Anisotropic flow measurements from the NA61/SHINE and NA49 beam momentum scan programs at the CERN SPS

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Results approved by the NA61/SHINE Collaboration

NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"

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Fundamental problems and applications

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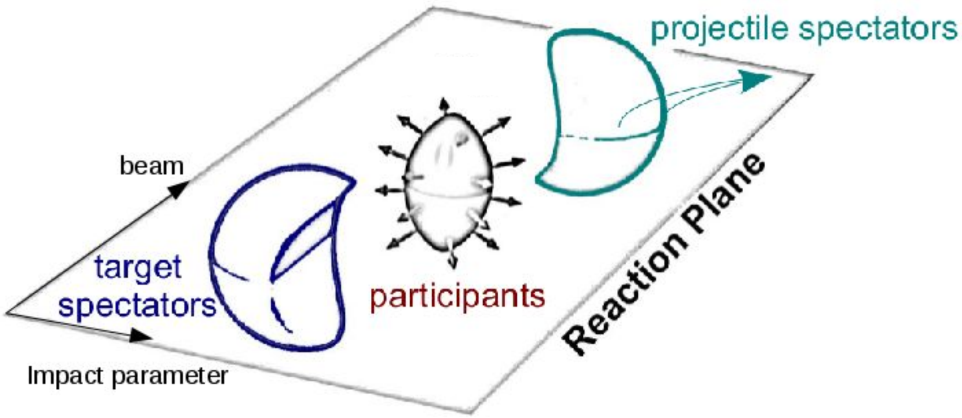
Collision geometry and the anisotropic transverse flow

Asymmetry in coordinate space converts due to interaction into momentum asymmetry with respect to the symmetry plane:

$$\rho(\phi) = \frac{1}{2\pi}[1+2\sum_{n=1}^{\infty} v_n \cos(n(\phi-\Psi_s))]$$

$$v_n = \langle \cos(n[\phi-\Psi_s]) \rangle$$

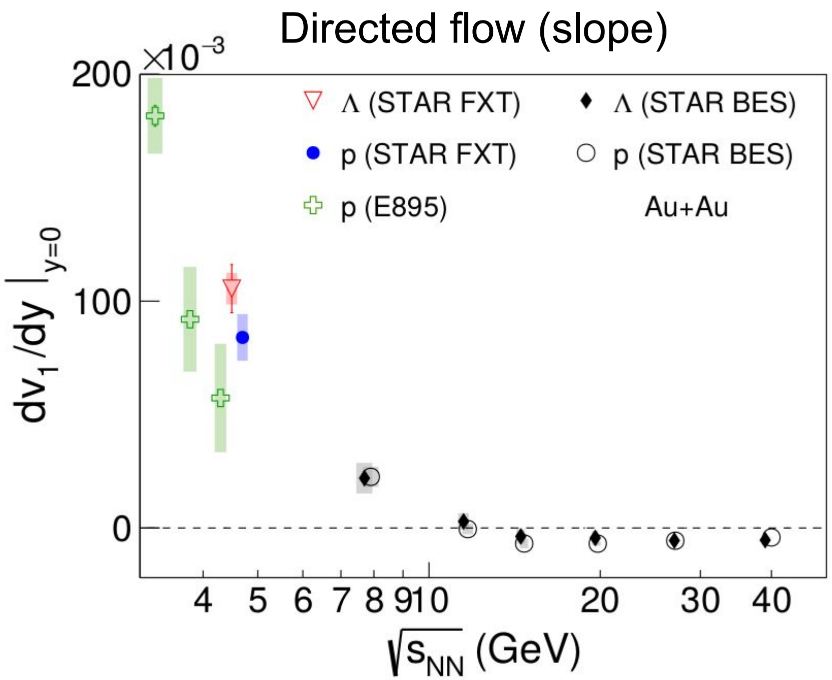


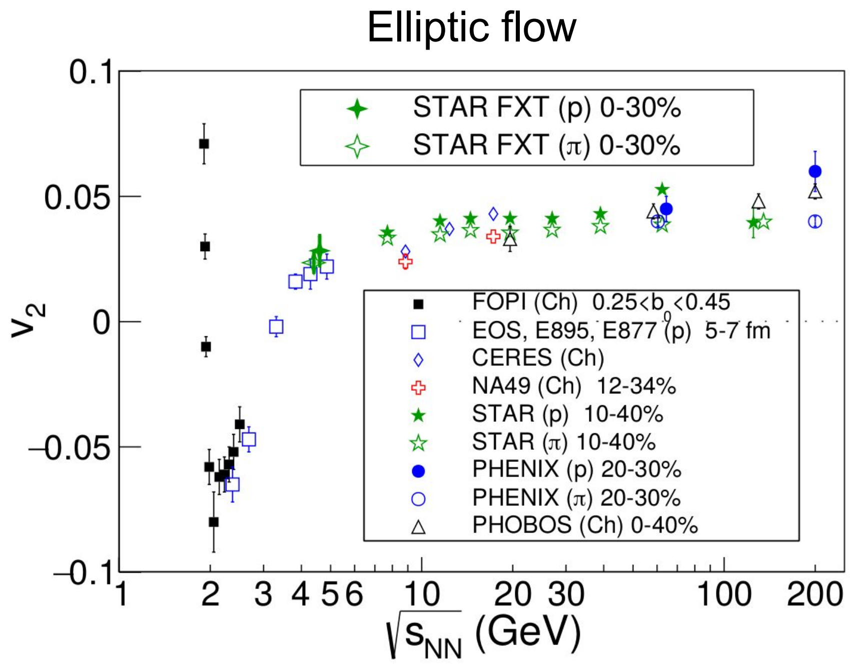
Ψ_s can be estimated with produced particles Ψ_{pp} or with projectile (target) spectators Ψ_{proj} (Ψ_{spec})

Needed components to calculate v_n:

- momentum (ϕ, y, p_T)
- centrality estimation
- particle identification
- Ψ_s estimation

Collective flow at different energies



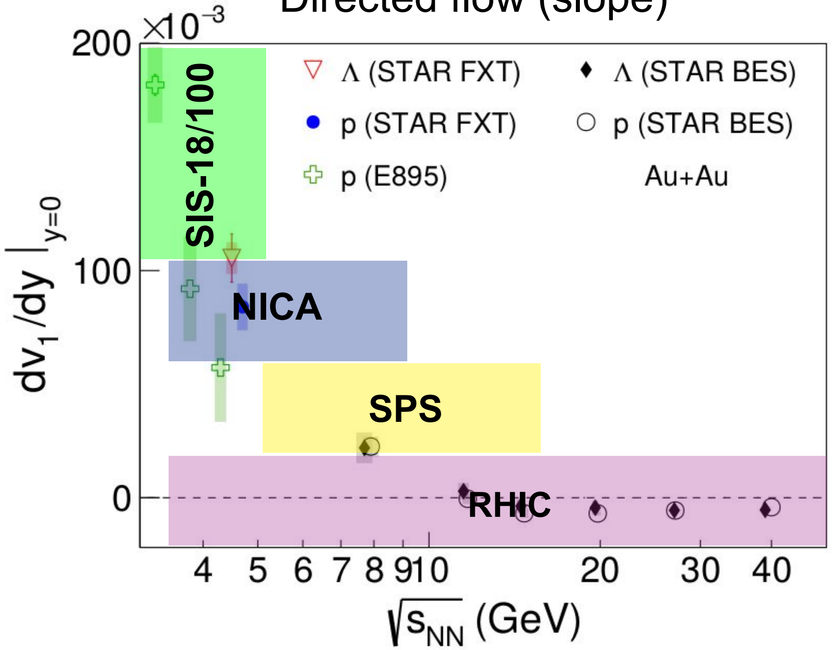


STAR Collaboration, PRC 103, 034908 (2021)

