U.S. DEPARTMENT OF ENERGY | Office of Science

Brookhaven National Laboratory

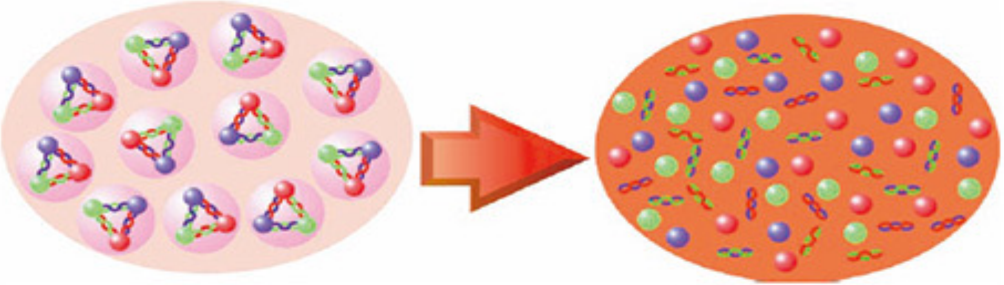
Quarkonia measurements at RHIC-STAR

Rongrong Ma, BNL
April 13th, 2023

India+ lectures on Heavy Ion Collision experiments

What is the QGP?

- **Quark-gluon plasma**: a state of QCD matter, consisting of asymptotically *free moving quarks and gluons* which are ordinarily confined within nucleons by color confinement.



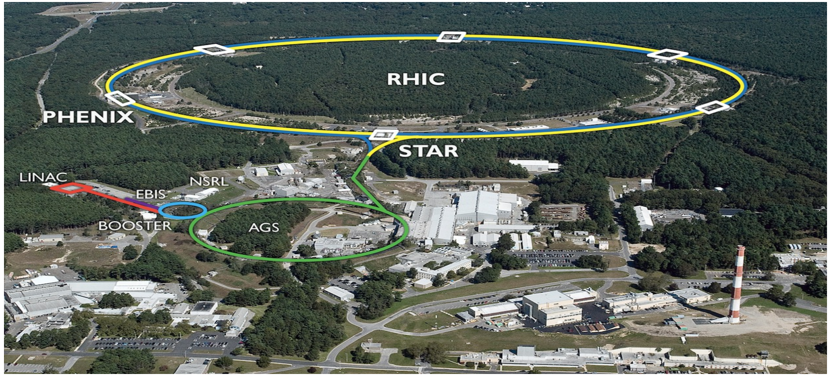
https://www.bnl.gov/riken/research/QGP.php

- **Believed to have existed at Early Universe**

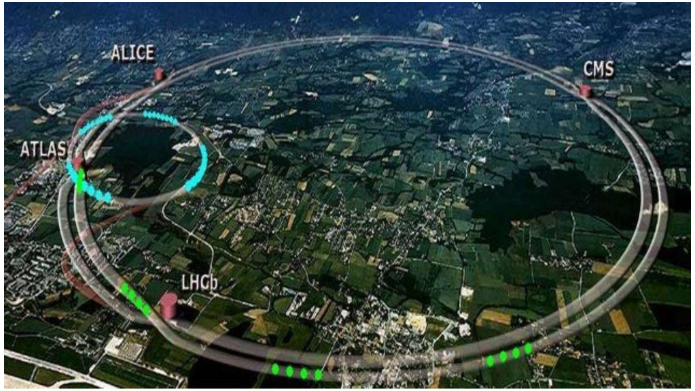
How to Create QGP in Lab?

- **Heavy-ion collisions**
  - T.D. Lee, 1974: We should investigate phenomena by distributing high energy or high nucleon density over a relatively large volume

RHIC: Au+Au



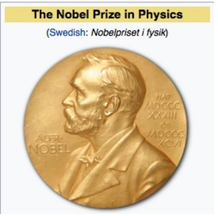
LHC: Pb+Pb



What is a Quarkonium?

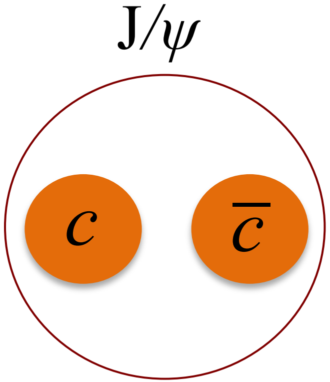
- A quarkonium is a meson made up of a pair of heavy quark and its anti-quark.

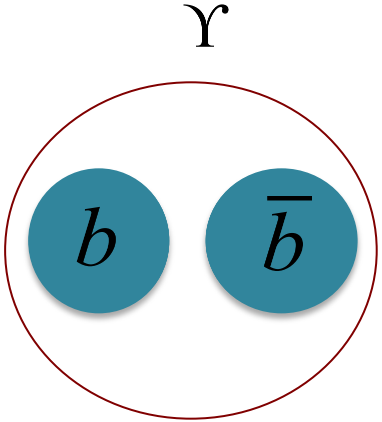
1976



The Nobel Prize in Physics

(Swedish: *Nobelpriset i fysik*)





Discovered in 1974 at both SLAC (Burton Richter) and BNL (Samuel Ting)

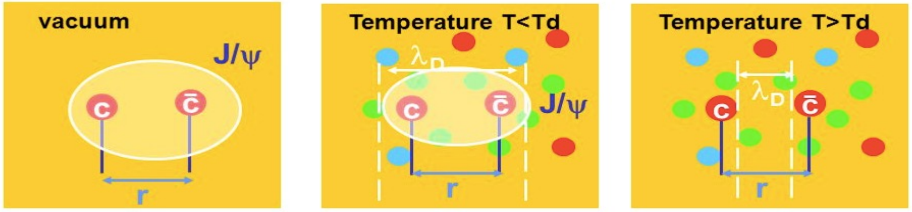
Discovered in 1977 at Fermilab (Leon Lederman)

Why Quarkonia?

- **Early creation:** experience entire evolution of quark-gluon plasma
- **Evidence of deconfinement**: quark-antiquark potential color-screened by surrounding partons → *(static) dissociation*

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

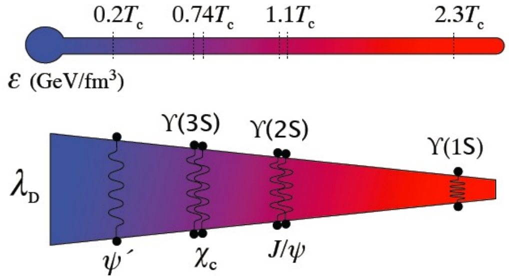
J/ψ suppression was proposed as a direct proof of QGP formation



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

- **"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

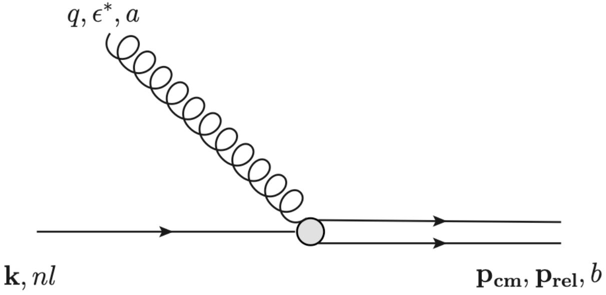


The Complications

Other effects

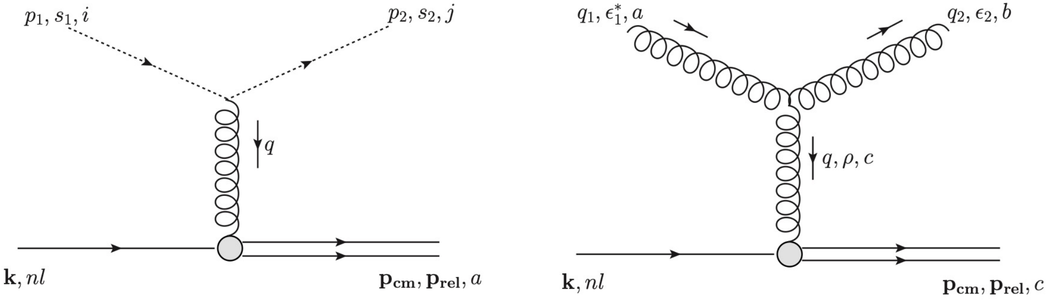
- Dynamic dissociation

X. Yao, B. Muller, PRD 100 (2019) 014008



Leading-Order

$g + \Upsilon \rightarrow b\bar{b}$



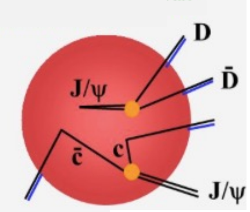
Next-to-Leading-Order

$g/q + \Upsilon \rightarrow g/q + b\bar{b}$

The Complications

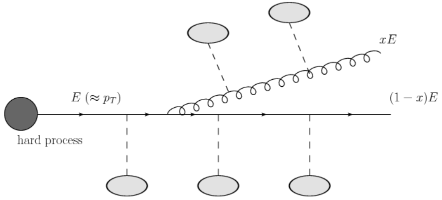
Other effects

- Dynamic dissociation
- **Regeneration**
  - *Deconfinement is a prerequisite*
  - Depend on species, energy, p_T, etc

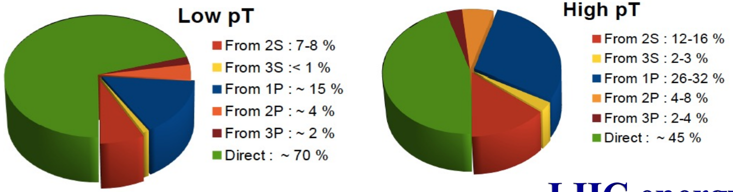


Central AA collisions	SPS 20 GeV	RHIC 200 GeV	LHC 5 TeV
N_{ccbar}/event	~0.2	~10	~115

- Medium-induced energy loss
  - Parton fragmentation



- Formation time
  - High p_T hadrons fly out of medium faster
- **Feed-down contributions**
  - Depend on species, energy, p_T, etc



A. Andronic, EPJC 76 (2016) 107

LHC energy

Cold Nuclear Matter (CNM) Effects

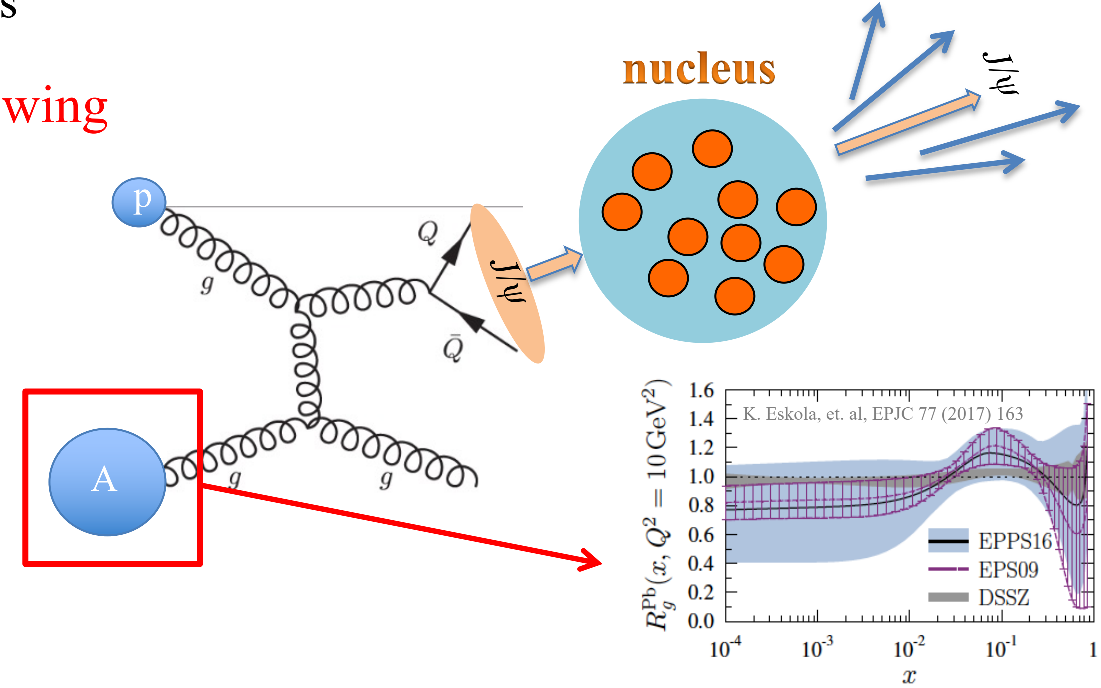
- Modification to the particle production ***due to the presence of a nucleus, not related to the creation of QGP***
  - Quantified via pA collisions

