Heavy flavor production and the properties of sQGP at top energies

Wei Xie for STAR Collaboration
(PURDUE University, West Lafayette)

- **Motivation**
- **Heavy Quarkonium Production**
  - J/ψ
  - ϒ(ns)
- **Open Heavy Flavor Production**
  - D meson direct measurement
  - Non-photonic electron (NPE)
- **Summary and future perspective**

Motivation

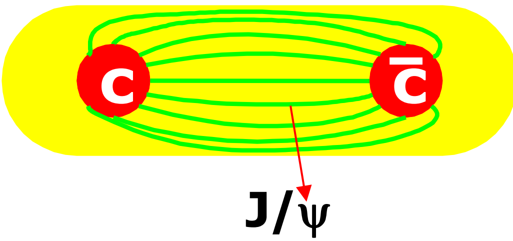
- **Heavy quarkonium production reveals critical features of the medium**
  - suppression from color screening or gluon scattering
  - enhancement from coalescence

- **Heavy quarks interact with the medium differently from light quarks**
  - gluon bremsstrahlung radiation
  - collisional energy loss
  - collision dissociation
  - Ads/CFT

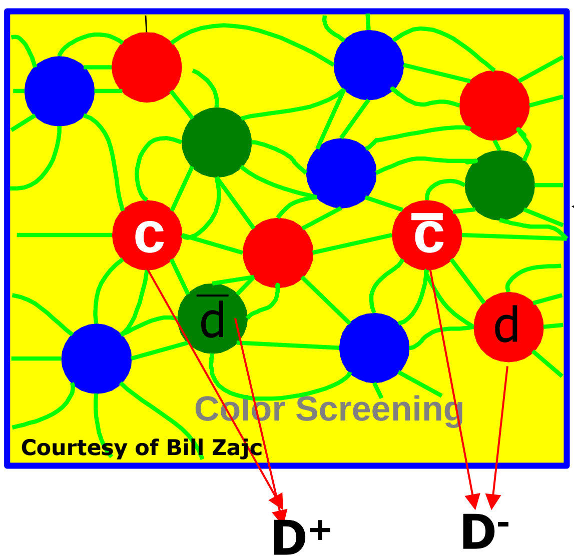
- **Cold Nuclear effects**
  - Gluon shadowing , Color glass condensate, Initial state energy loss, etc

- **Sensitive to the nuclear gluon distribution and medium initial gluon density**
  - produced mostly from gluon fusion

Quarkonium Suppression: "Smoking Gun" for QGP



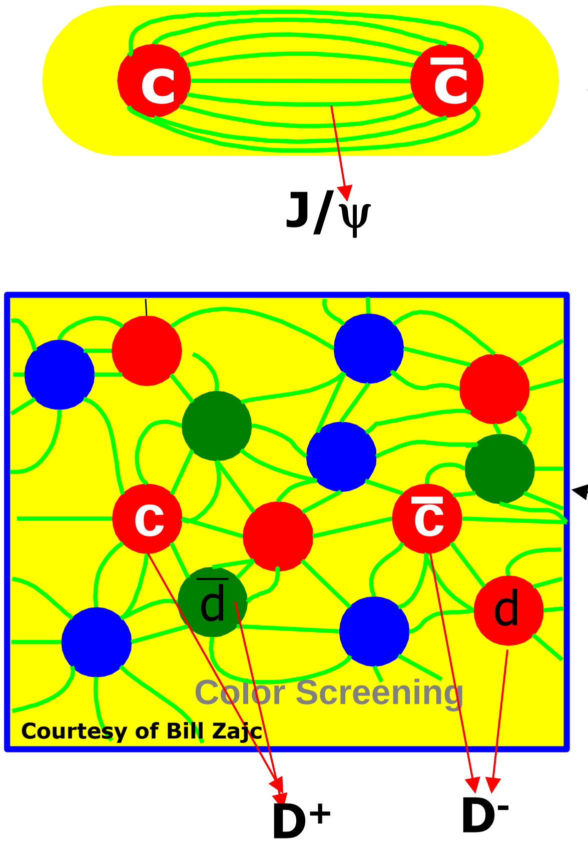
- Low temperature
- Vacuum

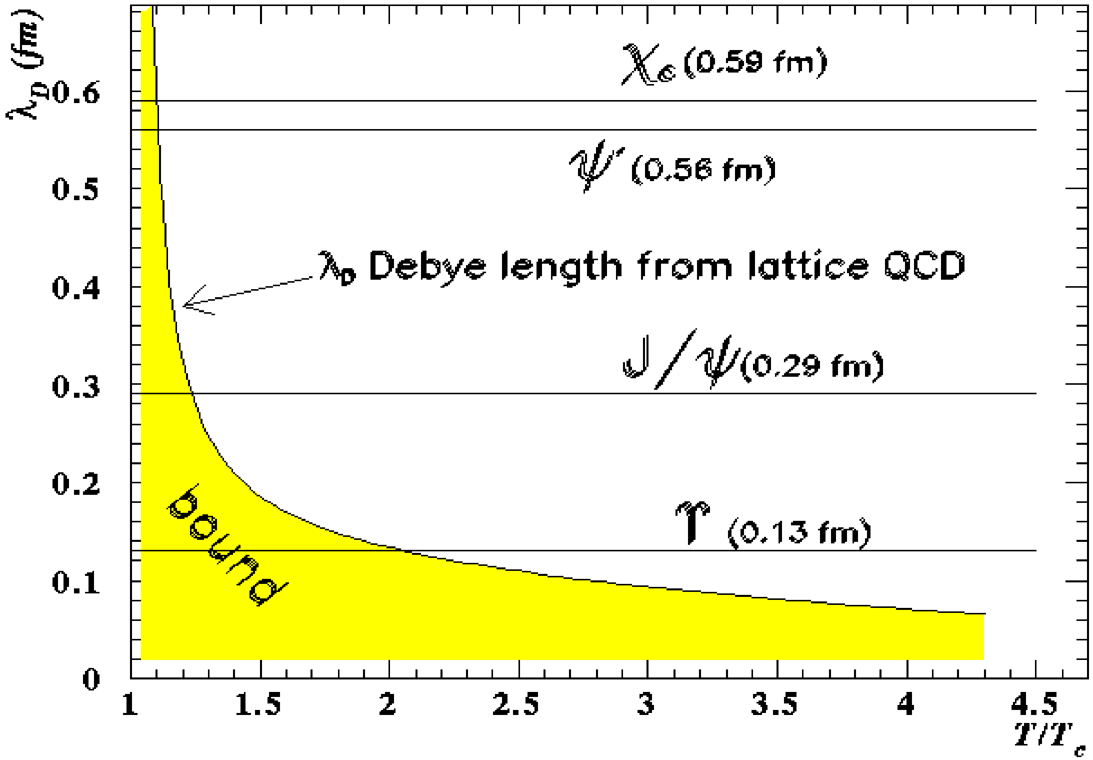


- High temperature
- High density

(screening effect takes place)

Quarkonium Suppression: "Smoking Gun" for QGP





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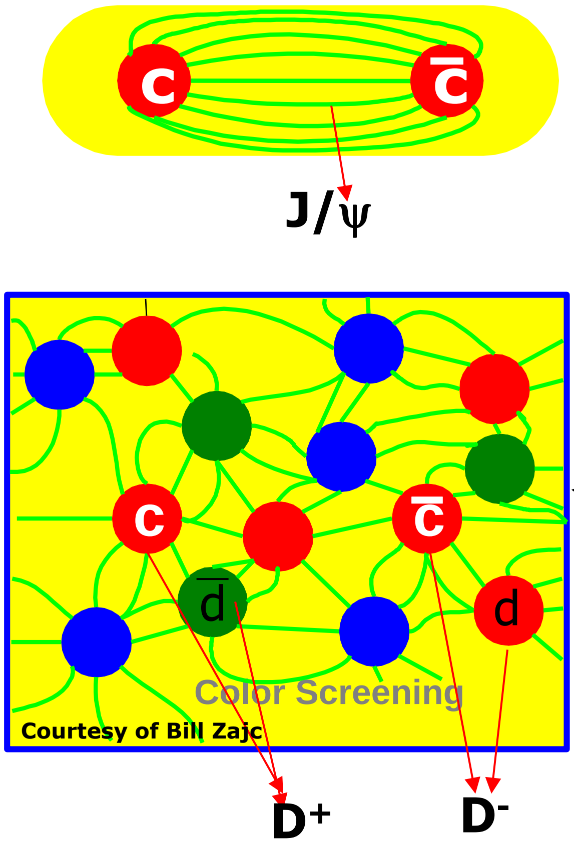
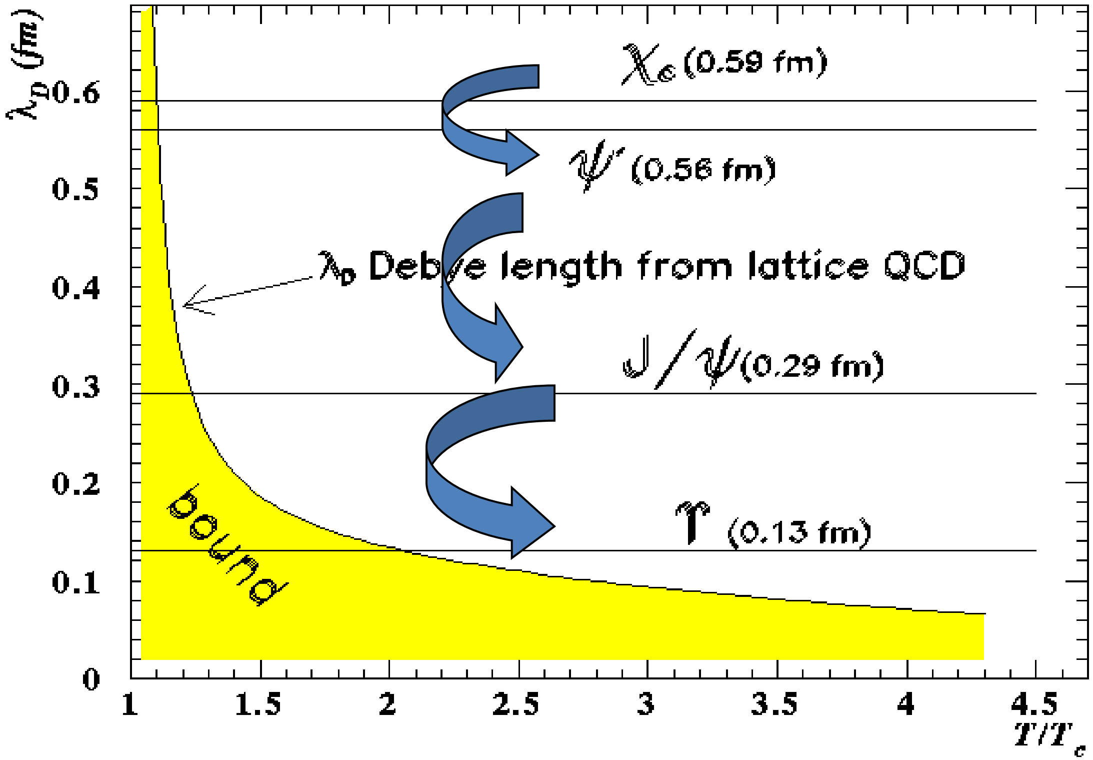




Sequential melting→a QGP thermometer

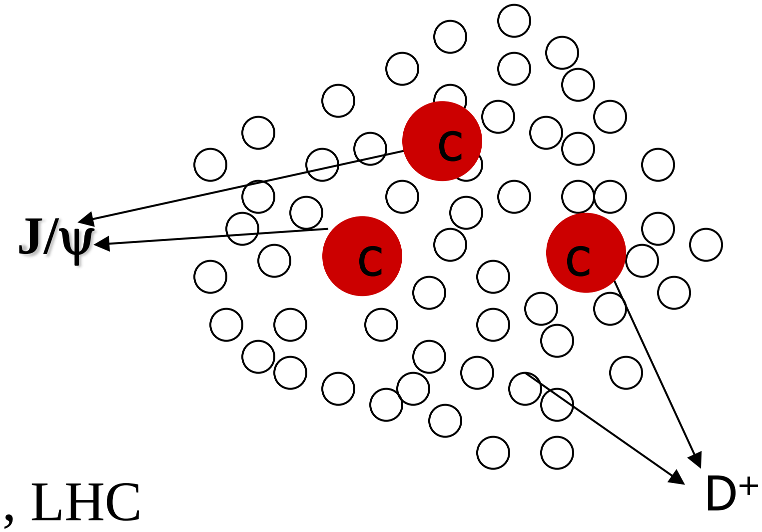
H. Satz, NPA 783 (2007) 249c.

The life of Quarkonia in the Medium can be Complicated

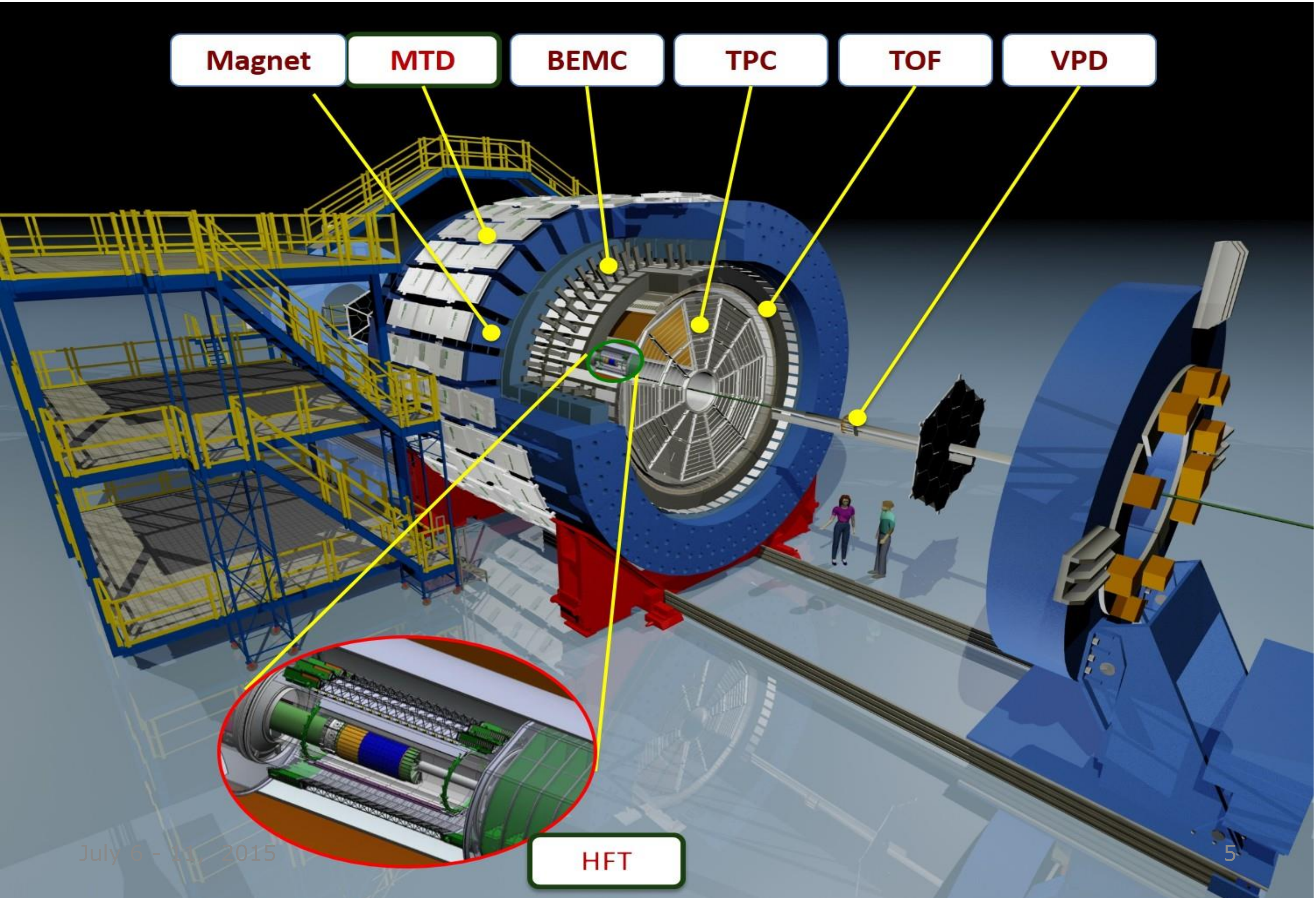
- Observed J/ψ is a mixture of direct production+feeddown (H.K.Wohri @QWG2014)
  - Prompt J/ψ : ~ 60% J/ψ(direct) + 30% χ_c feed down + ~10% ψ(2s) feed down
  - Non-prompt: B meson feed down.
    - Important to disentangle different components

- Suppression and enhancement in the “cold” nuclear medium
  - Nuclear Absorption, nuclear PDF effects, initial state energy loss, Cronin effect and gluon saturation (CGC)
  - Study p+A collisions

- Hot/dense medium effects
  - J/ψ, ϒ dissociation, i.e. suppression
  - Recombination, i.e. enhancement
  - Study different species, e.g. J/ψ, ϒ
  - Study at different energies, e.g. RHIC, LHC



How does STAR Measure Heavy Quarkonia

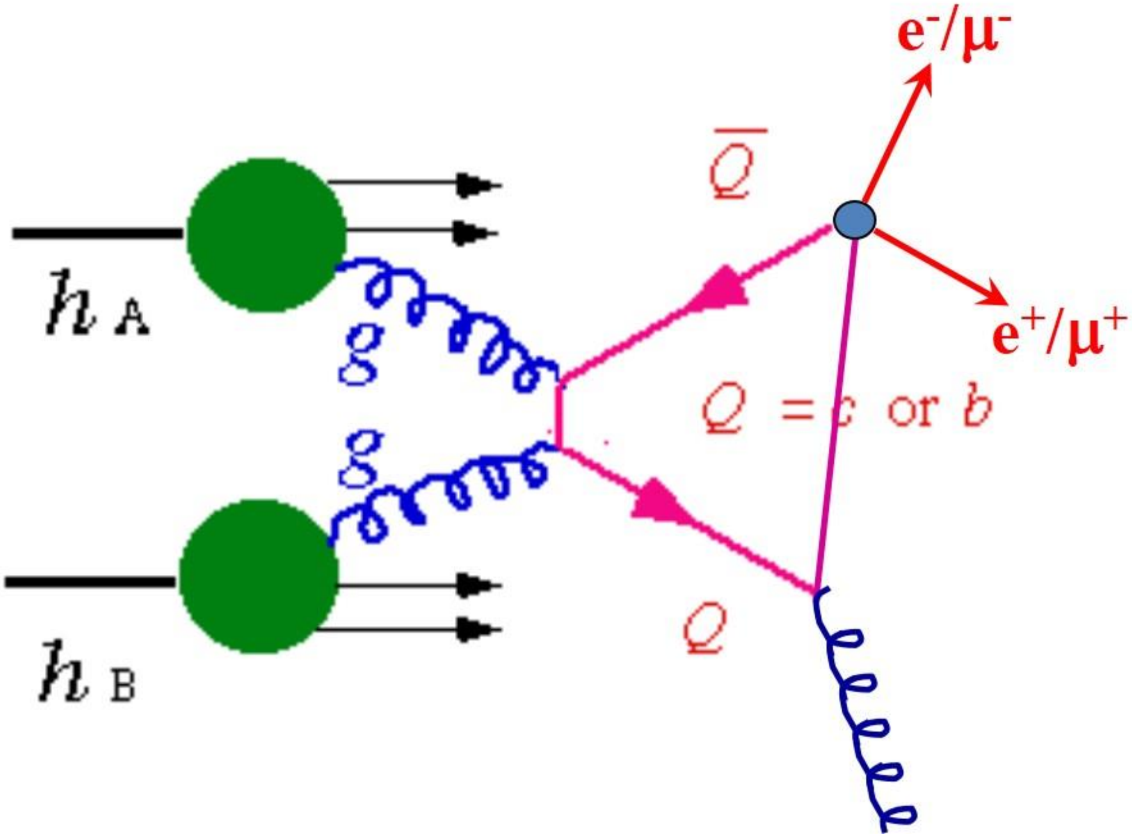


How does STAR Measure Heavy Quarkonia

Time Projection Chamber (TPC)
- $|\eta| \leq 1.0$, full azimuth
- Tracking.
- PID through dE/dx

Time of Flight (TOF)
- $|\eta| \leq 0.9$, full azimuth
- PID through TOF
- Timing resolution: ~85 ps

Barrel Electromagnetic Calorimeter (BEMC)
- $|\eta| \leq 1.0$, full azimuth
- p/E for electron ID
- Fast online trigger
- High resolution SMD
- e/h separation

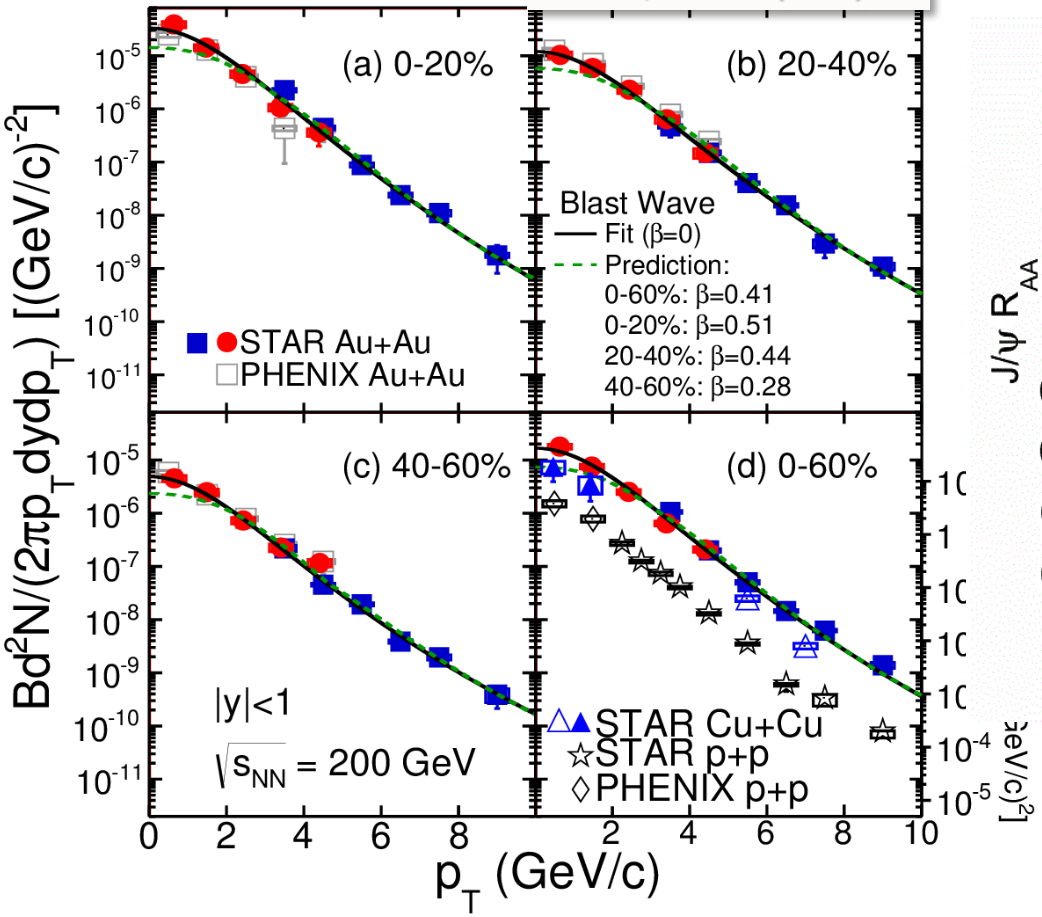


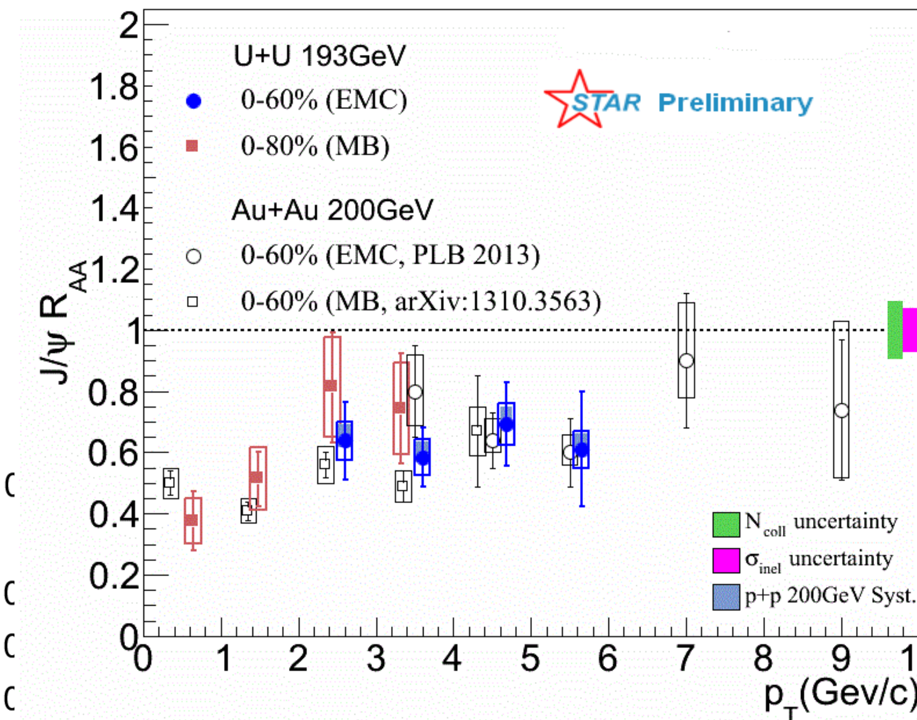
Heavy Flavor Tracker (HFT)
- $|\eta| \leq 1.0$, full azimuth
- PIXEL: X/X_0: ~0.4%/layer
- High DCA resolution
  - 46μm@p_T = 0.75GeV/c Kaon
  - ~30μm@high p_T

Muon Telescope Detector (MTD)
- $|\eta| \leq 0.5$, 45% in azimuth
- Muon identification
- Muon trigger
- High timing reso.: ~95ps
- Good hit position resolution: ~1cm

J/ψ R_{AA} in 200 GeV Au+Au Collisions

PRC 90, 024906 (2014)





- ❑ Broad p_T coverage

Tsallis Blast-Wave model: ZBT *et al.*, arXiv:1101.1912.

