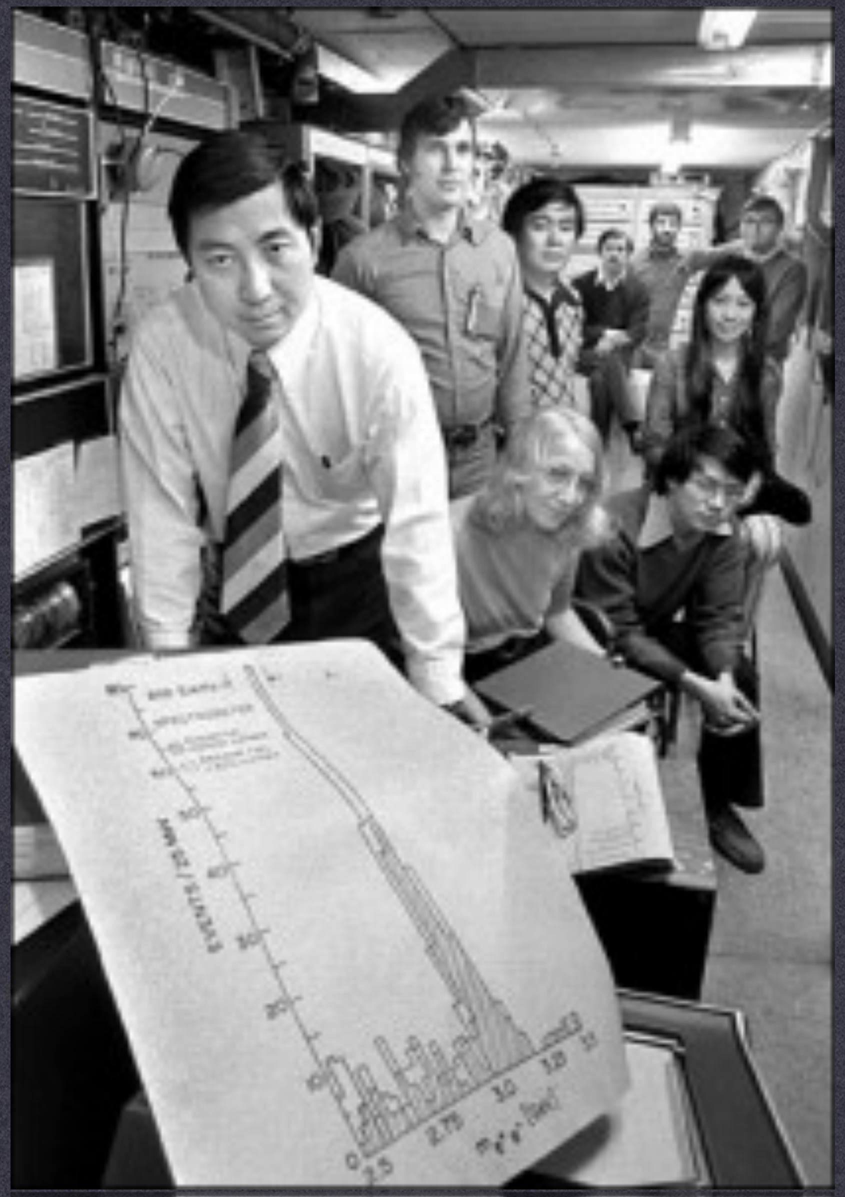


SAMUEL TING AND HIS BNL TEAM. CREDIT: BNL, 1974

QUARKONIA IN HIGH-ENERGY COLLISIONS

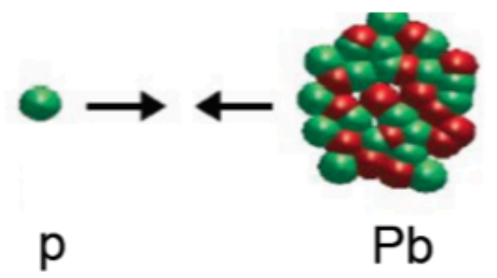
I. HEAVY-FLAVOUR IN PP
II. HEAVY-FLAVOUR IN PA
III. HEAVY-FLAVOUR IN AA

Recall from the very first talk

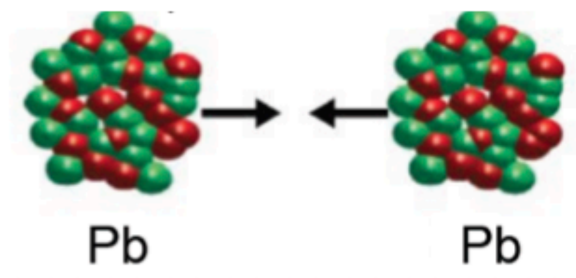
Where it gets 'messy'

The orthodoxe approach

- The QCD 'vacuum'.



- The confined matter.



- The QGP

The probes

Hard probes

- Heavy-quark mesons, quarkonia, jets…

Soft probes

- Charged particles, light hadrons, low-mass hadrons …

Electromagnetic probes

- Drell-Yan, photons, weak bosons …

The observables

Production

- Cross-sections, Nuclear modification factor, Relative ratios …

Correlations

- Multiplicity dependance, flow measurements…

A QGP physicist should know everything about his/her favorite probs !

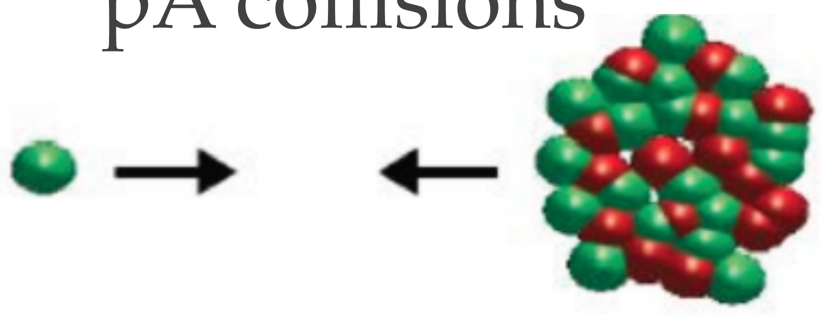
6

Today we do the exercise for Quarkonia !

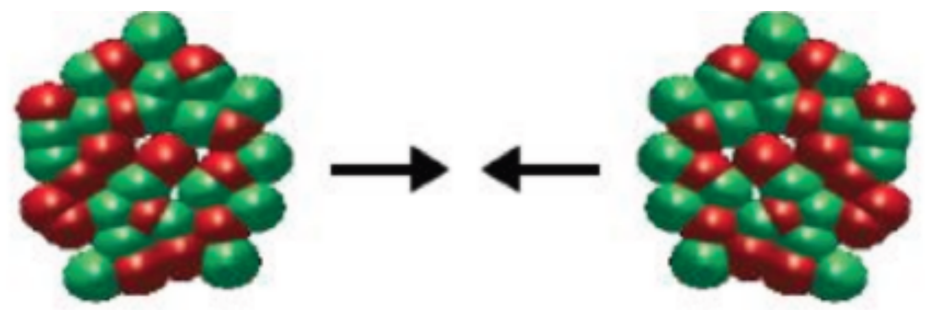
Quarkonia production and experimental measurements

pp collisions

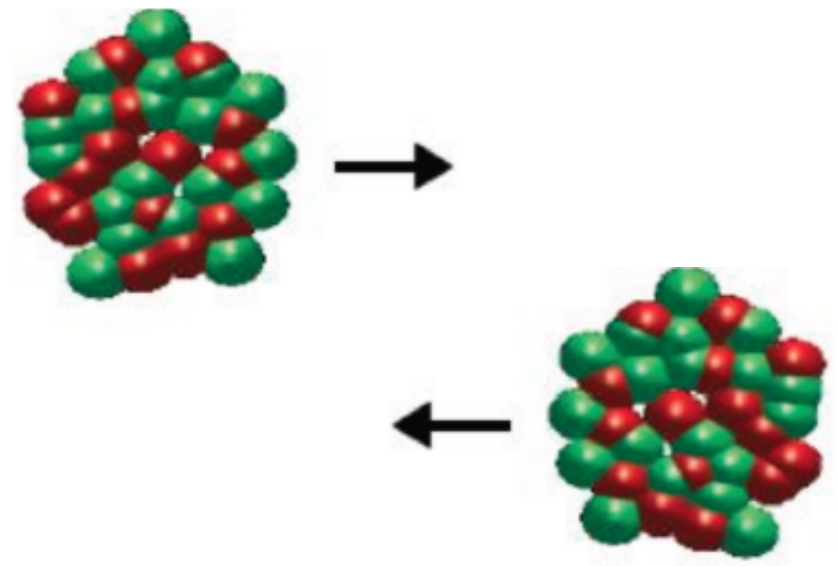
pA collisions



AA collisions



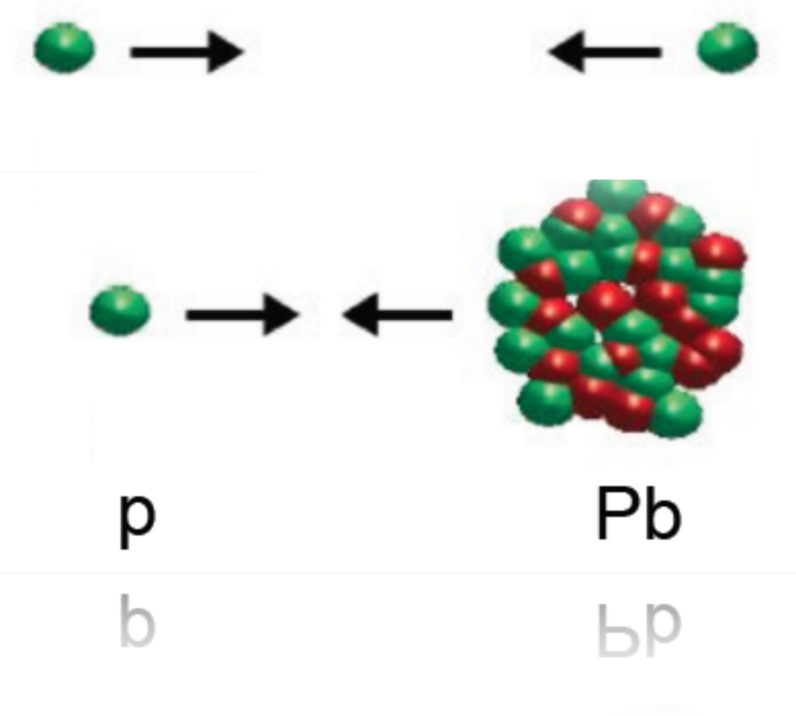
UPC collisions



- **$q\bar{q}$ production mechanism**
  - cross-section
  - Jets
  - polarisation
  - ….
- **Cold Nuclear Matter**
  - $q\bar{q}$ production in pA
  - Nuclear modification factor
  - …
- **QGP physics**
  - $q\bar{q}$ production in AA
  - Nuclear modification factor
  - Jets
  - Elliptic flow
  - …
- **Cold Nuclear Matter**
  - $q\bar{q}$ cross-section

General strategy with hard probes studies

- **How QGP affects your probe**
- Study the **production mechanism** in the **QCD « vacuum »**.
- Study **cold nuclear matter effect**.
- Build up observables :
  - Nuclear Modification Factor R_{AA}
  - Correlation observables (v_2, jet quenching …)
- The more precise measurements we have, the more we can constraint models !



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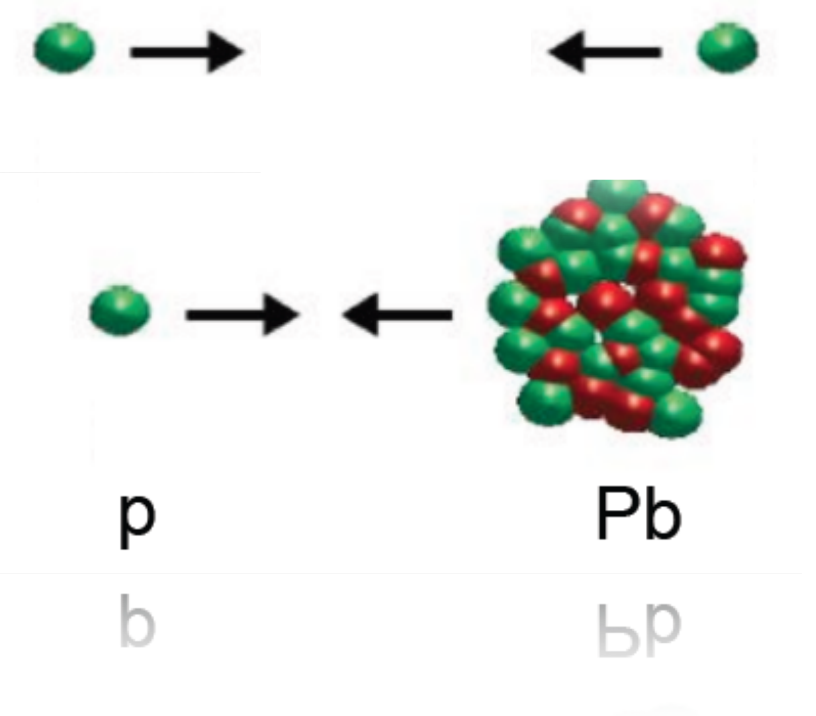


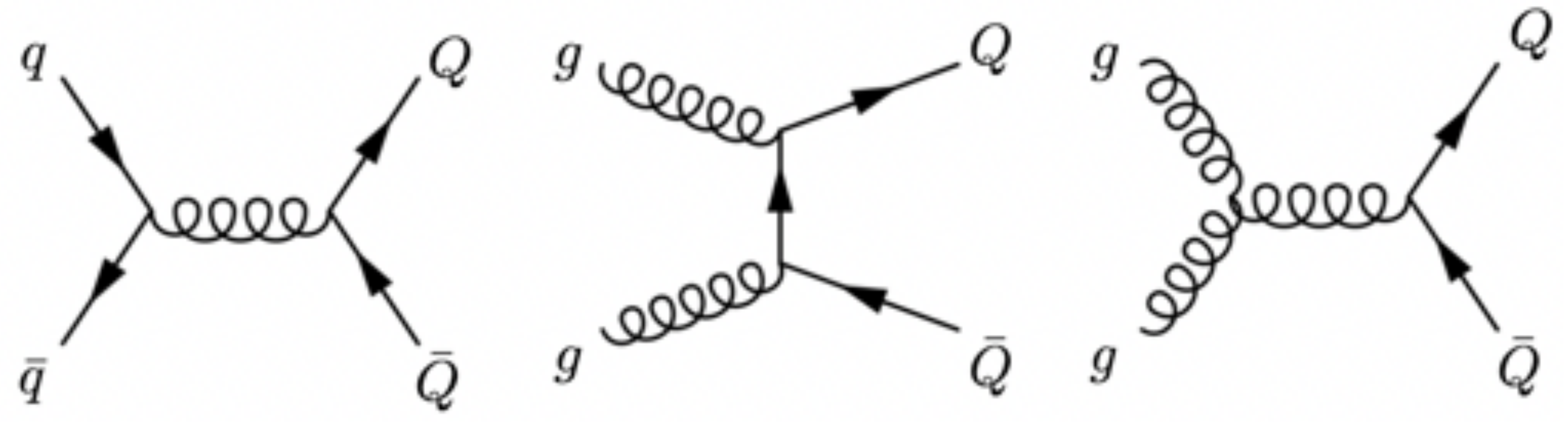
$$\boxed{R^{i}_{AA}(\Delta p_T, \Delta y) = \frac{Y^{Pb-Pb,i}(\Delta p_T, \Delta y)}{\langle N_{coll}\rangle Y^{pp}(\Delta p_T, \Delta y)}}$$

- The more precise measurements we have, the more we can constraint models !

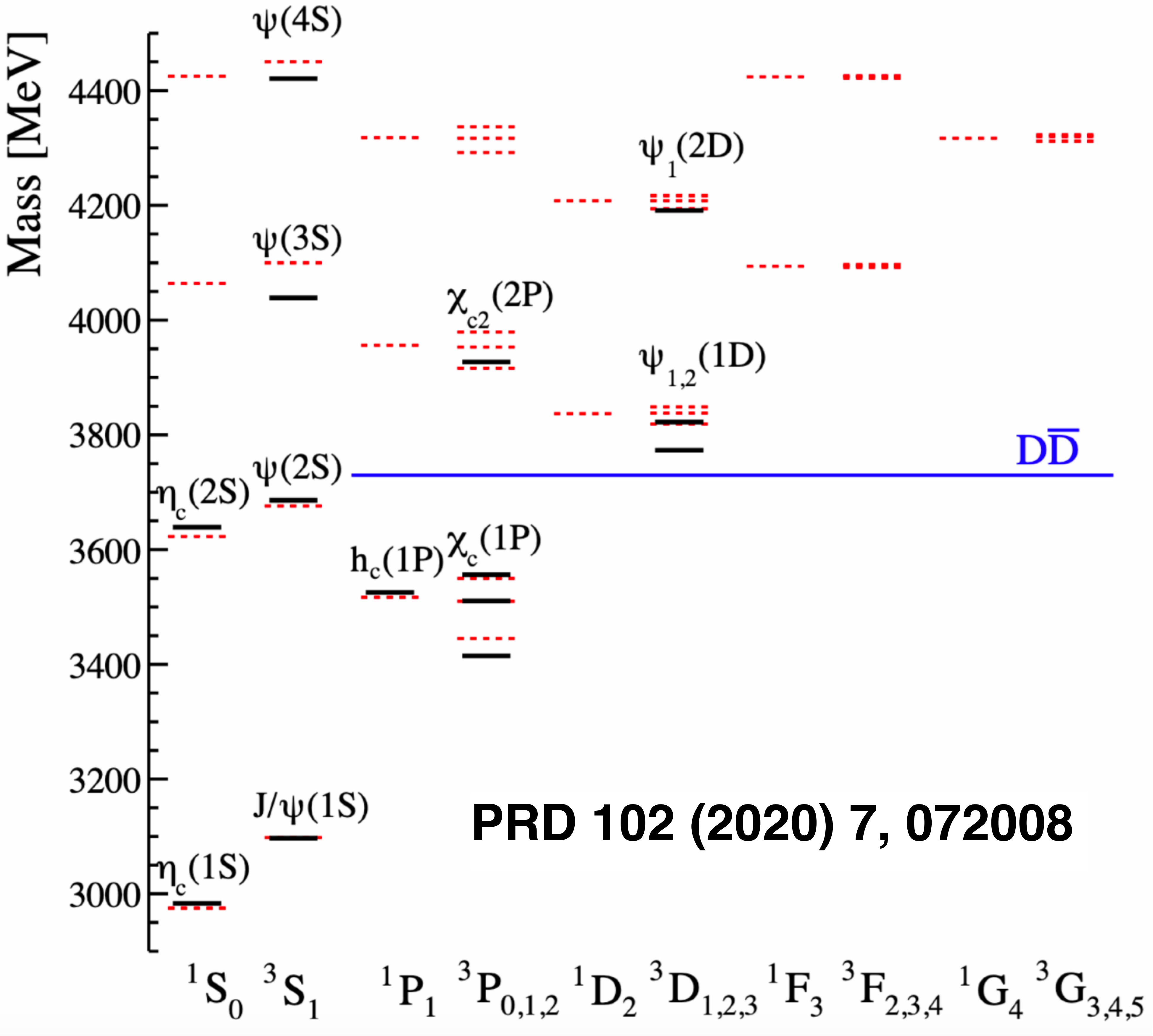
QUARKONIA IN PP

Quarkonia in pp collisions

- Quarkonia: bound state of charm and bottom quarks
  - High mass (m_c,m_b >> Λ_{QCD}) -> use pQCD to compute production cross-section in pp.
- Physics motivation in pp:
  - Test pQCD production models …
    - color singlet, color octet, NRQCD, GPDs, CGC …
  - … and all the ingredients that come with it !
    - PDFs, LDME …



Leading production diagram of QQ pair at LHC



PRD 102 (2020) 7, 072008

Exemple : J/ψ production

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- Three main approaches to J/ψ pp production :

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  - **Color Evaporation Model (CEM)**
    - Simple integral
    - Color neutralized by induced gluon
    - Proportionality factor independent of y / p_T / $\sqrt{s}$

$$\sigma_{\mathcal{Q}} = F_{\mathcal{Q}} \int_{2m_{\mathrm{Q}}}^{2m_H} \frac{d\sigma_{\mathrm{Q\bar{Q}}}}{dm_{\mathrm{Q\bar{Q}}}} m_{\mathrm{Q\bar{Q}}}$$

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  - **Color Singlet Model (CSM)**
    - pQCD based model
    - Direct colorless (singlet) production
    - Hadronization probability from data and/or lQCD

$$d\sigma_{\mathcal{Q}+X} = \sum_{i,j} f_i . f_j \otimes d\hat{\sigma}_{i+j\to\mathrm{Q\bar{Q}}+X} \otimes |\psi_{\mathcal{Q}}(0)|^2$$

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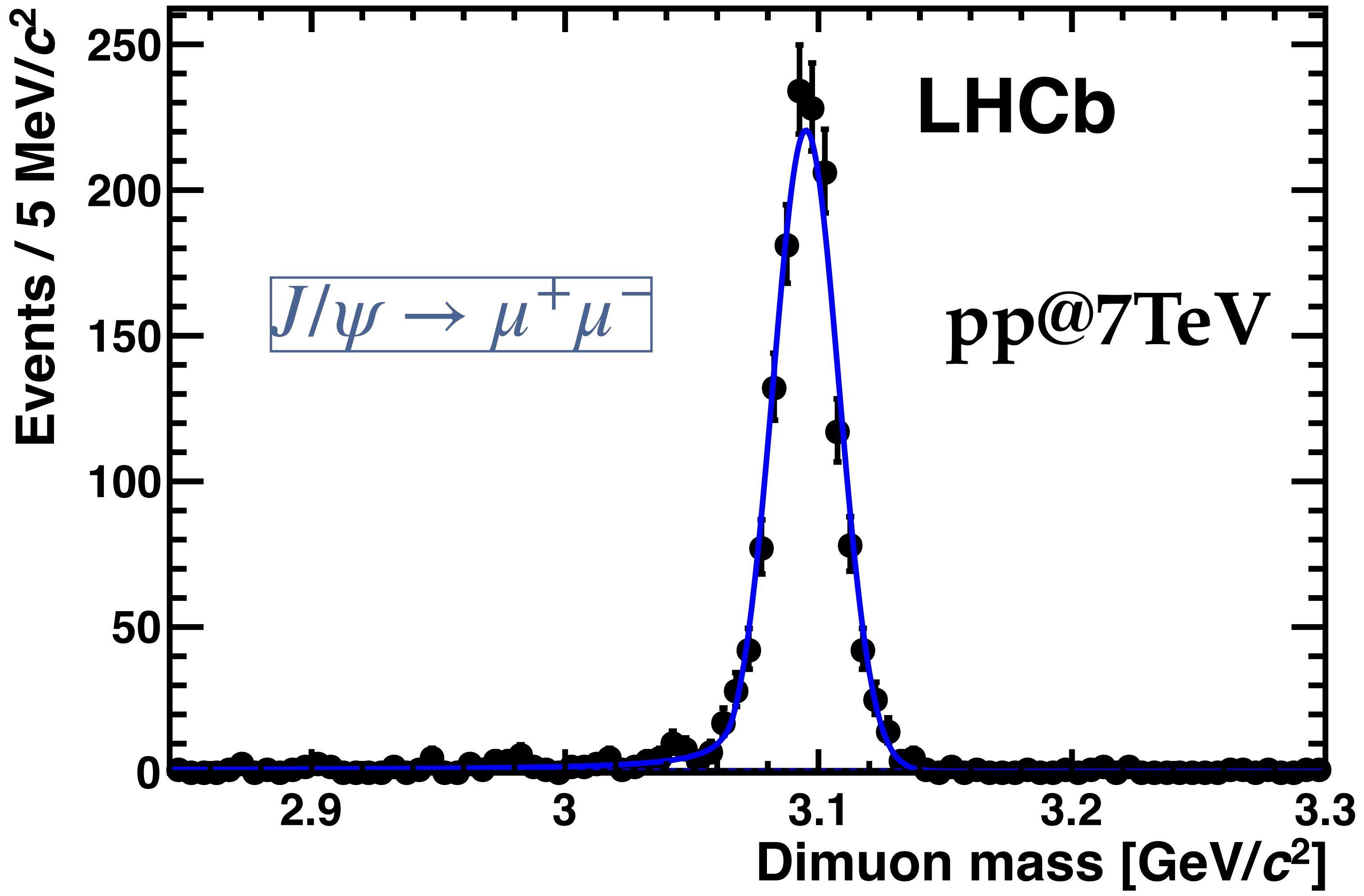
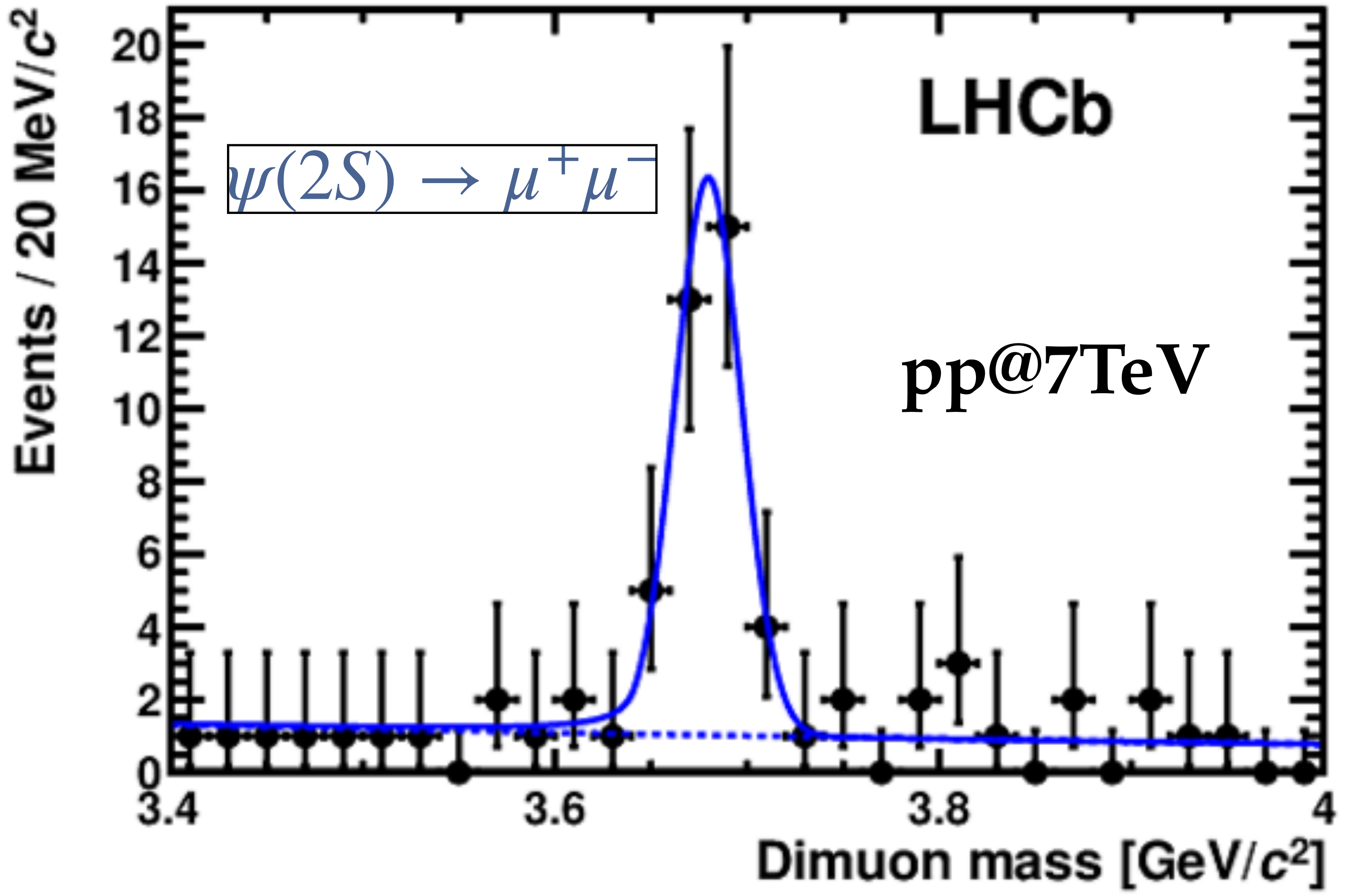
  - **Non-Relativistic QCD (NRQCD)**
    - pQCD based model
    - Both singlet and octet state are considered
    - Relative state contribution of the states are parametrized (LDME)

$$d\sigma_{\mathcal{Q}+X} = \sum_{i,j} f_i.f_j \otimes d\hat{\sigma}_{i+j\to\mathrm{Q\bar{Q}}+X} \otimes \langle \mathcal{O}^n_{\mathcal{Q}} \rangle$$

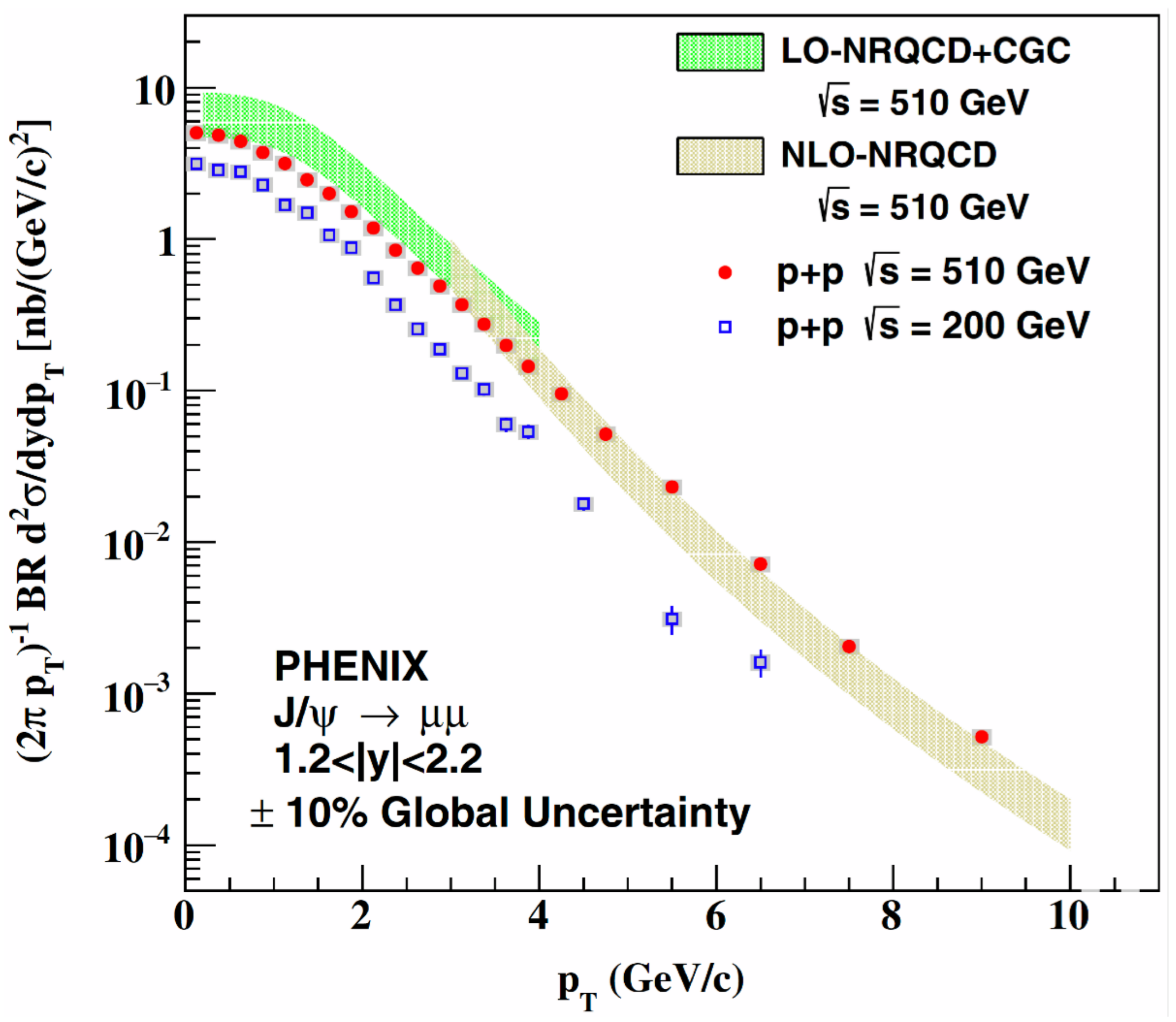
J/Ψ production in pp

J. PHYS. G40 (2013) 045001

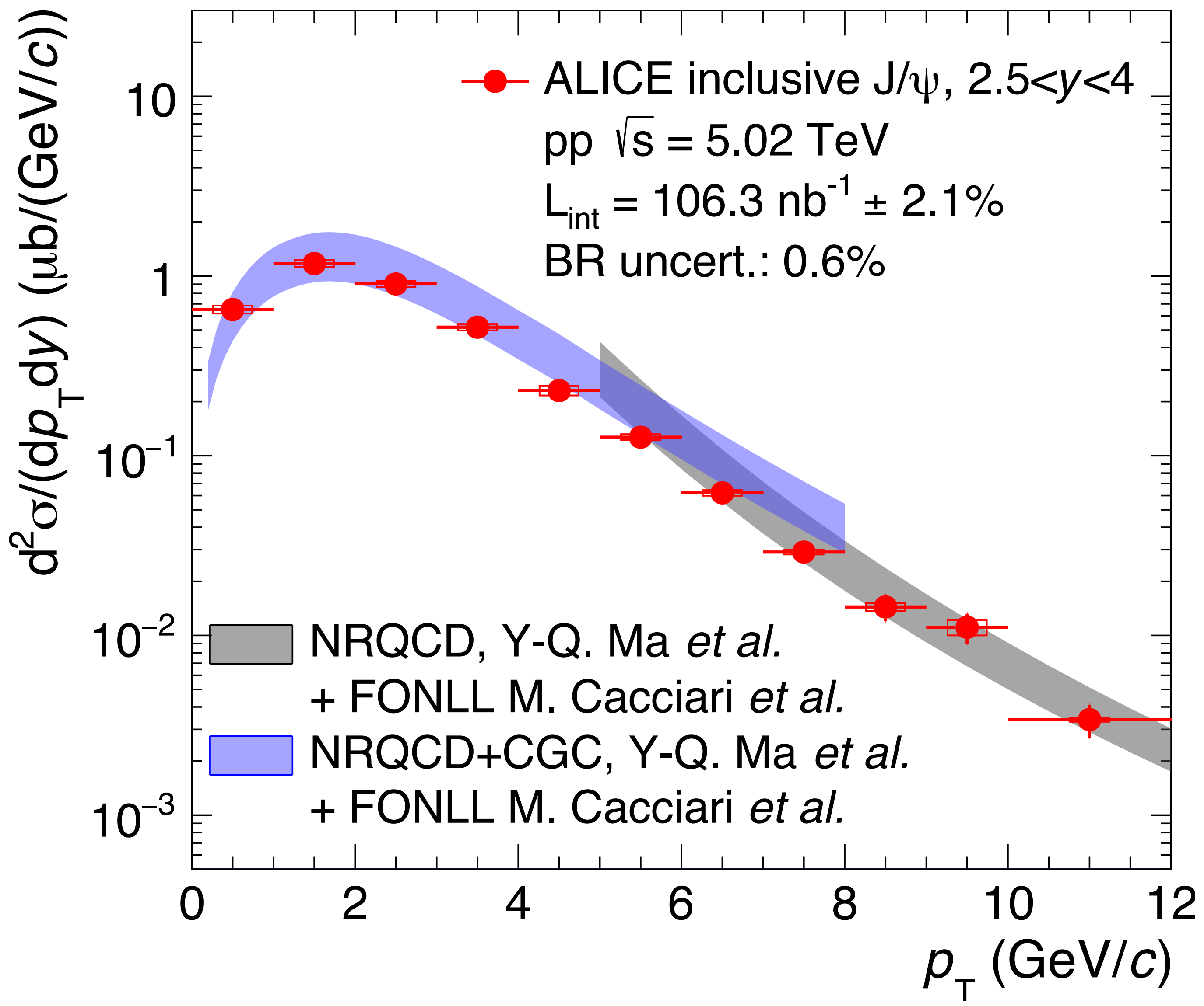




PRD 101 (2020) 5, 052006

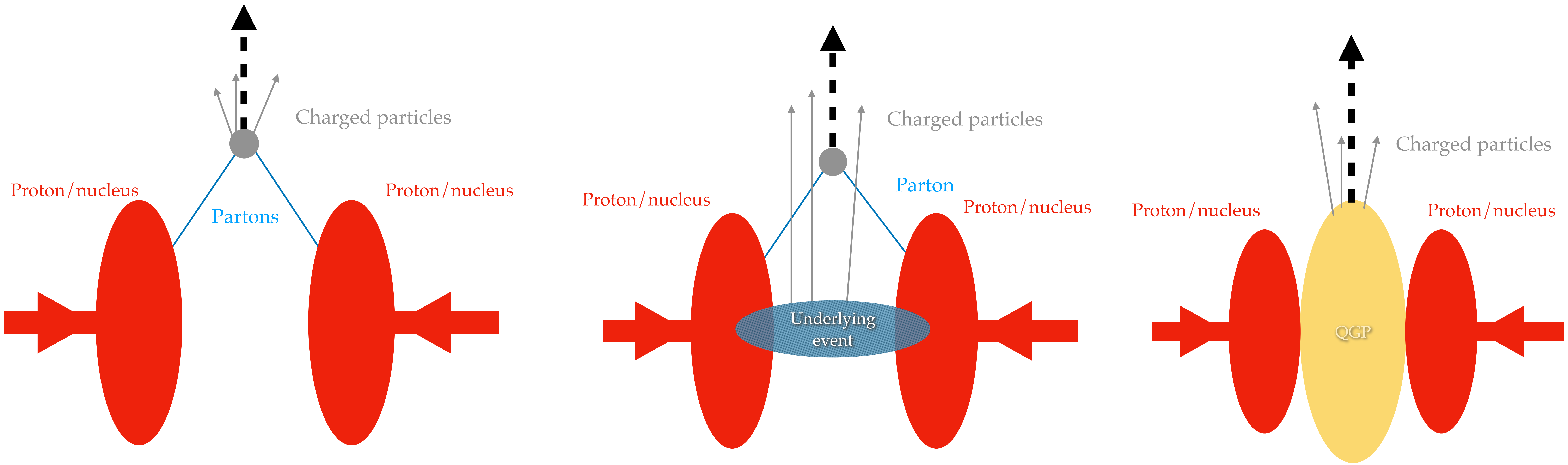


Eur. Phys. J. C 77 (2017)



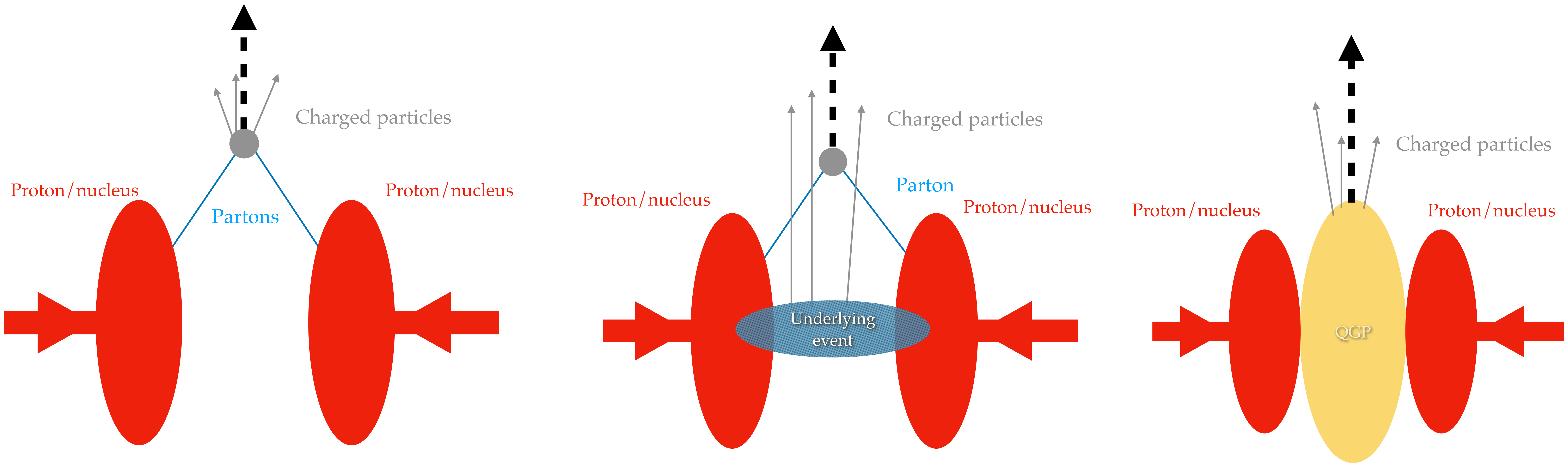
- Large number of precise measurements done by many different experiments, covering different colliding energies and rapidity ranges.
- Good descriptions by NRQCD-based formalisms at both RHIC and LHC.

Quarkonia versus multiplicity



- Production versus multiplicity prob correlations with:
  - Jets
  - Multi-parton interaction produced by the underlying event, QGP or not.
- Caveat: importance of the multiplicity estimator.