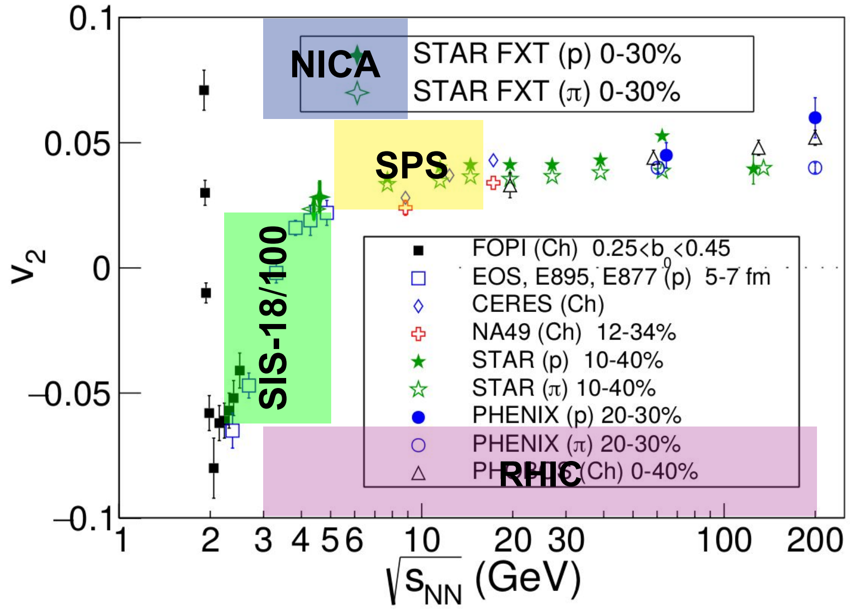
- NA61/SHINE Pb-ion beam energy scan: p_{LAB} = 13-150*A* GeV/*c* ($\sqrt{s_{NN}}$ = 5.1-16.8 GeV)
  - complementary to STAR@RHIC and NICA
  - bridge to FAIR/GSI beam energies
- Advantage of fixed target setup
  - forward rapidity tracking with TPC
  - projectile spectators (forward calorimeter – PSD)

Collective flow at different energies

Directed flow (slope)



Elliptic flow



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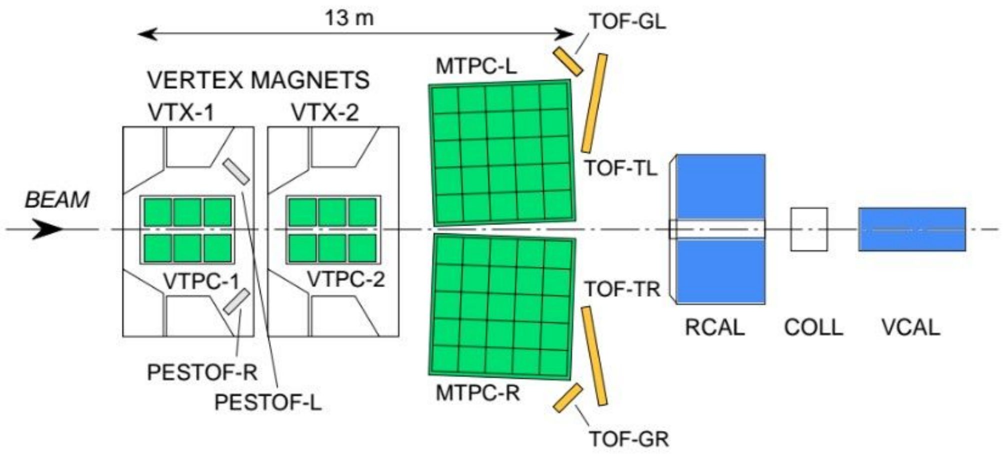
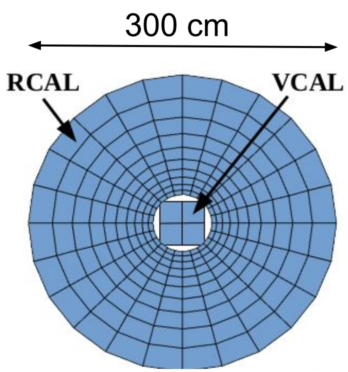
NA49 experiment (1996-2002)



Veto and Ring calorimeters (VCAL and RCAL)

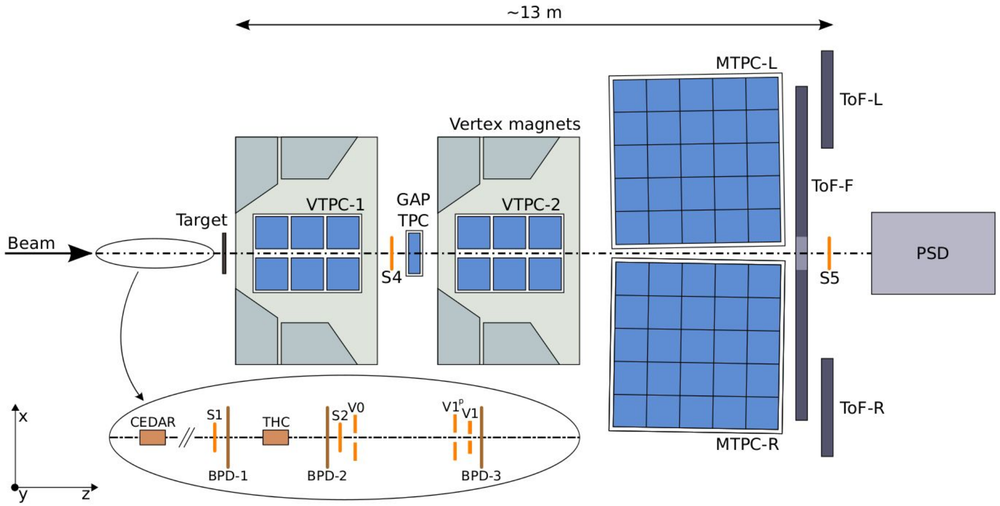


transverse layout

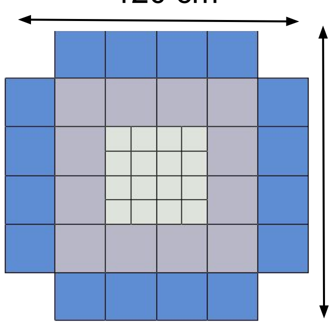
- Large acceptance hadron spectrometer (TPC)
  - full coverage of forward hemisphere
  - tracking + identification with dE/dx down to $p_T \sim 0$ GeV/c
- Forward rapidity calorimeters with transverse granularity (RCAL and VCAL)
- Pb+Pb beam energy scan:
  20A, 30A, 40A, 80A, 158A GeV*
  ($\sqrt{s_{NN}}$ = 6.4, 7.7, 8.9, 12.4, 17.3 GeV)

*minbias samples only for 40 and 158A GeV

NA61/SHINE experiment (2015-now)



Projectile Spectator Detector (PSD)



transverse layout

- Successor of NA49
- Similar TPC configuration
- Forward rapidity calorimeter with transverse granularity (PSD)
- Pb+Pb beam momentum scan: 13*A*, 30*A*, 150*A* GeV/*c* ($\sqrt{s_{NN}}$ = 5.1, 6.8, 16.8 GeV)
- System size scan (Xe+La, Ar+Sc, Be+Be)

Scalar product method with 1st harmonic Q-vector

u-vector

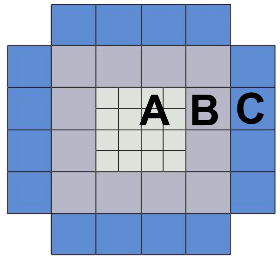
$$u_n = (u_x, u_y) = (\cos(n\varphi), \sin(n\varphi))$$

φ - azimuthal angle of particle momentum (or PSD module)

