Warsaw University of Technology

NATIONAL SCIENCE CENTRE POLAND

Highlights from the STAR experiment

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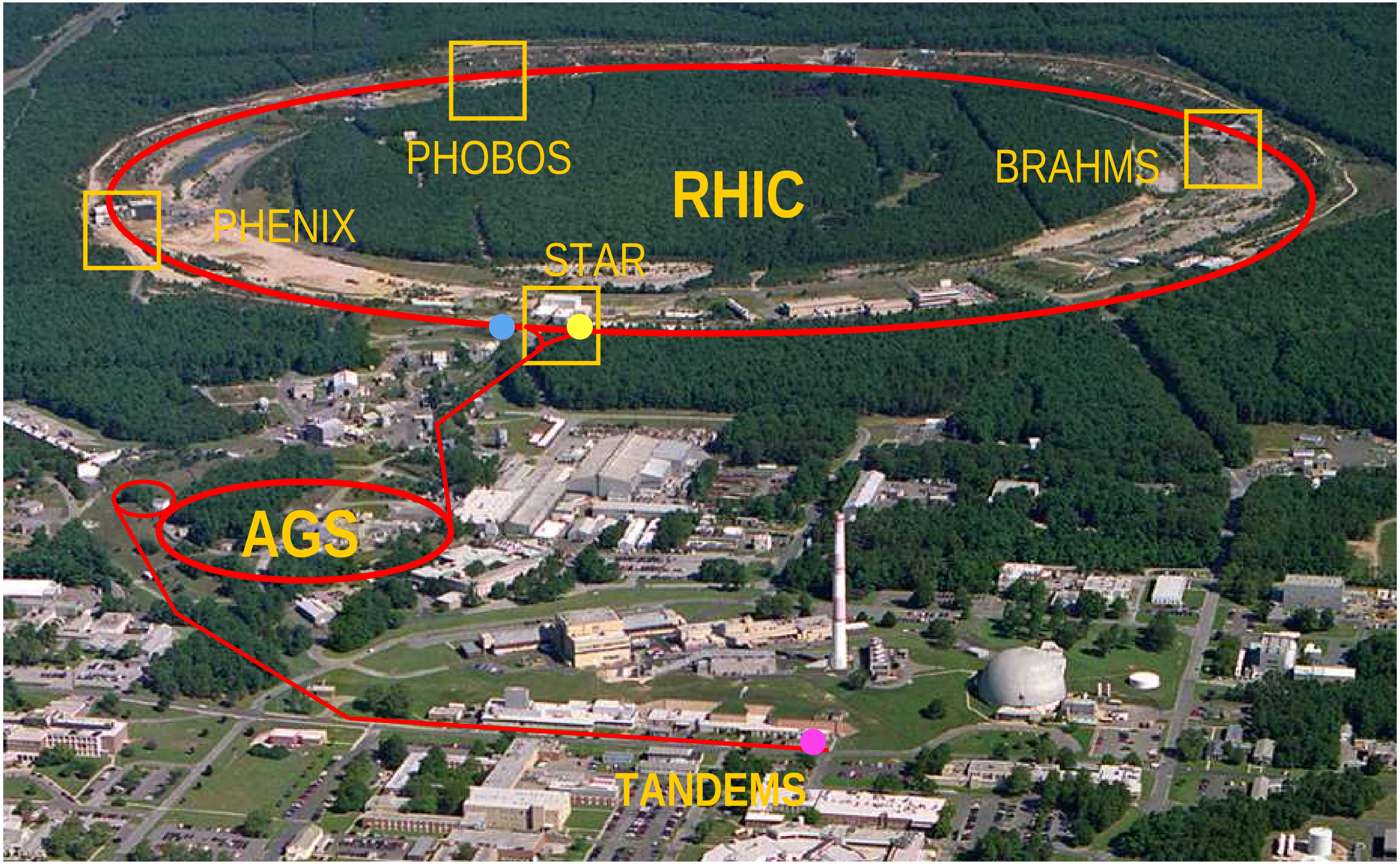
supported by **National Science Centre, Poland**

STAR

MESON 2018, Kraków, 9th June 2018

Introduction

Relativistic Heavy Ion Collider (RHIC)
Brookhaven National Laboratory (BNL), New York



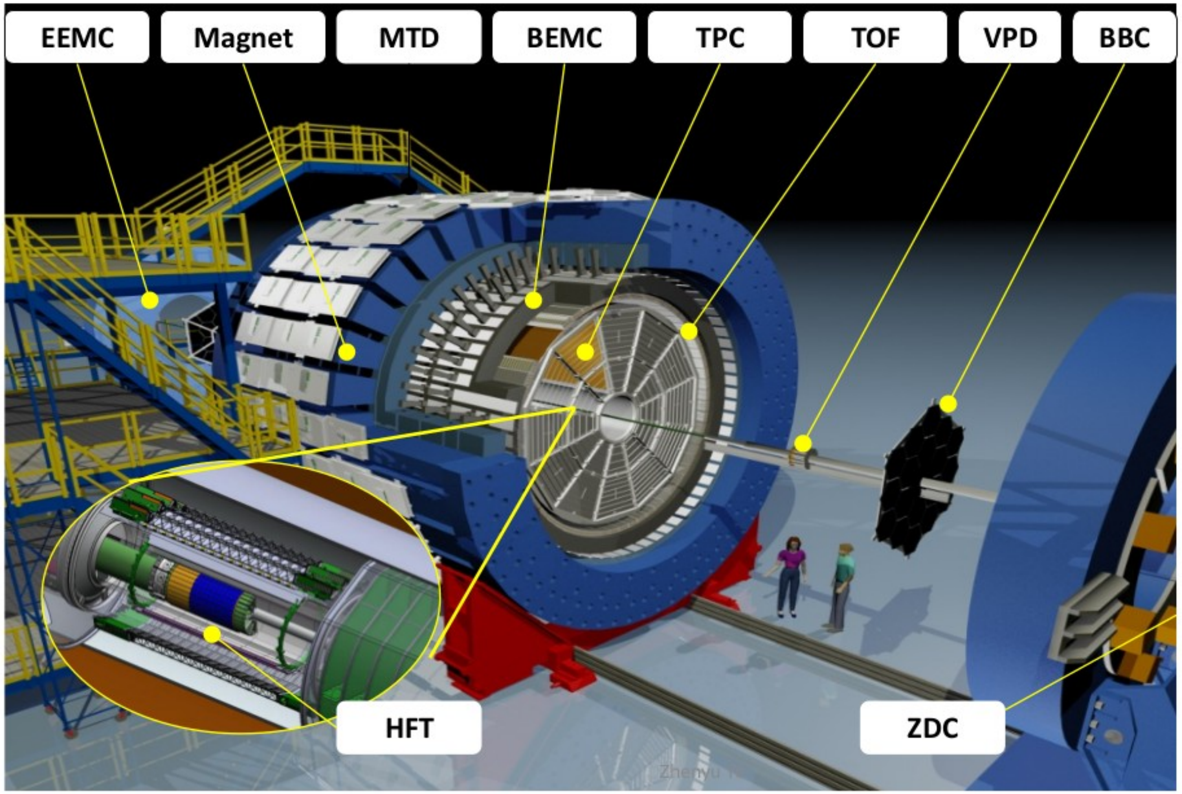
- 2 concentric rings of 1740 superconducting magnets
- 3.8 km circumference

The Solenoidal Tracker At RHIC

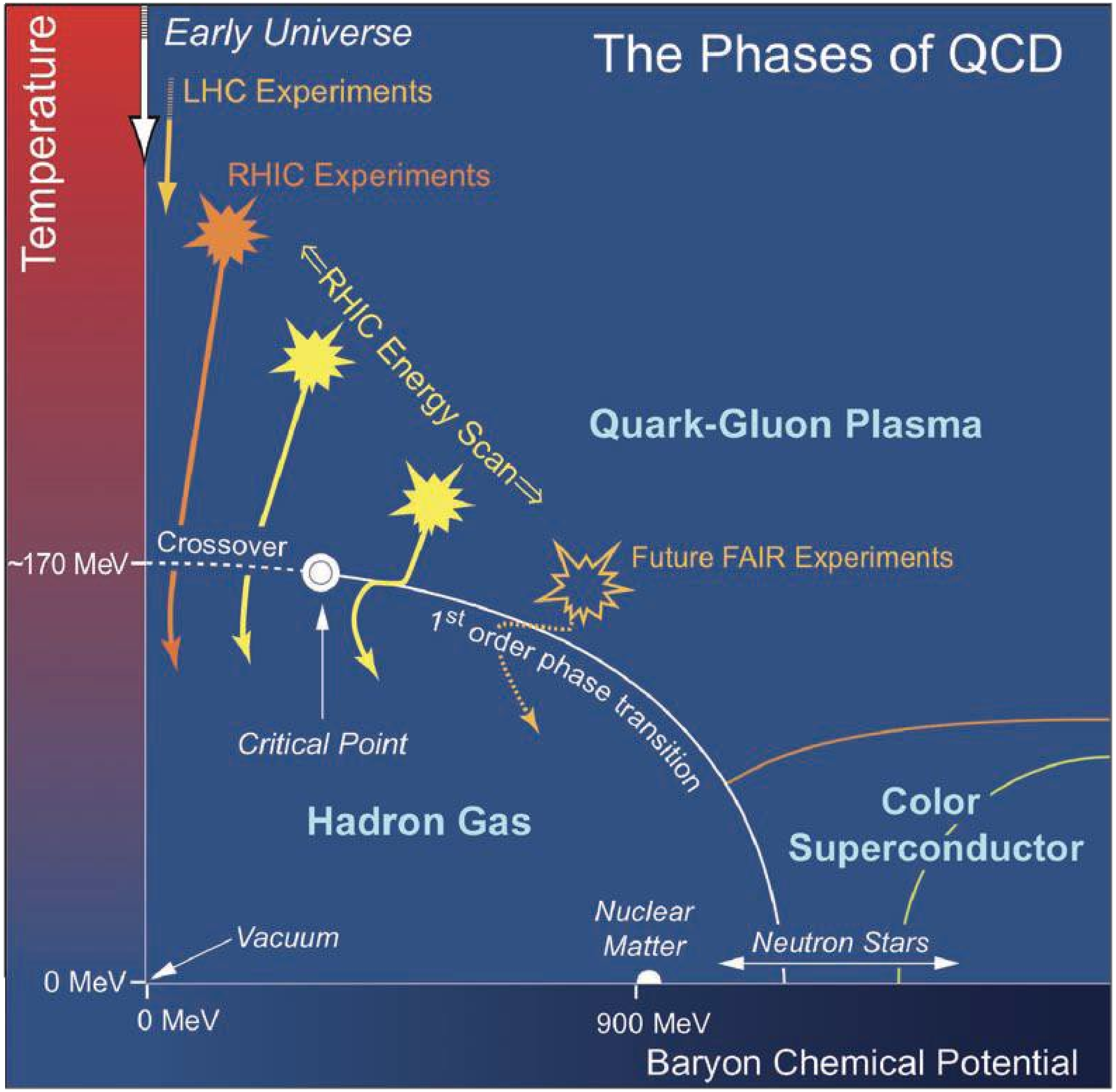
- **Tracking and PID (full 2π)**
  TPC: $|\eta| < 1$
  TOF: $|\eta| < 1$
  BEMC: $|\eta| < 1$
  EEMC: $1 < \eta < 2$
  HFT (2014-2016): $|\eta| < 1$
  MTD (2014+): $|\eta| < 0.5$

- **MB trigger and event plane reconstruction**
  BBC: $3.3 < |\eta| < 5$
  EPD (2018+): $2.1 < |\eta| < 5.1$
  FMS: $2.5 < \eta < 4$
  VPD: $4.2 < |\eta| < 5.1$
  ZDC: $6.5 < |\eta| < 7.5$

- **On-going/future upgrades**
  iTPC (2019+): $|\eta| < 1.5$
  eTOF (2019+): $-1.6 < \eta < -1$



Introduction



RHIC Top Energy
p+p, p+Al, p+Au, d+Au, ^{3}He+Au, Cu+Cu, Cu+Au, Ru+Ru, Zr+Zr, Au+Au, U+U
QCD at high energy density/temperature
Properties of QGP, EoS

Beam Energy Scan
Au+Au 7.7-62 GeV
QCD phase transition
Search for critical point
Turn-off of QGP signatures

Fixed-Target Program
Au+Au =3.0-7.7 GeV
High baryon density regime with 420-720 MeV

Introduction

1. Open heavy flavor - D^0 v_1, D^0 R_{AA} and R_{CP}, Λ_C

2. Quarkonium – Υ R_{AA}

3. Jet modification and high-p_T hadrons - di-jet imbalance, di-hadron correlation

4. Chirality, vorticity and polarization effects - Λ polarization, Φ polarization, CME, CMW

5. Initial state physics and approach to equilibrium - v_2 and v_3 fluctuations

6. Collectivity in small systems - v_2 in p+Au and d+Au

7. Collective dynamics - longitudinal decorrelation, identified particle v_1

8. High baryon density and astrophysics - v_1 from fixed target

9. Correlations and fluctuations – femtoscopy

10. Phase diagram and search for the critical point - net Λ and off-diagonal cumulants

11. Thermodynamics and hadron chemistry - triton, hypertriton mass

12. Upgrades - BES-II and forward upgrades

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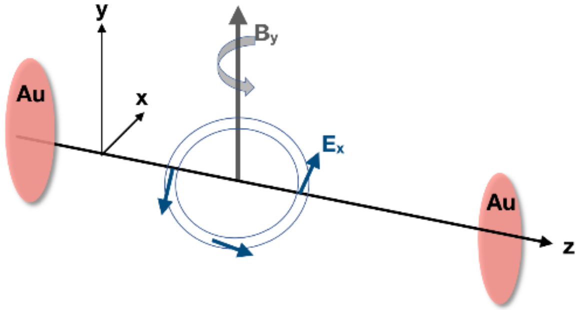
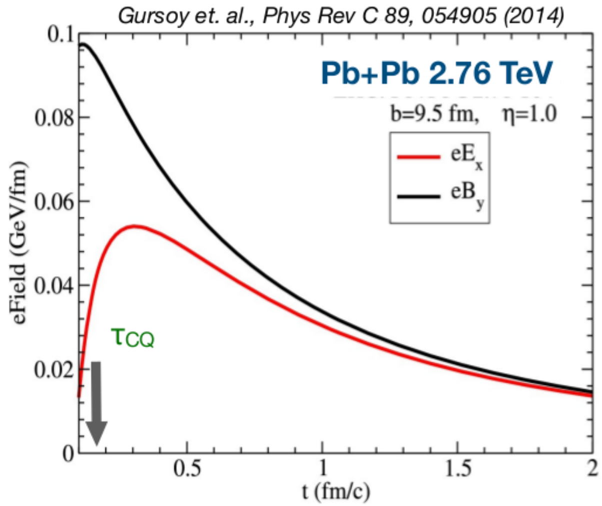
6. Upgrades - BES-II and forward upgrades (as summary)

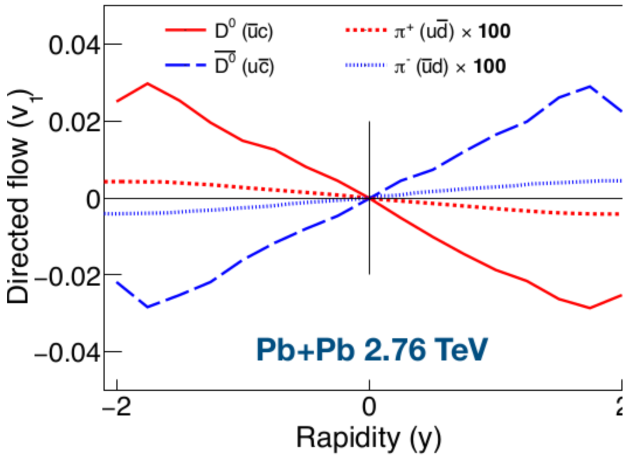
Results

1) D^0 – Open heavy flavor





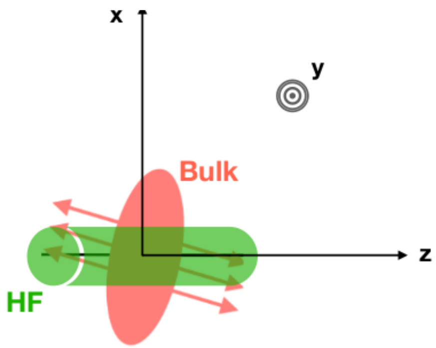
- The moving **spectators** can produce enormously large **electromagnetic field** (eB ~ 10^{18} G at RHIC)
- Due to **early** production of heavy quarks (τ_{CQ} ~ 0.1 fm/c) positive and negative charm quarks (CQs) can get **deflected** by the initial EM force

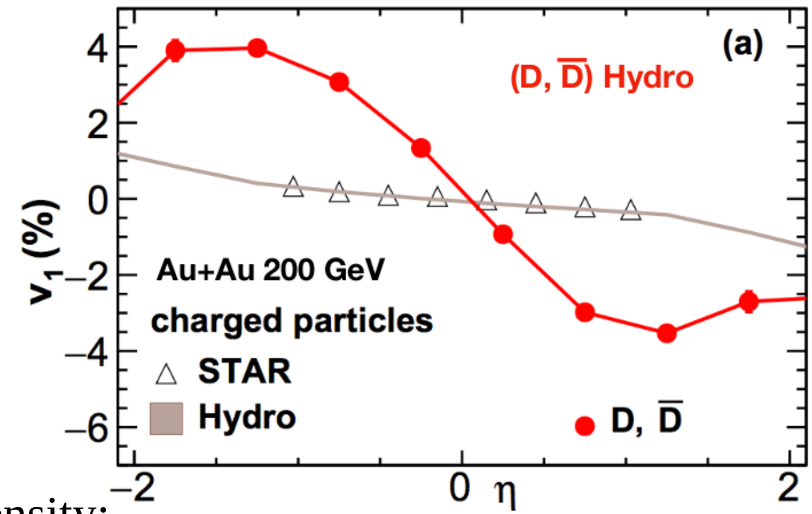


Das et. al., Phys Lett B 768, 260 (2017)

- Model predicts **opposite** v_1 for charm and anti-charm quarks induced by this initial EM field
- This induced v_1 depends on the balance between E and B fields
- The **magnitude** of such induced v_1 for heavy quarks is much **larger** than the light quarks