Quarkonia versus multiplicity



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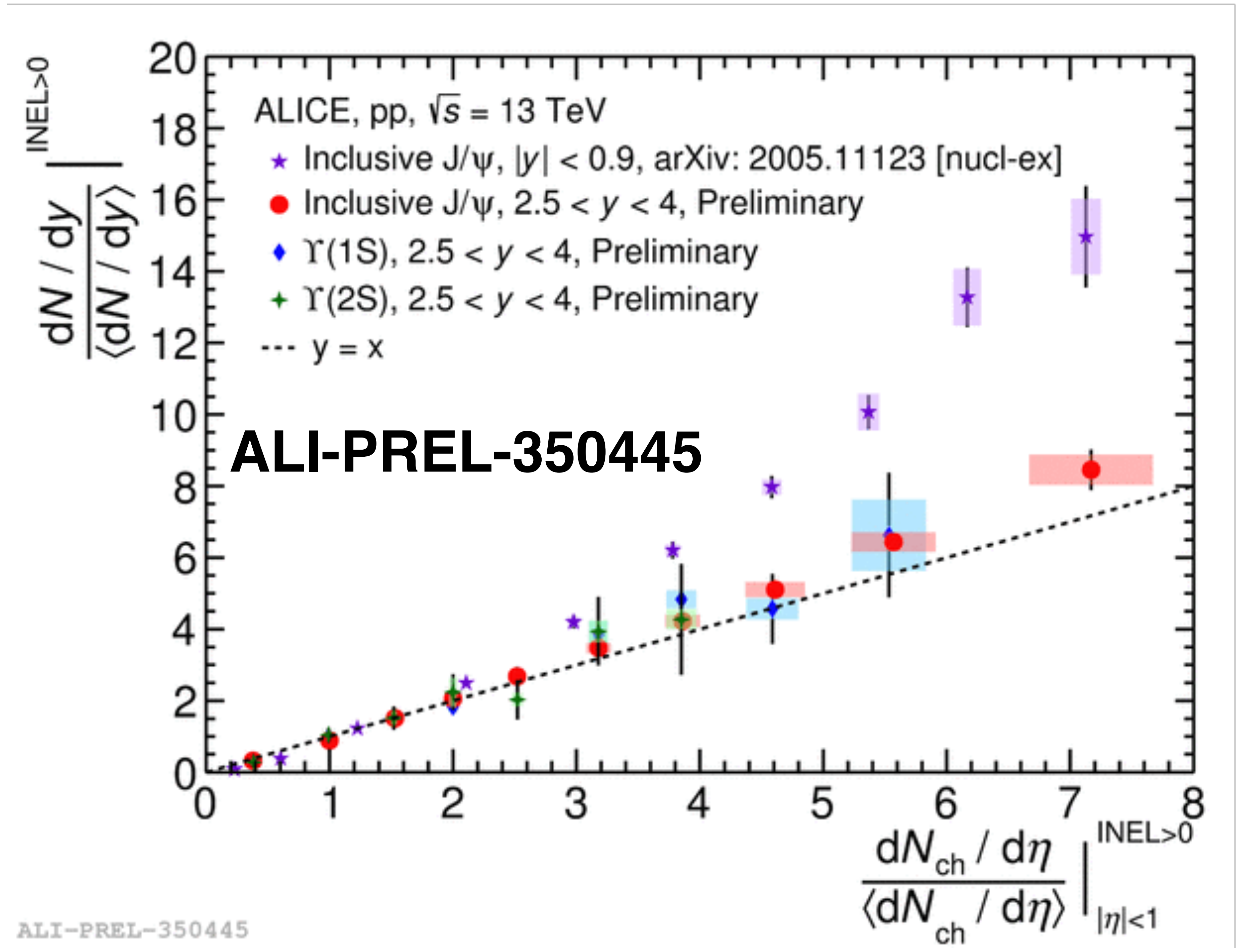
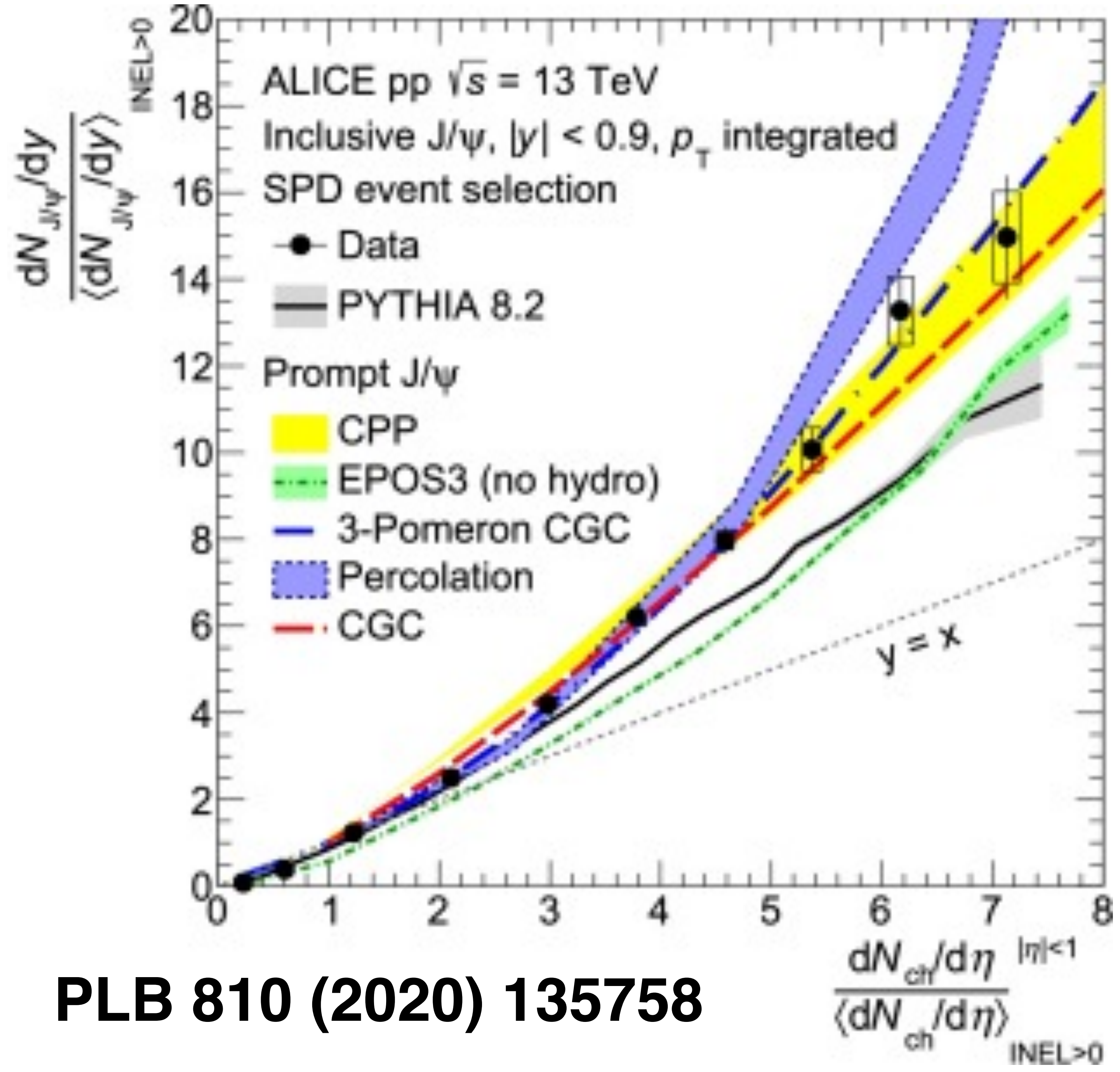


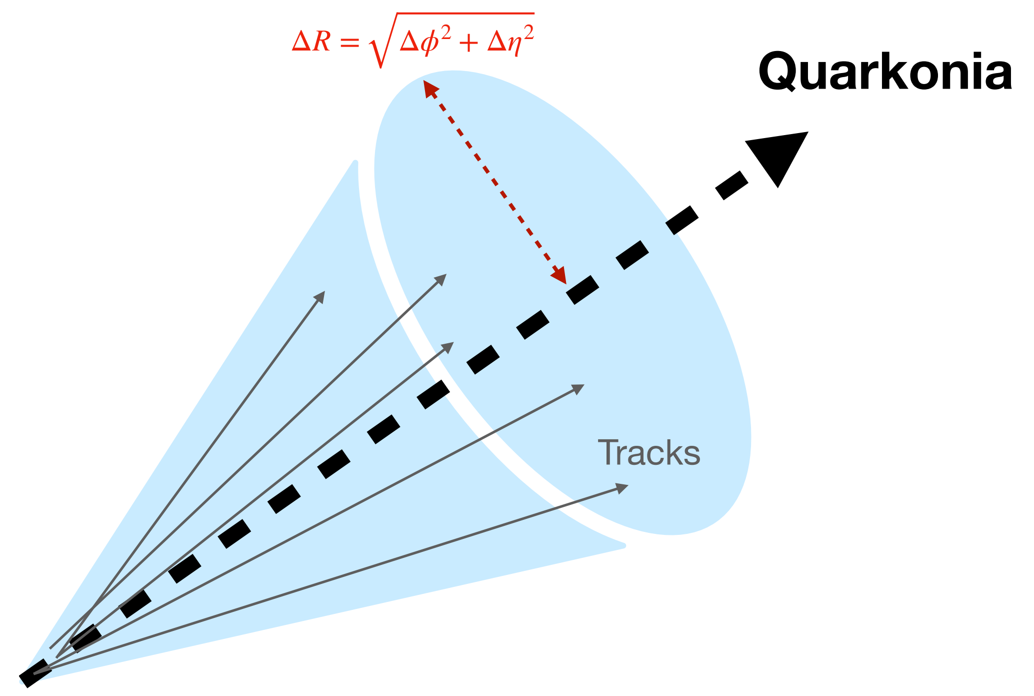


PLB 810 (2020) 135758

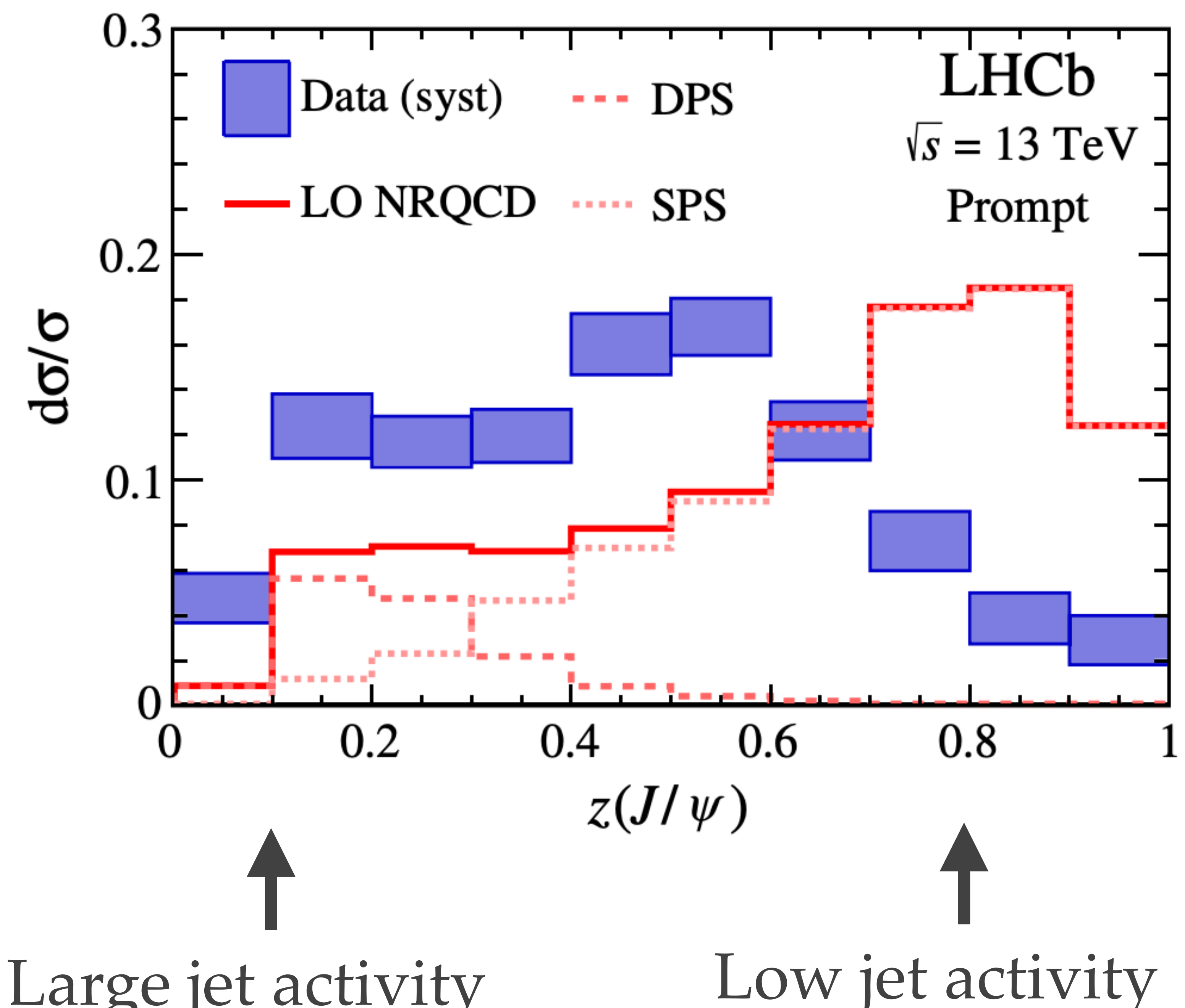
- Linear increase of quarkonia production with relative multiplicity at forward rapidity.
- Not the case at mid-rapidity.
- Caveat: keep in mind the multiplicity estimator.

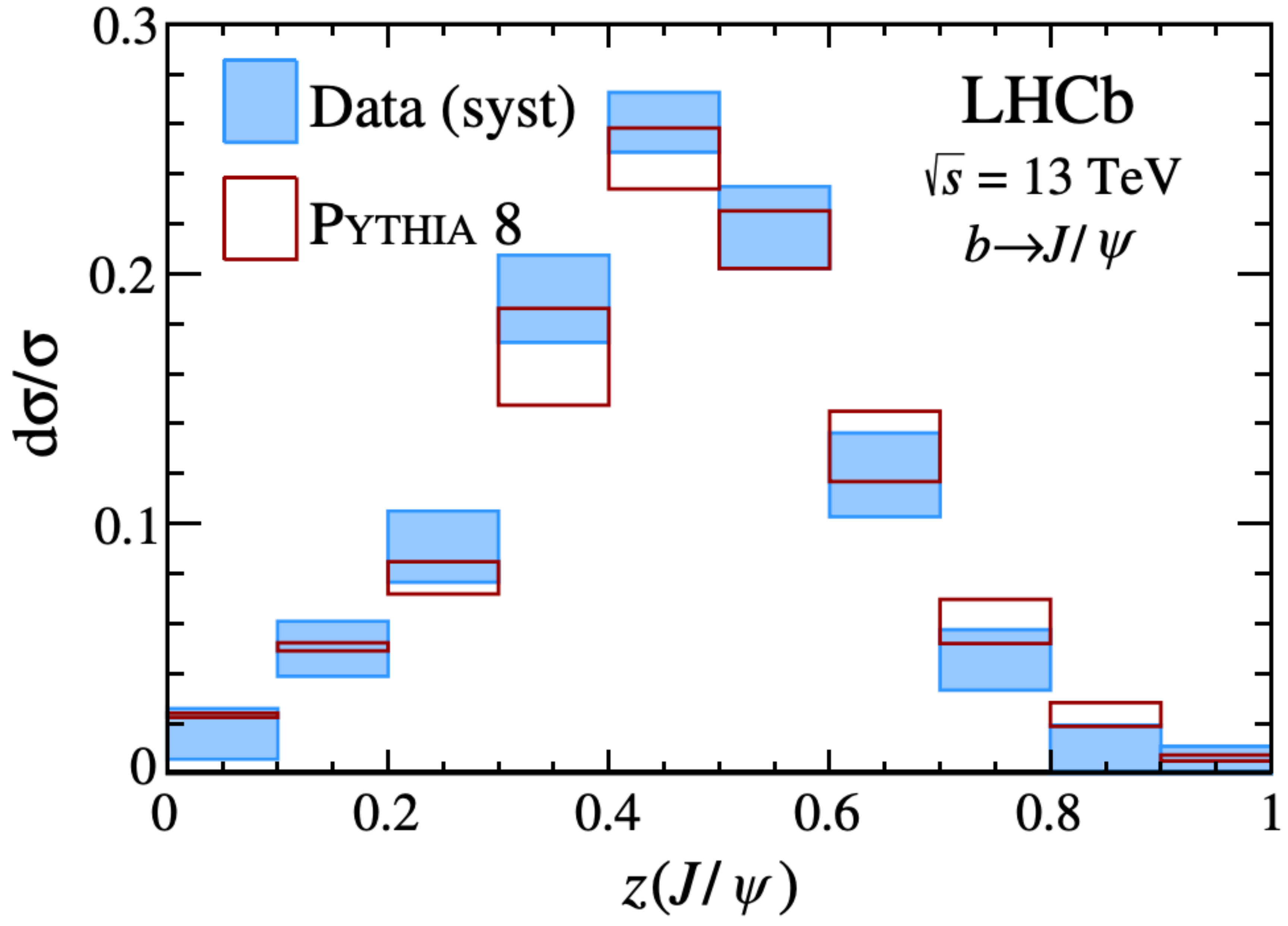
Quarkonia in jets

- Quarkonia in jets:
  - prob fragmentation parametrisation.
  - Generally algorithm dependent measurement.
- Results at LHC show that prompt J/Ψ is less isolated than expected by LO NRQCD in PYTHIA



$$Z = \frac{p_T^{\text{quarkonia}}}{p_T^{\text{jet}}}$$



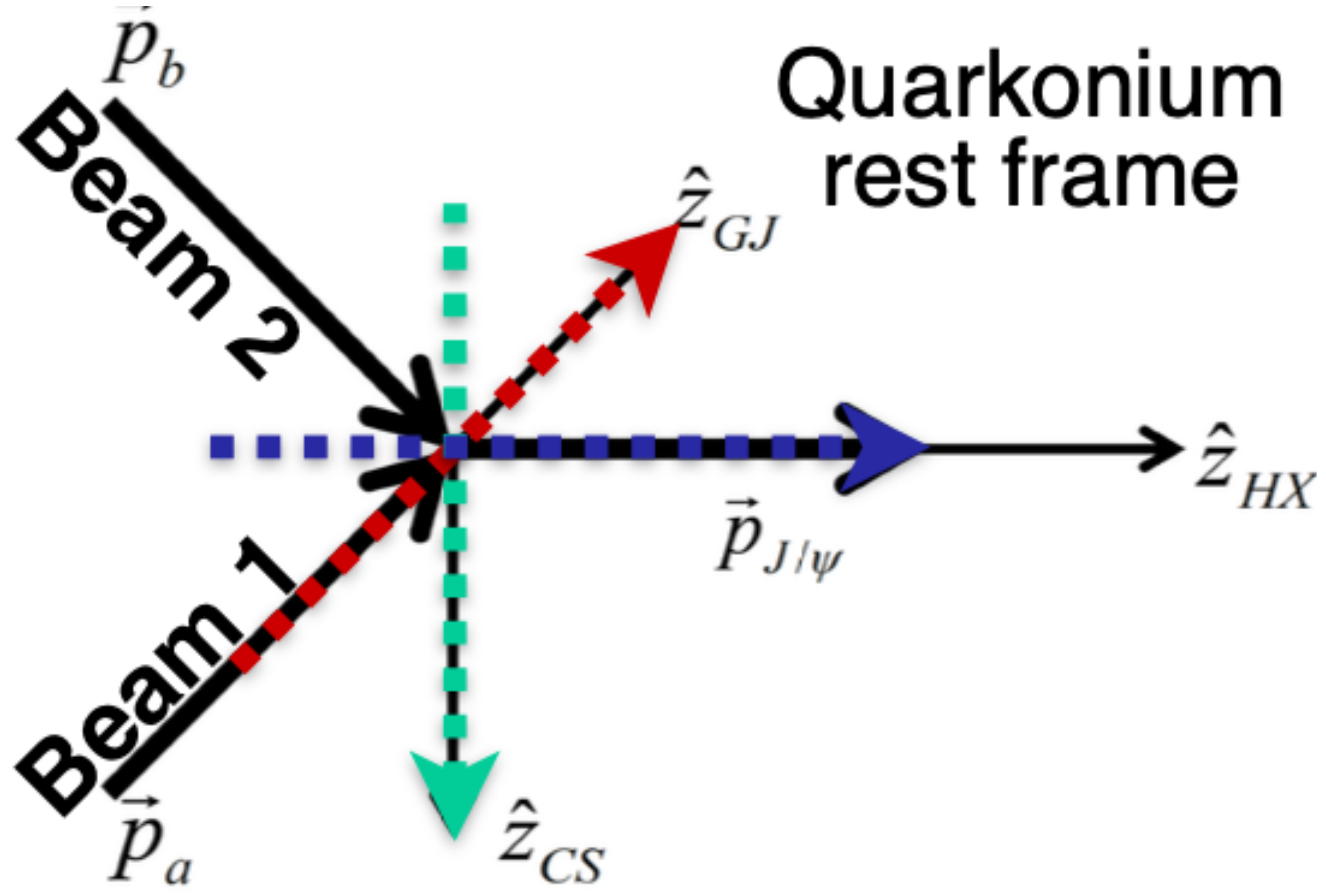


Quarkonia polarisation

- Polarization is defined as the spin alignment with respect to a chosen direction.

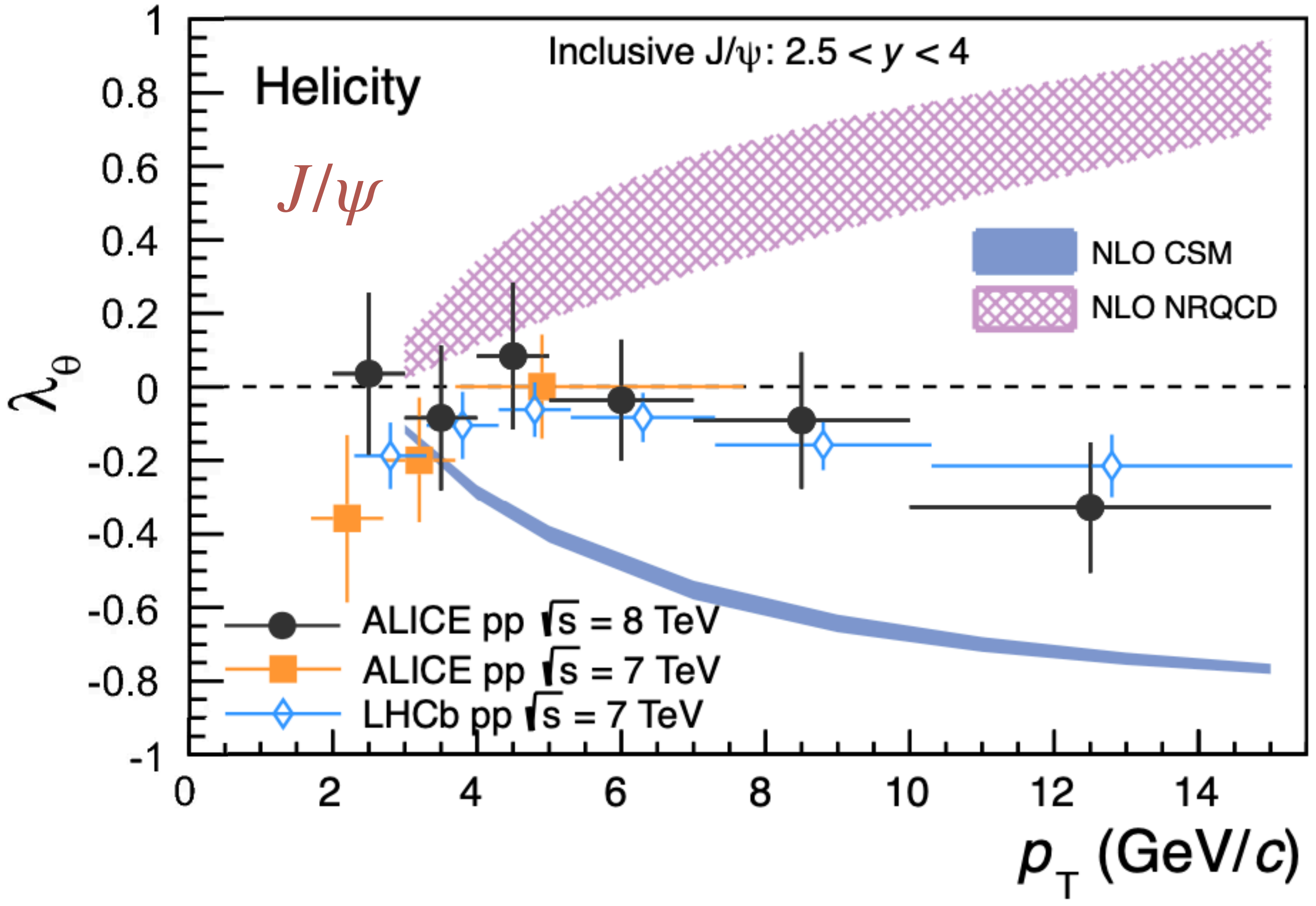
$$W(\theta,\phi) \propto \frac{1}{3+\lambda_\theta}\left(1+\boxed{\lambda_\theta}\cos^2\theta+\boxed{\lambda_\phi}\sin^2\theta\cos 2\phi+\boxed{\lambda_{\theta\phi}}\sin 2\theta\cos\phi\right)$$

- Measured as anisotropies in the angular distributions of decay products in the quarkonia CM
  - Helicity (HX): quarkonium pT direction.
  - Collins-Soper (CS): bisector of angle between beams.
  - Gottfried-Jackson (GJ): direction of one beam.
- Useful To constrain models:
  - LO NRQCD: transverse polarization ($\lambda_\theta > 0$).
  - NLO CSM: longitudinal polarization ($\lambda_\theta < 0$).
  - Medium-induced polarisation ?

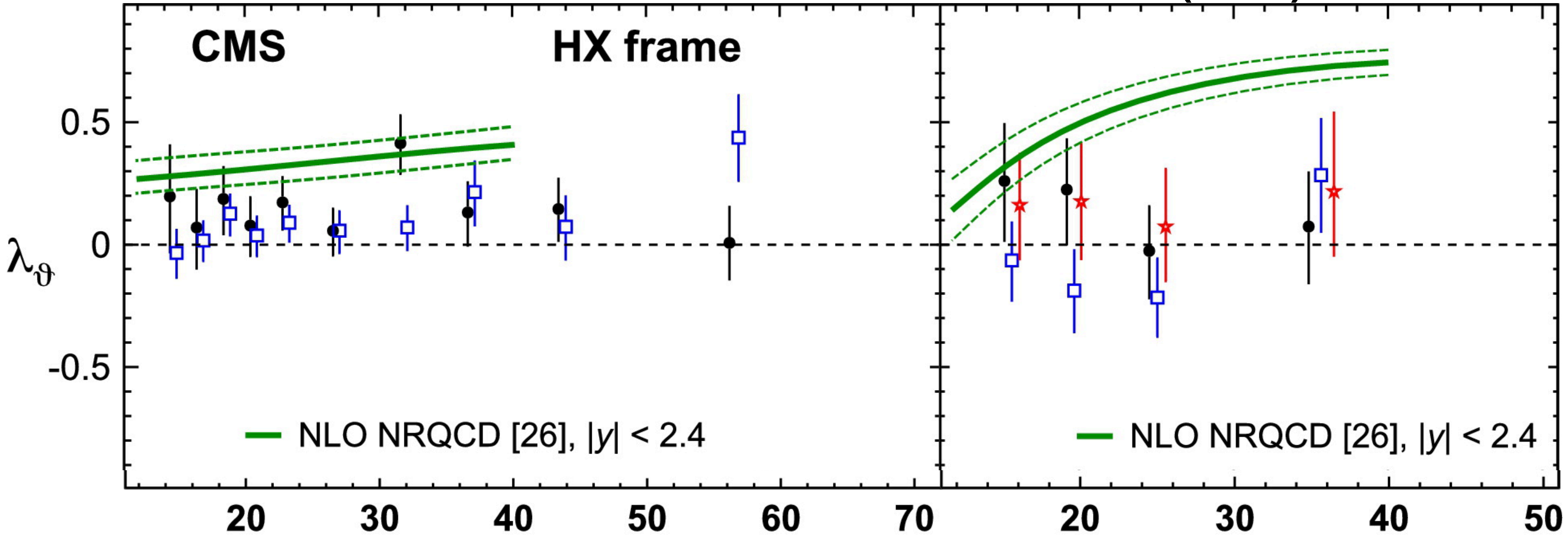


Quarkonia polarisation

EPJC 79 (2018) 7, 562



PLB 727 (2013) 381-402

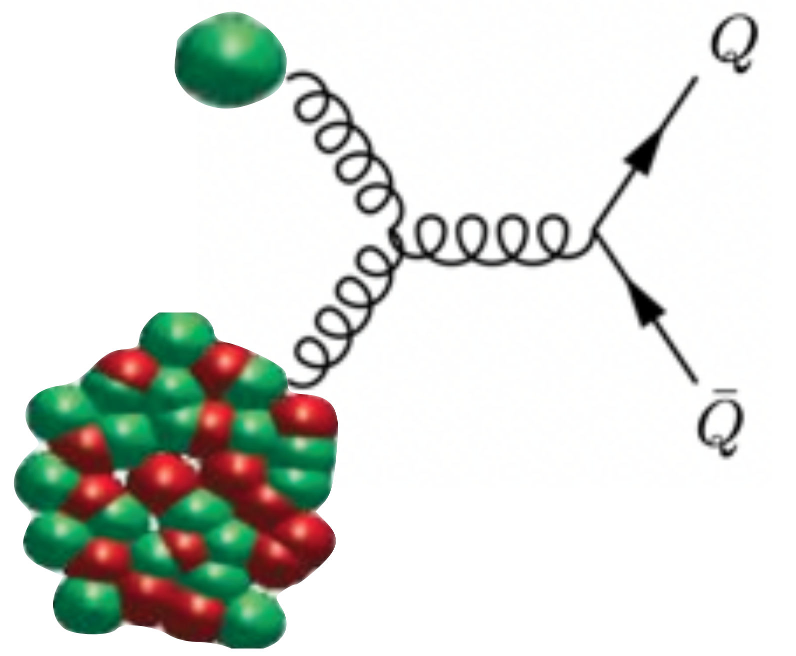


- No significant polarization up to p_T ~ 60 GeV for the J/ψ and the $\psi(2S)$.
- NRQCD and CSM also fail to describe Ψ(nS) polarization @ 8 TeV.

QUARKONIA IN PA

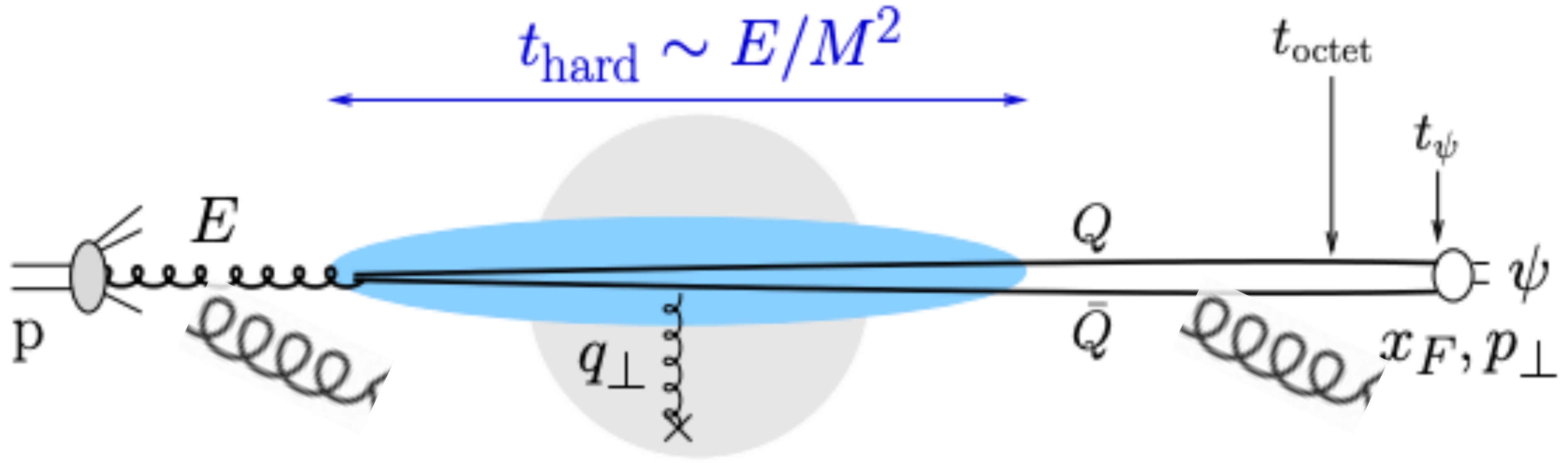
Quarkonia in pA collisions

- Same motivations as for pp collisions, but now with a nucleus !
- Allow to test/constrains the so-called 'Cold Nuclear Matter effects.'



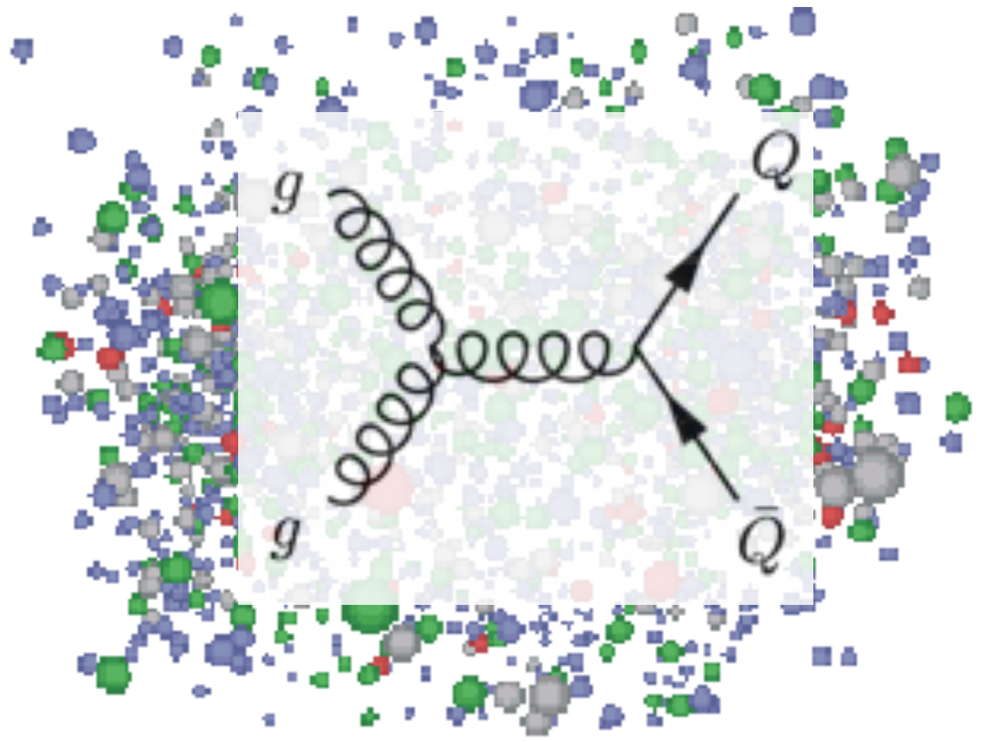
Nuclear PDFs

Coherent energy loss



arxiv:1212.0434

Interaction with co-moving medium



Phys. Lett. B731 (2014) 57–63

nPDFs - Eur. Phys. J. C **82**, 413 (2022)

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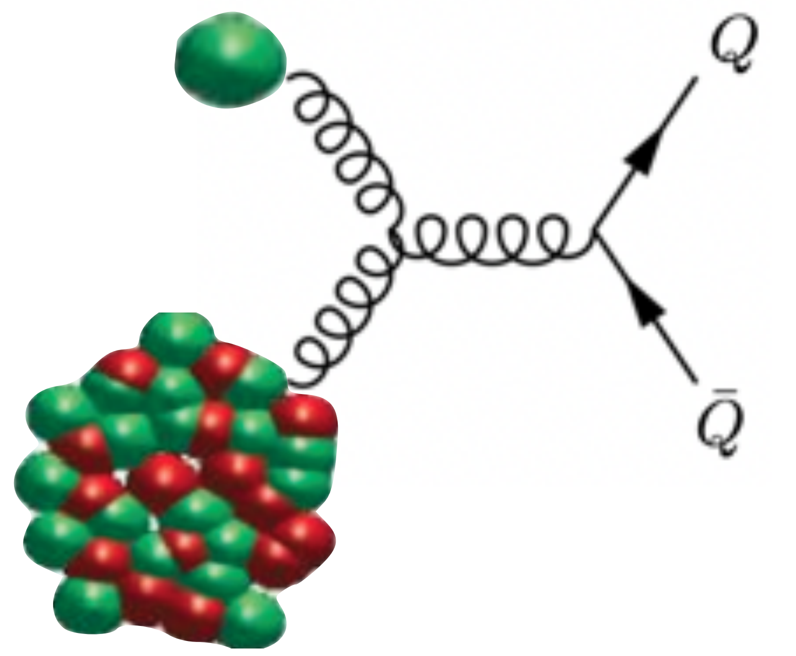

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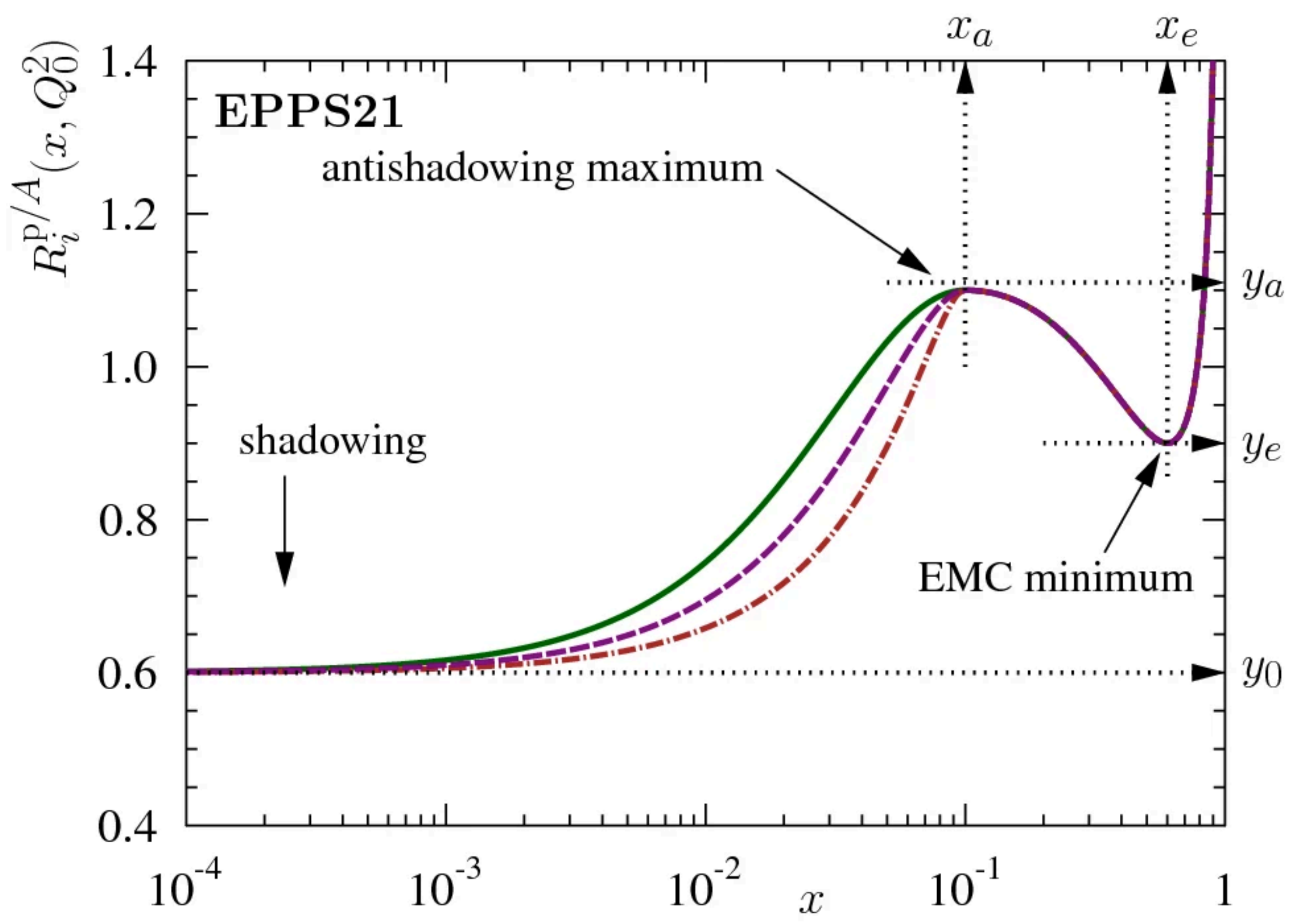

nPDFs - Eur. Phys. J. C **82**, 413 (2022)

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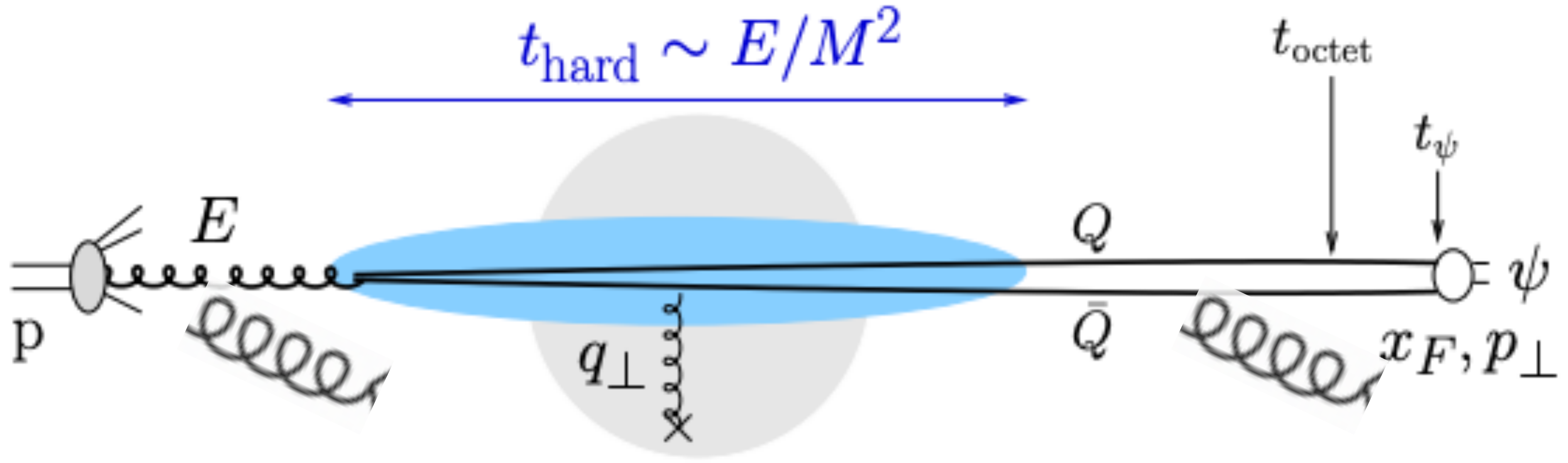

arxiv:1212.0434

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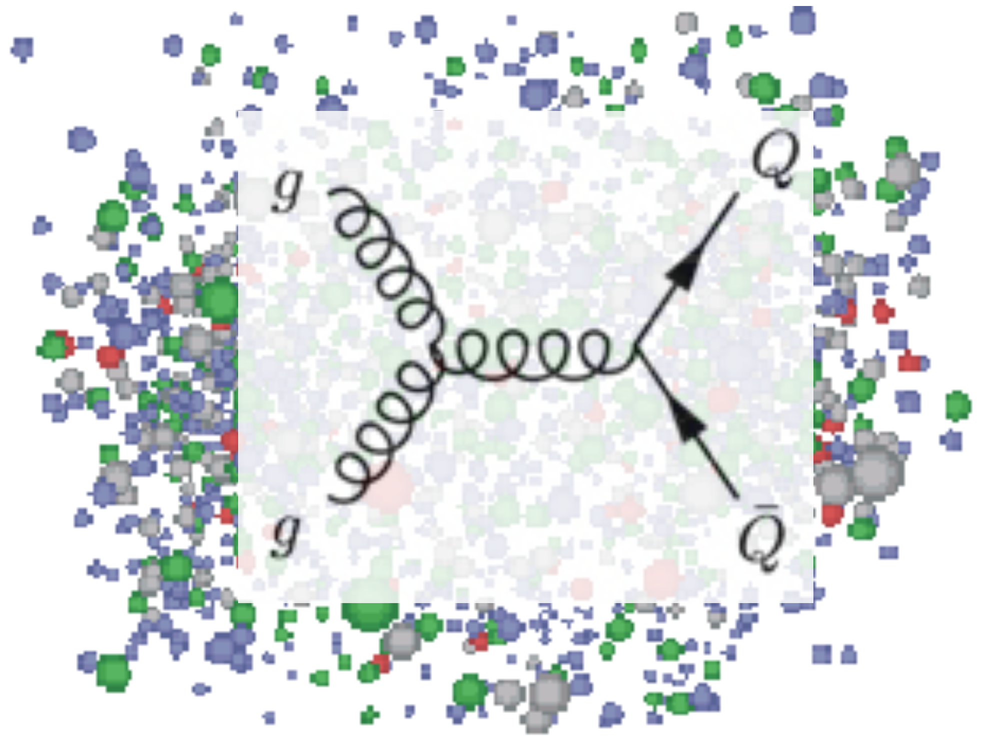
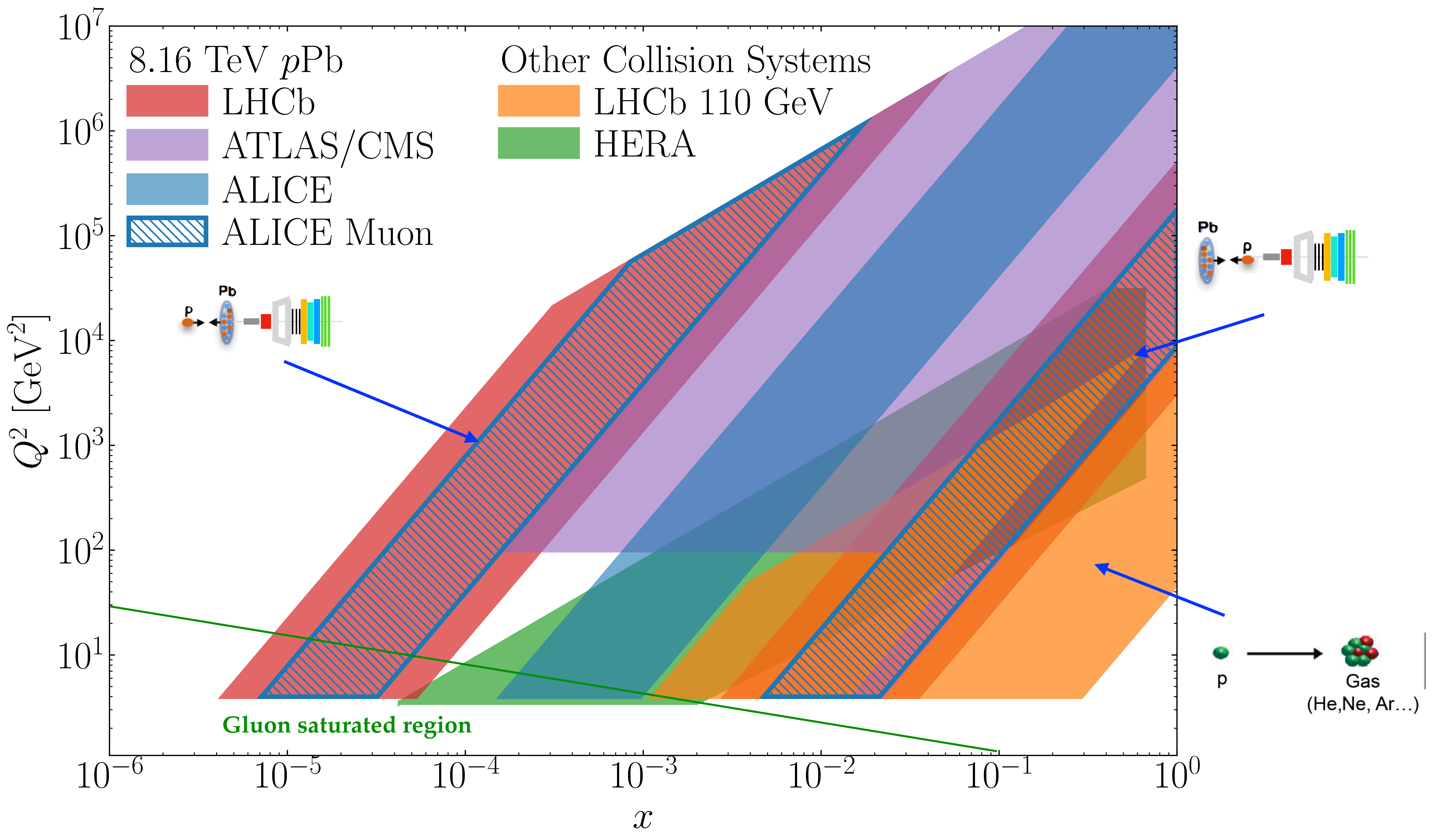


