Anisotropic flow relative to the spectator plane in Pb+Pb collisions

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for the NA61/SHINE Collaboration

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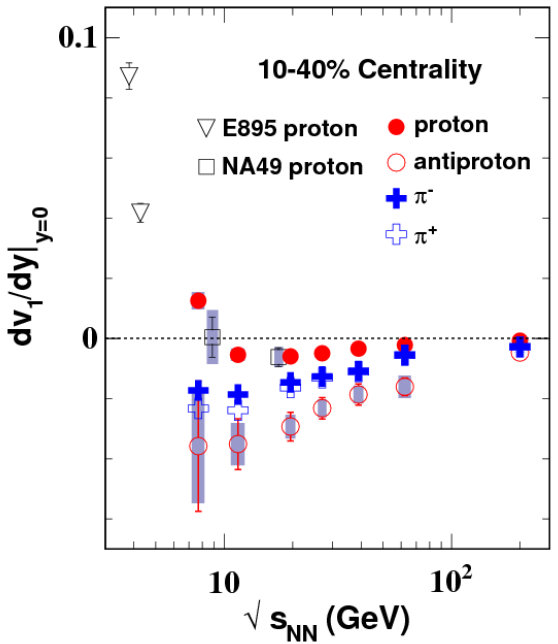
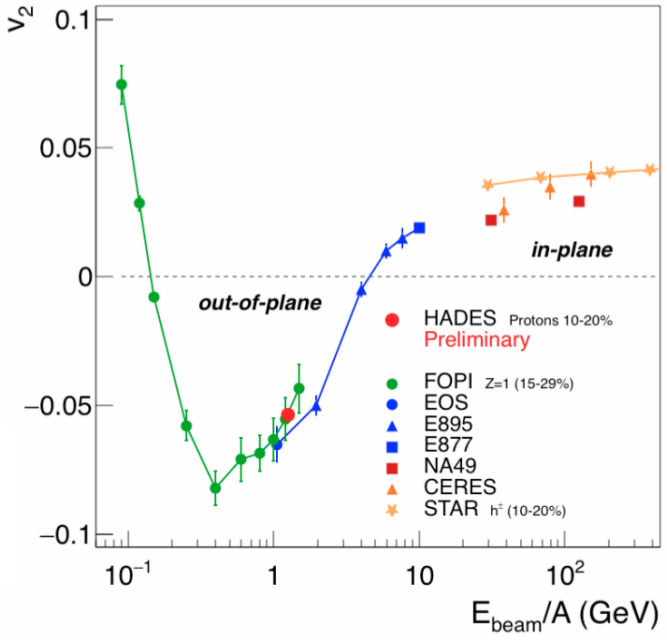
Collective flow at SPS / RHIC energies

Directed flow (slope)



STAR Collaboration
PRL 112 (2014) 162301

Elliptic flow



HADES Collaboration
JPCS 742 (2016) 012008

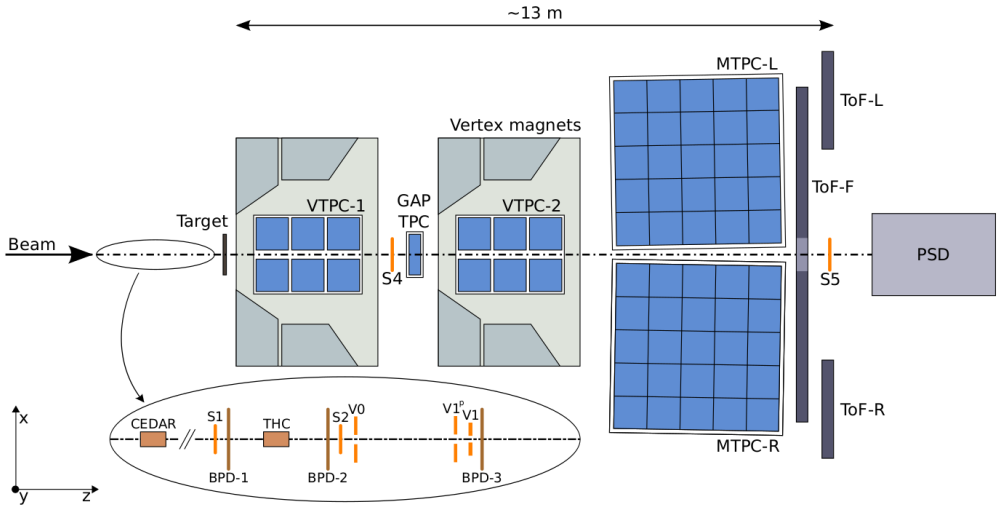
NA61/SHINE Pb-ion beam energy scan (p_{LAB} = 13-150*A* GeV/*c*):

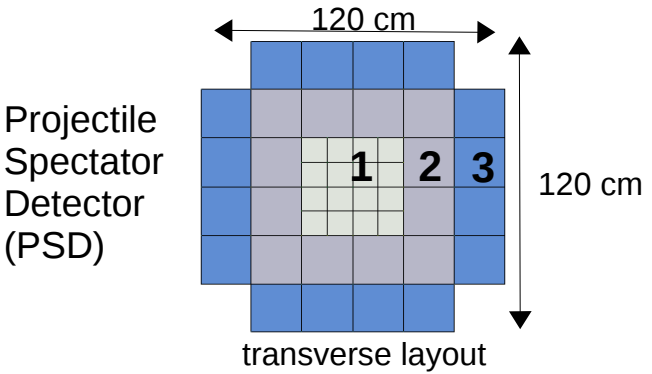
- Extend existing NA49 data
- Complementary to STAR@RHIC
- Bridge to FAIR/NICA beam energies

Advantage of the NA61/SHINE fixed target setup:

- Tracking and particle identification over wide rapidity range
- Projectile spectators measurement with forward calorimeter

Pb beam energy scan with NA61/SHINE at CERN SPS





- Fixed target experiment
- Forward rapidity calorimeter (PSD)
- Large acceptance hadron spectrometer (TPC)

  - Full coverage of forward hemisphere
  - tracking + identification down to p_T = 0 GeV/*c*

- Pb+Pb beam momentum scan:

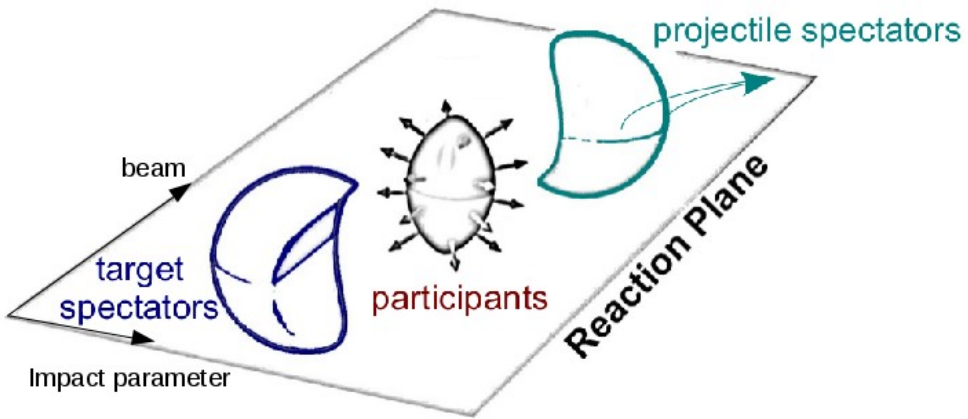
  - 13*A*, **30*A* GeV/*c*** recorded in 2016 (pilot run at 150*A* GeV/*c*)

