Overview of Recent Results from the STAR Experiment

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BERKELEY LAB
Lawrence Berkeley National Laboratory

U.S. DEPARTMENT OF ENERGY

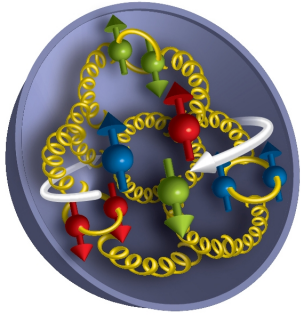
STAR

STAR Physics Program: **Study Emergent Properties of QCD**

Cold QCD

Polarized p+p/A:

- Study the partonic spin structure of protons
- Study proton and nuclear Parton Distribution Functions



Hot QCD:

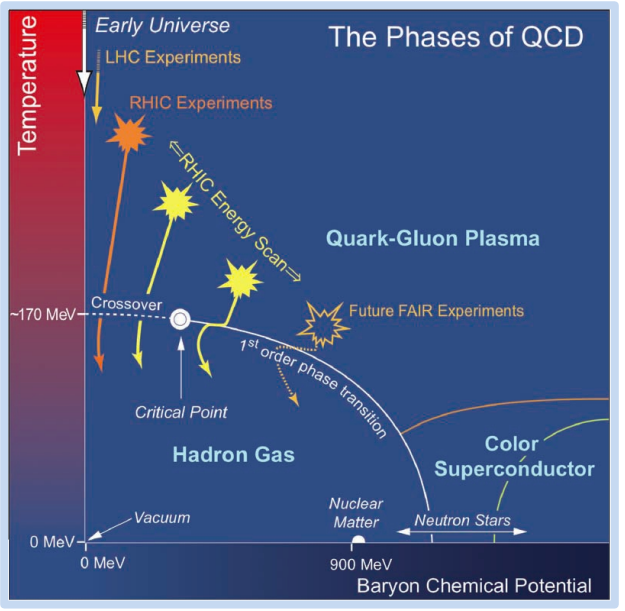
Top RHIC energy:

sQGP properties (η/s, $\hat{q}$, D_{HQ}, chirality, …)

Beam Energy Scan (BES):

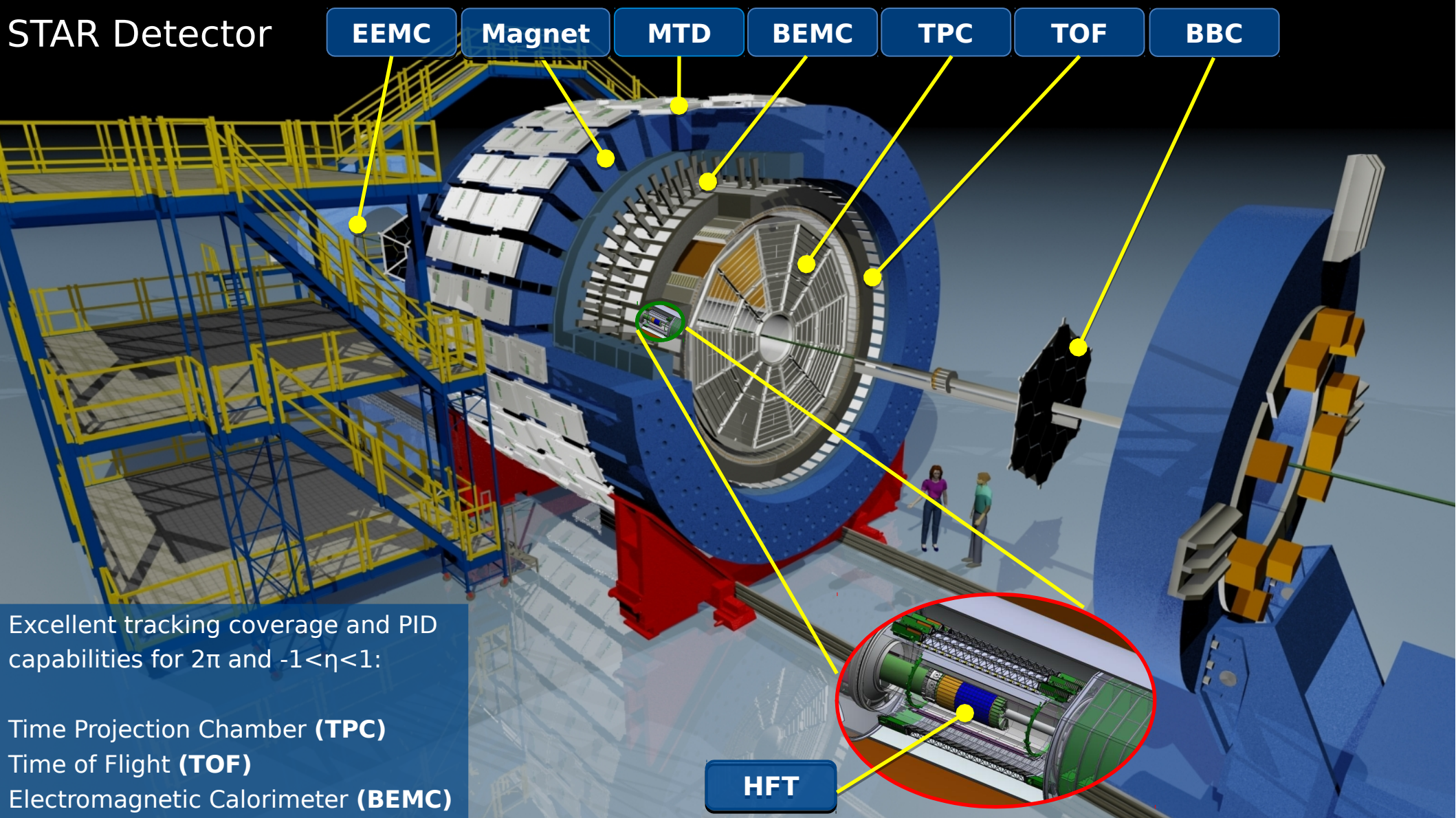
Phase diagram

- onset of QGP
- phase transition
- critical point



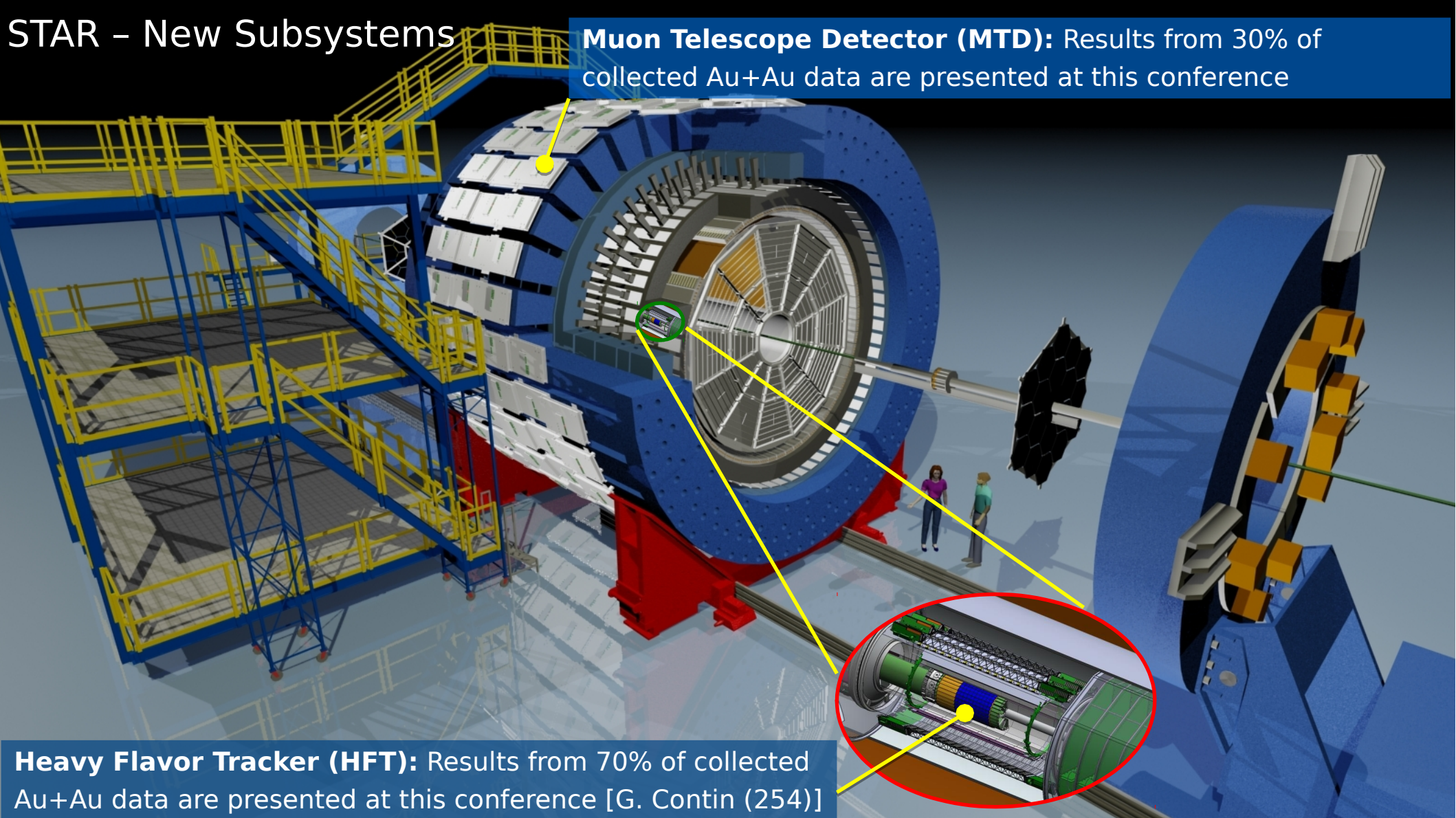
Outline (updates since last QM)

- Heavy Flavor:
  - Heavy Flavor Tracker (HFT)
    → First result of D^0 azimuthal anisotropy and nuclear modification factor
  - Muon Telescope Detector (MTD)
    → Quarkonia via di-muon channels
- Beam Energy Scan I (BES-I) completed with $\sqrt{s_{NN}} = 14.5\ GeV$
- Chirality
  - Di-electrons
  - Chiral Magnetic Effects
  - Effects of E-field (Cu+Au)
- Jets


STAR Detector
EEMC
Magnet
MTD
BEMC
TPC
TOF
BBC
HFT
Excellent tracking coverage and PID capabilities for 2π and -1<η<1:
Time Projection Chamber (TPC)
Time of Flight (TOF)
Electromagnetic Calorimeter (BEMC)

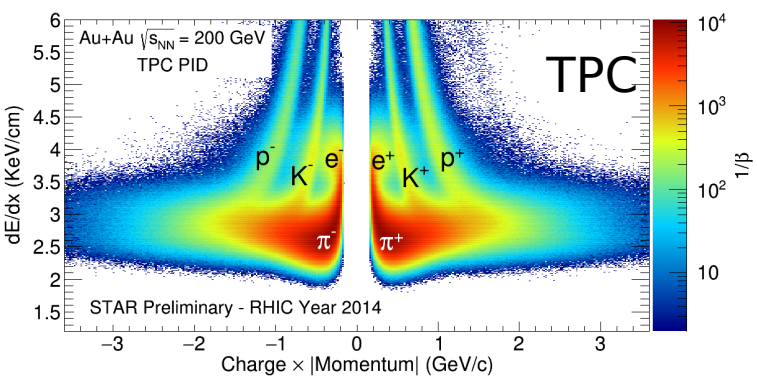
STAR – New Subsystems

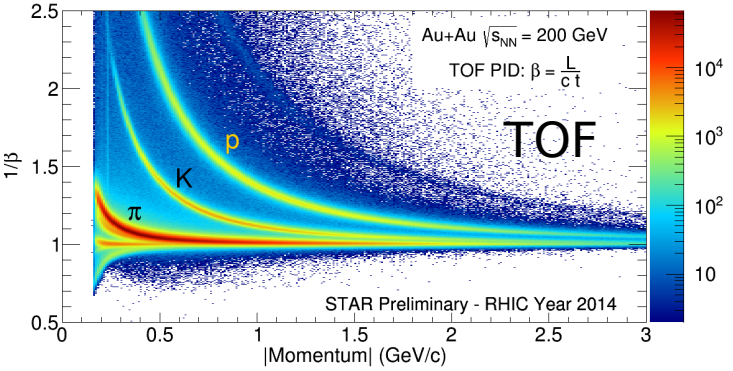
Muon Telescope Detector (MTD): Results from 30% of collected Au+Au data are presented at this conference



Heavy Flavor Tracker (HFT): Results from 70% of collected Au+Au data are presented at this conference [G. Contin (254)]

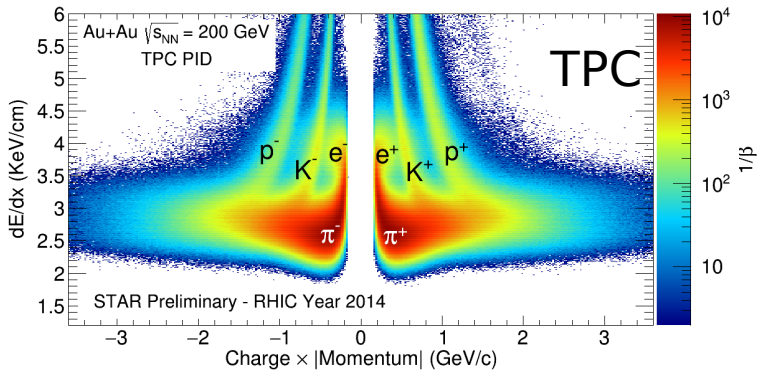
Particle Identification

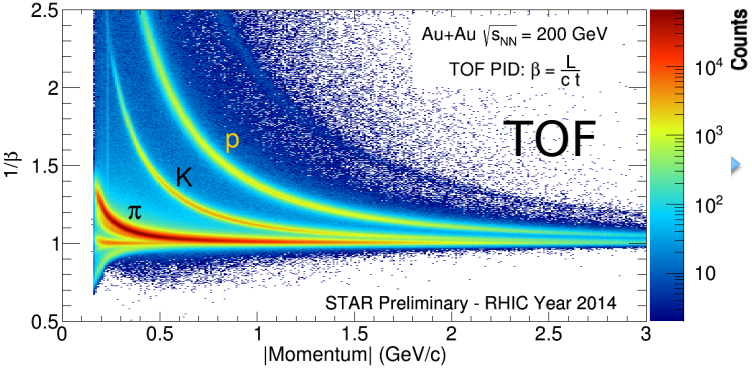


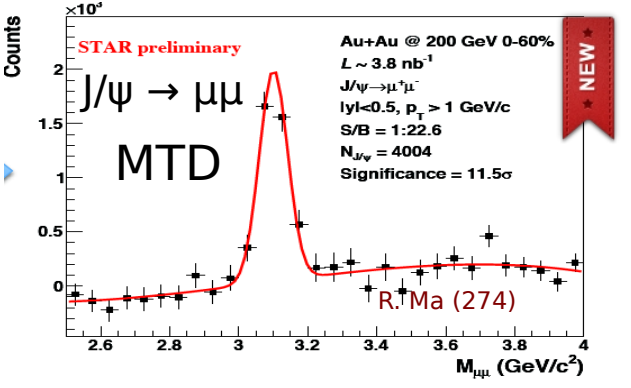


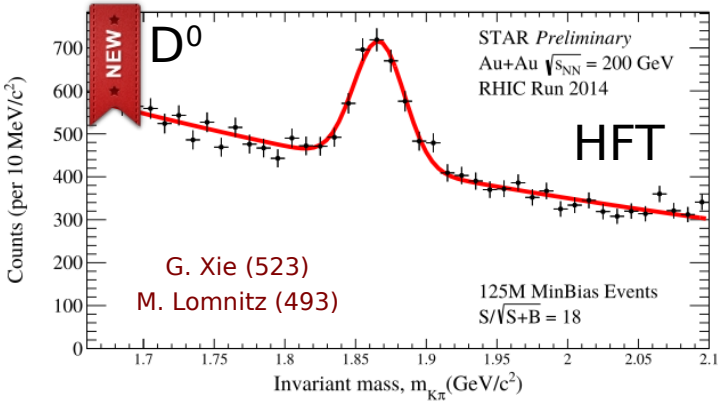
Excellent long-lived hadron and electron identification

