Anisotropic flow measurements from the NA61/SHINE beam momentum scan program at the CERN SPS

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Results approved by the NA61/SHINE Collaboration

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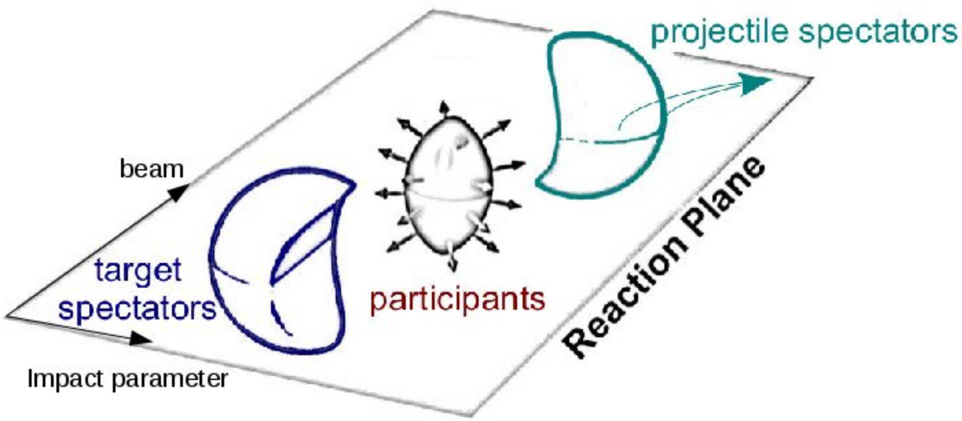
Collision geometry and the anisotropic transverse flow

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

$$\rho(\phi) = \frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n(\varphi - \Psi_{RP})\right]\right)$$

