# Anisotropic flow measurements from NA61/SHINE and NA49 experiments at CERN SPS

Ilya Selyuzhenkov (*GSI / MEPhI*)
Oleg Golosov (*MEPhI*)
Viktor Klochkov (*GSI / Frankfurt University*)
Evgeny Kashirin (*MEPhI*)

for the NA61/SHINE and NA49 Collaborations

CPOD2018, Corfu, Greece
20 September 2018

# Anisotropic flow measurements from NA61/SHINE and NA49 experiments at CERN SPS

Evgeny Kashirin
(MEPhI, Moscow)

Viktor Klochkov
(GSI / Frankfurt Uni.)

Oleg Golosov
(MEPhI, Moscow)

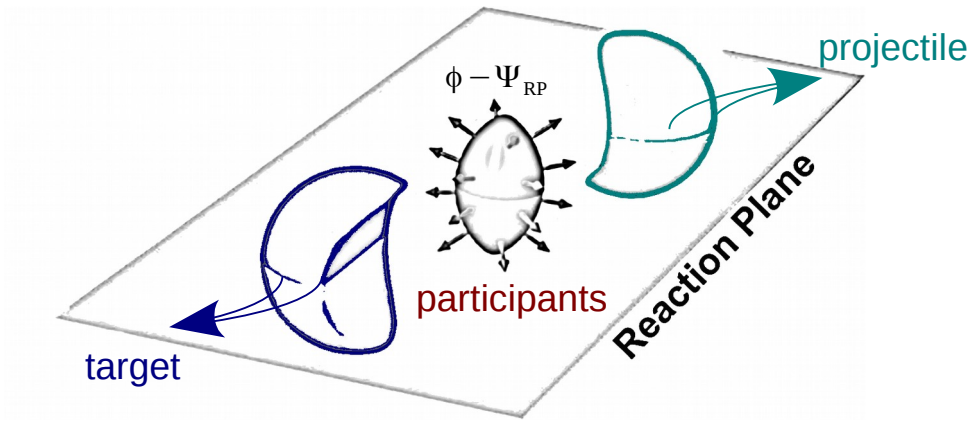
Ilya Selyuzhenkov
(GSI / MEPhI)

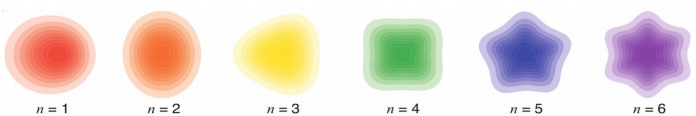
# Collision geometry and anisotropic transverse flow

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

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

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



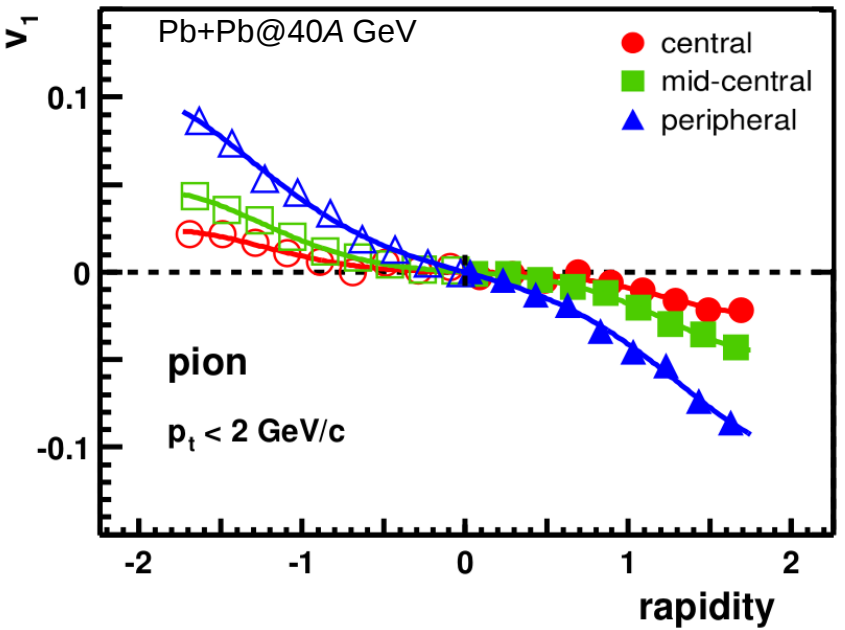

$\Psi_s$ can be estimated using produced particles $\Psi_{pp}$ or projectile (target) spectators $\Psi_{proj}$ ($\Psi_{spec}$)

Components needed for $v_n$ calculation:

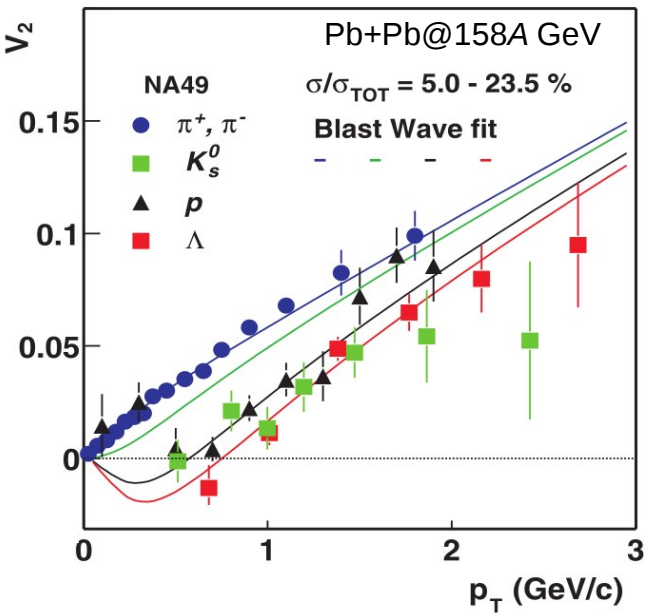
- particle type and momentum ($\phi$, $y$, $p_T$)
- centrality estimation
- $\Psi_s$ estimation

# Old results by the NA49 for anisotropic flow

NA49 Collaboration, PRC68 (2003) 034903



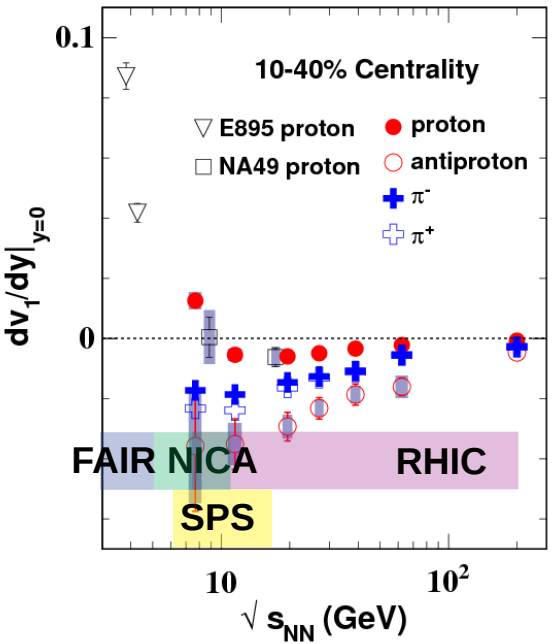

NA49 preliminary (G. Stefanek et al.)
PoS CPOD2006 (2006) 030




- Published: $v_1$ & $v_2$ of pions and protons for Pb+Pb at 40*A* and 158*A* GeV
- Preliminary: $v_2$ of Λ and $K^0_S$ for Pb+Pb at 158*A* GeV
- All measurements are relative to participant symmetry plane

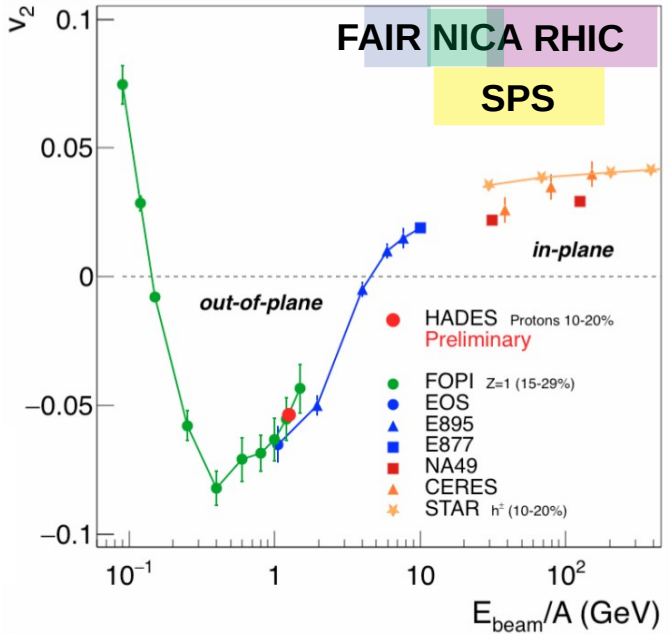
# Recent collective flow results at SPS / RHIC energies

Directed flow (slope)




