Ultrarelativistic Heavy-Ion Physics and the Quark-Gluon Plasma

Part 4

- Quarkonium
- Small systems
- Future

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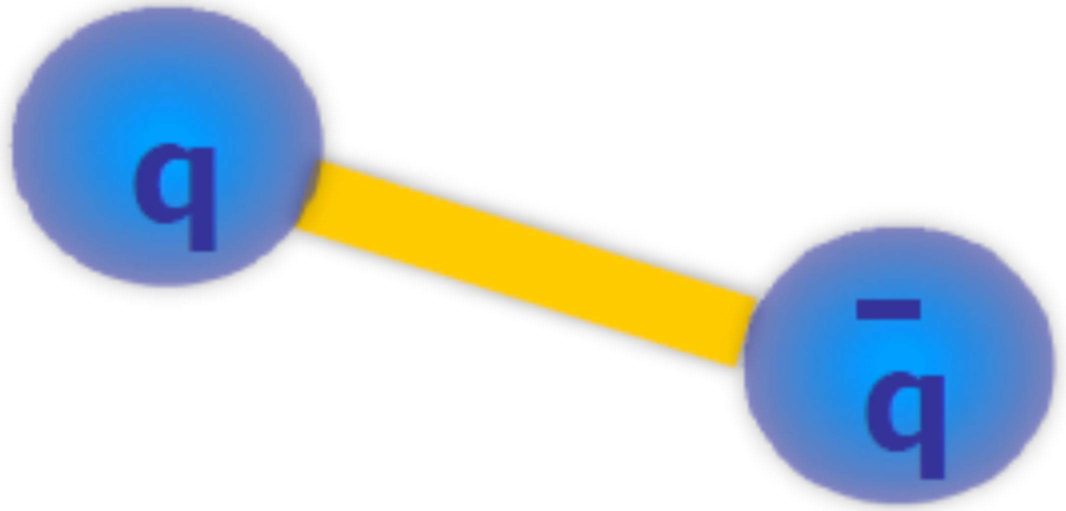
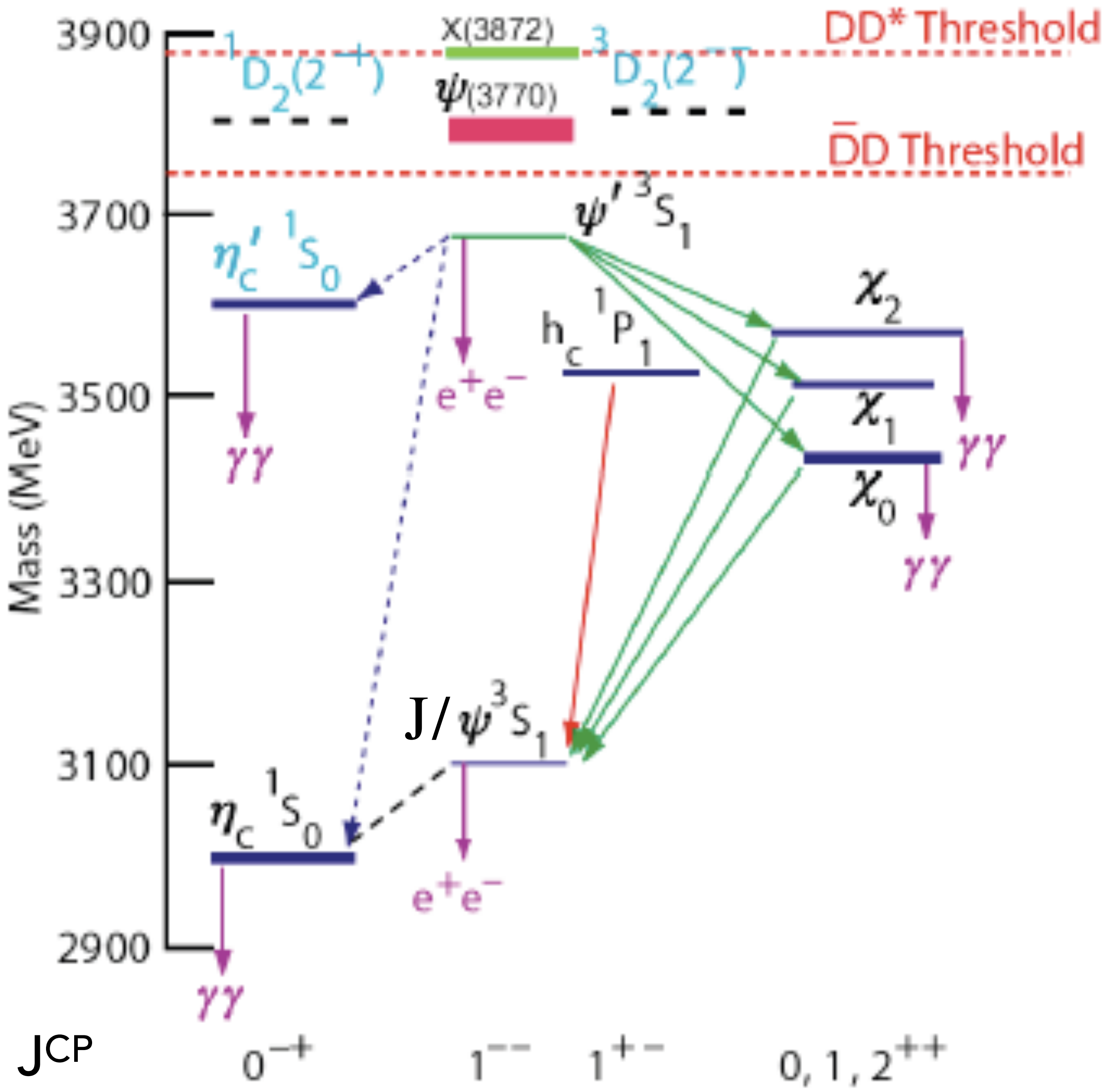
Quarkonium: charmonium and bottomonium

What is quarkonium?

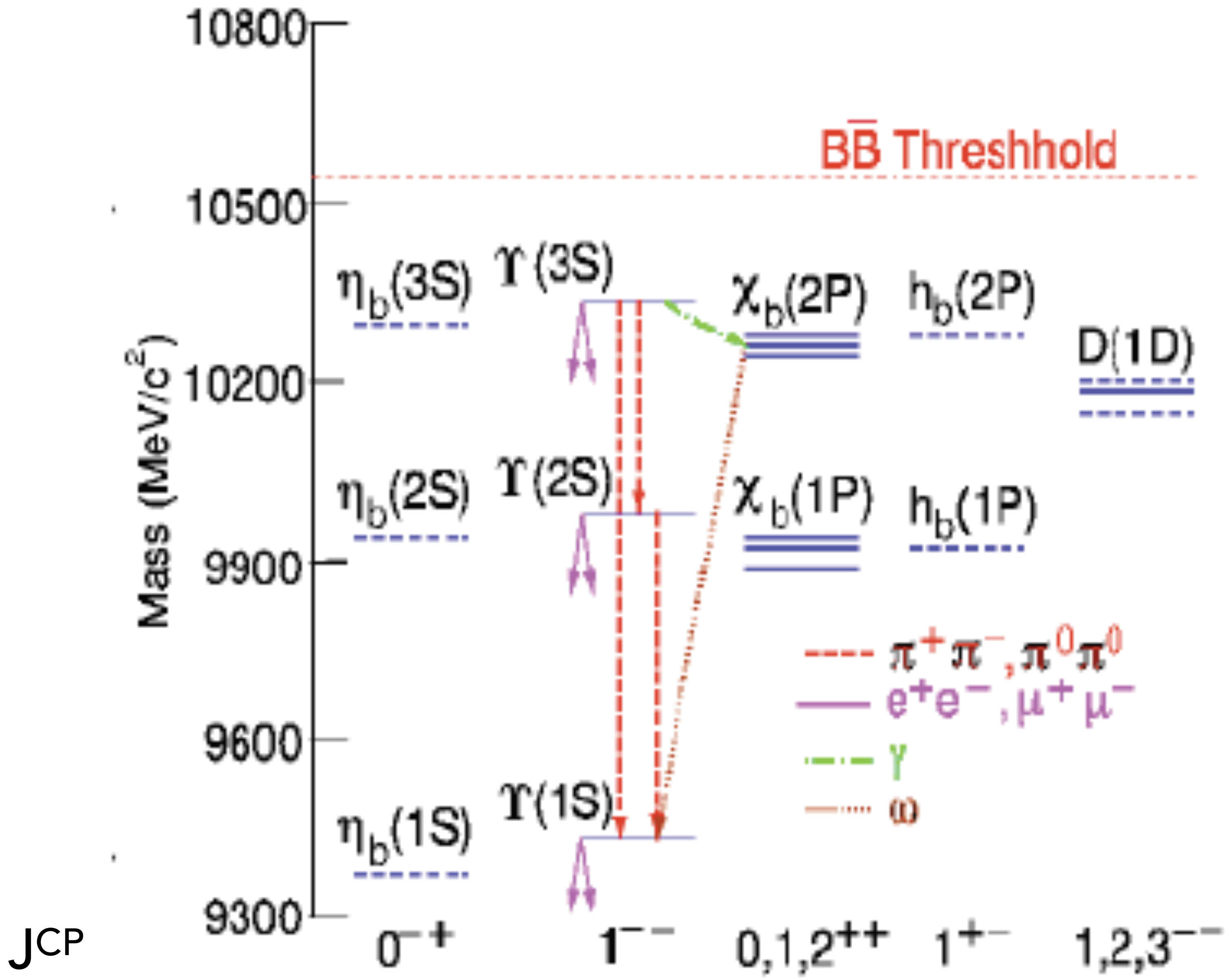
- Quarkonium is a bound state of q and $\bar{q}$
  - According to the quantum numbers, several quarkonium states exists



Charmonium family ($c\bar{c}$)



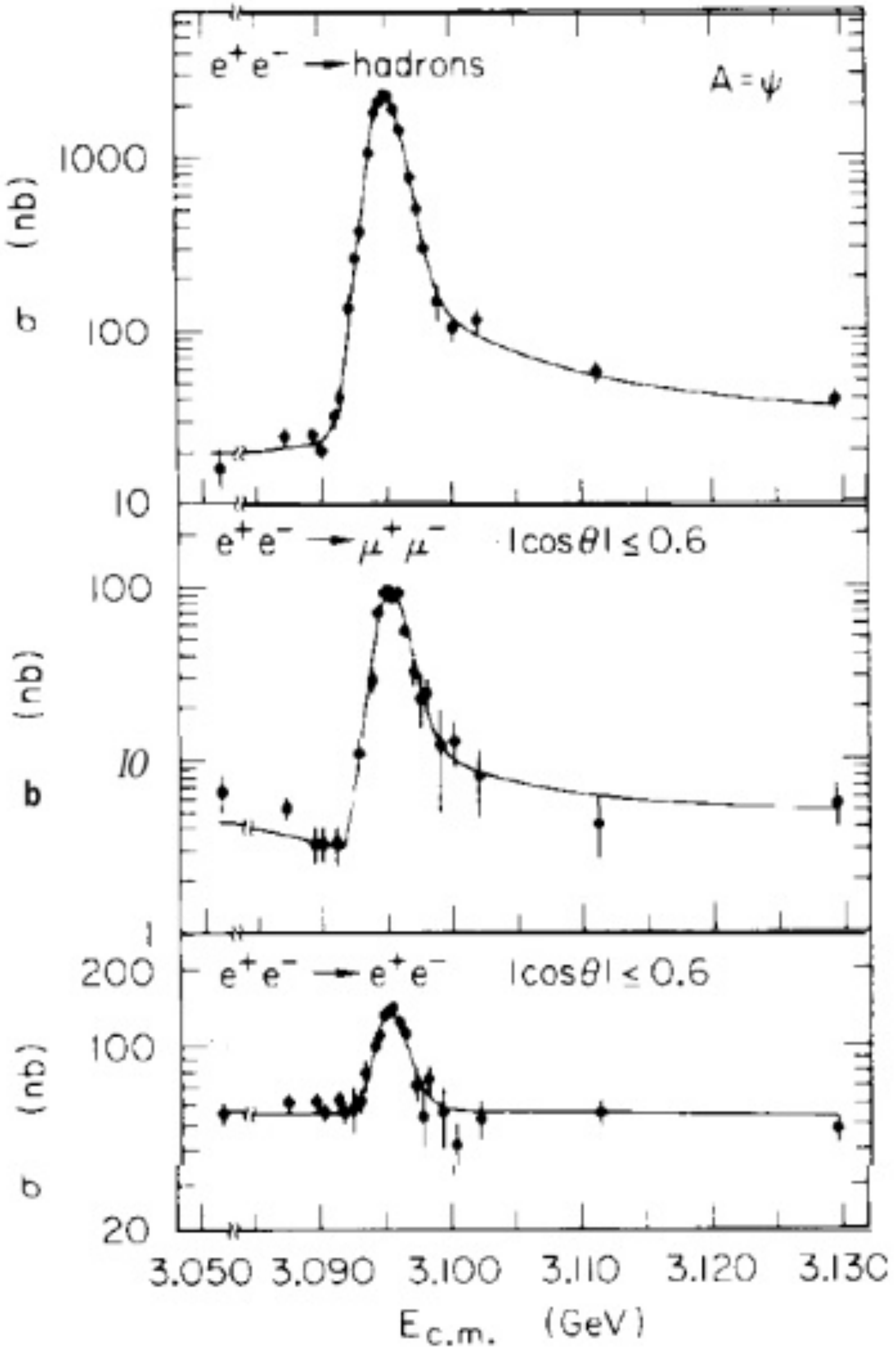
Bottomonium family ($b\bar{b}$)

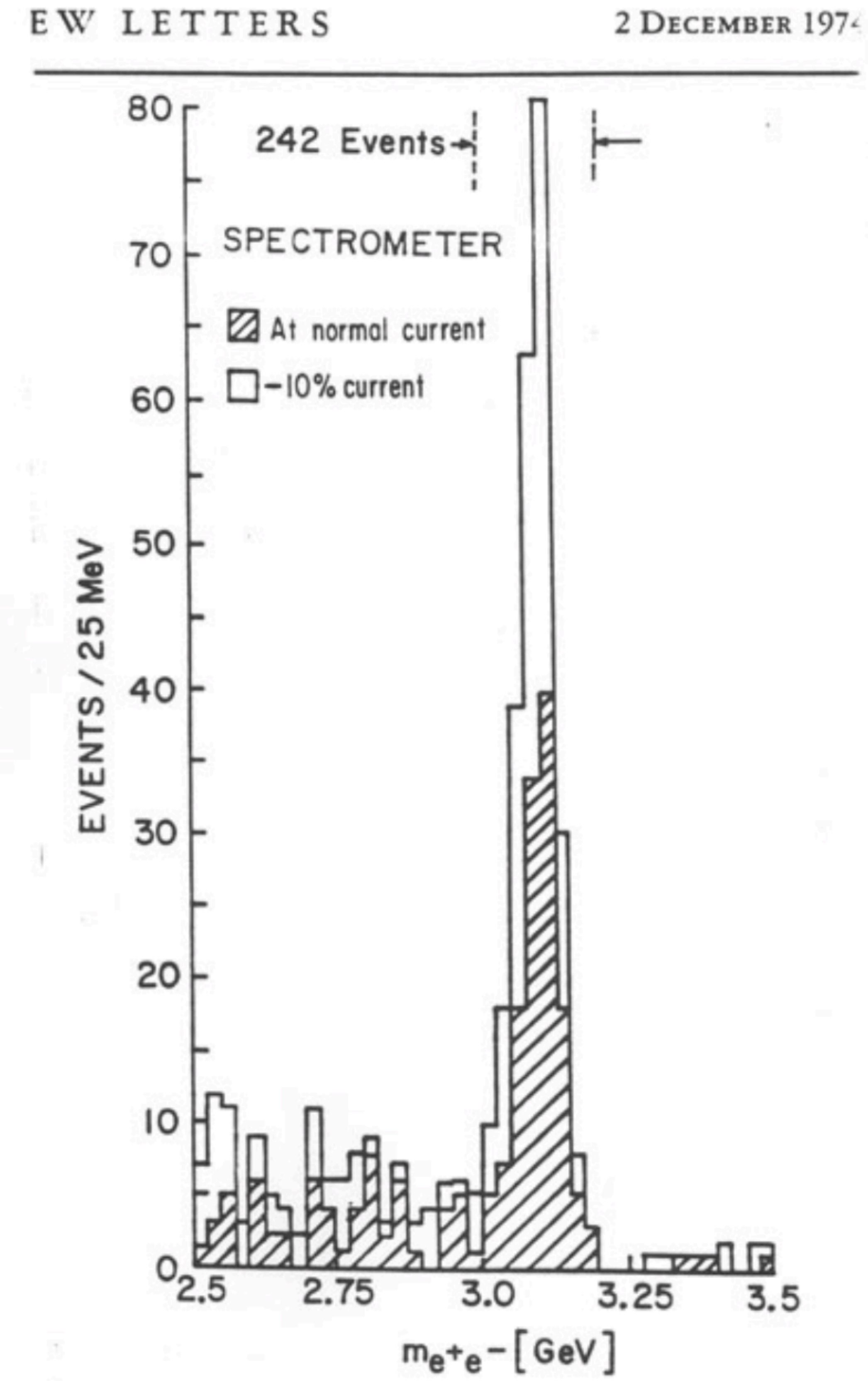


Discovery of the J/ψ

- Discovered 1974 simultaneously
  - J: S. Ting in p+A (BNL)
    - Phys. Rev. Lett. 33, 1404 - 1406 (1974)
  - **Ψ**: B. Richter in e+e- (SLAC)
    - Phys. Rev. Lett. 33, 1406 - 1408 (1974)
  - Nobel Prize 1976

- Bound state of charm and anti-charm
  - New flavour quantum number: small width of the resonance
  - Charm is heavy (m_c ~ 1300 MeV) → can be treated non-relativistically
  - In analogy to positronium, energy levels can be calculated and compared with experiment



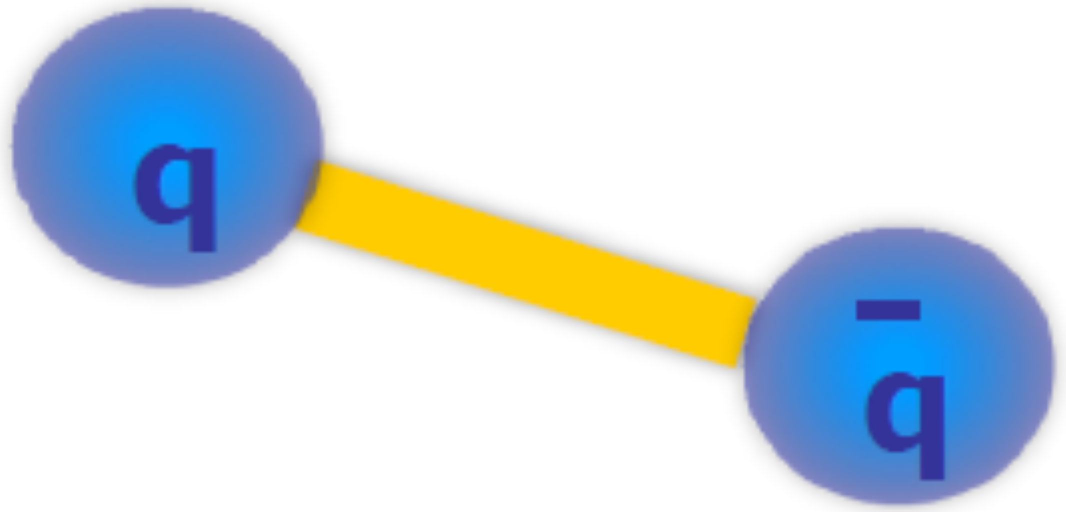


Quarkonium

- At $T = 0$, the binding of the q and $\overline{q}$ quarks can be expressed using the Cornell potential:

