Quarkonia as a Probe of QCD Matter: From LHC to FAIR

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Outline

Quarkonia in heavy-ion physics

Quark-Gluon Plasma (QGP)

J/ψ-suppression as QGP signature

Reference measurements: pp and pA

New effects at high energies (LHC)

Overview on existing results

SPS at CERN
RHIC at BNL
LHC at CERN

Outlook on future experiments

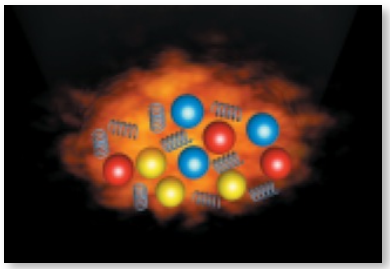
CBM at FAIR

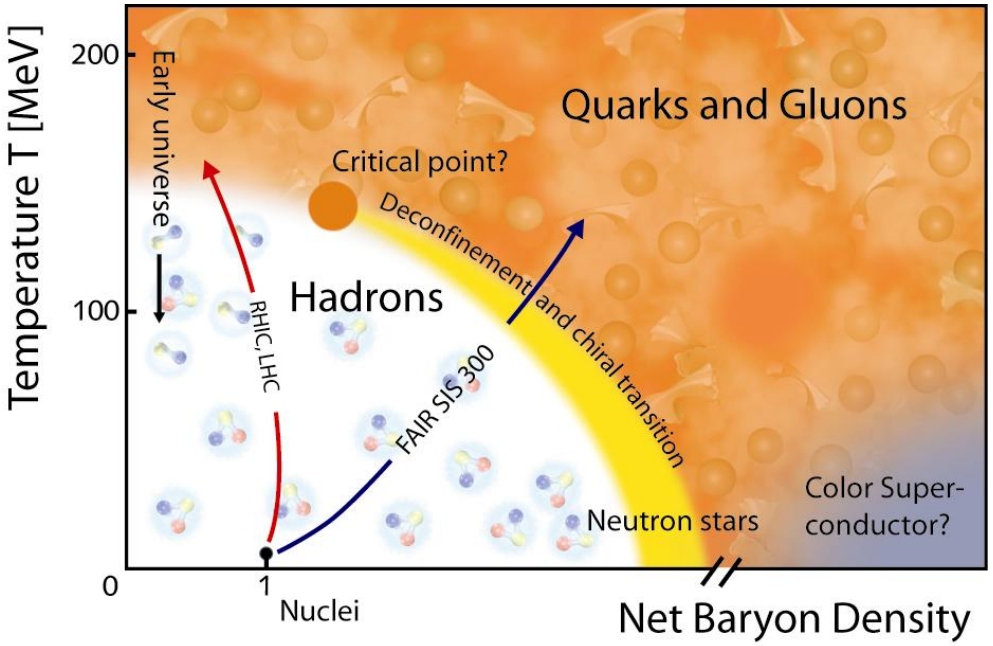
Heavy-Ion Physics
The QCD Phase Diagram

Quark-Gluon Plasma

Deconfined medium of quarks and gluons

Free color charges





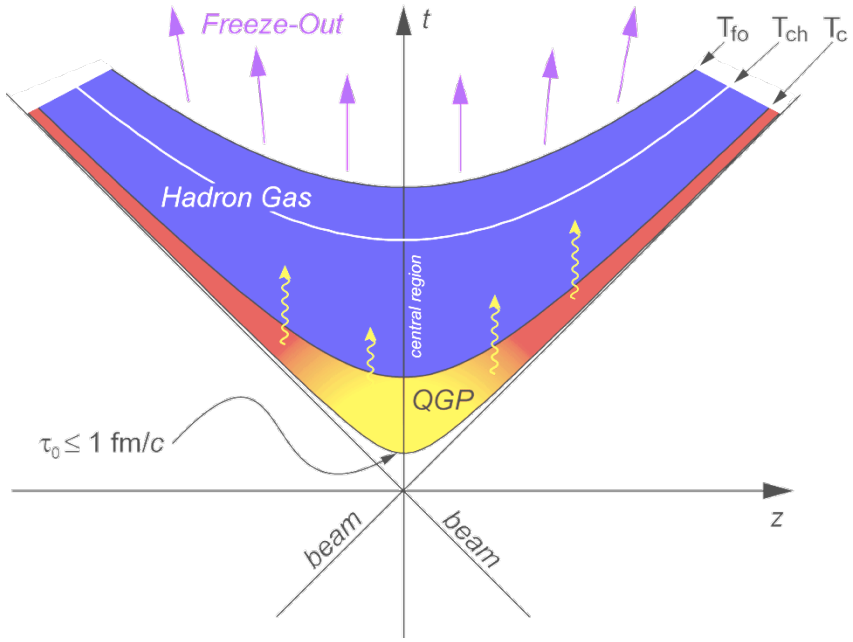
Phases of QCD Matter

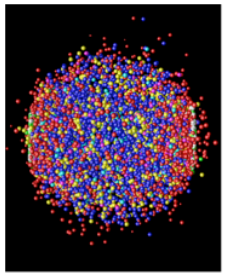
Areas of different densities and temperatures can be probed at different collision energies

Nature of deconfinement phase transition (1st order ⇔ cross over) ?

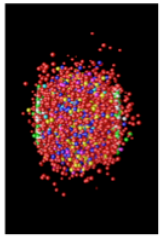
Properties of QGP matter ?

Heavy-Ion Physics
Time Evolution

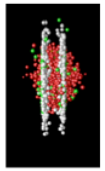




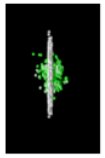
Freeze-Out



Hadronization



QGP formation



Initial hard scatterings

Incoming nuclei

Stages of a heavy ion collision

Lifetimes of the various stages depend on collision energy

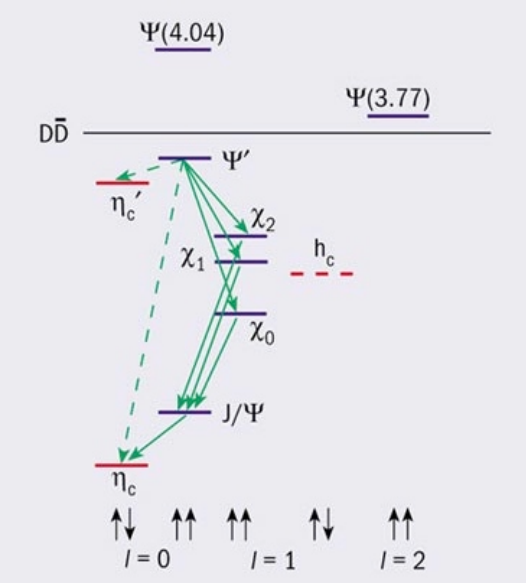
Need observable that is sensitive to early stages

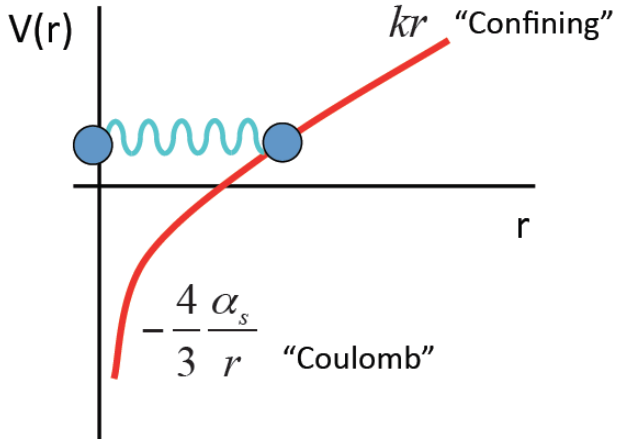
Bound states of heavy quark-antiquark pairs

Heavy: charm ($m_c \approx 1.3$ GeV)
beauty ($m_b \approx 4.7$ GeV)

Stable since $M_{cc} < 2\,M_D$ or $M_{bb} < 2\,M_B$

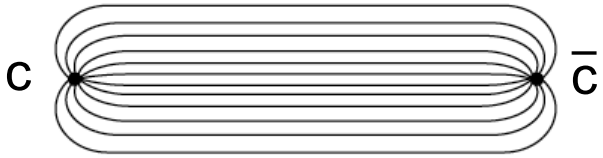
Non-relativistic description with potential





Cornell-potential

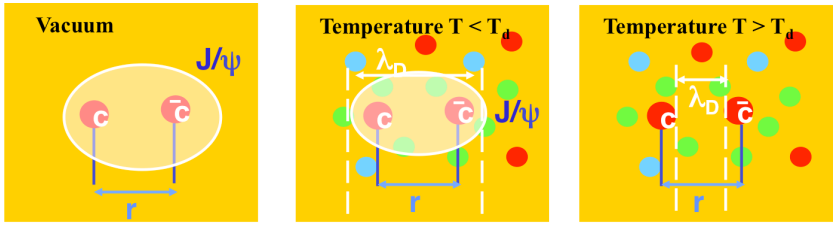
$$V_{q\bar{q}}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + k \cdot r$$



Heavy-Ion Physics
J/ψ Suppression as QGP Signature

Quark-Gluon Plasma (QGP)

Color charges in deconfined medium
⇒ screening of $q\bar{q}$-potential



Screening condition: $r > \lambda_D$

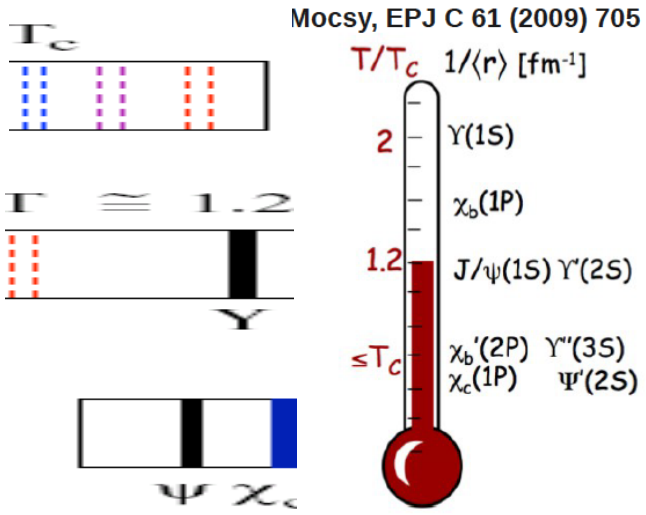
J/ψ suppression as QGP signature
T. Matsui and H. Satz, Phys. Lett. **B178**, 416 (1986).

Temperature dependent screening length λ_D
⇒ larger states are more easily dissociated

QGP thermometer

Different sensitivity of quarkonia states

State	J/ψ	χ_c	ψ(2S)	Υ(1S)	Υ(2S)	Υ(3S)
M(GeV)	3.10	3.53	3.69	9.46	10.0	10.36
ΔE (GeV)	0.64	0.20	0.05	1.10	0.54	0.20
r_o(fm)	0.25	0.36	0.45	0.28	0.56	0.78



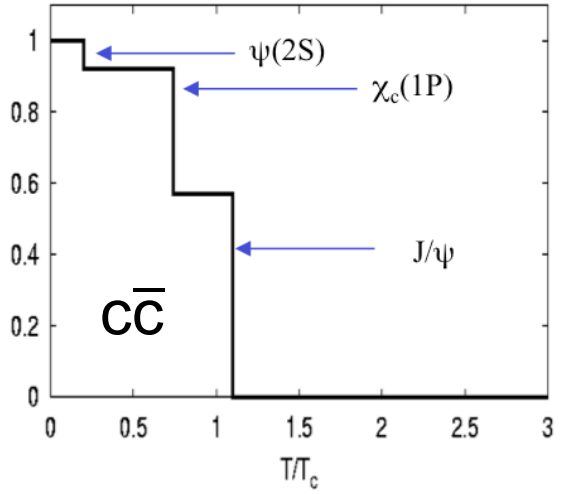
Heavy-Ion Physics
J/ψ Suppression as QGP Signature

Sequential melting pattern

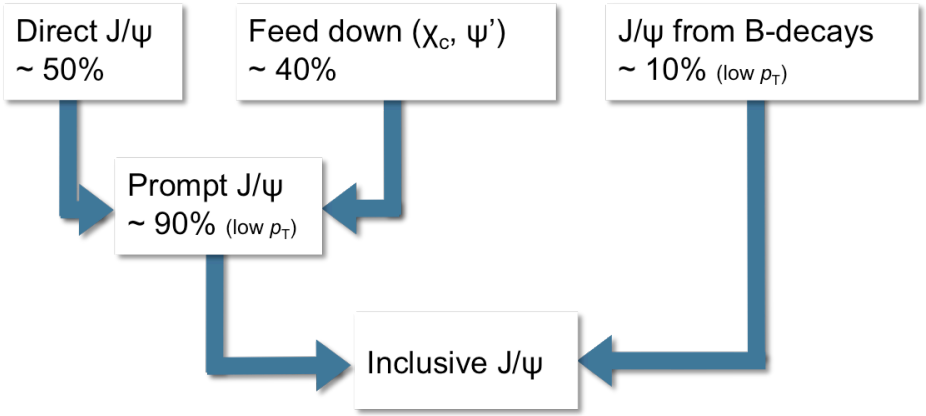
Heavier systems are more easily dissolved

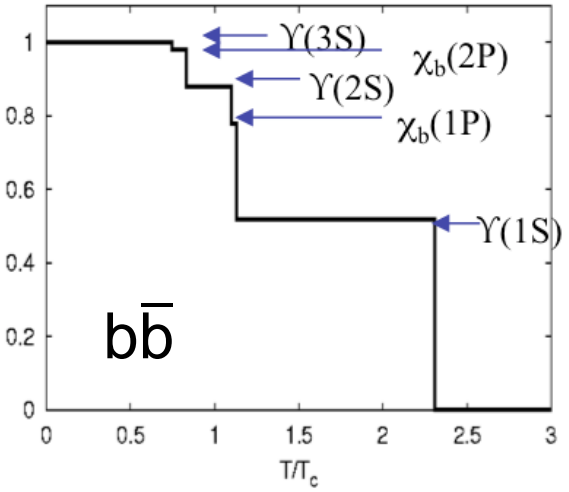
Reduction of feed down contribution, e.g.:

$$S_{J/\psi} = 0.6S^{dir}_{J/\psi} + 0.3S^{dir}_{\chi} + 0.1S^{dir}_{\psi'}$$



Contributions to inclusive J/ψ (LHC)





Heavy-Ion Physics
Reference: Proton-Proton Collisions

Proton-proton as reference for heavy-ion

Nuclear modification factor:

$$R_{AA} = \frac{\sigma^{pp}_{inel.}}{N_{coll}} \frac{\mathrm{d}^2 N^{AA}/(\mathrm{d}p_T \mathrm{d}y)}{\mathrm{d}^2 \sigma^{pp}/(\mathrm{d}p_T \mathrm{d}y)}$$

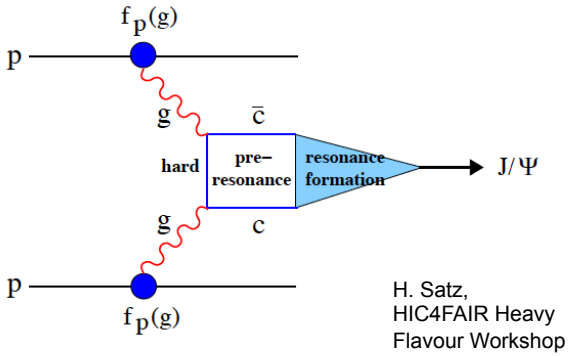
Quarkonia production in pp as hard process: scaling with $\boldsymbol{N_{coll}}$

Understanding of elementary production processes

Hard scattering ⇒ pre-resonance ⇒ bound state

Timescales:

0.05 fm		0.25 fm	
hard		pre–resonance	resonance
$\tau_{c\bar{c}} = 1/2m_c$		$\tau_g = 1/\sqrt{2m_c \Lambda_{qcd}}$	



H. Satz, HIC4FAIR Heavy Flavour Workshop

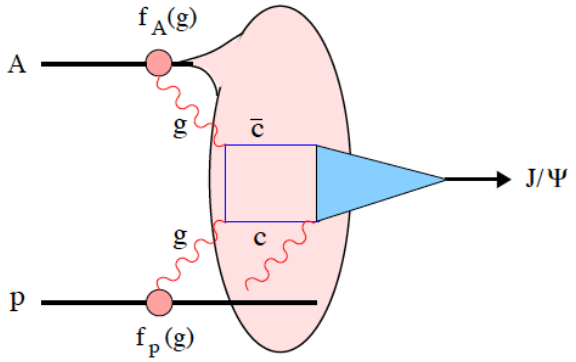
Formation of colorless state addressed in different model approaches:

- Color Singlet Model (CSM)
- Color Evaporation Model (CEM)
- NRQCD, includes Color Octet (CO) contribution

Heavy-Ion Physics
Reference: Proton-Nucleus Collisions

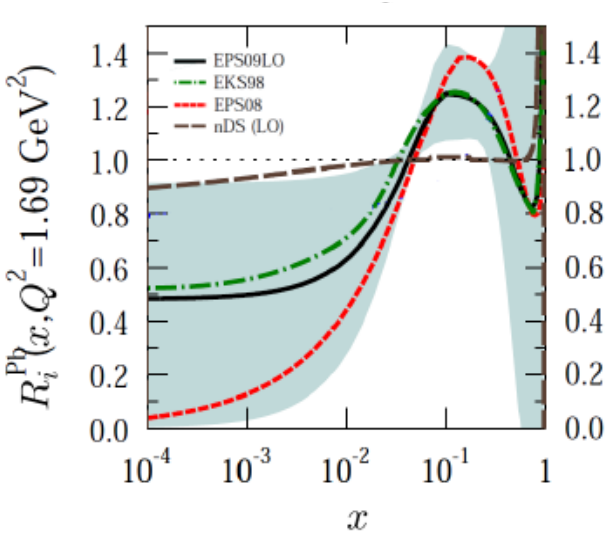
Cold Nuclear Matter (CNM) effects
Not QGP related effects affecting
J/ψ production in nuclear matter

Important for the interpretation of heavy-ion data



Nuclear absorption
Dominant at SPS (formation time ≈ collision time)
Small at LHC (formation time ≫ collision time)

Gluon shadowing
Large at LHC (small Bjørken-*x*),
but large uncertainties at low Q^2



Other effects
Gluon saturation (?)
Initial state energy loss of incoming parton

Heavy-Ion Physics
New Mechanisms at LHC Energies

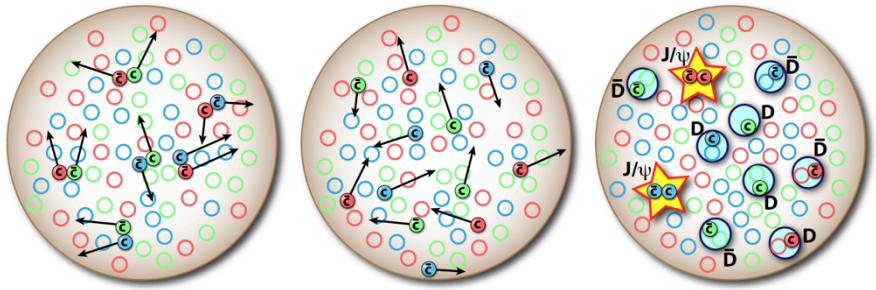
Regeneration

Large number of $c\bar{c}$ pairs at LHC

(Re-)combination to J/ψ possible

P. Braun-Munzinger and J. Stachel,
Phys. Lett. **B490,** 196 (2000).

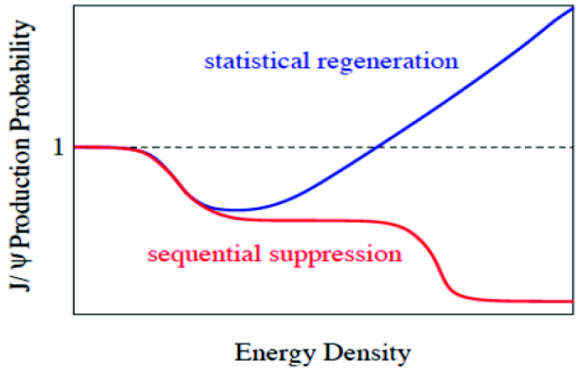
R.L. Thews, M. Schroedter, and J. Rafelski,
Phys. Rev. **C63**, 054905 (2001).



