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Heavy Flavor Measurements at STAR

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OP Vzdělávání pro konkurenceschopnost
INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

Heavy flavor physics at STAR

- sQGP signatures and properties using heavy quarks (c, b)

1. Open Heavy Flavor
2. Quarkonia

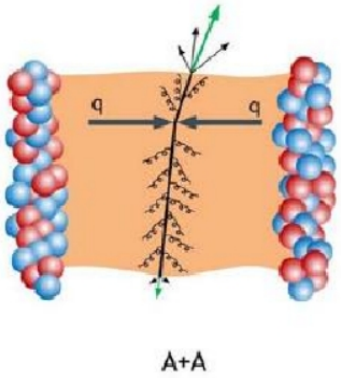
p+p	200 and 500 GeV
d+Au	200 GeV
Au+Au	39, 62.4 and 200 GeV
U+U	193 GeV

…many more not covered

- Outlook: data analysis with the newly installed HFT and MTD

1. Open heavy flavor

- Heavy quarks c, b
  - Produced in initial hard processes
  - Probe the strongly interacting Quark–Gluon Plasma
  - Modified spectrum: access parton energy loss
  - Flow: sensitive to dynamics, thermalization



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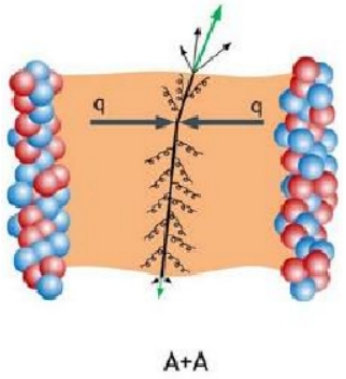
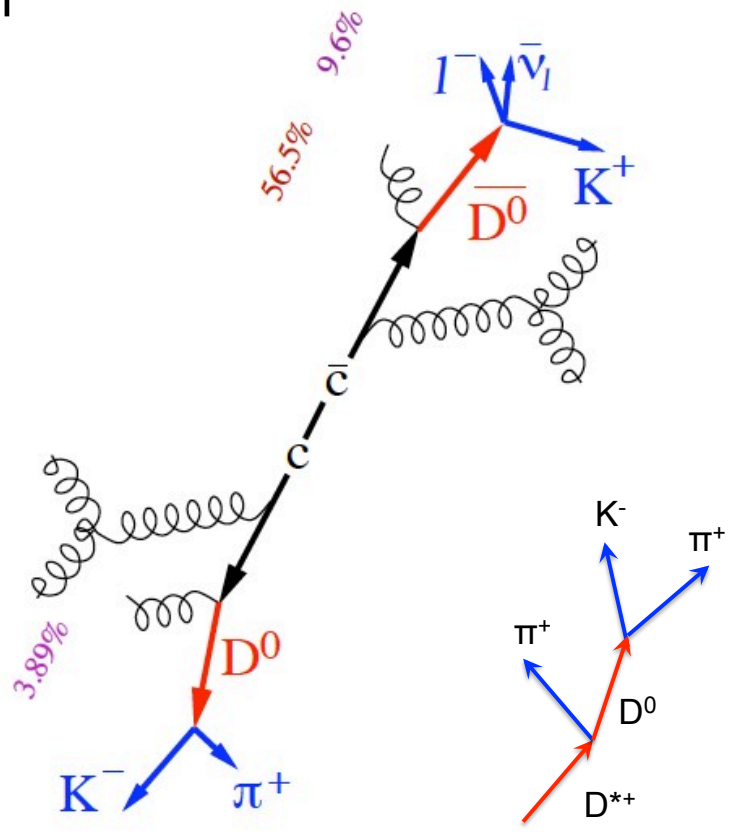


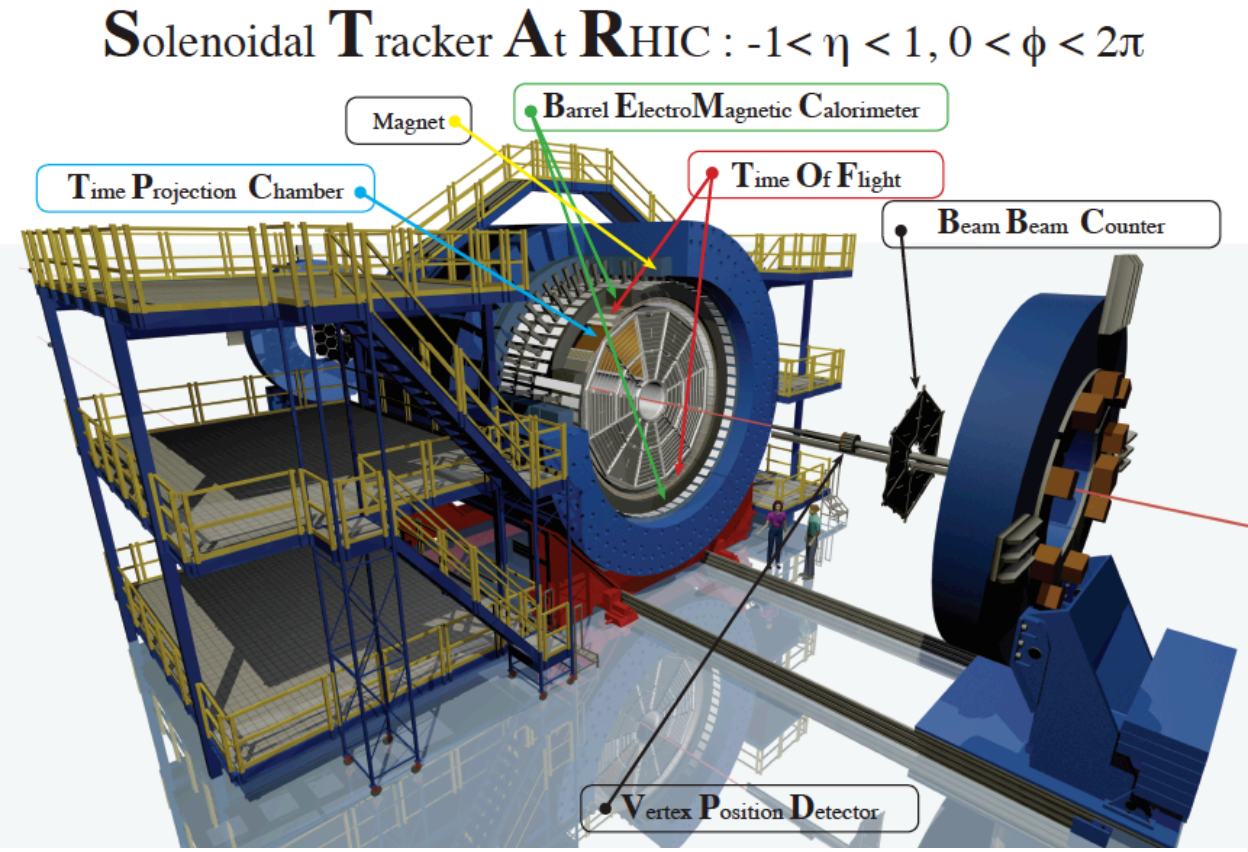
- Semi-leptonic decays
  - Higher branching ratio, easy to trigger on
  - Indirect access to kinematics, mixture of c and b contributions

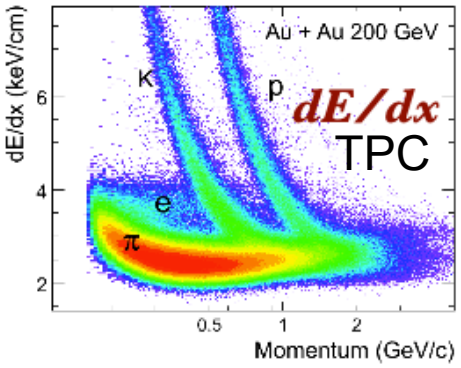
- Hadronic reconstruction
  - Direct access to kinematics
  - Large combinatorial bg., difficult to trigger

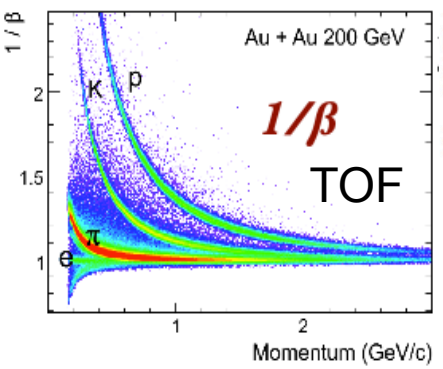


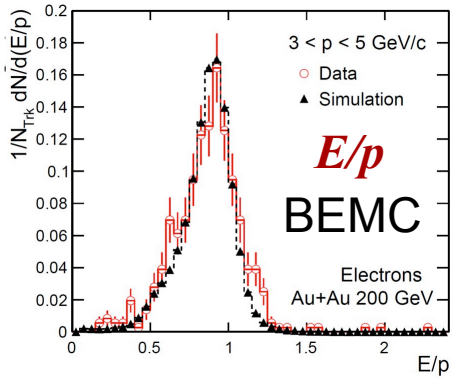
RHIC/STAR

- TPC
  - dE/dx PID
  - Large acceptance, uniform in a wide energy range
- TOF
  - PID using flight time
- BEMC
  - High-p_T trigger
  - PID using E/p ratio
- VPD
  - Trigger minimum bias events

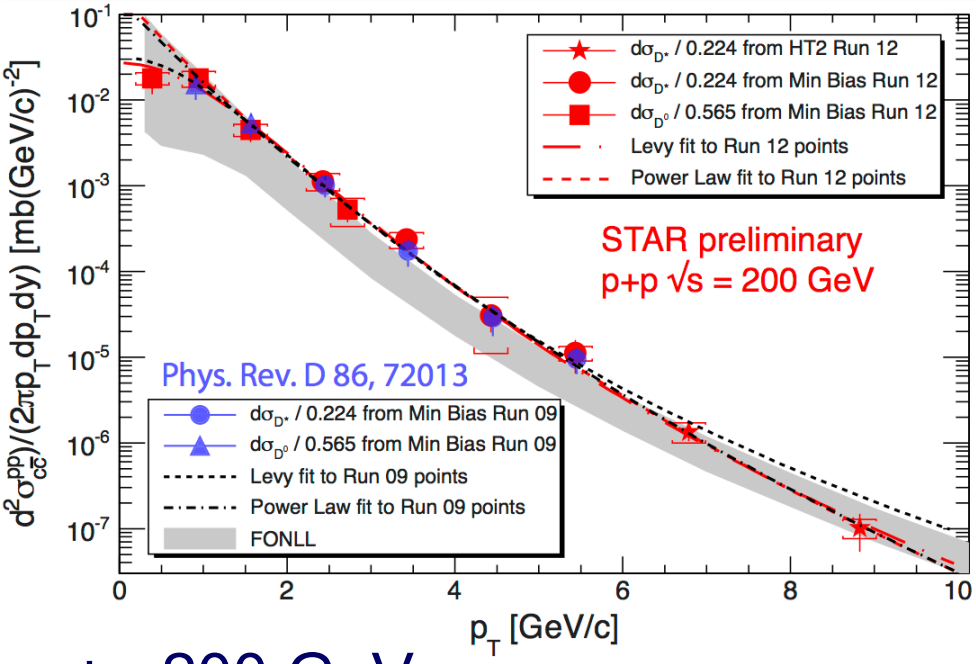








D^0 and D* production in p+p

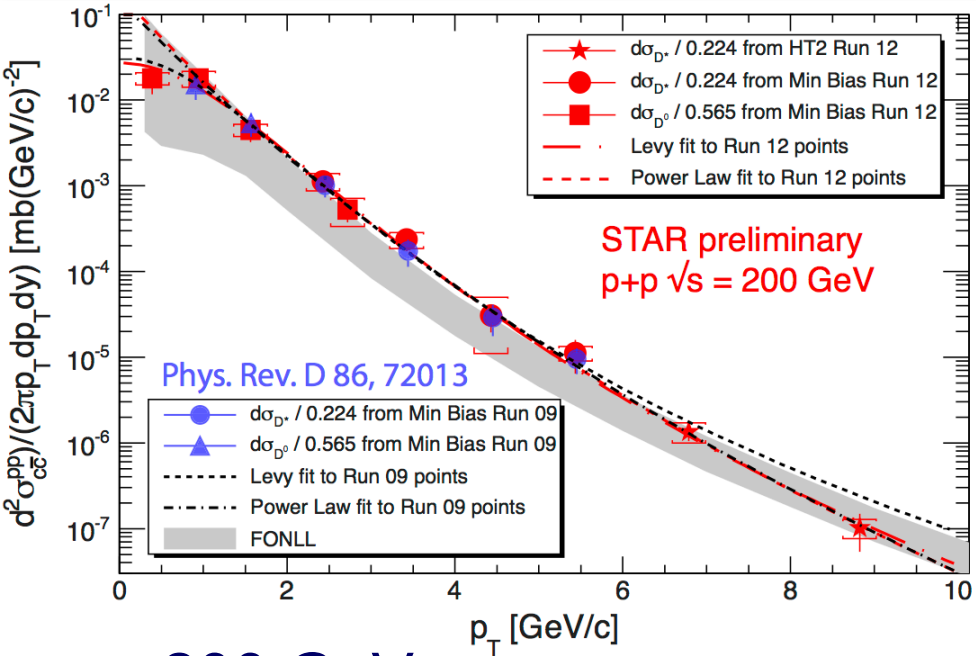


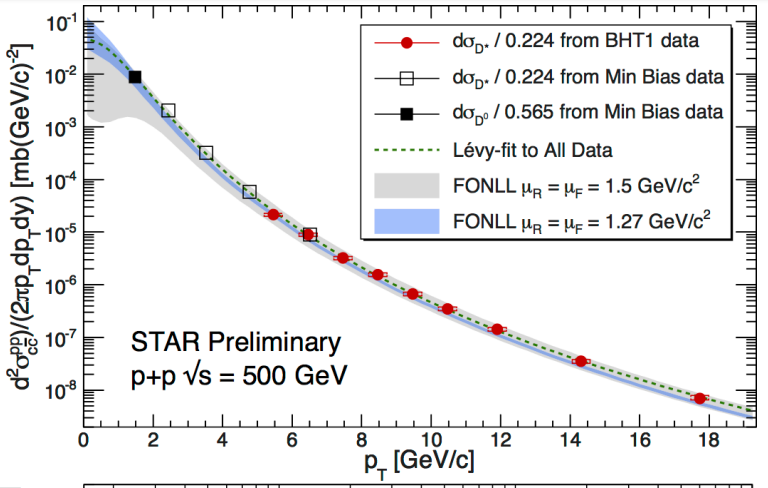
p+p 200 GeV

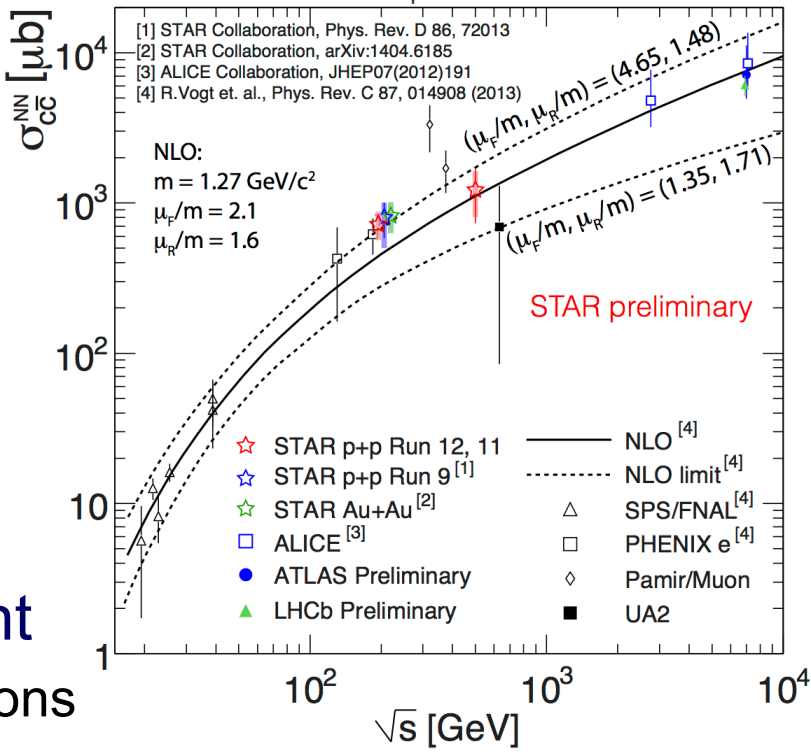
- Essential as a baseline for A+A
- Consistent with FONLL upper limit
- New point at $0<p_T<0.7$ GeV/c