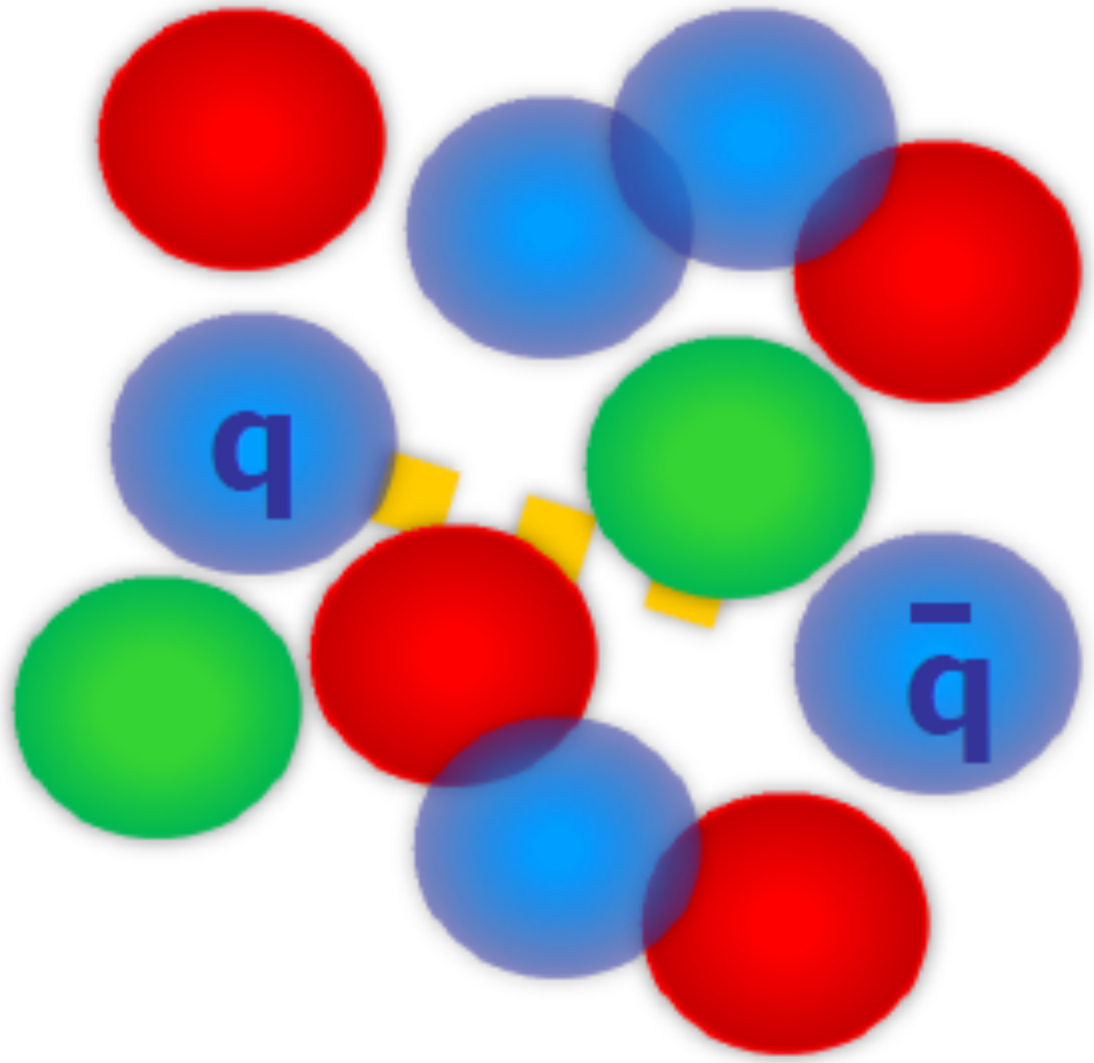
$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

Confinement term
string tension $k \approx 1$ GeV/fm



Quarkonium

- What happens to a $q\bar{q}$ pair placed in the QGP?
  - The QGP consists of deconfined colour charges
    - The binding of a $q\bar{q}$ pair is subject to the effects of colour screening
  - The "confinement" contribution disappears
  - Simple parameterisation of the screened potential ("Debye screening"):



$$V(r,T) = -\frac{\alpha}{r}e^{-\mu r} + \sigma r \frac{1 - e^{-\mu r}}{\mu r}$$

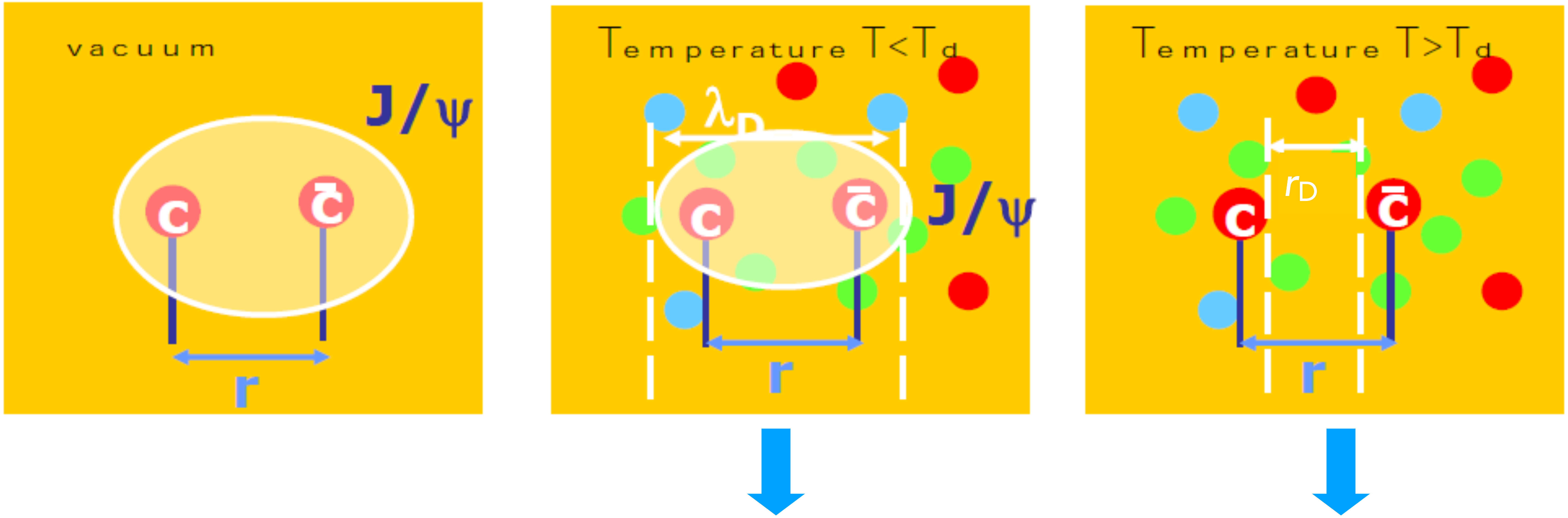
screening radius depends on temperature:

$$r_D = 1/\mu$$ ← Debye mass

$$\mu = \mu(T) \propto g(T)T$$

Debye screening

- The screening radius r_D (i.e. the maximum distance which allows the formation of a bound $q\bar{q}$ pair) decreases with the temperature T



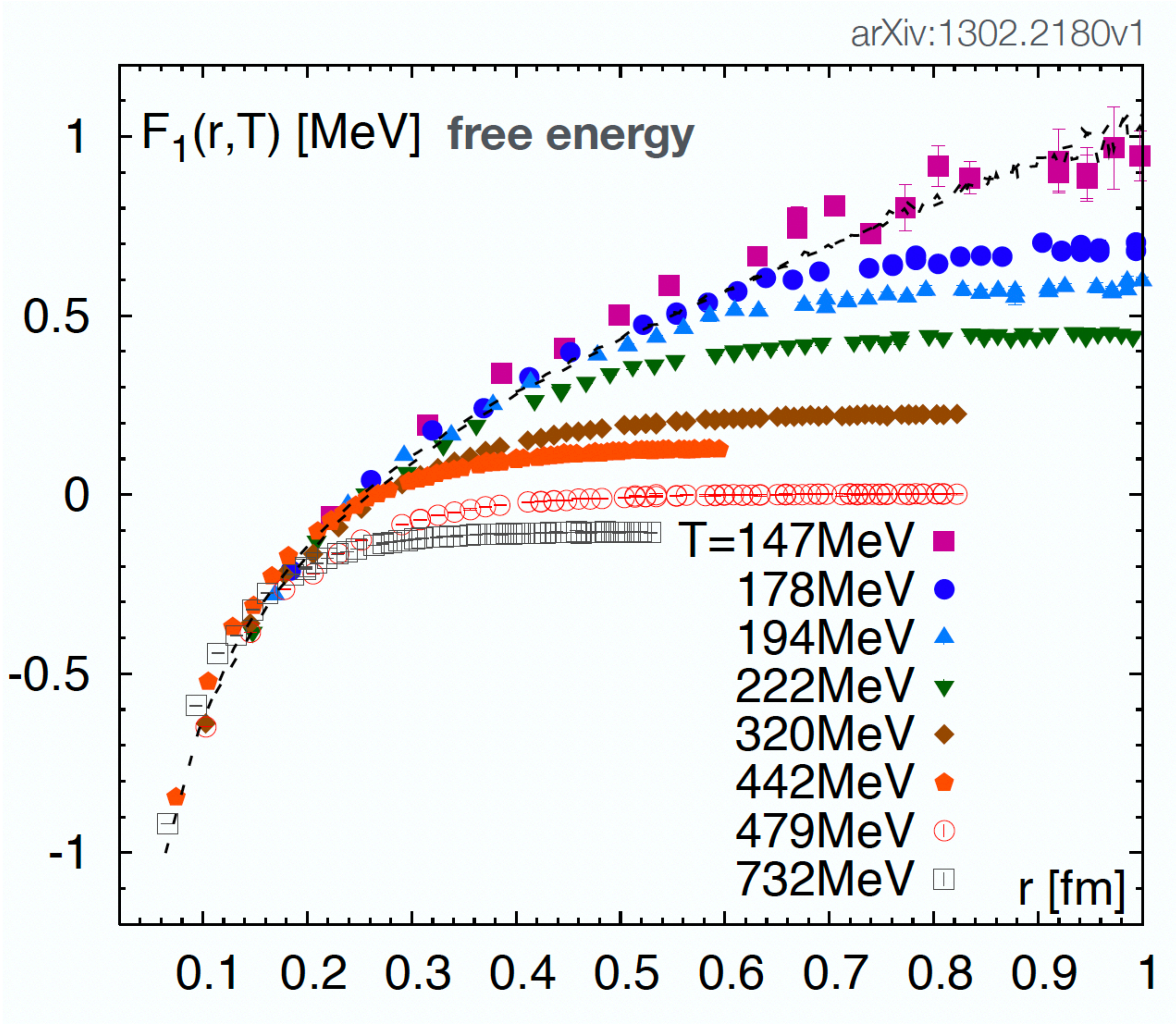
At a given T:

if resonance radius < r_D
→ resonance can be formed

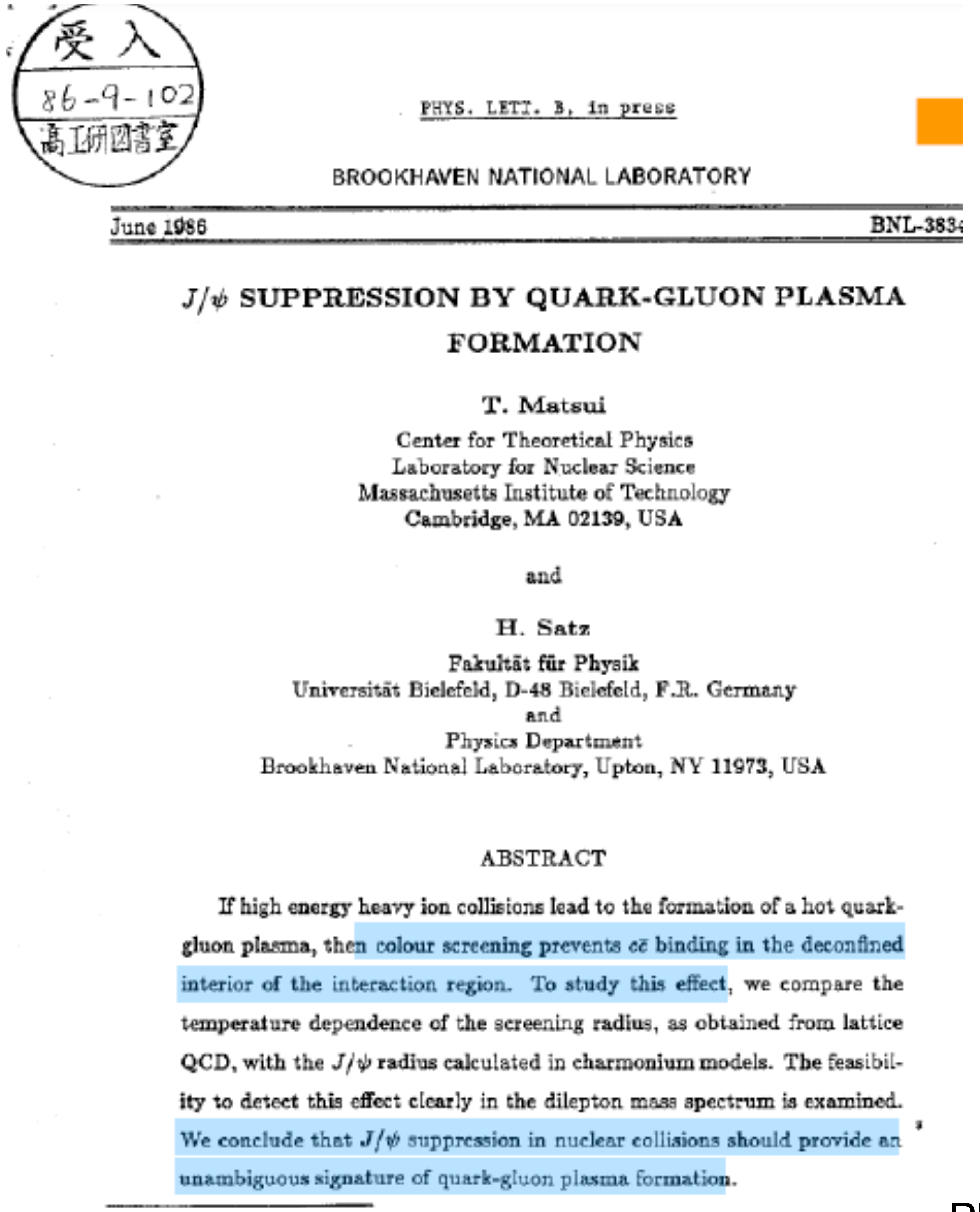
if resonance radius > r_D
→ no resonance can be formed

Results on Debye screening from lattice QCD

- Heavy quark potential for different temperatures from lattice QCD



Charmonium suppression



PHYS. LETT. B, in press

BROOKHAVEN NATIONAL LABORATORY

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J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

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ABSTRACT

If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice QCD, with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. We conclude that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.

Phys. Lett. B 178 (1986)

- This is the idea behind the suggestion (by Matsui and Satz) of the J/ψ as a signature of QGP formation (1986)
  - Potential between two heavy quarks is modified in the QGP, preventing initially produced charm and anticharm quarks to form a J/ψ

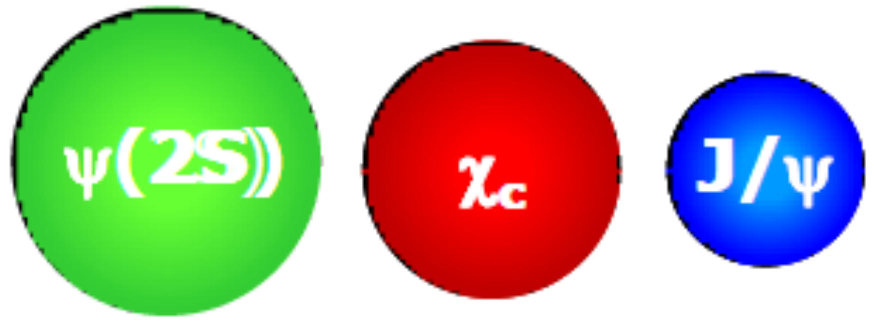
→ J/ψ suppression is a QGP signal

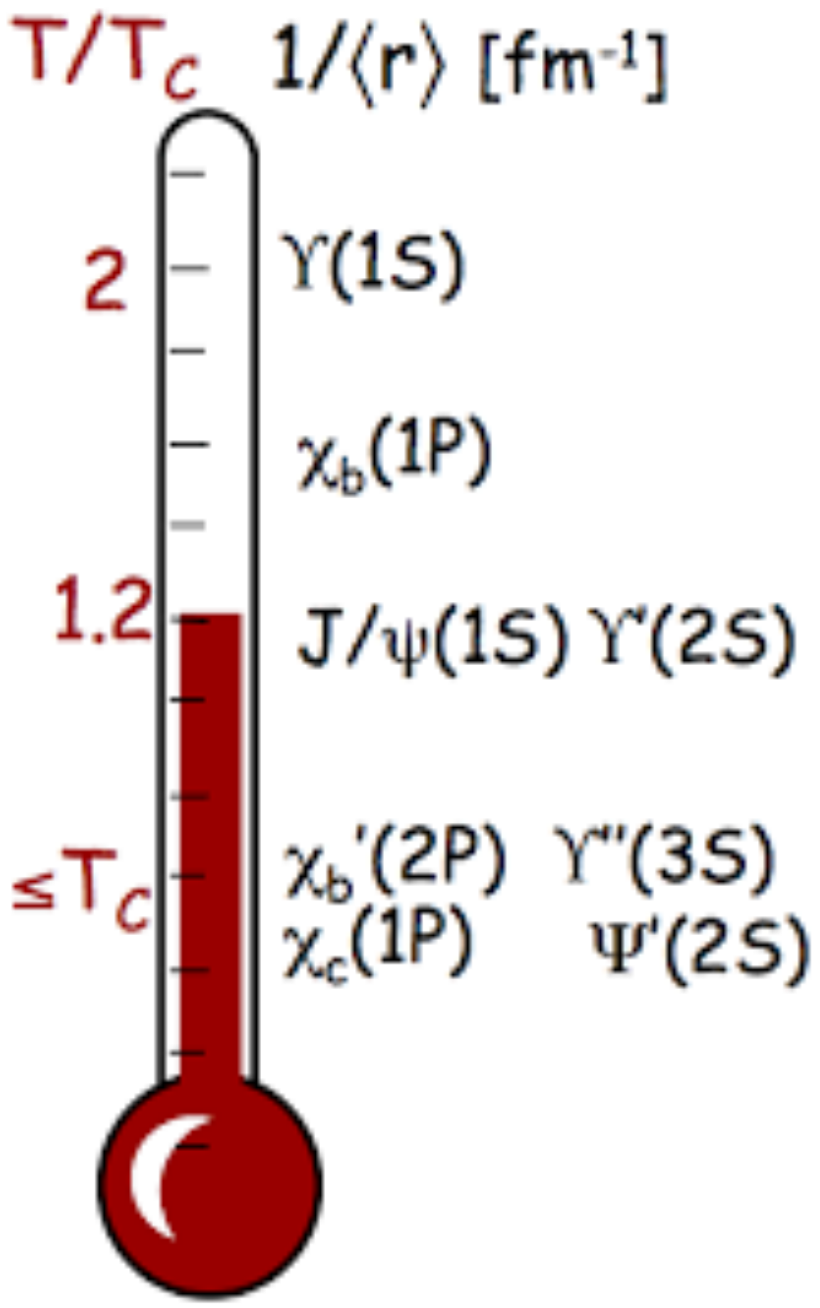
Sequential melting

- The quarkonium states can be characterised by
  - the binding energy $\Delta E = 2(M_{D,B} - m_i)$
  - the radius

→ More bound states have smaller size

→ Debye screening condition $r_{q\bar{q}} > r_D$ will occur at different T





State	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
Mass (GeV)	3.10	3.53	3.68	9.46	9.99	10.02	10.36	10.36
ΔE (GeV)	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
Radius (fm)	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

Quarkonium dissociation temperatures T_d

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

Quarkonium Production

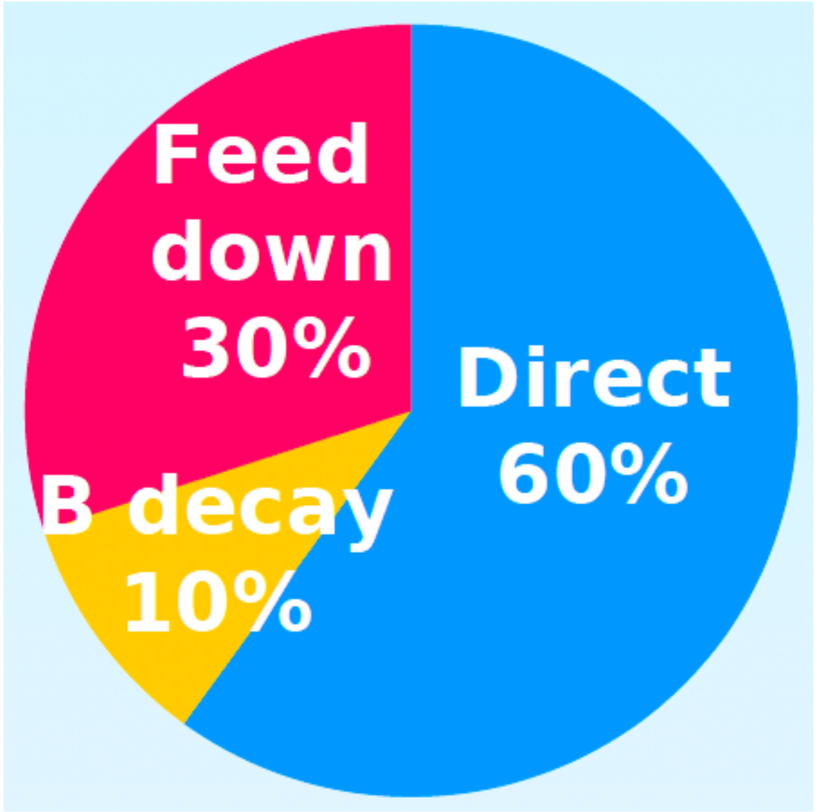
- Quarkonium production can proceed
  - Directly in the interaction of the initial partons
  - Via the decay of heavier hadrons (feed-down)