Dissociation Diffusion (Re-)combination

New source of J/ψ production

⇒ Can counteract initial suppression



Hadronic mechanisms

Comover suppression (secondary mesons): $\mathrm{J}/\Psi + \pi \rightarrow \mathrm{D} + \bar{\mathrm{D}} + X$

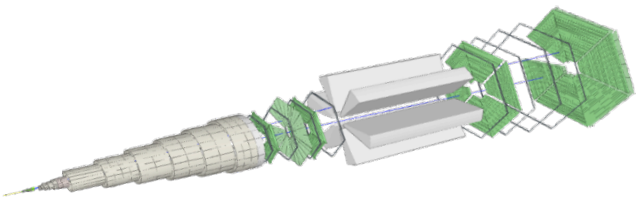
Recombination of D-mesons, if multiplicity is high enough

Heavy-Ion Physics
Experiments

CERN-SPS

NA50 and NA60 (NA38)

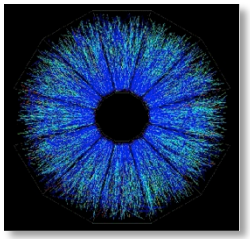
Energies (A+A): $\sqrt{s_{NN}}$ = 17.3 GeV



BNL-RHIC

STAR and PHENIX

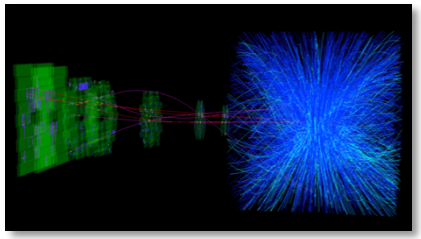
Energies (A+A): $\sqrt{s_{NN}}$ = 39 − 200 GeV



CERN-LHC

ALICE and CMS (ATLAS and LHCb)

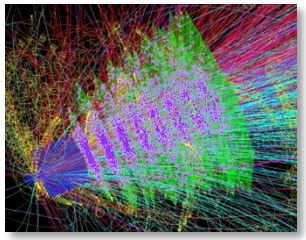
Energies (A+A): $\sqrt{s_{NN}}$ = 2.76 TeV



FAIR

CBM

Energies (A+A): $\sqrt{s_{NN}}$ = 4.7 − 8.3 GeV



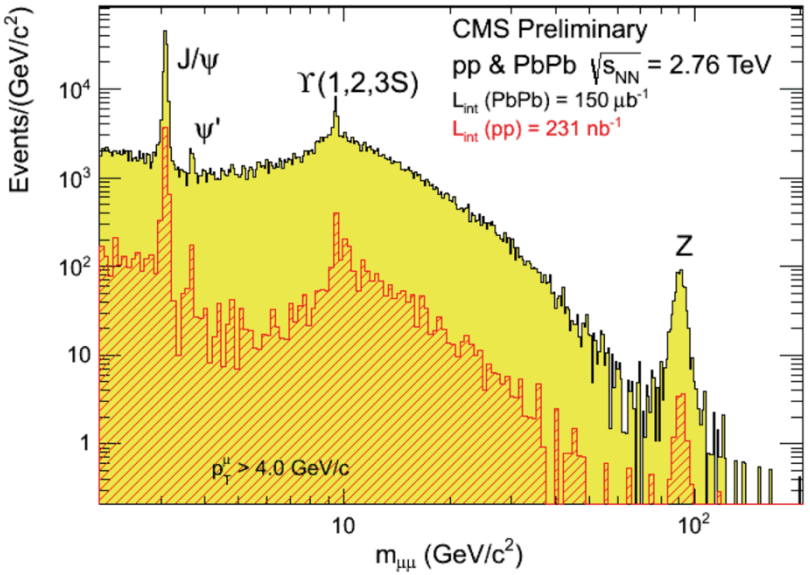
Measurement of Quarkonia

Decay channels

Di-electrons: J/ψ → e^+e^- (BR ≈ 5.9%)
Electron-ID: -dE/dx, RICH, TRDs

Di-muons: J/ψ → $\mu^+\mu^-$ (BR ≈ 5.9%)
Muon-ID via hadron absorber
Easy to trigger

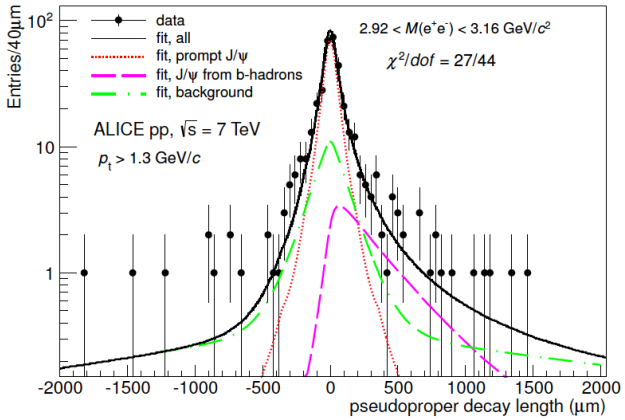
Hadronic decay channels play no role
too high combinatorial background



Separation of non-prompt J/ψ

B → J/ψ + X, J/ψ → e^+e^- / $\mu^+\mu^-$
Relevant at LHC energies

Needs resolution for secondary vertex
σ_{vtx} ~ 100 μm
E.g. with silicon pixel detectors

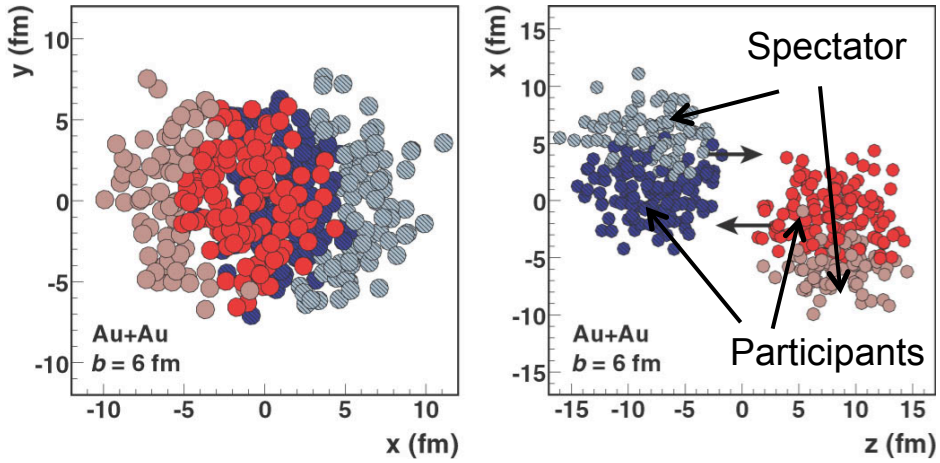


Centrality Selection

Event centrality

Number of participants N_{part}

Number of collisions N_{coll}
⇒ hard processes,
e.g. J/ψ production

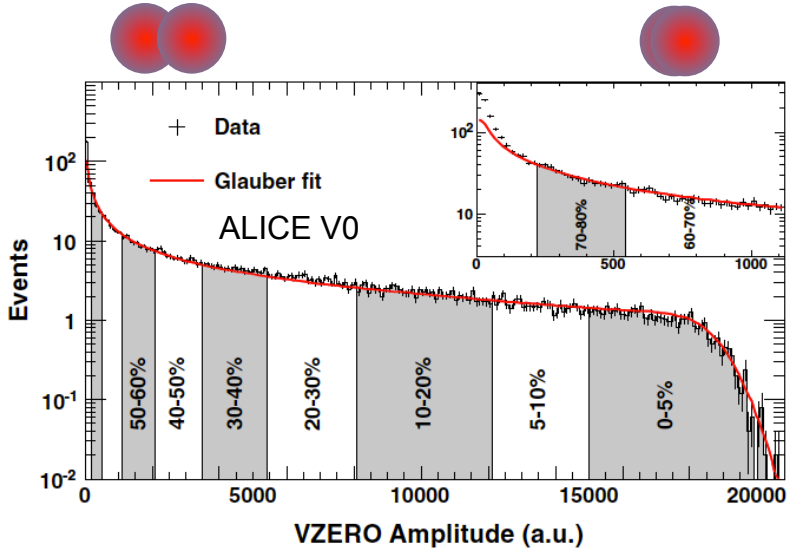


Observables

Forward energy (0º calorimetry)
⇒ Spectator energy

Charged particle multiplicity

Observables can be related
to N_{part} and N_{coll} using Glauber model



Results from SPS
NA60 / NA50 / NA38: J/ψ over Drell-Yan

Observable
Drell-Yan as reference
Hard process, scales with N_{coll}
Dominant in high mass region

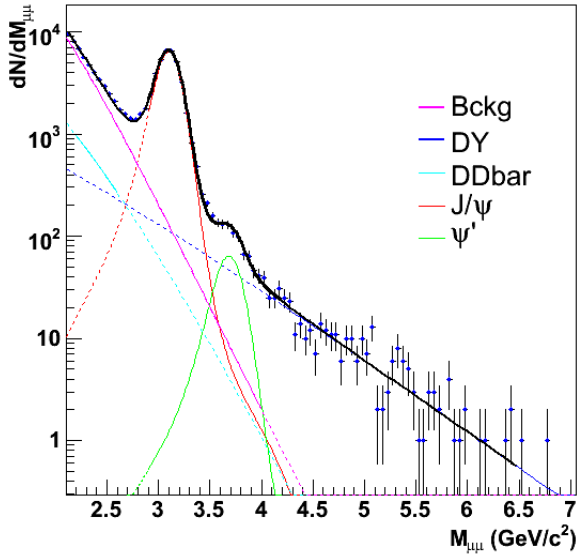
System size dependence of $\sigma^{J/\psi}/\sigma^{DY}$
(N_{part}: number of participating nucleons)

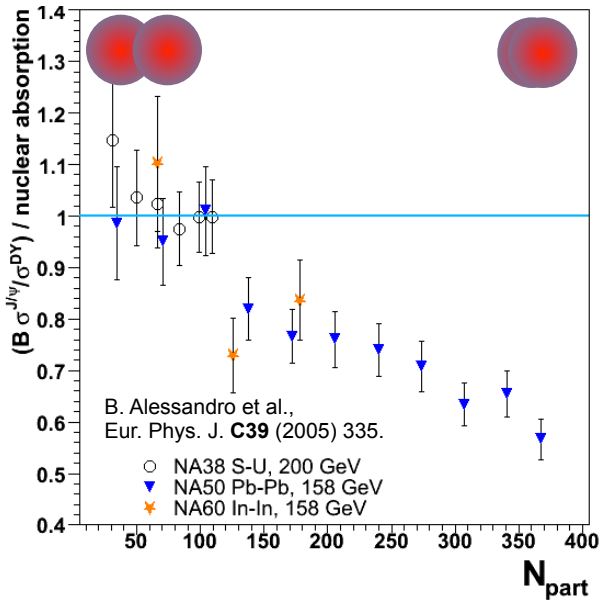
Normalize to nuclear absorption from p-A
⇒ take out normal J/ψ suppression

Anomalous suppression
Stronger than expectation from p-A

Seen in Pb-Pb and In-In(?)

Caveat: nuclear absorption not measured at $\sqrt{s_{NN}}$ = 17.3 GeV, but taken from higher energies!
(used: $\sigma_{abs}^{J/\psi}$ = 4.18 ± 0.35 mb)





Results from SPS
Nuclear Absorption in p-A Collisions

Evaluation of CNM effects

$\sigma_i^{J/\psi}/A_i$ / $\sigma_{Be}^{J/\psi}/A_{Be}$ as function of A_i
Fit with $\sigma^{J/\psi} = \sigma_o A^{\alpha}$

Strong $\sqrt{s_{NN}}$ dependence of α observed!

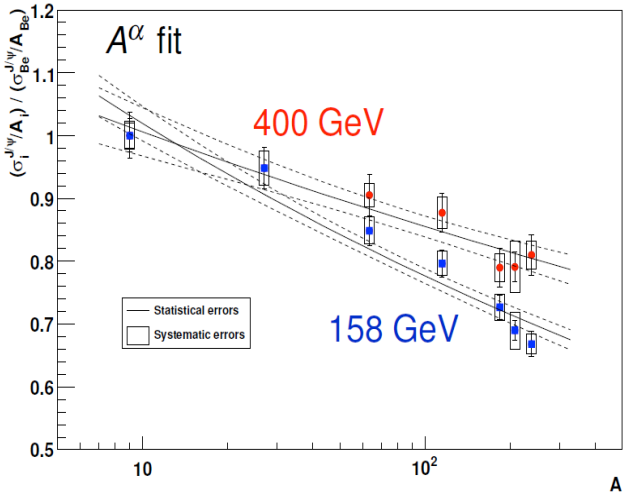
Nuclear absorption

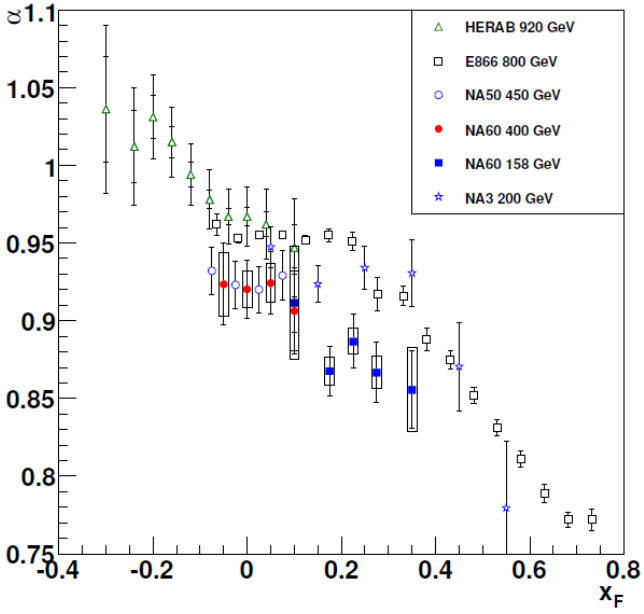
Higher at lower energies

$\sqrt{s_{NN}}$ = 17.3 GeV: $\sigma_{abs}^{J/\psi}$ = 7.6 mb
$\sqrt{s_{NN}}$ = 27.4 GeV: $\sigma_{abs}^{J/\psi}$ = 4.4 mb

Complicated dependence on kinematics

⇒ Important to measure p-A at same $\sqrt{s_{NN}}$ than A-A!



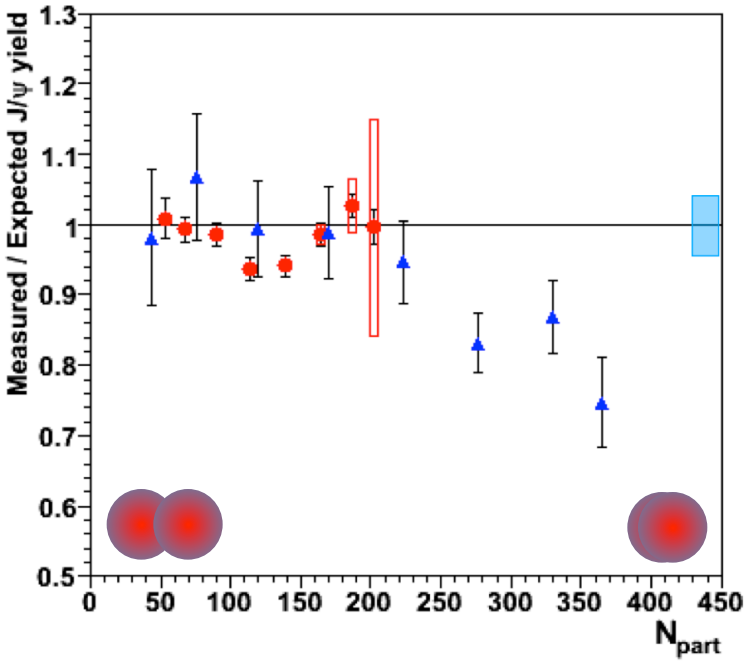


Results from SPS
Anomalous J/ψ Suppression

Reevaluated CNM effects
Higher nuclear absorption:
$\sqrt{s_{NN}}$ = 17.3 GeV: $\sigma_{abs}^{J/\psi}$ = 7.6 mb

Anomalous suppression
Seen in central Pb-Pb collisions
(not in In-In, though)

Evidence for J/ψ suppression beyond CNM effects at SPS
QGP signature?



B. Alessandro et al., Eur. Phys. J. **C39** (2005) 335.
R. Arnaldi et al., Nucl. Phys. **A830** (2009) 345.
R.Arnaldi, P. Cortese, E. Scomparin,
Phys. Rev. **C81** (2009) 014903.

Results from SPS
Summary

Significant suppression of J/ψ production

Important to understand cold nuclear matter effects (CNM): p-A collisions

Evidence for anomalous (i.e. beyond CNM) suppression

Seen in central Pb-Pb collisions

Clear QGP signature?

