U.S. DEPARTMENT OF ENERGY | Office of Science

Brookhaven National Laboratory

Quarkonia and Final State Interactions - Overview of RHIC & LHC Results

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Center for Frontiers in Nuclear Science
Workshop series

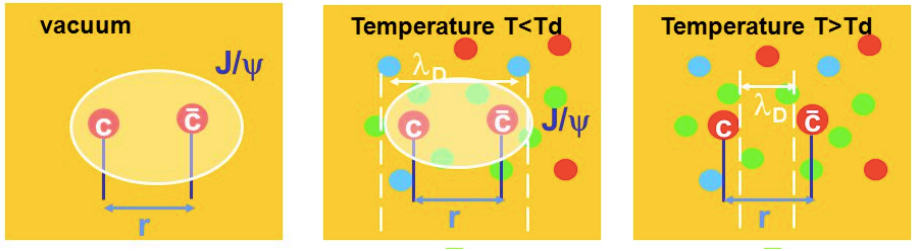
Physics Opportunities with Heavy Quarkonia at the EIC

25-27 October 2021
Online
US/Eastern timezone

The Starting Point

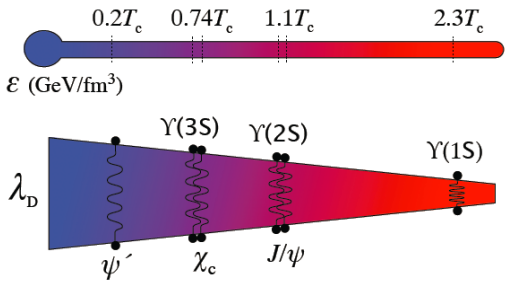
- **Evidence of deconfined matter (QGP)**: quark-antiquark potential color-screened by surrounding partons → *(static) dissociation*

T. Matsui and H. Satz, PLB 178 (1986) 416



$$r_{q\bar{q}} \sim 1/E_{binding} > r_D \sim 1/T$$

- **"Thermometer"**: different states dissociate at different temperatures → *sequential suppression*

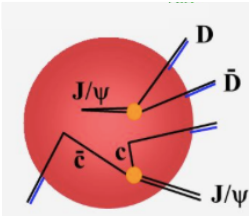


	J/ψ	ψ(2S)	ϒ(1S)	ϒ(2S)	ϒ(3S)
E_b (MeV)	~ 640	~ 60	~ 1100	~ 500	~ 200

Complications

Other effects

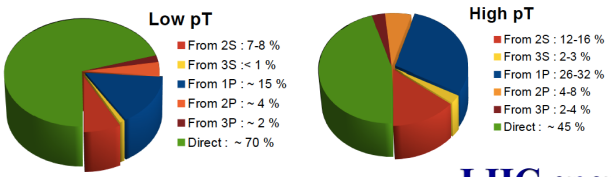
- **(Re)generation**
  - *Deconfinement is a prerequisite*
  - Depend on species, energy, p_T, y, etc



Central AA collisions	SPS 20 GeV	RHIC 200 GeV	LHC 5 TeV
N_{ccbar}/event	~0.2	~10	~115

- Medium-induced energy loss
  - Parton fragmentation

- **Feed-down contributions**
  - Depend on species, energy, p_T, etc



A. Andronic, EPJC 76 (2016) 107

LHC energy

- **Cold Nuclear Matter (CNM) effect**
  - Modification to particle production unrelated to QGP formation
  - Quantified via pA collisions

Main Observables

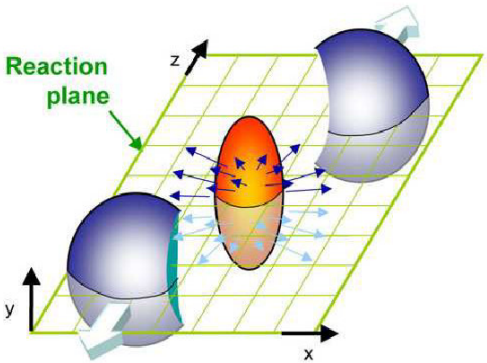
- Nuclear Modification Factor (R_{AA})

$$R_{AA} = \frac{\sigma_{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA} / dydp_T}{d^2\sigma_{pp} / dydp_T}$$

$R_{AA} = 1$ if no medium effects

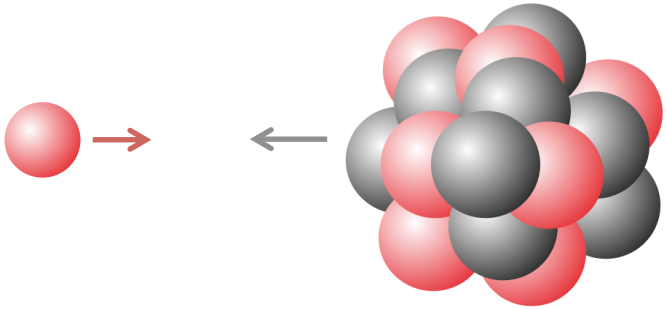
- Elliptic flow (v_2)

