Overview of Quarkonium Results at RHIC and the LHC

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8th Workshop of the APS Topical Group on Hadronic Physics

10-12 April 2019
Denver, CO

Outline

- Introduction
- Quarkonium in pp collisions
- Quarkonium in Medium - Small Systems
- Quarkonium in Medium - Larger Systems
- Exotics
- Future Facilities
- Summary

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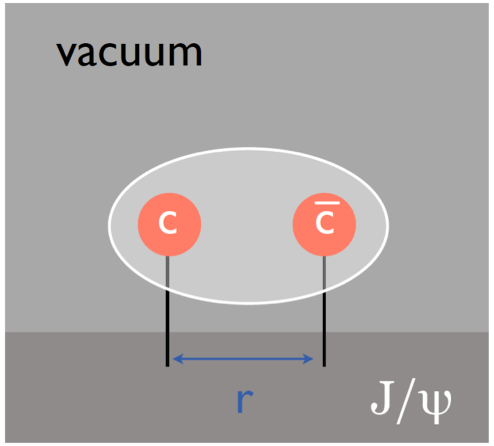
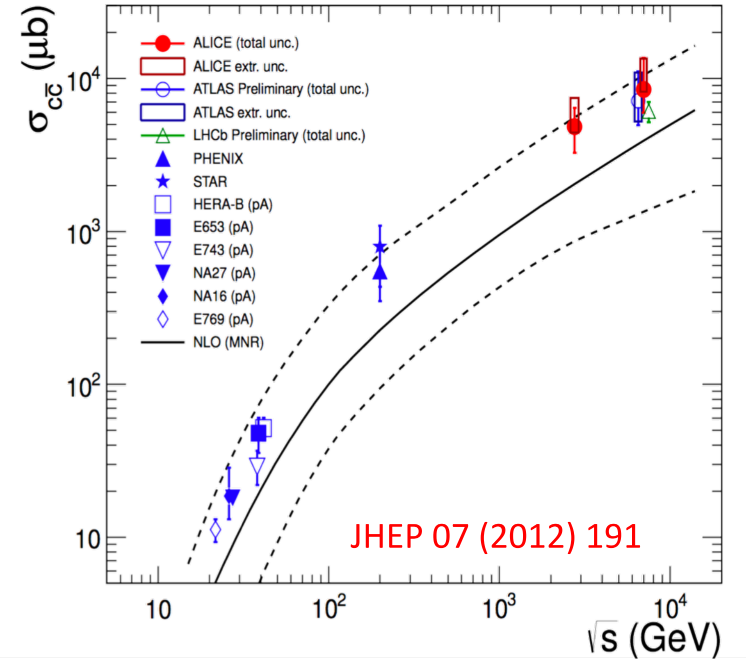
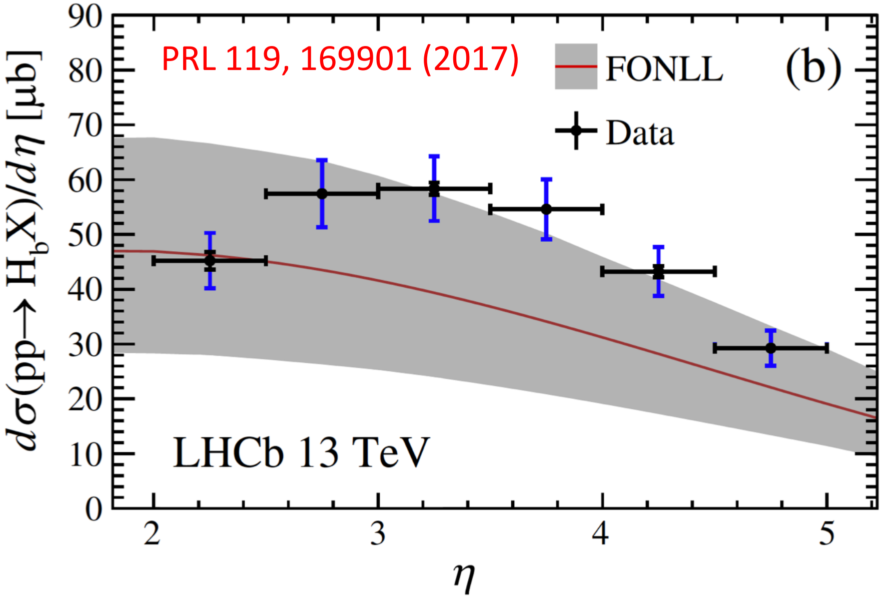
Heavy Flavor in Vacuum



$$\left.\begin{aligned} m_c &\approx 1.3\ GeV \\ m_b &\approx 4.2\ GeV \end{aligned}\right\} \gg \Lambda_{QCD}$$



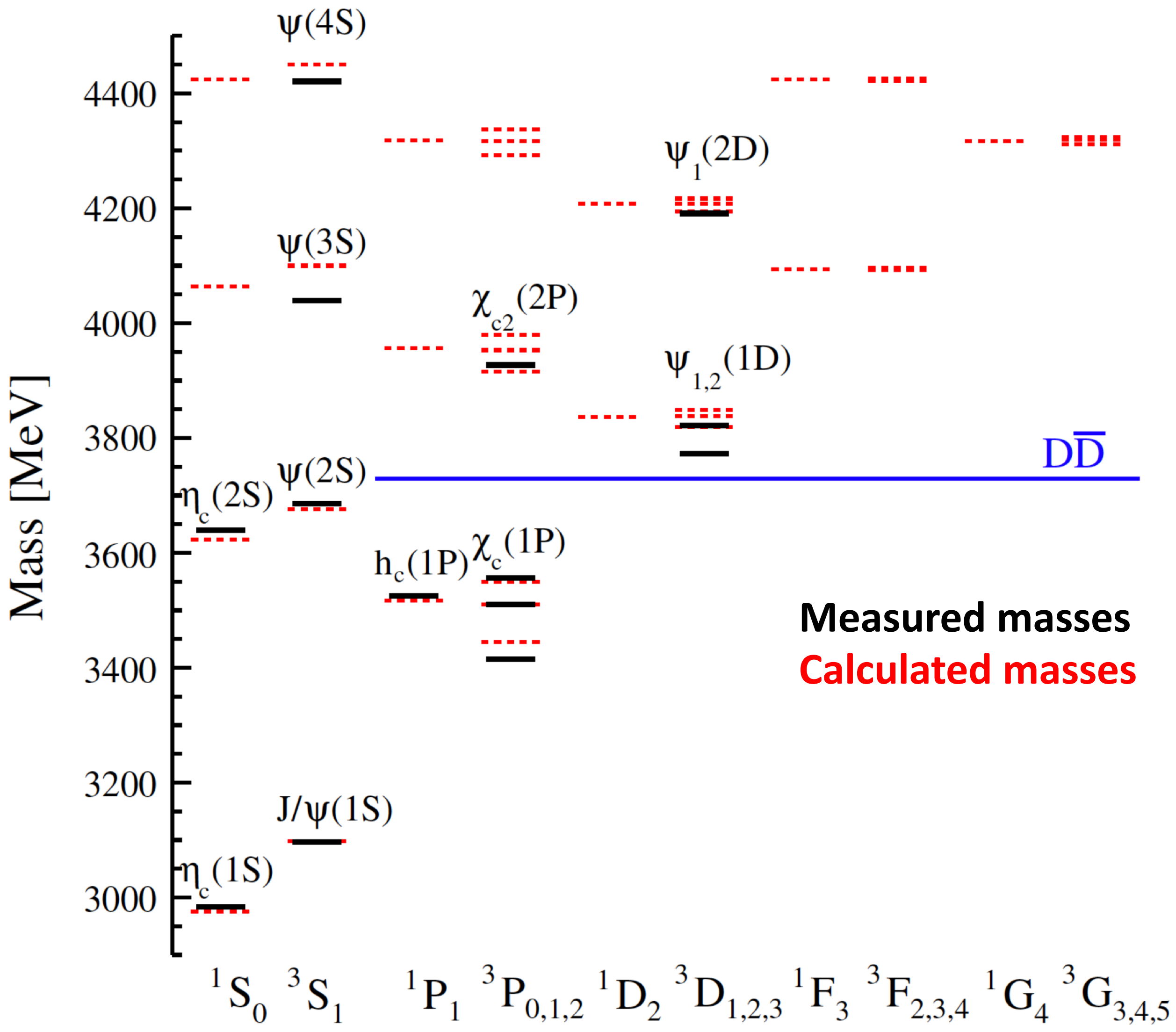


Dominantly produced only in initial hard parton interactions, not through fragmentation.

Total $c\bar{c}$ and $b\bar{b}$ cross sections can be described by perturbative QCD methods.

Baseline for interpreting quarkonium modification in medium.

Charmonium States in Vacuum



Rev. Mod. Phys. 90, 015003 (2018)

Nonrelativistic potential model: solve Schrodinger equation with the potential

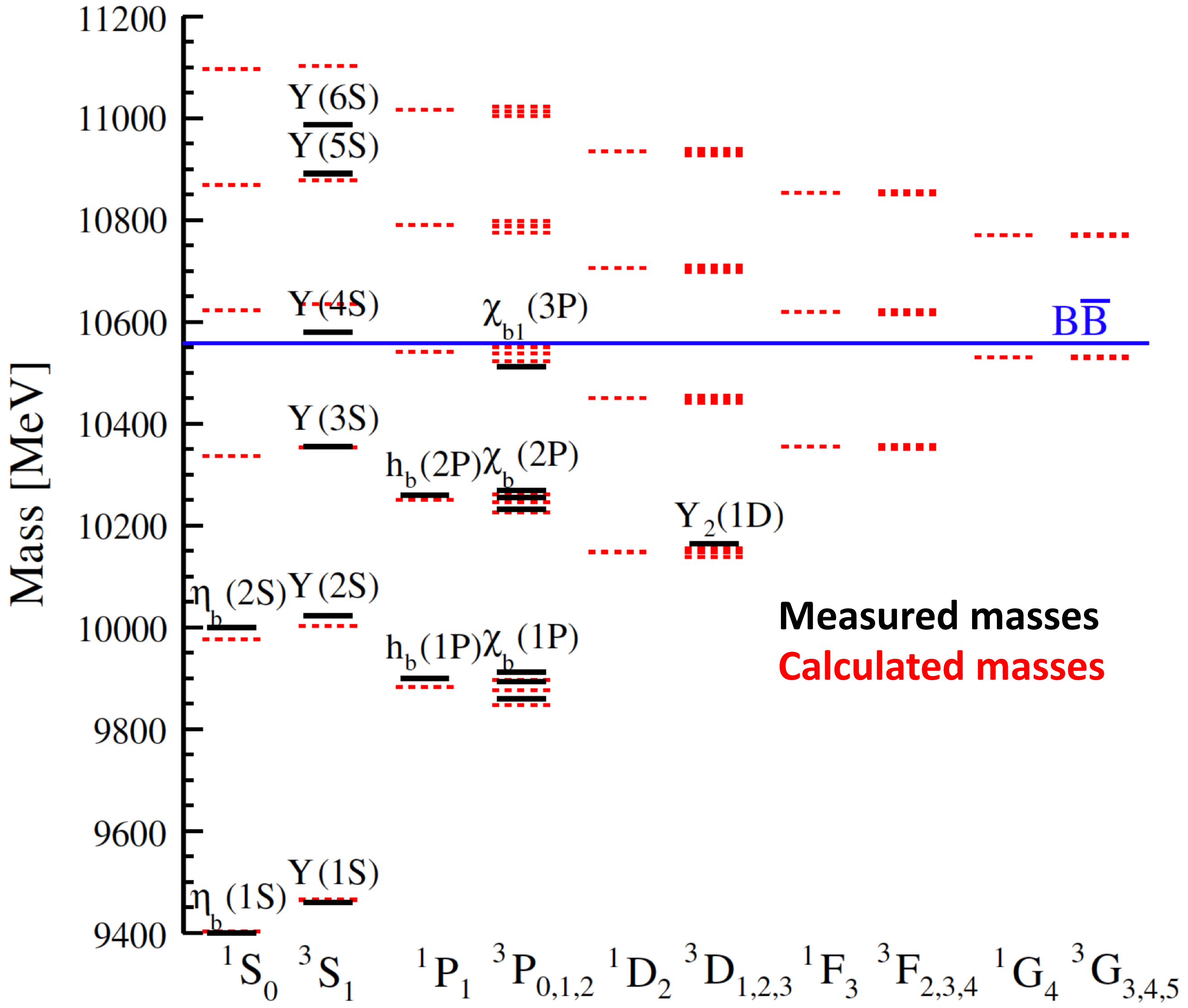
$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

Barnes, Godfrey, Swanson,
Phys. Rev. D 72, 054026 (2005)

NB: The precise mechanism for hadronization of $Q\bar{Q}$ into a color singlet is not yet understood

All expected $c\bar{c}$ states below $D\bar{D}$ threshold have been observed.

Bottomonium States in Vacuum



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Heavy quarkonium has incredibly rich structure that is accessible experimentally and theoretically.

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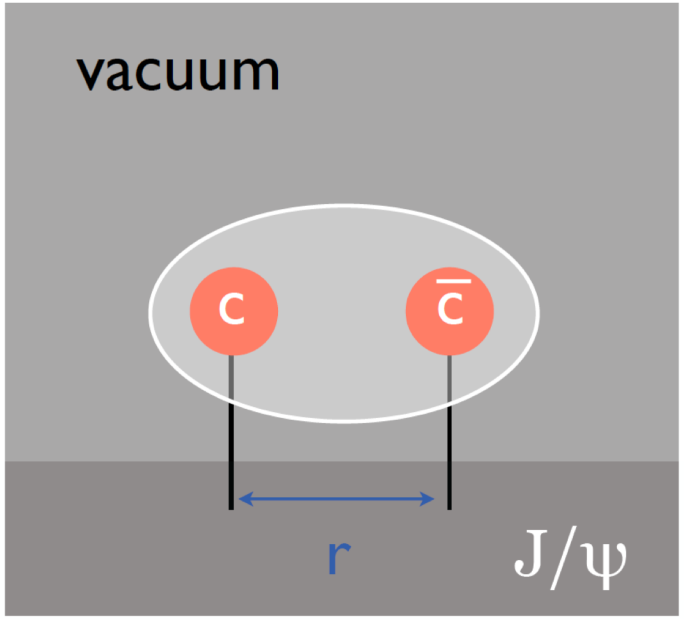
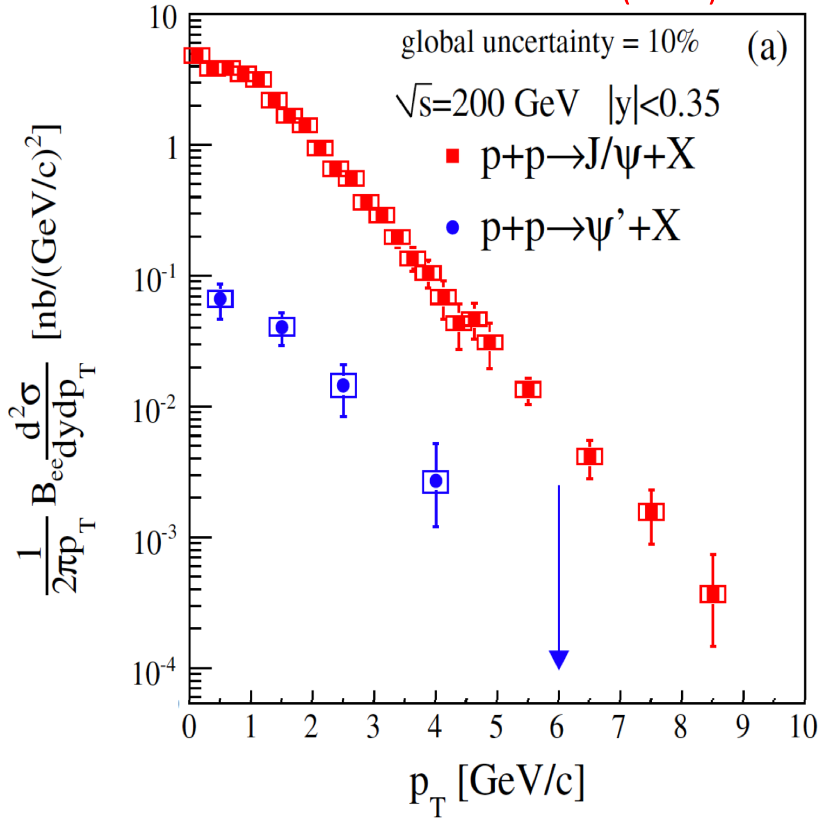
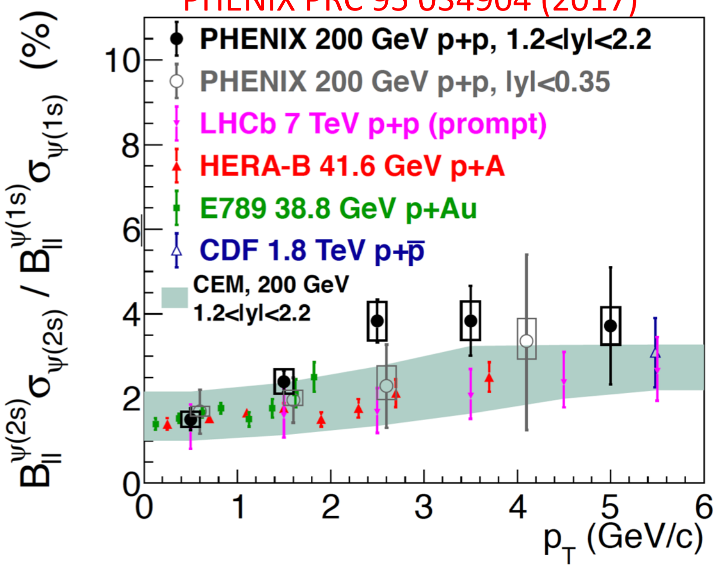


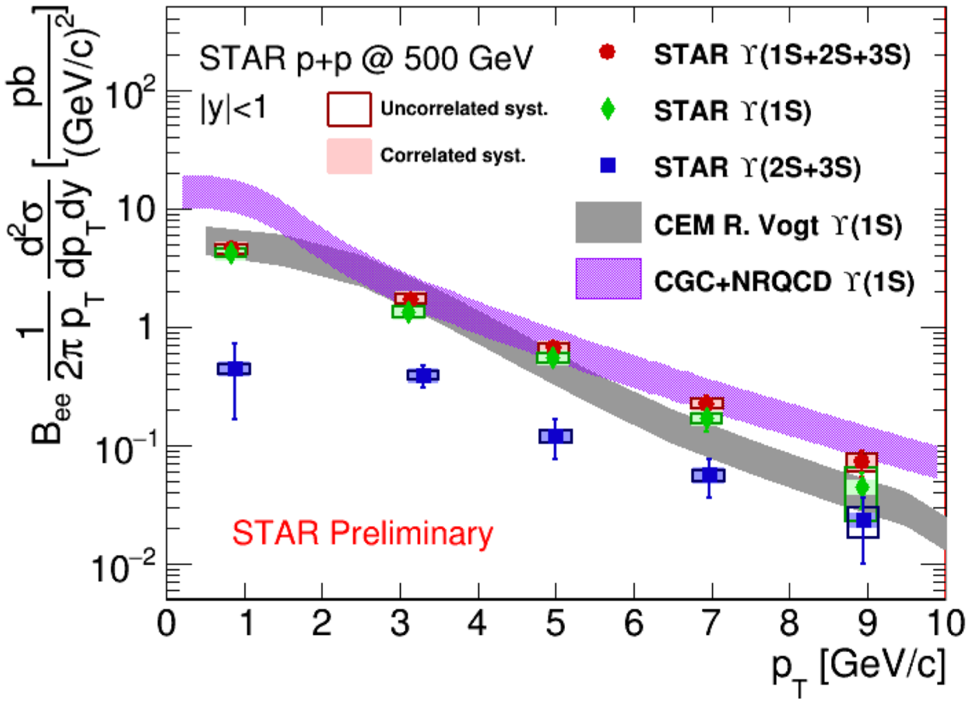
RHIC Results on Quarkonium in pp

PHENIX PRD 85 092004 (2012)



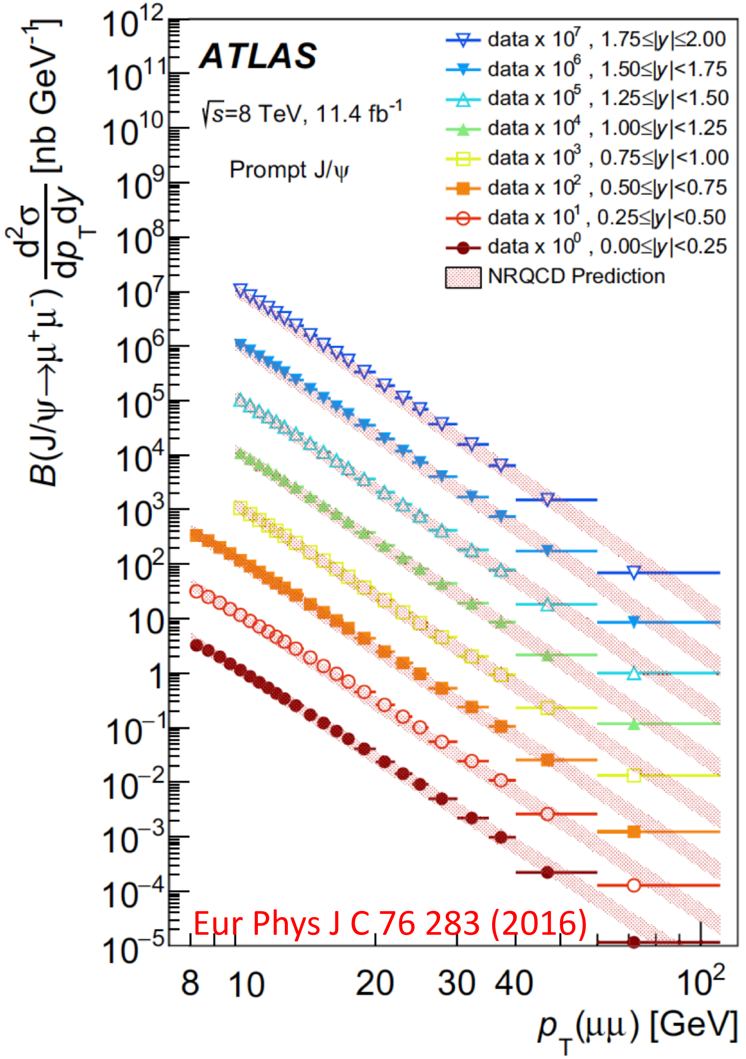
PHENIX PRC 95 034904 (2017)

