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BROOKHAVEN NATIONAL LABORATORY

Probe the Quark Gluon Plasma with Quarkonia at the STAR Experiment

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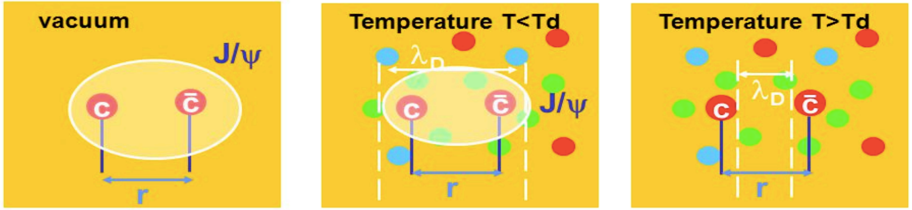
中国高能核物理网络论坛
HIGH ENERGY NUCLEAR PHYSICS IN CHINA

Why Quarkonia?

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

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

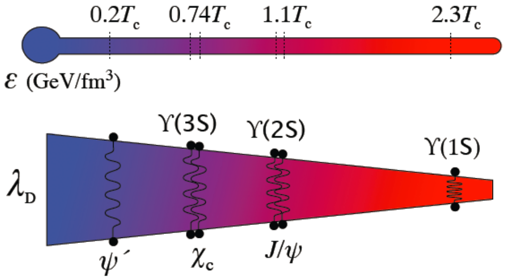
T. Matsui and H. Satz
PLB 178 (1986) 416



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

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

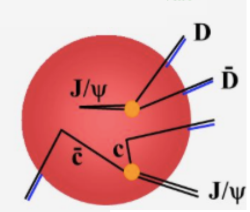
	J/ψ	ψ(2S)	ϒ(1S)	ϒ(2S)	ϒ(3S)
E_b (MeV)	~ 640	~ 60	~ 1100	~ 500	~ 200



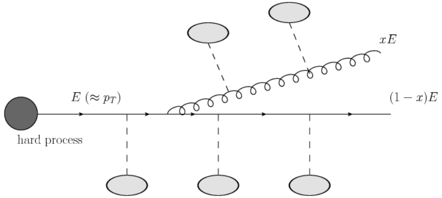
The Complications

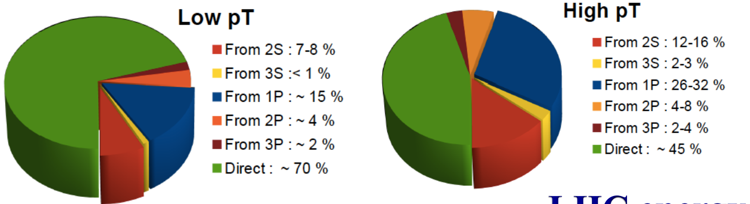
Other effects

- Dynamic dissociation
- **(Re)generation**
  - *Deconfinement is a prerequisite*
  - Depend on species, energy, p_T, etc
- Medium-induced energy loss
  - Color-octet states; parton fragmentation
- Formation time
  - High p_T hadrons fly out of medium faster
- **Feed-down contributions**
  - Depend on species, √s, p_T, etc



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





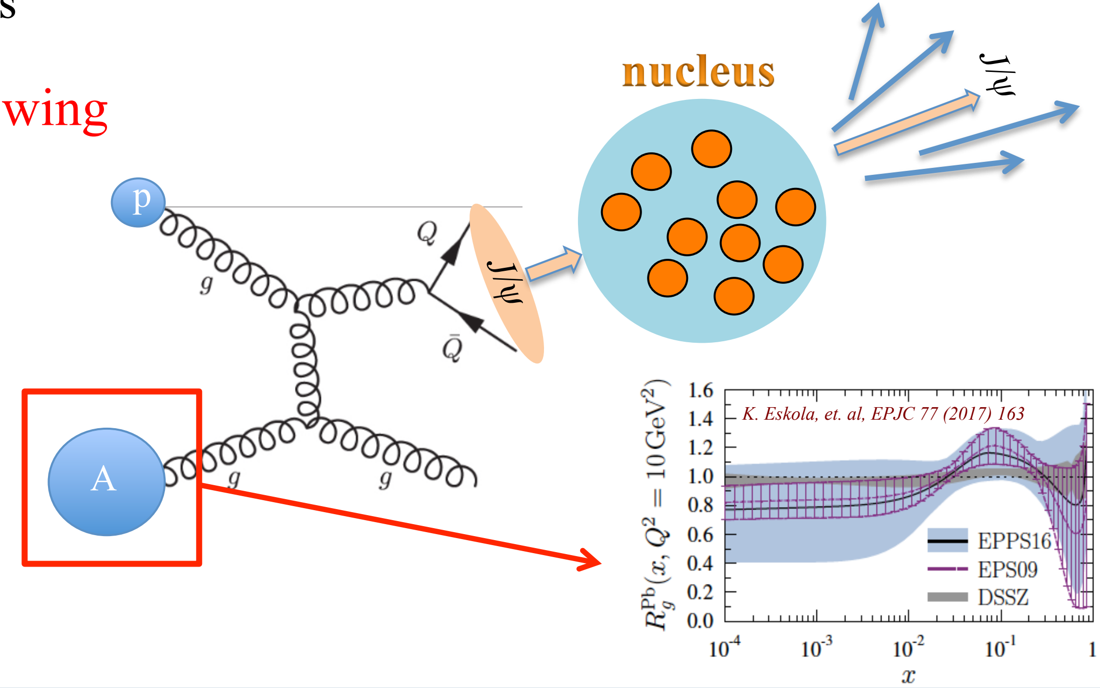
A. Andronic, EPJC 76 (2016) 107

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



K. Eskola, et. al, EPJC 77 (2017) 163

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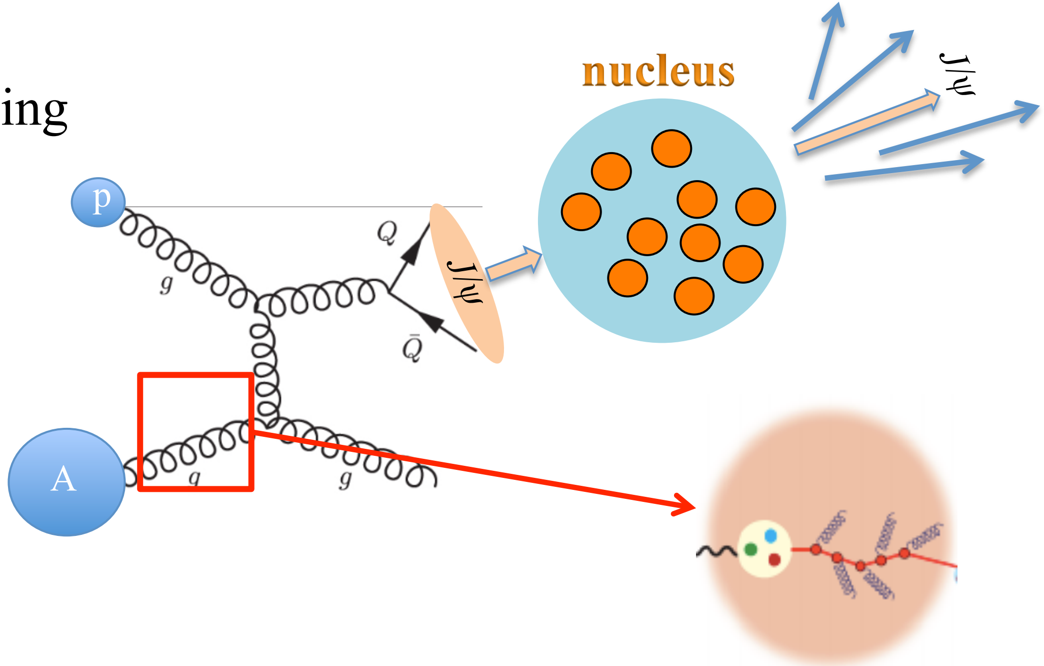

