Anisotropic flow measurement from NA61/SHINE experiment at CERN SPS

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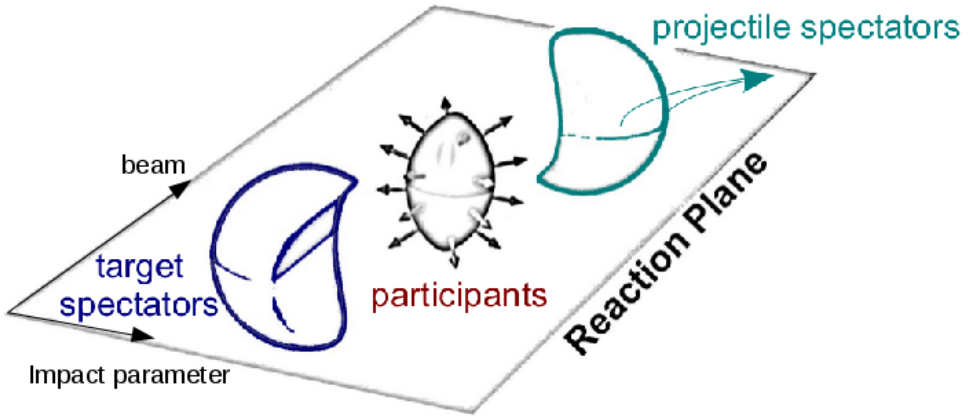
Collision geometry and anisotropic transverse flow

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

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

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



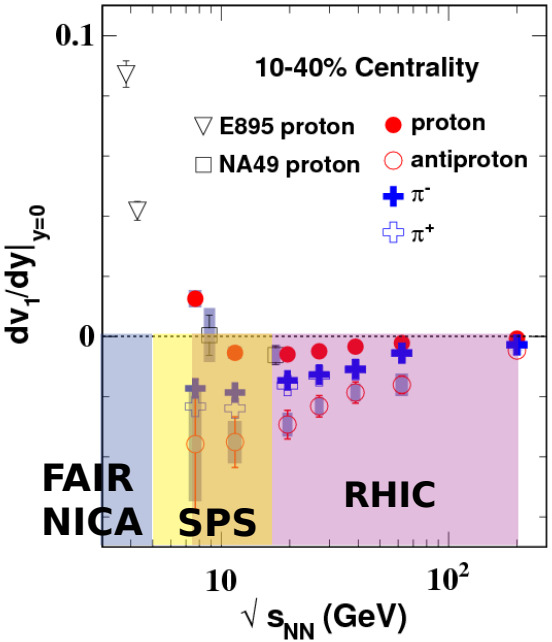
Components needed for v_n calculation:

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

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

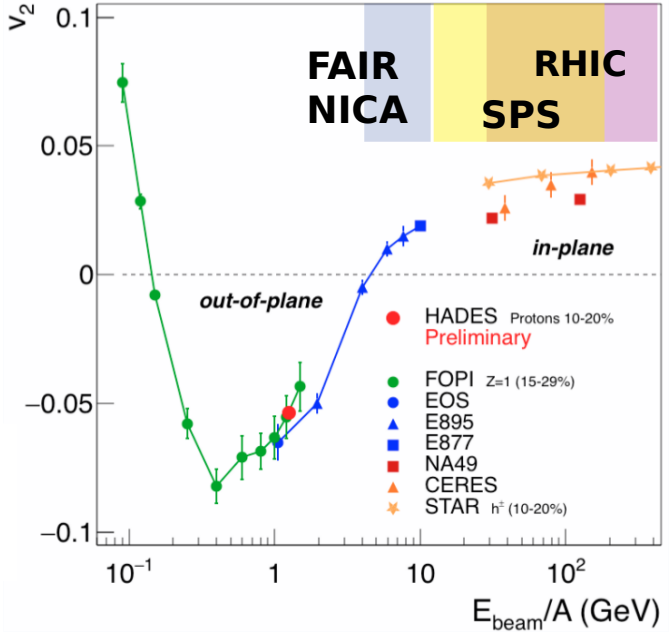
Collective flow at SPS / RHIC energies

Directed flow (slope)



STAR Collaboration
PRL 112 (2014) 162301

Elliptic flow



HADES Collaboration
JPCS 742 (2016) 012008

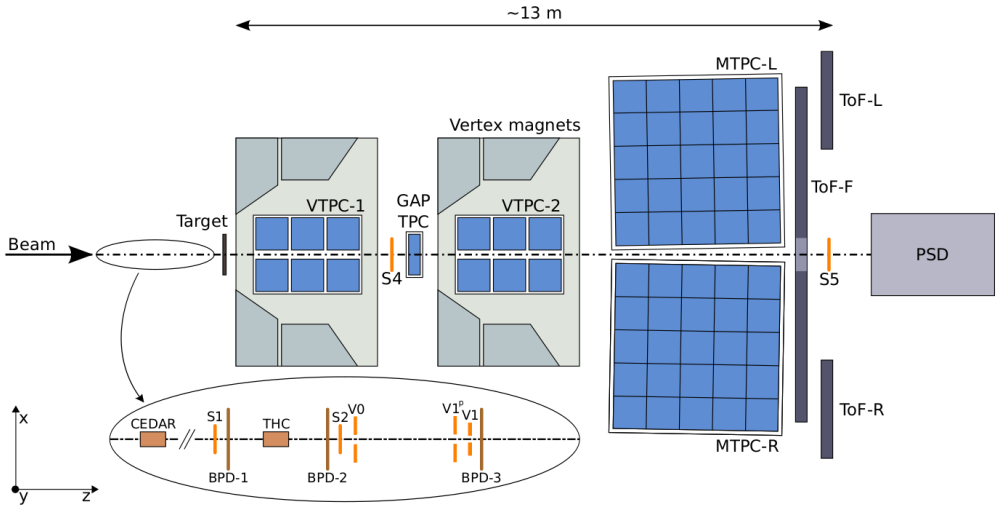
NA61/SHINE Pb-ion beam energy scan p_{LAB} = 13-150*A* GeV/*c*:

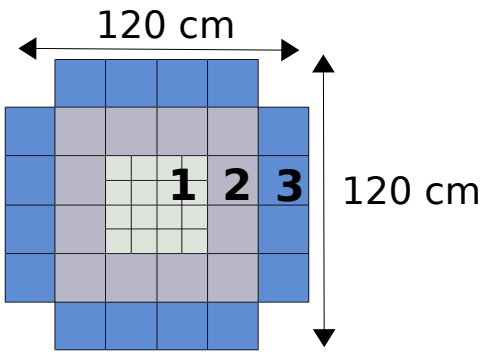
- extend existing NA49 data
- complementary to STAR@RHIC
- bridge to FAIR and NICA energies

