
# Hard Probes in STAR
# an overview

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(Rice University)
For the STAR Collaboration

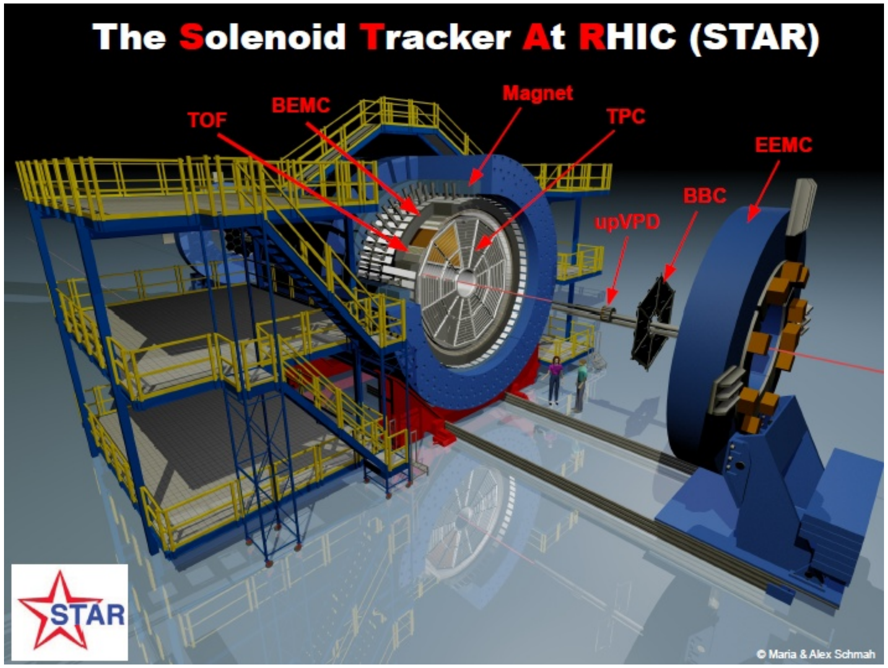
RICE

Office of Science
U.S. Department of Energy

# Outline

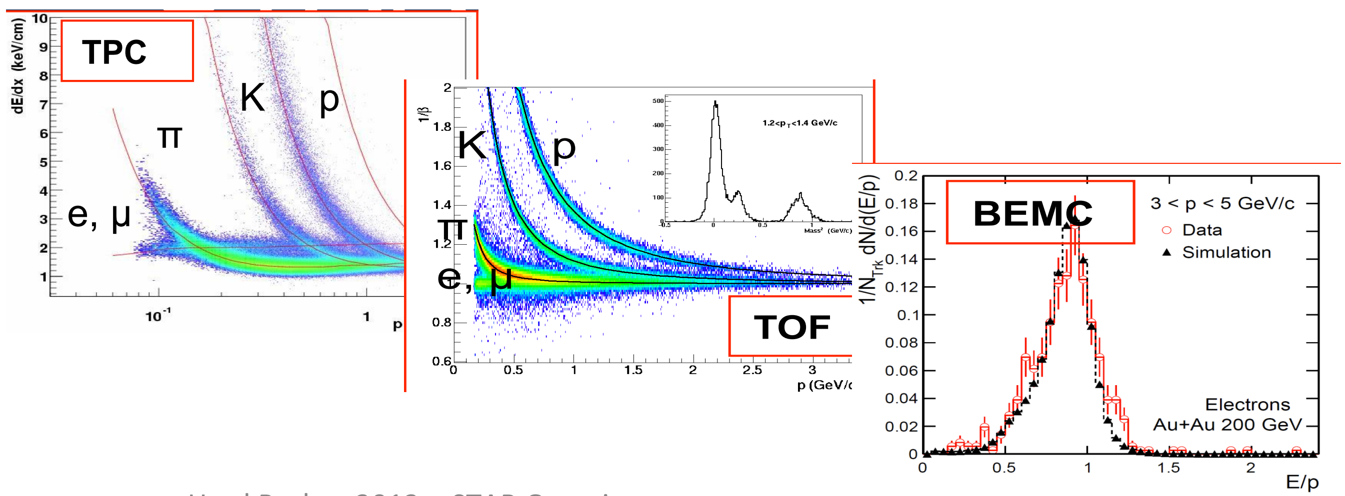
- The STAR detector
- Selected Results
  - heavy flavor: open charm, J/Ψ, and Υ
  - dielectron measurements
  - jets in Au+Au
  - direct photon correlation measurements
  - dihadron azimuthal correlations in d+Au
  - azimuthal anisotropy in U+U
- Future of HF Measurements at STAR

# The STAR experiment



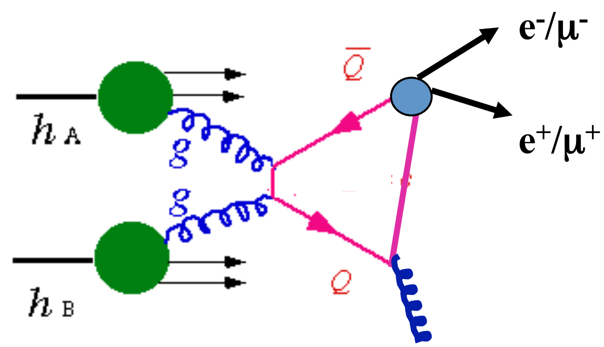

- Large and uniform acceptance at mid-rapidity
  $|\eta| < 1$ and $0 < \phi < 2\pi$
- Excellent particle identification
- Fast data acquisition
- Upcoming upgrades targeted at heavy-flavor measurements
  - improve tracking
  - improve muon PID

STAR detectors in these analyses
- TPC (dE/dx)
- TOF (1/β)
- BEMC (E/p)
- VPD, ZDC, FTPC

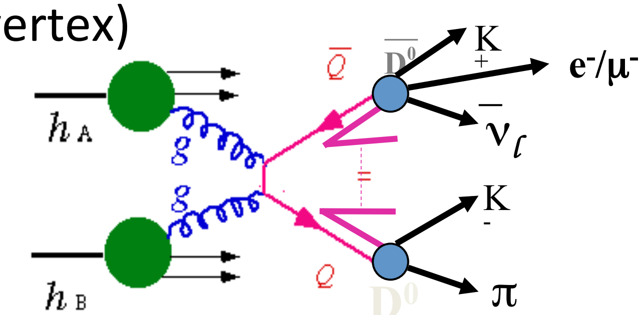


# Heavy-Flavor Measurements

- Heavy Flavor primarily from initial hard scattering
  - important probe for studying properties of the QGP
  - sensitive to the initial gluon distribution & density
  - parton energy loss in the medium
- Hadronic decay
  - small branching ratio
  - fully reconstructed
    - direct access to heavy quark kinematics
  - large combinatorial background (if no secondary vertex)
- Semi-leptonic decay
  - large branching ratio
  - single $e^{\pm}$: indirect access to kinematics
  - background from conversion and light hadron decay




