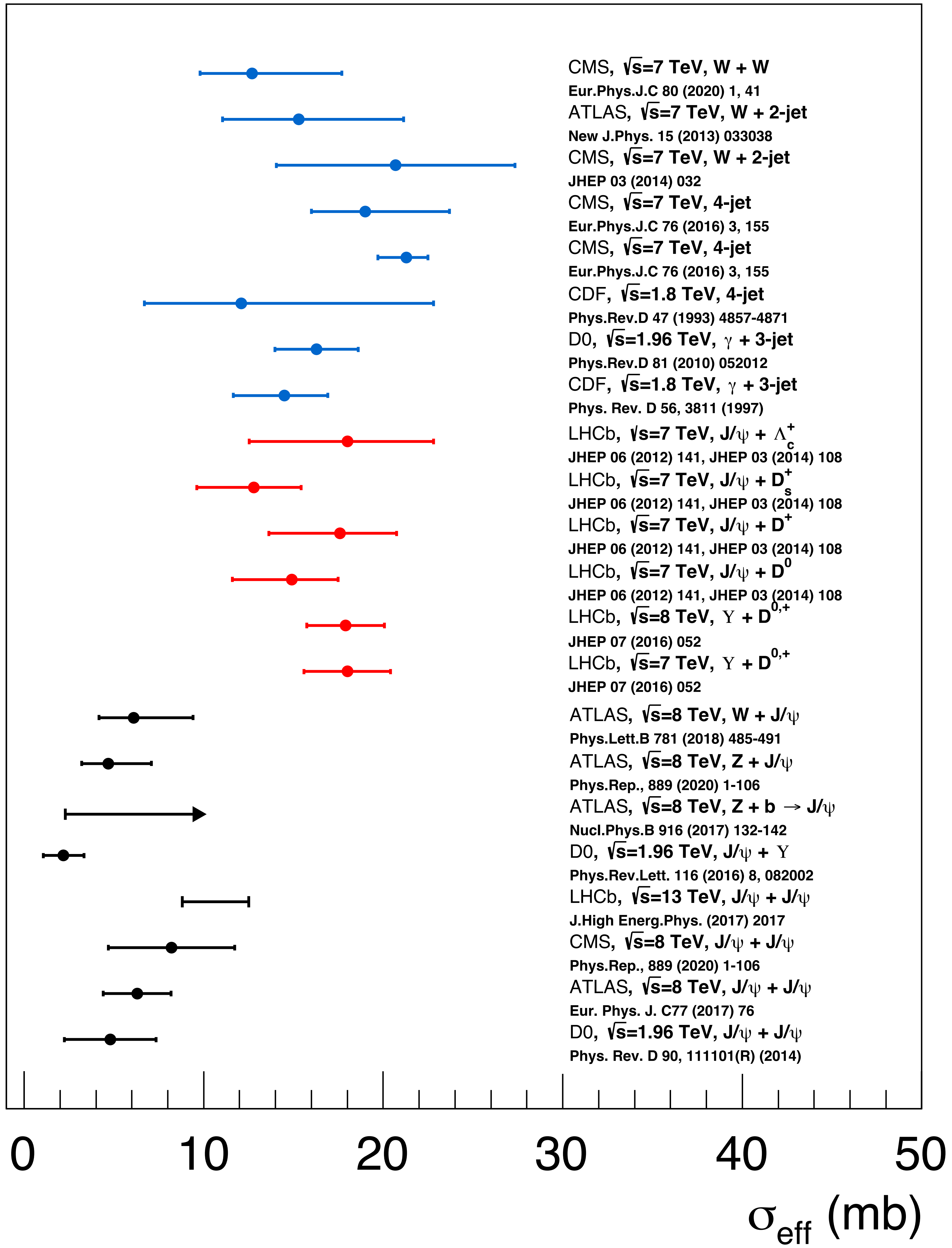

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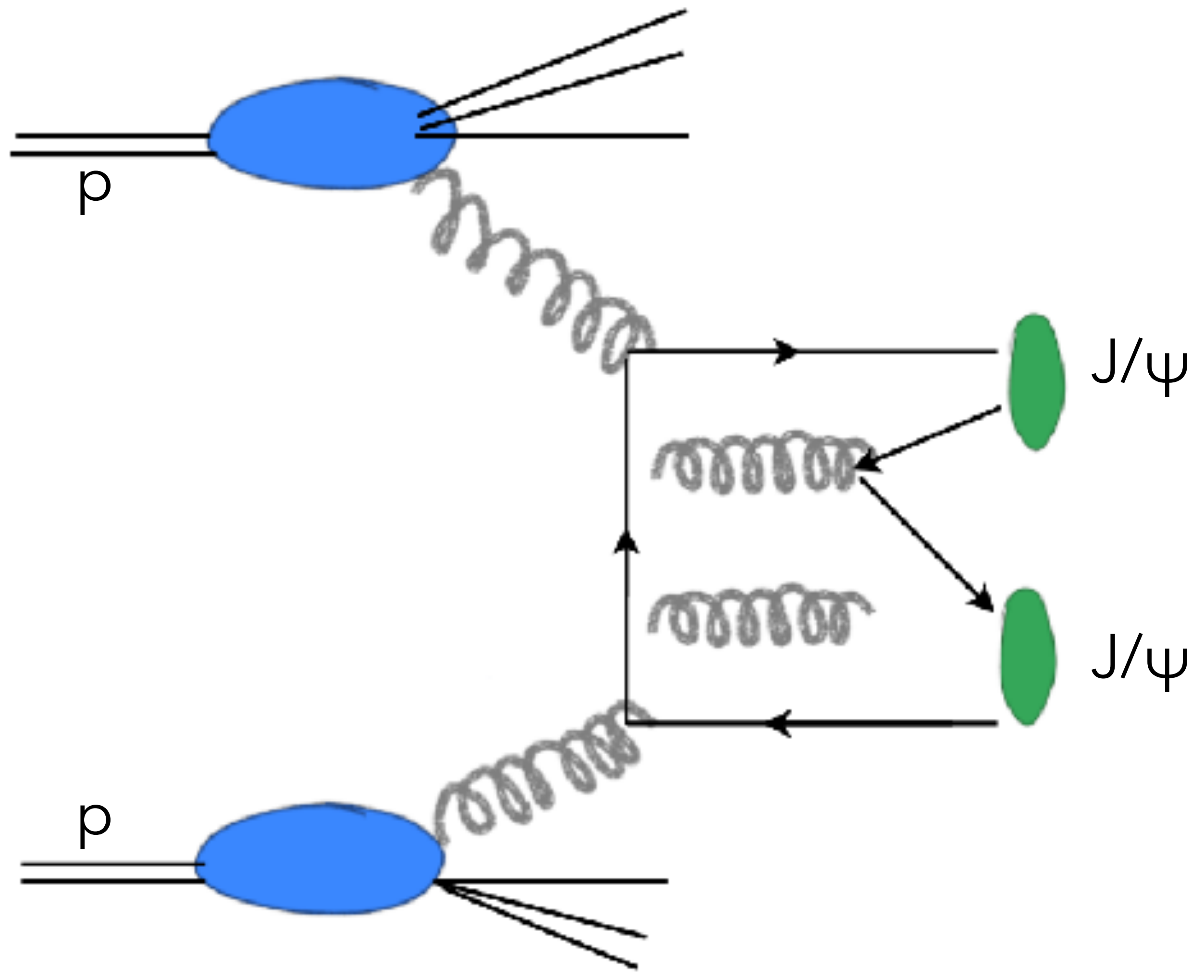

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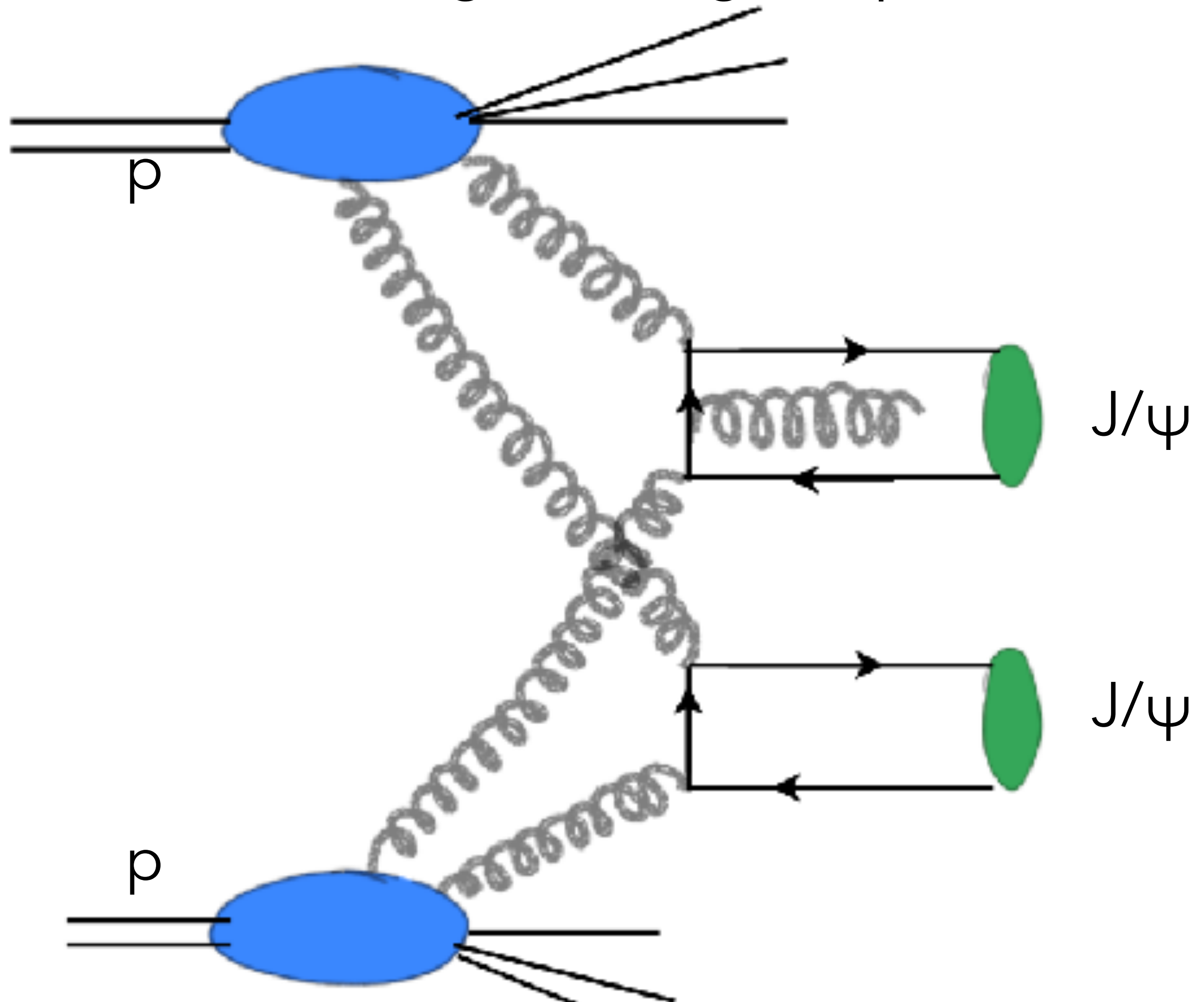