$$v_n = \langle \cos n(\varphi - \Psi_{RP}) \rangle$$

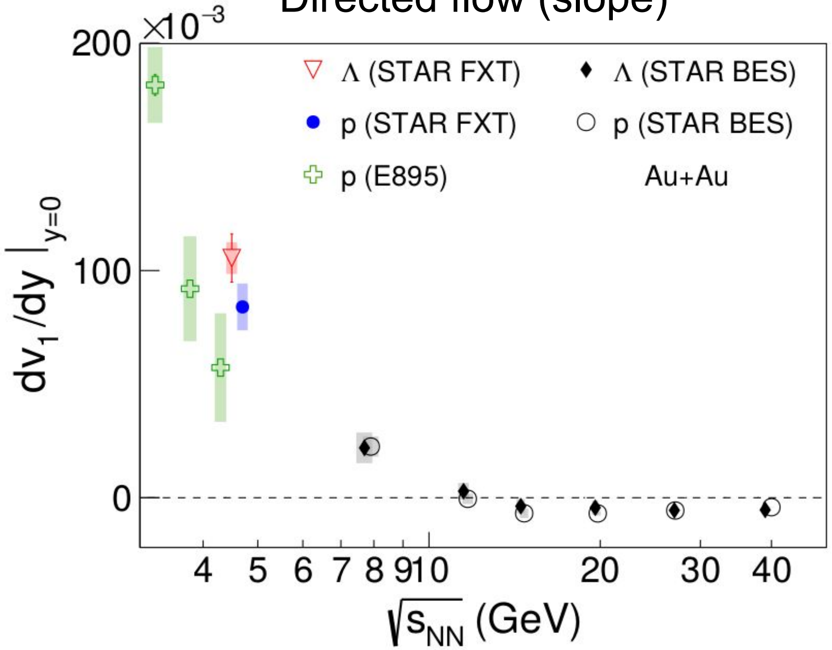


Components needed to calculate v_n

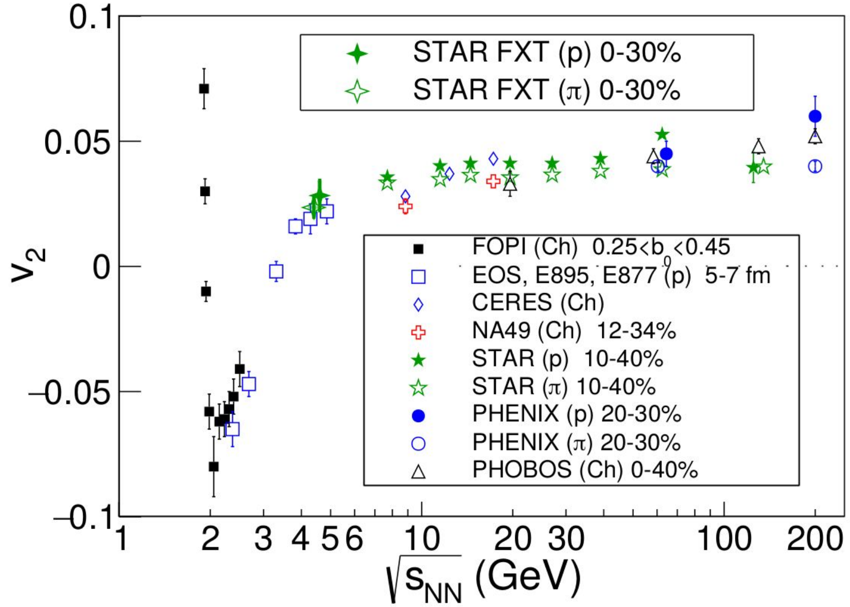
- momentum (ϕ, y, p_T)
- centrality estimation
- particle identification
- Ψ_{RP} estimate with symmetry planes of
  - participants
  - projectile / target spectators

Collective flow at different energies

Directed flow (slope)



Elliptic flow



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
  - bridge to FAIR/GSI and NICA beam energies
- Advantage of fixed target setup
  - forward rapidity tracking with TPC
  - projectile spectators energy with forward calorimeter

Collective flow at different energies

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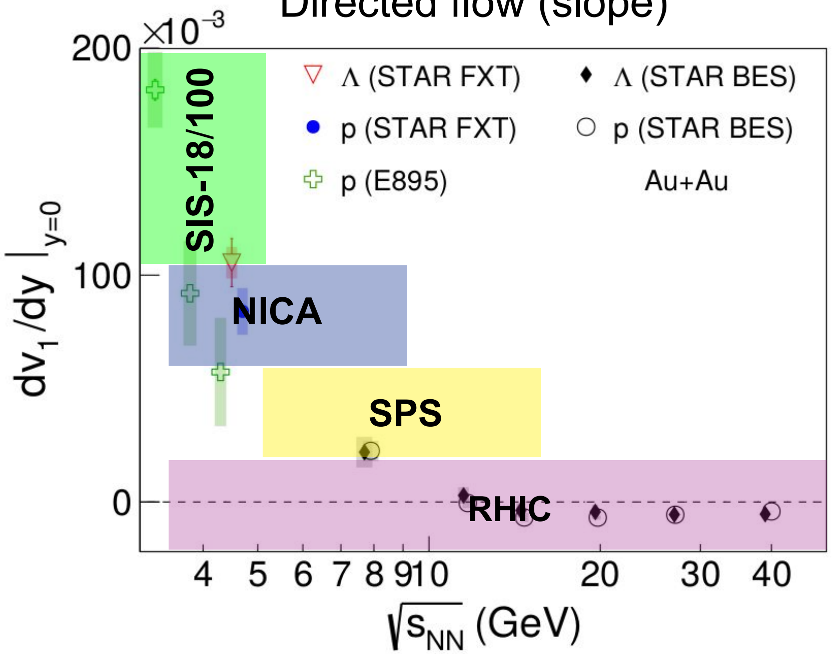