*heavy quarkonia*



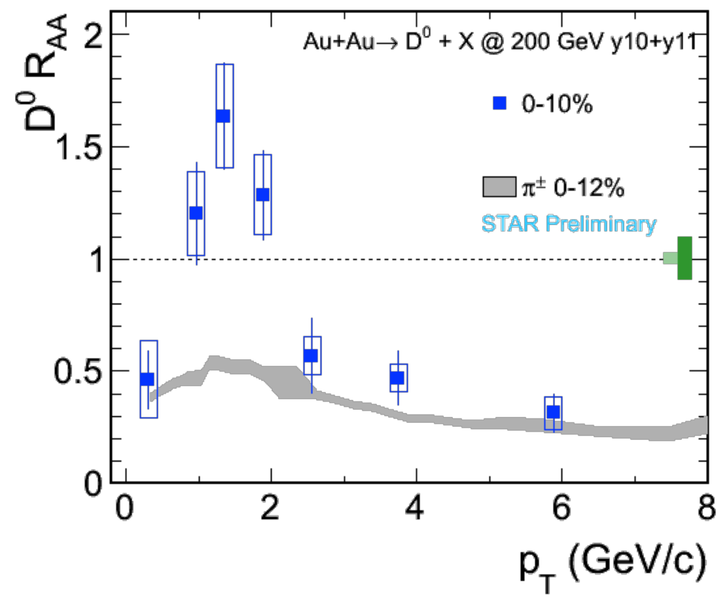

*open heavy flavor*

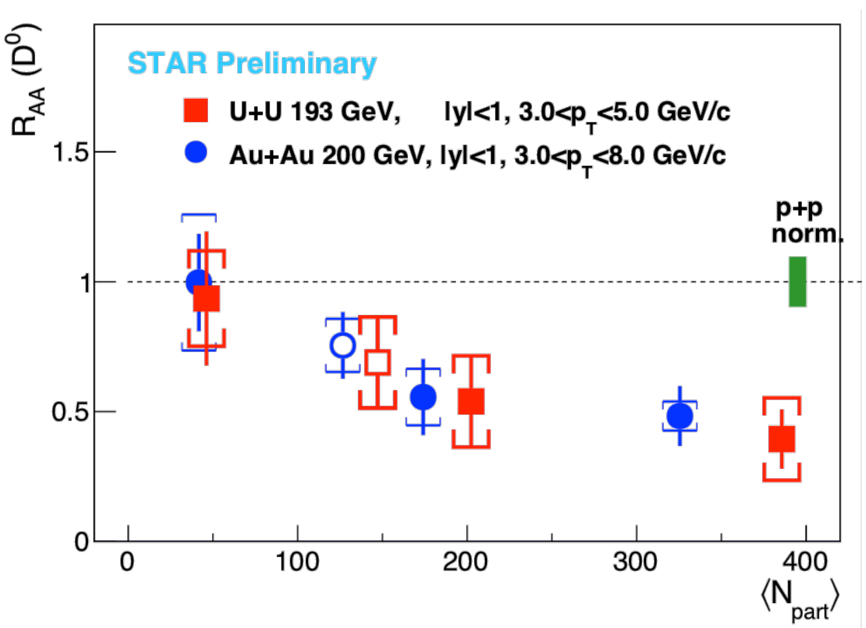
Zhenyu YE – Monday 14h30

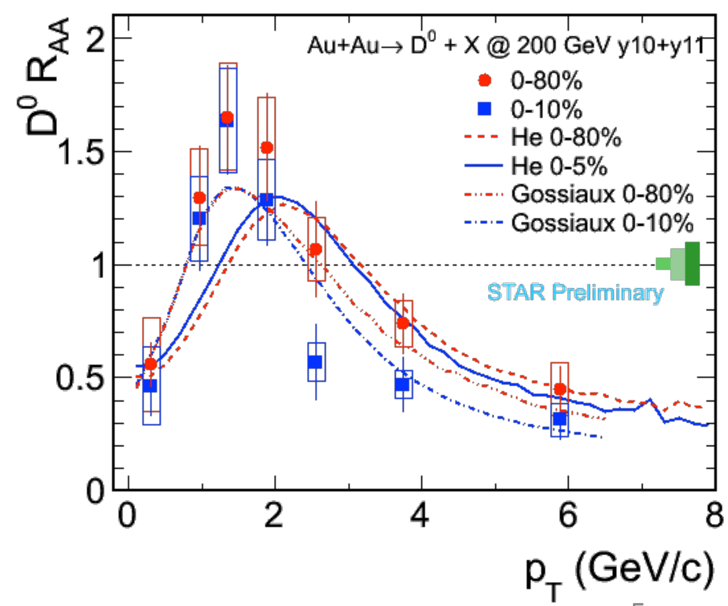
# $D^0$ in Au+Au and U+U

Hadronic channel in Au+Au at $\sqrt{s_{NN}}$=200 GeV

- Enhancement structure at low $p_T$
  - consistent with coalescence models
- Strong suppression for $D^0$ at high $p_T$
  - similar to $R_{AA}$ of $\pi^{\pm}$
  - similar in Au+Au and U+U ($\sqrt{s_{NN}}$=193 GeV)



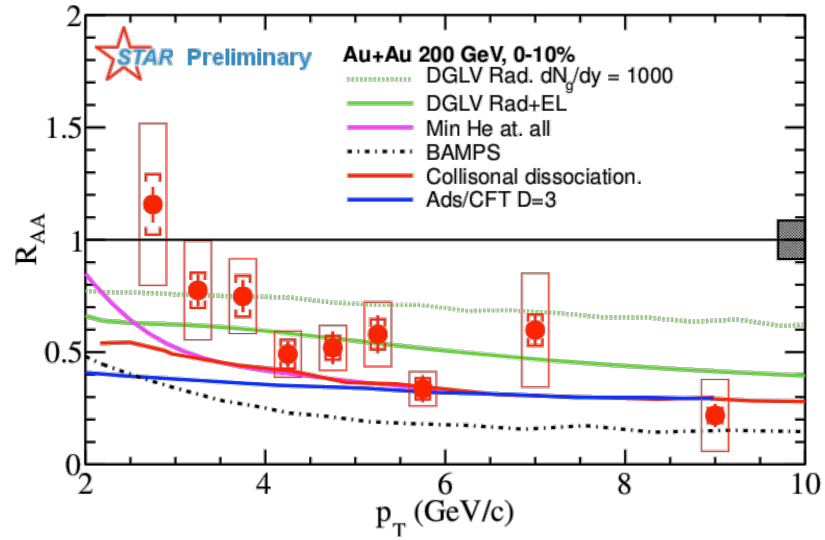



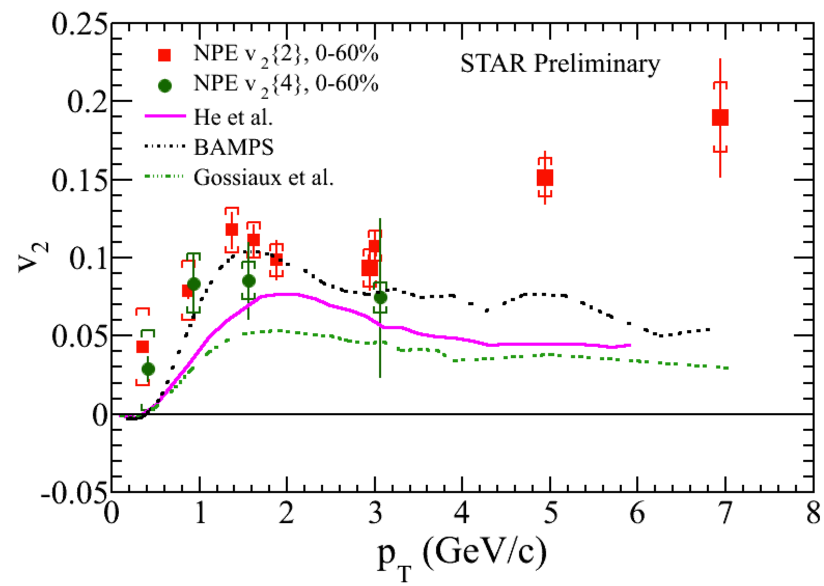
# Non-Photonic Electrons

Au+Au at $\sqrt{s_{NN}}$=200 GeV

- Strong suppression for NPE
  - Data disfavors radiative energy-loss-only models
  - need improvement p+p precision
  - no indication of suppression at 62GeV when comparing to FONLL ref.

- Significant $v_2$ for NPE
  - coalescence with light quarks or charm quark flow?



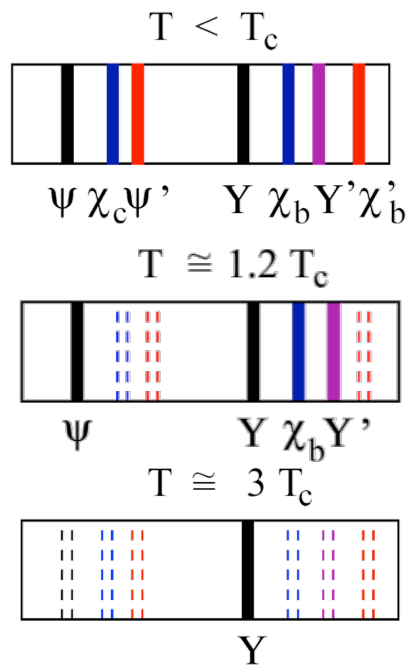
# Quarkonia

- Sensitive to color screening of quark potential: dissociation in QGP
- Suppression of different states determined by medium temperature and their binding energy
  - QGP thermometer
- Production mechanism not completely understood
  - p+p: Color-Singlet or Color-Octet?

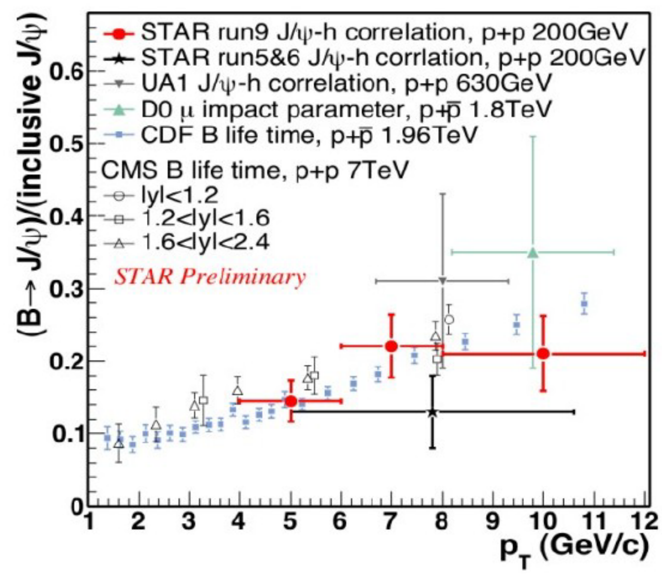
But, …

- Measured J/Ψ yields include significant feeddown contributions
  - B mesons carry 10-25% of charmonium yield
- Contributions from Cold Nuclear Medium effects
  - suppression mechanisms, *e.g.* nuclear absorption, gluon shadowing, initial state energy loss
  - enhancement mechanisms, Cronin effect
- Contributions from hot & dense medium effects
  - recombination from uncorrelated charm pairs