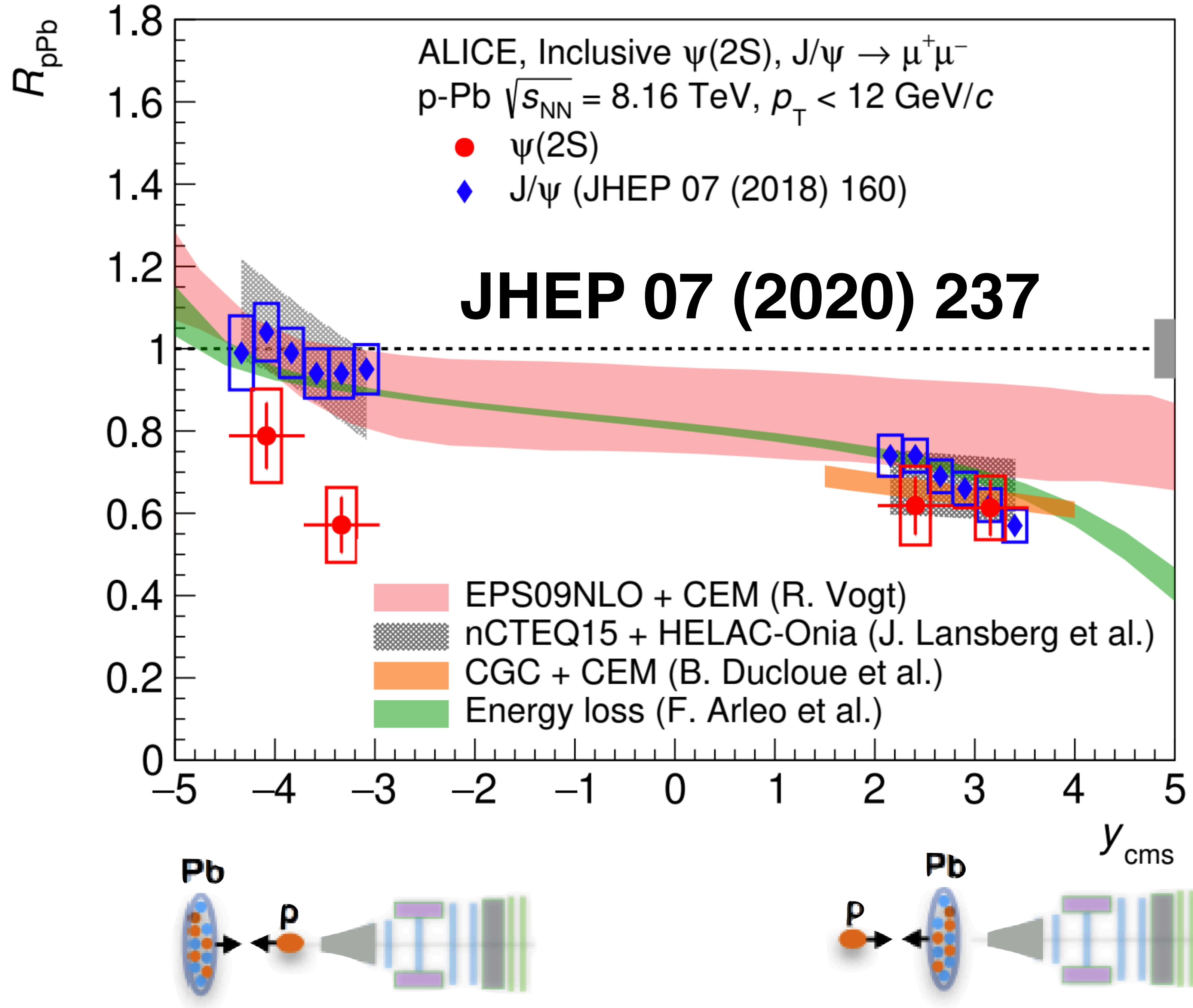
Phys. Lett. B731 (2014) 57–63

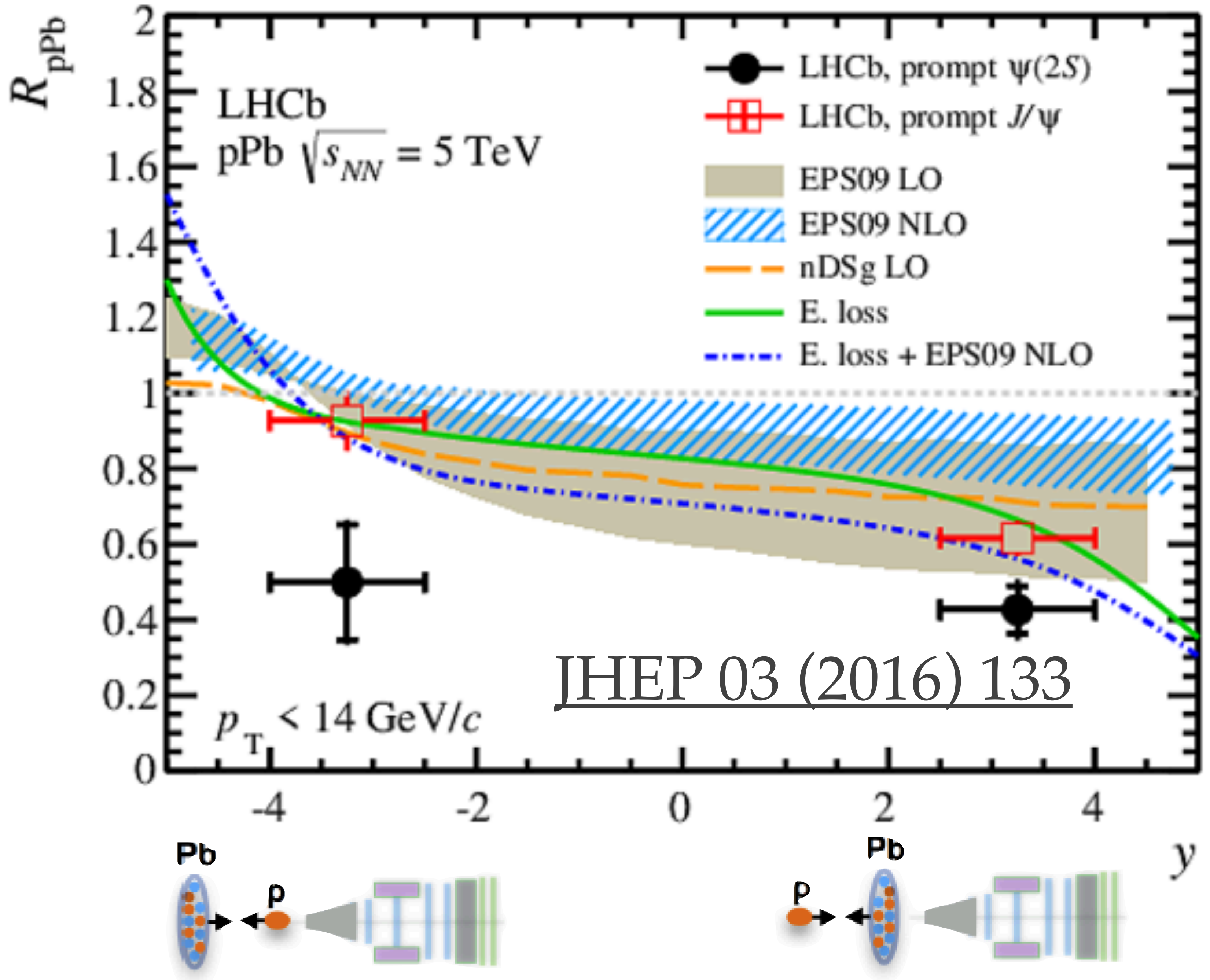
An important plot



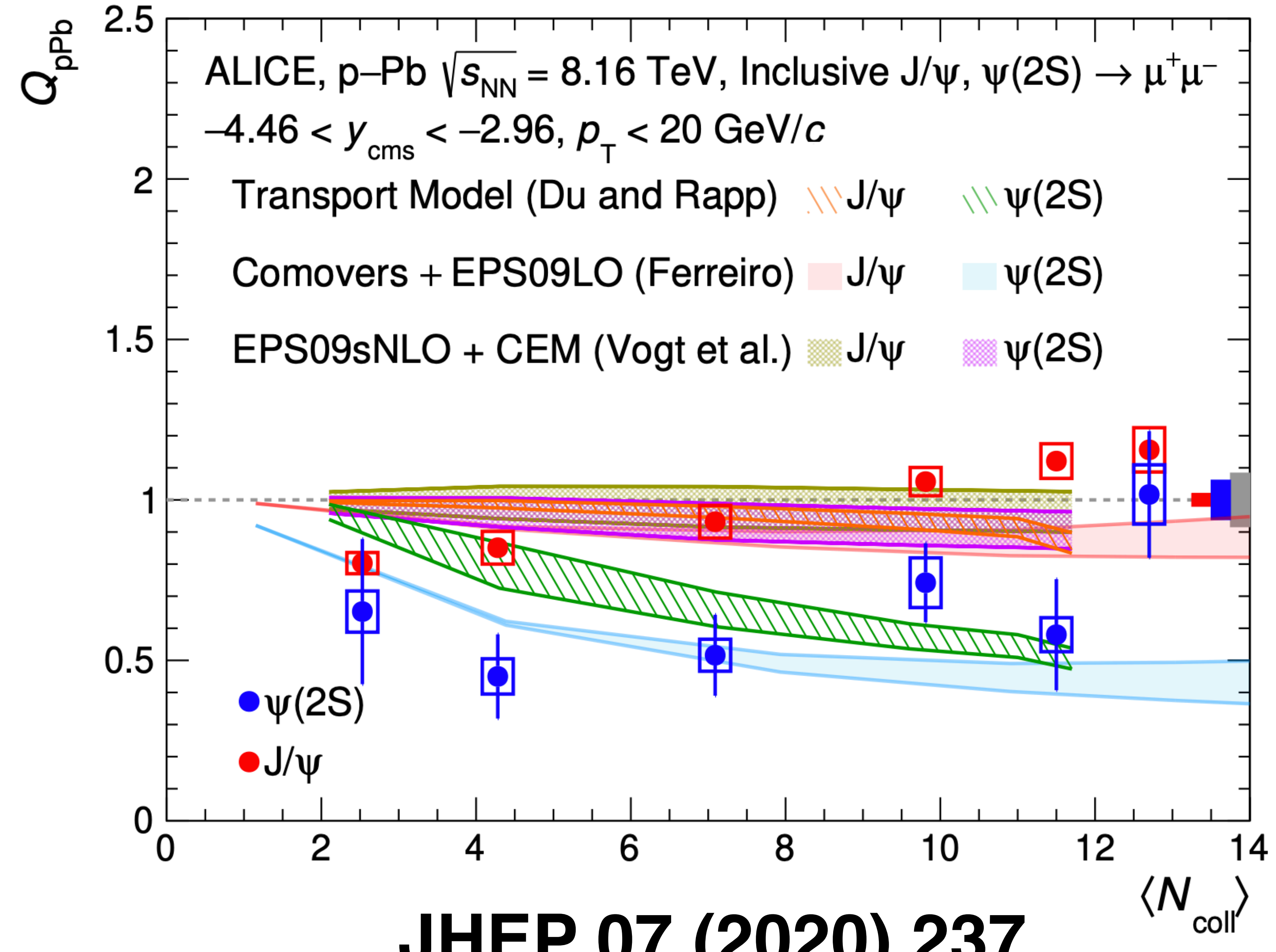
$\Upsilon(nS)$ production

$$R_{pA} = \frac{\sigma^{pA}}{A \times \sigma^{pp}}$$





$$Q_{pA} = \frac{Y^{pA}}{\langle N_{coll} \rangle \times Y^{pp}}$$

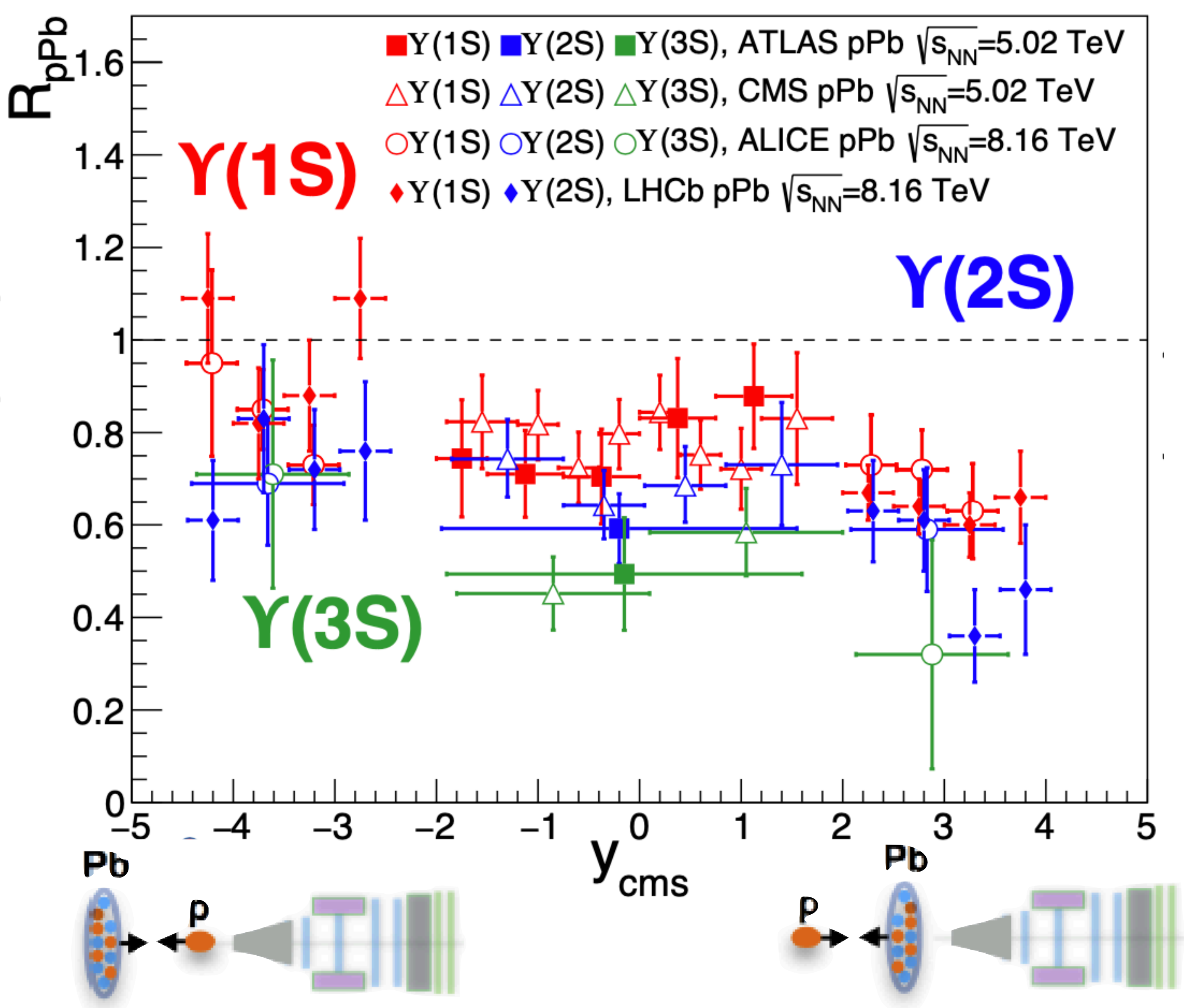


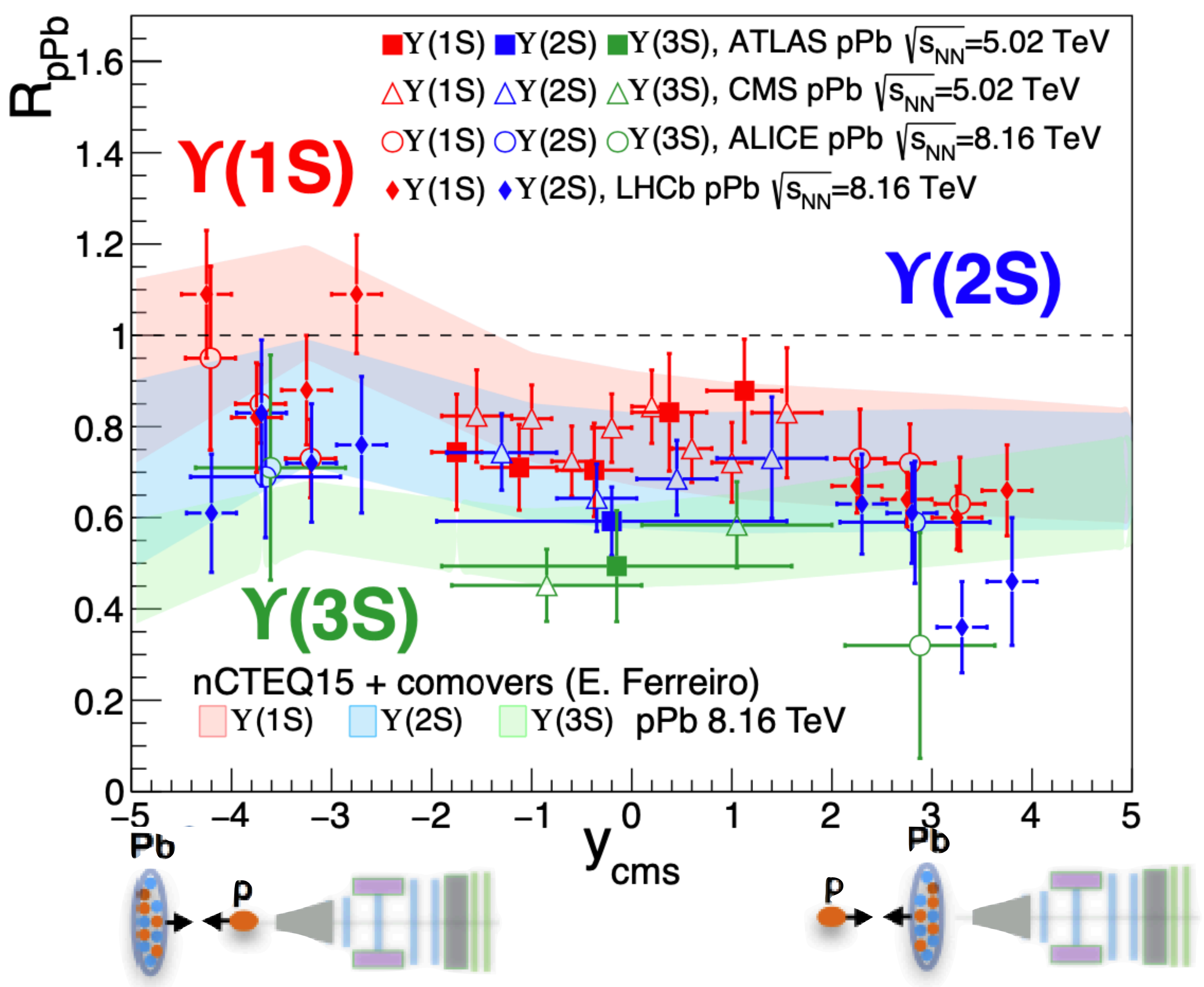
JHEP 07 (2020) 237

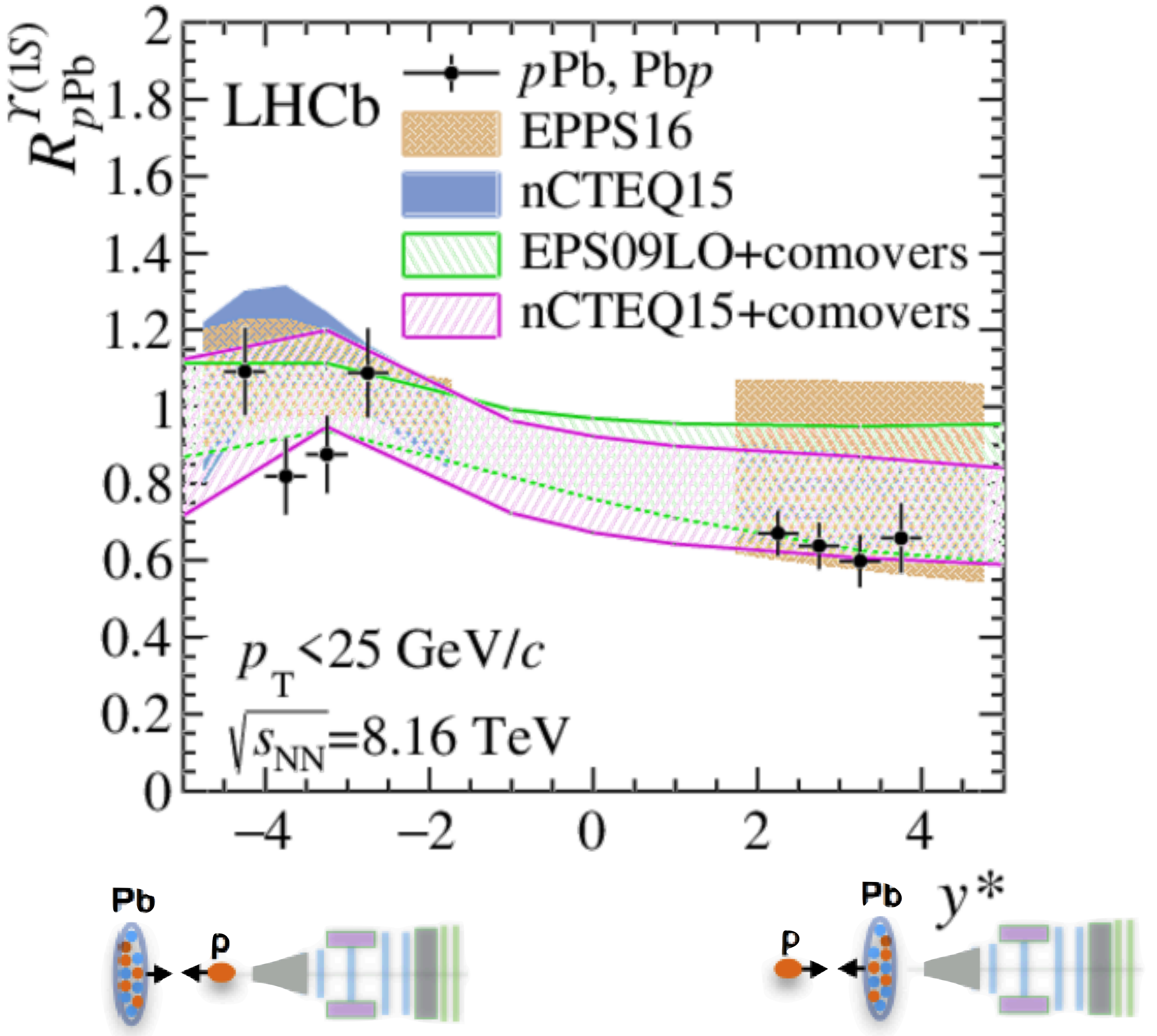
- $\psi(nS)$ measured at the LHC by many experiments.
- J/ψ production described by theory models (energy loss, nPDFs …)
- Relative $\psi(2S)/J/\Psi$ suppression better described by comovers model.

$\Upsilon(nS)$ production

JHEP 11 (2018) 194
EPJC 78 (2018) 3, 171
PLB 806 (2020) 135486

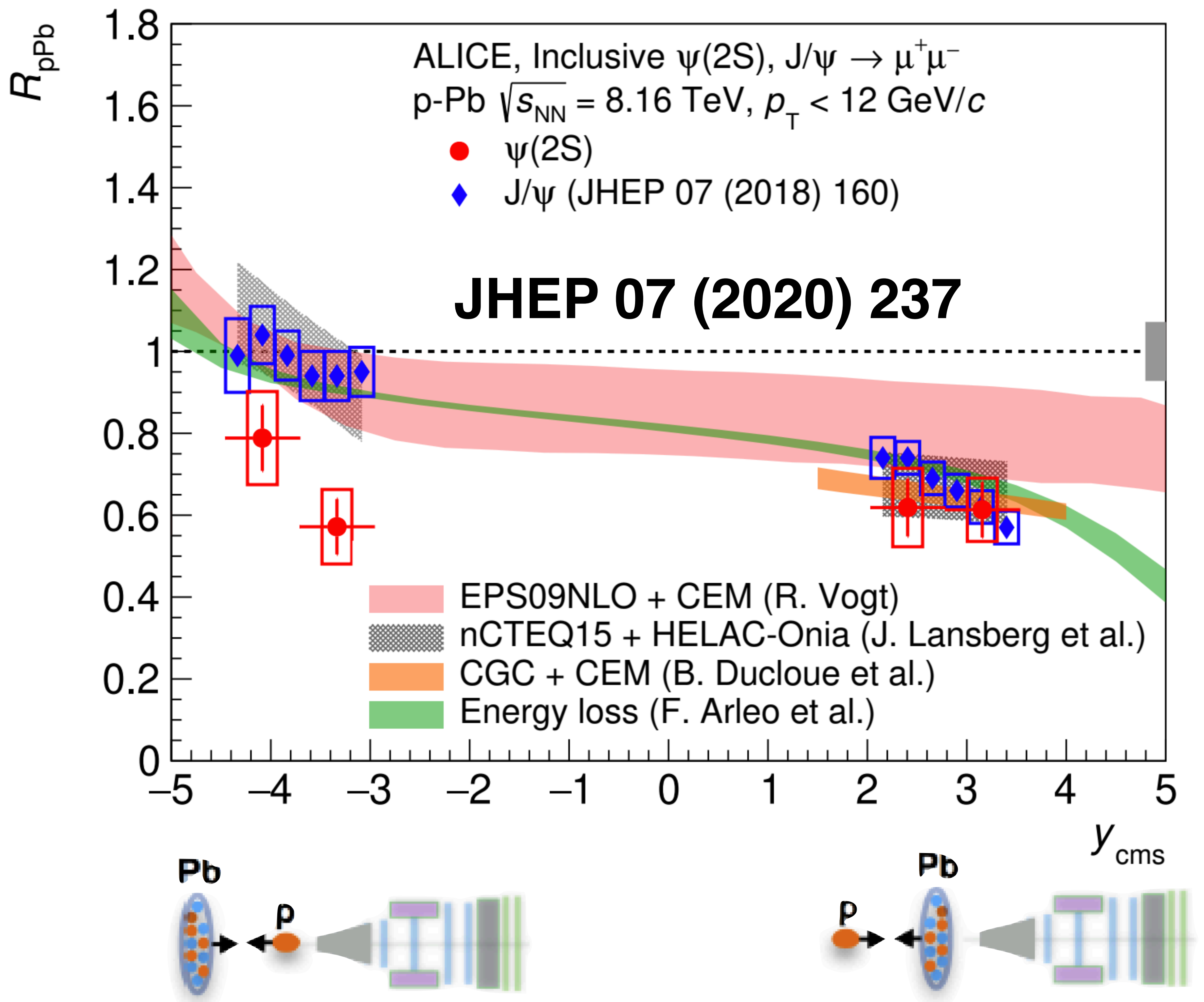


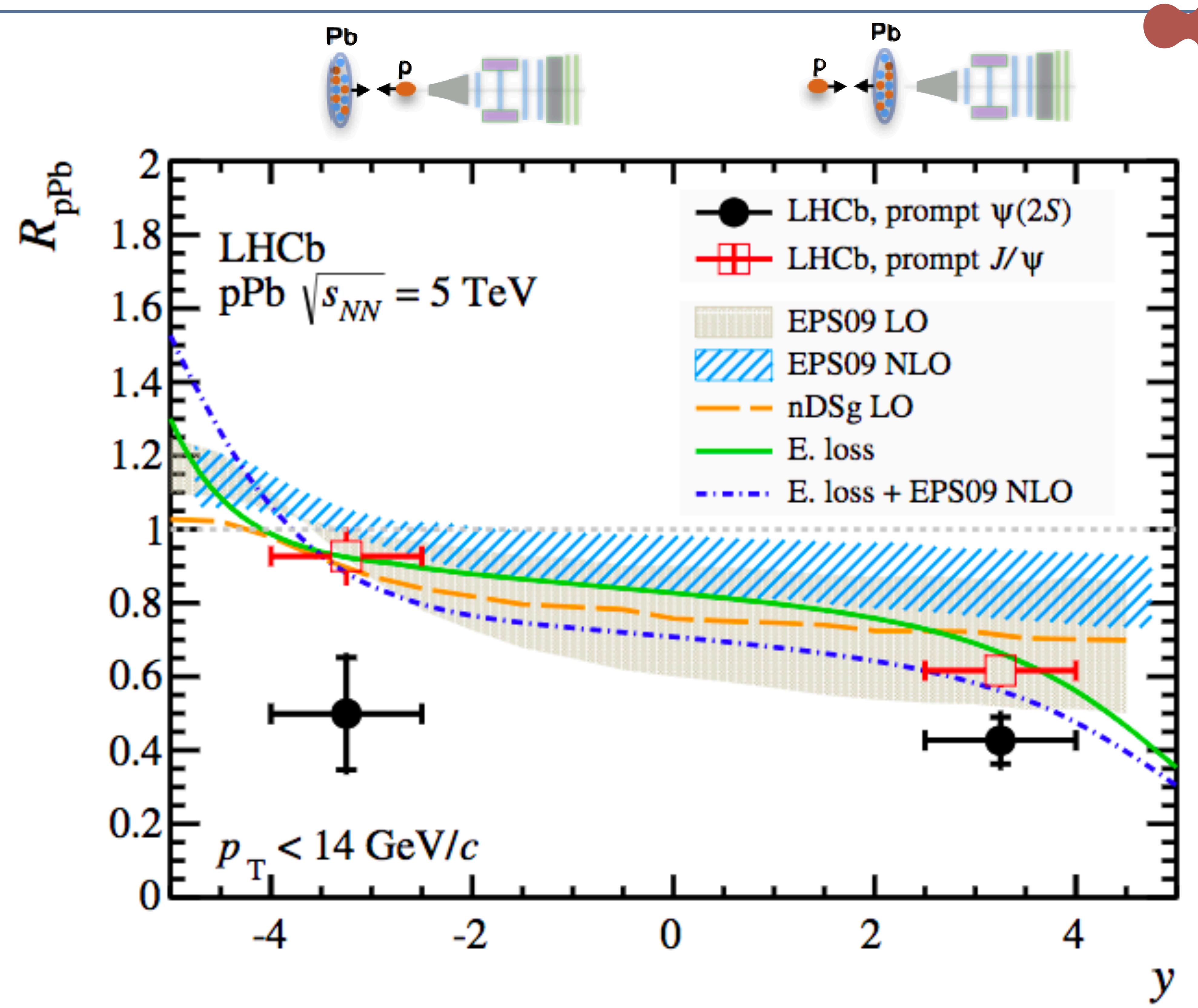




- $\Upsilon(nS)$ production measured by all the LHC's experiment.
- Difficult to have strong conclusions with the large uncertainties, but a relative suppression of higher $\Upsilon(nS)/\Upsilon(1S)$ seems to be observed.
- This trend is reproduced by comovers+ nPDFs predictions.

A last puzzle : ψ(2s) versus J/ψ





JHEP 1603 (2016) 133

- ψ(2S) more suppressed than J/ψ in pPb: the two have different binding energy.
  - Not explained by coherent energy loss or nPDFs alone.
- Sign of comovers effect ? QGP ?

Latte results by ALICE

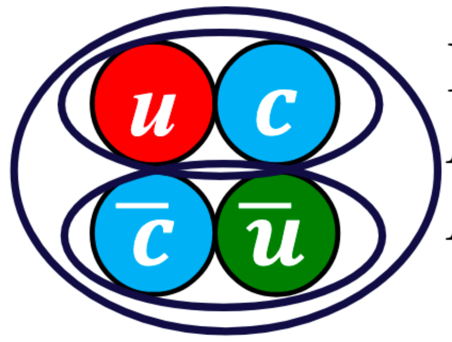
arXiv:2204.10253

- Puzzle not understood … but it seems that no comovers effet in pp collisions… or ?

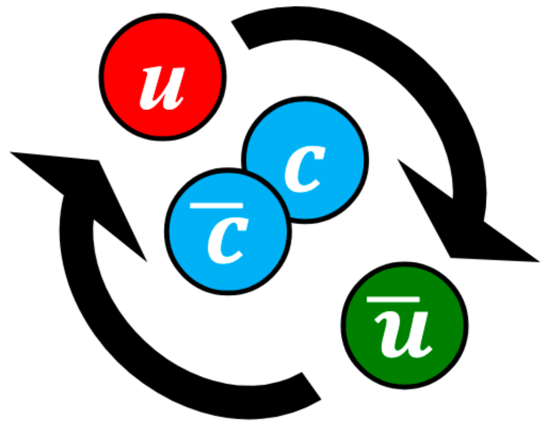
X(3872)/ψ(2S) in pp/PbPb collisions

- X(3872) : exotic state still not understood.
  - ➡ Tetraquark / hadronic molecule / something else ?
- Production yield in QCD medium strongly reflects internal structure.

Compact tetraquark/pentaquark

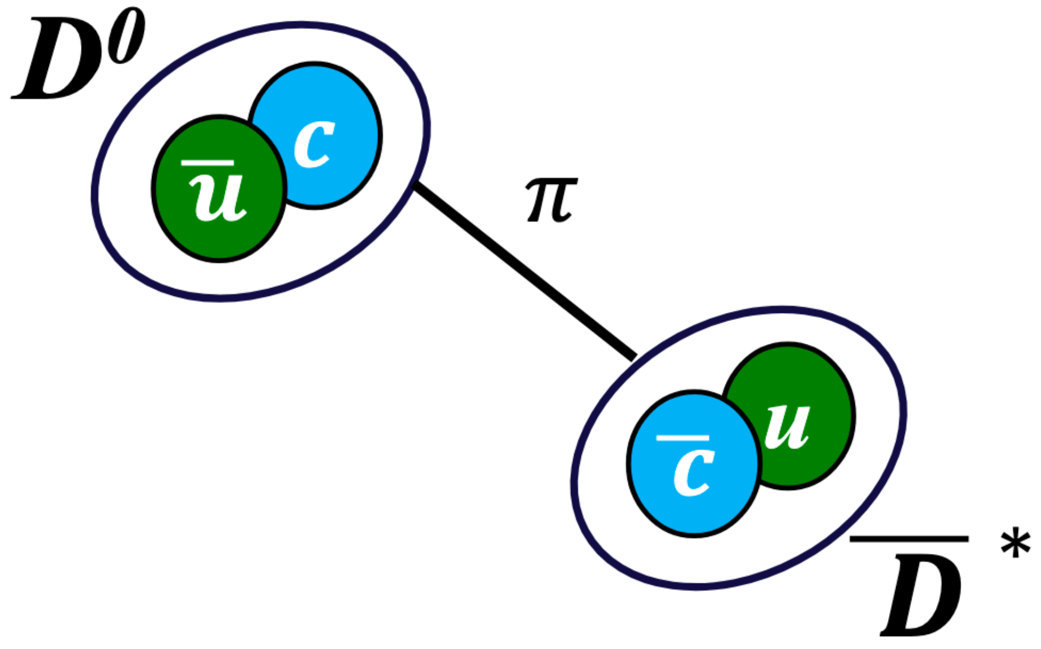


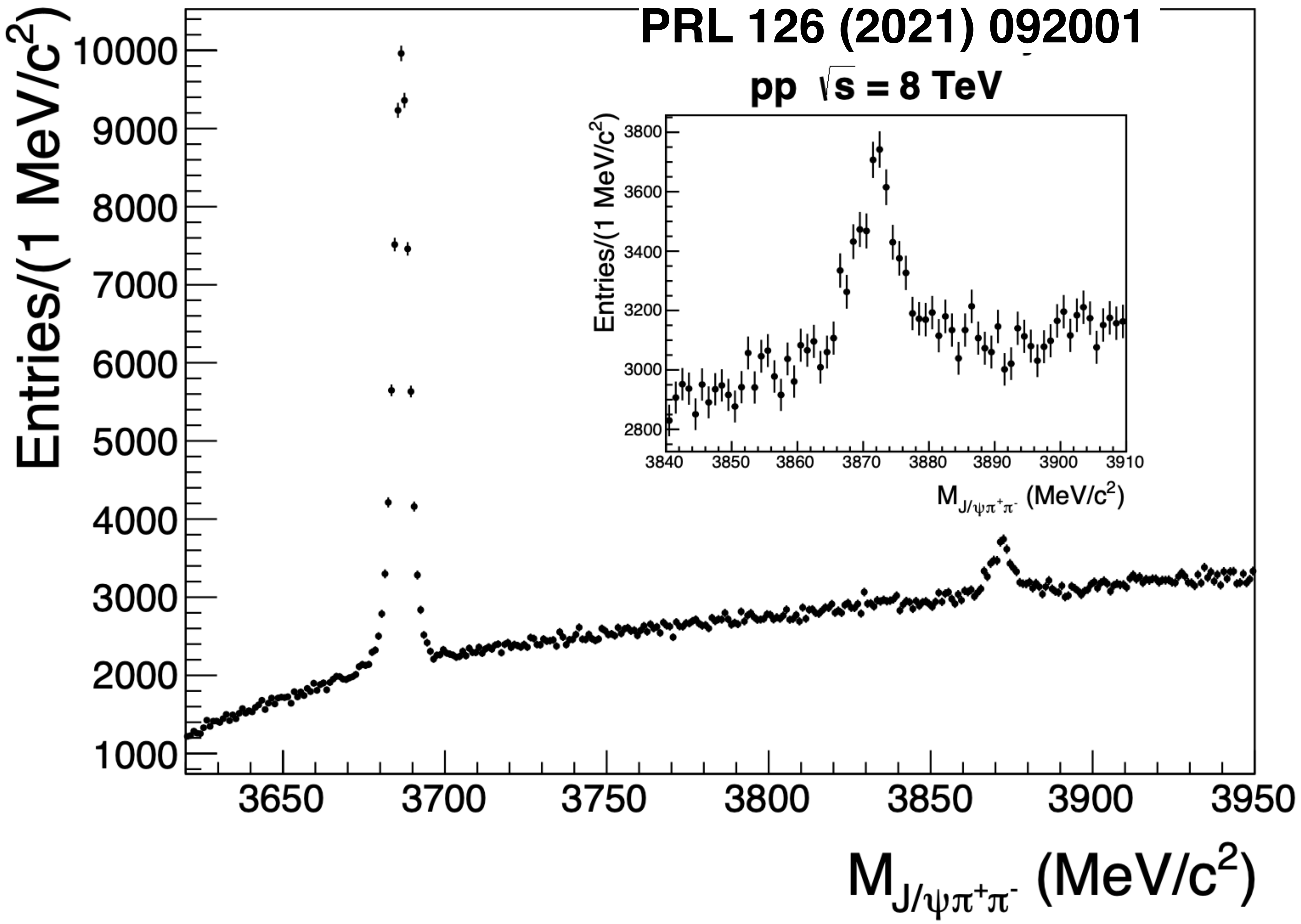
Diquark-diquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)



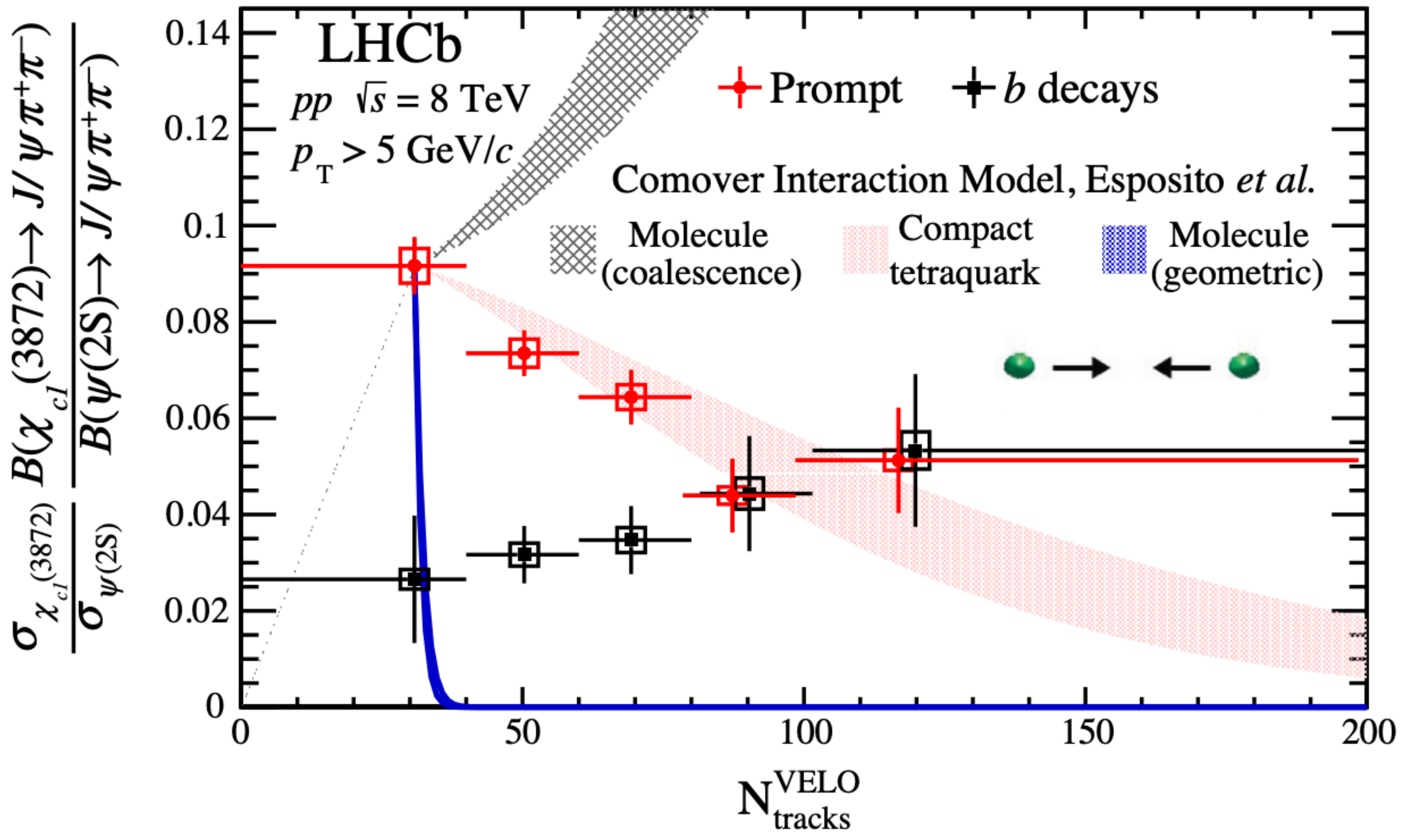
Hadrocharmonium/ adjoint charmonium
PLB 666 344 (2008)
PLB 671 82 (2009)

Hadronic Molecules
PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)



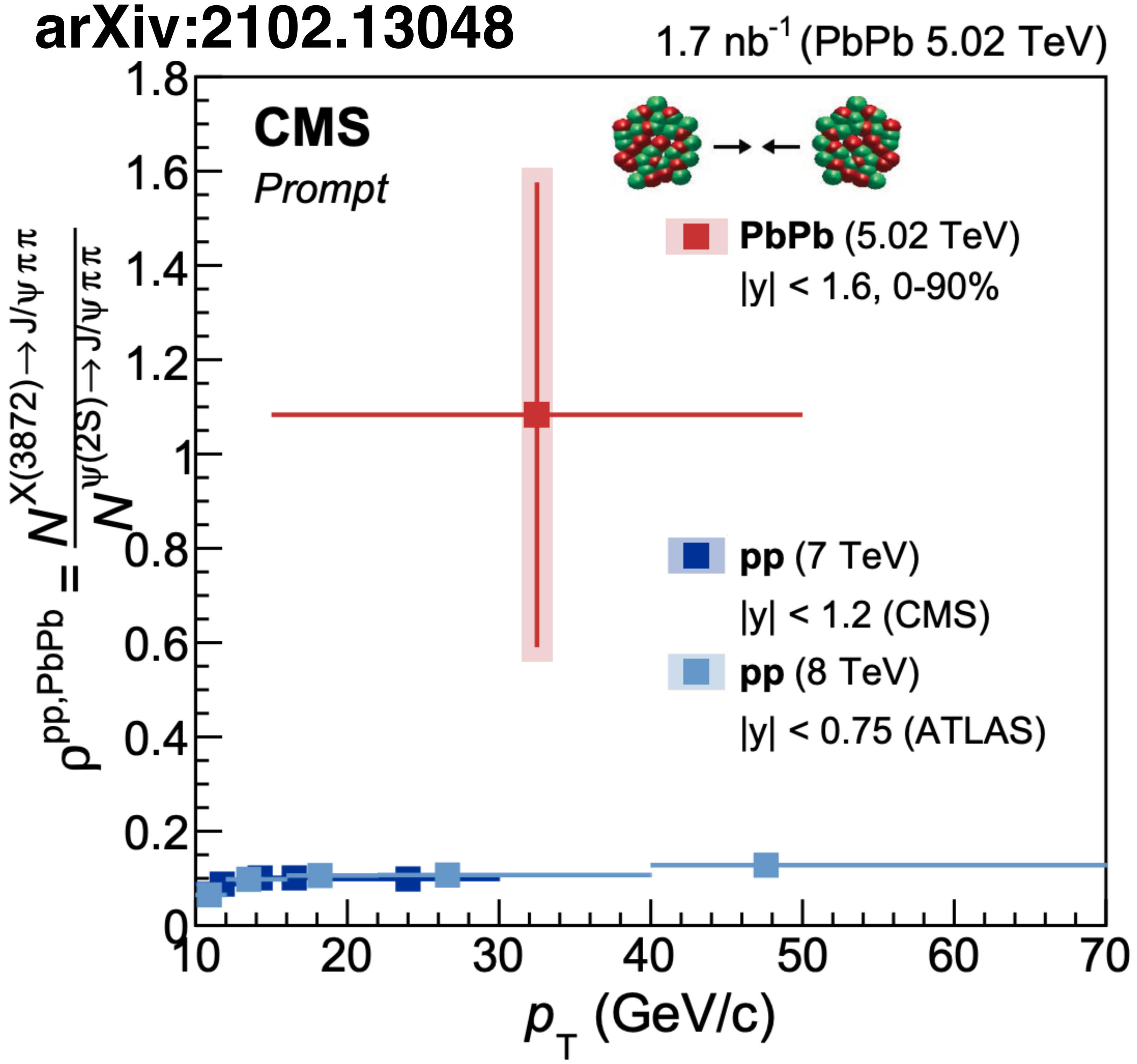


X(3872)/ψ(2S) in pp PbPb collisions



PRL 126 (2021) 092001

arXiv:2102.13048

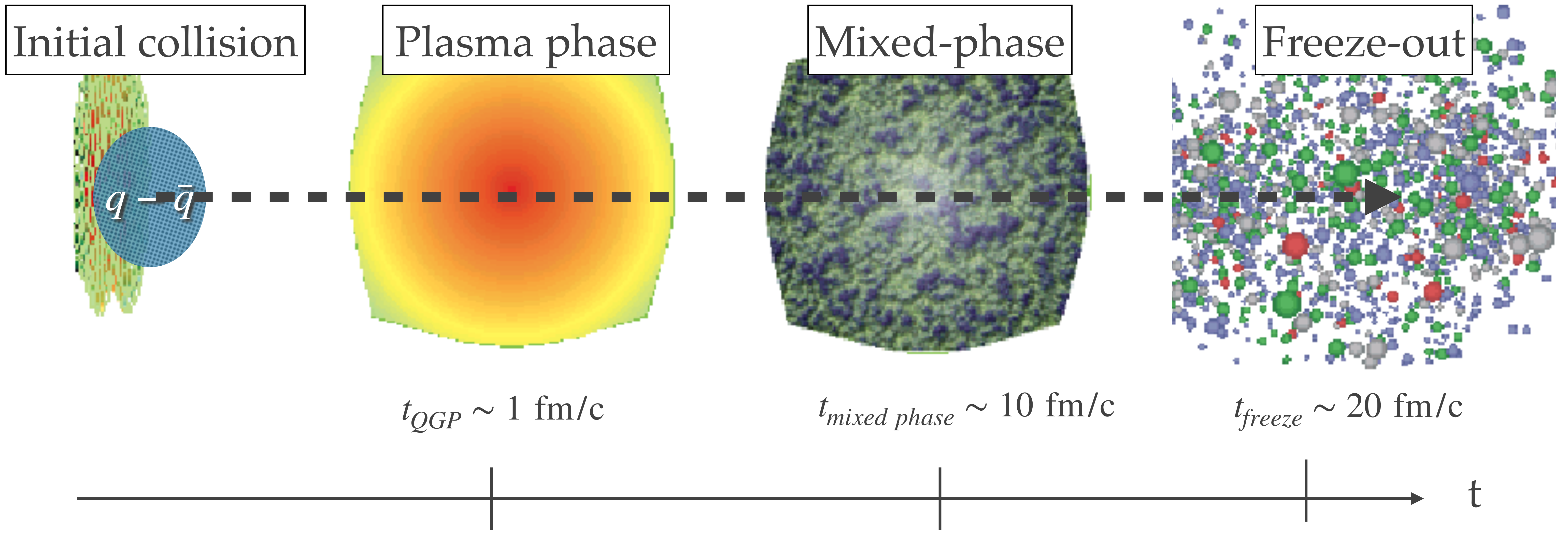


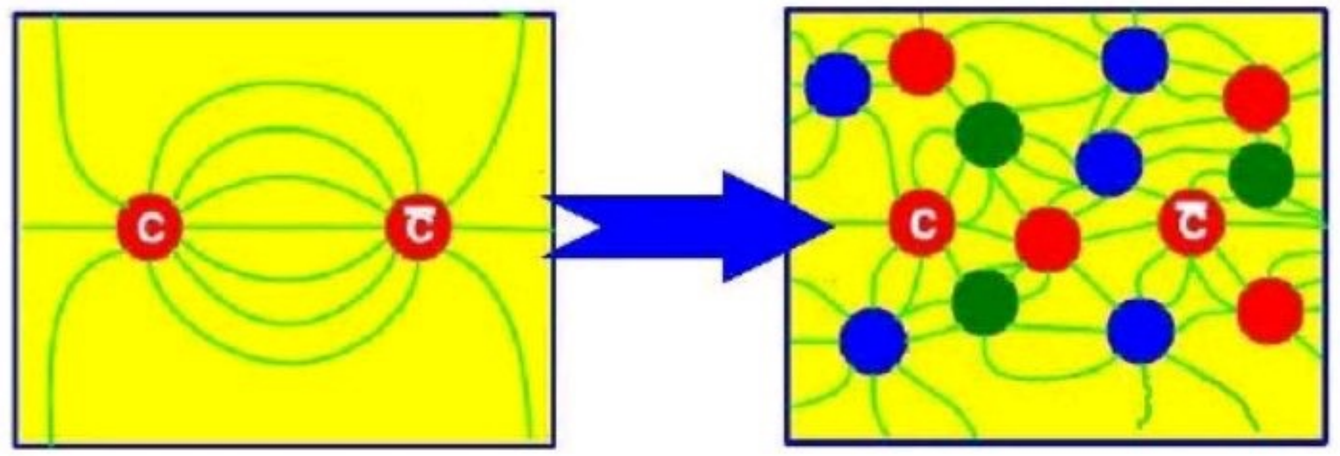
- Different trend measured by LHCb and CMS in pp and PbPb.
- pp results favour tetraquark nature of the $\chi_{c1}(3872)$, while PbPb enhancement favours molecular nature due to coalescence mechanisms.
- To be understood.