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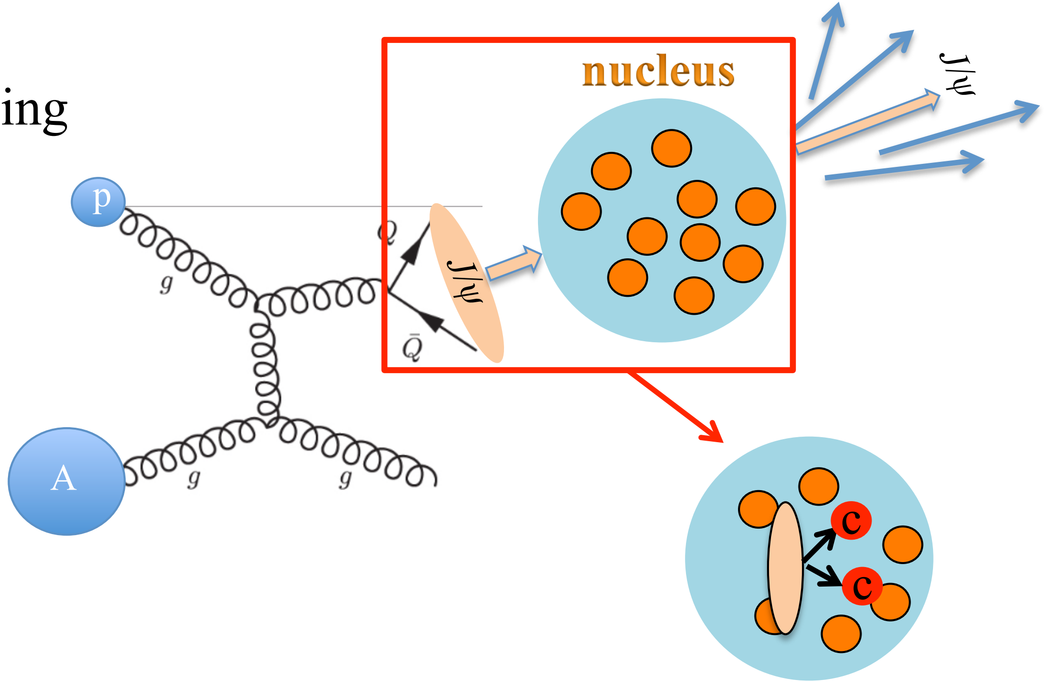

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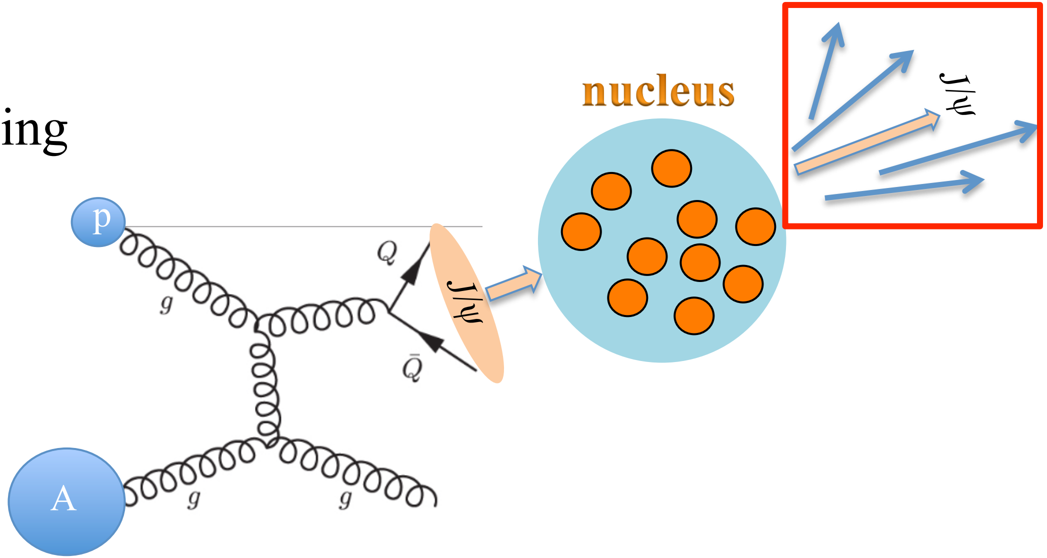
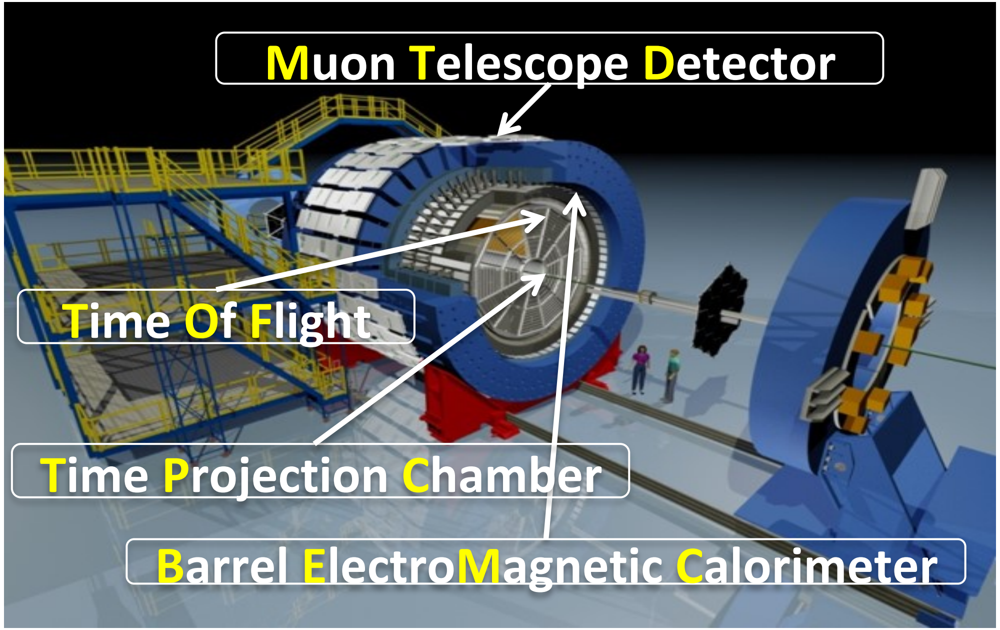


Quarkonium Production in p+p

- 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 …

The Solenoid Tracker At RHIC

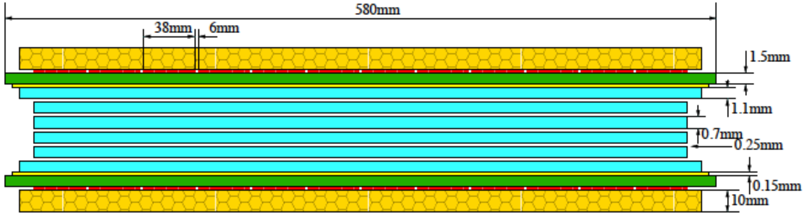
- Mid-rapidity detector: $|\eta| < 1$, $0 < \varphi < 2\pi$



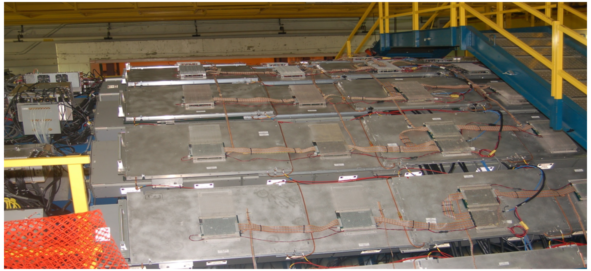
- **TPC**: measure momentum and energy loss
- **TOF**: measure particles' flight time to extend PID to higher p_T
- **BEMC**: trigger on and identify high-p_T electrons
- **MTD**: trigger on and identify muons
  - $p_T >\sim 1.2$ GeV/c

Muon Telescope Detector

- **MRPC** with double readout
  - Resolution: timing (~100 ps) and position (~1-2 cm)
- Trigger based on timing



- Located outside of the STAR magnet, acting as an absorber to other hadrons
- 122 trays; 1439 readout strips



Detector	PID	Kinematics	Acceptance	Bremsstrahlung
MTD (μ)	Timing & Position	Low-high p_T	$\lvert\eta\rvert<0.5$, φ~45%	Reduced
BEMC (e)	Energy	High-p_T	$\lvert\eta\rvert<1$, full φ	