STAR Collaboration
PRL 112 (2014) 162301

Elliptic flow




HADES Collaboration
JPCS 742 (2016) 012008

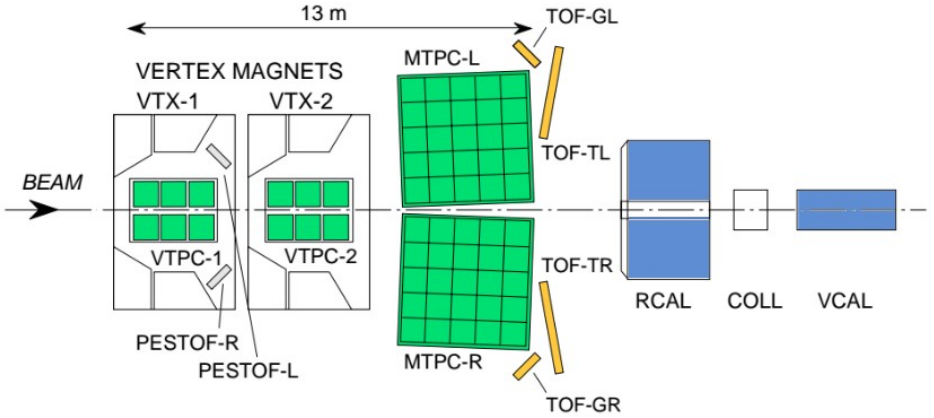
NA49 Pb+Pb beam energy scan
$E_{beam}$ = 20-158*A* GeV

NA61/SHINE Pb+Pb scan
$p_{LAB}$ = 13-150*A* GeV/*c*

Advantage of NA49 & NA61/SHINE fixed target setup:

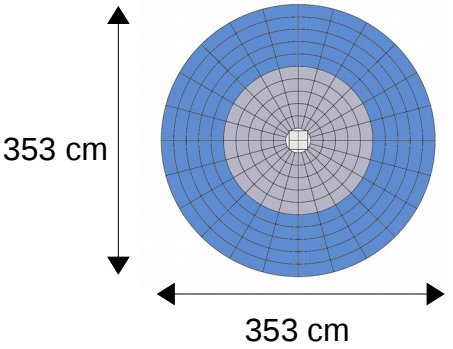
- tracking and particle identification over wide rapidity range with TPCs
- projectile spectators' measurements with forward calorimeters
- complementary to STAR@RHIC
- bridge to FAIR & NICA beam energies

# NA49 setup (1996-2002)



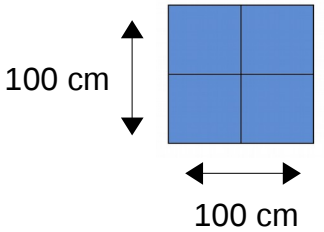

Ring (RCAL)

24 sections x 10 rings




Veto (VCAL)

2 x 2 modules



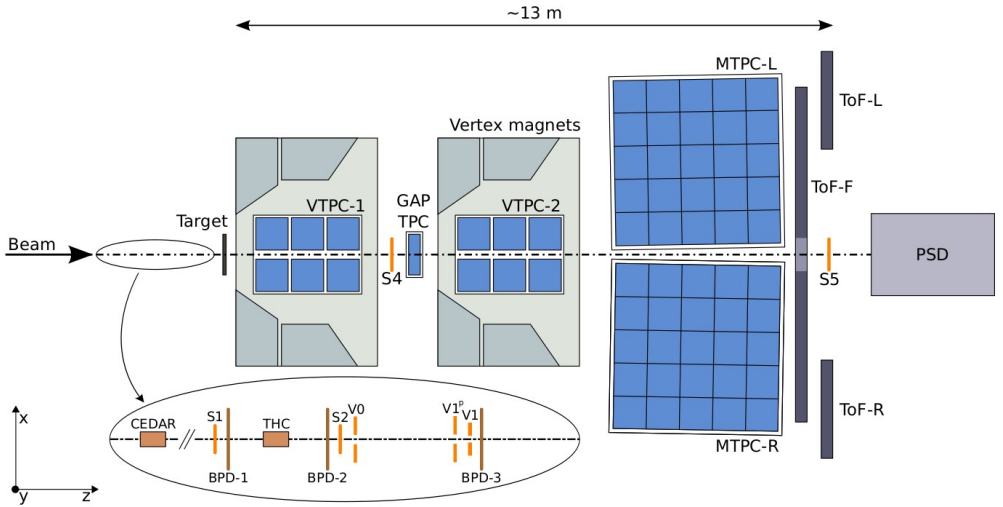

Large acceptance hadron spectrometer (TPC)

- ~ 2 units of rapidity coverage in forward hemisphere
- Tracking + identification down to $p_T$ ~ 0 GeV/*c*

Forward rapidity calorimeters:
sensitivity to spectator symmetry plane

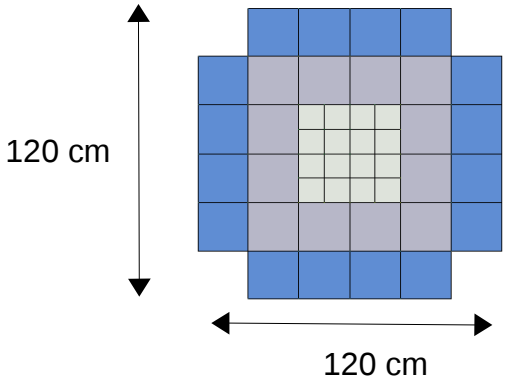
Pb beam energies:
20*A*, 30*A*, 80*A* GeV (central)
**40*A***, 158*A* GeV (minimum bias)

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




Projectile Spectator Detector (PSD)

45 modules

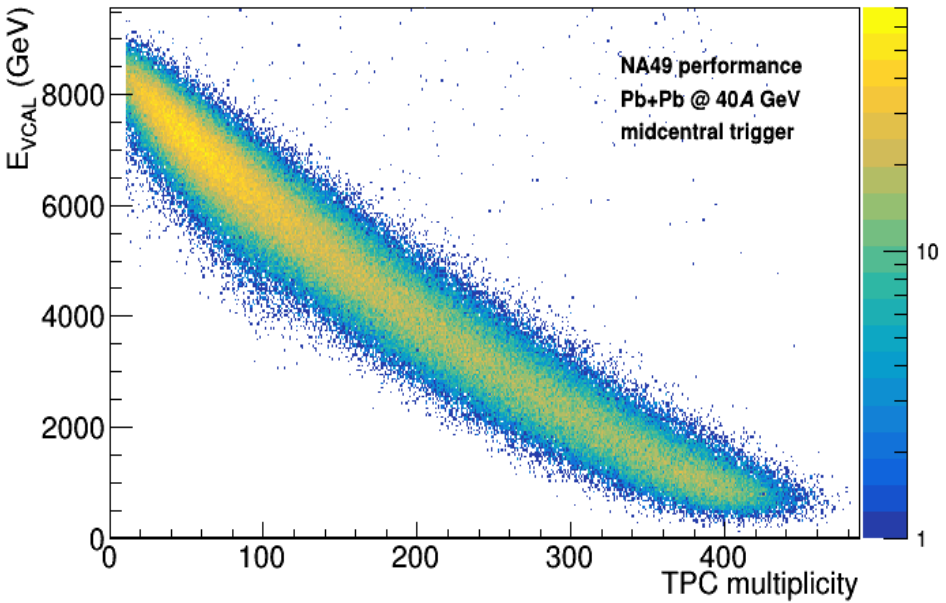



- Successor of the NA49 experiment
- Upgraded TPCs

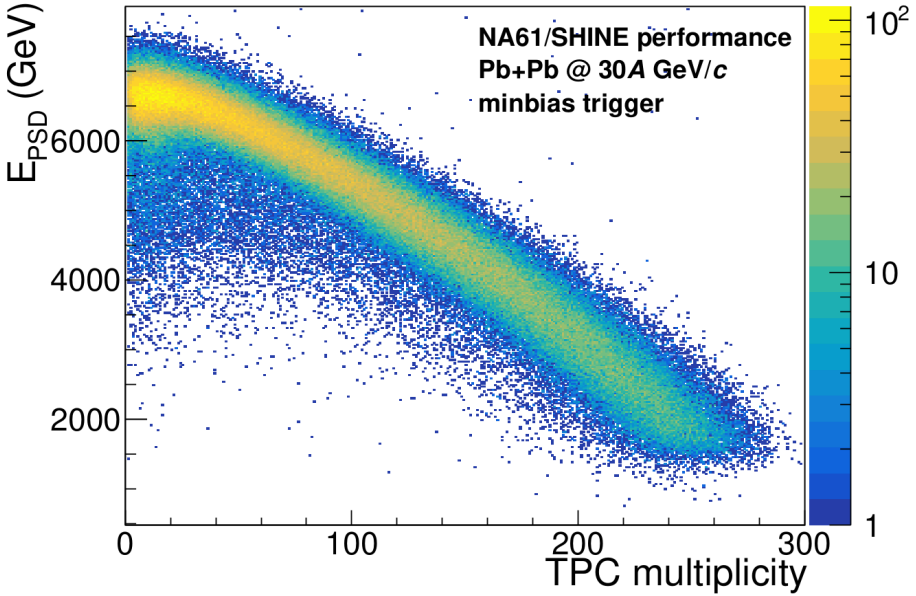
New high-granularity forward hadron calorimeter

Pb beam momentum:
13*A*, **30*A* GeV/*c***
150*A* GeV/*c* scheduled for November, 2018