Advantage of NA49 & NA61/SHINE fixed target setup:

- tracking and particle identification over wide rapidity range with TPCs
- projectile spectators' measurements with forward calorimeters

NA61/SHINE setup for Pb-ion beam energy scan (2016-2018)

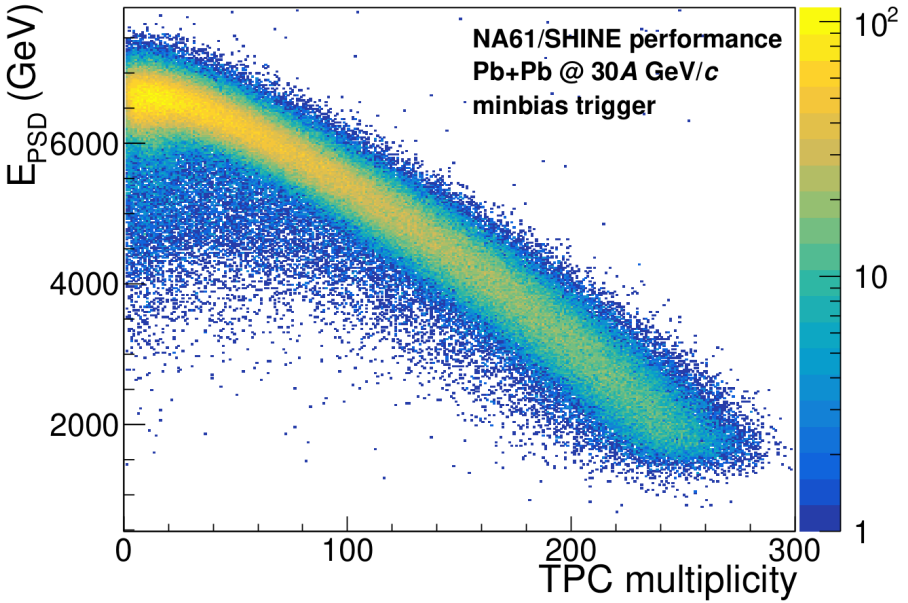


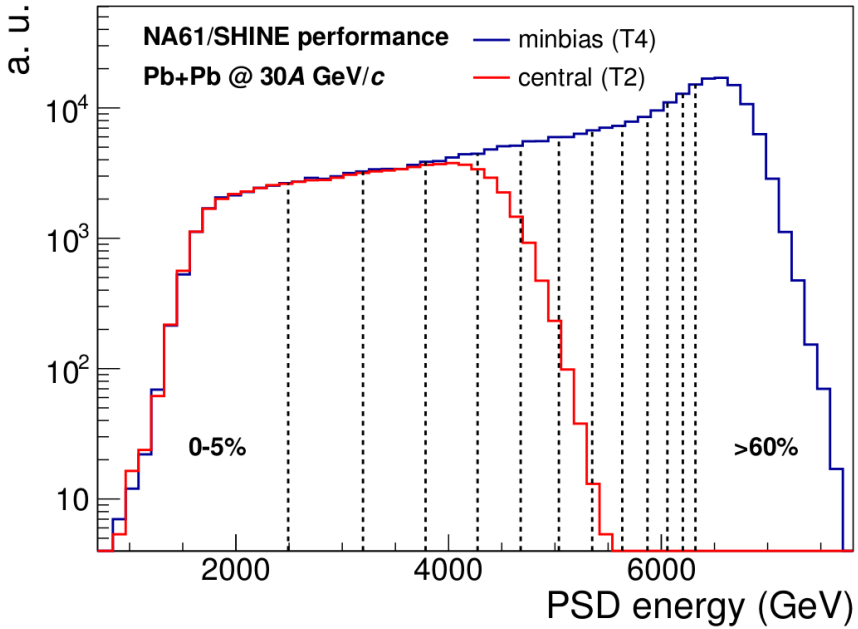


Projectile Spectator Detector (PSD)

- Successor of the NA49 experiment
- Full coverage of forward hemisphere with TPCs
- High-granularity forward calorimeter (PSD)
- 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* scheduled for November, 2018

Event selection & Centrality Estimation



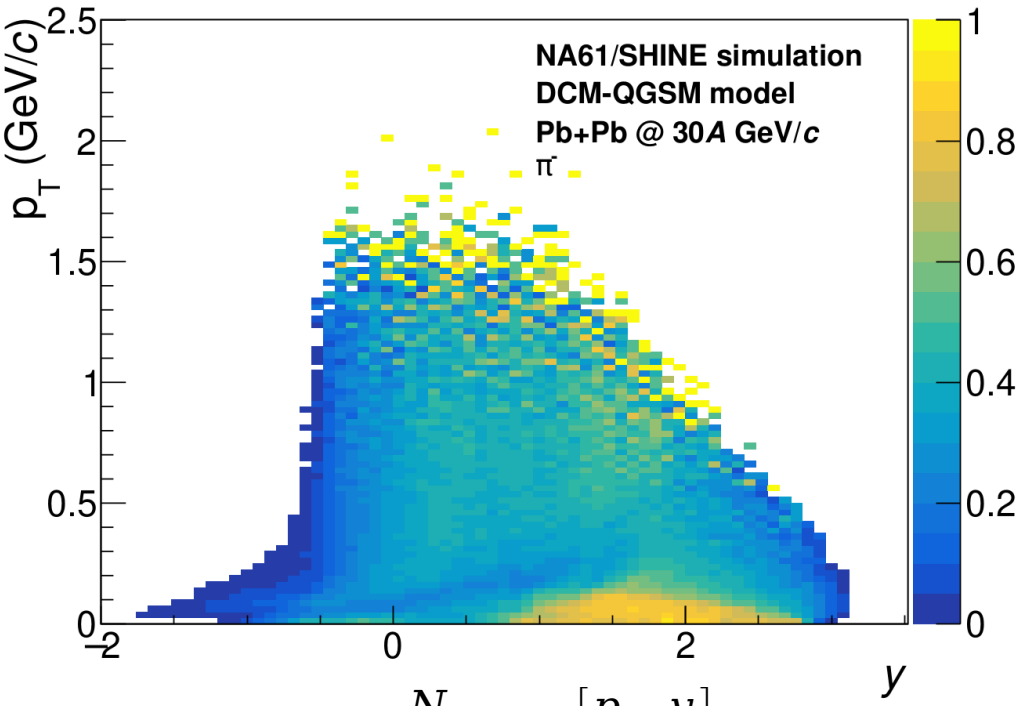


- Event has fitted vertex
- Good reconstructed vertex position
- Good beam position
- No overlap events / beam particles

