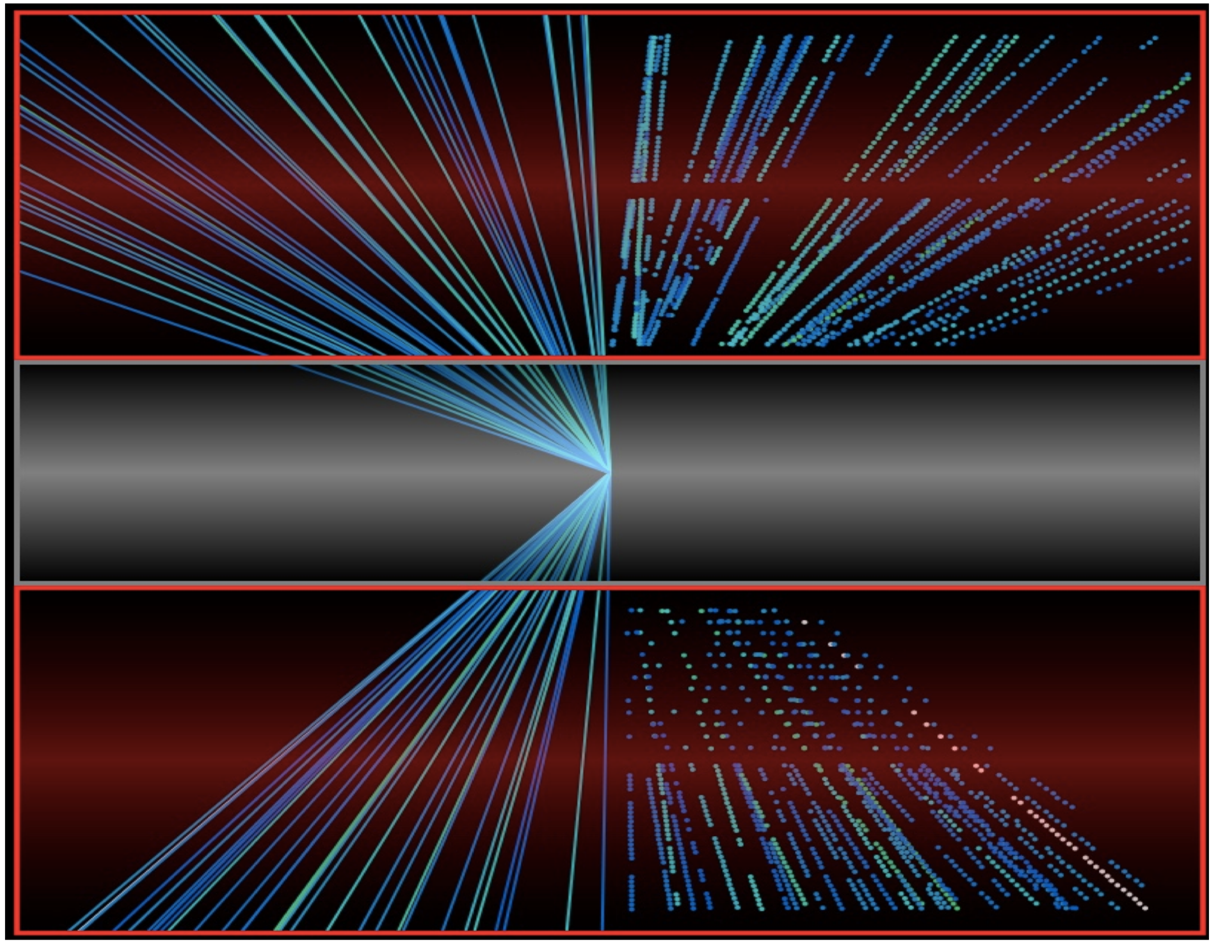
Highlights from the STAR Experiment

Zhangbu Xu
(BNL)
for the STAR Collaboration

Future
Present



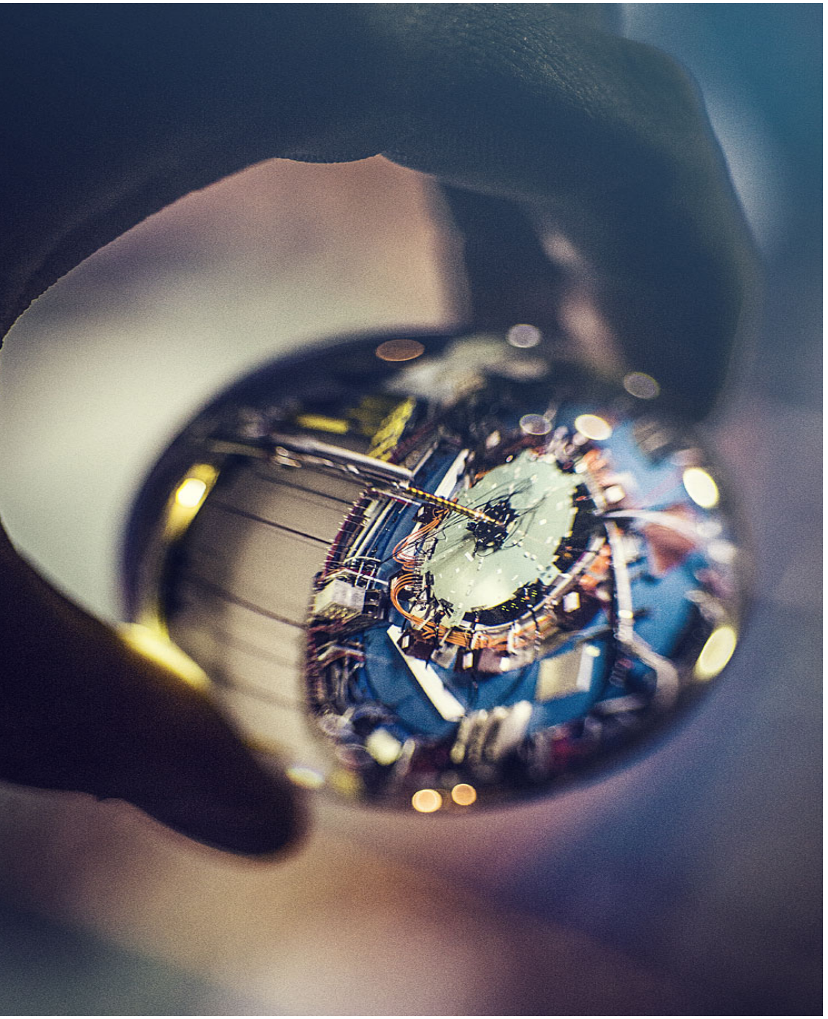
Past

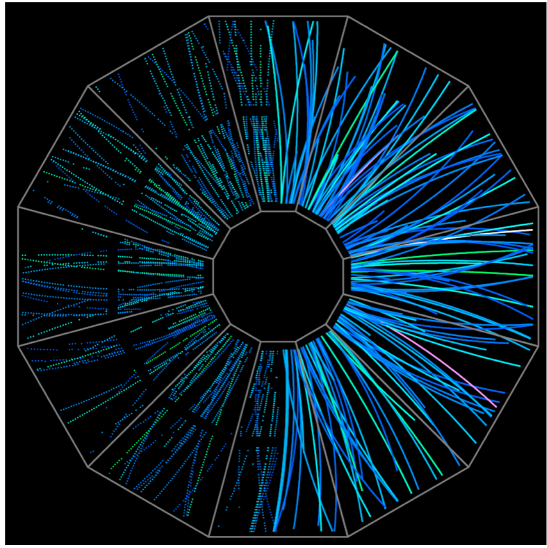
- **Discoveries** of Breit-Wheeler process and Vacuum Birefringence
- **Initial State** (PDF and small systems)
- **Viscosity [$\eta/s(T)$]:** Multiple Harmonics and Rapidity Correlations
- **Hard Probes** (Jets and Heavy-Flavor)
- Origin of global **polarization and vorticity**
- **Chiral and thermal** properties
- BES and **Critical Point** search
- **Upgrades** and Summary

19 Oral presentations and 38 posters

BROOKHAVEN NATIONAL LABORATORY
In part supported by U.S. DEPARTMENT OF ENERGY Office of Science

STAR Overview





- **Discoveries** of Breit-Wheeler process and Vacuum Birefringence (Daniel Brandenburg, Tue 9:00 HK)
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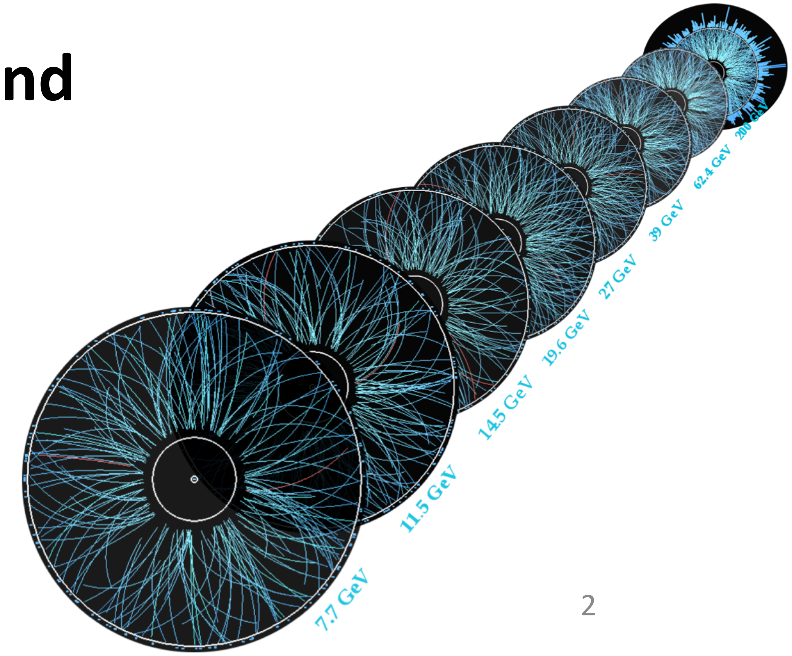

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The STAR experiment
at the Relativistic Heavy Ion Collider, Brookhaven National Laboratory

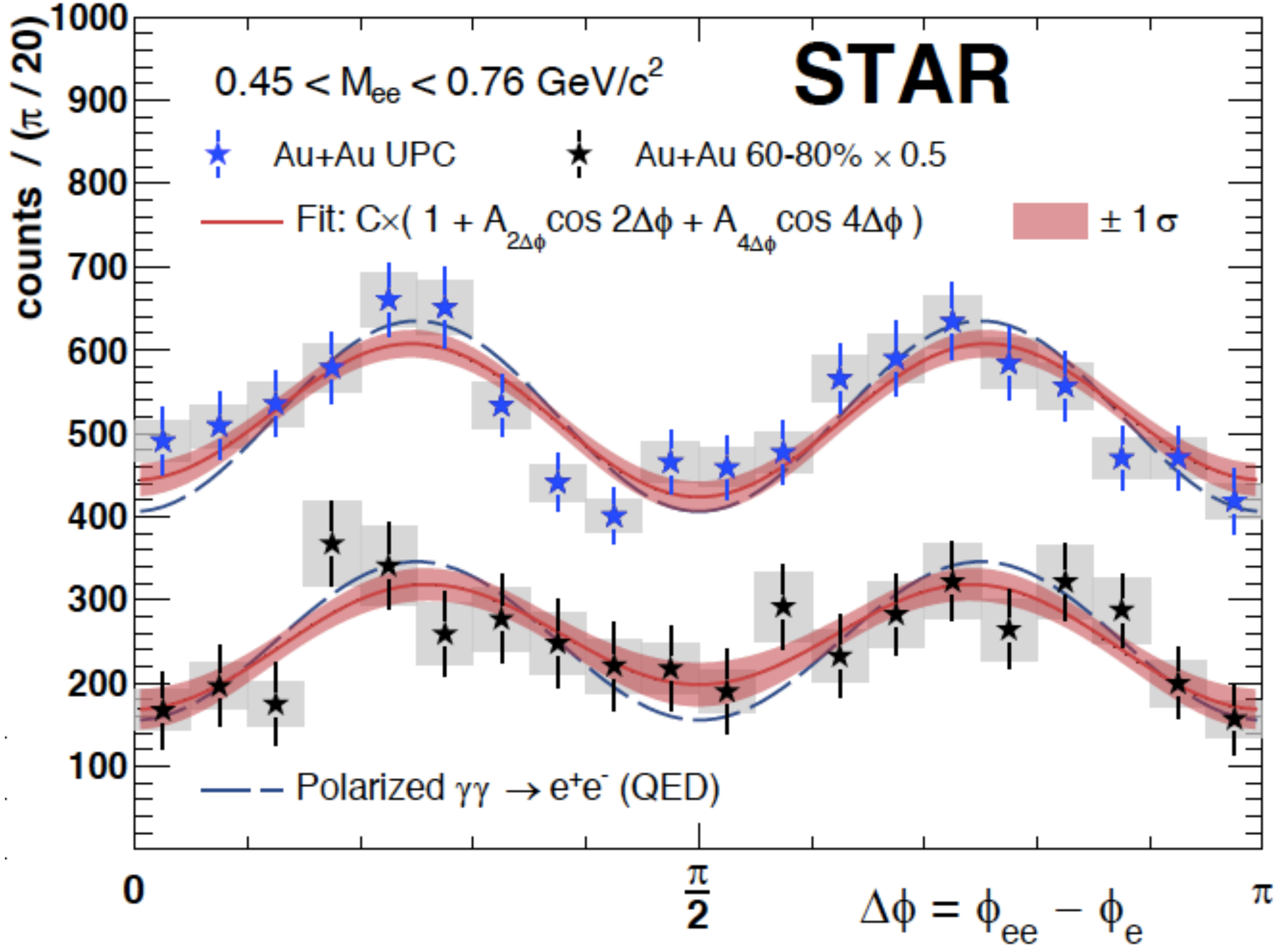
Observations of Breit-Wheeler process and Vacuum Birefringence

Daniel Brandenburg, Tue 9:00 HK

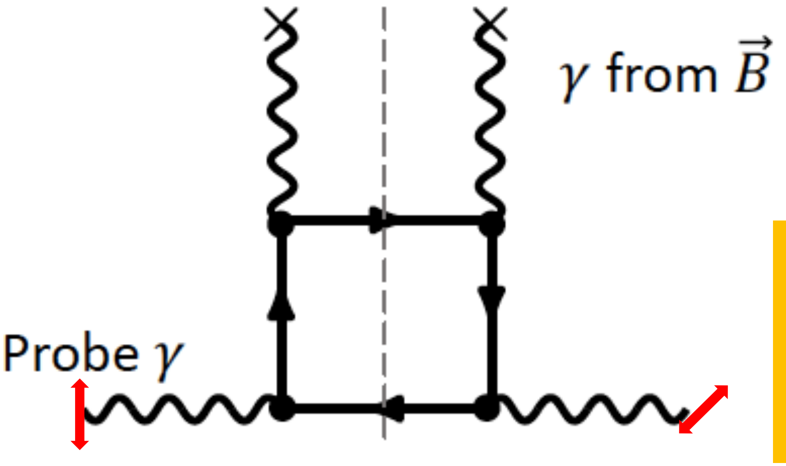
STAR arXiv:1910.12400

- 1934, Breit and Wheeler, **Collision of two light Quanta to create matter and antimatter (e^+e^-)**

> rather than exact relations. It is also hopeless to try to observe the pair formation in laboratory experiments with two beams of x-rays or γ-rays meeting each other on account of the smallness of σ and the insufficiently large available densities of quanta. In the considerations of Williams, however, the large nuclear electric fields lead to large densities of quanta in moving frames of reference. This, together with the large number

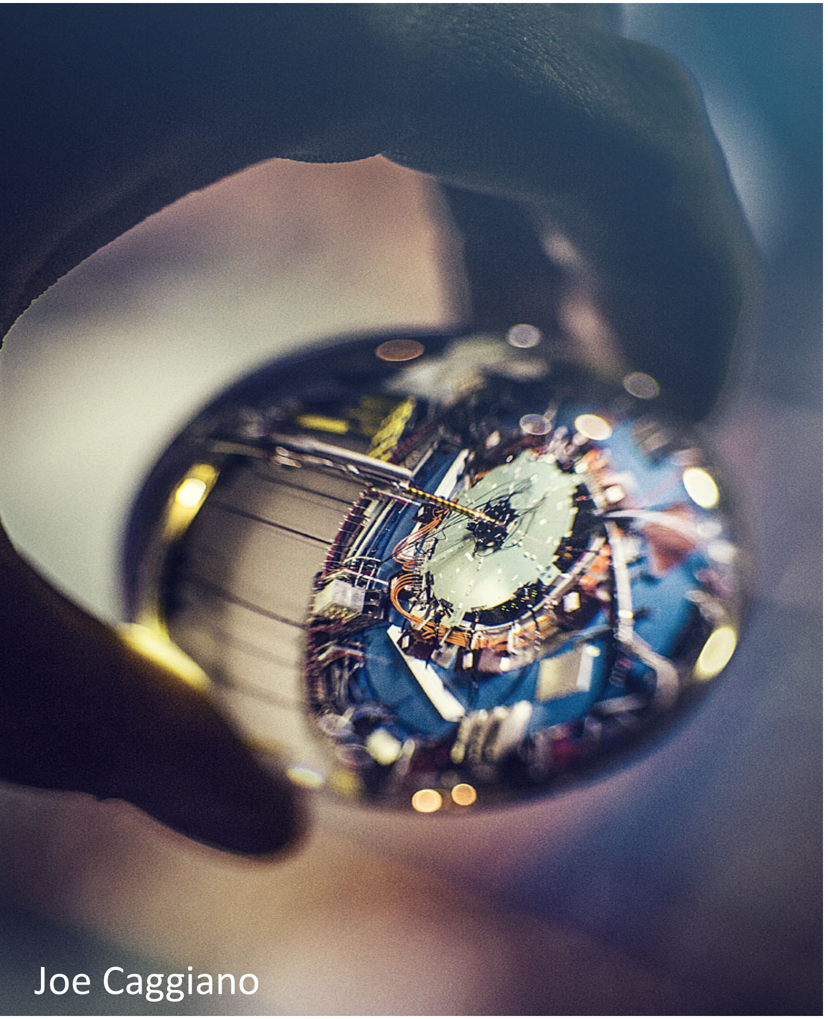


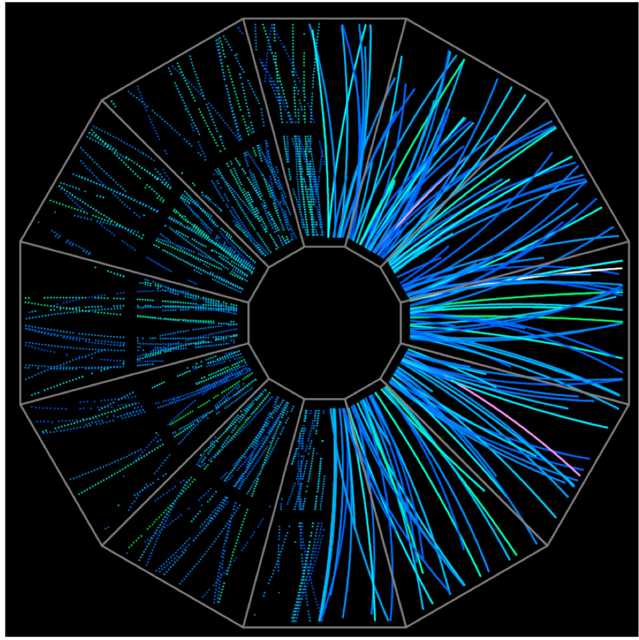
Feynman Diagram for Vacuum Birefringence



1. **Observation of exclusive Breit-Wheeler process with all possible kinematic distributions (yields, M_{ee}, P_T, angle)**
2. **Observation of Vacuum Birefringence at 6.7σ in UPC**

STAR Overview





- **Discoveries** of Breit-Wheeler process and Vacuum Birefringence
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  (Daniel Brandenburg, Tue 9:00 HK
  Roy Lacey, Tue 9:40 BR3
  Yanfang Liu, Tue 15:00 BR3)
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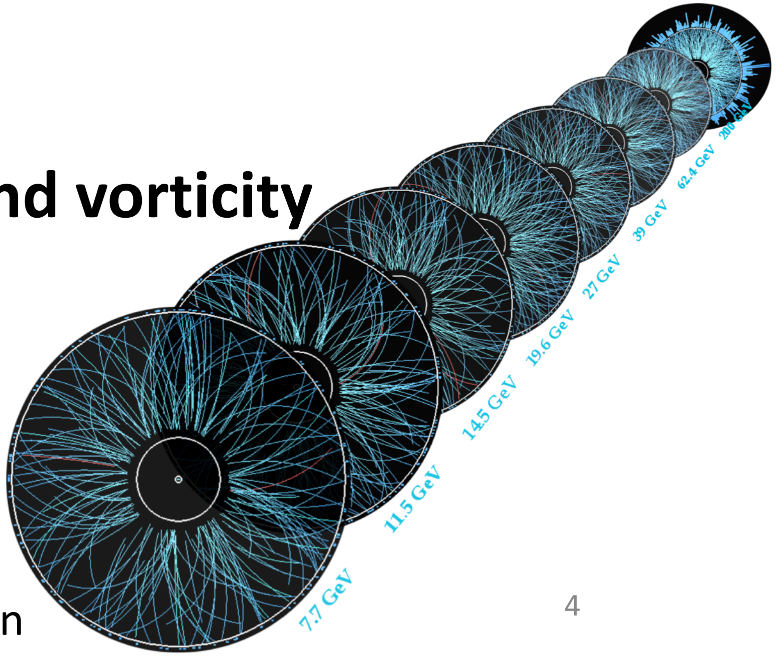