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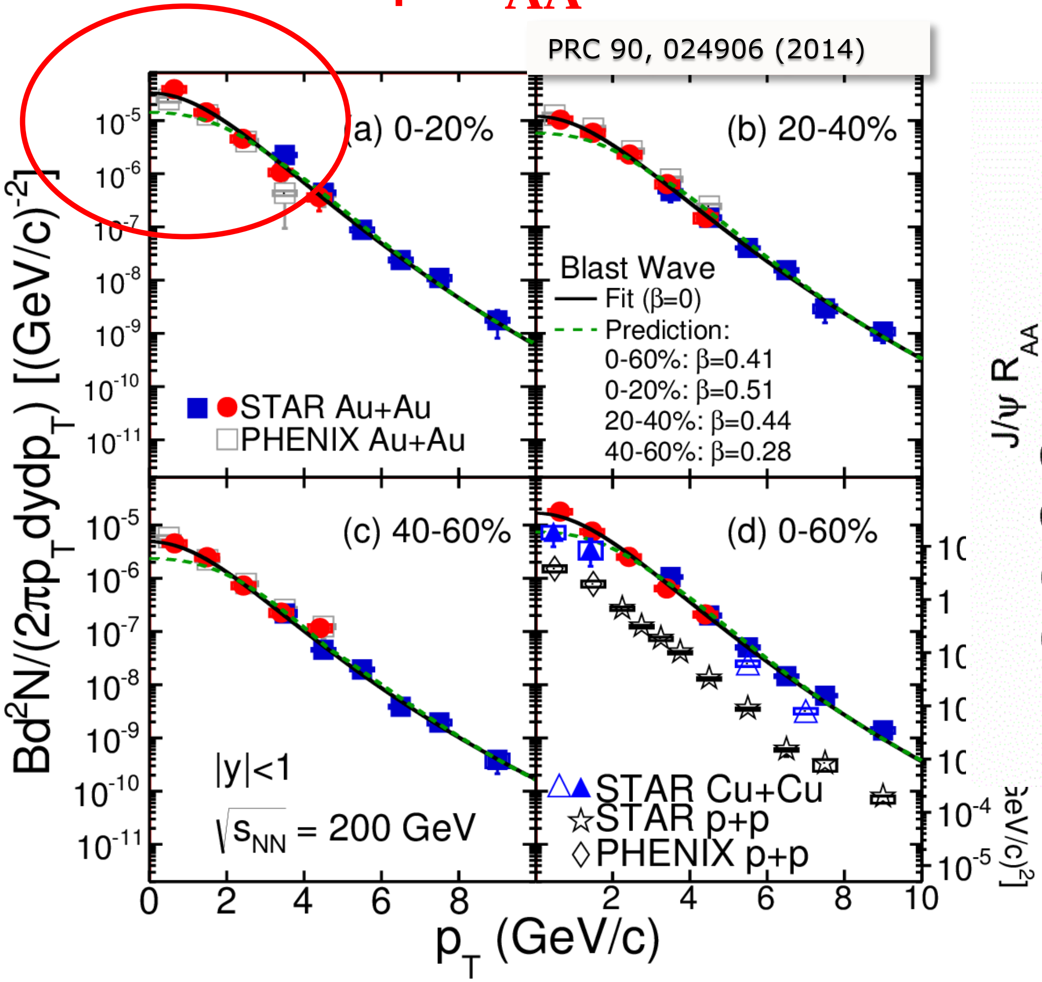
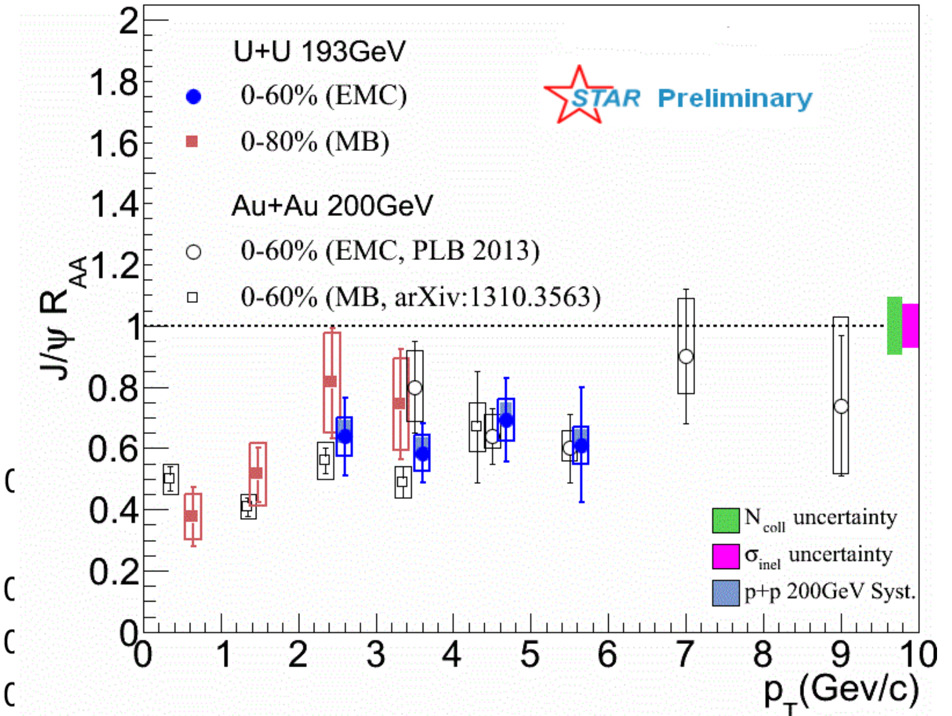


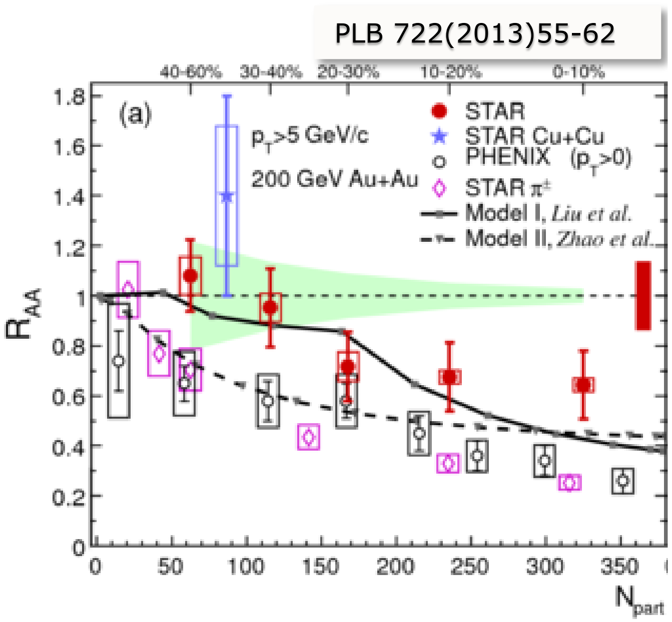


- **Much smaller radial flow?**
- **Regeneration at low p_T?**

Tsallis Blast-Wave model: ZBT *et al.*, arXiv:1101.1912.

- Broad p_T coverage
- TBW assuming J/ψ velocity
  - zero (solid curve). Fit data well for all p_T
  - same as light hadrons (dashed curve). Fit data at high p_T

J/ψ Suppression Pattern: $\sqrt{S_{NN}}$ dependence



- High p_T less suppressed than low p_T
  - Cronin effect?
  - Longer formation time?

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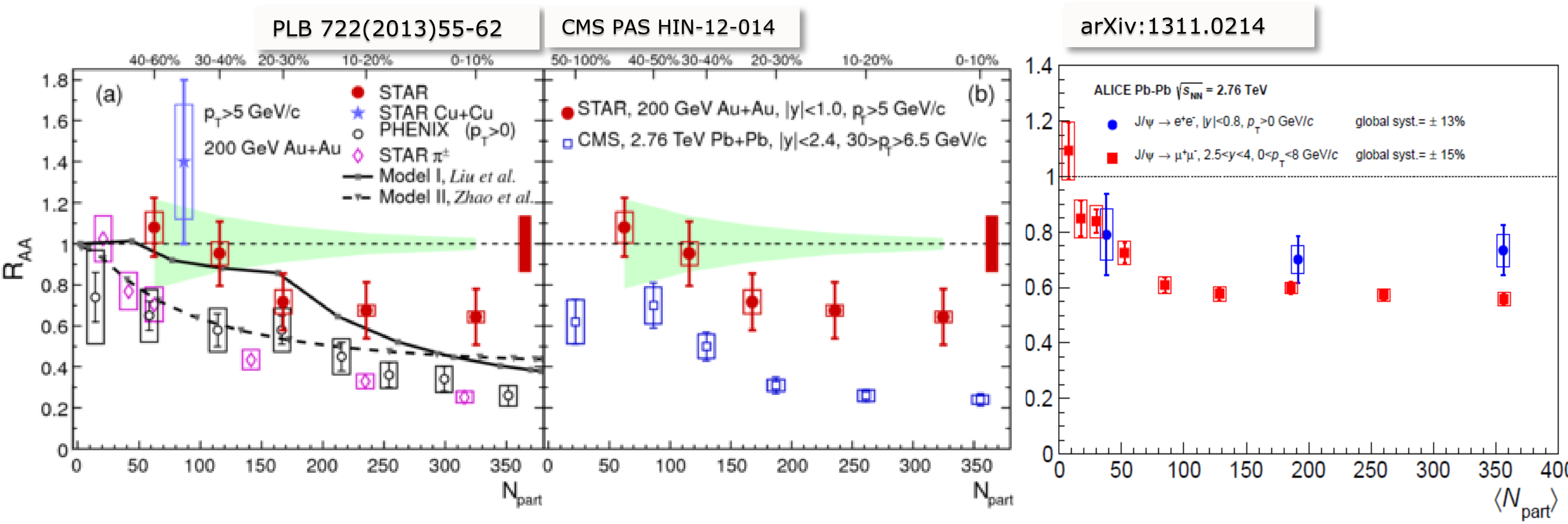
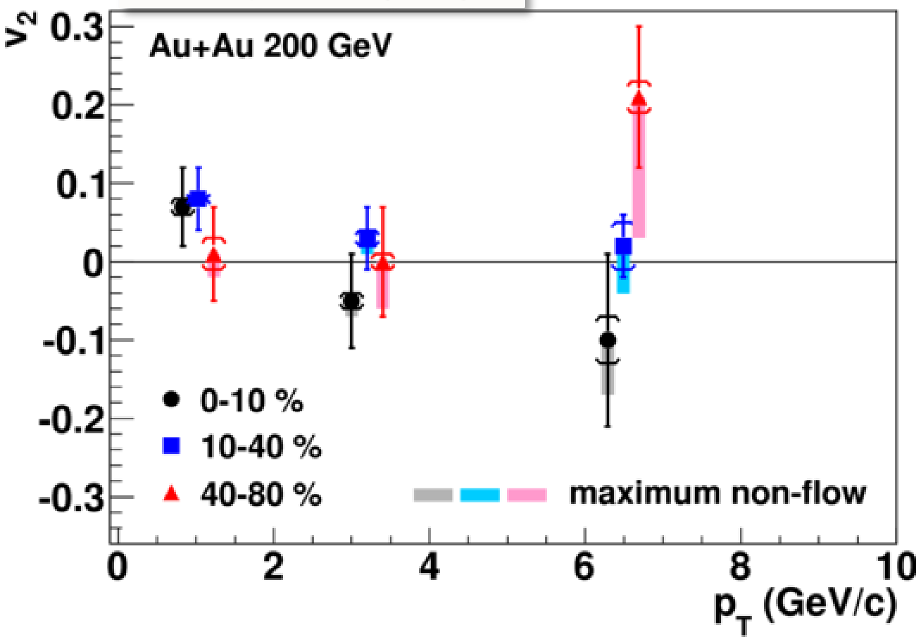
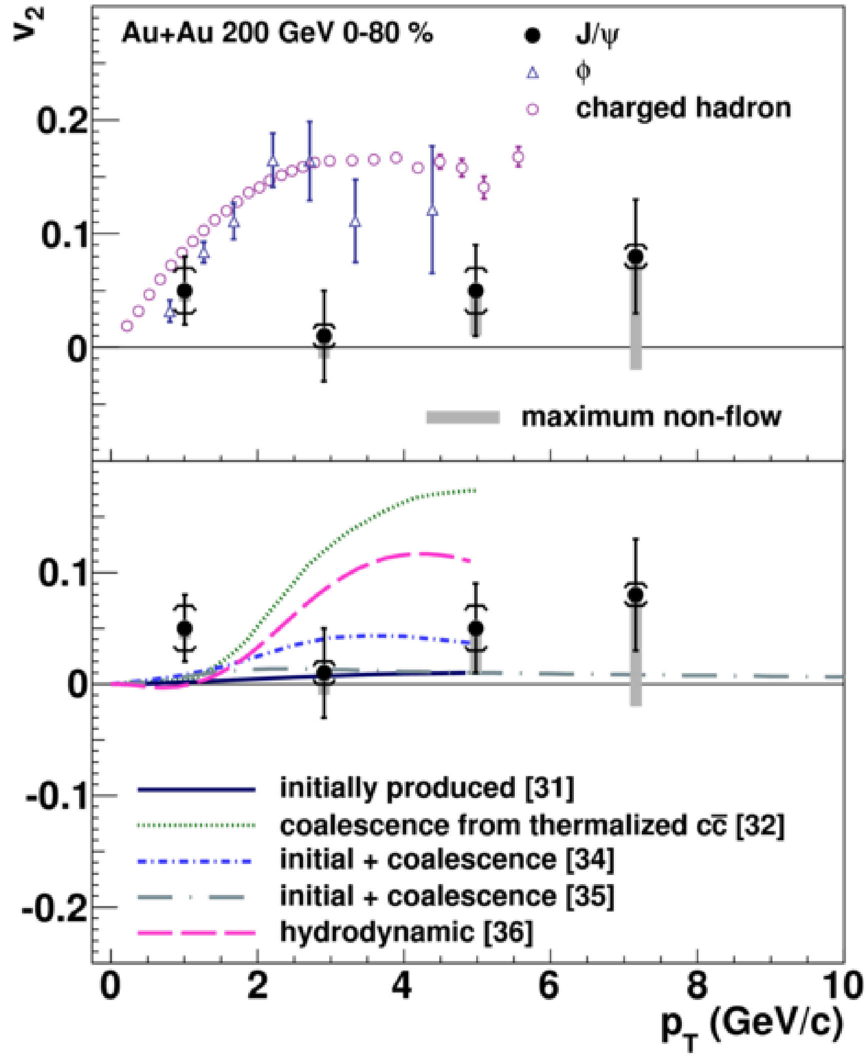


- ❑ High p_T less suppressed than low p_T
  - Cronin effect?
  - Longer formation time?
- ❑ Different dependence of R_{AA} on p_T at LHC
  - Less suppression at lower p_T & higher collision energies
  - Consistent with regeneration picture
- ❑ Less regeneration than at LHC?
- ❑ or larger shadowing at LHC?

J/ψ Elliptic Flow in 200 GeV Au+Au Collisions

PRL 111, 052301 (2013)





- ❑ Disfavors the case that J/ψ with $p_T > 2.0$ GeV/c is produced dominantly by coalescence from thermalized charm and anti-charm quarks

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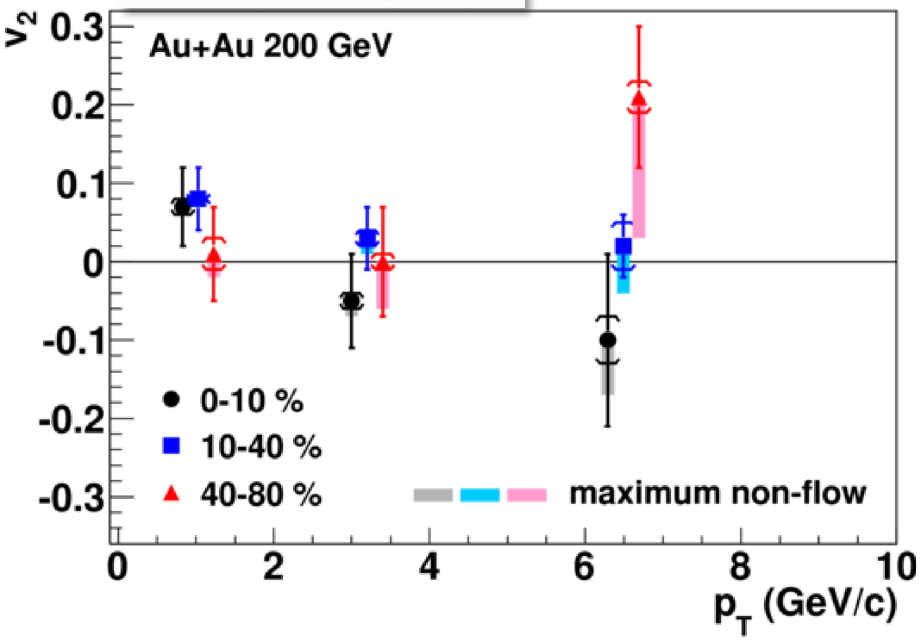

