Open heavy flavour and quarkonia production in dAu collisions at RHIC

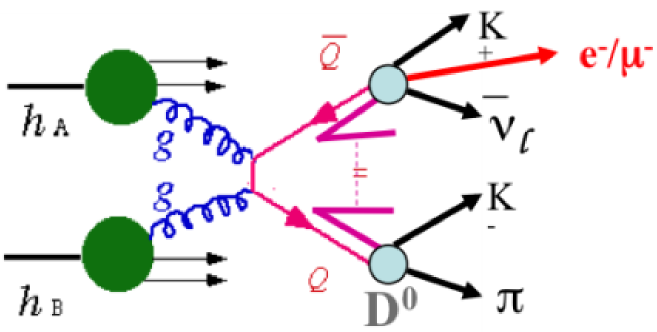
Petr Chaloupka

Czech Technical University
in Prague

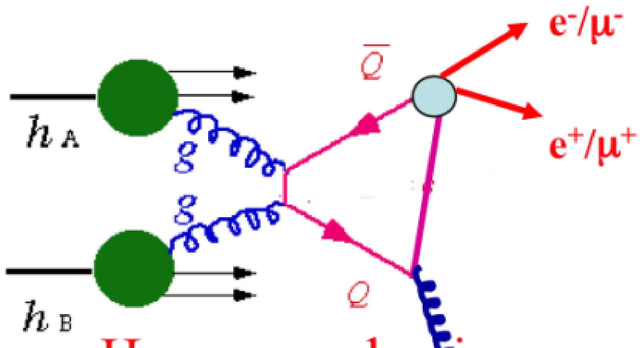
Sapore Gravis Workshop
Padova, 9-12 December 2014

Heavy quarks - motivation

- Excellent probes for the QGP
  - Large mass - produced in the initial stages of HI collisions.
  - $c\text{-}\bar{c}, b\text{-}\bar{b}$ production calculable by pQCD
  - Sensitive to initial gluon density and gluon distribution.
- Interact with the medium differently from light quarks.
  - medium-induced gluon radiation.
  - collisions with medium constituents.
  - expected energy loss:
    $\Delta Eg > \Delta Eu,d > \Delta Ec > \Delta Eb$
  - Suppression or enhancement pattern reveals critical features of the medium (temperature)

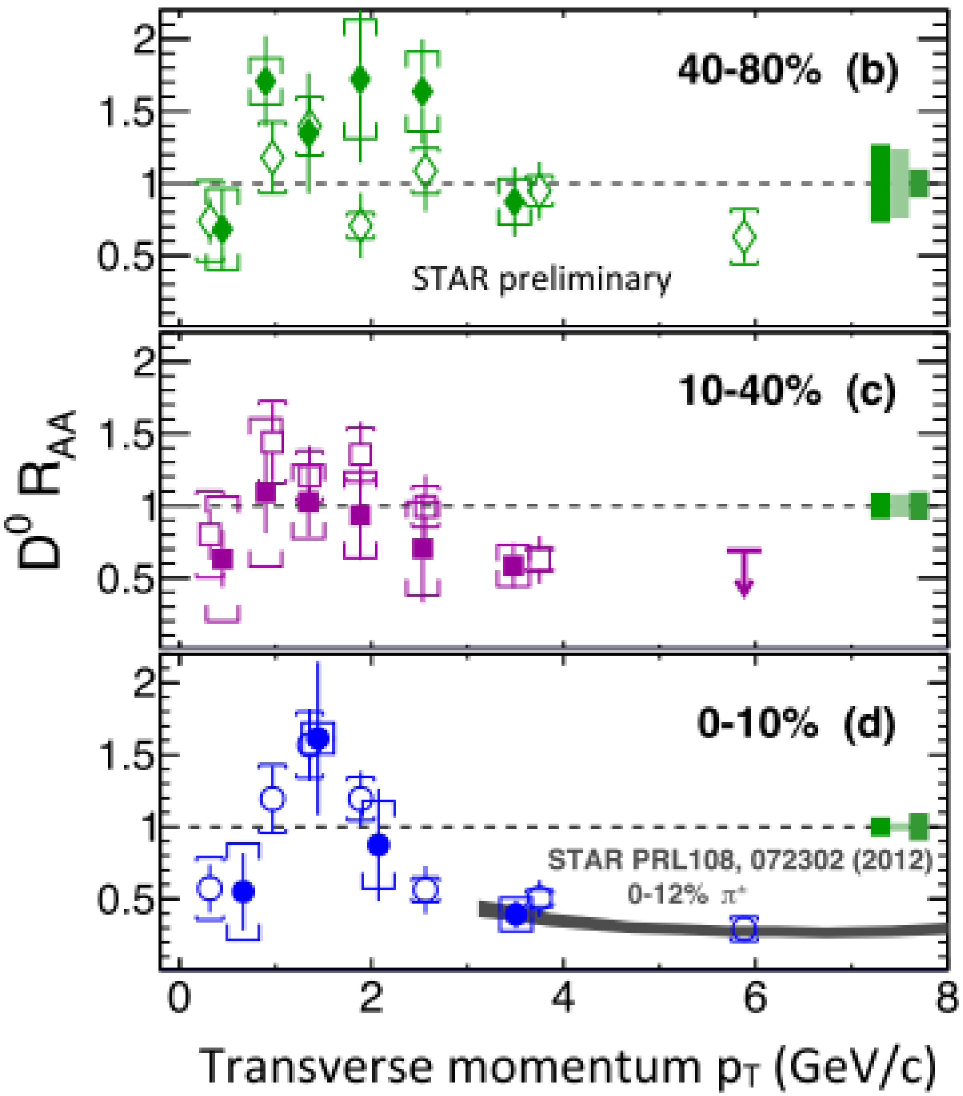


Open heavy flavor

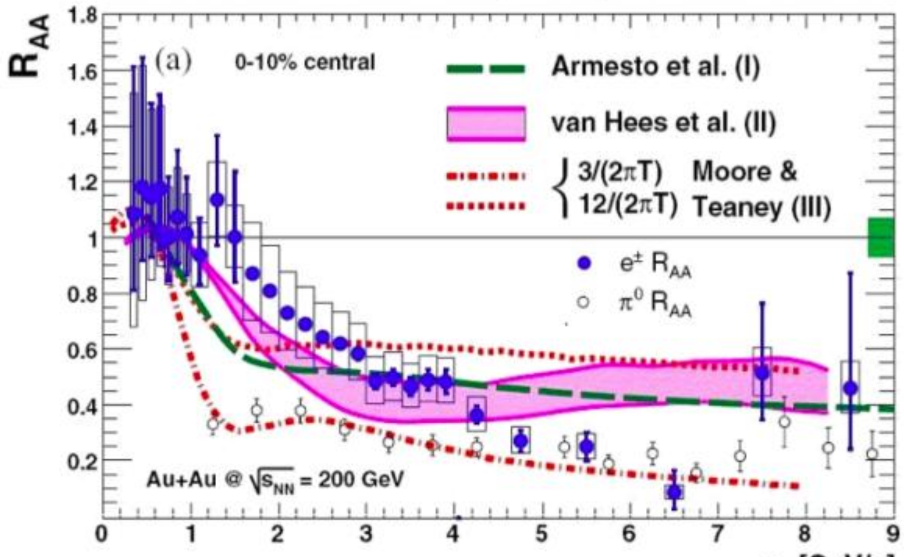


Heavy quarkonia

Open heavy flavor at RHIC



open symbols: Au+Au closed symbols: U+U



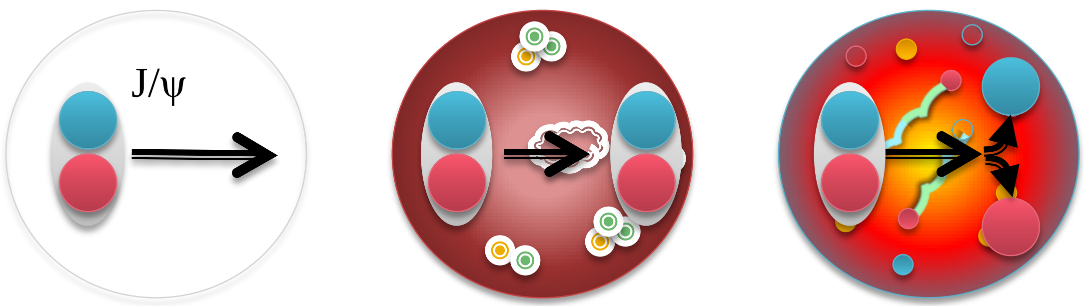
Phys. Rev. Lett. 98. 172301 (2007)

- In mid-peripheral and central
  - suppression at high p_T-similar to light hadrons
  - similar trend in U+U
- enhancement at intermediate p_T
  - coalescence with flowing light quarks?
  - cold nuclear matter effects?

Quarkonia as a probe of QGP

- Due to color screening of quark potential in QGP **quarkonium dissociation is expected**

Quarkonia family:
$\bar{c}$-c: J/ψ, ψ′, χc ...
$\bar{b}$-b: ϒ(1S), ϒ(2S), ϒ(3S),...



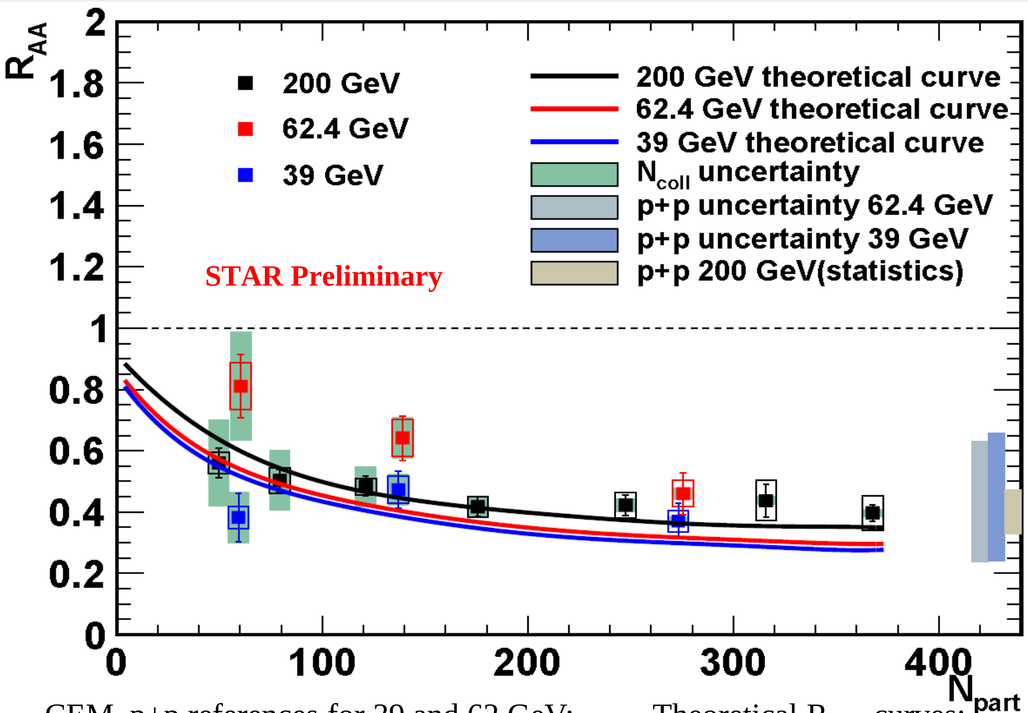
T=0 $0<T<T_C$ $T_C<T$

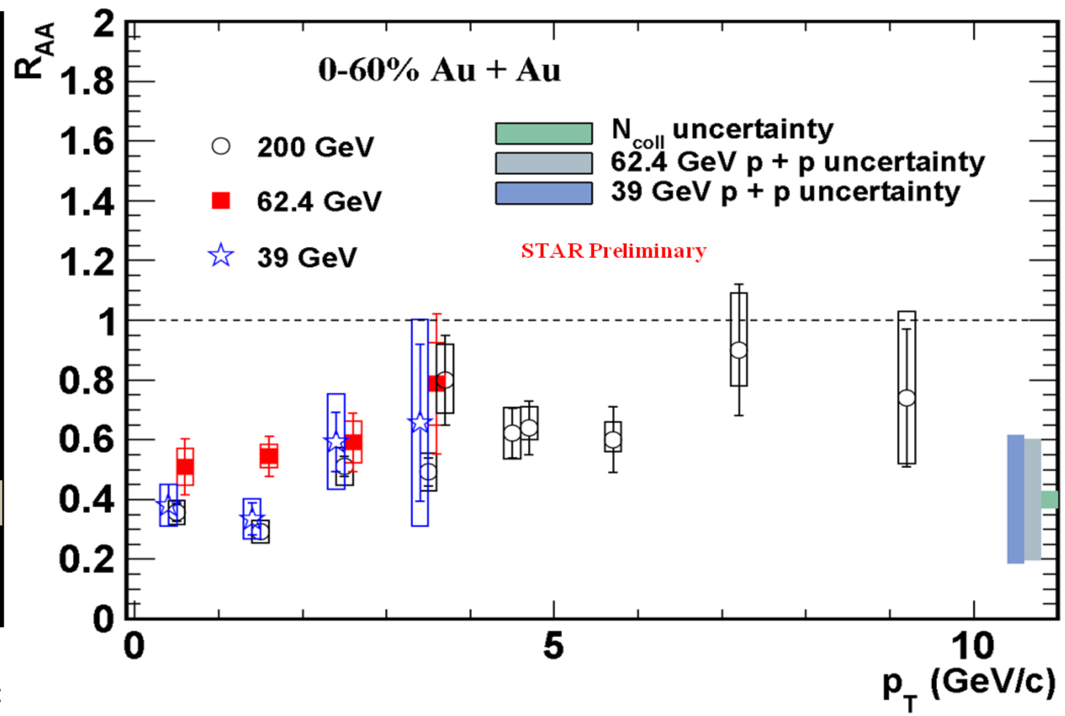
H. Satz, Nucl. Phys. A (783):249-260(2007)

- Suppression determined by medium temperature and binding energy.

Sequential suppression of different quarkonia states is expected.

RHIC quarkonia puzzle





CEM p+p references for 39 and 62 GeV:
Nelson, Vogt et al., PRC87, 014908 (2013)

Theoretical R_{AA} curves:
Zhao, Rapp PRC82, 064905 (2010)

- Similar suppression in Au+Au at 200, 62.4 and 39 GeV
  - p+p reference is based on CEM calculations
  - Large theoretical uncertainty
- Almost compensating interplay of melting and coalescence ?
  - Consistent with theoretical calculations
  - Additional confirmation from LHC results

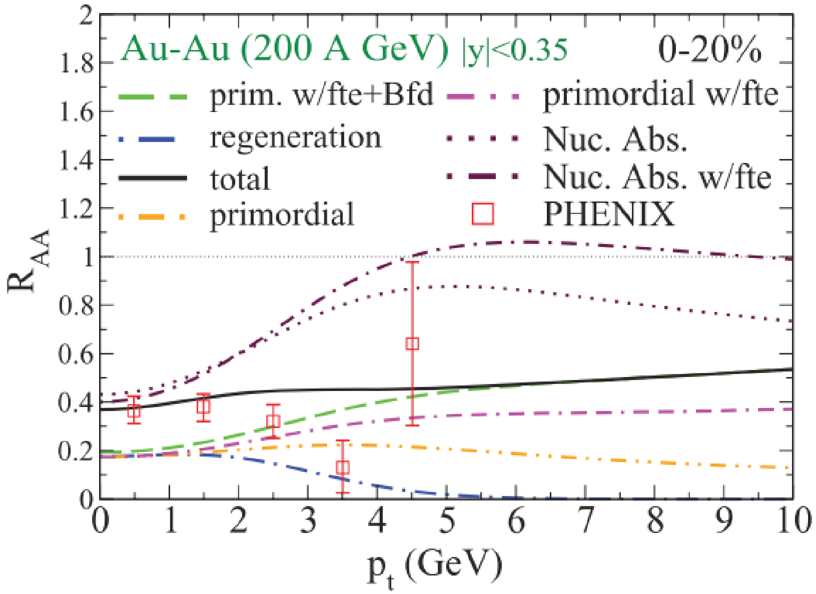
Other effects

- Quarkonium production mechanism is not well understood.
- Observed yields are a mixture of direct production + feed-down
  - direct J/ψ (~60%) +feed-down ~30% χ_c + ~10%ψ '
  - B-meson decay

.