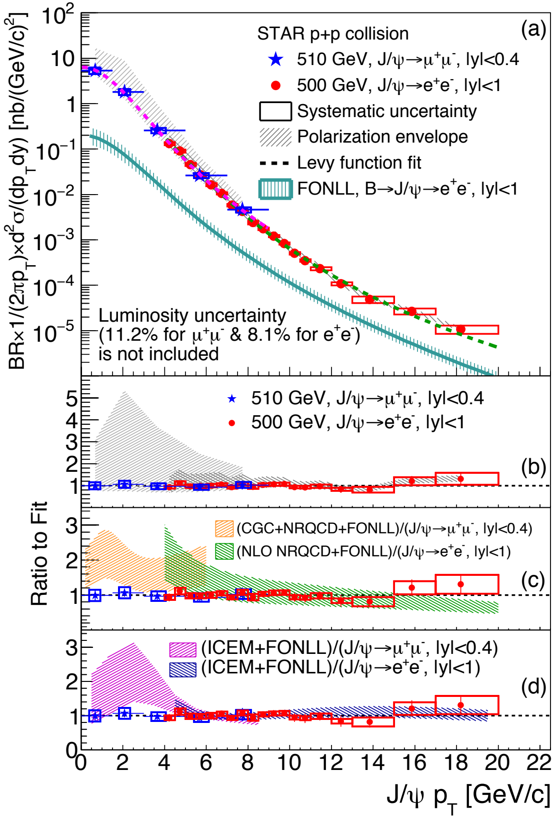
pp Collisions

pA Collisions

AA Collisions

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

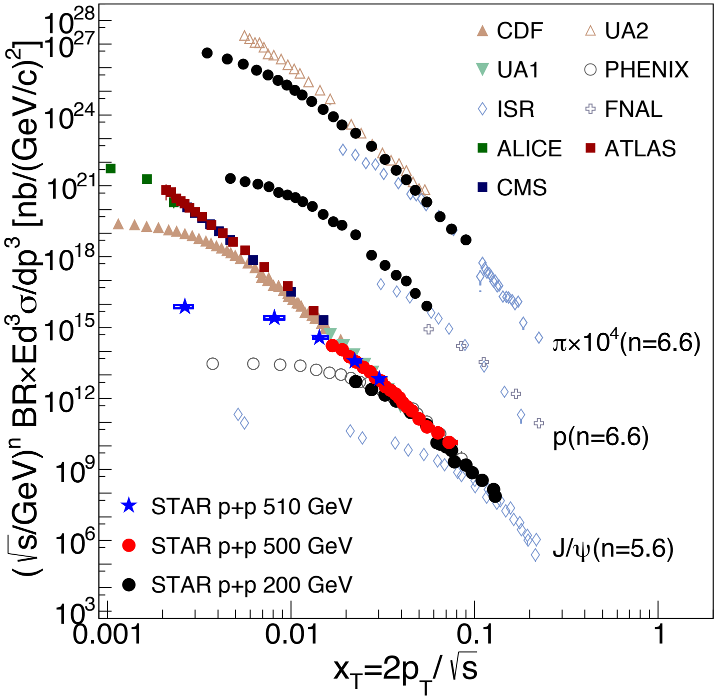
STAR: PRD 100 (2019) 52009



- **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

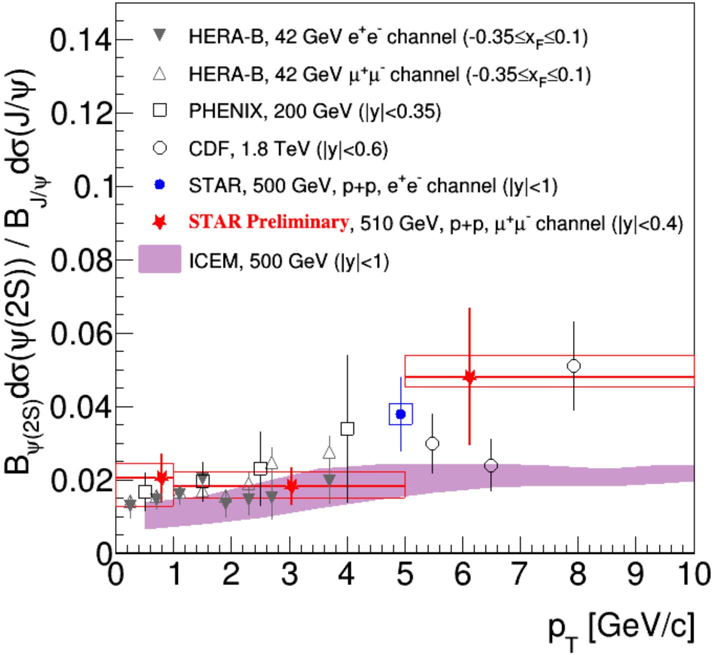
p+p @ 510 GeV: x_T scaling

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

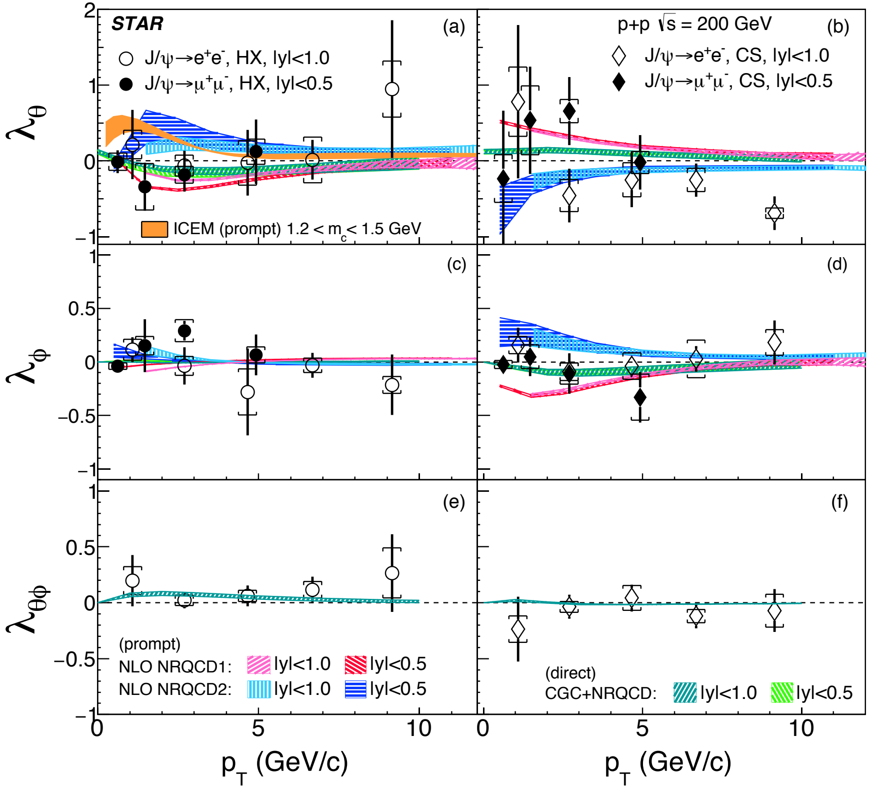
p+p @ 510 GeV: ψ(2S) to J/ψ Ratio



- 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: arXiv: 2007.04732



- 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*

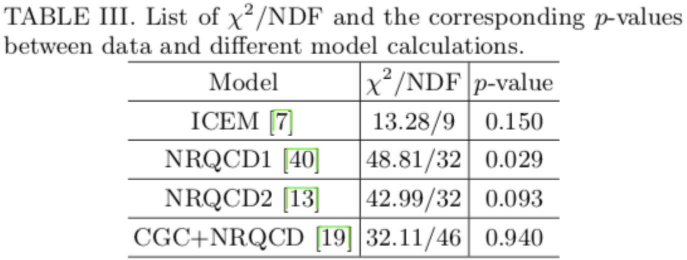
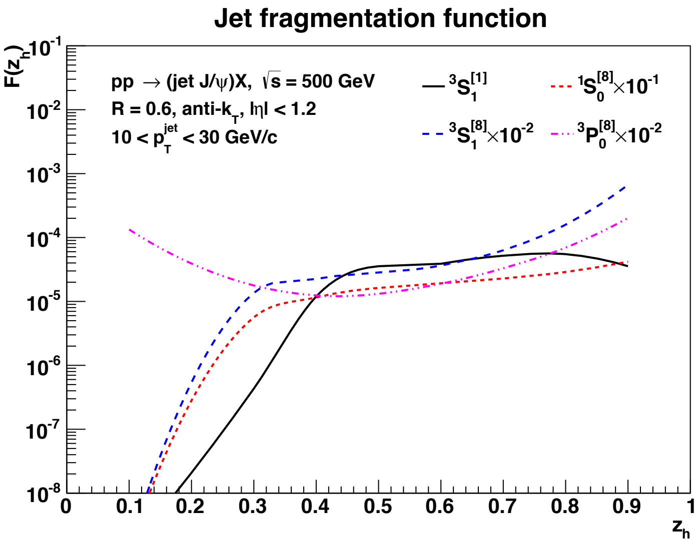


TABLE III. List of χ^2/NDF and the corresponding *p*-values between data and different model calculations.

