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

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For the NA61/SHINE and NA49 Collaborations

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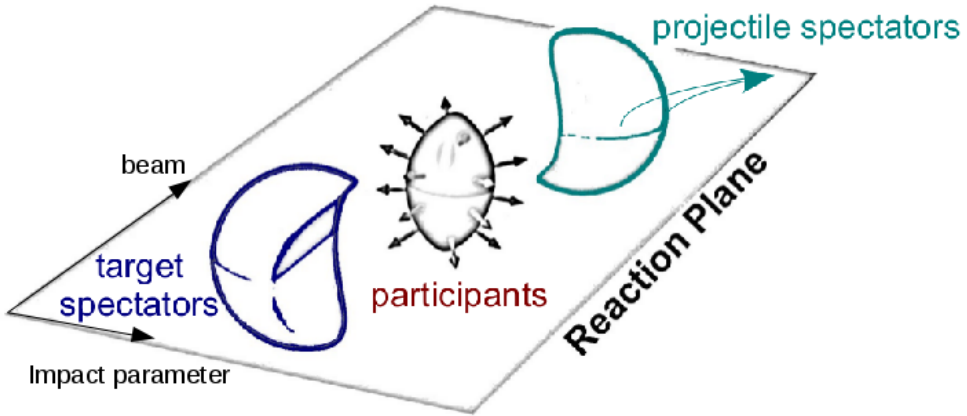
Collision geometry and anisotropic transverse flow

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

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

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



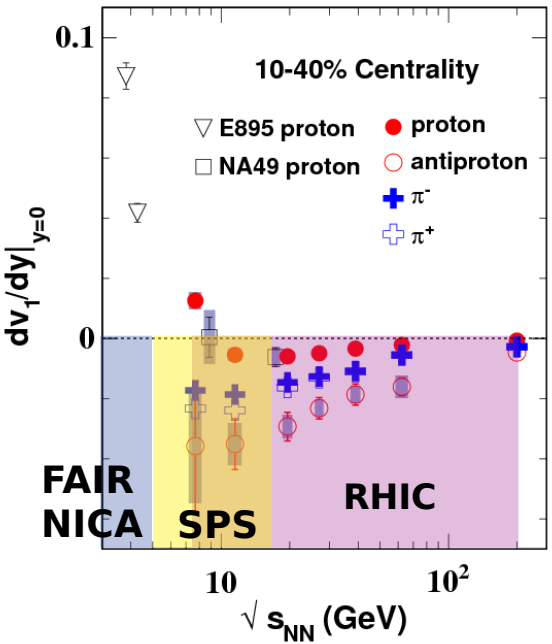
Components needed for v_n calculation:

- 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})

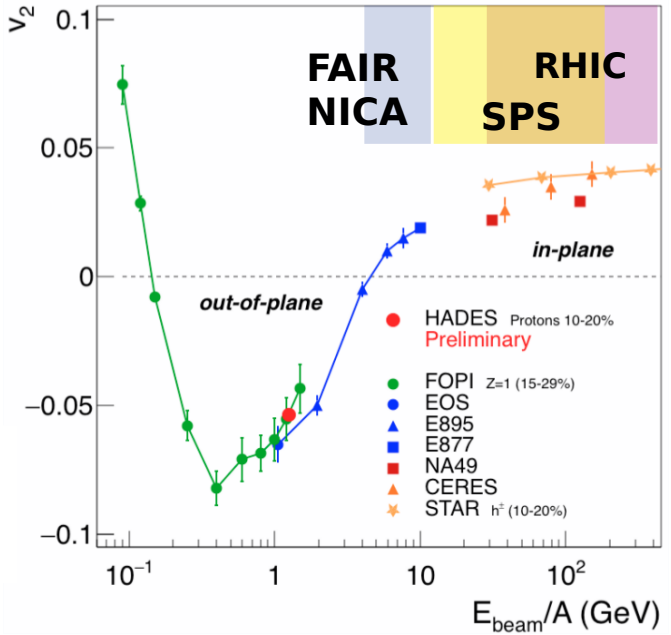
Collective flow at SPS / RHIC energies

Directed flow (slope)



STAR Collaboration
PRL 112 (2014) 162301

Elliptic flow



HADES Collaboration
JPCS 742 (2016) 012008

NA49 Pb-ion beam energy scan
E_{beam} = 20-158*A* GeV:

- minimum bias data available for 40*A* and 158*A* GeV

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

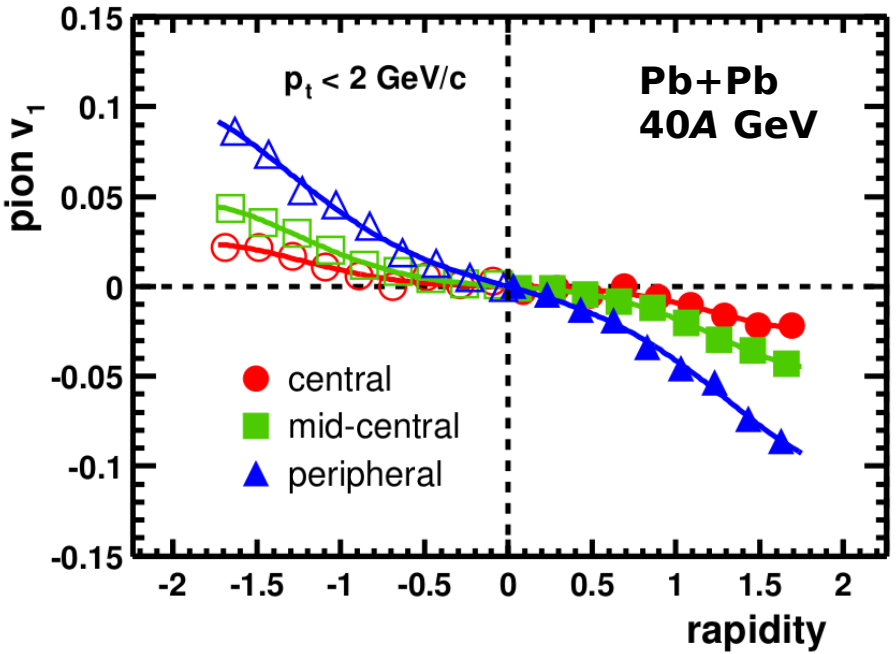
- extend existing NA49 data
- complementary to STAR@RHIC
- bridge to FAIR and NICA energies

Advantage of NA49 & NA61/SHINE fixed target setup:

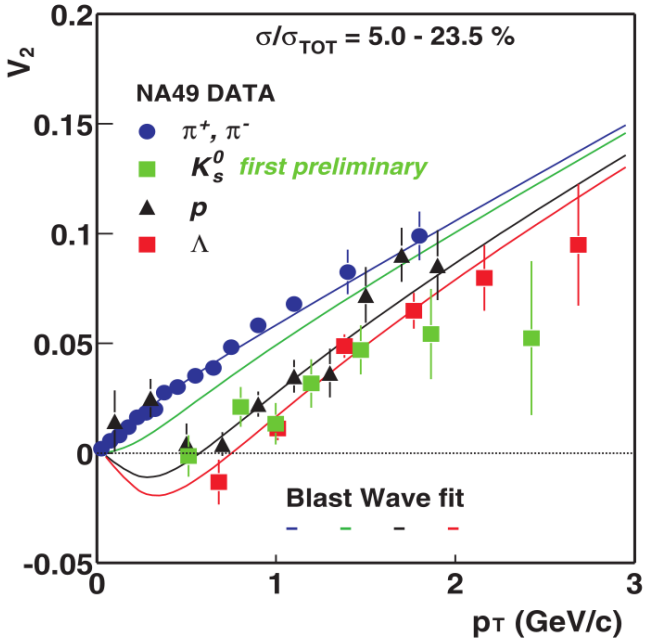
- tracking and particle identification over wide rapidity range with TPCs
- projectile spectators' measurements with forward calorimeters

Previously published NA49 results for anisotropic flow

NA49 Collaboration, PRC68 (2003) 034903

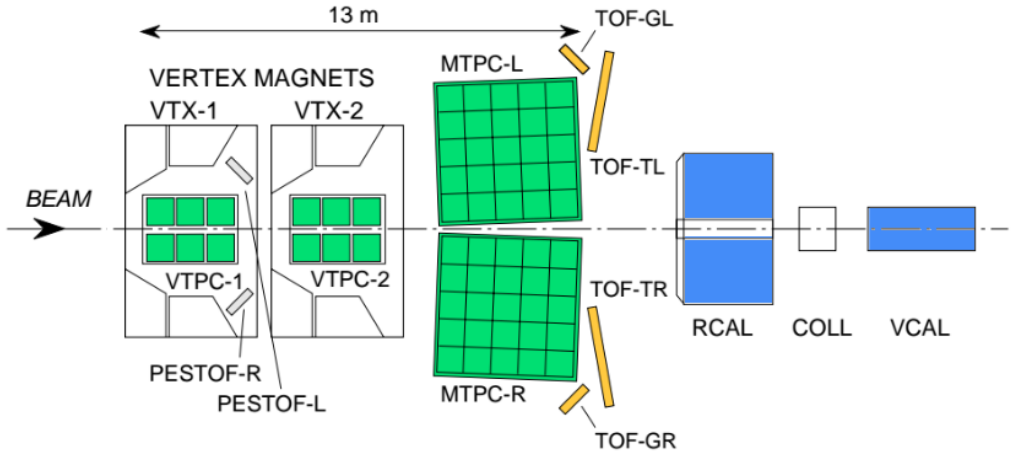


NA49 preliminary (G. Stefanek et al.)
PoS CPOD2006 (2006) 030

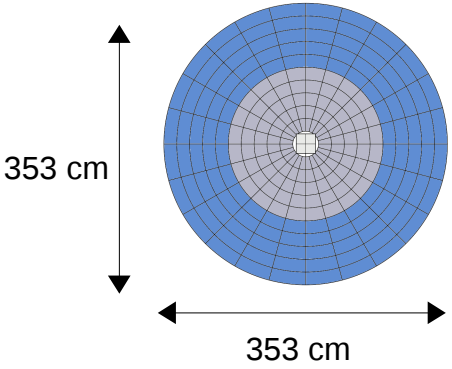


- Directed and elliptic flow of pions and protons for Pb+Pb at 40*A* and 158*A* GeV (published)
- Elliptic flow of Λ and K^0_S for Pb+Pb at 158*A* GeV (preliminary only)
- All measurements are relative to participant symmetry plane