- Suppression and enhancement in the "cold" nuclear medium
  - PDF modification in nucleus - shadowing , color glass condensate
  - Initial state energy loss
  - Cronin: Multiple scattering of the incoming parton on the nucleus.
  - Nuclear absorption – break up of bound state precursor by collisions with passing nucleons
  - Dissociation by interaction with co-movers in final state

X. Zhao, R.Rapp, PRC82, 064905 (2010)



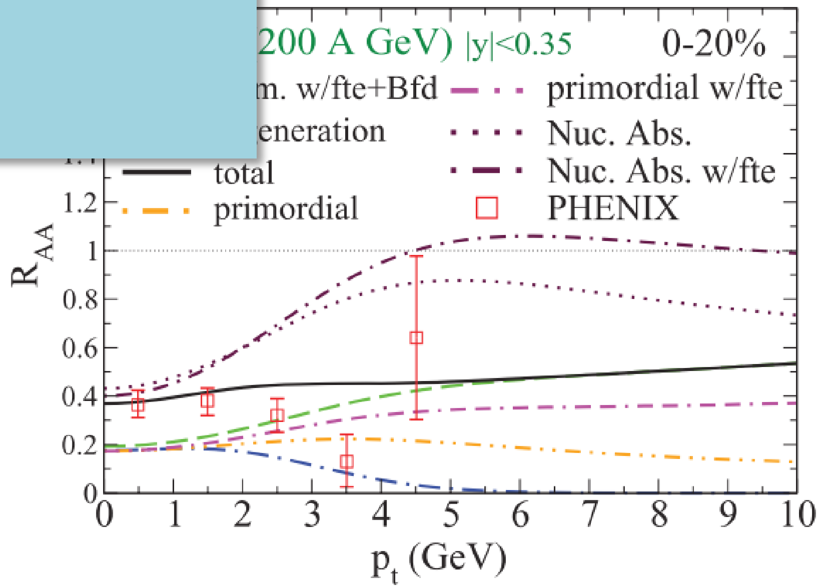
Other effects

d+Au - study of cold nuclear matter effects

Measurements of different observables at different p_T, in different colliding systems and collision energies are necessary.

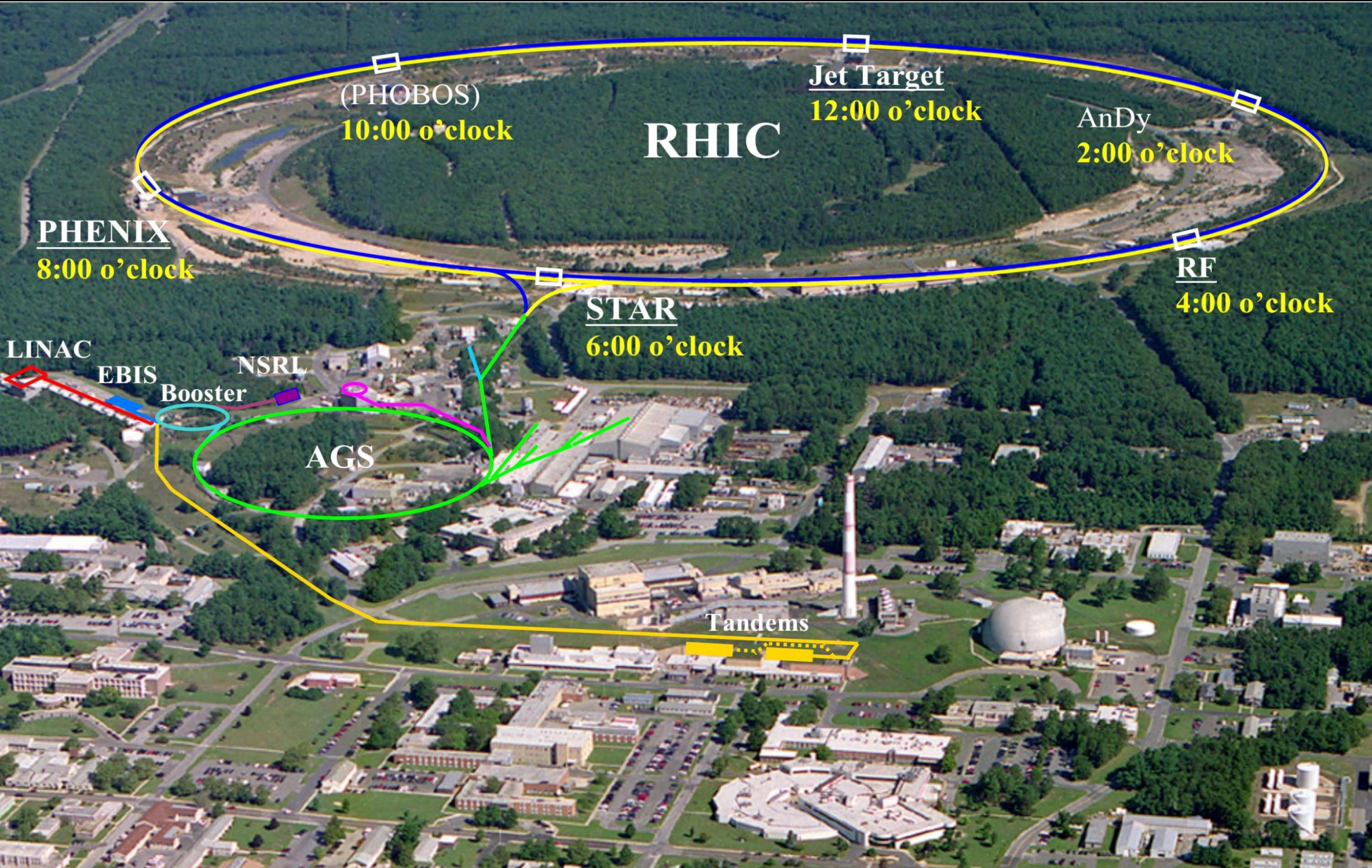
...possible at RHIC

R.Rapp, PRC82, 064905 (2010)

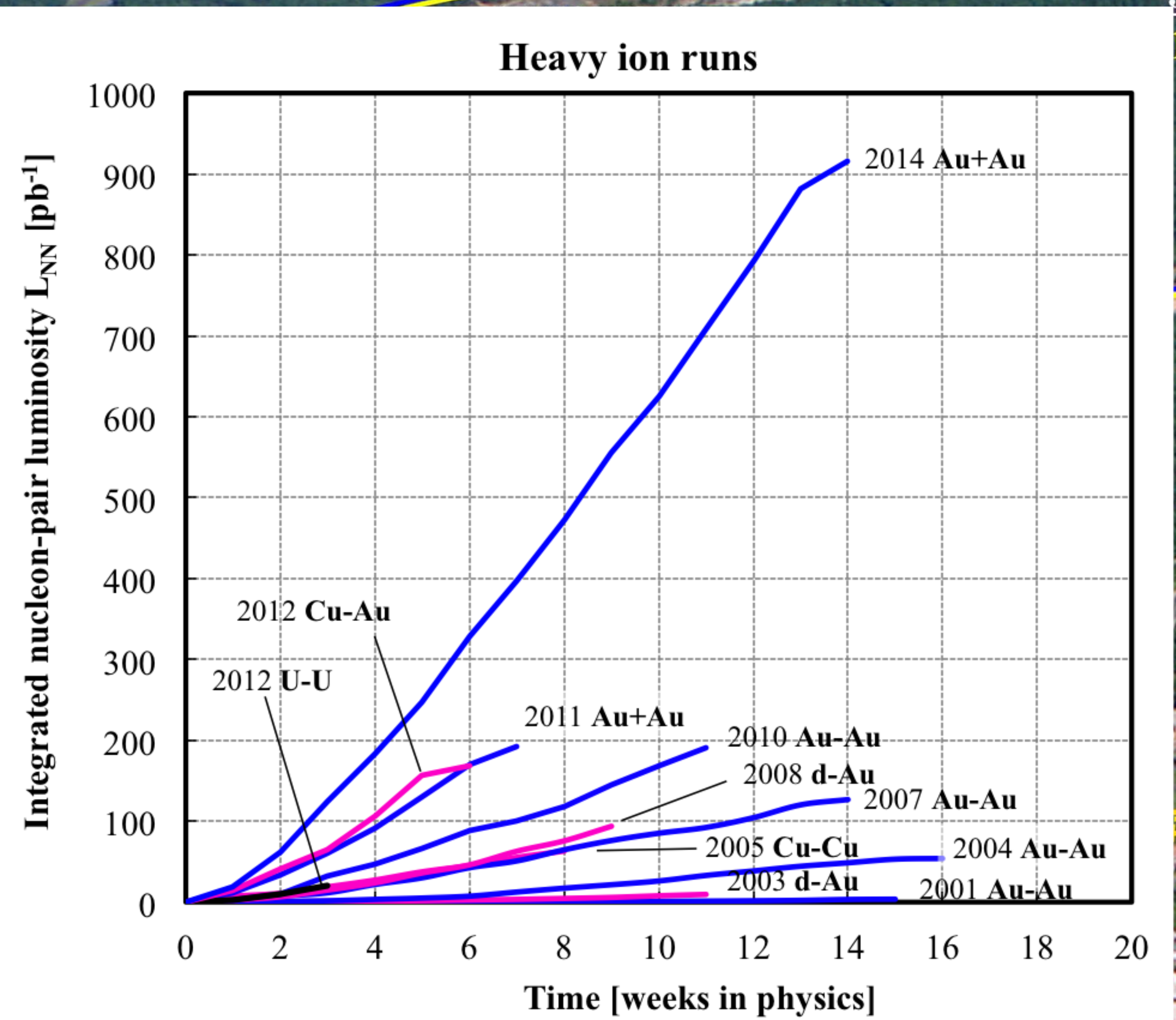


- Suppression and enhancement in the "cold" nuclear medium
  - PDF modification in nucleus - shadowing , color glass condensate
  - Initial state energy loss
  - Cronin: Multiple scattering of the incoming parton on the nucleus.
  - Nuclear absorption – break up of bound state precursor by collisions with passing nucleons
  - Dissociation by interaction with co-movers in final state

Relativistic Heavy Ion Collider

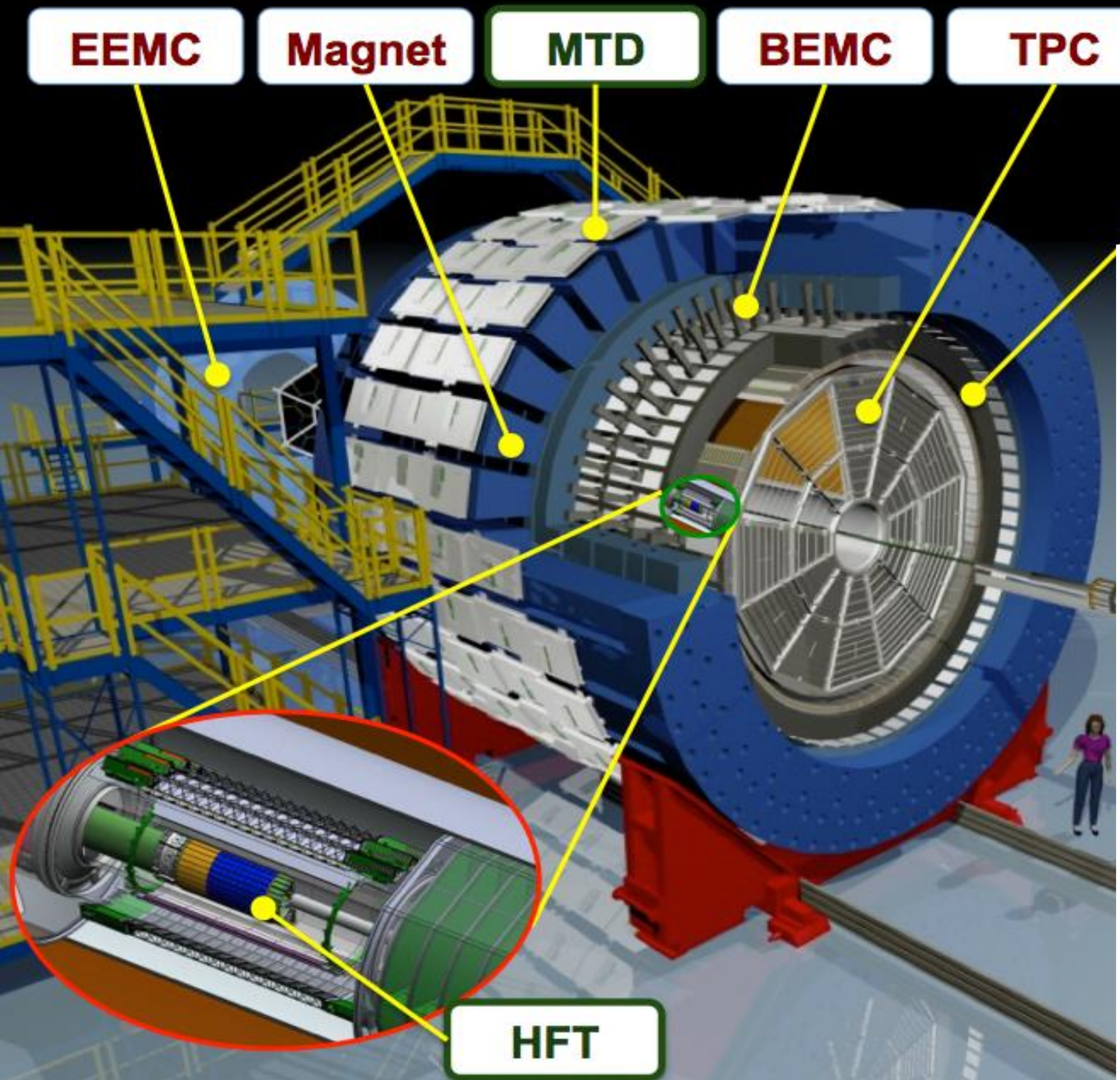


Relativistic Heavy Io



Year	System	$\sqrt{s_{NN}}$ [GeV]
2000	Au+Au	130
2001	Au+Au	200
2002	p+p	200
2003	d+Au	200
2004	Au+Au p+p	200, 62.4 200
2005	Cu+Cu	200, 62.4, 22
2006	p+p	62.4, 200, 500
2007	Au+Au	200
2008	d+Au p+p Au+Au	200 200 9.2
2009	p+p	200, 500
2010	Au+Au	200, 62.4, 39, 11.5, 7.7
2011	Au+Au p+p	200,19.6,27 500
2012	U+U Cu+Au p+p	193 200 200,510
2013	p+p	254.9
2014	Au+Au He+Au	7.3, 100 100