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

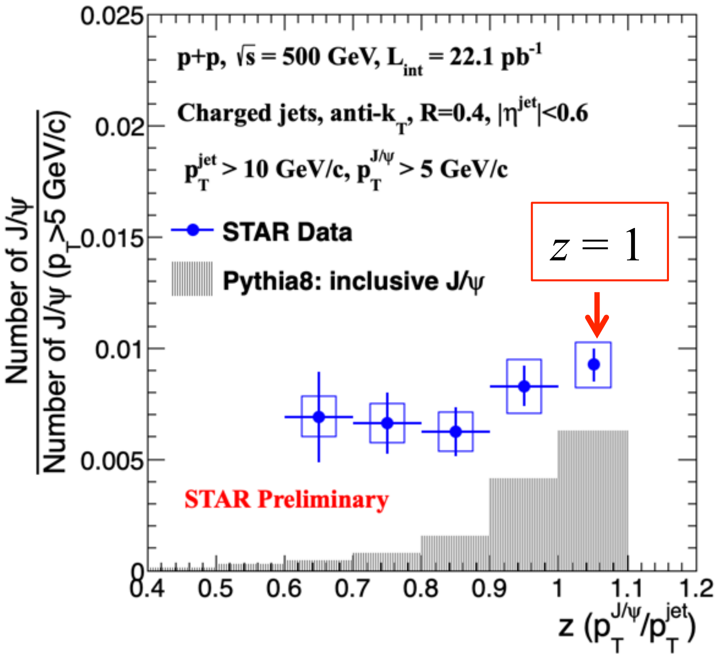
Z. Kang, et al, PRL 119 (2017) 032001
private communication



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

- 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

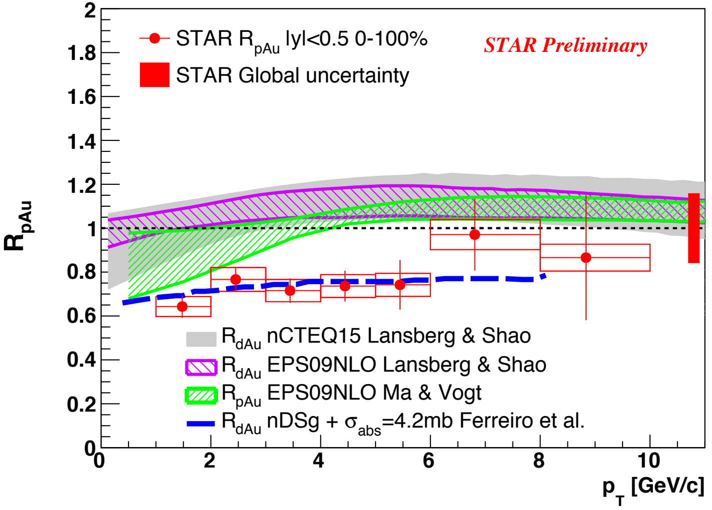
pp Collisions

pA Collisions

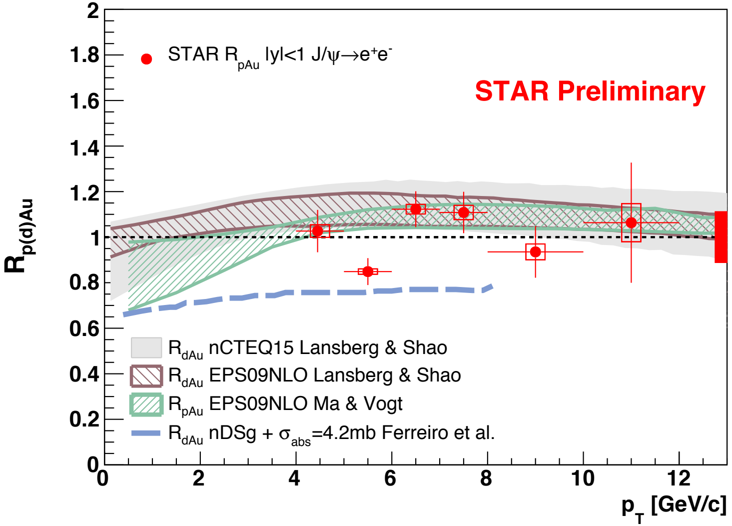
AA Collisions

J/ψ R_{pAu} at 200 GeV

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



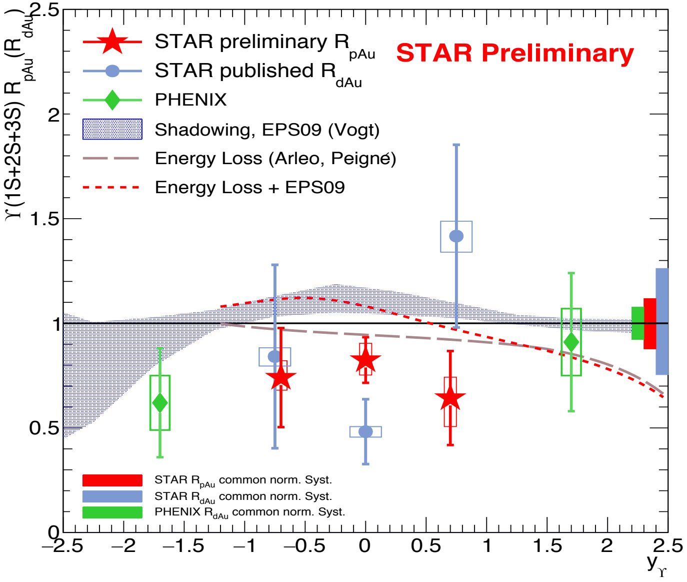
$J/\psi \rightarrow e^+ + e^-$



- R_{pAu} ~ 0.65 at 1 GeV/c and rises to 1 at high p_T
- Data agree with nPDF calculations at high p_T, but seem to favor additional nuclear absorption at low 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



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

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

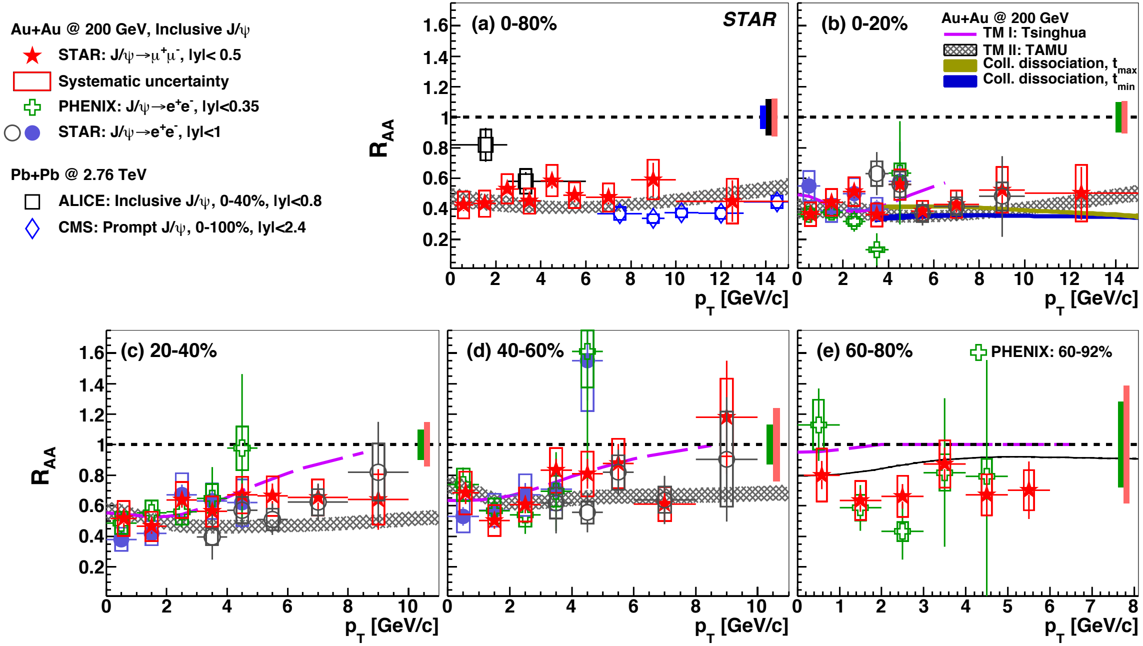
pp Collisions

pA Collisions

AA Collisions

Au+Au @ 200 GeV: J/ψ R_{AA} vs. p_T

STAR: PLB 797 (2019) 134917



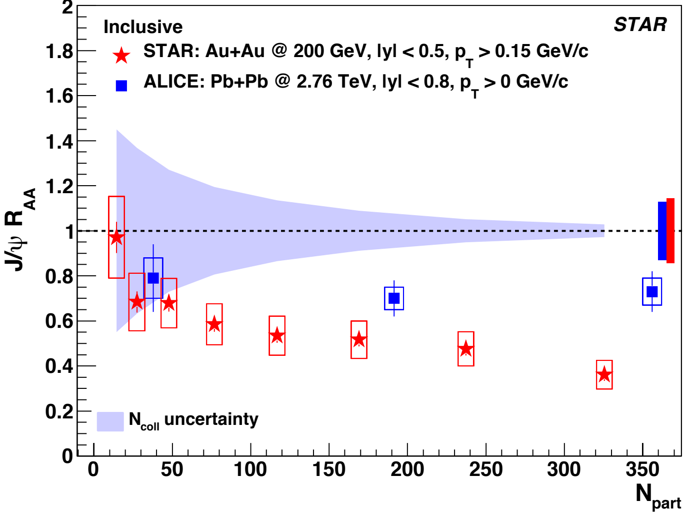
- *J/ψ* is suppressed up to 15 GeV/c
- No strong p_T dependence; interplay of different effects
  - Dissociation: decrease with p_T due to formation time effects
  - Regeneration: mostly at low p_T
  - CNM: more profound at low p_T
  - b-hadron feed-down
- Transport and energy loss models can qualitatively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