○ nPDF: shadowing/anti-shadowing

○ Coherent energy loss

○ Nuclear absorption

○ Interact with co-movers



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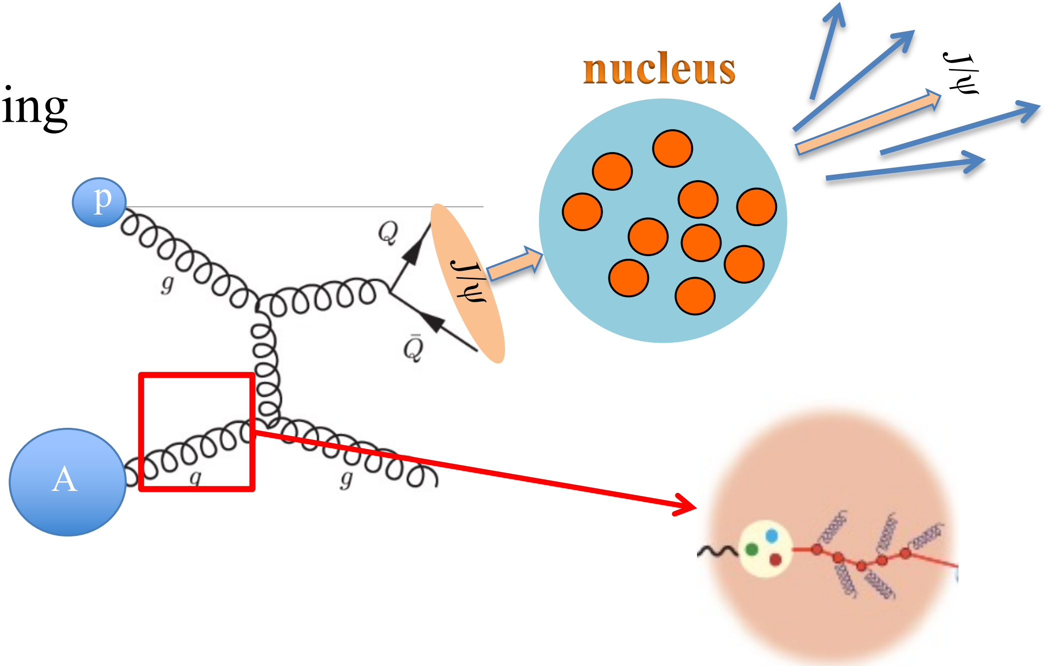

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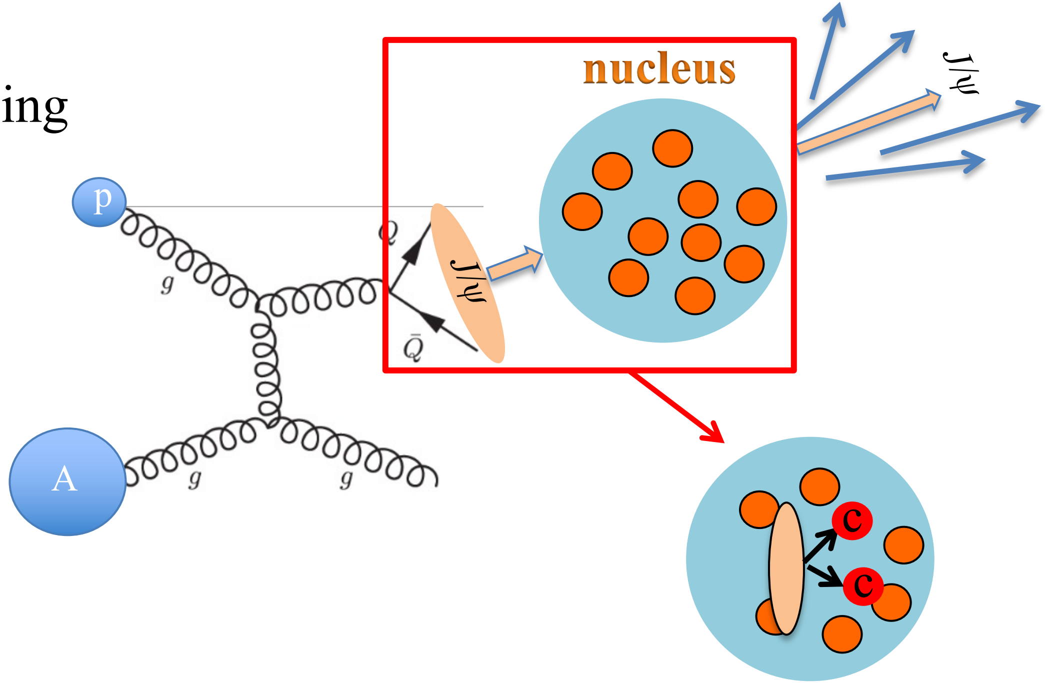

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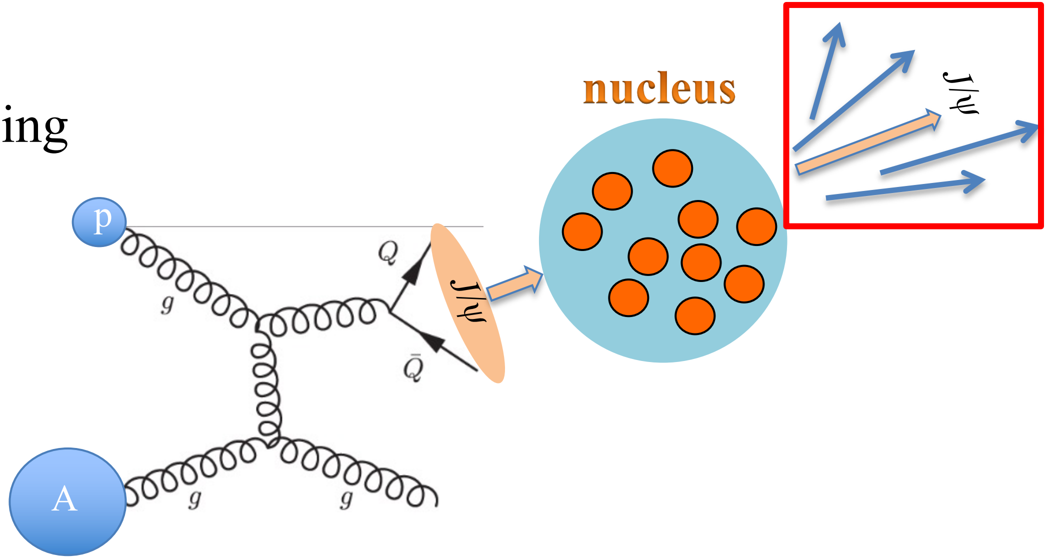
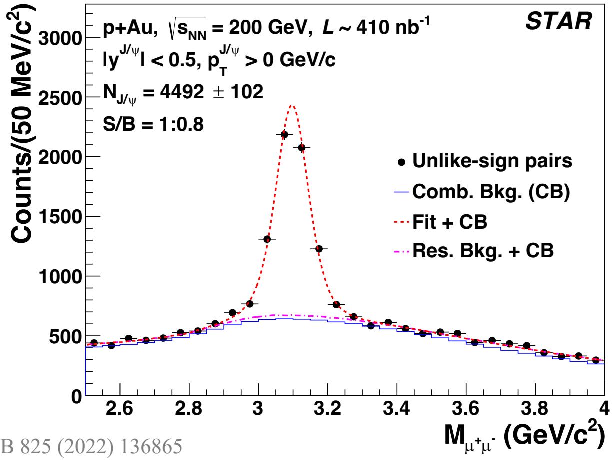


How to Measure Quarkonia?

- Invariant mass method: through its decay to dielectron or dimuon pairs
  - $m_{inv}^2 = (p_1 + p_2)^2 = 2m_l^2 + 2(E_1E_2 - \vec{p}_1\vec{p}_2)$

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



STAR, PLB 825 (2022) 136865

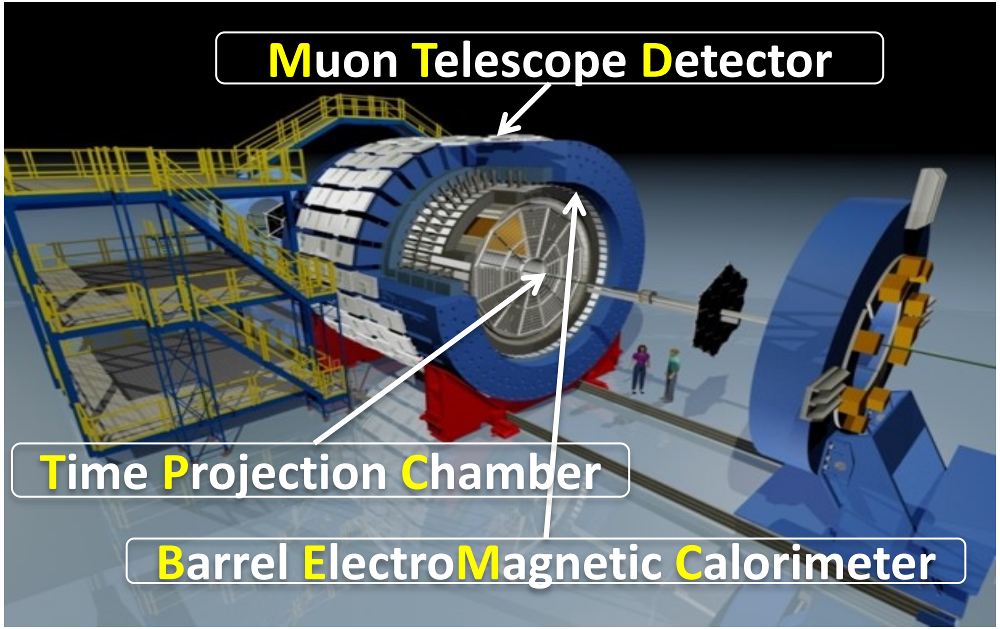
NEED

✓ Particle momentum

✓ Particle species

The Solenoid Tracker At RHIC

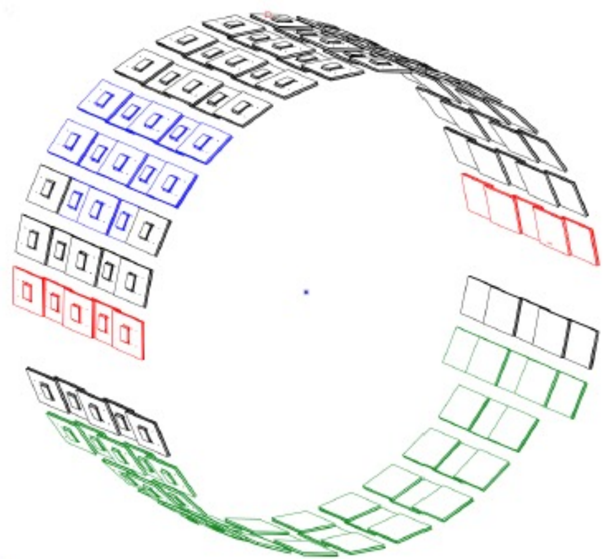
- Mid-rapidity detector: $|\eta| < 1$, $0 < \varphi < 2\pi$



- **TPC**: measure track momentum and energy loss
- **BEMC**: trigger on and identify high-p_T electrons
- **MTD**: trigger on and identify muons
  - $p_T >\sim 1.2$ GeV/c

Quarkonia are rare probes → important to trigger on them

Muon Telescope Detector



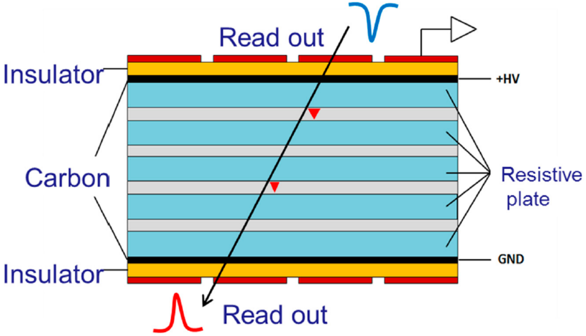
- Fully installed in 2014
- Located outside of the STAR magnet, acting as an absorber to other hadrons
- About 400 cm radially, covering $|\eta| < 0.5$, $\Delta\varphi \sim 45\%$
- 122 trays; 1439 readout strips