# Event selection & multiplicity vs. forward energy correlation



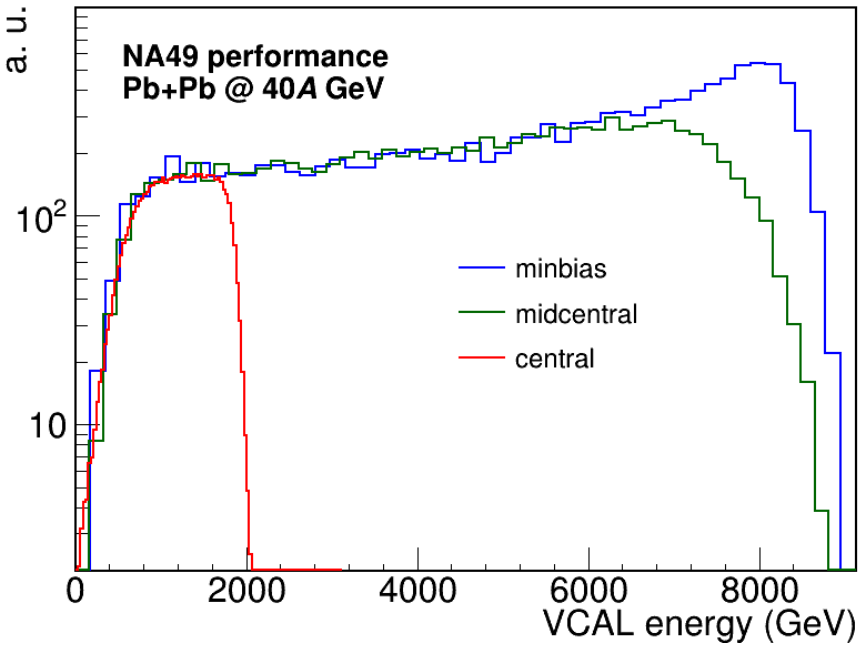

- Event has fitted vertex
- Good reconstructed vertex position
- At least 10 good tracks

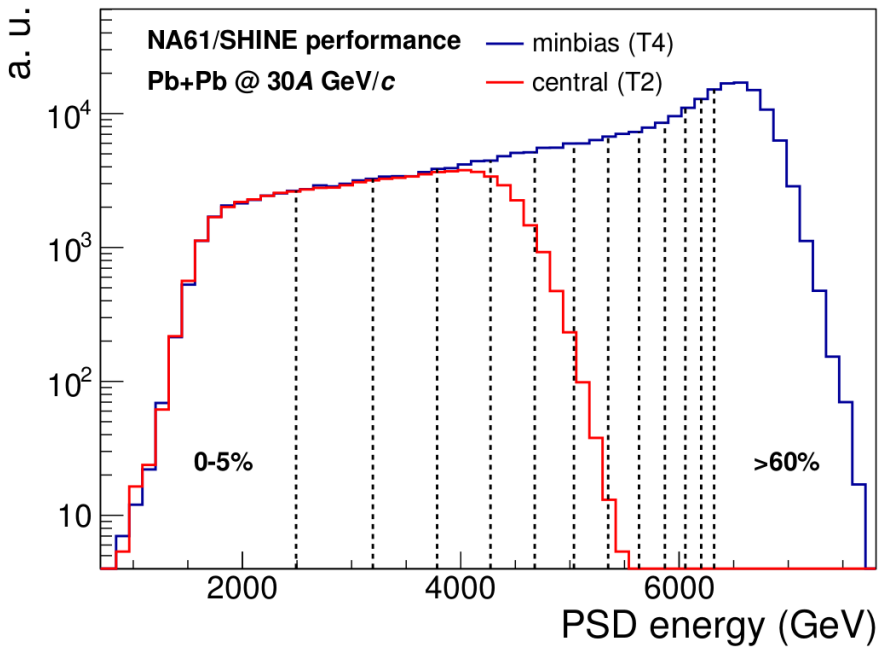



- Event has fitted vertex
- Good reconstructed vertex position
- Good beam position
- No overlap events / beam particles

more details in backup

# Centrality determination using forward energy



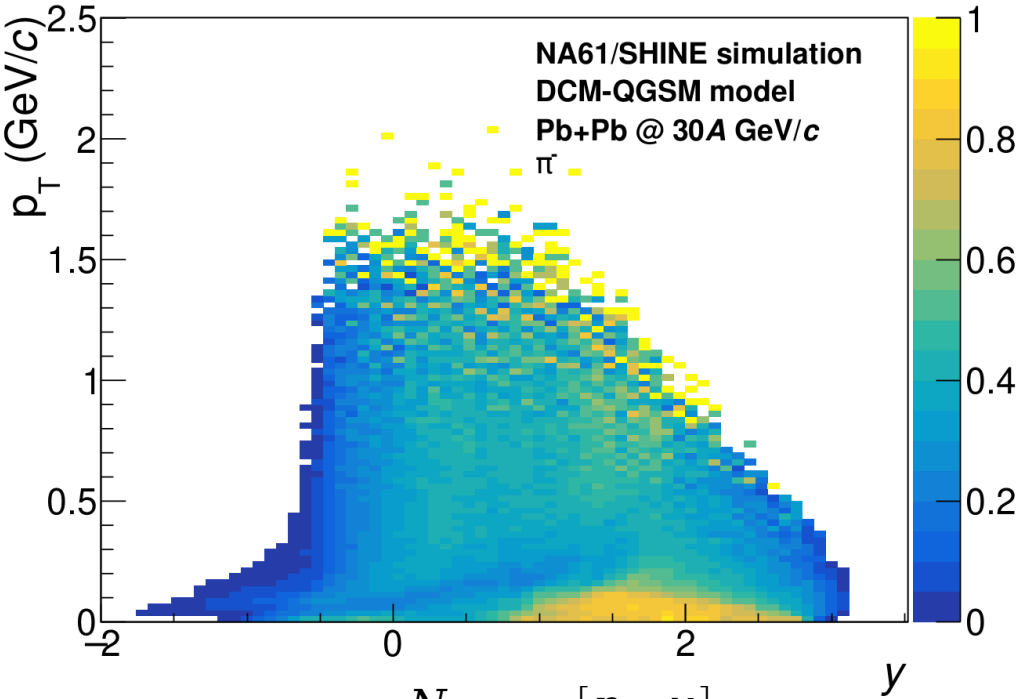




Statistics per trigger: 440k **central**
320k **midcentral**
20k **minbias**

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

# Track selection & $p_T/y$ corrections for detector non-uniformity

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 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 model

NA49 details in backup

# QnVector Corrections and Analysis framework

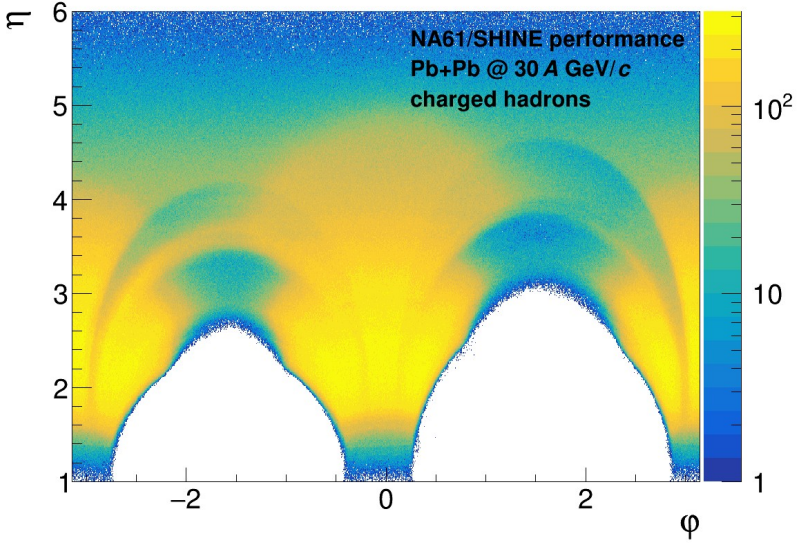
Jaap Onderwaater
(GSI / TU Darmstadt)

Victor Gonzalez
(CIEMAT, Madrid)

Ilya Selyuzhenkov
(GSI / MEPhI)

Lukas Kreis
(GSI / Heidelberg Uni)

# Corrections for detector azimuthal non-uniformity




**QnVector Corrections**

- 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/jonderwaater/FlowVectorCorrections
- Recentering, twist, and rescaling corrections applied time dependent (run-by-run) & as a function of centrality

**Flow Analysis Framework**

- Extended QnVector framework corrections for $p_T/y$
- Multi-dimensional correlations of QnVectors
  L. Kreis and I. Selyuzhenkov

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

# Flow measurement relative to the spectator plane
## (scalar product method)

$u_n$ 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:

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

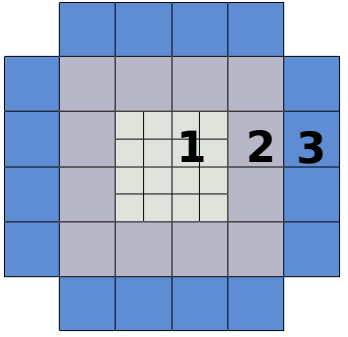
Elliptic flow:

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

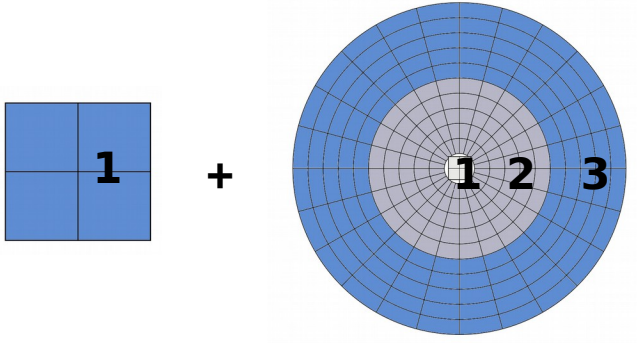
First harmonic resolution correction factor:

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

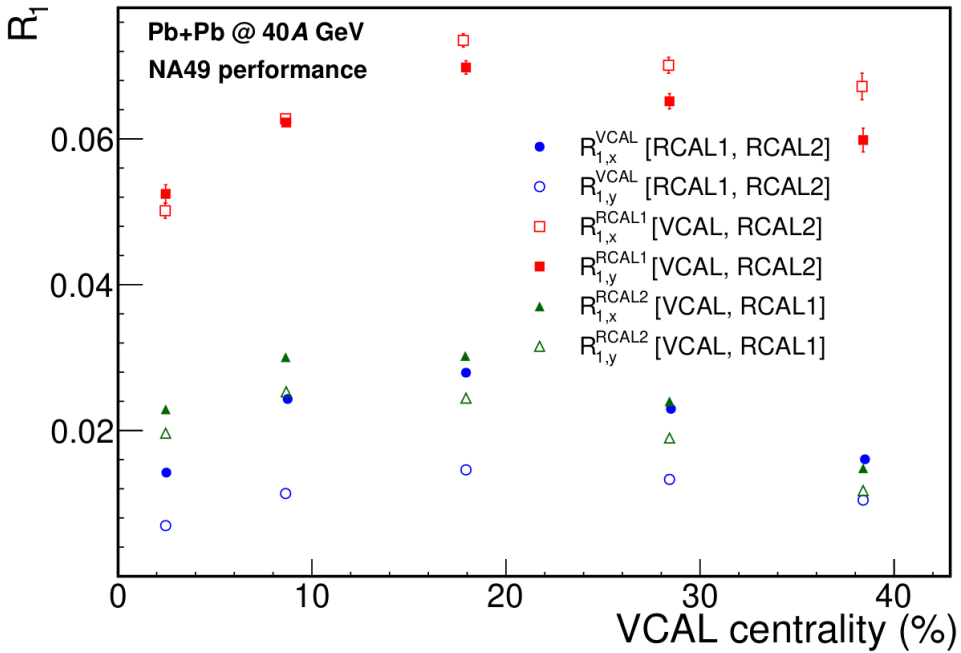
**PSD (NA61/SHINE)**

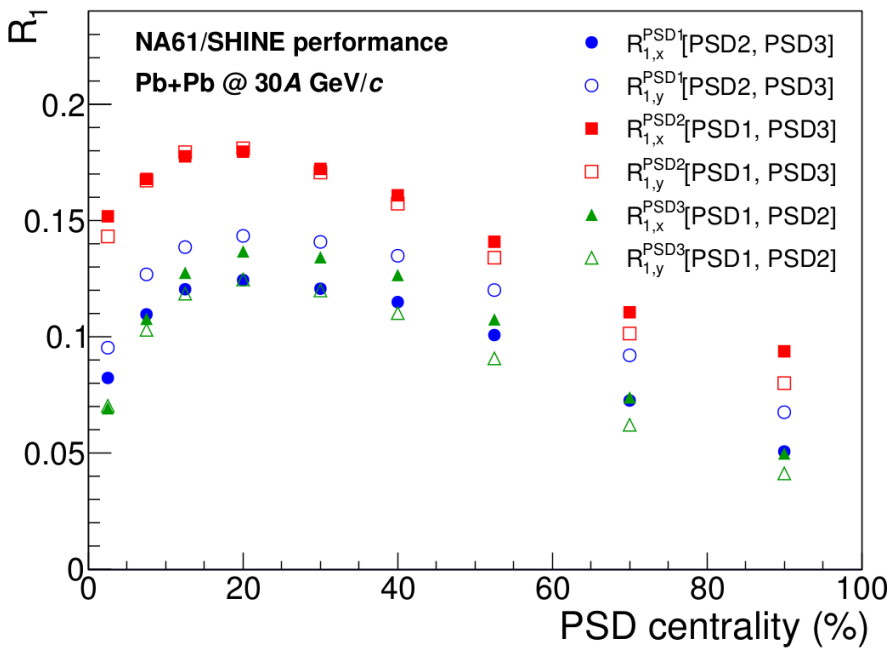



**VCAL + RCAL (NA49)**



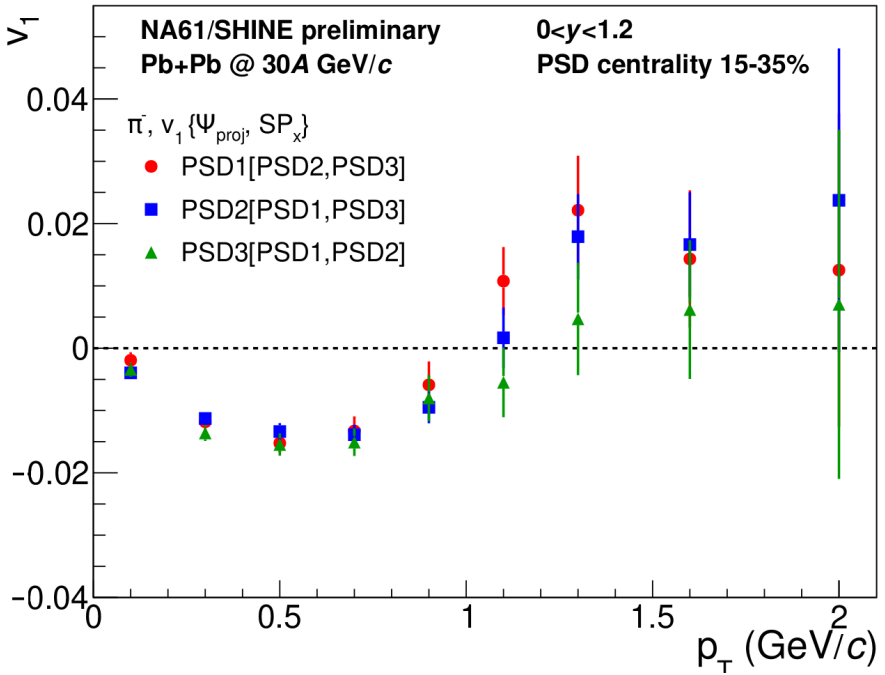
# 3-subevent resolution correction factors
## (scalar product method)



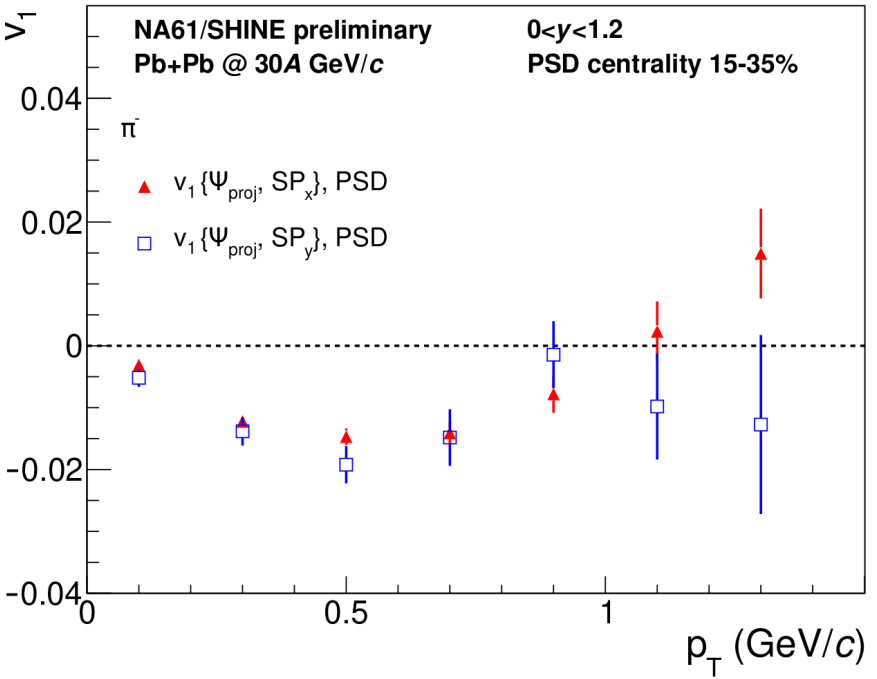




$$R_{1,i}^{A}=\sqrt{2\frac{\langle Q_{1,i}^{A}Q_{1,i}^{B}\rangle\langle Q_{1,i}^{A}Q_{1,i}^{C}\rangle}{\langle Q_{1,i}^{B}Q_{1,i}^{C}\rangle}}$$