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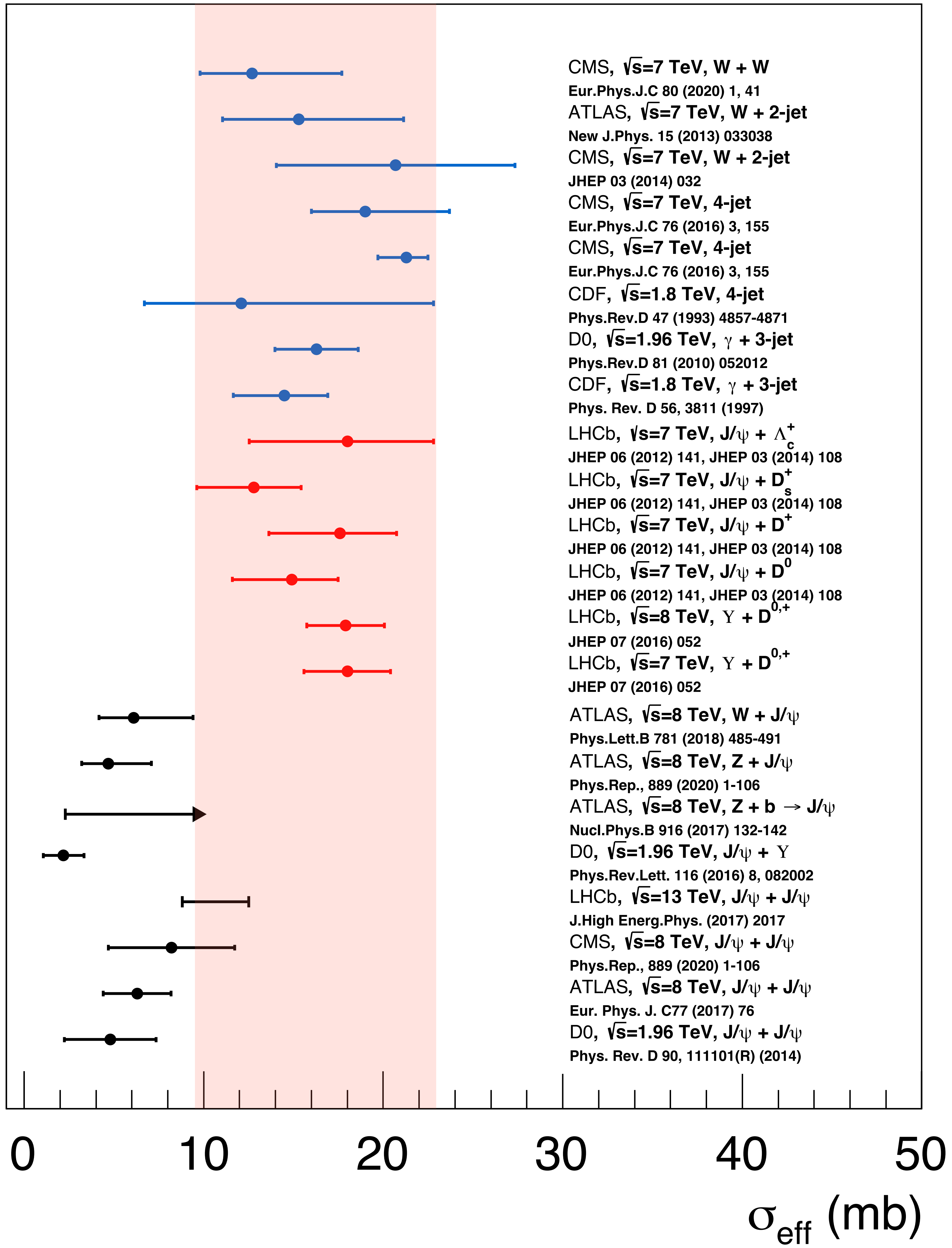

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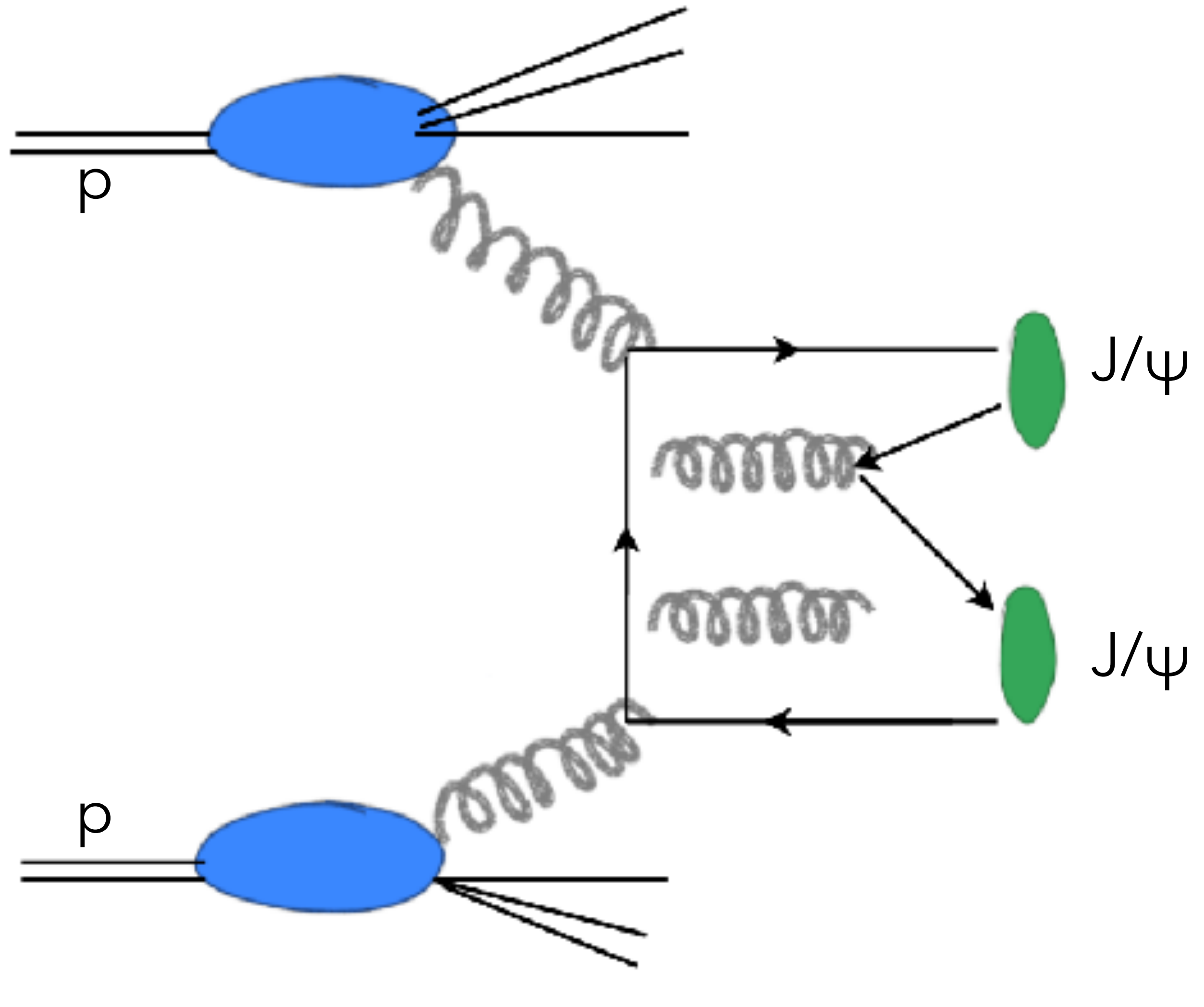

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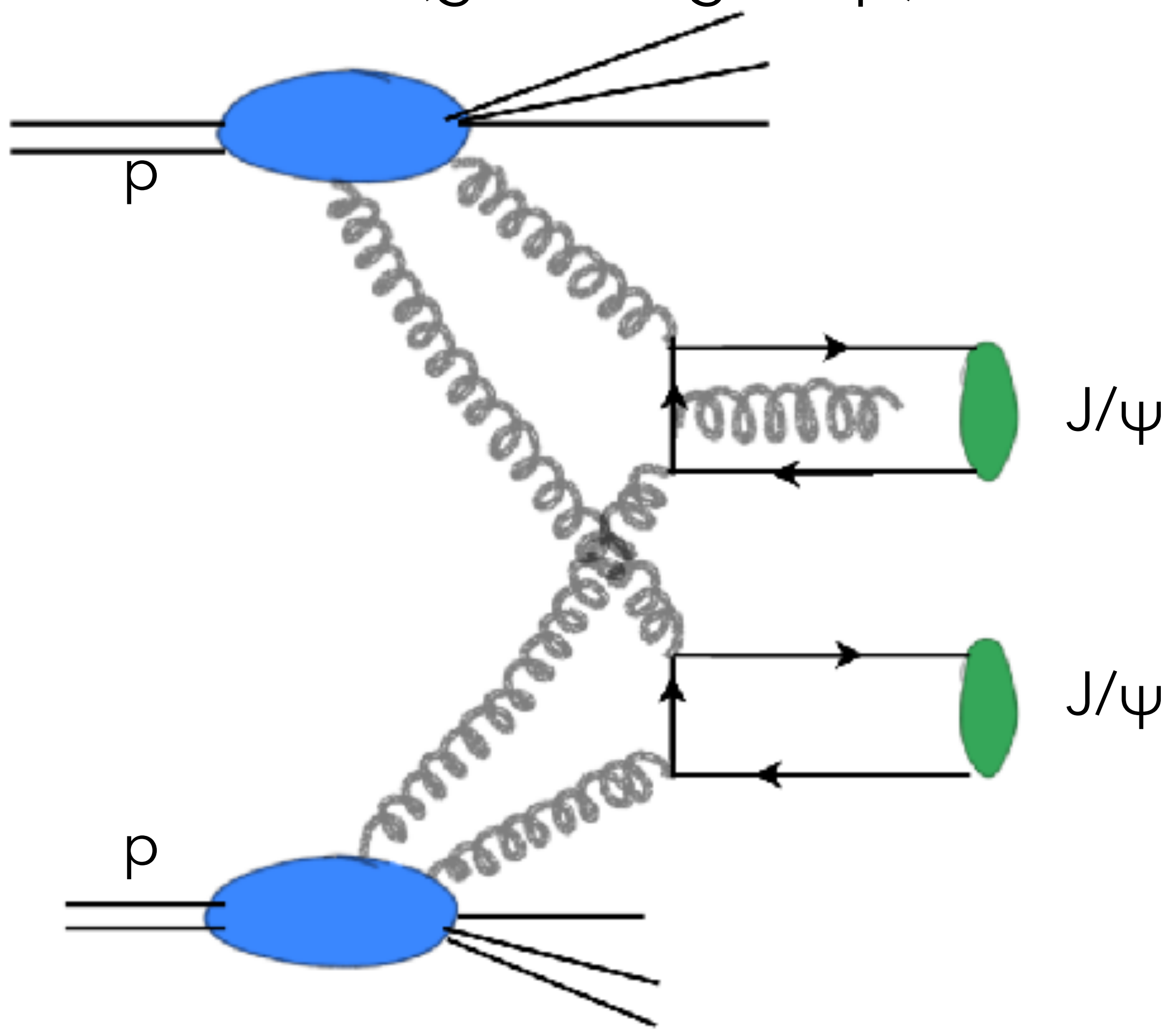

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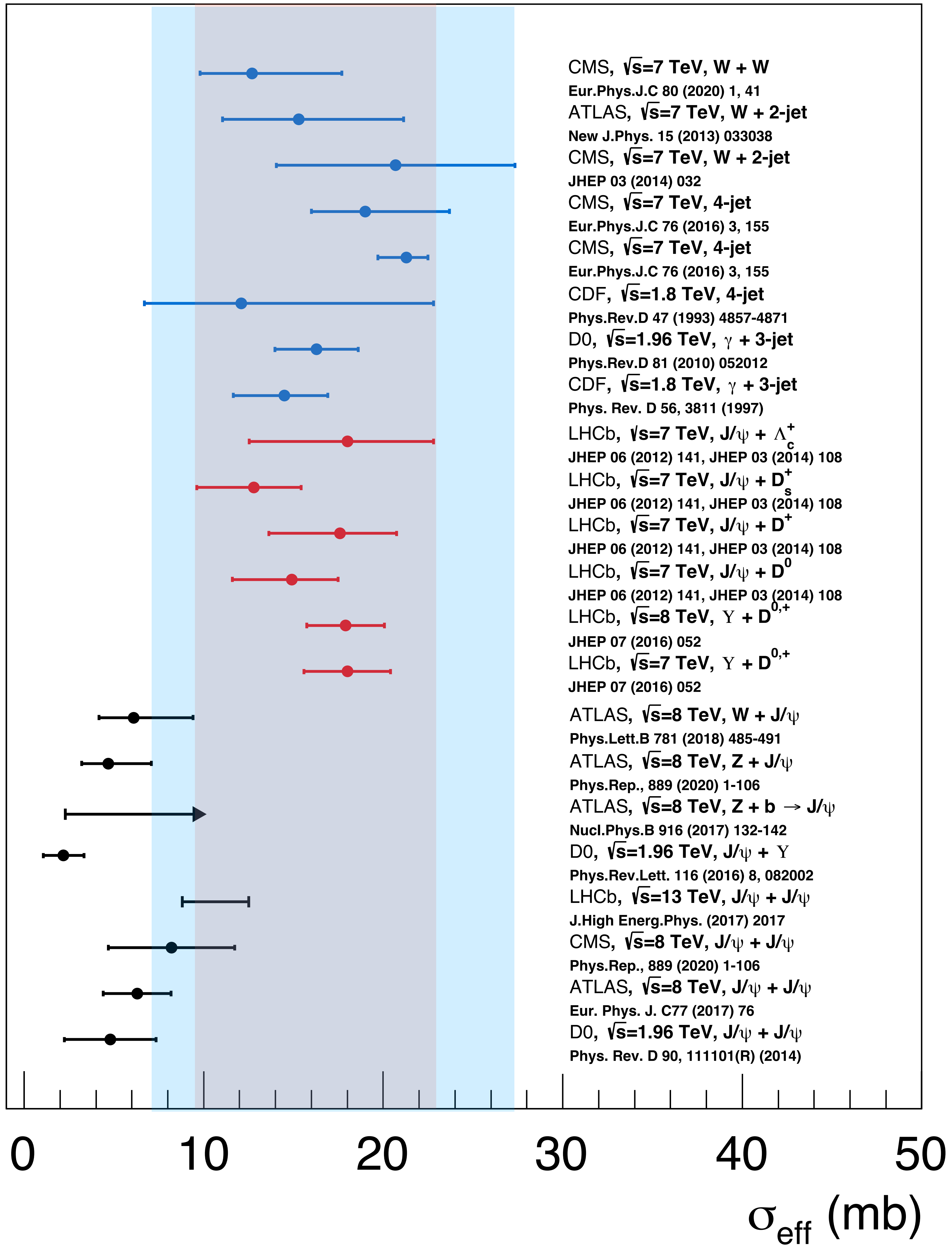

