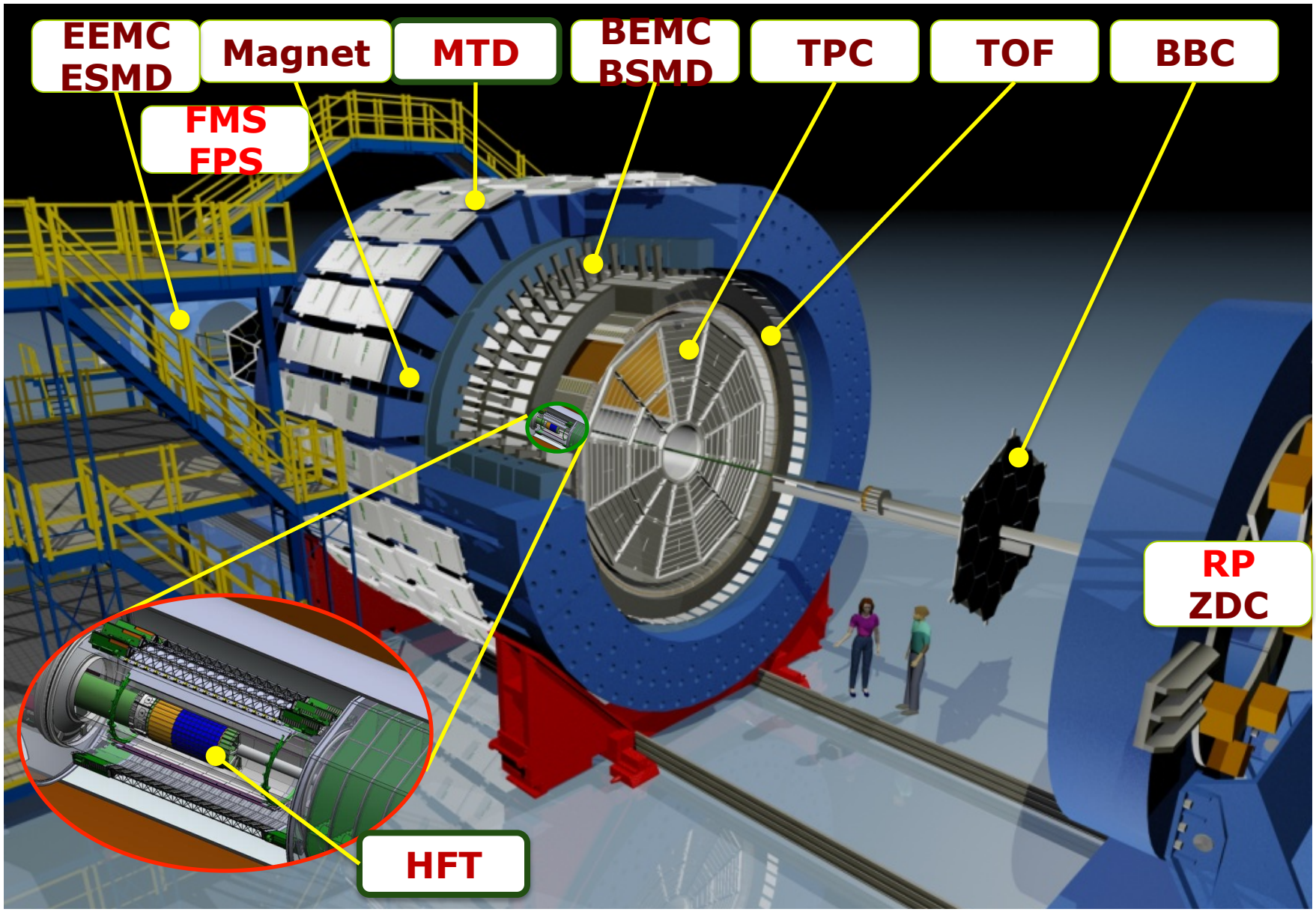
STAR Highlights

Lijuan Ruan for the STAR Collaboration
(*Brookhaven National Laboratory*)

Outline:

- **Cold QCD results**
- **Heavy ion results**
- **Future perspectives from STAR**
- **Conclusions**

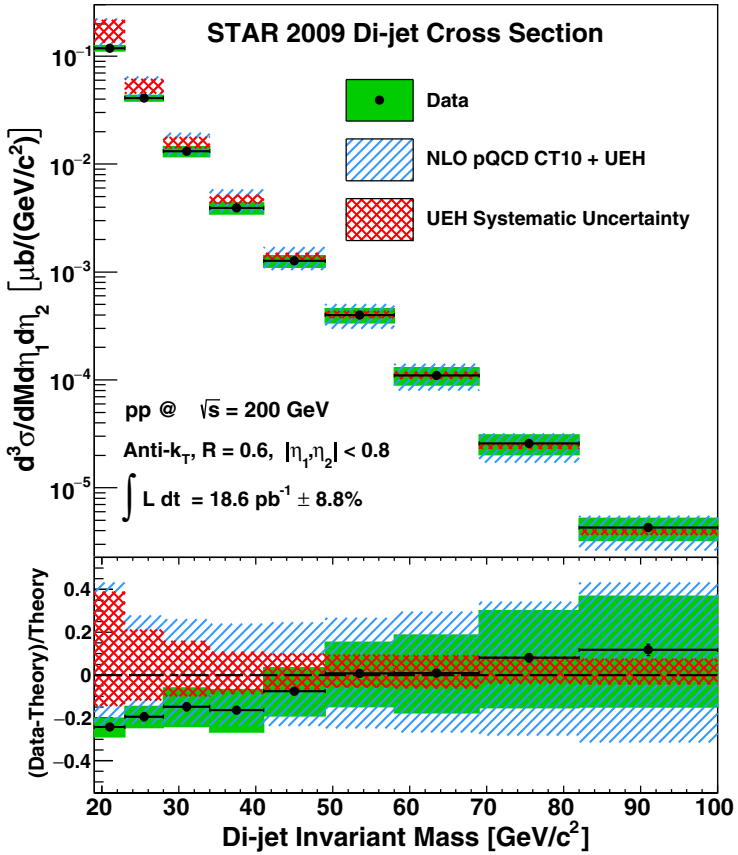
STAR detector

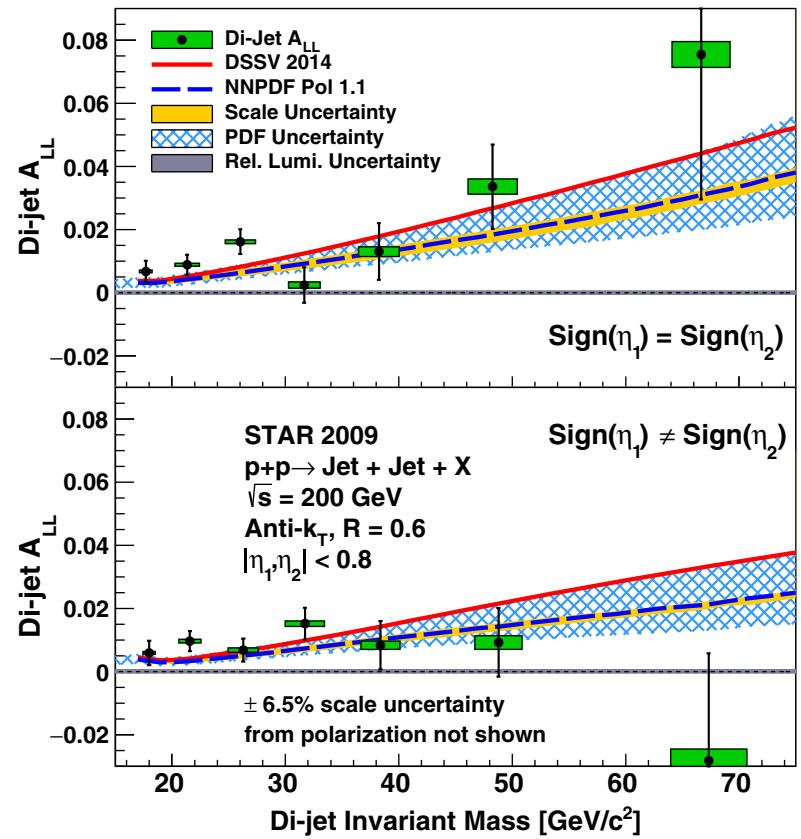


Mid-rapidity dijet A_{LL}

200 GeV p+p

Phys. Rev. D 95, 071103(R) (2017)



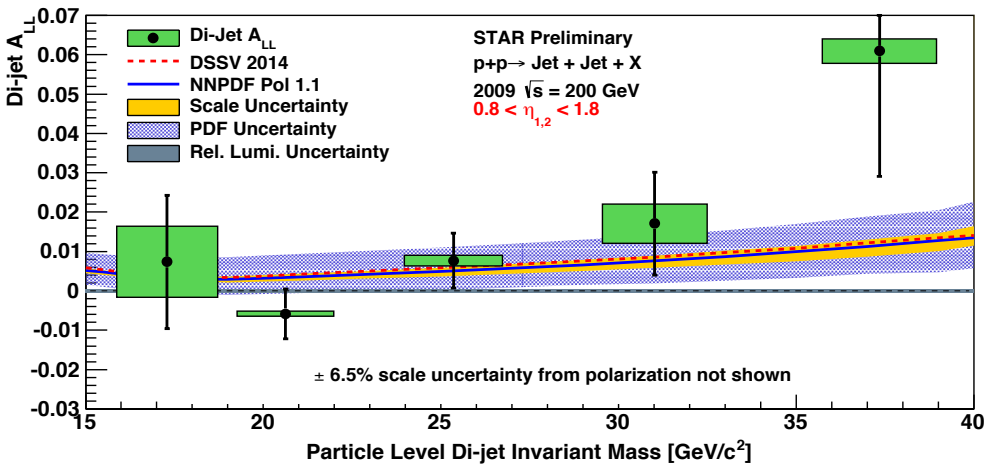


$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{a,b,c} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \cdot \hat{a}_{LL}^{f_a f_b \to f_c X} \otimes D_{f_c}^{h}}{\sum_{a,b,c} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \otimes D_{f_c}^{h}}$$

Gluon Polarization: integral of Δg(x) for 0.05<x<1 is $0.2^{+0.06}_{-0.07}$

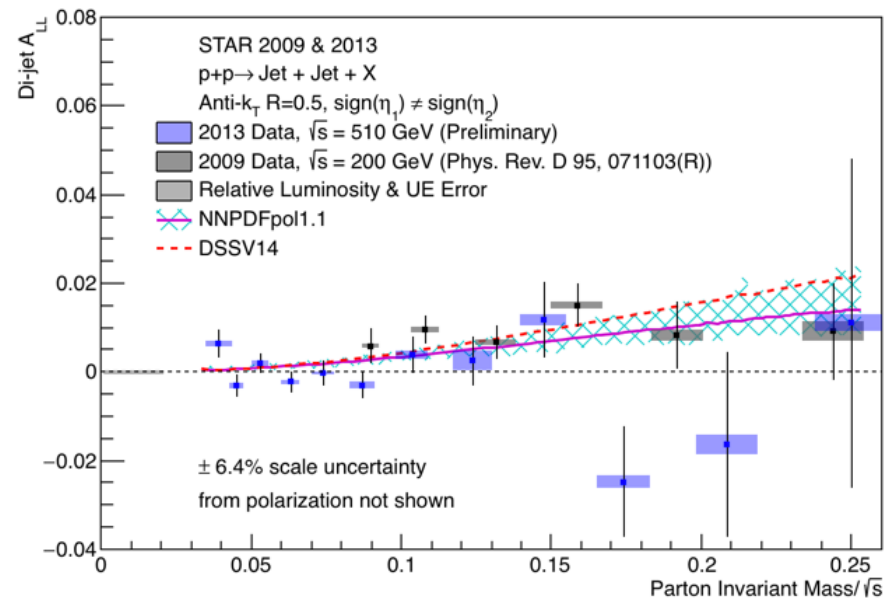
Extend to lower x

200 GeV, forward



First forward di-jet ALL results

510 GeV, mid-rapidity

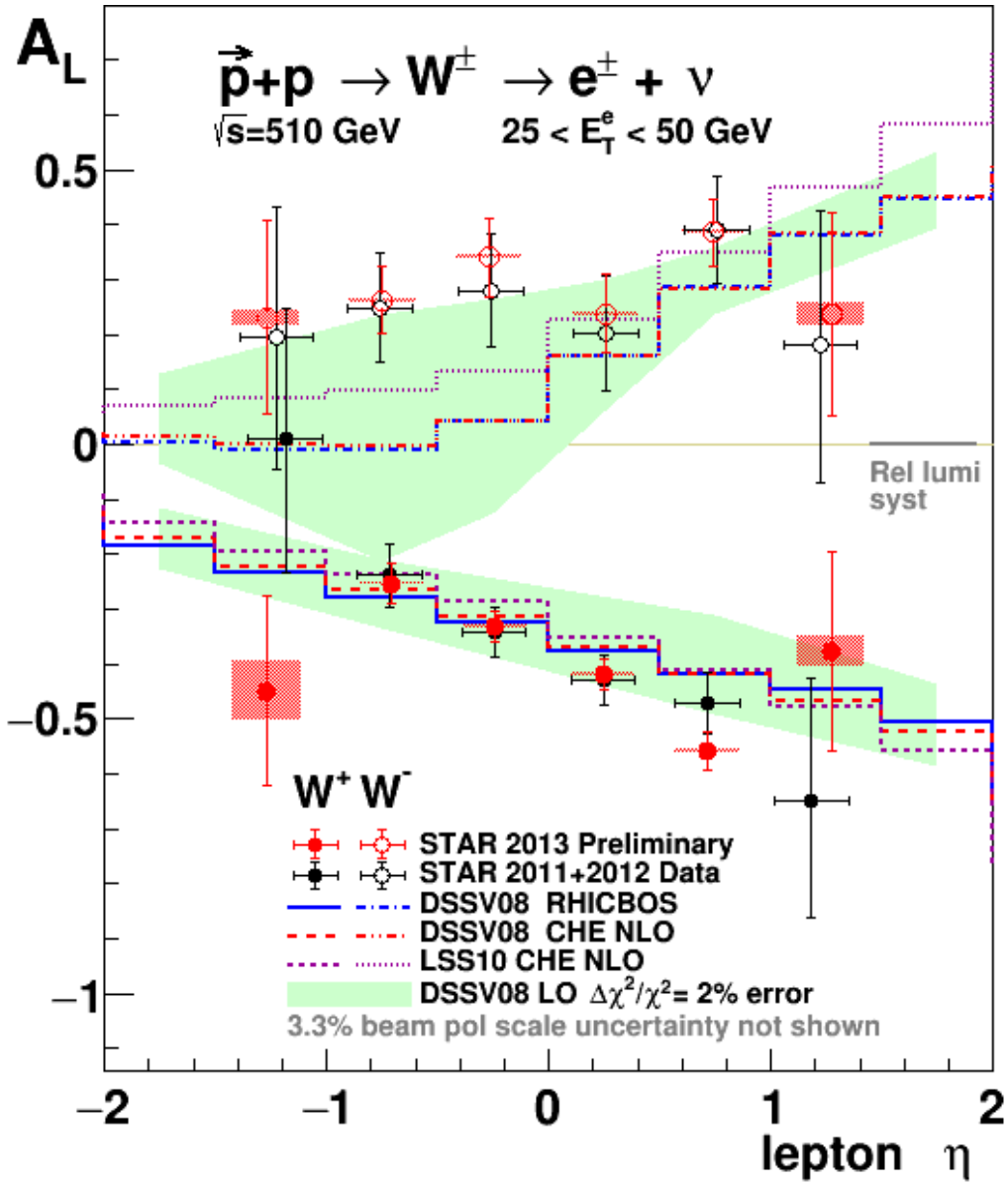


Extend to low x by going to forward rapidity, or higher energy:

Further constrain ΔG with improved statistical precision

New Run 12 results ready for final release, not shown here.
Run 13 preliminary on inclusive jet and dijet A_{LL}, see A. Quintero and D. Olvitt 's posters.