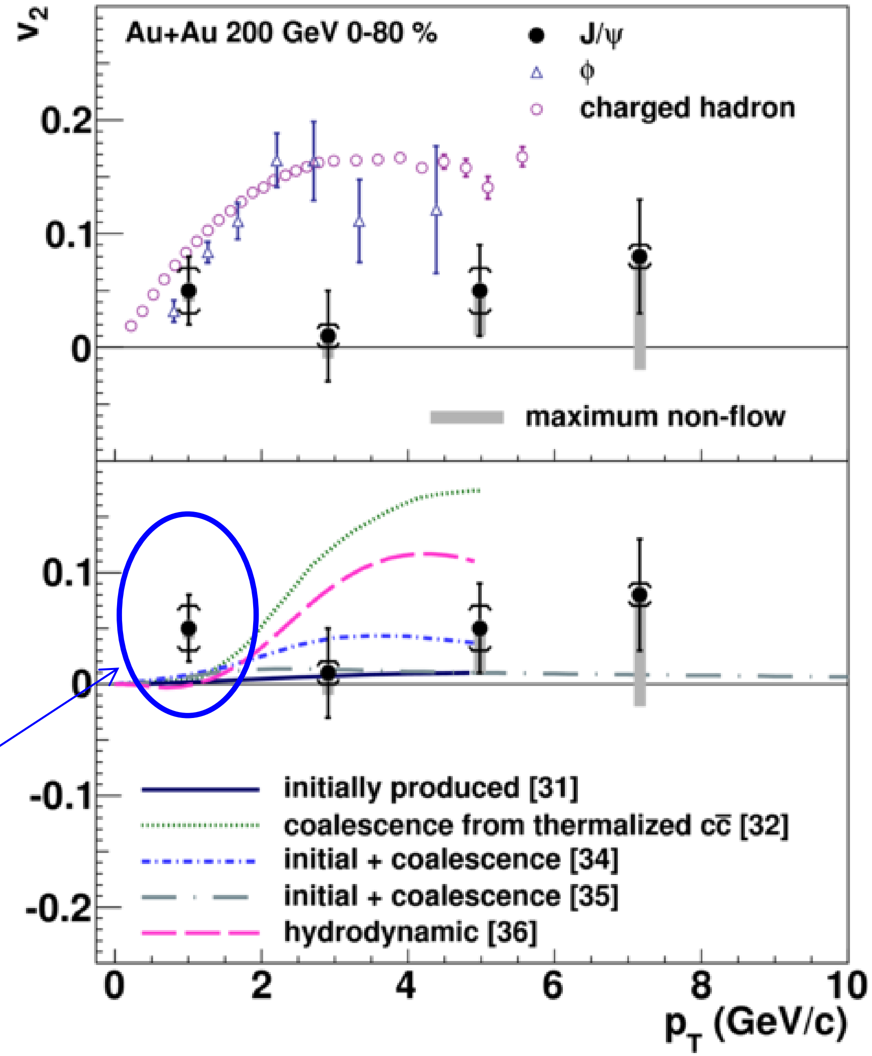

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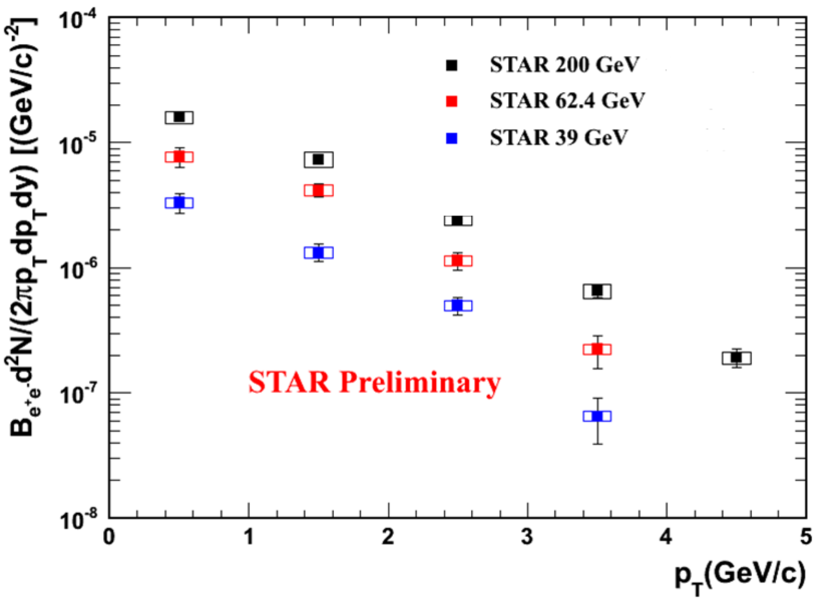
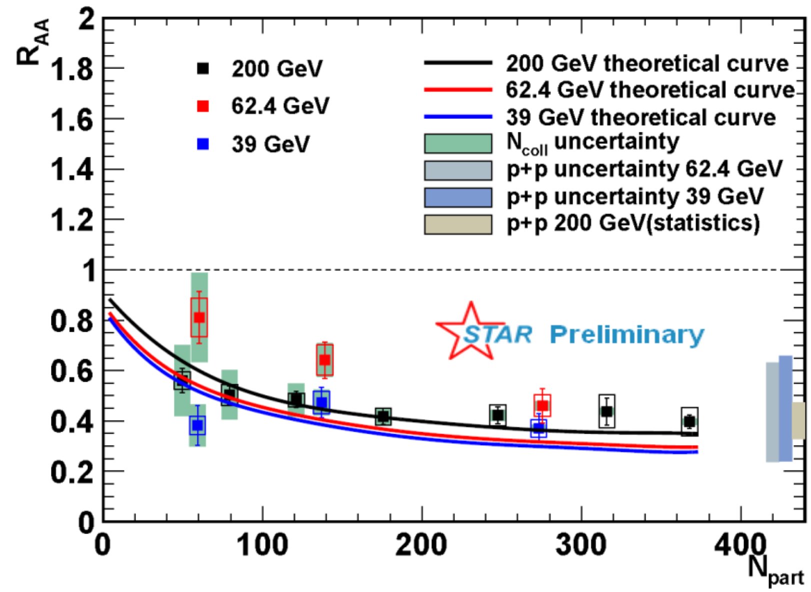
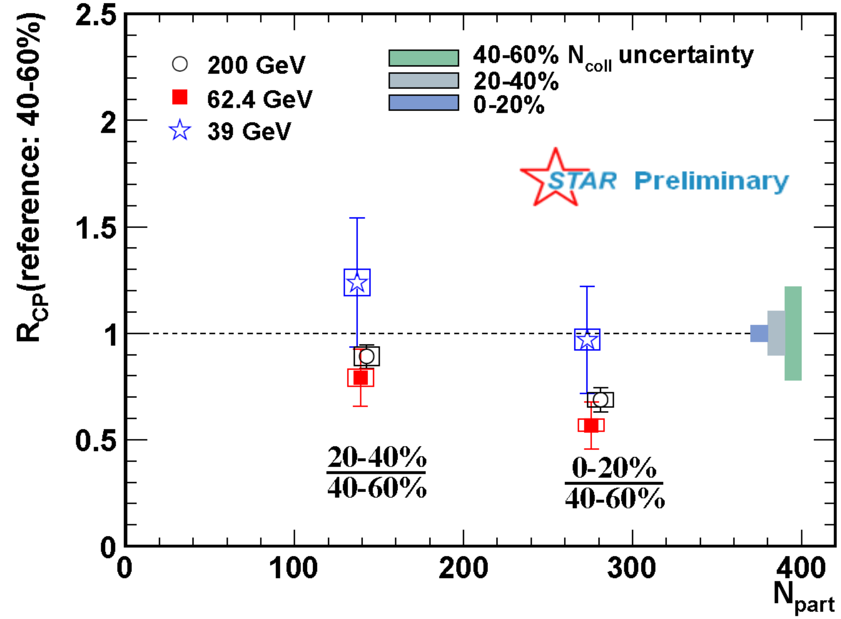
- Finite v_2 from charm quark coalescence ?

Suppression vs. Energy in Au+Au Collisions

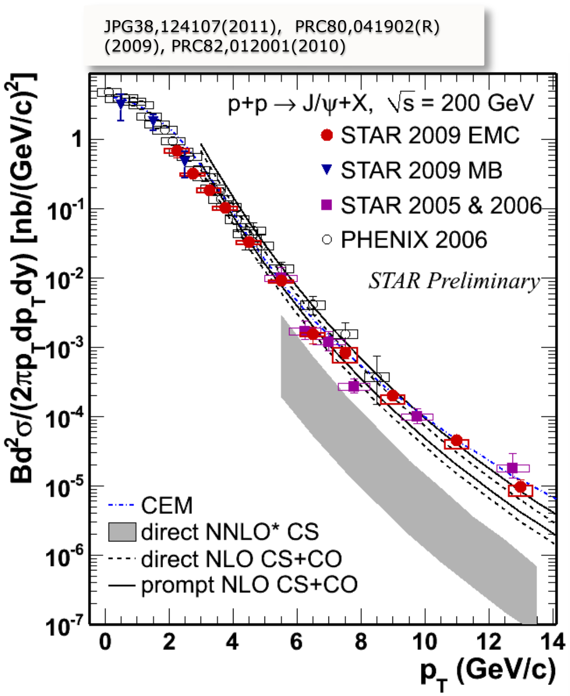


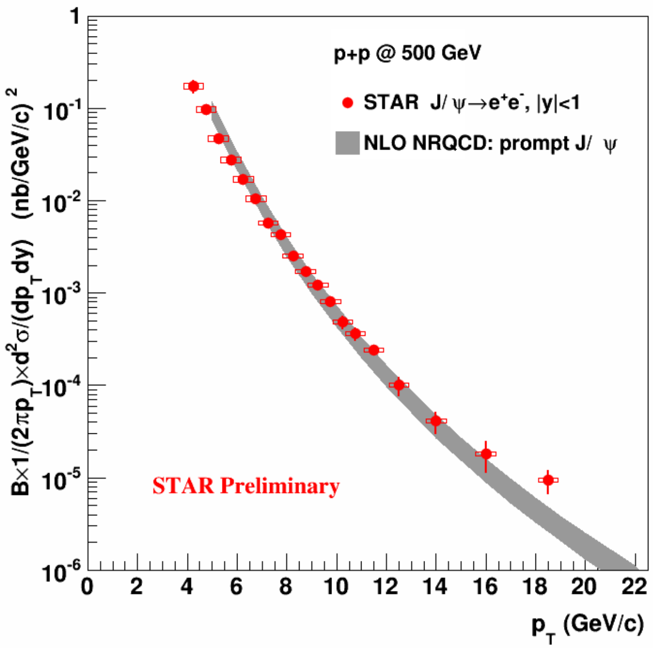




- ❑ Measurement up to ~4GeV/c for low energies
- ❑ pp baseline for 39 and 62.4 GeV is from CEM calculation
- ❑ No significant energy dependence for R_{AA} and R_{cp}
- ❑ Data can be described by theoretical calculations with color screening and $c\bar{c}$ recombination
  - ❑ X. Zhao, R. Rapp, PRC82,064905 (2010) and private communication

J/ψ Production in p+p Collisions





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  - disagree with data
  - P. Artoisenet et al., PRL. 101, 152001 (2008), and J.P. Lansberg private communication.
- NLO CS+ CO & Color Evaporation Model & NRQCD
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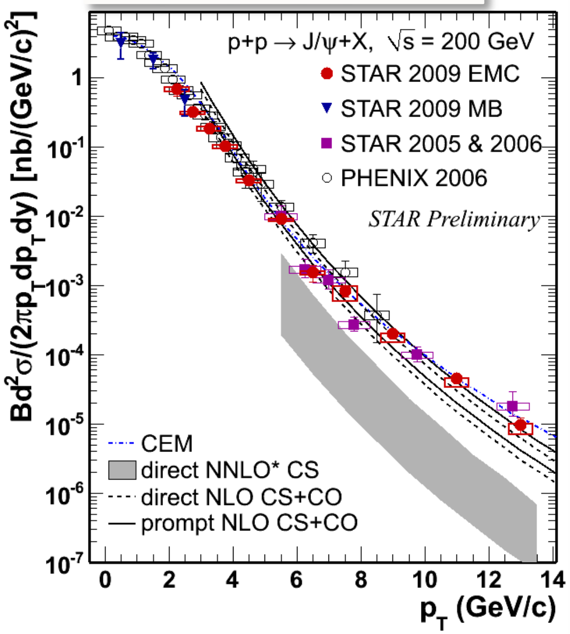
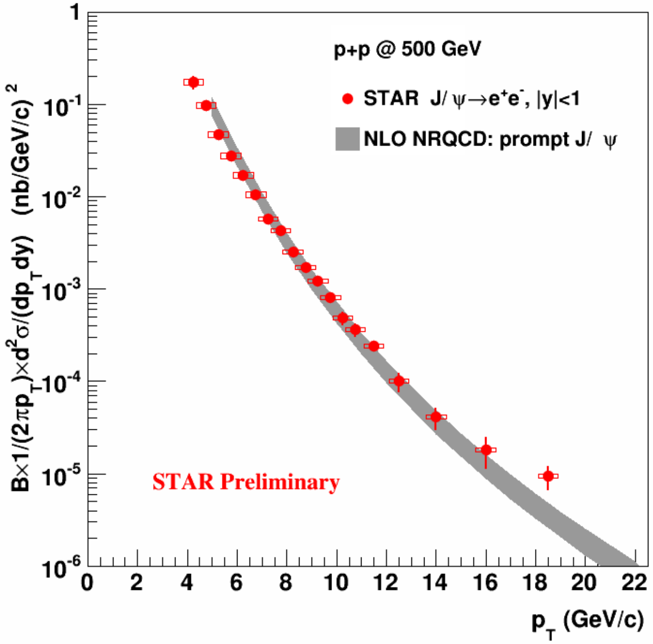
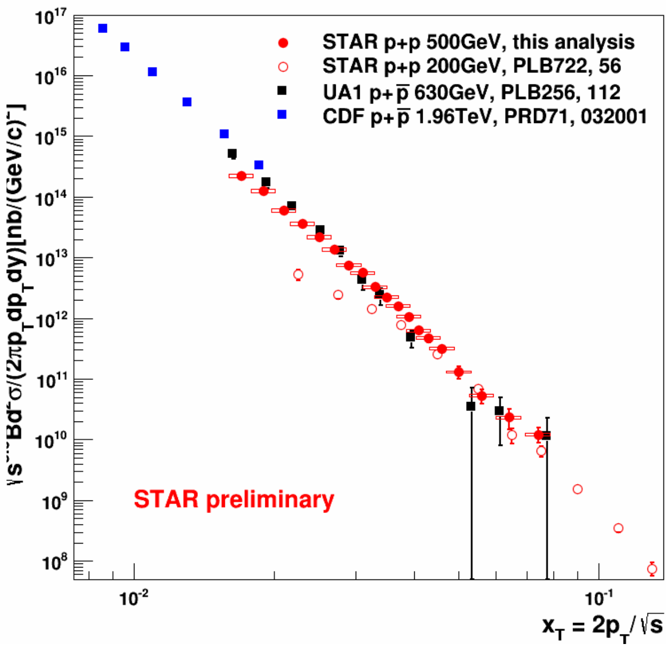
 Details see B. Trzeciak's talk

J/ψ Production in p+p Collisions

JPG38,124107(2011), PRC80,041902(R)(2009), PRC82,012001(2010)







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- Following x_T scaling in p+p collisions

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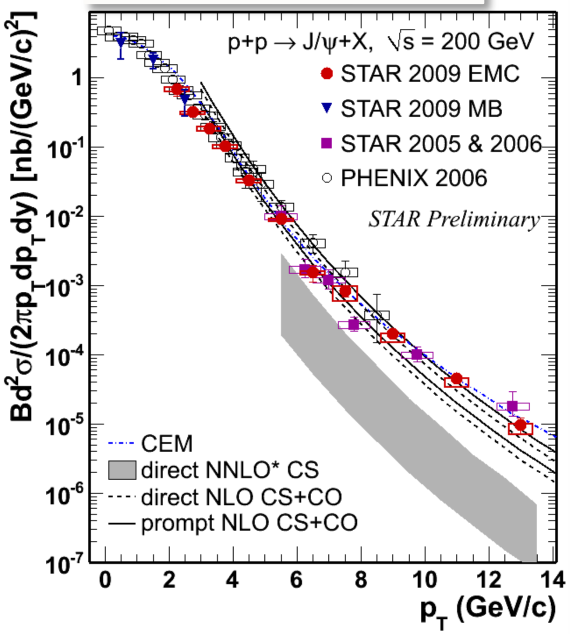

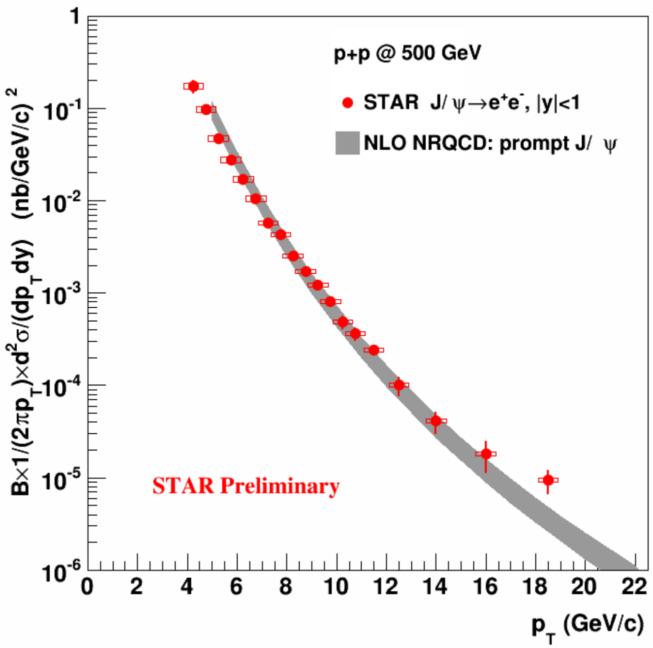

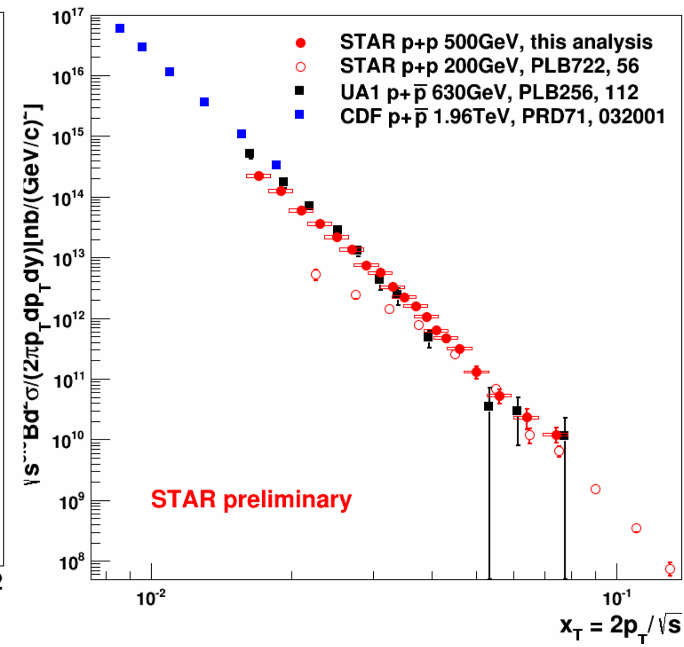

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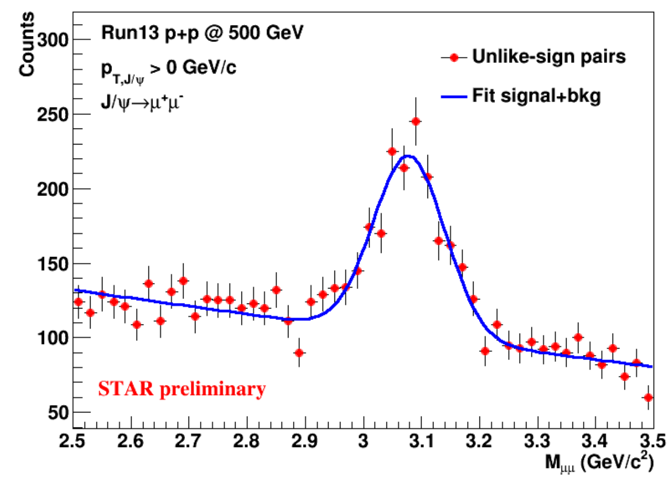
- Following x_T scaling in p+p collisions
- **MTD** dimuon trigger greatly increase low p_T J/ψ accuracy



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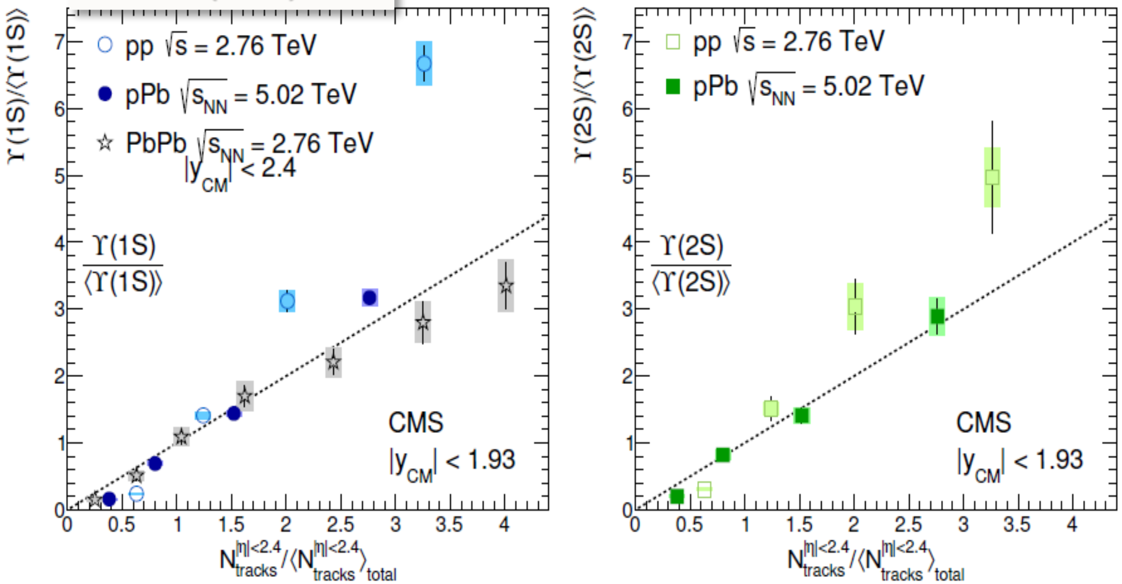
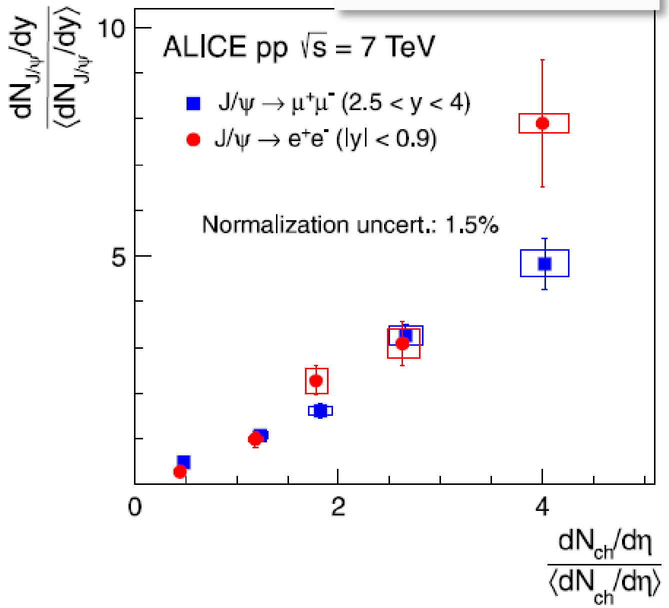
Enhancement in High Multiplicity p+p Collisions

JHEP 04 (2014)103



PLB 712 (2012)165-175



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  - different trend in p+p and HI collisions
  - Similar linear trend in p+Pb and Pb+Pb
  - Faster rise in p+p
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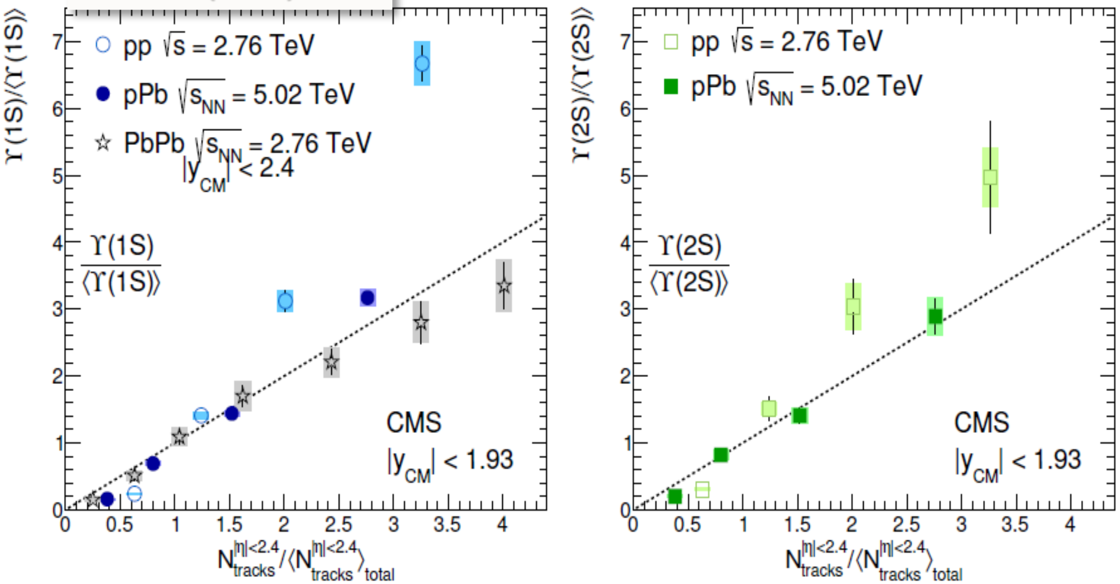

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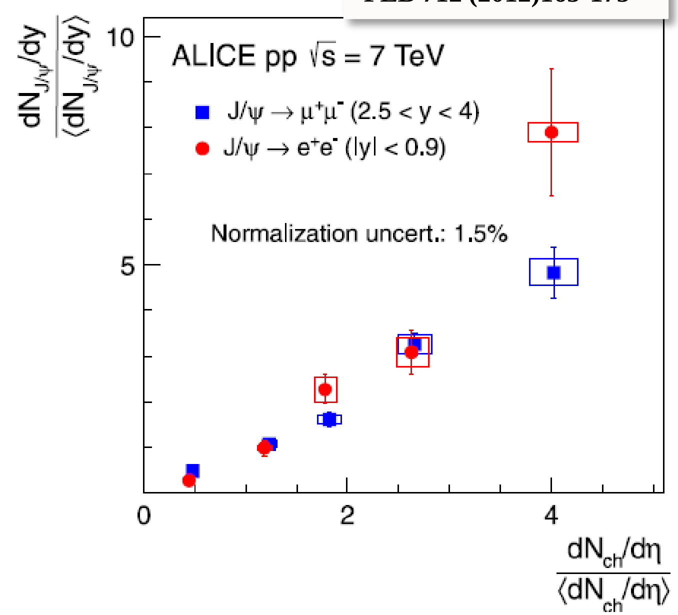