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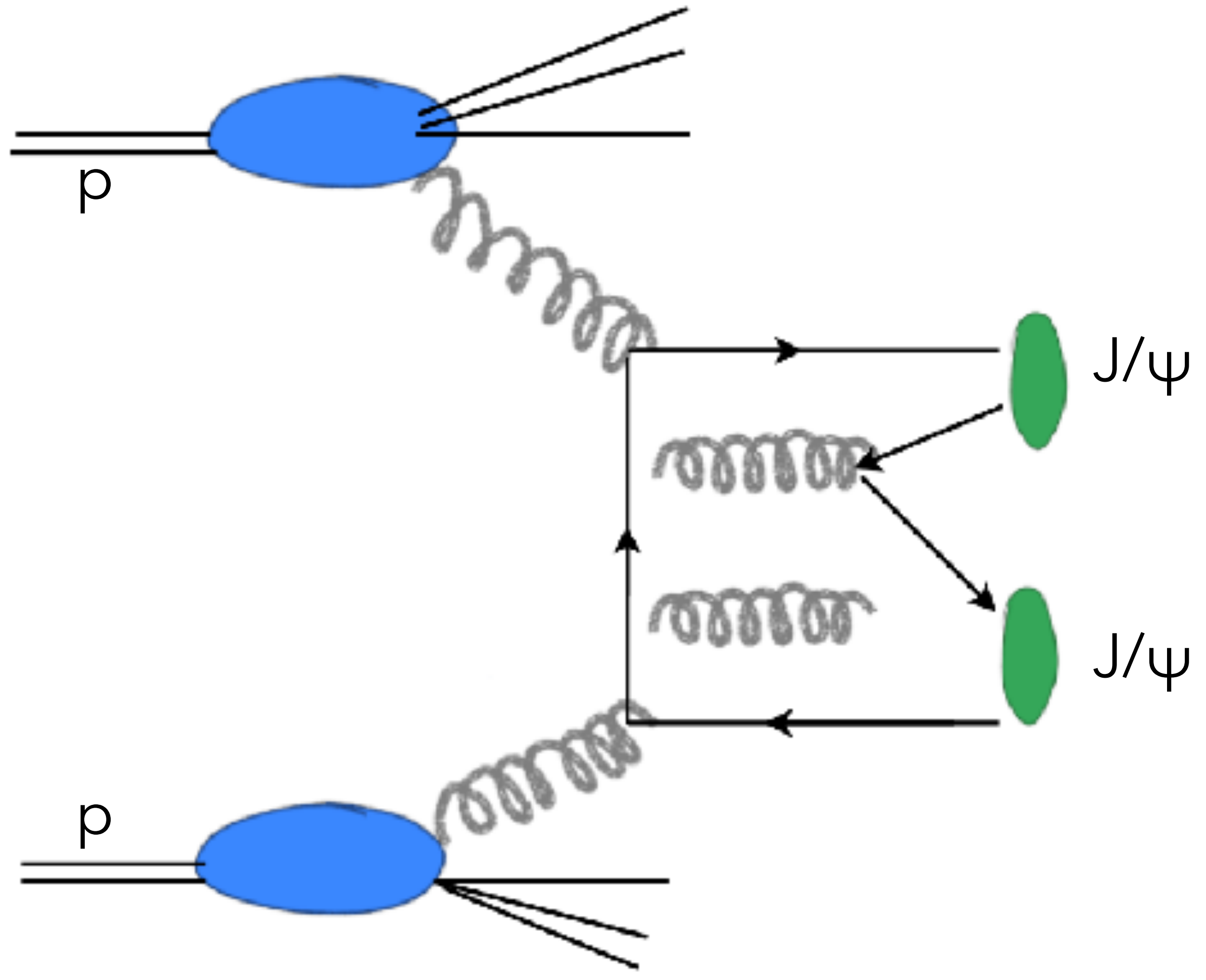

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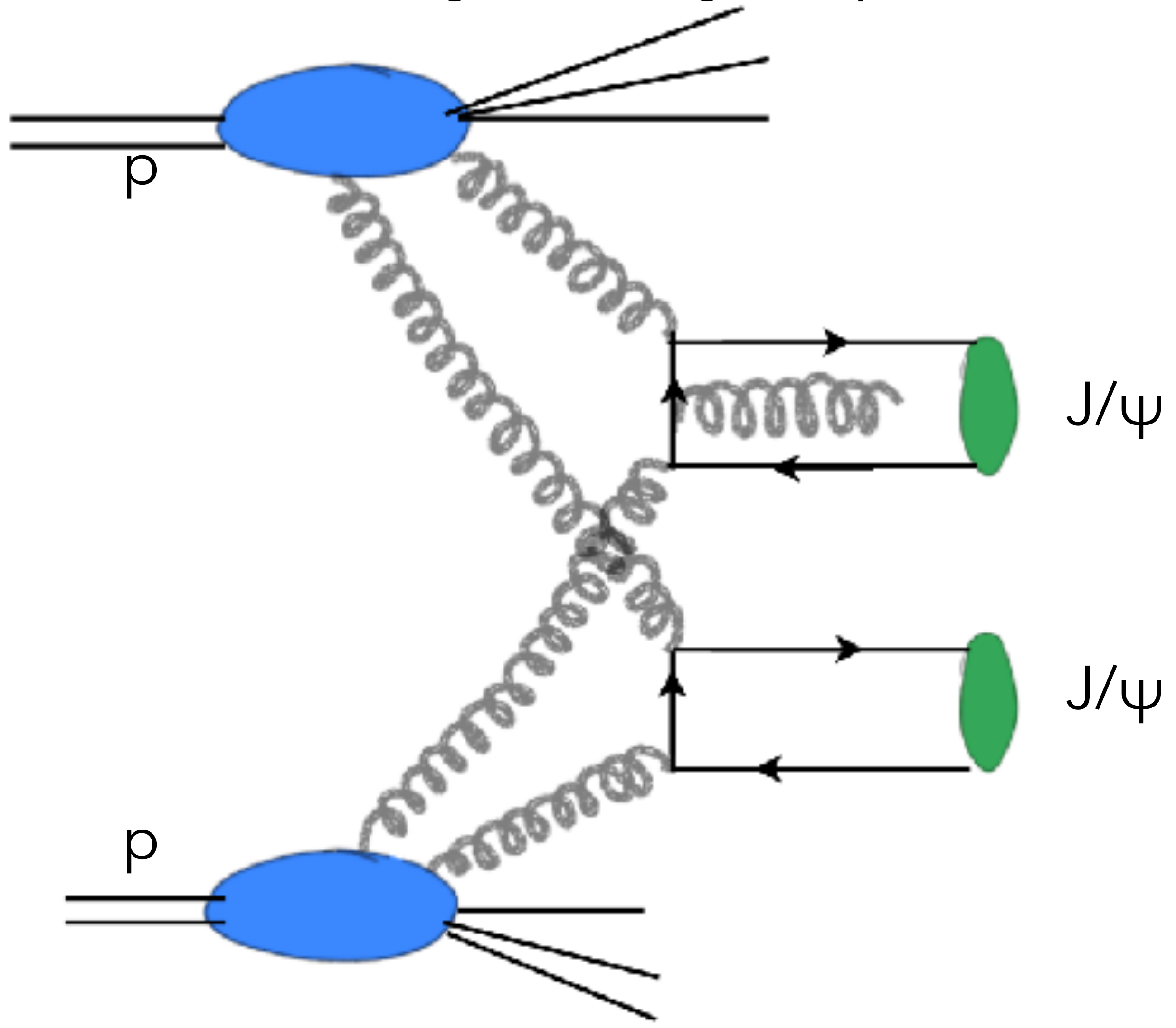

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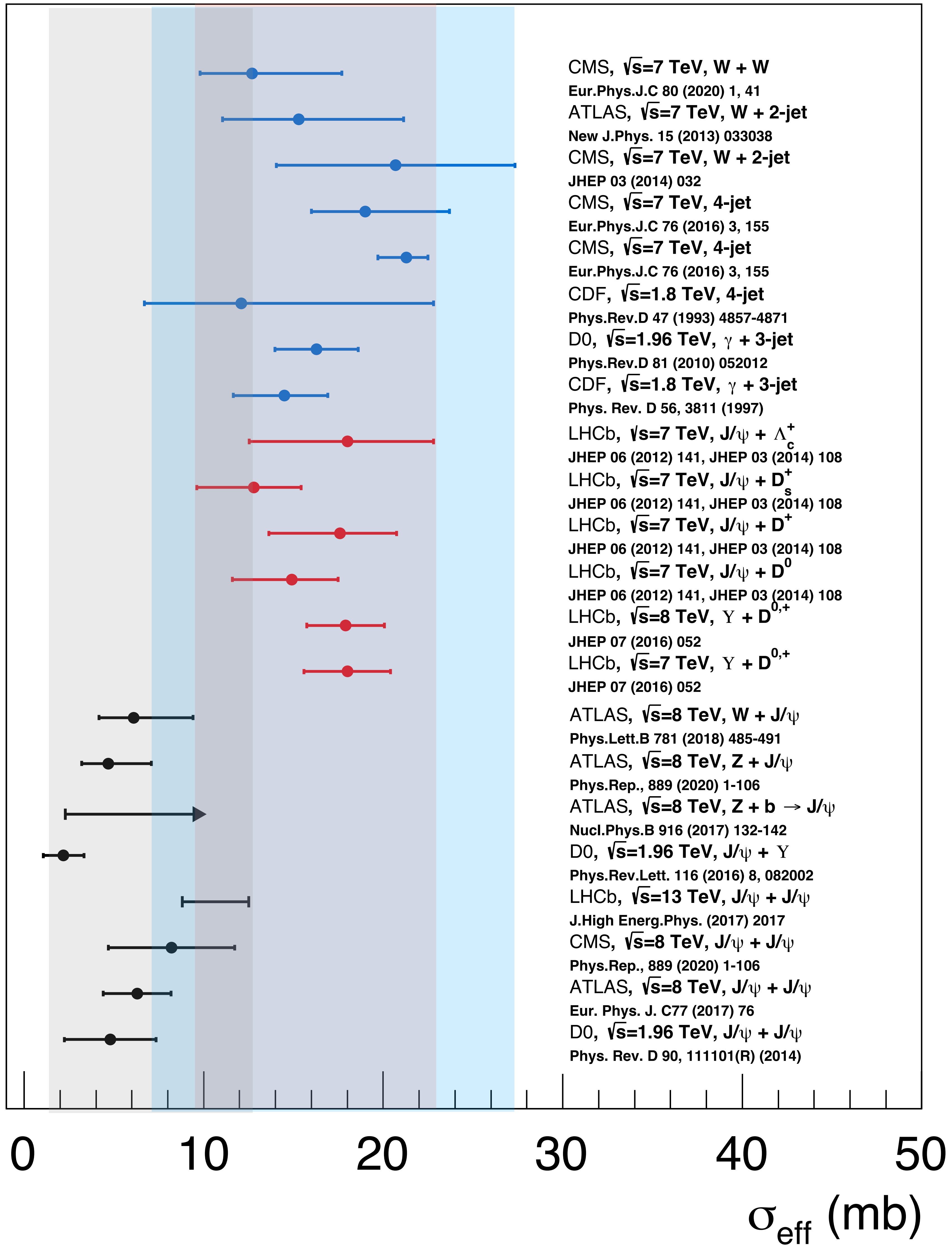
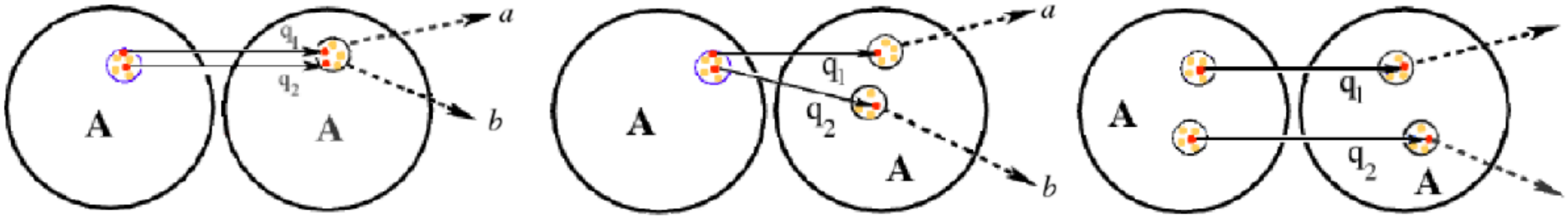
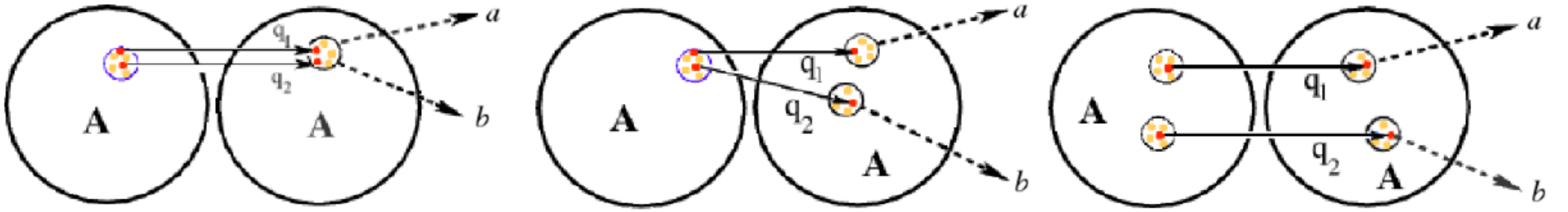