W A_L



$$A_L = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$$

Consistent with published 2011+2012 results, uncertainty reduced by 40%.

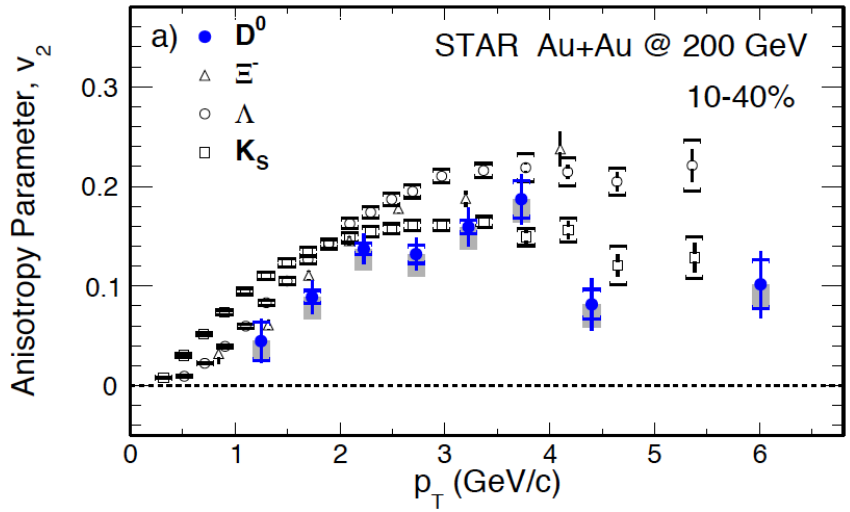
Further confirmed the preference of positive **Δubar**

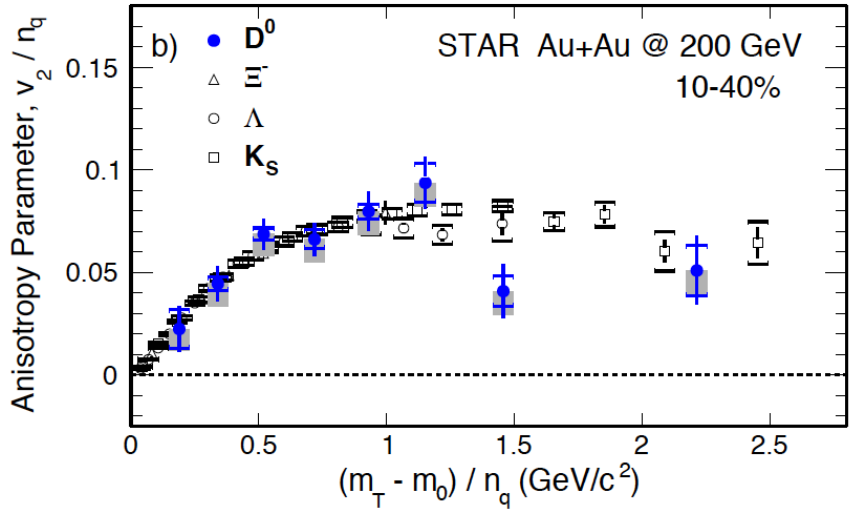
Can provide further constraints for **Δubar and Δdbar**.

See A. Kraishan and J. Zhang's posters.

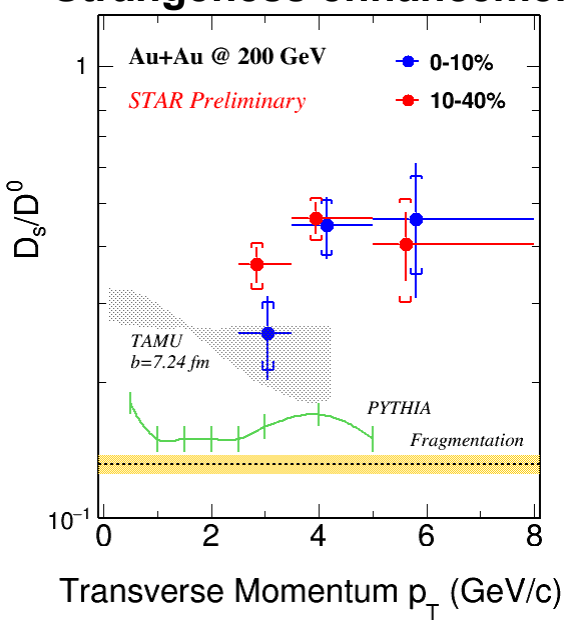
Open charmed hadrons with the HFT

Mass ordering **PRL118 (2017) 212301** **NCQ scaling**

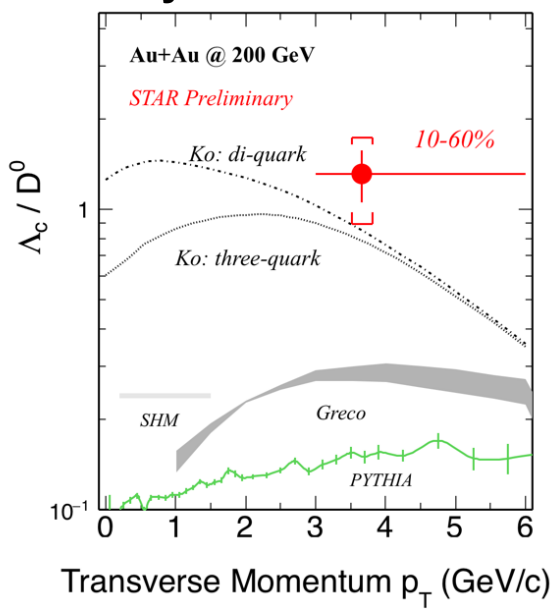




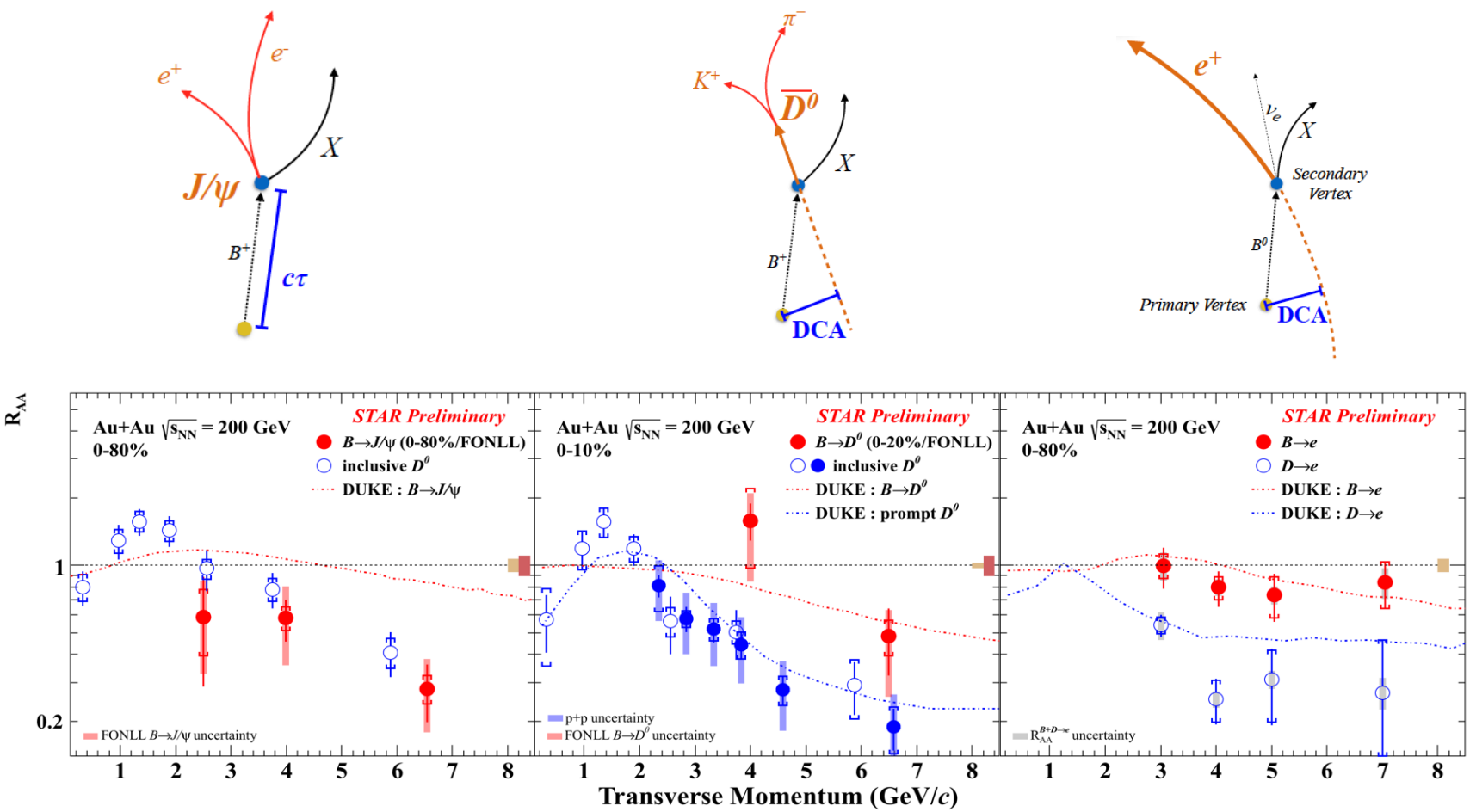
Strangeness enhancement



Baryon enhancement

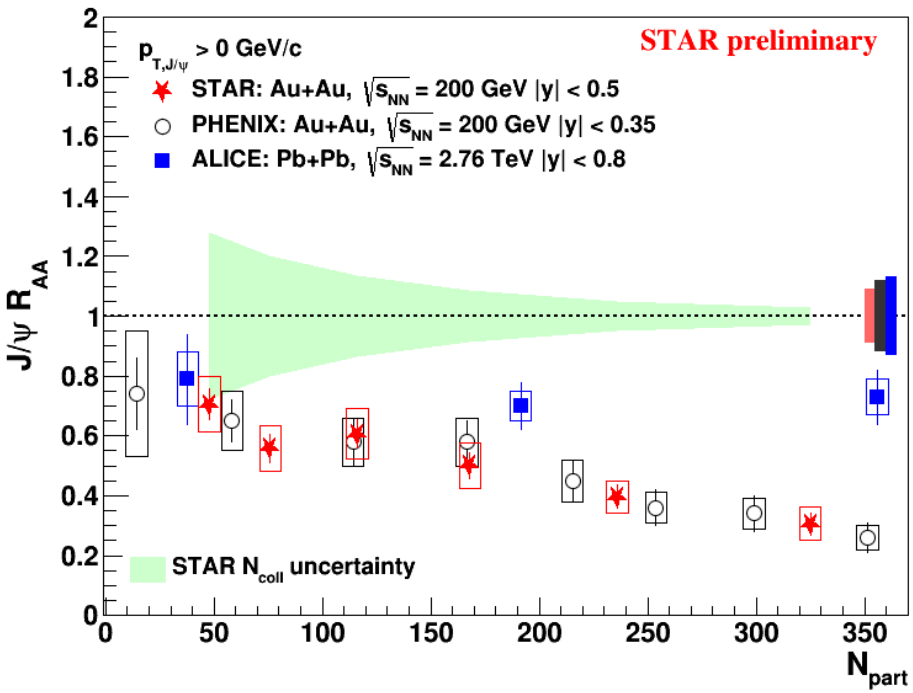


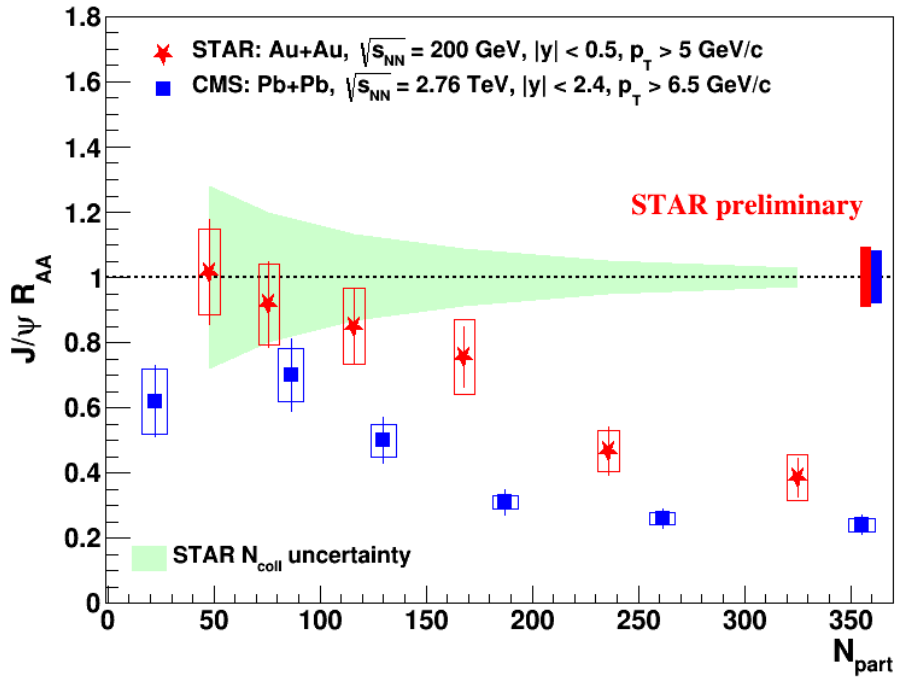
B production



B→e is less suppressed than D→ e (2 σ effect)