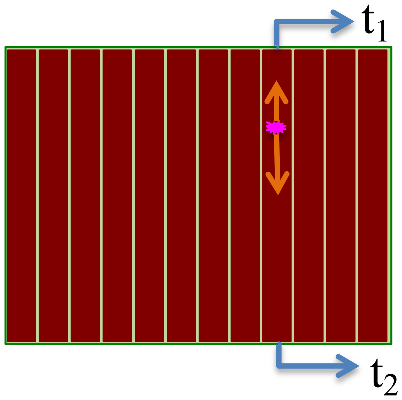
STAR, JPG 36 (2009) 095001

Muon Telescope Detector

- **Multigap Resistive Plate Chambers** with double-ended readout
  - Gaseous detector operating in the avalanche mode
  - Gas mixture: 95% Freon + 4.5% Isobutane + 0.5% SF_6
    - Isobutane and SF_6 are used to control ionization process
  - Large scale, cost effective
- Provide position and timing measurements
  - Intrinsic resolution: timing (~100 ps) and position (~1-2 cm)

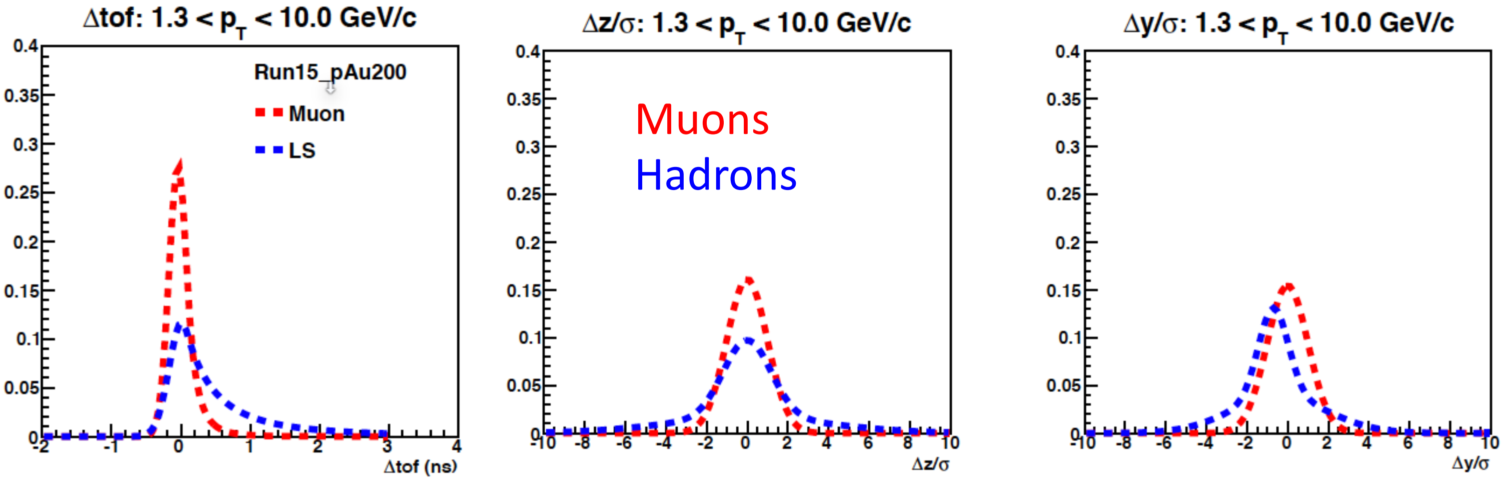
Y. Wang, Y. Yu, Appl. Sci. 11 (2021) 111.





MTD: Particle Identification

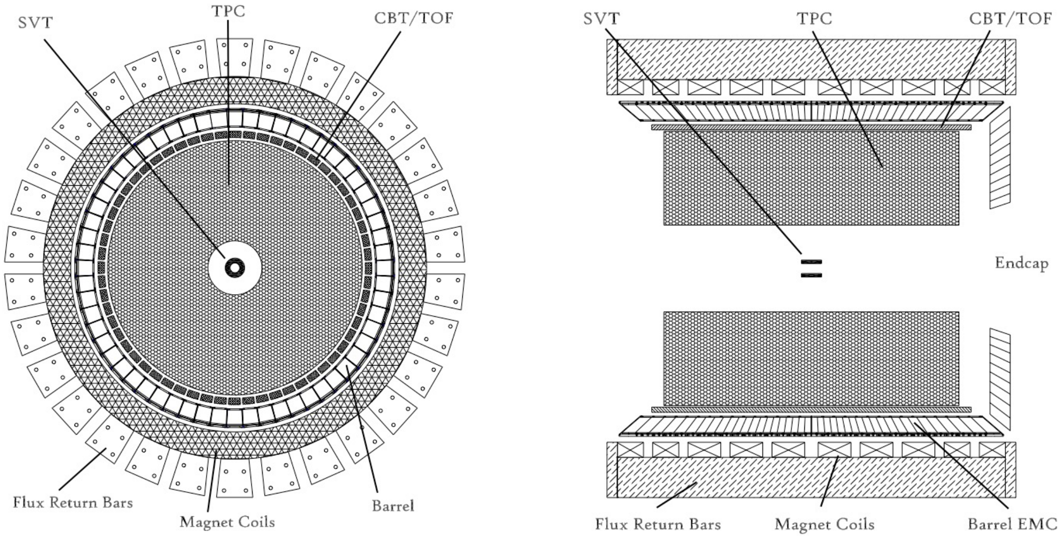
- Based on position and timing information from MTD



MTD: Dimuon Trigger

- Process: J/ψ,Υ → μ^{+}+μ^{-}
- Trigger condition: two signals in the MTD based on timing
- Can trigger on quarkonia down to zero p_T
- Rejection power: 1 to 30
  - Still dominated by background
- Triggered events are saved in dedicated files for later processing

Barrel Electromagnetic Calorimeter



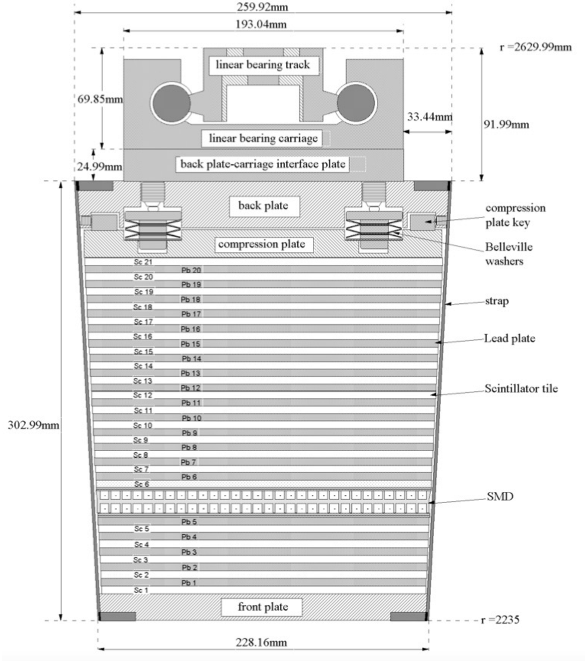
STAR, NIMA 499 (2003) 725

- Covers |η| < 1.0, $0 < \varphi < 2\pi$
- Front end about 220 cm away from the center radially
- 4800 towers, each covering $\Delta\eta\times\Delta\varphi \sim 0.05\times0.05$

Barrel Electromagnetic Calorimeter

- Pb-scintillator sampling calorimeter
  - 20 layers of Pb + 21 layers of scintillators interleaved
  - Pb: absorber; scintillator: active volume for energy measurement
- Provide energy measurement for PID and trigger
  - $\sigma(E)/E = 1.5\% + 15\%/\sqrt{E}$
- Shower Maximum Detector
  - Fine spatial resolution: 2.8mm+5.7mm/ $\sqrt{E}$
  - Critical for separating photon/π^0 based on shower shape

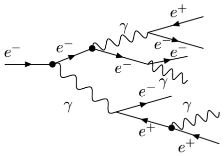
STAR, NIMA 499 (2003) 725

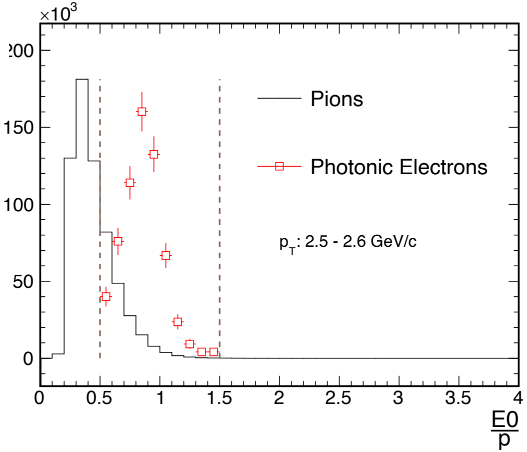


BEMC: PID & Trigger

- Both based on energy deposition of electrons in the BEMC

✓ PID: E/p
  - Electron: deposit full energy
  - Hadron: MIP



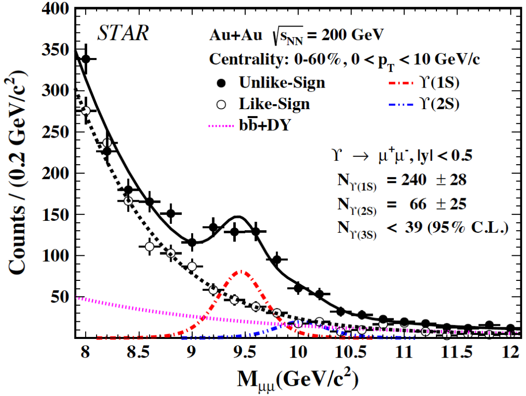


✓ Trigger
  - Could be based on a single tower (electron/photon) or a cluster of towers (jets)
  - Quarkonia: single tower above a trigger threshold
    - e.g. a threshold of 3.5 GeV is used for Upsilon measurements
  - One or both of quarkonium daughters should fire the trigger

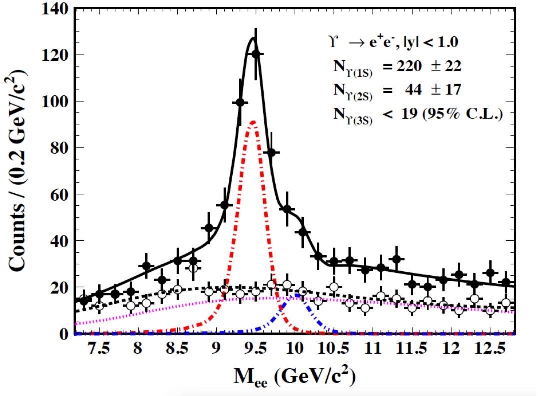
Comparison

Detector	PID	Kinematics	Acceptance	Bremsstrahlung
MTD (μ)	Timing & Position	J/ψ & ϒ down to zero p_T	|η|<0.5, φ~45%	Reduced
BEMC (e)	Energy & Position	J/ψ: high-p_T ϒ down to zero p_T	|η|<1, full φ	

$\Upsilon \rightarrow \mu^+\mu^-$



$\Upsilon \rightarrow e^+e^-$

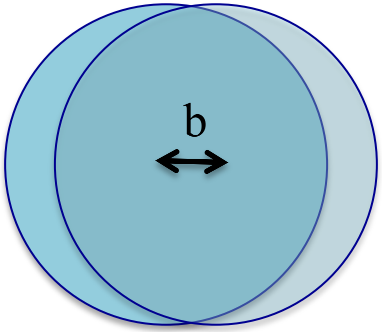


STAR, PRL 130 (2023) 112301

What is Centrality?

