Flow harmonics of Au-Au collisions at 1.23 AGeV with HADES

Behruz Kardan

for the
HADES Collaboration

FAIRNESS 2016
Garmisch-Partenkirchen

H-QM Helmholtz Research School Quark Matter Studies

HIC for FAIR Helmholtz International Center

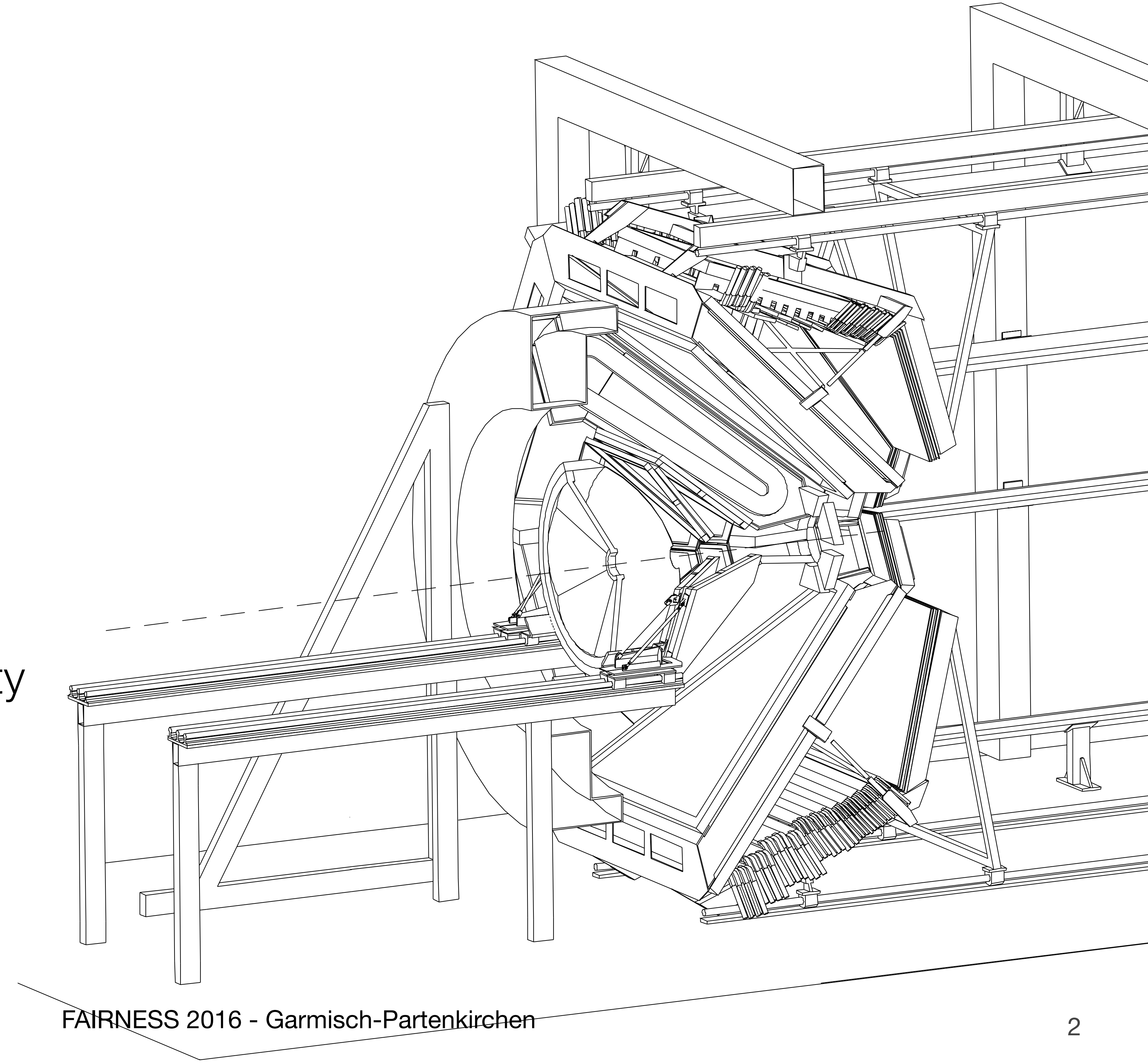
IKF Institut für Kernphysik Frankfurt

HADES

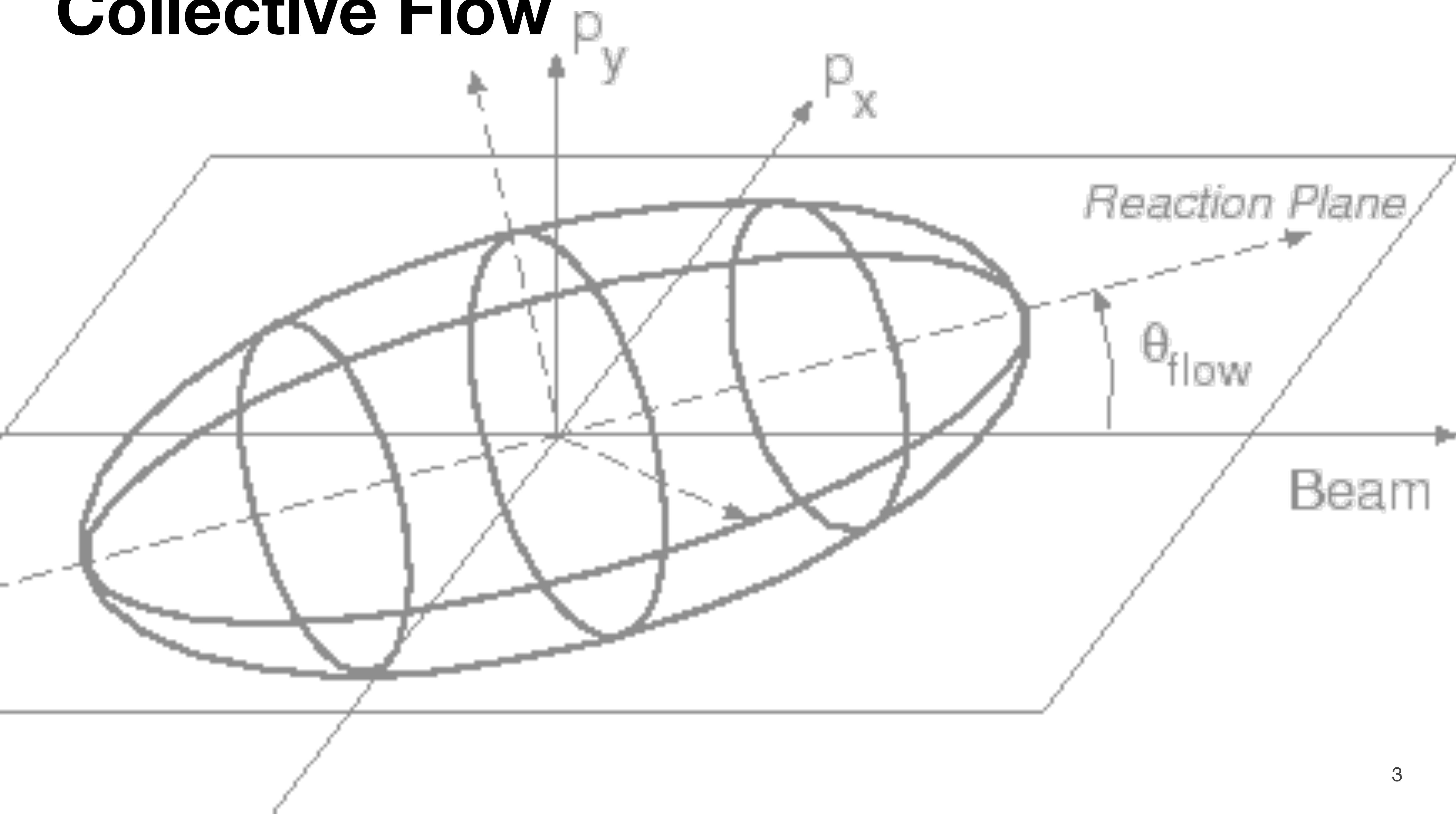
FAIRNESS

Outline

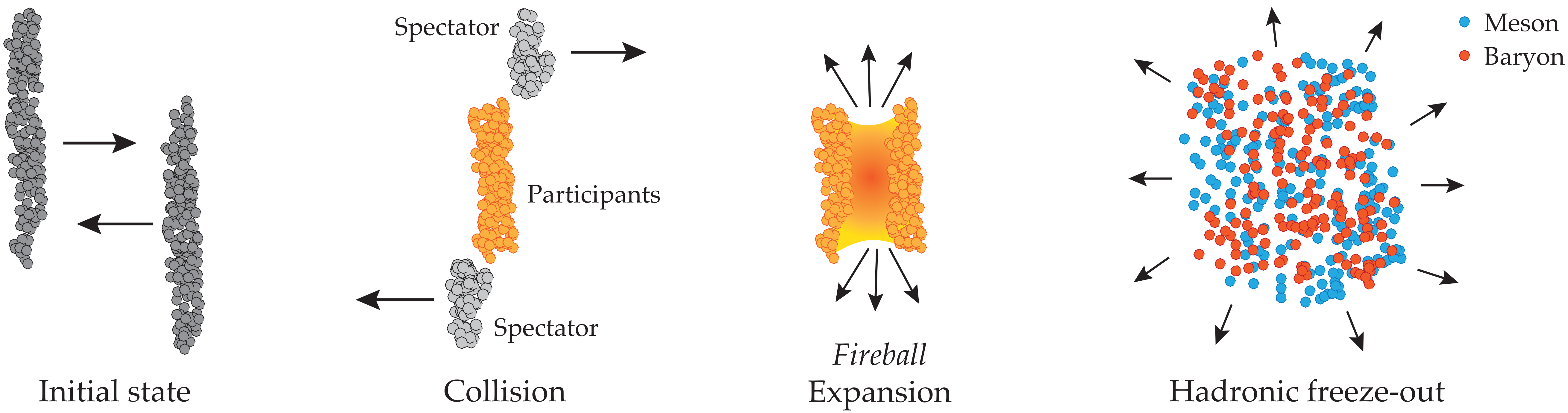
- Collective Flow
- Flow-Analysis Methods
- HADES and
  Au+Au 1.23AGeV Data
- Initial state calculations with
  Glauber Monte Carlo
  - Centrality and eccentricity



Collective Flow

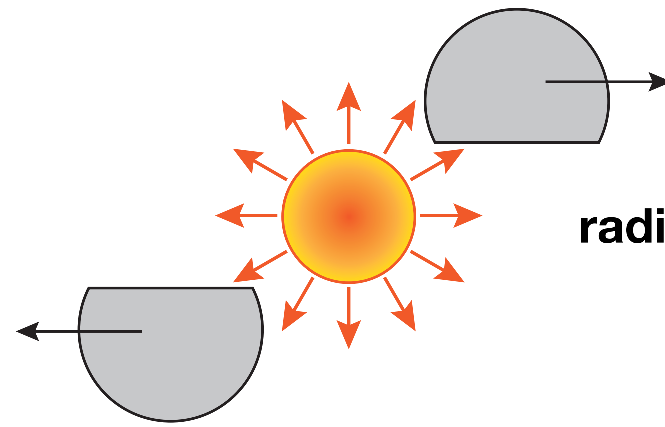


Heavy-Ion Reaction

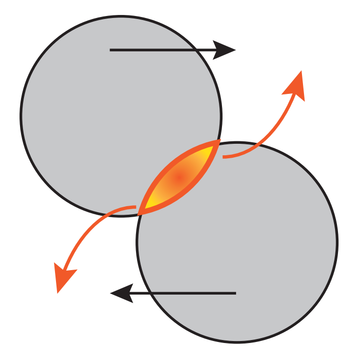


Collective Flow

- **Collective Properties of Nuclei**
  - Bulk properties of extreme nuclear matter
  - Equation of State
  - Effect of mean-field potentials