J/ψ suppression pattern with the MTD



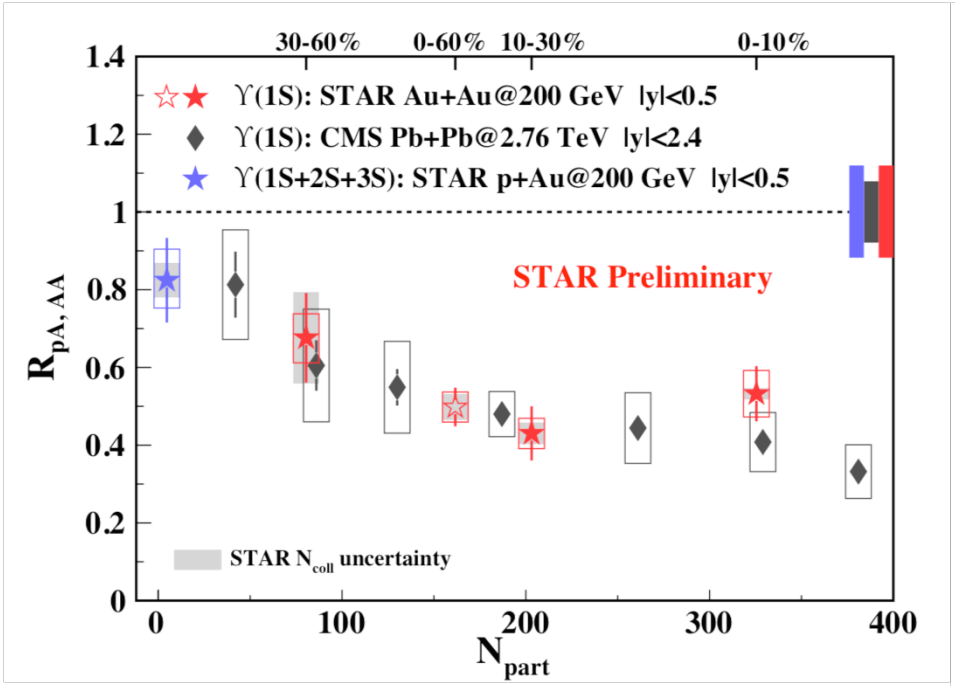


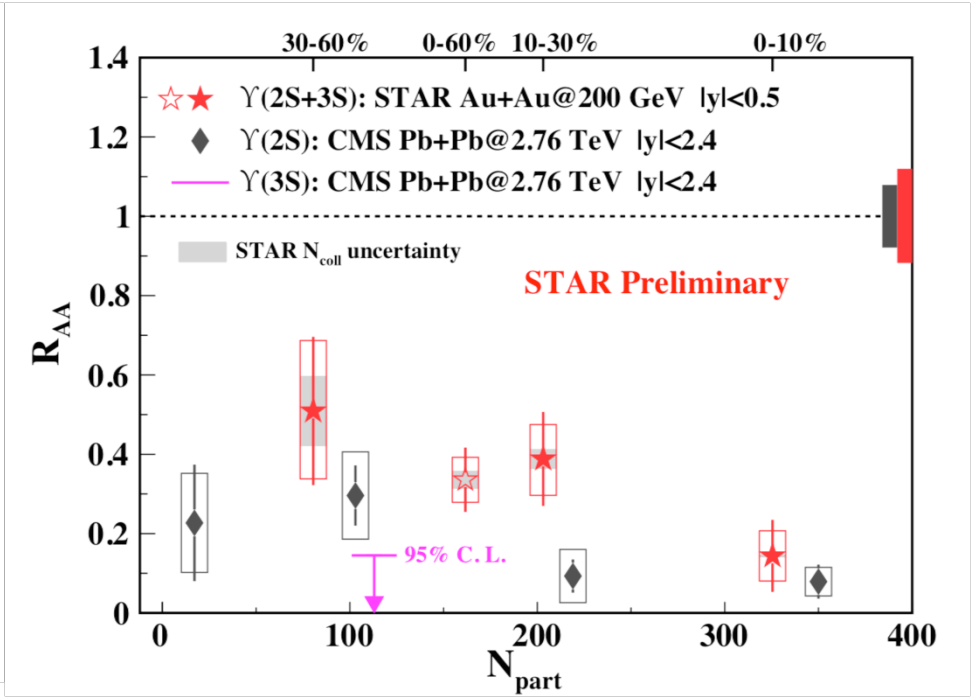
J/ψ through its dileptonic decay: indicator of deconfinement

consistent with more significant contribution from ccbar recombination at LHC energies

Interplay between color screening and recombination: describe the J/ψ suppression pattern and flow measurements

Different ϒ states suppression



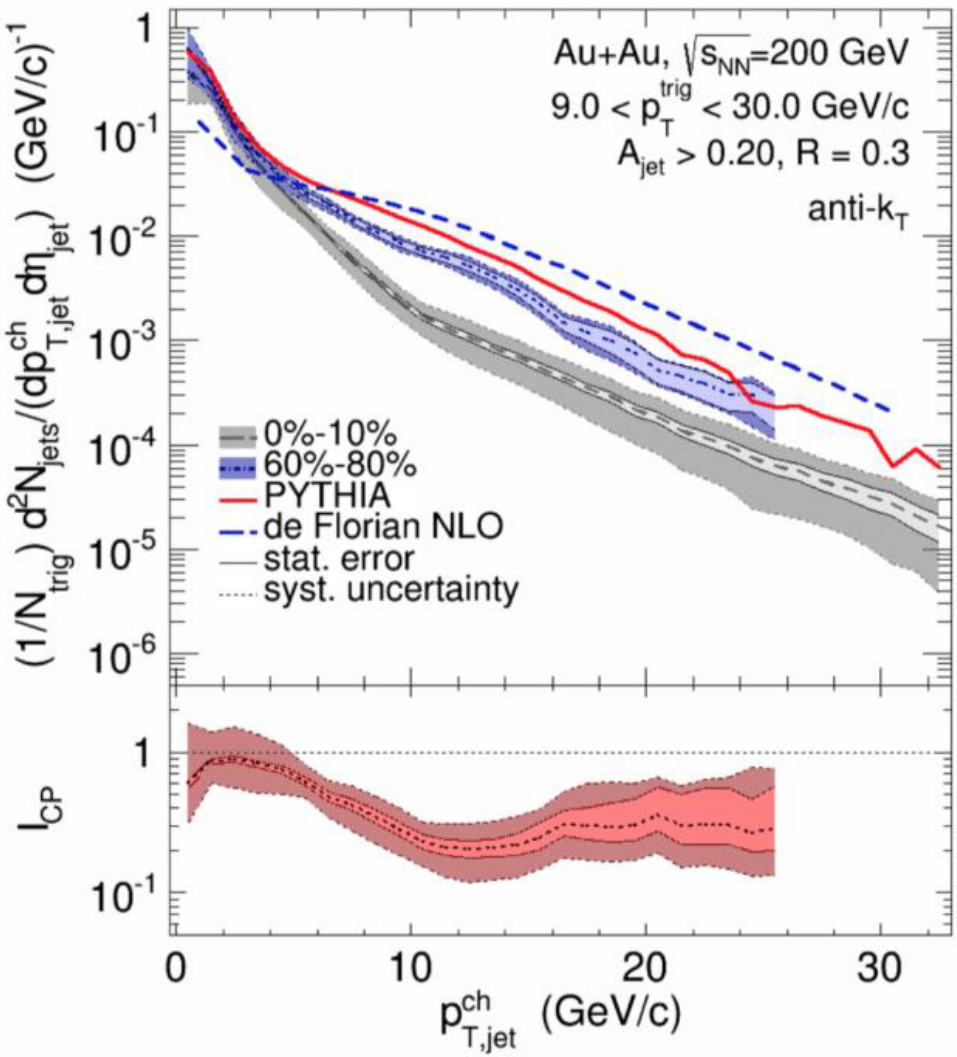


0.28, 0.56, 0.78 fm for ϒ(1S), ϒ(2S), ϒ(3S).
Negligible contribution from b and bbar recombination at RHIC
A better probe to study color-screening feature of QGP.

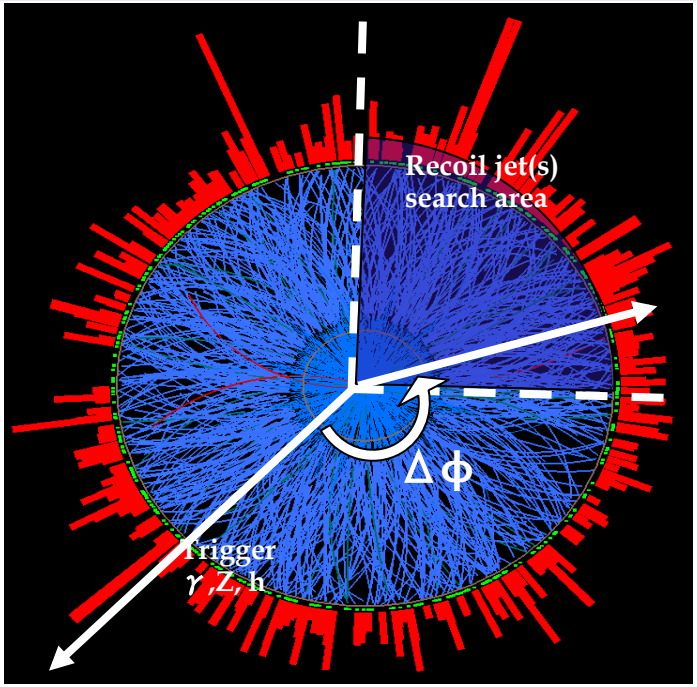
ϒ(1S): Similar magnitude of suppression at RHIC and LHC.

A hint of ϒ(2S+3S) less suppressed at RHIC than at LHC!

h-triggered recoiled jet



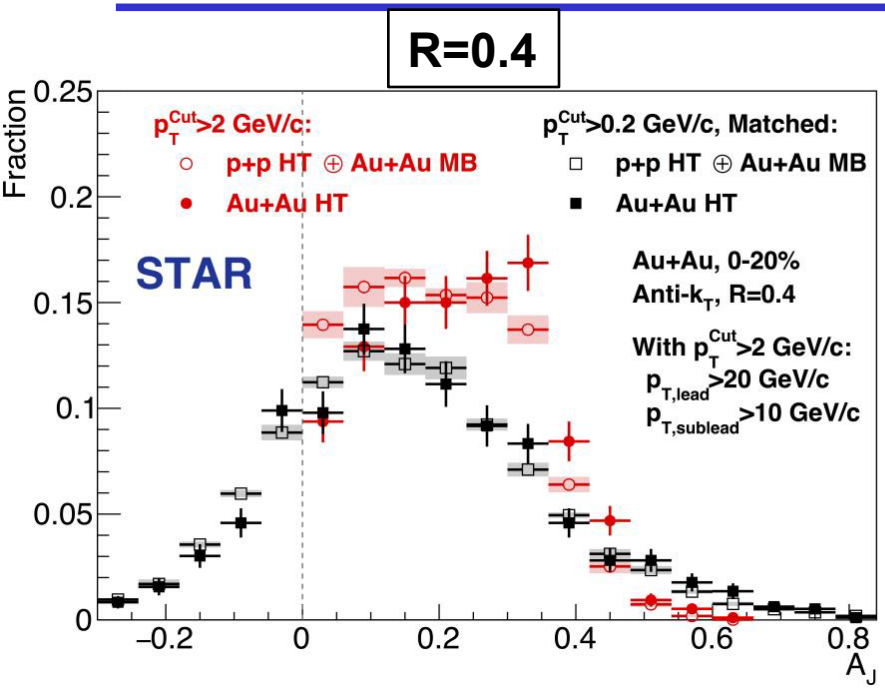
arXiv: 1702.01108, accepted by PRC

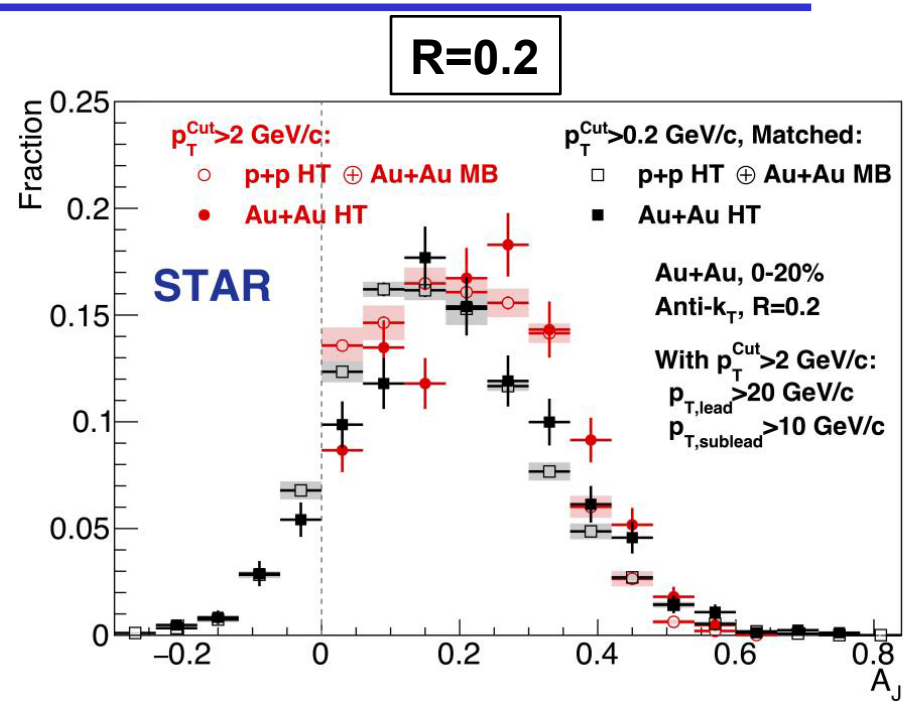


Removal the combinatorial background using mixed-event technique, allows to access low-p_T jets.

Hadron triggered recoiled jets:
I_{CP} shows strong suppression for R=0.3.

Dijet asymmetry A_J





$$A_J \equiv (p_{T,\mathrm{lead}} - p_{T,\mathrm{sublead}})/(p_{T,\mathrm{lead}} + p_{T,\mathrm{sublead}})$$

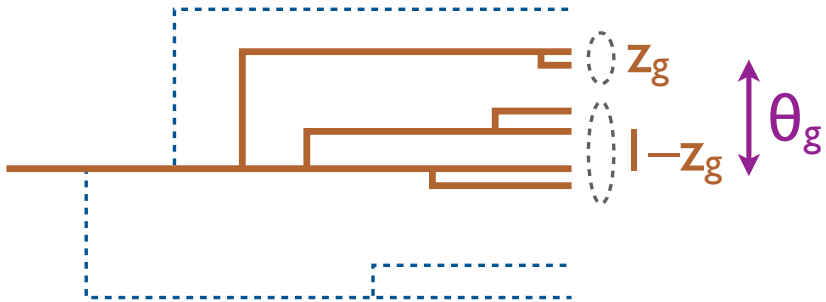
arXiv: 1609.03878, accepted by PRL, Editors' Suggestion

Dijet asymmetry:

- **Au+Au di-jet more imbalanced than p+p for "hard core" selection**
- **p+p balance recovered in matched di-jet for R=0.4 when soft particles included**
- **p+p balance not-recovered in matched di-jet for R=0.2 even when soft particles included**

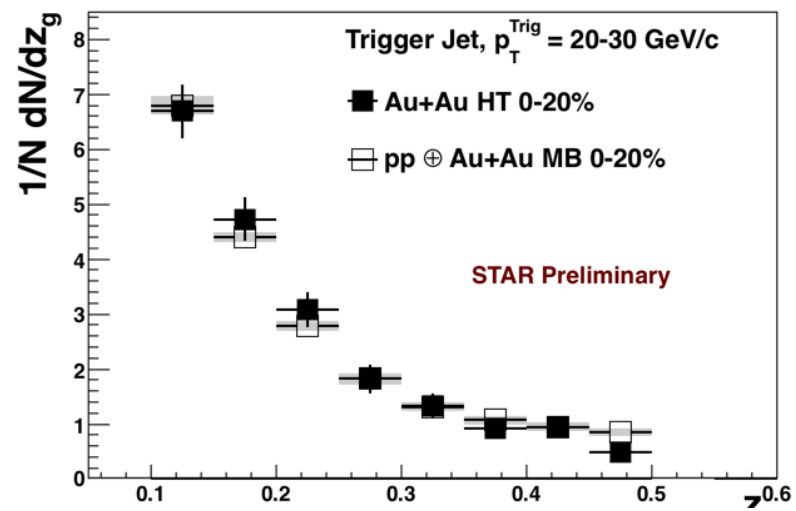
Energy shifted outwards, but remains inside R=0.4.

