Anisotropic flow measurements from NA61/SHINE and NA49 scans at SPS

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For the NA61/SHINE and NA49 Collaborations

ICPPA-2020
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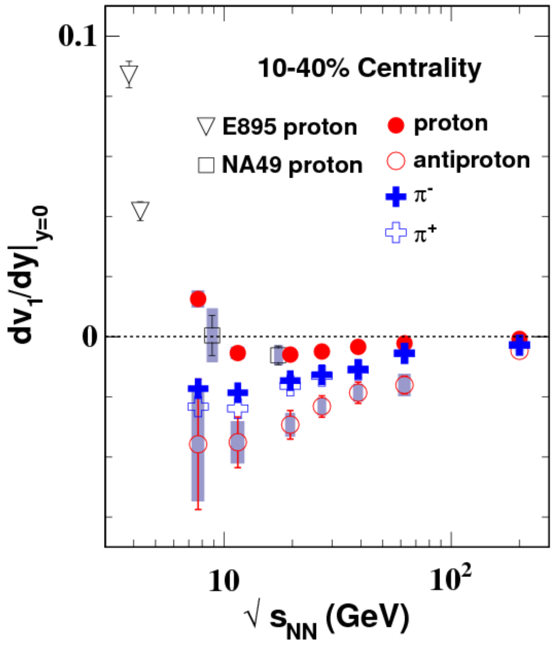
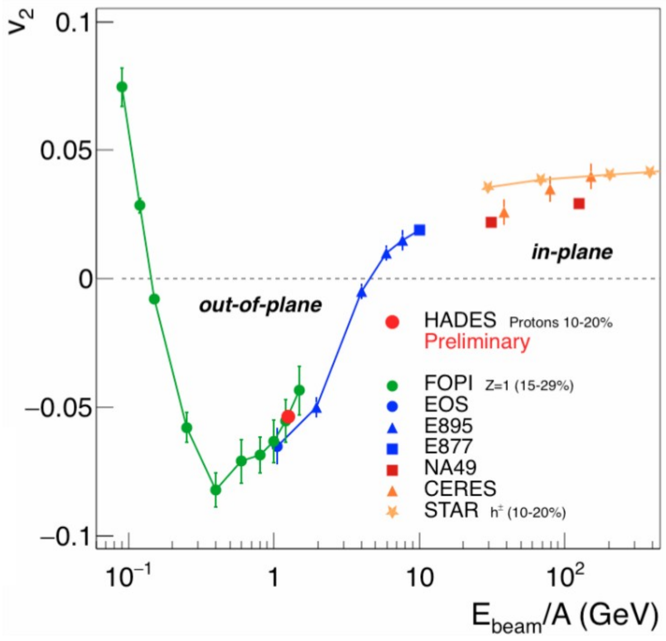
Collective flow at different energies

Directed flow (slope)



STAR Collaboration
PRL 112 (2014) 162301

Elliptic flow



HADES Collaboration
JPCS 742 (2016) 012008

- NA49 and NA61/SHINE Pb-ion beam energy scan (p_{LAB} = 13-158*A* GeV/*c*):
  - complementary to STAR@RHIC and NICA
  - bridge to FAIR/GSI beam energies
- Advantage of NA61/SHINE (NA49) fixed target setup
  - forward rapidity tracking with TPC
  - projectile spectators (forward calorimeter – PSD (VCAL))

Collective flow at different energies

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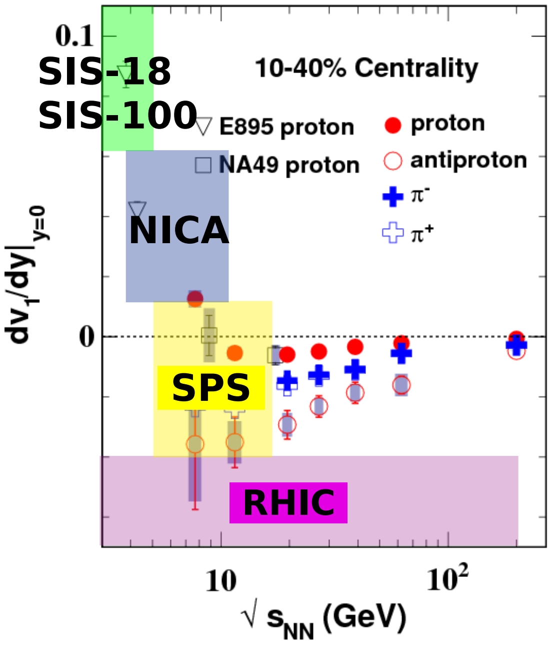

STAR Collaboration
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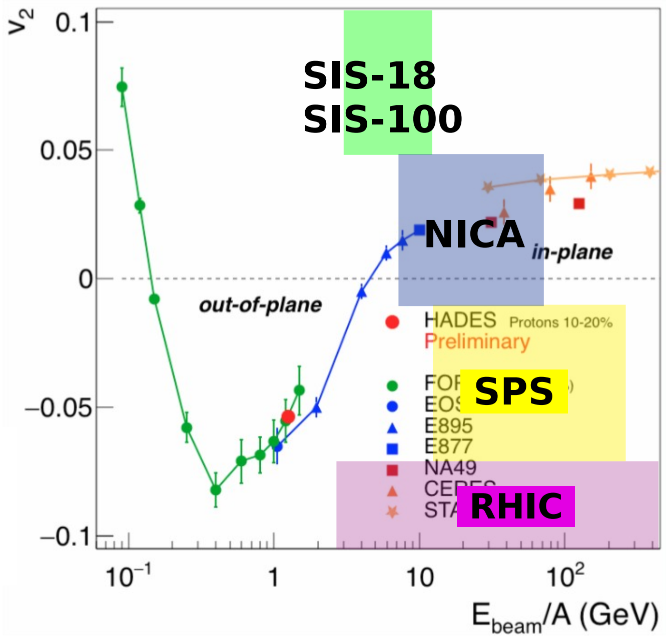
Elliptic flow



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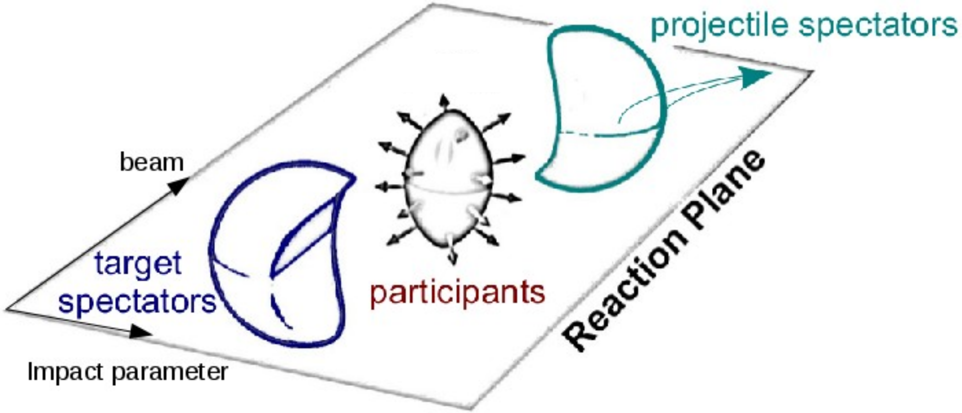
Collision geometry and the anisotropic transverse flow

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

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

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

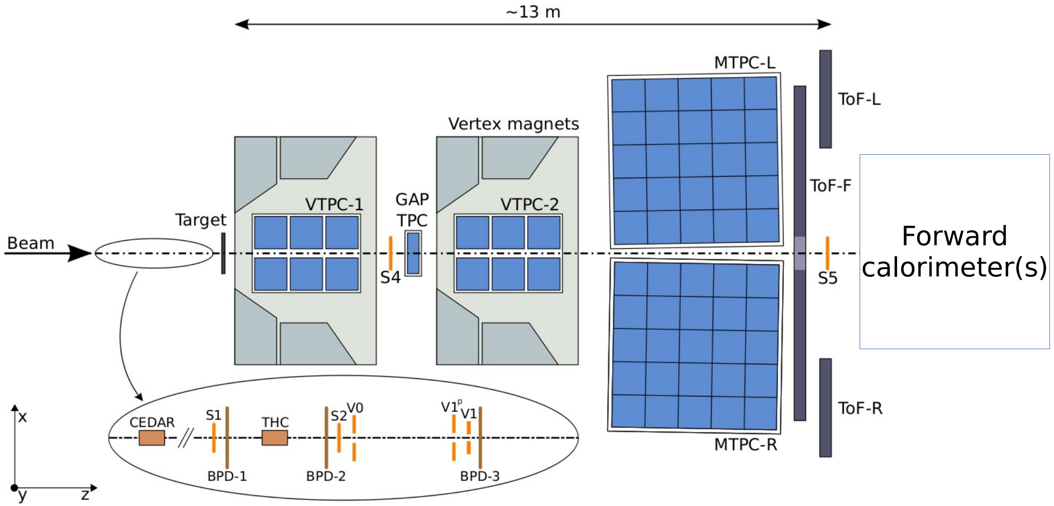


Ψ_s can be estimated with produced particles Ψ_{pp} or with projectile (target) spectators Ψ_{proj} (Ψ_{spec})

Needed components to calculate v_n:

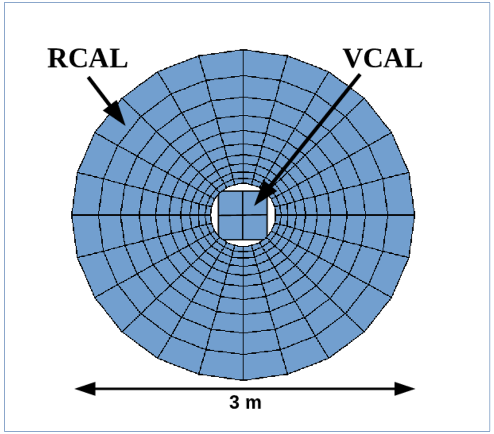
- momentum (ϕ, y, p_T)
- centrality estimation
- particle identification
- Ψ_s estimation