PSD subevents Q-vector

$$Q^S_{1,\alpha} = \frac{1}{E_S} \sum E_i u^\alpha_{1,i}$$

$$\alpha = x, y$$



S = A,B,C – PSD subevents
i - number of PSD module in subevent

Directed flow:

$$v^\alpha_1\{A\} = \frac{2\langle q_{1,\alpha} Q^A_{1,\alpha}\rangle}{R^A_{1,\alpha}}$$

6 independent combinations

Elliptic flow:

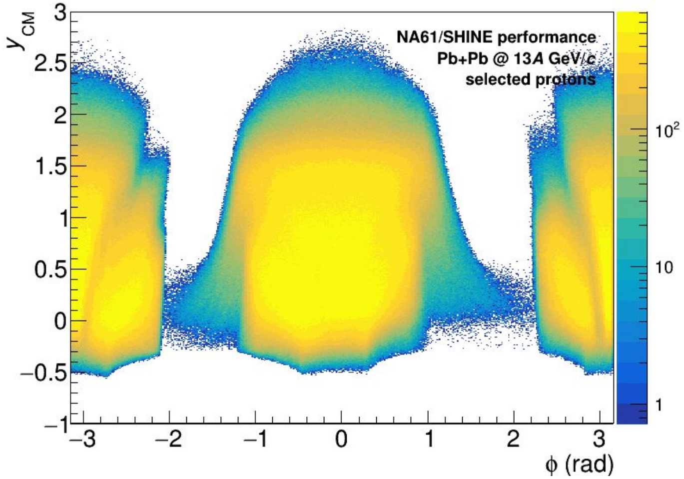
$$v^{\alpha\beta\gamma}_2\{A,B\} = \kappa_{\alpha\beta\gamma} \frac{4\langle q_{2,\alpha} Q^A_{1,\beta} Q^B_{1,\gamma}\rangle}{R^A_{1,\beta} R^B_{1,\gamma}}$$

12 non-zero combinations

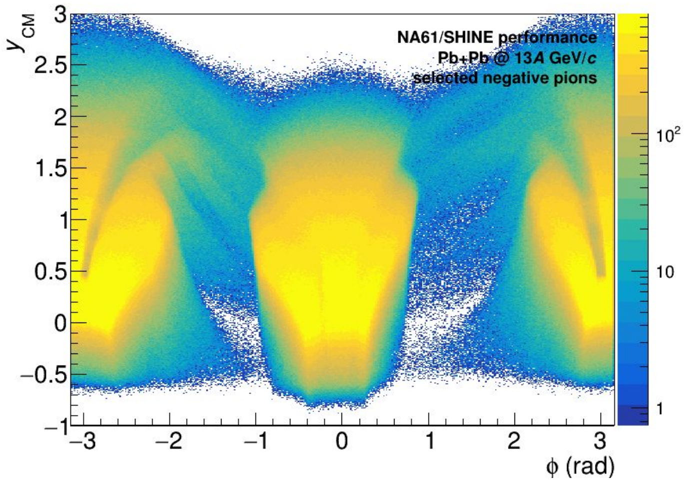
R_1^A – resolution correction factor for the subevent *A (see following slides)*

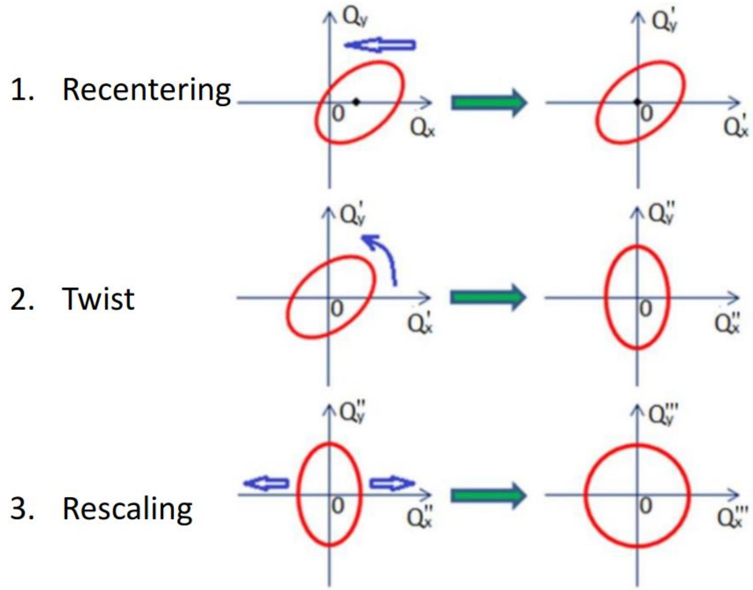
Data driven corrections for detector azimuthal non-uniformity

protons



negative pions

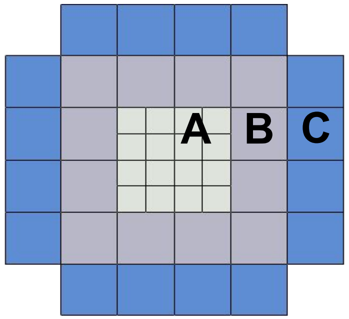




I. Selyuzhenkov and S. Voloshin [PRC77 034904 (2008)]

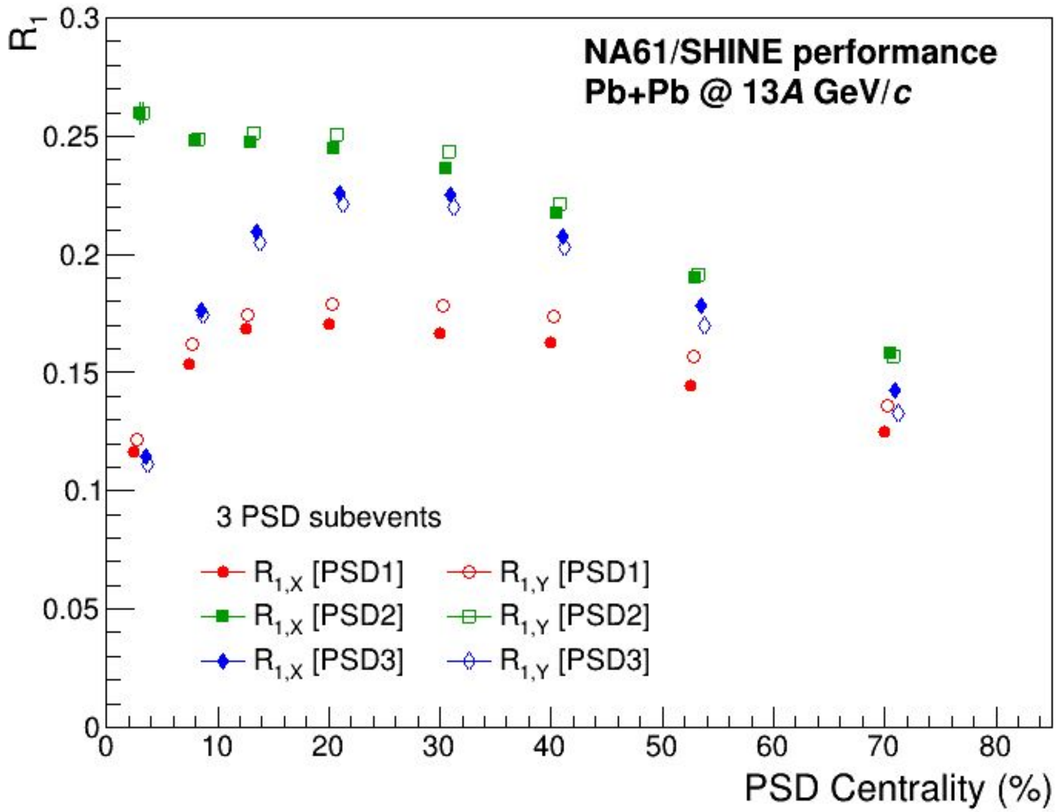
- Framework for multi-dimensional flow vectors corrections & correlations: L. Kreis (GSI / Heidelberg) and I. Selyuzhenkov (GSI / MEPhI) https://github.com/HeavyIonAnalysis/QnTools
- Recentering, twist, and rescaling corrections applied time dependent (run-by-run) and as a function of p_T, y and centrality