1) D^0 – Open heavy flavor





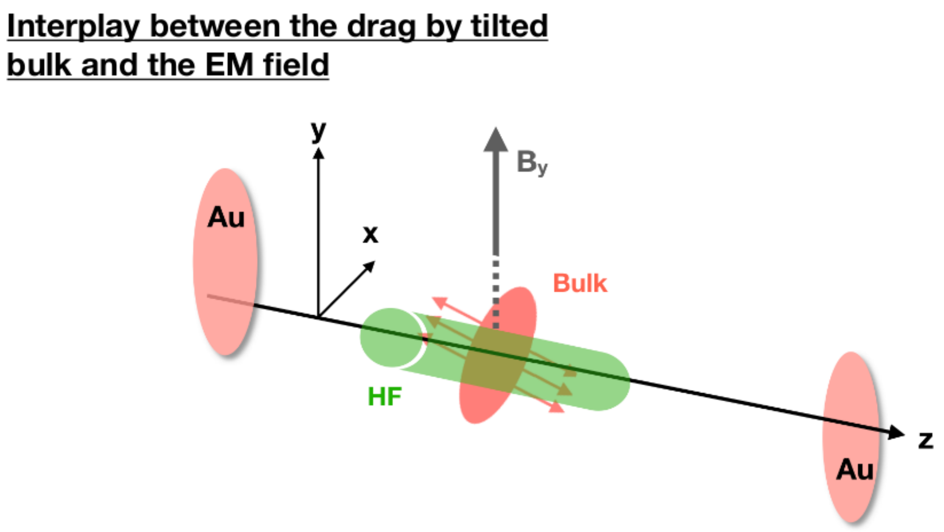
Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)

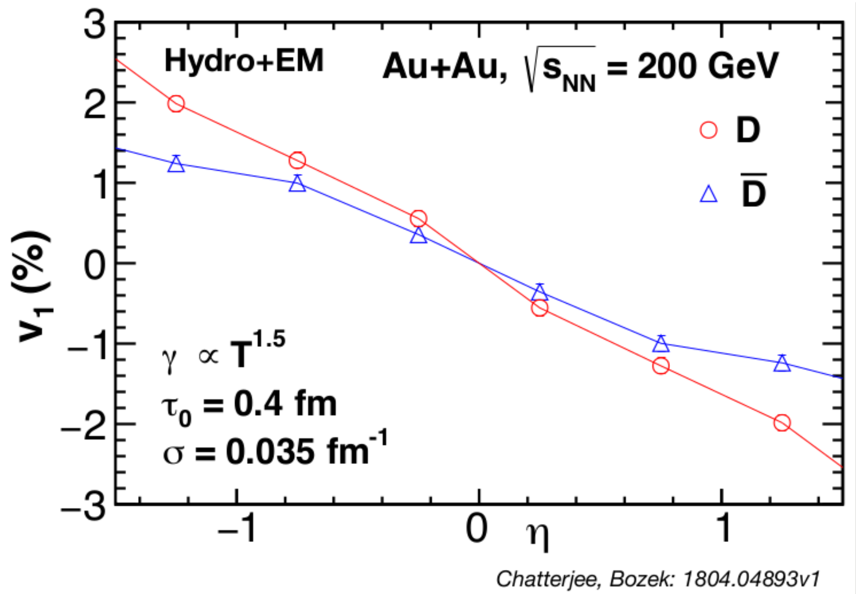
- Heavy quarks are produced according to N_{coll} density: symmetric in rapidity at non-zero rapidity, charm quarks production points are **shifted** from the bulk
- This can induce **larger** v_1 in charm quarks than light flavors
- Magnitude of charm quark v_1 depends on the drag parameter used in this model
- We can probe the longitudinal profile of the initial matter distribution through heavy flavor v_1

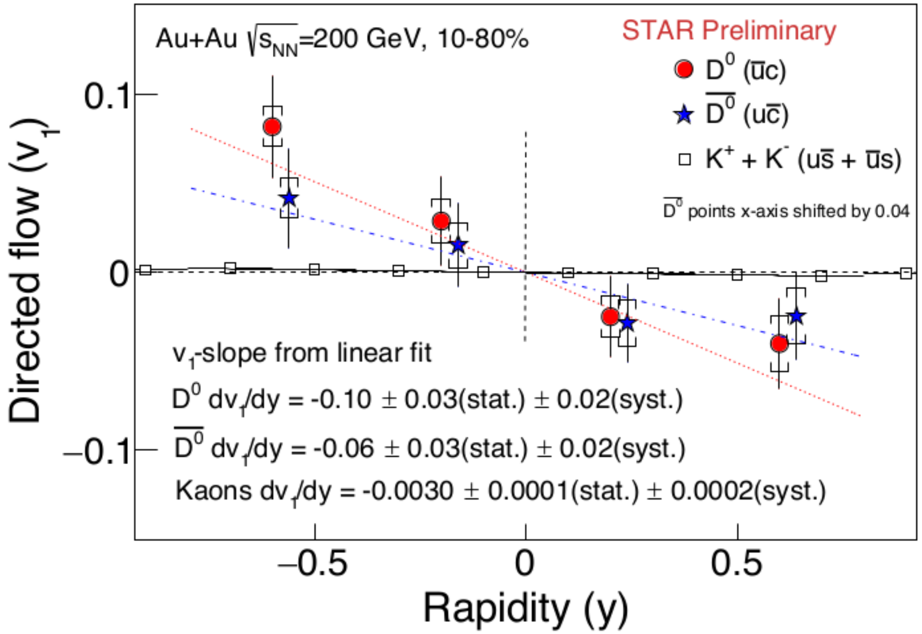
(v_1 -slope) Charm-Quark >> (v_1 -slope) Light-Quark

- Charm quarks much more sensitive to the initial tilt than the charged hadrons D^0 ($\bar{D}^0$) v_1 can be used to constrain drag coefficients in conjunction with v_2 and R_{AA}

1) D^0 – Open heavy flavor



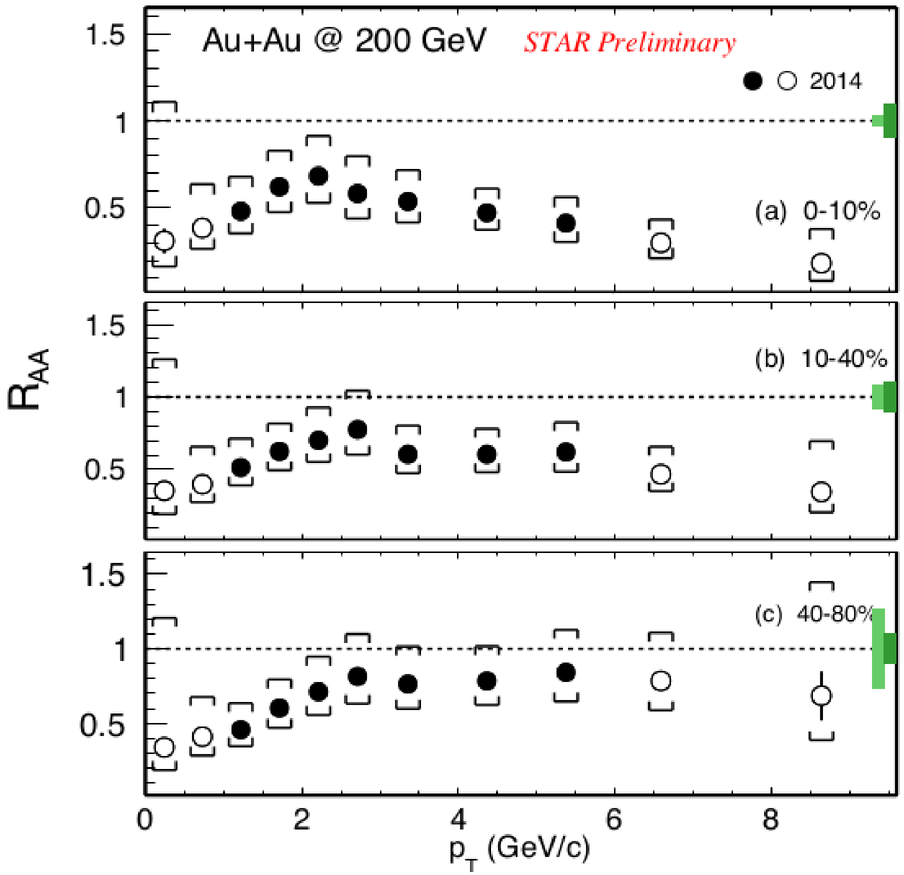


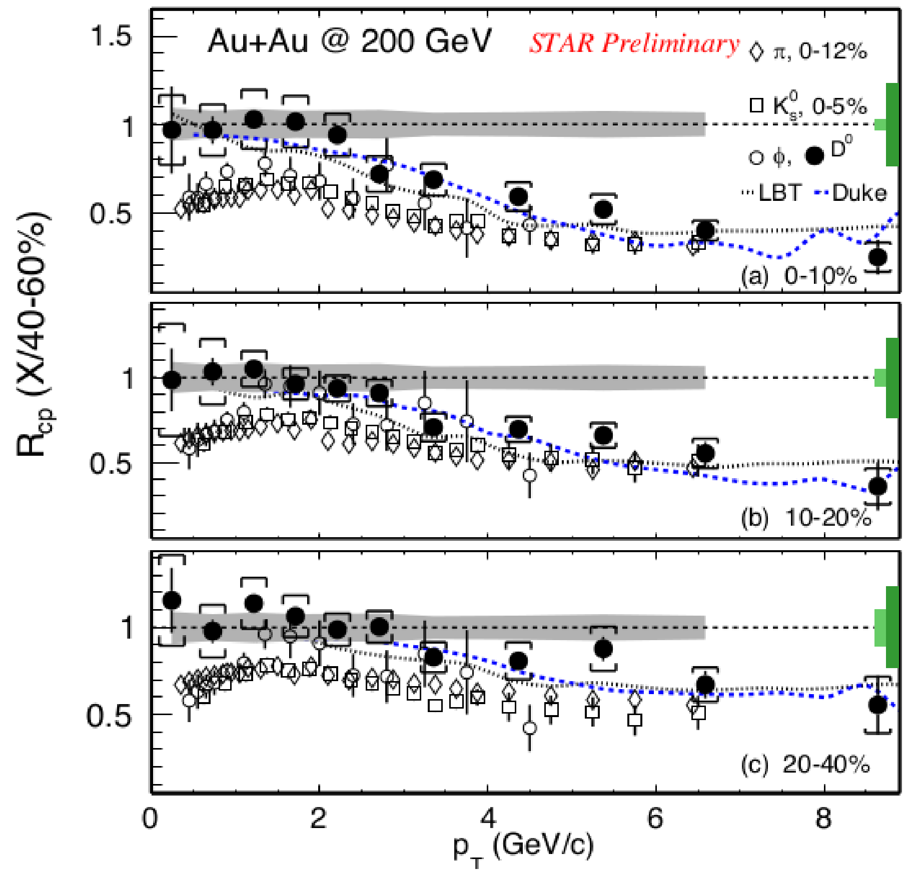


Recent hydro model with initial EM field predicts v_1 **-split** between the D and anti-D meson

D meson v_1 **greater** than the anti-D
Predicted difference in v_1 is about 10 times smaller than the average v_1

1) D^0 – Open heavy flavor





Significant suppression at **low p_T** with no strong centrality dependence,
Suppression at **high p_T** decreases towards more peripheral collisions.

Non-prompt D^0 R_{AA} study has been performed, need better precision measurements to understand mass dependence of energy loss.

STAR data was re-analysed due to error found durring analysis
→ **erratum** will be published soon

1) D^0 – Open heavy flavor

First evidence of non-zero directed flow for heavy flavor

Both D^0 and D^0 show **negative** v_1 -slope near mid-rapidity

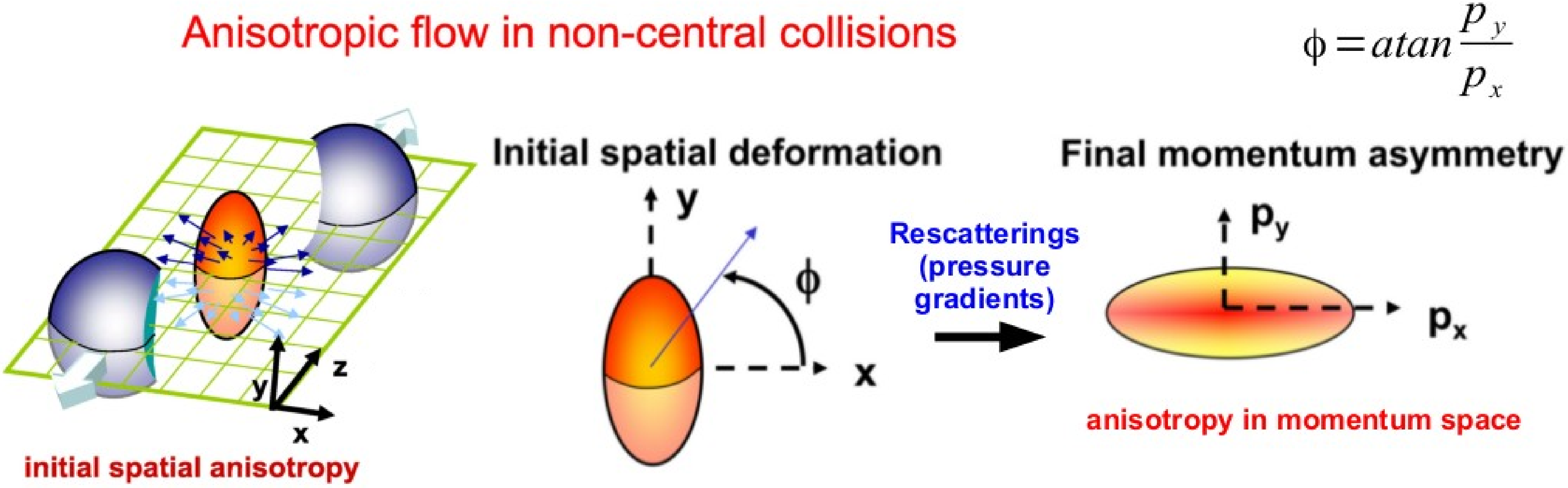
Heavy flavor v_1 > light flavor v_1

Data can be used to probe **initial** matter distribution

Current precision is **not sufficient** to draw conclusion on
magnetic field induced charge separation of heavy quarks

Non-prompt D^0 R_{AA} study has been performed, need better precision
measurements to understand mass dependence of energy loss.

2) Initial state physics



$$\phi = atan \frac{p_y}{p_x}$$

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n(\phi - \Phi_R)\right]\right)$$

2) Initial state physics

Q-cumulant method (traditional)

$$\langle 2\rangle_n = \left\langle e^{in(\phi_1-\phi_2)}\right\rangle$$

$$\langle 4\rangle_{nm} = \left\langle e^{in(\phi_1-\phi_2)+im(\phi_3-\phi_4)}\right\rangle$$

$$v_n^4\{4\} = \langle 4\rangle_{nn} - 2\langle 2\rangle_n\langle 2\rangle_n$$

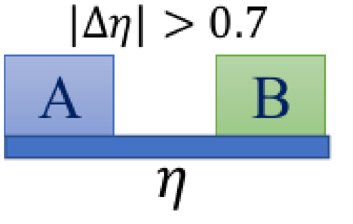
$$NSC(n,m) = \frac{\langle 4\rangle_{nm} - \langle 2\rangle_n\langle 2\rangle_m}{\langle 2\rangle_n^{Sub}\langle 2\rangle_m^{Sub}}$$

Φ - azimuthal angle

Two-subevent method

$$\langle 2\rangle_n^{Sub} = \left\langle e^{in(\phi_A-\phi_B)}\right\rangle$$

$$v_n^2\{2\} = c_n\{2\} = \langle 2\rangle_n^{Sub}$$



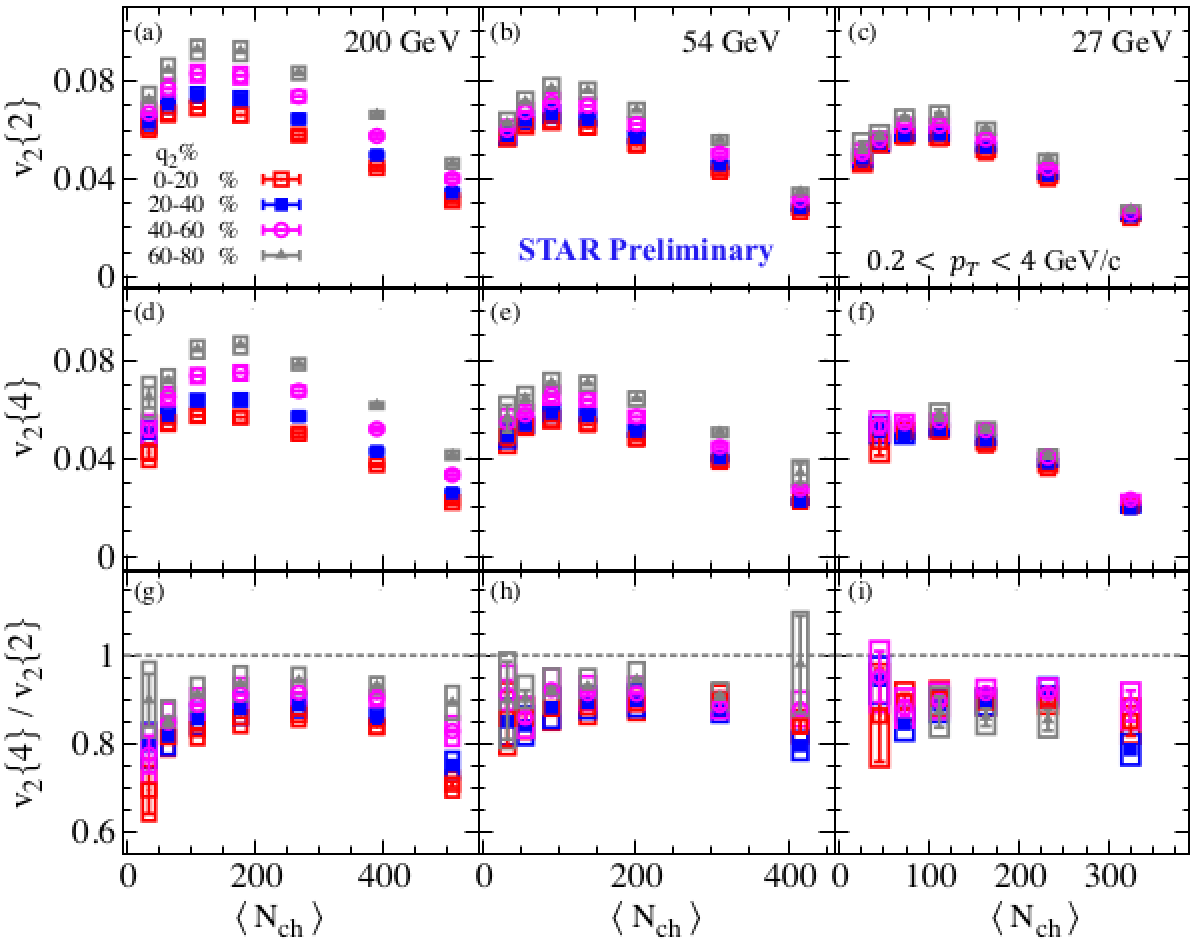
✓ Short-range non-flow contribution in $v_2\{2\}$ is suppressed by $|\Delta\eta| > 0.7$

$$v_n^4\{4\} = 2\langle v_n^2\rangle^2 - \langle v_n^4\rangle$$

$$\left[\frac{v_n\{4\}}{v_n\{2\}}\right]^4 = 2 - \frac{\langle v_n^4\rangle}{\langle v_n^2\rangle^2}$$