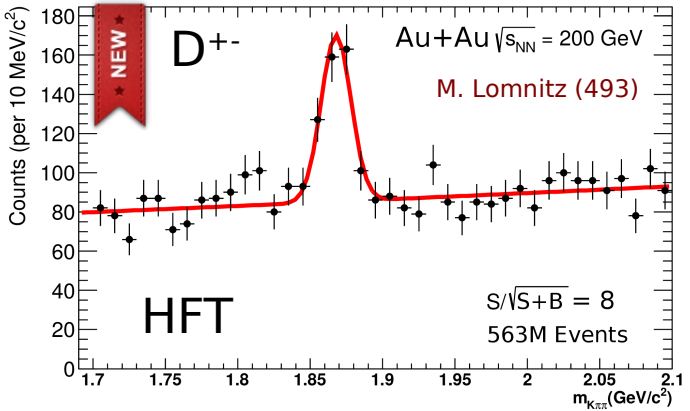
Particle Identification

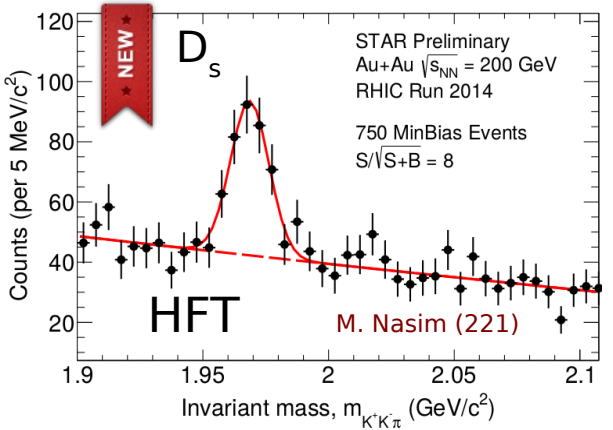












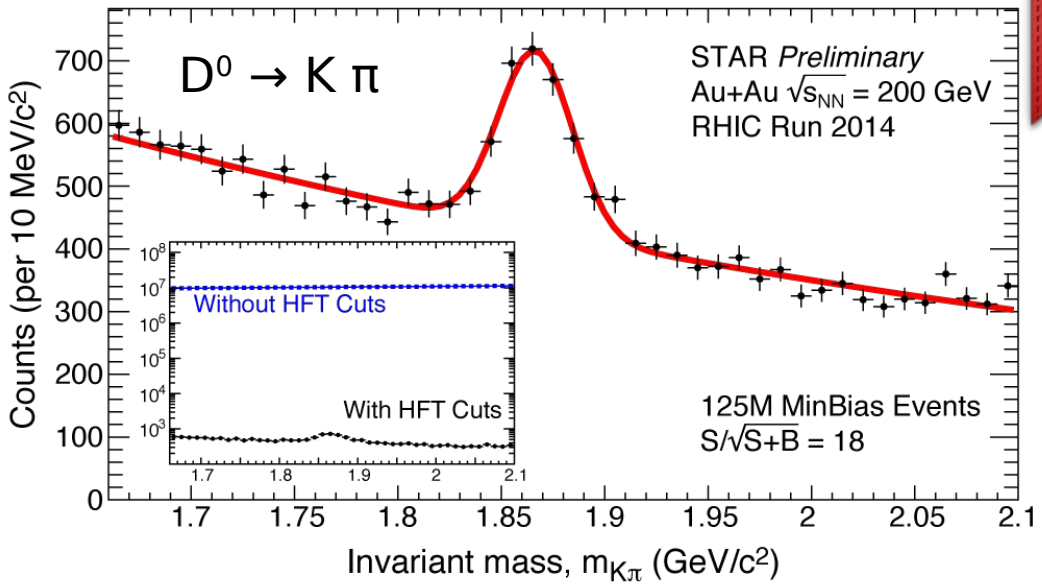
Excellent long-lived hadron and electron identification

Secondary vertex reconstruction with HFT → Full kinematics reconstruction of charmed hadron

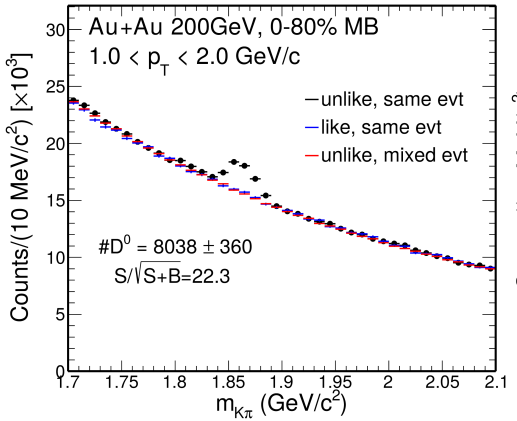
Muon/Quarkonia identification using MTD

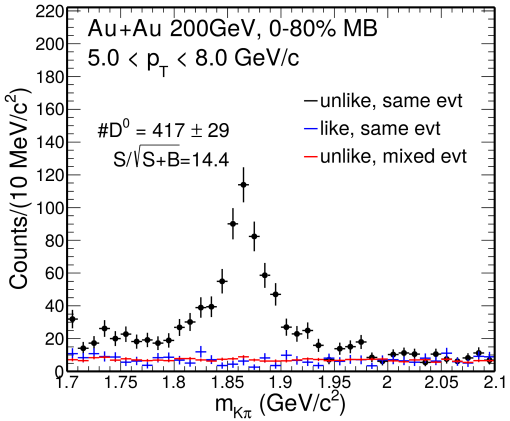
Topological Reconstruction of D^0

	w/o HFT	w HFT
significance/ billion events	13	51



- ~4 orders of magnitude reduction of combinatorial background
  → Highly enhanced S/B
- Total significance ~ 39 (MinBias – p_T inclusive)



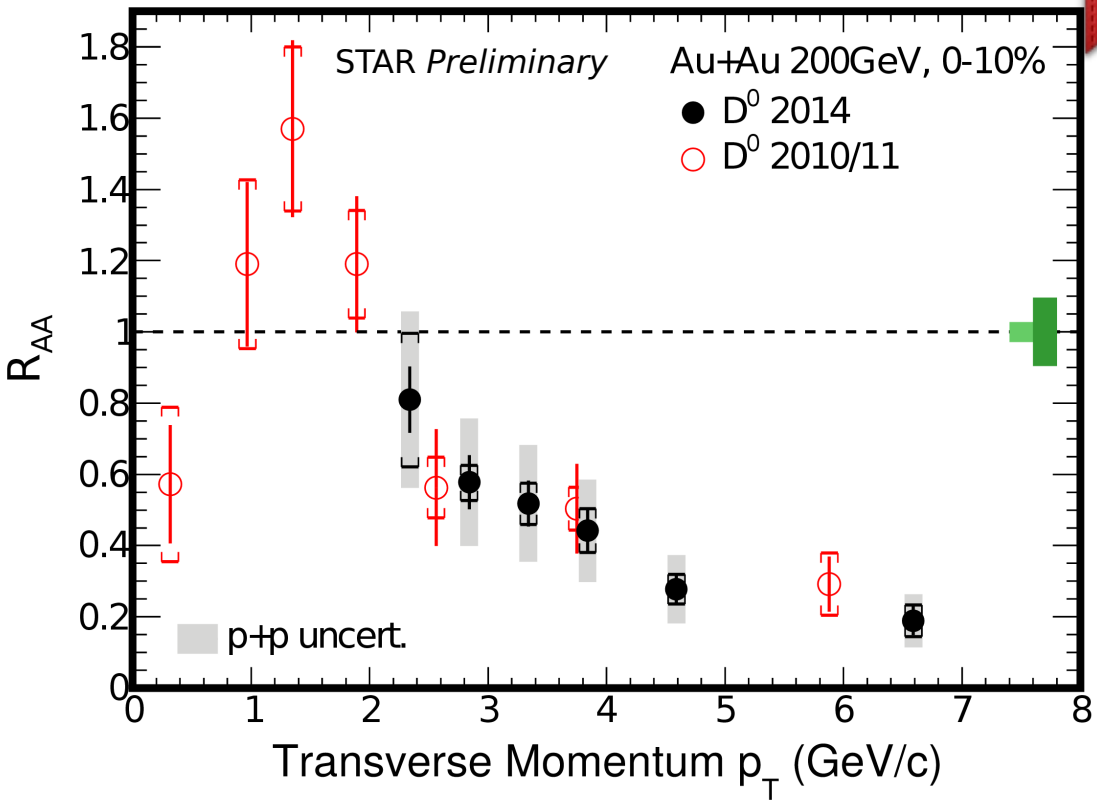


D^0 Nuclear Modification Factor (R_{AA})

- Significant improvement in central Au+Au D^0 measurement using HFT

- Enhanced D mesons for p_T < 2 GeV/c

  → Manifestation of charm coalescence with a flowing medium



STAR, PRL 113 (2014) 142301

NEW

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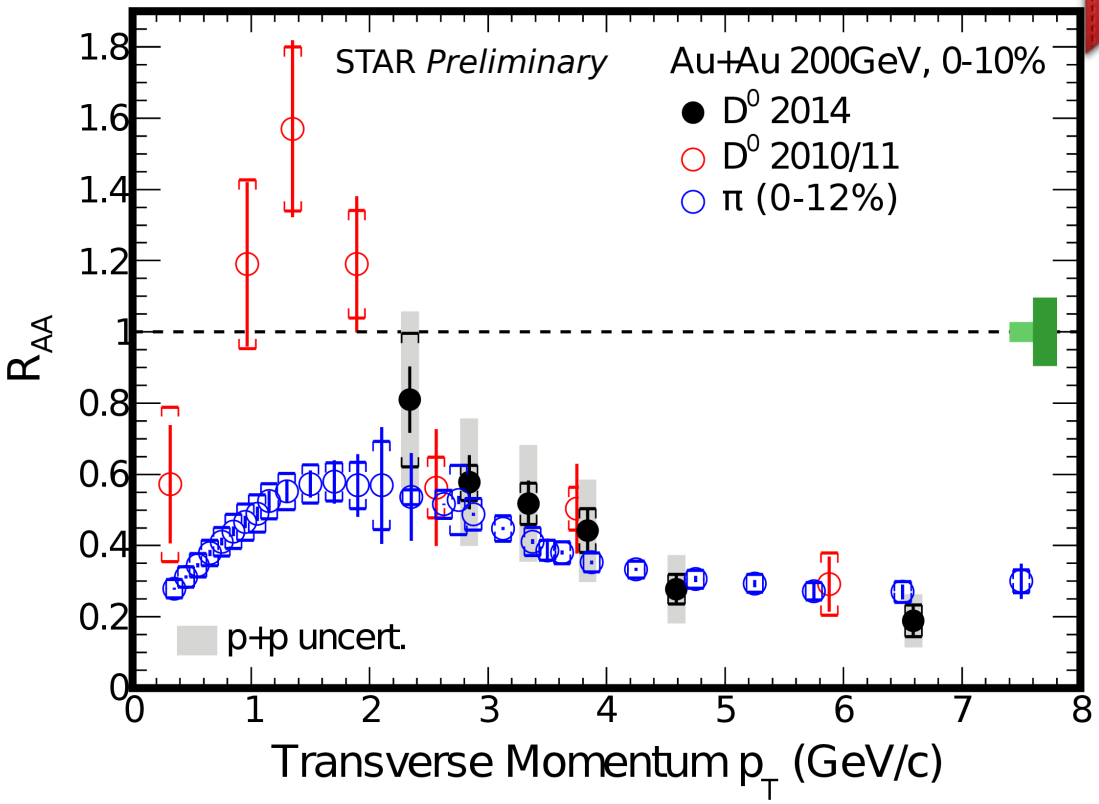
- D mesons are suppressed at high p_T
  → R_{AA} (h) ~ R_{AA} (D)
  → Charm energy loss is an interplay of elastic and radiative energy loss



STAR, PRL 113 (2014) 142301
STAR, PLB 655 (2007) 104

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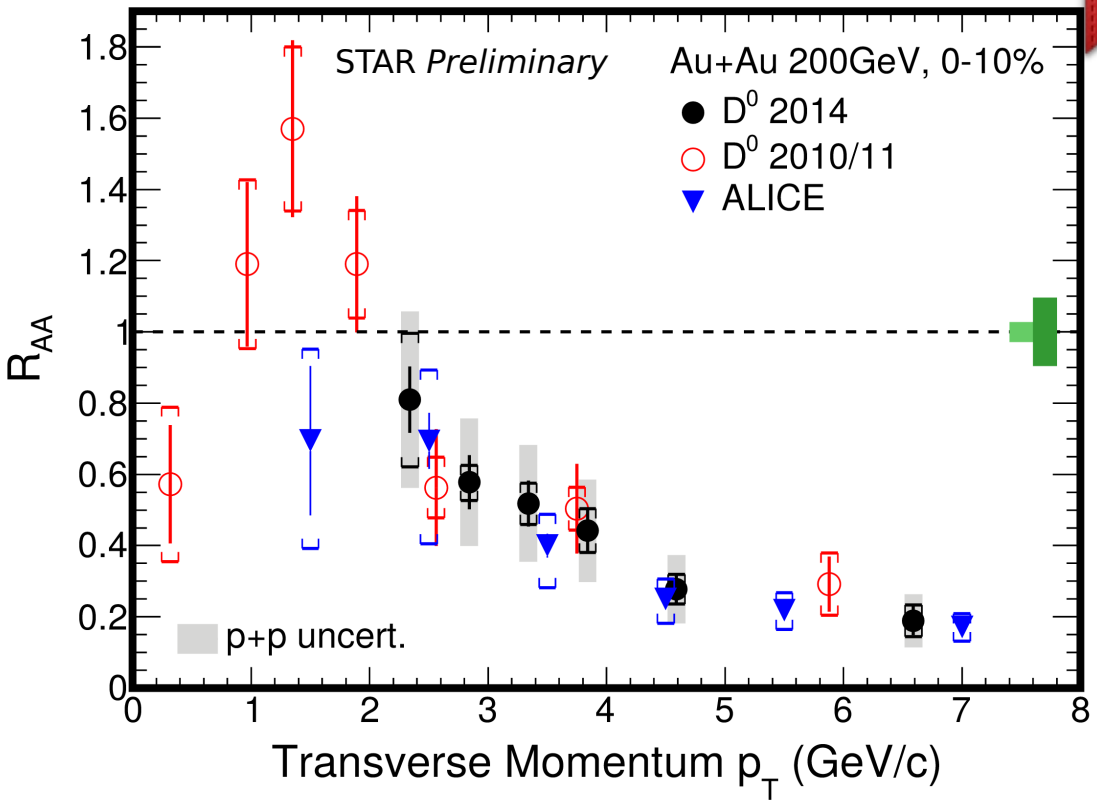
- D mesons are suppressed at high p_T
  → R_{AA} (h) ~ R_{AA} (D)
  → Charm energy loss is an interplay of elastic and radiative energy loss
  → R_{AA} @ RHIC ~ R_{AA} @ LHC

