Results on Heavy Flavor from STAR

14 October, 2020 @ TQCD Meeting

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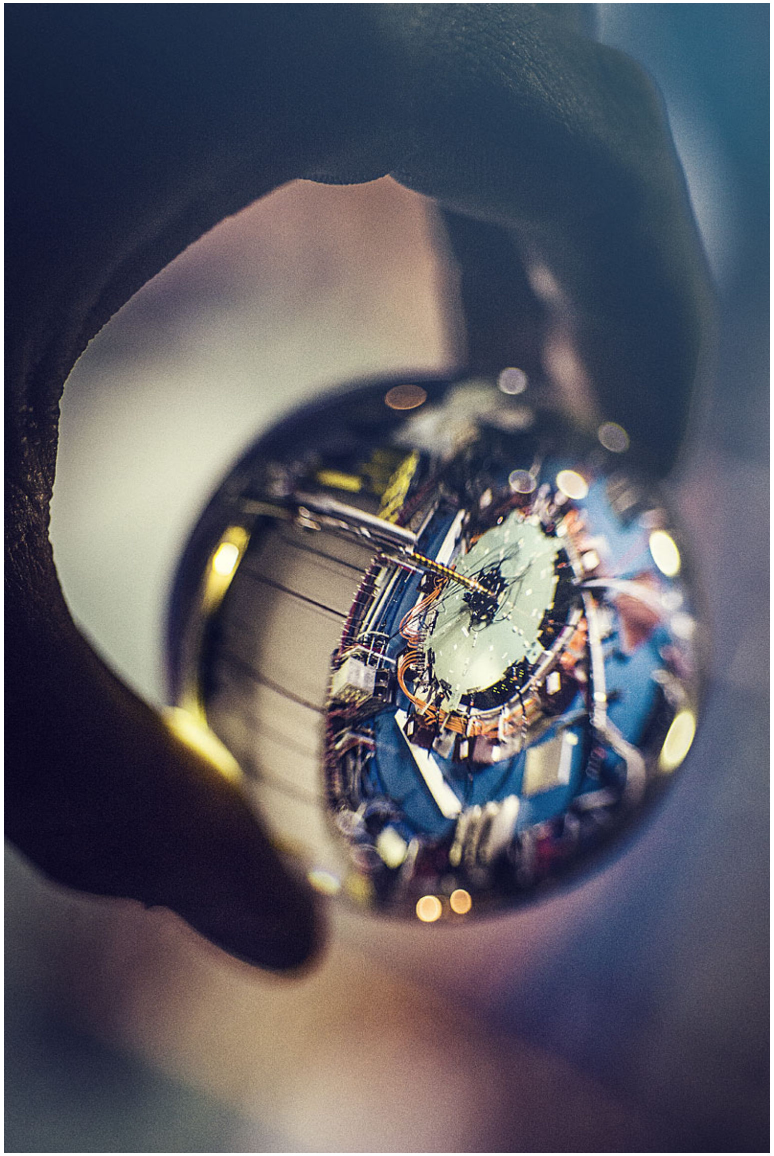
Outline

- ❑ Motivation
- ❑ Relativistic Heavy Ion Collider
- ❑ The STAR detector
- ❑ Physics measurements
  - Charmonium
  - Bottomonium
  - Open Heavy Flavor
- ❑ Summary

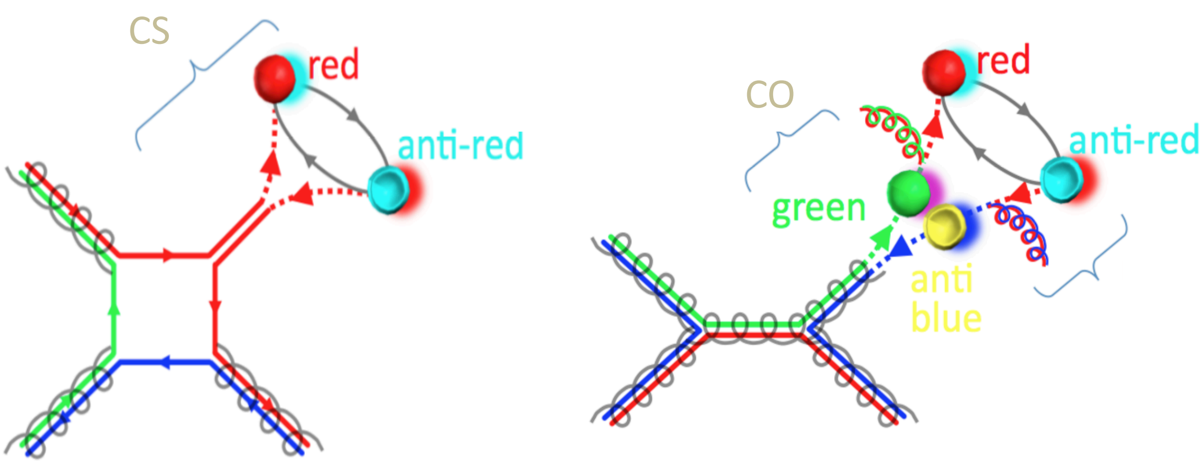


https://www.bnl.gov/photowalk/winners-2018.php

Quarkonium Production

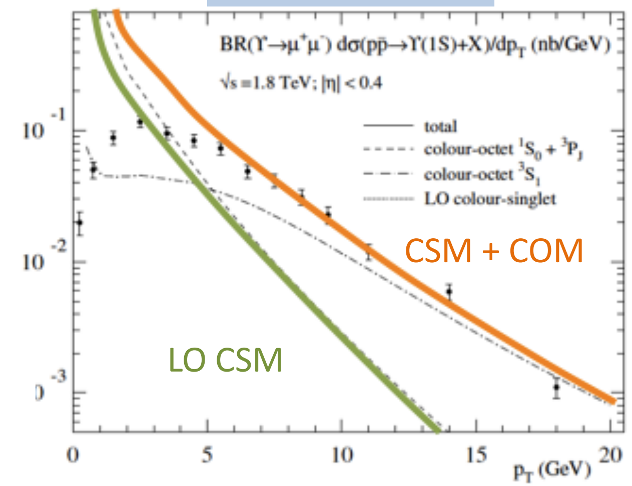
- Quarkonium production mechanism and polarization are still not fully understood in hadron-hadron collisions
- Some popular models on the market:
  - **Color Singlet Model (CSM)** → The quantum numbers (spin, color) of the final and initial states are the same
  - **Color Octet Mechanism (COM) / NRQCD**
    - **Color Glass Condensate effective theory (CGC)**
  - **Color Evaporation Model (CEM) / Improved CEM**

The quantum numbers of the initial and final quark pairs can be different



From Cristina Biino's Talk (FPCP2013)

CDF Υ(1S) result

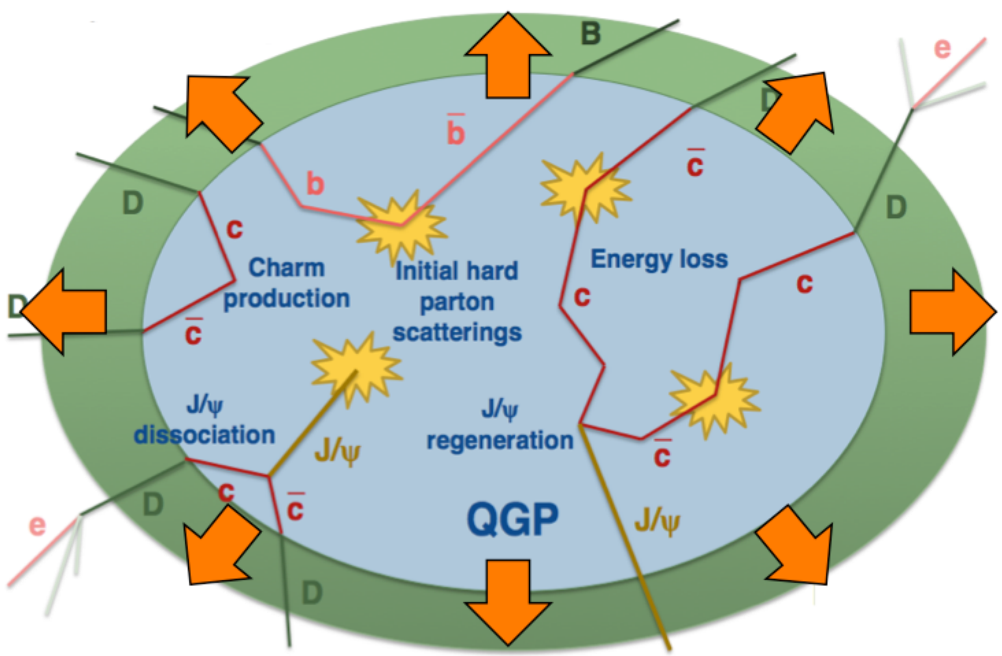


M. Kramer, Prog. Part. Nucl. Phys. 47, 141 (2001)

Study QGP via Heavy Flavor

- Heavy flavor quarks (open heavy flavor, quarkonia) are good probes for studying Quark Gluon Plasma in heavy-ion collisions
  - $m_{c,b} >> T_C, \Lambda_{QCD}, m_{u,d,s}$: produced dominantly by high-Q^2 scatterings in the early stage

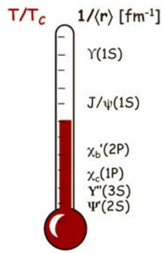
→ **Good candidates to study the evolution of QGP**



https://indico.cern.ch/event/443462/images/6069-hf_cartoon1.png

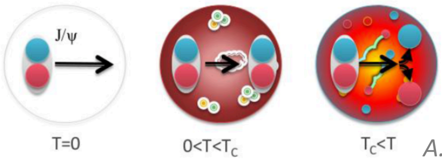
Study QGP via Quarkonium

- Quarkonium suppression is one of smoking guns of the QGP formation (by T. Matsui and H. Satz PLB 178 (1986) 416)
  - ➔ **Color-screening**: Quarkonium dissociates in the medium



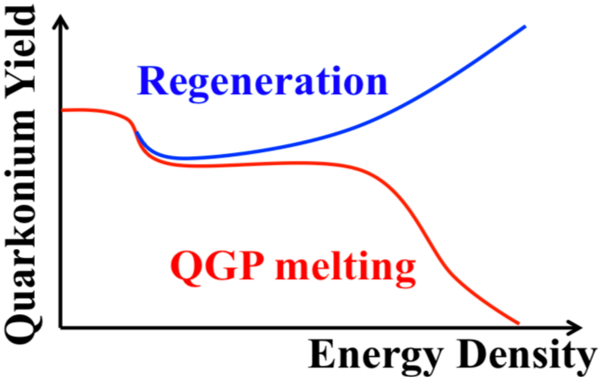
EPJ C61 (2009) 705

- **Sequential melting:** different states dissociate at different temperatures



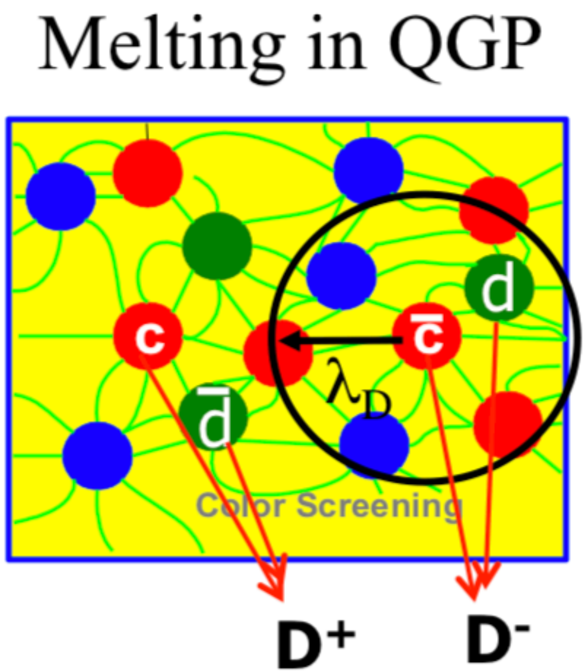
A. Rothkopf

- Interpretation of quarkonium suppression is complicated
  - *Hot nuclear matter effects*
    - Dissociation
    - Regeneration from deconfined quarks
    - Medium-induced energy loss
    - Formation time effect
  - *Cold nuclear matter effects*
    - nPDF, Nuclear absorption, Co-mover et.al
  - *Feed-down from excited charmonium states and B-hadrons*



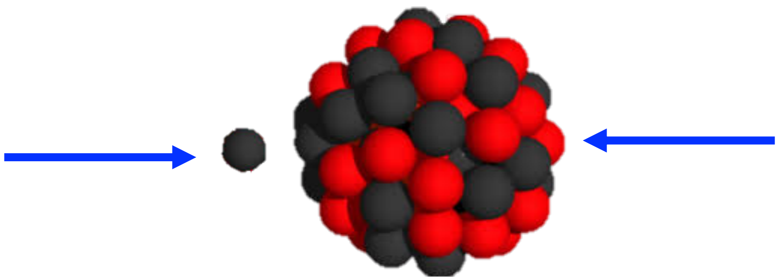
Study QGP via Open Heavy Flavor

- Open heavy flavors ($Q\bar{q}$, Qqq) are also good probes to study
  - **Flavor-dependence of in-medium energy loss**
    (Nature of heavy quark-medium interaction)
  - **Heavy quark collective behavior**
    (Degree of thermalization, spatial diffusion coefficient)
  - **Heavy quark hadronization**
    (QGP dynamics)

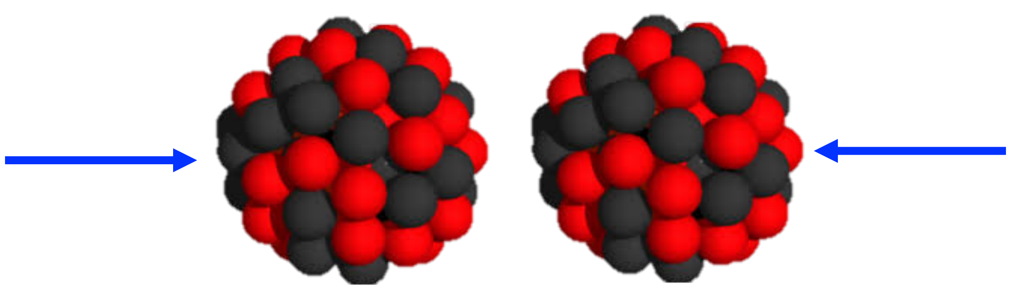


Probing QCD via hadrons and nuclei

p + p : Proton (QCD) structure,
evolution of final states,
hard processes…



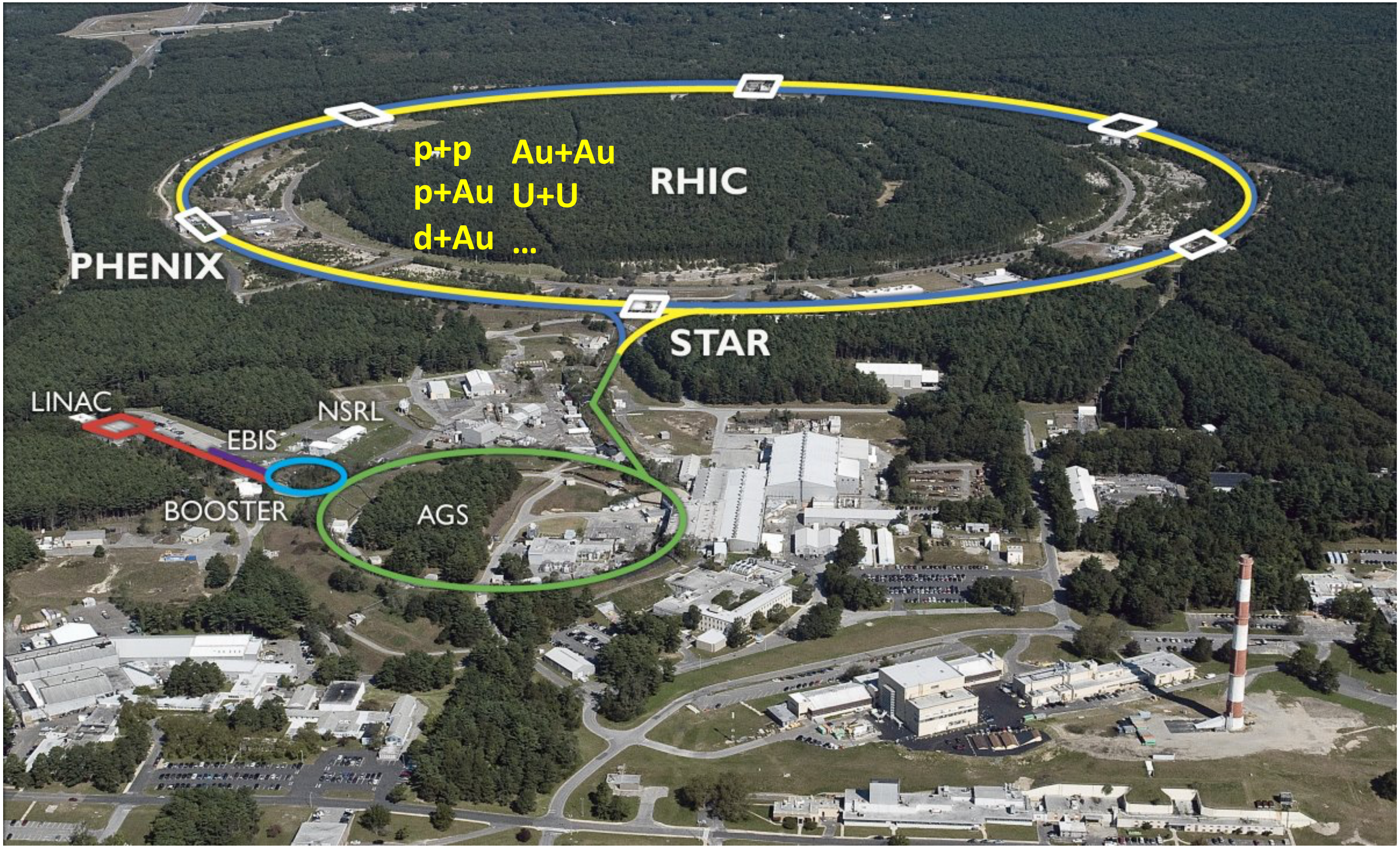
p + A : … + initial states/Cold Nuclear Matter effect (CNM), …



