First indication of the triangular (v_3) and quadrangular (v_4) flow of light hydrogen isotopes in Au+Au collisions at $\sqrt{s_{NN}}$=2.4 GeV

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(Moscow)

1) *Pictorial introduction*
2) *Reaction plane reconstruction in some experim.*
3) *HADES and its capability for azimuthal flows*
4) *Extraction and correction of flow parameters*
5) *Concluding remarks*

XXII International Baldin Seminar on High Energy Physics Problems "Relativistic Nuclear Physics and Quantum Chromodynamics", JINR, Dubna 15-20/08/2014

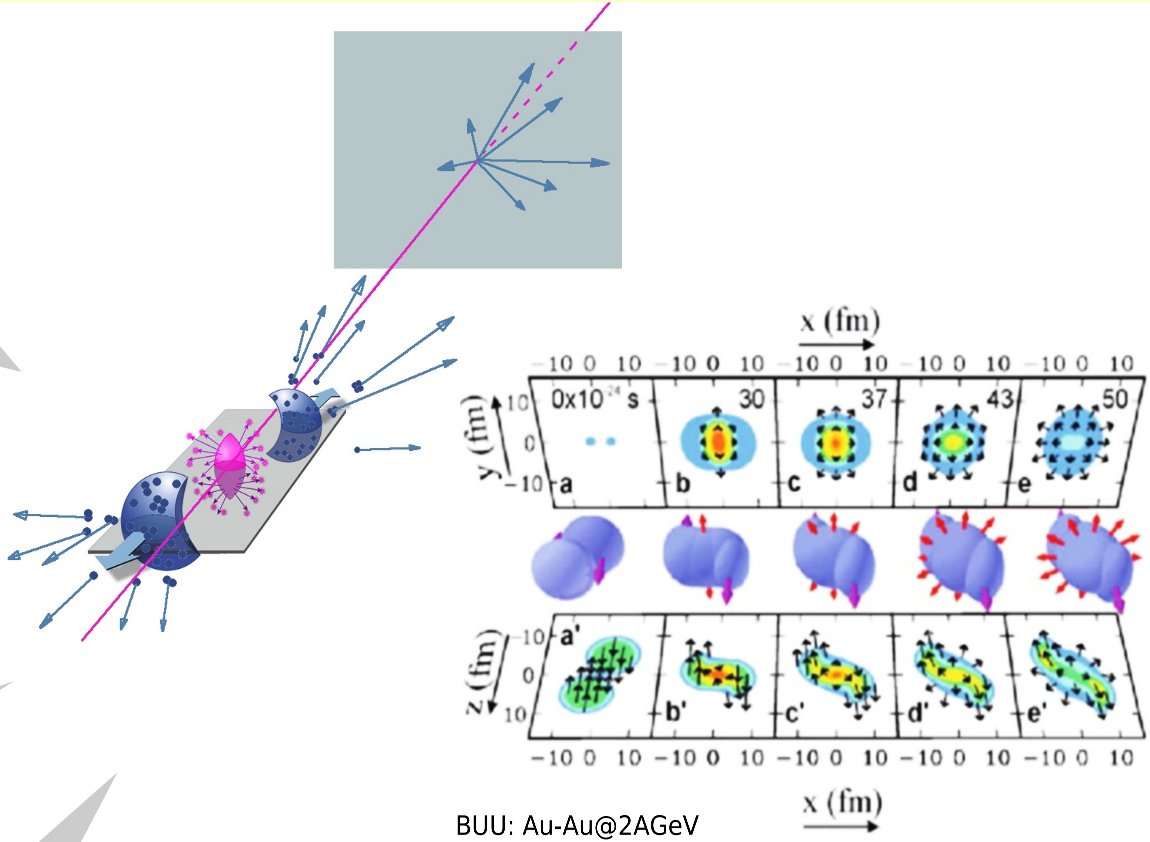
Physical information from azimuthal flows

Azimuthal flows give us a chance to interpret A-A collisions in 3-dimensions

Barometer for EOS at low and intermediate energies

Access to viscosity of the medium involved

Could be sensitive to QGP phase transition (SPS, RHIC, LHC)

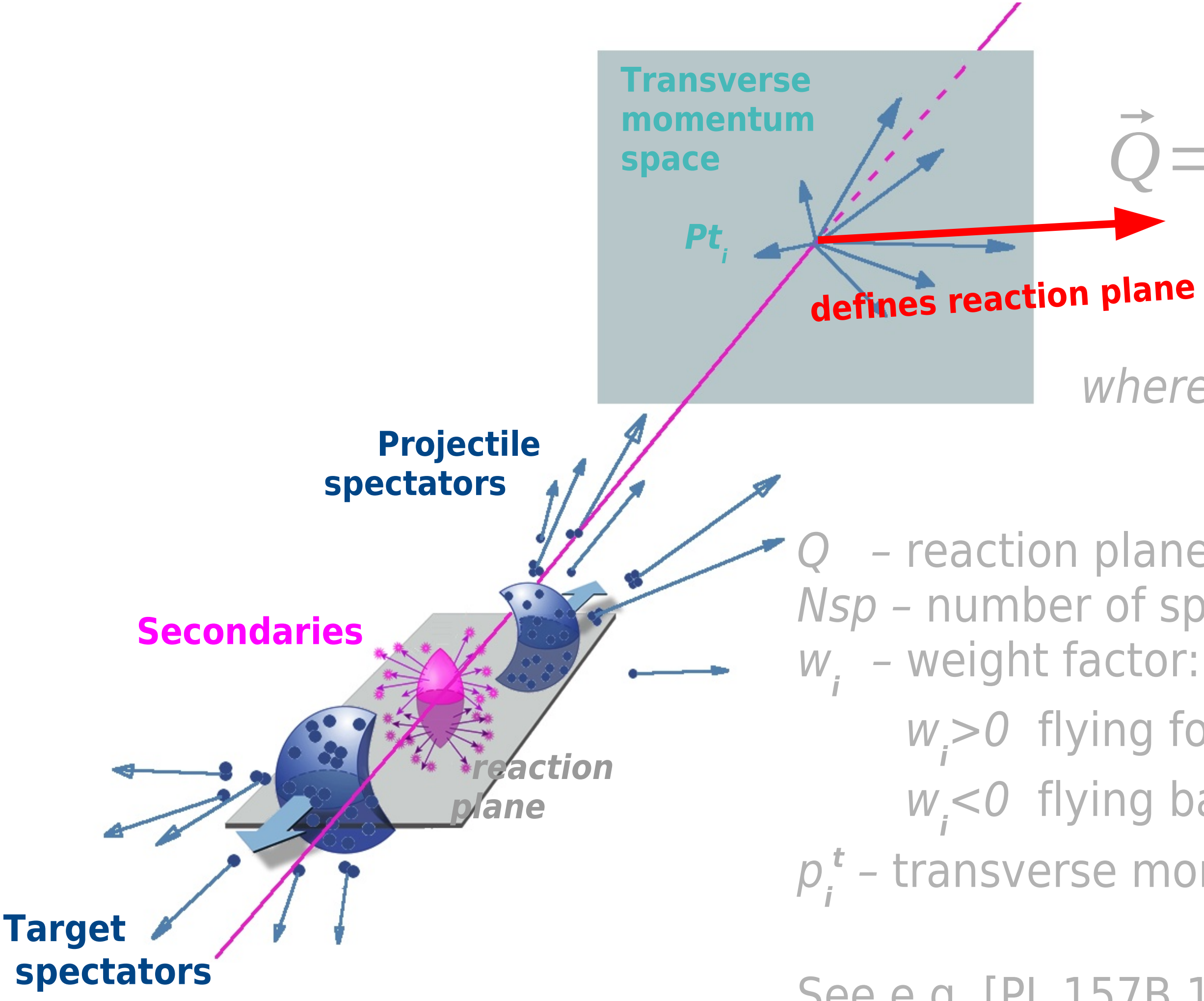


BUU: Au-Au@2AGeV
P. Danielewicz, at al., Science 298, 1592 (2002)

Hydrodynamics predict v_1, v_2 collapse at intermediate energy range of A-A (supported by NA49 results at 40AGeV)

Introduction

Definition of reaction plane, secondaries and spectators



$$\vec{Q}=\sum_{i=1}^{Nsp} w_i \vec{p}_i^{\,t}$$

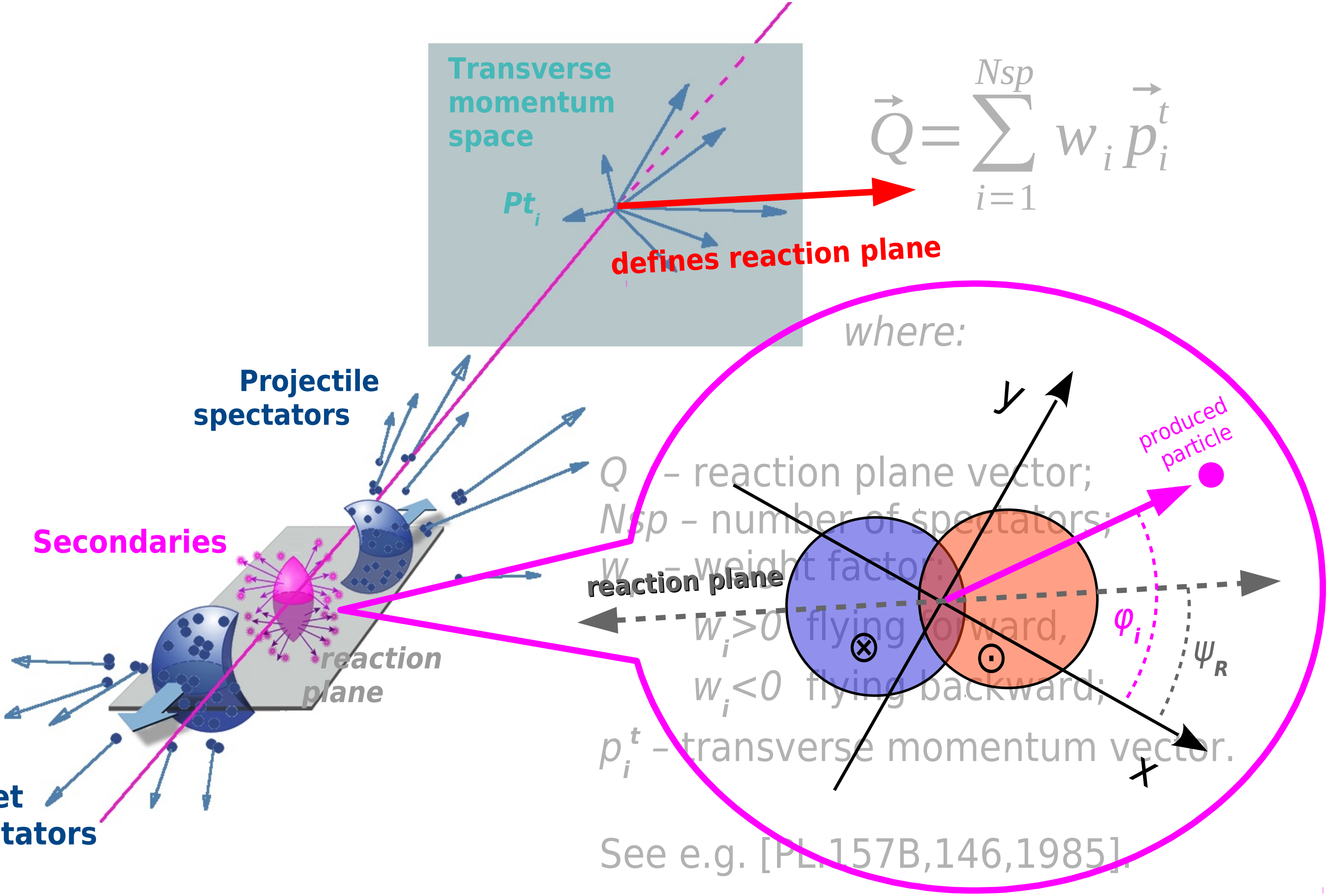
where:

Q – reaction plane vector;
Nsp – number of spectators;
w_i – weight factor:
$w_i>0$ flying forward,
$w_i<0$ flying backward;
p_i^t – transverse momentum vector.

See e.g. [PL.157B,146,1985].

Introduction

Reaction plane as a reference for azimuthal distributions



$$\vec{Q} = \sum_{i=1}^{Nsp} w_i \vec{p}_i^{\,t}$$

where:

Q – reaction plane vector;

Nsp – number of spectators;

w_i – weight factor:

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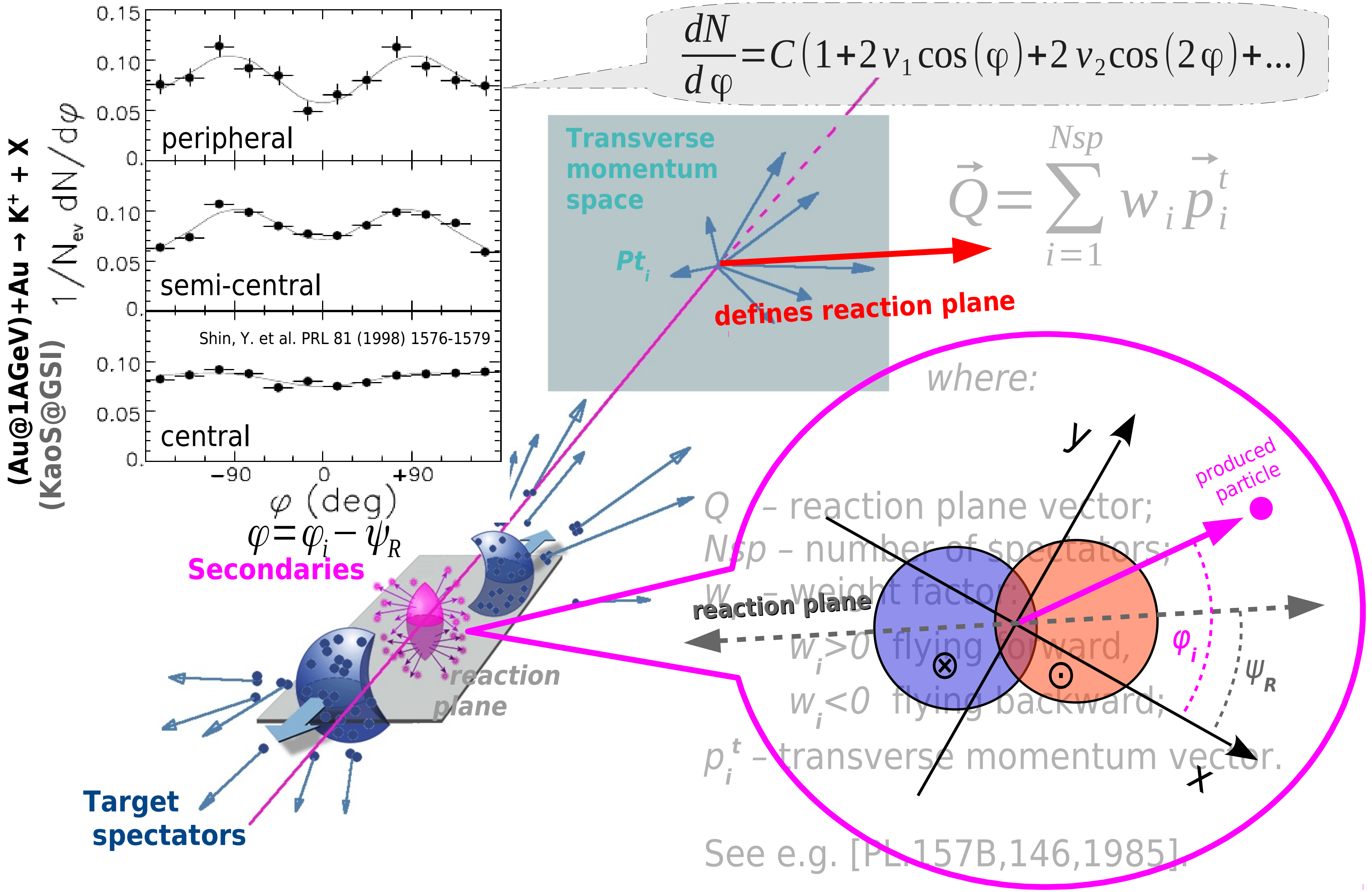
$w_i < 0$ flying backward;

p_i^t – transverse momentum vector.