# “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

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

plots for NA49 in backup

# NA61/SHINE & NA49 preliminary results

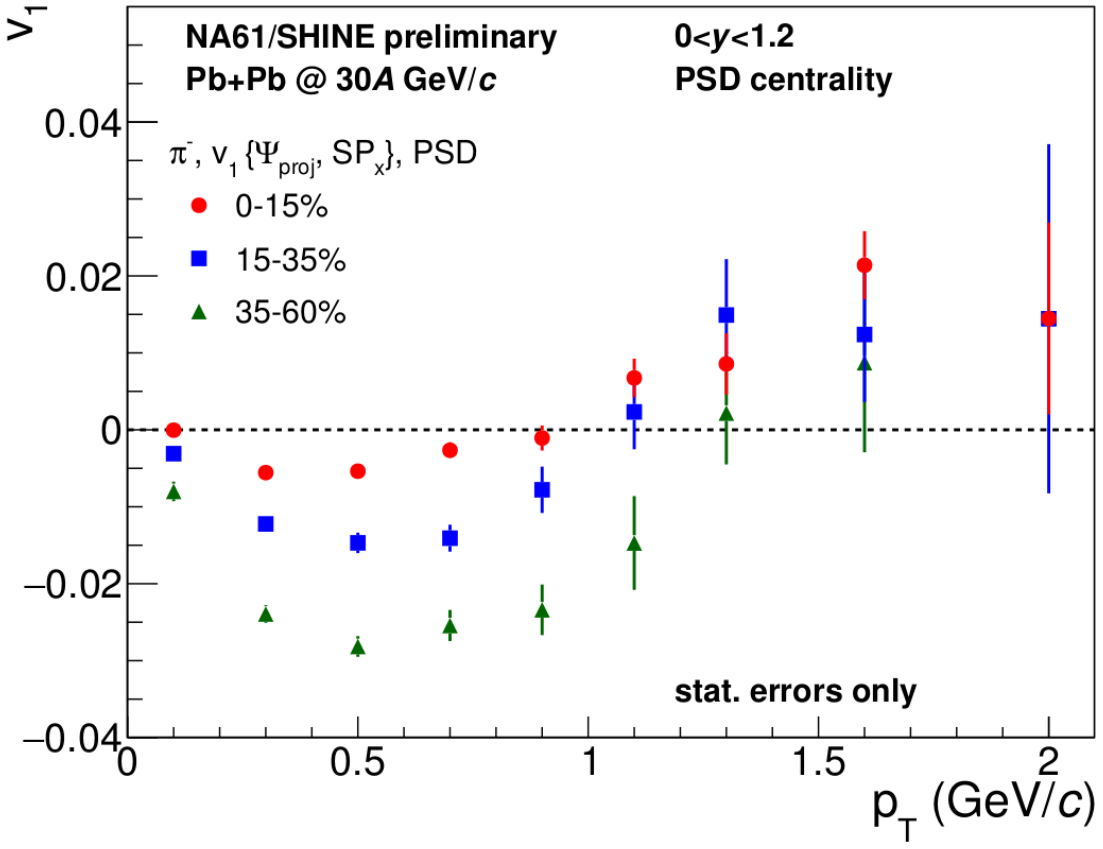
Results are presented for correlations between
charged pions and protons* (in the TPC acceptance) and
all hadrons at forward rapidity (in the PSD/VCAL acceptance)

The results are corrected 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*

NA49 and NA61/SHINE acceptance:
TPC https://edms.cern.ch/document/1549298/1
PSD https://edms.cern.ch/document/1867336/1

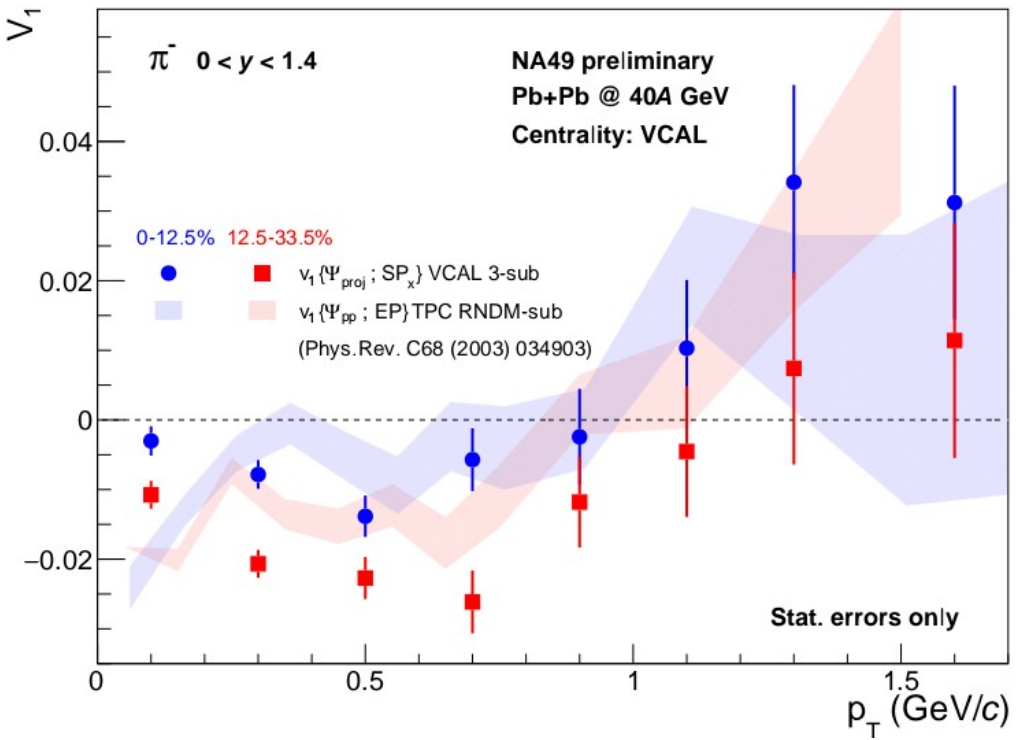
# Charged pion $v_1$ vs transverse momentum




General features:

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

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

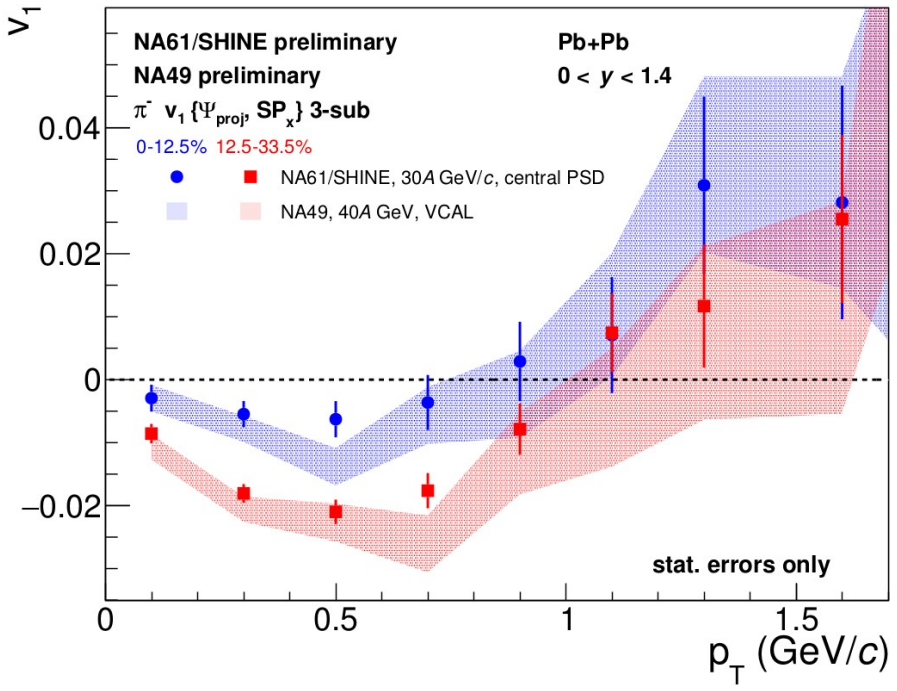


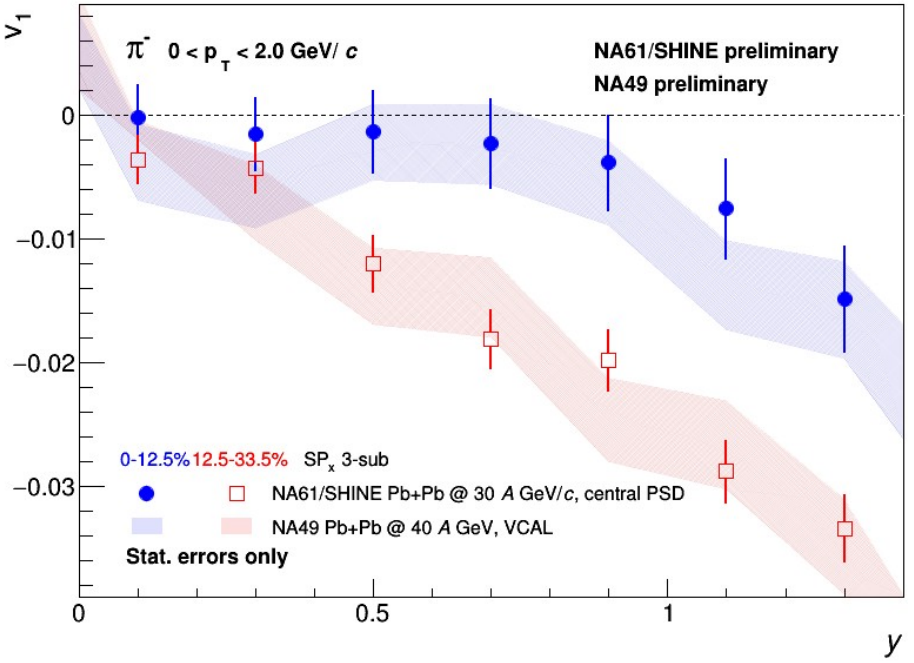

Observe difference between results relative to participant and spectator symmetry planes