Shared momentum fraction



Based on declustering an angular-ordered tree

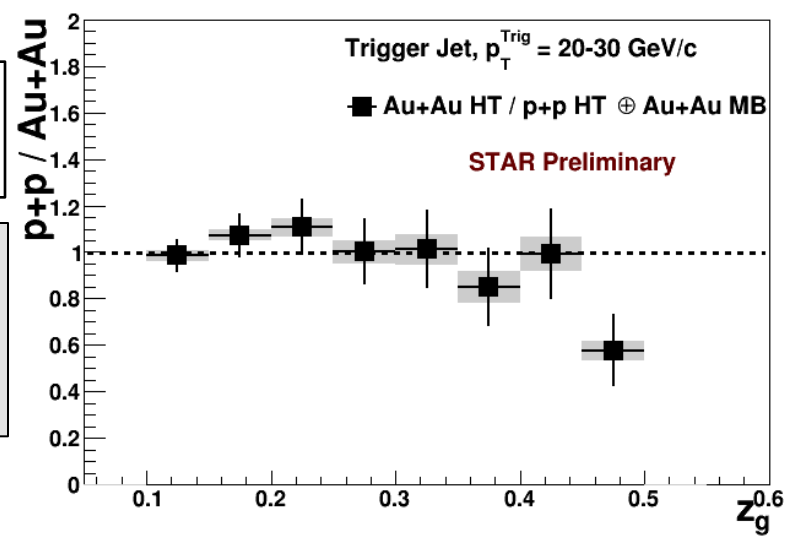
$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$



Di-jet Selection:

- **Jet p_T^{Trig} > 20 GeV/c**
- **Jet p_T^{Recoil} > 10 GeV/*c***
- **$|\Delta\Phi - \pi| < 0.4$**

$p_T^{Trig,Recoil}$: Calculated with p_T,cut > 2 GeV/c
***z_g*: on matched jets with p_T,cut > 0.2 GeV/c**

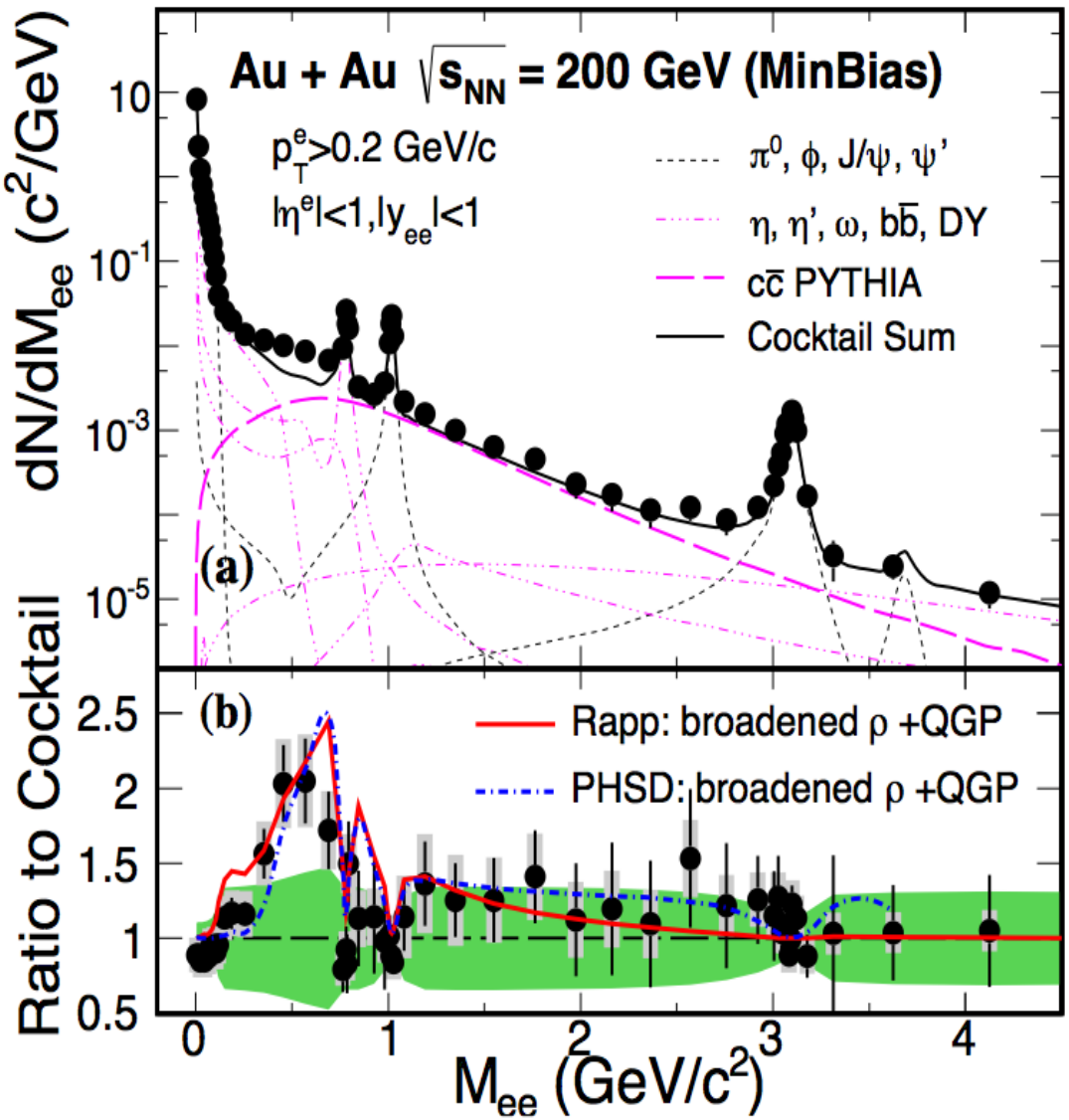


<u>Hard core di-jets:</u>

- ***z_g*: no significant splitting modification on near- or away-side**

Electron positron emission mass spectrum in 200 GeV Au+Au

Phys. Rev. Lett. 113 (2014) 22301

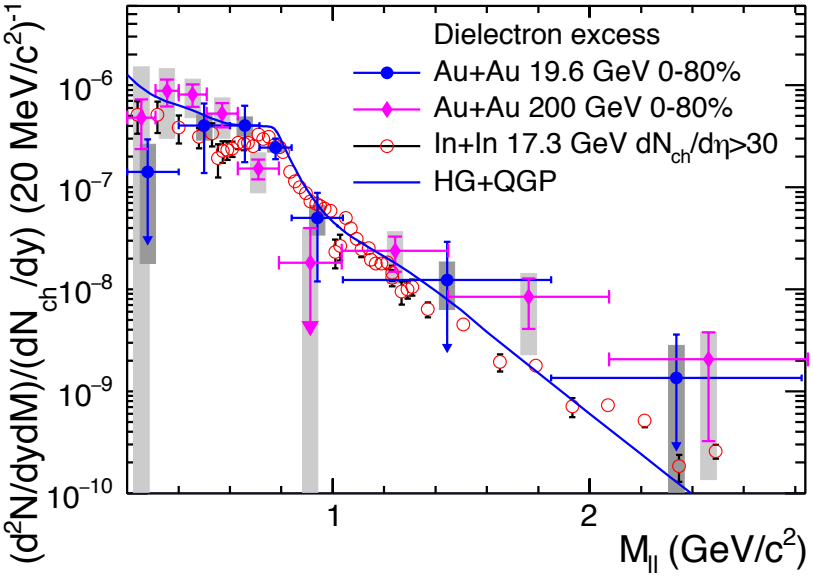


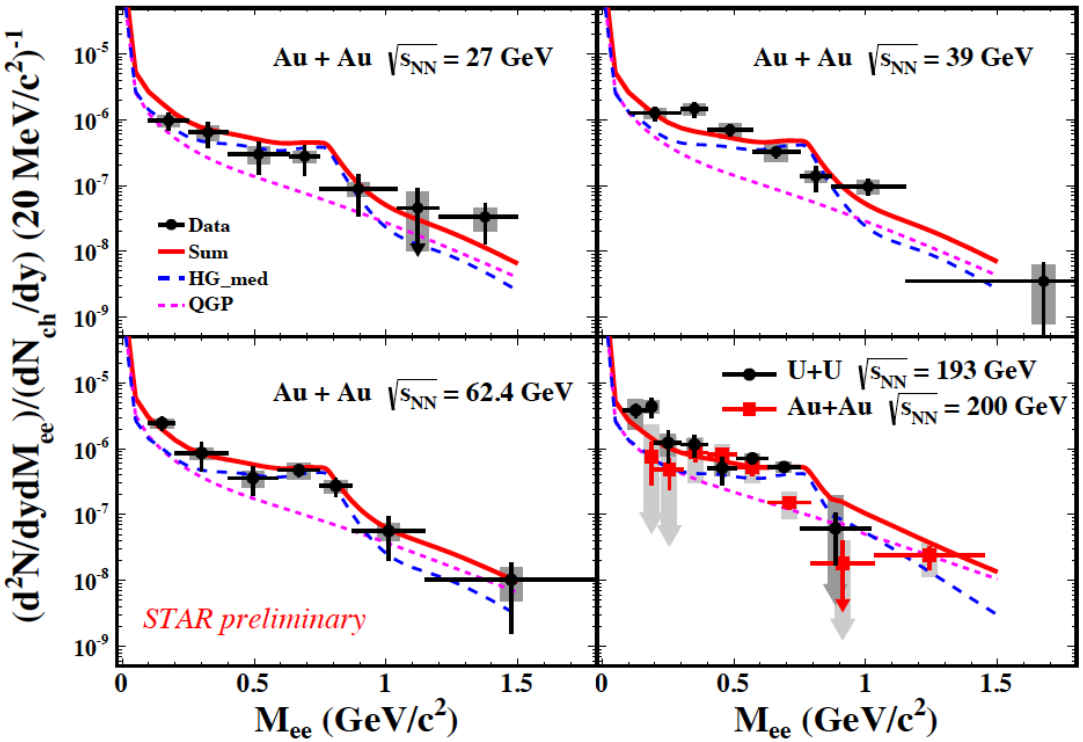
Significant excess is observed for $0.3<M_{ee}<0.8$ GeV/c^2, representing the hot, dense medium contribution.