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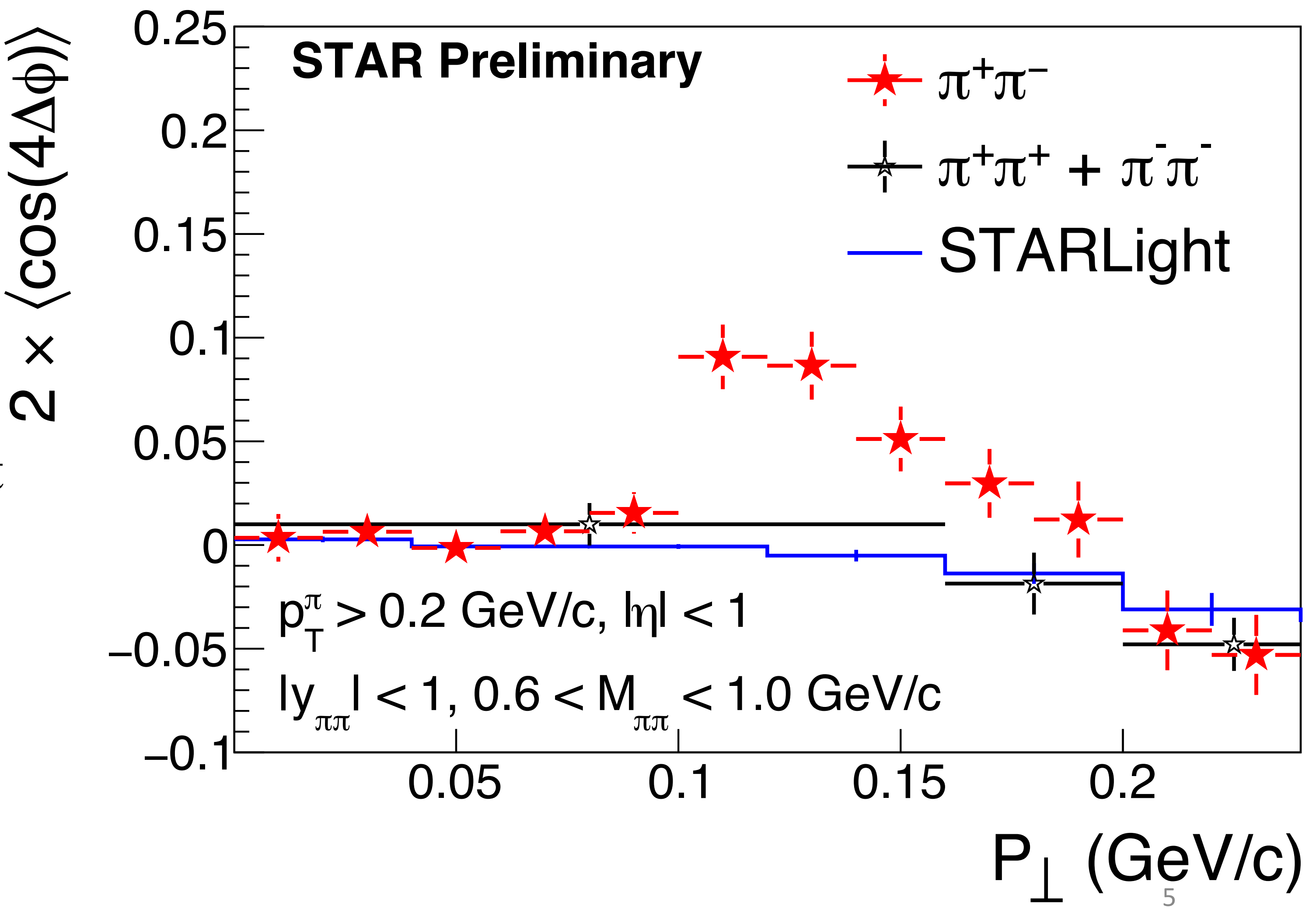
New observable in ρ photoproduction

Daniel Brandenburg, Tue 9:00 HK

Observation of 8σ statistical significance of cos(4ϕ) modulation QCD birefringence?

- Predicted to be sensitive to Generalized Transverse Momentum Distribution (GTMD): "offer direct access to the second derivative of the saturation scale w.r.t gluon spatial distribution"
- Expected magnitude scales with $(P_\perp/M_\rho)^2$
- Tensor Pomeron …

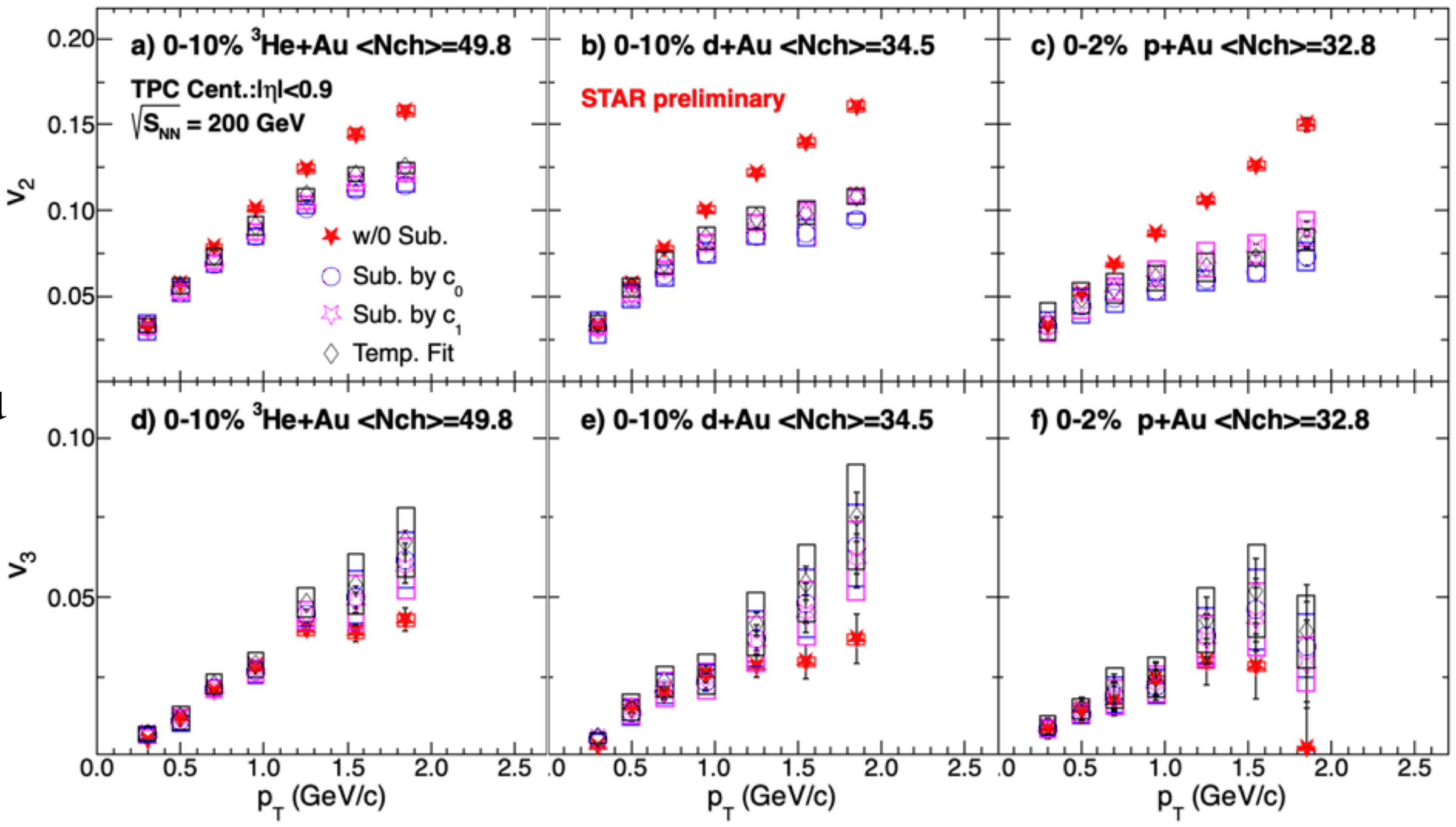


[1] J. Zhou, Phys. Rev. D 94 (2016) 114017

Differential $v_{2,3}$ in p/d/^{3}He+Au

Roy Lacey, Tue 9:40 BR3

- ^{3}He+Au and all v_3 data NEW
- Three non-flow subtraction methods give similar $v_n(p_T)$ in each system.
- $v_3(p_T)$ similar for central p/d/^{3}He+Au
- Glauber model shape ε_n are different between w/o and with sub-nucleon fluctuations.

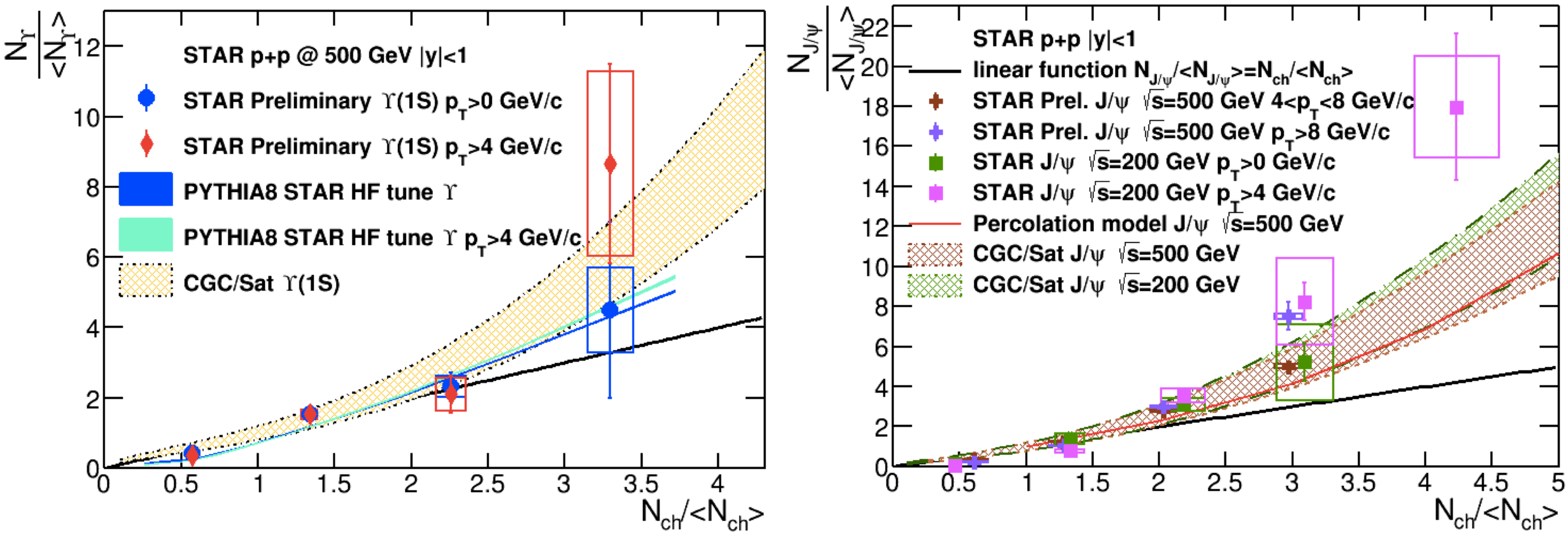


Comparison with other experiments and expectations from fluctuation-driven ε_n from quark Glauber model

STAR measurements consistent with dominant roles of multiplicity and fluctuation-driven shape (ε_n)

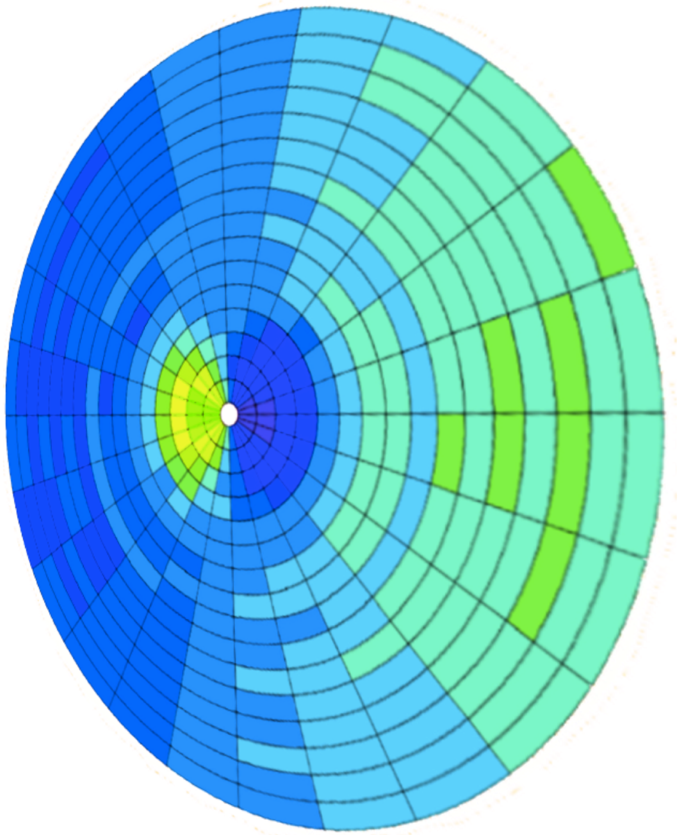
Quarkonium production in p+p

Yanfang Liu, Tue 15:00 BR3



- **Data show strong non-linear dependence (correlation between soft and hard processes)**
- **Models (MPI, CGC, Percolation) qualitatively describe data trends**

STAR Overview



Event-Plane Detector (EPD)
At 27 GeV

- **Discoveries** of Breit-Wheeler process and Vacuum Birefringence
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  (Maowu Nie, Tue 9:00 BR1
  Niseem Magdy, Wed 9:40 BR3)
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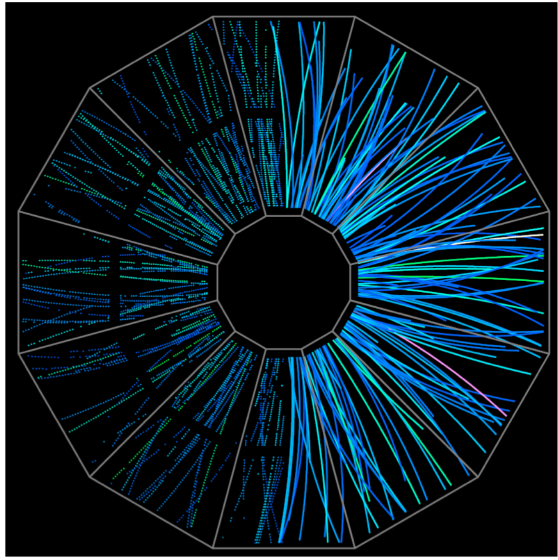

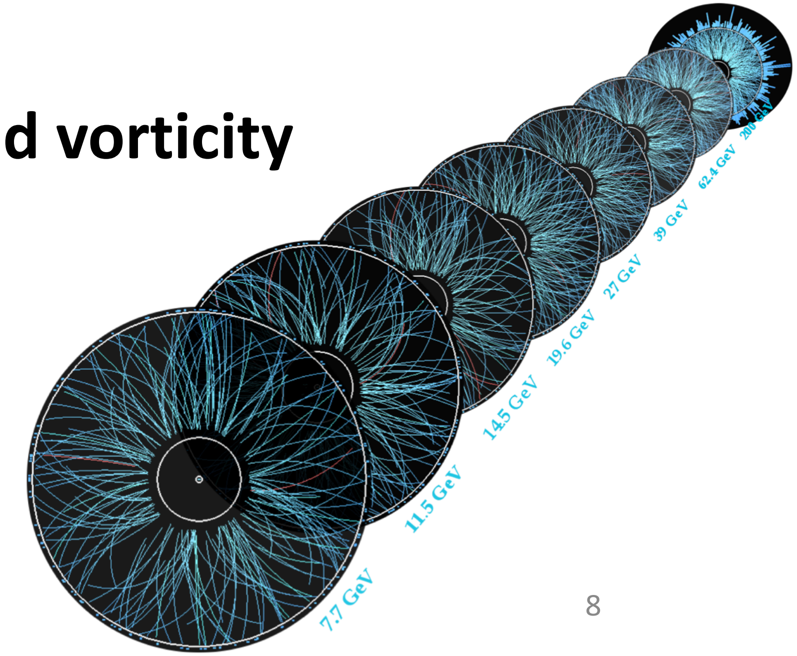

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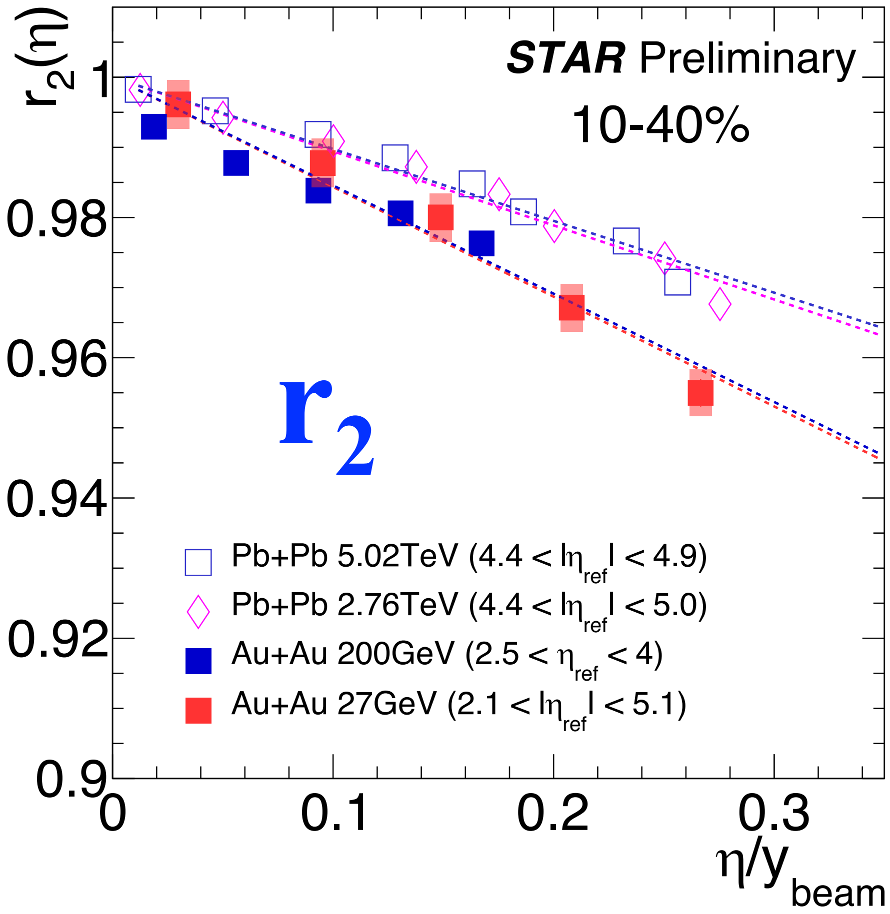
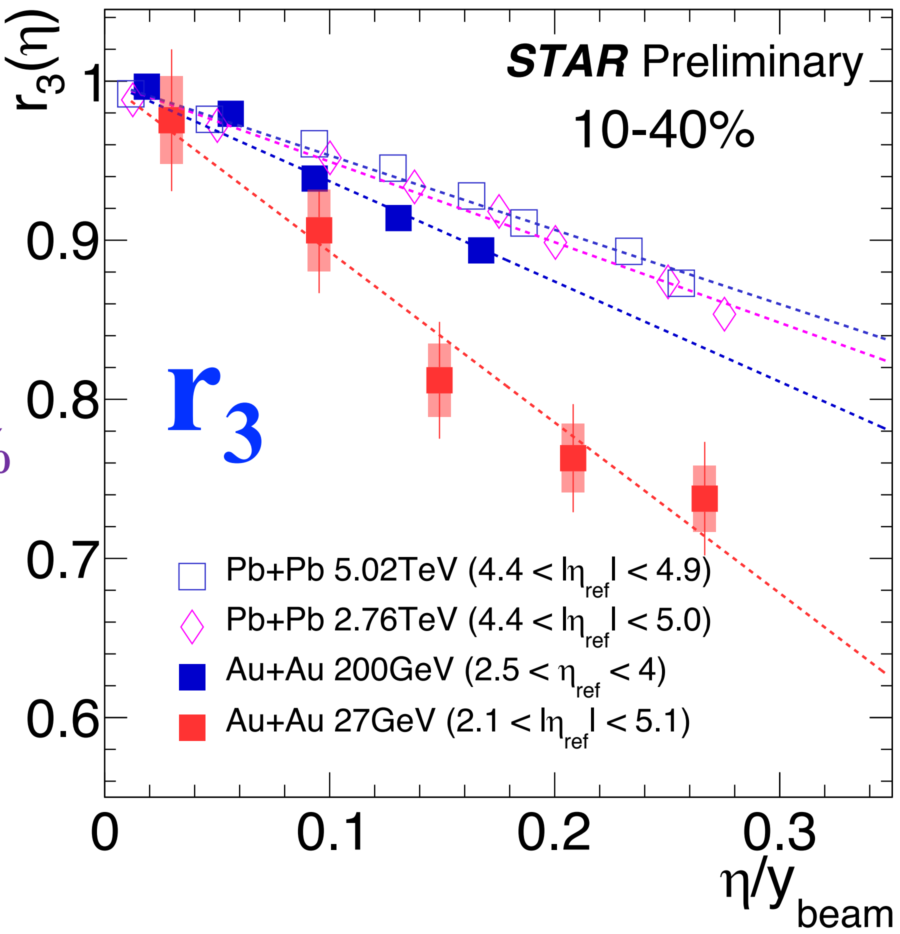
Longitudinal flow decorrelation at 27 GeV