  → Lévy fit describes data well

D^0 and D* production in p+p







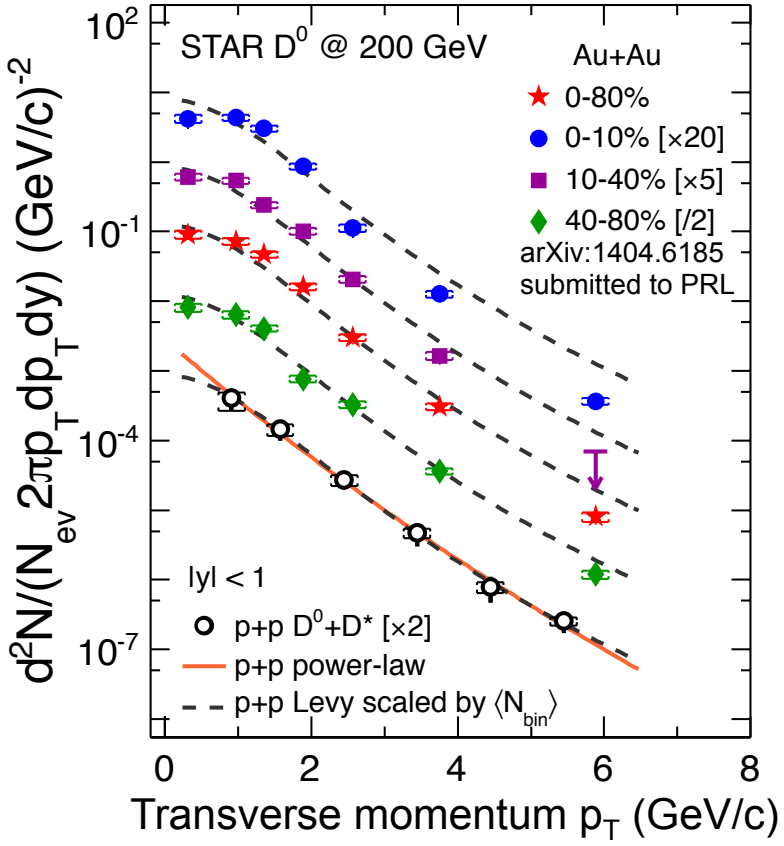
p+p 200 GeV

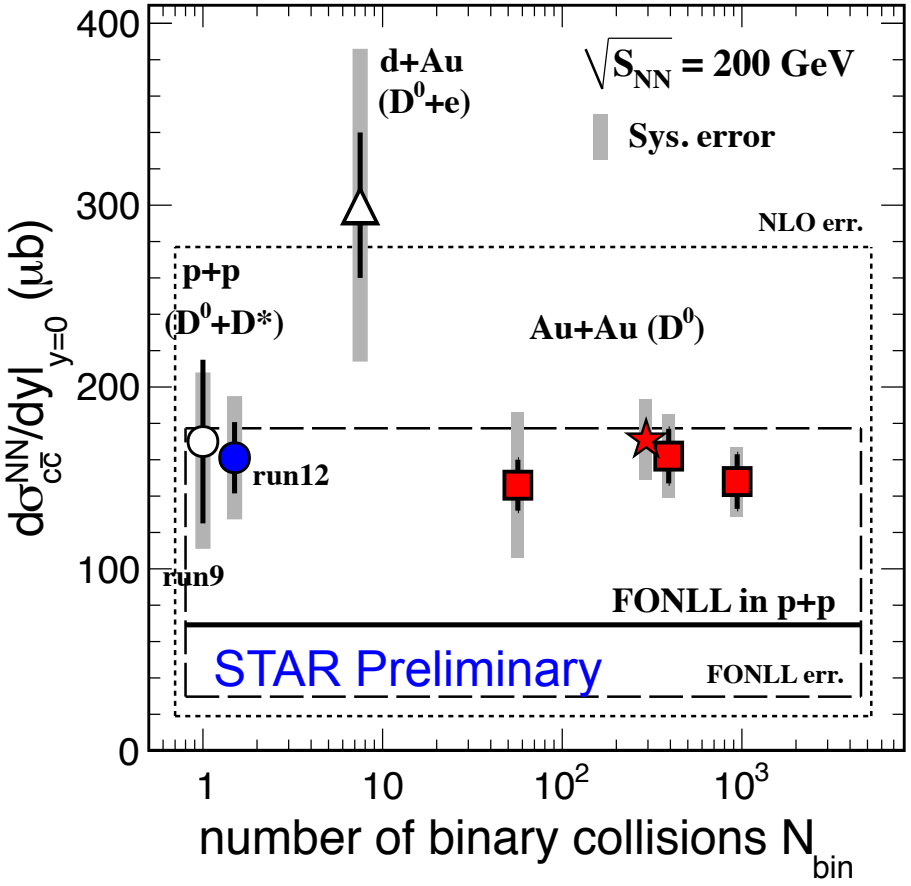
- Essential as a baseline for A+A
- Consistent with FONLL upper limit
- New point at $0<p_T<0.7$ GeV/c
  → Lévy fit describes data well