See e.g. [PL 157B,146,1985].

Introduction

Distributions of azimuthal flow



Shin, Y. et al. PRL 81 (1998) 1576-1579

$$\varphi=\varphi_i-\psi_R$$

$$\frac{dN}{d\varphi}=C(1+2v_1\cos(\varphi)+2v_2\cos(2\varphi)+\ldots)$$

$$\vec{Q}=\sum_{i=1}^{Nsp} w_i\,\vec{p}_i^{\,t}$$

where:

Q – reaction plane vector;

Nsp – number of spectators;

w_i – weight factor:

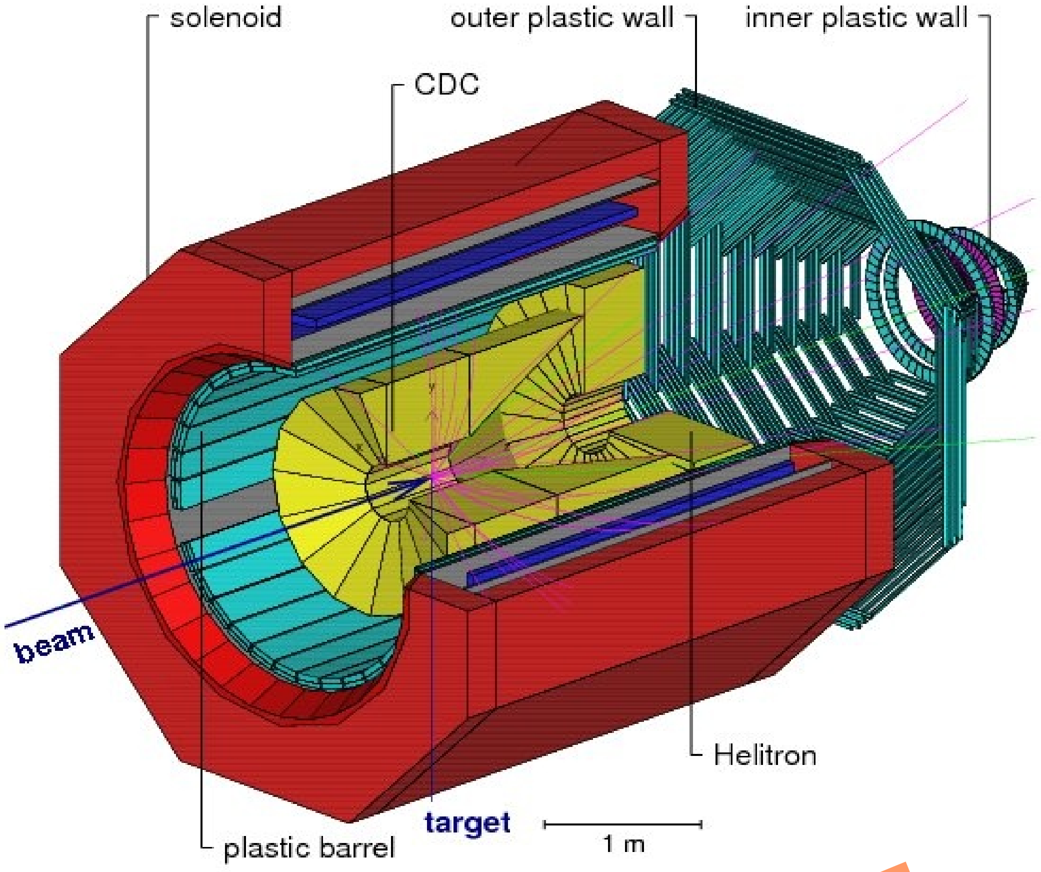
$w_i>0$ flying forward,

$w_i<0$ flying backward;

p_i^t – transverse momentum vector.

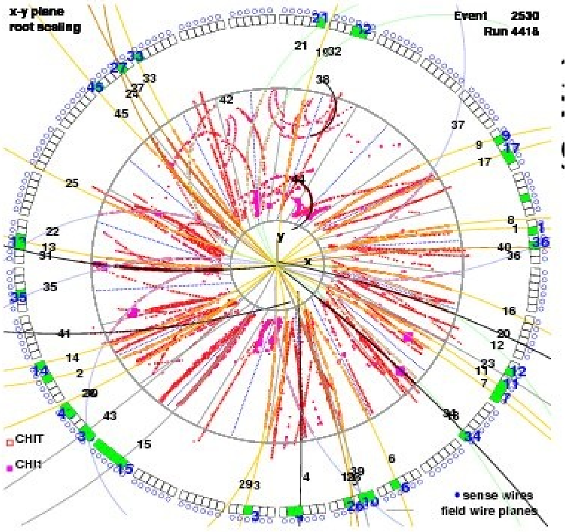
See e.g. [PL 157B,146,1985].

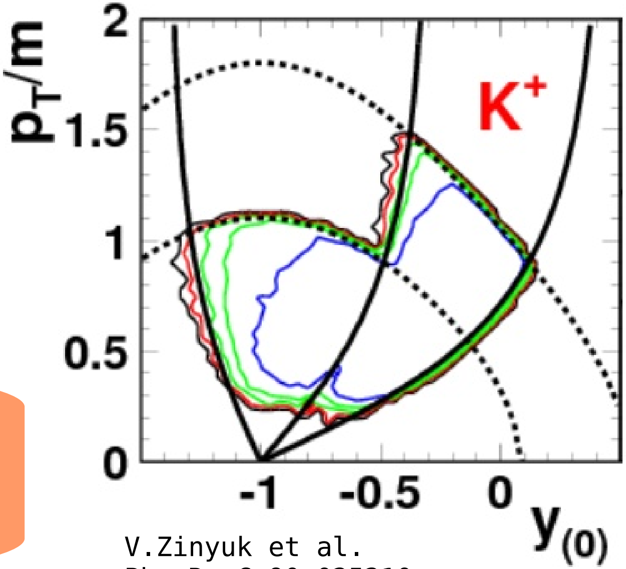
Typical experiments: FOPI @ GSI



Figures from: A. Devismes, Results from FOPI on strangeness production and propagation, SQM-2001 www-fopi.gsi.de/pub/conf/

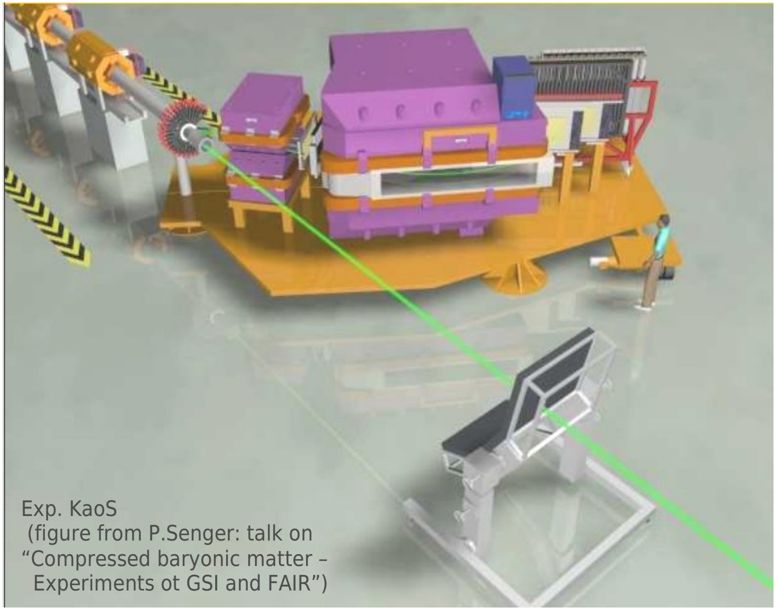
Detailed flow studies for π, p, d, t, ^{3}H, ^{3}He, α
with Au+Au in energy region of
{0.09, 0.12,0.25, 0.4, 0.6, 0.8, 1.0, 1.2, 1.5) AGeV



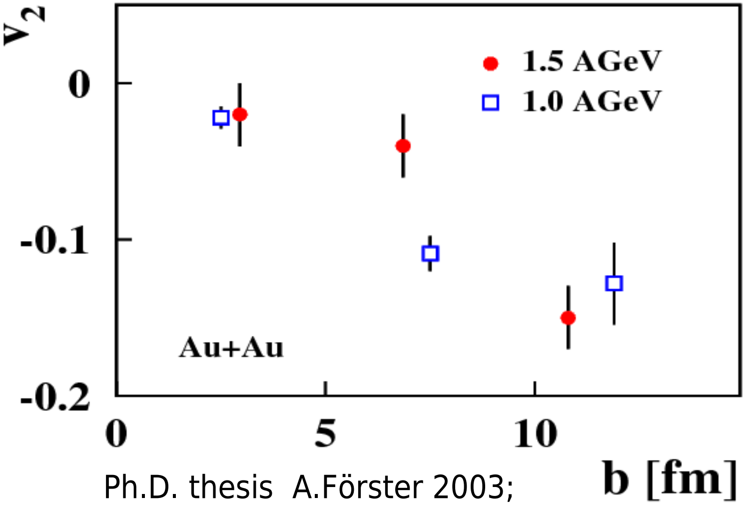


V.Zinyuk et al.
PhysRevC.90.025210

KaoS: azimuthal flow analysis based on reaction plane obtained with help of spectator distribution

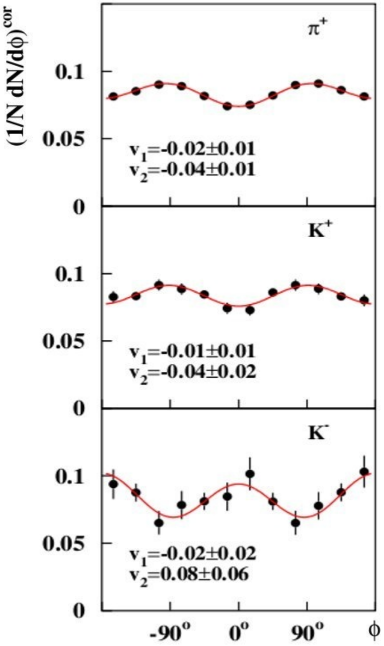


Exp. KaoS
(figure from P.Senger: talk on "Compressed baryonic matter – Experiments ot GSI and FAIR")

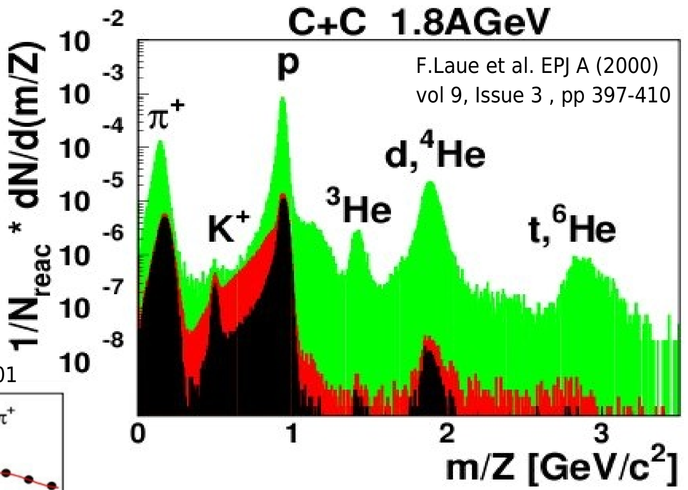


Ph.D. thesis A.Förster 2003;
Y.Shin et.al. PRL81, 1998.

F.Uhlig et al.
PhysRevLett.95.012301

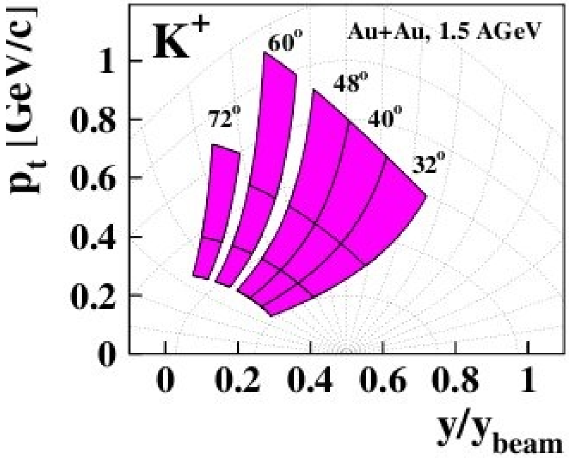


Azimuthal distribution of π^+, K^+ and K^- for semi-central Ni+Ni collisions at 1.93 A·GeV. The data are corrected for the resolution of the reaction plane and correspond to impact parameters of 3.8 fm$< b <$ 6.5 fm, rapidities of $0.3 < y/y_{beam} < 0.7$ and momenta of 0.2 GeV/c $< p_t <$ 0.8 GeV/c. The lines are fits with function (1) resulting in the values for v_1 and v_2 as given in the figure.