Jaro BIELCIK – Friday 9h30

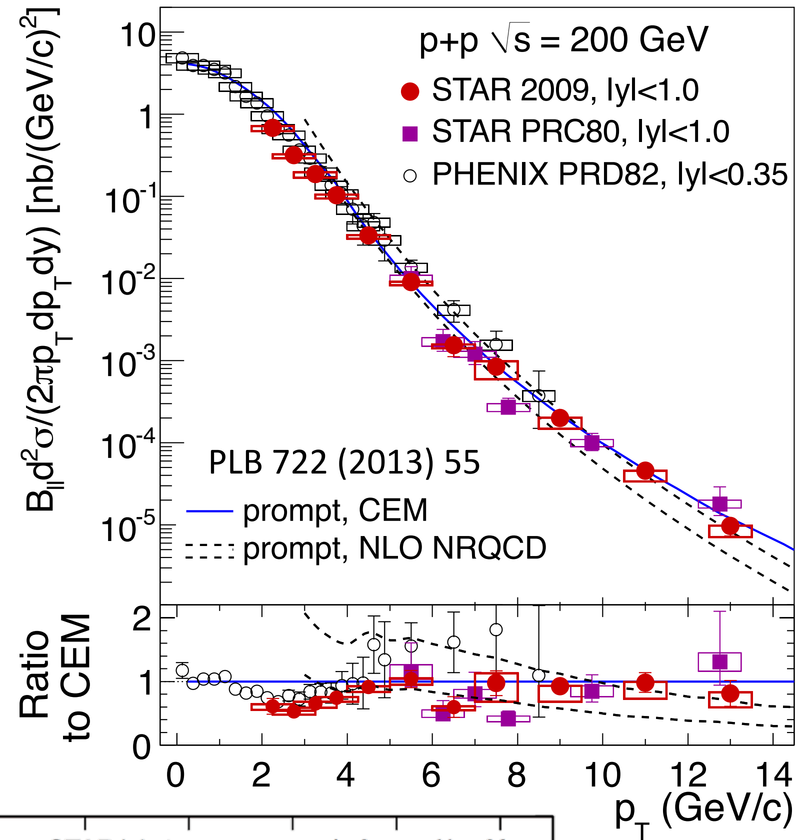


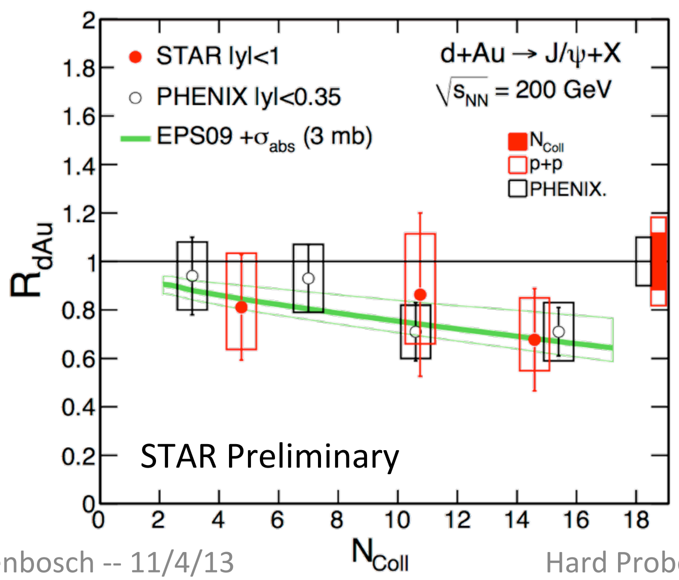

H. Satz, Nucl. Phys. A (783):249-260(2007)

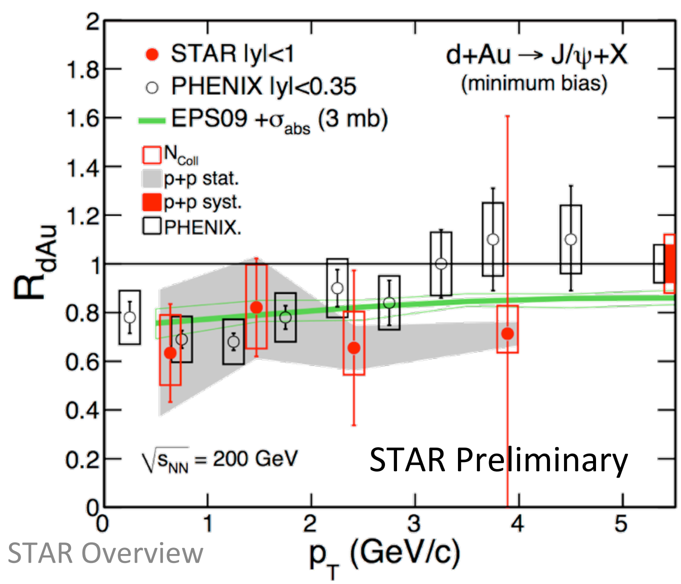


# J/Ψ in p+p and d+Au

- $p_T$ range in p+p extended to 14 GeV/c
  - prompt NLO CS+CO describes data
  - prompt CEM describes data at high $p_T$
  - direct NNLO CS underpredicts high $p_T$
- $R_{dAU}$ consistent with model calculations
  - shadowing from EPS09 nPDF
  - nuclear absorption: $\sigma_{abs}^{J/\Psi}$=3mb

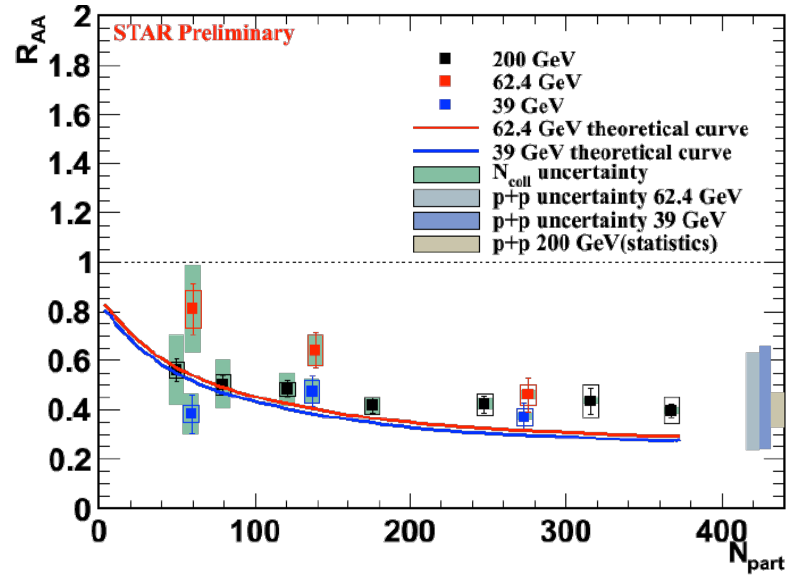


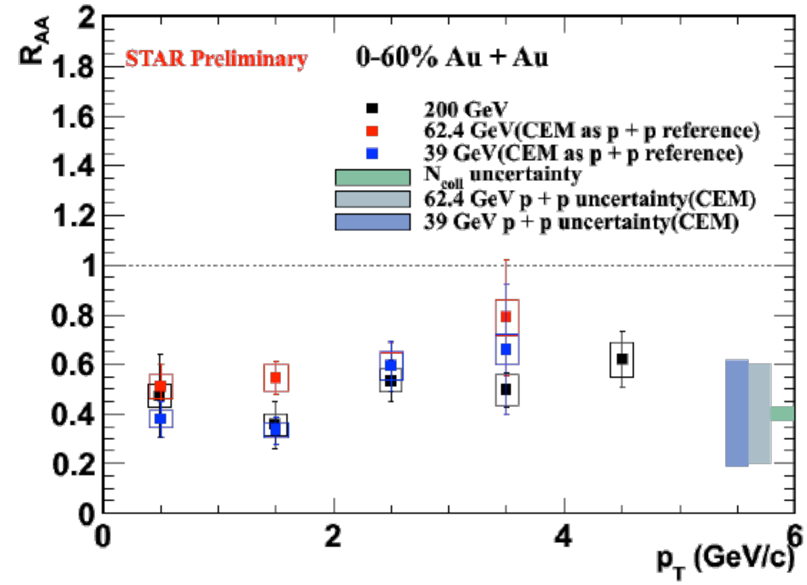



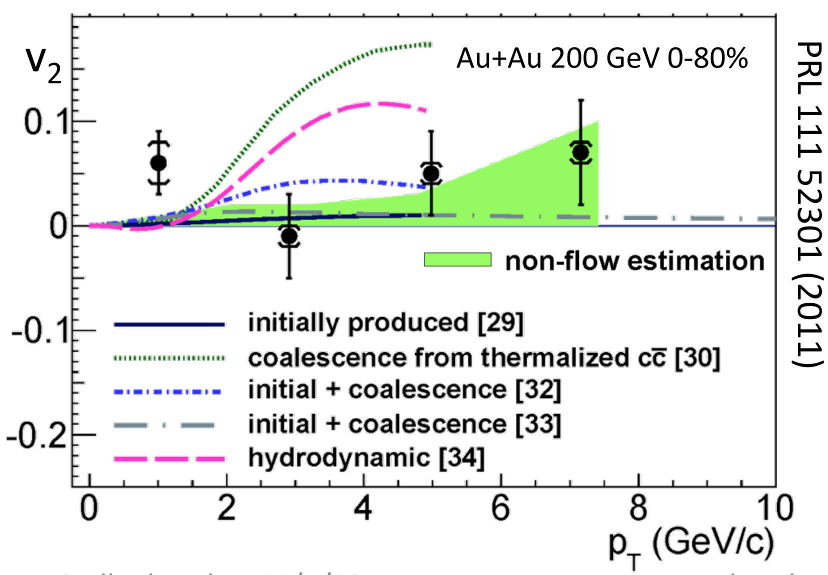



# J/Ψ in Au+Au

- Au+Au at 200 GeV: suppression observed
  - increase with centrality
  - decrease with $p_T$
- Au+Au at 39 and 62.4 GeV
  - similar centrality and $p_T$ dependence
- Au+Au $v_2$: consistent with no flow
  - disfavors production by coalescence of thermalized charm (for $p_T$>2 GeV/c)