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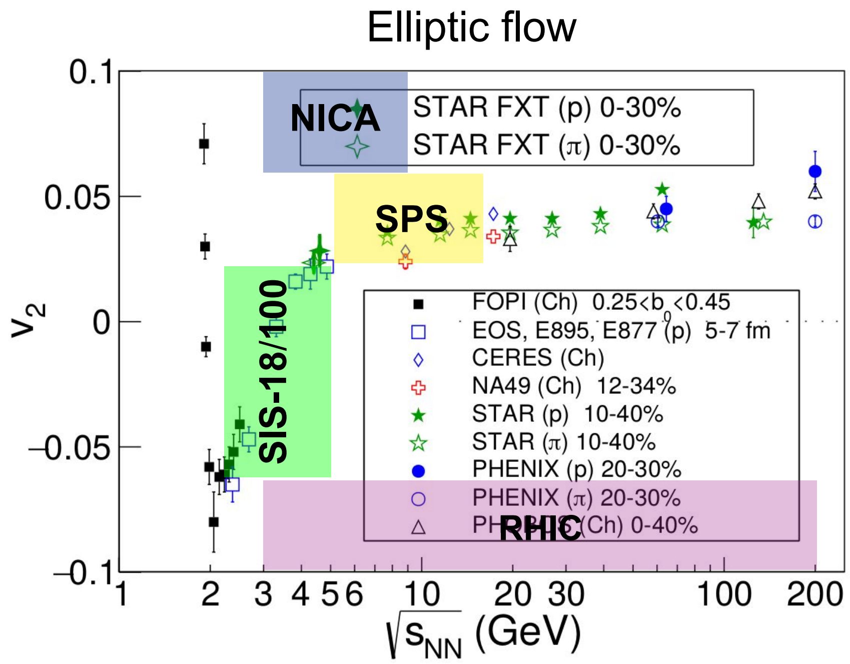

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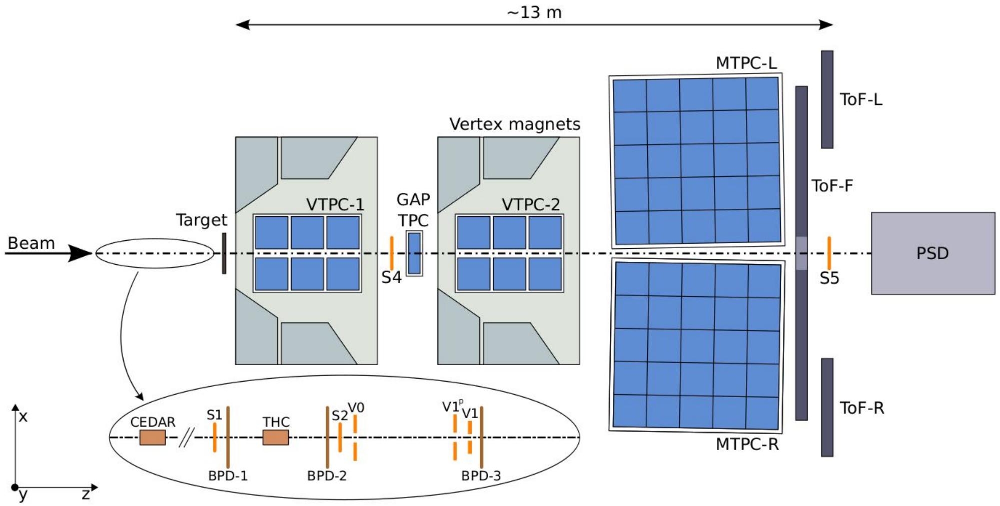
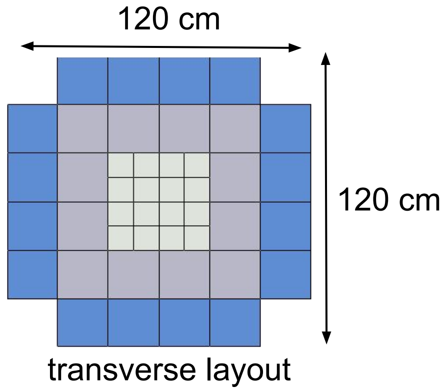
NA61/SHINE experiment



Projectile Spectator Detector (PSD)



- Large acceptance hadron spectrometer (TPC)
  - full coverage of forward hemisphere
  - tracking + identification with dE/dx down to p_T ~ 0 GeV/*c*
- 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