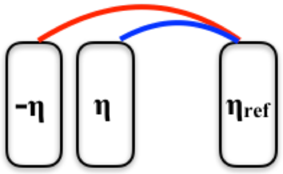
Maowu Nie, Tue 9:00 BR1



r_3 shows up to 30% decorrelation



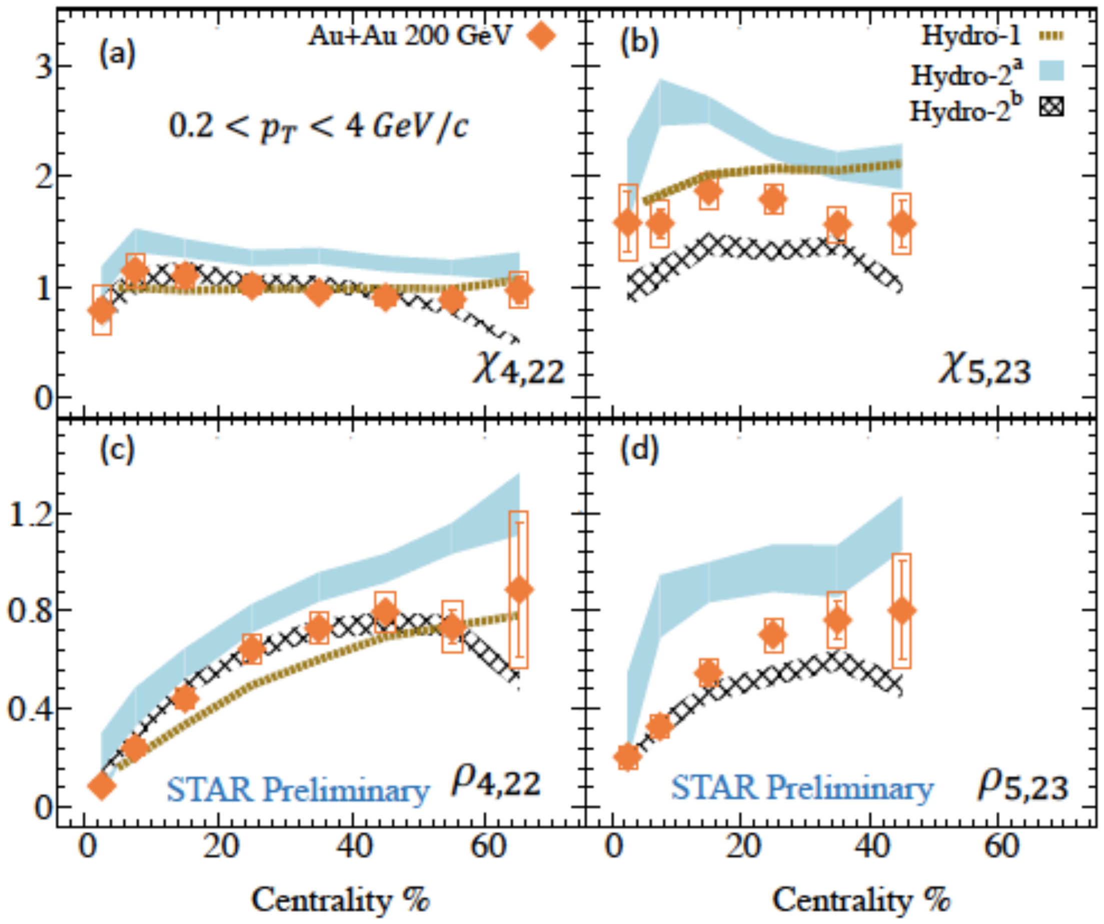
$$r_n(\eta) = \frac{\langle V_n(-\eta) V_n^*(\eta_{\rm ref})\rangle}{\langle V_n(\eta) V_n^*(\eta_{\rm ref})\rangle}$$



- **No energy dependence of r_2 at RHIC energies**
- **Clear energy dependence of r_3 at RHIC energies**

Nonlinear mode-coupling coefficients and EP angular correlations

Niseem Magdy, Wed 9:40 BR3



- $\chi_{k,nm}$ shows a weak centrality dependence
- $\rho_{k,nm}$ shows a strong centrality dependence

Nonlinear mode-coupling coefficient:

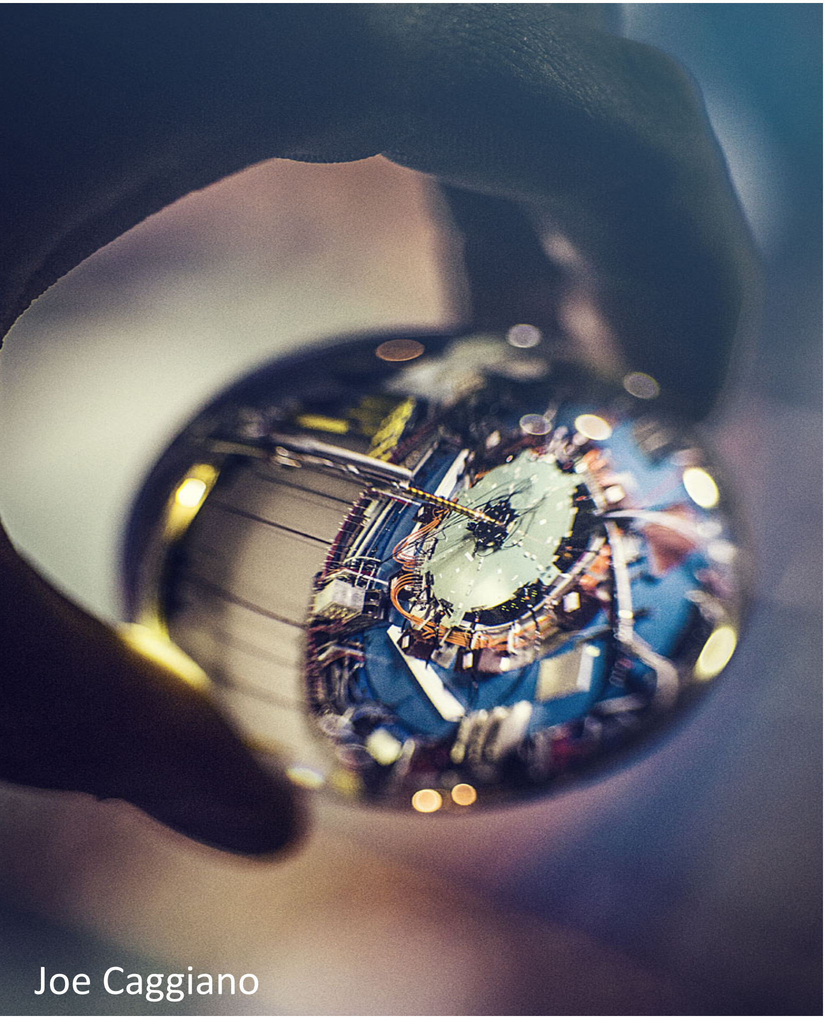
$$\chi_{n+2,2n} = \frac{\langle v_{n+2} \cos((n+2)\Psi_{n+2} - 2\Psi_2 - n\Psi_n)\rangle}{\sqrt{\langle v_2^2 v_n^2 \rangle}}$$

Event-Plane Angular Correlation:

$$\rho_{n+2,2n} \sim \langle \cos((n+2)\Psi_{n+2} - 2\Psi_2 - n\Psi_n)\rangle$$

Both coefficients can be used to distinguish hydrodynamic models

STAR Overview



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  David Stewart, Tue 12:20 BR2,
  Saehanseul Oh, Tue 9:00 BR2,
  Raghav Kunnawalkam Elayalli, Wed 9:20 BR2)
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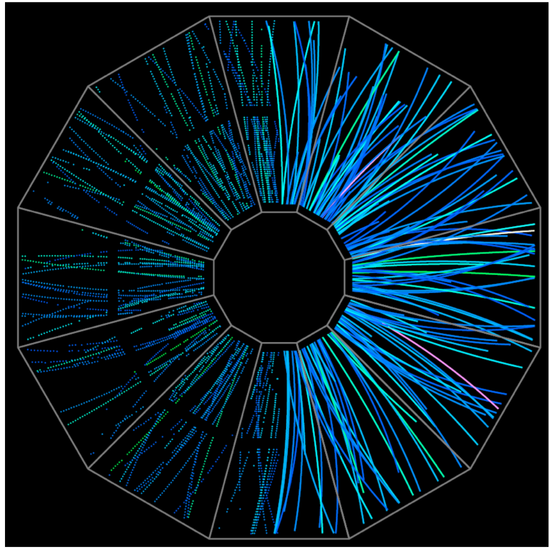

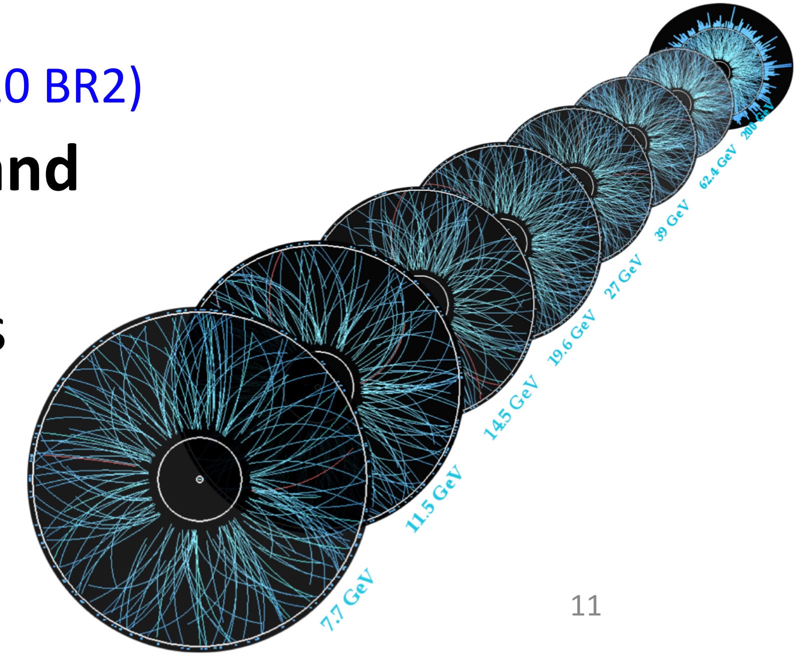

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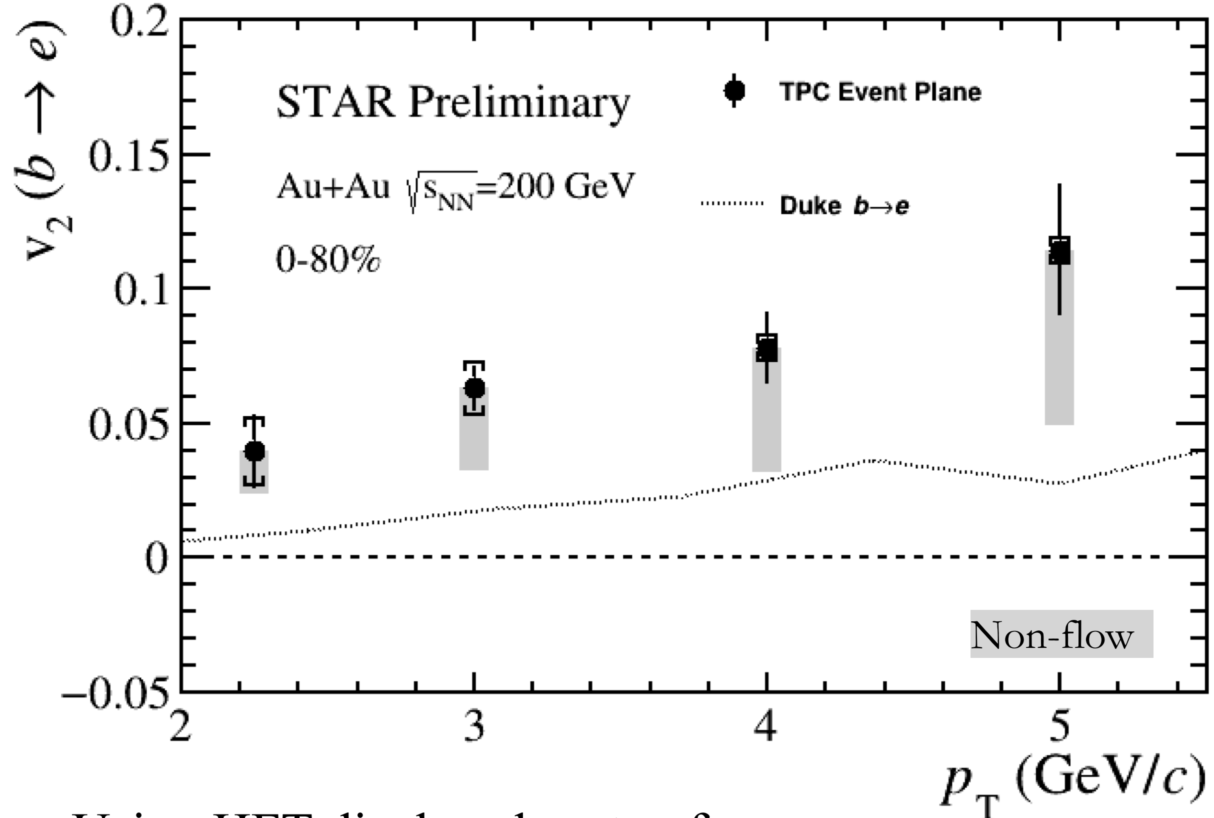
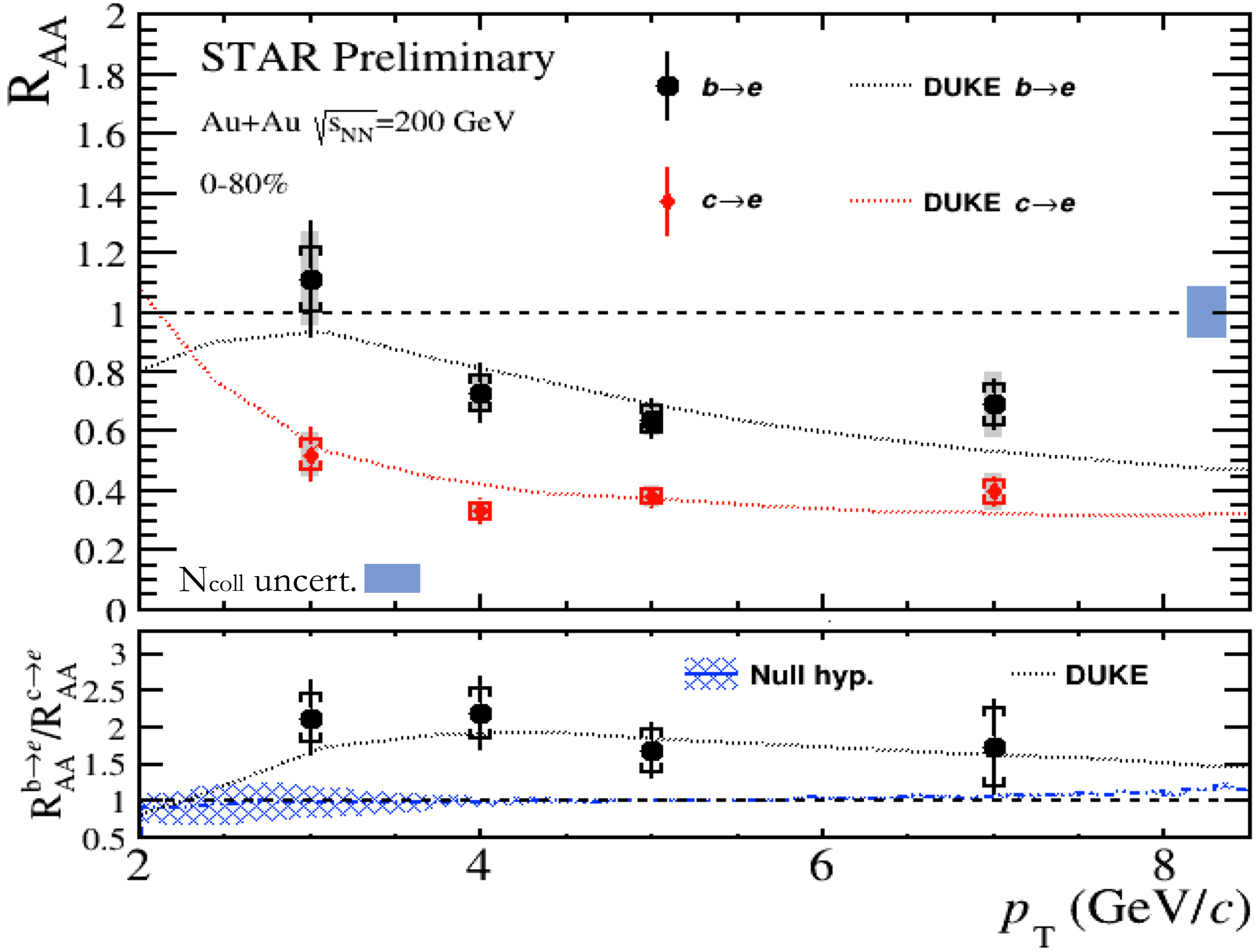
Open charm and bottom

Matthew Kelsey, Tue 15:40 BR3



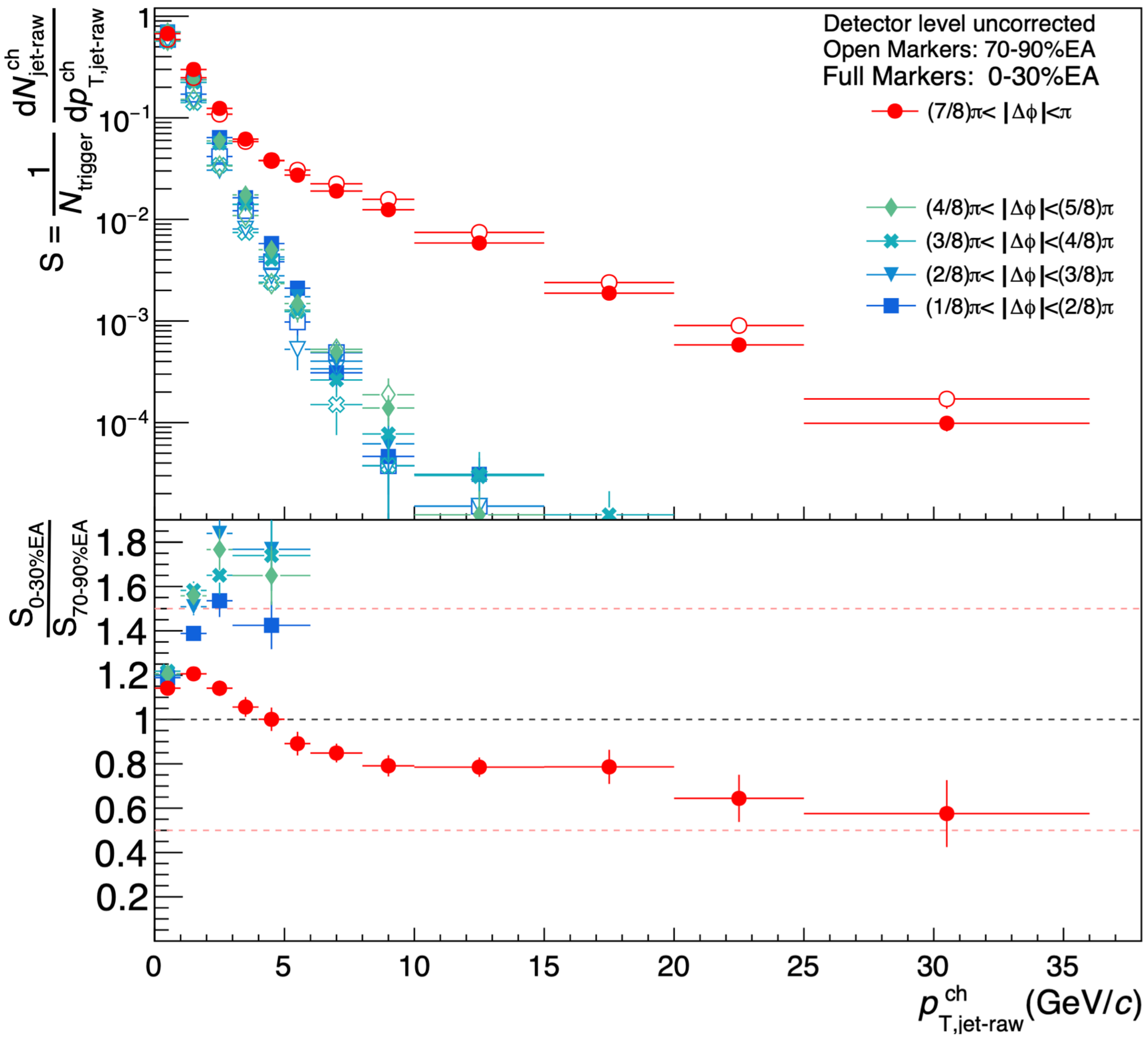


- Using HFT displaced vertex for heavy-flavor decay topology
- Observation of Λ_c/D enhancement: arXiv:1910.14628
- New charmed electron $v_{1,2}$ are consistent with D^0 measurements

- **First observation of significant non-zero bottom hadron flow (>3σ) at RHIC**
- **Observation of bottom suppression less than charm at RHIC (>3σ)**