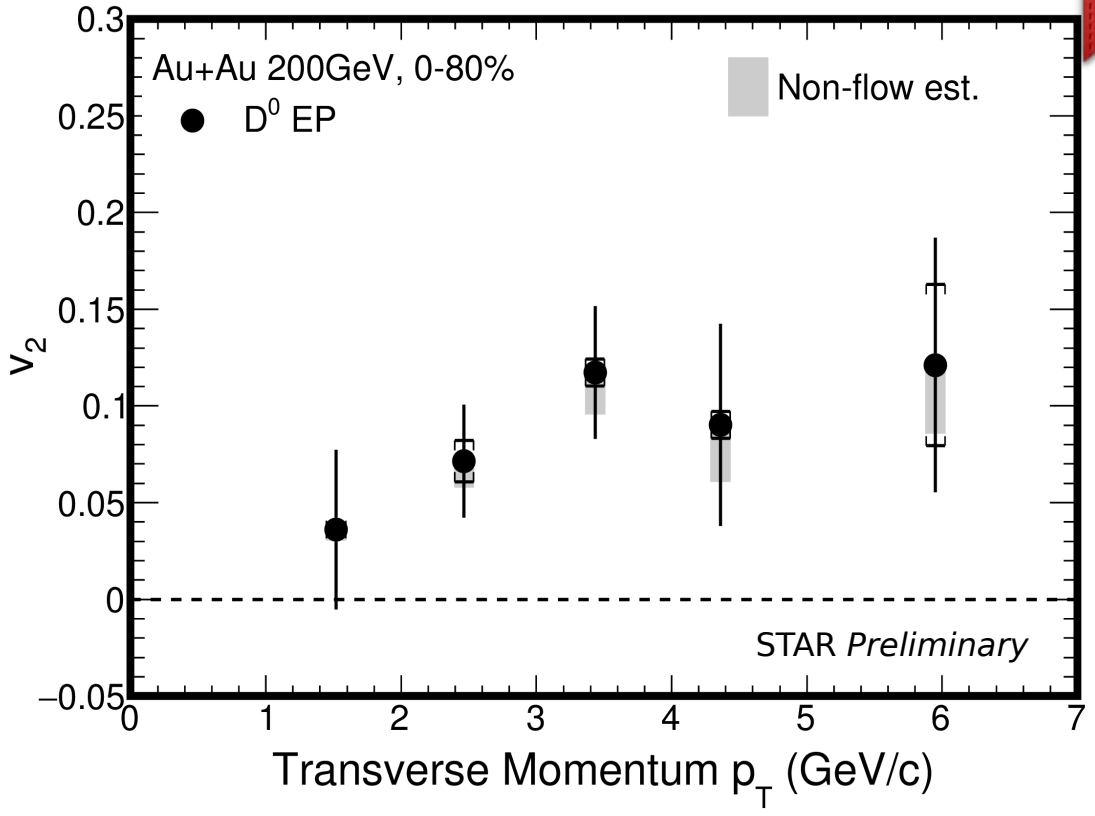


STAR, PRL 113 (2014) 142301
ALICE, arXiv: 1509.06888

NEW

D^0 Azimuthal Anisotropy (v_2)

- Finite D^0 v_2 observed (p_T > 2 GeV/c) at top RHIC energy

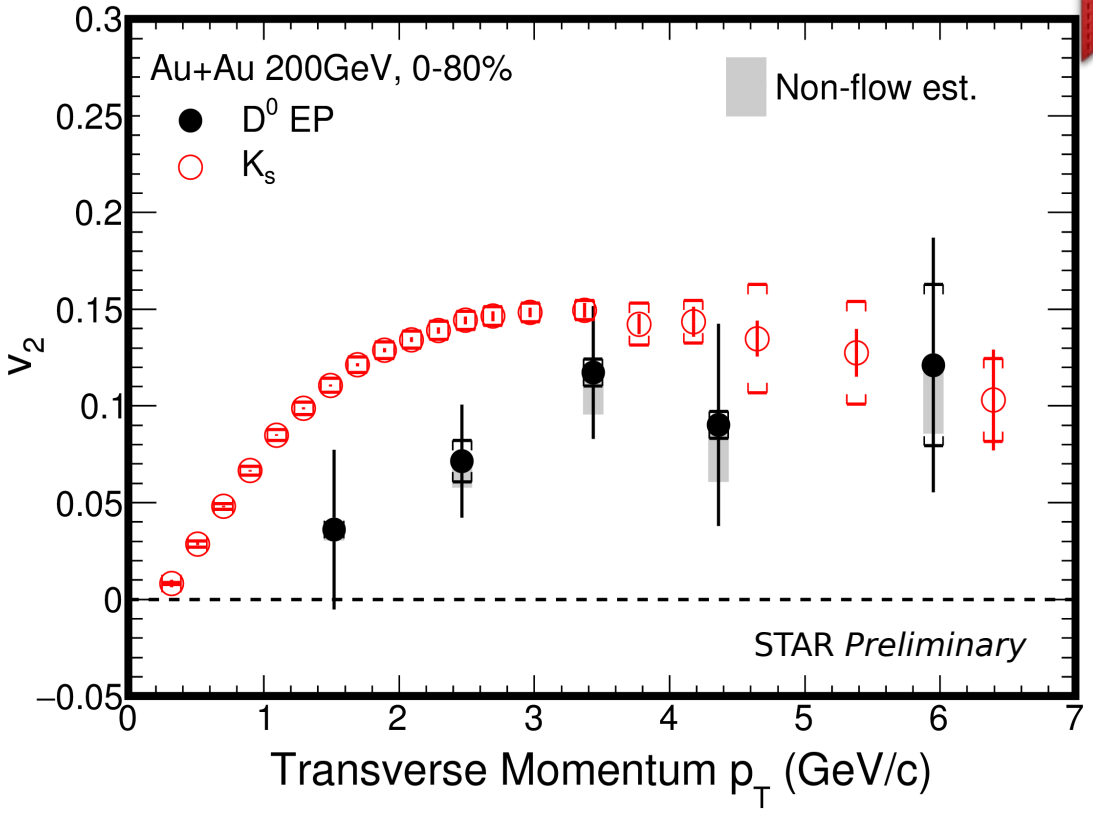


D^0 Azimuthal Anisotropy (v_2)

- Finite D^0 v_2 observed (p_T > 2 GeV/c) at top RHIC energy

- D^0 v_2 is lower than those of light hadrons for p_T < 4.0

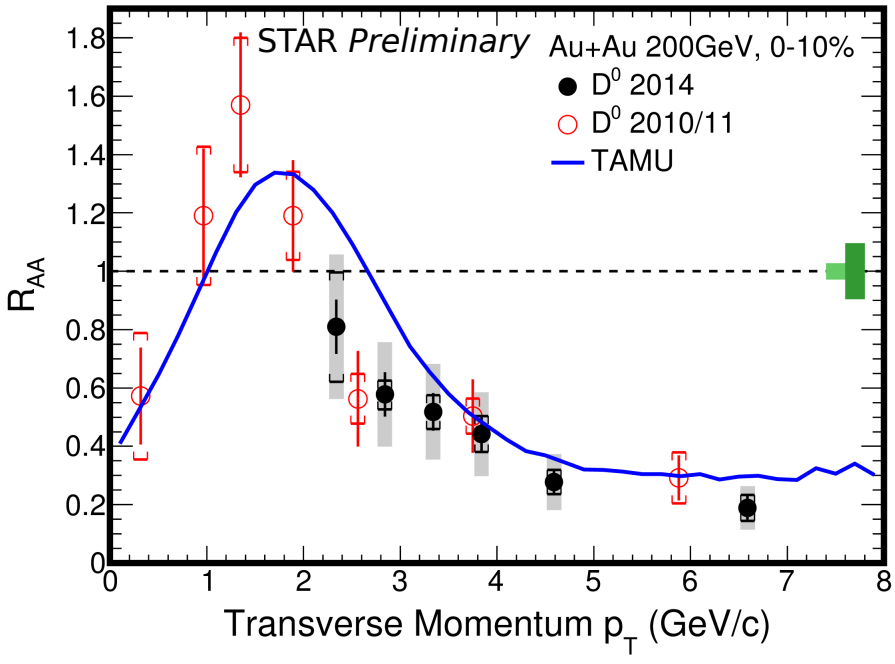
  → What can we learn about charm thermalization with the medium?

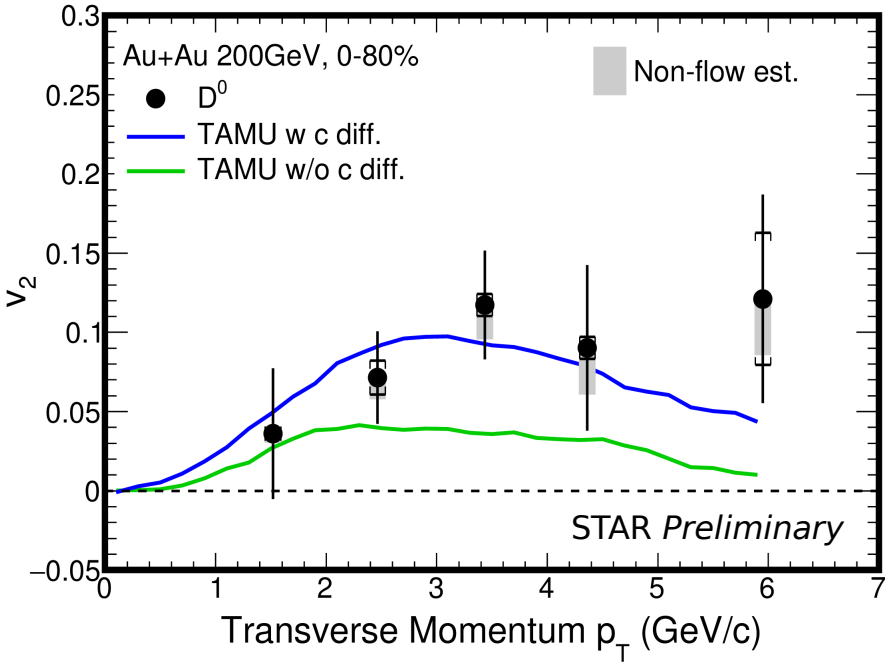


STAR, PRC 77 (2008) 54901

NEW

Comparison to Theory



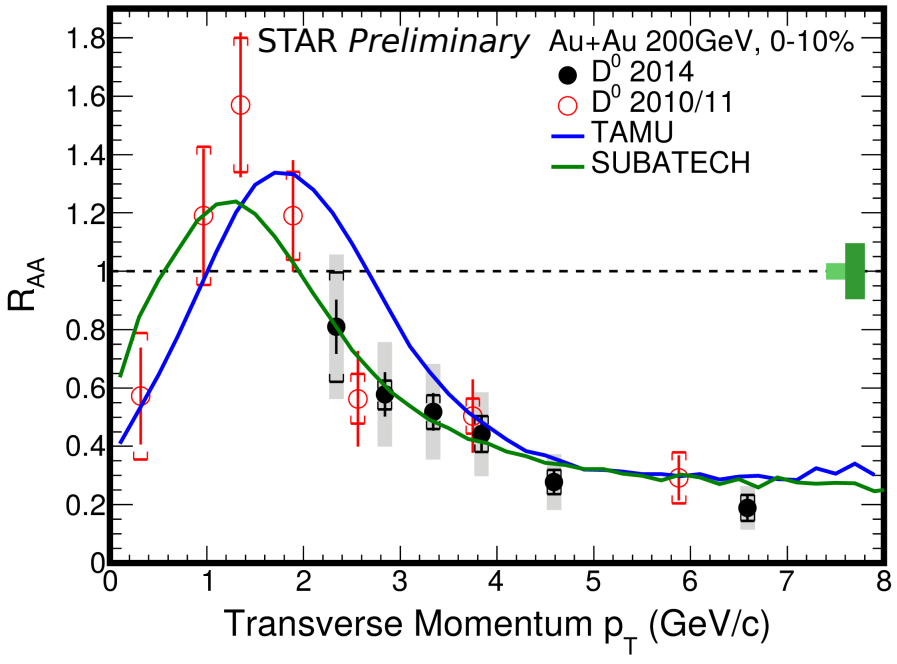


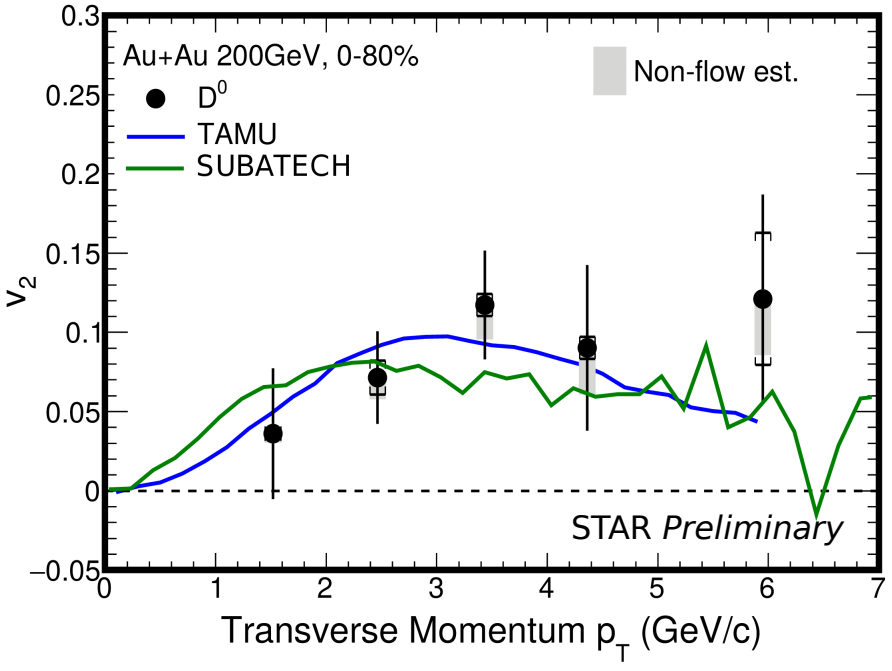
- Data favors models with charm diffusion
  → charm exhibits collectivity with the medium

	D × 2πT	Diff. Calculation
TAMU	2-11	T-Matrix

arXiv:1506.03981 (2015) & private comm.

Comparison to Theory





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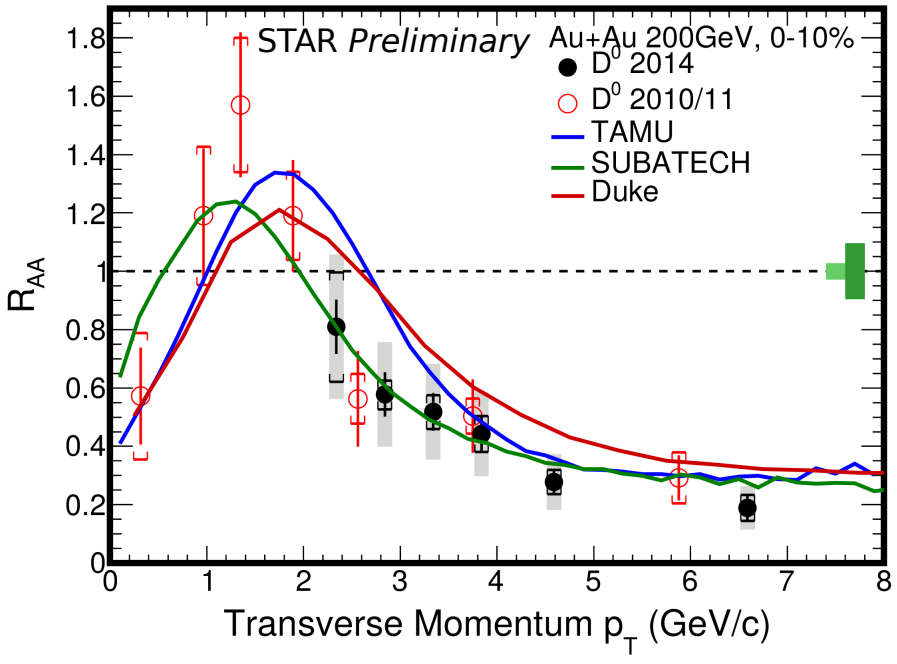