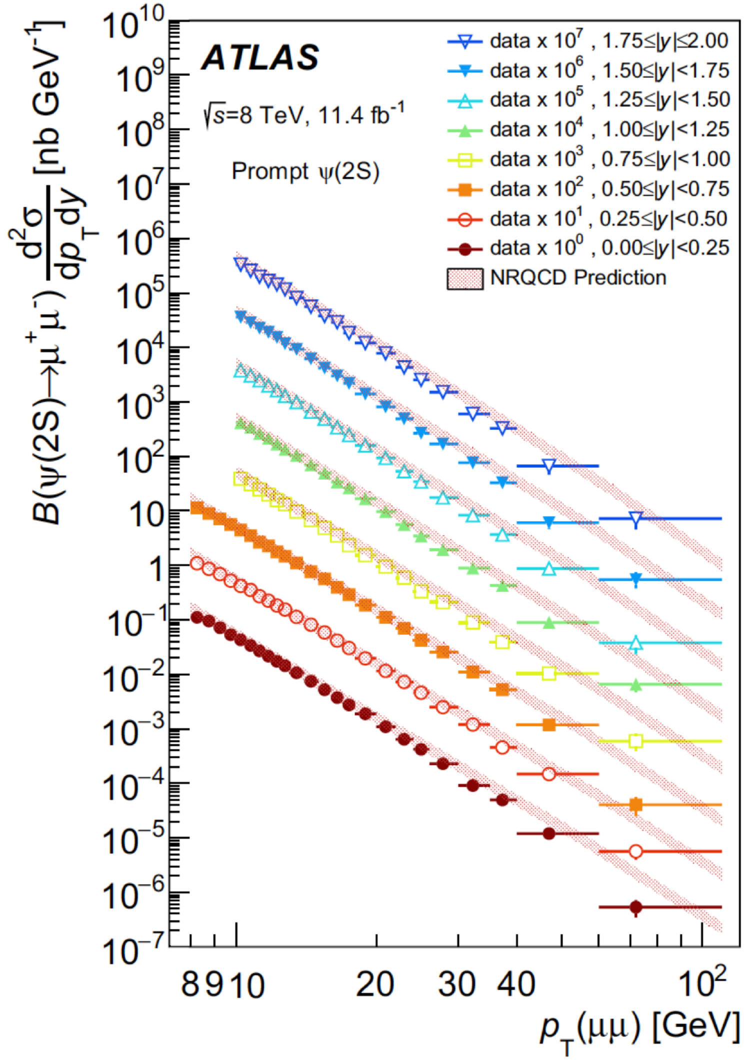


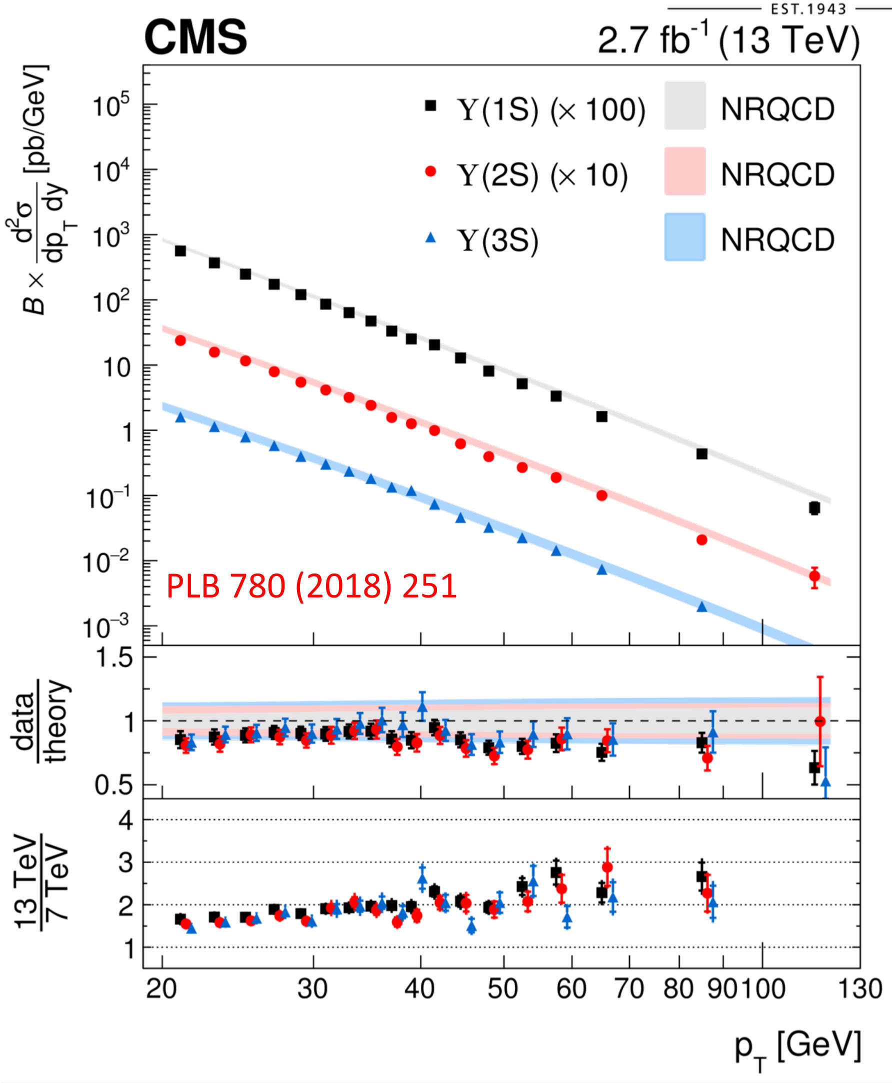


Upsilon data prefers CEM, Vogt PRC 92 (2017)
CGC + NRQCD from Ma, Venugopalan PRL 113 192301 (2014)

LHC Results on quarkonia in pp



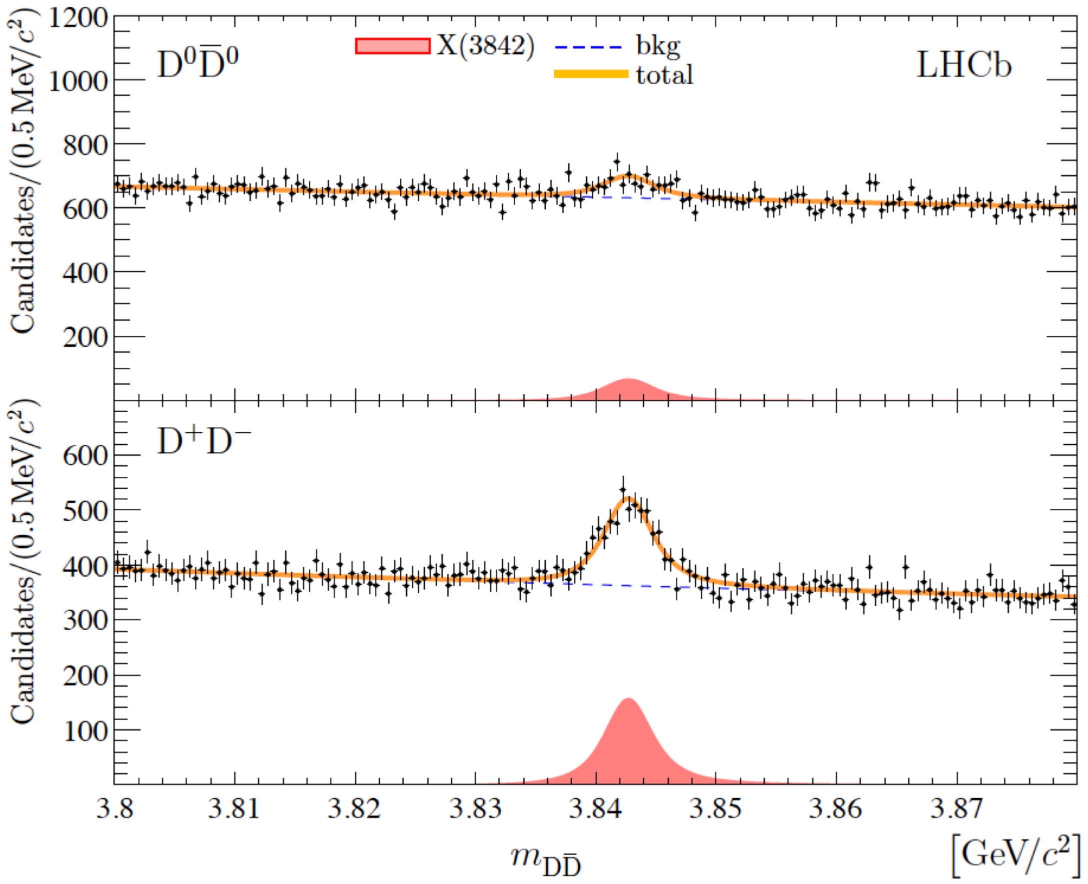




LHC data shows good agreement with NRQCD calculations over large range of transverse momentum

Recent progress: a new charmonium state

arXiv:1903.12240



Recent result from LHCb from full dataset of 9 fb^{-1}

Combined data from $\sqrt{s}$ = 7, 8, 13 TeV pp collisions

$$m_{X(3842)} = 3842.71 \pm 0.16 \pm 0.12\,\mathrm{MeV}/c^2$$

$$\Gamma_{X(3842)} = 2.79 \pm 0.51 \pm 0.35\,\mathrm{MeV}$$

Consistent with expectations for unobserved $\psi_3\ 1^3D_3$ state

Eichten, Lane, Quigg PRD 73 014014 (2006)
Radford, Repko, PRD 75 074031 (2007)

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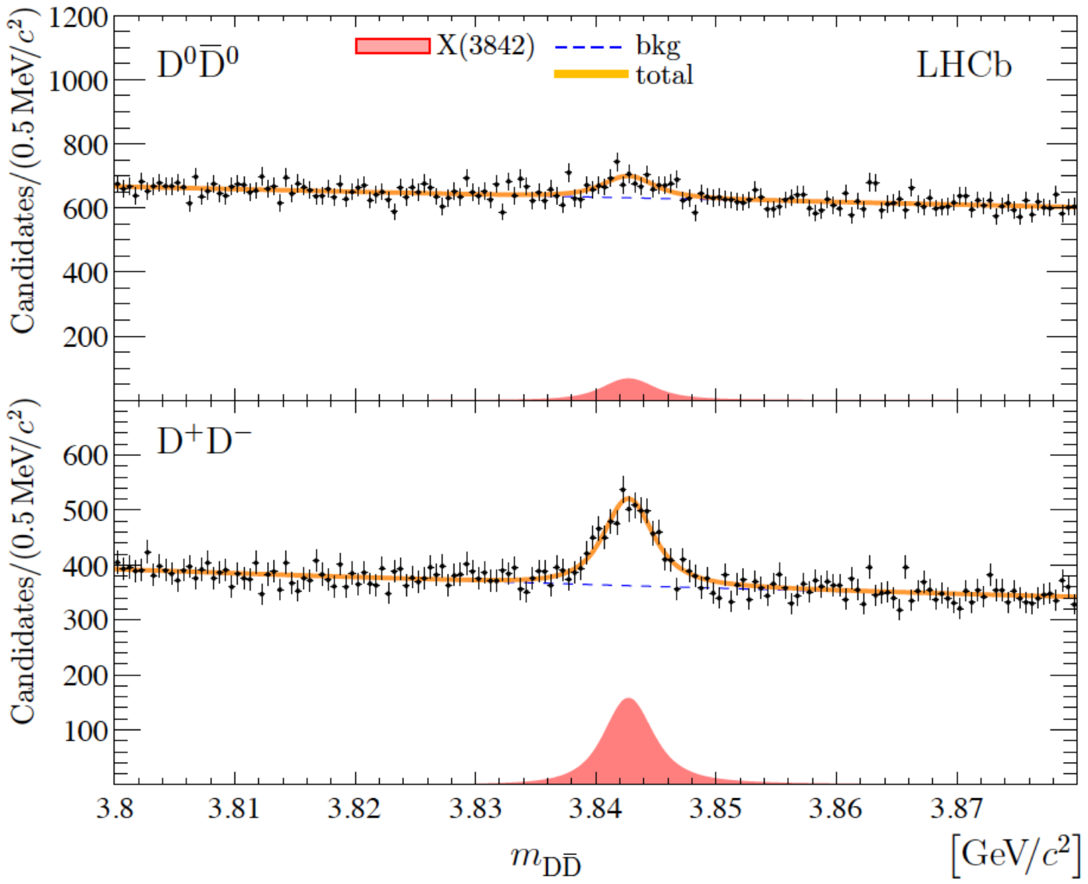

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Discovery in quarkonia is still highly active:

- Provides additional tests for production models
- Typical charmonia must be accounted for to identify any potential “exotic” states

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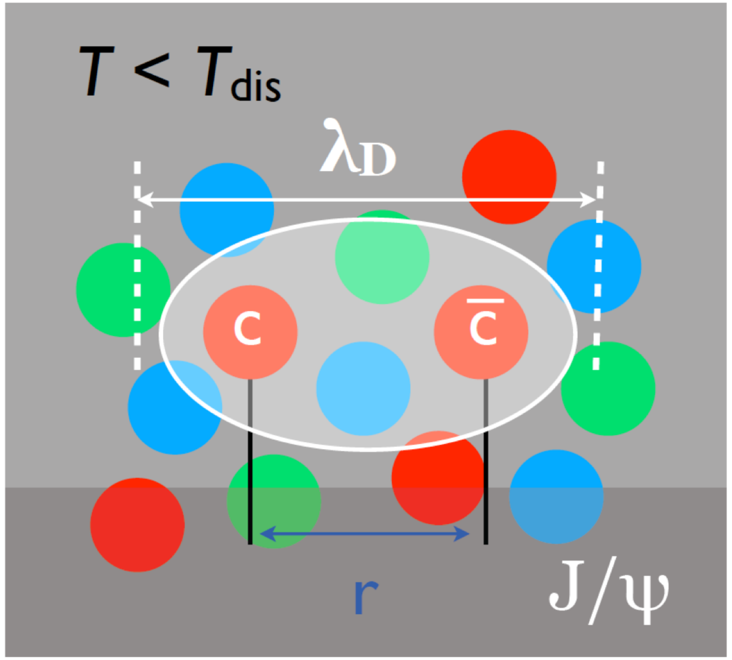
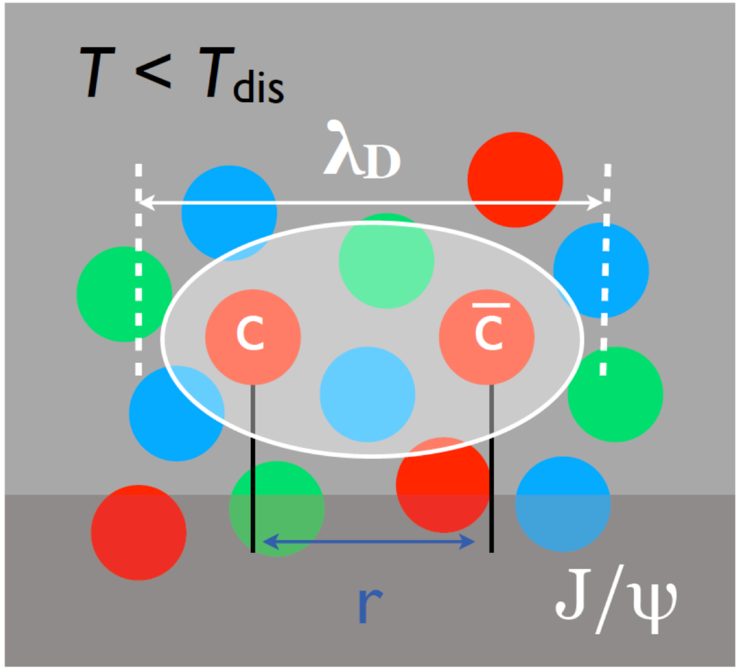


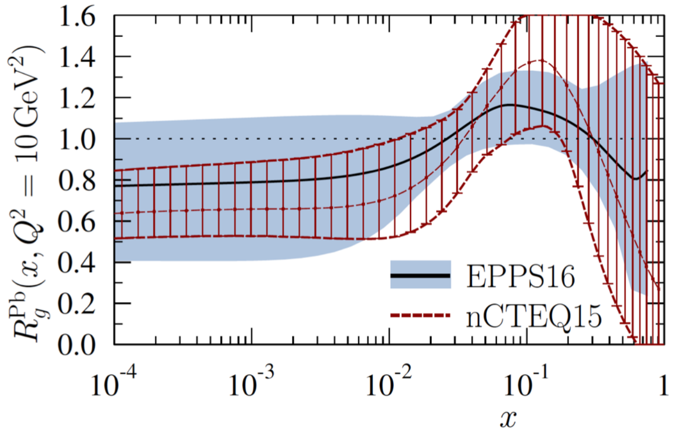
Quarkonium in Medium -pA

Sensitive to a range of effects that cannot be probed in pp collisions



Nuclear PDF is modified:

Examine forward/backward rapidity data to vary sampled *x*

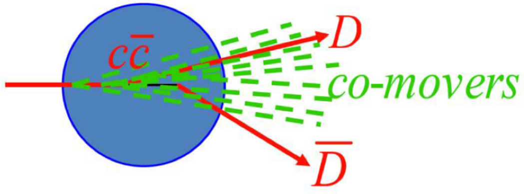


Interactions between $Q\bar{Q}$ precursor state and partons in nucleus can lead to kT broadening, QCD energy loss, and breakup

Measure pT spectra and quarkonium cross sections

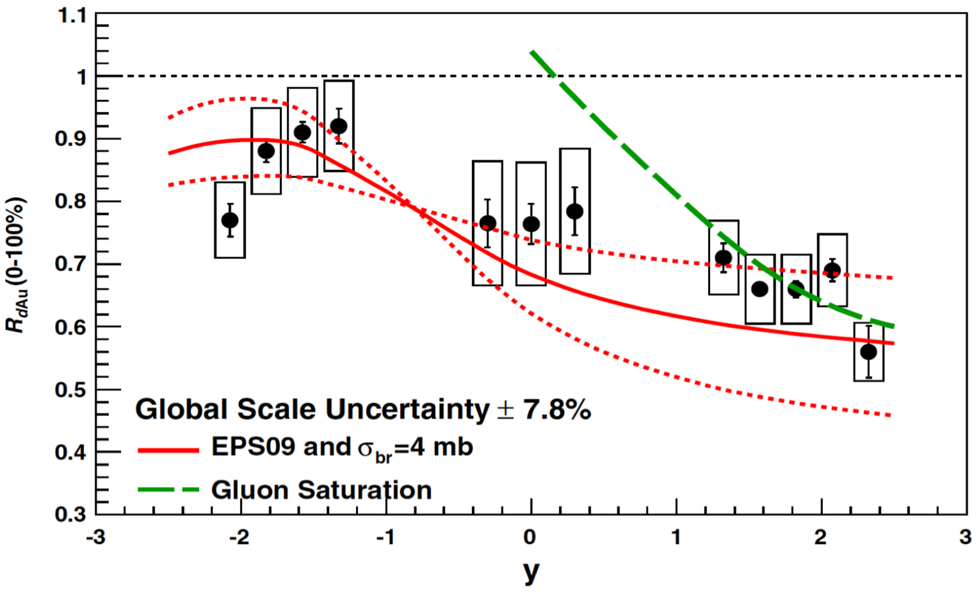
Late stage interactions outside nucleus can dissociate fully formed states

Look for differences in states with same quark content, eg J/ψ vs $\psi(2S)$



Nuclear Modification of J/ψ in small systems

PHENIX d+Au J/ Ψ data:
PRL 107 143301 (2011)



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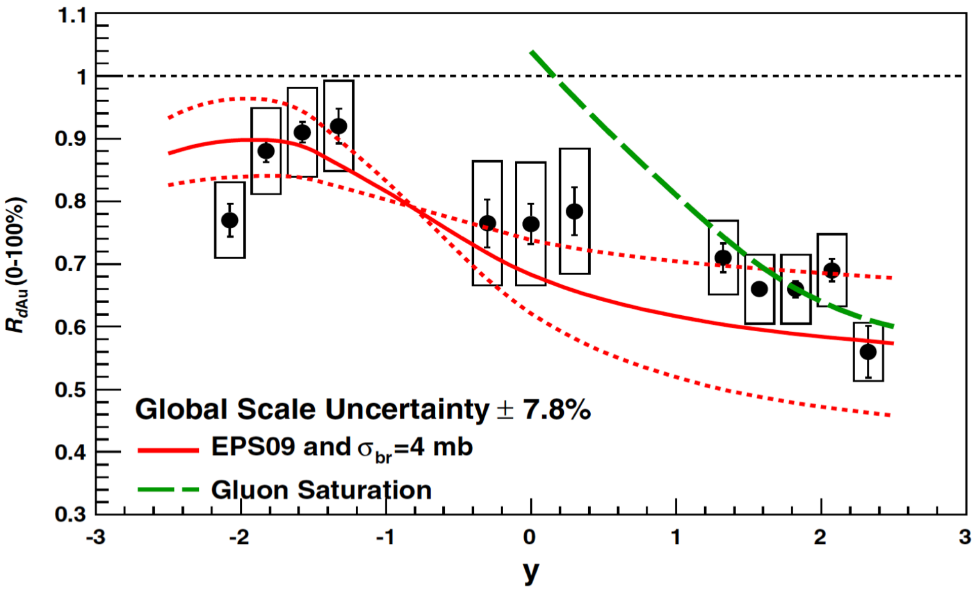
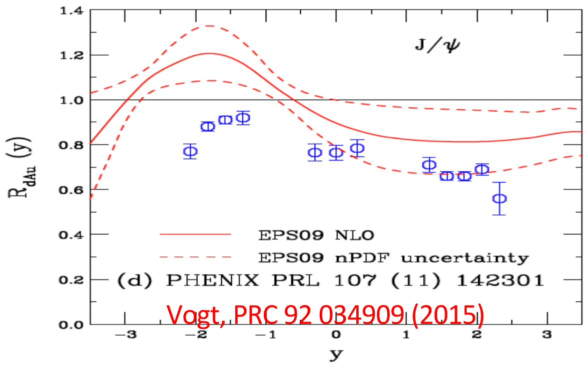
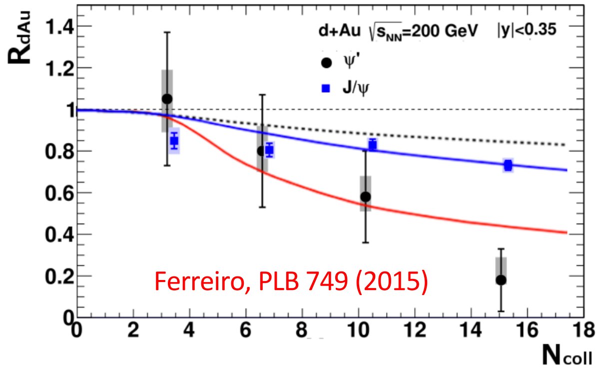
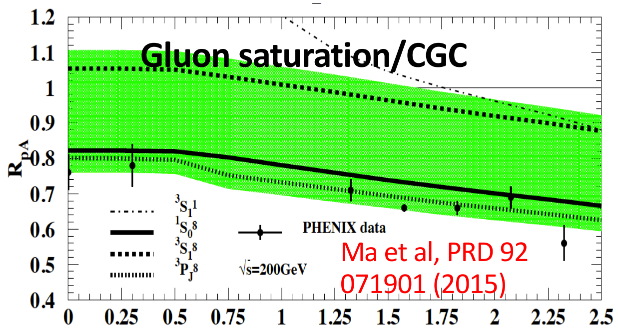