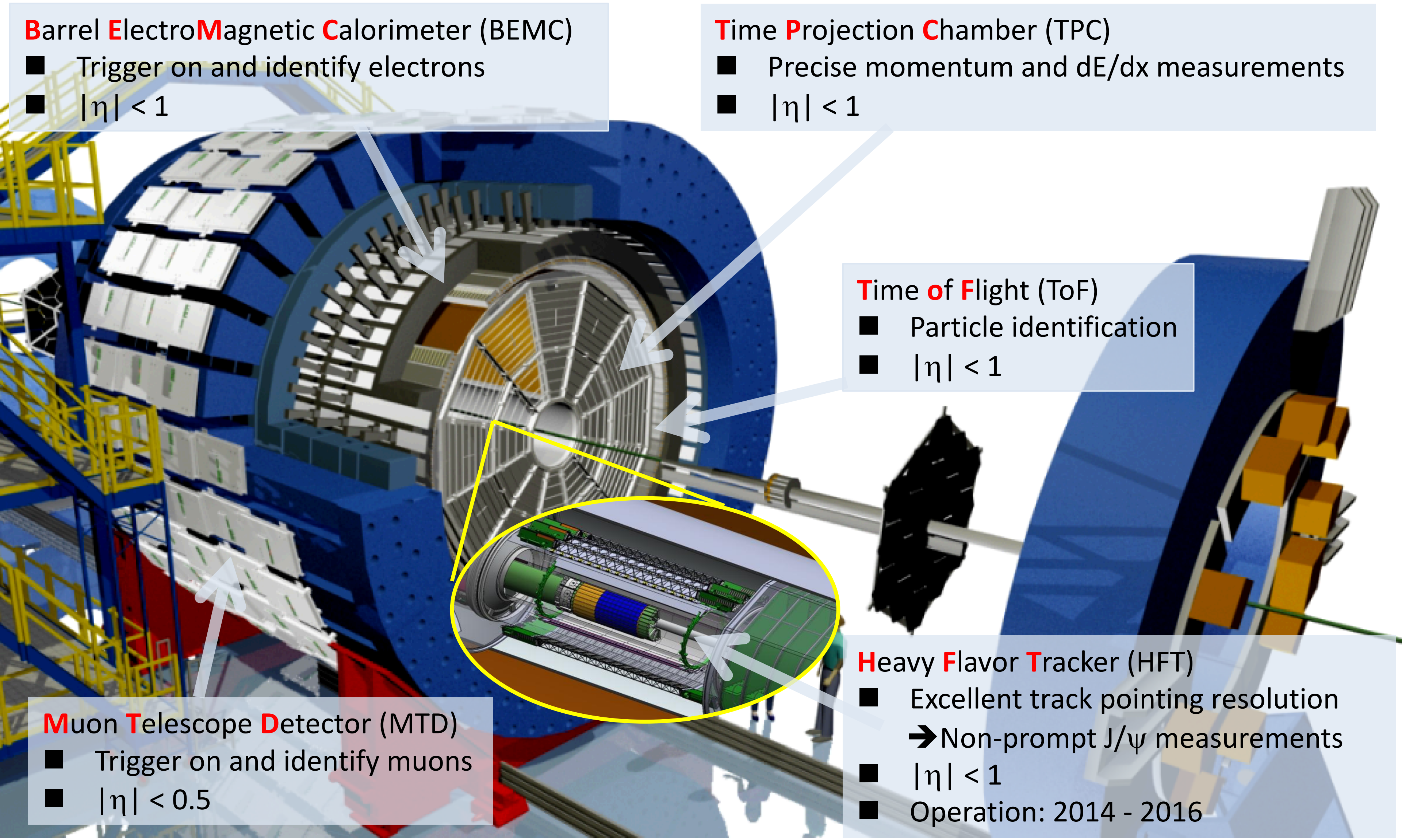
A + A : … + Quark-Gluon Plasma (QGP), …

Relativistic Heavy-Ion Collider (RHIC)

- The most versatile collider in the world!



The STAR Detector



Barrel ElectroMagnetic Calorimeter (BEMC)
- Trigger on and identify electrons
- $|\eta| < 1$

Time Projection Chamber (TPC)
- Precise momentum and dE/dx measurements
- $|\eta| < 1$

Time of Flight (ToF)
- Particle identification
- $|\eta| < 1$

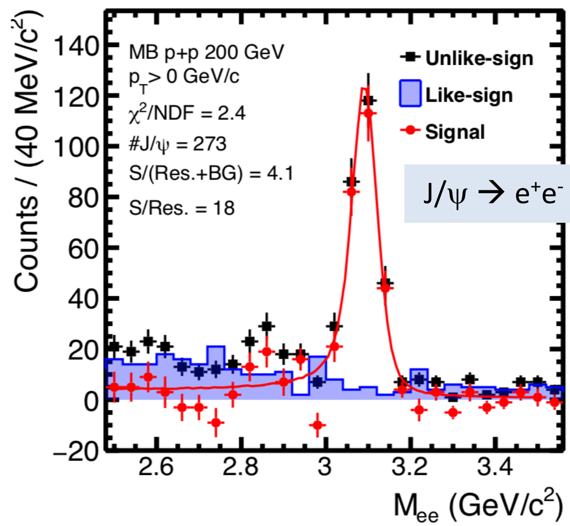
Heavy Flavor Tracker (HFT)
- Excellent track pointing resolution
  → Non-prompt J/ψ measurements
- $|\eta| < 1$
- Operation: 2014 - 2016

Muon Telescope Detector (MTD)
- Trigger on and identify muons
- $|\eta| < 0.5$

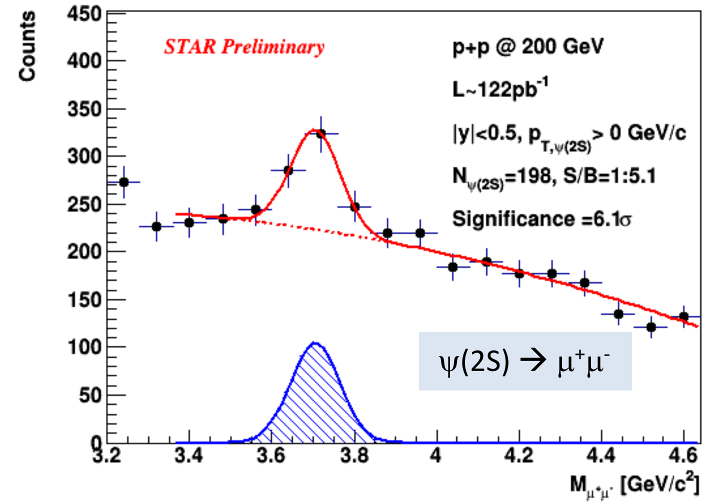
J/ψ & ψ(2S) in p+p @ 200 & 500 GeV

- J/ψ and ψ(2S) signals from the ***dielectron*** and ***dimuon*** channels

p+p @ 200 GeV

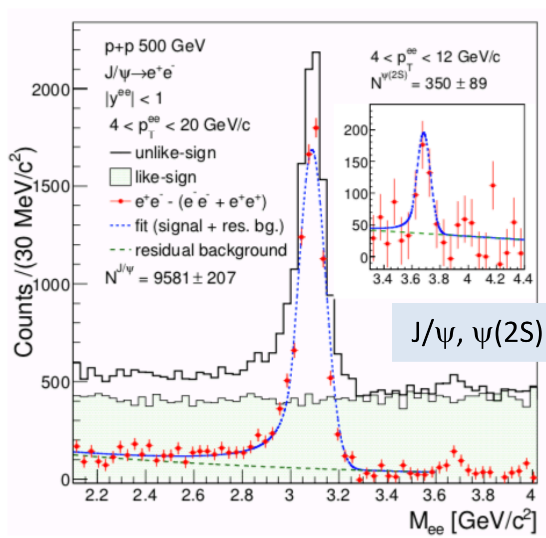


J/ψ → e^+e^-

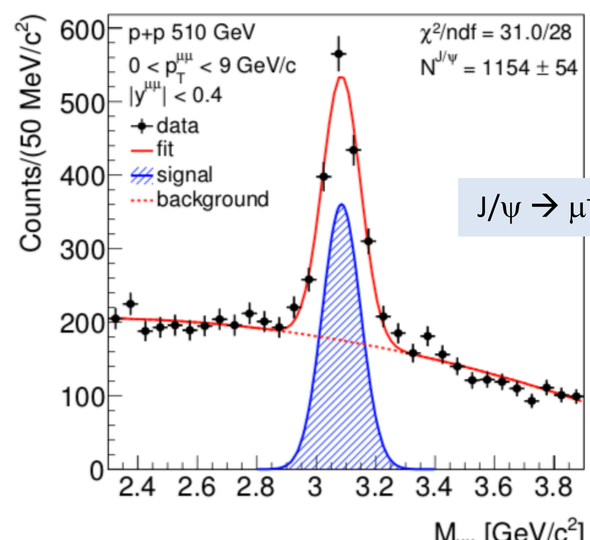


ψ(2S) → $\mu^+\mu^-$

p+p @ 500 GeV



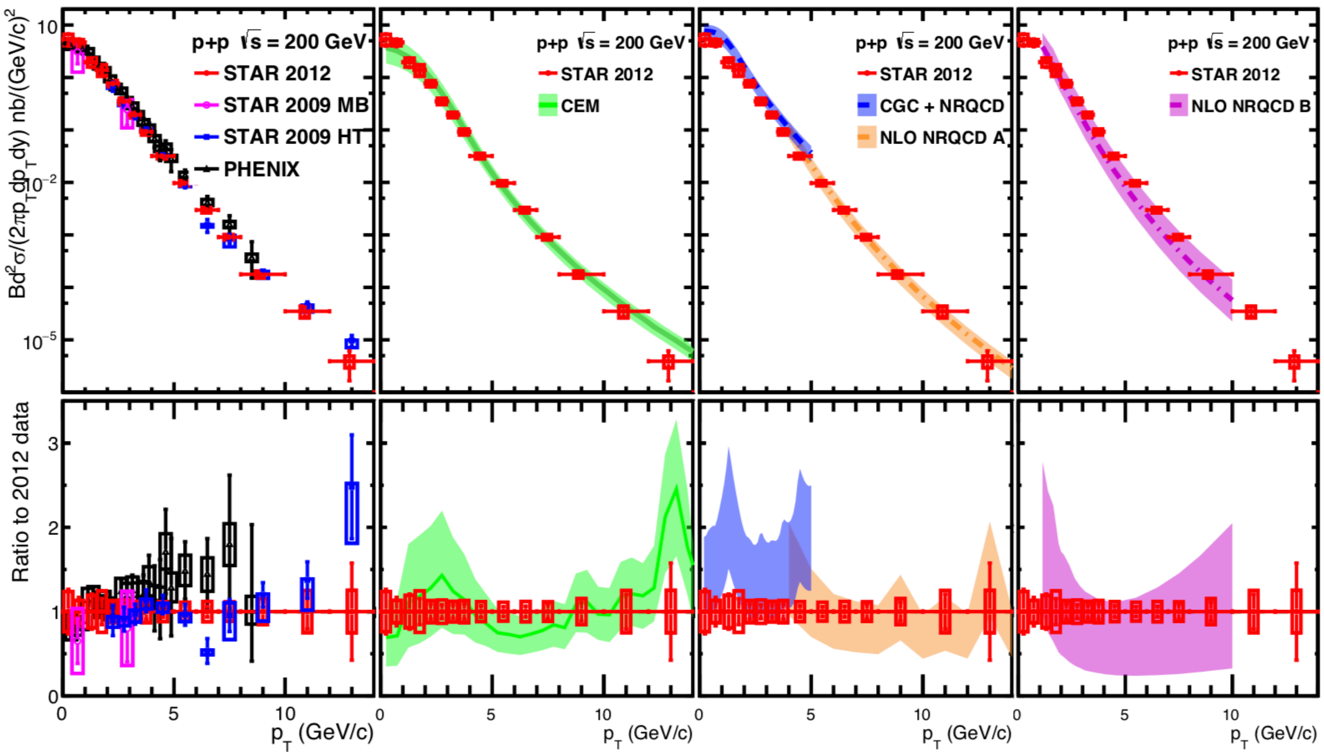
J/ψ, ψ(2S) → e^+e^-



J/ψ → $\mu^+\mu^-$

J/ψ Cross-Section in p+p Collisions @ 200 GeV

- Precision measurement of J/ψ production cross-section for $p_T^{J/\psi}$ from 0 to 14 GeV/c
- Consistent with CEM (direct J/ψ production only) and NLO NRQCD calculations (prompt J/ψ production)
- CGC+NRQCD seems to overestimate the data in the low p_T region

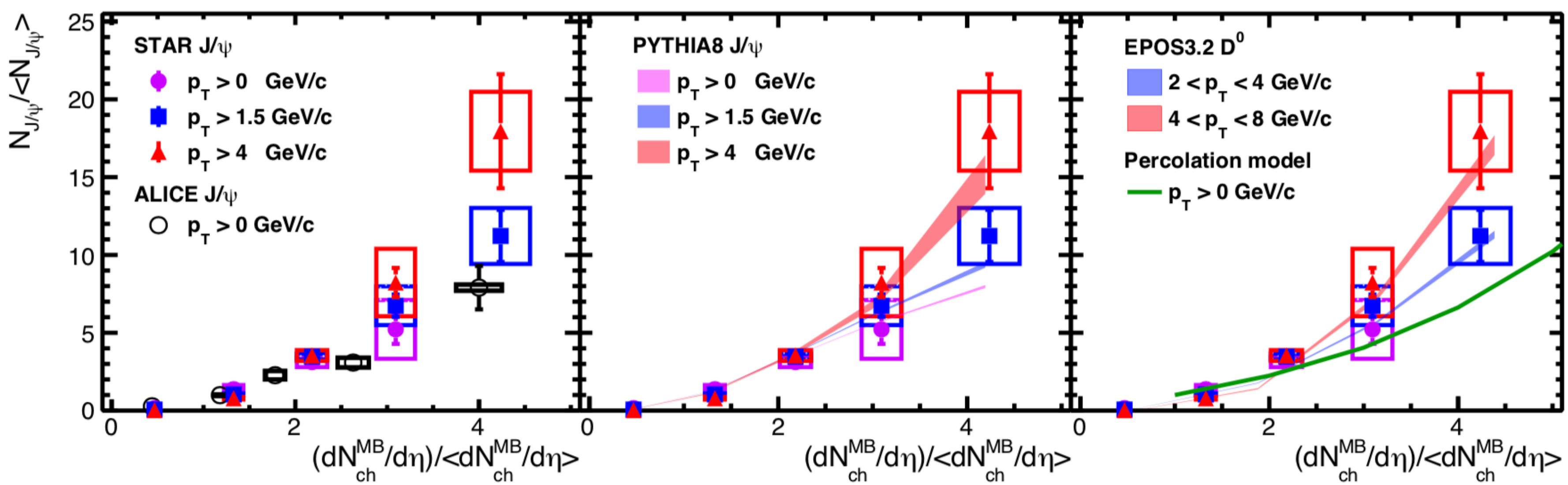


STAR 2012: PLB 786 (2018) 87-93
STAR 2009: PLB 722 (2013) 55;
PRC 93 (2016) 064904
PHENIX: PRD 82 (2010) 012001
CEM: Phys. Rept. 462 (2008) 125;
R. Vogt private communication (2009)
NLO+NRQCD A: PRD 84 (2011) 114001
CGC+NRQCD: PRL 113 (2014) 192301
NLO+NRQCD B: PRL 108 (2012) 172002

J/ψ vs. Event Activity in p+p Collisions @ 200 GeV

- Event activity = charged-particle multiplicity at mid-rapidity
- Relative J/ψ yield rises faster than a linear function
  - ➔ Similar global trend at different collision energies, and similarly as for the D meson
- PYTHIA, EPOS3 and Percolation model can qualitatively describe the rising behavior

STAR 2012: PLB 786 (2018) 87-93



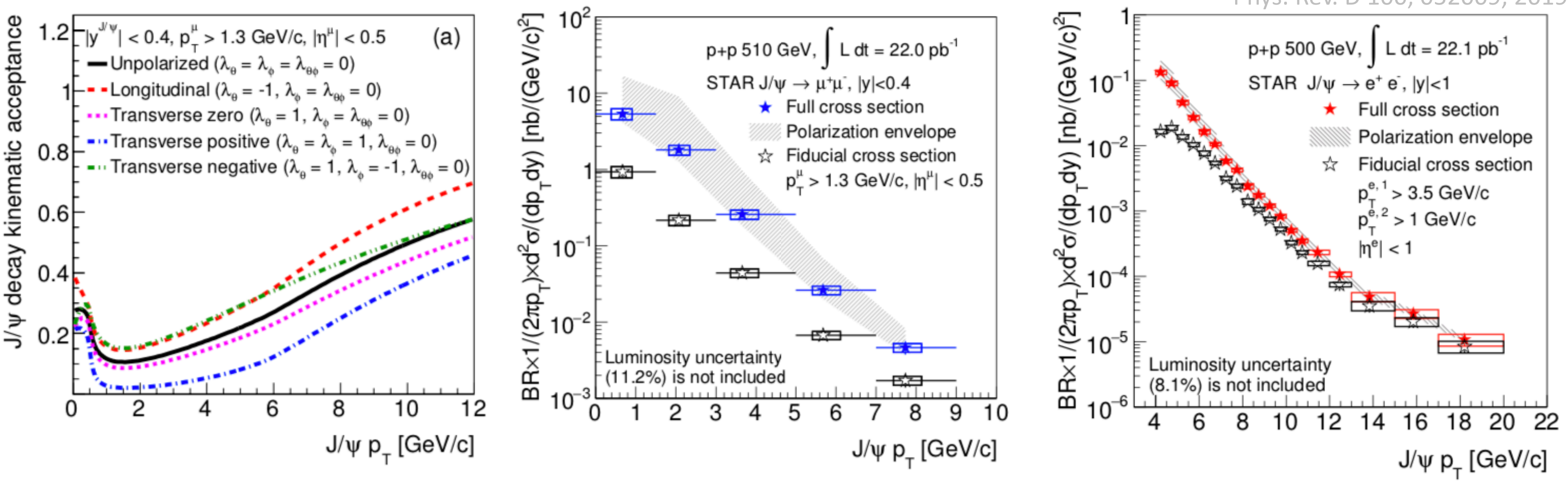
ALICE: JHEP 09 (2015) 148
Percolation model: Phys.Rev. C86 (2012) 034903

EPOS3.2: Phys. Rept. 350 (2001) 93.

