Quarkonia in Heavy Ions Collisions

26 Oct 2015

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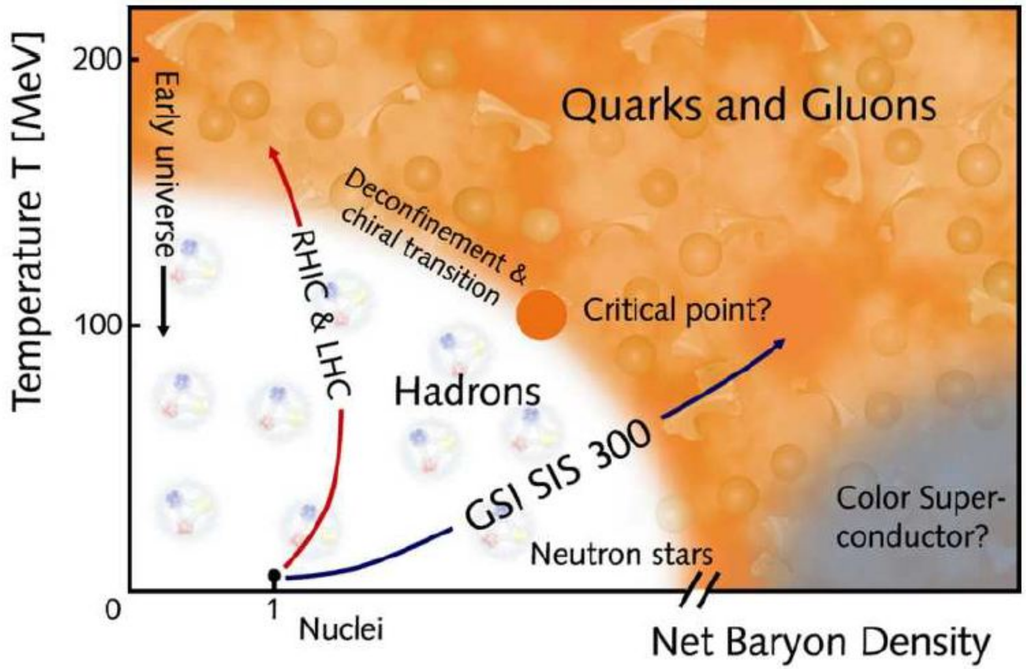
University of Illinois at Chicago

Outline
1) *Intro to Heavy Ions*
2) *Quarkonia in PbPb*
3) *Quarkonia in pPb*

SMU Physics Seminar

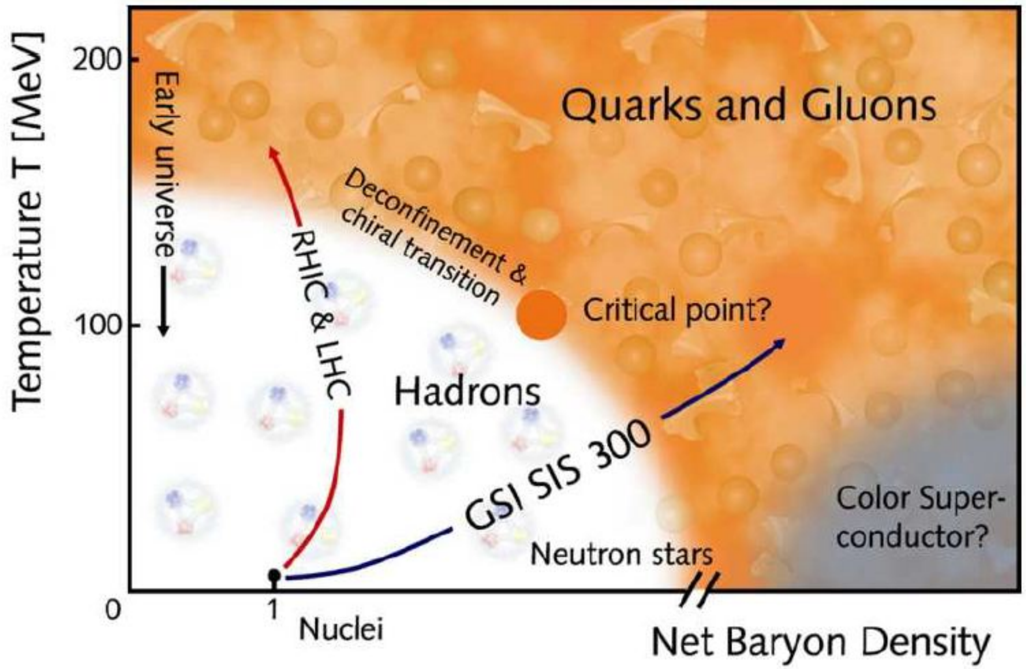
Heavy ion collisions aim to create Quark Gluon Plasma (QGP) in the lab:

- QCD medium where quarks and gluons are the relevant degrees of freedom



Heavy ion collisions aim to create Quark Gluon Plasma (QGP) in the lab:
- QCD medium where quarks and gluons are the relevant degrees of freedom

<u>High Density QCD</u>
- Verify QGP existence
- Study its thermodynamic and transport properties
  - temperature
  - entropy/viscosity
  - transport coefficients
- Investigate phase transition
  - determine critical point ?



Quark Gluon Plasma

phase transition

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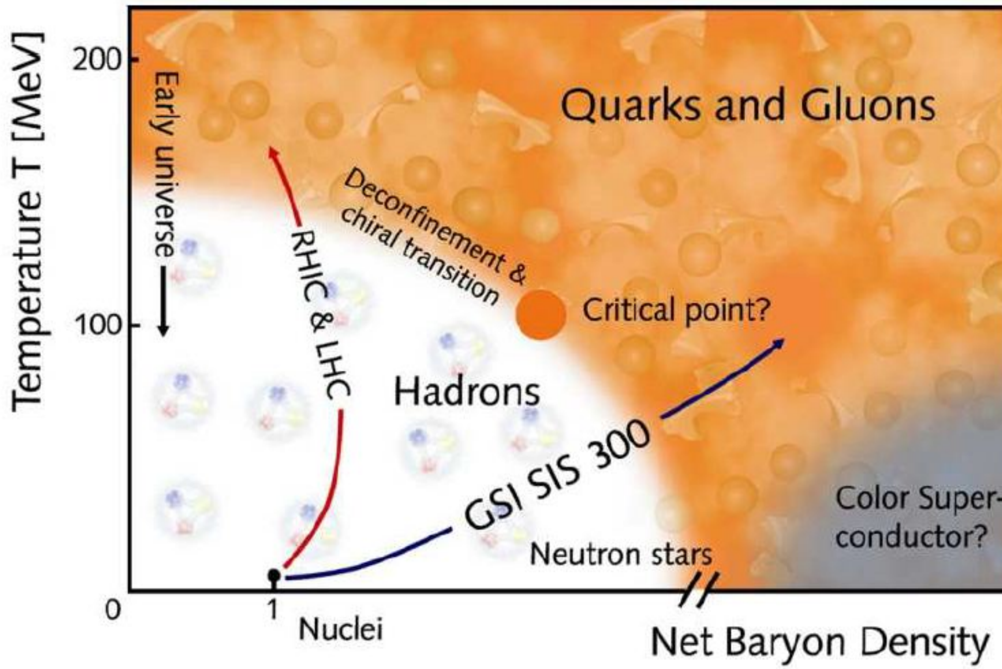
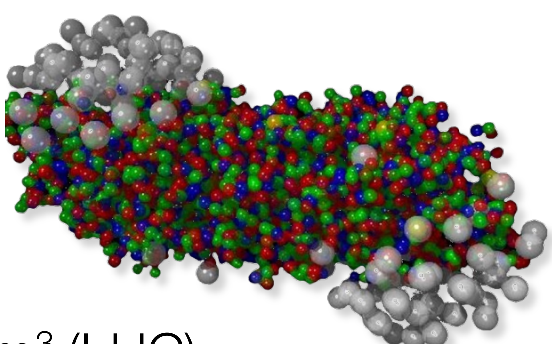
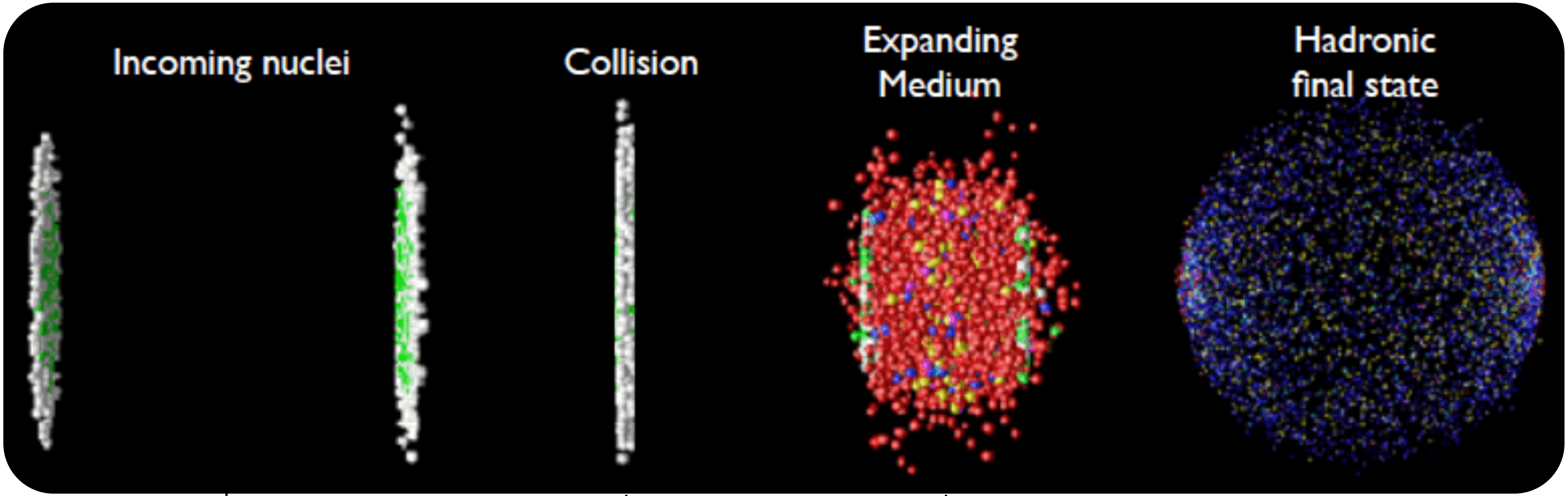




After 15 years of RHIC/LHC operation
- Clear evidence for formation of strongly coupled QGP !
- Entropy/density: $(\eta/s)_{min} \sim 1/4\pi$
- Energy density (τ_0 = 1 fm/c): ~5 GeV/fm^3 (RHIC), 14 GeV/fm^3 (LHC)

Stages of Heavy Ion Collision

evolution



<u>Initial state effects</u>
Modifications to the PDFs to account for nuclear shadowing and parton saturation

<u>Calculable</u>
Perturbatively, modeled as superposition of N_{Coll} binary partonic scatters

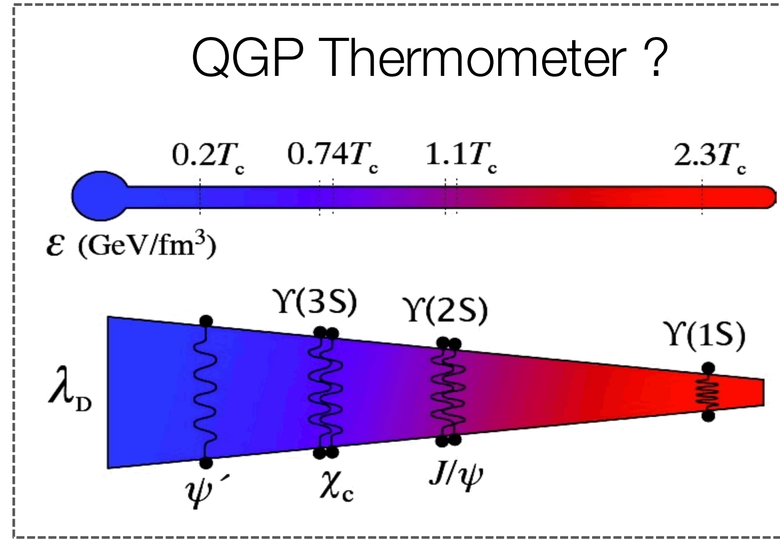
<u>Hydrodynamic evolution</u>
Modeled as (near) zero-viscosity fluid of quarks/gluons

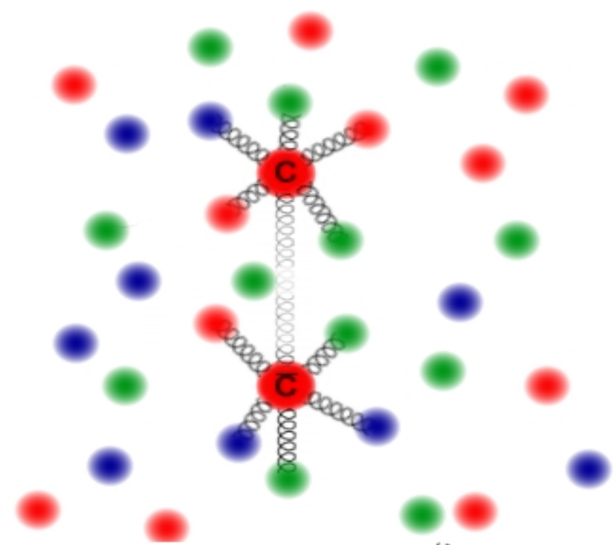
<u>Freeze-out</u>
~10^4 particles in detector

Thermal Dissociation (quarkonia "melting")

- Can QQ survive temperature of QGP ?
- Color screening in deconfined plasma dissolves QQ bound states *(Matsui-Satz 1986)*
- Debye length $\lambda_D < r_{binding}$ → bound state melts !

- Hierarchy in binding energies leads to thermometer





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

Quarkonia Modifications

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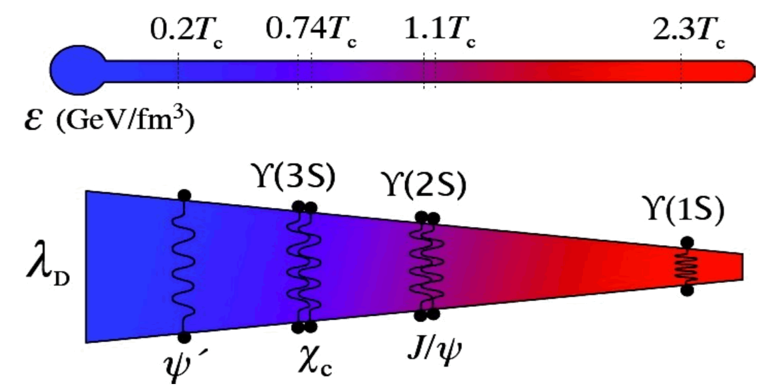
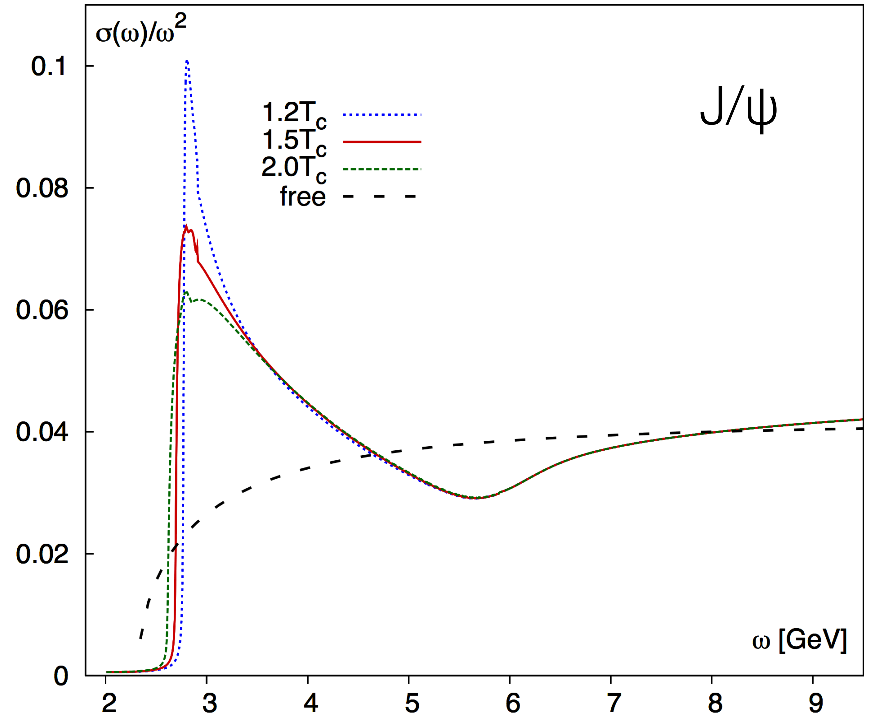
- Hierarchy in binding energies leads to thermometer
- Lattice QCD on quarkonia spectral functions predicts
  - ψ', χ_c dissolve ~ T_{crit}
  - J/ψ dissolves ~1.5-2 T_{crit}
  - Υ survives to ~3-4 T_{crit}
  - T_{crit} ~175 MeV

QGP Thermometer ?





(Mócsy, Petreczky, Strickland 2013)

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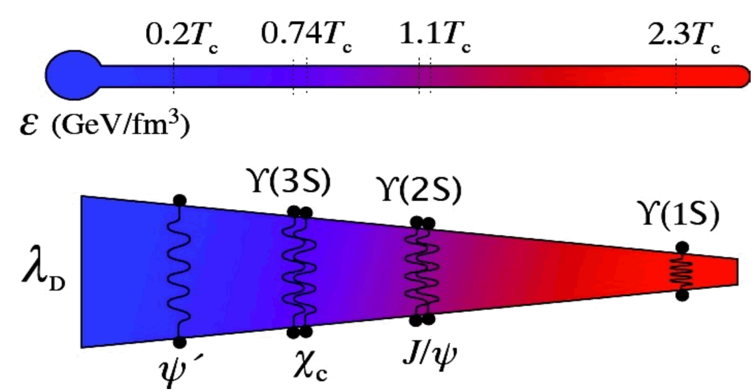
Statistical Regeneration

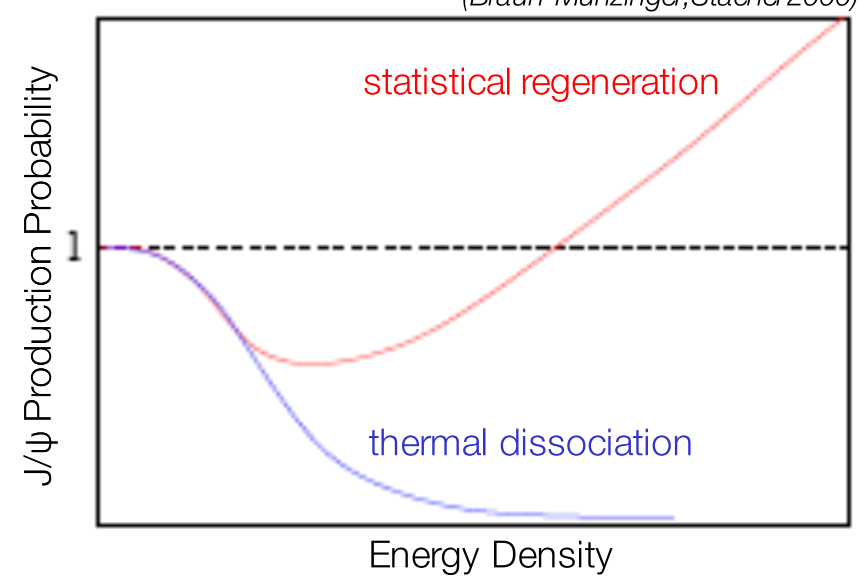
- Heavy quarks re-combining
- As cc multiplicity rises, probability to randomly "pair up" increases…
- Can lead to charmonium enhancement !
- Effect limited to p_T < 4 GeV/c

Most Central A-A Collisions	SPS 20 GeV	RHIC 200 GeV	LHC 2.76 TeV
$N_{c\bar{c}}$/event	~0.2	~10	~60

QGP Thermometer ?



