RESULTS ON FLUCTUATIONS AND CORRELATIONS IN NA61/SHINE

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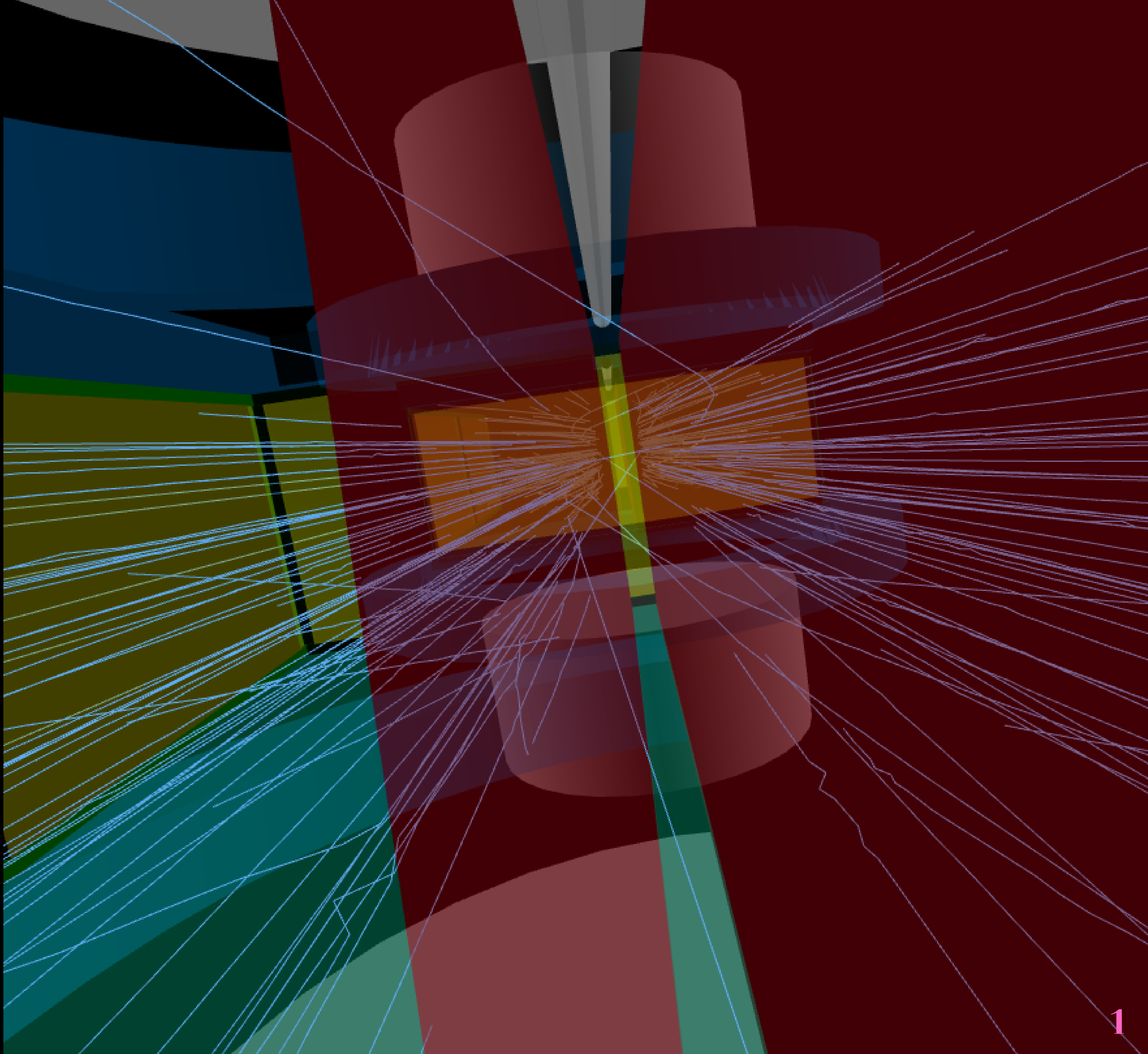
Warsaw University of Technology

2-6 December 2019, Zimanyi School, Budapest



Once upon a time there was nothing.
Once upon a time there was even no time.
Suddenly…

The matter was created.
The light has been turned on.
We've come a long way since then.

The matter was created.
The light has been turned on.
We've come a long way since then.

But what do we know about the Beginning of Everything?

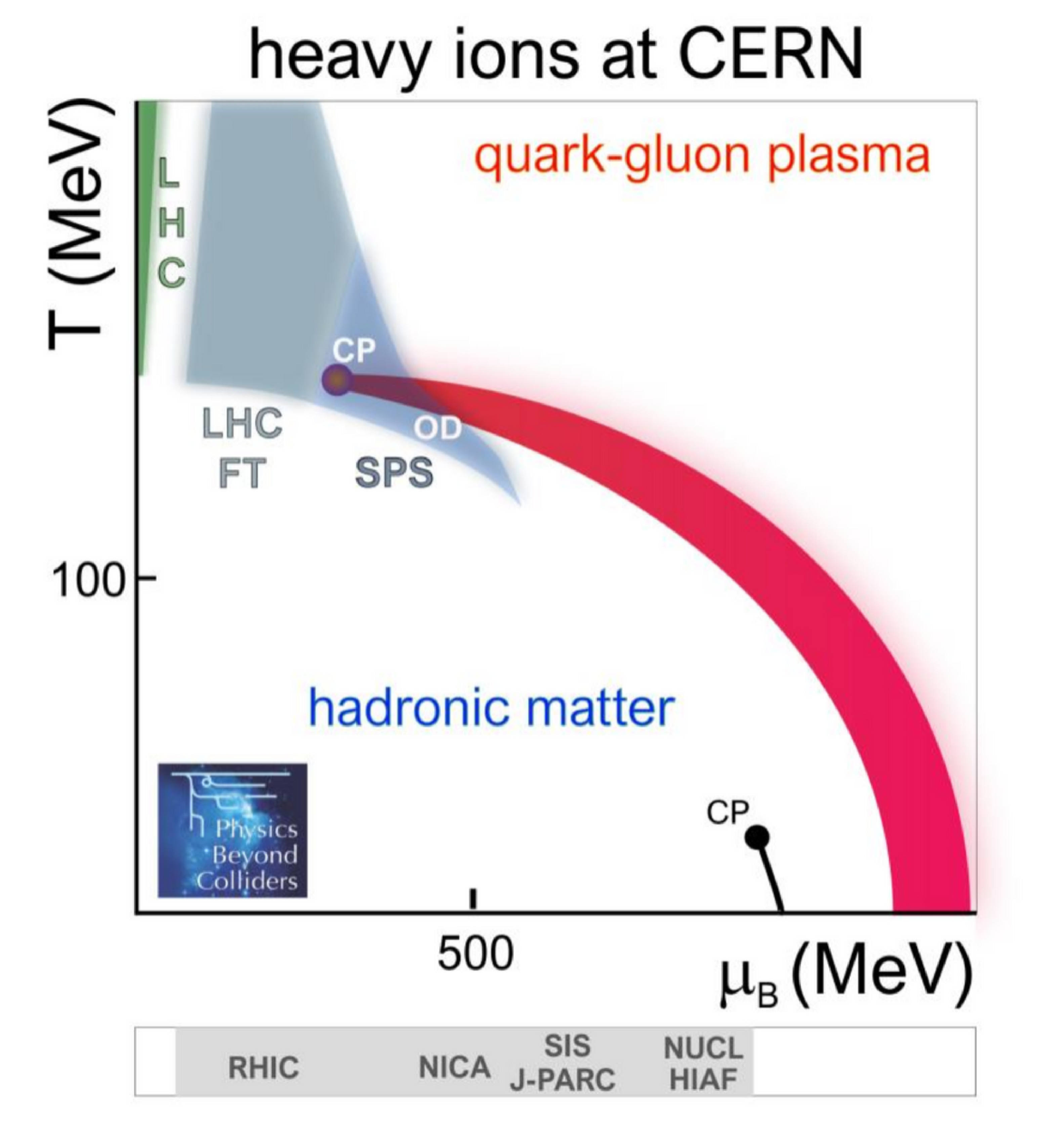
There is still a lot of questions.

NA61/SHINE is looking for answers.

The questions fluctuations and correlations are trying to answer are...

What are the properties of the phase transition between hadrons and quark-gluon plasma?

Where is the critical point? (if it exists)