PDF Modifications

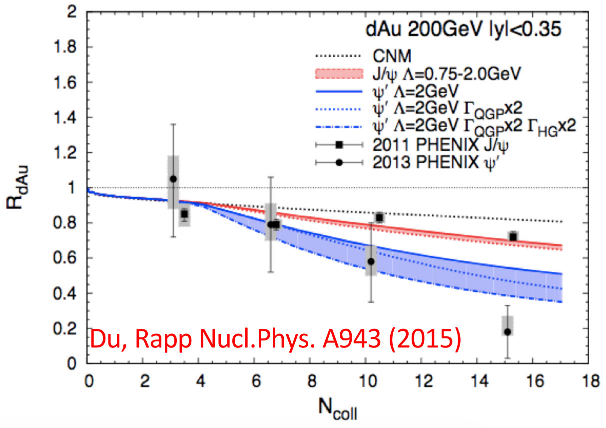


Comovers

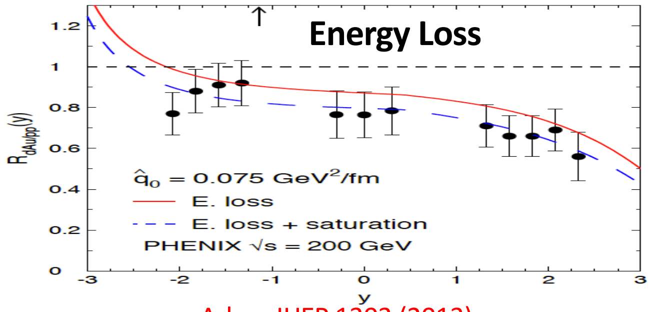




Short-lived plasma phase

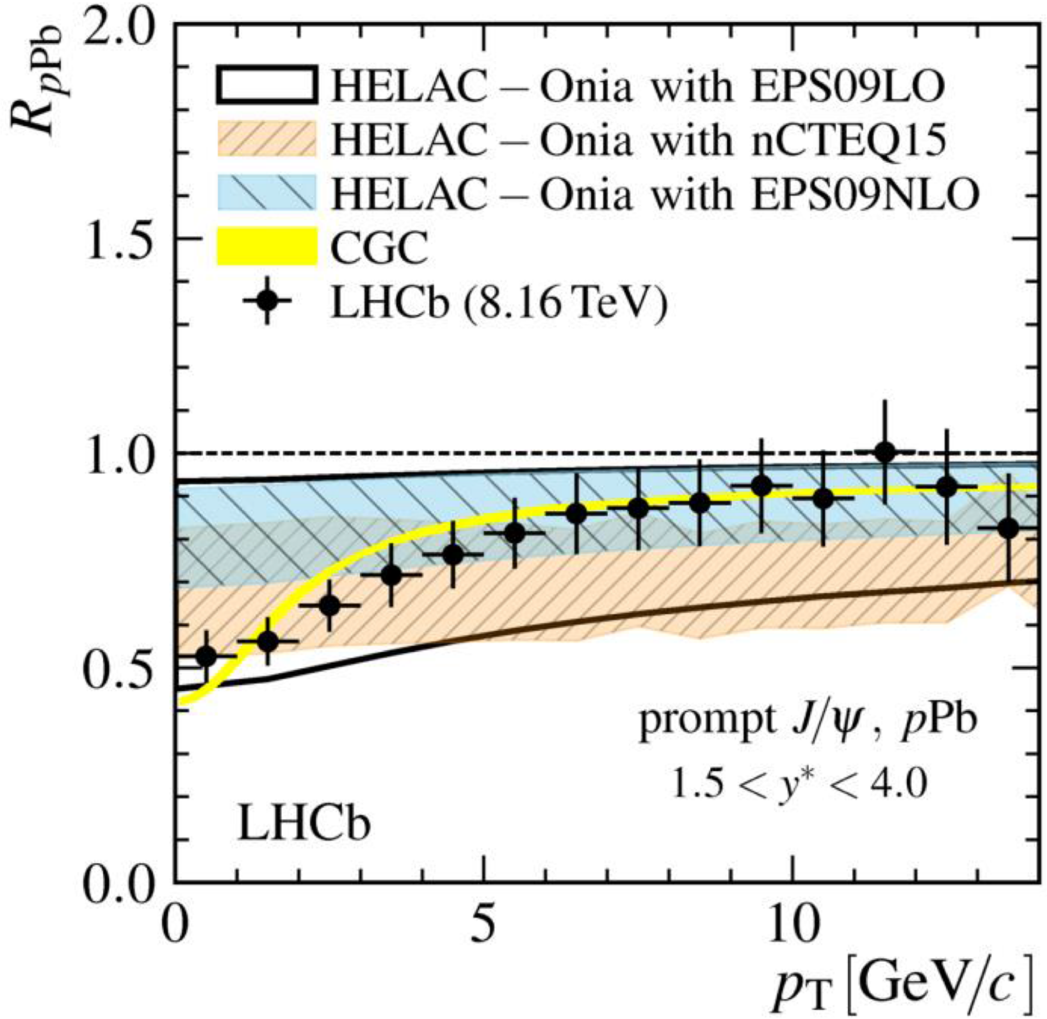


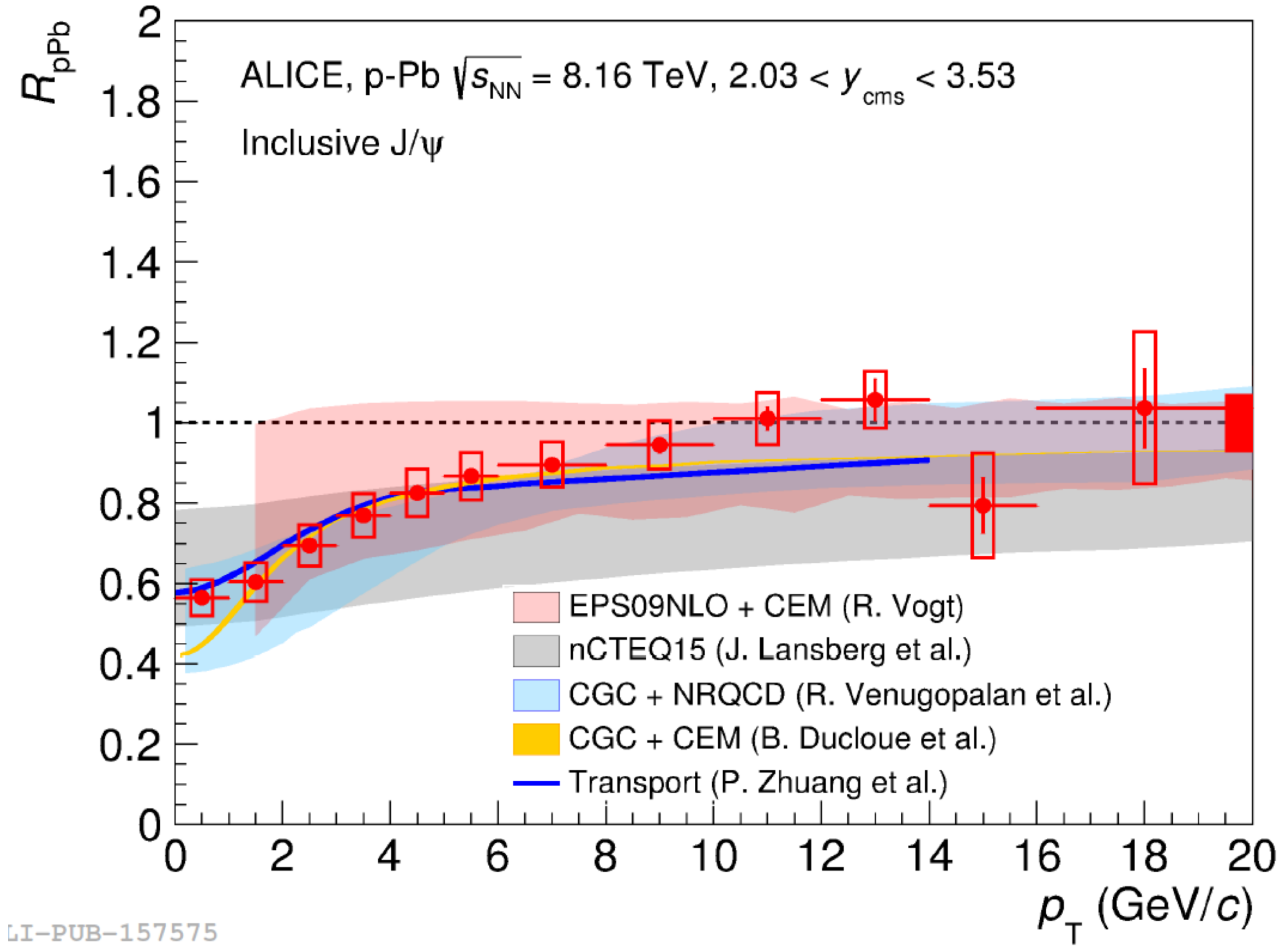
Many calculations based on very different physics can describe this data.



Arleo, JHEP 1303 (2013)

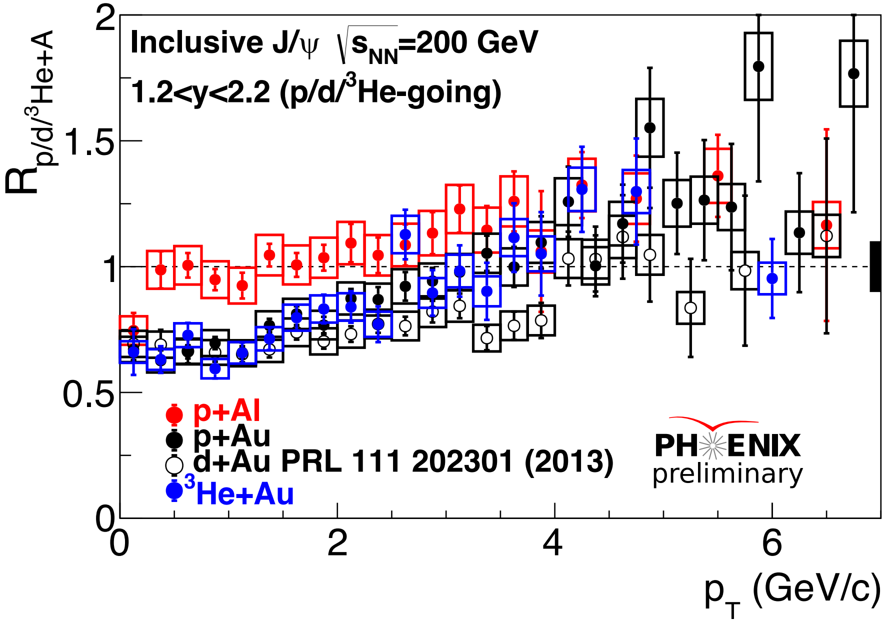
Nuclear Modification of J/ψ in small systems





Similar situation at LHC: many calculations based on very different physics can describe this data.

New Measurements: Nuclear Modification of J/ψ



RHIC: Beam species scan allows variation of projectile and target beam species:

Small dependence on projectile
Significant dependence on nuclear target (Al vs Au)
Could suggest nPDF is dominant effect at forward rapidity

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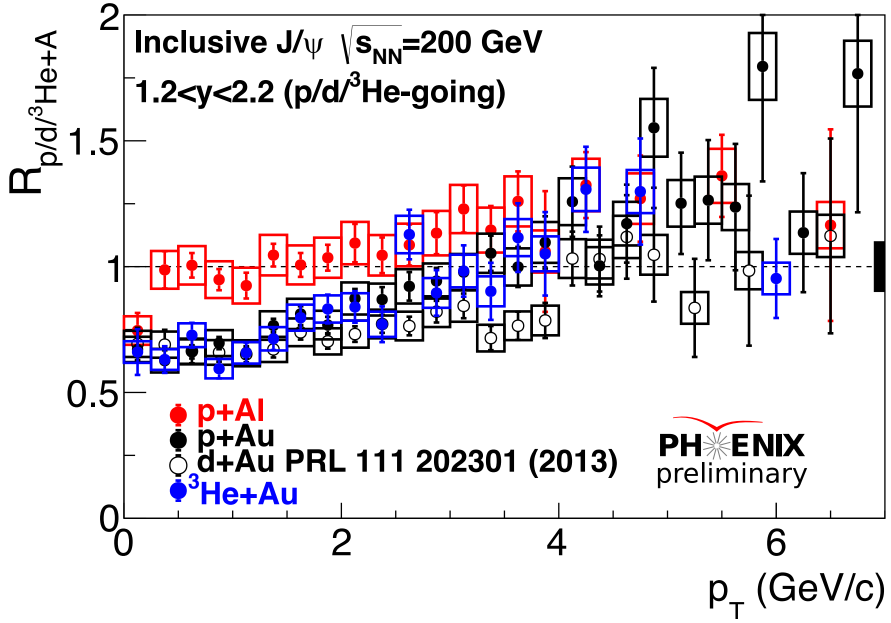

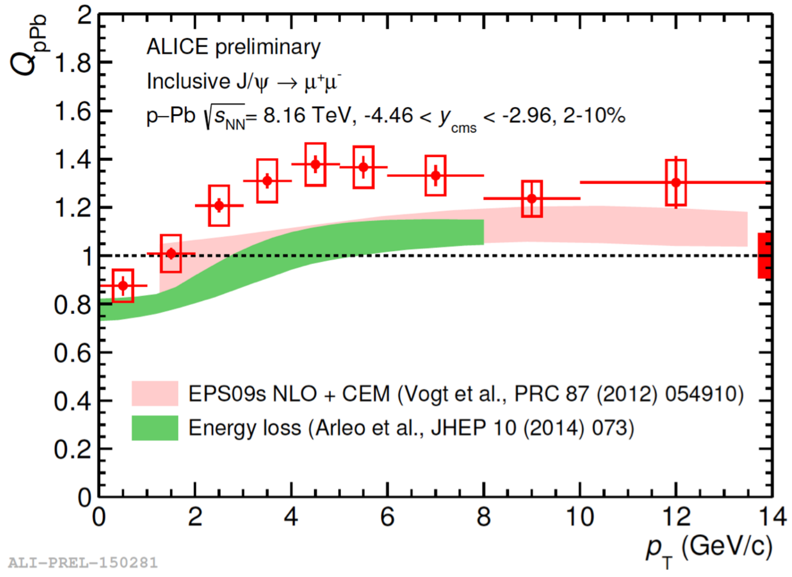

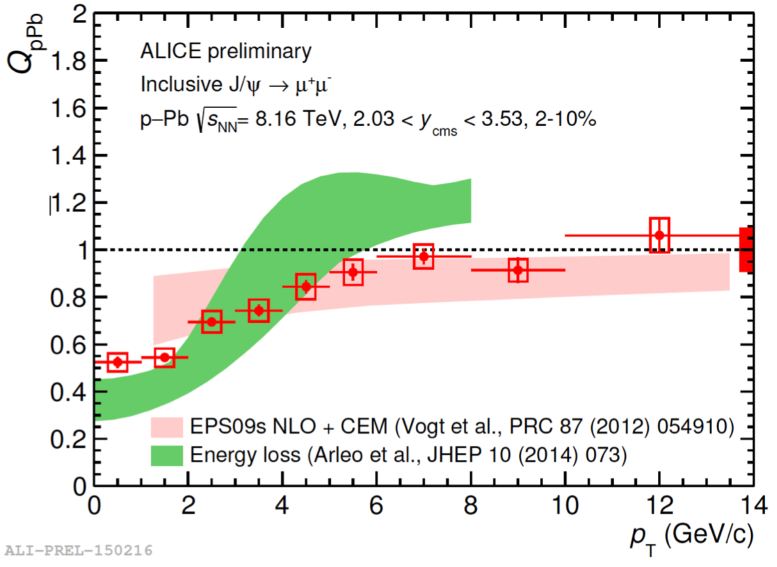

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Small dependence on projectile
Significant dependence on nuclear target (Al vs Au)
Could suggest nPDF is dominant effect at forward rapidity

LHC: New ALICE data from 8 TeV allows multi-differential measurements in rapidity/pT/centrality

→Critical for constraining models

Different states with same quark content

$\bar{c}$ c

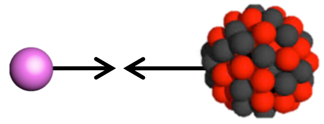
$J/\psi\ E_b \approx 600\ MeV$

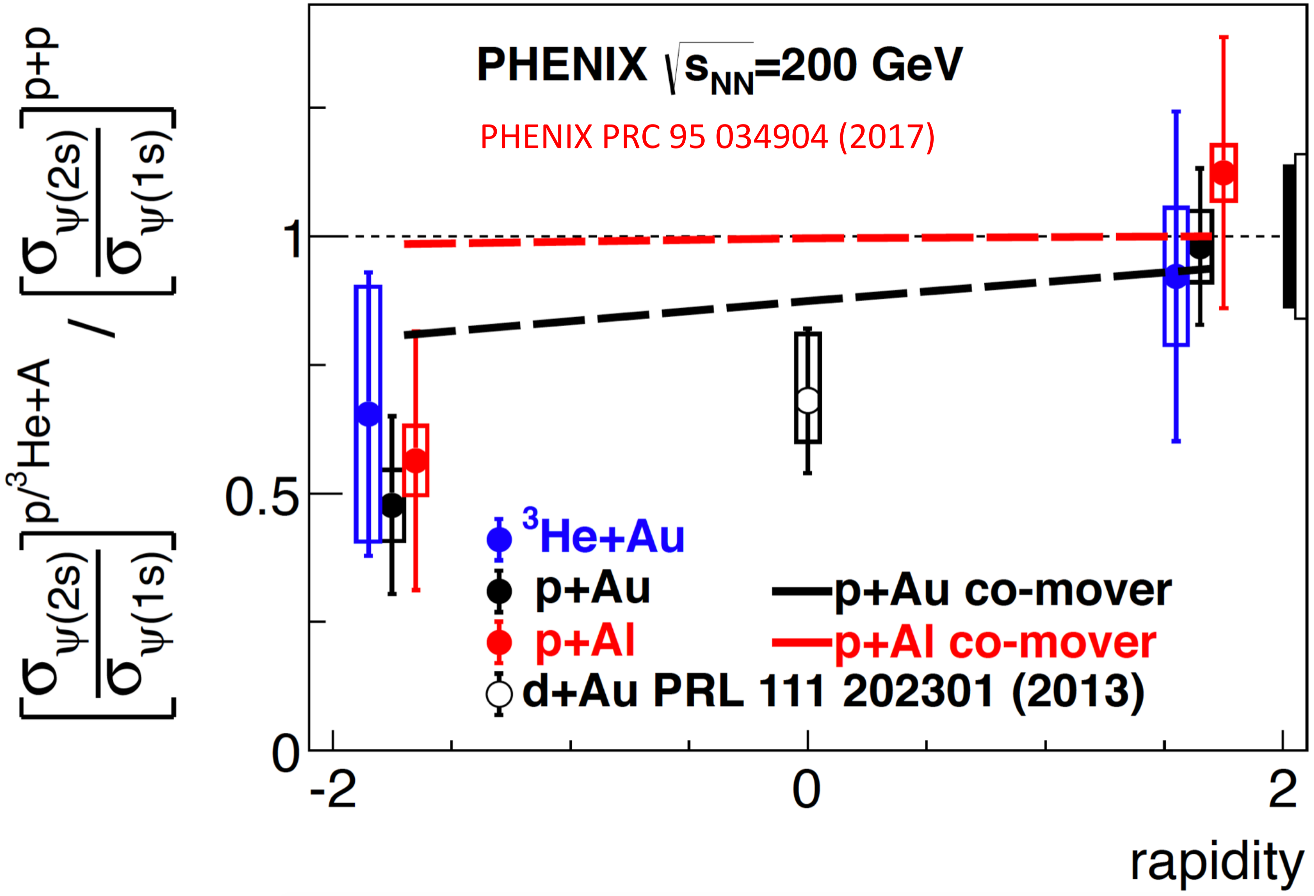
$\bar{c}$ c

$\psi(2S)\ E_b \approx 50\ MeV$

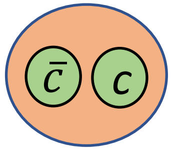
Initial state effects identical for all $c\bar{c}$

RHIC data qualitatively consistent with picture from co-mover interaction model





Different states with same quark content



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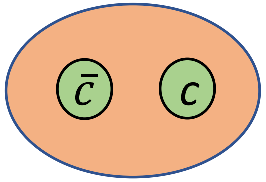

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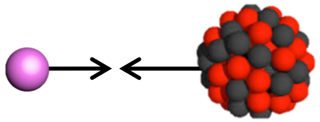

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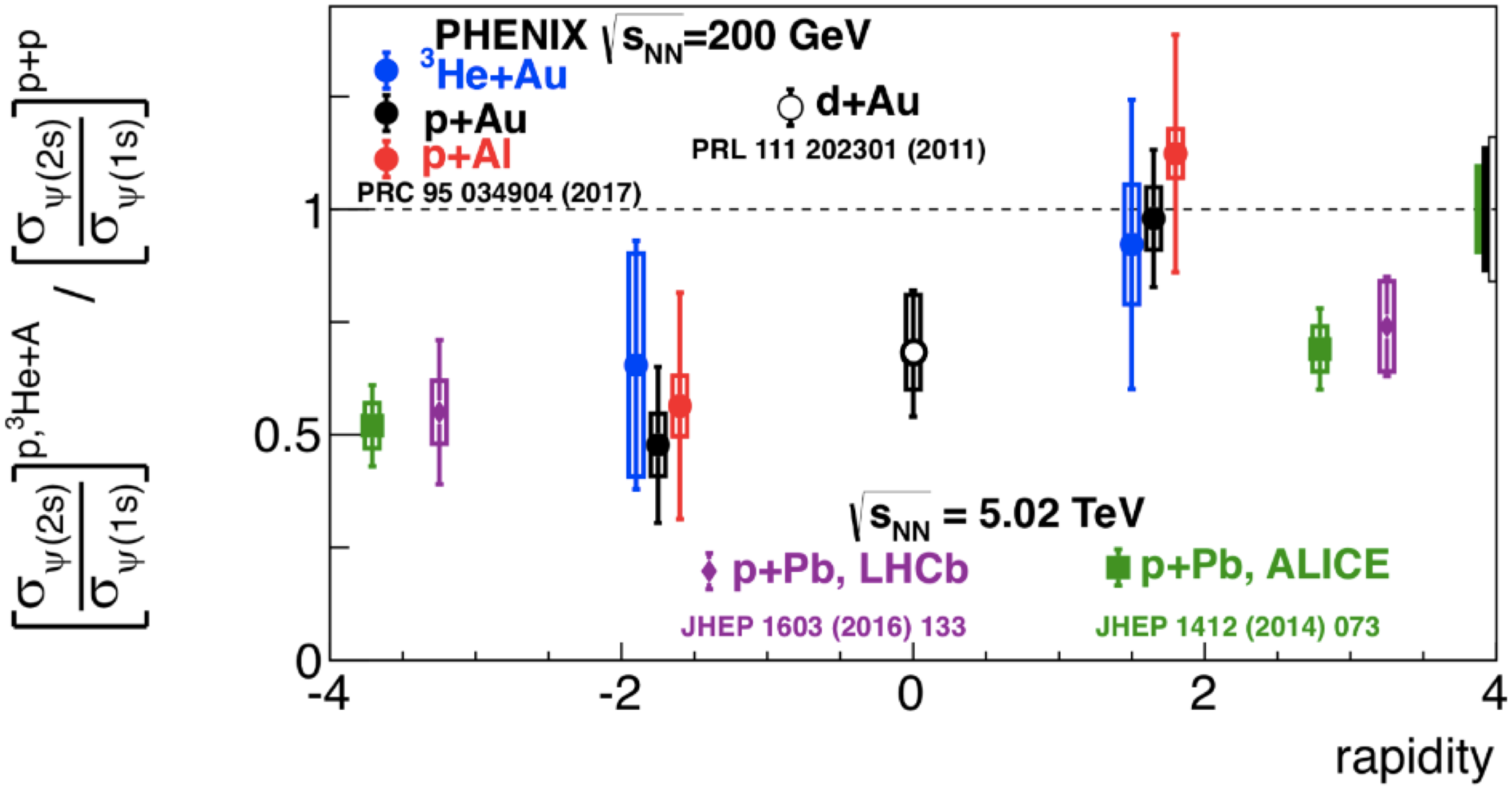
LHC data shows suppression at forward rapidity also?