$$\frac{dN}{d\varphi} \propto 1 + 2v_2 \cos[2(\varphi - \psi_R)]$$

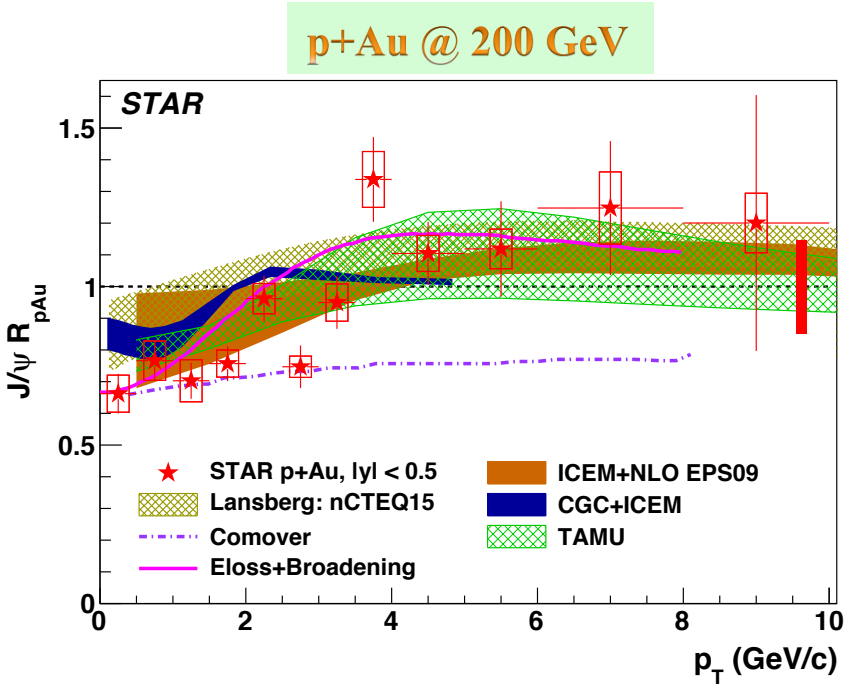


- ✓ pressure ingredient
- ✓ path-length dependent suppression

Cold Nuclear Matter: p/d+A



Midrapidity J/ψ R_{pA} at RHIC



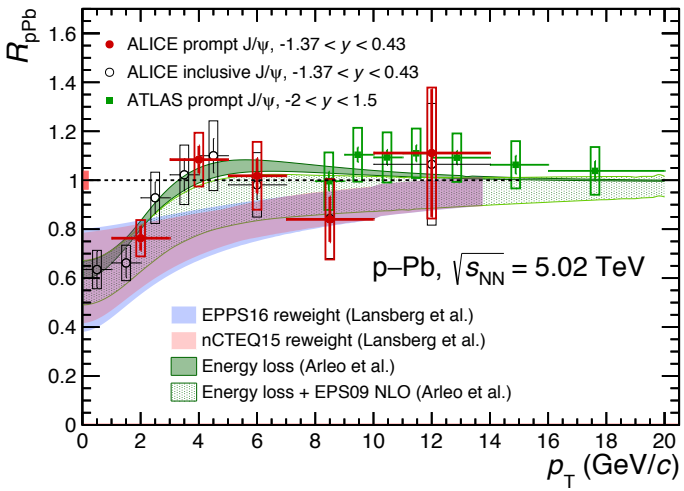
STAR, arXiv:2110.09666

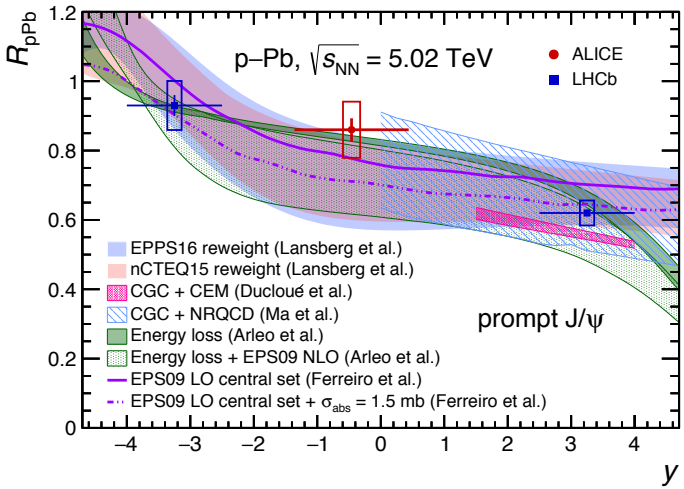
- ~30% suppression below 2 GeV/c, and consistent with unity above 3 GeV/c
  - CNM effects affect J/ψ measurement in AA at low p_T
- Different model calculations, e.g. nPDF, energy loss, CGC, small droplet of QGP, are consistent with data
  - Comover model overpredicts suppression at high p_T

J/ψ R_{pA} at the LHC

ALICE, arXiv:2105.04957

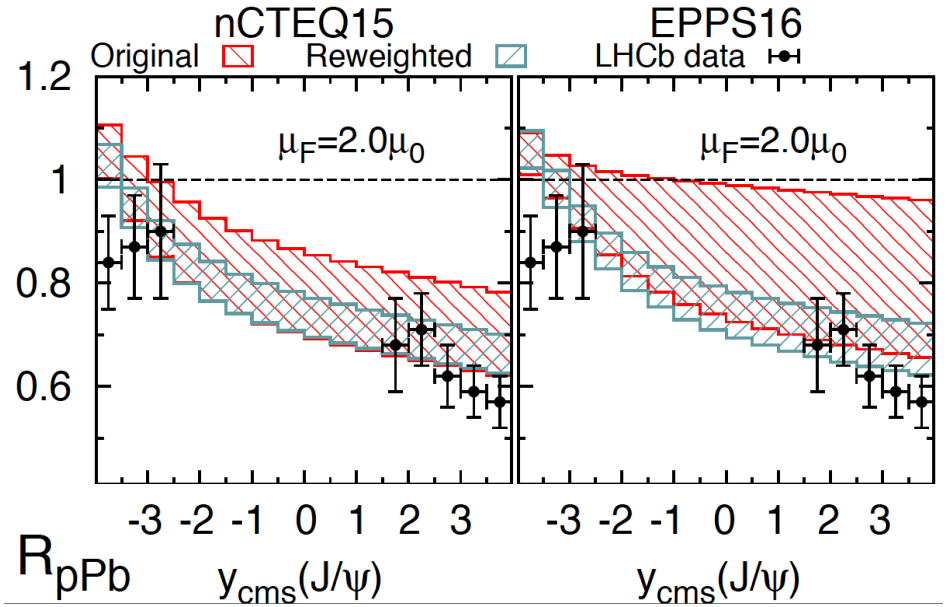
p+Pb @ 5.02 TeV





- Significant suppression at low p_T and forward rapidity
- Consistent with various model calculations, e.g. nPDF, ELoss, CGC, etc

Constrain nPDF

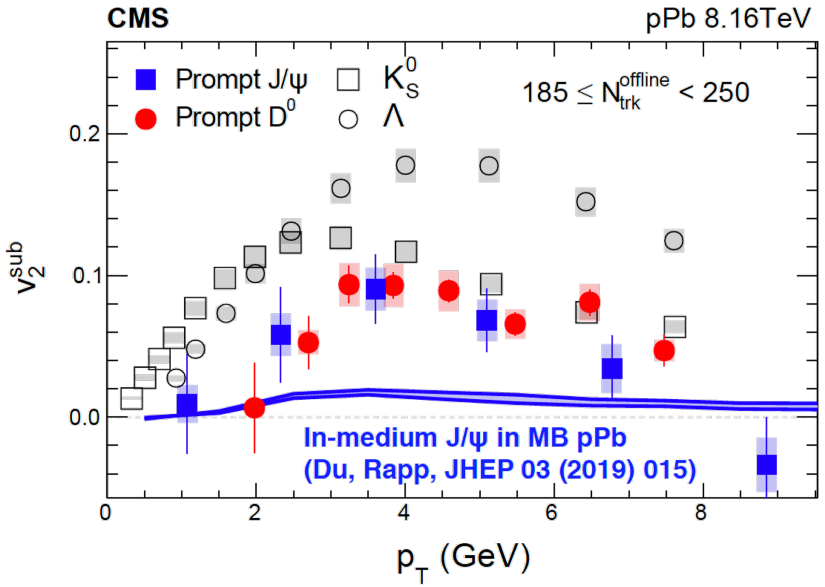


- High-precision heavy flavor R_{pPb} data from the LHC used to constrain nPDF through a reweighting procedure
- Significant impact on both central values and uncertainties

A. Kusina, J. Lansberg, I. Schienbein, H. Shao, PRL 121, (2018) 052004

Collective Motion for J/ψ in pPb: Initial-State vs. Final-State Effects?

CMS: PLB 791 (2019) 172



- Clear evidence of collective motion for J/ψ in pPb collisions
- Could not be explained by final state effects, e.g. small droplet of QGP formed in these collisions

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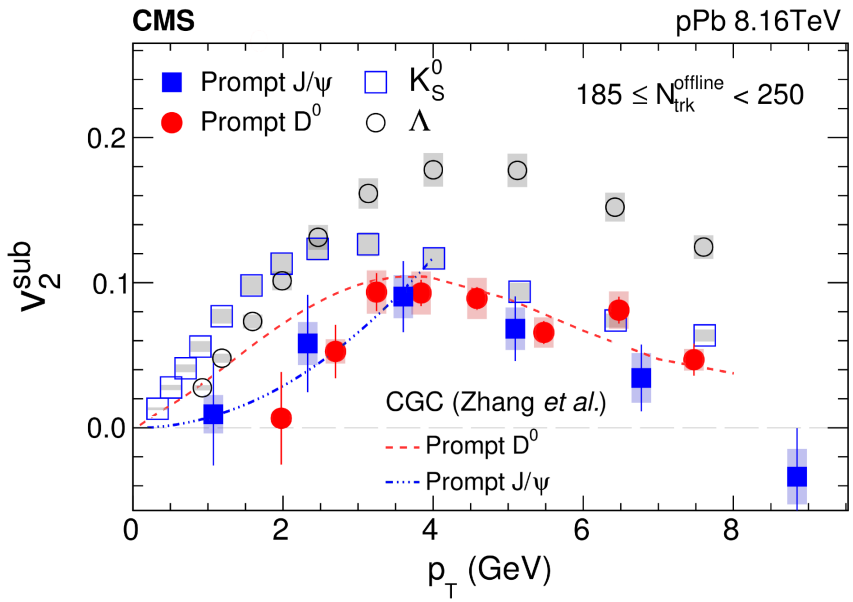
CMS: PLB 791 (2019) 172