The STAR detector

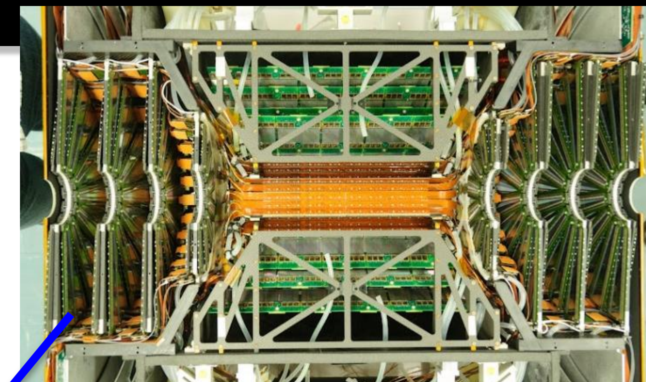


Large acceptance ID

- **Time Projection Chamber (TPC)**
  - charged particle tracking, 2π coverage in $|\eta|<1.3$
  - dE/dx PID
- **Time Of Flight(TOF)**
  - Timing resolution <100 ps
  - $1/\beta$ PID
  - e purity >90%
- **EM Calorimeter**
  - 2π coverage in $|\eta|<1$
  - Electron ID via E/p ~ 1
  - Triggering capability

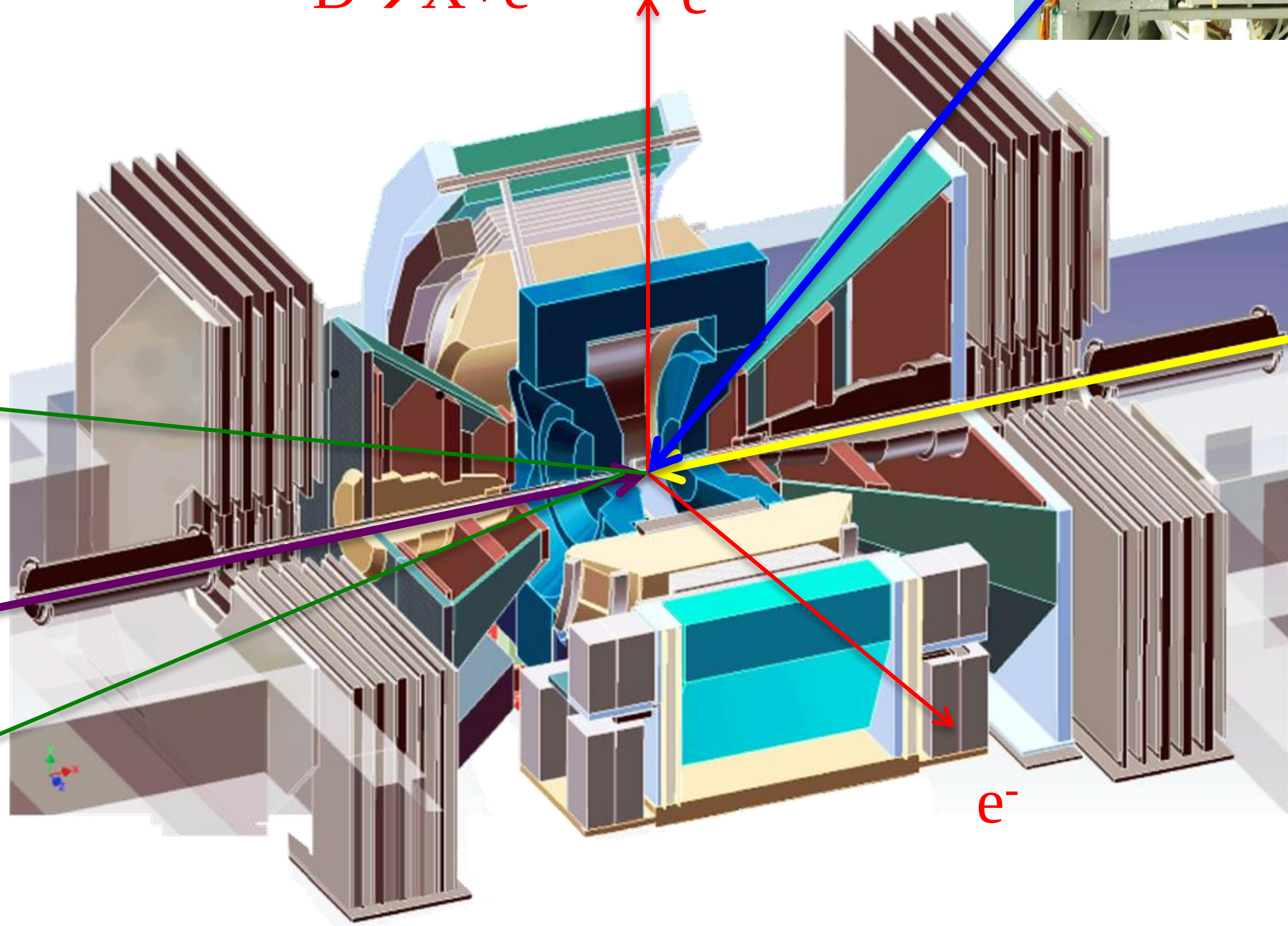
The PHENIX Detector

Central Arms:
- J/ψ, $\psi' \rightarrow e^+e^-$
- $D \rightarrow X+e$



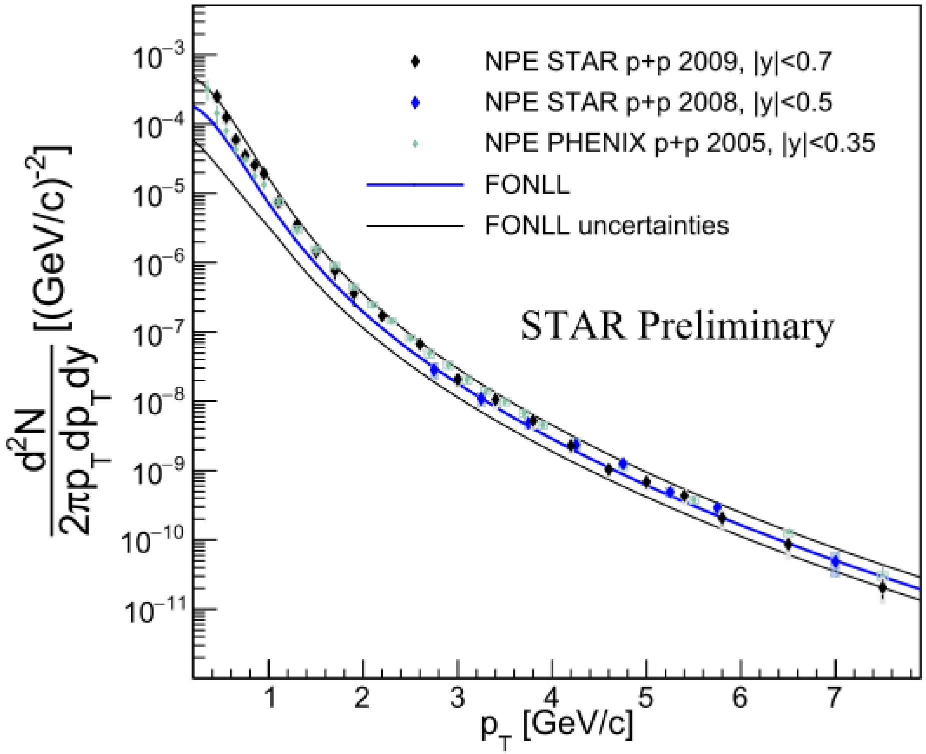
Adding FVTX:
- $\psi' \rightarrow \mu^+\mu^-$
- D, B

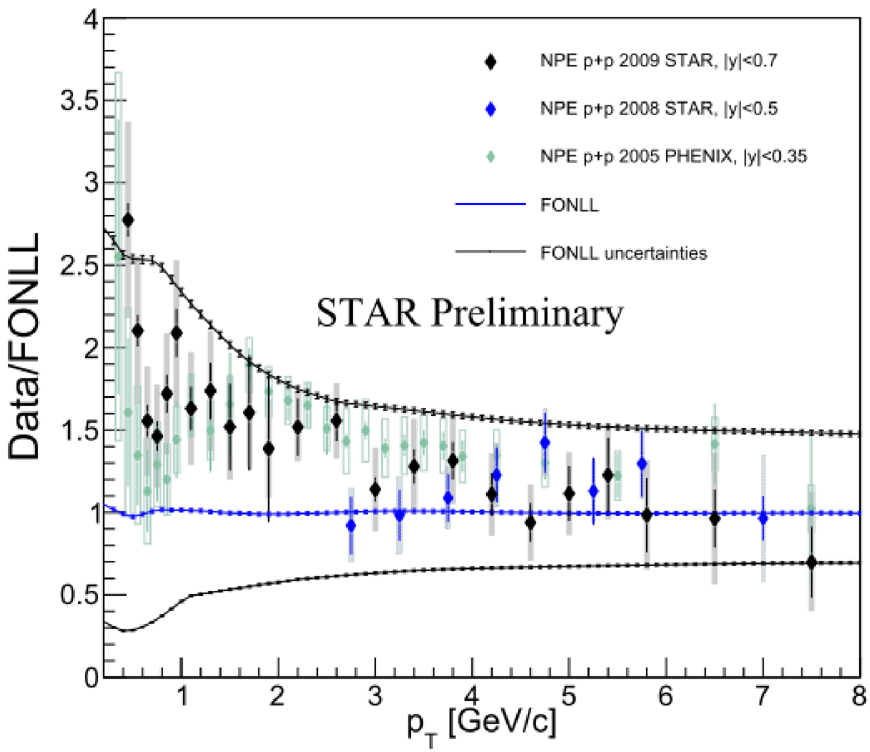
Muon Arms:
- $J/\psi \rightarrow \mu^+\mu^-$
- $D \rightarrow X+\mu$



Open heavy flavor measurements

STAR and PHENIX: Non- photonic electrons at mid-rapidity

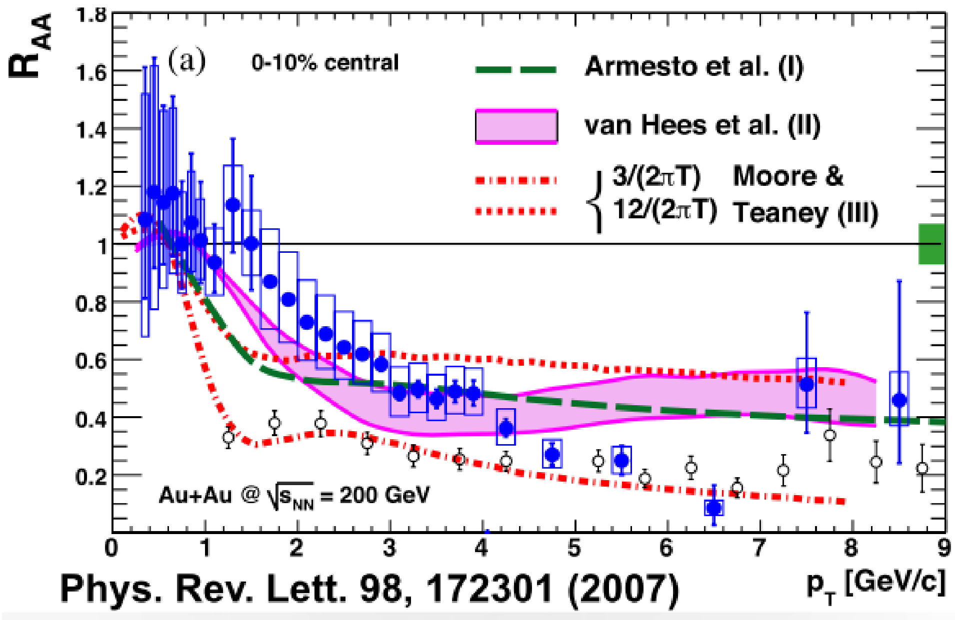




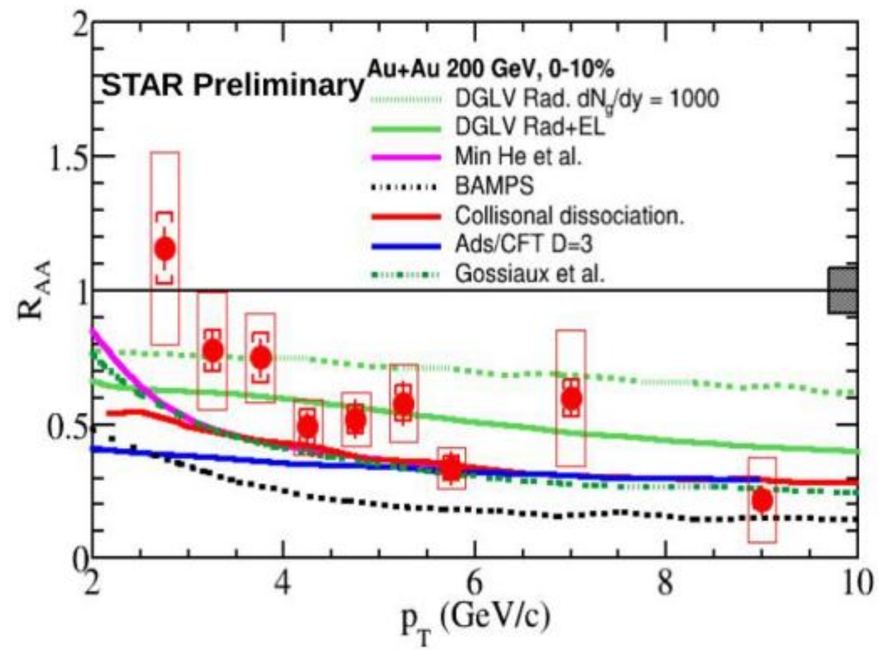
- in p+p
  - consistent with the FONLL calculations

Open heavy flavor measurements

STAR and PHENIX: Non- photonic electrons at mid-rapidity



Phys. Rev. Lett. 98, 172301 (2007)