Double parton scattering in pA/AA collisions



$\sigma^{\mathrm{DPS},1}_{AA\to ab} = A^2 \cdot \sigma^{\mathrm{DPS}}_{NN\to ab}$ $\quad$ $\sigma^{\mathrm{DPS},2}_{AA\to ab} = 2\sigma^{\mathrm{DPS}}_{NN\to ab} \cdot \sigma_{\mathrm{eff,pp}} \cdot (A-1) \cdot T_{AA}(0)$ $\quad$ $\sigma^{\mathrm{DPS},3}_{AA\to ab} \approx \sigma^{\mathrm{DPS}}_{NN\to ab} \cdot \sigma_{\mathrm{eff,pp}} \cdot A^2/2 \cdot T_{AA}(0)$

Double parton scattering in pA/AA collisions



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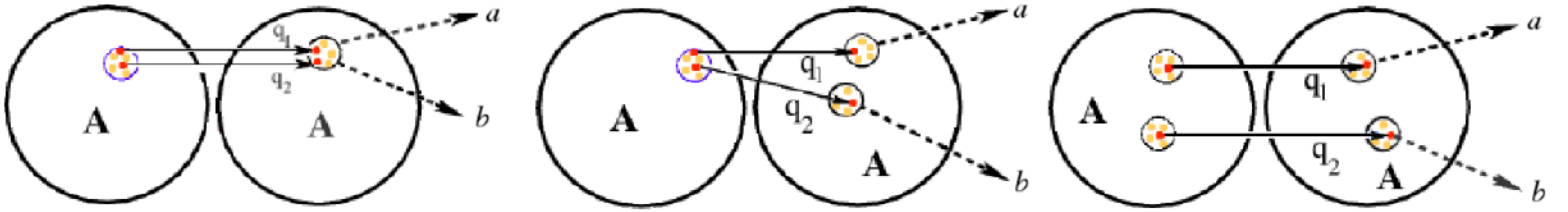
- Three contributions to the DPS cross section in AA collisions.
  Alternative to extract the effective cross section.

Double parton scattering in pA/AA collisions



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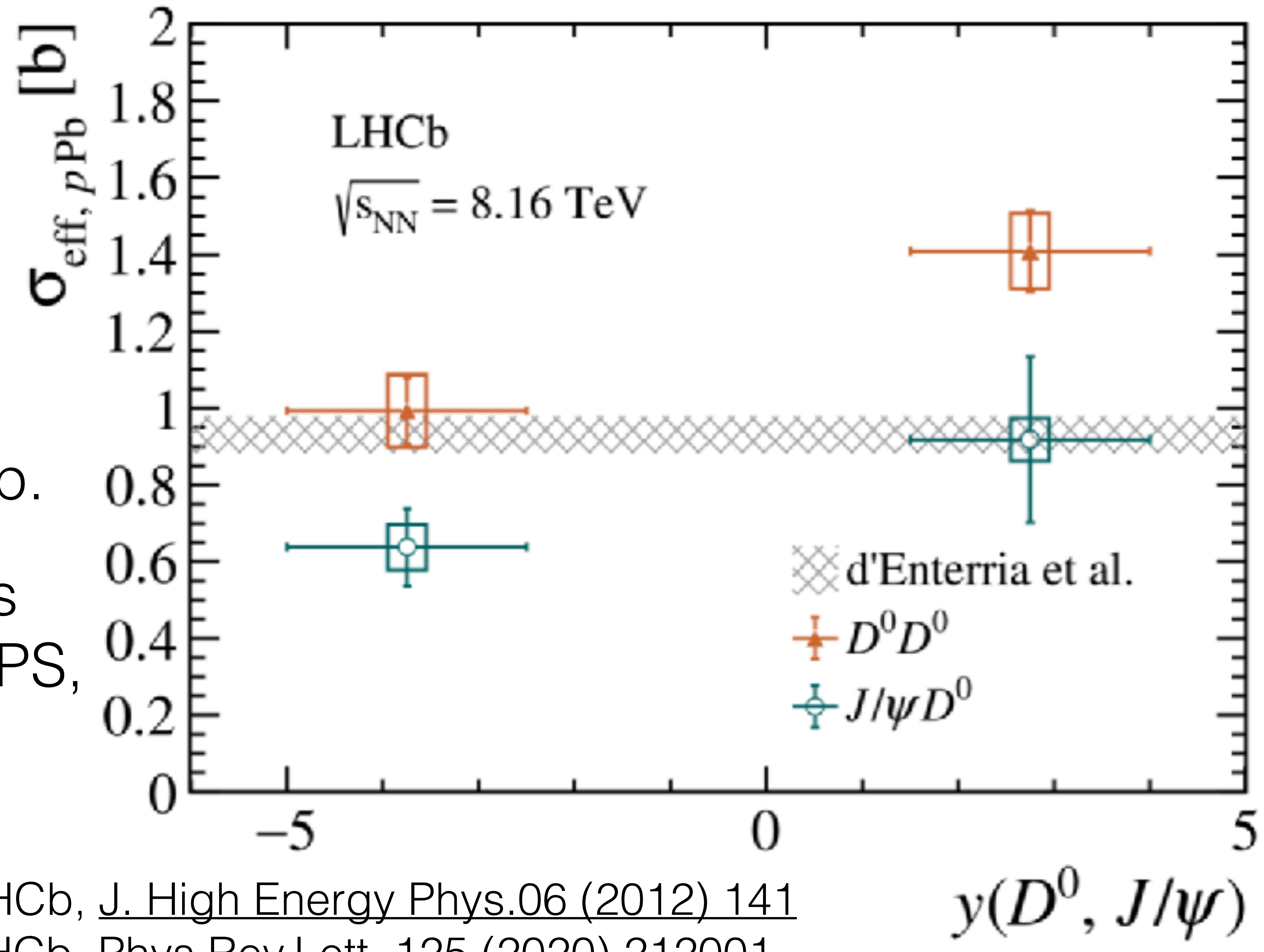
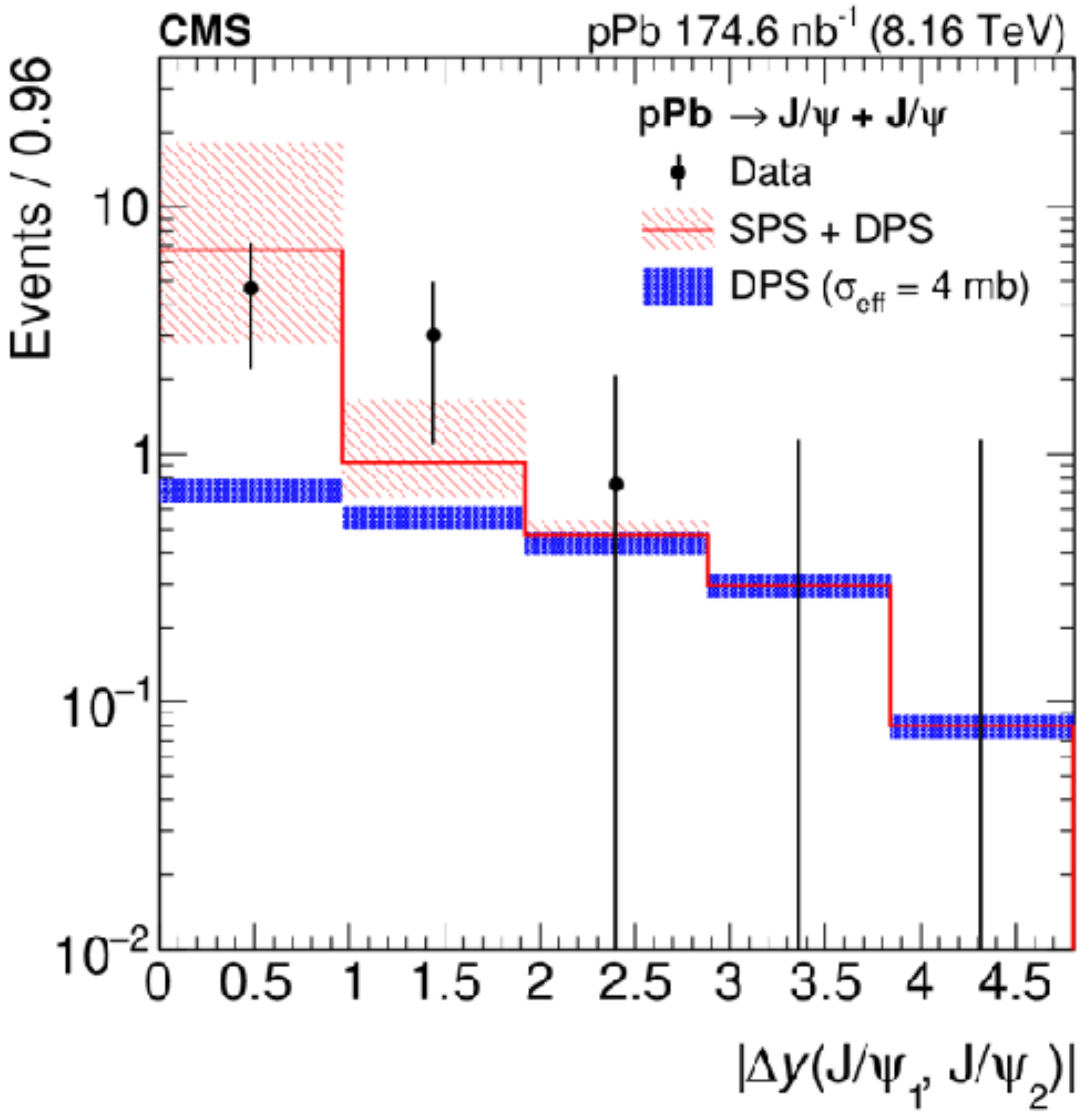
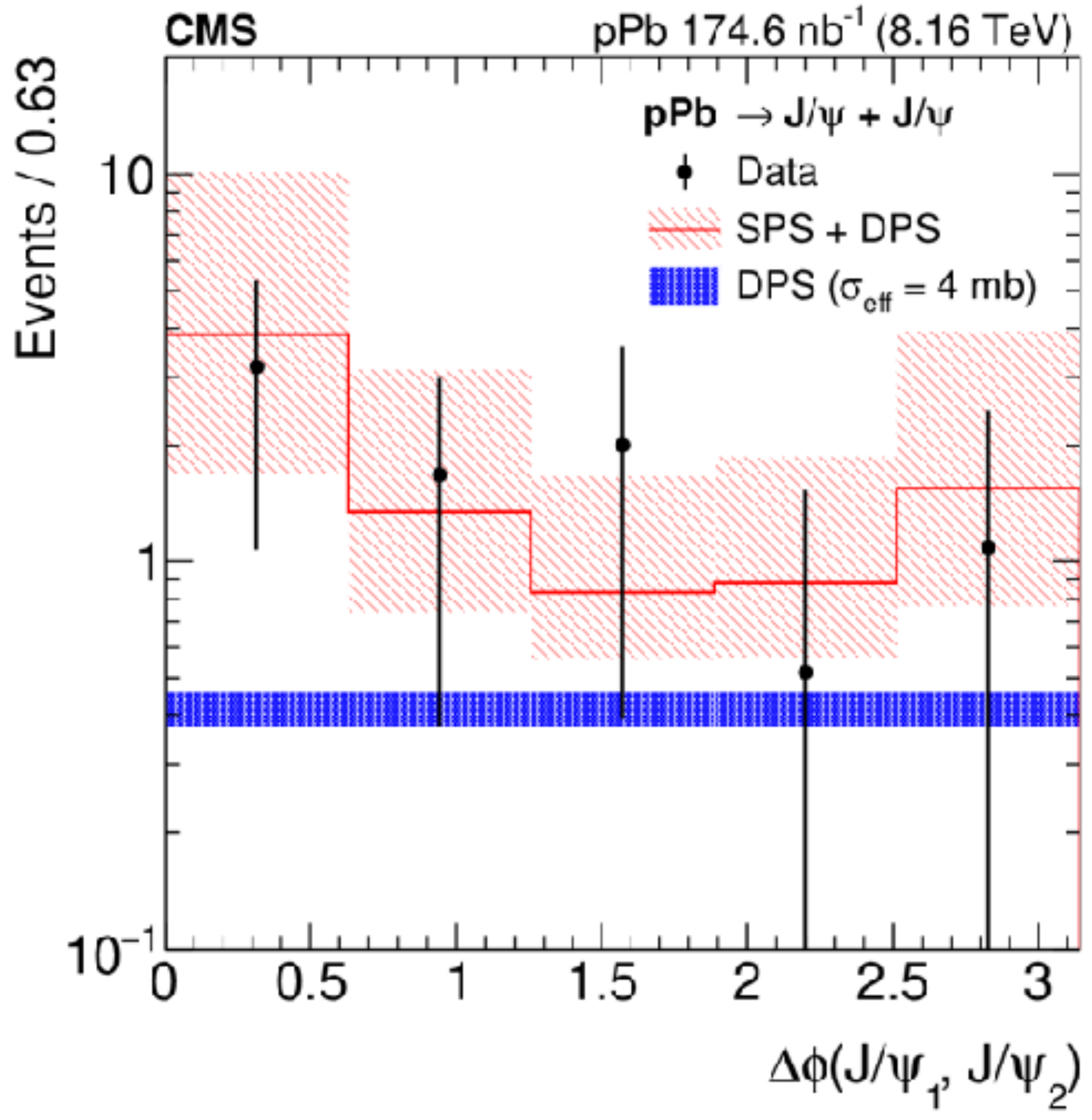
- Three contributions to the DPS cross section in AA collisions. **Alternative to extract the effective cross section**.
- **First observation of DPS in pPb** collisions by LHCb!
- DPS contribution enhanced in pPb by a factor of 3 with respect to pp.
- Interpretation challenged by the dominant contribution of scatterings among partons from different nucleons, in addition to the genuine DPS, where interactions take place among partons within a nucleon.

