Collective Flow in Nucleus-Nucleus Collisions at NICA and FAIR Energies

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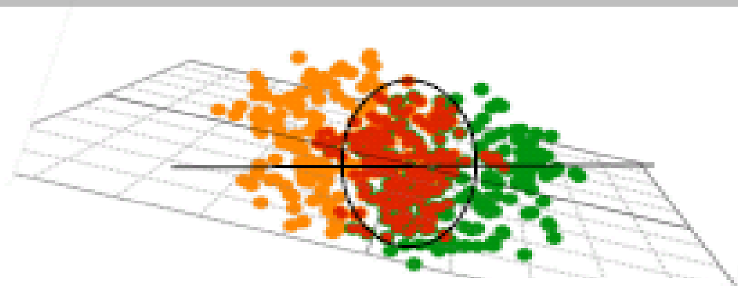
Many thanks to the Organizers!

II International Workshop on Simulations of HIC for NICA energies, JINR, Dubna, 16 - 18 April, 2018

OUTLINE

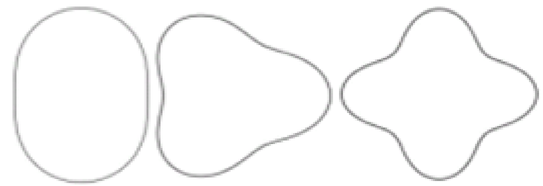
1) Introduction: V_n measurements and QGP
2) RHIC BES: Directed flow (V_1) and EOS
3) RHIC BES: Elliptic (V_2) and Triangular (V_3)
4) Flow results at SPS, AGS and SIS18.
5) Prospects for measurements in 2018-2019
6) Performance study for NICA experiments

Anisotropic Flow at RHIC/LHC - methods



Interactions

Density gradients

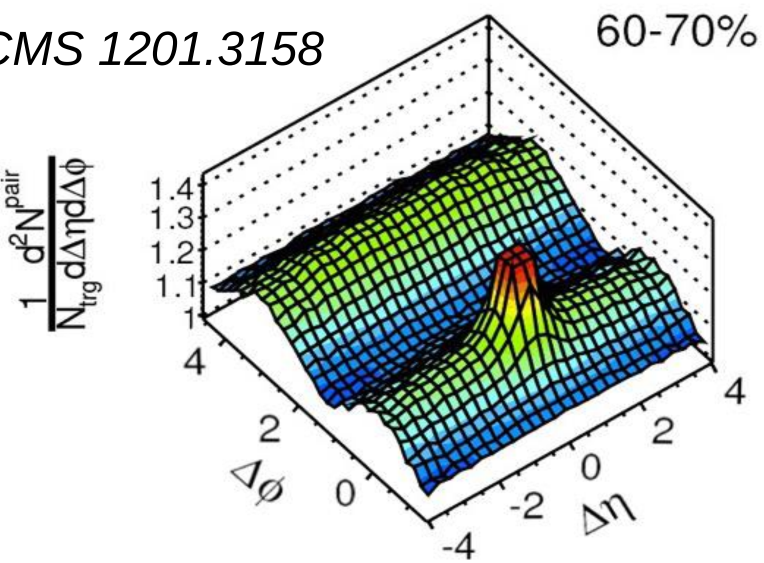


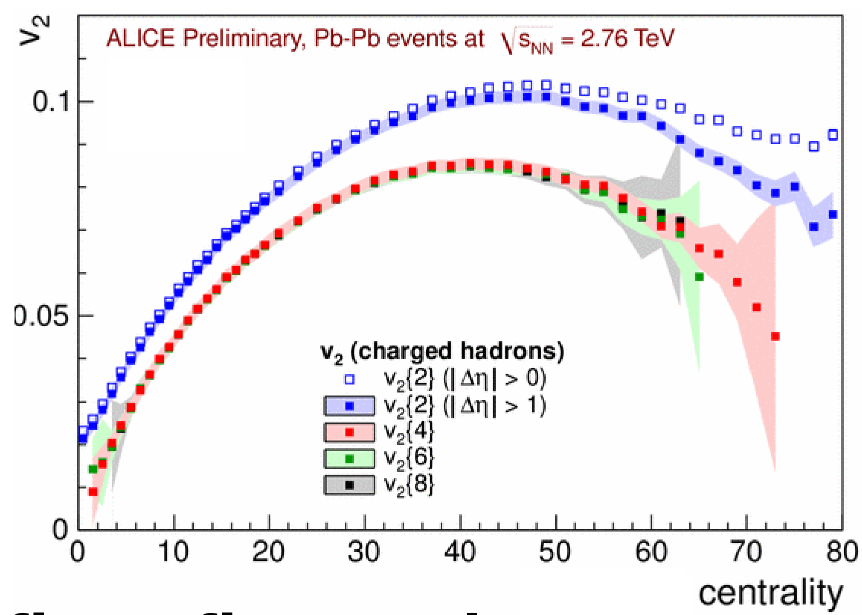
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}}$$

$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

Initial eccentricity (and its attendant fluctuations) ε_n drive momentum anisotropy v_n with specific viscous modulation

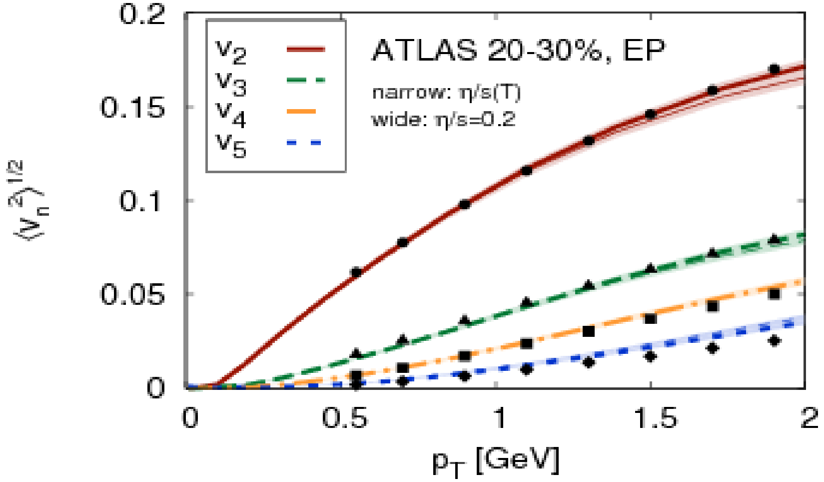
CMS 1201.3158

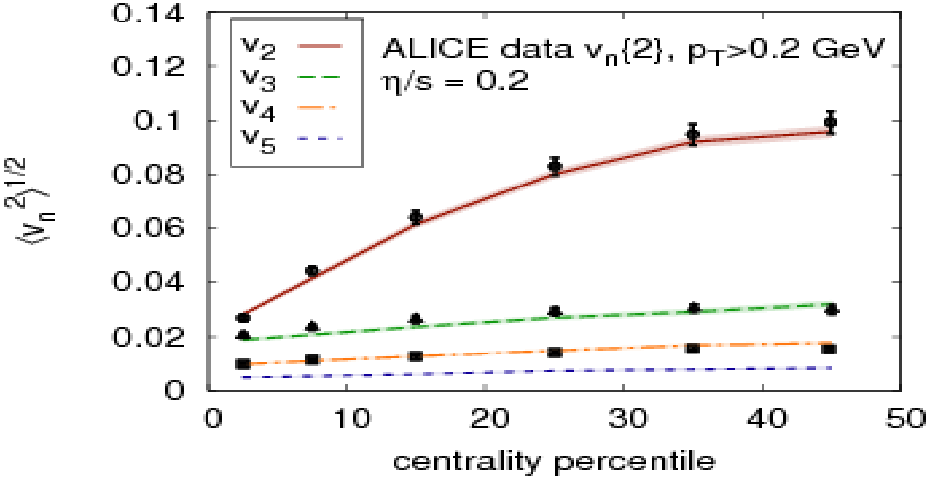




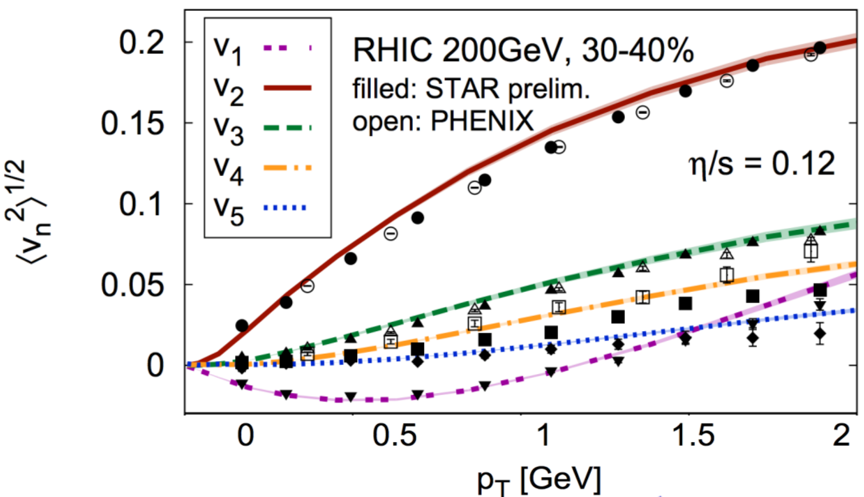
Different methods, non-flow, fluctuations

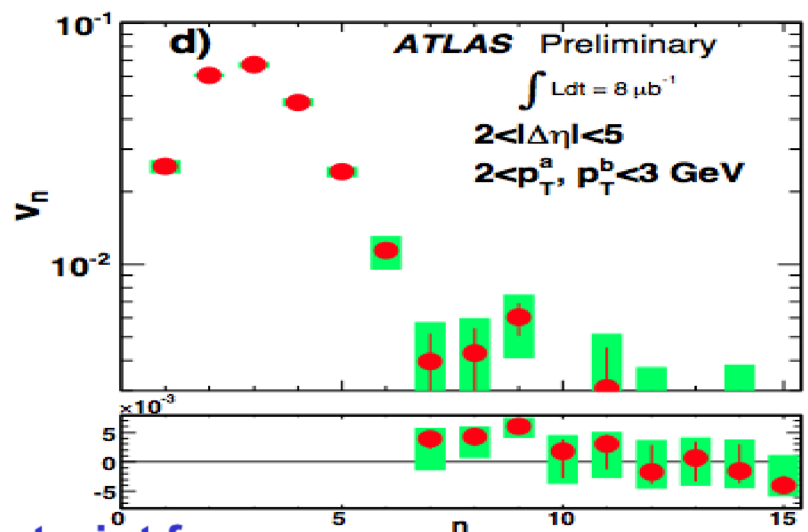
Anisotropic Flow at RHIC/LHC – Data vs Models





Gale, Jeon, et al., Phys. Rev. Lett. 110, 012302





- ✓ Important constraint for
- ✓ η/s (T,μ)
- ✓ ζ/s (T,μ)

Scaling properties of flow and correlations

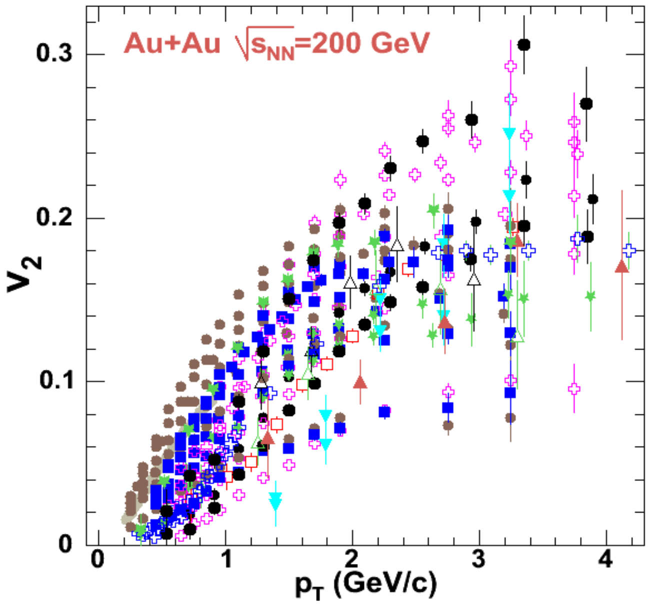
A. Bonasera, L.P. Csernai , Phys.Rev.Lett. 59 (1987) 630-633

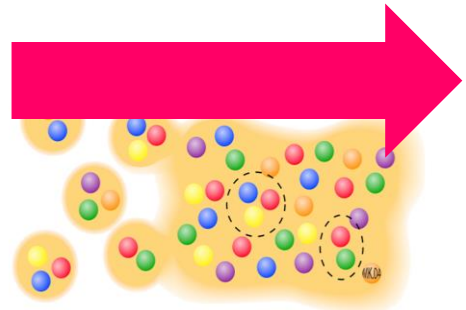
The general features of the collective flow could, in principle, be expressed in terms of scale-invariant quantities. *…the particular differences arising from the different initial conditions, masses, energies, etc. , can be separated from the general fluid-dynamical features. . ….*

W. Reisdorf, H.G. Ritter Ann.Rev.Nucl.Part.Sci. 47 (1997) 663-709 :

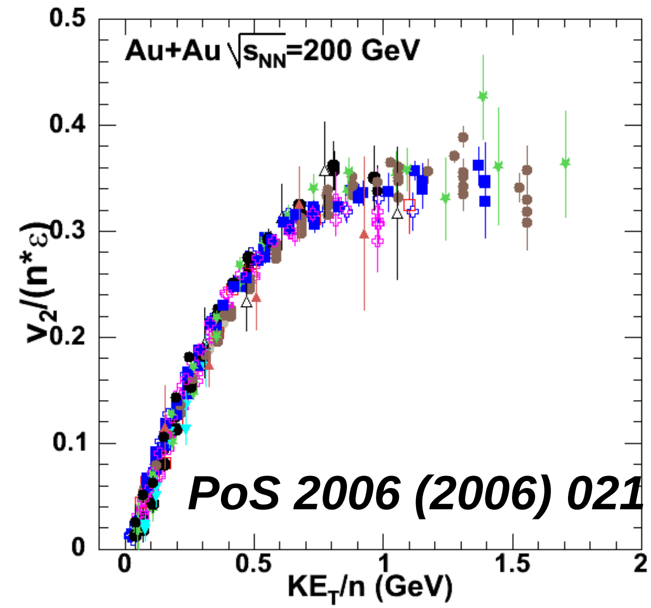
There is interest in using observables that are both coalescence and scale-invariant. *They allow comparison with theories that are limited to making predictions for single-particle observables. Under certain conditions the evolution in nonviscous hydrodynamics does not depend on the size of the system nor on the incident energy, if distances are rescaled in terms of a typical size parameter, such as the nuclear radius. Momenta and energies are rescaled in terms of the beam velocities, momenta or energies.*

Anisotropic Flow at RHIC/LHC – scaling relations



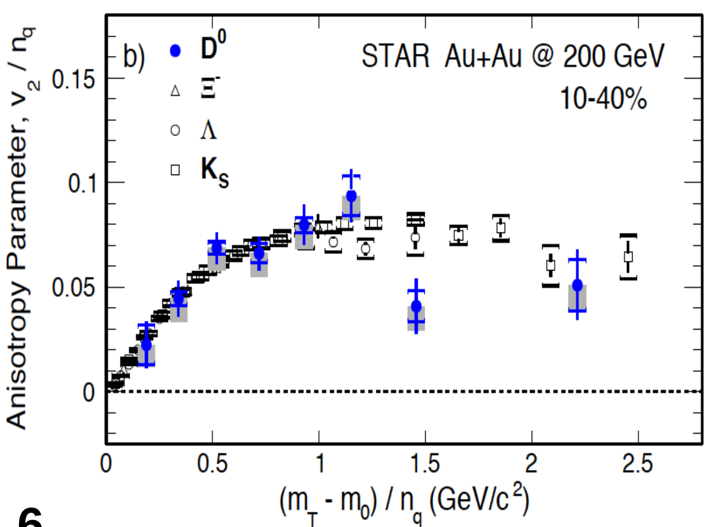


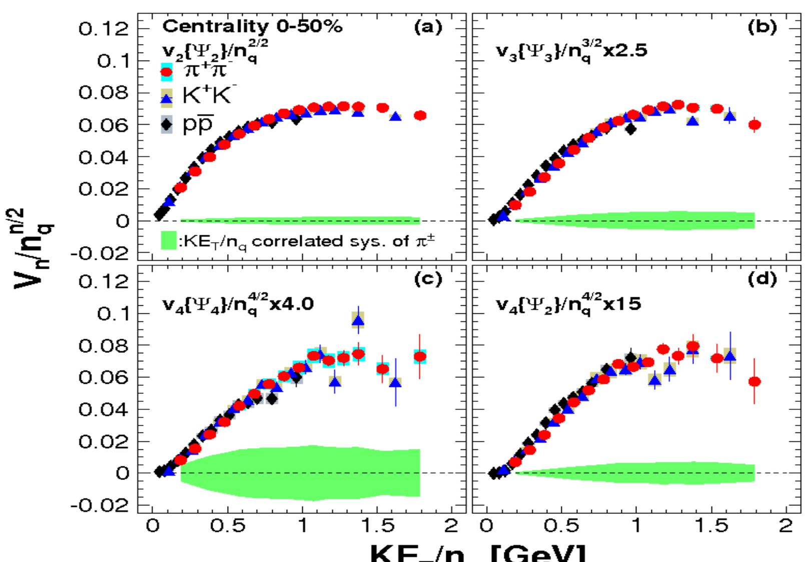
n=2 for mesons
and
n=3 for baryons



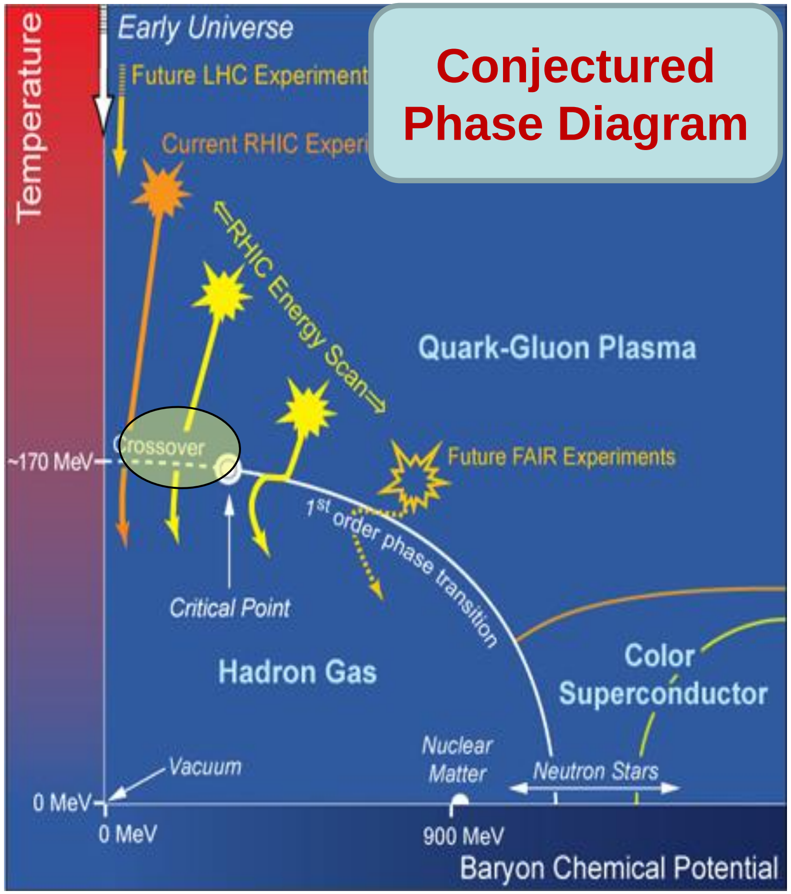
PRL118 (2017) 212301

Phys. Rev.C.93.051902(R)





Quantitative study of the QCD phase diagram



Validation of the crossover transition leading to the sQGP

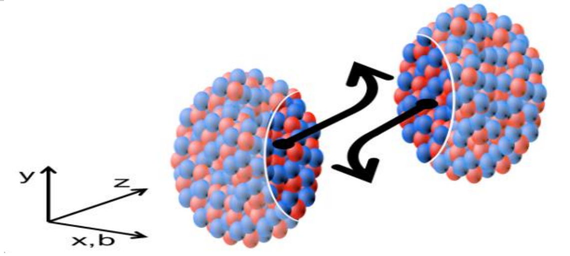
→ Necessary requirement for CEP

Strategy for RHIC BES1:

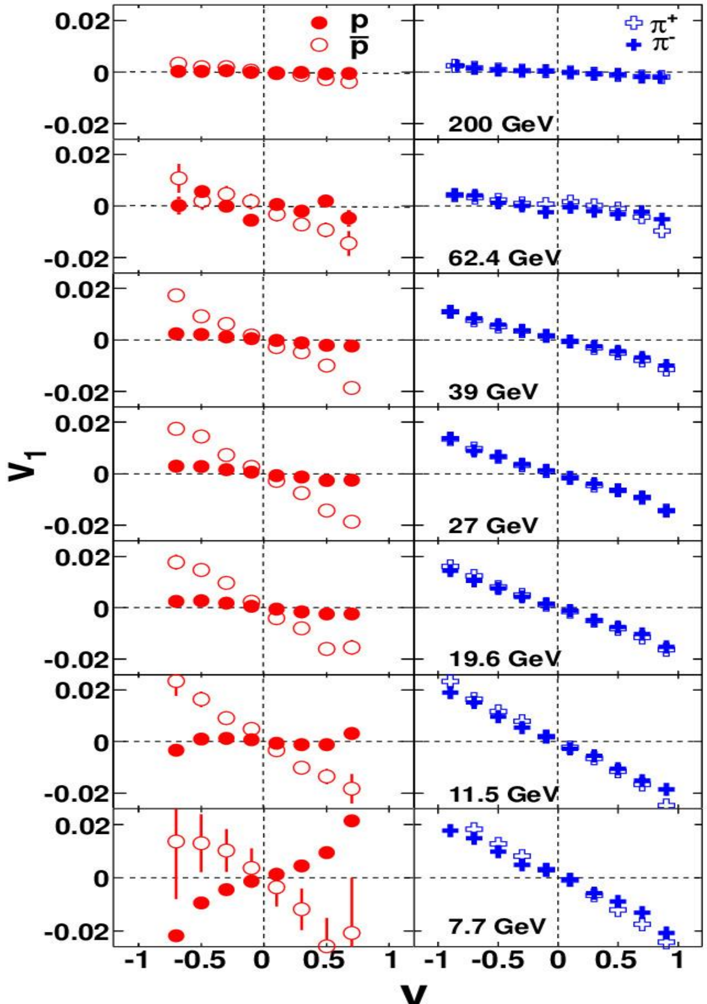
- Map turn-off of QGP signatures
- Location of the Critical End Point (CEP)?
- Location of phase coexistence regions?
- 1st order phase transition signs
- Detailed properties of each phase?

$$\frac{\eta}{s}(T,\mu),\ \frac{\zeta}{s}(T,\mu),\ c_s(T),\ \hat{q}(T),\ \alpha_s(T),\ \text{etc}$$

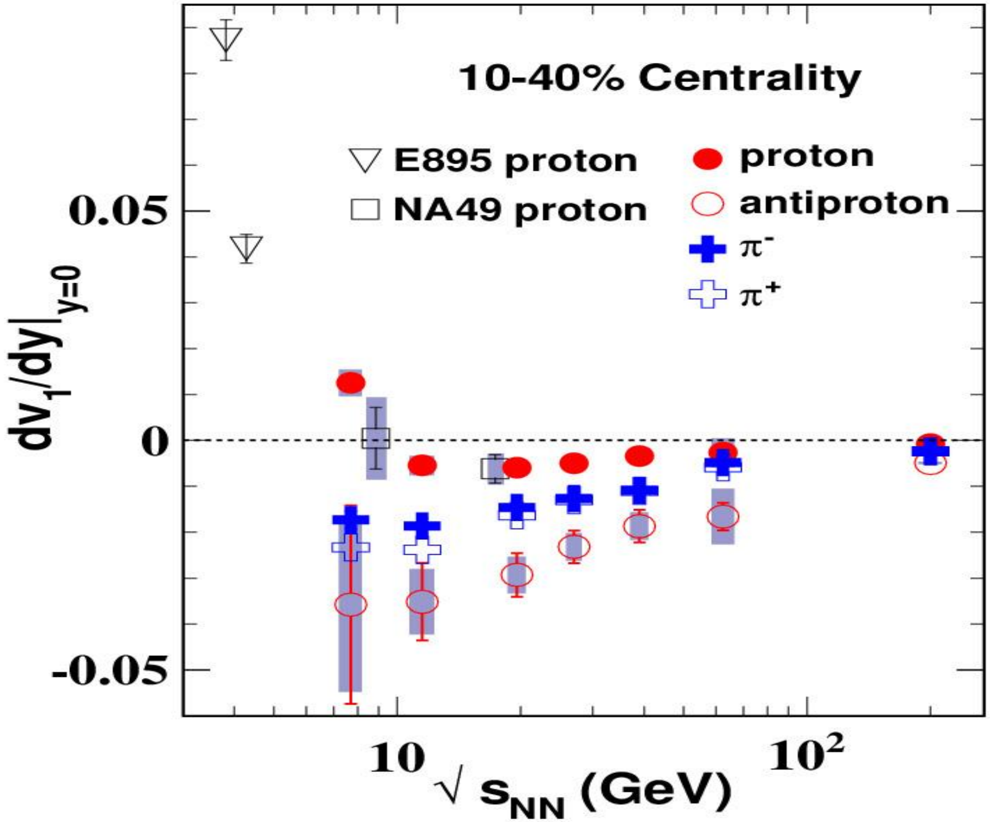
Beam Energy Dependence of Directed Flow (v_1)



- *Generated during the nuclear passage time (2R/γ) – sensitive to EOS*
- *RHIC 200 GeV (2R/γ) ~ 0.1 fm/c*
- *AGS: 3-4.5 GeV (2R/γ) ~ 9-5 fm/c*

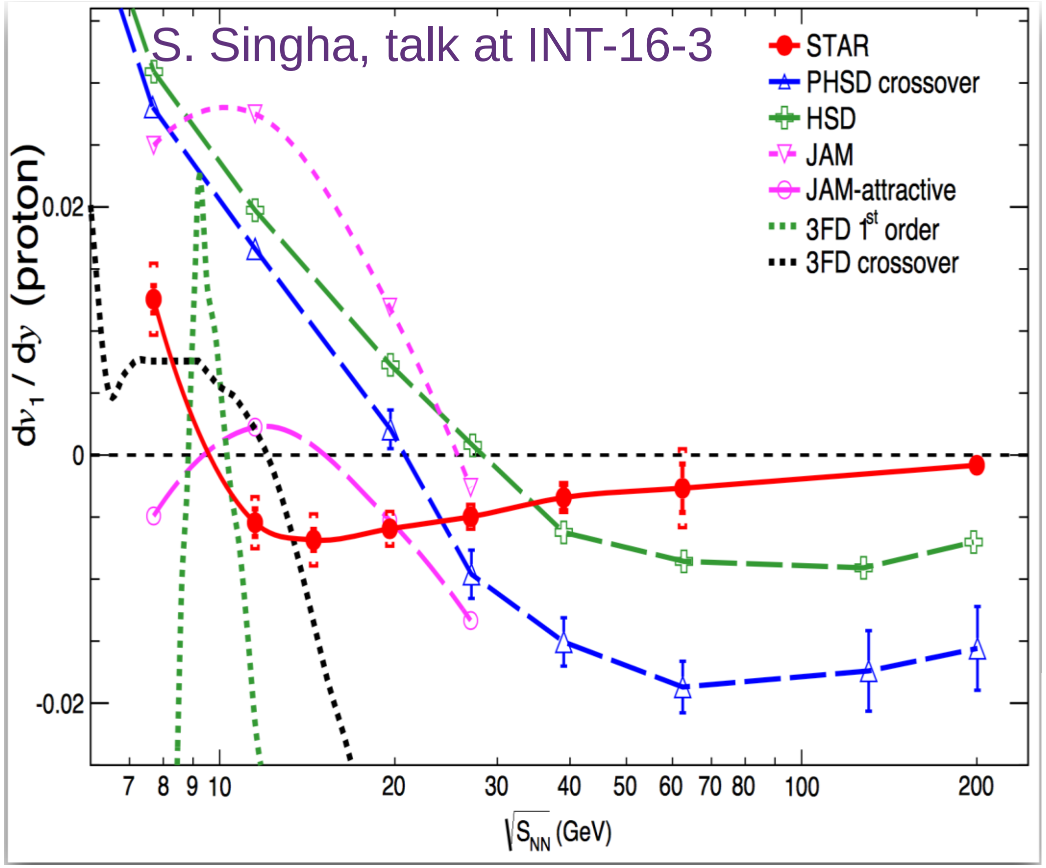


STAR: Phys.Rev.Lett. 112 (2014)



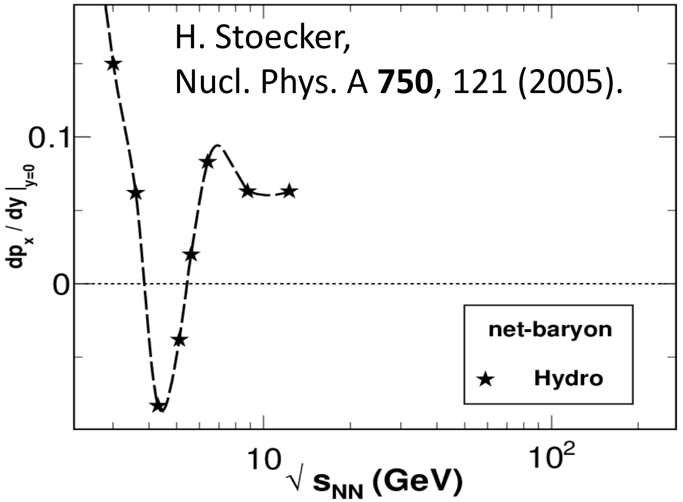
Trend observed by STAR inline with NA49 and E895 data

Beam Energy Dependence of Directed Flow (v_1)



Minimum in slope of directed flow (dv_1/dy) as a function of beam energy for baryons may suggest sudden softening of EOS - sign of the 1st order phase transition

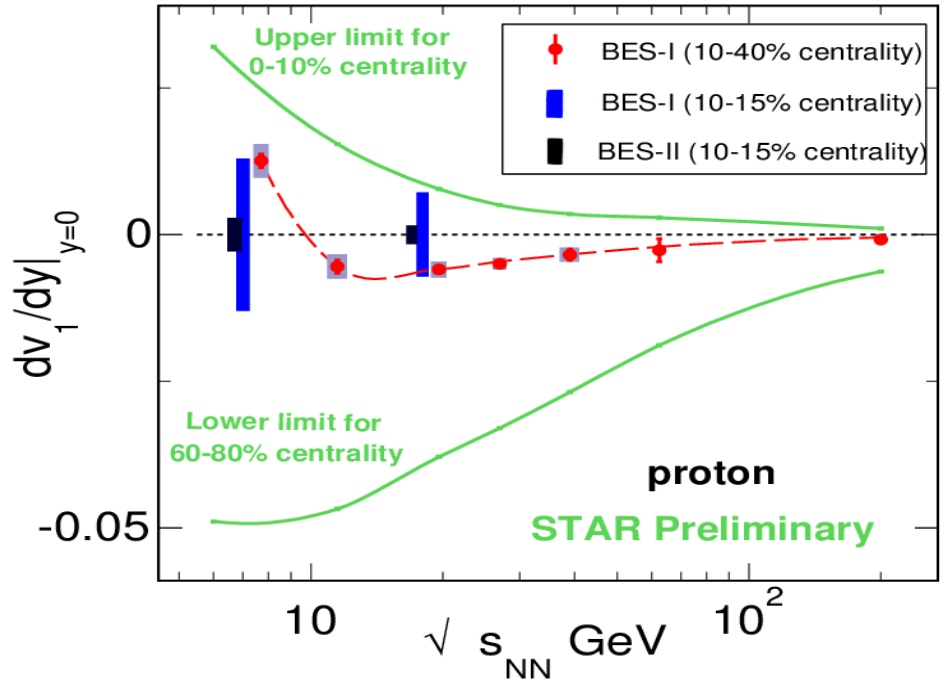
Proton v_1 probes interplay of baryon transport and hydro behavior



None of the models explains the data

- ***Systematics associated with the models is quite large***

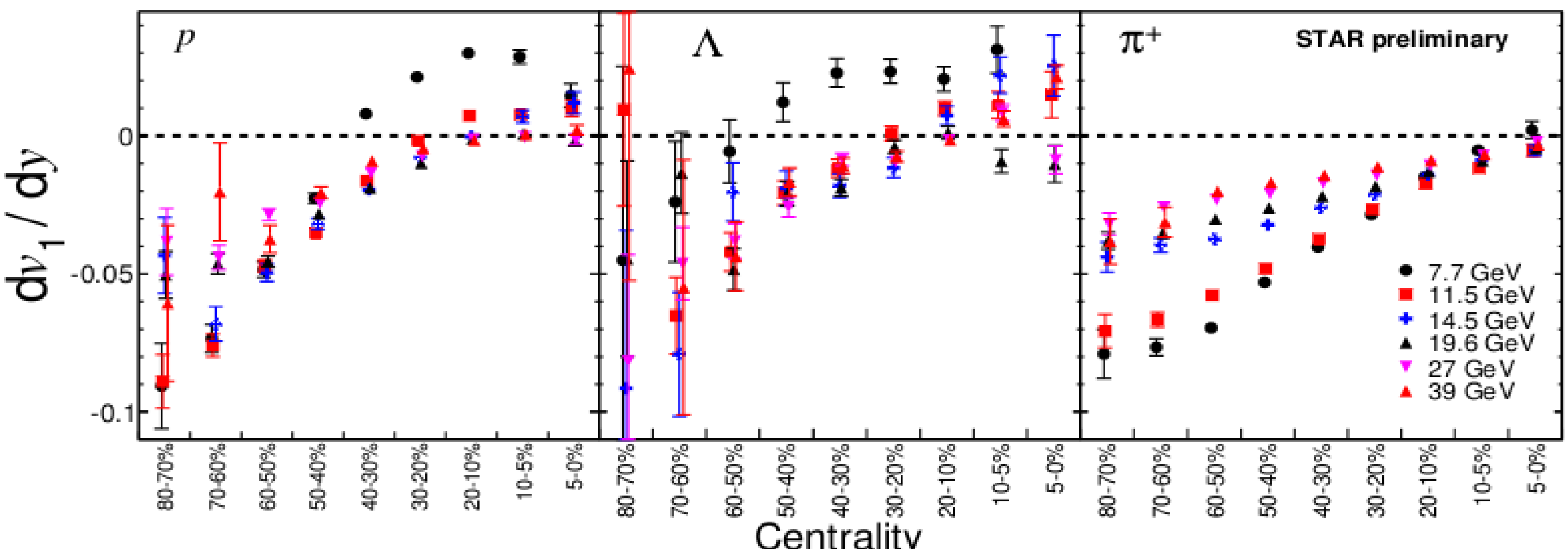
Centrality Dependence of Directed Flow (v_1)



1. Strong centrality dependence
2. Complicated Pt dependence
3. Non-linear terms are important for non-central collisions

STAR Preliminary, QM2015

Nucl.Phys. A956 (2016) 260-263



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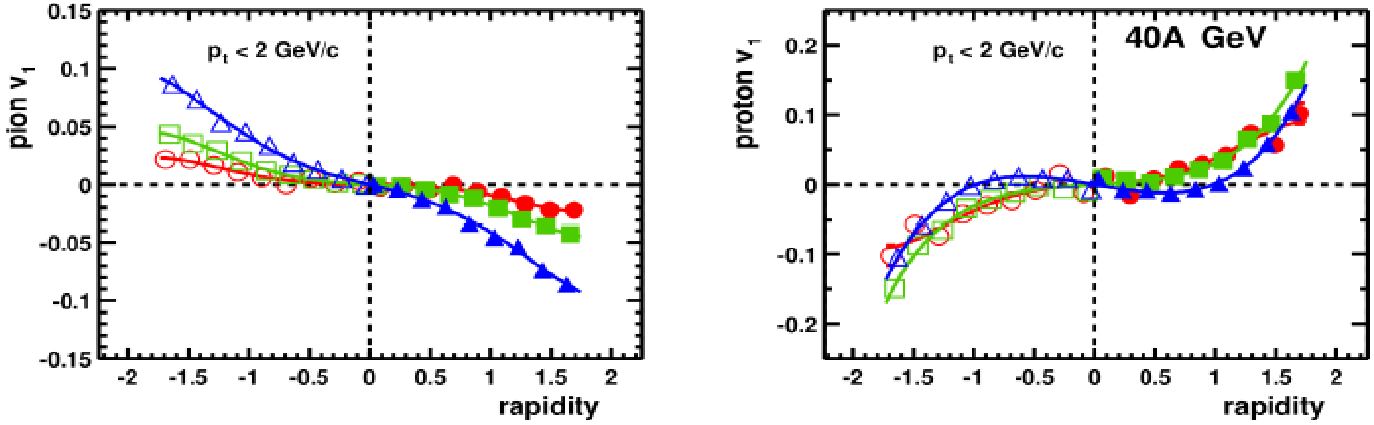
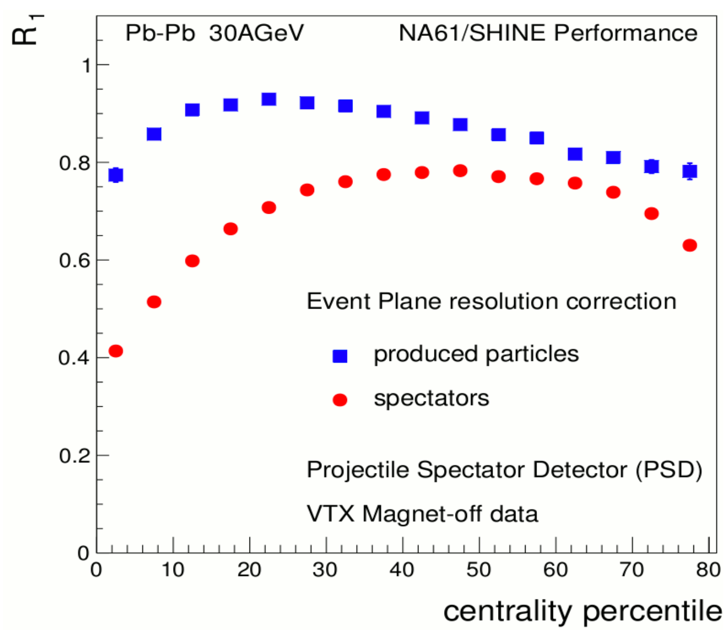
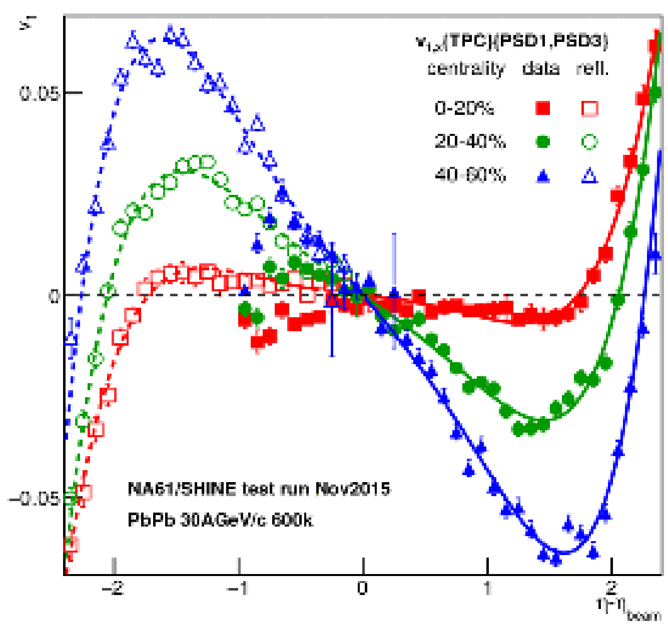
Prospects for directed flow measurements: NA61/SHINE