QUARKONIA IN HIC

Quarkonia in AA collisions

- Hadronic quarkonia:
  - High mass → short formation time → **ideal prob for the QGP.**

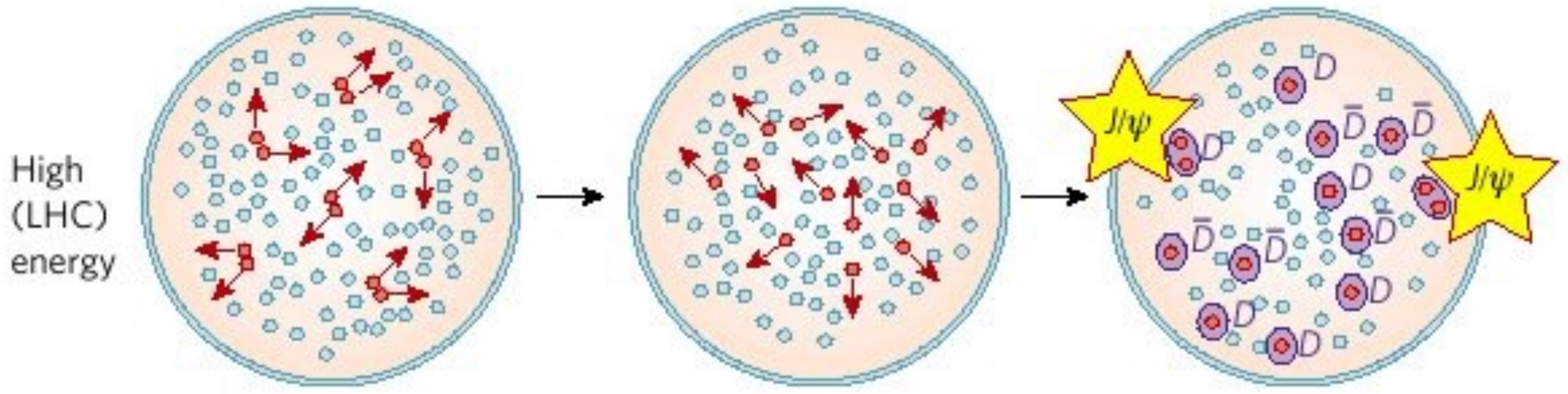




Color screening mechanism

Physics Letters B vol.178 n.4

versus

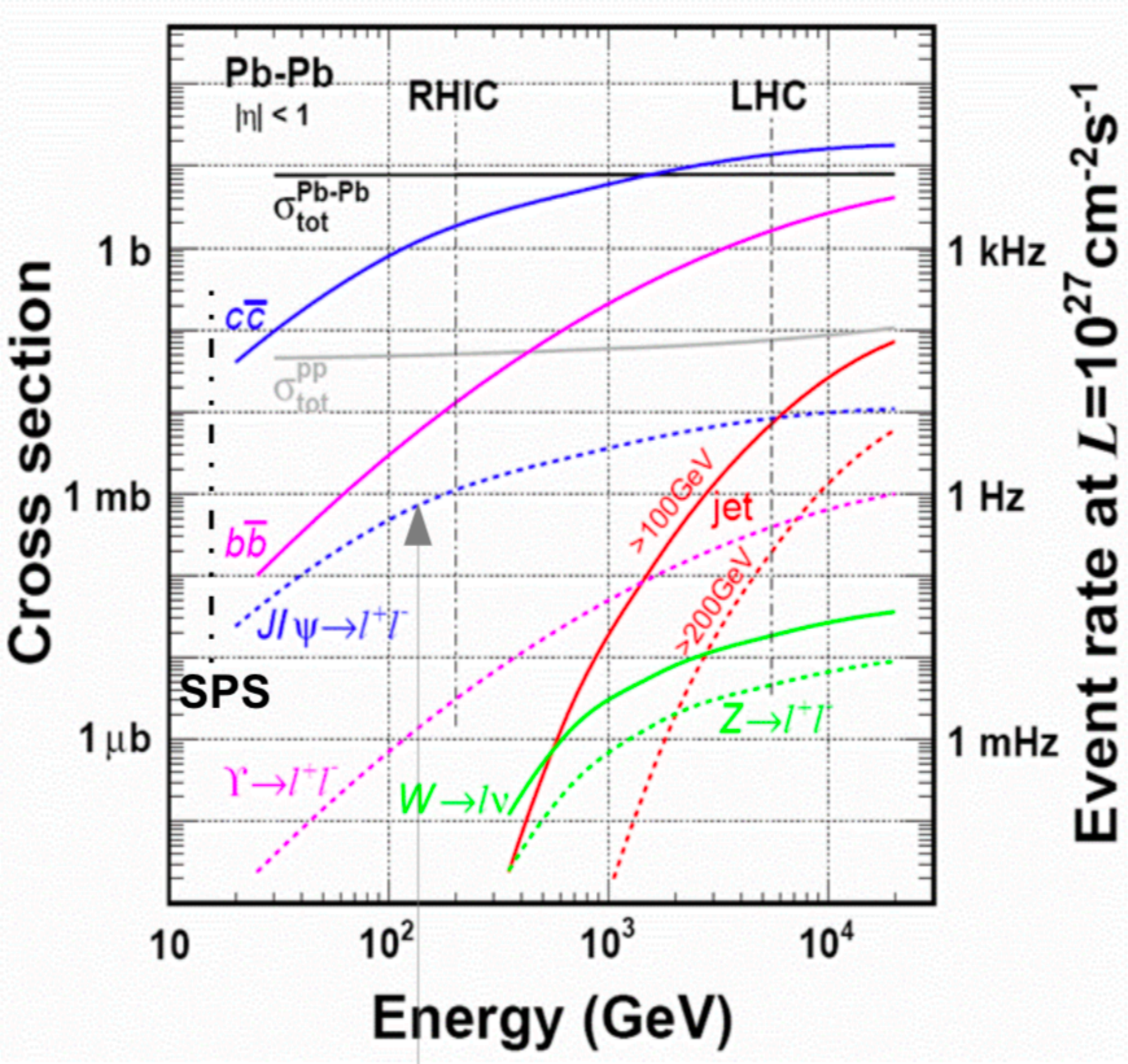


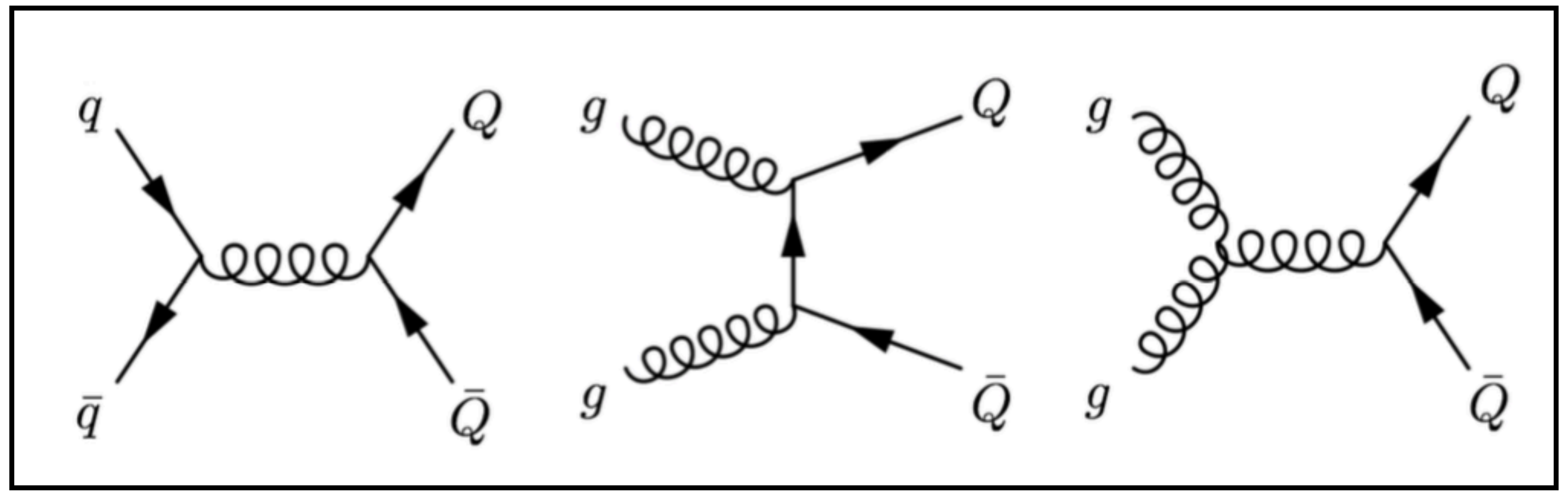
(re)combination

+ energy loss + nPDFS …

Production mechanism at the LHC

- Leading Feynman diagrams :

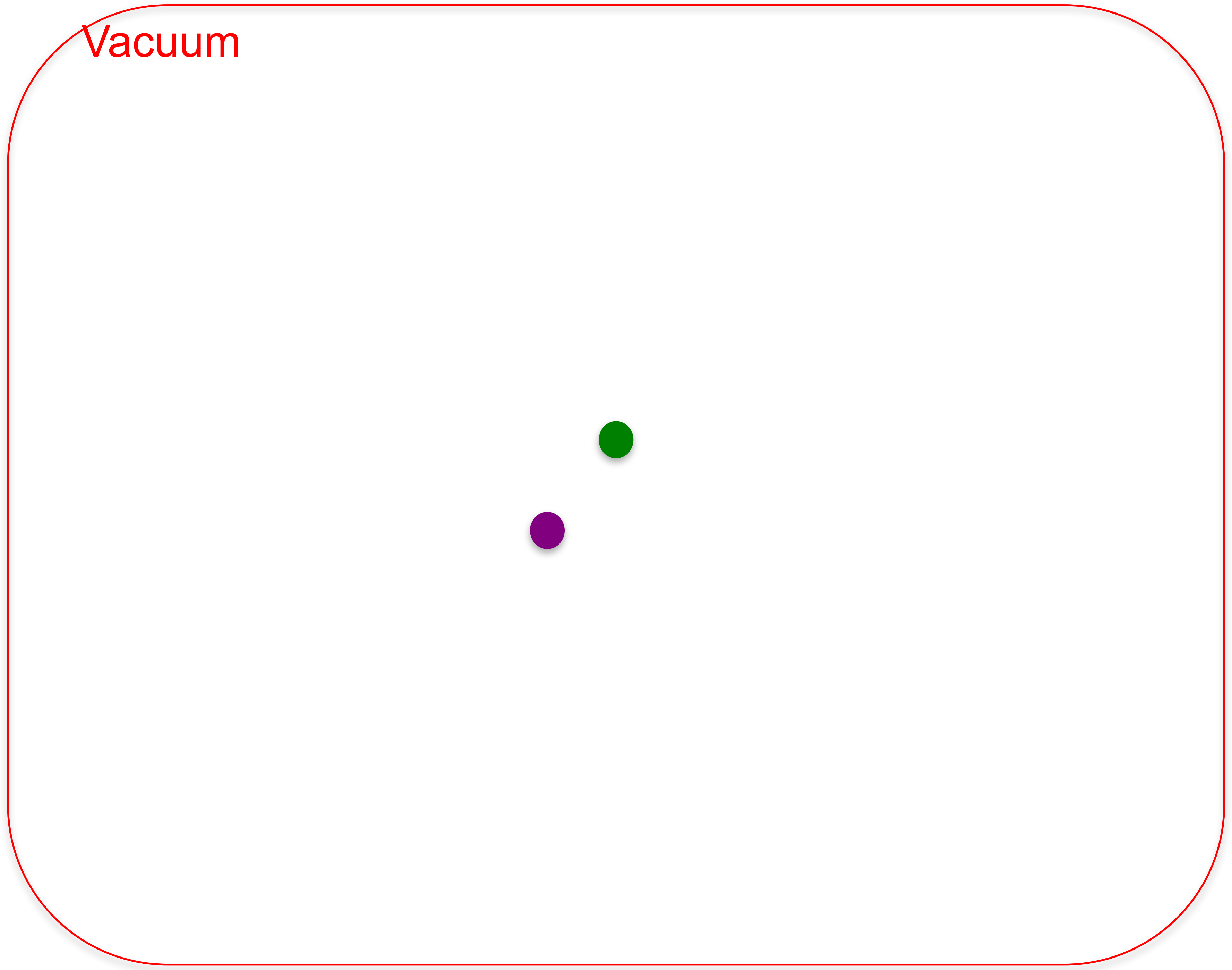


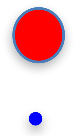


Expected number of Heavy-Quarks pairs in central AA collisions :

	SPS	RHIC	LHC
Charm	0.2	10	130
Beauty	—	0.05	5

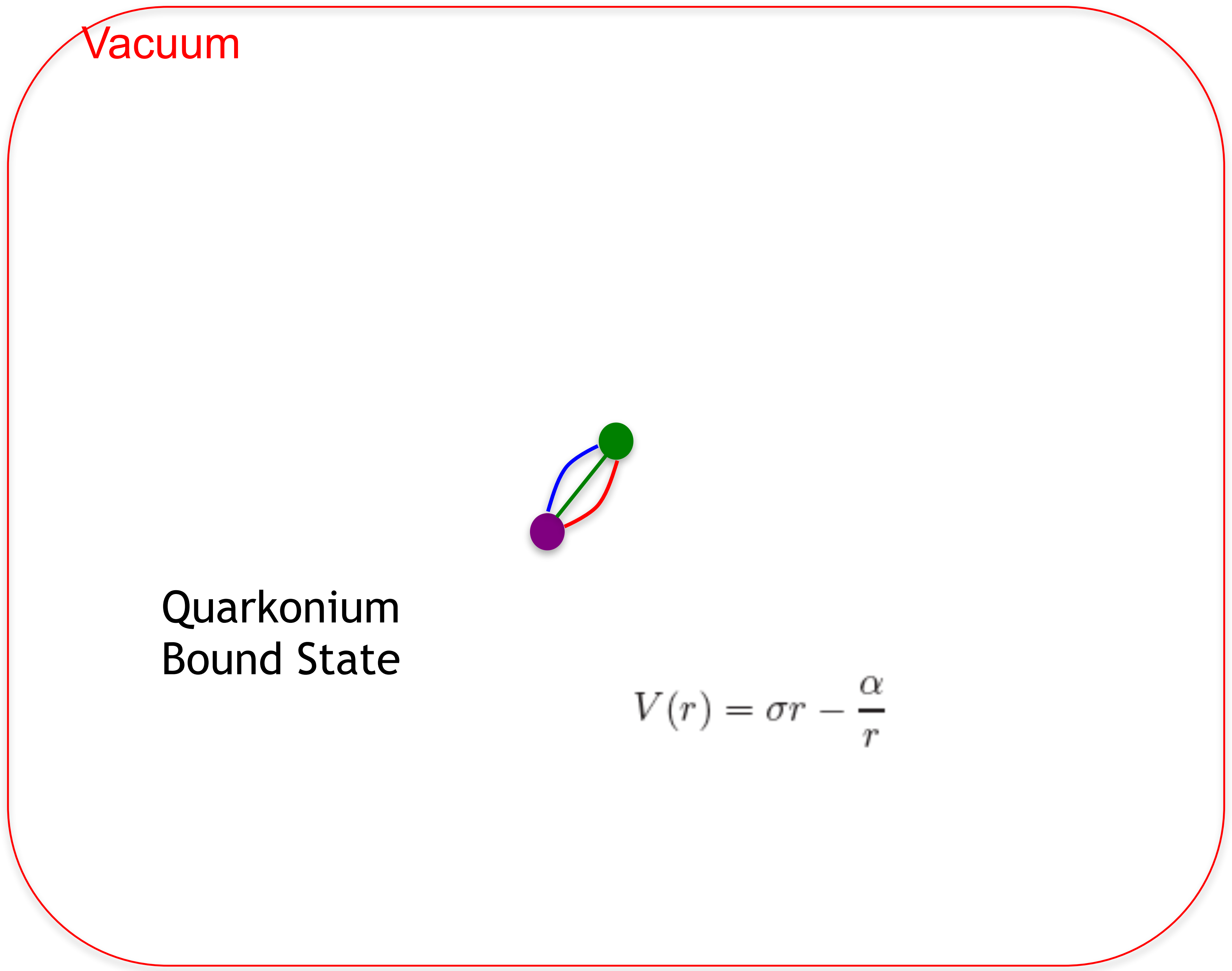
Quarkonia : Color screening mechanism





Matsui & Staz, PLB 178, 416 (1986)

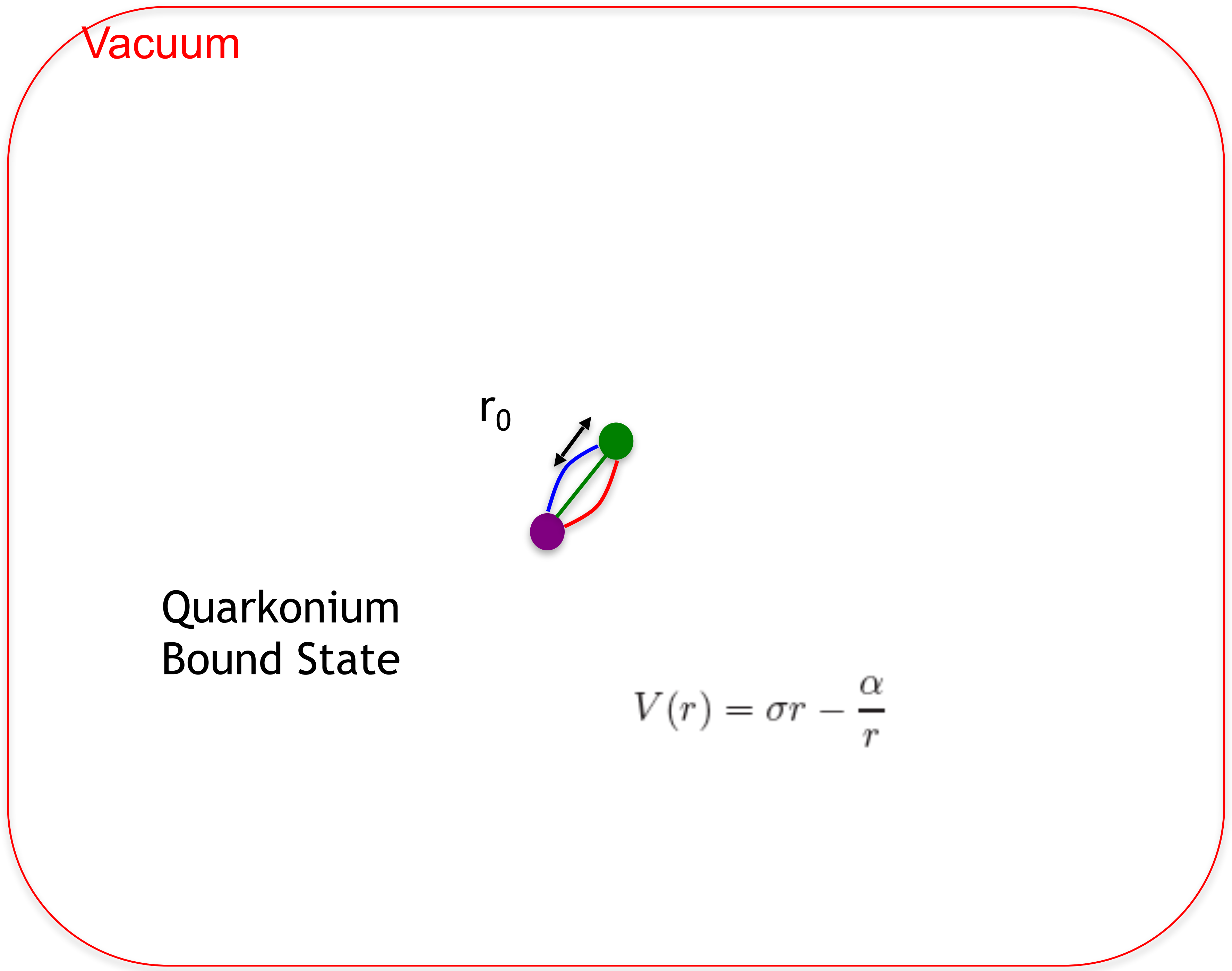
Quarkonia : Color screening mechanism



Heavy Quark: c or b
Light Quarks and Gluons

Matsui & Staz, PLB 178, 416 (1986)

Quarkonia : Color screening mechanism

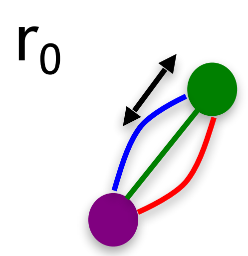


Heavy Quark: c or b
Light Quarks and Gluons

Matsui & Staz, PLB 178, 416 (1986)

Quarkonia : Color screening mechanism

Vacuum



Quarkonium
Bound State

$$V(r) = \sigma r - \frac{\alpha}{r}$$

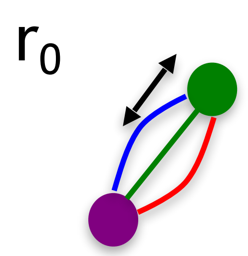
In medium

Heavy Quark: c or b
Light Quarks and Gluons

Matsui & Staz, PLB 178, 416 (1986)

Quarkonia : Color screening mechanism

Vacuum



Quarkonium
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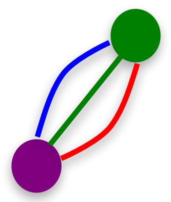
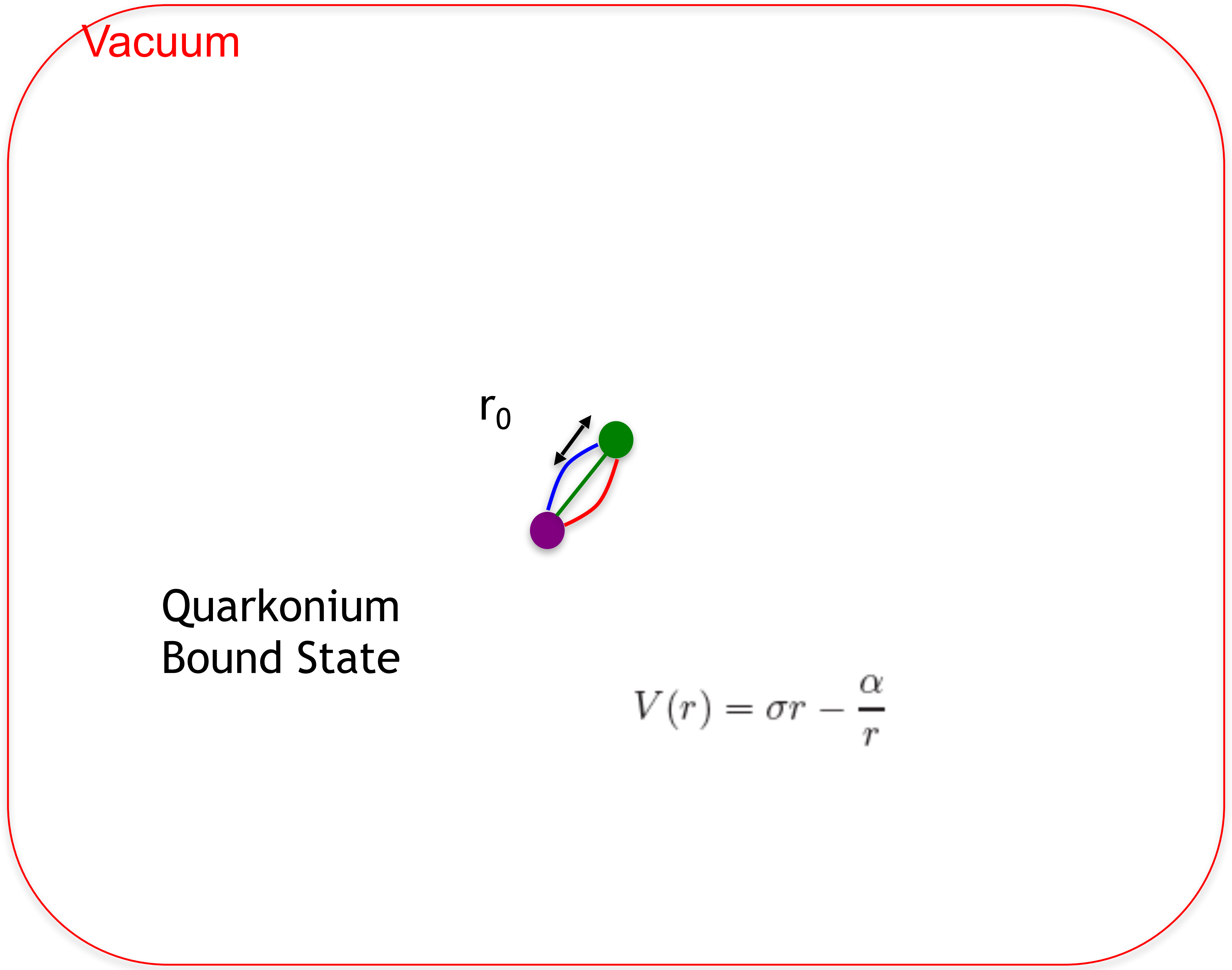
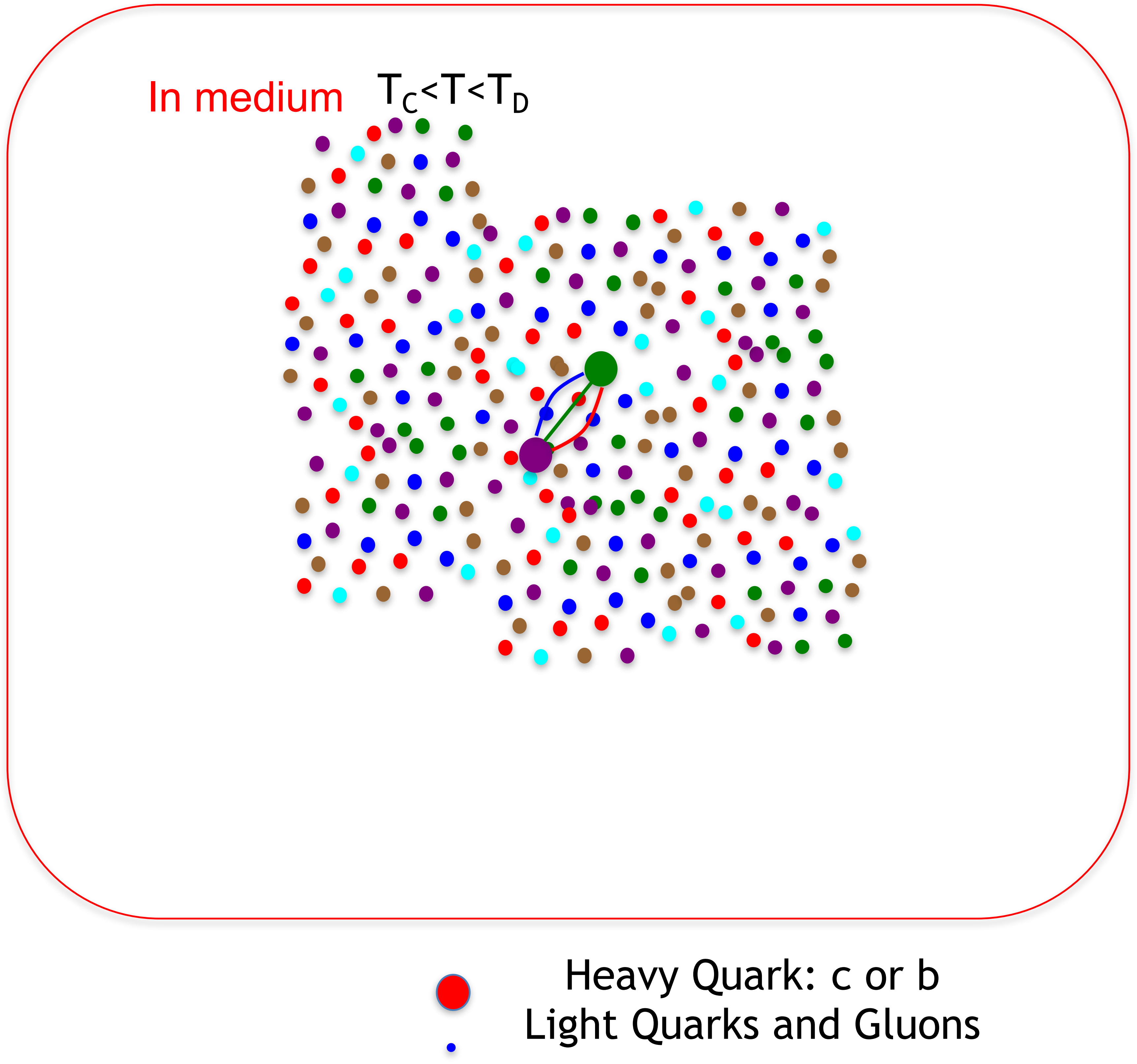


Heavy Quark: c or b
Light Quarks and Gluons

Matsui & Staz, PLB 178, 416 (1986)

Quarkonia : Color screening mechanism

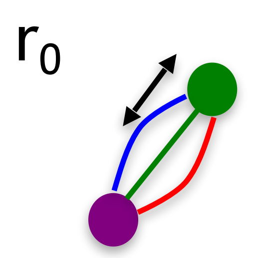




Matsui & Staz, PLB 178, 416 (1986)

Quarkonia : Color screening mechanism

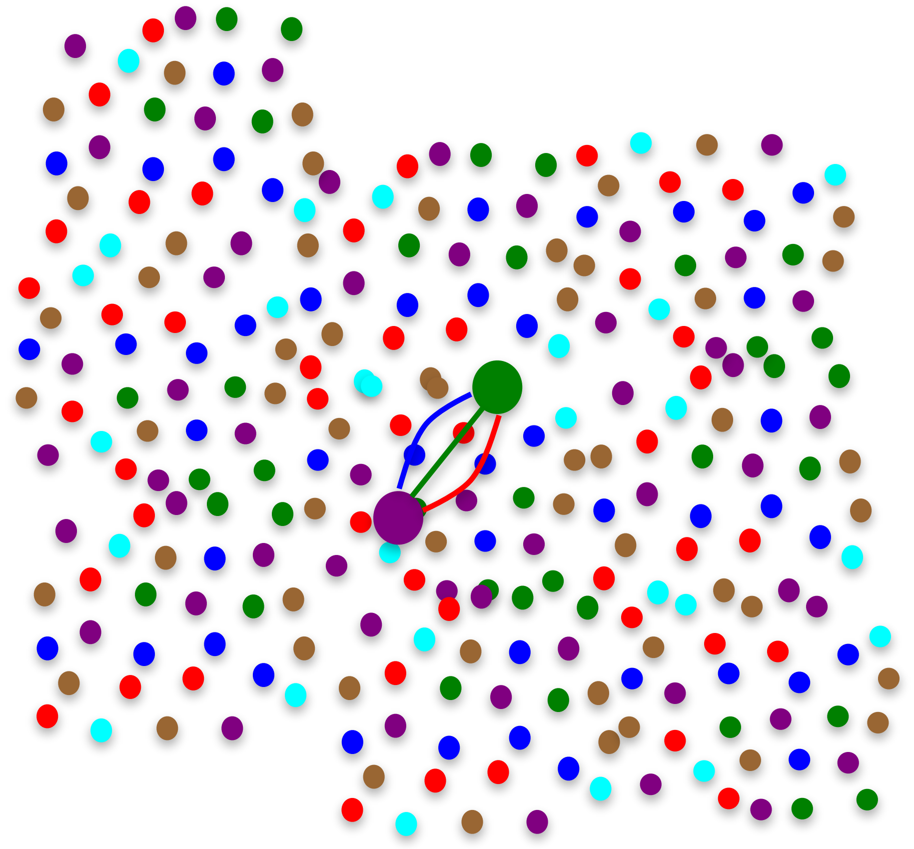
Vacuum



Quarkonium
Bound State

$$V(r) = \sigma r - \frac{\alpha}{r}$$

In medium $T_C<T<T_D$



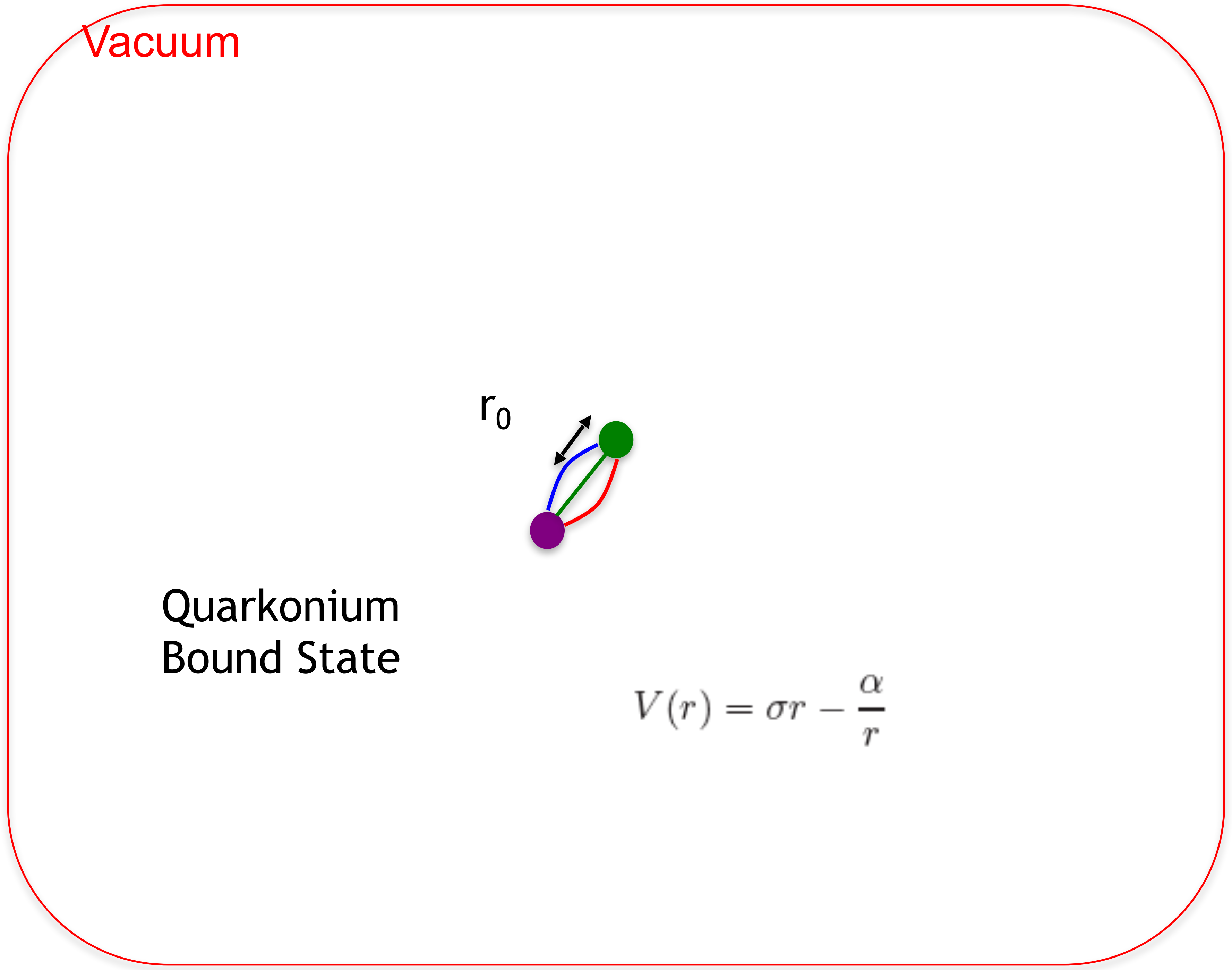
Bound State

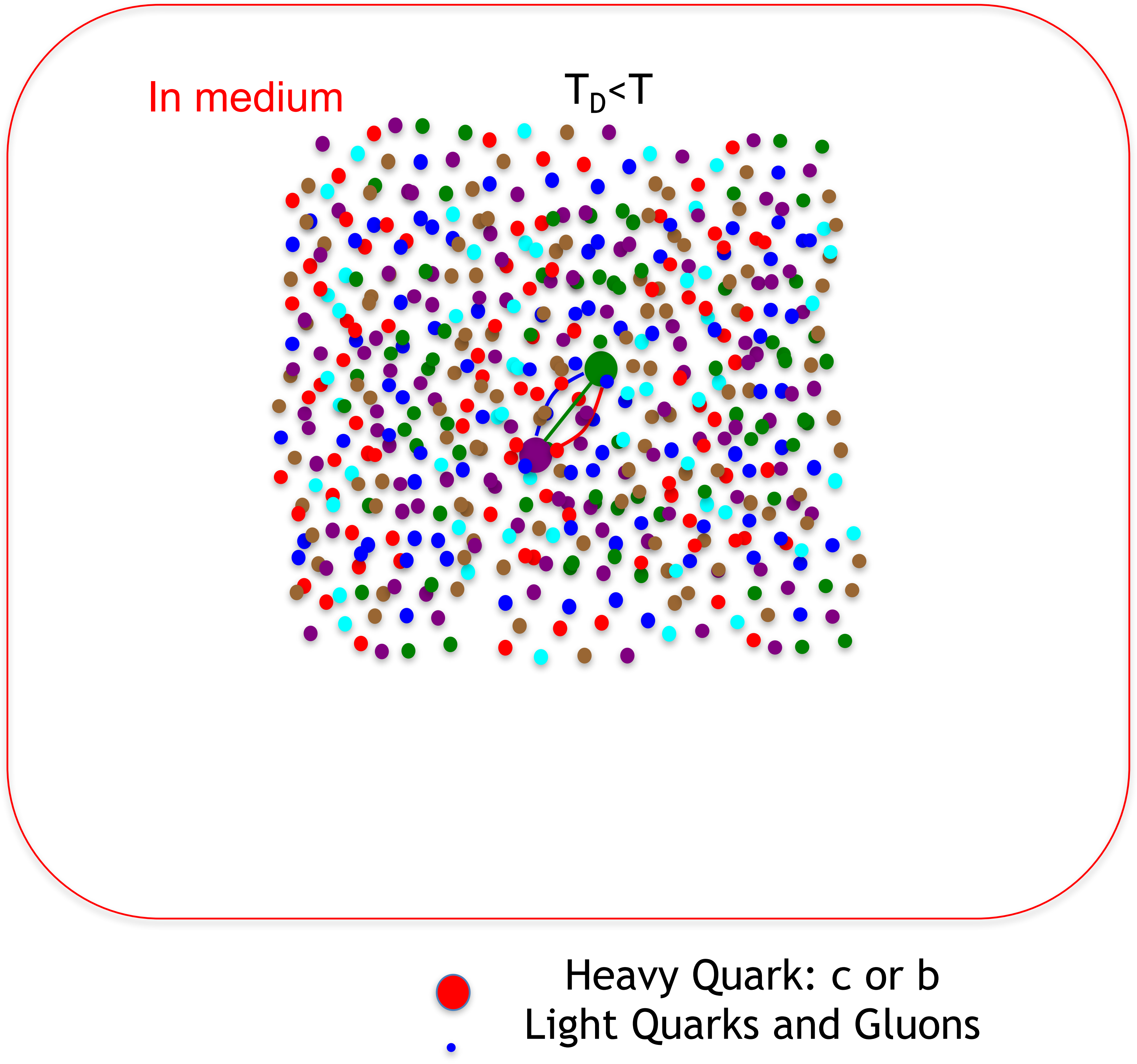
$$V(r) = -\frac{\alpha}{r} \times e^{(-r/\lambda_D)}$$