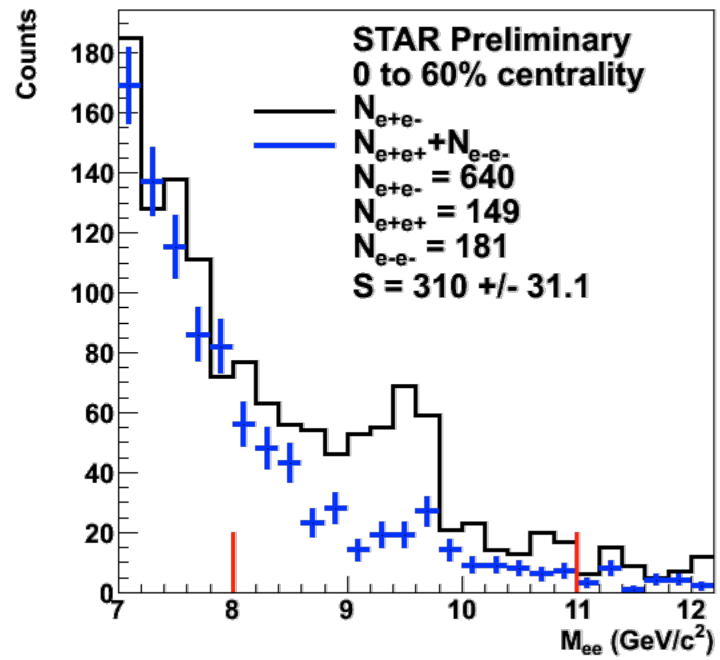



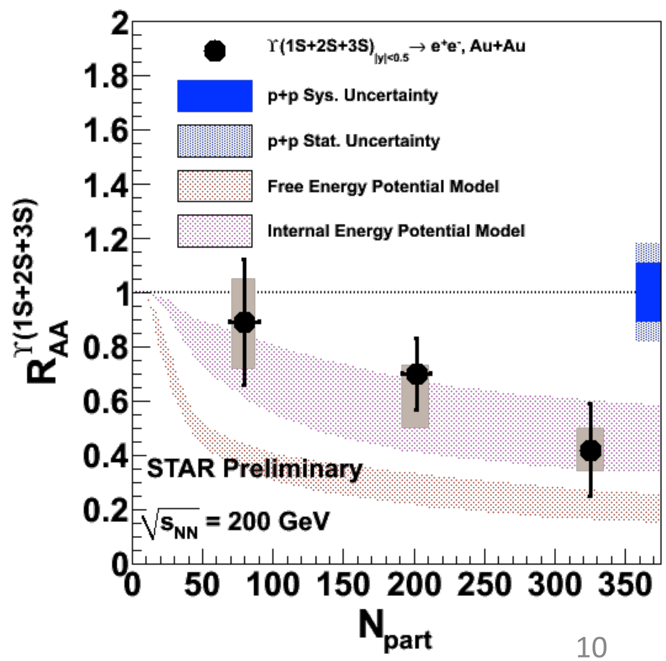

PRL 111 52301 (2011)

➢ J/Ψ in U+U see poster Ota KUKRAL

# Υ in Au+Au at 200 GeV

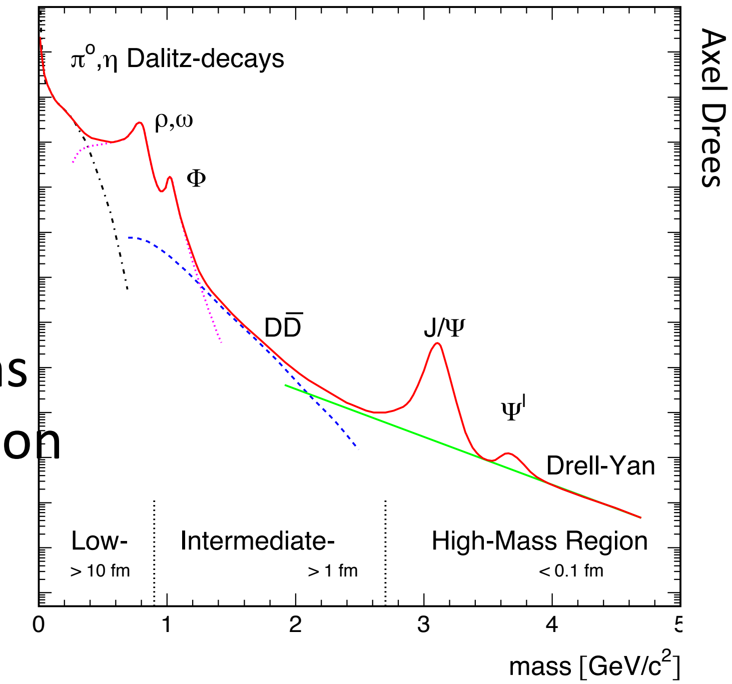
- Advantages over J/Ψ:
  - negligible recombination effect
    - at RHIC: $\sigma_{cc}$(~800μb) >> $\sigma_{bb}$(~1-2μb)
  - less co-mover absorption effect
    - Υ(1S) tightly bound, thus large kinematic threshold
    - expect $\sigma^{\Upsilon}_{abs}$ ~0.2mb < $\sigma^{J/\Psi}_{abs}$
      Lin & Ko, PLB 503 (2001) 104
- Disadvantage: low production rate …
  - STAR upgrades!
- Suppression of Υ(1S+2S+3S) observed
  - $R_{AA}$ decreases with centrality



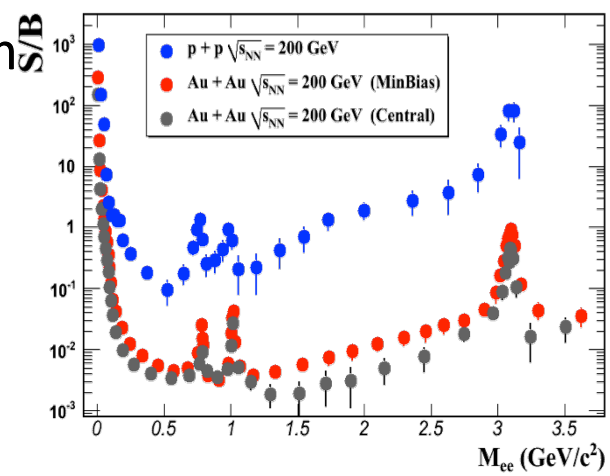



# Dielectron Measurements

- Intermediate Mass Range
  - QGP thermal radiation
  - heavy-flavor modification
- Low Mass Range
  - in-medium modification of vector mesons
  - possible link to chiral symmetry restoration



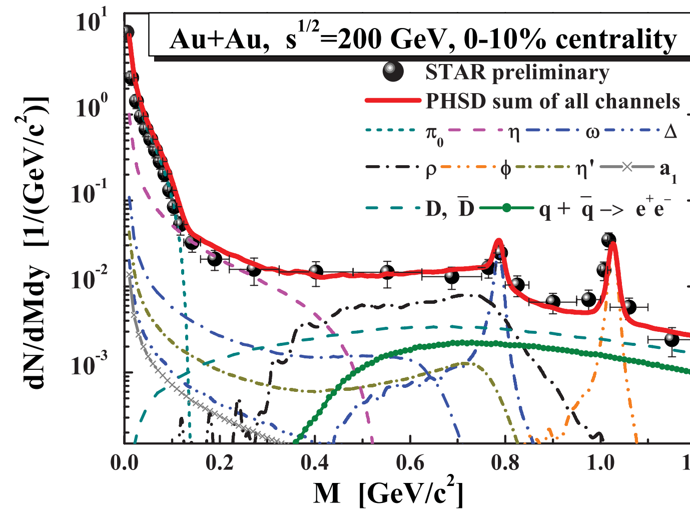

- Advantage:
  - very low cross section with QCD medium
  - created throughout evolution of the system
- Disadvantage
  - (very) low signal/background
  - requires low material budget



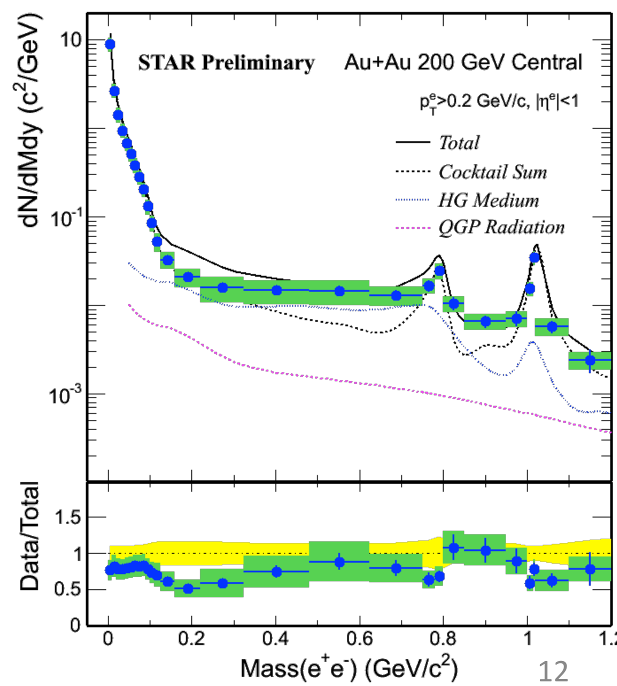
# Vector Meson Modification

- STAR and PHENIX confirm significant LMR excess
    - already observed at SPS energies
  - vacuum ρ description essentially fails
    - SPS: ρ broadening
  - PHENIX: yet to be explained by models
  - STAR: less excess, agreement with models
    - which involve ρ broadening
- At SPS: significant net-baryon density, baryons main contributor
- At RHIC: vanishing net baryon density, but comparable <u>total</u> baryon density
  - STAR Beam Energy Scan: close gap between RHIC & SPS