New 500 GeV measurement

- Consistent with NLO calculations

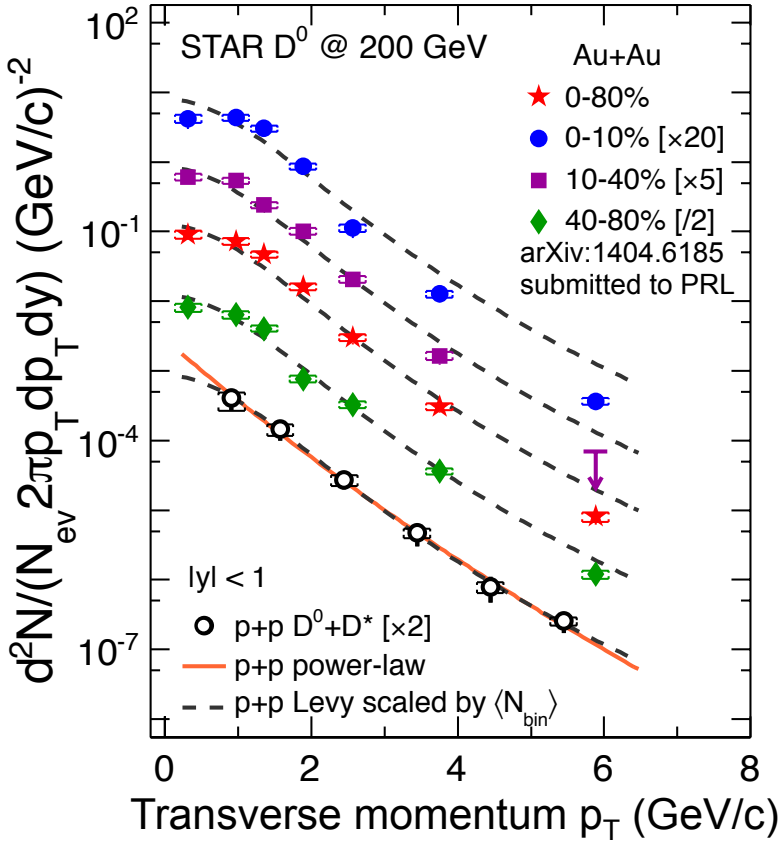
D^0 production in Au+Au

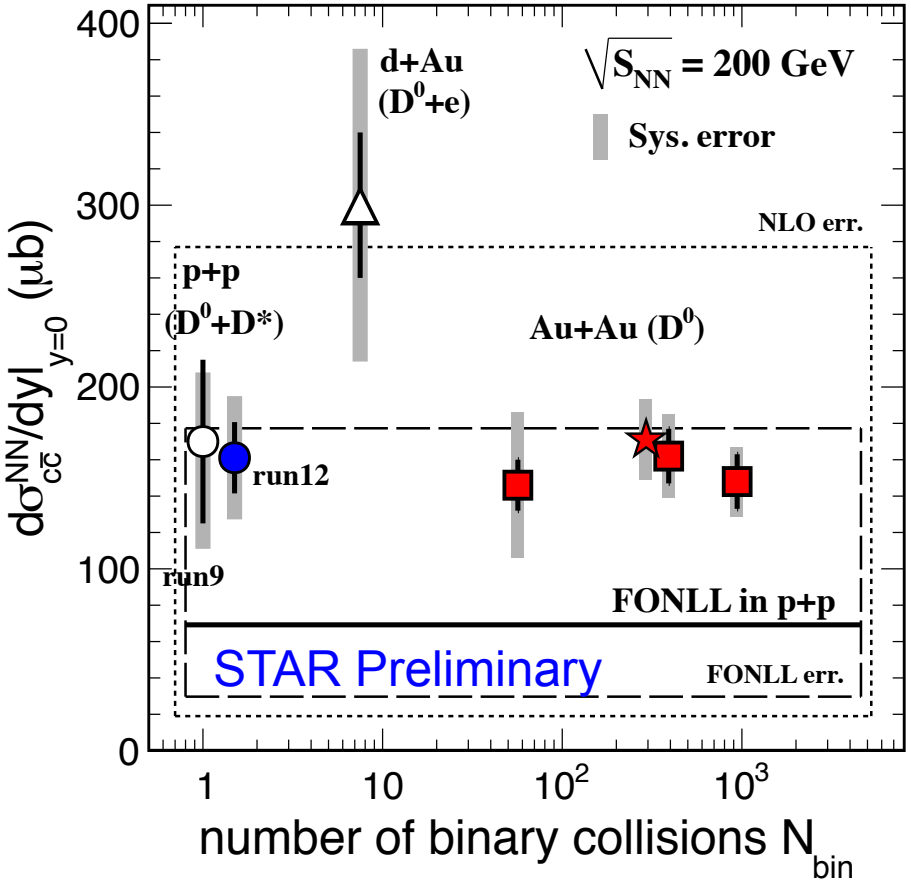




Total cross section scales with the number of binary collisions

D^0 production in Au+Au

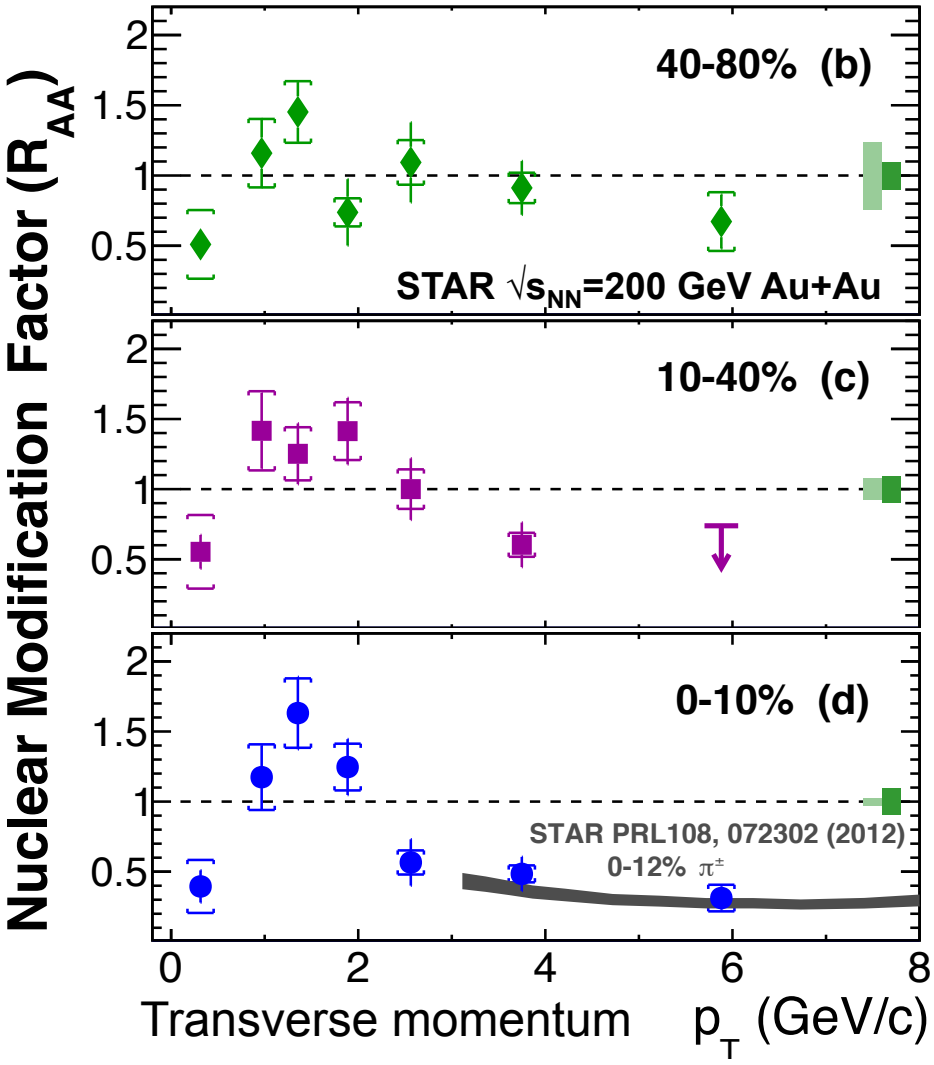




Total cross section scales with the number of binary collisions

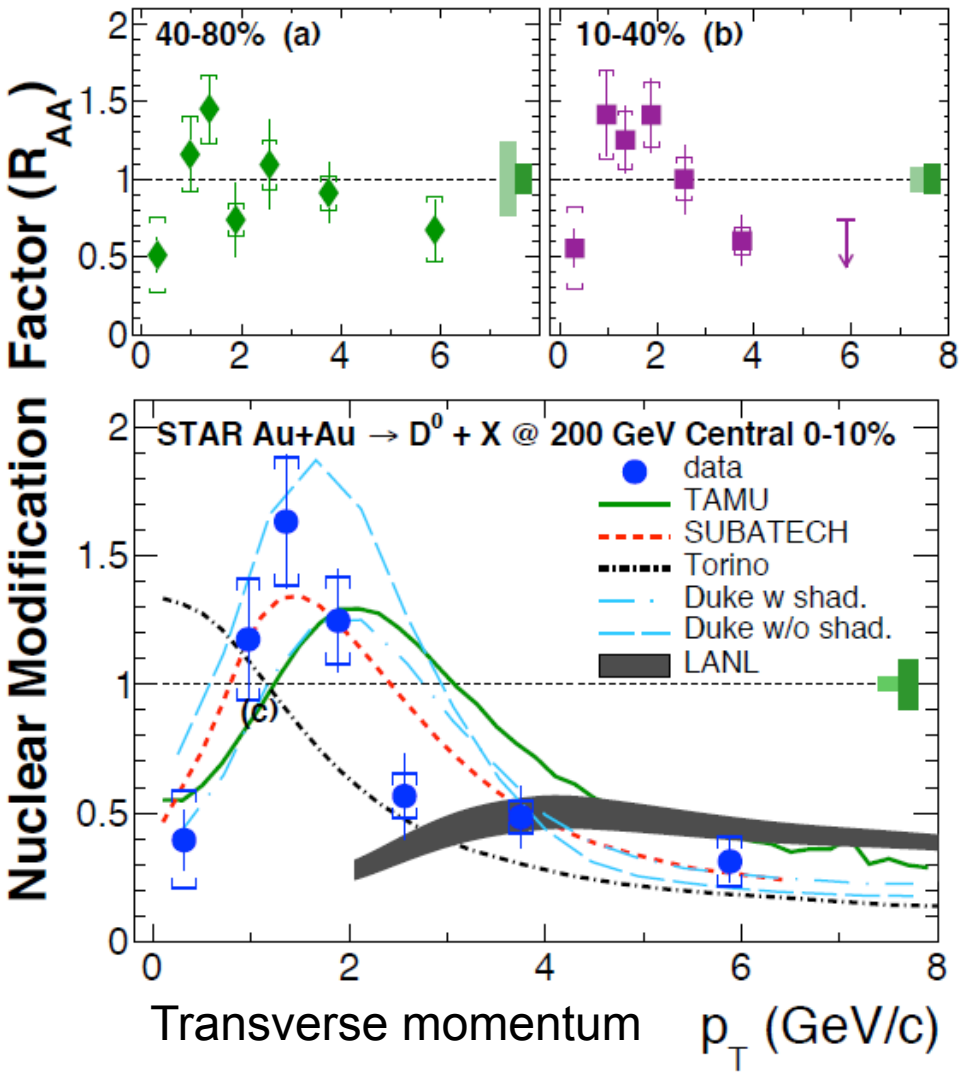
Charm is mostly produced in initial hard processes

D^0 suppression in Au+Au



- Strong suppression in central collisions at p_T>2 GeV/c
  - Identical to that observed for pions
- Enhancement at 1<p_T<2 GeV/c

D^0 suppression and models



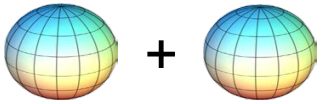
arXiv:1404.6185 (submitted to PRL)

- Strong suppression in central collisions at p_T>2 GeV/c
  - Identical to that observed for pions
- Enhancement at 1<p_T<2 GeV/c
- Understanding from models:
  - Characteristic low-p_T "hump" is described by models that include charm–light quark coalescence
  - High-p_T suppression is consistent with strong charm–medium interaction
  - CNM effects may be important

    → **Call for a high-statistics p+A (d+A) run**

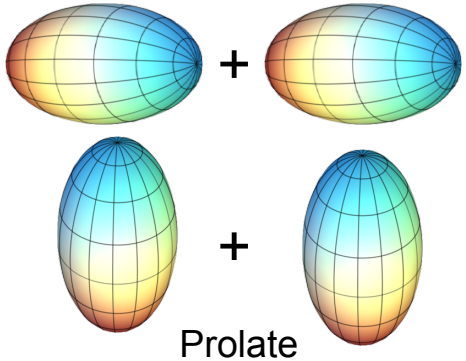
D^0 in U+U collisions

Au+Au Collisions



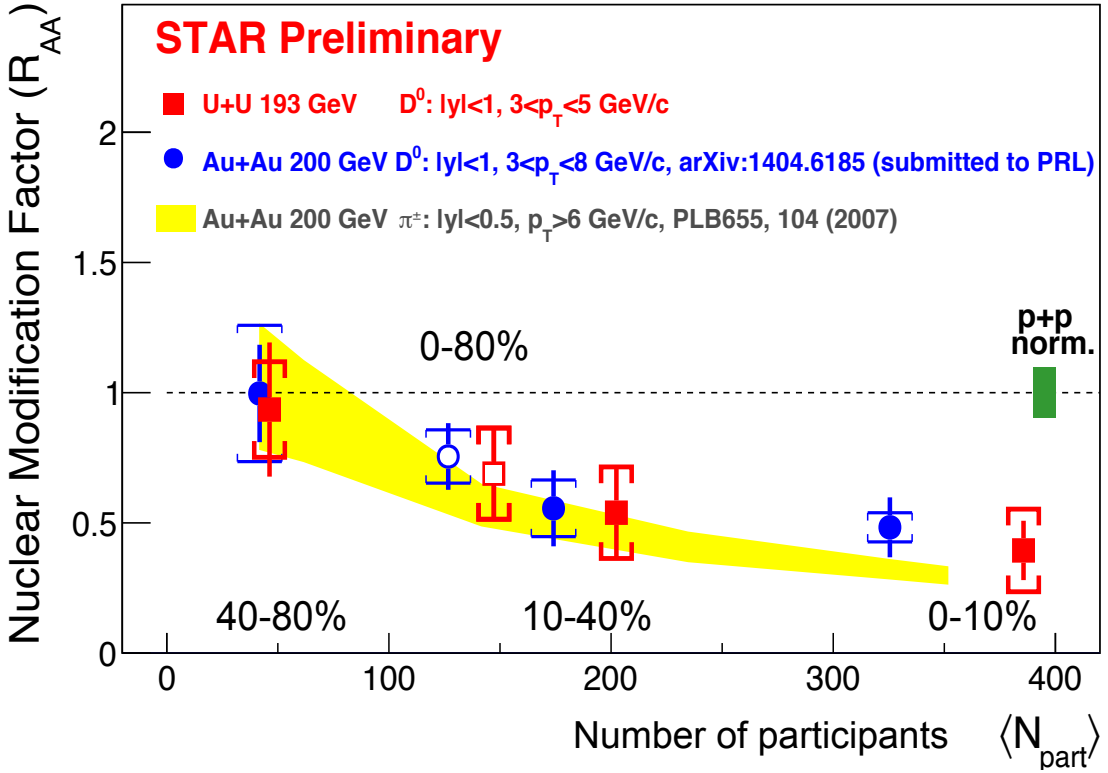
Oblate

U+U Collisions



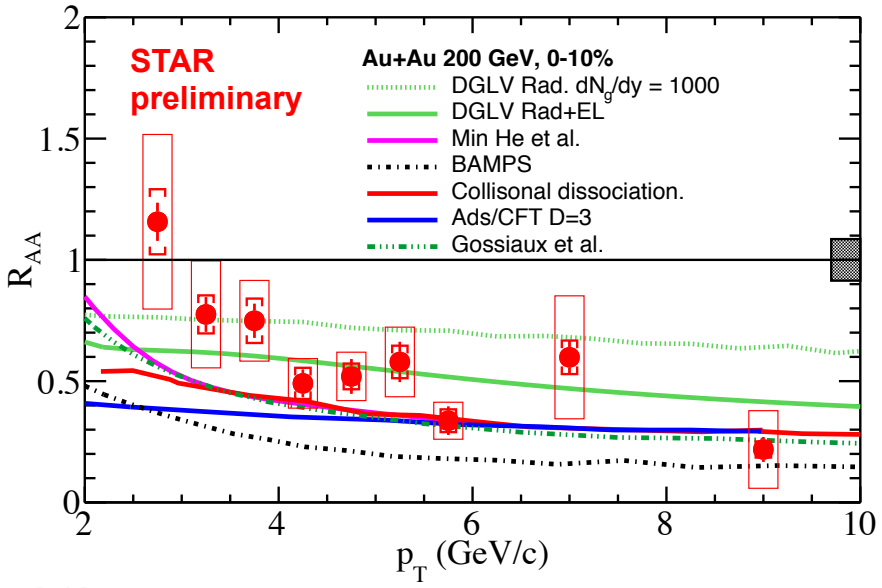
Prolate

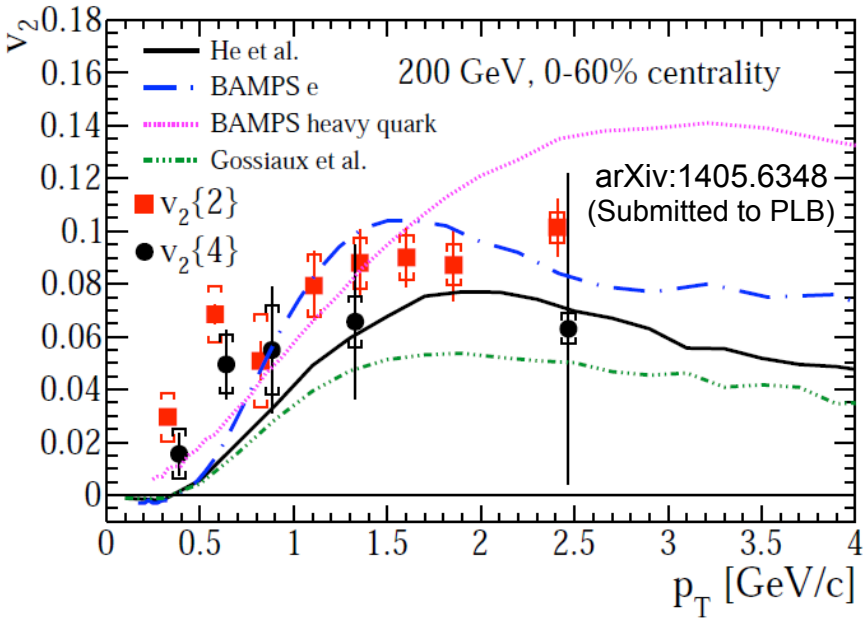
U+U collisions reach ~20% higher Bjorken energy density than Au+Au



- Trend in Au+Au continued in U+U
- Increasing suppression with N_{part}

Non-photonic electrons in 200 GeV Au+Au





Suppression

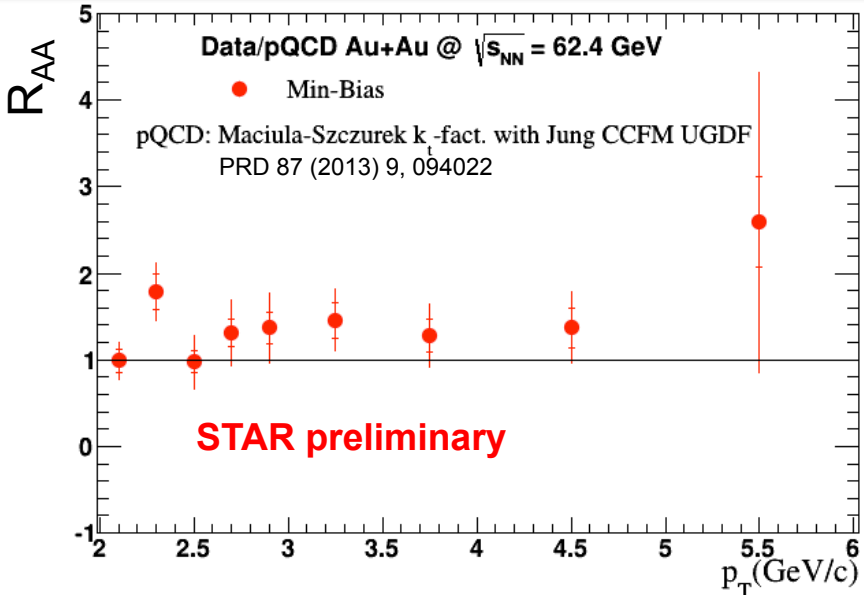
- Significant suppression of NPE in central collisions (p_T>4 GeV/c)
- Similar to that of D^0 and light hadrons
- Radiation energy loss alone not enough to explain suppression

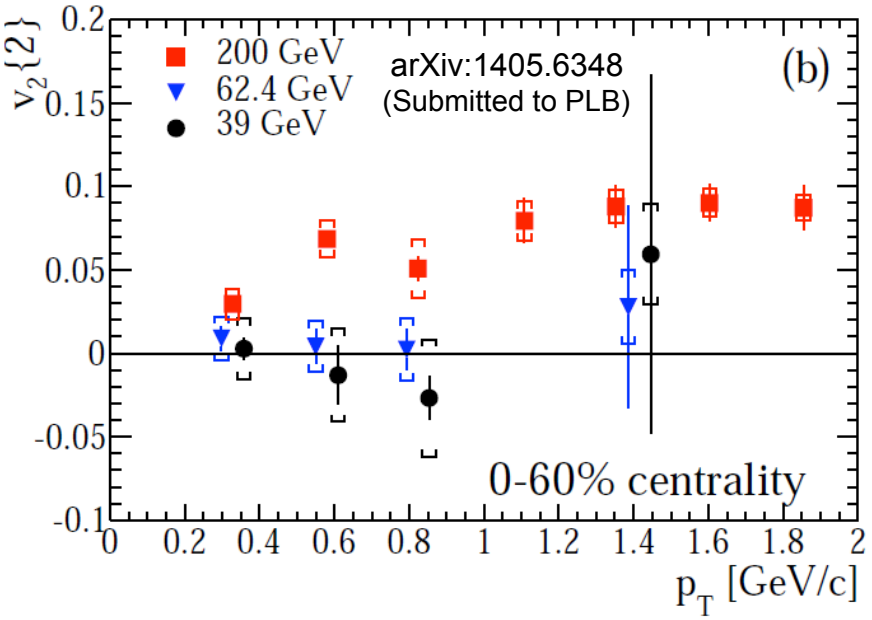
Anisotropy (v_2)