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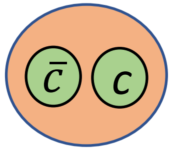

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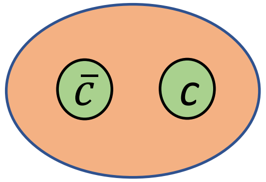

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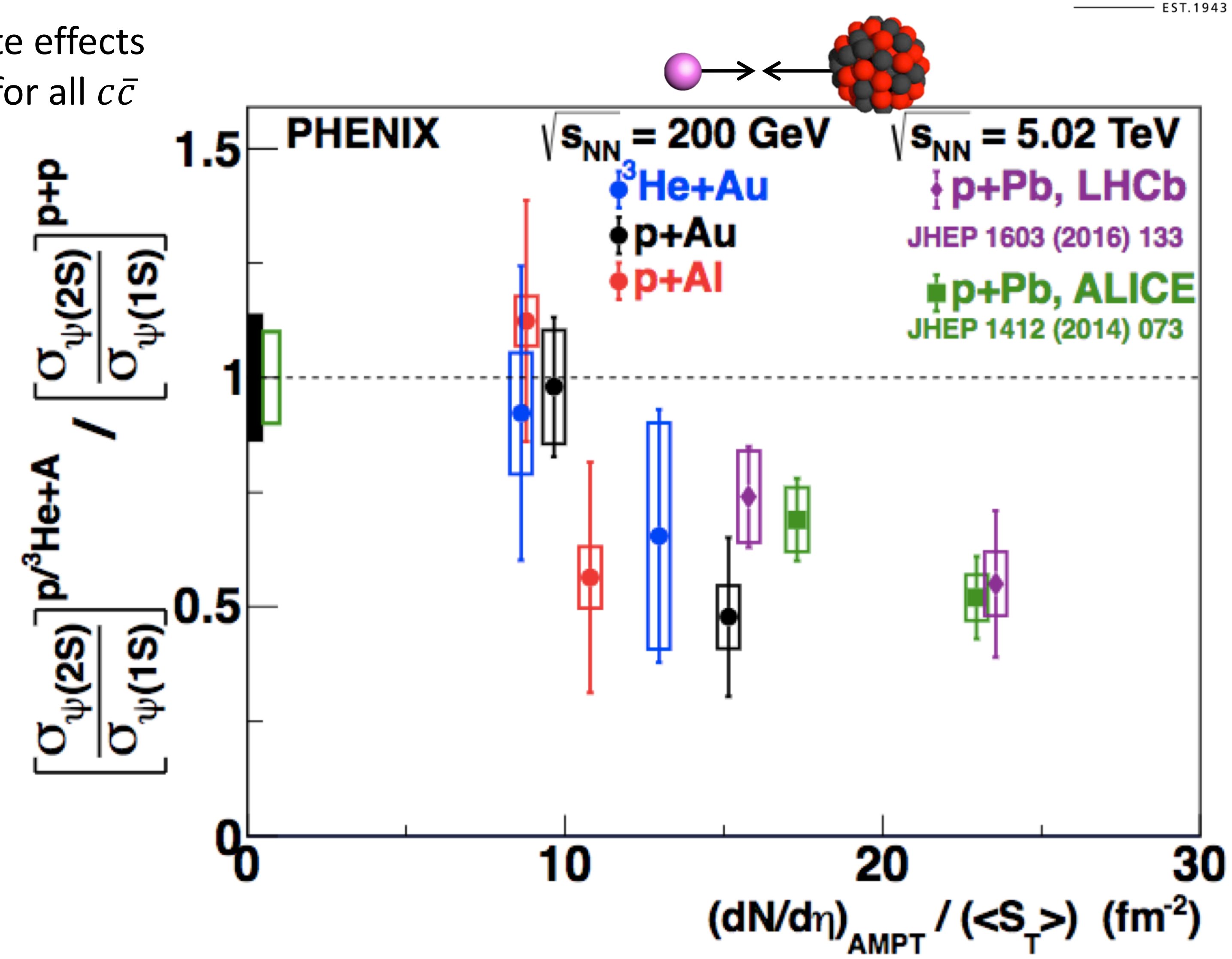
LHC data shows suppression at forward rapidity also?

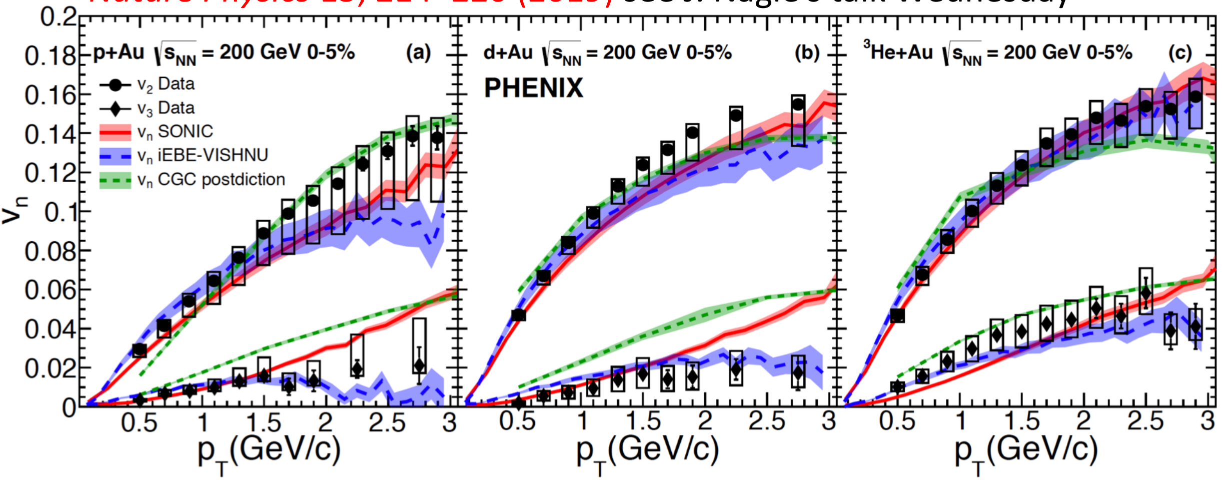
Seems to make sense when plotted as function of comover density. Higher ${}^{dN_{ch}}/_{d\eta}$ at LHC could cause suppression in p-going direction.



Strongly implies late-stage interactions outside the nucleus contributing to suppression

Flow in small systems

Nature Physics 15, 214–220 (2019) see J. Nagle's talk Wednesday



There are now many measurements of flow in small systems from RHIC and the LHC, consistent with expectations from hydrodynamics

Flow in small systems

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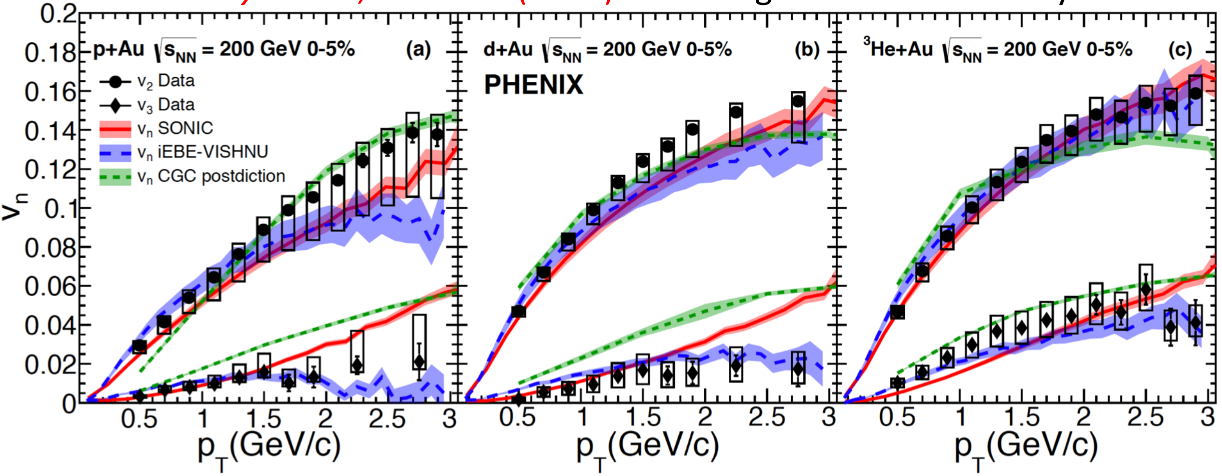

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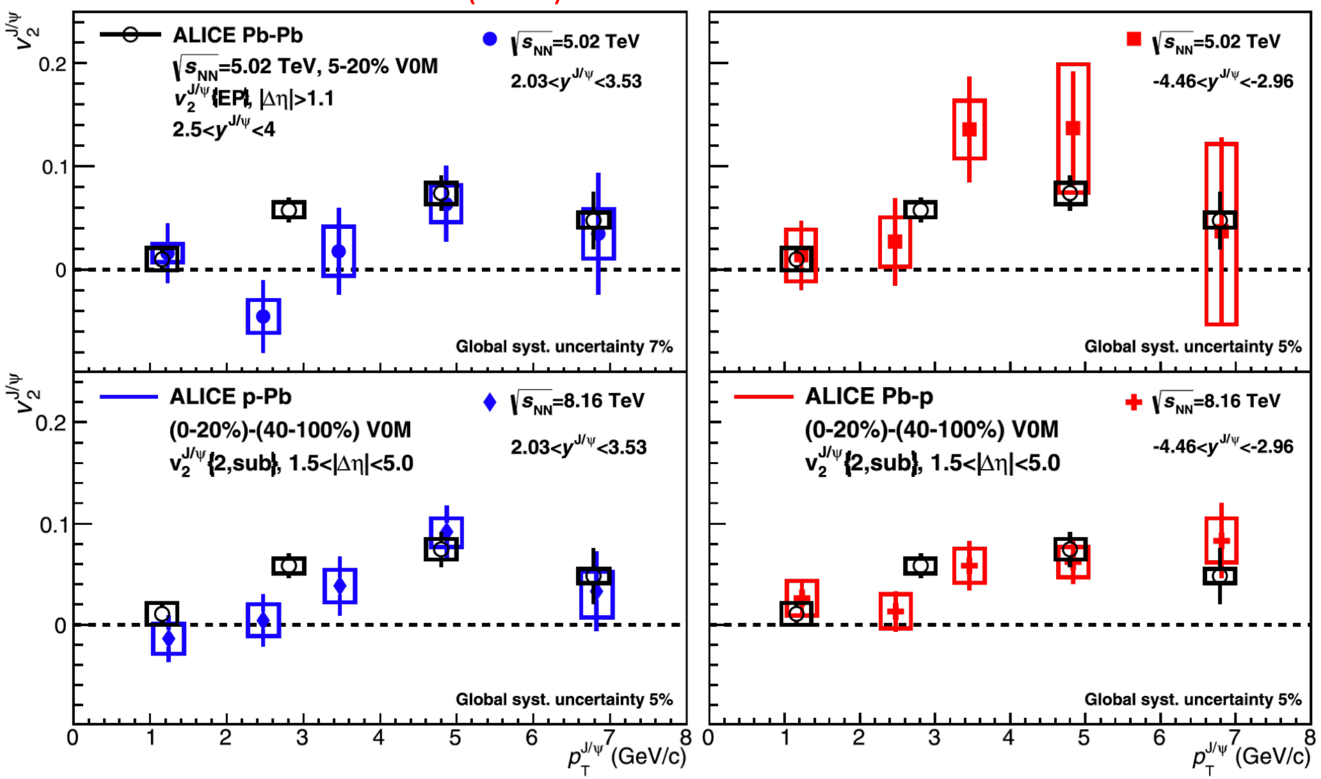
PLB 780 (2018) 7-20



ALICE results show consistent elliptic flow in pPb and PbPb
Suggests a common origin

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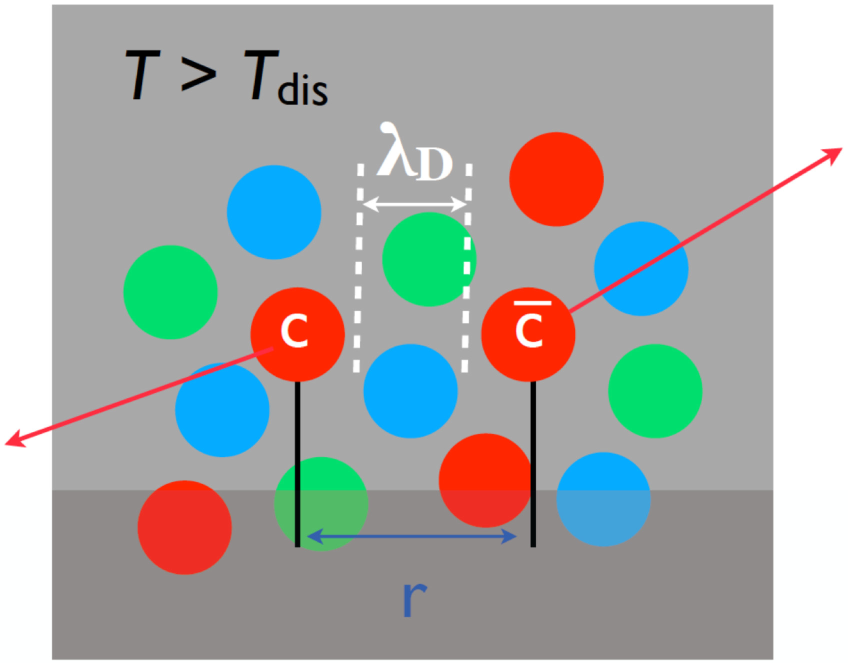
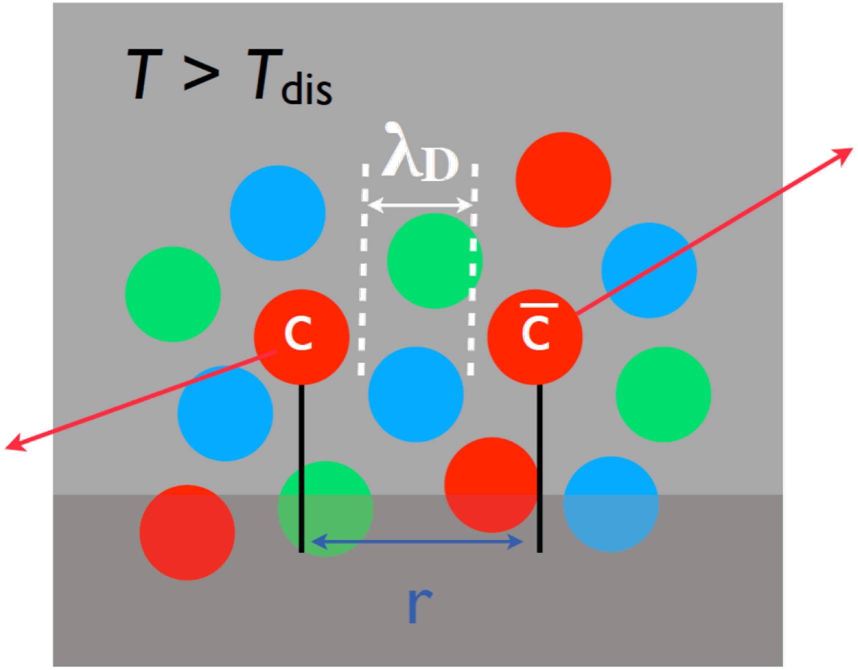


Quarkonium in Medium -AA

Sensitive to a range of effects that cannot be probed in pp collisions



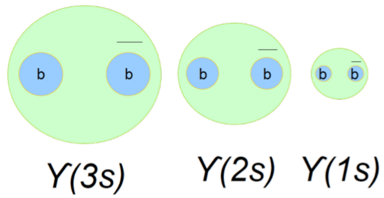
All the effects in pA are still here:

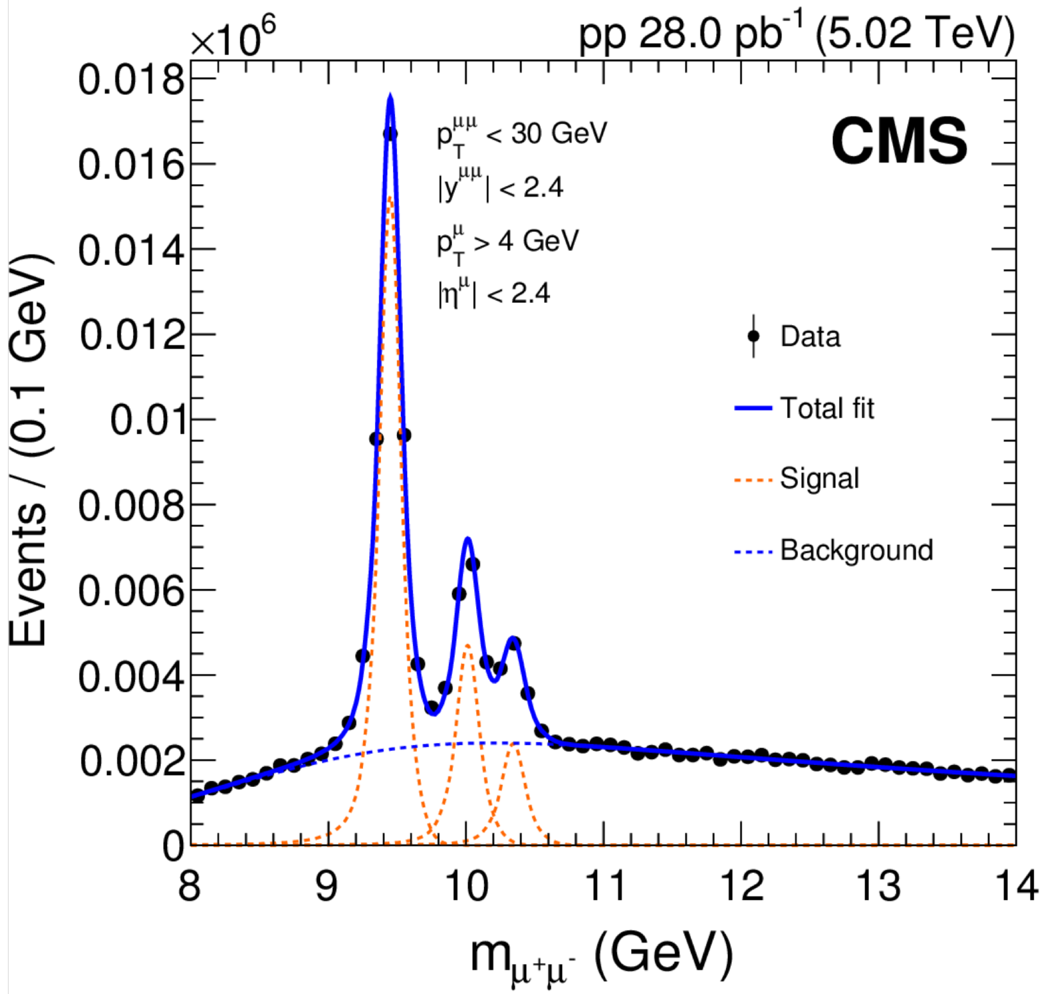
- nuclear PDFs
  - PDF in both beams modified
- QCD energy loss in medium
  - Additional effects from crossing deconfined plasma
- Comover interactions outside nucleus
  - Much higher $dN_{ch}/d\eta$

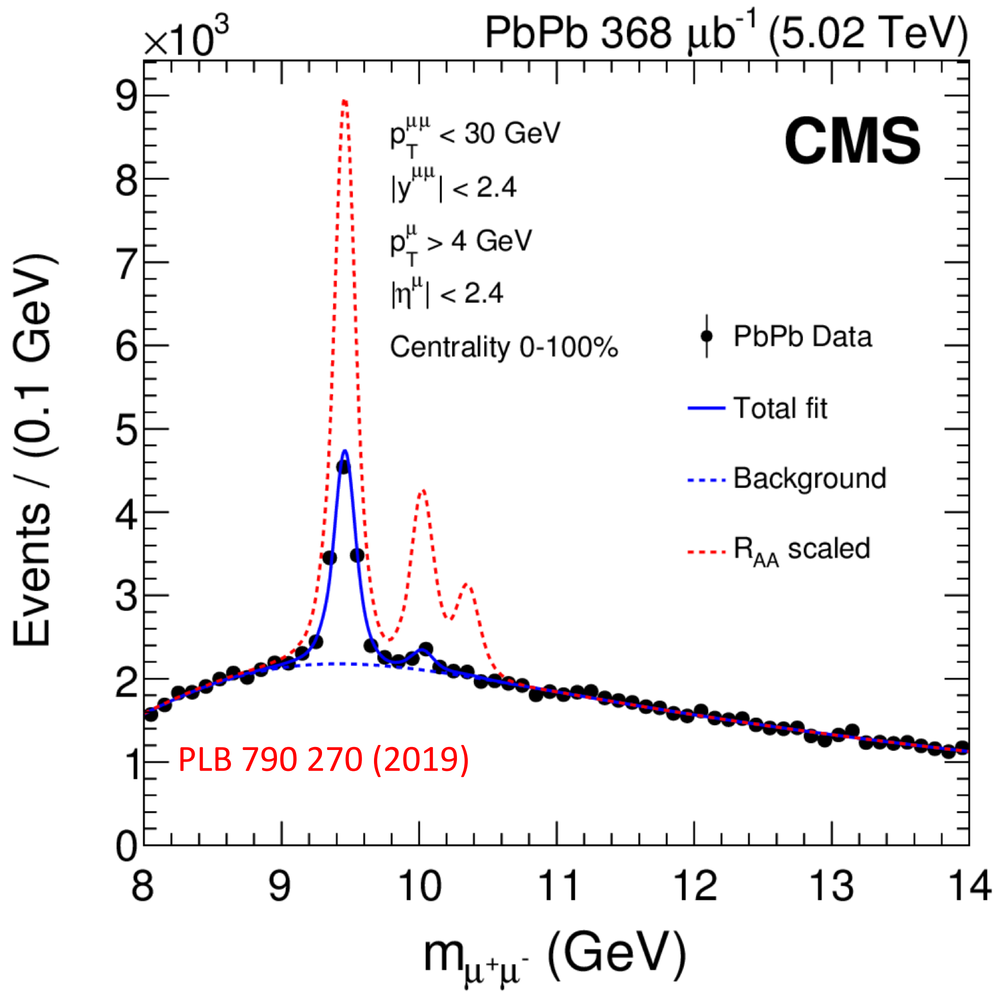
Additional effects from QGP phase:

- Strong hydrodynamic phenomena
- Dissociation via color screening
- Quarkonium production via recombination at freezeout

Bottomonium in AA at the LHC

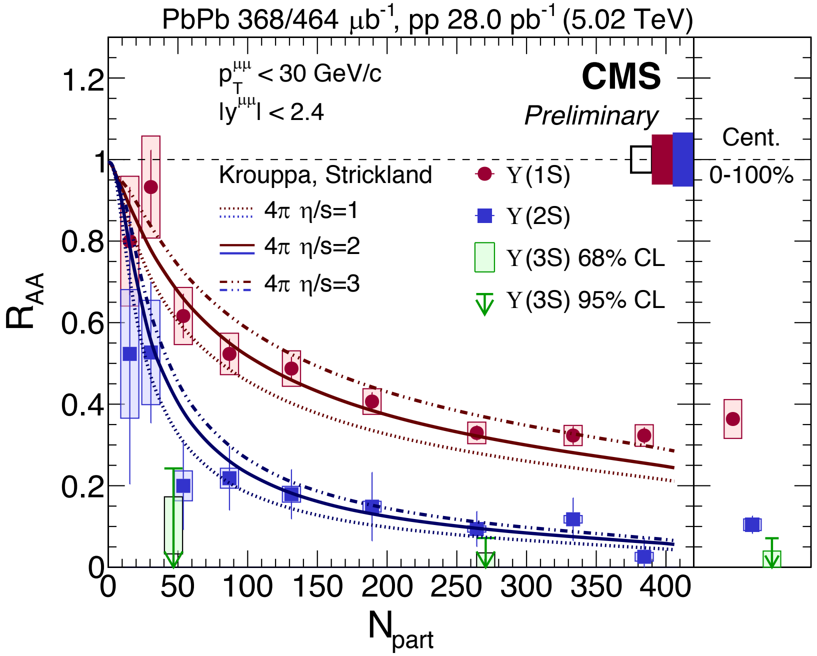




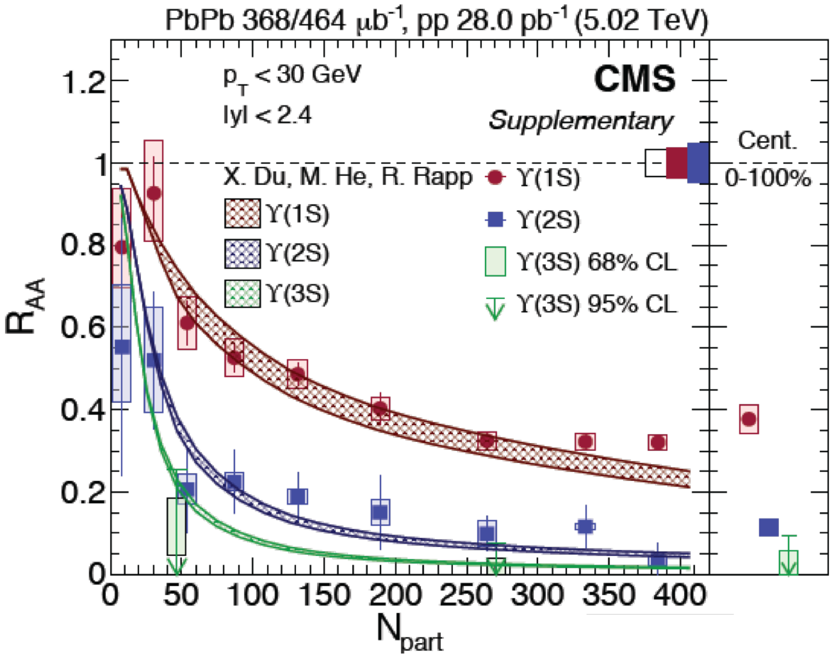


At the LHC: high energy and state-of-the-art instrumentation enables a precision bottomonium program
Remarkable results from CMS with clear interpretation: sequential melting in QGP, right?

Bottomonium in AA at the LHC



Krouppa, Strickland *Universe* 2016, *2*(3) 16



Du, He, Rapp PRC 96 (2017) 054901

Hydrodynamics w/ conditions extrapolated from comparisons with 2.76 TeV data

Dissociation temperatures:
ϒ(1S) 600 MeV
ϒ(2S) 230 MeV
ϒ(3S) 170 MeV

Transport model of heavy quark diffusion in quark gluon plasma

Dissociation temperatures:
ϒ(1S) 500 MeV
ϒ(2S) 240 MeV
ϒ(3S) 190 MeV

Bottomonium in AA at the LHC

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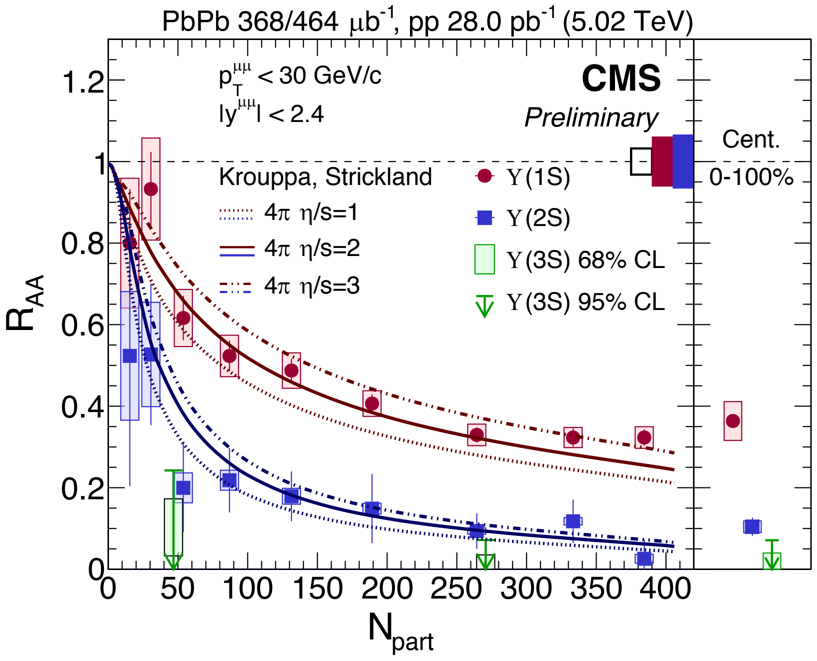

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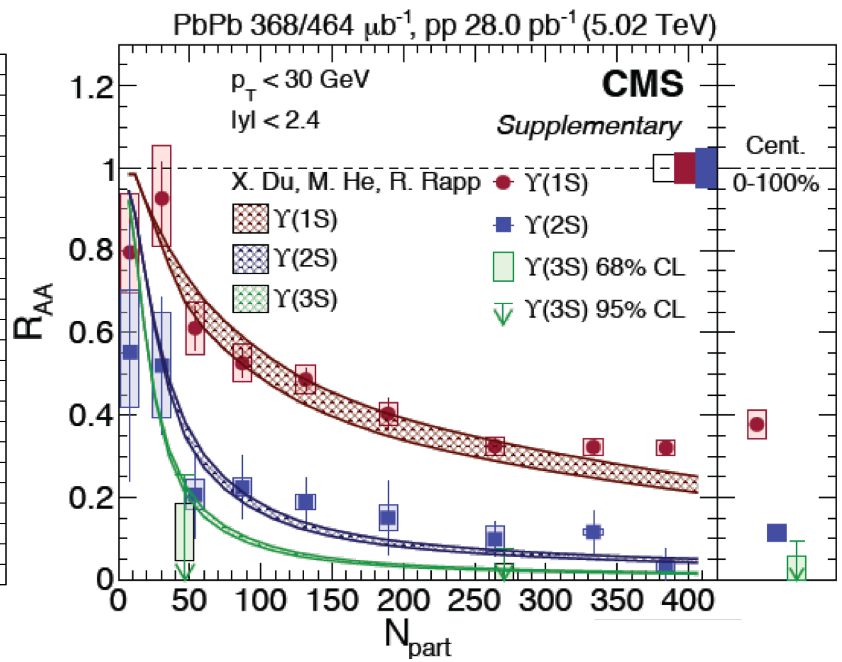

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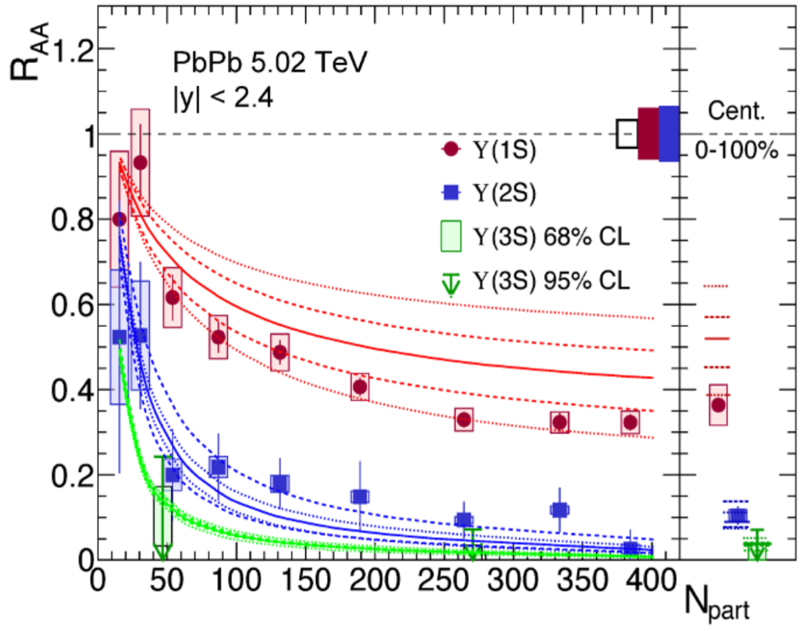

Ferreiro, Lansberg JHEP 10 (2018) 094

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Υ(2S) 230 MeV
Υ(3S) 170 MeV

Transport model of heavy quark diffusion in quark gluon plasma

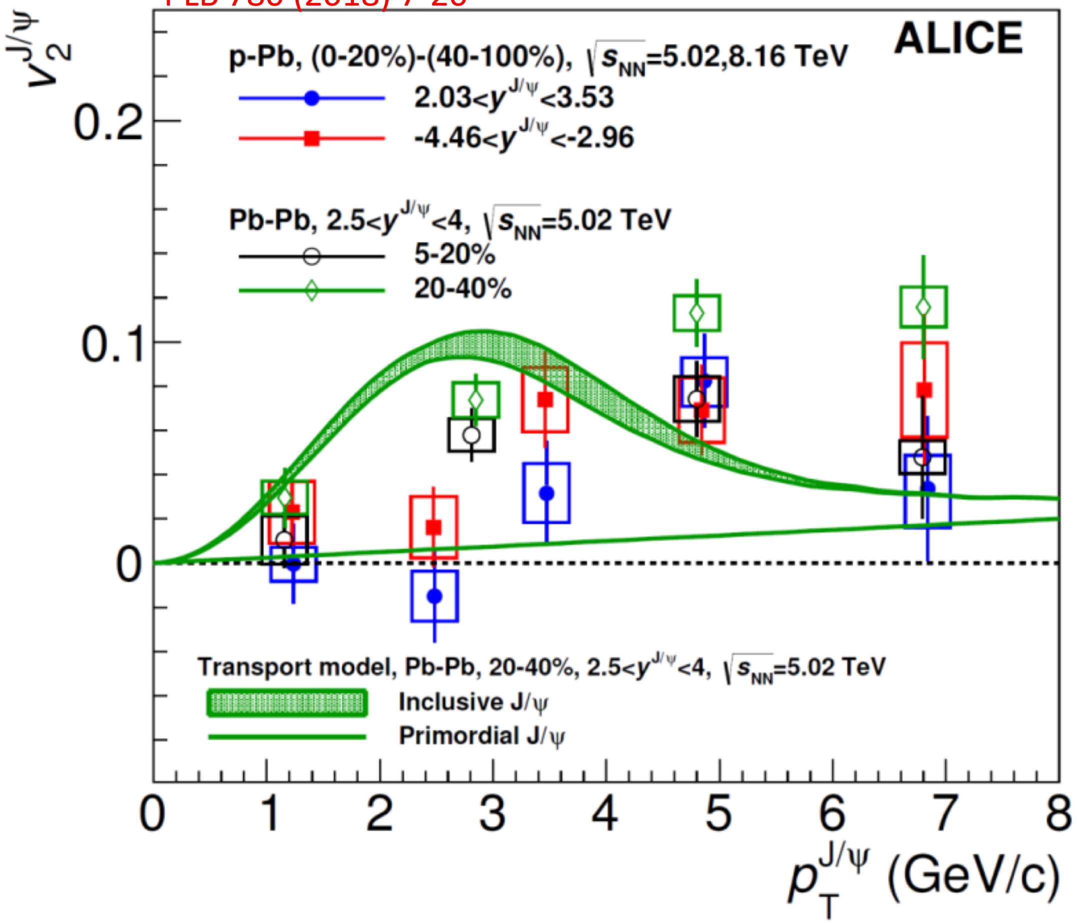
Dissociation temperatures:
Υ(1S) 500 MeV
Υ(2S) 240 MeV
Υ(3S) 190 MeV

Shadowing + comover interactions outside the nucleus, with comover interaction strength fixed by pPb data

NO PLASMA PHASE REQUIRED

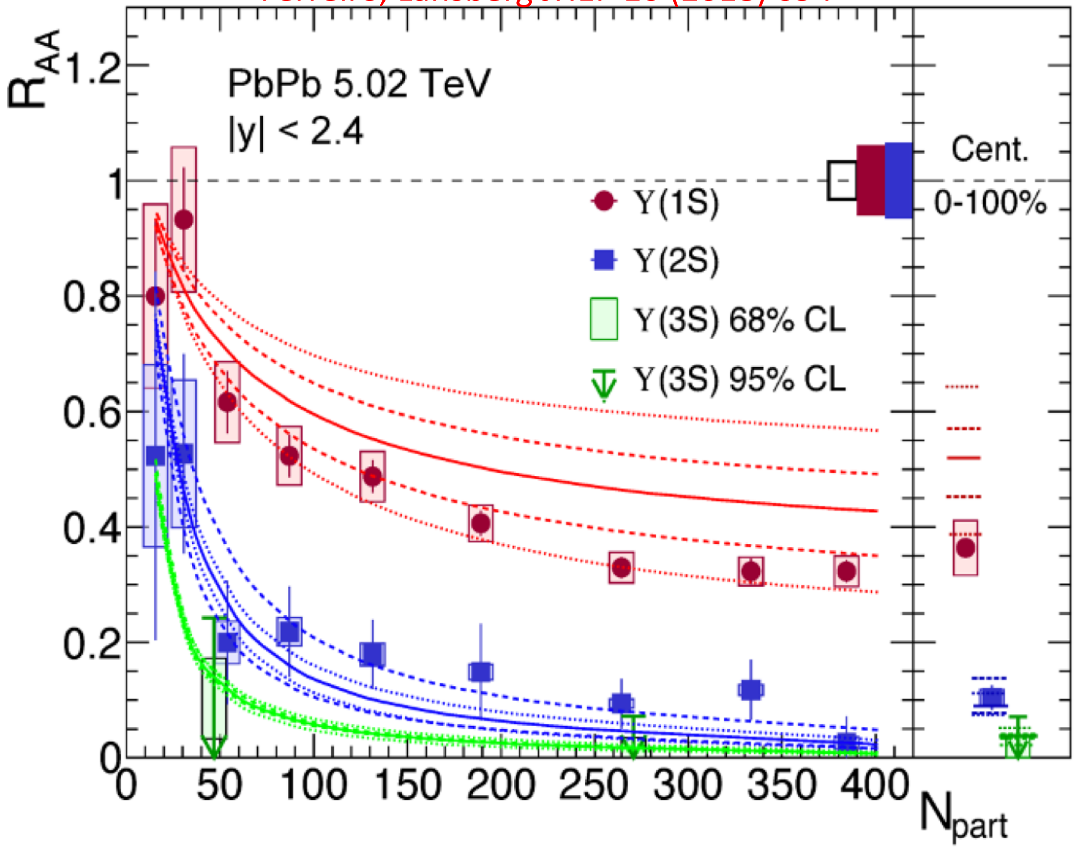
Rethinking our preconceptions

PLB 780 (2018) 7-20



Heavy quarks flowing in pPb, magnitude is consistent with PbPb

Ferreiro, Lansberg JHEP 10 (2018) 094

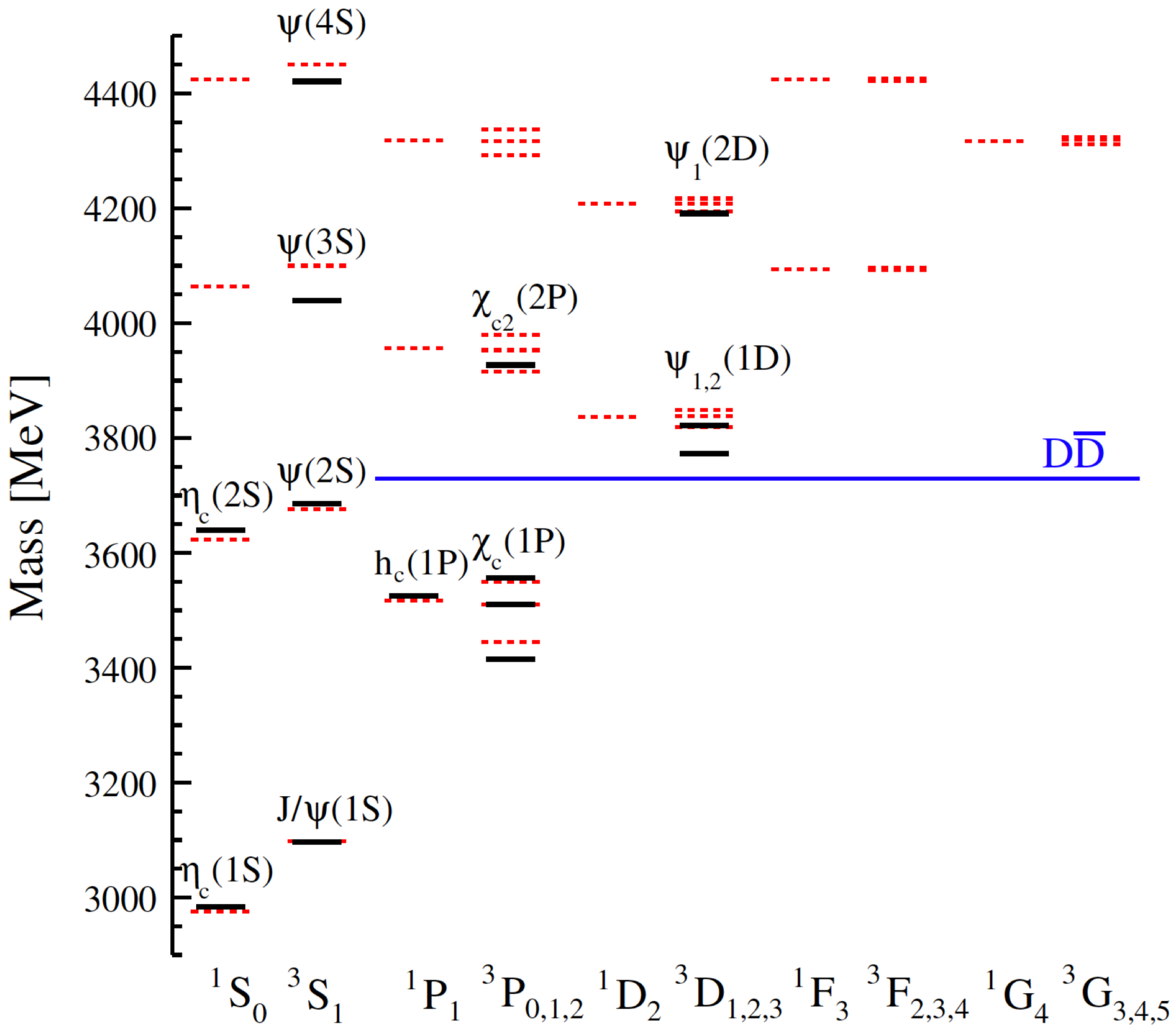


Comovers explain sequential suppression
No plasma necessary

Outline

- Introduction
- Quarkonium in pp collisions
- Quarkonium in Medium - Small Systems
- Quarkonium in Medium - Larger Systems
- Exotics
- Future Facilities
- Summary

Exotic $c\bar{c}$ States



Rev. Mod. Phys. 90, 015003 (2018)

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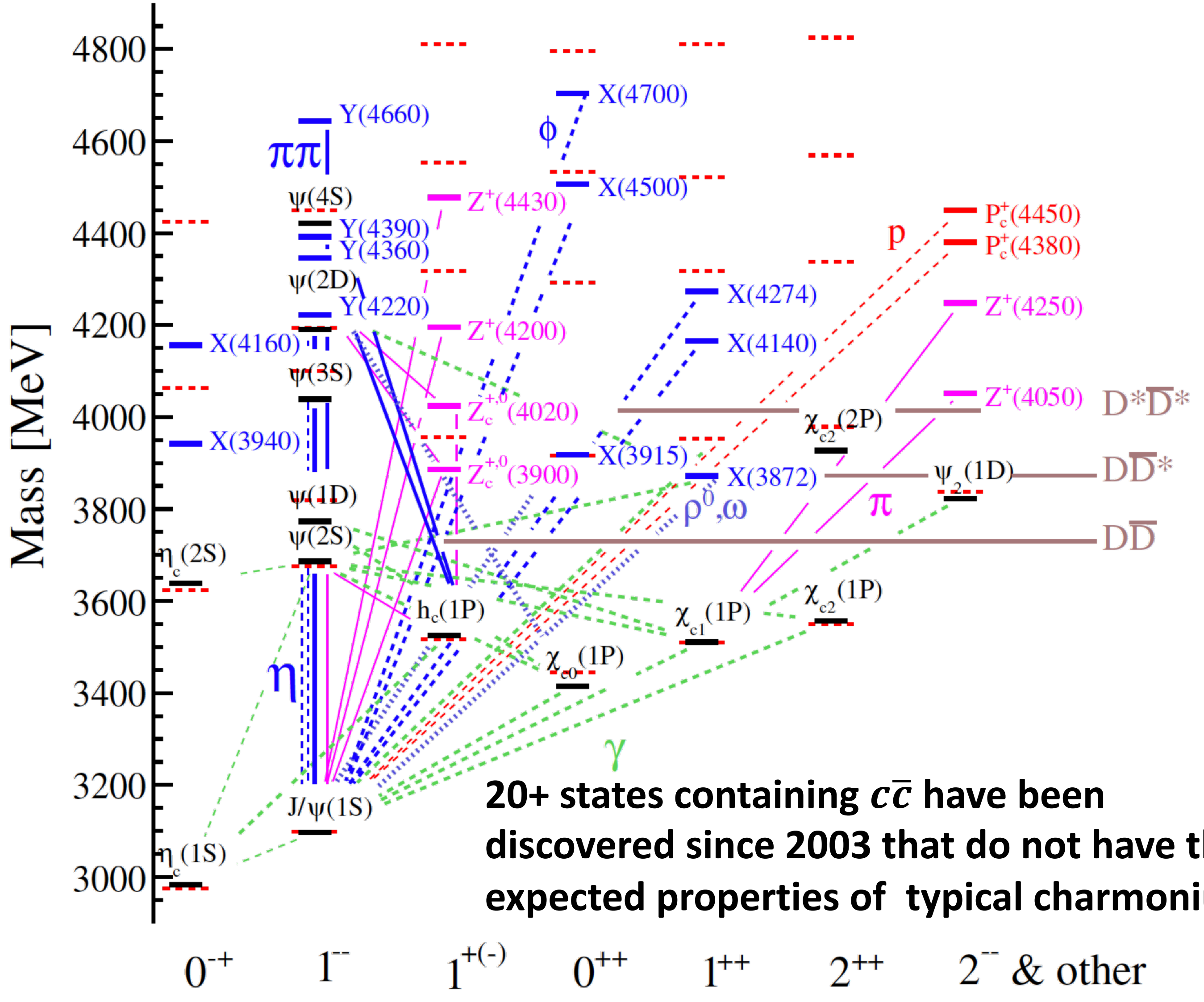