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

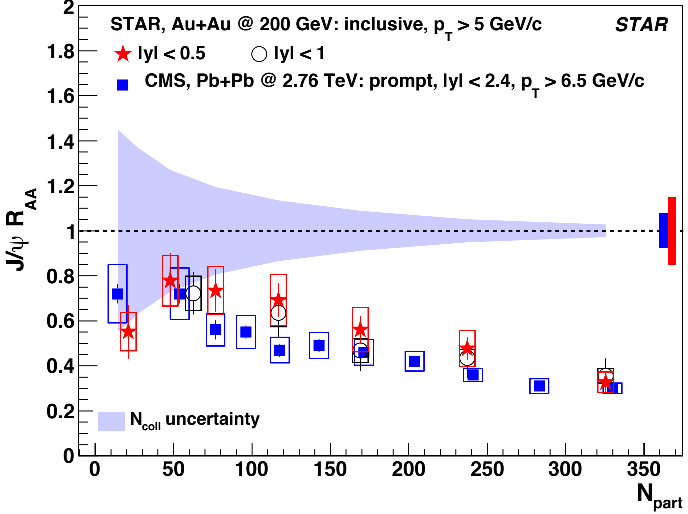
J/ψ R_{AA}: RHIC vs. LHC

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

p_T > 0 GeV/c



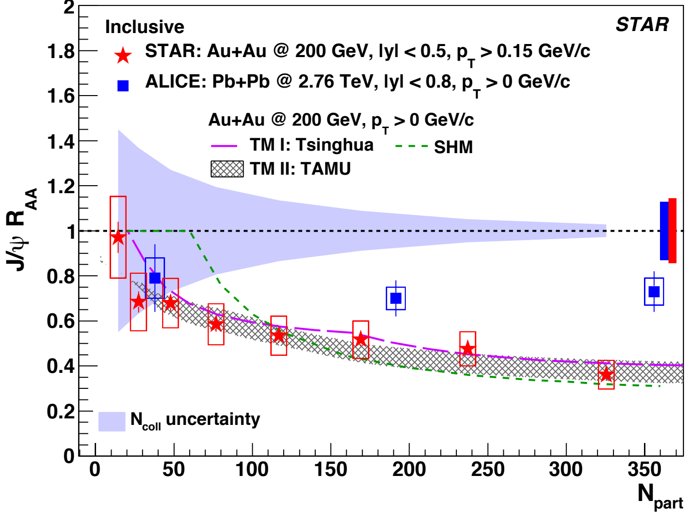
p_T > 5 GeV/c



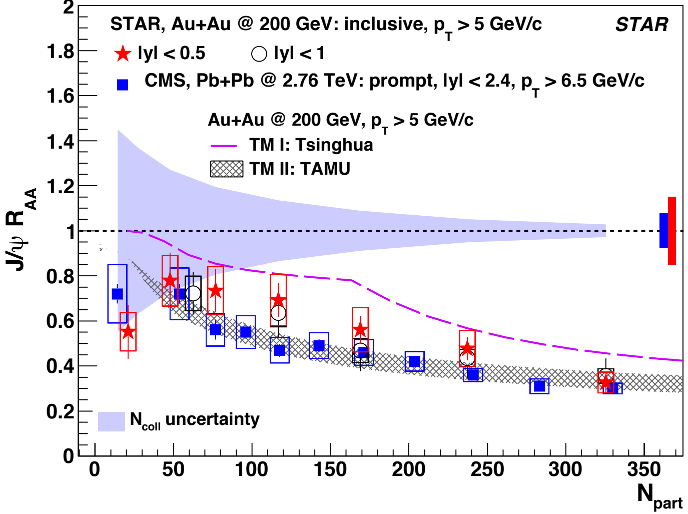
- p_T > 0 GeV/c: more suppressed at RHIC in central events → smaller regeneration contribution due to lower charm cross-section
- p_T > 5 GeV/c: less suppressed at RHIC in semi-central events → smaller dissociation rate due to lower temperature

$J/\psi\ R_{AA}$: Data vs. Transport Model

$p_T > 0$ GeV/c



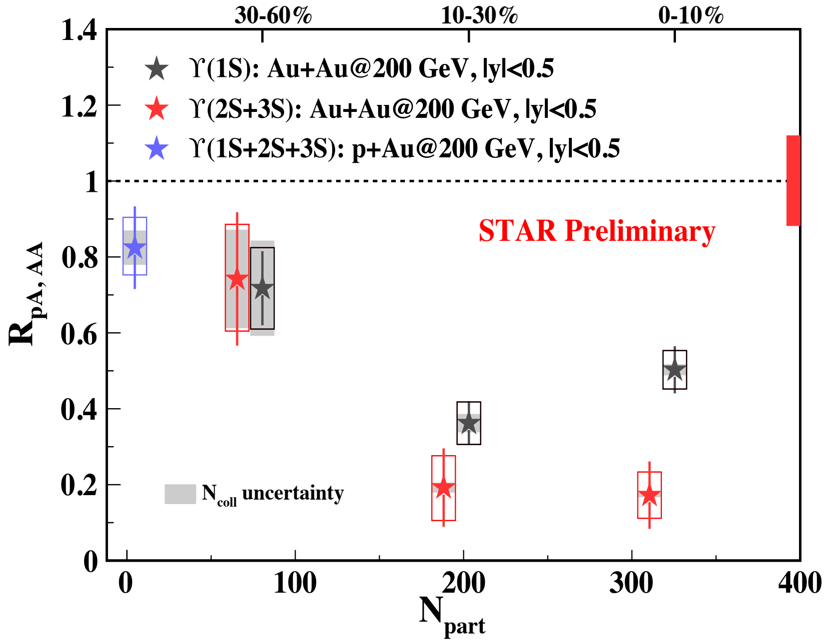
$p_T > 5$ GeV/c



- $p_T > 0$ 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

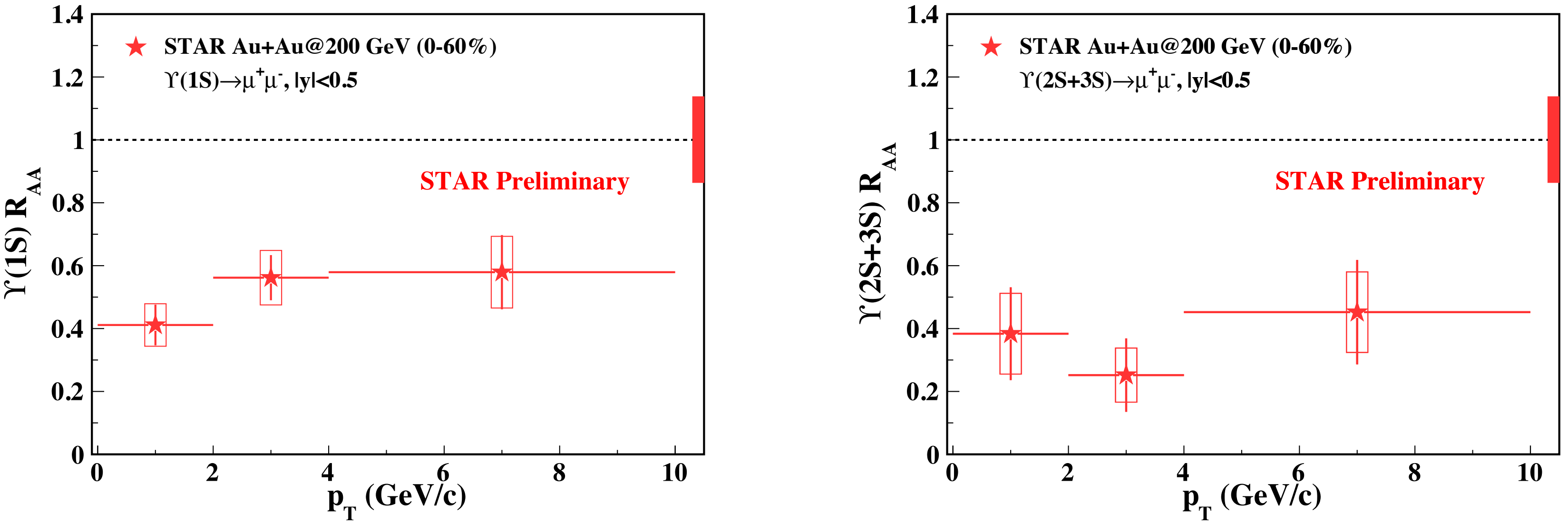
Au+Au @ 200 GeV: ϒ R_{AA} vs. Centrality