The electron-positron excess spectrum

PLB750(2015)64

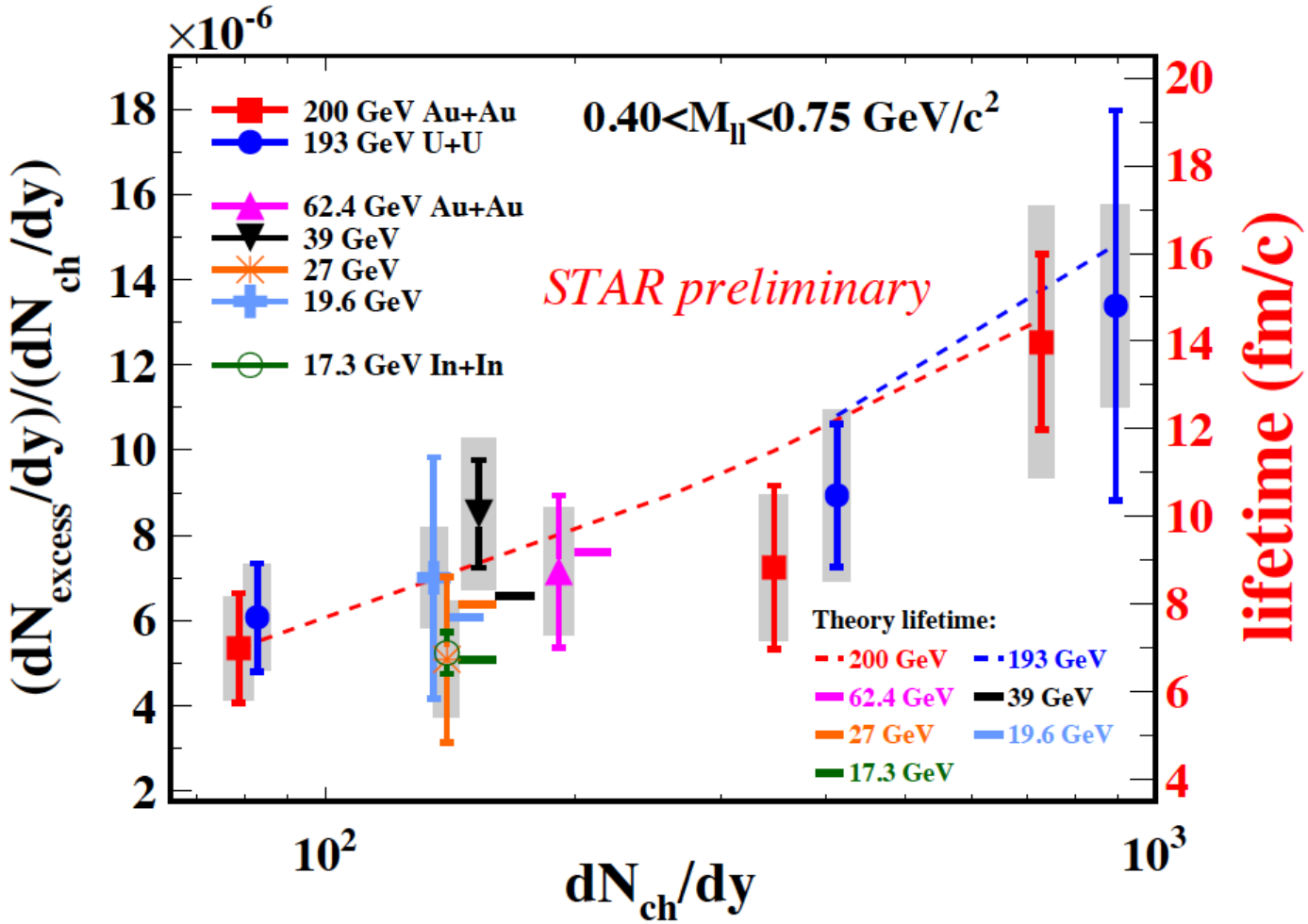
PRL113 (2014) 22301





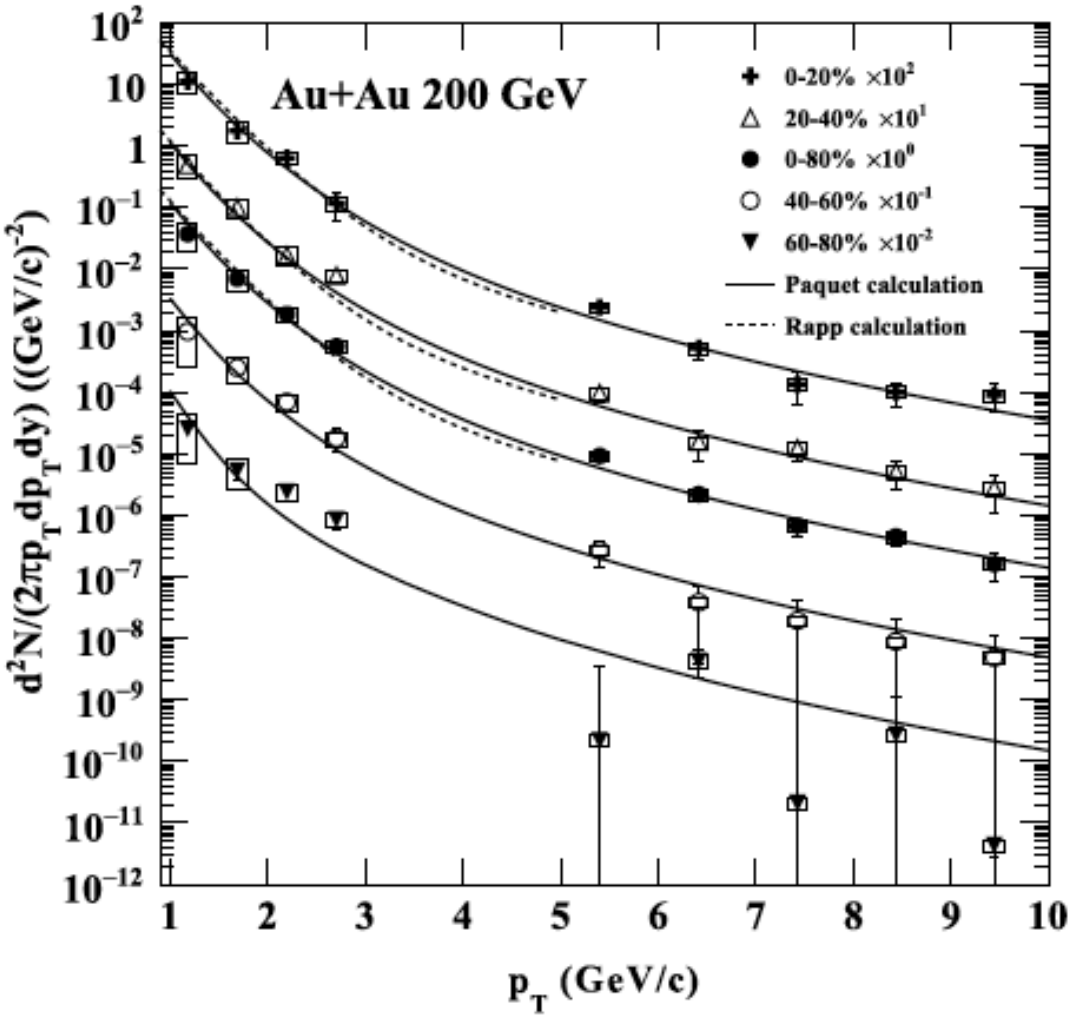
A broadened ρ spectral function consistently describes the low mass electron-positron excess for all the energies 19.6-200 GeV.

The low mass measurements



Low-mass electron-positron production, normalized by dN_{ch}/dy, is proportional to the life time of the medium from 17.3 to 200 GeV.

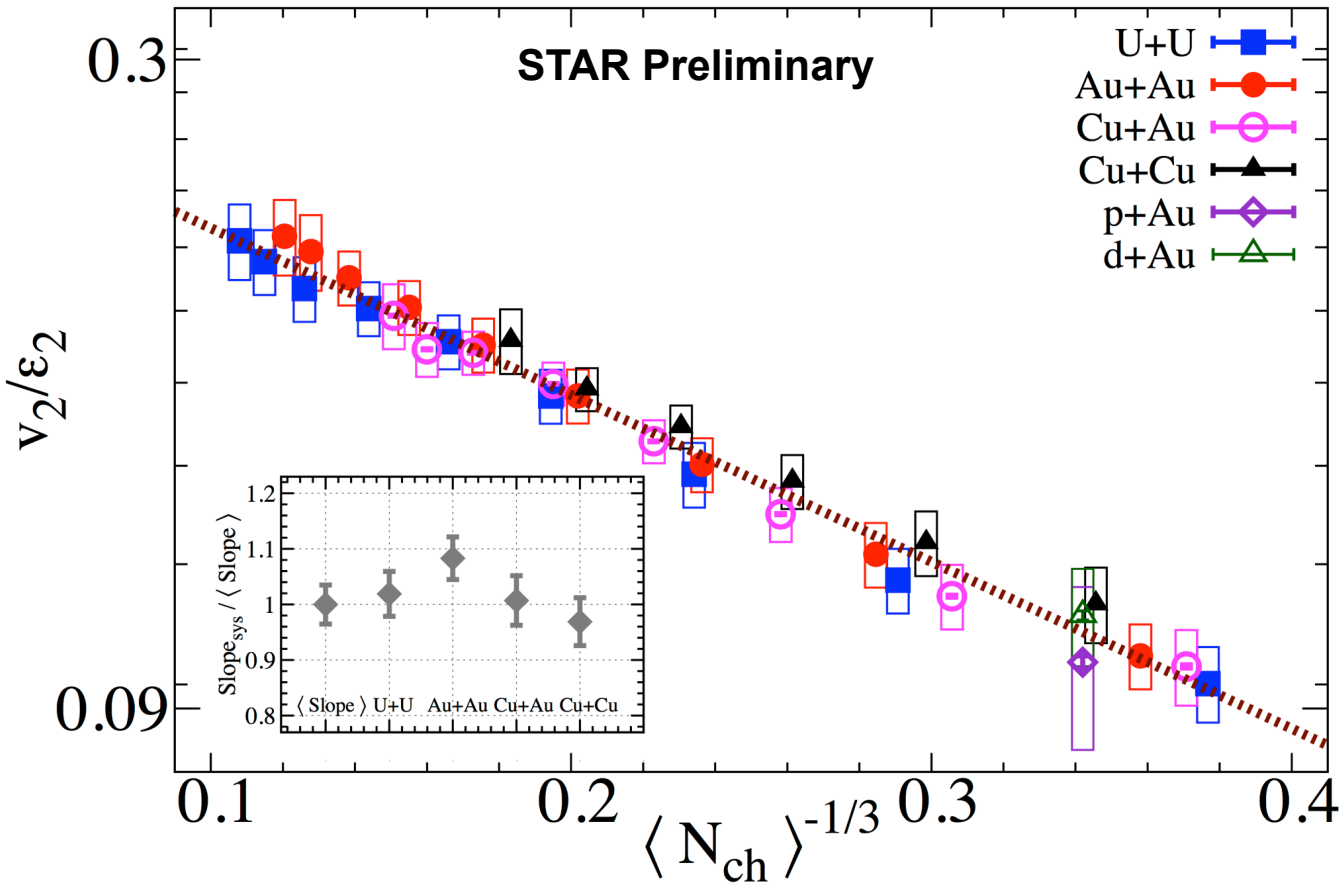
Direct virtual photon



PLB770(2017)451

Models describing the low-mass e^+e^- pairs agree with our photon data.

Small system v_2



$\ln(v_2/\epsilon_2)$ scales with $N_{ch}^{-1/3}$ for all systems

See N. Magdy's talk

Results from BES I

QGP turn off signatures

- jet quenching feature is gone for N_{bin} scaled particle yields as a function of N_{part} at $\sqrt{s_{NN}} < 14.5$ GeV.
- ϕ meson $v_2 \sim 0$ at $\sqrt{s_{NN}}$=11.5 and 7.7 GeV with large uncertainties.
- Higher harmonics $v_3 \sim 0$ at $N_{part} < 50$ at 7.7 GeV.

First order phase transition

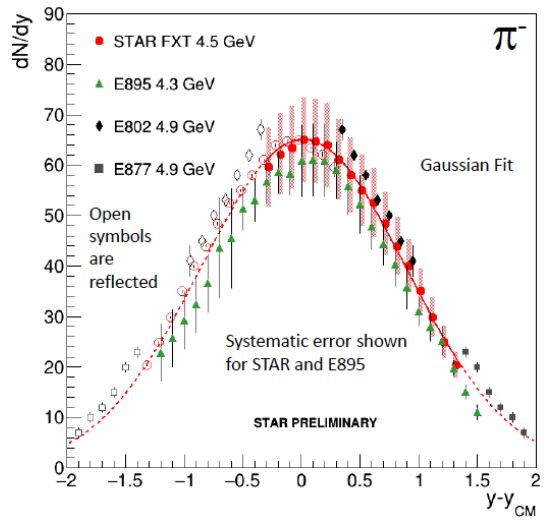
- When scaled by entropy density, v_3 shows a minimum near 15 GeV consistent with an increased bulk viscosity and decreased effective pressure.
- Non-monotonic behavior seen in net-proton v_1 slope as a function of $\sqrt{s_{NN}}$.
- Particle $\langle m_T \rangle - m_0$ and transverse energy per particle show a flat pattern At $\sqrt{s_{NN}} >$ 8 GeV and increases again.

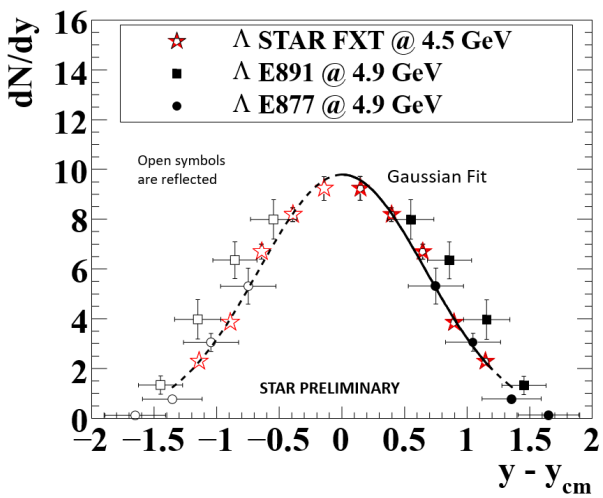
Critical point:

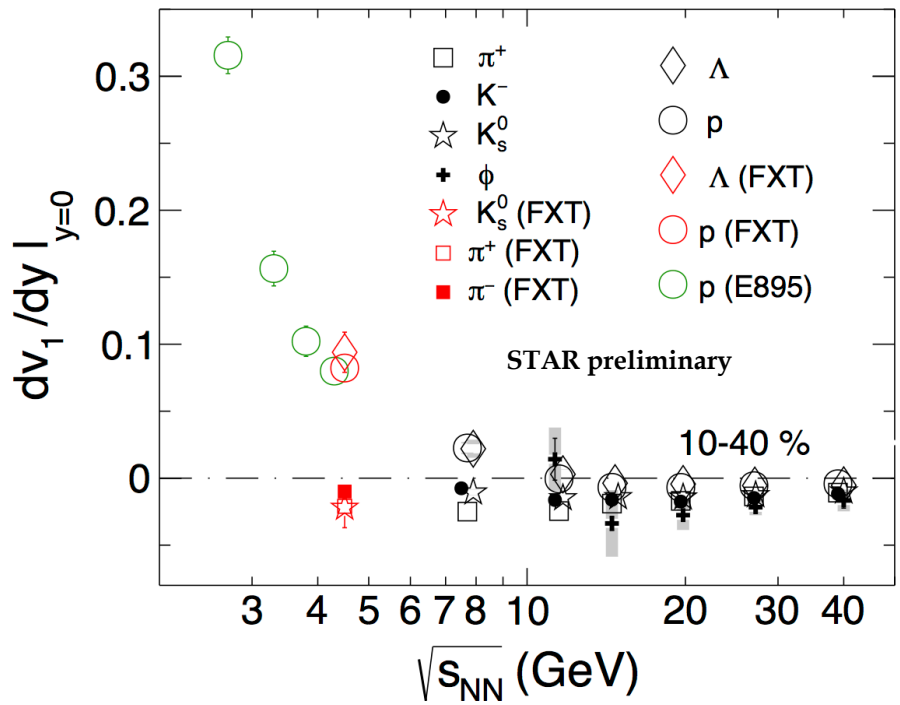
- Non-monotonic trend is seen in moments of net proton distributions in central Au+Au as a function of collision energy
- Non-monotonic trend is seen in the HBT radii as a function of collision energy

See Terry Tarnowsky's talk in detail

Spectra and flow from fixed target



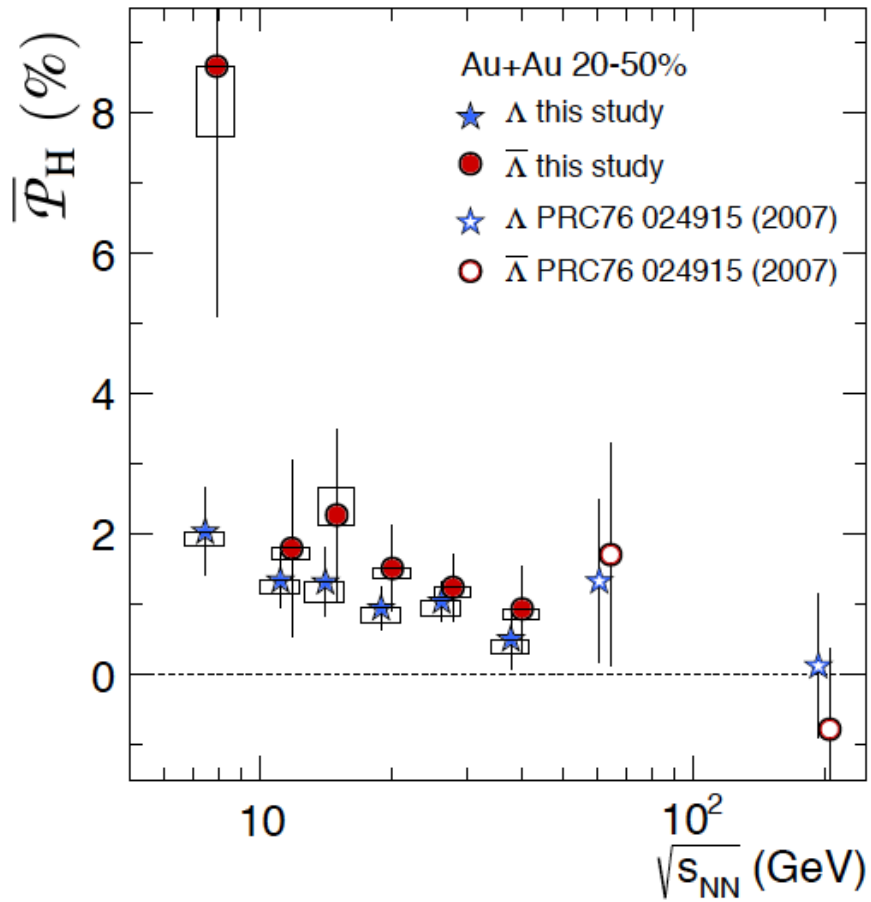


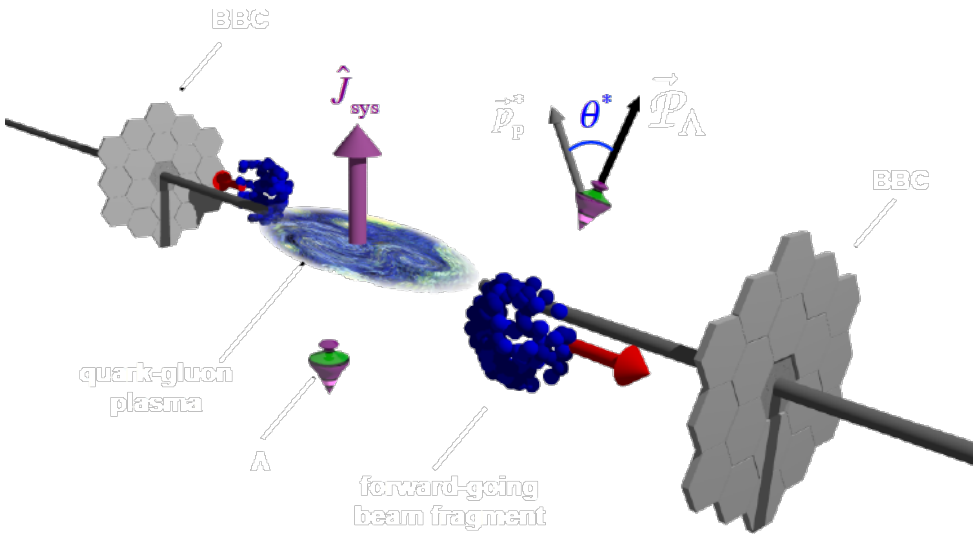


Dedicated fixed-target run in 2015: √sNN = 4.5 GeV

- 1 M events in 30 minutes!
- Excellent PID using dE/dx and ToF
- dN/dy and v_1 for charged particles and V0s are in good agreement with published results