Heavy Quark: c or b
Light Quarks and Gluons

Matsui & Staz, PLB 178, 416 (1986)

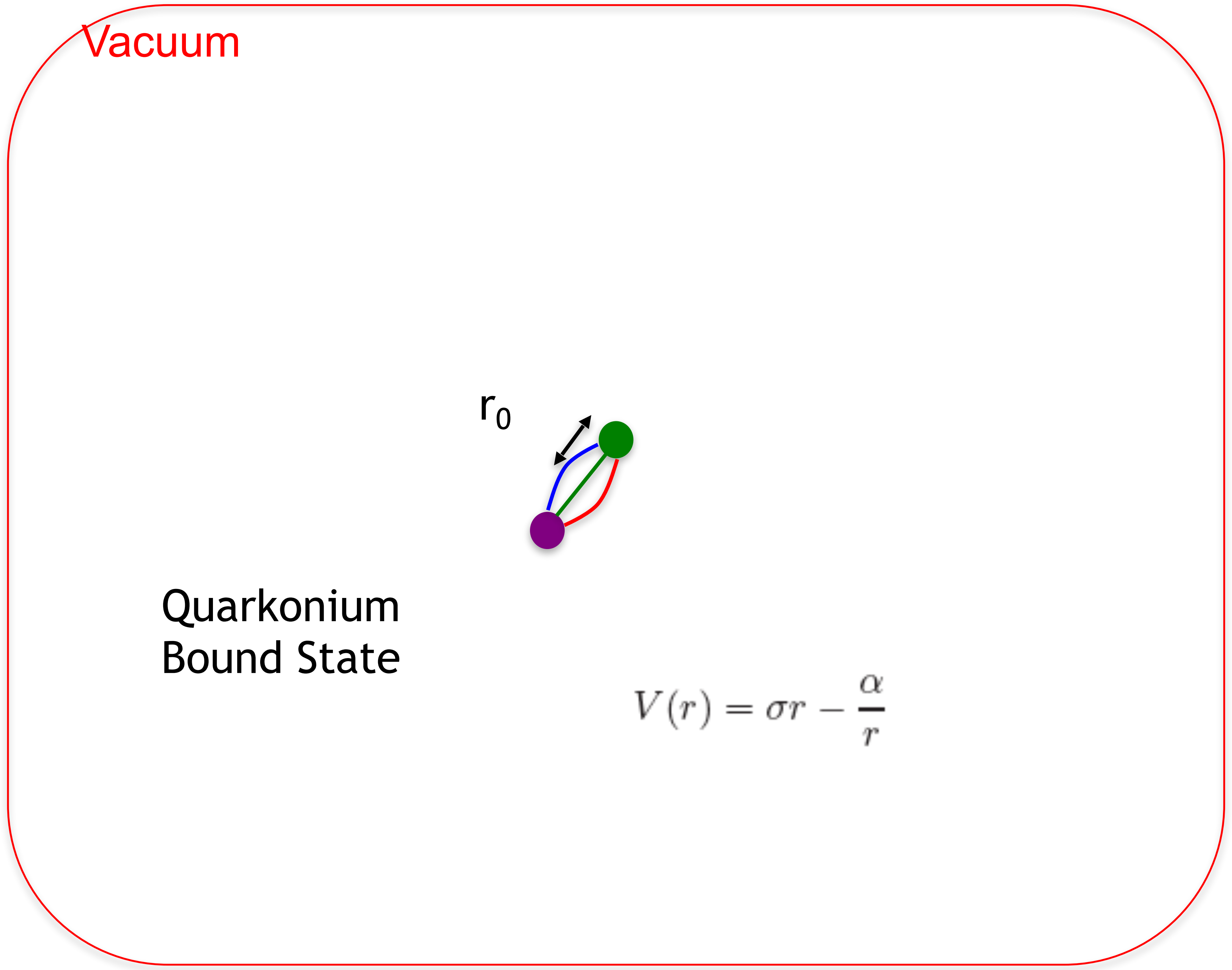
Quarkonia : Color screening mechanism



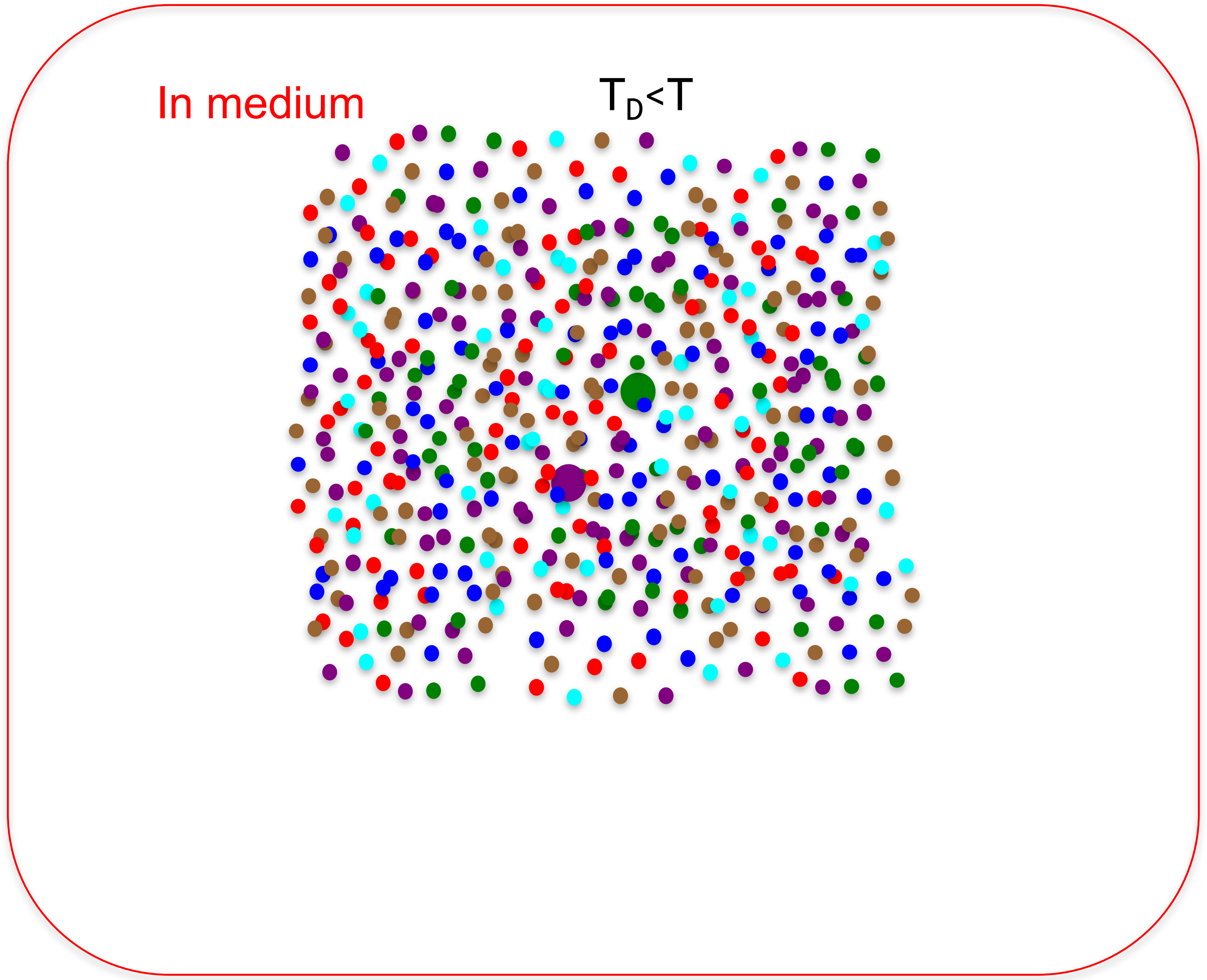


Matsui & Staz, PLB 178, 416 (1986)

Quarkonia : Color screening mechanism



$$V(r) = \sigma r - \frac{\alpha}{r}$$

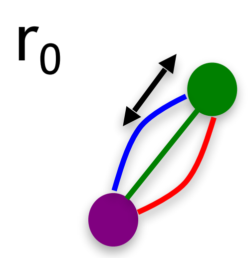


Heavy Quark: c or b
Light Quarks and Gluons

Matsui & Staz, PLB 178, 416 (1986)

Quarkonia : Color screening mechanism

Vacuum

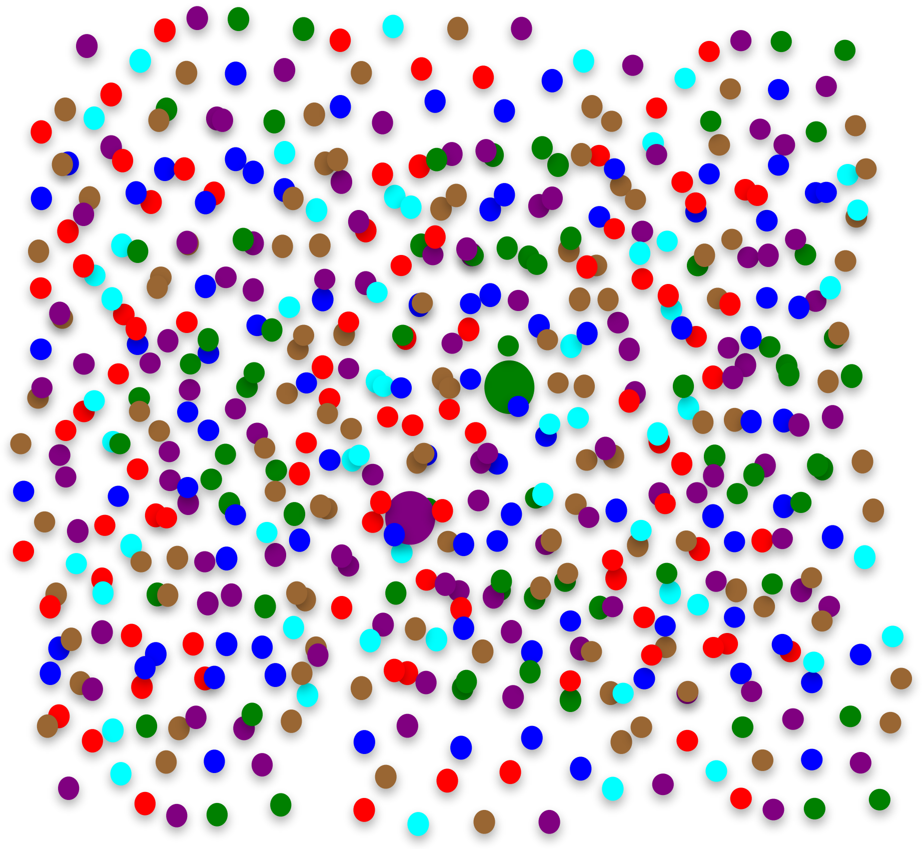


Quarkonium
Bound State

$$V(r) = \sigma r - \frac{\alpha}{r}$$

In medium

$T_D < T$



Melting of the Quarkonium
Deconfinement of Heavy Quarks

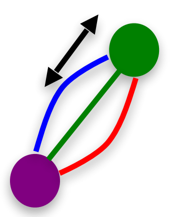
Heavy Quark: c or b
Light Quarks and Gluons

Matsui & Staz, PLB 178, 416 (1986)

Quarkonia : Color screening mechanism

Vacuum

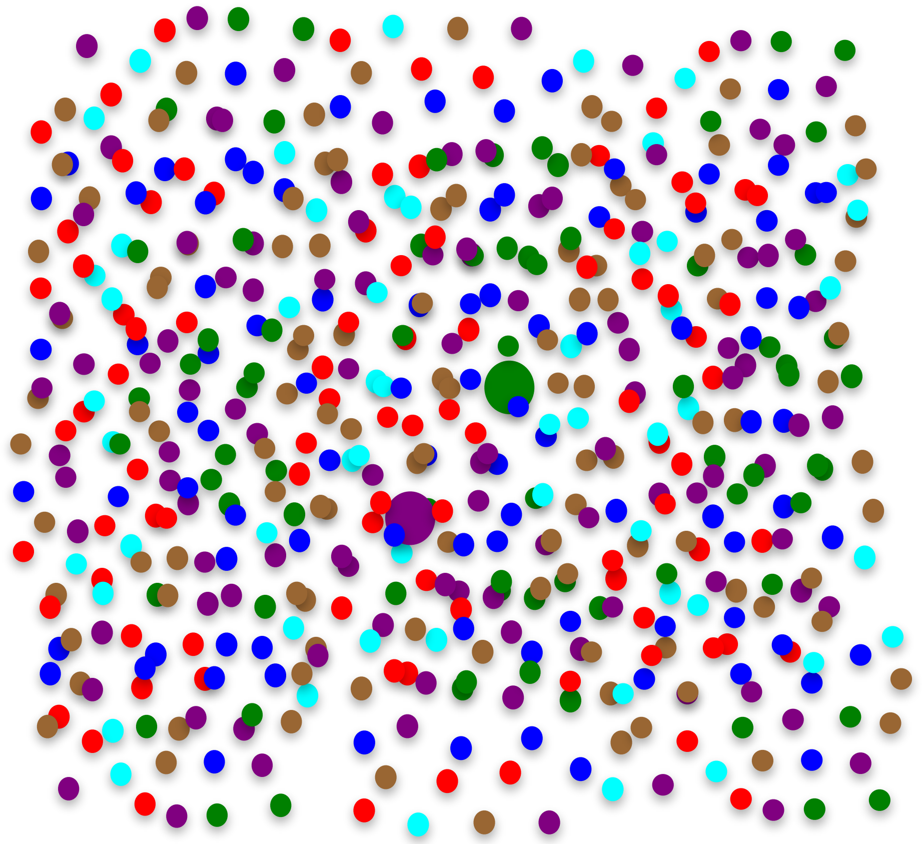
r_0



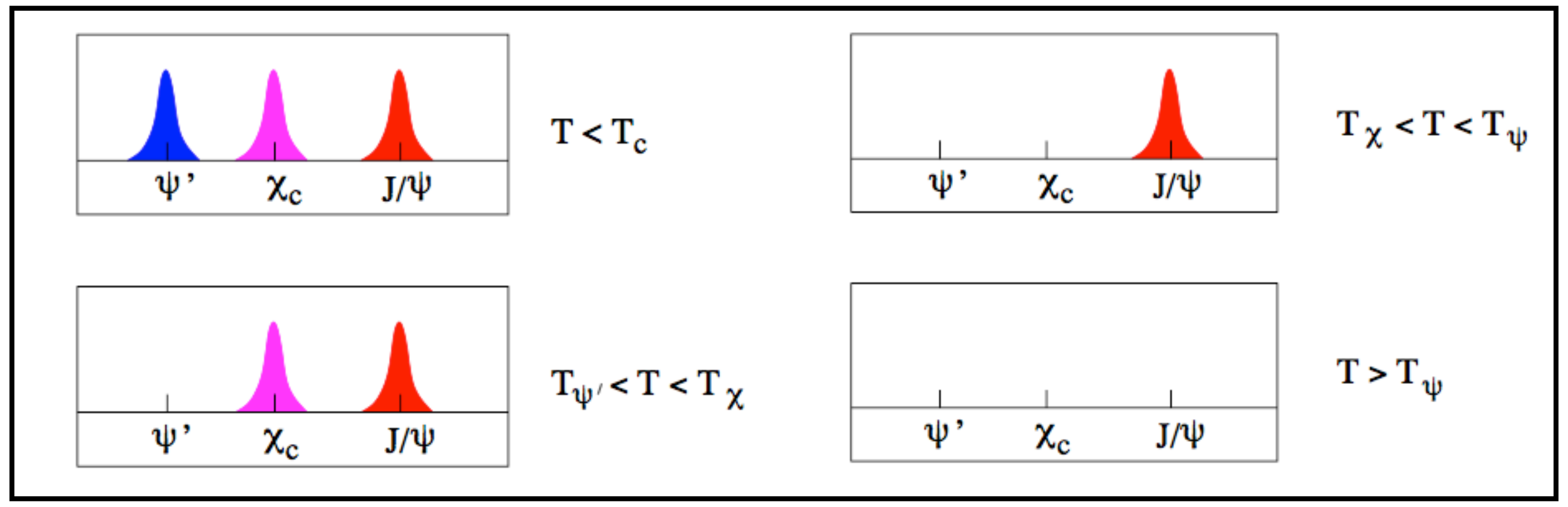
Quarkonium
Bound State

$$V(r) = \sigma r - \frac{\alpha}{r}$$

In medium $T_D < T$



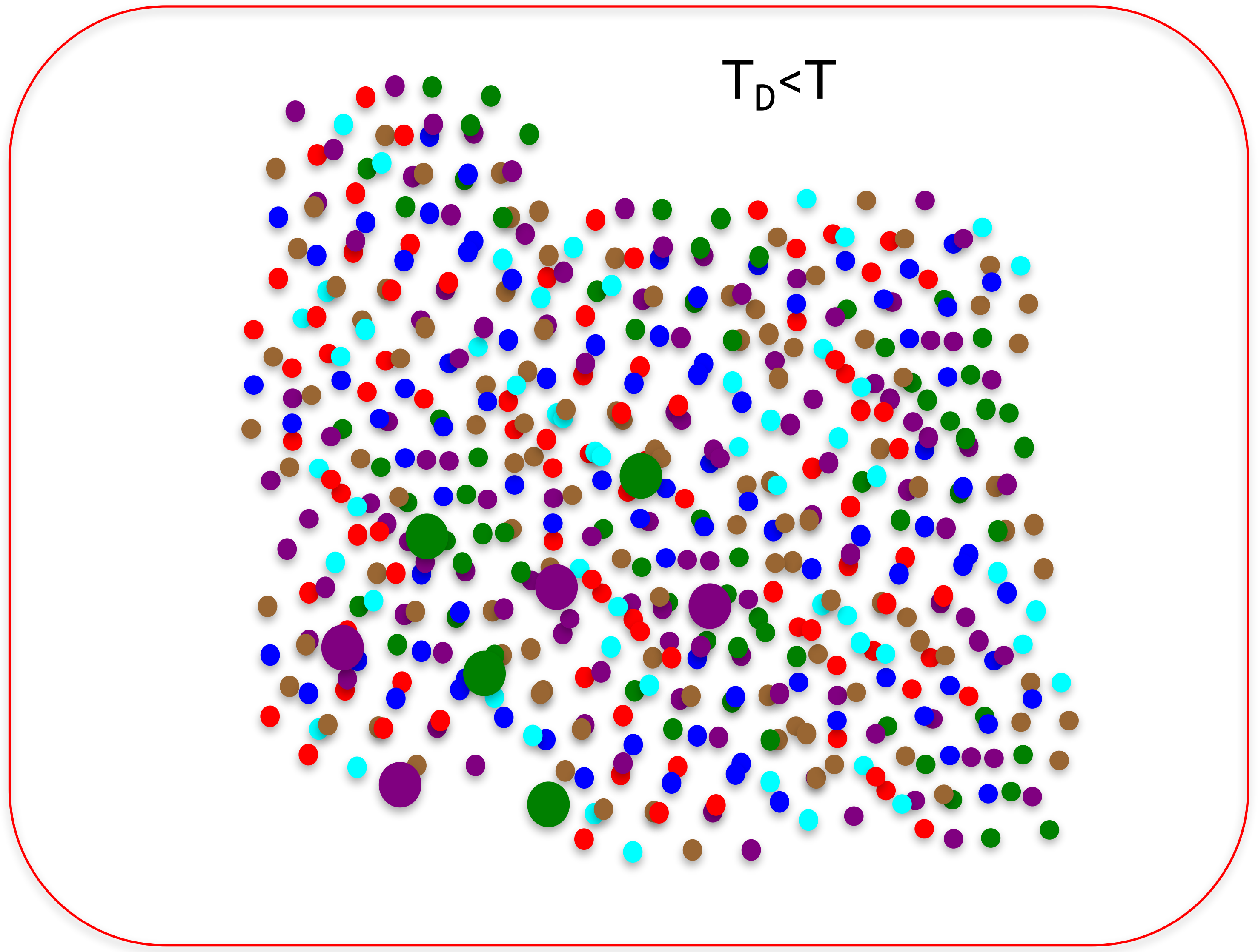
Melting of the Quarkonium
Deconfinement of Heavy Quarks



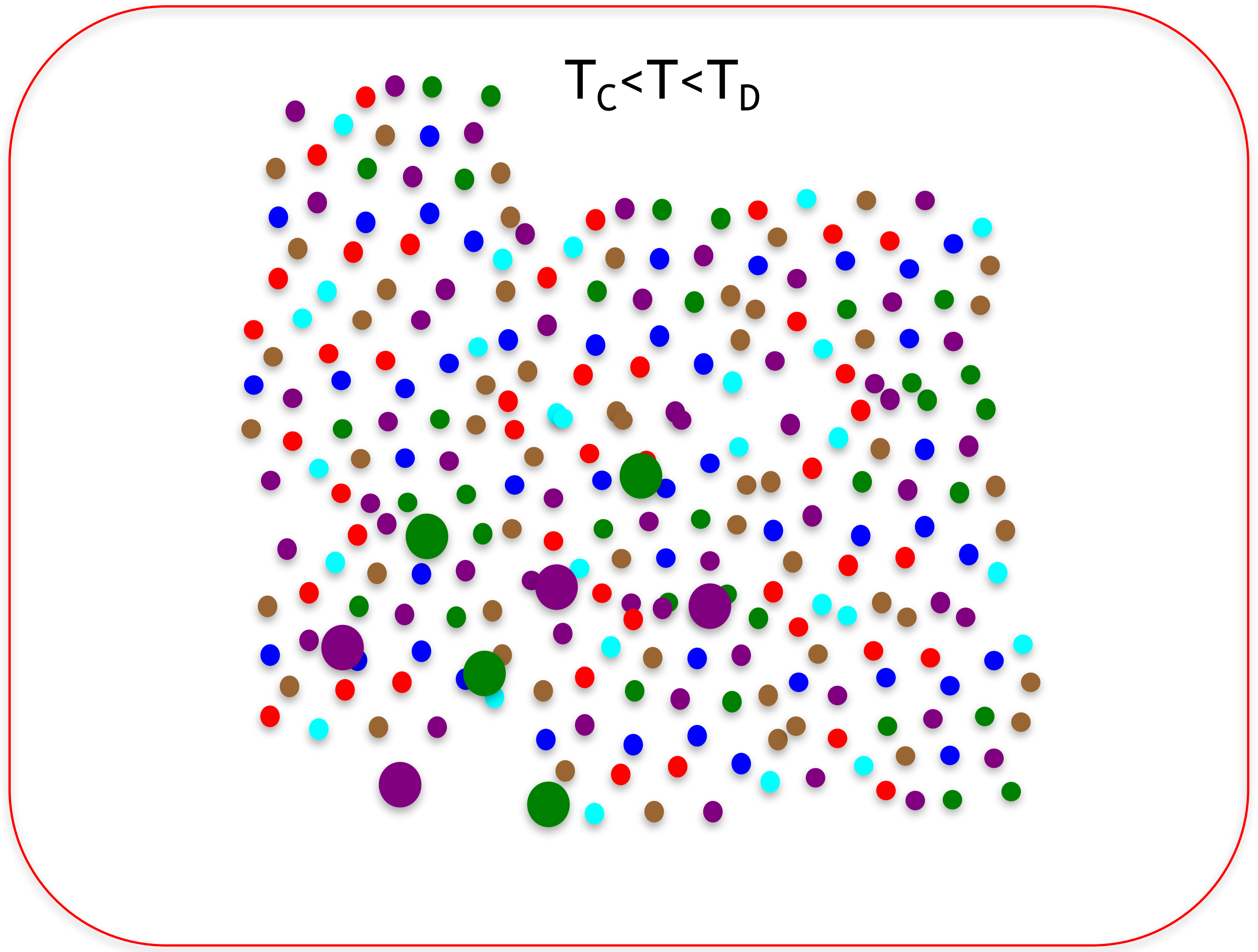
Heavy Quark: c or b
Light Quarks and Gluons

Matsui & Staz, PLB 178, 416 (1986)

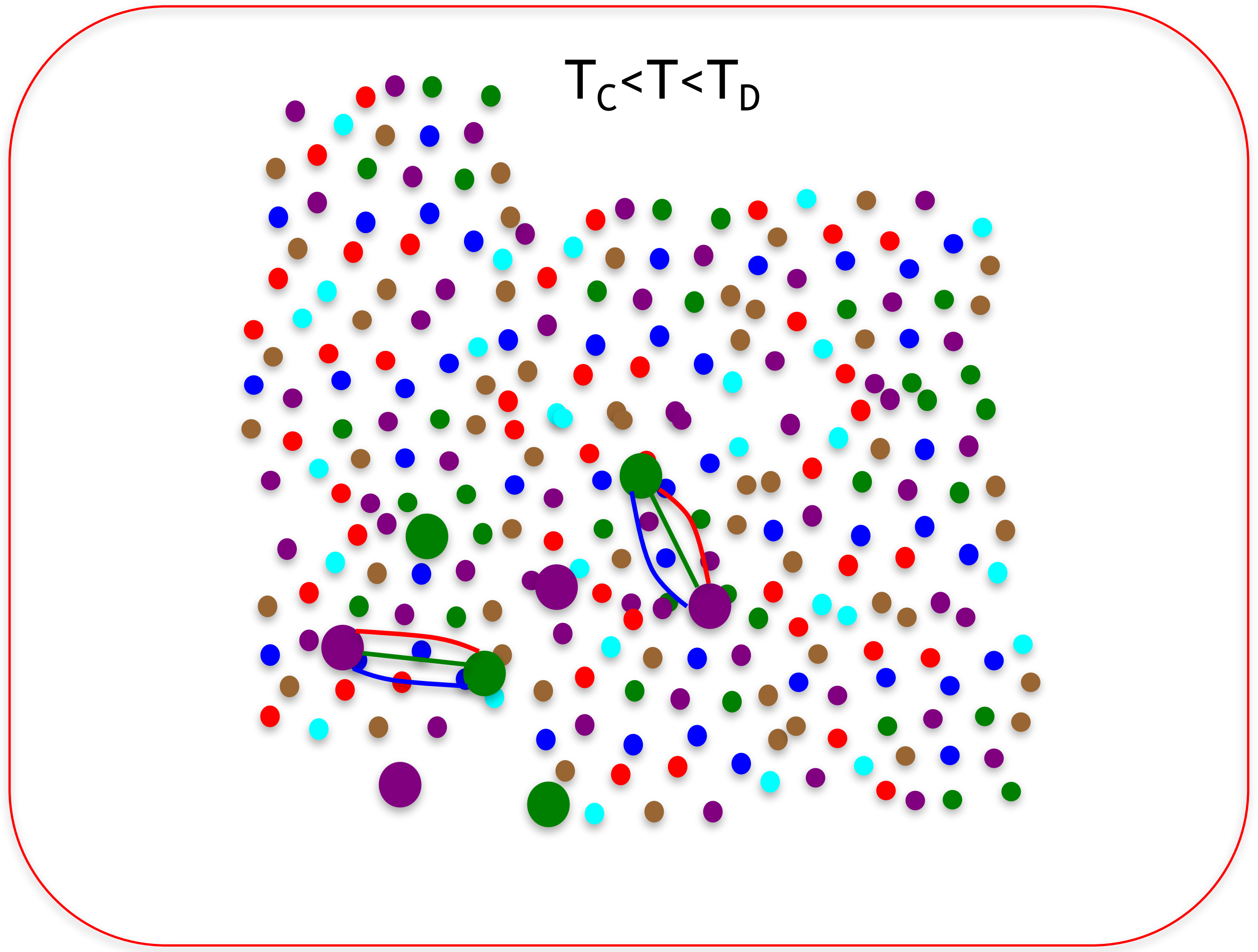
Quarkonia : charmonium (re)combination mechanism



Quarkonia : charmonium (re)combination mechanism

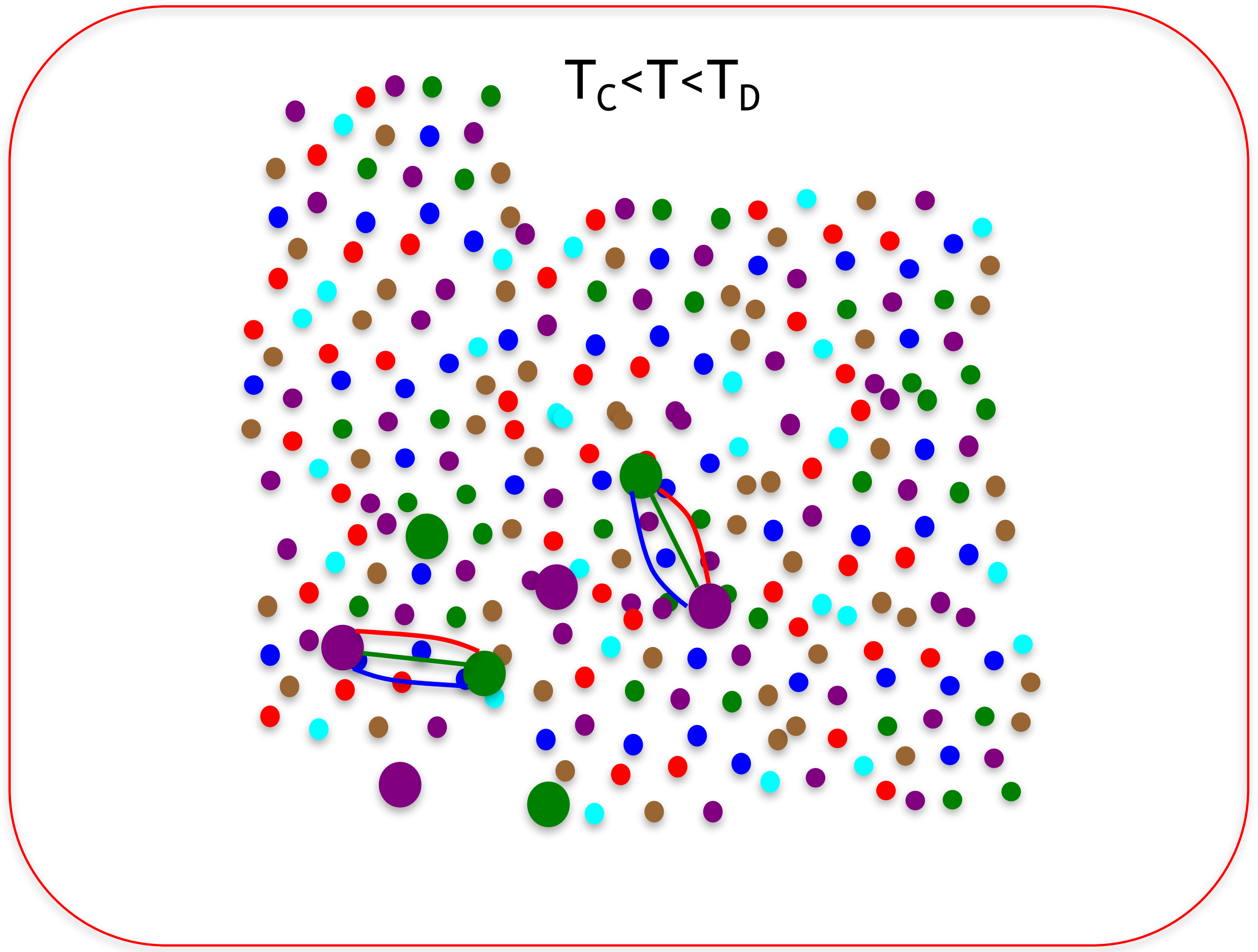


Quarkonia : charmonium (re)combination mechanism



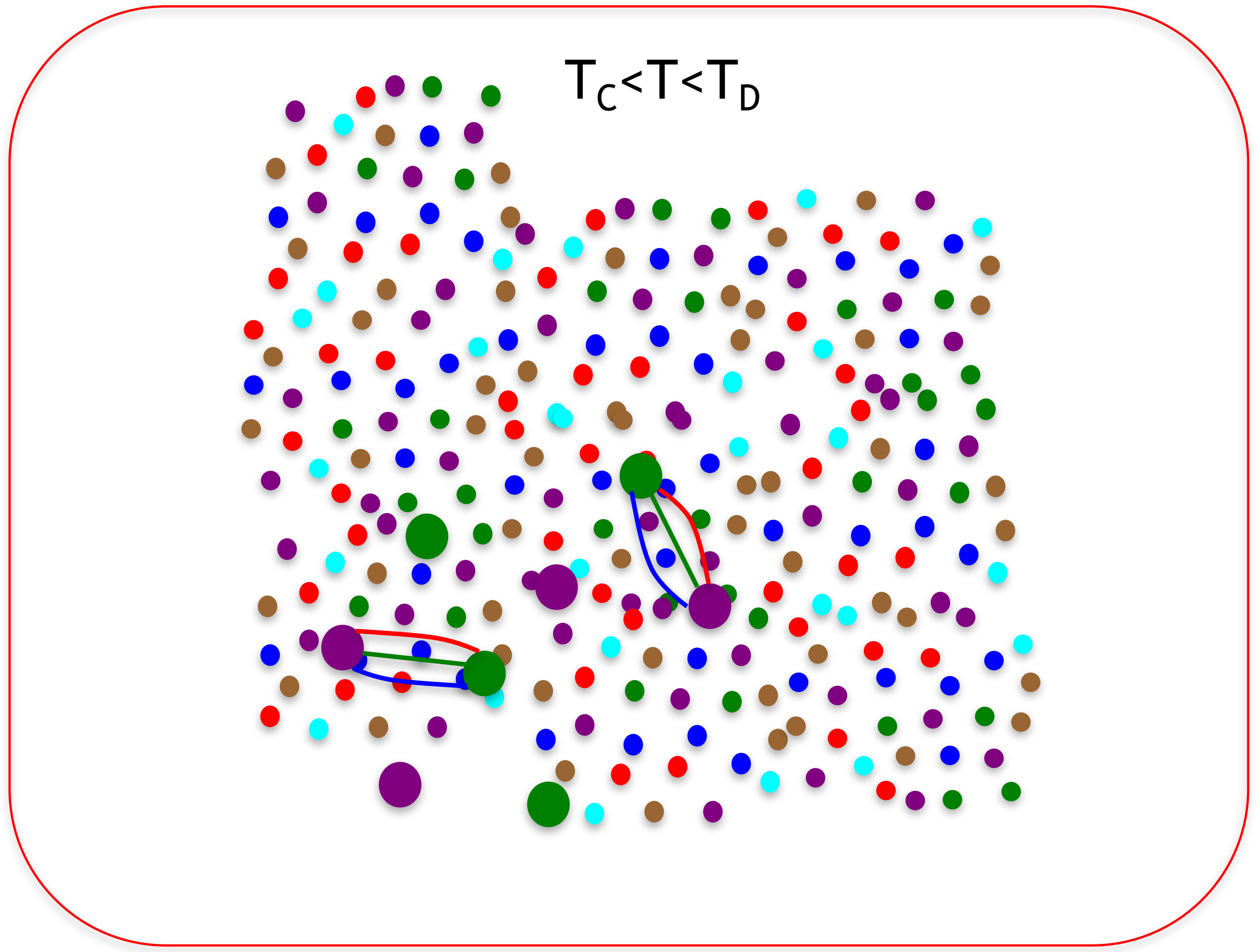
Quarkonia : charmonium (re)combination mechanism

- Possible (re)combination mechanism

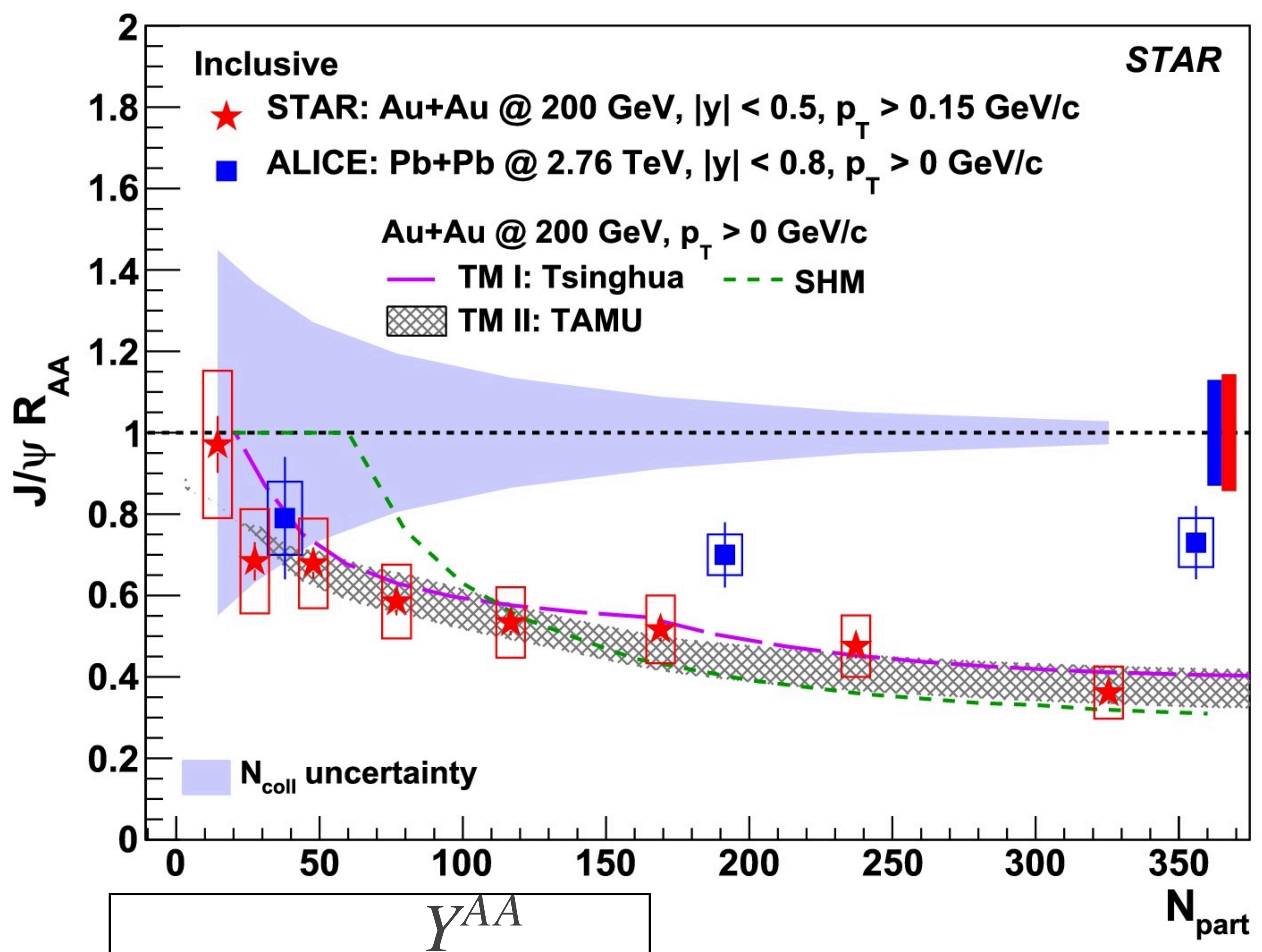


Quarkonia : charmonium (re)combination mechanism

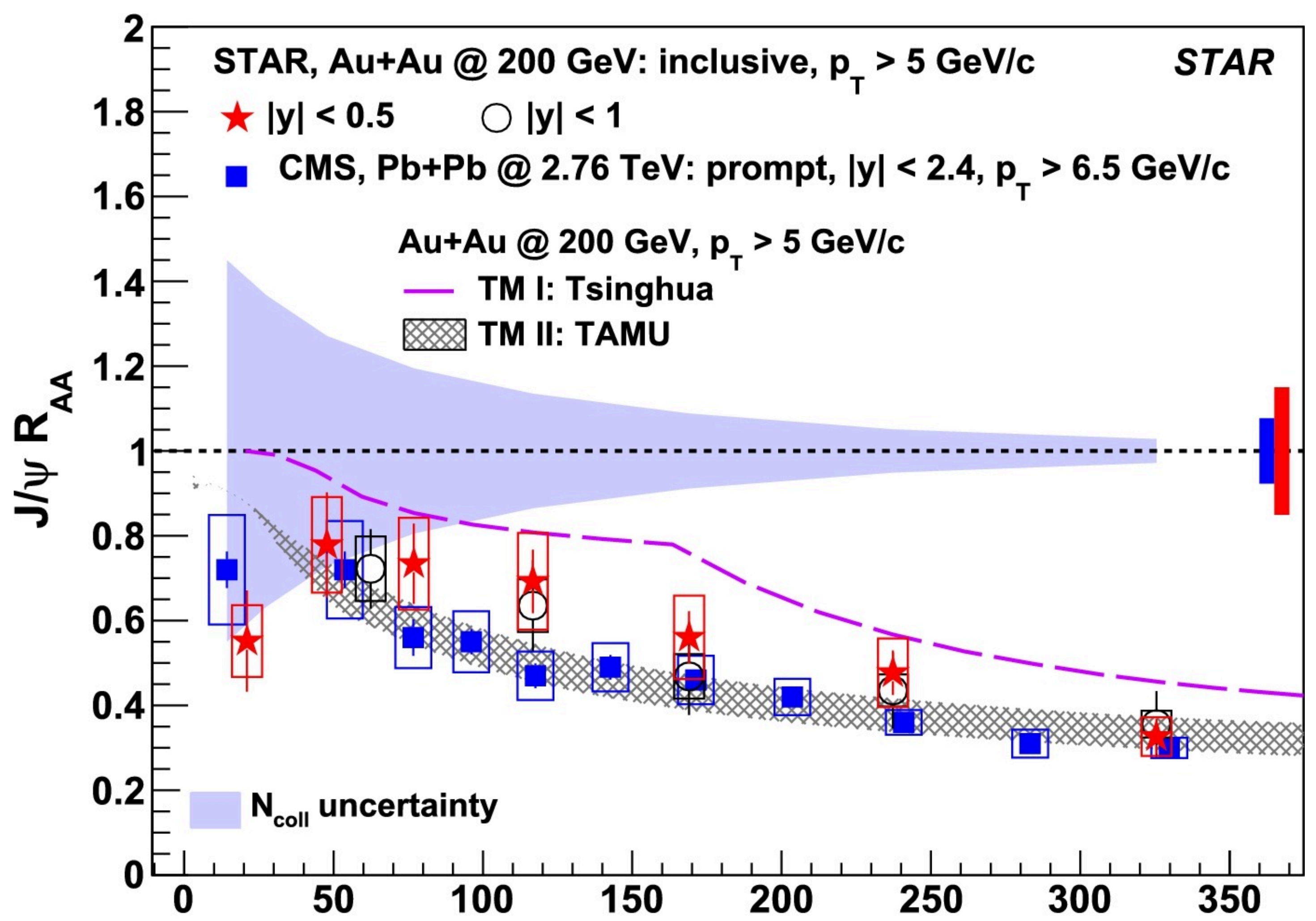
- Possible (re)combination mechanism
- Charmonia from (re)combination = ***thermalized*** !
    - Produced at low-p_T / central collisions.