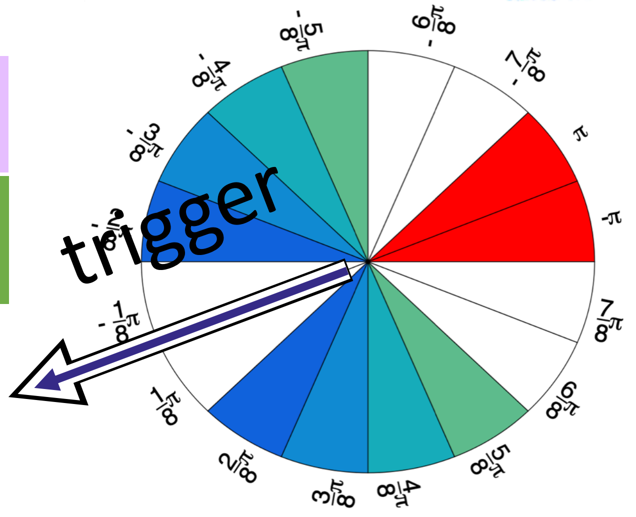
Recoil and transverse jets in p+Au

David Stewart, Tue 12:20 BR2



Open Markers: Low EA: 70-90%

Full Markers: High EA: 0-30%



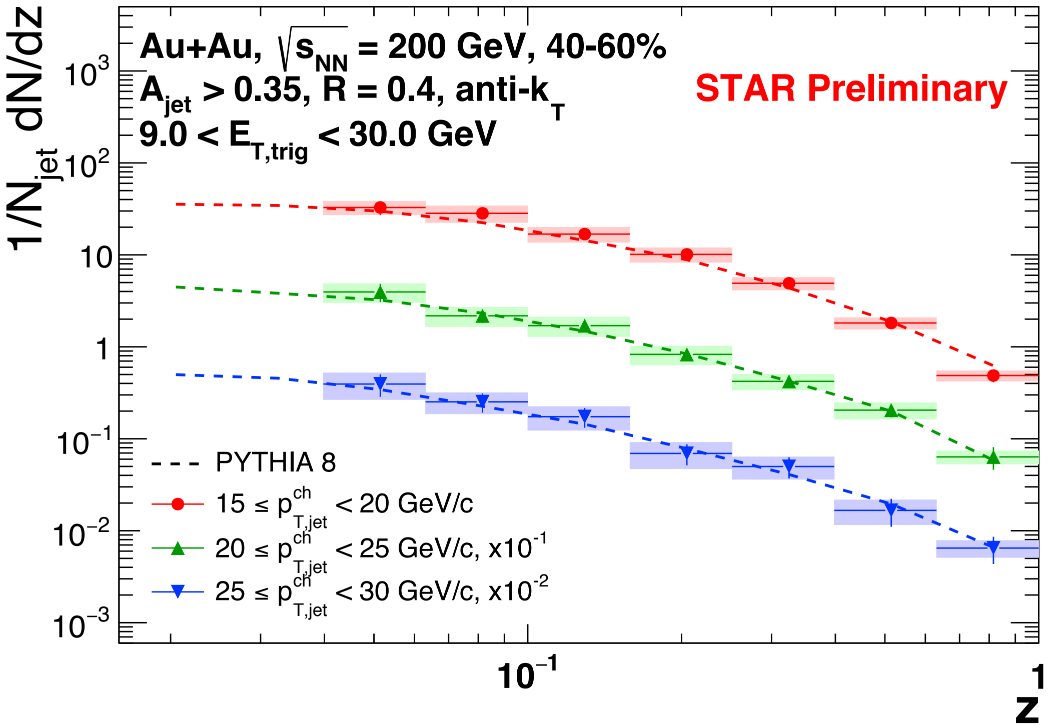
- At "jet-like" pT (>~8 GeV/c) transverse Δφ (background) negligible compared to recoil spectra
- Study with centrality defined by backward Beam-Beam Counter

Clear jet spectra per trigger suppression for high EA (event activity) relative to low EA

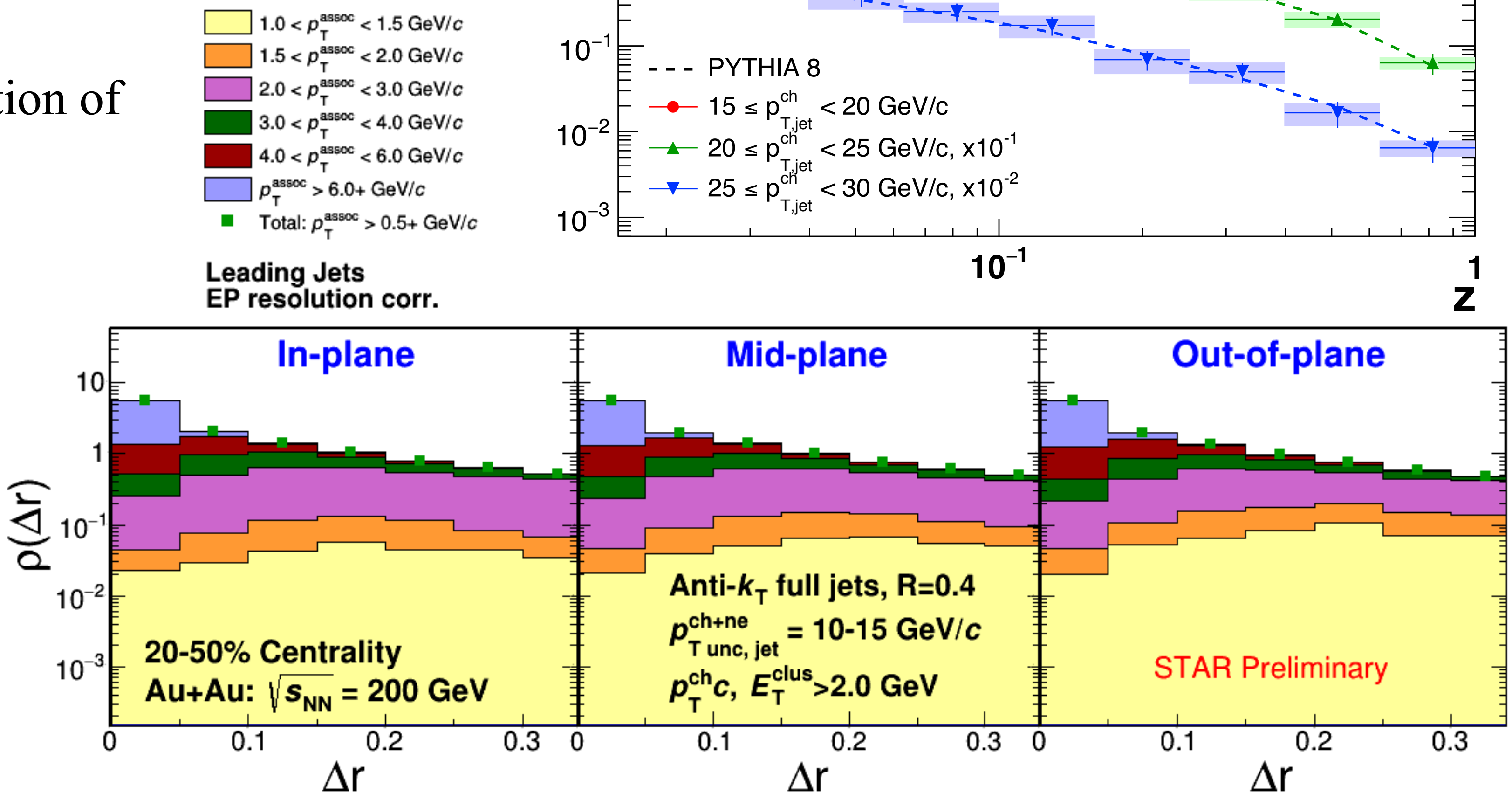
Jet fragmentation functions and shapes

Saehanseul Oh, Tue 9:00 BR2

- **First Au+Au jet fragmentation functions from STAR**
  - Jet fragmentation functions for charged jets in 40-60% events
  - Unfolded results compared to PYTHIA 8



- **Jet shapes**
  - Distribution of jet energy as a function of distance from the jet axis

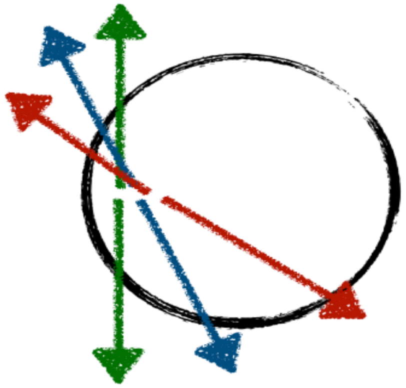


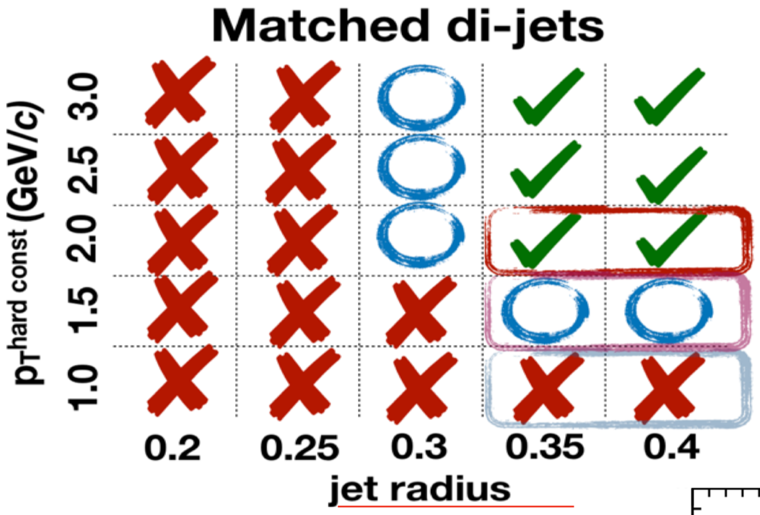
Event-plane dependent measurements
low-p_T particles: larger yields and pushed toward larger r in out-of-plane direction
→ In-medium path length effects of jet quenching

Jet substructure and differential energy loss

Jet Geometry Engineering

Raghav Kunnawalkam Elayavalli,
Wed 9:20 BR2





Vary energy loss and recovery by dijet finding parameters

➔ vary path length of recoil jet in medium

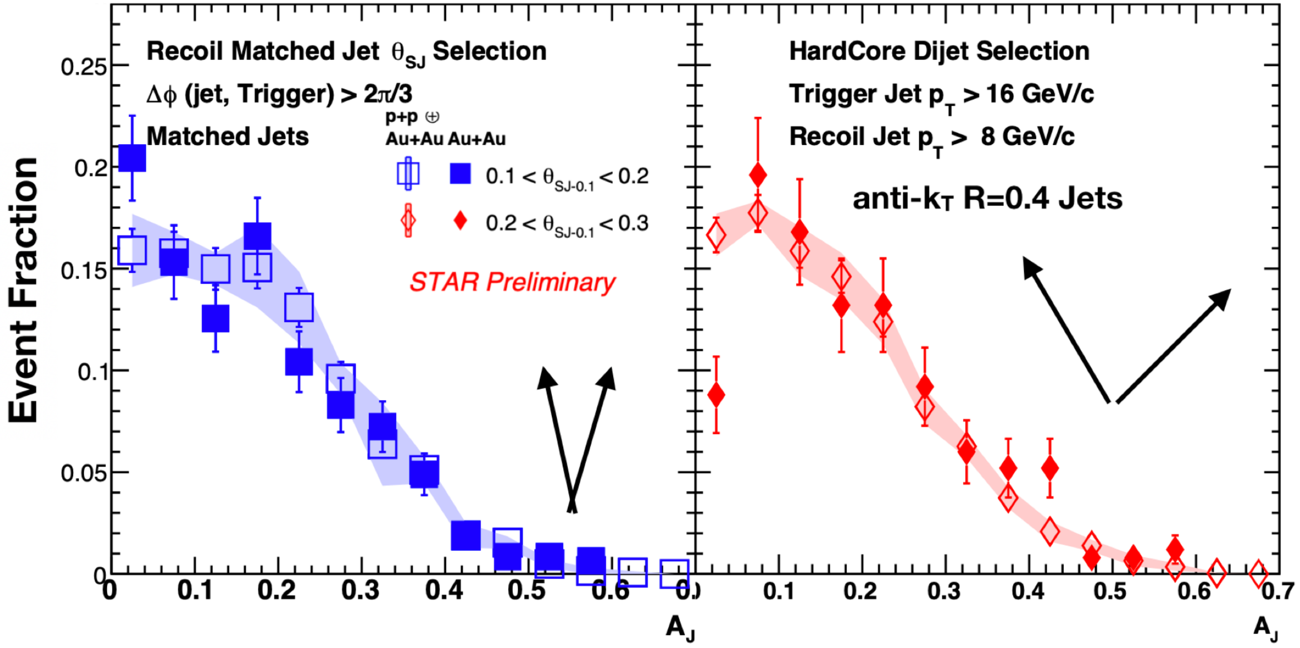
Also report new p+p results

- Jet substructure baseline - Well calibrated

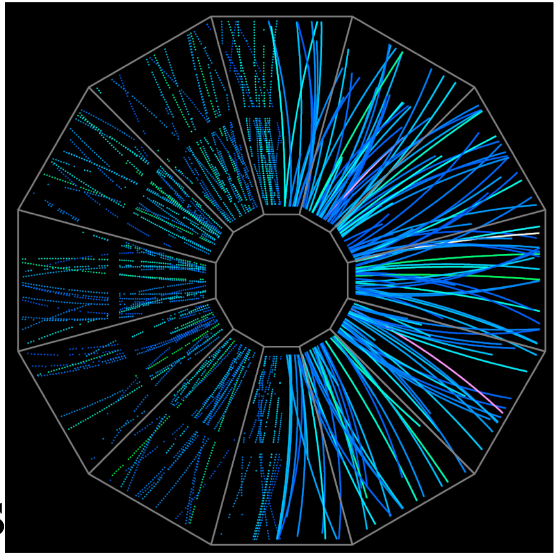
Matched dijet A_J for narrow and wide recoil jets!

For a given dijet definition wide and narrow jets appear to undergo similar levels of energy loss and recovery

These jets lose energy as single color jet and split outside medium



STAR Overview



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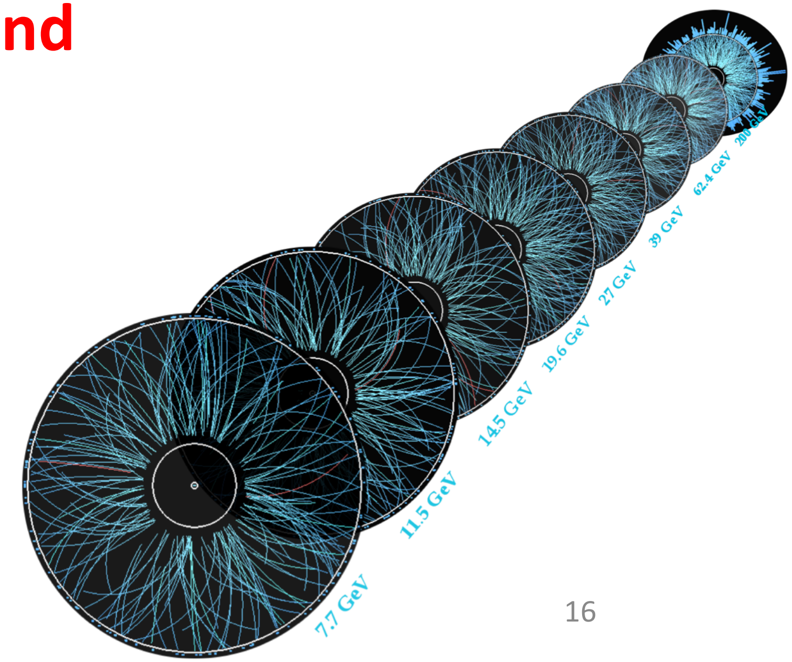

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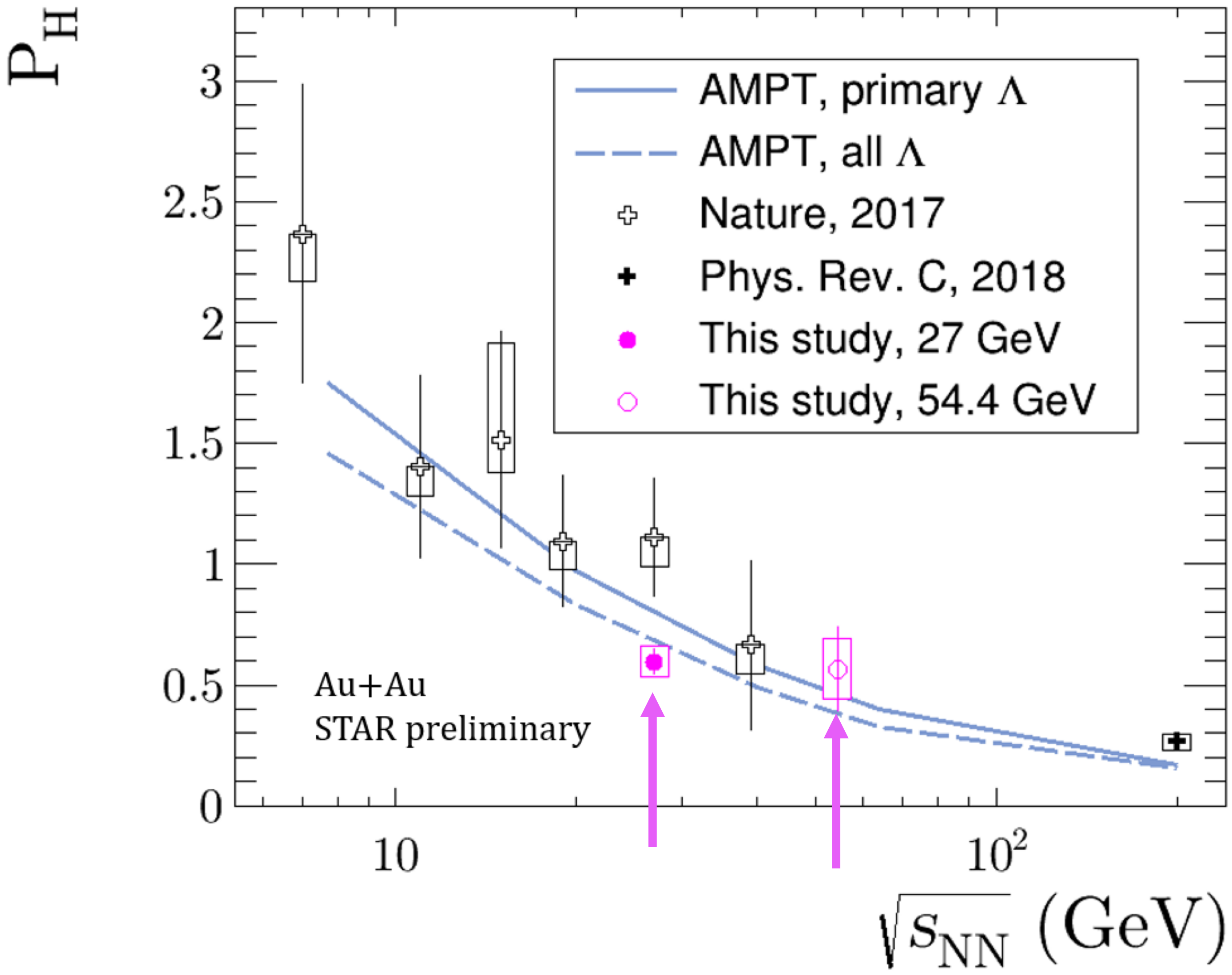
$\sqrt{s_{NN}}$ dependence of global polarization

Joey Adams, Wed 14:00 BR1

- Previous study across broad range of $\sqrt{s_{NN}}$ suggests strong beam energy dependence
- New data at 27 & 54.4 GeV with high statistics for $\Lambda/\bar{\Lambda}$, centrality, rapidity and p_T dependence

New datasets with high statistics follow previous measured trend

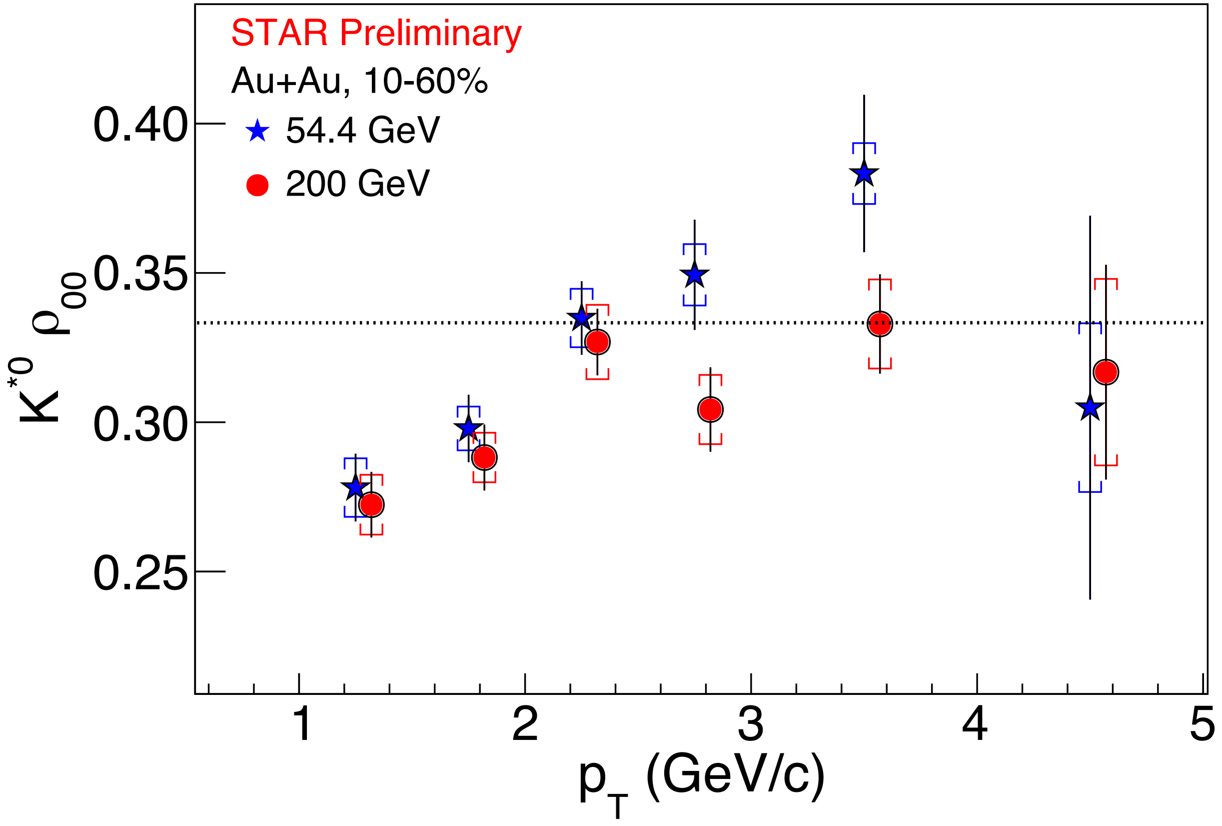


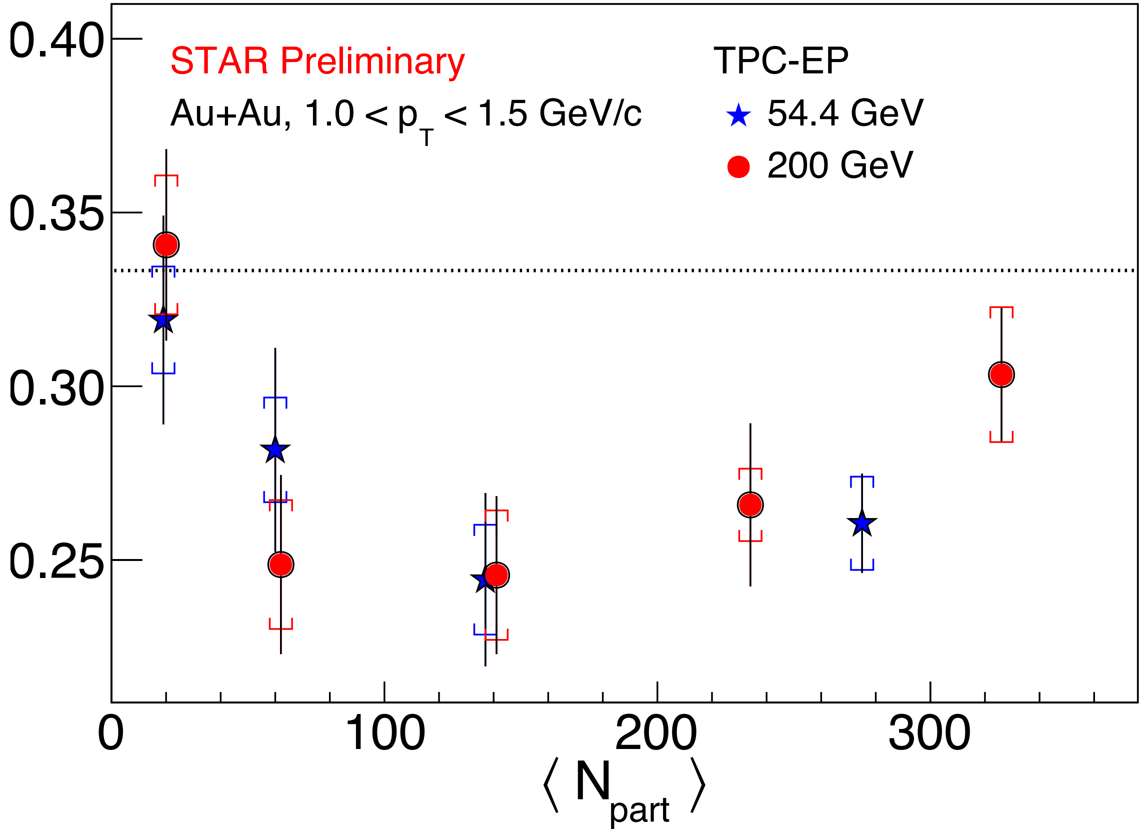
[2] The STAR Collaboration, *Global Lambda hyperon polarization in nuclear collisions: evidence for the most vortical fluid.* Nature **548** (2017) 62