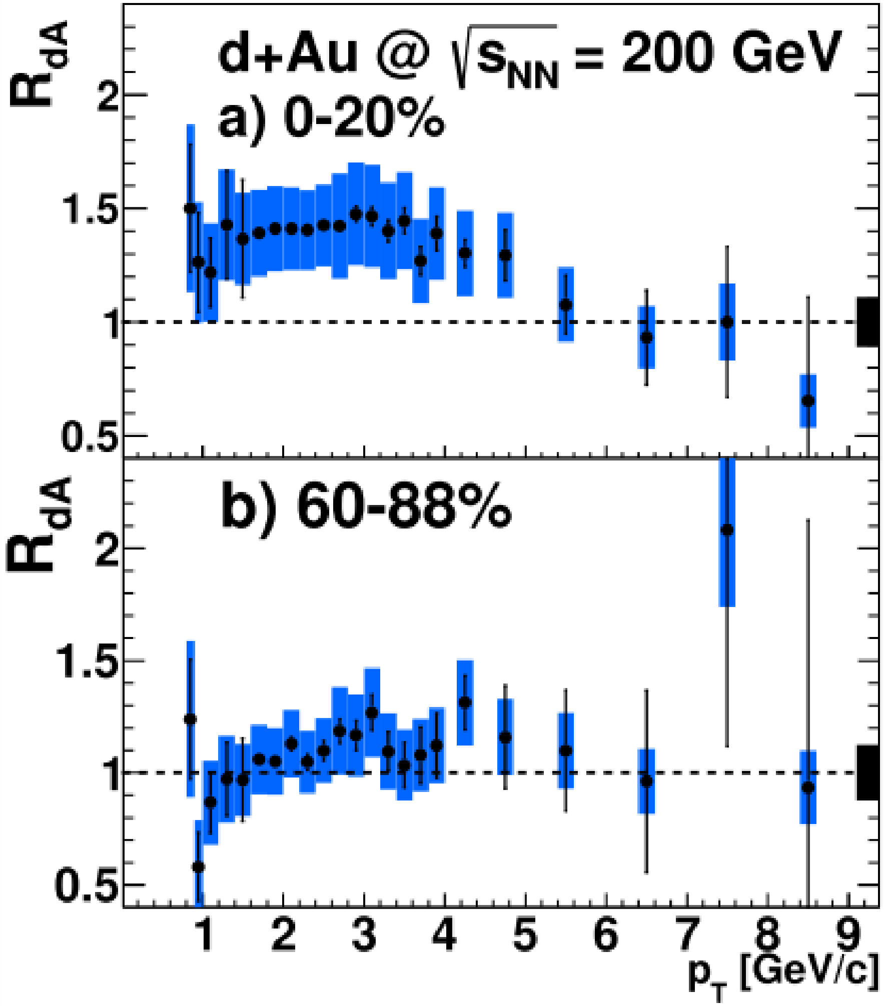


arXiv:1412.2112

- in Au+Au
  - Significant suppression
  - Needs to quantify CNM effects

Heavy Flavor e^{+-} in d+Au at midrapidity

d+Au $\sqrt{s_{NN}}$=200GeV , $|y|<0.35$

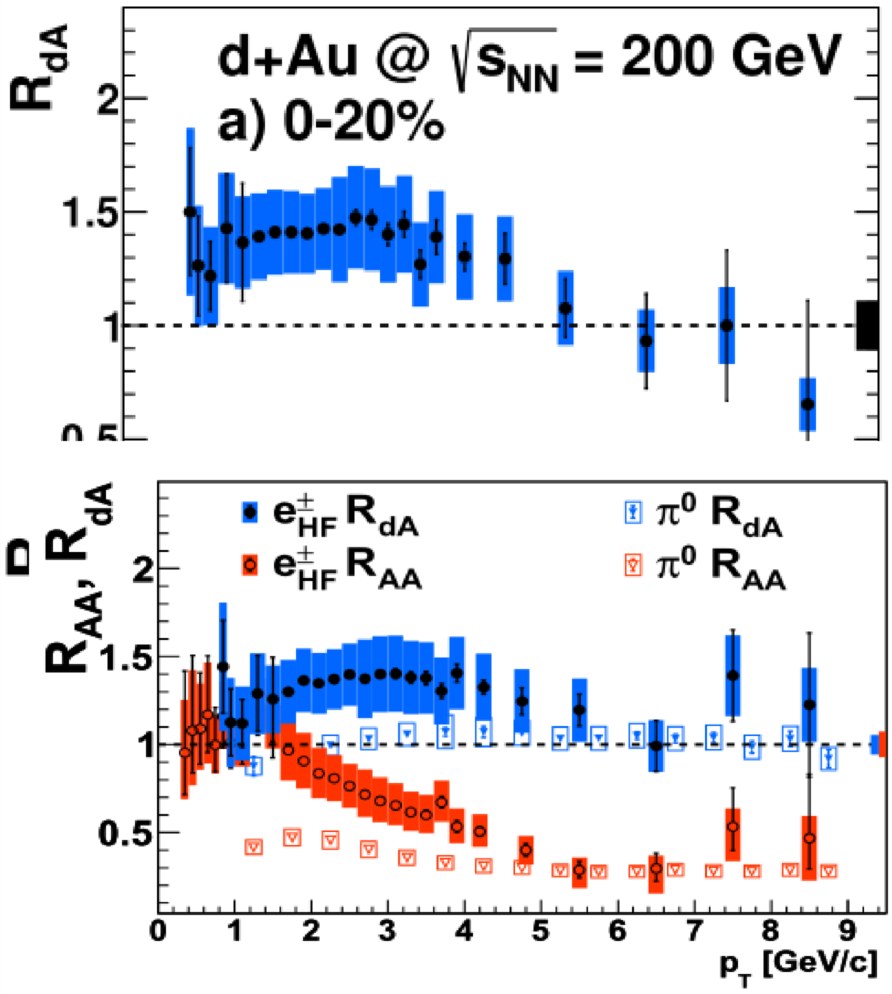


Phys. Rev. Lett. 109, 242301 (2012)

- Peripheral collisions
  - <Ncoll> = 3.2
  - Consisten with scaled p+p data
- Most central collisions
  - <Ncoll> = 15.1
  - Enhancement at intermediate p_T
- Interpretations
  - Cronin: scattering of incoming partons

Heavy Flavor e^{+-} in d+Au at midrapidity

d+Au $\sqrt{s_{NN}}$=200GeV , |y|<0.35

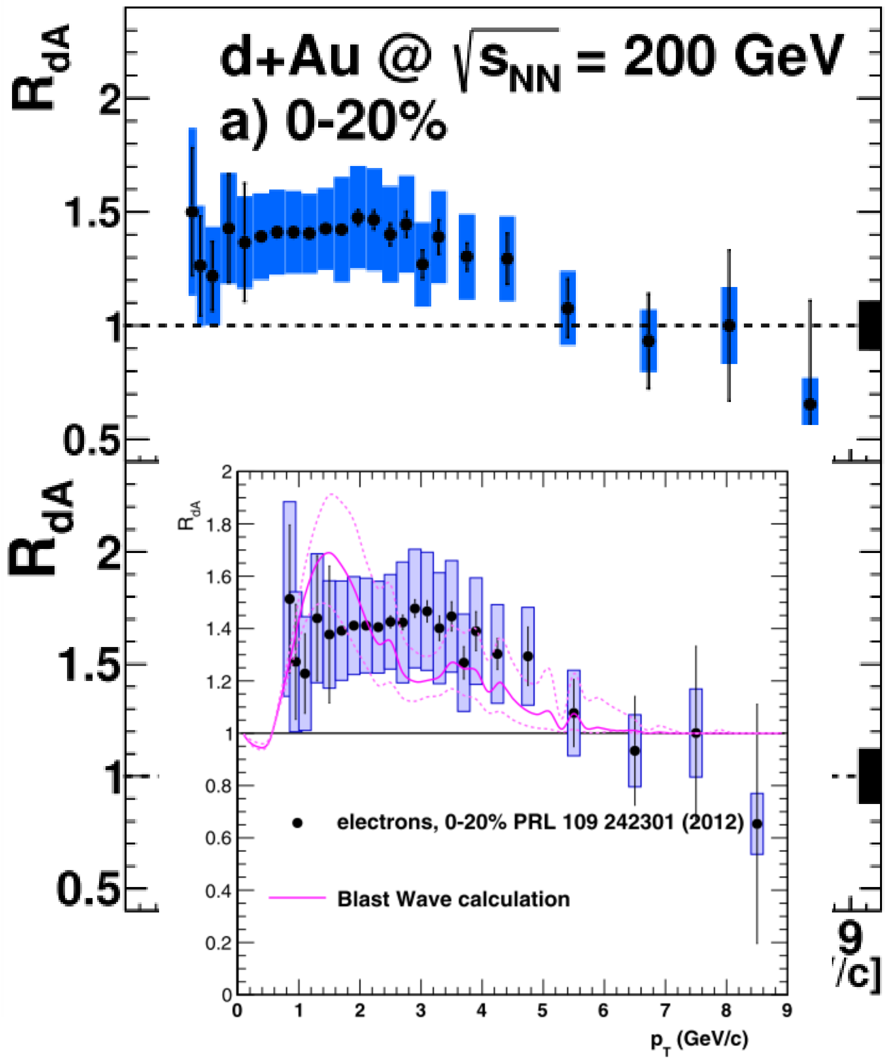


Phys. Rev. Lett. 109, 242301 (2012)

- Peripheral collisions
  - <Ncoll> = 3.2
  - Consisten with scaled p+p data
- Most central collisions
  - <Ncoll> = 15.1
  - Enhancement at intermediate p_T
- Interpretations
  - Cronin: scattering of incoming partons

Heavy Flavor e^{+-} in d+Au at midrapidity

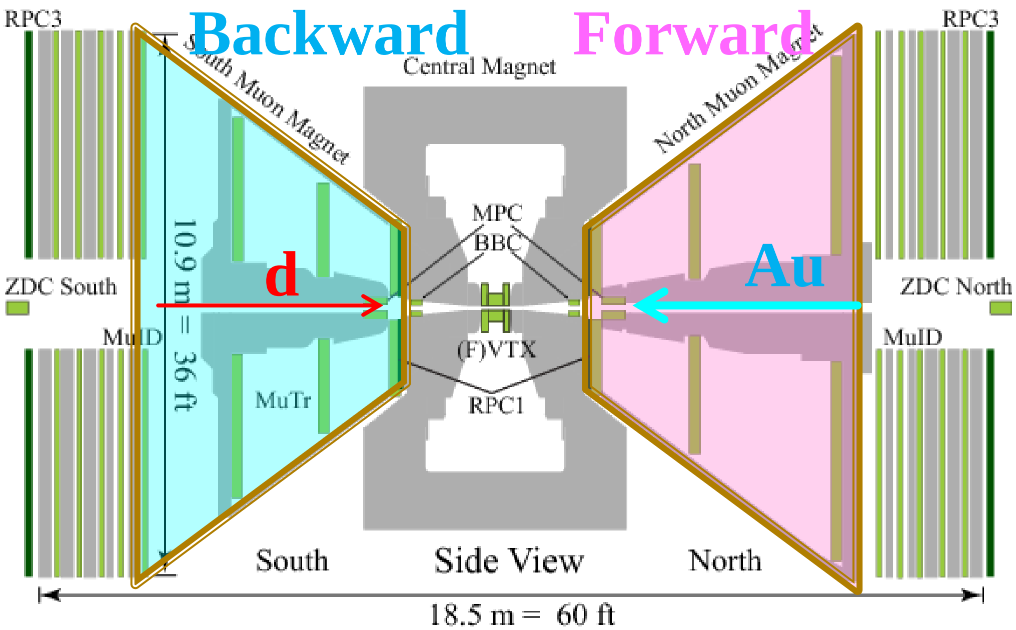
d+Au $\sqrt{s_{NN}}$=200GeV , $|y|<0.35$

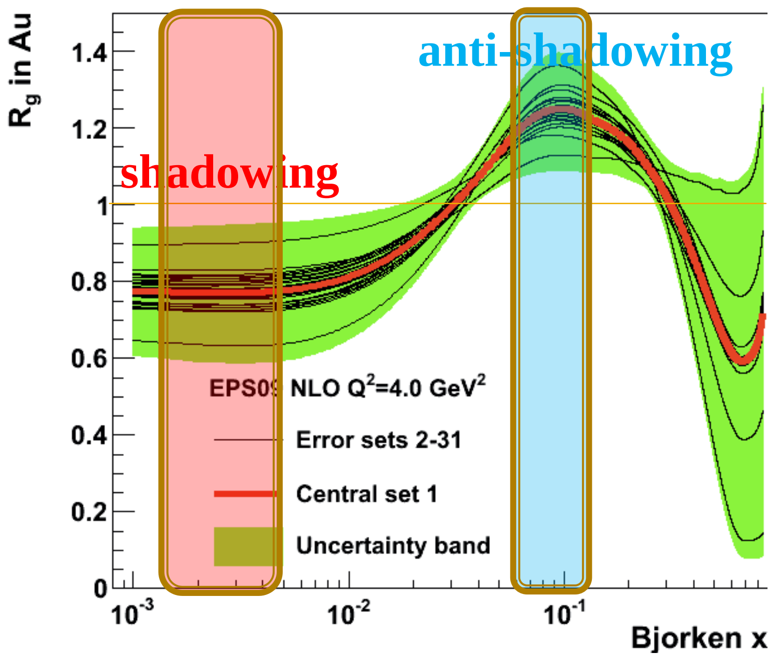


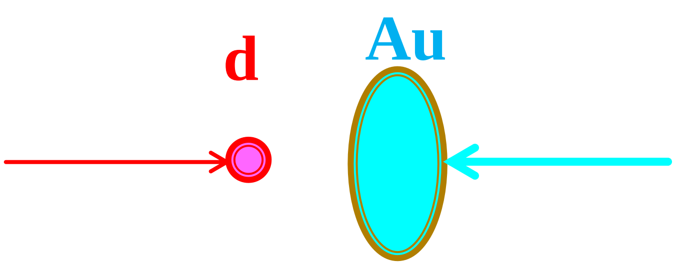
Sickles, arXiv:1309.6924

- Peripheral collisions
  - <Ncoll> = 3.2
  - Consistent with scaled p+p data
- Most central collisions
  - <Ncoll> = 15.1
  - Enhancement at intermediate p_T
- Interpretations
  - Cronin: scattering of incoming partons
  - Radial flow in dAu?