Statistics per trigger:
1.1M **minimum bias (T4)**
600k **central (T2)**

Track selection & Corrections for detector non-uniformity in p_T/y

Example of p_T/y correction map



$$w[p_T, y] = \frac{N_{identified}[p_T, y]}{N_{simulated}[p_T, y]}$$

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 the fitted vertex

$|b_x| < 2$ cm

$|b_y| < 1$ cm

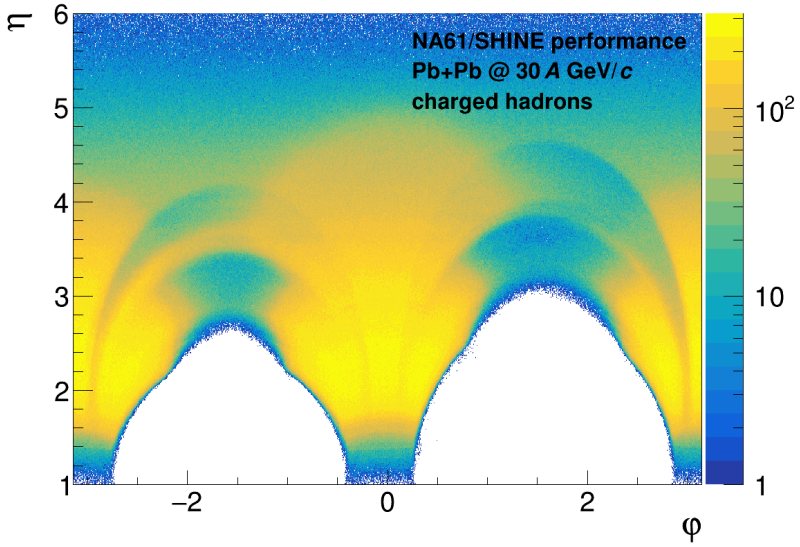
TPC energy loss (dE/dx)

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

- QnVector Corrections Framework
  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

Flow Analysis Framework

Extended flow-vector for p_T/y-differential corrections

- Multi-dimensional correlations of flow-vectors
  L. Kreis (GSI / Heidelberg) and I. Selyuzhenkov (GSI / MEPhI)

Framework has been tested and used in:
ALICE@LHC, NA49 and NA61/SHINE@SPS, CBM@FAIR and HADES@SIS18

Scalar product method for flow measurement with 1st harmonic Q-vector

u_n and Q_n vectors:

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

Directed flow:

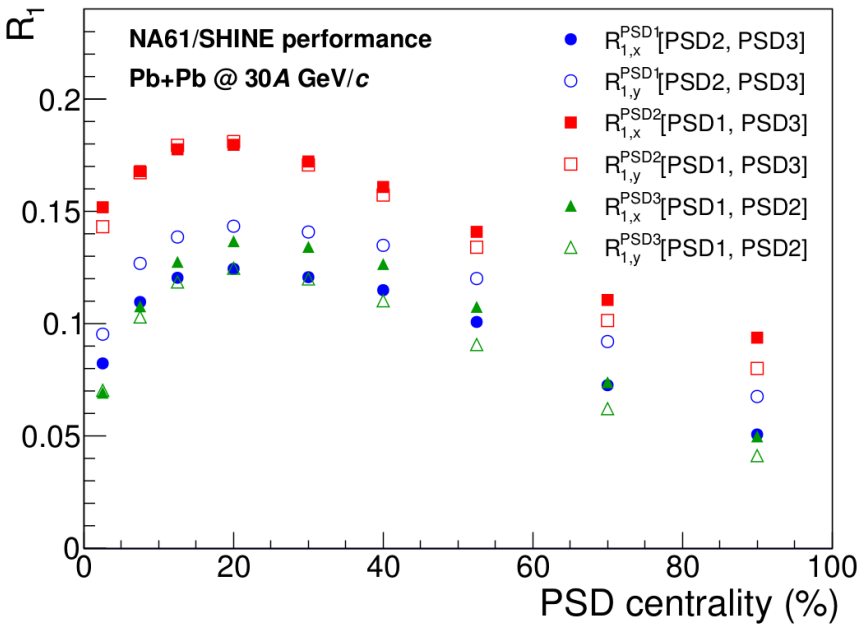
$$v_{1,i} = \frac{2\langle u_{1,i} Q^A_{1,i} \rangle}{R^A_{1,i}} \qquad i, j, k = [x, y]$$

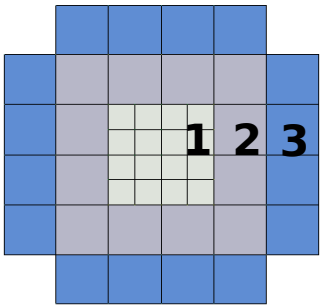
Elliptic flow:

$$v_2 = \frac{4\langle u_{2,i} Q^A_{1,j} Q^B_{1,k} \rangle}{R^A_{1,j} R^B_{1,k}}$$

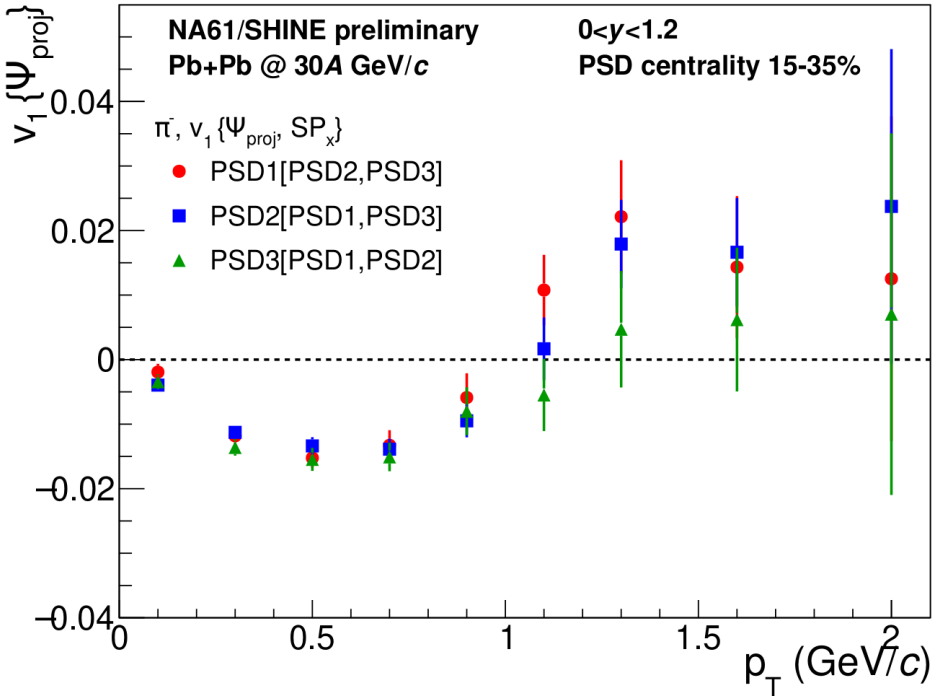
First harmonic resolution correction factor:

$$R^A_{1,i} = \sqrt{2 \frac{\langle Q^A_{1,i} Q^B_{1,i} \rangle \langle Q^A_{1,i} Q^C_{1,i} \rangle}{\langle Q^B_{1,i} Q^C_{1,i} \rangle}}$$

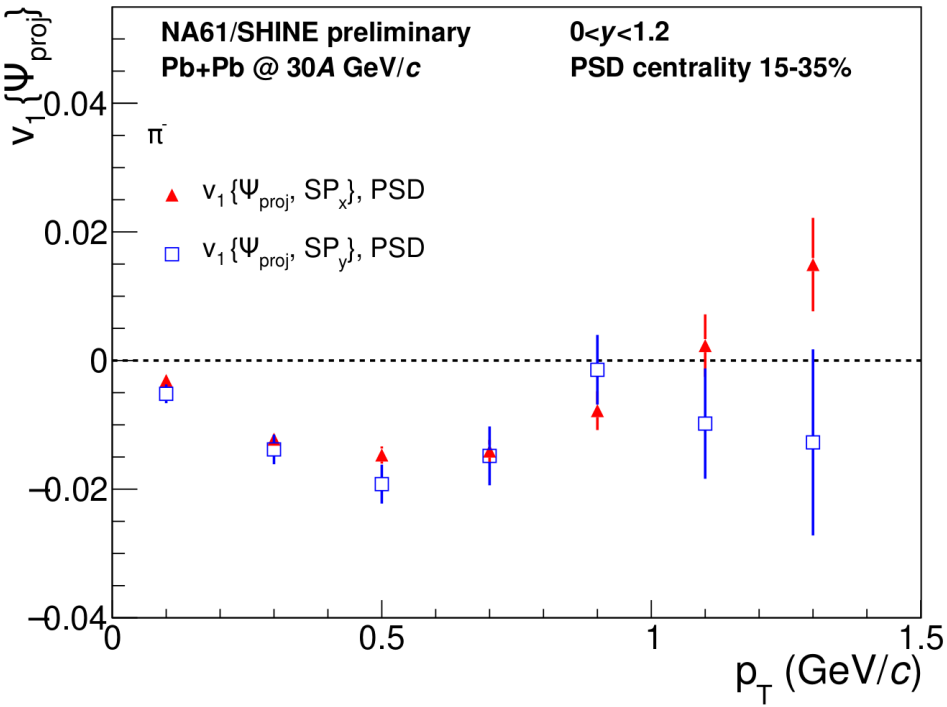




“Systematics” for directed flow (v_1) components



Consistent results for PSD subevents



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

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

NA61/SHINE preliminary results

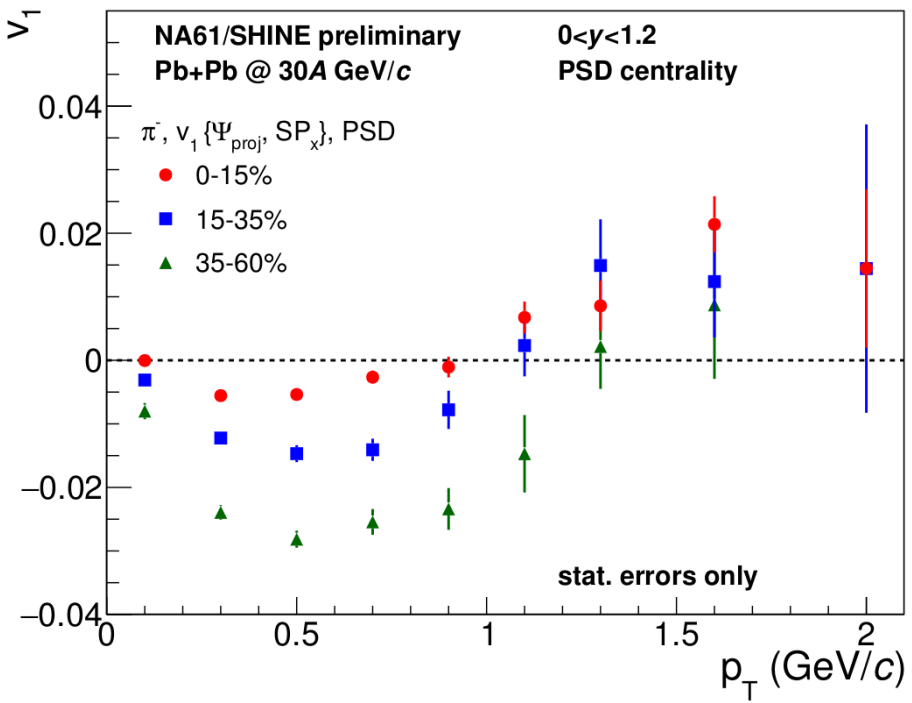
Results are presented for correlations between
charged pions and protons* (in the TPC acceptance) and
all hadrons at forward rapidity (in the PSD acceptance)

The results are corrected for detector non-uniformity.
No corrections for secondary interactions and weak decays are done yet.
Only statistical uncertainties are shown.