- Substantial elliptic flow of NPE is seen in 200 GeV Au+Au collisions

Note: it's challenging for models to describe suppression and flow at the same time

Non-photonic electrons: 39, 62.4 GeV





Suppression

- **No sign of suppression** of NPE in 62.4 GeV Au+Au collisions

  Note: pQCD-scaled p+p reference

Anisotropy (v_2)

- NPE in 39 and 62.4 GeV Au+Au collisions **consistent with no flow** (p_T<1 GeV/c)

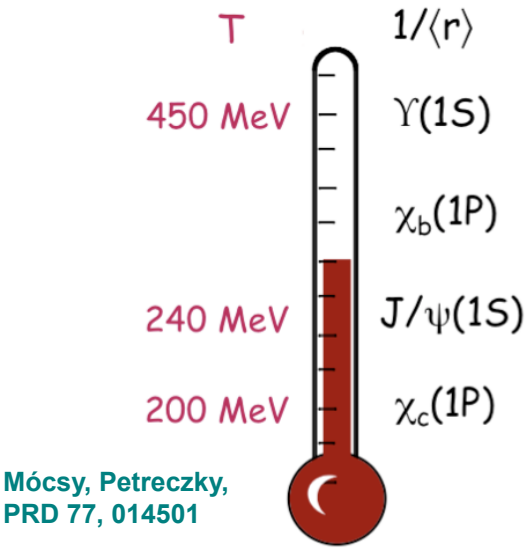
2. Quarkonia

Quarkonia probe thermal properties of the sQGP

- J/ψ suppression due to color screening
- Sequential melting of states → sQGP thermometer

However: picture is complicated by…

- Cold nuclear matter effects
- Co-mover absorption
- Regeneration in the sQGP…



Mócsy, Petreczky, PRD 77, 014501

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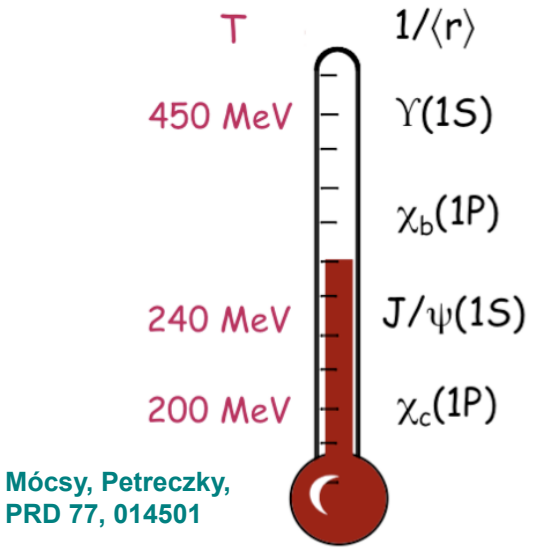

Mócsy, Petreczky, PRD 77, 014501

However: picture is complicated by…

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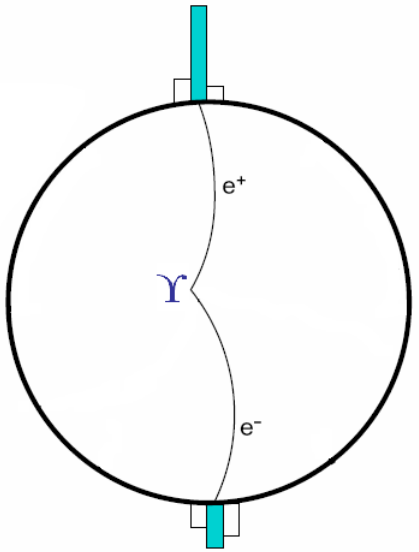
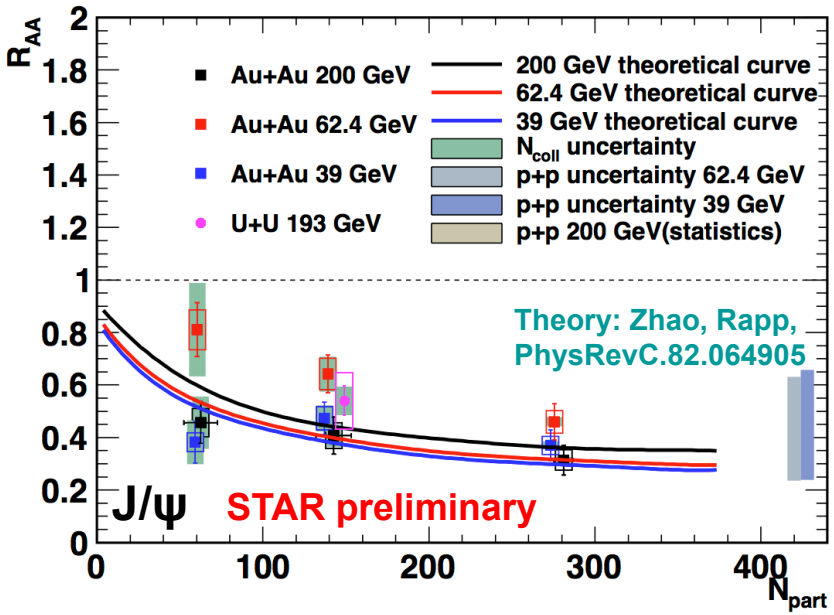
Precise measurements to disentangle various effects

- p+p → reference
- d+Au → CNM effects
- Vary collision energy: 39 GeV, 62.4 GeV, 200 GeV
- Vary colliding systems: U+U vs. Au+Au
- High-p_T J/ψ → suppress CNM and regeneration
- Υ → negligible recombination and co-mover absorption



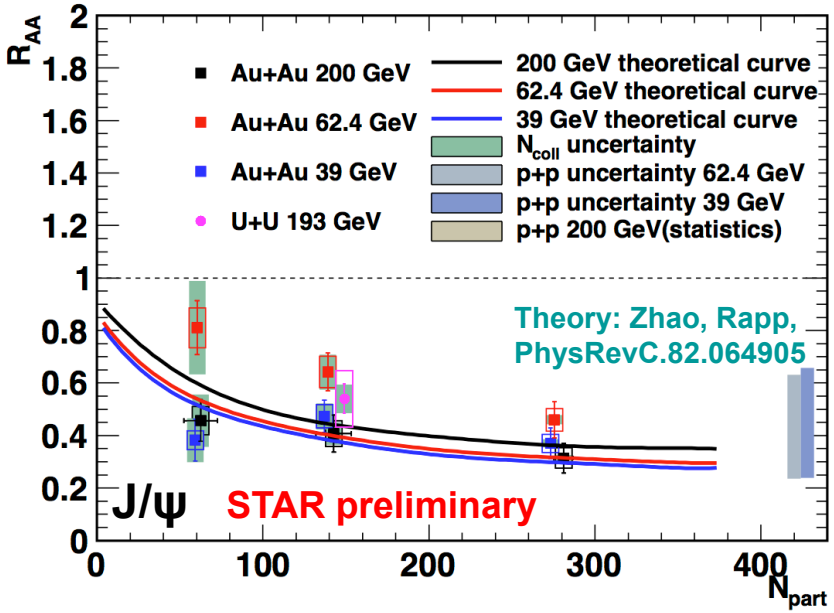
J/ψ suppression: 39, 62.4, 200 GeV

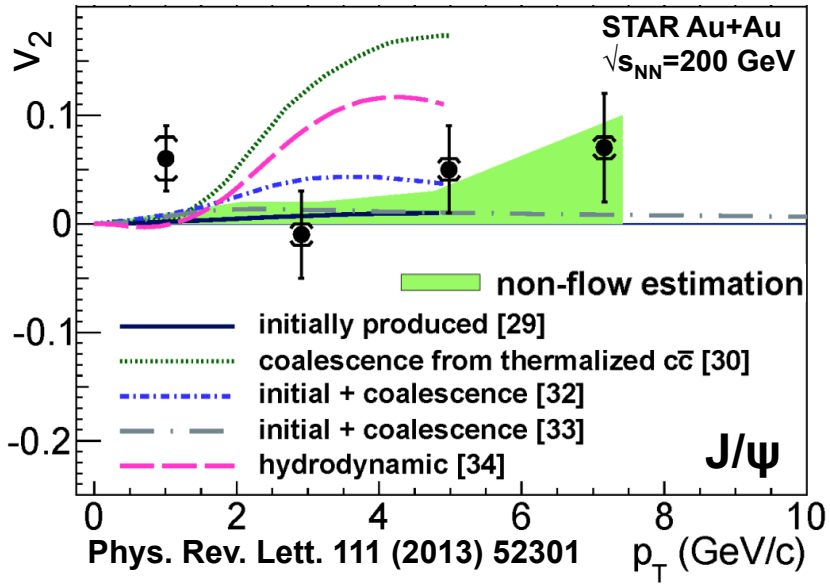


Suppression

- Similar to light hadrons
- Similar in central collisions from **39** thru **62.4** up to **200** GeV
  Note: 39 and 62.4 GeV CEM references have large uncertainties
- Similar in **U+U** and **Au+Au**
- Model with prompt production and regeneration consistent with data

J/ψ suppression and flow in Au+Au





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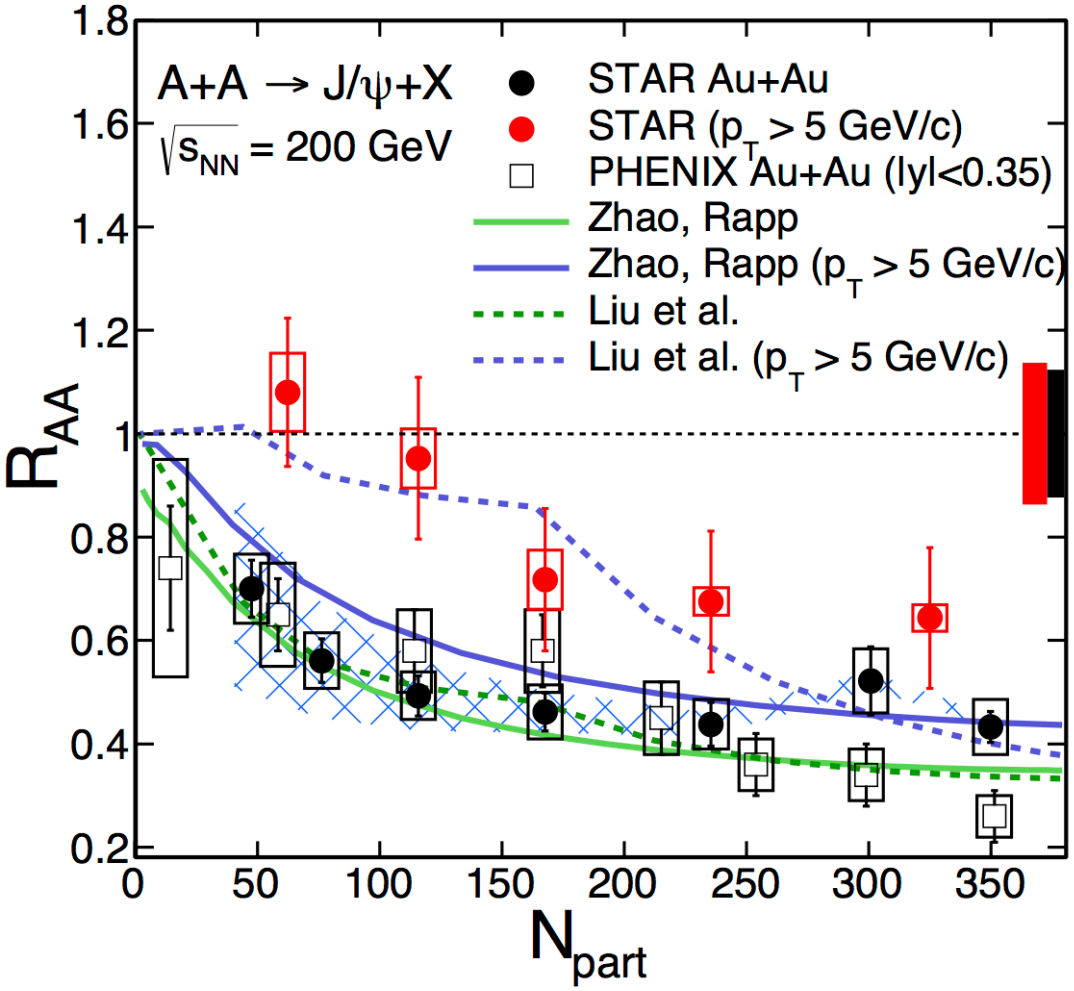
Anisotropy (v_2)

- **J/ψ v_2 consistent with non-flow** (p_T>2 GeV/c; unique among hadrons)
- Model with thermalized charm quark coalescence disfavored

[29] Yan, Zhuang,Xu, PRL97 (2006) 232301
[30] Greco, Ko, Rapp, PLB595 (2004) 202
[32] Zhao, Rapp, PLB 655 (2007) 126
[33] Liu,Xu,Zhuang, NPA834 (2010) 317c
[34] Heinz, Chen (2012)

High-p_T J/ψ in Au+Au



- CNM effects are small
- Less regeneration
- Suppression of high-p_T J/ψ in central collisions

STAR low-p_T : arXiv:1310.3563
STAR high-p_T : PLB722, 55 (2013)
Liu et al., PLB 678, 72 (2009)
Zhao and Rapp, PRC 82, 064905(2010), PLB 664, 253 (2008)
PHENIX Phys. Rev. Lett. 98, 232301 (2007)