Heavy Flavor μ^- at forward and backward rapidity in d+Au





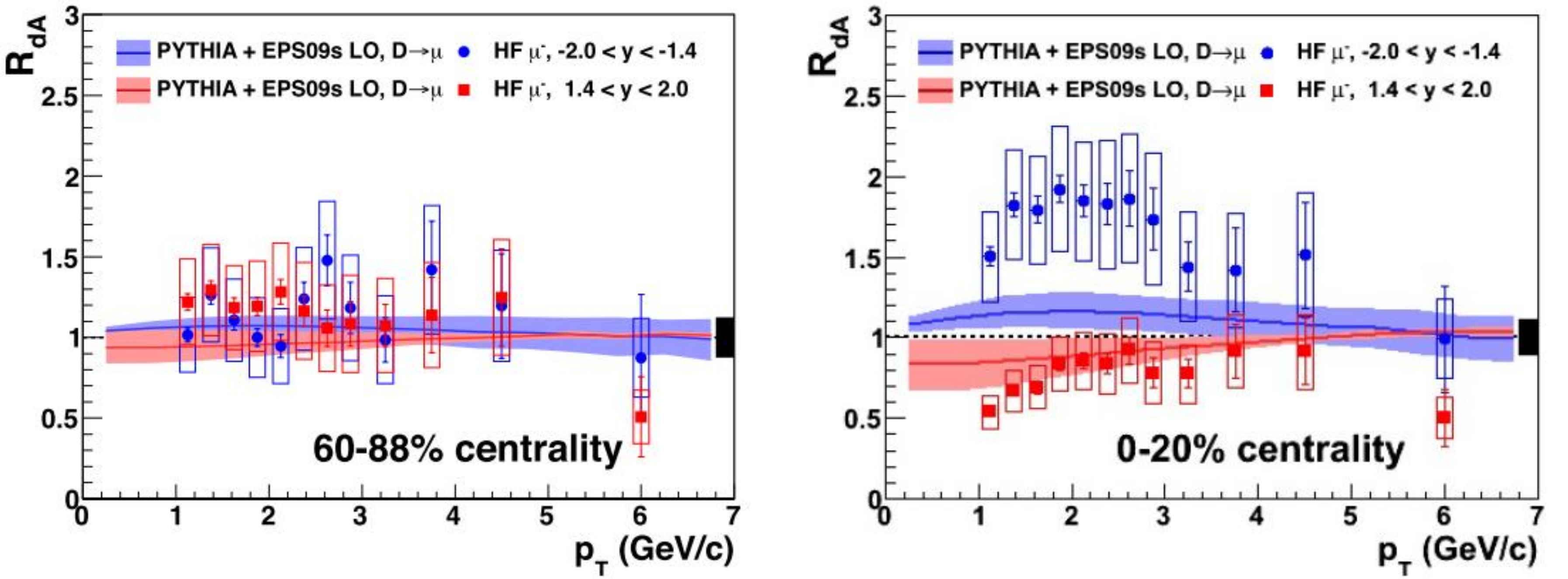


Forward Backward

$1.4 < |\eta| < 2.0$ $-2.0 < |\eta| < -1.4$

- Asymmetric system
  - Access to different x in Au
  - Different time spent passing the nucleus
  - Different density of comovers

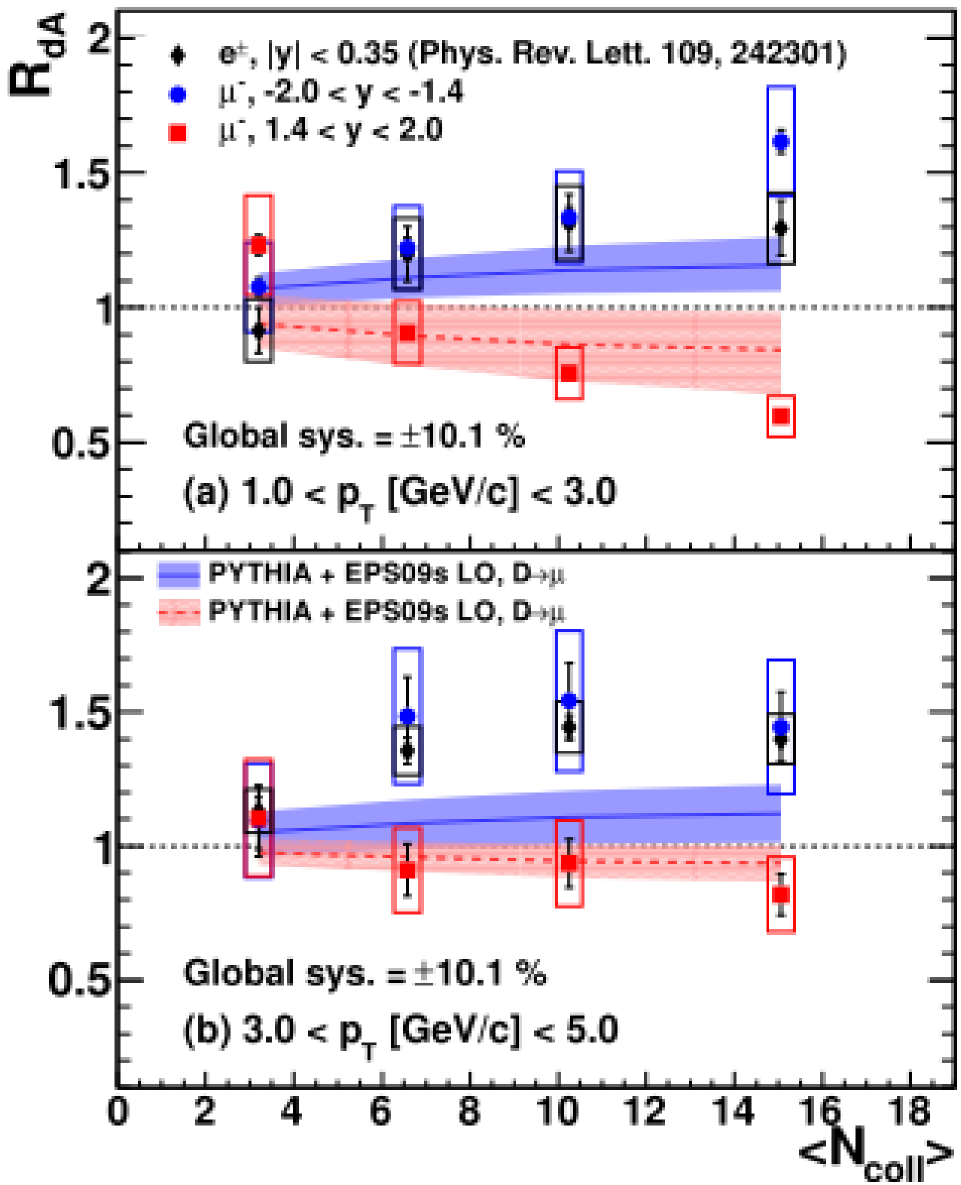
Heavy-Flavor μ R_{dAu}



PRL 112 (2014) 25, 252301

- Peripheral - no CNM effect
- Central - enhancement in backward rapidity
- Stronger then expected from anti-shadowing (PYTHIA+EPS09)

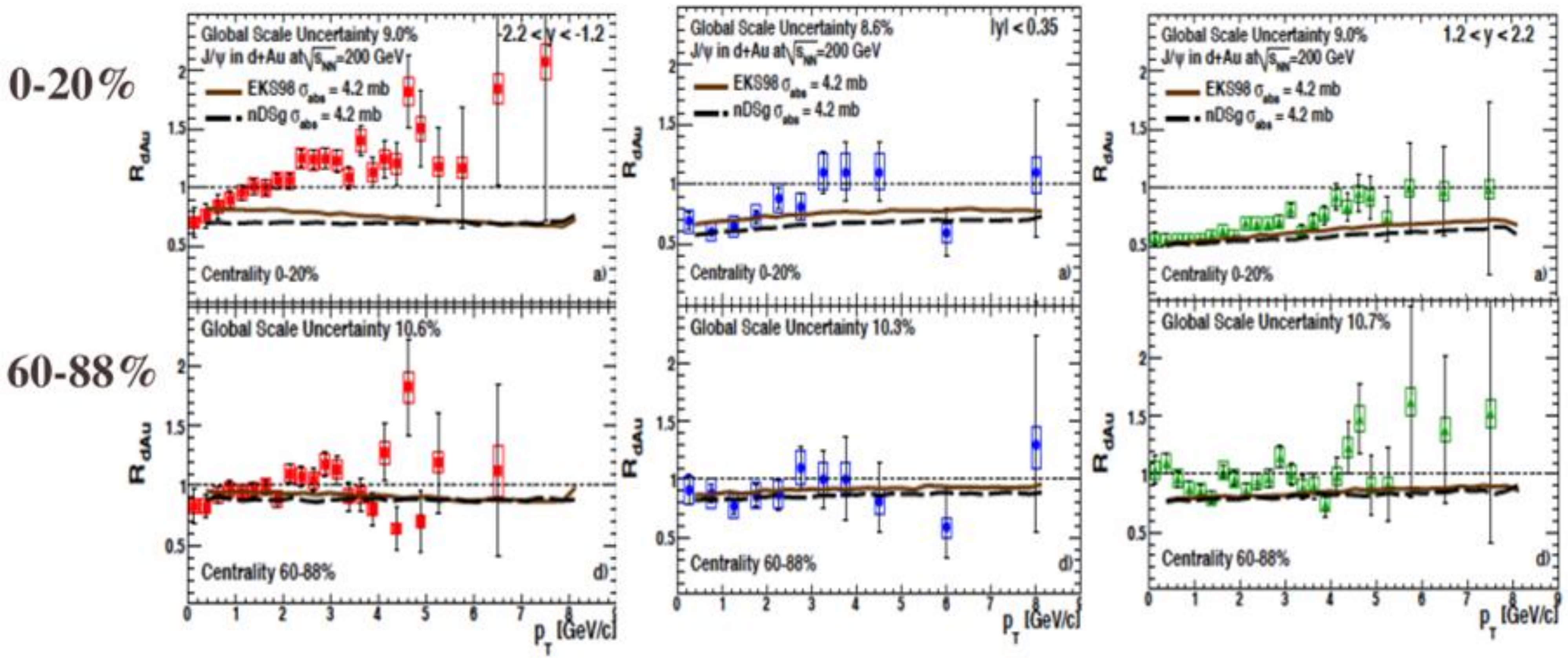
Centrality dependence μ R_{dAu}



- Top $1<p_T<3$ GeV/c
  Bottom $3<p_T<5$ GeV/c
- Comparison of *e* and μ R_{dAu}
- Enhancement in central and backward direction
- Additional effects beyond anti-shadowing are necessary to explain the data.

arXiv:1310.1005

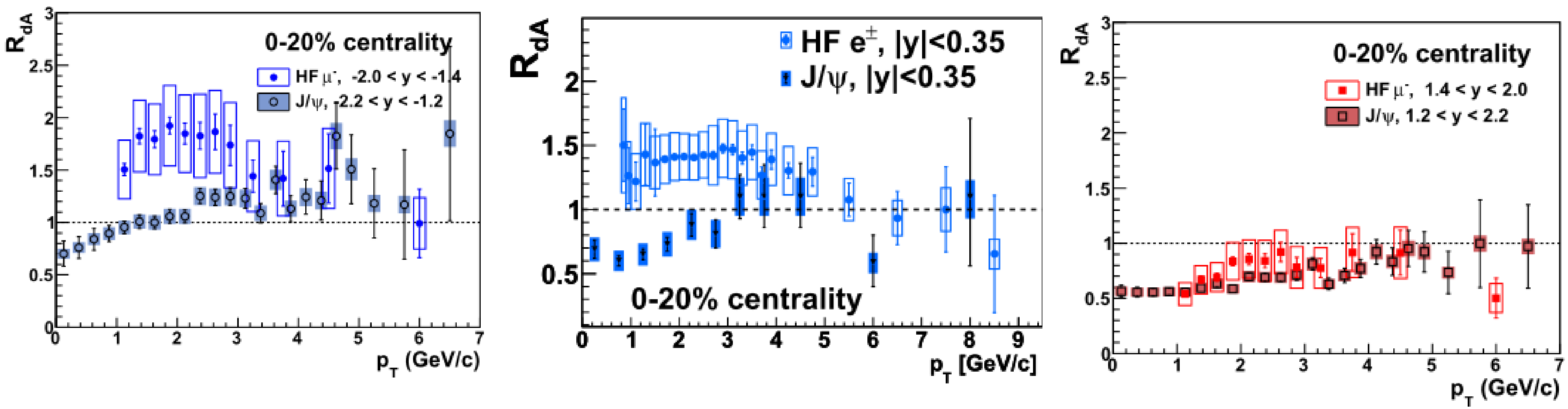
J/ψ suppression in d+Au



- Full p_T , y and centrality dependence
- Stronger modification in central collisions
- In peripheral R_{dAu} ~1
- Difference between backward and forward direction

- Calculations with two different PDFs
  - Shadowing, no Cronin
- Challenging to describe simultaneously forward and backward direction

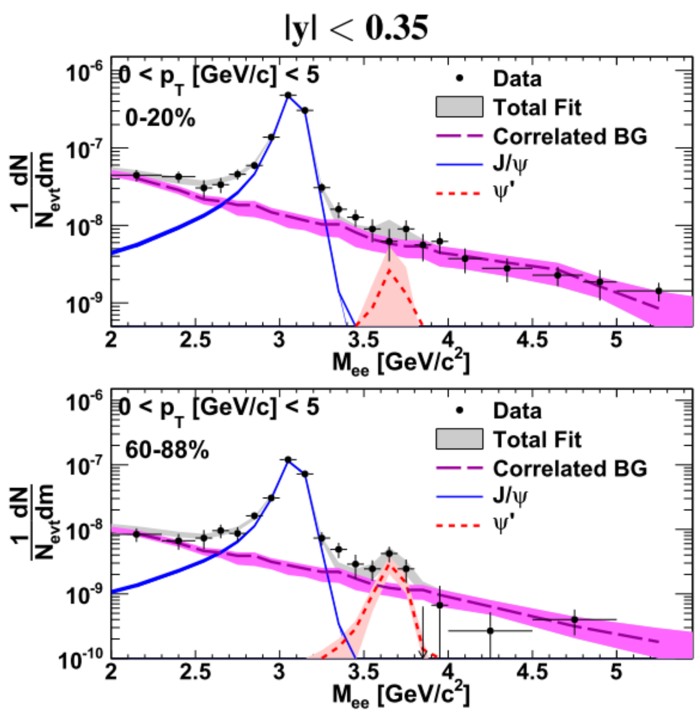
Comparison of J/ψ vs HF lepton R_{dAu}

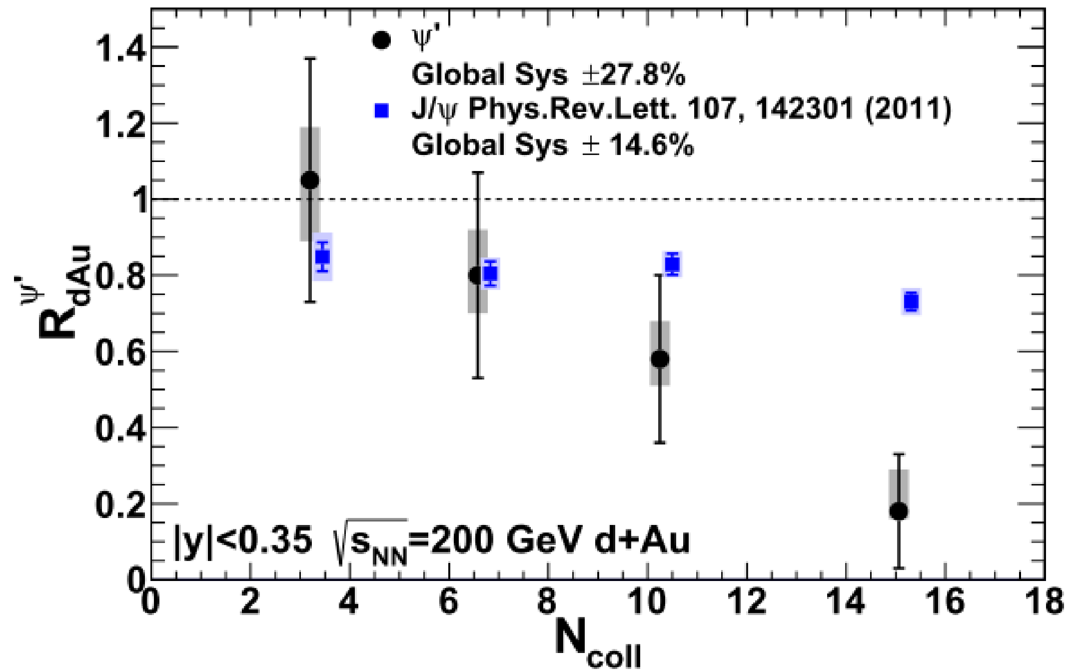


- J/ψ and HF leptons are sensitive to the same initial state effects
- In addition J/ψ can be affected by nuclear break-up.
- Forward direction: same suppression
  - J/ψ suppresion is driven by supression in c-c̄ production
- At mid and backward rapidity: stronger J/ψ suppression
  - Additional effect beyond the underlying c-c̄ production.