*Phys Rev C **68**, 034903 (2003) (NA49 Coll)*



NA49



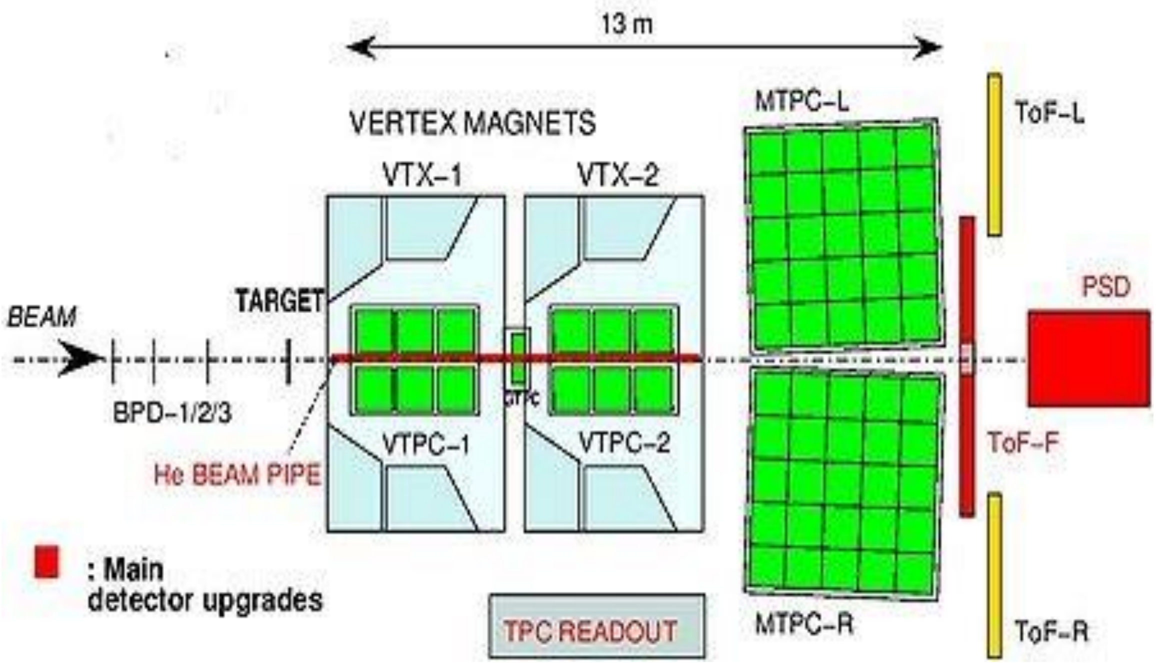


NA61/SHINE

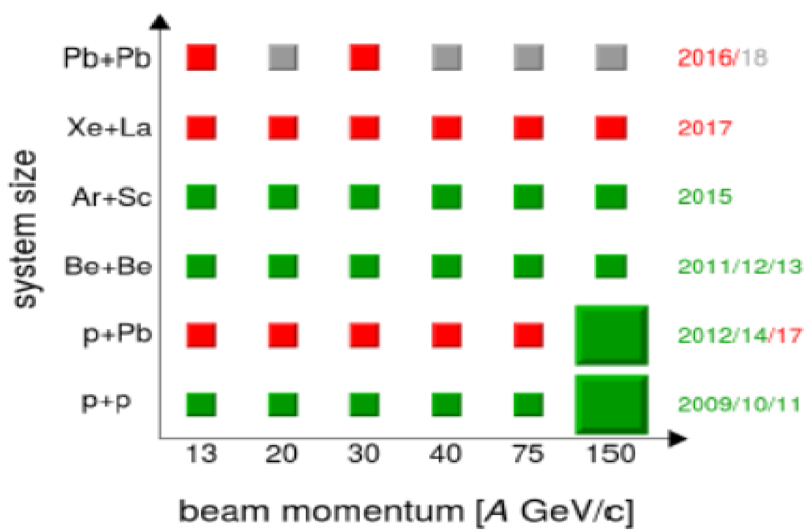
First preliminary v1 results – QM2018

Addendum to the NA61/SHINE program http://cds.cern.ch/record/2059811

Prospects for directed flow measurements: NA61/SHINE



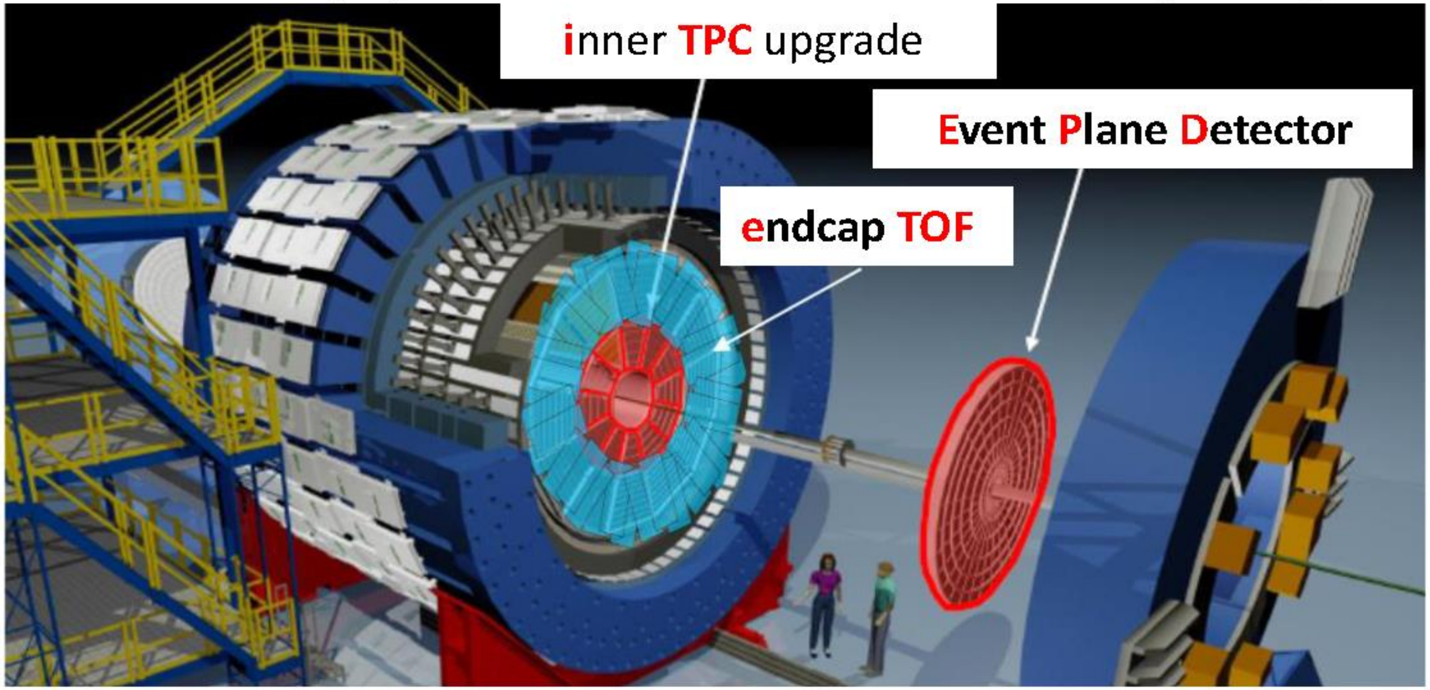
INR RAS + MEPhI



- Results will be important for flow measurements at BM@N, MPD (NICA) and CBM(FAIR)

- Different colliding systems – study the effect of spectator matter

The STAR Upgrades and the FXT program



iTPC Upgrade:
- Improves tracking and acceptance
- Ready in 2019

Star Note 0644 : Technical Design Report for the iTPC Upgrade

EndCap TOF Upgrade:
- Improves PID and acceptance
- Ready in 2019

https://arxiv.org/pdf/1609.05102.pdf

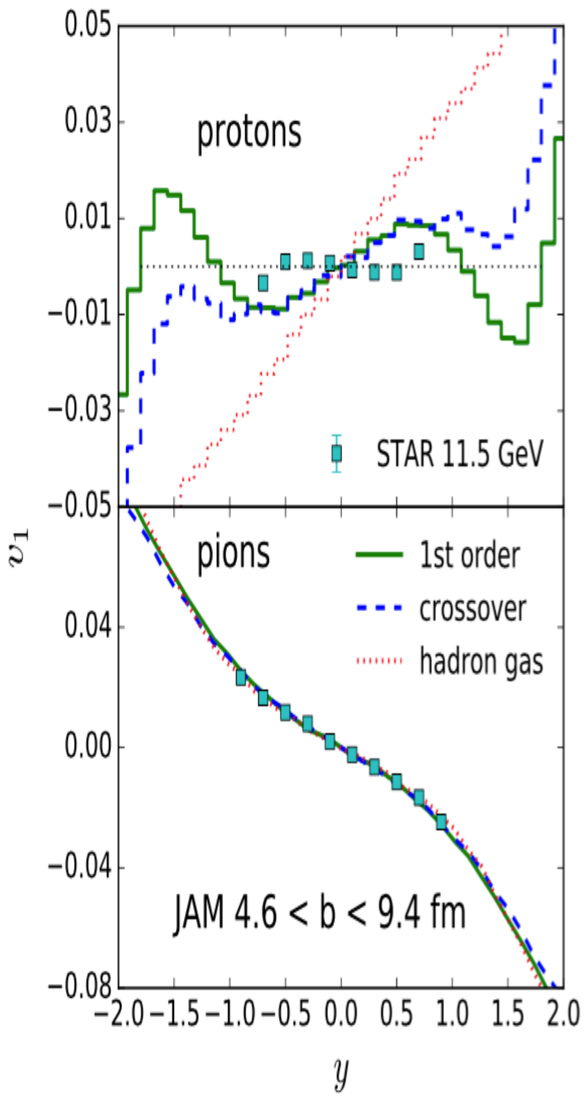
EPD Upgrade:
- Improves event plane resolution and centrality definition
- Ready in 2018

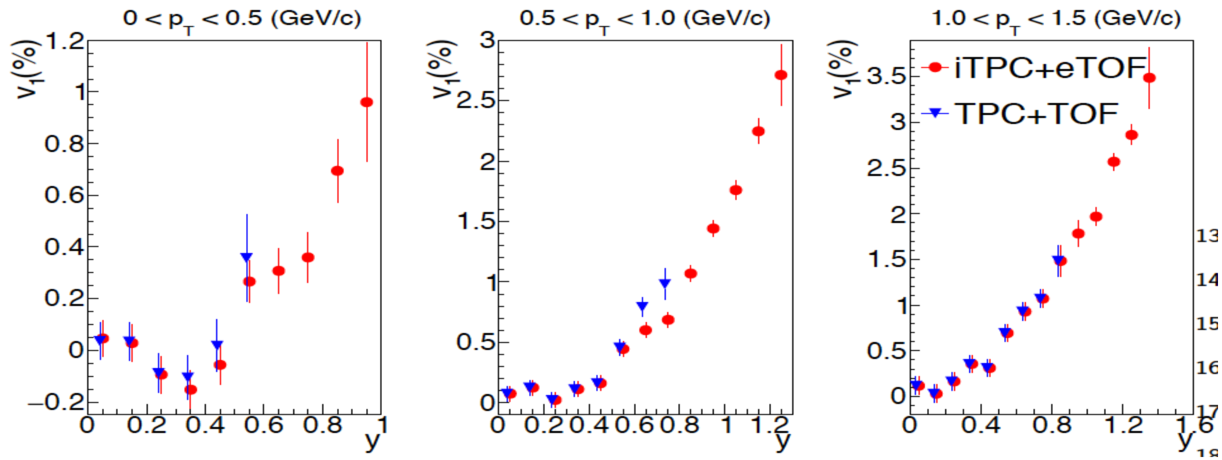
Star Note 0666 : An Event Plane Detector for STAR

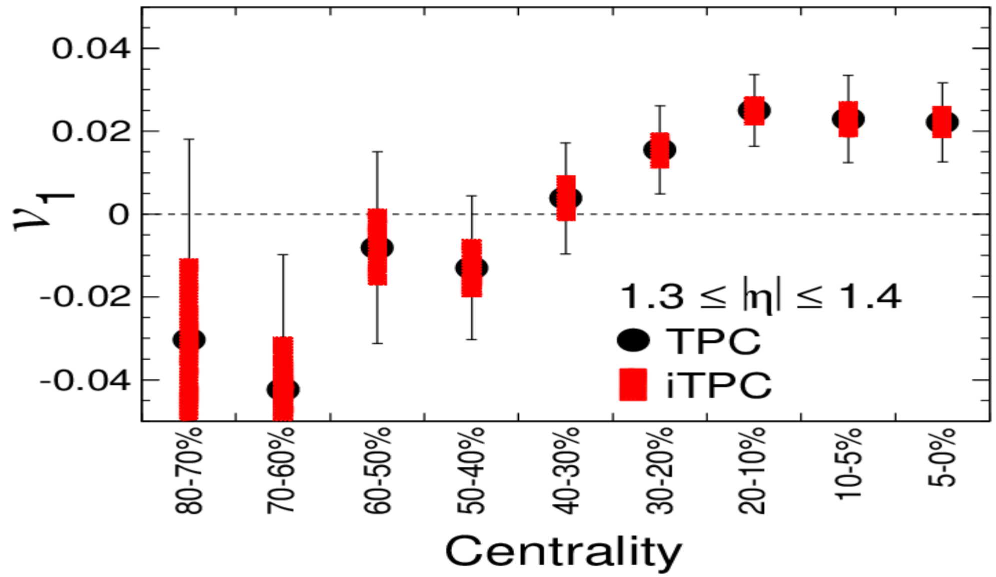
Prospects for directed flow measurements: STAR BES2

Phys.Rev. C94 (2016)

arXiv:1609.05100







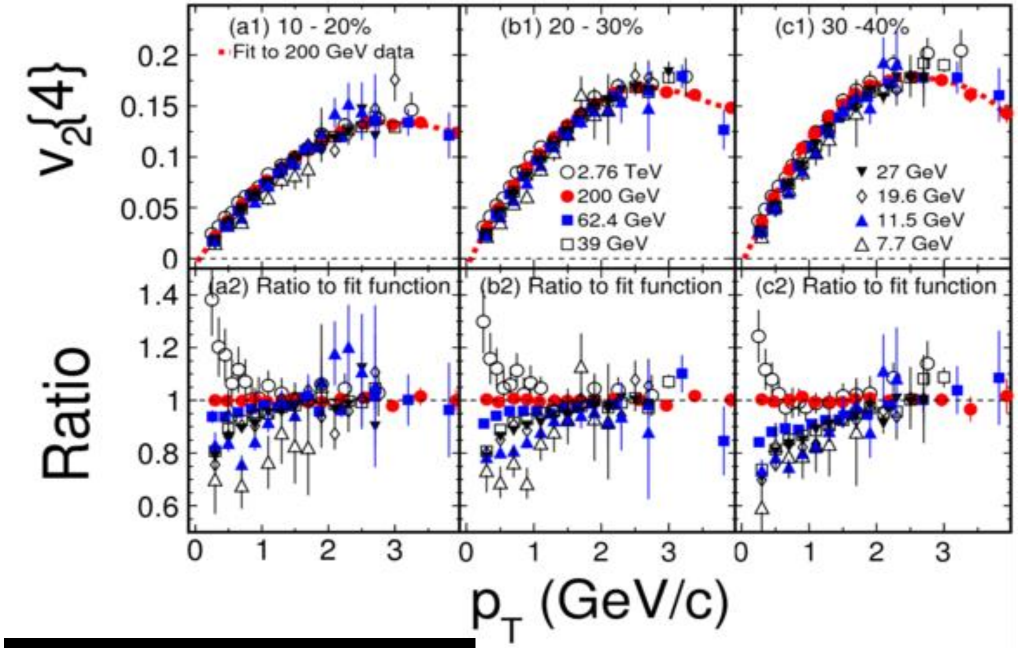
FXT in BES-II: Run 19

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

- iTPC and eTOF upgrades will be available
- Would need 100 Million Events at each energy to make the sensitivity of BES-II, 2 days per energy (3.5 GeV – 7.7 GeV)
- Data rate is DAQ limited
- Data at 7.7 GeV would provide an overlap energy with the collider mode

Beam Energy Dependence of Elliptic Flow (v_2)

STAR: Phys. Rev. C 86 (2012) 54908



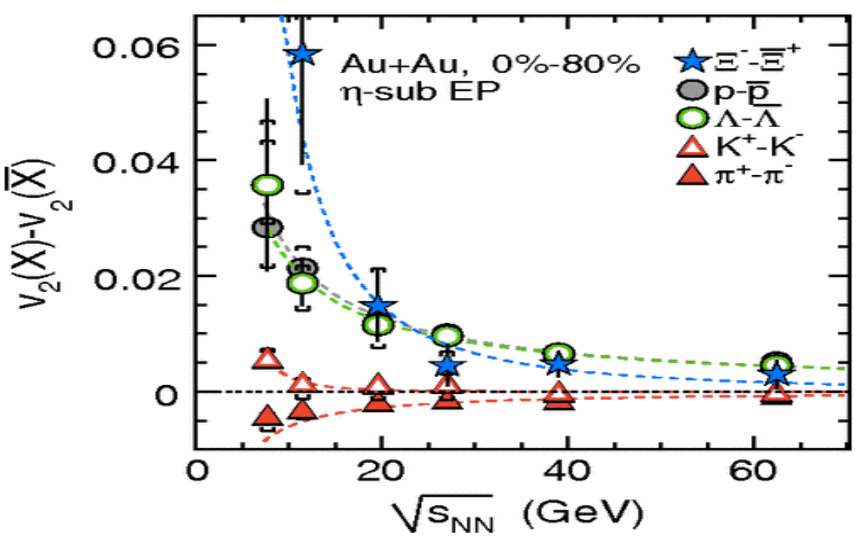
Surprisingly consistent as the energy changes by a factor ~400

Initial energy density changes by nearly a factor of 10

No evidence from v2 of charged hadrons for a turn off of the QGP

How sensitive is v_2 to QGP?

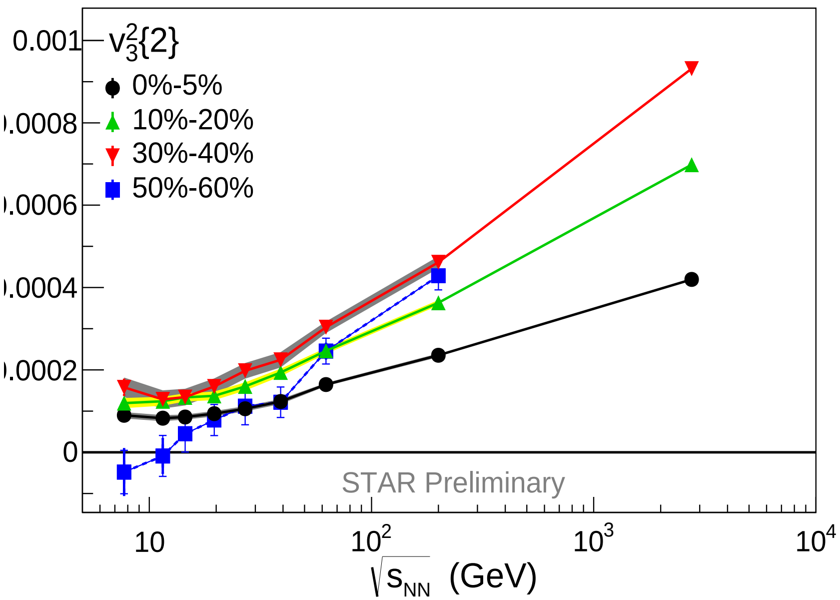
Phys. Rev. Lett. 110, 142301 (2013)

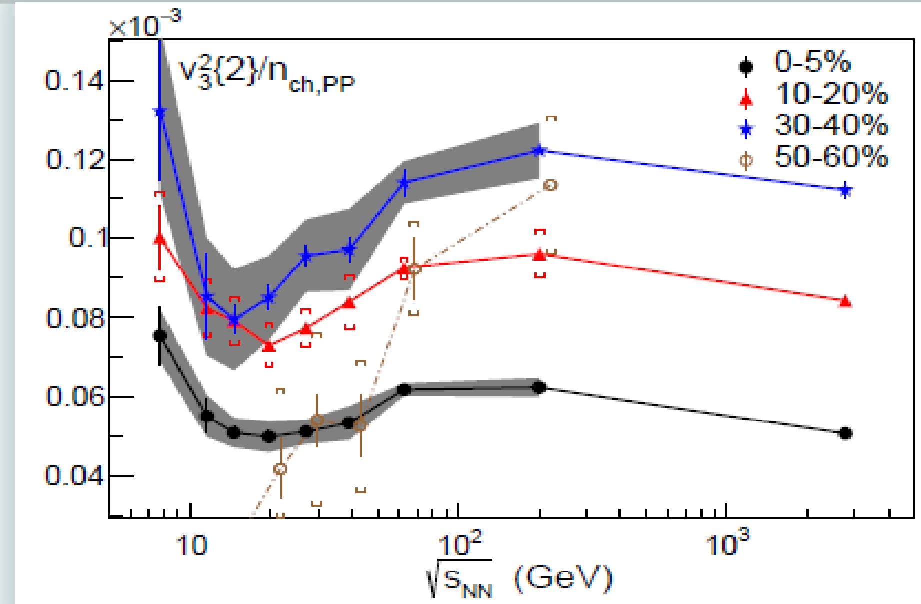


Substantial particle-antiparticle split at lower energies

- The number of quark scaling in elliptic flow is broken at low energies
- Do ϕ-mesons or multi-strange particles deviate?