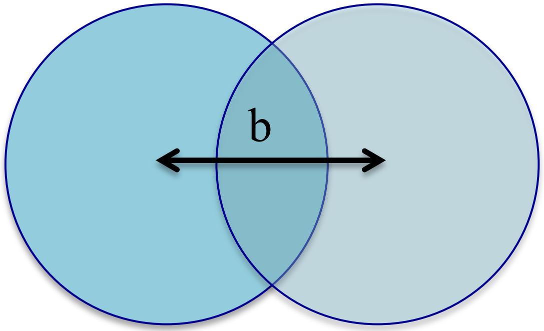
- Used to quantify the collision geometry/impact parameter

central



- Small impact parameter
- Large N_{coll}
- Larger/hotter medium

peripheral



- Large impact parameter
- Small N_{coll}
- Smaller/no medium

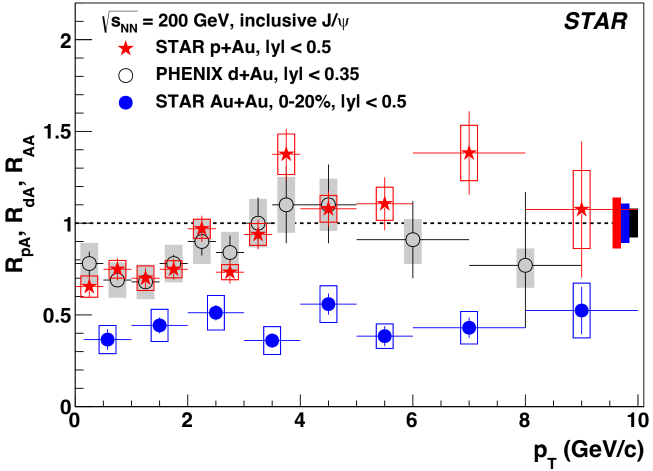
Nuclear Modification Factor (R_{AA})

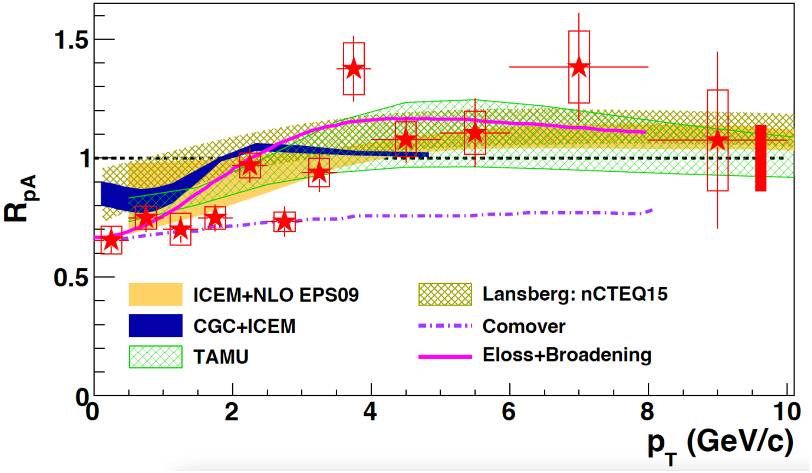
- Used to quantify modification to particle production by the QGP

$$R_{AA} = \frac{\sigma_{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA} / dy dp_T}{d^2 \sigma_{pp} / dy dp_T} \left\{ \begin{array}{l} R_{AA} < 1\text{: suppression} \\ R_{AA} = 1\text{: no (net) medium effects} \\ R_{AA} > 1\text{: enhancement} \end{array} \right.$$

Cold Nuclear Matter Effects

J/ψ R_{pAu} at 200 GeV

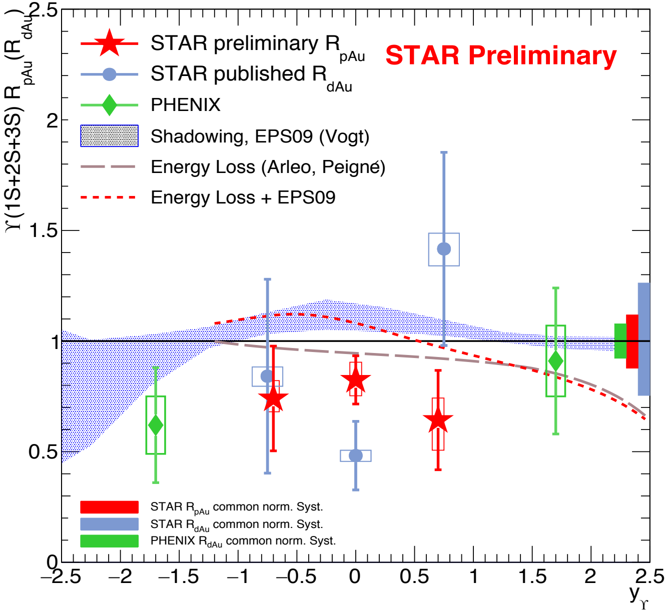




- Small CNM effects at high p_T
  - R_{pAu} ~ 0.7 at 1 GeV/c and rises to 1 at high p_T
- Data consistent with different model calculations, but disfavor co-mover breakup at high p_T

EPS09+NLO: Ma & Vogt, Private Comm.
nCTEQ, EPS09+NLO: Lansberg Shao, Eur.Phys.J. C77 (2017) no.1, 1
Comp. Phys. Comm. 198 (2016) 238-259
Comp. Phys. Comm. 184 (2013) 2562-2570
Ferreriro et al., Few Body Syst. 53 (2012) 27

Υ R_{pAu} at 200 GeV



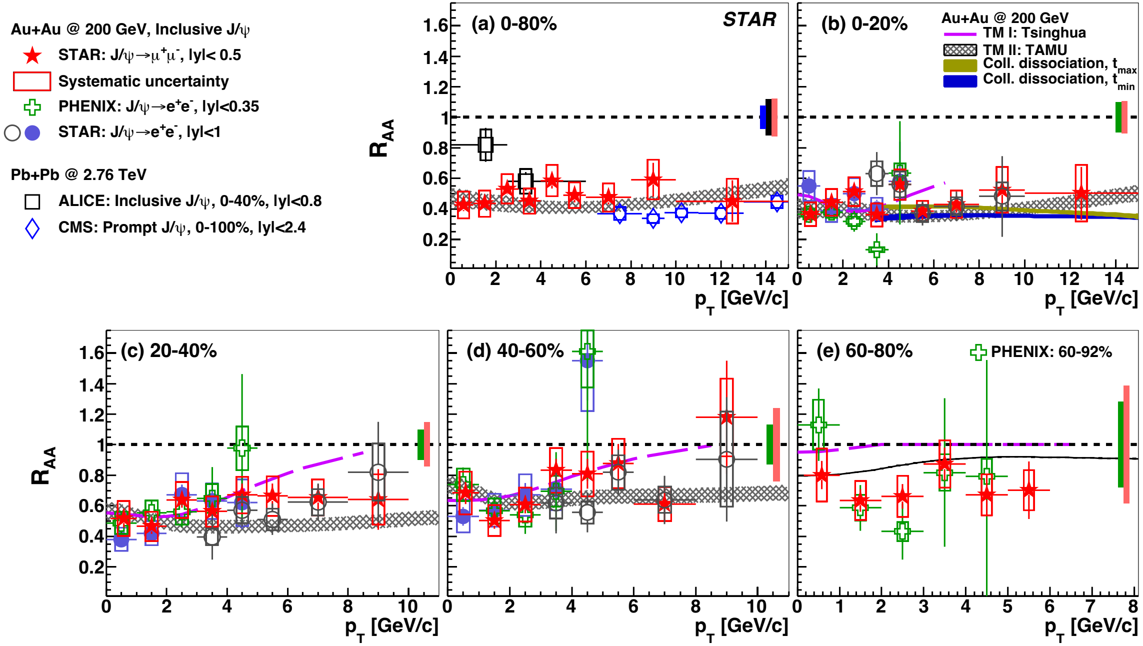
STAR: PLB 735 (2014) 127
PHENIX: PRC 87 (2013) 044909
R. Vogt, et. al, PoS ConfinementX 203 (2012)
F. Arleo, S. Peigne, JHEP 1303 (2013) 122
K. J. Eskola, et. al, JHEP 0904 (2009) 065

- Indication of Υ suppression in p+Au collisions
  - $R_{pAu} = 0.82 \pm 0.10(stat) + 0.08(syst) - 0.07(syst) \pm 0.10(global)$
  - A factor of two better precision than R_{dAu} measurement
- Additional suppression mechanism might be needed beyond nPDF effects

Hot Nuclear Matter Effects

Au+Au @ 200 GeV: J/ψ R_{AA} vs. p_T

STAR: PLB 797 (2019) 134917



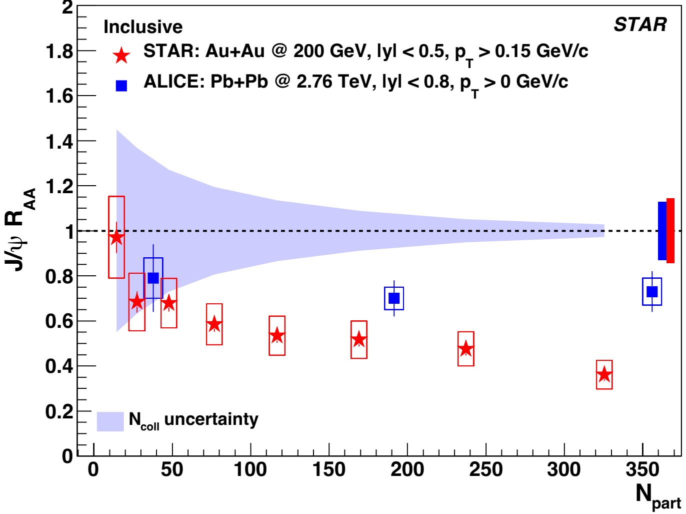
- J/ψ is suppressed up to 15 GeV/c
- No strong p_T dependence; interplay of different effects
  - Dissociation: decrease with p_T due to formation time effects
  - Regeneration: mostly at low p_T
  - CNM: more profound at low p_T
  - b-hadron feed-down
- Transport and energy loss models can qualitatively describe data

Central: R_{AA} ~ 0.4 for p_T > 5 GeV/c → **dissociation in effect**

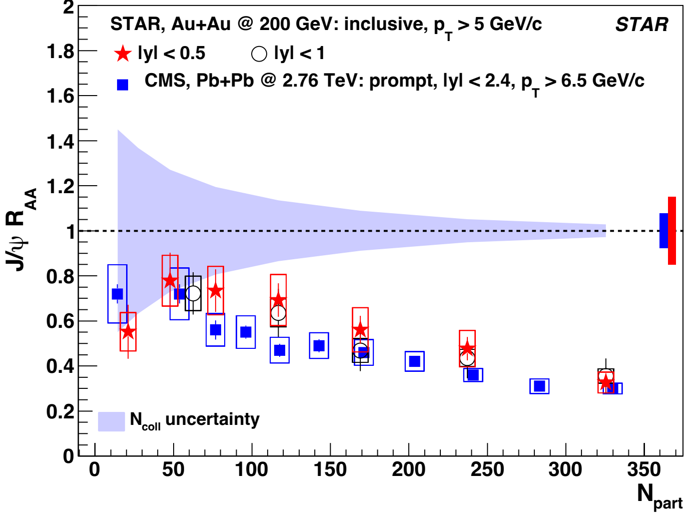
$J/\psi\ R_{AA}$: *RHIC vs. LHC*

STAR: PLB 797 (2019) 134917
ALICE: JHEP 07 (2015) 051
CMS: EPJC 77 (017) 052

$p_T > 0$ GeV/c



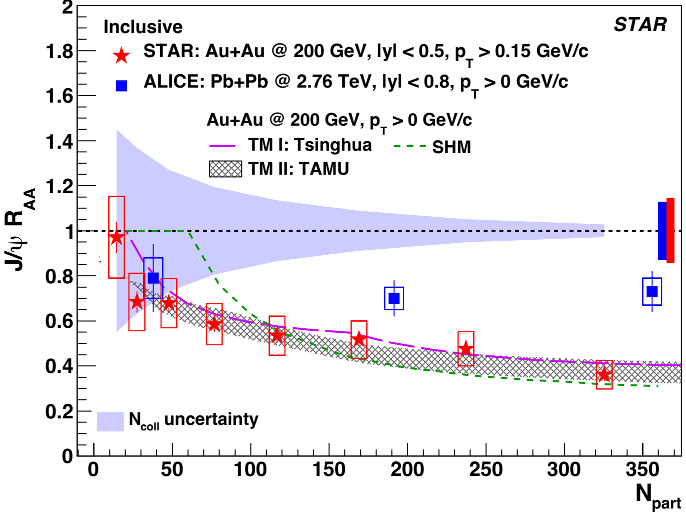
$p_T > 5$ GeV/c



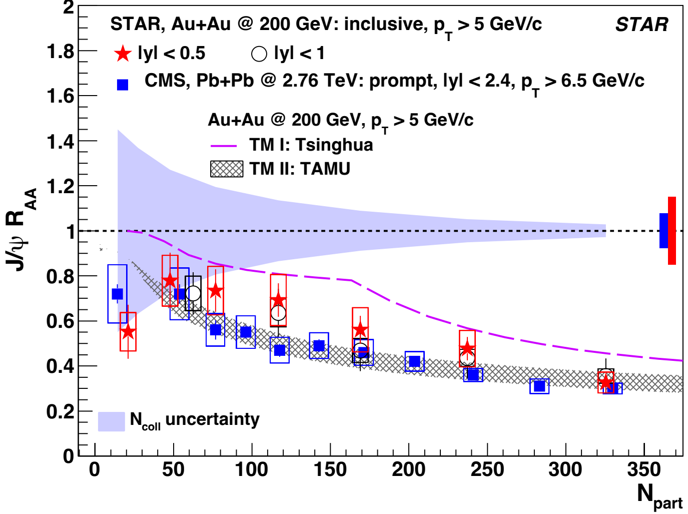
- $p_T > 0$ GeV/c: more suppressed at RHIC in central events → smaller regeneration contribution due to lower charm cross-section
- $p_T > 5$ GeV/c: less suppressed at RHIC in semi-central events → smaller dissociation rate due to lower temperature