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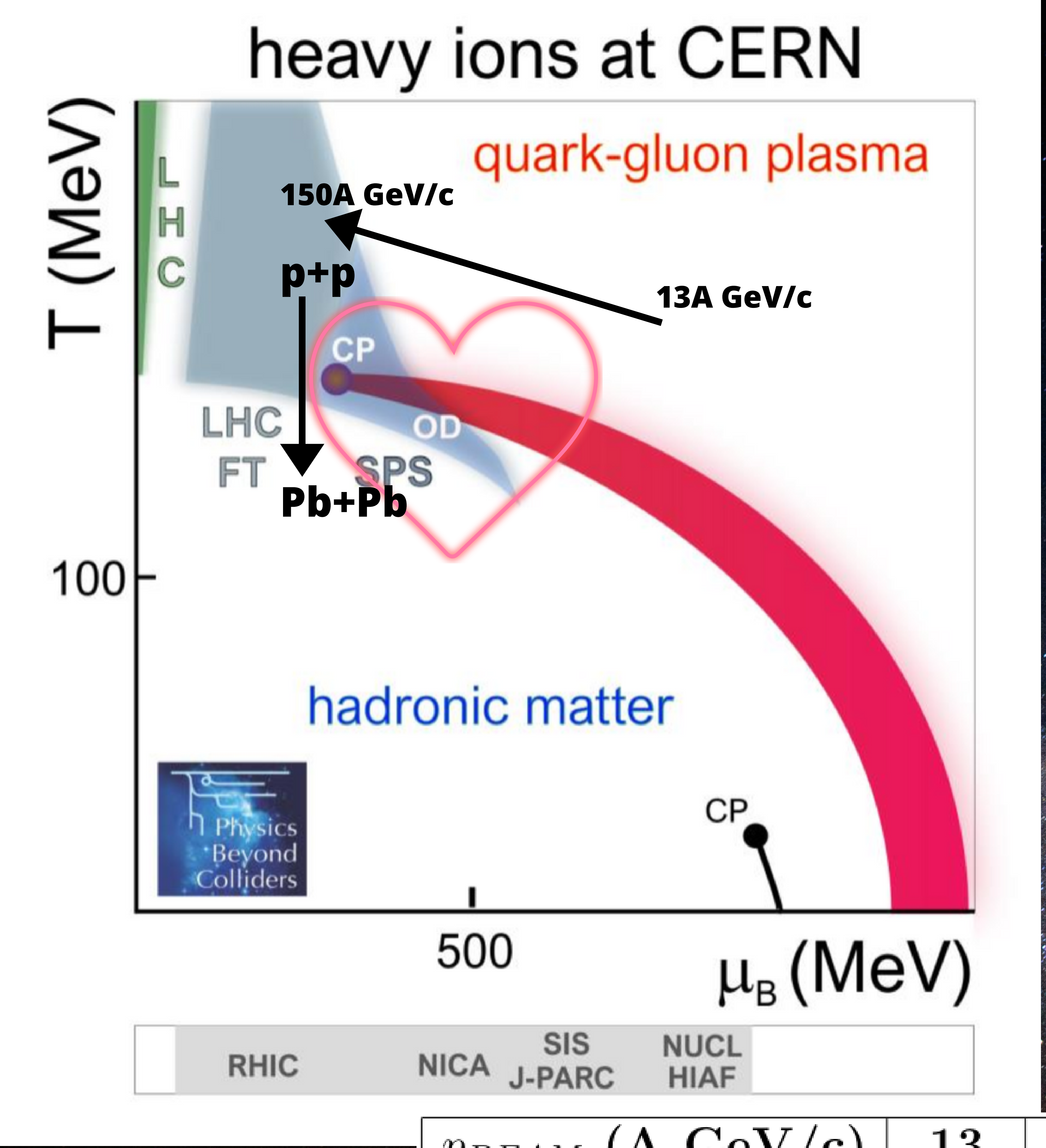
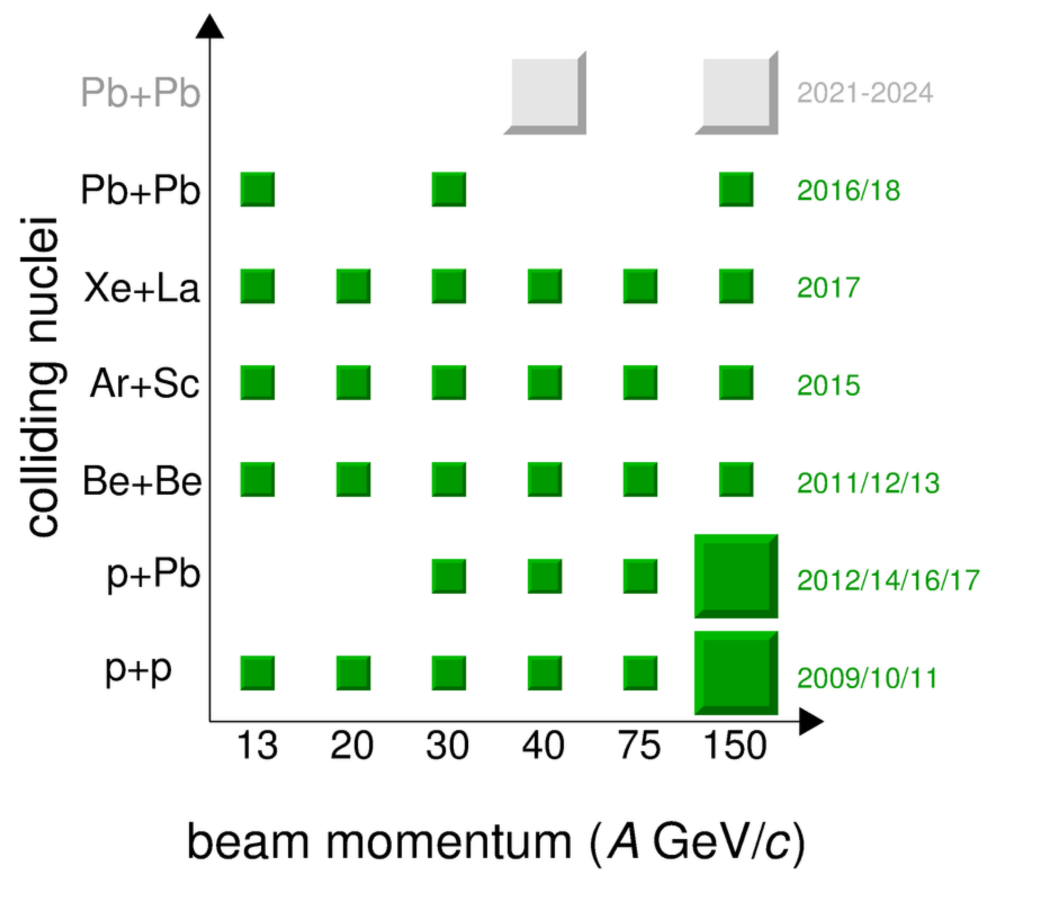
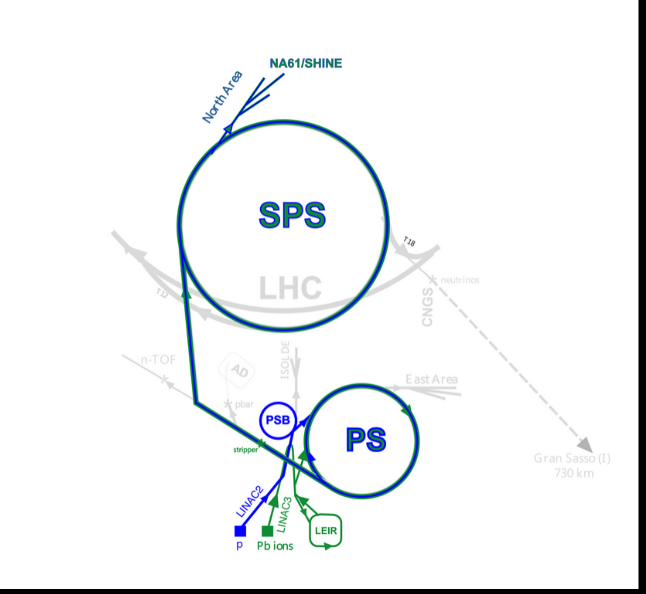


system size - beam energy scan



p_{BEAM} (A GeV/c)	13	19	30	40	75	150
$\sqrt{s_{NN}}$ (GeV)	5.12	6.12	7.62	8.77	11.94	16.84