- Improved precision for ϒ suppression
  - 2014+2016: dimuon
  - 2011: dielectron
- CNM plays a role
- $R_{AA}^{peri} > R_{AA}^{cent}$: increasing hot medium effects
- 0-10% central: $R_{AA}^{\Upsilon(2S+3S)} < R_{AA}^{\Upsilon(1S)}$

  → **sequential suppression**
  - Similar to that observed at the LHC

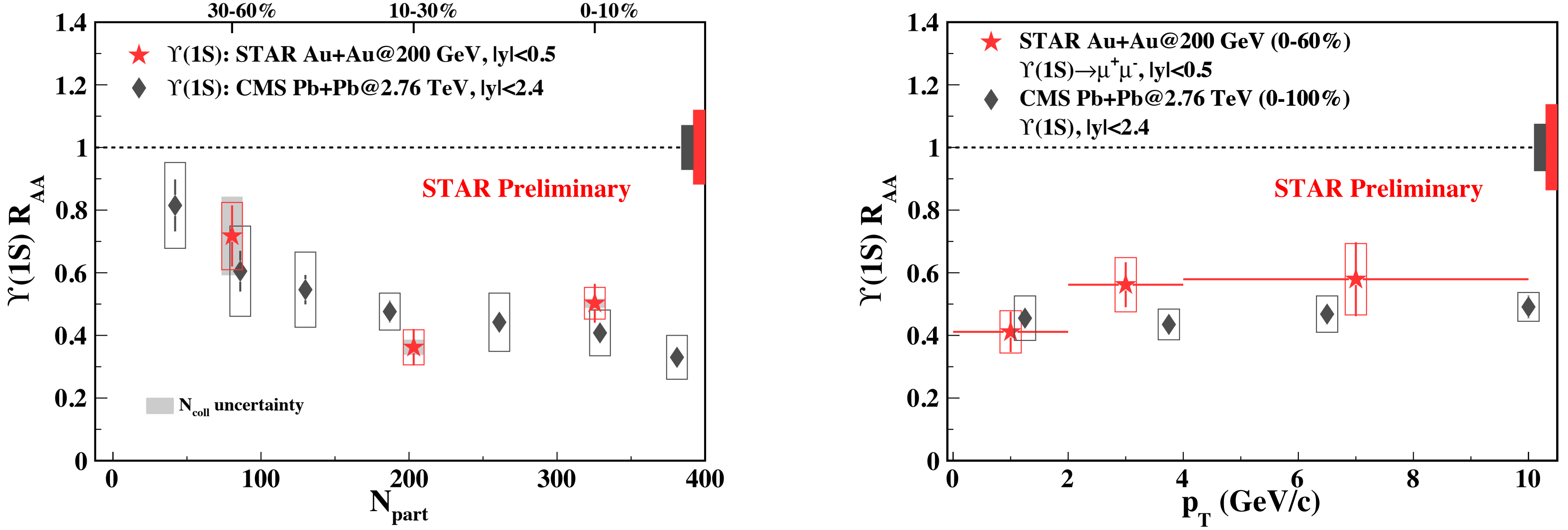
Au+Au @ 200 GeV: Υ R_{AA} vs. p_T



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

$\Upsilon(1S)$ R_{AA}: RHIC vs. LHC

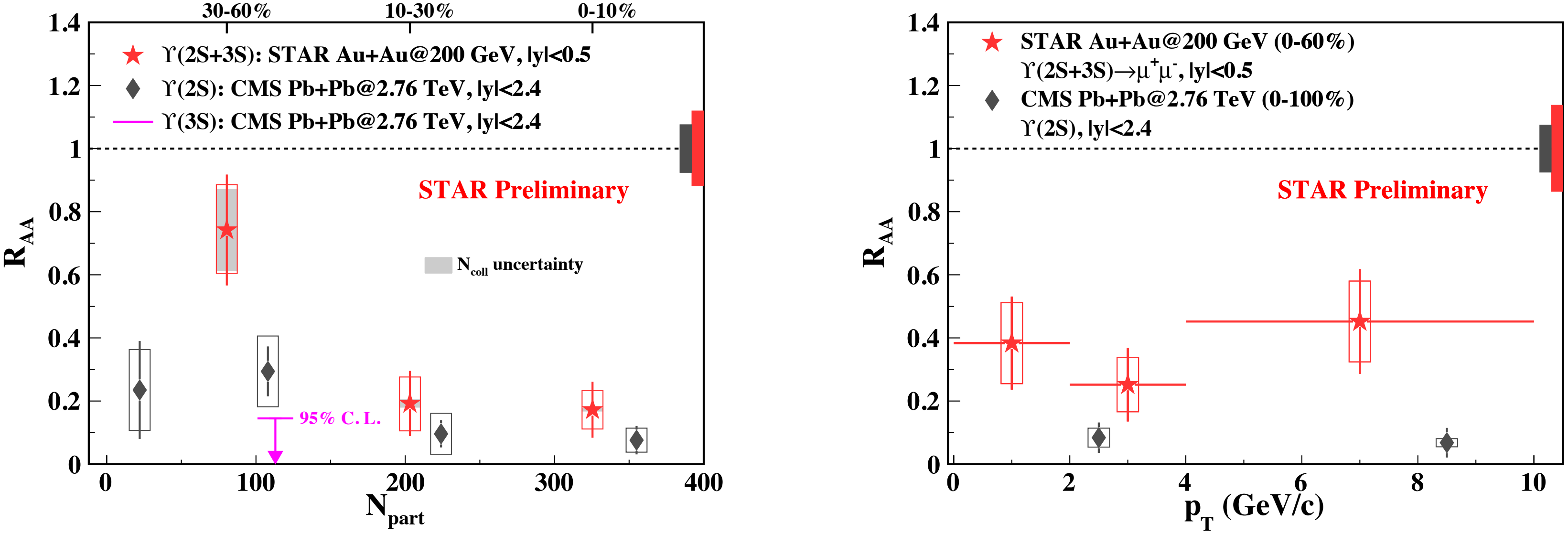
0.2 TeV vs. 2.76 TeV



- $R_{AA}^{0.2TeV} \sim R_{AA}^{2.76TeV}$: could be due to similar CNM (~20%) + suppression of excited states

Υ(2S+3S) R_{AA}: RHIC vs. LHC

0.2 TeV vs. 2.76 TeV



- $R_{AA}^{RHIC} >\sim R_{AA}^{LHC}$: hint of less melting at RHIC peripheral

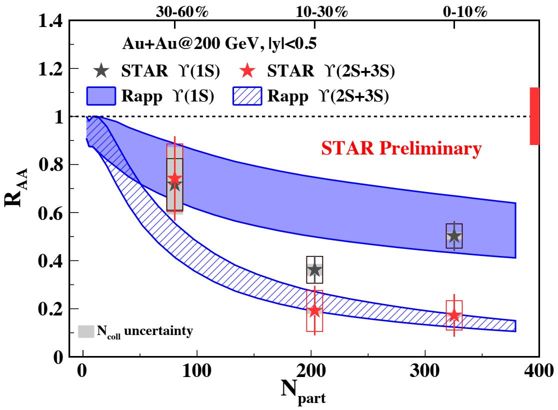
Υ Suppression: Data vs. TAMU model

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

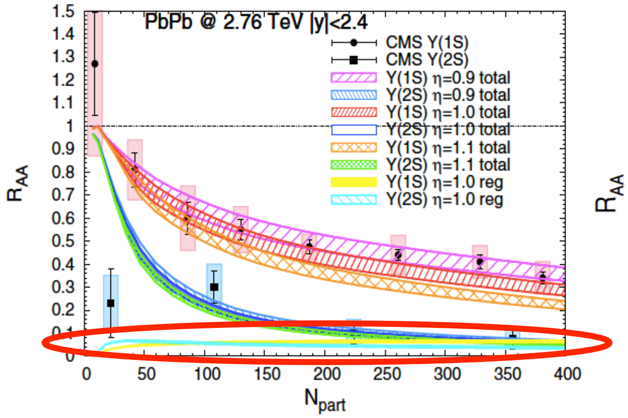
	Υ(1S)	**Υ(2S)**	**Υ(3S)**
T_{disso}(MeV)	500	240	190