J/ψ production in AA collisions at RHIC and LHC

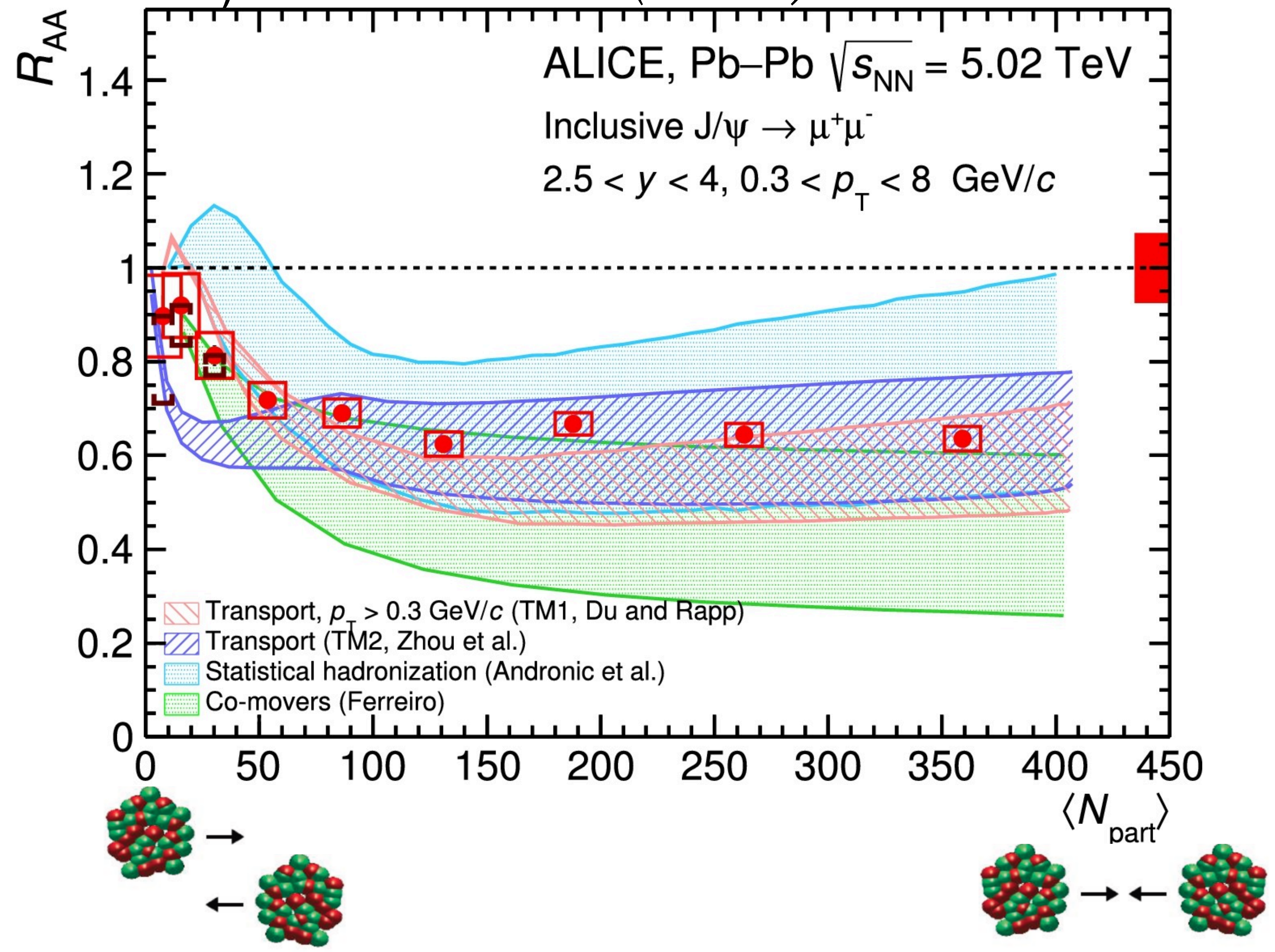


$$R_{AA} = \frac{Y^{AA}}{\langle N_{coll}\rangle \times Y^{pp}}$$



PLB 797 (2019) 134917

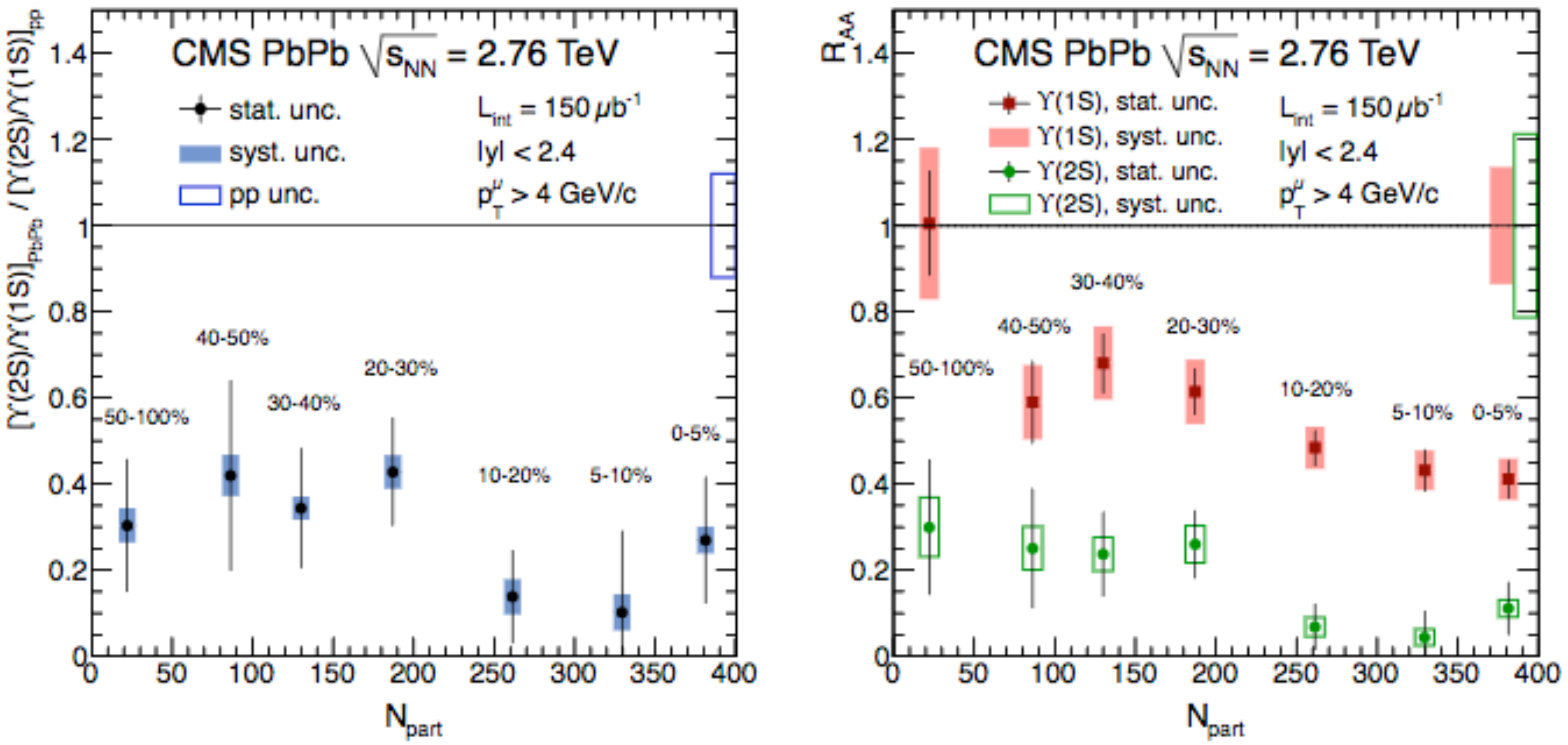
Phys. Lett. B 766 (2017) 212-224



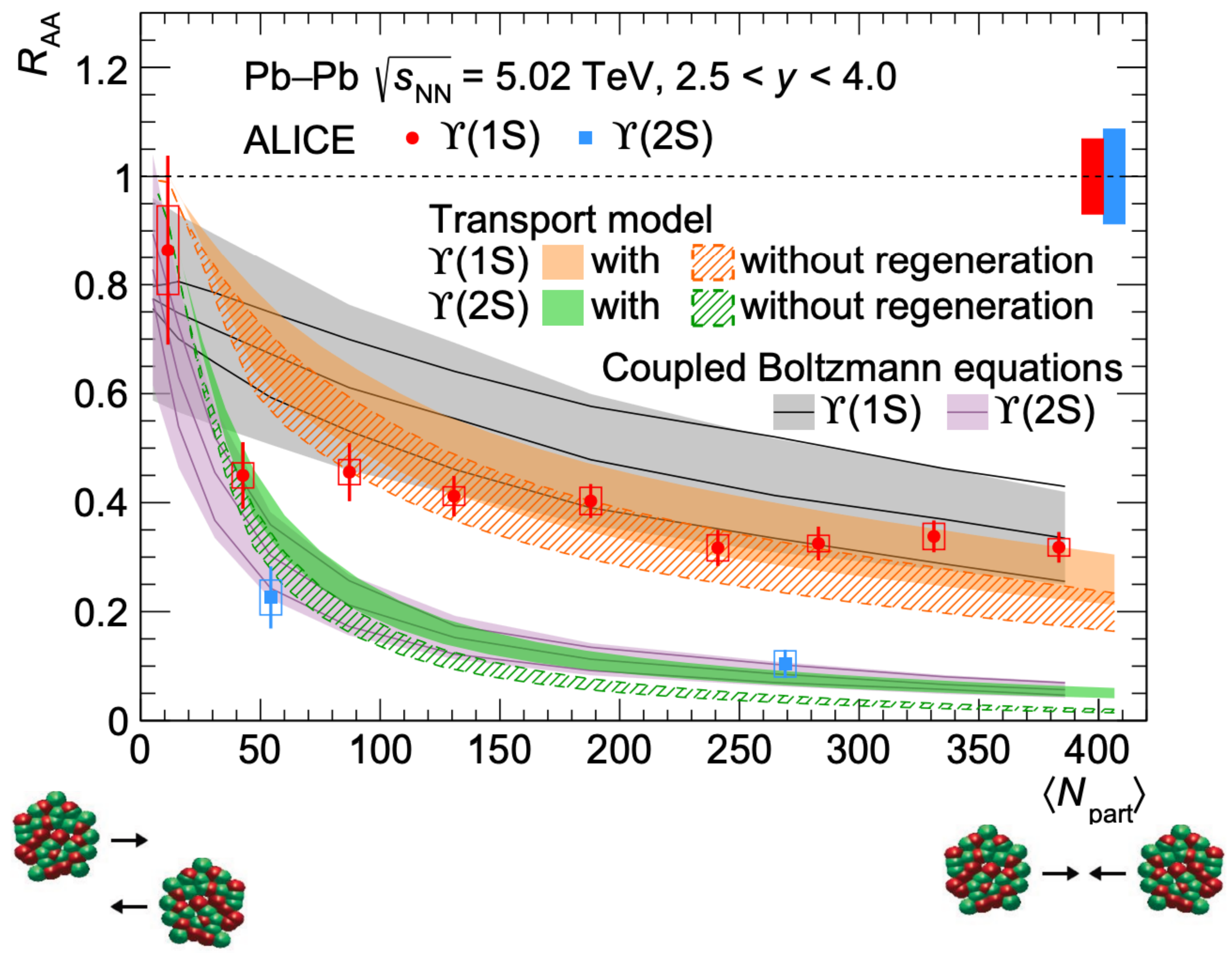
- Relative J/ψ suppression measured at RHIC and the LHC, increasing with centrality.
- LHC > RHIC R_{AA} at low p_T -> interpreted as recombination mechanism.
- LHC < RHIC R_{AA} at low p_T -> interpreted as larger suppression due to colour screening.
- Data reproduced by theory models which include recombination mechanisms.

$\Upsilon(nS)$ production

Phys. Rev. Lett. 109 (2012) 222301

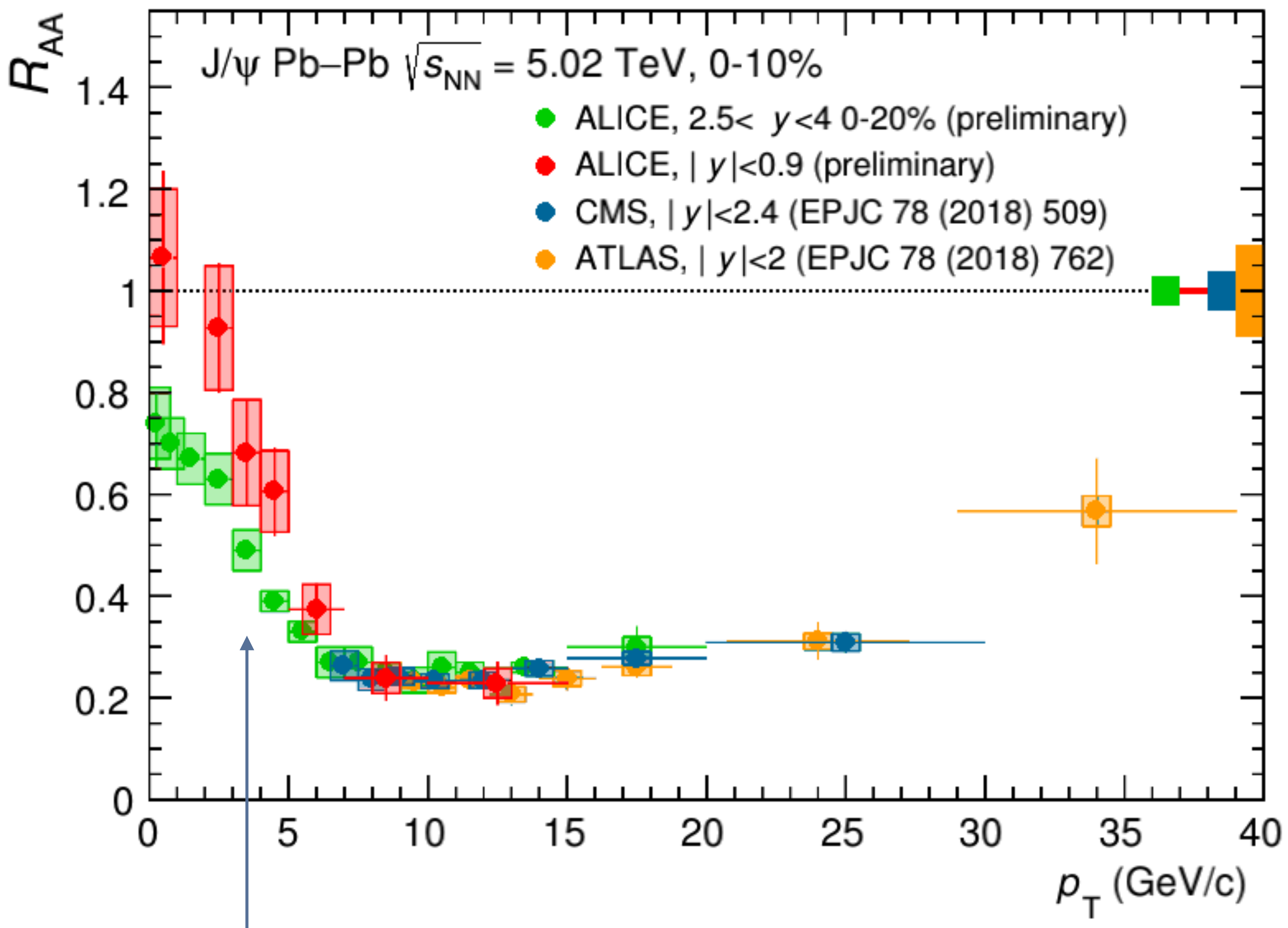


arxiv:2011.05758

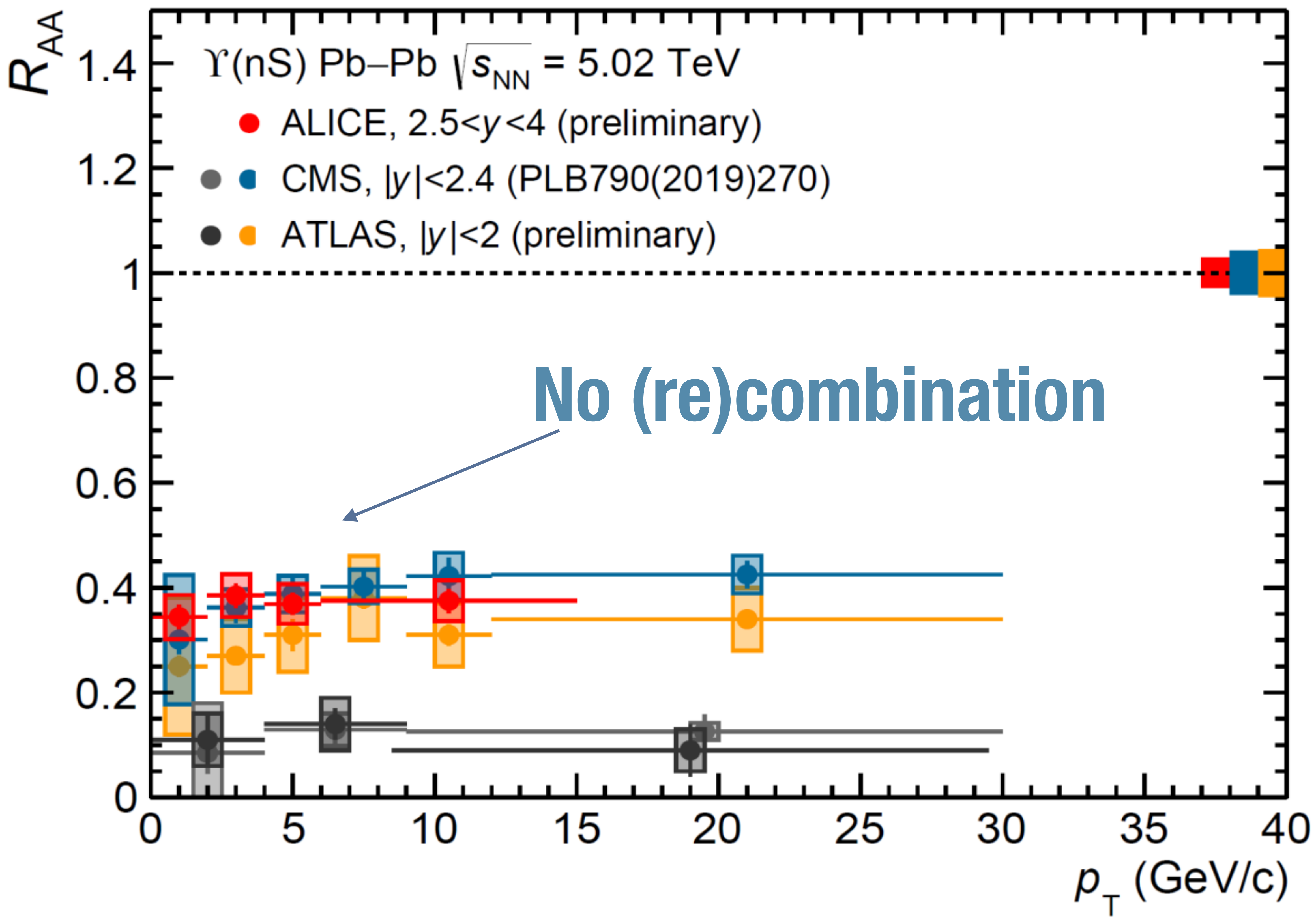


- Relative $\Upsilon(2S)/\Upsilon(1S)$ suppression measured by CMS in 2012 also measured by ALICE.
- LHC data described by transport models which includes hydrodynamics and regeneration.
- Interpreted as a consequence of the sequential suppression (?)

Quarkonia : LHC@5.02 TeV



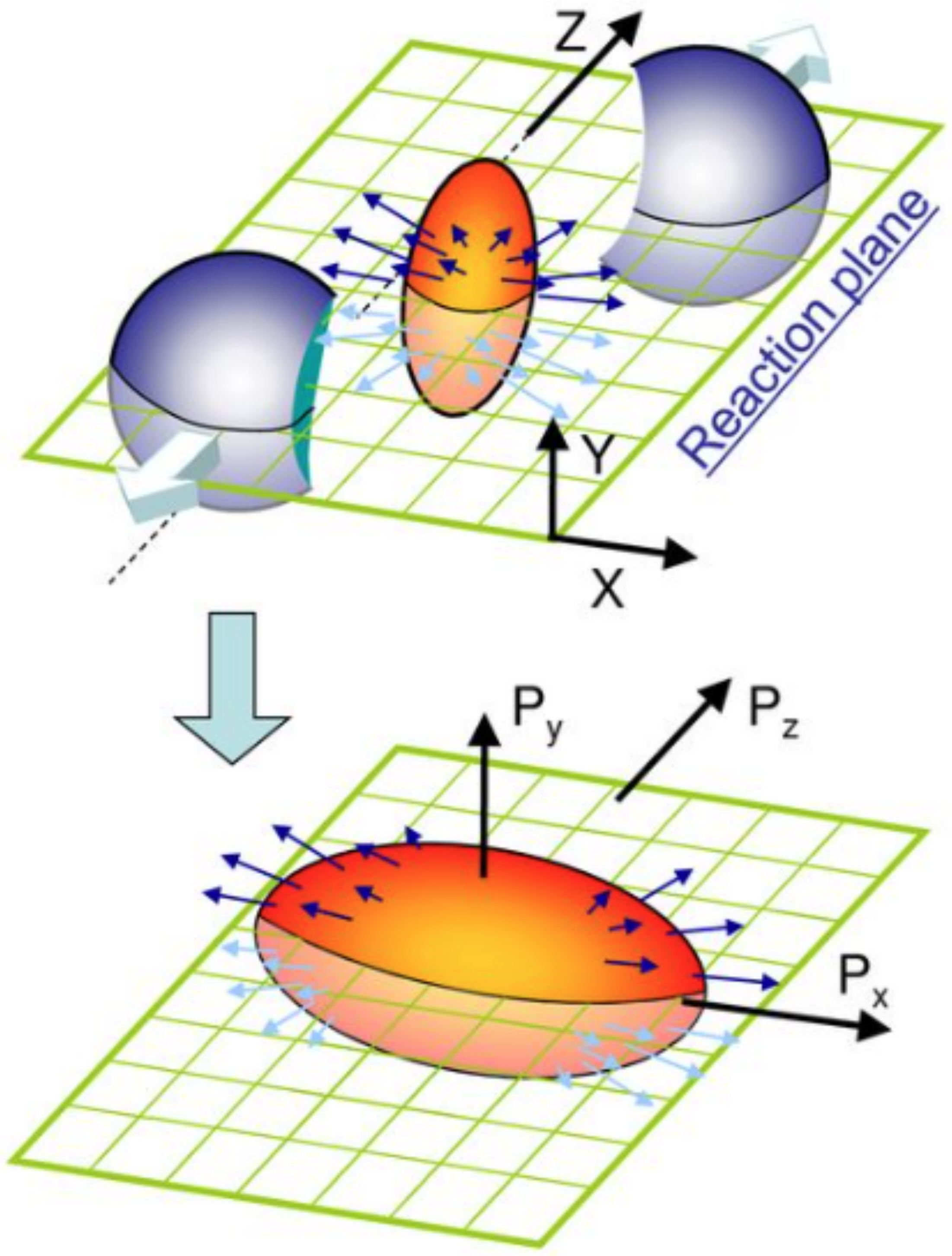
(re)combination (?)

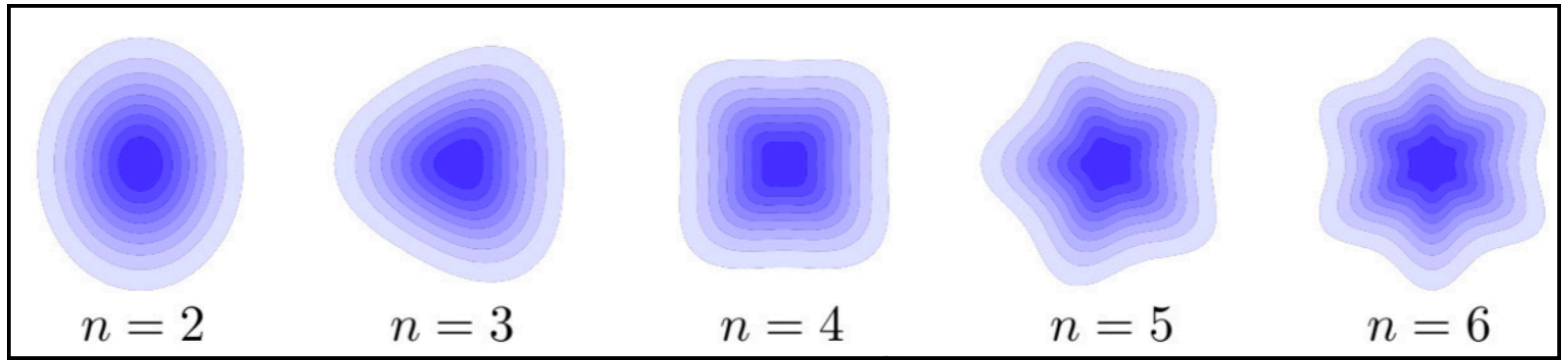


No (re)combination

What about the elliptic flow ?

- Flow : measure azimuthal dependence of particle production
  - Initial spatial anisotropy -> momentum-space anisotropy
  - Second order v_2 = elliptic flow

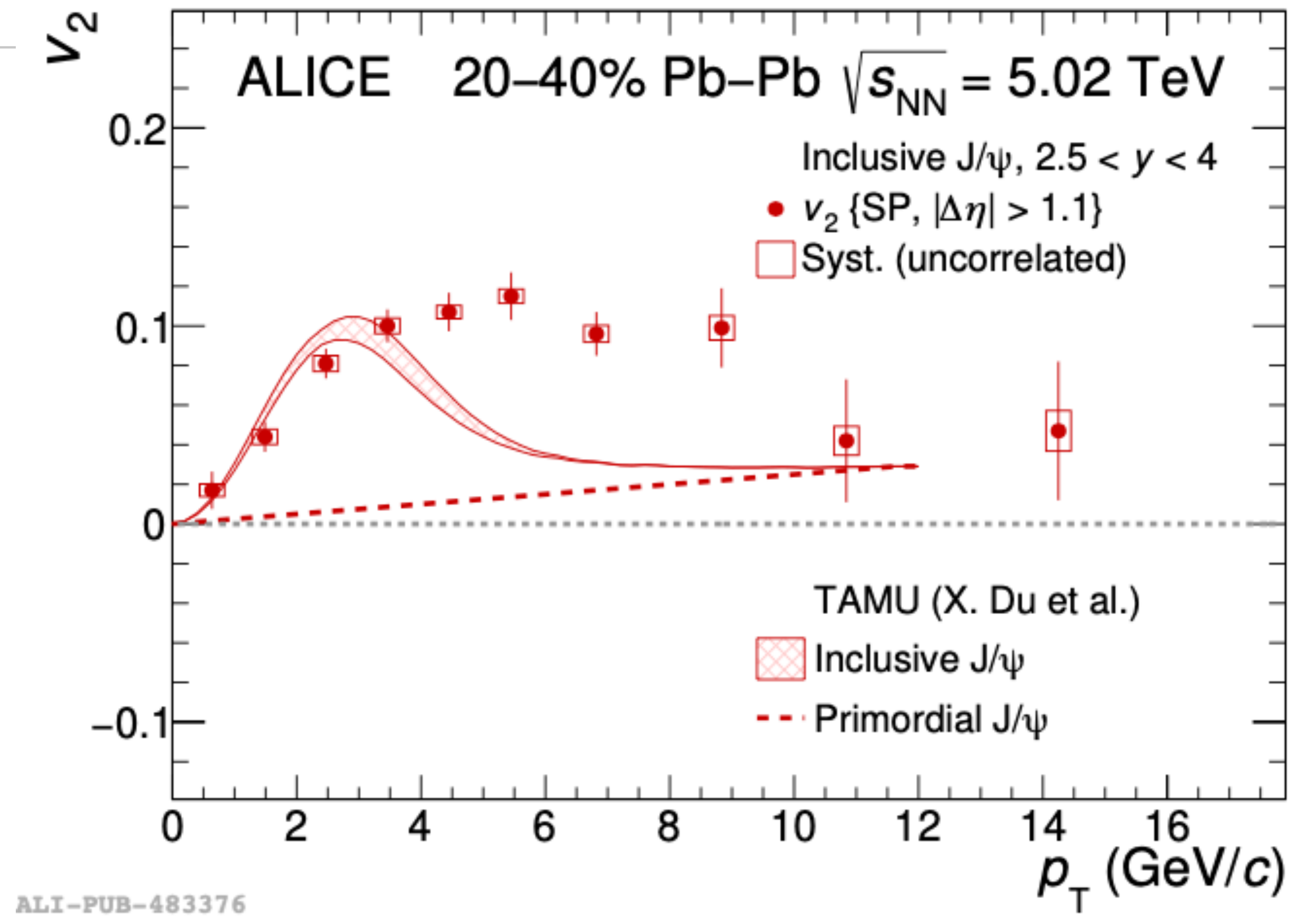


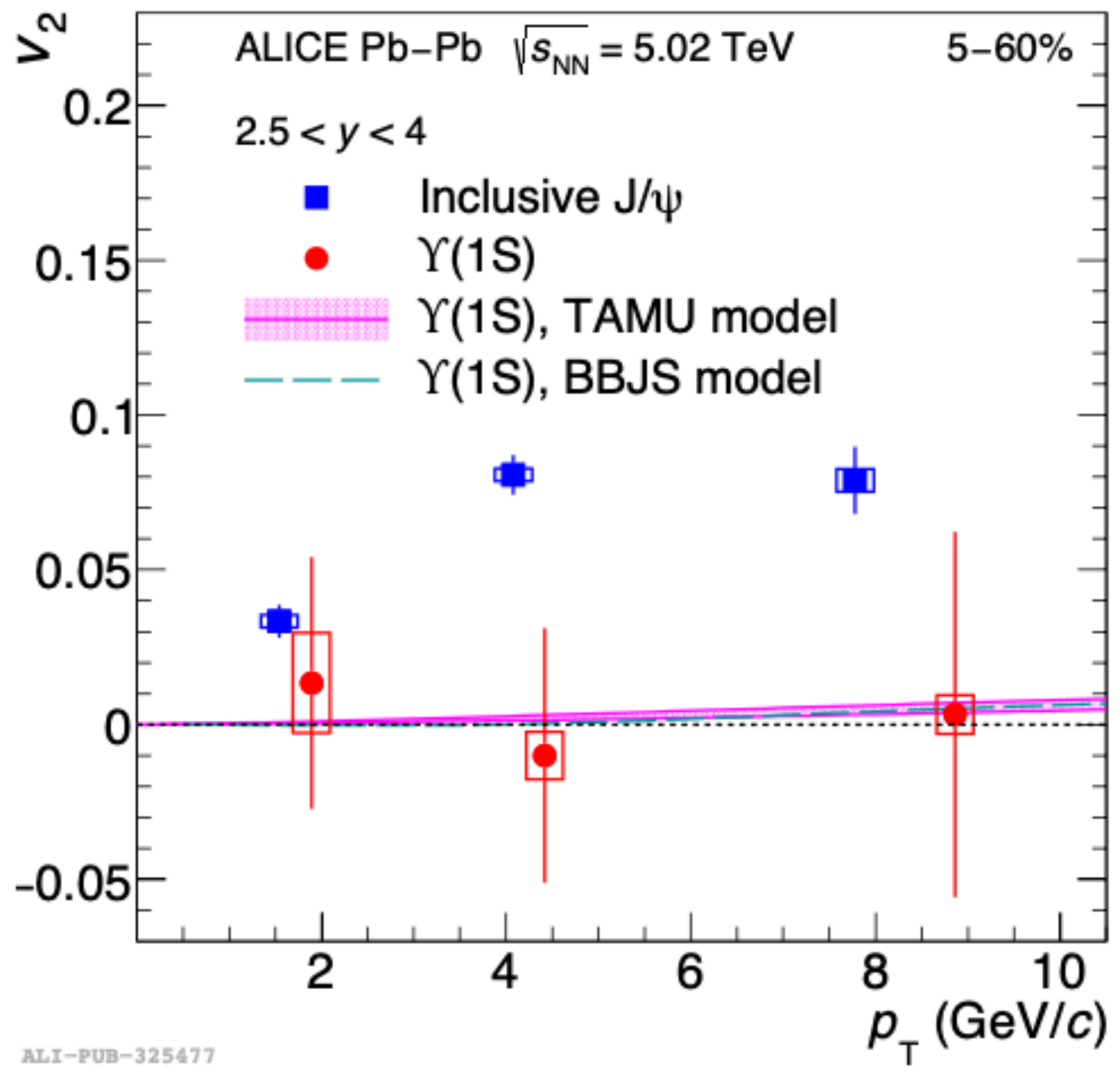


$$\frac{dN}{d\phi} \sim 1 + 2\sum_n v_n \cos[n(\phi - \Psi_n)]$$

What about the elliptic flow ?

- Flow : measure azimuthal dependence of particle production
  - ➡ Initial spatial anisotropy -> momentum-space anisotropy
  - ➡ Second order v_2 = elliptic flow

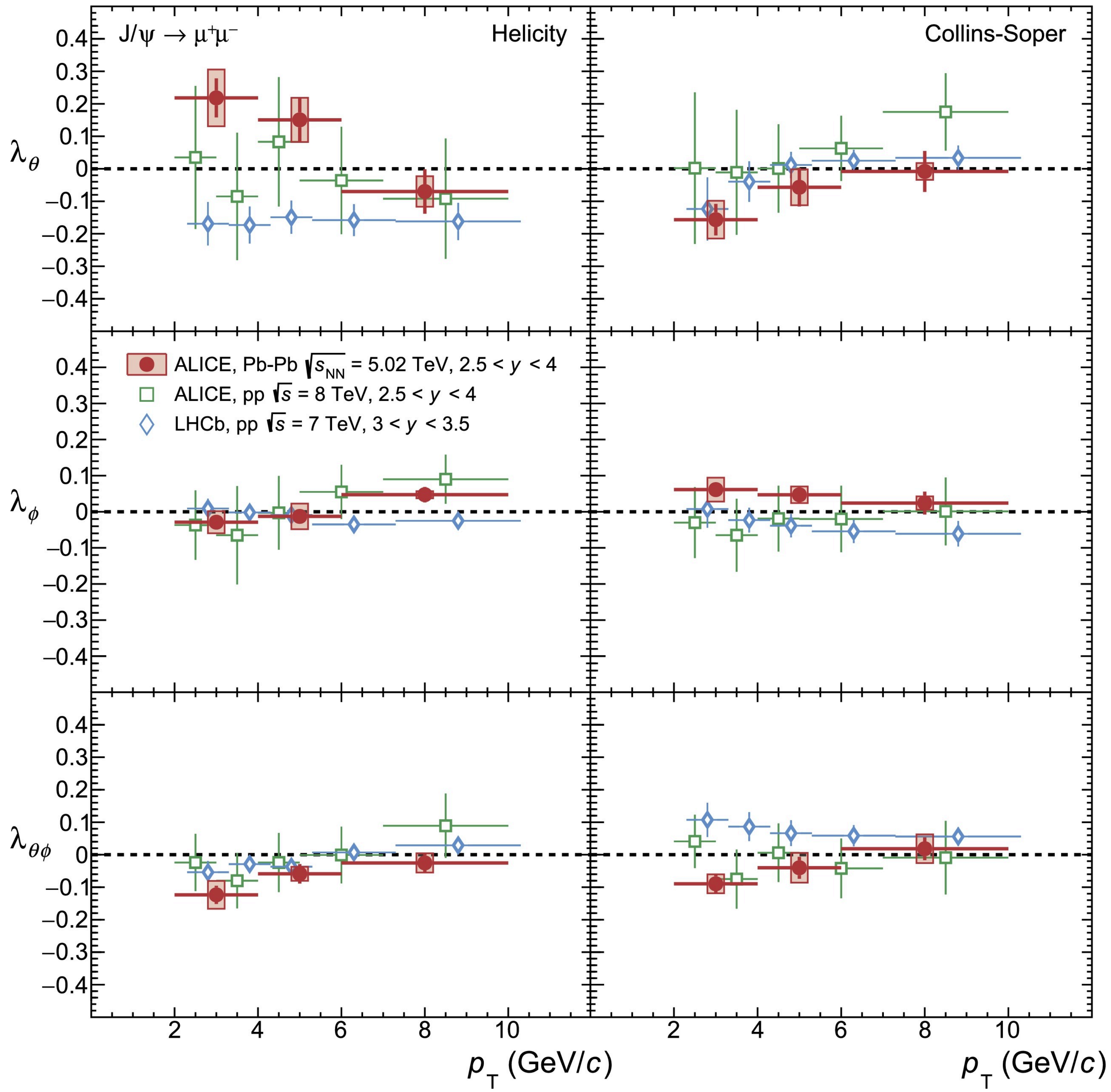




- Positive v_2 measured for the J/ψ up to hight p_T
  - ➡ Data not reproduced but the models.
- Zero v_2 measured for the $\Upsilon(1S)$.

Quarkonium polarization in PbPb

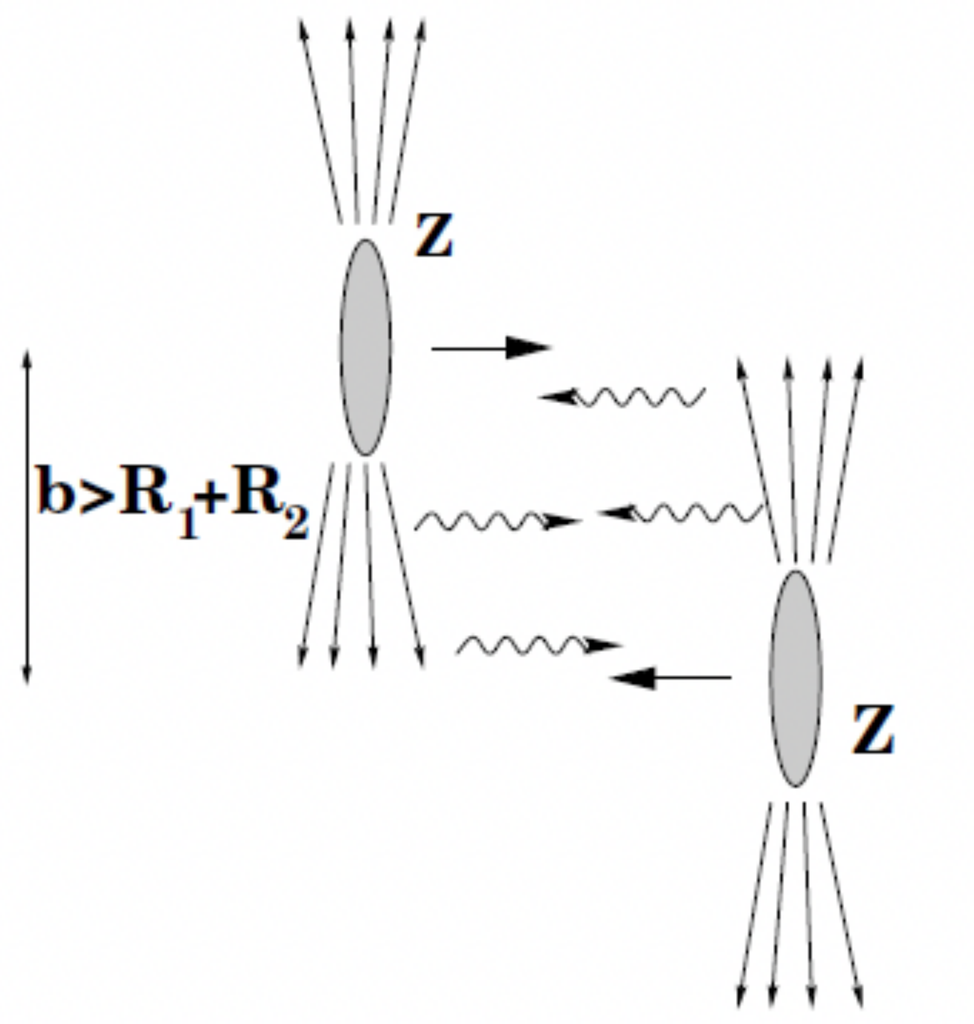
PLB 815 (2021) 136146



- ALICE has measured J/Ψ polarization in PbPb
- Tensions (3σ) between ALICE (PbPb) and LHCb (pp) in the helicity frame.
  - ➡ Medium-induced effects on polarization in Pb-Pb ?