Evidence for sequential melting?

Need more information

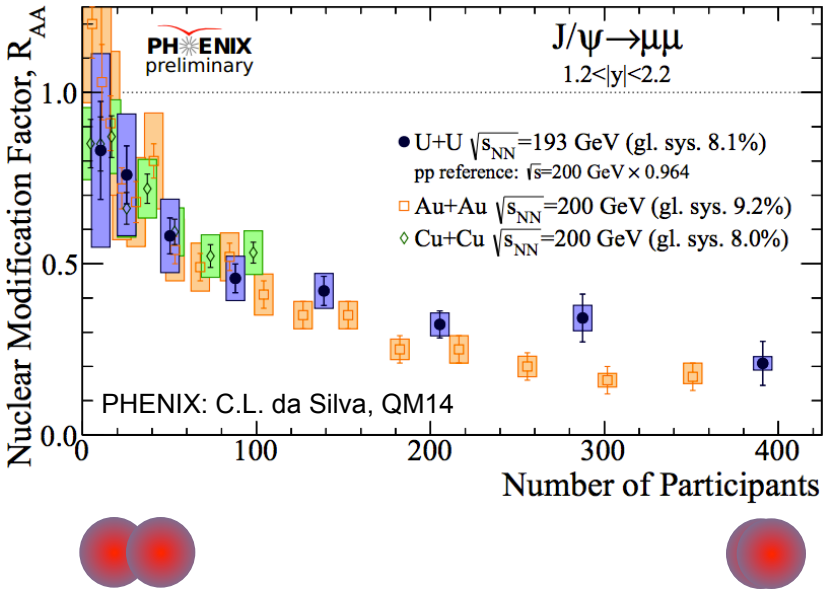
Results from RHIC
J/ψ in A-A compared to pp

Nuclear modification factor

$$R_{AA} = \frac{\sigma^{pp}_{inel.}}{N_{coll}} \frac{\mathrm{d}^2 N^{AA}/(\mathrm{d}p_T \mathrm{d}y)}{\mathrm{d}^2 \sigma^{pp}/(\mathrm{d}p_T \mathrm{d}y)}$$

J/ψ are suppressed relative to pp (R_{AA} < 1 for large systems)

Similar N_{part} dependence for all systems (U-U, Au-Au, Cu-Cu)



Any anomalous suppression?

Need to subtract CNM expectation from p-A first

Stronger suppression than at SPS?
Should be since energies densities are higher

Results from RHIC
CNM Effects in d-Au Collisions

Differential measurement

Backward-forward asymmetry

R_{dA} increases with p_T

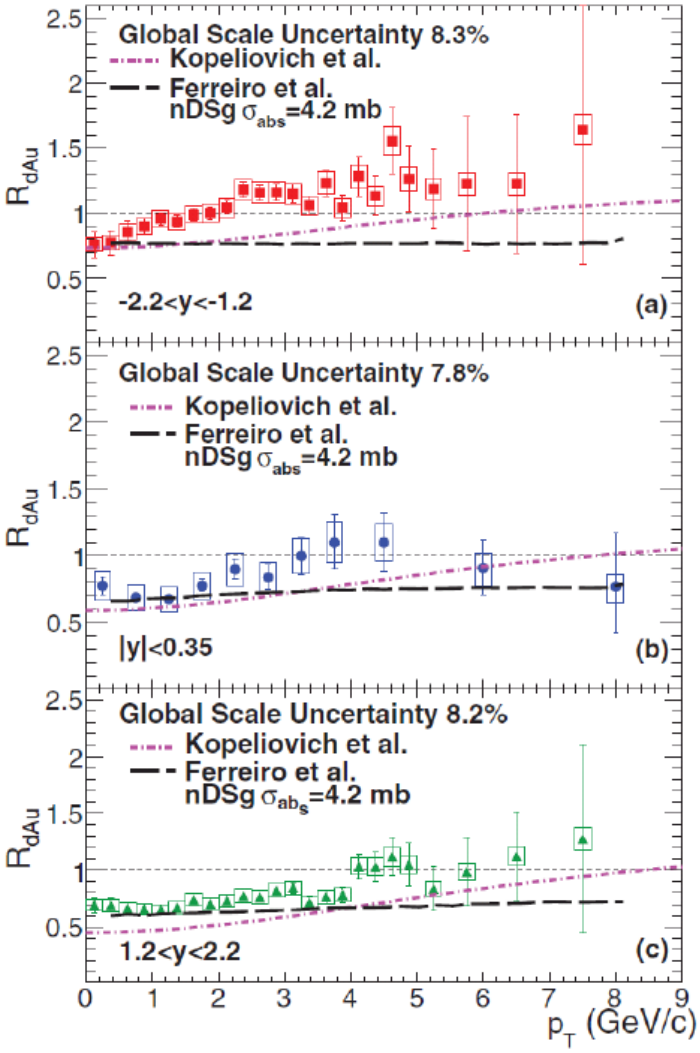
PHENIX: D. Juoan, SQM13 conference.

Difficult to model

Gluon PDFs not very constrained

Absorption in cold nuclear matter

Cronin enhancement (initial state multiple scattering)



Results from RHIC
Comparison to SPS Results

SPS and RHIC data

Significant suppression relative to Cold Nuclear Matter (CNM) effects

NA50: Eur. Phys. J. **C39**, 335 (2005).
NA60: Nucl. Phys. **A830**, 345 (2009).,
PHENIX: Phys. Rev. **C84**, 054912 (2011).
Figure: N. Brambilla et al., Eur. Phys. J. **C71**, 1534 (2011).

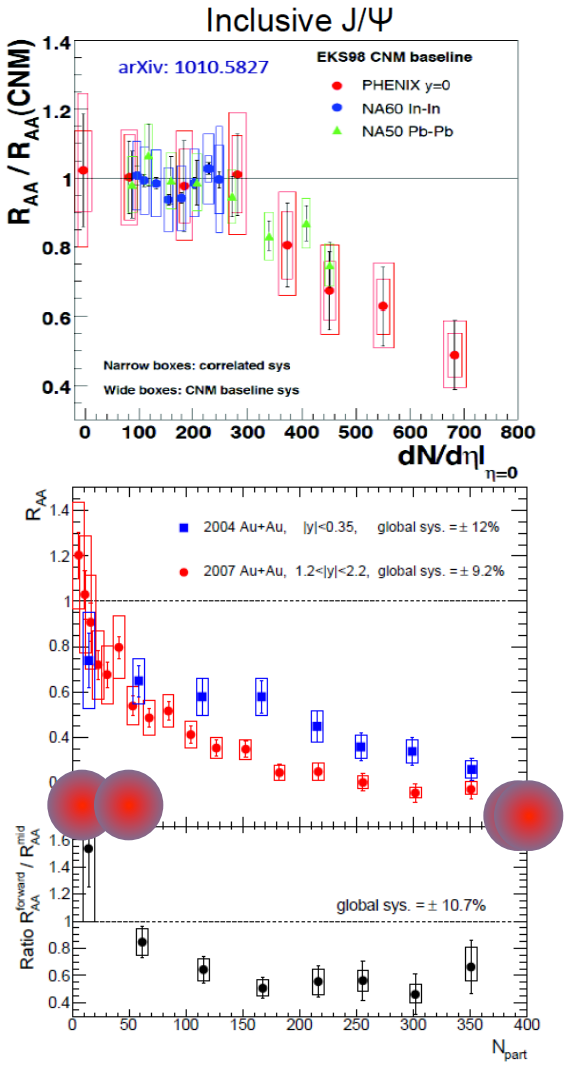
Anomalous suppression very similar

Surprising, since factor two in $\sqrt{s_{NN}}$ and therefore higher energy densities at RHIC

Another unexpected observation

Larger suppression at forward than at mid-rapidity seen at RHIC

Energy densities higher at mid-rapidity!

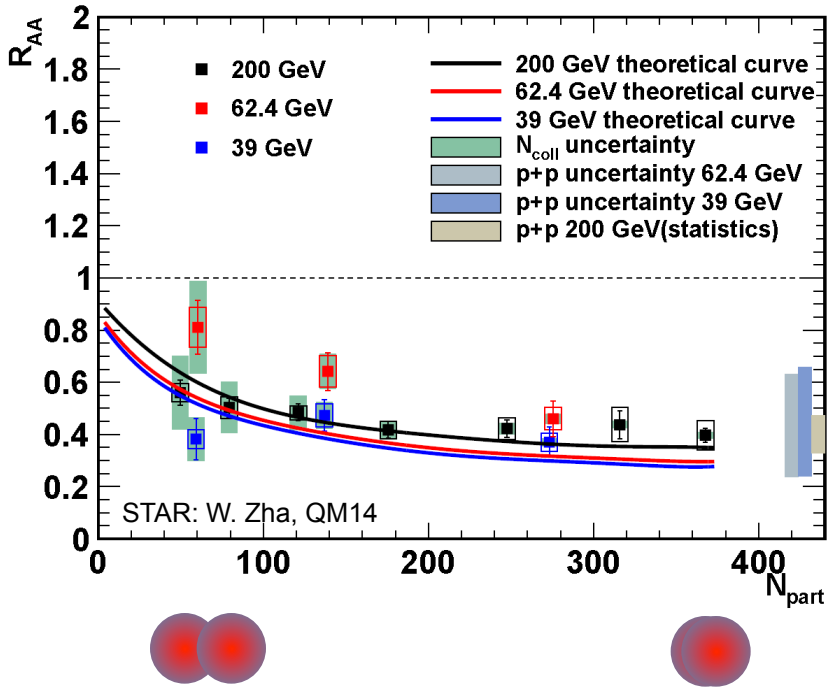


Results from RHIC
Energy Dependence of J/ψ Suppression

Au-Au at different $\sqrt{s_{NN}}$

No significant energy dependence of nuclear modification factor

J/ψ suppression on the same level over large $\sqrt{s_{NN}}$ region
SPS ⇒ RHIC



Consistent with QGP effect?

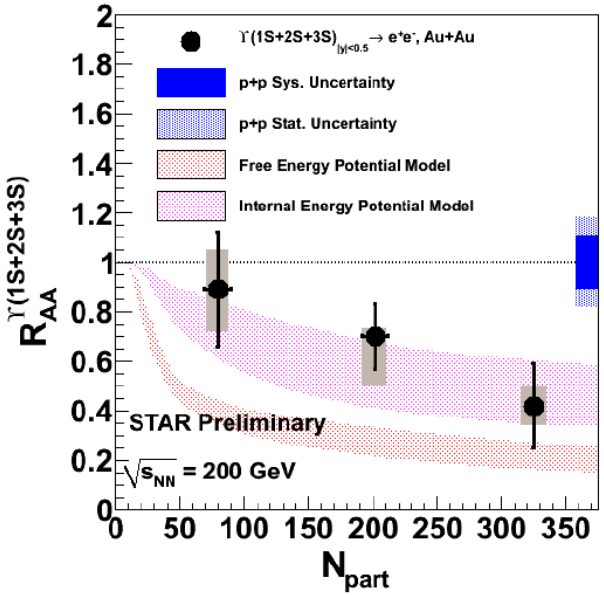
Why does it not depend on energy density? ⇒ higher energies (LHC)
Where does the anomalous suppression set in? ⇒ lower energies (FAIR)

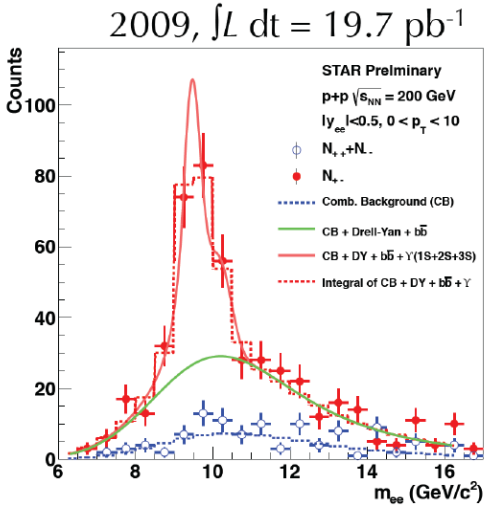
Results from RHIC
Υ (1S+2S+3S) Suppression

Clear centrality dependence
STAR: D. Kikola, SQM13 conference.

Consistent with model assuming complete Υ(2S) and Υ(3S) suppression
M. Strickland et al., Phys. Rev. Lett. **107**, 132301 (2011).

Caveat: CNM effects might be significant





Results from RHIC
Summary

Same anomalous (i.e. beyond CNM) J/ψ suppression than SPS

No significant energy dependence between SPS and RHIC

Is suppression mechanism independent of energy density / temperature?

Or is suppression by coincidence cancelled by other mechanism (regeneration)?

Stronger suppression at forward than at mid-rapidity

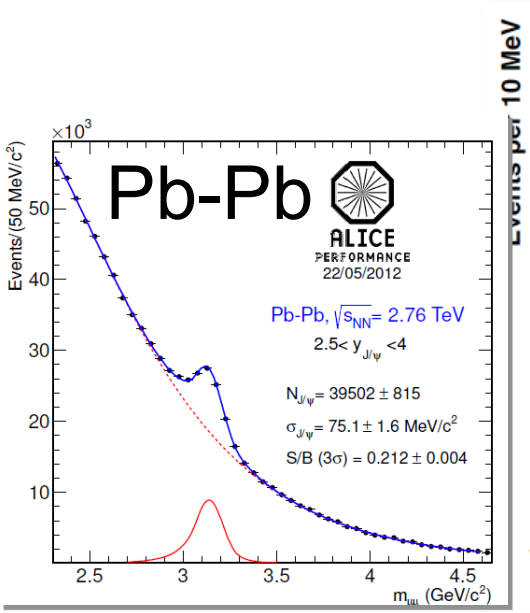
Unexpected, if suppression only driven by energy density

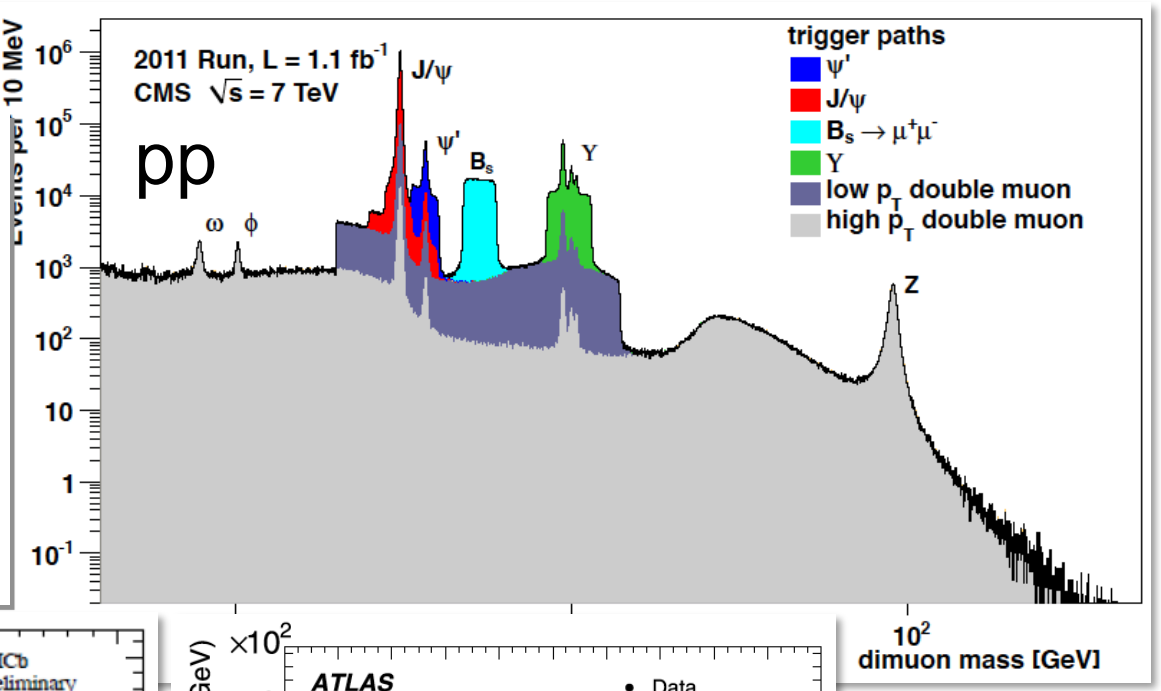
Could be understood in regeneration scenario

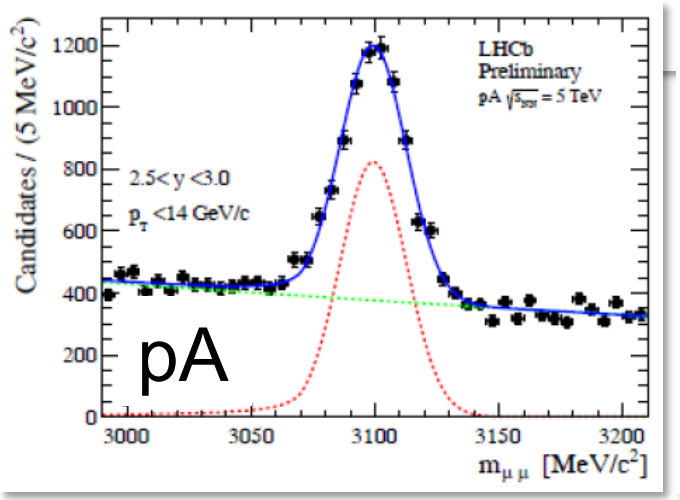
Evidence for ϒ suppression

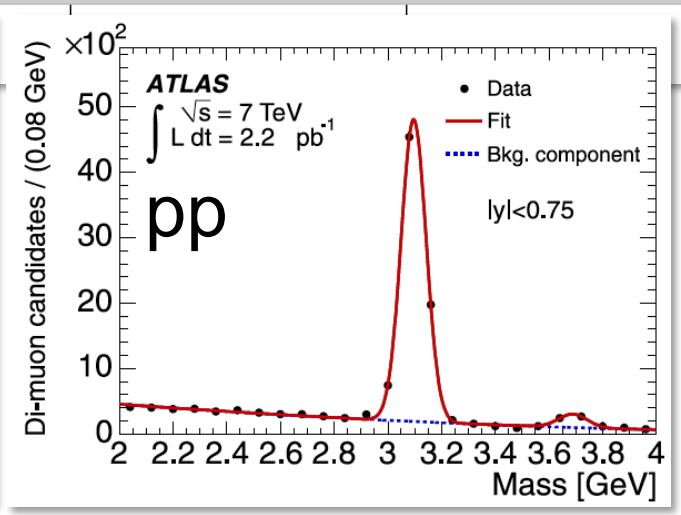
Difficult to resolve different ϒ states

Results from LHC
Signals









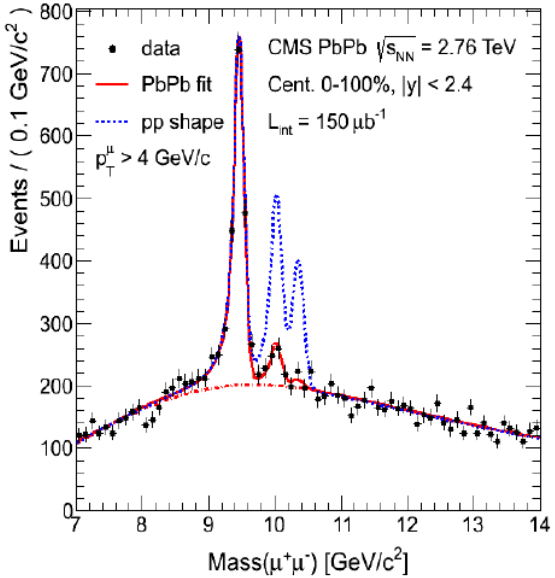
Results from LHC
Υ Suppression (all p_T)

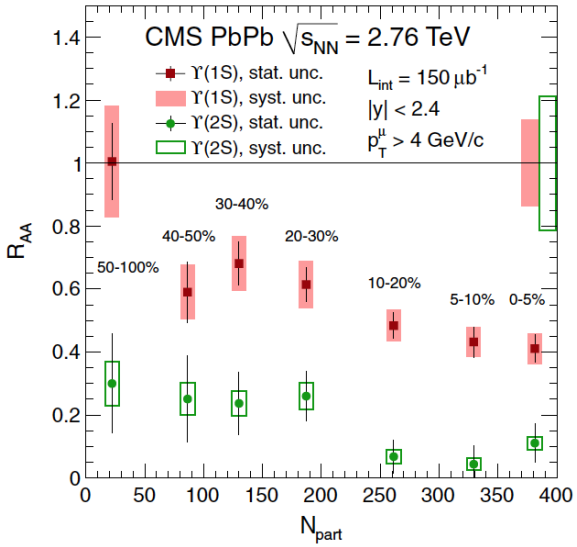
Clear suppression of Υ(2S) and Υ(3S)
Already visible from mass plot!