(Braun-Munzinger,Stachel 2000)



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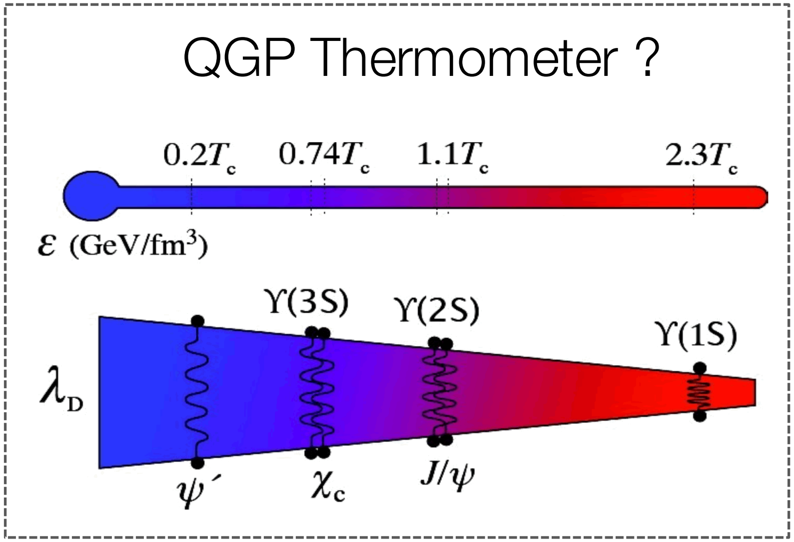
Initial state effects

- nPDF modification
- gluon saturation/shadowing
- suppression of quarkonia production *before* QGP forms



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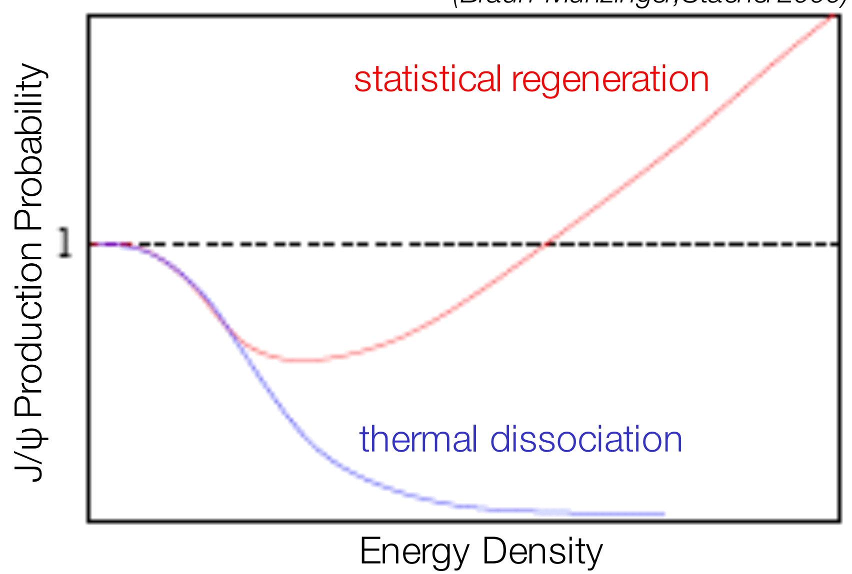

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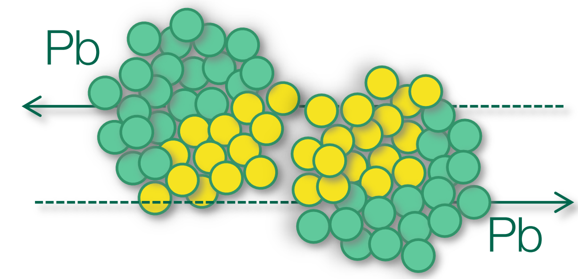
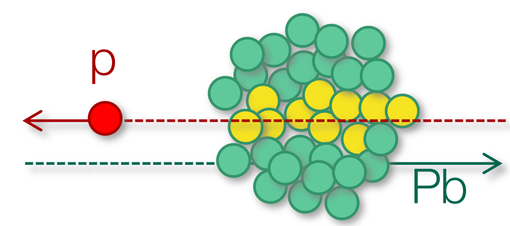
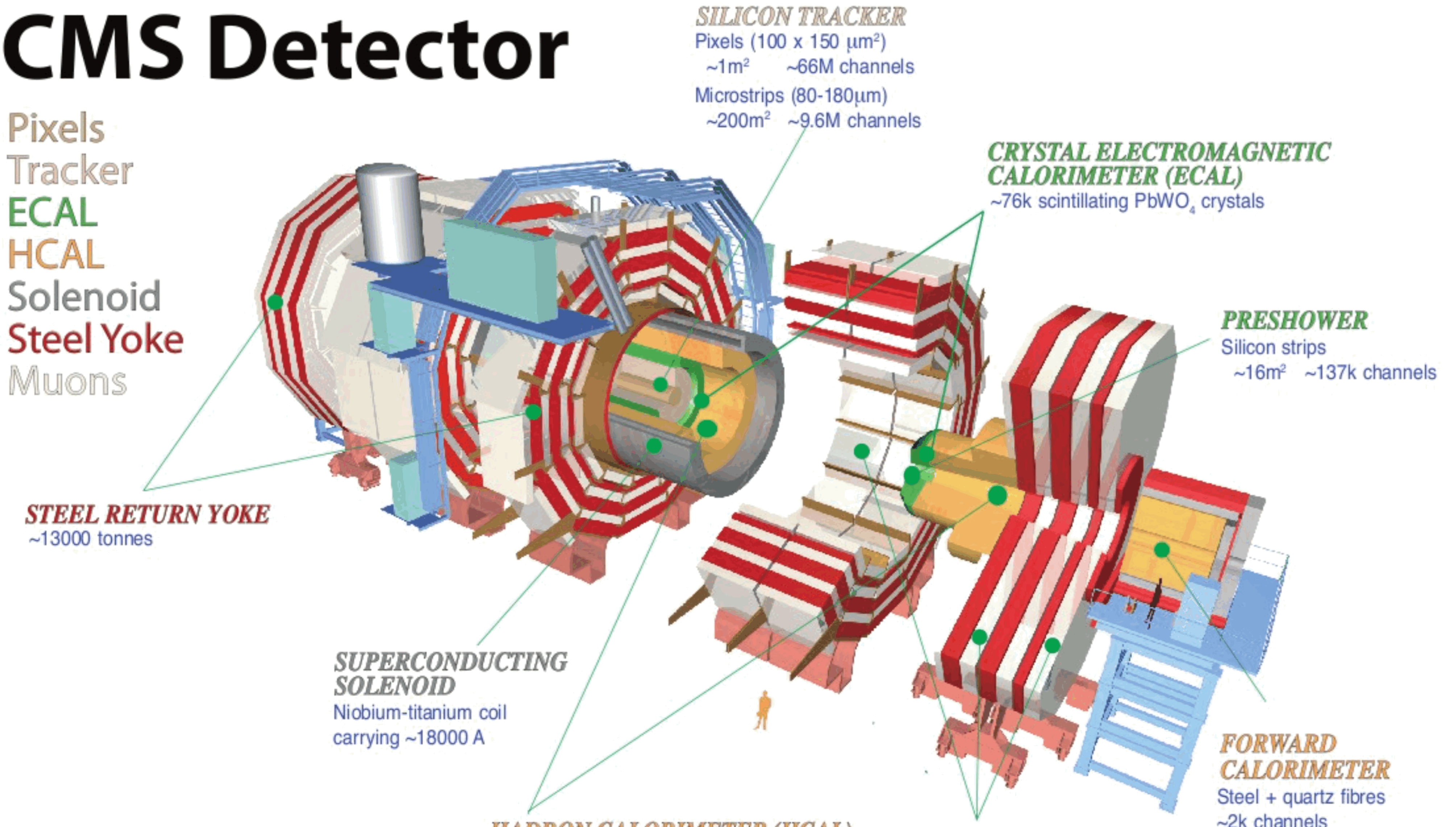
Lead – Lead Collisions



Proton – Lead Collisions

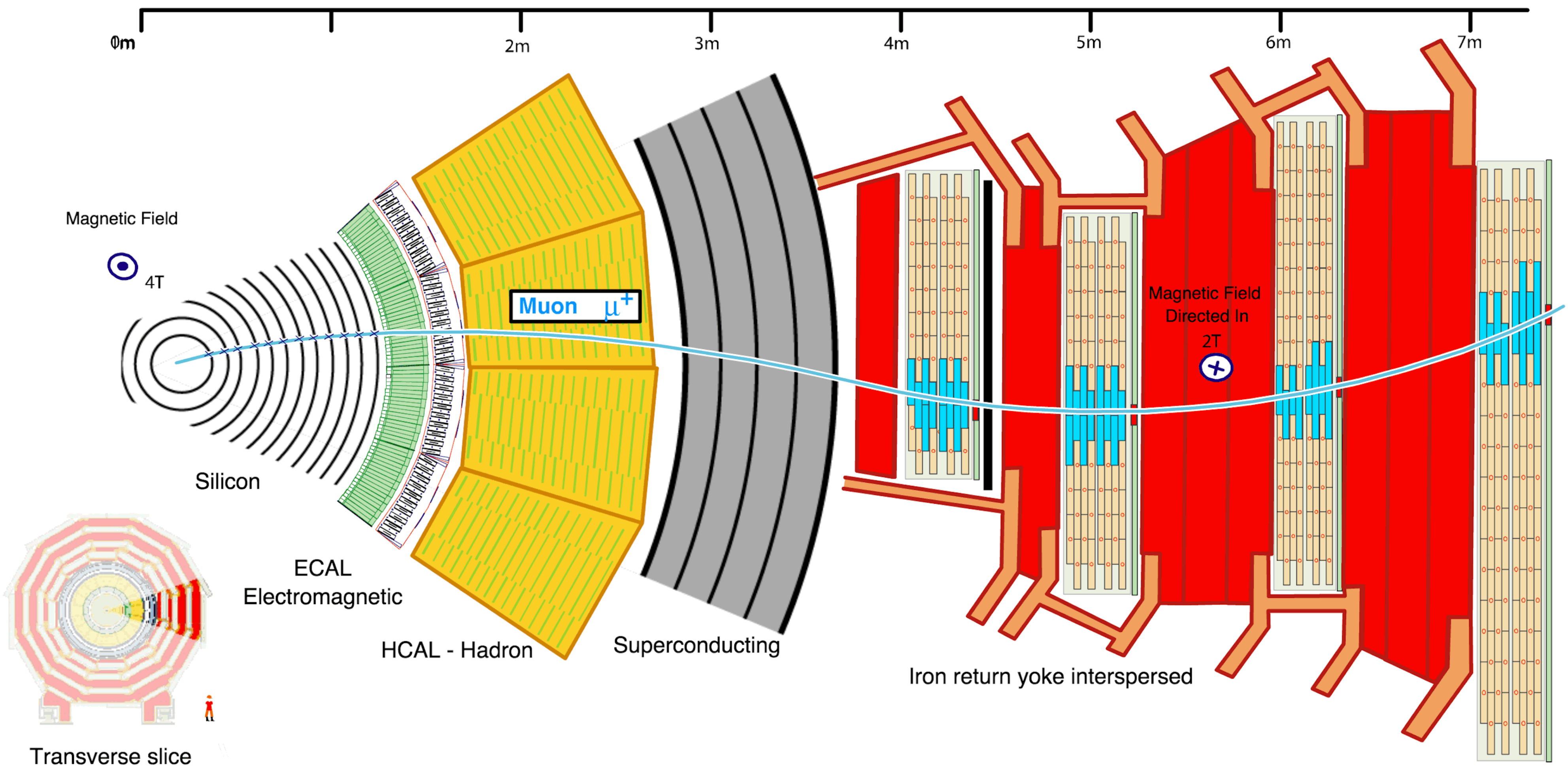


CMS Detector



Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

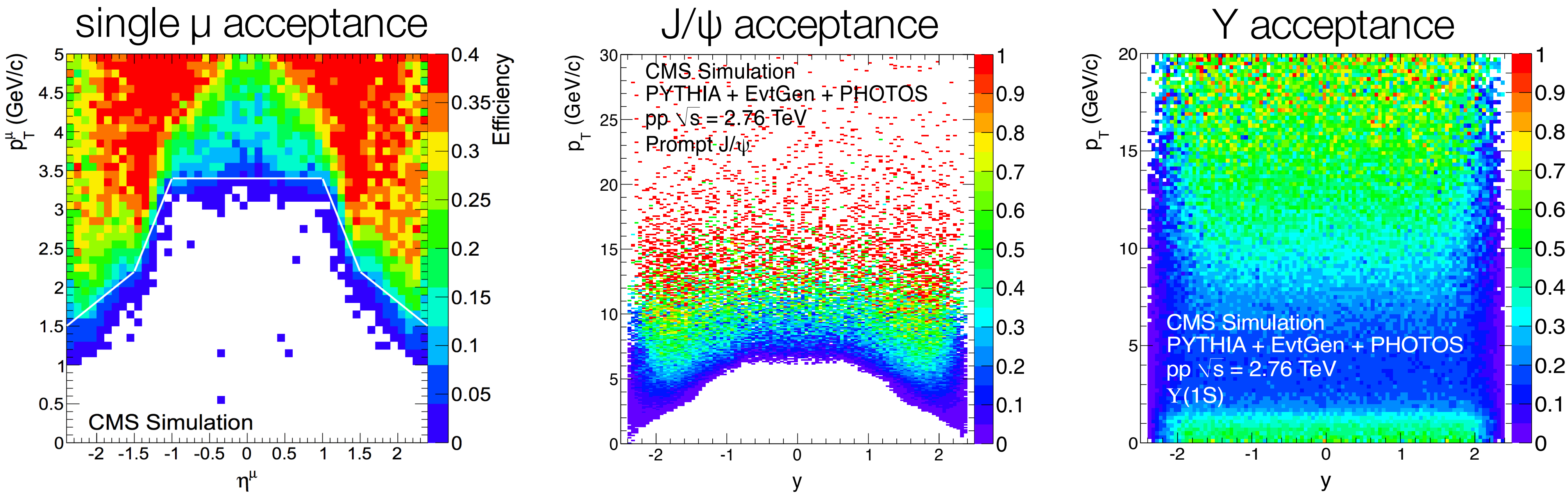
CMS Muons



Transverse slice through CMS

- 3.8 T solenoid magnet
- Use silicon tracker and outer muon stations
- Excellent muon ID and triggering (DT, CSC, RPC)
- High mass/momentum resolution

CMS Acceptance



- Due to B-Field and E-loss in absorber, minimum momentum to reach muon stations is ~3.5 GeV/*c*

J/ψ acceptance:

- mid-rapidity, $p_T > 6.5$ GeV/*c* , $|y| < 0.9$
- Forward rap, $p_T > 3$ GeV/*c* , $1.5 < |y| < 2.4$

Υ acceptance

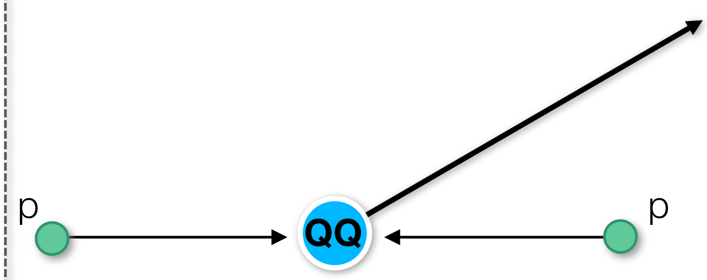
- $p_T > 0$ GeV/*c* , $|y| < 2.4$

Terminology

R_{AA} / centrality

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle dN_{pp}/dp_T} = \frac{\text{“hot/dense QCD medium”}}{\text{“QCD vacuum”}}$$

- Quantifies spectral modification due to nuclear effects
  - *How different are AA collisions compared to a superposition of N_{coll} pp collisions?*
- $R_{AA} \approx 1 \rightarrow$ no modification from N_{coll} independent pp hard scatterings – no medium effects!



cartoon of pp collision

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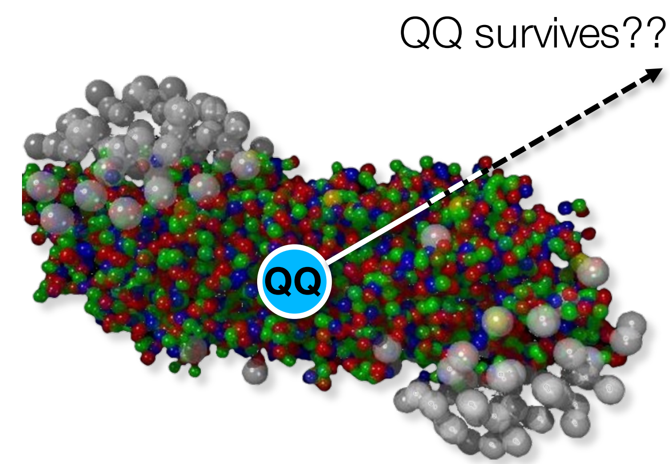

cartoon of PbPb collision

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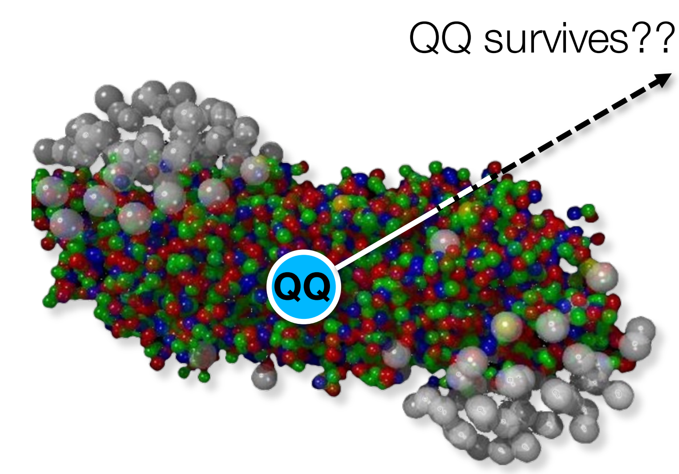

cartoon of PbPb collision

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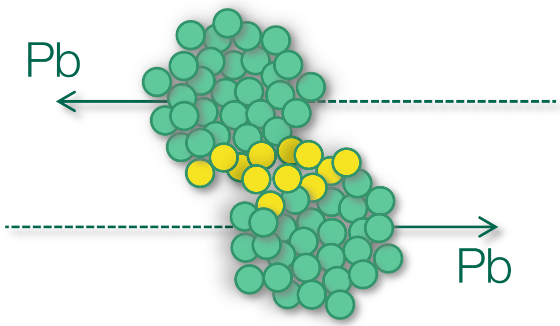
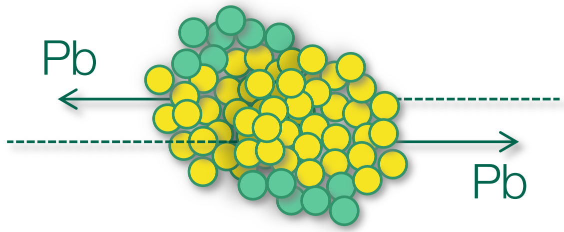
Centrality

Measure of amount of nuclear overlap.

Represents system moving towards a larger, hotter, denser medium.