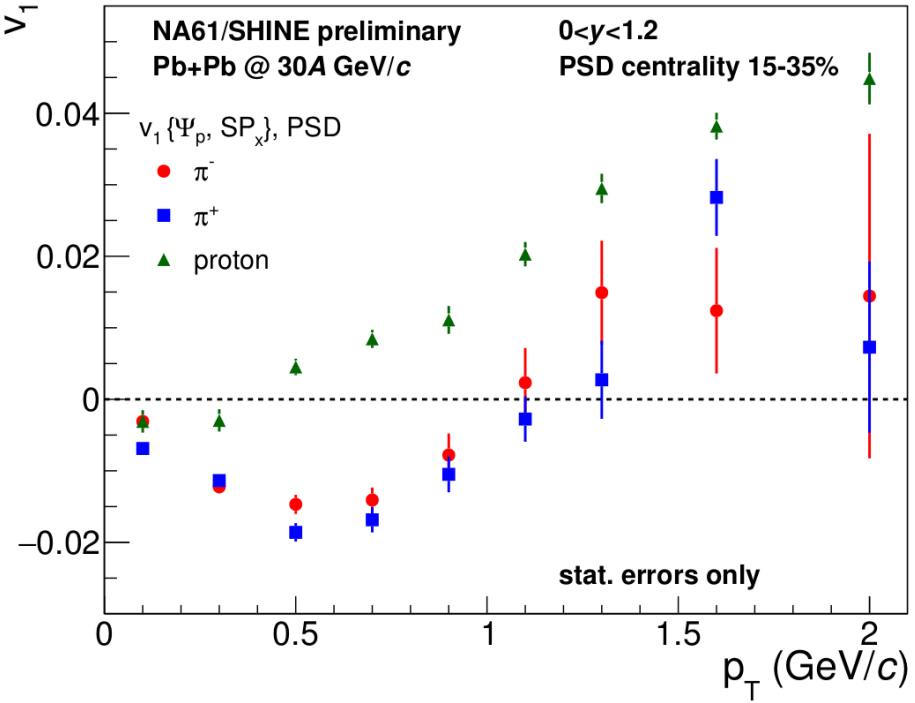
**hadrons produced by strong interaction processes and their electromagnetic decays*

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



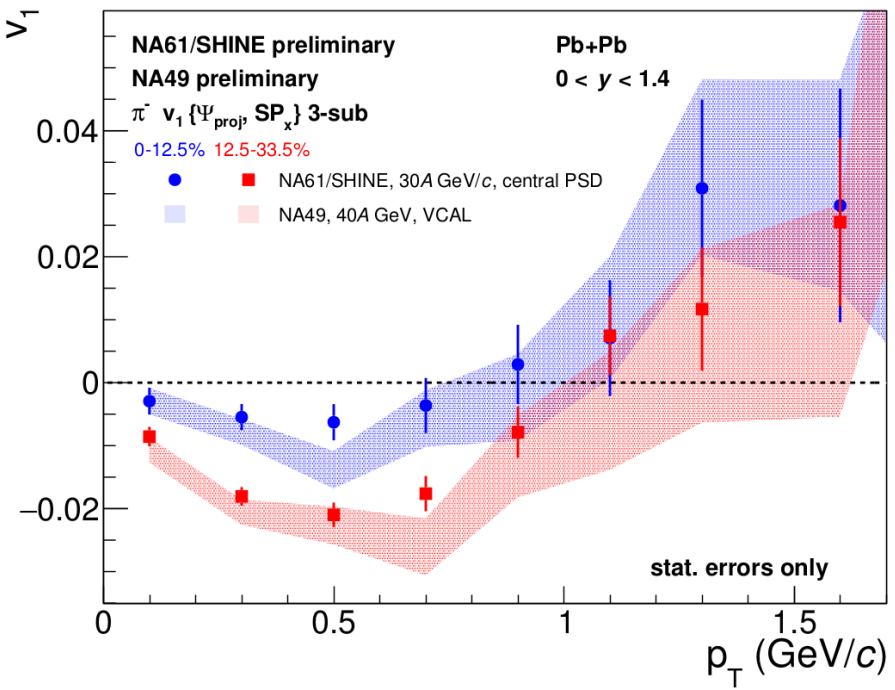
- Strong centrality dependence of v_1
- $v_1(p_T \sim 0\ \mathrm{GeV}/c) = 0$
- v_1 changes sign at $p_T \sim 1\ \mathrm{GeV}/c$

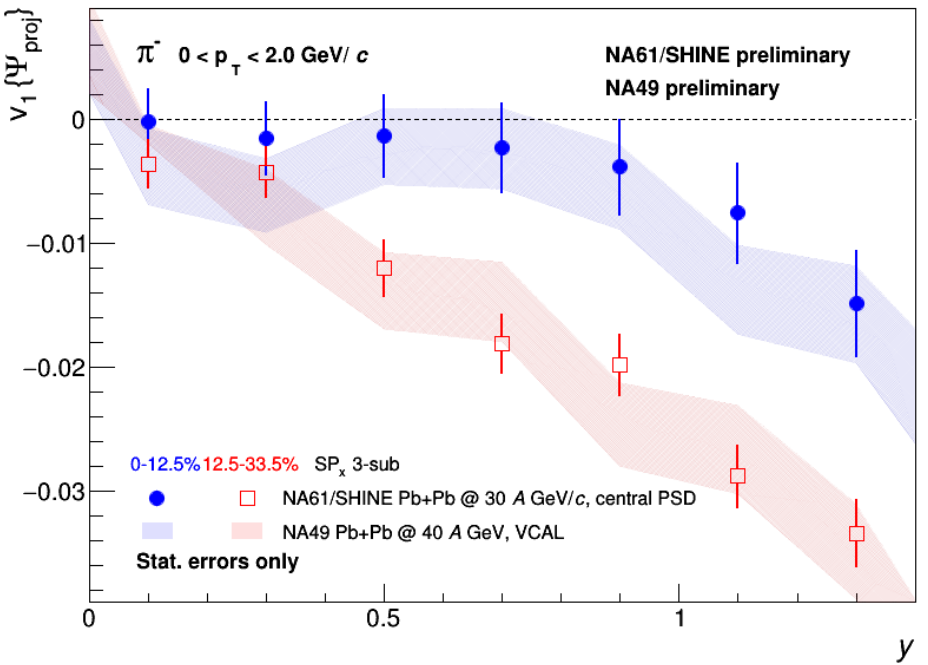


- Significant mass dependence of v_1
- Difference between π^+ and π^- v_1 is sensitive to the electromagnetic effects*

