STAR Results From New Regimes of the Beam Energy Scan

Au+Au, Al+Au, and Au_{like}+Al Collisions at $\sqrt{s_{NN}}$ = 3.0 - 200 GeV

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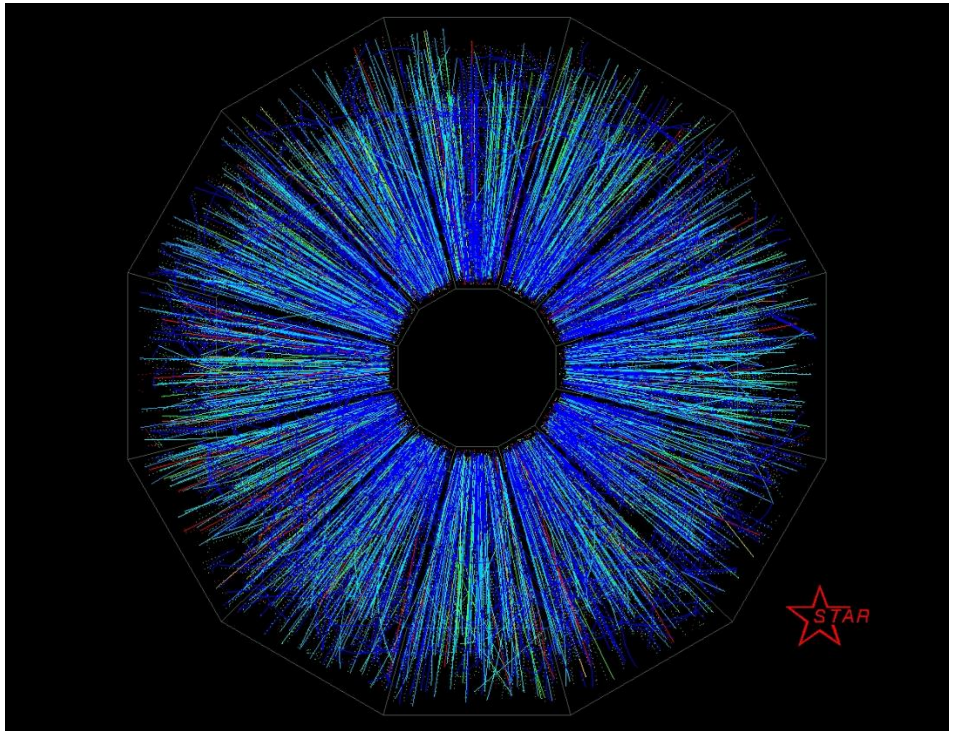
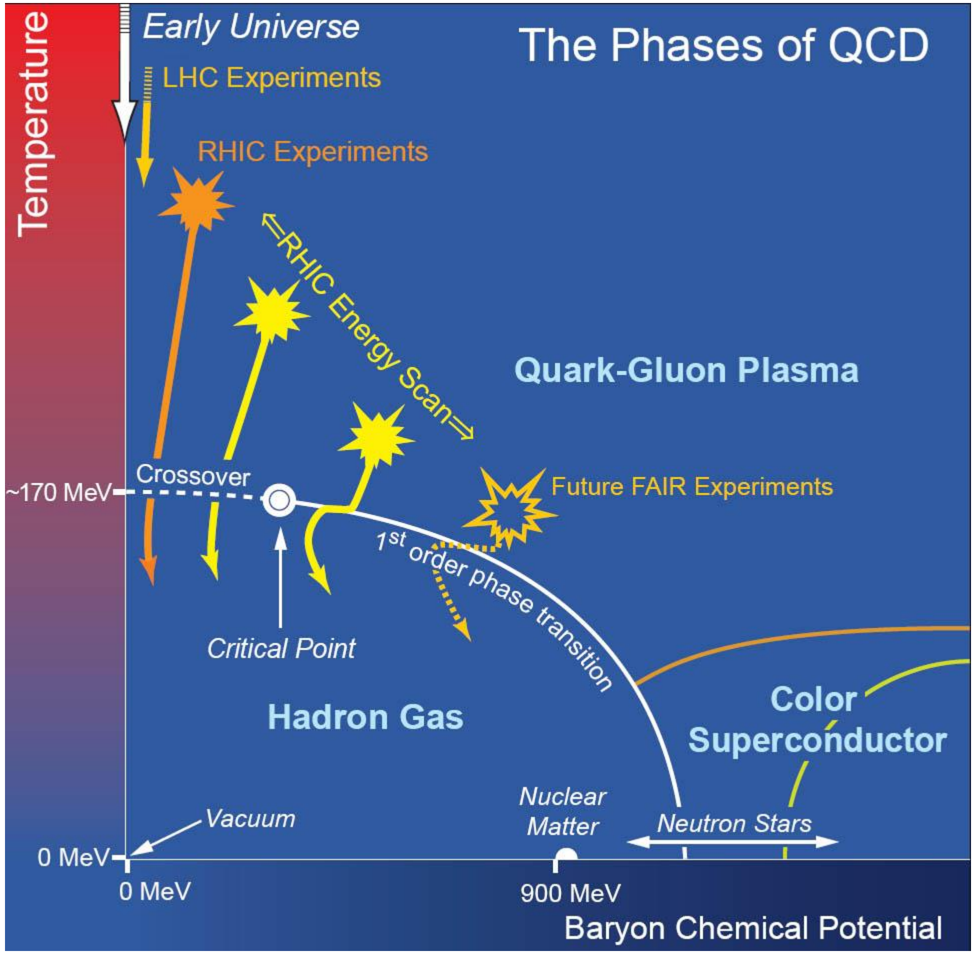
Outline

- Introduction to the QCD Critical Point Search
- Results from the First Phase of the Energy Scan
- Results from the Expanded Energy Scan
- Summary



RHIC "Energy Scan"

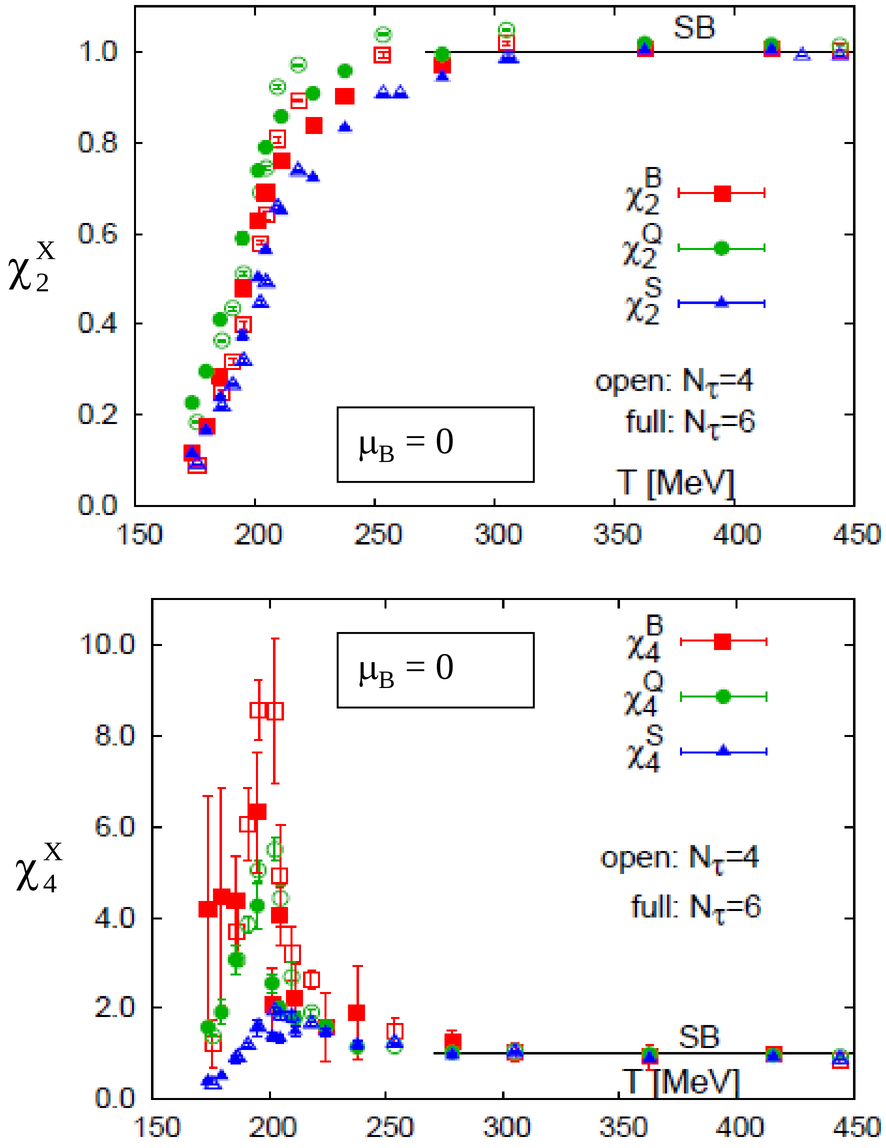


- Indications from experiment and theory that the transition at RHIC and LHC energies is a crossover, while at SPS energies (and below) possibly first order.
  - If correct, where the first order transition line meets crossover should be a critical point (CP).
  - This part of the QCD phase diagram is uncertain, there may not be a first order transition, which would mean no CP.
- Using RHIC to run an "energy scan" to search for predicted QCD CP.
- Data were taken from Au+Au collisions at $\sqrt{s_{NN}}$ = 200, 62.4, 39, 27, 19.6, 14.5, 11.5, and 7.7 GeV.
  - Recently added d+Au energy scan at $\sqrt{s_{NN}}$ = 200, 62.4, 39, 19.6 GeV.
- Can examine our observables to look for non-monotonic behavior as a function of collision energy.
  - Turn off of QGP "signatures" (e.g. jet quenching, n_{cq} scaling of v_2, etc.)?