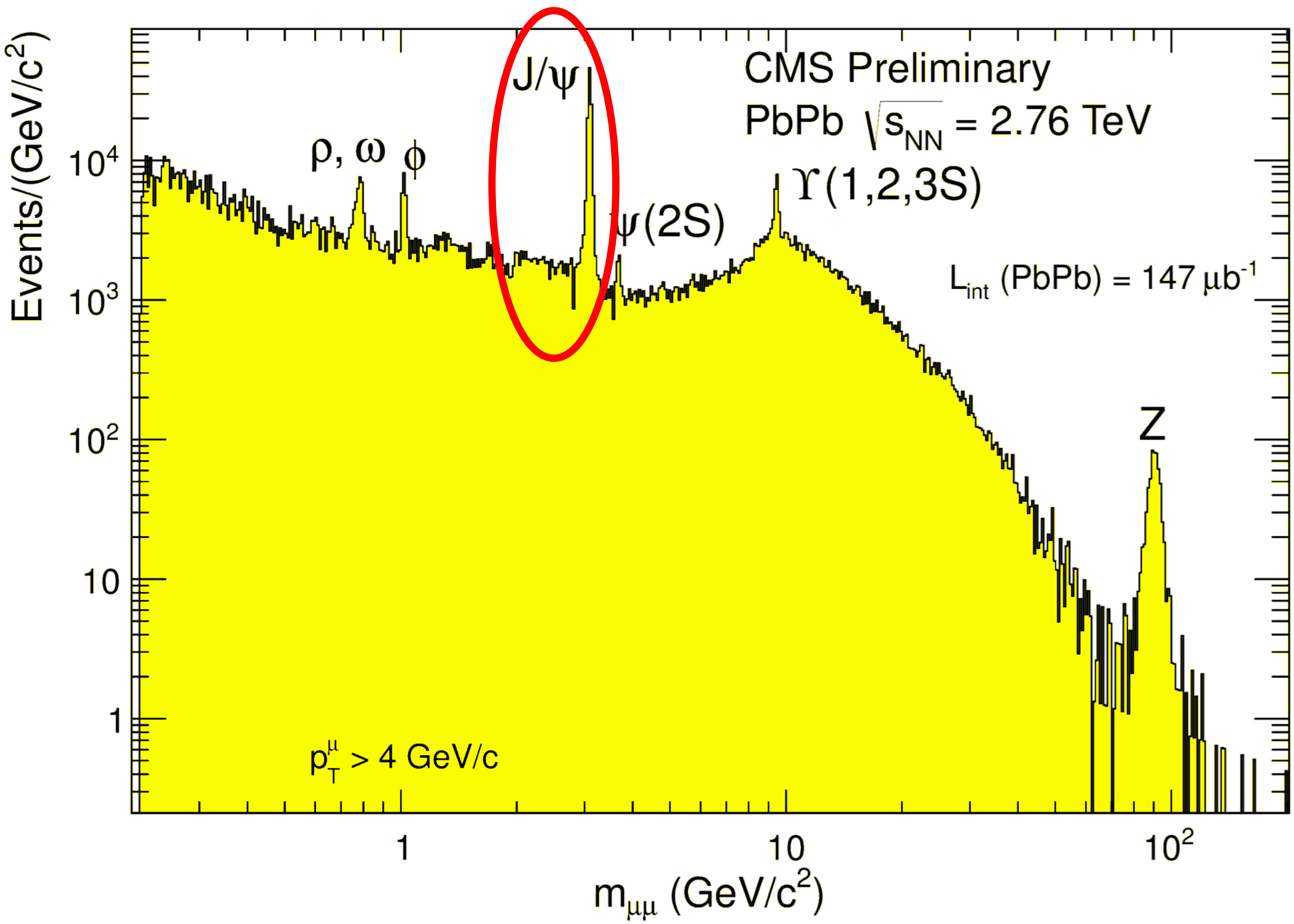


Peripheral (100%)



Central (0%)

J/ψ



CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
L_{int} (PbPb) = 147 μb^{-1}
ρ, ω
ϕ
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ψ(2S)
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p_T^μ > 4 GeV/c
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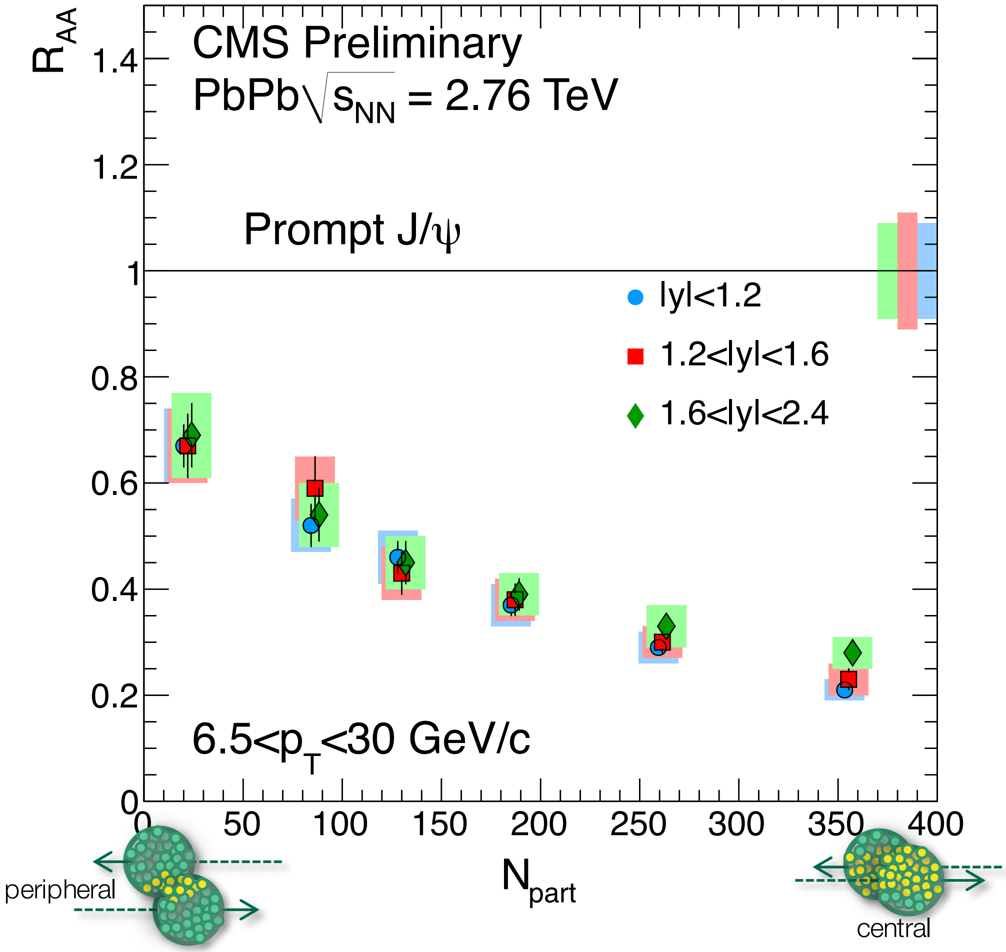
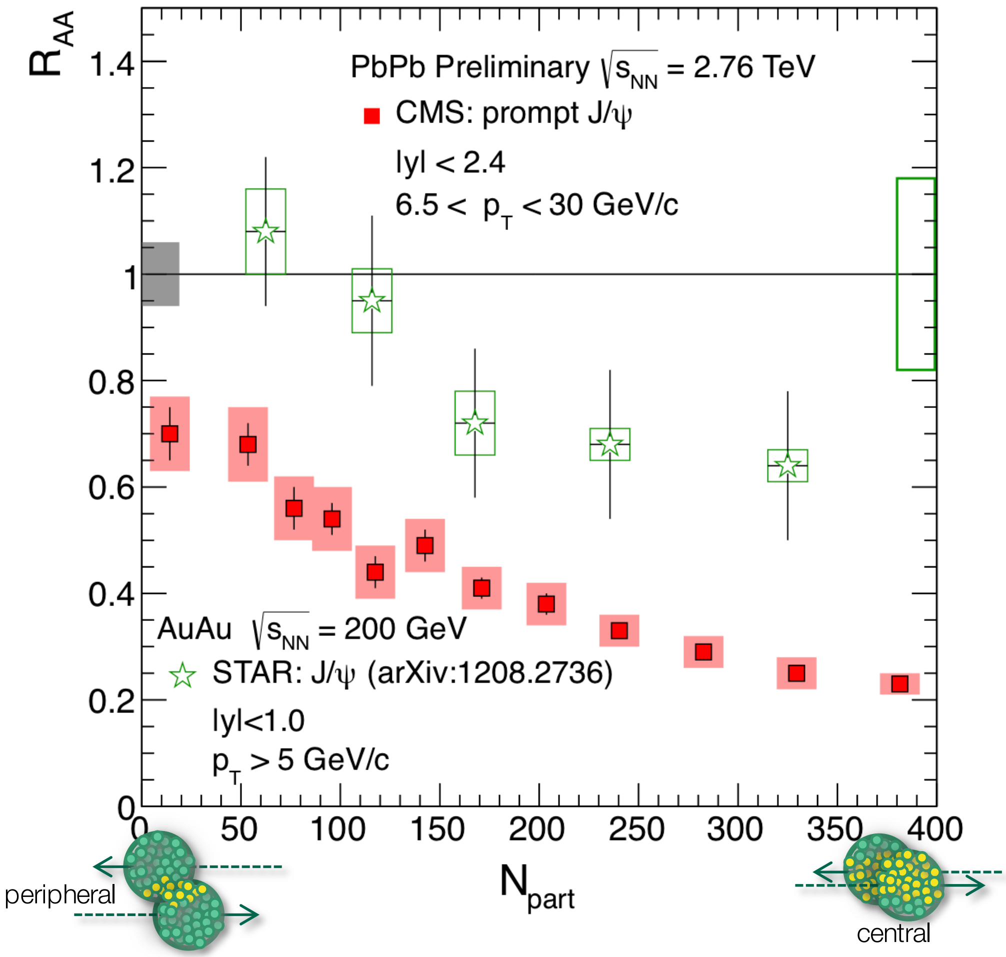
J/ψ Suppression in PbPb



- Suppression independent of rapidity
  - note p_T > 6.5 GeV/c

J/ψ Suppression in PbPb (AuAu)

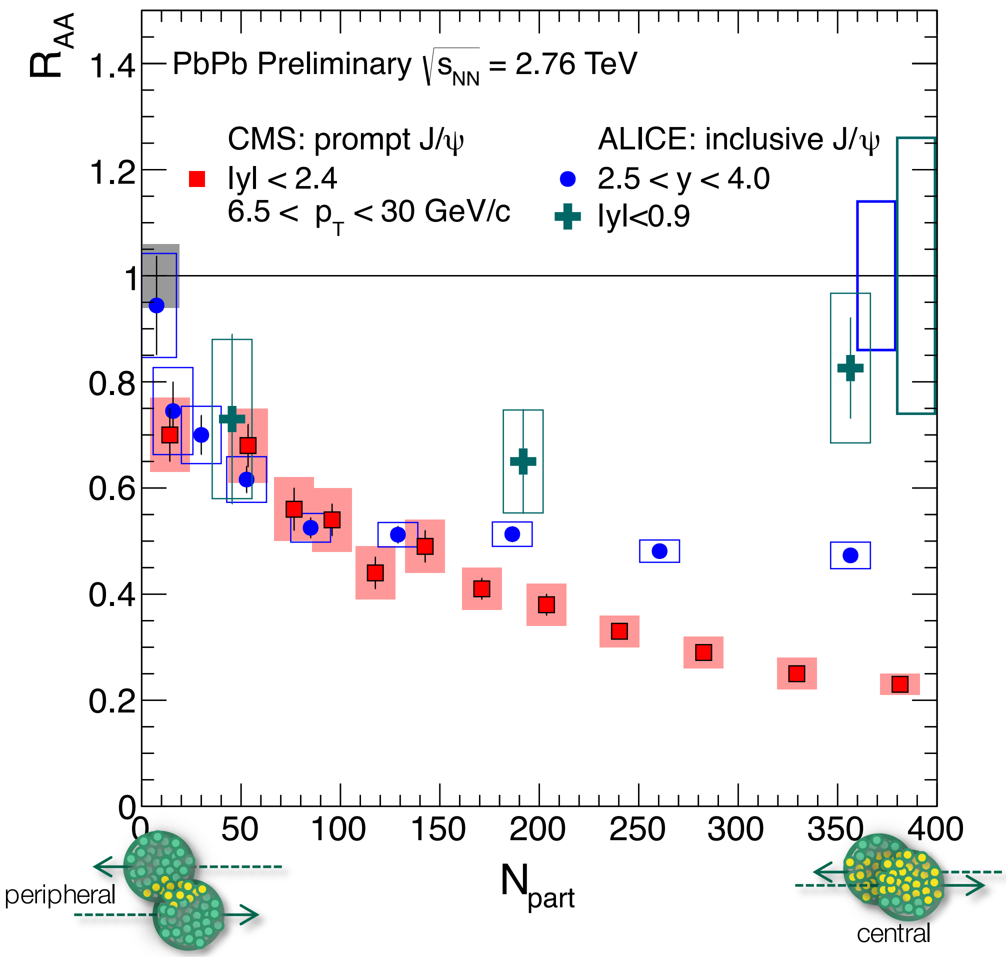
vs centrality at high p_T



- Suppression independent of rapidity
  - note p_T > 6.5 GeV/c
- LHC *more* suppressed than RHIC
  - supports thermal melting

J/ψ Suppression in PbPb

vs centrality at different p_T



- Suppression independent of rapidity
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- LHC *more* suppressed than RHIC
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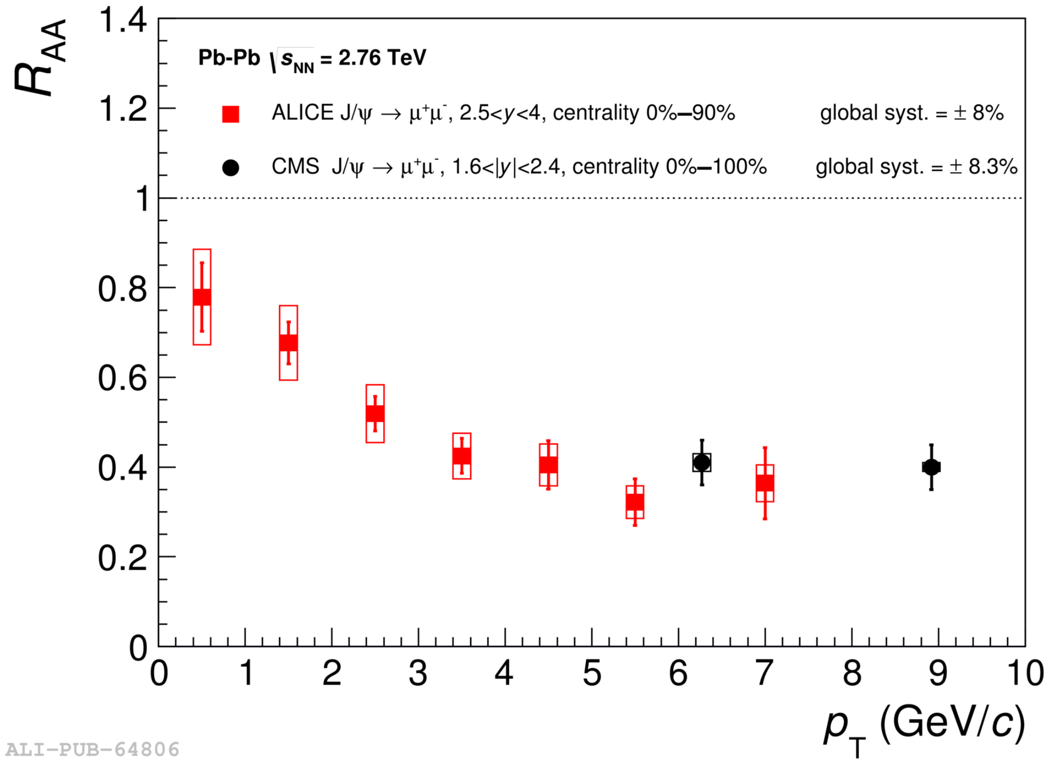
- High p_T more suppressed than low p_T
  - supports statistical recombination (should only affect below ~4 GeV/c)

J/ψ Suppression in PbPb

vs p_T at LHC



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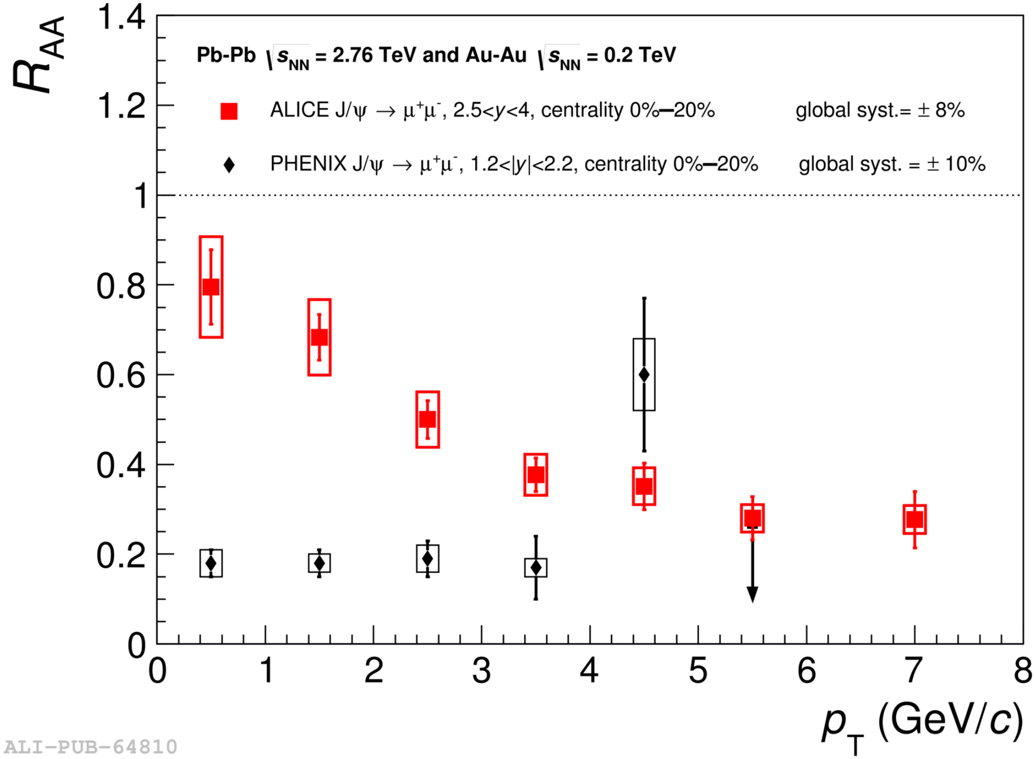
- ALICE consistent with CMS