20+ states containing $c\bar{c}$ have been discovered since 2003 that do not have the expected properties of typical charmonium

Rev. Mod. Phys. 90, 015003 (2018)

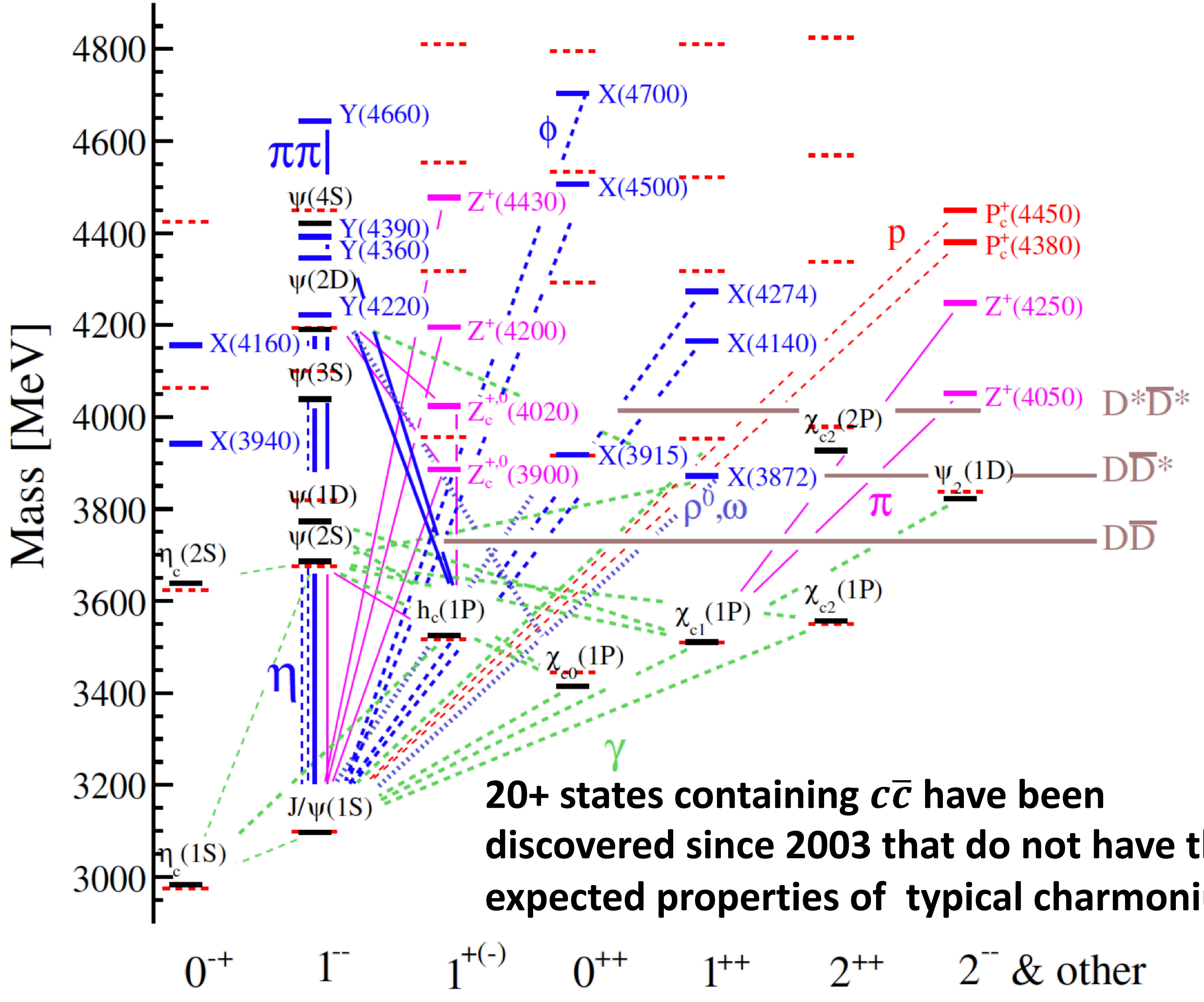
Los Alamos NATIONAL LABORATORY EST. 1943

The most studied is the X(3872):
See Johan Messchendorp's talk Thurs.

Multiple interpretations:

Charmonium
Barnes, Godfrey PRD 69, 054008 (2003)
Tetraquark
Dubnicka *et al*., Phys. Rev. D 81, 114007 (2010)
Hadronic molecule
Thomas, Close Phys. Rev. D 78, 034007
Many other possibilities explored in literature

Exotic $c\bar{c}$ States



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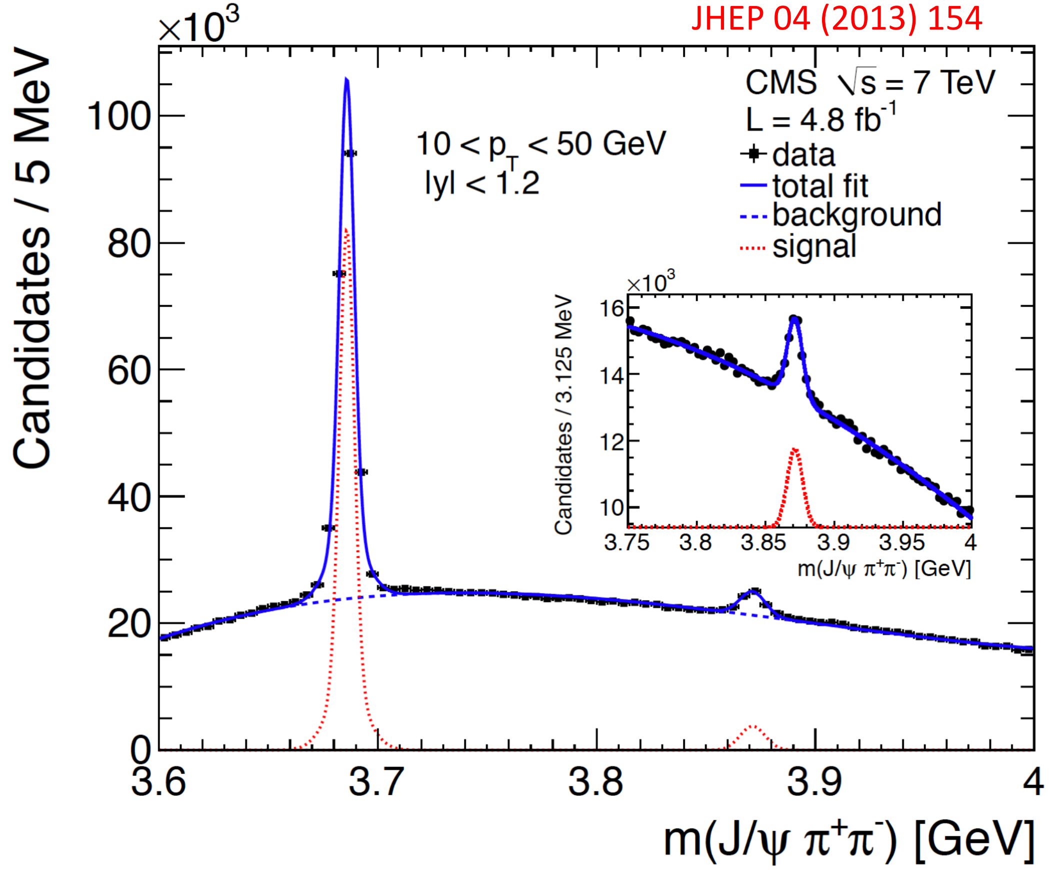
JHEP 04 (2013) 154



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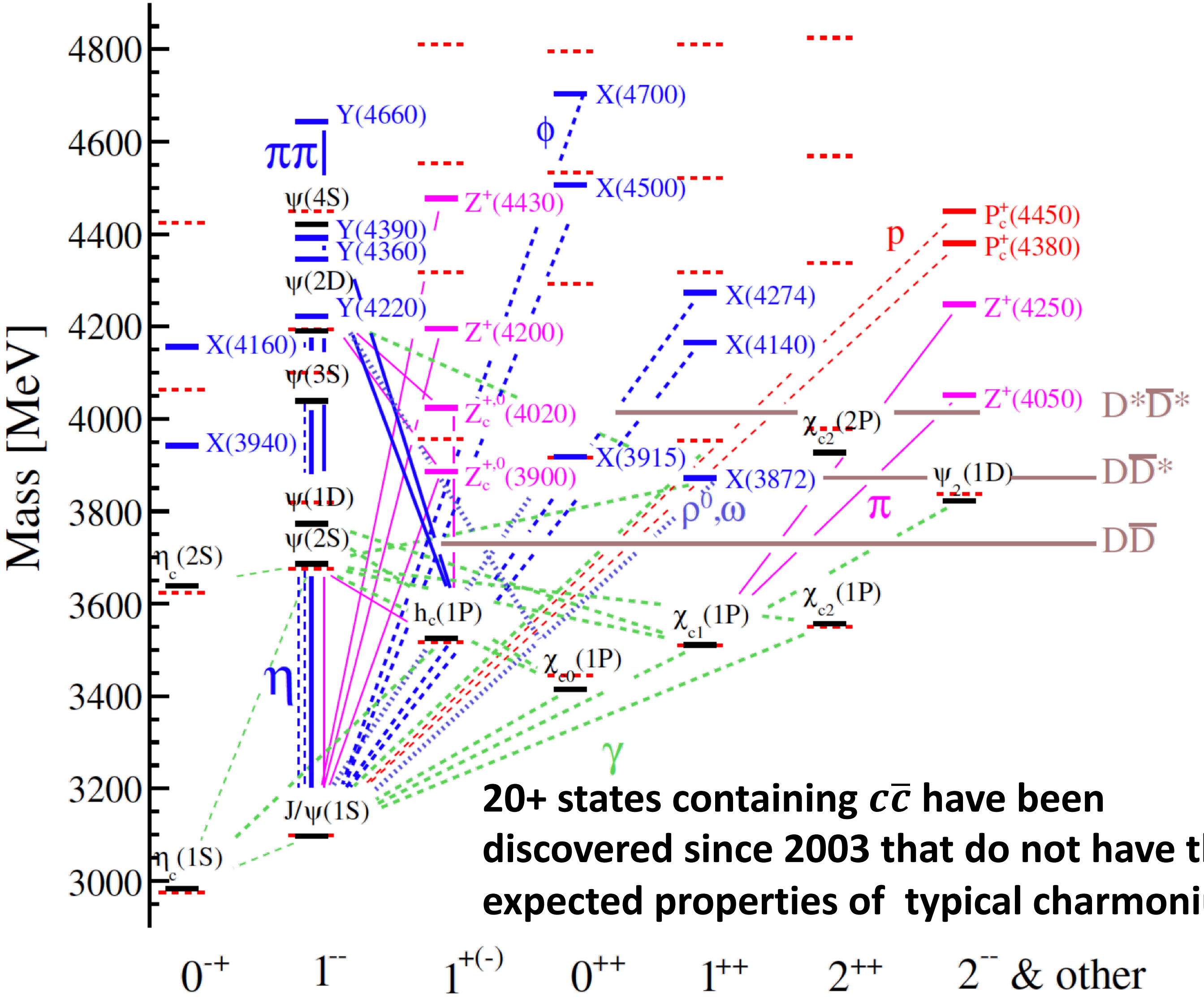

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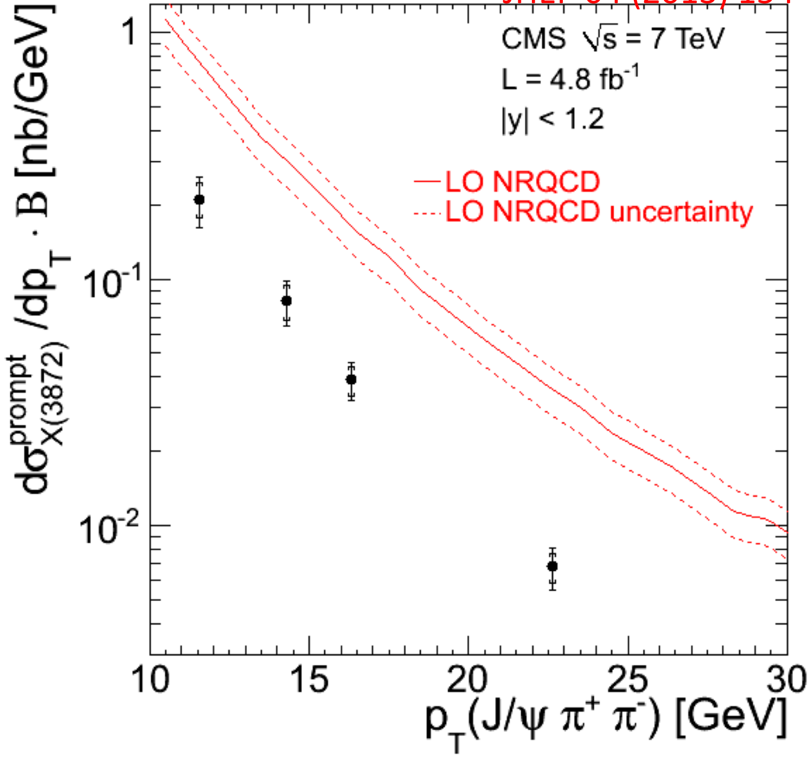
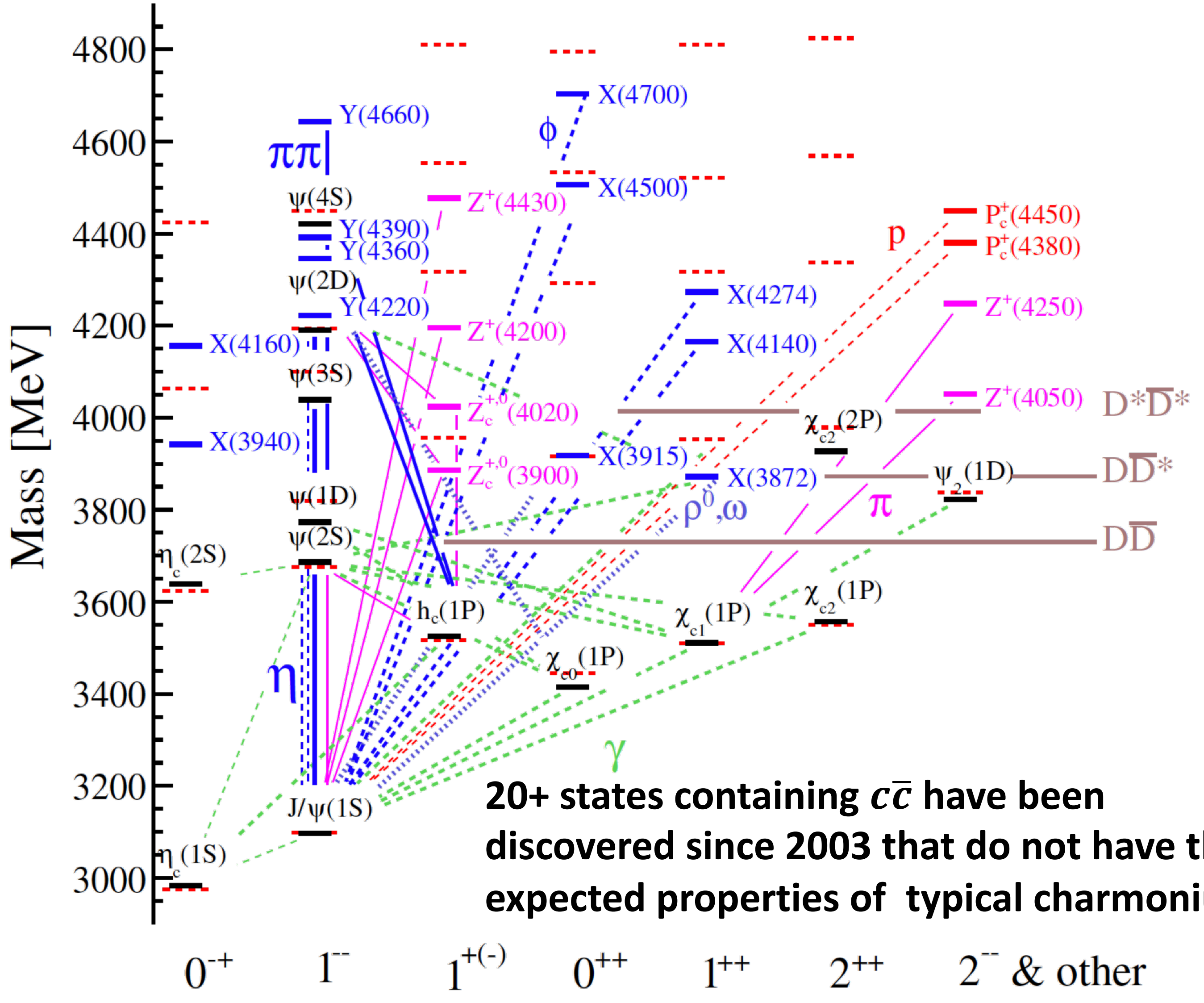


NRQCD fails to describe CMS data on X(3872) cross section

Exotic $c\bar{c}$ States



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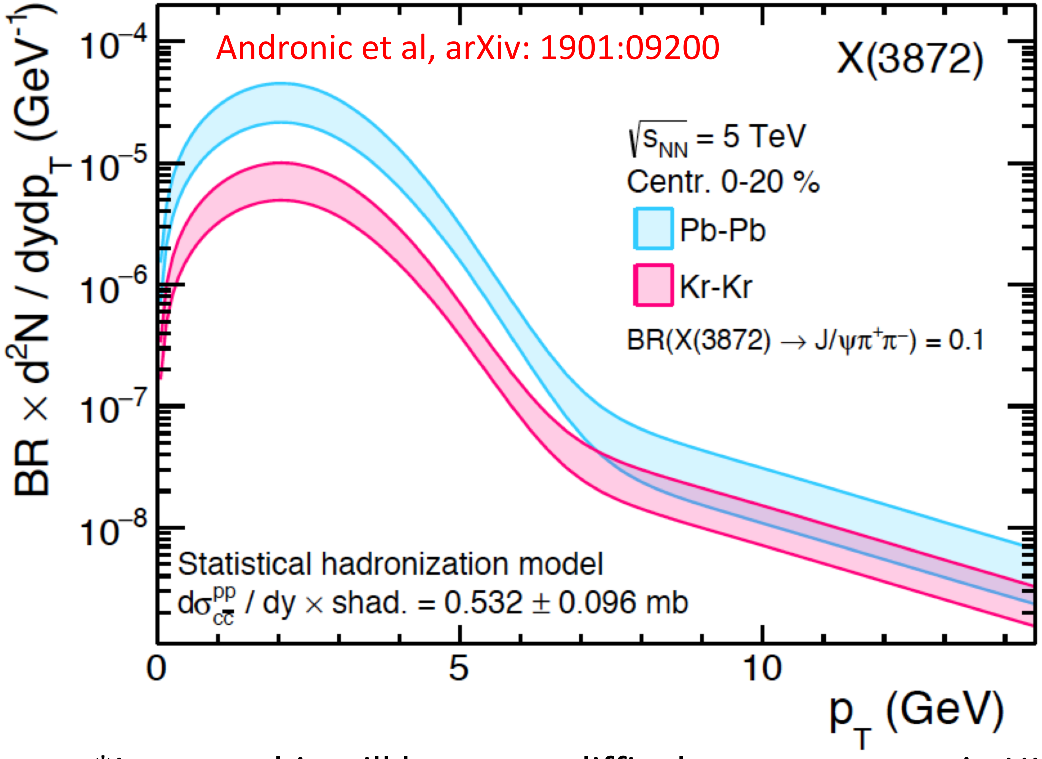
Statistical hadronization model predicts X(3872) yields ~1% of *J/ψ yield*

A unique way to test recombination models/explore structure of exotic particles, potentially accessible in future LHC runs



*I expect this will be a very difficult measurement in HI collisions due to combinatorial backgrounds