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

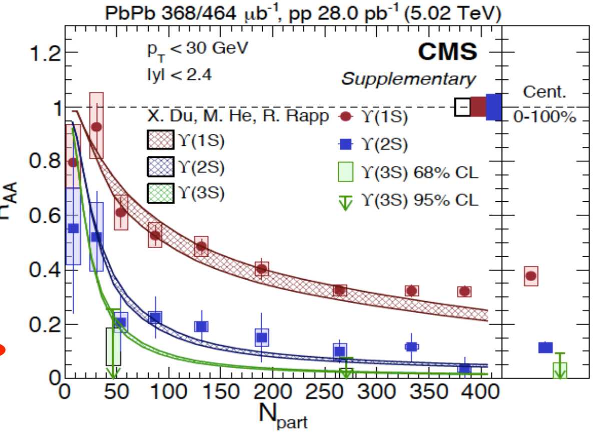
0.2 TeV



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

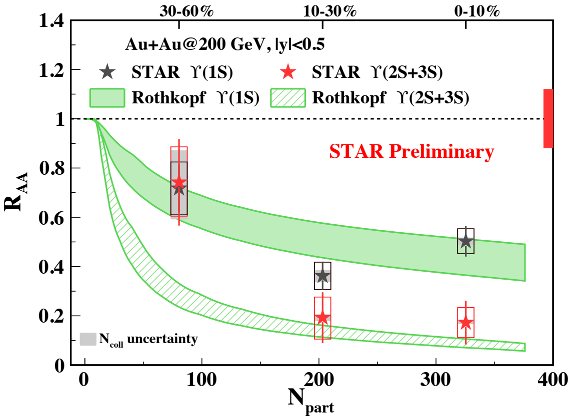
Υ Suppression: Data vs. lattice-potential model

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

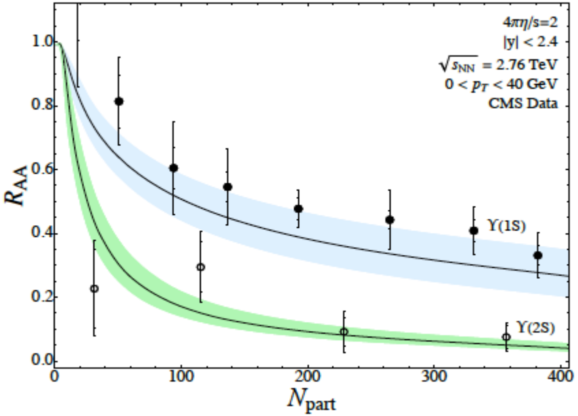
	Υ(1S)	**Υ(2S)**	**Υ(3S)**
T_{disso}(MeV)	600	230	170

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

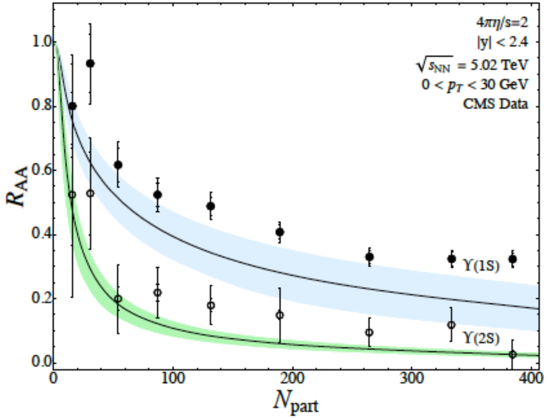
0.2 TeV



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

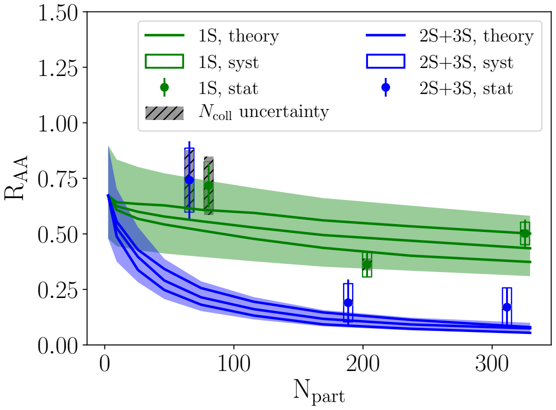
- Coupled Transport Equation; Correlated recombination; CNM

X. Yao, et al, arXiv: 2004.06746

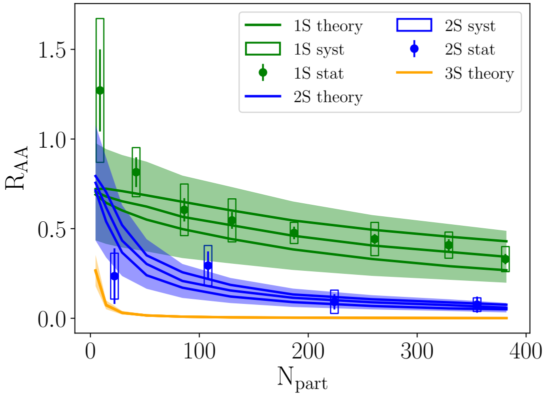
	Υ(1S)	**Υ(2S)**	**Υ(3S)**
T_{disso}(MeV)	450*	225*	154

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

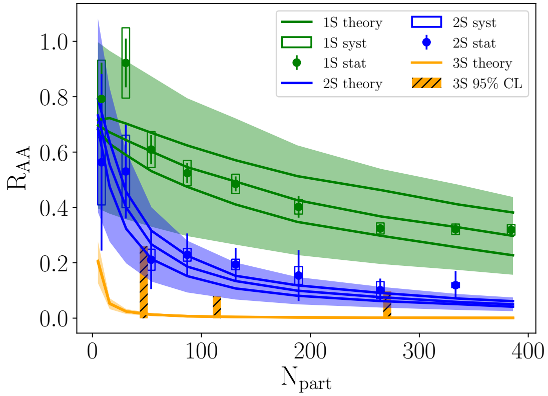
0.2 TeV



2.76 TeV



5.02 TeV



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

*Melting temperature at
$1/m_D$ = Υ size

Summary

pp collisions

- It remains a challenge to fully understand quarkoinum production mechanism
- Measurements of improved precision; new measurements?

pA collisions

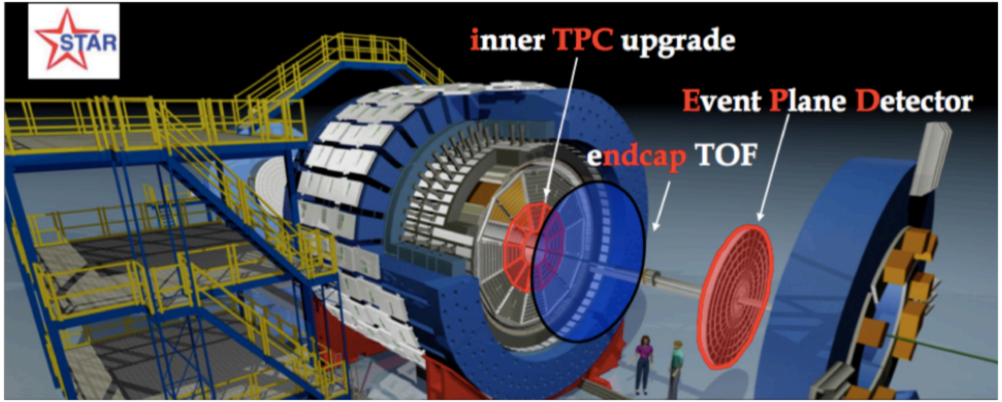
- Sizable suppression for low p_T J/ψ & Υ
  - Need to be taken into account when interpreting measurement in AA collisions