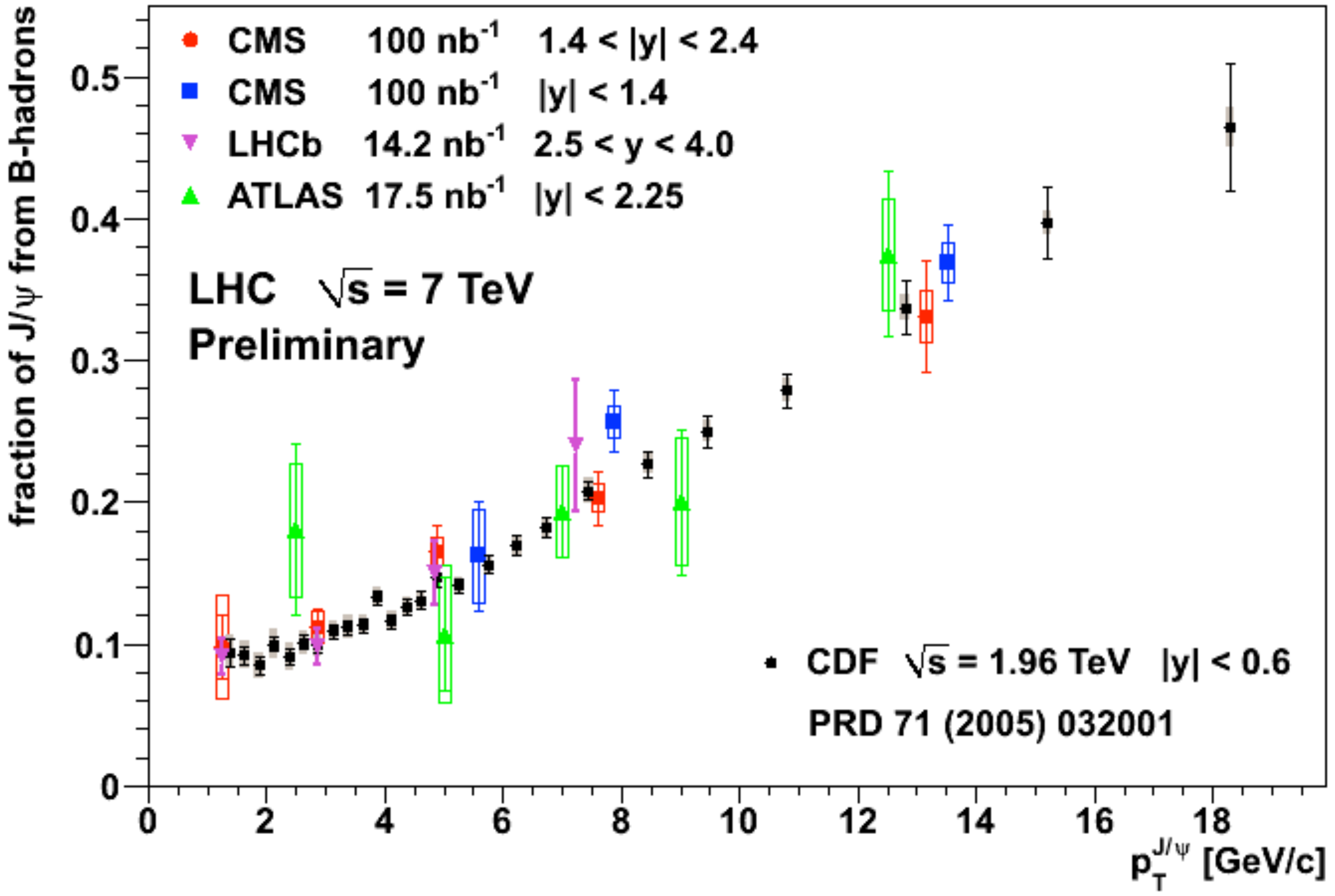
- For J/ψ (LHC energies) the contributing mechanisms are
  - Direct production
  - Feed-down from higher charmonium states
    ~ 8% from ψ(2S), ~25% from χ_c

    } Prompt

  - B decay
    - contribution is p_T dependent
      ~10% at p_T ~1.5 GeV/c

    } Displaced





Production of Charmonia in Hadronic Collisions

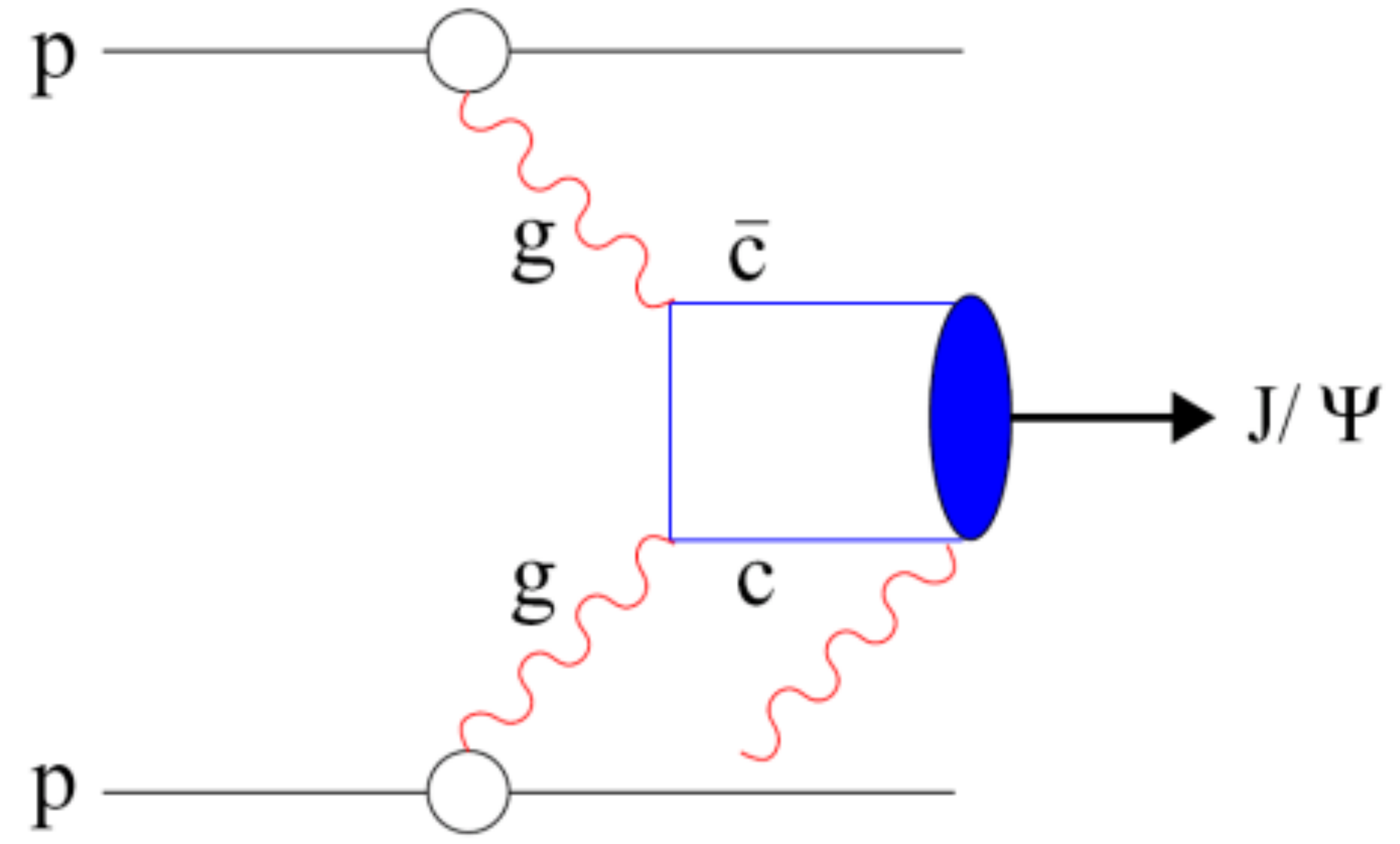
- Most important Feynman diagram: gluon fusion

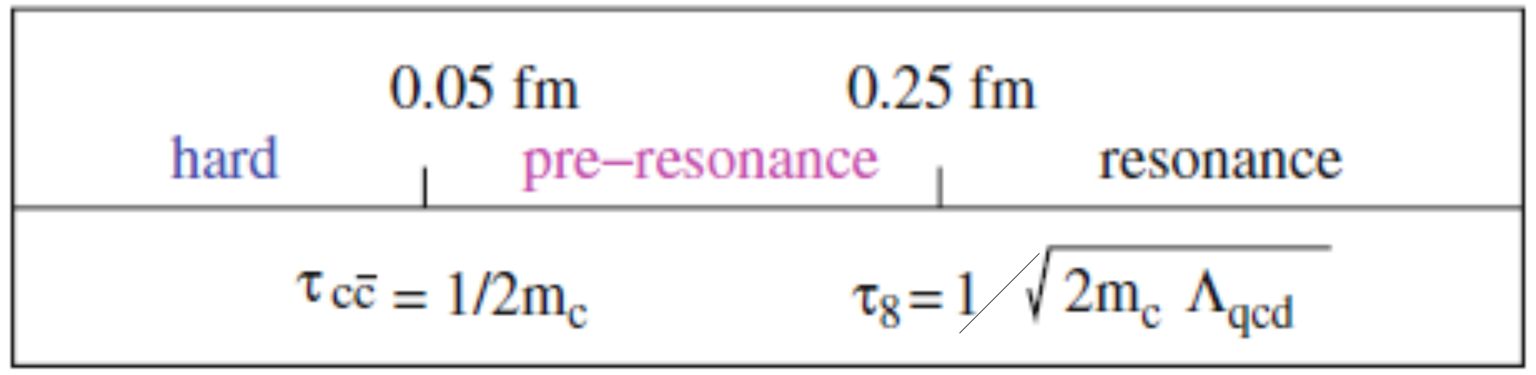
- Charm and beauty quarks are produced in early hard scattering processes
  - Formation time $\tau_{c\bar{c}} = 1/2m_c = 0.05\text{fm}$
  - non-relativistic; pQCD

- Formation of quarkonia requires transition to a color singlet state
  - Still only moderately successful
  - Not pure pQCD anymore, some modelling required
    - CEM Color Evaporation Model
    - CSM Color Singlet Model
    - Color Octet Model

  - Colour neutralisation time with lowest *p*
    - Compare to QGP lifetime $\tau_8 = 1/\sqrt{2m_c\Lambda_{qcd}}$

      → No J/ψ suppression at high p_T ?





	crossing time $2R/\gamma c$	QGP life time	Freeze-out time
SPS	1.5 fm/*c*	< 2 fm/*c*	10 fm/*c*
RHIC	0.13 fm/*c*	2-4 fm/*c*	20-30 fm/*c*
LHC	0.006 fm/*c*	> 10 fm/*c*	30-40 fm/*c*

Quarkonium decays

J/ψ (quarkonium) can be studied through its decays: (B.R. ~6%)

$J/\psi \rightarrow \mu^+\mu^-$

$J/\psi \rightarrow e^+e^-$

$c\bar{c}$ MESONS

$J/\psi(1S)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 3096.916 \pm 0.011$ MeV
Full width $\Gamma = 92.9 \pm 2.8$ keV (S = 1.1)
$\Gamma_{ee} = 5.55 \pm 0.14 \pm 0.02$ keV

$J/\psi(1S)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
hadrons	(87.7 ±0.5) %		–
virtual $\gamma \rightarrow$ hadrons	(13.50 ±0.30) %		–
$g g g$	(64.1 ±1.0) %		–
$\gamma g g$	(8.8 ±0.5) %		–
e^+e^-	(5.94 ±0.06) %		1548
$\mu^+\mu^-$	(5.93 ±0.06) %		1545

$\psi(2S)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 3686.09 \pm 0.04$ MeV (S = 1.6)
Full width $\Gamma = 304 \pm 9$ keV
$\Gamma_{ee} = 2.35 \pm 0.04$ keV

$\psi(2S)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
hadrons	(97.85±0.13) %		–
virtual $\gamma \rightarrow$ hadrons	(1.73±0.14) %	S=1.5	–
$g g g$	(10.6 ±1.6) %		–
$\gamma g g$	(1.02±0.29) %		–
light hadrons	(15.4 ±1.5) %		–
e^+e^-	(7.72±0.17) $\times 10^{-3}$		1843
$\mu^+\mu^-$	(7.7 ±0.8) $\times 10^{-3}$		1840
$\tau^+\tau^-$	(3.0 ±0.4) $\times 10^{-3}$		490

$b\bar{b}$ MESONS

$\Upsilon(1S)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 9460.30 \pm 0.26$ MeV (S = 3.3)
Full width $\Gamma = 54.02 \pm 1.25$ keV
$\Gamma_{ee} = 1.340 \pm 0.018$ keV

$\Upsilon(1S)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\tau^+\tau^-$	(2.60±0.10) %		4384
e^+e^-	(2.48±0.07) %		4730
$\mu^+\mu^-$	(2.48±0.05) %		4729

$\Upsilon(2S)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 10.02326 \pm 0.00031$ GeV
Full width $\Gamma = 31.98 \pm 2.63$ keV
$\Gamma_{ee} = 0.612 \pm 0.011$ keV

$\Upsilon(2S)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\Upsilon(1S)\pi^+\pi^-$	(18.1 ± 0.4) %		475
$\Upsilon(1S)\pi^0\pi^0$	(8.6 ± 0.4) %		480
$\tau^+\tau^-$	(2.00± 0.21) %		4686
$\mu^+\mu^-$	(1.93± 0.17) %	S=2.2	5011
e^+e^-	(1.91± 0.16) %		5012

$\Upsilon(3S)$

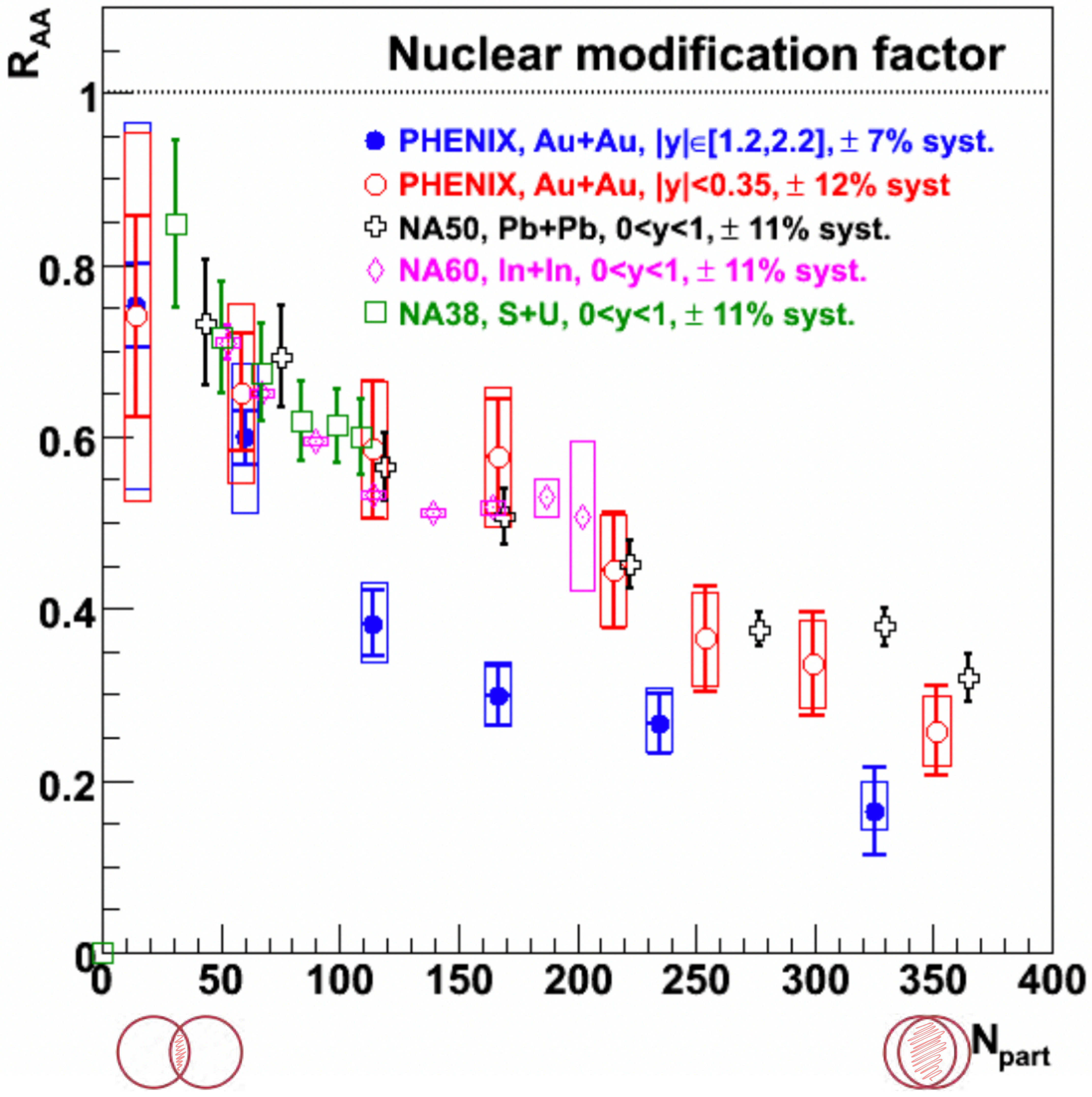
$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 10.3552 \pm 0.0005$ GeV
Full width $\Gamma = 20.32 \pm 1.85$ keV
$\Gamma_{ee} = 0.443 \pm 0.008$ keV

$\Upsilon(3S)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\Upsilon(2S)$ anything	(10.6 ±0.8) %		296
$\tau^+\tau^-$	(2.29±0.30) %		4863
$\mu^+\mu^-$	(2.18±0.21) %	S=2.1	5177
e^+e^-	seen		5178

J/ψ suppression at the CERN SPS and at RHIC

- Same suppression at midrapidity at the CERN SPS and at RHIC, in spite of larger energy density at RHIC
- RHIC: suppression large at forward rapidity, in spite of larger energy density at midrapidity
- Not easy to explain in pure dissociation picture