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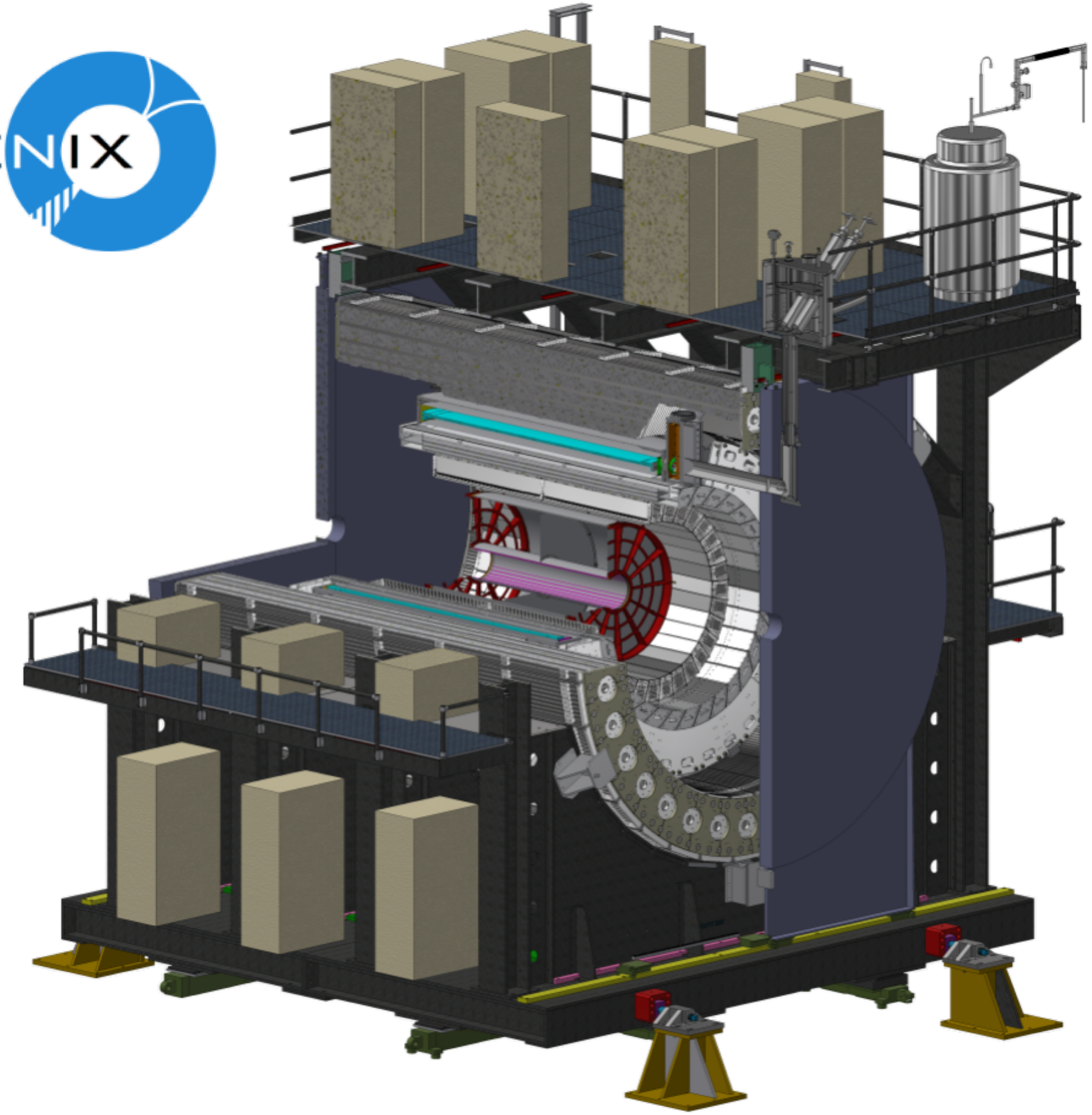
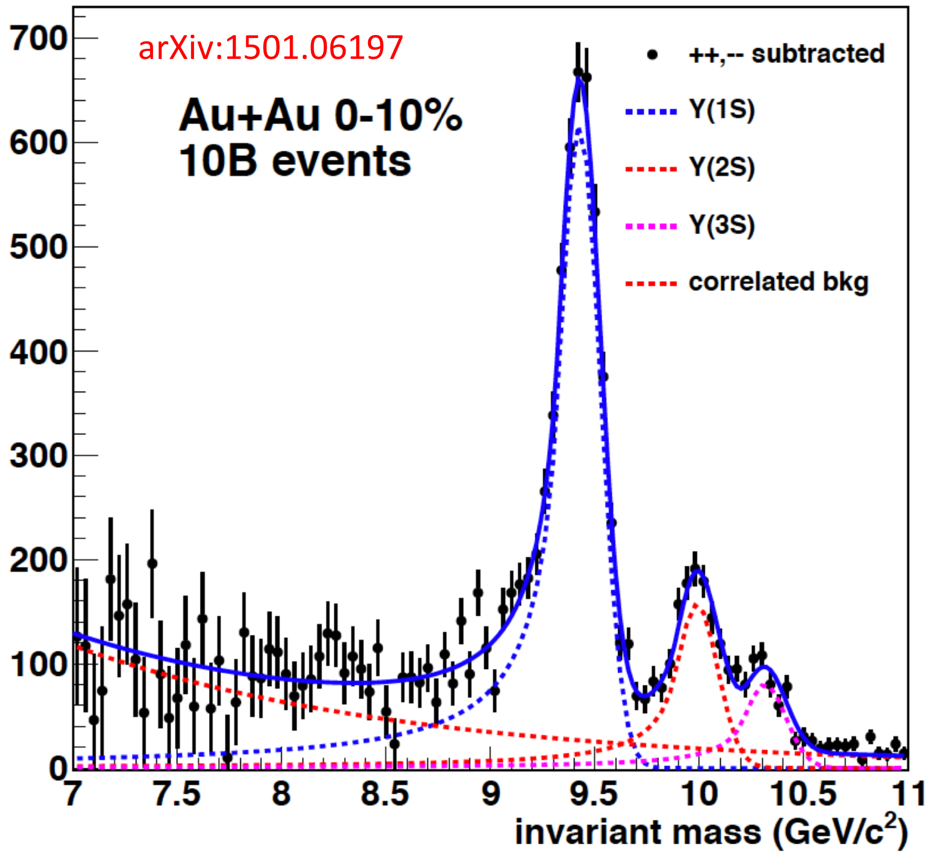
Future Facilities:





Precision bottomonium measurements at RHIC are a major focus of sPHENIX

Interest in Next-Generation LHC Experiment

arXiv.org > physics > arXiv:1902.01211

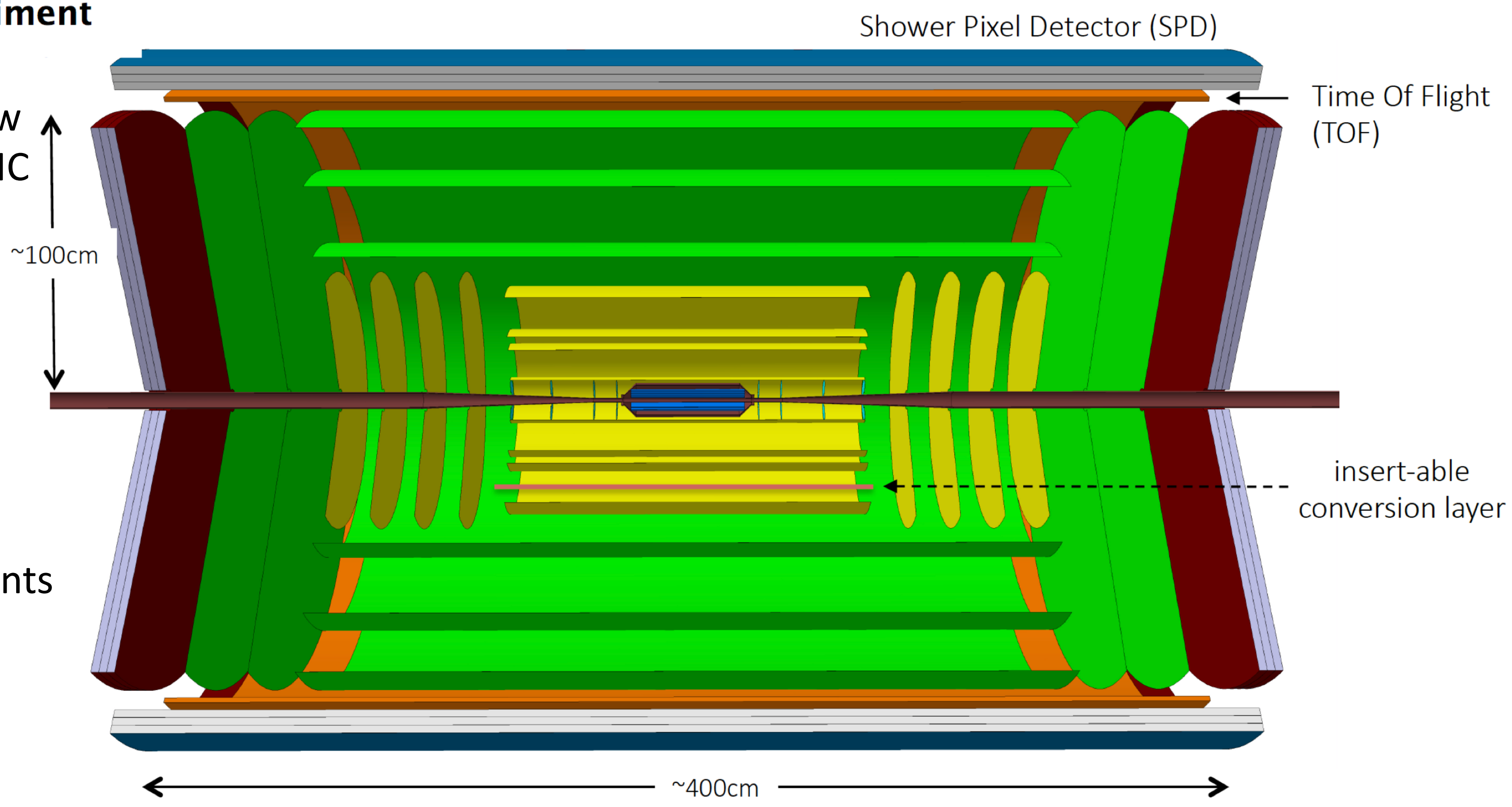
Physics > Instrumentation and Detectors

A next-generation LHC heavy-ion experiment

Very recent expression of interest in a new dedicated heavy ion experiment at the LHC to replace ALICE

All MAPS tracking
Measure tracks down to pT~10s of MeV
Particle ID by ~10ps TOF

Converter for low mass dielectrons
Precision low pT quarkonium measurements



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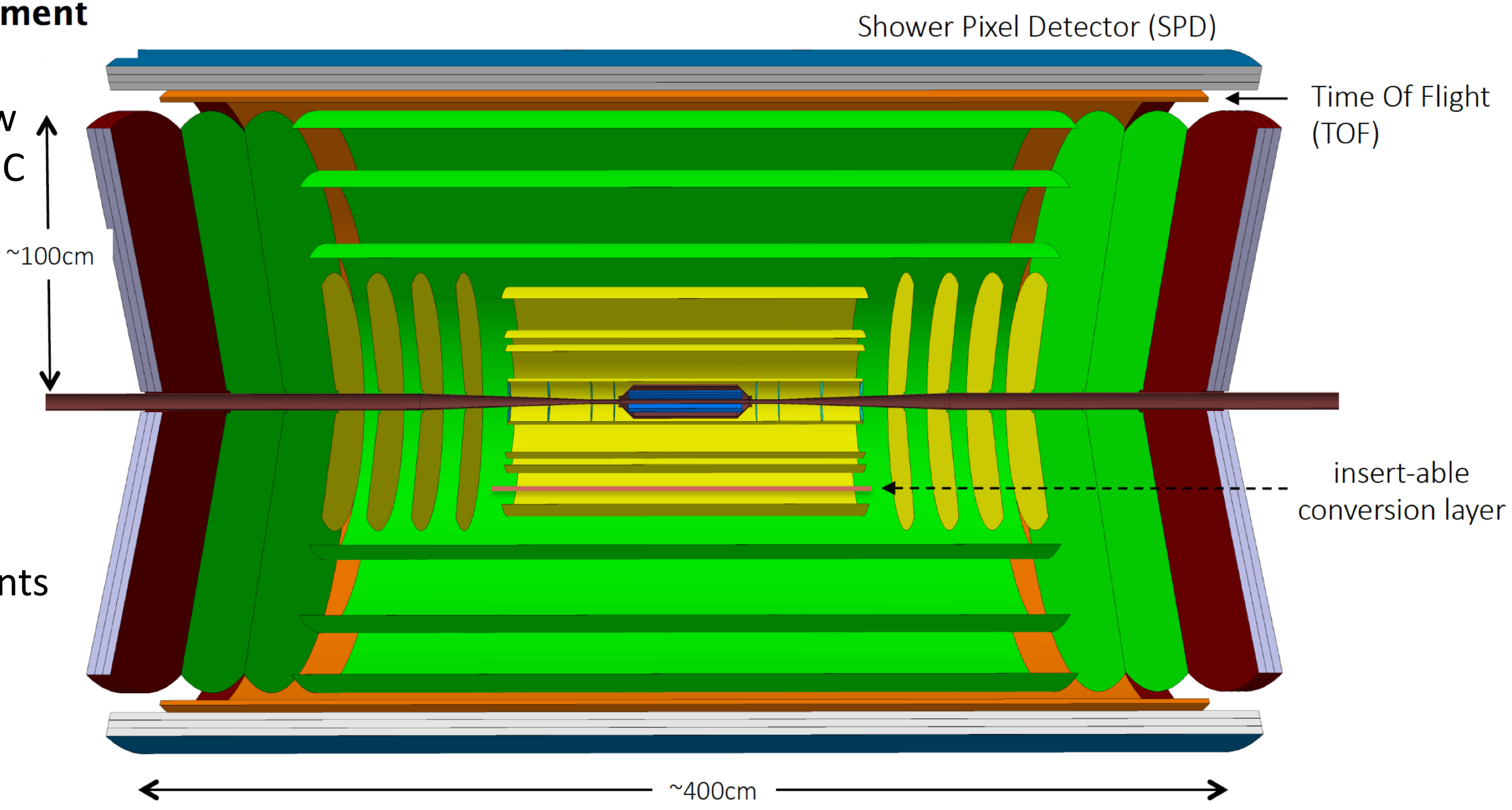

Summary

- Heavy quarkonium research is still going strong >40 years after charm discovery
    - Precise measurements and newly observed states to constrain production models
    - Large slate of exotic candidates that require more scrutiny

- Quarkonium in nuclear collisions is sensitive to a wide range of phenomena:

Properties of the nucleus:
PDF modifications

Properties of cold QCD:
Quark energy loss in nuclear matter
Hadron-hadron interactions in vacuum

Properties of quark gluon plasma:
Temperature
Color screening length
Hydrodynamics

- Future facilities and datasets will undoubtedly lead to new questions

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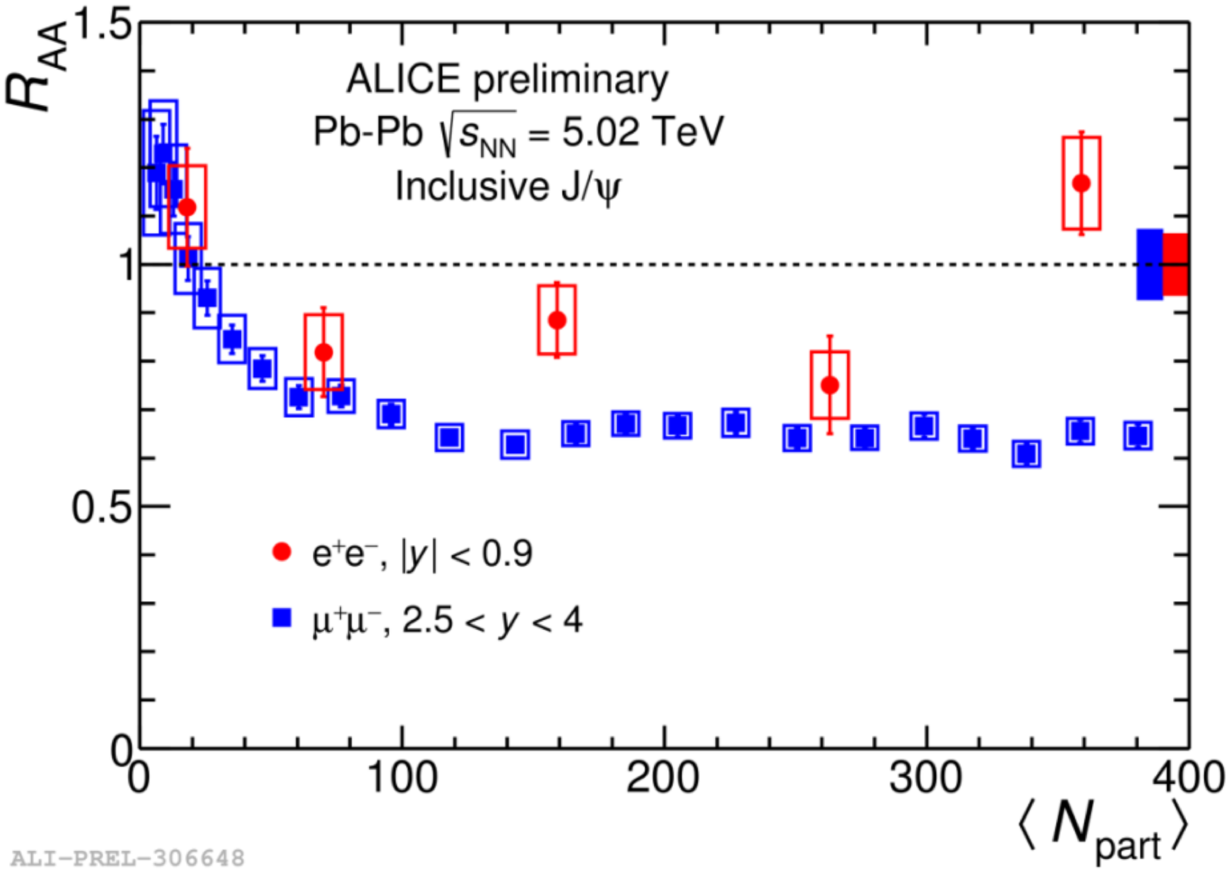
- …maybe even some answers