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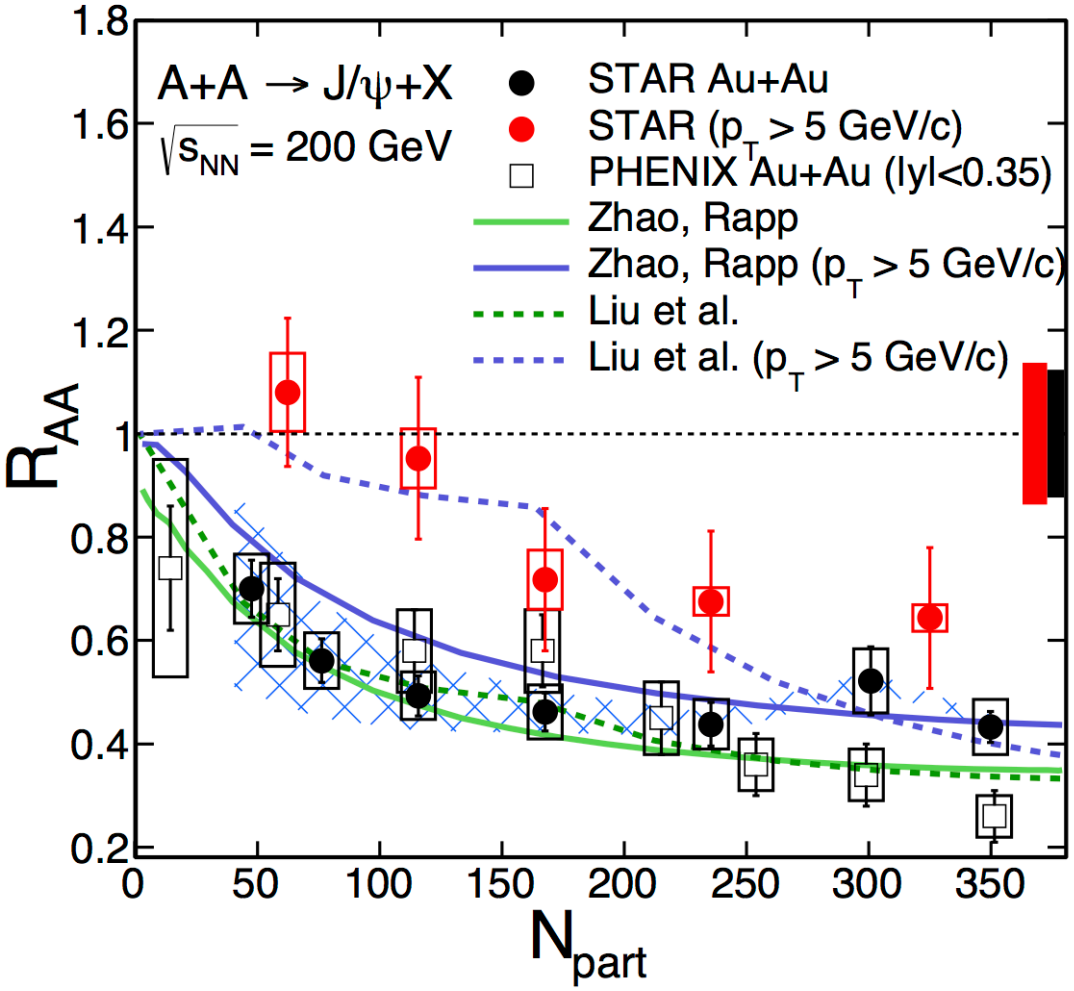

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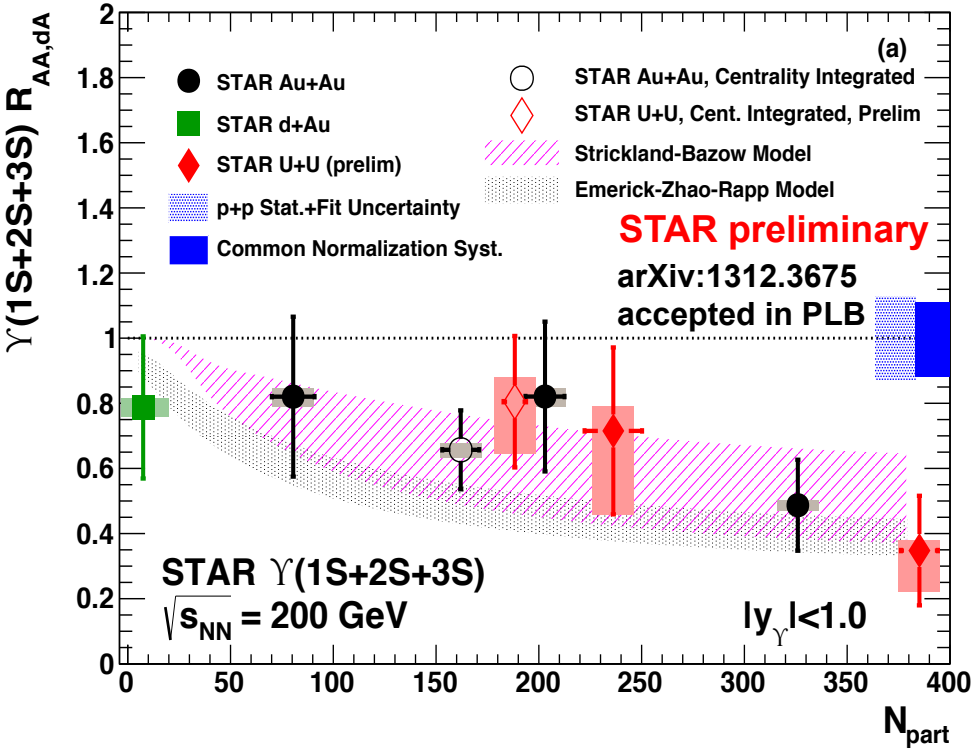
High-p_T J/ψ suppression is clearly an sQGP effect

Upsilons in A+A

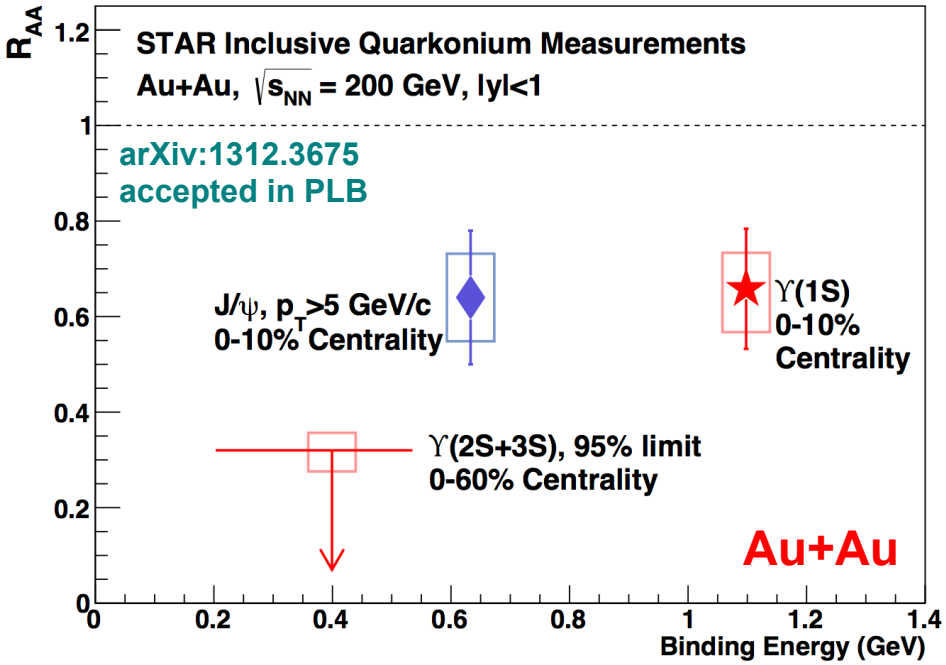


- Co-mover absorption and recombination negligible at RHIC
- Suppression in 200 GeV central Au+Au
- Trend continues in 193 GeV U+U (20% more energy density)

Model calculations:

- Potential based on internal energy assumes 428<T<443 MeV
  Strickland-Bazov, Nucl. Phys. A**879**, 25 (2012)
- Strong binding scenario, CNM effects included
  A. Emerick, X. Zhao, R. Rapp, Eur. Phys. J A**48**, 72 (2012)

Excited Υ states in Au+Au

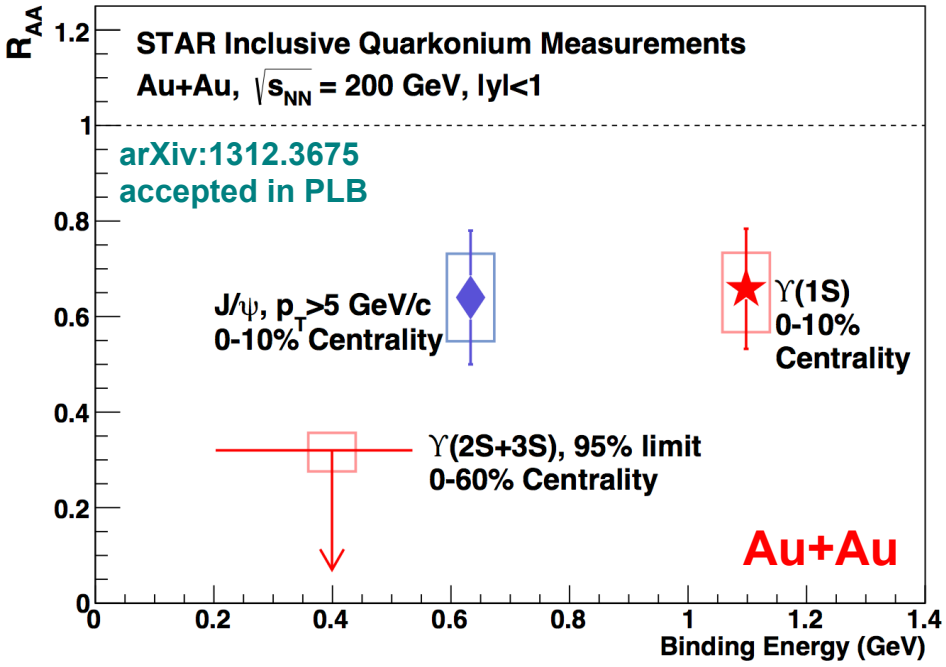


Central Au+Au:

- No evidence of excited states Υ(2S) and Υ(3S)
- Υ(1S) suppression is similar to high-p_T J/ψ

Suppression of Υ is an indication of color deconfinement

Excited Υ states in Au+Au



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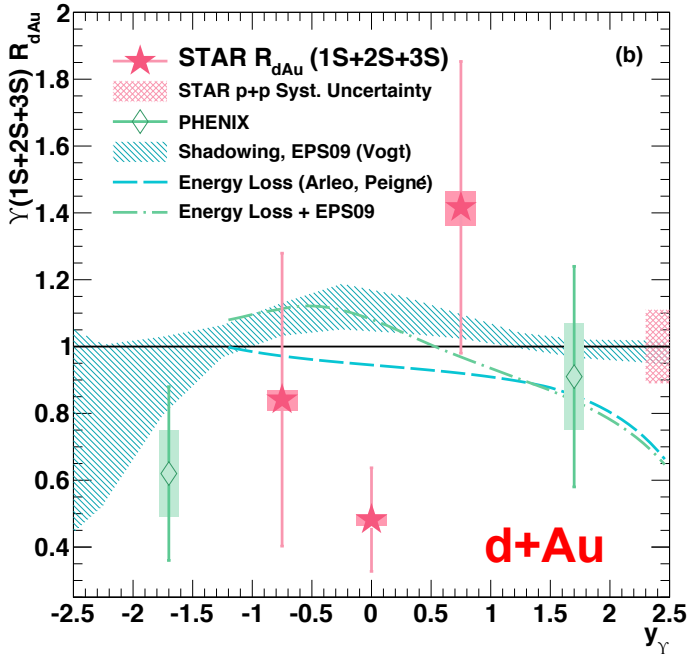
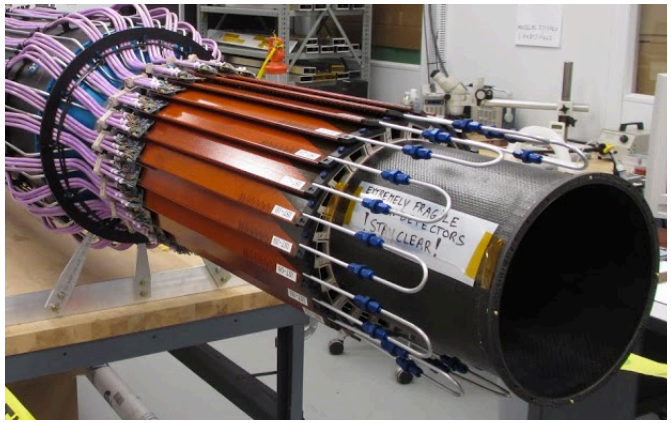
However…

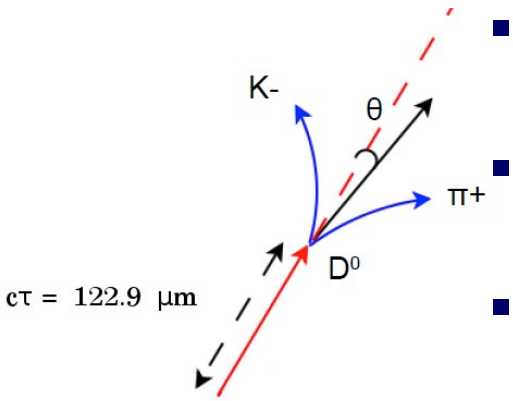
- d+Au data indicates that CNM effects can be important
- Models do not explain mid-rapidity d+Au data

→ Better understanding requires high-statistics p+A (d+A)