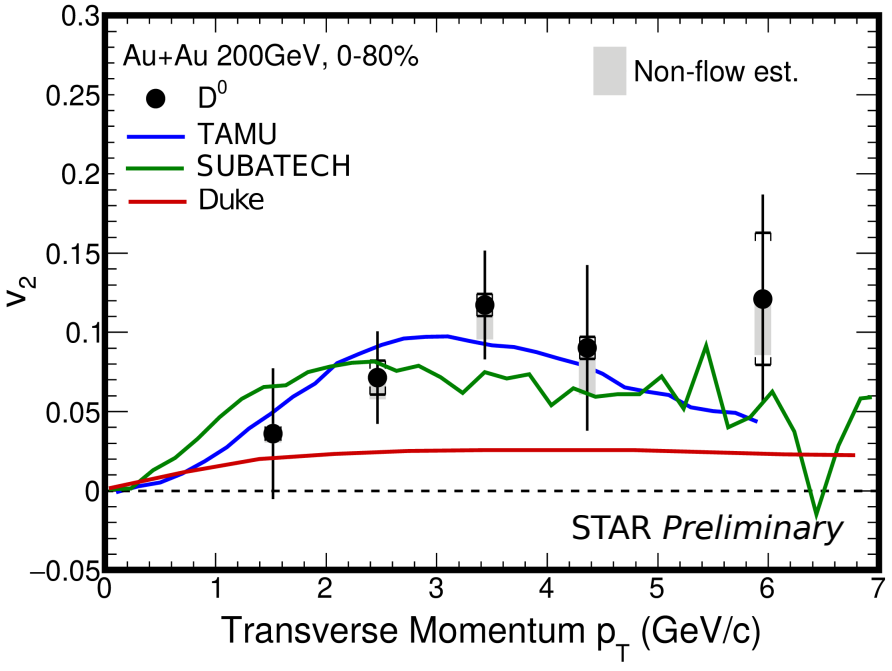

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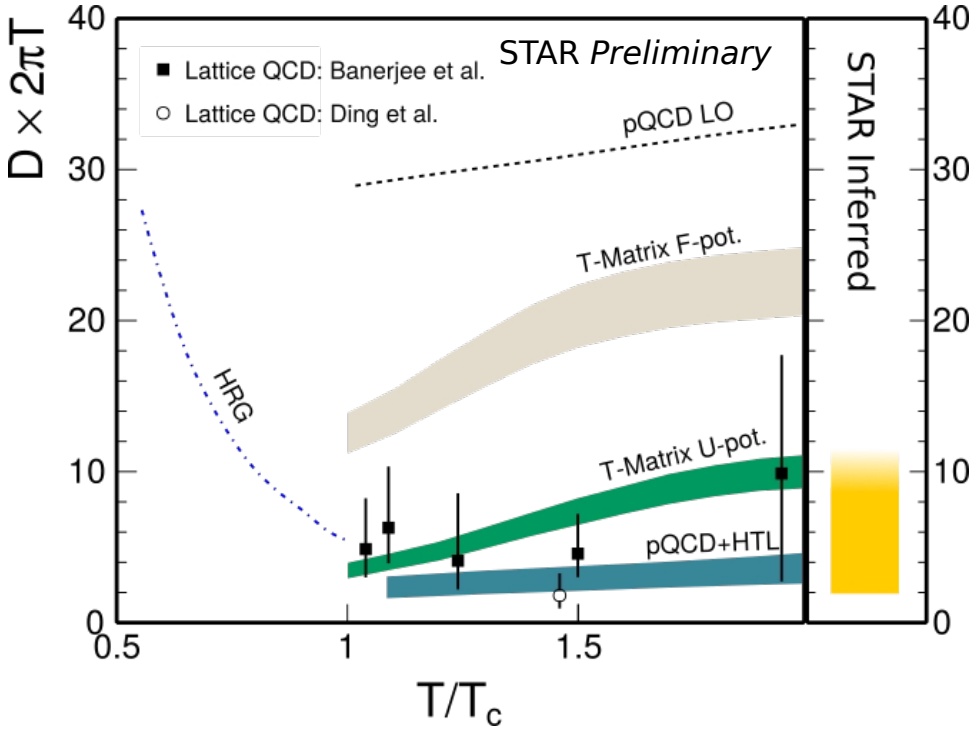
SUBATECH	2-4	pQCD+HTL
Duke	7	Free parameter

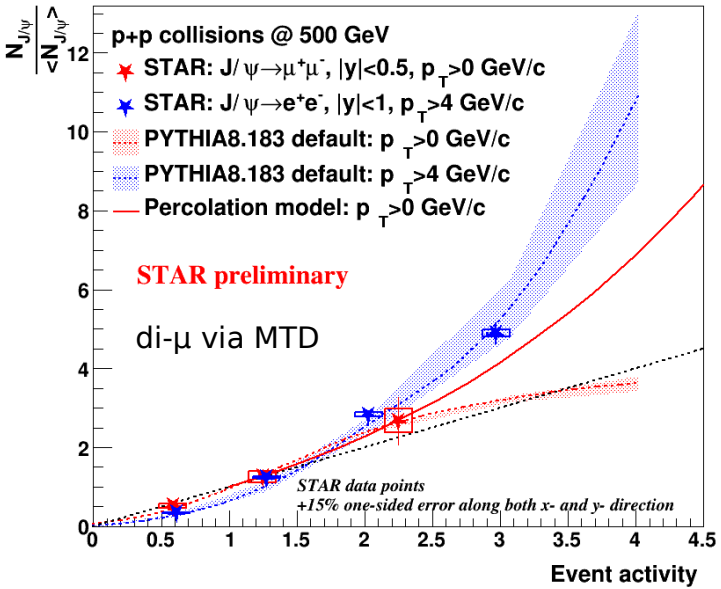
arXiv:1506.03981 (2015) & private comm.

Comparison to Theory II – Charm Diffusion Coefficient



- Models with charm diffusion coefficient of 2 - ~10 describe STAR R_{AA} and v_2 data
- Lattice calculations are consistent with values inferred from data

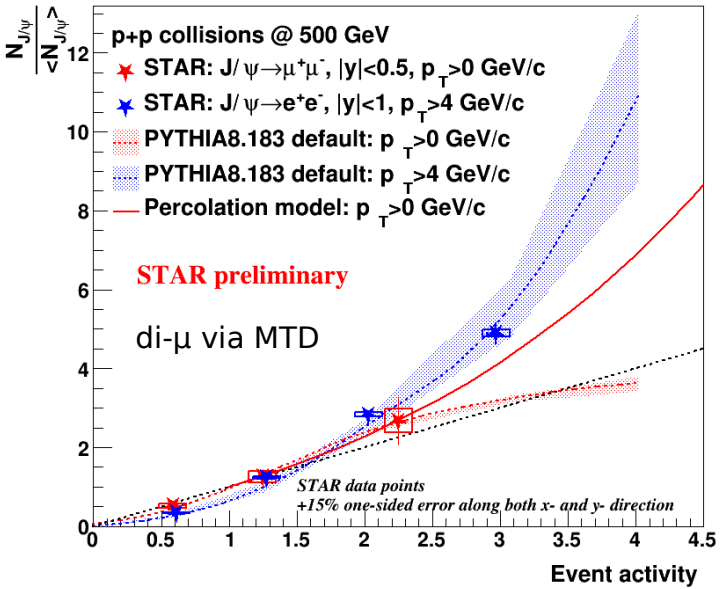
Quarkonia in p+p highlights

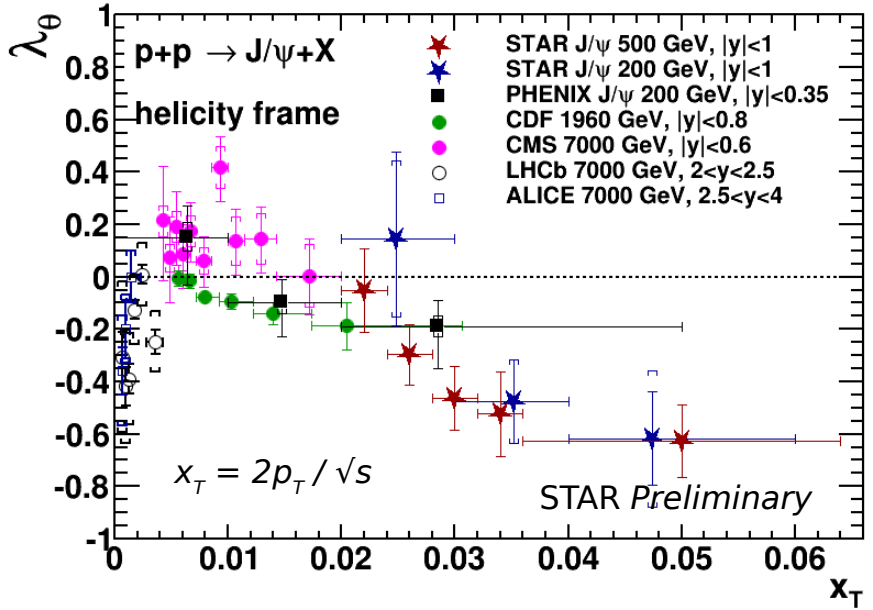


- Correlation between relative J/ψ yields and relative charged particles multiplicity (event activity), and for higher multiplicities stronger than linear growth at p_T > 4 GeV/c observed

- PYTHIA 8 and Percolation Model describe the observed increase Percolation: Ferreiro et. al., PRC 86 (2012) 034903

Quarkonia in p+p highlights





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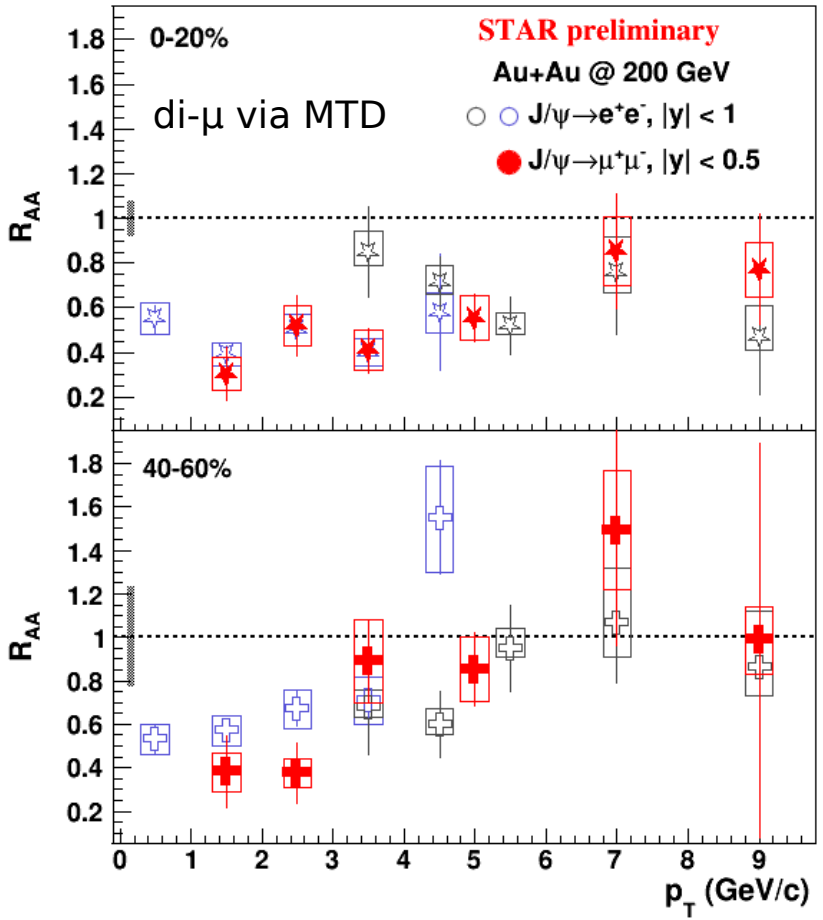
- J/ψ polarization (λ_θ): common trend towards strong negative values with x_T (in the helicity frame)

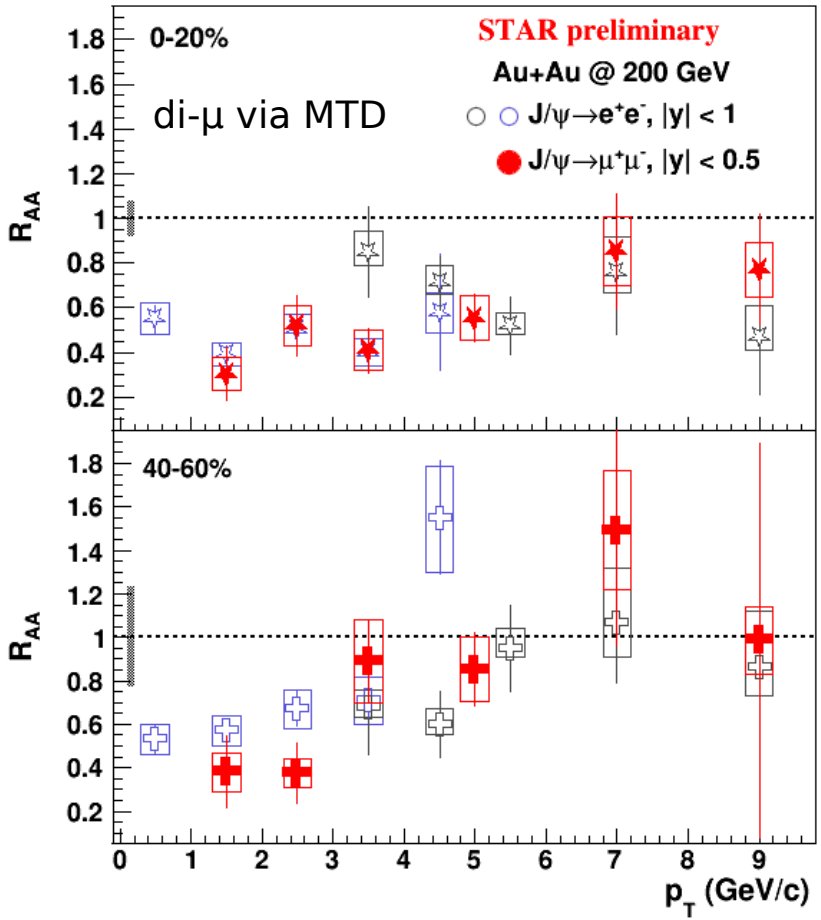
Quarkonia in Au+Au



- p_T < 5 GeV/c: suppression in all centralities. Rising trend with p_T
- Consistent R_{AA} using di-muon and di-electron channels

Di-electron: PLB 722 (2013) 55, PRC 90, 024906 (2014)

Quarkonia in Au+Au



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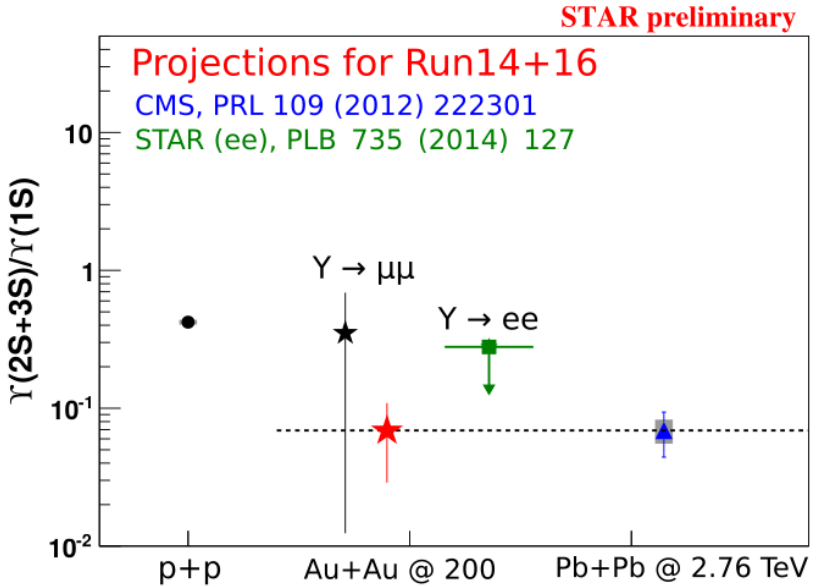
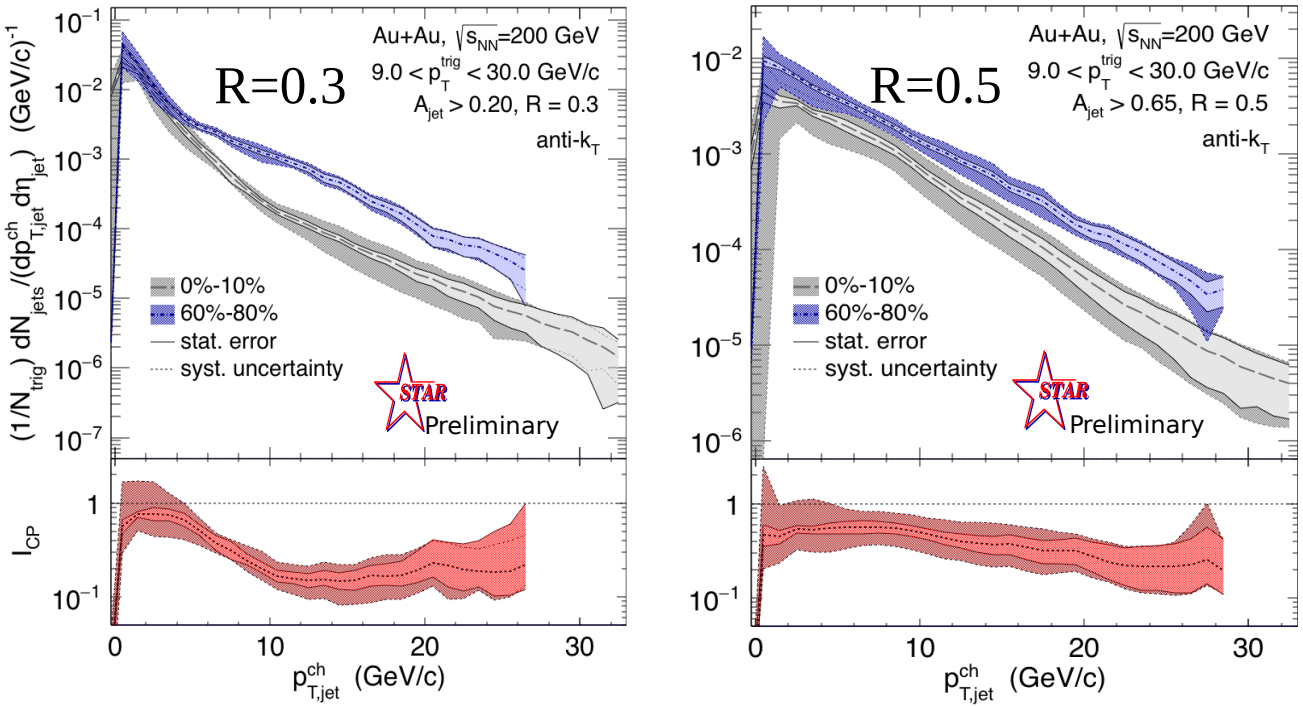
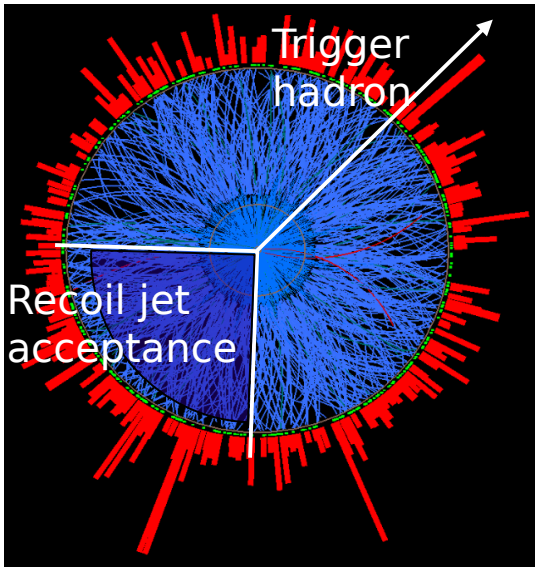


- p_T < 5 GeV/c: suppression in all centralities. Rising trend with p_T
- Consistent R_{AA} using di-muon and di-electron channels
- Y signal observed in di-muon channel, full data production on the way.