Pb beam energy scan with NA49 and NA61/SHINE

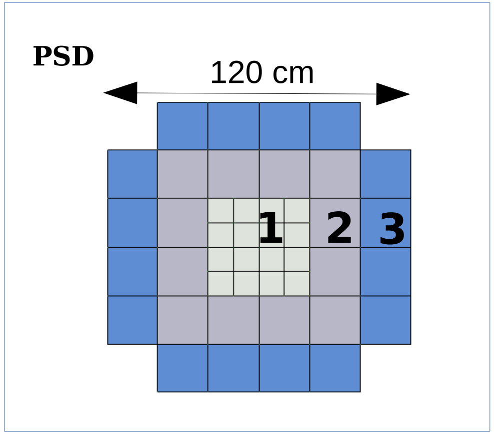


- Four large-acceptance TPC-s
  - full coverage of forward hemisphere
  - tracking + identification down to $p_T \sim 0$ GeV/c
- Forward rapidity calorimeter
  NA49: Ring (RCAL) + Veto (VCAL) calorimeters
  NA61/Shine: Projectile spectator detector (PSD)
- Pb+Pb beam energy (momentum) scan:
  NA49: 20*A*, 30*A*, ***40A***, 80*A*, 158*A* GeV data
  NA61/Shine: ***13A, 30A***, 150*A* GeV/*c*

NA49:



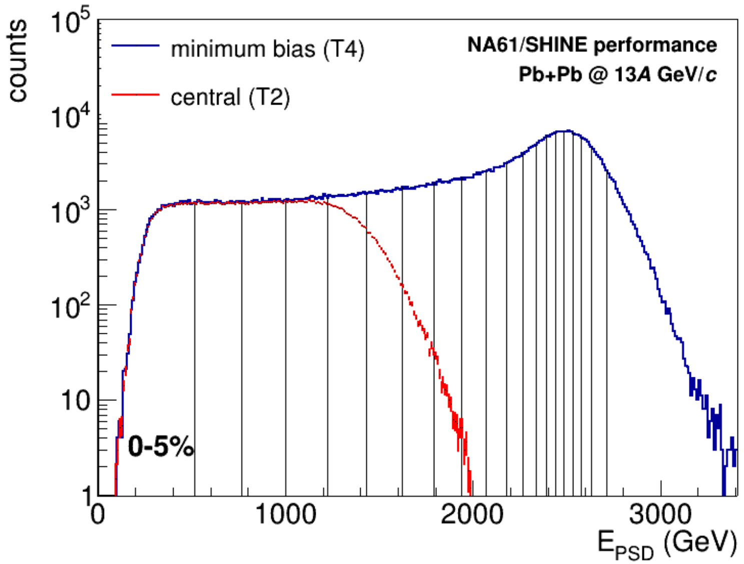
NA61/Shine:



Event & tracks selection, centrality estimation

Event Selection:

- Event has fitted vertex
- Good reconstructed vertex position
- Good beam position
- No overlap events



Centrality estimated using energy in PSD

Track selection:

Number of clusters:

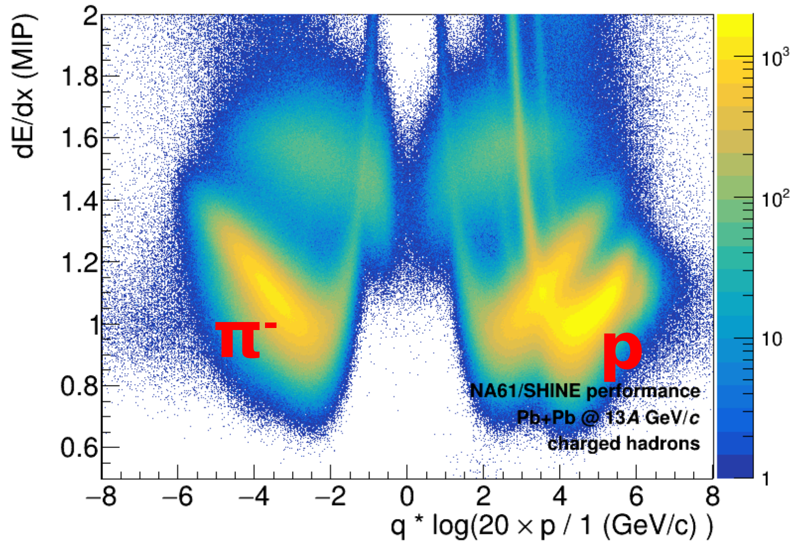
$N_{clusters}$ [VTPC1+VTPC2] > 15

$N_{clusters}$ [Total] > 30

$0.55 < N_{cl}[\text{ Total }] / N_{cl}[\text{ Total, Pot }] < 1.1$

Distance of closest approach to vertex

$|b_x| < 2$ cm; $|b_y| < 1$ cm



Negative pions and protons identified using track energy losses (dE/dx)

Scalar product method with 1st harmonic Q-vector

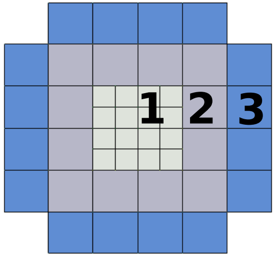
***TPC u*-vector**

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

PSD subevents Q-vector

$$Q_{1,i}^{A} = \frac{1}{E_A} \sum_{j=1}^{N_A} E_j u_{1,i}^{j} \quad i = [x, y]$$

A,B,C – PSD subevents



Directed flow:

$$v_{1,i} = \frac{2\langle u_{1,i} Q_{1,i}^{A} \rangle}{R_{1,i}^{A}}$$

6 combinations

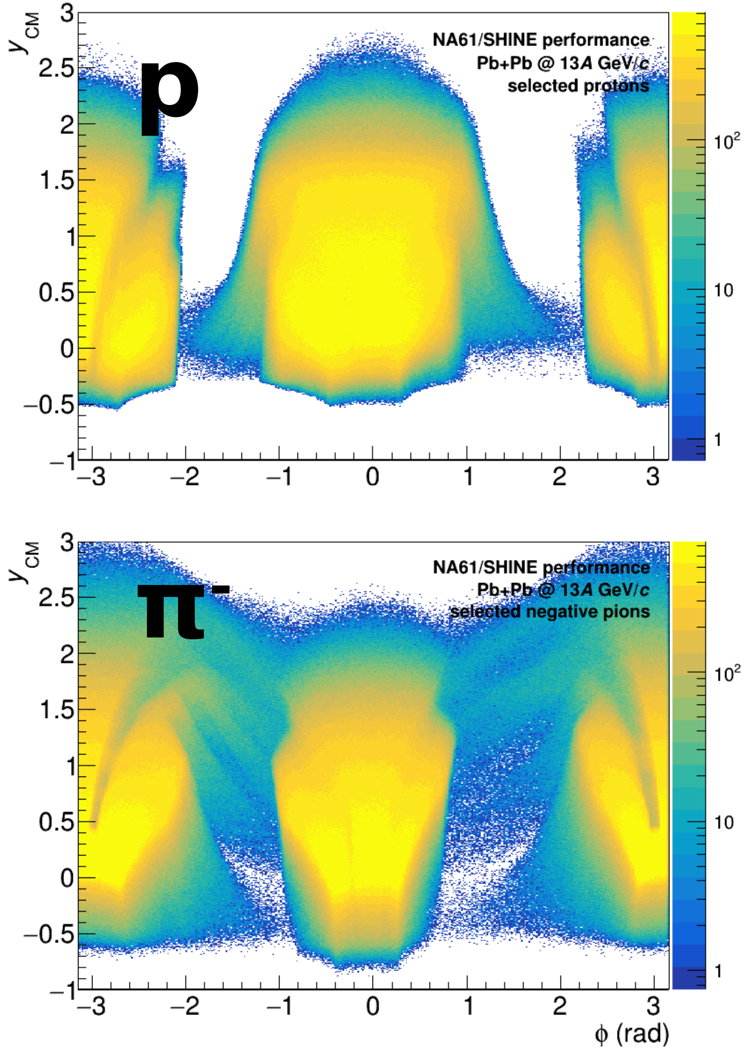
Elliptic flow:

$$v_2 = \frac{4\langle u_{2,i} Q_{1,j}^{A} Q_{1,k}^{B} \rangle}{R_{1,j}^{A} R_{1,k}^{B}}$$

12 combinations

R_1^A – resolution correction factor

Corrections for detector azimuthal non-uniformity



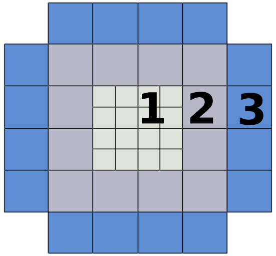
QnVector Corrections Framework

- Data driven corrections for azimuthal acceptance non-uniformity
  I. Selyuzhenkov and S. Voloshin [PRC77 034904 (2008)]
- QnVector Corrections Framework (used by ALICE)
  J. Onderwaater, V. Gonzalez, I. Selyuzhenkov
  https://github.com/FlowCorrections/FlowVectorCorrections
- Recentering, twist, and rescaling corrections applied
  time dependent (run-by-run) and as a function of centrality