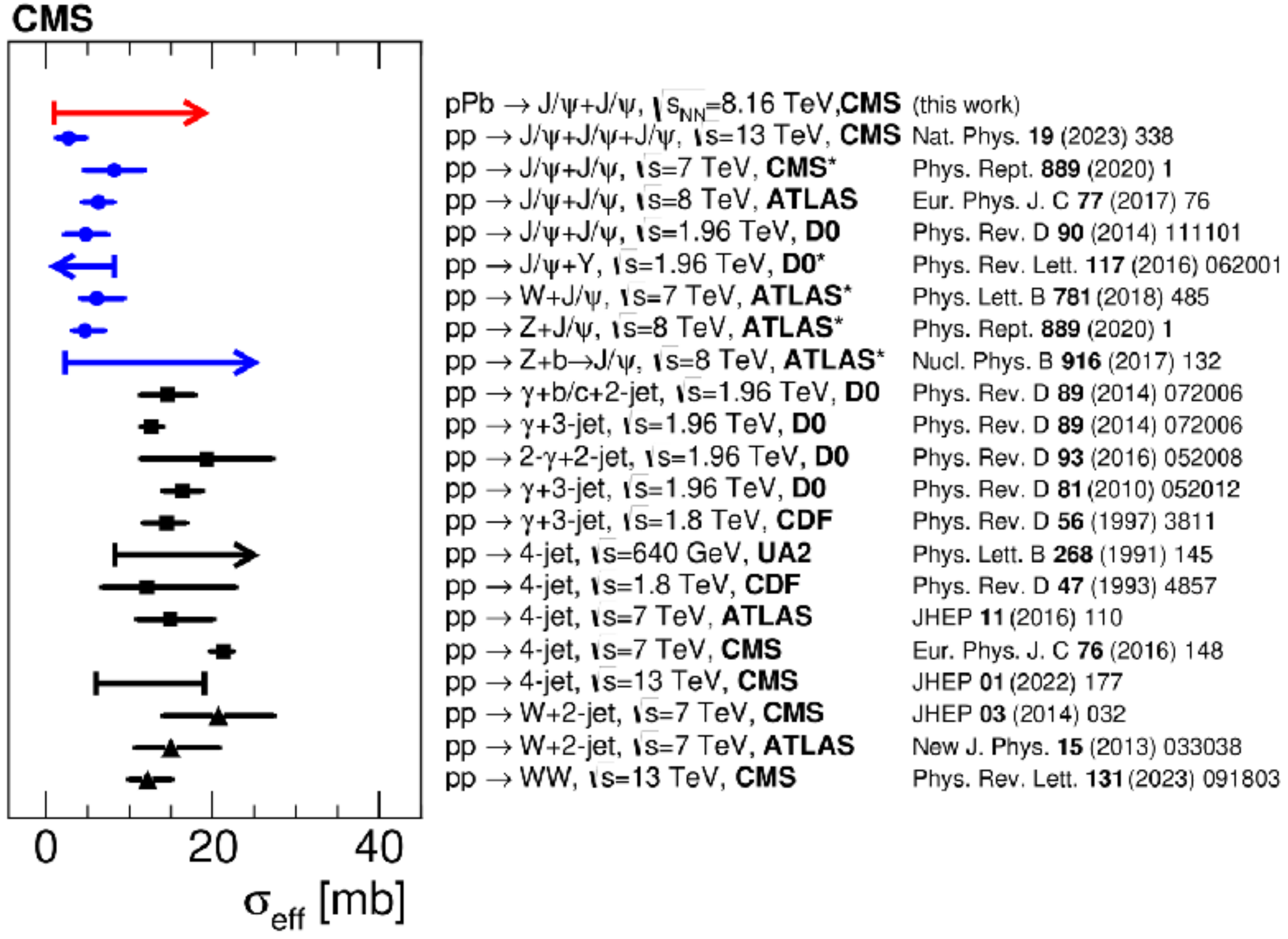


LHCb, J. High Energy Phys.06 (2012) 141
LHCb, Phys.Rev.Lett. 125 (2020) 212001

Double J/ψ production in pPb collisions







CMS, arXiv:2407.03223

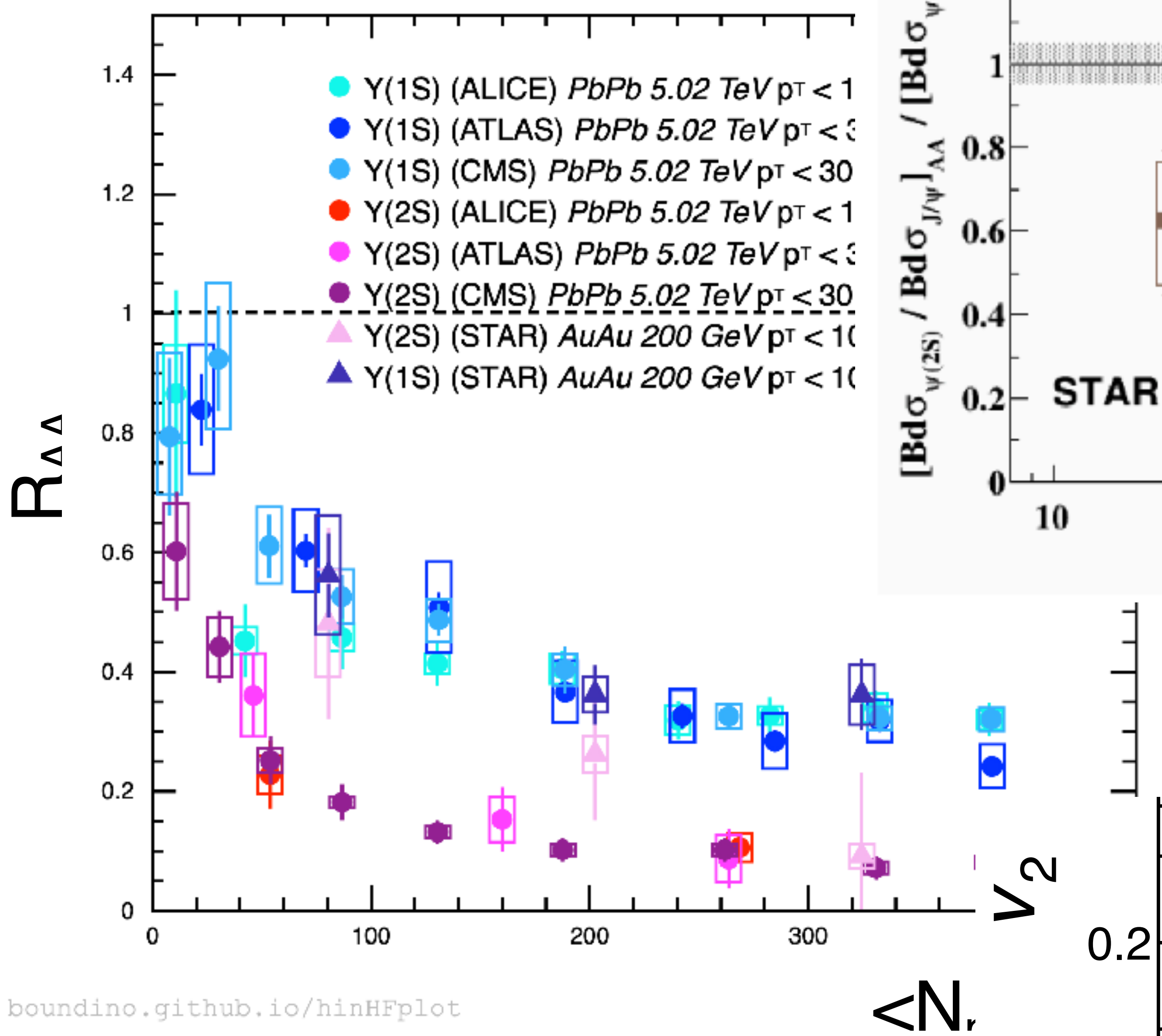
- **First observation of double J/ψ in pPb** collisions by CMS!
- Interpretation challenged by the dominant contribution of scatterings among partons from different nucleons, in addition to the genuine DPS, where interactions take place among partons within a nucleon.