Semi-Inclusive Charged Jets in Au+Au

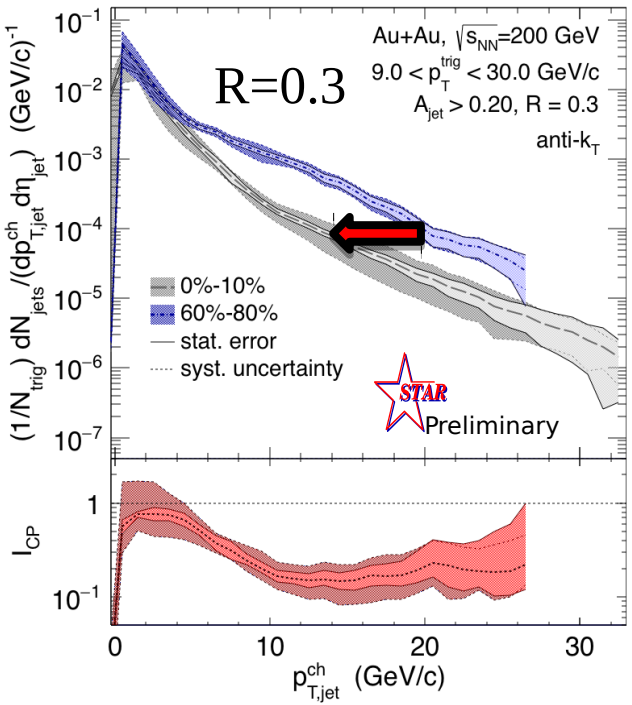


Trigger-normalized yield of jets recoiling from a high p_T hadron trigger.

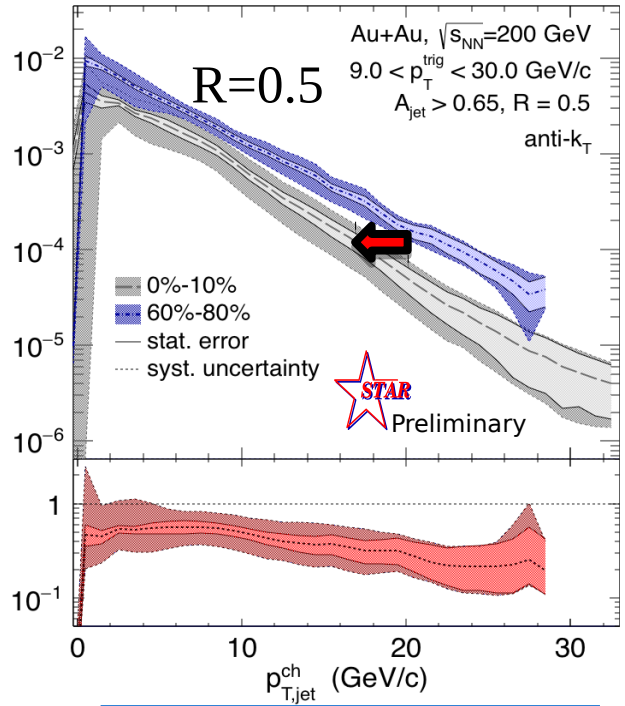


$$\frac{1}{N_{trig}^{h}} \frac{dN_{jet}}{dp_{T,jet}} = \frac{1}{\sigma^{AA \to h+X}} \frac{d\sigma^{AA \to h+jet+X}}{dp_{T,jet}}$$

Semi-Inclusive Charged Jets in Au+Au

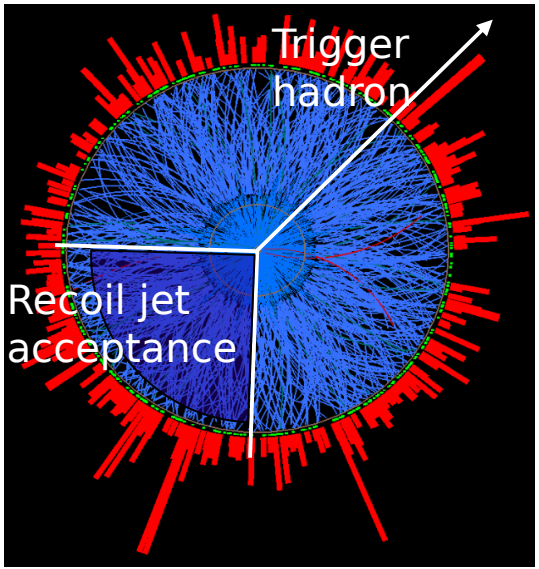


Δp_T = -6.3 ± 0.6 ± 0.8 GeV



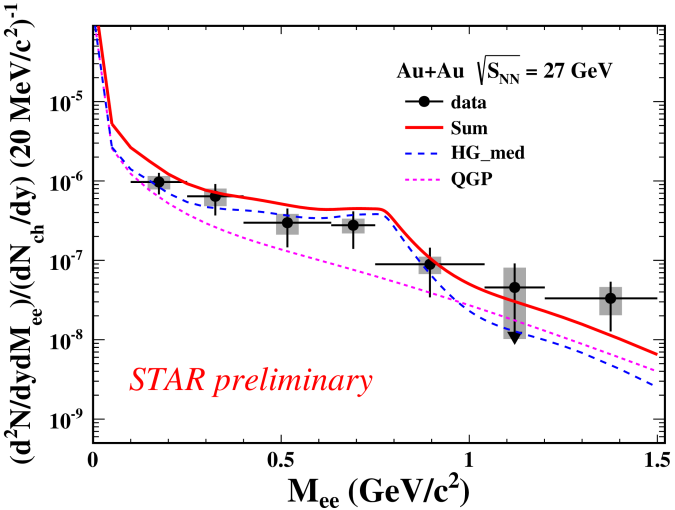
Δp_T = -3.8 ± 0.5 ± 1.8 GeV

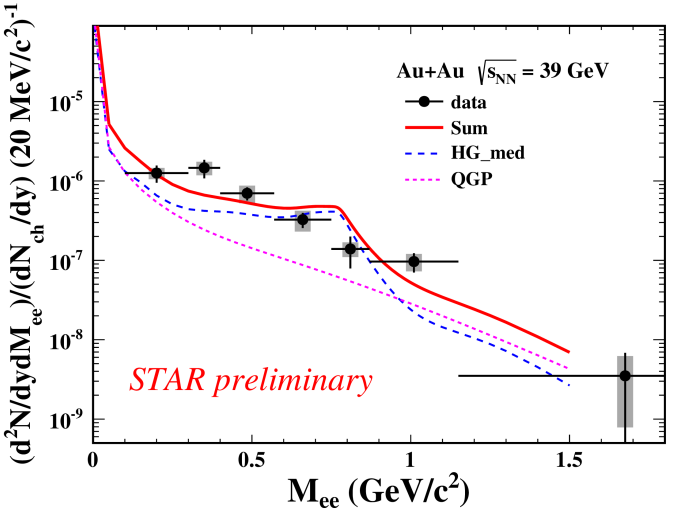
Trigger-normalized yield of jets recoiling from a high p_T hadron trigger.

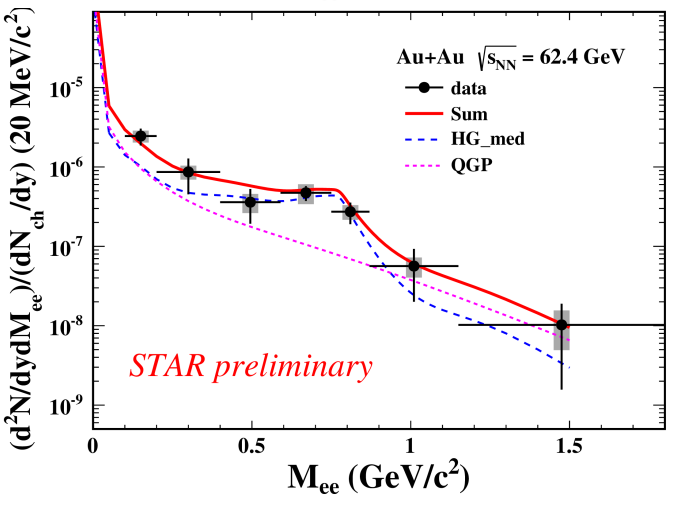


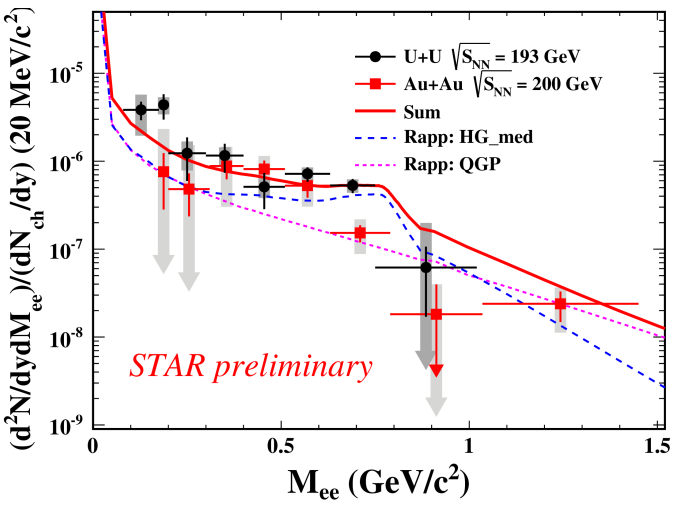
- Direct comparison to similar measurements at LHC
- Out-of-cone energy transport: hint of reduction for larger R; smaller vs. LHC
- Molière scattering of low energy jets in QGP: proof of principle

Quantifying the effect of Chiral Symmetry Restoration: Di-electrons







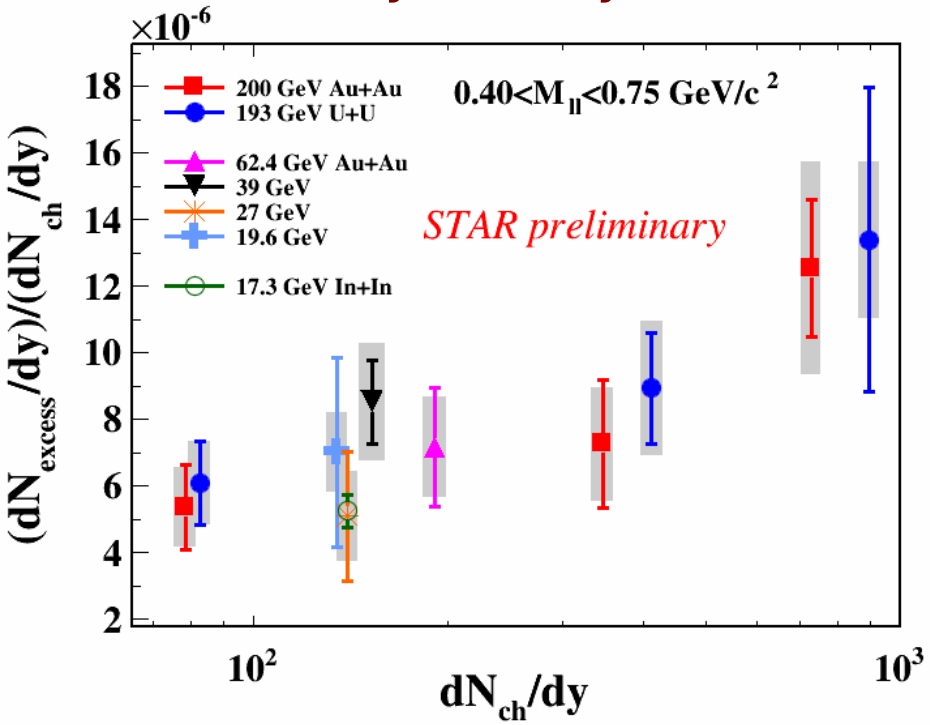


- Acceptance-corrected di-electron excess mass in 27, 39, 62.4 GeV Au+Au, and 193 U+U collisions
- In-medium ρ broadening calculations describe data across all collision energies, centralities and p_T

Theory:
R. Rapp, PRC 63 (2001) 054907

STAR, PLB 750 (2015) 64
STAR, PRC 92 (2015) 024912

Quantifying the effect of Chiral Symmetry Restoration: Di-electrons



Acceptance-corrected low-mass dielectron excess production, normalized by dN_{ch}/dy, is proportional to the lifetime of the medium from 17.3 to 200 GeV

Given that the total baryon density is nearly a constant and that the emission rate is dominant in the near-T_c region.