3 PSD subevents resolution



$$R^{A}_{1,\alpha} = \sqrt{\frac{\langle Q^{A}_{1,\alpha} Q^{C}_{1,\alpha} \rangle \langle Q^{A}_{1,\alpha} Q^{B}_{1,\alpha} \rangle}{\langle Q^{B}_{1,\alpha} Q^{C}_{1,\alpha} \rangle}}$$

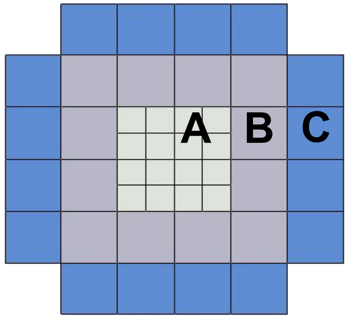
$$\alpha = x, y$$



Resolution correction is biased due to subevent self correlations: hadronic shower sharing across PSD subevents. Momentum separation of subevents is required.

3 PSD + 1 TPC subevents resolution

PSD



$+ \quad Q_1^{TPC}$

protons

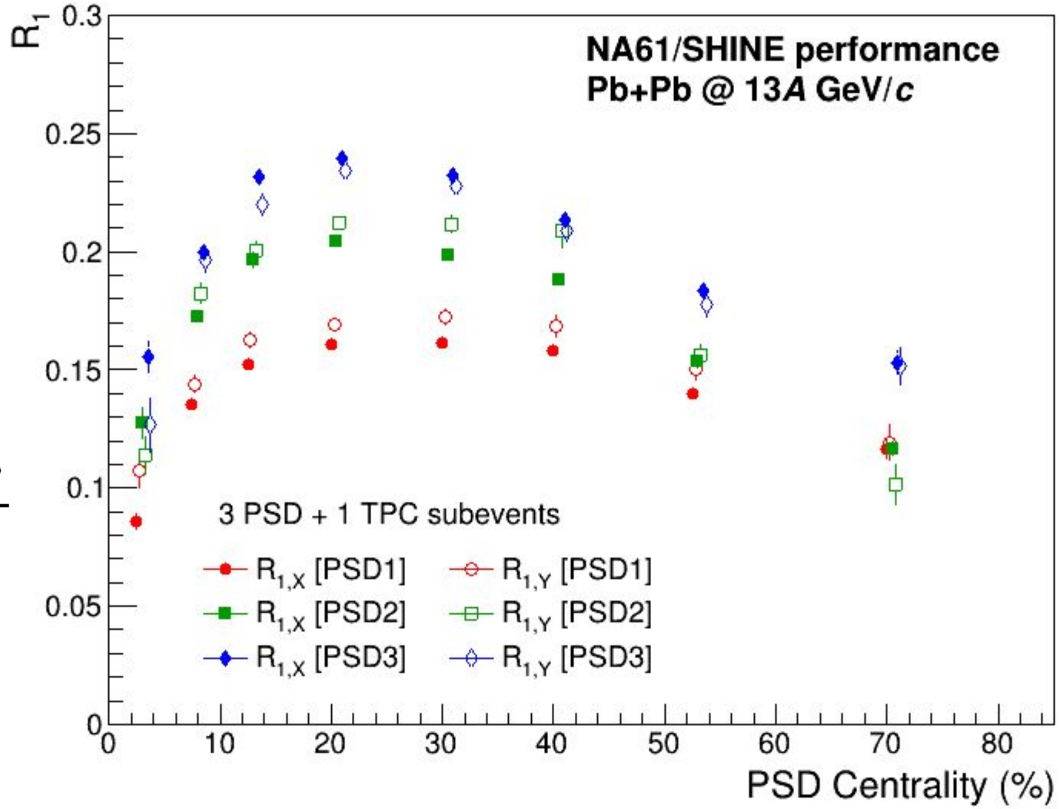
$0.8 < y < 1.2$

$p_T > 0$

$$R^{A,C}_{1,\alpha} = \sqrt{\frac{\langle Q^A_{1,\alpha} Q^C_{1,\alpha}\rangle \langle Q^{A,C}_{1,\alpha} Q^T_{1,\alpha}\rangle}{\langle Q^T_{1,\alpha} Q^{C,A}_{1,\alpha}\rangle}} \quad R^B_{1,\alpha} = \frac{\langle Q^B_{1,\alpha} Q^T_{1,\alpha}\rangle}{R^T_{1,\alpha}}$$

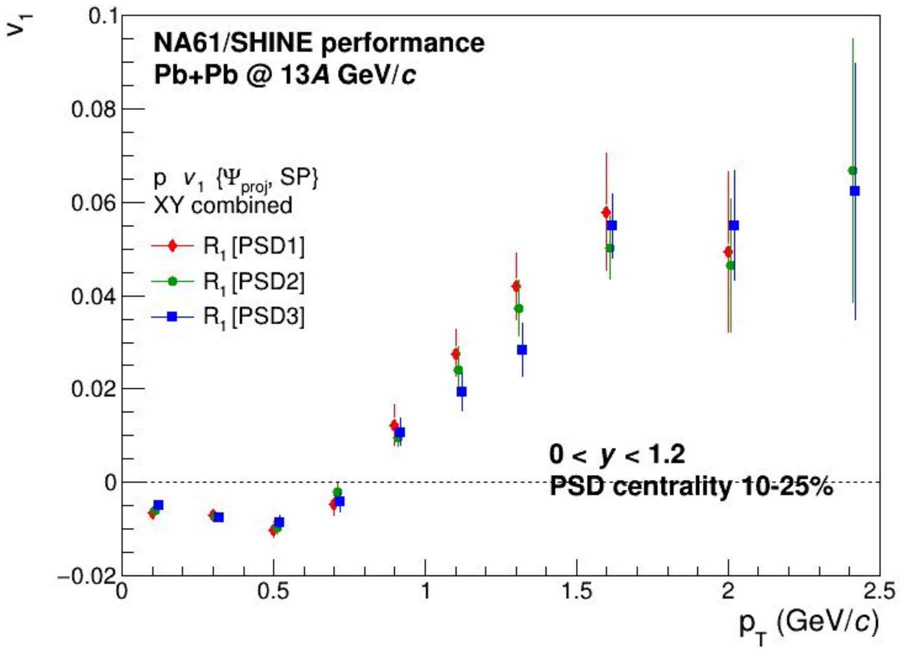
TPC subevent resolution:

$$R^T_{1,\alpha} = \sqrt{\frac{\langle Q^T_{1,\alpha} Q^C_{1,\alpha}\rangle \langle Q^T_{1,\alpha} Q^B_{1,\alpha}\rangle}{\langle Q^B_{1,\alpha} Q^C_{1,\alpha}\rangle}} \qquad \alpha = x, y$$