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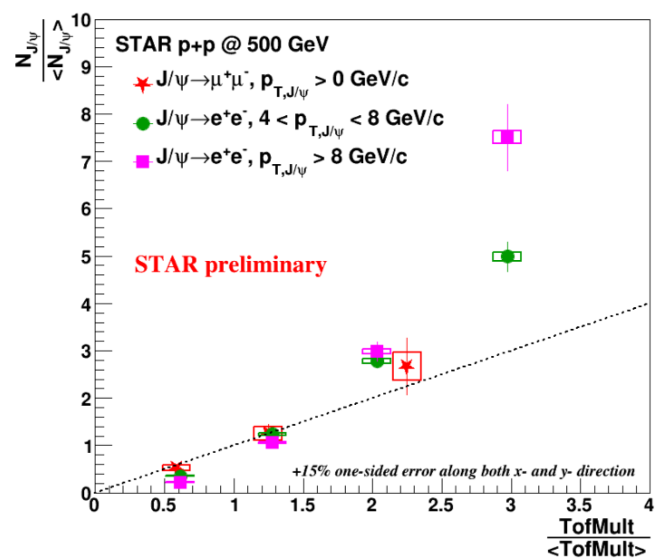

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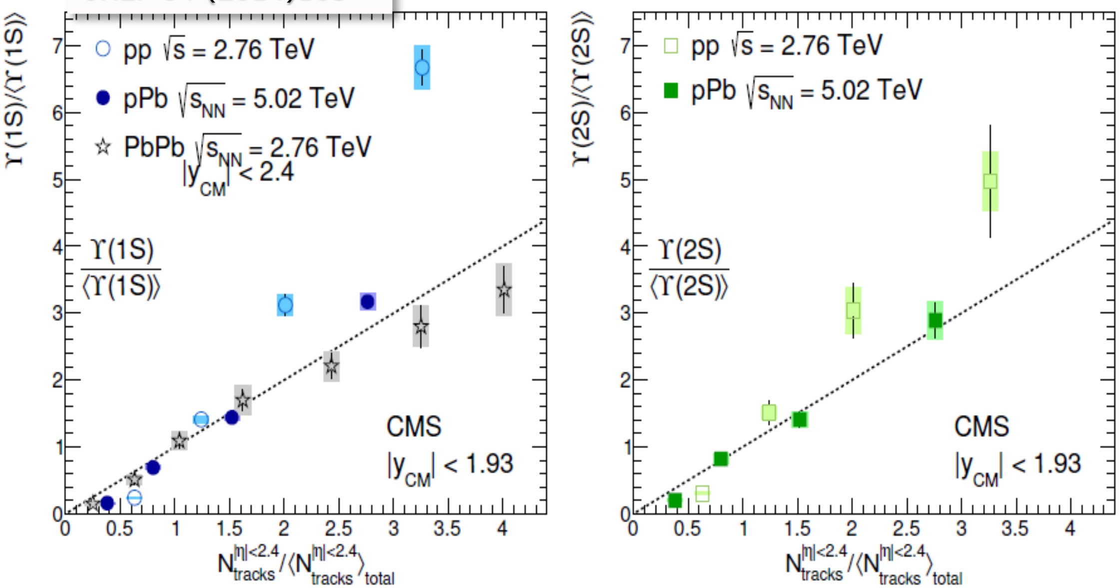

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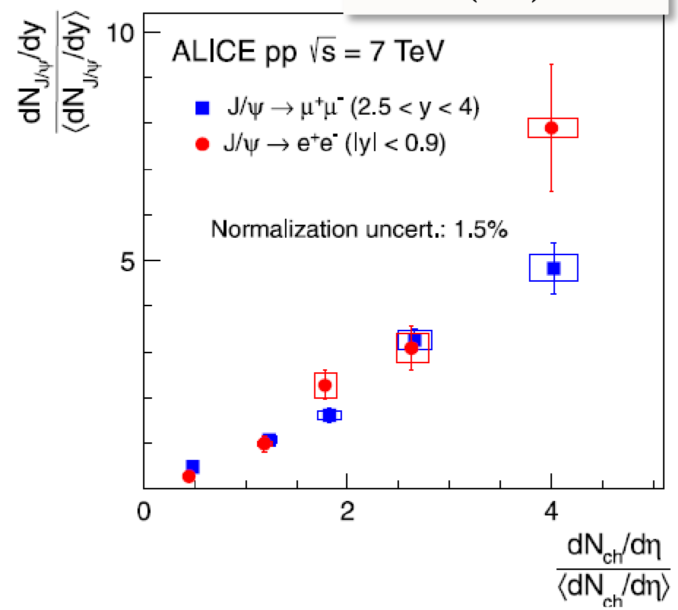

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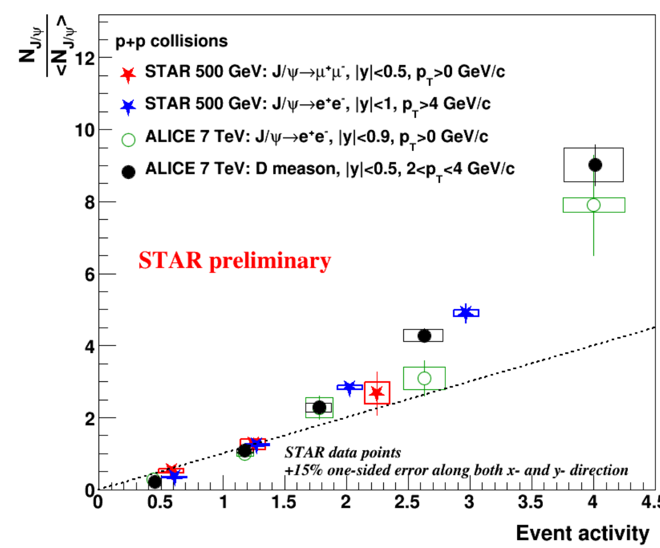
- ❑ Similar results in 500 GeV p+p @RHIC
  - Rising trend seems similar
- ❑ Multi-parton interaction, CGC in p+p collisions, etc?
- ❑ How does it affect heavy-ion collisions?



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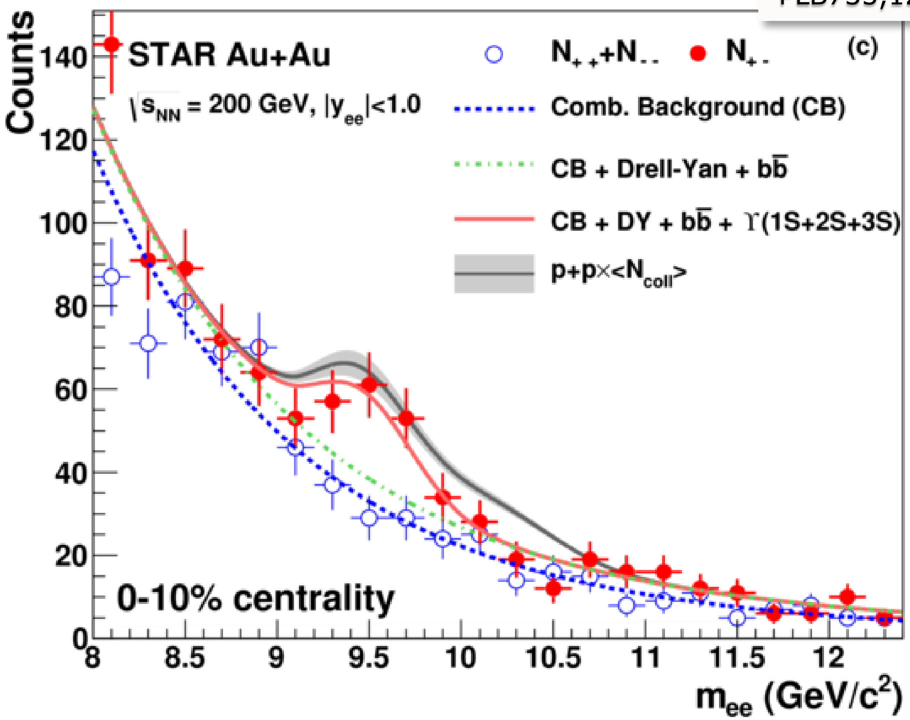
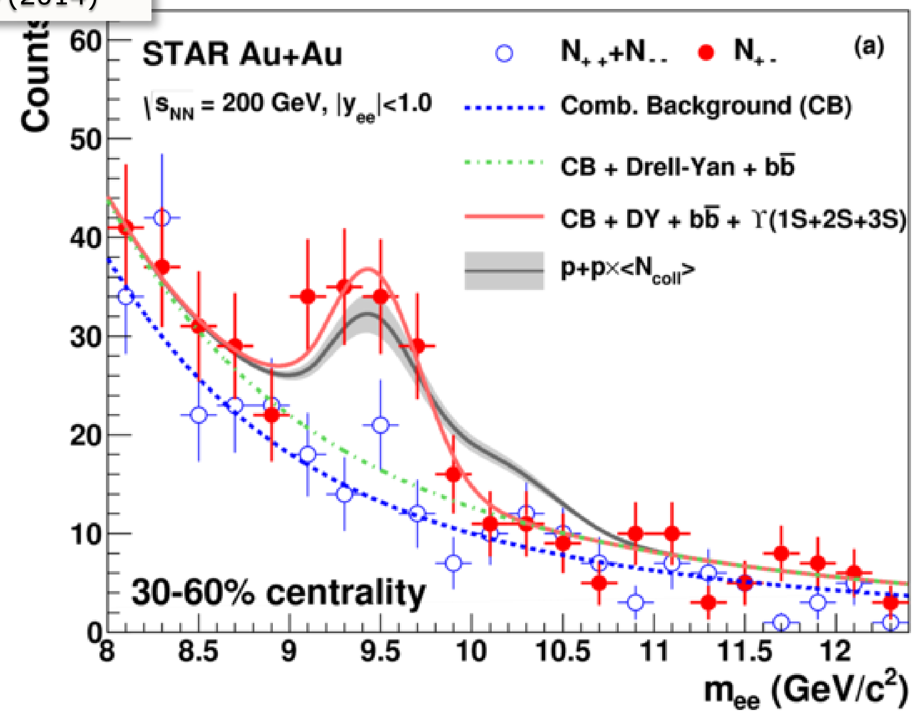
$\Upsilon(ns)$ are Cleaner Probes

PLB735,127(2014)





Compared to J/ψ

- ❑ recombination can be neglected at RHIC
- ❑ Final state co-mover absorption is expected to be small

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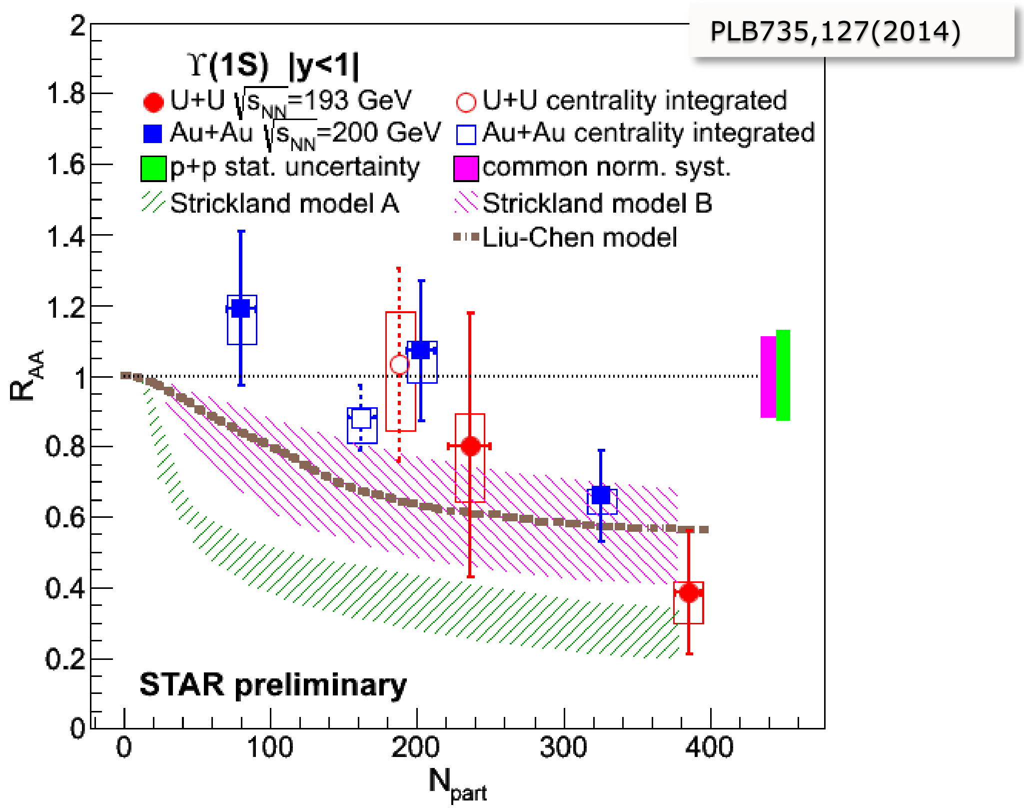

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- ❑ For ϒ(1S) more suppressed in more central collisions

- ❑ Consistent with prediction from a model requiring strong 2S and complete 3S suppression

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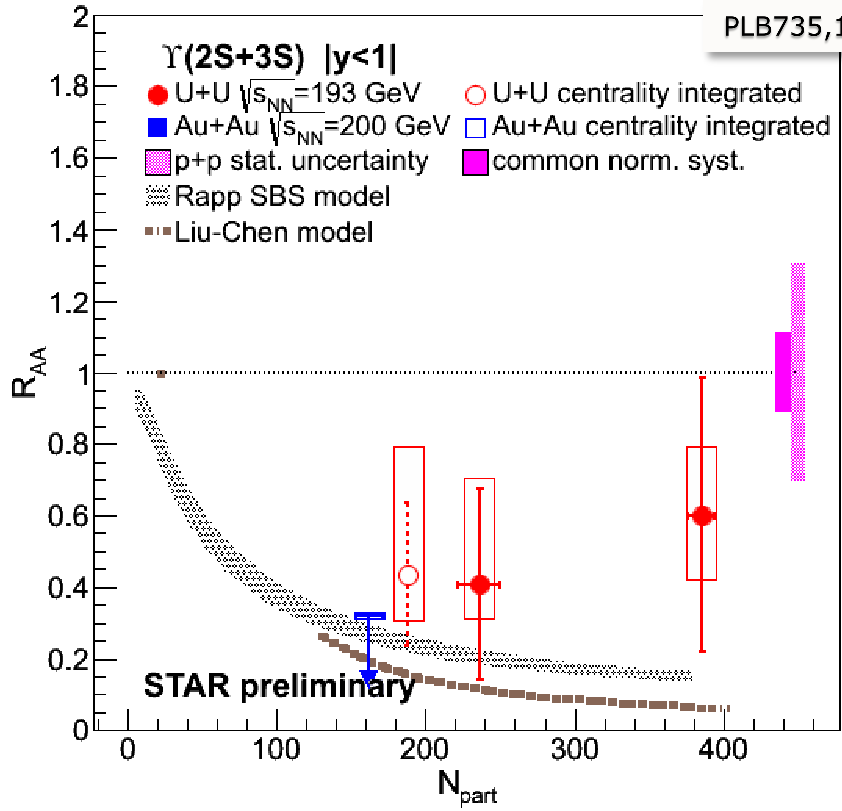

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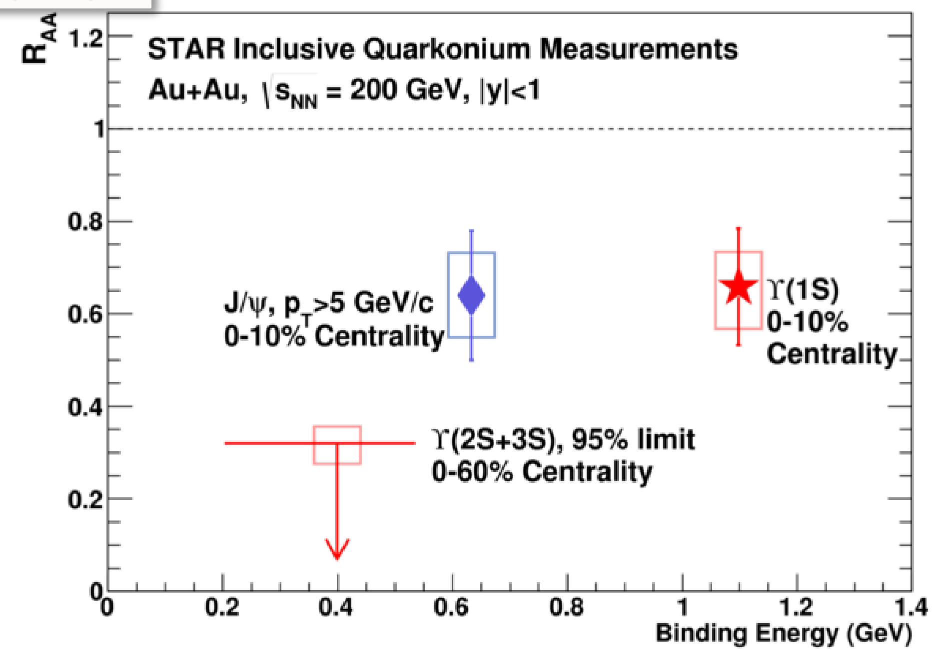

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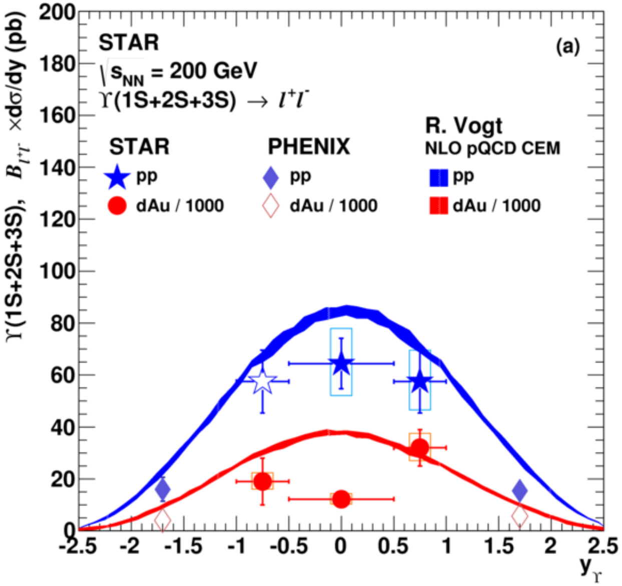
- ❑ For ϒ(1S) more suppressed in more central collisions

- ❑ Consistent with prediction from a model requiring strong 2S and complete 3S suppression
- ❑ ϒ(nS) suppression are ordered by binding E
- ❑ Some models doesn’t include CNM effect.
  - e.g. Strickland, Liu-Chen models

Cold Nuclear Matter Effect on Upsilon Production

PLB735,127(2014)



- ❑ $R_{dAu}(1S) = 0.83 \pm 0.15(dAu\ stat.) \pm 0.11(pp\ stat.)^{+0.03}_{-0.07}(dAu\ syst.) \pm 0.10(pp\ syst.)$
- ❑ $R_{dAu}(nS) = 0.79 \pm 0.14(dAu\ stat.) \pm 0.10(pp\ stat.) \pm 0.03\ (dAu\ syst.) \pm 0.09(pp\ syst.)$

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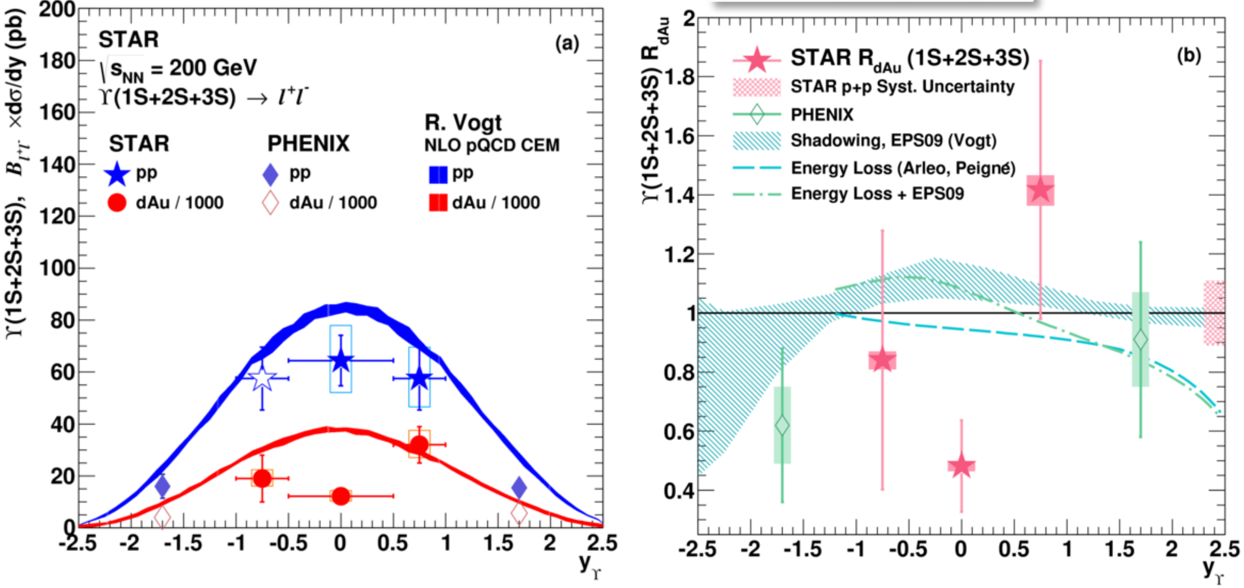

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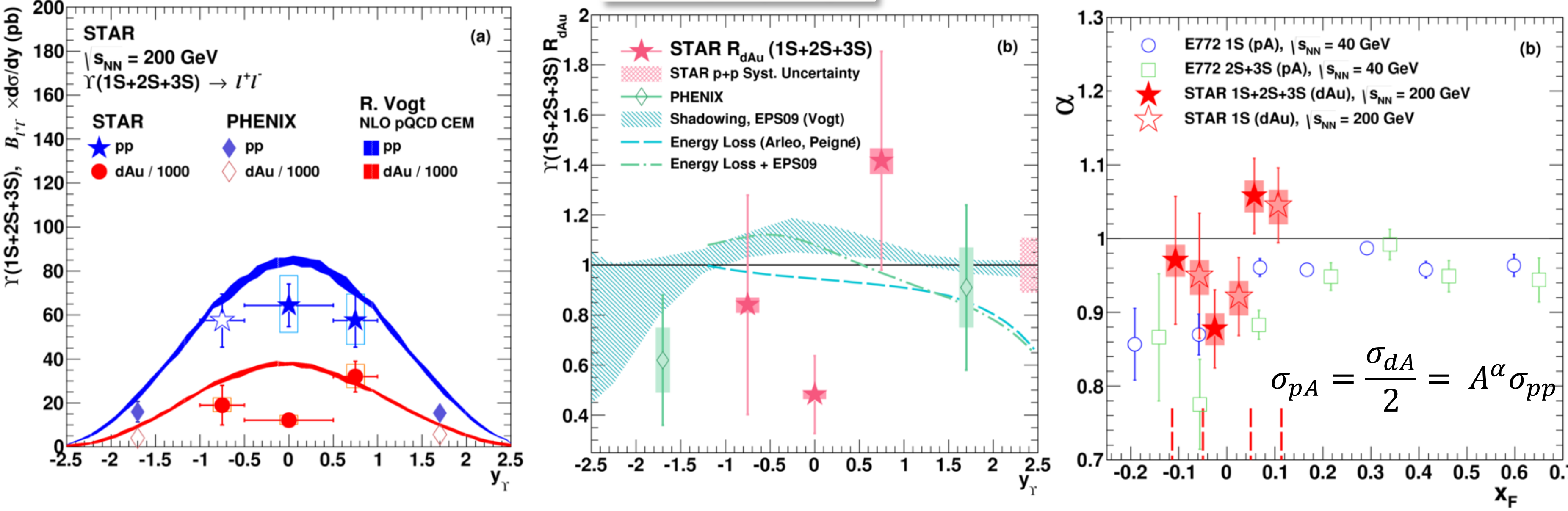
- ❑ Indication of suppression in d+Au in |y|<0.5.
  - Indicative of effect beyond shadowing, initial state E-loss or absorption by spectator nucleons

Cold Nuclear Matter Effect on Upsilon Production

PLB735,127(2014)



- ❑ $R_{dAu}(1S) = 0.83 \pm 0.15(dAu\ stat.) \pm 0.11(pp\ stat.)^{+0.03}_{-0.07}(dAu\ syst.) \pm 0.10(pp\ syst.)$
- ❑ $R_{dAu}(nS) = 0.79 \pm 0.14(dAu\ stat.) \pm 0.10(pp\ stat.) \pm 0.03\ (dAu\ syst.) \pm 0.09(pp\ syst.)$
- ❑ Indication of suppression in d+Au in |y|<0.5.
  - Indicative of effect beyond shadowing, initial state E-loss or absorption by spectator nucleons
  - The suppression is consistent with E772 results.