Beam Energy Dependence of Triangle Flow (v_3)



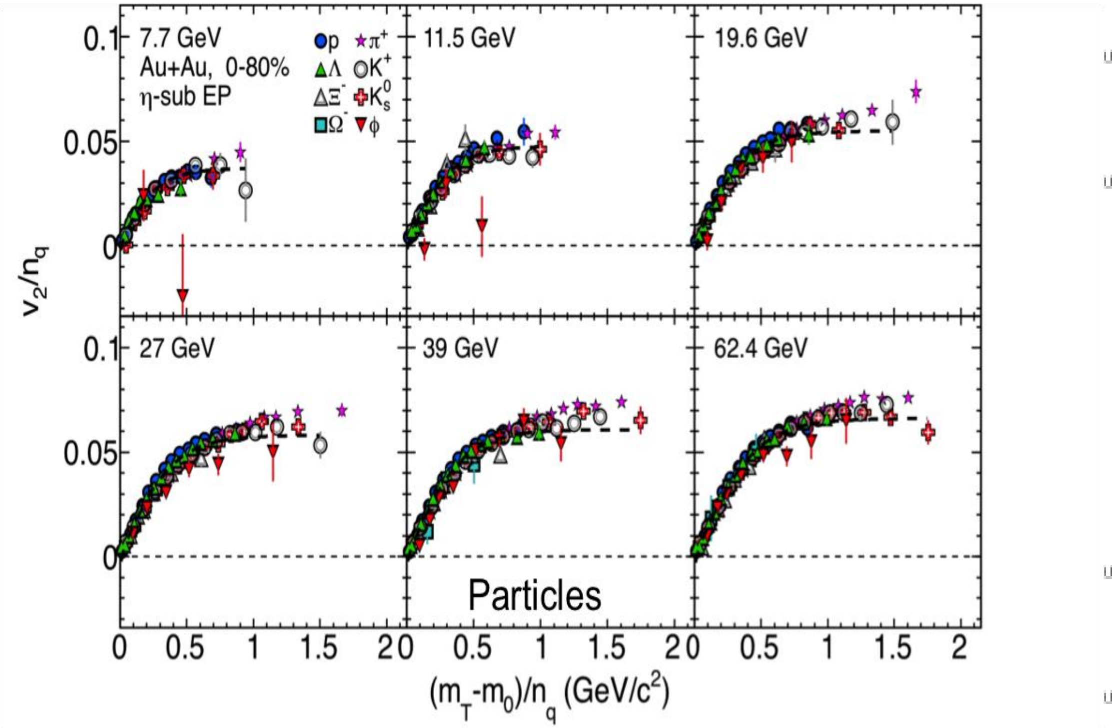


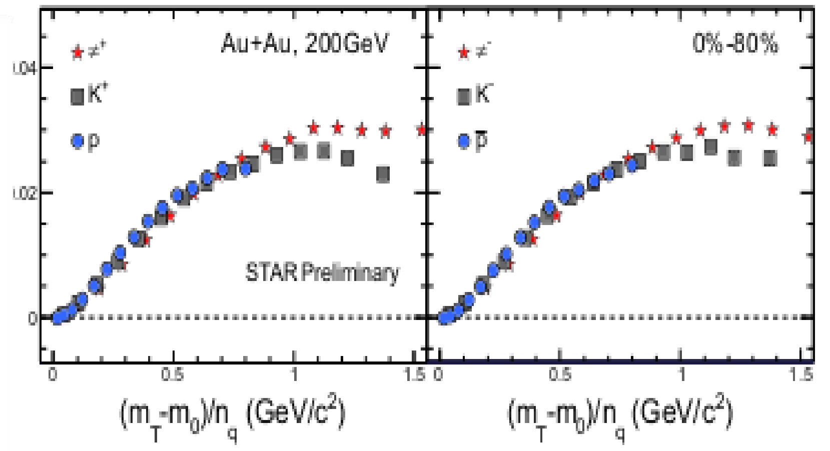
Models show that higher harmonic coefficients are more sensitive to the existence of a QGP phase. In models, v_3 goes away when the QGP phase disappears *J. Auvinen, H. Petersen, Phys. Rev. C 88, 64908, B. Schenke et.al., Phys. Rev. C 85, 024901*

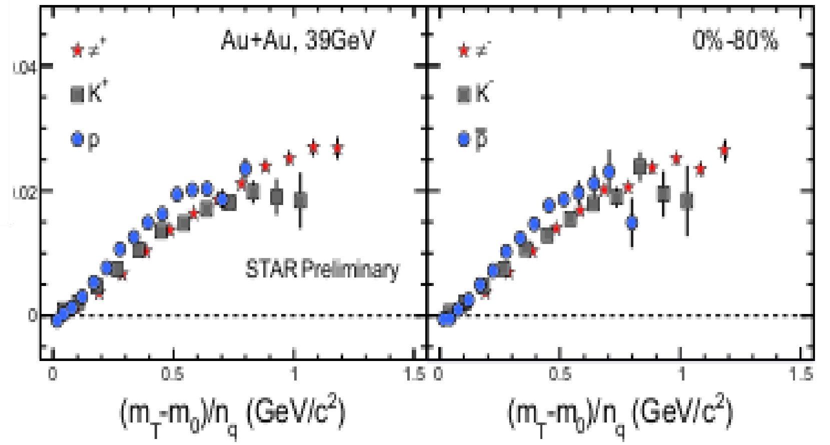
STAR results show that v_3 vanishes for peripheral collisions at lowest RHIC BES energy. Minimum are observed for centralities bins in 0-50% collisions for $v_3^2/n_{ch,pp.}$ (pseudorapidity density of charged-particle multiplicity per participating nucleon pair) (***PRL 116, 112302 (2016)***)

Prospects for (v_3) PID measurements: STAR BES 1-2

Phys. Rev. C 88, 014902 (2013)

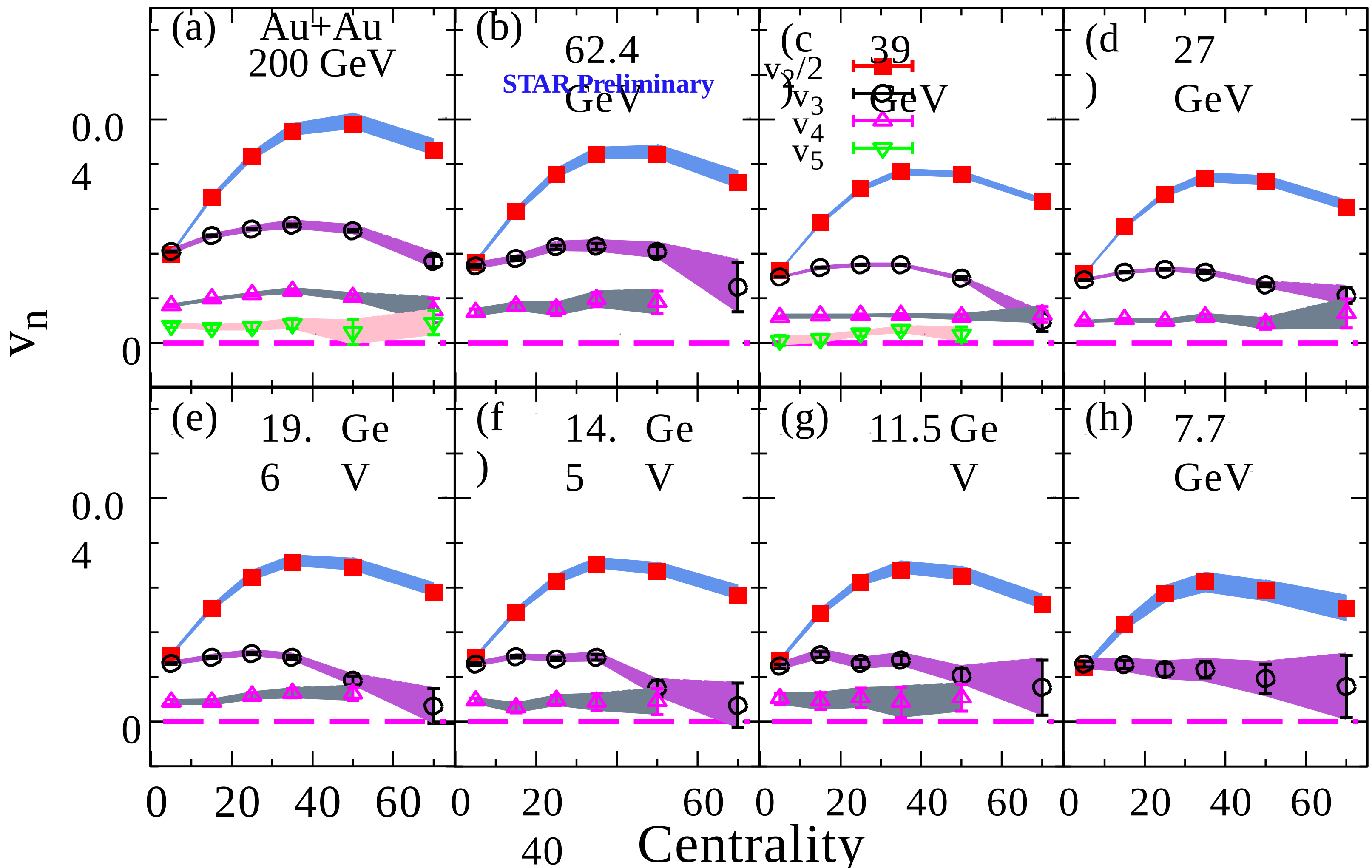






- NCQ-scaling holds for v2 of particles and anti-particles separately at all energies
- Do ϕ-mesons or multi-strange particles deviate?
- NCQ-scaling is broken for v3 of particles and anti-particles separately for < 39 GeV

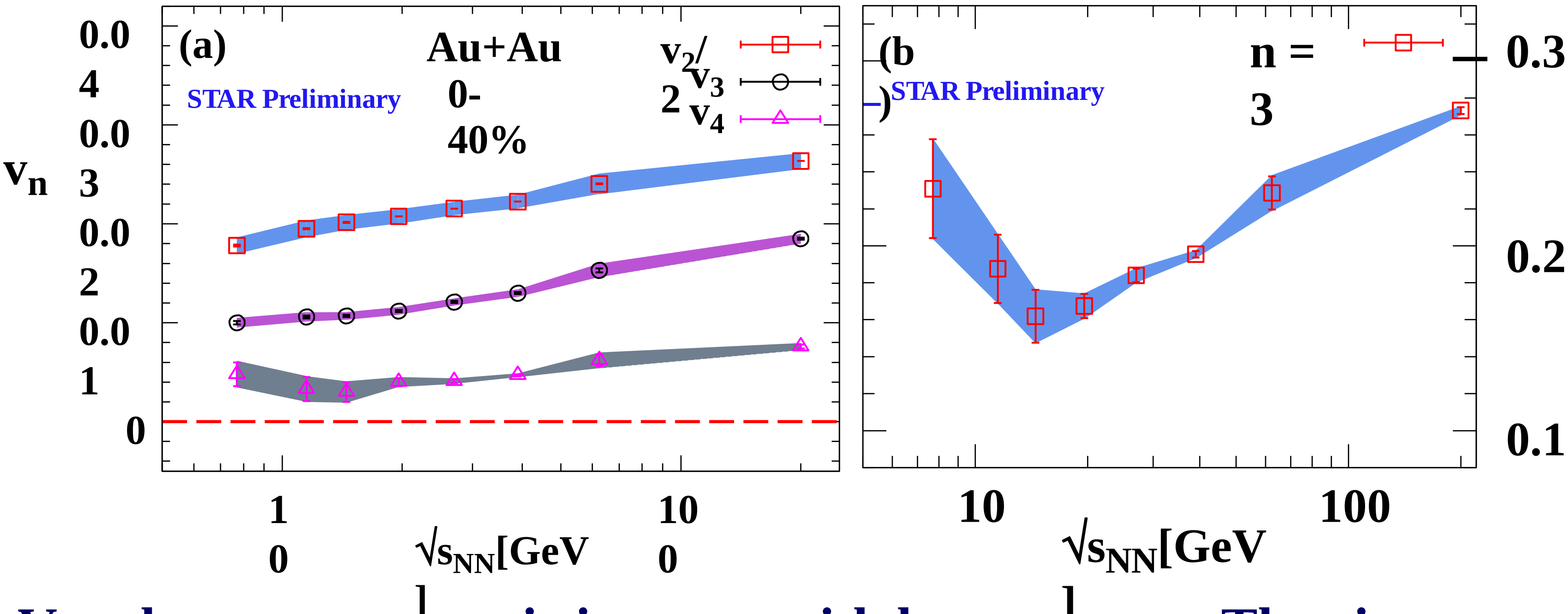
V_n (centrality) as a function of beam energy



V_n (centrality) shows the same trend for all energies from RHIC BES1: decreases with harmonic order n.

$$VC = ln\left(\frac{(v_n)^{\frac{1}{n}}}{(v_2)^{\frac{1}{2}}}\right)\left(\frac{dN}{d\eta}\right)^{\frac{1}{3}}$$

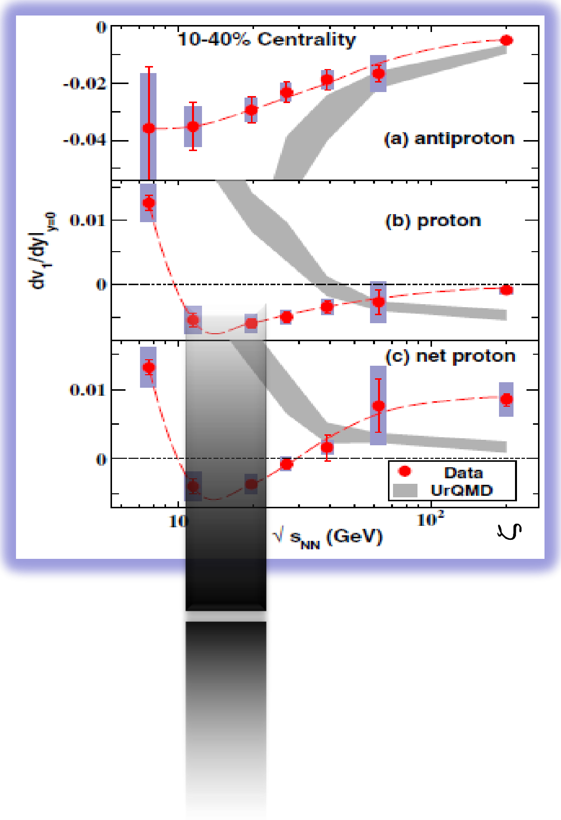
$$VC \propto \frac{\eta}{s}$$

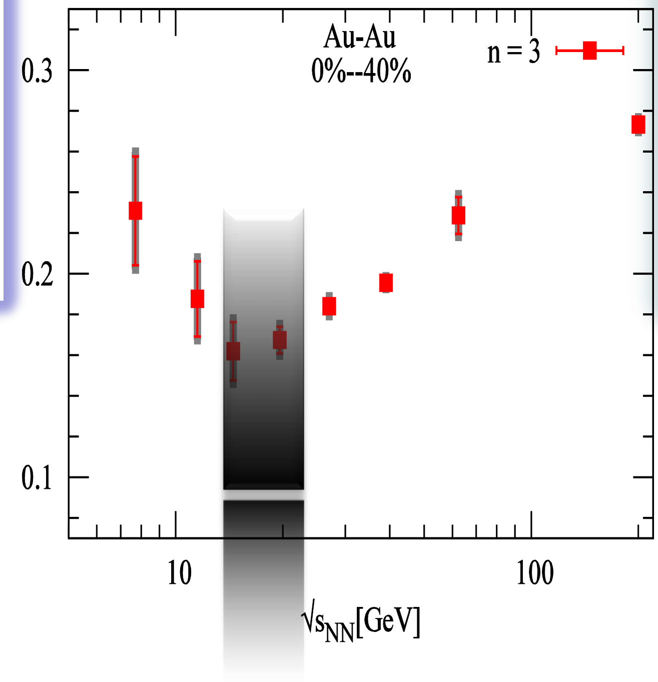


V_n shows a monotonic increase with beam energy. The viscous coefficient, which encodes the transport coefficient (η/s), indicates a non-monotonic behavior as a function of beam energy.

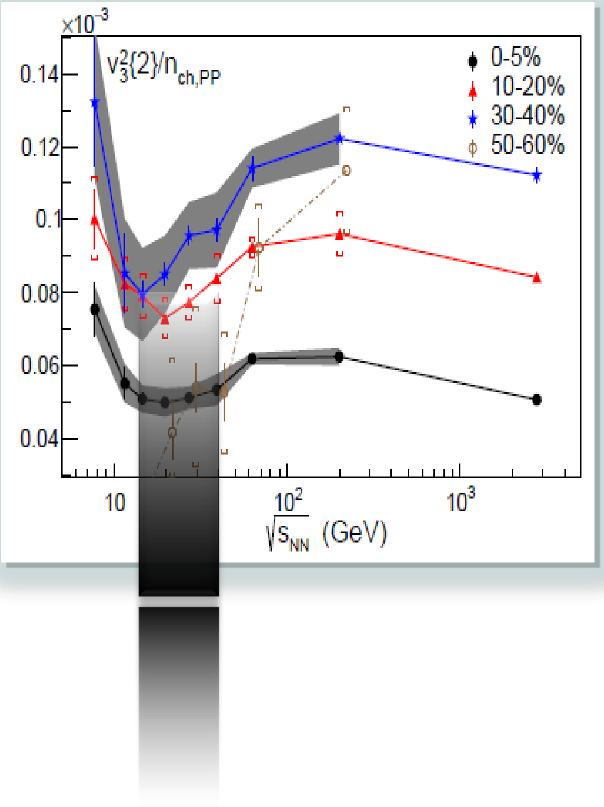
STAR data: Anomalies in the Pressure and η/s?

PRL 112,162301(2014)





PRL 116, 112302



Region of interest $\sqrt{s_{NN}} \lesssim 20$ GeV, however, is complicated by a changing B/M ratio, baryon transport dynamics, longer nuclear passing times, etc. ***Requires concerted modeling effort.***

Elliptic Flow at AGS, SIS: from in-plane to out-of-plane (1)

VOLUME 83, NUMBER 7 PHYSICAL REVIEW LETTERS 16 AUGUST 1999

Elliptic Flow: Transition from Out-of-Plane to In-Plane Emission in Au + Au Collisions

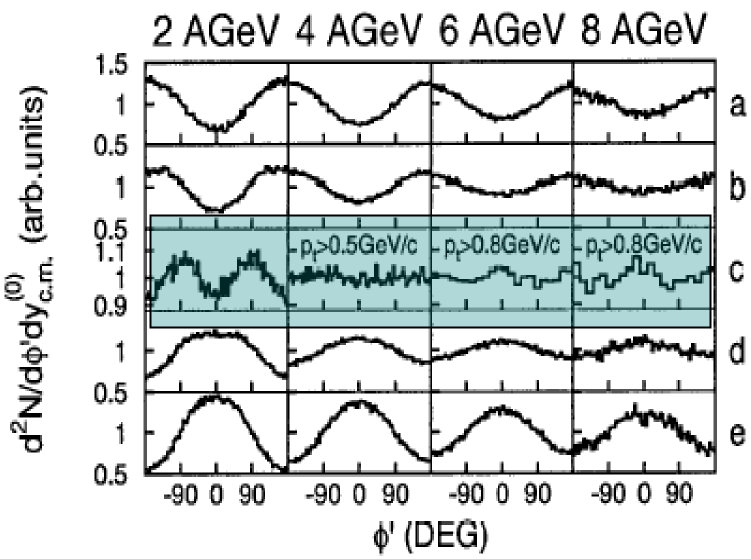
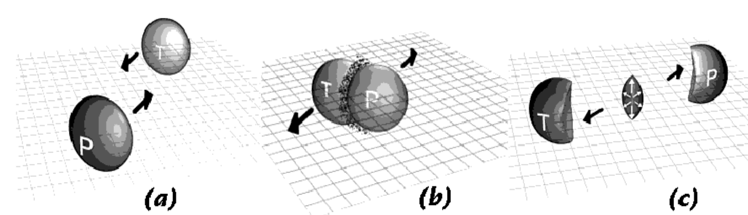
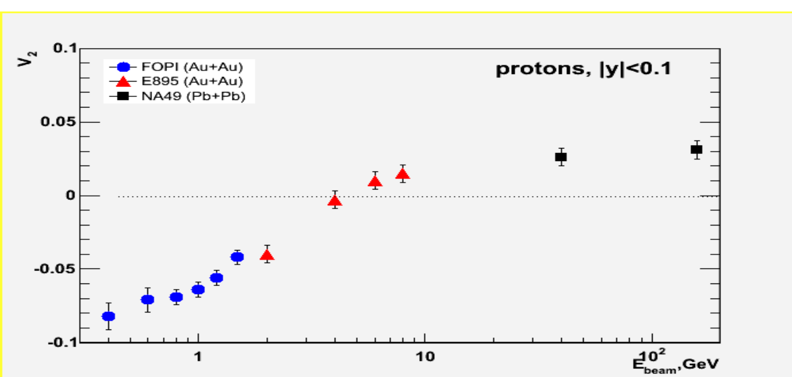
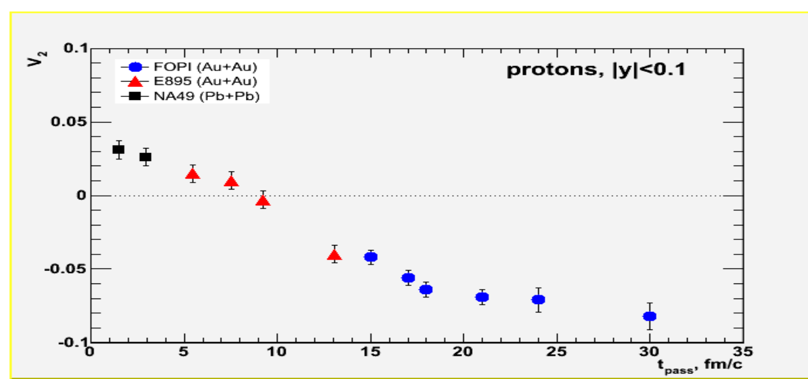


FIG. 2. Azimuthal distributions (with respect to the reconstructed reaction plane) for 2*A*, 4*A*, 6*A*, and 8*A* GeV Au + Au.