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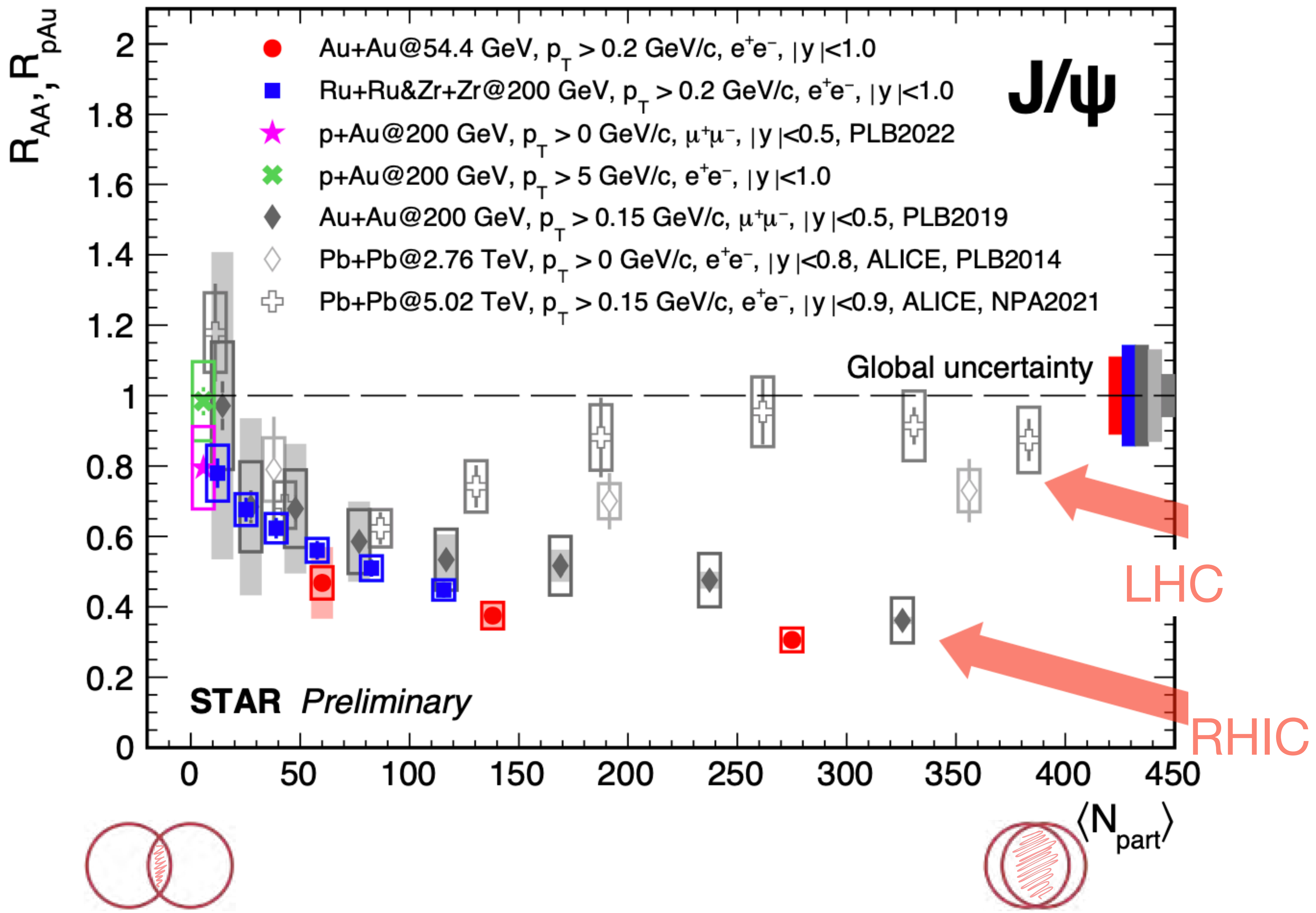
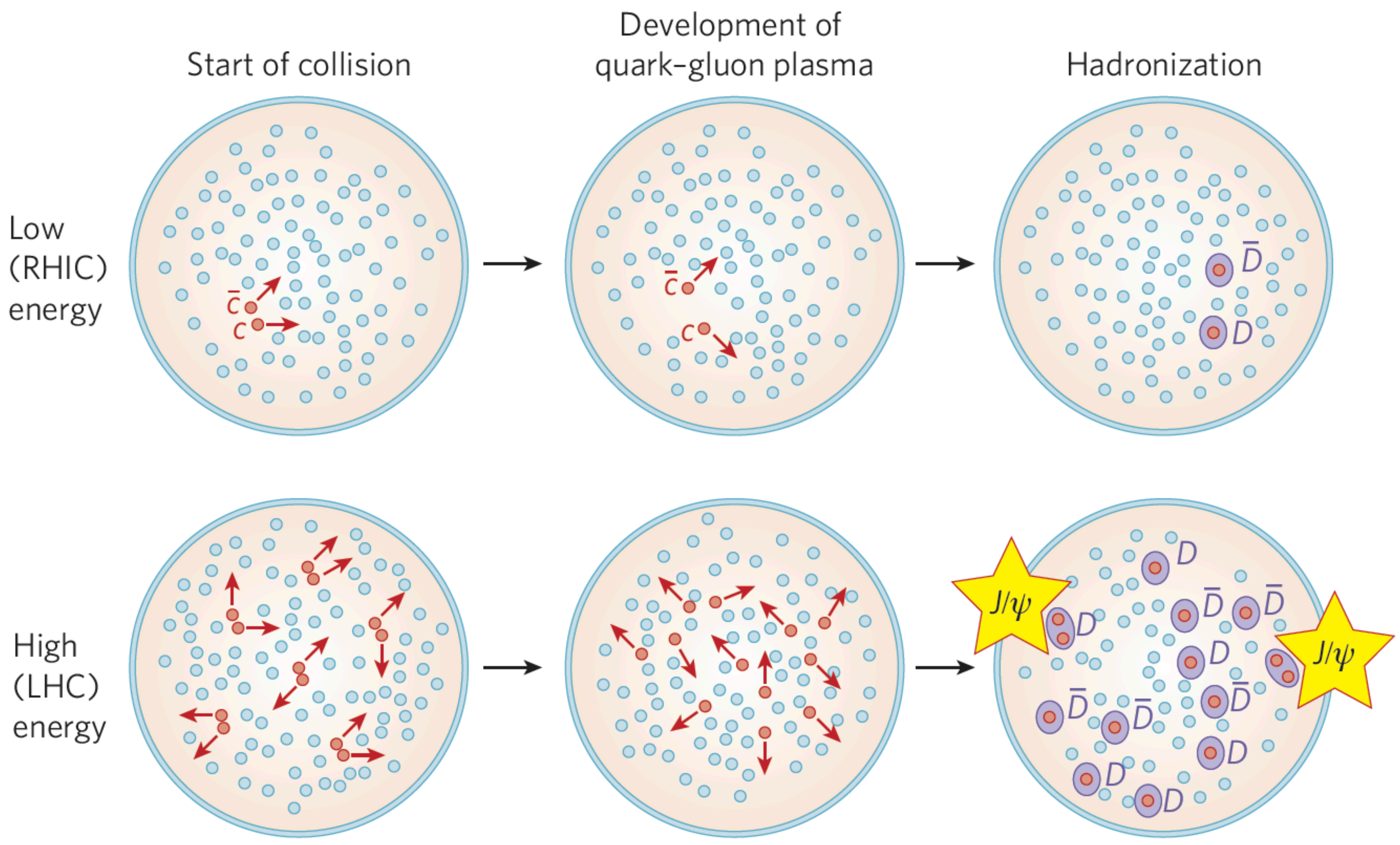
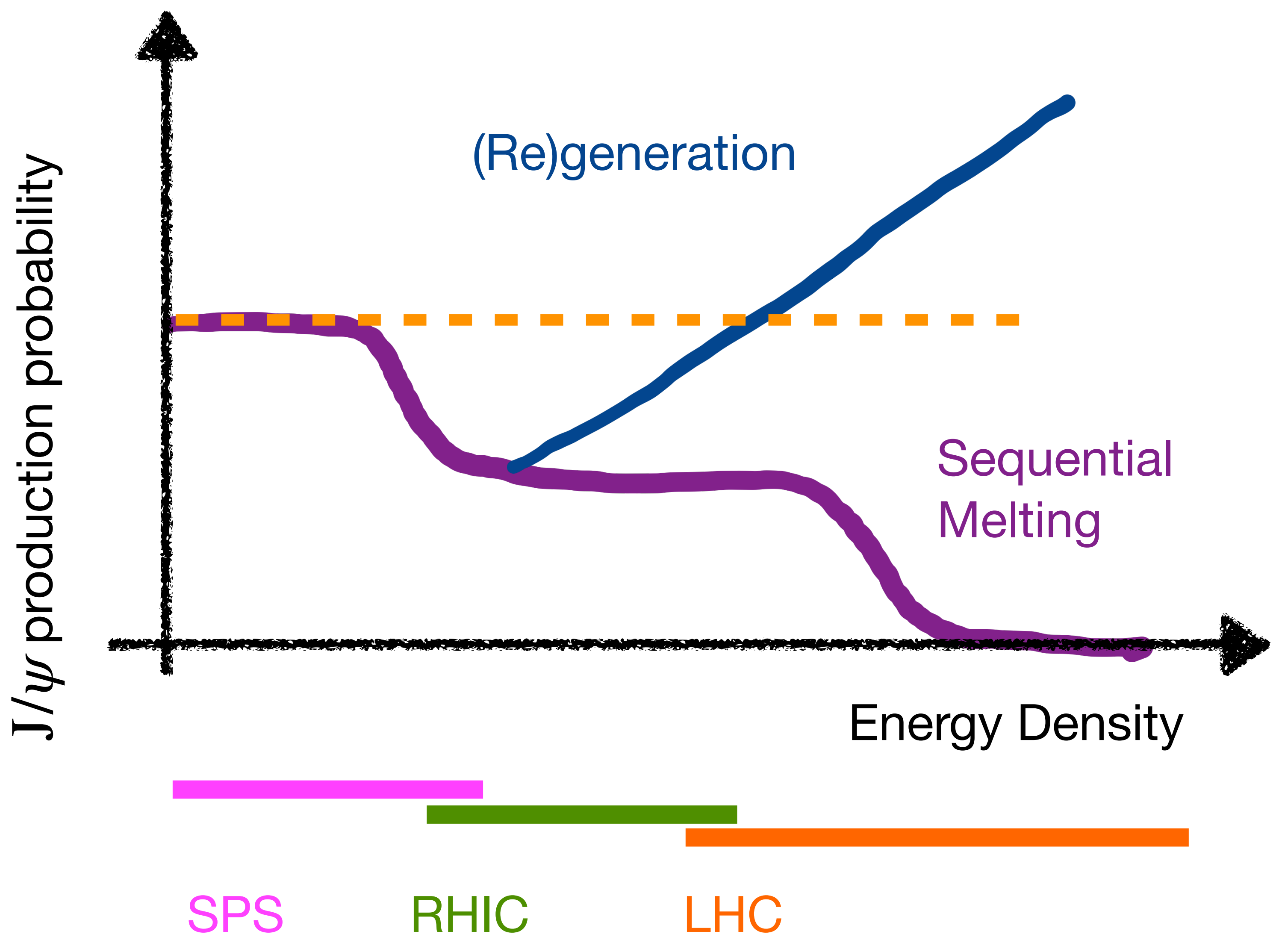


New idea - (re)combination

Braun-Munzinger, Stachel, PLB 490 (2000) 196; NPA 789 (2006) 334, PLB 652 (2007) 259



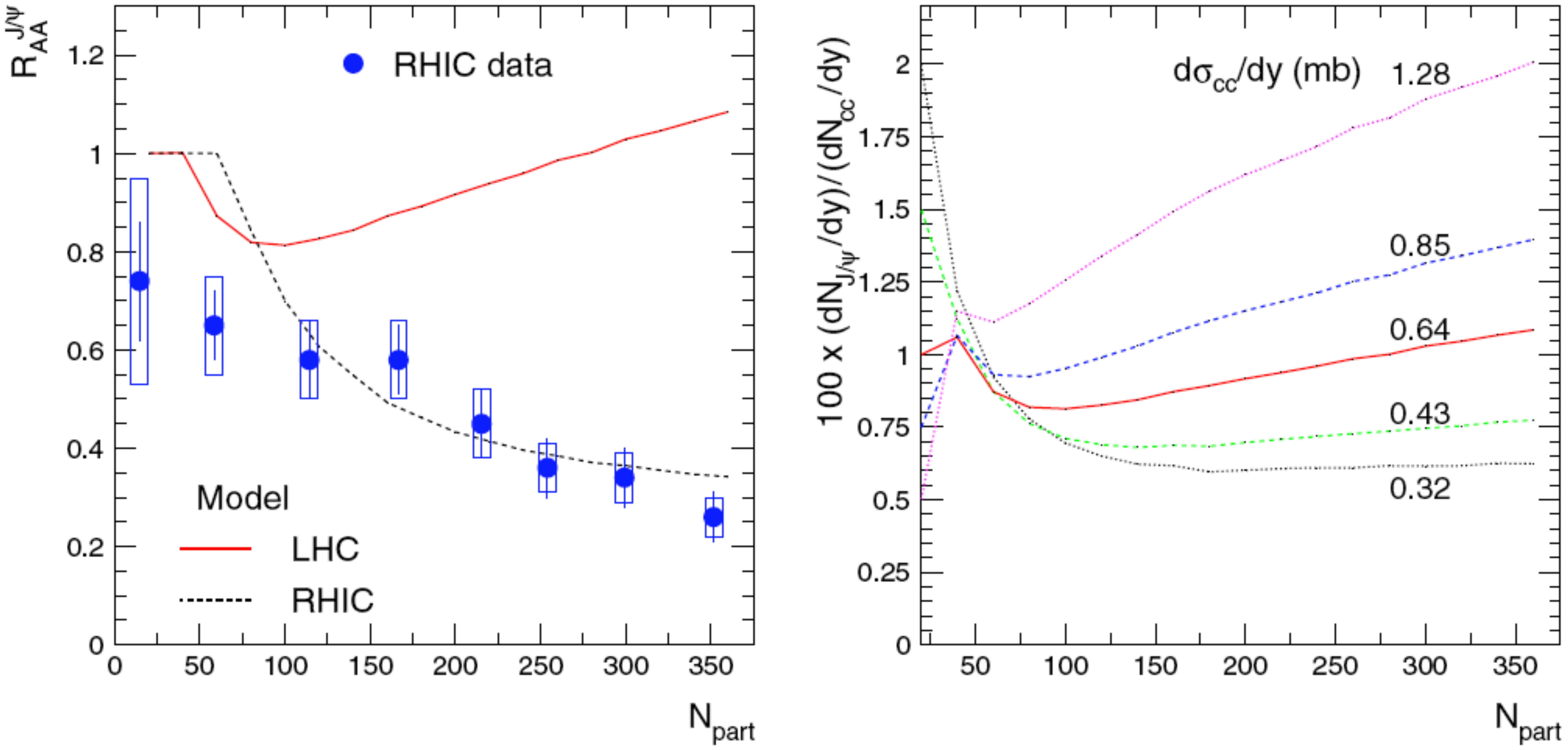
$$\mathrm{N}_{J/\psi} \sim \left(N_{c\bar{c}}^{dir}\right)^2$$



- QGP screens all charmonia, but charmonium production takes place at the phase boundary
  → Enhanced production at high energy → Signal for deconfinement

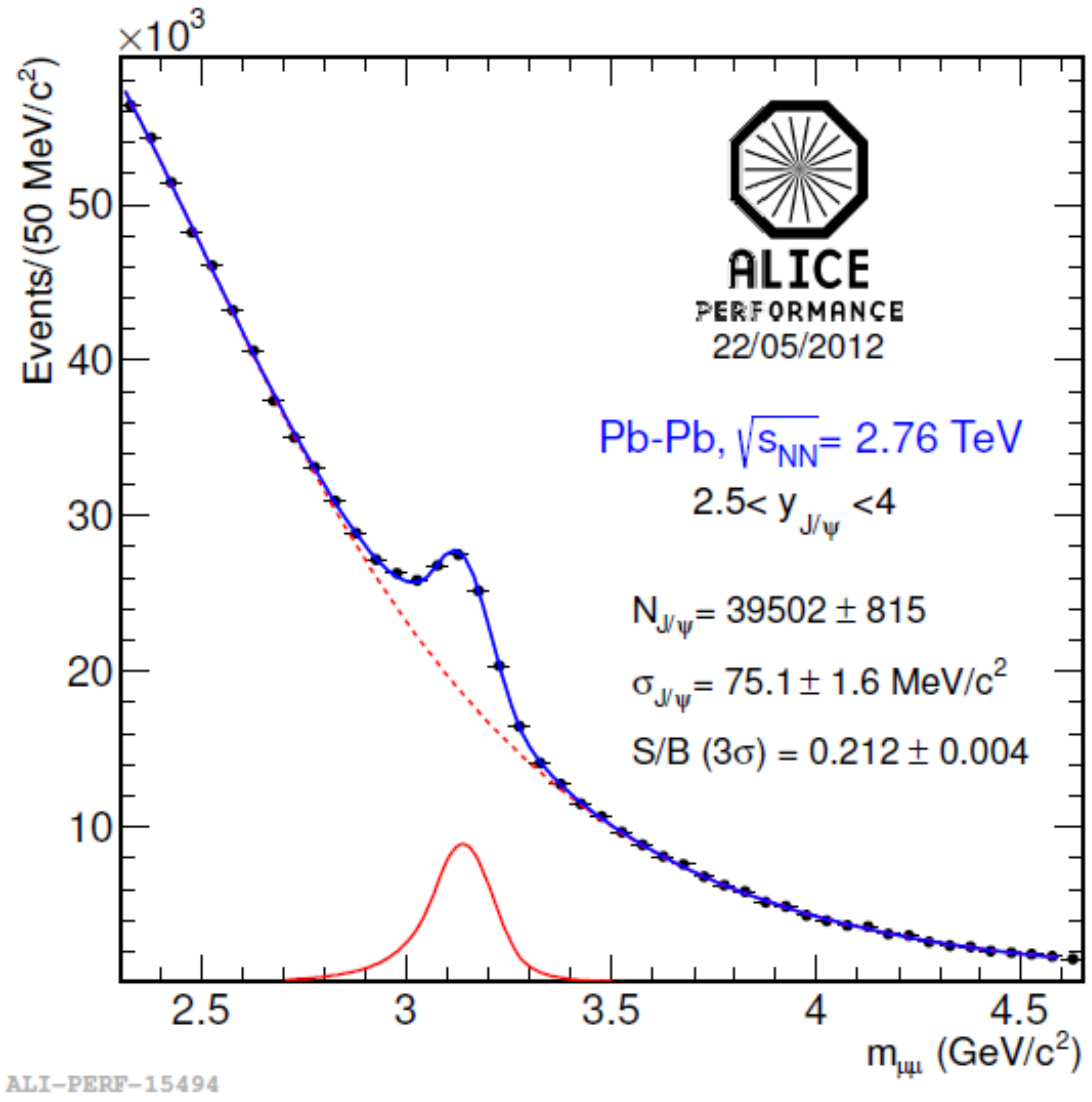
LHC Prediction
Statistical Model

Braun-Munzinger, Stachel, PLB 490 (2000) 196;
NPA 789 (2006) 334, PLB 652 (2007) 259

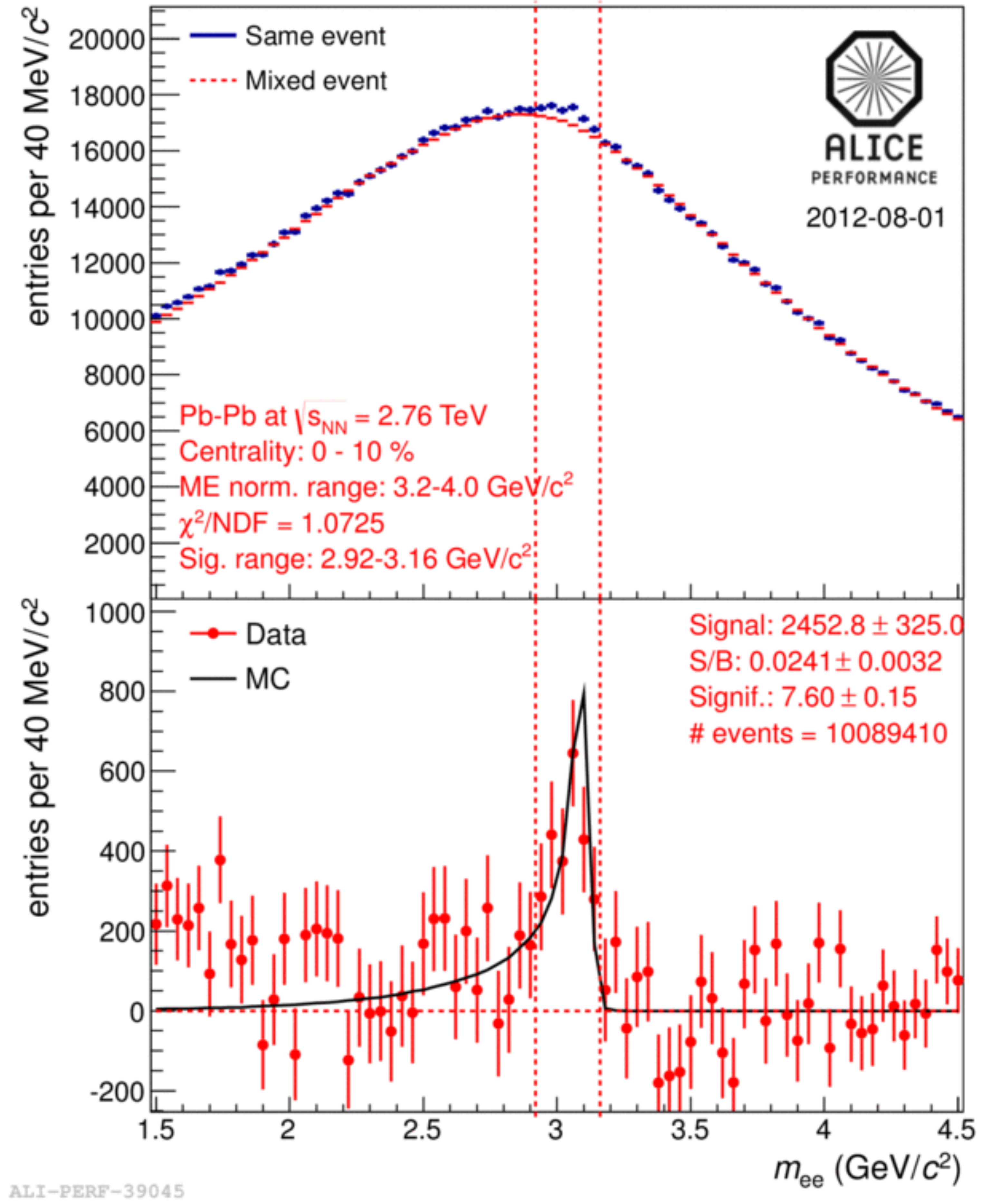


- If regeneration takes place it will be even larger at LHC -> J/ψ enhancement becomes a signature for the QGP
- Total charm cross section crucial reference
- Bottomonium states become the new tool for studying medium effects on bound quarkonium states
  - More tightly bound, less beauty pairs produced initially, less recombination

ALICE, focus on low-p_T J/ψ



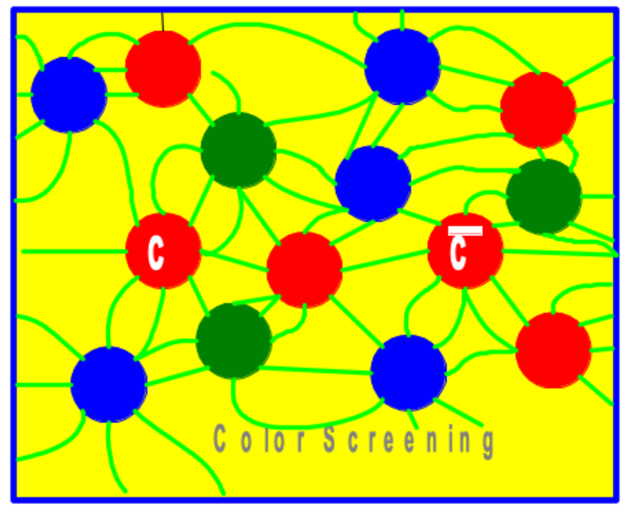
Muon analysis:
- fit to the invariant mass spectra
- signal extraction by integrating the Crystal Ball line shape