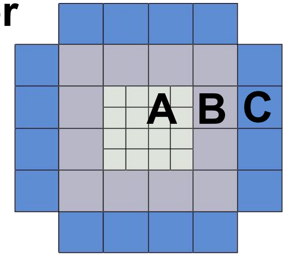
u-vector

$$\mathbf{u_n} = (u_{n,x}, u_{n,y}) = (\cos(n\phi), \sin(n\phi))$$

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

PSD subevents Q_1-vector

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



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

$$\alpha, \beta, \gamma = x, y$$

Directed flow:

$$v_{1,\alpha}\{S\} = \frac{2\langle u_{1,\alpha} Q^S_{1,\alpha}\rangle}{R^S_{1,\alpha}}$$

6 independent combinations

Elliptic flow:

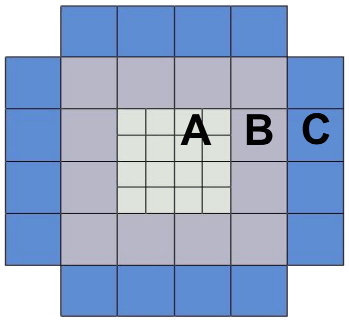
$$v_{2,\alpha\beta\gamma}\{S1, S2\} = \frac{4\langle u_{2,\alpha} Q^{S1}_{1,\beta} Q^{S2}_{1,\gamma}\rangle}{R^{S1}_{1,\beta} R^{S2}_{1,\gamma}}$$

12 non-zero combinations

R_1^S – resolution correction factor for the subevent S *(see the following slide)*