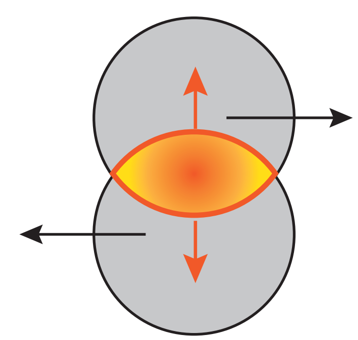


radial flow



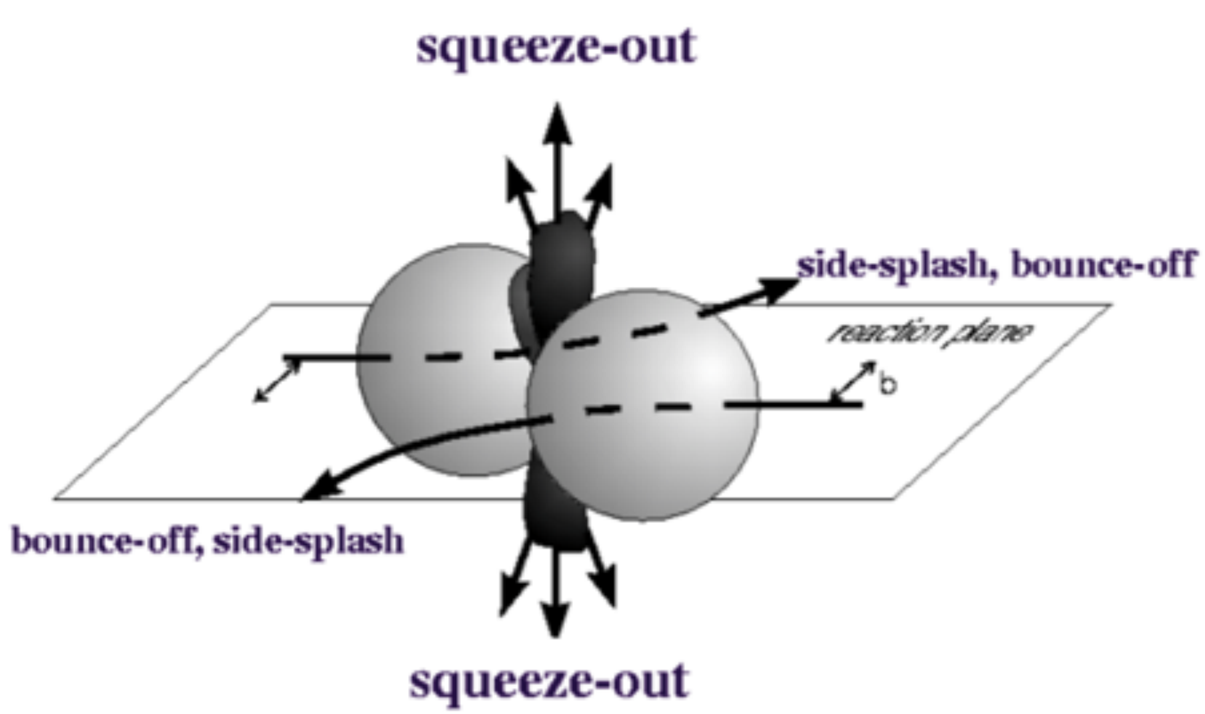
directed flow (v1)

$$v_1 = \langle cos(\phi - \Psi_{RP}) \rangle = \langle p_x / p_T \rangle$$



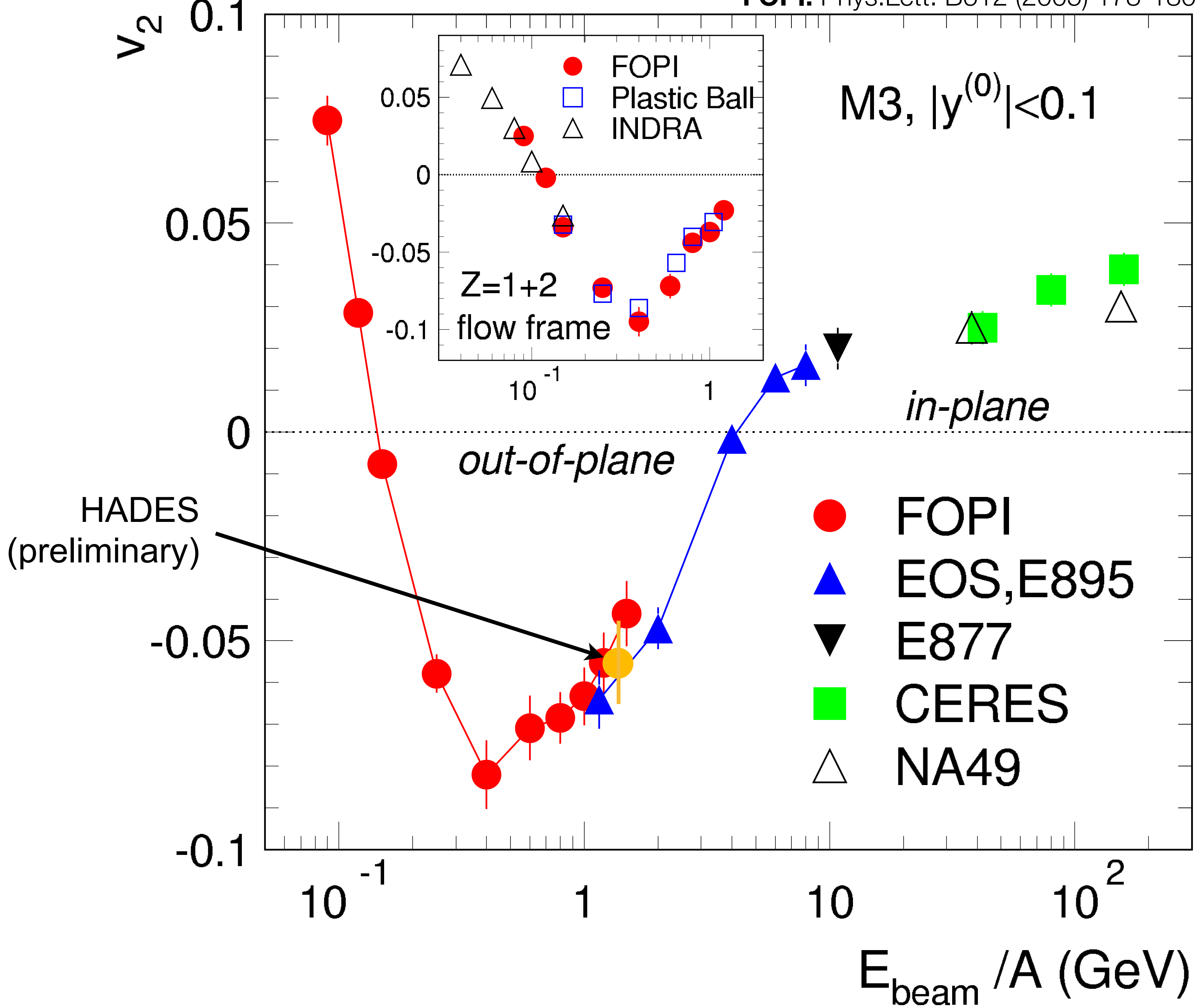
elliptic flow (v2)

$$v_2 = \langle cos2(\phi - \Psi_{RP}) \rangle = \langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \rangle$$

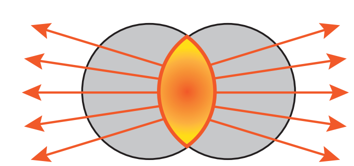


v2 - Elliptic Flow

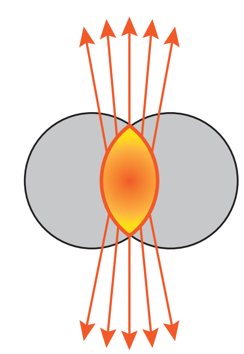
FOPI: Phys.Lett. B612 (2005) 173-180



mid-rapidity
centrality:~15%-29%



v2>0
short spectator passing time
$\tau_{passing} \ll \tau_{expansion}$
pressure gradient

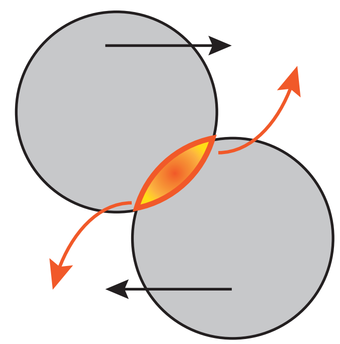


v2<0
long spectator passing time
$\tau_{passing} \geq \tau_{expansion}$
squeeze-out

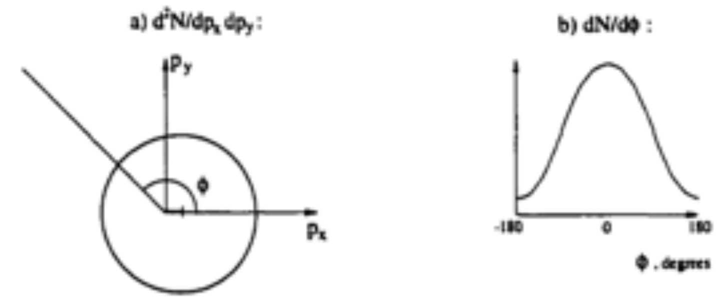
Higher Order Flow

momentum distribution over phi

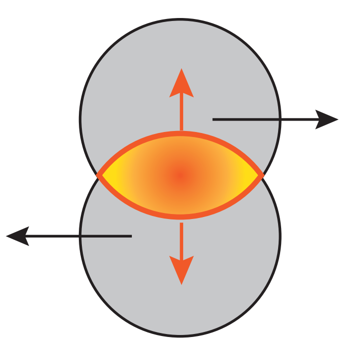
v1



+



v2



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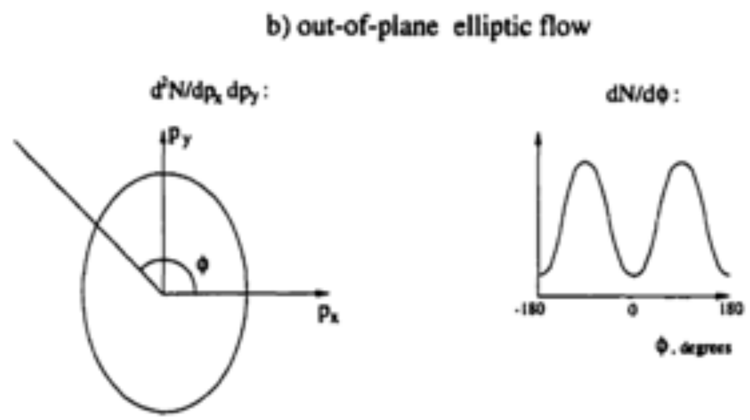
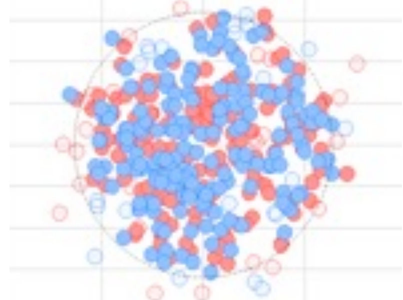


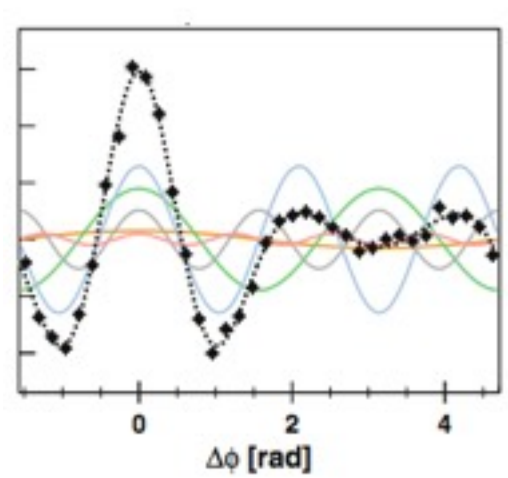
v3

v4

...

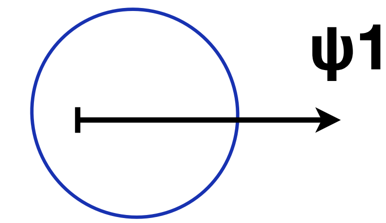
additional perturbations on top due to fluctuations