F.Laue et al. EPJ A (2000)
vol 9, Issue 3 , pp 397-410

Excellent single track PID



HADES @ SIS-18, GSI, Darmstadt

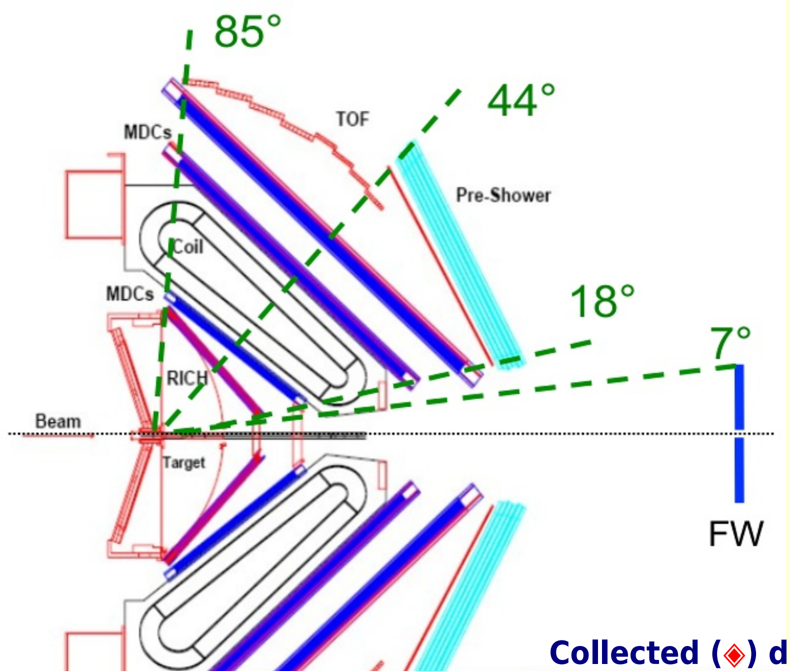
Systematic measurements of di-electron and strangeness in AA, NN, pA, πN and πA collisions:

Excitation function for low-mass lepton pairs and (multi-)strange baryons and mesons

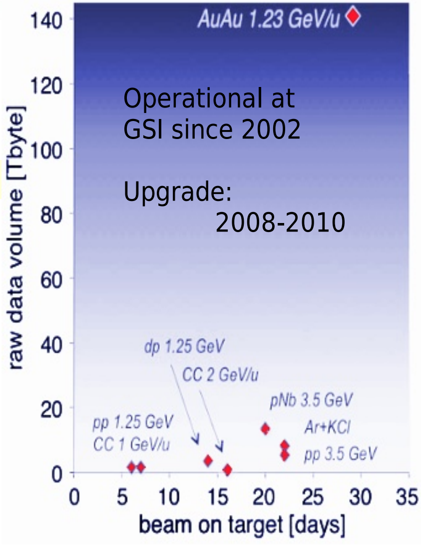
Various aspects of baryon-resonance physics

Detector

- * Fixed target experiment, large acceptance
- * Full azimuthal coverage
- * Hadron and lepton identification
- * e+e- pair acceptance 35%, inv.mass resolution 2% (ρ/ω region)
- * Event plane reconstruction
- * Electronics ~ 80.000 channels
- * DAQ: now up to 50 kHz event rate

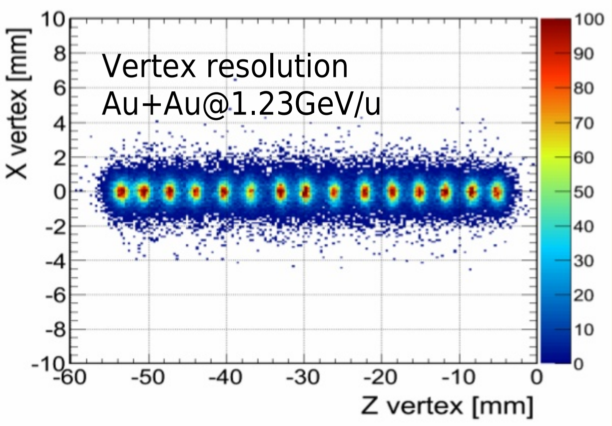


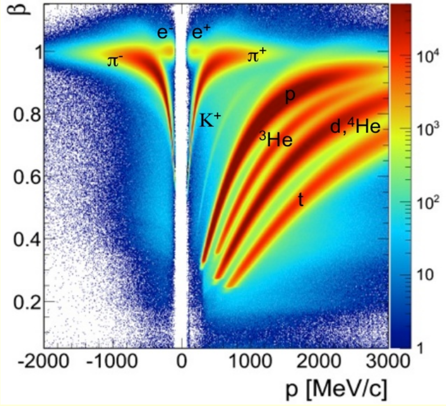
Collected (◈) data



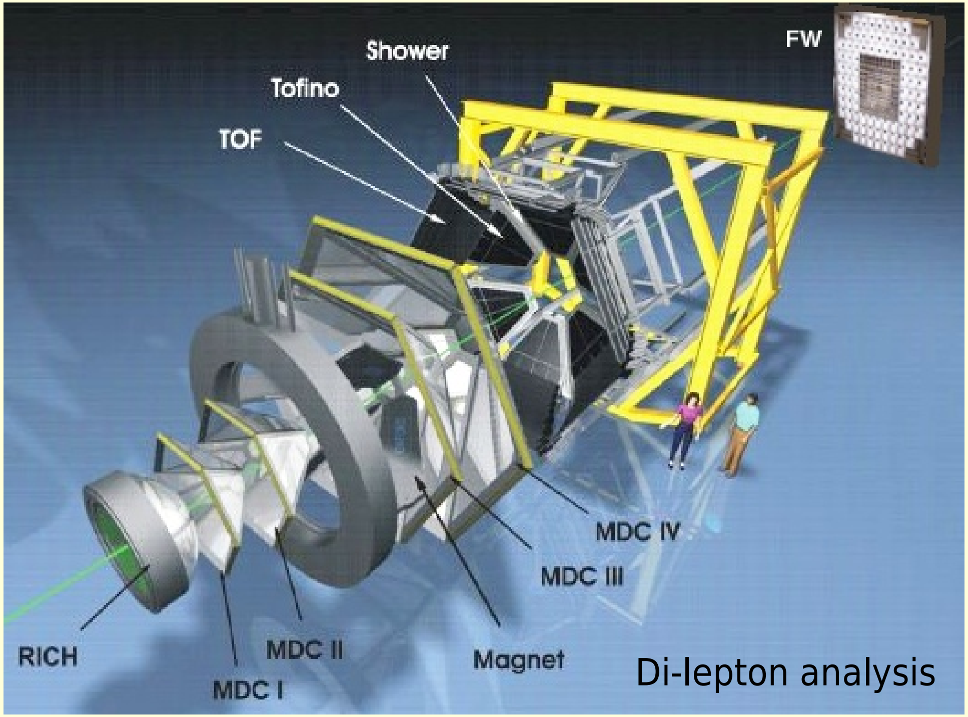
Operational at GSI since 2002

Upgrade: 2008-2010





HADES: Forward Wall technique

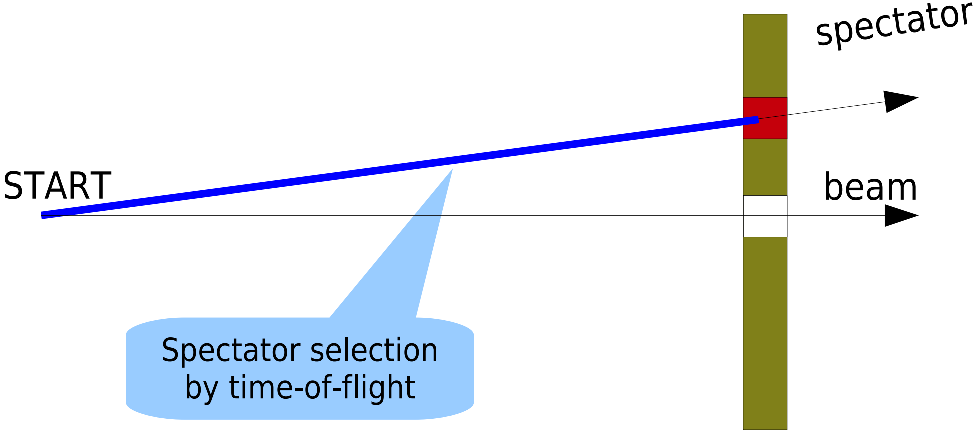


Di-lepton analysis

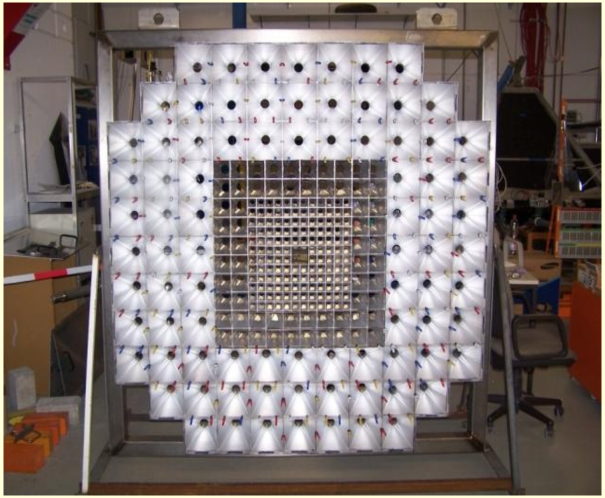
→ beam position monitoring
→ determination of event plane
→ flow analysis

Forward wall: 288 cells

140 small 4x4cm $(0^\circ < \theta < 2^\circ)$
64 middle 8x8cm $(2^\circ < \theta < 3.3^\circ)$
84 large 16x16cm $(3.3^\circ < \theta < 7.2^\circ)$

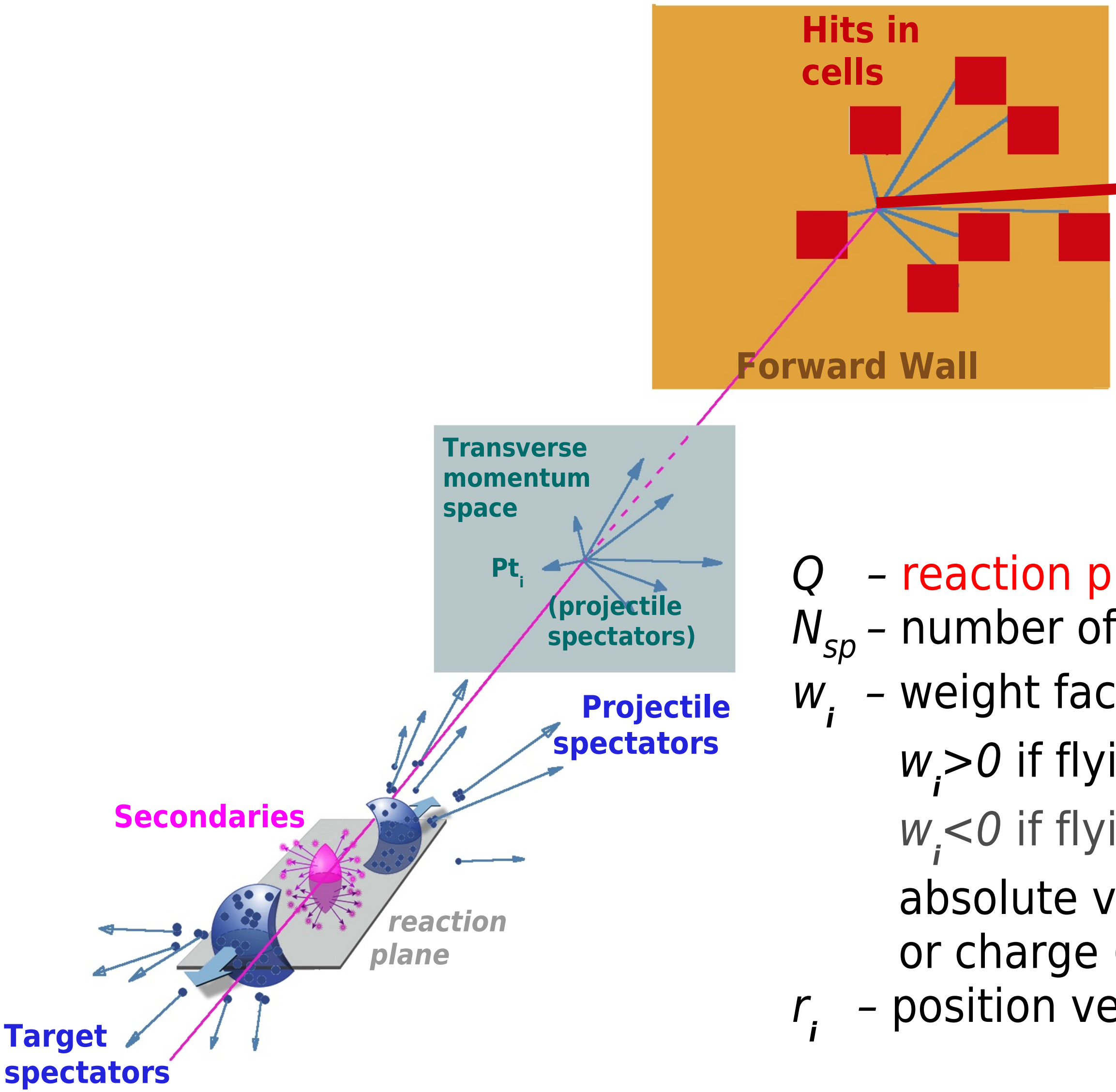


Spectator selection by time-of-flight



Reconstruction of reaction plane

(illustration: modified transverse momentum method)



$$\vec{Q} = \sum_{i=1}^{Nsp} w_i \frac{\vec{r}_i}{|\vec{r}_i|}$$

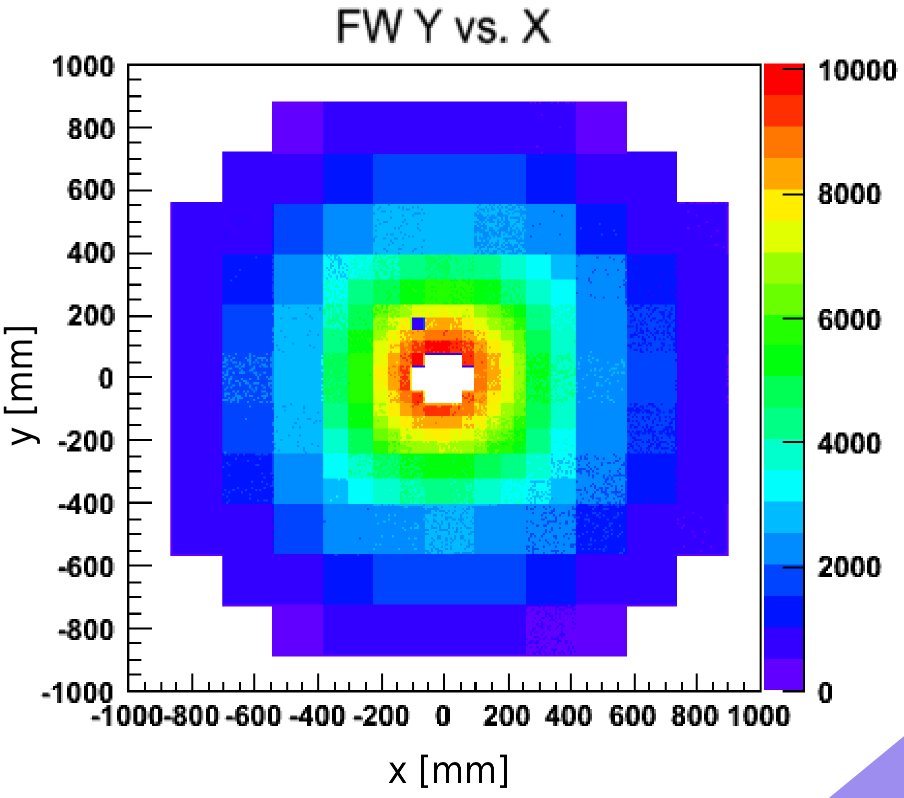
where:

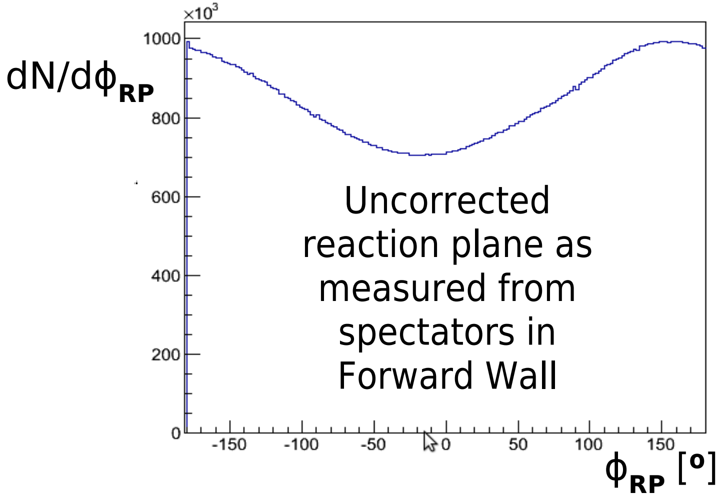
Q – reaction plane vector estimate;
N_{sp} – number of fragments;
w_i – weight factor:
$w_i > 0$ if flying forward,
$w_i < 0$ if flying backward,
absolute value is set to mass (m) or charge (Z) of the spectator;
r_i – position vector of cell with a hit-i.