Results relative to the participant plane are corrected for global momentum conservation

(following procedure in N. Borghini et al. PRC66 (2002) 014901)

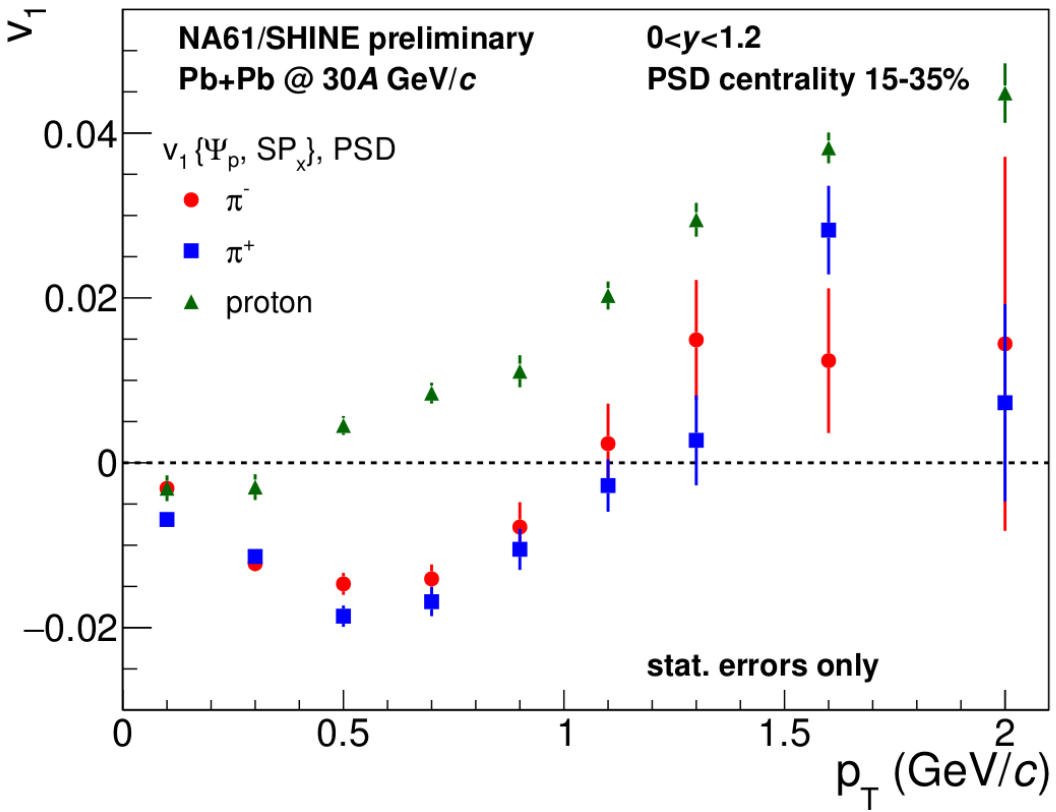
# Comparison of negative pion $v_1$: NA61/SHINE vs NA49




Similar results for $v_1$ relative to the spectator plane using data from NA49 and NA61/SHINE

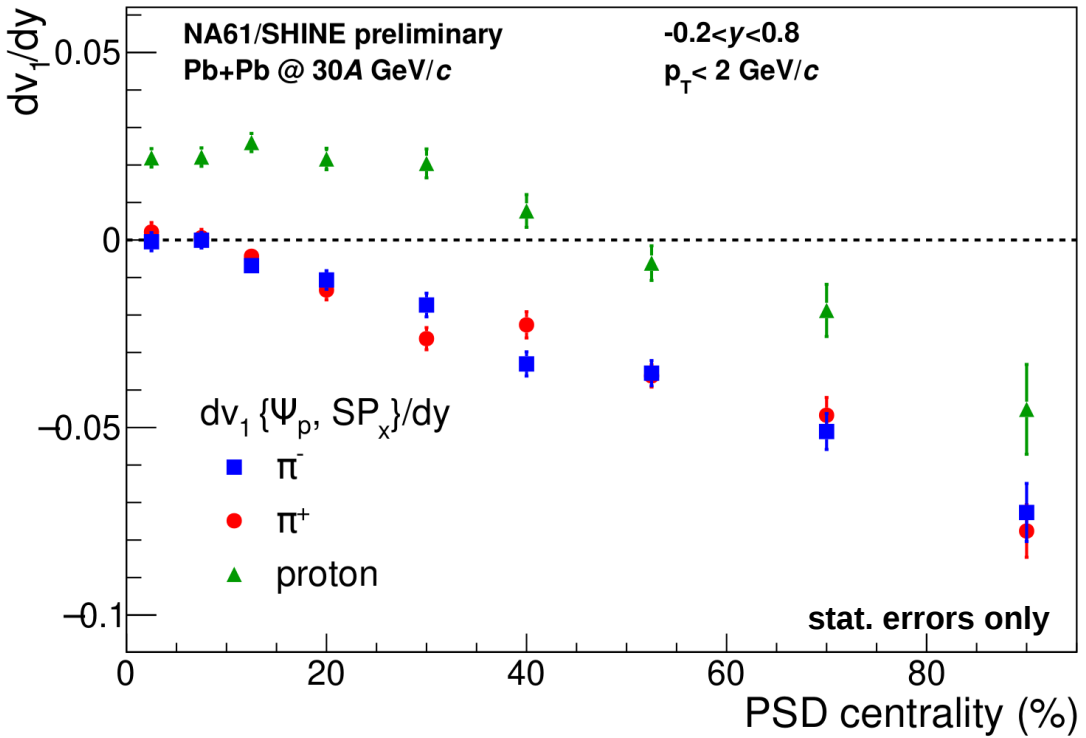
# Particle type dependence of $v_1(p_T)$




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

* *A. Rybicki, et al., Acta Phys. Polon. B46 (2015) 737*
*A. Rybicki, A. Szczurek, Phys. Rev. C87 (2013) 054909*

# Slope of $v_1$ at midrapidity vs. centrality



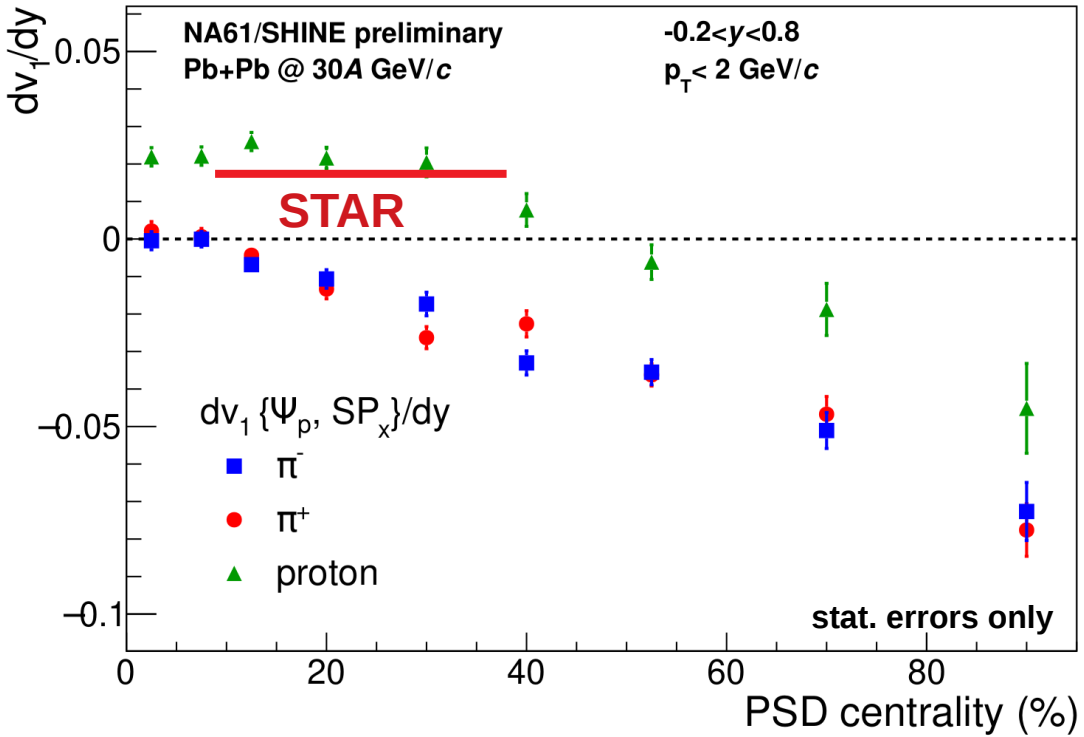

Slope extraction procedure:

- 1st order polynomial fit with 2 parameters (slope and offset):
- offset for $\pi^+/\pi^-$ consistent with 0 (all centrality)
- Offset for protons is below $6\times10^{-3}$ for centrality 0-60% and increasing up to $3\times10^{-2}$ for centrality >60%.