Ψ` in d + Au

PRL 111, 202301 (2013)



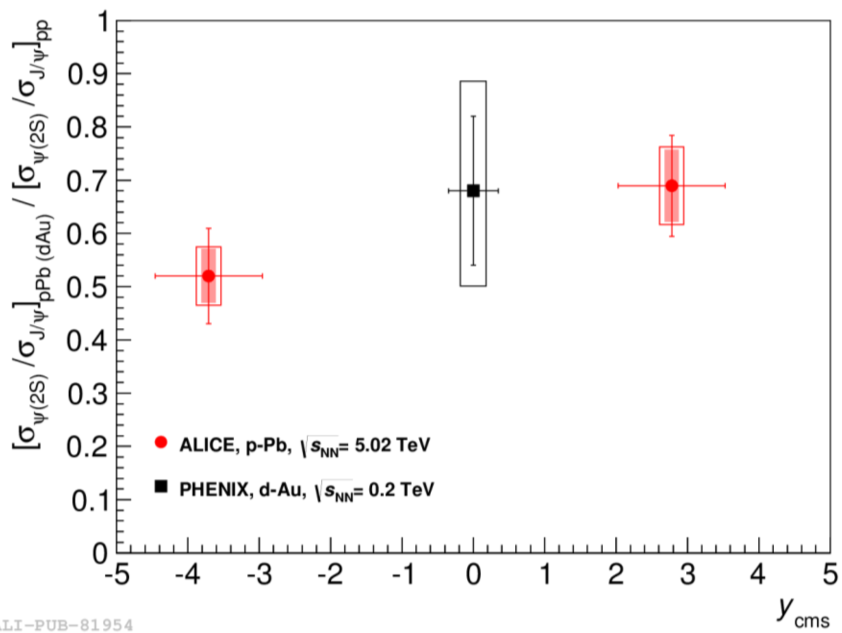


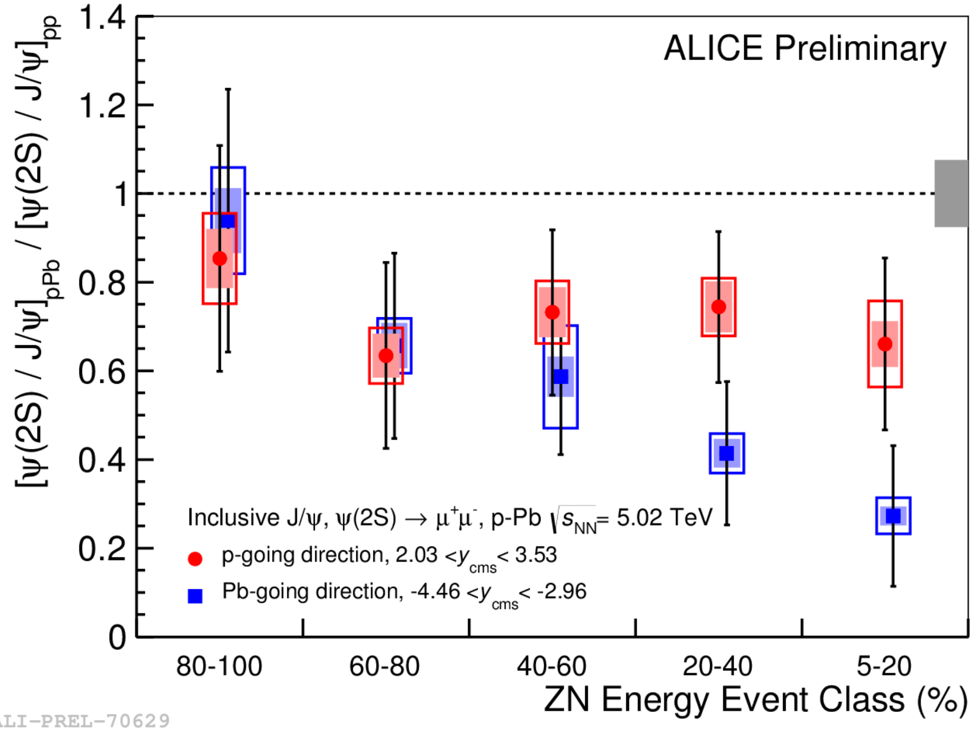
- Strong suppression of ψ′ with increasing N_{coll} at the mid-rapidity
- More suppressed than J/ψ in most central collisions
- Ψ` binding energy is 12× smaller than J/ψ.
  - No melting expected in d+Au
  - Nuclear break up?

Comparing CNM for J/ψ, ψ′

- ψ′ suppression in d+Au - hard to explain by nuclear break up.
  - Time spent in nucleus short (~0.0.5 fm) when compared to ψ' formation time (~0.15 fm).
- Alice p-Pb data show similar suppression pattern

arXiv:1405.3796

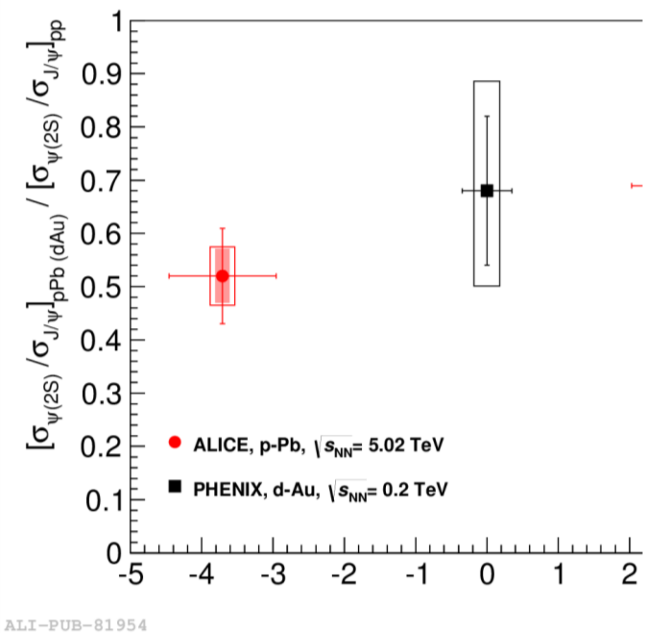


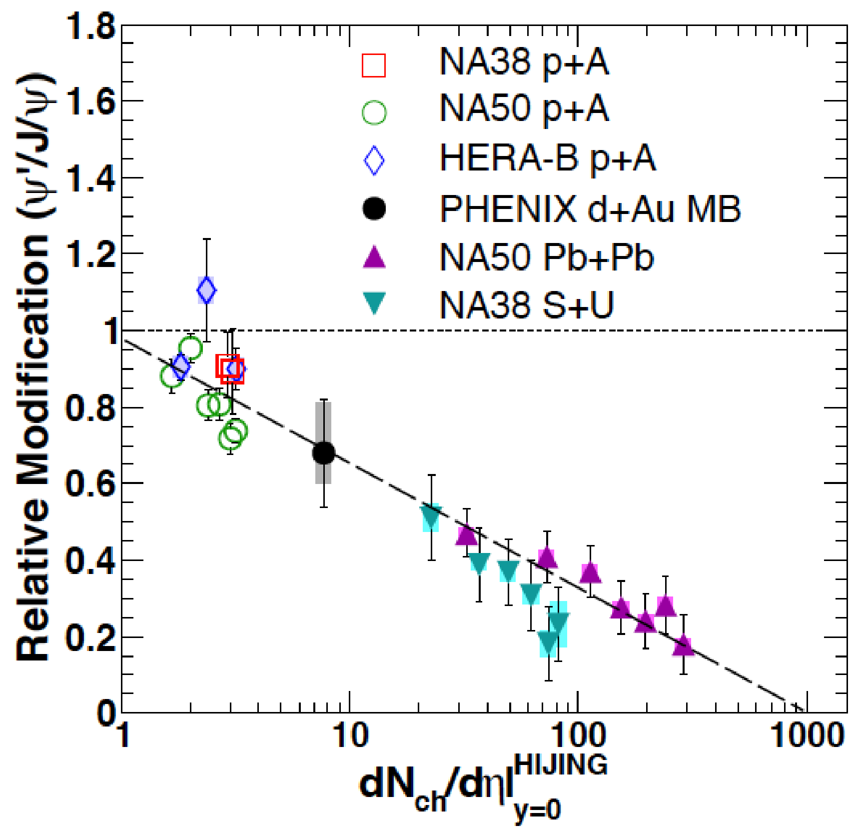


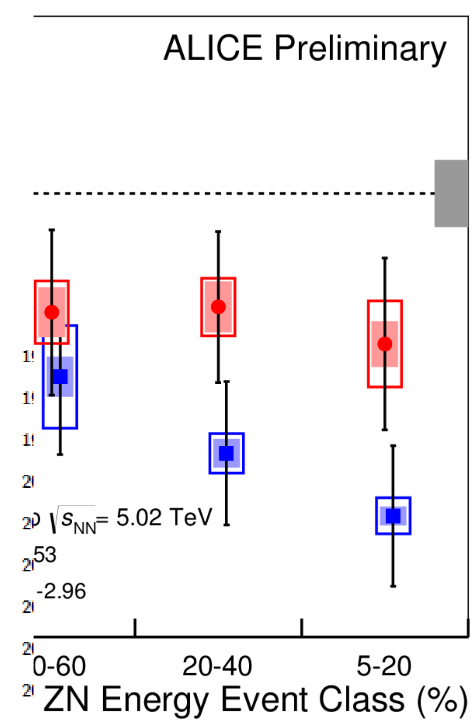
Comparing CNM for J/ψ, ψ′

- ψ′ suppression in d+Au - hard to explain by nuclear break up.
  - Time spent in nucleus short (~0.0.5 fm) when compared to ψ’ formation time (~0.15 fm).
- Alice p-Pb data show similar suppression pattern
- Universal trend with $dN_{ch}/d\eta$ for several systems, up to 200 GeV