Event plane flattening (1)

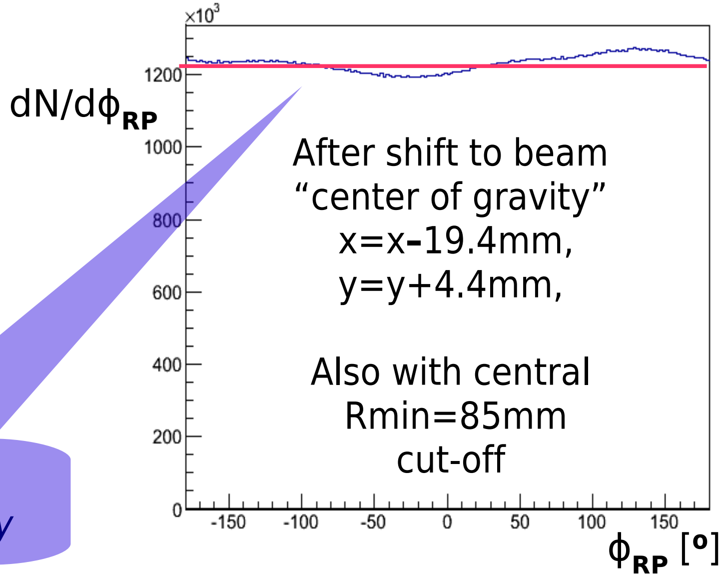
Re-centering to get expected angular isotropy

Cell occupancy
(for spectators)





Uncorrected reaction plane as measured from spectators in Forward Wall



After shift to beam "center of gravity"
x=x-19.4mm,
y=y+4.4mm,

Also with central Rmin=85mm cut-off

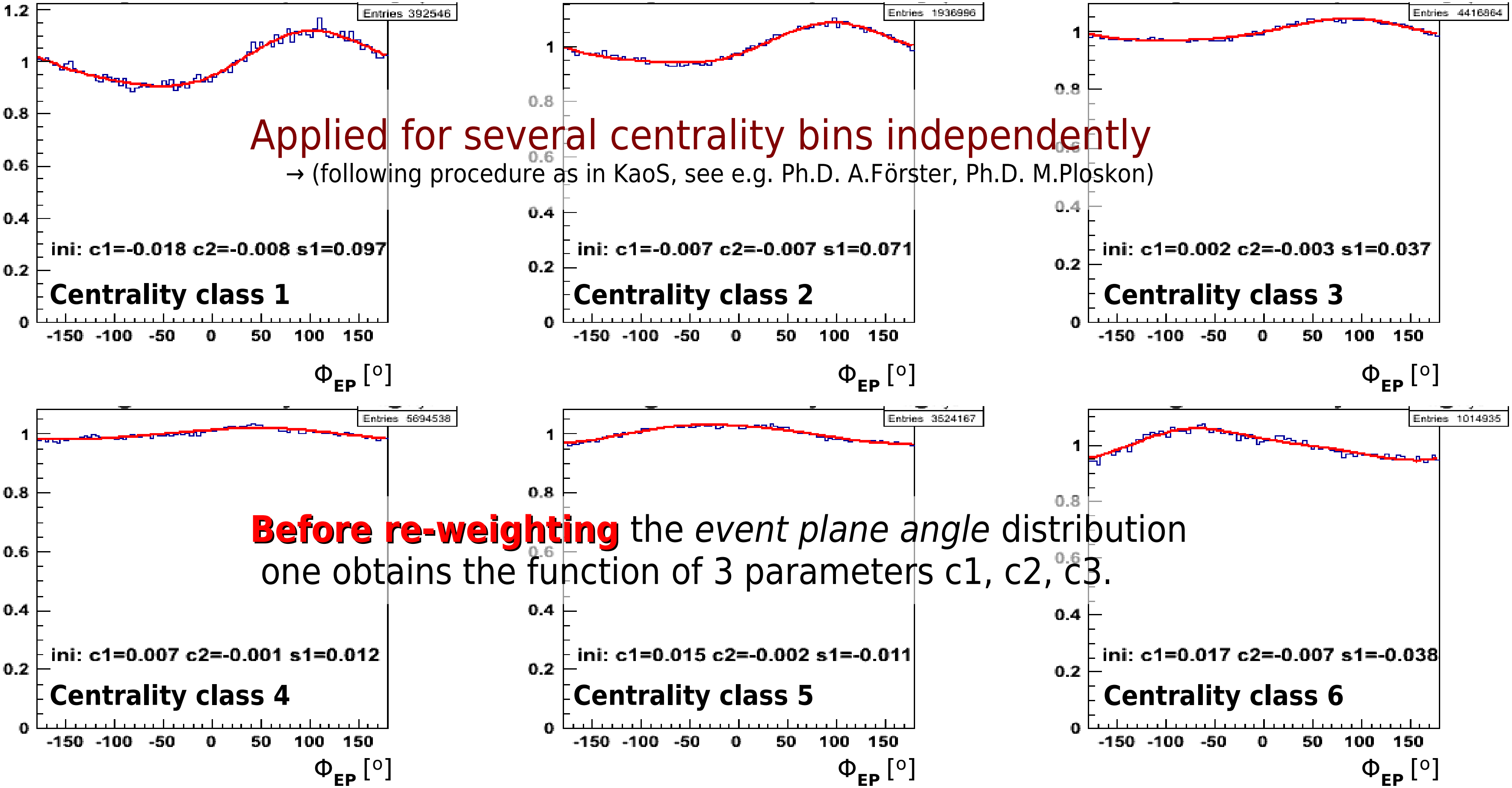
Acceptable level of remaining anisotropy

Event plane flattening (2)

Re-weighting to cancel remaining anisotropy

Small remaining anisotropy can be eliminated by re-weighting event plane angles to get flat the resulting distribution:

$$\frac{dN}{d\varphi_{EP}} \sim 1 + c_1 \cos(\varphi_{EP}) + c_2 \cos(2\varphi_{EP}) + c_3 \sin(\varphi_{EP})$$



Applied for several centrality bins independently

→ (following procedure as in KaoS, see e.g. Ph.D. A.Förster, Ph.D. M.Ploskon)

Before re-weighting the *event plane angle* distribution one obtains the function of 3 parameters c1, c2, c3.

Event plane flattening (2)

Re-weighting to cancel remaining anisotropy

Small remaining anisotropy can be eliminated by re-weighting event plane angles to get flat the resulting distribution:

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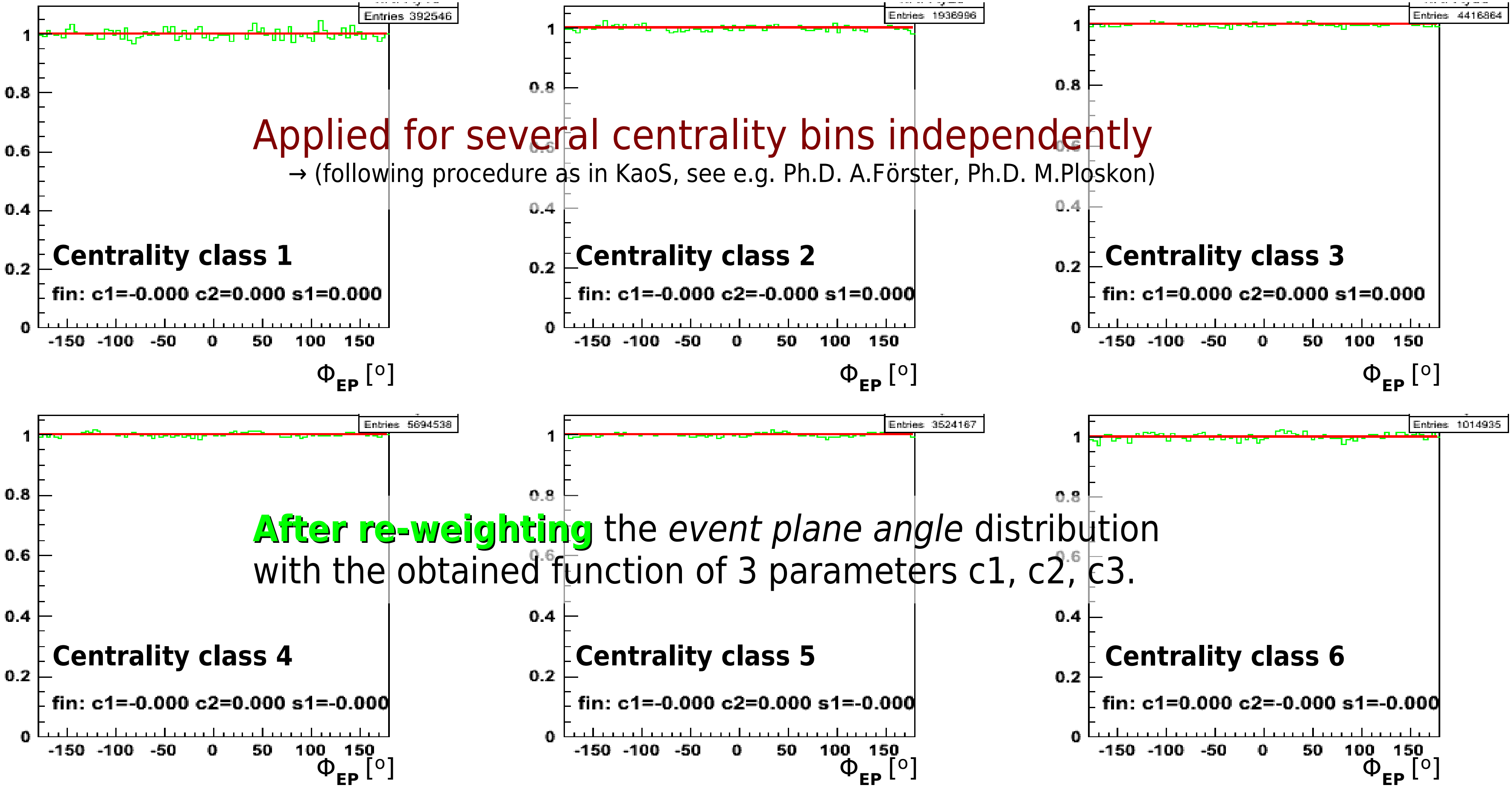


Applied for several centrality bins independently

→ (following procedure as in KaoS, see e.g. Ph.D. A.Förster, Ph.D. M.Ploskon)

After re-weighting the *event plane angle* distribution with the obtained function of 3 parameters c1, c2, c3.

Flow parameters

correction on finite resolution

An estimate of v_1 and v_2 flow parameters can be done with correction (*Ollitrault method*) by reaction plane resolution due to limited angular resolution of the detector.

$$\frac{dN}{d(\varphi_\pi-\varphi_{EP})} \sim 1+2v_1^{(fit)}\cos(\varphi_\pi-\varphi_{EP})+2v_2^{(fit)}\cos(2(\varphi_\pi-\varphi_{EP}))+\ldots$$

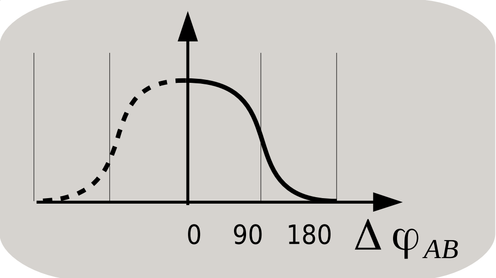
$$\Delta\phi=\phi_{EP}-\phi_{RP}=\phi_{measured}-\phi_{true}$$

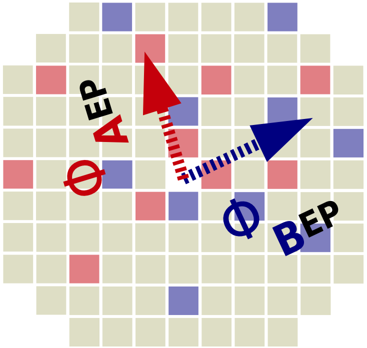
$$v_1=\frac{v_1^{(fit)}}{\langle\cos(\Delta\phi)\rangle}$$

$$\langle\cos(n\Delta\phi)\rangle=\frac{\sqrt{\pi}}{2}\chi e^{-\chi^2/2}\left[I_{\frac{n-1}{2}}\left(\frac{\chi^2}{2}\right)+I_{\frac{n+1}{2}}\left(\frac{\chi^2}{2}\right)\right]$$

$$v_2=\frac{v_2^{(fit)}}{\langle\cos(2\Delta\phi)\rangle}$$

$$\frac{N(90^o<|\Delta\phi_{AB}|<180^o)}{N(0^o<|\Delta\phi_{AB}|<180^o)}=\frac{e^{-\chi^2/2}}{2}$$



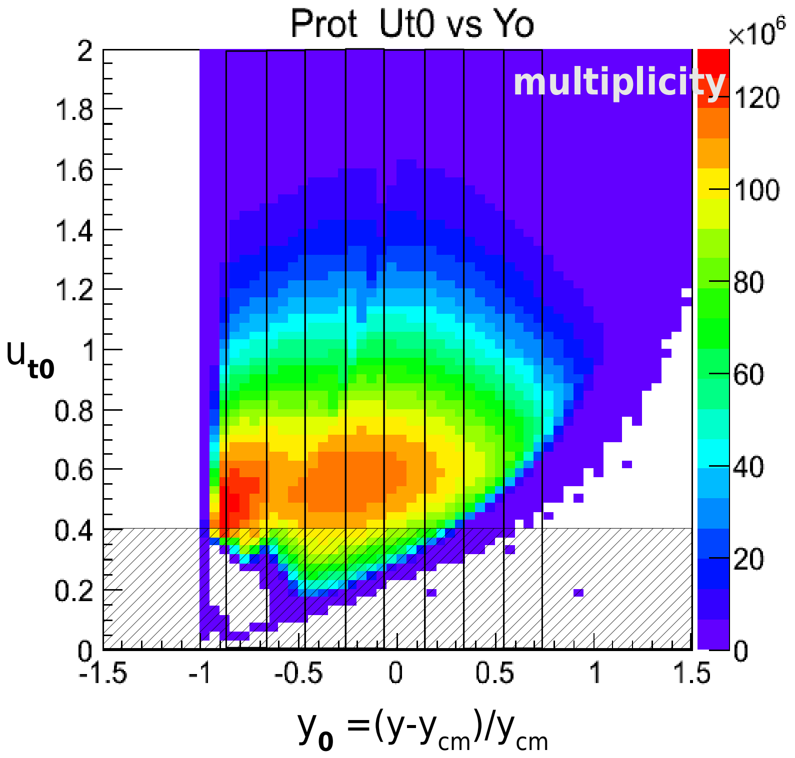


(see: arxiv.org/pdf/nucl-ex/9711003v2)