Observations:

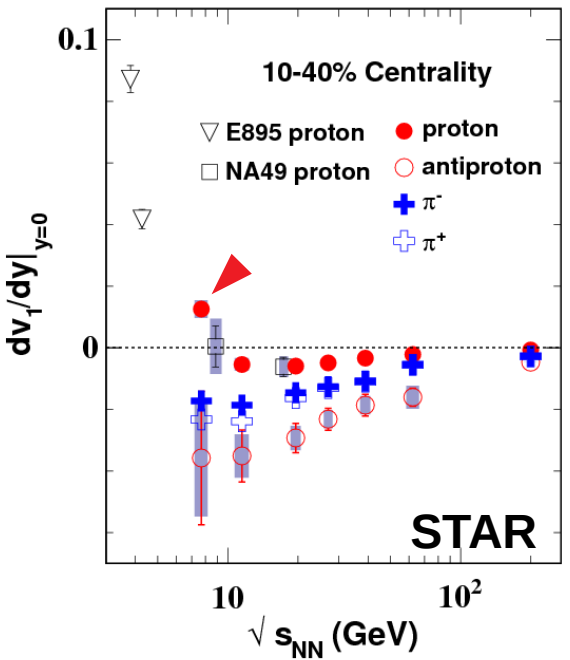
- Slope of proton $v_1$ changes sign at about 50% centrality
- Slope of pion $v_1$ is always negative

# Slope of $v_1$ at midrapidity: comparison with STAR



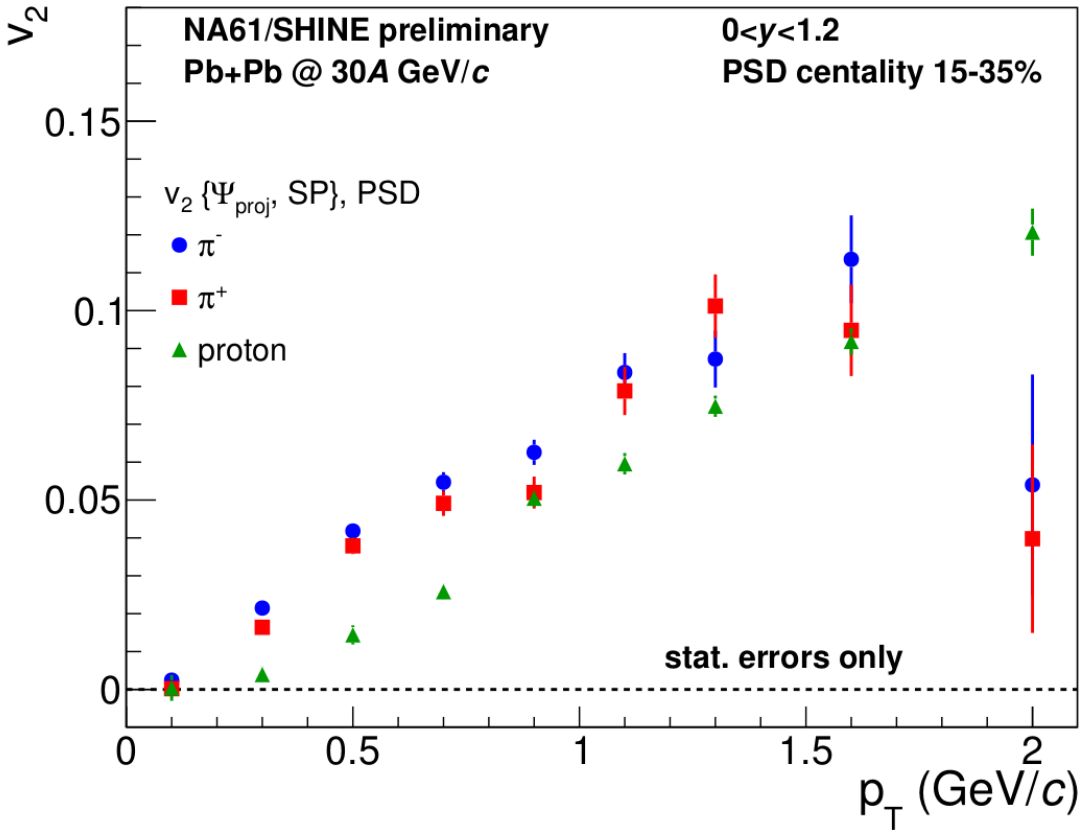

Slope extraction is sensitive to fit function and rapidity range

STAR Collaboration PRL 112 (2014) 162301



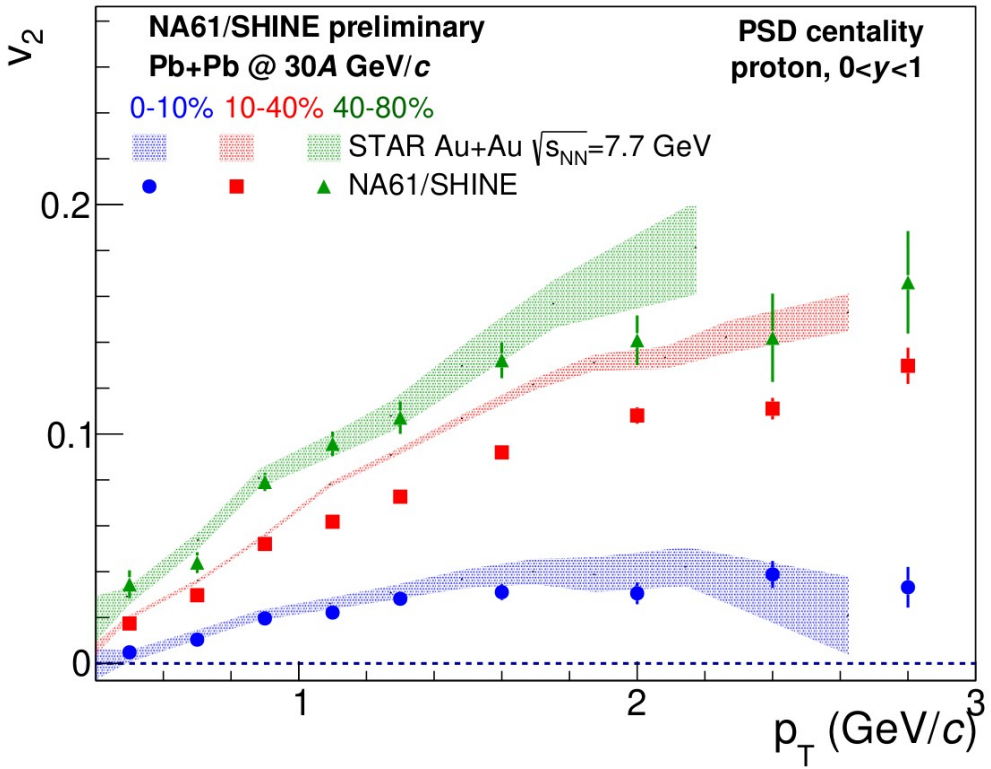

Preliminary results for centrality dependence presented by STAR Collaboration:
NPA 956 (2016) 260

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




- Clear mass dependence
- Difference between $\pi^+$ and $\pi^-$ $v_2$ is small

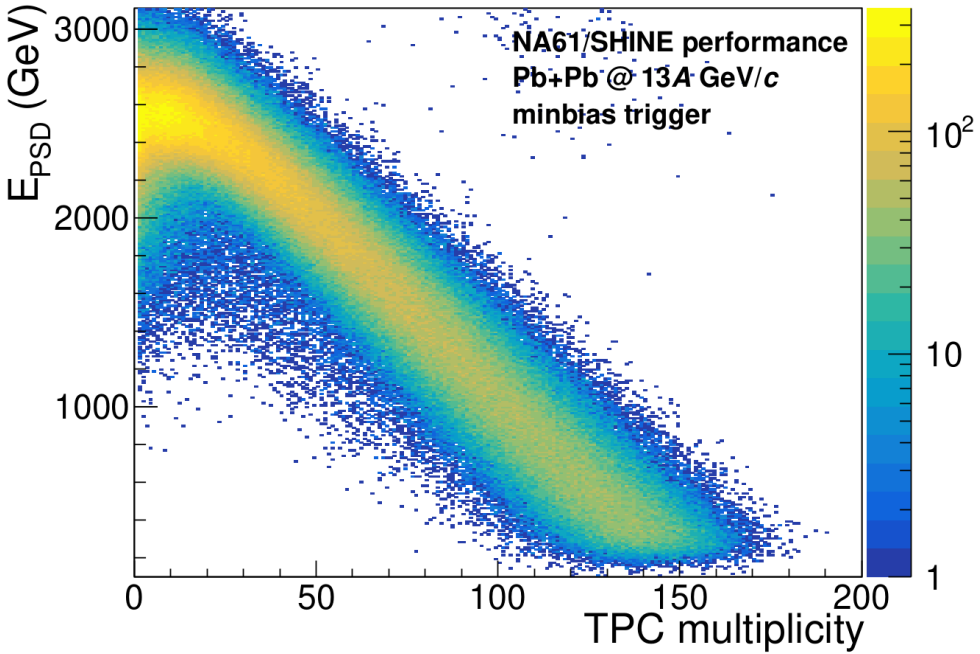
# Comparison of proton $v_2$ with STAR data