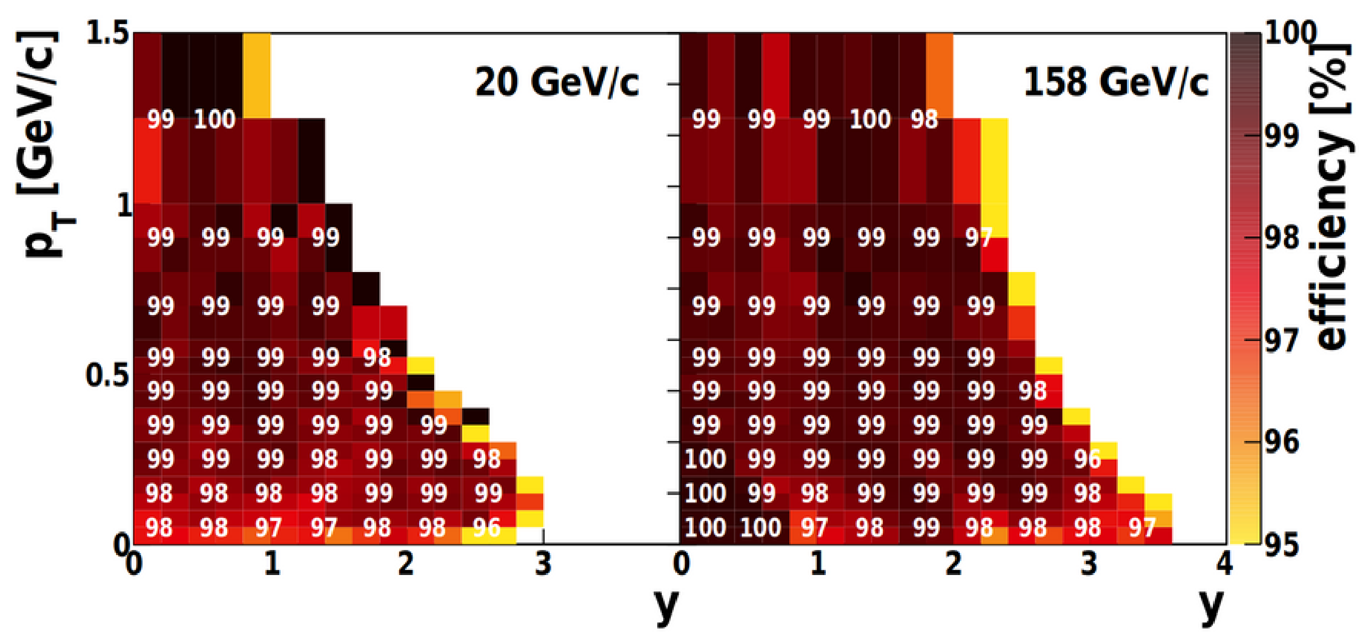


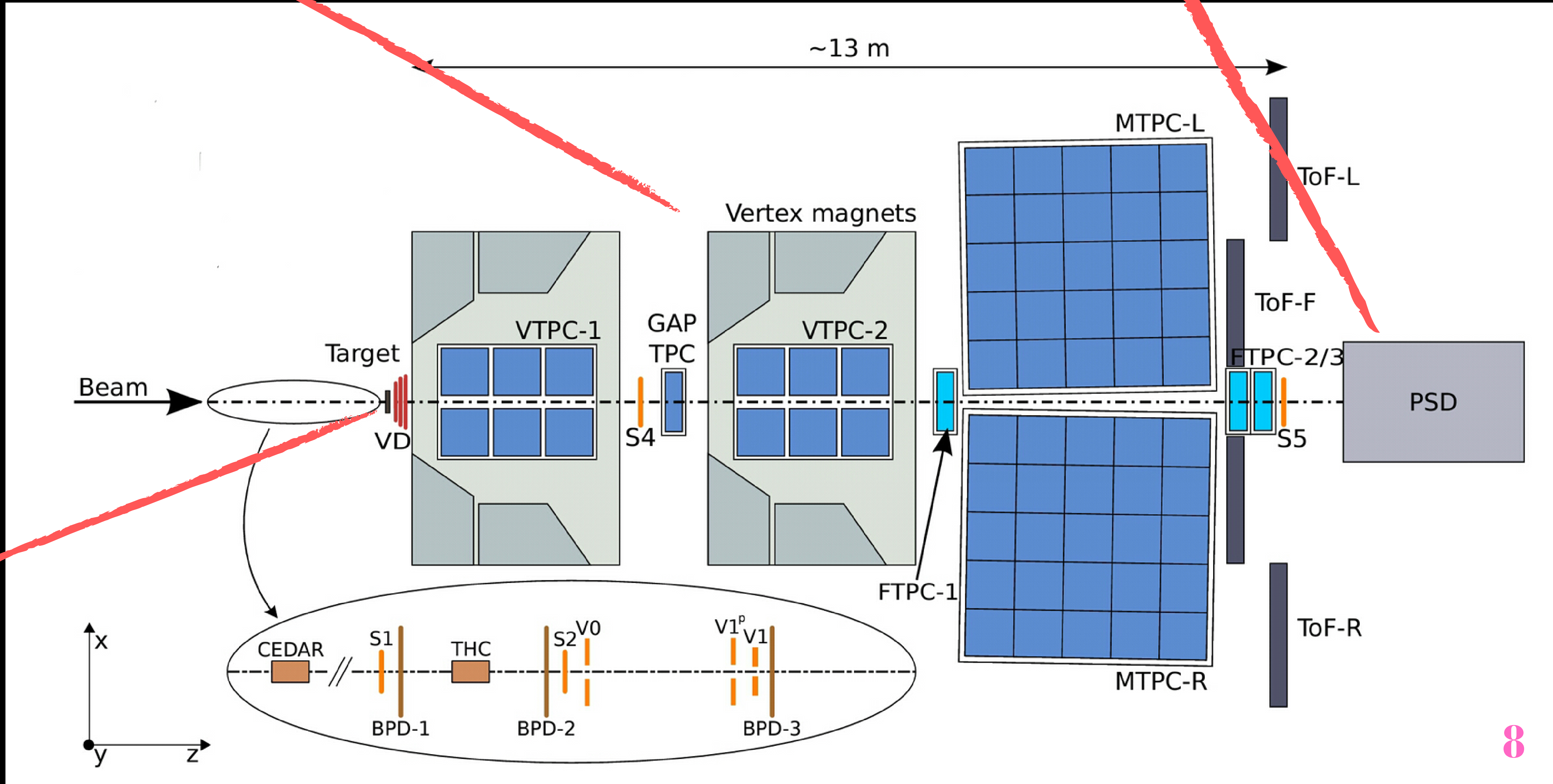
NA61/SHINE is located at CERN SPS.

Centrality selection and event plane determination in nucleus-nucleus collisions possible thanks to Projectile Spectator Detector (PSD)

Large acceptance hadron spectrometer (TPC)

- full coverage in the forward hemisphere (down to $p_T = 0$)
- high tracking efficiency (>90%)





Fixed target

multiplicity and net-charge fluctuations

critical point

collective flow

onset of deconfinement

FLUCTUATIONS AND CORRELATIONS IN NA61/SHINE

multiplicity and net-charge fluctuations

in the **critical point** the correlation length (ξ) diverges, what causes the increase of fluctuations signal. Cumulants of multiplicity or net-charge distributions are measures of this signal.

cumulant ~ ξ^n ← **n increase with the order of the cumulant**

collective flow

onset of deconfinement

FLUCTUATIONS AND CORRELATIONS IN NA61/SHINE

Multiplicity and net-charge fluctuation measures

extensive quantities

- **dependent on the system size: *W* (WNM)**
- **dependent on the fluctuations of the system size: *P(W)* (WNM)**

WNM - Wounded Nucleon Model

Moments (μ) or cumulants (κ) of the multiplicity (net-charge) distribution.

$$\kappa_1 = \langle N \rangle$$
$$\kappa_2 = \langle (\delta N)^2 \rangle = \sigma^2$$
$$\kappa_3 = \langle (\delta N)^3 \rangle = S\sigma^3$$
$$\kappa_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2 = K\sigma^4$$

N - multiplicity, $\delta N = \langle N - \langle N \rangle \rangle$,
σ - standard deviation, S - skewness
K - kurtosis

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intensive quantities

- independent of the system size: *W* (WNM)
- dependent on the fluctuations of the system size: *P(W)* (WNM)

Ratio of two extensive quantities.

scaled variance:
$$\omega[N] = \kappa_2/\kappa_1$$
scaled skewness:
$$S\sigma[N] = \kappa_3/\kappa_2$$
scaled kurtosis:
$$K\sigma^2[N] = \kappa_4/\kappa_2$$

multiplicity → Poisson
net-charge → Skellam

Skellam distribution: difference of two statistically independent random variables, each Poisson-distributed

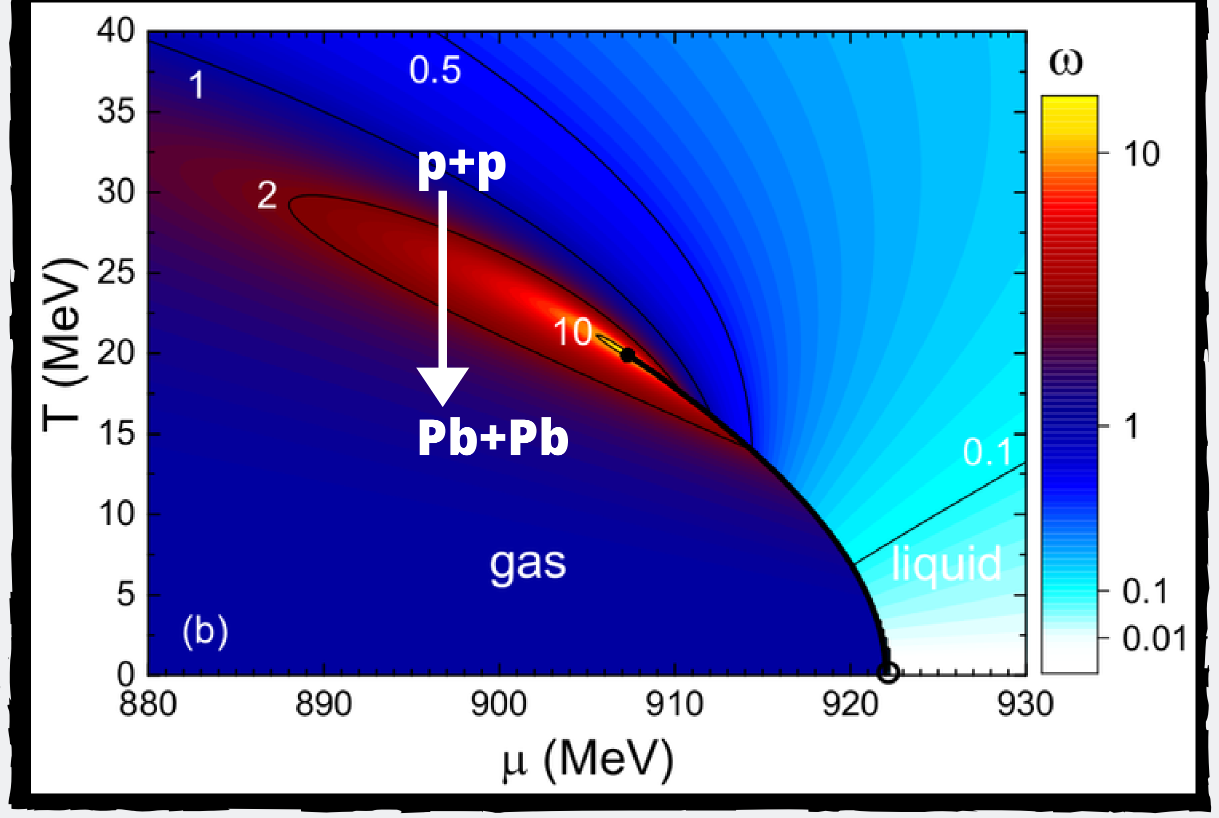
Reference values:
- no fluctuations: 0
- Poisson: 1
- Skellam: reference depends on $\langle h^+ \rangle$ and $\langle h^- \rangle$