Proton acceptance vs. y_0 and p_t

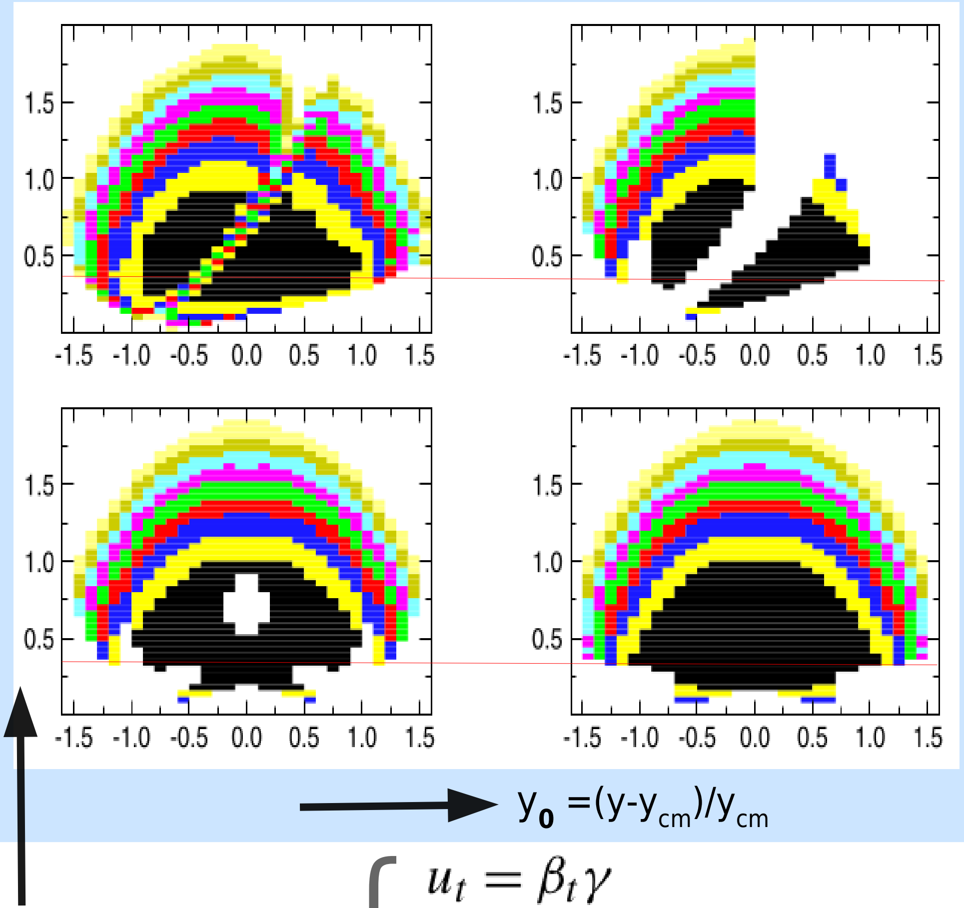
Selection for **protons** :
& good tracks selected
& dE/dx in gaseous tracking chambers
& appropriate reconstructed mass
& similar to FOPI p_t -acceptance (u_{t0}>0.4)

Azimuthal flow extracted for a set of y_o with efficiency correction



Following FOPI acceptance selection: u_{t0} vs y_0

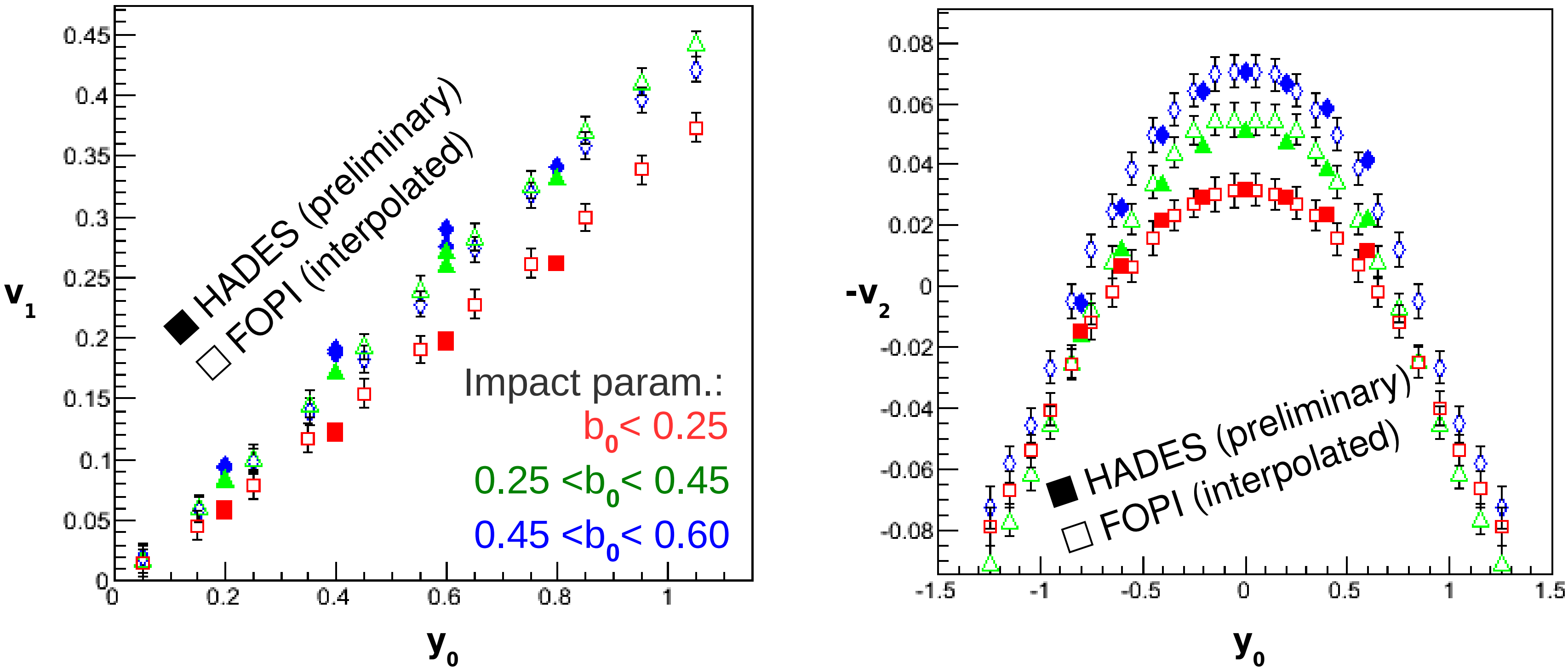
W.Reisdorf et al. NPA876 (2012)



$$u_{t0} = u_t / u_p \quad \begin{cases} u_t = \beta_t \gamma \\ u_p = \beta_p \gamma_p \end{cases}$$

'***p***' – denotes incident projectile particle in c.o.m. system

Protons flow Au+Au @ 1.23GeV/u
HADES (preliminary) vs. FOPI



Empty symbols – FOPI Au+Au @ 1.2 and 1.5 GeV/u
(W. Reisdorf et al. Nucl. Phys. A 876 (2012) : arXiv:1112.3180v1)
Interpolated to Ekin=1.23 GeV/u to compare with HADES

Filled symbols – HADES Au+Au Ekin=1.23 GeV/u (preliminary)*
*** results obtained with help of GSI infrastructure**

Protons: preliminary results azimuthal flow vs. y_0 [15]

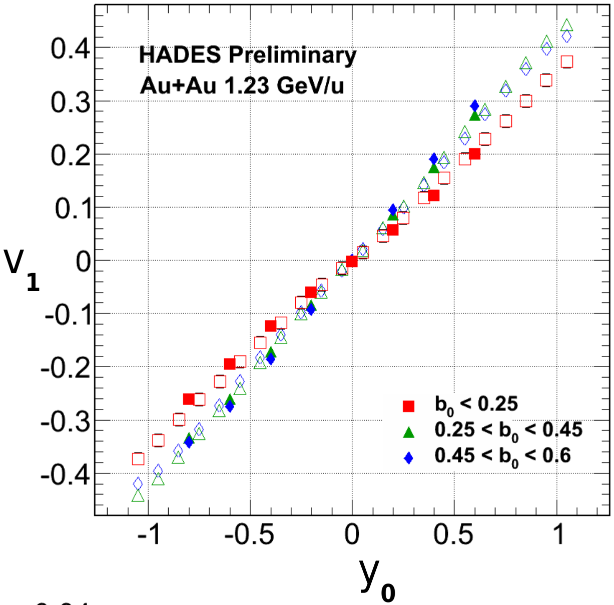
Good agreement for v_1 and v_2 with FOPI data in same energy range interpolated to Ekin=1.23 GeV/u

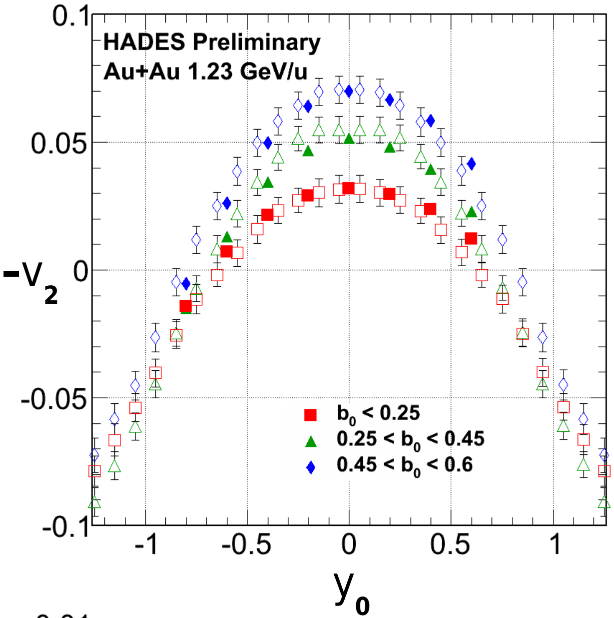
However available statistics allows HADES to reconstruct higher Fourier harmonics v_3 and v_4

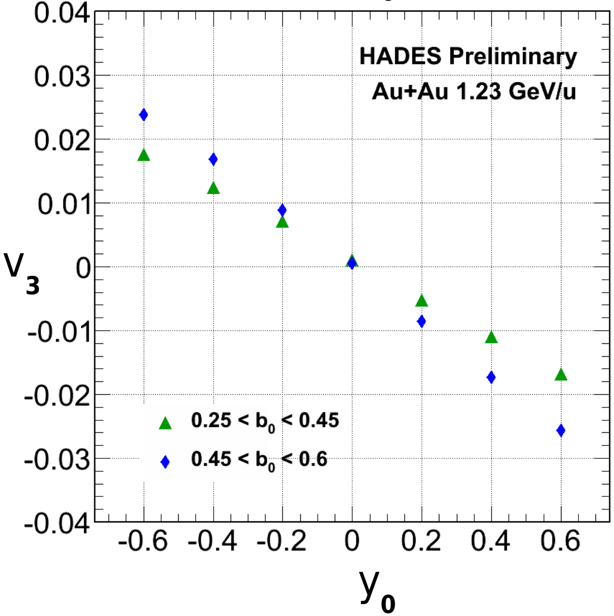
(Errors – stat. only.)

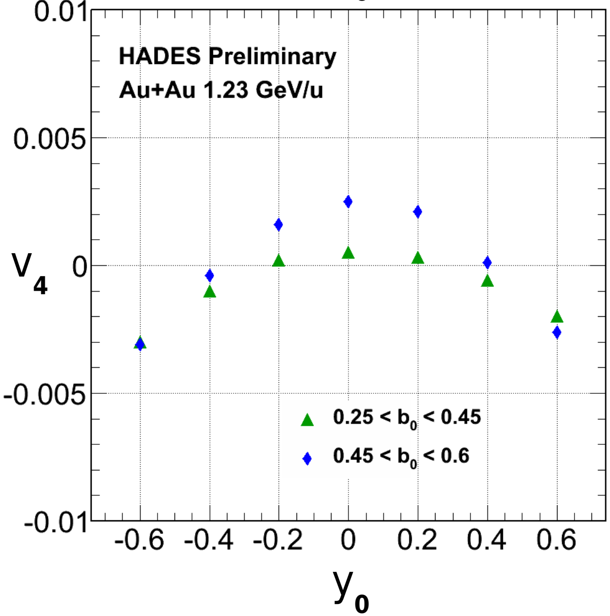
Rapidity distributions (integrated p_t) demonstrate odd v_3 and even v_4 harmonics

– i.e. reasonable from considerations of symmetry





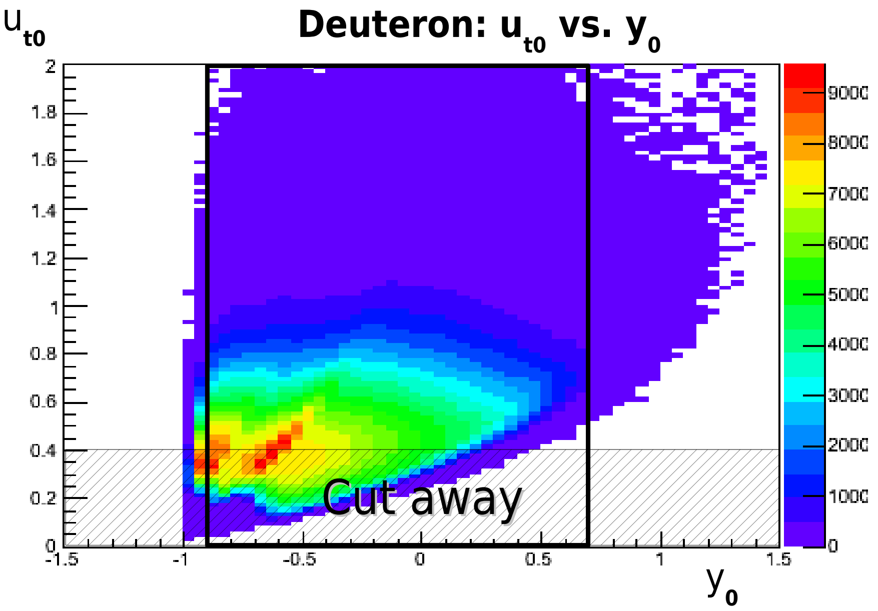


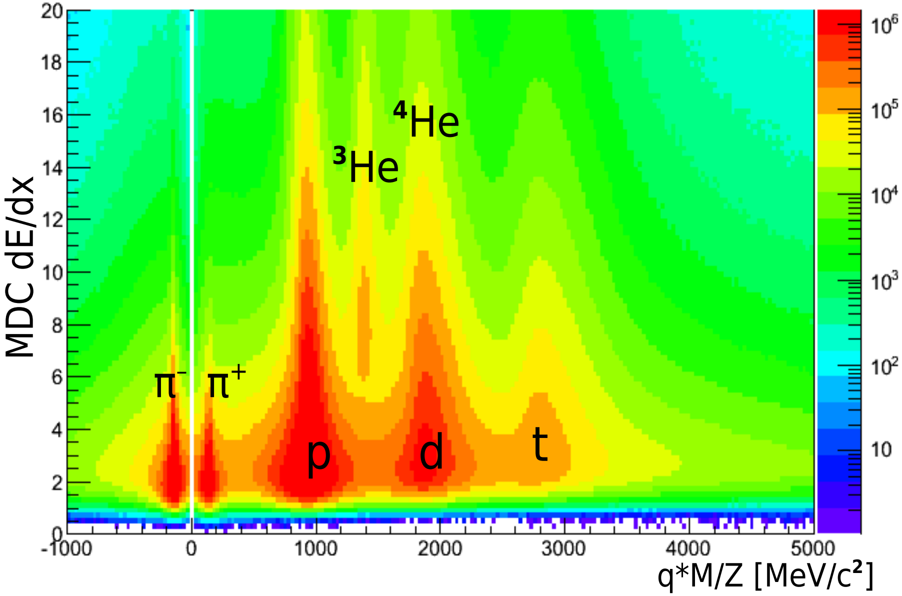


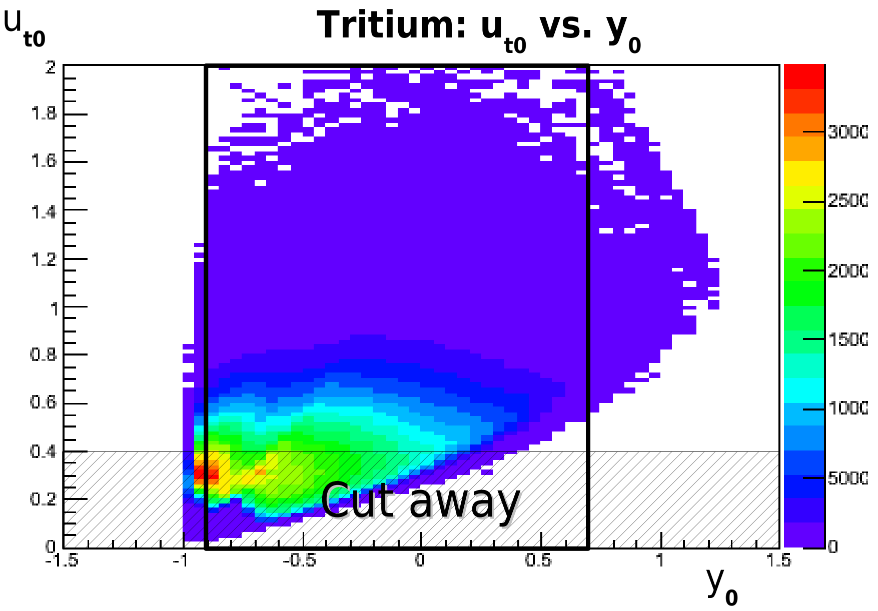
Comparing deuteron and triton in HADES with FOPI