Passage time: 2R/($\beta_{cm}\gamma_{cm}$)
Expansion time: R/c_s
$c_s = c\sqrt{dp/d\varepsilon}$ - speed of sound



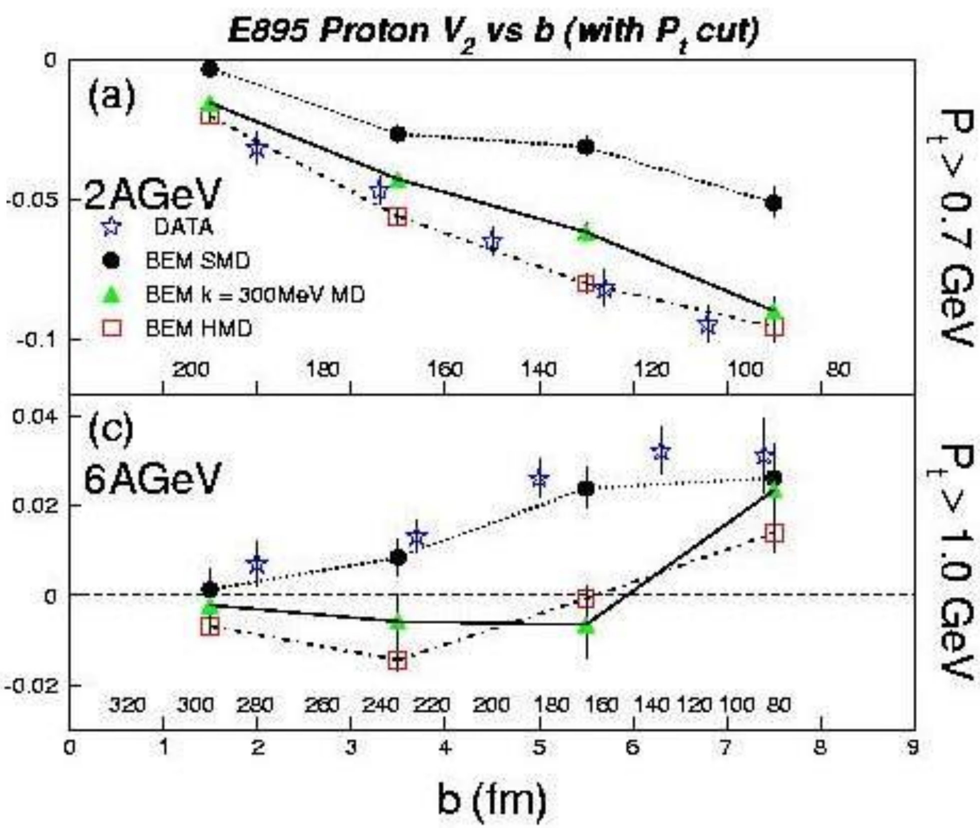


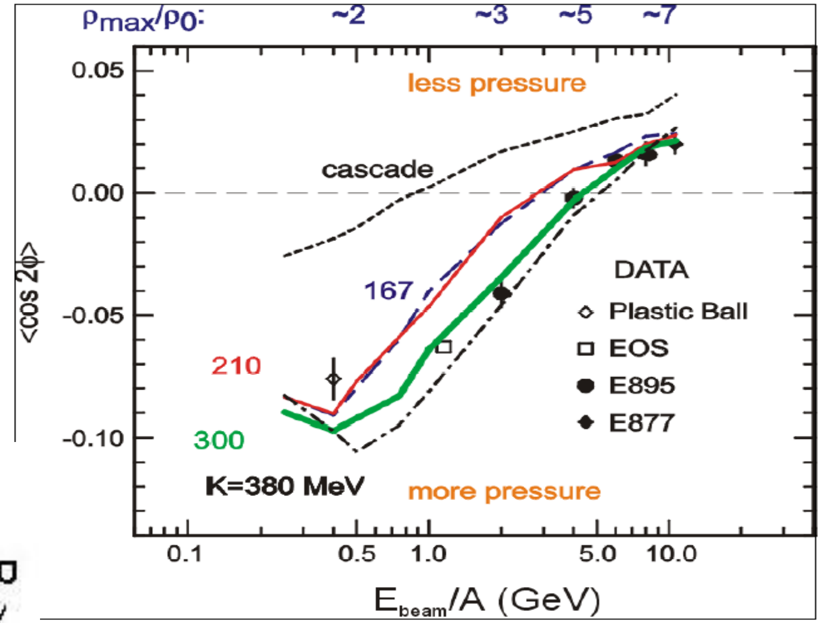


Elliptic Flow at AGS, SIS: from in-plane to out-of-plane (2)

Good Constraints for the Hadronic EOS

Differential Elliptic Flow in 2 - 6 A GeV Au + Au Collisions: Tighter Constraint for the Nuclear EOS
Phys. Rev. C **66**, 021901 (2002).

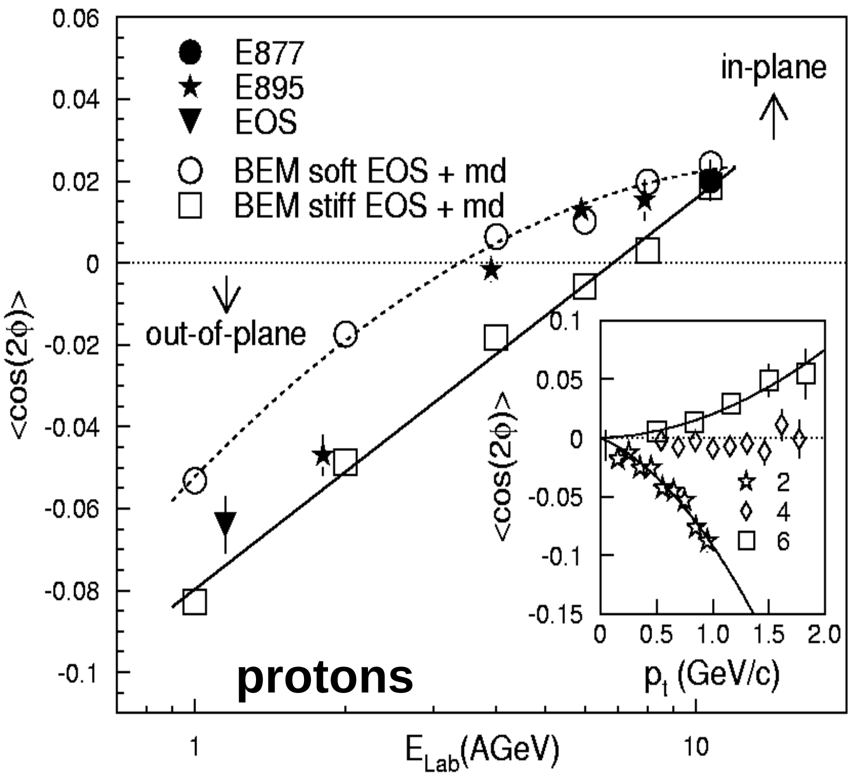




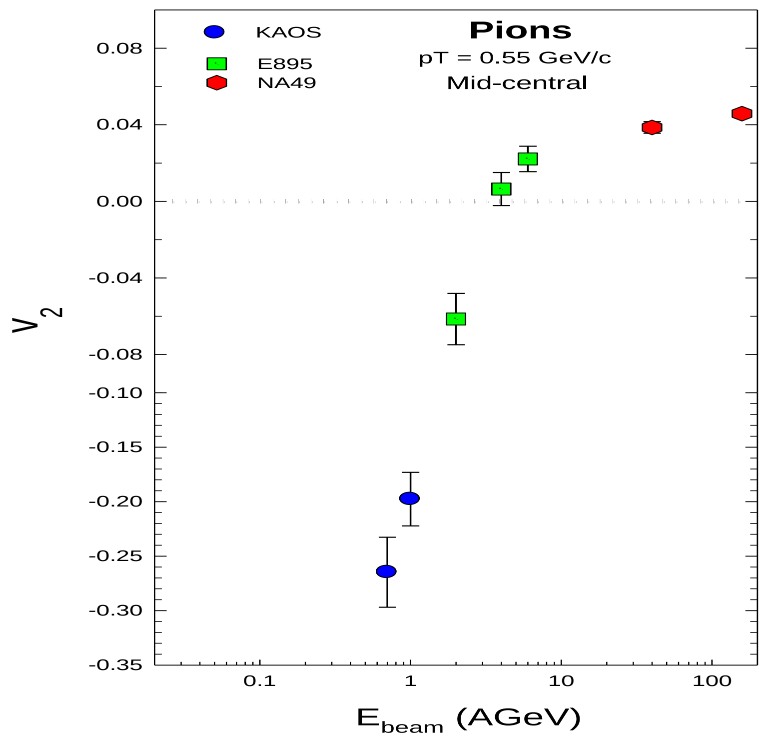
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592

v_n Flow at AGS, SIS: from in-plane to out-of-plane (3)

Phys. Rev. Lett. **83**, 1295 (1999). E895



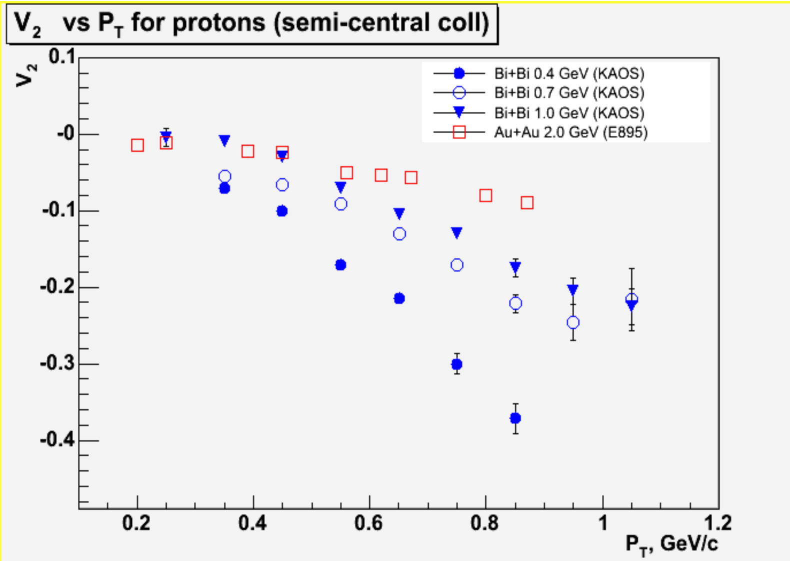
E895 preliminary ; SQM2004

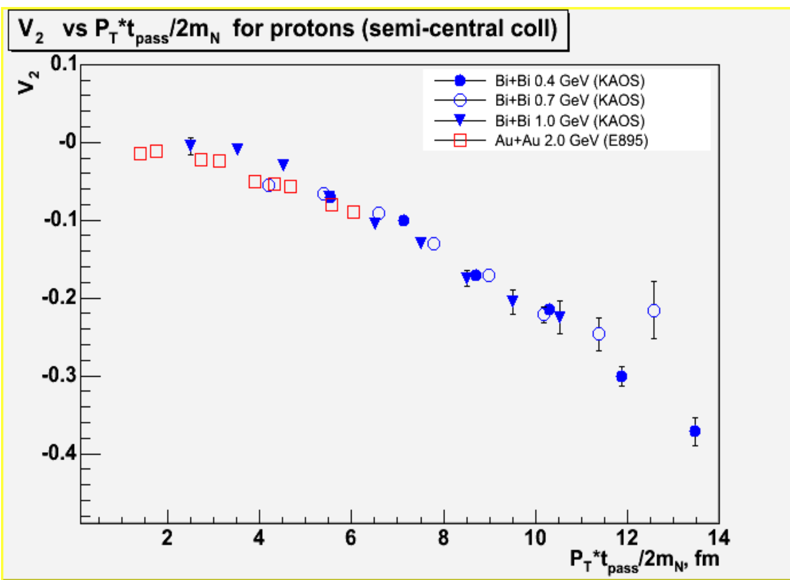


E895: for protons V2 changes sign at Elab=4 GeV. What about the other particle species? Other harmonics? Questions for STAR BES2, BM@N, CBM, NICA .

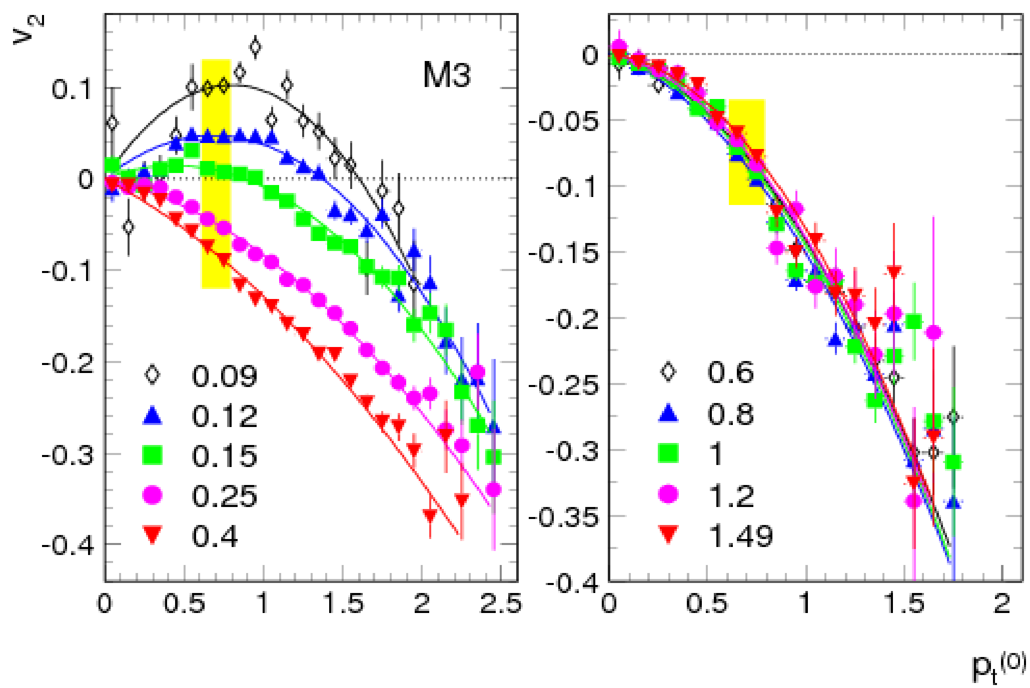
v_2 Flow at SIS-AGS: scaling relations

(KAOS – Z. Phys. A355 (1996);
(E895) - PRL 83 (1999) 1295





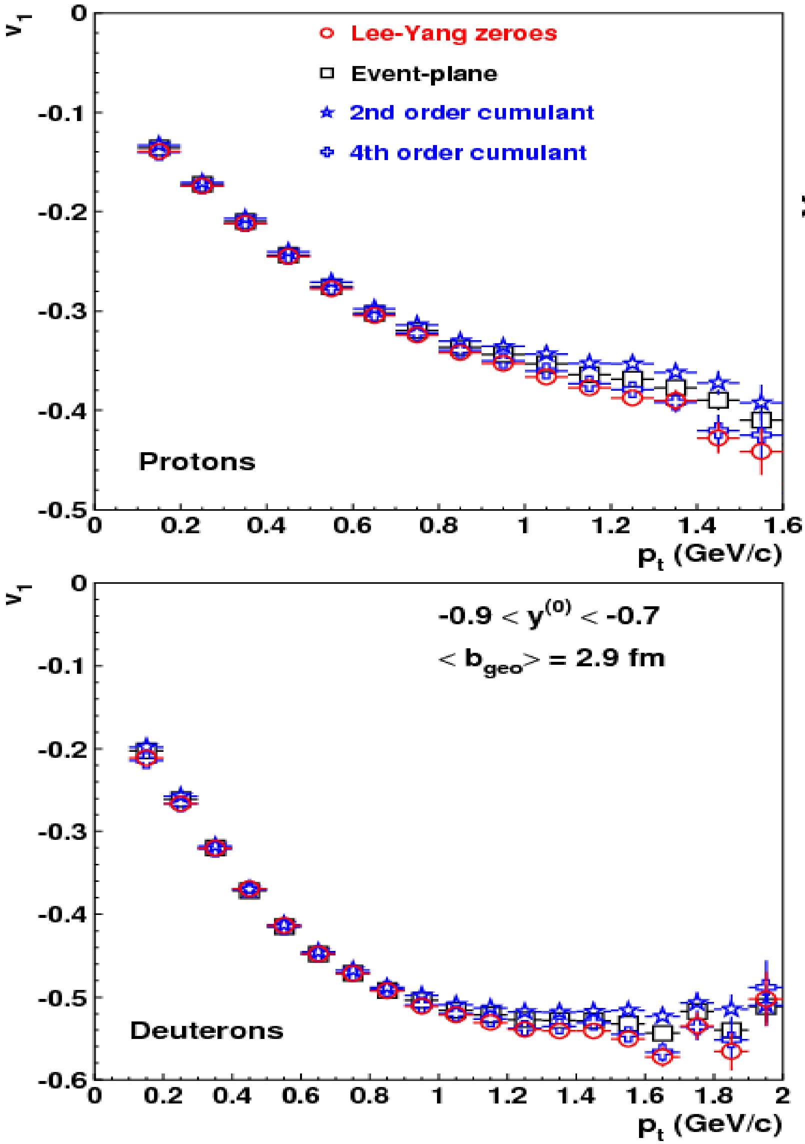
FOPI: v_2 of protons from
Elab=0.09 to 1.49 GeV
Phys.Lett. B612 (2005) 173-180



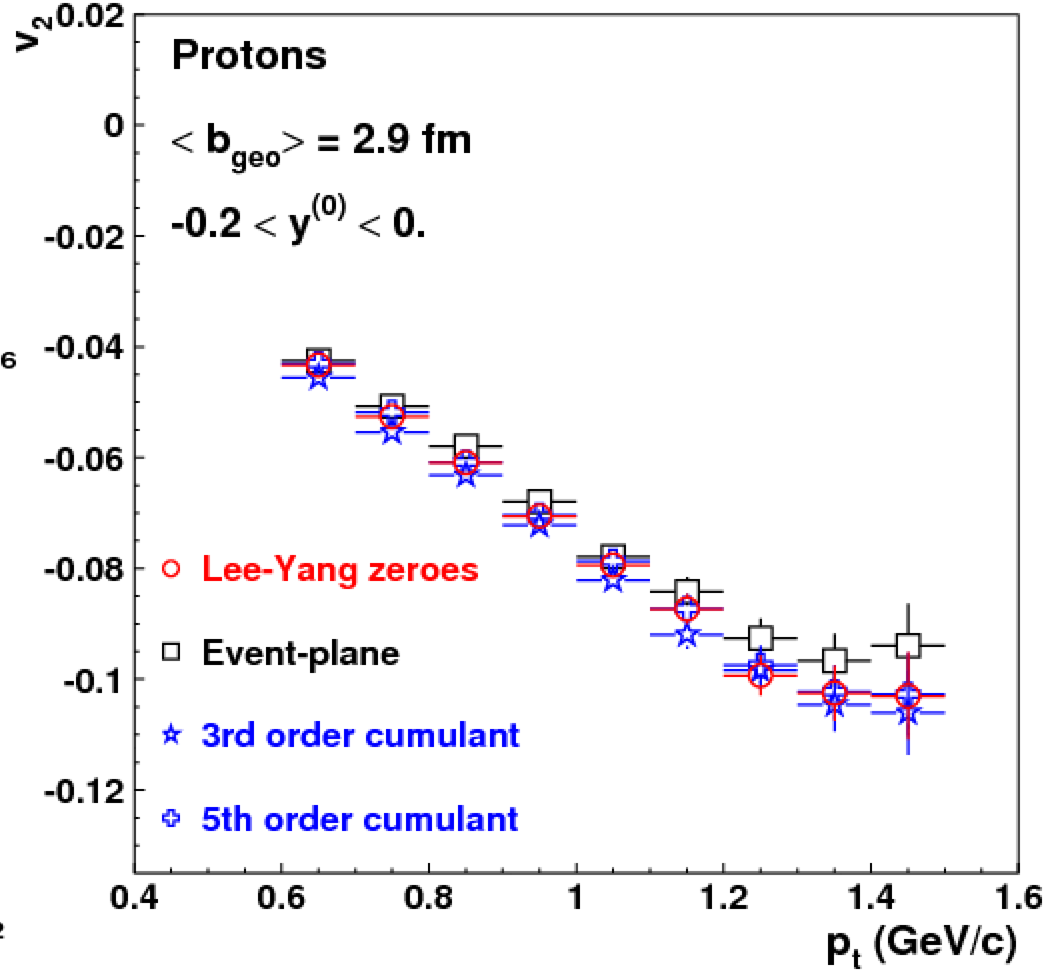
Pt dependence of v2 of protons revealing a rapid change with incident energy below 0.4 AGeV, followed by an almost perfect scaling at the higher energies: 0.4 -2AGeV

.