Essential to understand Open Heavy Flavor Production

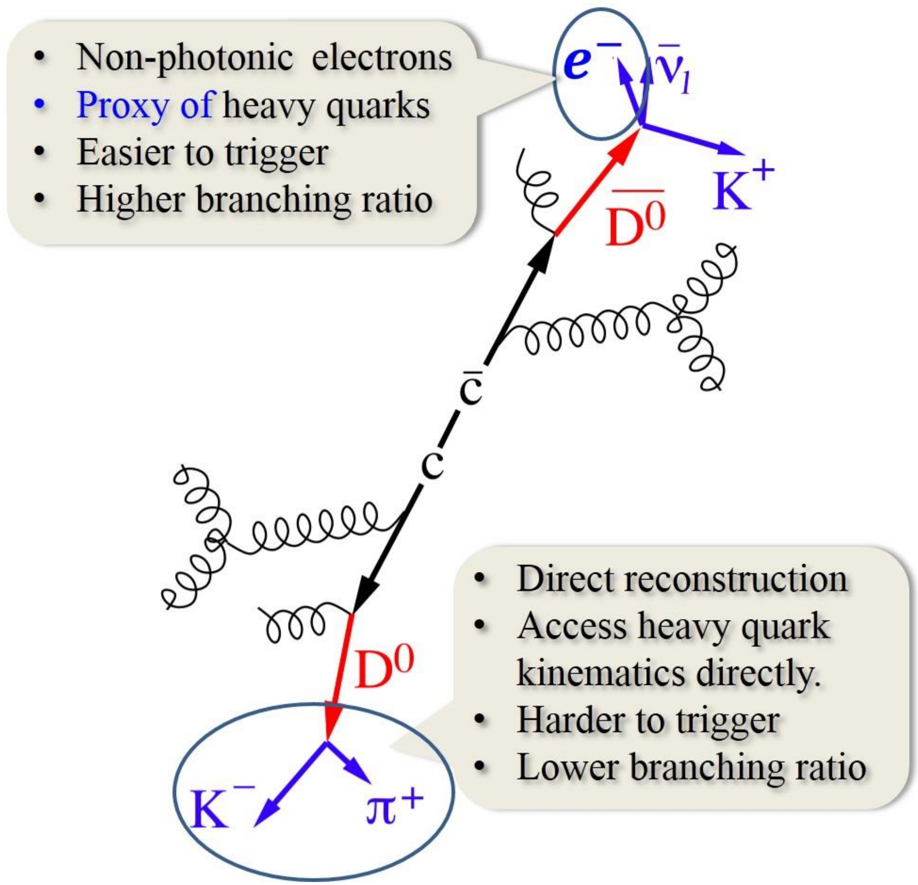
- A good reference to quarkonium production
  - Similar initial state effects
    - CGC, Shadowing, initial state energy loss, etc.
  - Large cross section (compared to J/ψ).
    - Accurate reference measurements
- One of the most important probes for sQGP
  - Dominated by initial hard scatterings
  - Interactions between heavy quark and medium are quite different from the ones for light quarks
    - gluon radiation, collisional energy loss, collisional disassociation, etc
  - allow further understanding of the medium properties
  - A **"Gold Mine"** to be fully explored very soon

How does STAR Measure Heavy Open Heavy Flavors

Time Projection Chamber (TPC)
- $|\eta| \leq 1.0$, full azimuth
- Tracking
- PID through dE/dx

Time of Flight (TOF)
- $|\eta| \leq 0.9$, full azimuth
- PID through TOF
- Timing resolution: ~85 ps

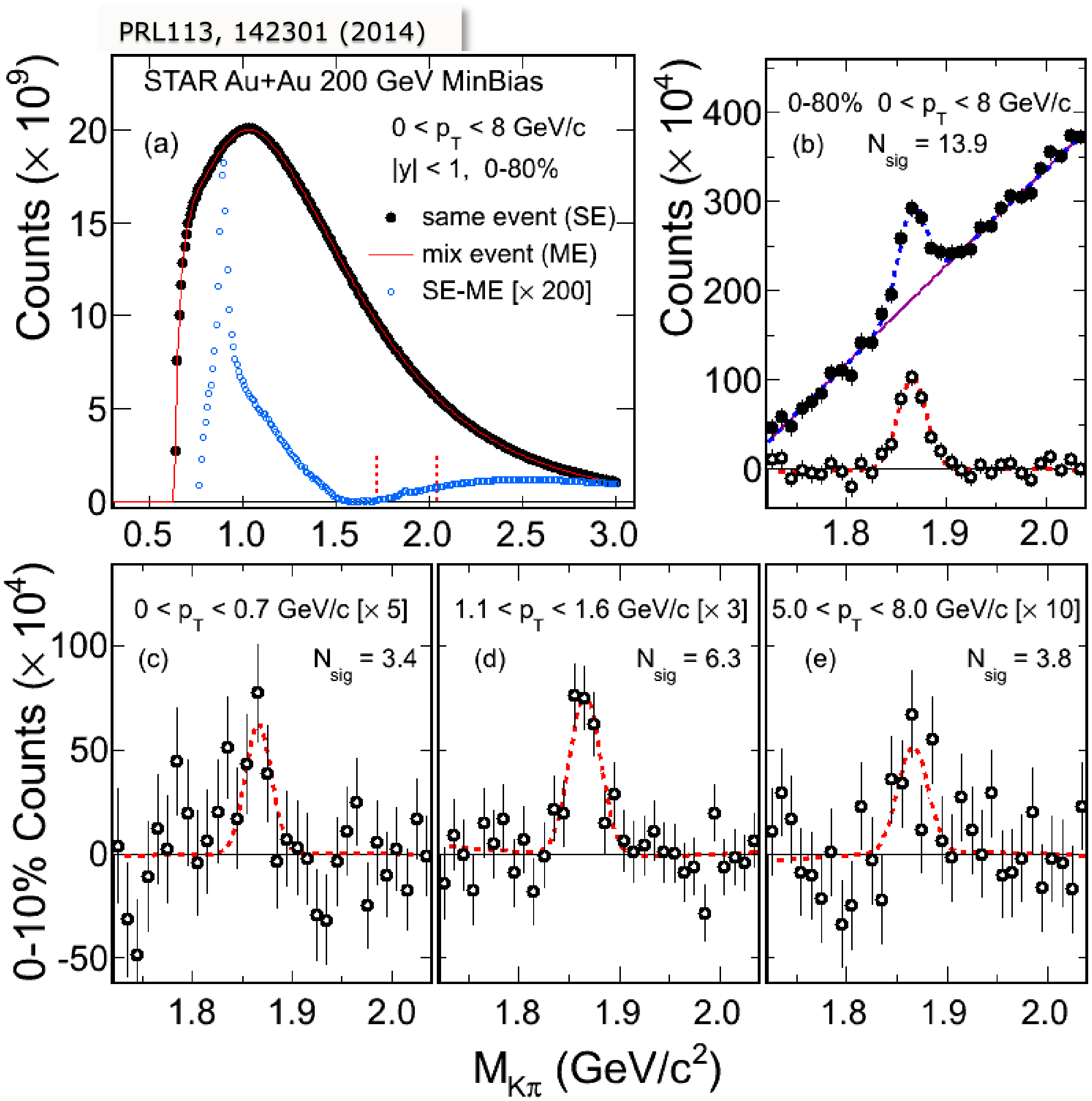
Barrel Electromagnetic Calorimeter (BEMC)
- $|\eta| \leq 1.0$, full azimuth
- p/E for electron ID
- Fast online trigger
- High resolution SMD
- e/h separation



Heavy Flavor Tracker (HFT)
- $|\eta| \leq 1.0$, full azimuth
- PIXEL: X/X_0: ~0.4%/layer
- High DCA resolution
  - ~46μm@p_T = 0.75GeV/c Kaon
  - ~30μm@high p_T

Muon Telescope Detector (MTD)
- $|\eta| \leq 0.5$, 45% in azimuth
- Muon identification
- Muon trigger
- High timing reso.: ~95ps
- Good hit position resolution: ~1cm

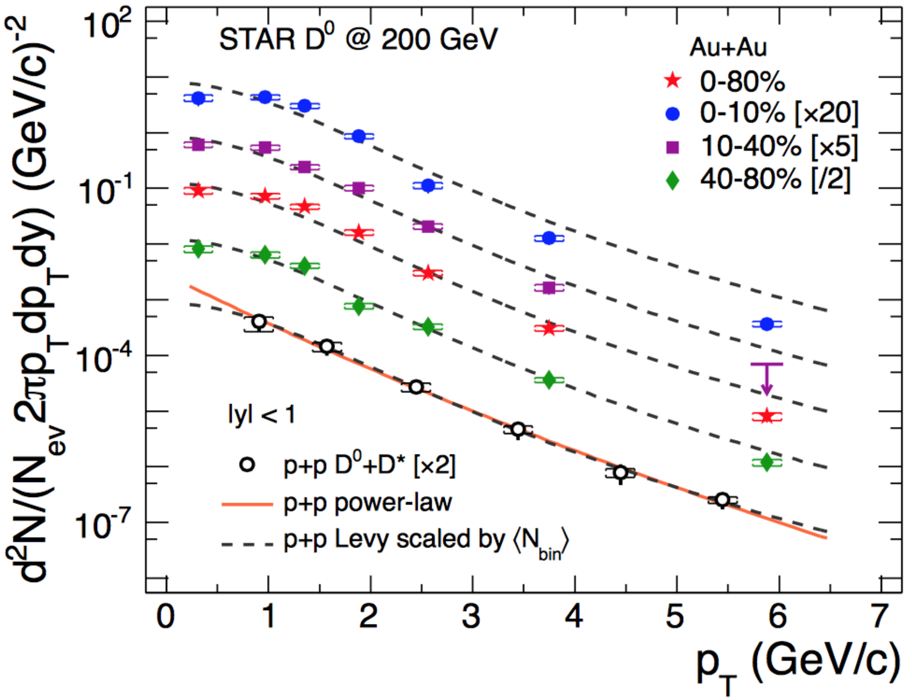
D^0 Signal in Au+Au 200 GeV



- Combining data from Run2010 & 2011
- Total: ~800 M Min.Bias events
- Significant signals are observed
- In all centrality bins

Centrality dependence of D^0 Suppression in Au+Au 200 GeV

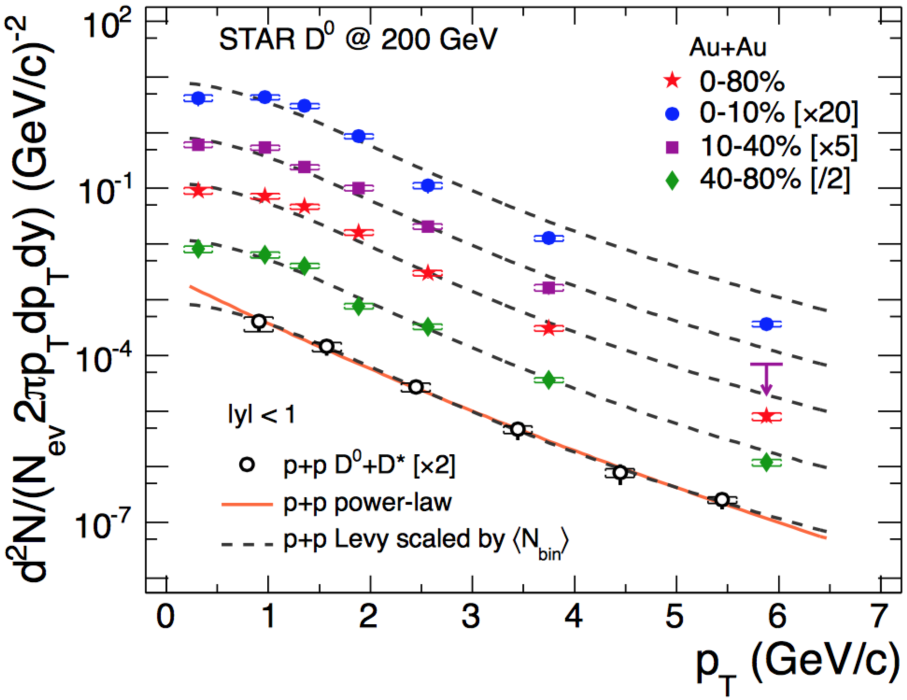
PRL113, 142301 (2014)

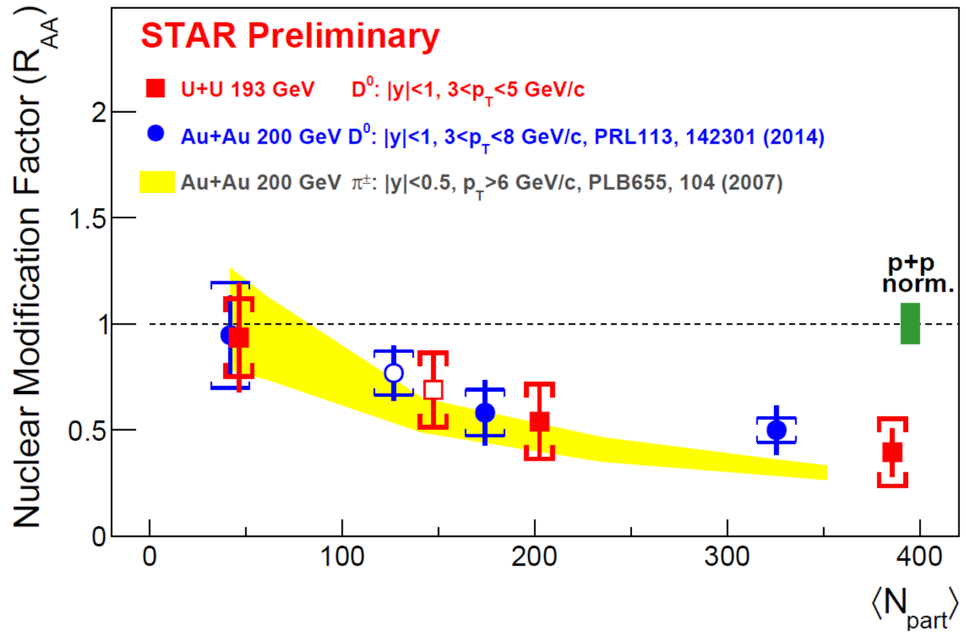


- Suppression at high p_T in central and mid-central collisions

Centrality dependence of D^0 Suppression in Au+Au 200 GeV

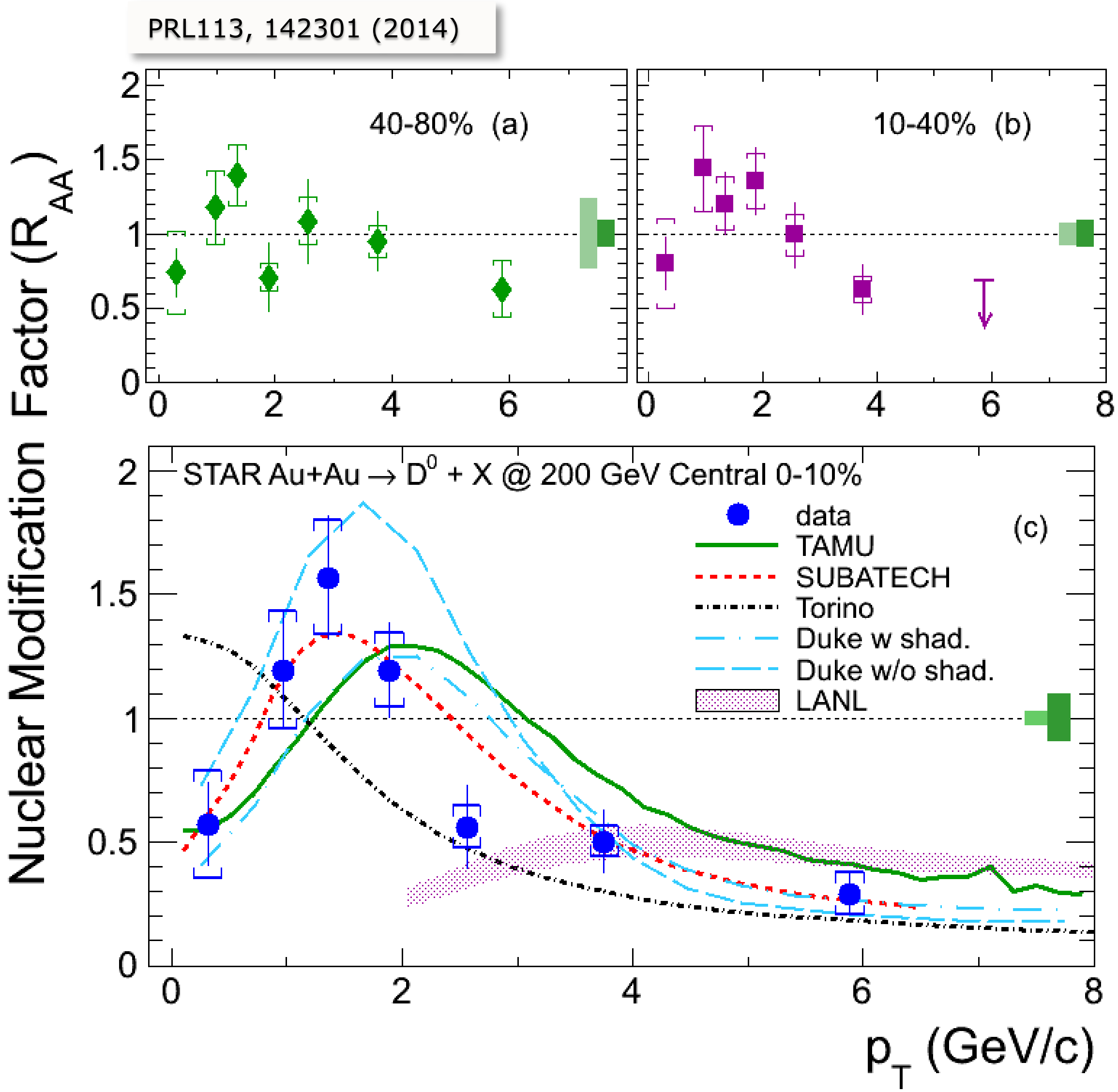
PRL113, 142301 (2014)





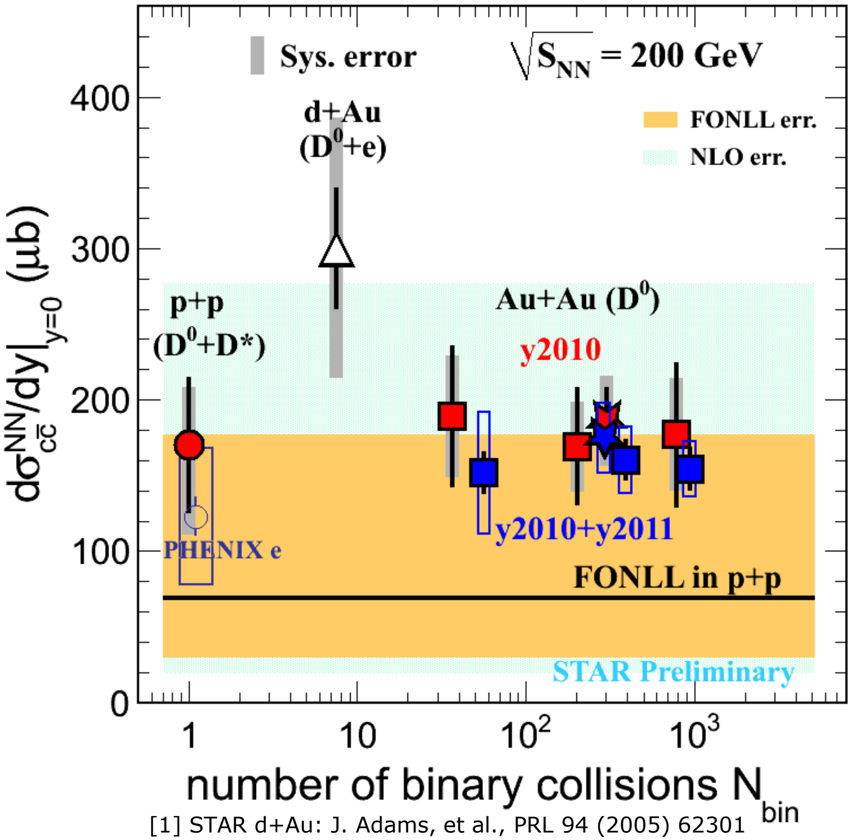
- Suppression at high p_T in central and mid-central collisions
- D suppression pattern is similar to that of charged pions

Enhancement of D^0 production at Intermediate p_T in Au+Au 200 GeV



- Suppression at high p_T in central and mid-central collisions
- Enhancement at intermediate p_T
  - Can be described by models including coalescence between charm quark and light quark
  - Cold nuclear matter effects may also contribute

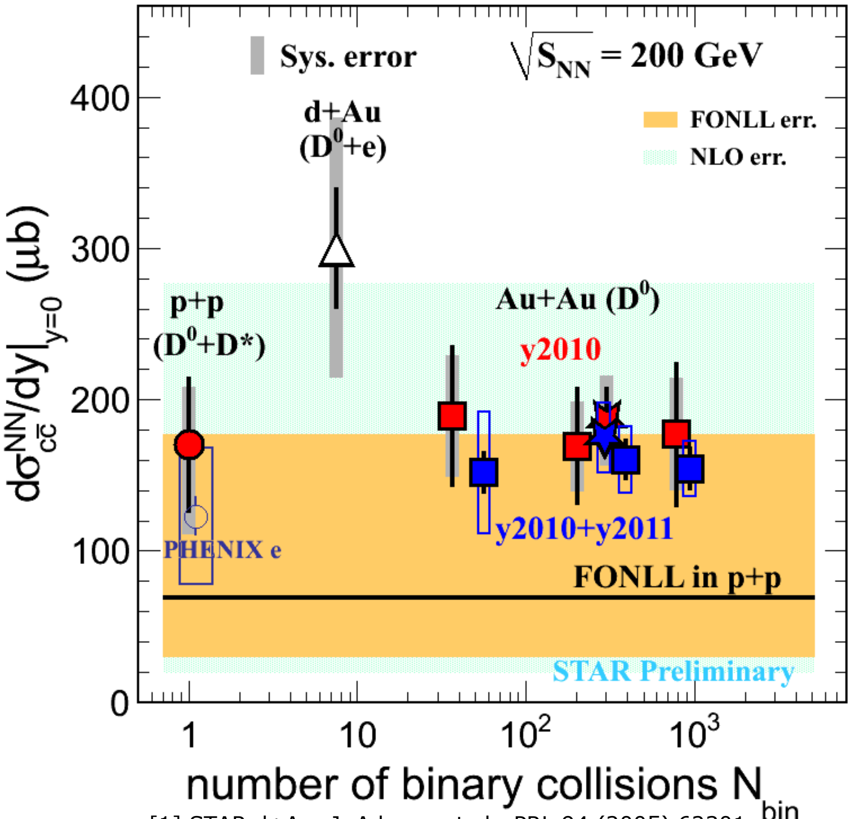
N_{coll} Scaling of D^0 Production in Au+Au 200 GeV

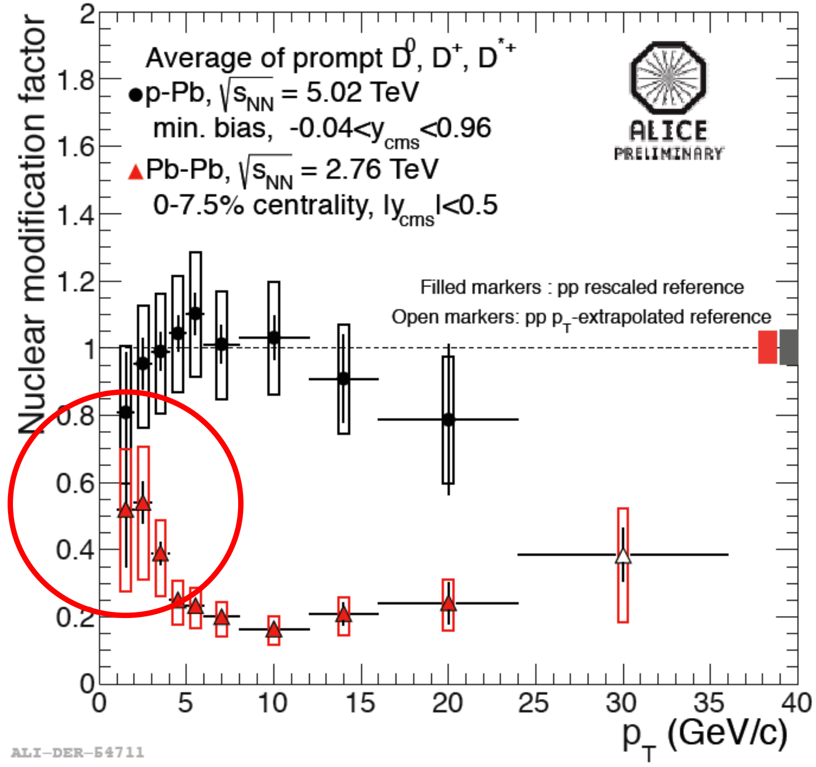


[1] STAR d+Au: J. Adams, et al., PRL 94 (2005) 62301
[2] FONLL: M. Cacciari, PRL 95 (2005) 122001.
[3] NLO: R. Vogt, Eur.Phys.J.ST 155 (2008) 213
[4] PHENIX e: A. Adare, et al., PRL 97 (2006) 252002.