NA61/SHINE RESULTS

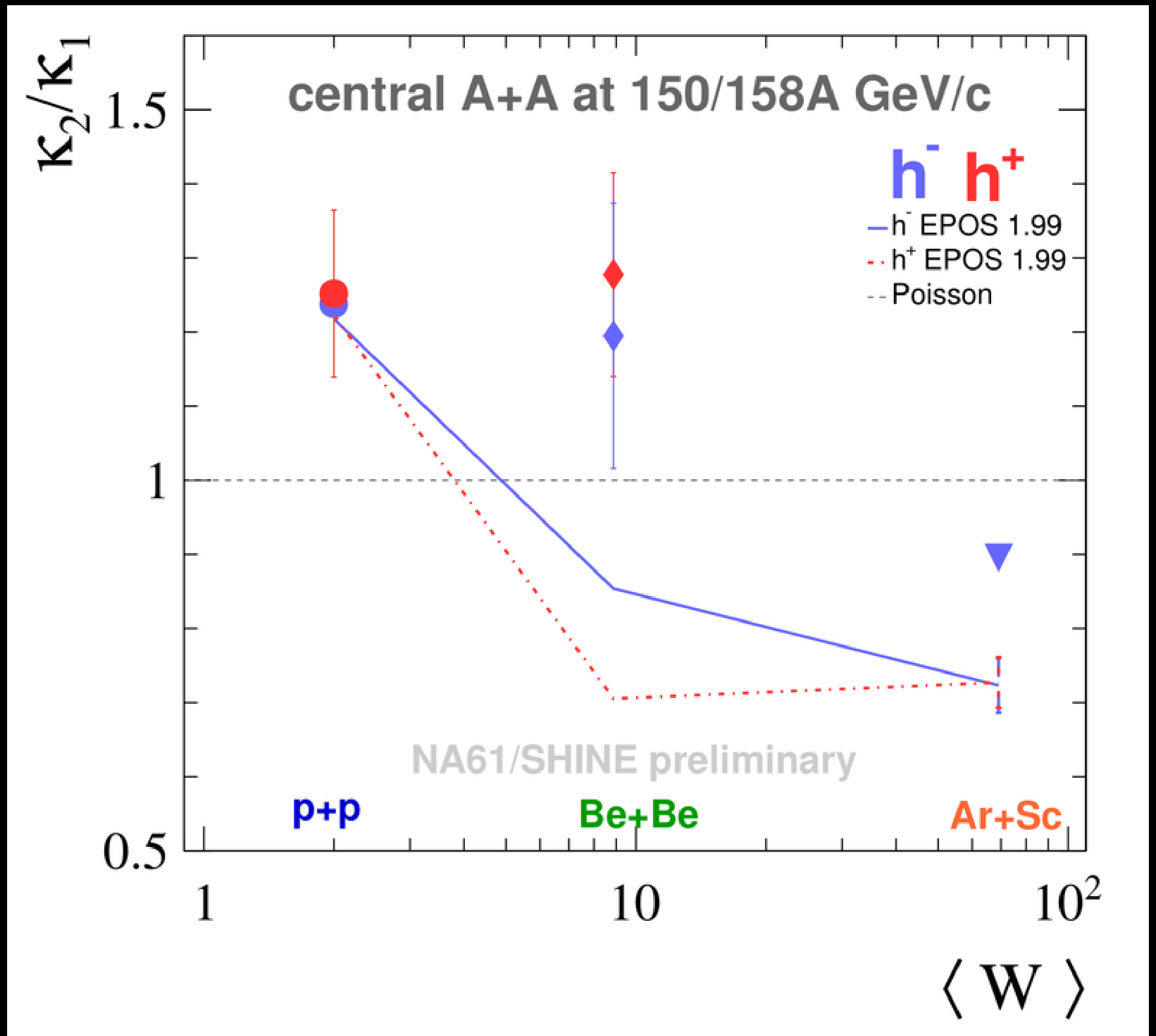
intensive quantities - ω[N]

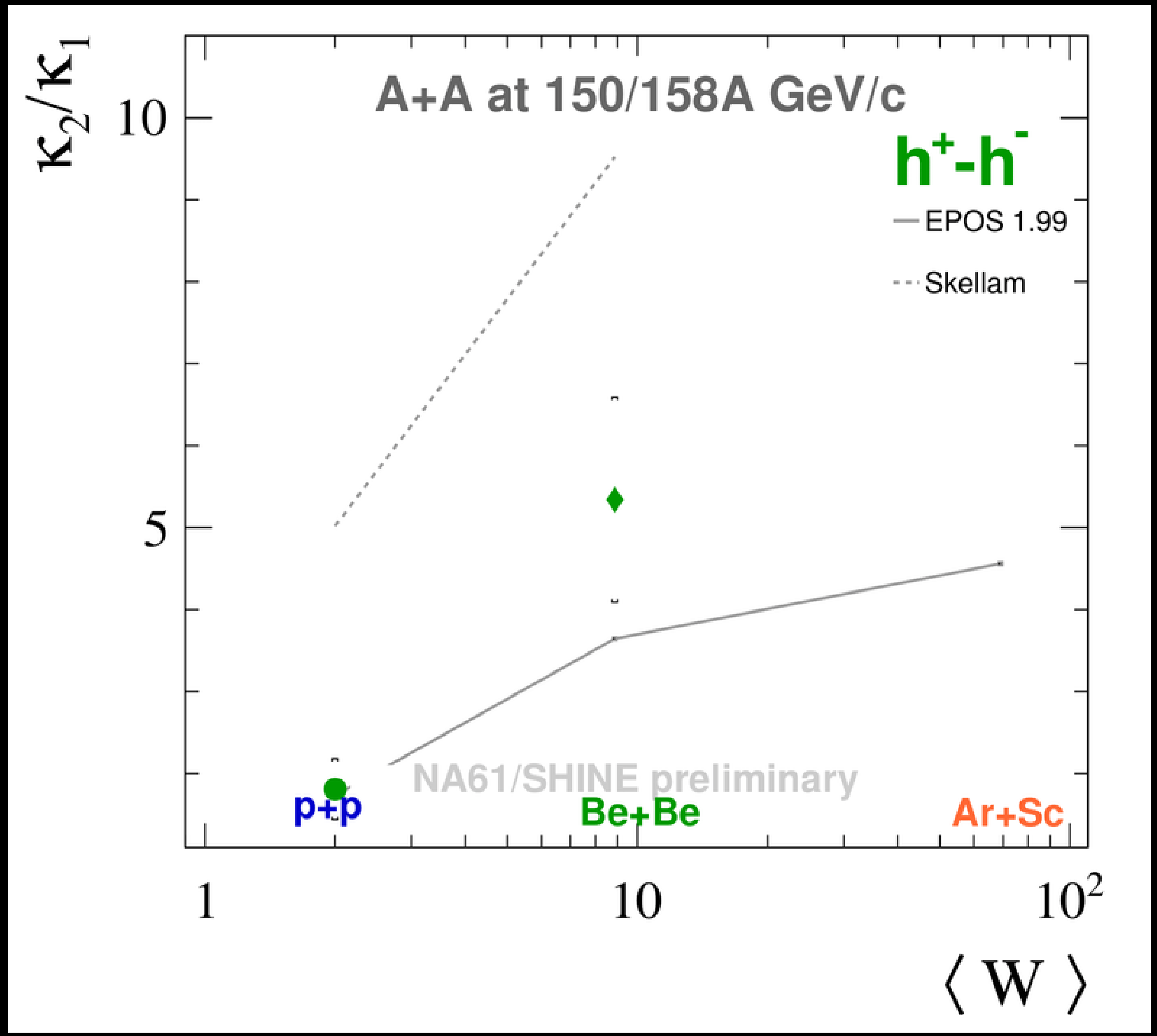
expected behaviour

Vovchenko et al., Physical Review C, 92(5):054901, 2015



system size dependence





remarks

- A+A centrality selection:
  0-1% most central events
- statistical uncertainties calculated with subsample or bootstrap methods
- p+p data are corrected for detector effects, Be+Be are uncorrected, estimation of systematic bias is included in uncertainty, Ar+Sc are corrected, systematic bias under study

conclusions:

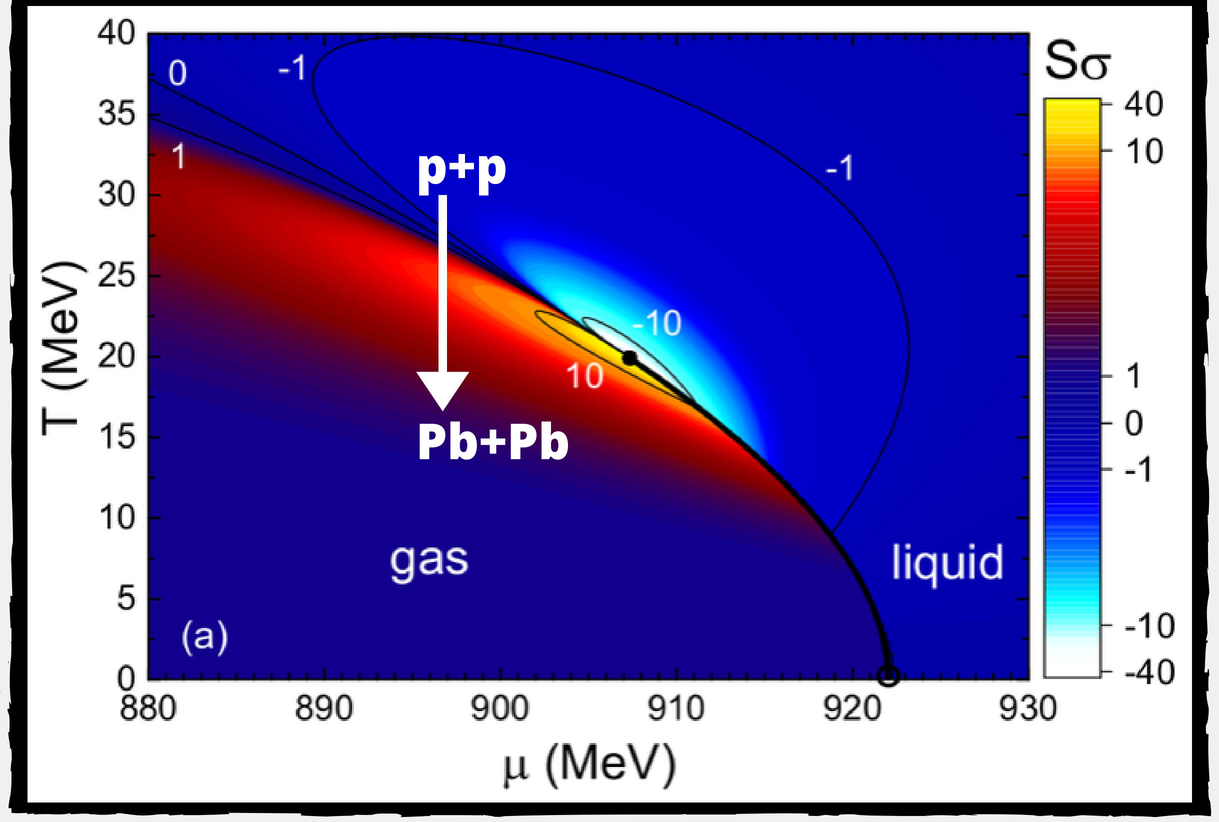
- no structures indicating critical point in net-charge
- EPOS1.99 does not describe properly system size dependence of charged particles
- Ar+Sc results - coming soon!