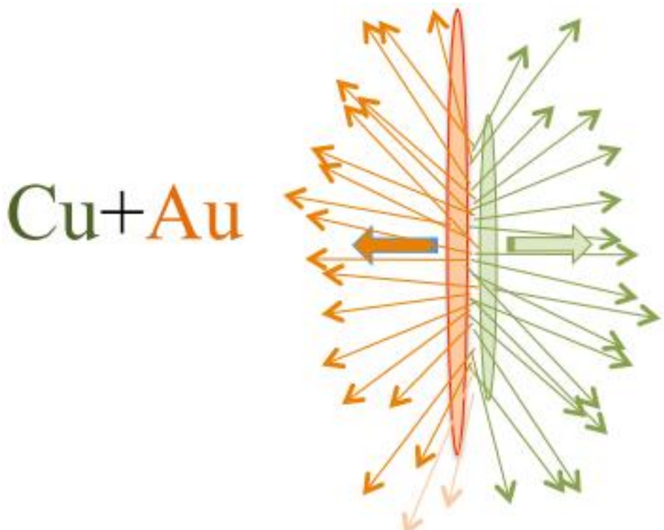
arXiv:1405.3796

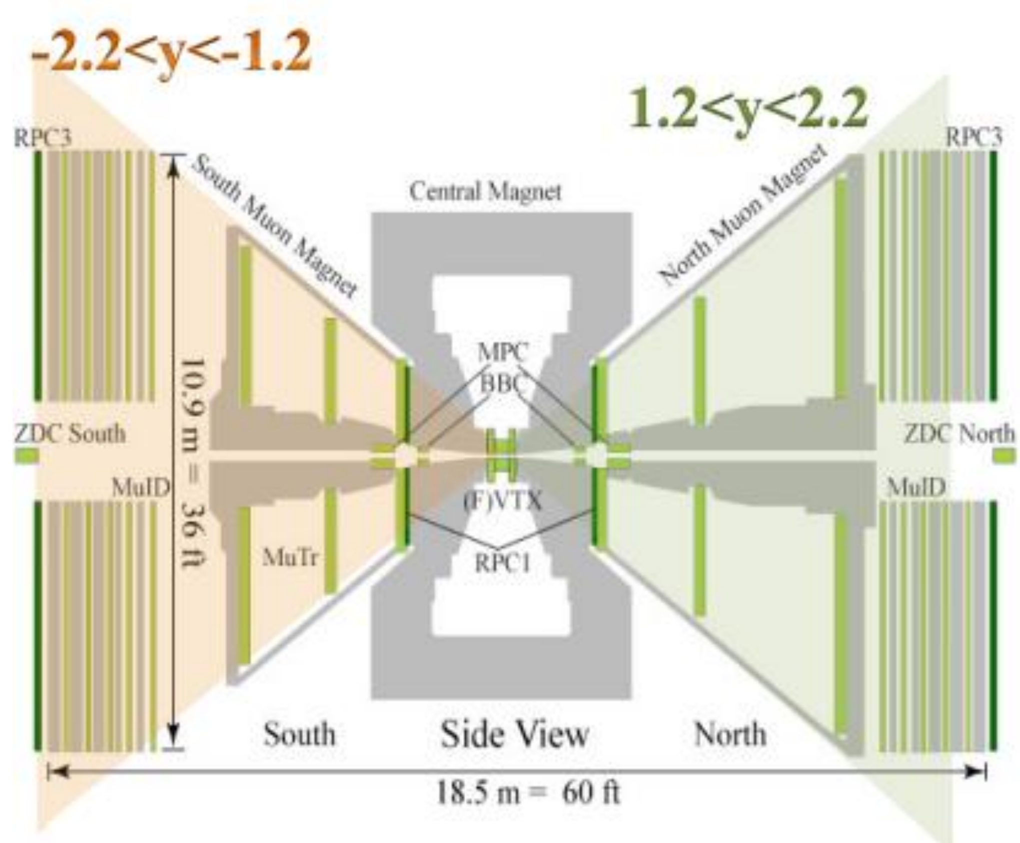






Cu+Au collisions

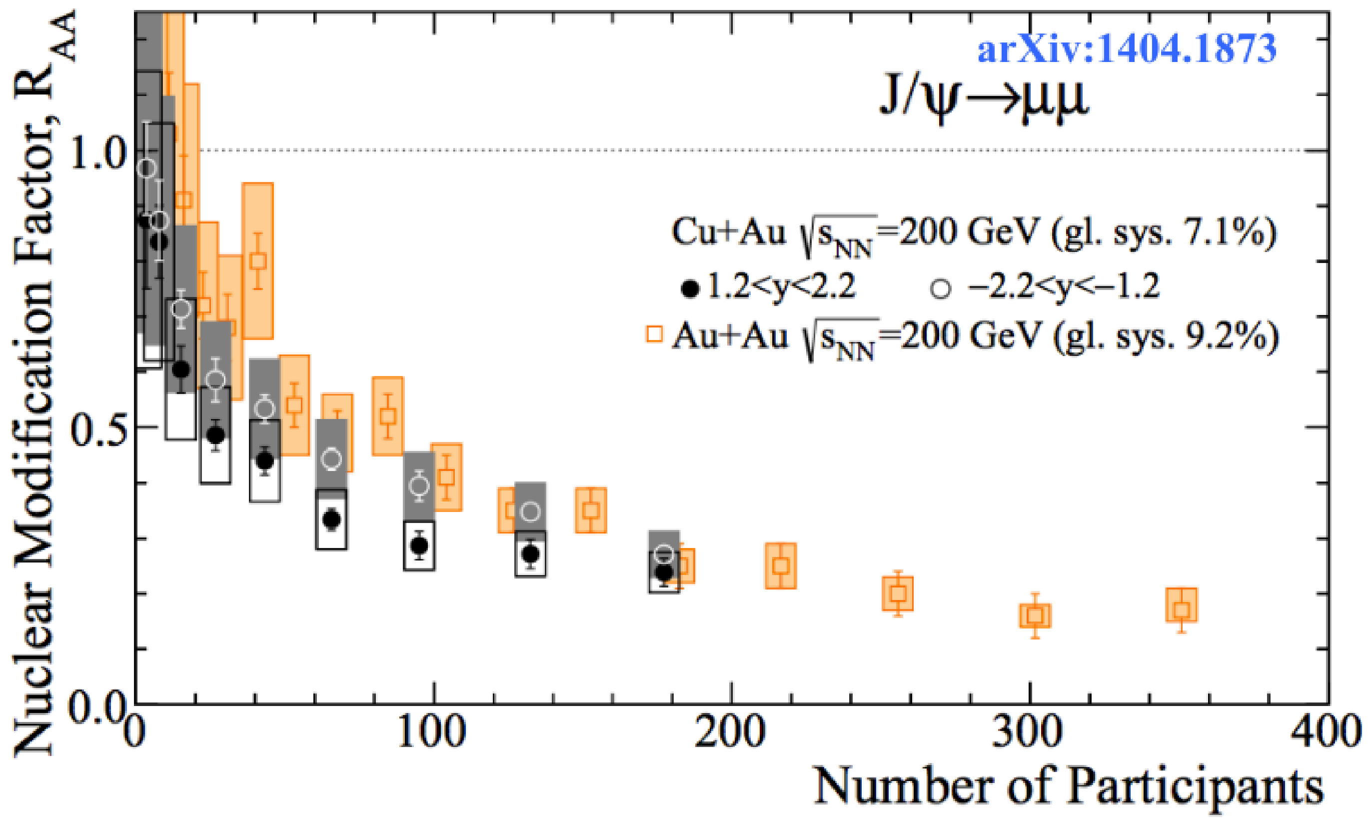




Initial asymmetry should result in asymmetric distribution of final particle density:

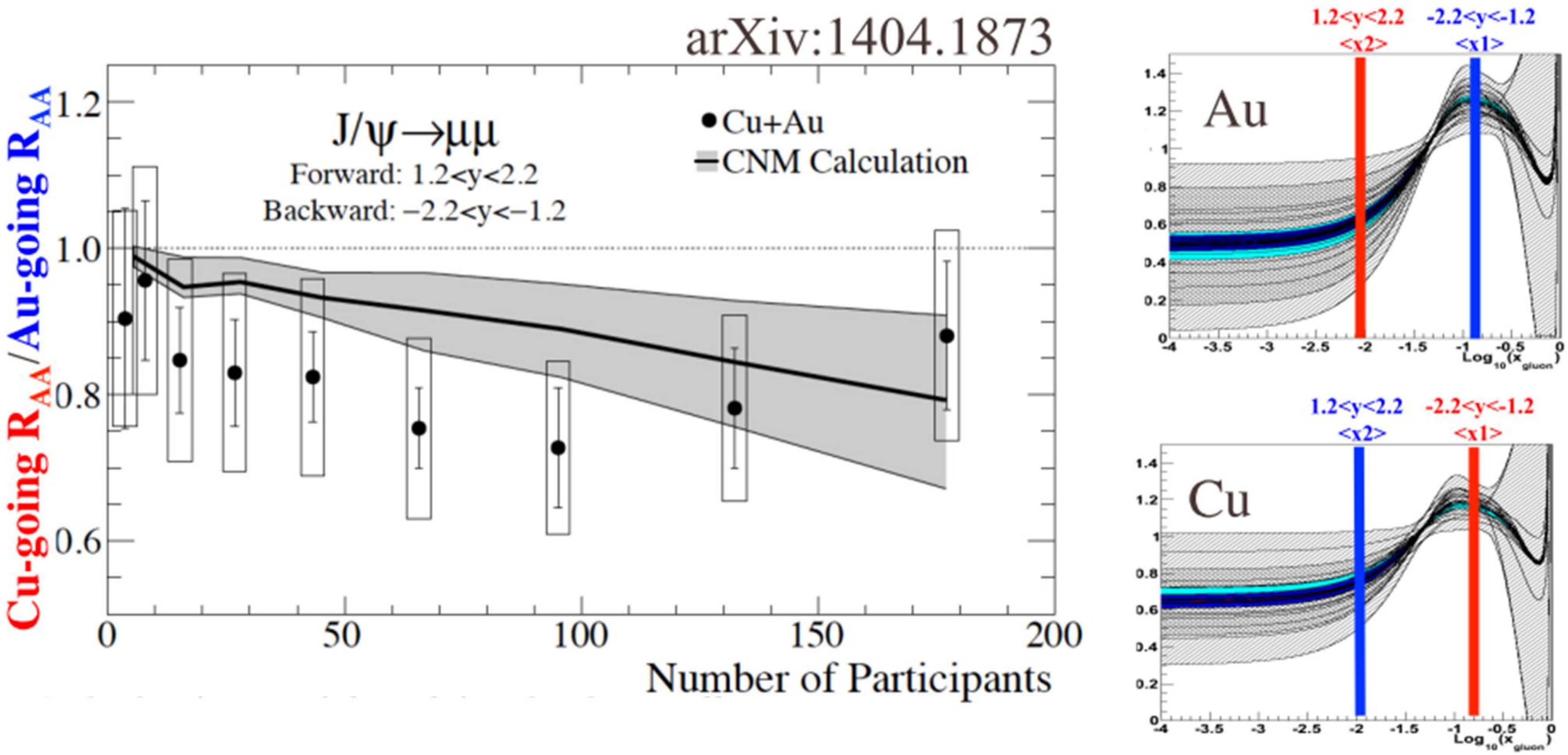
- Asymmetric CNM effects.
  - parton distribution modifications
  - nucleus crossing time of the c -c precursor
  - initial state energy loss
  - breakup in the hadronic phase
- HNM effects possibly asymmetric (N part (Cu) < N part (Au)).

J/ψ suppression in Cu+Au



- Au-going direction (backward) similar to Au+Au.
- Cu-going direction (forward) - more suppressed.
  - Qualitatively agrees with shadowing expectations

Forward/ backward ratio



Ratio of forward/backward R_{AA} cancels some systematic errors.

Simple model to estimate effects of shadowing

- Uses EPS09 nPDF and a 4 mb effective absorption cross section
- Reflects only the difference in shadowing.
- Data compatible with shadowing - correct sign.

Upsilon measurements

Υ-cleaner probe compared to J/ψ

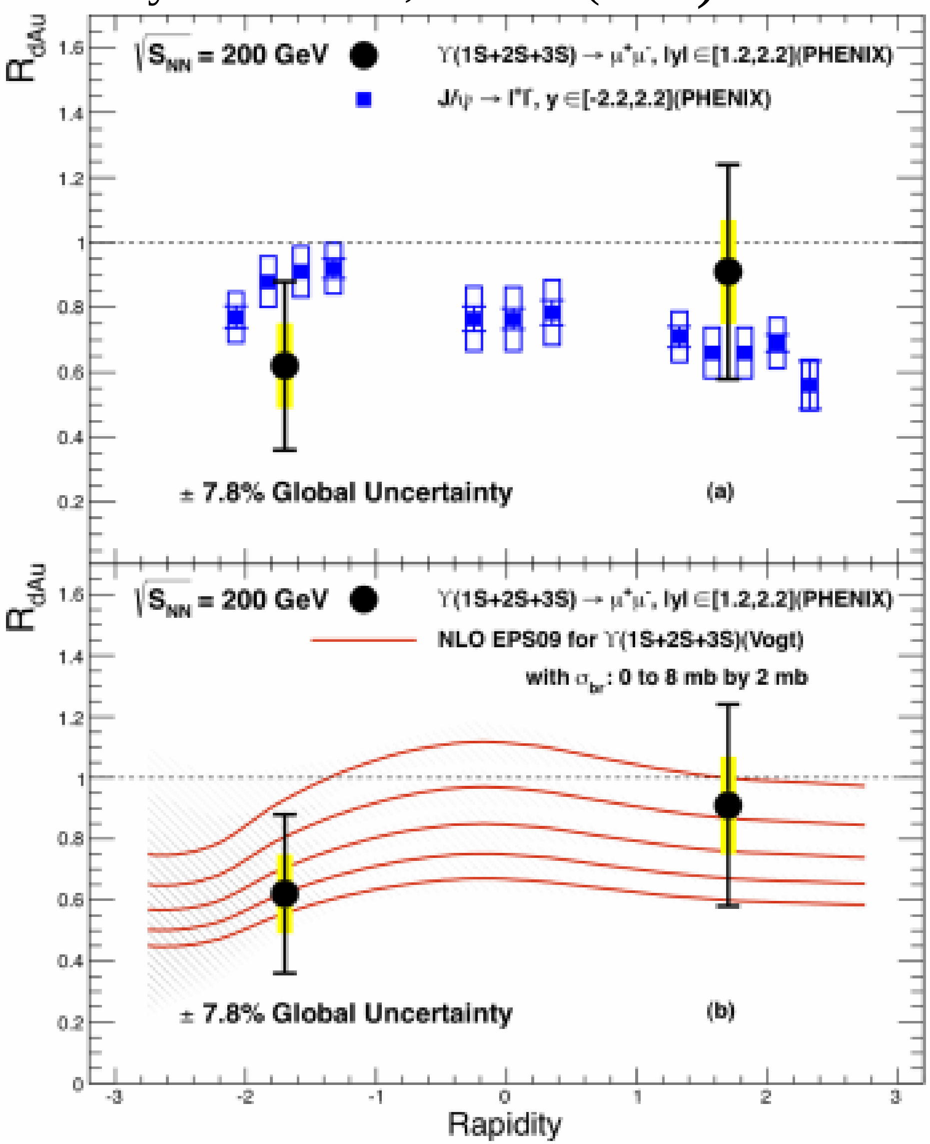
- Less feed down
- Co-mover absorption $\longrightarrow$ negligible
  - Υ(1s): tightly bound, larger kinematic threshold.
  - Expect $\sigma \sim 0.2$ mb, 5-10 times smaller than for J/ψ

    Lin & Ko, PLB 503 (2001) 104
- Recombination $\longrightarrow$ negligible
  - at RHIC: $\sigma_{cc} \sim 800\mu b >> \sigma_{bb} \sim (1\text{-}2)\mu b$
- Excited states: expect sequential suppression of Υ(1s), Υ(2s), Υ(2s) states
- Challenge: low rate, rare probe
  - Need large acceptance, efficient trigger

Υ production in dAu

PHENIX: forward/ backward rapidity

Phys. Rev. C 87, 044909 (2013)



Suppression consistent with NLO+EPS09 (R. Vogt, Phys. Rev. C81, 044903, 2010) trend.

Suggests a backward suppression

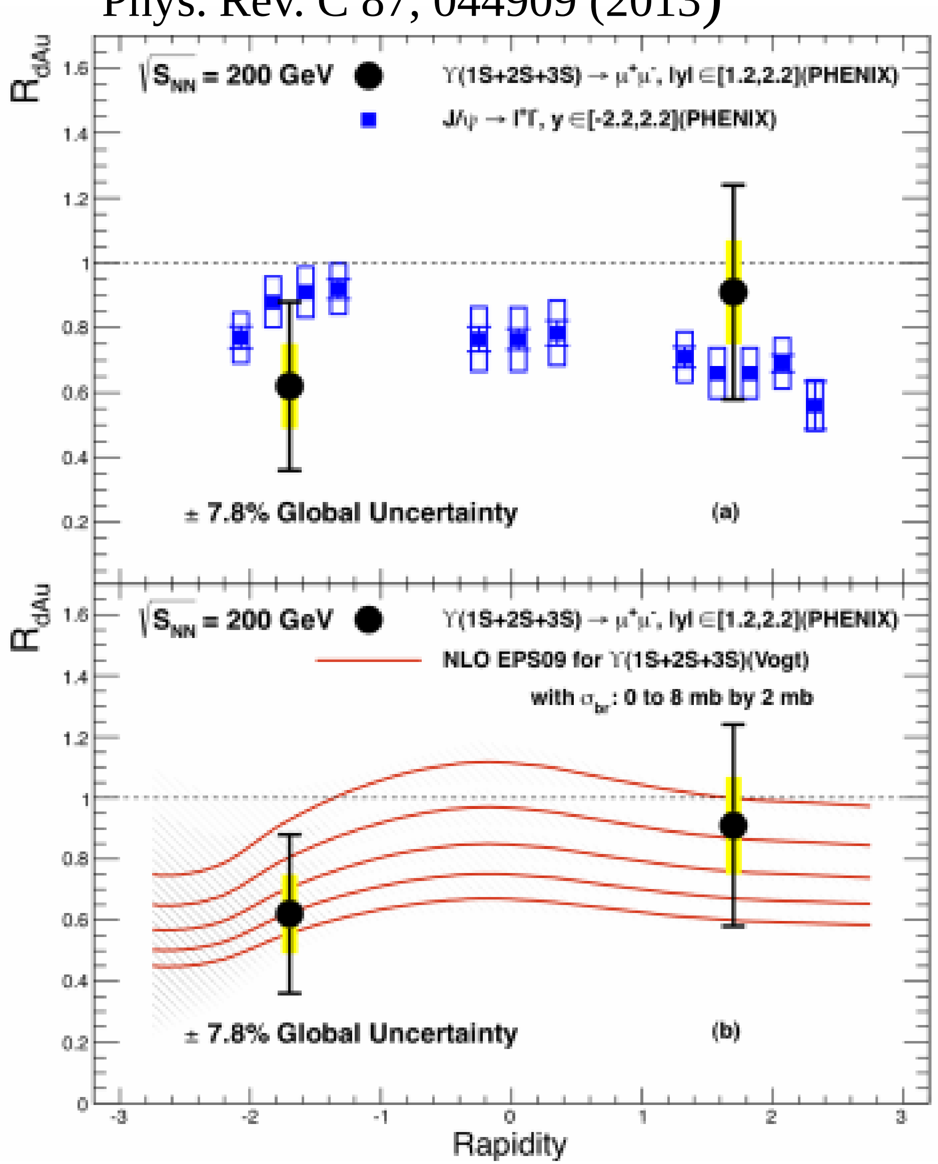
Unable to constrain breakup cross section due to large experimental uncertainties.