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

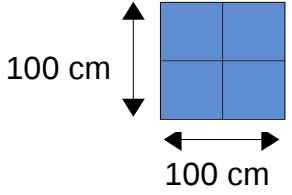


RCAL



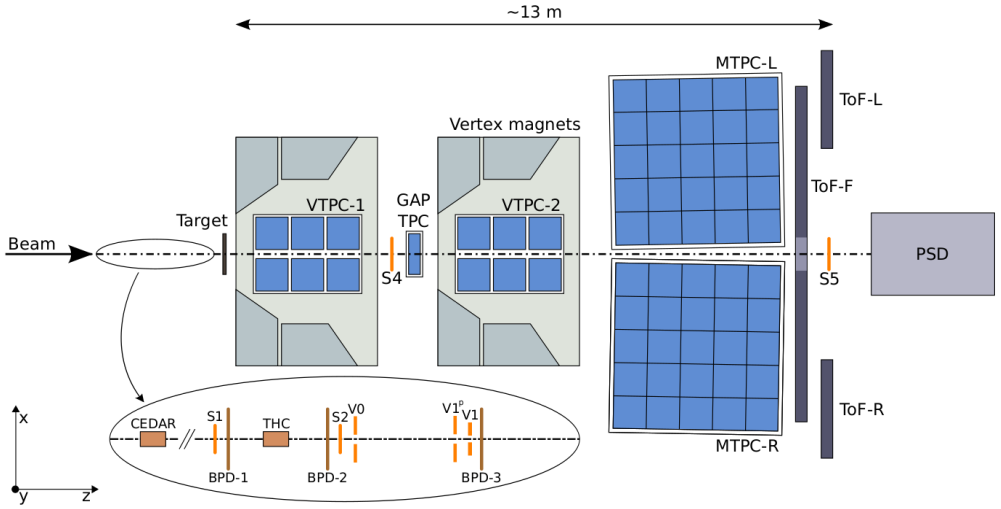
24 sections x 10 rings

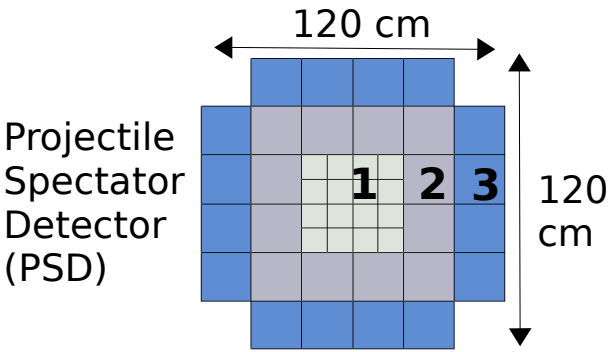
VCAL



- 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)

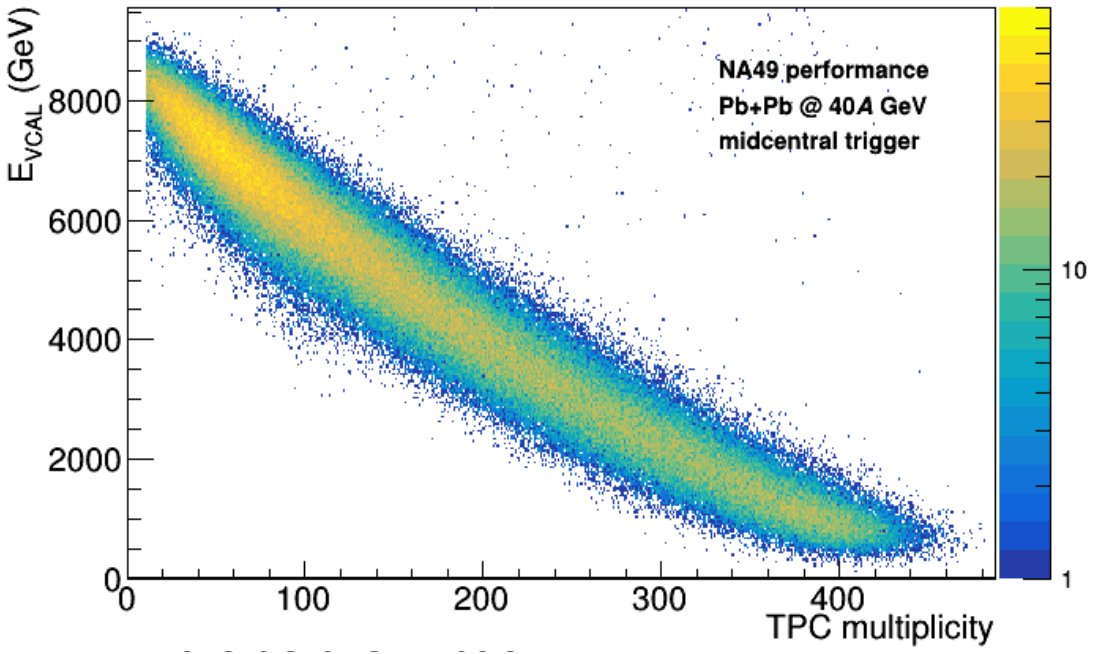
NA61/SHINE setup for Pb-ion beam energy scan (2016-2018)

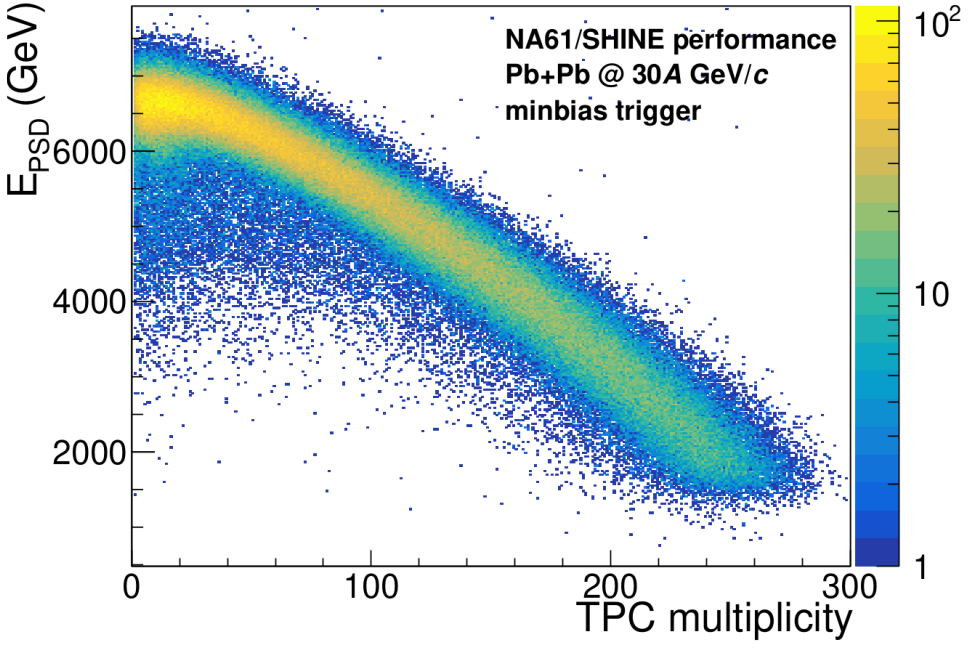




- Successor of the NA49 experiment
- Upgraded TPCs
- New high-granularity forward calorimeter (PSD)
- Pb+Pb beam momentum scan:
  - 13*A*, **30*A* GeV/*c*** recorded in 2016 (pilot run at 150*A* GeV/*c*)
  - 150*A* GeV/*c* scheduled for November, 2018