Nuclear modification factor
R_{AA} of inclusive Υ states
Stronger suppression of Υ(2S) than Υ(1S)
(R_{AA} (Υ(2S)) < R_{AA}(Υ(1S))

Feed down to Υ(1S) ~ 50%
⇒ direct Υ(1S) might not be suppressed

CMS: JHEP **05**, 063 (2012).
CMS: Phys. Rev. Lett. **109**, 222301 (2012).





Results from LHC
J/ψ Suppression (high p_T)

Nuclear modification factor
R_{AA} of prompt J/ψ
Relative to pp reference

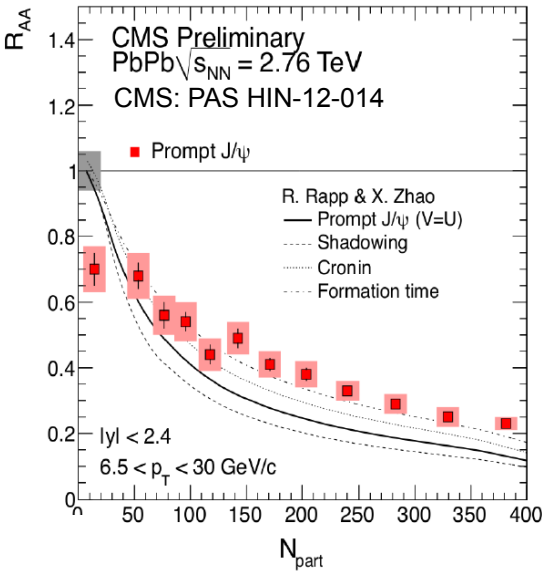
$$R_{AA} = \frac{\sigma^{pp}_{inel.}}{N_{coll}} \frac{\mathrm{d}^2 N^{AA}/(\mathrm{d}p_T \mathrm{d}y)}{\mathrm{d}^2 \sigma^{pp}/(\mathrm{d}p_T \mathrm{d}y)}$$

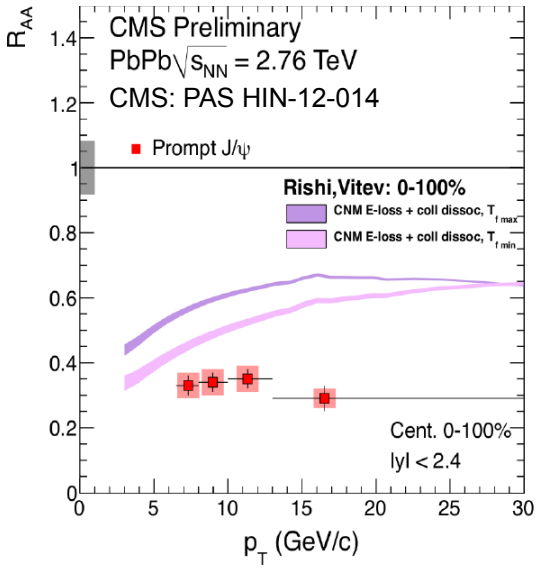
p_T > 6.5 GeV/c !

Similar than at SPS and RHIC?
But: high p_T threshold!

Anomalous suppression
R_{AA} smaller than CNM expectations

Caveat: CNM effects from calculations





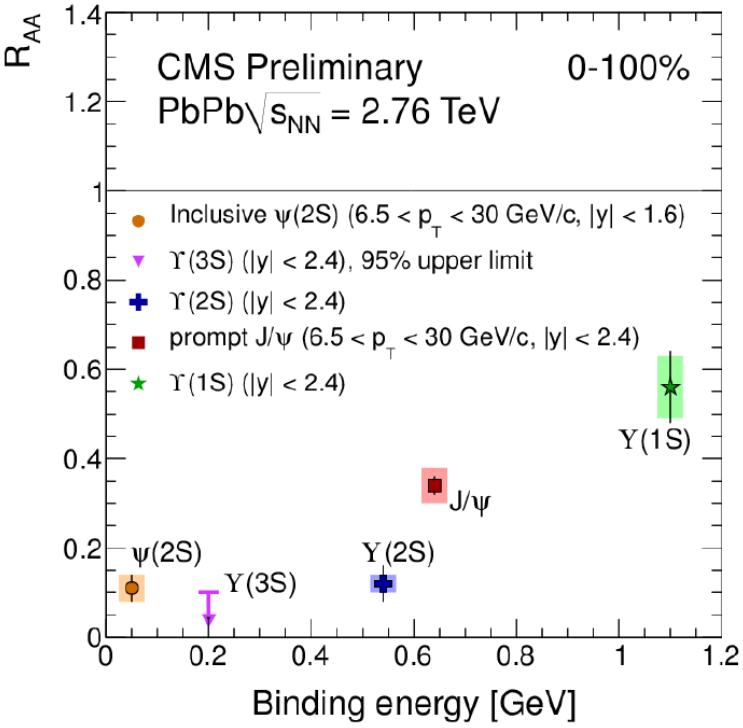
Results from LHC
Suppression Pattern (J/ψ: high p_T, ϒ: all p_T)

R_{AA} vs binding energy

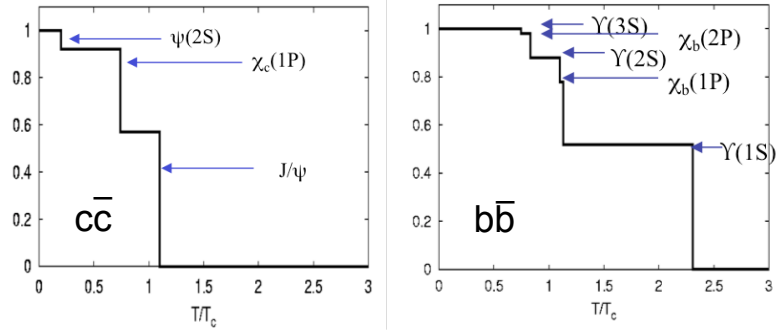
More weakly bound states are stronger suppressed

Caveat: feed down contributions and different p_T ranges

CMS: JHEP **05**, 063 (2012).
CMS: Phys. Rev. Lett. **109**, 222301 (2012).



Picture as expected from QGP suppression scenario?



Results from LHC
J/ψ Suppression at low p_T

ALICE: 0 < p_T < 8 GeV/*c*

R_{AA} ≈ 0.5 for N_{part} > 100, independent of centrality

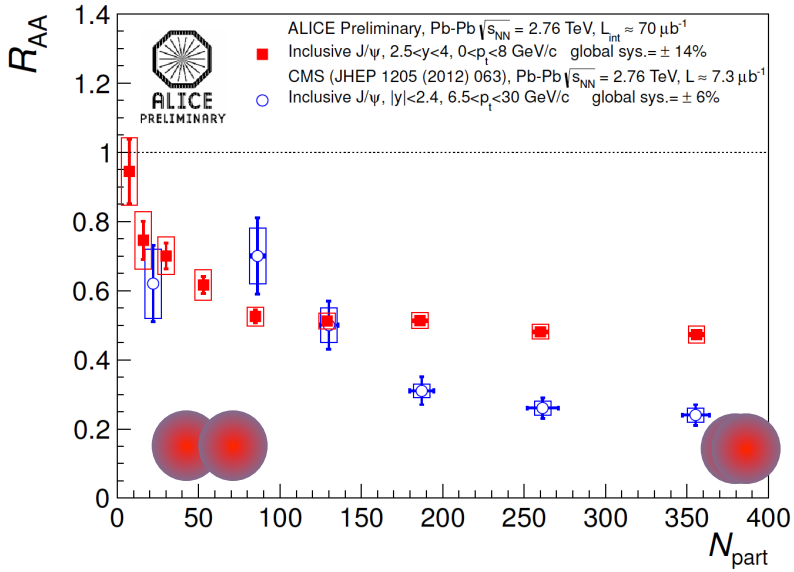
CMS: 6.5 < p_T < 30 GeV/*c*

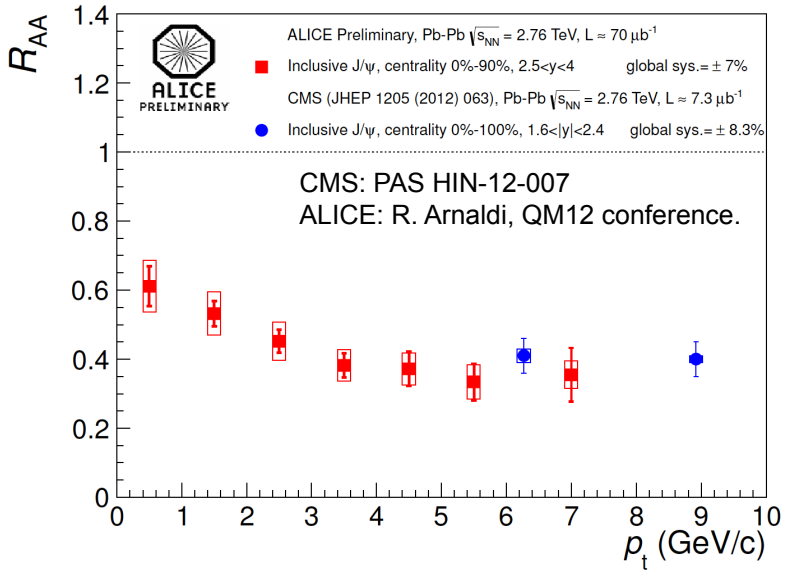
R_{AA} decreases continuously with increasing cent. down to R_{AA} = 0.24

Clear p_T dependence of J/ψ suppression observed

Suppression stronger at high p_T

Opposite trend than seen at RHIC (there supp. was stronger at low p_T)





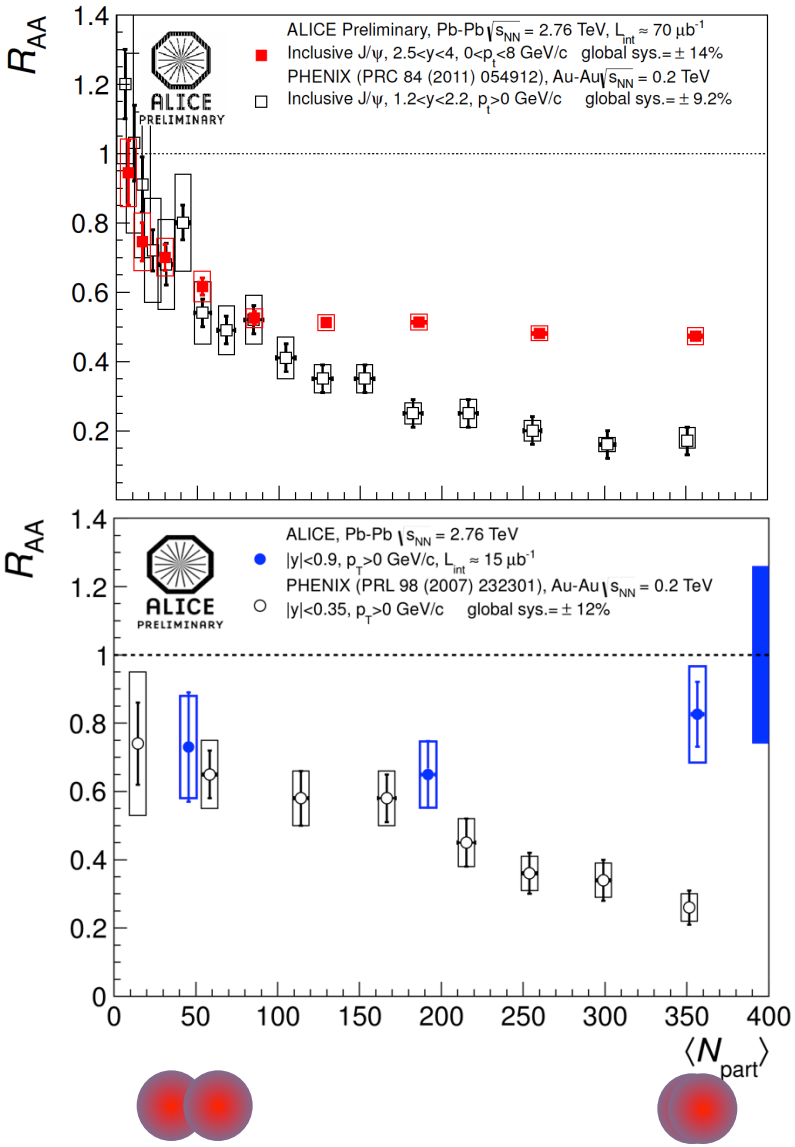
Results from LHC
Comparison to RHIC

R_{AA}(LHC) > R_{AA}(RHIC)
Measurement w/o lower p_T threshold

First evidence for an $\sqrt{s_{NN}}$ dependence

Naïve expectation:
R_{AA}(LHC) < R_{AA}(RHIC) because of higher energy densities at LHC

New physics?
Contribution from J/ψ regeneration?



Results from LHC
Comparison to RHIC: p_T Dependence

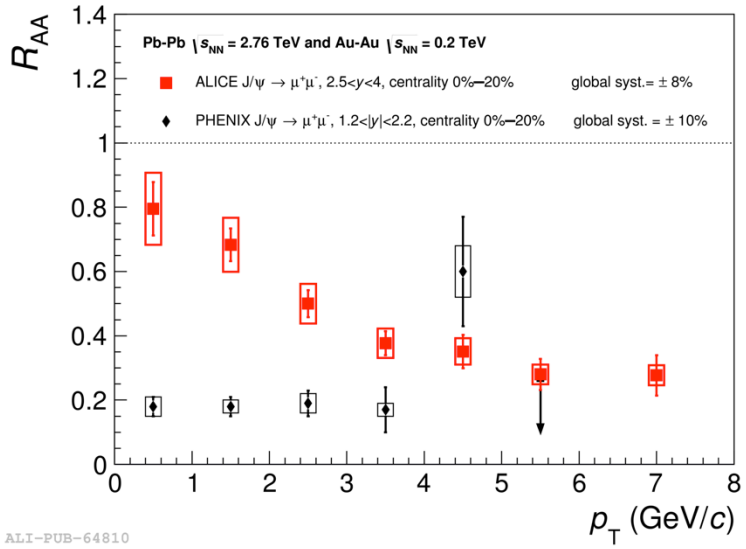
Strong p_T dependence

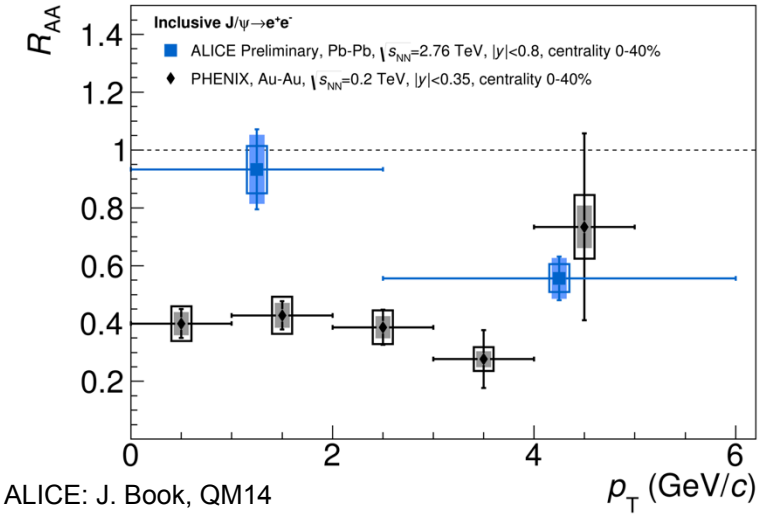
R_{AA} decreases with p_T at LHC
Almost no suppression at low p_T

Clearly different to RHIC data

New contribution at low p_T?