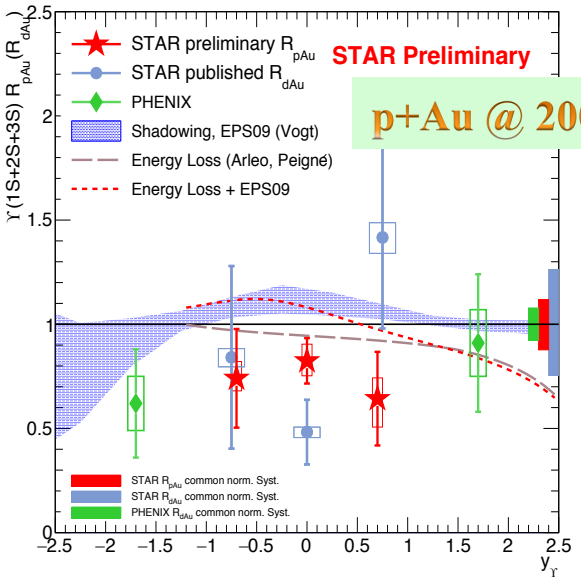


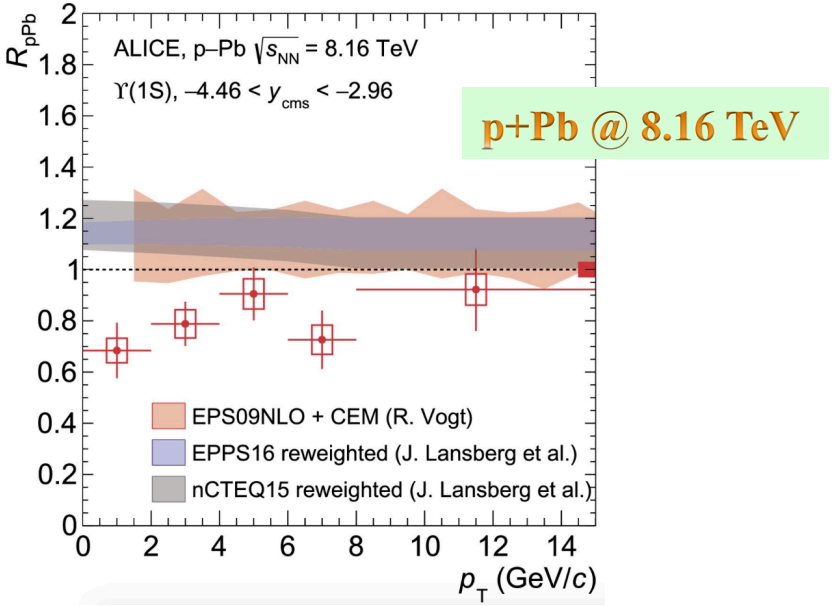
- Clear evidence of collective motion for J/ψ in pPb collisions
- Could not be explained by final state effects, e.g. small droplet of QGP formed in these collisions
- Initial state effect, such as CGC, can reasonably describe data.
  - Need to pass all the tests

CNM Effects for ϒ

STAR: PLB 735 (2014) 127, PHENIX: PRC 87 (2013) 044909
R. Vogt, et. al, PoS ConfinementX 203 (2012)
F. Arleo, S. Peigne, JHEP 1303 (2013) 122
K. J. Eskola, et. al, JHEP 0904 (2009) 065

ALICE, PLB 806 (2020) 135486

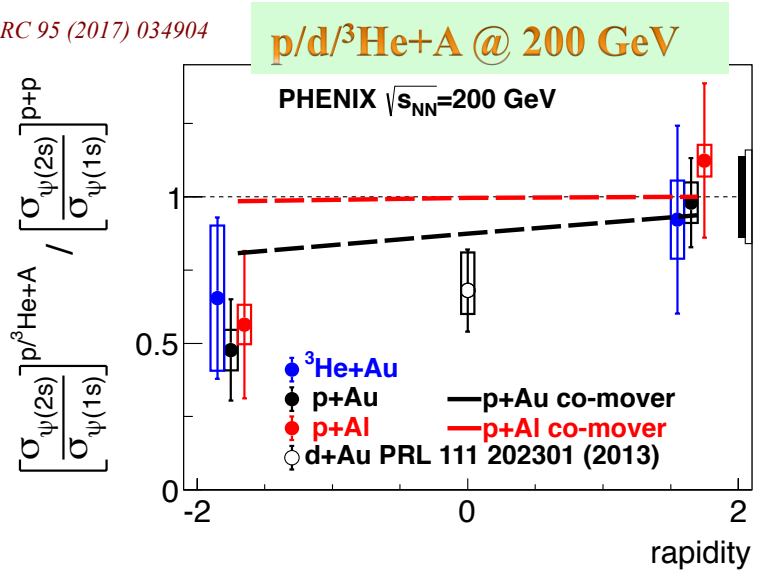


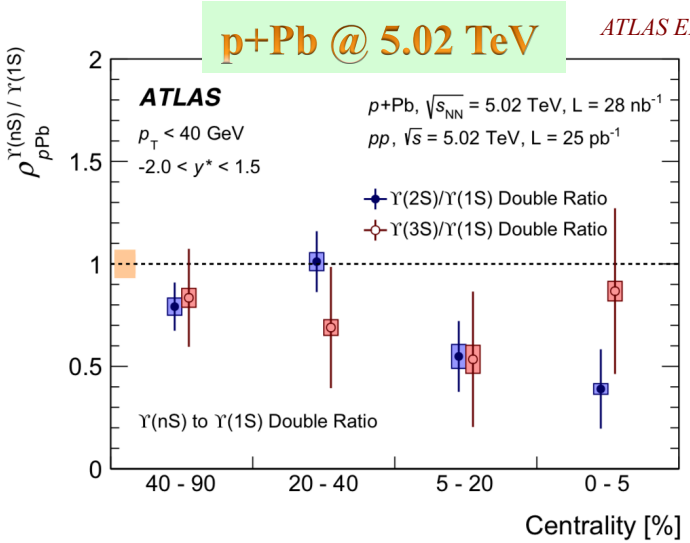


- Sizable CNM effects for ϒ
  - RHIC: ϒ(1S+2S+3S) R_{pAu} ~ 0.8 within |y| < 1.0
  - LHC: ϒ(1S) R_{pPb} ~ 0.8 at low p_T in Pb-going direction
- nPDF effects alone are not able to describe data. Other effects needed.

Excited States Further Suppressed

PHENIX, PRC 95 (2017) 034904

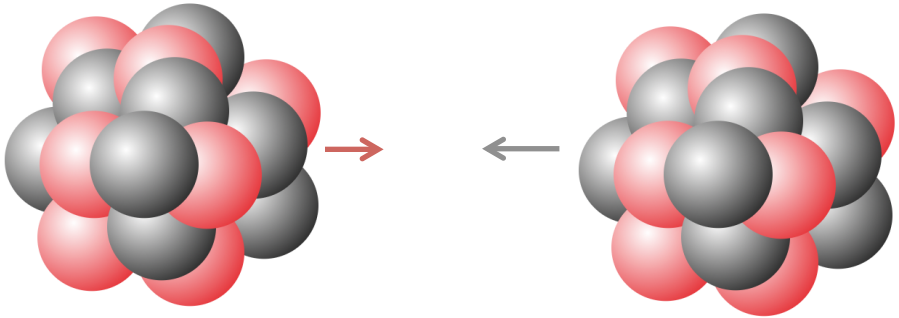




ATLAS EPJC 78 (2018)171

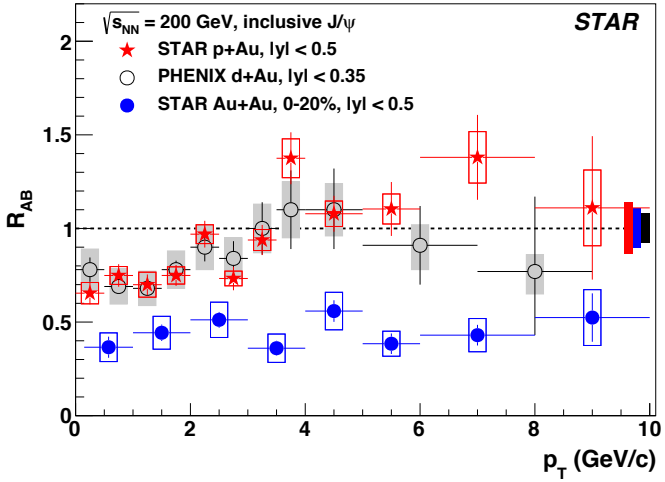
- Excited quarkonium states are further suppressed than ground states in case of large event activities
  - FS effects, such as co-mover suppression, are needed to explain them