  - 150*A* GeV/*c* coming later this year 2018

Collision geometry and the anisotropic transverse flow

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

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

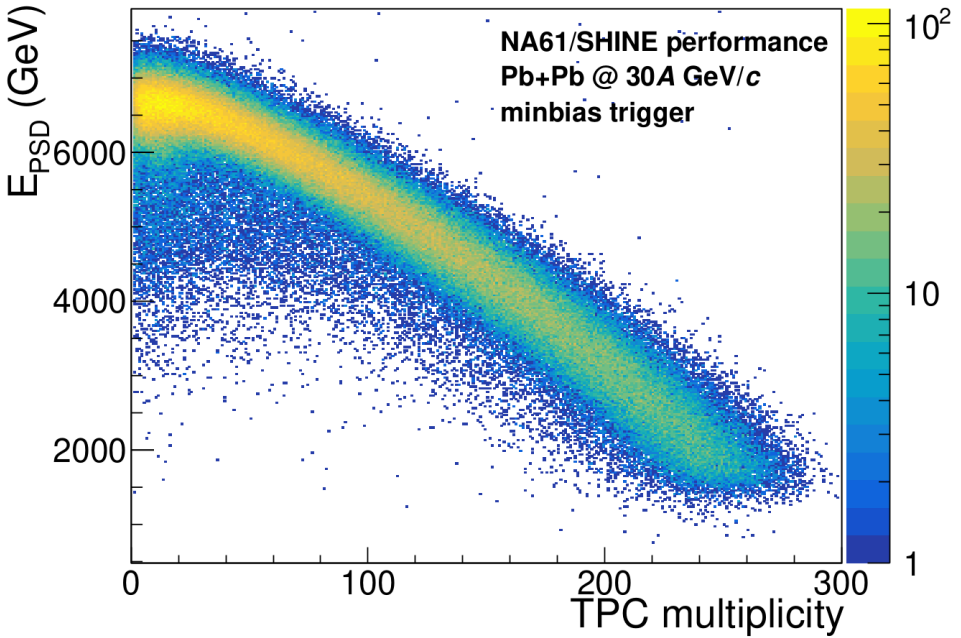


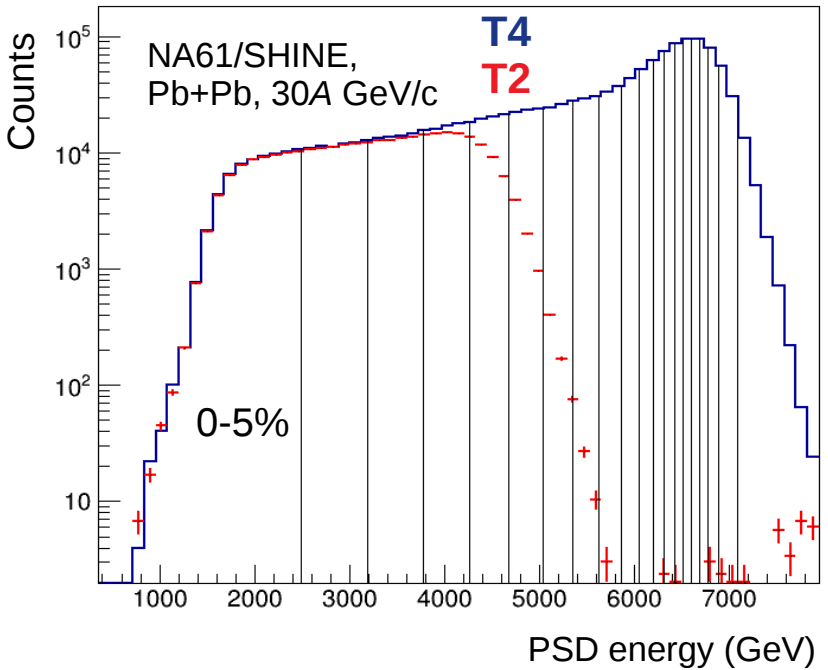
Ψ_s can be estimated from produced particles (Ψ_{pp}) or projectile (target) spectators Ψ_{proj} (Ψ_{targ})

Needed components to calculate v_n:

- momentum (φ, Y, p_T)
- centrality estimation
- particle identification
- symmetry plane (Ψ_s) estimation

Event selection





Event has fitted vertex
Good beam position
No overlap events / beam particles

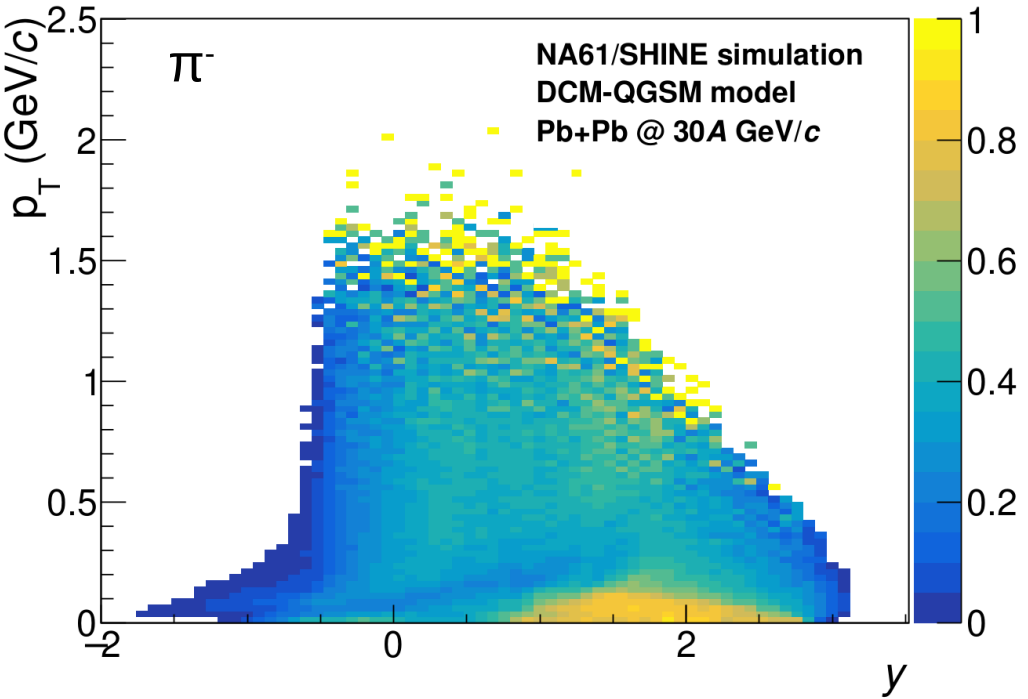
$-593 < Z_{vtx}$ (cm) < -591
$-1.1 < X_{vtx}$ (cm) < 0.0
$-0.8 < Y_{vtx}$ (cm) < 0.4