Search for the QCD Critical Point

- In a phase transition near a critical point, an increase in non-statistical fluctuations is expected.
- Finite system-size effects may influence fluctuation measurements.
  - Finite-size scaling of fluctuations may indicate existence of critical point.
  - E.g. Change in behavior of quark susceptibilities.

    Aoki, Endrodi, Fodor, Katz, and Szabó *Nature* **443**, 675-678 (2006)
- These may manifest in final-state measurements.
- Lattice results continue to evolve as capabilities improve.



M. Cheng et al., Phys. Rev. D 79 (2009) 074505

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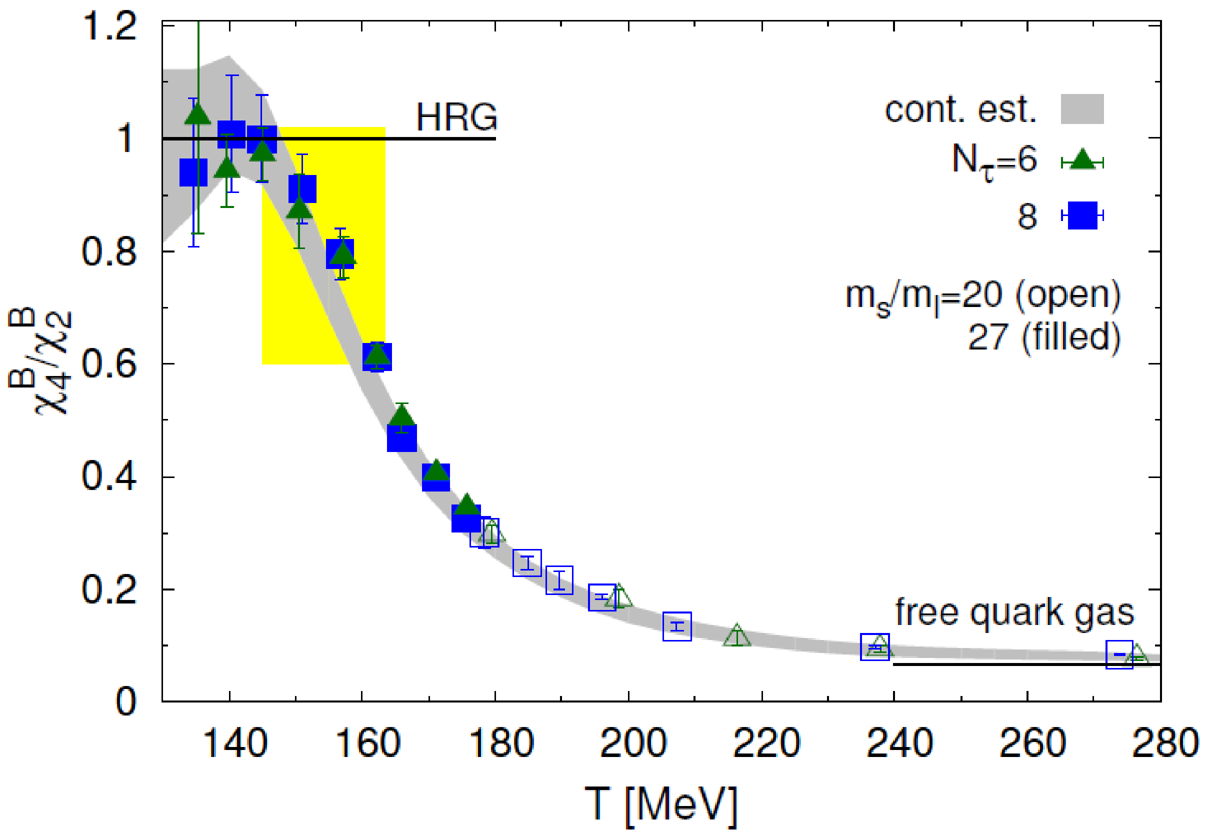
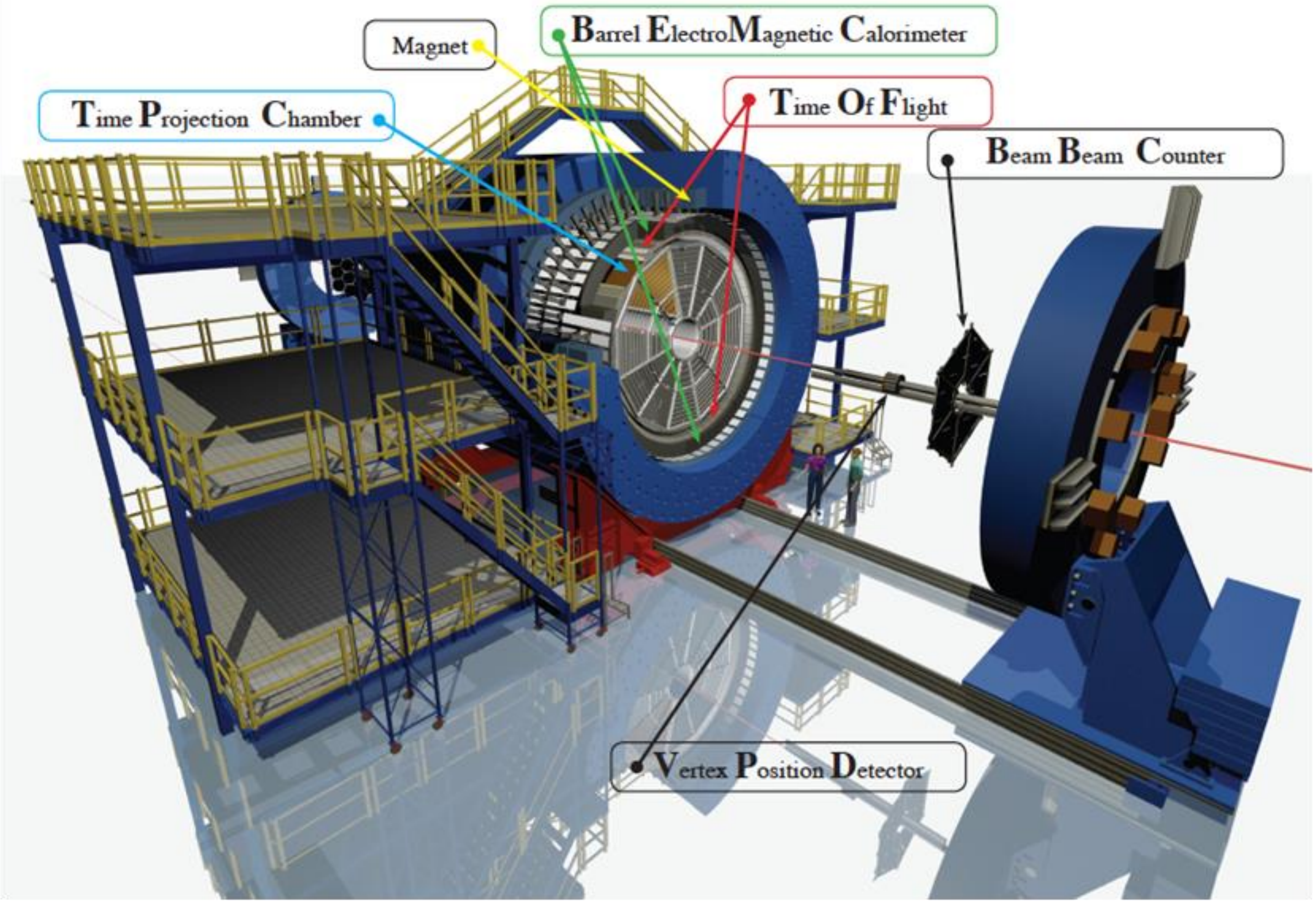
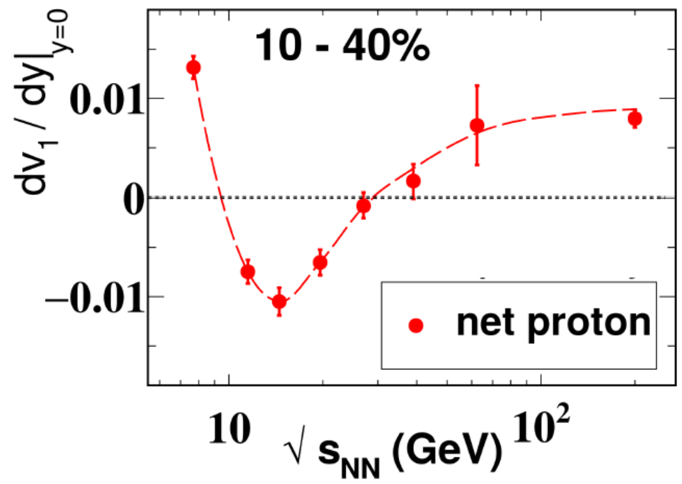