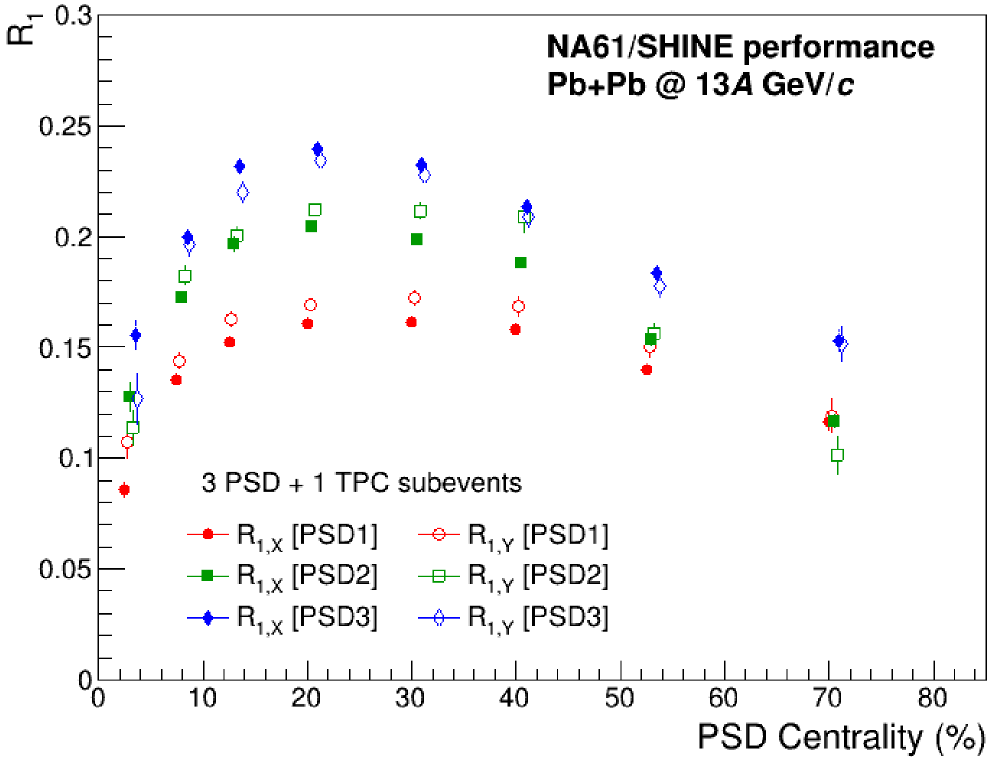
QnTools Framework

- Extended flow-vector corrections for p_T/y-differential
- Multi-dimensional correlations of flow-vectors
  L. Kreis (GSI / Heidelberg) and I. Selyuzhenkov (GSI / MEPhI)
  https://github.com/HeavyIonAnalysis/QnTools

3 PSD + 1 TPC subevents resolution

PSD  $+ \; Q_1^{\mathrm{TPC}}$

protons $0.8 < y < 1.2$



PSD subevents EP resolution factors

$$R_{P1} = \langle Q_{P1} Q_{P3} \rangle R_T / \langle Q_T Q_{P3} \rangle$$

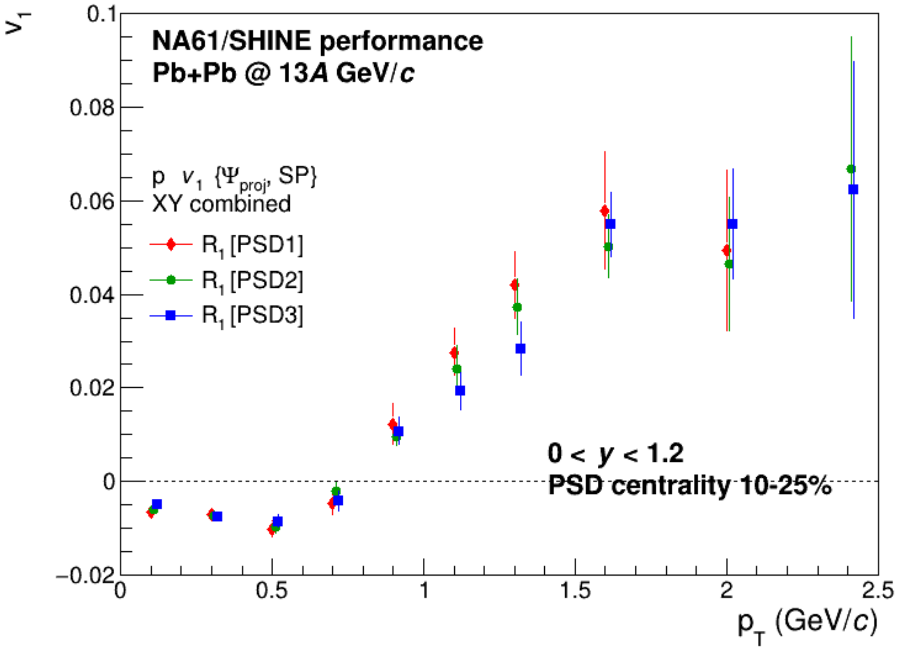
$$R_{P2} = \langle Q_{P2} Q_T \rangle / R_T$$

$$R_{P3} = \langle Q_{P3} Q_{P1} \rangle R_T / \langle Q_T Q_{P3} \rangle$$

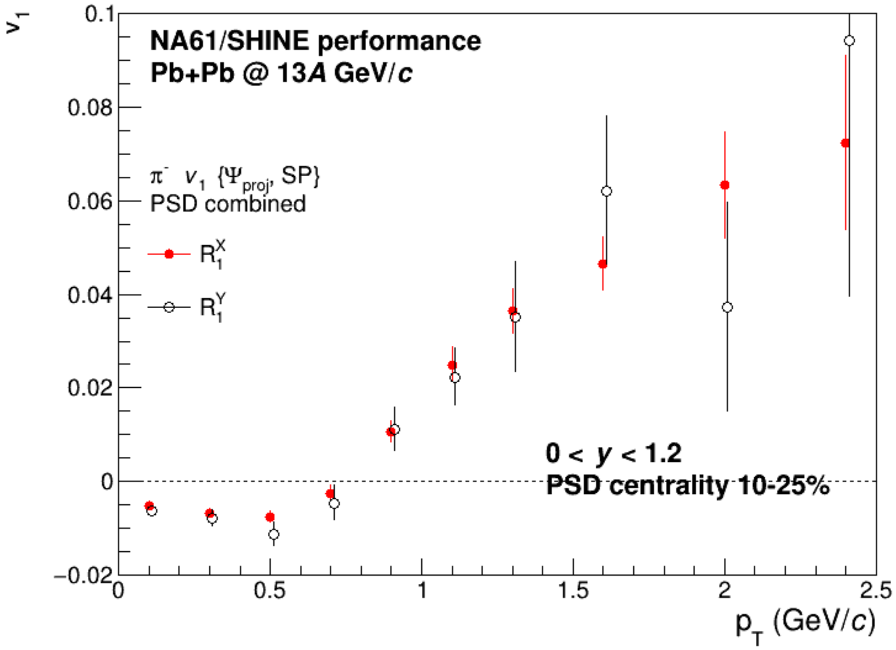
TPC subevent EP resolution factor

$$R_T[Q_{P1}, Q_{P3}] = \sqrt{2 \frac{\langle Q_T Q_{P1} \rangle \langle Q_T Q_{P3} \rangle}{\langle Q_{P3} Q_{P1} \rangle}}$$

“Systematics” for directed flow (v_1) negative pions



Consistent results for PSD subevents



x/y components are consistent

NA61/SHINE Preliminary results

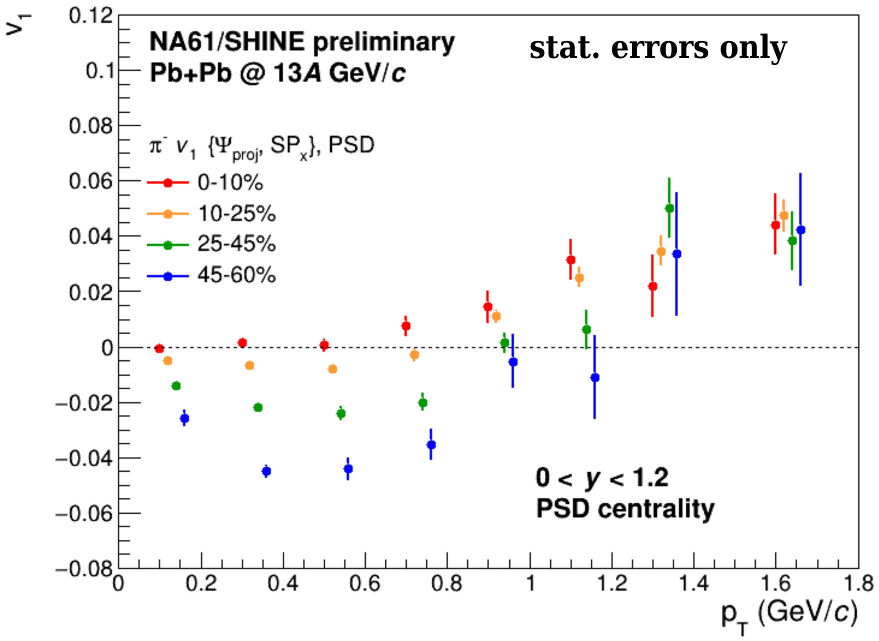
Results are presented for correlations between
charged pions and protons* (in the TPC acceptance) and
all hadrons at forward rapidity (in the PSD (VCAL) acceptance)

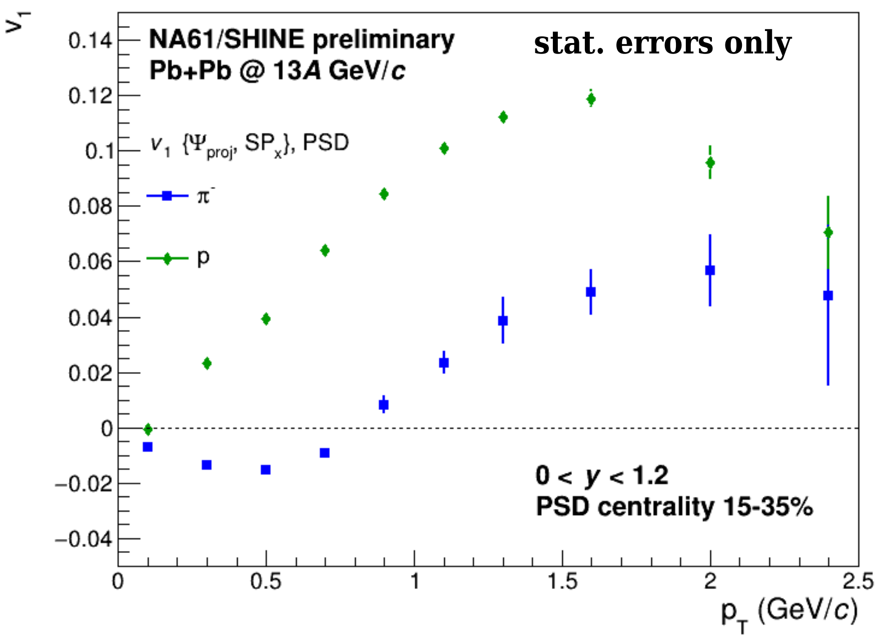
The results are corrected only for azimuthal detector non-uniformity.
No p_T/Y dependent efficiency correction applied.
No corrections for secondary interactions and weak decays are done yet.
Only statistical uncertainties are shown.