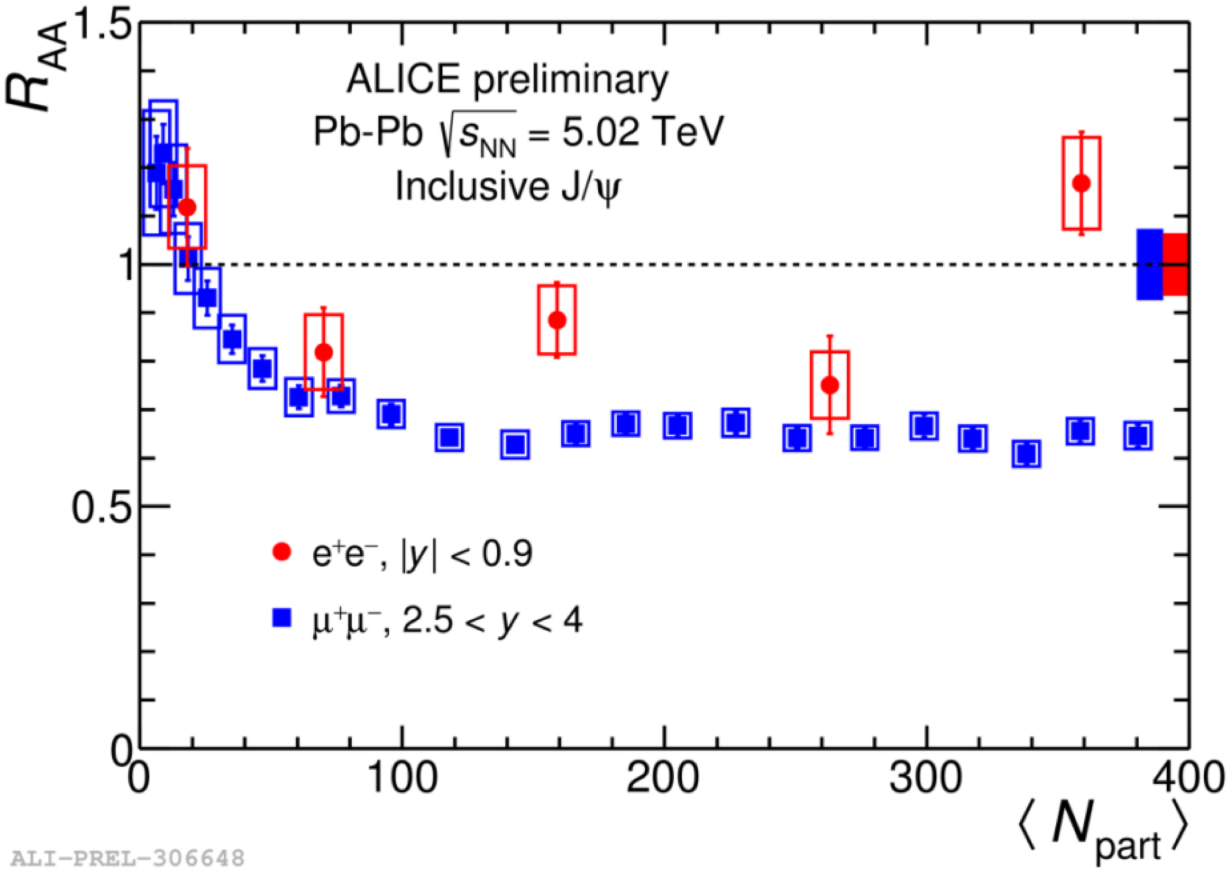
Backups

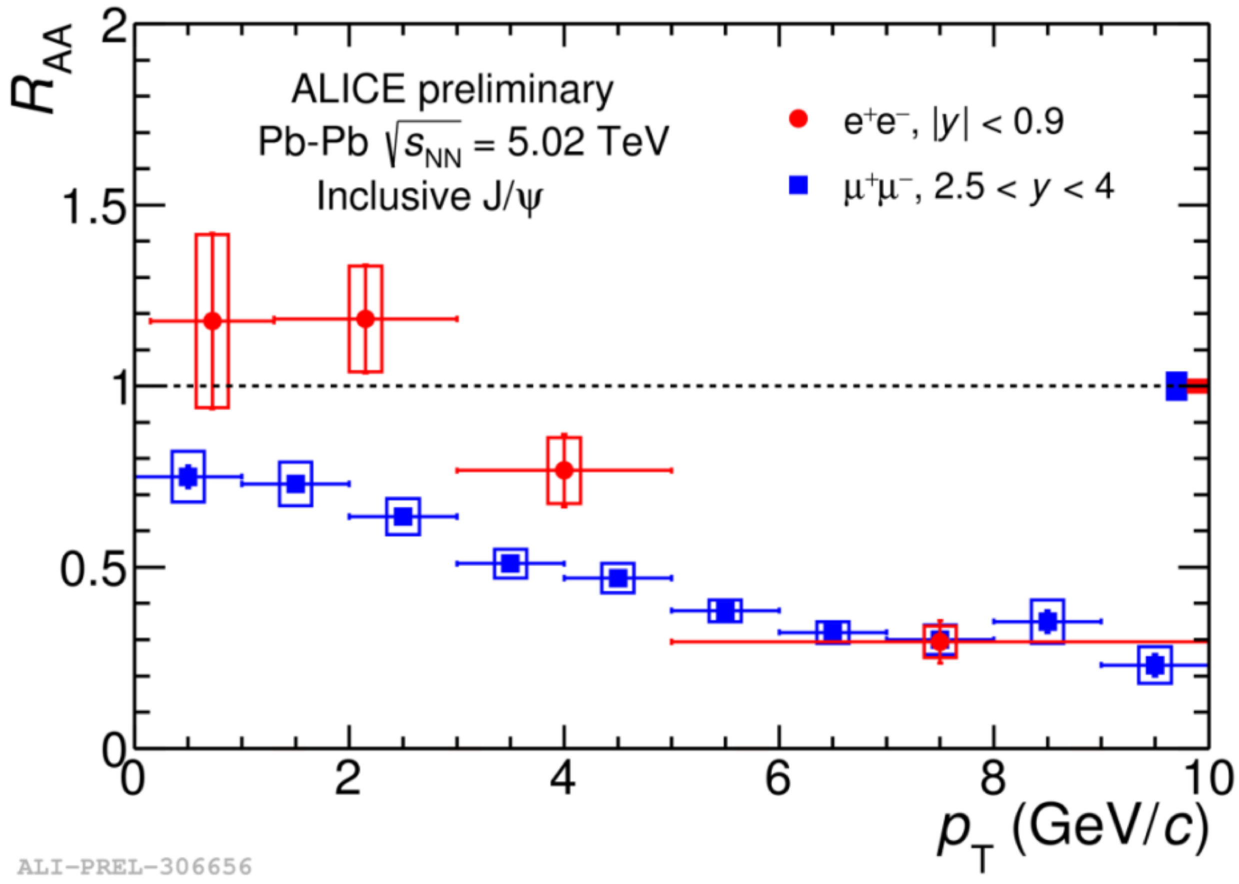
Mid vs forward rapidity J/ψ suppression



Significant difference observed in mid and forward rapidity suppression at ALICE

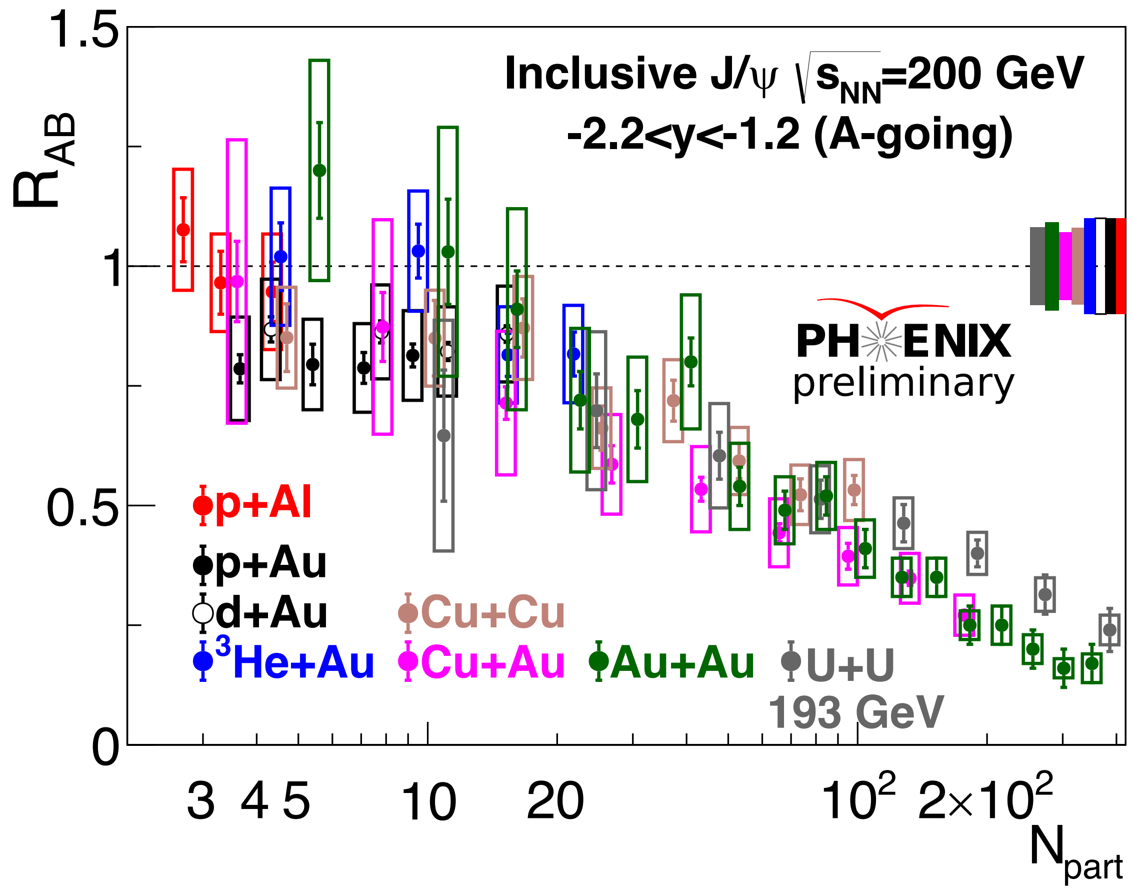
Mid vs forward rapidity suppression

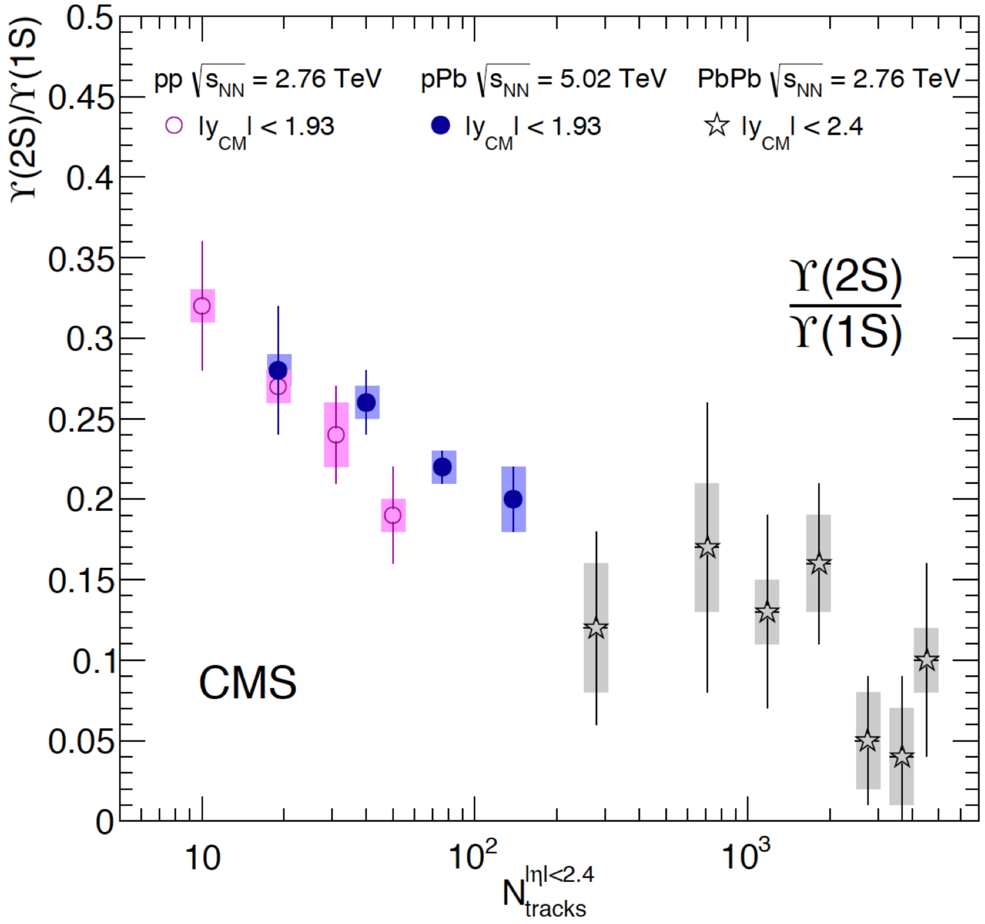




Difference comes from low-pT behavior at midrapidty, as expected from a recombination scenario.

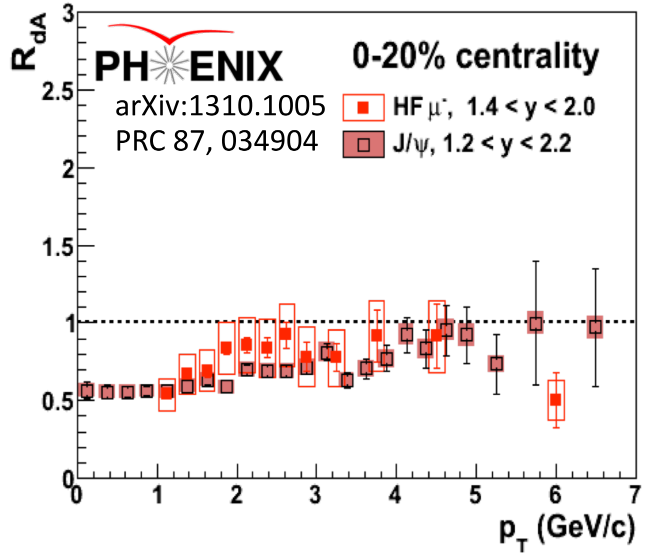
Summary of System Size Dependence

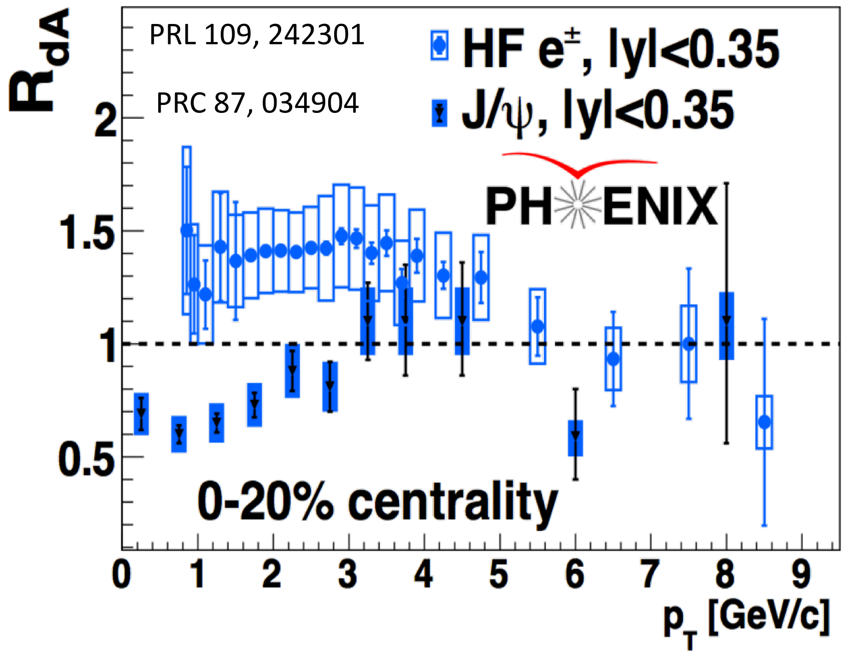


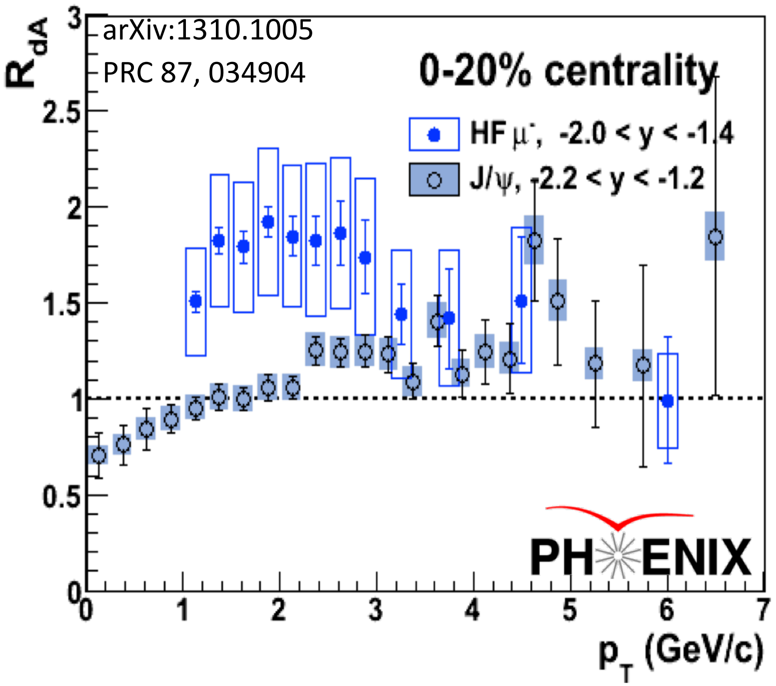


Smooth transition across all systems for suppression observables.

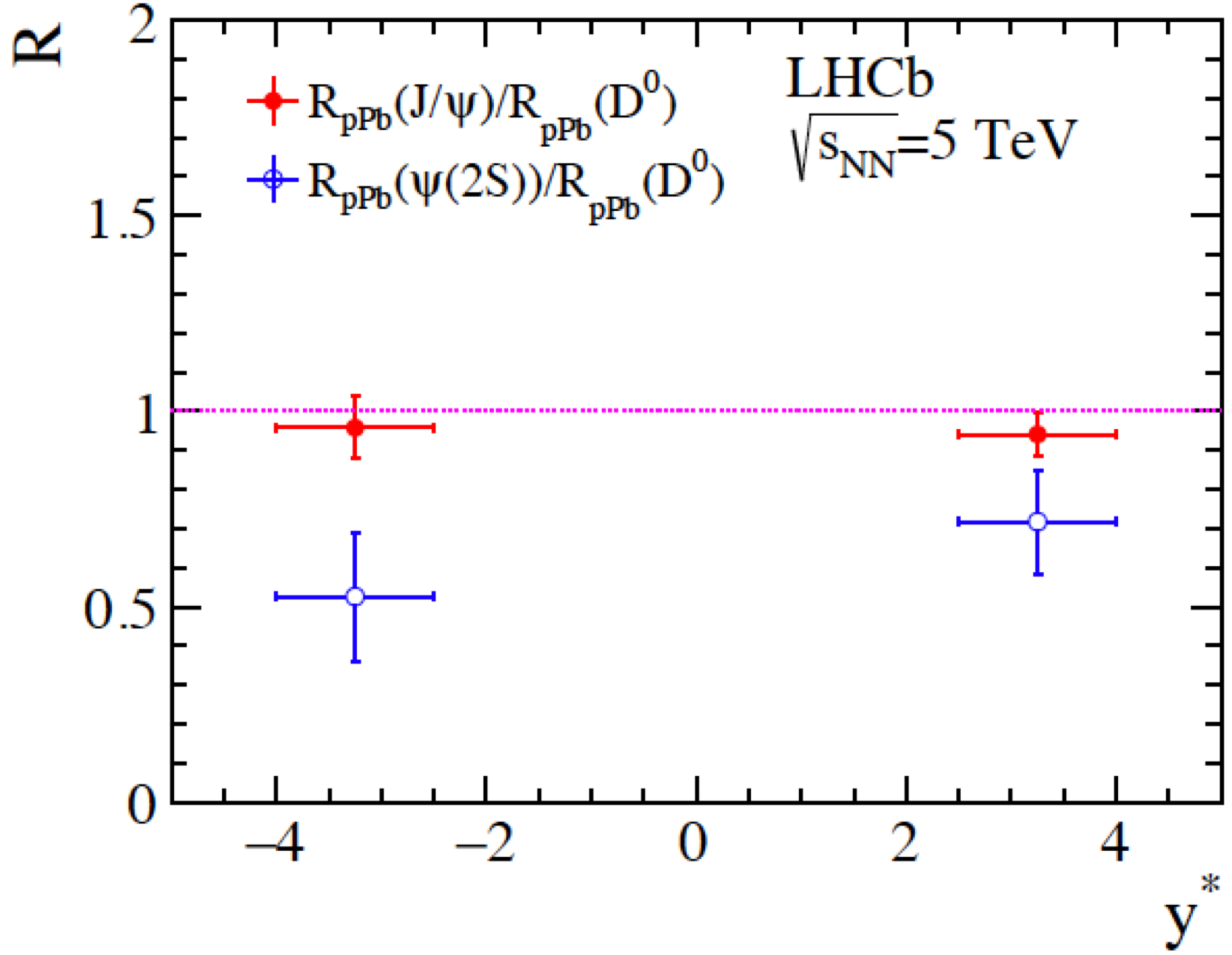
Open vs Hidden charm:

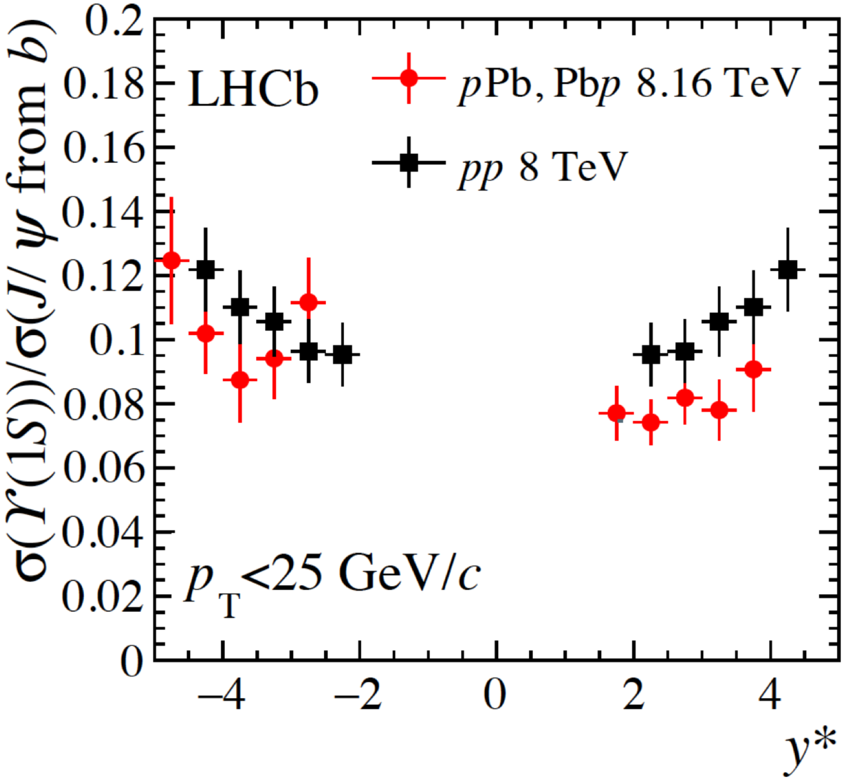






Nuclear Modification of hidden and open charm





Experimental Facilities

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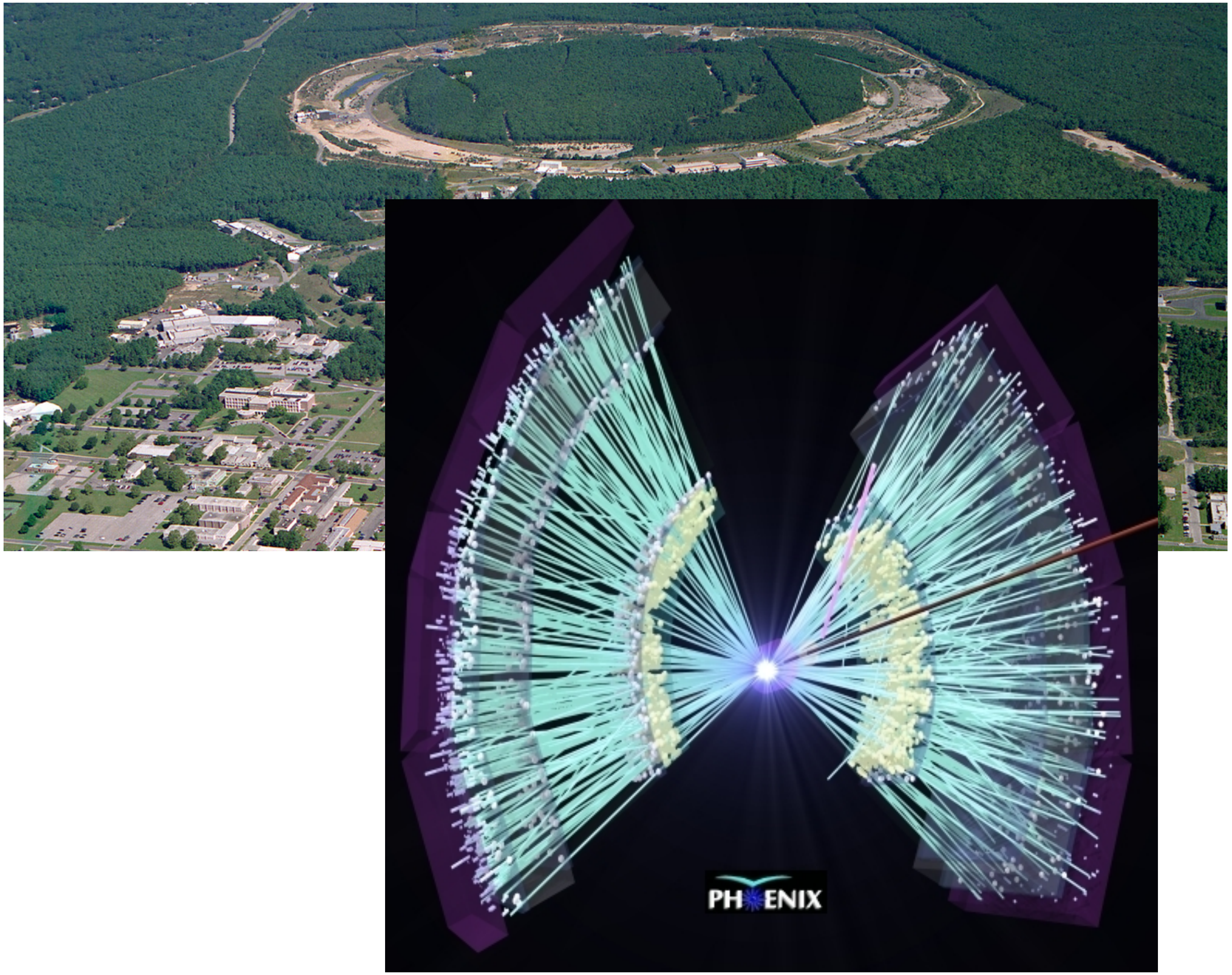
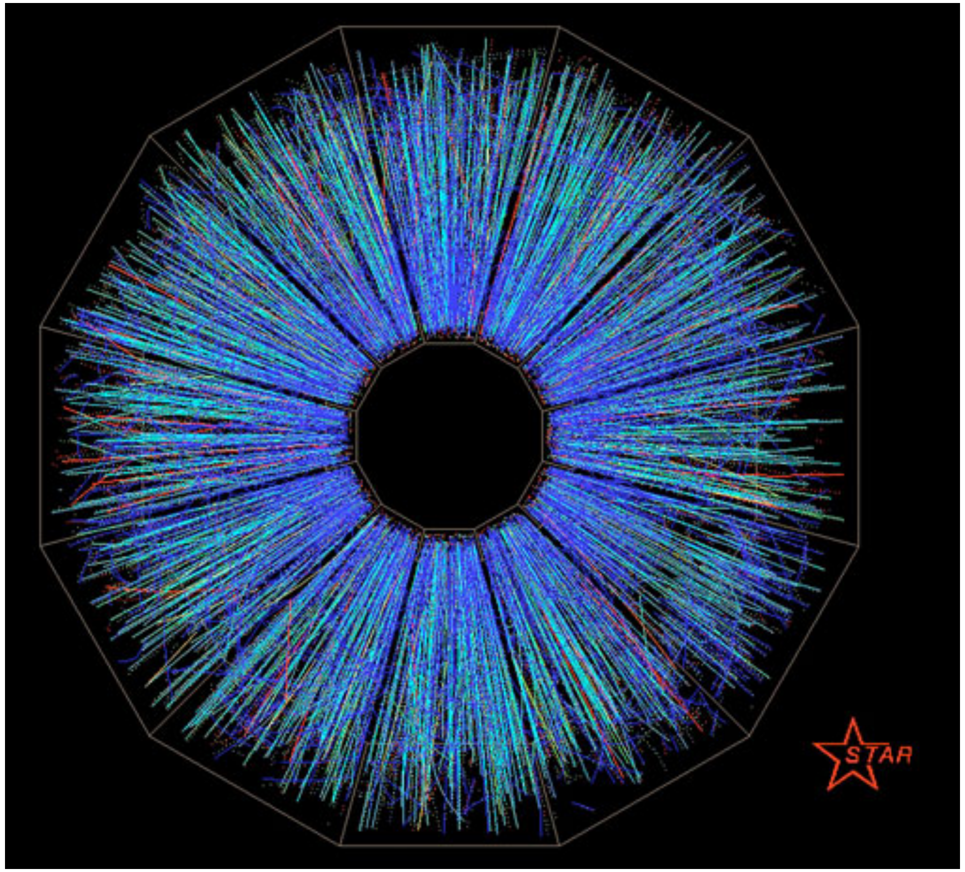
Relativistic Heavy Ion Collider - BNL





Experimental Facilities