A. Bazavov et al., Phys. Rev. D 95 (2017) 054504

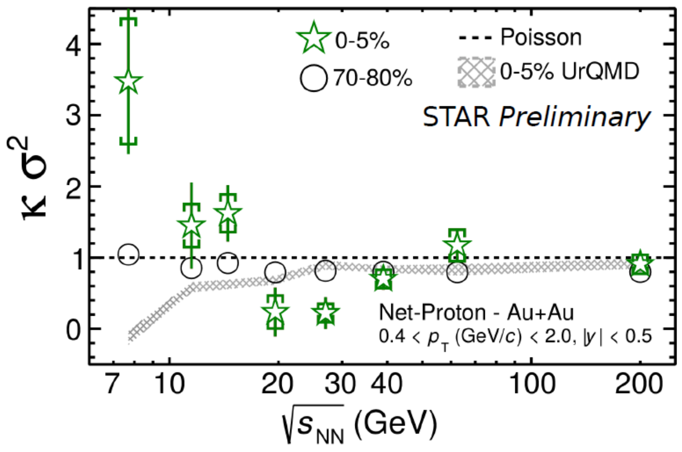
Solenoidal Tracker At RHIC : $-1 < \eta < 1, 0 < \phi < 2\pi$

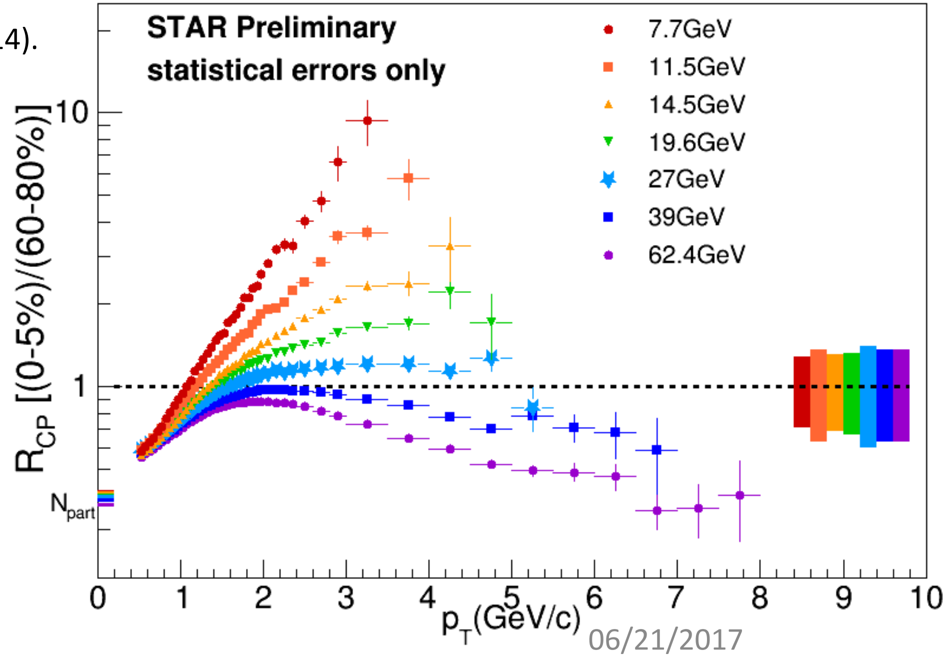


Some BES-I Results



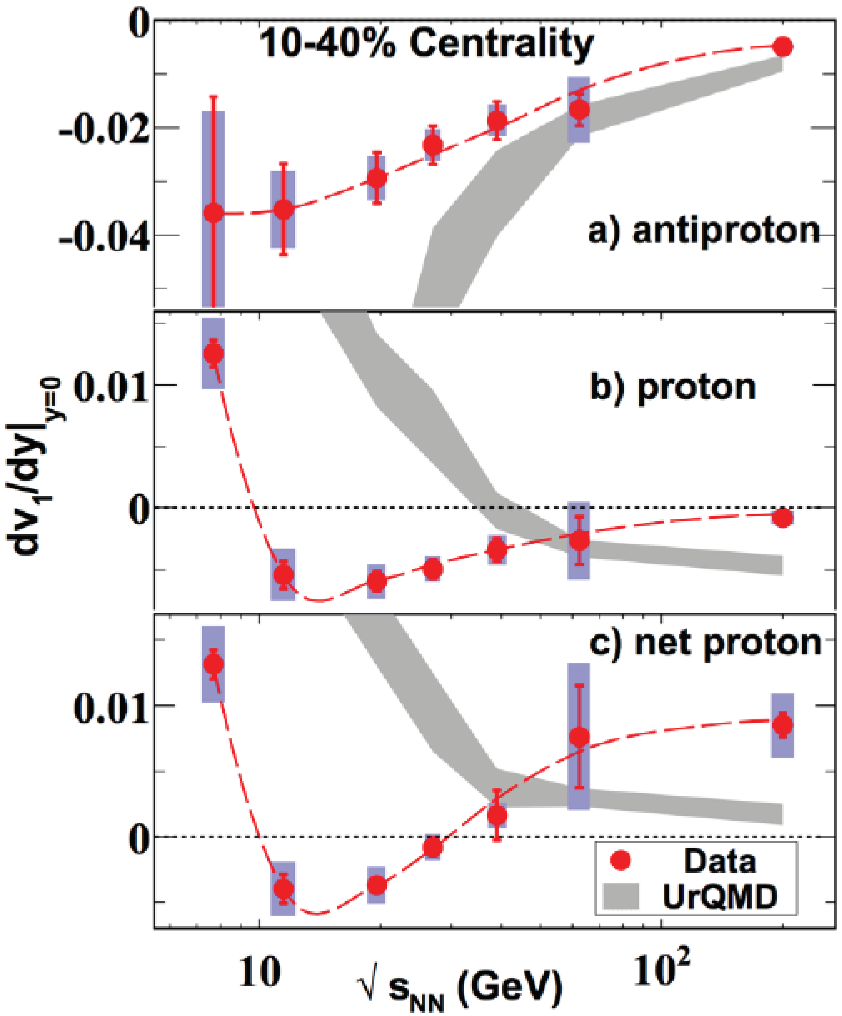
L. Adamczyk et al. [STAR Collab.]
Phys Rev. Lett. 112, 162301 (2014).





- Interesting signatures around $\sqrt{s_{NN}}$ = 10 – 20 GeV.
  - Disappearance of "typical" QGP signatures.
  - Signals from the QCD critical point?
  - Softening of EoS → 1st order phase transition?
- A lot of interesting physics!

Energy Dependence of Directed Flow (v_1)



- Net-proton v_1 isolates flow of transported baryons.
- Valley in net-proton v_1 as a function of $\sqrt{s_{NN}}$.
- Not seen in net-kaon v_1 analysis.
- Cannot be reproduced by models.