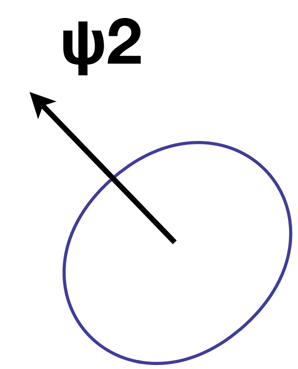
decomposition of harmonics

ε1



+

ε2



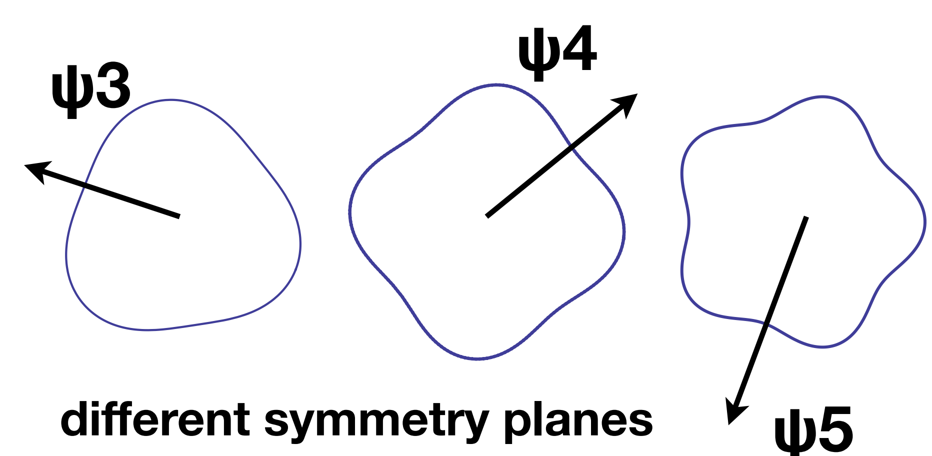
+

ε3

ε4

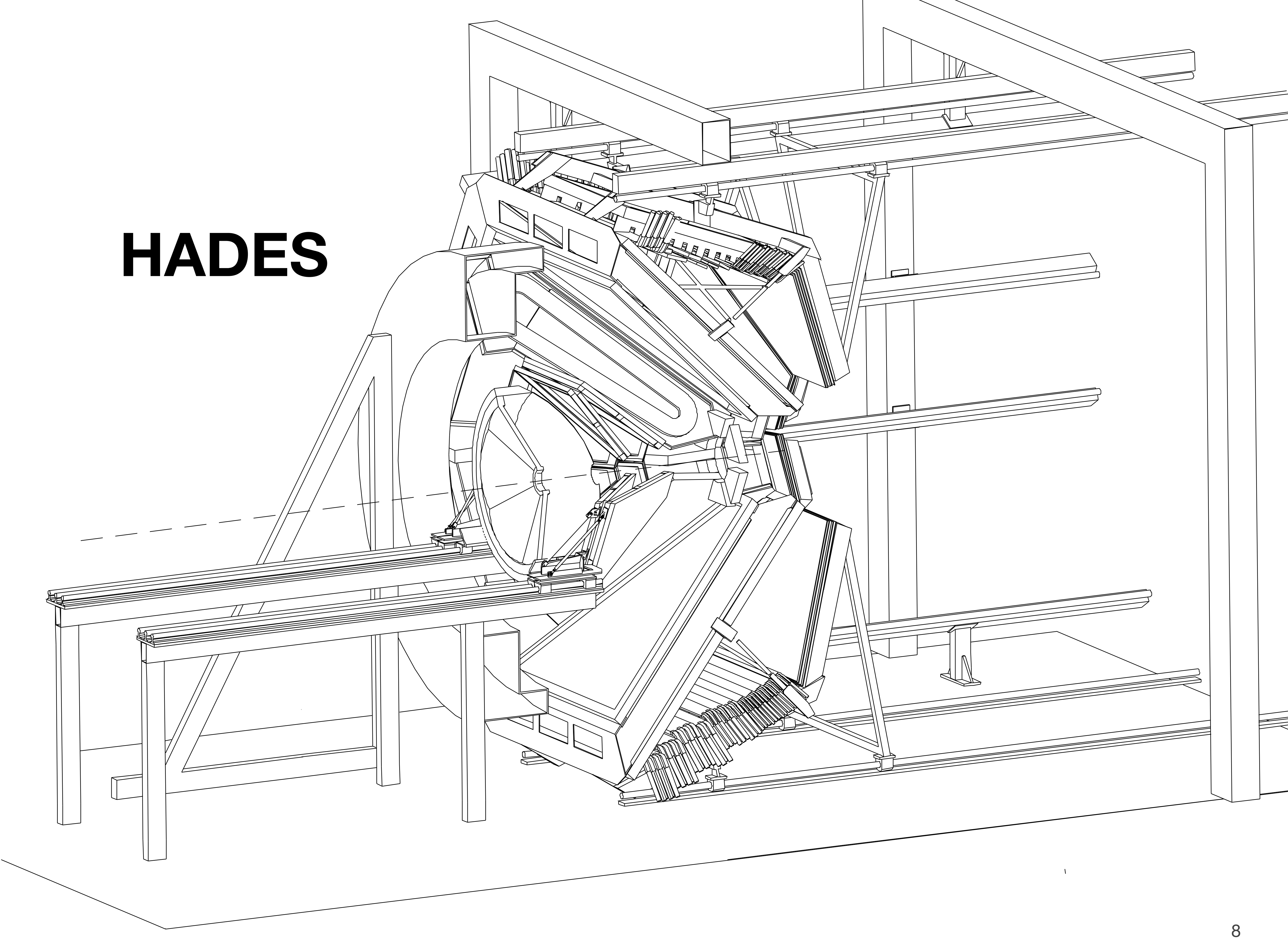
ε5

...

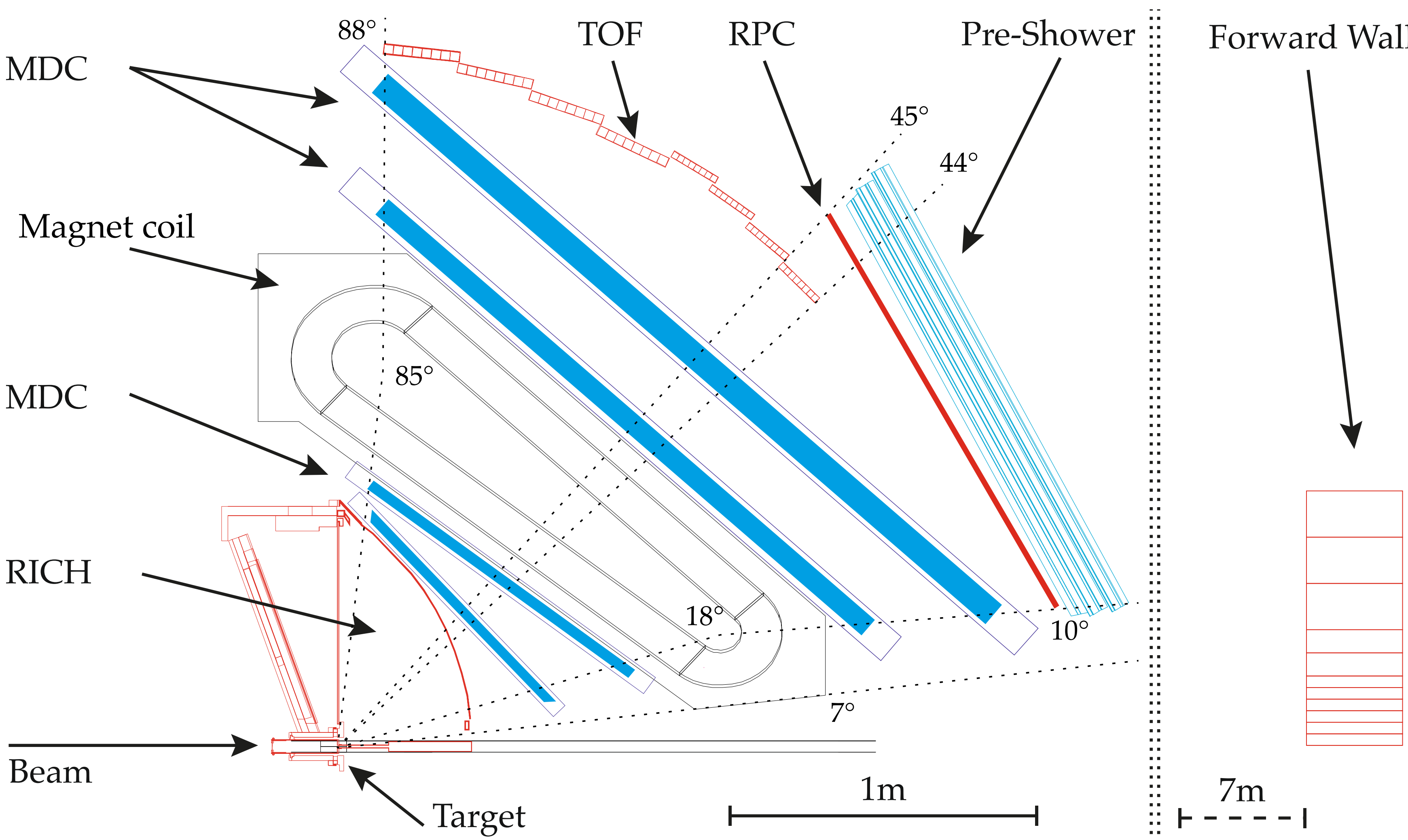


different symmetry planes for each harmonic

HADES



High Acceptance Di-Electron Spectrometer

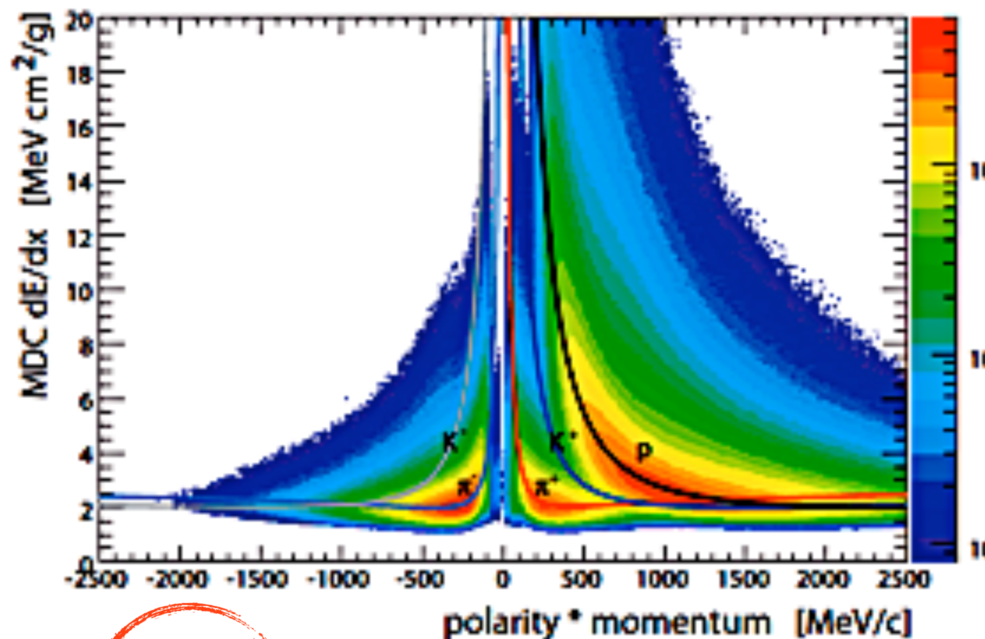


- Fixed-target experiment located at GSI, Darmstadt
- **Large acceptance**
  - symmetric azimuthal coverage
  - 18°-85° in polar angle
- **Tracking system and magnetic spectrometer**
  - 4 planes of low-mass mini-drift chambers (MDC)
  - superconducting toroidal magnet
- **Forward Wall**
  - reaction plane reconstruction

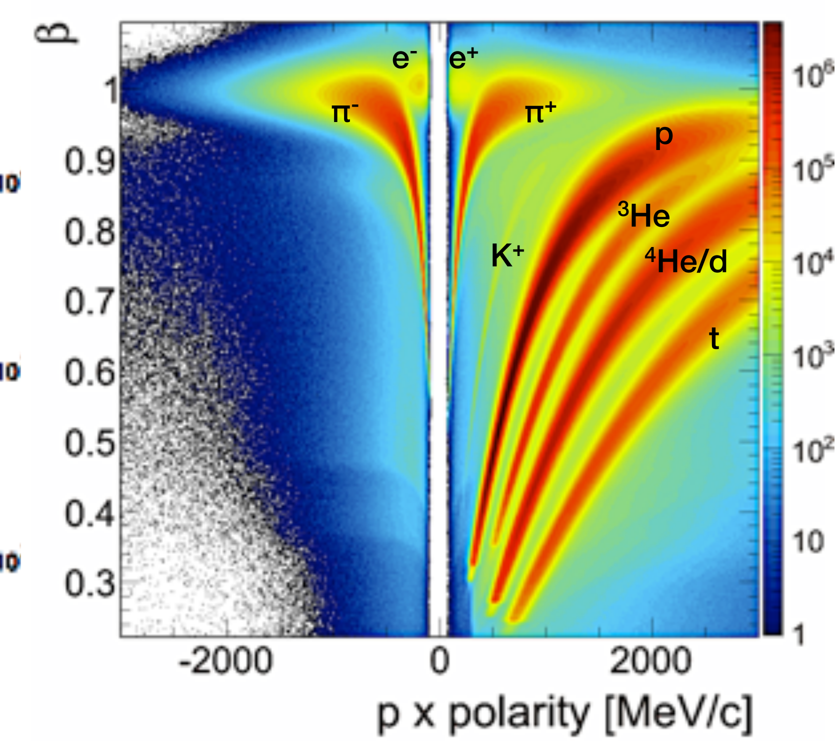
Au-Au at 1.23AGeV - April 2012

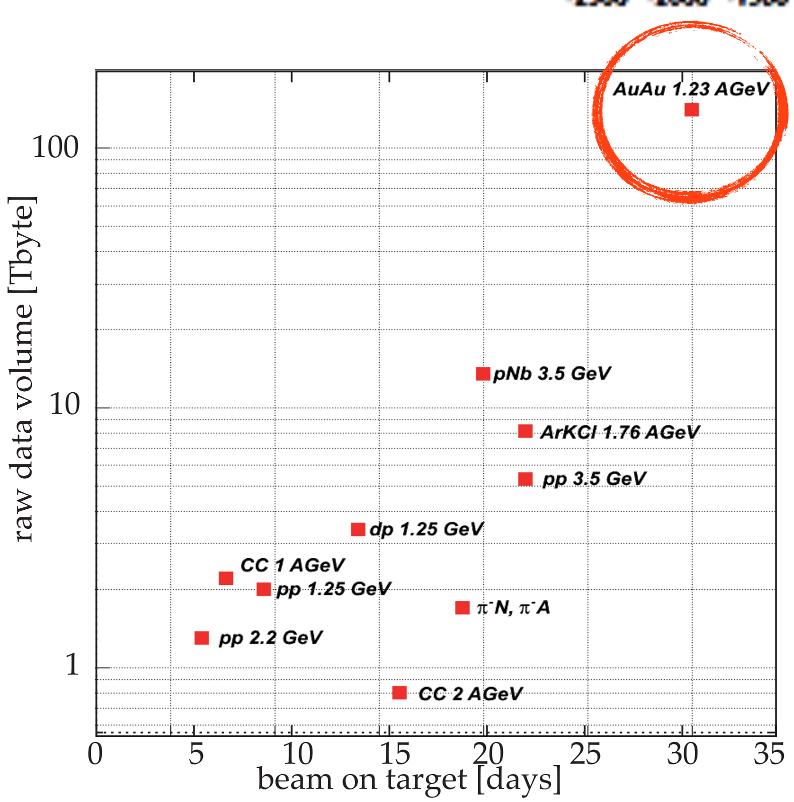
excellent particle identification via:

dE/dx in the MDC and ToF



Velocity vs. momentum



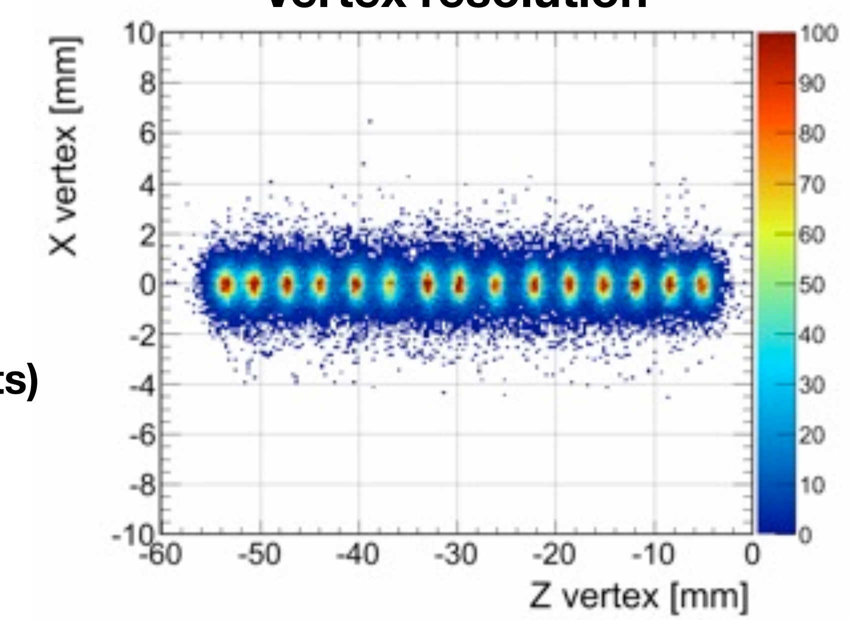


558.3 hours - 33 days
138 Tbyte of data

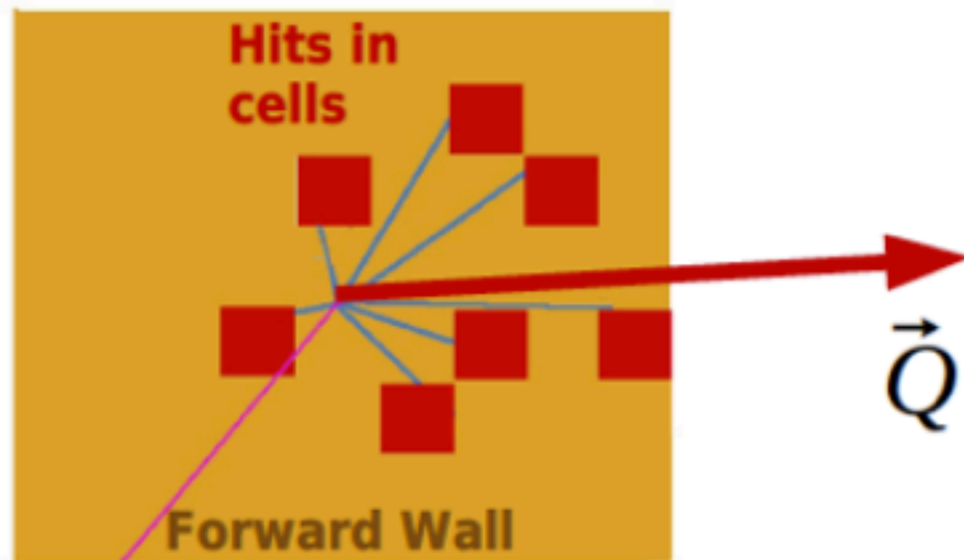
total event count: 7.31 × 10⁹
(incl. trigger and calibration events)

5.85 × 10⁹ most central(PT3)

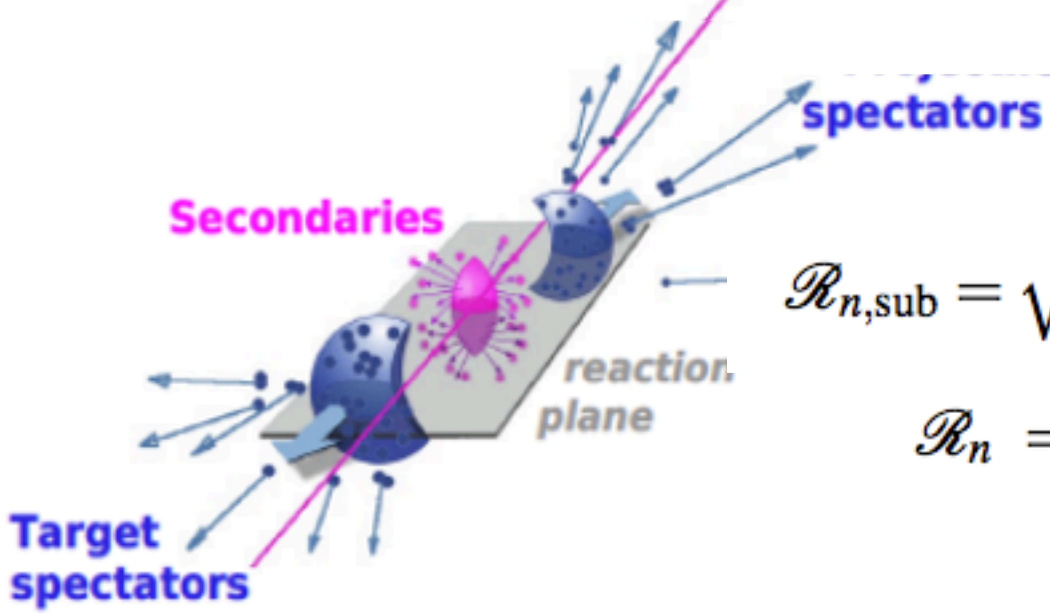
Vertex resolution



Event Plane Reconstruction



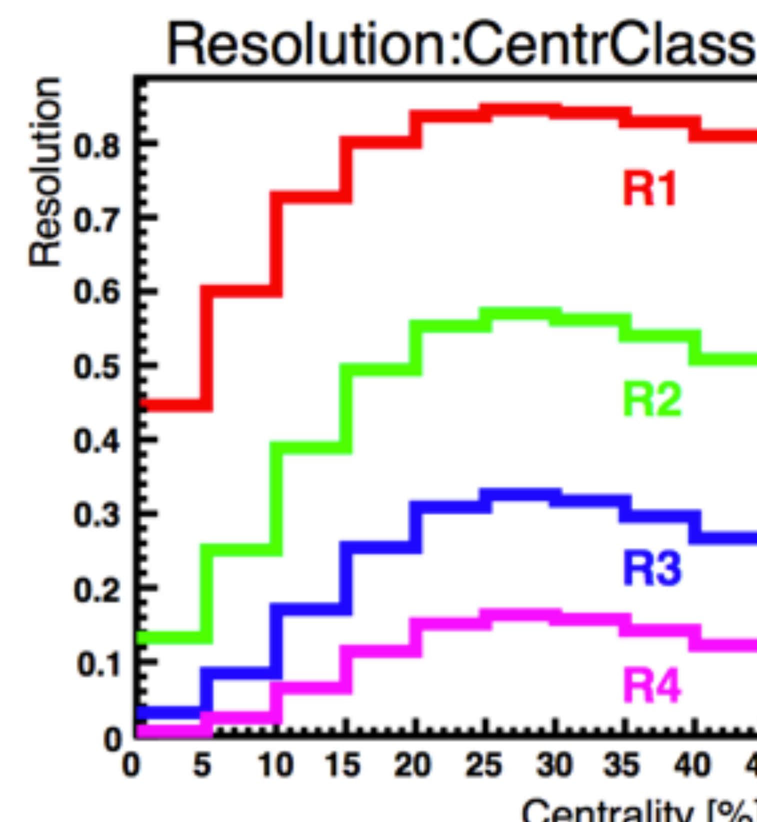
$$\vec{Q} = \sum_{i=1}^{Nsp} w_i \frac{\vec{r}_i}{|\vec{r}_i|}$$



$$\mathcal{R}_{n,\mathrm{sub}} = \sqrt{\langle \cos[n(\Psi_n^A - \Psi_n^B)]\rangle},$$

$$\mathcal{R}_n = \langle \cos[n(\Psi_n - \Psi_{\mathrm{RP}})]\rangle,$$

$$v_n = \frac{v_n^{\mathrm{obs}}}{\mathcal{R}_n}.$$

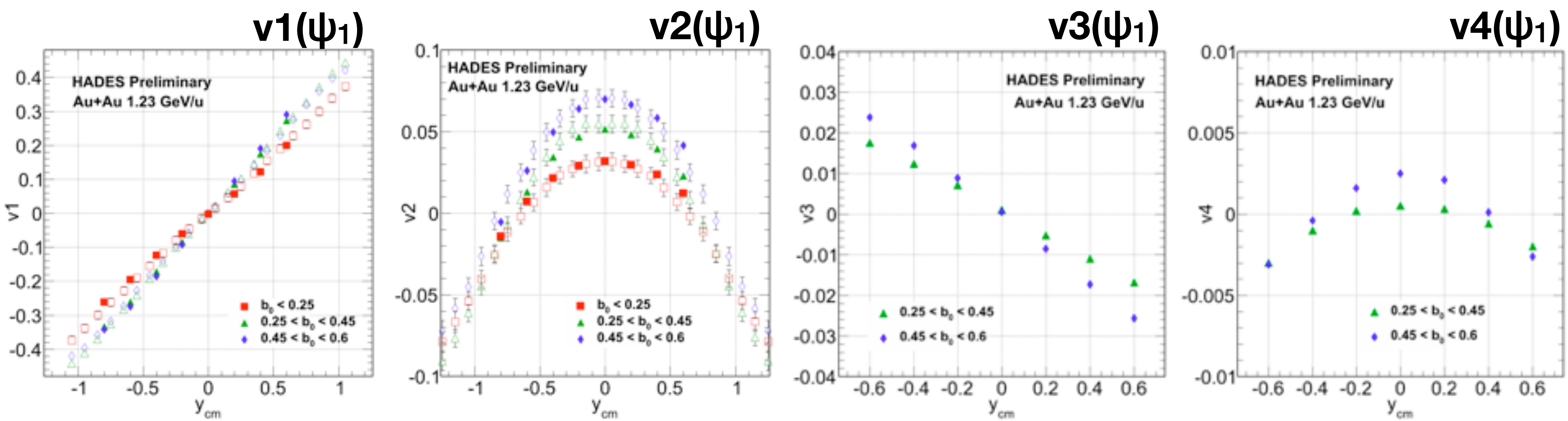


Analysis-note: A. Sadovsky

v1, v2 and Higher Order Flow in HADES

proton-flow

- most central 0-6.3%
- semi-central 6.3-21%
- peripheral 21-30.9%



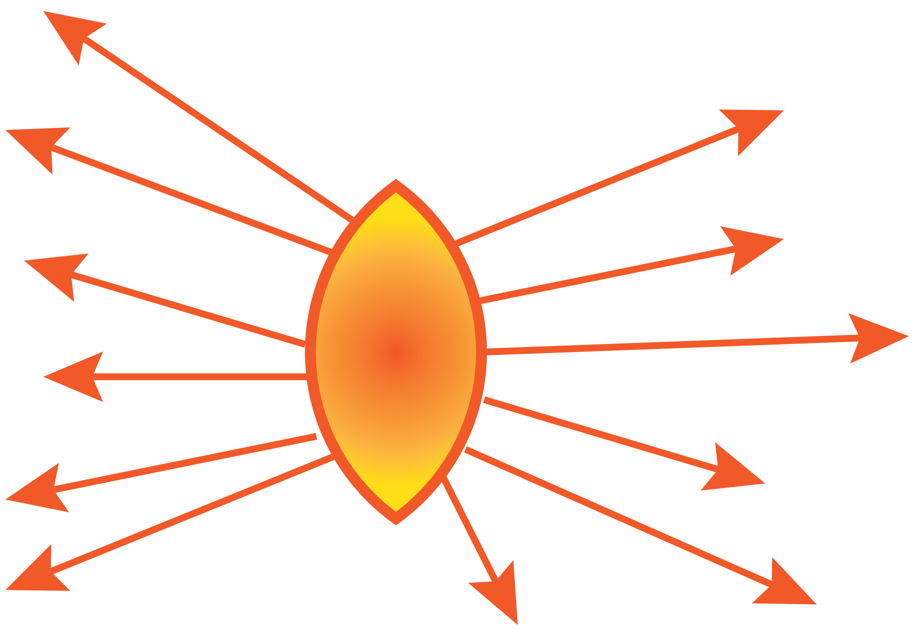
Open symbols: W. Reisdorf et. al. FOPI collab., Nucl. Phys. A 876 (2012)
v1 and v2 components are in agreement with FOPI data

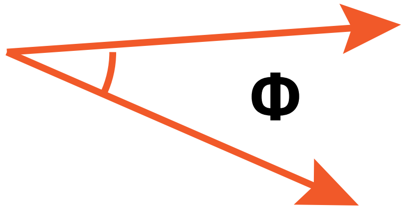
demonstrates that statistics sufficient for higher order

please note all flow components relative to spectator reaction plane (ψ_1)!