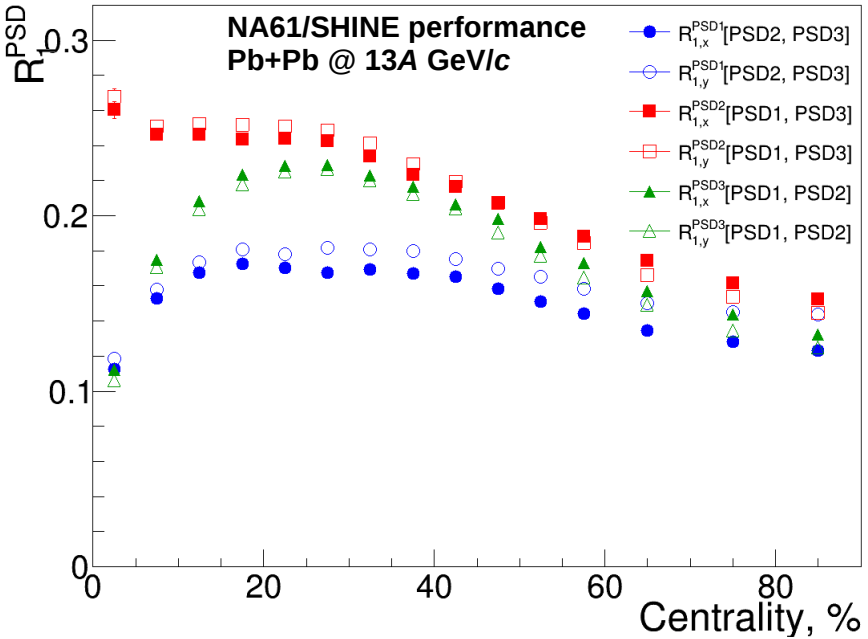

STAR Collaboration PRC 88 (2013) 014902

- 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)

# 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

# Summary

- Preliminary results for anisotropic flow relative to spectator plane from NA49 and 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
  - negatively charged pions directed flow for Pb+Pb collisions at 40*A* GeV recorded in 2000 by the NA49 experiment
- New results are compared to:
  - Previously published results by NA49 for directed flow of charged pions in Pb+Pb collisions at 40*A* GeV. Observed difference between results relative to participant and spectator symmetry planes.
  - Existing data for $v_1$ , $v_2$ from STAR@RHIC Beam Energy Scan.

# 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

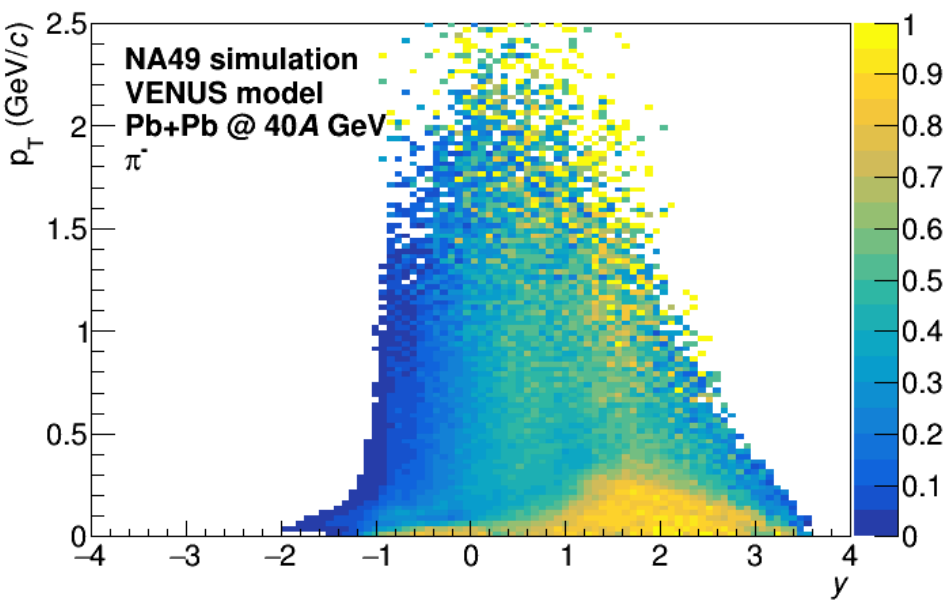
# BACKUP

# Event selection

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

# NA49: Track selection & Corrections for $p_T/y$ non-uniformity

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 ] > 20

or

$N_{clusters}$ [ MTPC ] > 30

$0.55 < N_{cl}[\text{ Total }] / N_{cl}[\text{ Total, Pot }] < 1$

Distance of closest approach to vertex

$|b_x| < 2$ cm

$|b_y| < 0.5$ cm

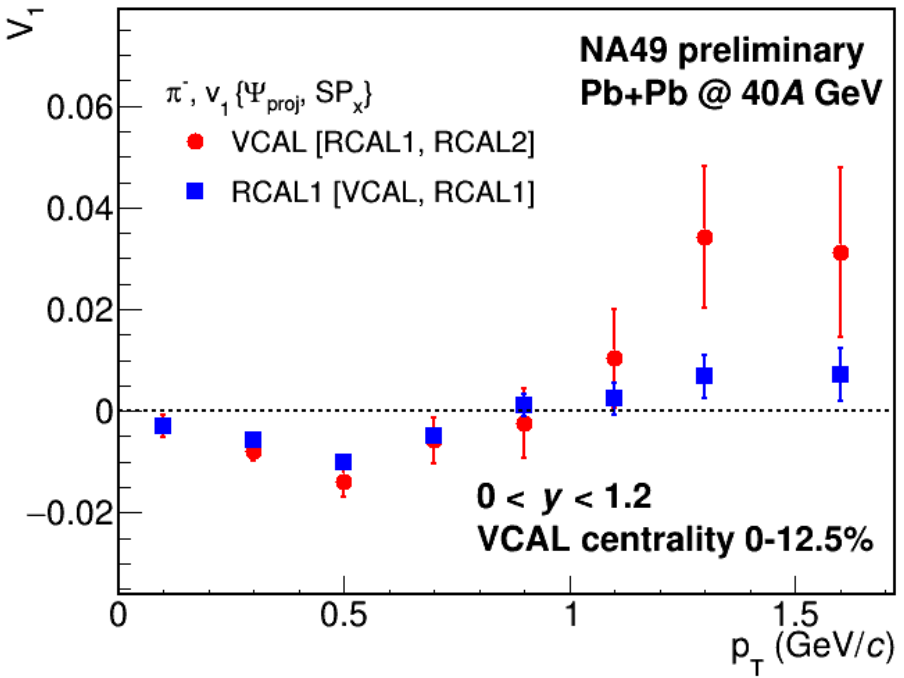
TPC energy loss (dE/dx)

charged pions & proton identification

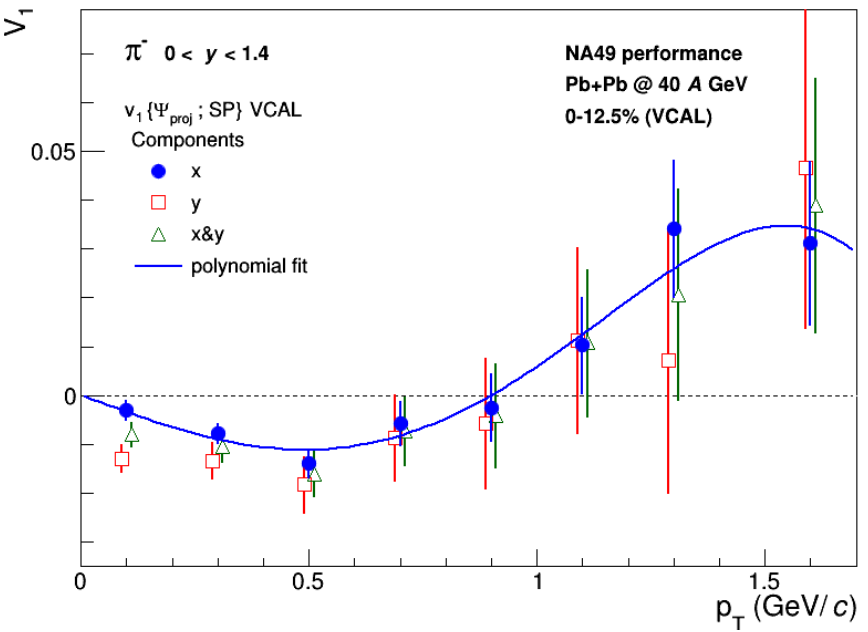
Tracking efficiency

GEANT3 with VENUS

# “Systematics” for directed flow ($v_1$) components (NA49)




Consistent results for VCAL and inner RCAL subevents for lower $p_T$ range




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

For preliminary results: only x-component with VCAL is used

# Slope of $v_1$ (STAR Preliminary)

STAR Collaboration NPA 956 (2016) 260