Sensitive to flow fluctuations

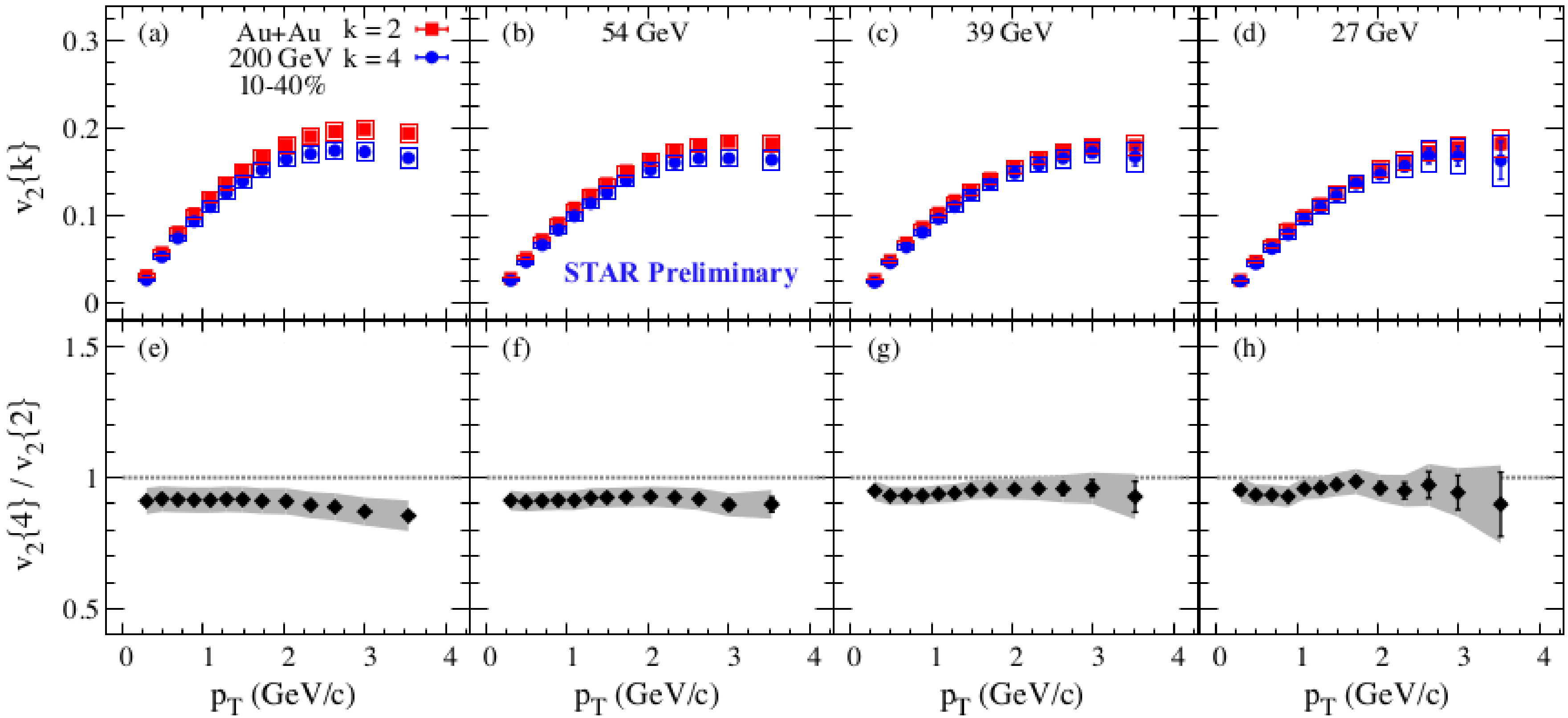
2) Initial state physics



Strong dependence of $v_2\{2\}$ and $v_2\{4\}$ on collision centrality more significant for higher collision energies

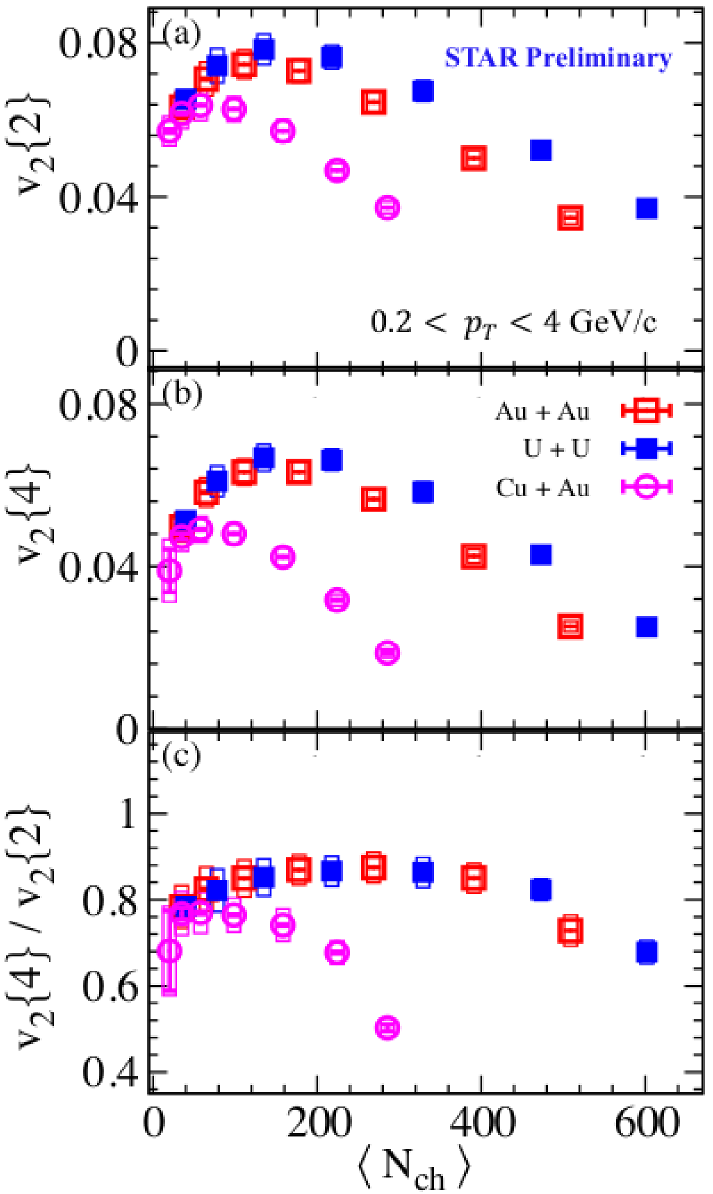
Weak dependence of $v_2\{2\}/v_2\{4\}$ on collision centrality

2) Initial state physics



Weak dependence of $v_2\{2\}$, $v_2\{4\}$ and $v_2\{2\}/v_2\{4\}$ on transverse momentum

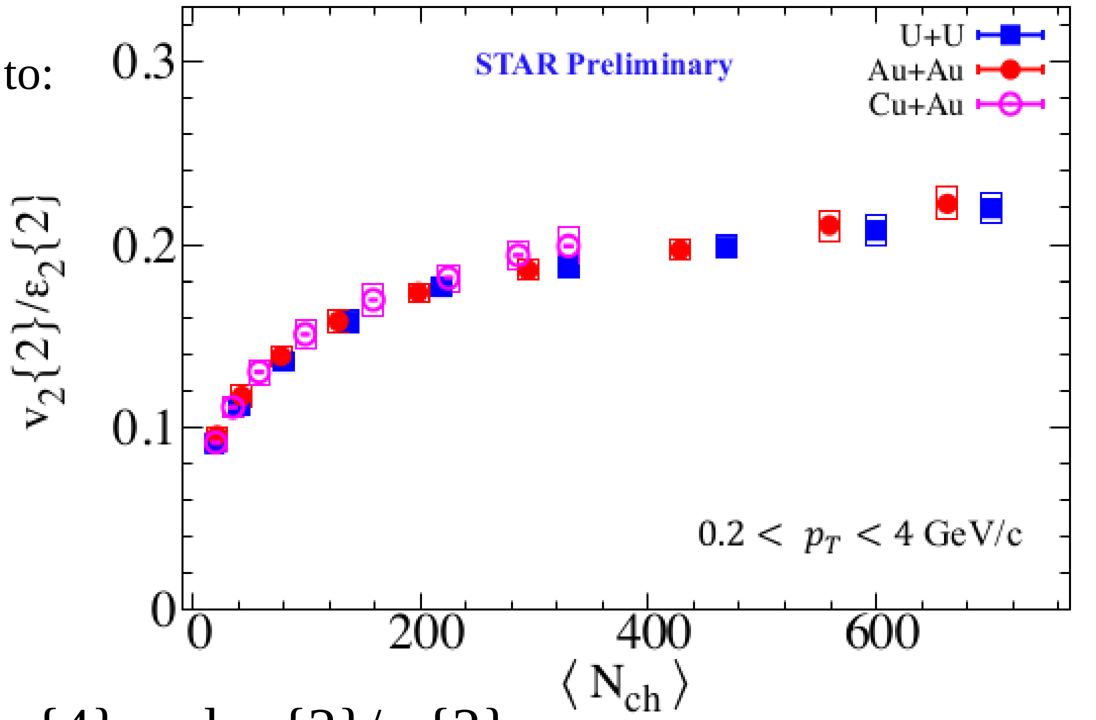
2) Initial state physics



Significant dependence of $v_2\{2\}$, $v_2\{4\}$ and $v_2\{2\}/v_2\{4\}$ on collision centrality for different A+A collisions

2) Initial state physics

Anisotropic flow magnitude is sensitive to:
- initial-state spatial anisotropy
- flow fluctuations and correlations
- viscous attenuation ($\propto \eta/s\ (T)$)



Weak dependence of $v_2\{2\}$, $v_2\{4\}$ and $v_2\{2\}/\varepsilon_2\{2\}$ on collision centrality for various systems.

Are dynamical final-state fluctuations significantly less than the initial-state fluctuations?

2) Initial state physics

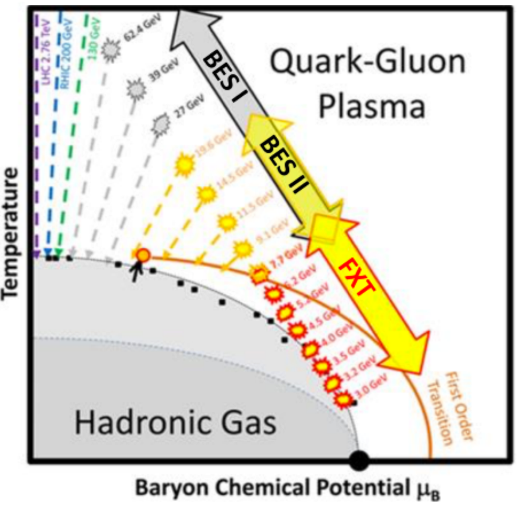
Strong dependence of $v_2\{2\}$, $v_2\{4\}$ on collision centrality, collision energy, transverse momentum

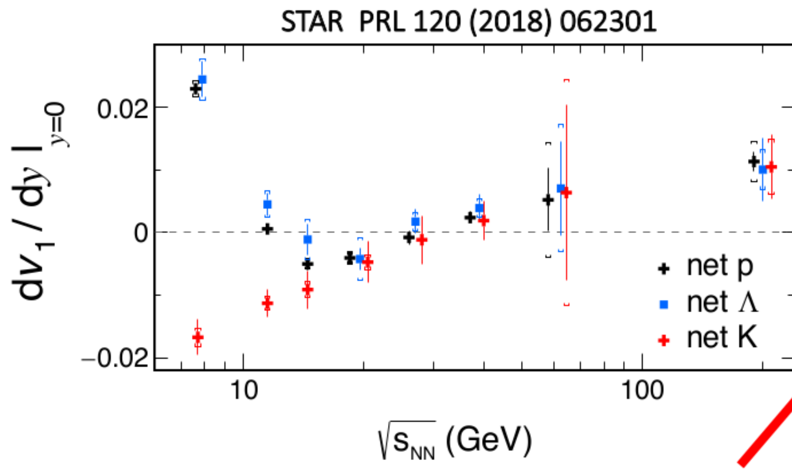
Weak dependence of $v_2\{4\}/v_2\{2\}$ and $v_2\{2\}/\varepsilon_2\{2\}$ (elliptic flow fluctuations) on the size of colliding system and:
collision centrality, collision energy, transverse momentum

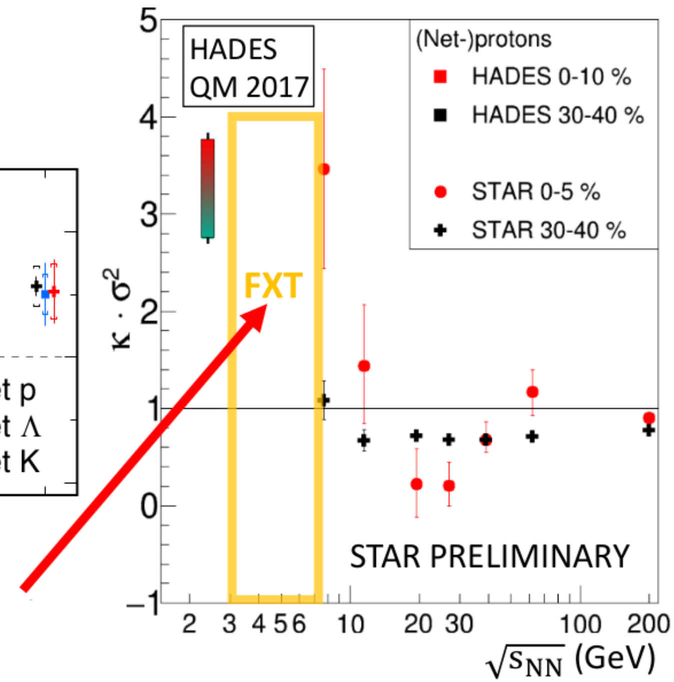
Flow flucuations are dominated by the fluctuations of the **initial state eccentricity**

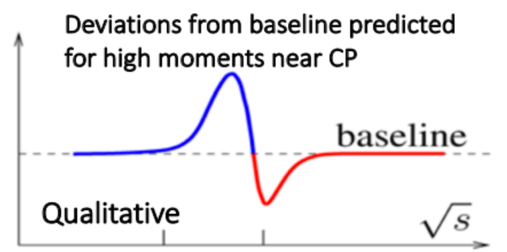
Similar viscous coefficient for different colliding systems

3) Fixed target mode









I. Stephanov J Phys G: Nucl Part Phys 38 (2011) 124147

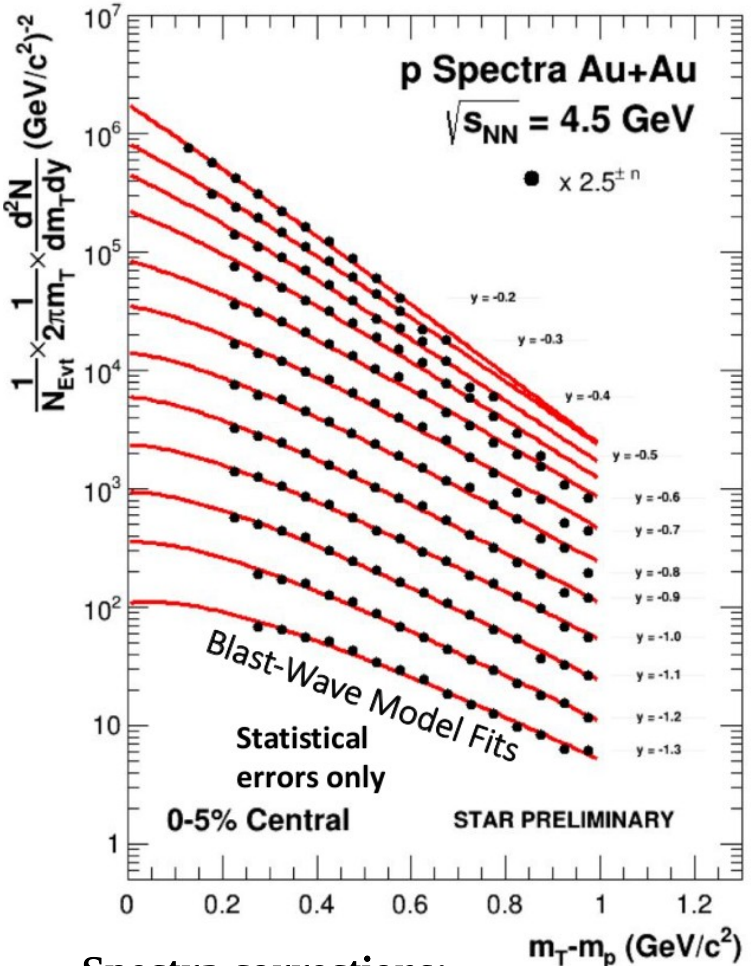
BES goals:

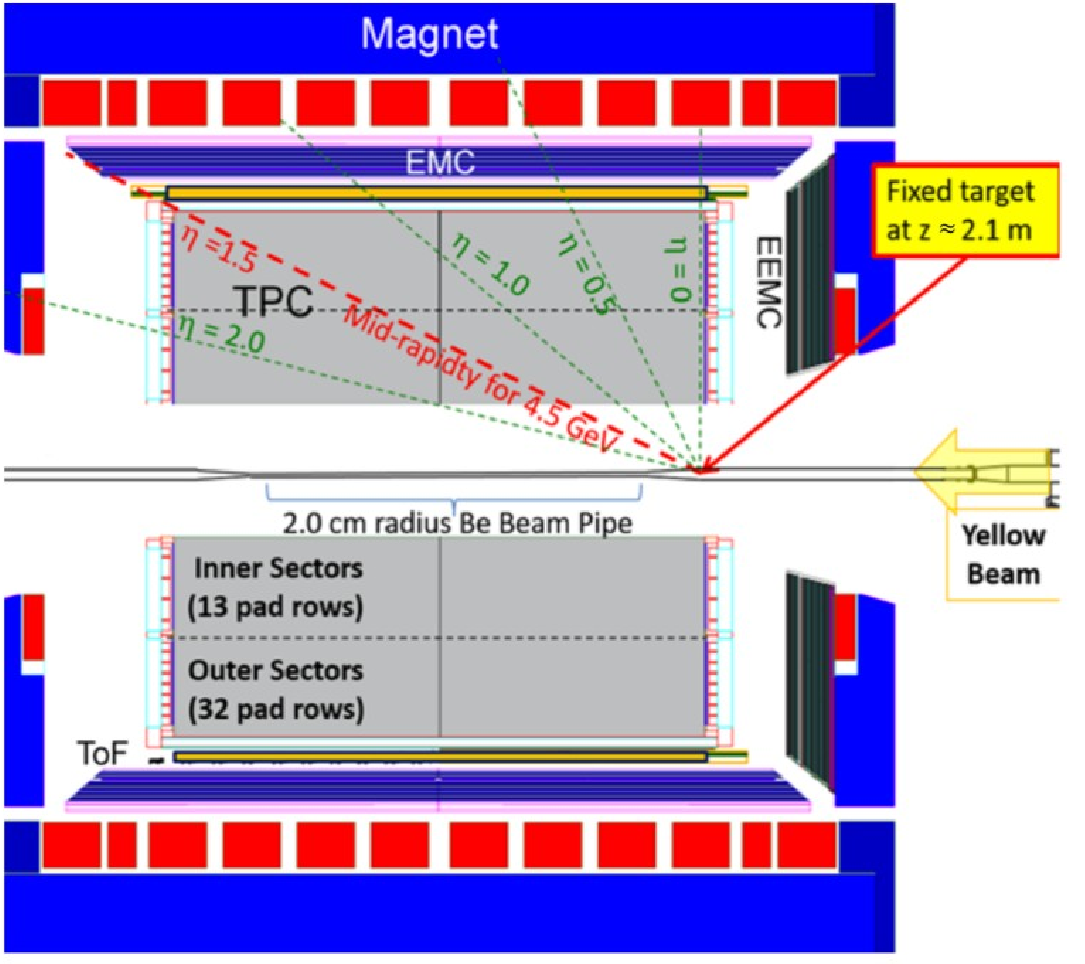
- Search for 1st order phase transition
- Search for existance of the Critical Point
- Search for turn-off QGP signatures

Collider mode is unusable for $\sqrt{s_{NN}}$<7.7 GeV

Fix target mode is able to cover $\sqrt{s_{NN}}$ from 3.0 GeV to 7.7 GeV

3) Fixed target mode

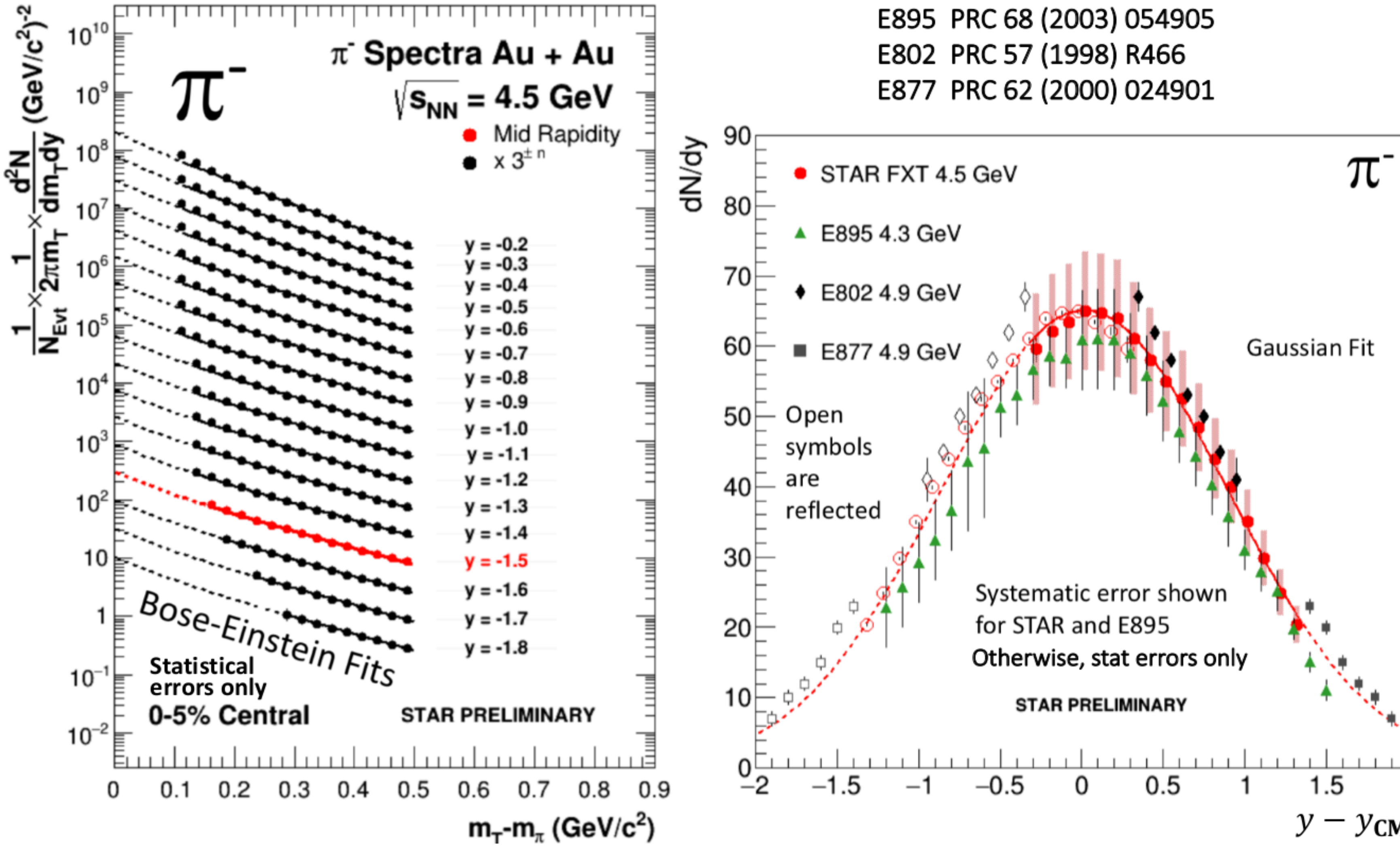




Spectra corrections:

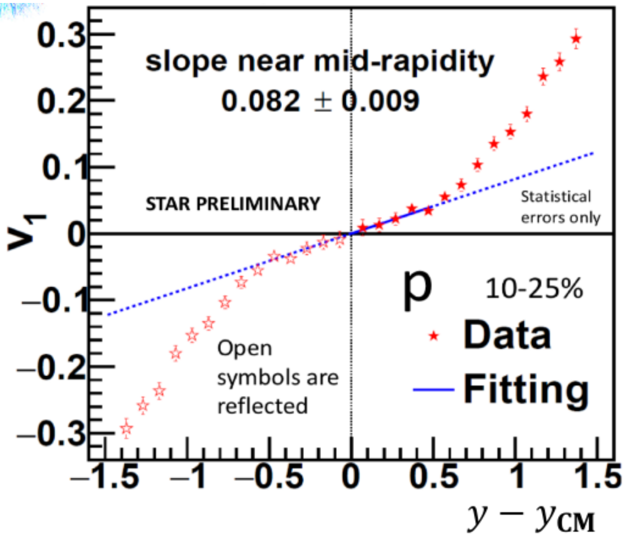
Detector efficiency
Detector acceptance
(each rapidity window)
Energy loss

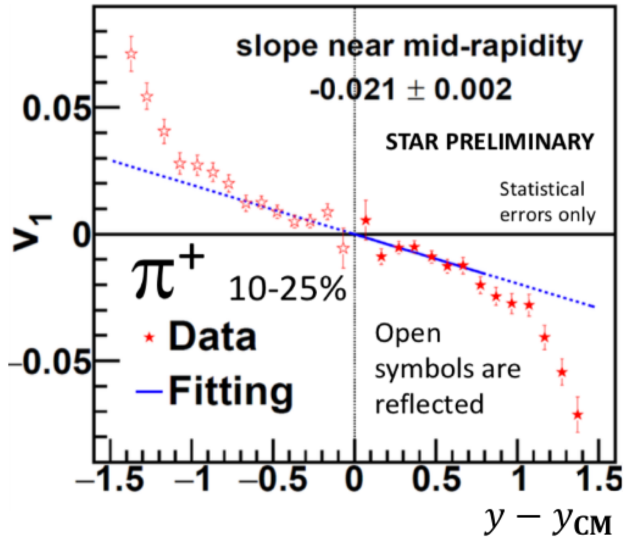
3) Fixed target mode

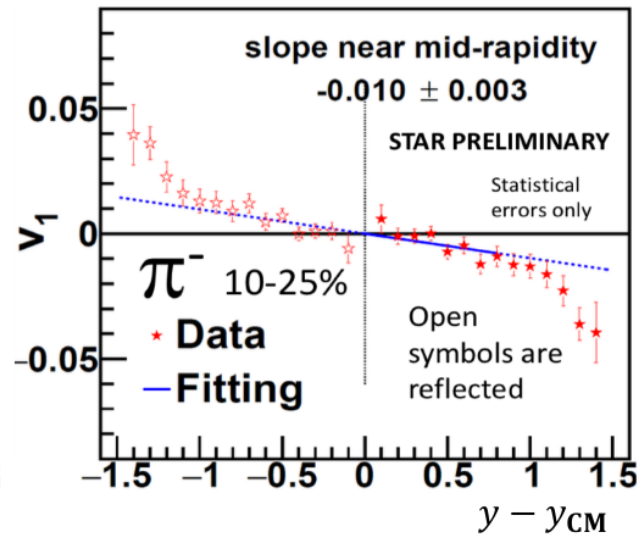


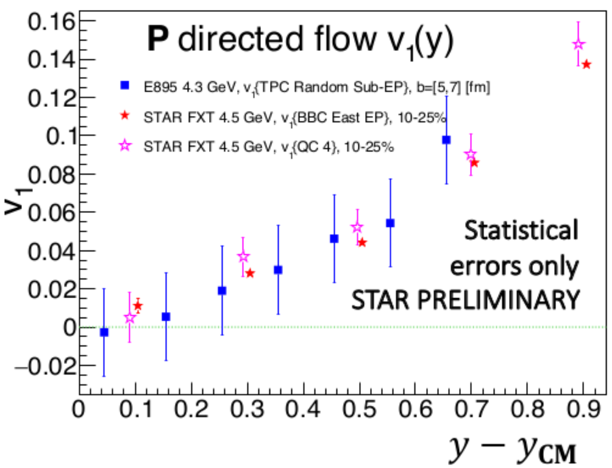
Negavtive pions spectra **are consistent** with AGS results.

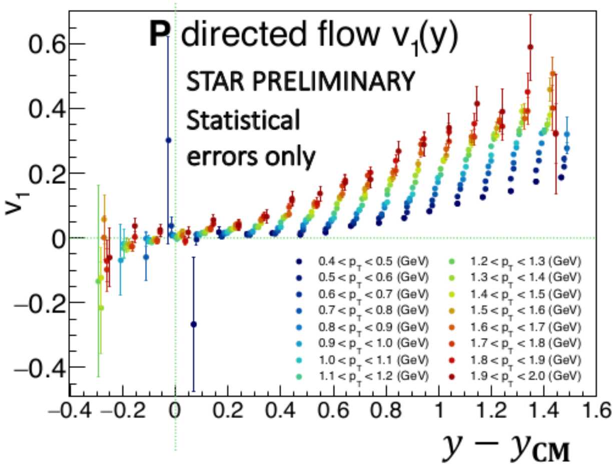
3) Fixed target mode







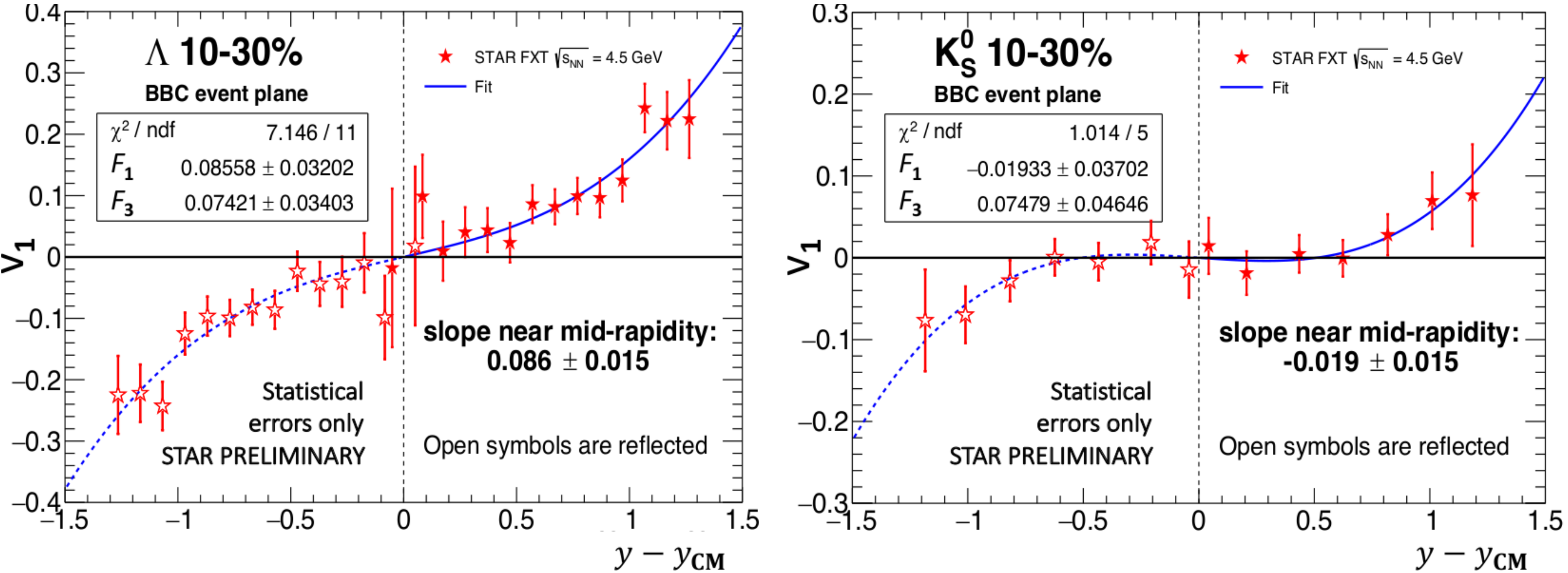




Directed flow for pions and protons with fit describing mid-rapidity region.

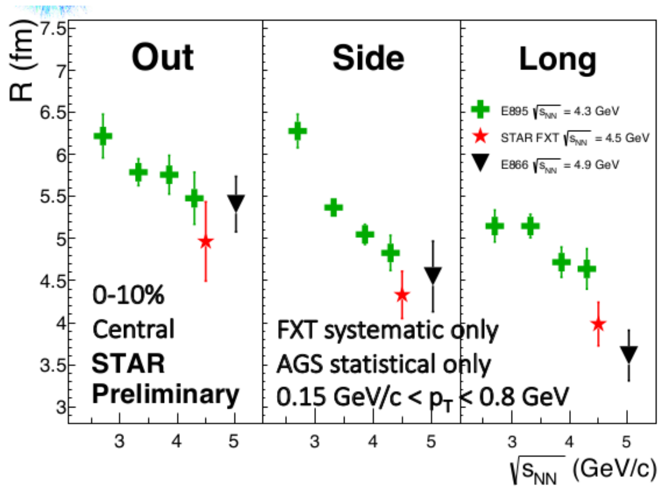
Directed flow of protons **agrees** with AGS results.