3 PSD + 1 TPC subevents resolution

PSD



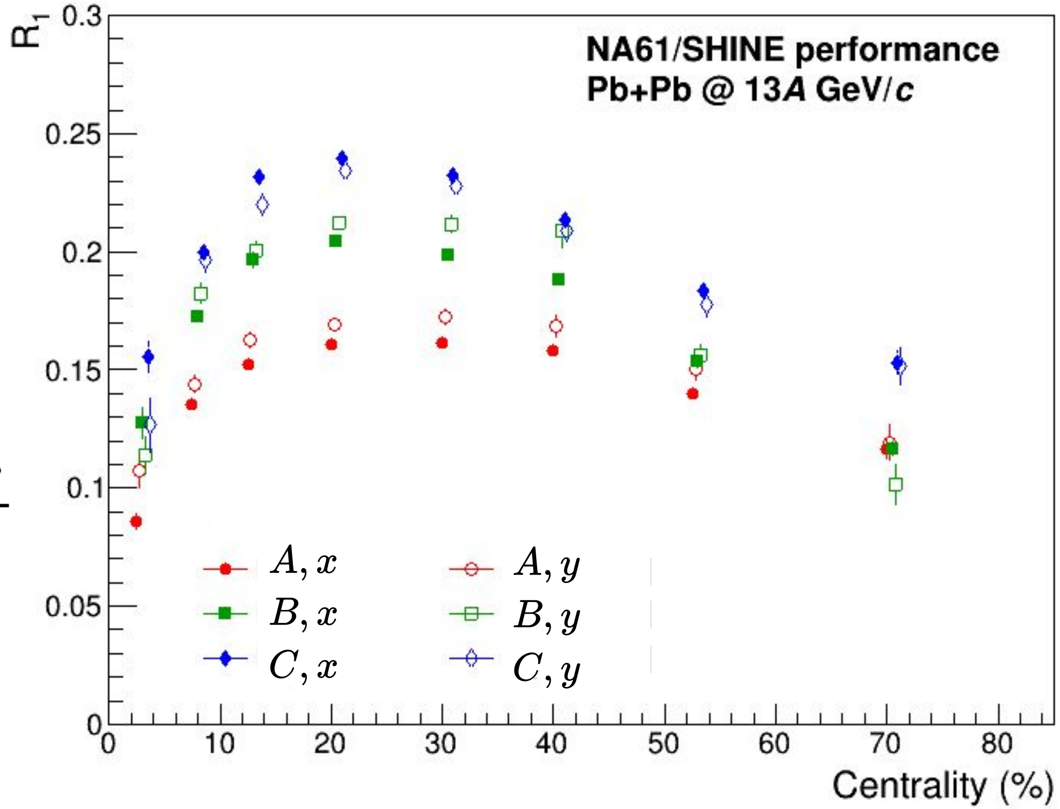
+ Q_1^{TPC}

protons

$0.8 < y < 1.2$

$p_T > 0$

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

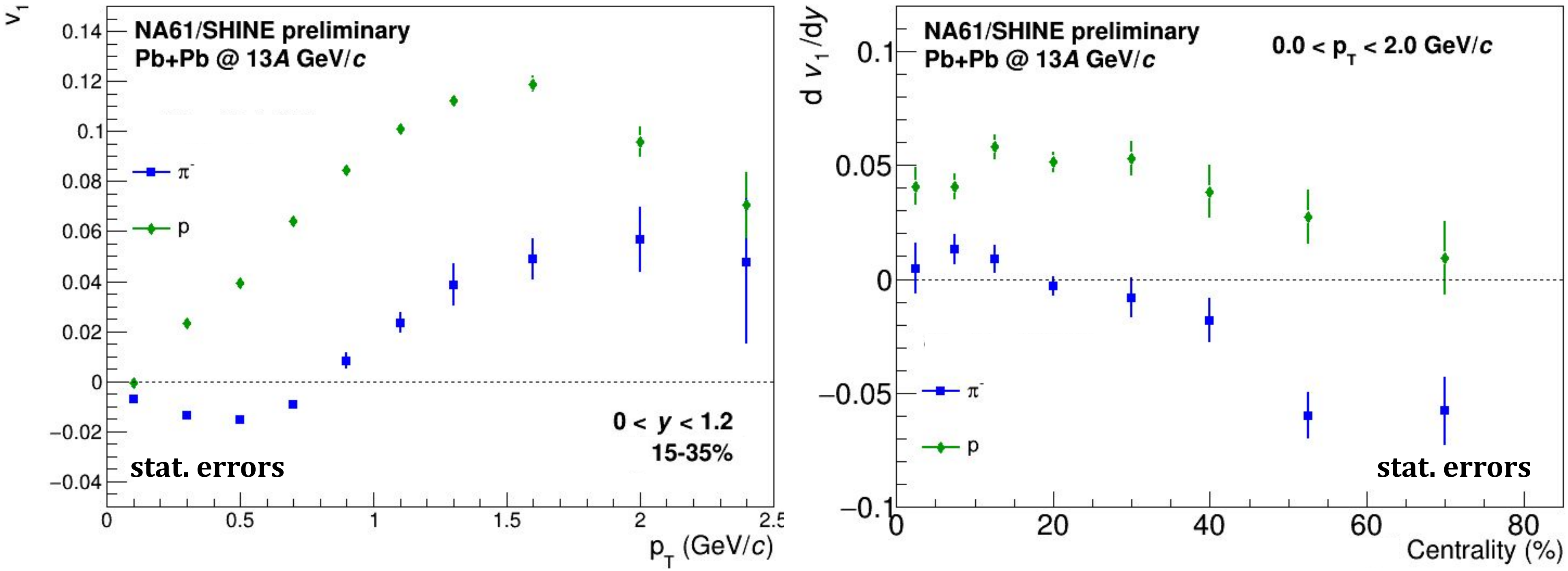


TPC subevent resolution:

$$R^{T}_{1,\alpha} = \sqrt{\frac{\langle Q^{T}_{1,\alpha} Q^{C}_{1,\alpha}\rangle \langle Q^{T}_{1,\alpha} Q^{B}_{1,\alpha}\rangle}{\langle Q^{B}_{1,\alpha} Q^{C}_{1,\alpha}\rangle}} \qquad \alpha = x, y$$