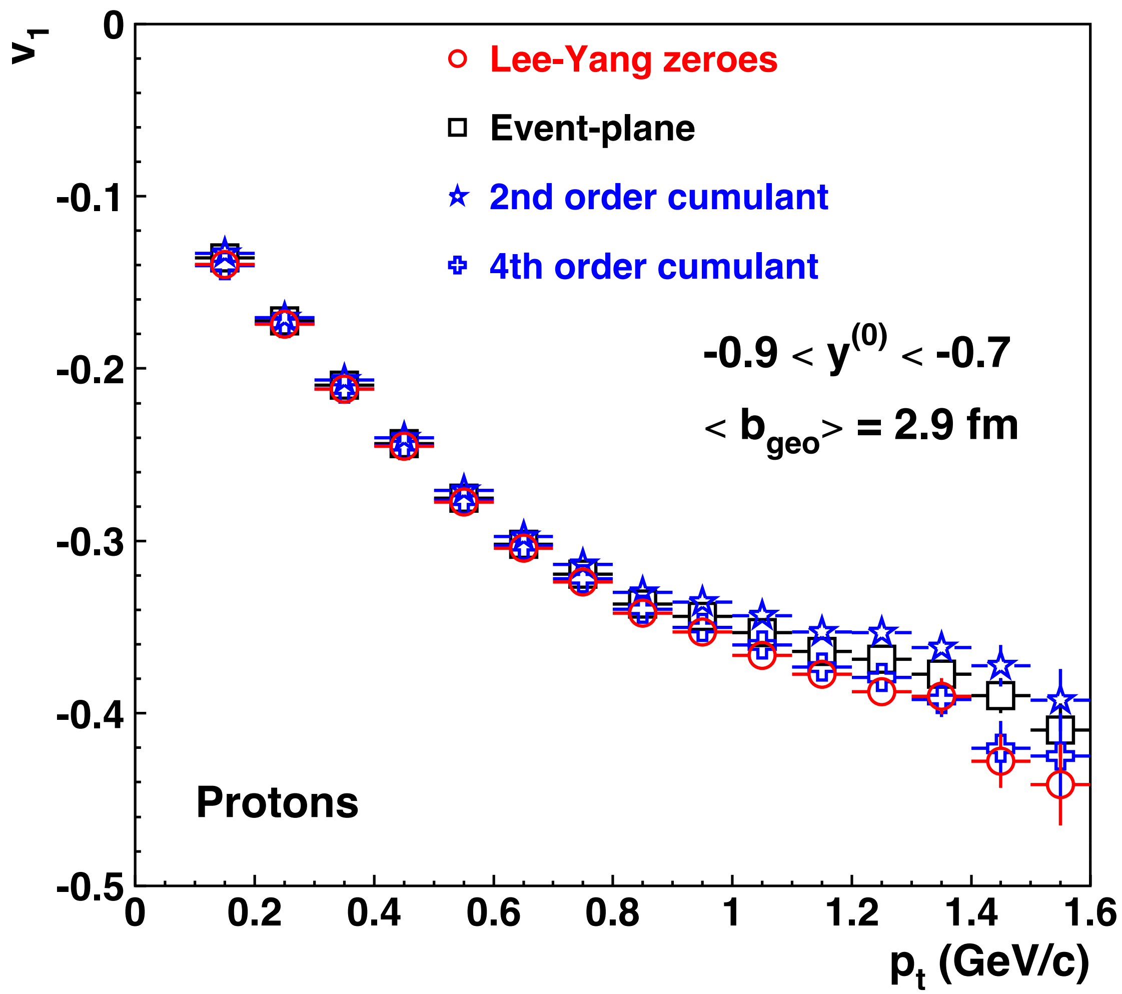
Multi-Particle Flow-Analysis Methods

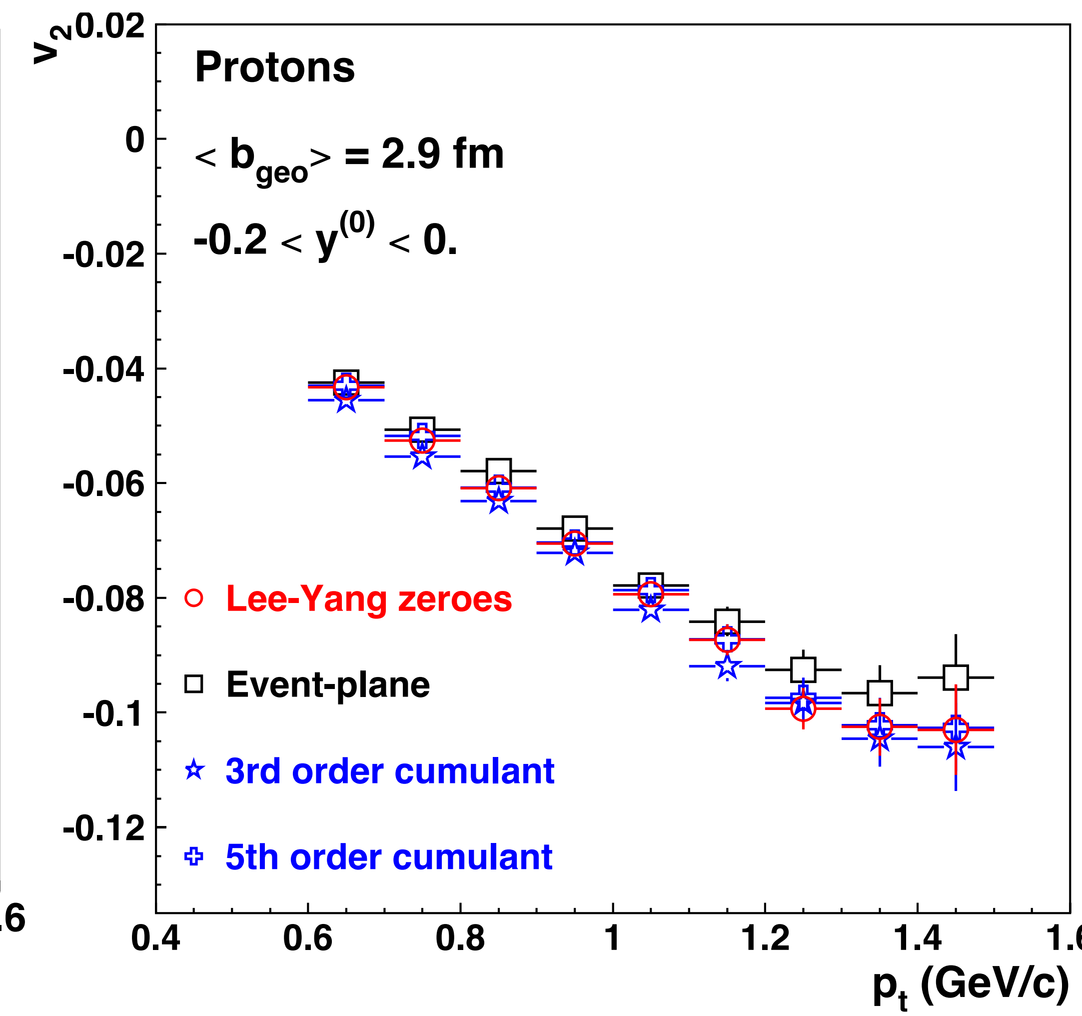
- **no eventplane determination needed**
- **Pair-wise correlation**
    - combinatorial background
      (estimation with mixed event/ like sign)
- Two- & Multi-Particle **Cumulant** $v_n\{2\}$, $v_n\{3\}$, $v_n\{4\}$
    - detect non-flow via differences $v_n\{2\} \neq v_n\{4\}$
- **Lee-Yang Zeroes** $v_n\{\infty\}$
    - all-particle correlation with generating function
- allow to separate **non-flow effects**:
    - momentum conservation, HBT, resonance
      decays, final state interactions, etc.





Flow Cumulant Measurements





FOPI
Ru+Ru 1.69A GeV
centrality: 2-12%
2.9 x 10^6 events

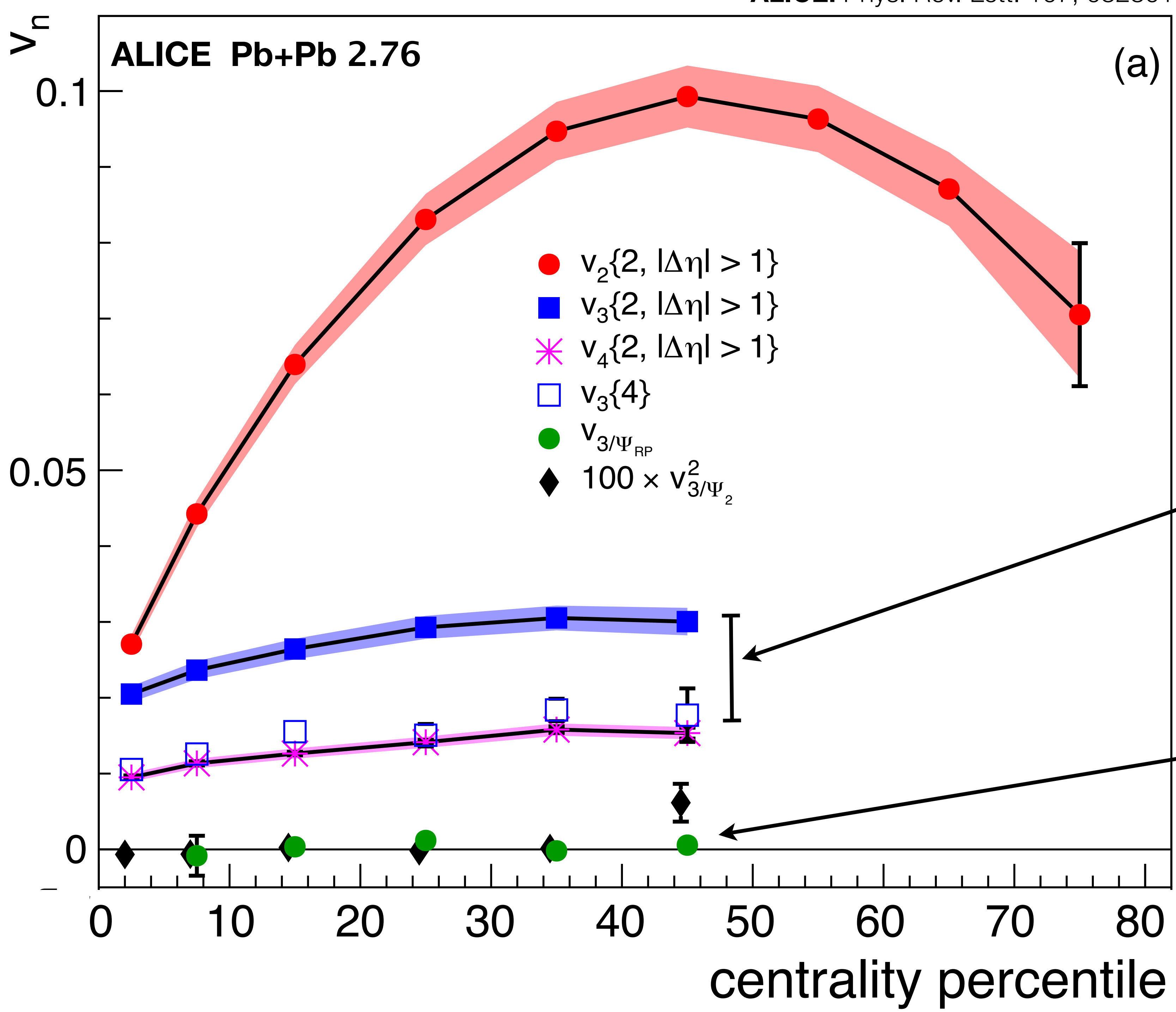
N. Bastid et al. (**FOPI**)
Phys. Rev. C 72, 011901(R)

- other methods differ to event-plane results
  - Lee-Yang Zero and 4-particle cumulant compatible
  - non-flow effects seen but small