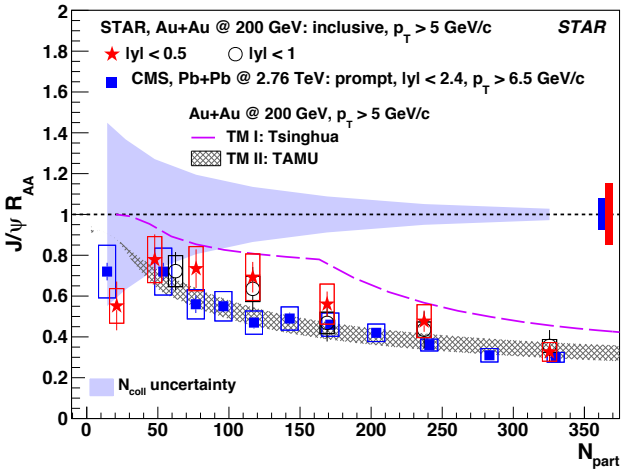
Hot Nuclear Matter: A+A



High-p_T J/ψ Suppression in the QGP

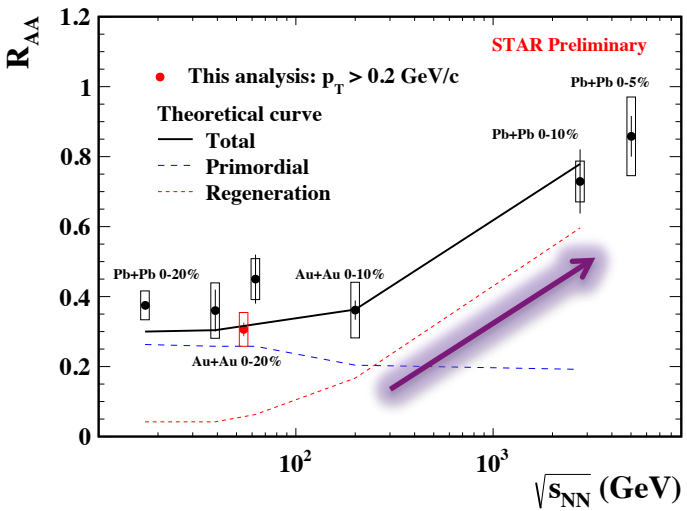
STAR, arXiv:2110.09666
STAR, PLB 797 (2019) 134917
CMS, Eur. Phys. J. C77 (2017) 252

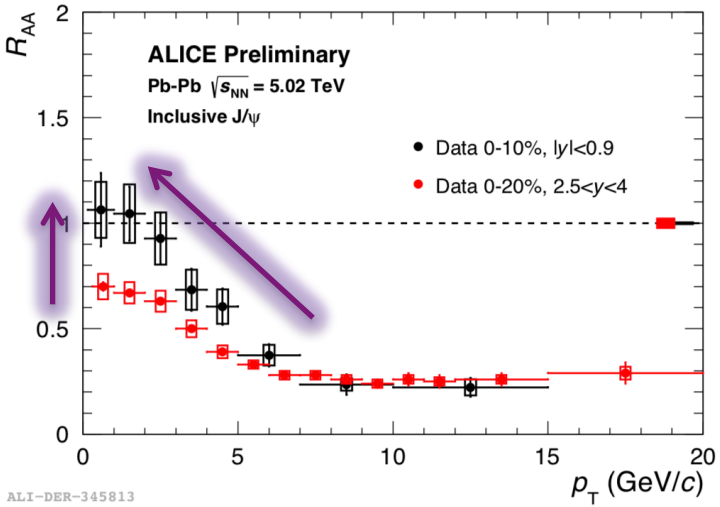




- High-p_T J/ψ strongly suppressed beyond CNM effects → **Dissociation**
  - Regeneration expected to be small
- Dependence on QGP properties
  - More central collision, higher temperature -> stronger suppression

Regeneration Is Visible





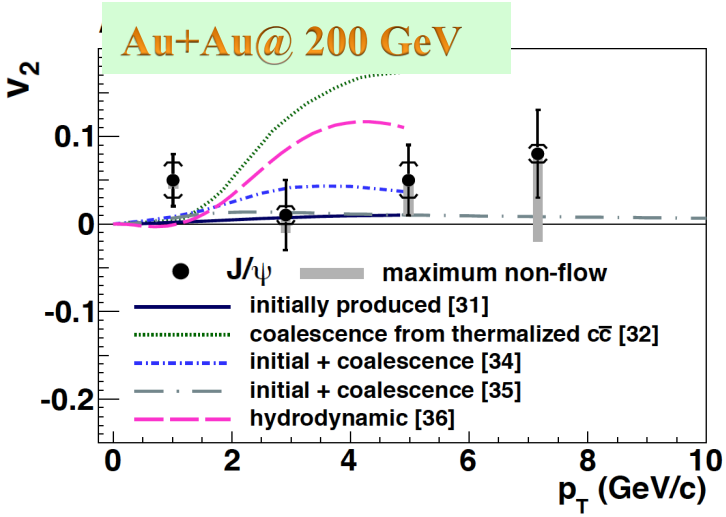
ALICE, PLB 805 (2020) 135434, ALICE, JHEP02 (2020) 041

ALICE, PLB 734 (2014) 314; ALICE, NPA 1005 (2021) 121769
STAR, PLB 771 (2017) 13; STAR, PLB 797 (2019) 134917
X. Zhao, R. Rapp, PRC 82 (2010) 064905
L. Kluberg, EPJC 43 (2005) 145.; NA50, PLB 477 (2000) 28

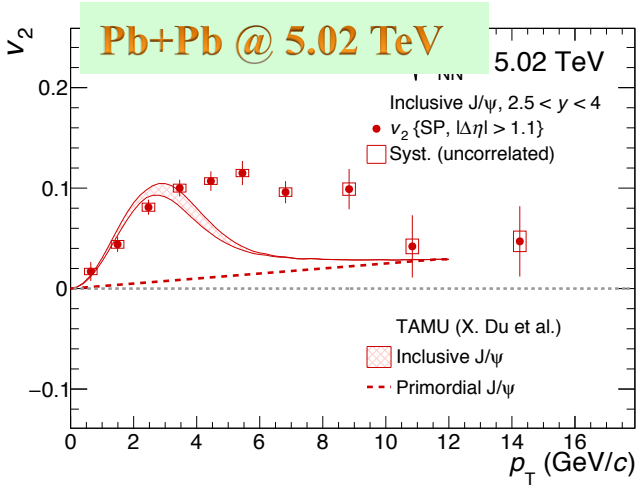
- Low-p_T J/ψ R_{AA} increases from RHIC to LHC: regeneration
- Depends on charm quark population: increases at low p_T and midrapidity
  - Precise charm quark cross section measurements are critical inputs to theory

J/ψ v_2: a Different Perspective

STAR, PRL 111 (2013) 052301



ALICE, JHEP 10 (2020) 141

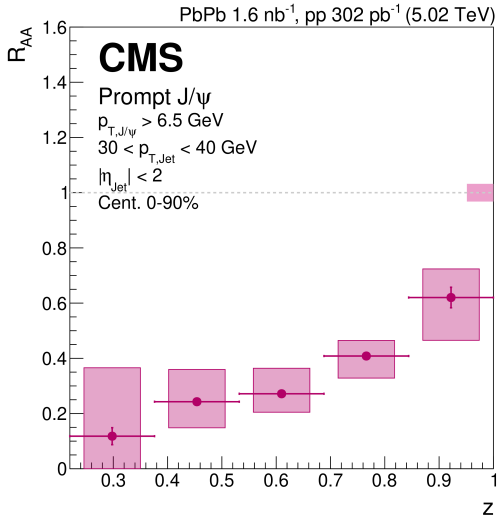


- Low-p_T J/ψ v_2: regeneration contribution from thermalized charm quarks
- Could not describe sizable high-p_T v_2 at the LHC
  - Produced in jets that suffer from parton energy loss?

J/ψ Production in Jets

- In 5.02 TeV p+p collisions at midrapidity, high-p_T J/ψ are mostly produced during parton showers
  - ~85% of J/ψ above 15 GeV are produced in jets above 19 GeV.