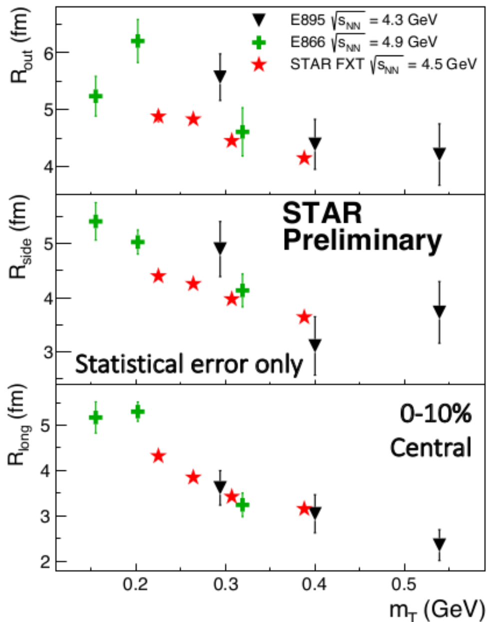
3) Fixed target mode



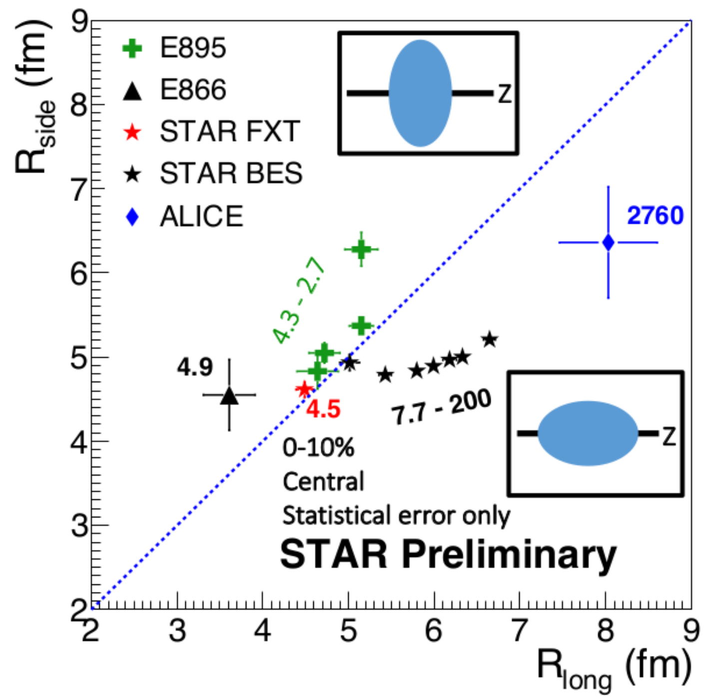
Directed flow for Λ and K^0_S particles and their fits describing mid-rapidity region.

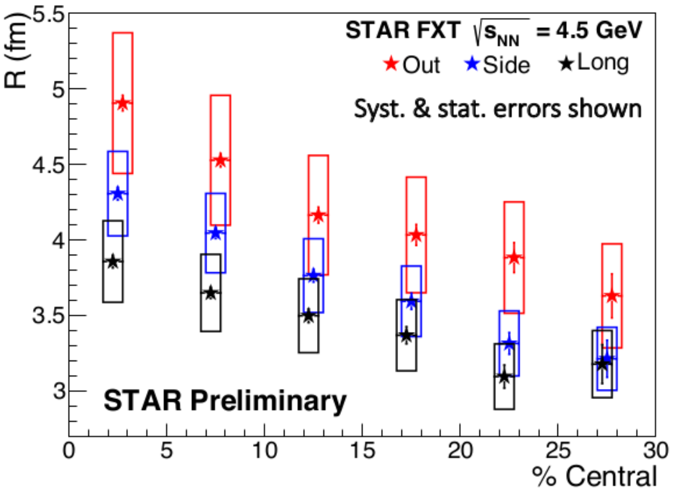
3) Fixed target mode





E866 PRC 66 (2002) 054096
E895 PRL 84 (2000) 2798
ALICE PRB 696 (2011) 328
STAR PRC 92 (2015) 14904





HBT radii for pions are **consistent** with AGS results.

3) Fixed target mode

- **STAR is ready** to operate with the Fixed Target mode

- **Spectra** and **particle yields** agree with AGS results

- **Proton directed flow** v_1 agrees with AGS results

- **HBT radii** agree with AGS results

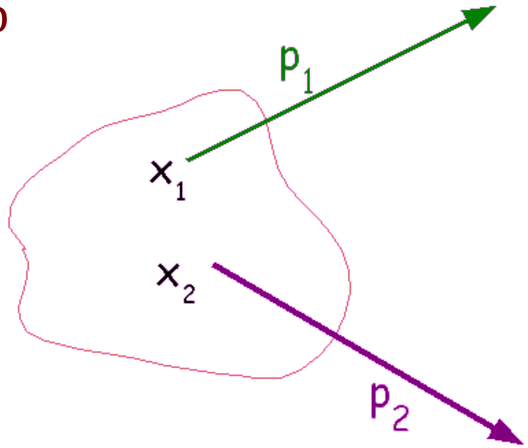
High-baryon density regime will be accessible with the Fix Target mode in STAR!

4) Femtoscopy

Single- and two- particle distributions

$$P_1(p)=E\frac{dN}{d^3p}=\int d^4x\,S(x,p)$$

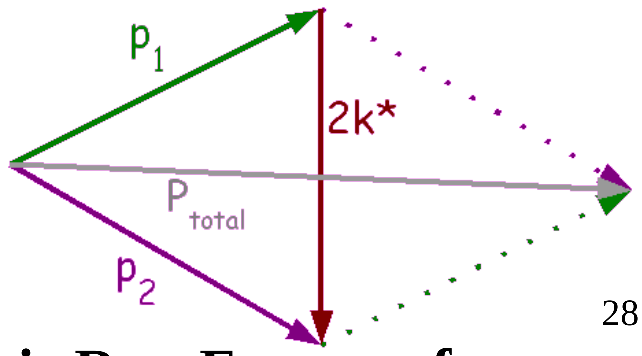
S(x,p) – emission function: the distribution of source density probability of finding particle with x and p



$$P_2(p_1,p_2)=E_1E_2\frac{dN}{d^3p_1d^3p_2}=\int d^4x_1S(x_1,p_1)d^4x_2S(x_2,p_2)\Phi(x_2,p_2|x_1,p_1)$$

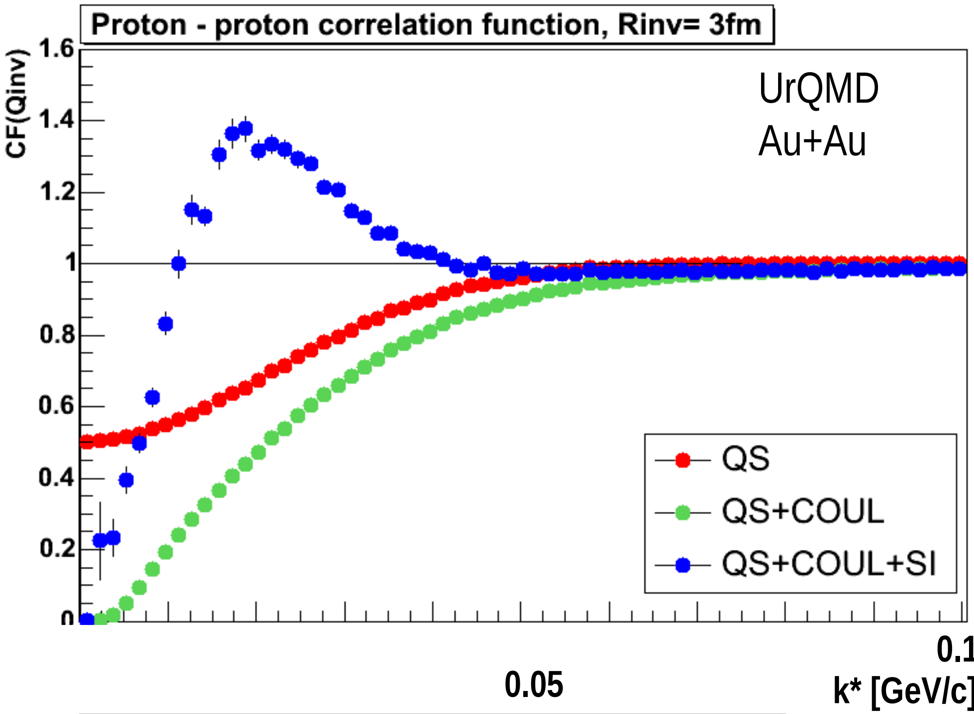
The correlation function

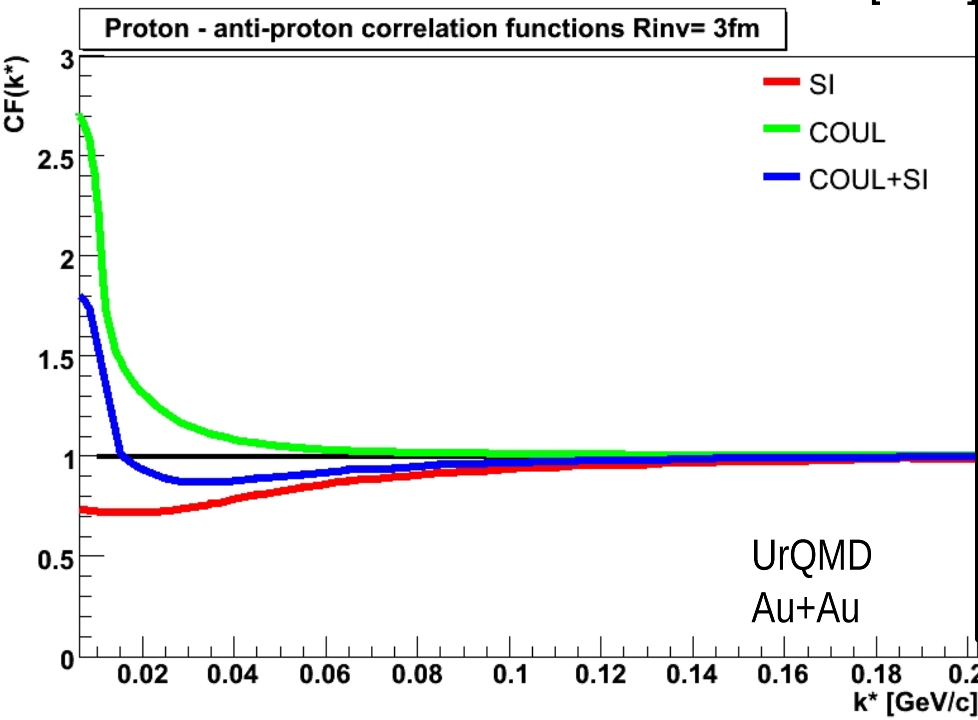
$$C(p_1,p_2)=\frac{P_2(p_1,p_2)}{P_1(p_1)P_1(p_2)}$$



Pair Rest Frame reference

4) Femtoscopy





Identical baryon- baryon

- Quantum Statistics- **QS**

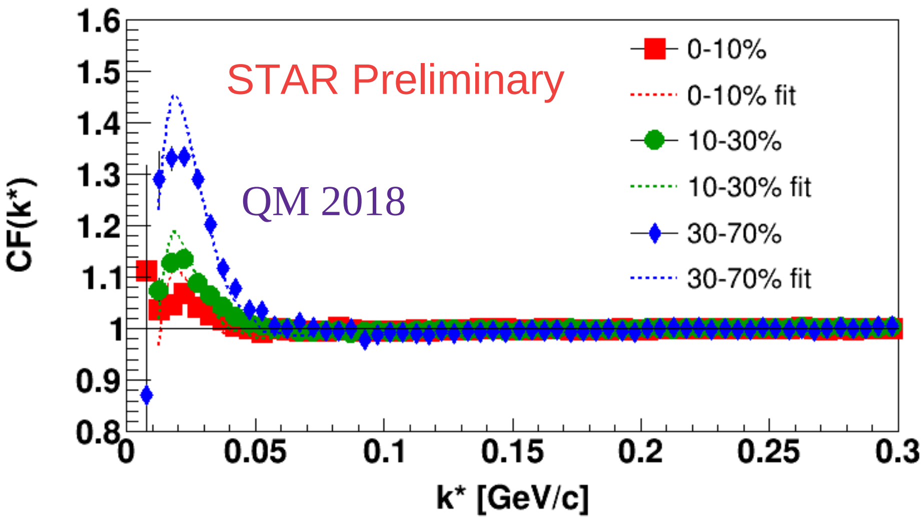
- Final State Interactions- **FSI**
  - **Coulomb**
  - **Strong**

Non-identical baryon- (anti)baryon

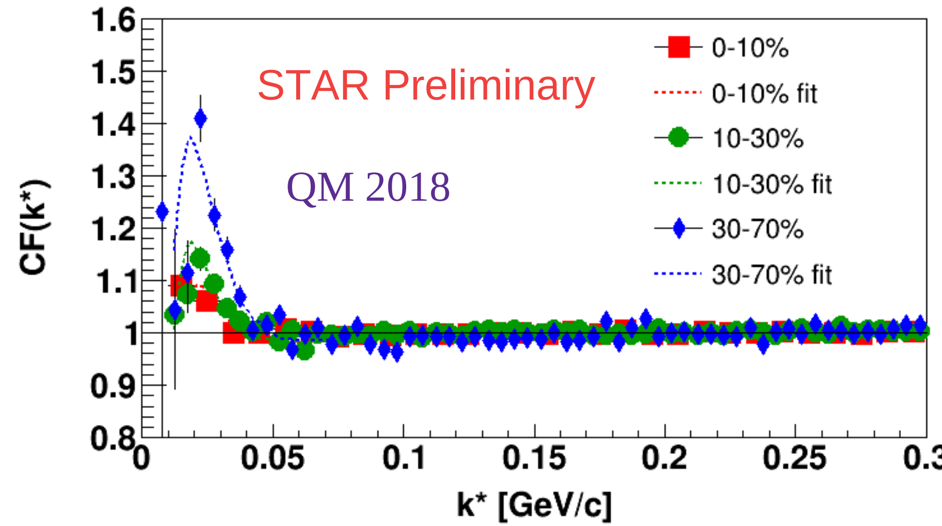
- Final State Interactions- **FSI**
  - **Coulomb**
  - **Strong**

4) Femtoscopy

proton-proton @39 GeV



antiproton-antiproton @39 GeV

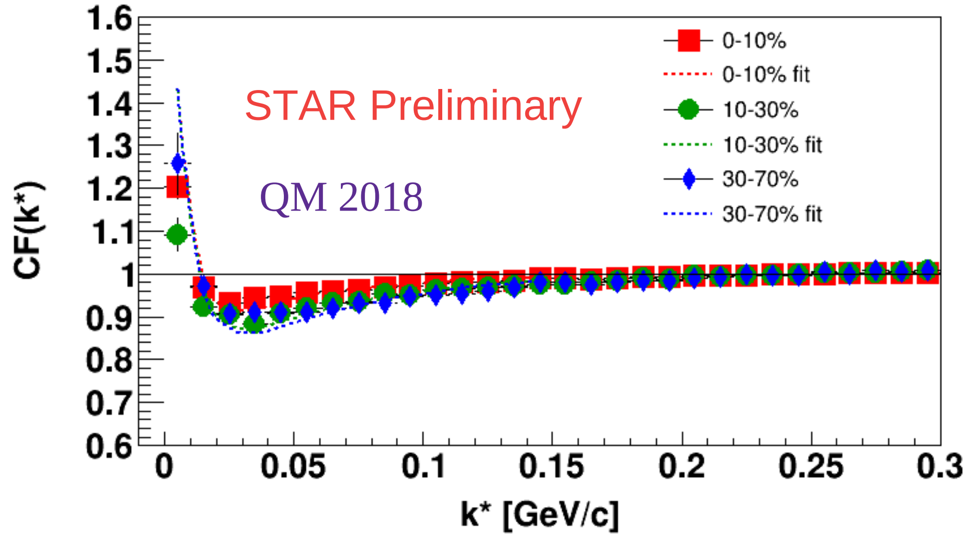


centrality	R_{inv} $p-p$ [fm]	R_{inv} $\overline{p}-\overline{p}$ [fm]	R_{inv} $p-\overline{p}$ [fm]
0-10%	$\mathbf{4.00} \pm 0.15 \pm 0.02$	$\mathbf{3.83} \pm 0.20 \pm 0.03$	$\mathbf{3.39} \pm 0.12 \pm 0.14$
10-30%	$\mathbf{3.61} \pm 0.13 \pm 0.17$	$\mathbf{3.68} \pm 0.15 \pm 0.11$	$\mathbf{2.69} \pm 0.10 \pm 0.12$
30-70%	$\mathbf{2.72} \pm 0.07 \pm 0.07$	$\mathbf{2.95} \pm 0.11 \pm 0.08$	$\mathbf{2.56} \pm 0.09 \pm 0.12$

No significant difference between proton-proton and antiproton-antiproton correlation functions

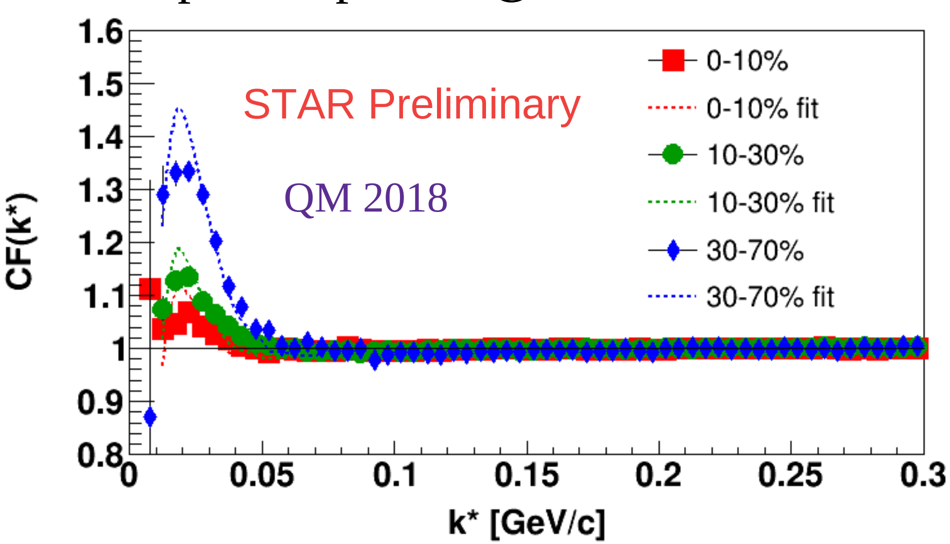
4) Femtoscopy

Radii from proton-proton and antiproton-antiproton systems differ from those from proton-antiprootn system →
→ **Residual Correlations**.
Residual feed-down correction needs to be applied.