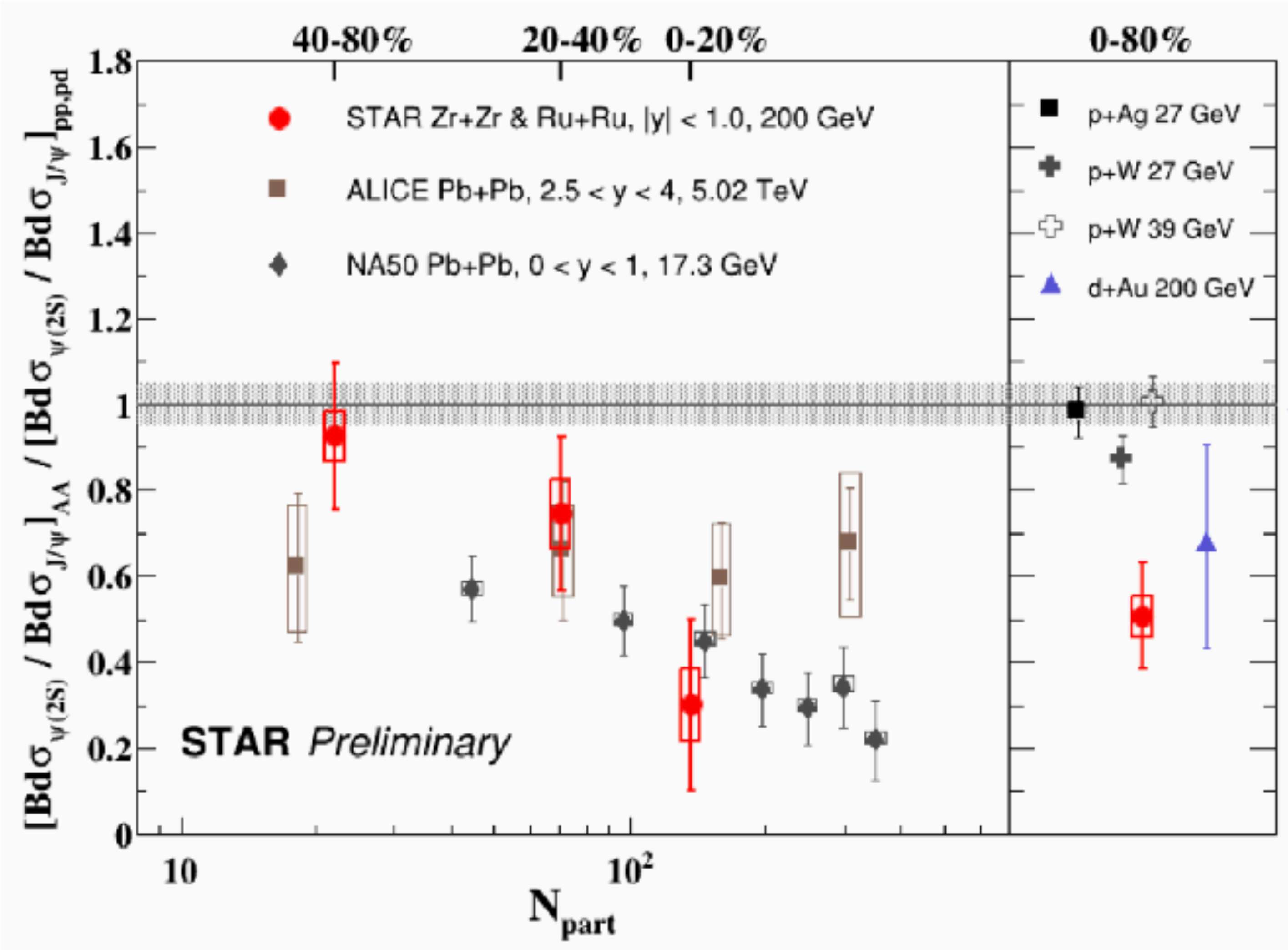
Take home message

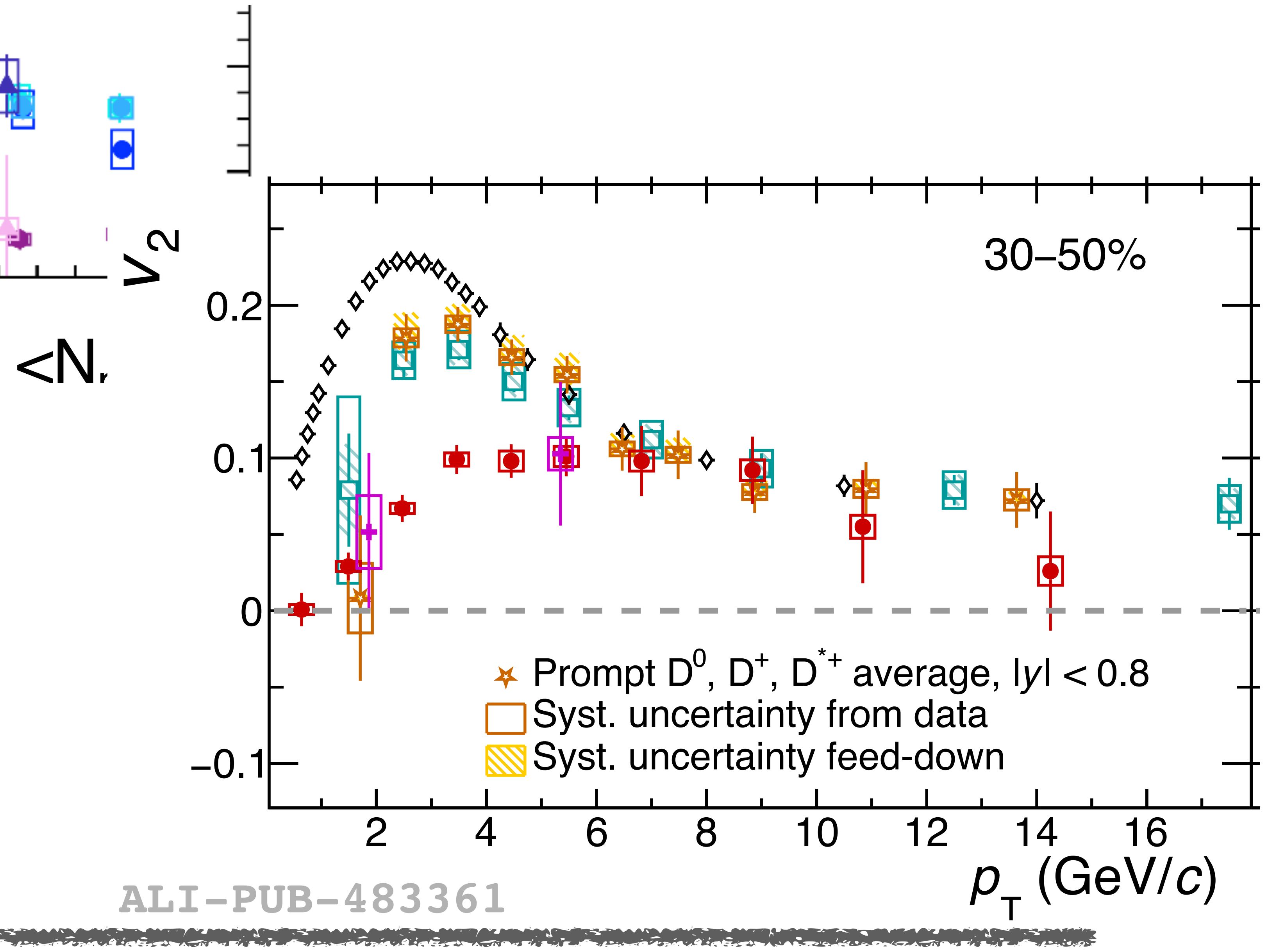
Laboratoire de Physique des 2 Infinis Irène Joliot-Curie

- Sequential dissociation of charmonia and bottomonia in heavy-ion collisions.
- Positive v_2 of J/ψ in PbPb and pPb collisions at high multiplicity.
- Interpreted as interplay of dissociation, regeneration and energy loss.
- The origin of the collective motion in small systems is still under debate. Important role of initial state effects and/or influence of final state effects?
- Non-negligible influence of multiparton interactions.

- Crucial to better quantify yields and collective motion of charmonia and bottomonia excited states across collision systems!







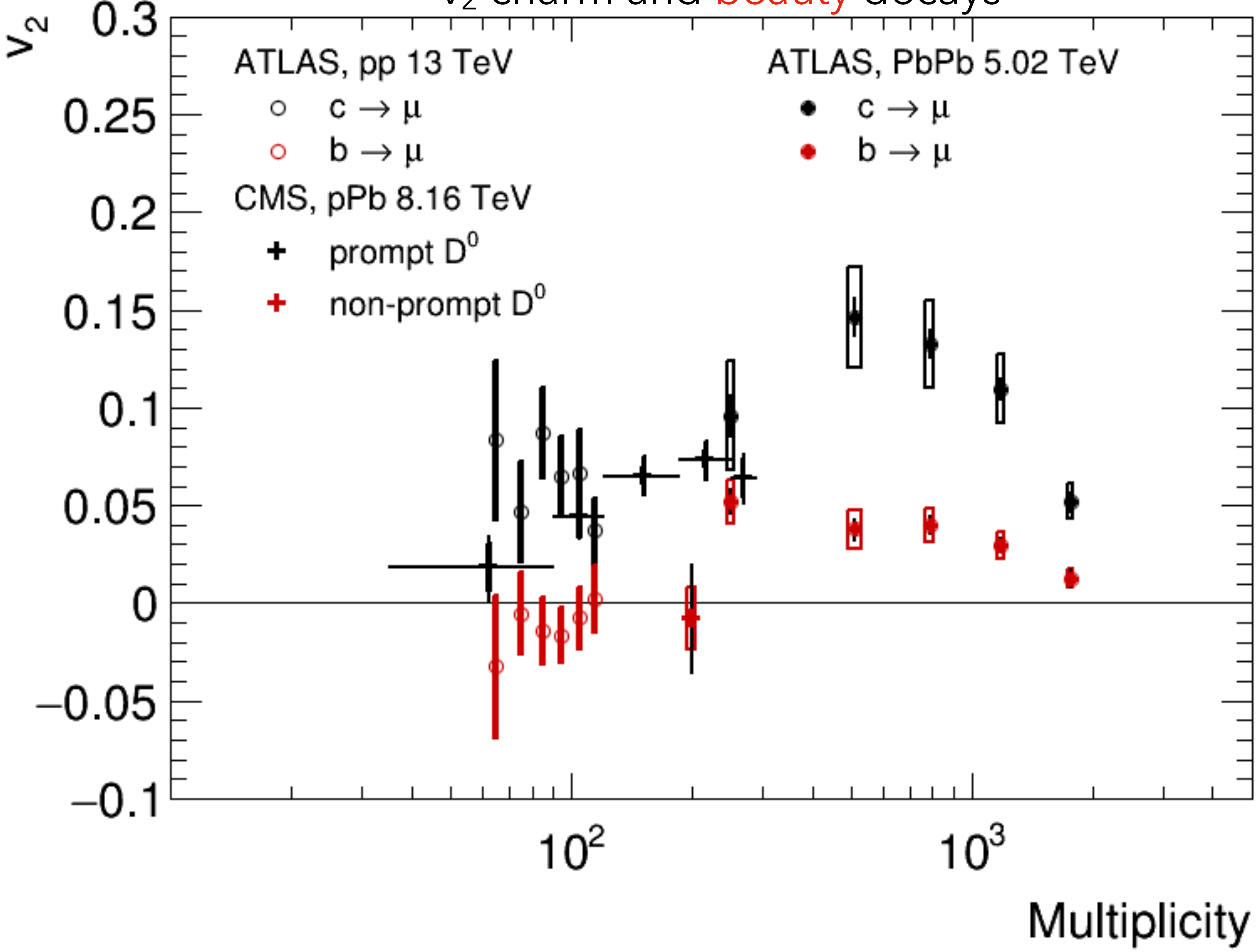
Big thank you to the organisers!

Special thanks to E. Ferreiro, L. Massacrier
for fruitful discussions and suggestions

Additional material

Zooming on v_2 across system size

v_2 charm and beauty decays

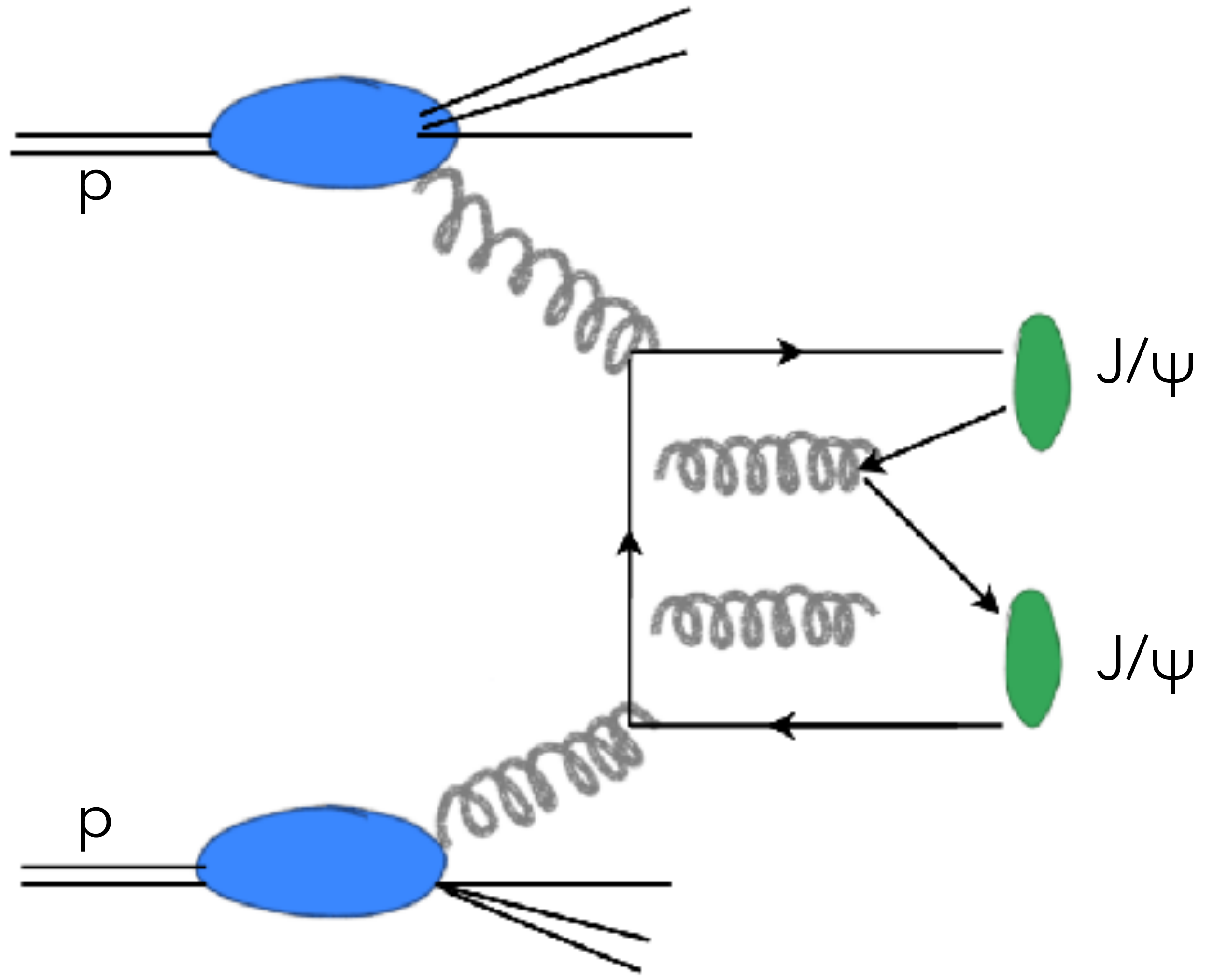


STAR, PLB 844 (2023) 138071
ATLAS, pp, PRL 124 (2020) 082301
ATLAS, PbPb, PLB 807 (2020) 135595
CMS, pPb, prompt D^0, PRL 121 (2018) 8, 082301
CMS, pPb, non-prompt D^0, PRL 813 (2021) 136036
ALICE, pPb, JHEP 2019 (2019) 92
LHCb, D^0, arXiv:2205.03936

- Heavy flavour v_2 follows **a smooth evolution with charged-particle multiplicity**
  - non-zero values for charm in pp and pPb collisions
  - important role of initial state effects and/or influence of final state effects?
- Crucial to quantify beauty v_2 in small systems

Associated production and multiparton interactions in pp

- Production of multiple (two, three,…) heavy flavour particles, be it D^0, J/ψ, ϒ,…
- Single parton scattering: can be treated by pQCD
- **n-parton scattering** (double, triple,…): need to reformulate quantum field theories
  - Generalised PDFs (x, Q_2, b) of the proton, including the unknown energy evolution of the proton transverse profile.
  - Role of partonic correlations in the wave functions (x, p, flavour, spin, colour,…).
  - Constrain heavy-flavour modelling.
  - Background for other studies (e.g. BSM resonance decays of multiple heavy particles).