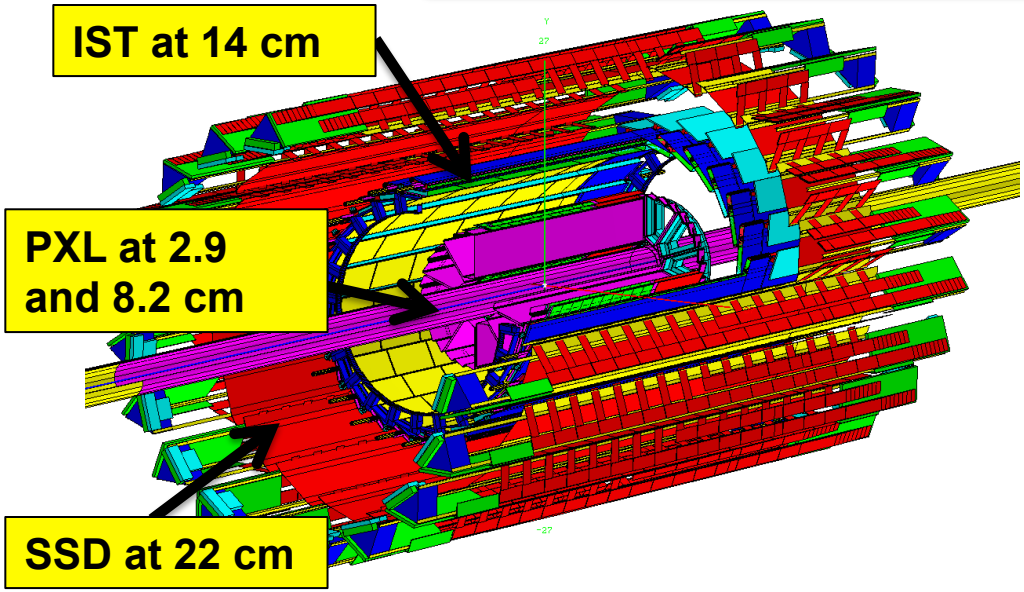
Outlook: Heavy Flavor Tracker

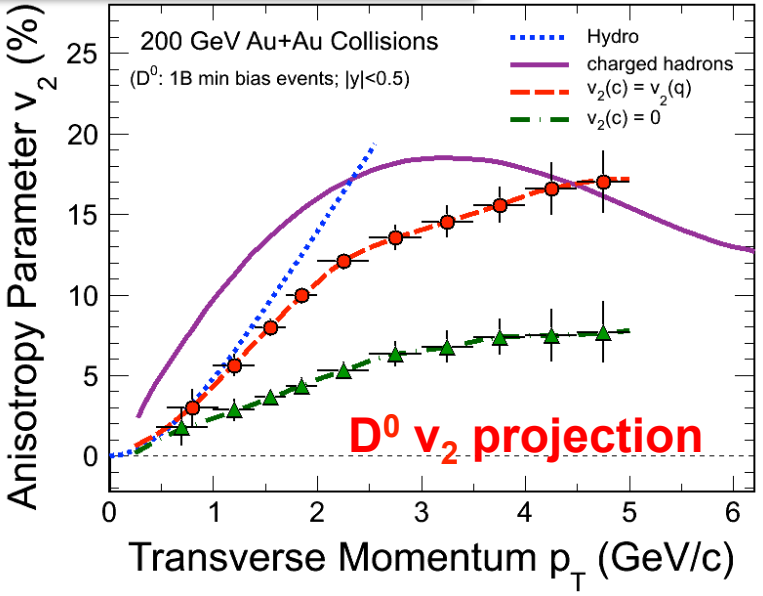




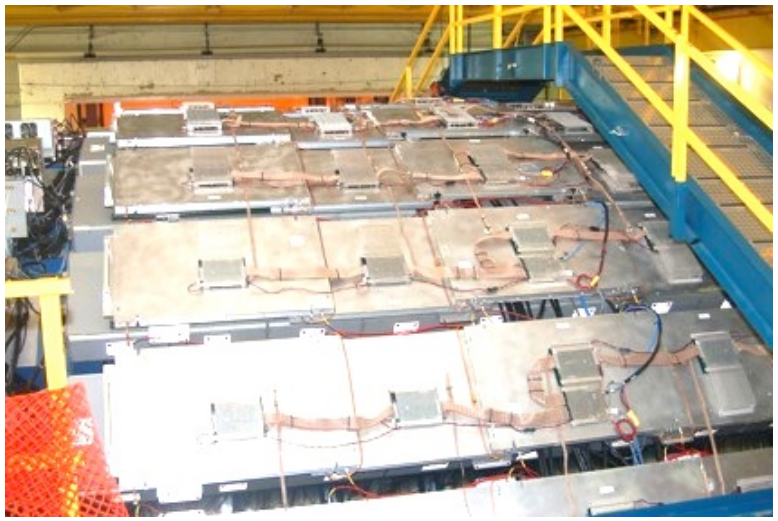
- Innermost, silicon detectors (3 subsystems)
- Resolves secondary vertex
- Physics goal: **Precision measurement of heavy quark production**

Complete and taking data in Run14



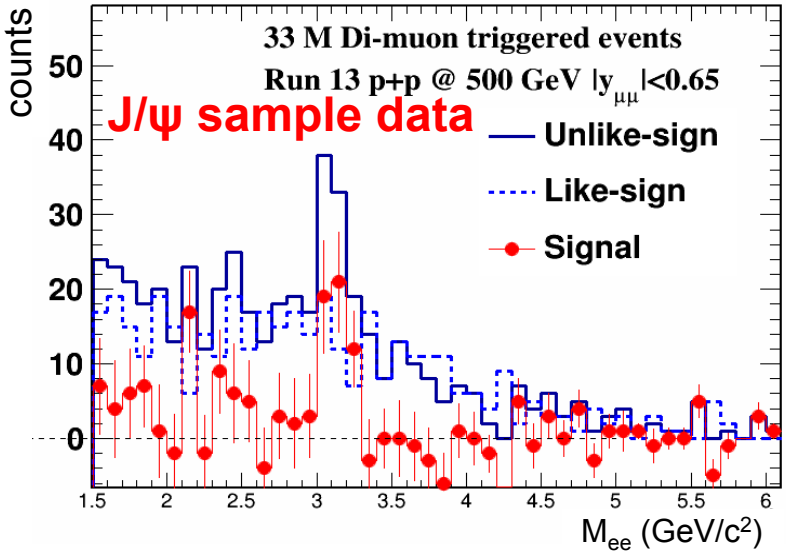


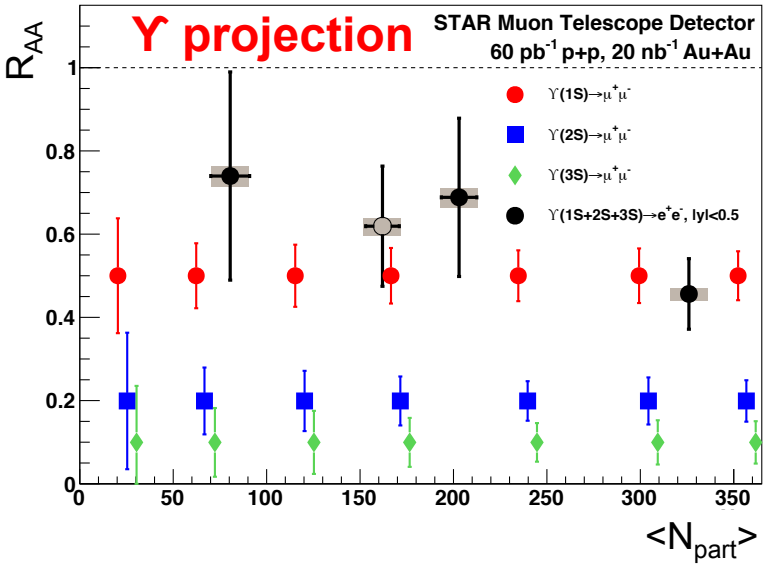
Outlook: Muon Telescope Detector



- Outermost, gas detector
- Physics goal: **Precision measurement of heavy quarkonia through the muon channel**
- Acceptance:
  45% in azimuth, |y|<0.5

Complete and taking data in Run14





Summary

Open heavy flavor

- Total D^0 x-section follows N_{bin} scaling → *early charm production*
- Low-p_T D^0 "hump" → *suggests charm–light quark coalescence*
- High-p_T suppression → *indicates strong charm–medium interaction*
- No 62.4 GeV NPE suppression or flow observed, contrary to 200 GeV

Quarkonia

- J/ψ suppression similar in central 39, 62.4 and 200 GeV collisions
- No J/ψ elliptic flow is observed → *thermalized cc-coalescence unlikely*
- Significant high-p_T J/ψ and similar Υ(1S) suppression in central A+A, hint for a complete Υ(2S) and Υ(3S) suppression
  → *clear signal of a deconfined medium*

U+U measurements show similar suppression patterns to Au+Au

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Stay tuned for new great results with HFT and MTD

Thank You!

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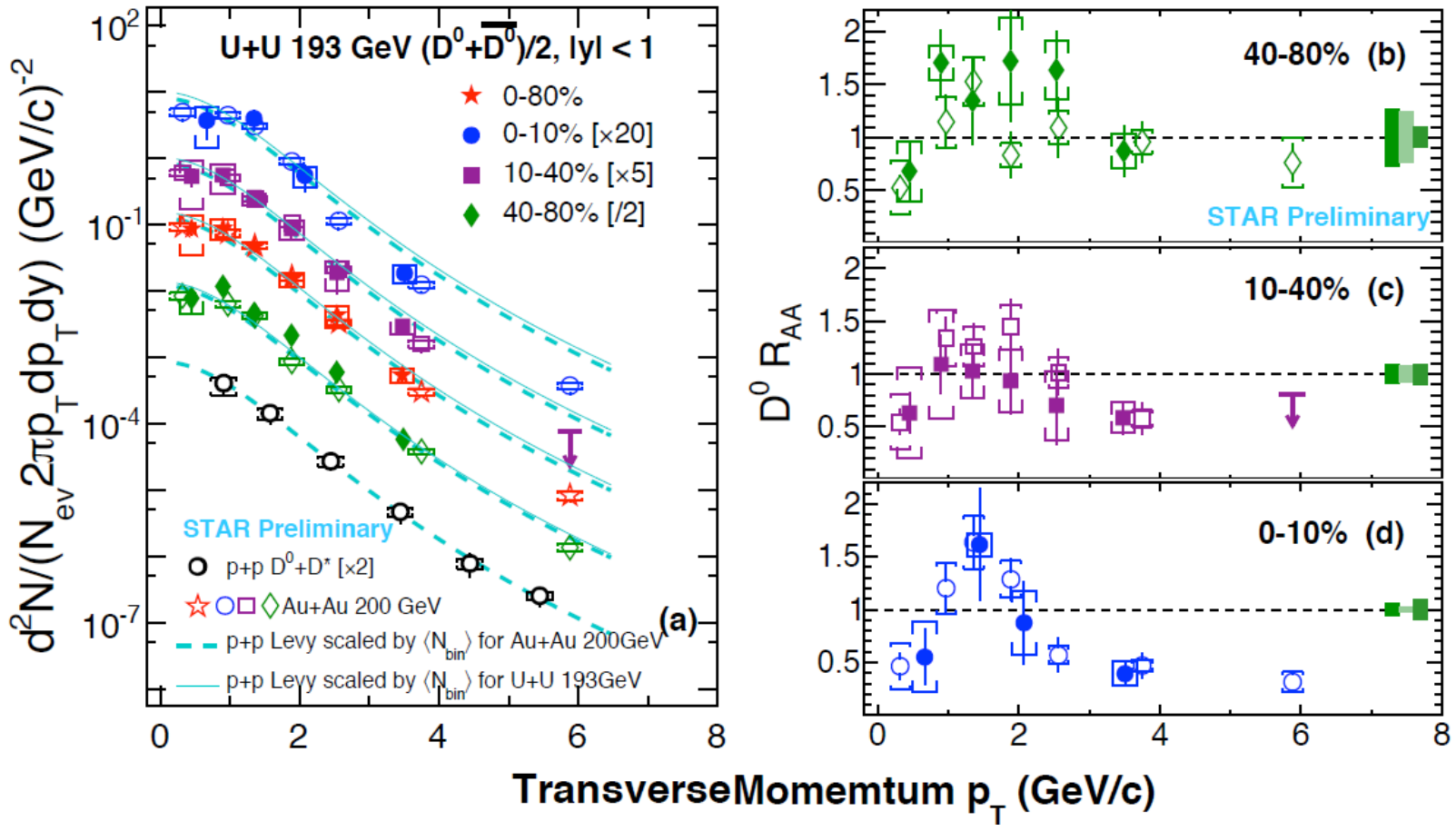
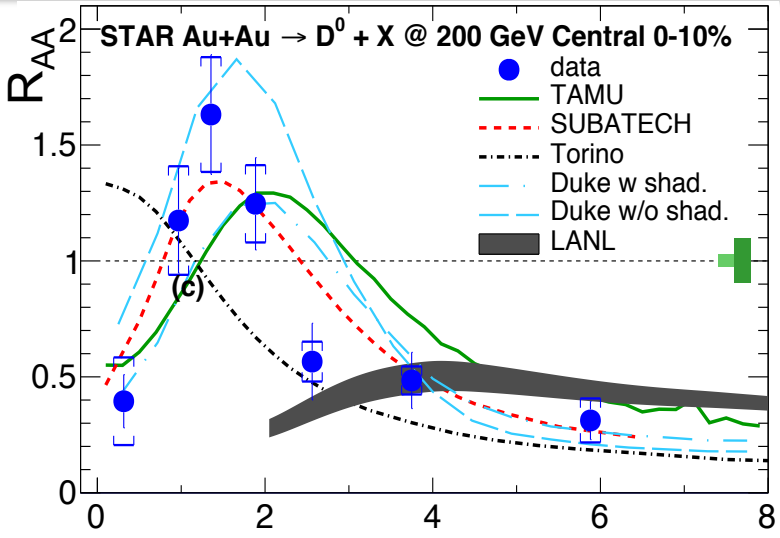
STAR Collaboration

D^0 in U+U, spectra and R_{AA}



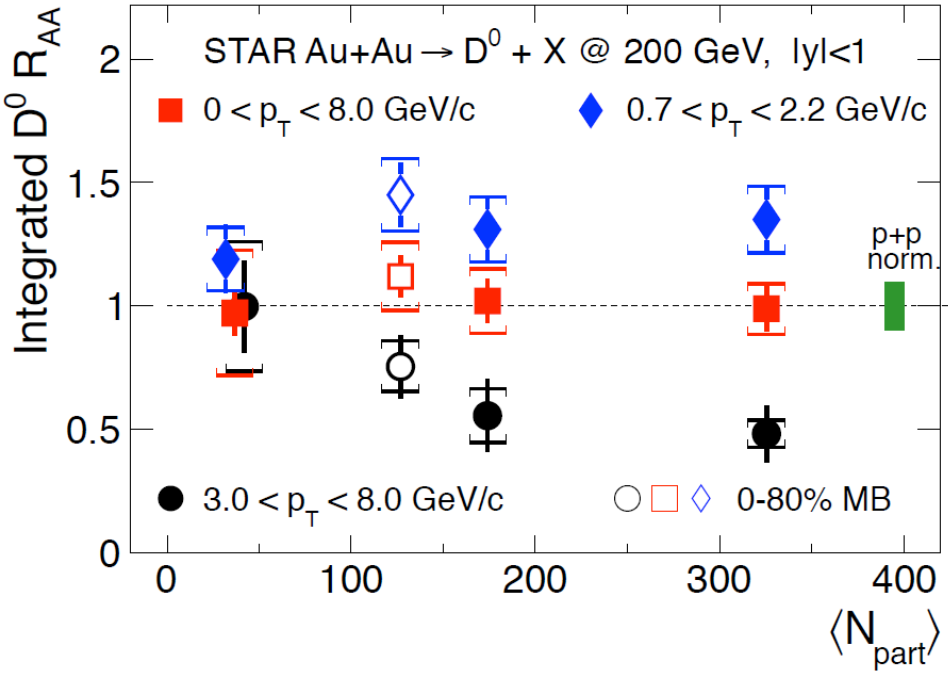
D^0, model ingredients

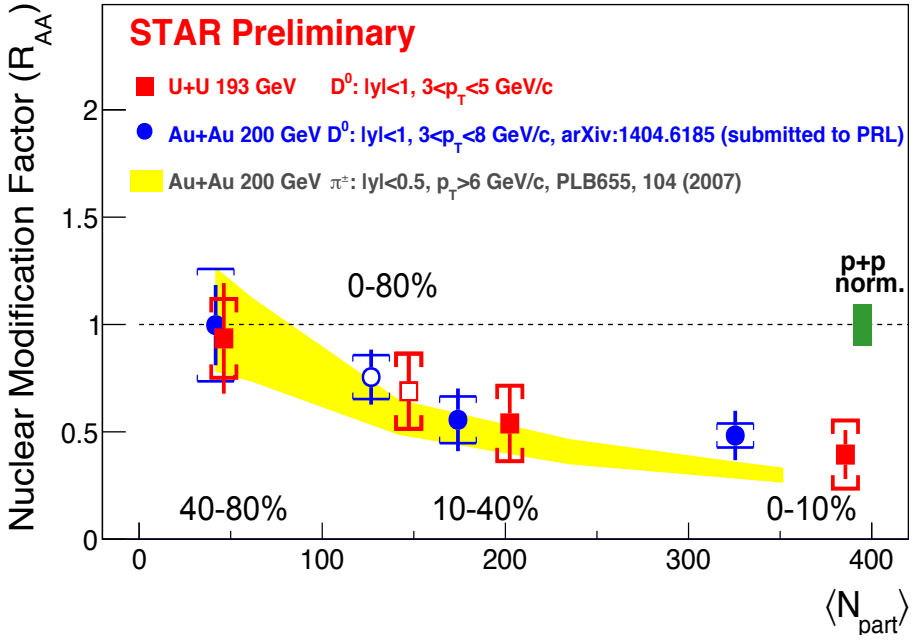


p_T (GeV/c)	TAMU	SUBATECH	Torino	Duke	LANL
HQ prod.	LO	FNOLL	NLO	LO	LO
QGP-Hydro	ideal	ideal	viscous	viscous	ideal
HQ eLoss	coll.	coll. +rad.	coll. +rad.	coll. +rad.	diss. +rad.
Coalescence	Yes	Yes	No	Yes	No
Cronin effect	Yes	Yes	No	No	Yes
Shadowing	No	No	Yes	Yes/No	Yes