Lambda global polarization



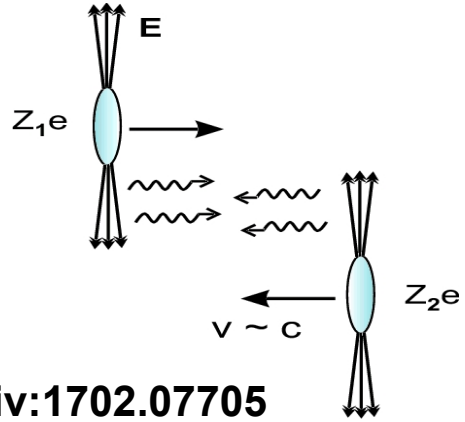


arXiv: 1701.06657
Accepted by Nature, still under embargo.

Lambda and anti-Lambda polarized.

Most vortical system!

ρ and J/ψ in ultra-peripheral A+A collisions



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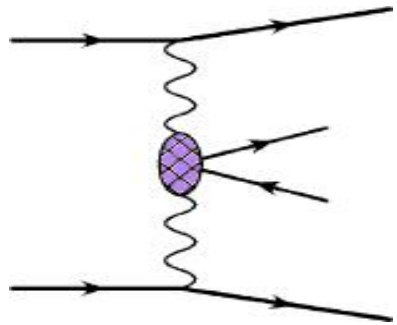

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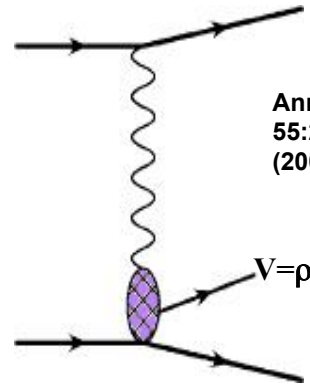
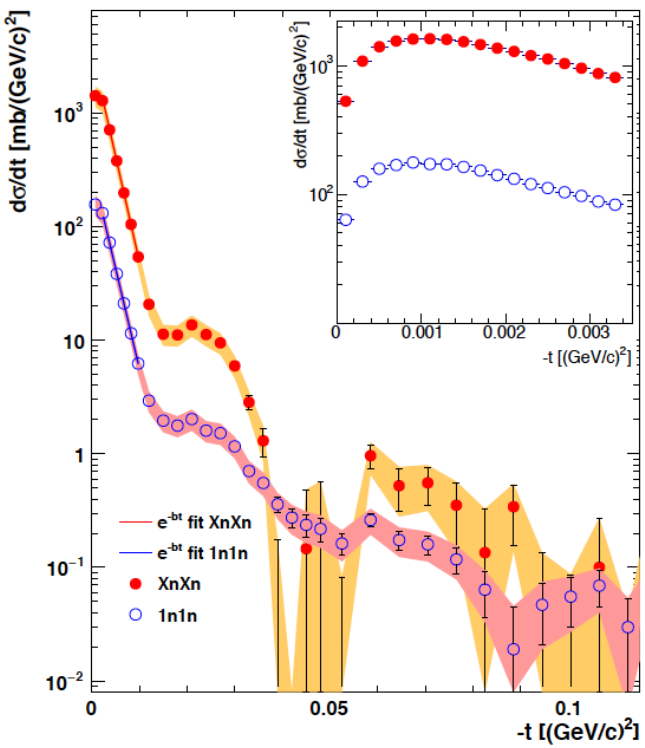


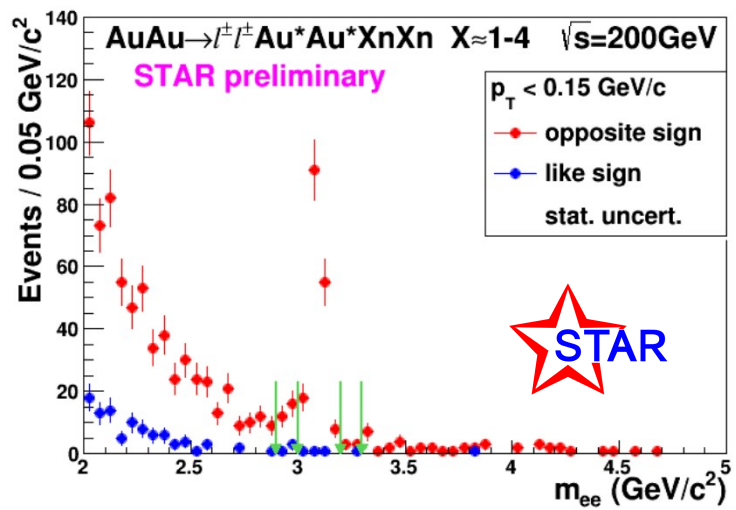
Ann. Rev. Nucl. Part. Sci.
55:271
(2005)

Two-photon

photonuclear

arXiv:1702.07705

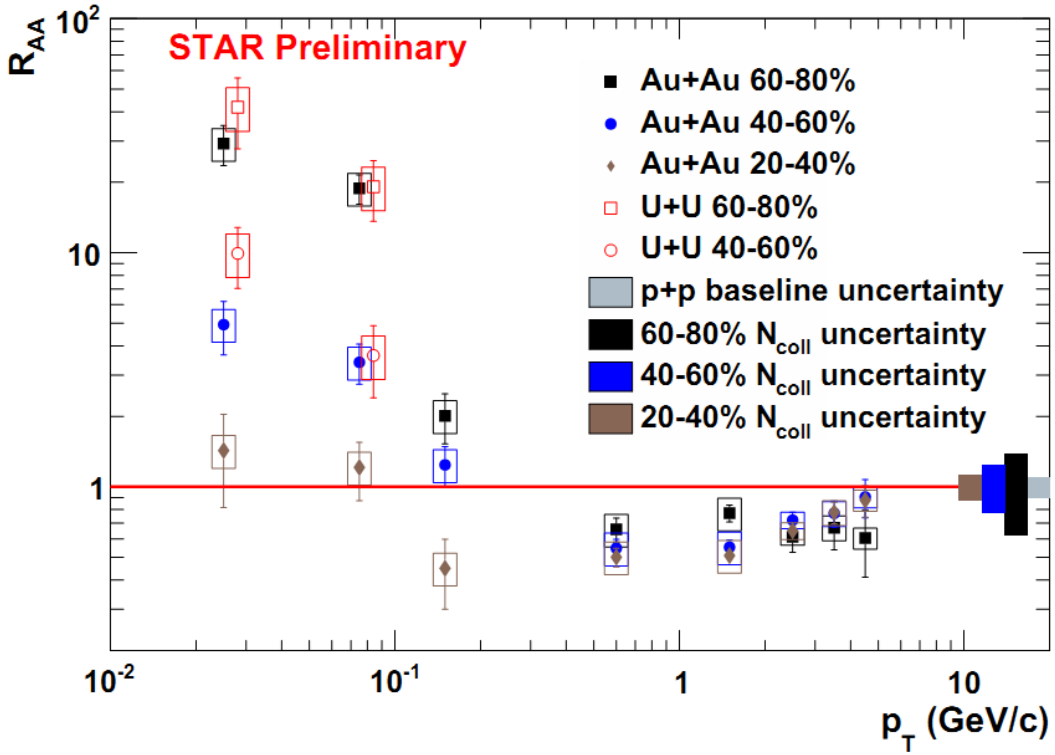




J/ψ signal

ρ: characteristic diffractive dips observed

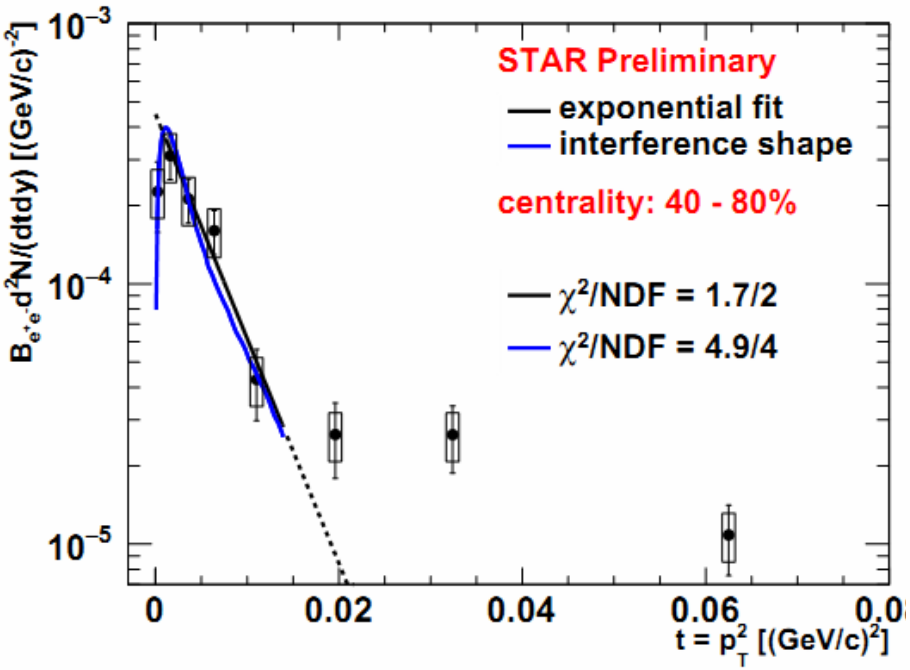
Very low p_T J/ψ in heavy ion collisions

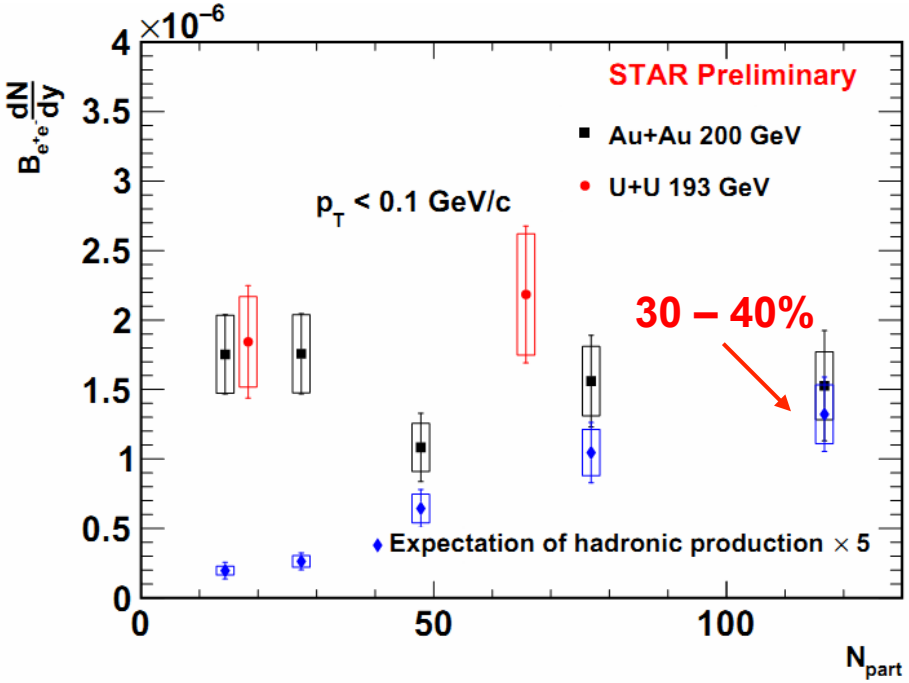


Large enhancement of J/ψ yield observed in peripheral A+A collisions!

Prominent centrality and p_T dependence.

J/ψ yield :$t=p_T^2$ and centrality dependence



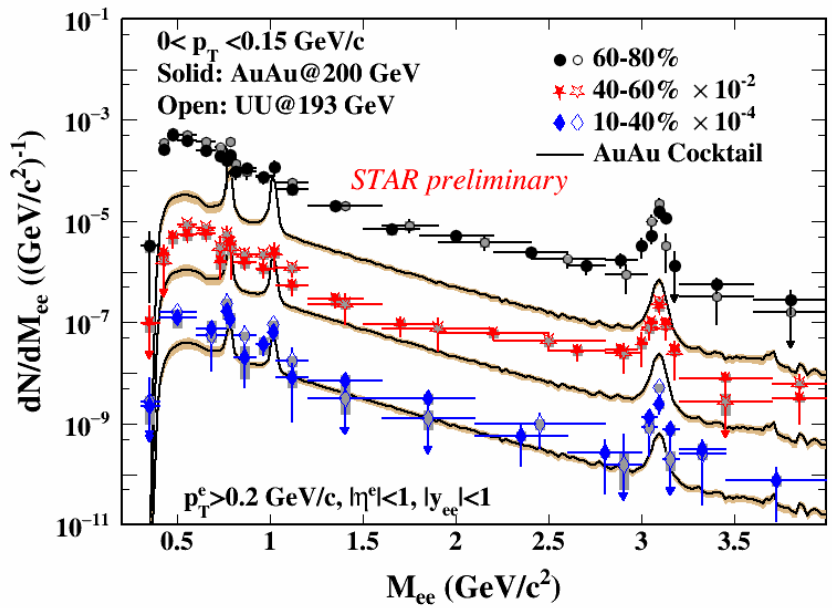


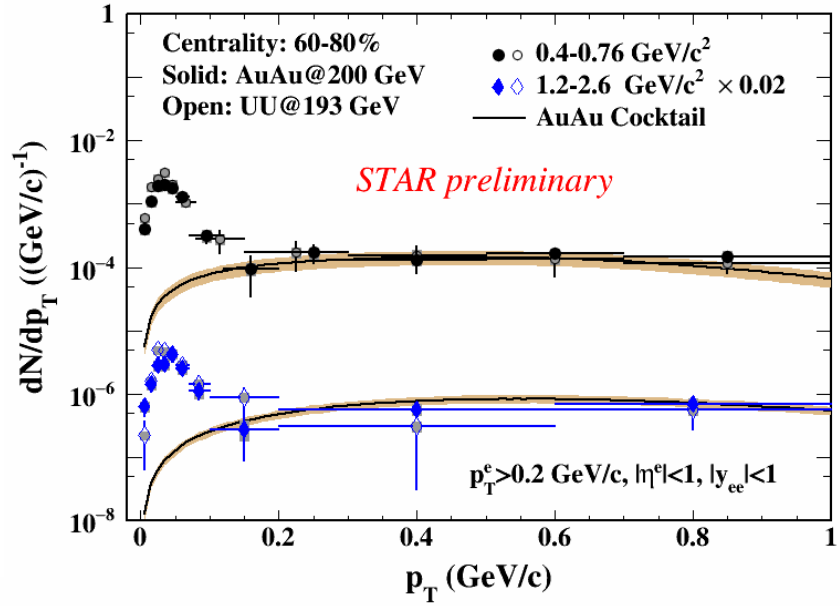
Slope parameter consistent with the size of the Au nucleus. Interference structure observed. Coherent photon-nucleus interactions!