NA61/SHINE RESULTS

intensive quantities - Sσ[N]

expected behaviour

Vovchenko et al., Physical Review C, 92(5):054901, 2015



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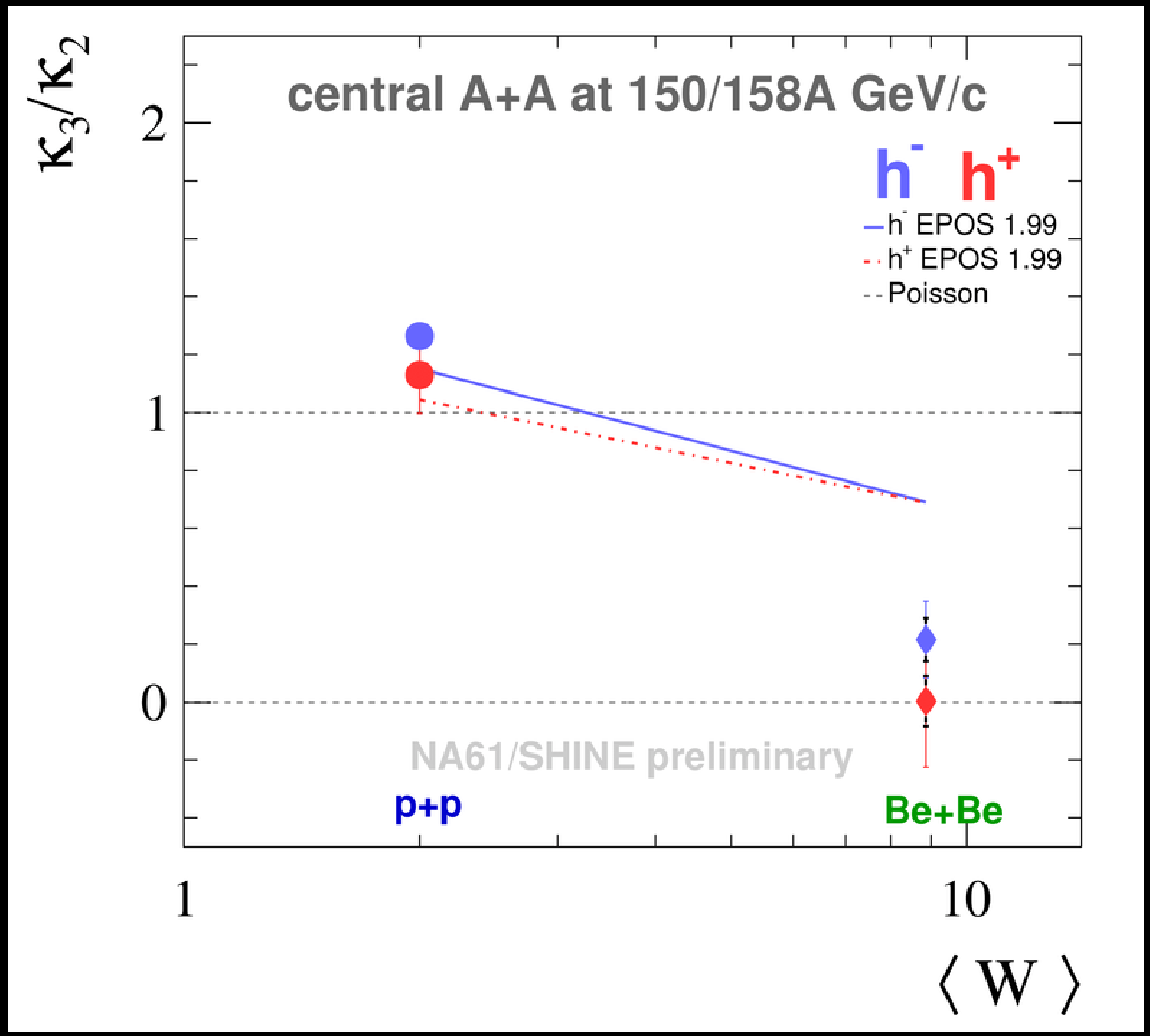
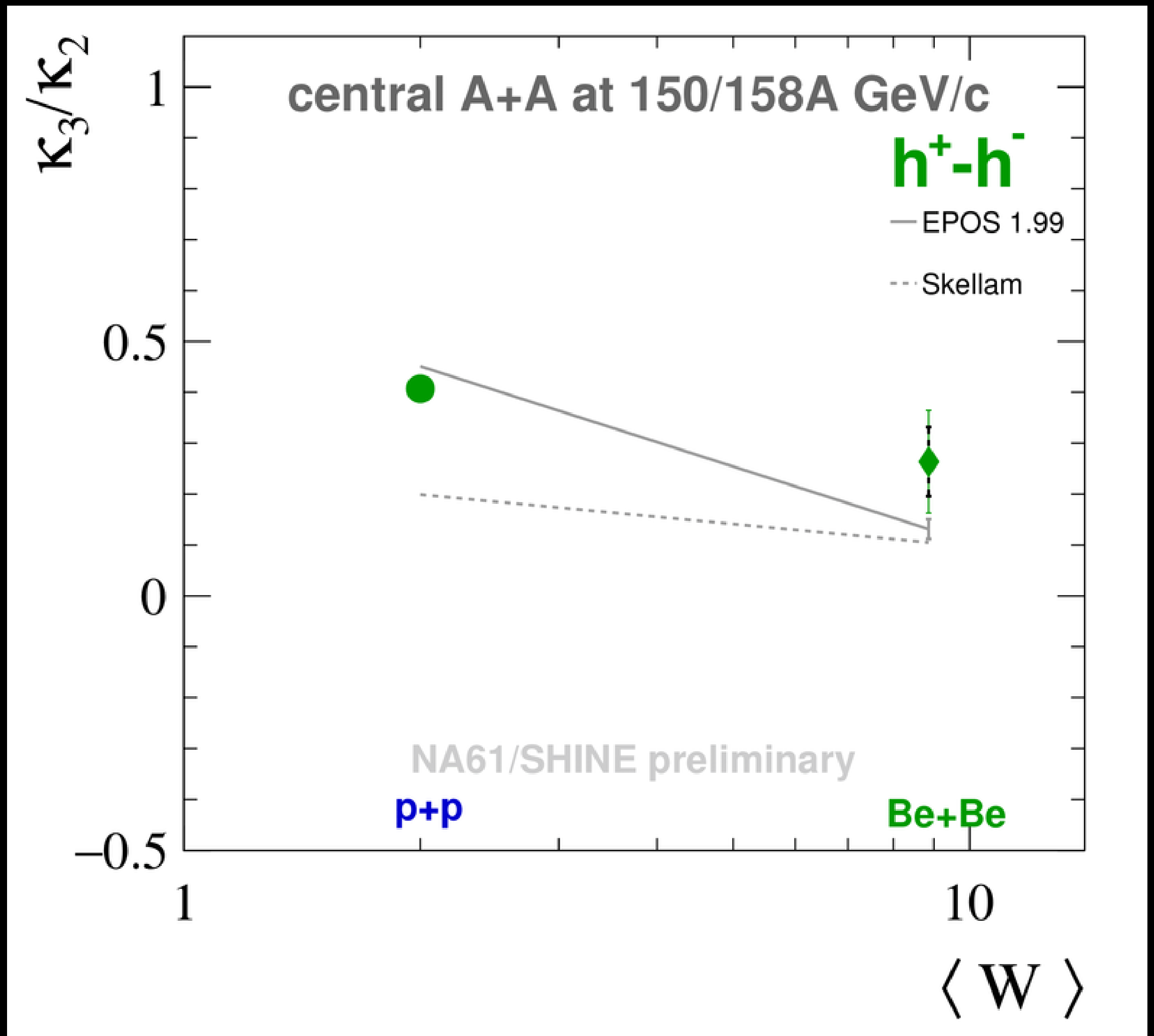
system size dependence





conclusions:

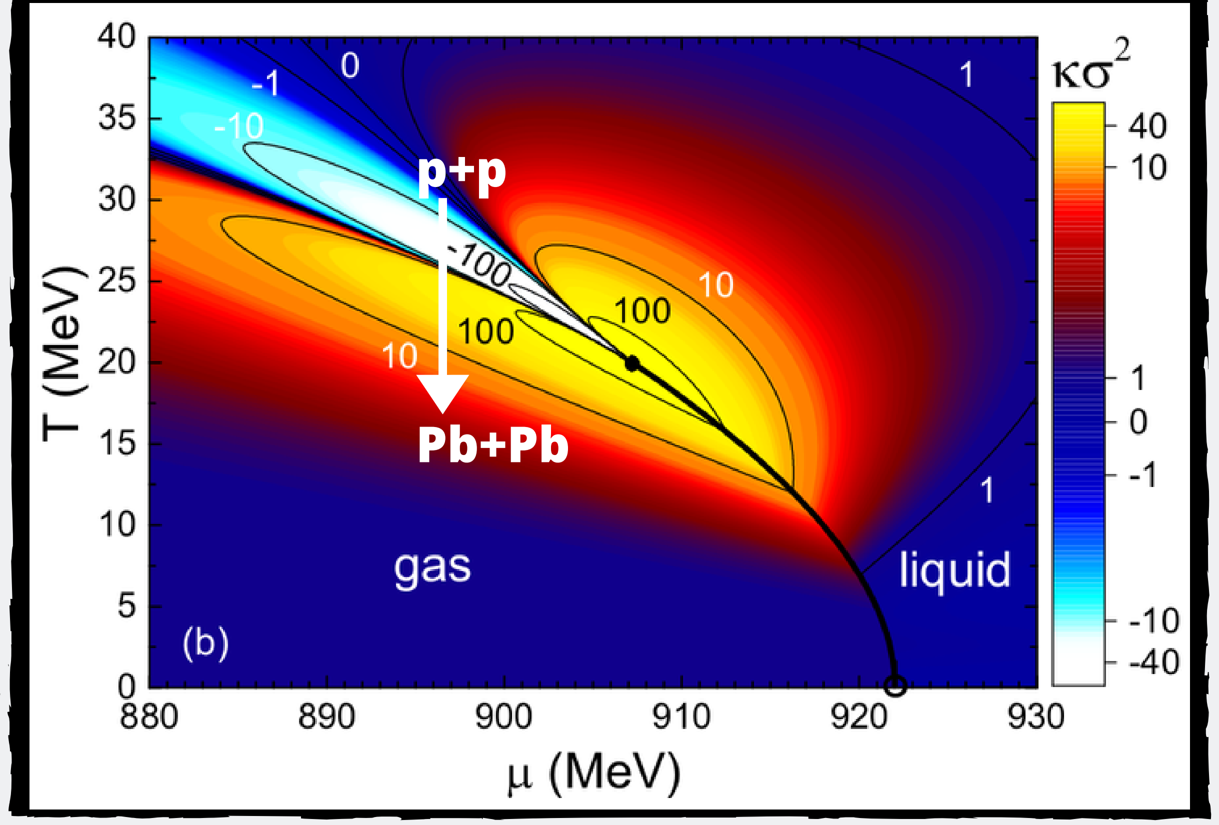
- no structures indicating critical point in net-charge
- interesting behaviour of charged particles
- Ar+Sc results - coming soon!