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

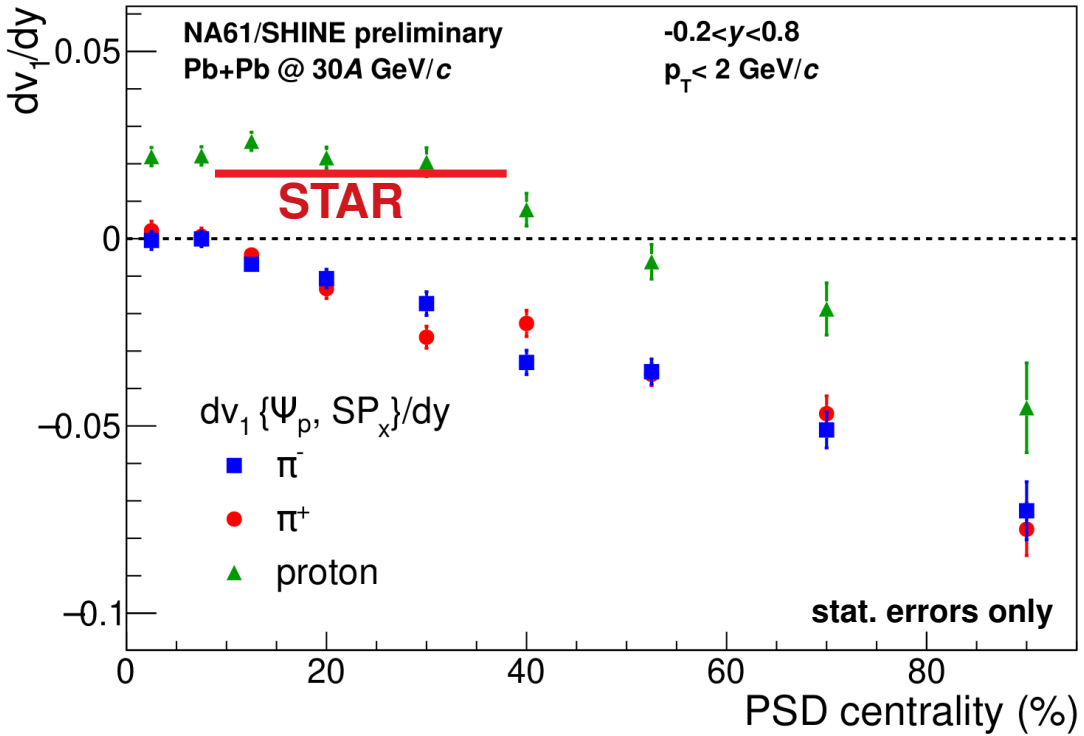
Comparison of negative pion v_1: NA61/SHINE vs NA49





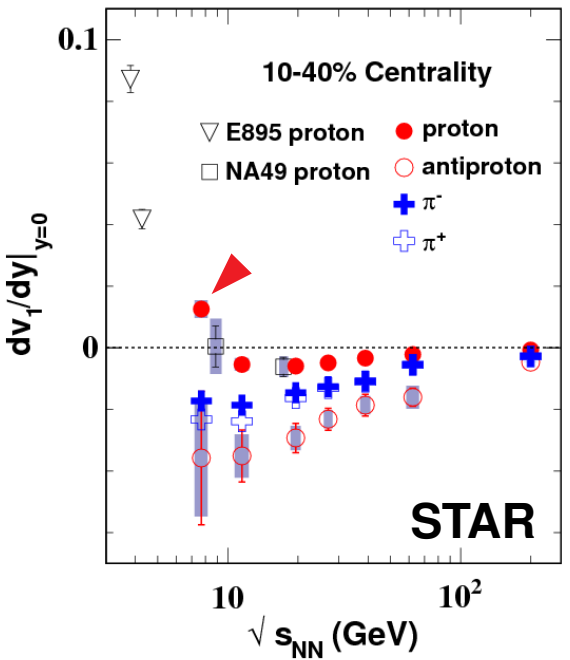
Similar flow results relative to the spectator plane using data from NA49 and NA61/SHINE

Slope of v_1 at midrapidity vs centrality
Comparison with STAR results



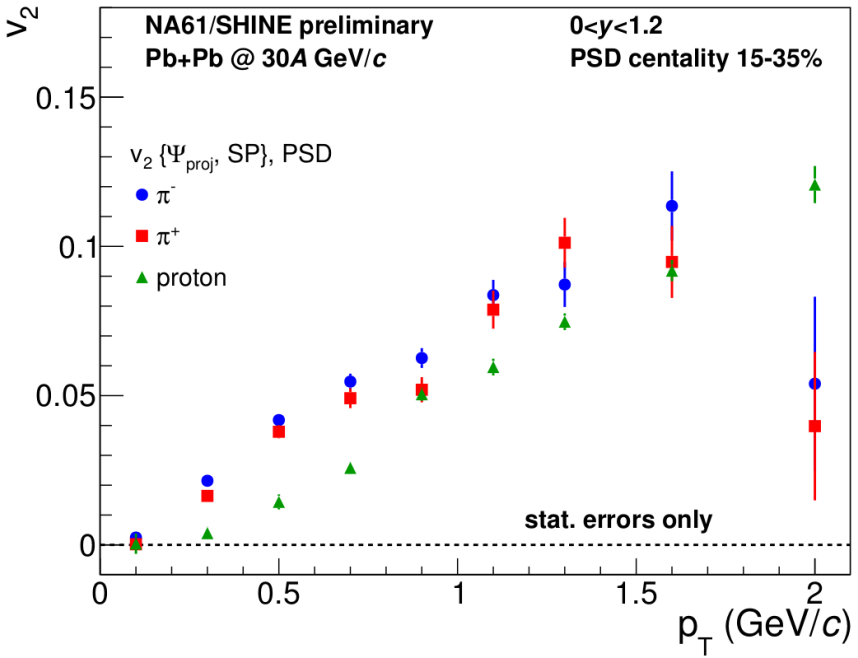
Slope extraction is sensitive to fit function and rapidity range