Measurements at $\sqrt{s_{NN}}$ = 19.6, 27, 39, 62.4 GeV

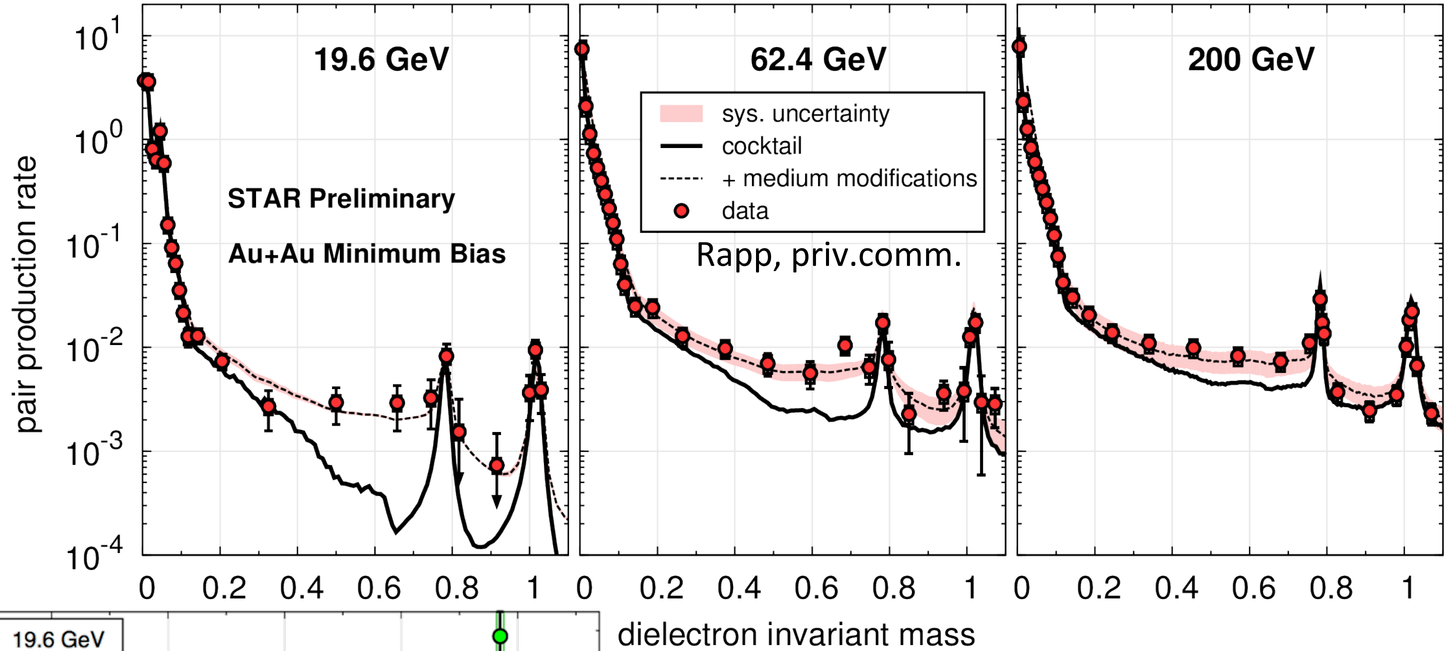


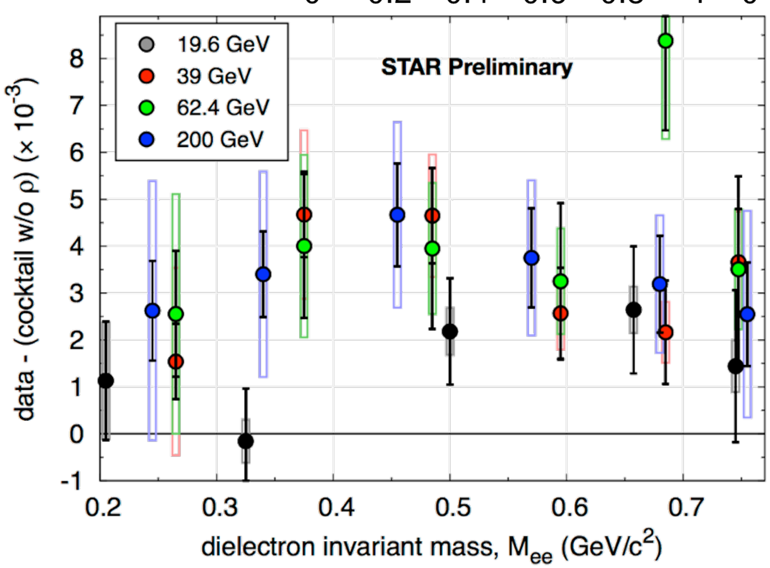

Linnyk et al. PRC 85 024910 (2012)




Rapp, PRC 63 (2001) 054907; priv.comm.

# Beam Energy Scan: Dielectrons

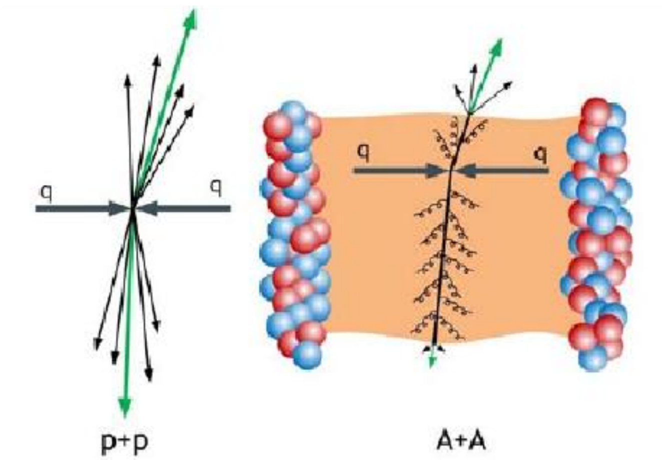


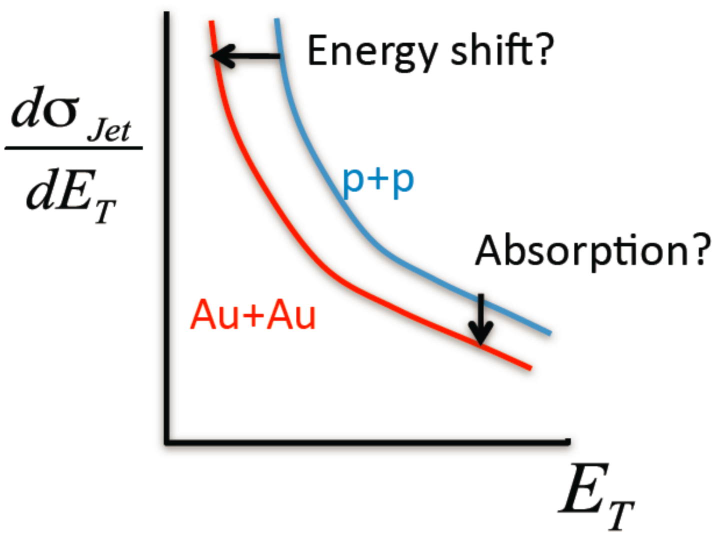




- LMR excess observed for all energies
- systematic measurement of excess
- Model calculations appear to provide robust description from RHIC down to SPS energies
- Measurements consistent with in-medium ρ broadening
  - expected to depend on total baryon density

Jan RUSNAK – Tue 9h00

# Jets as Probes of Nuclear Matter




- In p+p: hard-scattered partons fragment and hadronize into collimated sprays of hadrons, *i.e.* jets

- In A+A: expect jet quenching in hot & dense medium
  - softening and broadening of fragmentation when compared to p+p

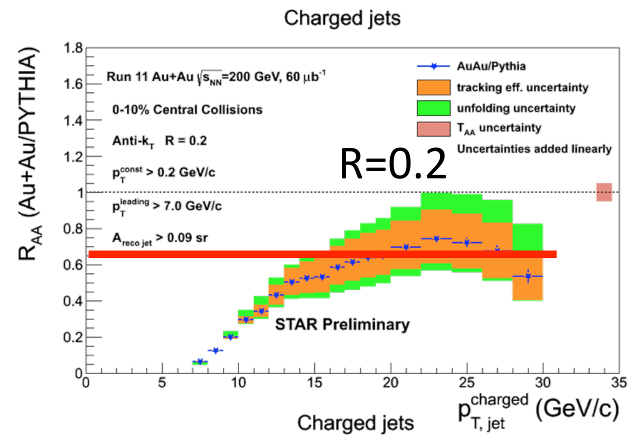
➢ Jets probe nuclear medium
  - but, very challenging in high multiplicity environment