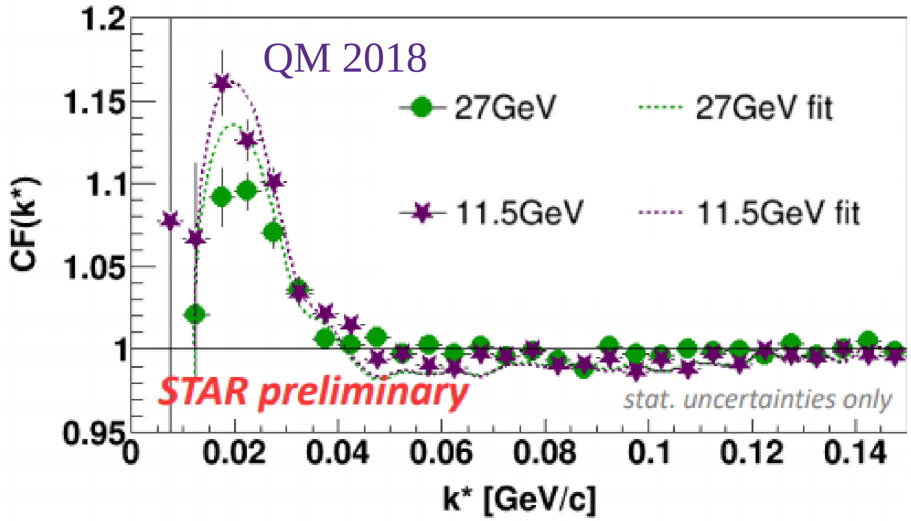
proton-proton @39 GeV

proton-antiproton @39 GeV

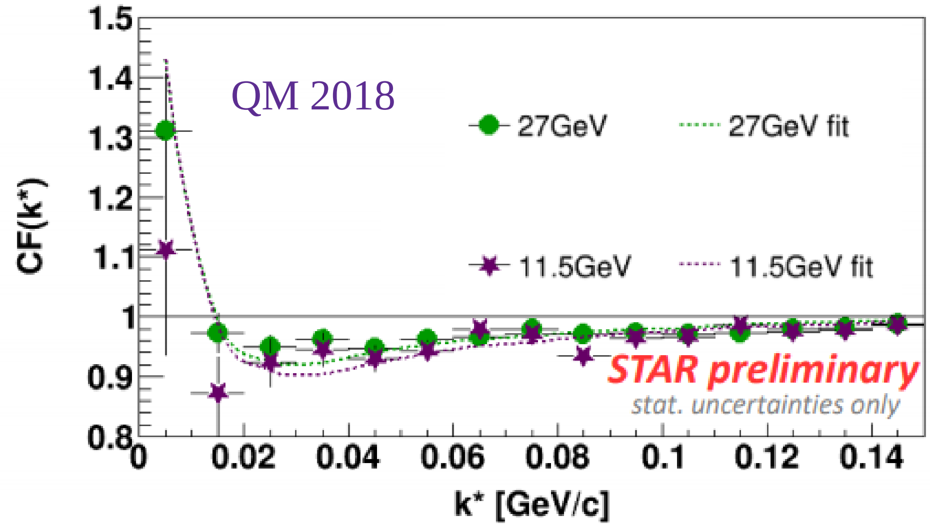


4) Femtoscopy

proton-proton, centrality 0-10%



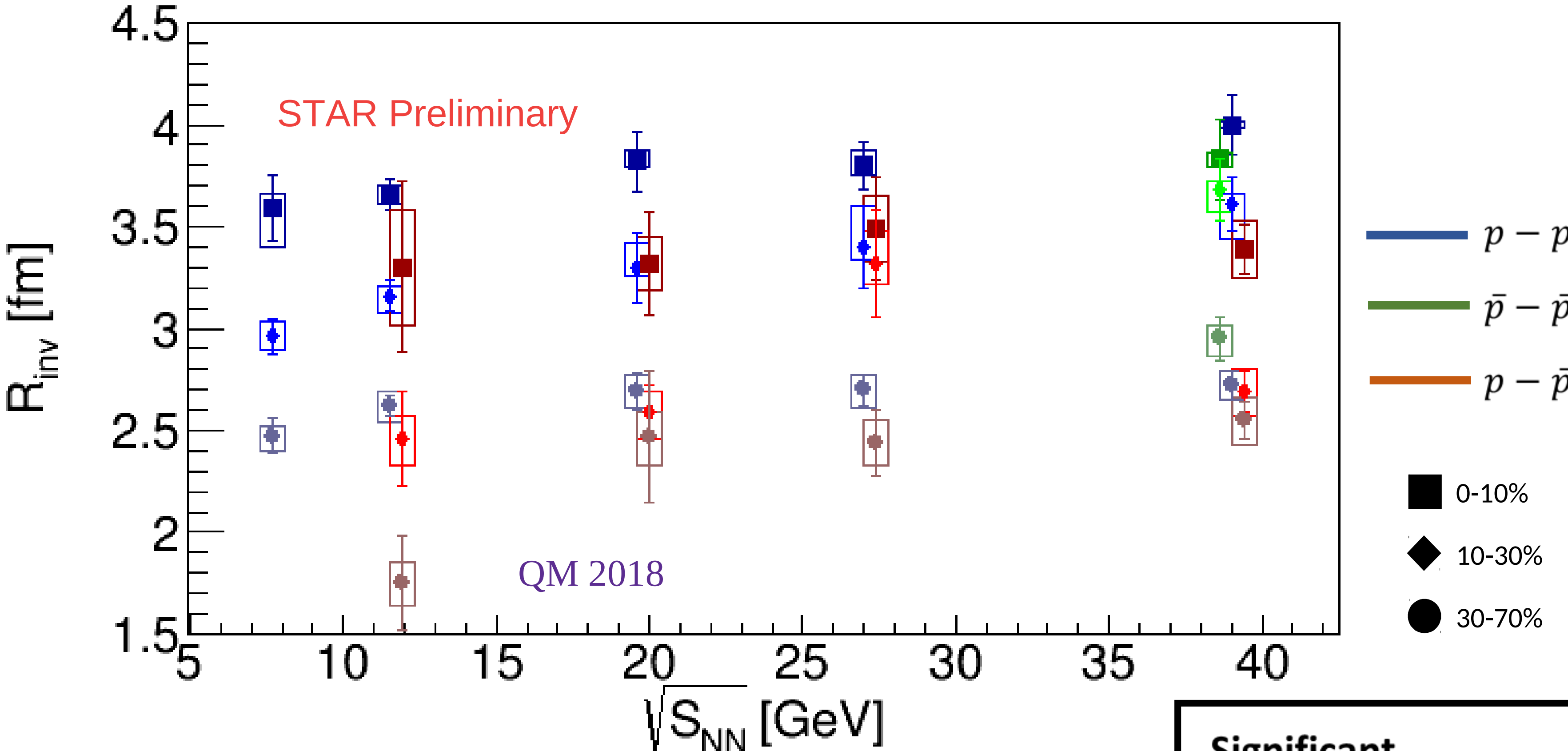
proton-antiproton, centrality 0-10%



energy	R_{inv} $p-p$ [fm]	R_{inv} $p-\overline{p}$ [fm]
7.7 GeV	$\mathbf{3.59} \pm 0.16 \pm 0.19$	
11.5 GeV	$\mathbf{3.66} \pm 0.08 \pm 0.05$	$\mathbf{3.30} \pm 0.42 \pm 0.28$
19.6 GeV	$\mathbf{3.82} \pm 0.15 \pm 0.06$	$\mathbf{3.32} \pm 0.25 \pm 0.13$
27 GeV	$\mathbf{3.80} \pm 0.12 \pm 0.08$	$\mathbf{3.49} \pm 0.25 \pm 0.16$
39 GeV	$\mathbf{4.00} \pm 0.15 \pm 0.02$	$\mathbf{3.39} \pm 0.12 \pm 0.14$

Energy dependence more significant for proton-proton than for proton-antiproton system.

4) Femtoscopy



Feed-down correction may decrease significance of centrality dependence.

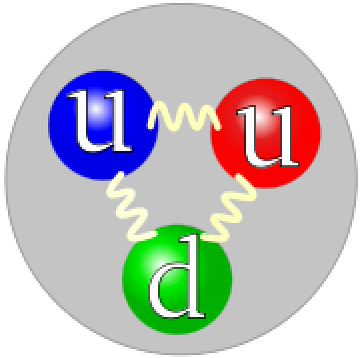
No significant difference between $p-p$ and $\bar{p}-\bar{p}$ correlation functions at $\sqrt{s_{NN}}$ = 39 GeV

Significant centrality dependence.

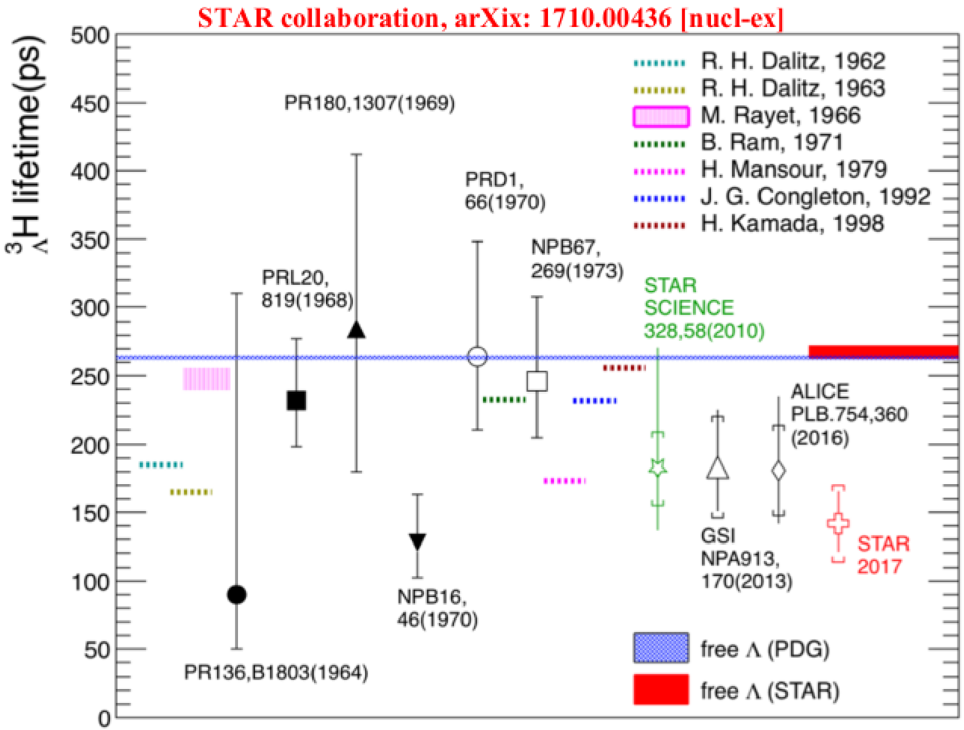
$\sqrt{s_{NN}}$ dependence weak for all centralities.

4) Femtoscopy

- Clear centrality dependence of source size at BES energies
- Visible energy dependence of source size at BES energies
- **No visible difference between proton-proton and antiproton-antiproton correlation functions at $\sqrt{s_{NN}}$ = 39 GeV**
- **Correlation functions contaminated by residual correlations – residual correction required**



5) Hypertriton



Hyperon-Nucleon:

- play an important role in neutron star and QCD theory

- measurements of masses of hypertriton and anti-hypertriton provide insight into H-N interactions and the CPT symmetry

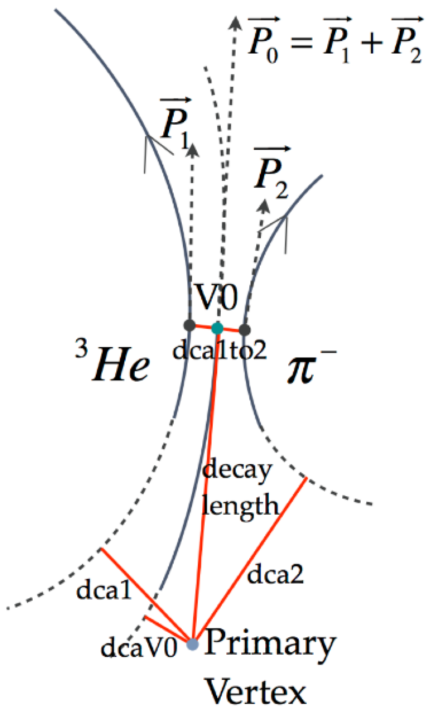
- measurements sensitive to the temperature and nucleon phase-space of the system freeze-out.

- excellent tool to explore the QCD properties

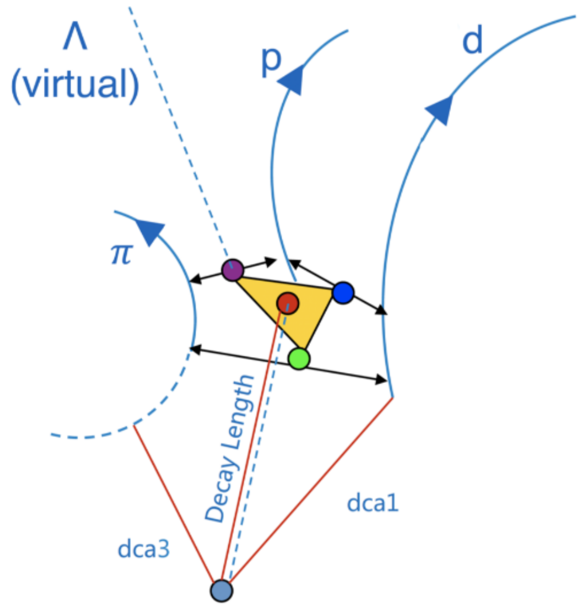
[1] R. O. Gomes, V. Dexheimer, S. Schramm, and C. A. Z. Vasconsellos, The Astrophys. J. 808, 8 (2015).
[2] L. L. Lopes and D. P. Menezes, Phys. Rev. C 89, 025805 (2014).
[3] J. Antoniadis et al., Science 340, 448 (2013).
[4] László P. Csernai, Joseph I. Kapusta, Phys. Reps. 131, 223 (1986).
[5] A. Z. Mekjian, Phys. Rev. C 17, 1051 (1978).
[6] Kaijia Sun et al., Phys. Lett. B 774, 103 (2017).

5) Hypertriton

$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$



$^{3}_{\Lambda}H \rightarrow p + \pi^{-} + d$



$^{3}_{\Lambda}$H has many decay channels:

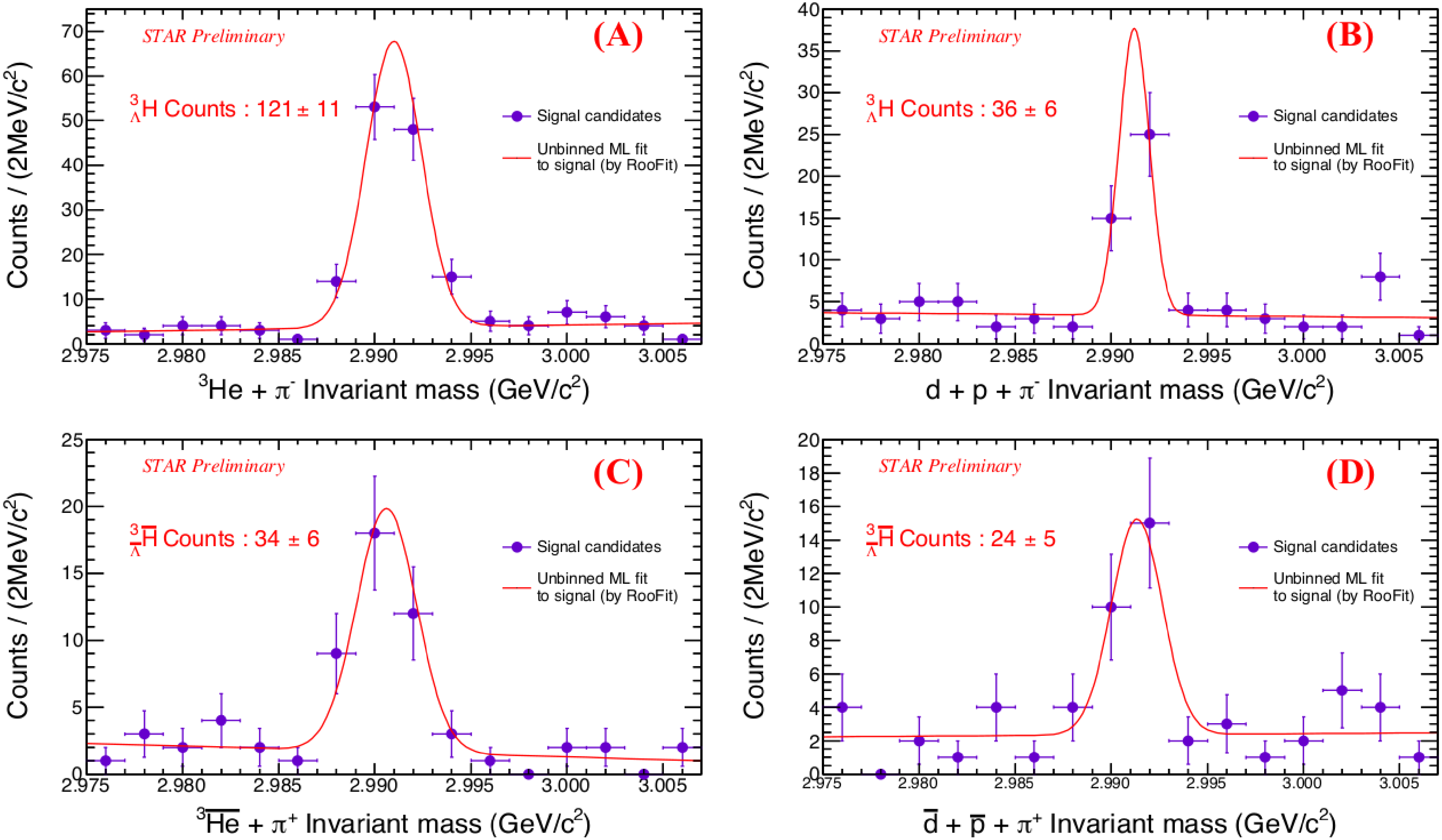
- ✓ **Non-meson decay channels:**
  - $^{3}_{\Lambda}H \rightarrow d + n$
  - $^{3}_{\Lambda}H \rightarrow p + n + n$
- ✓ **Meson decay channels:**
  - $^{3}_{\Lambda}H \rightarrow {}^{3}He\ ({}^{3}H) + \pi^{-}\ (\pi^{0})$
  - $^{3}_{\Lambda}H \rightarrow d + p\ (n) + \pi^{-}\ (\pi^{0})$
  - $^{3}_{\Lambda}H \rightarrow p + n + p\ (n) + \pi^{-}\ (\pi^{0})$

Good PID of charged particles in STAR detector.