- Charm quarks are mostly produced via initial hard scatterings
- Quantify other sources of production via high luminosity and upgrade

N_{coll} Scaling of D^0 Production in Au+Au 200 GeV





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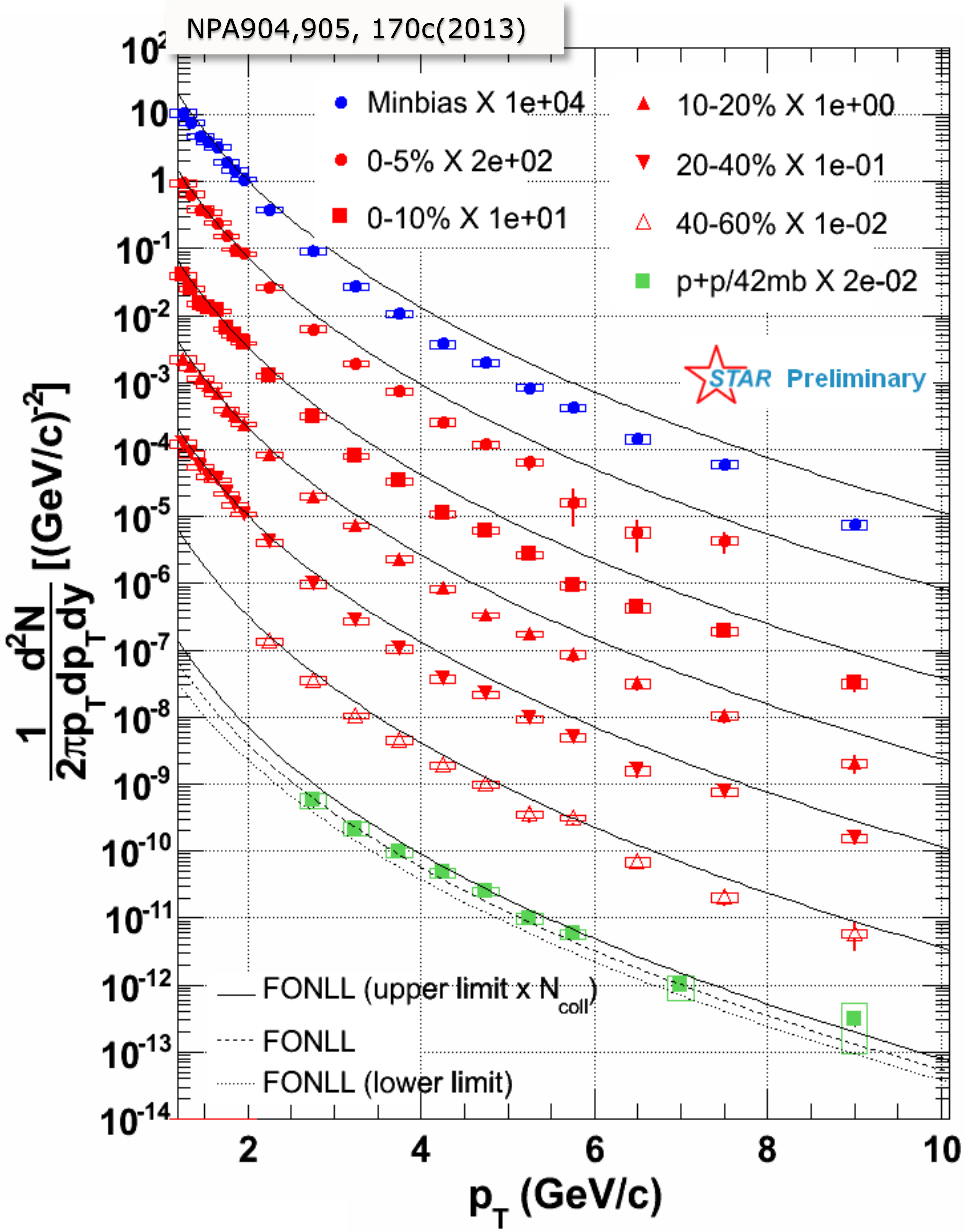
[4] PHENIX e: A. Adare, et al., PRL 97 (2006) 252002.

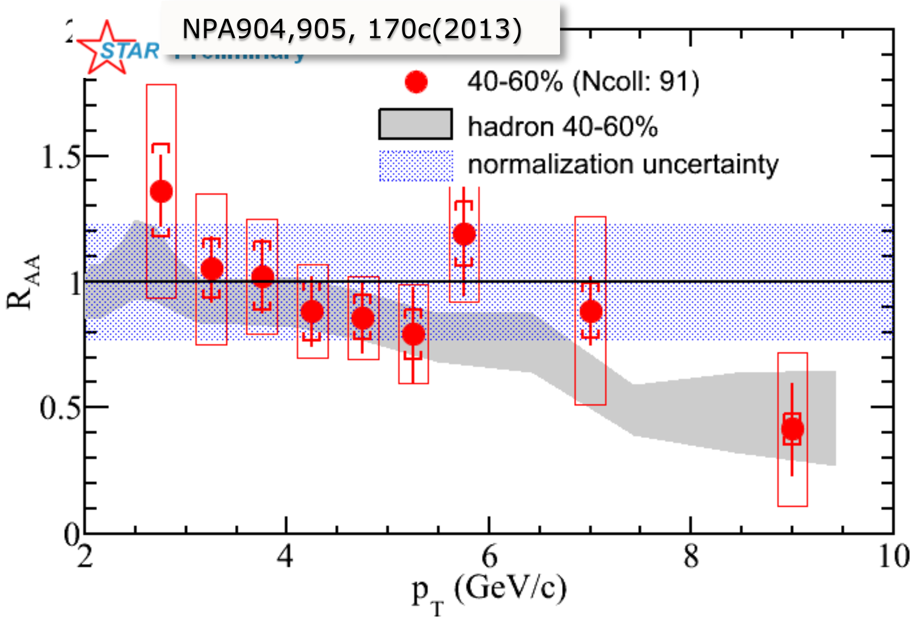
- Charm quarks are mostly produced via initial hard scatterings
- Quantify other sources of production via high luminosity and upgrade
- Indication of a breakdown of the N_{coll} scaling at LHC
  - Shadowing?

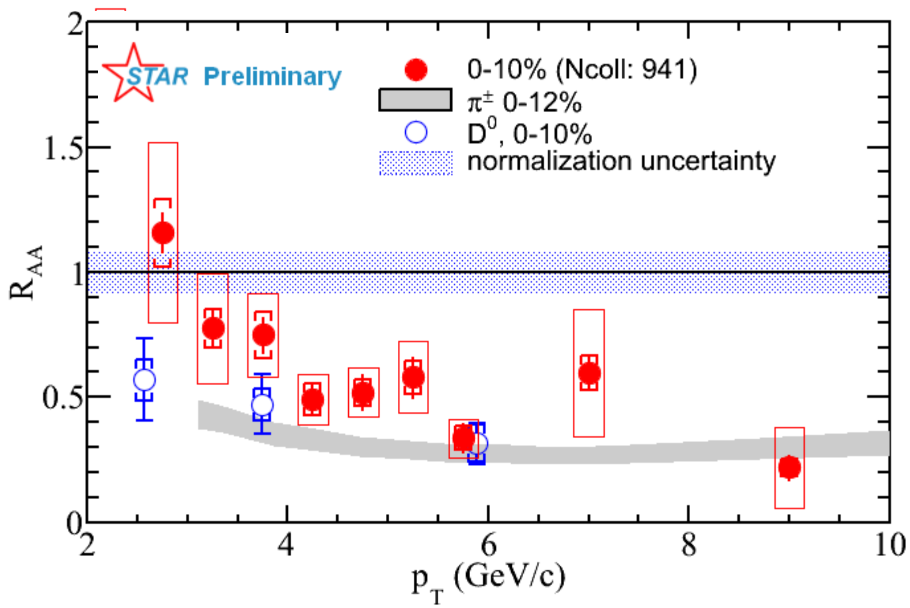
Non-photonic Electron R_{AA} in Au+Au 200 GeV



- ~1 nb^{-1} sampled luminosity in Run 2010 Au+Au collisions

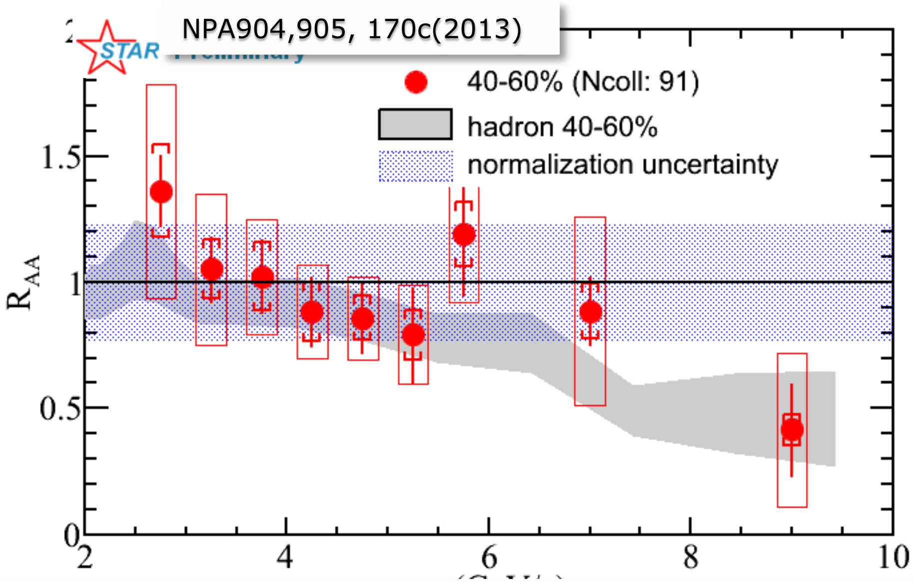
Non-photonic Electron R_{AA} in Au+Au 200 GeV

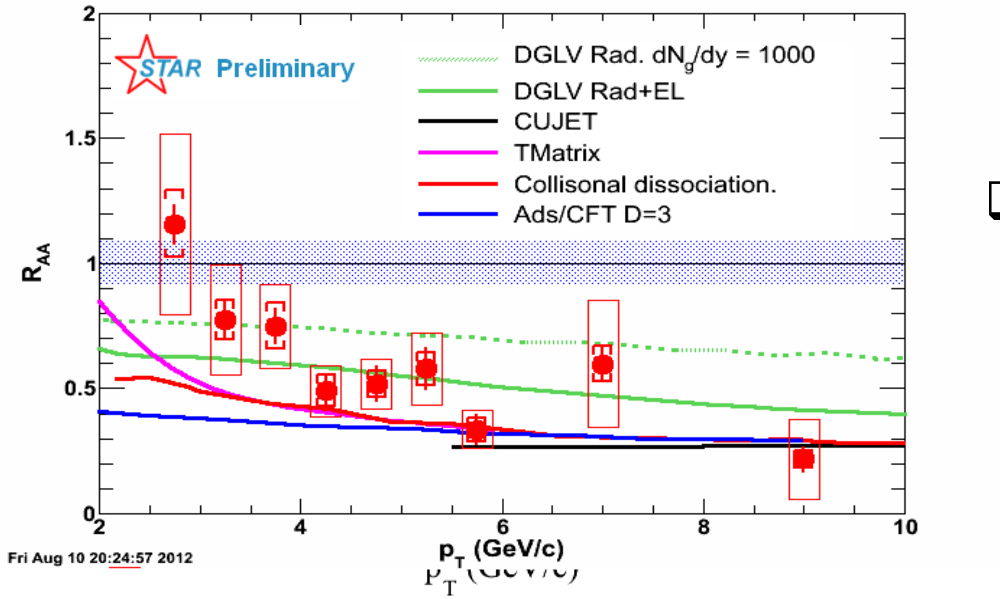




- ❑ ~1 nb^{-1} sampled luminosity in Run 2010 Au+Au collisions
- ❑ Strong suppression at high p_T in central collisions
- ❑ D^0, NPE results seems to be consistent
  - kinematics smearing & charm/bottom mixing

Non-photonic Electron R_{AA} in Au+Au 200 GeV

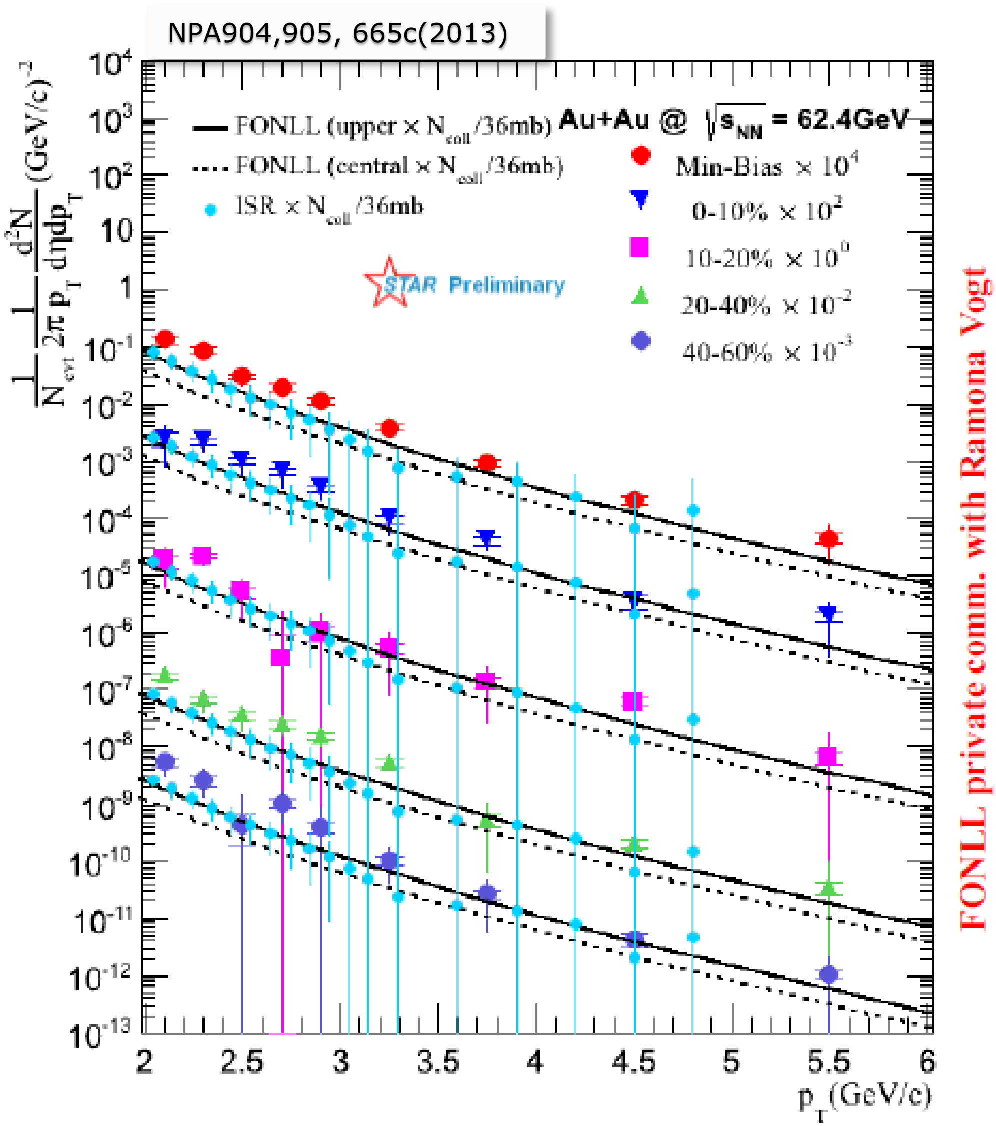


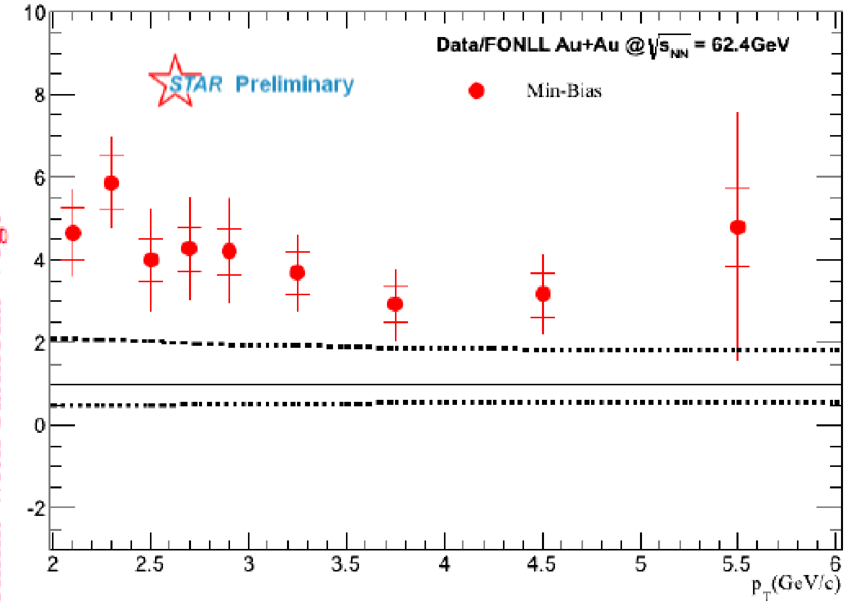


- ~1 nb^{-1} sampled luminosity in Run 2010 Au+Au collisions
- Strong suppression at high p_T in central collisions
- D^0, NPE results seems to be consistent
  - kinematics smearing & charm/bottom mixing
- Models with radiative energy loss alone underestimate the suppression
  - Uncertainty dominated by p+p

DGLV: Djordjevic, PLB632, 81 (2006)
CUJET: Buzzatti, arXiv:1207.6020
T-Matrix: Van Hees et al., PRL100,192301(2008).
Coll. Dissoc. R. Sharma et al., PRC 80, 054902(2009).
Ads/CFT: W. Horowitz Ph.D thesis.

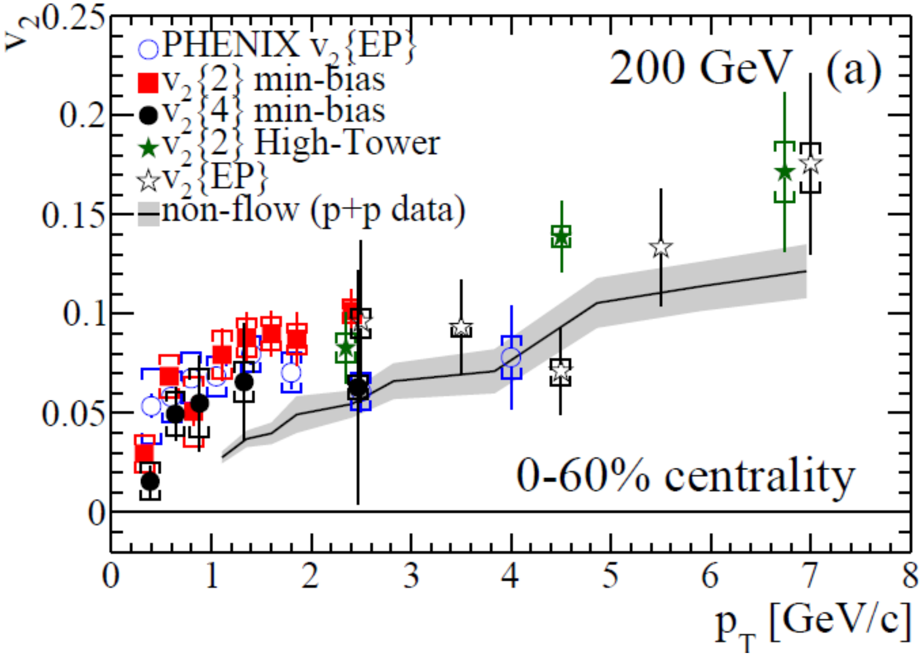
NPE Enhancement at Lower Energy





- J/ψ not subtracted
- Indication of "enhancement" at 62.4 GeV
  - Shape ≈ pQCD
  - Radial flow and/or CNM enhancement compensate suppression at lower energy?