J/ψ R_{AA}: Data vs. Transport Model

$p_T > 0$ GeV/c



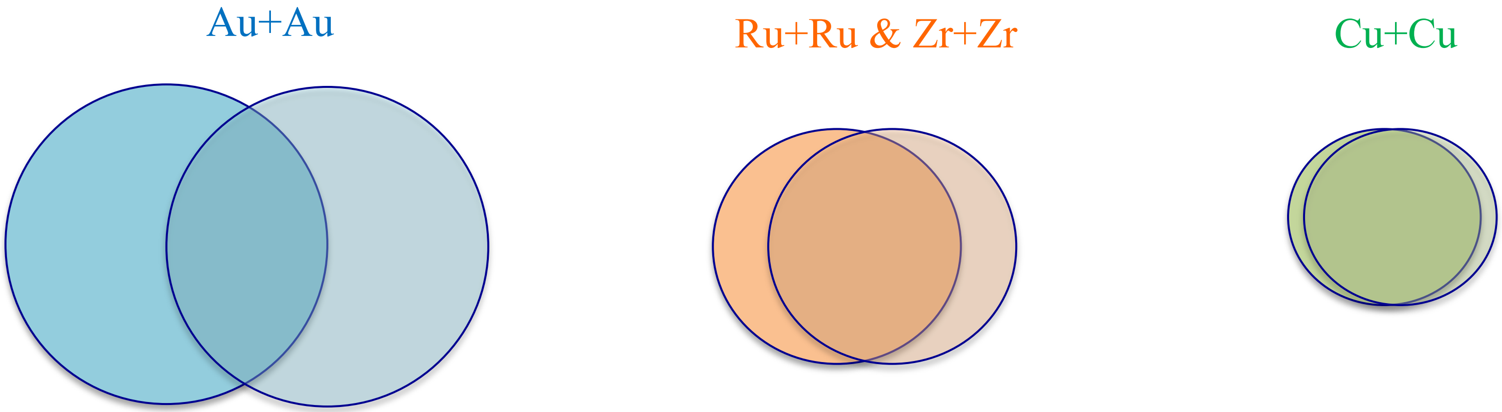
$p_T > 5$ GeV/c



- $p_T > 0$ GeV/c: describe centrality dependence quite well
  - SHM: no CNM
- $p_T > 5$ GeV/c: Tsinghua model overshoots data while TMAU model is below data in semi-central collisions

L. Yan, et al, PRL 97 (2006) 232301
K. Zhou, et al, PRC 89 (2014) 054911
X. Zhao, et al, PRCC 82 (2010) 064905

System Size Dependence

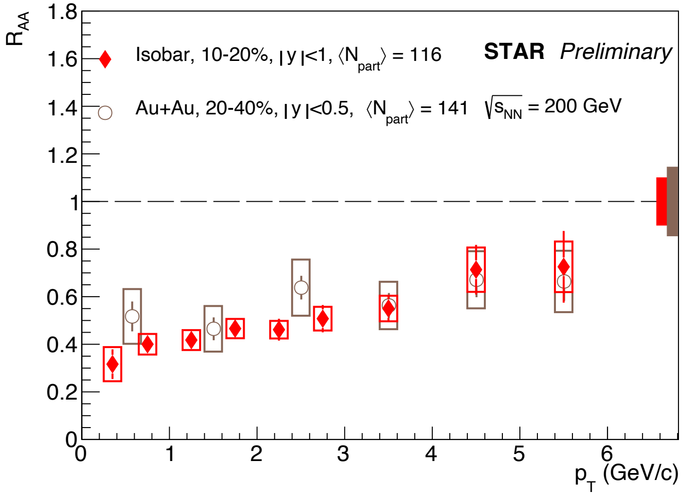


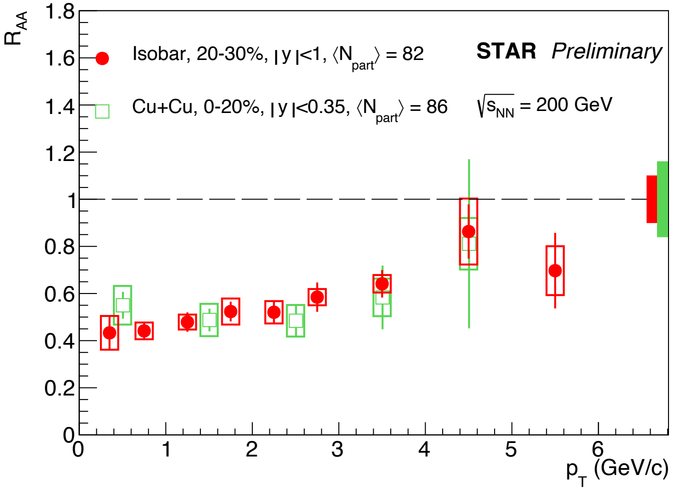
- What drives suppression, *centrality geometry vs. energy density*?

→ Compare J/ψ R_{AA} at similar $\langle N_{\mathrm{part}} \rangle$

J/ψ R_{AA}: Au+Au vs. Isobar vs. Cu+Cu

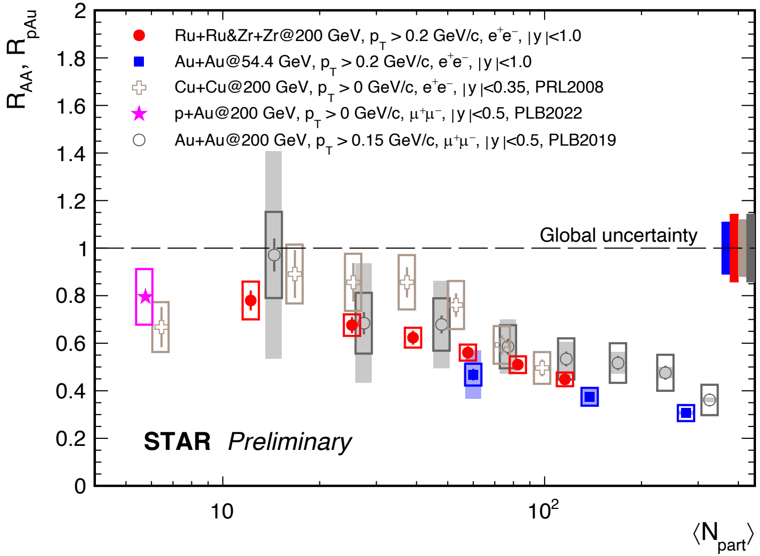
Au+Au: STAR, PLB 797 (2019) 134917
Cu+Cu: PHENIX, PRL 101 (2018) 122301





- Isobar collisions: $R_{AA} < 1$ and rises with p_T
- Consistent J/ψ R_{AA} between different collision species at similar $<N_{part}>$

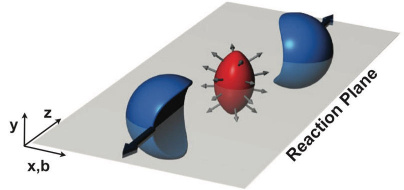
J/ψ R_{AA} vs. N_{part}



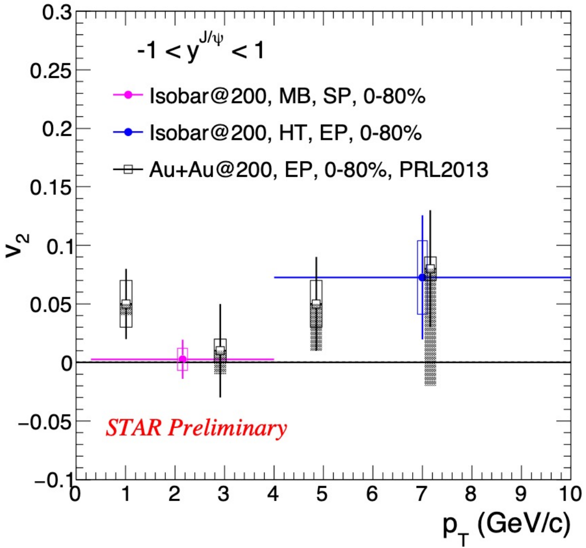
- There seems a universal scaling for J/ψ R_{AA} vs. N_{part} regardless of collision species and energy

Does J/ψ R_{AA} Flow?

- Measure elliptic flow v_2
  - Primordial: little or zero v_2
  - Regenerated: inherit v_2 from the constituent charm quarks



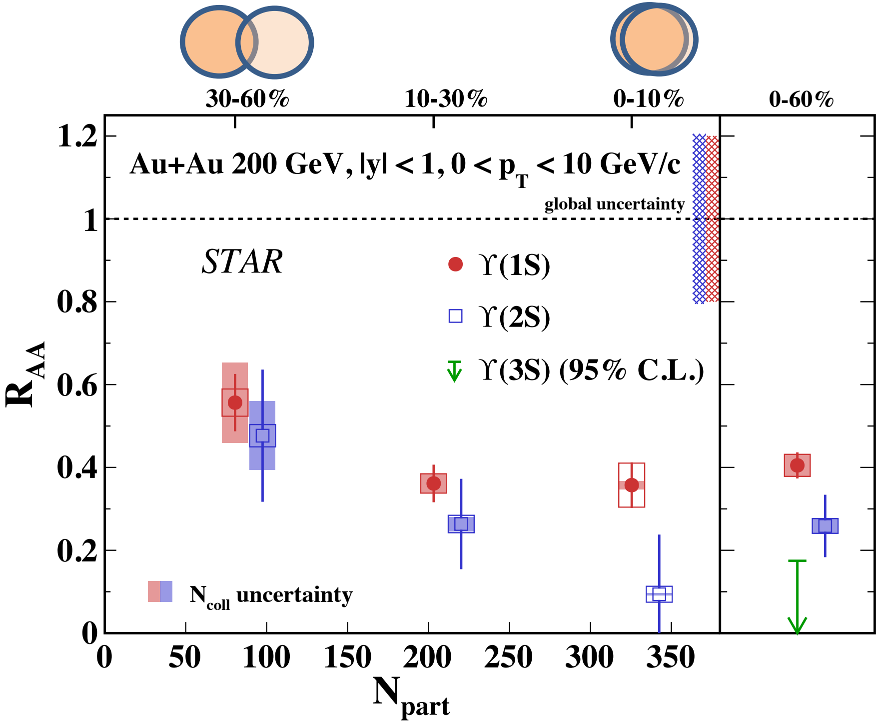
R. Snellings, New J. Phys. 13 (2011) 055008



Au+Au: STAR, PRL 111 (2013) 052301

- Measured J/*ψ* *v_2* consistent with 0
  - Need better precision for Au+Au measurements (more statistics & better control of non-flow)
  - Isobar: small regeneration and/or small charm quark flow

Au+Au @ 200 GeV: Υ R_{AA} vs. Centrality

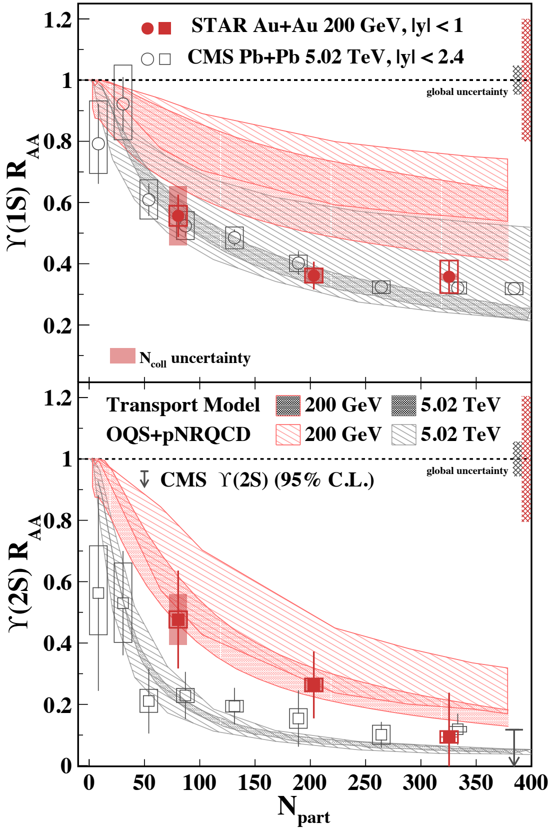


STAR, PRL 130 (2023) 112301

- All three Υ states are suppressed
- Hint of increasing suppression from peripheral to central collisions