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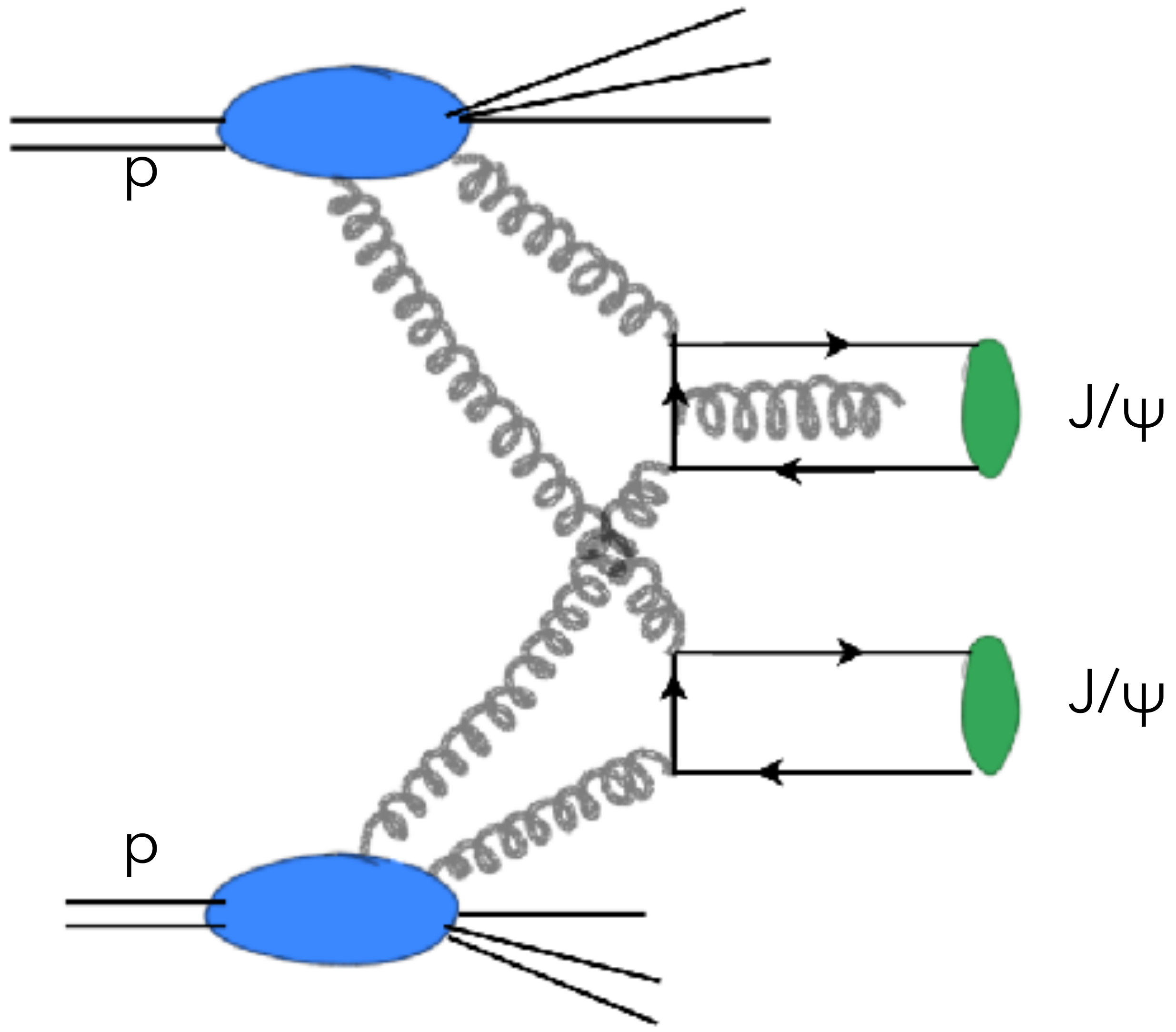

Double Parton Scattering

Brief picture of double parton scattering in pp

- In the **collinear factorisation approach**, assuming two parton GPD can be decomposed in longitudinal and transverse components, and neglecting correlations in the proton:

  $$\sigma_{1,2}^{\mathrm{DPS}} = \frac{m}{2\,\sigma_{\mathrm{eff}}}\,\sigma_1^{\mathrm{SPS}}\,\sigma_2^{\mathrm{SPS}}$$

  m=1 if 1=2, and 2 otherwise.
  The **effective cross section** is a (universal) constant related to the transverse overlap function between the partons of the proton.

- **Double particle production exploited to study DPS**: double quarkonium (J/ψ+J/ψ, J/ψ+ϒ,…), electroweak boson + quarkonium, double charm, charm+quarkonium, multi-jets, γ+n-3-jet, W+2-jet,…

- Effective cross section results:
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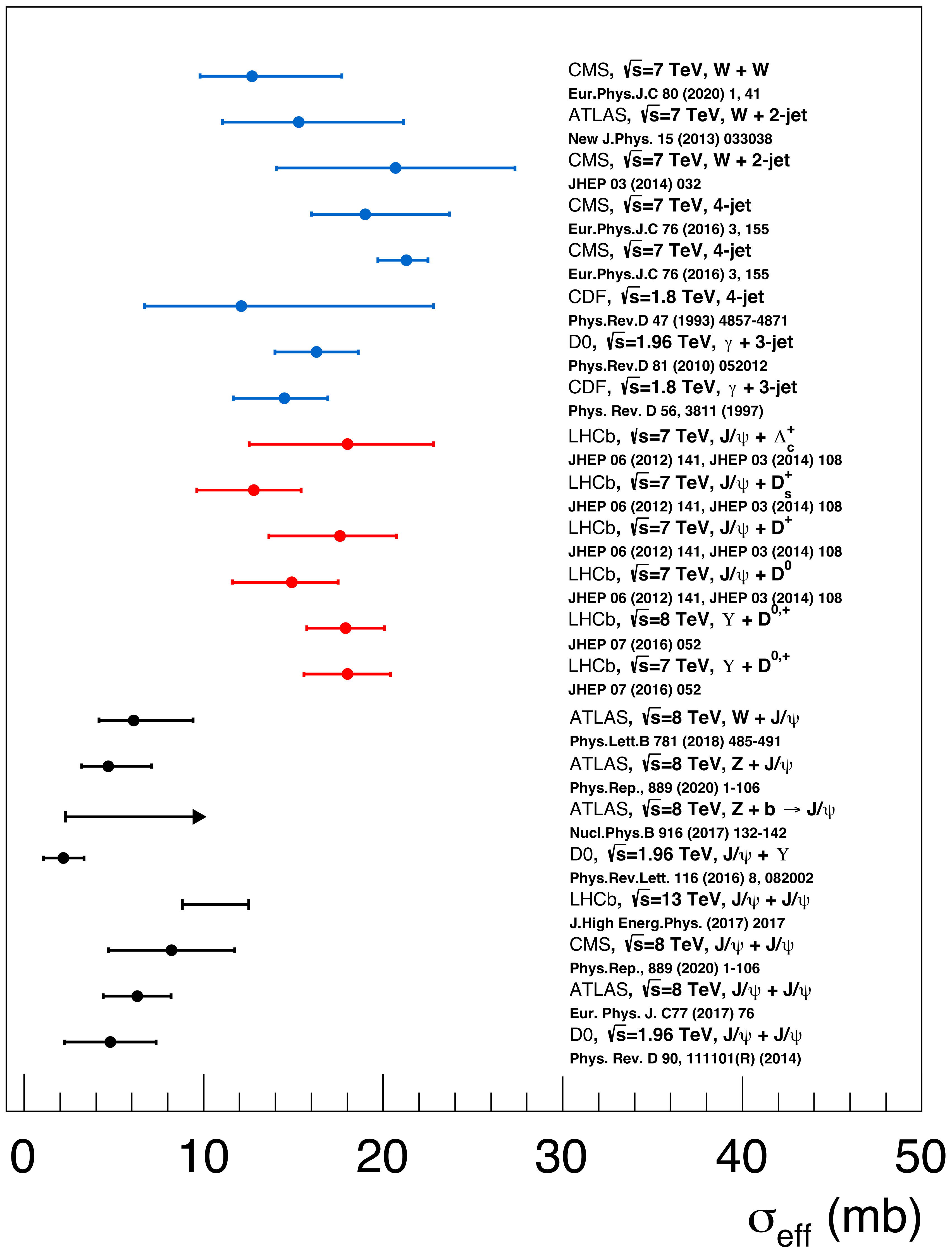

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  - J/ψ+C in agreement with multi-jet and double W,
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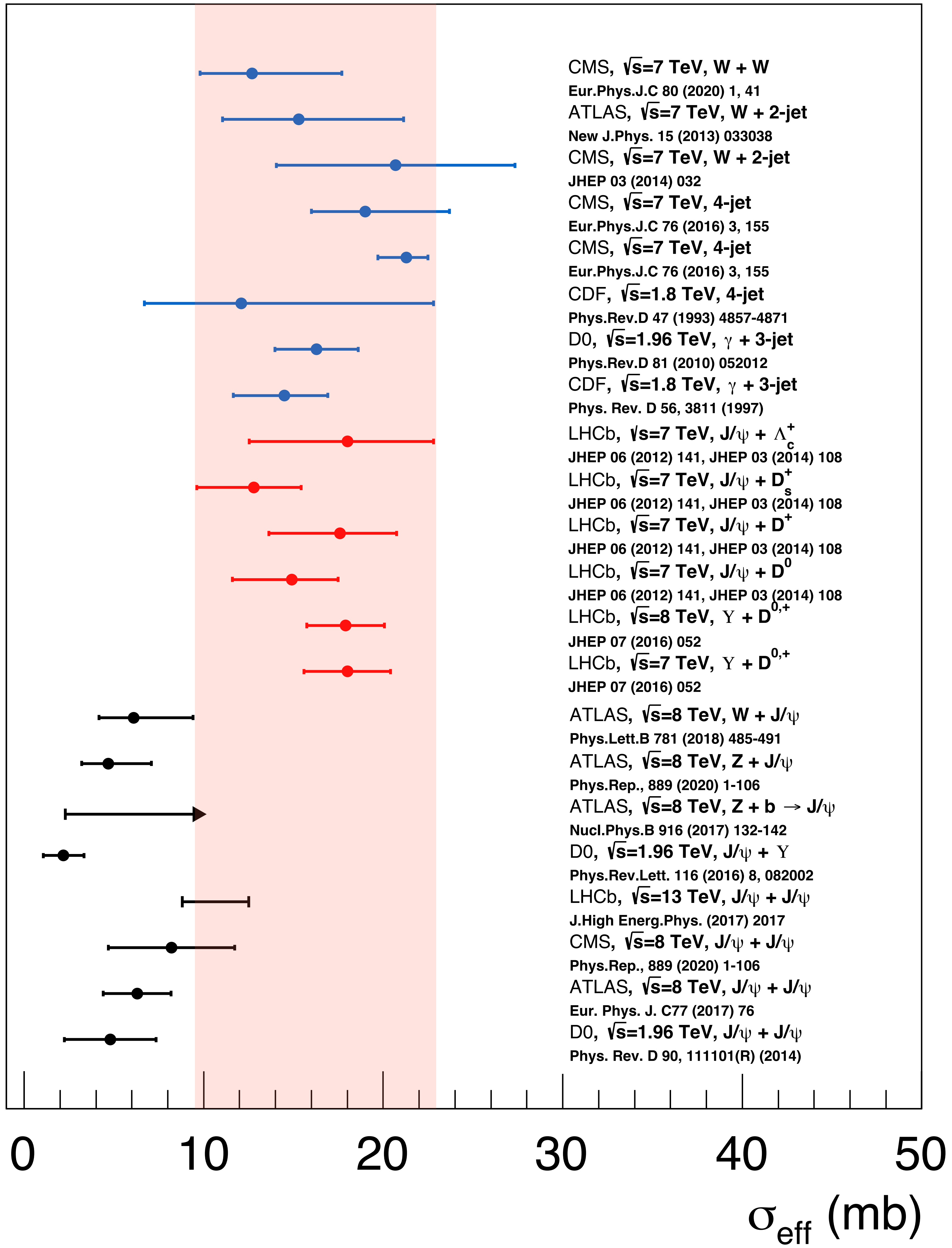

- Note: experimentally challenging to separate SPS-DPS (go to large Δη?)