J/ψ regeneration should mainly contribute at low p_T





ALICE: J. Book, QM14

Results from LHC
J/ψ Suppression: Model Comparisons

Transport models
Cold nuclear matter effects
(shadowing, absorption)
Suppression in hot medium
Feed down from B mesons
J/ψ from regeneration (≥ 50%)

X. Zhao and R. Rapp, Nucl. Phys. **A859**, 114 (2011).
Y.-P. Liu et al., Phys. Lett. **B678**, 72 (2009).

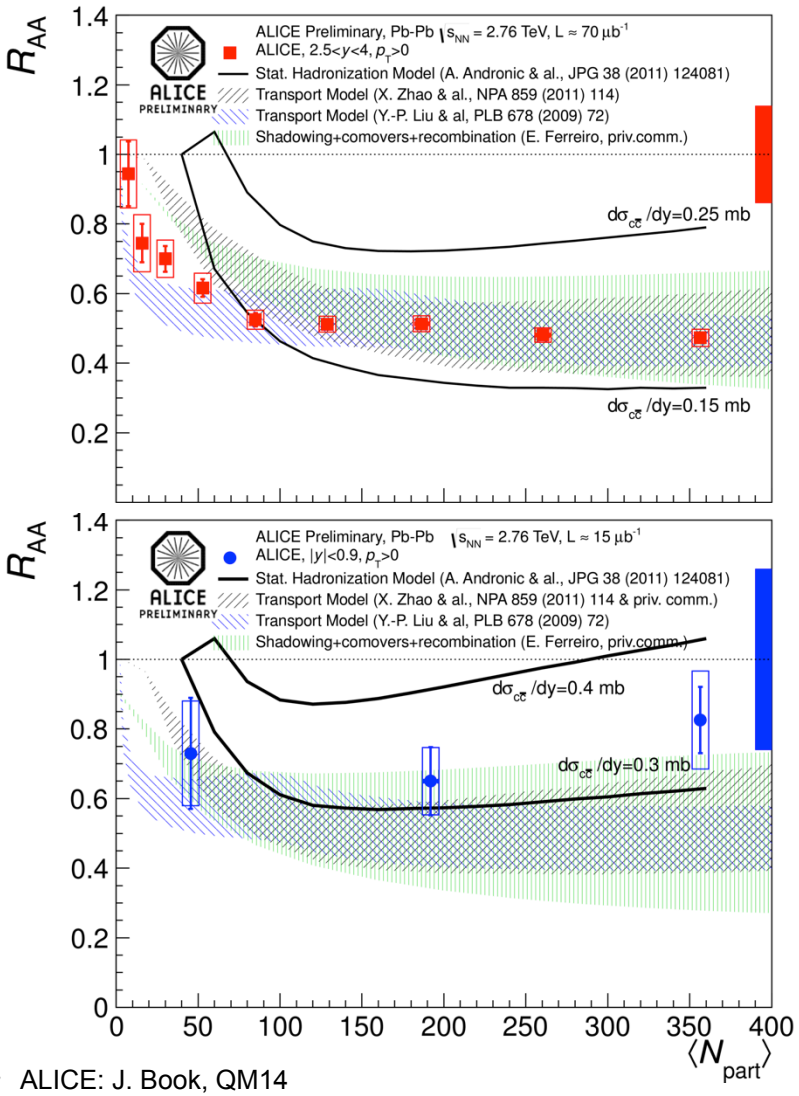
Statistical hadronization
Charm from initial hard processes
All J/ψ formed at hadronization

A. Andronic et al., J. Phys. **G38**, 124081 (2011).

Shadow.+comovers+regen.

E. Ferreiro, priv. comm.

Regeneration component can be important at LHC !



ALICE: J. Book, QM14

Results from LHC
Comparison to CNM Effects

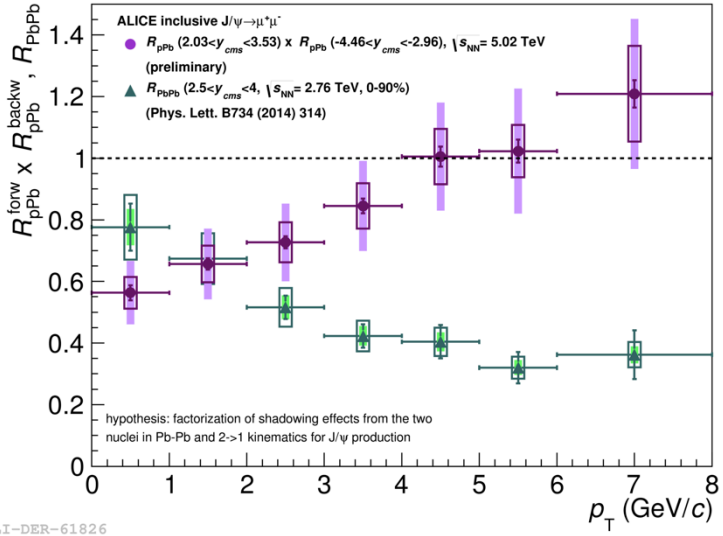
Constructed CNM estimate

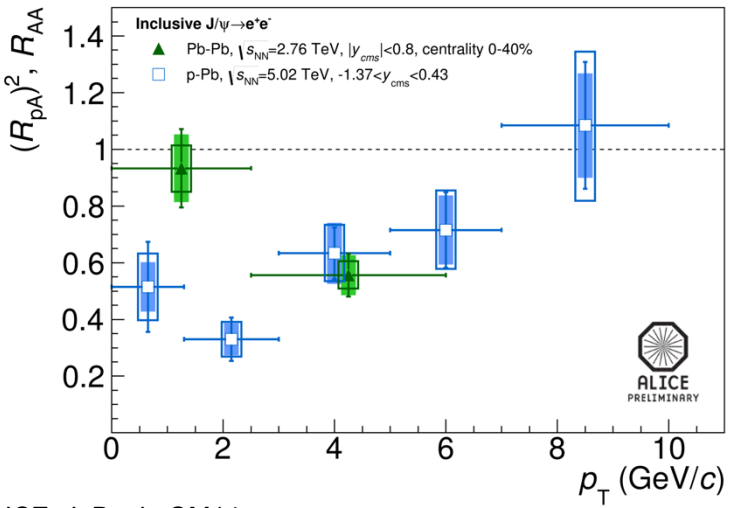
Assumption: shadowing main effect
2→1 kinematics

Measured p-A collisions:
$(R_{pA}^{mid})^2$ and $R_{pA}^{forward}$ x $R_{pA}^{backward}$ are good estimates of CNM expectation (similar gluon-x in p-Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV and Pb-Pb @ $\sqrt{s_{NN}}$ = 2.76 TeV)

Enhancement at low p_T (?)

Strong suppression at high p_T relative to CNM estimate





ALICE: J. Book, QM14

Results from LHC
Summary

Quarkonia suppression pattern

Suppression roughly increases with decreasing binding energy of state

Caveat: p_T-thresholds, CNM effects

Quantitative evaluation needed

Evidence for new phenomena at low p_T

J/ψ regeneration via quark coalescence might be important at LHC

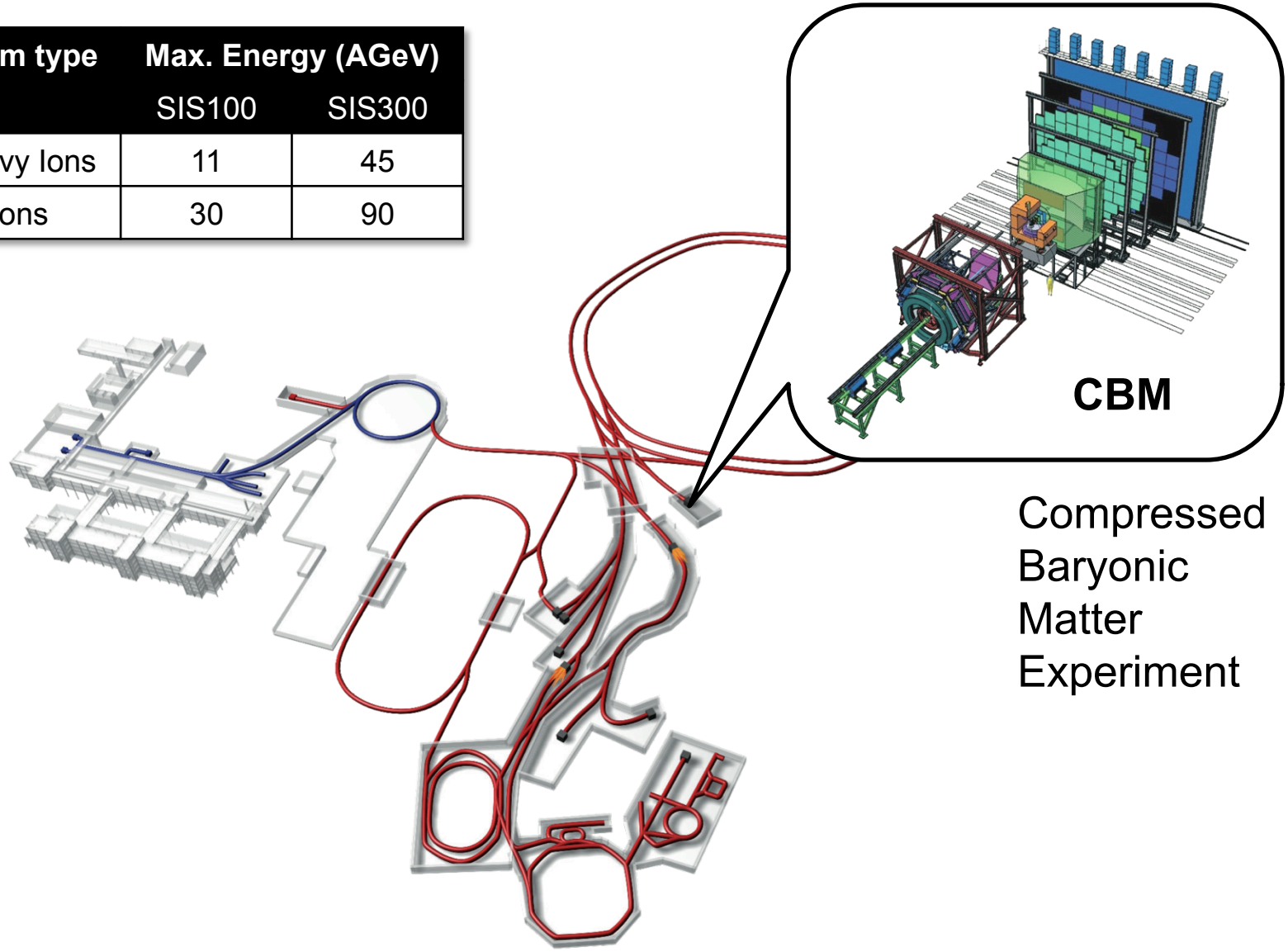
Should counteract suppression mechanisms ⇒ higher RAA than at SPS and RHIC

Enhancement relative to CNM baseline at low p_T?

Plans for FAIR

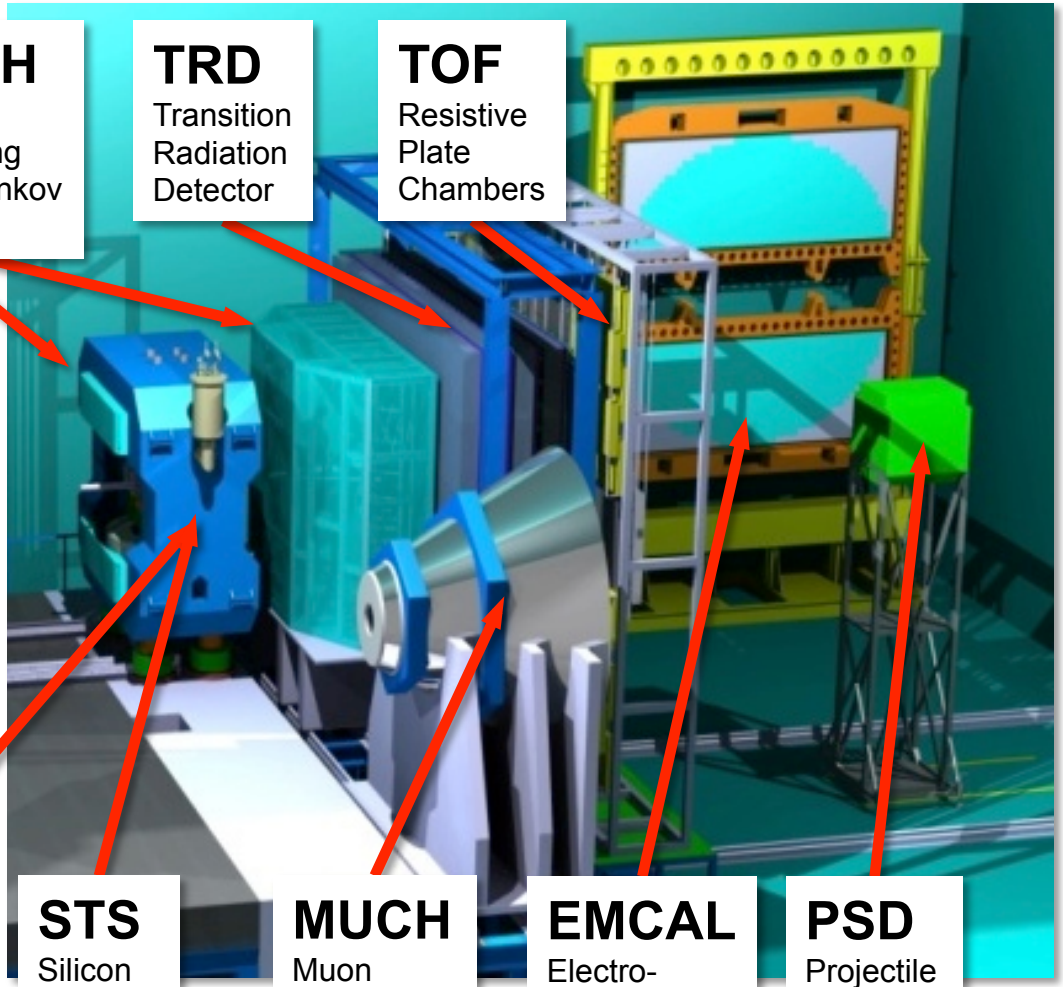
Facility for Antiproton and Ion Research

Beam type	Max. Energy (AGeV)	
	SIS100	SIS300
Heavy Ions	11	45
Protons	30	90



Compressed Baryonic Matter Experiment

Plans for FAIR
The CBM Experiment



Dipole

RICH
Ring Imaging Cherenkov

TRD
Transition Radiation Detector

TOF
Resistive Plate Chambers

Acceptance
$p_t > 0$

Forward rapidities

MVD
Micro Vertex Detector

STS
Silicon Tracking System

MUCH
Muon Detection System
(parking pos.)

EMCAL
Electro-Magnetic Calorimeter
(parking pos.)

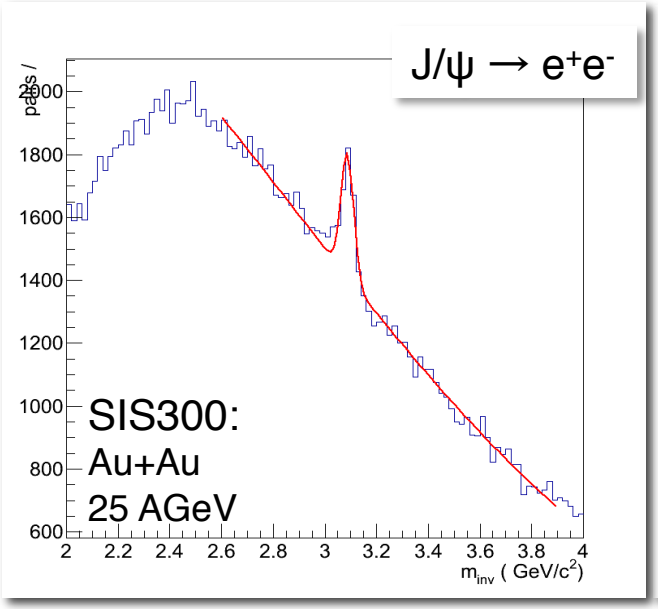
PSD
Projectile Spectator Detector

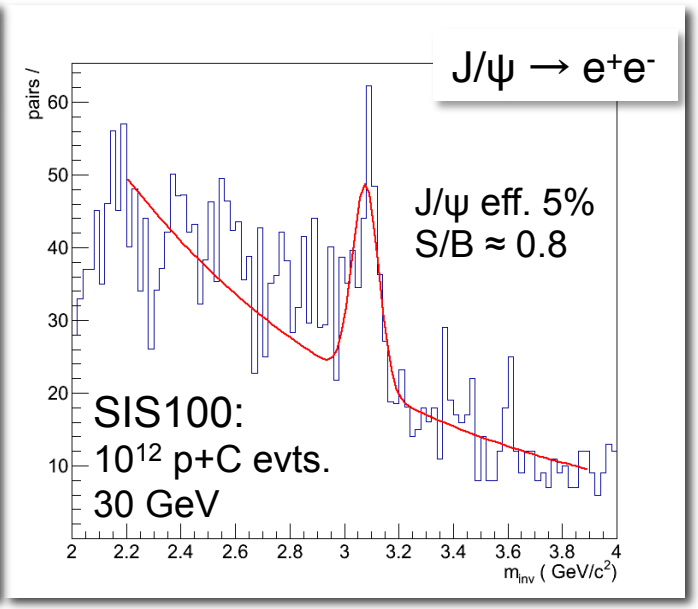
Plans for FAIR

J/ψ via e^+e^- and $\mu^+\mu^-$

STS+ RICH+ TRD

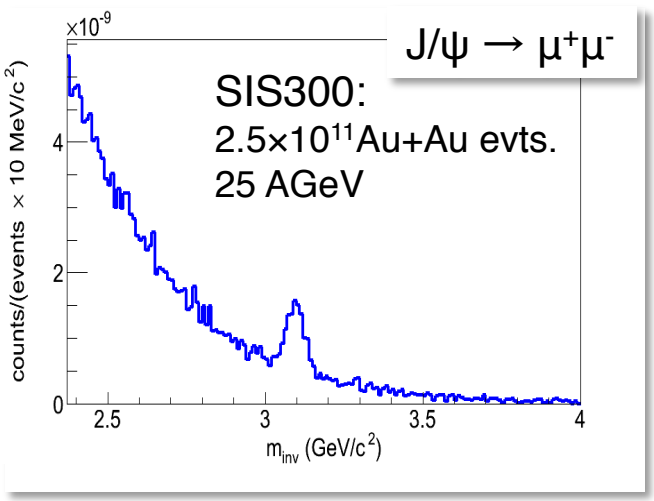
$J/\psi \rightarrow e^+e^-$

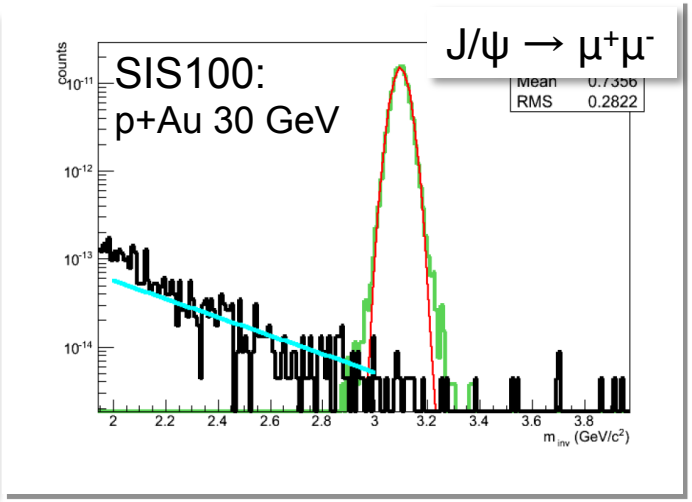




STS+ MUCH+ TOF

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





Plans for FAIR
Quarkonia with CBM

Look for onset of J/ψ suppression

No significant energy dependence above SPS

How does it evolve towards lower energies?