R. Rapp, H. van Hees, arXiv:1411.4612

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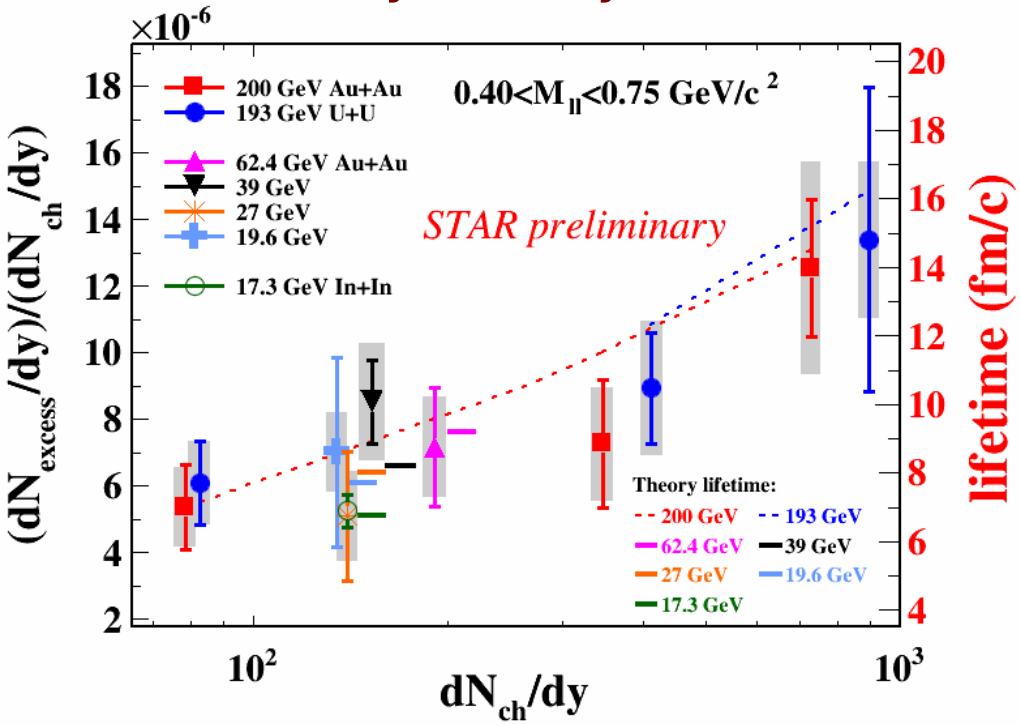

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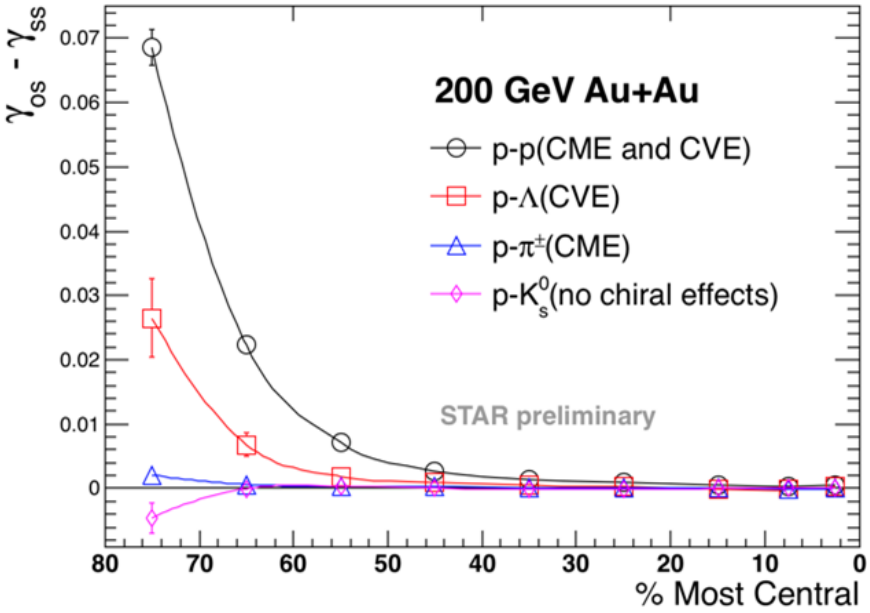
Study of Chiral Effects via PID Correlations

Chiral Magnetic Effect (CME): local chirality imbalance + magnetic field → electric charge separation
Chiral Vortical Effect (CVE): local chirality imbalance + fluid vorticity → baryonic charge separation



Separation w.r.t reaction plane was studied via a three-point correlator

$$\gamma = \left\langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \right\rangle$$

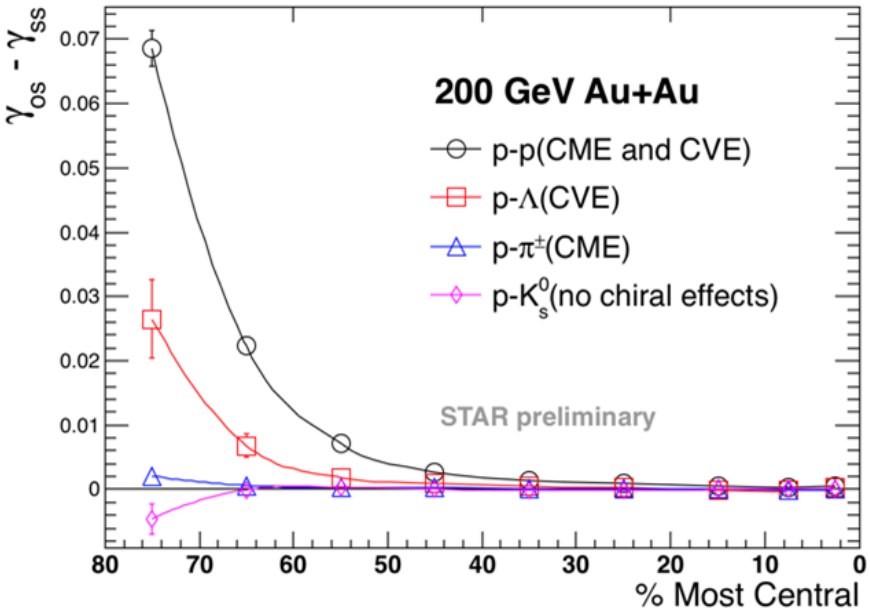
Here α and β denote particle charge, $\gamma_{os} - \gamma_{ss}$ quantifies the strength of charge separation

Correlation of different particle species → different sensitivity to CME/CVE

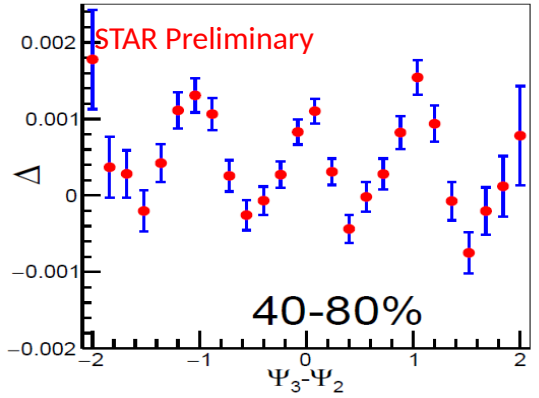
Study of Chiral Effects via PID Correlations

NEW

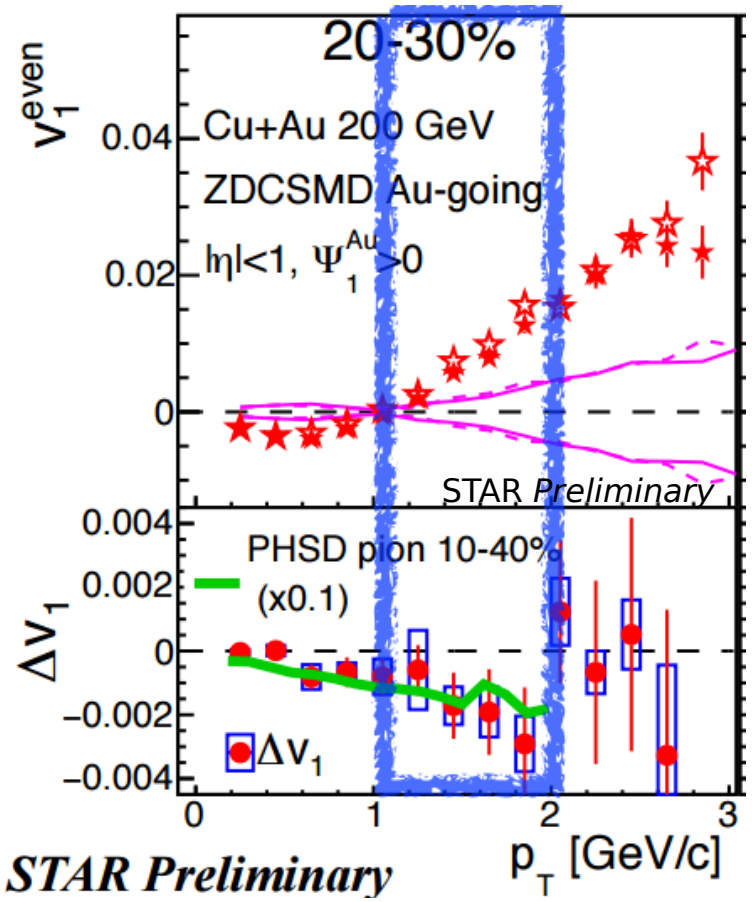
Chiral Magnetic Effect (CME): local chirality imbalance + magnetic field → electric charge separation
Chiral Vortical Effect (CVE): local chirality imbalance + fluid vorticity → baryonic charge separation

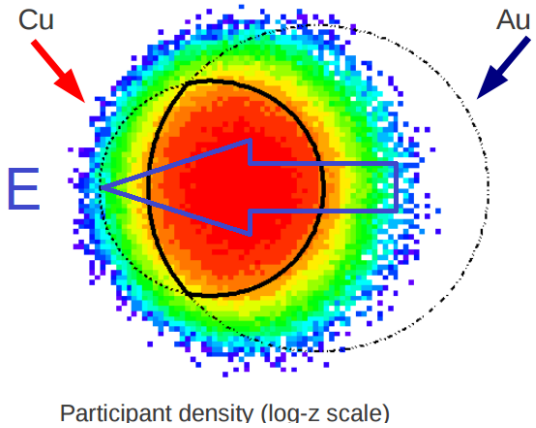


- A clear hierarchical structure was observed, which meets the expectation of chiral effects
- On-going background studies to decouple B-field, v_2 and charge separation
  - Select events with $v_2 = 0$ in non-central collisions [STAR, PRC, 89 (2014) 044908], much smaller effects observed
  - Collide nuclei with special configurations ($^{238}U+^{238}U$, $^{96}Ru+^{96}Ru$, $^{96}Zr+^{96}Zr$)
  - Measure impact of initial E-field independently (Cu+Au)



Study of initial E-field via v_1 in Cu+Au





Sizable E-field pointing from Au to Cu

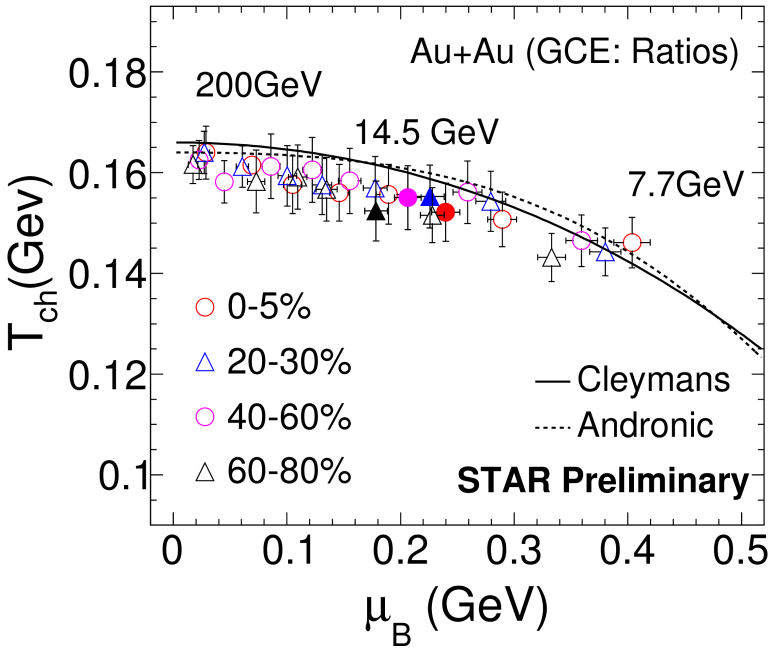
→ Expect charge dependent v_1 relevant to CME/CMW

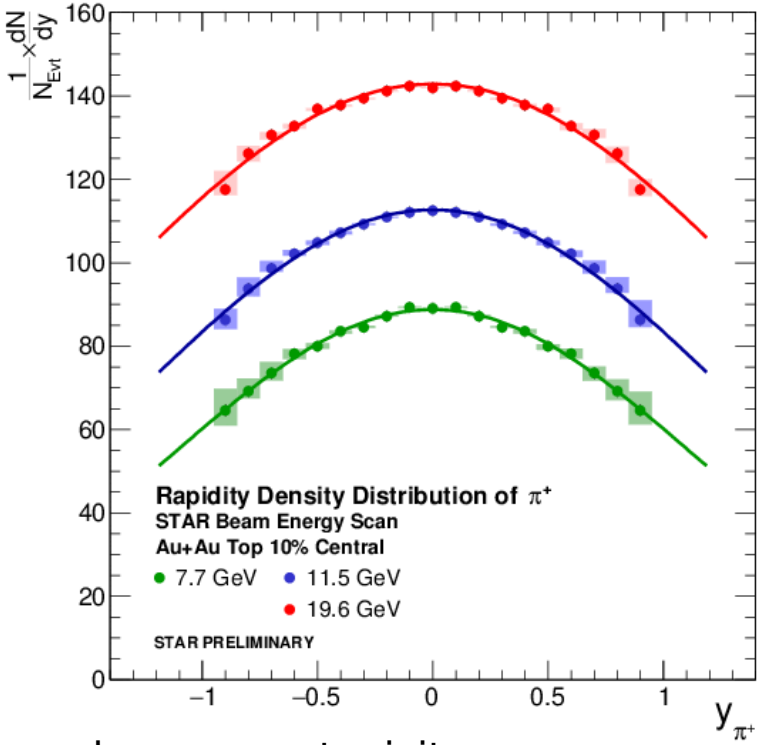
quark/anti-quark creation time

- $\Delta v_1 = v_1 (h^+) - v_1 (h^-)$ shows the right sign as expected by the model with initial E-field
- E-field does leave an imprint. So should the B-field? (CME/CMW)
- Help constrain the initial quark/anti-quark production

Beam Energy Scan I (BES-I)

$\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39GeV



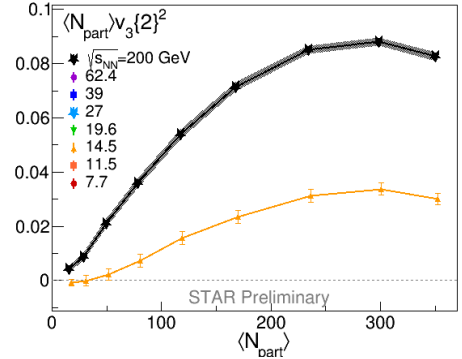


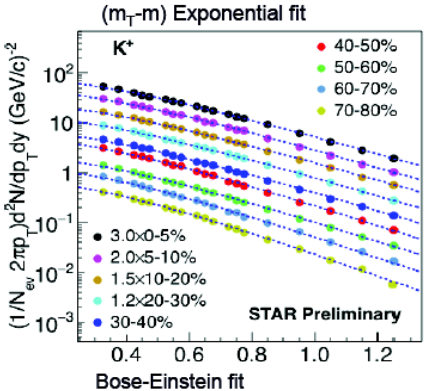
- BES-I: $20 < \mu_B$ (MeV) < 420.
- A suite of observables are studied for rapid changes and non-monotonicity
  - Directed, elliptic and triangular flow
  - Spectra, and nuclear modification factors
  - Femtoscopy
  - Higher moments

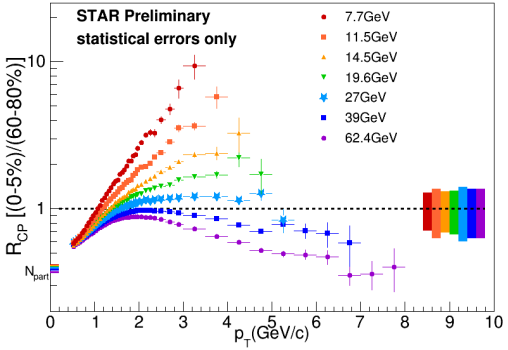
New measurements at $\sqrt{s_{NN}}$ = *14.5 GeV*