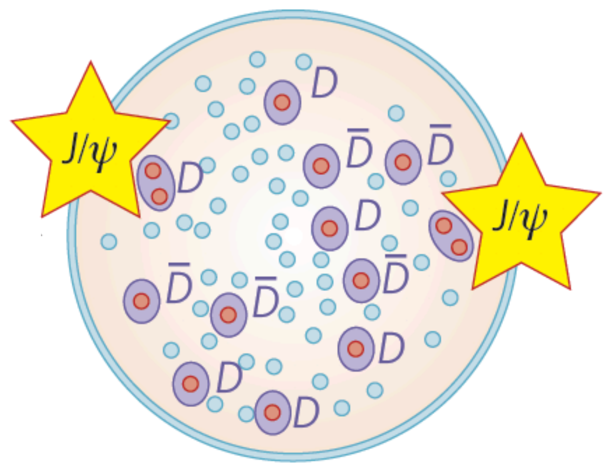


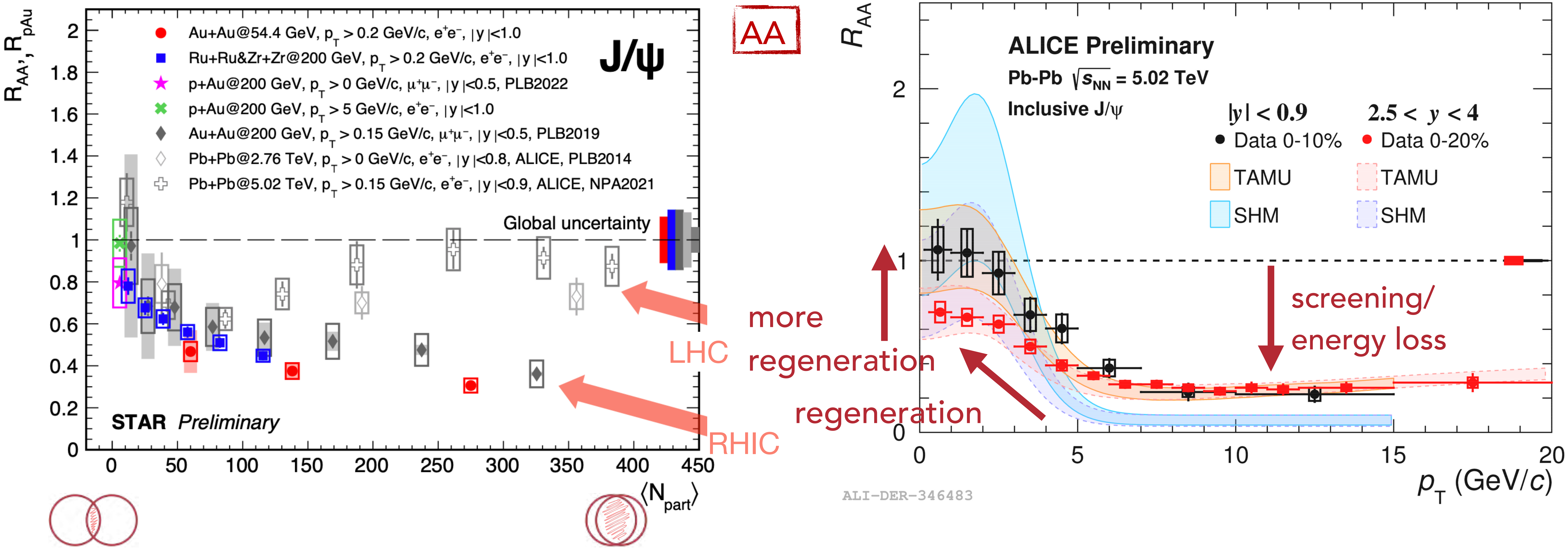
$J/\psi \rightarrow e^+ + e^-$

Electron analysis:
- Background subtracted with event mixing
  - Signal extraction by counting

Quarkonia: J/ψ





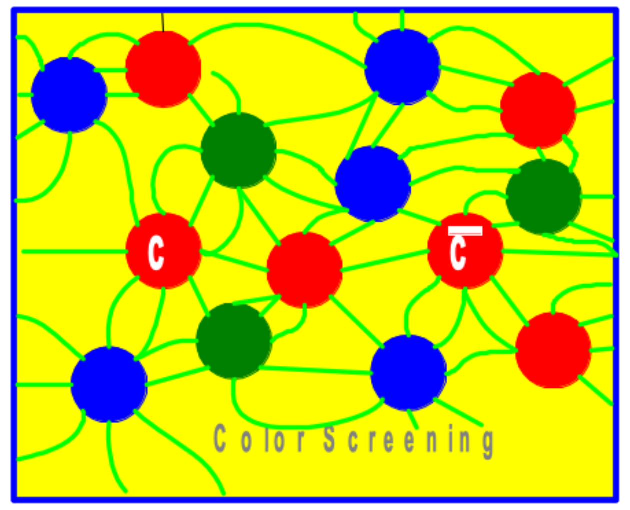


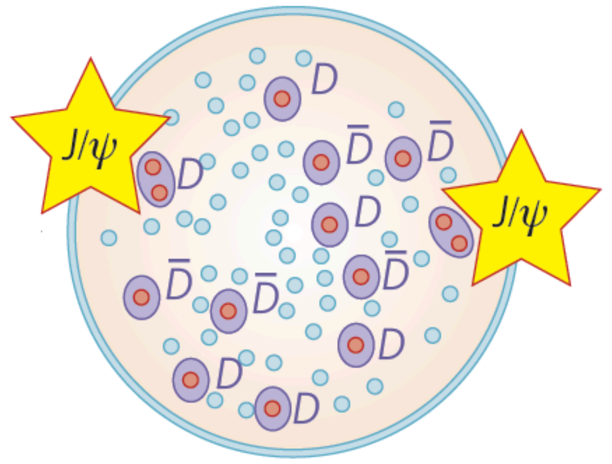
- Quarkonium production mechanism
  - Suppression due to colour screening
  - Production via (re)generation during QGP phase/at hadronisation

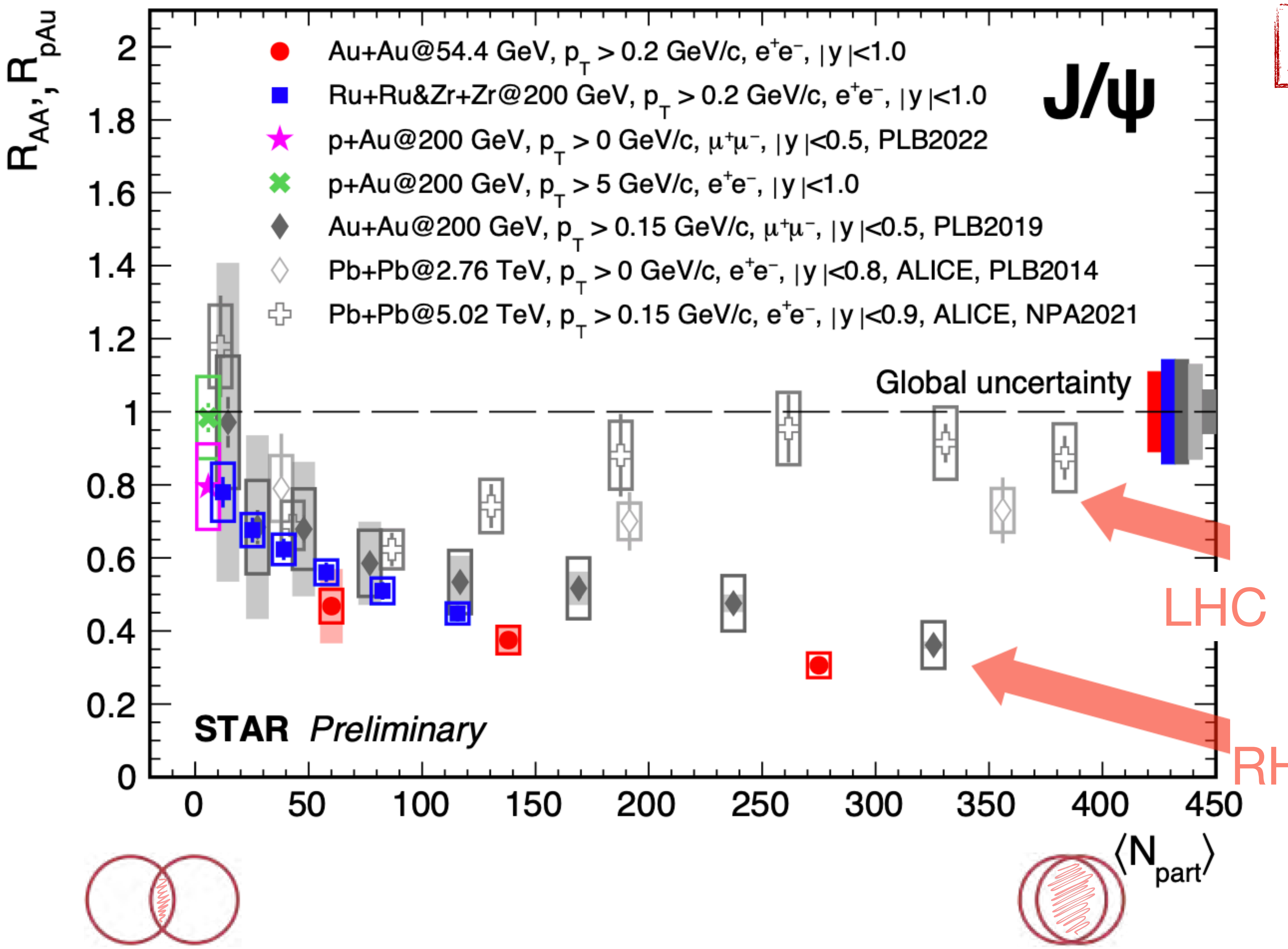
T. Matsui and H. Satz,PLB178(1986)416, P. Braun-Munzinger and J. Stachel,PLB490(2000)196, L.Grandchamp and R.Rapp, PLB523(2001)60

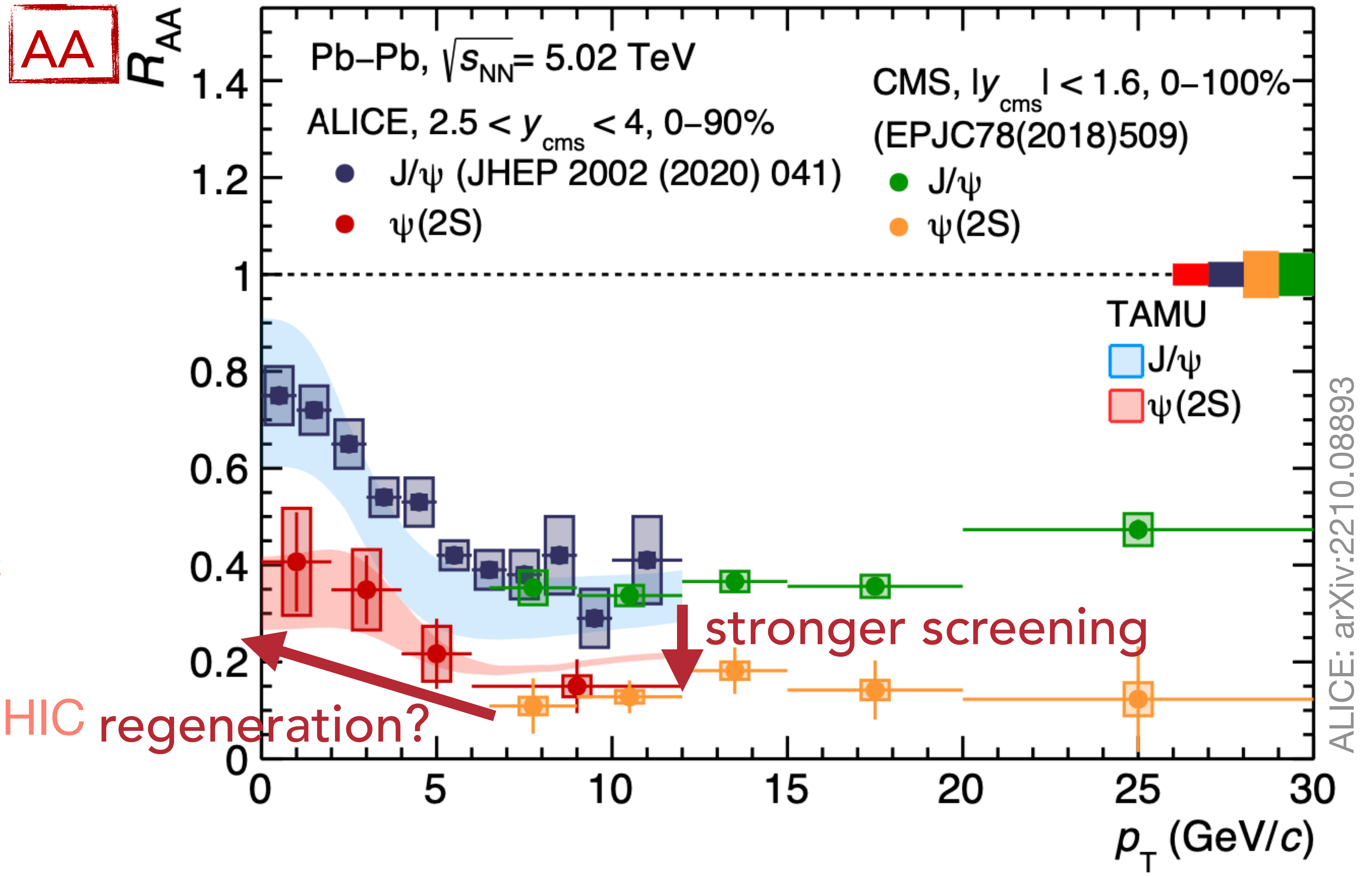
→ Suppression at RHIC energies scales with $< N_{part} >$
→ No suppression at LHC full energy
→ (Re)generation scenario dominates at low p_T

Quarkonia: J/ψ and $\psi(2S)$









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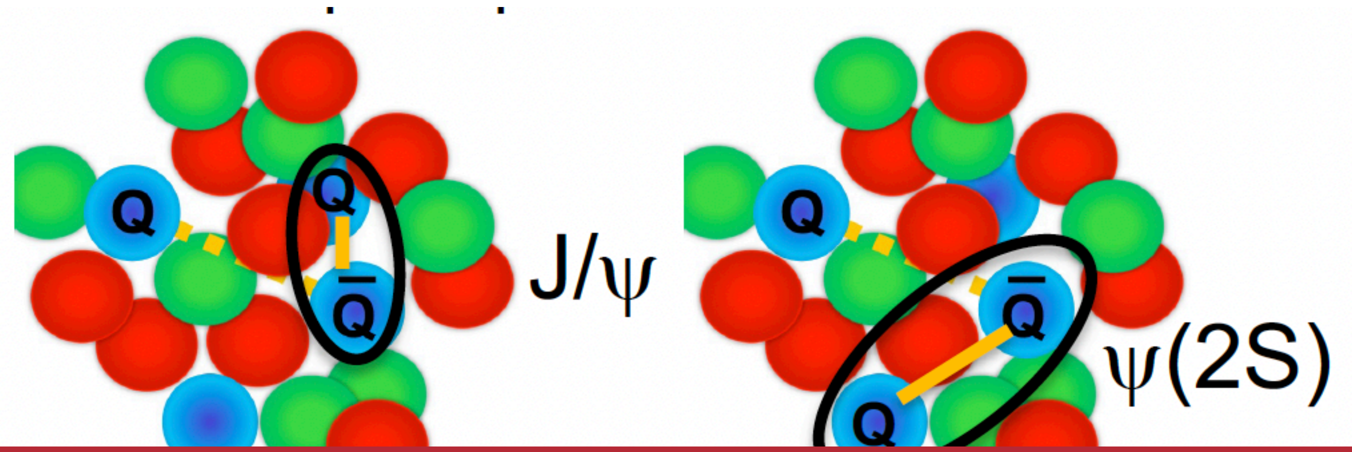

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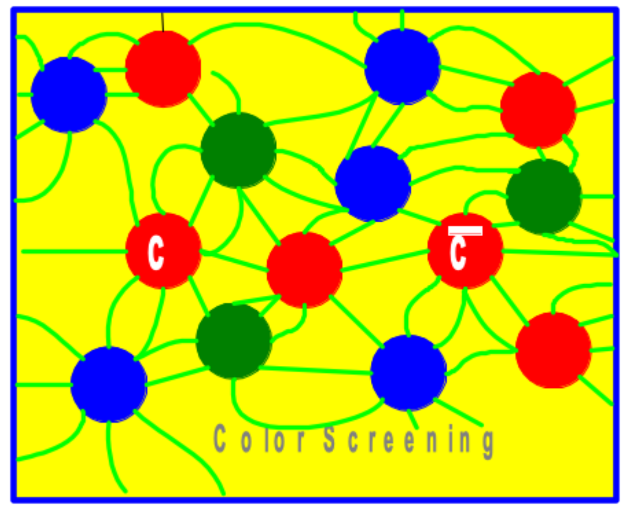
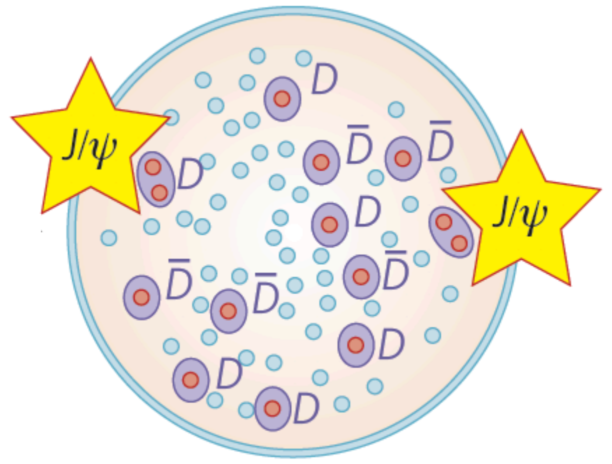
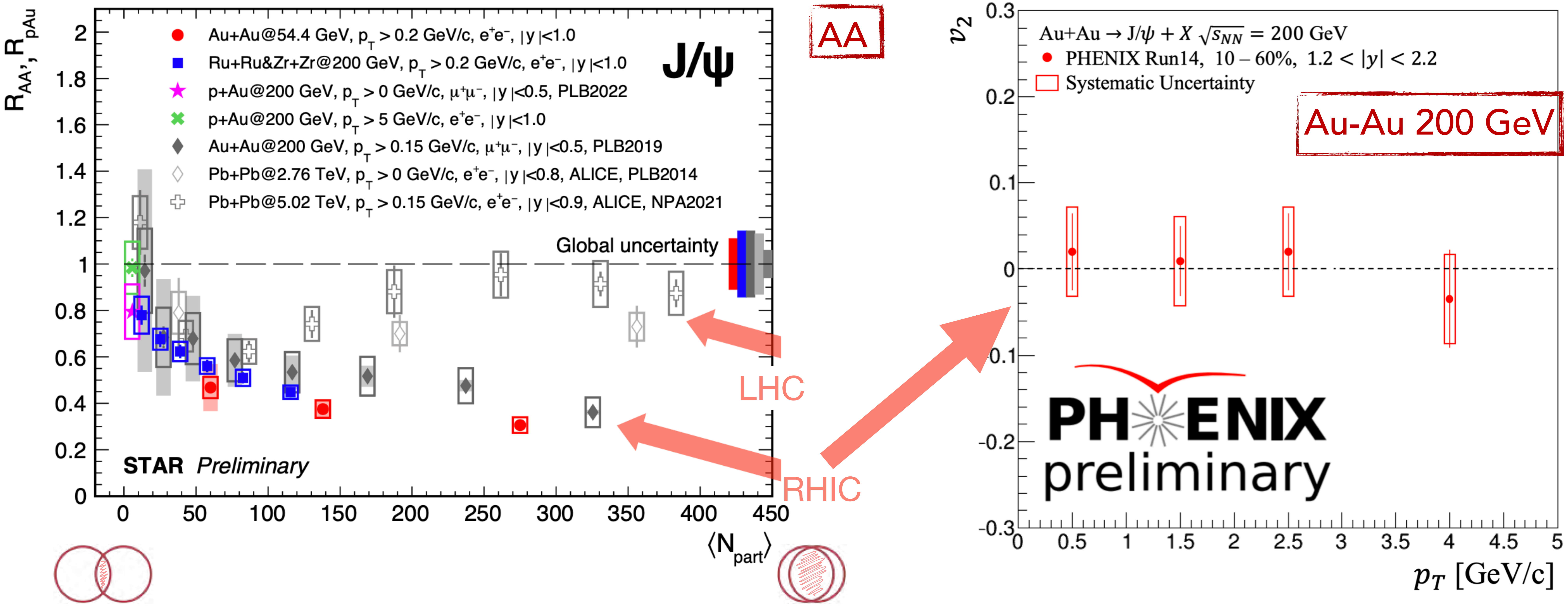
Quarkonia: J/ψ flow







- Quarkonium production mechanism
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  - Production via (re)generation during QGP phase/at hadronisation

→ J/ψ flow consistent with zero at RHIC

T. Matsui and H. Satz,PLB178(1986)416, P. Braun-Munzinger and J. Stachel,PLB490(2000)196, L.Grandchamp and R.Rapp, PLB523(2001)60

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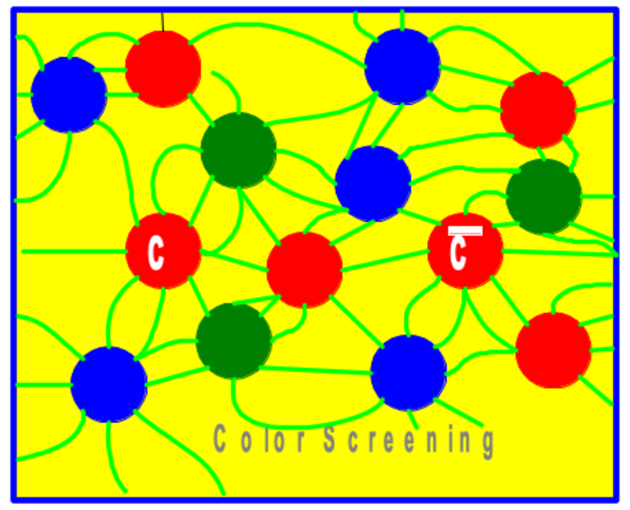