Deconfinement phase boundary visible?

Different timescales

J/ψ can form inside nuclear medium, since passing times of nuclei are larger

How does it interact with nuclear medium (→ p-A collisions)?

Conclusions

Quarkonia are an important probe of QCD matter

Many observables and collisions systems investigated

J/ψ, ψ(2S), ϒ(1S), ϒ(2S), ϒ(3S)

A-A, p-A, pp

Many interesting phenomena

J/ψ suppression

Regeneration via $c\bar{c}$ coalescence

Every energy regime provides new insights

Still more to come

Continue with LHC

Low energy frontier: CBM @ FAIR

Backup

Results from RHIC
J/ψ Suppression

Suppression depends on p_T

$R_{AA}(p_T > 5\ \mathrm{GeV}/c) > R_{AA}(\text{all } p_T)$

Low p_T data agree with model including color screening and regeneration effects

STAR: Phys. Lett. **B722**, 55 (2013).
D. Kikola, SQM13 conference.

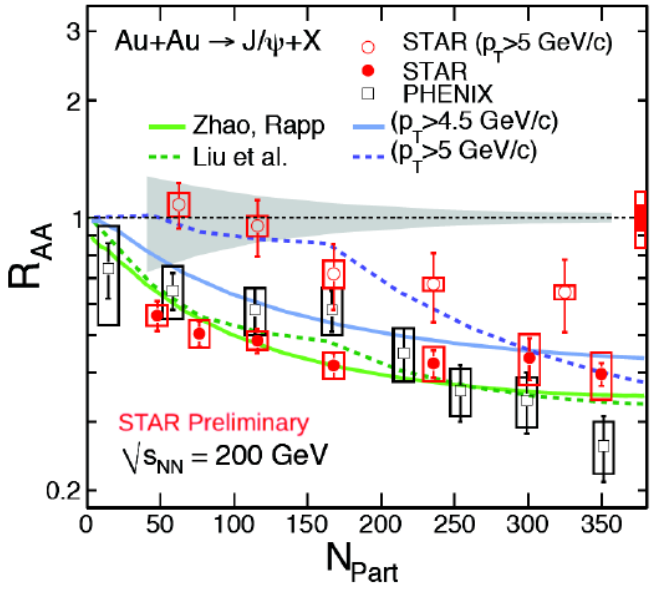
$$R_{AA}^{J/\psi}(y, p_T) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}^{J/\psi}/(dydp_T)}{d\sigma_{pp}^{J/\psi}/(dydp_T)}$$

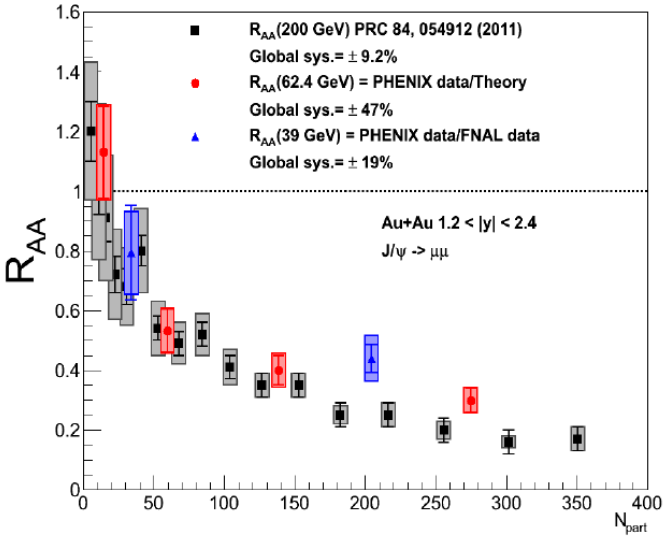
Very weak energy dependence

Even though energy density increases

Compensation by onset of regeneration effects ?

PHENIX: D. Jouan, SQM13 conference.



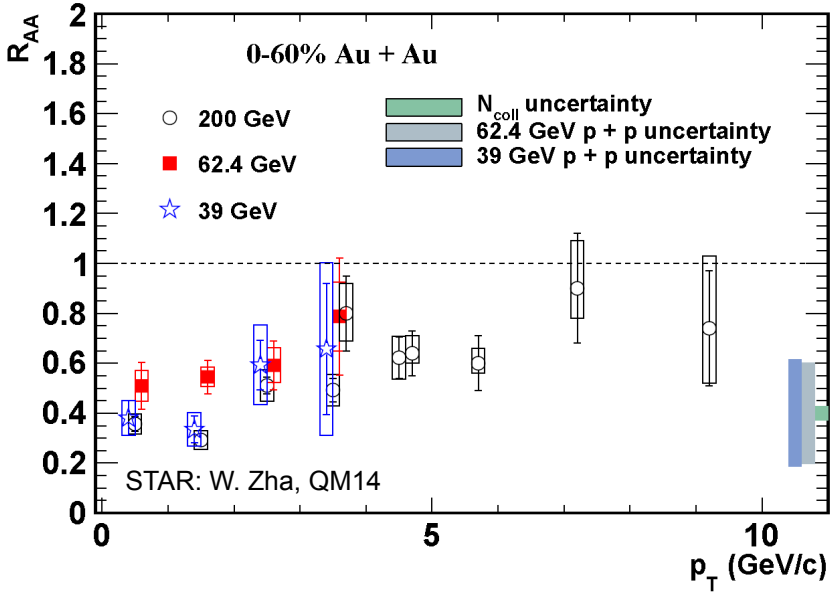


Results from RHIC
p_T Dependence of J/ψ Suppression

Significant p_T dependence

Strong suppression at low p_T

Consistent with no suppression at very high p_T



Slow J/ψ more strongly affected

Results from LHC
J/ψ Suppression at low p_T

ALICE: 0 < p_T < 8 GeV/*c*

Clear rapidity dependence of J/ψ suppression observed

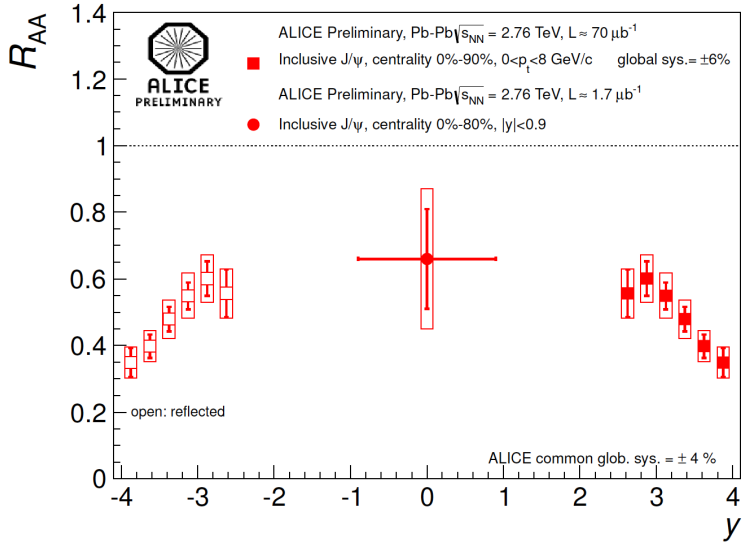
Supp. stronger at forward rapidities

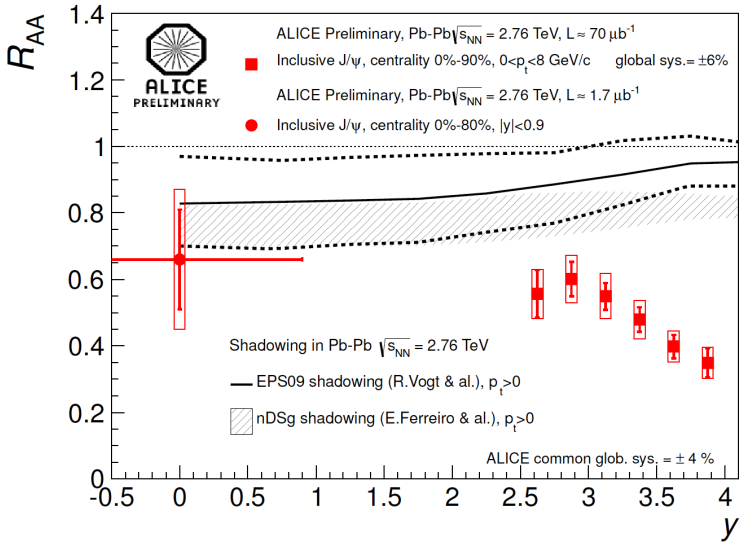
Similar trend than seen at RHIC

Not explained by CNM eff.

Dominated by nuclear shadowing

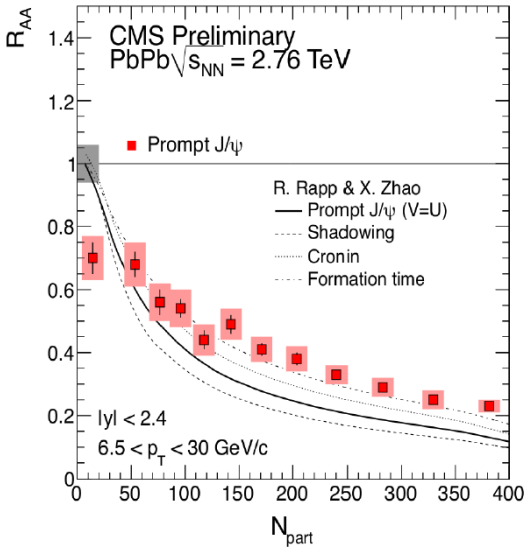
Predicts opposite trend in rapidity dependence

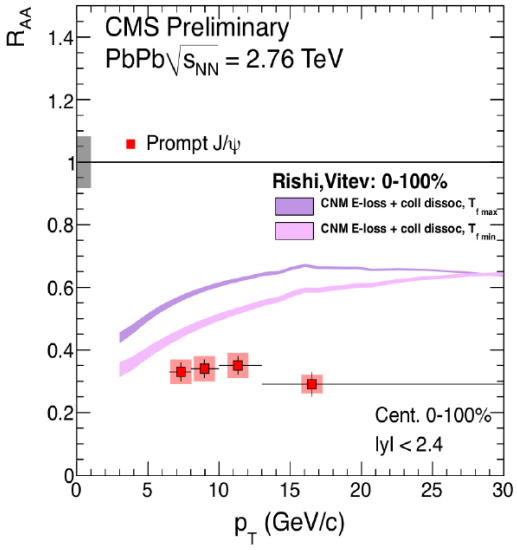


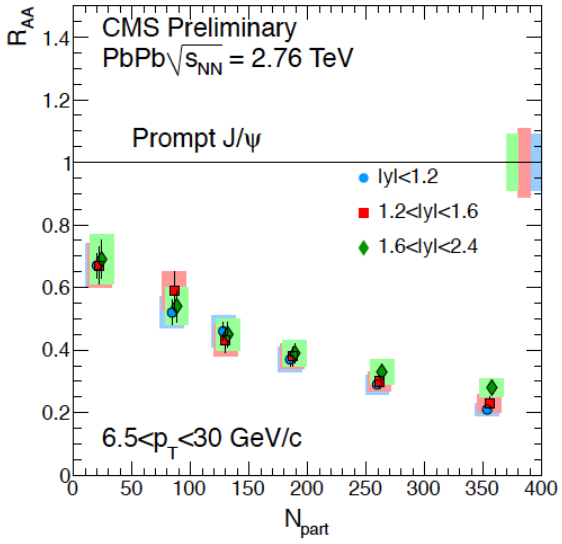


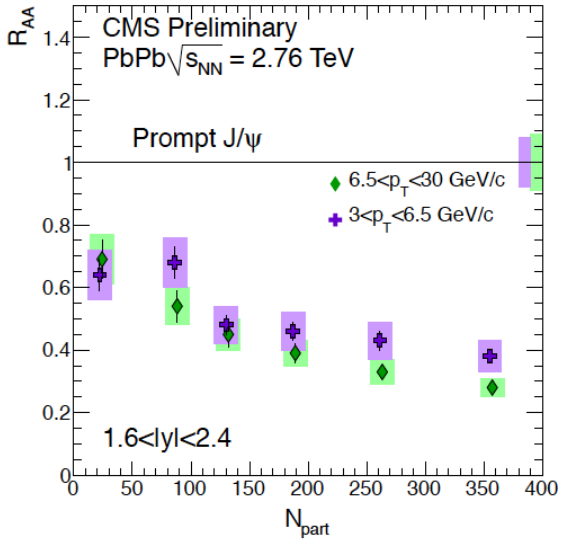
Results from LHC
J/ψ Suppression (high p_T)

CMS: PAS HIN-12-014









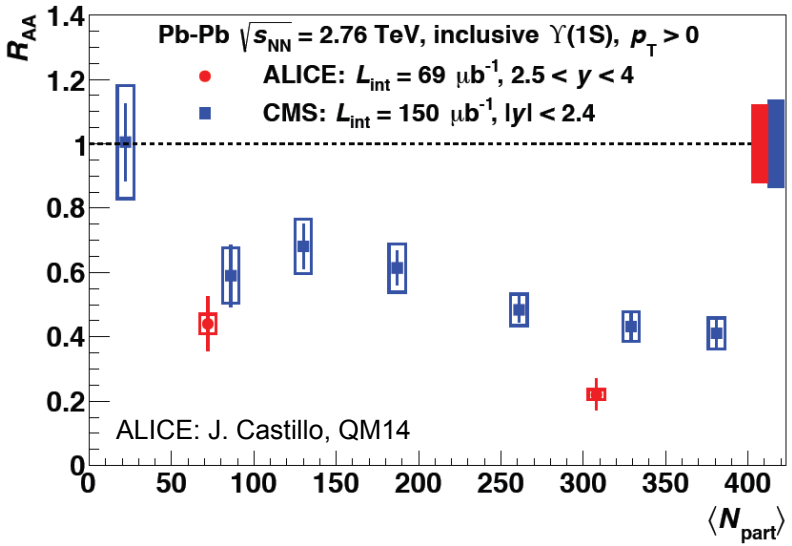
Results from LHC
Υ Suppression (all p_T)

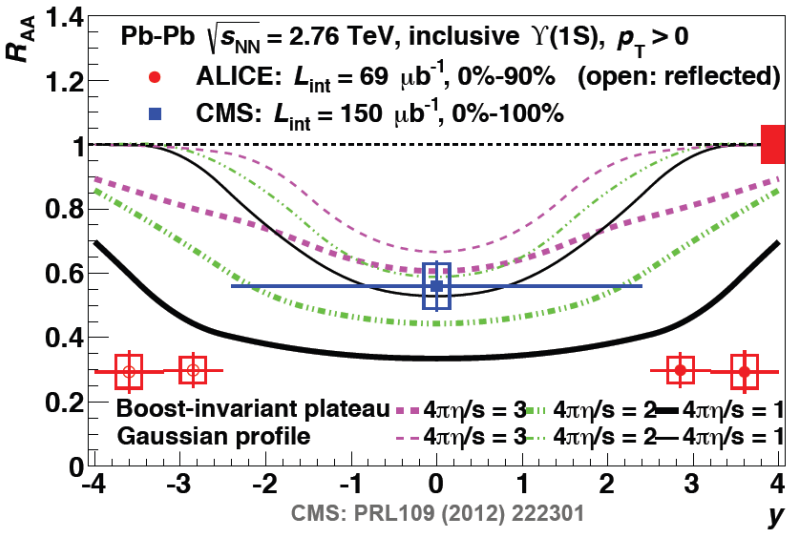
Nuclear modification factor R_{AA} of Υ(1S)

Suppression increases with system size

Stronger suppression at forward rapidities seen, while models predict rather opposite trend

Evaluation of CNM effects pending





Results from LHC
J/ψ Suppression at low p_T

J/ψ → μμ

$2.5 < y < 4$, $0 < p_T < 8$ GeV/c

Inclusive J/ψ suppressed relative to pp

$R_{AA} \approx 0.5$ for $N_{part} > 100$, independent of centrality

Averaged R_{AA}(0-90%)
= 0.497 ± 0.006(stat.) ± 0.078(syst.)

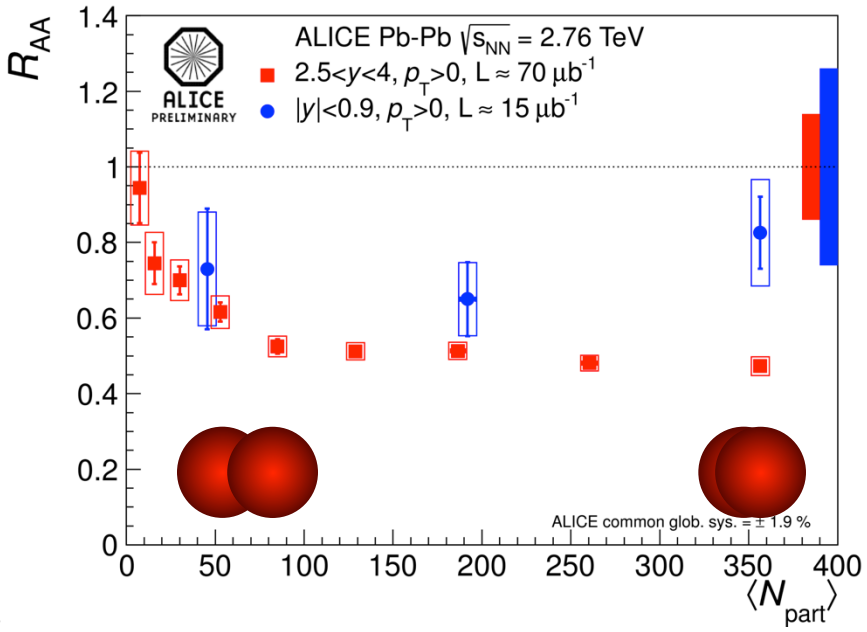
J/ψ → ee

$|y| < 0.9$, $p_T > 0$

Indication for less suppression at mid-rapidity for most central (?)