Minimum bias trigger (**T4**): 1.1 M events

Central trigger (**T2**): 0.6 M events

Track selection and efficiency maps

Example of efficiency map



Number of clusters:

$N_{clusters}\{VTPC1+VTPC2\} > 15$

$N_{clusters}\{Total\} > 30$

$0.55 < N_{cl}\{Total\}/N_{cl}\{Total, pot\} < 1$

Distance of closest approach to vertex

$|b_x| < 2$ cm

$|b_y| < 1$ cm

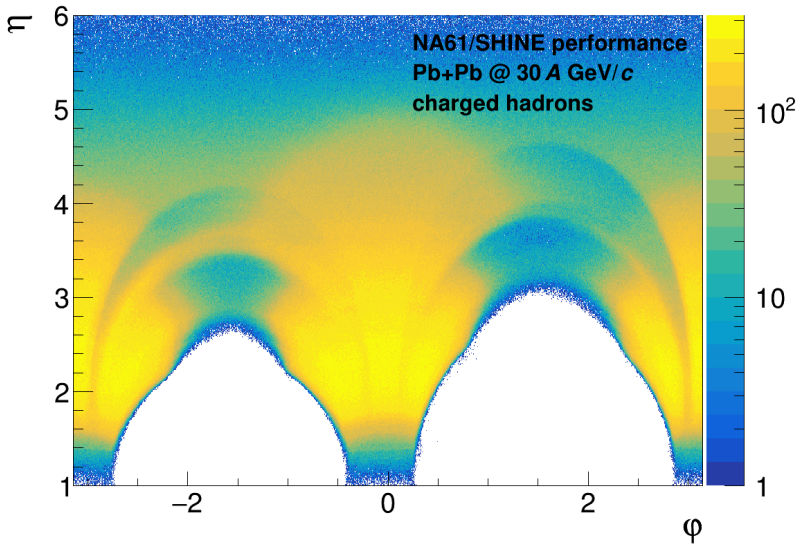
TPC energy loss (dE/dx)

charged pions & proton identification

Tracking efficiency

GEANT4 Monte-Carlo with DCM-QGSM

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

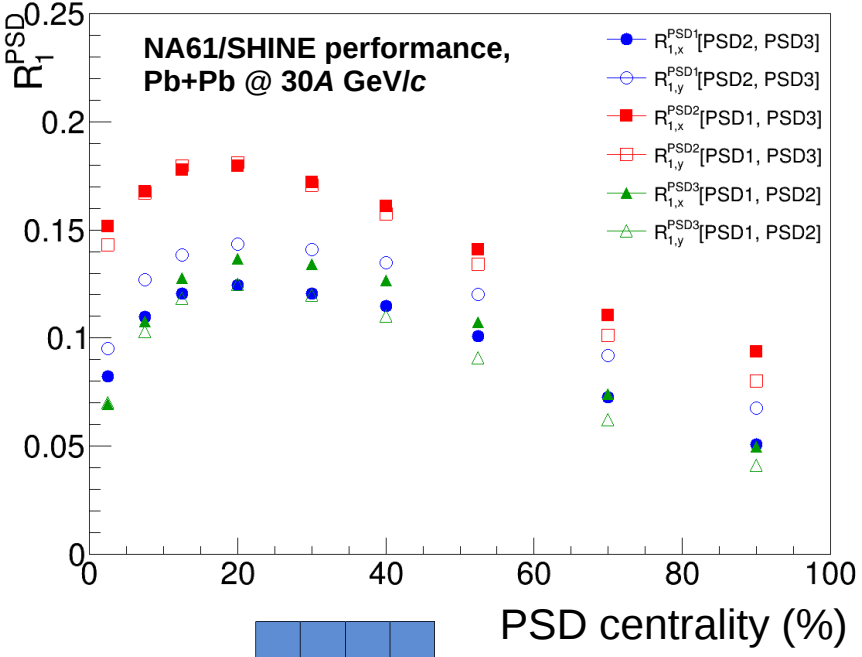
  https://github.com/jonderwaater/FlowVectorCorrections
- Recentering, twist, and rescaling corrections applied
  time dependent (run-by-run) and as a function of centrality

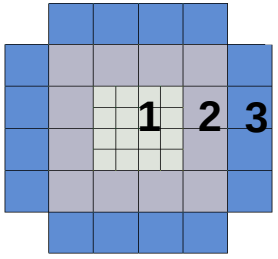
Flow Analysis Framework

- Extended Q_n-vector corrections for p_T/*y*-differential
- Multi-dimensional correlations of u and Q-vectors
  L. Kreis (GSI / Heidelberg) and I. Selyuzhenkov (GSI / MEPhI)

Scalar product method with 1st harmonic Q-vector

Scalar product correction factor





u and Q-vectors:

$$u_n = \begin{pmatrix} \cos n\varphi \\ \sin n\varphi \end{pmatrix} \qquad Q_n = \sum_j u_n^j$$

Directed flow:

$$v_1 = \frac{\langle 2 u_{1,i} Q_{1,i} \rangle}{R_{1,i}} \qquad i,j,k = [x,y]$$

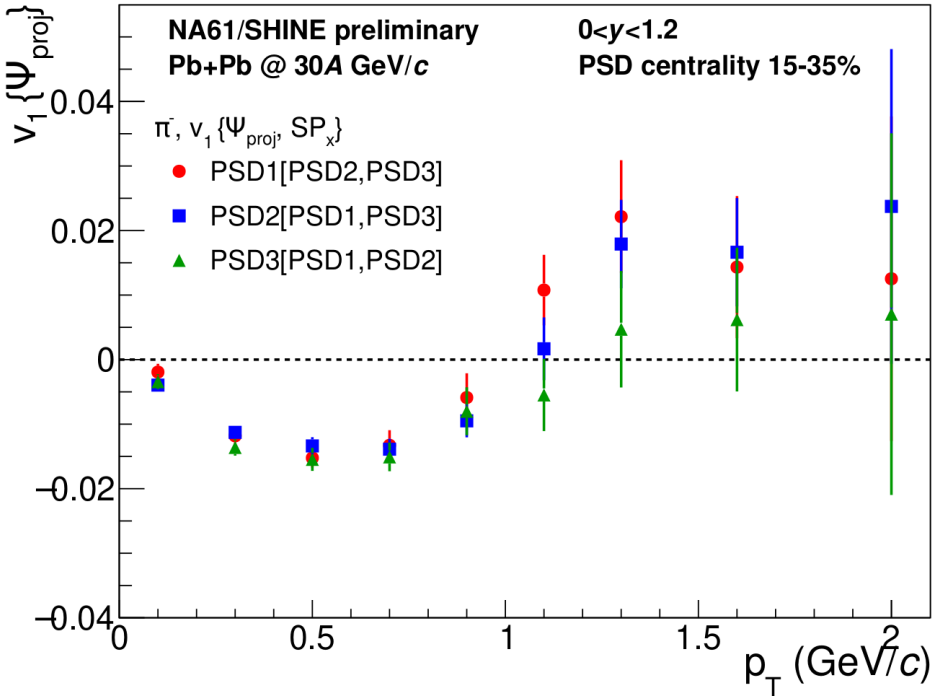
Elliptic flow:

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

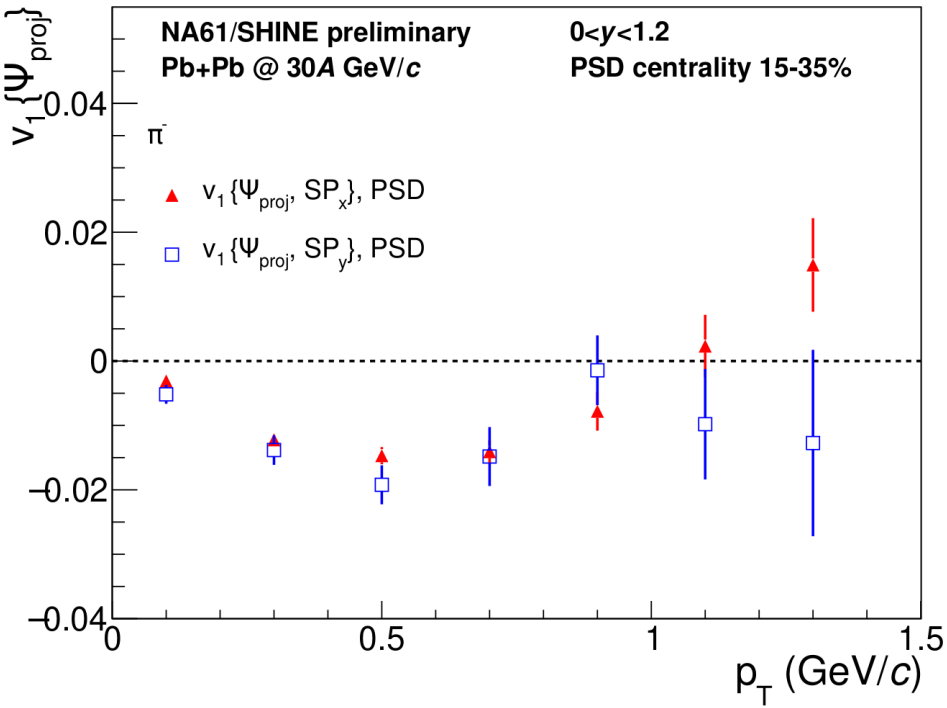
First harmonic resolution correction factor:

$$R_{1,i}^A[B,C] = \sqrt{2 \frac{\langle Q_{1,i}^A Q_{1,i}^B \rangle \langle Q_{1,i}^A Q_{1,i}^C \rangle}{\langle Q_{1,i}^B Q_{1,i}^C \rangle}}$$

“Systematics” for directed flow (v_1) components



Consistent results for PSD subevents



x/y components show consistent results, while results for y-component shows larger errors

For preliminary results: only x-component is used and PSD subevents are combined

Preliminary results
&
comparisons with NA49 and STAR

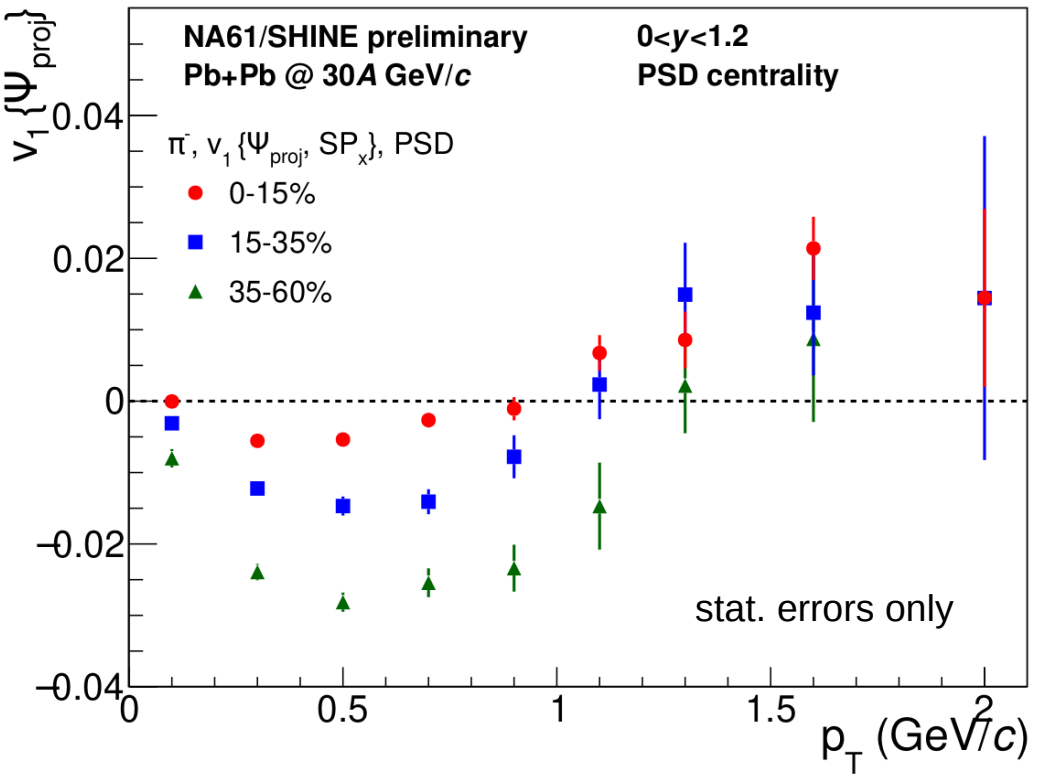
Results are presented for correlations between
charged pions and protons* (in the TPC acceptance) and
all hadrons at forward rapidity (in the PSD acceptance)

The results are corrected for detector non-uniformity.
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
PSD: https://edms.cern.ch/document/1867336/1