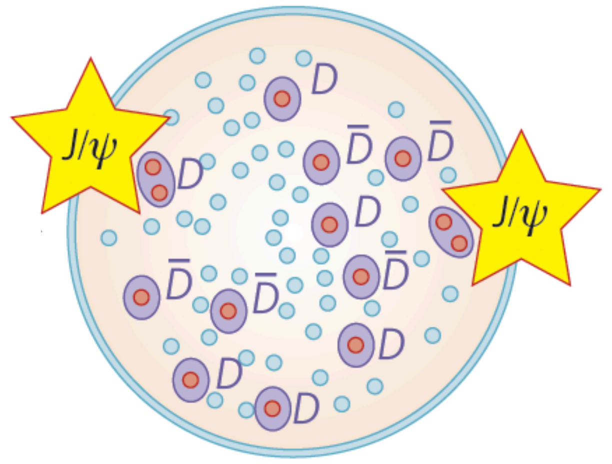

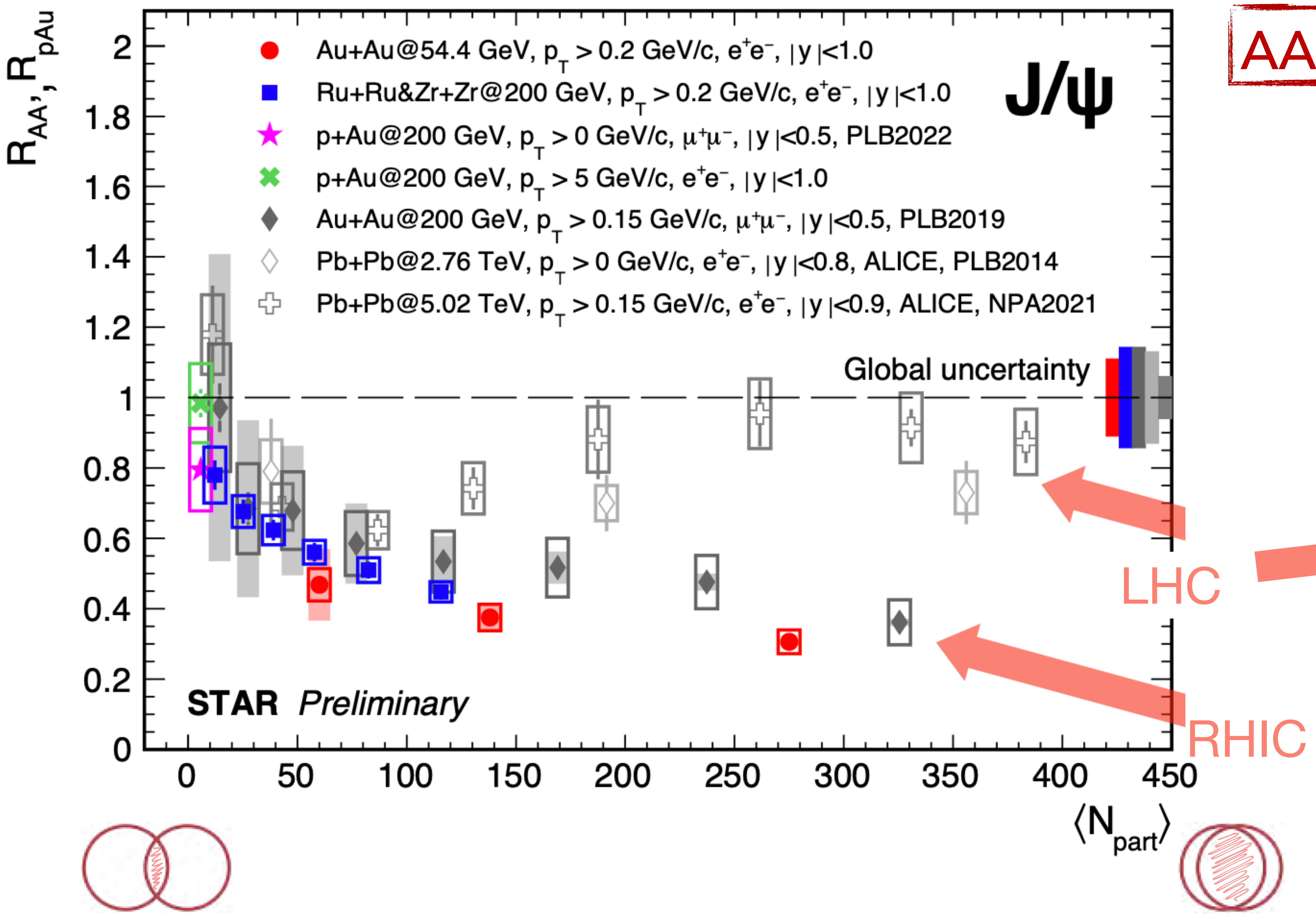

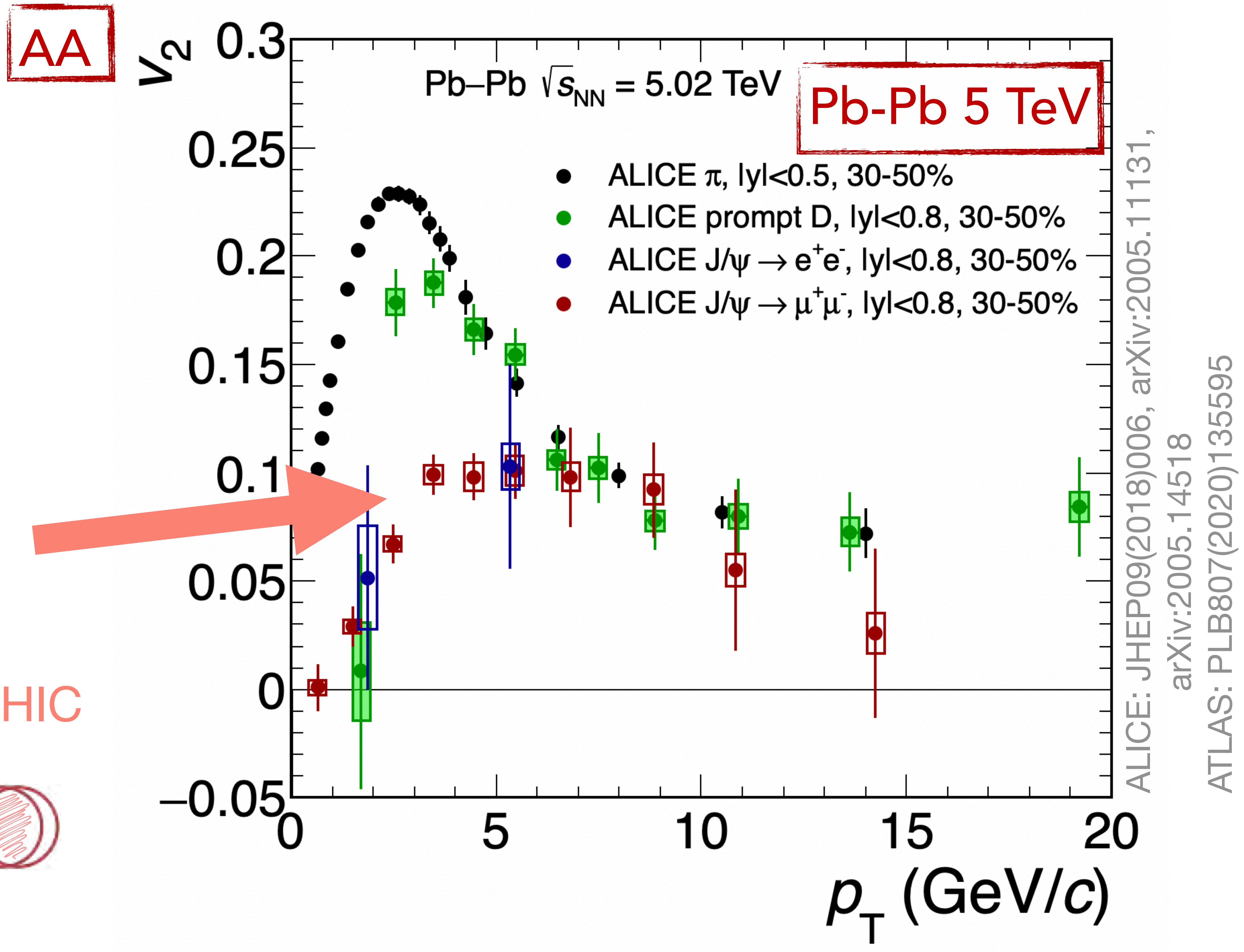

- Quarkonium production mechanism
  - Suppression due to colour screening
  - Production via (re)generation during QGP phase/at hadronisation

→ J/ψ flow consistent with zero at RHIC
→ J/ψ flows at LHC
→ Signature of deconfinement

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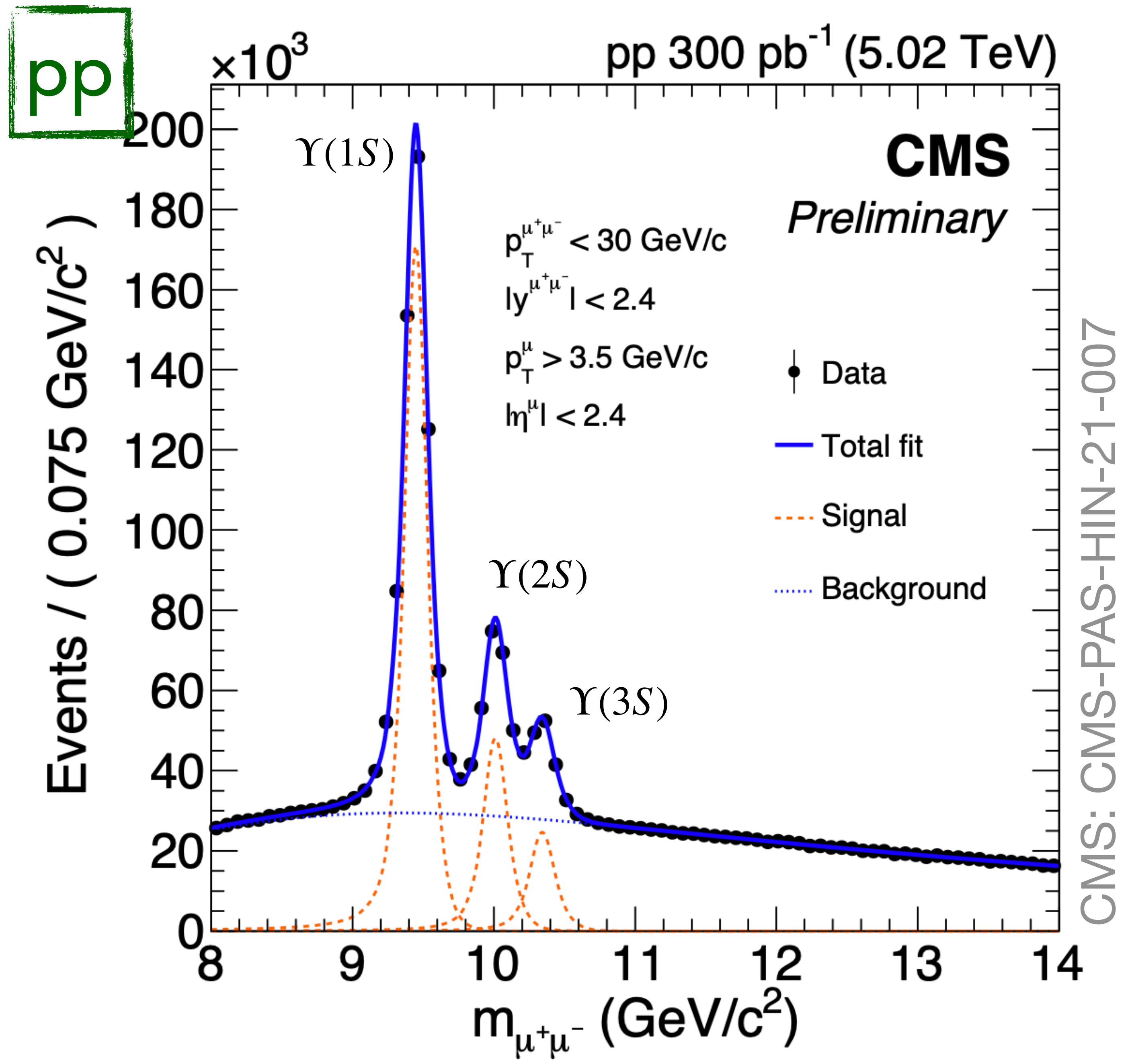
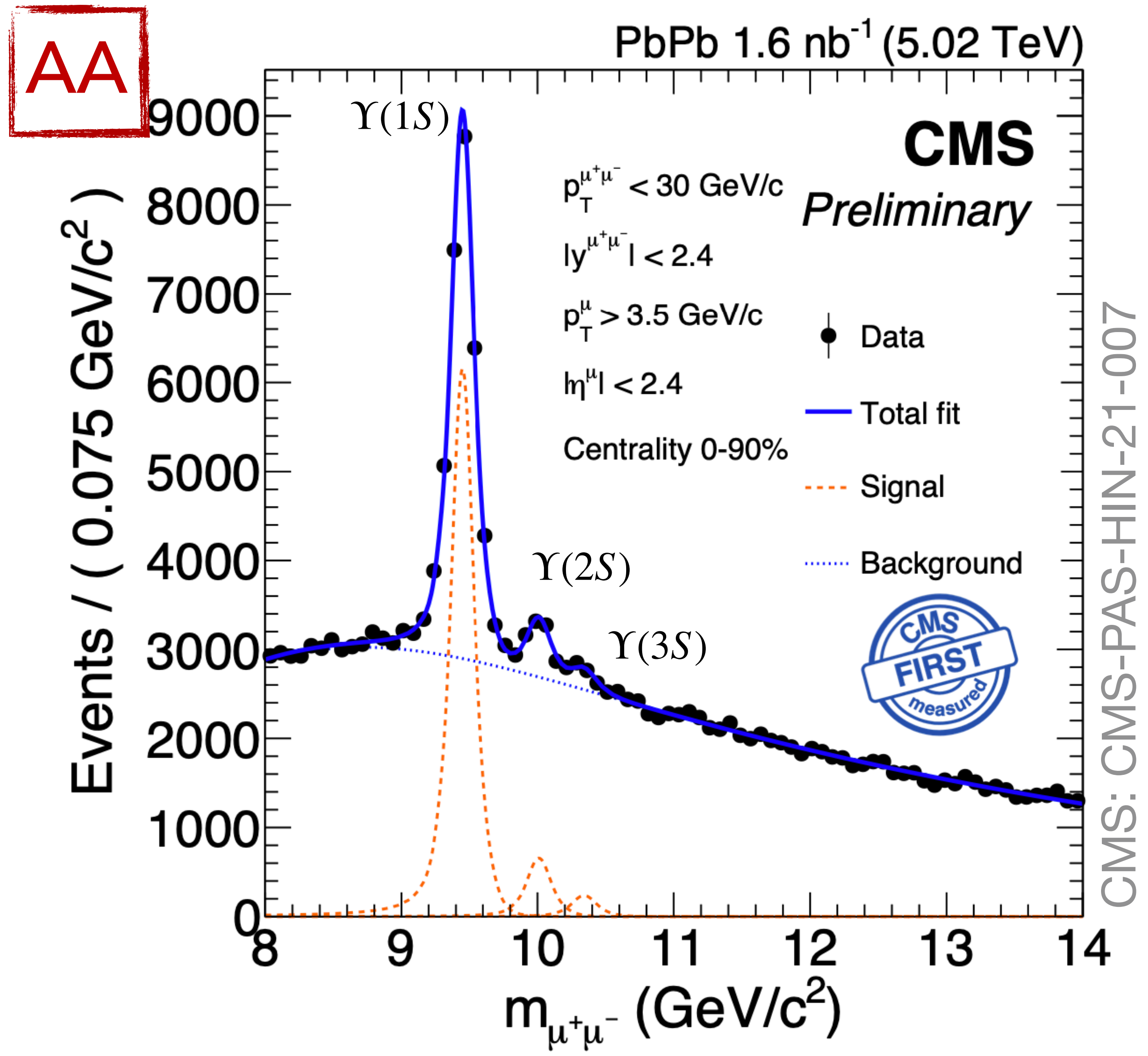
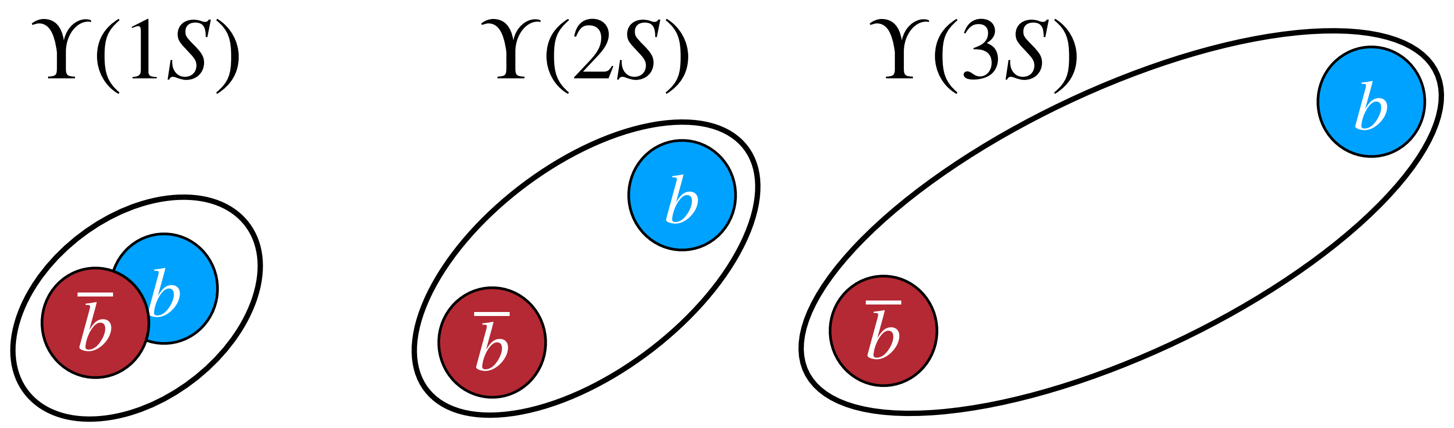
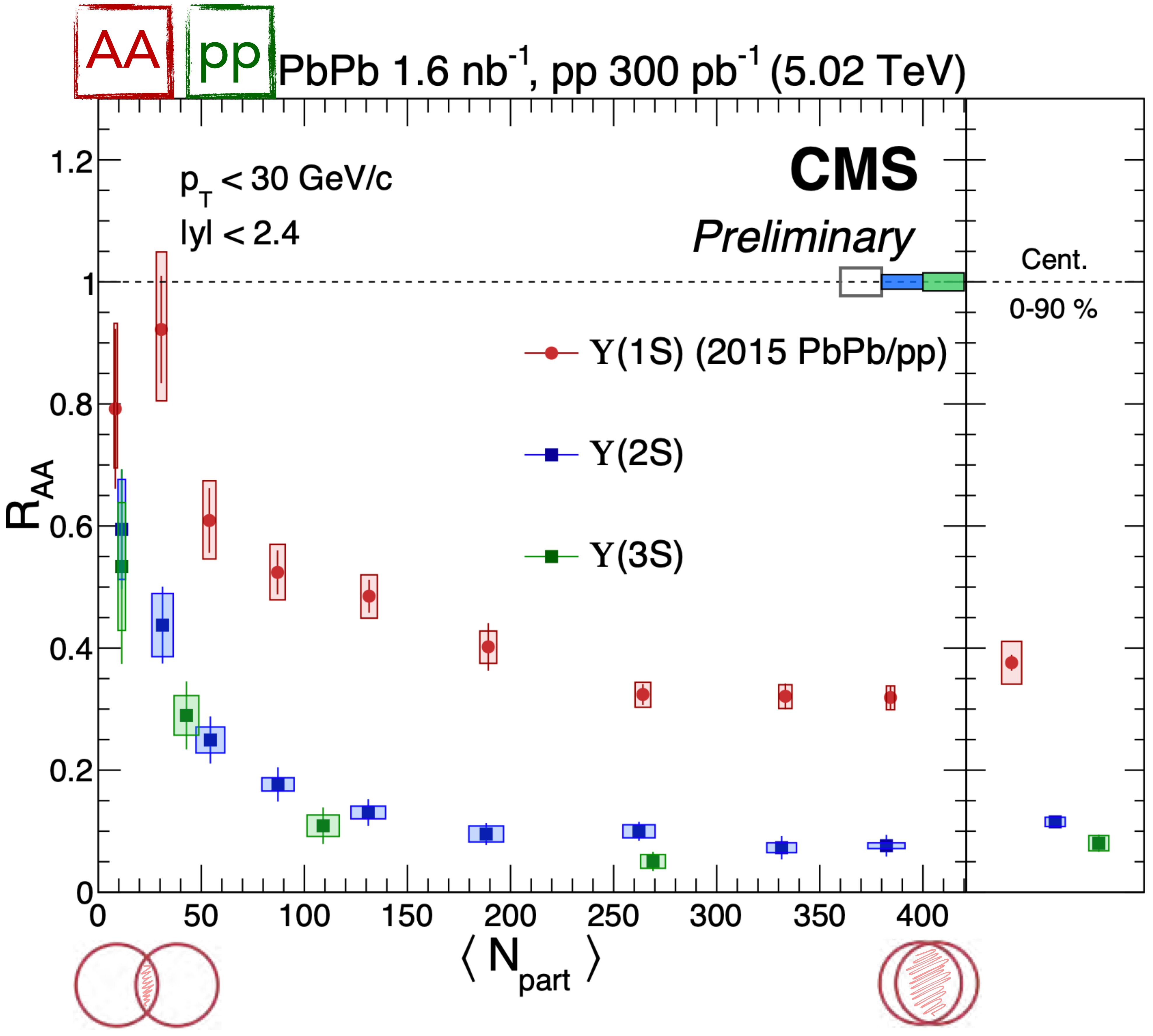
Quarkonia: Bottomonium Family









$R_{AA}(1S) > R_{AA}(2S) > R_{AA}(3S)$

→ Suppression mechanism dominates for bottomonium family

Summary: Quarkonium

- J/ψ suppression proposed in 1986 as "unambiguous" QPG signal

- Two main mechanisms at play
  - Suppression in a deconfined medium
  - Re-generation (for charmonium only!) at high $\sqrt{s}$

  can qualitatively explain the main features of the results

- Crucial input needed: Total charm cross section

- Does the melting scenario hold for **ϒ** production at the LHC?
  - Can yields of **ϒ** states serve as a QGP thermometer?