**hadrons produced by strong interaction processes and their electromagnetic decays*

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

Negative pion v_1 vs transverse momentum



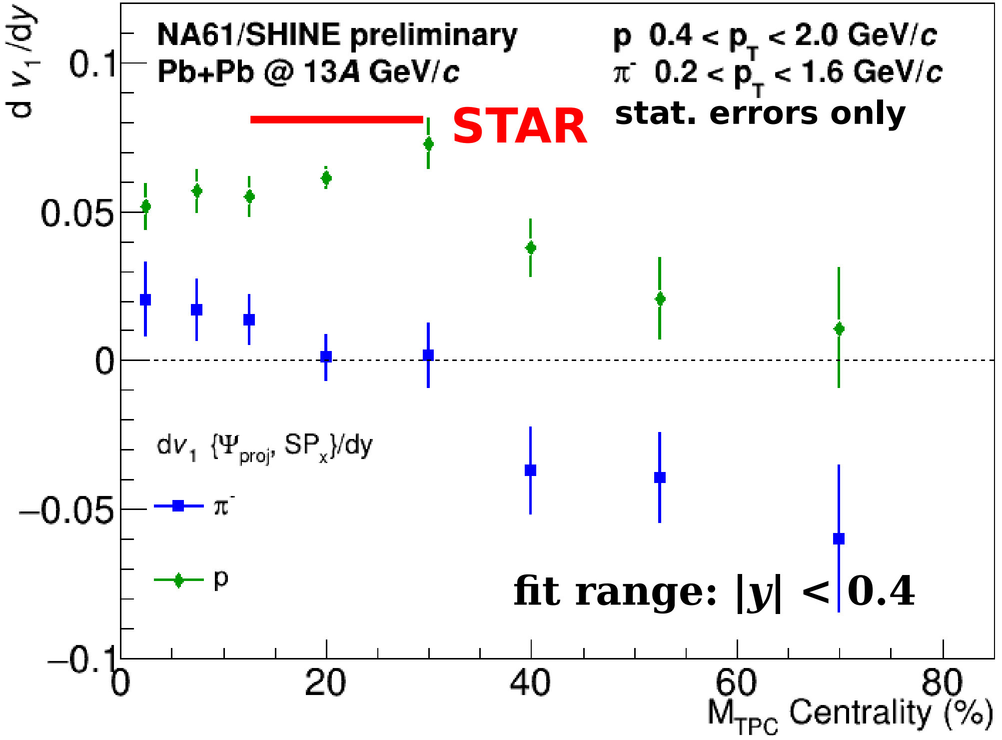


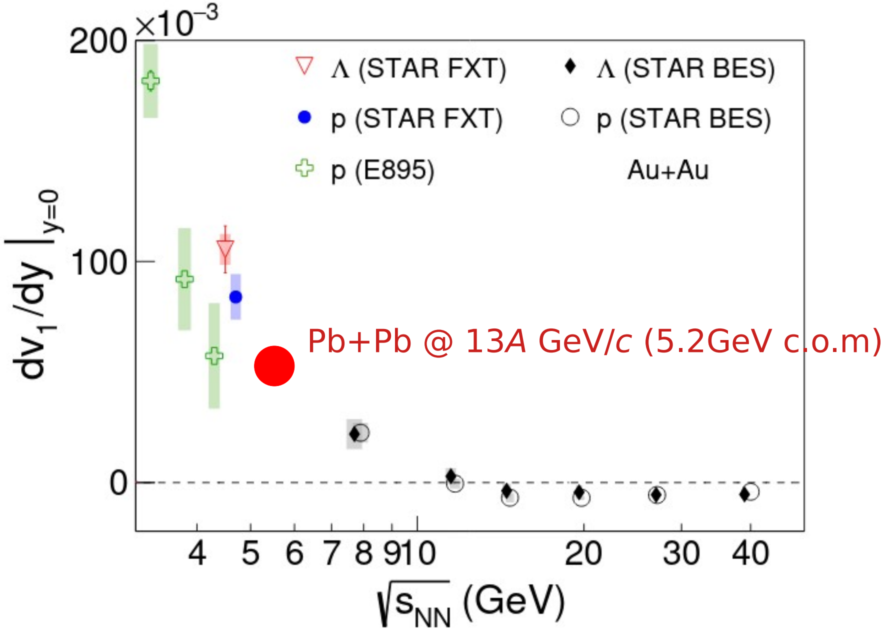
- Strong centrality dependence of $v_1(p_T)$
- $v_1(p_T \sim 0$ GeV/$c) \rightarrow 0$
- For mid-central v_1 changes sign at $p_T \sim 1$ GeV/c

- Significant mass dependence of $v_1(p_T)$

Slope of v_1 at midrapidity: comparison with STAR

* Proton and π^- selection is tuned to fit STAR fxt acceptance



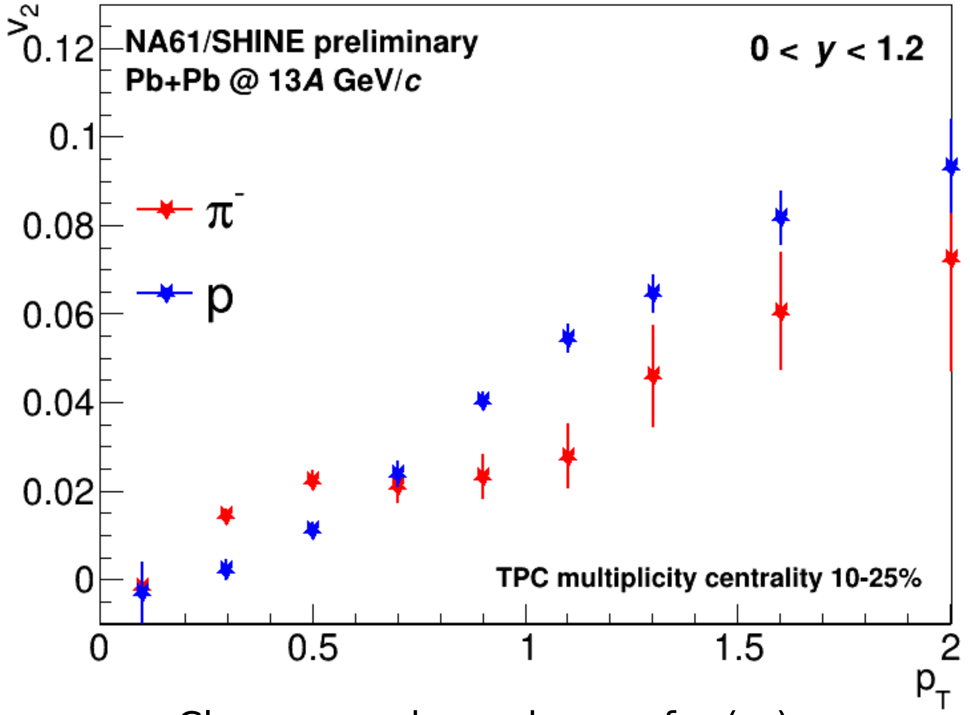


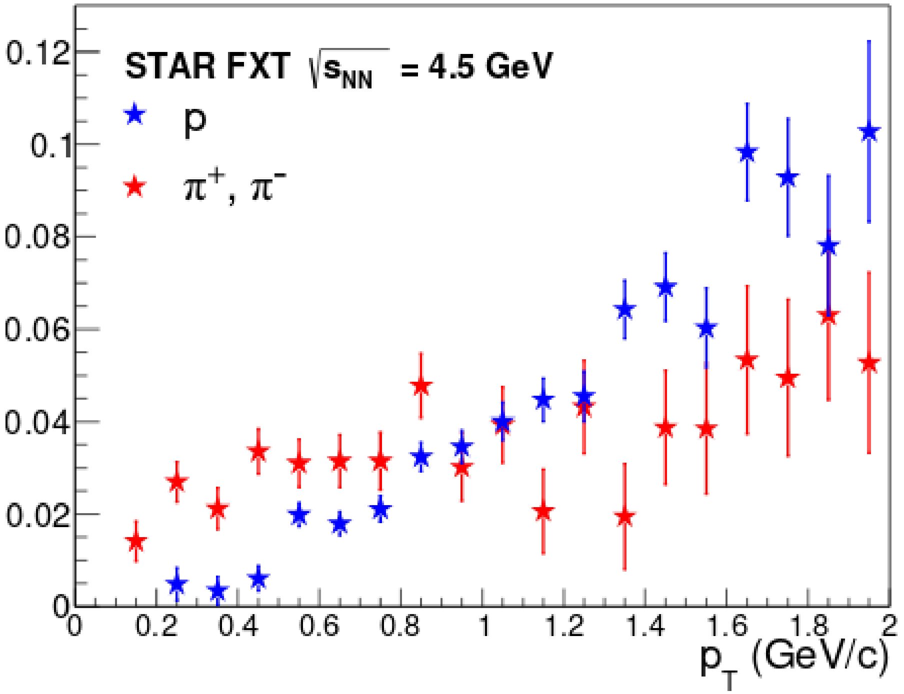
arXiv:2007.14005 [nucl-ex]