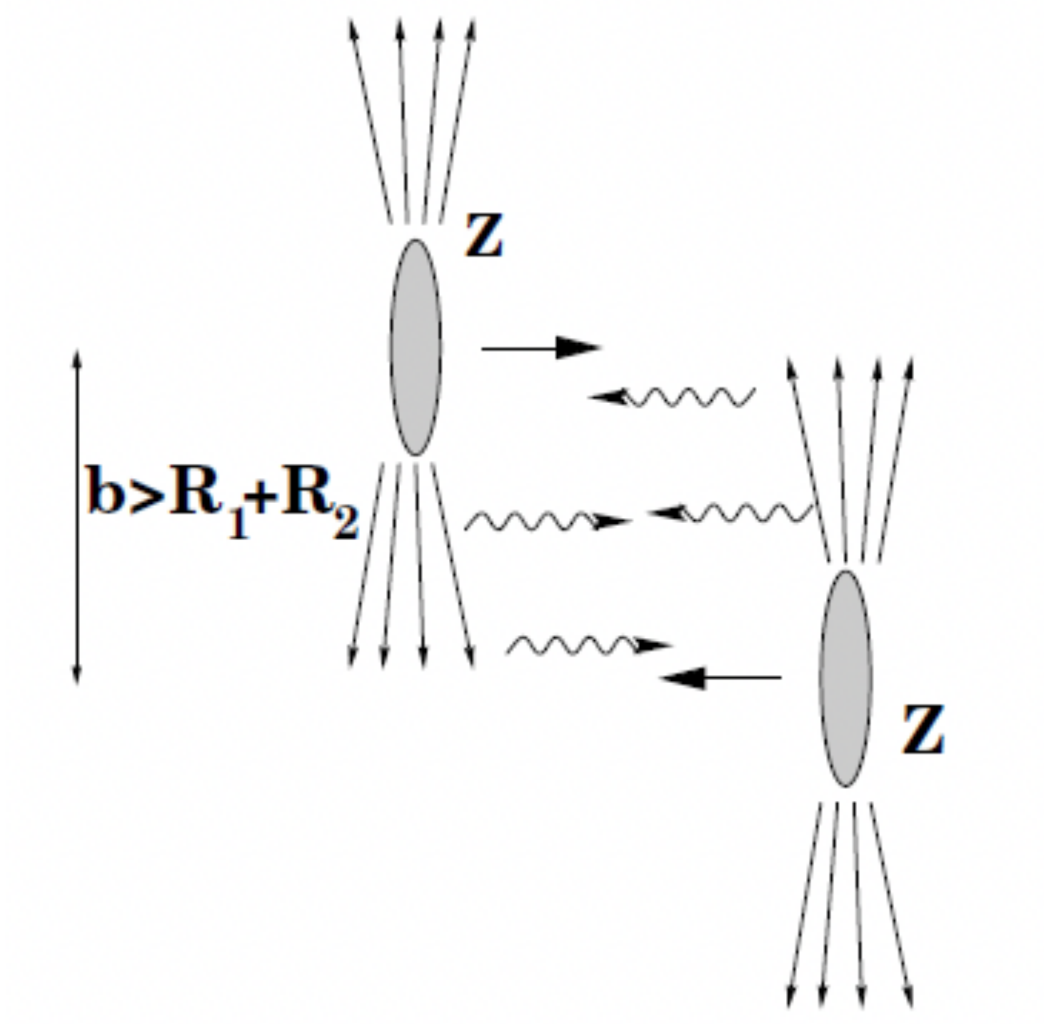
QUARKONIA IN UPC

Quarkonia in AA collisions : UPC

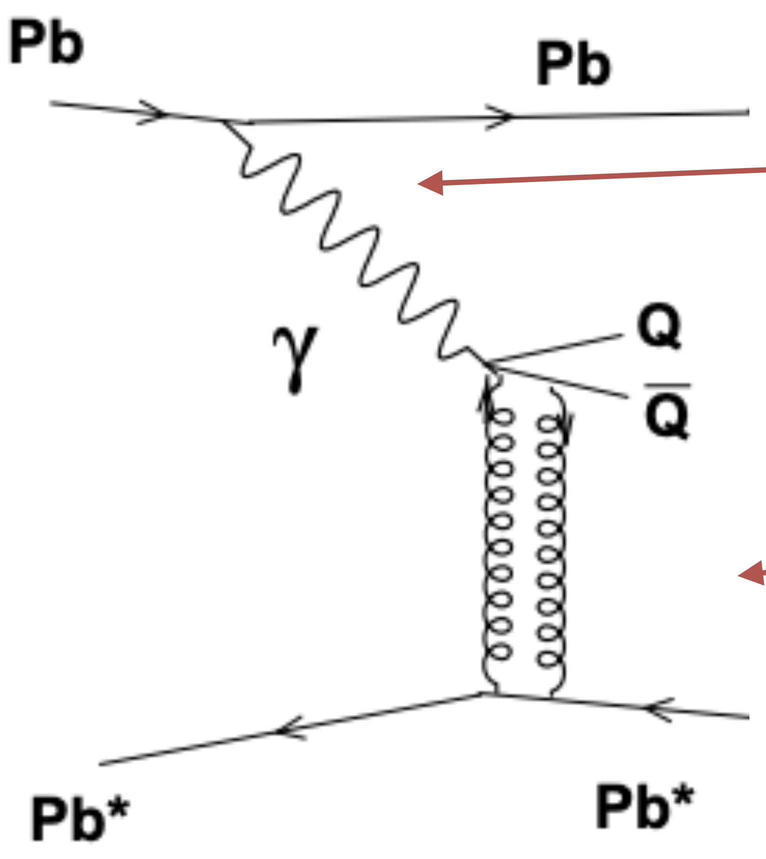


Ultra-peripheral collision

Quarkonia in AA collisions : UPC



Ultra-peripheral collision

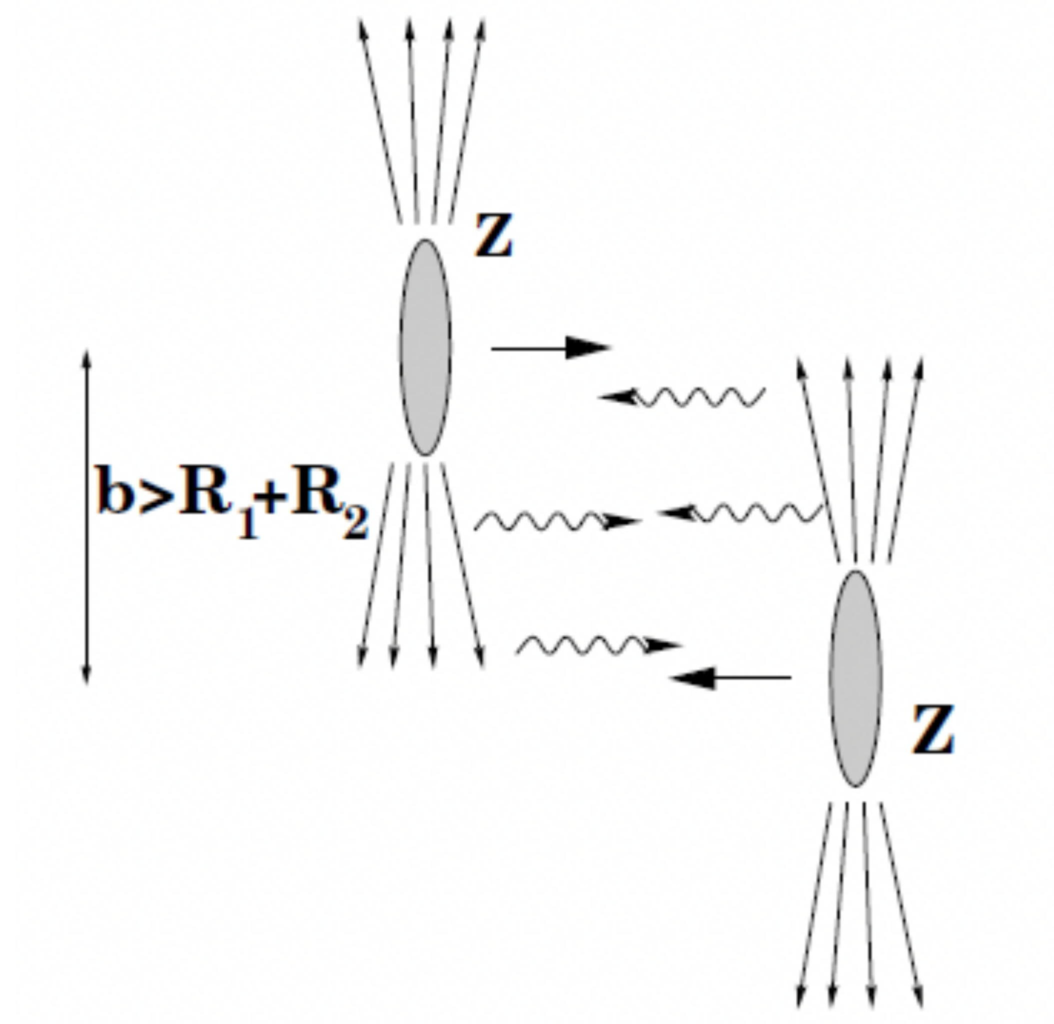


Quark pair production

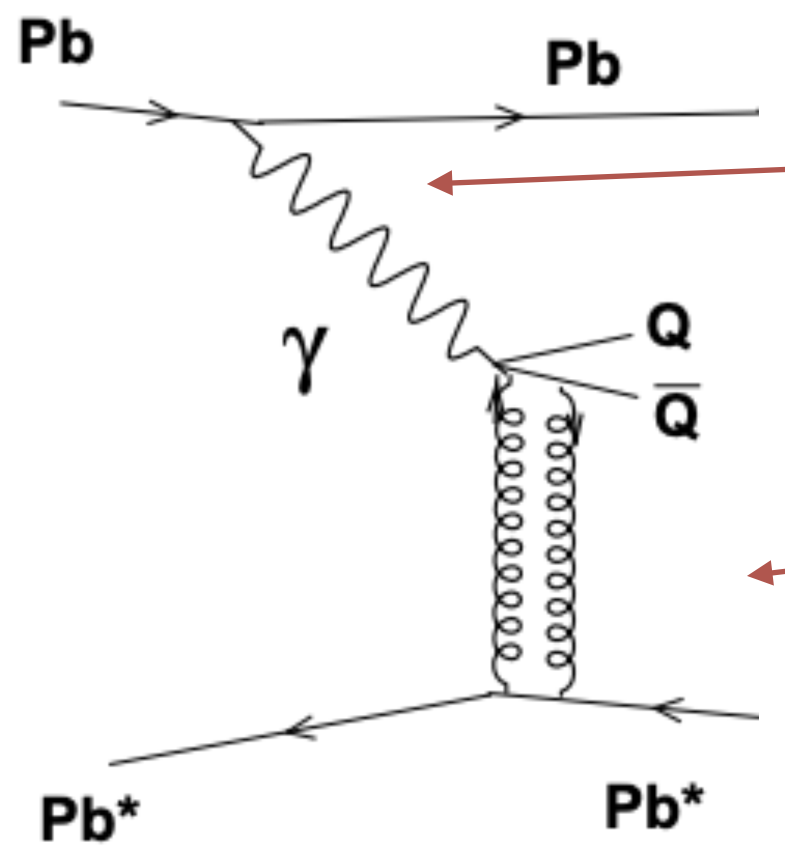
Photon flux ∝ Z^2

Double gluon exchange

Quarkonia in AA collisions : UPC



Ultra-peripheral collision



Photon flux $\propto Z^2$

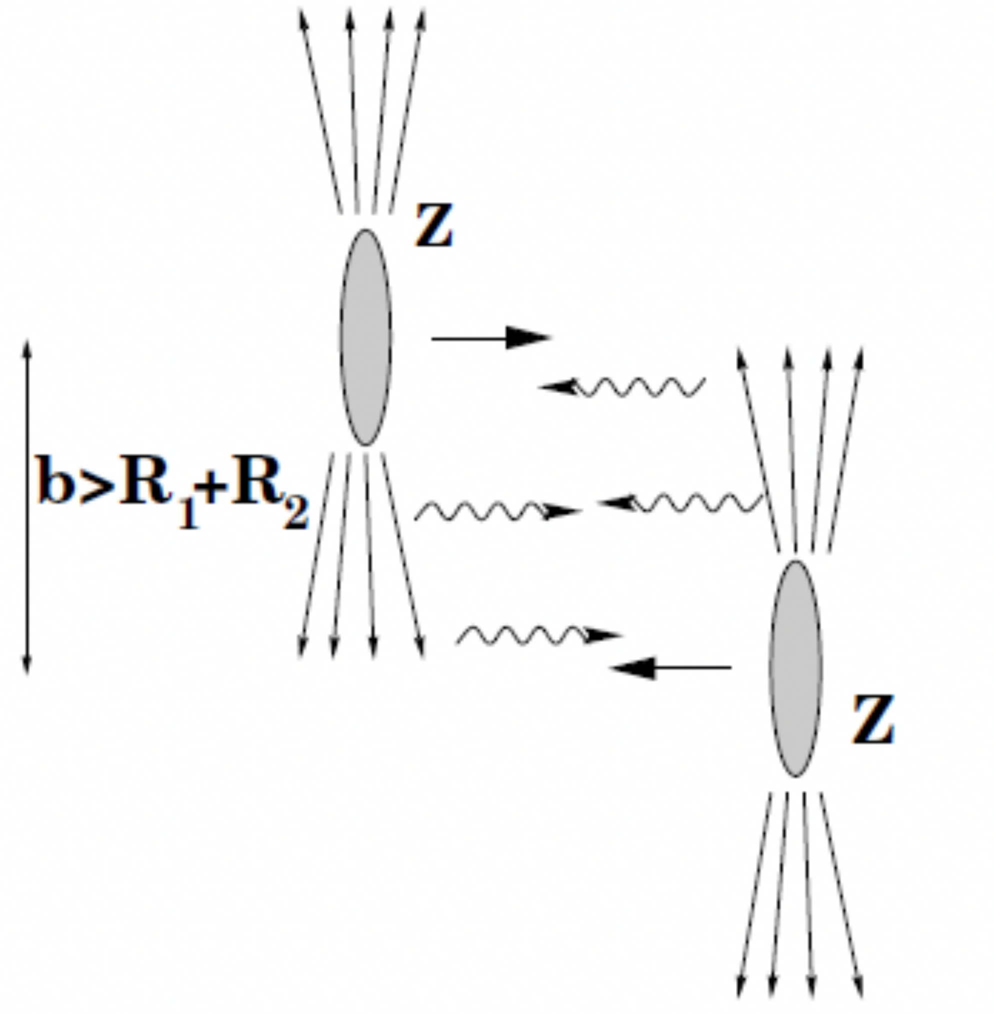
Double gluon exchange

Quark pair production

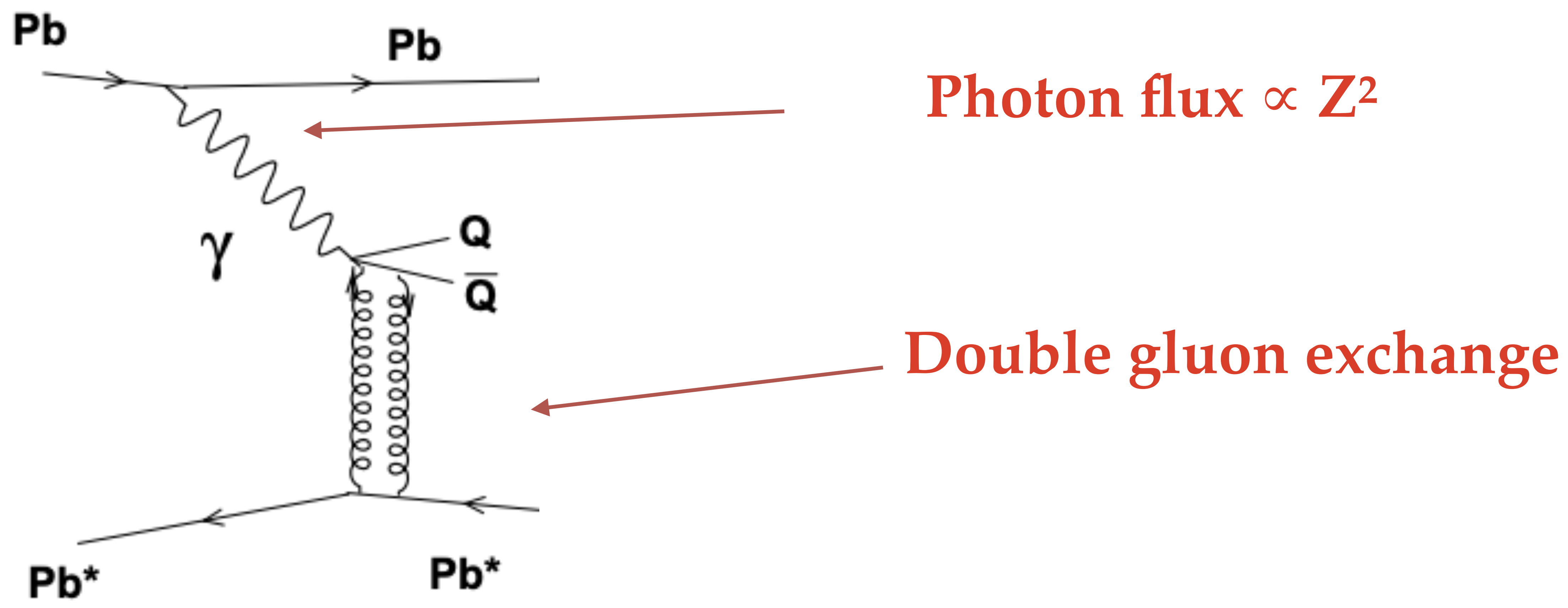
<u>Experimental characteristics :</u>

- clean signal with low activity in the detector
- very low $p_T \propto 1/r_{target}$

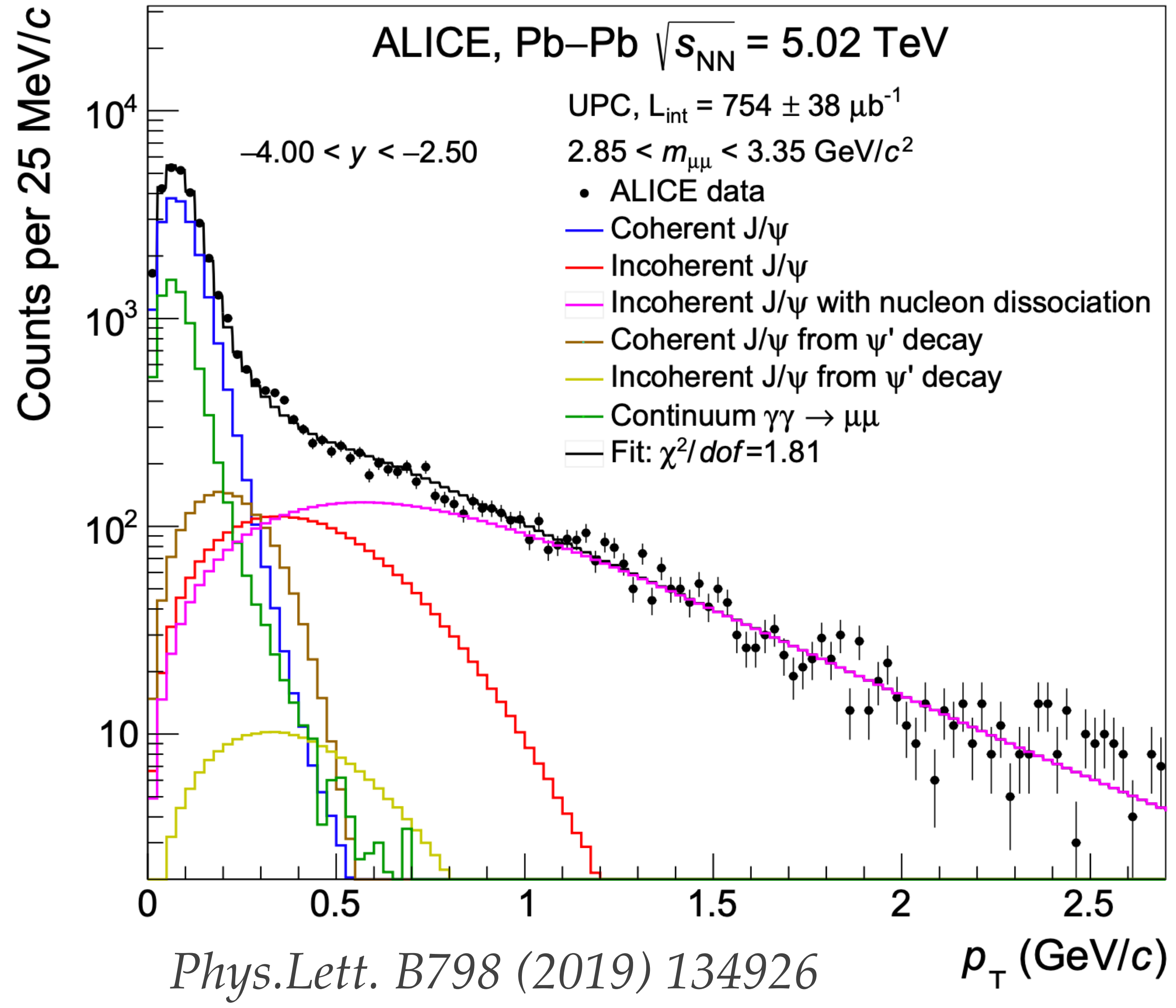
Quarkonia in AA collisions : UPC



Ultra-peripheral collision



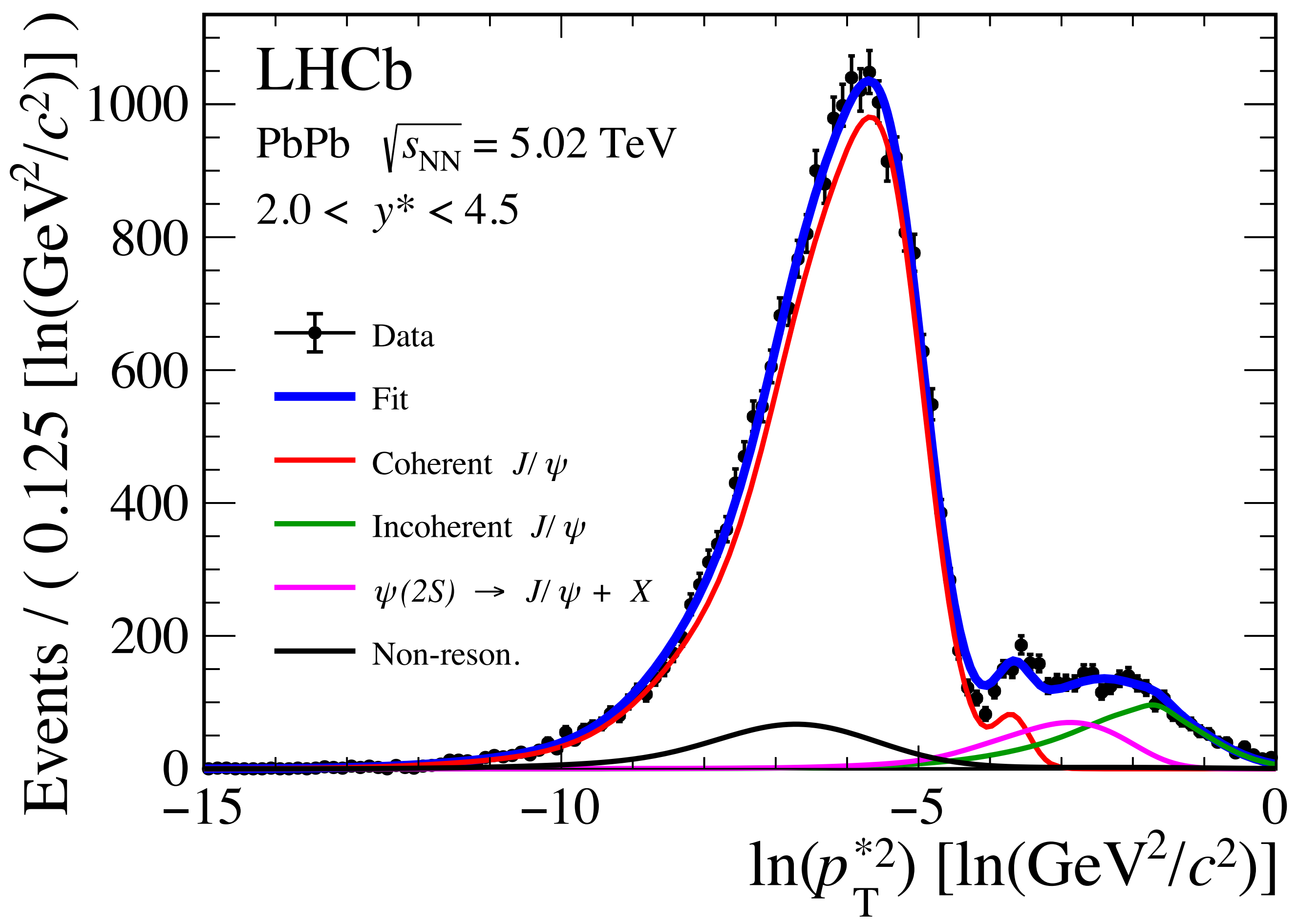
Quark pair production

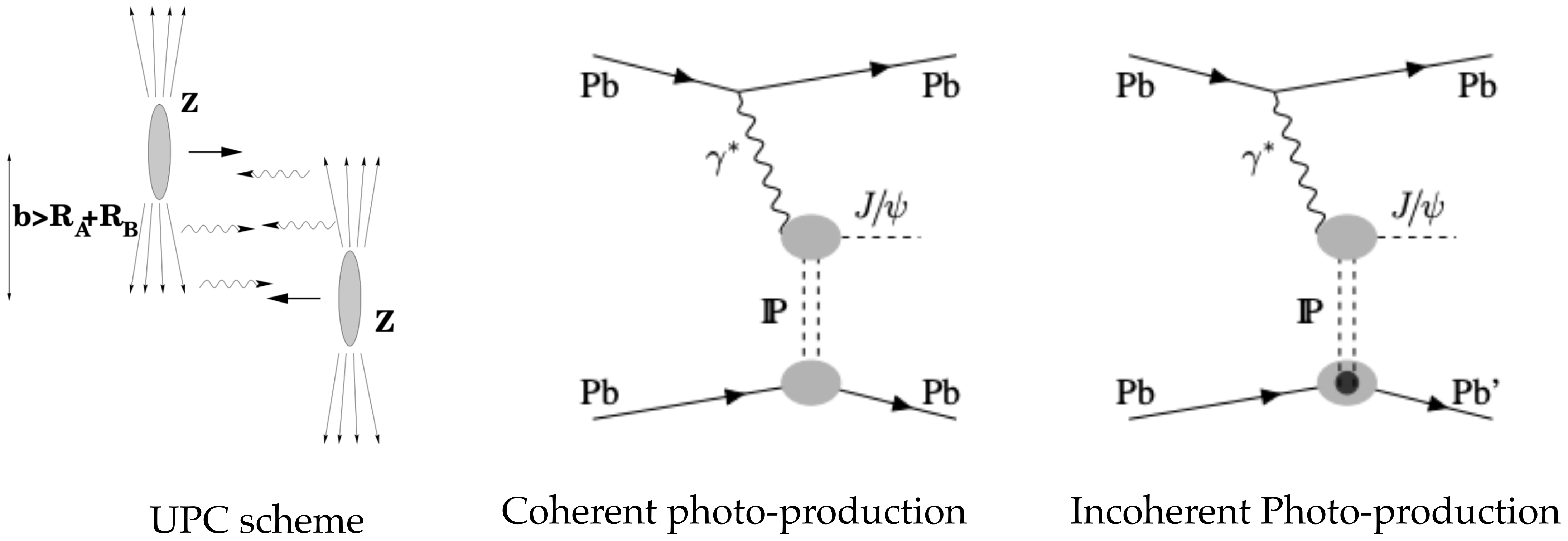


Phys.Lett. B798 (2019) 134926

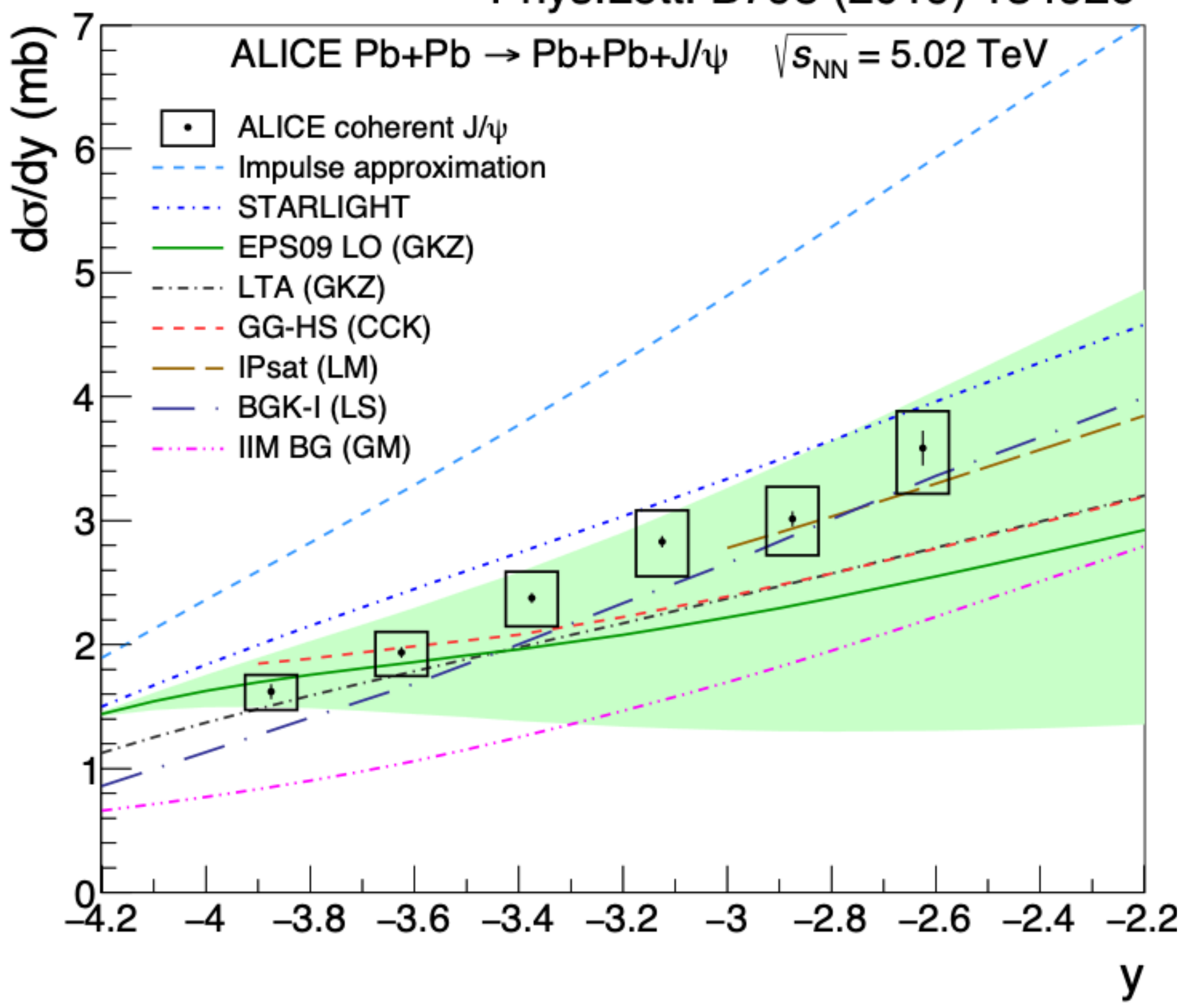
J/ψ production in ultra-peripheral collisions

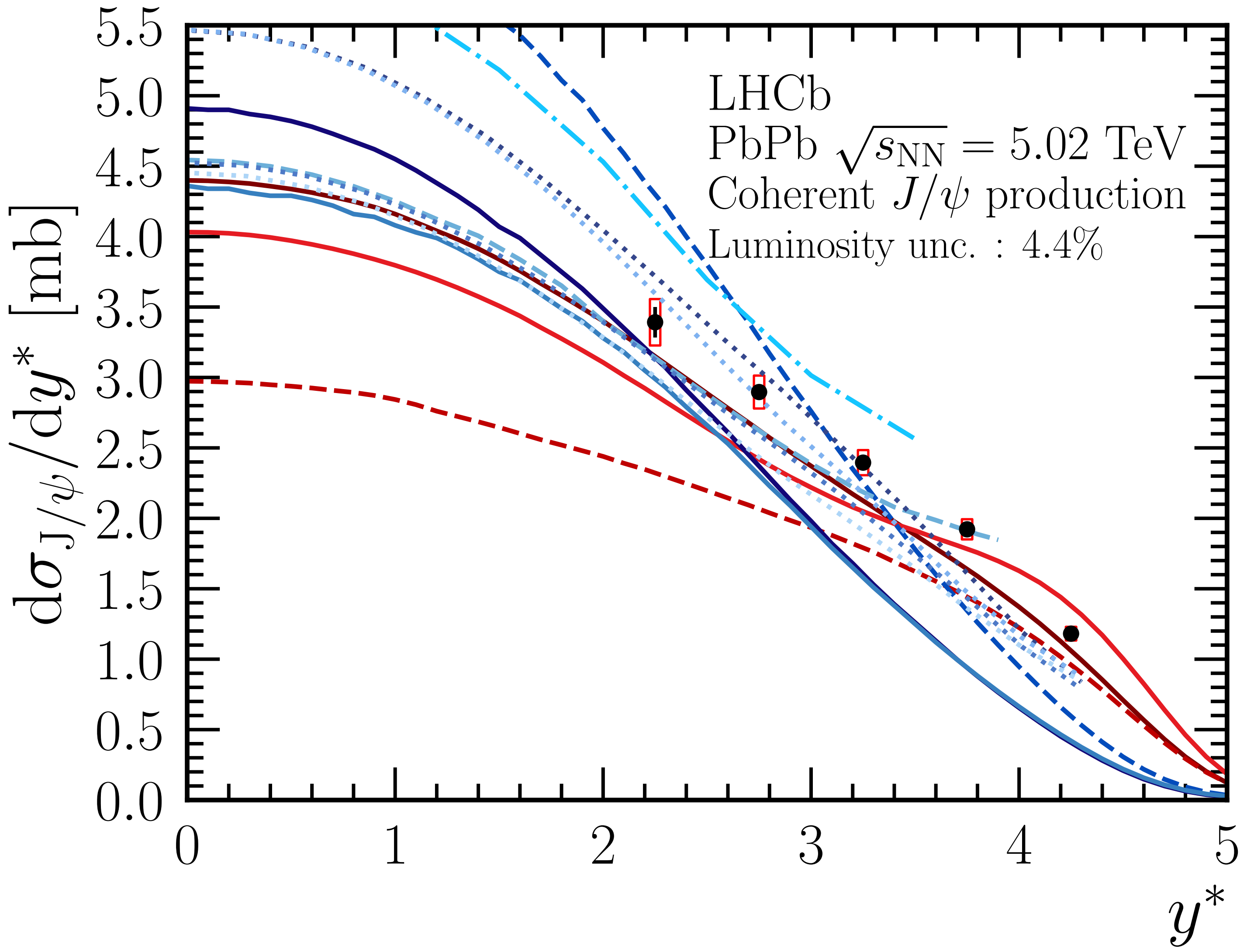
[ARXIV:2206.08221]





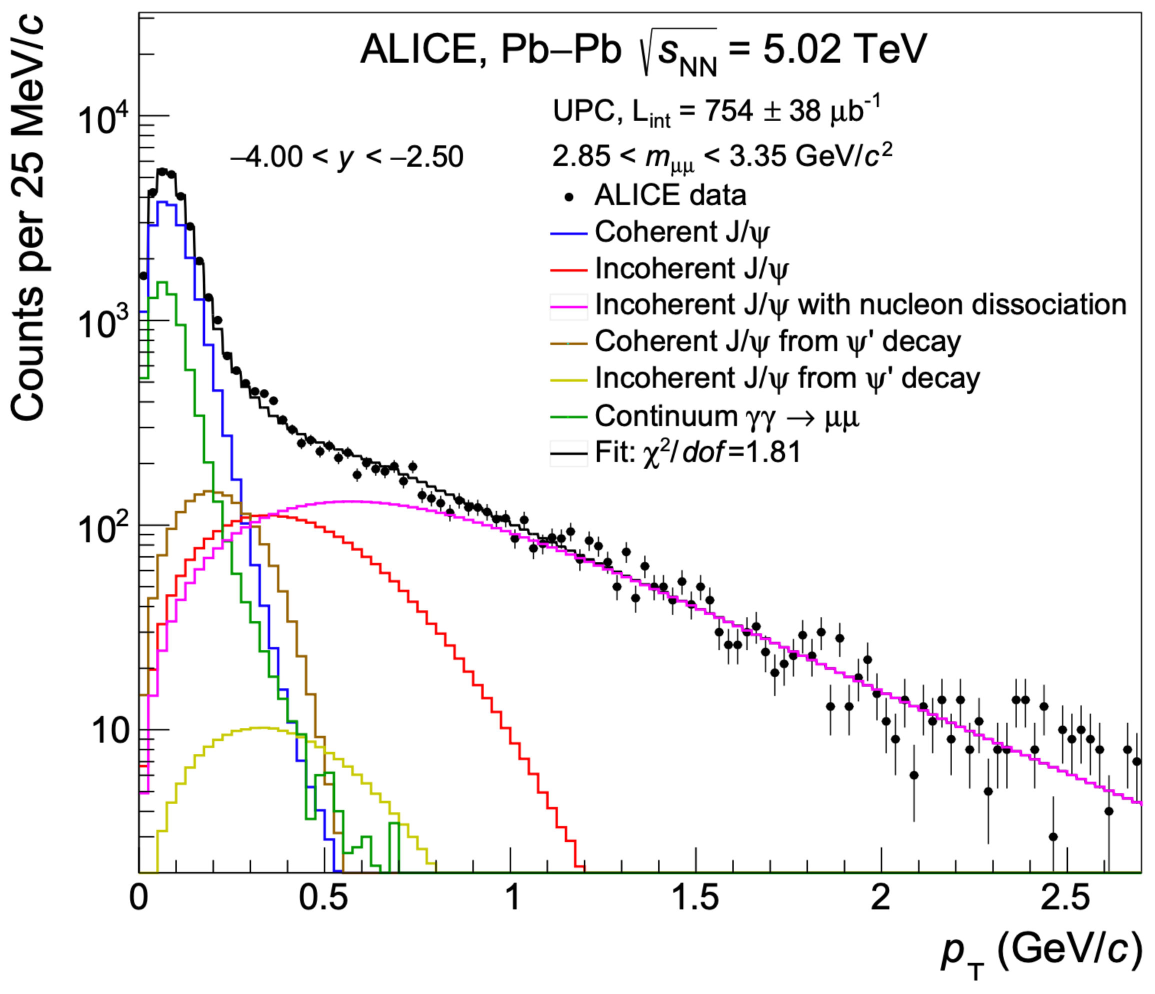
Phys.Lett. B798 (2019) 134926



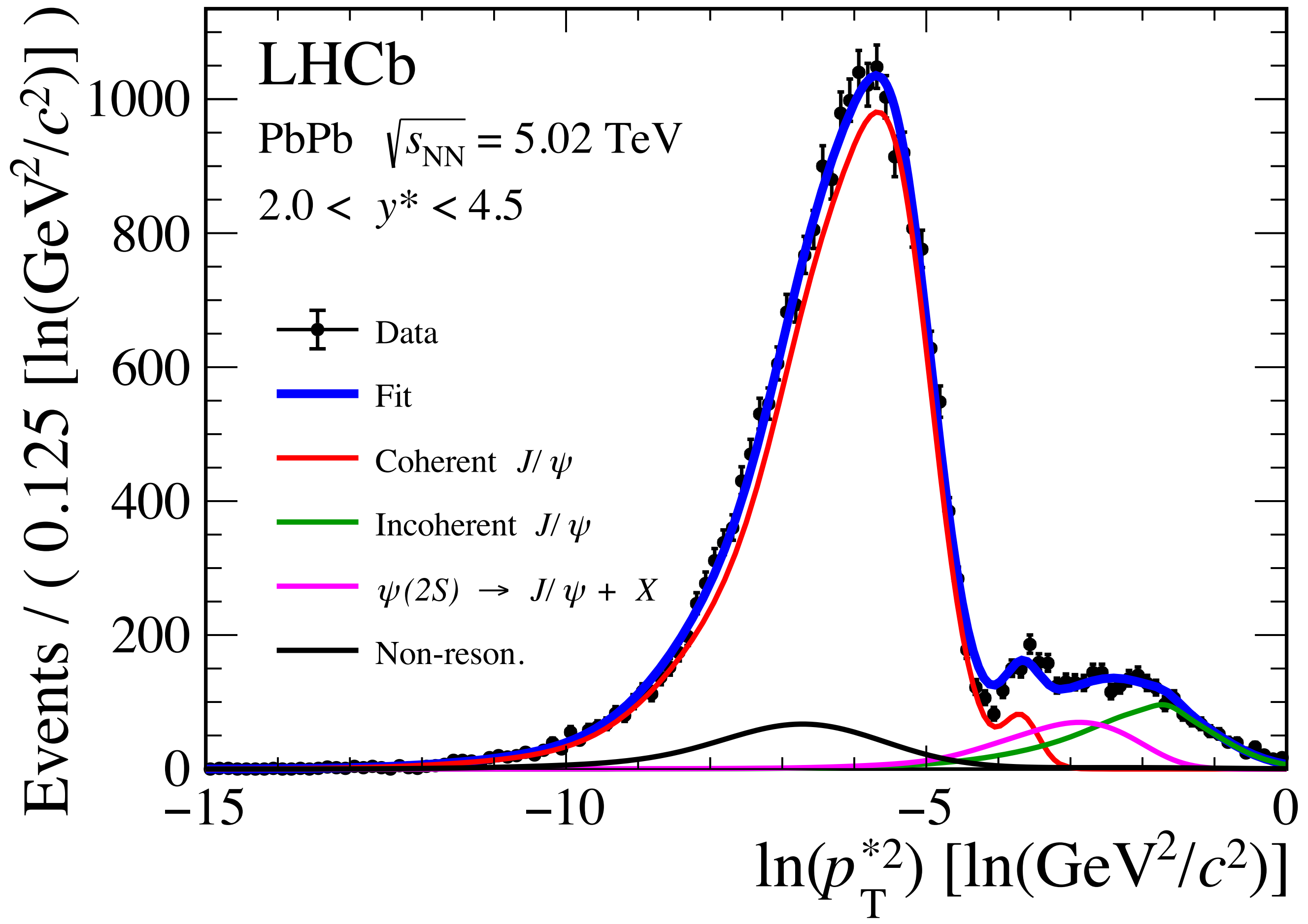


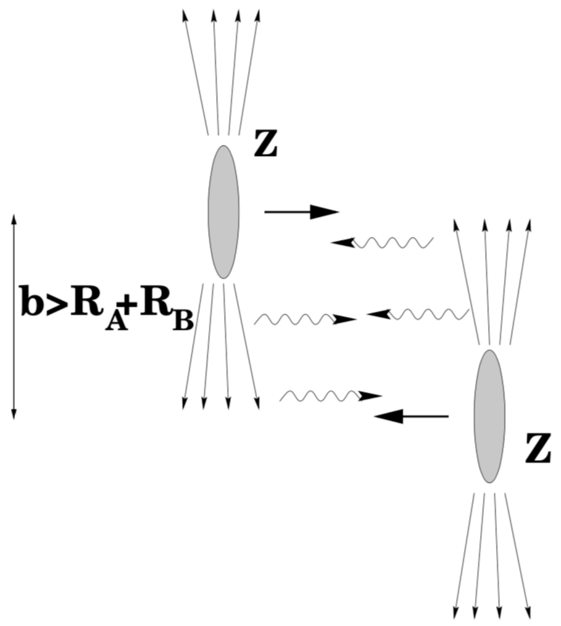
- Coherent J/ψ production measured at forward rapidity by ALICE and LHCb at the LHC.

J/ψ production in ultra-peripheral collisions

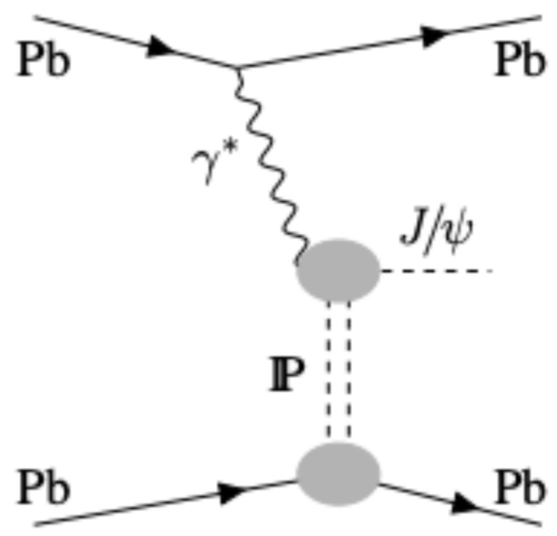


[ARXIV:2206.08221](https://arxiv.org/abs/2206.08221)

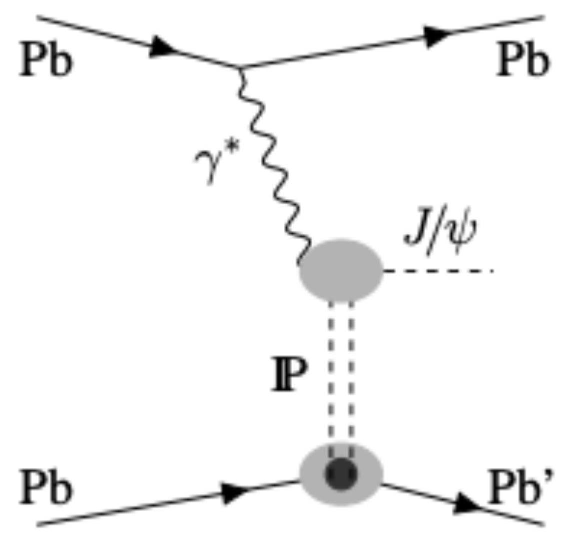




UPC scheme

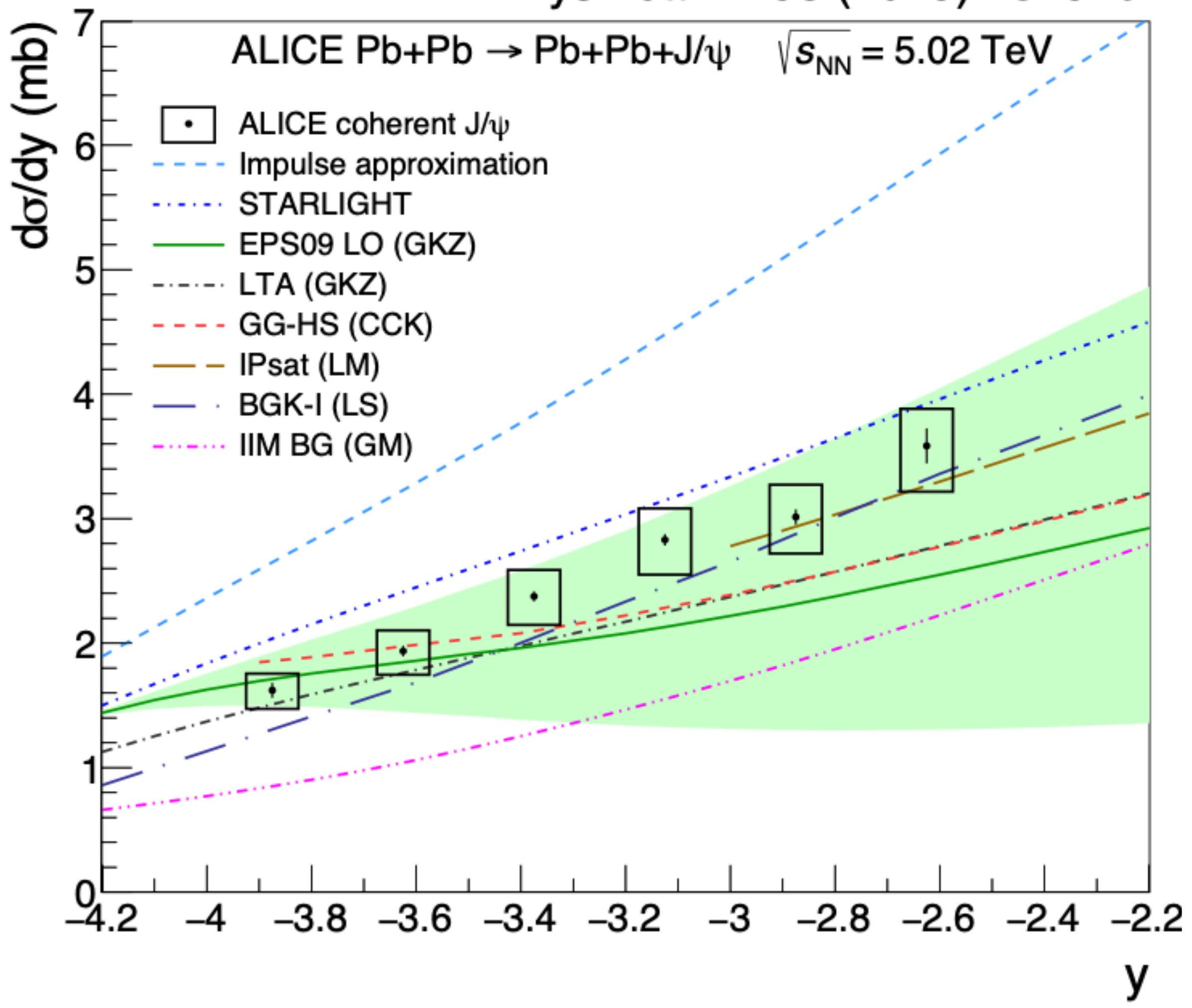


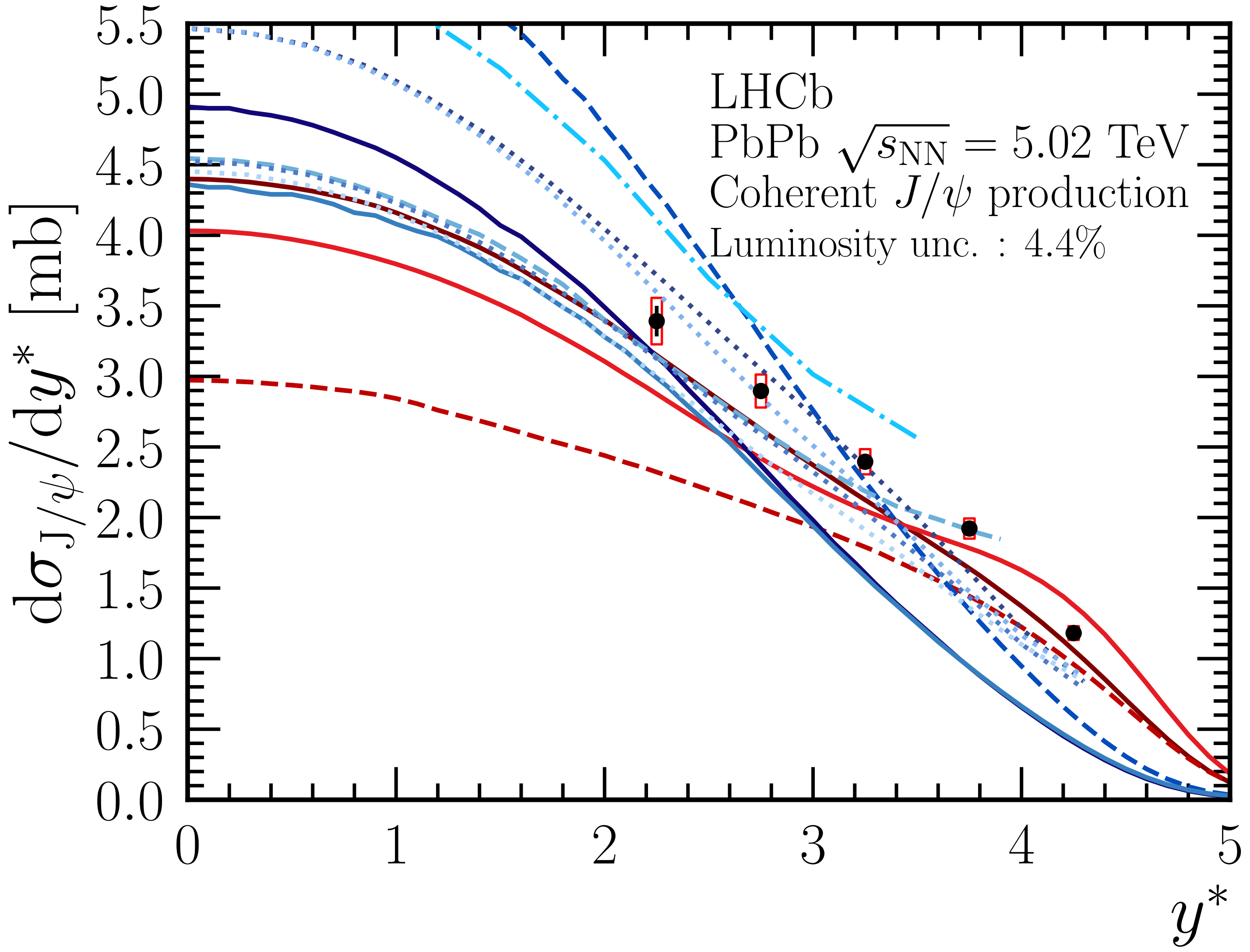
Coherent photo-production



Incoherent Photo-production

Phys.Lett. B798 (2019) 134926

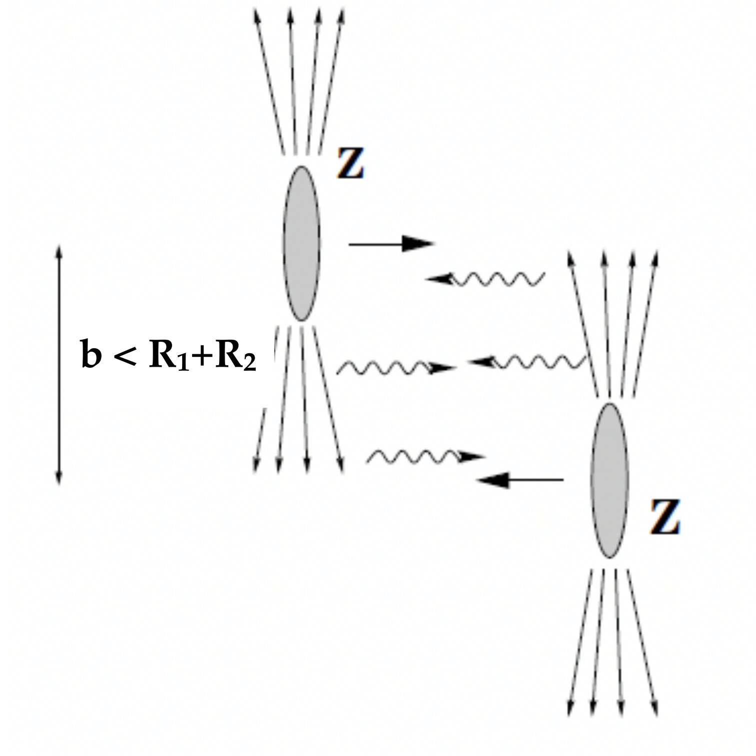




- Coherent J/ψ production measured at forward rapidity by ALICE and LHCb at the LHC.