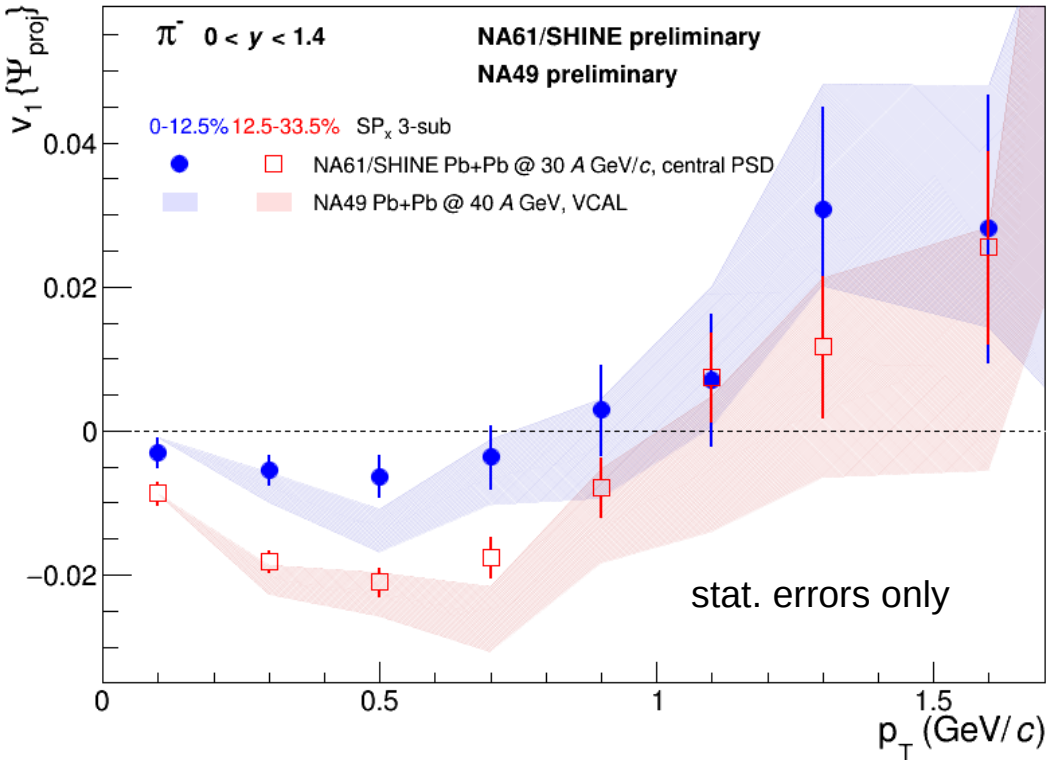
Charged pion v_1 vs transverse momentum



General features:

- Strong centrality dependence of v_1
- $v_1(p_T \sim 0\ \text{GeV}/c) = 0$
- v_1 changes sign at $p_T \sim 1\ \text{GeV}/c$

Comparison with the NA49 data



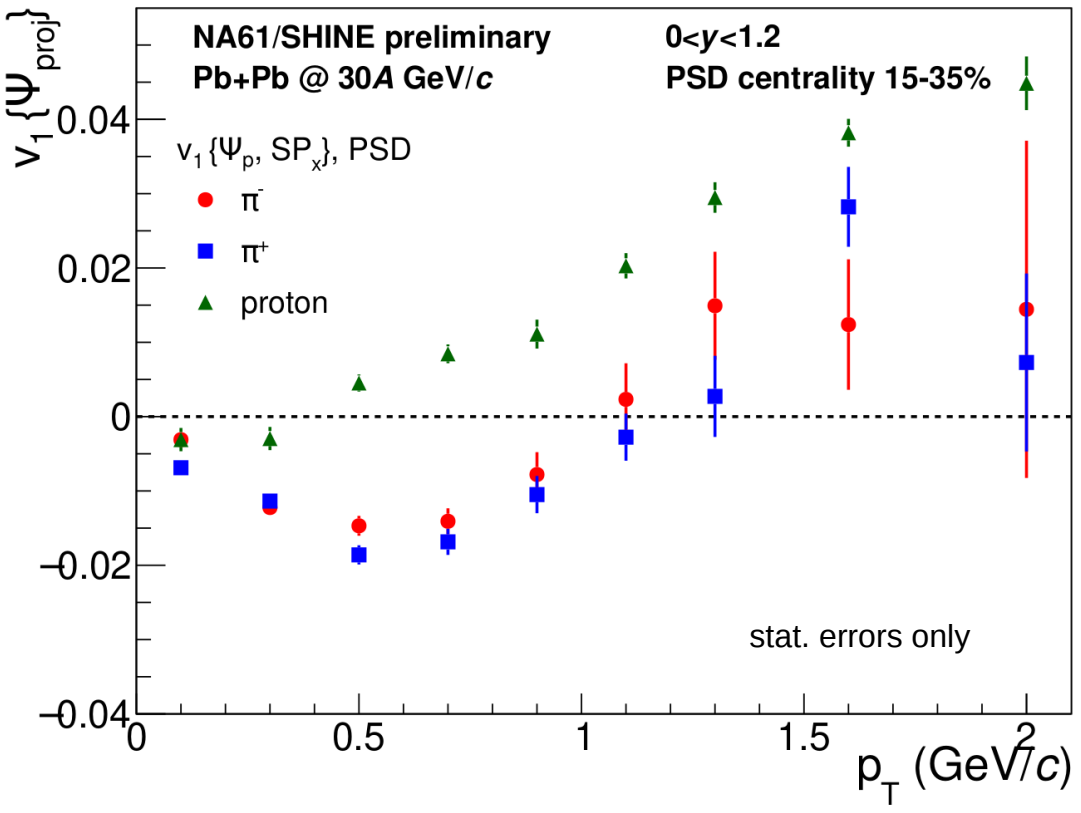
- Similar results to new NA49 analysis of pions relative to the spectator plane
- More details about new NA49 analysis and comparison with published NA49 data:

Poster #367:

O. Golosov, I. Selyuzhenkov,
V. Klochkov, and E. Kashirin

https://indico.cern.ch/event/656452/contributions/2859496

Particle type dependence of $v_1(p_T)$

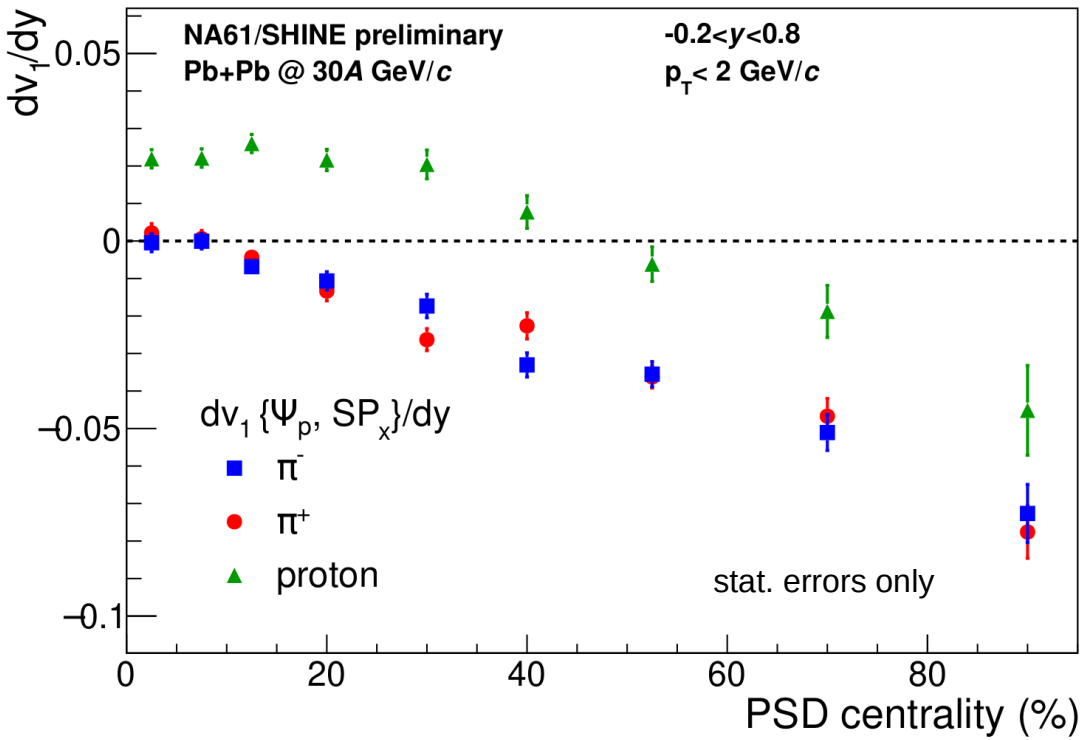


- Significant mass dependence of v_1
- Difference between π^+ and π^- v_1 is sensitive to the electromagnetic effects*

  Charged pions yield asymmetry from NA61/SHINE will be presented next week at WPCF2018 (M. Kielbowicz for NA61/SHINE)

* A. Rybicki, et al., Acta Phys.Polon. B46 (2015) no.3, 737
A. Rybicki, A. Szczurek, Phys.Rev. C87 (2013) no.5, 054909

Slope of v_1 at midrapidity vs. centrality



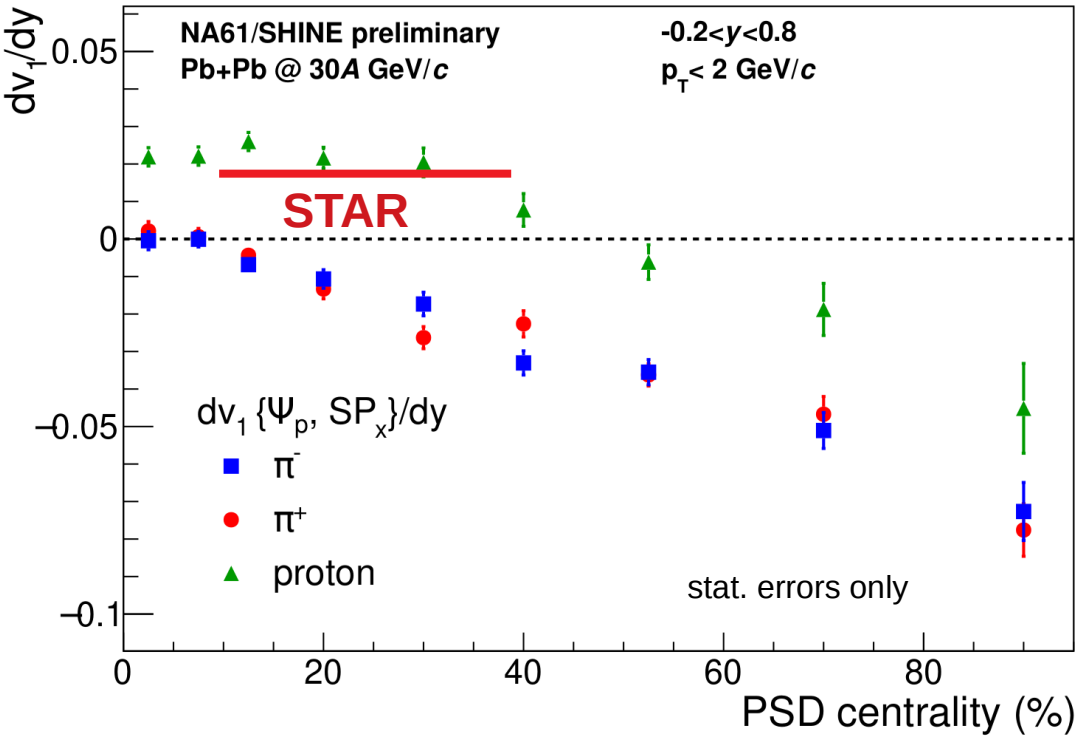
Slope extraction procedure:

- 1st order polynomial fit with 2 parameters (slope and offset):
  - offset for π^+/π^- consistent with 0 (all centrality)
  - Offset for protons is below 6×10^{-3} for centrality 0-60% and increasing up to 3×10^{-2} for centrality >60%.

Observations:

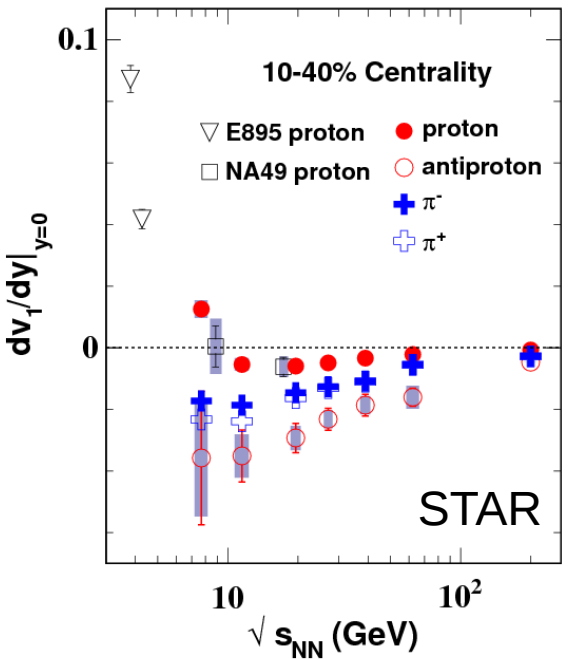
- Slope of proton v_1 changes sign at about 50% centrality
- Slope of pions v_1 is always negative