- Clear mass dependence
- Slope of $v_1(y)$ changes sign at ~70% centrality (protons) and ~20% centrality (π-)
- $v_1(y)$ slope extraction is sensitive to fitting function and rapidity range

Pion and proton $v_2(p_T)$ vs STAR FXT

* Proton and π^- selection is tuned to fit STAR fxt acceptance

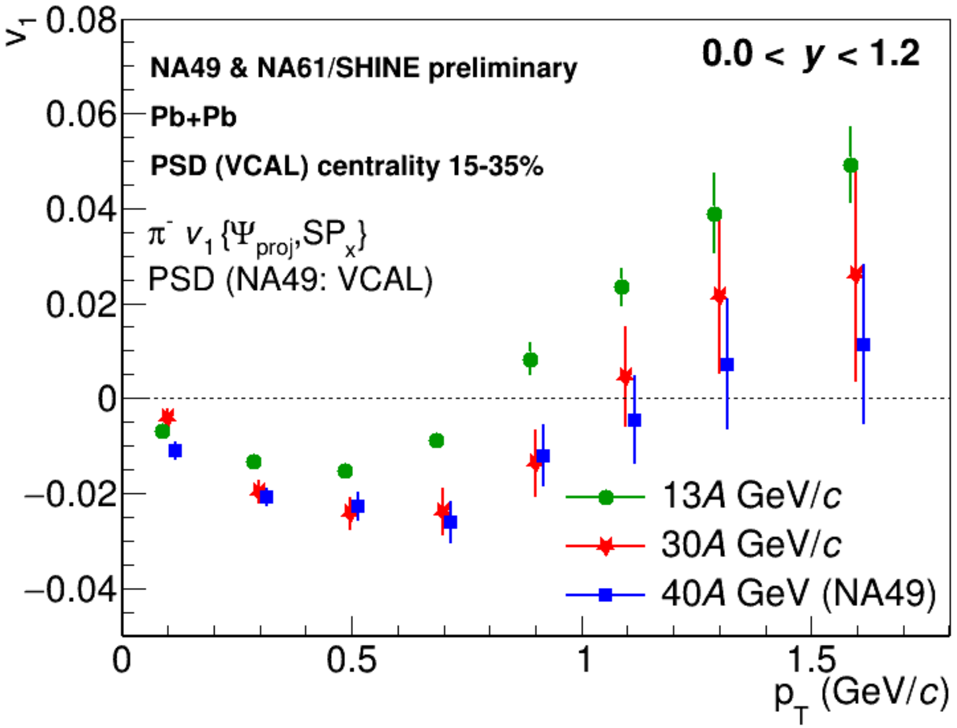


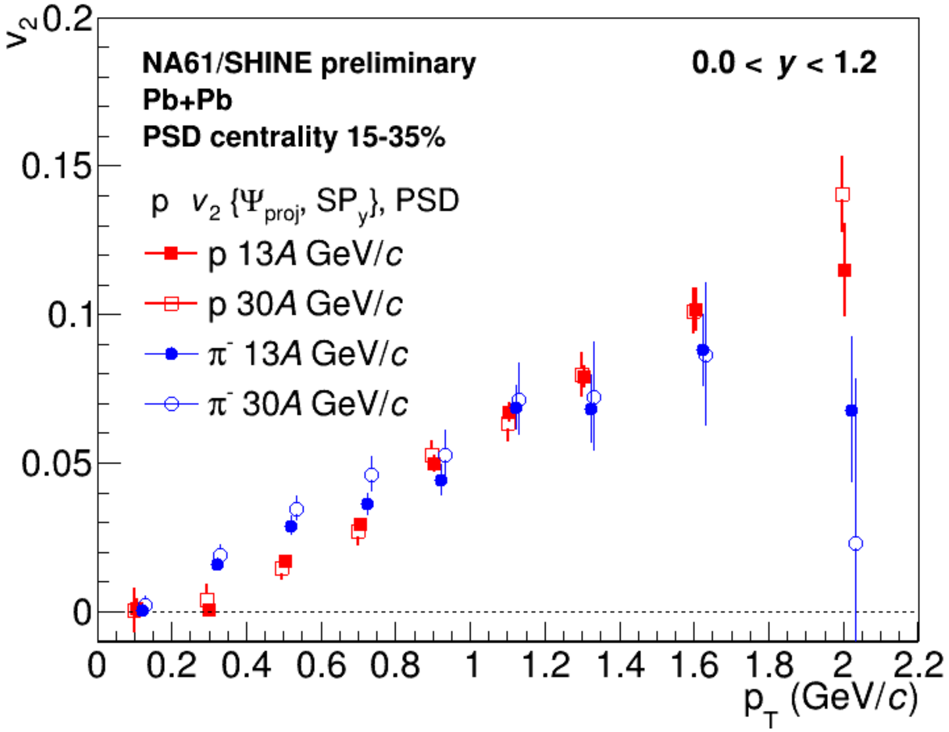


- Clear mass dependence of $v_2(p_T)$

arXiv:2007.14005 [nucl-ex]

Directed and elliptic flow energy dependence





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

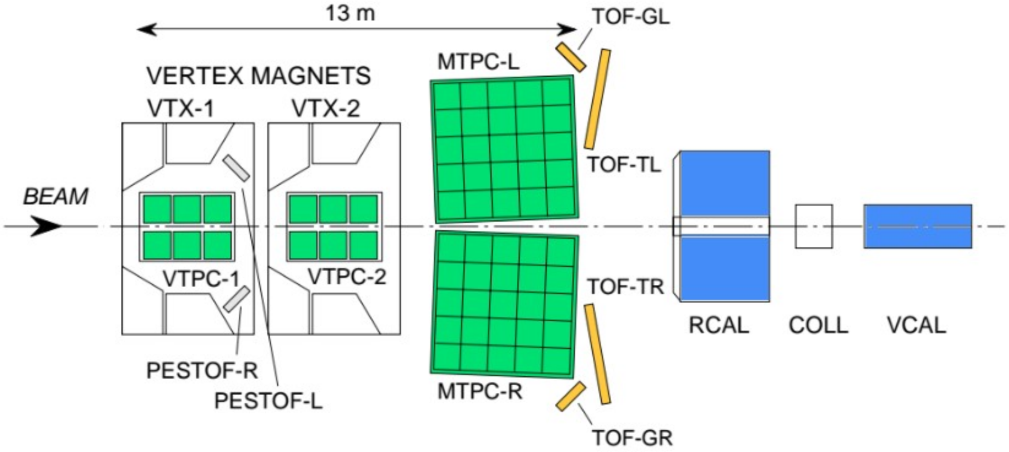
Weak energy-dependence

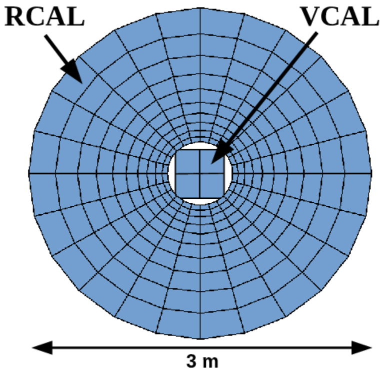
Summary

- Obtained preliminary results on directed and elliptic flow relative to spectator plane from NA49 and NA61/Shine Pb+Pb beam energy (momentum) scan data. Results are presented differentially vs transverse momentum, rapidity and centrality.
  - Negative pions and protons v_1 and v_2 for collisions at 13*A* GeV/*c* (NA61/Shine, 2015)
  - Charged pions and protons v_1 and v_2 for collisions at 30*A* GeV/*c* *(NA61/Shine, 2016)*
  - Negative pions v_1 for collisions at E_{beam} = 40*A* GeV (NA49)
- New results are compared to STAR@RHIC beam energy scan program
- Energy dependence of v_1 and v_2 is presented