J/ψ Suppression in PbPb (AuAu)

vs p_T, comparing colliders



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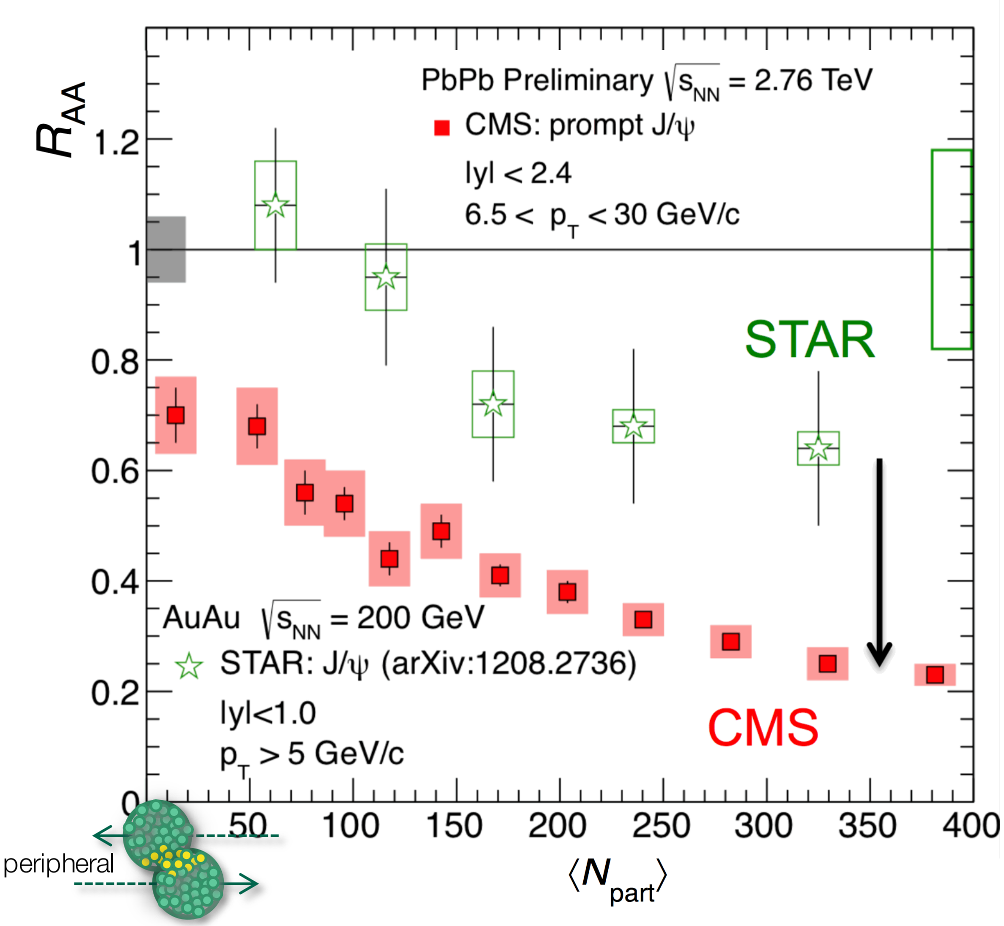
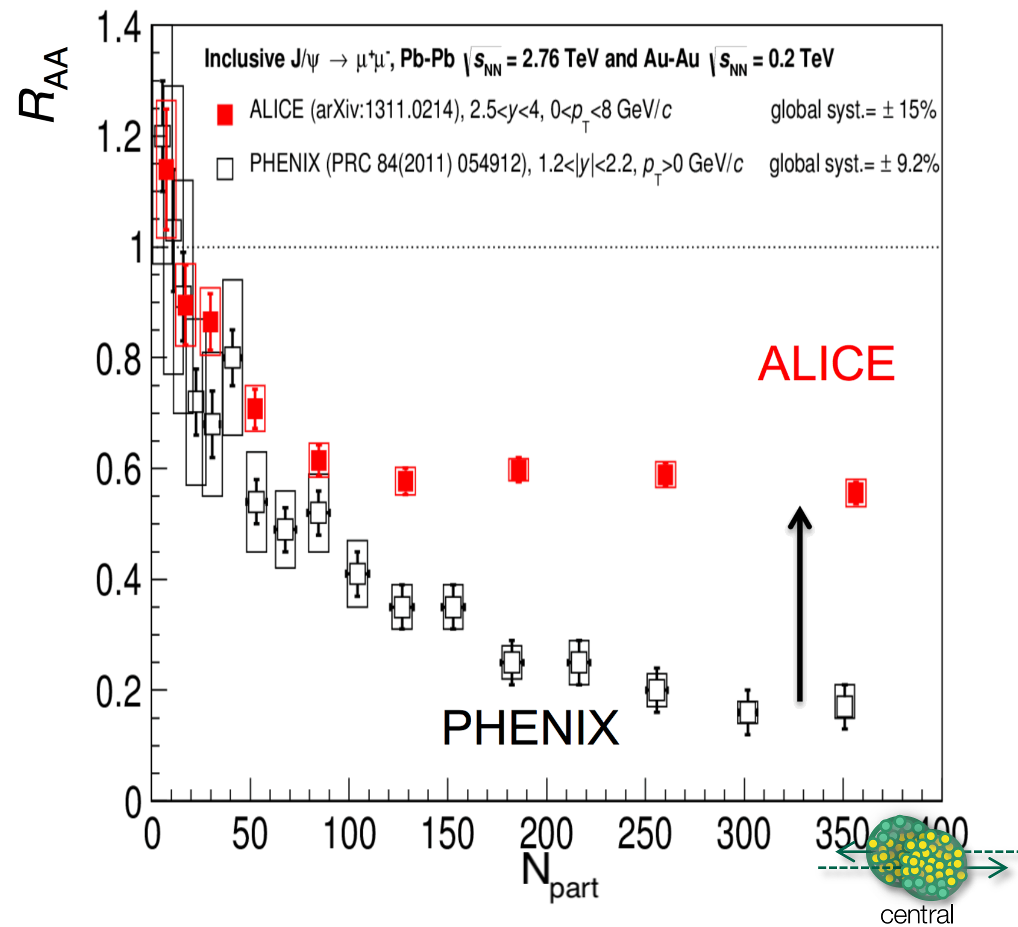
- LHC *more* suppressed than RHIC
  - supports thermal melting
- High p_T more suppressed than low p_T
  - supports statistical recombination (should only affect below ~4 GeV/c)
  - diff btwn RHIC & LHC at p_T < 4 GeV/c
- ALICE consistent with CMS
- PHENIX *not* consistent with ALICE at low p_T (regeneration!)

J/ψ Suppression in Heavy Ions

vs centrality, LHC vs RHIC





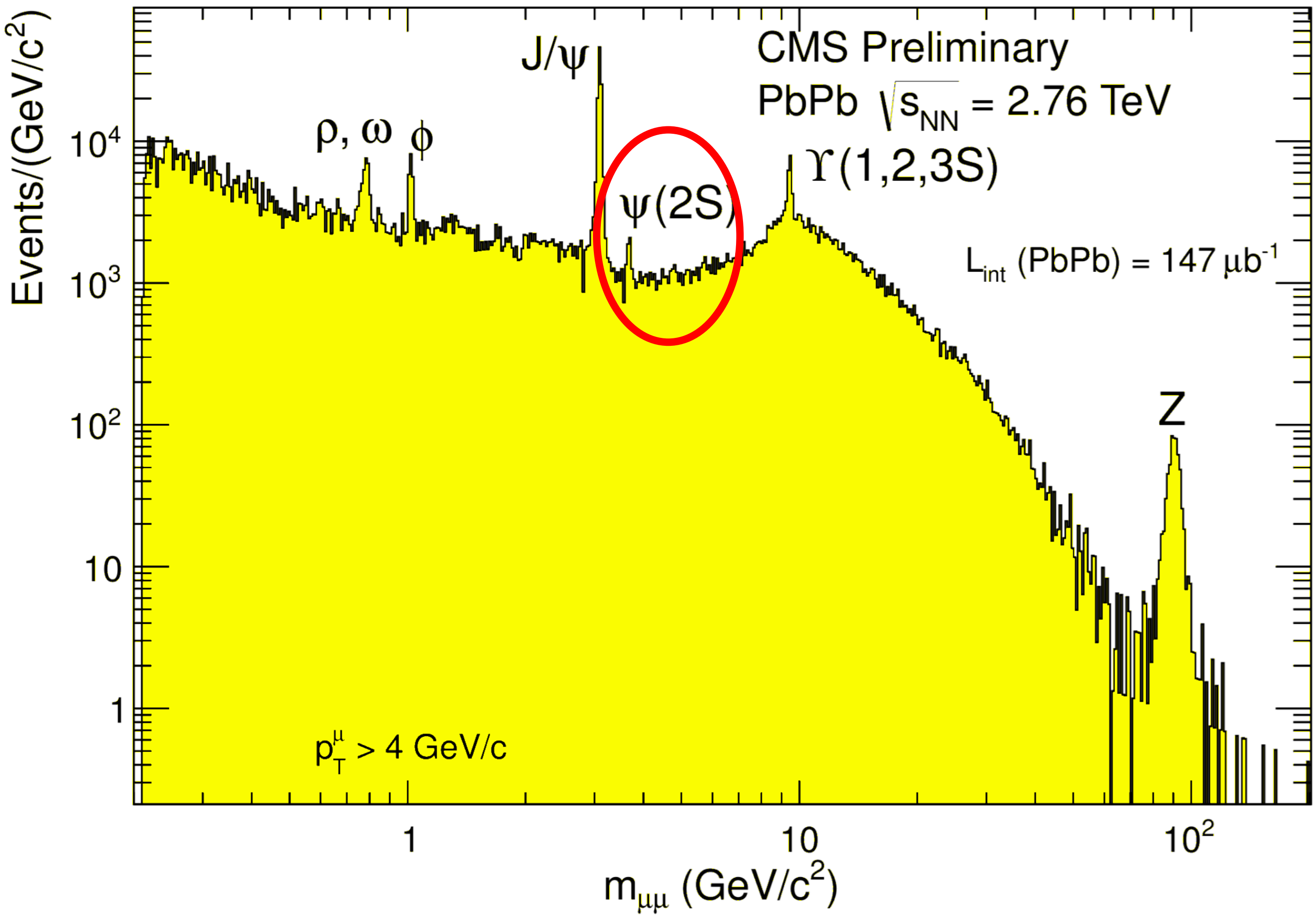
Thermal Dissociation
- more high p_T suppression at LHC

Statistical Regeneration
- low p_T J/ψ central collisions enhanced at LHC

CMS, PLB734 (2014) 314
STAR, PLB722 (2013) 55

ALICE, PLB734 (2014) 314
PHENIX, PRC84 (2011) 054912

ψ'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10^3
10^2
10
1
10
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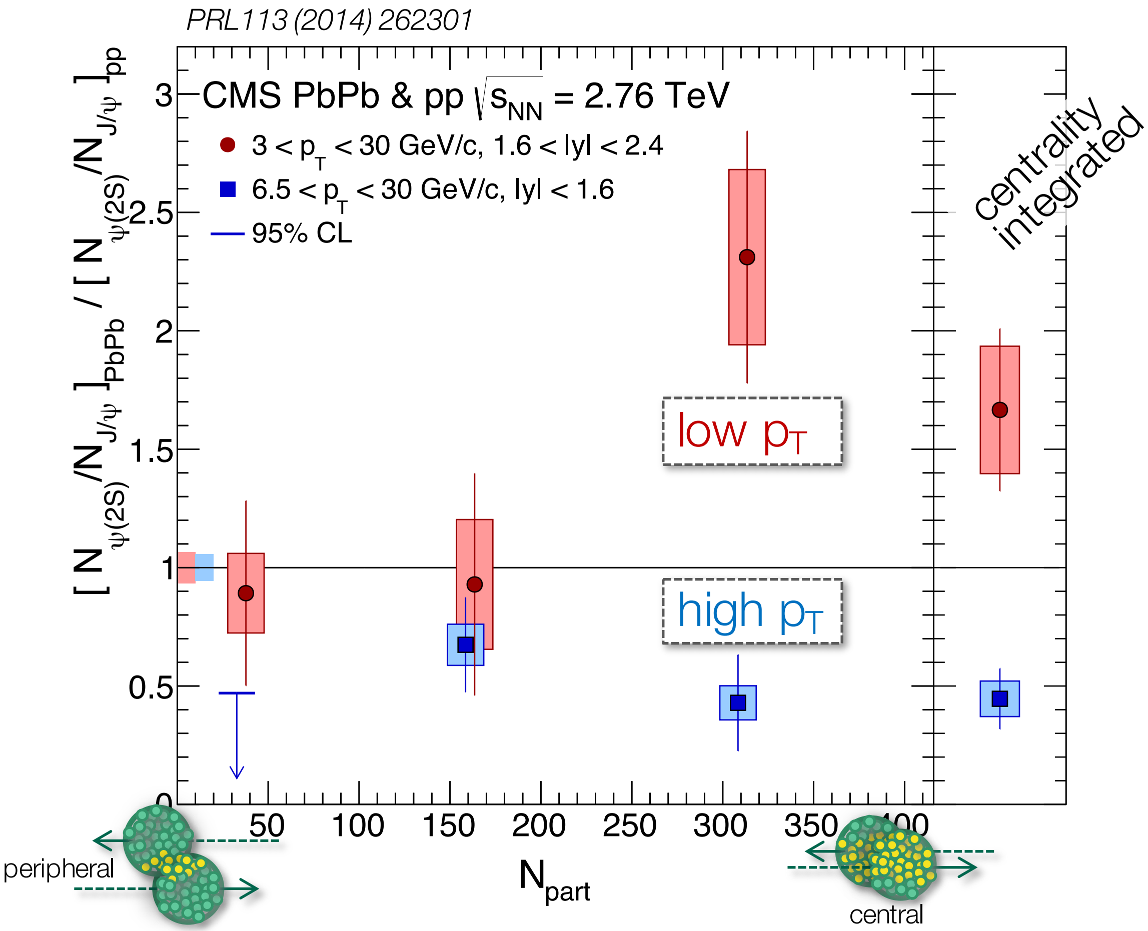
ψ' Suppression in PbPb

double ratio



$$\frac{\left(\frac{\psi(2S)}{J/\psi}\right)_{PbPb}}{\left(\frac{\psi(2S)}{J/\psi}\right)_{pp}}$$

- ψ' very suppressed at high p_T (more than J/ψ)
  - $R_{AA}(\psi') = 0.13 \pm 0.05$ hints at sequential melting ?
- Less suppression at low p_T
  - $R_{AA}(\psi') = 0.67 \pm 0.19$ can regeneration play a role ?
  - rapidity ?
- Large uncertainties…

ψ' Suppression in PbPb

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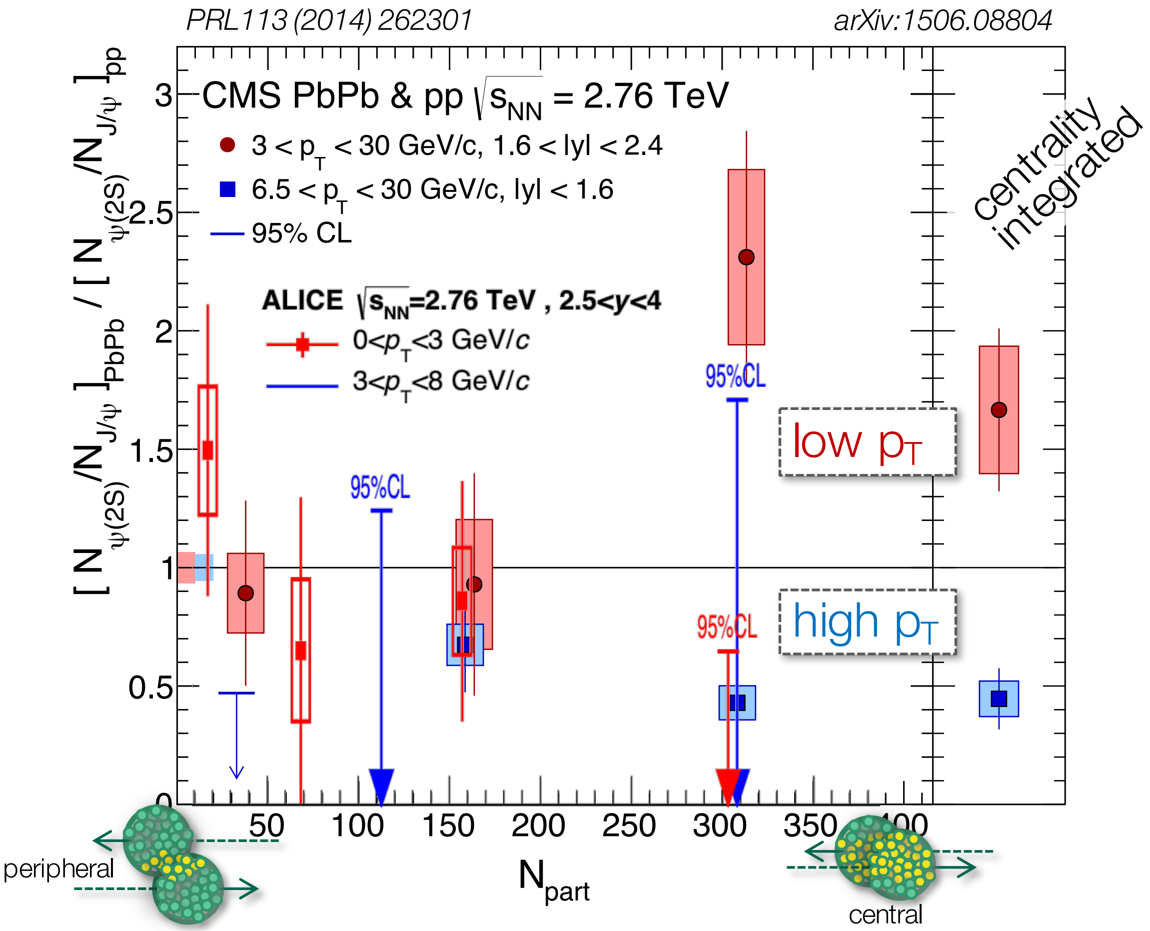

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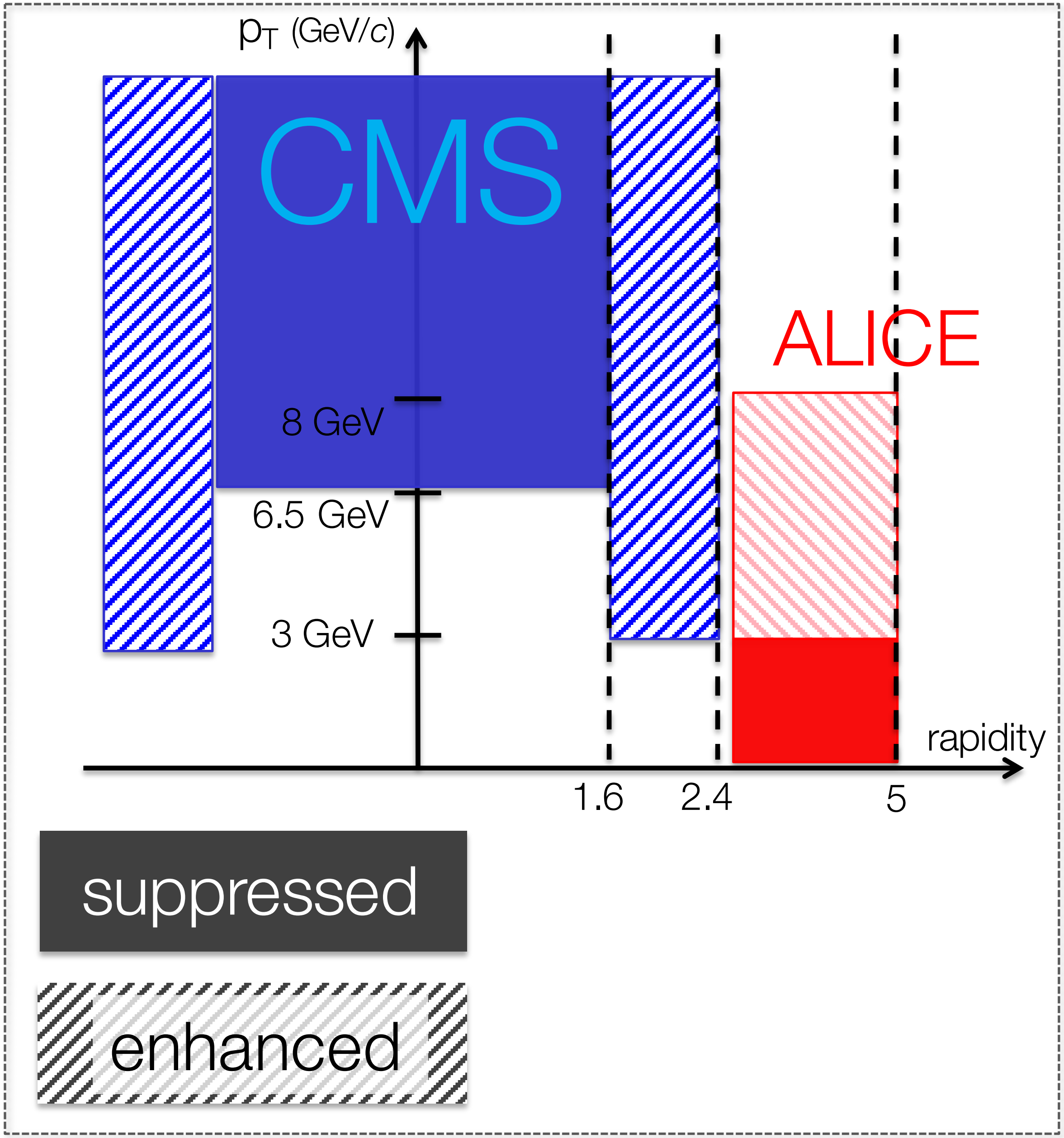
- ALICE (maybe) sees different trend ?
- Kinematic ranges aren't perfectly aligned