Flow at SIS: non-flow / fluctuations



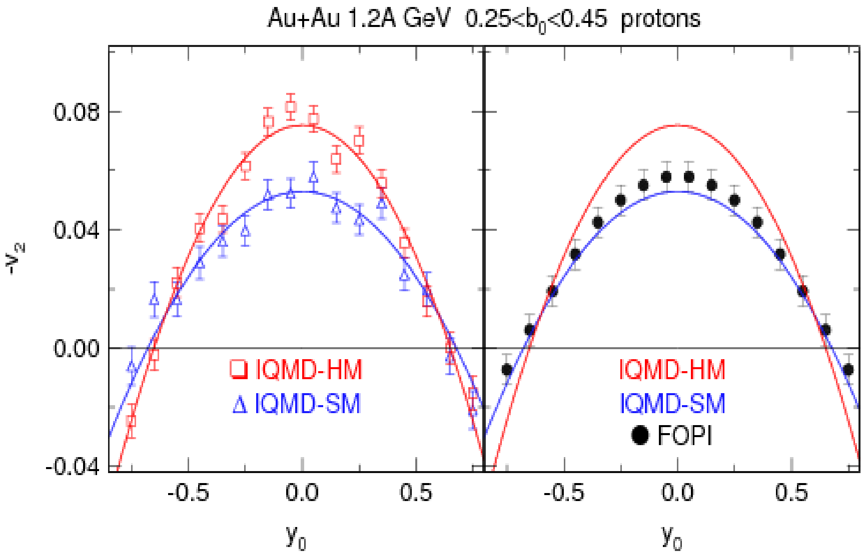
FOPI: Au+Au at 1AGeV
Phys. Rev. C 72 (2005) 011901

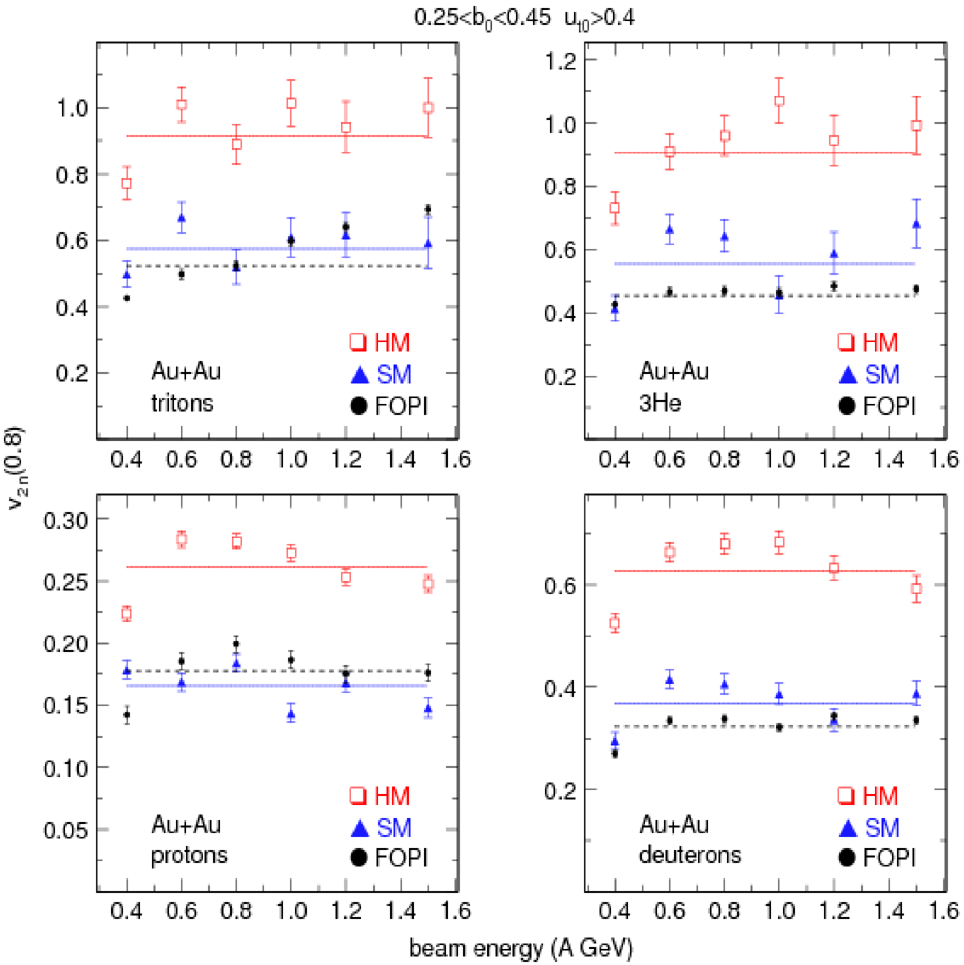


Flow at SIS: rapidity dependence of v2 and EOS

HM – stiff momentum dependent with K=376 MeV
SM – soft momentum dependent with K=200 MeV

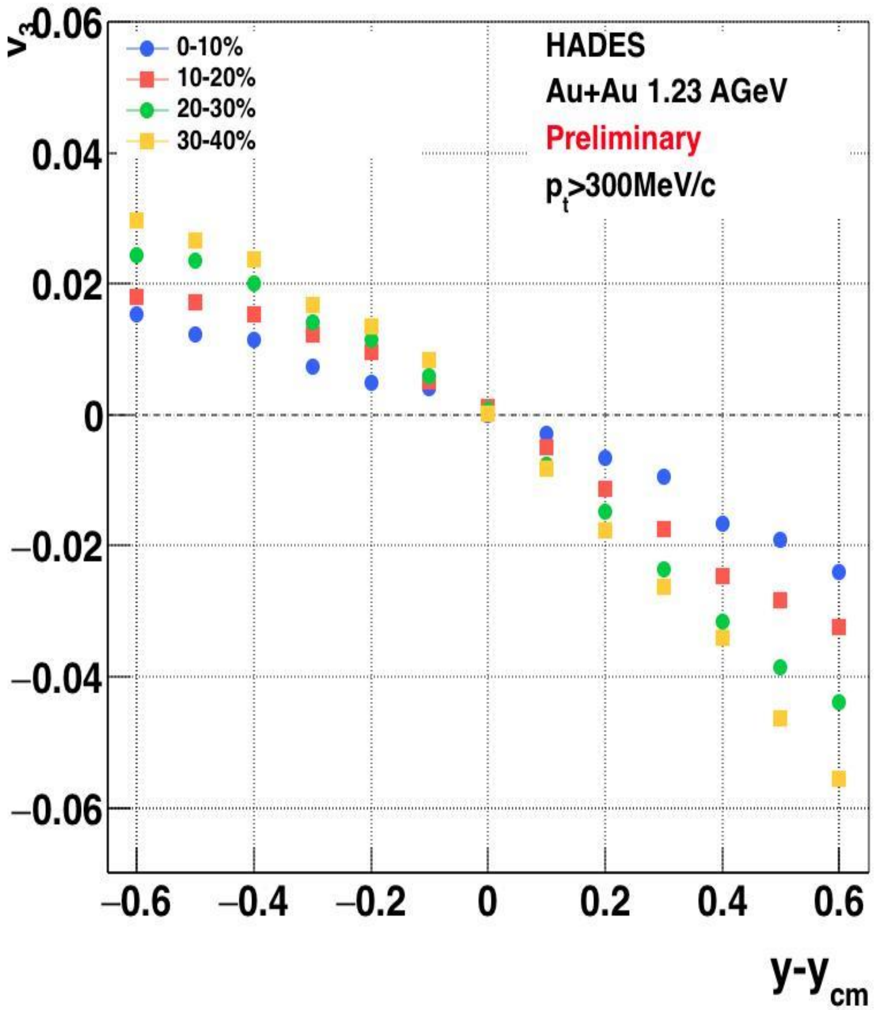
FOPI data : Nucl. Phys. A 876 (2012) 1
IQMD : Nucl Phys. A 945 (2016)

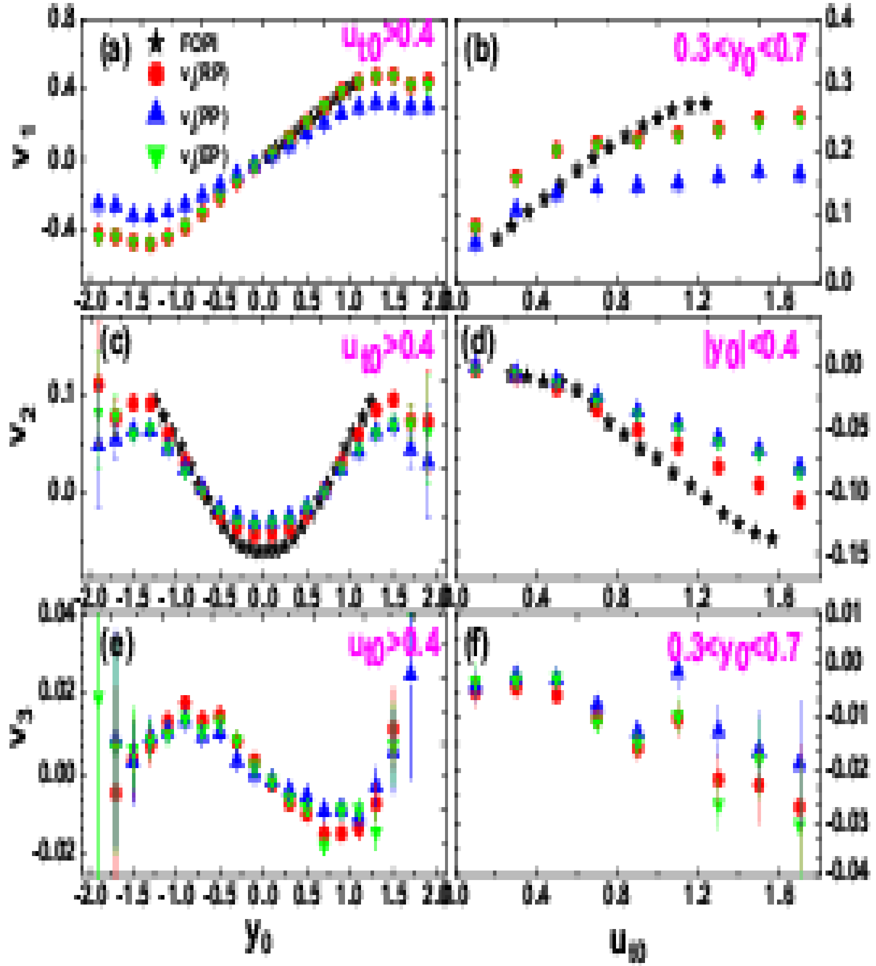




V2n=|V20|+|V22|
Fit: V2(y0)=V20+V22*Y0^2

HADES results at SIS: Vn harmonics n>2





HADES preliminary QM2017

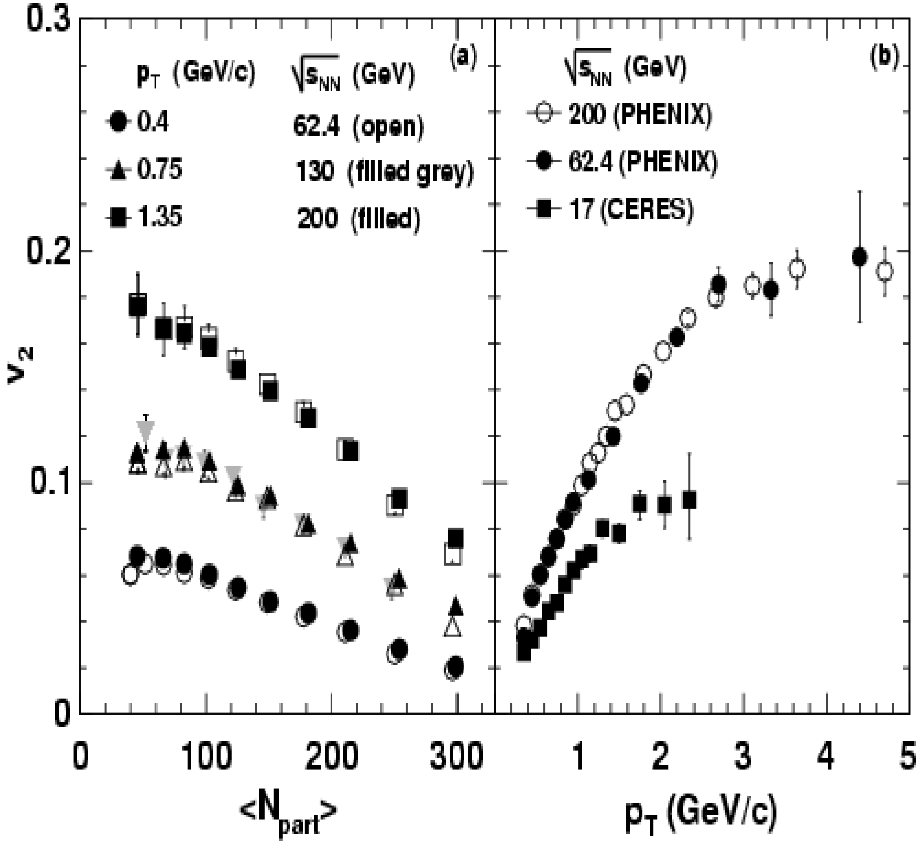
IQMD: Phys.Rev.C. 90(2014)

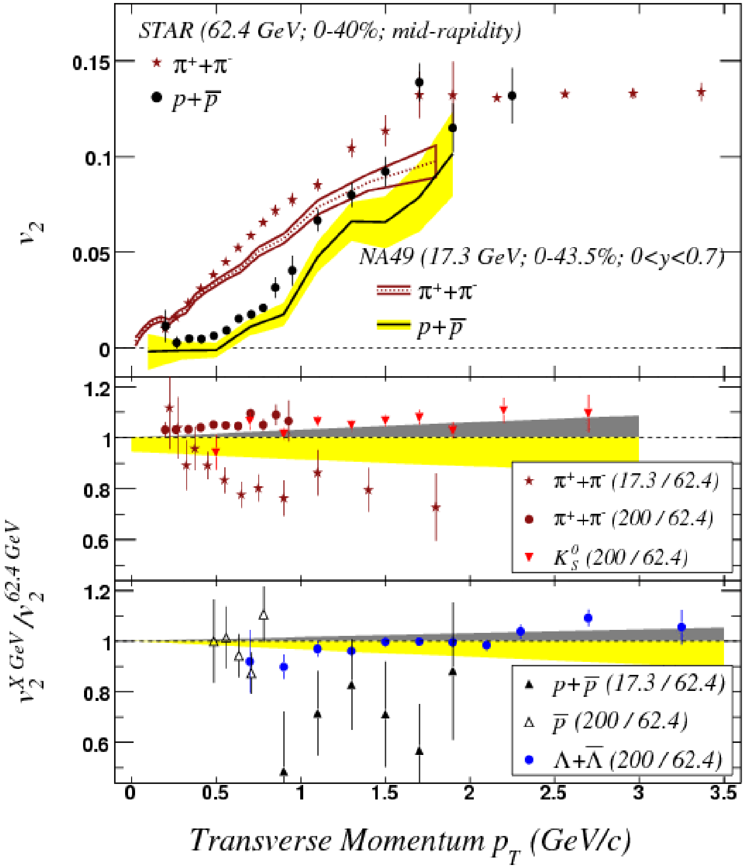
MPD(NICA): Flow performance study

Are flow measurements at SPS reliable?

Phenix: Phys. Rev. Lett. 94, 232302 (2005)

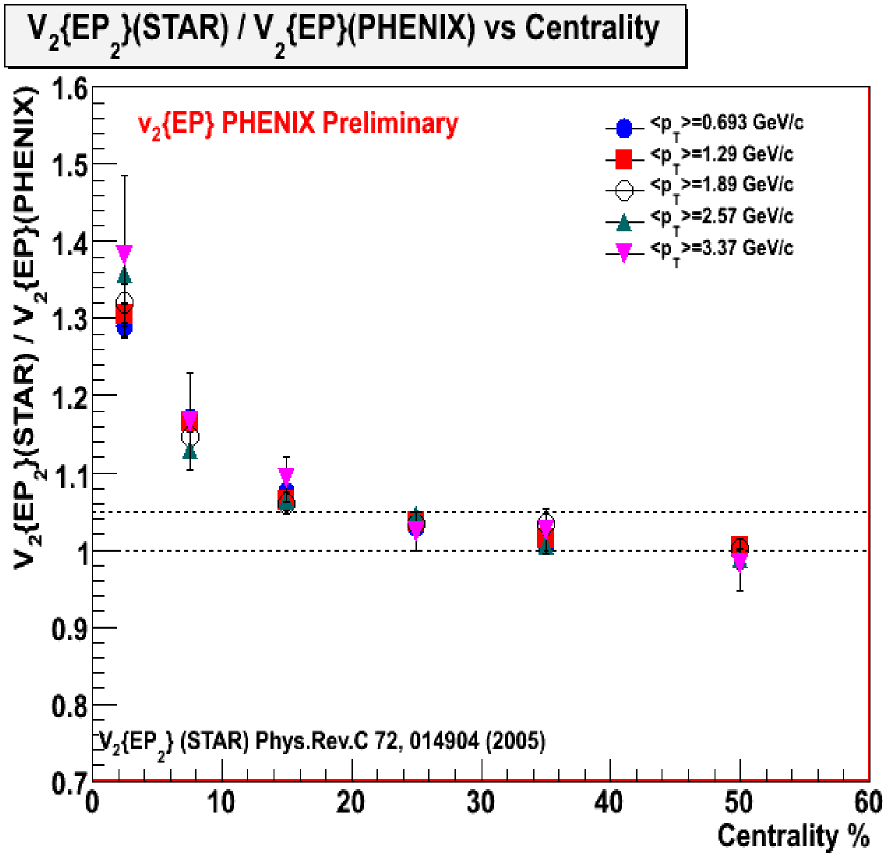
STAR: Phys.Rev.C75:054906,2007

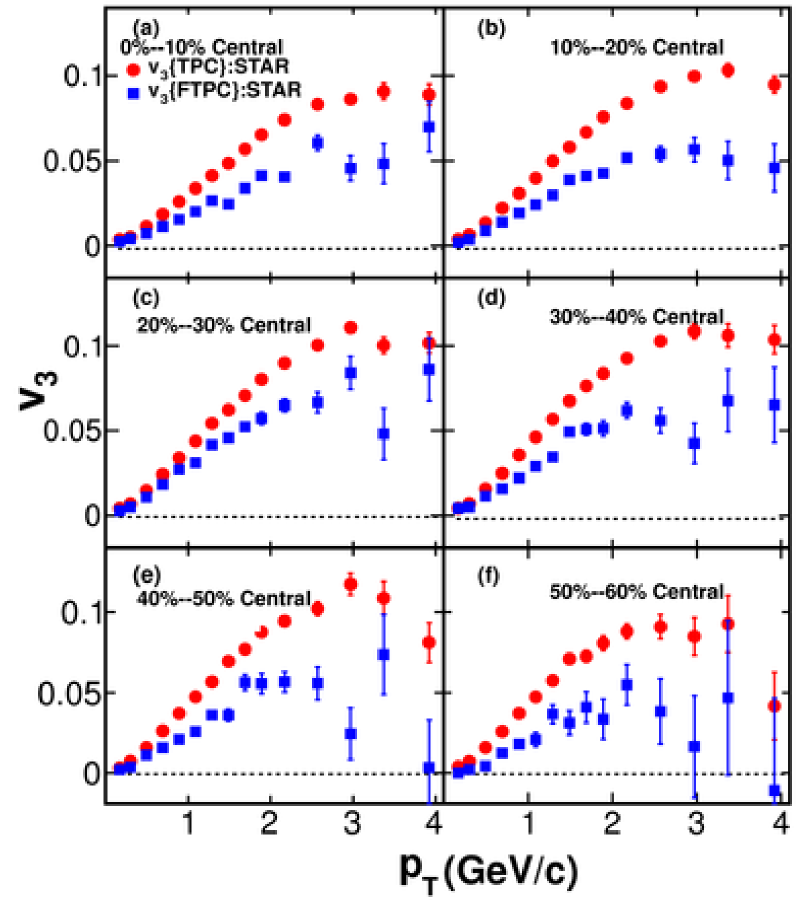




PHENIX: RHIC/SPS: ~ 50% difference . STAR: RHIC/SPS ~ 10-15% difference in the differential flow results !