HADES:
≳10^8 events each centrality class

Flow Cumulant Measurements: Higher Orders

ALICE: Phys. Rev. Lett. 107, 032301

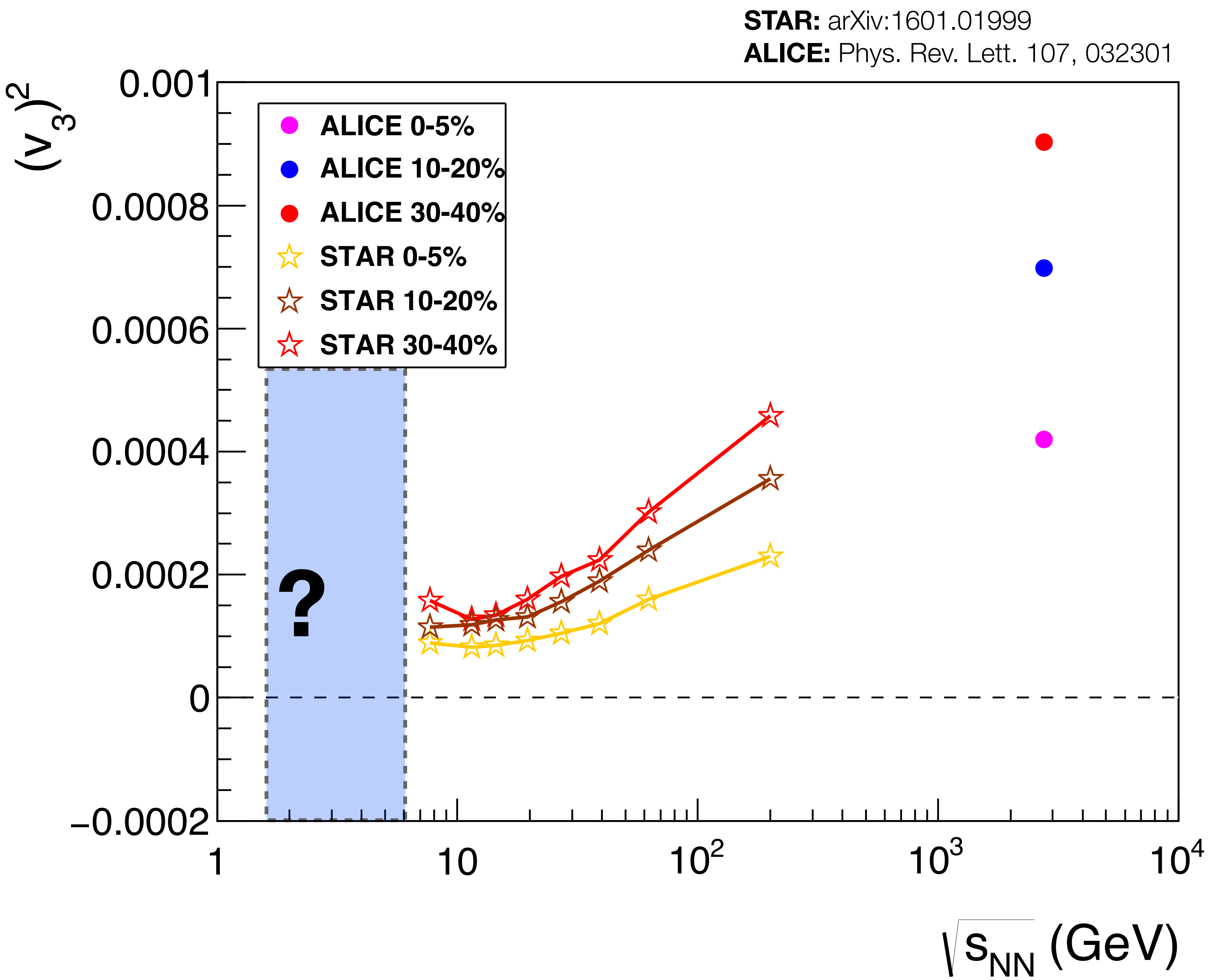


difference v3{2} & v3{4} due to non-flow

v_3 w.r.t Ψ_{RP}

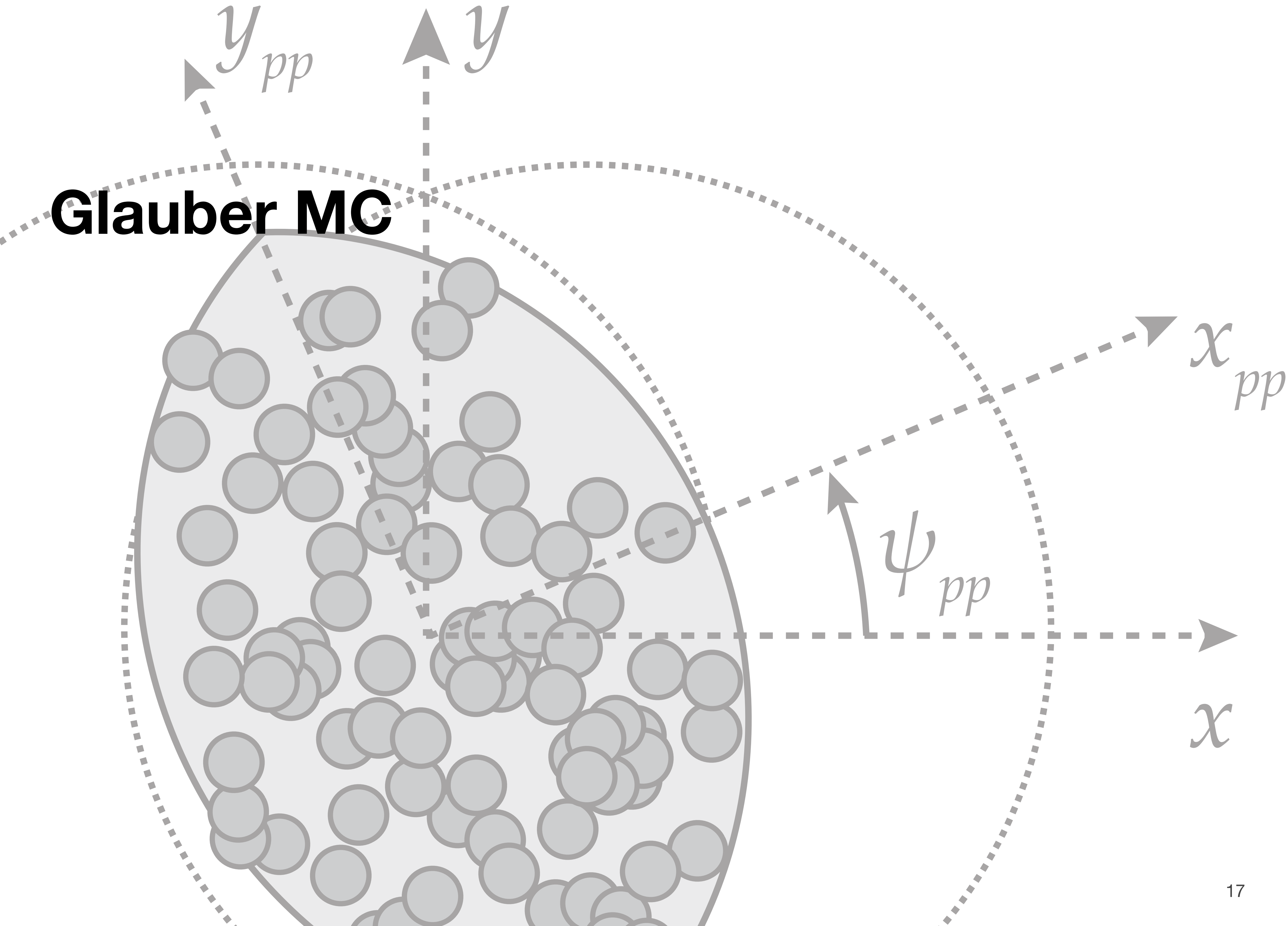
v_3^2 w.r.t Ψ_2 (x100)

Energy-dependence $v_3^2\{2\}$



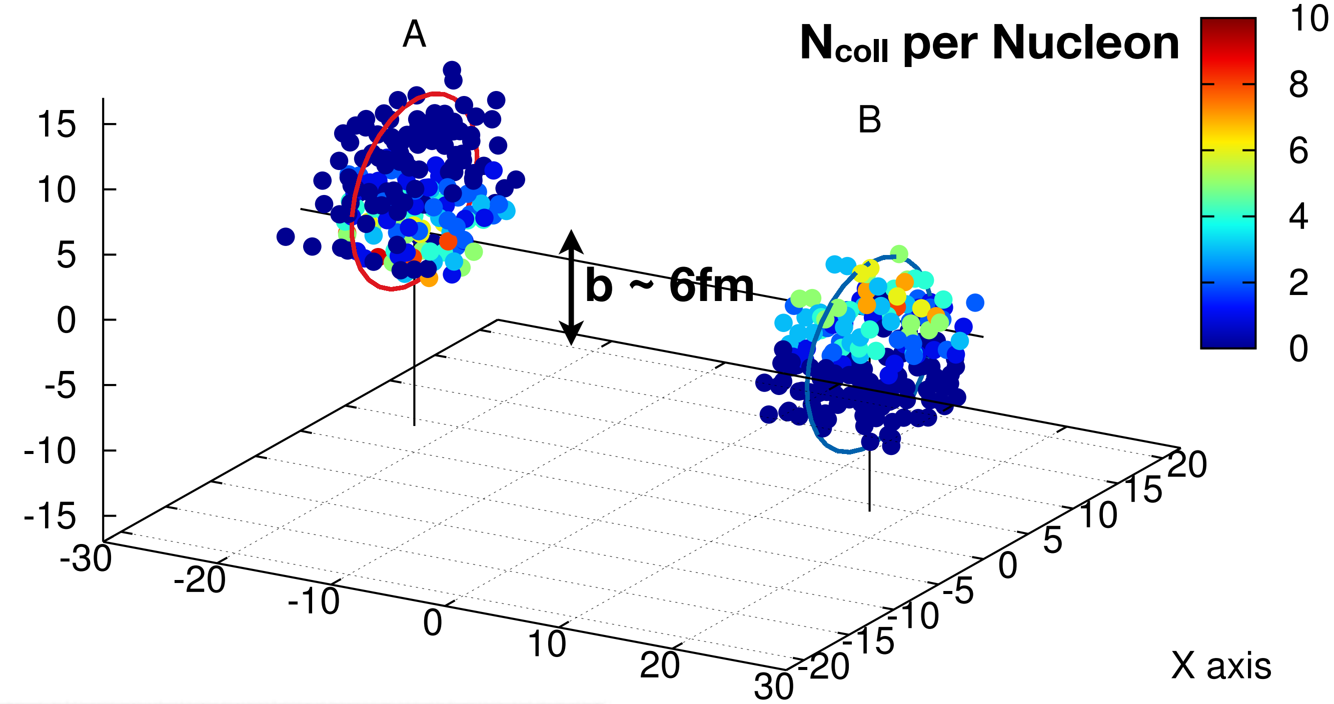
- v_3 w.r.t Ψ_3 symmetry plane
- origin: initial state fluctuation (at higher energies)
- other explanation for lower energies

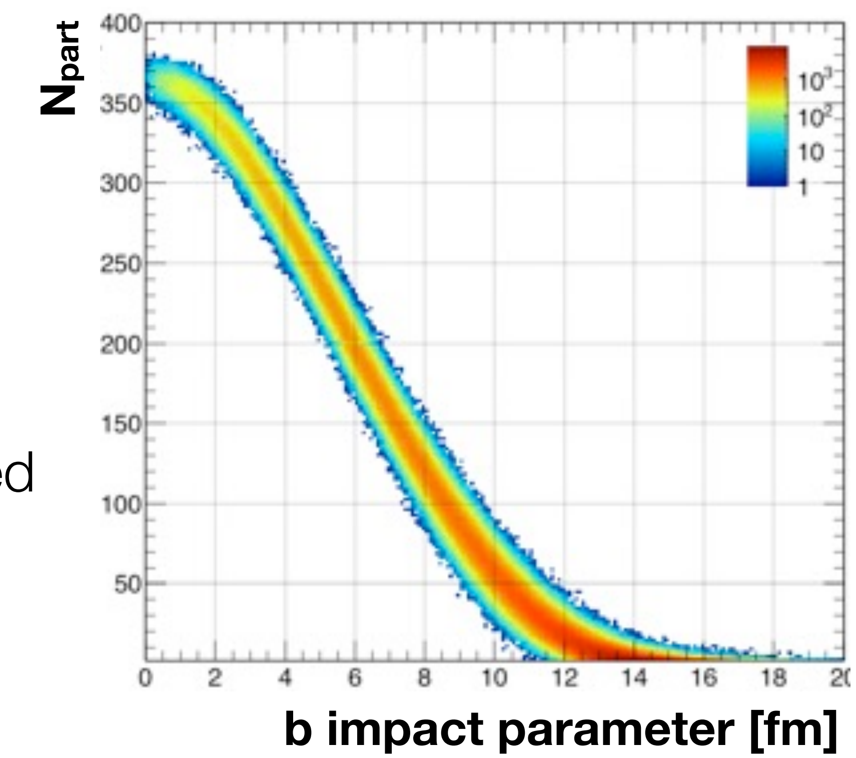
Glauber MC



Glauber Monte Carlo Calculations

- **Calculation** event-by-event
- **Generation of nuclei (energy independent)**
  individual nucleon distributed according
- **Collision Process (energy dependent)**
  - straight-line trajectories (eikonal approximation)
  - nucleons interact inelastic cross section σ_{NN}
  - nucleons are tagged as wounded or spectator
- **Geometric Quantities calculated**