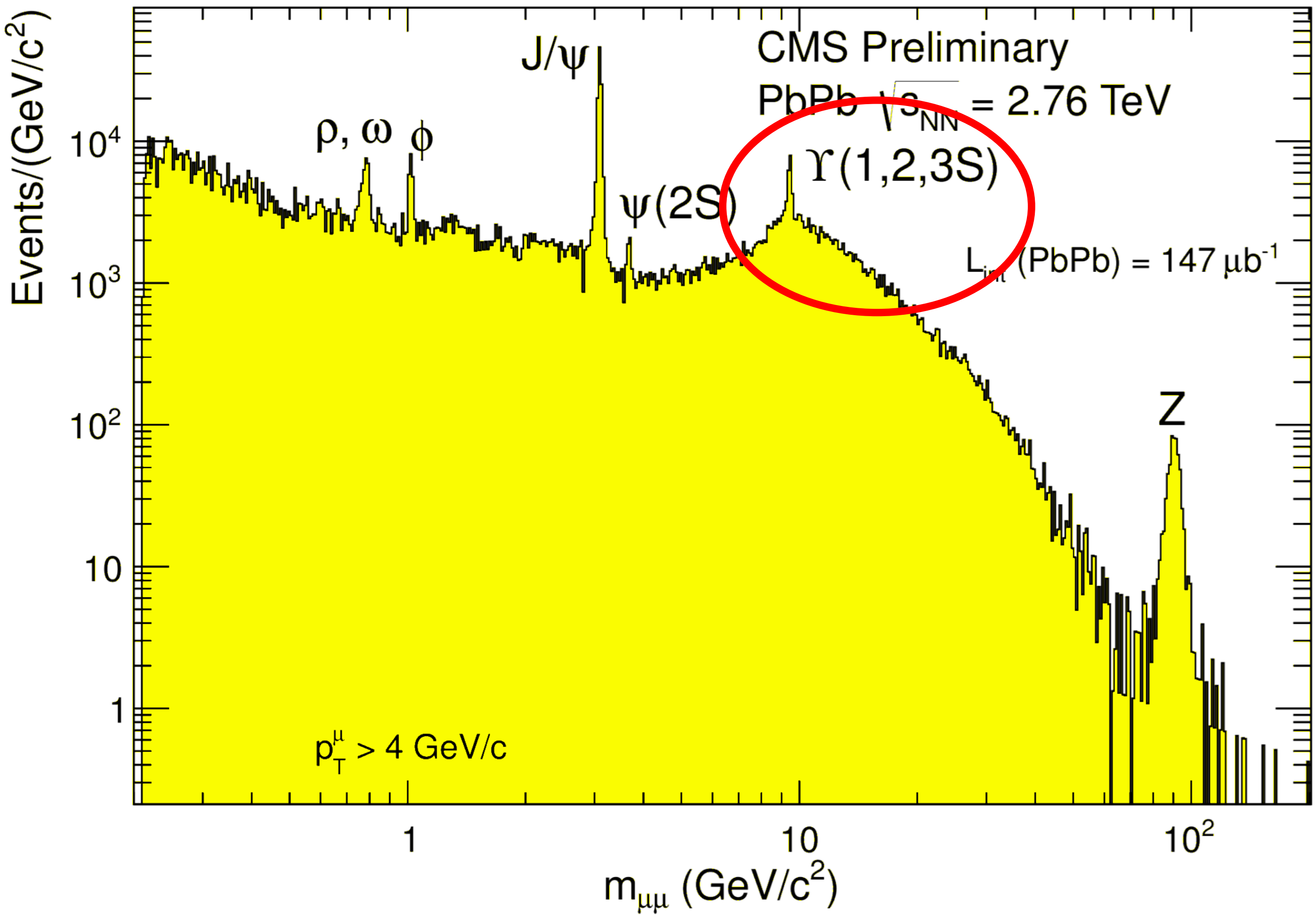
ψ' Suppression in PbPb

kinemtic coverage



$$\frac{\left(\frac{\psi(2S)}{J/\psi}\right)_{PbPb}}{\left(\frac{\psi(2S)}{J/\psi}\right)_{pp}}$$

- Odd relative suppression pattern
- CMS and ALICE don't overlap kinematically
- Large uncertainties !
- Picture not yet clear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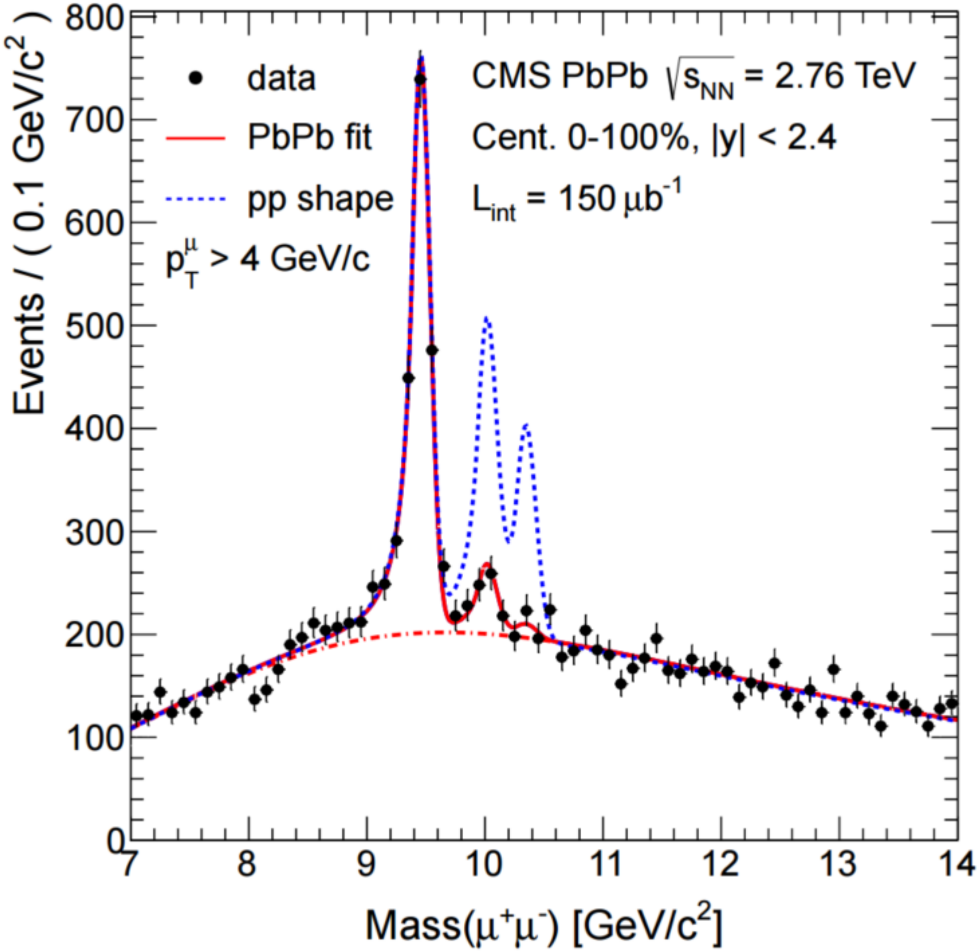
Towards Higher Mass…

PbPb

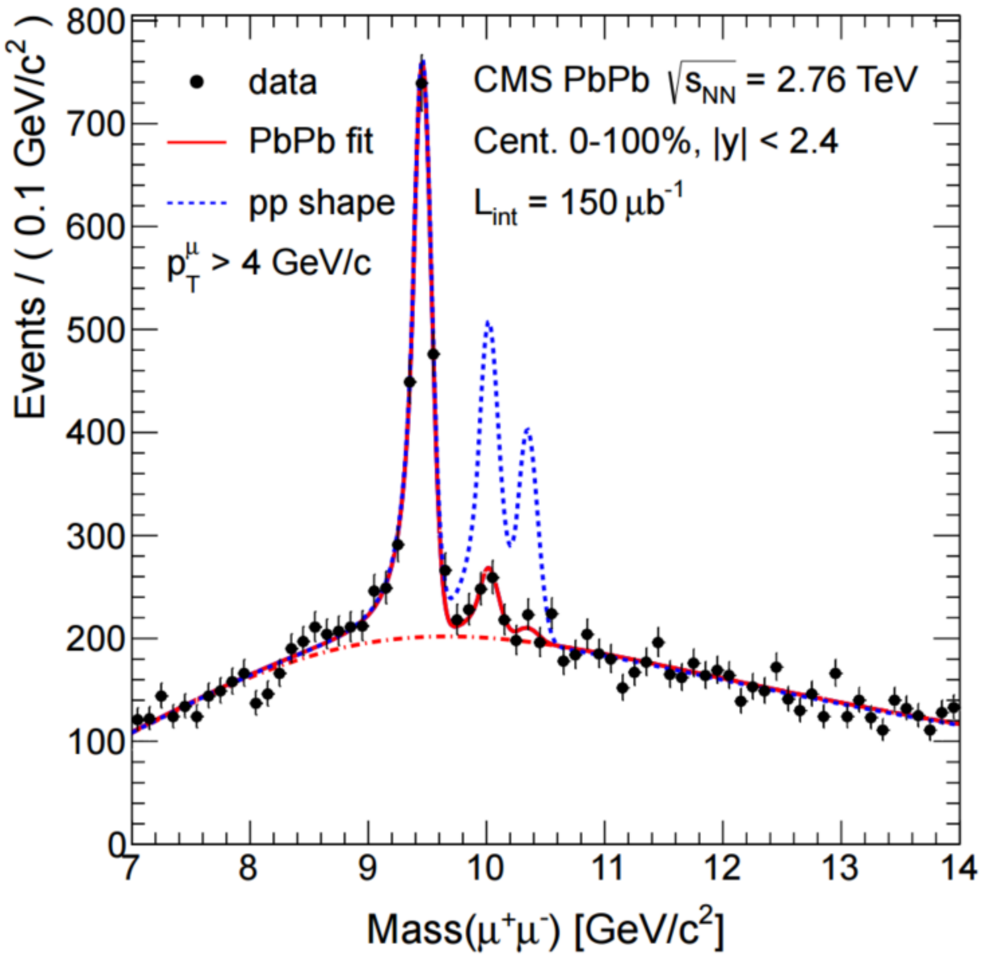


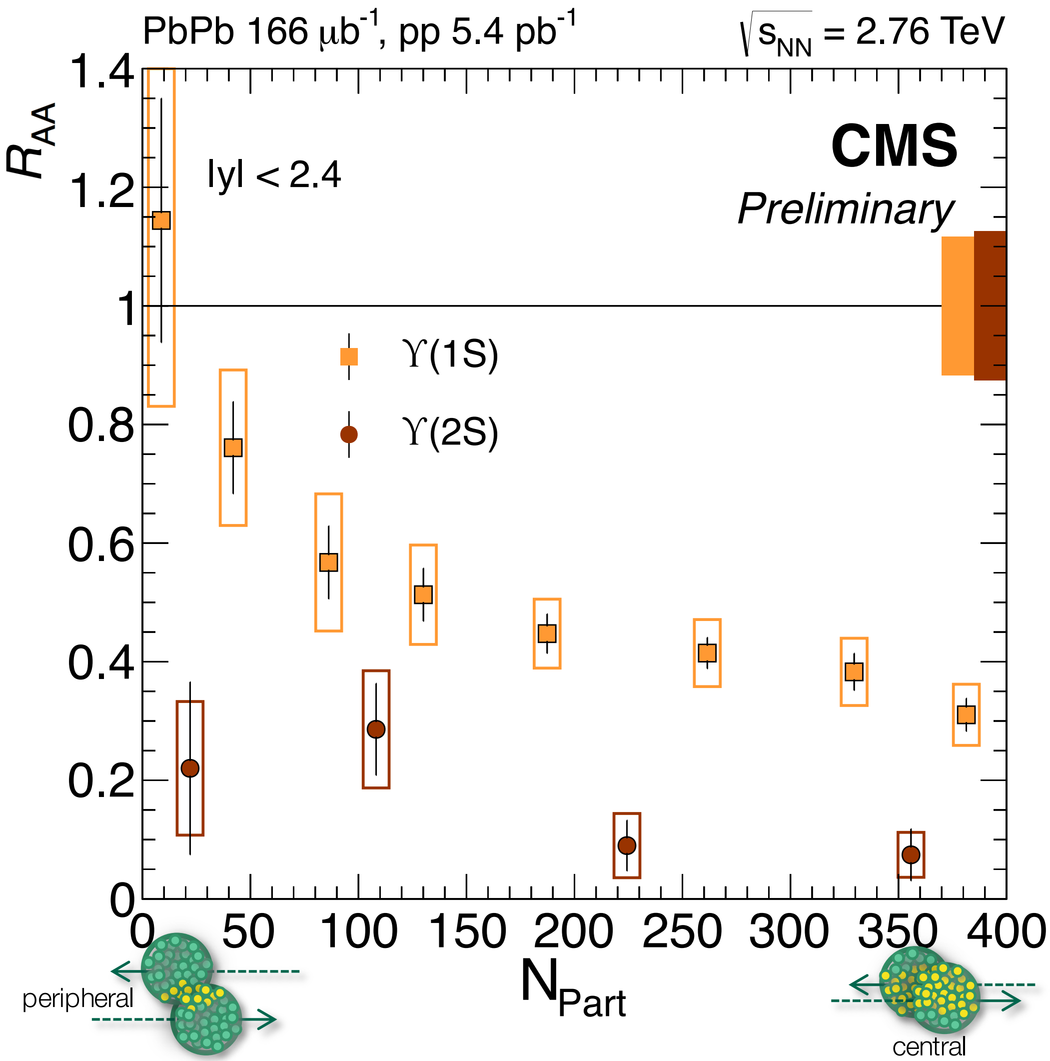
Advantages of bottomonium

- No feeddown from open heavy flavor to deal with.
- Recombination expected to be smaller
- Tightly bound 1S state expected not to melt much
- Higher b quark mass makes calculations more robust

However,

- Much (~20X) smaller production xsec than charmonium



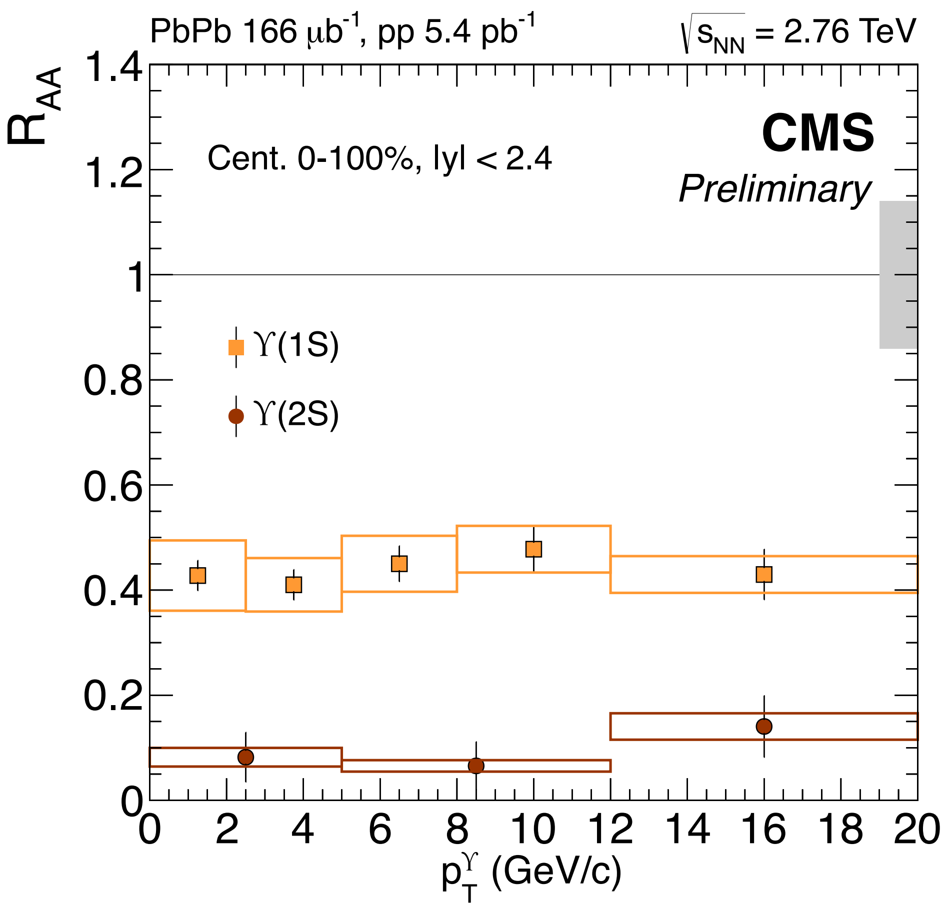


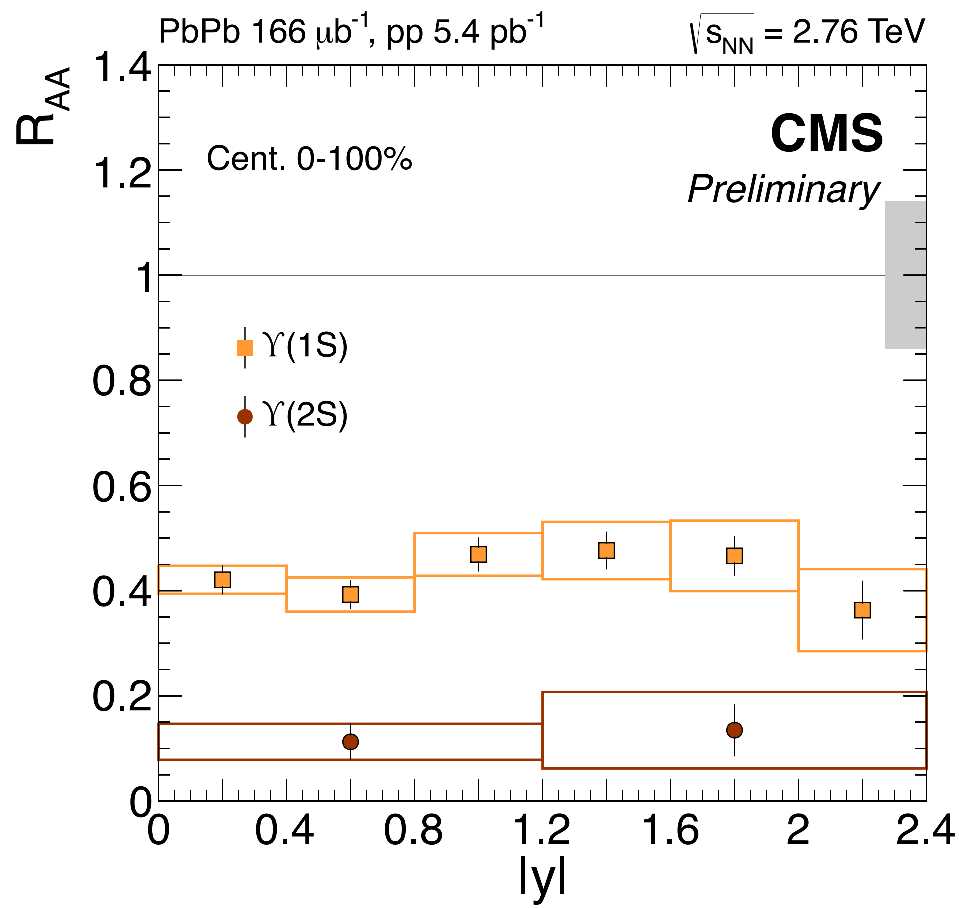
Sequential suppression of three states in order of their binding energy…

0-100% R_{AA} (Y(3S)) <0.1 (at 95% C.L.)