CMS, PLB 804 (2020) 135409



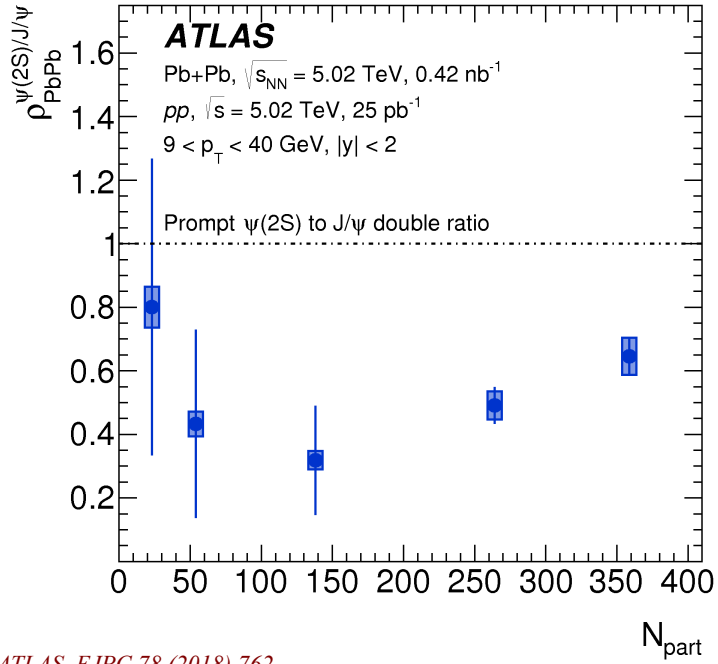
$$z = \frac{p_T^{J/\psi}}{p_T^{jet}}$$

- In Pb+Pb collisions, J/ψ suppression increases with decreasing z → parton energy loss plays a role
  - Smaller z means J/ψ is likely produced later in the parton shower

CMS, arXiv:2106.13235

ψ(2S) Suppression at LHC

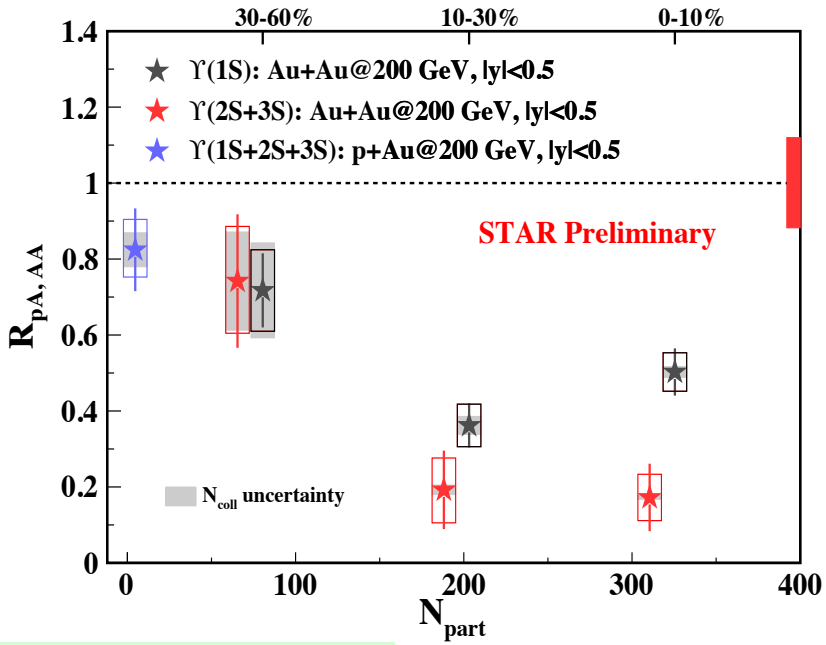
Pb+Pb @ 5.02 TeV



ATLAS, EJPC 78 (2018) 762

- ψ(2S) is further suppressed by about a factor of 2 in the QGP than J/ψ
  - Consistent with that ψ(2S) has a smaller binding energy

RHIC: Υ R_{AA} vs. Centrality

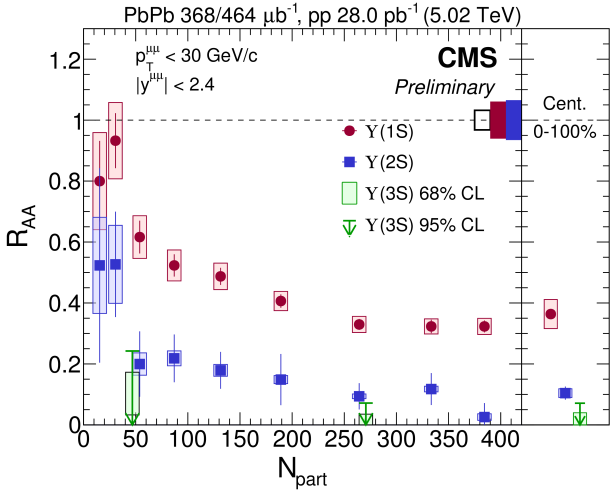


Au+Au @ 200 GeV

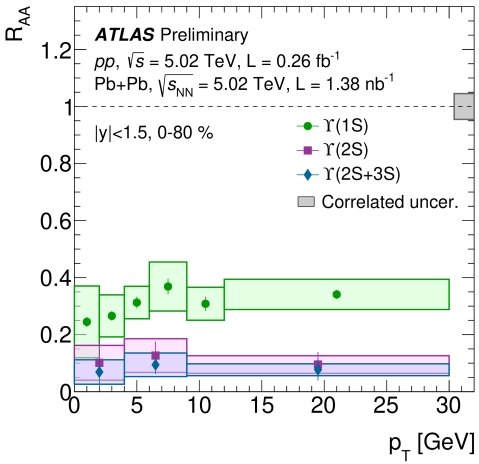
- 0-10% central: $R_{AA}^{\Upsilon(2S+3S)} < R_{AA}^{\Upsilon(1S)}$
  → **sequential suppression**
- $R_{AA}^{peri} > R_{AA}^{cent}$: increasing hot medium effects
- CNM plays a role

LHC: Υ R_{AA} vs. Centrality, p_T, y

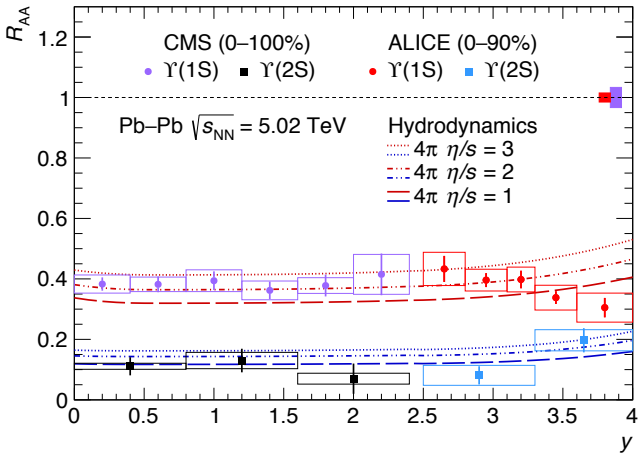
CMS: PLB 790 (2019) 270



ATLAS-CONF-2019-054

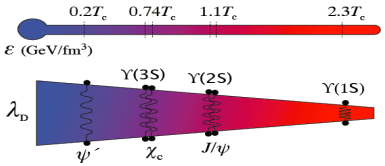


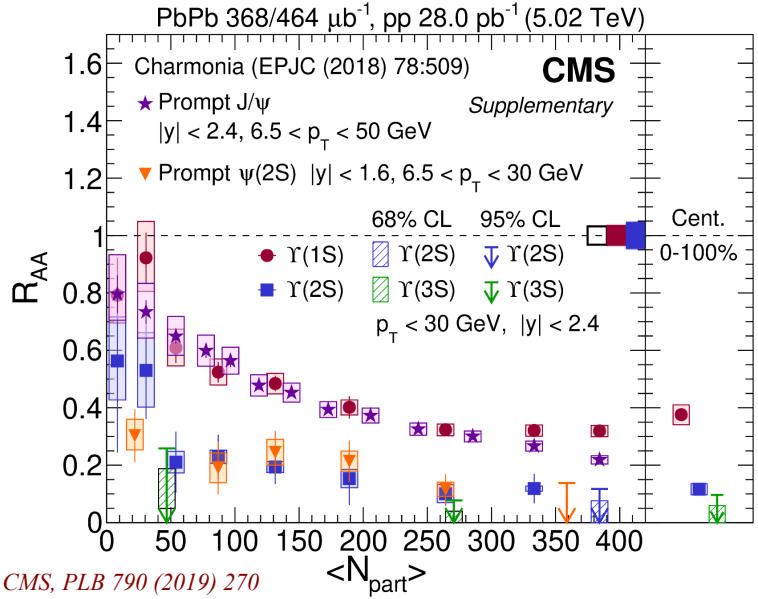
ALICE, PLB 822 (2021) 136579



- $R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)}$ → **sequential suppression**
  - Increasing suppression from peripheral to central collisions
  - Weak p_T dependence
  - Hint of smaller $R_{AA}^{\Upsilon(1S)}$ at large y. Not seen in theory or $R_{AA}^{\Upsilon(2S)}$

Medium Thermometer?