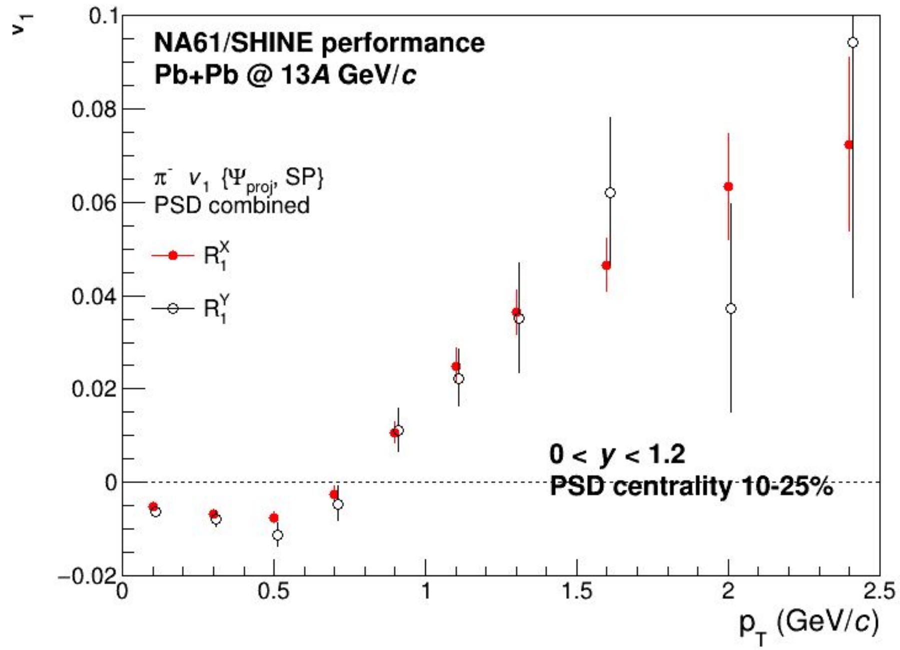


Additional correlations are suppressed by using pseudorapidity-separated subevents.

“Systematics” for directed flow (v_1) of negative pions

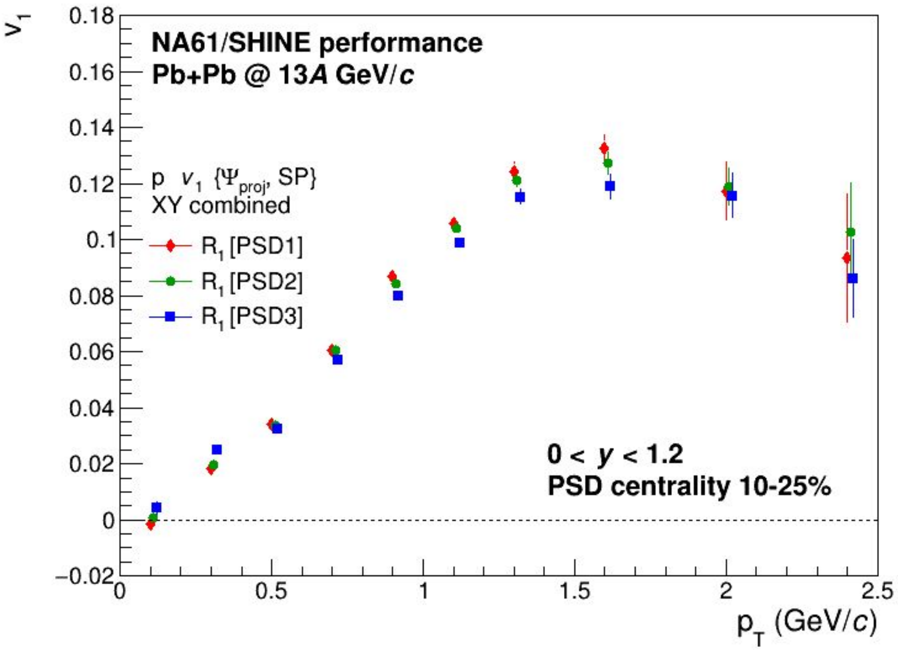


Consistent results for PSD subevents

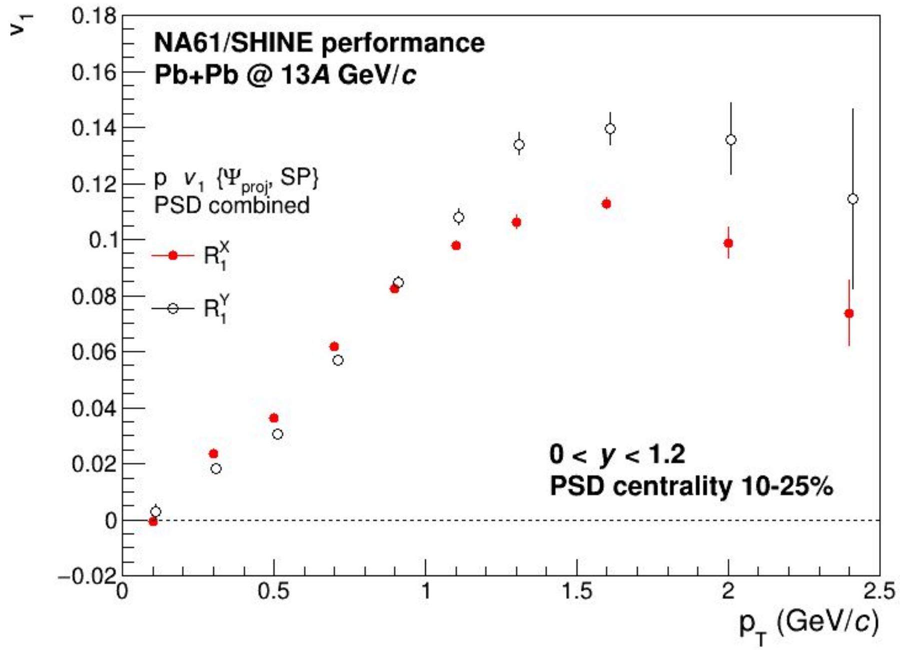


X/Y components are consistent

“Systematics” for directed flow (v_1) of protons



Consistent results for PSD subevents



X/Y difference: protons seen in TPC are deflected in the same direction as spectators in the PSD

Preliminary results for π^- and p: only X-component, PSD subevents are combined

NA61/SHINE Preliminary results

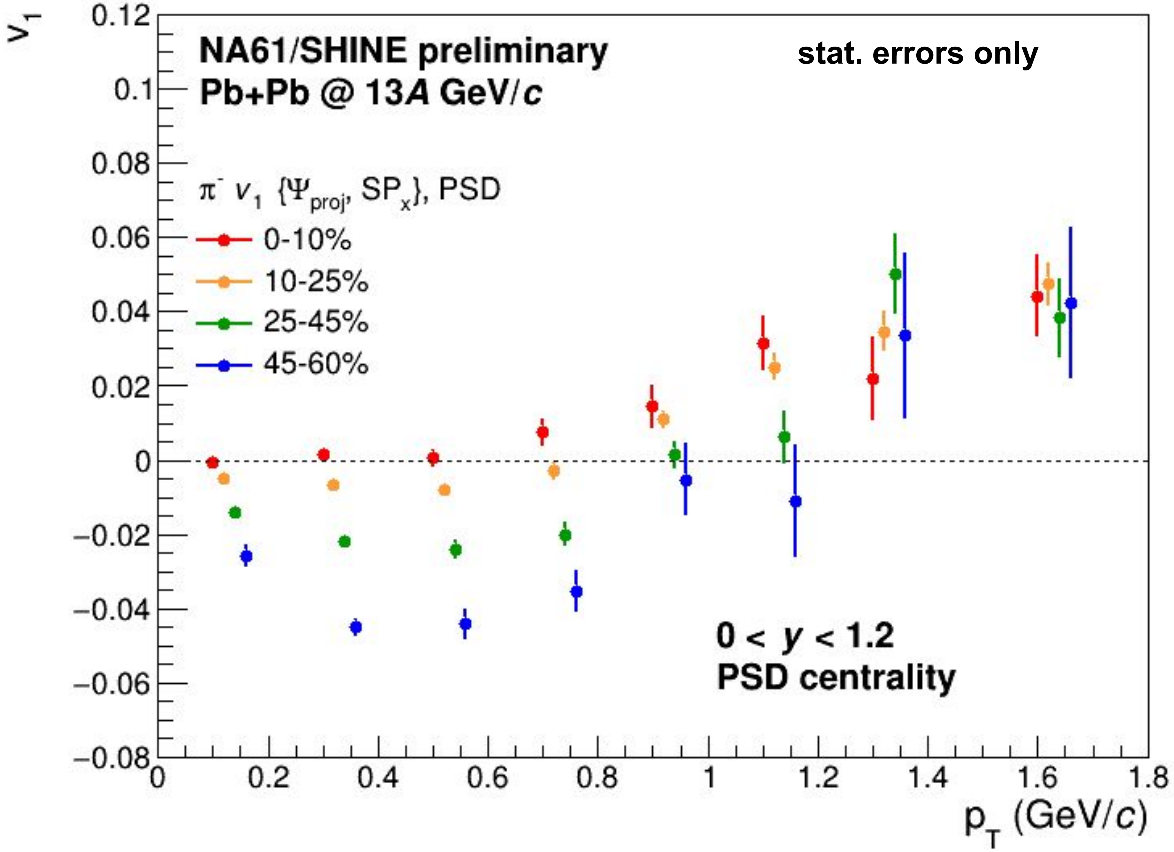
Results are presented for correlations between
charged pions and protons* (in the TPC acceptance) and
all hadrons at forward rapidity (in the PSD (VCAL) acceptance)