Event selection & multiplicity vs forward energy correlation





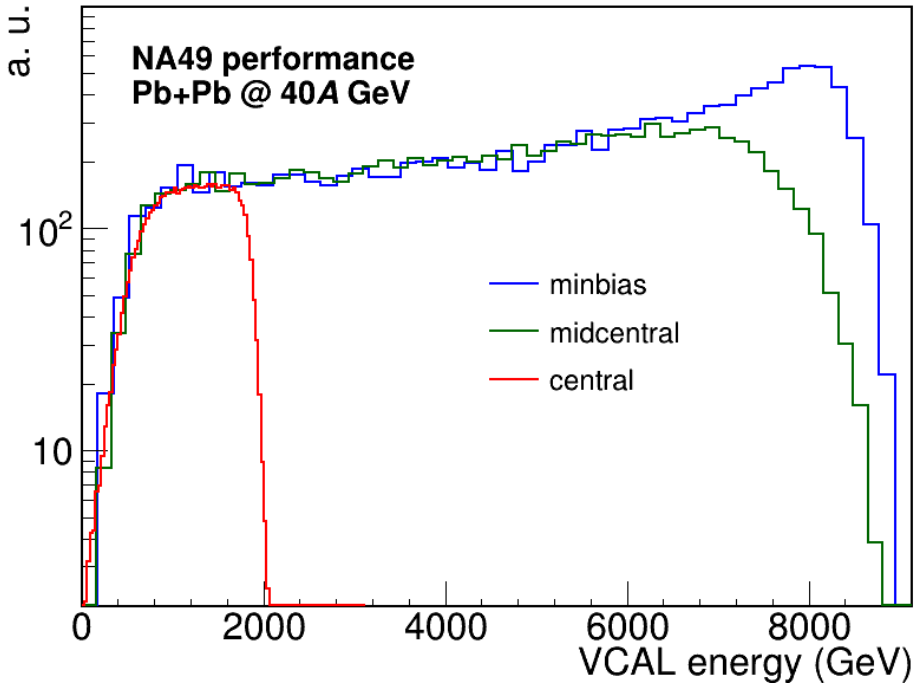
- Event has fitted vertex
- Good reconstructed vertex position

- At least 10 selected particles

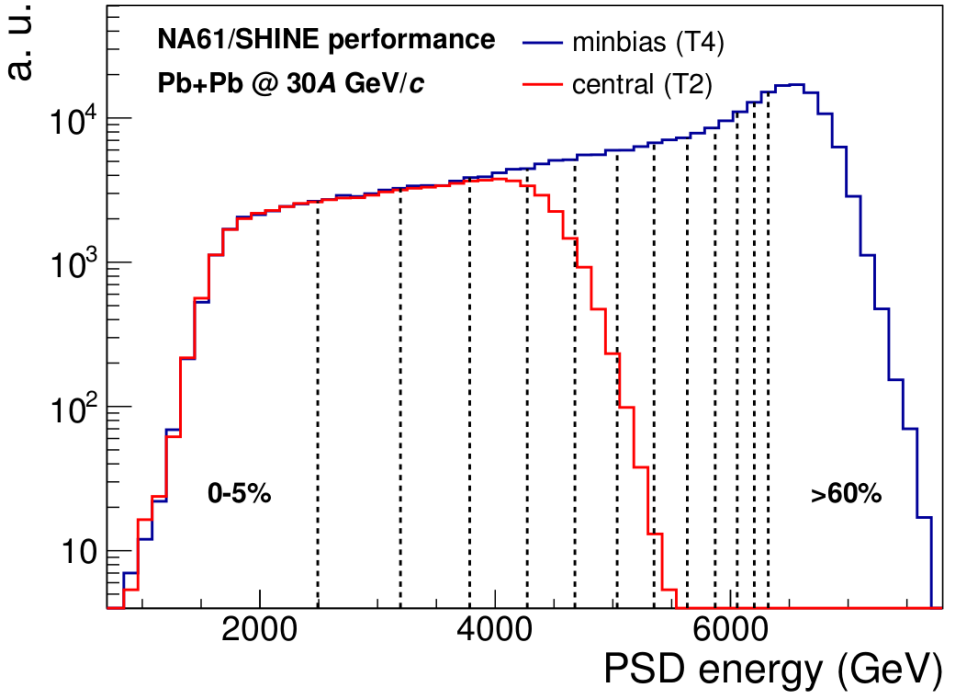
* more details in backup

- Good beam position
- No overlap events / beam particles

Centrality determination using forward energy



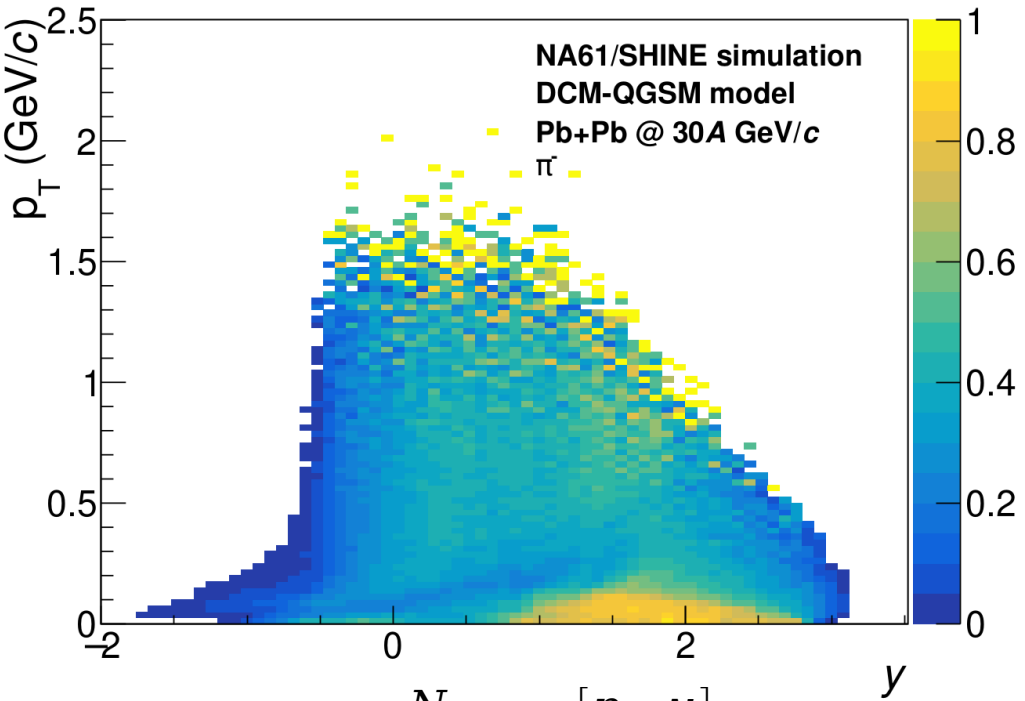
Statistics per trigger:
20k **minimum bias**
320k **midcentral**
440k **central**



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 vertex

$|b_x| < 2$ cm

$|b_y| < 1$ cm

TPC energy loss (dE/dx)

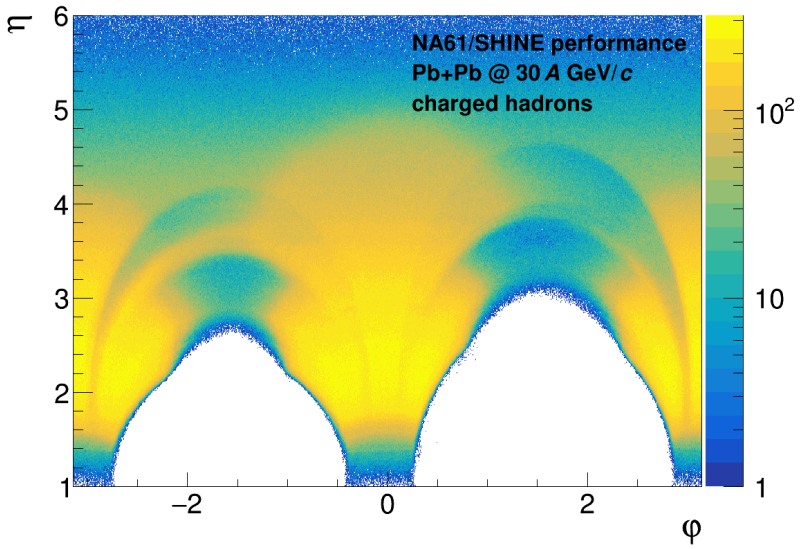
charged pions & proton identification

Tracking efficiency

GEANT4 Monte-Carlo with DCM-QGSM

***NA49 details in backup**

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/jonderwaater/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:

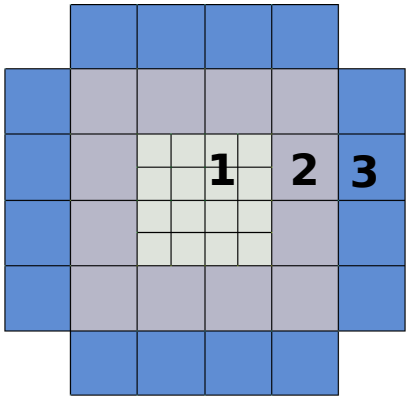
ALICE@LHC, NA49 and NA61/SHINE@SPS, CBM@FAIR and HADES@SIS18

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

u_n and Q_n vectors:

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

NA61/SHINE PSD:



Directed flow:

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

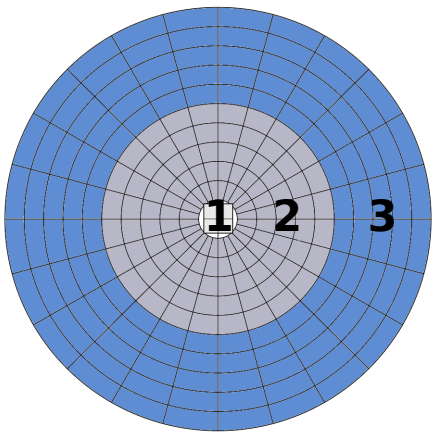
Elliptic flow:

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

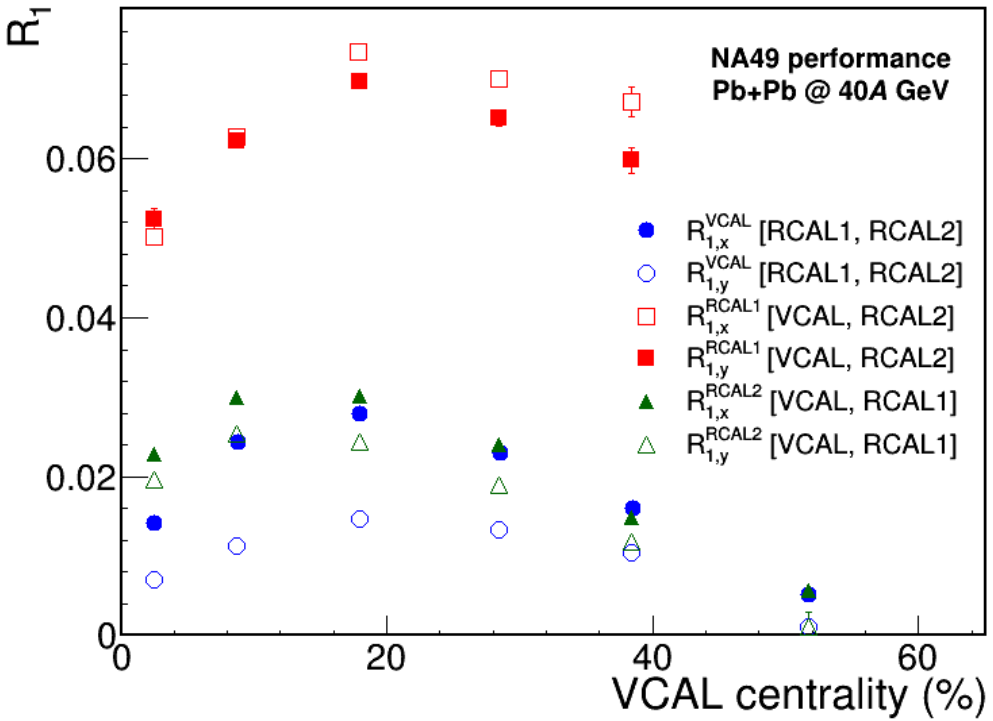
First harmonic resolution correction factor:

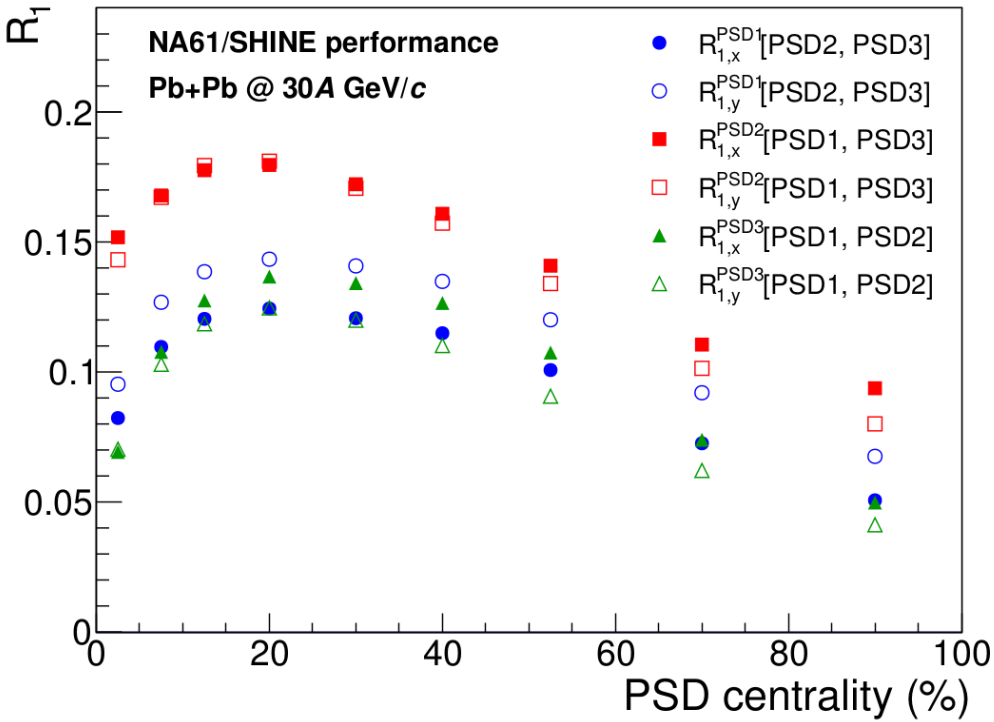
$$R^A_{1,i} = \sqrt{2 \frac{\langle Q^A_{1,i} Q^B_{1,i} \rangle \langle Q^A_{1,i} Q^C_{1,i} \rangle}{\langle Q^B_{1,i} Q^C_{1,i} \rangle}}$$

NA49 VCAL + RCAL :



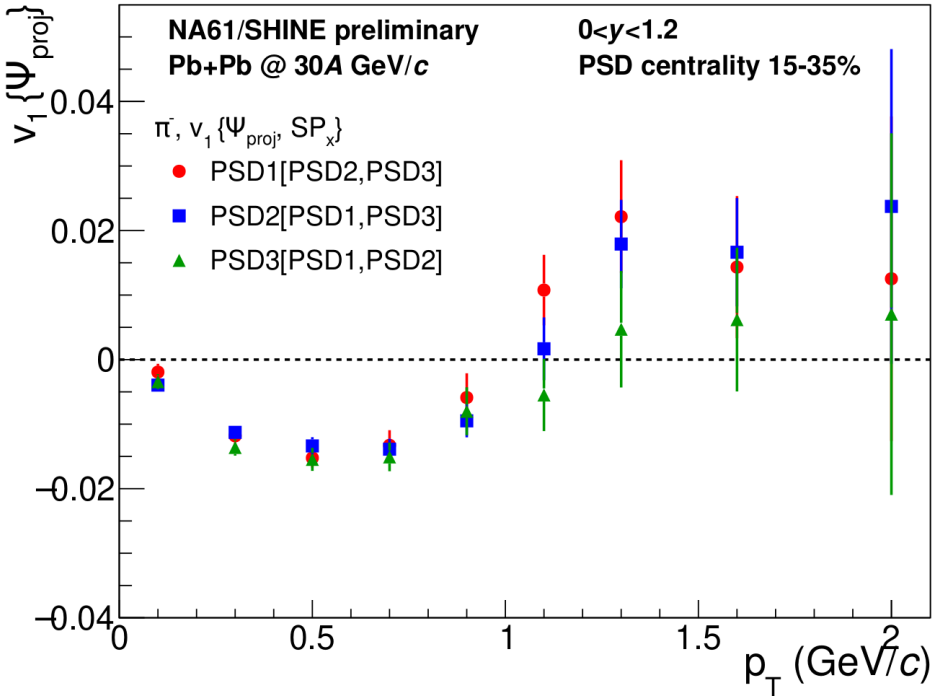
3-subevent resolution correction factors for scalar product method



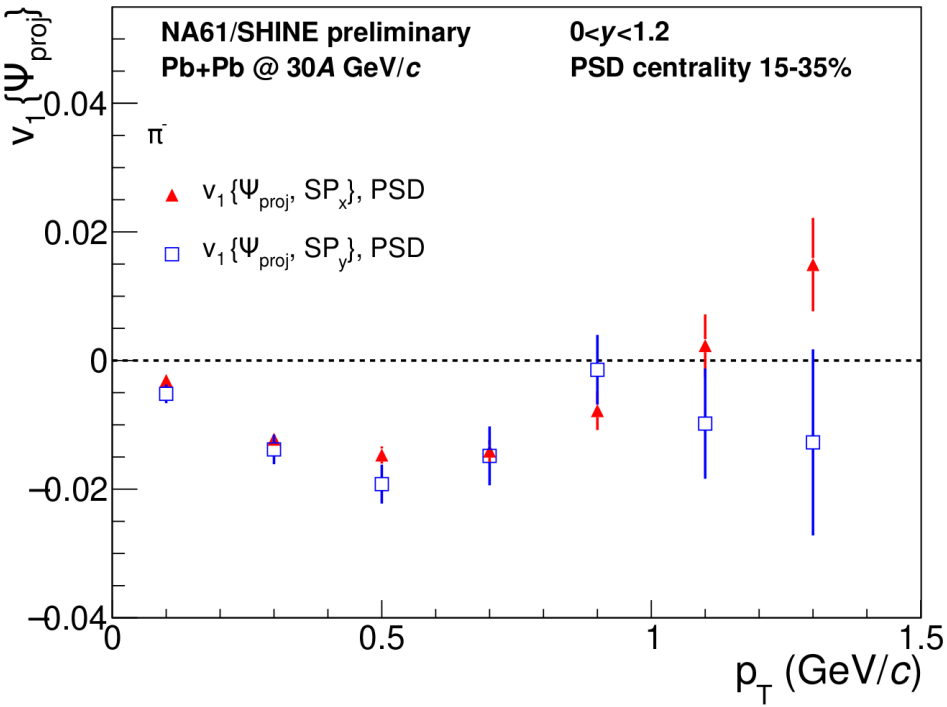


$$R_{1,i}^{A}=\sqrt{2\frac{\langle Q_{1,i}^{A}Q_{1,i}^{B}\rangle\langle Q_{1,i}^{A}Q_{1,i}^{C}\rangle}{\langle Q_{1,i}^{B}Q_{1,i}^{C}\rangle}}$$