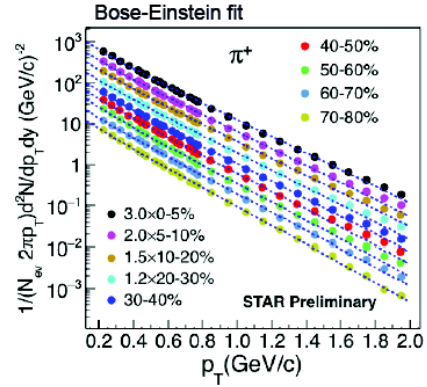
STAR *Preliminary*

NEW



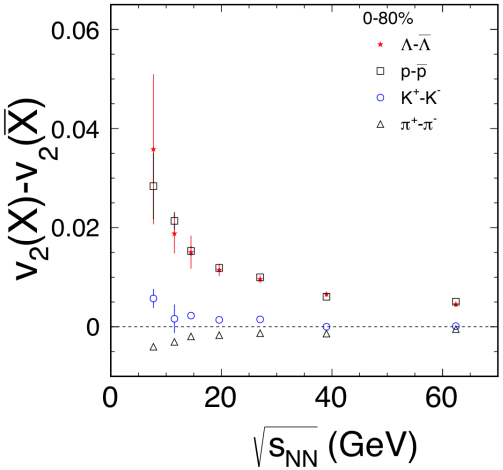




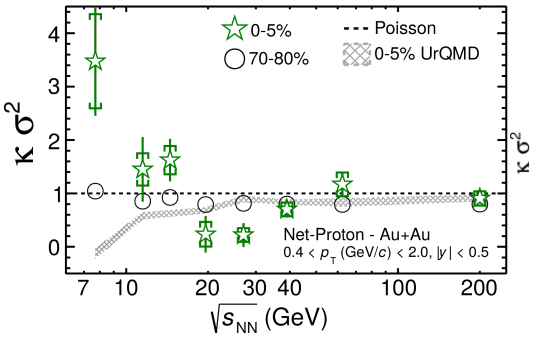


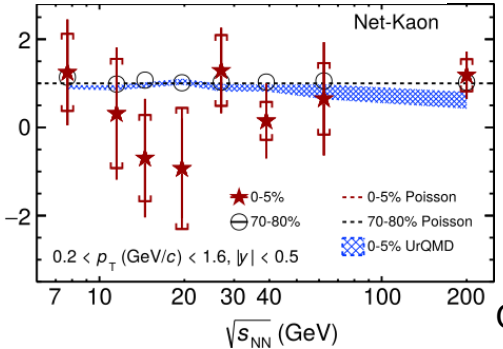
Fills the 205 < μ_B < 315 gap

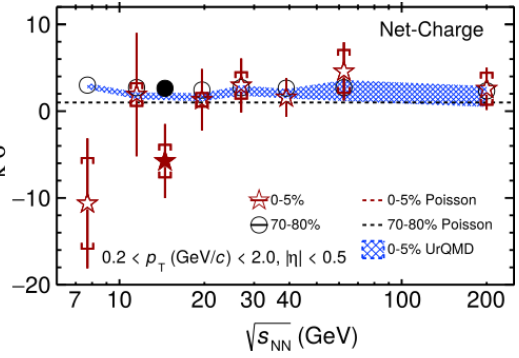
All measurements follow the trends of BES-I

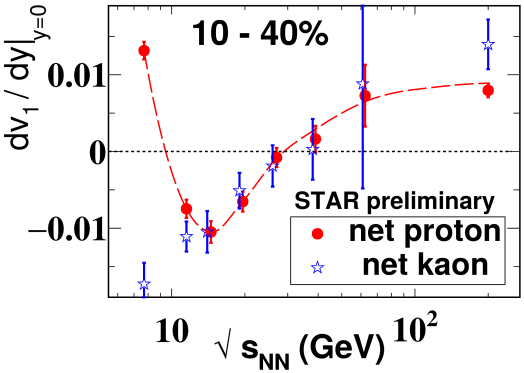


Jochen Thaeder (153)
Prashanth Shanmuganthan (398)
Liao Song (258)
Vipul Bairathi (492)
Daniel Brandenburg (606)
Chris Flores (320)
Stephen Horvat (323)

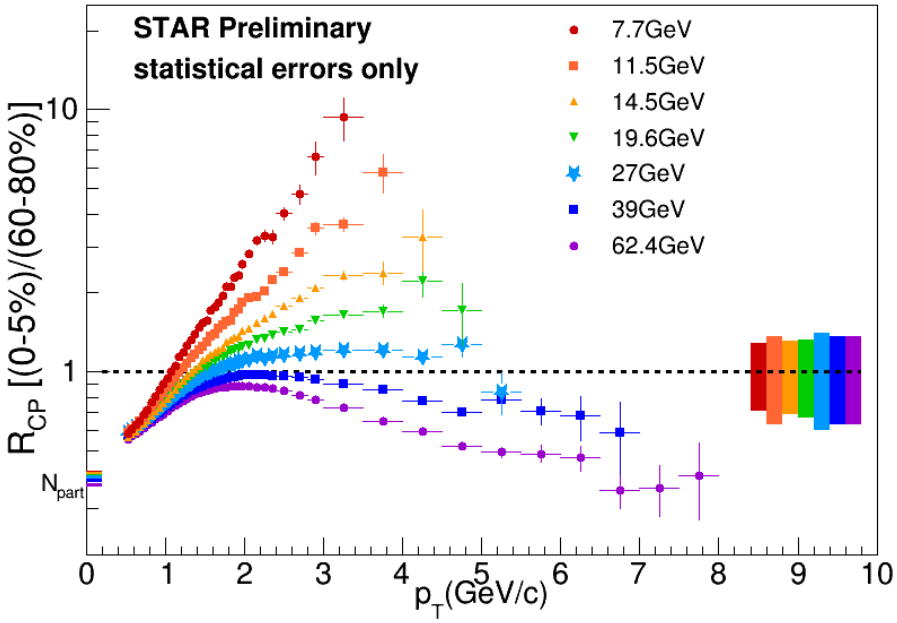






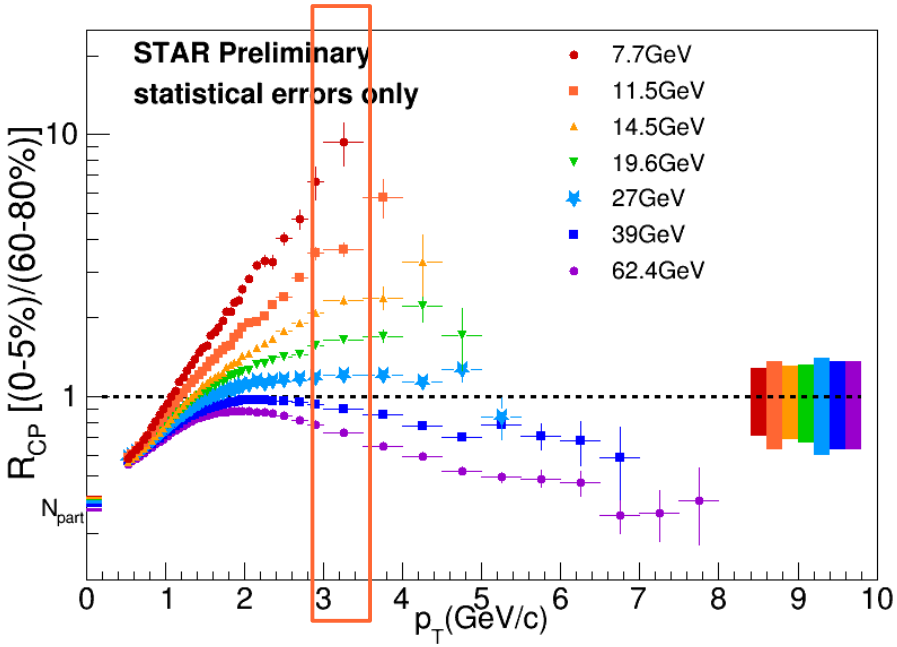


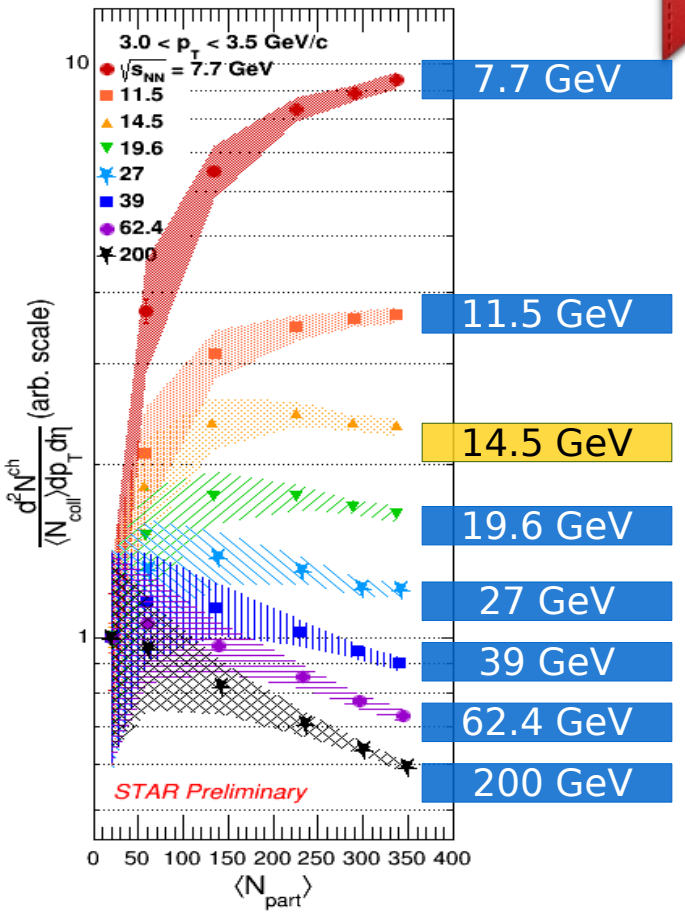
Search for the Onset of QGP Formation: Charged Hadrons R_{cp}



- Smooth transition from a strong suppression at high energies to enhancement at lower beam energies.
- Cronin effects play a bigger role at lower energies.

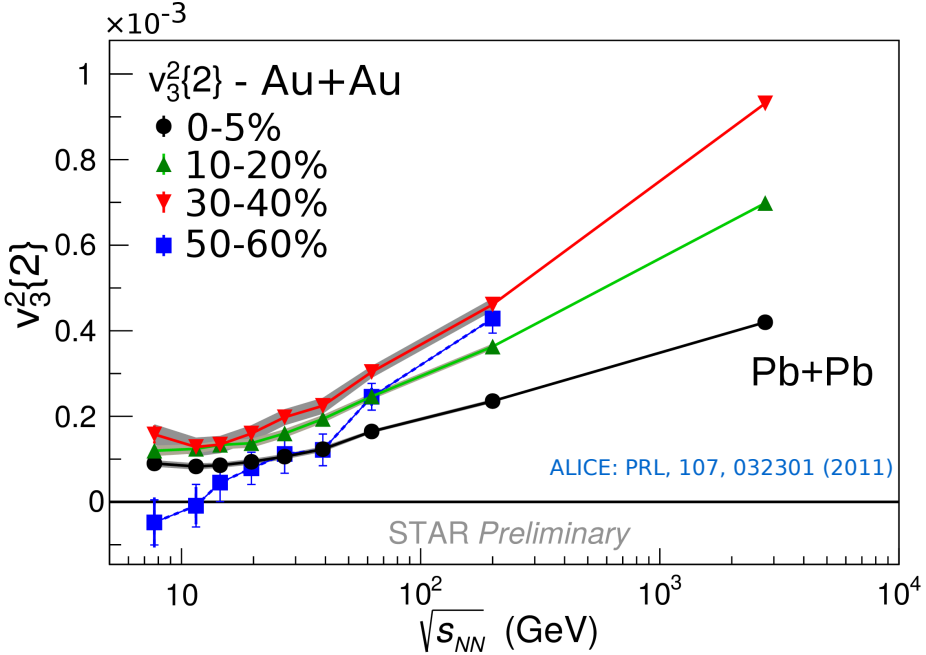
Search for the Onset of QGP Formation: Charged Hadrons R_{cp}





- Smooth transition from a strong suppression at high energies to enhancement at lower beam energies.
- Cronin effects play a bigger role at lower energies.
- Yields per binary collision show indicates a balance of enhancement and suppression effects at $\sqrt{s_{NN}}$ = 14.5 GeV.

Search for the Onset of QGP Formation: v_3

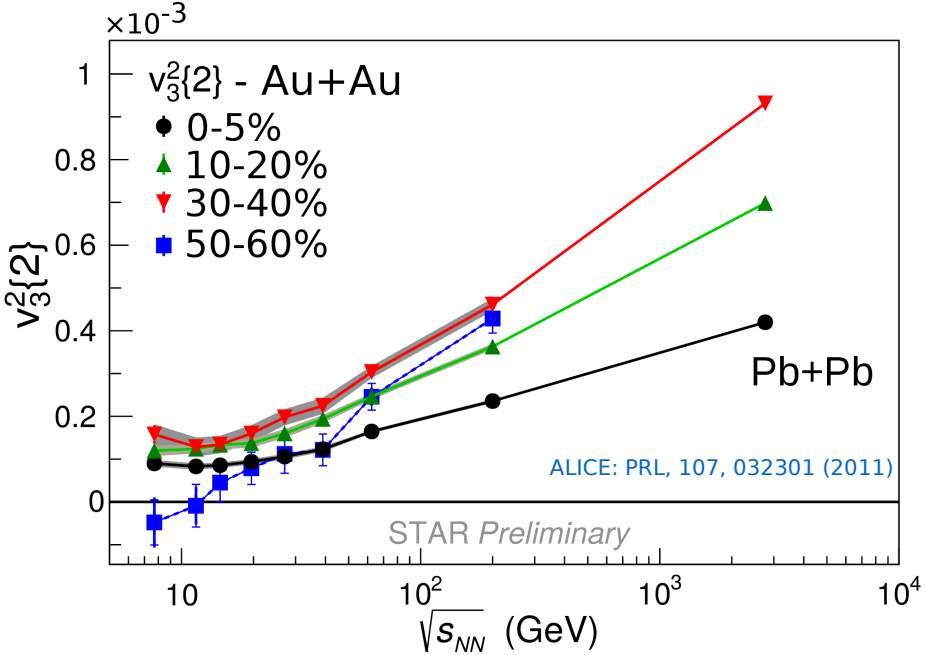


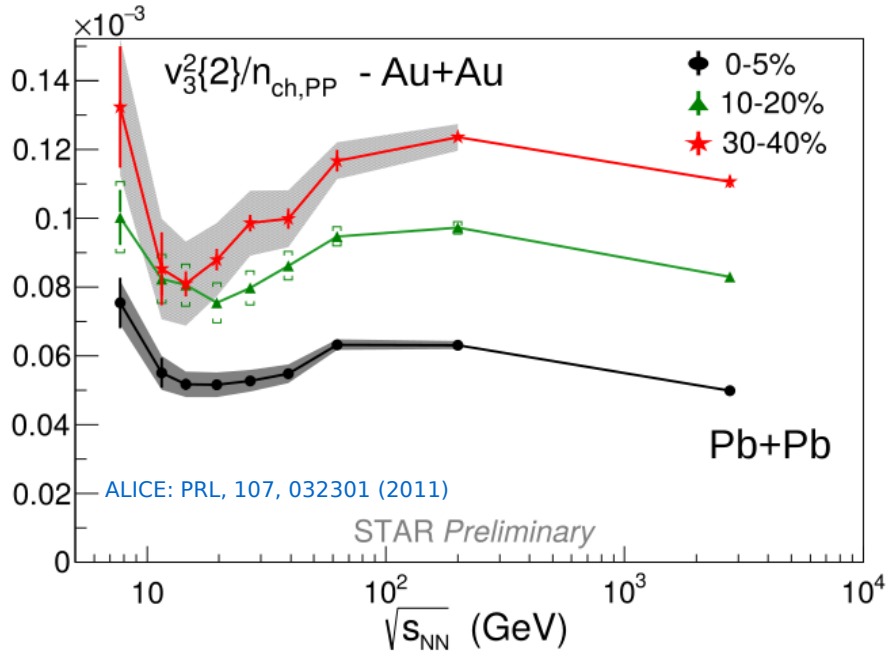
Triangular flow is argued to be almost directly proportional to the duration of the low-viscosity (η/s) phase

[J. Aunvine, H. Petersen PRC 88, 064908]

- Sizable v_3 at lower energies in central to mid-central centralities
- Peripheral collisions v_3 consistent with zero for $\sqrt{s_{NN}}$ less than *14.5 GeV*