The results are corrected only for azimuthal detector non-uniformity.
No p_T/Y dependent efficiency correction applied.
No corrections for secondary interactions and weak decays are done yet.
Only statistical uncertainties are shown.
Most results are shown for the beam momentum of 13*A* GeV/*c* ($\sqrt{s_{NN}}$ = 5.1 GeV),
energy dependence plots contain results for 30*A* GeV/*c* ($\sqrt{s_{NN}}$ = 6.8 GeV)
and 40*A* GeV ($\sqrt{s_{NN}}$ = 7.7 GeV).

**hadrons produced by strong interaction and electroweak processes*

NA61/SHINE acceptance:
TPC https://edms.cern.ch/document/1549298/1

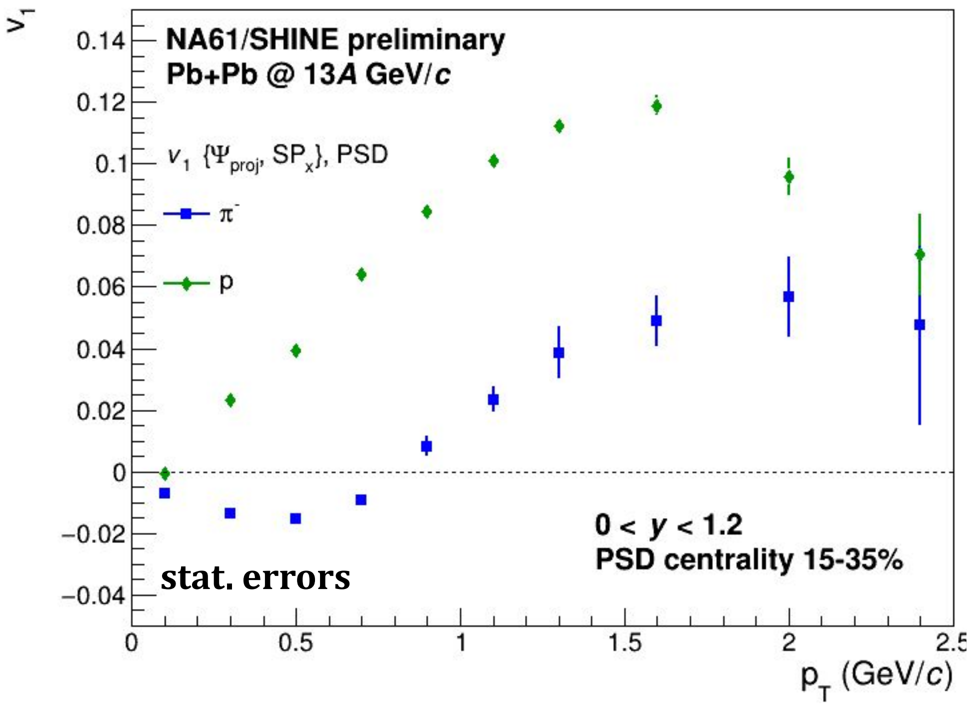
Negative pion v_1 vs transverse momentum

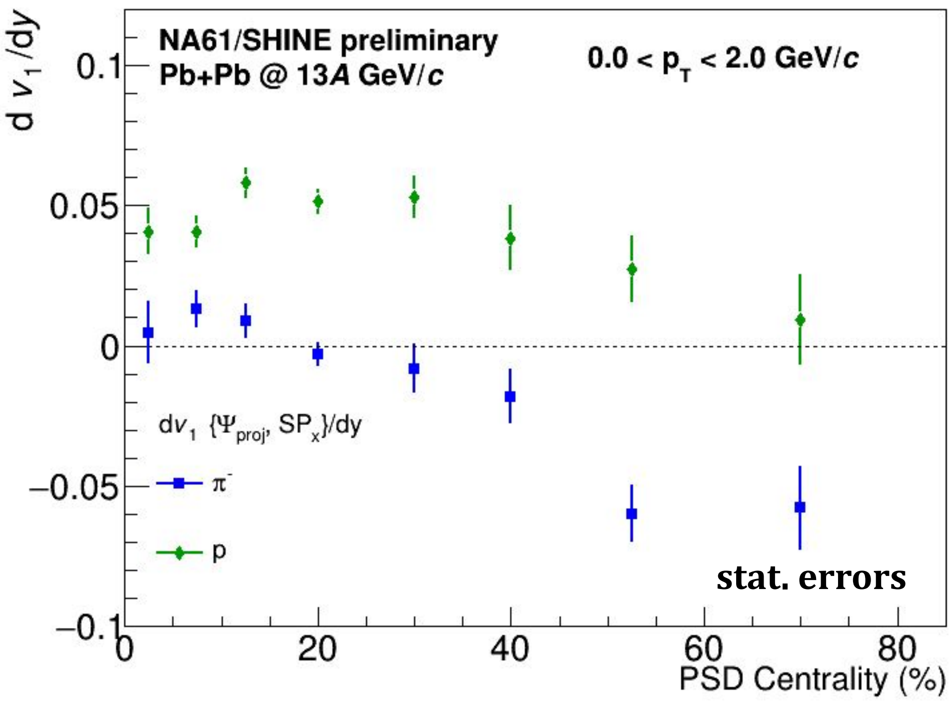


General features:

- Strong centrality dependence of v_1
- $v_1(p_T \sim 0$ GeV/*c*$) = 0$
- For mid-central v_1 changes sign at $p_T \sim 1$ GeV/*c*