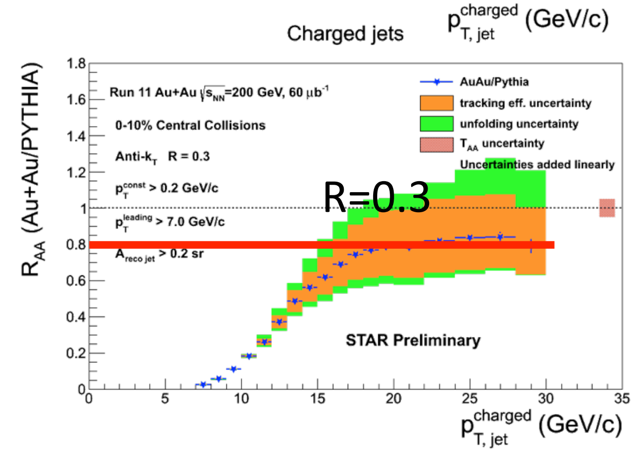
# Inclusive Charged Jet $R_{AA}$

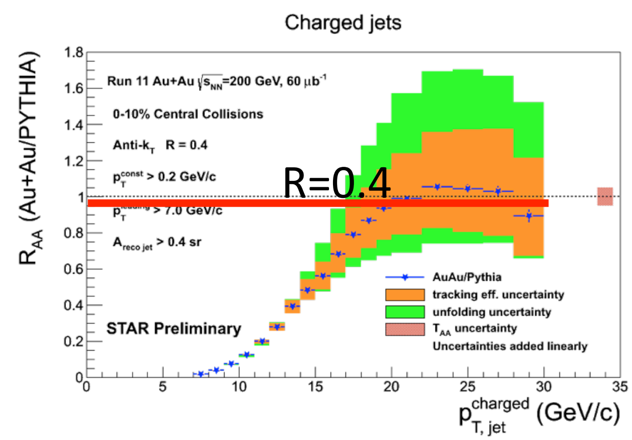
Jet reconstruction method similar to ALICE

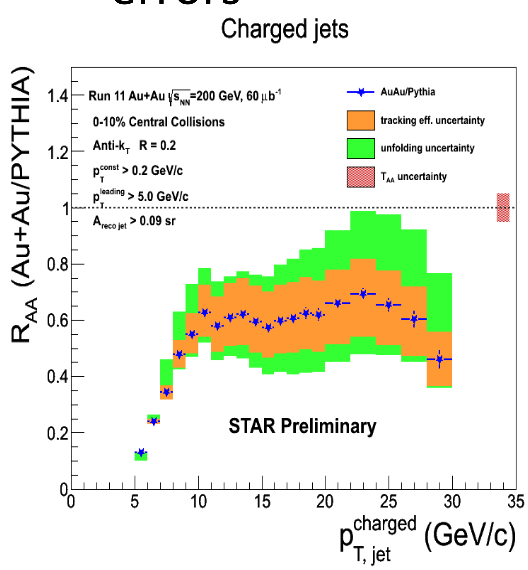
- dominant uncertainty: tracking efficiency

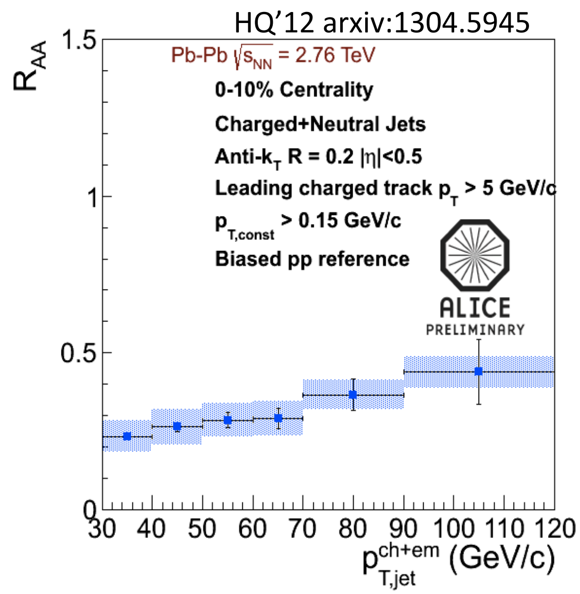
- $R_{AA} > 0.5$ for Au+Au at 200GeV
- $R_{AA}$(RHIC) > $R_{AA}$(LHC)
  - at same jet $p_T$
- Central $R_{AA}$ value increase with size of jet R ?
  - uncertainties large
  - careful assessment of correlated/uncorrelated errors



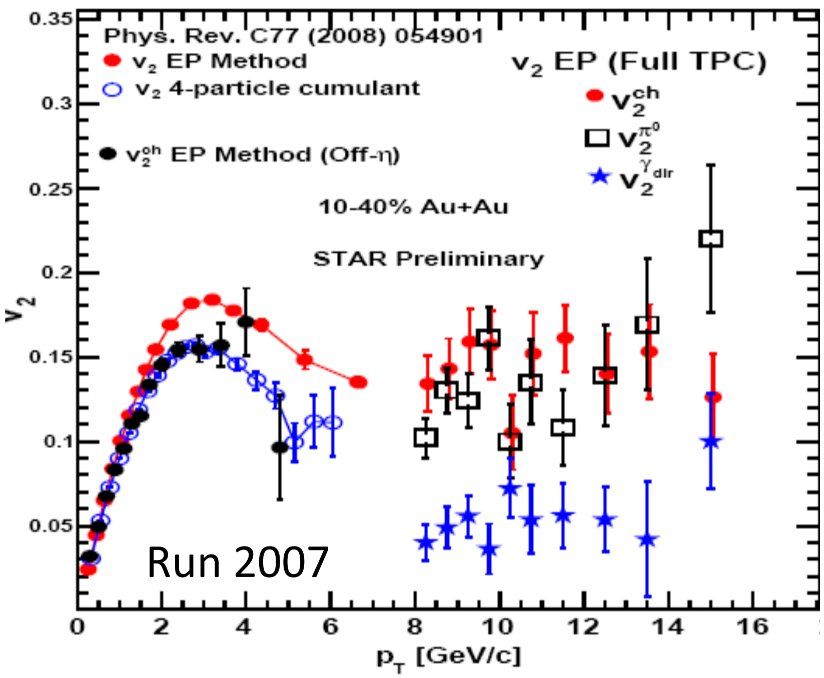



Ahmed HAMED
@High-pT Physics at LHC (Sept.2013)

# $v_2$ of direct photons

At high $p_T$, the azimuthal anisotropy could constrain the path length dependence of energy loss "jet quenching"

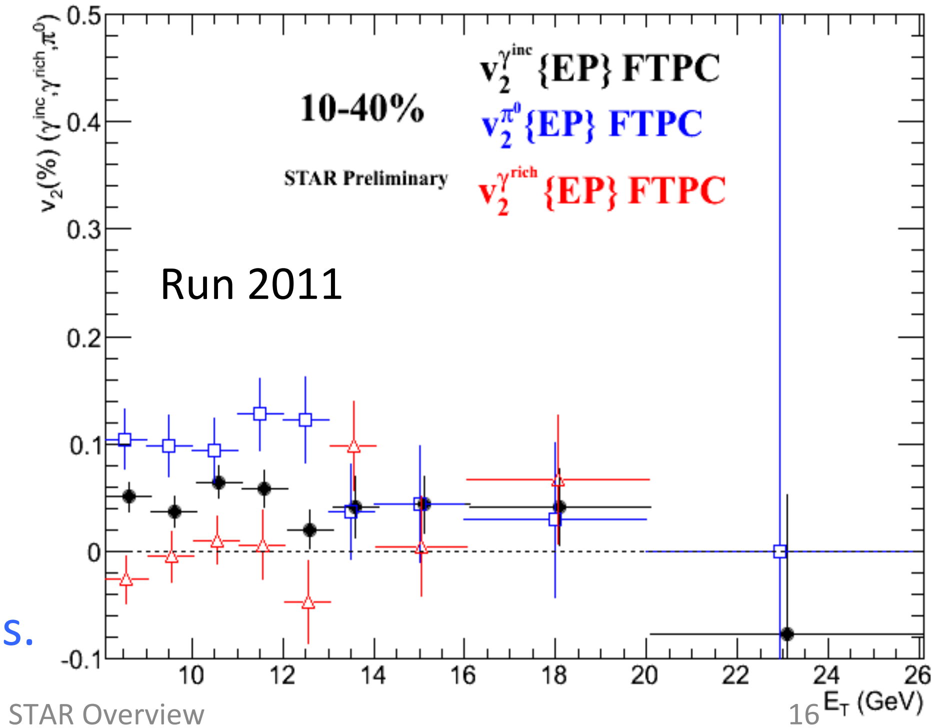



Expect $v_2^{\gamma\text{-dir}} \sim 0$ at high $p_T$

- no preferred direction w.r.t. reaction plane

✓ Event-plane reconstruction biases.

✓ Fragmentation photons contributions?




- $v_2$ (FTPC) of direct photons is zero
- $v_2$ of $\pi^0$ using the FTPC apparently due to the path-length dependence of energy loss.