BACKUP

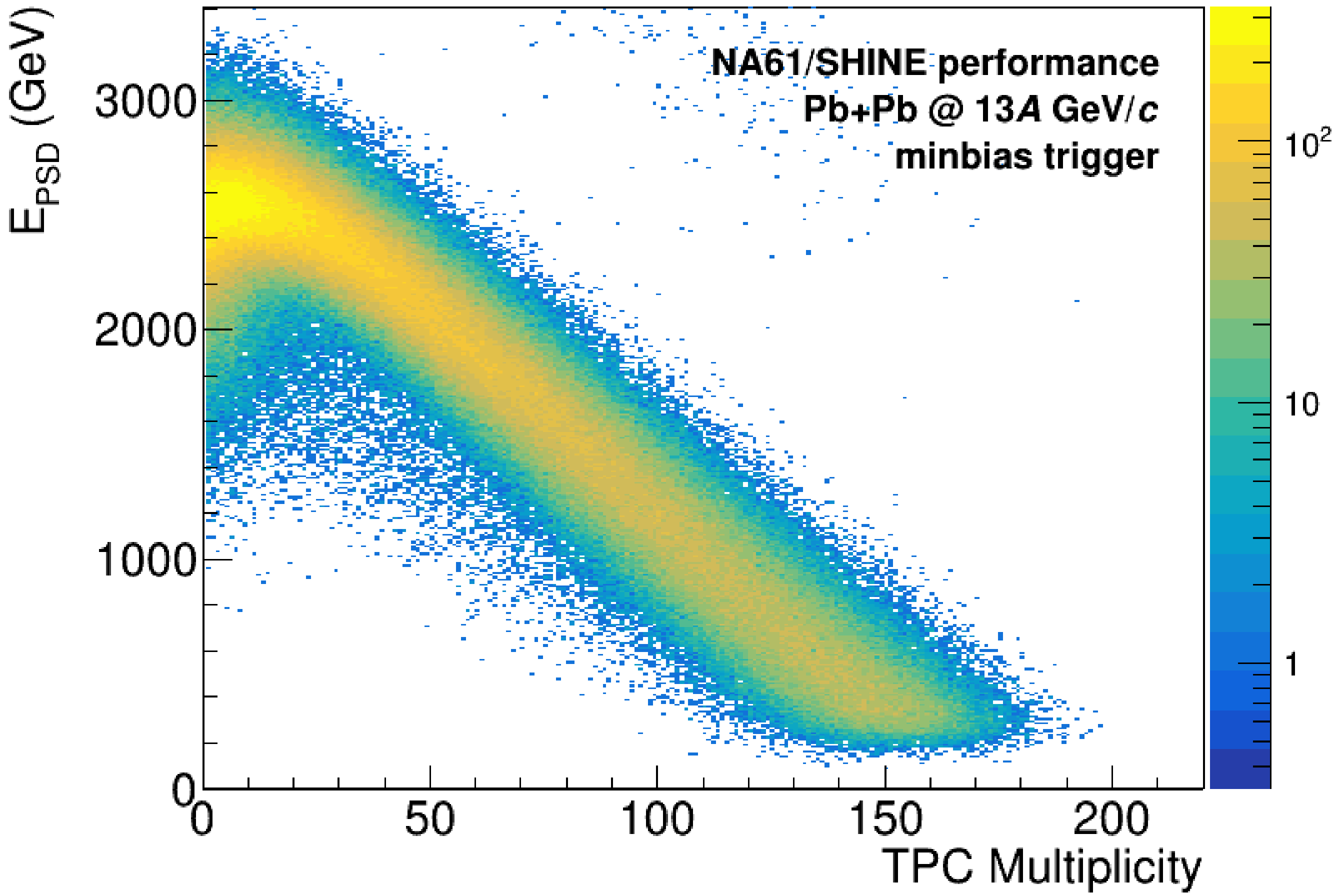
Pb-ion beam energy scan with NA49 (1996-2002)





- Large acceptance hadron spectrometer (TPC)
  - full coverage of forward hemisphere
  - tracking + identification down to $p_T \sim 0$ GeV/c
- Forward rapidity calorimeters
- Pb+Pb beam energy scan
  20*A*, 30*A*, 40*A*, 80*A*, 158*A* GeV data

PSD Energy vs Charged tracks multiplicity



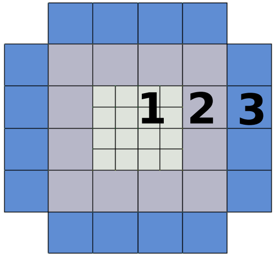
Clear anti-correlation – mostly spectators in PSD

QnTools setup for *u*- and *Q*-vectors

	u-vector	*Q*-vector
Subevents	Protons (TPC) Negative pions (TPC) Positive pions (TPC)	PSD1 PSD2 PSD3
Weights	1	Energy in PSD module
Correction steps	Recentering Twist Rescale	Recentering
Correction axes	P_T: [0.0, 3.0] GeV/*c*, 10 bins *Y* : [-0.8, 1.6] 20 bins Centrality: 8 bins	Centrality: 8 bins
Total amount of *u*- and *Q*-vectors	10 x 20 x 8 x 3 = 4800	8 x 3 = 24

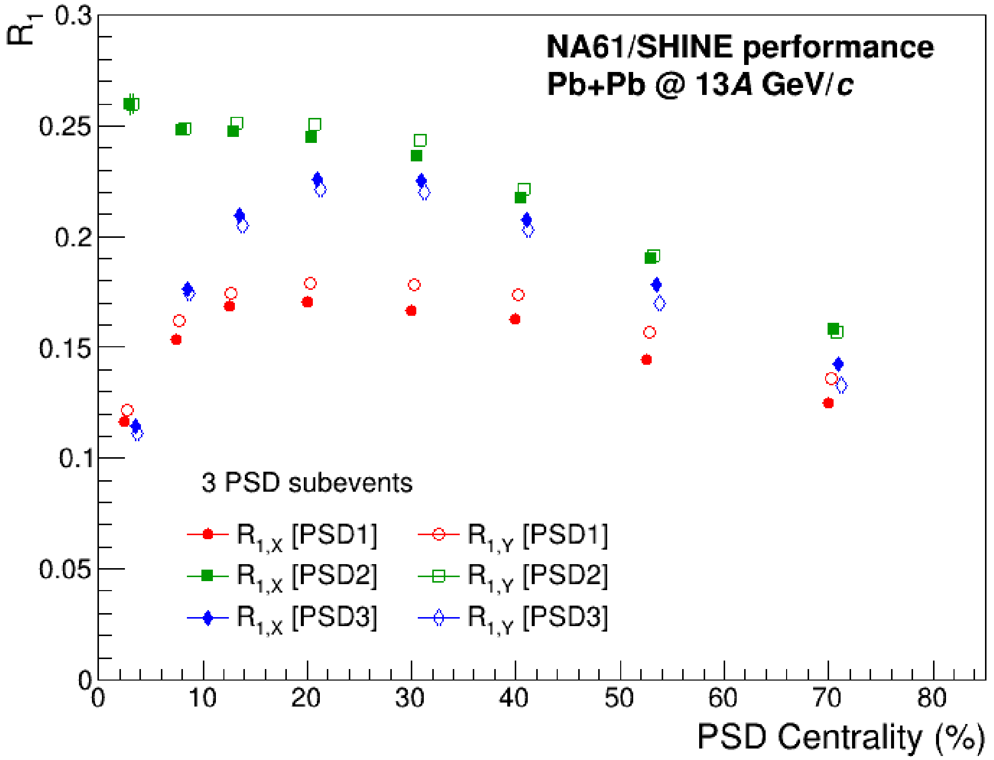
3 PSD subevents resolution

PSD

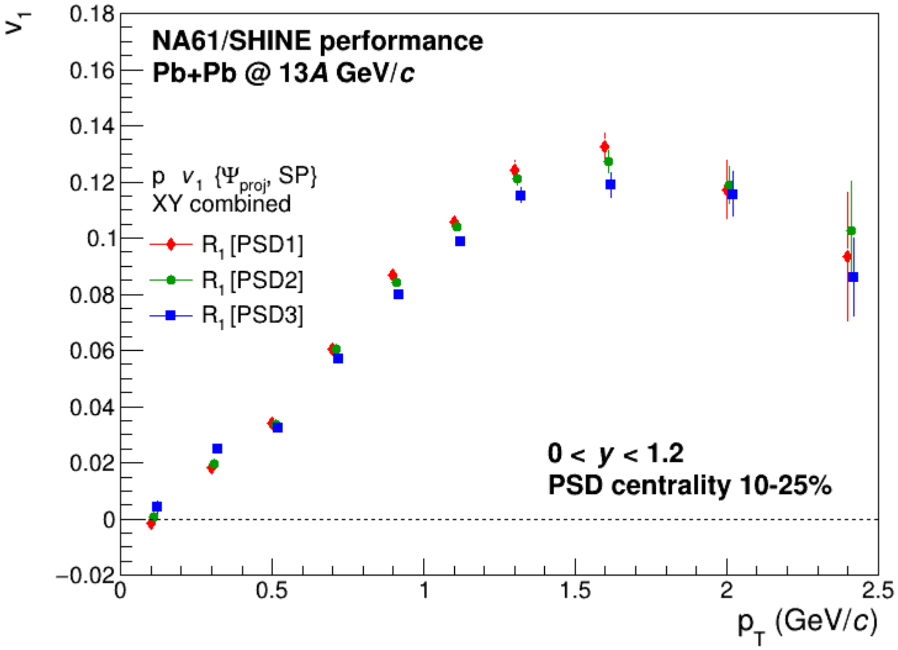


$$R_{i,A}[B,C]=\sqrt{2\frac{\langle Q_{i,A}Q_{i,B}\rangle\langle Q_{i,A}Q_{i,C}\rangle}{\langle Q_{i,B}Q_{i,C}\rangle}}$$

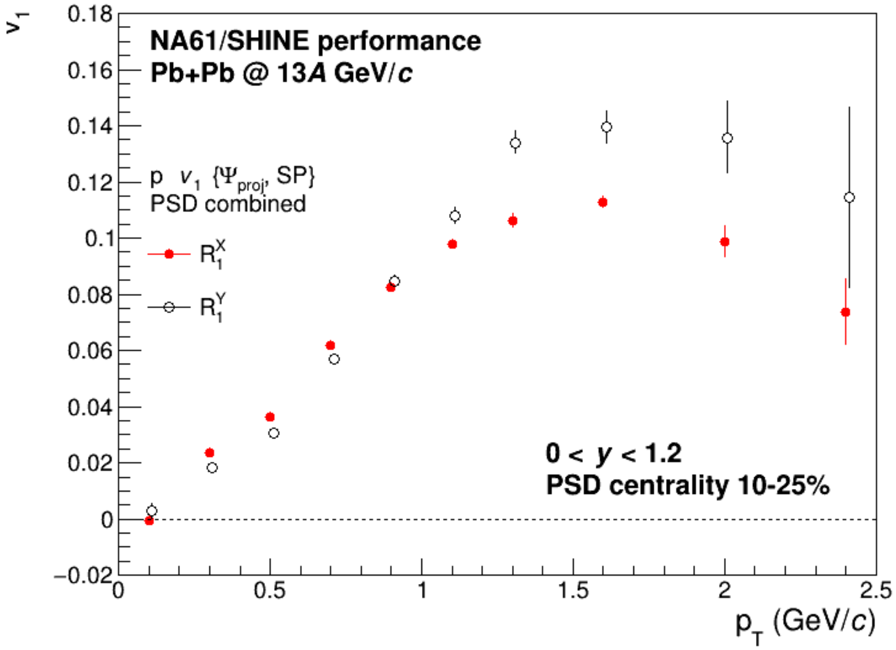
Resolution is biased due to self correlations: hadronic shower sharing between PSD subevents.