Averaged R_{AA}(0-10%)
= 0.83 ± 0.09(stat.) ± 0.26(syst.)

ALICE: I. Arsene,QM12 conference.



Results from LHC

J/ψ R_{AA} vs p_T : Model Comparisons

ALICE measurement

Di-muon channel, $2.5 < y < 4$

Different centrality selections

Smaller R_{AA} at higher p_T

Clear p_T dependence for central coll.

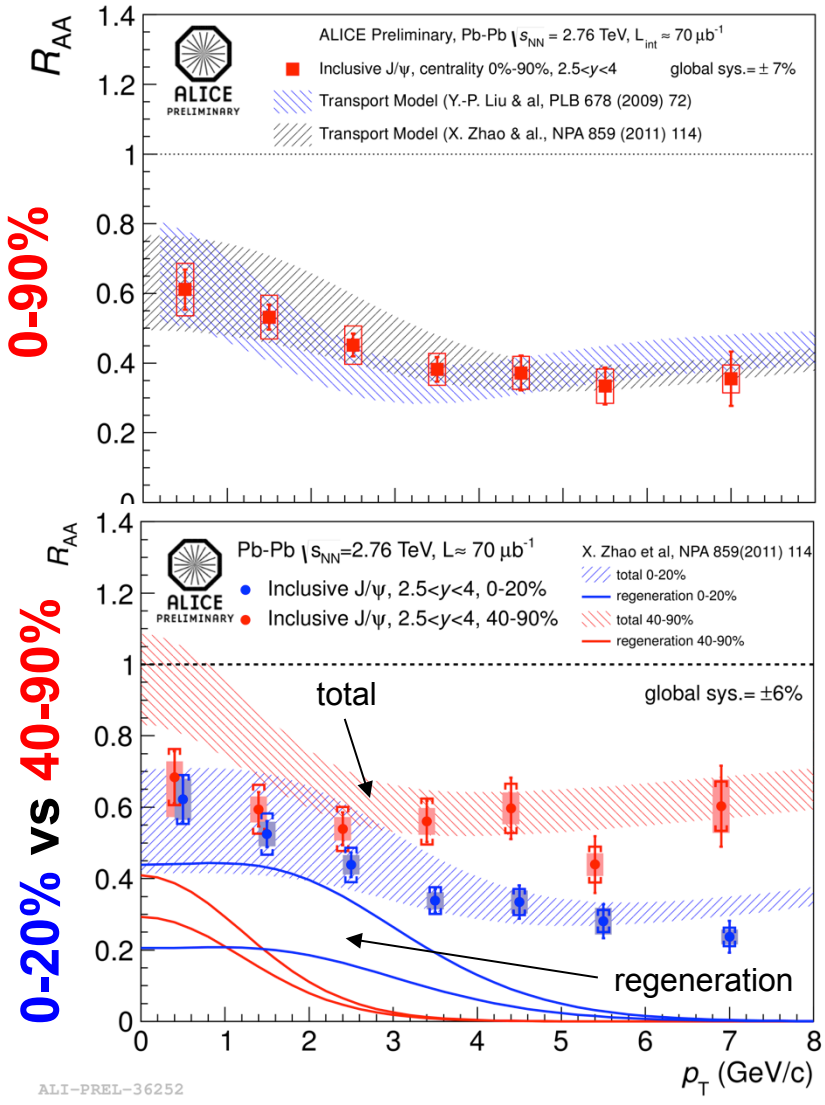
Not significant for peripheral

Transport model

Fair agreement with data

Significant contribution from regeneration (~50% for central, ~30% for peripheral)

X. Zhao and R. Rapp, Nucl. Phys. **A859**, 114 (2011).



Results from LHC
J/ψ R_{AA} vs Centrality: Model Comparisons

ALICE measurement

Di-muon channel, 2.5 < y < 4

0 < p_T < 2 GeV/c and 5 < p_T < 8 GeV/c

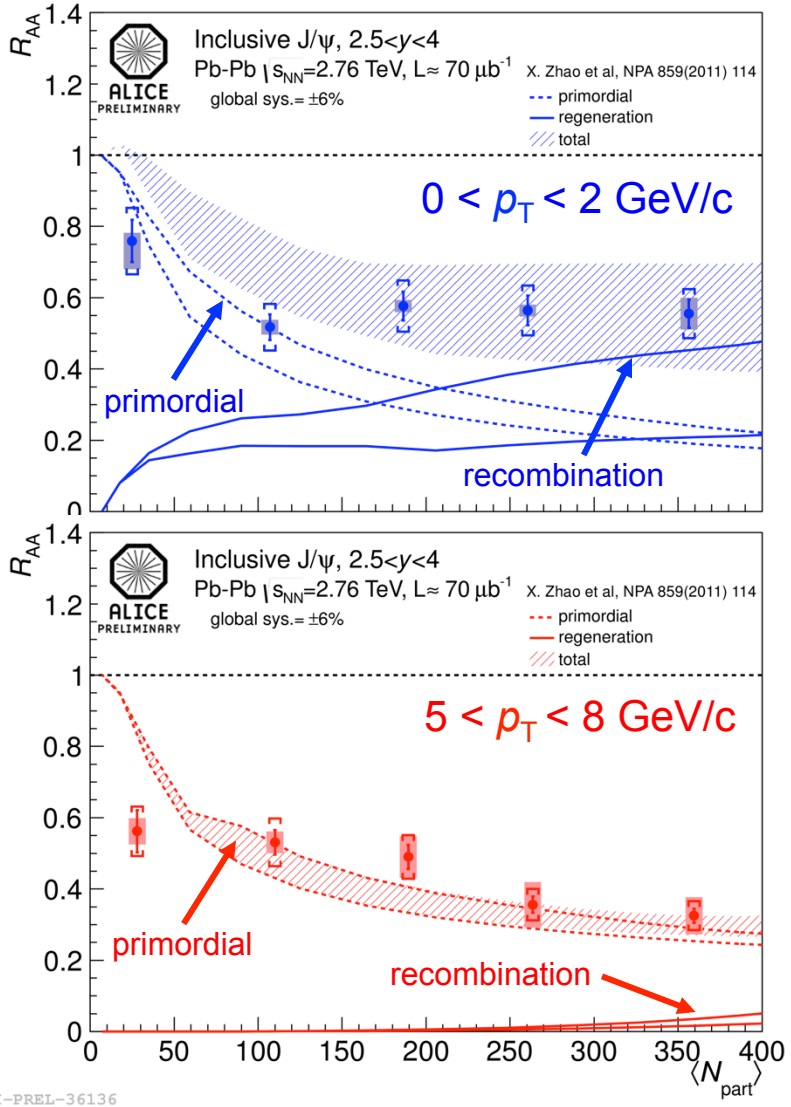
Smaller R_{AA} at higher p_T

Transport model

50% contribution from recombination at low p_T for central collisions

Negligible for higher p_T

X. Zhao and R. Rapp, Nucl. Phys. **A859**, 114 (2011).



Results from LHC
CNM Effects on J/ψ: p-Pb Data

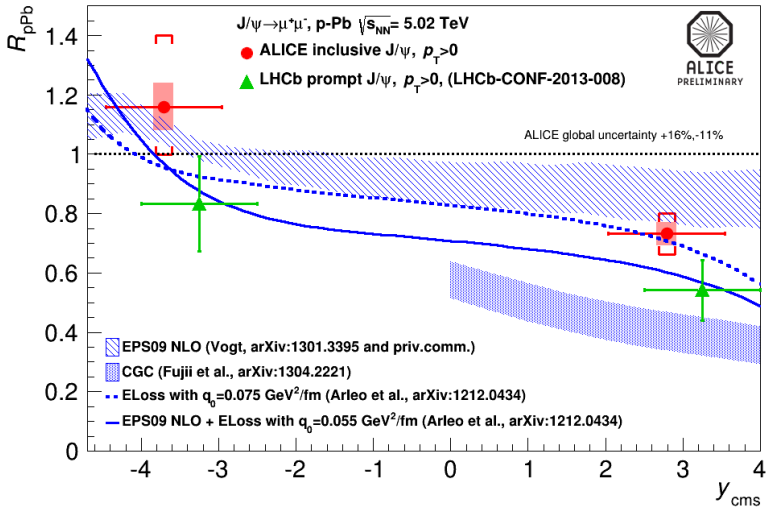
Nuclear modification factor
pp reference from interpolation
to $\sqrt{s}$ = 5.02 TeV

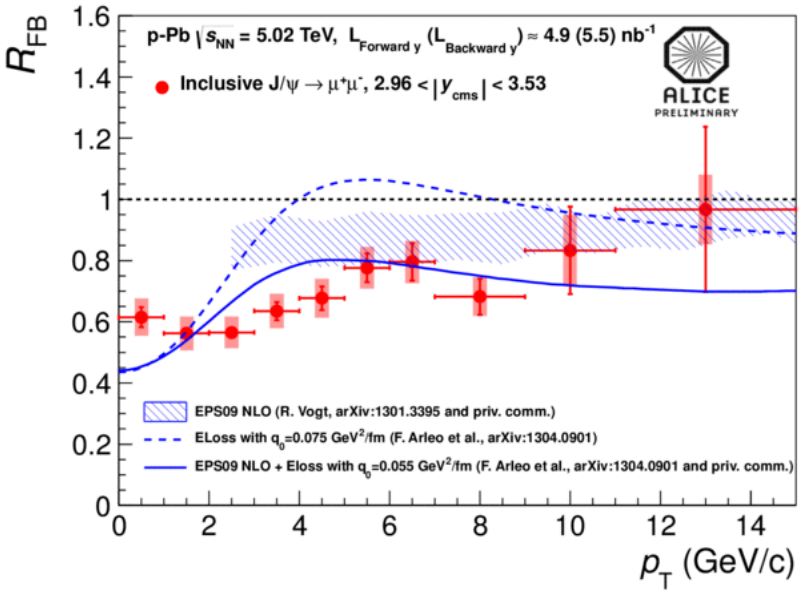
Suppression in forward region
Reasonably described by models
including shadowing (EPS09)
and initial parton energy loss

Color Glass Condensate (CGC)
seems to be disfavored

Suppression depends on p_T
Stronger at low p_T

ALICE: G. Bruno, SQM13 conference.
R. Arnaldi, CERN LHC seminar.
LHCb: LHCb-CONF-2013-008.





Results from LHC
CNM Effects on J/ψ: p-Pb Data

Forward / backward ratio

No pp reference needed

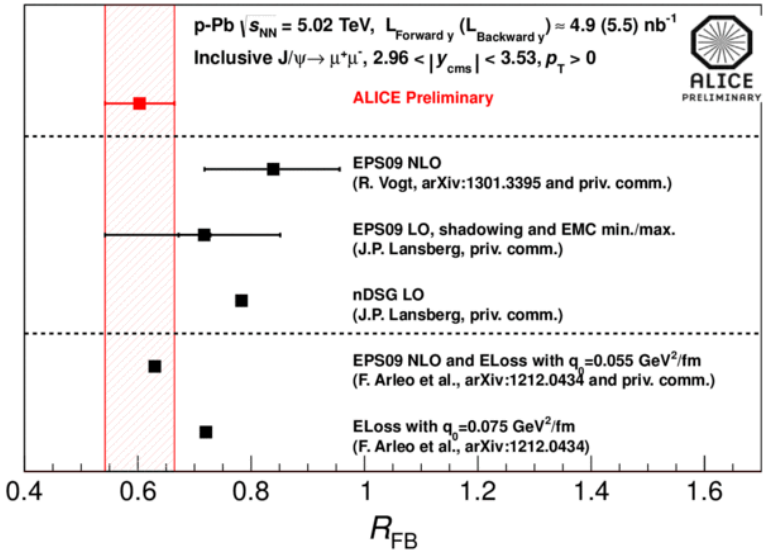
Same rapidity interval ($2.96 < |y| < 3.53$)

$$R_{FB} = \frac{R_{pPb}}{R_{Pbp}} = \frac{dN^{J/\psi}_{\text{forward}}/(dydp_T)}{dN^{J/\psi}_{\text{backward}}/(dydp_T)}$$

Model comparison

Pure shadowing (EPS09) seems to overestimate R_{FB}

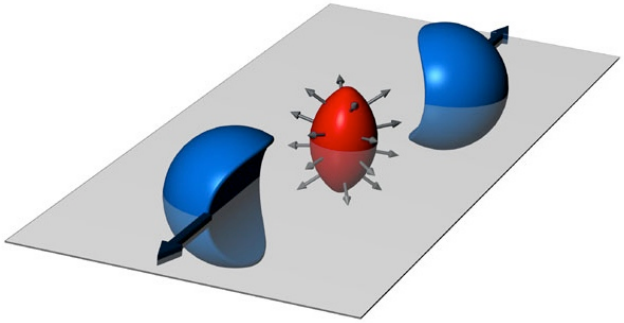
Better agreement if initial parton energy loss is included



ALICE: G. Bruno, SQM13 conference.
R. Arnaldi, CERN LHC seminar.

Results from LHC
J/ψ Elliptic Flow

J/ψ relative to event plane
Di-muon channel, 2.5 < *y* < 4

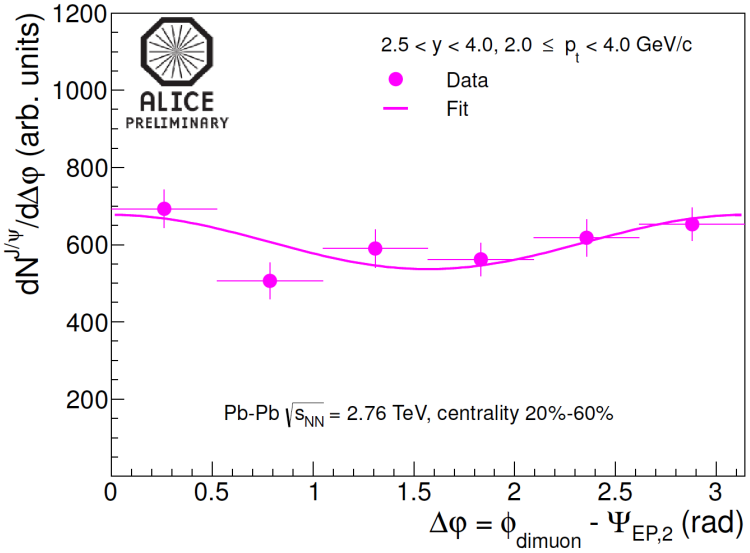


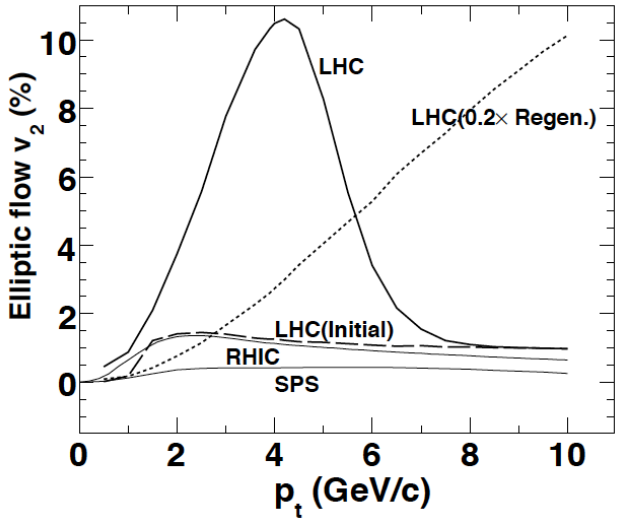
Fourier decomposition:

$$\frac{dN^{J/\psi}}{d\Delta\phi} \propto 1 + 2\, v_2^{obs} \cos(2\,[\phi_{dimuon} - \Psi_{EP,2}])$$

J/ψ from regeneration
Can cause significant v_2 at intermediate p_T, since charm quarks participate in collective expansion

Y. Liu, N. Xu, P. Zhuang, Nucl. Phys. **A834**, 317c (2010).





Results from LHC
J/ψ Elliptic Flow: v_2 vs p_T

20%-60% most central Pb-Pb

ALICE: arXiv:1303.5880

Indication for $v_2 > 0$

p_T –Range: 2 – 6 GeV/c

Significance: **2.7 σ**

Different than at RHIC

STAR: J. PHYS. **G38**, 124107 (2011), arXiv:1212.3304.