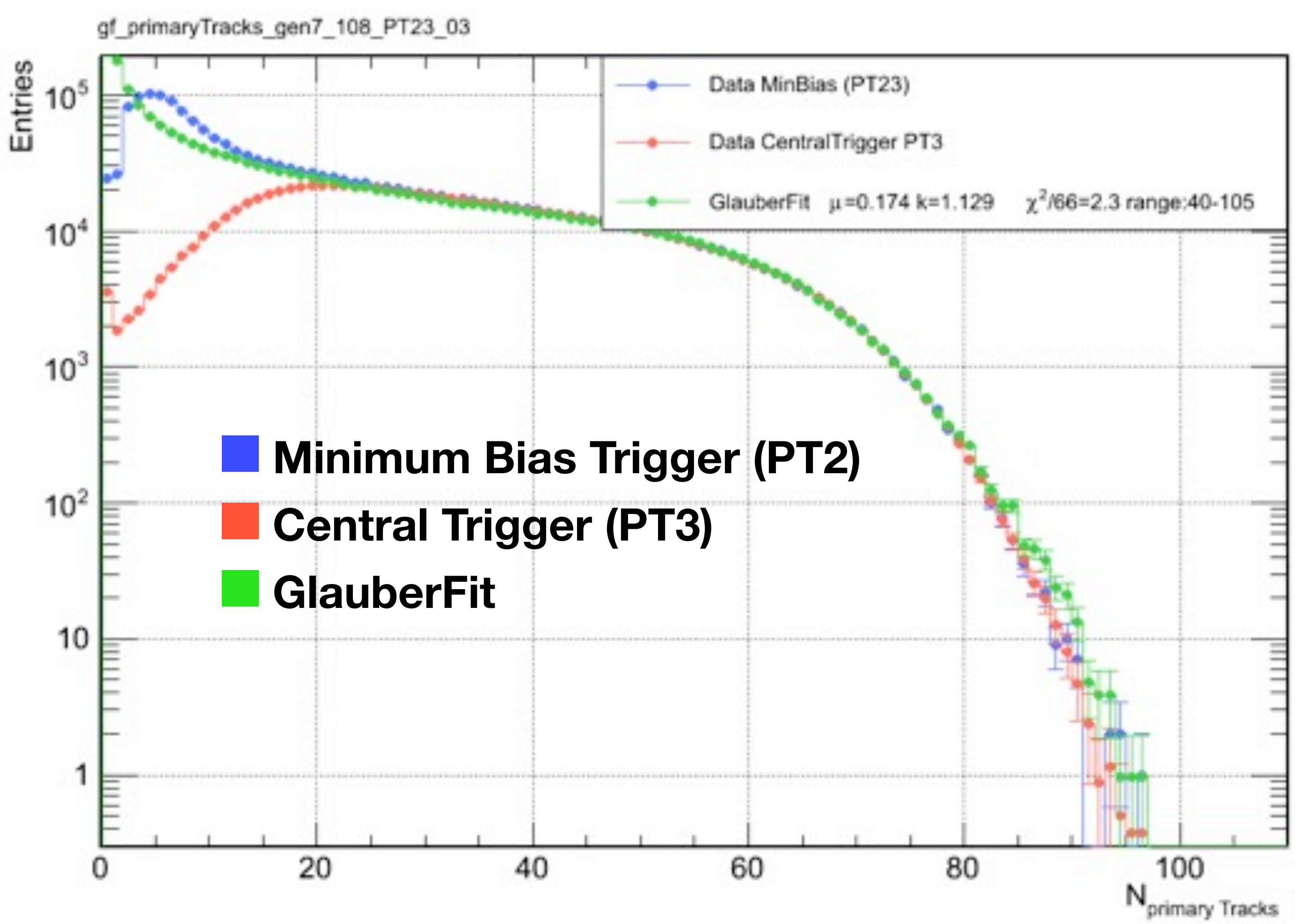


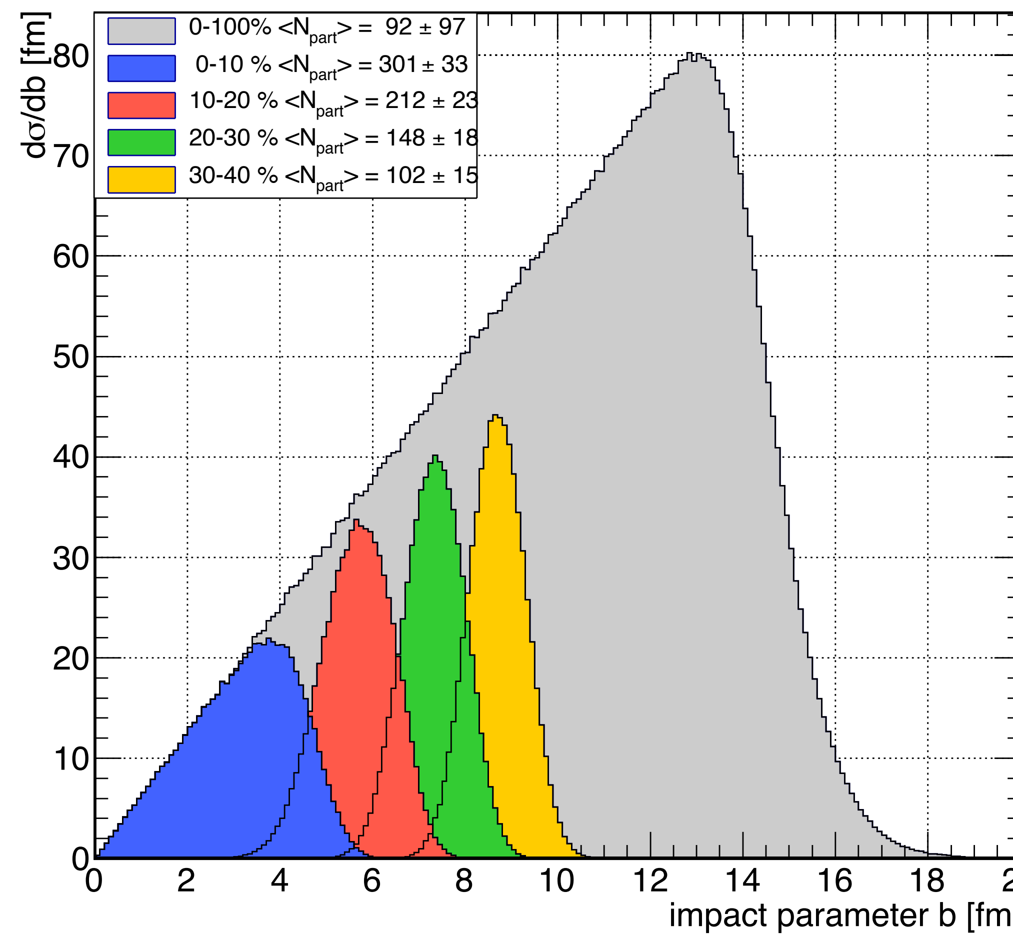


Glauber modeling in high energy nuclear collisions
Miller, Michael L. et al.
Ann.Rev.Nucl.Part.Sci. 57 (2007) 205-243
10.1146/annurev.nucl.57.090506.123020

PHOBOS Glauber Monte Carlo
https://tglaubermc.hepforge.org/

Centrality Determination





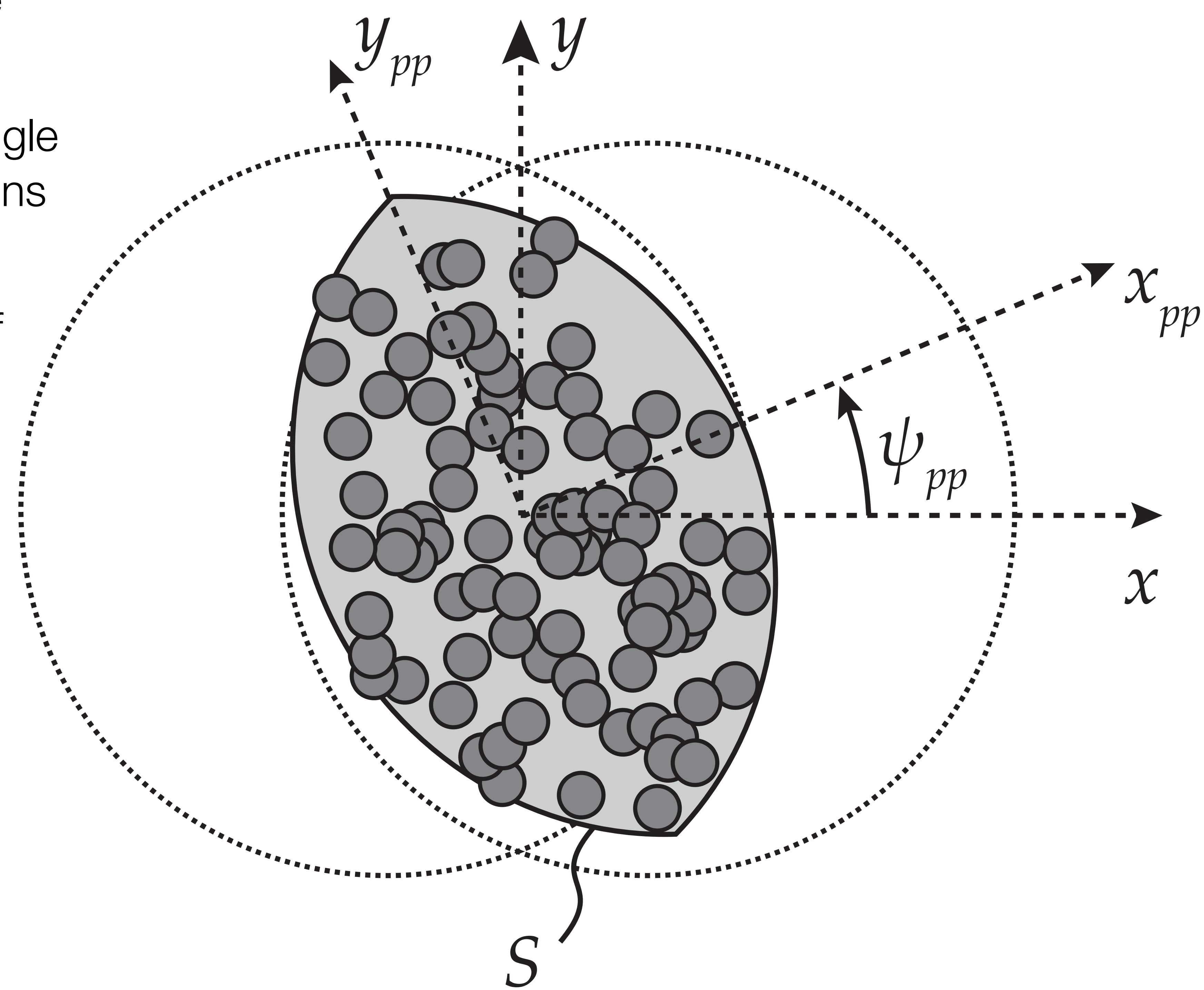
- measured observable modeled by GlauberMC

Total cross section:

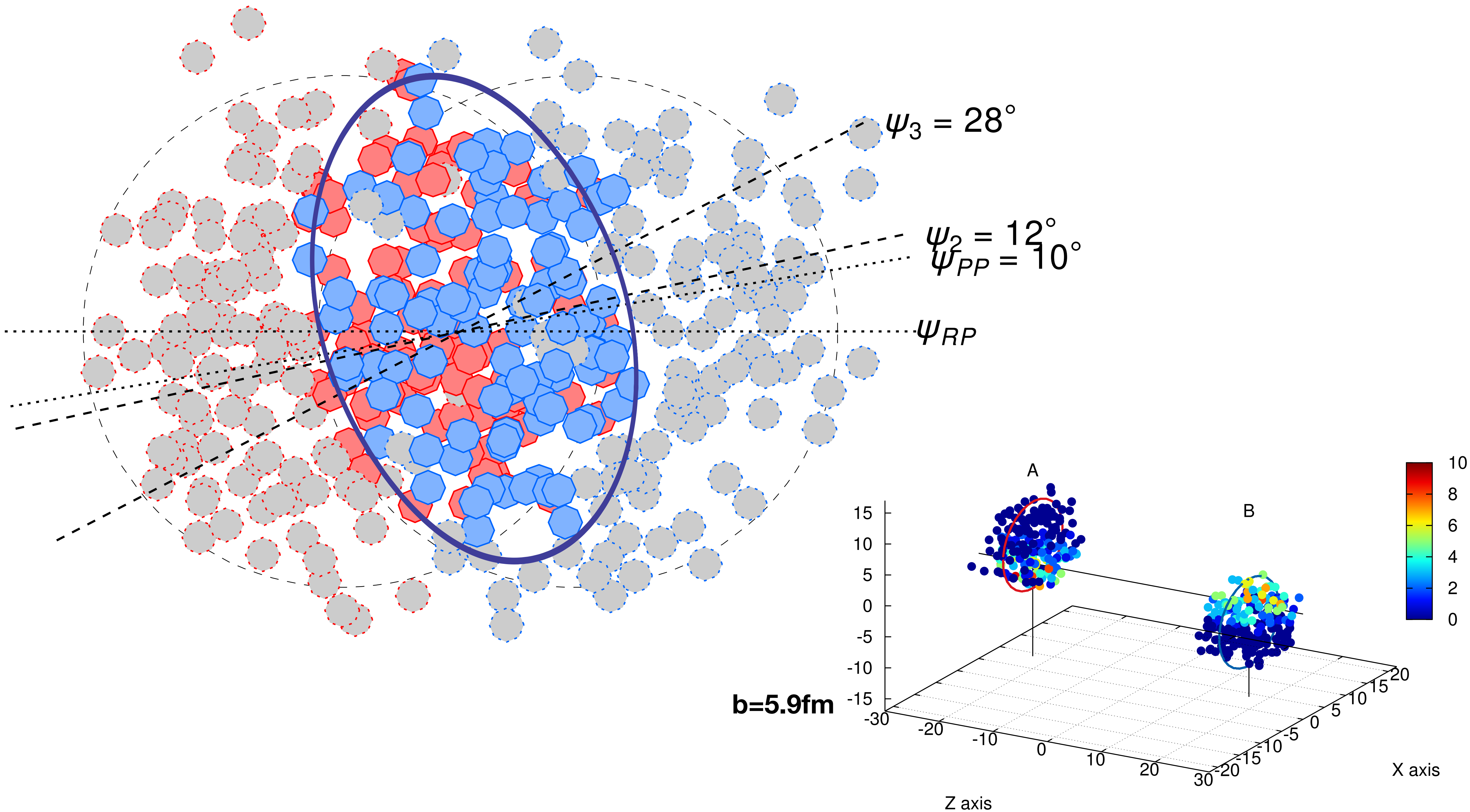
$$\sigma_{tot}^{AuAu} = (6833 \pm 430)\ \mathrm{mb}$$

Fluctuations of the Participant Plane

- **ψ_{rp}** - reaction-plane angle
- **ψ_{pp}** - participant-plane angle tilted to **ψ_{rp}** due fluctuations
- **ψ_n** - n^{th}-order harmonic of participant plane angle