STAR Collaboration PRL 112 (2014) 162301

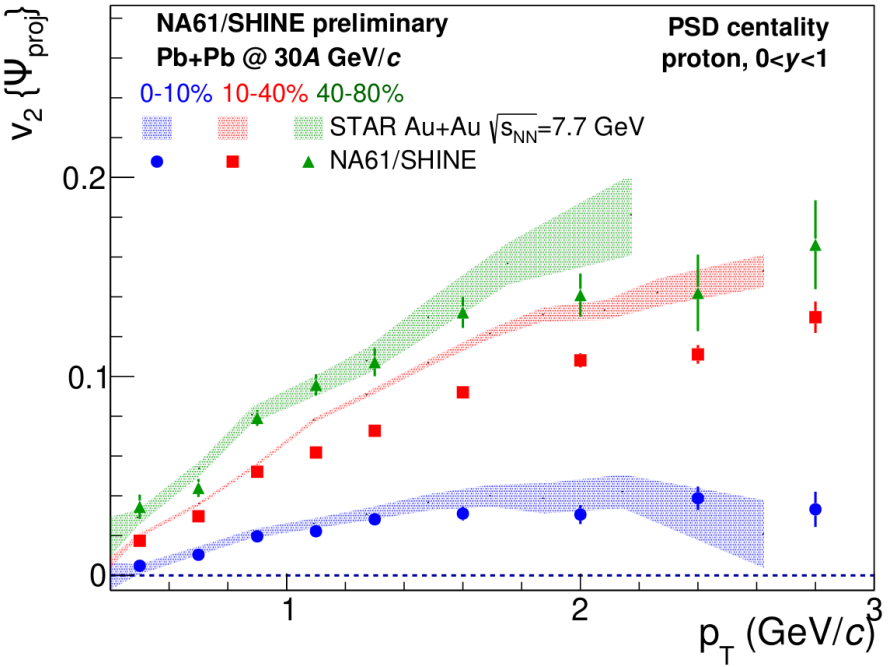


Preliminary results for centrality dependence presented by STAR Collaboration: NPA 956 (2016) 260

Elliptic flow vs transverse momentum
Comparison with STAR



- Clear mass dependence
- Difference between π^+ and π^- v_2 is small



Tension for mid-central collisions could be due to different centrality estimators:

- Particle multiplicity at midrapidity (STAR)
- Projectile spectators (NA61/SHINE)

Summary

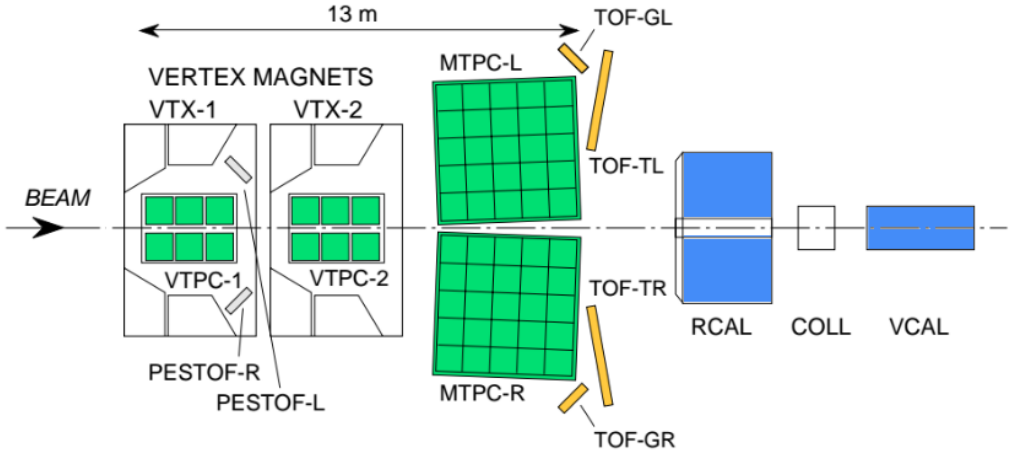
- Preliminary results for anisotropic flow relative to spectator plane from NA61/SHINE are presented differentially (vs. centrality, rapidity, p_T) for:
  - charged pions and protons directed and elliptic flow for Pb+Pb collisions at 30*A* GeV/*c* recorded in 2016 by the NA61/SHINE experiment
- New results are compared to:
  - Existing data for v_1 , v_2 from STAR@RHIC Beam Energy Scan
  - New analysis of flow wrt spectator plane for 40A GeV data by NA49

Outlook

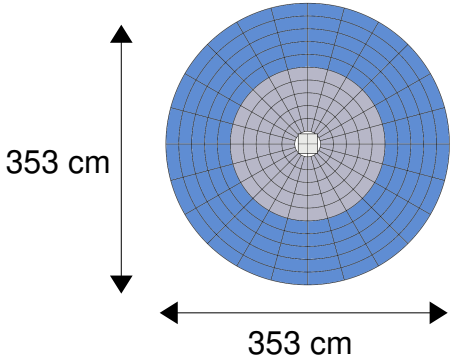
- Complete systematic analysis of the Pb ion beam energy scan data: 13*A* (2016) and 150*A* GeV/*c* (November, 2018)
- Study collective effects in smaller collision systems available from NA61/SHINE system size (Be+Be, Ar+Sc, Xe+La) and beam energy (13*A*–158*A* GeV/*c*) scan

BACKUP

NA49 setup for Pb-ion beam energy scan (1996-2002)