# Dihadron correlations in d+Au

Ridge seen in smaller systems at LHC

- Ridge in d+Au at RHIC?
  - ➢ STAR: large acceptance $|\Delta\eta_{TPC}|<2$
  - – with FTPC $1.8 < |\Delta\eta_{FTPC}| < 4.8$
- *central-peripheral* technique
  - – should remove centrality-independent correlations

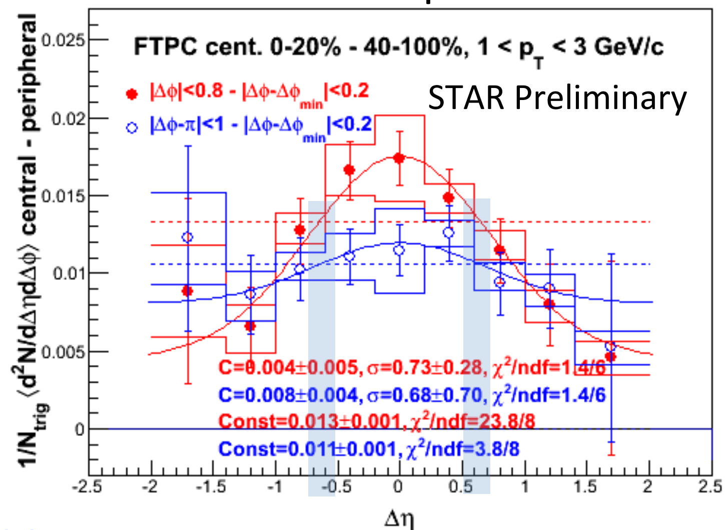
➢ *Central-peripheral* resembles jet correlations

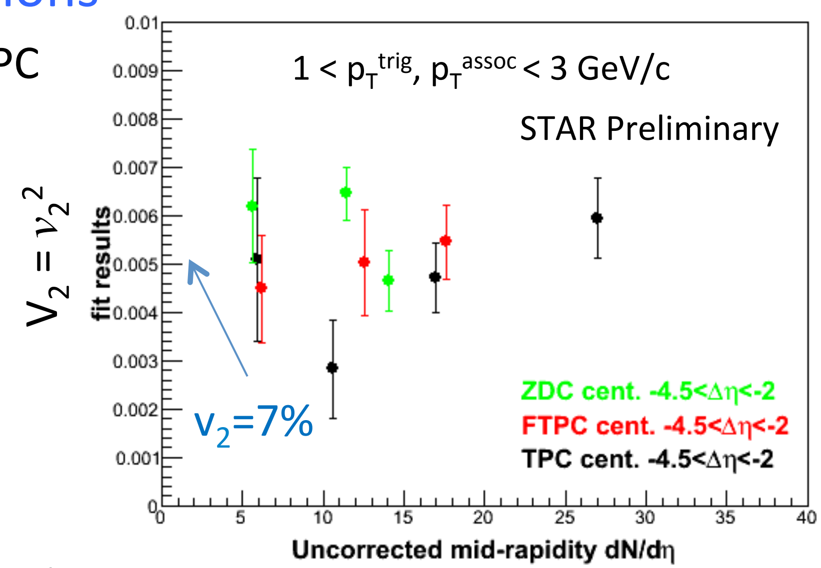
- – FTPC-Au multiplicity selection biases jets in TPC

➢ Fourier decomposition of correlations functions:

- – correlations have $V_1$ and $V_2$ components
- – $V_1$ appears ~1/multiplicity
- – $V_2$ is approximately constant vs. multiplicity

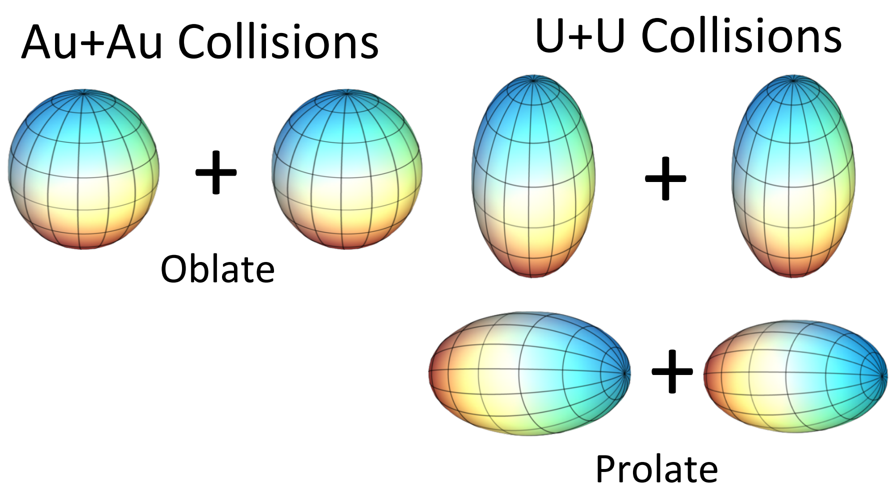
Central – Peripheral



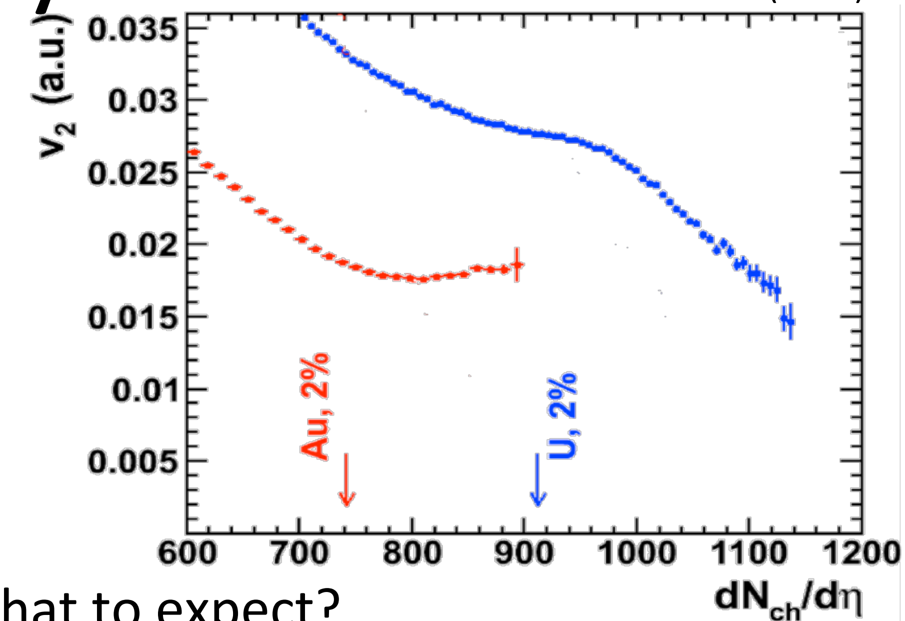



# Azimuthal Anisotropy in U+U

- Prolate shape of Uranium nucleus provides possibilities to study ...
  - multiplicity dependence on $N_{part}$ and $N_{coll}$
  - path-length dependence of jet quenching
- Can we see the differences between Au+Au and U+U?
  - and, can we separate between body-body and tip-tip collisions?




PRL 105 172301 (2010)



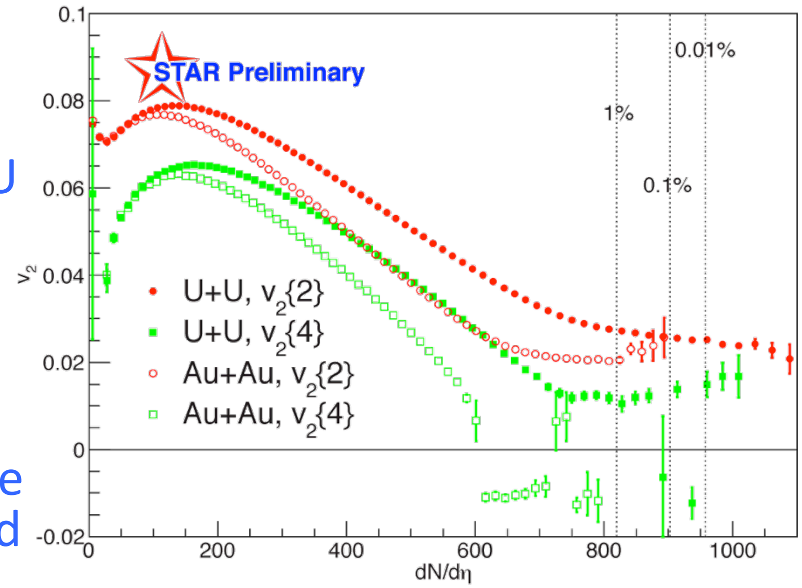

<u>What to expect</u>?

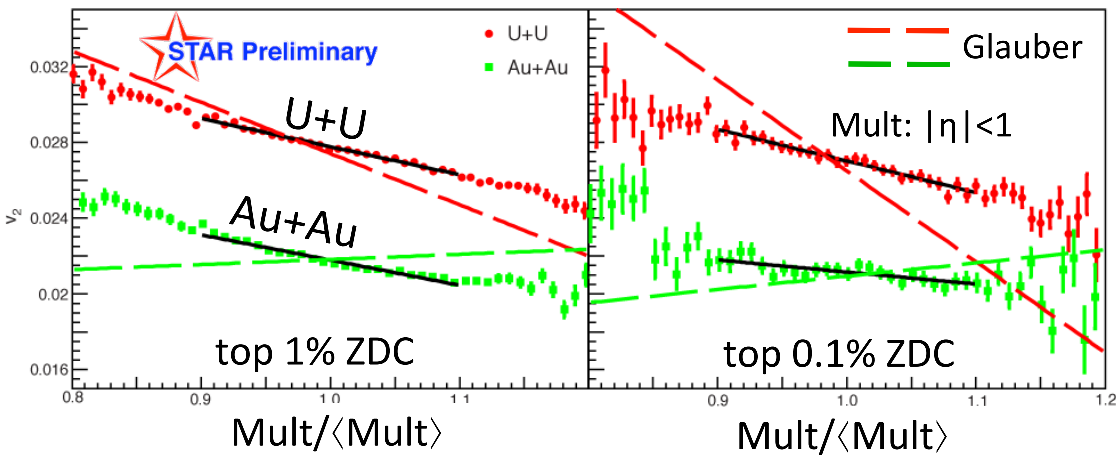
- body-body:
  - large initial ε, thus large $v_2$
- tip-tip:
  - larger $N_{coll}$ (given $N_{part}$), thus larger dN/dη