NA61/SHINE RESULTS

intensive quantities - $\kappa\sigma^2[N]$

expected behaviour

Vovchenko et al., Physical Review C, 92(5):054901, 2015



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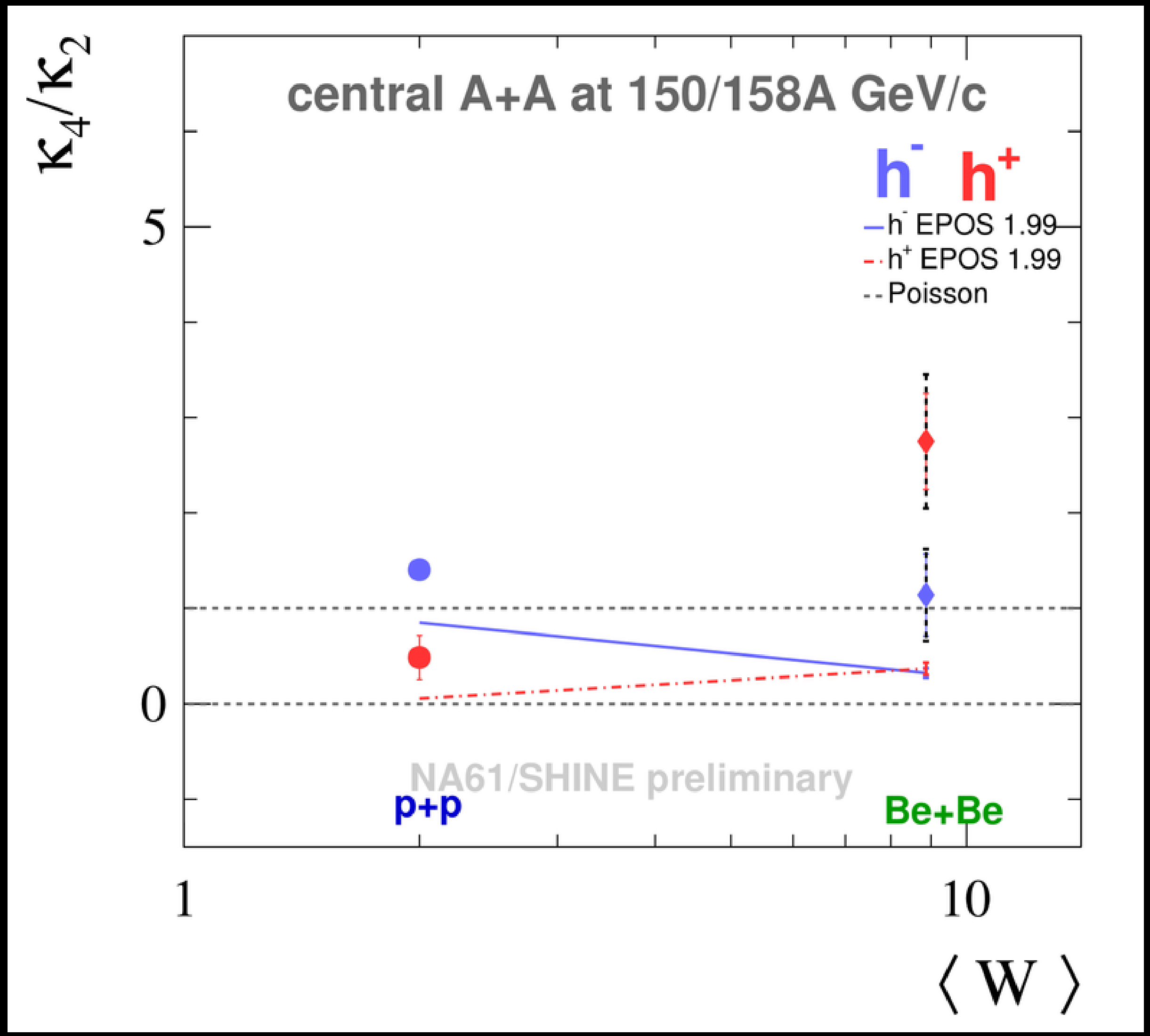

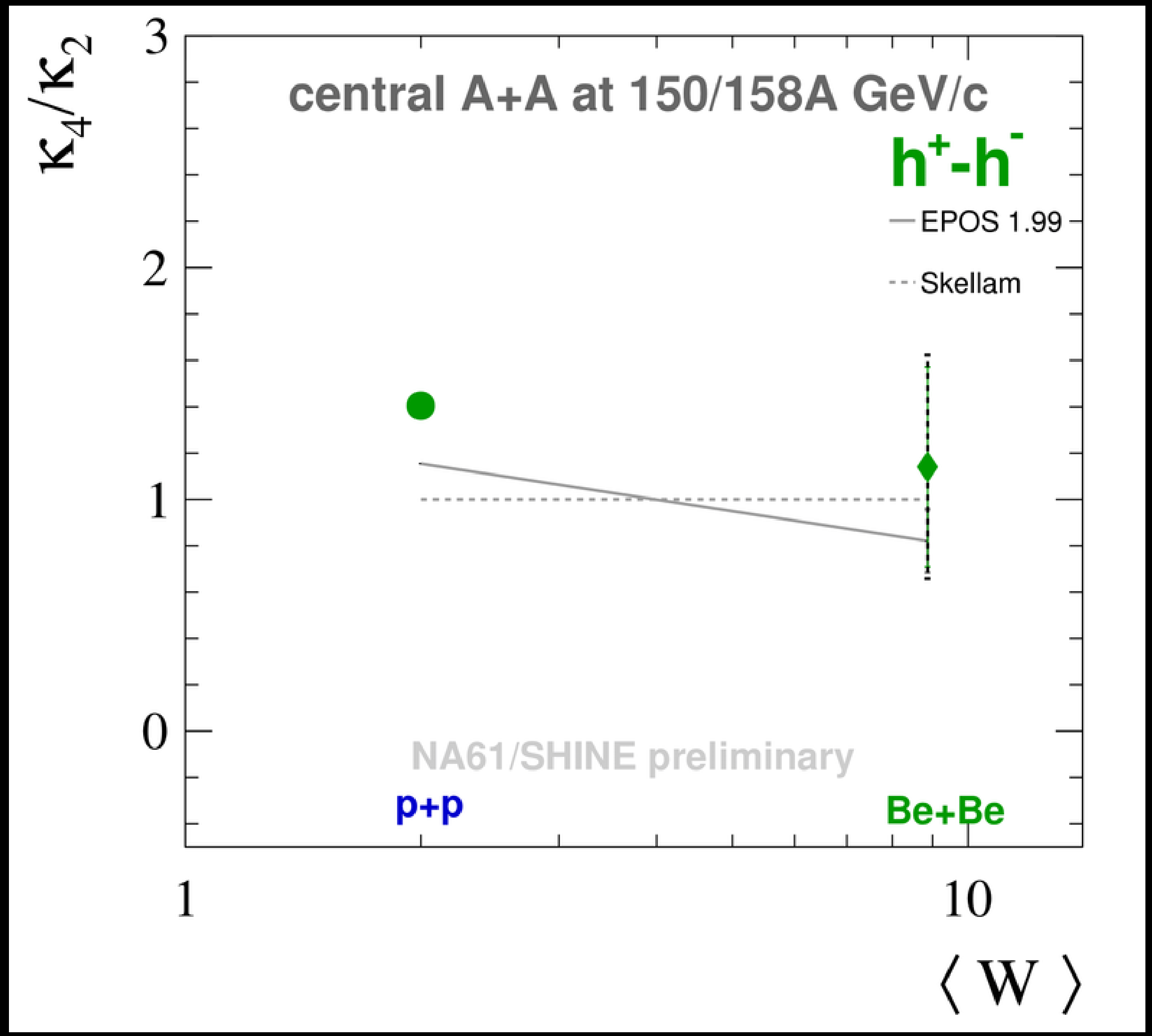

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- statistical uncertainties calculated with subsample or bootstrap methods
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conclusions:

- no structures indicating critical point in net-charge
- different system size dependence of h^+ and h^-
- Ar+Sc results - coming soon!