Vector meson (K*) spin alignment

Subhash Singh, Wed 11:20 BR3

$$dN/d(\cos\theta^*) = N_0 \times [(1 - \rho_{00}) + (1/3\,\rho_{00} - 1)\cos(\theta^*)]$$

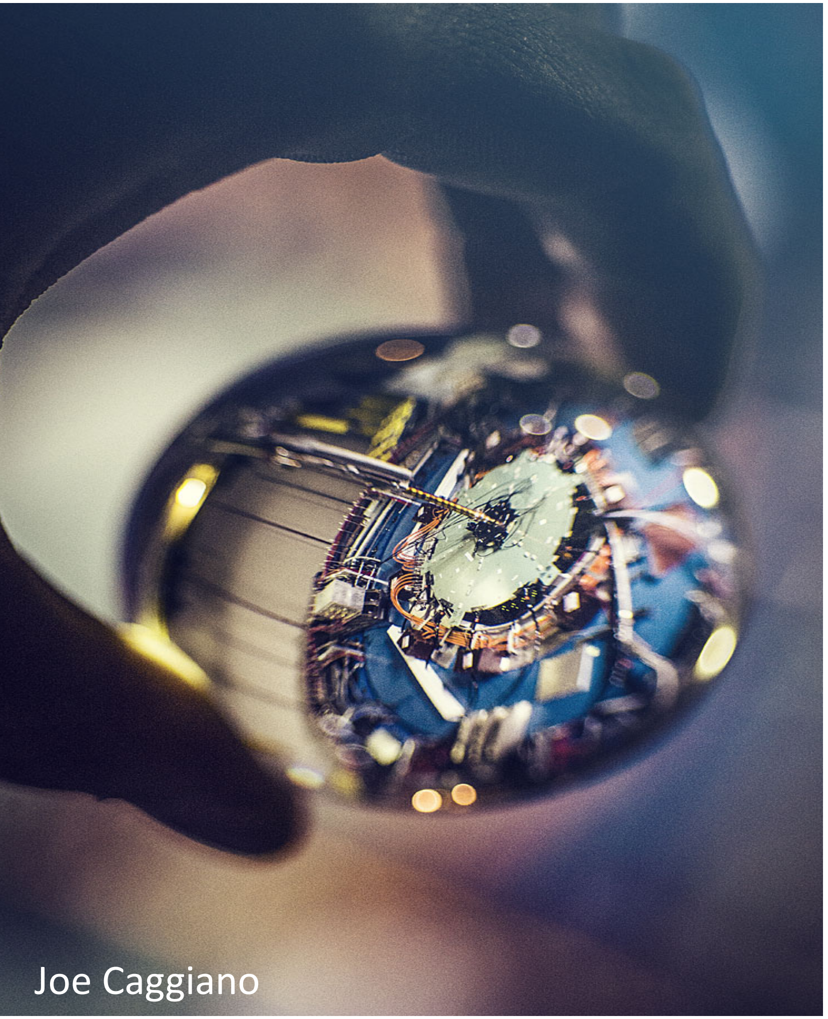


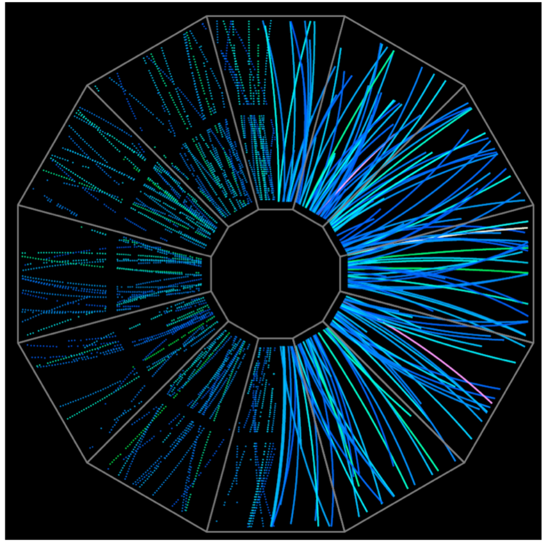


For both 54.4 and 200 GeV

- **ρ_{00} < 1/3 at low p_T and for mid-centrality**
- **qualitatively consistent with coalescence of polarized quarks but lack quantitative agreement**

STAR Overview





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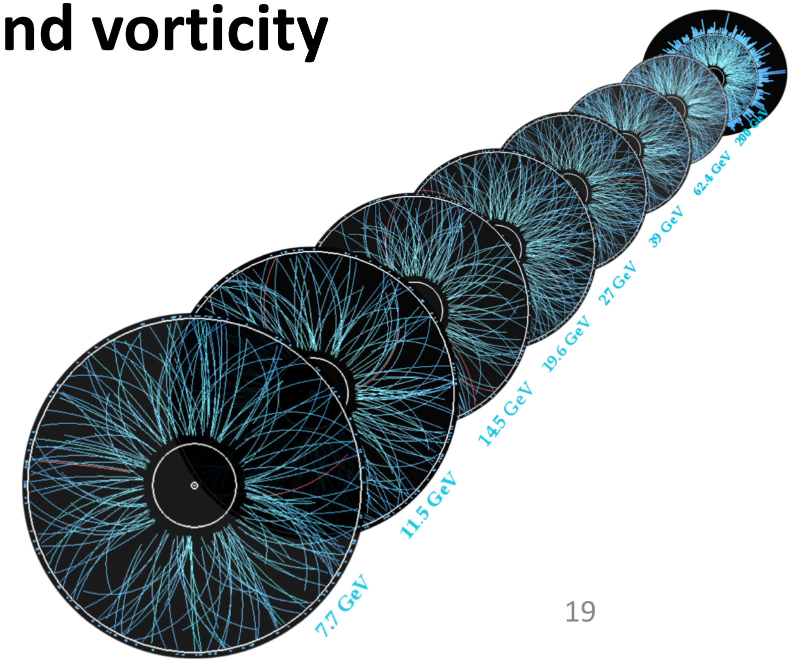

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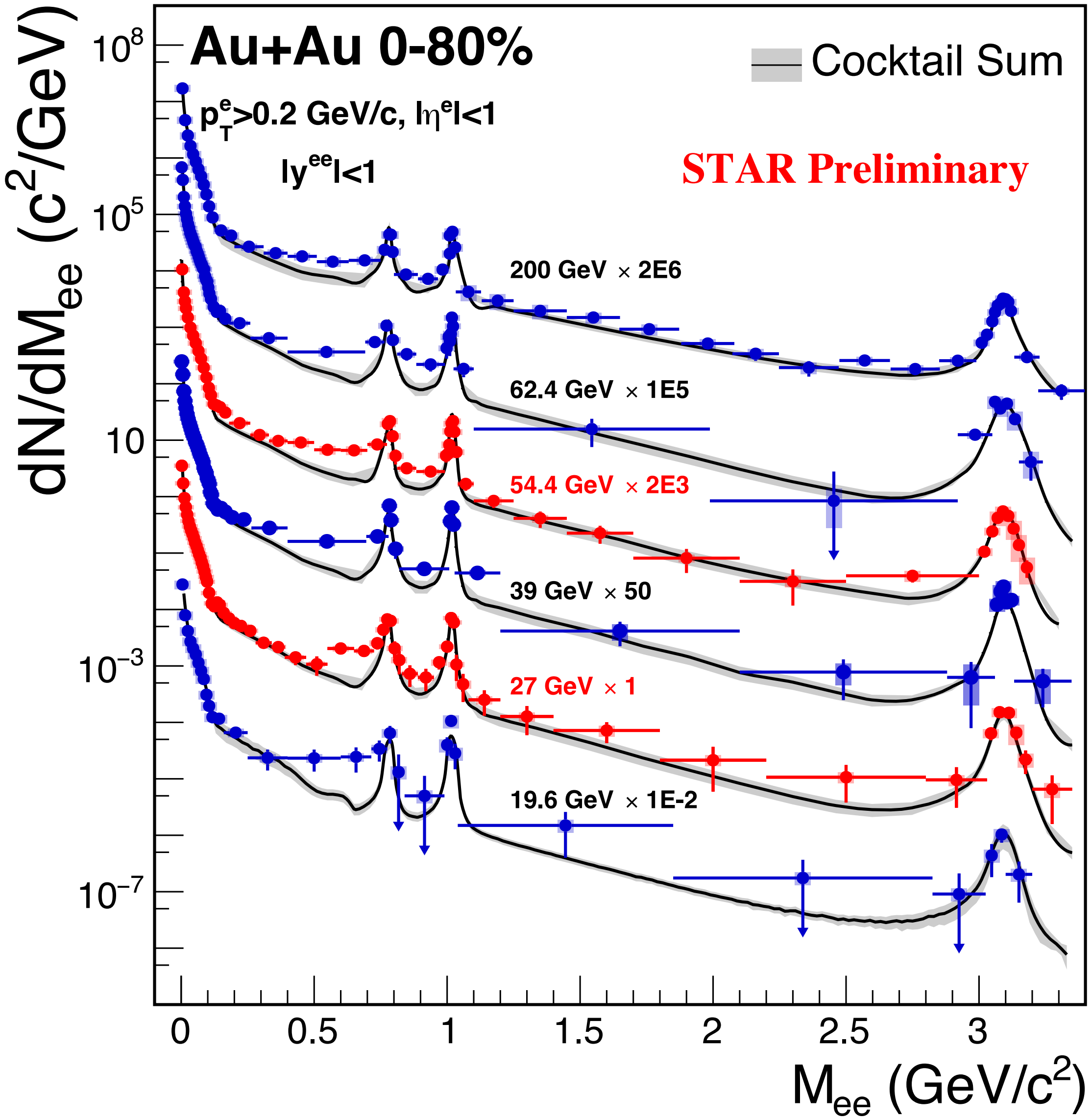
New dielectron spectra at 27 and 54.4 GeV

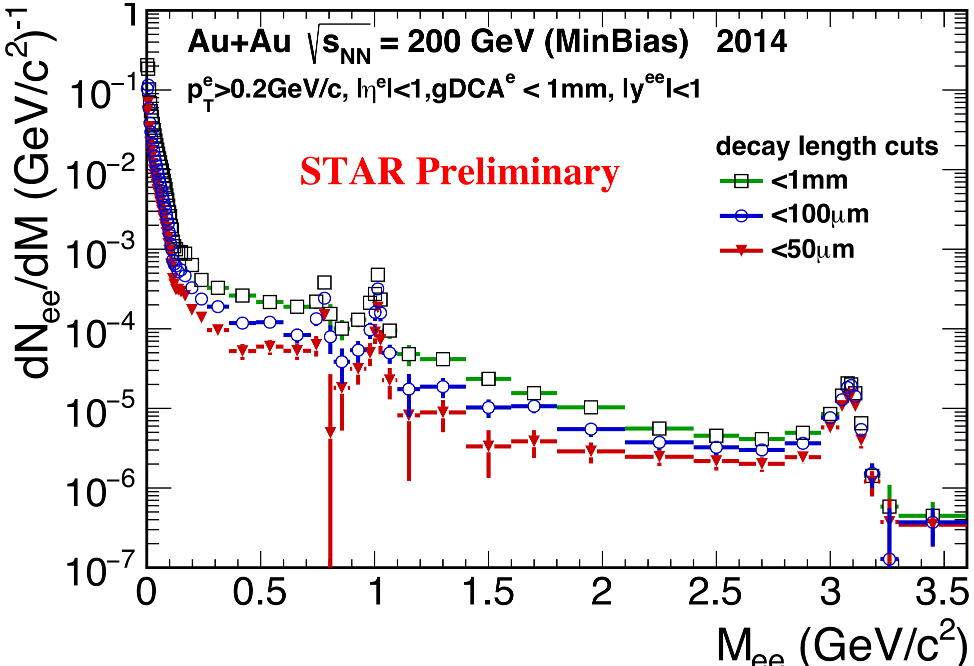
Florian Seck, Wed 16:20 BR3



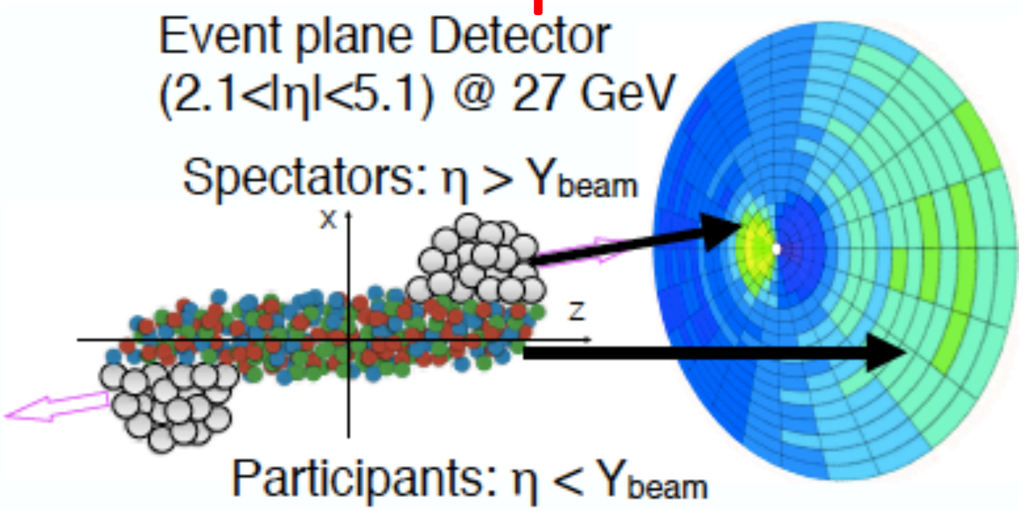
Enough statistics to perform (multi-)differential measurements

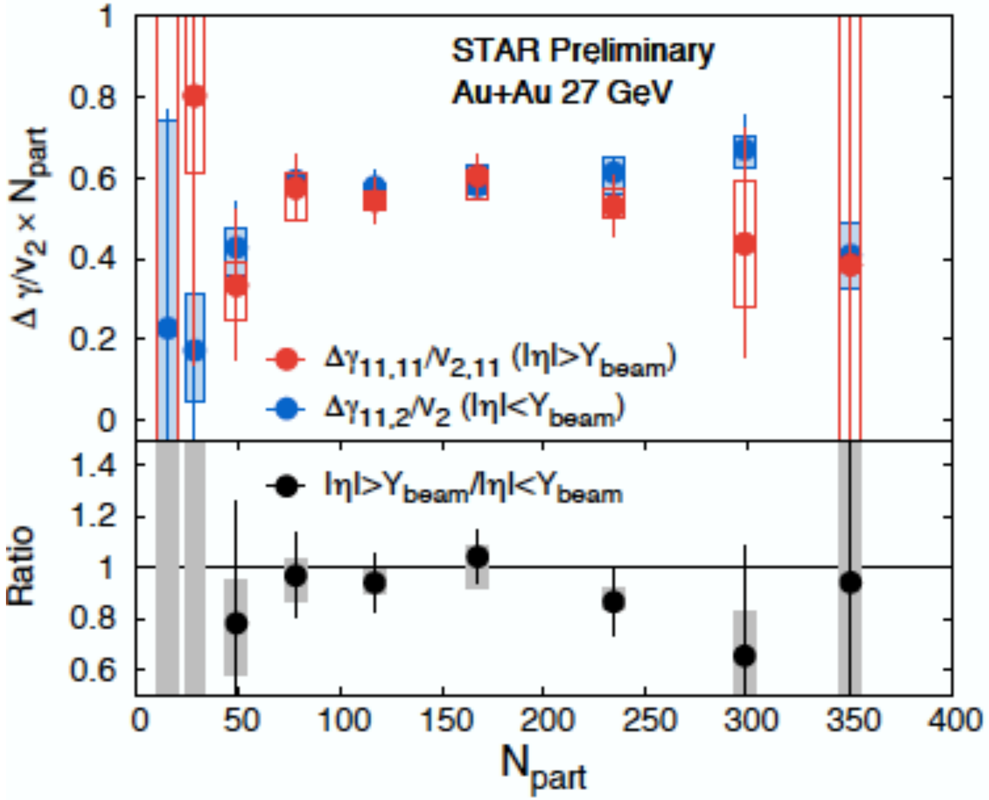
New dielectron spectra at 54.4 GeV
Improved measurement at 27 GeV with larger data sample
- **Consistent with published data**
- **Hints of excess at IMR**

Use HFT capability to disentangle thermal and charm contributions at IMR



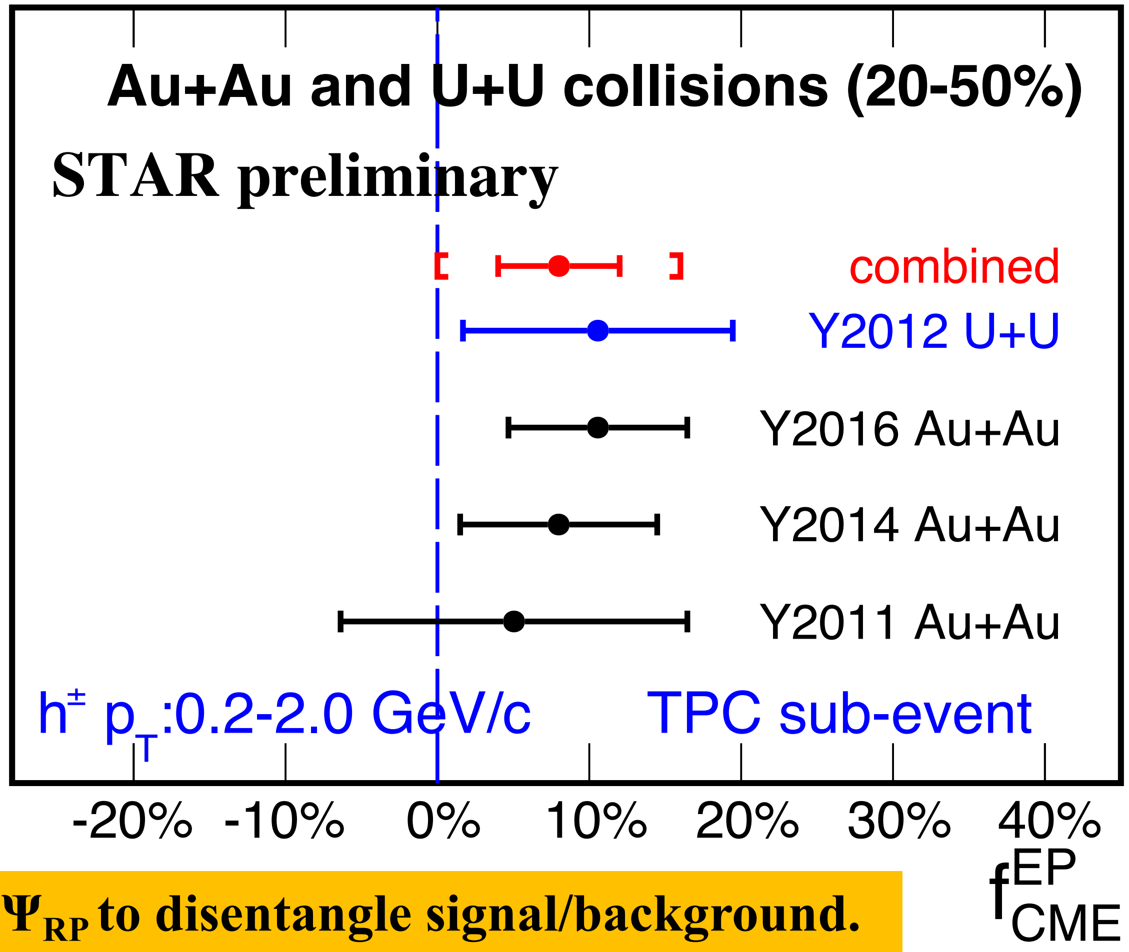
CME developments





Jie Zhao, Tue, 14:20 BR2

Measure participant and reaction planes in EPD
New STAR capability for CME search at 27 GeV