L. Adamczyk et al. (STAR Collab.), Phys. Rev. Lett. 112, 162301 (2014).

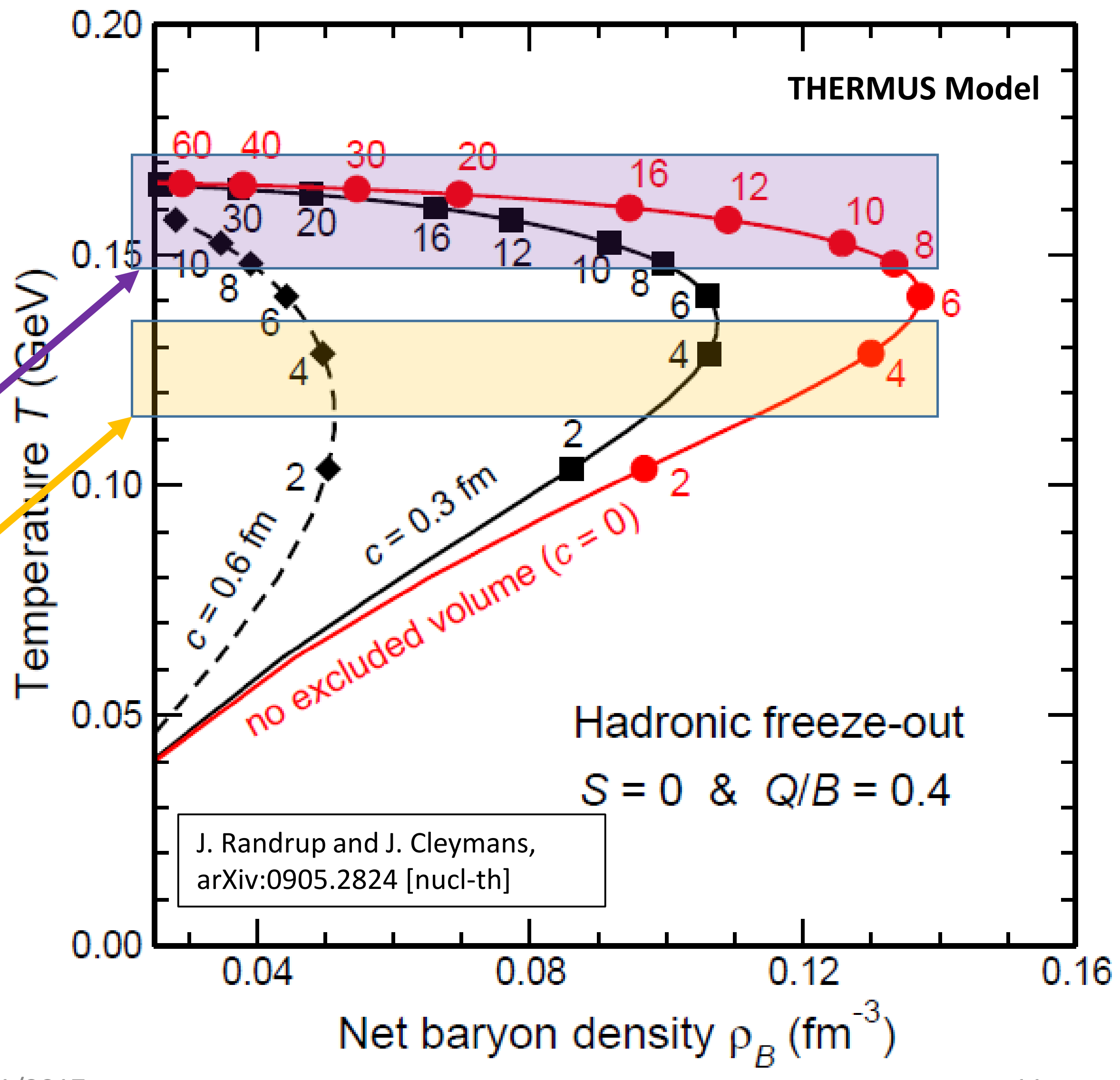
STAR Fixed Target (FXT) Program

STAR Fixed Target (FXT) Program

- Initial plan for BES-I was to run Au+Au at RHIC as low as $\sqrt{s_{NN}}$ = 5.0 GeV.
  - Efforts by accelerator operators to deliver beam at that energy maxed out at a beam lifetime of 4 minutes.
  - Integrating enough luminosity to have viable physics program was not possible in a reasonable amount of time.
    - Event rate ≈ $\gamma^{(-3)}$, about 2.5 months for 5 Mevts.
- Interesting trends in some observables below $\sqrt{s_{NN}}$ = 19.6 GeV might indicate "turn-off" of QGP.
- How to achieve the high μ_B initial conditions below $\sqrt{s_{NN}}$ = 7.7 GeV?
  - Install a fixed target inside the beam pipe and use one of the RHIC beams as the projectile.
  - Provides access to energies below $\sqrt{s_{NN}}$ = 5.0 GeV (μ_B > 550 MeV).

QCD Matter Around Maximum Freeze-Out ρ_B

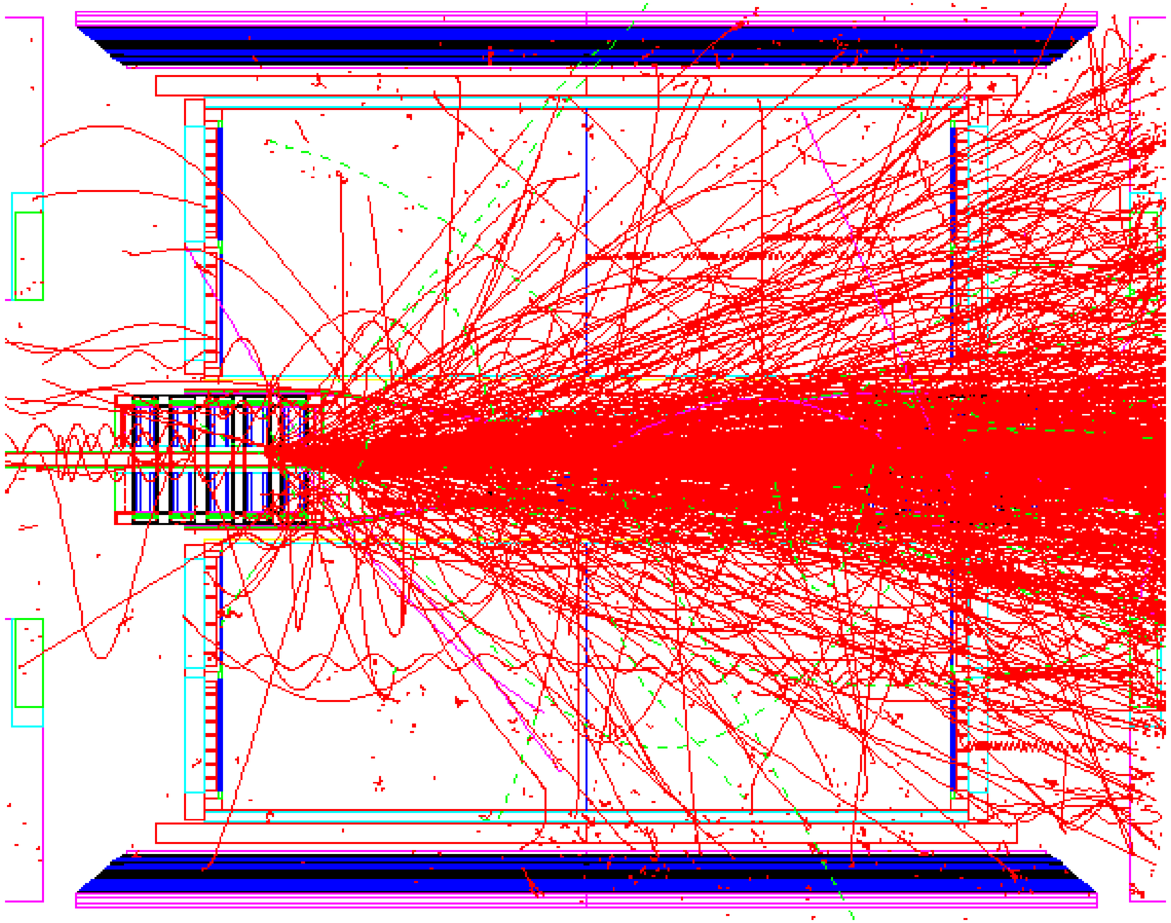
- Freeze-out points in ρ_B-T space obtained from statistical model fits to data.
- Predicted maximum net-baryon density reached around $\sqrt{s_{NN}}$ = 6 GeV.
  - Collider mode at RHIC reaches as low as $\sqrt{s_{NN}}$ = 7.7 GeV.
- FXT collisions cover an energy range on the other side of the maximum ρ_B.
  - In this region there may be a transition from hadronic matter to a mixed-phase.
  - Could potentially observe onset of the deconfinement transition from hadronic to partonic matter.



Fixed Target (Au+Au FXT, Au+Al [beam pipe])

- Proof of principle: There are millions of Au+Al collisions, particularly at low energies where Au beam halo was more diffuse.
  - Beam pipe collisions at $\sqrt{s_{NN}}$= 3.0, 3.5, 3.9 and 4.5 GeV.

- QGP in a Au+Al collision at $\sqrt{s_{NN}}$= 3.0 - 4.5 GeV?
  - Doubtful, but cold nuclear matter effects would be present.
  - Baseline to compare with fixed target Au+Au.
  - Baryon chemical potentials range from 587 < μ_B < 720 MeV.
  - Proton/pion dominated system.
  - Overlaps with the initial energy range of study at CBM/FAIR ($\sqrt{s_{NN}}$ ≈ 3 - 4.7 GeV).