J/ψ Cross-Section in p+p Collisions @ 500 GeV

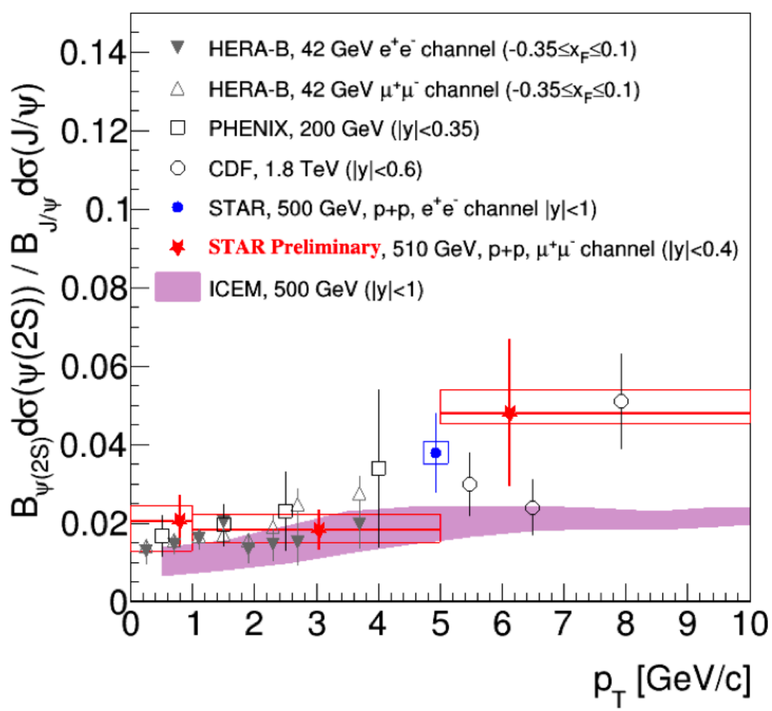
- Precision measurement of J/ψ production cross-section for $p_T^{J/\psi}$ from 0 to 20 GeV/c
- J/ψ kinematic acceptance strongly depends on the polarization assumption
  - **Fiducial cross-section**: restricted phase-space (no uncertainty from polarization)
  - **Full cross-section**: full phase-space (more models for comparison)

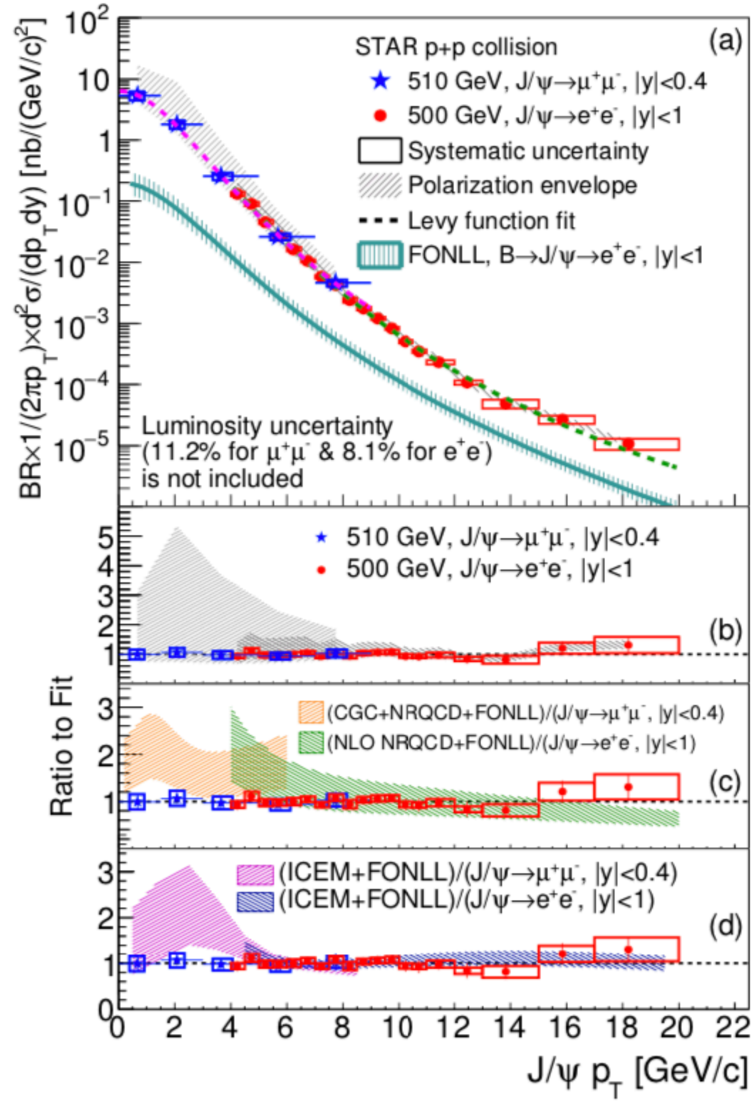
Phys. Rev. D 100, 052009, 2019



J/ψ Cross-Section in p+p Collisions @ 500 GeV

- Consistent with CGC+NRQCD, NLO NRQCD calculations and ICEM (prompt J/ψ)
- ψ(2S) to J/ψ ratio follows the world trend (adding 2017 data)





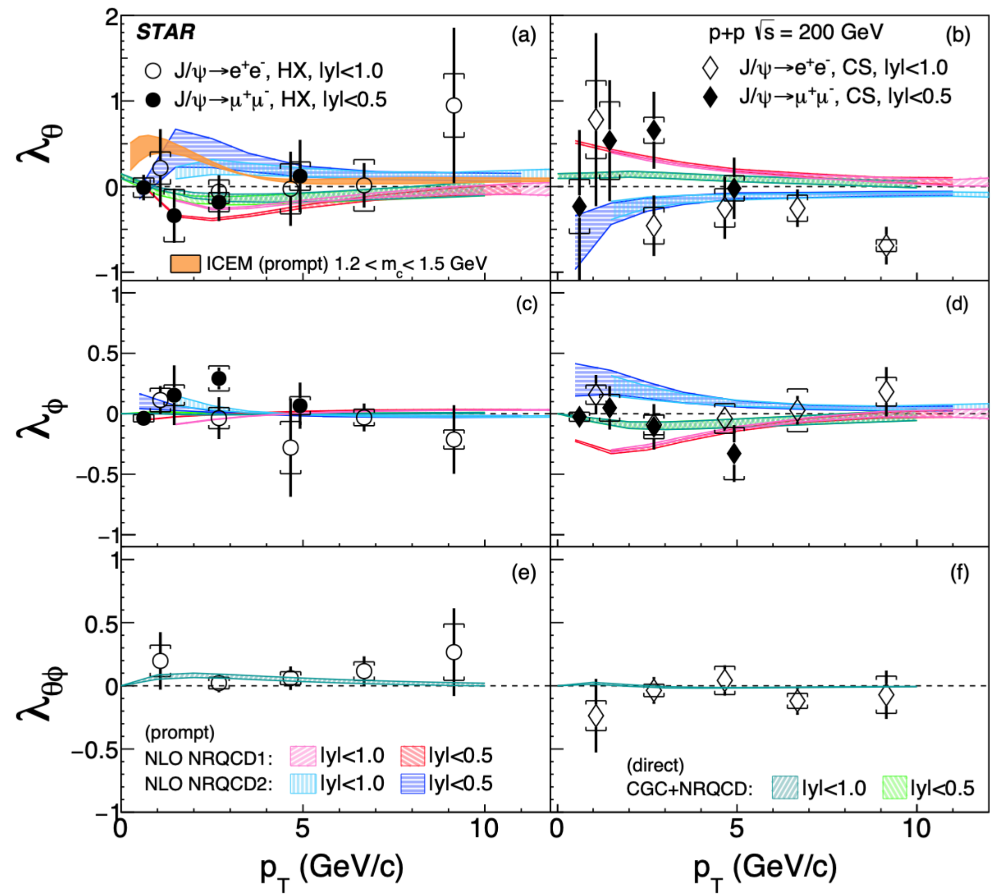
Phys. Rev. D 100, 052009, 2019

J/ψ Polarization Measurement

- First STAR J/ψ polarization measurements in Helicity (HX) and Collins-Soper (CS) frame from the ***dimuon*** channel in p+p collisions @ 200 GeV
- At this p_T range, it is sensitive to constraint NRQCD Long Distant Matrix Elements (LDMEs)
- λ_θ, λ_ϕ, and $\lambda_{\theta\phi}$ are consistent with **ZERO** within uncertainties
- NRQCD and CGC+NRQCD predictions can both qualitatively describe data
- Possible to distinguish different NRQCD predictions with larger statistics at low p_T

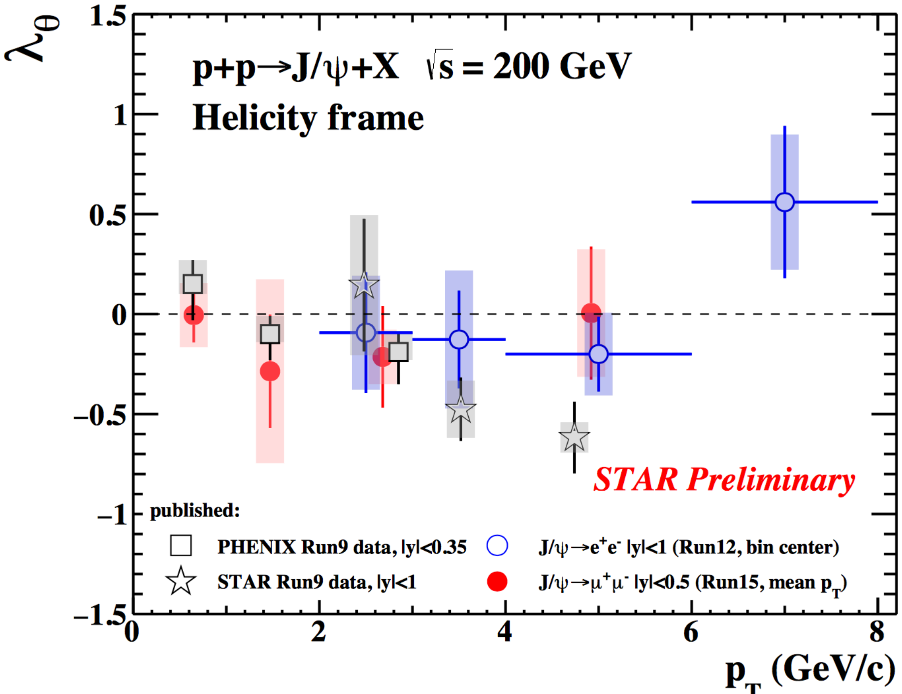
NRQCD1: Phys. Rev. Lett 114 (2015) 092006
NRQCD2: Phys. Rev. Lett 110 (2013) 042002
CGC+NRQCD:JHEP12 (2018) 057

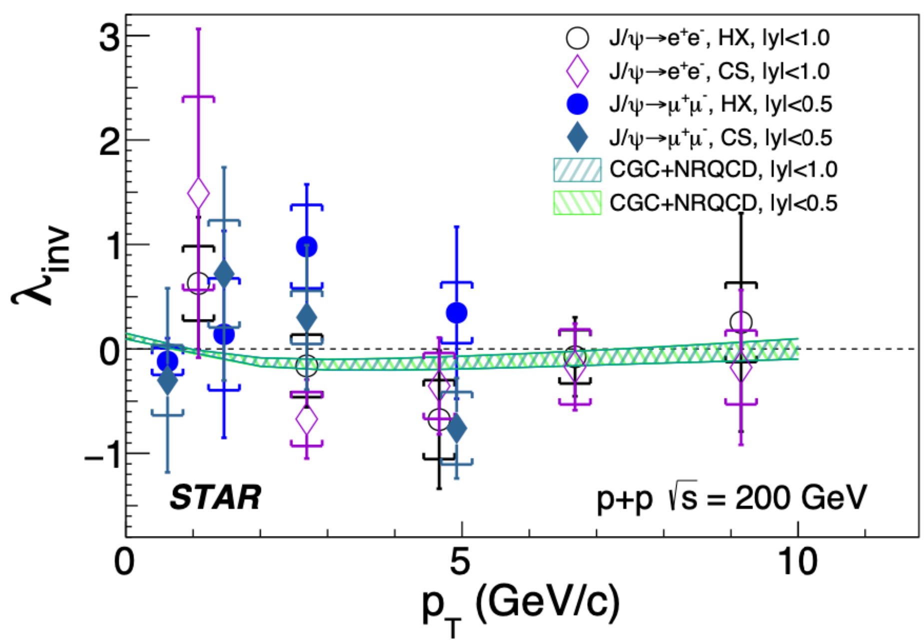
arXiv:2007.04732



J/ψ Polarization Measurement

- Frame invariant quantity: $\lambda_{inv} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$
  - Good cross-check on measurements performed in different frames
- Consistent with the previous measurements from STAR and PHENIX