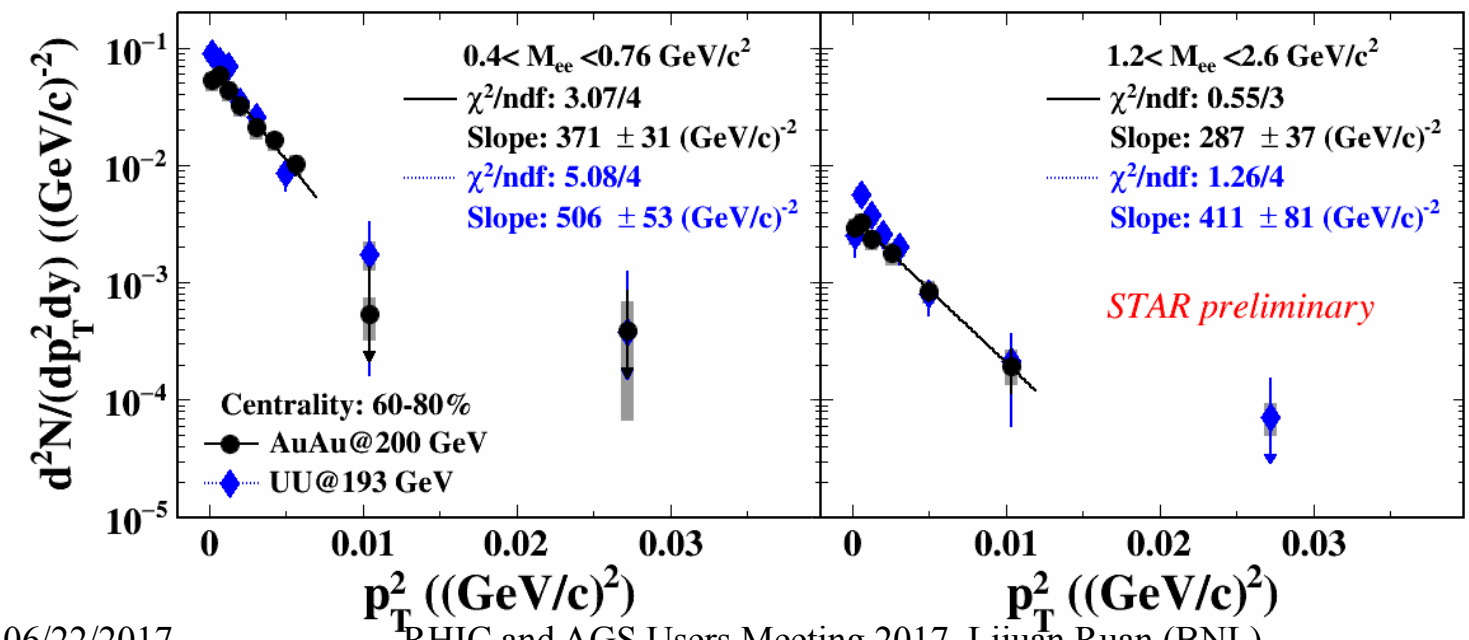
No significant centrality dependence of the excess yield!

W. Zha et al., arXiv: 1705.01460

Very low p_T electron-positron excess





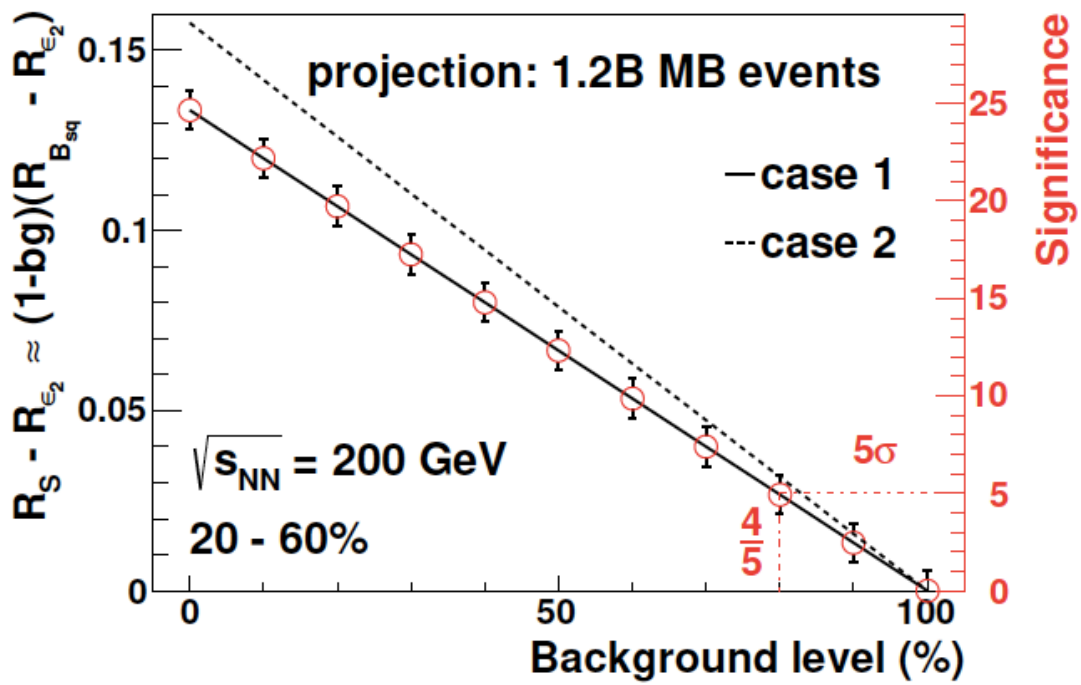


Towards isobar collisions in 2018

Decisive test of role of magnetic field in charge separation measurements

1.2 billion MB events in each species:
$^{96}_{40}Zr+^{96}_{40}Zr$, $^{96}_{44}Ru+^{96}_{44}Ru$

5 sigma significance if 80% observed correlation is background



Further study the photo-nuclear and photon-photon processes in J/ψ and e^+e^- measurements→ constrain the initial EM field in heavy ion collisions

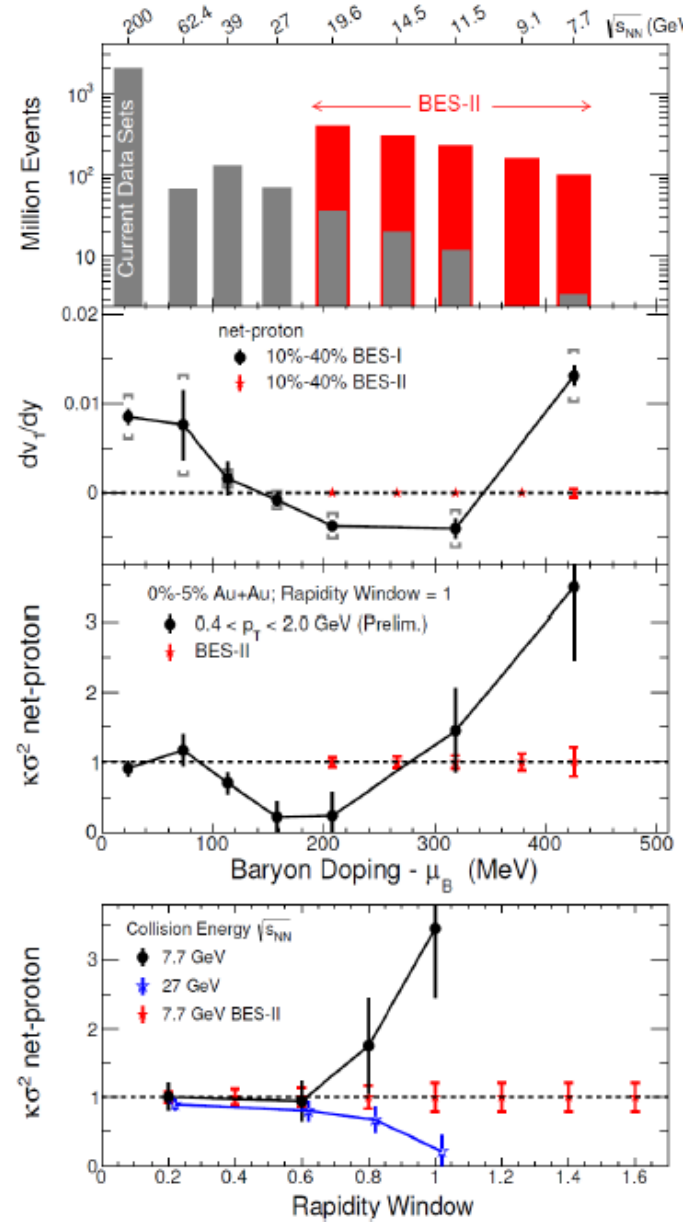
Towards BESII in 2019 and 2020

Many interesting features have been observed for the signatures of

- QGP turn off
- First-order phase transition
- Critical point

Turn the qualitative features to quantitative understandings.

- exciting results from the future BESII program including FXT program
- BEST Theory Collaboration



Beyond 2020+

Mid-rapidity: e^+e^- measurement at μ_B~0

Connection to chiral symmetry restoration

Thermal radiation from QGP

Forward rapidity upgrade: v_n, r_n

Longitudinal structure of initial condition;

η/s vs. temperature

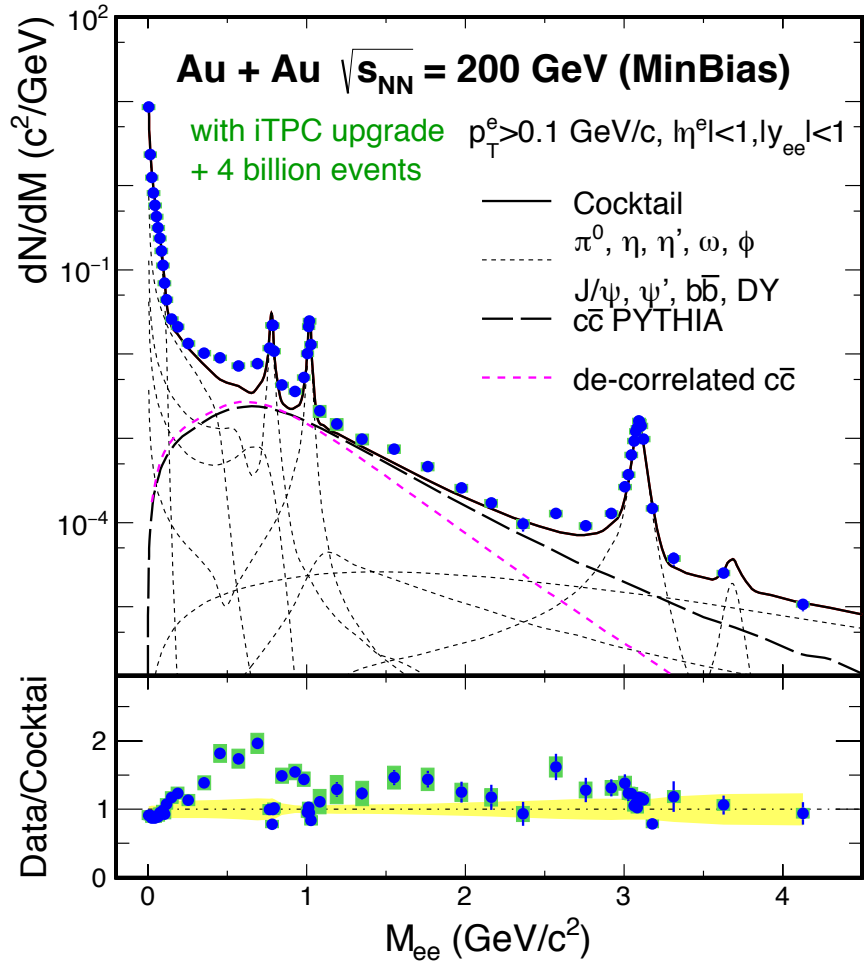
Cold QCD in pp, pA: A_N for charged hardons and jets, A_{LL} for dijet and jets, A_{UT} for Collins observables, R_{pAu} for direct photos and Drell-Yan, …

Subprocess driving the large A_N at high x_F & η

$\Delta g(x)$ at small x

TMDs at low and high x

The nature of initial state and hadronization in nuclear collisions



Summary

Many exciting results from cold QCD program and heavy ion collisions

- W A_L and dijet A_{LL} → sea quark and gluon polarization
- HF, quarkonium →heavy quark dynamics, QQbar potential in the medium
- Jets → jet quenching
- e+e- and photon: thermal radiation, in-medium modification of vector mesons
- Lambda(anti-Lambda) polarization: spin-orbit coupling, vorticity
- Interesting results on small system v_2 …
- UPC and low-p_T J/ψ and e^+e^- in heavy ion collisions …

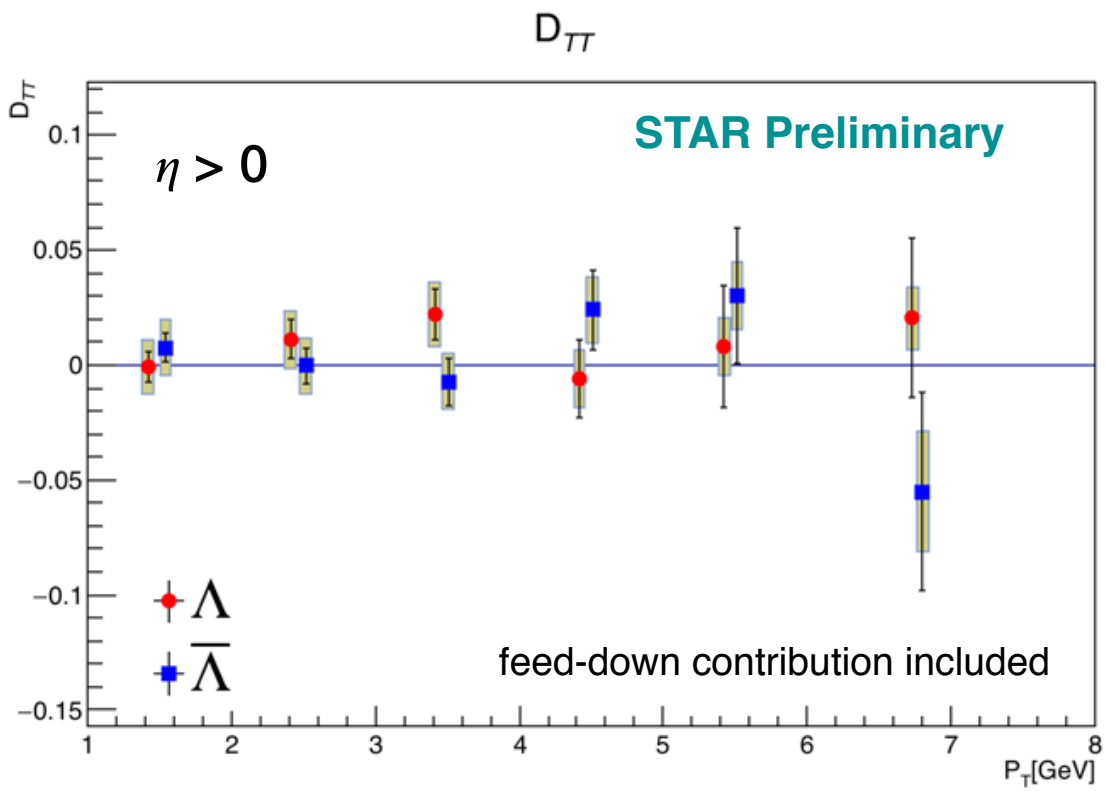
Look forward to isobar runs in 2018, BESII in 2019 and 2020, and pp, pA and AA program beyond 2020+.