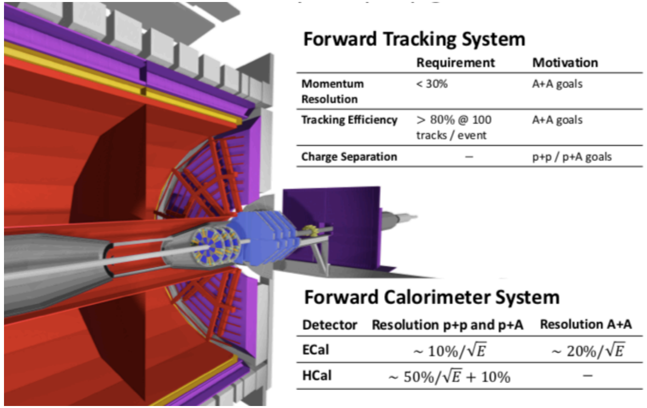
AA collisions

- High-p_T J/ψ strongly suppressed in central collisions → **dissociation**
- Ground and excited Υ exhibit different suppression → **sequential suppression**
- Complementary RHIC & LHC measurements place stringent constraints on model calculations → ***medium temperature?***
  - Pin down other knobs: CNM, feed-down, energy loss, recombination …

Outlook

- **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

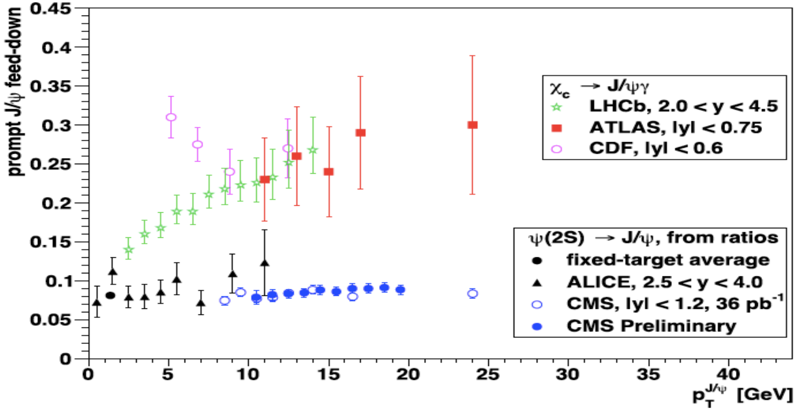
- **Complementarity between electron and muon channels**
- Greatly enhanced statistics → **improve precision**

Year	System	Measurements
2017+2022	p+p @ 500 GeV	✓ J/ψ polarization ✓ J/ψ in jets ✓ J/ψ vs. event activity …
2024	p+p @ 200 GeV	
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 in jets ✓ Υ suppression (sample full L) …

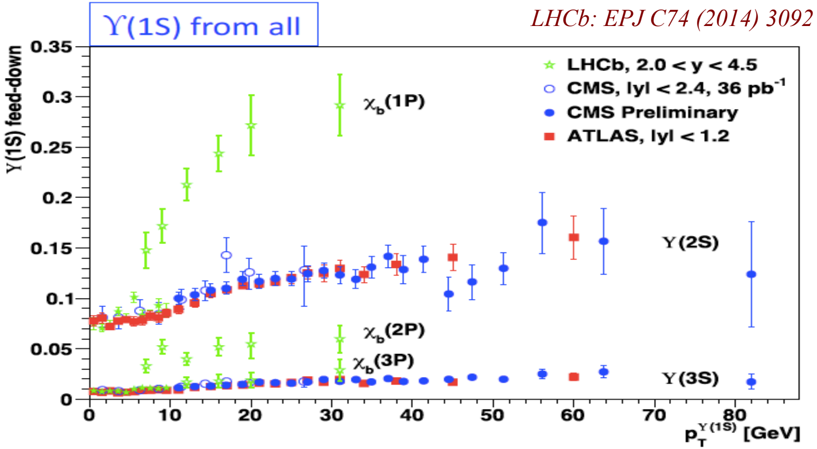
Backup

And the Feed-down Contribution

Woehri@Quarkonia'14



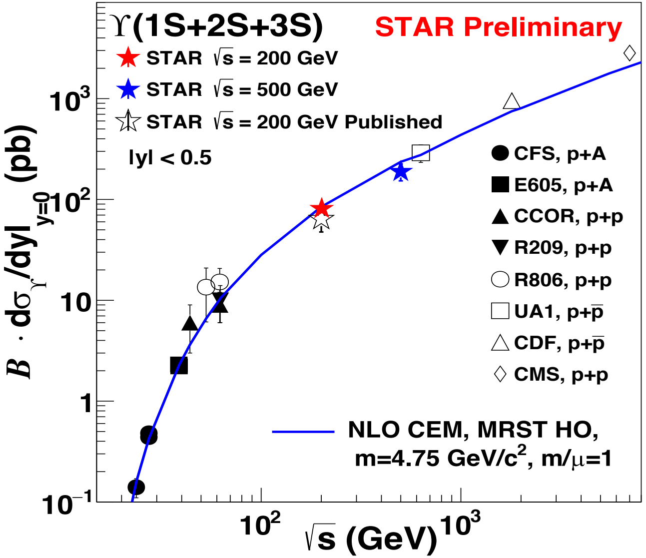
LHCb: EPJ C74 (2014) 3092

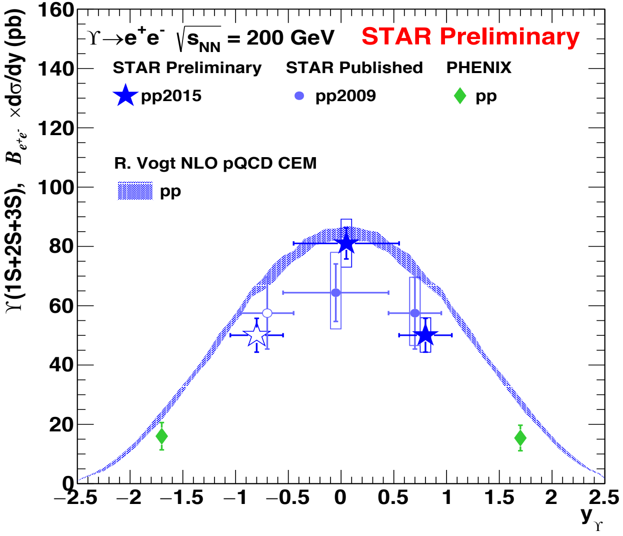


J/*ψ* feed-down	
χ_c	10-30% (vs. p_T)
ψ(2S)	~ 8%
B-hadron	0-50% (vs. p_T, √s)

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

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. KSU model

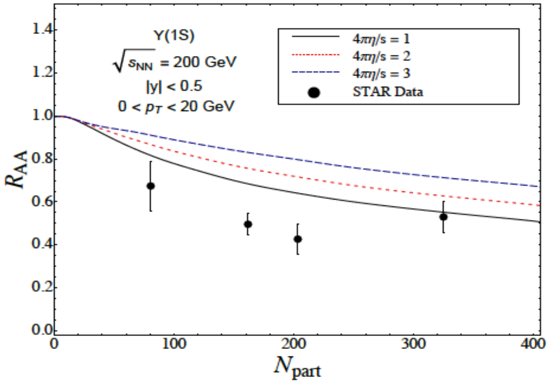
B. Krouppa, R. Ryblewski, M. Strickland
NPA 967 (2017) 604

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

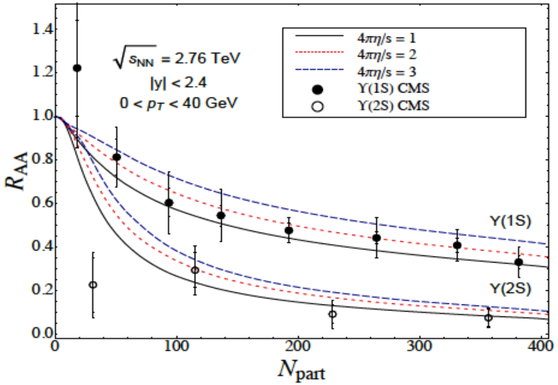
	ϒ(1S)	**ϒ(2S)**	**ϒ(3S)**
T_{disso}(MeV)	600	230	170

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

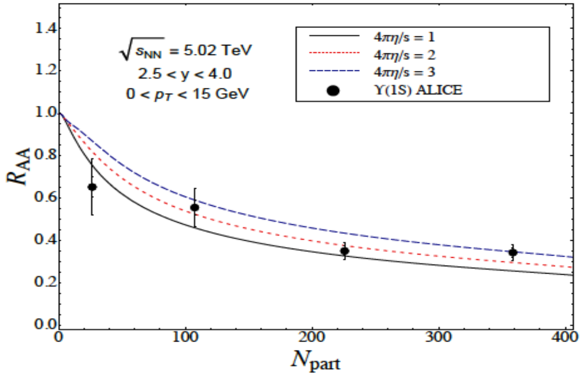
0.2 TeV



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.