multiplicity and net-charge fluctuations

critical point

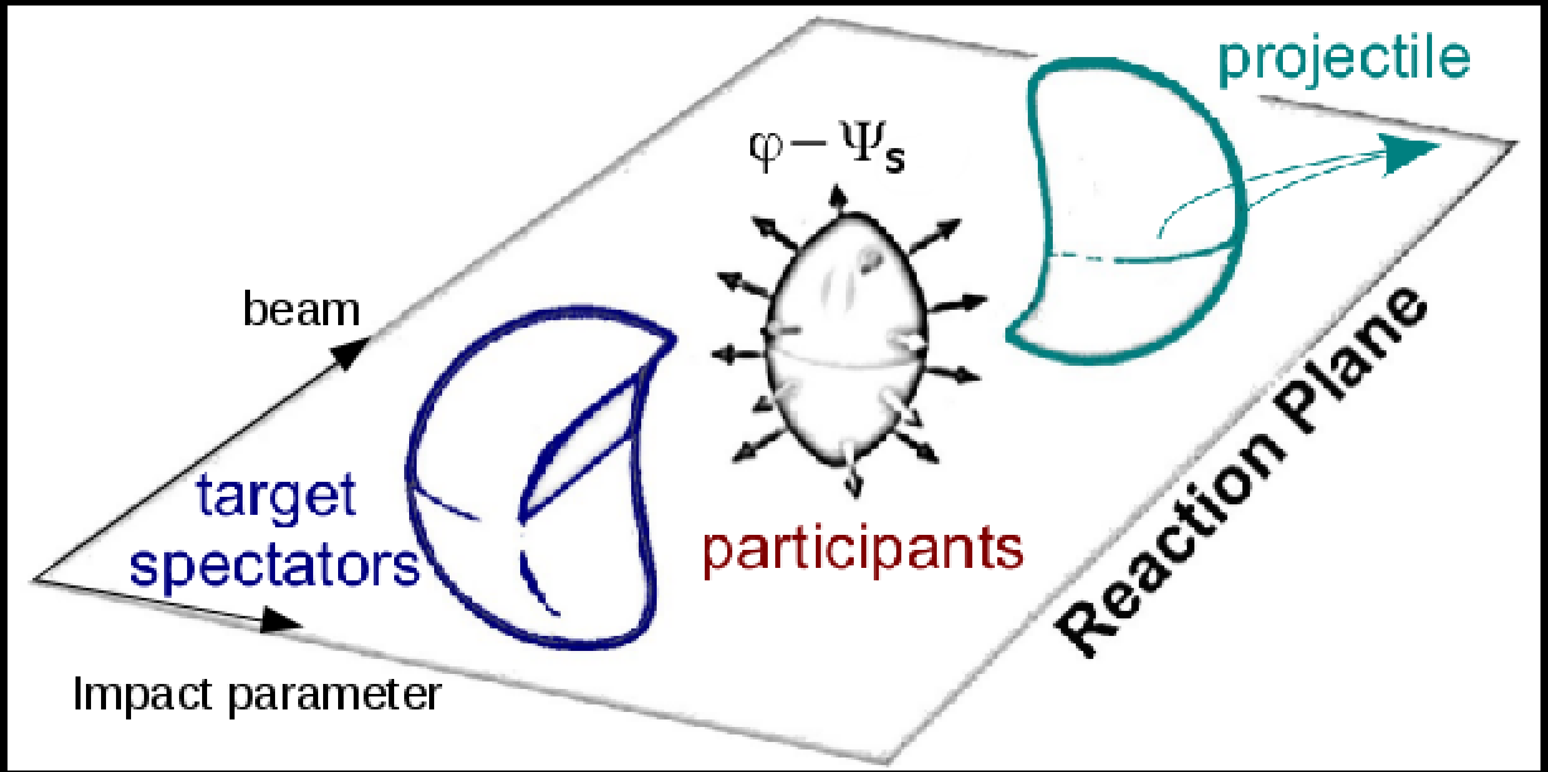
collective flow

Flow measurement provides information about the the properties of the initial stage of A+A collision. Directed flow is considered to be sensitive to **1st order phase transition**.

FLUCTUATIONS AND CORRELATIONS IN NA61/SHINE

Flow

Anisotropic transverse flow is a measure of the spatial anisotropy in the initial phase of A+A collision.



v_1- directed flow (momentum transfer in the reaction plane)

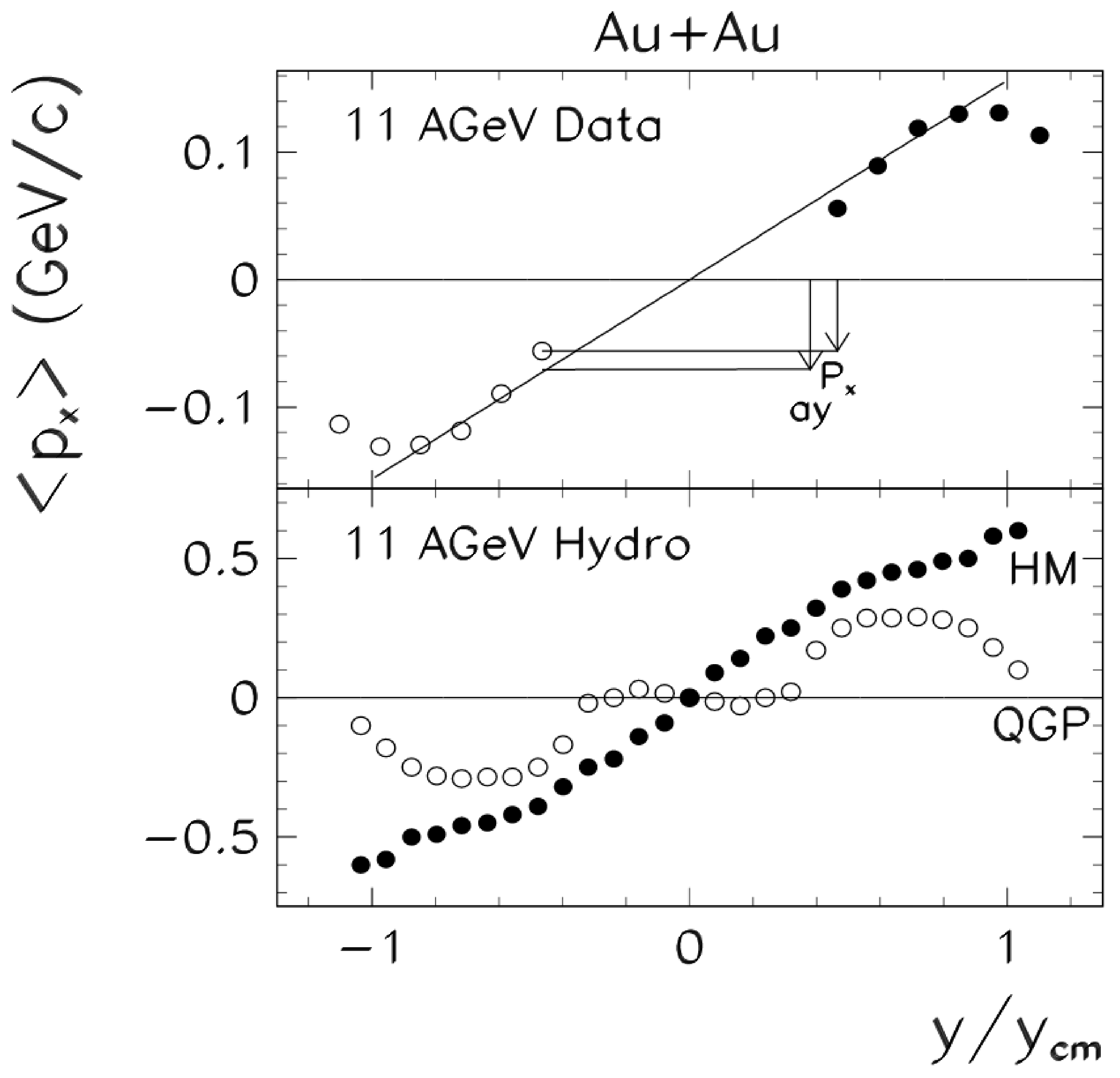
v_2- elliptic flow (momentum transfer in the transverse plane)

Why NA61/SHINE measurements are special?

- flow measured in large aceptance
- Ψ determined with spectators in PSD

Flow

Directed flow (v_1) and onset od deconfinement: why should we care?



Csernai L. P., Rohrich D. "Third flow component as QGP signal"

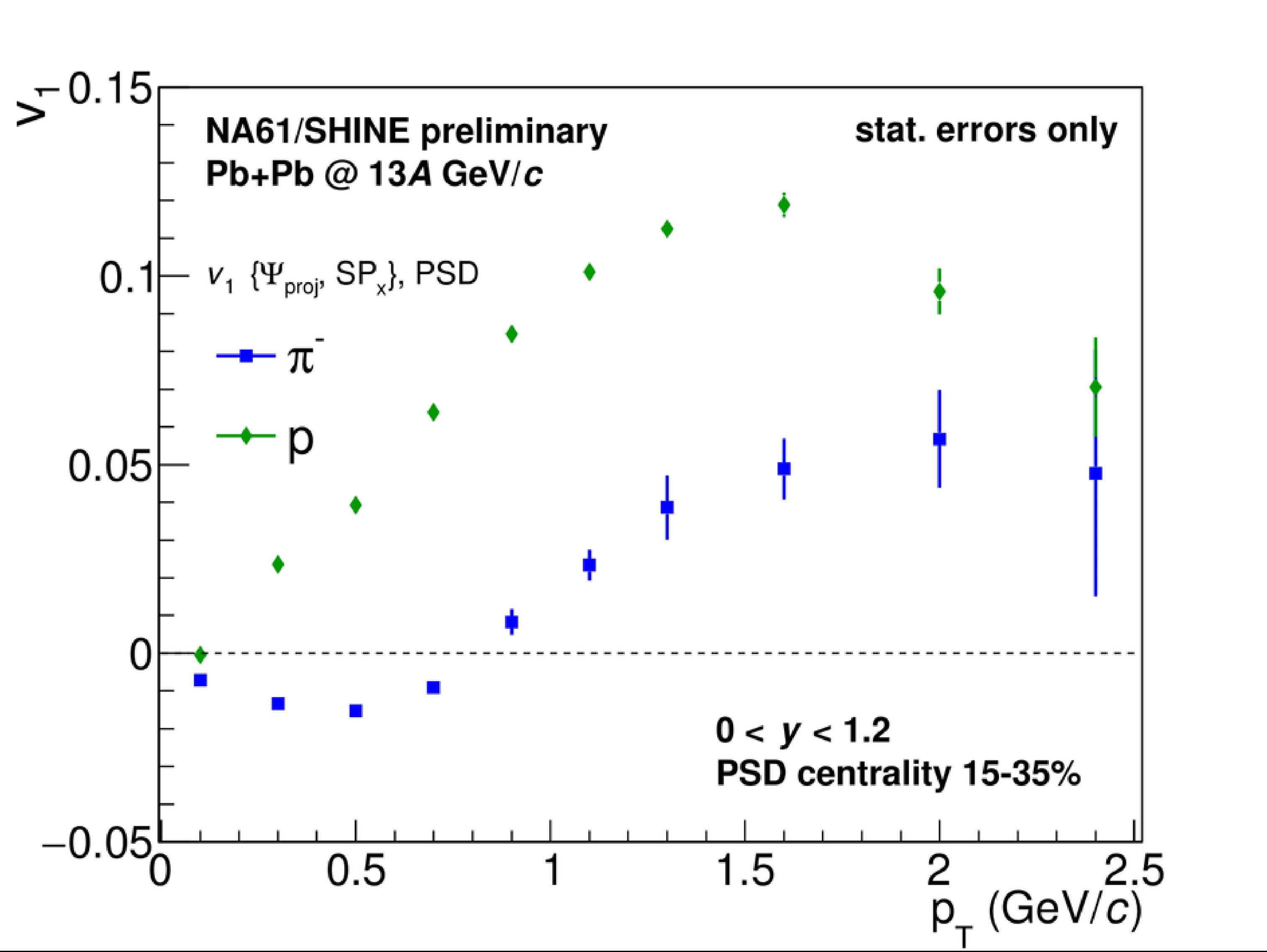
Directed flow for fluid dynamical calculations with Hadronic and QGP EoS.