“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

For preliminary results: only x-component is used and PSD subevents are combined
*similar plots for NA49 in backup

NA61/SHINE & NA49 preliminary results

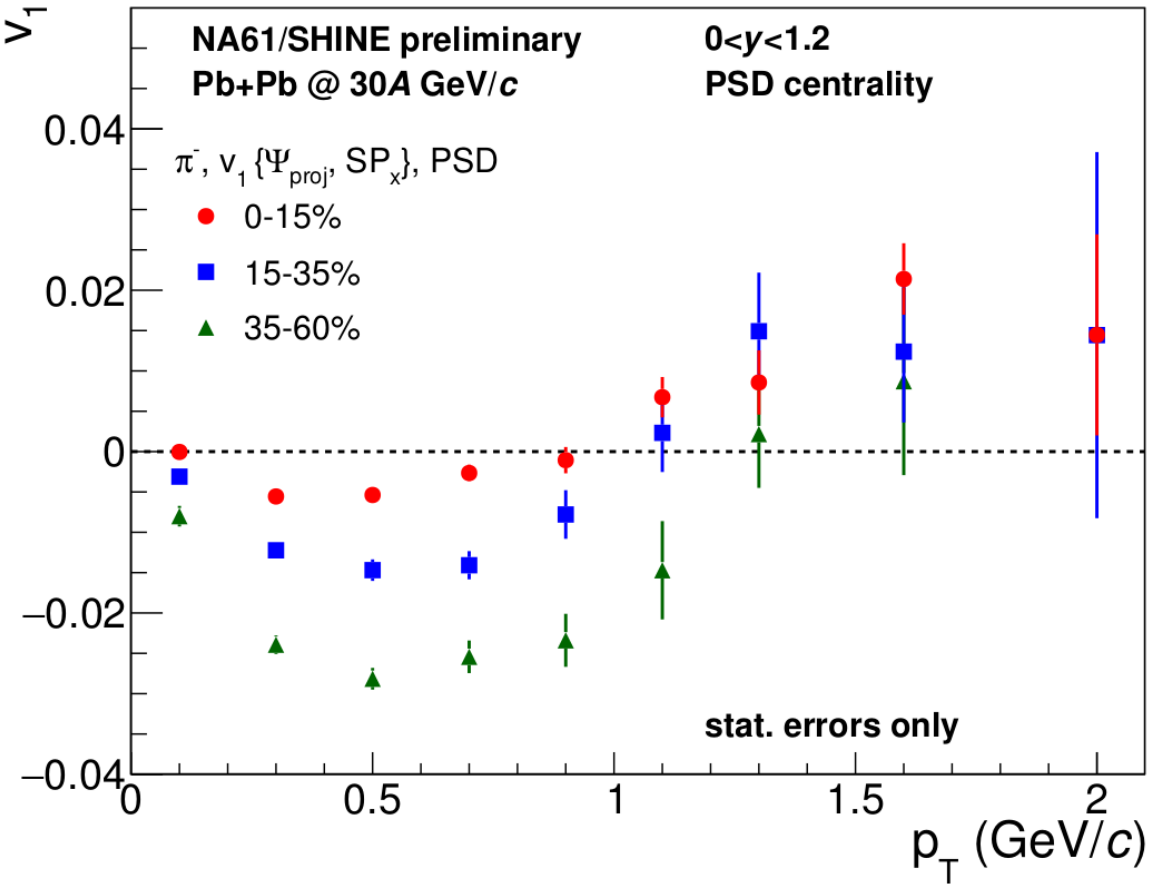
Results are presented for correlations between
charged pions and protons* (in the TPC acceptance) and
all hadrons at forward rapidity (in the PSD/VCAL acceptance)

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

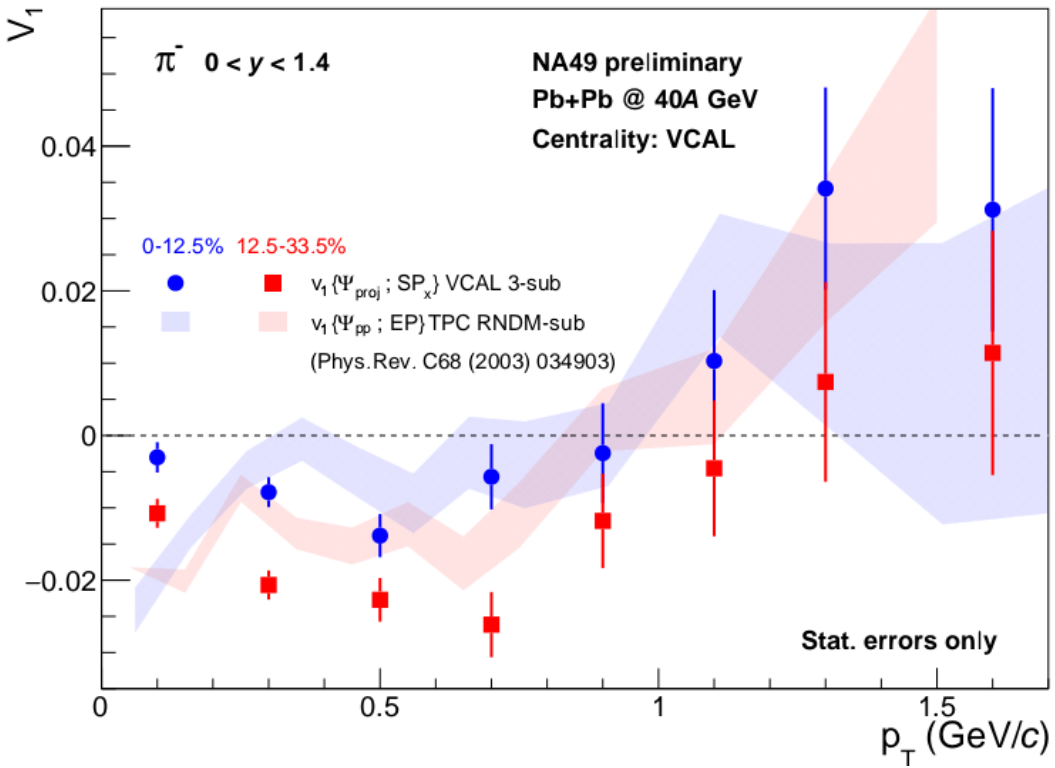
Charged pion v_1 vs transverse momentum



General features:

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

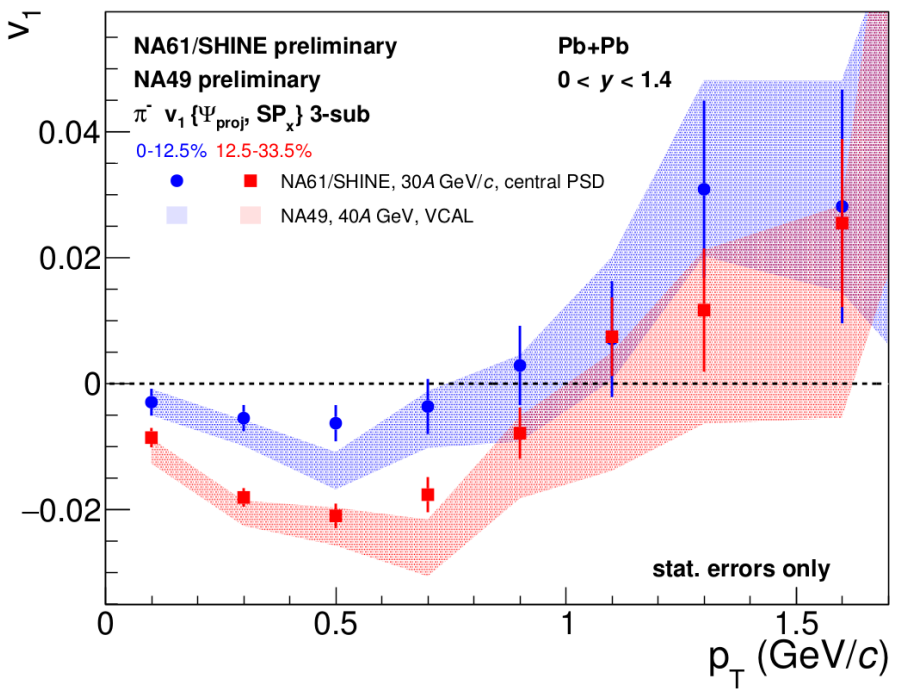
NA49 results:
spectator (new) vs participant (published) plane