Fixed Target Kinematics

- Beam of energy *E* hitting fixed target:

$$\sqrt{s_{NN}} = \sqrt{2m_{amu}^2 + 2Em_{amu}}, E = E_{kin} + m_{amu}$$

$$p_z = \sqrt{E^2 - m_{amu}^2}$$

$$y_{beam} = 0.5\left[ln\frac{E + p_z}{E - p_z}\right]$$

$$y_{cm} = 0.5 * y_{beam}$$

$$m_{amu} = 0.9315 \, {}^{GeV}/_{c^2}$$

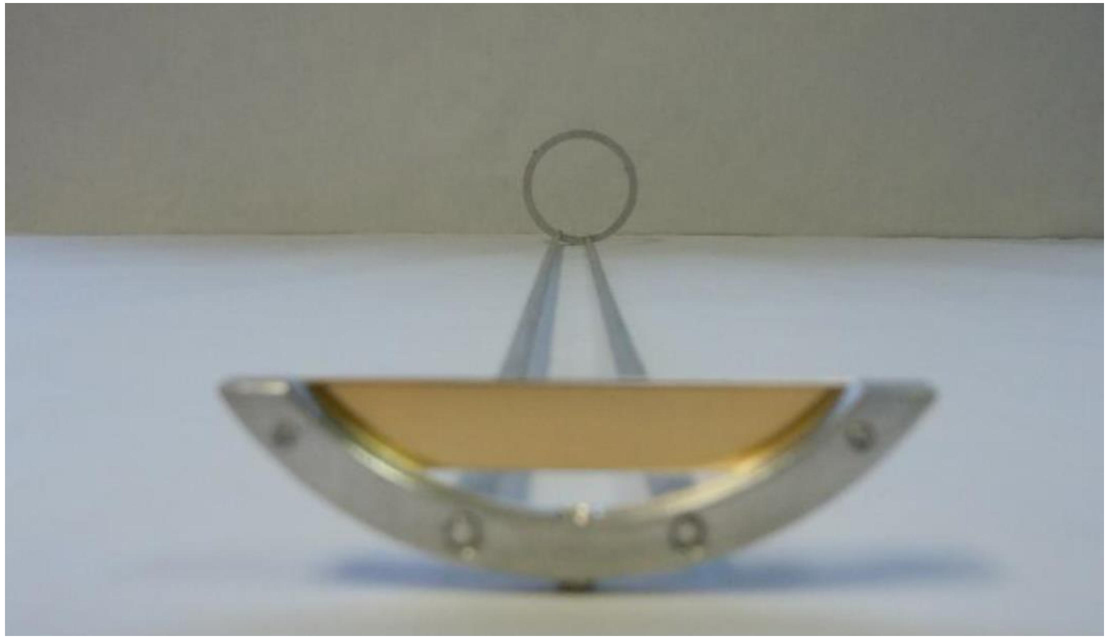
Estimate of μ_B: $\mu_B = \frac{1.308}{1+(0.273*\sqrt{s_{NN}})}$

J. Cleymans, et al. J. Phys. G32:S165, 2006

Collider Mode $\sqrt{s_{NN}}$ (GeV)	E_{kin} (GeV)	Fixed Target $\sqrt{s_{NN}}$ (GeV)	y_{cm}	μ_B (MeV)
7.7	3.841	2.98→3.0	1.05	721
11.5	5.727	3.52→3.5	1.25	667
14.5	7.273	3.91→3.9	1.37	633
19.6	9.782	4.47→4.5	1.52	589
Au-beam, Au-target	9.782	4.47→4.5	1.52	589
Al-beam, Au-target	11.729	4.86→4.9	1.61	562

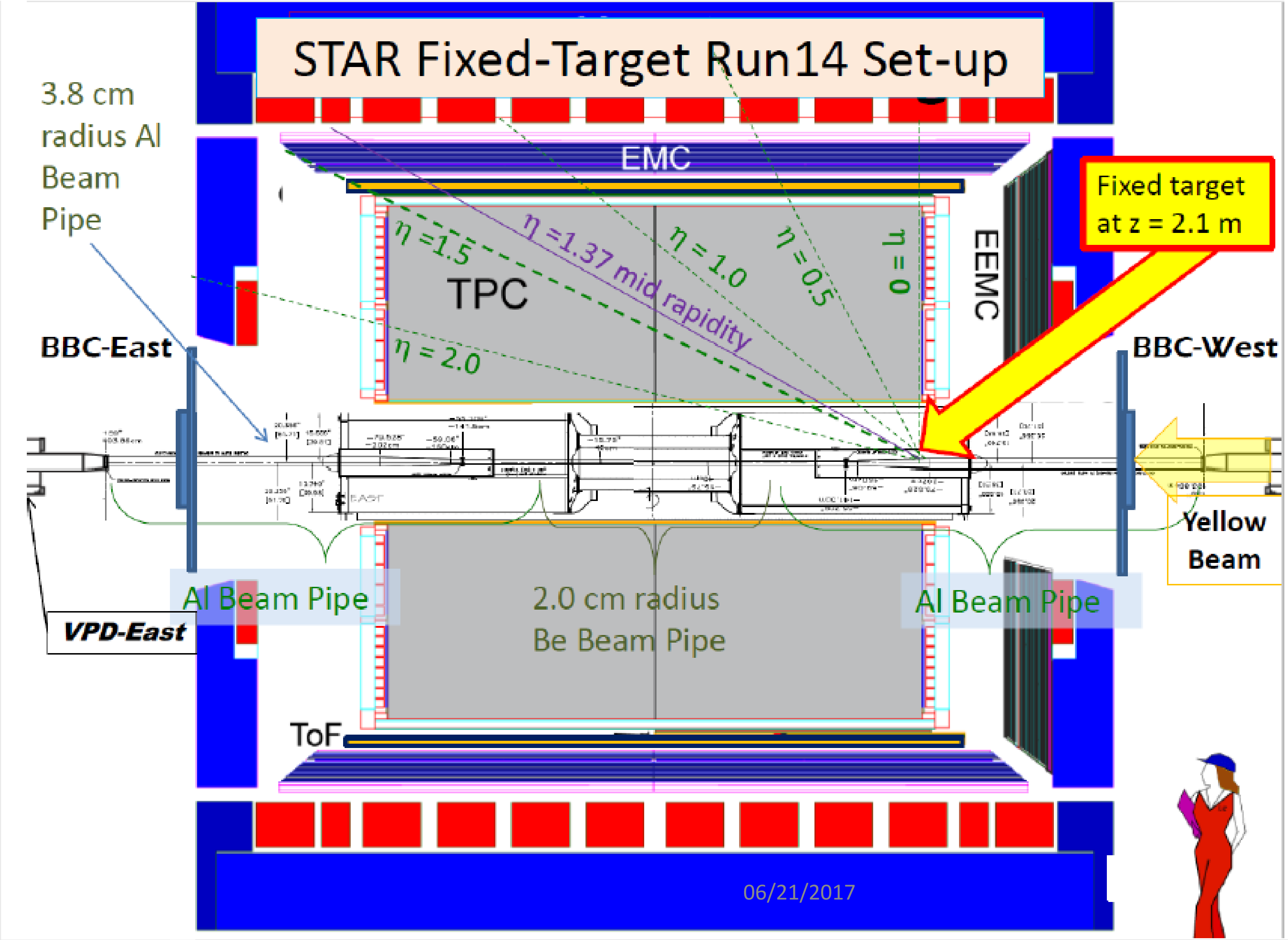
STAR FXT Picture

- Slides in to the 7.62 cm diameter aluminum beam pipe.