Ψ_{PP} and Ψ_{RP} to disentangle signal/background.
Fractions are extracted in U+U and Au+Au,
Averaged CME fraction = (8±4±8)%

CME developments

Yufu Lin, Tue, 14:40 BR2

1) Count pair's momentum ordering in p_y

$$B_{P,y}(S_y) = \frac{N_{+-}(S_y) - N_{++}(S_y)}{N_+}$$

$$B_{N,y}(S_y) = \frac{N_{-+}(S_y) - N_{--}(S_y)}{N_-}$$

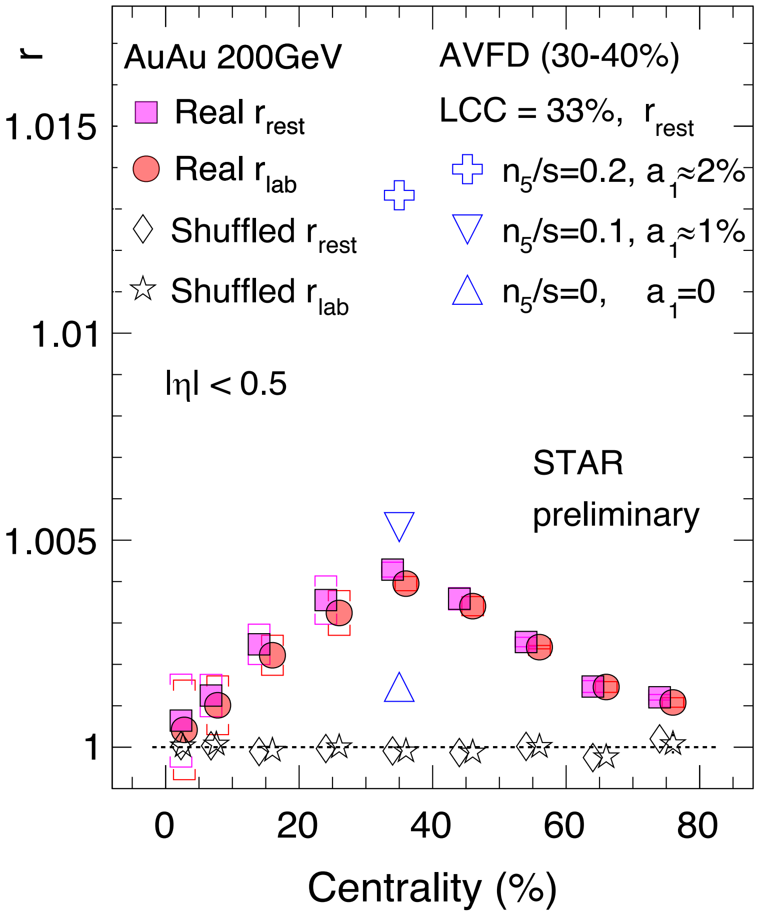
2) Count net-ordering (e.g. excess of pos. leading neg.) for each event :

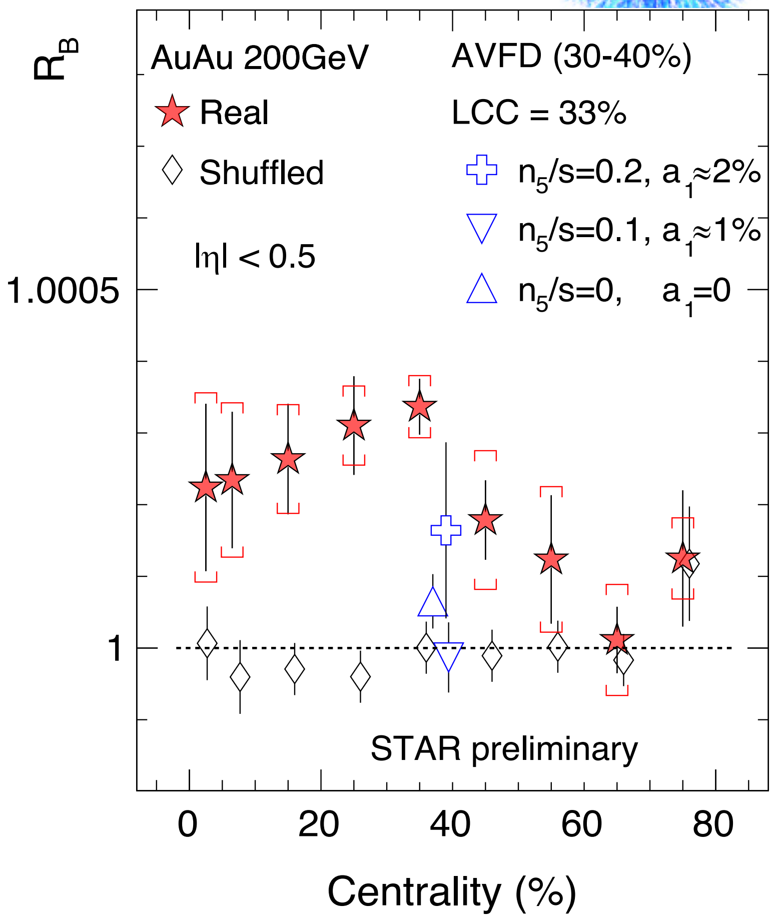
$$\delta B_y(\pm 1) = B_{P,y}(\pm 1) - B_{N,y}(\pm 1)$$

$$\Delta B_y = \delta B_y(+1) - \delta B_y(-1)$$

3) Look for enhanced event-by-event fluctuation of net-ordering in y direction.

$$r = \frac{\sigma_{\Delta B_y}}{\sigma_{\Delta B_x}}$$ (>1 with CME)



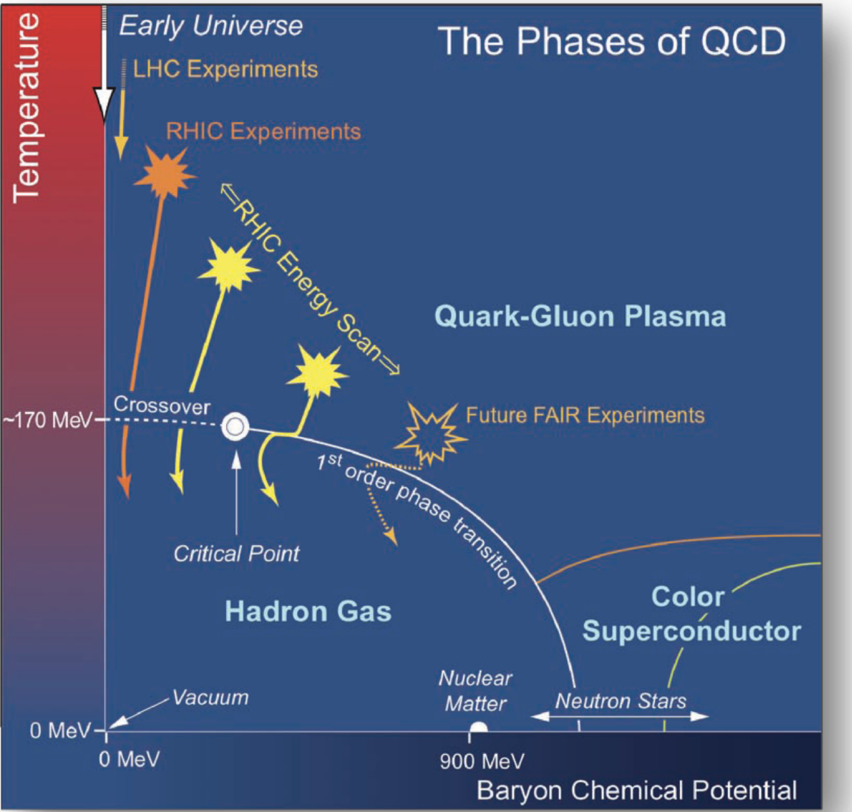


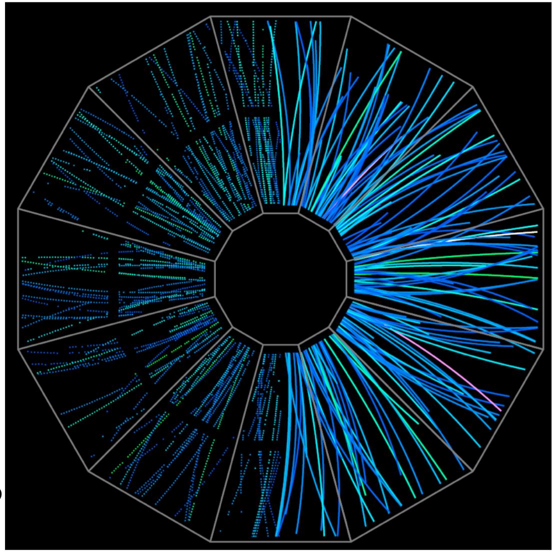
New Search with Signed Balance Function:

Both $r_{rest(lab)}$ and R_B are larger than realistic model with no CME.

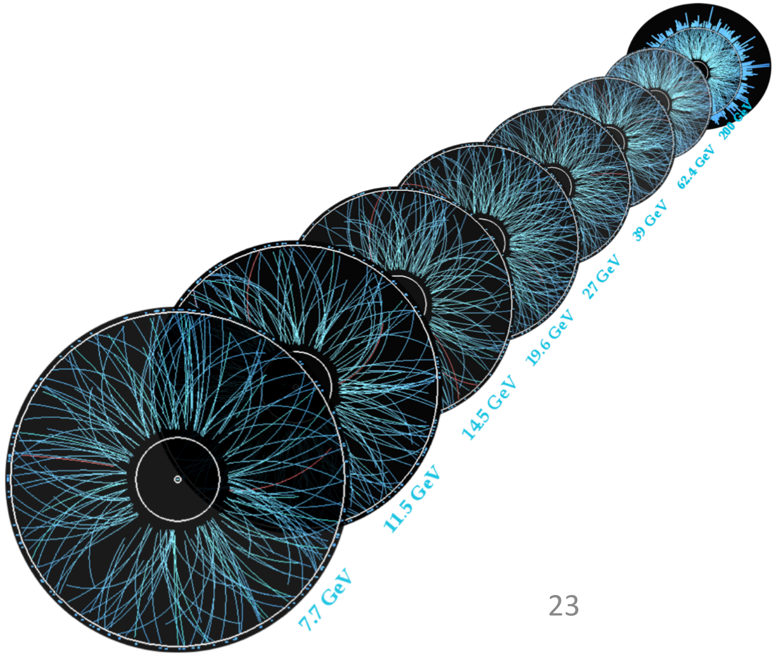
Data difficult to explain by backgrounds only.

STAR Overview





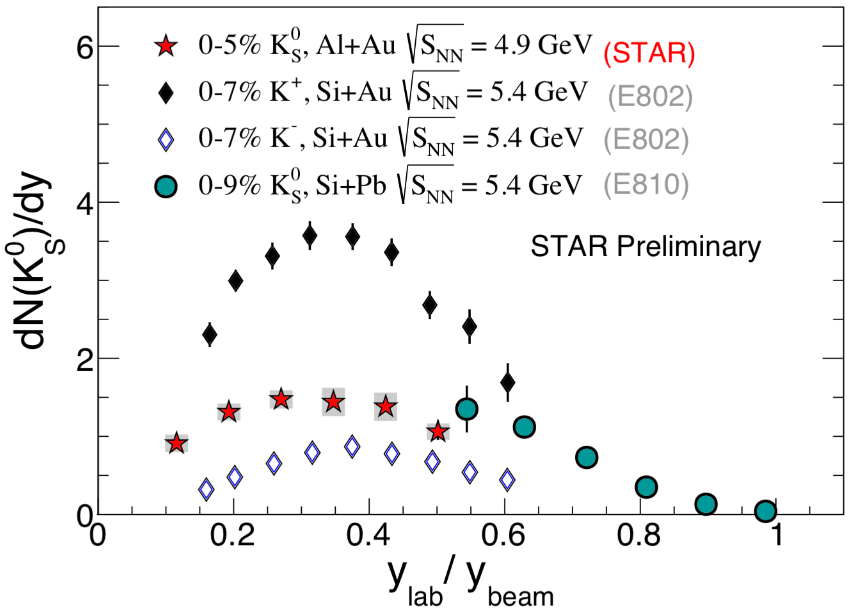
- **Discoveries** of Breit-Wheeler process and Vacuum Birefringence
- **Initial State**
- **Viscosity [η/s(T)]:** Multiple Harmonics and Rapidity Correlations
- **Hard Probes**
- Origin of global **polarization and vorticity**
- **Chiral and thermal** properties
- BES and **Critical Point** search
  (Muhammad Usman, Wed 11:40 HK
  Dingwei Zhang, Wed 9:00 BR1
  Kishora Nayak, Tue 14:20 BR1
  Ashish Pandav, Tue 11:20 BR3)
- Upgrades and Summary

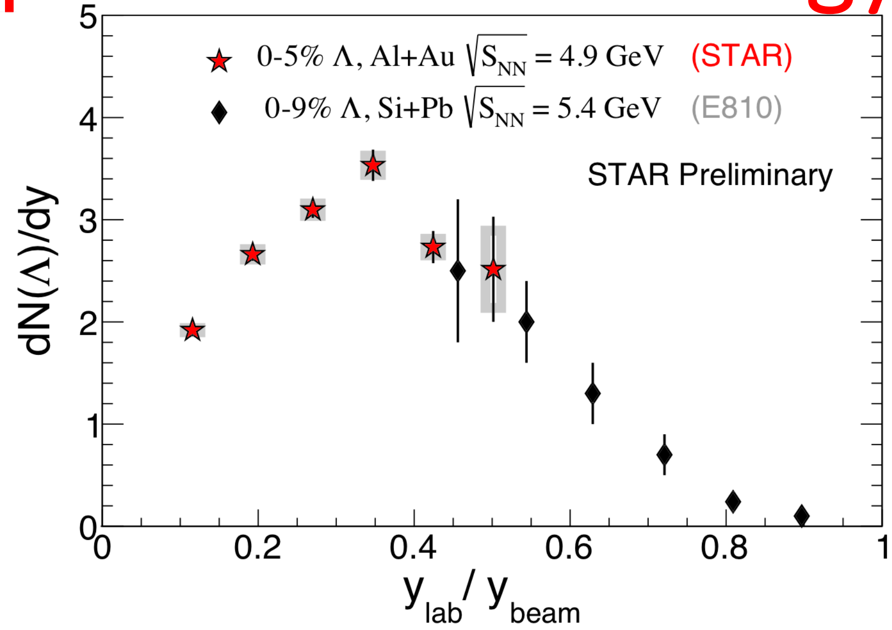


www.star.bnl.gov

The STAR experiment
at the Relativistic Heavy Ion Collider, Brookhaven National Laboratory

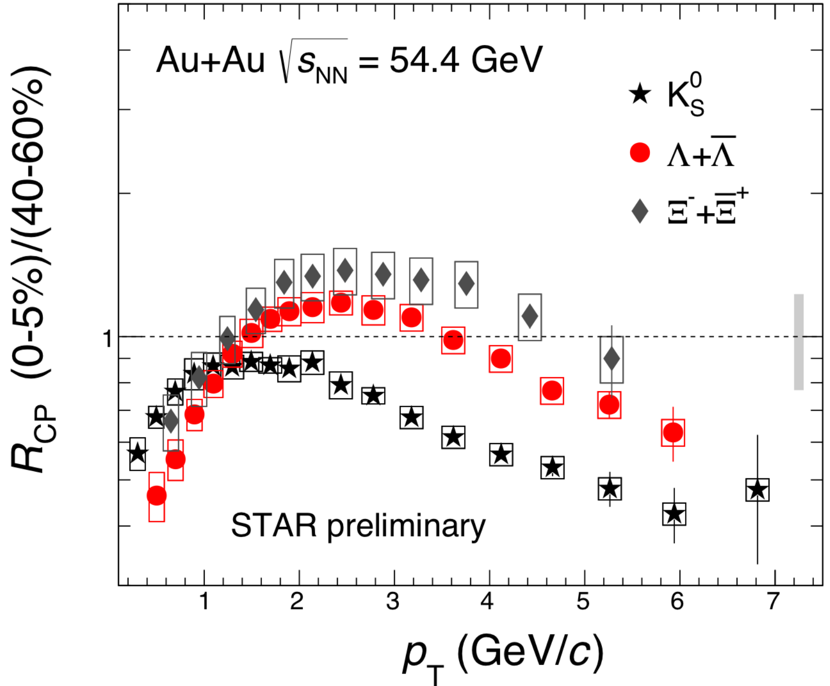
Identified particle spectra at new energy and FXT





Muhammad Usman, Wed 11:40 HK

New Energies with high statistics presented:
Au+Au: 54.4 GeV
(FXT) Al+Au: 4.9 GeV



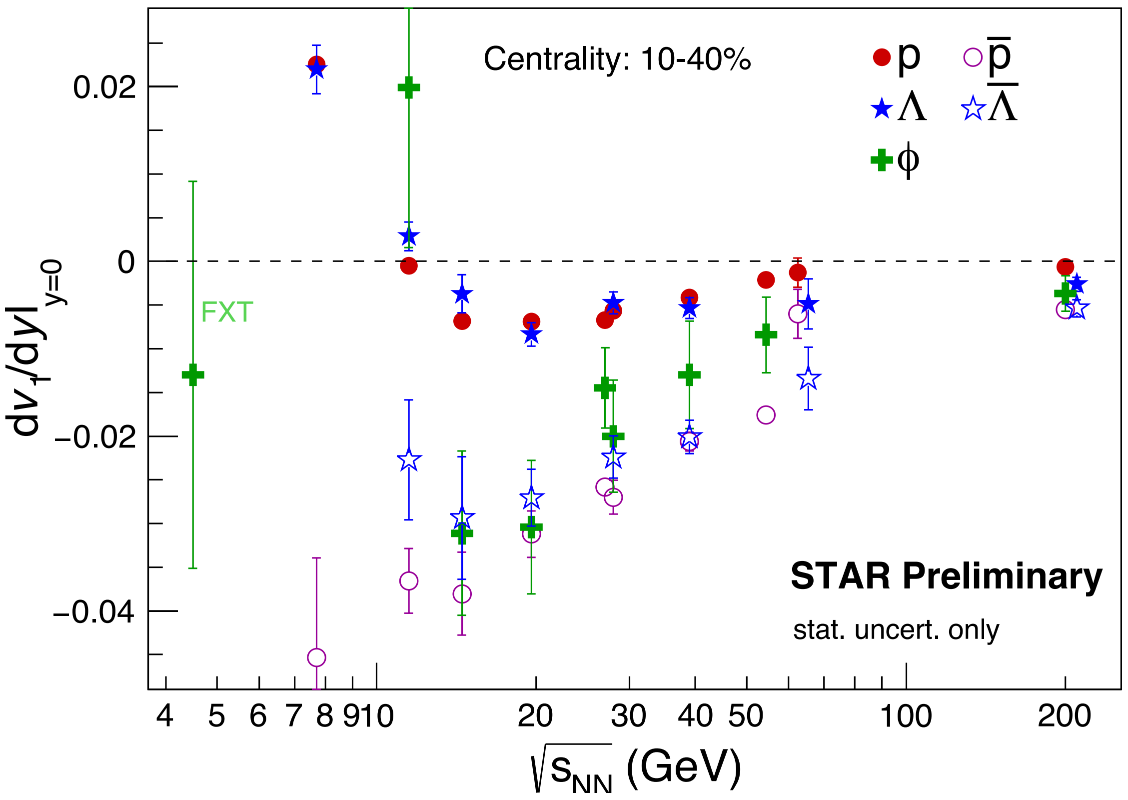
Extend AGS results in fixed-target data

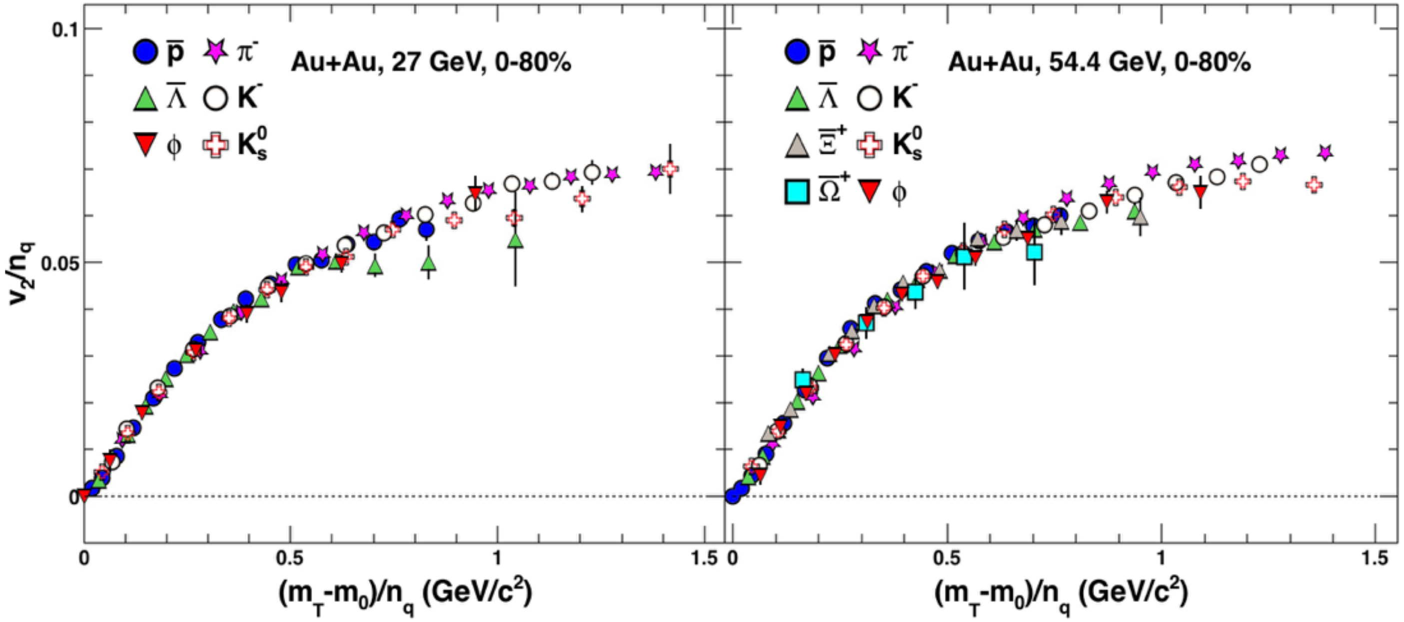
- **Chemical and kinetic freeze-out**
- **Quark coalescence and jet quenching in large p_T range**