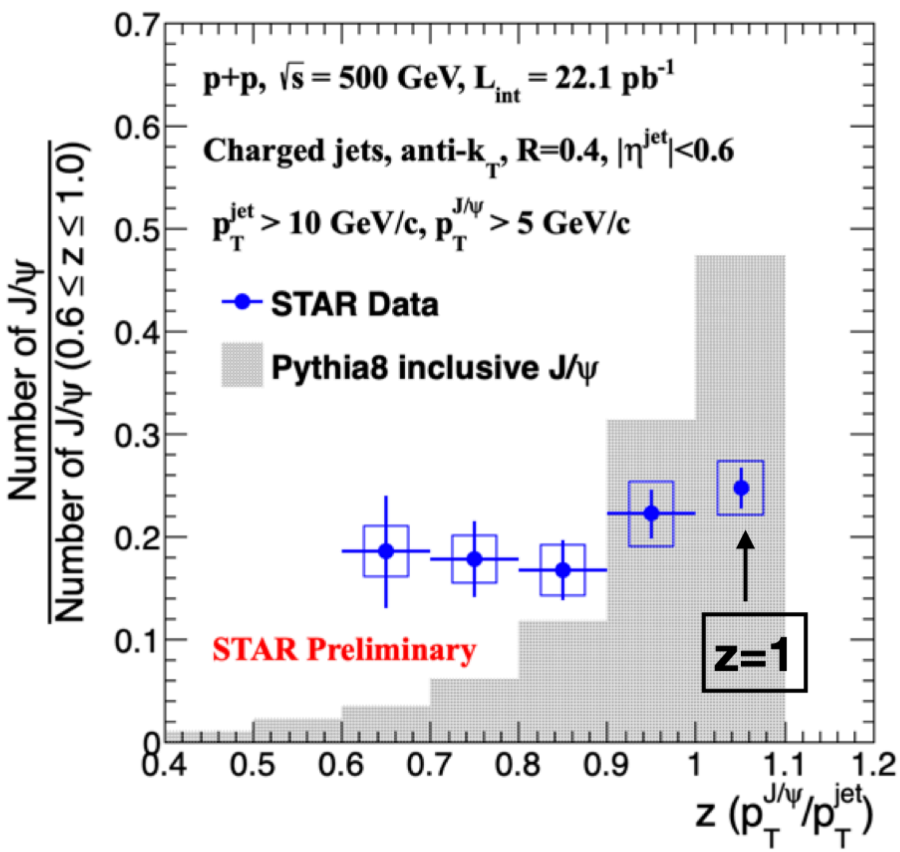


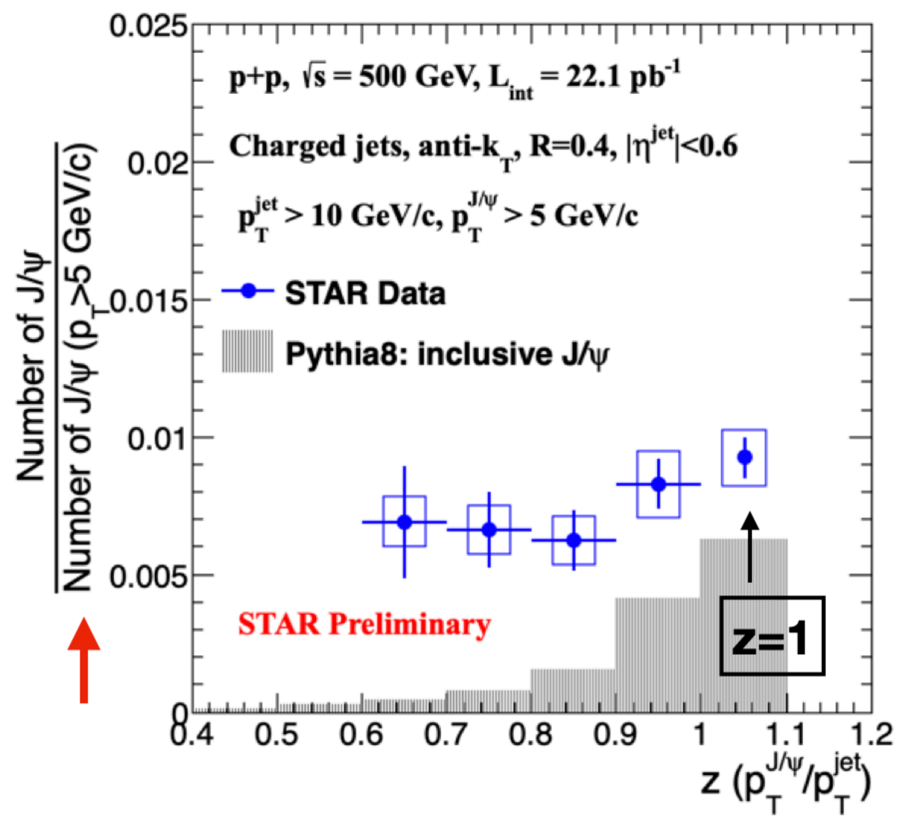
STAR Run 9: Phys. Lett. B739 (2014) 180–188
PHENIX: Phys. Rev. D **95**, 092003

arXiv:2007.04732

J/ψ Production in a jet

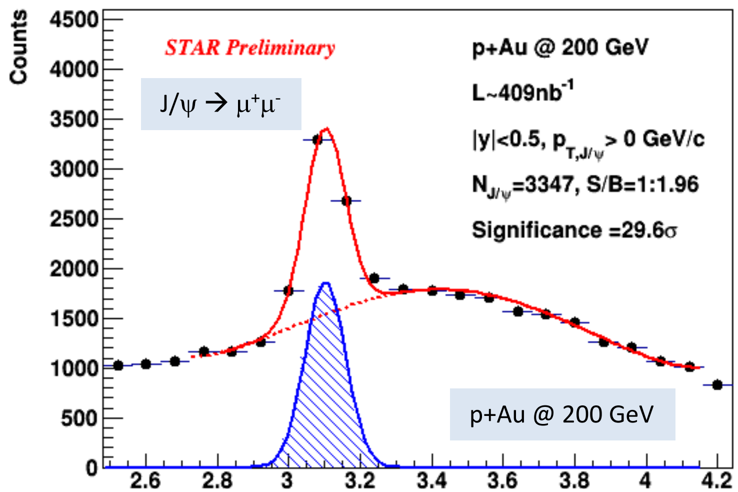
- Charged jet to J/ψ fragmentation function :
  No significant z dependence observed within uncertainties for z <1
- Different trend and probability of producing a J/ψ in charged jet for the measured kinematics range

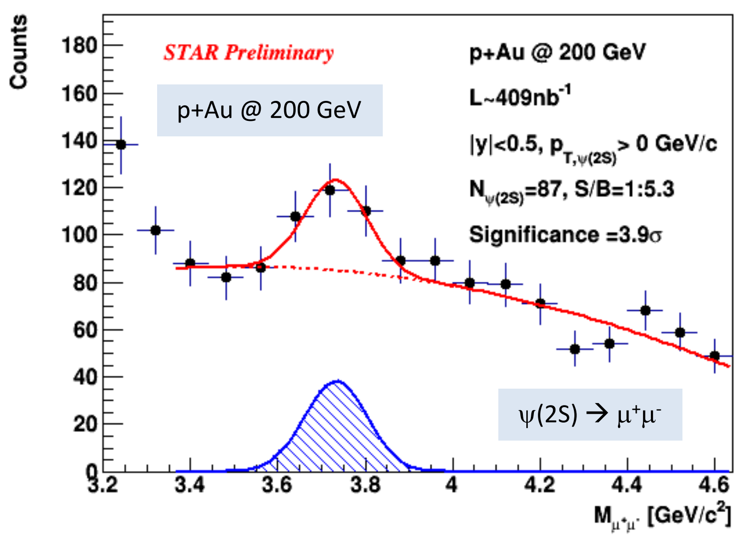


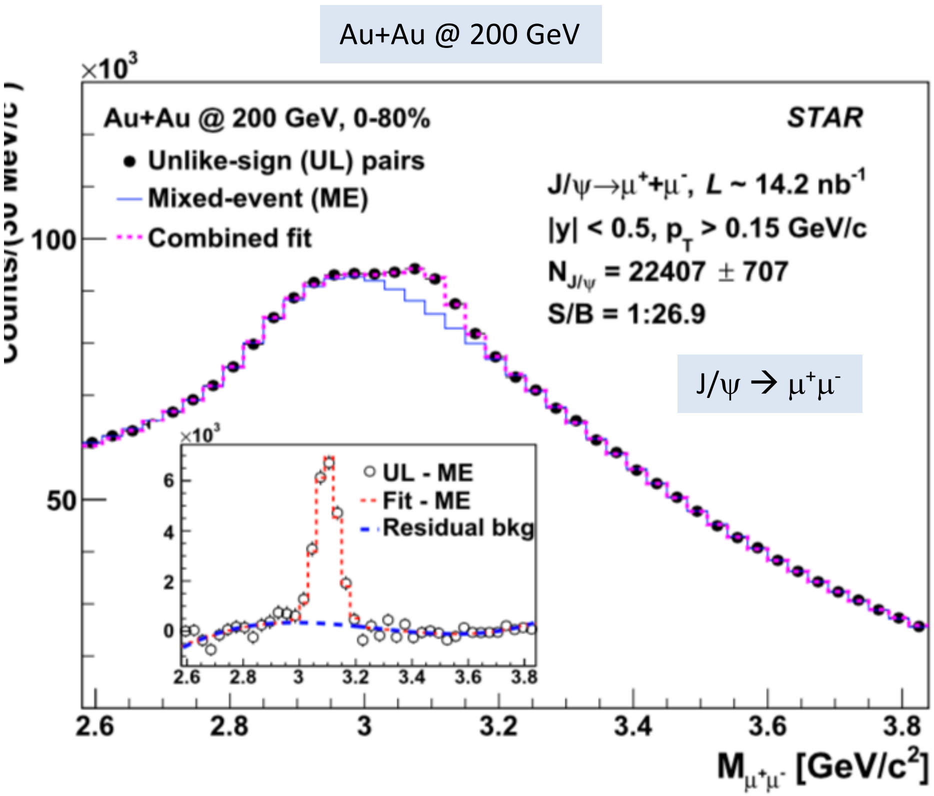


J/ψ & ψ(2S) in p+A & Au+Au @ 200 GeV

- Clear J/ψ and ψ(2S) signals in p+Au and Au+Au collisions



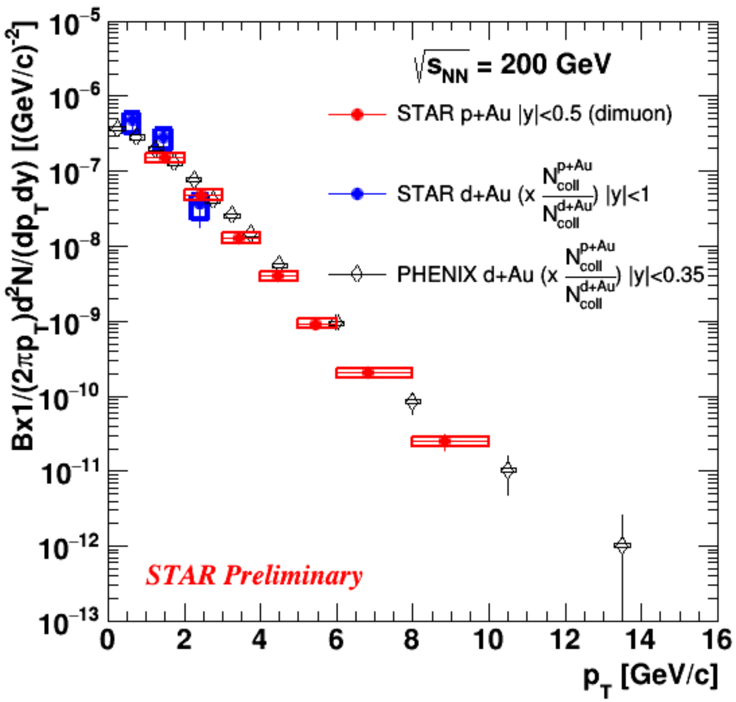


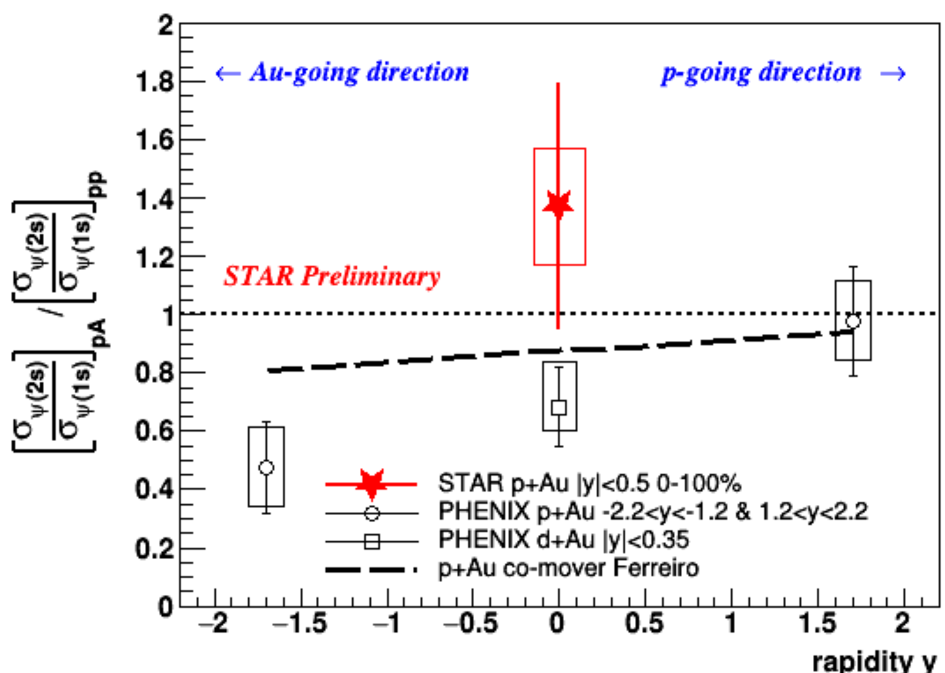


Invariant Yields and Double Ratio in p+Au

- Precision measurements of J/ψ invariant yield in p+Au
- First ψ(2S) to J/ψ double ratio measurement from STAR between p+p and p+Au at midrapdity at RHIC:

1.37 ±0.42(stat.) ±0.19(syst.)

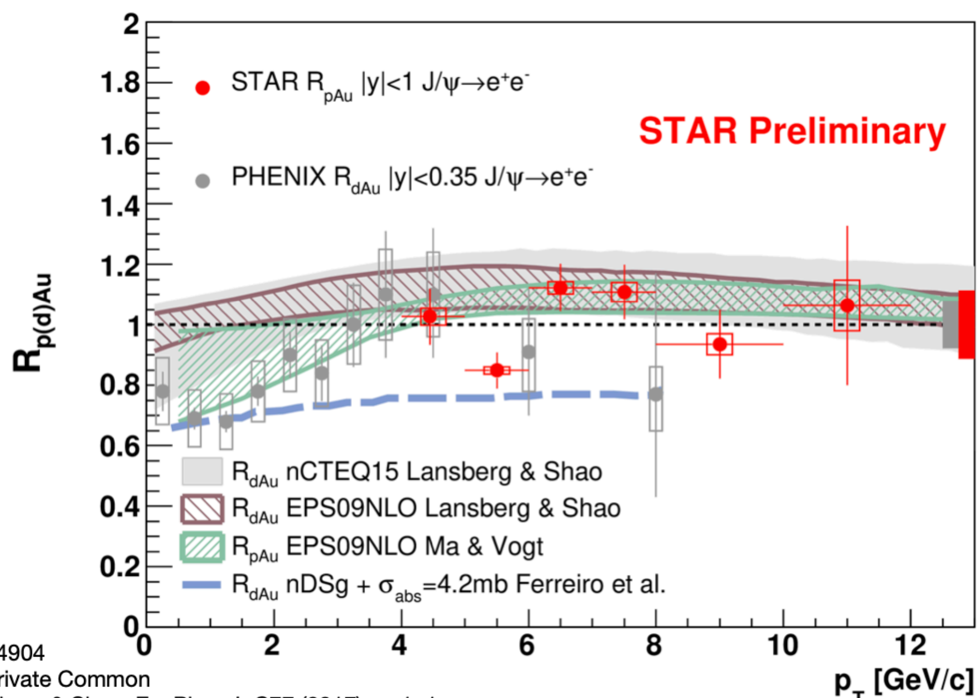




PHENIX p+Au, PRC**95** (2017) 034904
PHENIX d+Au, PRL**111** (2013) 202301
Co-mover calculation, Ferreiro, private comm.

J/ψ R_{pAu} vs. p_T

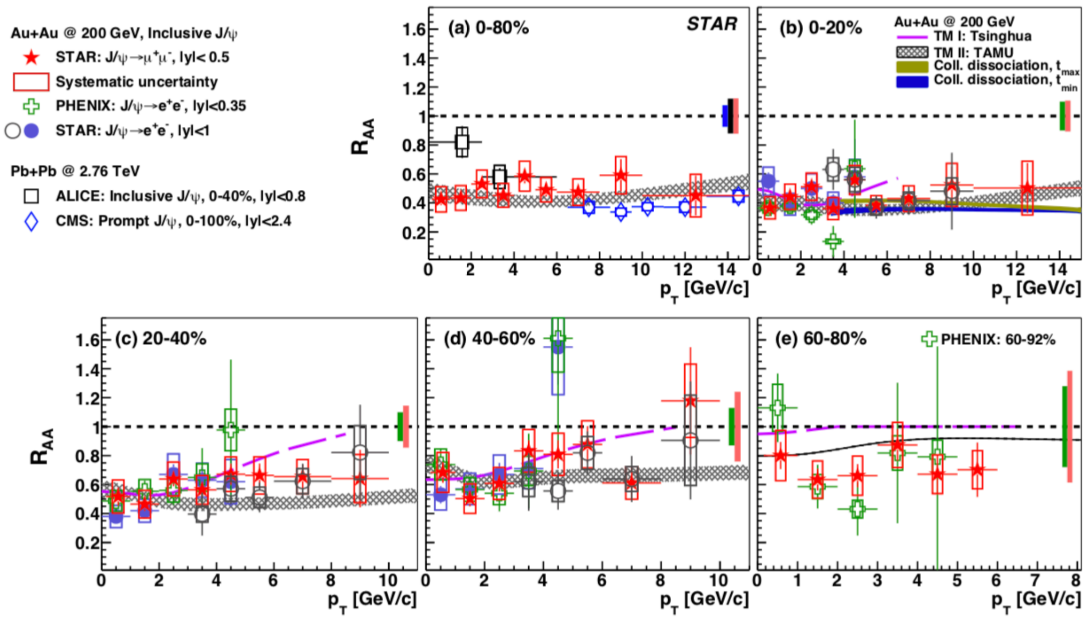
- R_{pAu} from STAR has similar trend as R_{dAu} from PHENIX
  ➔ Similar CNM effects in p+Au and d+Au
- The model calculation with additional nuclear absorption on top of nuclear PDF effects can qualitatively describe the data



PHENIX, PRC 87 (2013) 034904
EPS09+NLO, Ma & Vogt, Private Common
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

J/ψ R_{AA} vs. p_T

- No obvious p_T dependence in R_{AA} in 0 - 20% centrality bin
- Rising R_{AA} with p_T in 20 - 40% and 40 - 60% centrality bins
  - Rising trend at high p_T could be due to formation time effects, B-hadron feed-down
- Suppression at low p_T: dissociation, Cold Nuclear Matter (CNM) effect, regeneration
- Strong suppression at high p_T in central collisions is a clear sign of dissociation since regeneration contribution and CNM effects are small