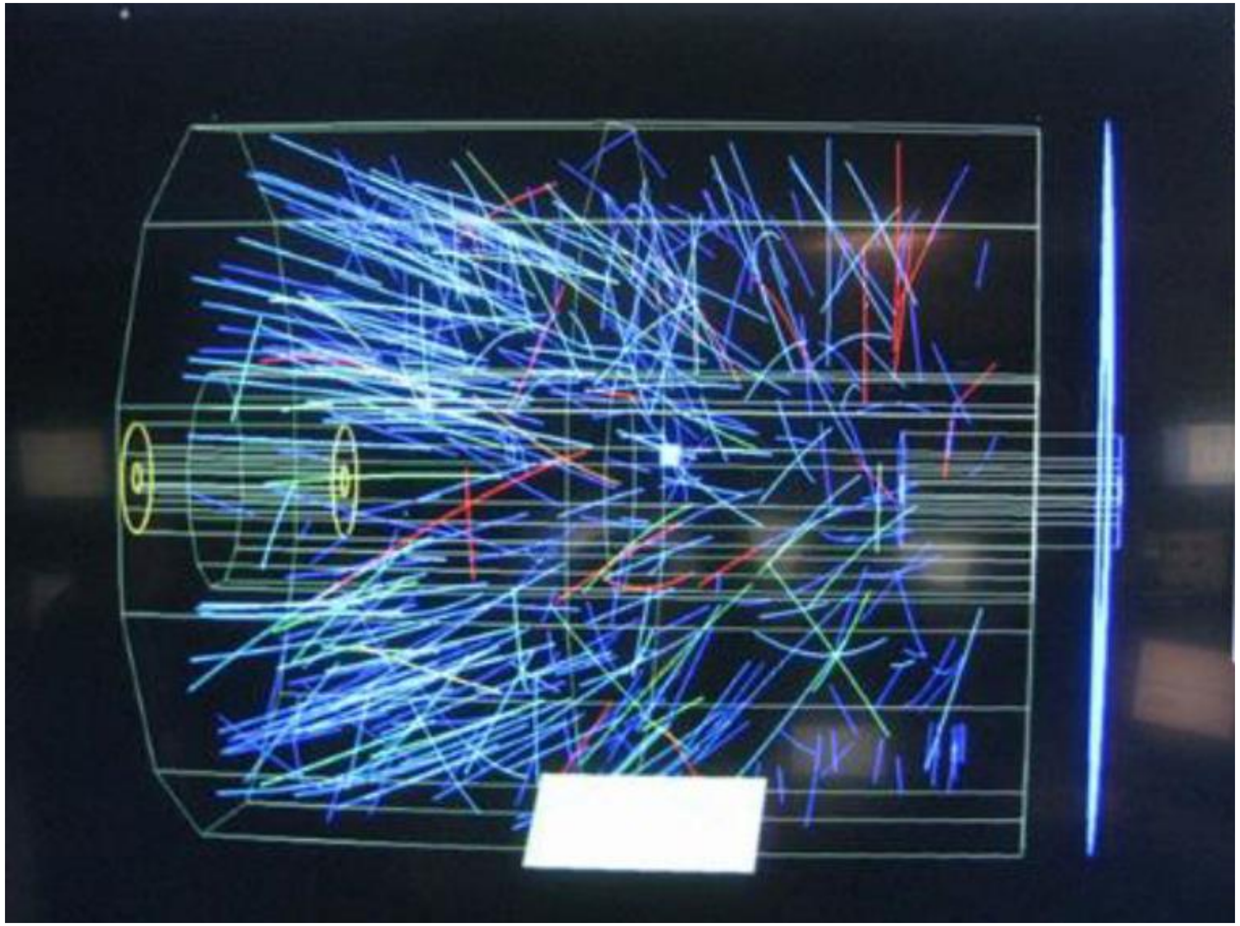


- Au-foil is 1 mm thick (4%).
- 2 cm below beam axis.
- Beam is steered to impact/graze target.
- Not a ring (or annulus) to avoid abort kicker, which deflects in horizontal plane).

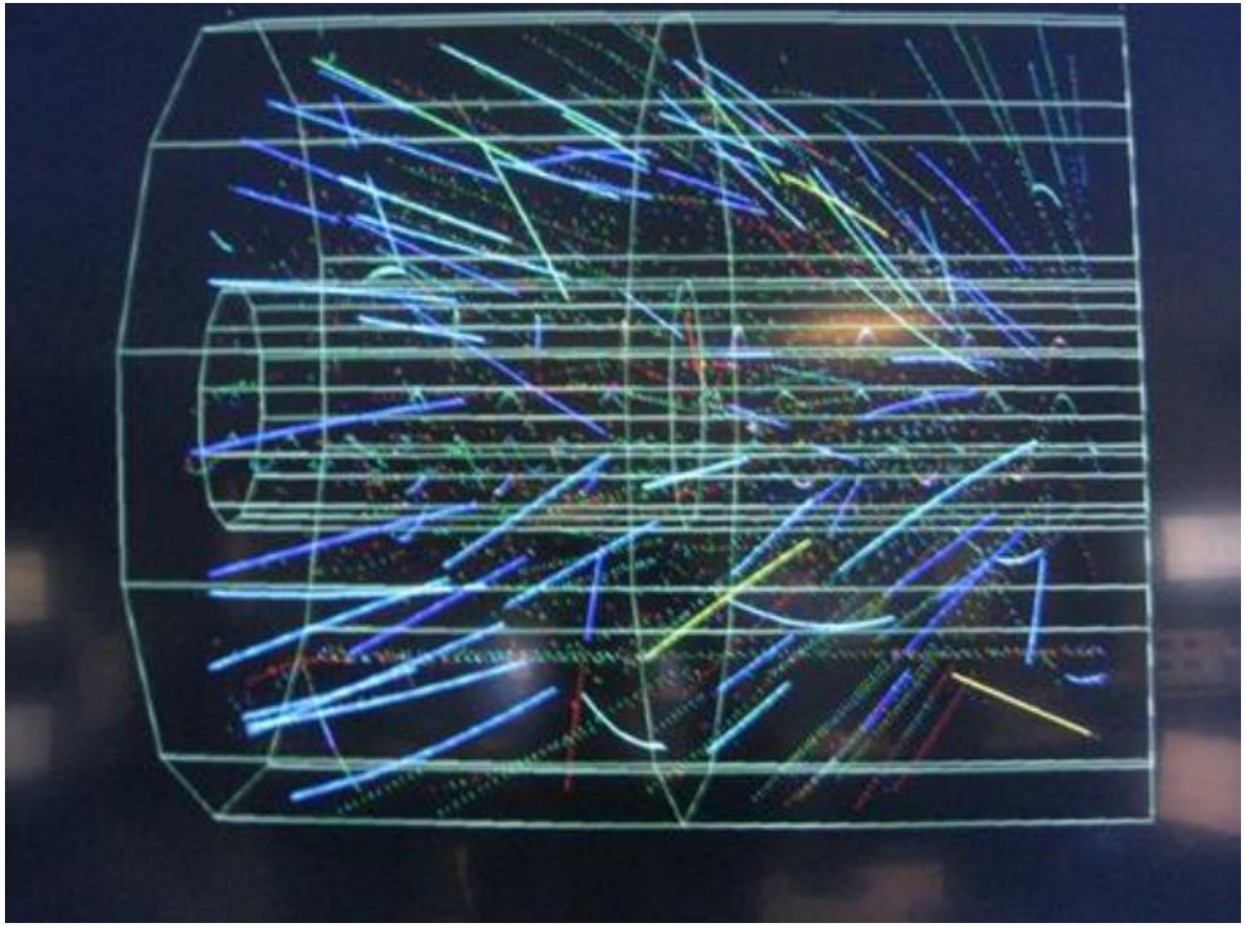
STAR FXT Configuration



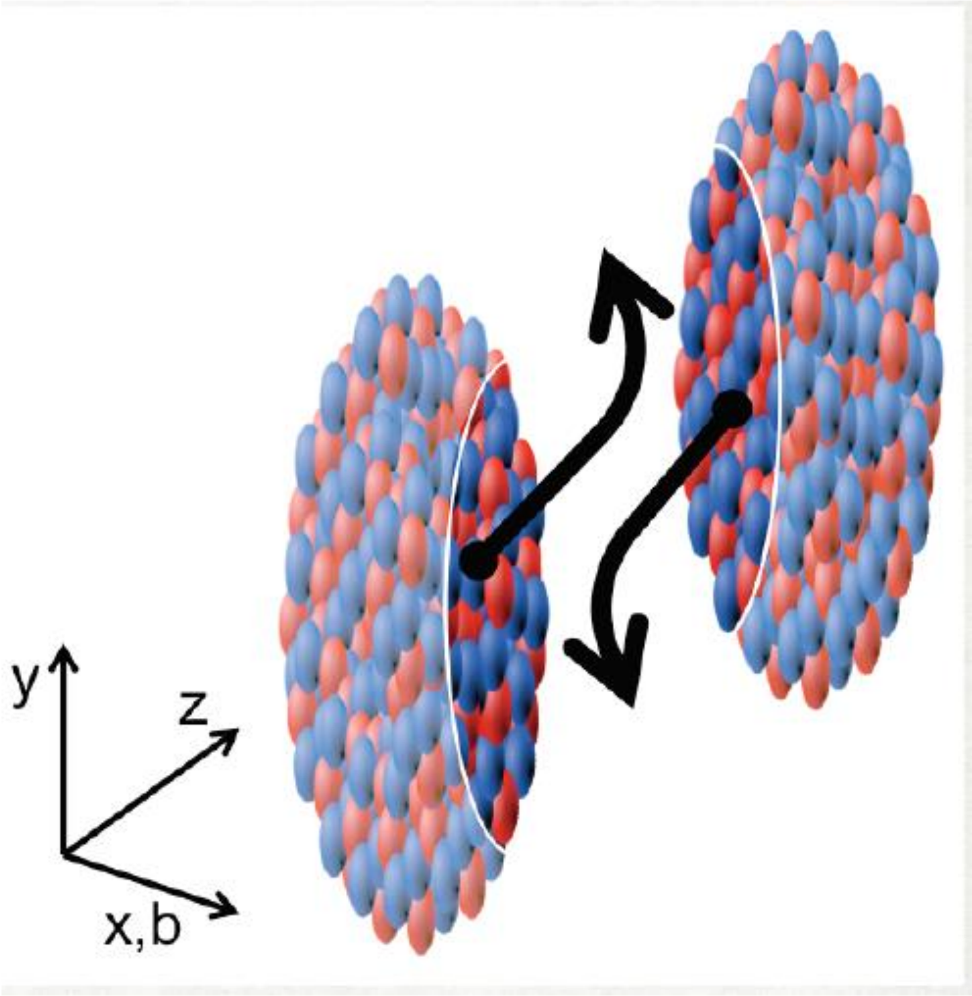
Au + Au FXT, $\sqrt{s_{NN}}$ = 4.5 GeV.