Slope of v_1 at midrapidity: comparison with STAR



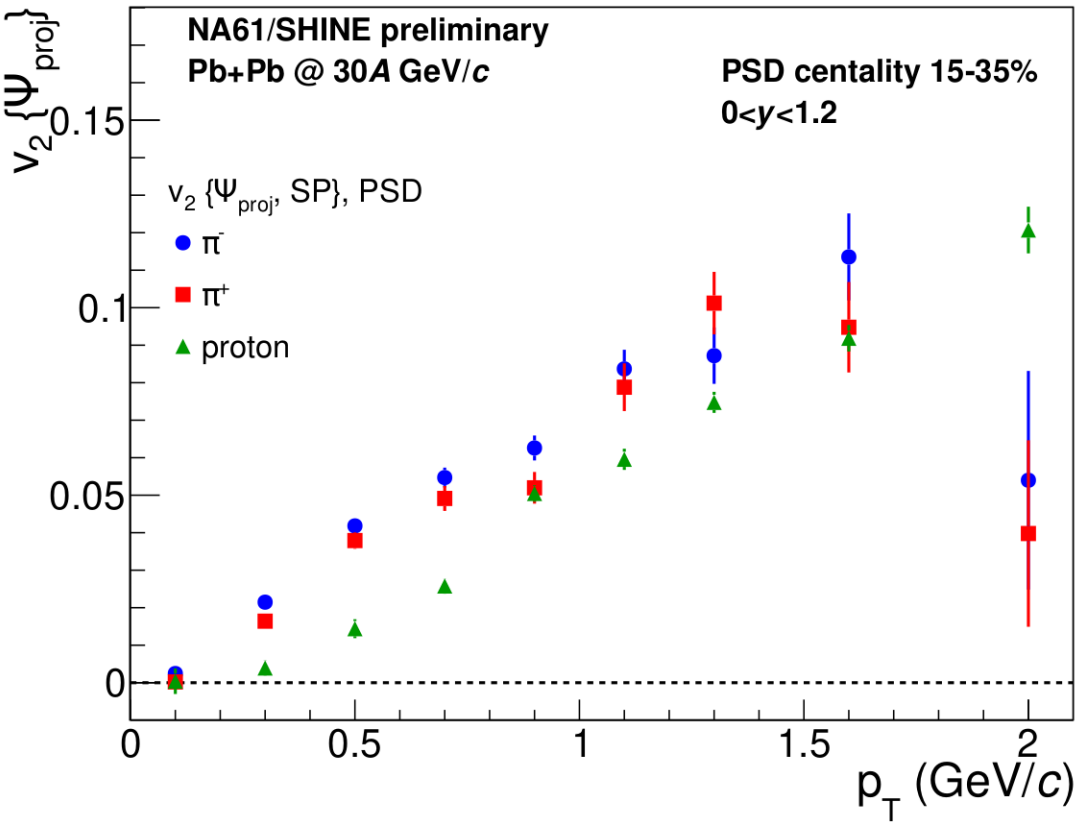
Slope extraction is sensitive to fit function and rapidity range