Excitation functions of v_1 slope and v_2

Kishora Nayak, Tue 14:20 BR1

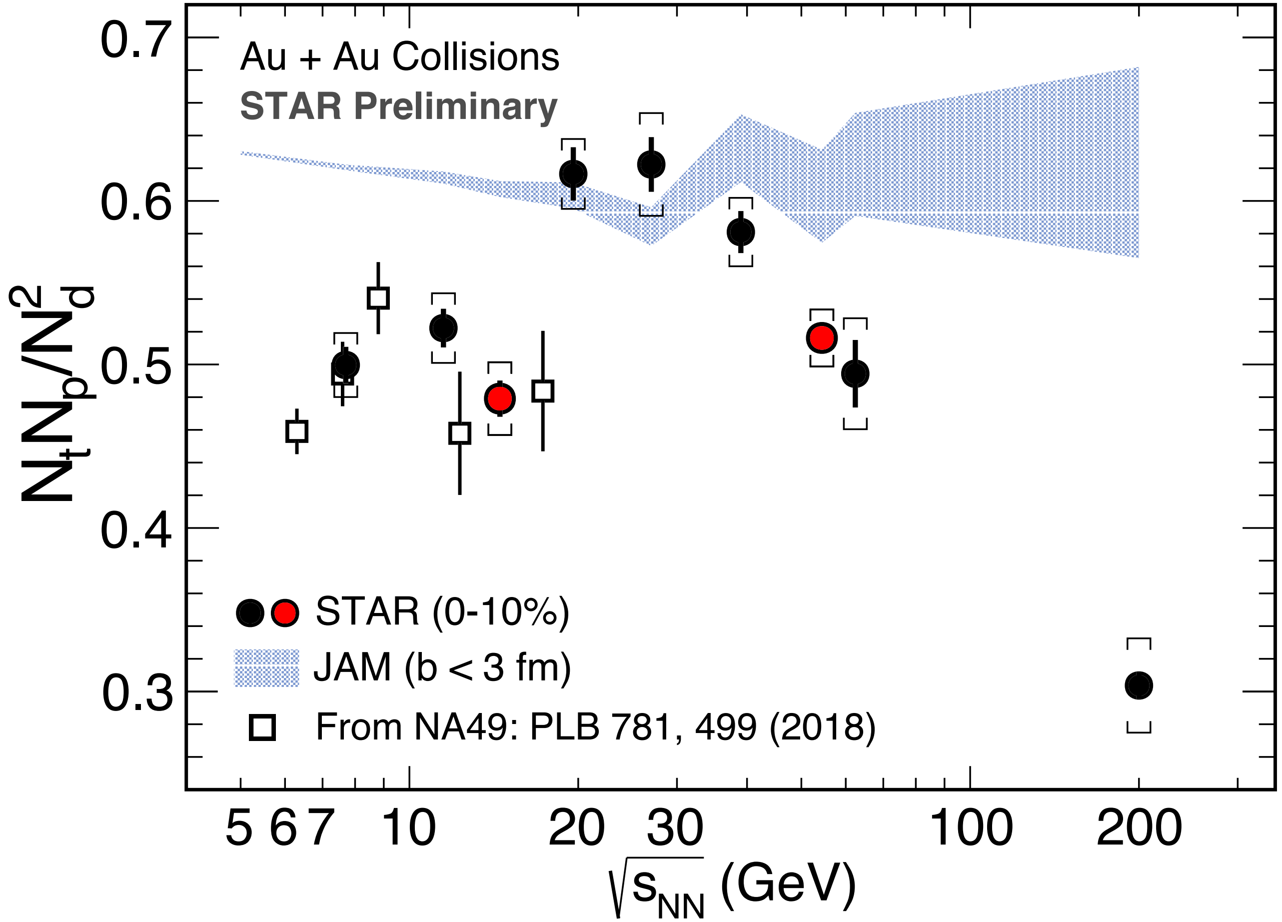
New data at FXT, 27 and 54.4 GeV





Mesons and produced baryons: negative v_1 slope
NCQ scaling for produced particles

Nucleus yield ratio -- Neutron density fluctuations



Dingwei Zhang, Wed 9:00 BR1

$$N_t \cdot N_p / N_d^2 = g(1 + \Delta n),$$

$$with\ g = 0.29$$

Yield ratio is related to neutron density fluctuations.

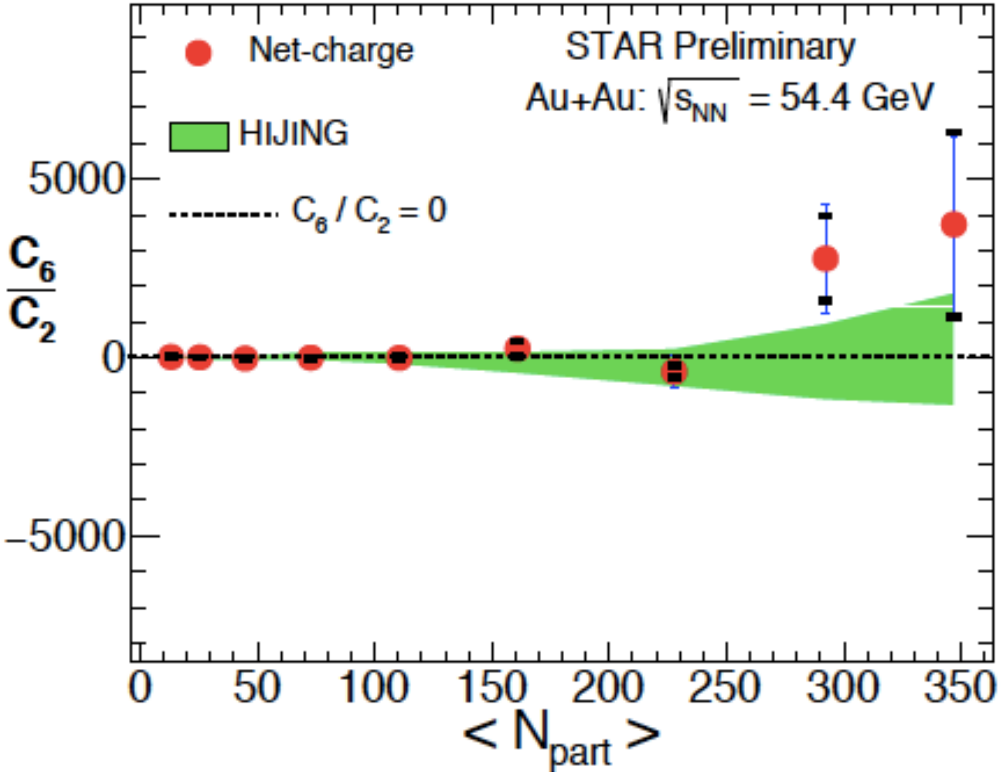
Yield ratio shows non-monotonic behavior on collision energy in 0-10% Au+Au collisions.

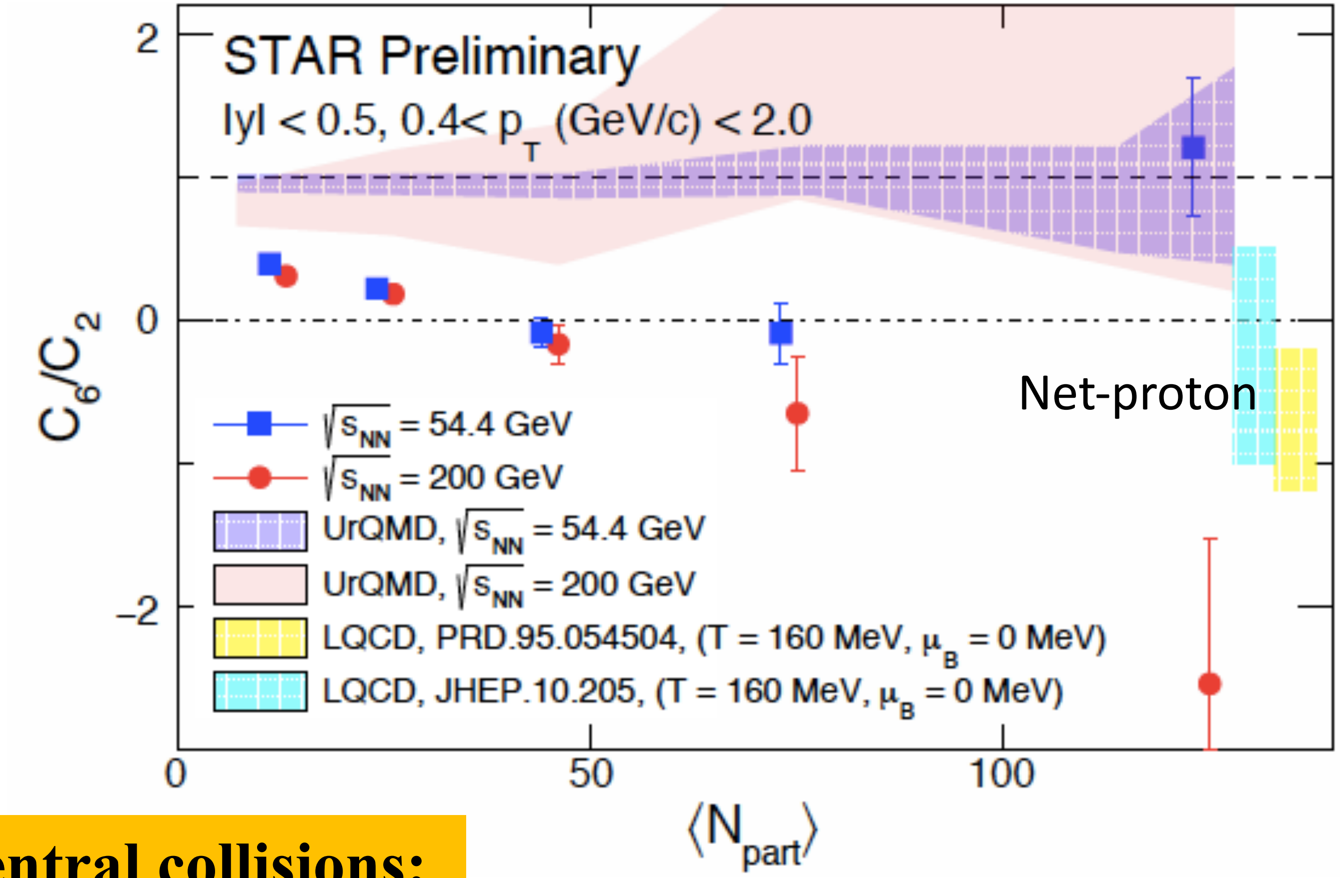
Flat energy dependence of yield ratio observed in JAM model - does not describe data.

Sixth-order cumulants of baryon and charge

O(4) chiral theory: C_6 of baryon number and electric charge fluctuations remain negative at chiral transition temperature.

Ashish Pandav, Tue 11:20 BR3





For most central collisions:
$C_6/C_2<0$ for 200 GeV
$C_6/C_2>0$ for 54.4 GeV

Beam Energy Scan Phase II upgrades and events

Yi Yang, Tue 16:20 HK

Collider mode

Collision Energy (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV) in 0-5% central collisions	420	370	315	260	205
Observables					
R_{CP} up to $p_T = 5$ GeV/c	-	-	160	125	92
Elliptic Flow (ϕ mesons)	80	120	160	160	320
Chiral Magnetic Effect	50	50	50	50	50
Directed Flow (protons)	20	30	35	45	50
Azimuthal Femtoscopy (protons)	35	40	50	65	80
Net-Proton Kurtosis	70	85	100	170	340
Dileptons	100	160	230	300	400
$>5\sigma$ Magnetic Field Significance	50	80	110	150	200
Required Number of Events	100	160	230	300	400
Achieved in BES-I (Millions)	4.3	N/A	11.7	12.6	36
Achieved in BES-II so far	**3***			**324**	**581**

BES-II started this year

Fixed-Target Mode

Energy (GeV)	**7.7**	**3.9**	**3.2**	**3.0**
μ_B(MeV)	420	633	699	721
FXT (GeV)	31.2	7.3	4.55	3.85
Achieved in BES-II so far	**51**	**53**	**200**	**300**

Typically factor 20 more than for BES-I
with iTPC+EPD+eTOF upgrades
Two more runs in 2020+2021

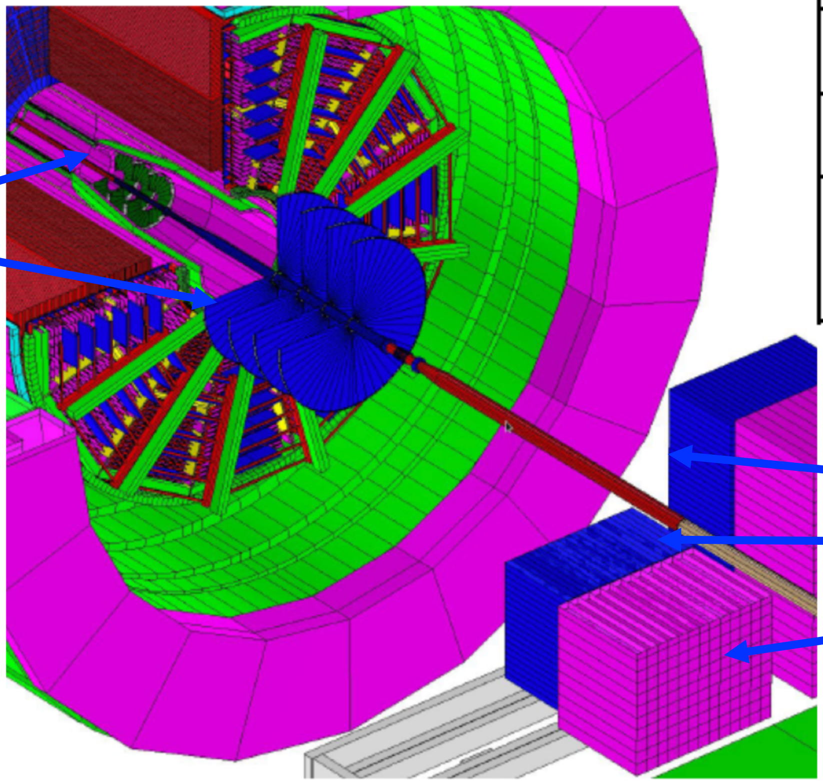
STAR forward physics program

Yi Yang, Tue 16:20 HK

- The forward upgrade in STAR includes **Calorimeters (ECAL & HCAL)** and **Trackers (silicon microstrip tracker & sTGC)** dedicated for studying the nuclear structure, QGP (rapidity correlation/hyperon polarization)

Detector	pp and pA	AA
ECAL	~10%/√E	~20%/√E
HCAL	~60%/√E	---
Tracking	Charge separation Photon suppression	$0.2 < p_T < 2$ GeV/c with 20 – 30% $1/p_T$

Forward Tracker
- ❑ 3 silicon disks
- ❑ 4 sTGC layers



Forward Calorimeters
- ❑ Pre/post-shower: scintillator
- ❑ ECAL: PbSc towers (18 X_0)
- ❑ HCAL: FeSc plates (4.5 λ)

Preparing for data-taking from 2021+

STAR oral presentations in parallel sessions

736	**Kishora Nayak**	CCNU	Tue 14:20 BR1	T4	Directed and elliptic flow of high-pT charged hadrons, identified hadrons and light nuclei in Au+Au collisions
743	**Niseem Magdy**	UIC	Wed 09:40 BR3	T4	Beam energy and collision-system dependence of the linear and mode-coupled flow harmonics at RHIC energies
680	**Roy Lacey**	SBU	Tue 09:40 BR3	T3	Long-range collectivity in small collision systems with two- and four-particle correlations
671	**Maowu Nie**	SDU/SBU	Tue 09:00 BR1	T4	Longitudinal De-correlation of Anisotropic Flow in 27 and 54 GeV Au+Au Collisions
750	**Joey Adams**	OSU	Wed 14:00 BR1	T6	Differential measurements of Λ polarization in Au+Au collisions at 54 GeV and asearch for the magnetic field at 27 GeV
438	**Subhash Singh**	KSU	Wed 11:20 BR3	T6	Measurement of global spin alignment of K^{*0} and $K^{*\pm}$ vector mesons
667	**Jie Zhao**	Purdue	Tue 14:20 BR2	T6	Search for CME in U+U and Au+Au collisions in STAR with different approaches of handling backgrounds
669	**Yufu Lin**	CCNU/BNL	Tue 14:40 BR2	T6	Measurement of the charge separation along the magnetic field with Signed Balance Function in 200 GeV Au + Au collisions
739	**Ashish Pandav**	NISER	Tue 11:20 BR1	T5	Measurement of the Cumulants of Conserved Charge Multiplicity Distributions in Au+Au Collisions
378	**Matthew Kelsey**	LBNL	Tue 17:40 BR3	T8	Nuclear modification factors, directed and elliptic flow of electrons from open heavy flavor decays in Au+Au collisions
557	**Yanfang Liu**	TAMU	Tue 15:00 BR3	T8	Recent Measurements of Heavy Quarkonium Production in p+A and p+p Collisions
439	**David Stewart**	Yale	Tue 12:20 BR2	T3	Correlation measurements of charged particles and jets at mid-rapidity with event activity at forward-rapidity in 200 GeV p+Au collisions
381	**Raghav Kunnawalkam Elayavalli**	WSU	Wed 09:20 BR2	T7	Constraining parton energy loss via angular and momentum based differential jet measurements in Au+Au collisions
355	**Saehanseul Oh**	Yale/BNL	Tue 09:00 BR2	T7	Jet shapes and fragmentation functions in Au+Au collisions at sqrt(sNN)=200 GeV
646	**Daniel Brandenburg**	SDU/BNL	Tue 09:00 HK	T9	Measurements of the $\gamma\gamma \rightarrow e^+e^-$process and its angular correlations in UPC and peripheral Au+Au collisions
287	**Florian Seck**	Darmstadt	Wed 16:20 BR3	T9	Measurements of dielectron production in Au+Au collisions at sqrt(sNN) = 27, 54 and 200 GeV
462	**Dingwei Zhang**	CCNU	Wed 09:00 BR1	T5	Light Nuclei (d, t) Production in Au+Au Collisions at sqrt(sNN) =7.7-200 GeV
384	**Muhammad Usman**	CCNU/THU	Wed 11:40 HK	T1	Strangeness production in sqrt(sNN) = 54.4, 27 GeV and fixed-target program
388	**Yi Yang**	NCKU	Tue 16:20 HK	T12	The STAR detector upgrades for the BES II and beyond physics program

Talks and posters available at https://drupal.star.bnl.gov/STAR/presentations


20 years
STAR
COLLABORATION
STAR

Backup slides

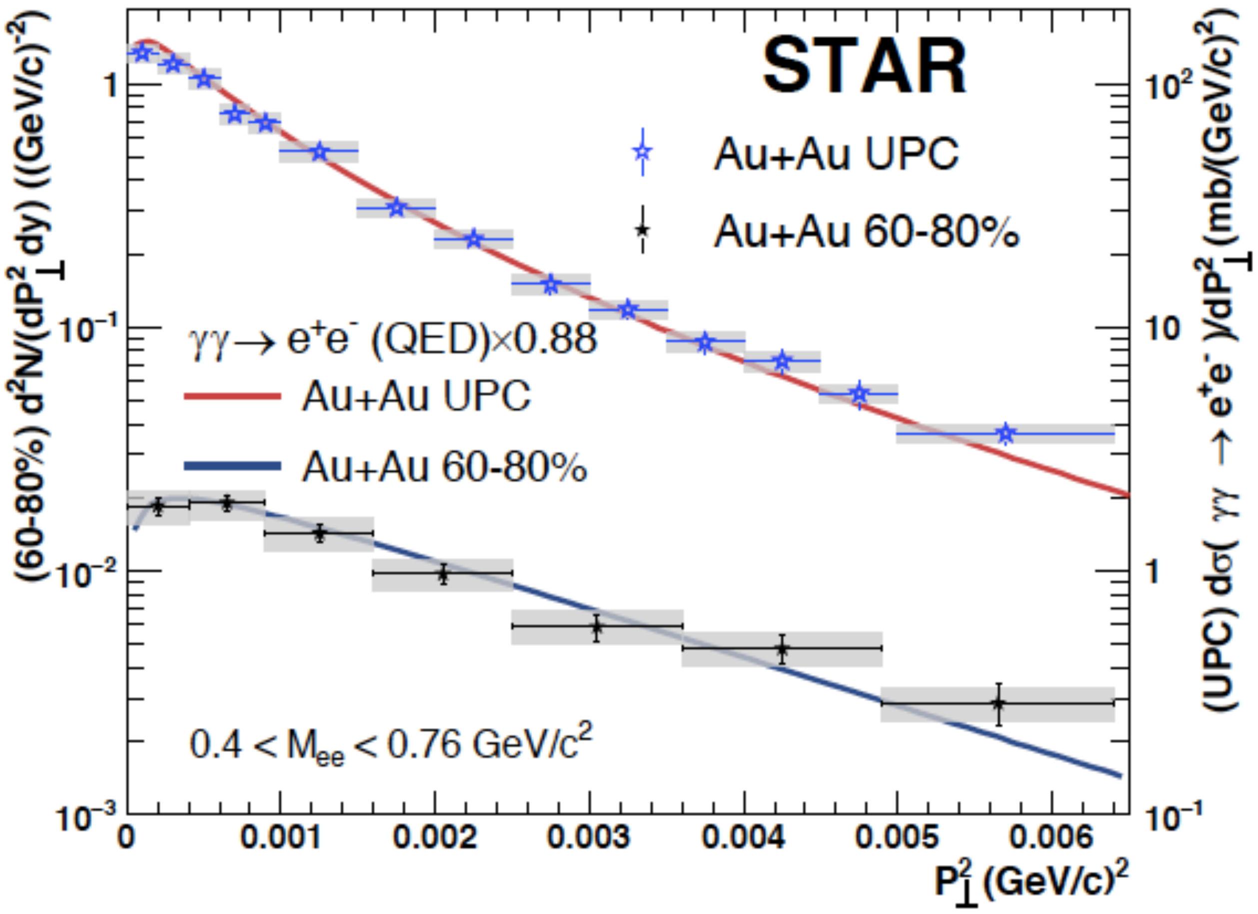
STAR is composed of 67 institutions from 13 countries and region, with a total of 679 collaborators.