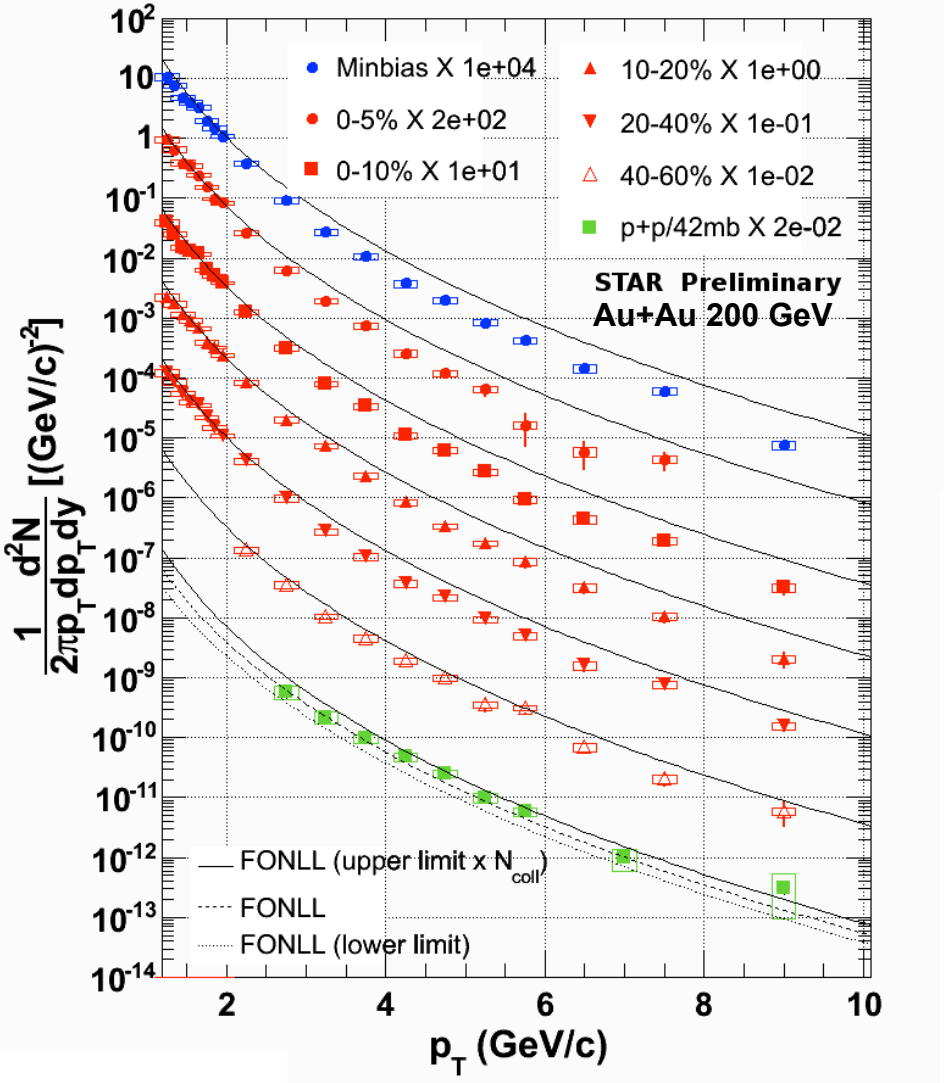
Zhenyu Ye, QM2014

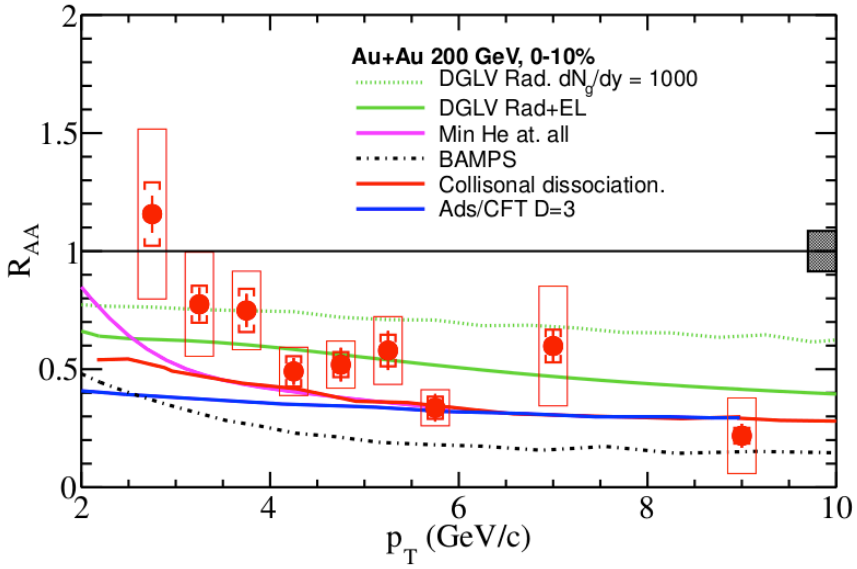
D^0 R_{AA}

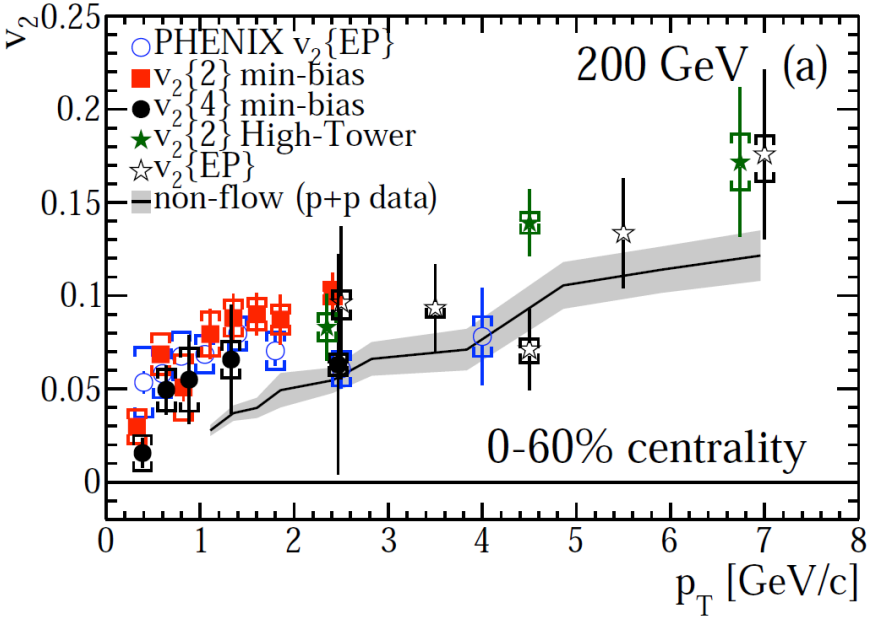

STAR Au+Au → D⁰ + X @ 200 GeV, |y|<1
0 < p_T < 8.0 GeV/c
0.7 < p_T < 2.2 GeV/c
3.0 < p_T < 8.0 GeV/c
0-80% MB
p+p norm.
Integrated D⁰ R_AA
⟨N_part⟩


STAR Preliminary
U+U 193 GeV D⁰: |y|<1, 3<p_T<5 GeV/c
Au+Au 200 GeV D⁰: |y|<1, 3<p_T<8 GeV/c, arXiv:1404.6185 (submitted to PRL)
Au+Au 200 GeV π±: |y|<0.5, p_T>6 GeV/c, PLB655, 104 (2007)
0-80%
40-80%
10-40%
0-10%
p+p norm.
Nuclear Modification Factor (R_AA)
⟨N_part⟩