✓ First measurement of three Υ suppression separately at RHIC
  - Upper limit for Υ(3S) in 0-60%
  - $> 3\sigma$ difference between Υ(1S) and Υ(3S)
  - Υ(2S) lies in between

Υ R_{AA}: RHIC vs. LHC



✓ Υ(1S): similar level of suppression at RHIC and LHC

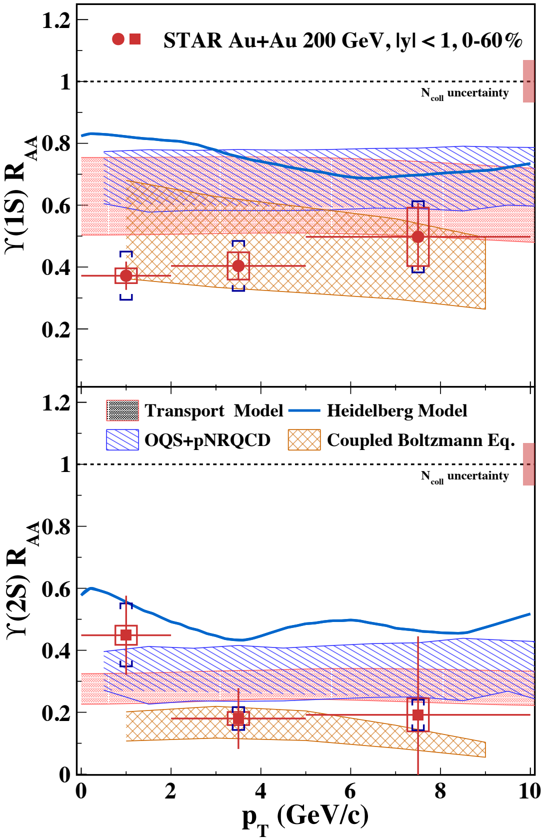
- Mostly due to strong suppression of excited states that feeddown to Υ(1S) and CNM effects
- Primordial Υ(1S) might not be significantly suppressed

✓ Υ(2S): indication of less suppression at RHIC in peripheral collisions

✓ Model calculations:

- Υ(1S): larger separation between RHIC and LHC
- Υ(2S): consistent with data

Au+Au @ 200 GeV: Υ R_{AA} vs. p_T



- ✓ No significant p_T dependence
  - Similar to the *J/ψ* case
  - Possible explanation: CNM + correlated regeneration

- Model comparison
  - Heidelberg model overshoots data due to lack of CNM effects and/or QGP temperature too low

Summary

pA collisions

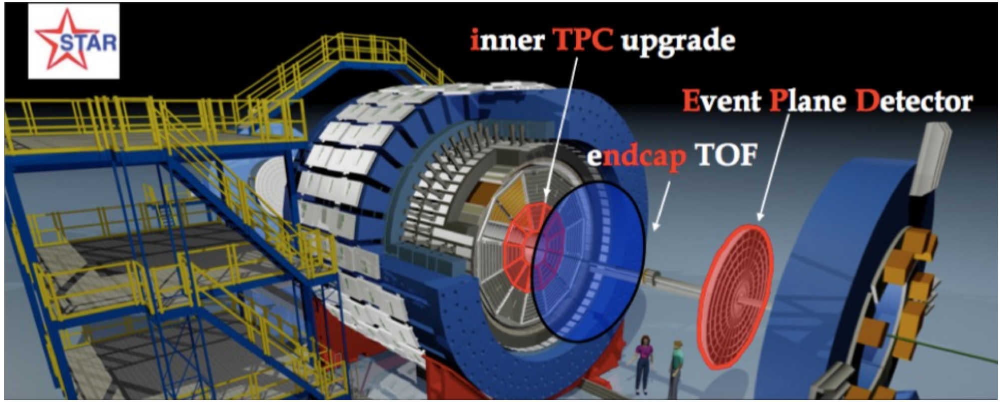
- Sizable suppression for low p_T J/ψ & Υ
  - Need to be taken into account when interpreting measurement in AA collisions

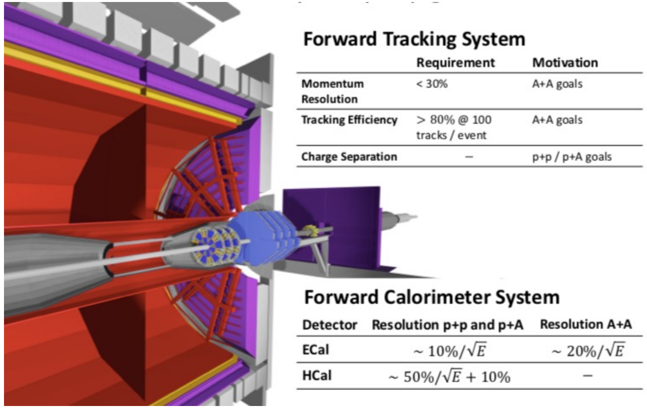
AA collisions

- High-p_T J/ψ strongly suppressed in central collisions → **dissociation**
  - Seems a universal scaling for J/ψ R_{AA} vs. N_{part} regardless of collision species and energy
- Ground and excited Υ exhibit different suppression → **sequential suppression**
- Complementary RHIC & LHC measurements place stringent constraints on model calculations → ***Medium temperature, in-medium QCD force, etc***
  - Pin down other knobs: CNM, feed-down, energy loss, recombination …

Outlook (2023-25)

- **STAR detector configuration**
  - 2017+: Heavy Flavor Tracker removed → low material budget for electrons
  - 2018+: Event Plane Detector at forward-y → improve EP resolution; reduce non-flow
  - 2019+: iTPC upgrade → improved resolution; increased efficiency; extended acceptance
  - 2022+: forward tracking + calorimetry → event activity





Forward Tracking System

	Requirement	Motivation
Momentum Resolution	< 30%	A+A goals
Tracking Efficiency	> 80% @ 100 tracks / event	A+A goals
Charge Separation	–	p+p / p+A goals

Forward Calorimeter System

Detector	Resolution p+p and p+A	Resolution A+A
ECal	$\sim 10\%/\sqrt{E}$	$\sim 20\%/\sqrt{E}$
HCal	$\sim 50\%/\sqrt{E} + 10\%$	–

Outlook (2023-25)

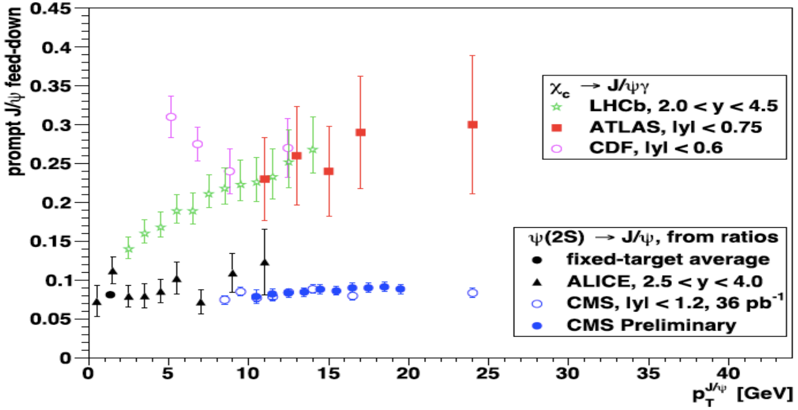
- **Complementarity between electron and muon channels**
- Greatly enhanced statistics → **improve precision**

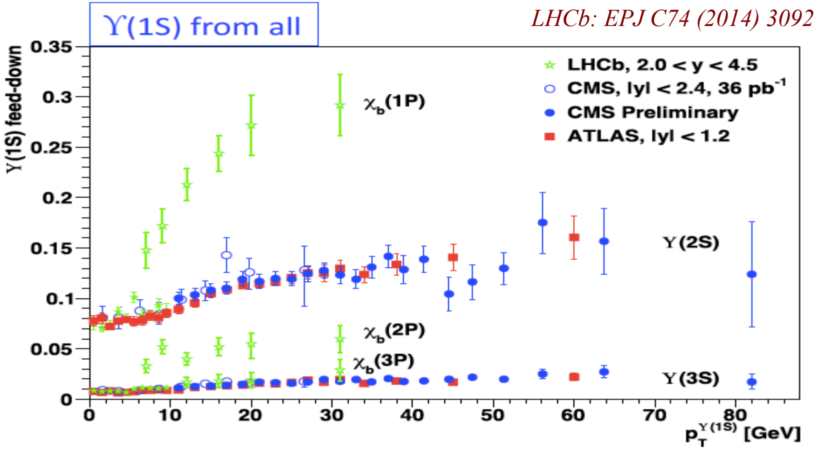
Year	System	Measurements
2024	p+Au @ 200 GeV	✓ J/ψ & Υ CNM …
2023+2025	Au+Au @ 200 GeV	✓ J/ψ v_2, especially at low p_T ✓ J/ψ v_1 ✓ J/ψ spin alignment ✓ Υ suppression …

Backup

And the Feed-down Contribution

Woehri@Quarkonia'14





LHCb: EPJ C74 (2014) 3092

J/ψ feed-down	
χ_c	10-30% (vs. p_T)
ψ(2S)	~ 8%
B-hadron	0-50% (vs. p_T, √s)

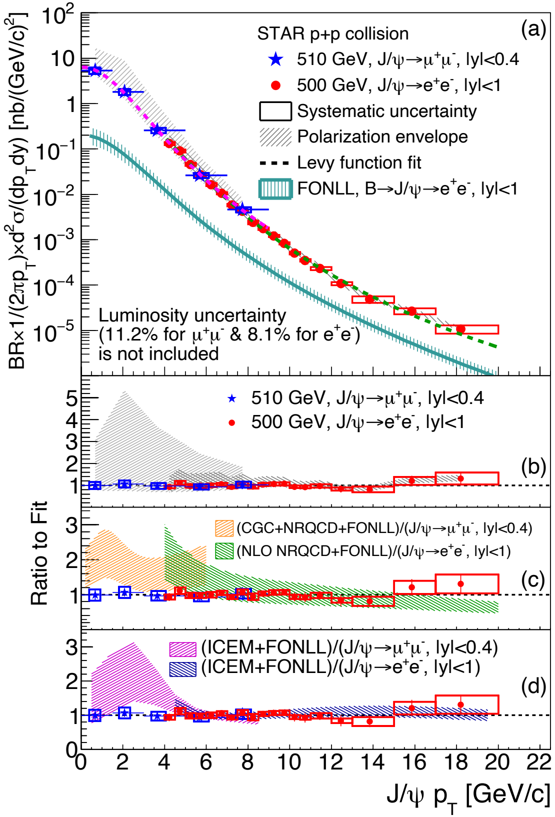
Υ(1S) feed-down	
$\chi_b(1P)$	10-30% (vs. p_T)
$\chi_b(2P+3P)$	~5%+1-2%
Υ(2S+3S)	8-13%+1-2%