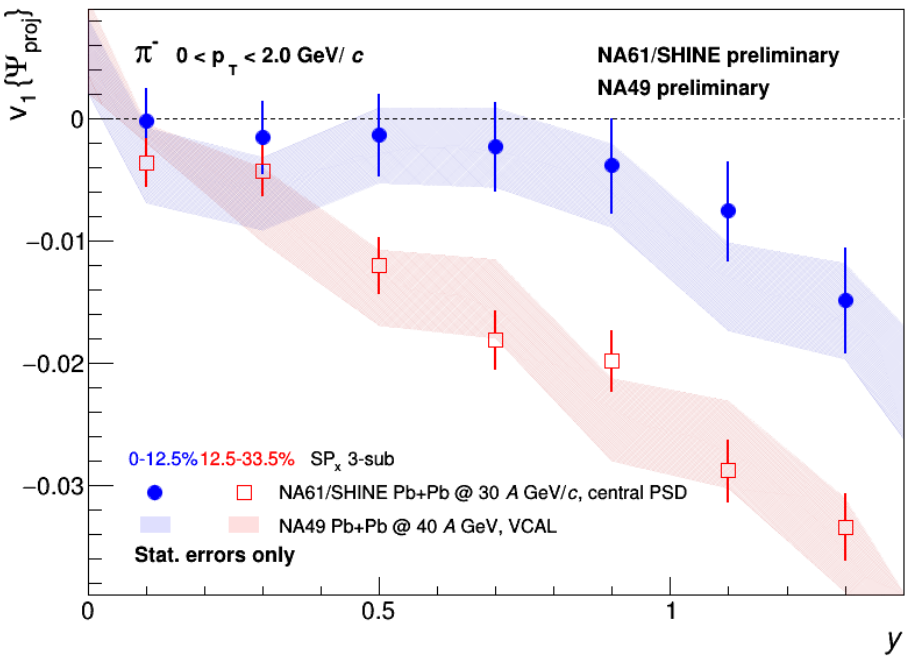


Observed difference between results relative to participant and spectator symmetry planes

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

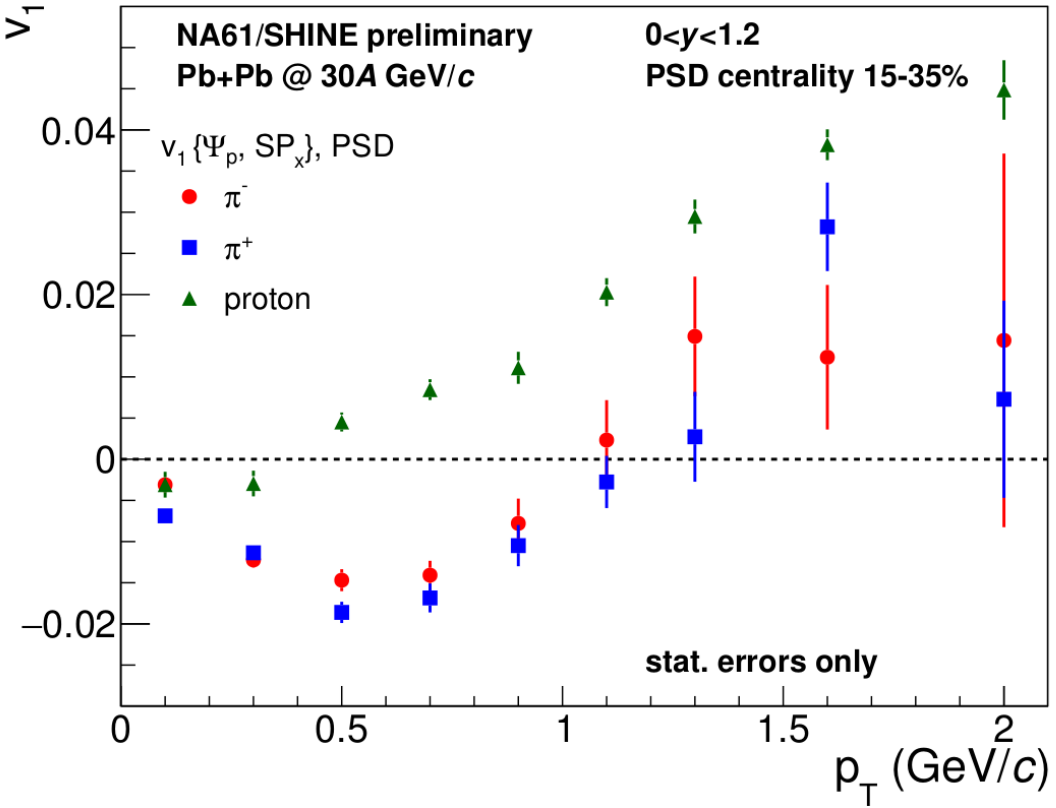
Comparison of negative pion v_1: NA61/SHINE vs NA49





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

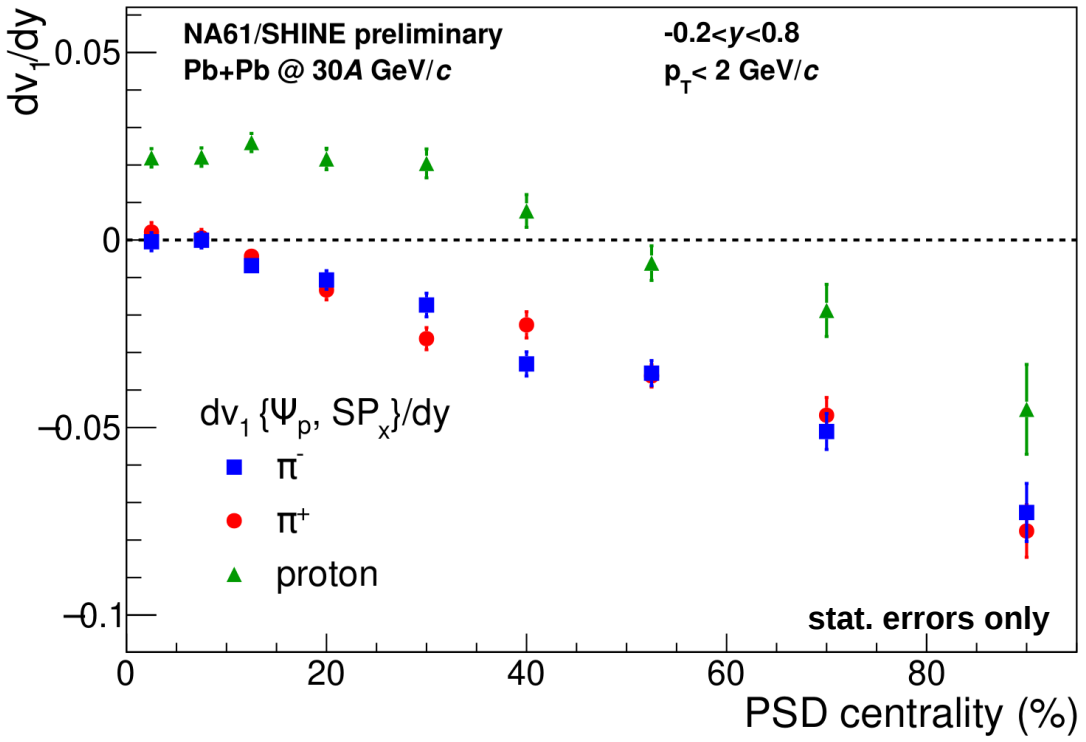
Particle type dependence of $v_1(p_T)$



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

* *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



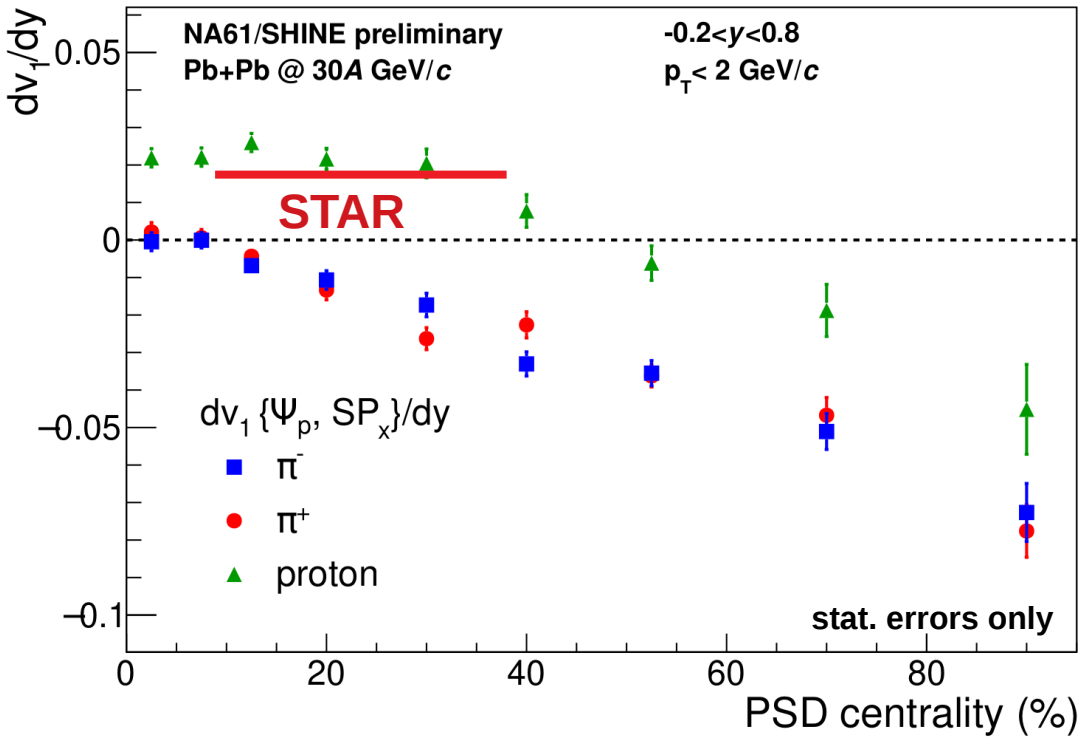
Slope extraction procedure:

- 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:

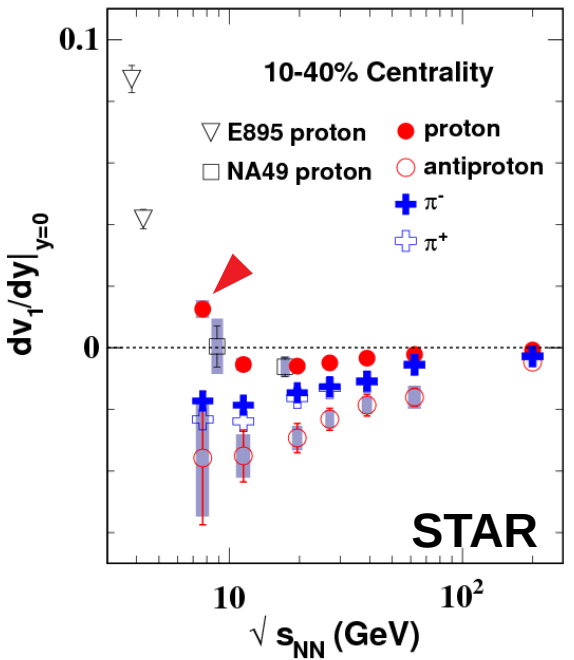
- Slope of proton v_1 changes sign at about 50% centrality
- Slope of pions v_1 is always negative

Slope of v_1 at midrapidity: comparison with STAR



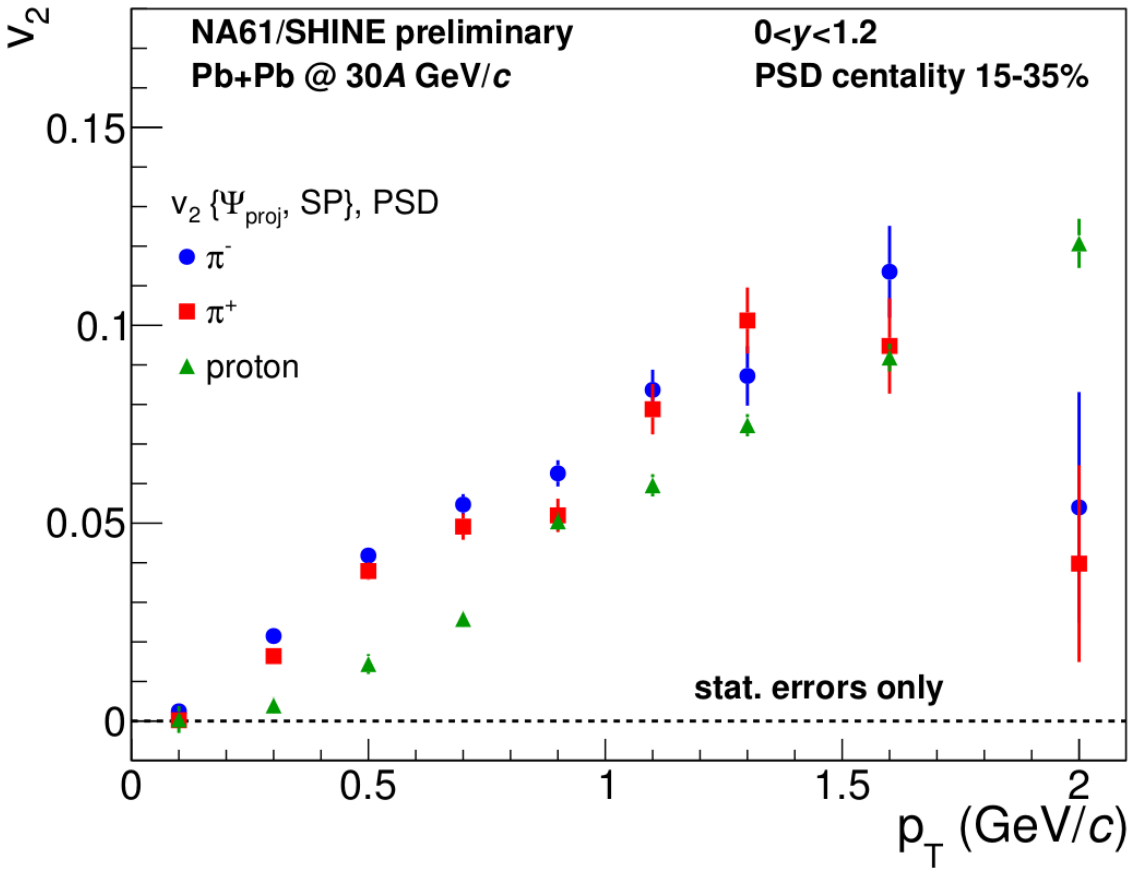
Slope extraction is sensitive to fit function and rapidity range

STAR Collaboration PRL 112 (2014) 162301



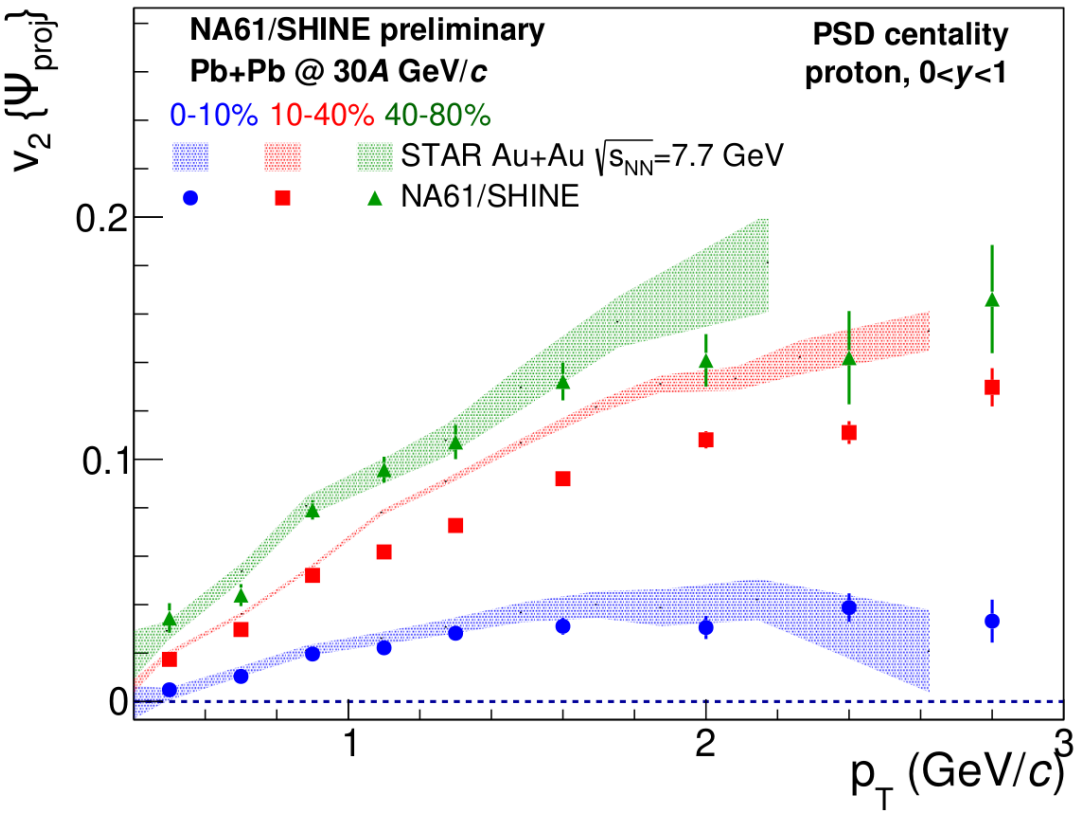
Preliminary results for centrality dependence presented by STAR Collaboration: NPA 956 (2016) 260