Al + Au FXT, $\sqrt{s_{NN}}$ = 4.9 GeV.

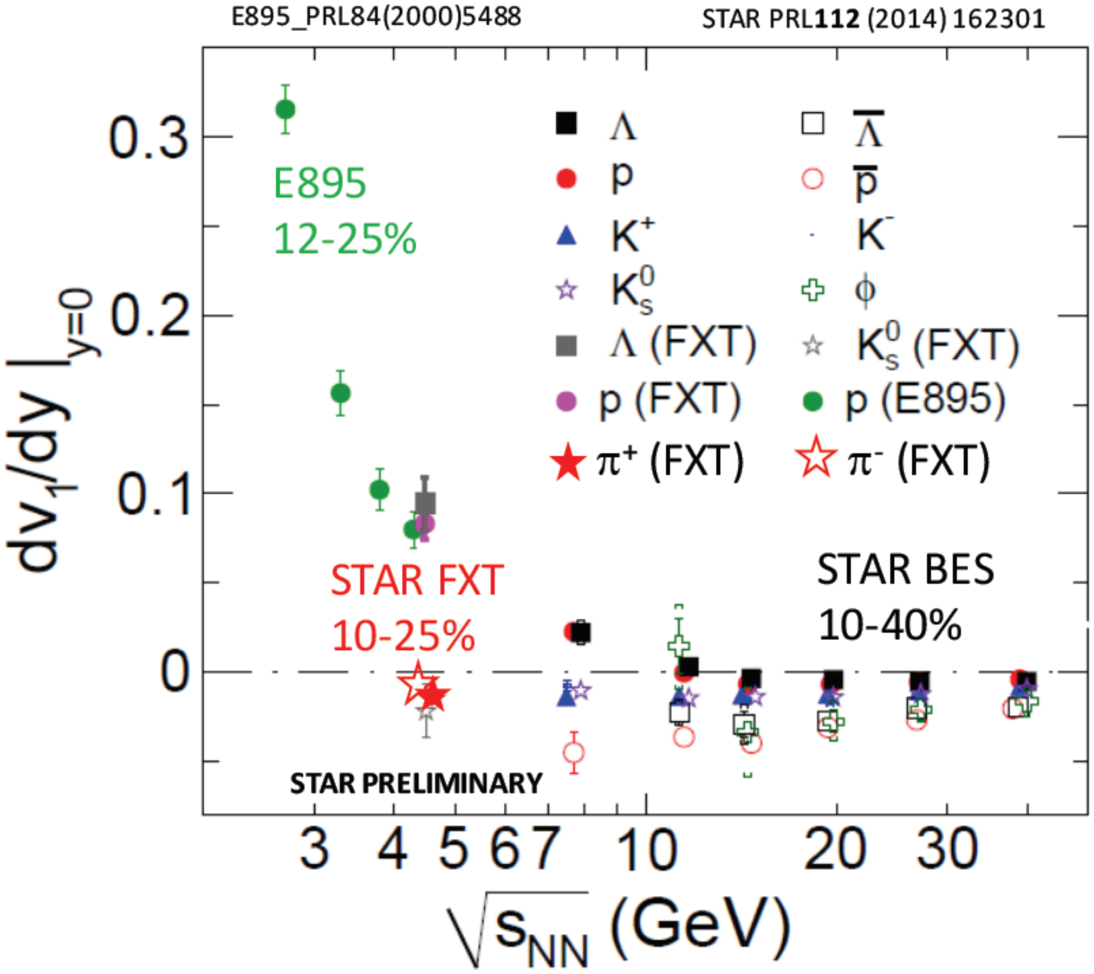


Directed Flow (v_1)



- Properties of the medium created in heavy ion collisions dictate flow properties.
  - Related to the EoS of the system.
- Directed flow is created at early times in the collision.
- Softest point near phase transition in the EoS…possible signal for first order phase transition.
  - Y. Nara, et.al., Phys. Rev. C 94, 034906 (2016).

Energy Dependence of Directed Flow (v_1)



- Proton and Λ v_1 slope at collision energies below $\sqrt{s_{NN}}$ = 10 GeV is positive.
  - Indicates initial state compression of the system.
- Meson v_1 slope is negative at all energies.
- Baryon v_1 is generated by both:
  - Transported baryons from beam rapidity.
  - Pair-produced particles.
- Net-particle v_1 studies isolate transported baryon flow.

Charge Fluctuations

- Fluctuations in net-charge are expected to be different for QGP vs. hadronic case.
  - Smaller charge fluctuation in QGP vs hadron gas (HG).
    - For equilibrated QGP: $\langle N_{ch}\rangle * \nu_{dyn,+-} < -2.5$.
    - For hadron gas: $\langle N_{ch}\rangle * \nu_{dyn,+-} \approx -1.0$
    - For non-equilibrated QGP the difference may only be ≈30%. (A. Bialas, Phys.Lett. B532 (2002) 249-251).
    - Other dynamical effects may wash out fluctuation signal.

- Previous STAR/PHENIX papers: B.I. Abelev et al. [STAR Collab.] Phys. Rev. C 79, 024906 (2009); K. Adcox et al., [PHENIX Collab.] Phys. Rev. Lett. 89, 082301 (2002).
    - Before BES-I: Au+Au ($\sqrt{s_{NN}}$= 19.6, 62.4, 130, 200 GeV), Cu+Cu ($\sqrt{s_{NN}}$= 22.4, 62.4, 200 GeV), and pp ($\sqrt{s}$= 200 GeV).

- NA49 studied charge fluctuations using $\Phi_q(\Delta\Phi_q)$: C. Alt et al. [NA49 Collab.] Phys. Rev. C 70, 064903 (2004).

ν_{dyn}

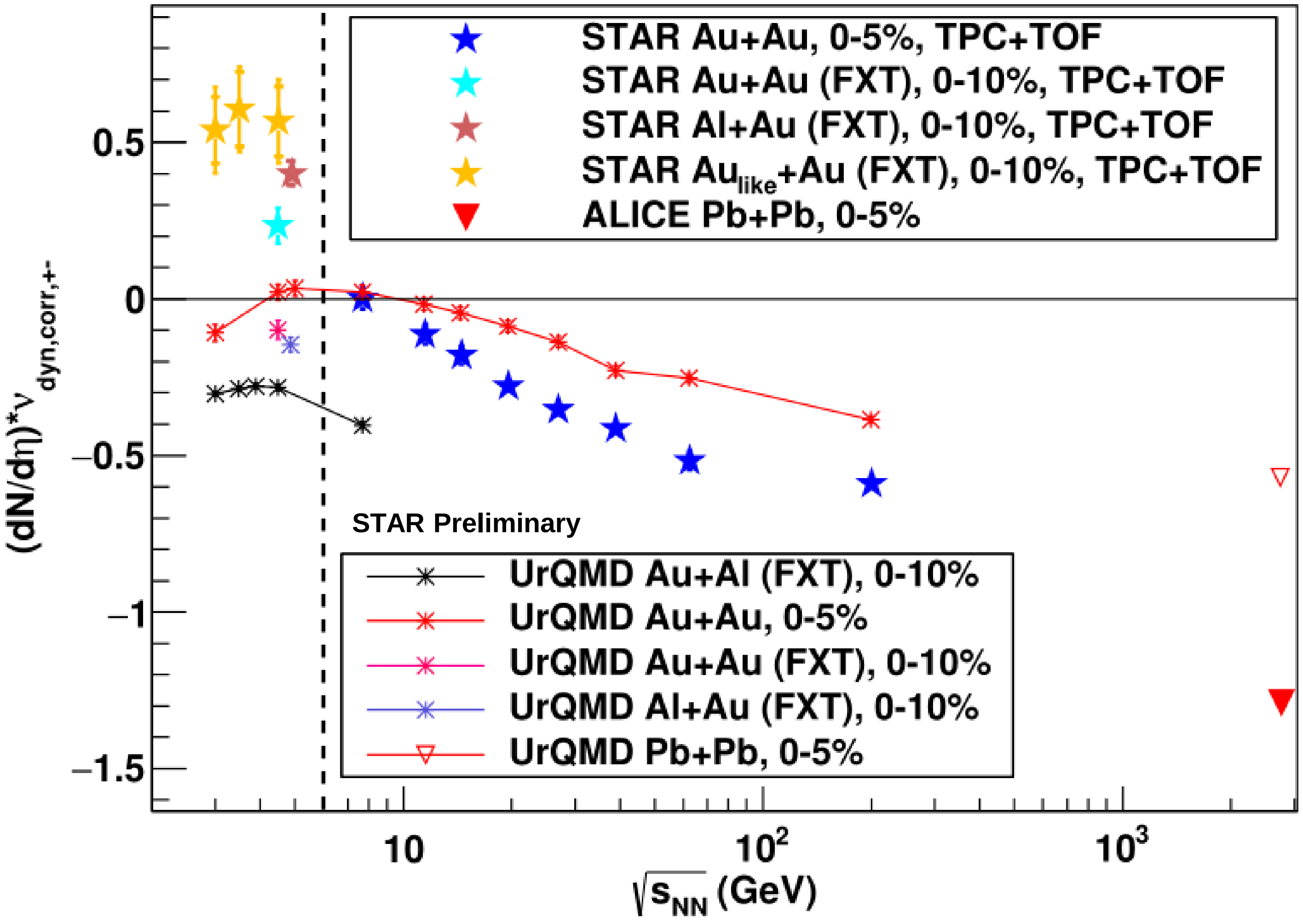
- Has dependence on volume (number of sources), but independent of fluctuations in number of sources.
- Independent collisions: Dependence on inverse of multiplicity.
  - Larger system, smaller ν_{dyn} and vice-versa.
  - Not intensive.
- Independent of efficiency and shape of underlying multiplicity distribution.
- Measure deviations from statistical baseline.