Quarkonium Production in p+p

- Production mechanism still not fully understood
  - Process: perturbative (QQ) + *non-perturbative* (hadronization)
- Models on the market
  - **(Improved) Color Evaporation Model**: a fixed fraction of ccbar evolve into a given charmonium state
  - **Color Singlet Model**: same quantum state for ccbar and charmonium
  - **Non-Relativistic QCD**: relative contributions of different color-singlet and color-octet pairs encoded in LDMEs
    - Large discrepancies in LDMEs among different groups
  - **CGC+NRQCD** at low p_T
- More differential measurements of better precision are crucial
  - Cross-section; event activity; production in jets; polarization …

p+p @ 510 GeV: Inclusive J/ψ Cross Section

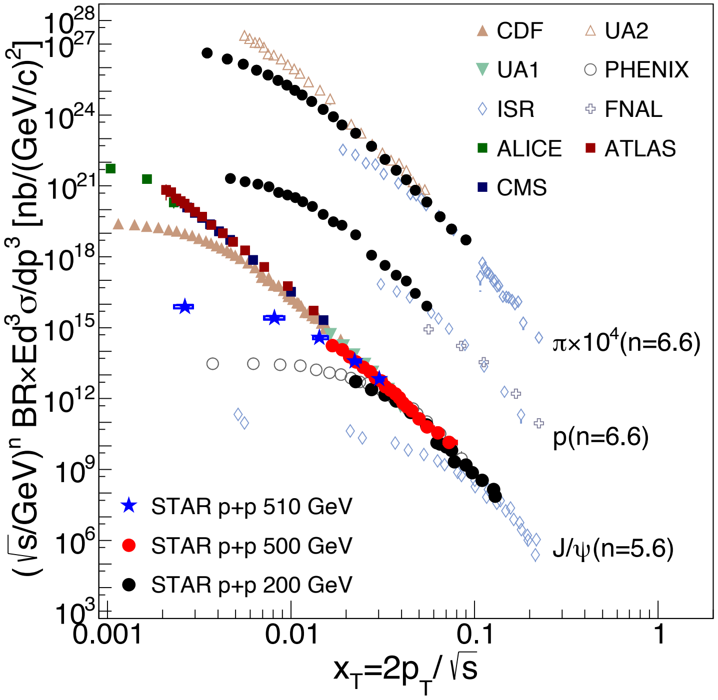
STAR: PRD 100 (2019) 52009



- **Inclusive *J/ψ* cross section spanning from 0 – 20 GeV/c**
  - Low p_T: muon channel
  - High p_T: electron channel
- Sizable polarization envelope for the muon channel with relatively small acceptance
- Comparison to theory
  - b-hadron feed-down calculated by FONLL
  - Low p_T: CGC+NRQCD and ICEM above data; consistent within polarization envelope
  - High p_T: NLO NRQCD and ICEM are consistent with data within uncertainties

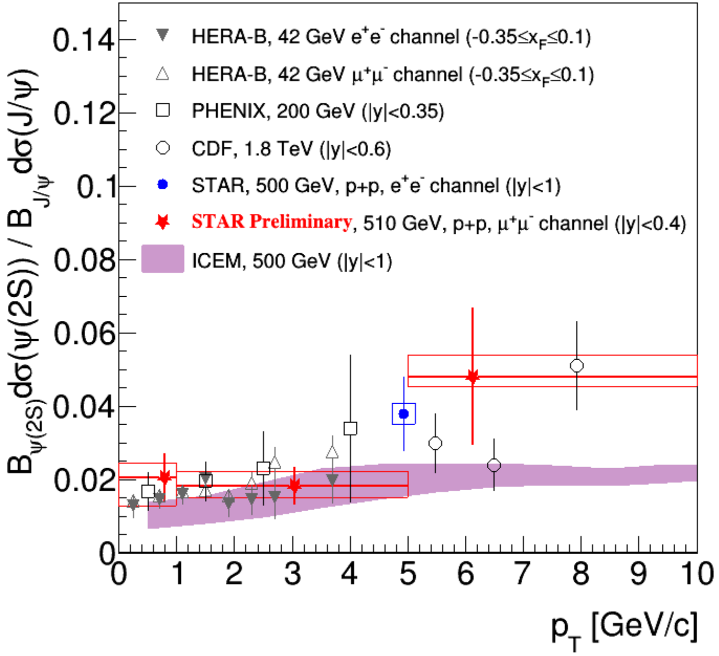
p+p @ 510 GeV: x_T scaling

STAR: PRD 100 (2019) 52009



- High p_T *J/ψ* follows x_T scaling with n = 5.6 ± 0.1
  - Close to the CO and CEM predictions of n ~ 6
  - Smaller than NNLO* CSM prediction of n ~ 8
- Scaling breaks up at low p_T

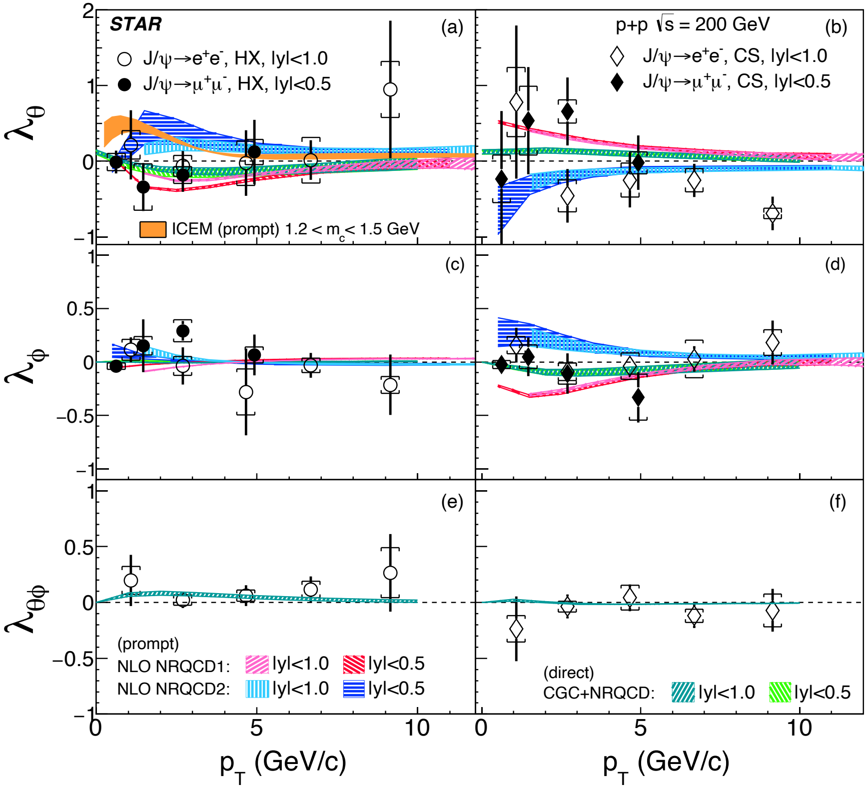
p+p @ 510 GeV: ψ(2S) to J/ψ Ratio



- Indication of rising trend for inclusive ψ(2S) to *J/ψ* ratio as a function of p_T
- Consistent with world-wide data and ICEM calculation
- Constrain feed-down contribution to *J/ψ*

p+p @ 200 GeV: J/ψ Polarization

STAR, PRD 102 (2020) 092009



- Inclusive *J/ψ* polarization parameters as a function of p_T
  - Helicity and CS frames
- *J/ψ* polarization consistent with 0 within uncertainties
  - CS, $p_T \sim 9$ GeV/c: 3σ deviation
- Comparison to theory calculation of prompt or direct *J/ψ*

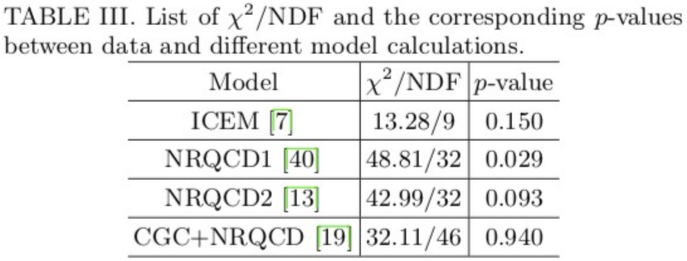
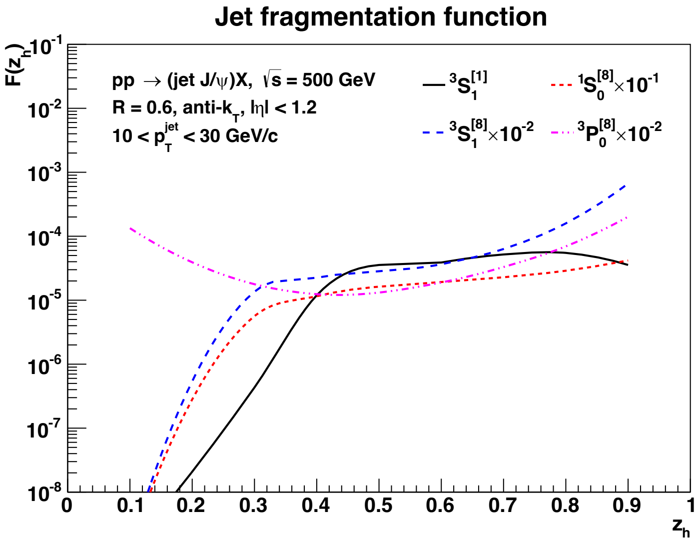


TABLE III. List of χ^2/NDF and the corresponding *p*-values between data and different model calculations.

Model	χ^2/NDF	*p*-value
ICEM [7]	13.28/9	0.150
NRQCD1 [40]	48.81/32	0.029
NRQCD2 [13]	42.99/32	0.093
CGC+NRQCD [19]	32.11/46	0.940

p+p @ 500 GeV: J/ψ in Jets

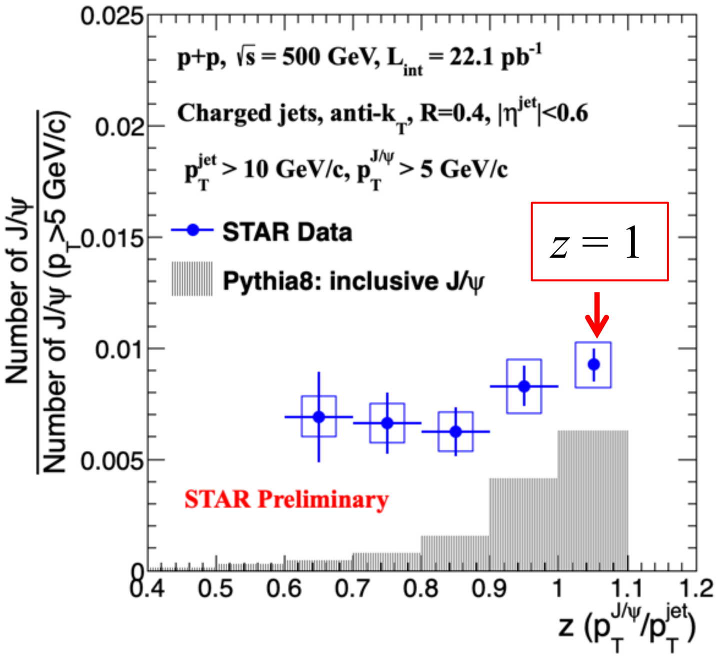
Z. Kang, et al, PRL 119 (2017) 032001
private communication



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

- Jet fragmentation patterns to *J/ψ* are different for different channels

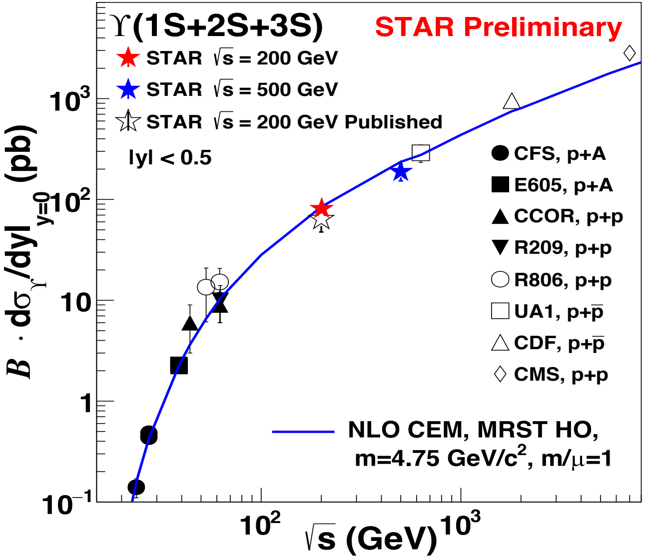
p+p @ 500 GeV: J/ψ in Jets

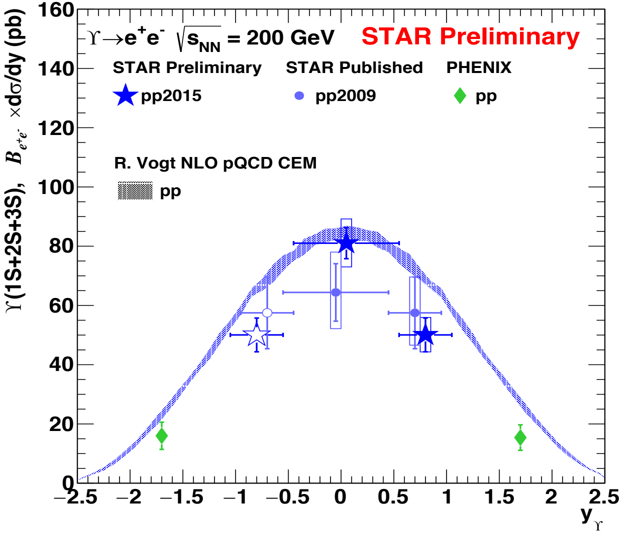


$$z = p_T^{J/\psi} \; / \; p_T^{jet}$$

- Jet fragmentation patterns to *J/ψ* are different for different channels
- First measurement of *J/ψ* in charged jets at RHIC
- No significant *z* dependence for *z* < 1
- Compared to Pythia, *J/ψ* in data is more likely to be produced in jets, and carries a smaller fraction of jet energy

p+p @ 200 GeV: ϒ cross-section





R. Vogt Phys. Rept. 462 (2008) 125

- ϒ cross section
  - follows world-wide data trend and calculation from NLO CEM
  - exhibits narrower rapidity distribution than NLO CEM
- Improved reference for p+Au and Au+Au measurements