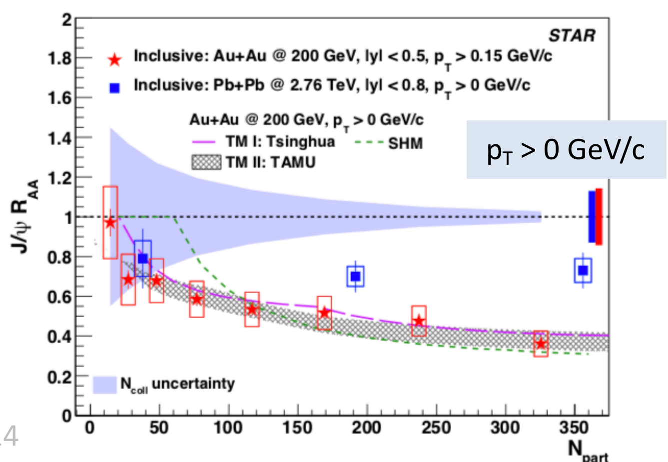
PLB 797 134917, 2019

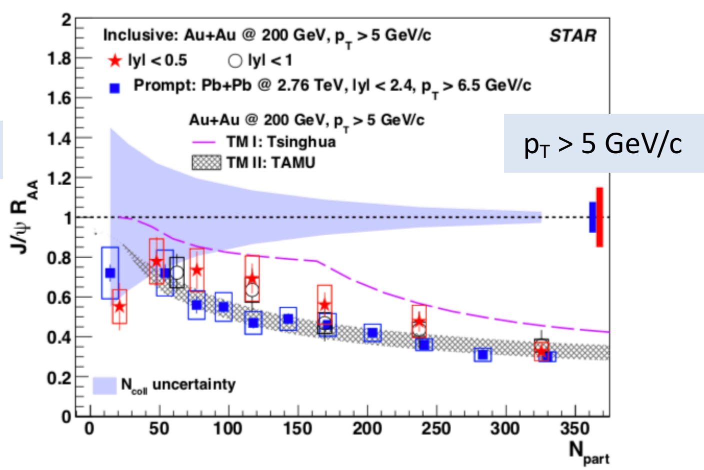
J/ψ R_{AA} vs. N_{part}

Transport model:
Model I at RHIC: PLB 678 (2009) 72
Model I at LHC: PRC 89 (2014) 054911
Model II at RHIC: PRC 82 (2010) 064905
Model II at LHC: NPA 859 (2011) 114

- RHIC vs. LHC
  - p_T > 0 GeV/c: at RHIC suppression increases with centrality, for central collision larger suppression compared to LHC
    - ➔ Larger contribution from regeneration at LHC
  - p_T > 5 GeV/c: less suppression in central collisions at RHIC compared to LHC
    - ➔ Larger dissociation rate at LHC
- Data vs. transport models (dissociation + regeneration effects)
  - p_T > 0 GeV/c: both models can describe the centrality dependence at RHIC, but tend to overestimate suppression at LHC
  - p_T > 5 GeV/c: there is tension among data and models

PLB 797 134917, 2019





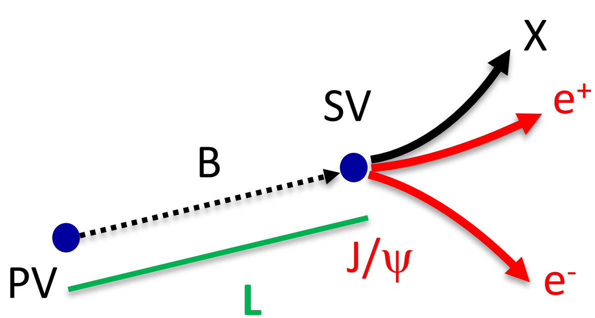
ALICE : PLB 734 (2014) 314
PHENIX : PRL 98 (2007) 232301

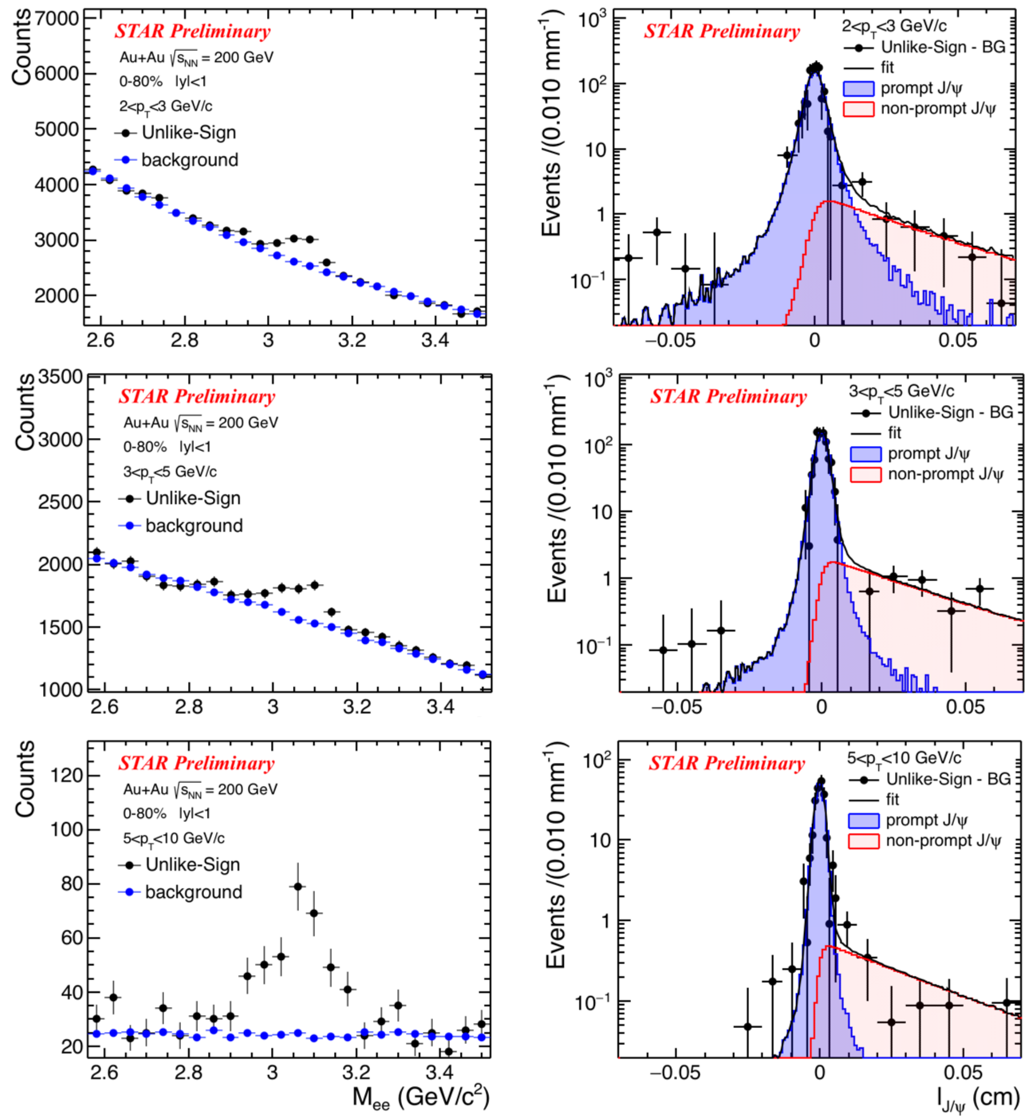
Extract Non-prompt J/ψ Fraction

- Fit the distribution of the pseudo proper decay length with templates to extract non-prompt J/ψ fraction

- Pseudo proper decay length:

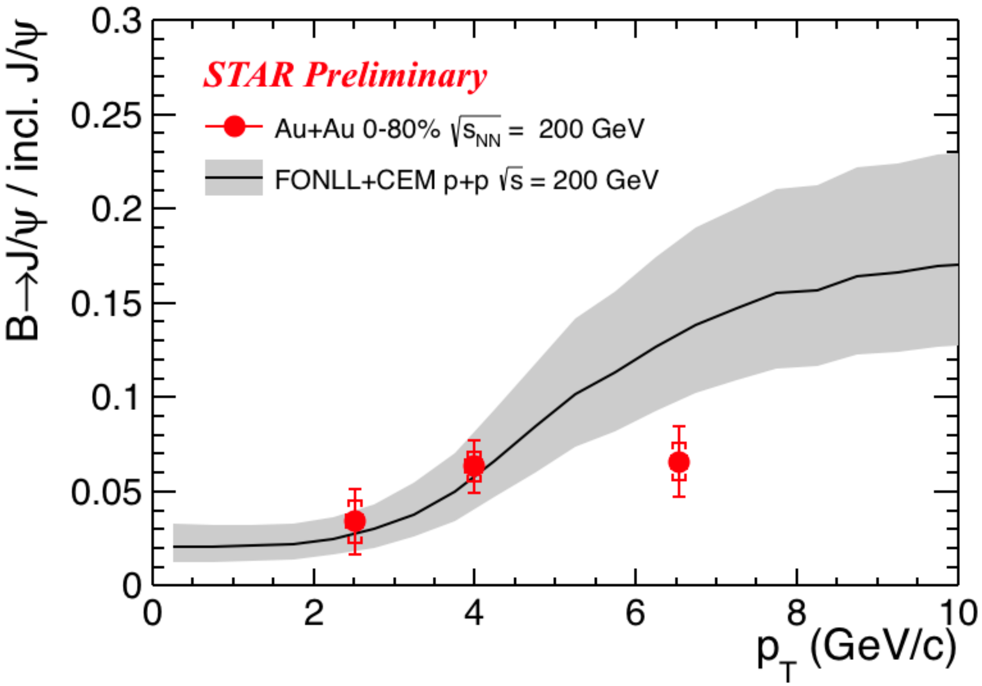
$$l_{J/\psi} = \frac{\vec{L} \cdot \hat{p}}{|\vec{p}|/c} \cdot M_{J/\psi}$$

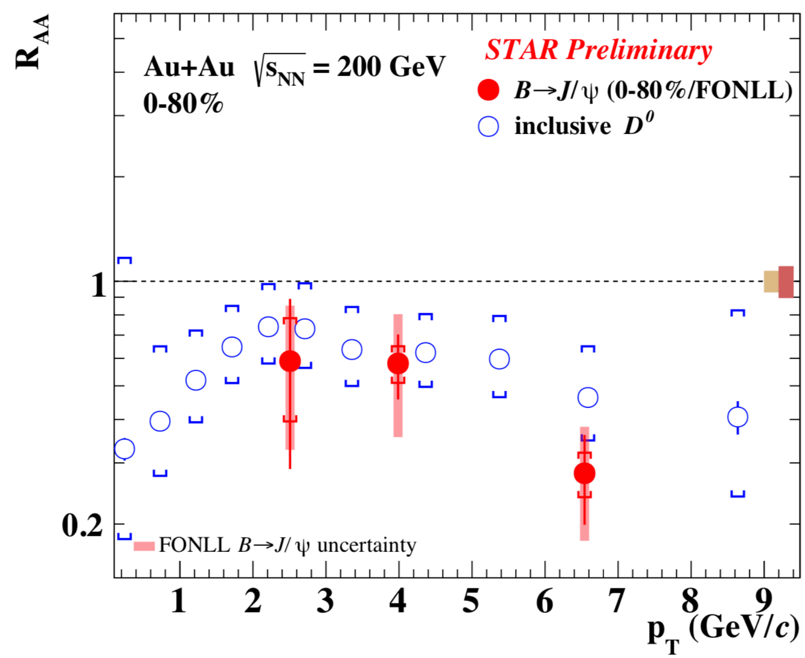




Non-prompt J/ψ Fraction and R_{AA}

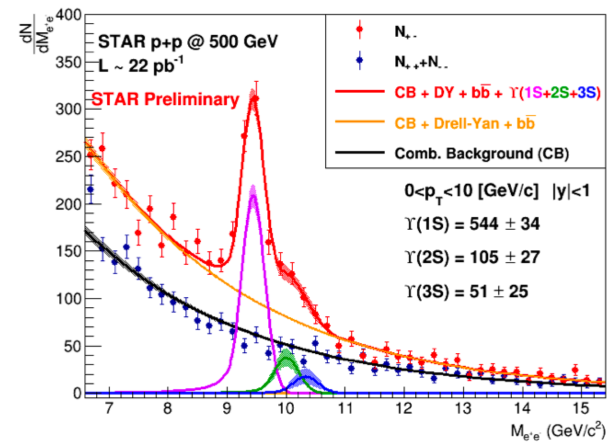
- $$R_{AA}^{B\to J/\psi} = \frac{f_{Au+Au}^{B\to J/\psi}(Data)}{f_{p+p}^{B\to J/\psi}(Theory)} R_{AA}^{inc.J/\psi}(Data)$$
- Observe strong suppression of B → J/ψ at high p_T (> 5 GeV/c)
- Similar to inclusive D^0 R_{AA}

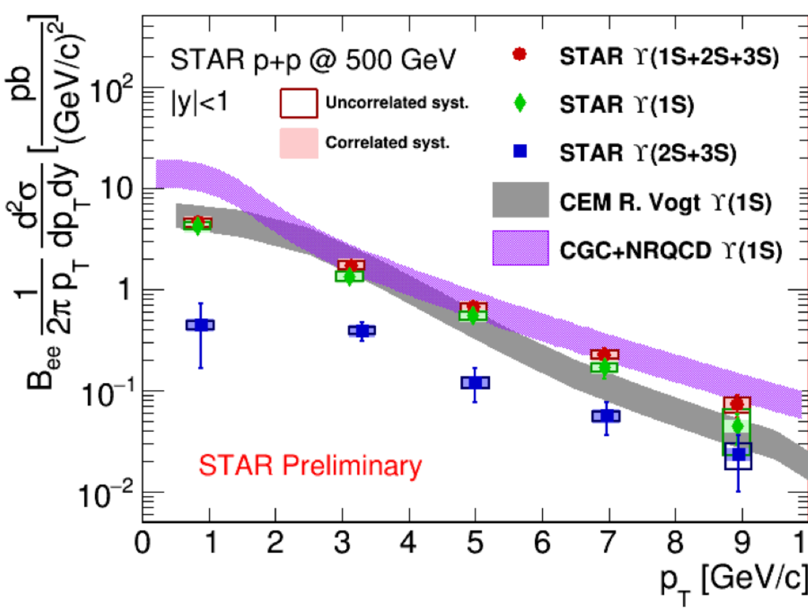


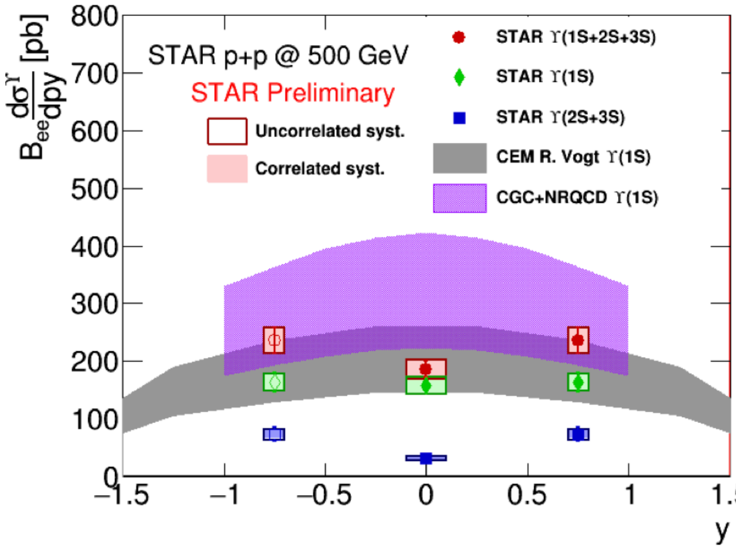


Υ in p+p Collisions @ 500 GeV

- The inclusive $\Upsilon(1S)$ production can be described by CEM predictions
- CGC+NRQCD calculation including only direct $\Upsilon(1S)$ overestimates the inclusive $\Upsilon(1S)$ measurement





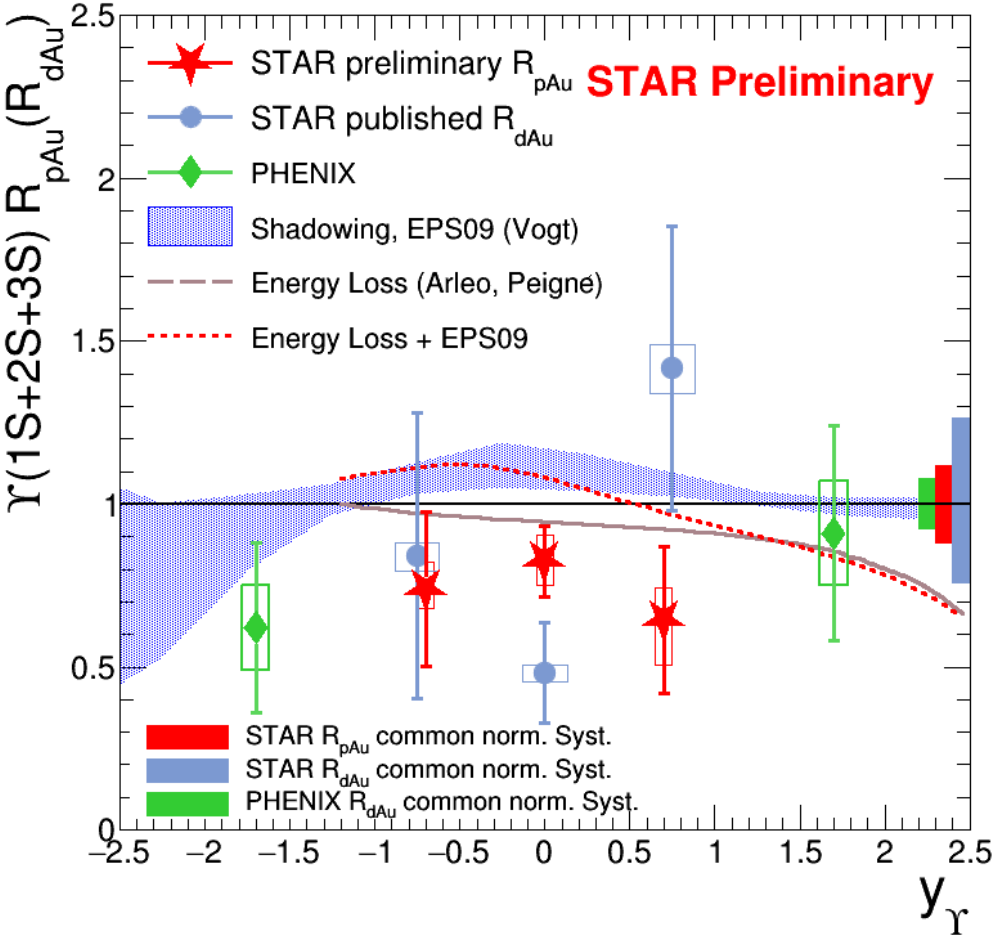


CEM: Phys.Rev.C 92 034909(2015)