Quarkonia in AA collisions : photo-production with nuclear overlap

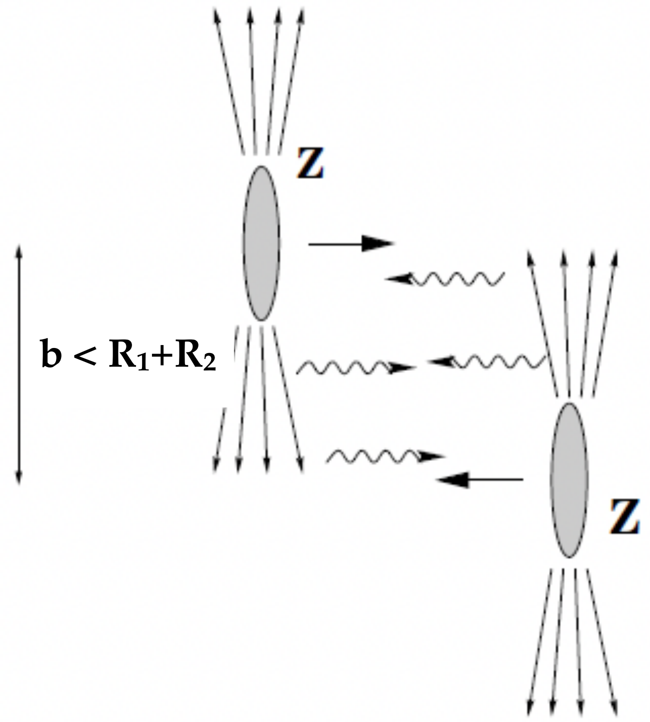
Peripheral collision

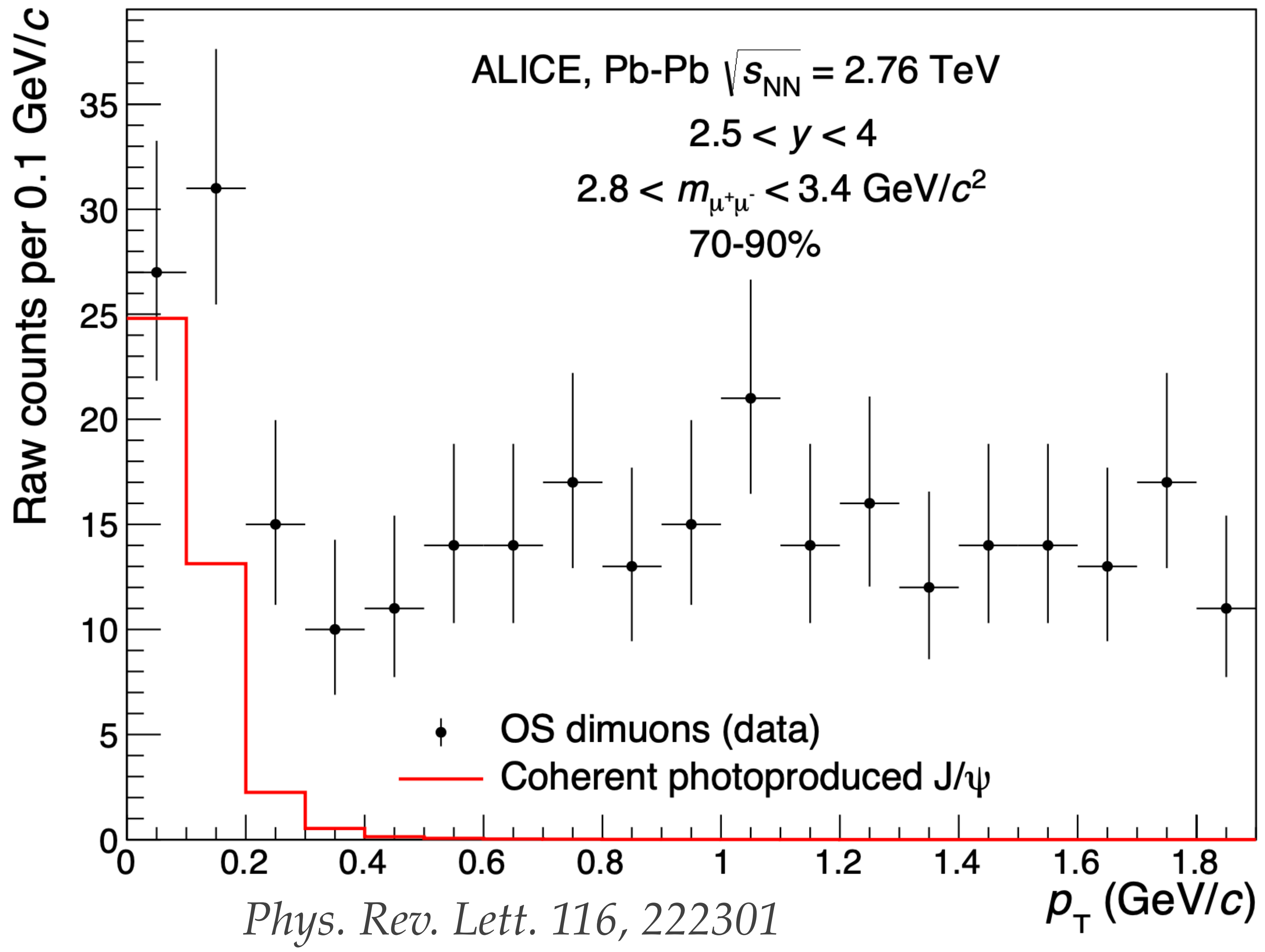


Quarkonia in AA collisions : photo-production with nuclear overlap

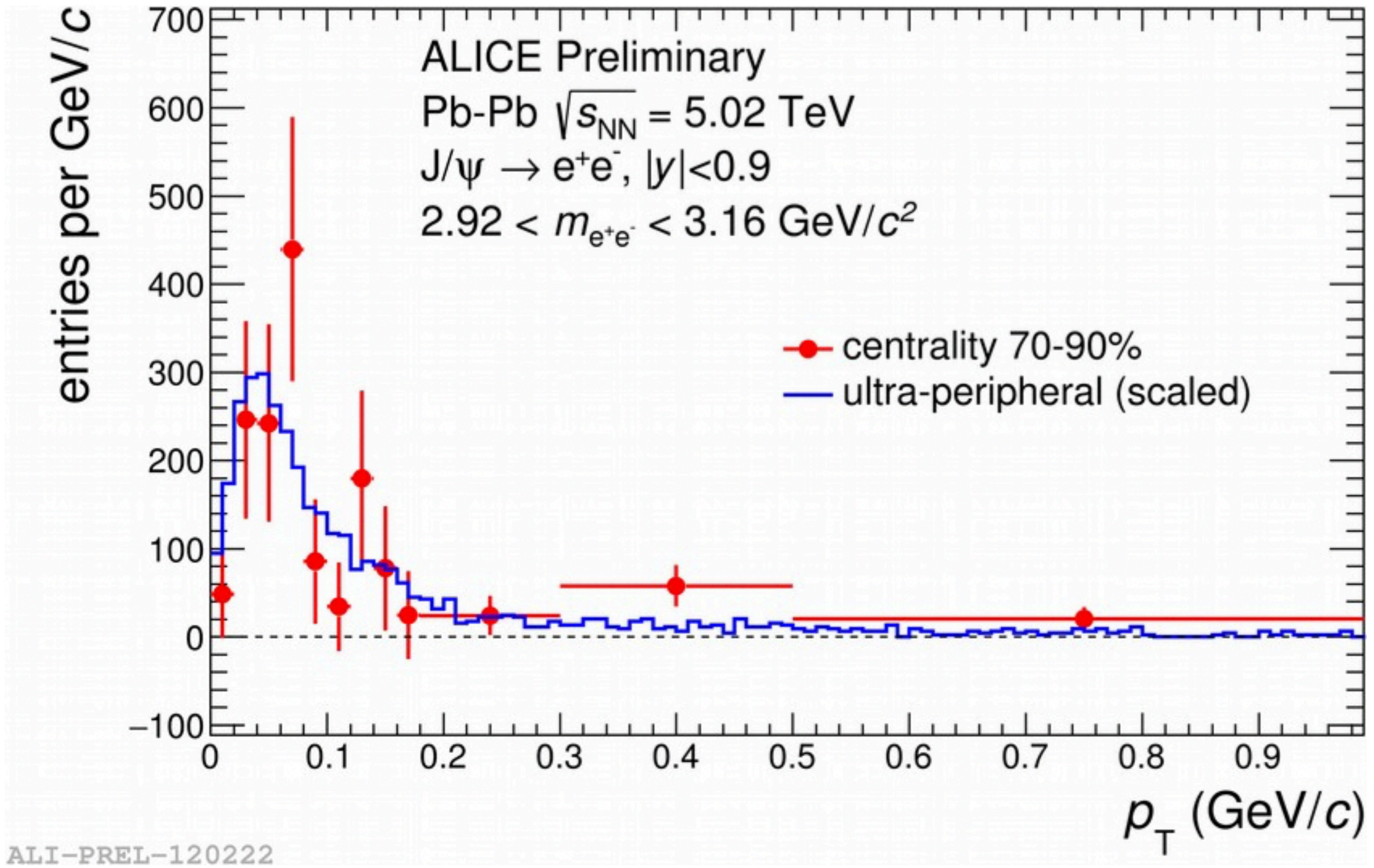
- Very-low p_T excess measured by ALICE at LHC
  - Mostly likely photo-production → good p_T resolution

Peripheral collision





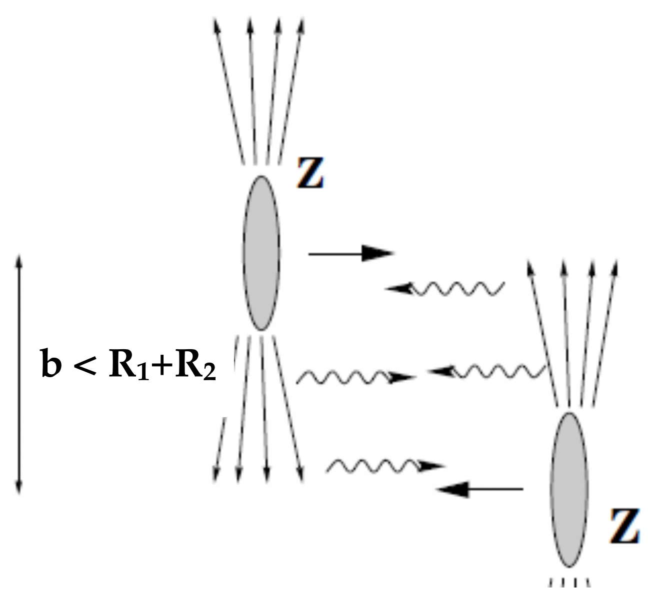
Phys. Rev. Lett. 116, 222301

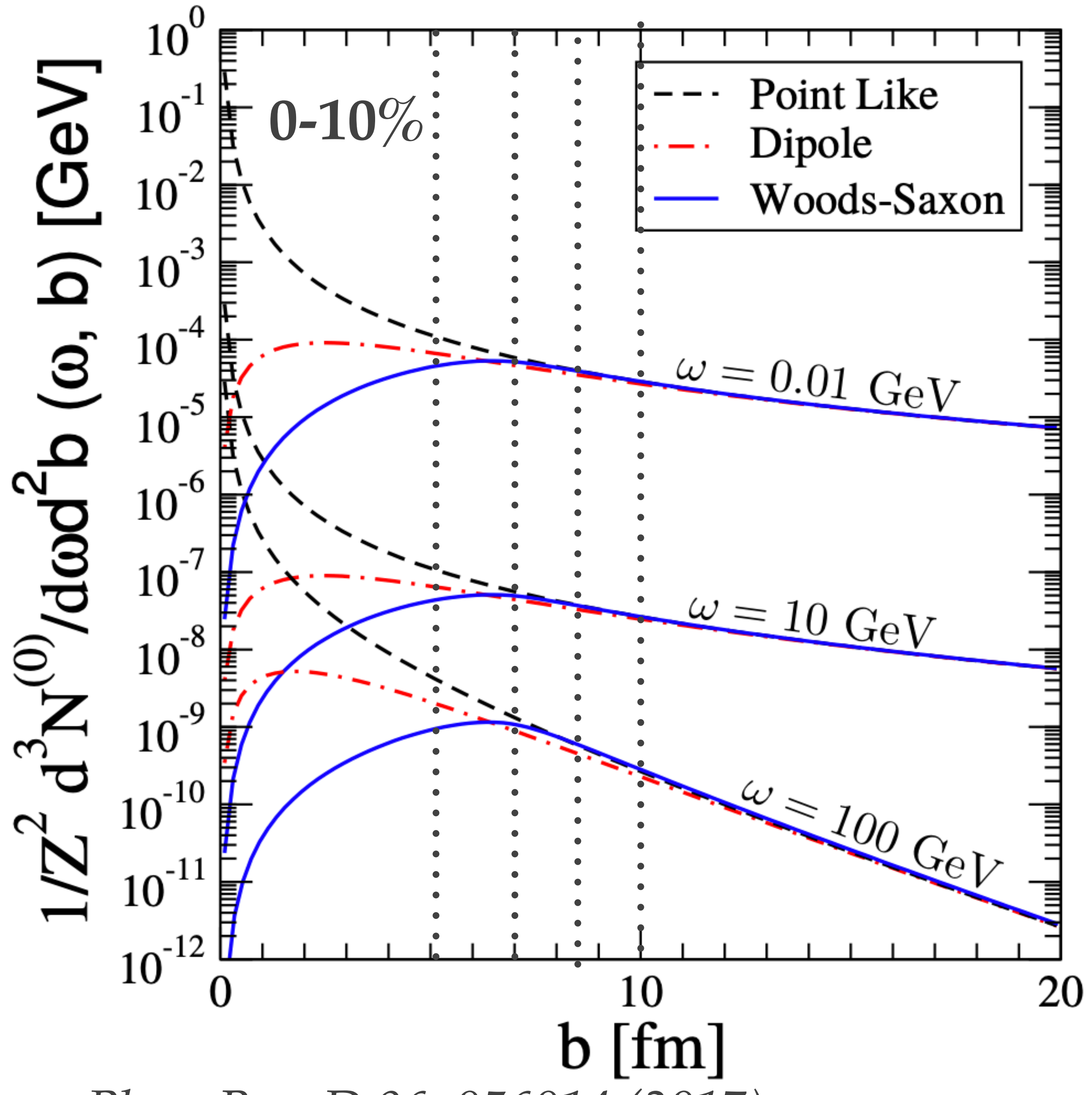


Quarkonia in AA collisions : photo-production with nuclear overlap

- Very-low p_T excess measured by ALICE at LHC
  - Mostly likely photo-production → good p_T resolution
- Prob for the **photon flux** and **the geometry** of the collisions

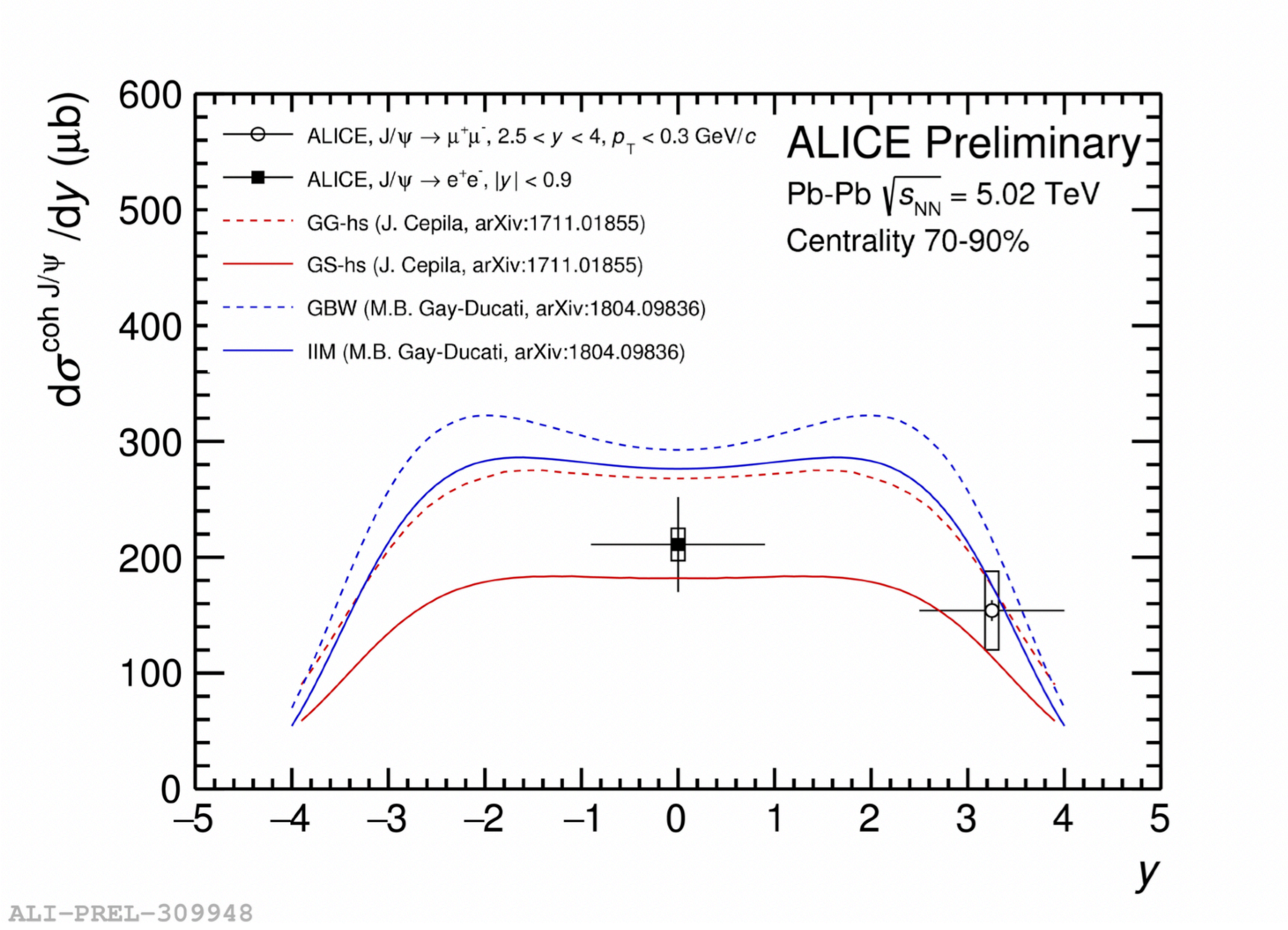
Peripheral collision



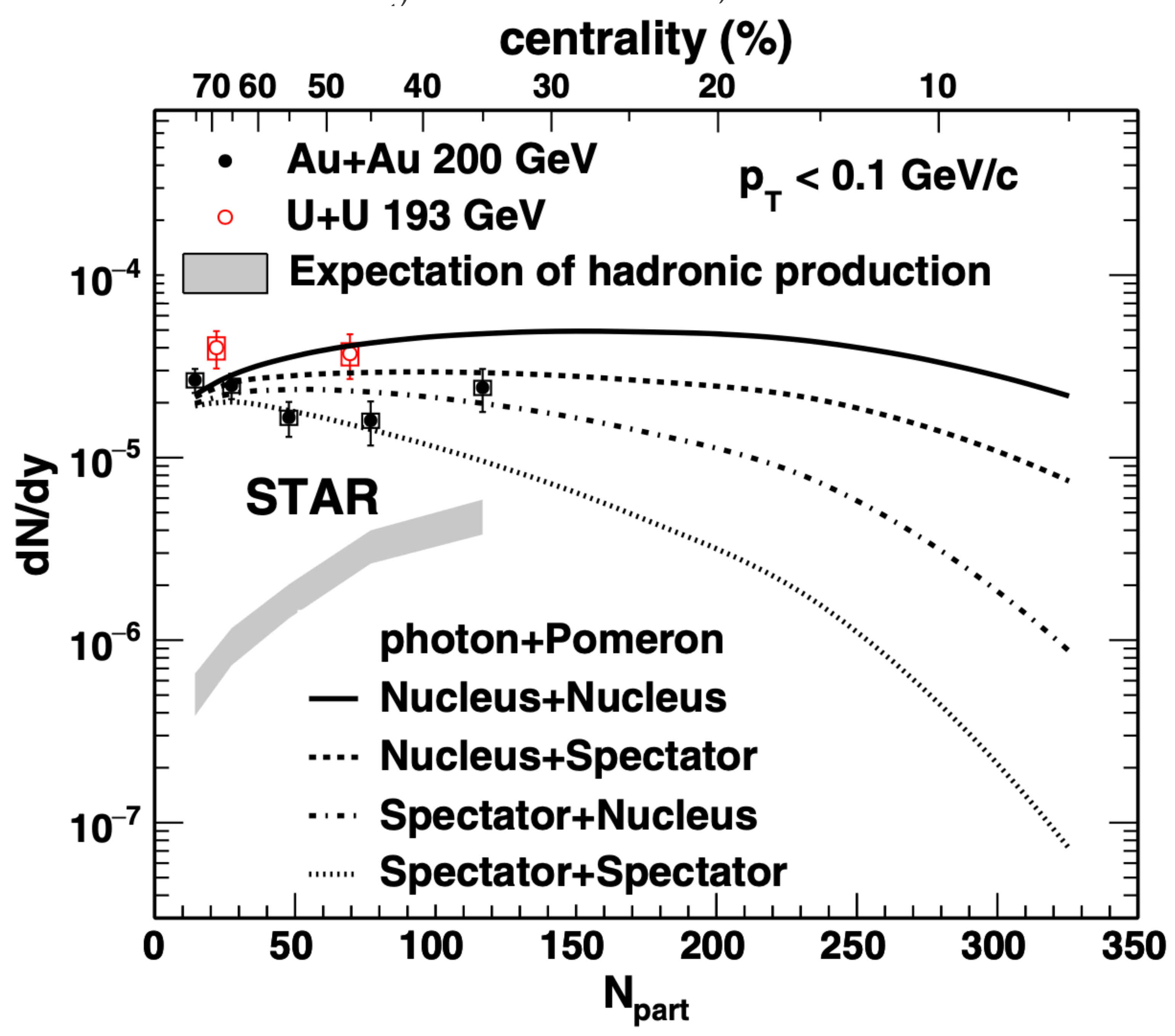


Phys. Rev. D 96, 056014 (2017)

FIG. 1: The b-dependence photon flux distribution for the different form factors of the lead nuclei.



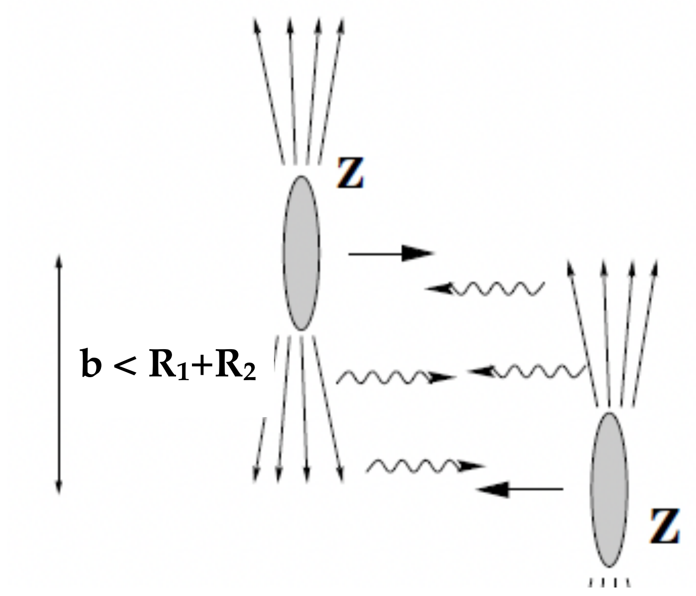
Phys. Rev. Lett. 123, 132302

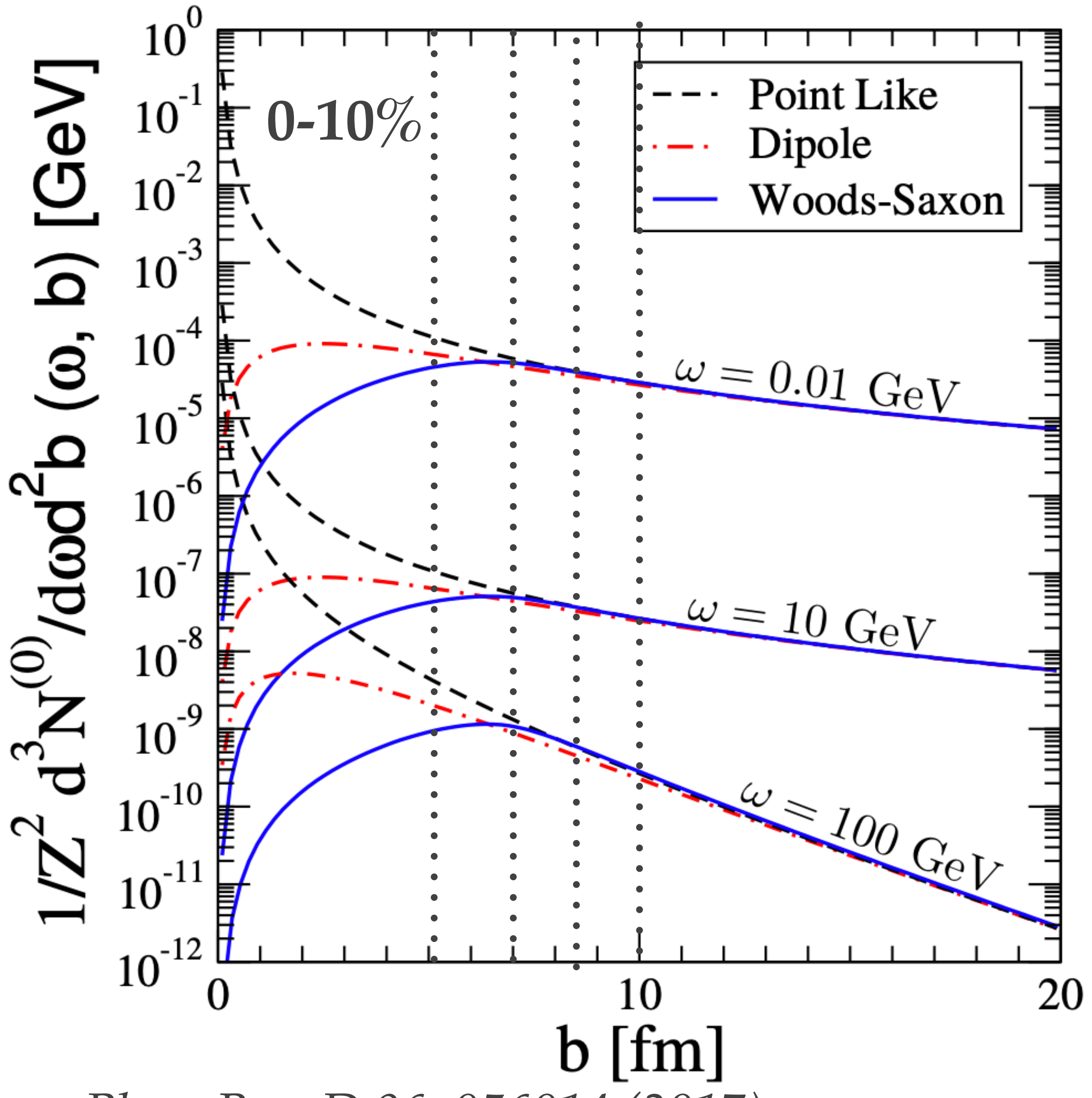


Quarkonia in AA collisions : photo-production with nuclear overlap

- Very-low p_T excess measured by ALICE at LHC
  - Mostly likely photo-production → good p_T resolution
- Prob for the **photon flux** and **the geometry** of the collisions
- Open-question : Could it be useful for QGP studies ?

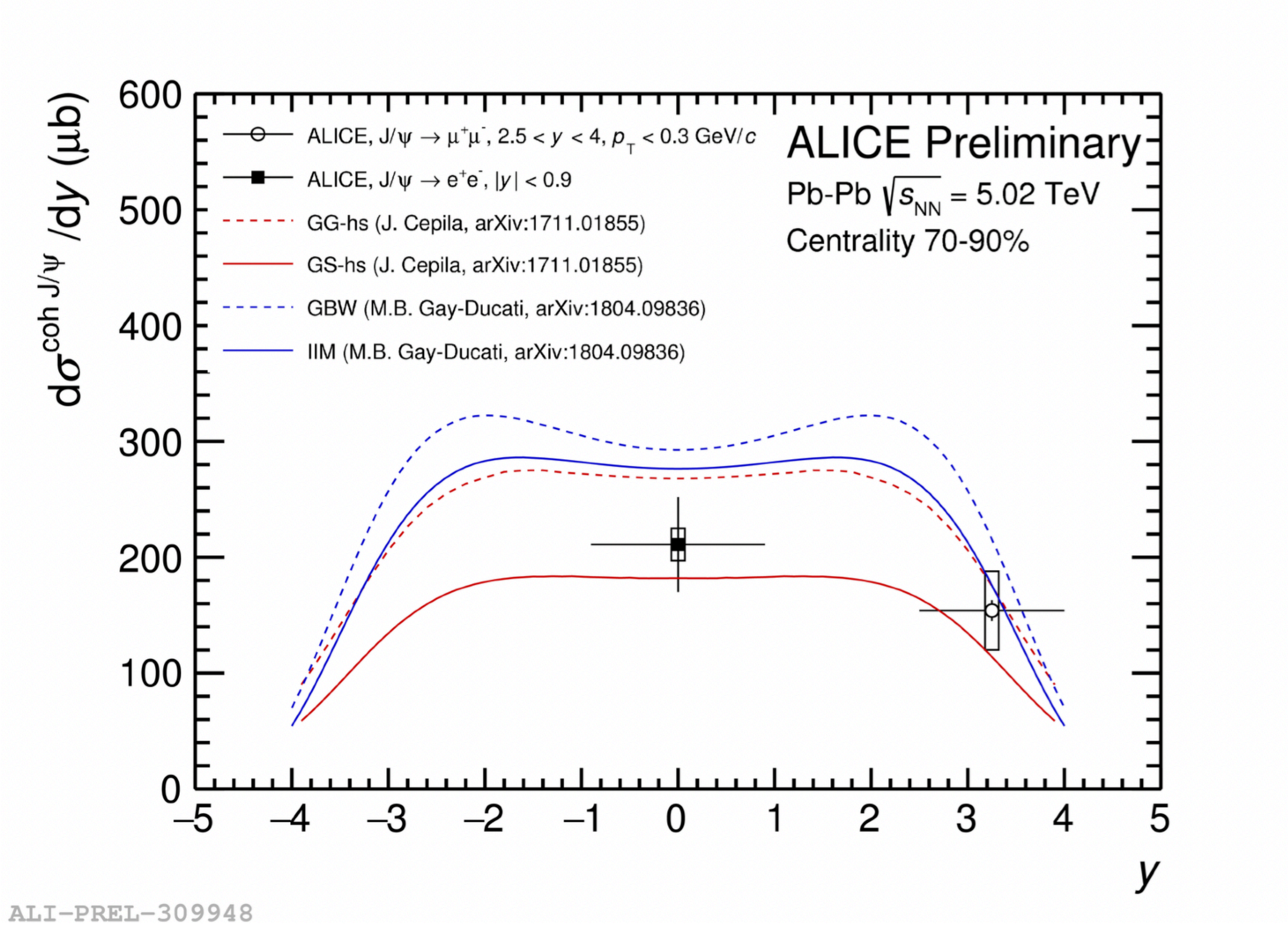
Peripheral collision



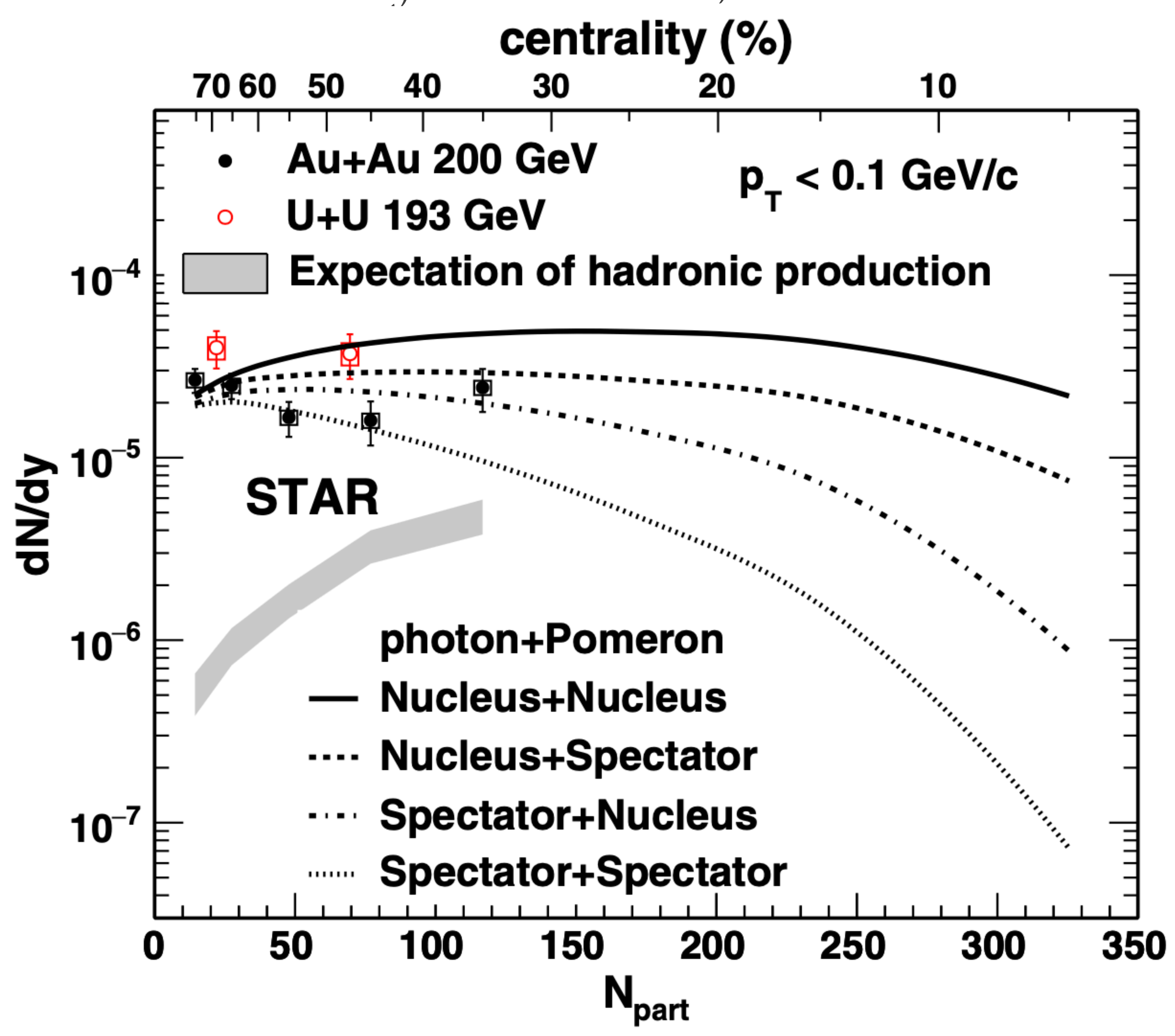


Phys. Rev. D 96, 056014 (2017)

FIG. 1: The b-dependence photon flux distribution for the different form factors of the lead nuclei.

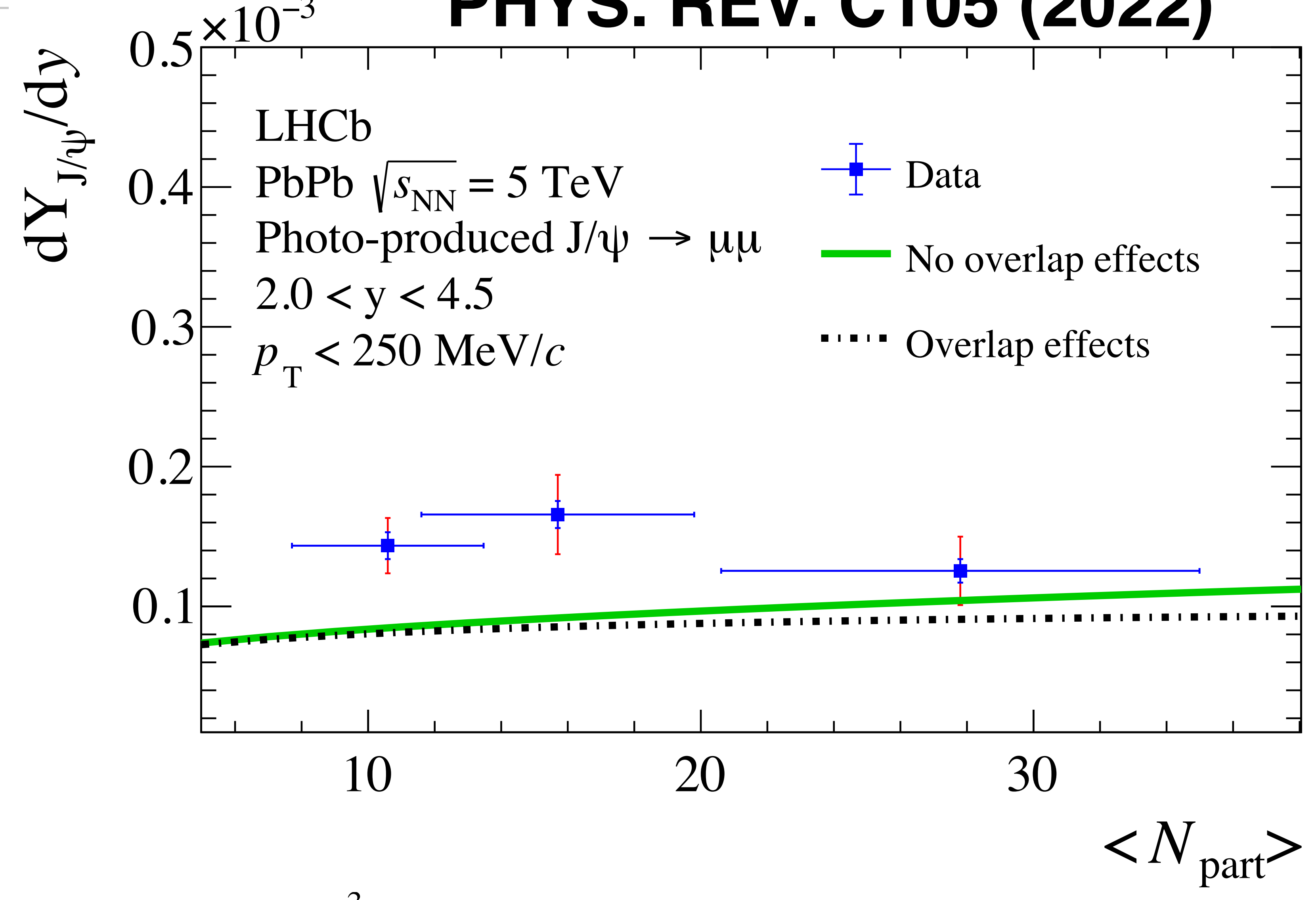


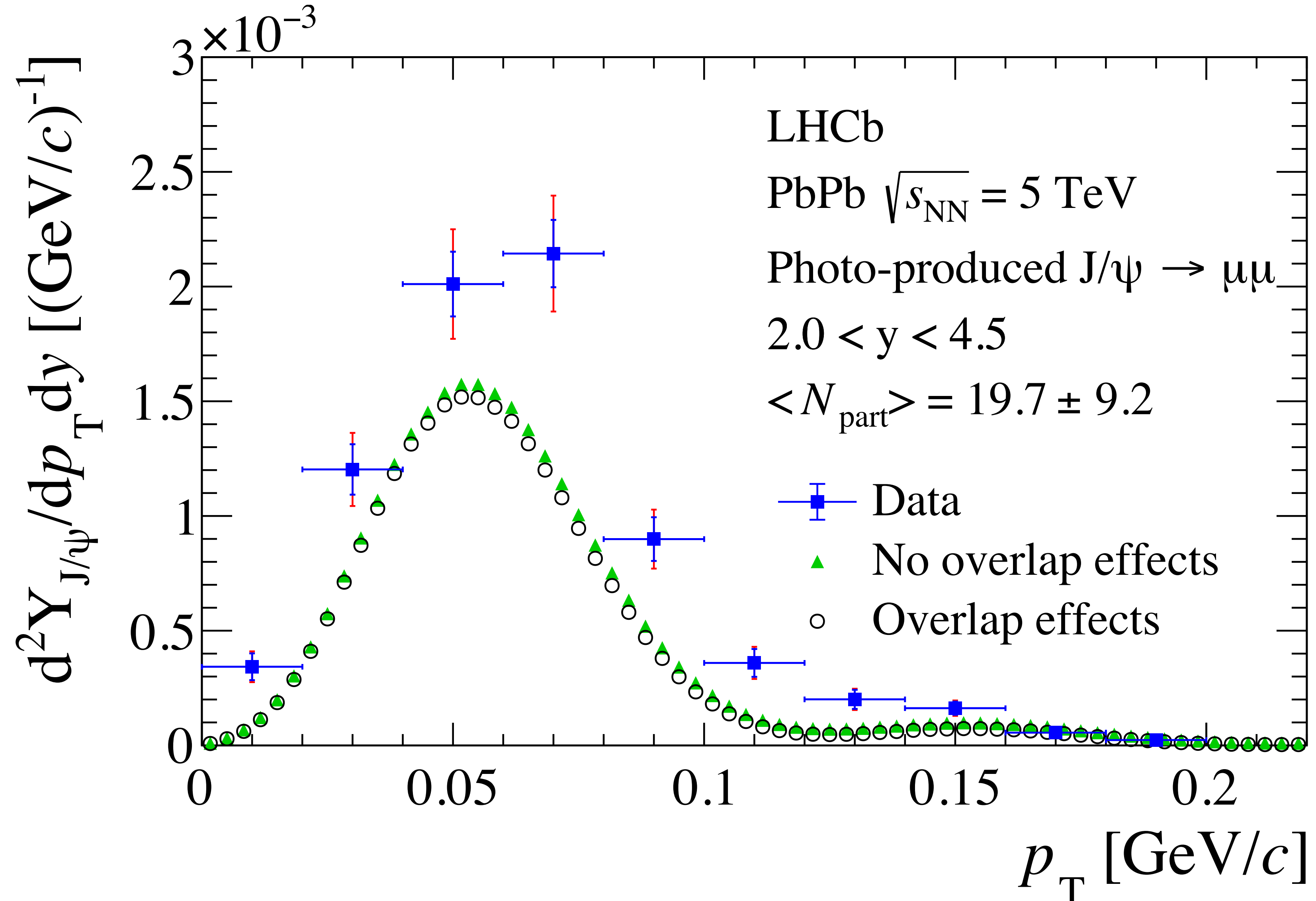
Phys. Rev. Lett. 123, 132302



Quarkonia in AA collisions : photo-production with nuclear overlap

PHYS. REV. C105 (2022)





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