Search for the Onset of QGP Formation: v_3

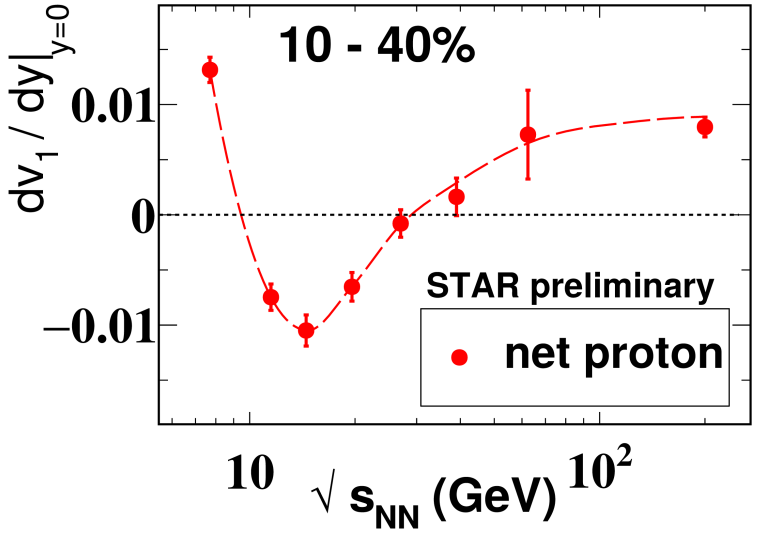




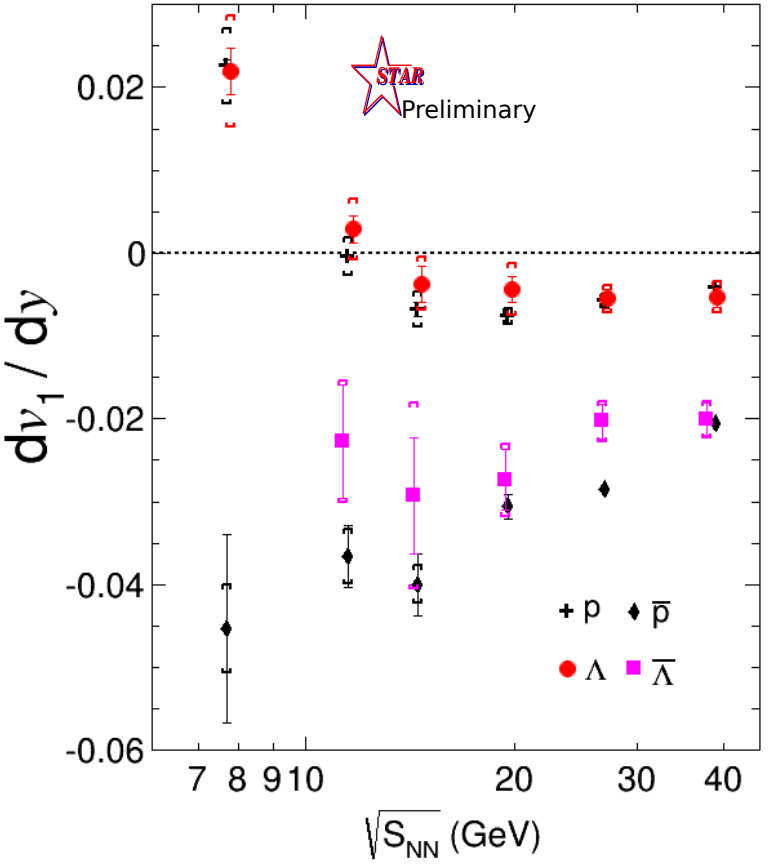
$n_{ch,PP} = dN_{ch}/d\eta/(N_{part}/2)$ is the multiplicity per participant pair, proportional to the system energy density

- Scaling out the increase in the system energy density reveals a flat trend $\sqrt{s_{NN}}$ = *7.7 – 20 GeV*
- Signature of softening of EoS?

Search for Phase Transition: Directed Flow

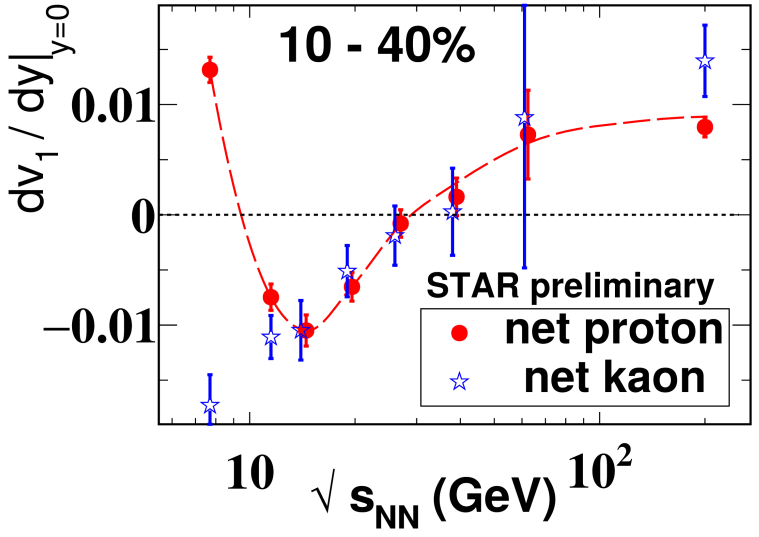


- The dip in $dv_1/dy|_{y=0}$ is argued to indicate an interplay between hydro and baryon transport dynamics (and baryon/anti-baryon annihilation)
- (Anti)-Lambdas dv_1/dy closely follow those of (anti)-protons

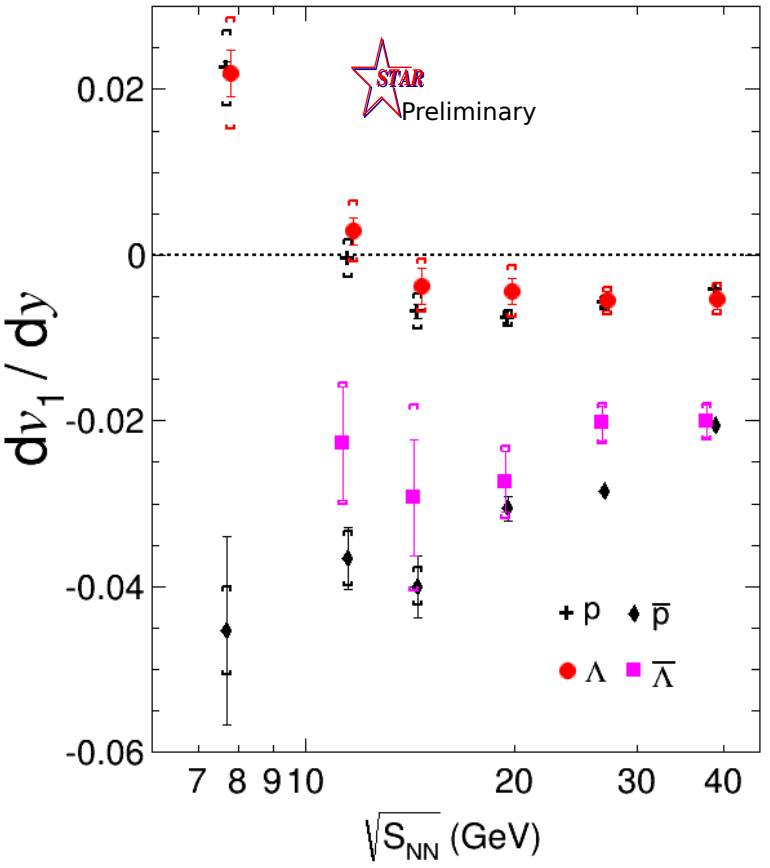


π^{+-}/ K^{+-}/ (anti-)p/ (anti-)Lambda

Search for Phase Transition: Directed Flow



- The dip in $dv_1/dy|_{y=0}$ is argued to indicate an interplay between hydro and baryon transport dynamics (and baryon/anti-baryon annihilation)
- (Anti)-Lambdas dv_1/dy closely follow those of (anti)-protons
- dv_1/dy for net-K and net-p are consistent with each other down to ~14.5 GeV, and deviate at lower energies



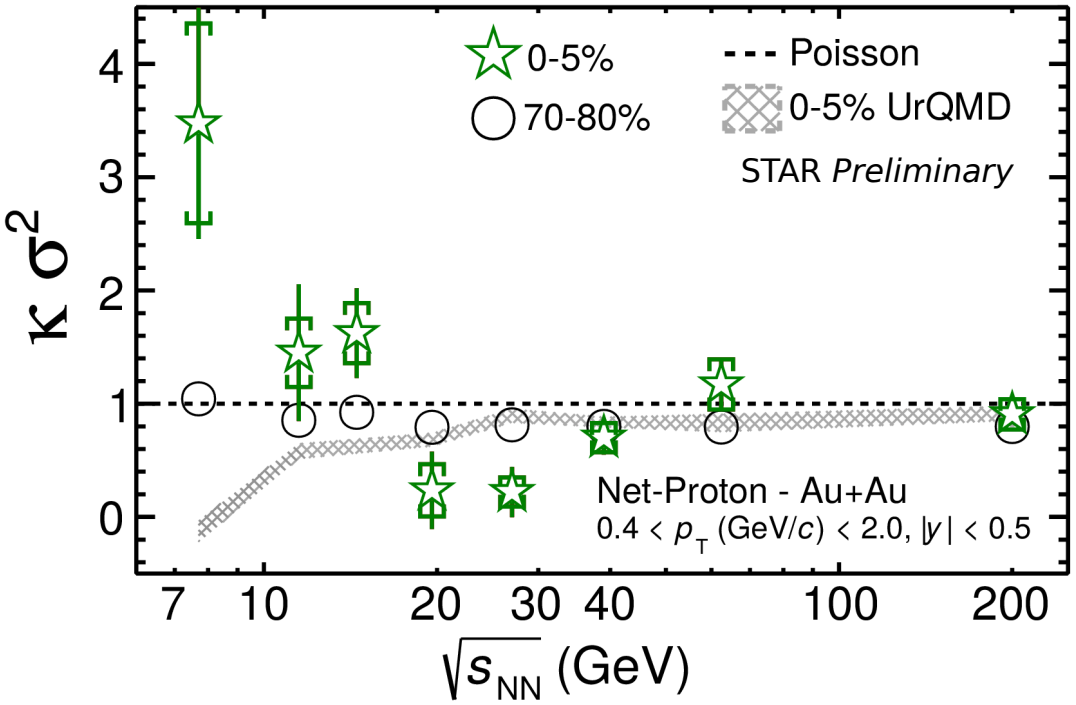
π^{+-}/ K^{+-}/ (anti-)p/ (anti-)Lambda

Search for the Critical Point: Higher Moments Fluctuations (Net-Protons)

NEW

- Higher moments of conserved quantum numbers (Q, S, B) are expected to be sensitive to the proximity to a critical point

  Higher order moments → higher sensitivity to criticality



- New: extended phase space volume of net-proton higher moments measurement

  $0.4 < p_T\ (GeV/c) < 0.8 \rightarrow 0.4 < p_T\ (GeV/c) < 2.0$

- Non-monotonic change of $\kappa\sigma^2$ for in central *Au+Au* collisions

Beam Energy Scan II (2019-2020)

<u>Planned hardware upgrades:</u>

- inner Time Projection Chamber:
  Larger acceptance : $|\eta| < 1 \rightarrow |\eta| < 1.5$
  higher dE/dx resolution

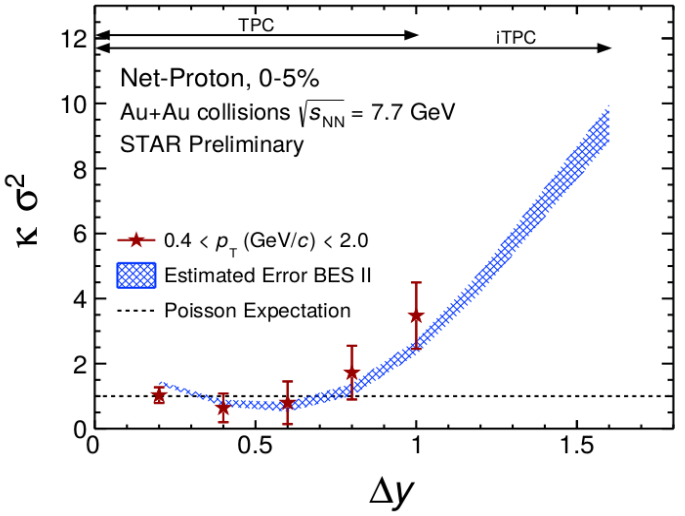
- Event Plane Detector
- Endcap Time of Flight

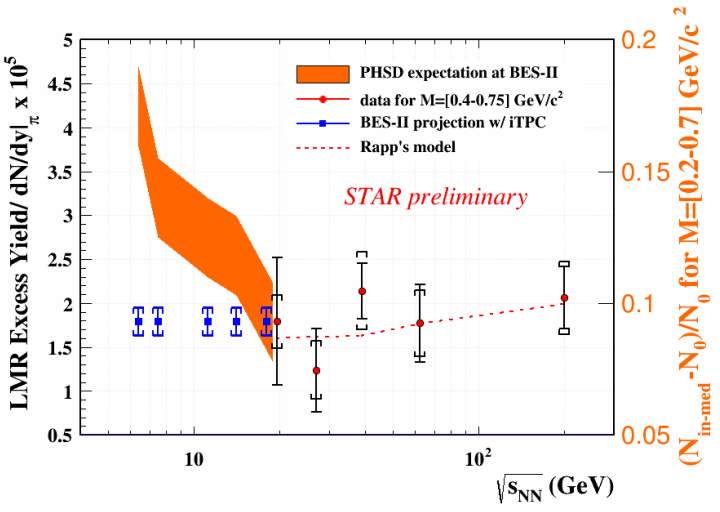
<u>Higher luminosity with electron cooling.</u>

Scan of $205 < \mu_B < 420$ MeV with high events statistics

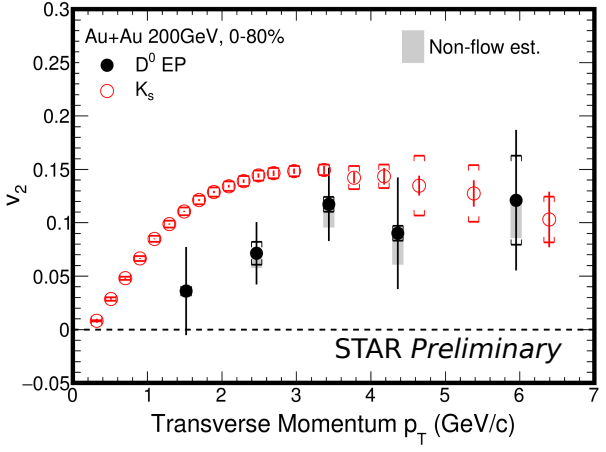
<u>Physics focus:</u>

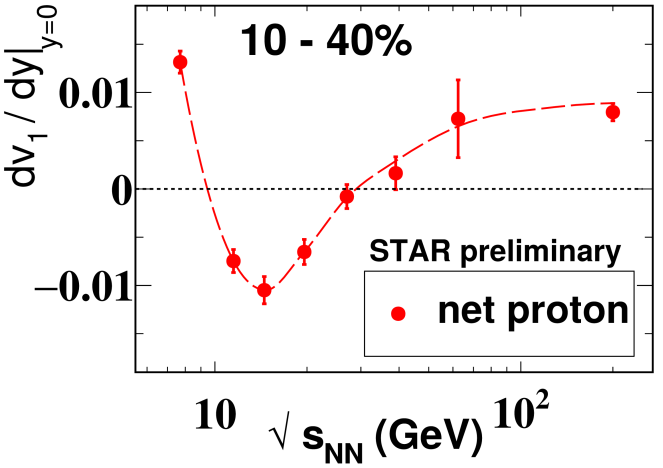
- Search for critical point
- Search for onset of QGP
- Quantify the effect of Chiral Symmetry Restoration via total baryon density on vector meson in-medium modifications.

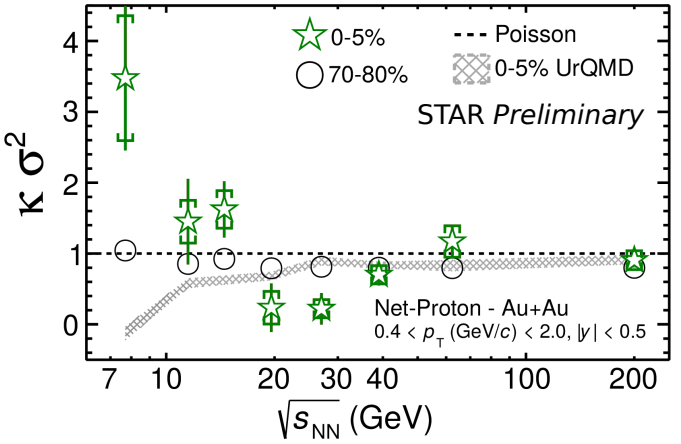




Summary







- Heavy Flavor Tracker (HFT) delivers its first results → Charm flows at RHIC top energy
- First result of quarkonia suppression from the Muon Telescope Detector (MTD)
- Beam Energy Scan I (BES-I) completed with $\sqrt{s_{NN}}$= *14.5 GeV*
  → Net-protons $\kappa\sigma^2$, baryons $dv_1/dy|_{y=0}$, and charged hadron scaled-v_3^2 exhibit non-monotonicity at similar energies

STAR Future Plans