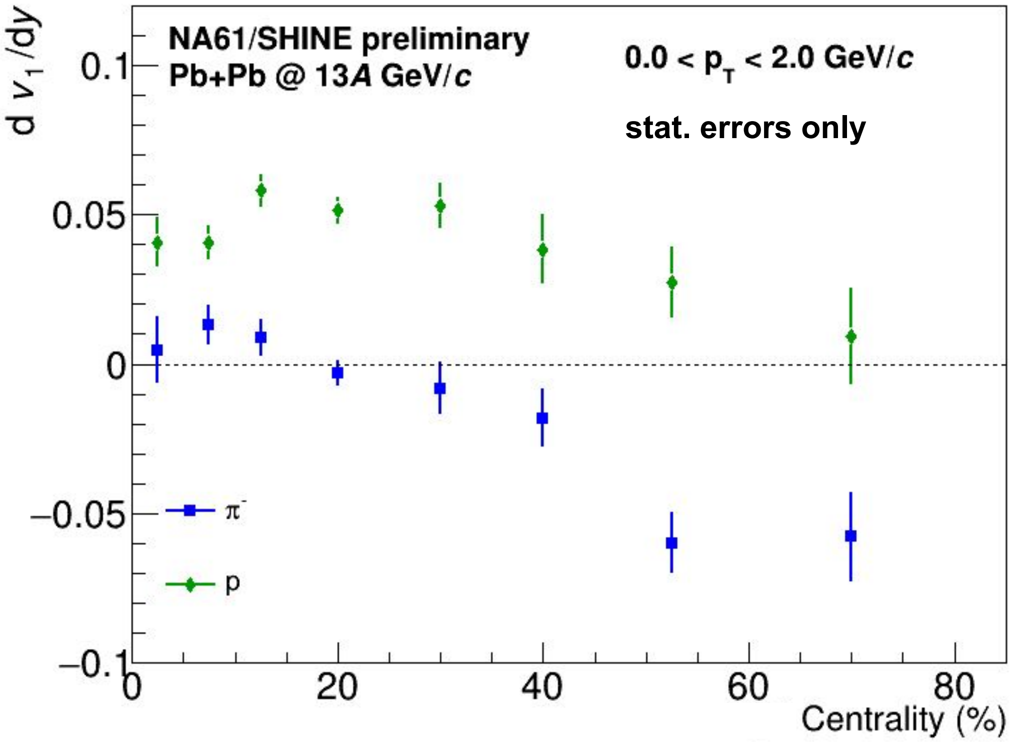
Additional correlations are suppressed by using pseudorapidity-separated subevents.

Directed flow v_1 of protons and negative pions



Strong mass and centrality dependence

Slope of v_1 at midrapidity: centrality dependence



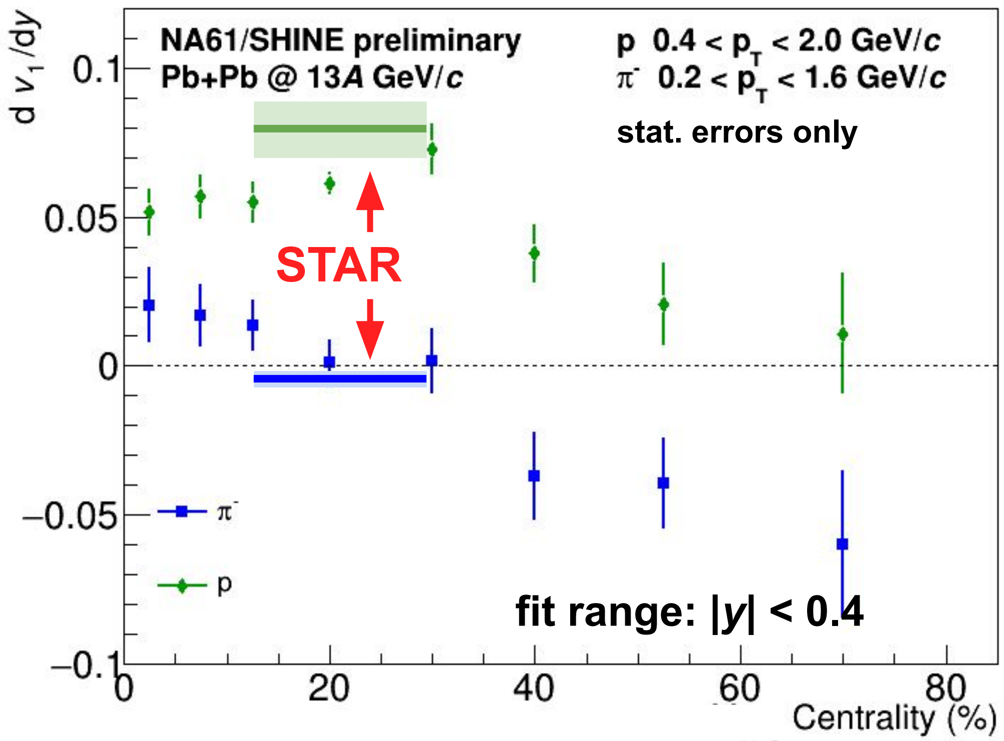
Slope extraction procedure:

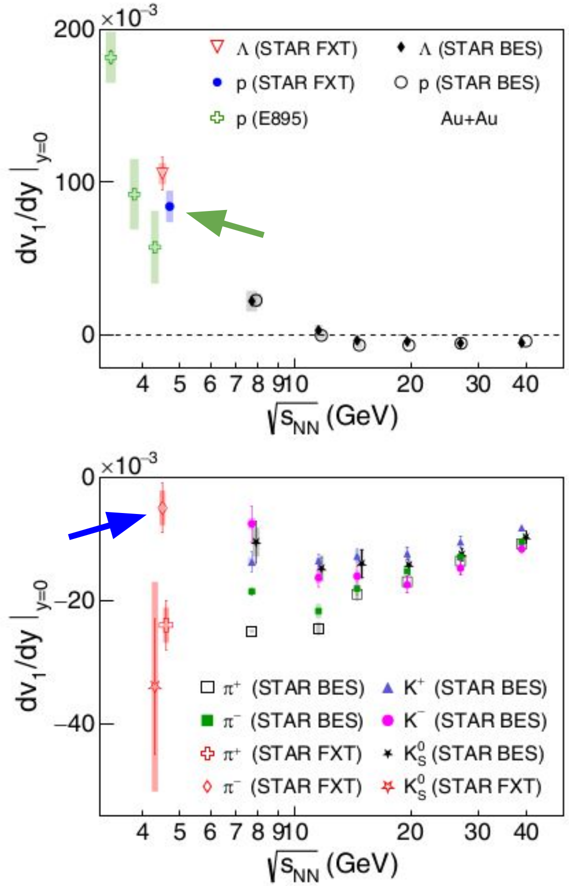
- 1st order polynomial fit with 2 parameters (slope and offset) at $|y| < 0.4$.
- Slope extraction is sensitive to fit function and rapidity range

Observations:

- Offset for protons is below 6×10^{-3} for centrality 0-60% and increases up to 3×10^{-2} for centrality > 60%.
- Slope of v_1 changes sign at
  - 70% centrality for protons
  - 20% centrality for pions

Slope of v_1 at midrapidity: comparison with STAR





- Proton and π⁻ selection is tuned to fit STAR fxt acceptance
- Centrality estimation is based on track number