Brief picture of double parton scattering in pp

- In the **collinear factorisation approach**, assuming two parton GPD can be decomposed in longitudinal and transverse components, and neglecting correlations in the proton:

  $$\sigma^{\mathrm{DPS}}_{1,2} = \frac{m}{2\,\sigma_{\mathrm{eff}}}\,\sigma^{\mathrm{SPS}}_{1}\,\sigma^{\mathrm{SPS}}_{2}$$

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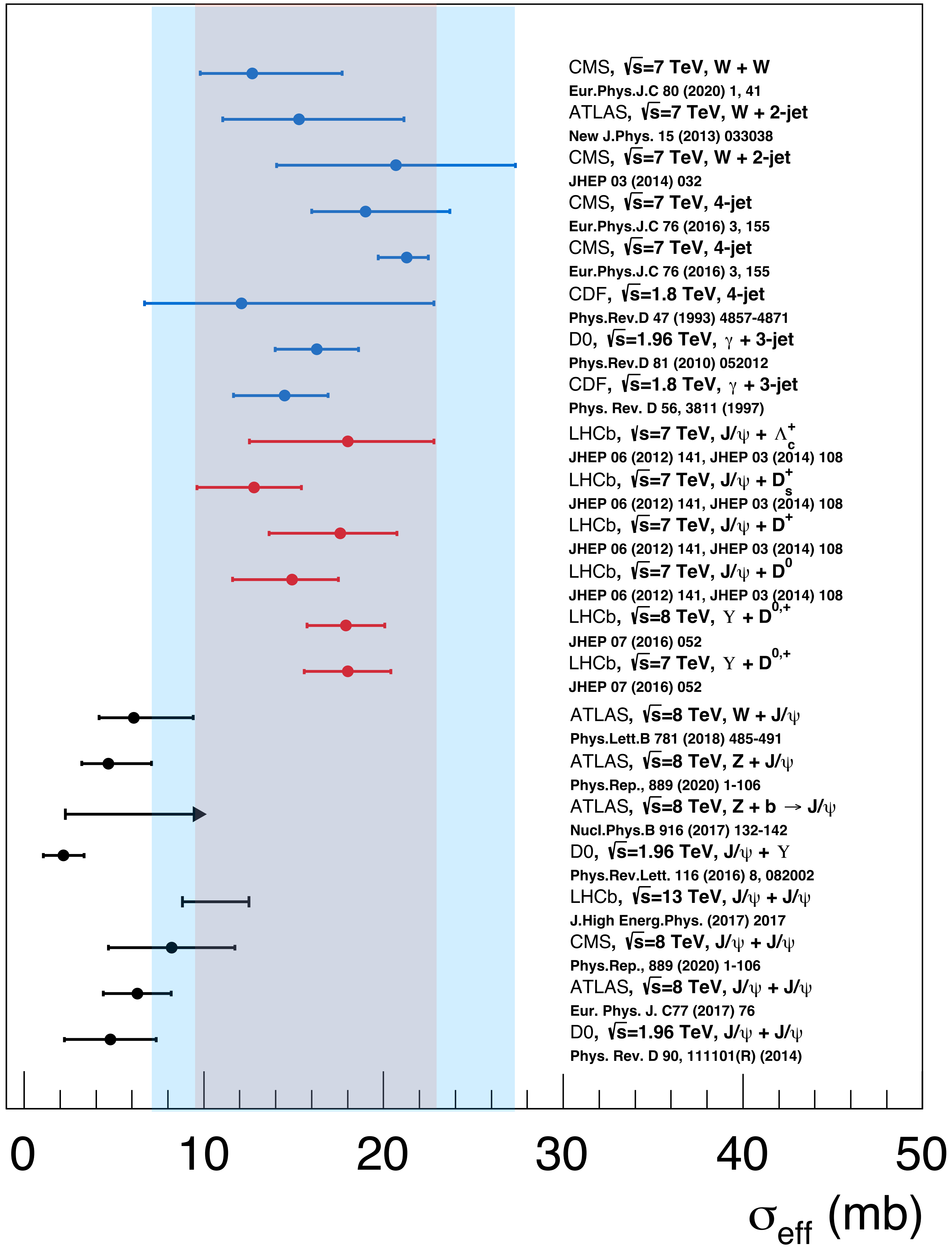

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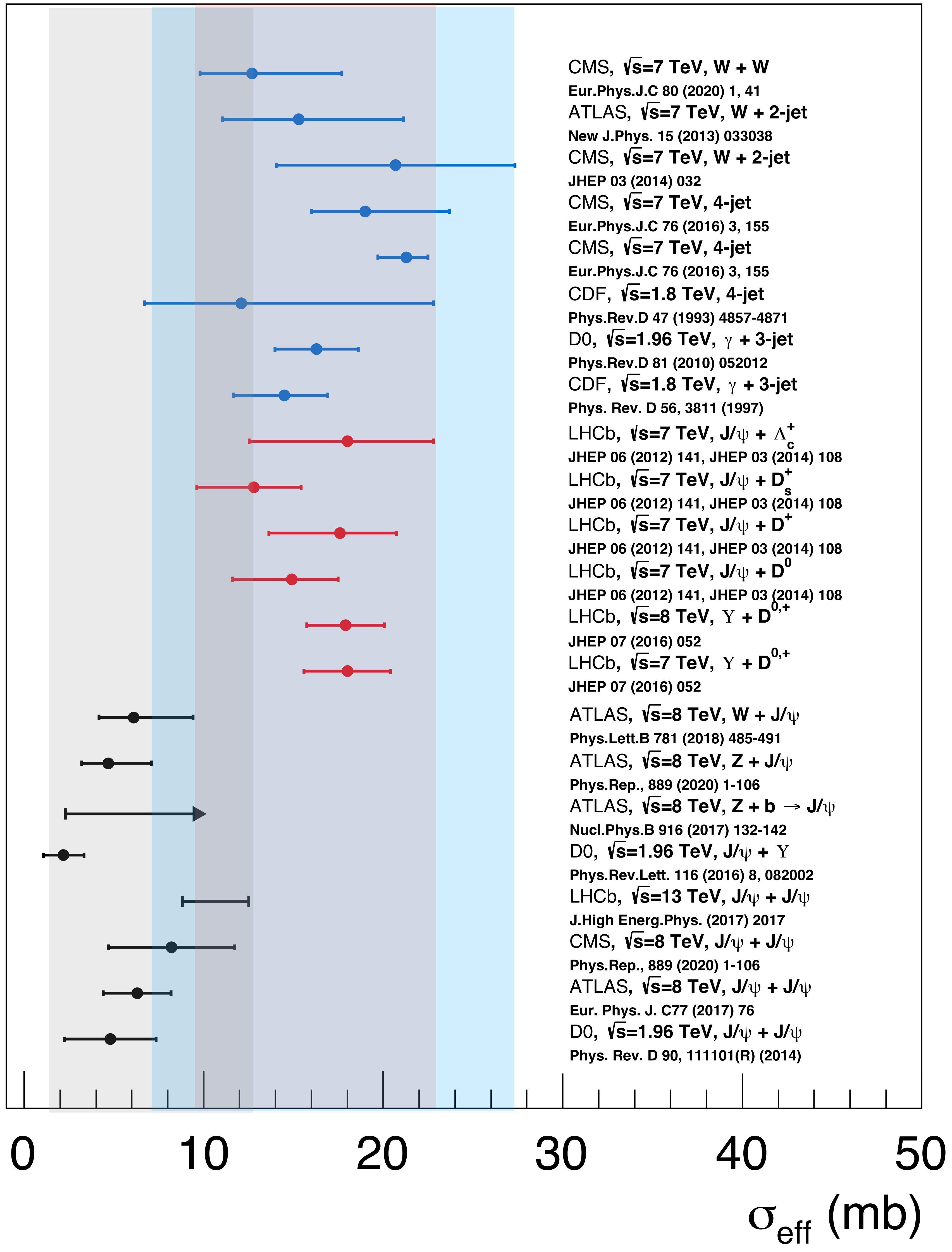
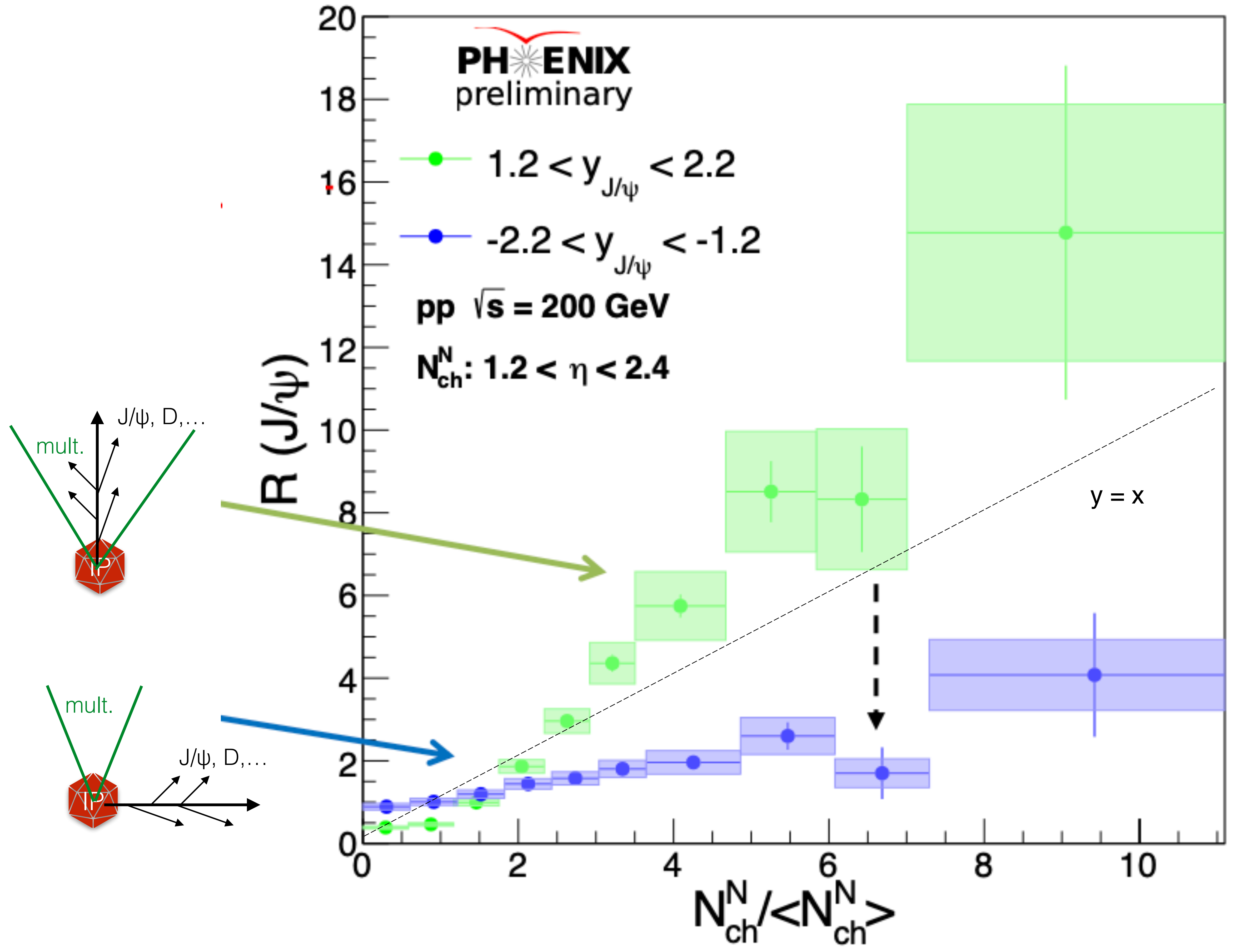


Quarkonium yields vs. charged-particle multiplicity in pp



- Underlying event or associated particle influence?
- Faster than linear increase when overlap in rapidity between Nch and J/ψ
- Reduced increase with multiplicity for large Δy gap between Nch and J/ψ