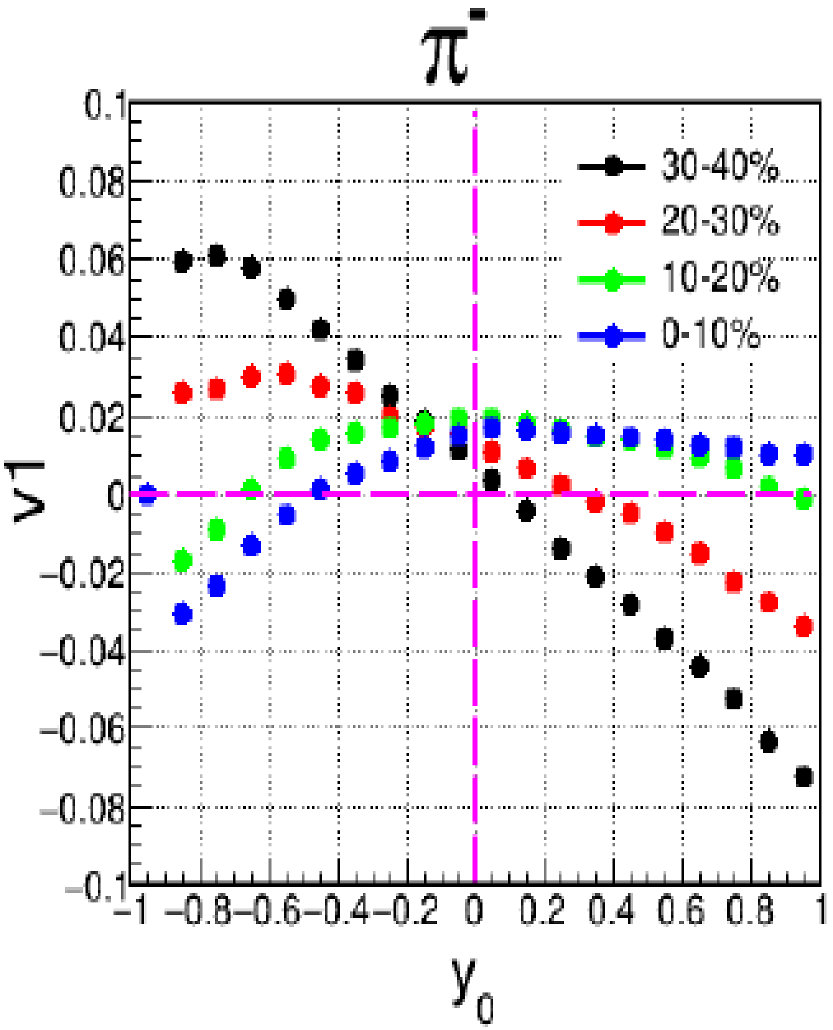
Are flow measurements at RHIC reliable?

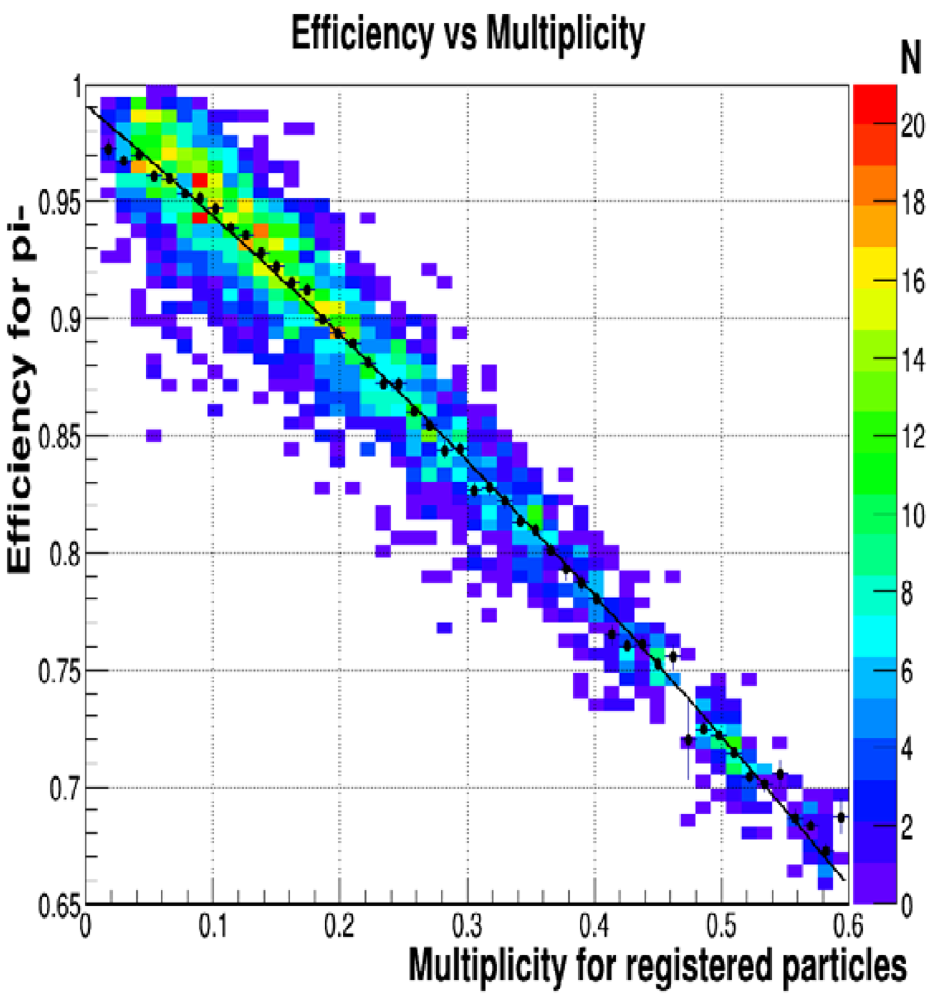




Do we understand the difference in v2 and v3 measurements between STAR and PHENIX ?

Are flow measurements at SIS reliable?





Occupancy effect on directed flow of pions in HADES

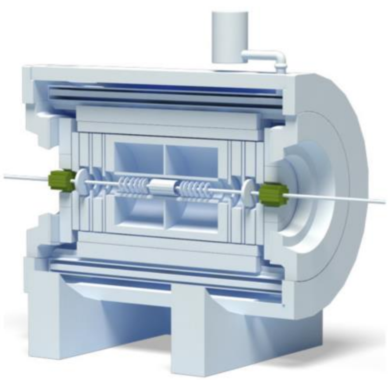
Flow performance study for FHCAL TDR (2016 -)

NICA

Technical Design Report for the MPD Experiment

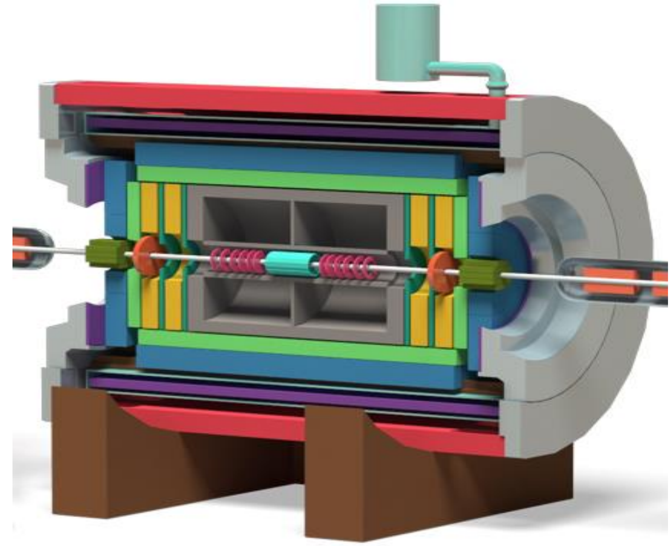
Nuclotron Based Ion Collider Facility

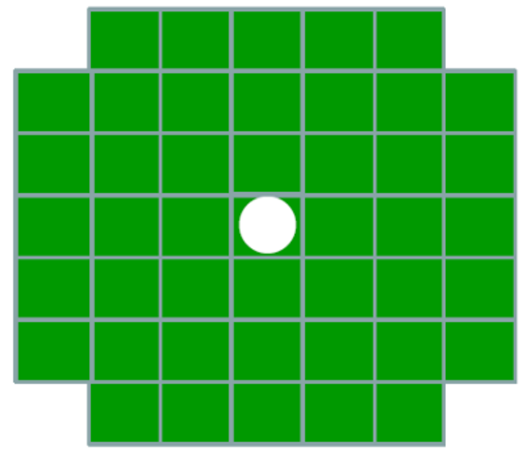
Forward Hadron Calorimeter (FHCal)



December 2016

http://mpd.jinr.ru/doc/mpd-tdr/

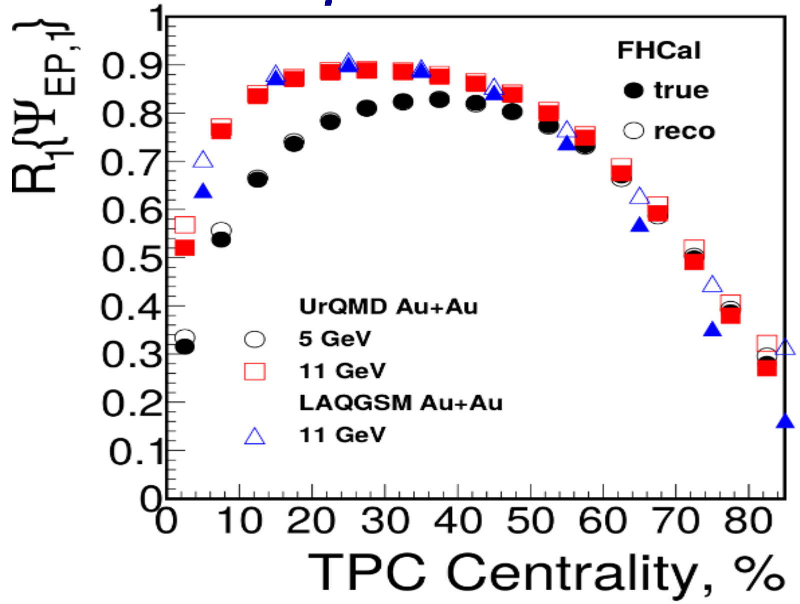


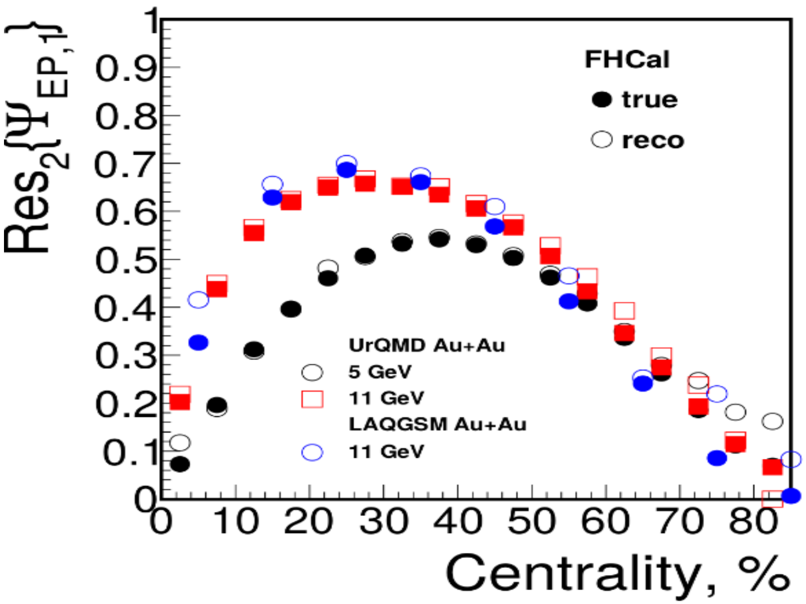


FHCal coverage: 2.2<|η|< 4.8

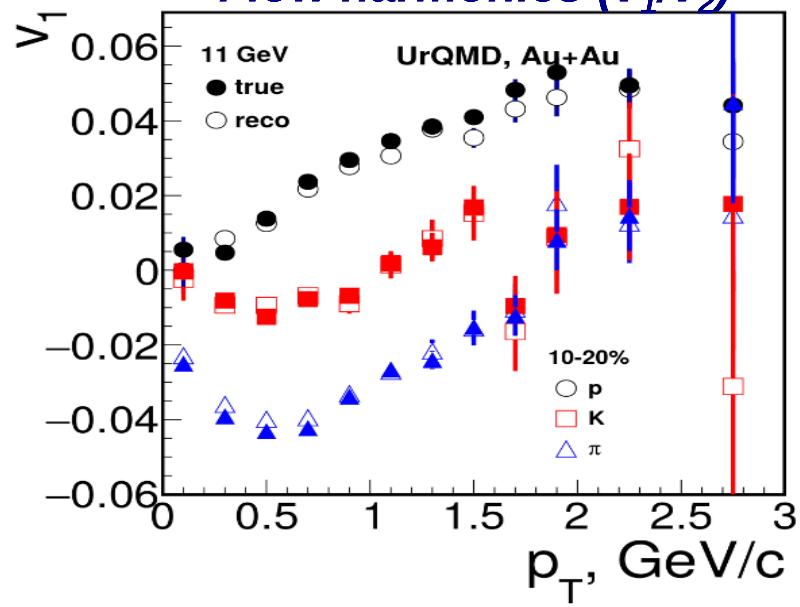
Flow performance: v_n of charged hadrons: MPD (NICA)

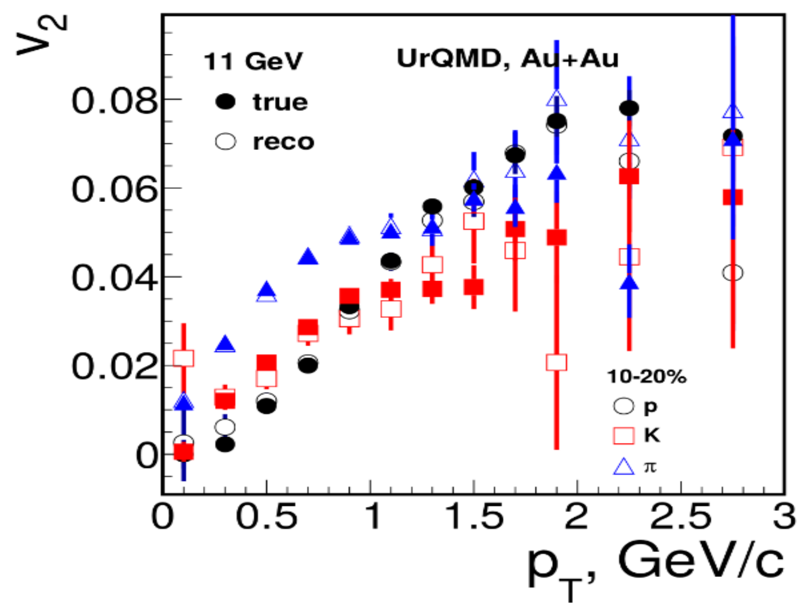
Event plane resolution





Flow harmonics (v_1/v_2)





Backup Slides

Flow is acoustic ! (R.A Lacey (SUNY))

PRC 84, 034908 (2011)
P. Staig and E. Shuryak.

- v_n **measurements are sensitive to system shape** (ε_n)**, system** size (RT) **and transport coefficients** $\left(\frac{\eta}{s}, \frac{\zeta}{s}, \ldots\right)$.

arXiv:1305.3341
Roy A. Lacey, et al.

- **Acoustic ansatz**
  - ✓ **Sound attenuation in the viscous matter reduces the magnitude of** v_n.
- **Anisotropic flow attenuation,**

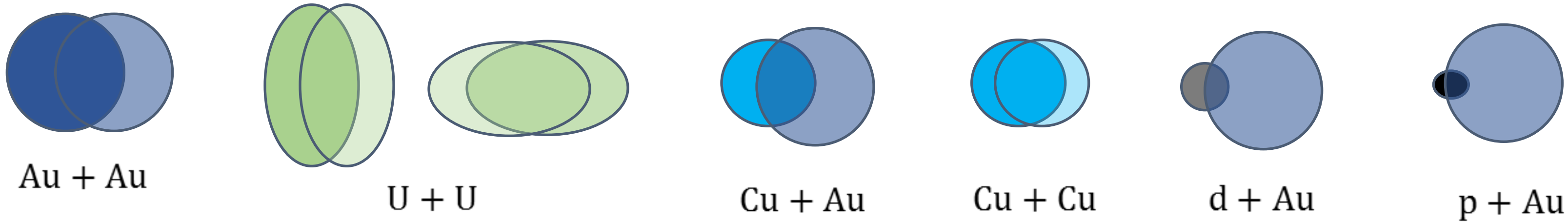
$$\frac{v_n}{\varepsilon_n} \propto e^{-\beta n^2}, \ \beta \propto \frac{\eta}{s}\frac{1}{RT}$$

arXiv:1601.06001
Roy A. Lacey, et

PRC 88, 044915 (2013)
E. Shuryak and I. Zahed

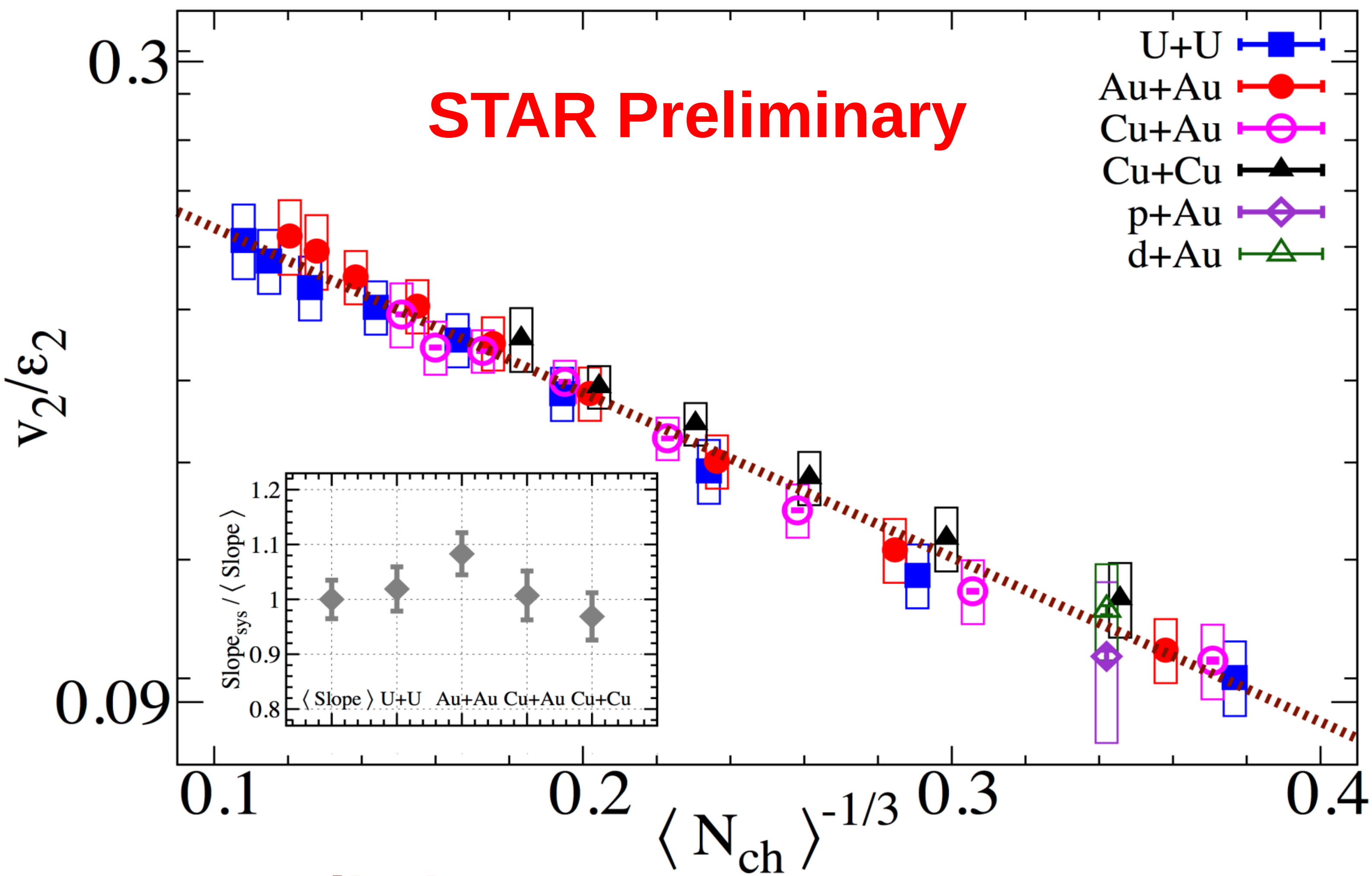
- **From macroscopic entropy considerations** $S \sim (RT)^3 \propto \frac{dN}{d\eta}$

$$ln\left(\frac{v_n}{\epsilon_n}\right) \propto A\,\frac{\eta}{s}\left(\frac{dN}{d\eta}\right)^{\frac{-1}{3}}$$