Upsilon Suppression in PbPb

vs p_T, vs rapidity





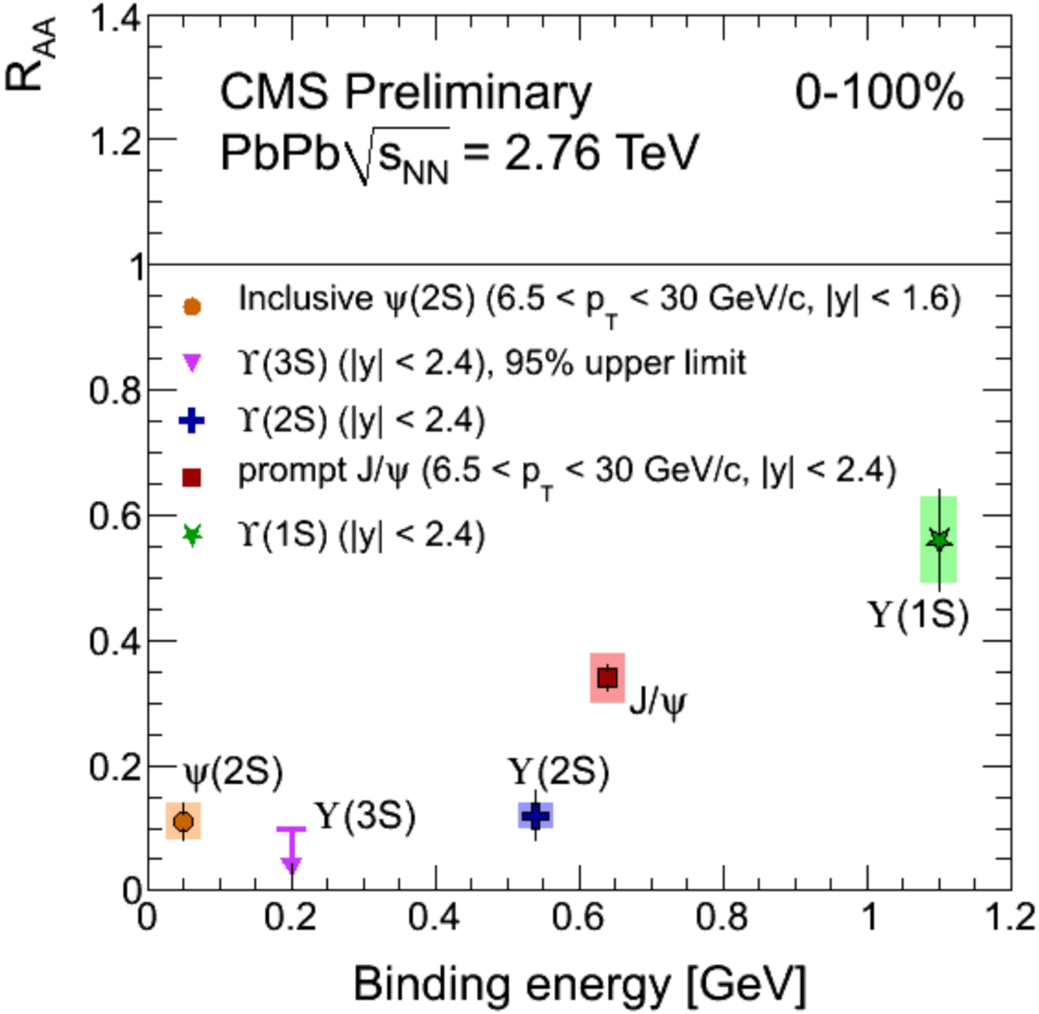
- Flat p_T dependence
- No apparent regeneration

- Flat rapidity dependence
- Uniform suppression

0-100% R_{AA} (Y(3S)) <0.1 (at 95% C.L)

The Thermometer

PbPb



- Under the caveat/assumption that low p_T J/ψ, ψ' effects are due to regeneration
- R_{AA} appears ordered with respect to binding energy !
- Need more data vs centrality
- Disentangle feeddown
- Unravel p_T dependence
- Must unfold cold nuclear effects (pPb)
- Calibrating/tuning the thermometer… Stay tuned for Run II

Initial State Effects ?

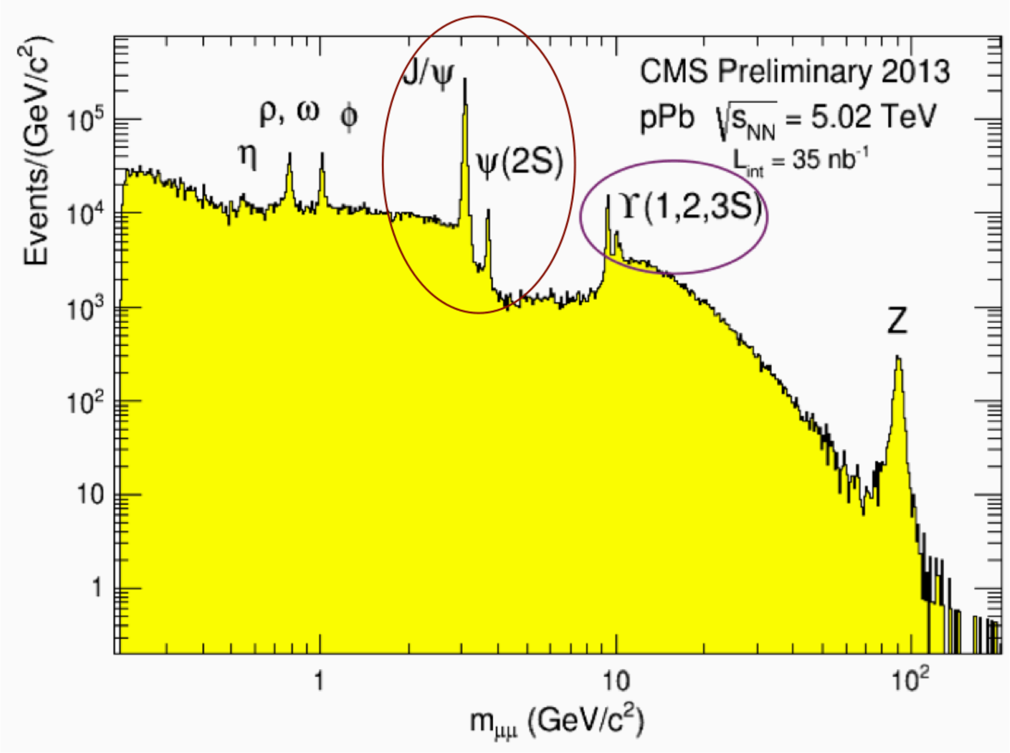
Two major effects in AA collisions:

- Thermal dissociation (breakup)
- Statistical regeneration (recombination)

Must disentangle pA effects:

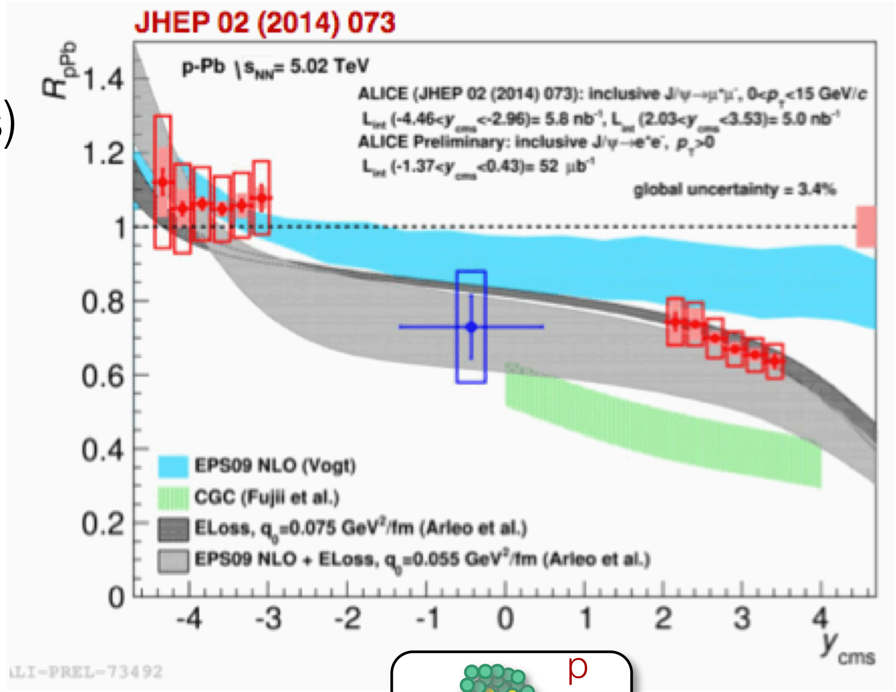
- PDF modifications in nuclei (shadowing)
- Gluon saturation
- Energy loss
- Nuclear absorption

- In addition, pA heavy flavor can help constrain nPDFs



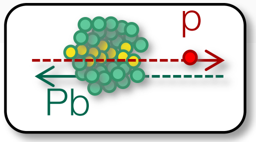
J/ψ Cold Nuclear Effects

rapidity



<u>Rapidity dependence of R_{pPb}:</u>

- Suppression in positive-y (low-*x* in Pb nucleus)
- Little modification at negative-y



Described reasonably well by models:

- NLO with ESP09 shadowing
- Coherent energy loss (w/wo ESP09)
- CGC models, less well

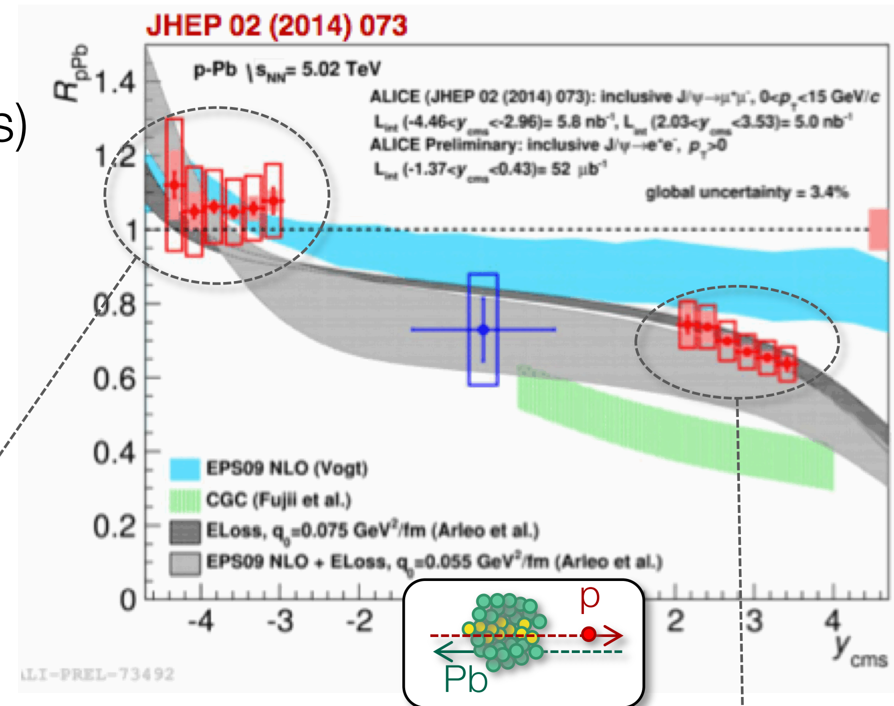
J/ψ Cold Nuclear Effects

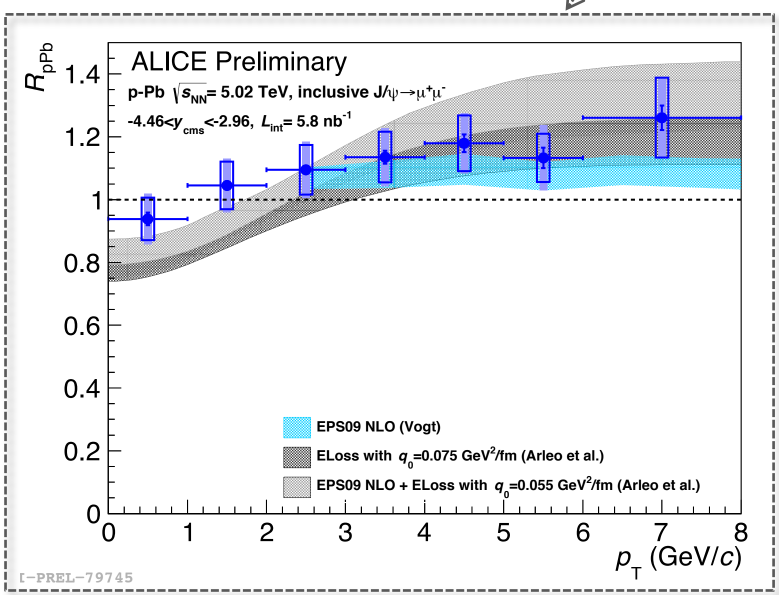
transverse momentum

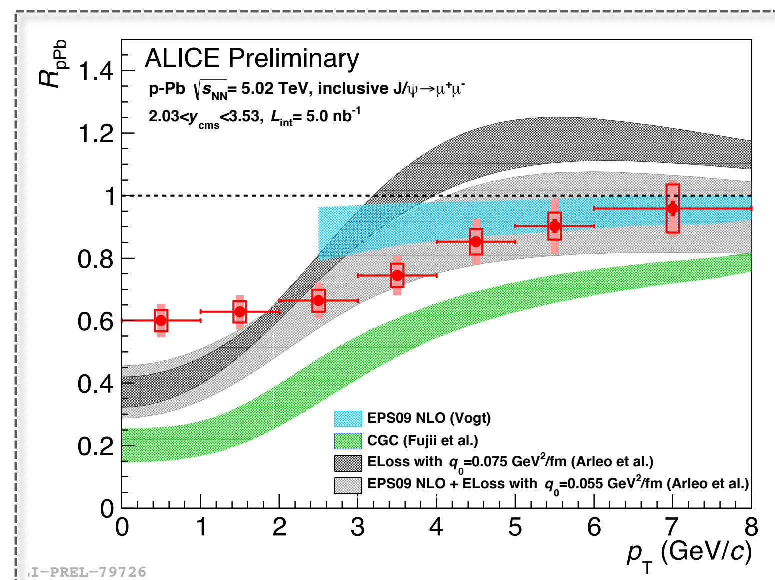
<u>Rapidity dependence of R_{pPb}</u>:
- Suppression in positive-y (low-*x* in Pb nucleus)
- Little modification at negative-y

<u>p_T dependence of R_{pPb}</u>:
- Suppression at low p_T

Described reasonably well by models:
- NLO with ESP09 shadowing
- Coherent energy loss (w/wo ESP09)
- CGC models, less well





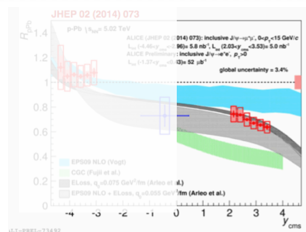


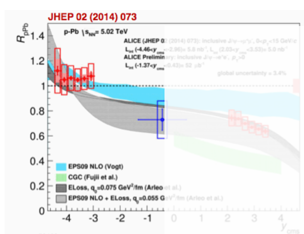
J/ψ Cold Nuclear Effects

inter-experiment agreement

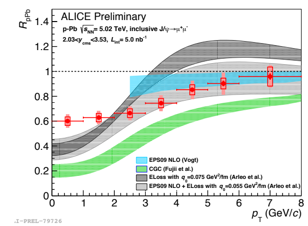
R_{FB} = ratio of *forward/backward*

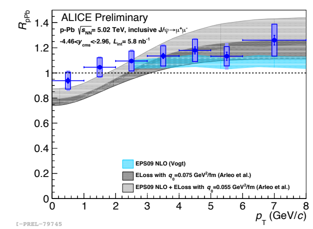
$R_{FB}(y) =$

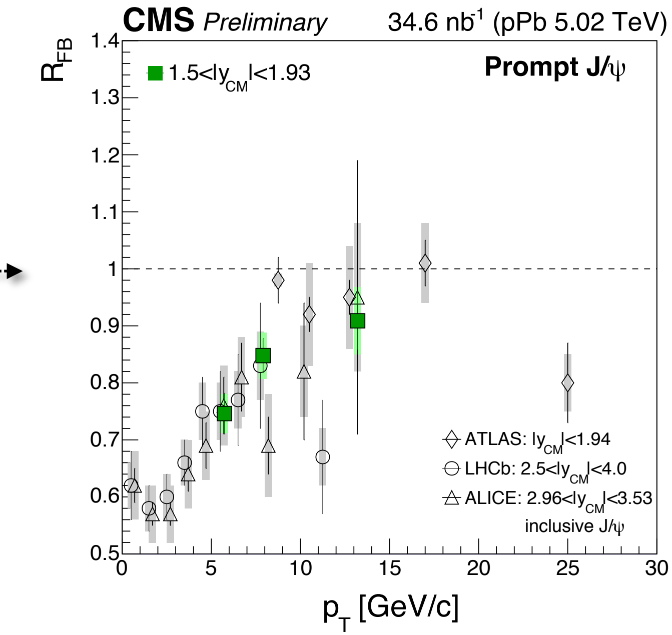


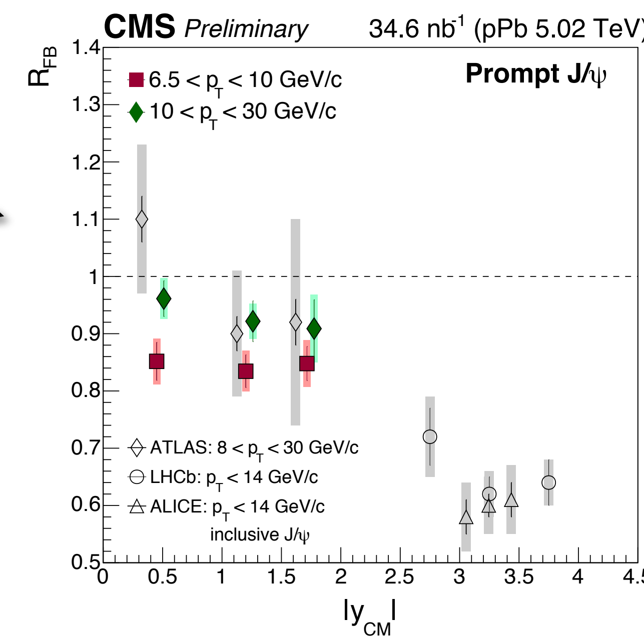


$R_{FB}(p_T) =$









Agreement between all LHC experiments

- Supports picture of low-x gluon shadowing
- More prevalent at low p_T

ψ’