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

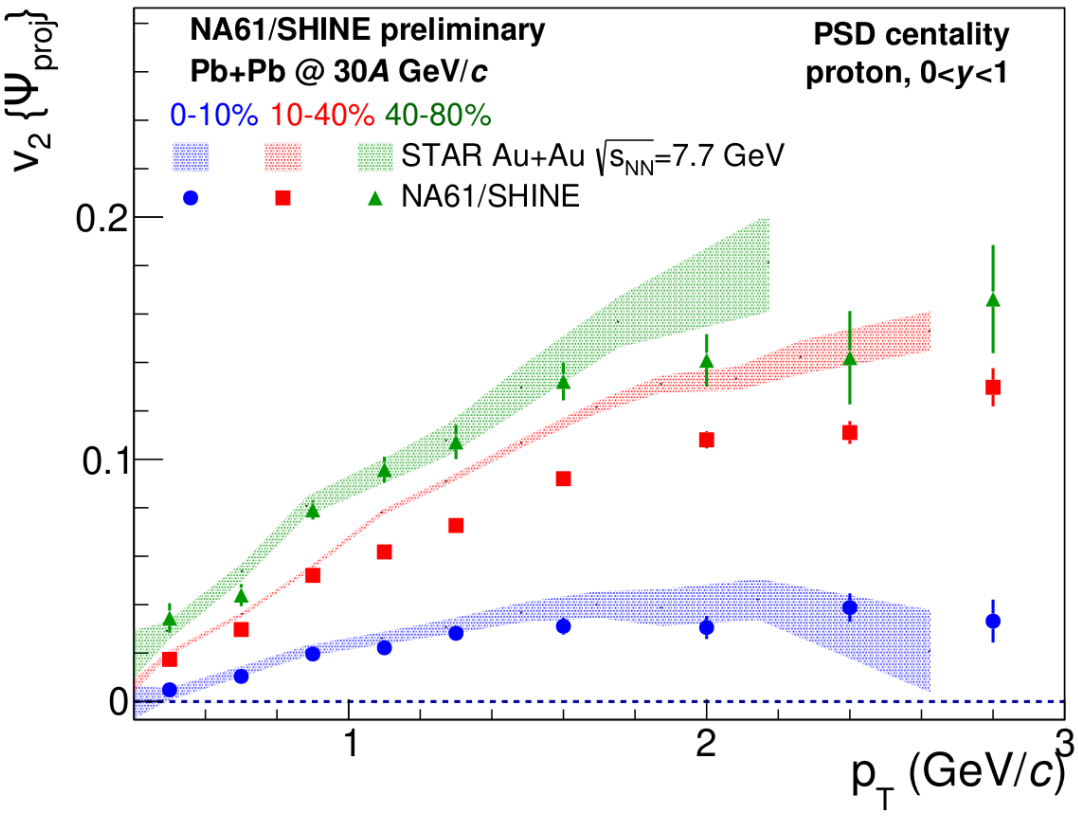


- Clear mass dependence

  → radial flow

- Difference between π^+ and π^- v_2 is small

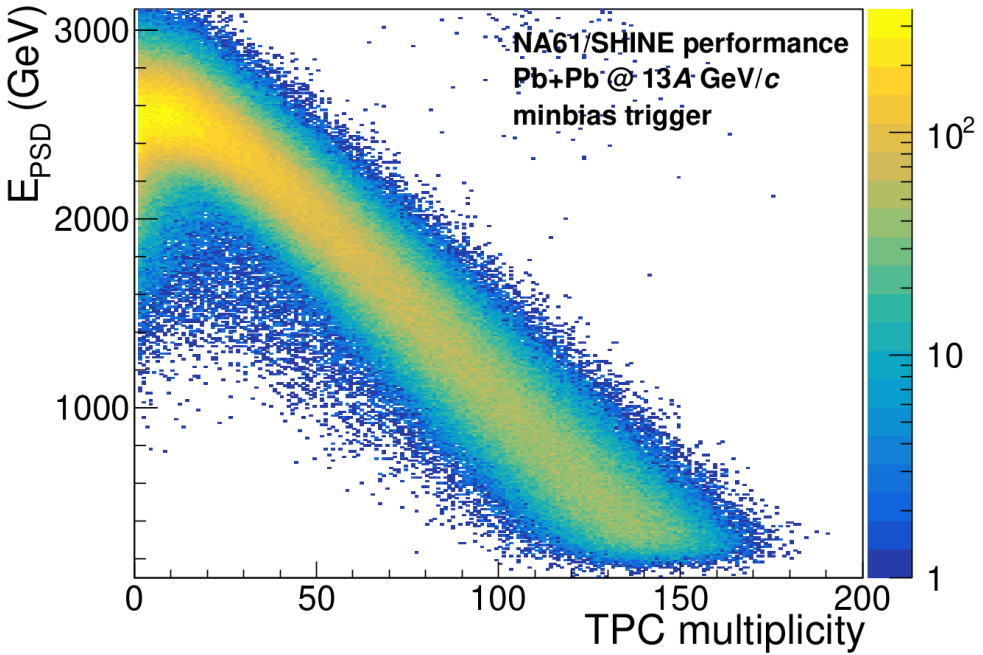
Comparison of proton v_2 with STAR

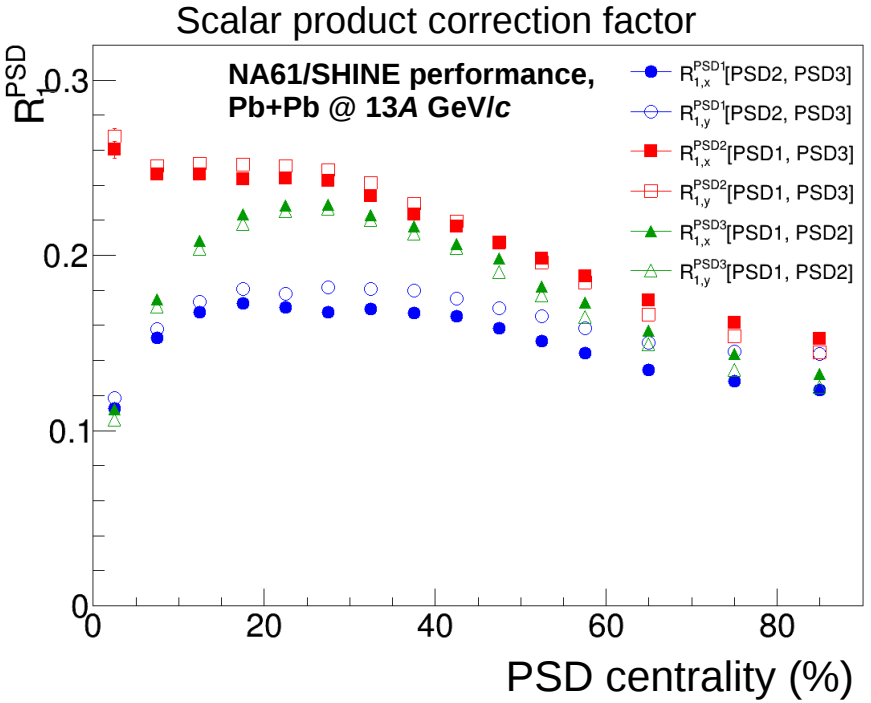


STAR Collaboration PRC 88 (2013) 014902

- Similar results for central and peripheral
- Tension for mid-central collisions could be due to different centrality estimators:
  - Particle multiplicity at midrapidity (STAR)
  - Projectile spectators (NA61/SHINE)

Outlook for Pb ion beam energy scan: Pb+Pb @ 13*A* GeV/*c*





- Good performance of the Projectile Spectator Detector at lowest SPS energy
  - very close to the top energy of CBM @ FAIR
    (CBM will have a similar forward calorimeter for centrality and spectator plane determination)

Summary

- Preliminary results for charged pions and protons directed and elliptic flow for Pb+Pb collisions at 30*A* GeV/*c* recorded in 2016 by the NA61/SHINE experiment are presented differentially vs. centrality, rapidity and transverse momentum

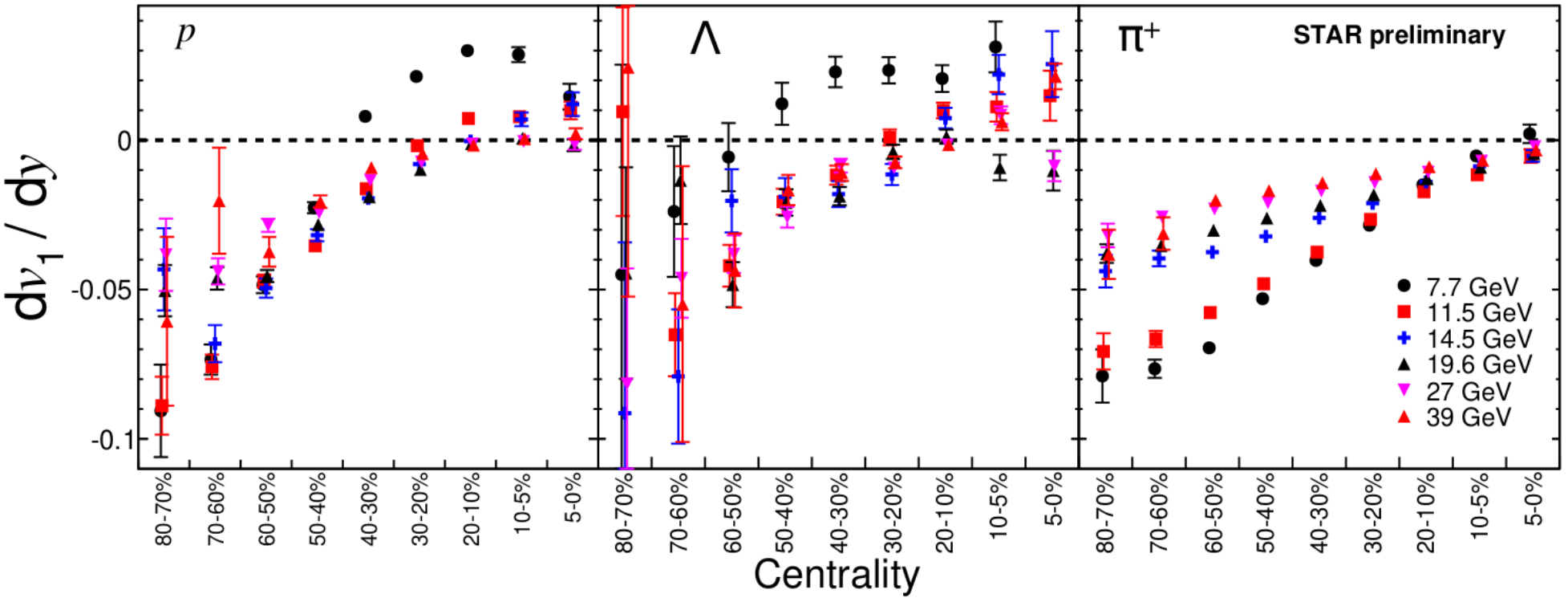
- Results are compared to the new analysis of the NA49 data using forward calorimeters and to the STAR@RHIC Beam Energy Scan data

Outlook

- Complete systematic analysis of the Pb ion beam energy scan data: 13*A* (2016) and 150*A* GeV/*c* (fall this year 2018)

- Study collective effects in smaller collision systems available from NA61/SHINE system size (Be+Be, Ar+Sc, Xe+La) and beam energy (13A–158*A* GeV/*c*) scan

BACKUP

Slope of v_1 (STAR Preliminary)

STAR Collaboration NPA 956 (2016) 260