CGC+NRQCD: Phys.Rev.D 94, 014028(2016), Phys.Rev.Lett. 113, 192301(2014)

Υ in p+Au Collisions @ 200 GeV

- $R_{pAu} = 0.82 \pm 0.10$ (stat.) $^{+0.08}_{-0.07}$ (syst.) ± 0.10 (global)
  - ➔ Quantify CNM effects

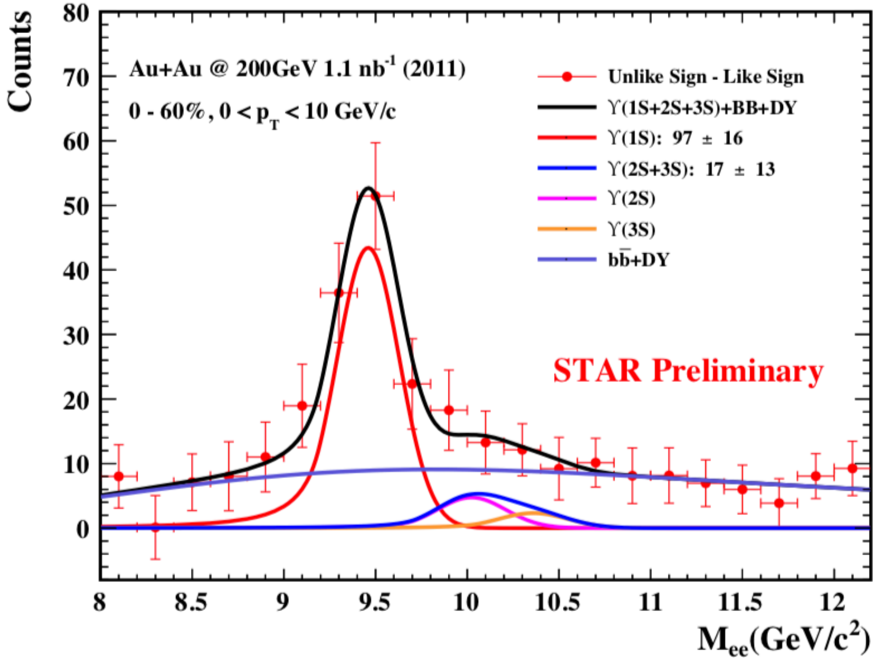


STAR, PLB 735 (2014) 127
PHENIX, PRC 87 (2013) 044909
JHEP 1303, 122 (2013)

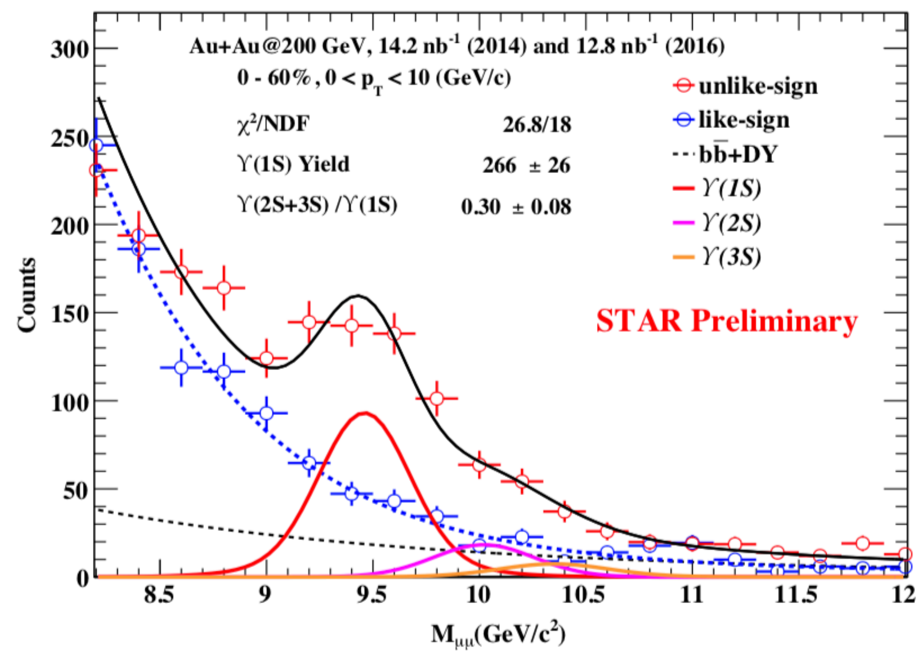
Υ in Au+Au Collisions @ 200 GeV

- Clear Υ(1S, 2S, 3S) signals in Au+Au collisions
  - ➔ First Υ(1S, 2S, 3S) → $\mu^+\mu^-$ measurement at STAR

$\Upsilon \to e^+e^-$

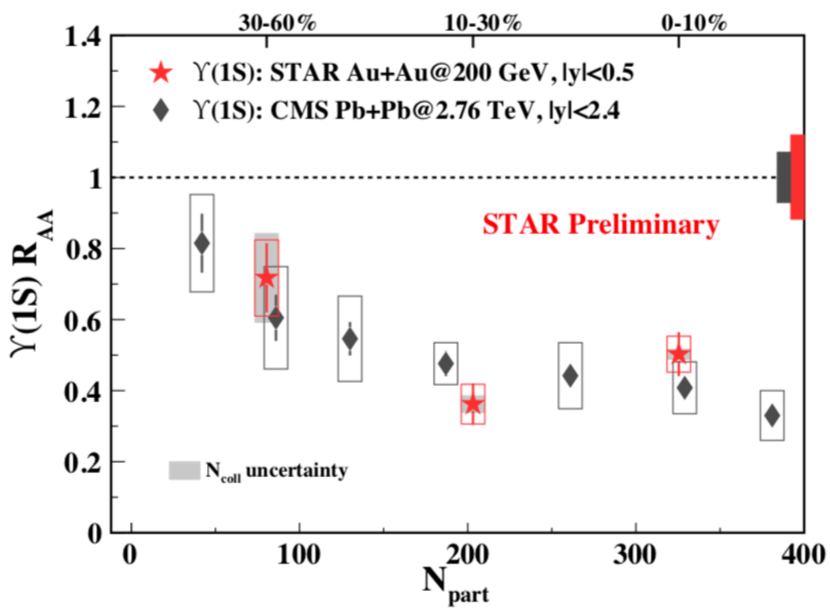


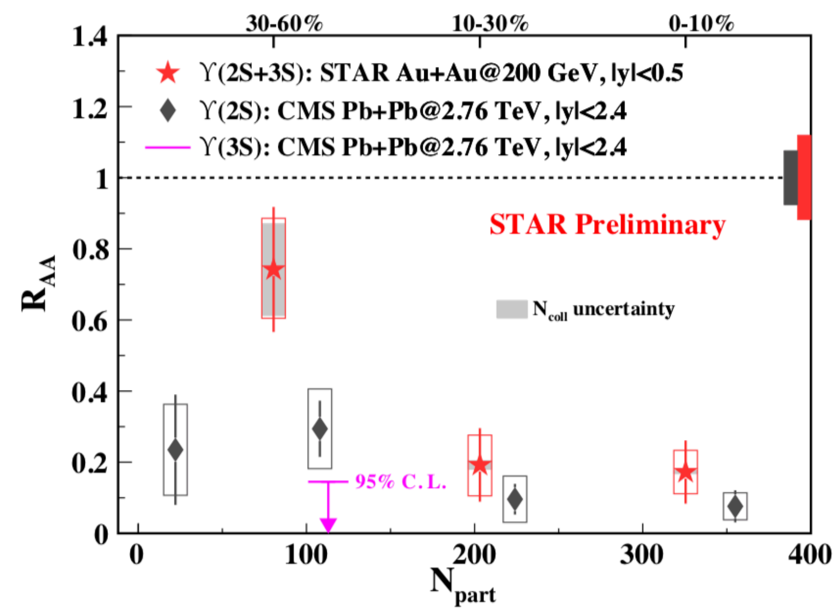
$\Upsilon \to \mu^+\mu^-$



Υ R_{AA} vs. N_{part}

- Suppression increasing with centrality
- Υ(2S+3S) is more suppressed than Υ(1S), in central collisions
  - ➔ **Sequential melting**
- RHIC vs. LHC:
  - Υ(1S): similar suppression as the CMS measurement
  - Υ(2S+3S): hint of less suppression at RHIC than at LHC

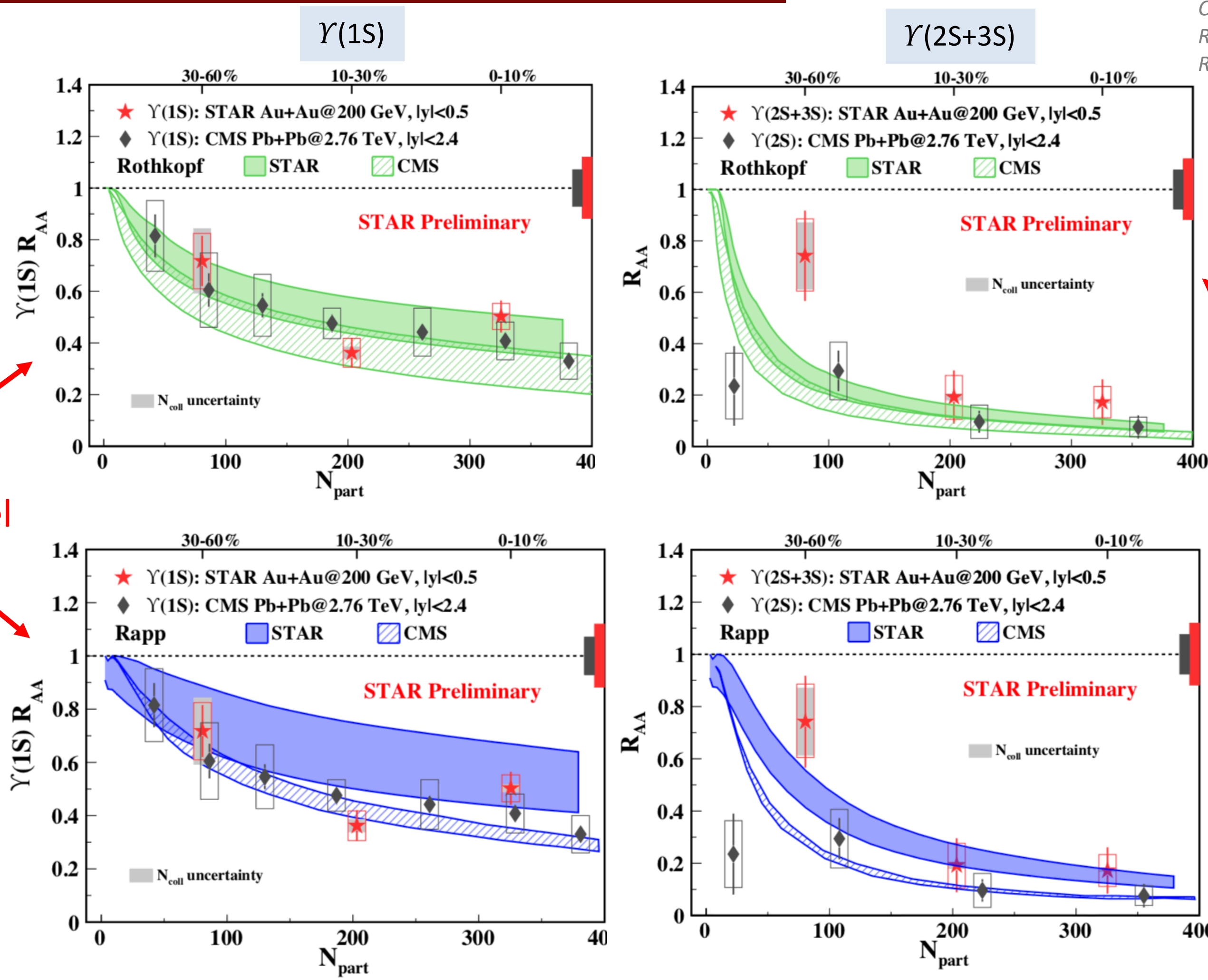




CMS: Phys. Lett. B 770 (2017) 357–379

Υ R_{AA} vs. Models

CMS: PLB 770, 357 (2017)
Rothkopf: PRD 97, 016017 (2018)
Rapp: PRC 96, 054901 (2017)



Both Rothkopf's and Rapp's model can describe Υ(1S)

Rapp's model can describe Υ(2S+3S), but Rothkopf's model slightly Underestimates data in 30-60%

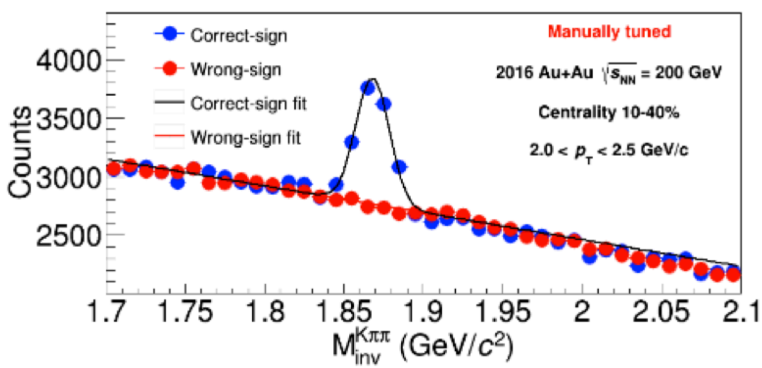
Rothkopf: using a lattice QCD vetted, complex-valued, heavy-quark potential embedded in a realistic, hydrodynamically evolving medium background

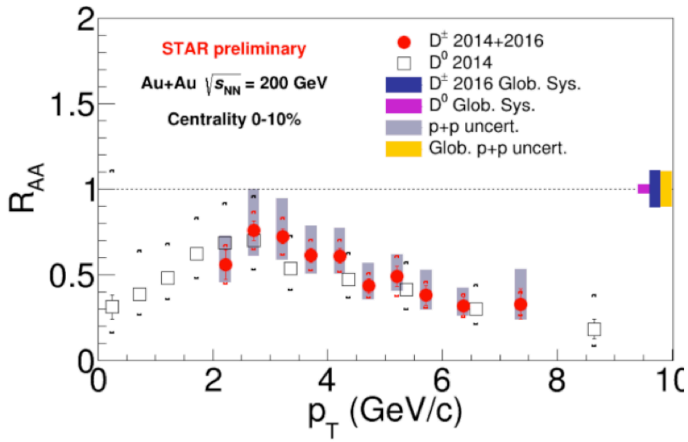
Rapp: using temperature-dependent binding energies and pertinent reaction rates, B-meson resonance states in the equilibrium limit near the hadronization temperature, and a lattice-QCD based equation of state for the bulk medium

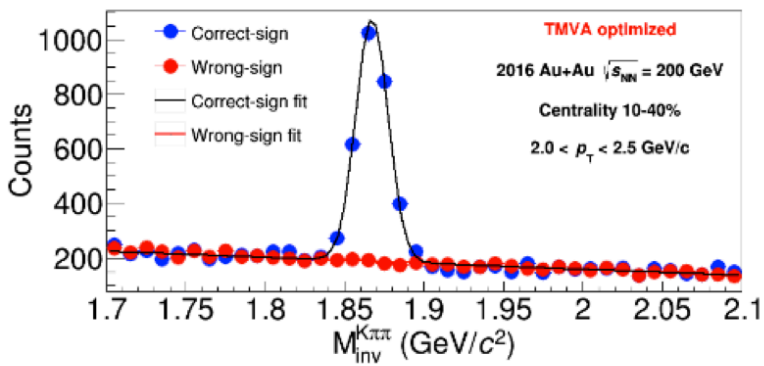
$D^{\pm}$ in Au+Au Collisions @ 200 GeV

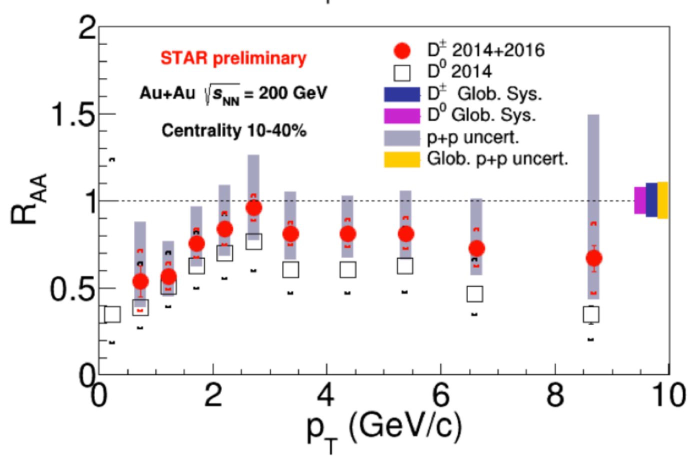
- $D^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}$ reconstructed topologically using HFT detector
- Measured $D^{\pm}$ R_{AA} is comparable to D^0 within uncertainties