CMS, PLB 790 (2019) 270

- Expectation:

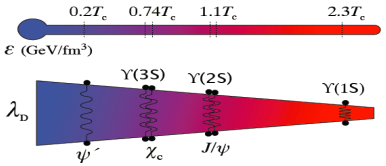
  $R_{AA}^{\psi(2S)} < R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} \sim R_{AA}^{J/\psi} < R_{AA}^{\Upsilon(1S)}$

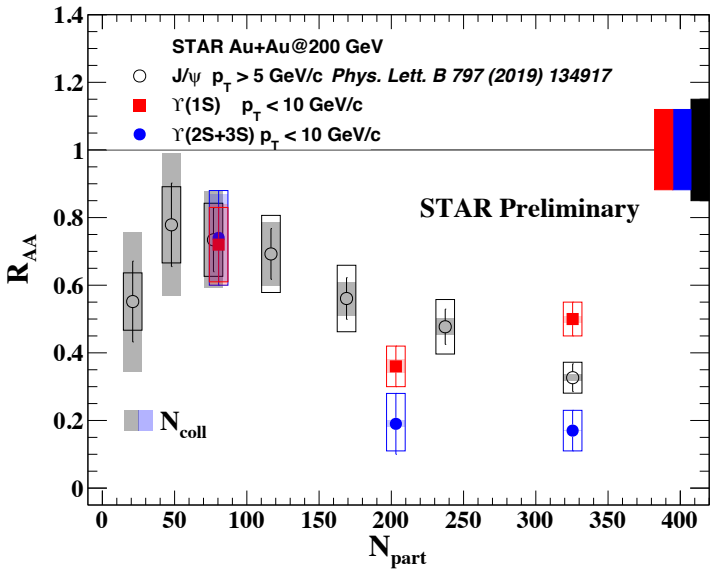
- Measurements at the LHC:

  $R_{AA}^{\Upsilon(3S)} <\sim R_{AA}^{\psi(2S)} \sim R_{AA}^{\Upsilon(2S)} < R_{AA}^{J/\psi} \sim R_{AA}^{\Upsilon(1S)}$

- Two caveats:
  - Feeddown contribution
  - Different p_T range: charmonia spend less time in the QGP than bottomonia

Medium Thermometer?





- Expectation:

  $R_{AA}^{\psi(2S)} < R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} \sim R_{AA}^{J/\psi} < R_{AA}^{\Upsilon(1S)}$

- Measurements at RHIC:

  $R_{AA}^{\Upsilon(2S+3S)} < R_{AA}^{J/\psi} \sim R_{AA}^{\Upsilon(1S)}$

- Two caveats:
  - Feeddown contribution
  - Different p_T range: charmonia spend less time in the QGP than bottomonia
- Need more measurements with better precision
  - STAR & sPHENIX in 2023-25

Medium Thermometer?

	Dissociation T (MeV)			Initial QGP T (MeV)		
	ϒ(1S)	ϒ(2S)	ϒ(3S)	0.2 TeV	2.76 TeV	5.02 TeV
Transport	500	240	190	310	555	594
lQCD+a Hydro	600	230	170	440	546	632
OQS	450*	225*	154*	376	484	511

*Melting temperature at $1/m_D = \Upsilon$ size

Transport: D. Xu, et al., PRC 96 (2017) 054901
lQCD+aHydro: B. Krouppa, et al., PRD 97 (2018) 016017
OQS: X. yao, et al., JHEP 01 (2012) 046

- Despite many differences, model calculations are all consistent with measurements
- Where do we go from here?
  - Better experimental precision
  - Common treatment of QGP evolution in theoretical calculations
  - Connect to other measurements

Summary

- Cold nuclear matter effects (p/d+A collisions)
  - Sizable suppression for low p_T J/ψ (~30%) and ϒ (~20%)
  - Enhanced suppression of excited states than ground states → final state effects
  - Constrain initial state effects → nPDF reweight; collective motion

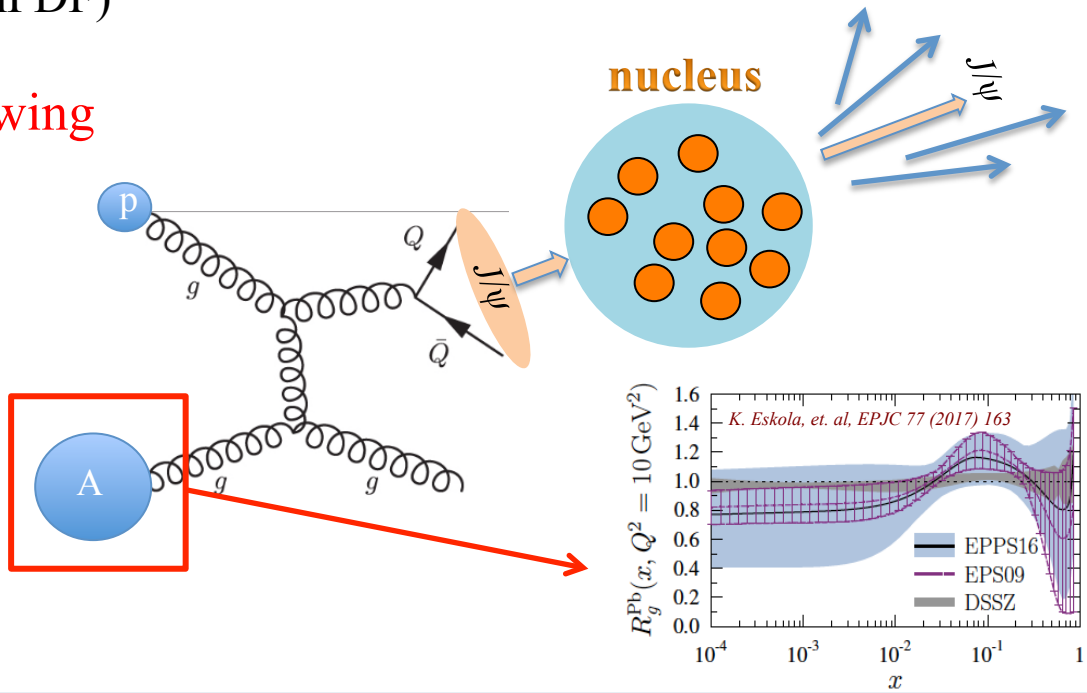
- Hot medium effects (A+A collisions)
  - Strong suppression of high-p_T J/ψ beyond CNM effects → **dissociation**
  - J/ψ regeneration increases towards higher energy, lower p_T, and midrapidity
  - Enhanced suppression of excited states than ground states → **sequential suppression**
    - CNM vs. QGP contributions
  - **QGP thermometer: need concerted efforts from experiment and theory**

Backup

Cold Nuclear Matter (CNM) Effects

- **Modification to particle production unrelated to QGP**
  - Quantified via pA collisions; baseline for AA measurements
  - Constrain initial state (e.g. nPDF)

- nPDF: shadowing/anti-shadowing
- Coherent energy loss
- Nuclear absorption
- Interact with co-movers



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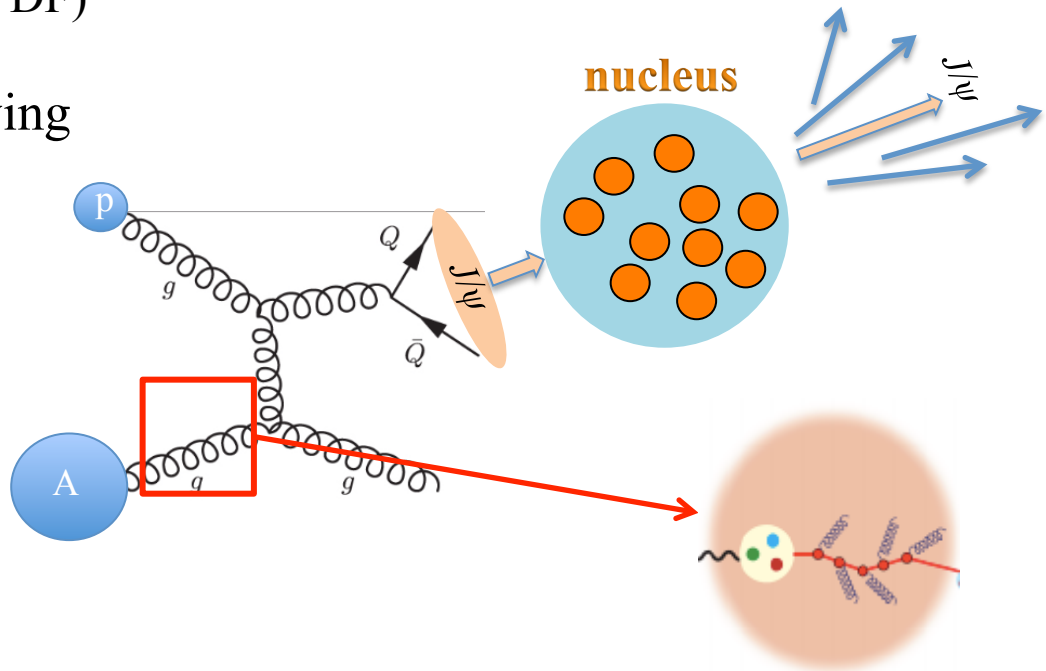