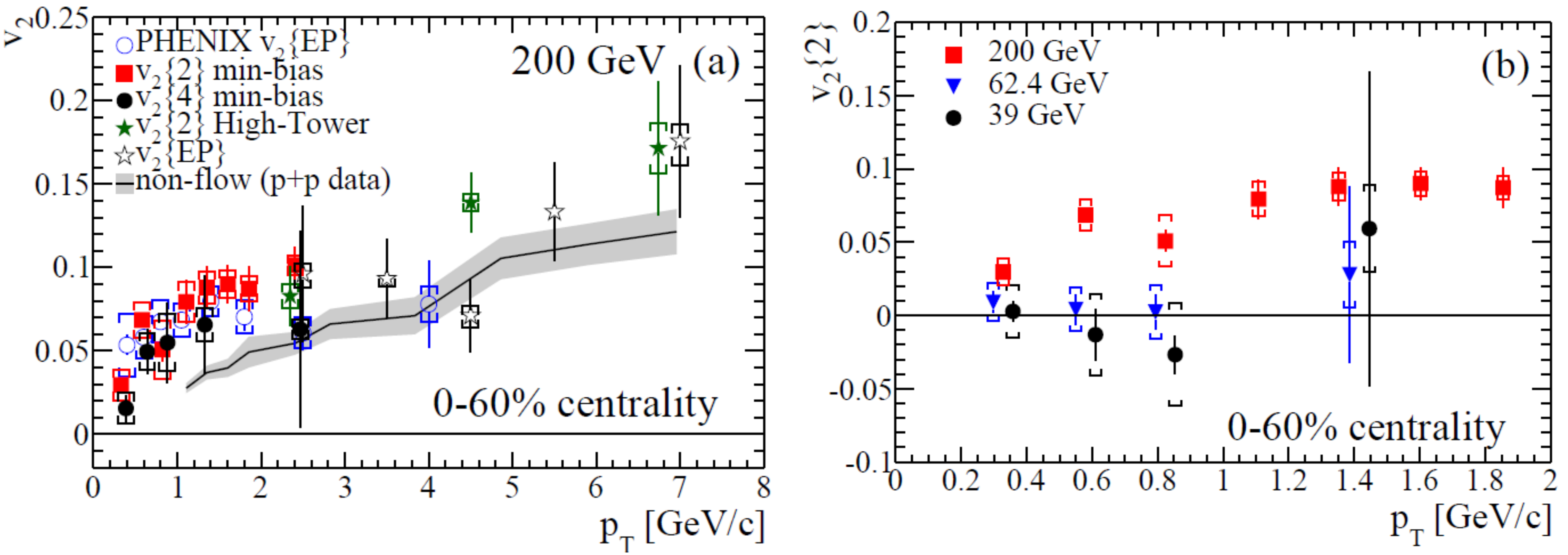
NPE Elliptic Flow Depend on Energy



<u>200 GeV Au+Au:</u>

- Large NPE v_2 observed at low p_T → strong charm-medium interaction
- v_2 increase at $p_T > 3$ GeV/c
    - Jet-like correlation

NPE Elliptic Flow Depend on Energy



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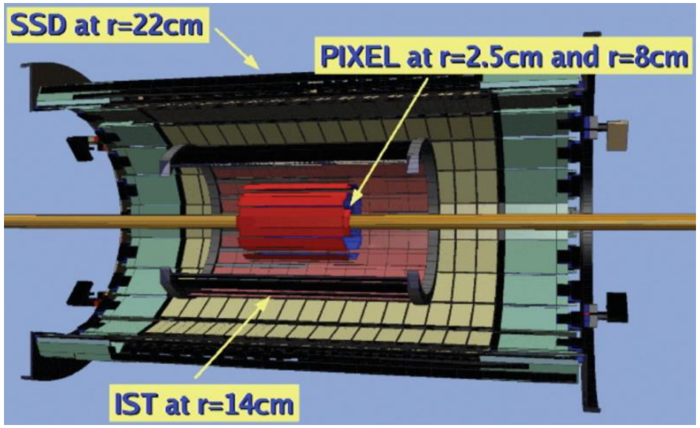
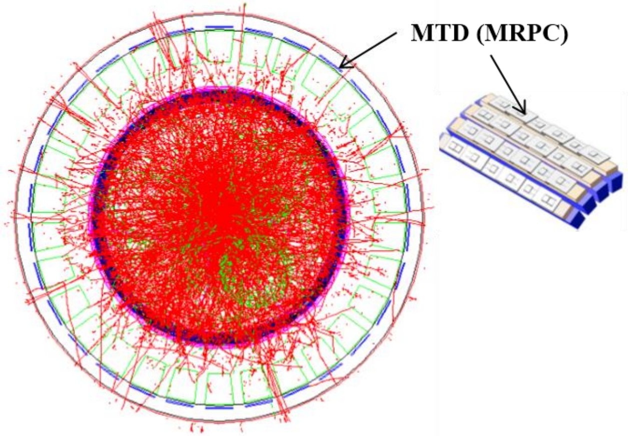
- ❑ Large NPE v_2 observed at low p_T → strong charm-medium interaction
- ❑ v_2 increase at p_T > 3 GeV/c
  - Jet-like correlation

<u>39 and 62.4GeV Au+Au:</u>

- ❑ v_2 consistent with zero
  - different from 200GeV results (p-value: 0.0014@62.4GeV, 0.005@39GeV)
- ❑ Might suggest charm –medium interaction is not as strong as in 200 GeV

New Era of Heavy Flavor Measurement at STAR



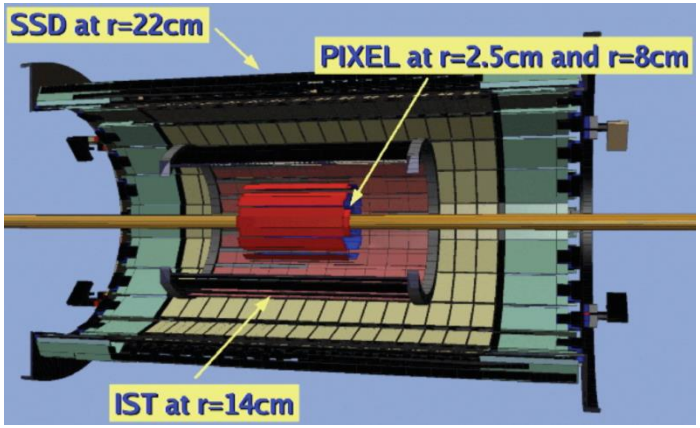


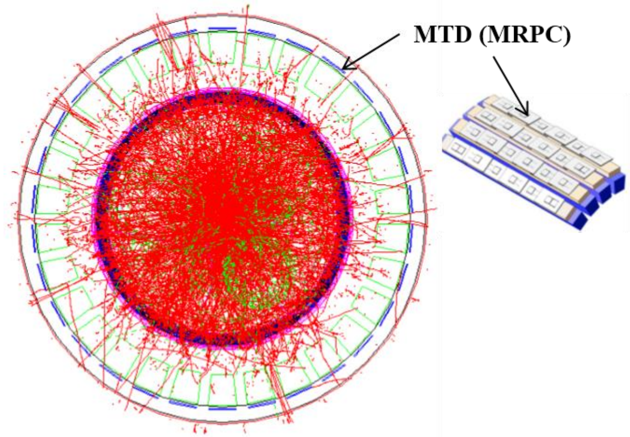
PIXEL:

- high hit resolution: 20.7μm pitch
- low thickness: X/X_0 = 0.4%/layer

- ❑ Muon identification
- ❑ Muon trigger

New Era of Heavy Flavor Measurement at STAR





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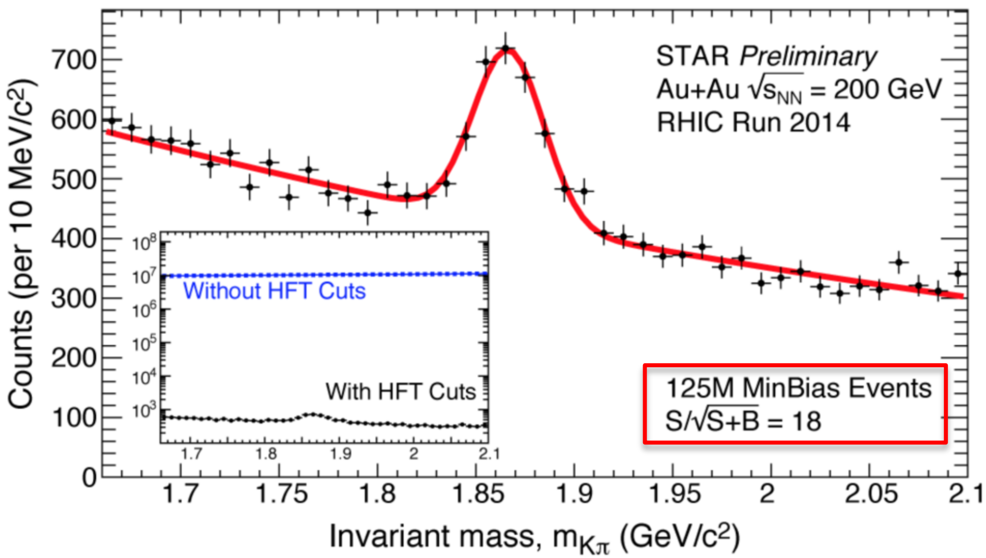
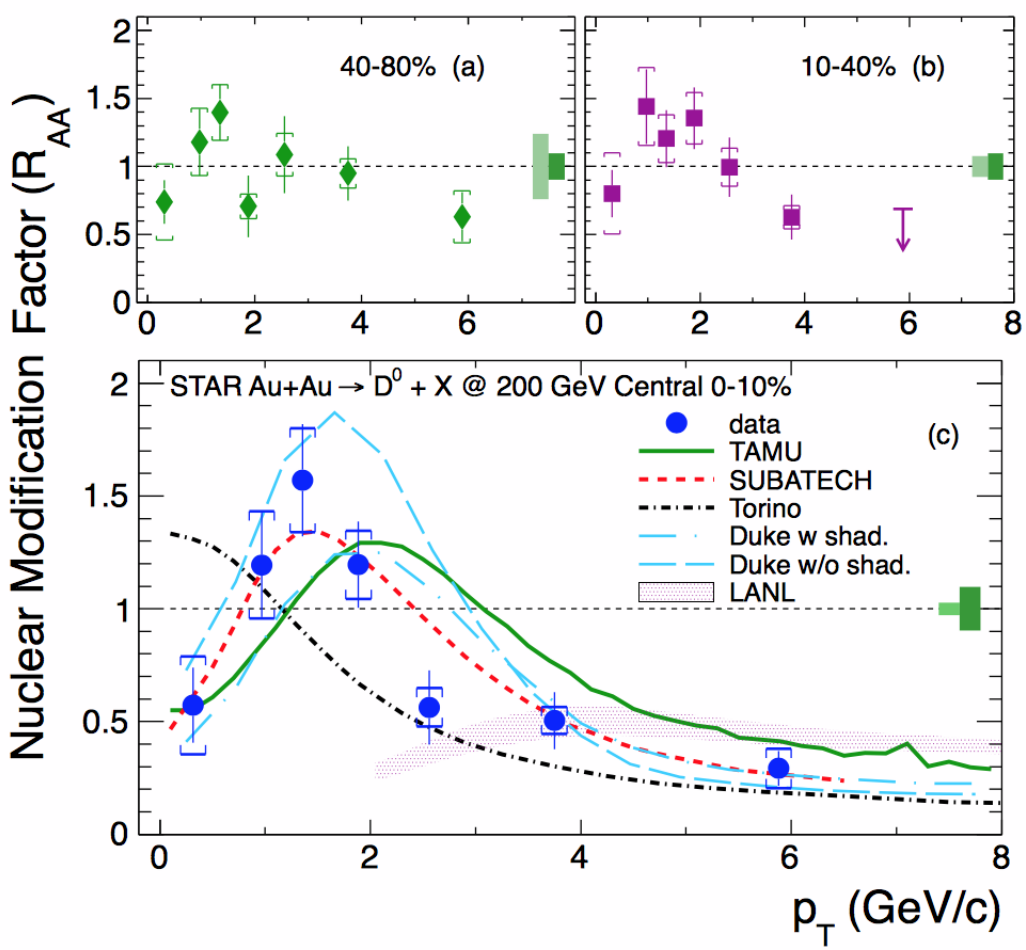


- ❑ significantly enhance STAR capability on measuring heavy flavor production at RHIC.
  - Direct D meson reco at low and high p_T
  - B→J/ψ→μμ+X, ϒ→μμ
  - etc
- ❑ study QGP thermal dilepton radiation
  - Understanding background through e-μ correlation

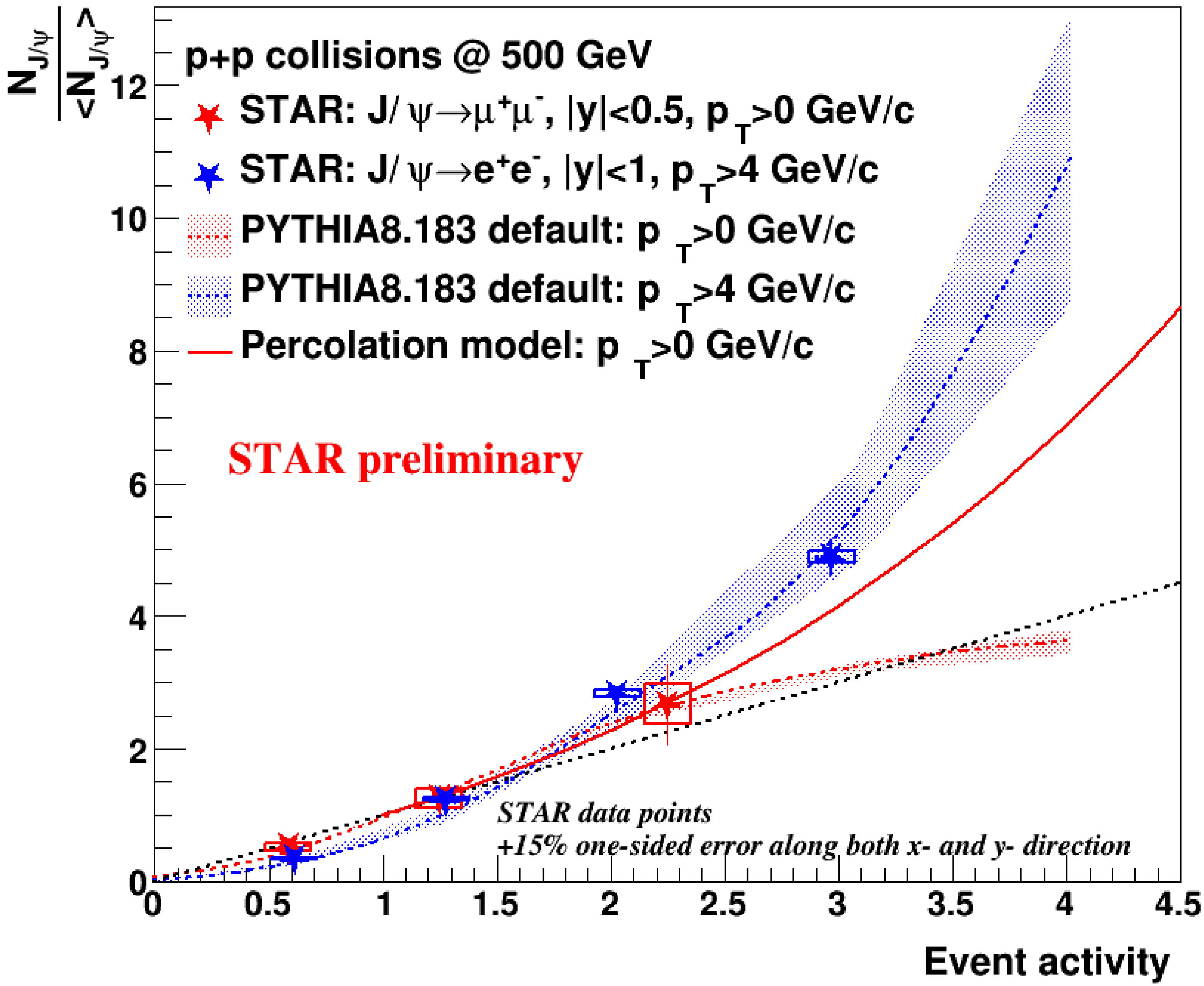
Summary

- No significant energy dependence for J/ψ R_{AA} and R_{cp}
- J/ψ v_2 measurements disfavor the case that coalescence of thermalized $c\bar{c}$ dominates the production at p_T > 2 GeV/c in 200 GeV Au+Au collisions
- Upsilon suppression consistent with prediction from models requiring strong 2S and complete 3S suppression in 200 GeV Au+Au collisions
  - Indication of suppression in 200 GeV d+Au collisions (CNM effect).
- Large suppression of heavy quark production through NPE and D^0 meson measurements in 200 GeV Au+Au collisions
- Larger NPE v_2 in 200 GeV than in 39 and 62.4 GeV Au+Au collisions, indicating the strength of charm-medium interaction increase with energy
- Indication of an enhancement of NPE production at 62.4 GeV
- **With HFT and MTD, more interesting results with good precision will come up soon**

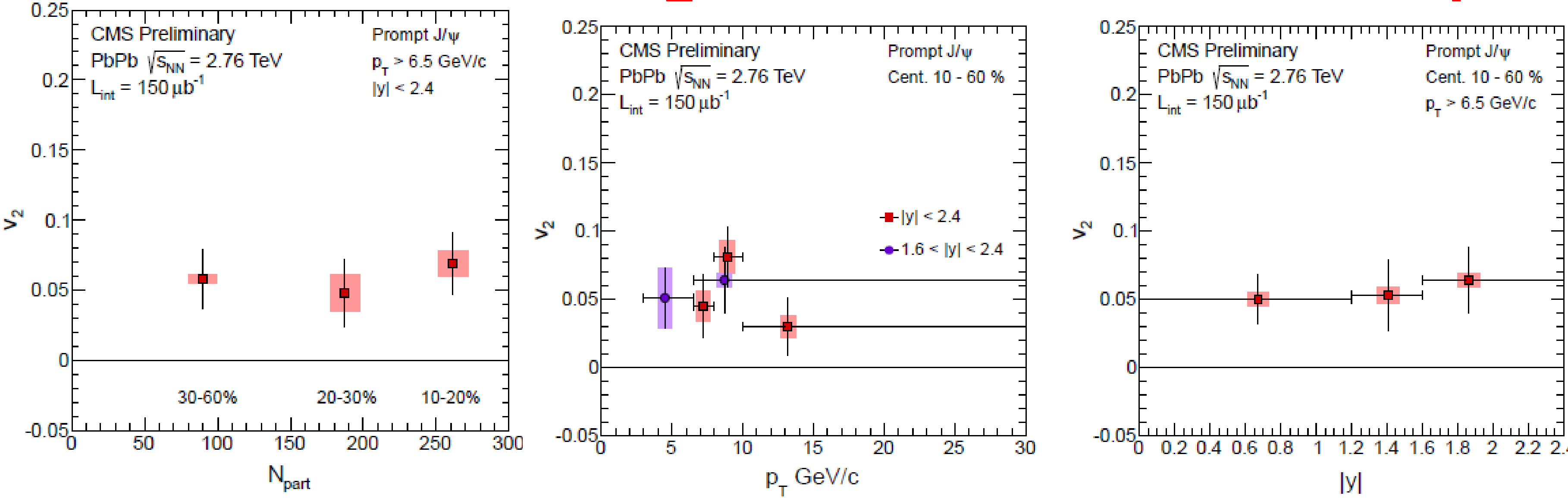
Backup Slides



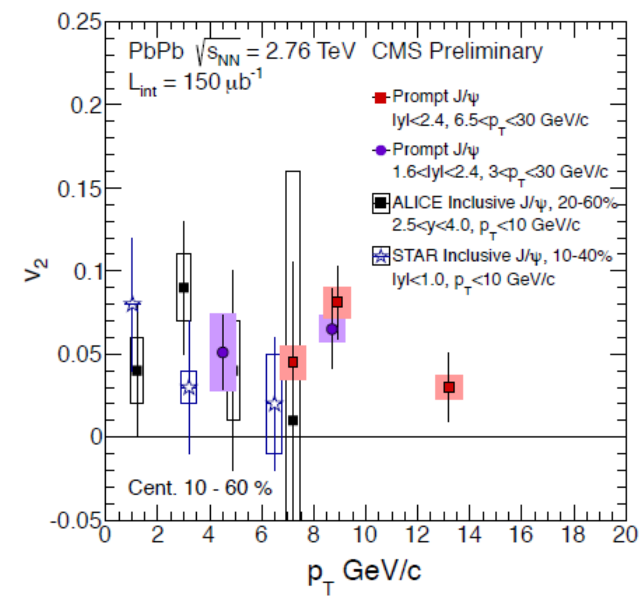
	TAMU	SUBATECH	Torino	Duke	LANL
HQ prod.	LO	FNOLL	NLO	LO	LO
QGP-Hydro	ideal	ideal	viscous	viscous	ideal
HQ eLoss	coll.	coll. +rad.	coll.+rad.	coll.+rad.	diss. +rad.
Coalescence	Yes	Yes	No	Yes	No
Cronin effect	Yes	Yes	No	No	Yes
Shadowing	No	No	Yes	Yes/No	Yes


p+p collisions @ 500 GeV
STAR: J/ψ→μ⁺μ⁻, |y|<0.5, p_T>0 GeV/c
STAR: J/ψ→e⁺e⁻, |y|<1, p_T>4 GeV/c
PYTHIA8.183 default: p_T>0 GeV/c
PYTHIA8.183 default: p_T>4 GeV/c
Percolation model: p_T>0 GeV/c
STAR preliminary
STAR data points
+15% one-sided error along both x- and y- direction
Event activity
N_J/ψ / <N_J/ψ>

Significant v_2 observed at high p_T



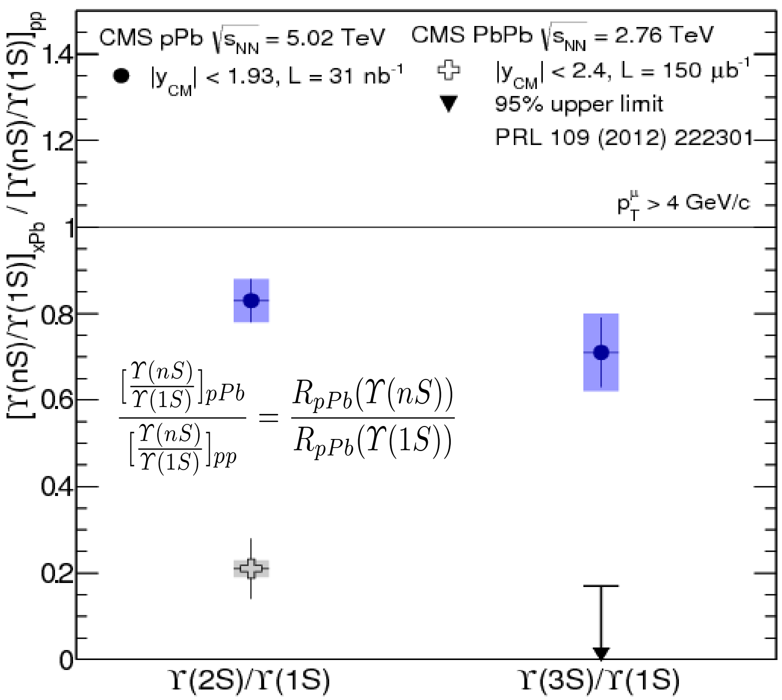
- ❑ Non-zero v_2 observed at high p_T
  - No significant dependence on y and p_T.
  - V_2 =0.054±0.013±0.006 in |y|<2.4 for p_T > 6.5 GeV in 10-60% centrality.
  - Indicating path length dependence of suppression
- ❑ Indication non-zero v_2 at low p_T
  - Consistent with regeneration from charm quark of significant v_2.