Selection for **d , t** :
& good tracks selected
& dE/dx in gaseous tracking chambers
& appropriate reconstructed mass
& similar to FOPI p_t -acceptance (u_{t0}>0.4)

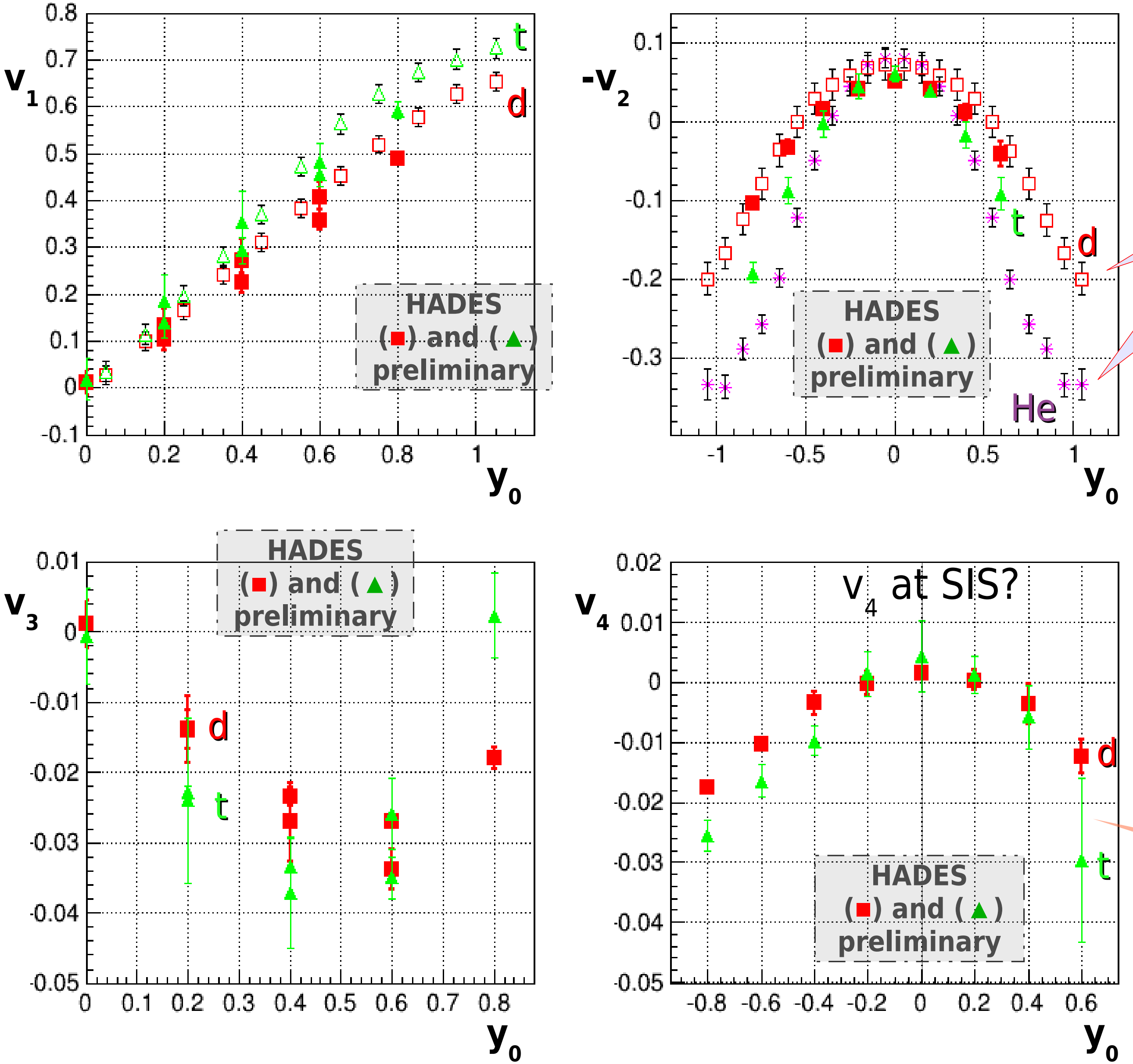
Yet no detailed efficiency correction
(actually rather flat response)


Deuteron: u_{t0} vs. y_0


Secondaries PID based on tracking, TOF/RPC and dE/dx in MDC


Tritium: u_{t0} vs. y_0

Deuteron and triton in comparison with FOPI



FOPI (v_1, v_2) data
Ekin=1.2 AGeV, p_t>0.4
W.Reisdorf et al.
NPA876 (2012)

Symbols on plots
- □ deuteron (FOPI)
- ■ deuteron (HADES)
- △ triton (FOPI)
- ▲ triton (HADES)
- * alpha (FOPI)

HADES (all 31 days):
Centrality selection
$0.25<b_0<0.45$

Systematics:
partially included

Azimuthal flow data 1GeV – 3TeV

[18]

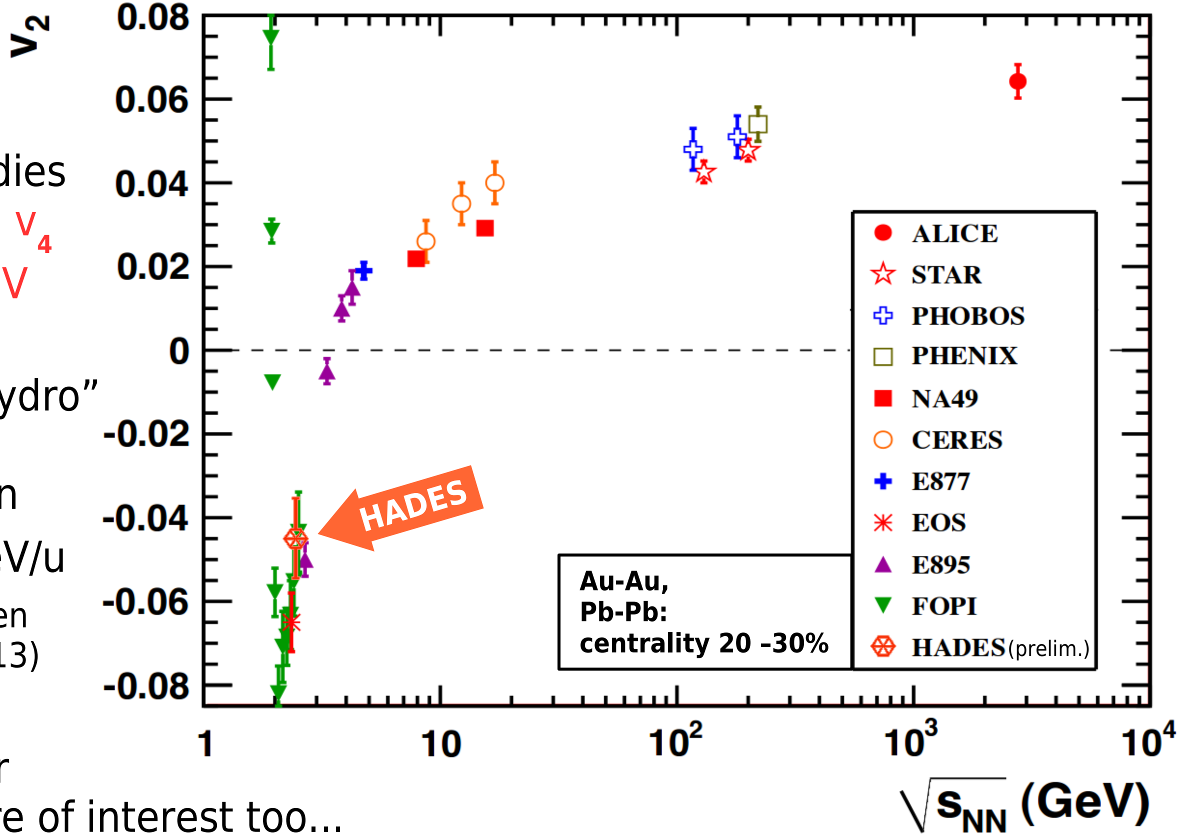
- Access to EOS at Ekin=1 – 2 GeV/u energies → soft EOS (KaoS, FOPI, **HADES**)
  Ongoing K^+ -flow analysis, plans for Λ

- Reasonable agreement of v_2 with some of hydrodynamical models at high energies

- Hope to contribute in studies of higher harmonic v_3 and v_4 starting from $\sqrt{s_{NN}}=2.4$ GeV

- Recently: “transport”+”hydro” hybrid model made predictions for v_2 and v_3 in range of $\sqrt{s_{NN}}=5...200$ GeV/u
  See: J.Auvinen and H.Petersen Phys. Rev. C 88, 064908(2013)

HADES point preliminary added on top of an existing compilation by: K. Aamodt et al., Phys. Rev. Lett. 105, 252302 (2010)



- Predictions for even lower energies $\sqrt{s_{NN}}=2$ GeV/u are of interest too...

Concluding remarks

- **Obtained preliminary azimuthal flow results from Au+Au collisions at beam kinetic energy of 1.23A GeV performed in 2012 by using High-Acceptance Di-Electron Spectrometer (HADES) installed at GSI Darmstadt**
- **Accumulated High statistics data allow measuring flow components with respect to event plane. The event plane has been reconstructed with help of a projectile fragments detector**
- **Well known Fourier coefficients of direct (v1) and elliptic (v2) flows are in agreement with previously measured ones by FOPI collaboration**
- **Our preliminary analysis indicates a possibility to extract higher: triangular (v3) and quadrangular (v4) flow harmonics for proton deuteron and tritium, which were not seen yet at SIS-18 energy range** $\sqrt{s_{NN}} \sim 2$ **GeV/u**
- **This measurement may offer additional constraints for the equation of state of the nuclear matter at high densities. Ongoing analysis to extract flow of strangeness.**

NB: results obtained with help of GSI infrastructure

Thank you for your attention

The HADES Collaboration: 156 members,
composed of 19 institutions from 10 European countries,
(See: hades.gsi.de)

Backup slides

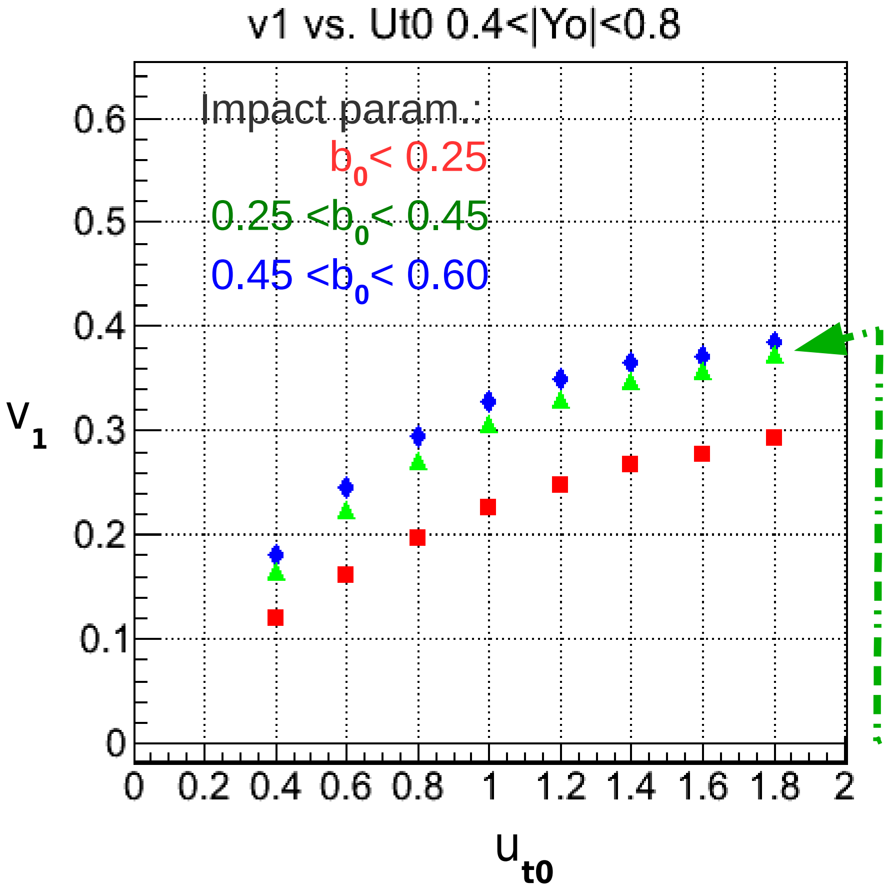
Prot. $\{v_1:u_{t0}\}$ preliminary HADES vs. FOPI

[A1]

HADES preliminary

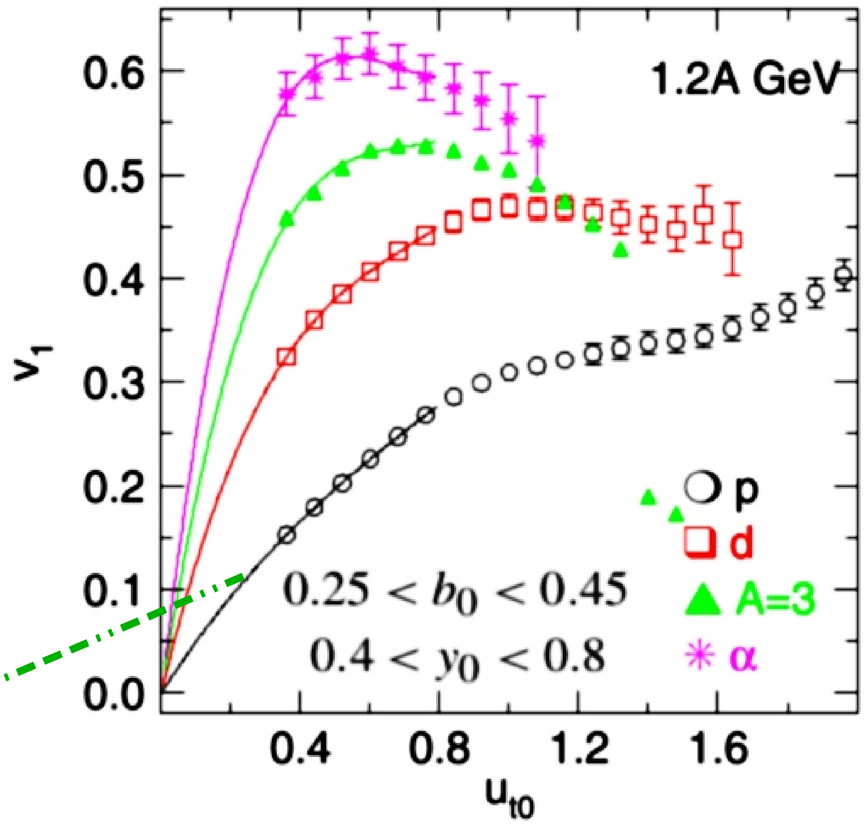
Note: HADES only for protons, but in 3 centrality classes compared with FOPI data {p,d,t} for single centrality class.