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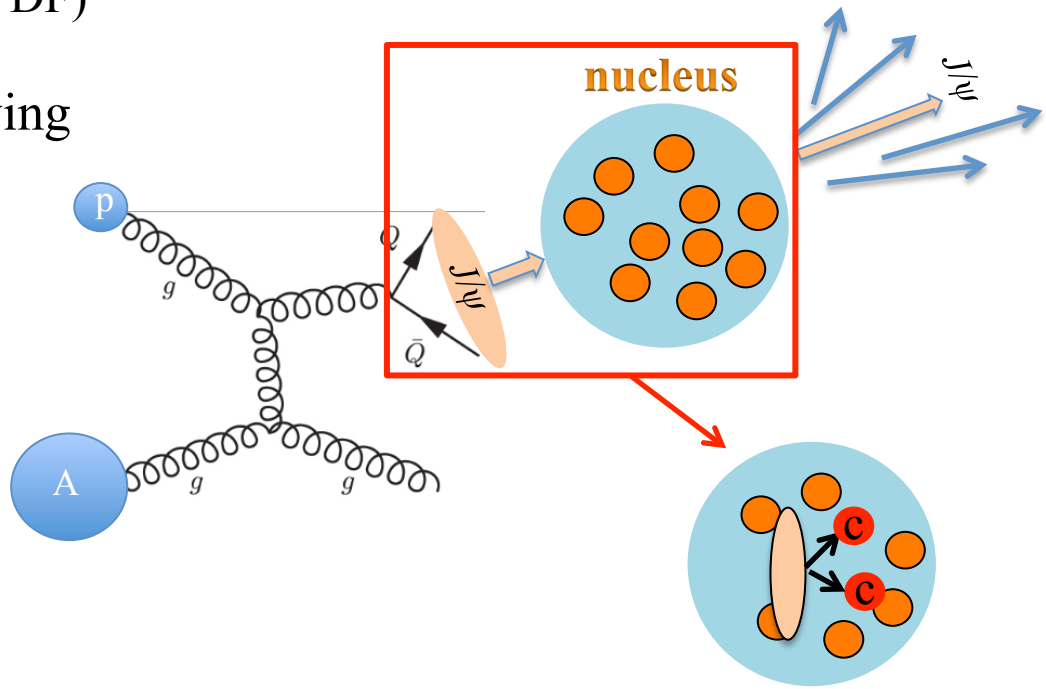

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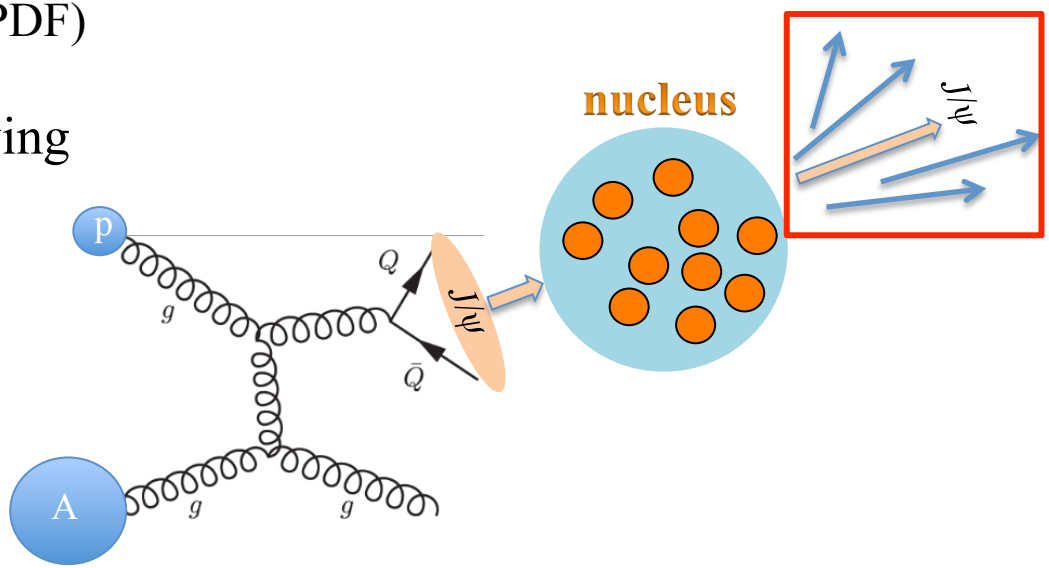
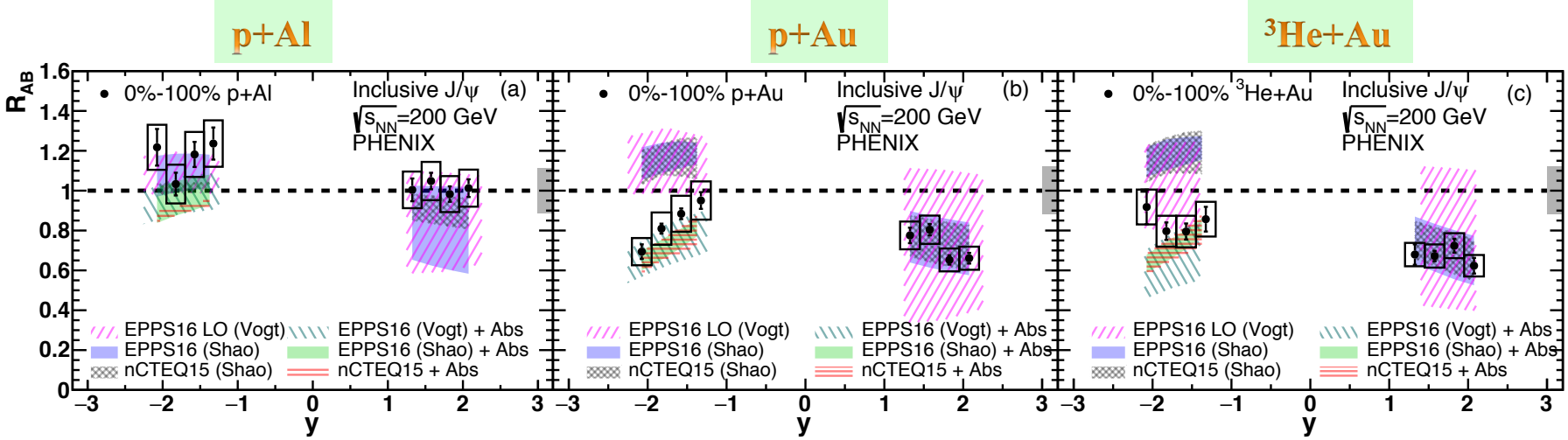