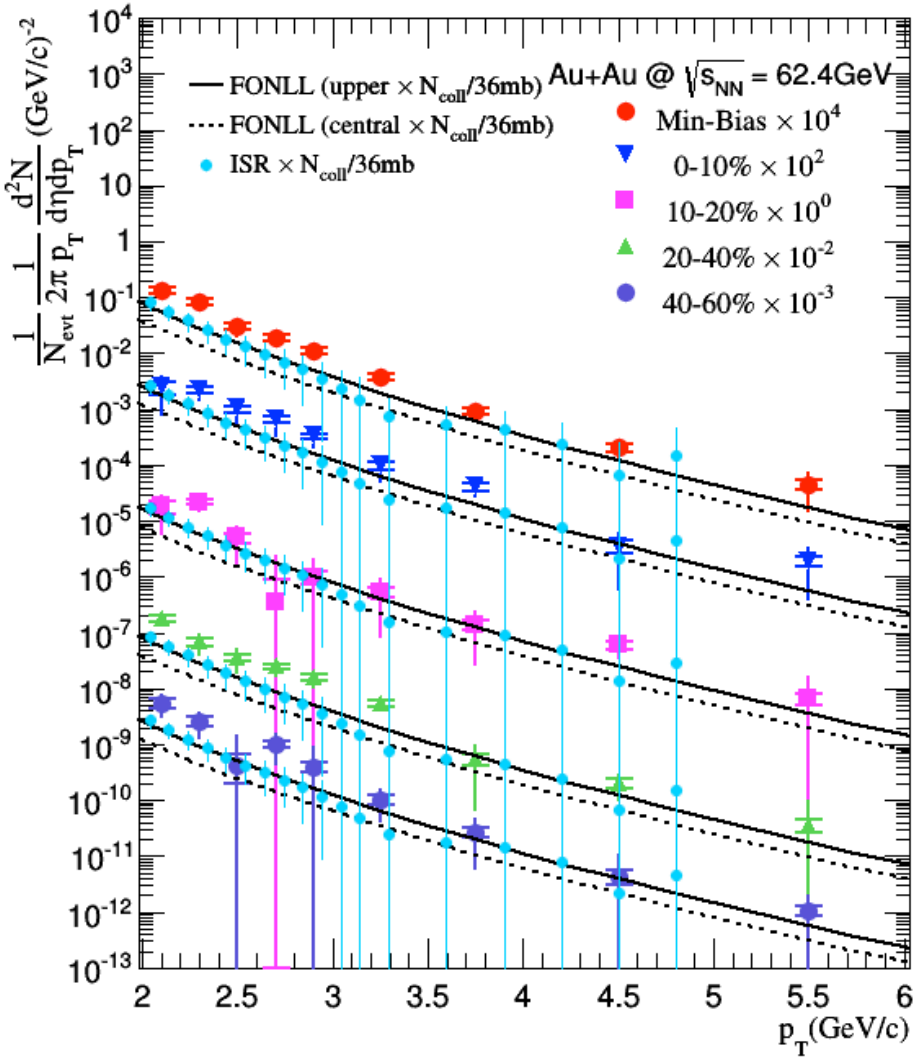
NPE Au+Au 200 GeV

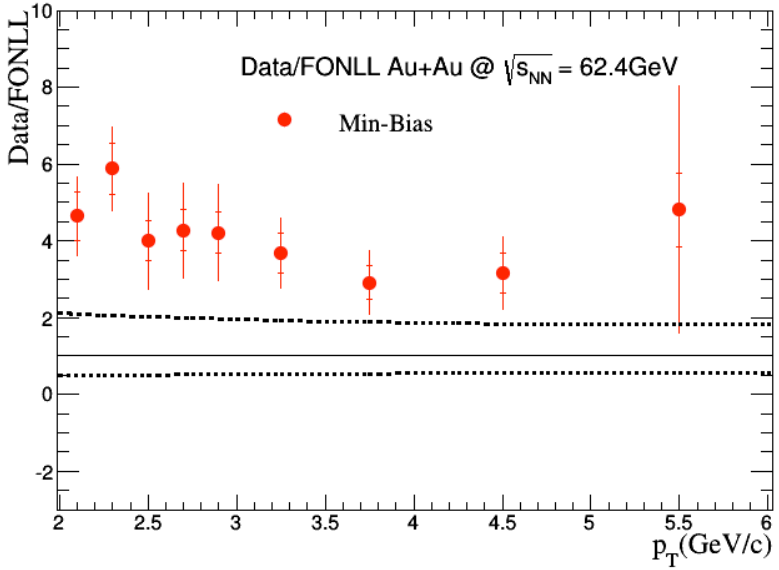


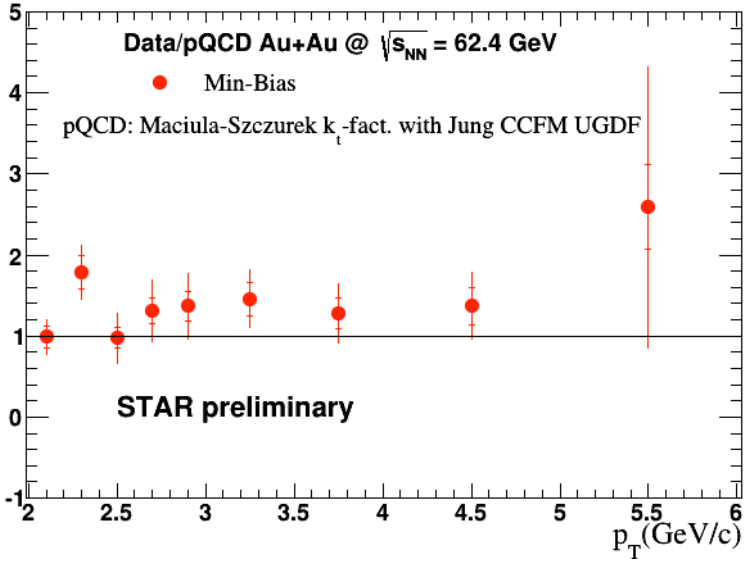




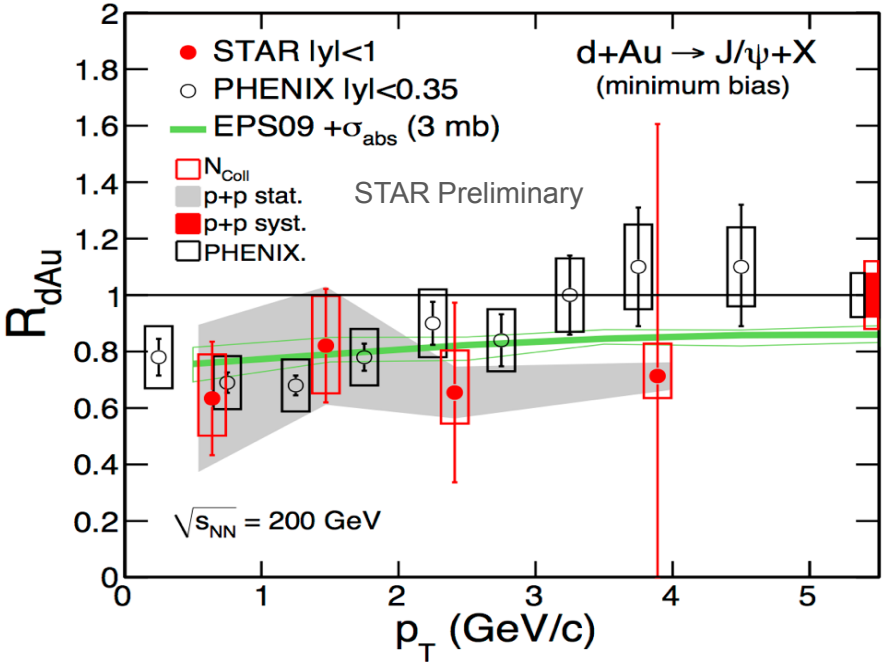
NPE 62.6 GeV FONLL vs. pQCD

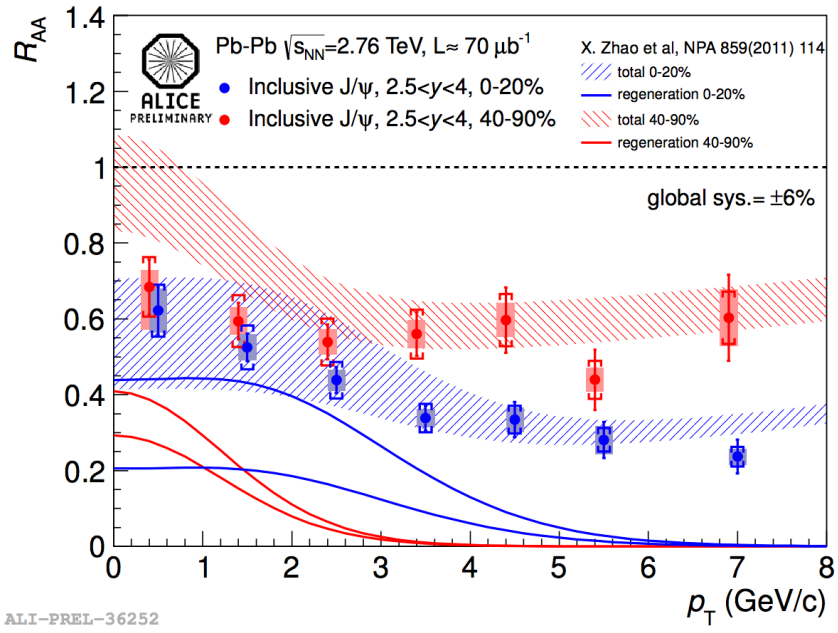






High-pT J/ψ – motivation



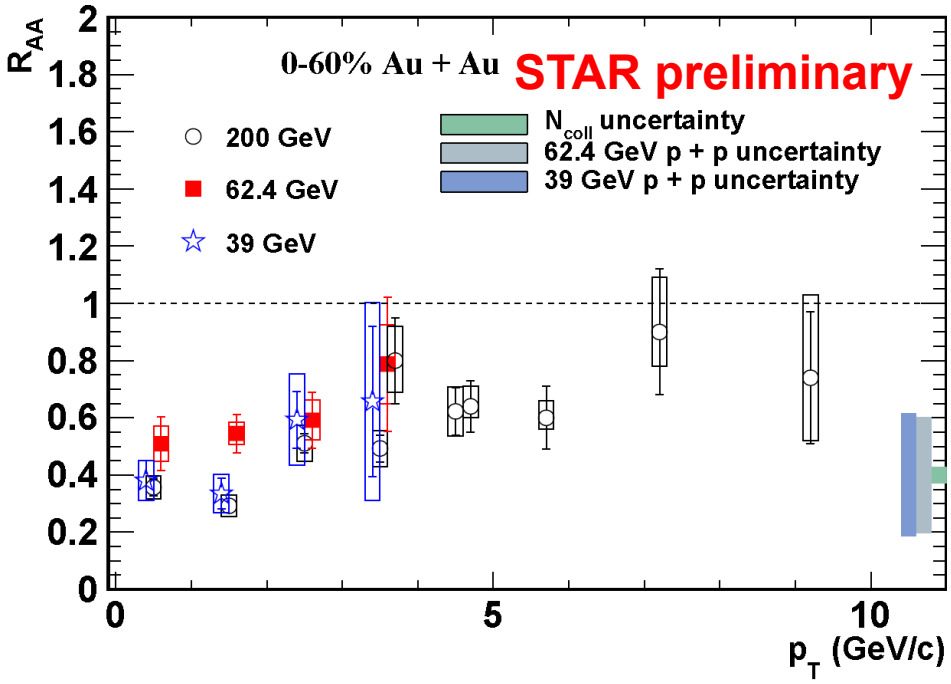


R_{dAu} ~ 1 at high P_T
→ CNM effects do not play a strong role

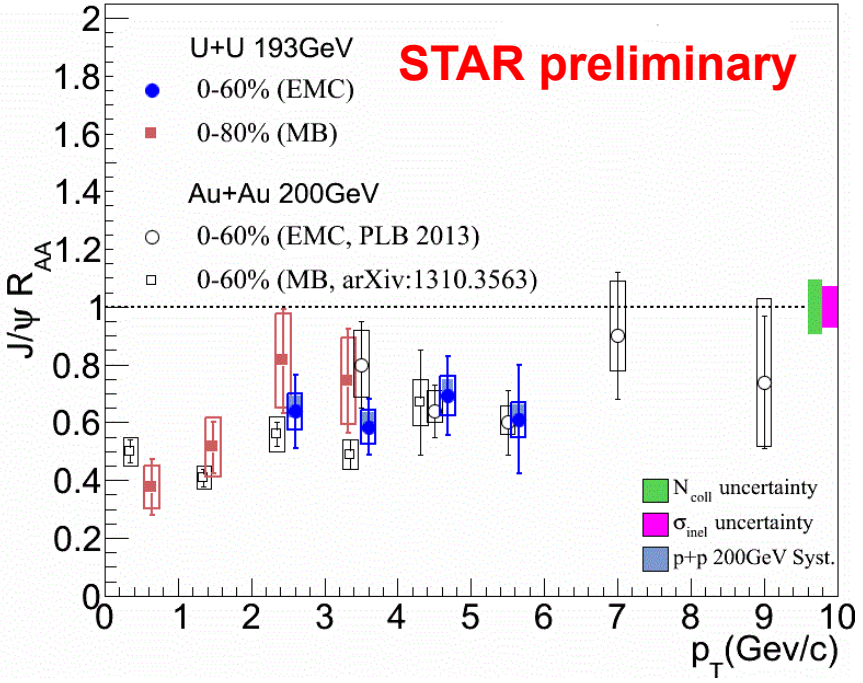
Less regeneration at high P_T

PHENIX data: Phys. Rev. C 87, 034904 (2013)
Model: E.Eskola, H.Paukkunenea and C.Salgo, Nucl. Phys. A 830, 599 (2009)

J/ψ vs pT, energy / system

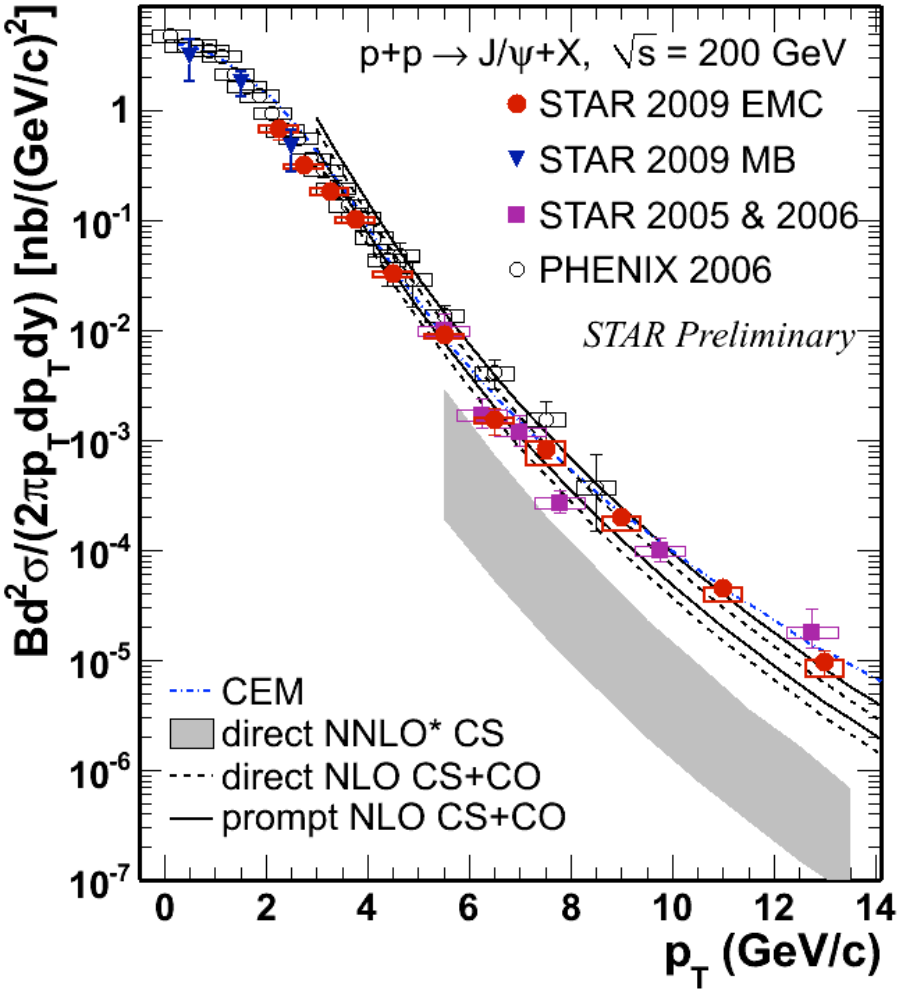


39, 62, 200 GeV Au+Au



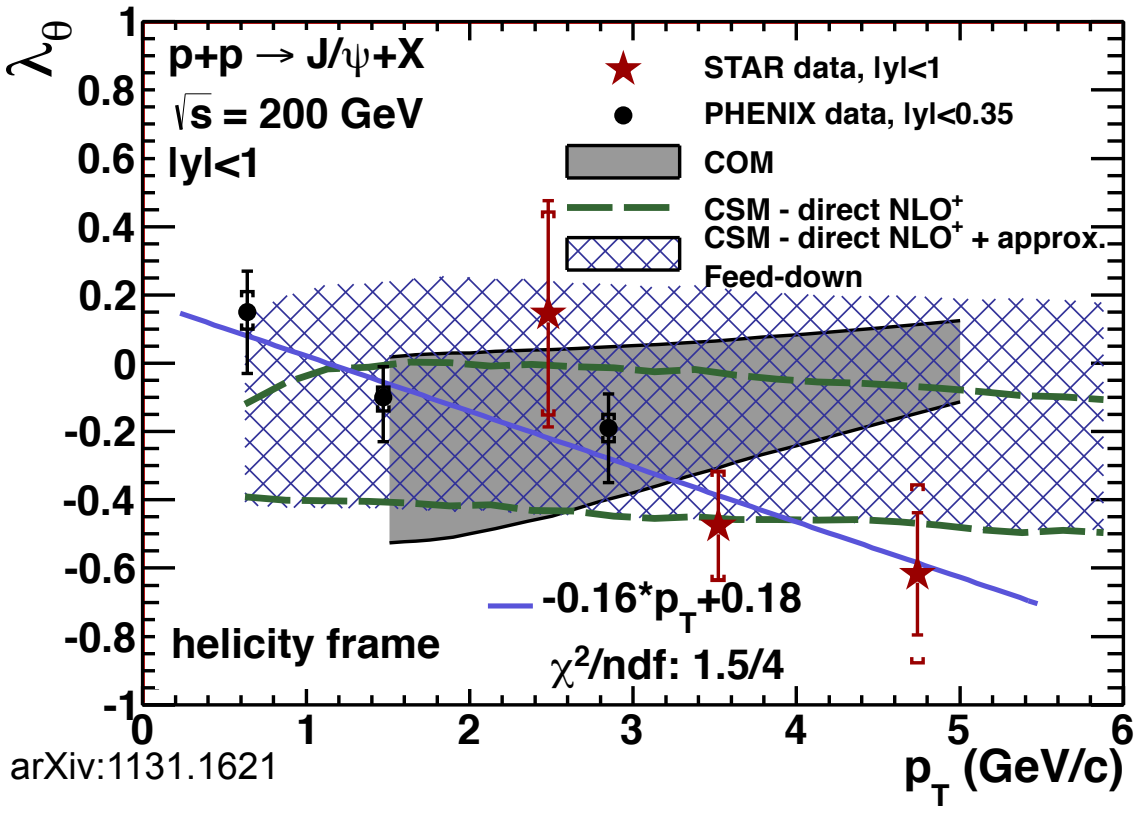
U+U vs. Au+Au

J/ψ in p+p 200 GeV



- STAR coverage out to 14 GeV/c
- Prompt NLO CS +CO describes the data
- Prompt CEM better at high-pT

J/ψ in p+p – polarization



- 2<pT<6 GeV/c
- STAR+PHENIX consistent with NLO +CSM
  - Higher statistics needed to discriminate
- p+p 500 GeV results will improve precision for future CNM calculations

Υ in p+p 200 GeV