- $\nu_{dyn,AB} = \frac{\langle N_A(N_A-1)\rangle}{\langle N_A\rangle^2} + \frac{\langle N_B(N_B-1)\rangle}{\langle N_B\rangle^2} - 2\frac{\langle N_A N_B\rangle}{\langle N_A\rangle\langle N_B\rangle}$
  - A, B: K, π, p, +, -, etc

- Ratio fluctuations cancel volume fluctuation to first order.

- Properly scaling $\nu_{dyn,AB}$ creates an intensive quantity.

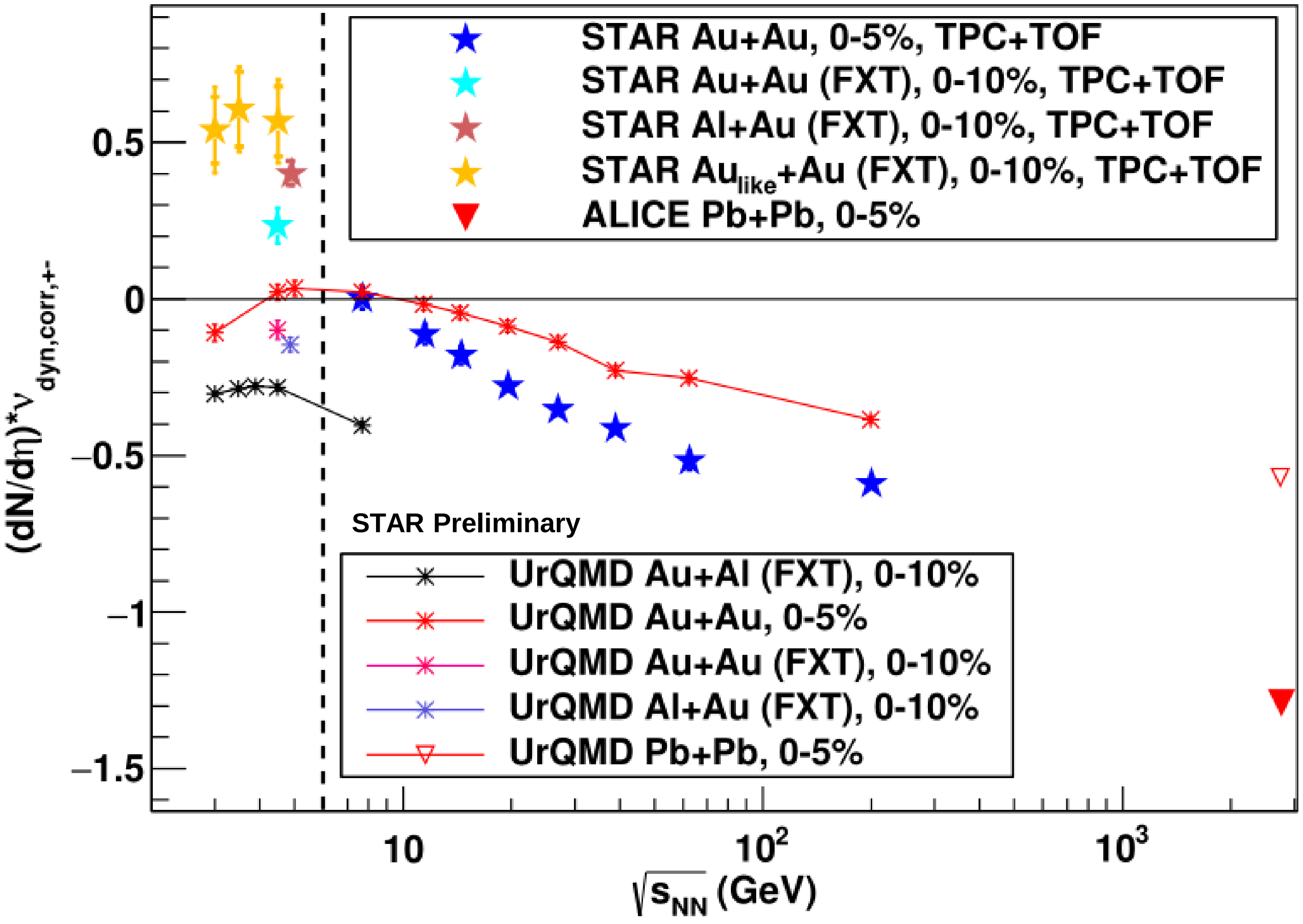
$\nu_{dyn,corr,+-}$ From Central Au+Au, Al+Au, Au_{like}+Al, and Pb+Pb



ALICE: B. Abelev *et al.* Phys. Rev. Lett. 110, 152301

- $\nu_{dyn,corr,+-}$ (corrected for global charge conservation) scaled by dN/dη calculated using PHOBOS or ALICE parameterization.
  - $\nu_{dyn,corr,+-} = \nu_{dyn,+-} + \frac{4}{\langle N_{Total} \rangle}$
- Removes system size dependence and not affected by detector acceptance or efficiency.
  - Different scaling parameterizations yield same trend.
- Data trends are similar regardless of measured or parameterized multiplicity scaling
- Scaled $\nu_{dyn,corr,+-}$ measured in Au_{like}+Al collisions between $\sqrt{s_{NN}}$= 3.0 - 4.5 GeV is positive and approximately constant. ≈ 0.6.
- STAR Au+Au result for scaled $\nu_{dyn,corr}$ are negative, near zero at $\sqrt{s_{NN}}$= 7.7 GeV and decreases to -0.5 - -0.6 at $\sqrt{s_{NN}}$= 200 GeV.

$\nu_{dyn,corr,+-}$ From Central Au+Au, Al+Au, Au_{like}+Al, and Pb+Pb



- Distinct difference between STAR at $\sqrt{s_{NN}}$ = 200 GeV (-0.6) and ALICE Pb+Pb result at $\sqrt{s_{NN}}$ = 2760 (-1.3).
  - This is more than 2x larger in magnitude.
- Large multiplicity means the correction factor is small at LHC energy. ALICE $\nu_{dyn,corr,+-} \approx \nu_{dyn,+-}$.
- Three or four different regimes.
  - $\sqrt{s_{NN}}$ < 7 GeV:
    - Au_{like}+Al, Al+AuFXT: No partonic phase.
    - Au+AuFXT: Intermediate region with mixed phase?
  - $\sqrt{s_{NN}}$ > 7 GeV, Au+Au: Formation and growth of partonic volume.
  - $\sqrt{s_{NN}}$ > 2000 GeV, Pb+Pb: Larger partonic volume.
- This may indicate the onset of the deconfinement phase transition and growth of the partonic volume as collision energy increases.

ALICE: B. Abelev *et al.* Phys. Rev. Lett. 110, 152301

Summary

- The first phase of the Au+Au Beam Energy Scan was highly successful and productive.
  - From an experimental, RHIC operations, and theory perspective.

- The BES has already been expanded beyond the original design with the installation of a Au-foil fixed target in the beam pipe at STAR.

- STAR now has the capability to perform comprehensive studies of QCD matter:
  - Total energy range covered at RHIC is $\sqrt{s_{NN}}$ = 3.0 - 200 GeV.
  - Lowest collision energies correspond to baryon chemical potentials as large as 720 MeV.
    - This is also the same energy range as FAIR.