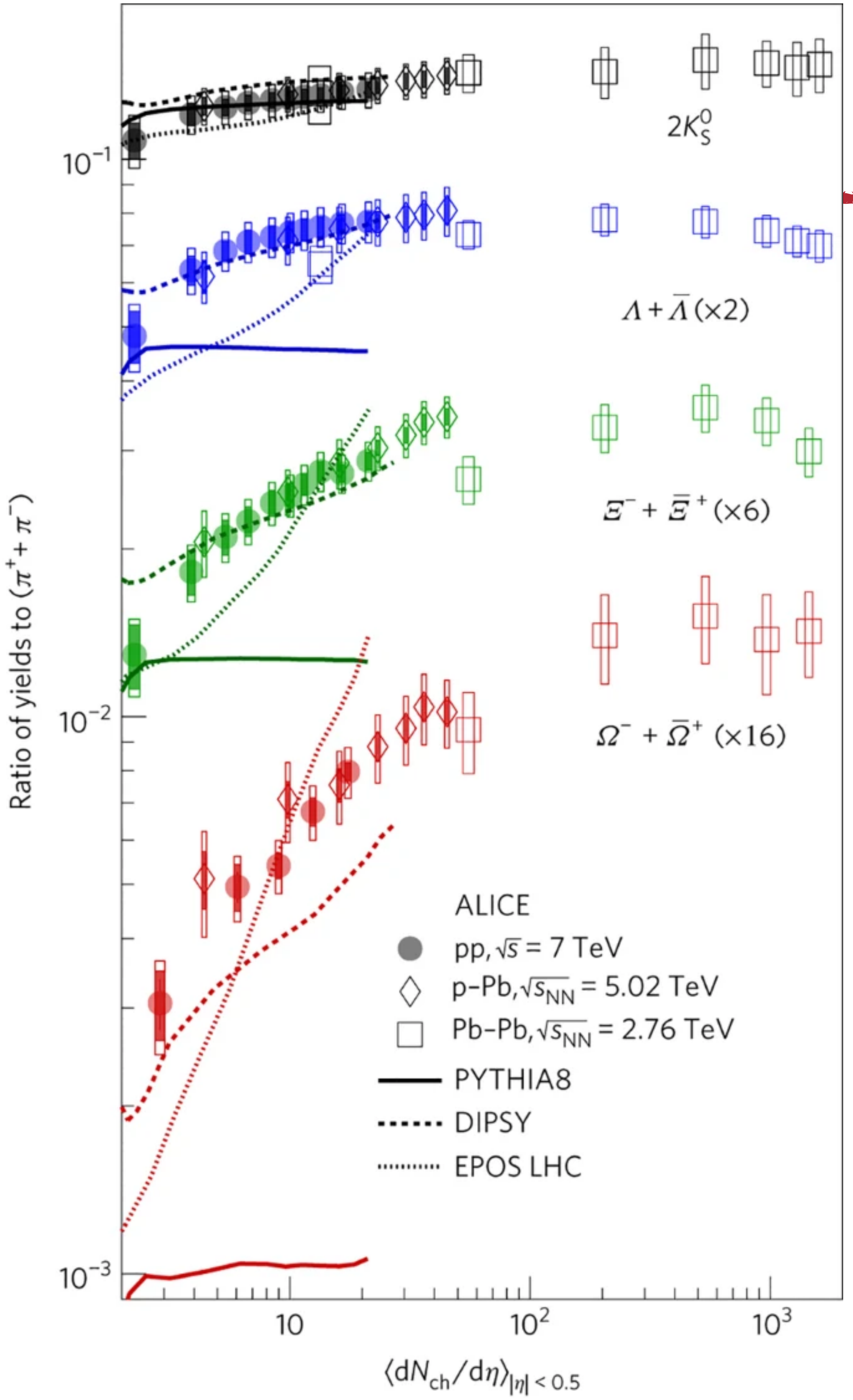

ALICE
Run number: 529397
First TF orbit: 5589120
Date: Fri Nov 18 16:57:27 2022
Detectors: ITS,TPC,TRD,TOF,PHS,EMC,MFT,MCH,MID

Small systems

- What about high-multiplicity pp and p-Pb collisions?

Particle chemistry across system size

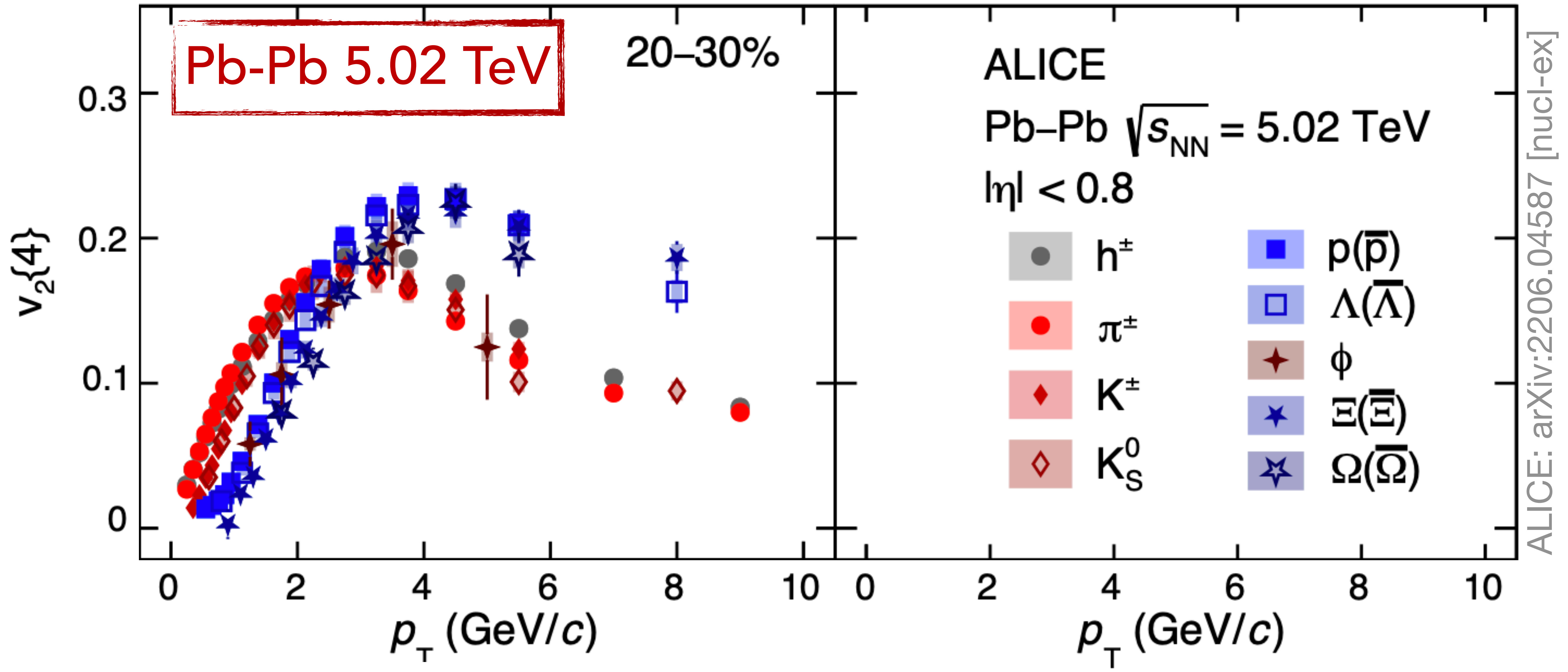
- Enhancement increases with strangeness content
- Smooth evolution of particle chemistry from small to large systems as function of charged particle multiplicity
  - → common origin in all systems?
  - increasing strangeness production with increasing multiplicity until saturation (grand-canonical plateau) is reached → lifting of strangeness suppression in pp collisions

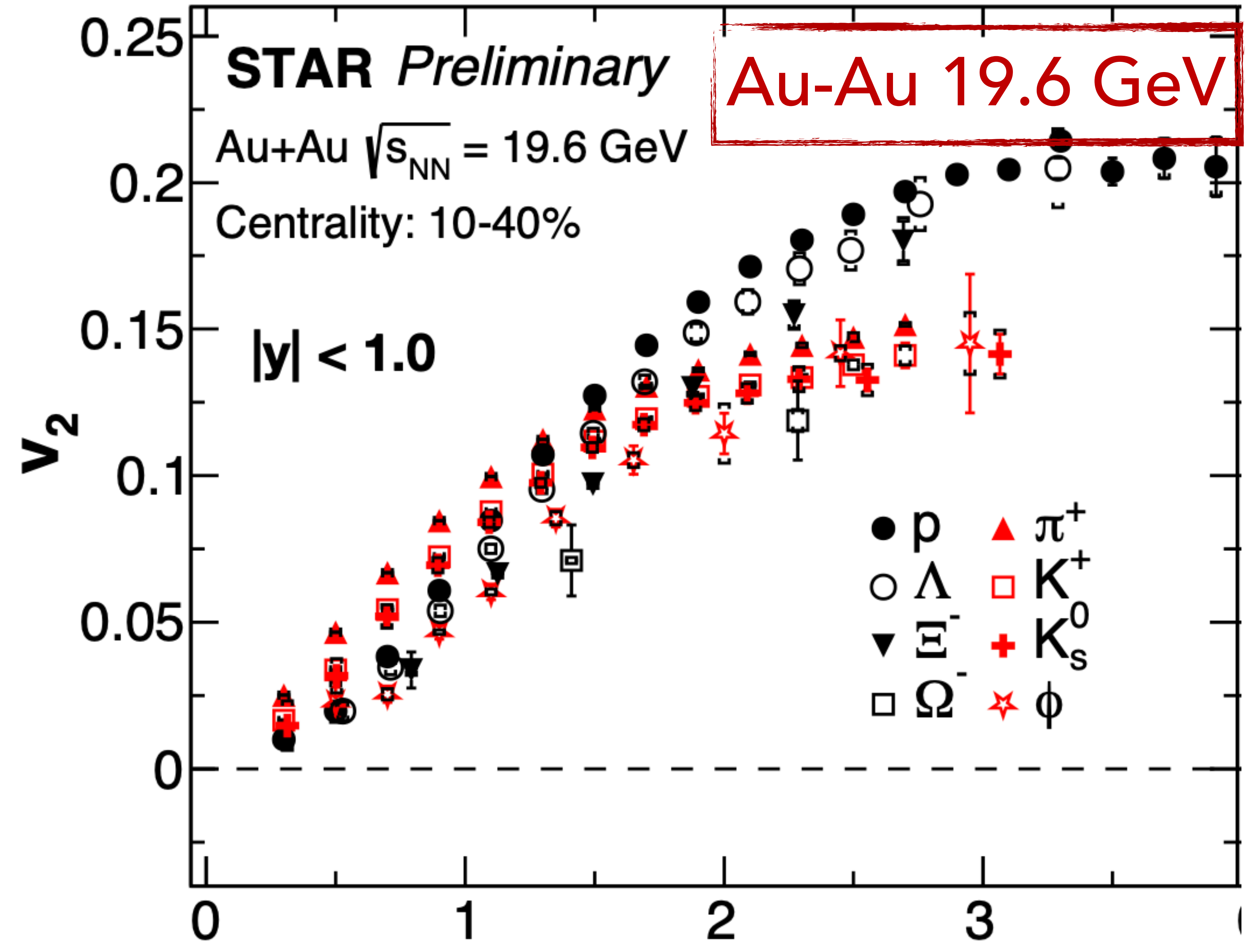


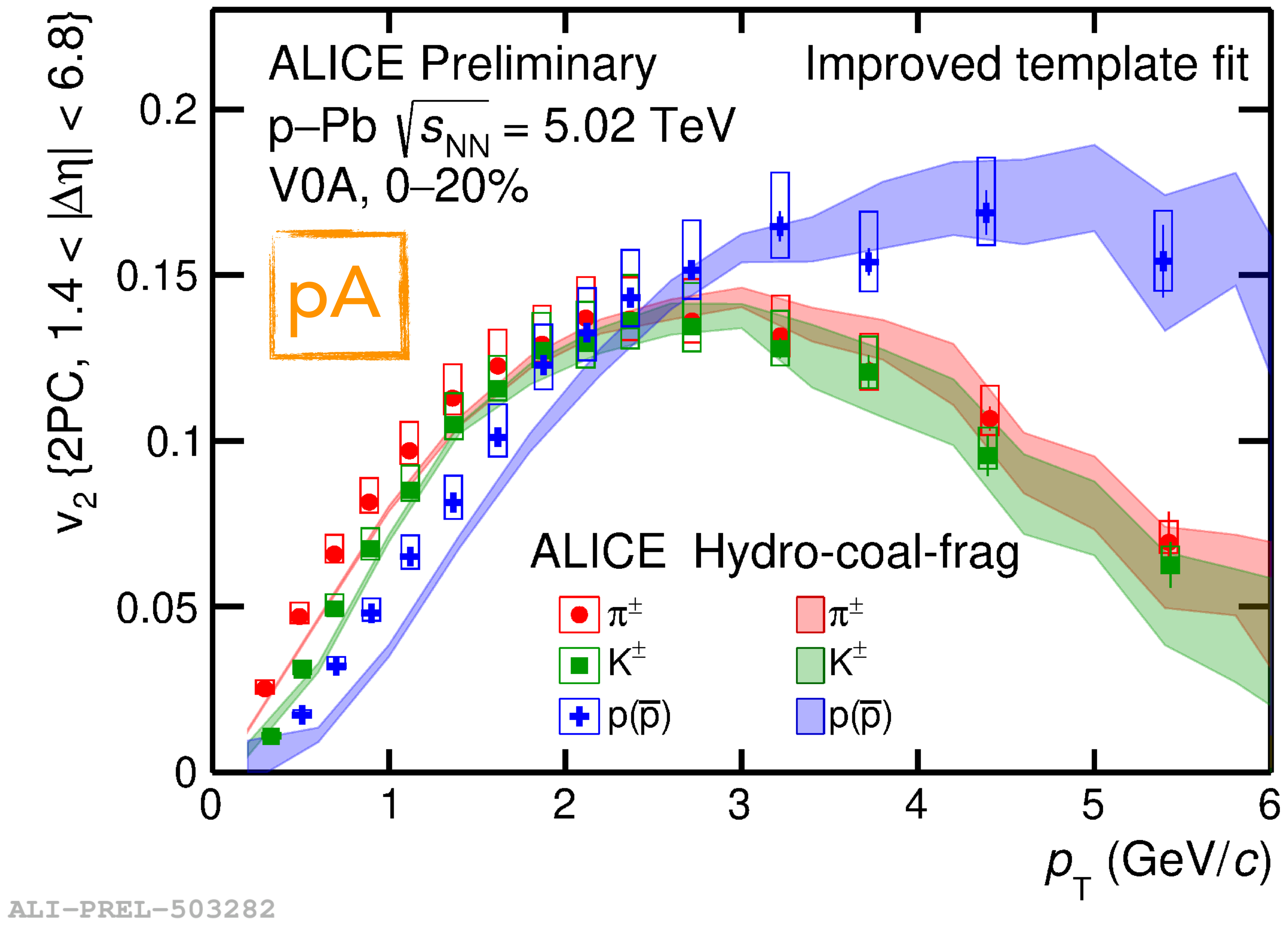
ALICE Collaboration, Nature Physics 13 (2017) 535

Collective effects

Elliptic flow



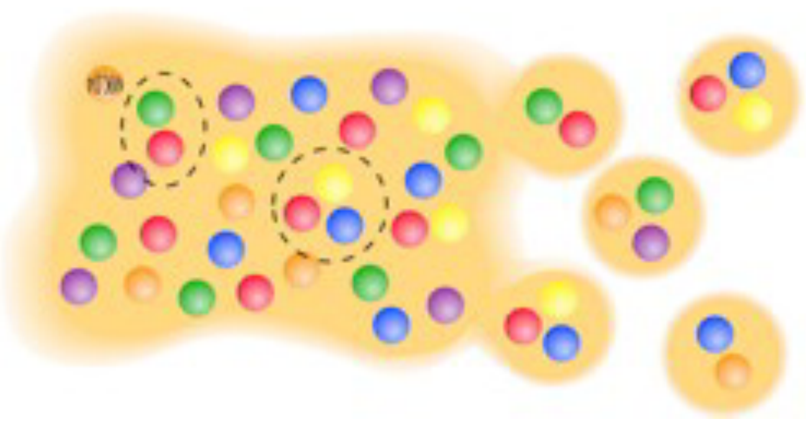




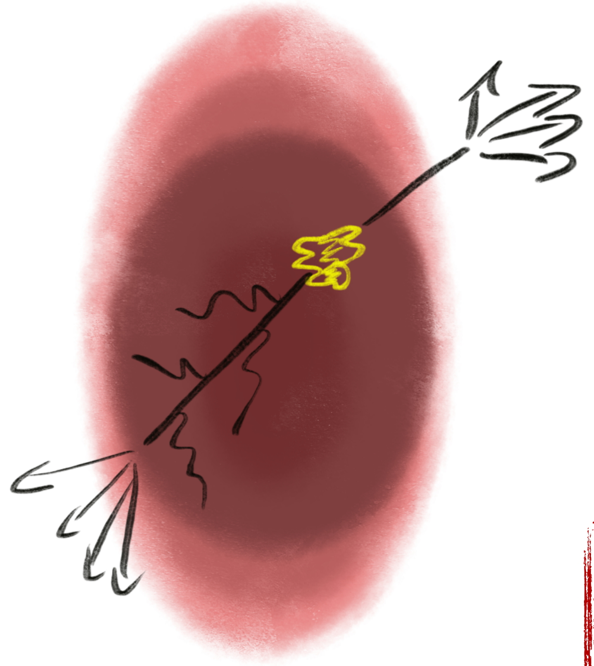
Mass ordering at low p_T → hydrodynamic flow

Baryon vs. meson grouping at high p_T
→ quark-level flow + recombination ?