Directed flow v_1 of protons and negative pions

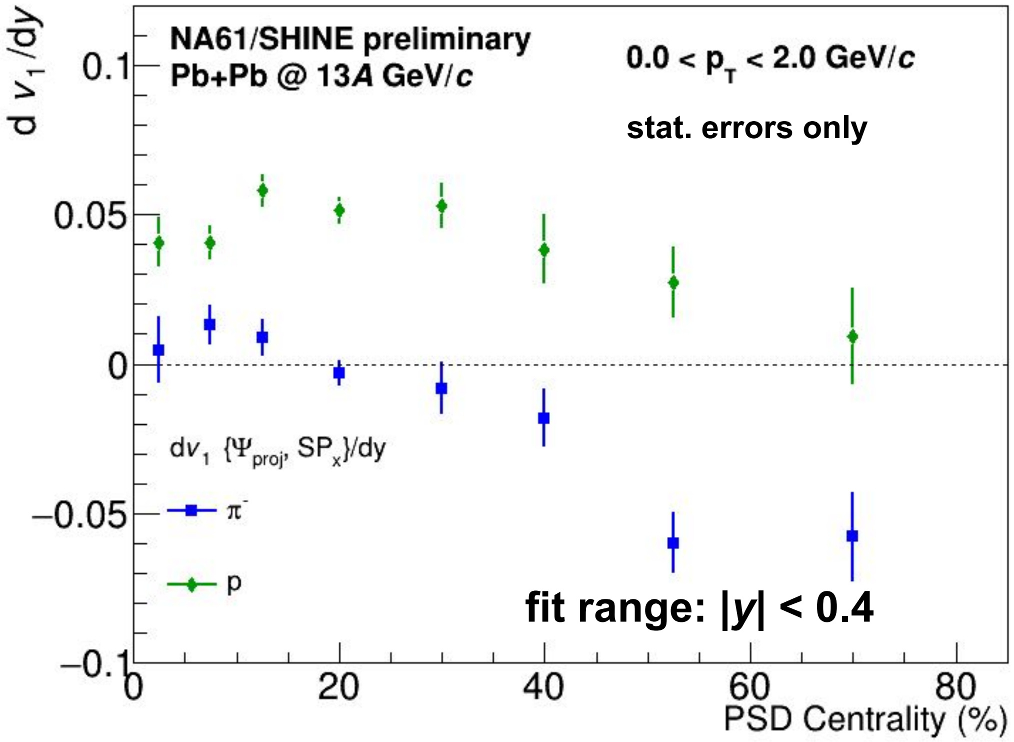




Observed strong mass, centrality, and energy dependence (more details in [1])

[1] E. Kashirin, et.al. [for the NA61/SHINE Collaboration] Phys.Part.Nucl. 51 (2020) 3, 301

Slope of v_1 at midrapidity vs. centrality



Slope extraction procedure:

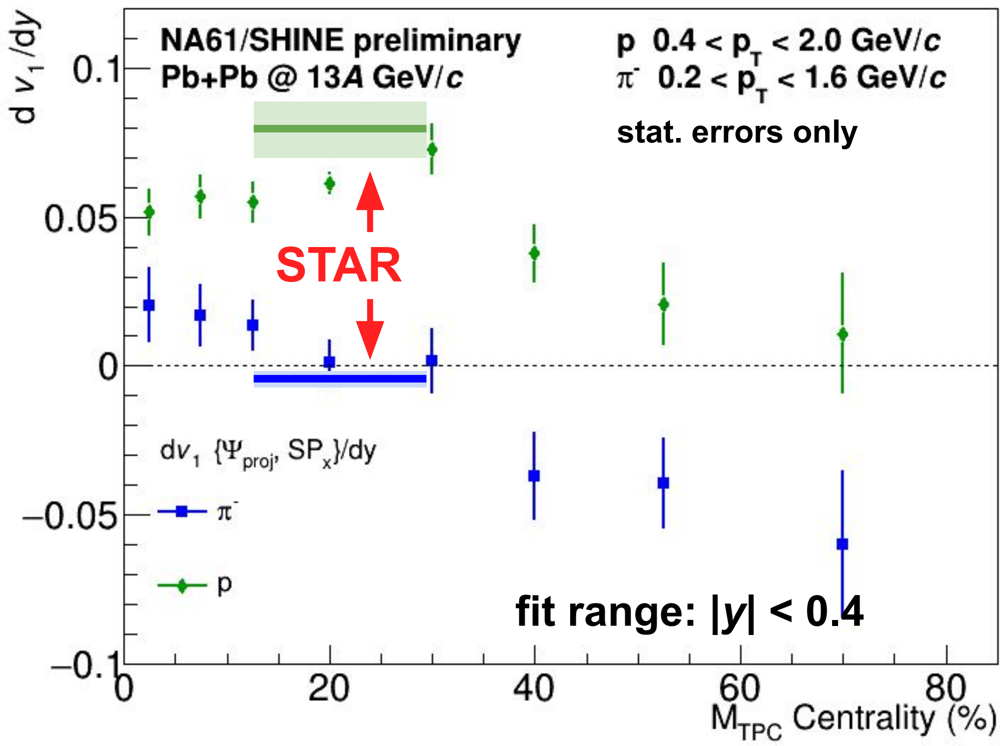
- 1st order polynomial fit with 2 parameters (slope and offset):
- Offset for protons is below $6x10^{-3}$ for centrality 0-60% and increasing up to $3x10^{-2}$ for centrality >60%.

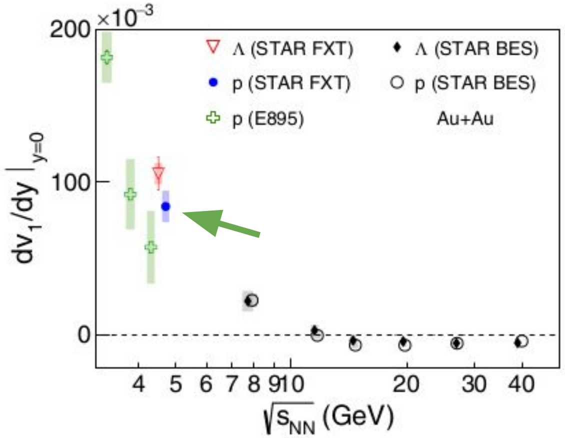
Observations:

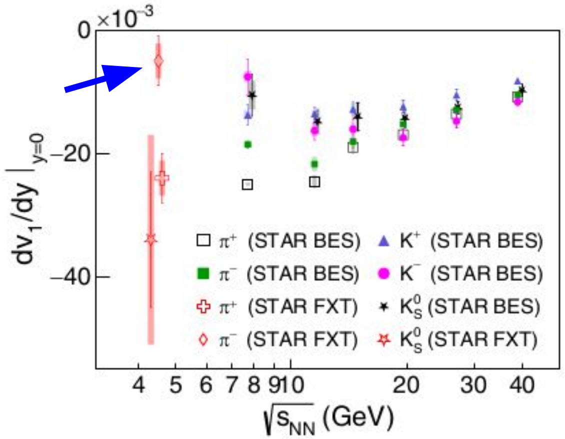
- Slope of proton v_1 changes sign at about 70% centrality
- Slope of pions v_1 changes sign at about 20% centrality