SN0669: The STAR midrapidity pp, pA, AA physics program beyond BES-II
https://drupal.star.bnl.gov/STAR/files/STAR_Midrapidity_Beyond_BESII.pdf

SN0648: The STAR Forward Calorimeter System and Forward Tracking System beyond BES-II: https://drupal.star.bnl.gov/STAR/files/ForwardUpgrade.v20.pdf

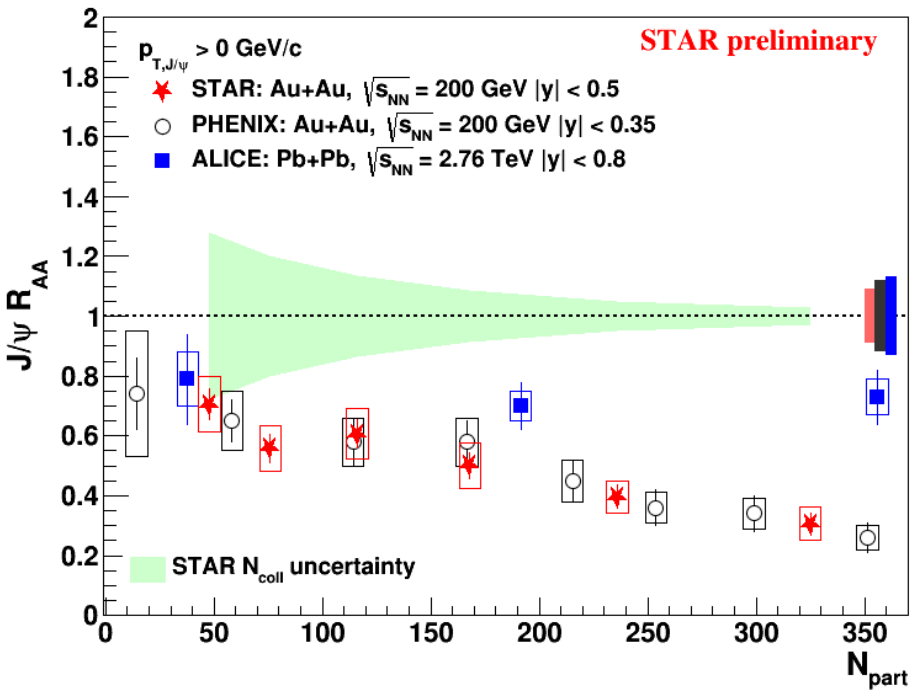
Backup

Lambda transverse spin transfer

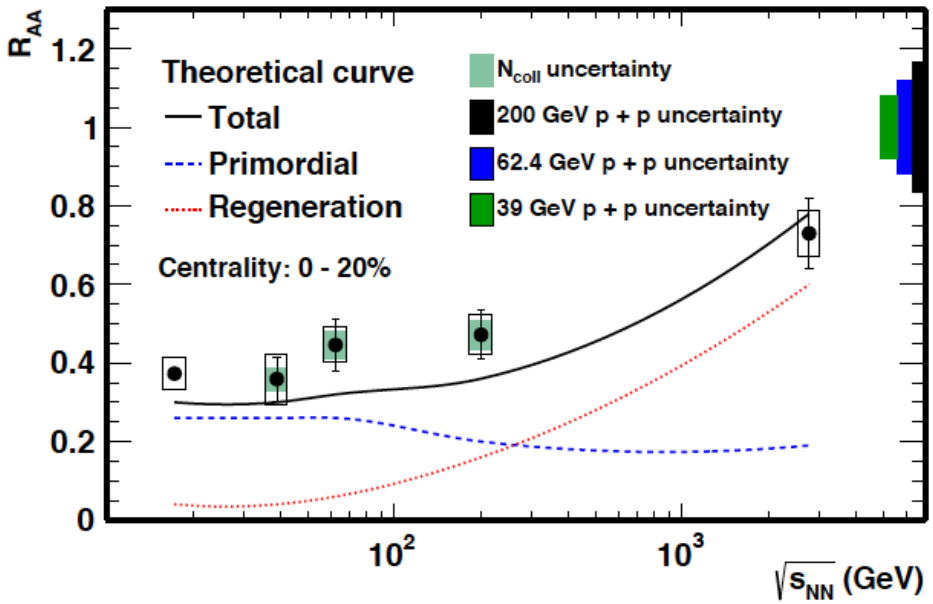


Sensitive to transversely polarized fragmentation function and transversity distribution.

J/ψ suppression pattern with the MTD



STAR Collaboration, SQM2016



STAR Collaboration, 1607.07517, accepted by PLB

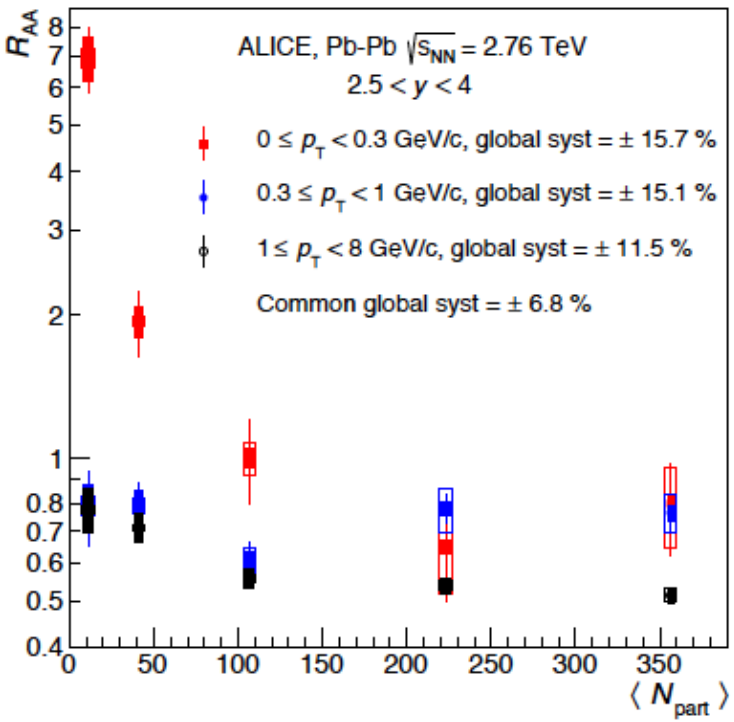
J/ψ through its dileptonic decay: indicator of deconfinement

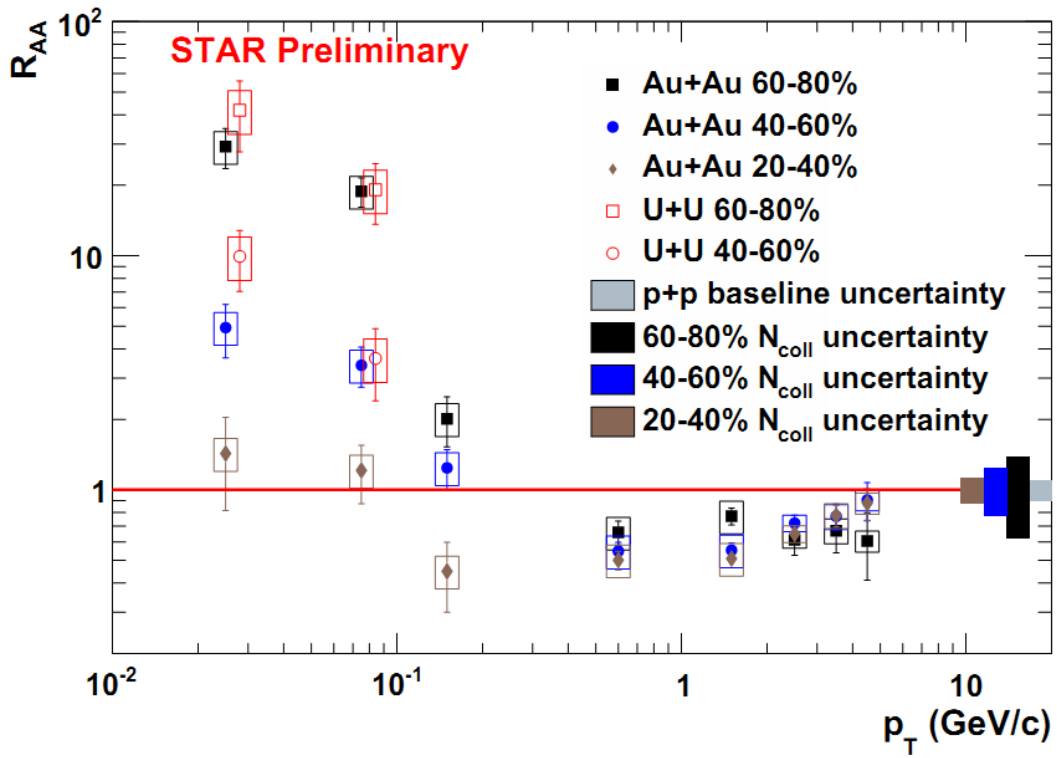
consistent with more significant contribution from ccbar recombination at LHC energies

Interplay between color screening and recombination: describe the J/ψ suppression pattern and flow measurements

Very low p_T J/ψ in heavy ion collisions

PRL116(2016)222301

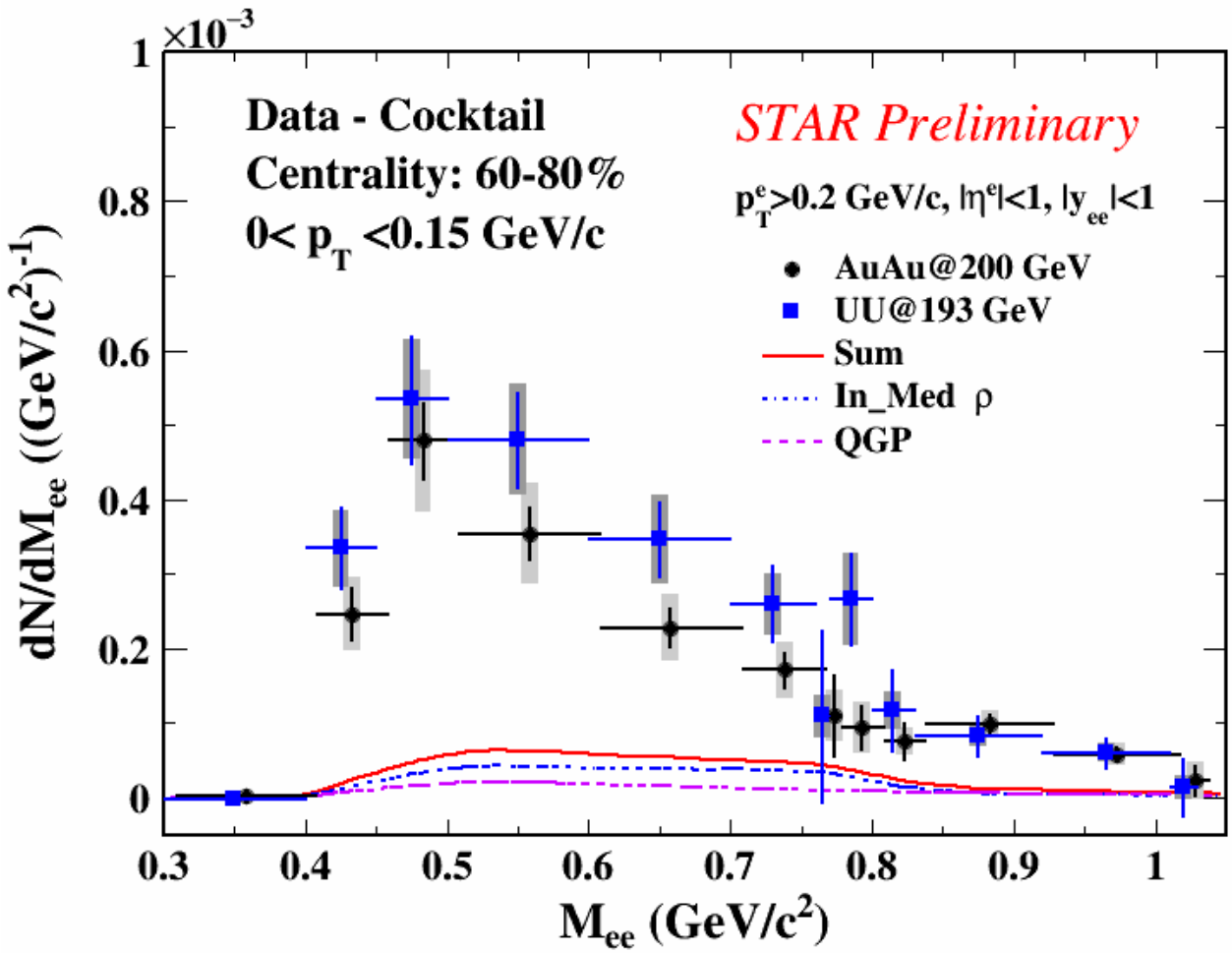




Large enhancement of J/ψ yield observed in peripheral A+A collisions!

Prominent centrality and p_T dependence.

Very low p_T electron-positron



Large enhancement of e^+e^- yield observed in peripheral A+A collisions!