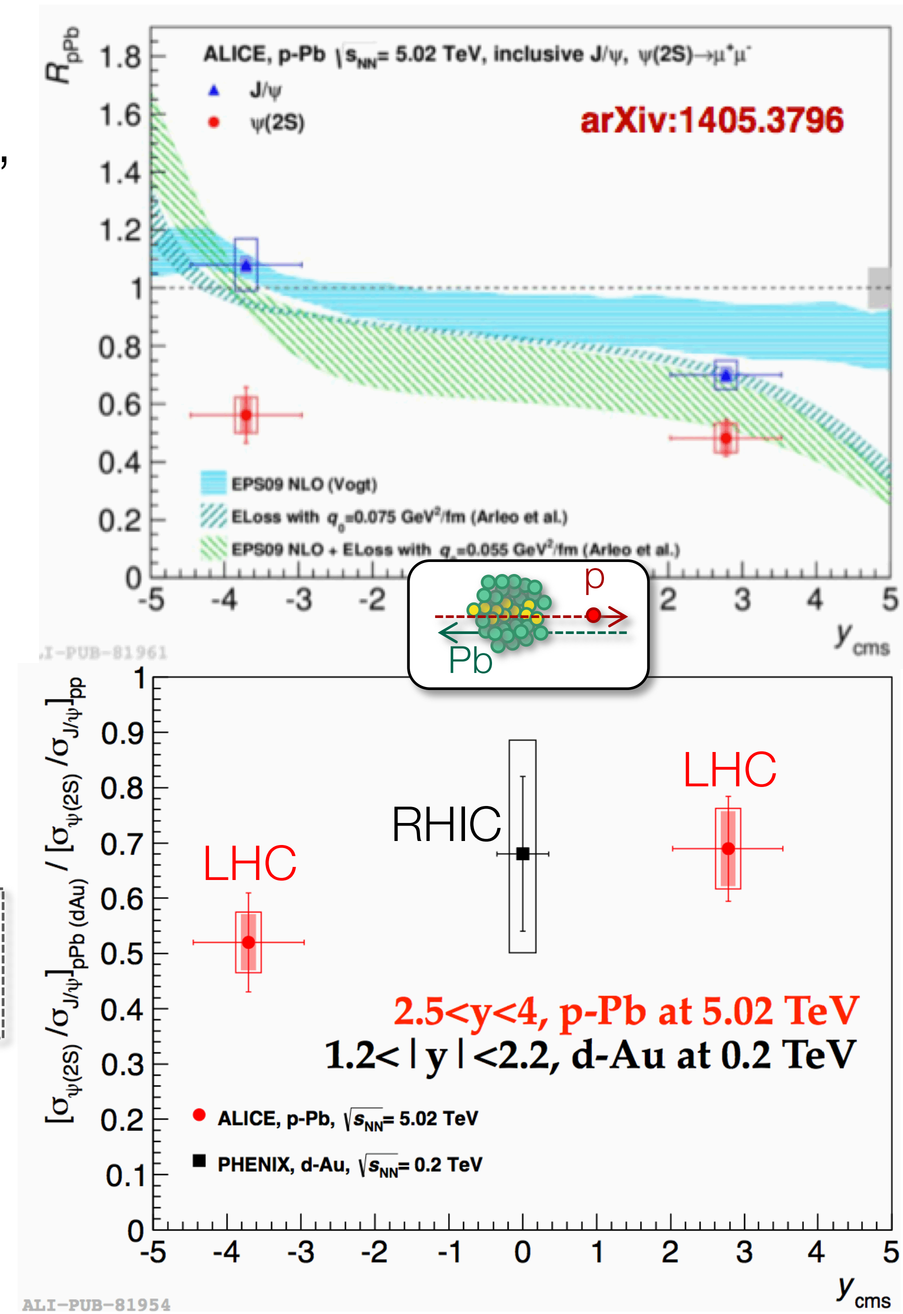
relative to J/ψ

Rapidity dependence of R_{pPb}:

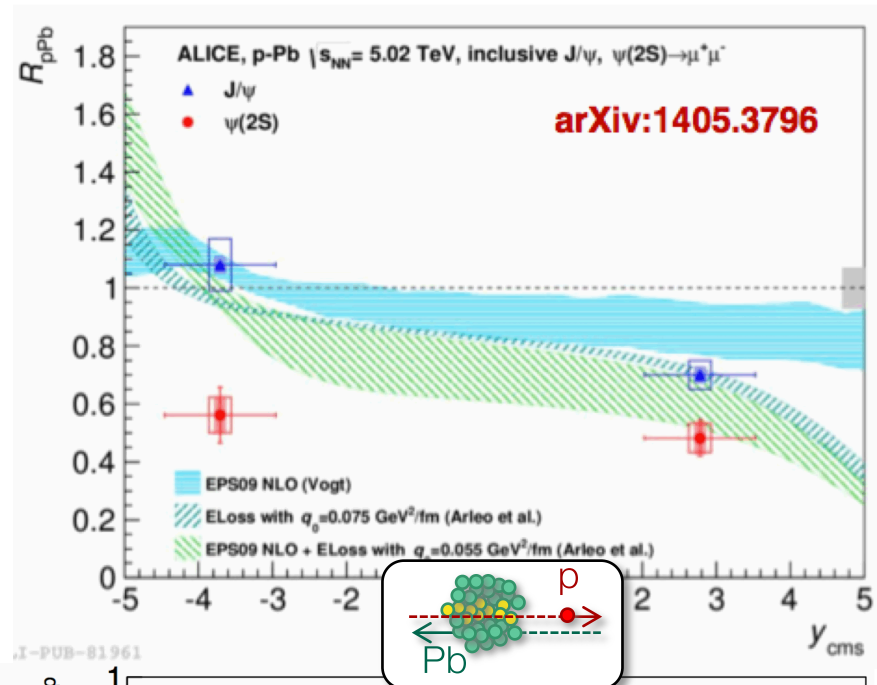
- ψ’ is more suppressed than J/ψ
- Models predict similar behavior for J/ψ and ψ’
- Ratio of R_{pA} for ψ’ to J/ψ similar at RHIC
  - RHIC: 200 GeV, d+Au

- Hints at final state effect?
- Unexpected since charmonia formation time larger than $c\bar{c}$ crossing time in nucleus

$$\frac{R^{\psi(2S)}_{\mathrm{pPb}}}{R^{\mathrm{J}/\psi}_{\mathrm{pPb}}} = \frac{\sigma^{\psi(2S)}/\sigma^{\mathrm{J}/\psi}\big|_{\mathrm{pPb}}}{\sigma^{\psi(2S)}/\sigma^{\mathrm{J}/\psi}\big|_{\mathrm{pp}}}$$



ψ’
relative to J/ψ



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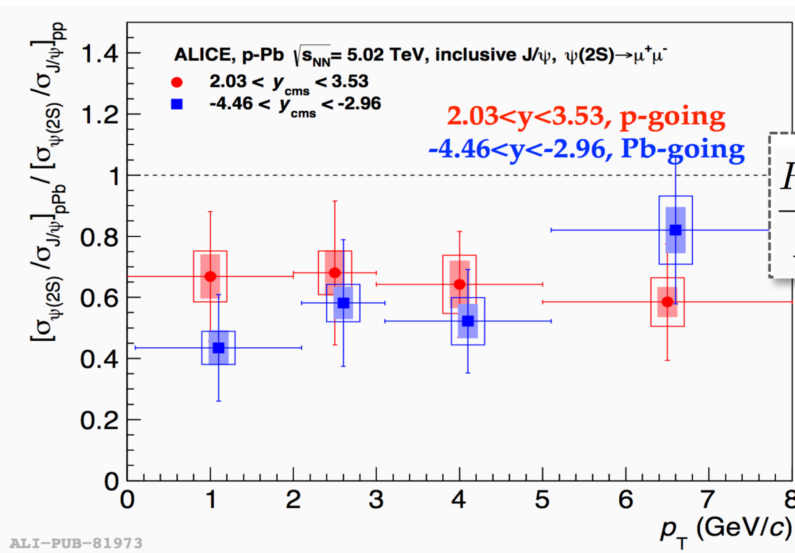
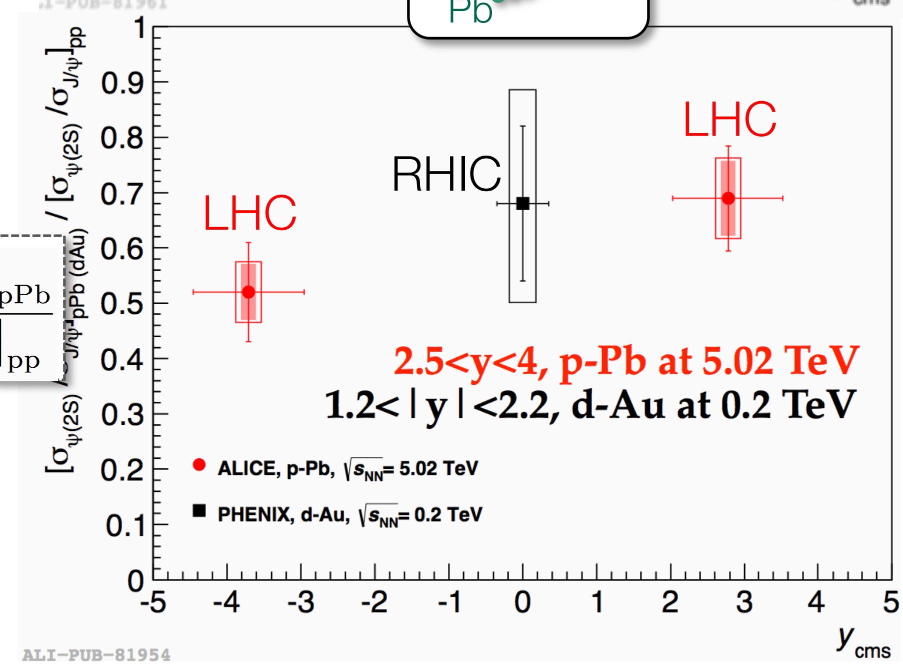
p_T dependence of relative R_{pPb}:

- Constant, within uncertainties

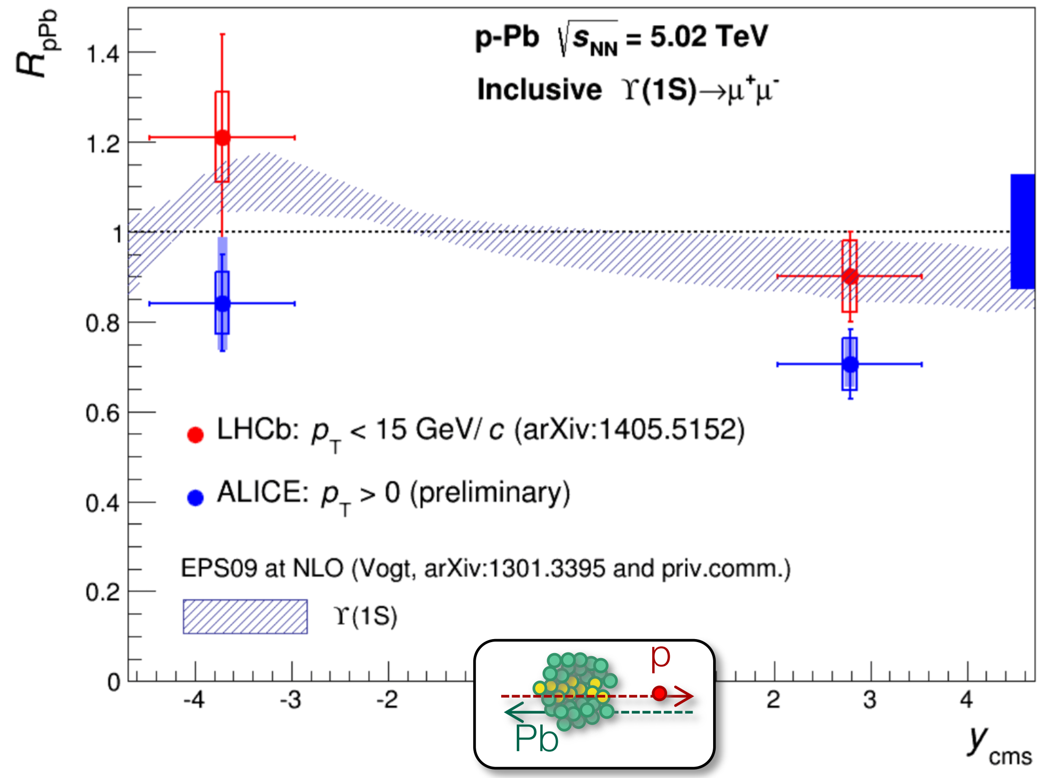


$$\frac{R_{pPb}^{\psi(2S)}}{R_{pPb}^{J/\psi}} = \frac{\sigma^{\psi(2S)}/\sigma^{J/\psi}\big|_{pPb}}{\sigma^{\psi(2S)}/\sigma^{J/\psi}\big|_{pp}}$$



Upsilon 1S

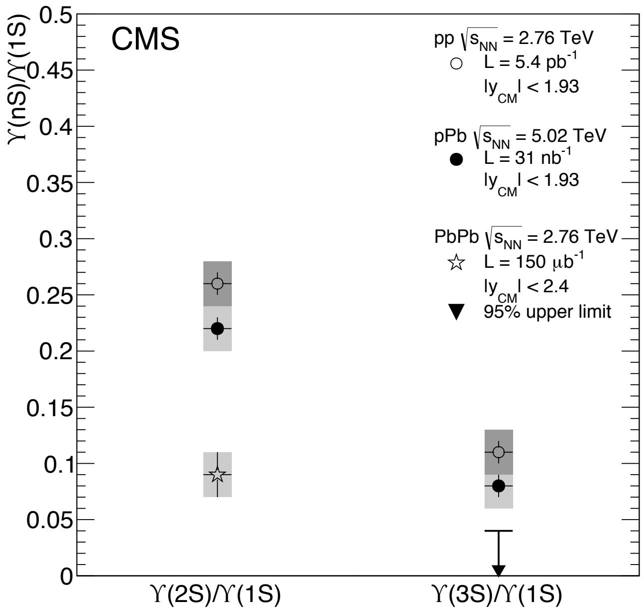
pPb



- Y(1S) agrees with NLO (+ nuclear modification)
  - Similar to J/ψ though different PDF scale

Upsilon 2S,3S

pPb



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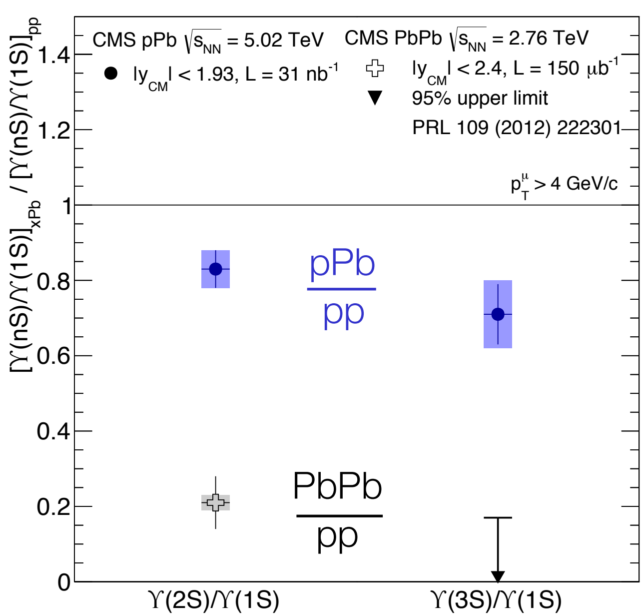
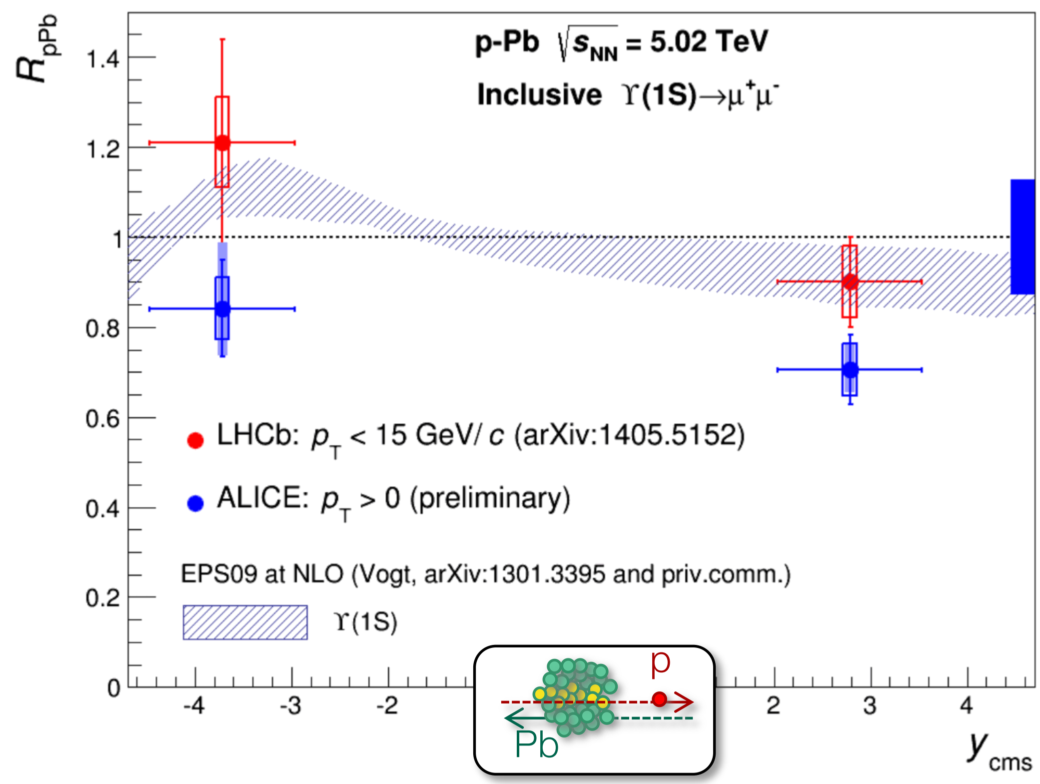




- Y(1S) agrees with NLO (+ nuclear modification)
  - Similar to J/ψ though different PDF scale
- Small relative suppression of 2S,3S wrt 1S at mid-rapidity
- CNM cannot account for effects observed in PbPb

Summary

Quarkonia serve as a useful probe of QGP

Illuminate two primary mechanisms:

- **Thermal dissociation**
  - Sequential melting of quarkonia bound states with binding energy
  - Y and high p_T (J/ψ) and central collisions
- **Statistical regeneration**
  - Pairing of random quarks in the medium
    - Relevant for LHC !
  - Low p_T ψ family

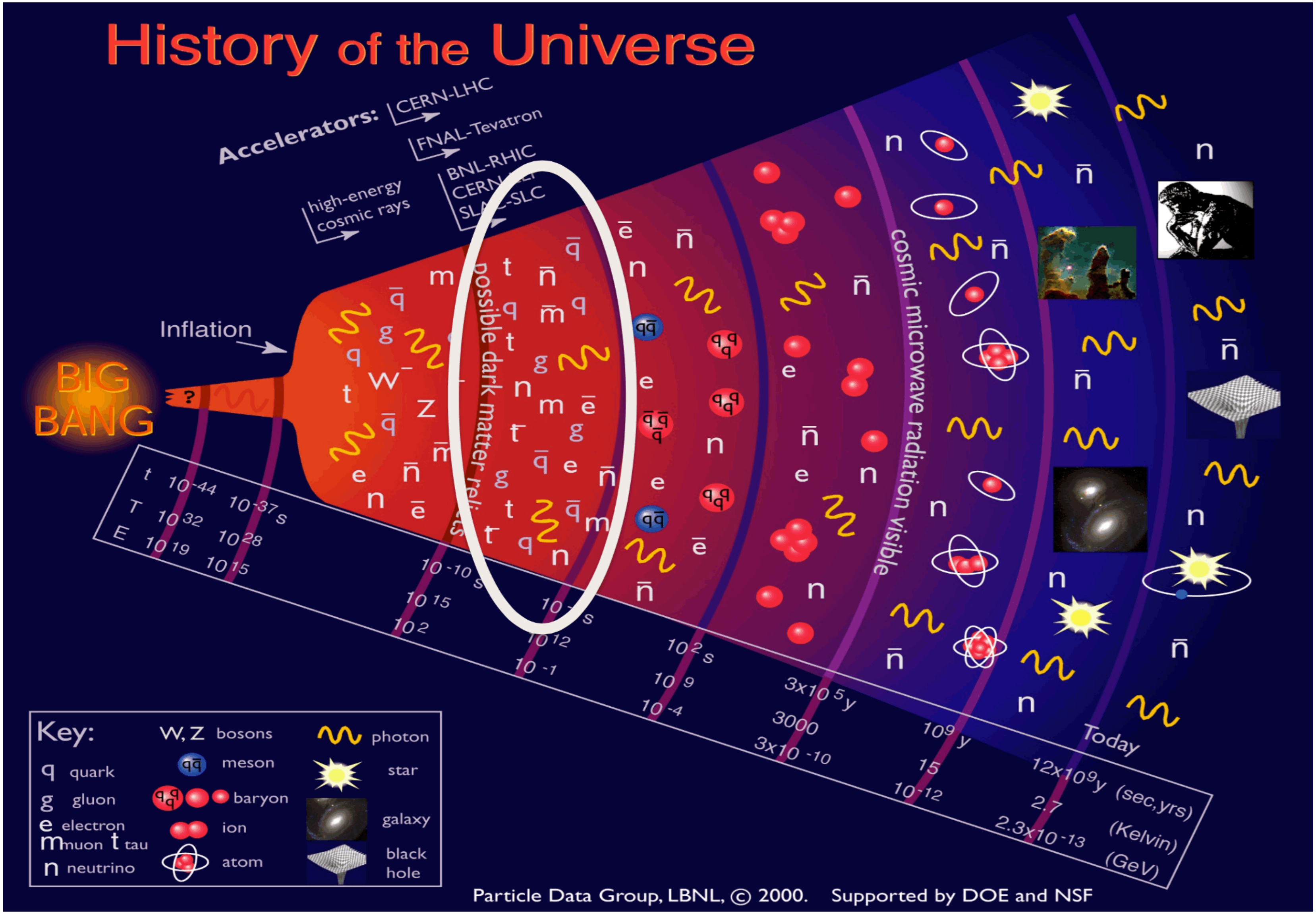
- Cold nuclear effects are relevant!