Reconstructing $^{3}_{\Lambda}$H ($^{3}_{\bar{\Lambda}}\bar{H}$) through:

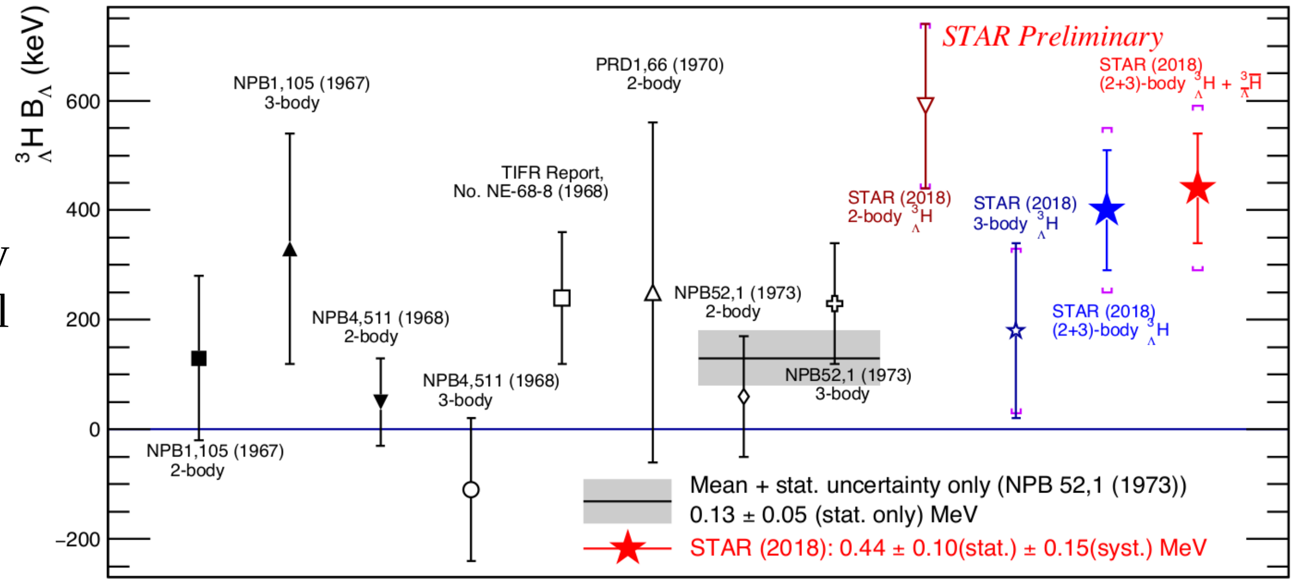
- $^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$
- $^{3}_{\Lambda}H \rightarrow d + p + \pi^{-}$

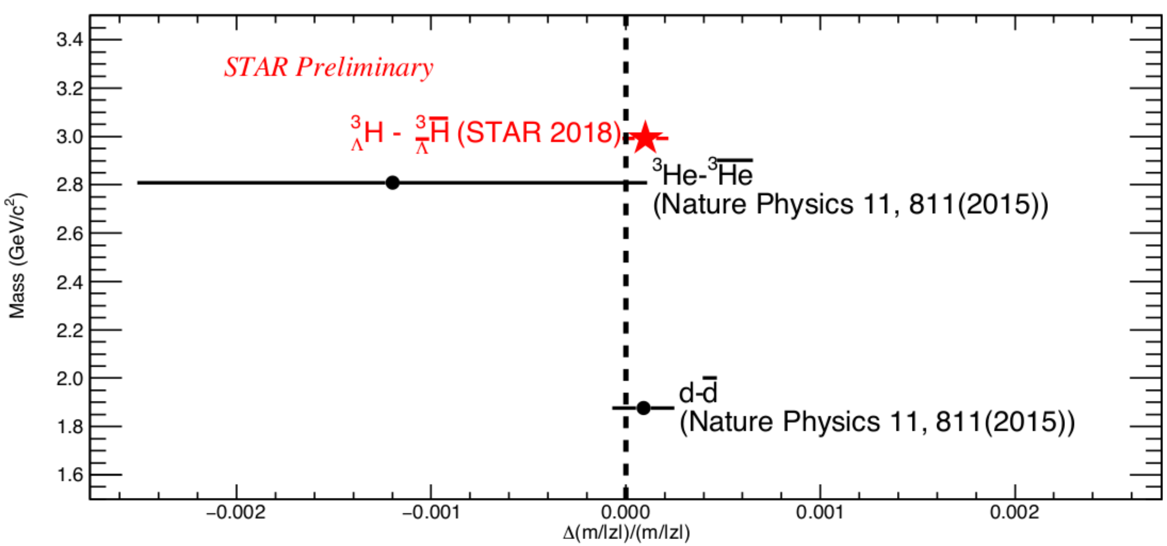
5) Hypertriton



5) Hypertriton

Worldwide binding energy of ${}^{3}_{\Lambda}H$ of experimental measurements.





Measurements of the mass-over-charge ratio differences between light nuclei and anti-nuclei.

Conclusions & Summary

Summary

1. Open heavy flavor - D^0 v_1, D^0 R_{AA} and R_{CP}, Λ_C

2. Quarkonium – Υ R_{AA}

3. Jet modification and high-p_T hadrons - di-jet imbalance, di-hadron correlation

4. Chirality, vorticity and polarization effects - Λ polarization, Φ polarization, CME, CMW

5. Initial state physics and approach to equilibrium - v_2 and v_3 fluctuations

6. Collectivity in small systems - v_2 in p+Au and d+Au

7. Collective dynamics - longitudinal decorrelation, identified particle v_1

8. High baryon density and astrophysics - v_1 from fixed target

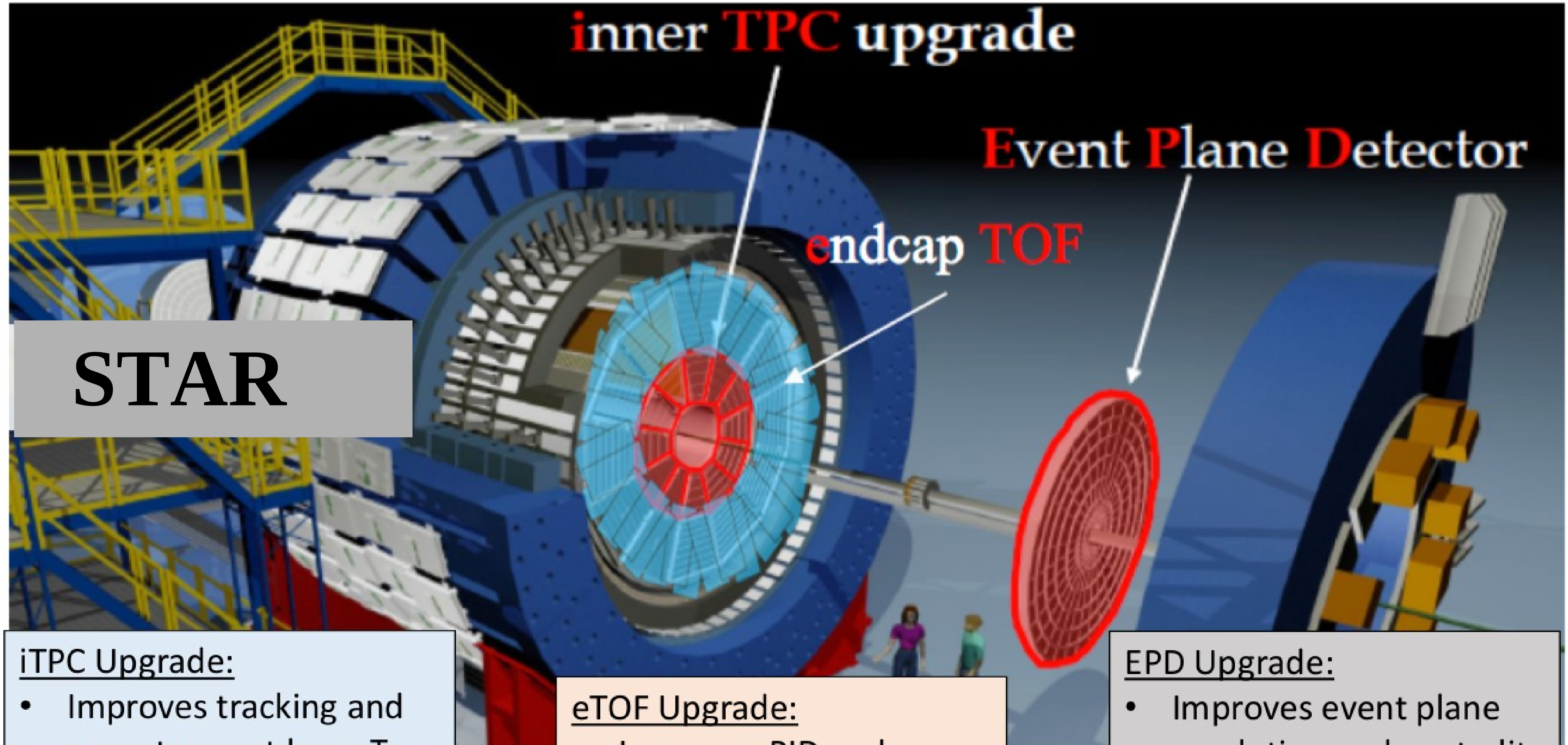
9. Correlations and fluctuations – femtoscopy

10. Phase diagram and search for the critical point - net Λ and off-diagonal cumulants

11. Thermodynamics and hadron chemistry - triton, hypertriton mass

12. Upgrades - BES-II and forward upgrades

Upgrades



iTPC Upgrade:

- Improves tracking and acceptance at low pT and extra y acceptance
- Ready in 2019

eTOF Upgrade:

- Improves PID and acceptance
- Ready in 2019

EPD Upgrade:

- Improves event plane resolution and centrality definition
- Taking data in 2018 run

STAR Note 0644: Technical Design Report for the iTPC Upgrade

arXiv:1609.05102v1 [nucl-ex]

STAR Note 0666: An Event Plane Detector for STAR

Upgrades

STAR Note 0696: STAR Collaboration Beam Use Request for Run 19+ (Scenario 1)

Single Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	Run Year	Run Time	Species	Min-Bias Events Number
5.75	3.5 (FXT)	2020	2 days	Au+Au	100M
7.3	3.9 (FXT)	2019	2 days	Au+Au	100M
9.8	4.5 (FXT)	2019	2 days	Au+Au	100M
13.5	5.2 (FXT)	2020	2 days	Au+Au	100M
19.5	6.2 (FXT)	2020	2 days	Au+Au	100M
31.2	7.7 (FXT)	2019	2 days	Au+Au	100M

- iTPC & eTOF upgrades will be available
- Need 100M events at each energy to match sensitivity of BES-II: 2 days per energy (3.5 GeV – 7.7 GeV)
- Data rate is DAQ limited
- Data at 7.7 GeV will provide an overlap energy with collider mode

FXT in Run 18

Trigger commissioning occurring now

1 Billion events at 7.2 GeV

100 Million events at 3.0 GeV

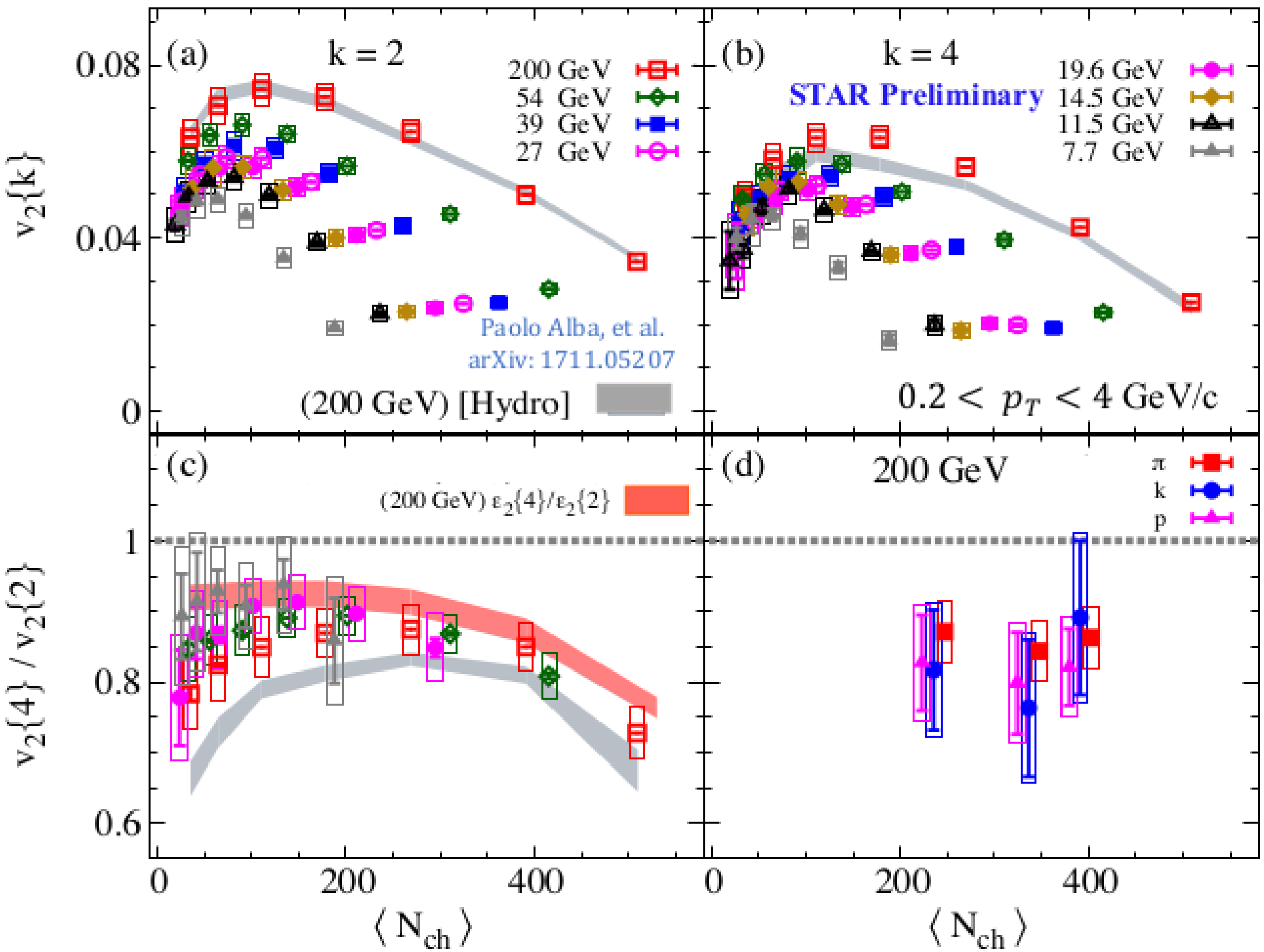
EPD ready and available for flow analyses

Can obtain fluctuation measurement at energies below BES-I

Thank you!

Backup slides

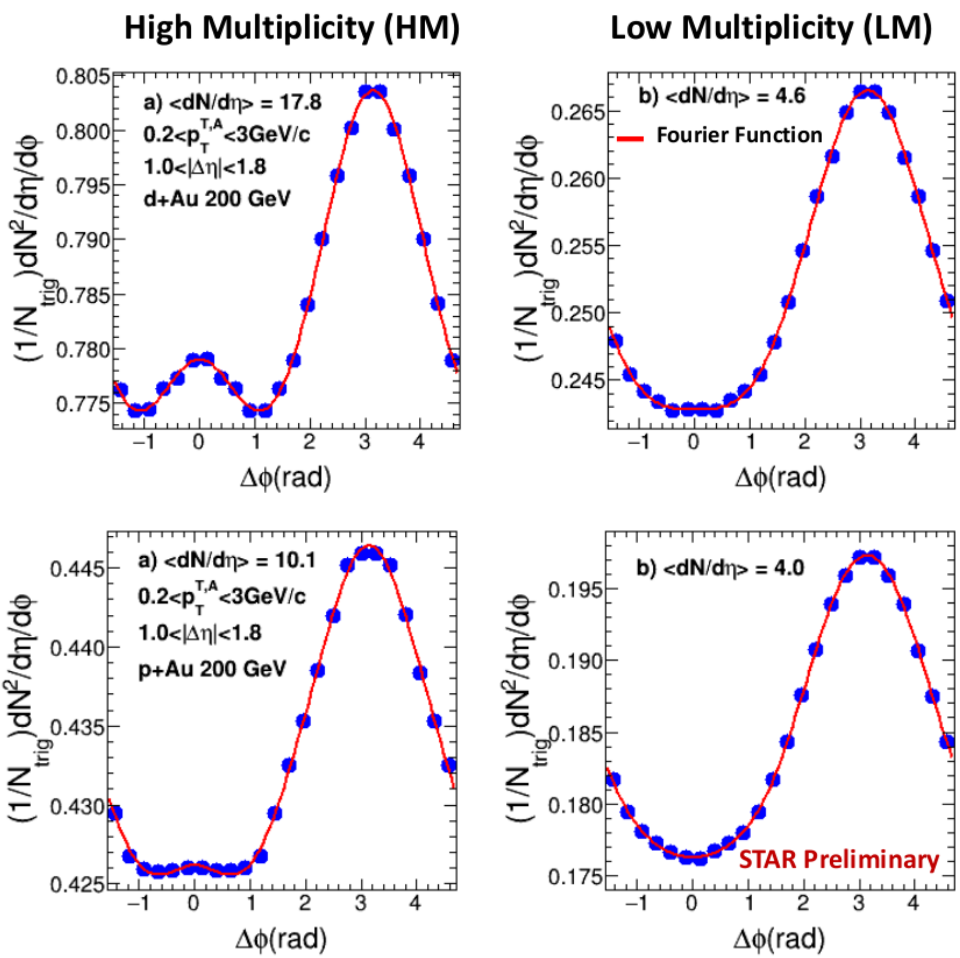
2) Initial state physics



Strong dependence on collision energy

Weak dependence on collision centrality

3) Small systems



d+Au 200 GeV

Near-side ridge observed in High Multiplicity (HM) of d+Au collisions

p+Au 200 GeV

$$dN/d\Delta\phi \sim 1 + \sum_{n=1}^{4} 2V_{n,n} \times \cos(n\Delta\phi))$$

Integral $v_n = \text{sqrt}(V_{n,n})$; $v_n(p_T) = V_{n,n}(p_T)/v_n$

3) Small systems

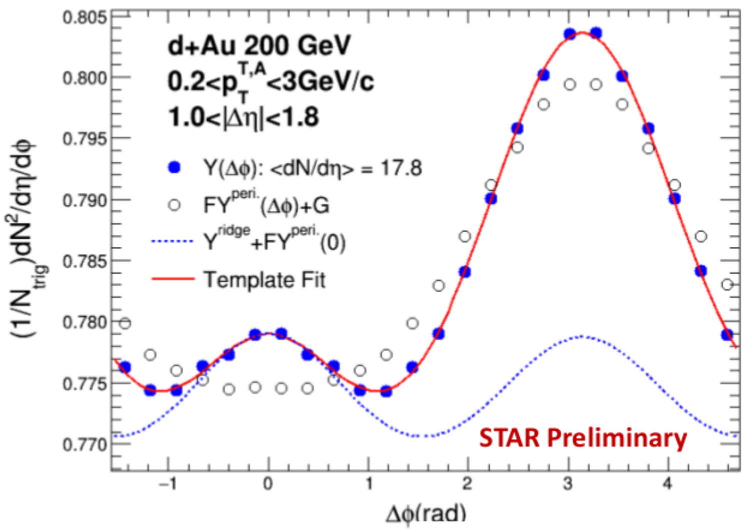
Low multiplicity subtraction scaled by short-range near-side (|Δη|<0.5) jet yield

$$V_{n,n}^{HM}(subtracted) = V_{n,n}^{HM} - V_{n,n}^{LM} \times \frac{N_{asso.}^{LM}}{N_{asso.}^{HM}} \times \frac{Y_{jet,near-side}^{HM}}{Y_{jet.near-side}^{LM}}$$