STAR Collaboration Acknowledgements:

We thank the RHIC Operations Group and RCF at BNL, the NERSC Center at LBNL, and the Open Science Grid consortium for providing resources and support. This work was supported in part by the Office of Nuclear Physics within the U.S. DOE Office of Science, the U.S. National Science Foundation, the Ministry of Education and Science of the Russian Federation, National Natural Science Foundation of China, Chinese Academy of Science, the Ministry of Science and Technology of China and the Chinese Ministry of Education, the National Research Foundation of Korea, Czech Science Foundation and Ministry of Education, Youth and Sports of the Czech Republic, Hungarian National Research, Development and Innovation Office, New National Excellency Programme of the Hungarian Ministry of Human Capacities, Department of Atomic Energy and Department of Science and Technology of the Government of India, the National Science Centre of Poland, the Ministry of Science, Education and Sports of the Republic of Croatia, RosAtom of Russia and German Bundesministerium fur Bildung, Wissenschaft, Forschung and Technologie (BMBF) and the Helmholtz Association.

$\gamma\gamma \rightarrow e^+e^-$ in UPC vs. Peripheral Au+Au

[1] STAR, Phys. Rev. Lett. 121, 212301 (2018)
[2] S. Klein, et. al, Phys. Rev. Lett. 122, 132301 (2019).
[3] ATLAS Phys. Rev. Lett. 121, 212301 (2018)



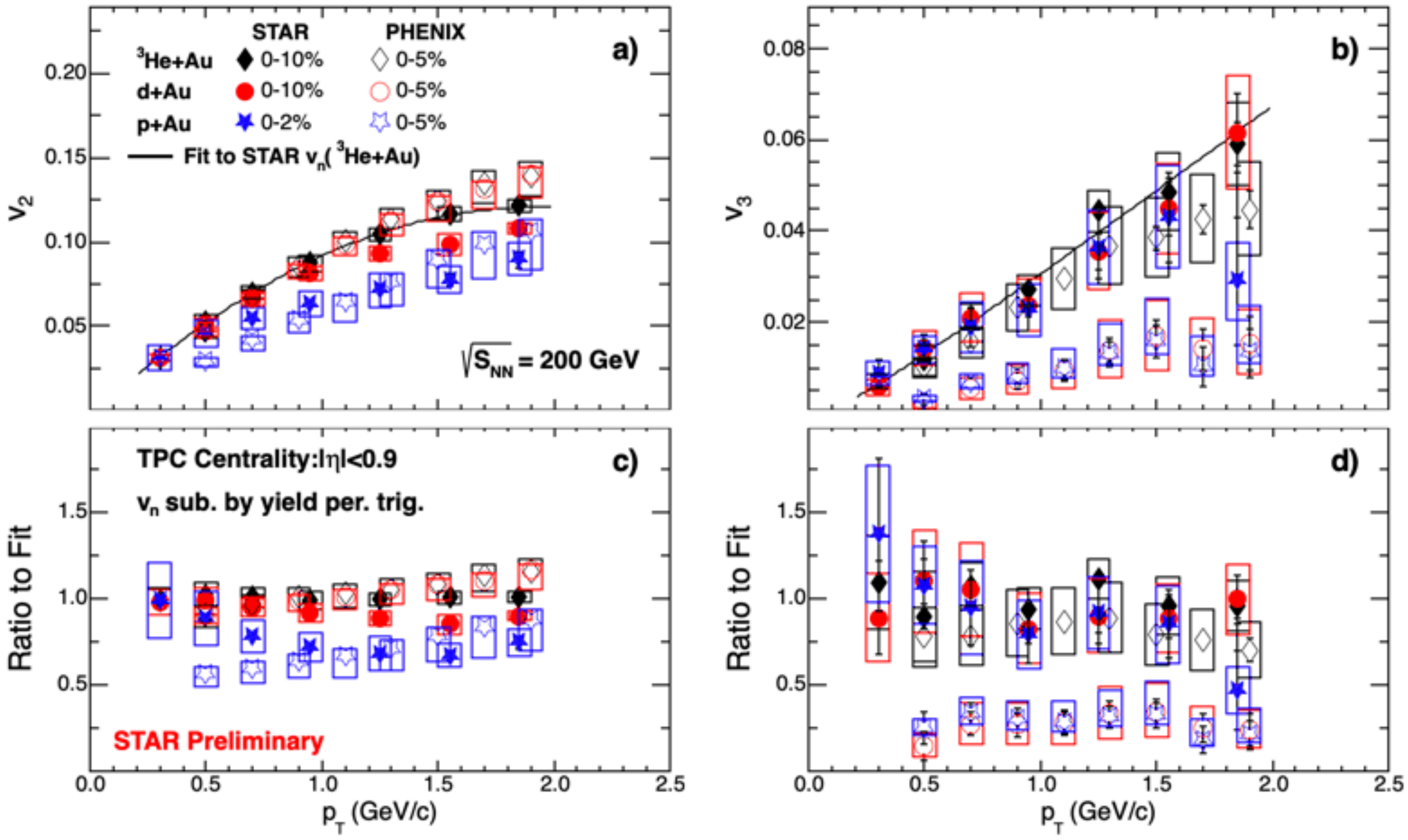
Characterize difference in spectra vis $\sqrt{\langle P_\perp^2 \rangle}$

$\sqrt{\langle P_\perp \rangle}$	UPC Au+Au	60-80% Au+Au
Measured	38.1 ± 0.9	50.9 ± 2.5
QED	37.6	48.5
$\langle \boldsymbol{b} \rangle$ **range**	≈ 20 fm	$\approx 11.5 - 13.5$ fm

- Lowest order QED calculation of $\gamma\gamma \rightarrow e^+e^-$ describes both spectra ($\pm 1\sigma$)
- Best fit for spectra in 60-80% collisions found for Breit-Wheeler shape plus 14 ± 4 (stat.)± 4 (syst.) MeV/c broadening
- Proposed as probe of trapped magnetic field or Coulomb scattering in QGP [1-3]

STAR Observes 4.8σ difference in $\sqrt{\langle P_\perp \rangle}$ for the $\gamma\gamma \rightarrow e^+e^-$ process in UPC vs. 60-80% Au+Au collisions

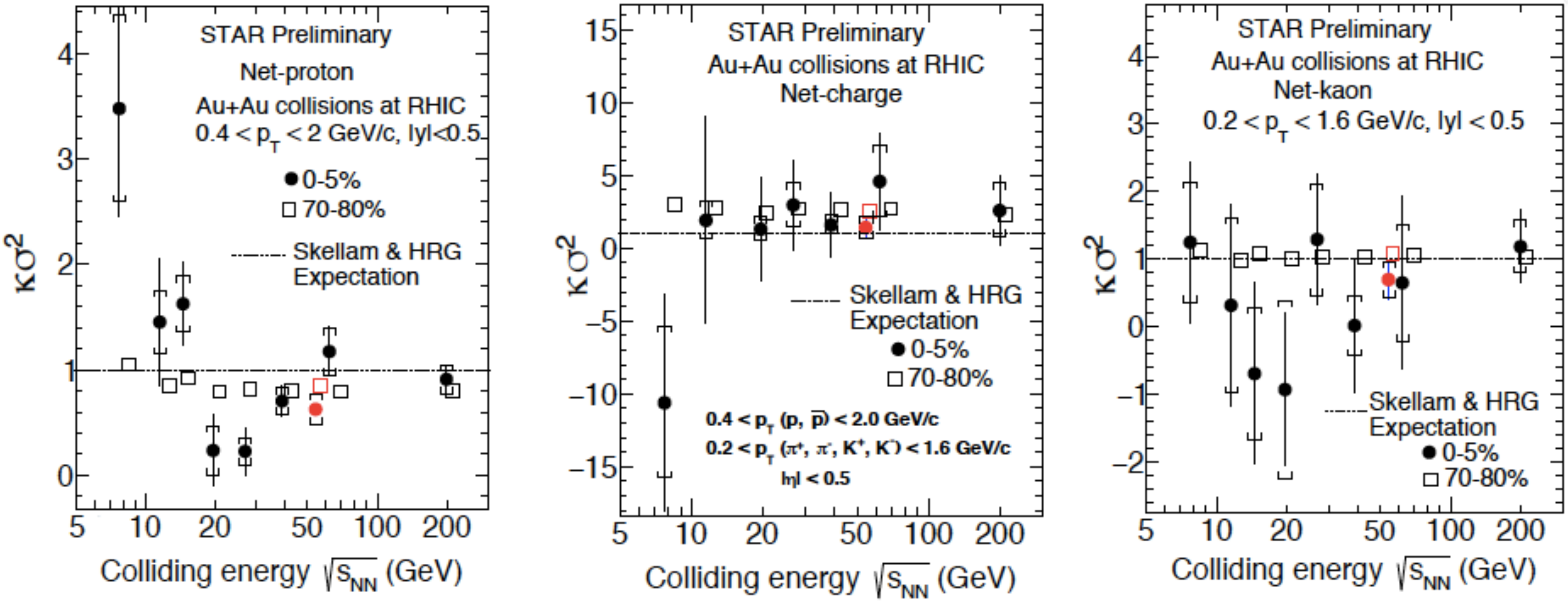
p/d/^{3}He+Au results between STAR and PHENIX



v_2 results are similar between STAR and PHENIX

v_3 measured by STAR is similar to v_3 from PHENIX for ^{3}He+Au, and more than a factor of 3 larger for p/d+Au collisions

Energy Dependence of Cumulants Ratios

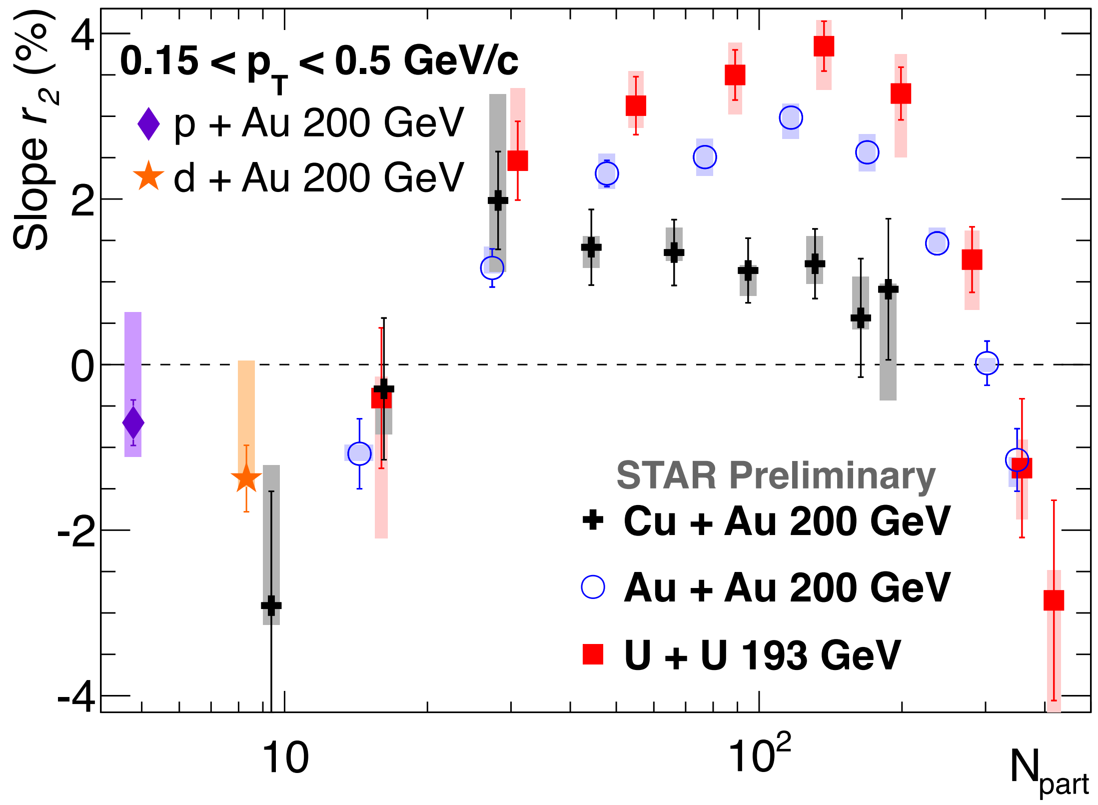


STAR: PoS CPOD2014 (2015) 019
[STAR Collaboration] PRL, 113, 092301 (2014)
[STAR Collaboration] PLB, 785, 551 (2018)

$\kappa\sigma^2$ measurement at 54.4 GeV agrees with existing BES-I measurement's trend.
Form precise baseline for critical fluctuation at lower beam energies.

CMW Developments

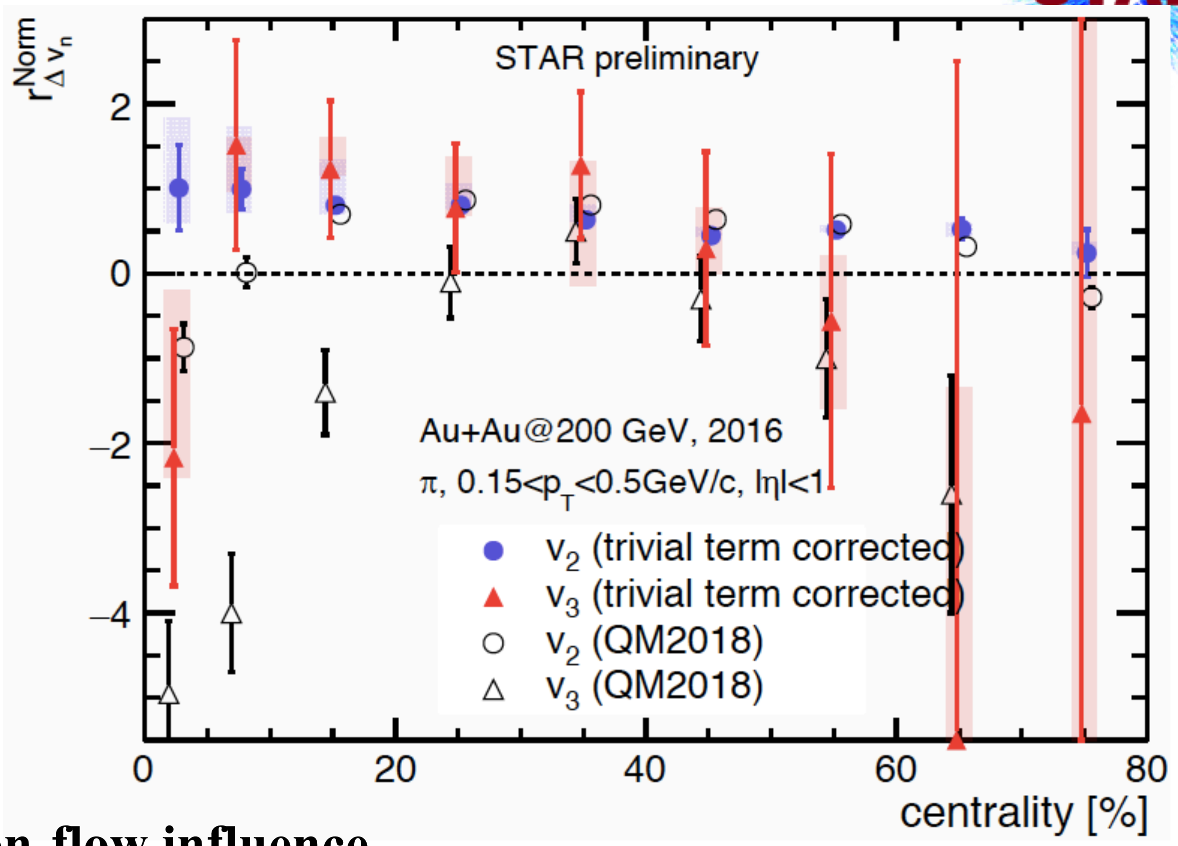
M. Sergeeva (STAR) poster 560



Slope of $v_{2,3}(\pi^+ - \pi^-)$ vs $N(h^+ - h^-)$

Slope ordering The slope increases with the expected strength of magnetic field in three systems (CuAu, AuAu, UU).

H-J. Xu (STAR) poster 668

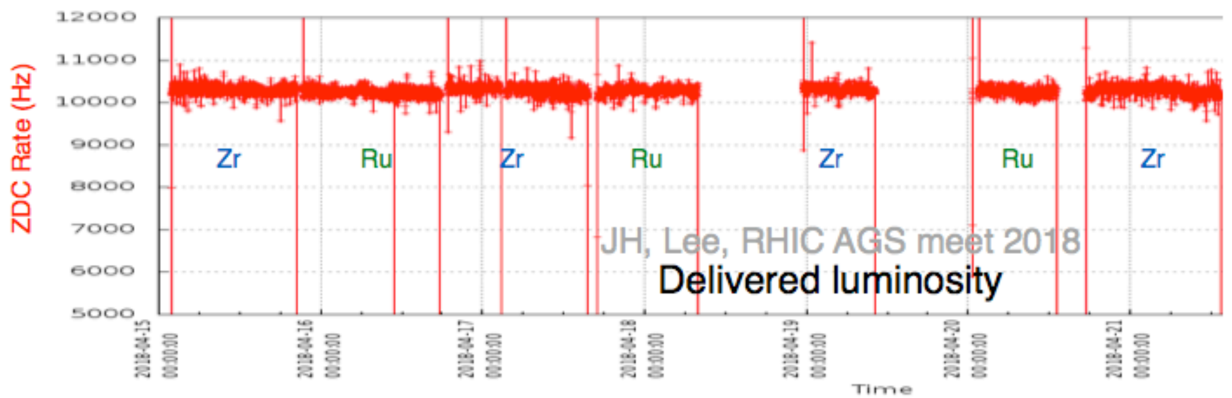


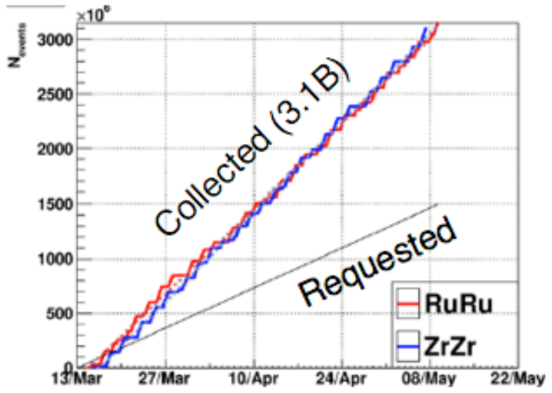
Non-flow influence.

Removing the trivial contribution, normalized v_3 slope is consistent with v_2 slope within 0.2σ, dominated by large v_3 slope uncertainty, while normalized v_3 slope is 1.5σ above zero. Results suggest background contributions.

*

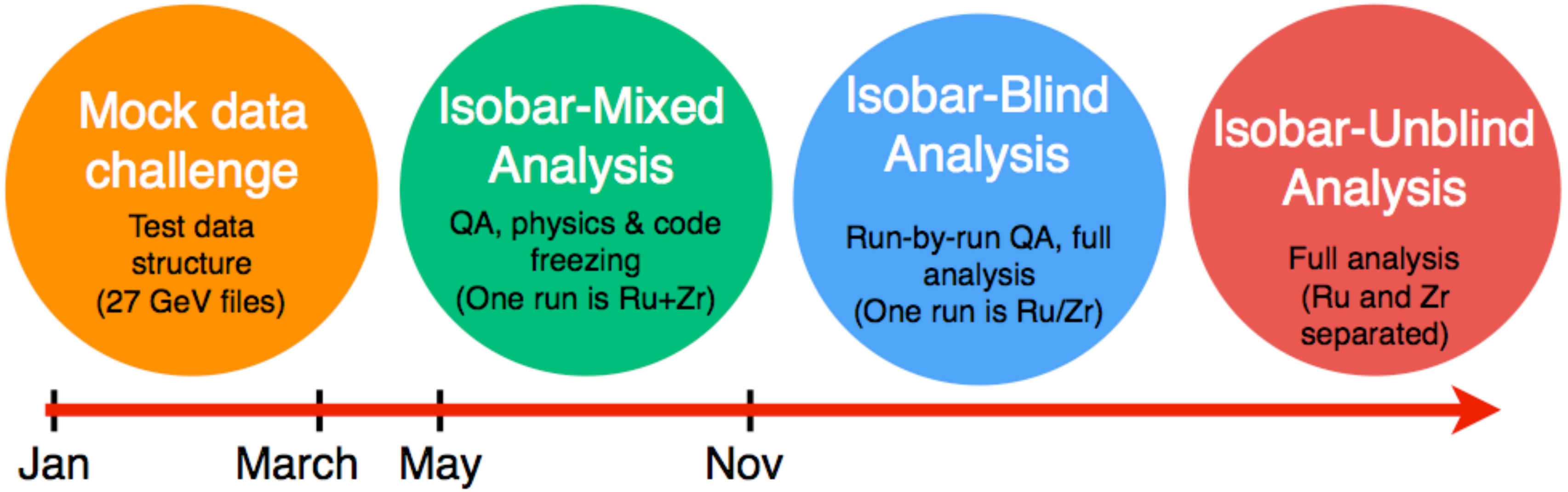
Test of CME with Isobar collisions





3.1B events for both Ru+Ru, Zr+Zr collected over 8 weeks
Plans for blind analyses of the data was laid down from the beginning

Blinding method document in arXiv



Blind analysis (by 5 separate STAR groups)
Status: Analysis codes developed from "mixed" data now frozen & documented
Next: short period of run-by-run QA checks (still blinded) before running each analysis