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



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

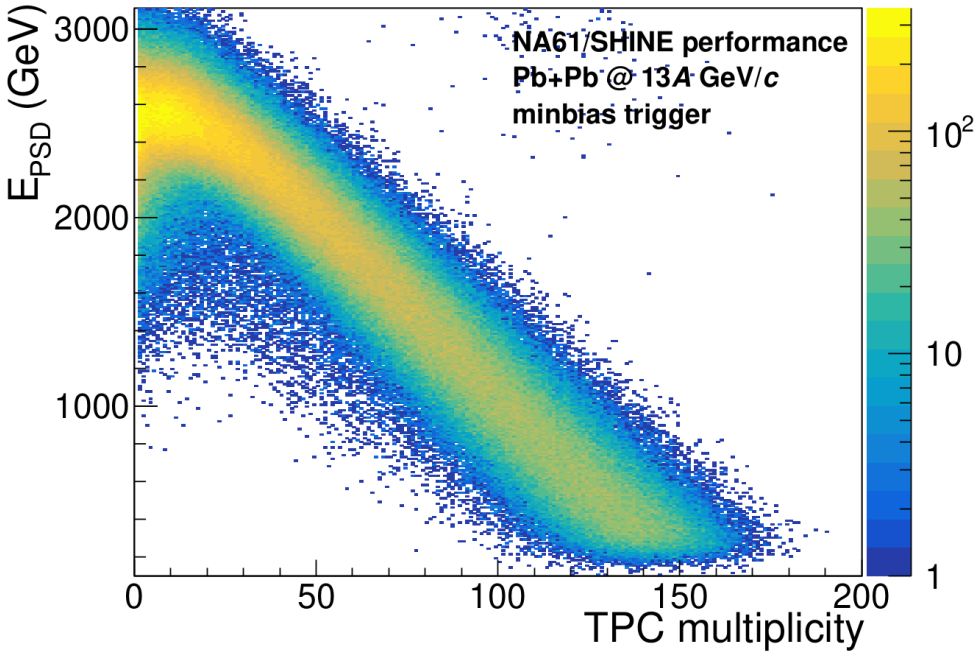
Comparison of proton v_2 with STAR



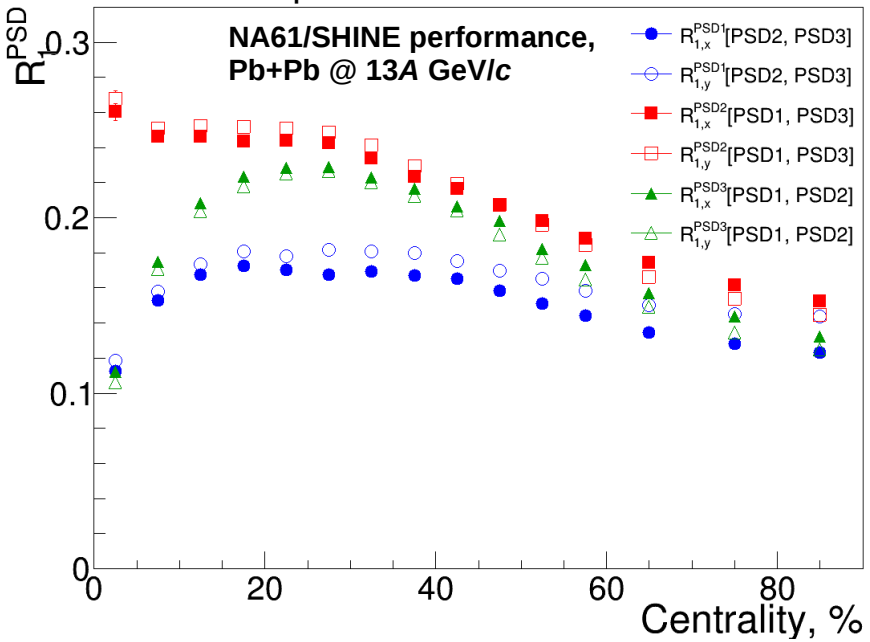
STAR Collaboration PRC 88 (2013) 014902

- 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)

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

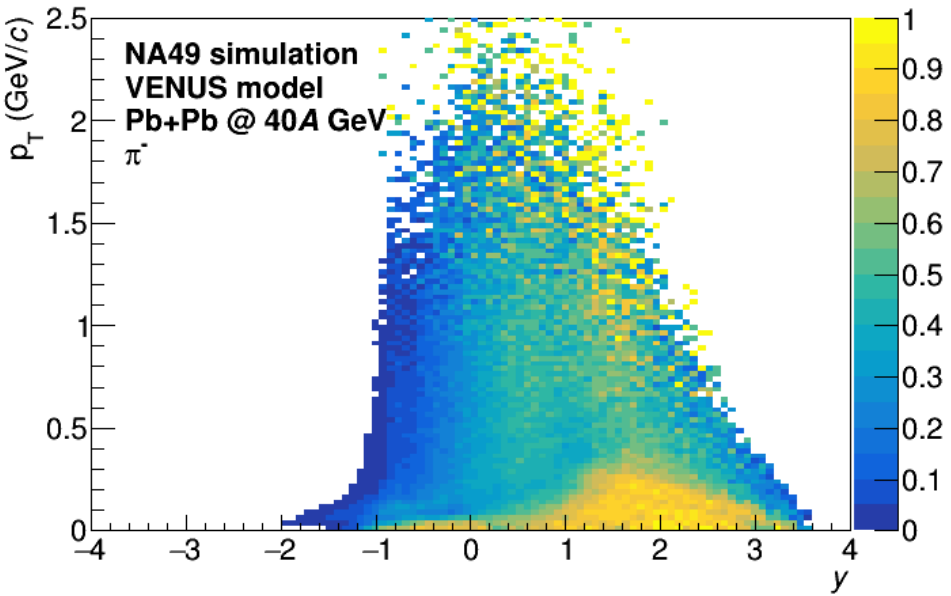
BACKUP

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: 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] > 20

or

$N_{clusters}$ [MTPC] > 30

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

Distance of closest approach to vertex

$|b_x| < 2$ cm

$|b_y| < 0.5$ cm

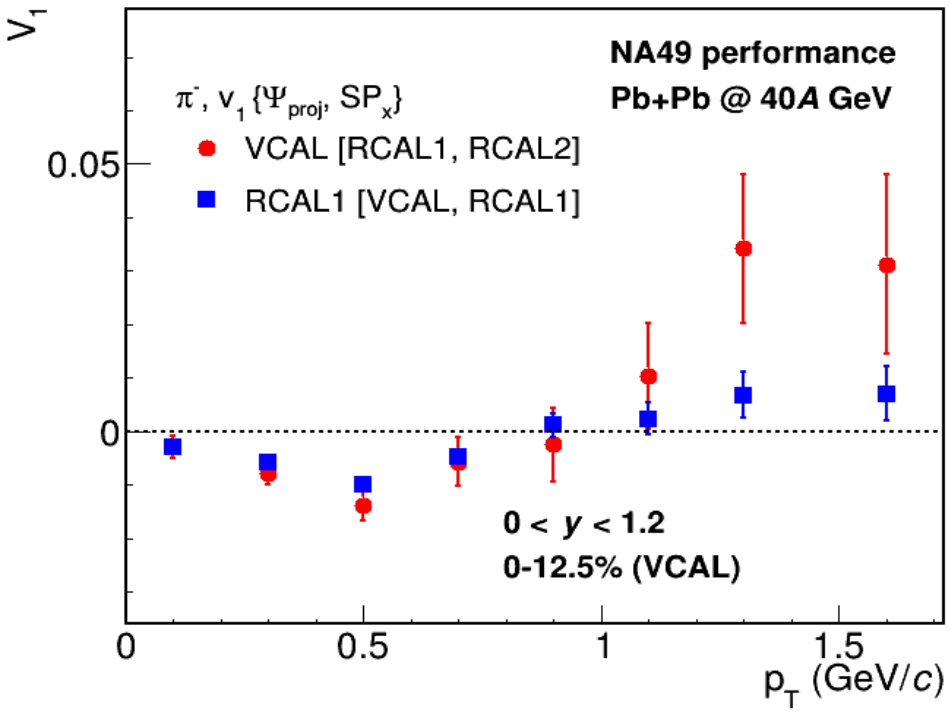
TPC energy loss (dE/dx)

charged pions & proton identification

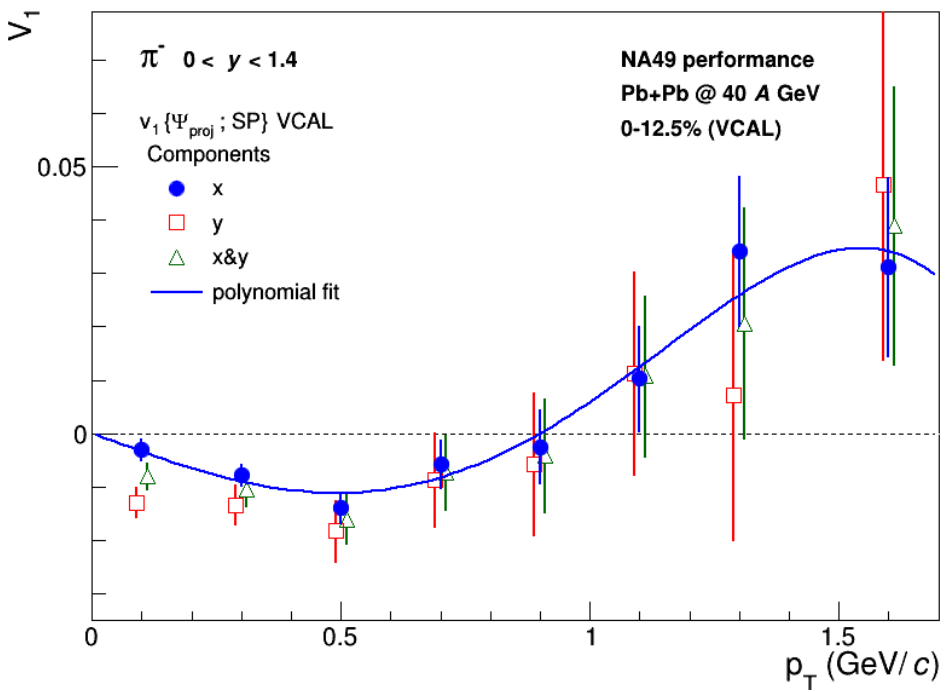
Tracking efficiency

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)

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