Model calculations

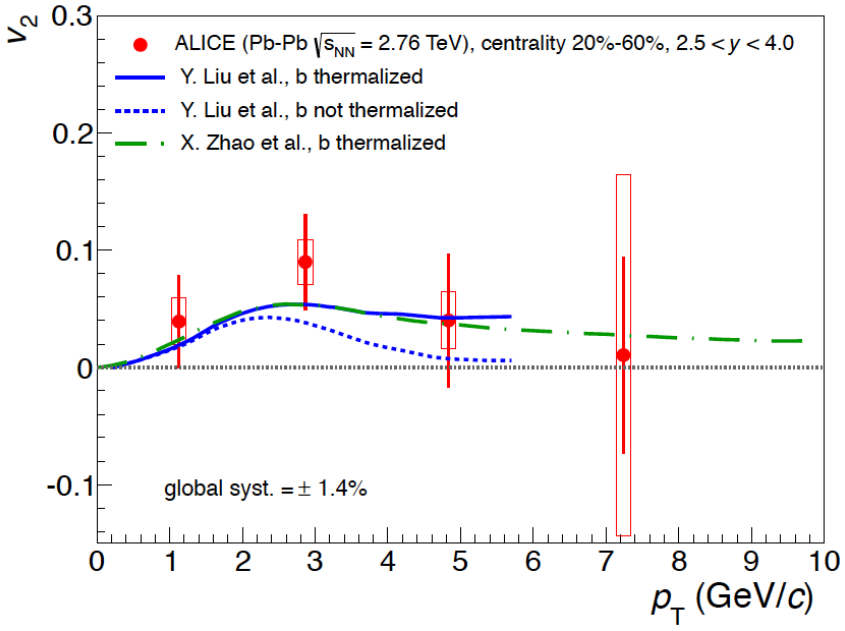
Parton transport model 1

P. Zhuang et al., priv. comm.

Charm cross section: 0.38 mb
Shadowing included
With and w/o thermalized b-quarks

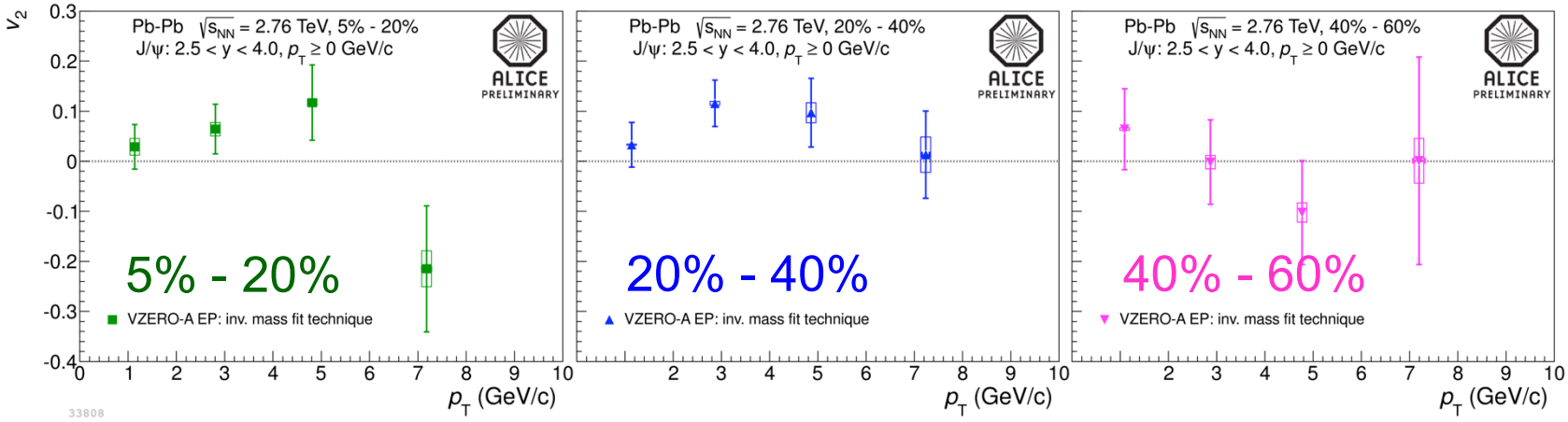
Parton transport model 2

R. Rapp et al., priv. comm.



Results from LHC

J/ψ Elliptic Flow: v_2 vs p_T



Centrality selected Pb-Pb

Di-muon channel, 2.5 < y < 4

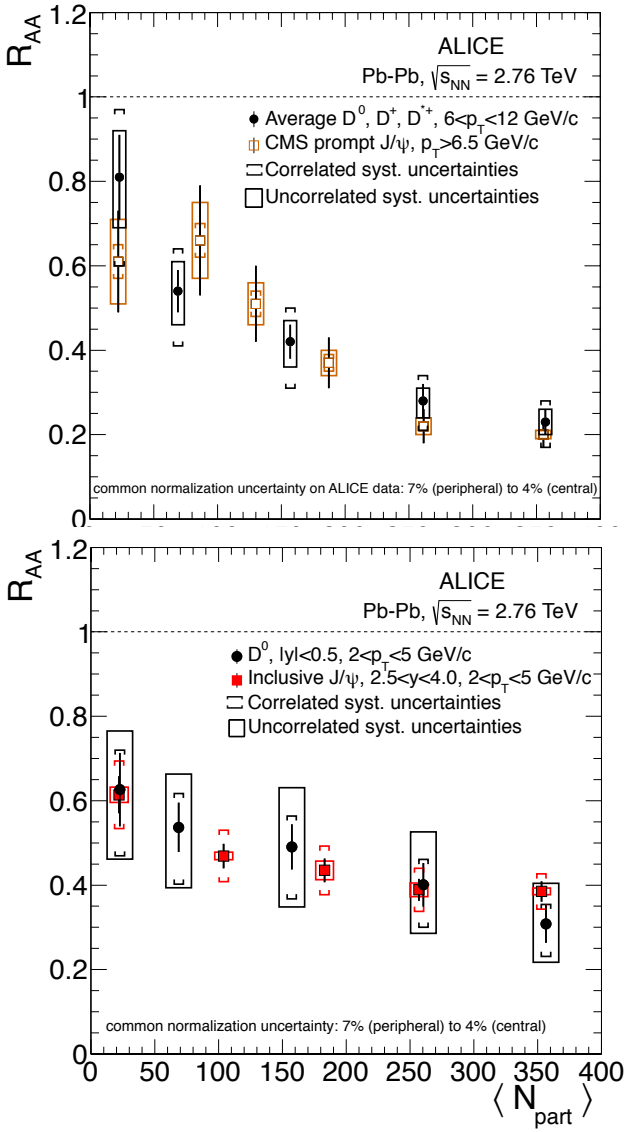
Non-zero v_2 for intermediate p_T (2 – 6 GeV/c)

5% - 20%: ~ 2.2 σ

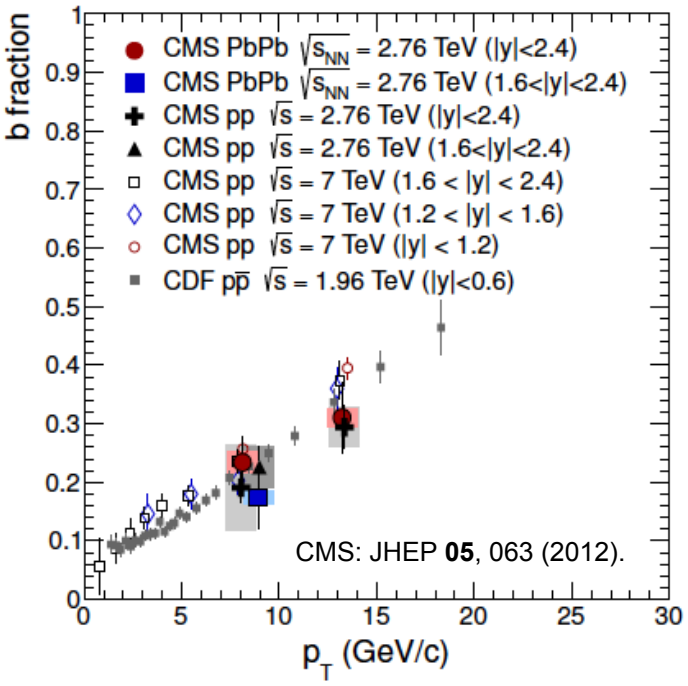
20% - 40%: ~ 3.0 σ

Results from LHC

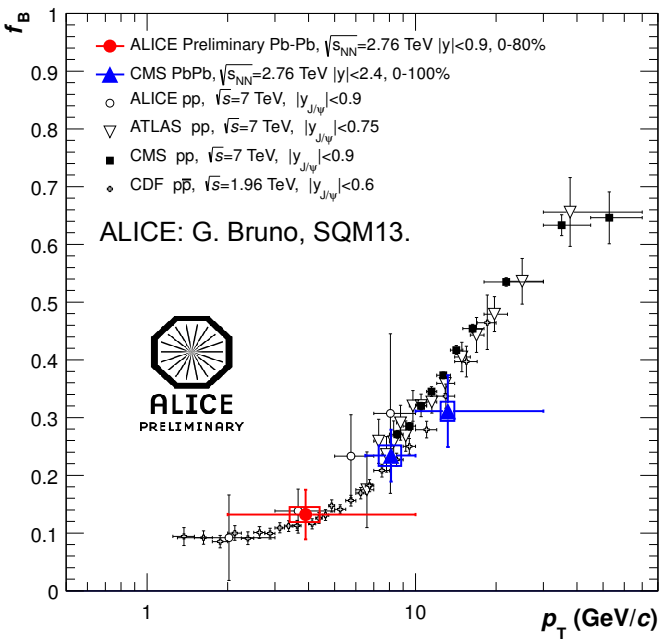
J/ψ and D Suppression Compared (high p_T)

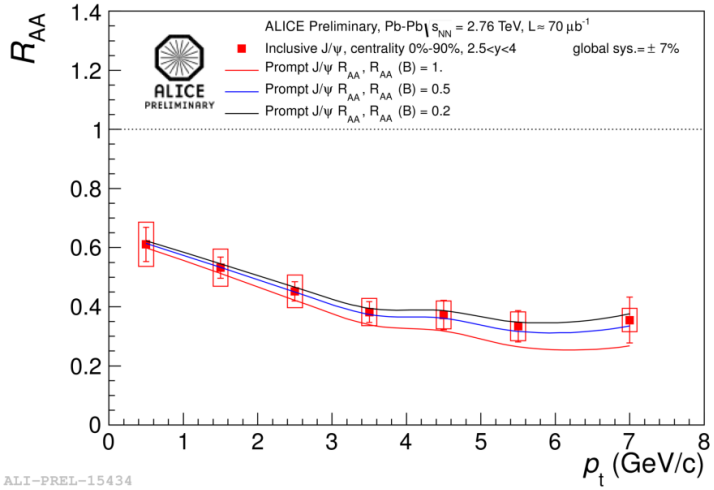


Results from LHC
J/ψ from B-Decays

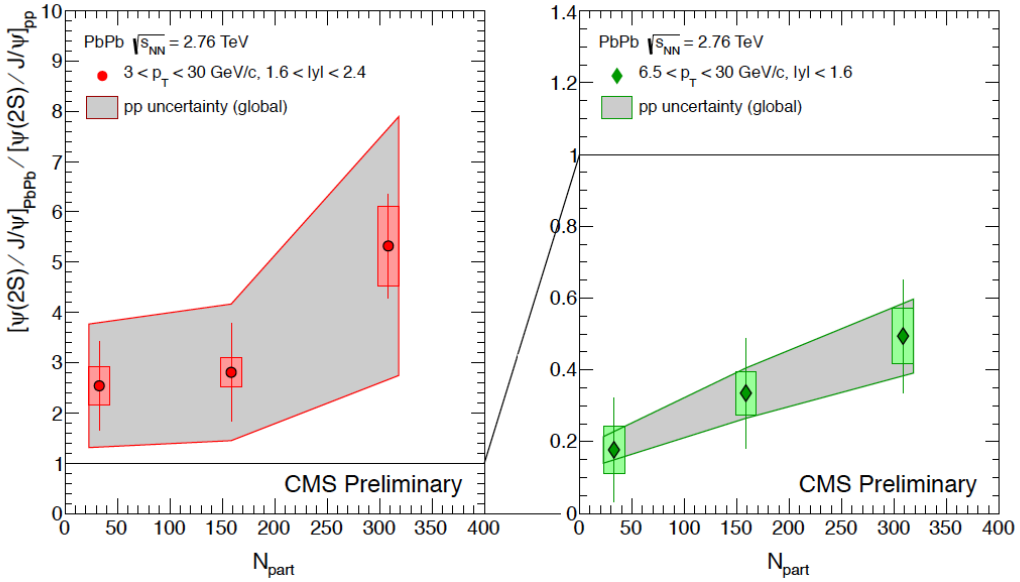


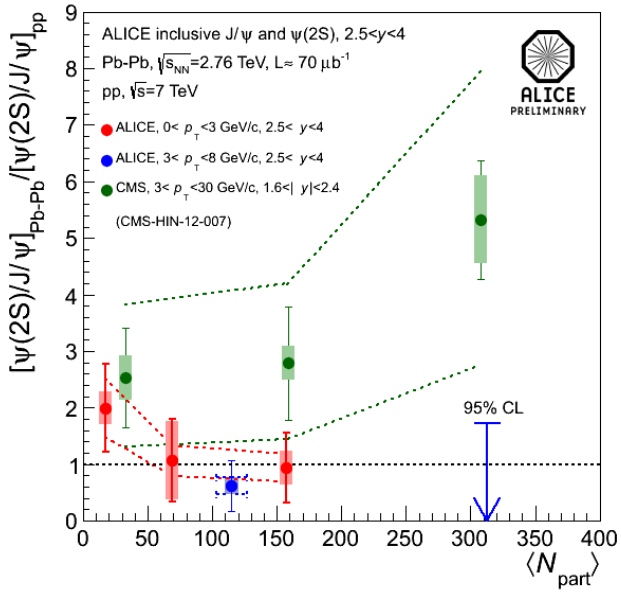
Pb-Pb Collisions
@ $\sqrt{s_{NN}}$ = 2.76 TeV





Results from LHC
ψ(2S) Puzzle





Double ratio $[\psi(2S)/J/\psi]_{Pb\text{-}Pb}$ / $[\psi(2S)/J/\psi]^{pp}$

pp reference from $\sqrt{s}$ = 2.76 TeV (CMS) and $\sqrt{s}$ = 7 TeV (ALICE, incl in systematics)

Large enhancement at forward rapidities seen by CMS

Not confirmed by ALICE measurement

CMS: PAS HIN-12-007
ALICE: R. Arnaldi, QM12 conference.

Results from LHC
J/ψ Production compared to Z Production

J/ψ suppression at LHC

Nuclear modification relative to most peripheral reactions (w/o pp reference)

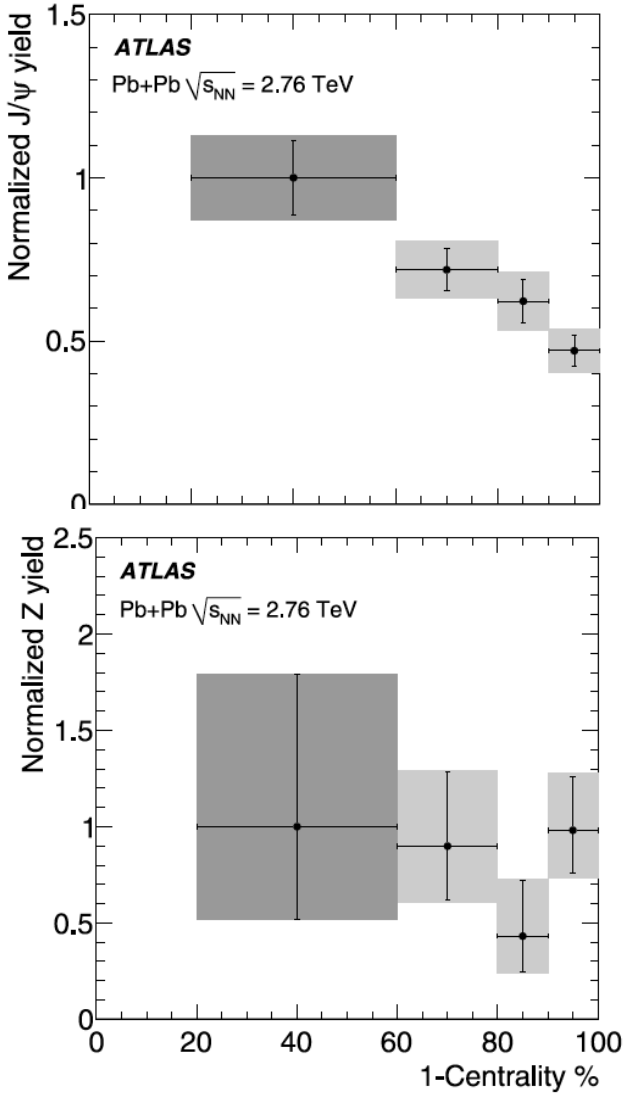
$$R_{CP} = \frac{N_{coll}(\text{per.})}{N_{coll}(\text{cen.})} \frac{dN^{J/\psi}/dy(\text{cen.})}{dN^{J/\psi}/dy(\text{per.})}$$

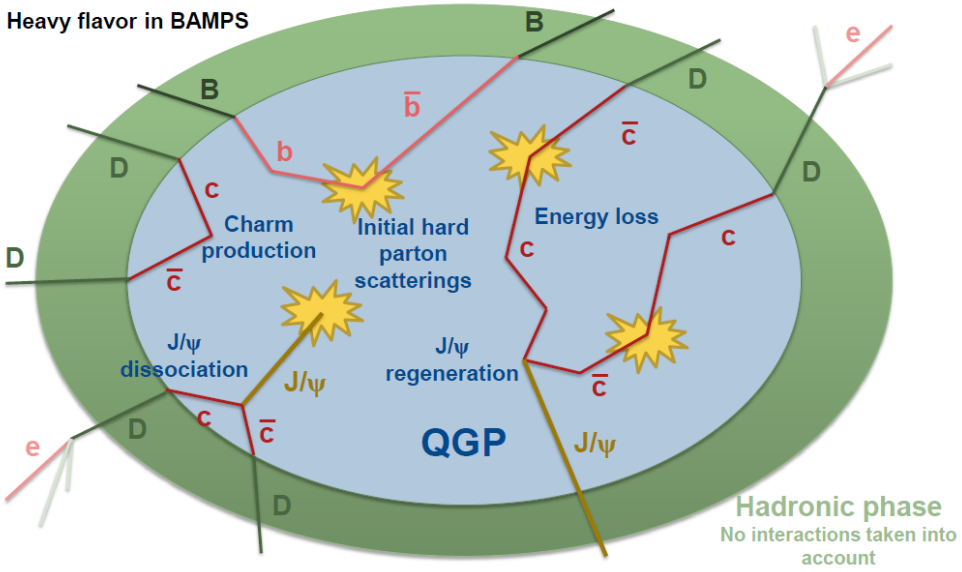
Evidence for medium modification of inclusive J/ψ, similar to lower energies

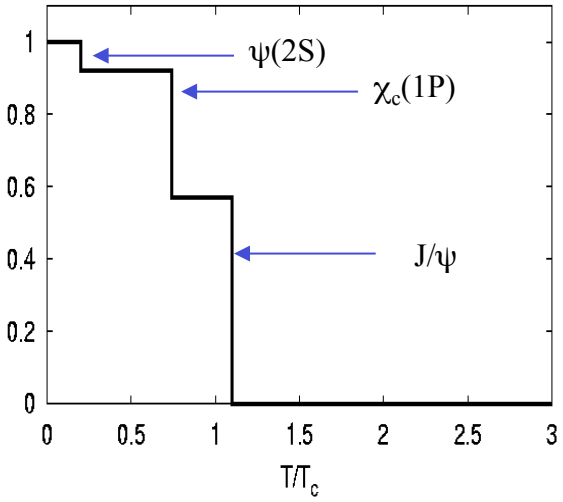
Different behavior of Z-boson

Yield scales with N_{coll}
⇒ no medium effect

ATLAS: Phys. Lett. **B697**, 294 (2011).




Heavy flavor in BAMPS
B
B
D
D
D
D
b
b̄
c
c̄
Charm production
Initial hard parton scatterings
Energy loss
J/ψ dissociation
J/ψ
J/ψ regeneration
QGP
J/ψ
e
e
Hadronic phase
No interactions taken into account


1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
3
T/T_c
ψ(2S)
χ_c(1P)
J/ψ