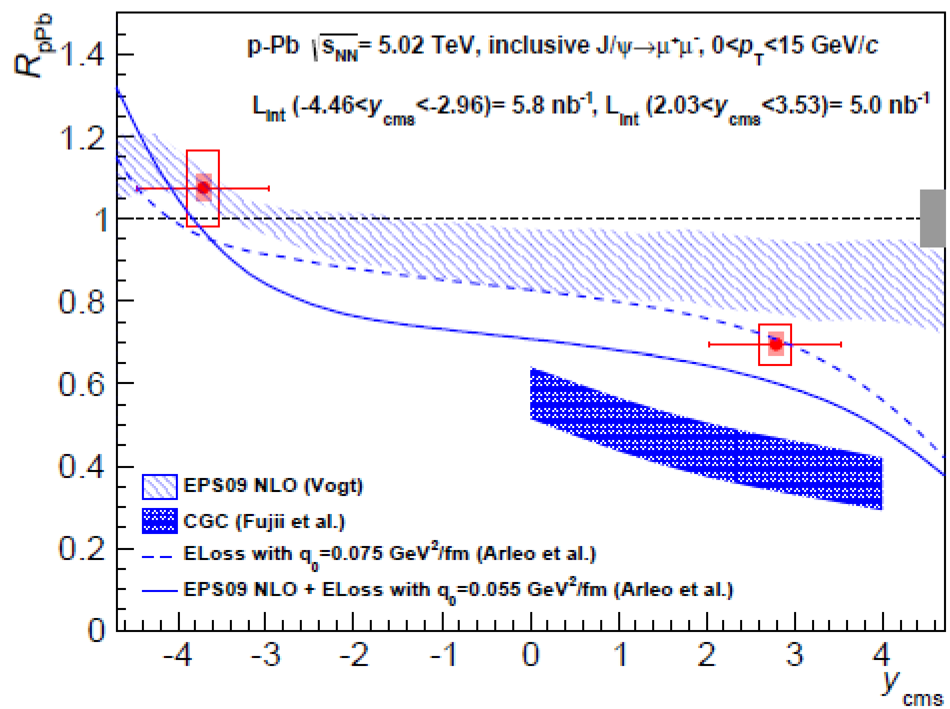


CMS PAS HIN-12-001

PRL 111(2013)162301

How CNM plays a role in the suppression





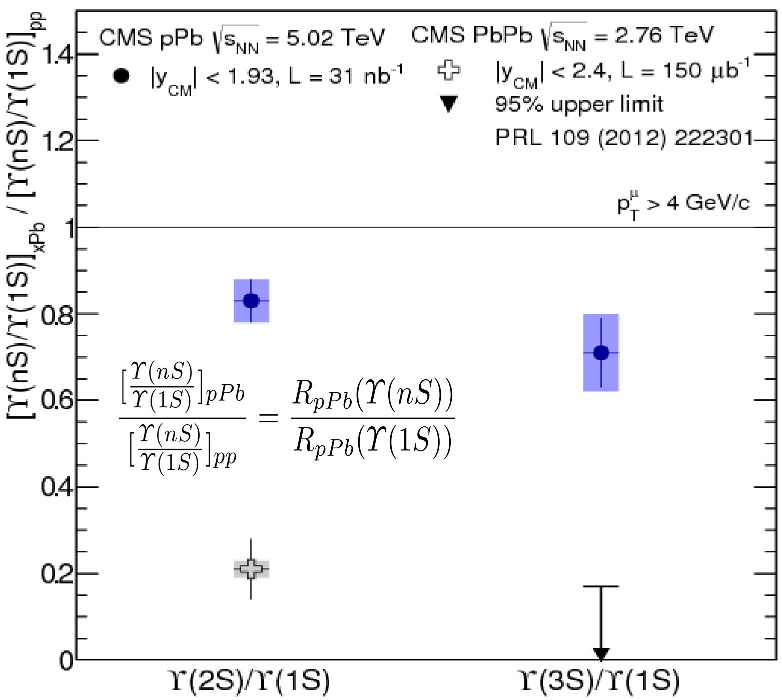
Upsilon double ratio:

- ❑ Much lower in Pb+Pb.
- ❑ Initial state effect likely cancelled in the comparison
- ❑ Suppression in Pb+Pb is a final state effect.

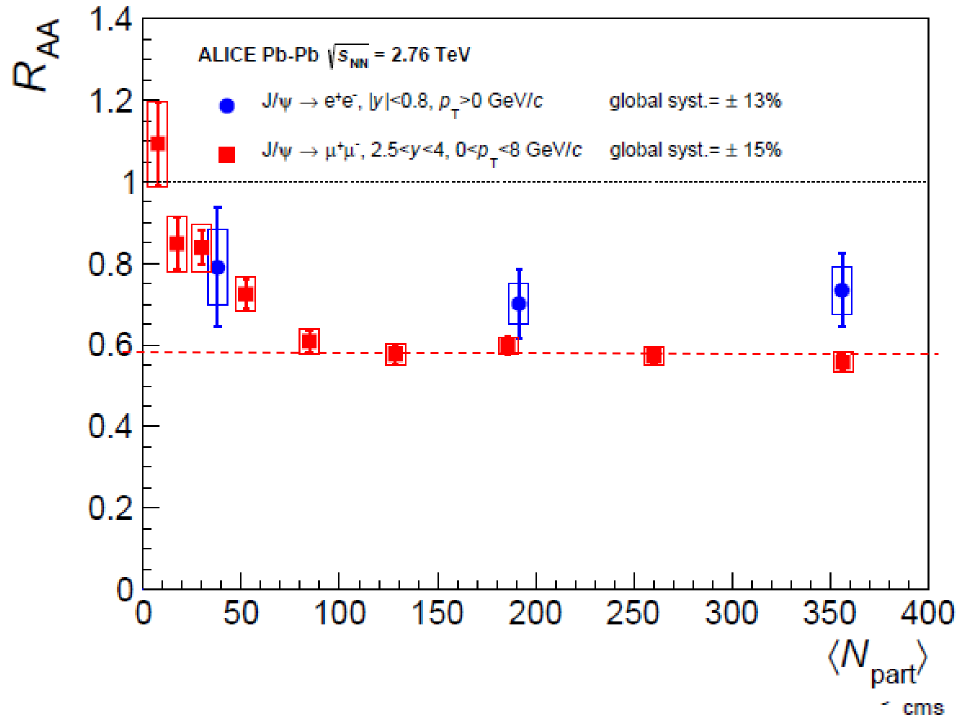
J/ψ in pPb:

- ❑ Significant suppression from CNM at low p_T
  - Close to R_{PbPb}
  - Pb+Pb partially compensated by regenerated J/ψ?

How CNM plays a role in the suppression



$$\frac{[\frac{\Upsilon(nS)}{\Upsilon(1S)}]_{pPb}}{[\frac{\Upsilon(nS)}{\Upsilon(1S)}]_{pp}} = \frac{R_{pPb}(\Upsilon(nS))}{R_{pPb}(\Upsilon(1S))}$$



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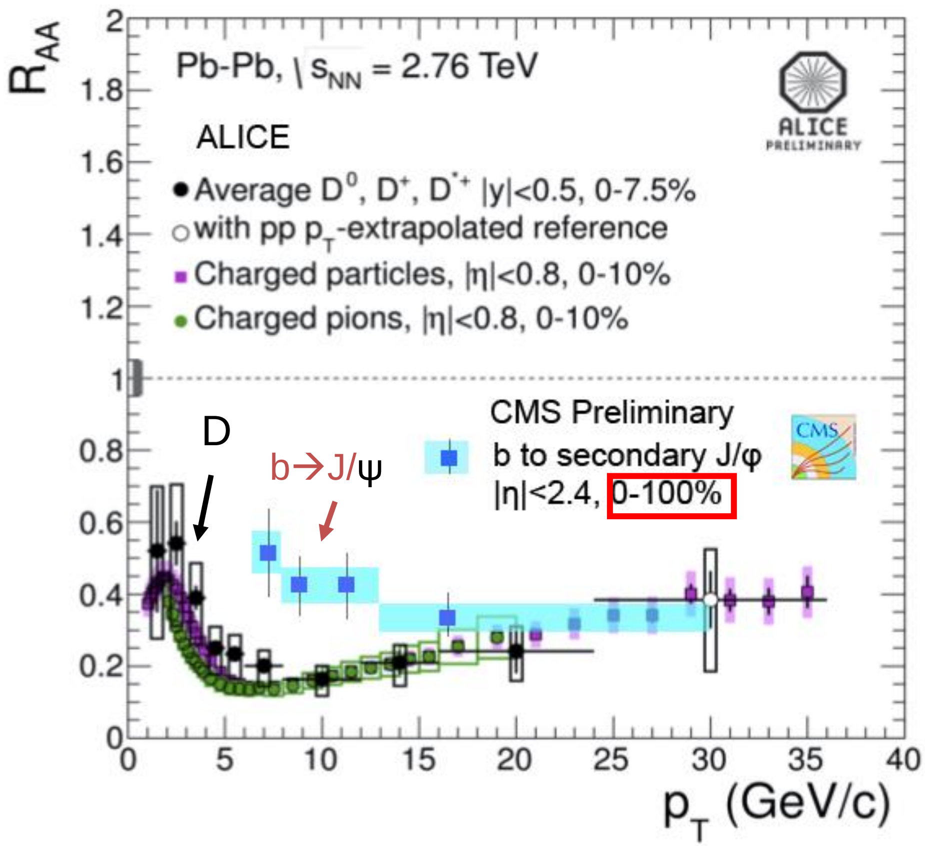
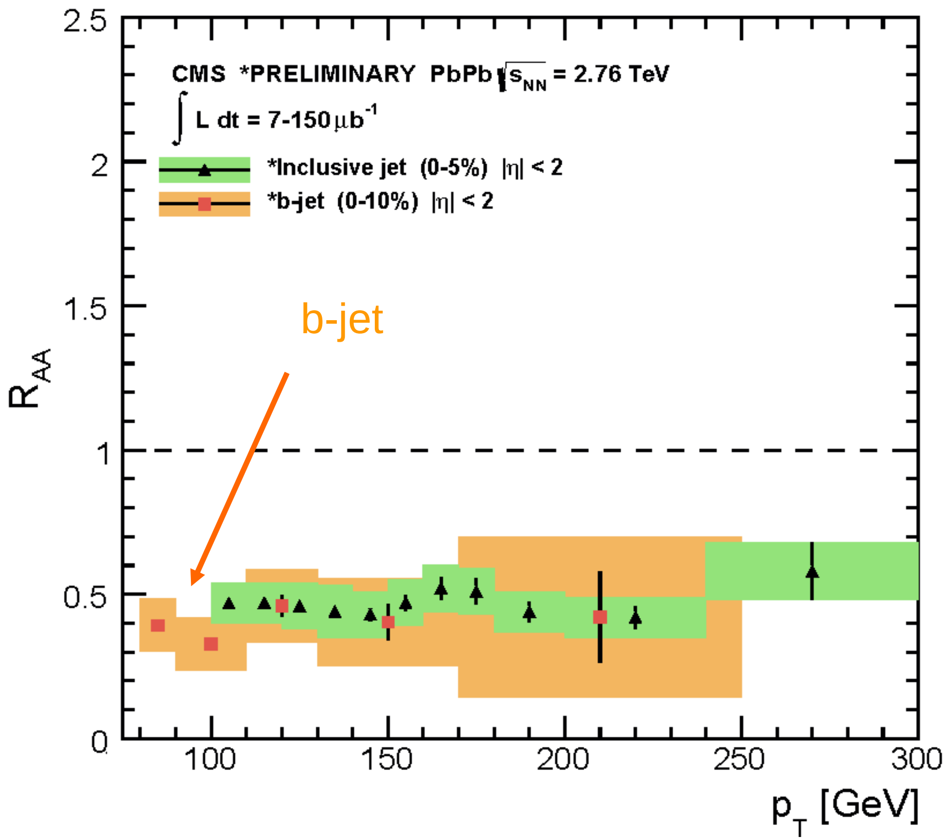
Suppression in Pb+Pb is a final state effect





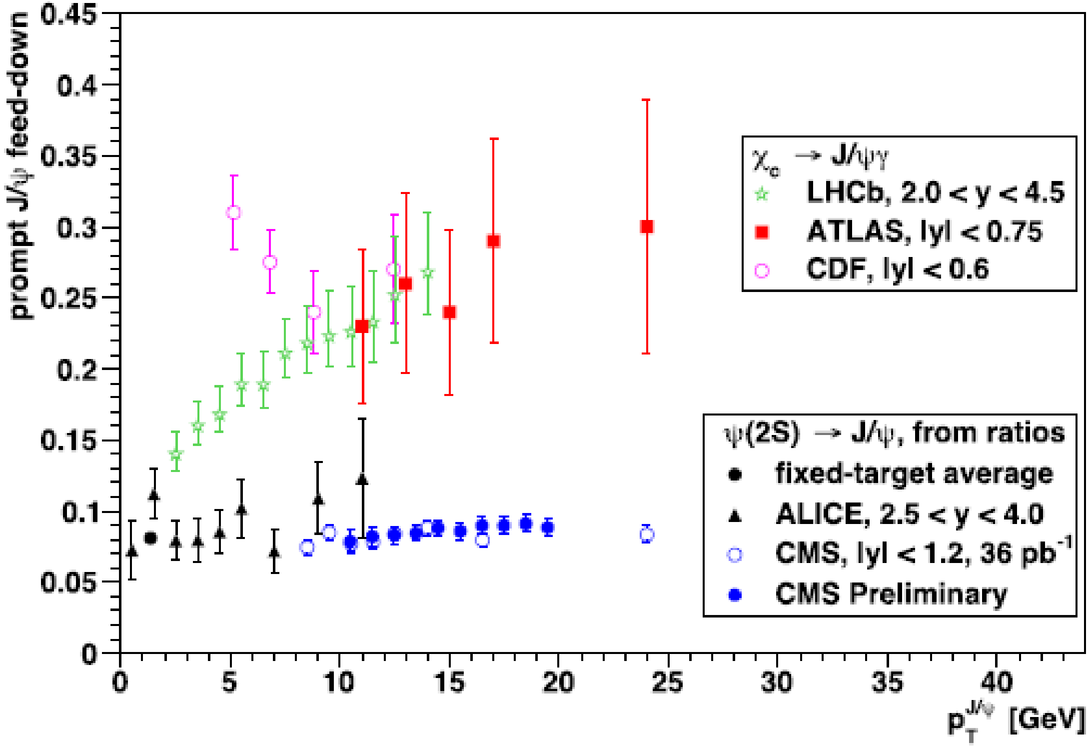
From low p_T to intermediate p_T

- ❑ $R_{AA}(D) \sim R_{AA}(\pi)$ within uncertainties
- ❑ $R_{AA}(B) > R_{AA}(D)$
  - Different energy loss?
  - What's the impact of, e.g. production spectrum.

At high p_T

- ❑ R_{AA}(b-jet) ~ R_{AA}(all jets)

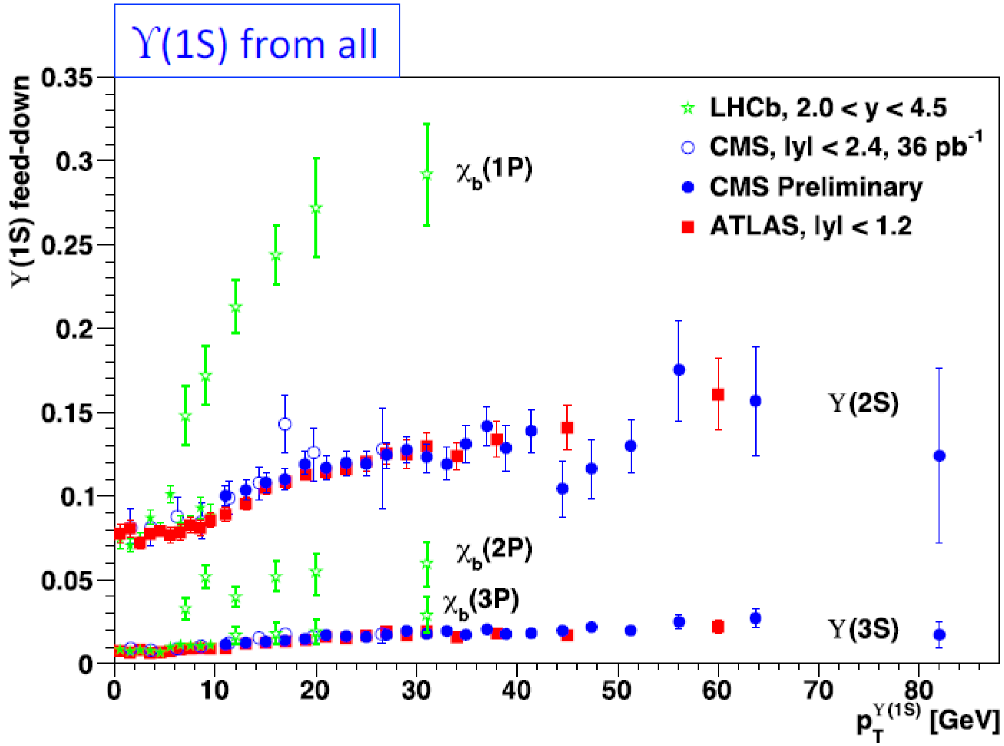
What's the NLO effect, e.g. FEX, GSP?

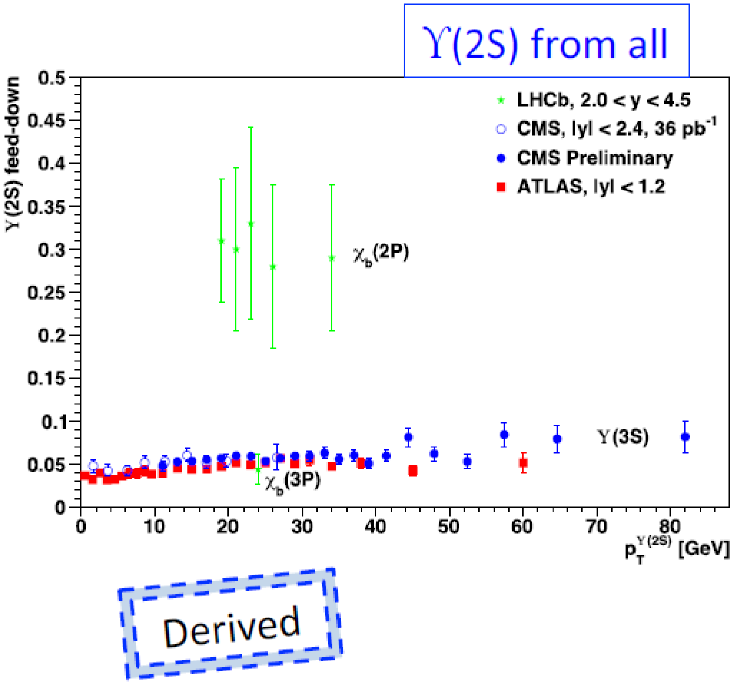


ALICE points from *inclusive* ratio

Derived

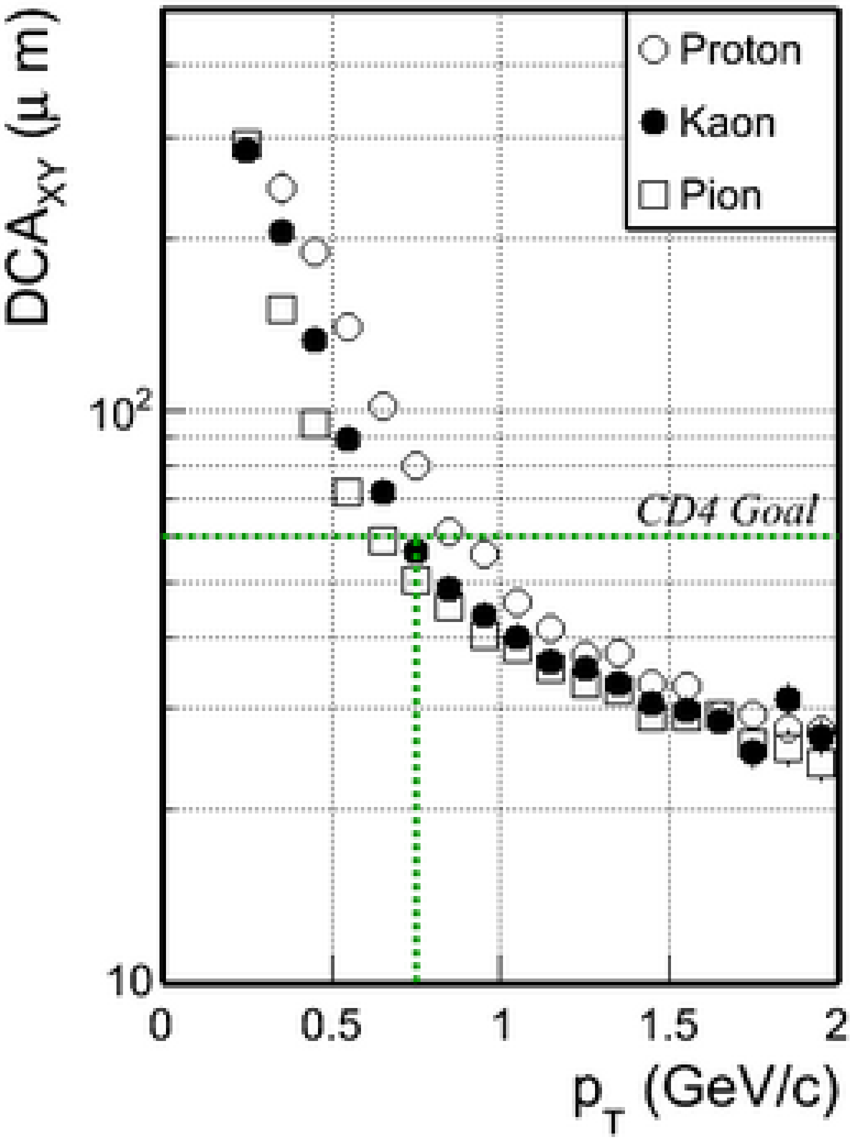
H.K. Wohri @ QWG2014



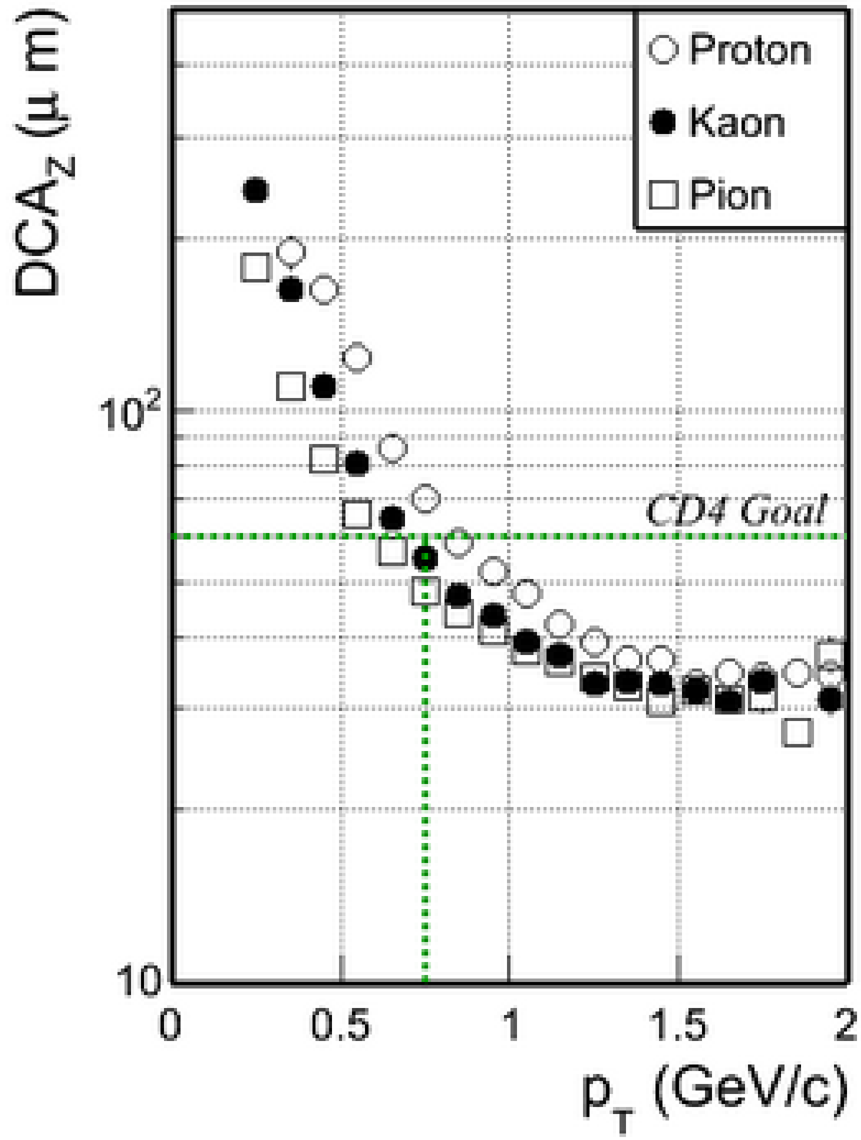


H.K. Wohri @ QWG2014

Au + Au @ 200 GeV



Proton
Kaon
Pion
CD4 Goal
DCA_{XY} (μ m)
10^2
10
0
0.5
1
1.5
2
p_T (GeV/c)



Proton
Kaon
Pion
CD4 Goal
DCA_Z (μ m)
10^2
10
0
0.5
1
1.5
2
p_T (GeV/c)