Scaling expected For *similar* $\frac{\eta}{s}$ *and* $\frac{dN}{d\eta}$

STAR: V_2 for different colliding systems

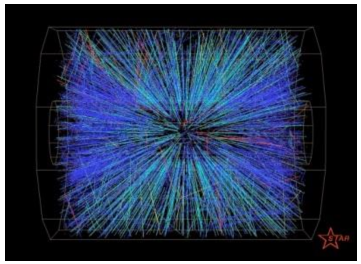


STAR Preliminary

Flow Measurements at RHIC with STAR/PHENIX

ZDC/SMD FTPC TPC FTPC ZDC/SMD

STAR



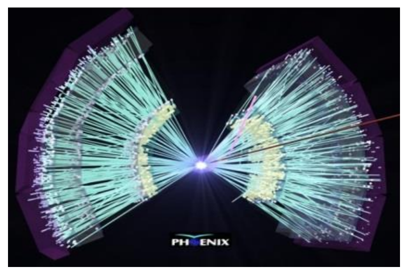
|η| < 1.0

2.5 <|η|< 4.0

|η| > 6.3

η

comparison



ZDC/SMD BBC/MPC Central Arms BBC/MPC ZDC/SMD

RXN RXN

η

PHENIX

|η|<0.35

1.0<|η|<2.8

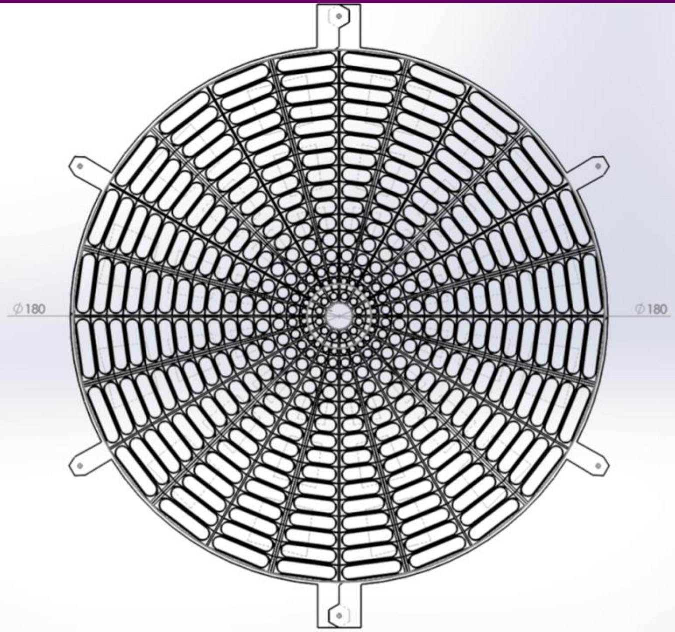
3.1<|η|<3.7

3.1<|η|<3.9

|η| > 6.6

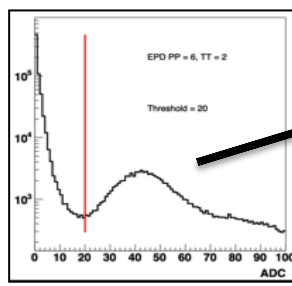
2012- FVTX 1 < |η| < 3

STAR Event Plane Detector

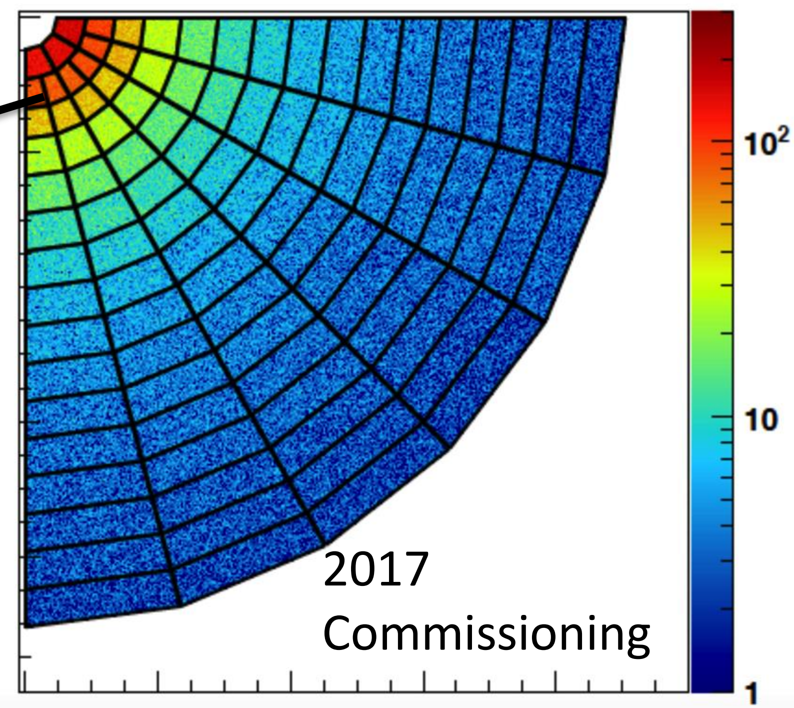


- 2 Wheels of 12 supersectors with 31 optically-isolated tiles
  - 1.2-cm-thick scintillator
  - 3 turns of Wavelength shifting (WLS) fiber
- Total of 12x31x2=**744 channels**

- Successful install of 1/8th in 2017
- Construction complete
  - Install in Jan 2018
- EP resolution improved by ~1.5
- Time Resolution ~1 ns

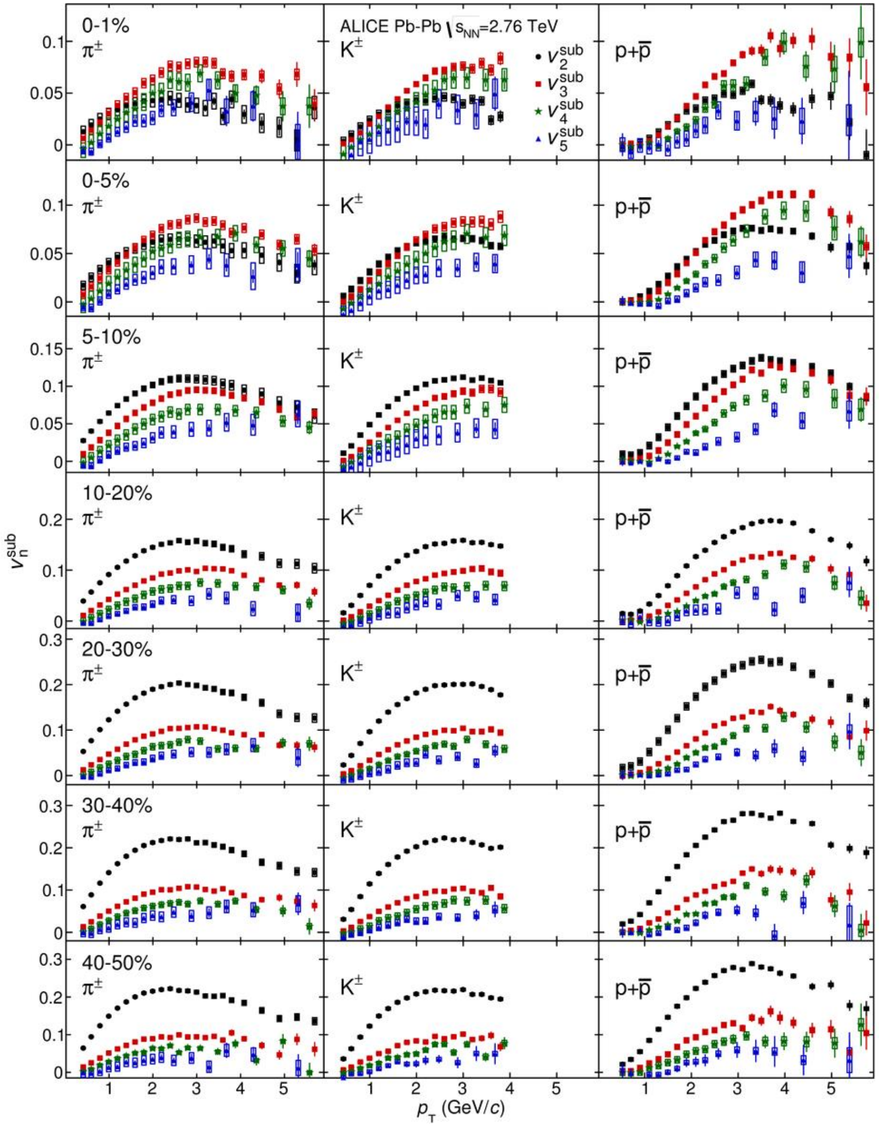


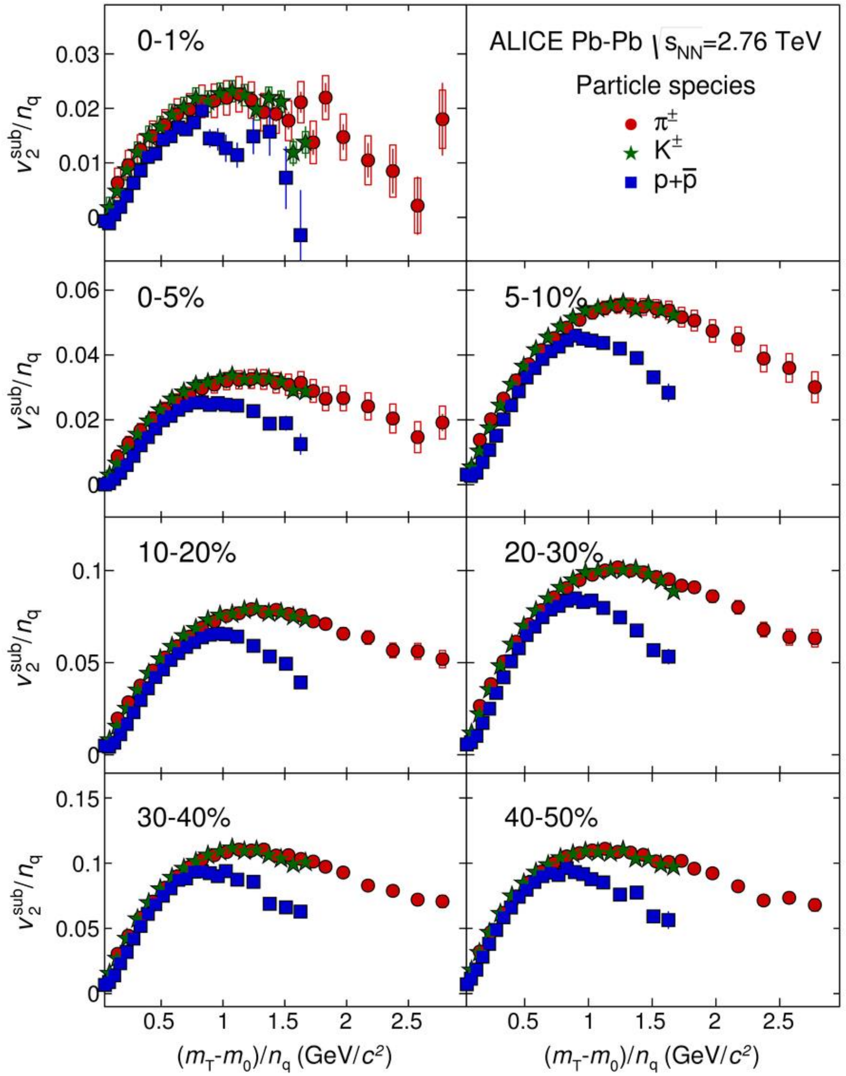
All 93 channels show good signals ✓



Flow is partonic @ LHC

Alice - arXiv:1606.06057





KE_T & $(n_q)^{n/2}$ scaling validated for v_n→ Partonic flow

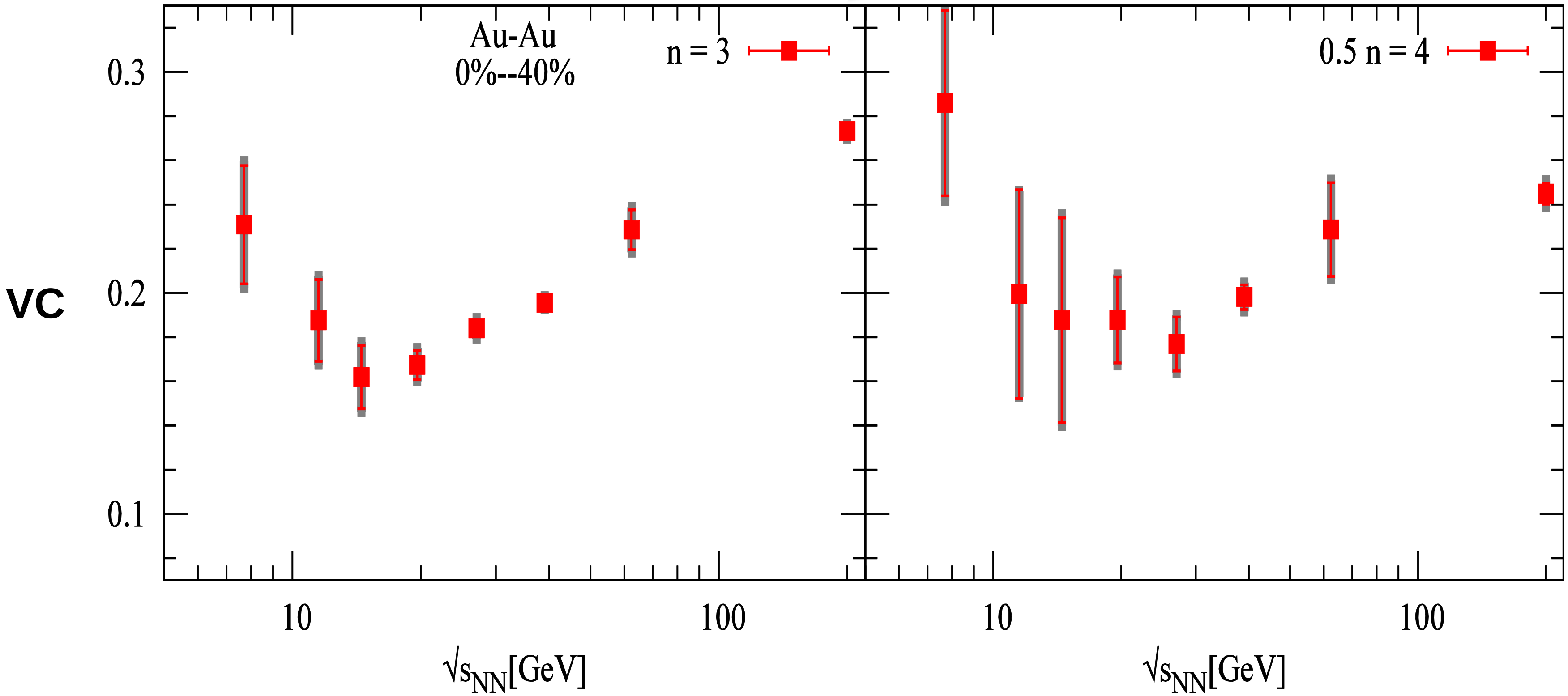
Viscous coefficient

$|\eta| < 1$ and $|\Delta\eta| > 0.7$

$0.2 < p_T < 4\text{GeV/c}$

$$VC = ln\left(\frac{(v_n)^{\frac{1}{n}}}{(v_2)^{\frac{1}{2}}}\right)\left(\frac{dN}{d\eta}\right)^{\frac{1}{3}}$$

$$VC \propto \frac{\eta}{s}$$



➢ **The viscous coefficient vc shows a non-monotonic behavior with beam energy in both cases, n = 3 and n = 4.**

STAR Collaboration, Niseem Magdy, SQM 2016

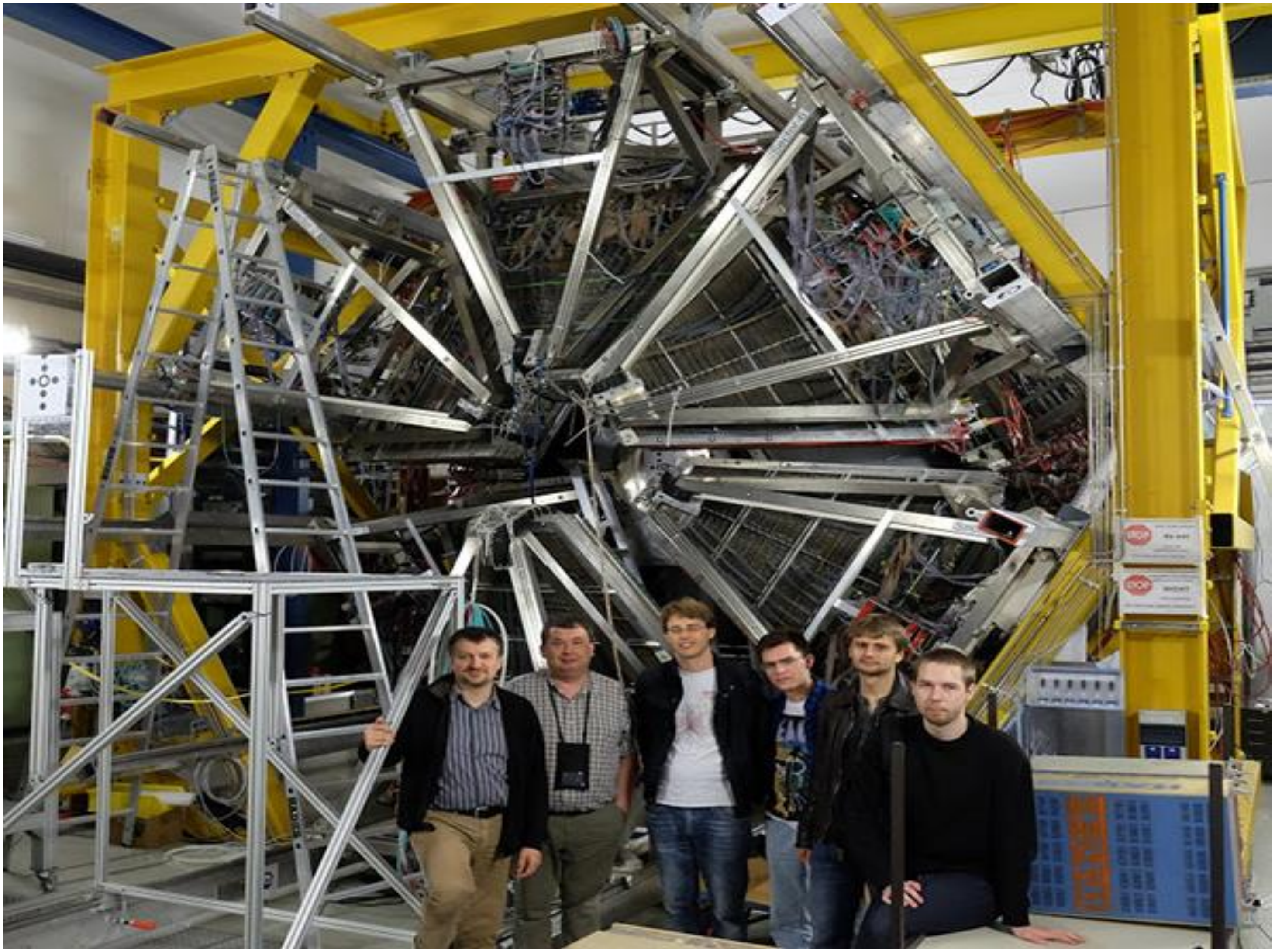
MEPhI Relativistic Heavy-Ion Group

One of the youngest group in MEPhI. Est. in 2015

P. Parfenov (PhD student, MEPhI):
Flow performance studies
in MPD at NICA , FHCAL TDR (2016-2018)

NA61/SHINE [CERN SPS]

HADES (GSI) SIS-18



Эксперимент ХАДЕС