Green *one corresponds to FOPI*



$\{v_1:u_{t0}\}$ results from FOPI

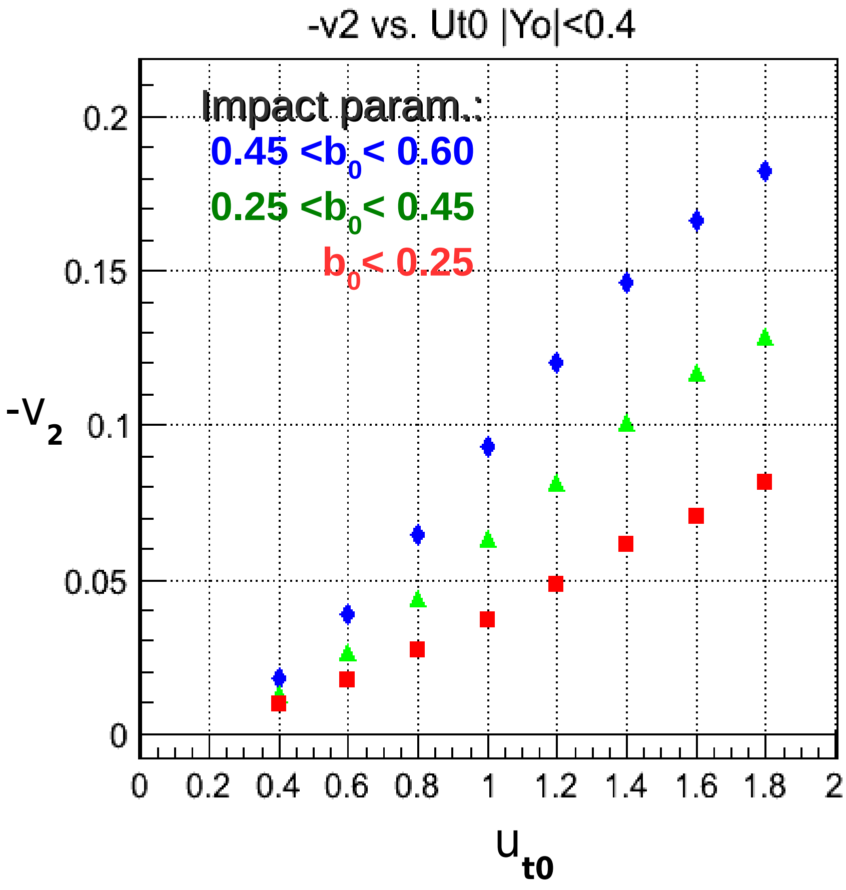
→ W.Reisdorf et al. NPA876(2012)



Prot. $\{v_2:u_{t0}\}$ preliminary HADES vs. FOPI

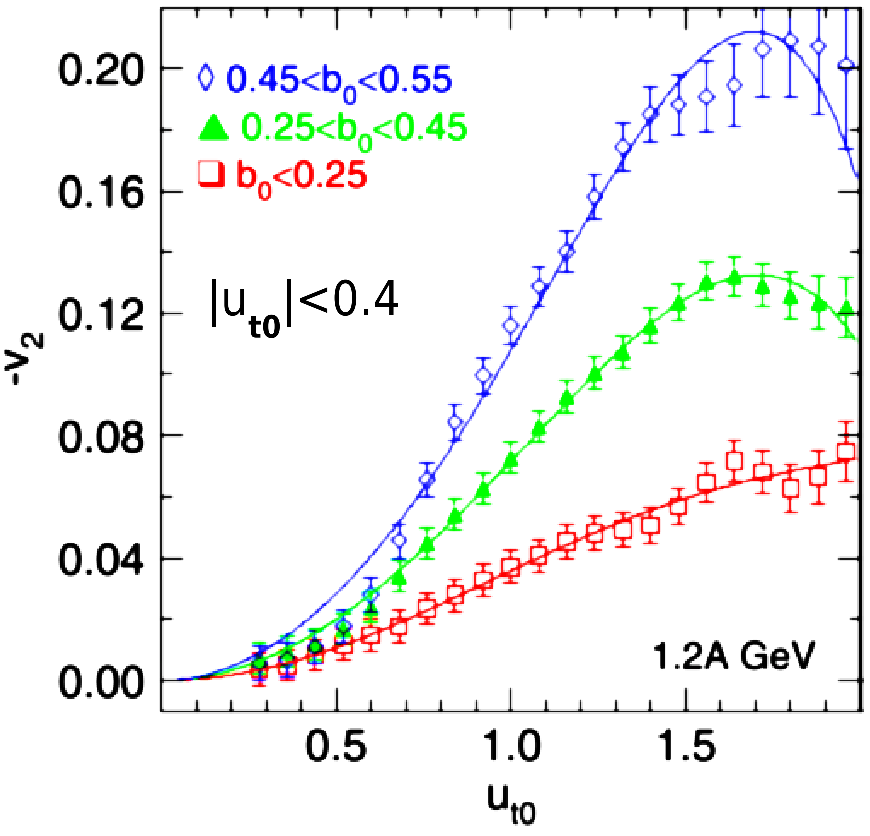
[A2]

HADES preliminary
Protons, in 3 centrality classes.
Green and red nicely agree with FOPI,
blue – underestimated by ~<15%



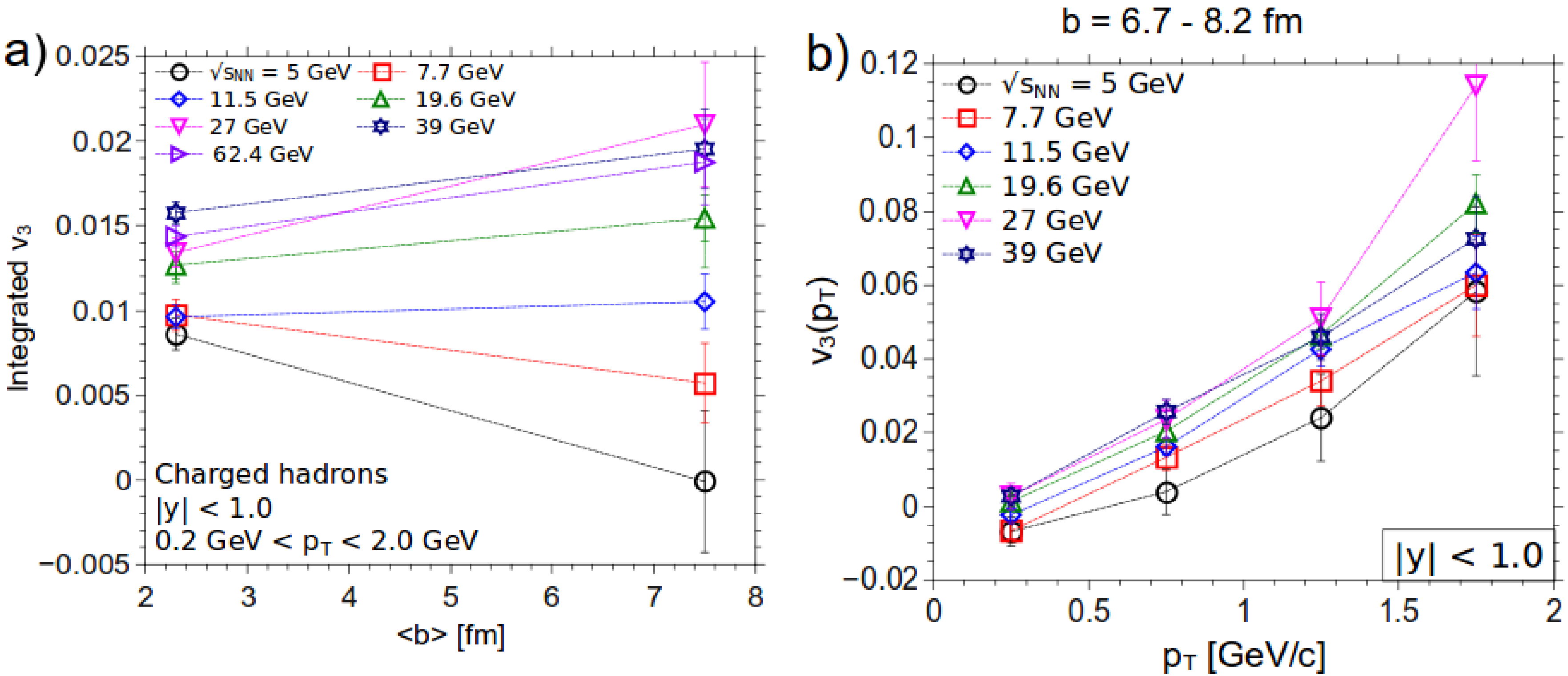
$\{v_2:u_{t0}\}$ results from FOPI

→ W.Reisdorf et al. NPA876(2012)



New predictions for v_2 and v_3 with hybrid model

(transport at the beginning of collision, hydrodynamics for hot and dense phase for flow production, and transport in the end)

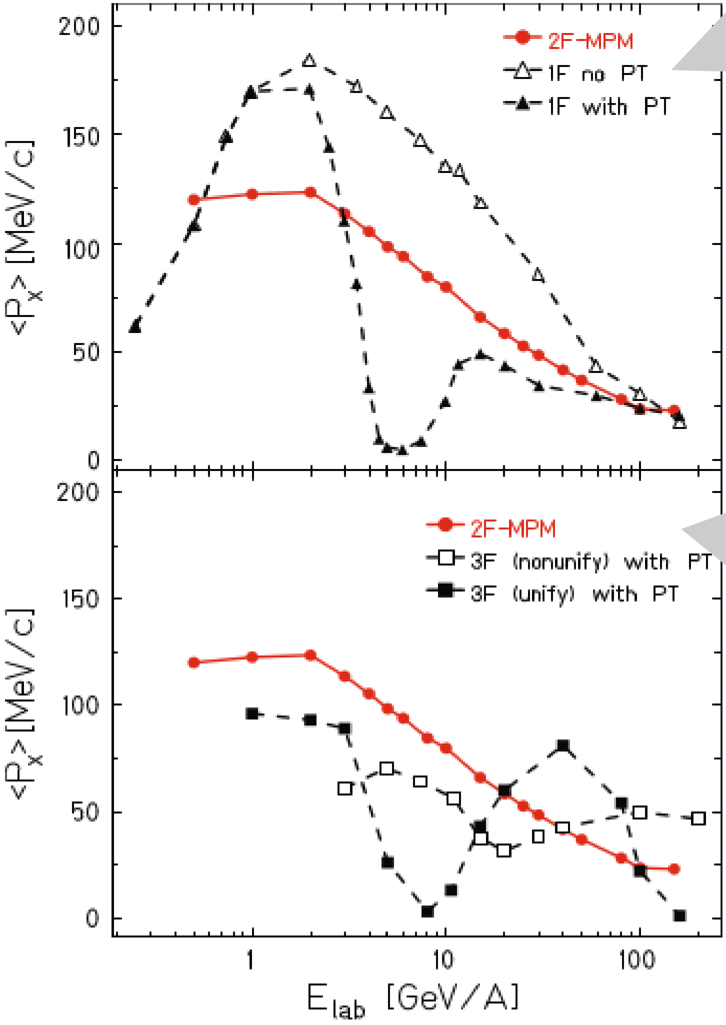


a) Integrated v_3 at midrapidity $|y| < 1.0$ in central ($b = 0 - 3.4$ fm) and midcentral ($b = 6.7 - 8.2$ fm) collisions for collision energies $\sqrt{s_{NN}} = 5 - 62.4$ GeV. b) $v_3(p_T)$ in midcentral collisions for $\sqrt{s_{NN}} = 5 - 39$ GeV.

See: J. Auvinen, H. Petersen, arXiv:1310.7751v1, Phys.Rev.C88, 064908 (2013)

Collective flows and phase transition

Excitation function of average directed flow
for baryons at different E_{lab}



Central Au + Au collisions
calculated with:

2F-MPM: two-fluid hydrodynamics with the EoS from the Mixed-Phase model,

1F no PT: one-fluid with phase transition
1F with PT: one-fluid w/o phase transition

Central Au + Au collisions
calculated with:

2F-MPM: two-fluid hydrodynamics with the EoS from the Mixed-Phase model,

3F (nonunity) with PT,
3F (unity) with PT:
three-fluid hydro with bag model EoS and with phase transition

See: [Y.B. Ivanov, E.G. Nikonov, W. Nörenberg, A.A. Shanenko, V.D. Toneev, Heavy Ion Phys. 15, 117 (2002) 752]

Prediction: v_2 flows at Au+Au@25AGeV[A5]

Collective flow ↔ space-time evolution of fireball

Elliptic flow v_2 and its dependence on the p_t of particle sheds light on the degrees of freedom which prevail in the early stage of the collision.

Predictions from several transport model calculations for hadron v_2-flow at midrapidity for mid-central b~7 fm (Au@25AGeV)+Au collisions

Large v_2 values are expected due to the partonic pressure built up in the early phase of the collision.