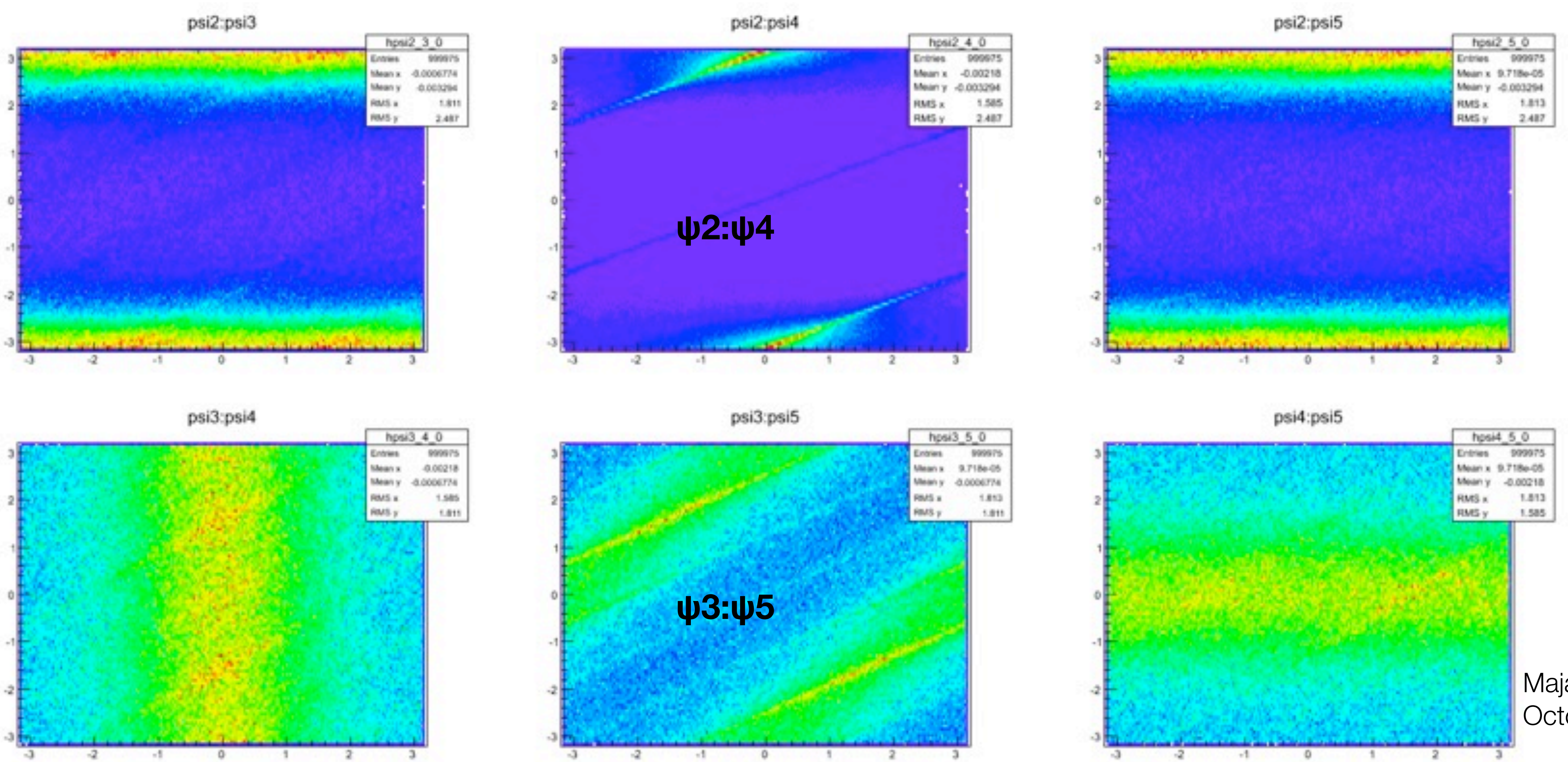


Higher Order Participant Plane Angles



Correlations Participant Plane Angles

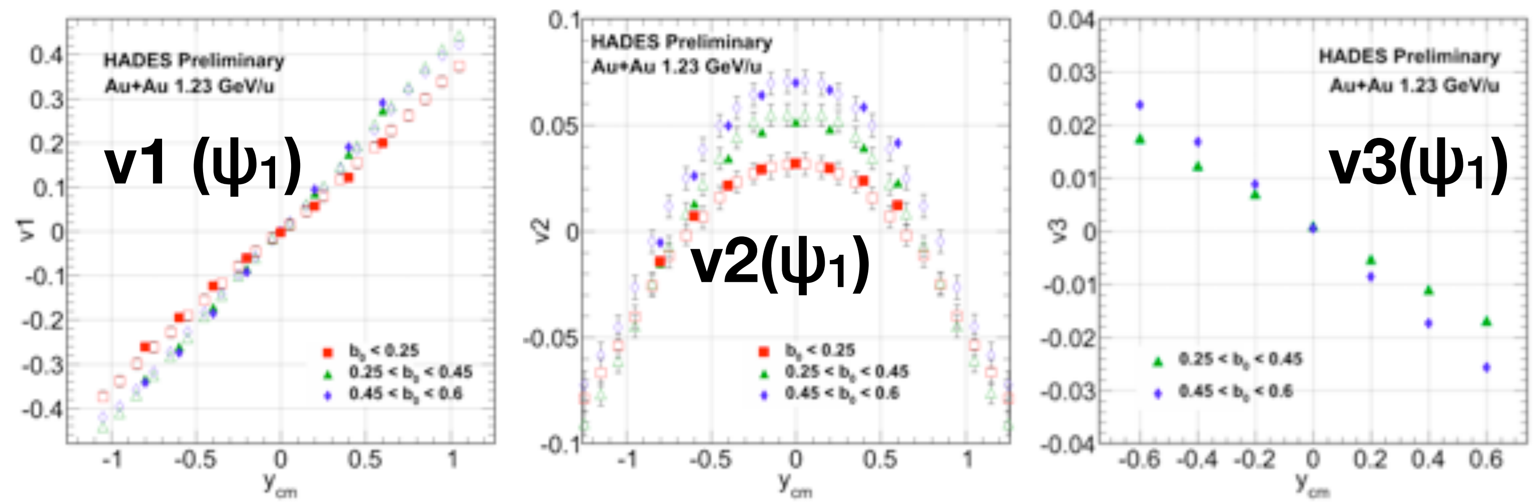
- “**cross-talk**” between harmonics of participant plane angles
- **correlation** between even ψ2:ψ4 and odd ψ3:ψ5

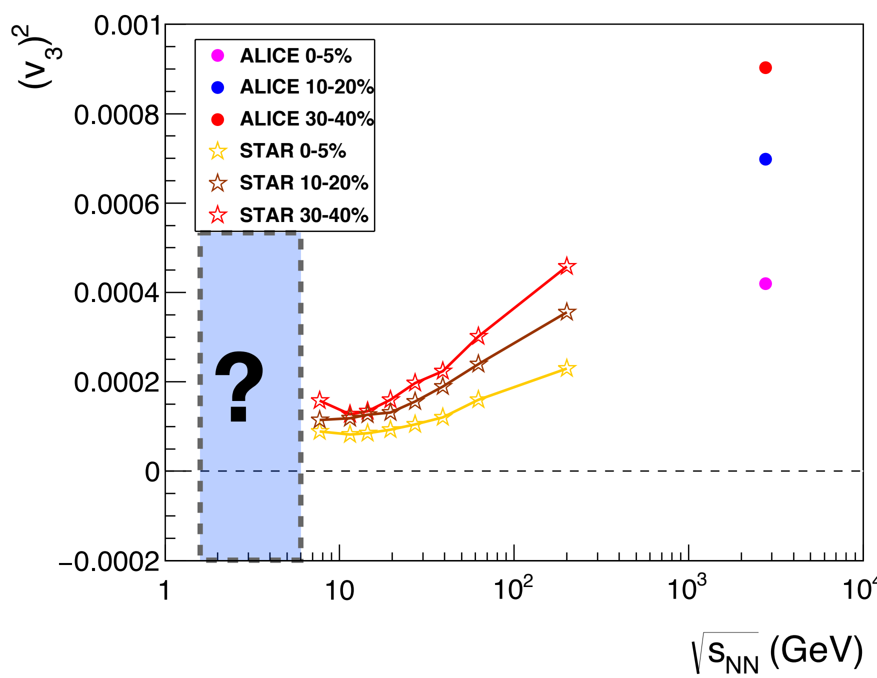


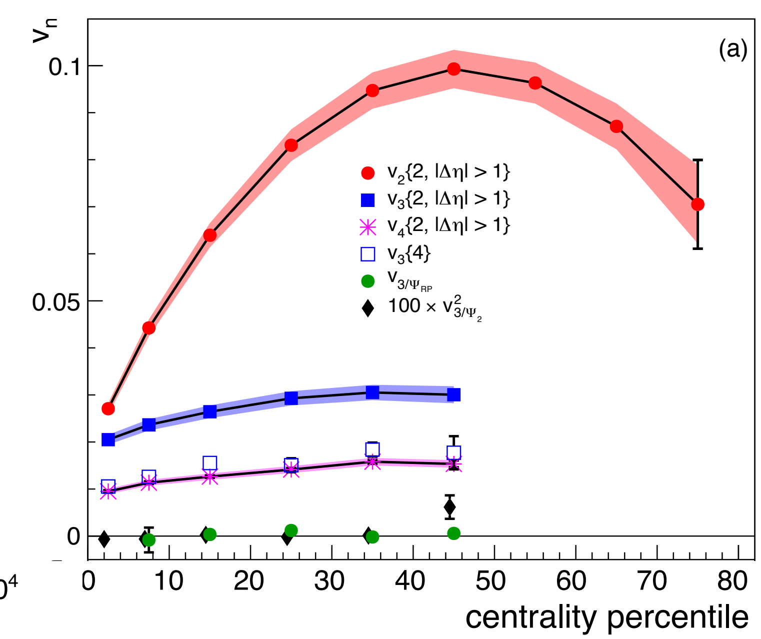
Maja Subotic
Octobre 2014

Conclusion

- Flow Measurements of v1 and v2 with HADES
  - good agreement with existing data
- Non-Flow Effects
  - small but relevant
  - measurements requeres other methods beyond EP method
- Higher Order Harmonics
  - systematic study of v3 at 1.23 AGeV ongoing
  - provide new insights in to the properties of extrem matter
- Initial state calculations with Glauber Monte Carlo





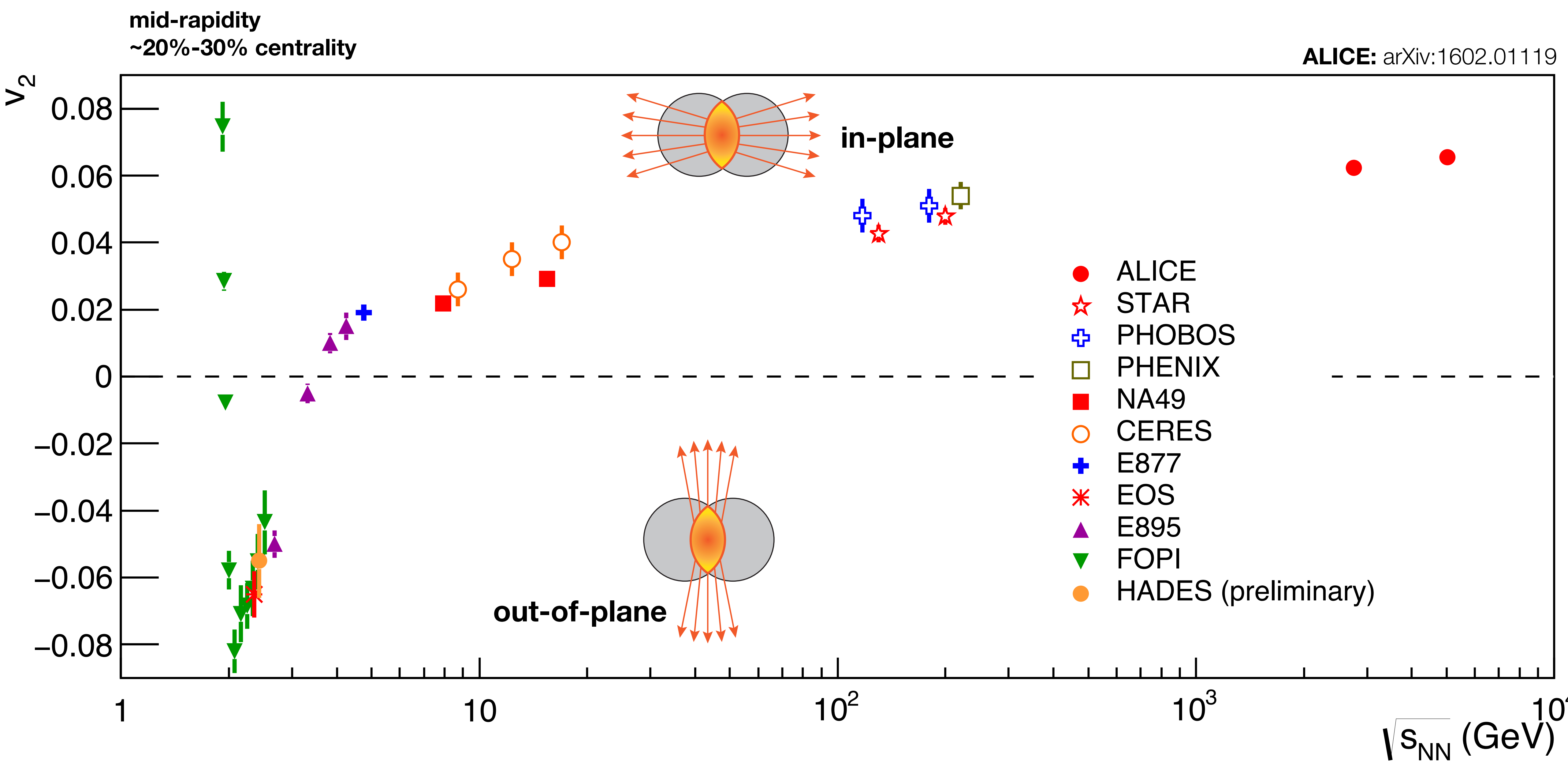


HADES Collaboration

Thank you for your attention!

Backup

v2 - Elliptic Flow



Flow-Analysis Methods

- "standard" **EventPlane** $v_n\{EP\}$
  - oriented to **symmetry plane**(Ψ_1 or Ψ_2) of spectator or reference particle
  - correction for **eventplane resolution** needed

$$\frac{dN}{d(\phi - \Phi_R)} \propto (1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Phi_R))),$$

$$v_n\{EP\} \equiv \frac{\langle \cos n(\varphi - \Psi_R) \rangle}{\langle \cos n\Delta\varphi_R \rangle},$$

- **Scalar Product** $v_n\{SP\}$
  - uses the magnitude of the flow vector as weight
  - correction for eventplane resolution included
- **Pair-wise correlation**
  - combinatorial background (estimation with mixed event/ like sign)

$$\frac{dN^{pairs}}{d\Delta\phi} \propto (1 + \sum_{n=1}^{\infty} 2v_n^2 \cos(n\Delta\phi)) \qquad C(\Delta\phi) = \frac{N_{cor}(\Delta\phi)}{N_{uncor}(\Delta\phi)}$$

- Two- & Multi-Particle **Cumulant** $v_n\{2\}$, $v_n\{3\}$, $v_n\{4\}$
  - no additional eventplane determination needed

$$v_n\{2\}^2 = \langle \cos[n(\phi_1 - \phi_2)] \rangle$$

- **Lee-Yang Zeroes** $v_n\{\infty\}$
  - all-particle correlation with generating function

$$G^\theta(ir) = \left\langle \exp\left(ir \sum_\nu \omega_\nu \cos(\varphi_\nu - \theta) \right) \right\rangle_{\text{events}}$$