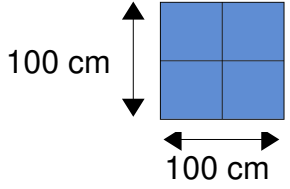


RCAL



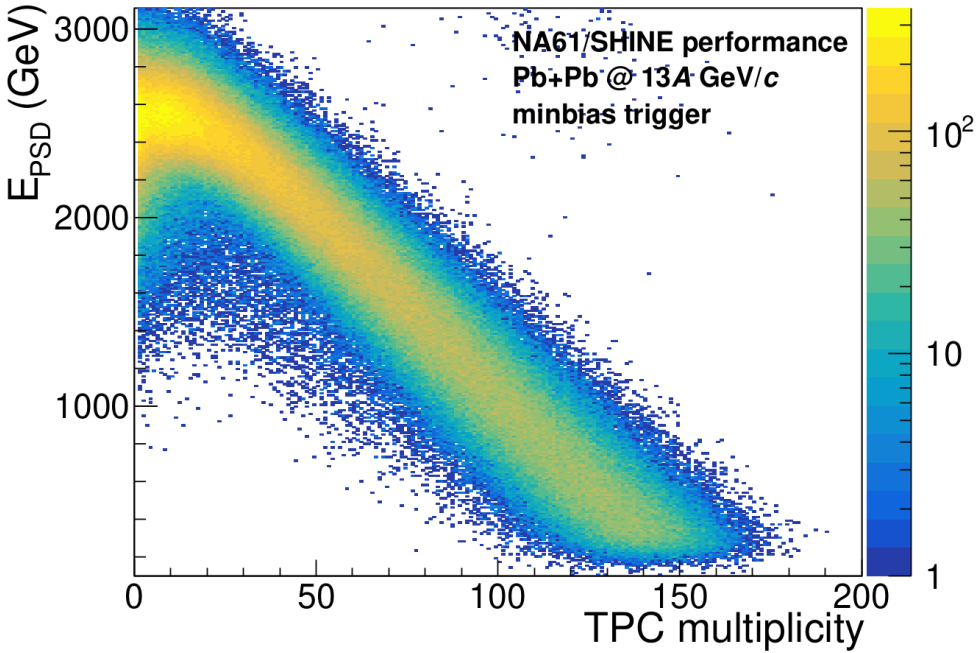
24 sections x 10 rings

VCAL

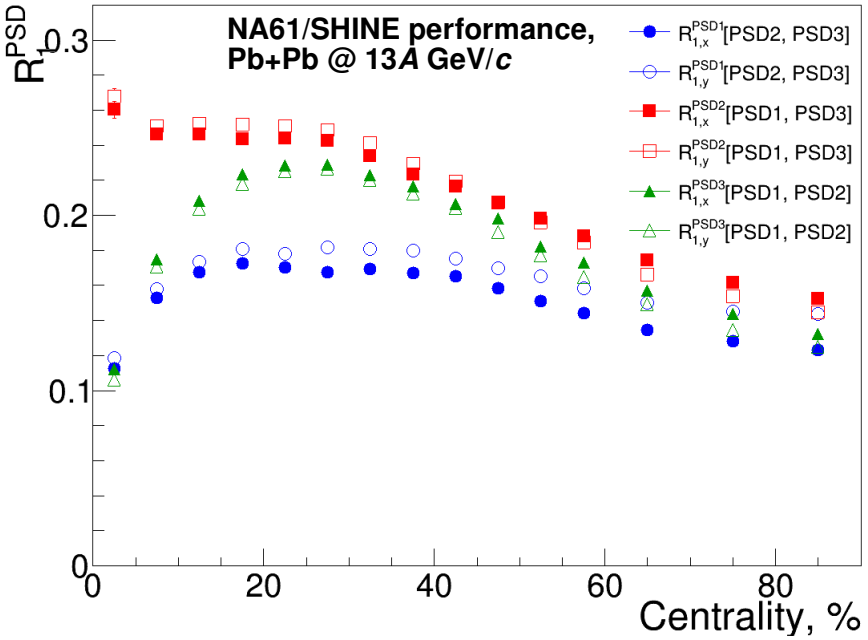


- Large acceptance hadron spectrometer (TPC)
  - ~ 2 units of rapidity coverage
  - tracking + identification down to p_T ~ 0 GeV/*c*
- Forward rapidity calorimeters (RCAL & VCAL):
  - sensitivity to spectator symmetry plane
- Beam energies:
  - 20*A*, 30*A*, 80*A* GeV (central)
  - **40*A***, 158*A* GeV (minimum bias)

Preview for Pb+Pb @ 13*A* GeV/*c*



Scalar product correction factor

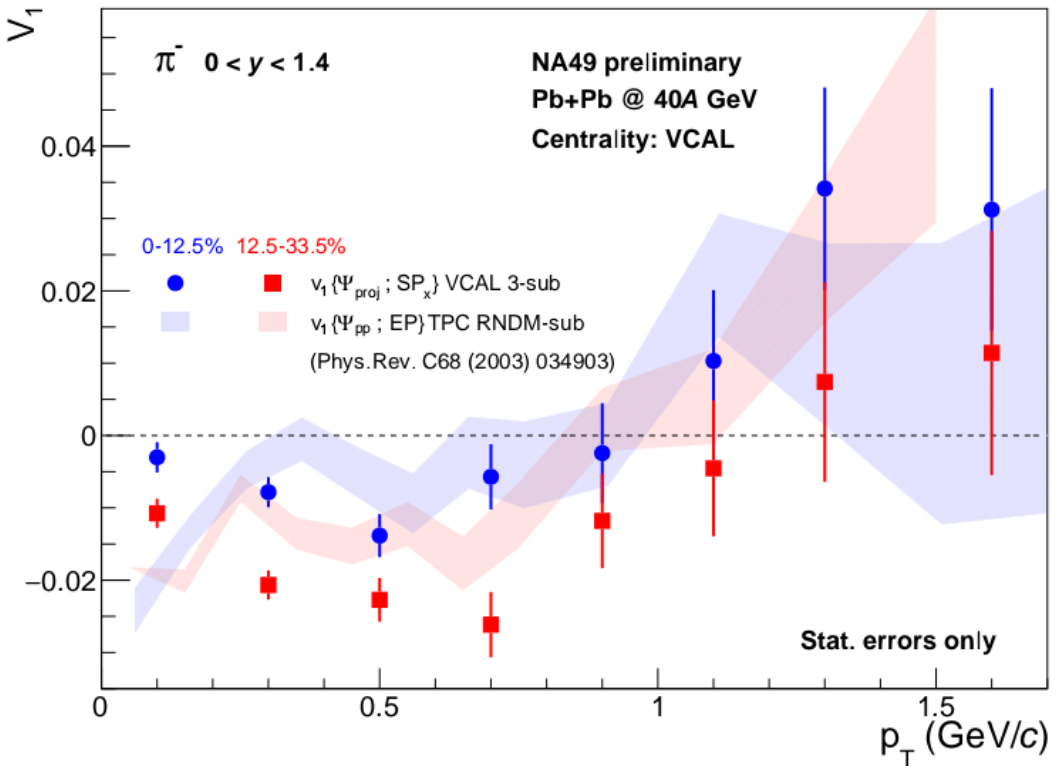


Good performance of the Projectile Spectator Detector at lowest SPS energy
- very close to the top energy of CBM @ FAIR which
will have a similar forward calorimeter for centrality and spectator plane determination

Backup: Event selection

	Pb-Pb@30*A* GeV/c (NA61)	Pb-Pb@40A GeV (NA49)
Vertex Fit	-0.35 < x < 0.3 -0.37 < y < 0.8 -594 < z < -590 good vertex fit	-0.05 < x < 0.95 -0.50 < y < 0.50 579.5 < z < -578.5 good vertex fit
Beam Position Detector	BPD1 x [-0.4, 0.0] y [-0.6, 0.8] BPD2 x [-0.2, 0.1] y [-0.3, 0.3] BPD3 x [-0.34, 0.22] y [-0.35, 0.05]	
Trigger	Minbias T4, Central T2	Minbias, Midcentral, Central
WFA	Beam: 4000ns Interaction: 25000ns	
Minimum number of selected tracks		10

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)

Slope of v_1 (STAR Preliminary)

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