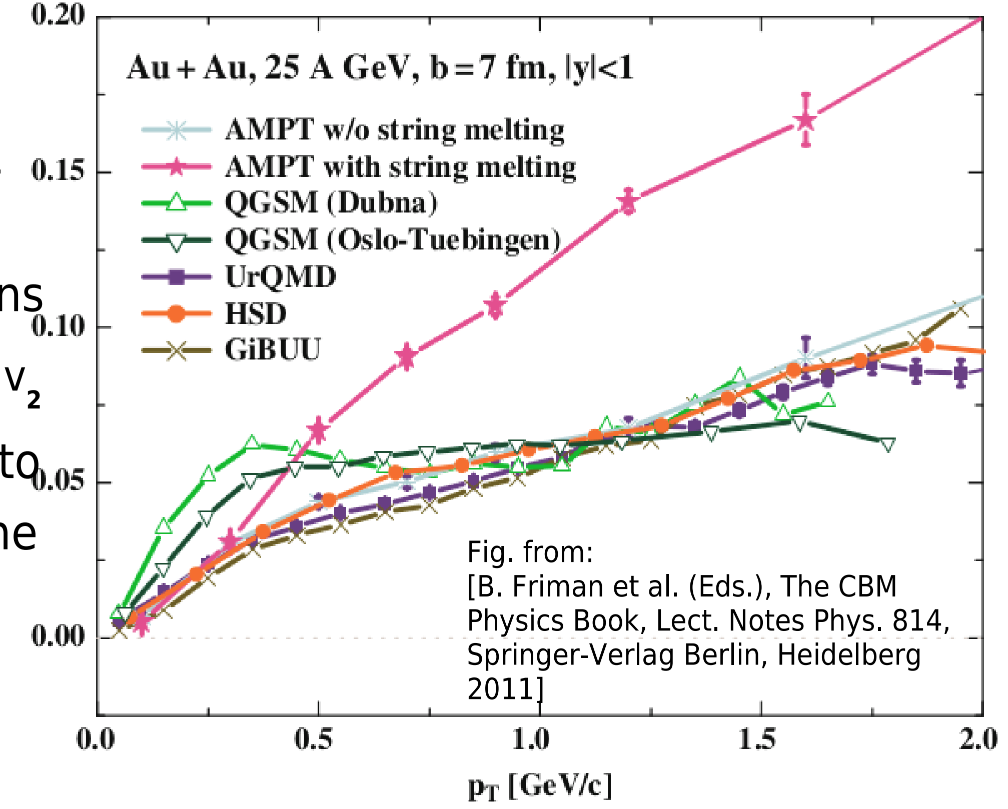


Fig. from:
[B. Friman et al. (Eds.), The CBM Physics Book, Lect. Notes Phys. 814, Springer-Verlag Berlin, Heidelberg 2011]

Flow analysis and azimuthal angular distributions[A6]

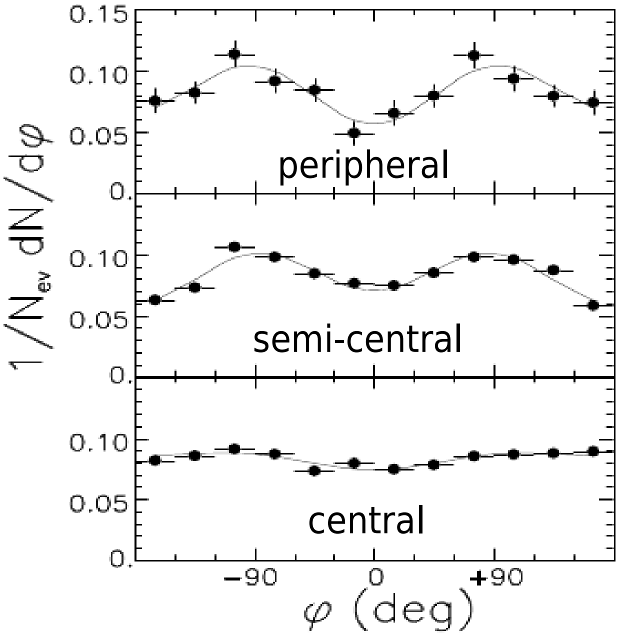
Azimuthal angular distribution of K^+ for peripheral, semi-central and central events in collisions of *(Au@1AGeV)+Au by KaoS collaboration.*
PRL.81(1998)1576-1579

In the frames of Fourier decomposition of obtained azimuthal distributions:

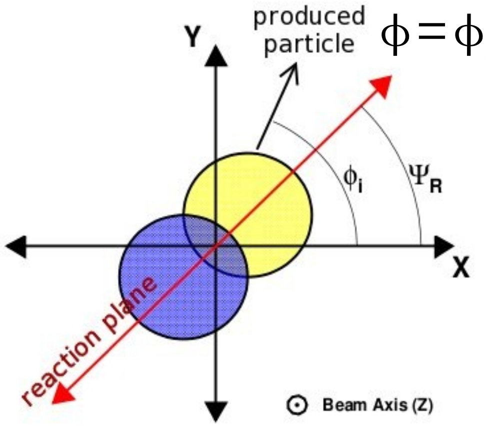
$$\frac{dN}{d\varphi} = C\left(1 + 2a_1\cos(\varphi) + 2a_2\cos(2\varphi) + \ldots\right)$$

which allows determination of directed (a_1) and elliptic (a_2) flows one may draw conclusions about the in-plane and out-of plane emission, in-medium potential…

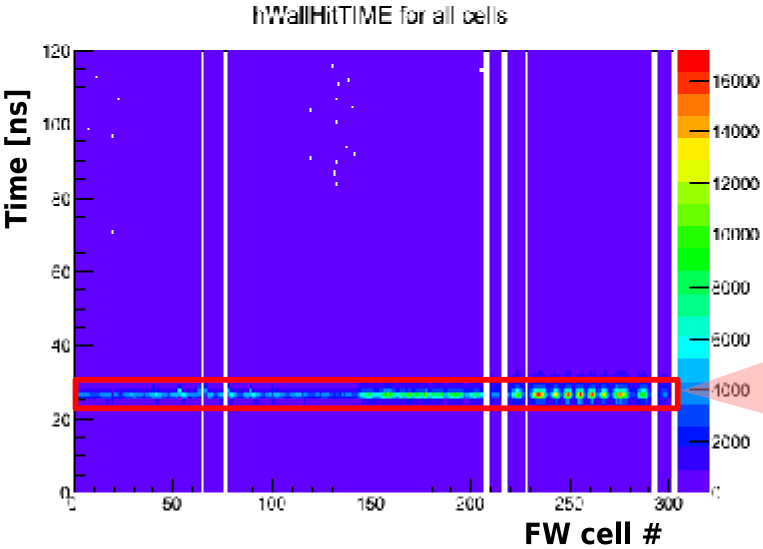
K^+ in (Au@1AGeV)+Au by (KaoS)



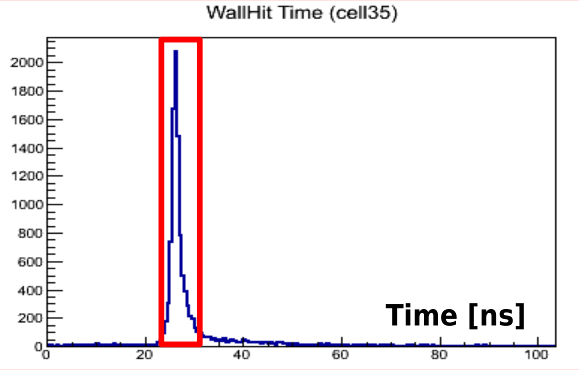
$$\phi = \phi_i - \psi_R$$

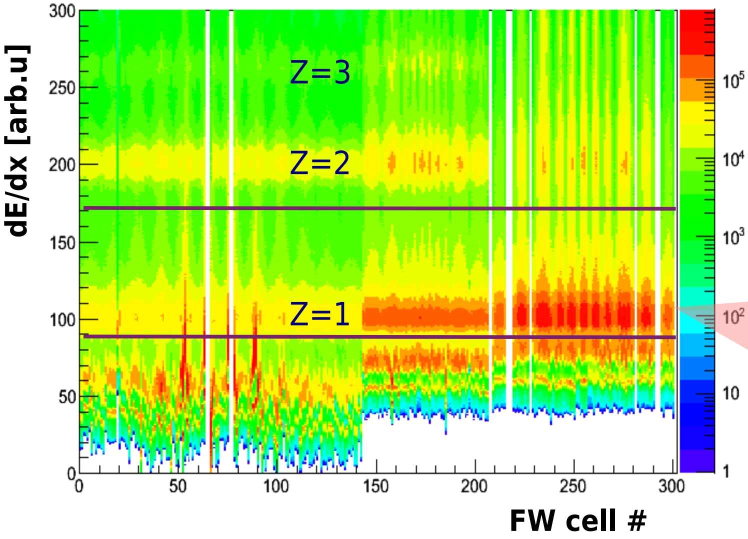


Spectator selection with HADES FW

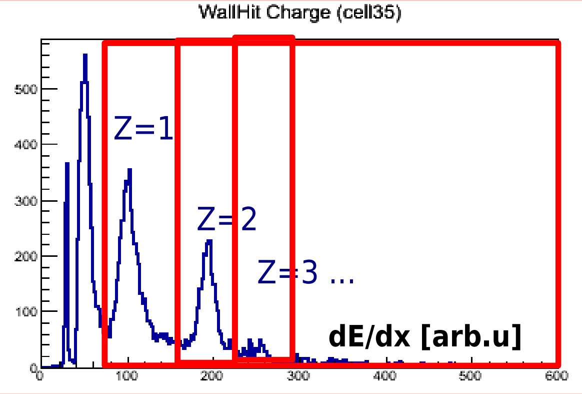


Time-of-flight needed by spectators to travel from target to FW cell is selected



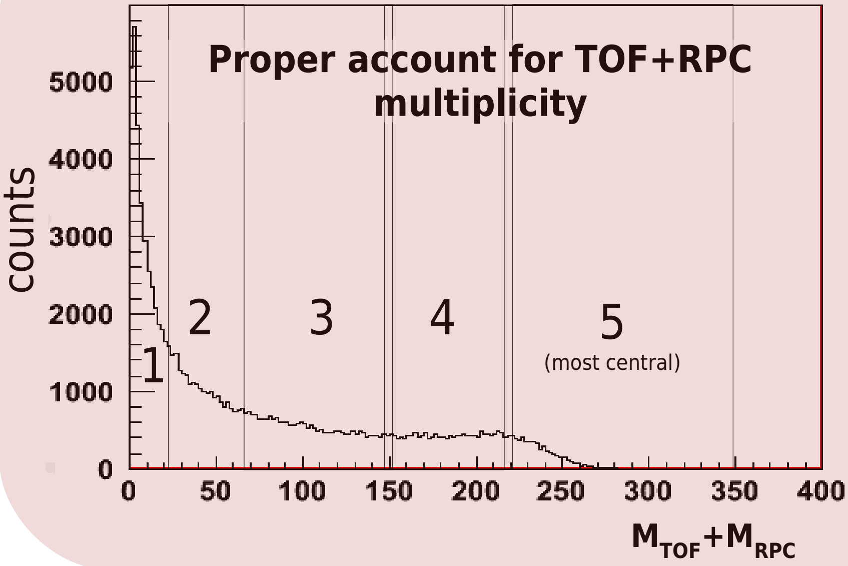


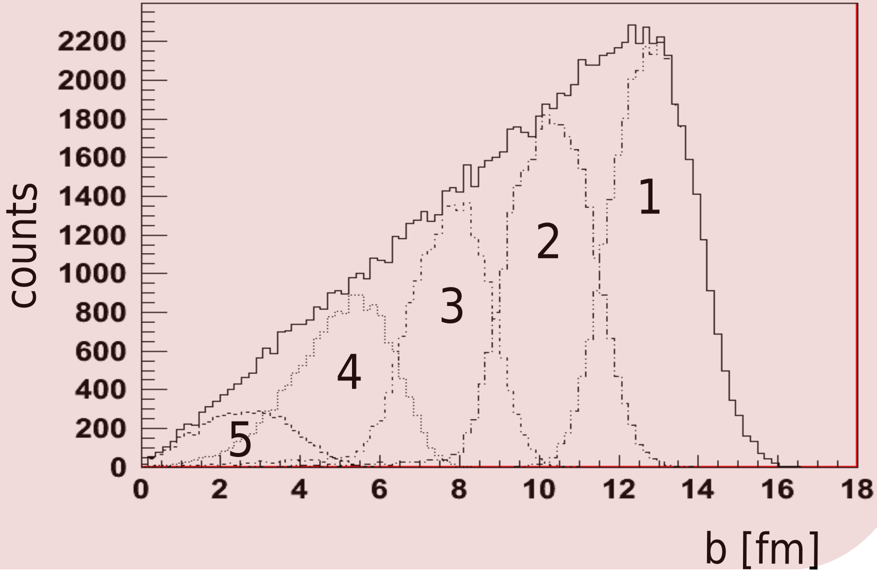
All charges accepted, but noise and magic peak are taken away individually



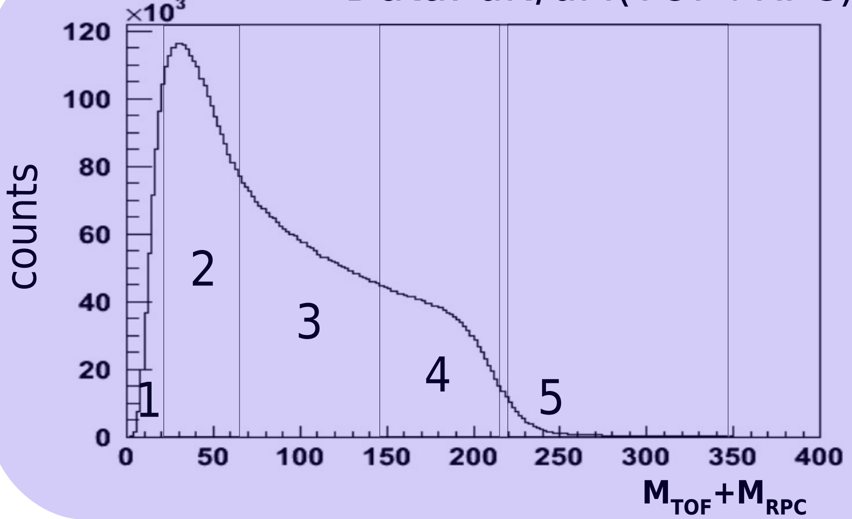
Estimating RP-angular resolution of FW

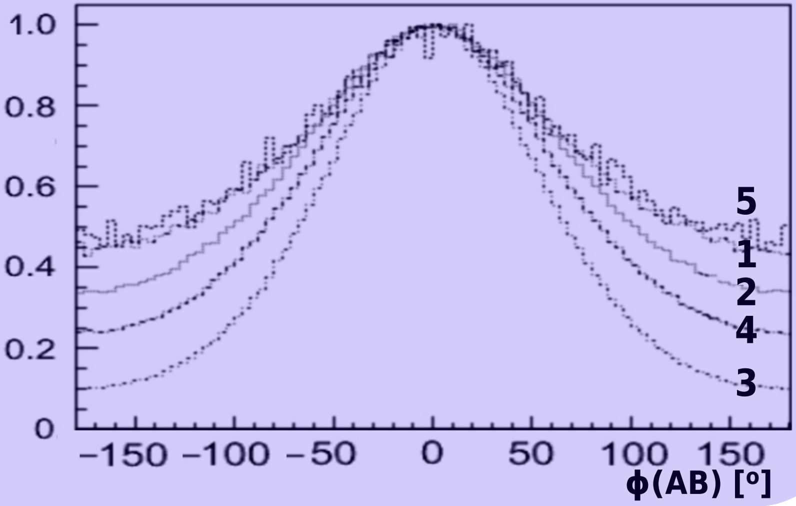
Simulation: dN/dM(TOF+RPC) SHIELD AuAu@1.25AGeV, hGeant, DST





Data: dN/dM(TOF+RPC) (DST-gen-0, M5 trigger)





Estimating RP-angular resolution of FW
(with A^B subevent method)

RMS(A^B)={1,2,3,4,5}={91.1^{O}, 80.9^{O}, 68.7^{O} ,86.4^{O},92.4^{O}}

RMS(RPA)={45.5^{O}, 40.5^{O}, **34.3^{O}**, 43.2^{O},46.2^{O}}

χ{1,2,3,4,5}={0.74 , 1.06 , 1.40 , 0.91 , 0.71}

<cos(φ-φ$_{RP}$)>{1,2,3,4,5}={0.577,0.735, 0.841, 0.669,0.559}

<cos2(φ-φ$_{RP}$)>{1,2,3,4,5}={0.230,0.399, 0.562, 0.320,0.215}