- QGP "thermometer" is tantalizingly close
  - Run II will provide higher precision for more differential measurements

Backups

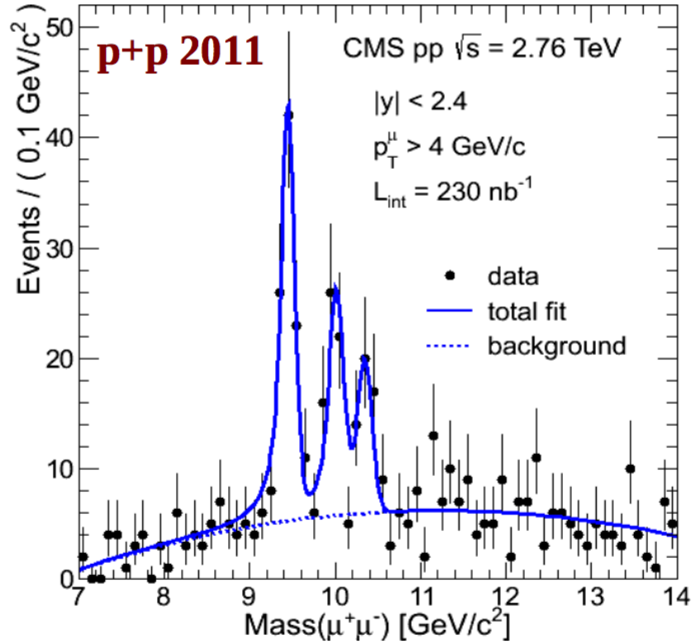
History of Universe

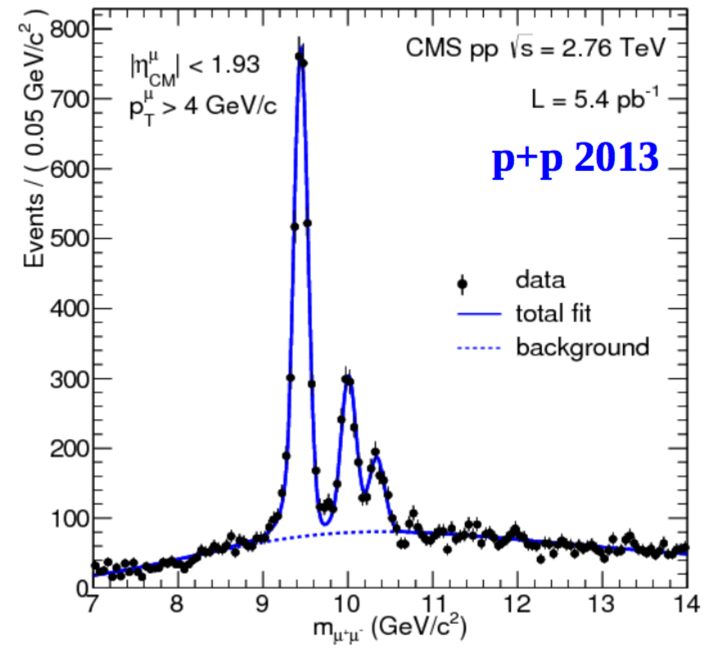
evolution

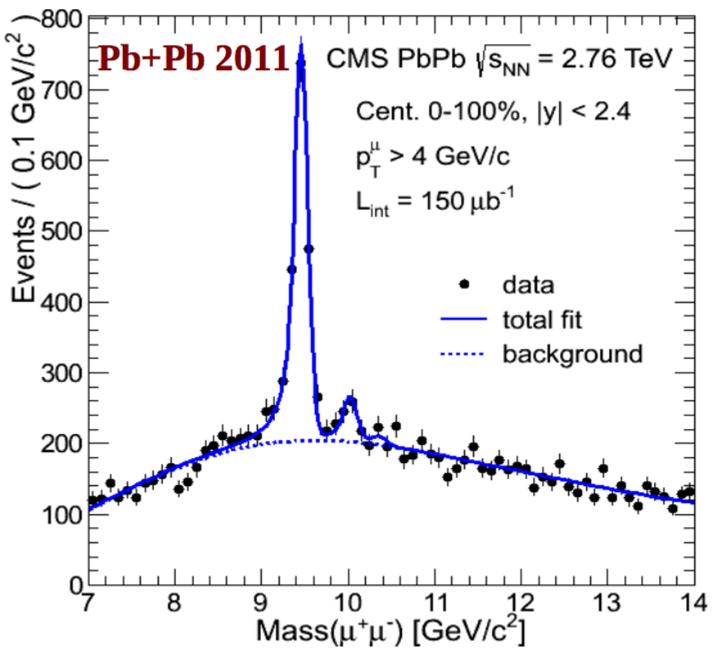


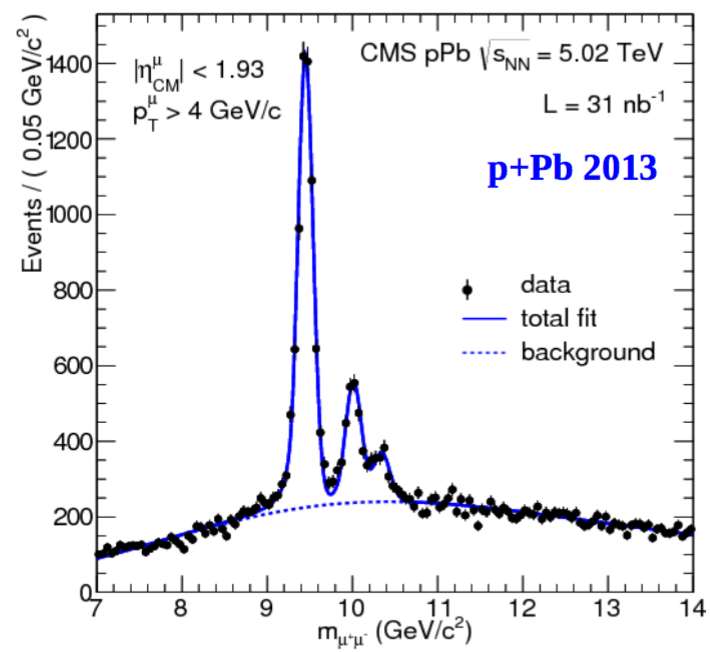
Upsilon Mass Spectra

systems of interest

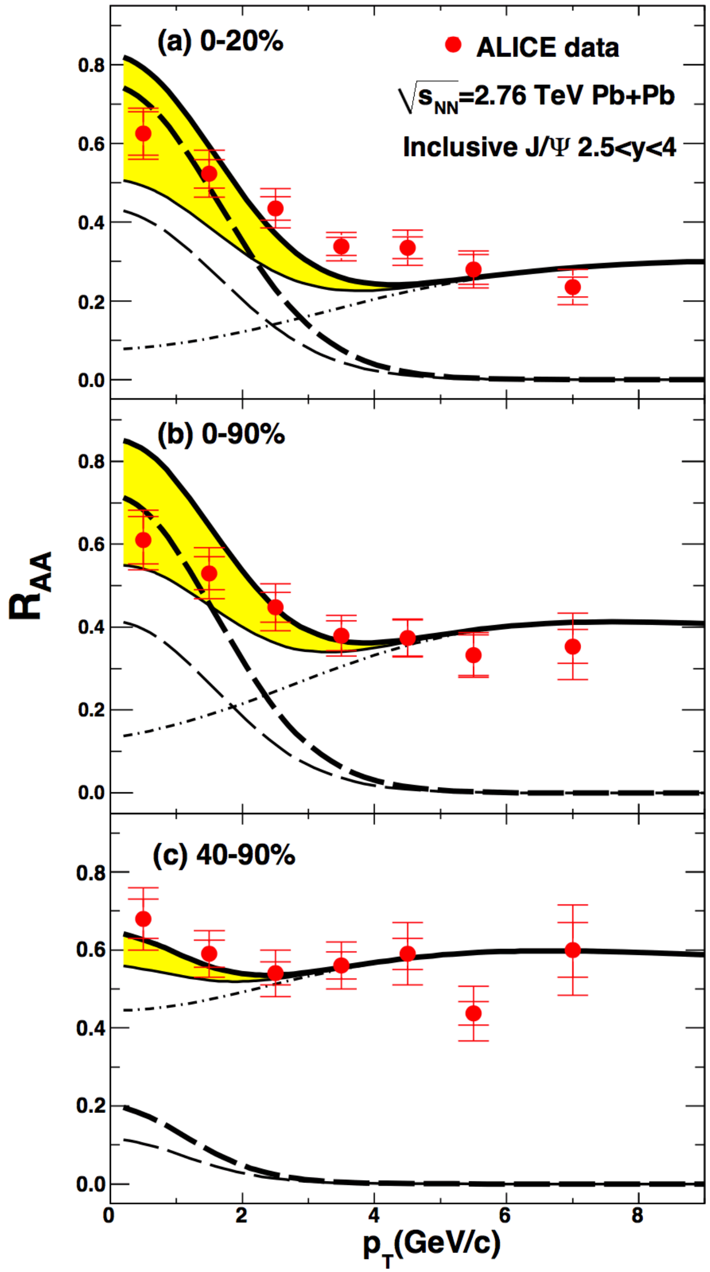




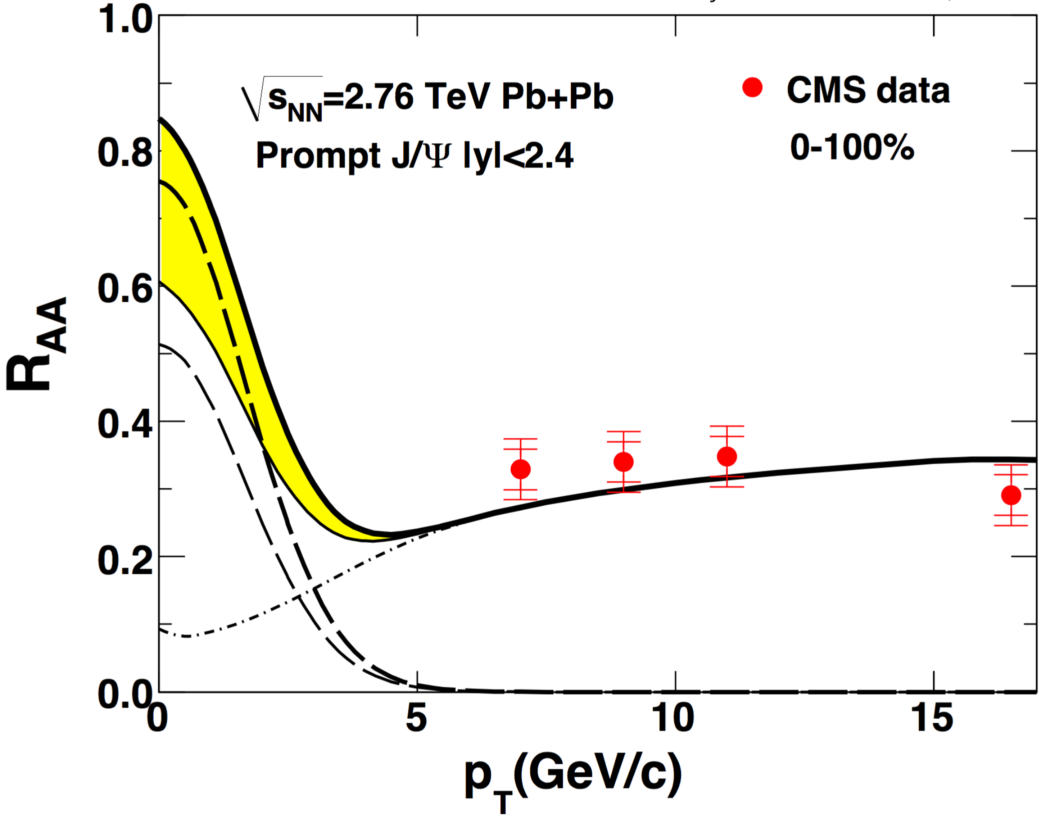




Regeneration
J/ψ



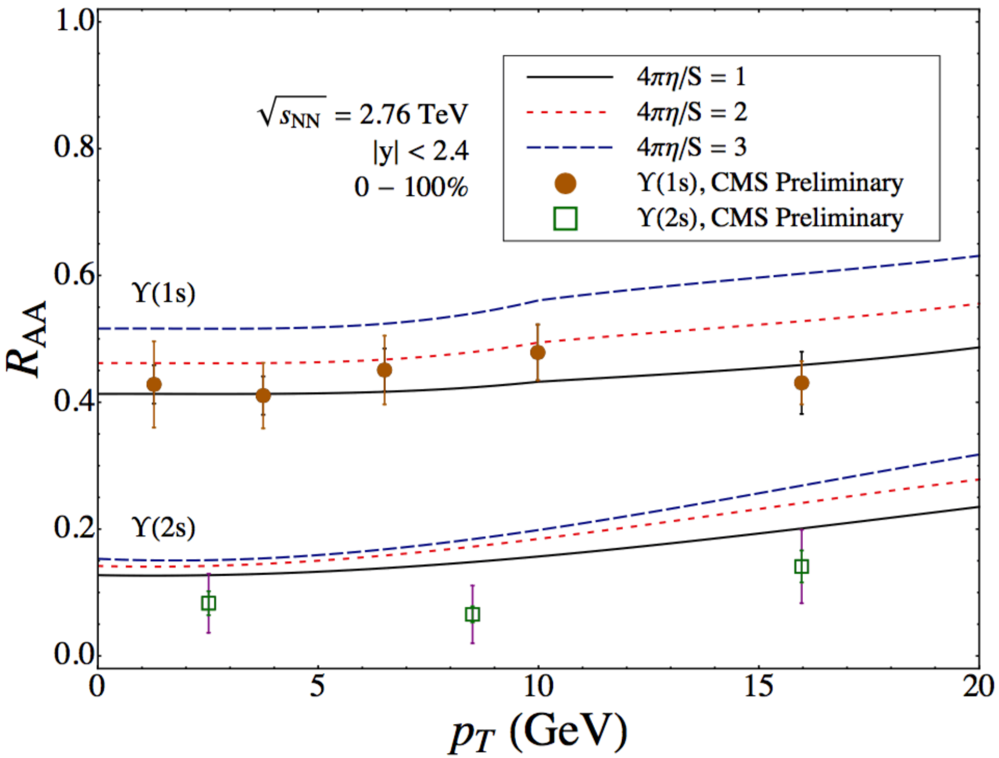
PhysRevC.89.054911, 2014

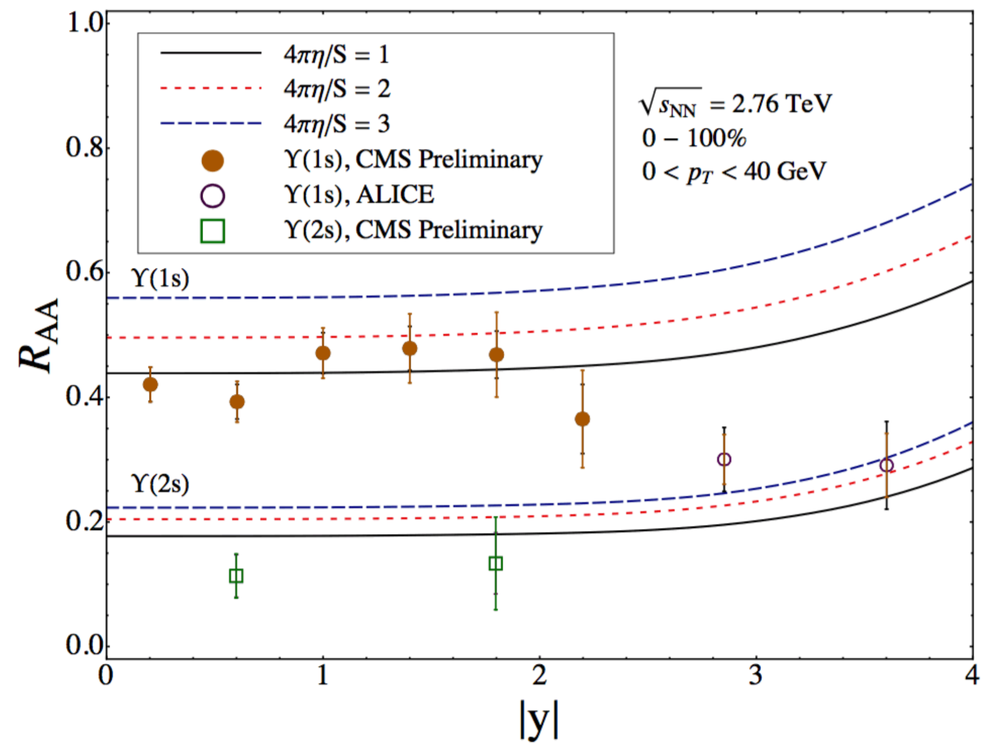


- Regeneration limited to ~p_T < 4 GeV/c

Upsilon Suppression

PbPb





- Flat p_T dependence
- No apparent regeneration

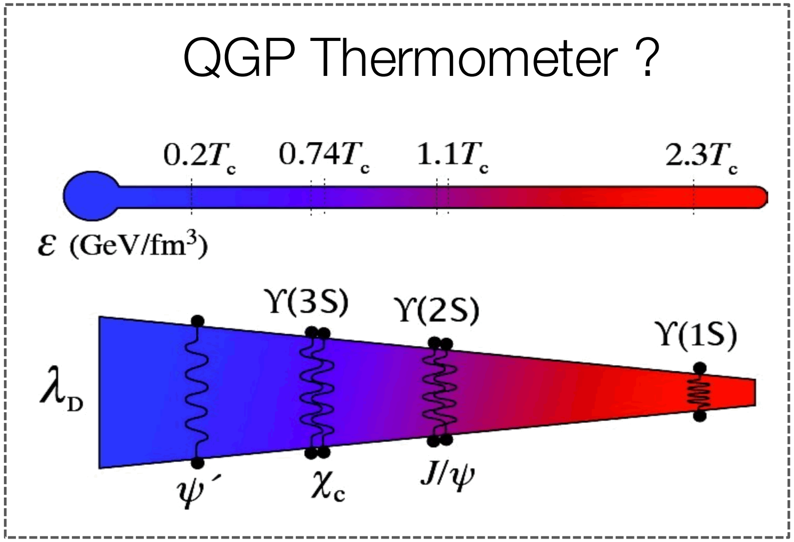
- Flat rapidity dependence
- Uniform suppression

- Latest calculations match

Quarkonia Modifications

Thermal Dissociation (quarkonia "melting")

- Can QQ survive temperature of QGP ?
- Color screening in deconfined plasma dissolves QQ bound states
- Hierarchy in binding energies leads to thermometer



Statistical Regeneration

- Heavy quarks re-combining
- As cc multiplicity rises, probability to randomly "pair up" increases…
- Can lead to charmonium enhancement !
- Effect limited to p_T < 4 GeV/c

Most Central A-A Collisions	SPS 20 GeV	RHIC 200 GeV	LHC 2.76 TeV
$N_{c\bar{c}}$/event	~0.2	~10	~60