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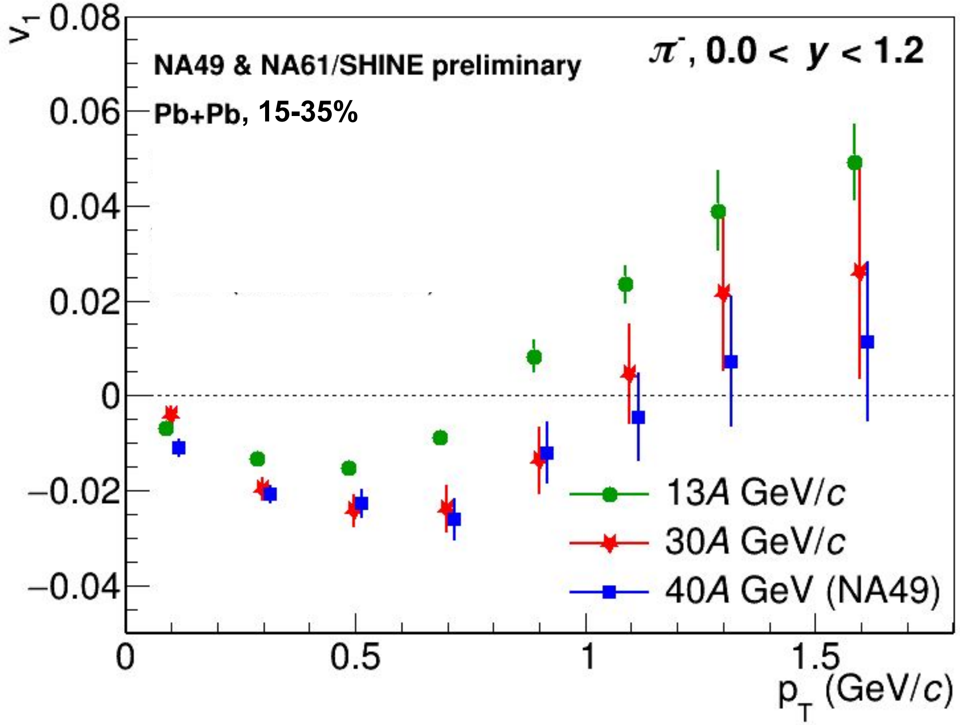
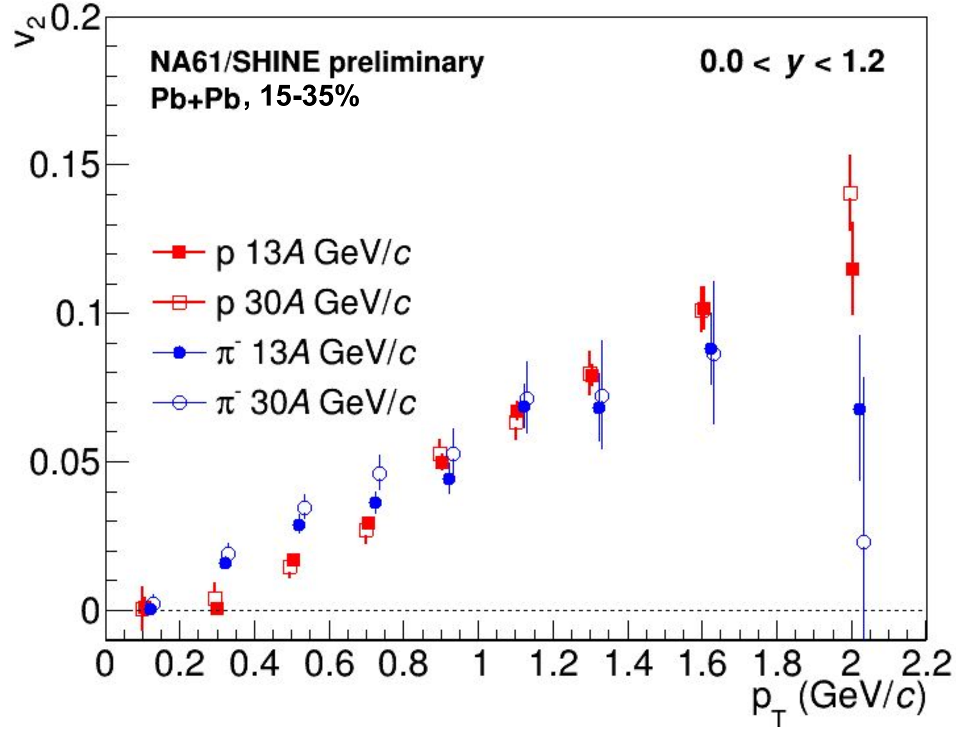
Directed and elliptic flow energy dependence





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

- clear mass dependence
- weak energy dependence

Summary

Presented NA61/SHINE preliminary results for π^- and proton v_1 and v_2 for Pb+Pb @ 13A and 30A GeV/c relative to projectile spectator symmetry plane

- differentially vs centrality, y, and p_T
- good agreement with results from STAR FXT and reanalysis of NA49 data

Outlook

- Complete systematic analysis for 13 and 30A GeV/c
- Comparisons with available models
- Collective effects scan with beam momentum (13-150A GeV/c) and system size (Be+Be, Ar+Sc, Xe+La) and