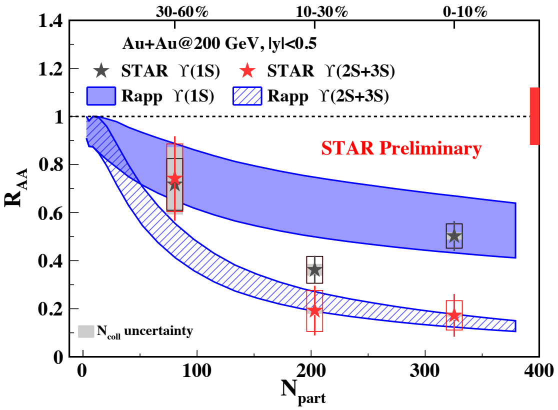
ϒ Suppression: Data vs. TAMU model

- T-dependent binding energy; Kinetic rate equation; Include CNM and regeneration

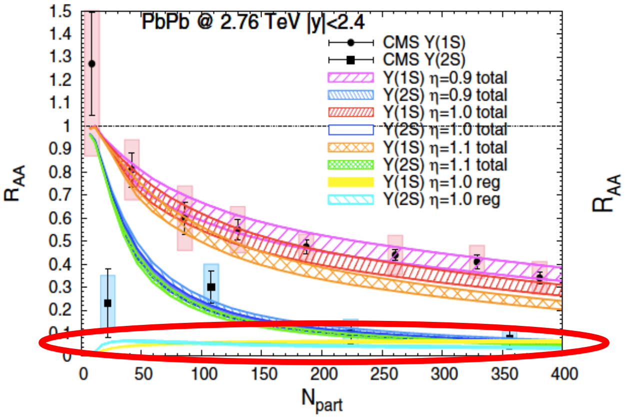
	ϒ(1S)	**ϒ(2S)**	**ϒ(3S)**
T_{disso}(MeV)	500	240	190

√s (TeV)	**0.2**	**2.76**	**5.02**
T_0^{QGP}(MeV)	310	555	594

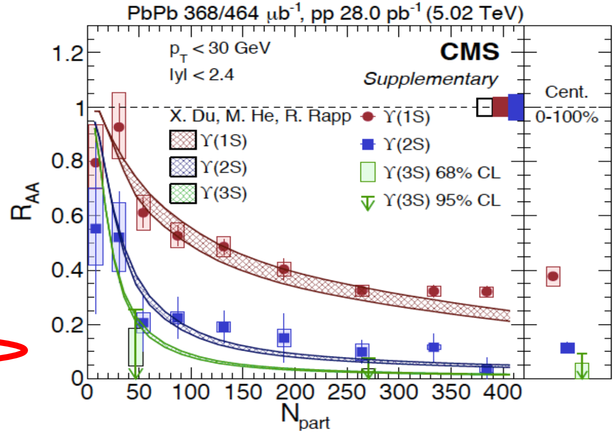
0.2 TeV



2.76 TeV



5.02 TeV



- Good description of ϒ suppression from RHIC to LHC energies.
- Non-negligible regeneration, especially for ϒ(2S)

X. Du, M. He, R. Rapp PRC 96 (2017) 054901

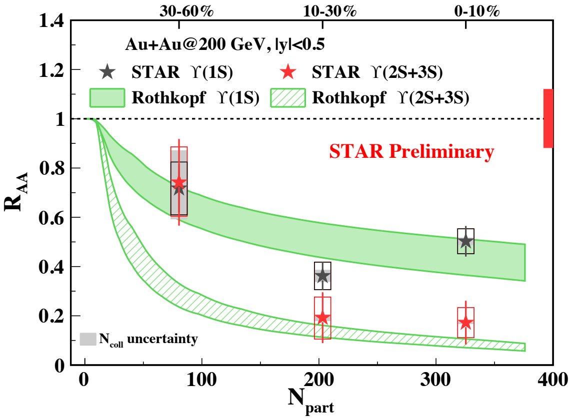
Υ Suppression: Data vs. lattice-potential model

- Complex potential (lQCD); aHydro medium; No regeneration or CNM

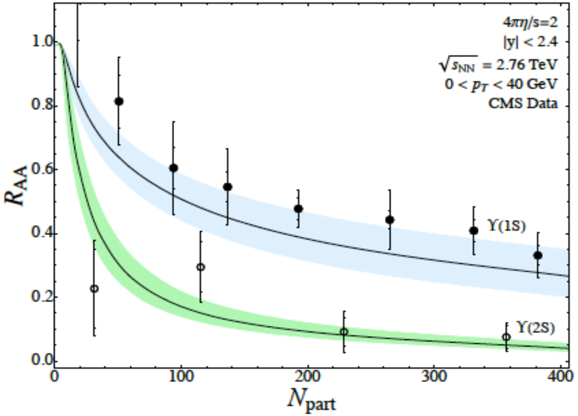
	Υ(1S)	**Υ(2S)**	**Υ(3S)**
T_{disso}(MeV)	600	230	170

√s (TeV)	**0.2**	**2.76**	**5.02**
T_0^{QGP}(MeV)	440	546	632

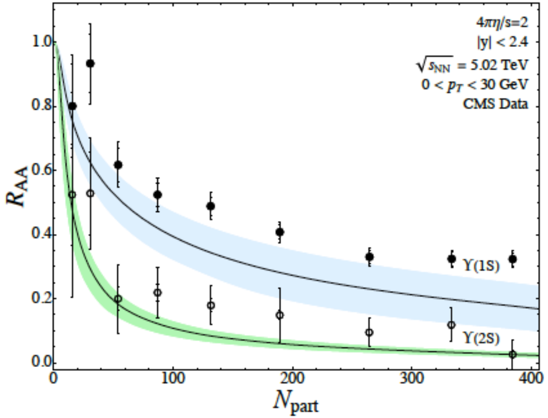
0.2 TeV



2.76 TeV



5.02 TeV



B. Krouppa, et al, PRD 97 (2018) 016017

- Consistent with 200 GeV and 2.76 TeV data
- Lay below the 5.02 TeV data

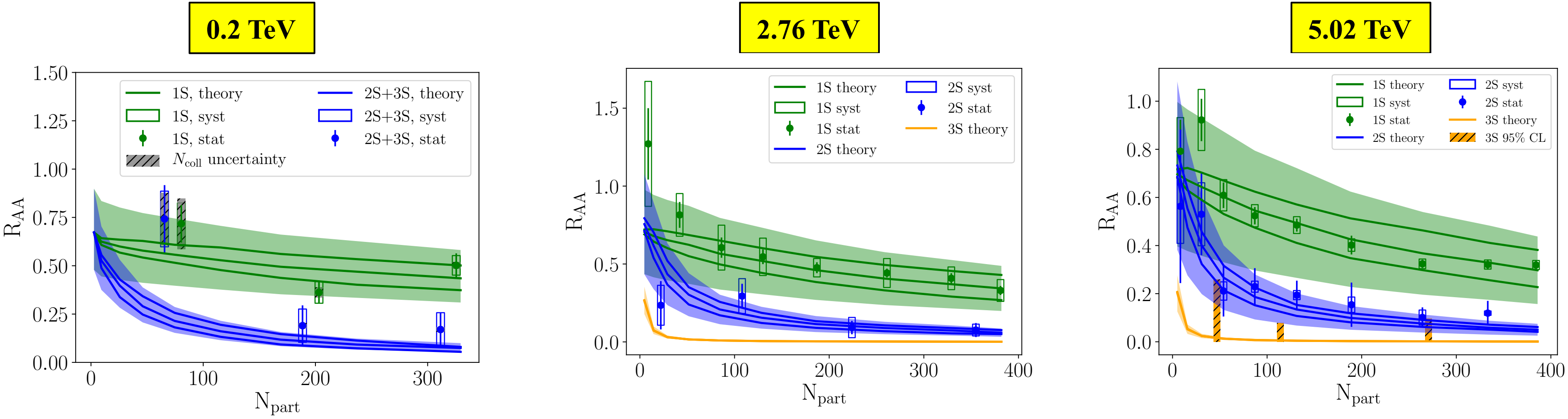
Υ Suppression: Data vs. Coupled HF Transport

- Coupled Transport Equation; Correlated recombination; CNM

X. Yao, et al, arXiv: 2004.06746

	ϒ(1S)	**ϒ(2S)**	**ϒ(3S)**
T_{disso}(MeV)	450*	225*	154

√s (TeV)	**0.2**	**2.76**	**5.02**
T_0^{QGP}(MeV)	376	484	511


0.2 TeV

2.76 TeV

5.02 TeV

- Describe RHIC and LHC data reasonably well
- Significant theoretical uncertainties

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

ϒ Suppression: Data vs. KSU model

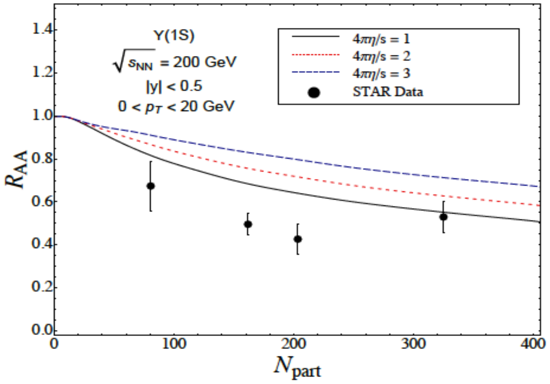
B. Krouppa, R. Ryblewski, M. Strickland
NPA 967 (2017) 604

- Complex potential (Perturbative); aHydro medium; No regeneration or CNM

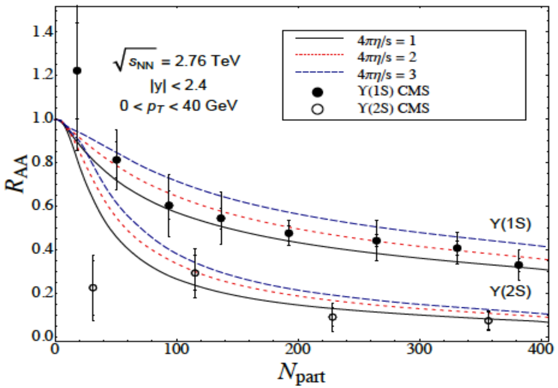
	ϒ(1S)	**ϒ(2S)**	**ϒ(3S)**
T_{disso}(MeV)	600	230	170

√s (TeV)	**0.2**	**2.76**	**5.02**
T_0^{QGP}(MeV)	440	546	632

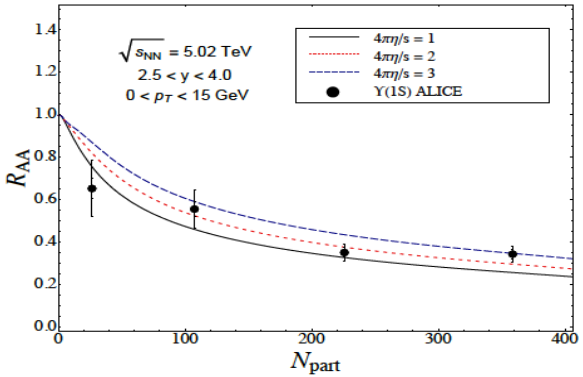
0.2 TeV



2.76 TeV



5.02 TeV



CMS: PLB 790 (2019) 270
CMS: PLB 770 (2017) 357

- Captures the LHC measurements quite well but over-predicts ϒ(1S) R_{AA} at RHIC.