Similar observations at LHC full energy,
RHIC low energy and for p-Pb collisions at LHC



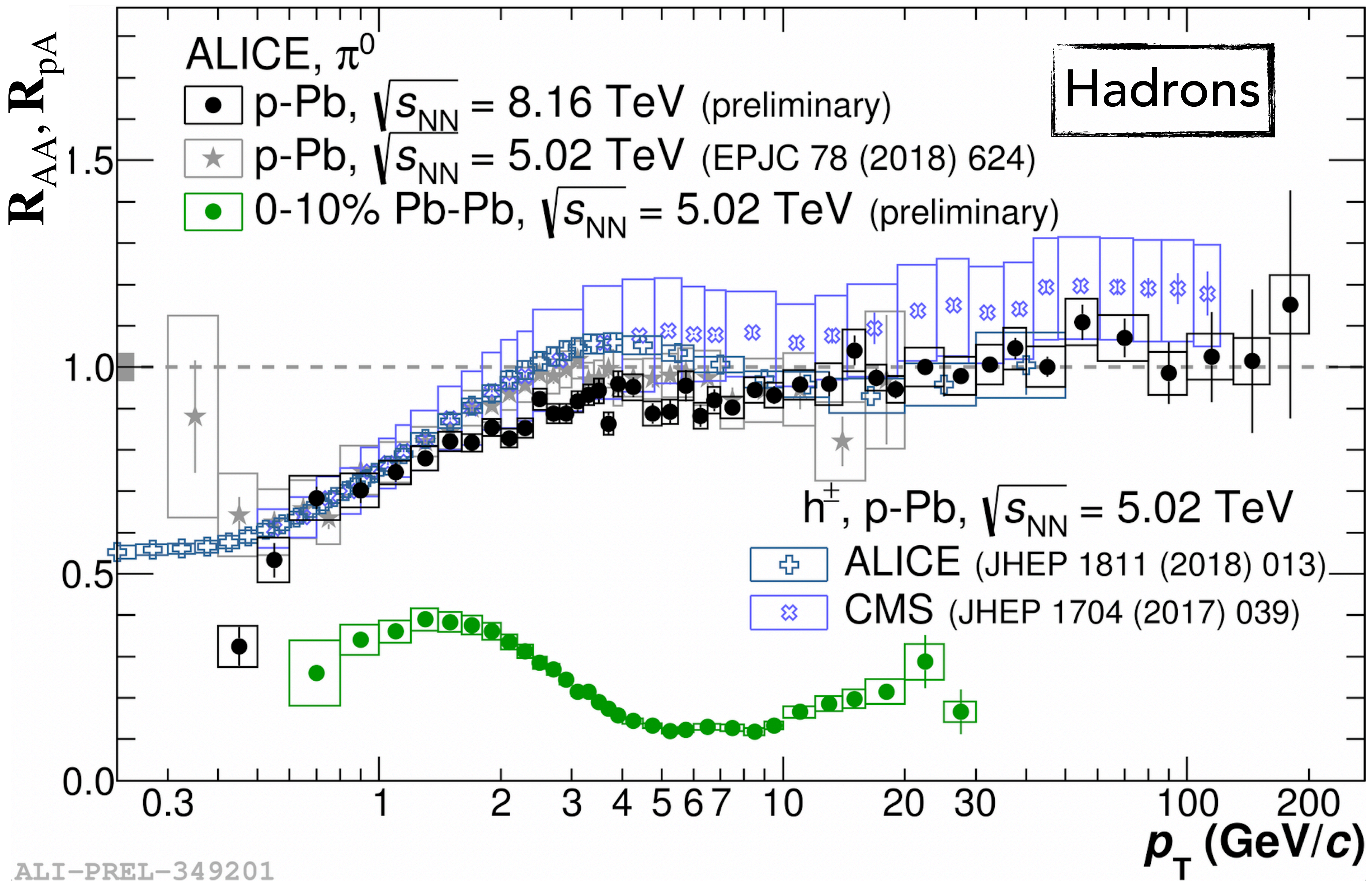
Parton Energy Loss: R_{AA}



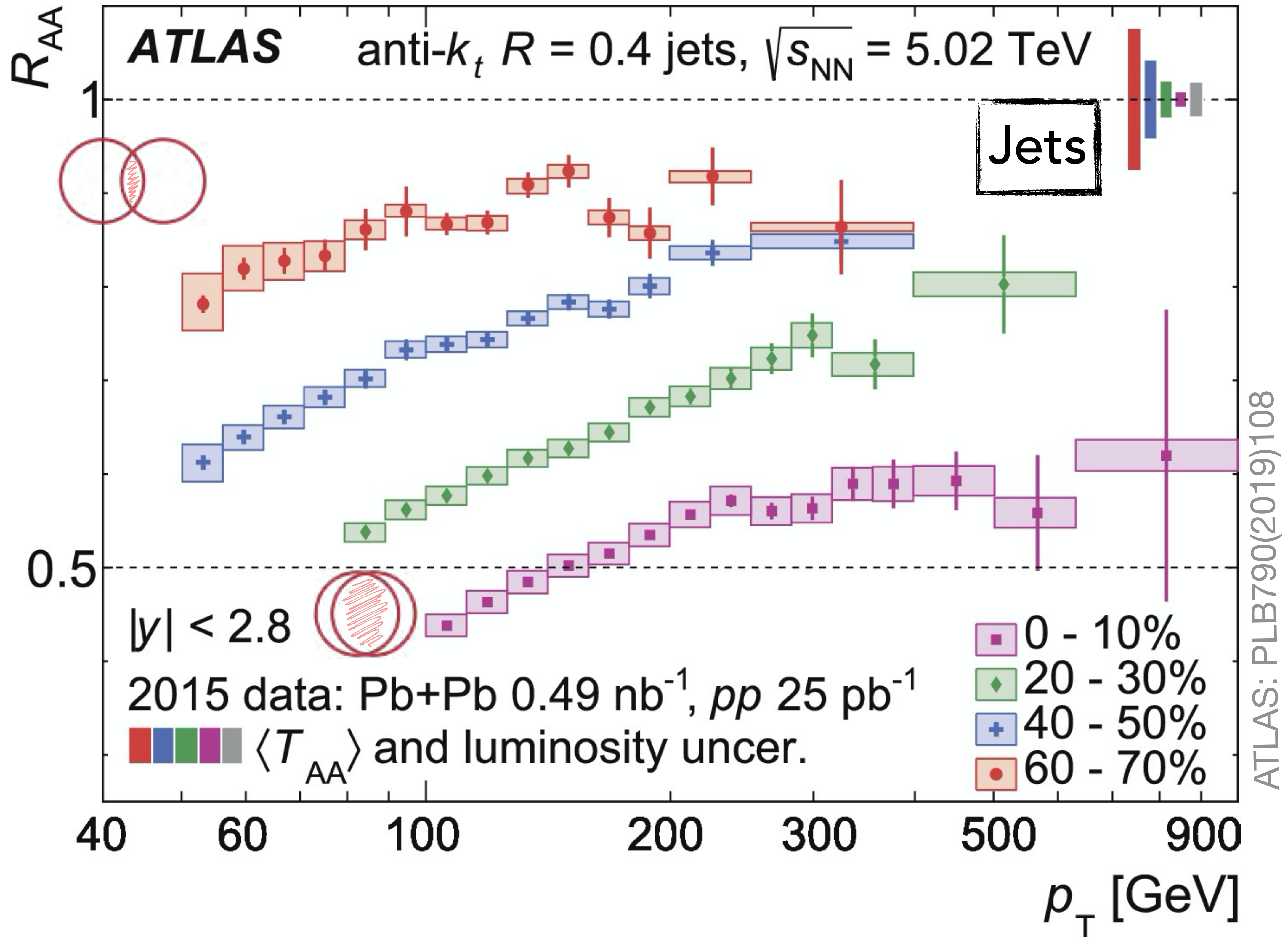
→ Energy loss in large systems up to very high p_T
→ Not yet observed in small collision systems

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN^{AA}/dp_T}{dN^{pp}/dp_T}$$

AA pA



AA



Final Remarks

- QGP formation in heavy-ion collisions considered to by established
  - Hydro models with strongly-coupled thermalised partonic phase (i.e., a QGP phase) nicely describe a wealth of data
  - High-p_T suppression, hints for mass dependent in-medium energy loss, …
  - Clear signs of deconfinement (quarkonium states)

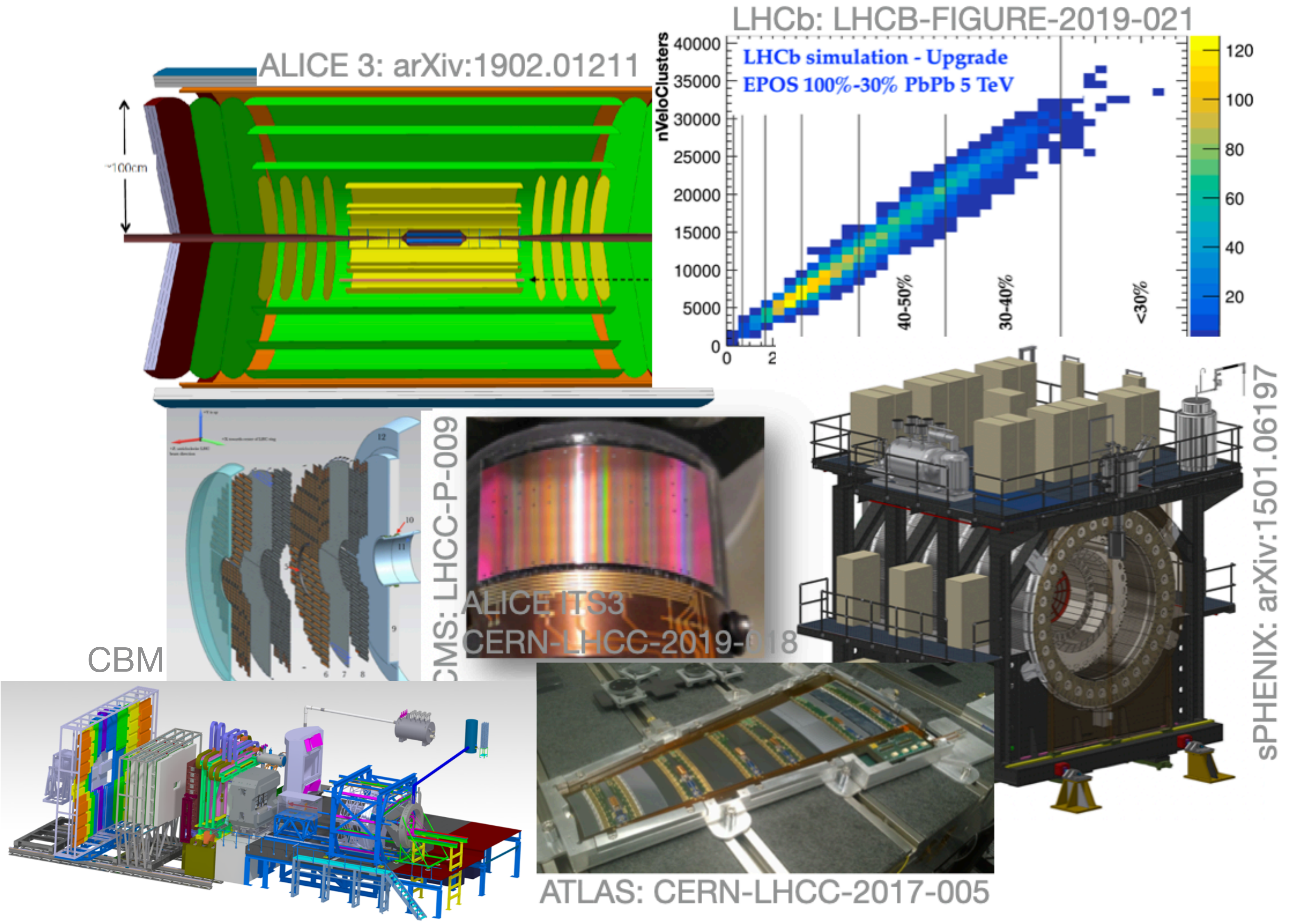
- Next steps
  - Characterise the medium in more detail
  - In particular: Establish connections between observables and quantities calculated from first QCD principle (example: q-hat from lattice QCD)
  - Establish QCD phase diagram
  - Establish/disprove QGP formation in small systems (high-multiplicity pp and p=Pb collisions)

- Connect to other physical systems (e.g. ultra-cold atoms) to better understand universal aspects of the underlying physics

- Stay tuned …

Future of Heavy-Ion Physics

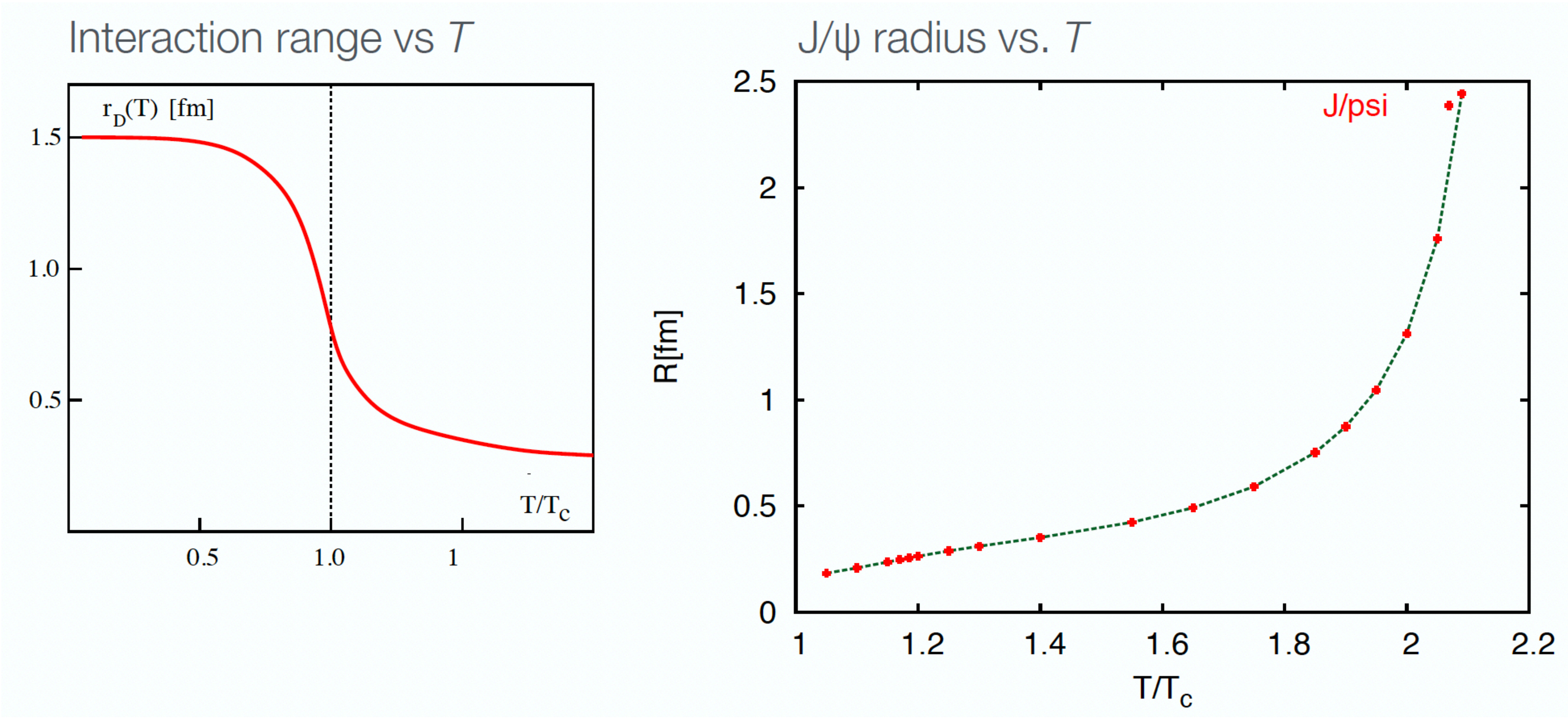
- Wealth of beautiful new results from heavy-ion experiments
- European strategy → encouraging the heavy-ion programme at CERN in HL-LHC era
- New era for ultra-relativistic heavy-ion physics → improving precision/reach for rare probes
  - LHC Run 3 and 4
    - LHC upgrades (ALICE, ATLAS, CMS, LHCb)
    - Collider and fixed-target program at CERN
  - sPHENIX and STAR at RHIC (incl. Beam Energy Scan, fixed target)
- LHC Run 5 and beyond
  - A next-generation LHC heavy-ion experiment: ALICE 3
  - LHCb Upgrade II
- High net-baryon number density frontier - facilities coming up at lower center-of-mass energies: NICA, FAIR, …
- Electron-ion collisions at the EIC
  - nPDF, diffraction, saturation, …



Backup slides

Interaction range and J/ψ radius in the medium vs temperature

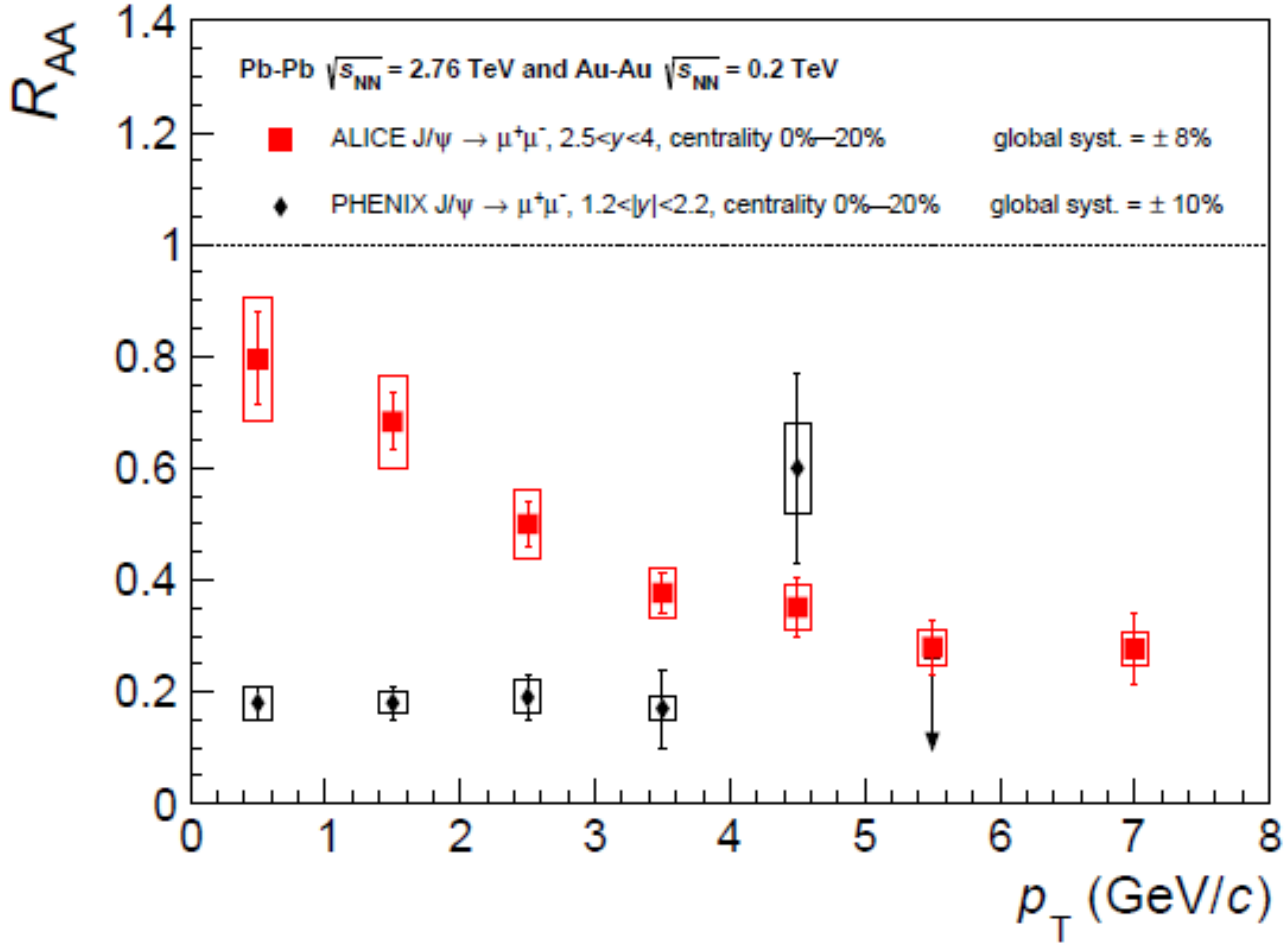
H. Satz, hep-ph/0512217

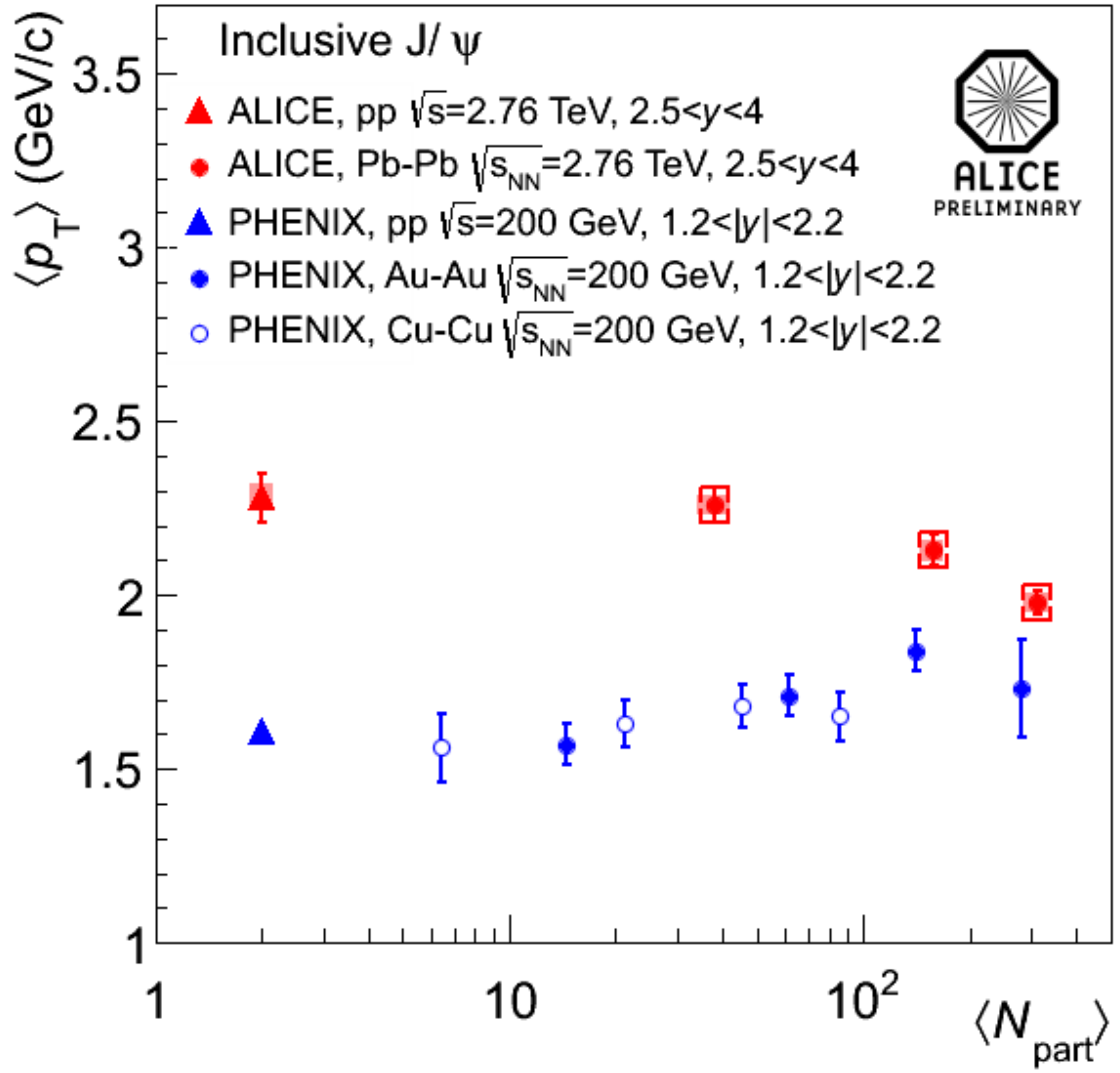


- J/ψ radius becomes larger with increasing T
- No bound state anymore for $T \gtrsim 2\ T_c$

Results from LHC

B. Abelev et al., ALICE
arXiv:1311.0214





- Expect smaller suppression for low-p_T J/ψ observed!
- The trend is different wrt the one observed at lower energies, where an increase of the $<p_T>$ with centrality was obtained