➔ Significant suppression at in central Au+Au at high p_T



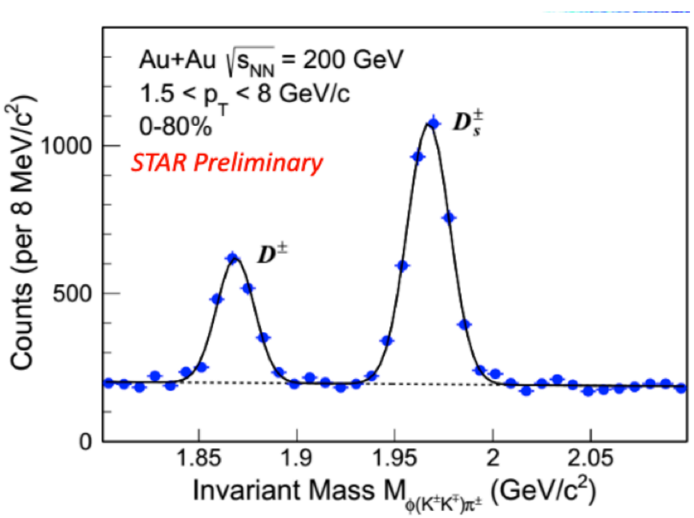


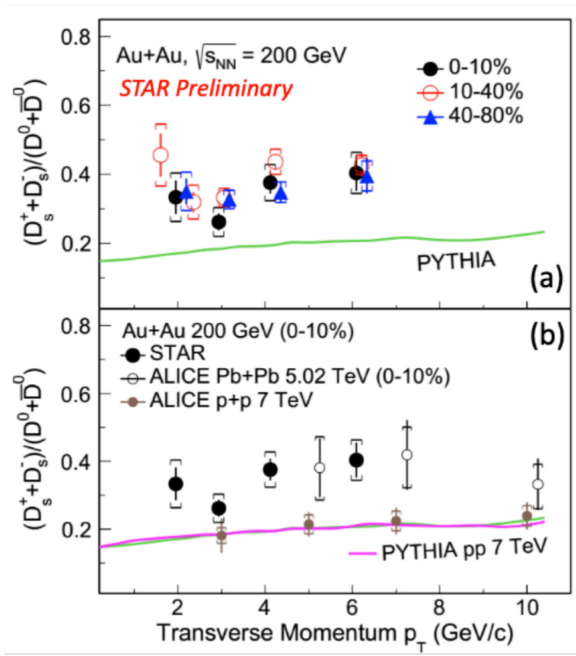


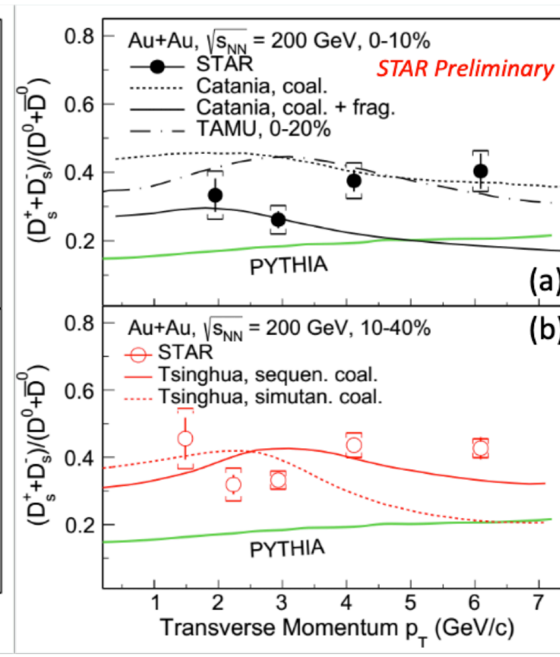


$D_s^{\pm}$ in Au+Au Collisions @ 200 GeV

- Good probe of **strangeness enhancement** and **coalescence hadronization**
- Significant enhancement in $D_s^{\pm}/D^0$ ratio compared to PYTHIA and p+p
  - No strong centrality dependence
  - Comparable to ALICE Pb+Pb data
- Various models describe data at high or low p_T with varying degree of quality

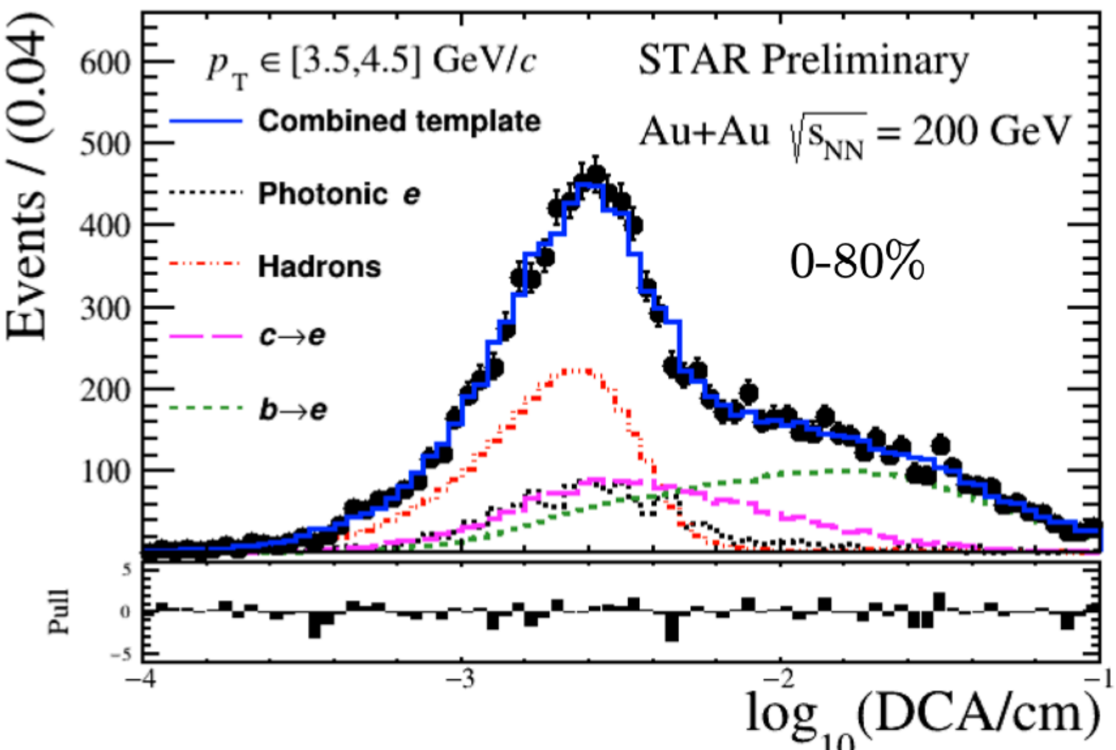


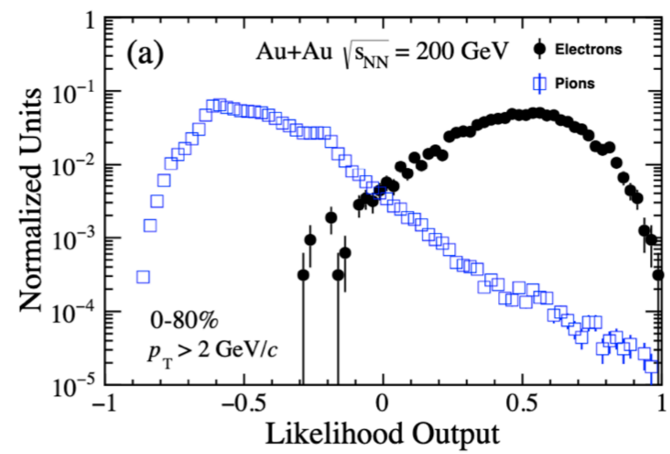


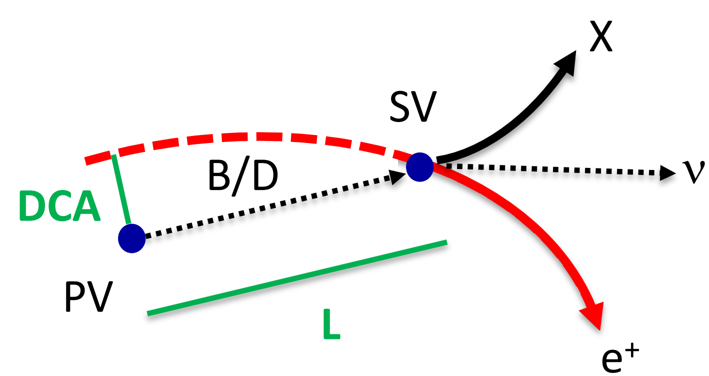


B/D → e (HFE) Fraction in Au+Au 200 GeV

- Excellent track pointing resolution from HFT enables the usage of the DCA distribution to distinguish different sources contributing to inclusive electrons



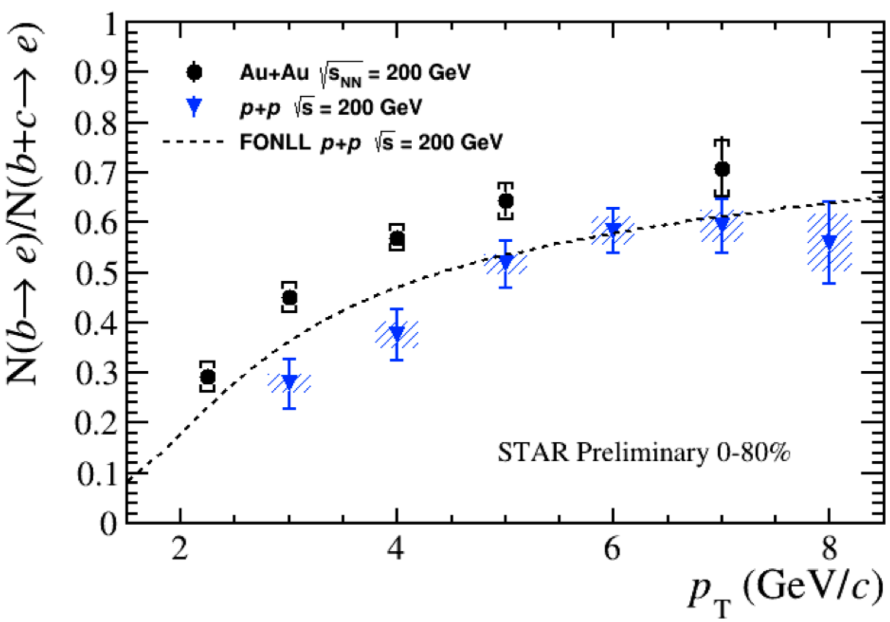


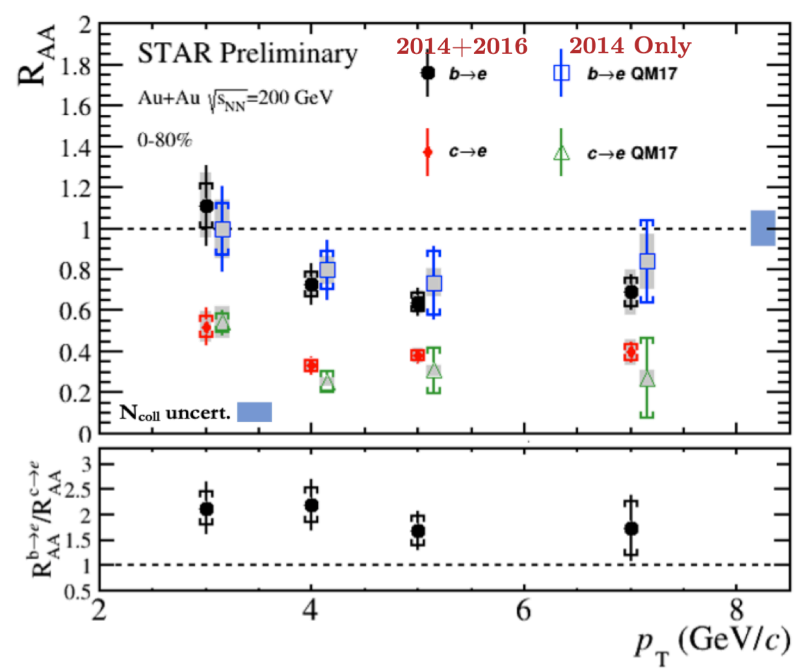


b/c → e (HFe) R_{AA} in Au+Au 200 GeV

$$R_{AA}^{B\to e} = \frac{f_{Au+Au}^{B\to e}(Data)}{f_{p+p}^{B\to e}(Data)} R_{AA}^{HF_e}(Data) \qquad R_{AA}^{D\to e} = \frac{1 - f_{Au+Au}^{B\to e}(Data)}{1 - f_{p+p}^{B\to e}(Data)} R_{AA}^{HF_e}(Data)$$

- b → e fraction shows an enhancement relative to that measured in p+p collisions at STAR
- Clear picture of the *e*nergy loss for c and b quark which is consistent with ΔE(b) < ΔE(c)





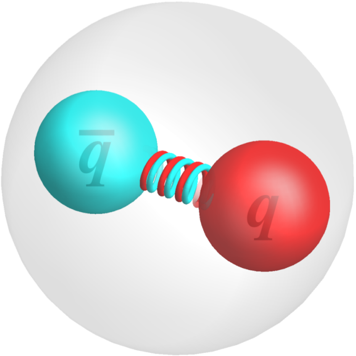
Summary

Stay tuned for more Heavy Flavor results from STAR in the next few years!

Backup

Heavy Quarkonium

- The bound state of two heavy quarks ($q\bar{q}$)
  - **J/ψ** is a $c\bar{c}$ (1974) and **ϒ** is a $b\bar{b}$ (1977) bound state
- Historically physicists tried to understand the production mechanism and polarization
- The production includes two parts:
  - **Hard process (short distance):** the production of $q\bar{q}$ pair and it can be calculated by pQCD
  - **Soft process (long distance):** the formation of quarkonium from $q\bar{q}$ and it can be parameterized by phenomenological models



Promptly/Non-promptly Produced Quarkonium

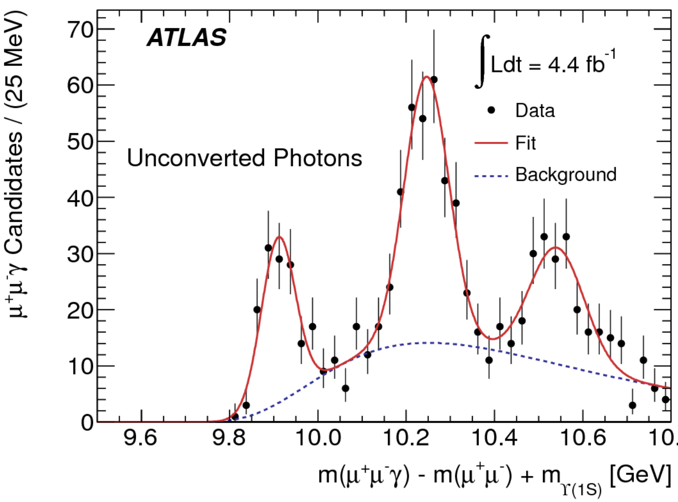
- **Prompt quarkonium** includes two contributions:
  - Direct production from hard process
  - Decays of excited (heavier) states
- **Non-prompt quarkonium (J/ψ)** comes from decays of B-hadron

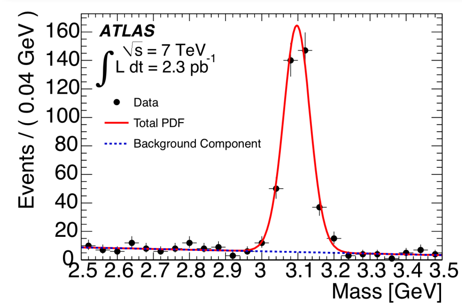
➔ Simultaneous fit on mass and pseudo-proper time to extract the non-prompt contribution

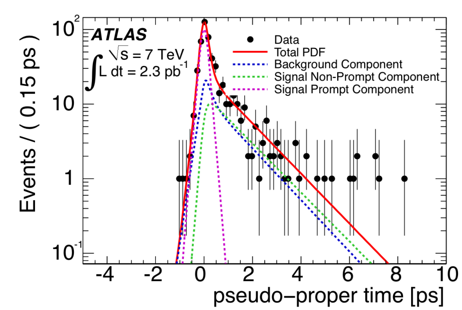
Pseudo-proper time: $\tau = \frac{L_{xy}\, m^{J/\psi}_{\mathrm{PDG}}}{p_T^{J/\psi}}$.