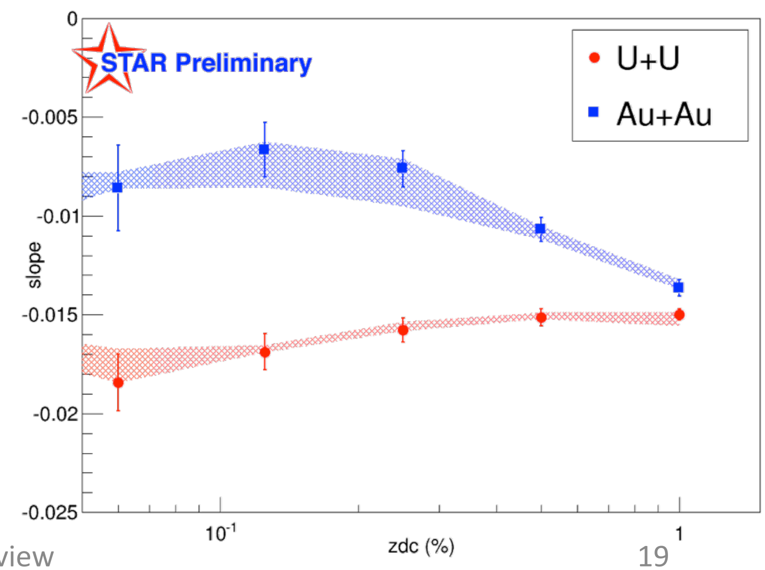
➢ large dN/dη correlates with small $v_2$?
  - simulations say yes
  - knee structure in $v_2$ at high dN/dη

# Multiplicity dependence of $v_2$ in Central U+U and Au+Au Collisions

- No evidence of kink structure
  - additional fluctuations besides NBD?
- $v_2\{4\}$ data distinguishes central Au+Au from U+U
  - $v_2 \neq 0$ due to intrinsic prolate shape
- $v_2/\varepsilon_2$ drops in very central collisions
  - overestimation $\varepsilon_2$?
  - non-flow, fluctuations?
- ➢ Combine slope of $v_2$ vs. multiplicity and compare with ZDC to enhance samples for body-body and tip-tip
  - expect in central (ZDC) larger $v_2$ with small dN/dy

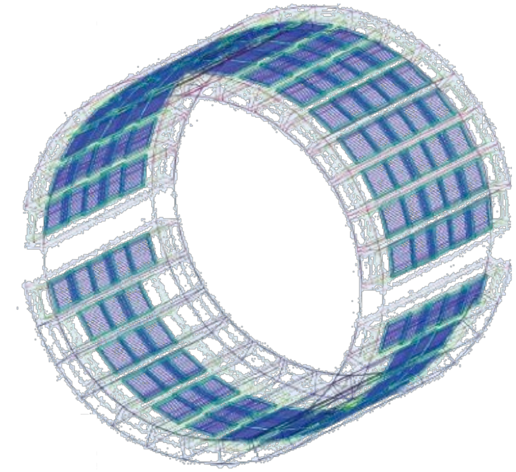


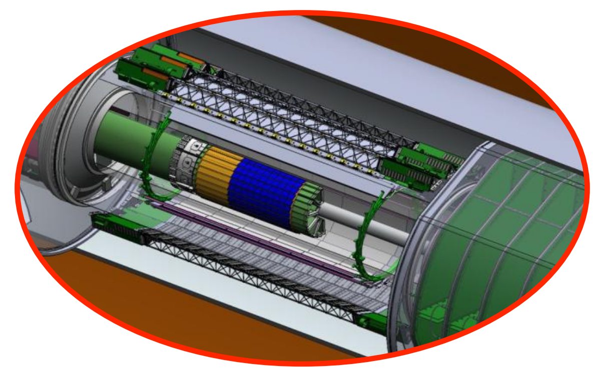



# STAR Upgrades: HFT +MTD

- Heavy Flavor Tracker + Muon Telescope Detector on track for RHIC Run 14
  - major focus: heavy-flavor & dilepton measurements
  - revisit Au+Au, p+p, and p+Au at $\sqrt{s_{NN}}$=200 GeV
- Separate charm and bottom, study open heavy flavor (HFT), quarkonia (MTD), thermal dileptons (MTD)
  - combine HFT+MTD: separate secondary J/Ψ from prompt
  - combine MTD+BEMC: trigger on e-μ pairs to disentangle charm contributions to the dilepton IMR



Muon Telescope Detector



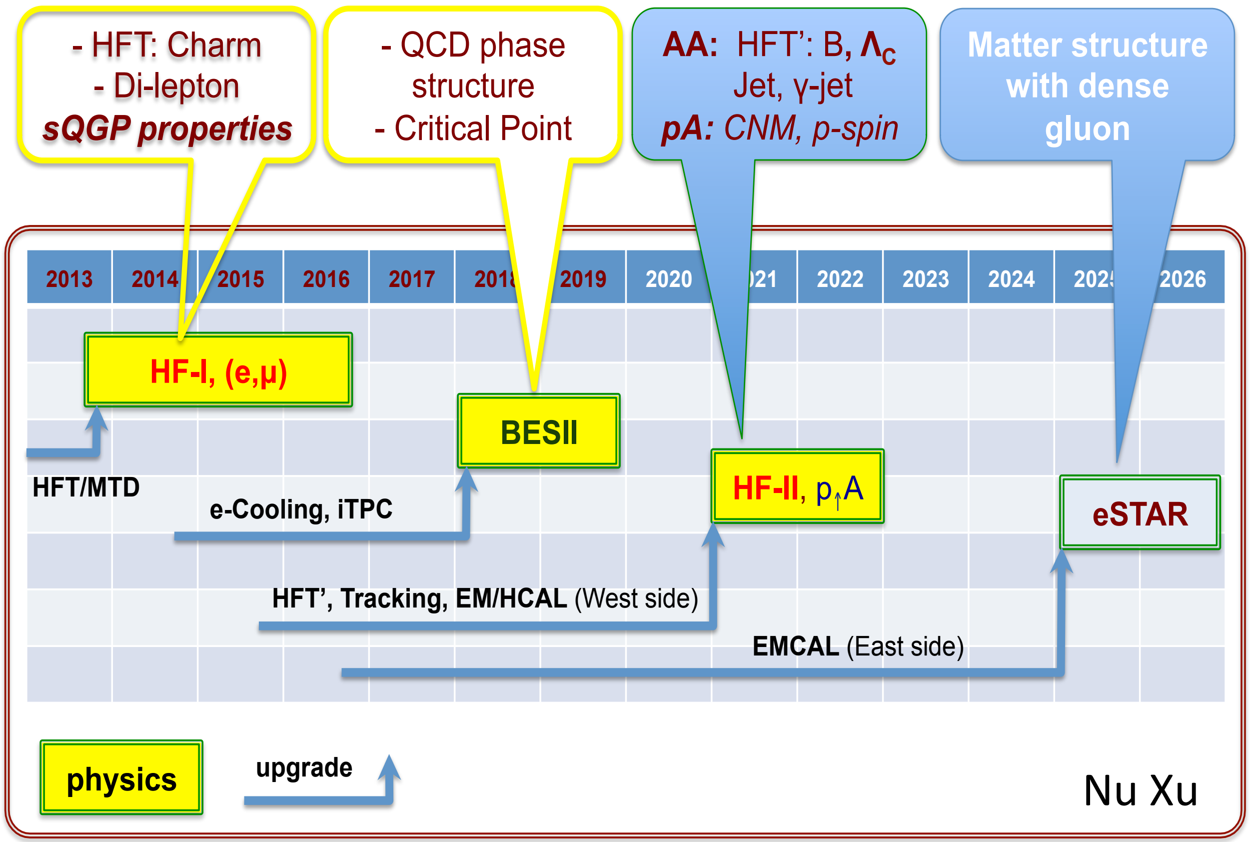
Heavy Flavor Tracker

# Summary

- STAR @ HP2013: wide range of results from hard probes, electromagnetic probes, initial conditions based on TPC, TOF, EMC
  - but also forward detectors such as ZDC and FTPC

- HF-I (2014-2016)
  - Au+Au, p+p, p+Au
  - HFT and MTD upgrade significantly improve STAR's hard-probes potential

- HF-II/pA (2021/2022)
  - A+A and p+A
  - further upgrades to improve B, $\Lambda_C$, and jet physics in A+A
  - CNM



# STAR Contributions at HP'13

Monday

Parallel: High Transverse Momentum Light and Heavy Flavor Hadrons …

- **80 Zhenyu Ye -** **Measurements of Open Heavy Flavor Hadrons in STAR Experiment**

Parallel: Initial State and Proton-Nucleus Collision Phenomena …

- **83 Paul Sorensen -** **Azimuthal anisotropy $v_2$ in U+U collisions at STAR**

Tuesday

- **187 Jan Rusnak -** **Fully Reconstructed Charged Jets in Central Au+Au Collisions at $\sqrt{s_{NN}}$=200 GeV from STAR**

Wednesday

- **197 Joey Butterworth -** **Dielectron production in Au+Au collisions at $\sqrt{s_{NN}}$ = 19.6, 27, 39, and 62.4 GeV from STAR**

Thursday

Parallel: Initial State and Proton-Nucleus Collision Phenomena …

- **86 Fuqiang Wang -** **Dihadron azimuthal correlations at large pseudo-rapidity difference in multiplicity-selected d+Au collisions by STAR**

Friday

- **209 Jaro Bielcik -** **Quarkonium measurements in the STAR experiment**

Poster

- **Ota Kukral – J/Ψ production in U+U collisions at 193 GeV in the STAR experiment**