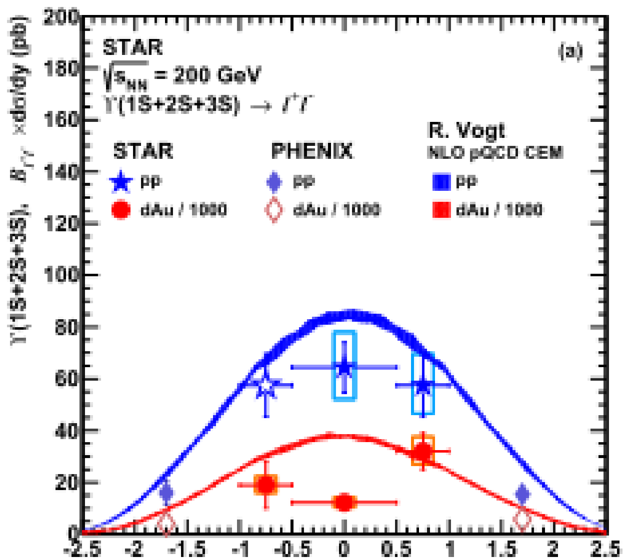
Υ production in dAu

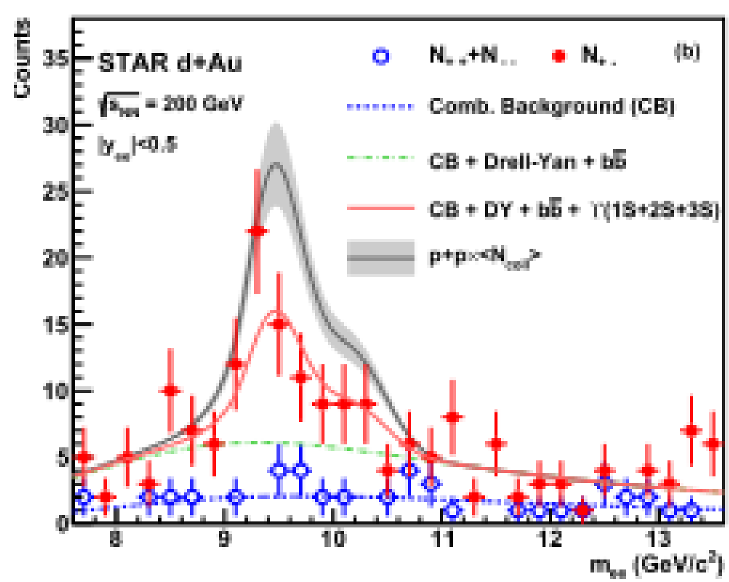
PHENIX: forward/ backward rapidity

STAR: midrapidity

Phys. Rev. C 87, 044909 (2013)



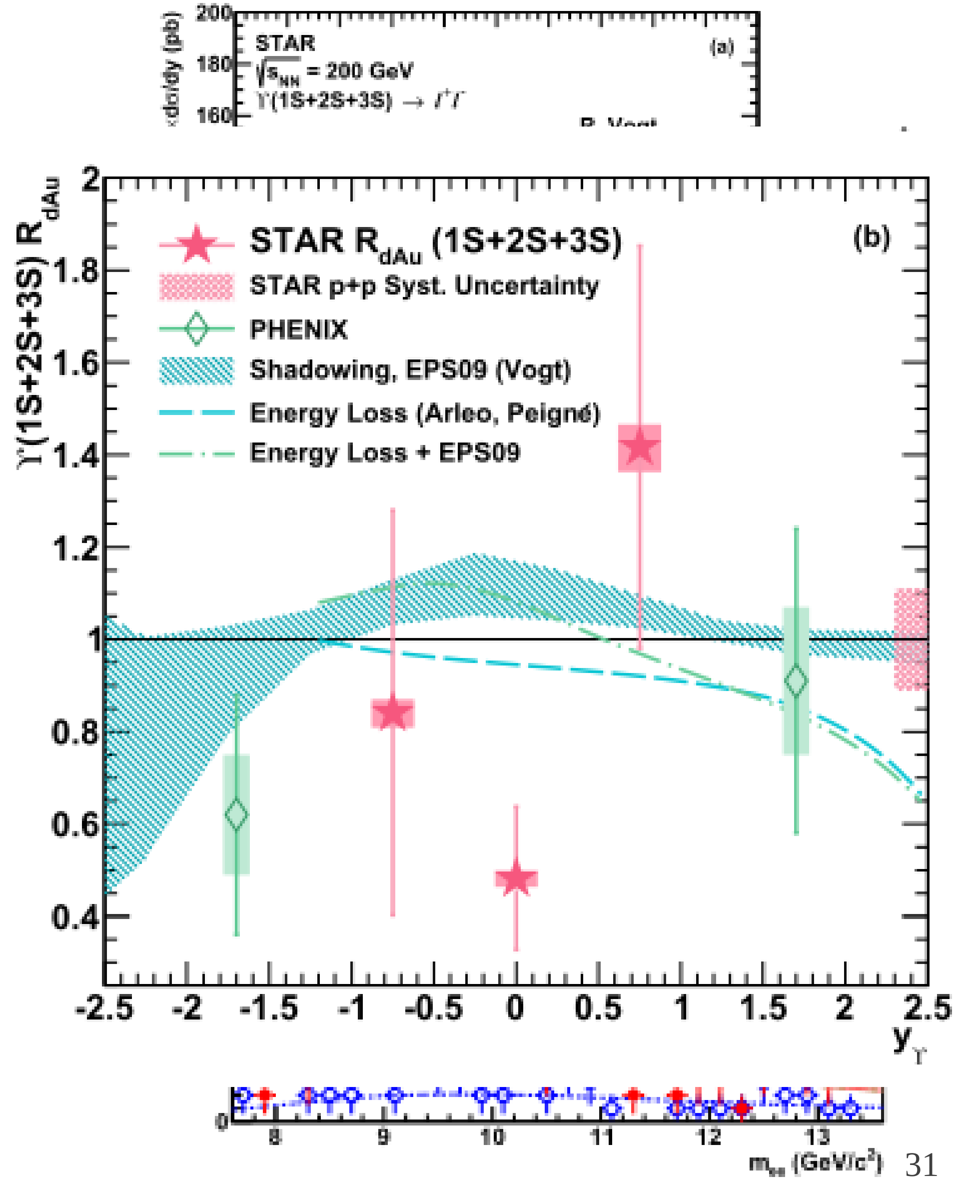




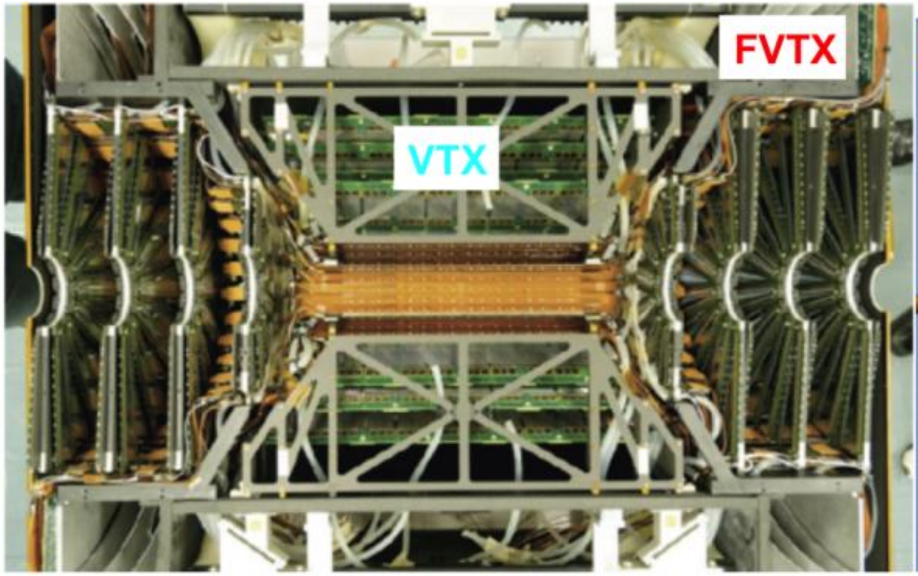
ϒ production in dAu

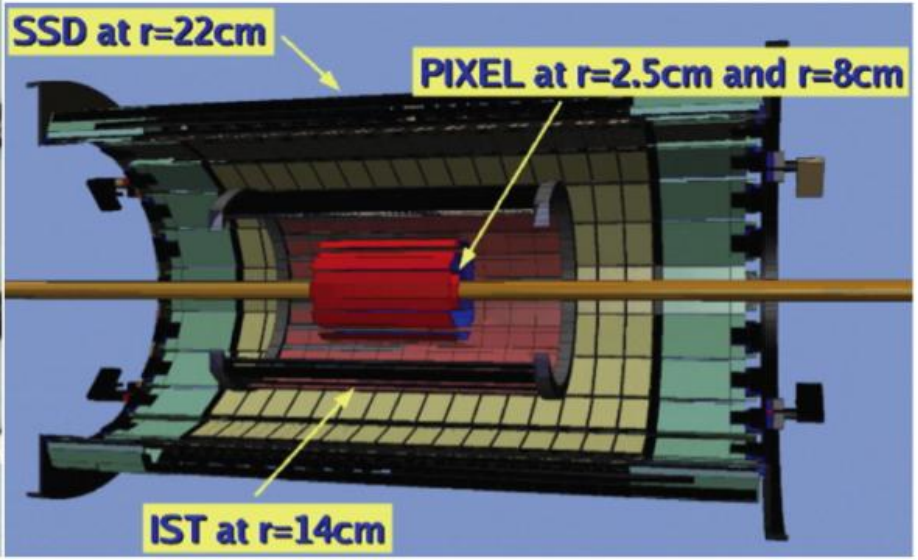
- Comparison to CEM calculations
  - Shadowing/Antishadowing of gluon nPDF
  - Initial parton energy loss
  - No absorption
- CNM effect
  - Models expect slight enhancement at mid-rapidity.
  - Agreement with models except y~0
  - Data indicate suppression at y~0 beyond these effects.

STAR: midrapidity



Future – detector upgrades





PHENIX VTX and FVTX

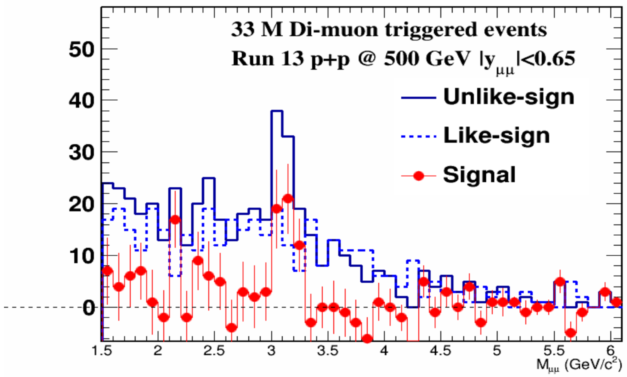
- (F)VTX installed
- Forward μ, J/ψ production in p+Au
- direct displaced D decay vertices at midrapidity

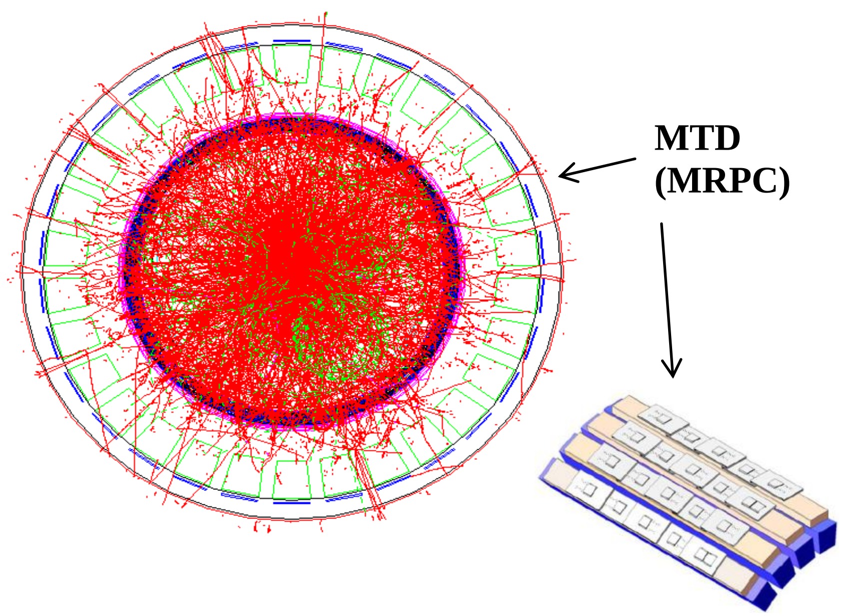
STAR HEAVY FLAVOR TRACKER

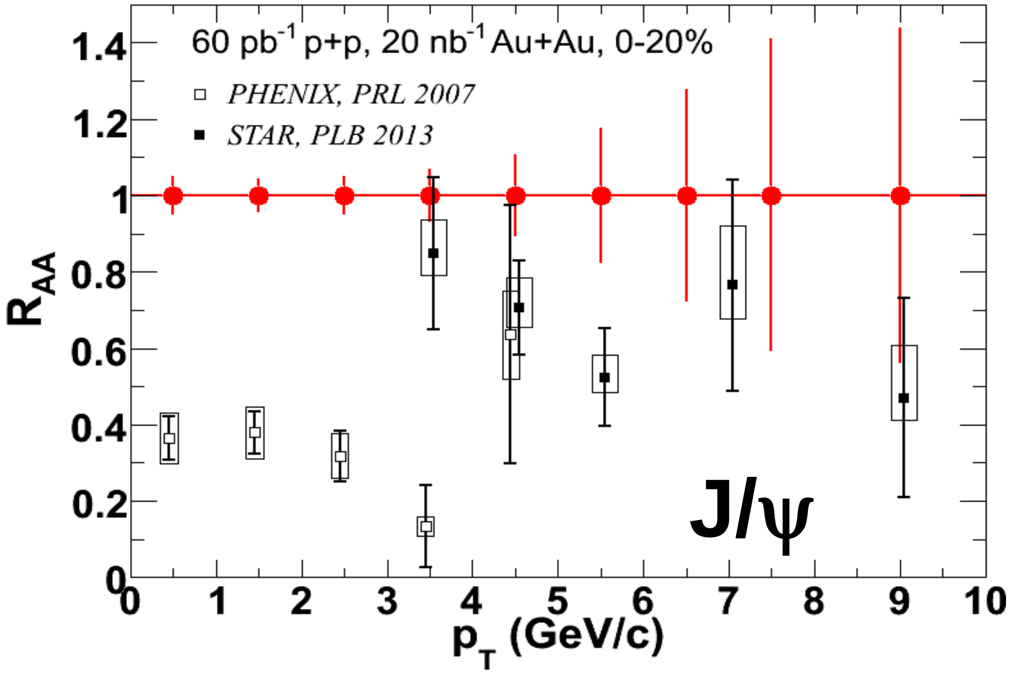
- Installed for year 2014
- Precise pointing resolution
- Study of non-prompt J/ψ
  (B → J/ψ + X; cτ ≈ 500 μm)

Muon Telescope Detector (MTD)

- $J/\psi \rightarrow \mu^{+}\mu^{-}$ (B.R. 5.9%)
  - No γ conversion, less contribution from Dalitz decays
  - Trigger capability for J/ψ in central A+A collisions







Summary

- CNM effects are important for correct interpretation of A+A results
- RHIC experiments can measure quarkonia over a wide kinematic ranges
  - Important for disentangling CNM effects
- Different CNM effects play role in forward and backward rapidity
- Large CNM effects on HF electrons - Backward and central rapidity
- J/ψ more suppressed then HF at central and backward rapidity
- ψ' suppressed beyond J/ψ in d+Au, proportional to $dN_{ch}/d\eta$ independent of energy
- Cu+Au: significantly stronger J/ψ suppression in the Cu-going direction – consitent with shadowing
- New data on p+A collisions help us better understant CNM effects