"Systematics" for directed flow (v_1) protons



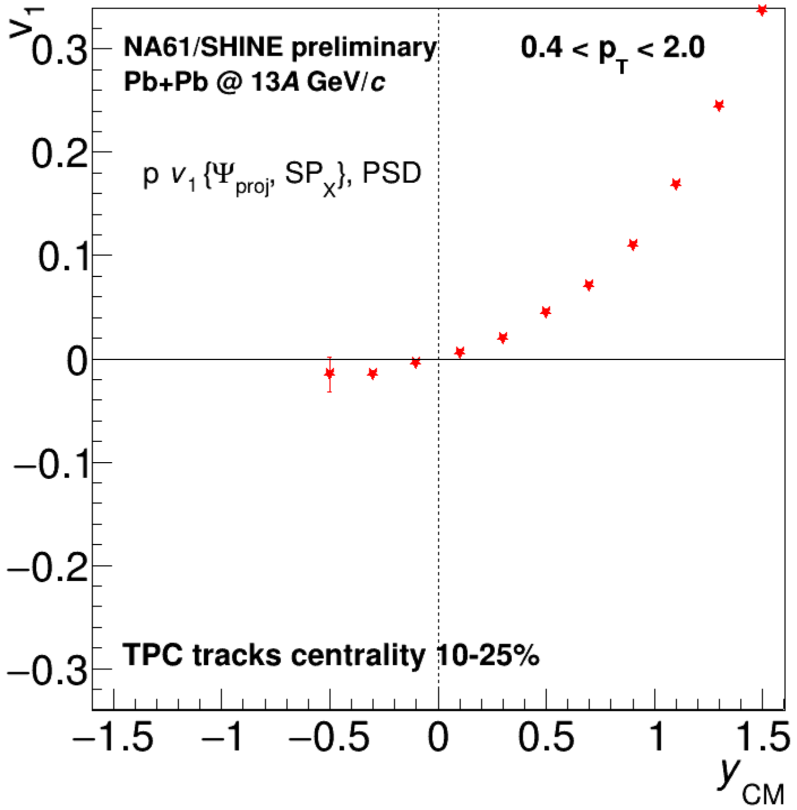
Consistent results for PSD subevents



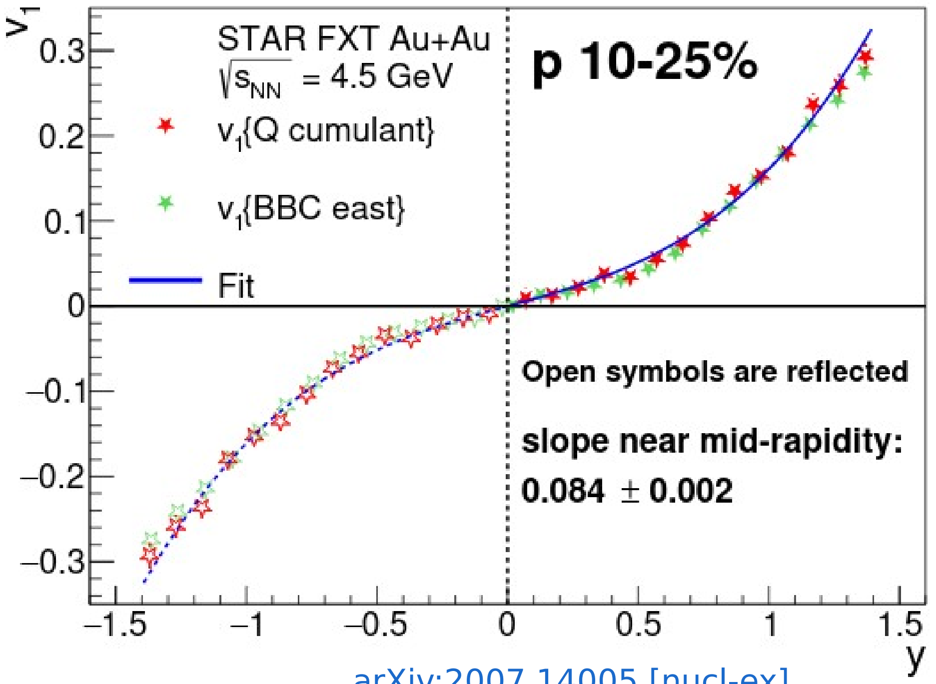
X/Y difference: protons seen in TPC deflected in the same direction as spectators in the PSD

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

Proton $v_1(y)$ vs with STAR FXT (13*A* GeV/*c*)



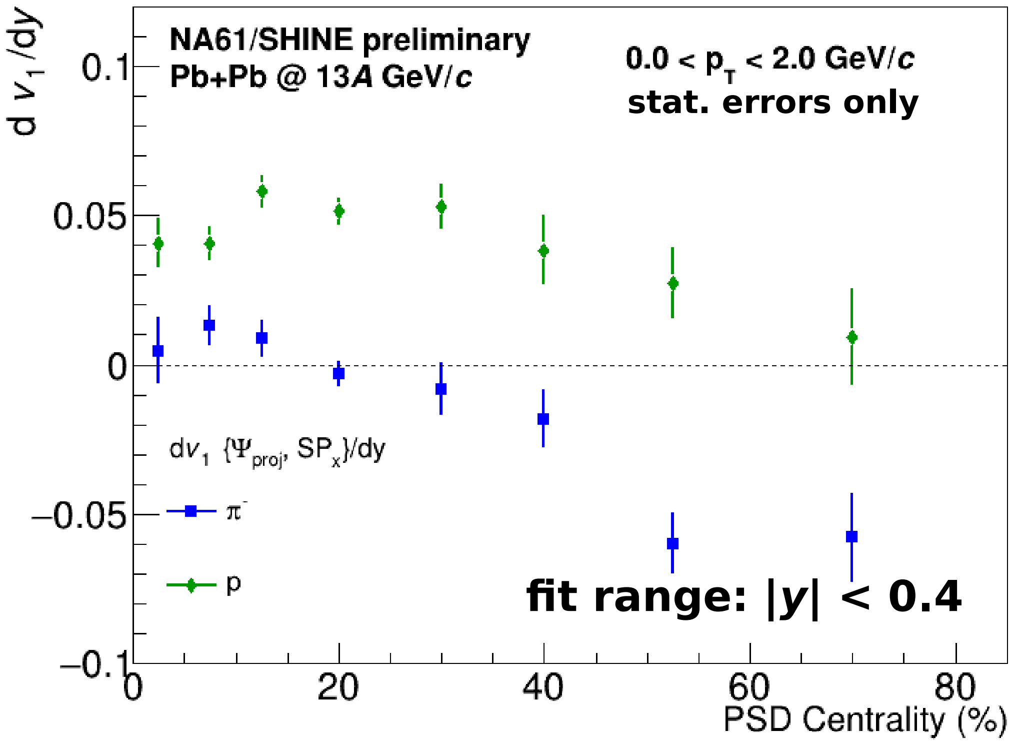
Au+Au @ 4.5 GeV (p_{LAB} = 9.8*A* GeV/*c*)



arXiv:2007.14005 [nucl-ex]

Proton selection is tuned to fit STAR fxt acceptance

Slope of v_1 at midrapidity vs. centrality (13*A* GeV/*c*)



Slope extraction procedure:

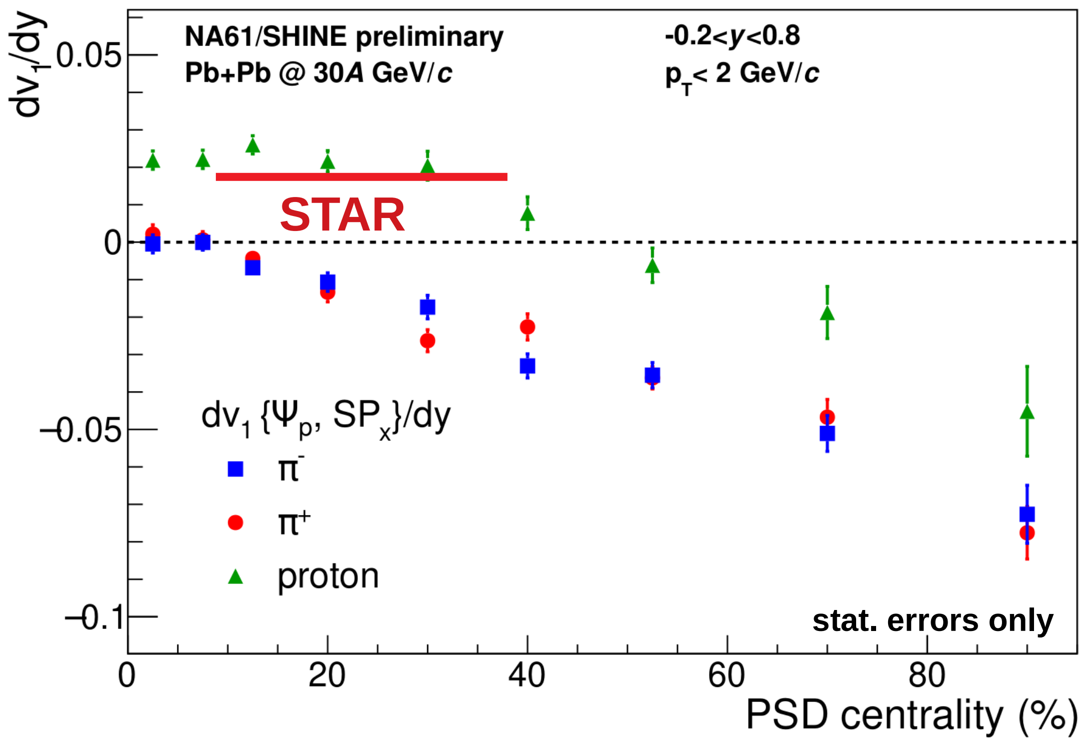
- 1st order polynomial fit with 2 parameters (slope and offset):
- Offset for protons is below $6x10^{-3}$ for centrality 0-60% and increasing up to $3x10^{-2}$ for centrality >60%.