ATLAS:PRC90(2014)044906
CMS:PLB765(2017)193
STAR: PLB743(2015)333

Short-range near-side jet modification = long-range away-side jet modification

Template fit



$$Y_{templ.}(\Delta\phi) = F \times Y_{LM}(\Delta\phi) + Y_{ridge}(\Delta\phi)$$
where
$$Y_{ridge}(\Delta\phi) = G \times (1 + 2 \times \sum_{n=2}^{4} V_{n,n} \times \cos(n\Delta\phi))$$

ATLAS:PRL(116)172301

A new method by ATLAS Collaboration away-side jet shape can be measured in Low Multiplicity (LM) events scaled by ”F” parameter
(due to jet modification)

3) Small systems

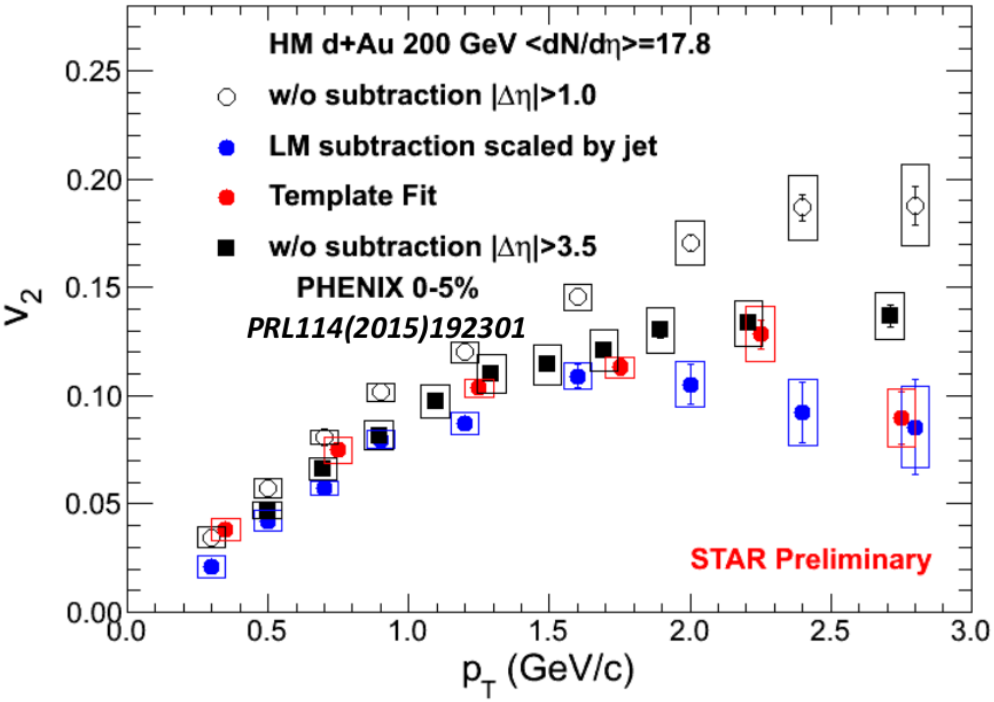
v_2 without subtraction is **larger** than that with subtraction for both methods.

The subtraction of non-flow contributions are very **important** for STAR results are comparable with PHENIX results, except at high pT.

At lowet p_T v_2 from Low Multiplicity subtraction is **35% lower** than from template fit

At intermediate p_T they **agree** with each other

STAR results are **comparable** with PHENIX ones.

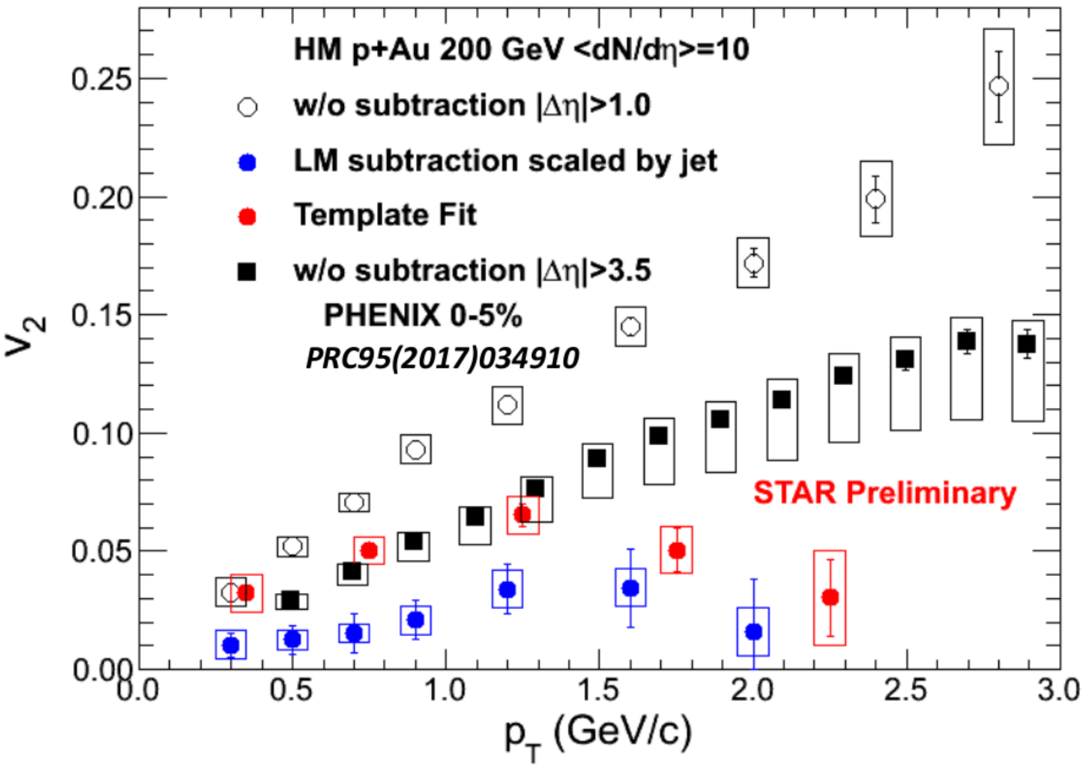


3) Small systems

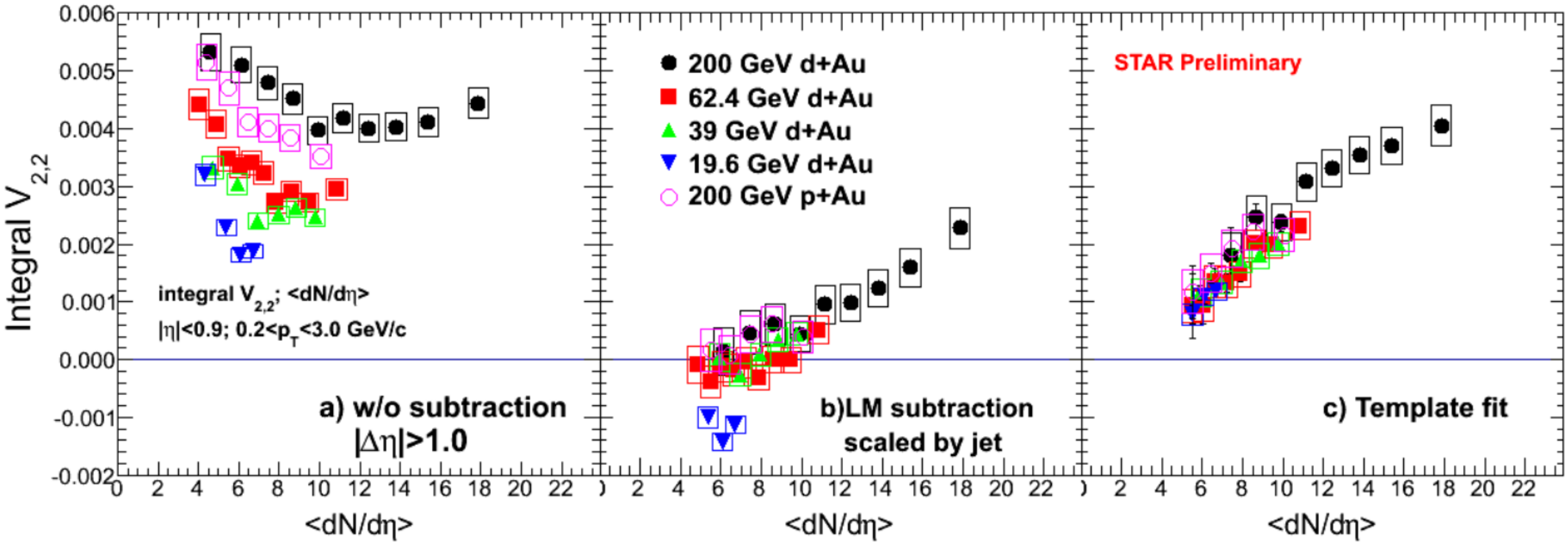
v_2 in p+Au collisions without subtraction is **larger** than v_2 in d+Au collisions that with subtraction for both methods.

v_2 in p+Au collisions from Low Multiplicity subtraction is **lower** than from template fit.

STAR results are **comparable** with PHENIX results, except at high pT. The STAR data is clearly lower than PHENIX for p_T>1.5 GeV/c



3) Small systems



Large **difference** between subtraction method and template fit

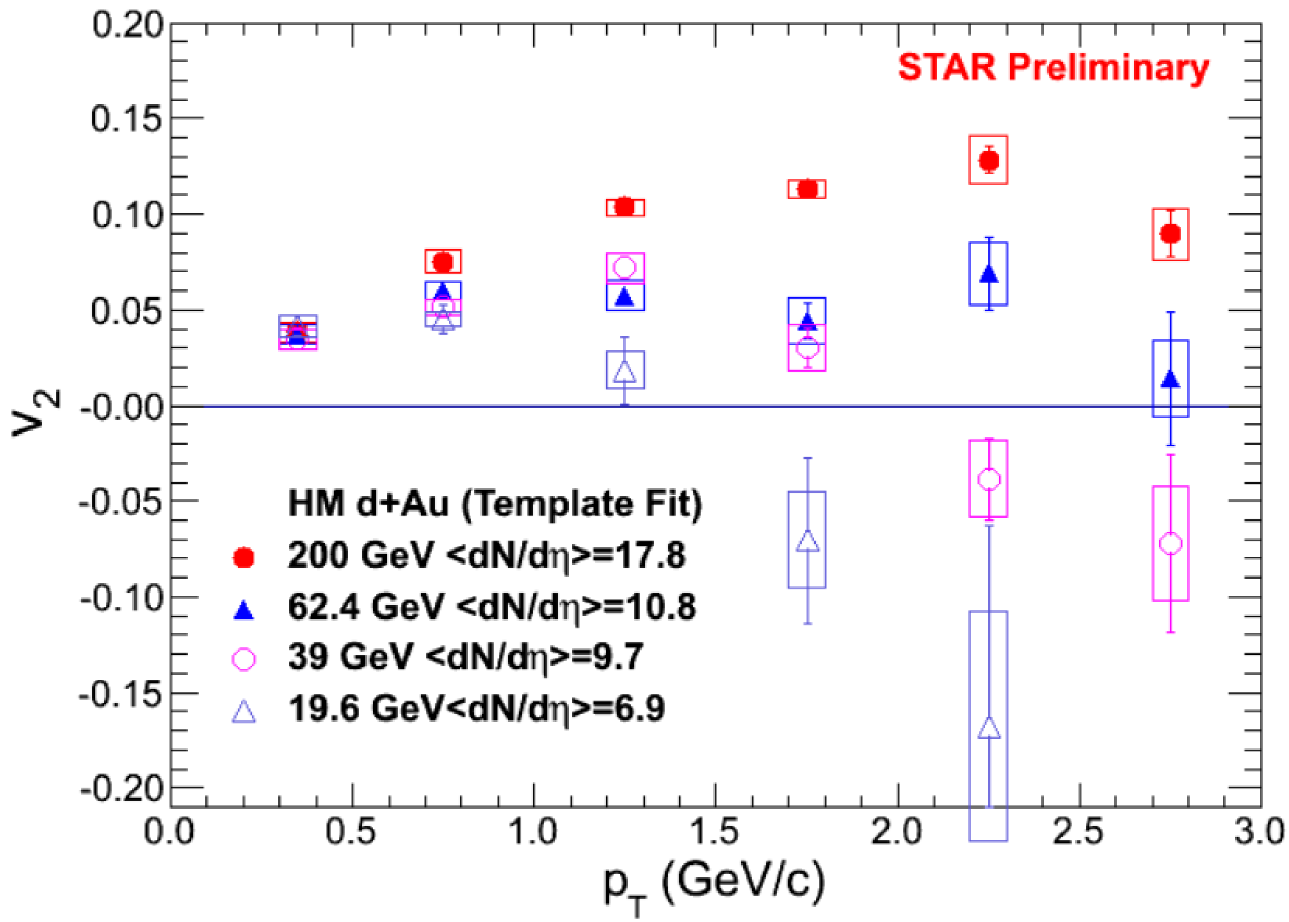
v_2 from subtraction method is **negative** at lower collision energies (different kinematics between near-side and away-side jet-like correlations?)

v_2 from template fit **increases** with collision centrality

3) Small systems

v_2 becomes **negative** at high transverse momentum in d+Au collisions at low collision energy

The correlation from away-side jet is **stronger** at high transverse momentum



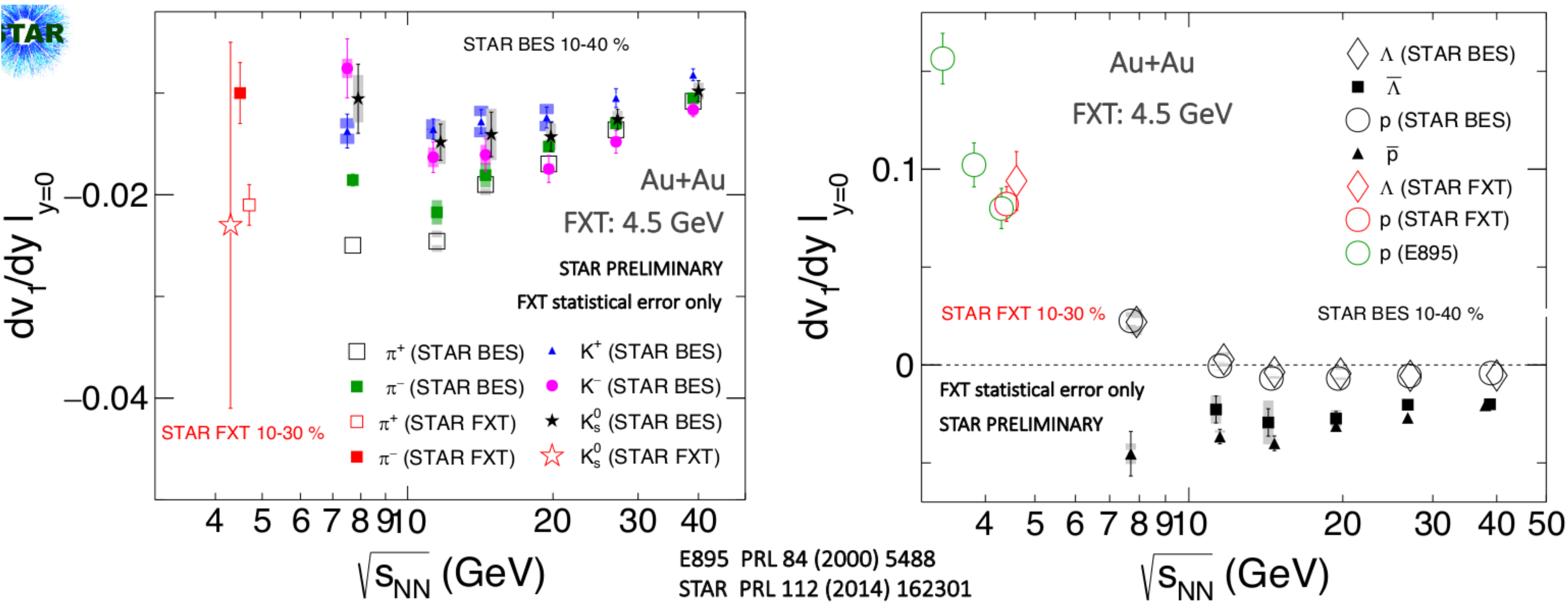
3) Small systems

Large **difference** between v_2 from two methods has been observed at low energy → large uncertainties in the non-flow subtraction in small systems.

We do see **similar v_2** between p+Au and d+Au collisions for same multiplicity → v_2 is not only driven by initial geometry.

The integral v_2 extracted by a template fit shows an **universal** trend as a function of $\langle dN/d\eta \rangle$ for different small systems at different energies → multiplicity plays an important role in small systems.

3) Fixed target mode



Directed flow for identified particles **agrees** with AGS results.

6) Hipertriton