Slope extraction is sensitive to fit function and rapidity range

Slope of v_1 at midrapidity: comparison with STAR



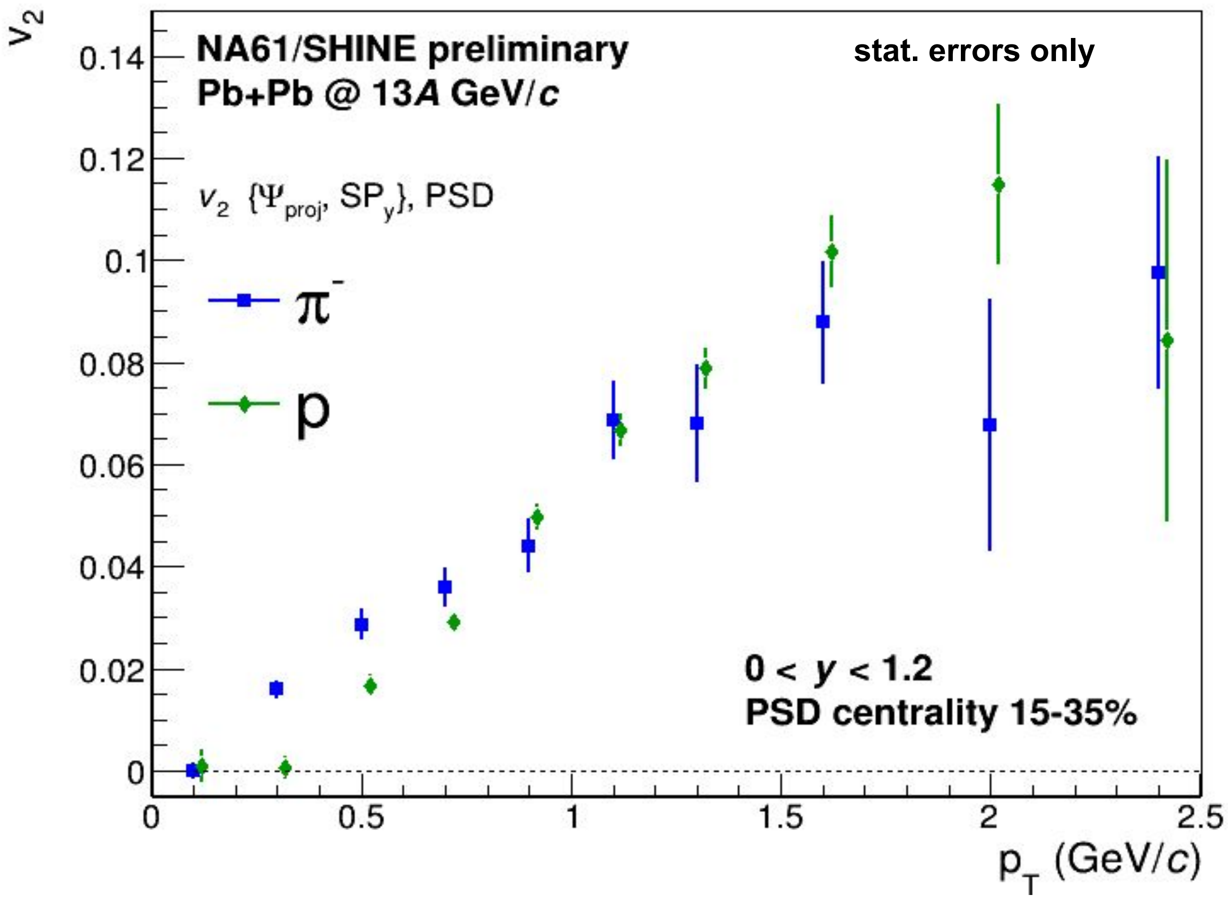




Proton and π⁻ selection is tuned to fit STAR fxt acceptance

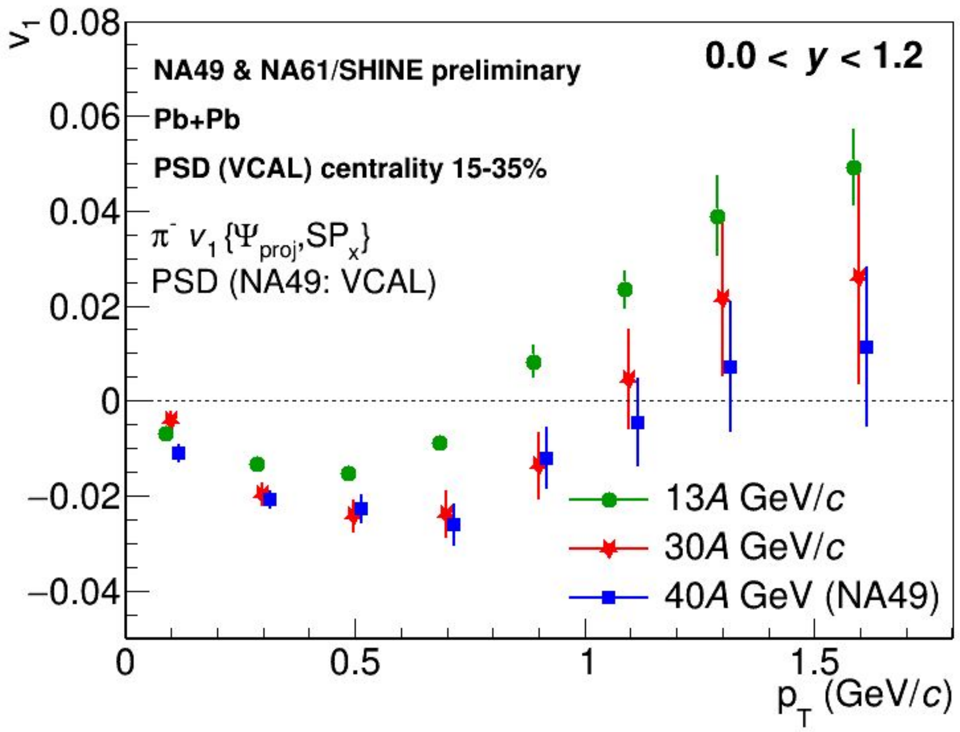
STAR Collaboration, PRC 103, 034908 (2021)c

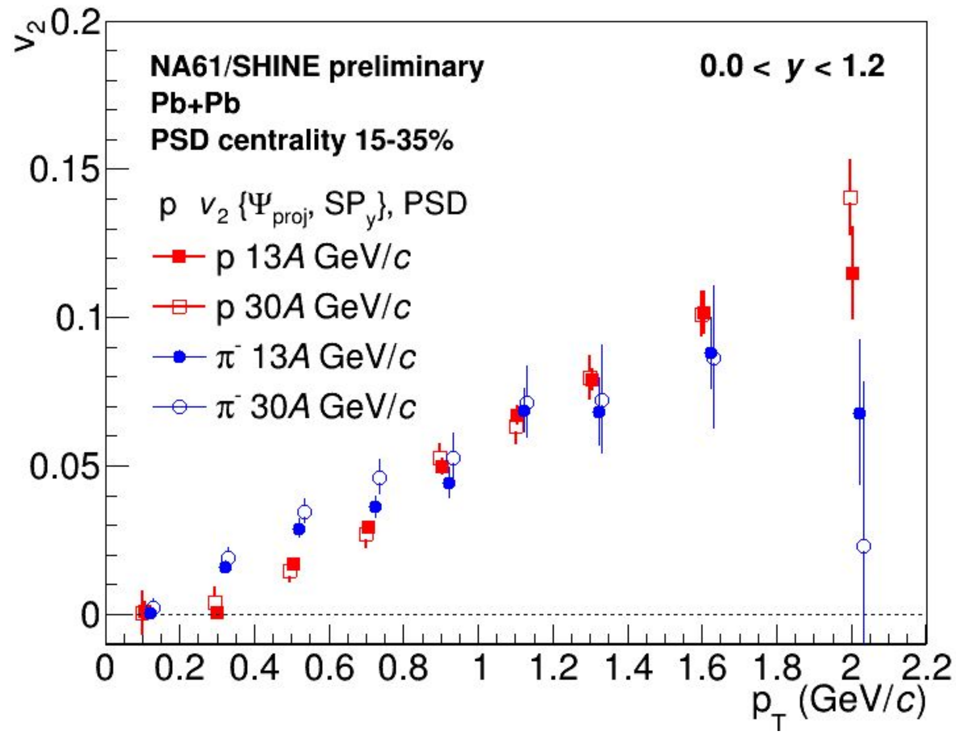
Elliptic flow v_2 of protons and negative pions



Clear mass dependence

Directed and elliptic flow energy dependence





- strong energy dependence
- change of sign moves to high-p_T with increasing energy

Weak energy dependence

Summary

Presented NA61/SHINE preliminary results for π^- and proton v_1 and v_2 for Pb+Pb @ 13A GeV/c

- differentially vs centrality, y, and p_T
- compared to STAR FXT and available data from SPS NA49 and NA61/SHINE

Outlook

- Complete systematic analysis of the Pb ion beam energy scan data:
  150A GeV/c (latest run in 2018)
- Complete analysis of π^+ for 13 and 30A GeV/c (utilizing Bayesian PID)
- Collective effects scan with smaller systems (Be+Be, Ar+Sc, Xe+La) and beam energies (13-150A GeV/c)