Forward-rapidity J/ψ R_{pA} at RHIC

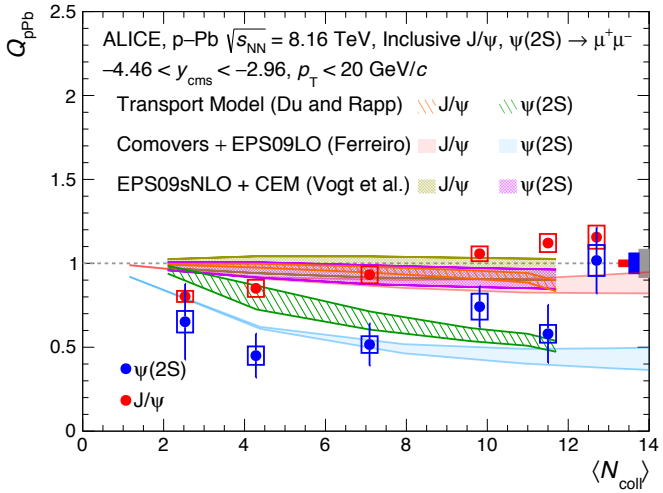


PHENIX, PRC 102 (2020) 014902

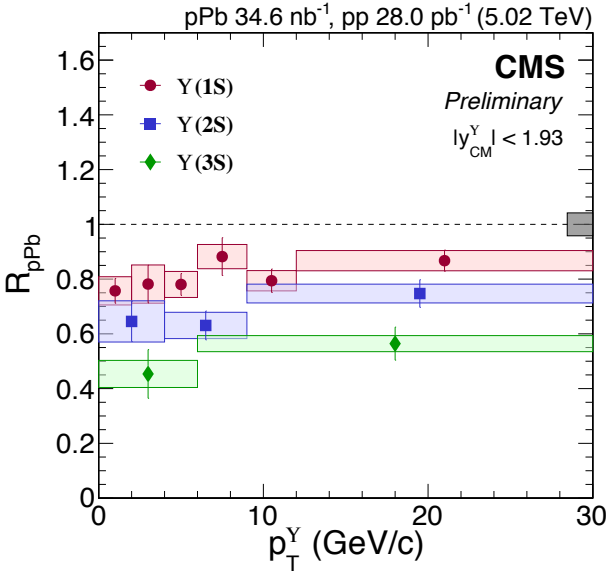
- **Forward**: suppression increases with increasing nucleus size. Consistent with nPDF calculations.
- **Backward**: suppression seen with Au. Nuclear absorption, on top of nPDF (anti-shadowing) is needed to describe data.

Excited States are Further Suppressed

ALICE JHEP 02 (2021) 002

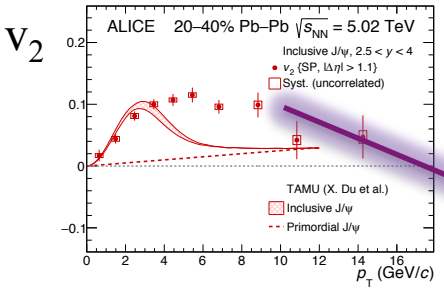


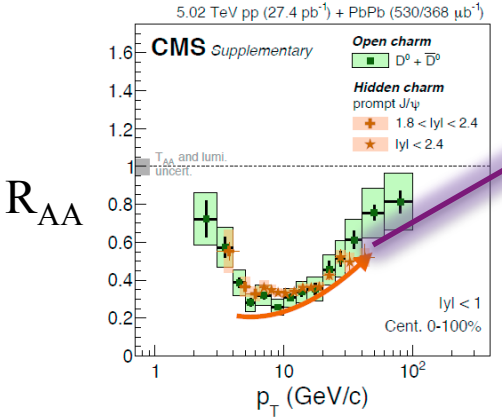
CMS-PAS-HIN-18-005



J/ψ Production in Jets

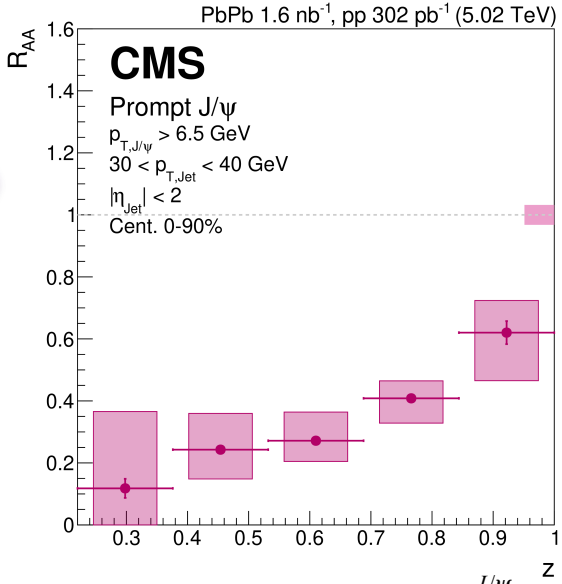
ALICE, JHEP 10 (2020) 141





CMS, PLB 782 (2018) 474

CMS, arXiv:2106.13235



Pb+Pb @ 5.02 TeV

$$z = \frac{p_T^{J/\psi}}{p_T^{jet}}$$

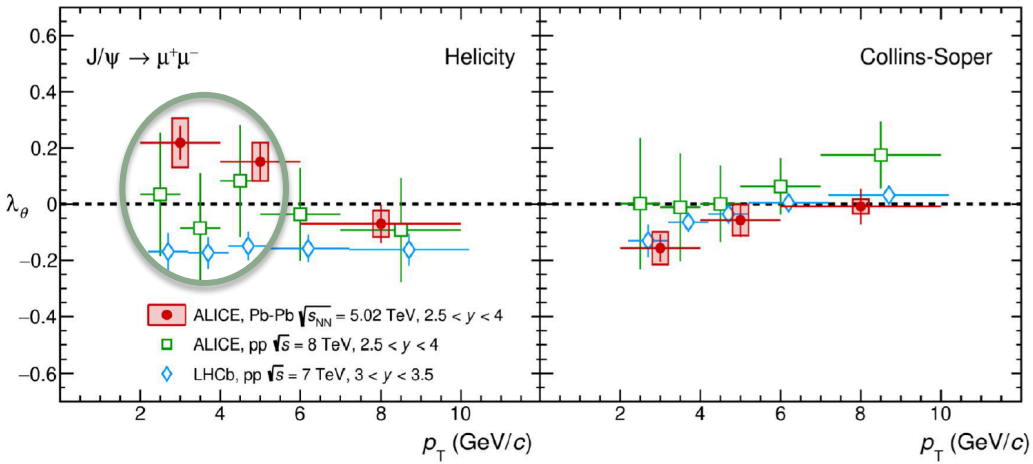
CMS, PLB 804 (2020) 135409

- In 5.02 TeV p+p collisions at midrapidity, high-p_T J/ψ are mostly produced during parton showers
  - ~85% of J/ψ above 15 GeV are produced in jets above 19 GeV.
- In Pb+Pb collisions, J/ψ suppression increases with decreasing z → parton energy loss plays a role
  - Large high-p_T v_2
  - $R_{AA}^{J/\psi} \sim R_{AA}^{D}$

J/ψ Polarization in A+A Collisions

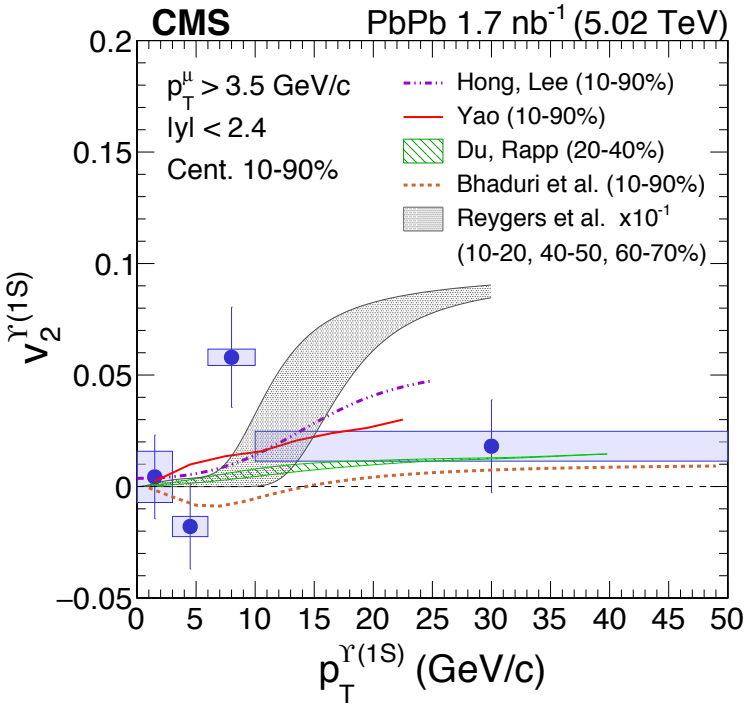
ALICE, PLB 815 (2021) 136146

Pb+Pb @ 5.02 TeV



- First ever such measurements in HI collisions
- Hint of transverse polarization at low p_T in helicity frame ~2σ
  - LHCb data show longitudinal polarization in the same p_T region
    - Hot medium effect? Change of feeddown?
  - Impact on experimental efficiency estimation

How About $\Upsilon(1S)$ v_2?



CMS PLB 819 (2021) 136385

- Small $\Upsilon(1S)$ v_2 at low p_T
  - Small regeneration contribution
  - Consistent with model calculation
- Small v_2 also at high p_T; a blast-wave model (grey) is disfavored