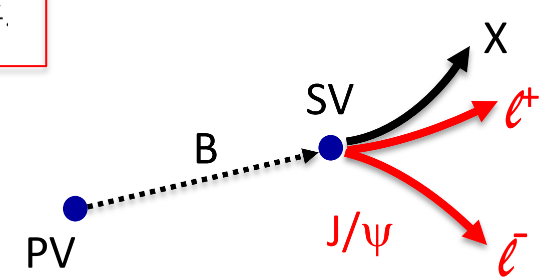
pp at 7 TeV:
$\chi_b(3P) \rightarrow \Upsilon(1S) + \gamma \rightarrow \mu^+\mu^-\gamma$

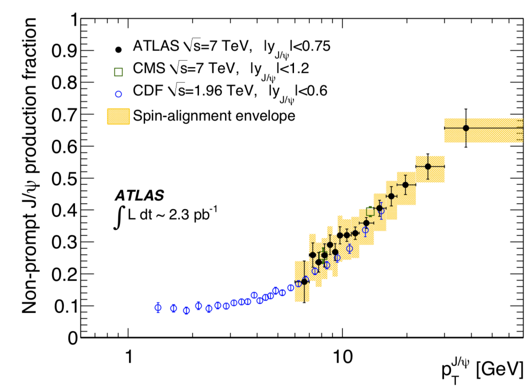
ATLAS: Phys. Rev. Lett. 108 152001, 2012









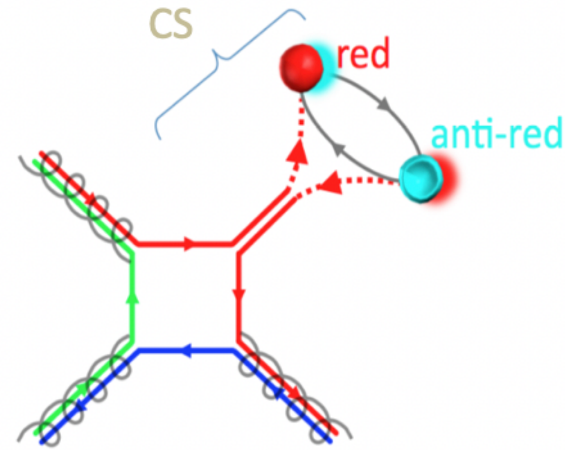


Quarkonium Production: CSM

- **Color Singlet Model (CSM):**
  - The quantum numbers (spin, color) of the final and initial states are the same

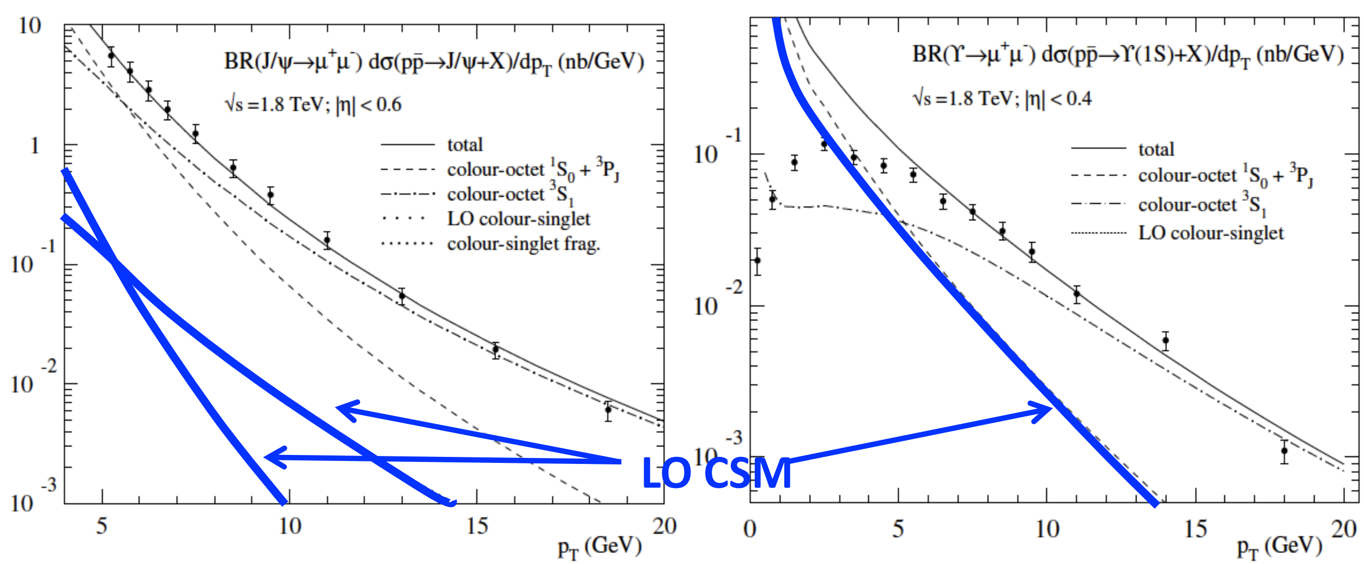
    ➔ The final state must be color singlet (colorless)
  - Large discrepancies between experimental results and predictions

C-H. Chang, Nucl. Phys. B 172, 425 (1980);
R. Baier and R. Ru ckl, Phys. Lett. B 102, 364 (1981);
Z. Phys. C 19, 251 (1983);
E. L. Berger, D. L. Jones, Phys. Rev. D 23, 1521 (1981).



From Cristina Biino's Talk (FPCP2013)

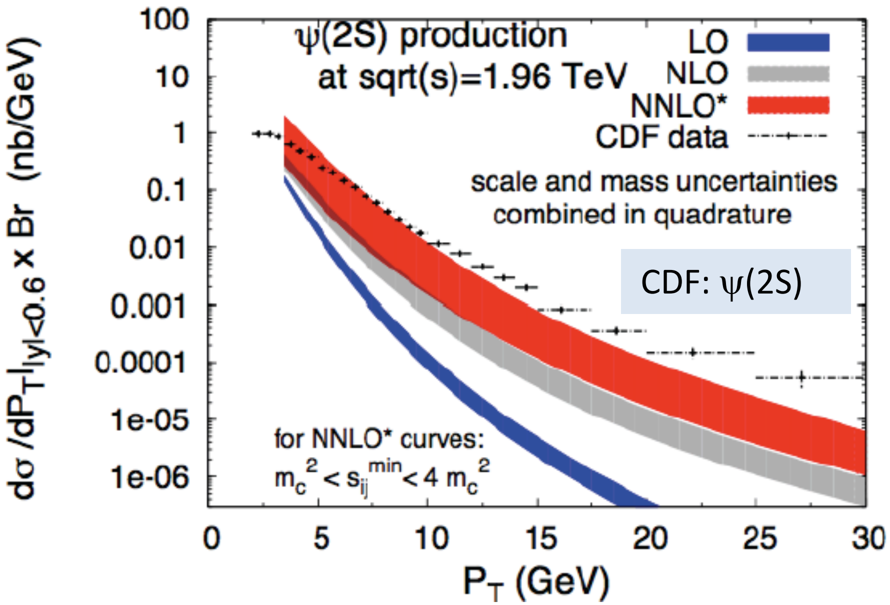
CDF: J/ψ

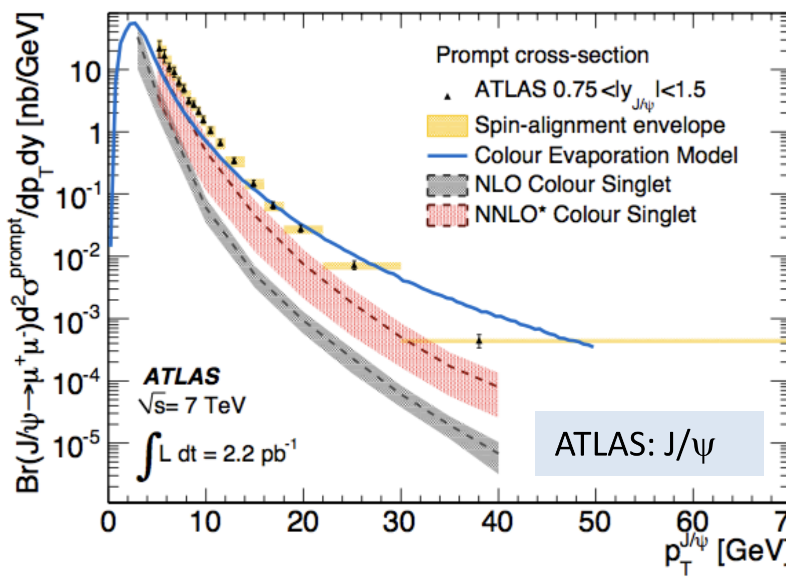


CDF: ϒ(1S)

Higher Order Predictions in CSM

- The contribution from NNLO* contribution in CSM is found to be significant
- Good agreement with Tevatron and LHC results (generally)





J.P. Lansberg arXiv:1303.2858

ATLAS: Nucl. Phys. B 850, 3, 2011

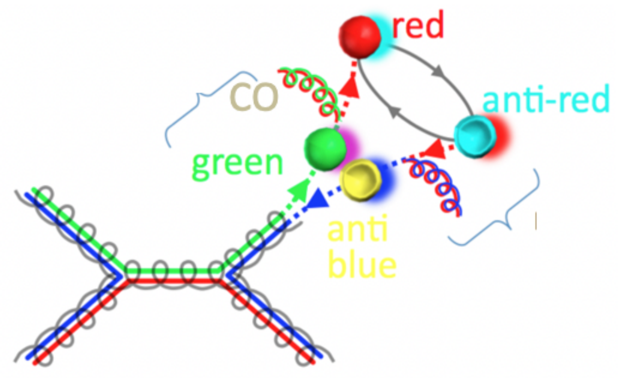
Note : NNLO* is not full NNLO calculation, currently only real contribution up to α_s^5 has been calculated (corresponds to sum of the NLO yield and contributions from $pp \rightarrow Q + jjj$)

Quarkonium Production: COM/NRQCD

- **Color Octet Mechanism (COM)/NRQCD:**
  - The quantum numbers of the initial and final quark pairs can be different

➔ Can be evolved into a particular quarkonium state through radiation of soft gluons

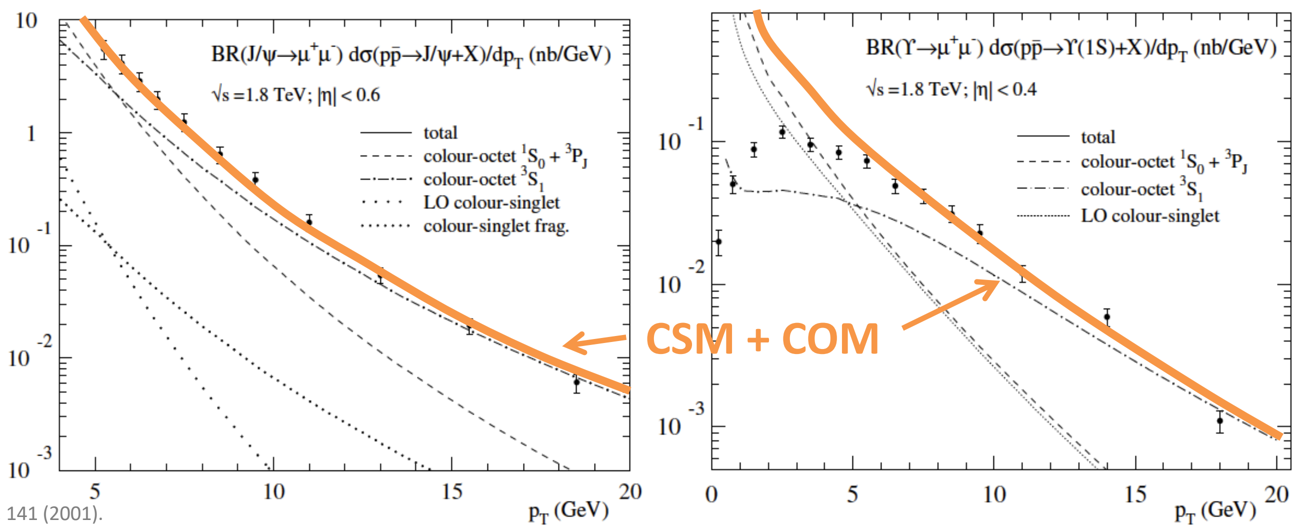
➔ Great success!



From Cristina Biino's Talk (FPCP2013)

Y.Q. Ma et al., Phys. Rev. Lett. 106, 042002 (2011).

CDF: J/ψ



CDF: ϒ(1S)

M. Kramer, Prog. Part. Nucl. Phys. 47, 141 (2001).

Quarkonium Production: CEM

- **Color Evaporation Model (CEM):**
  - Similar to the COM, it allows the initial quark pairs to be produced in a color-octet state

    ➔ But it can't provide the polarization prediction
  - **"Improved" CEM (ICEM)** overcomes this issue by sorting out different spin states

    ➔ Can provide the polarization prediction!
- **Color Glass Condensate effective theory (CGC):**
  - A systematic weak coupling framework

    ➔ Combining with NRQCD can provide low-p_T cross-section for quarkonium

CEM:
H. Fritzsch, Phys. Lett. B 67, 217 (1977);
F. Halzen, Phys. Lett. B 69, 105 (1977);
M. Gluck, J. F. Owens, and E. Reya, Phys. Rev.D 17, 2324 (1978);
V. D. Barger, W. Y. Keung, and R. J. N. Phillips, Phys. Lett. B 91, 253 (1980);
J. F. Amundson, O. J. P. Eboli, E. M. Gregores and F. Halzen, Phys. Lett. B 372, 127 (1996);
J. F. Amundson, O. J. P. Eboli, E. M. Gregores and F. Halzen, Phys. Lett. B 390, 323 (1997).

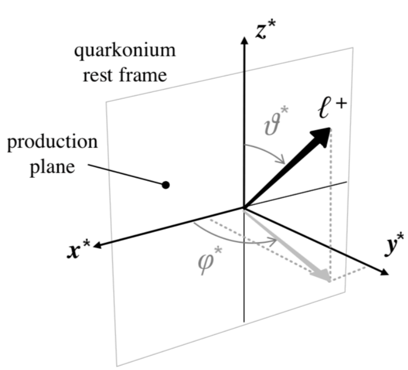
ICEM: Y. Q. Ma and R. Vogt, Phys. Rev. D 94, 114029 (2016).

CGC: Y.Q. Ma and R. Venugopalan, Phys. Rev. Lett. 113, 192301 (2014).

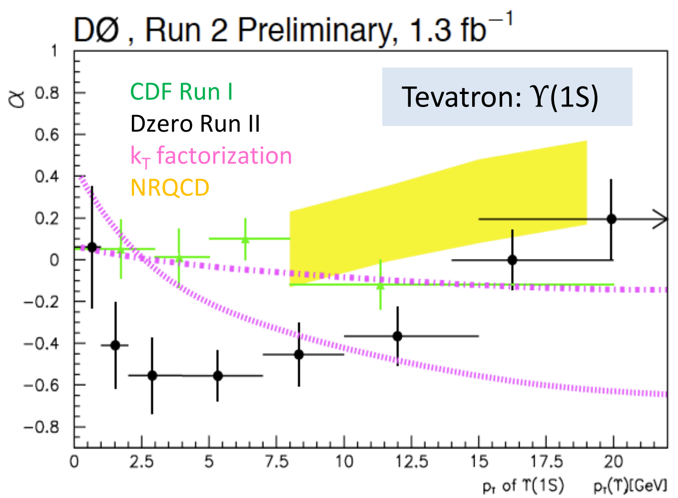
Quarkonium Polarization Puzzle

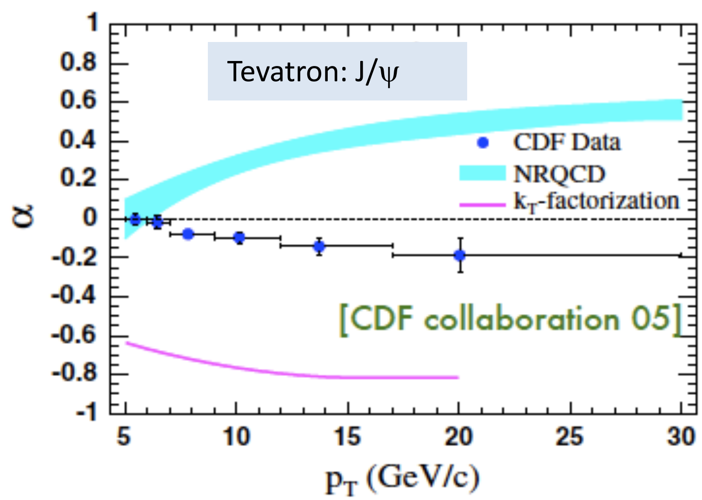
- The previous Tevatron results show the discrepancy between "data and theoretical prediction" and even "CDF and Dzero results"
  - ➔ Only considered 1D polarization: $1 + \alpha\cos^2\theta$
  - ➔ Need λ_θ, λ_ϕ and $\lambda_{\theta\phi}$:

$$\frac{d^2N}{d\cos\theta^\star d\phi^\star} \propto 1 + \lambda_\theta \cos^2\theta^\star + \lambda_\phi \sin^2\theta^\star \cos 2\phi^\star + \lambda_{\theta\phi} \sin 2\theta^\star \cos\phi^\star$$



P. Faccioli et al., Eur. Phys. J. C 69, 657673 (2010)





Quarkonium Polarization

- The helicity axis (HX) corresponding to the quarkonium flight direction in the center-of-mass of the colliding beams
- The Collins-Soper (CS) axis defined by the direction of the relative velocity of the colliding beams in the quarkonium rest-frame.