Observations:

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

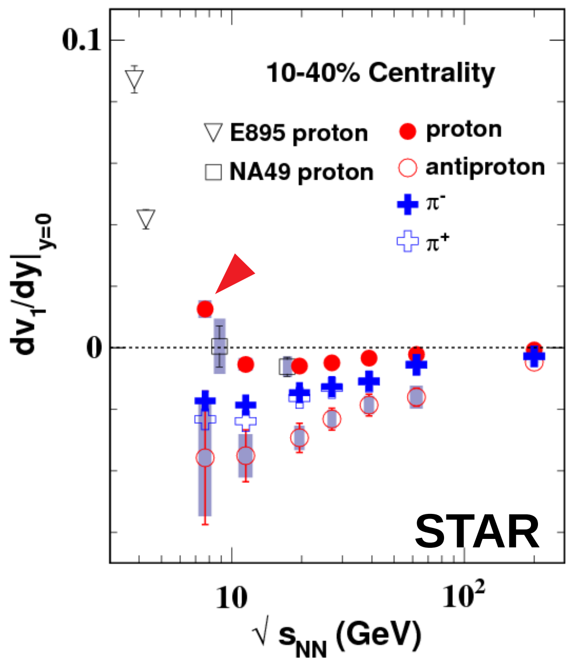
Slope extraction is sensitive to fit function and rapidity range

Slope of v_1 at midrapidity vs. centrality (30*A* GeV/*c*)



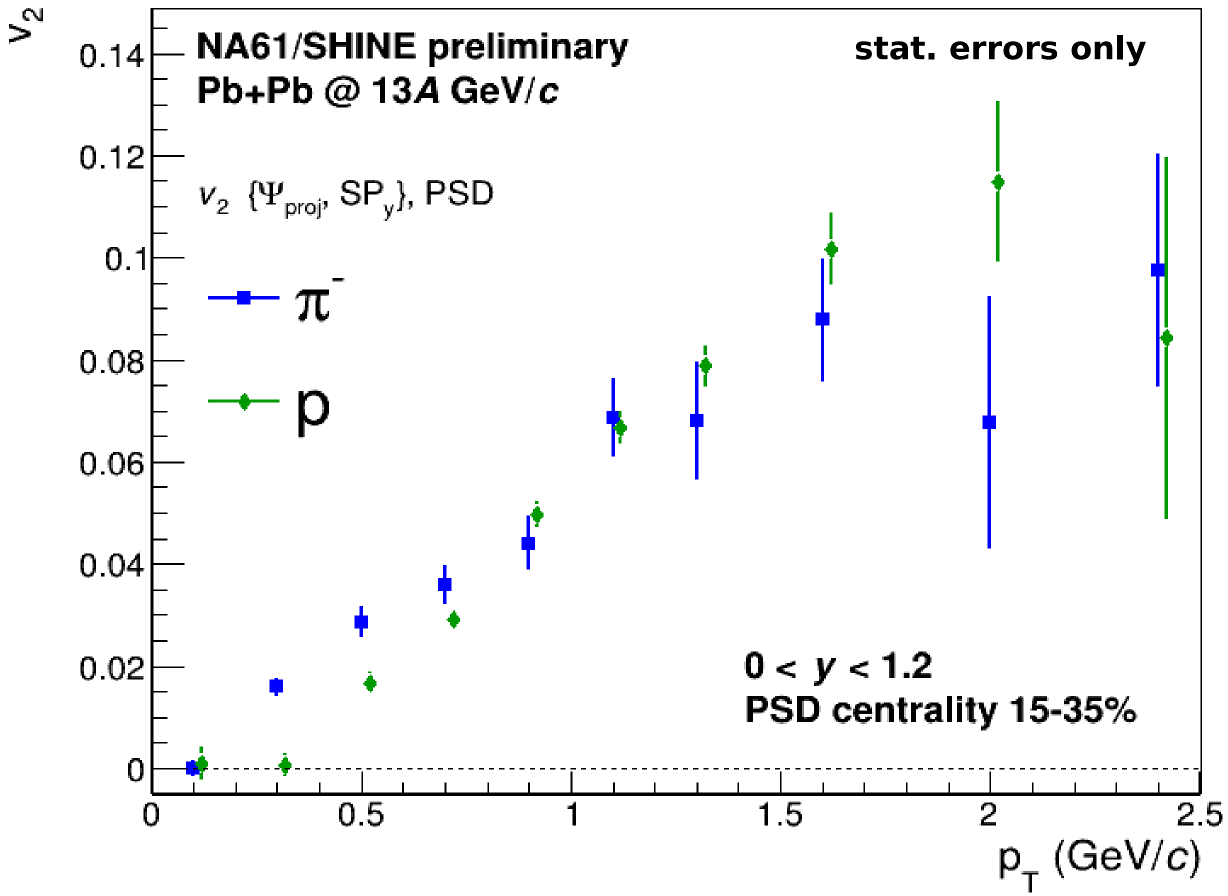
Slope extraction is sensitive to fit function and rapidity range

STAR Collaboration PRL 112 (2014) 162301



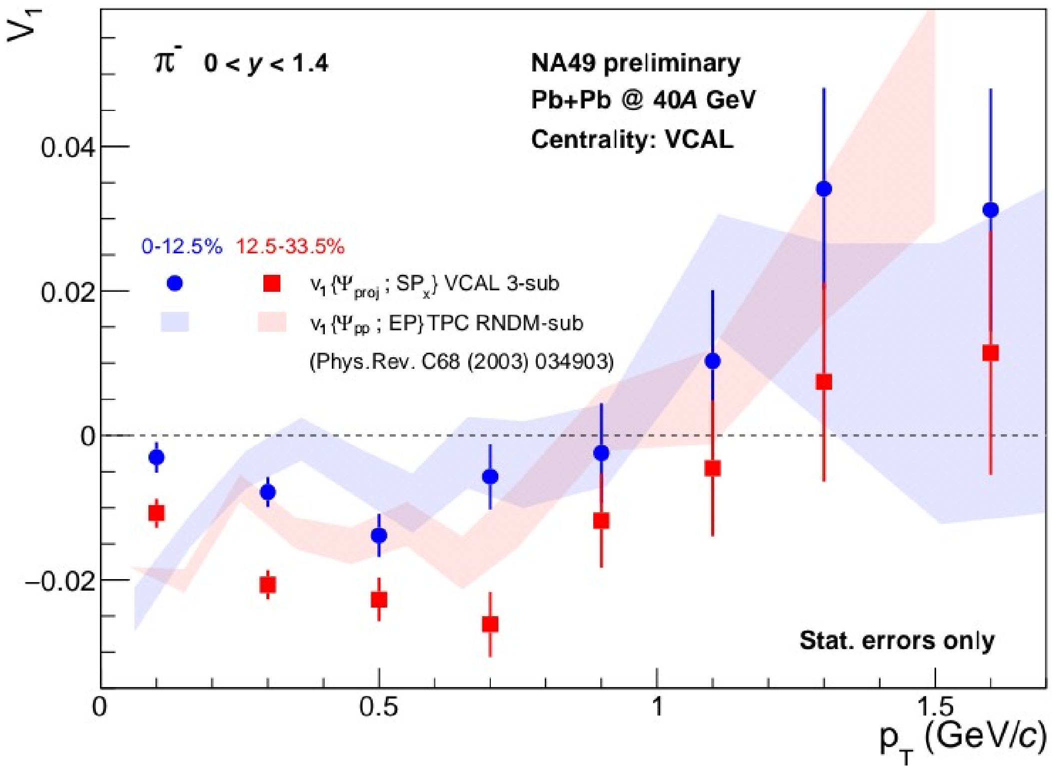
Preliminary results for centrality dependence presented by STAR Collaboration: NPA 956 (2016) 260

Elliptic flow $v_2(p_T)$: particle type dependence



Clear mass dependence

NA49 results:
spectator (new) vs participant (published) plane



Observed difference between results relative to participant and spectator symmetry planes

Results relative to participant plane are corrected for global momentum conservation (following procedure in
N. Borghini et al. Phys.Rev. C66 (2002) 014901)

Backup: Pb+Pb flow results in NA49 & NA61/SHINE

- preliminary - published - in progress/to be done

- 13*A* GeV/*c*:
  - Present talk
- 30*A* GeV/*c*:
  - NA61/SHINE measurements of anisotropic flow relative to the spectator plane in Pb-Pb collisions over a wide rapidity range (QM2018 talk) link
  - NA61/SHINE measurements of anisotropic flow relative to the spectator plane in Pb+Pb collisions at 30A GeV/c link
- 40*A* GeV (NA49)
  - *(TPC only analysis)* Directed and elliptic flow of charged pions and protons in Pb+Pb collisions at 40A and 158A GeV (2003) link
  - Anisotropic flow measured in Pb-Pb collisions with the NA49 experiment at the CERN SPS (QM2018 poster) link
- 150*A* GeV/*c*
- 158*A* GeV (NA49)
  - *(TPC only analysis)* Directed and elliptic flow of charged pions and protons in Pb+Pb collisions at 40A and 158A GeV (2003) link

Negative pion v_1 vs rapidity: comparison with STAR FXT Au+Au @ 4.5 GeV ($p_{LAB} = 9.8A$ GeV/c)

D.Cebra, EMMI Workshop 2019, GSI