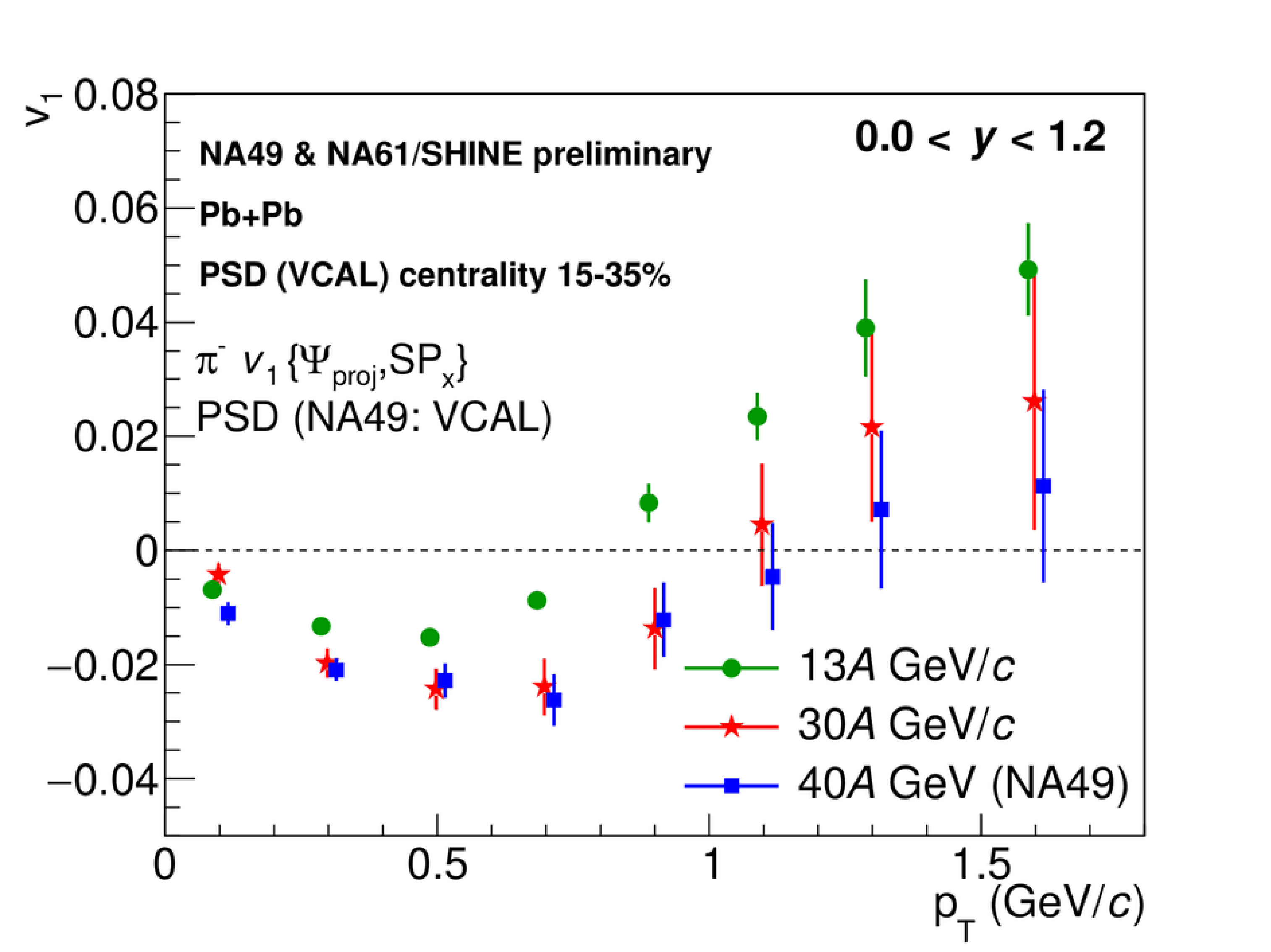
Negative slope visible in case of first order phase transition!

Non-monotonic behaviour of dv_1/dy in function of beam energy is expected.

NA61/SHINE RESULTS

Directed Flow v_1





p_{BEAM} (A GeV/c)	13	19	30	40	75	150
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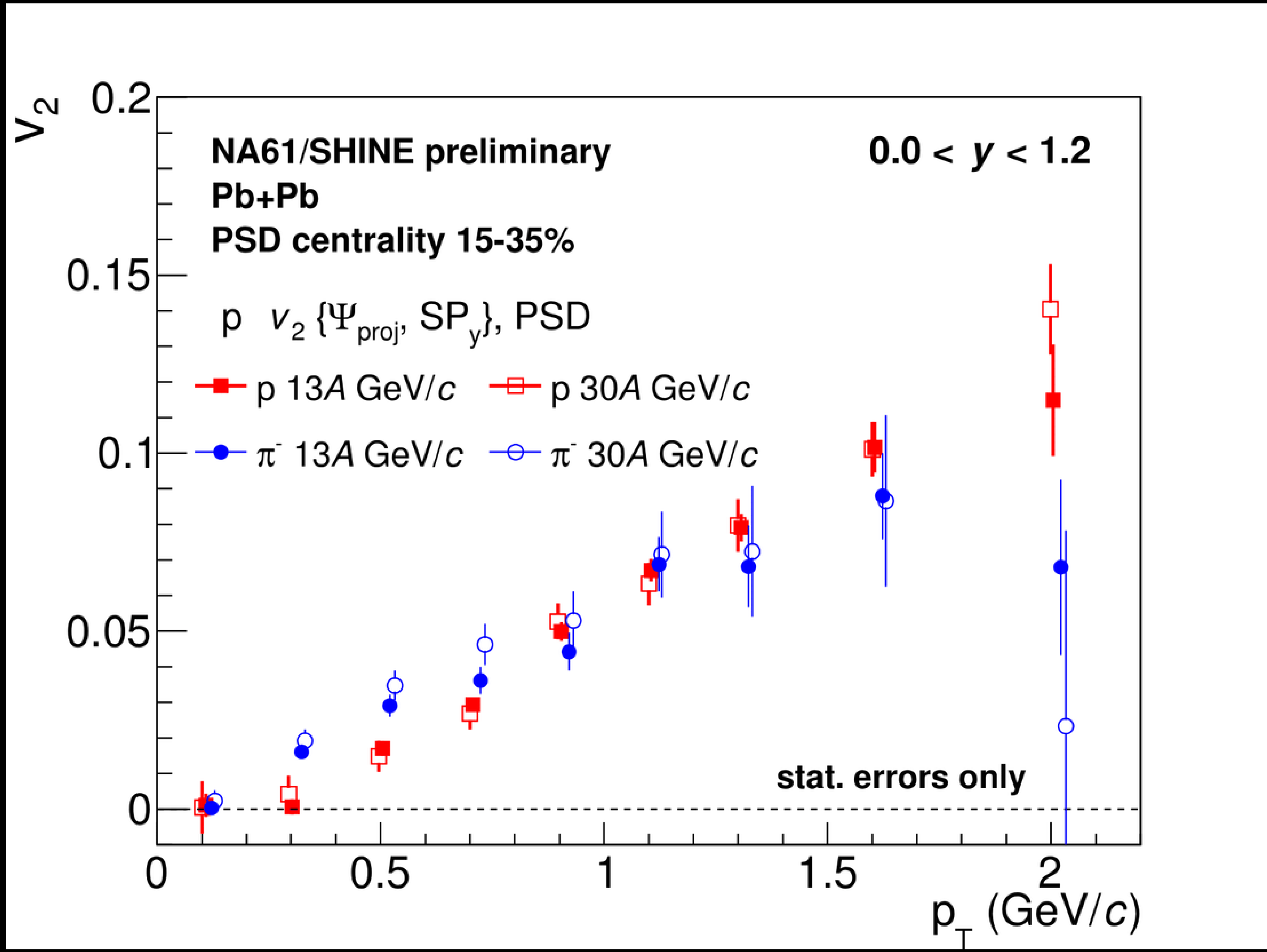
CONCLUSIONS

- **mass dependence is observed in directed flow, flow of π− changes sign**
- **directed flow shows energy dependence: flow in Pb+Pb collisions at 13A GeV/c differs from 30A and 40A GeV/c**

NA61/SHINE RESULTS

Elliptic Flow v_2



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CONCLUSIONS

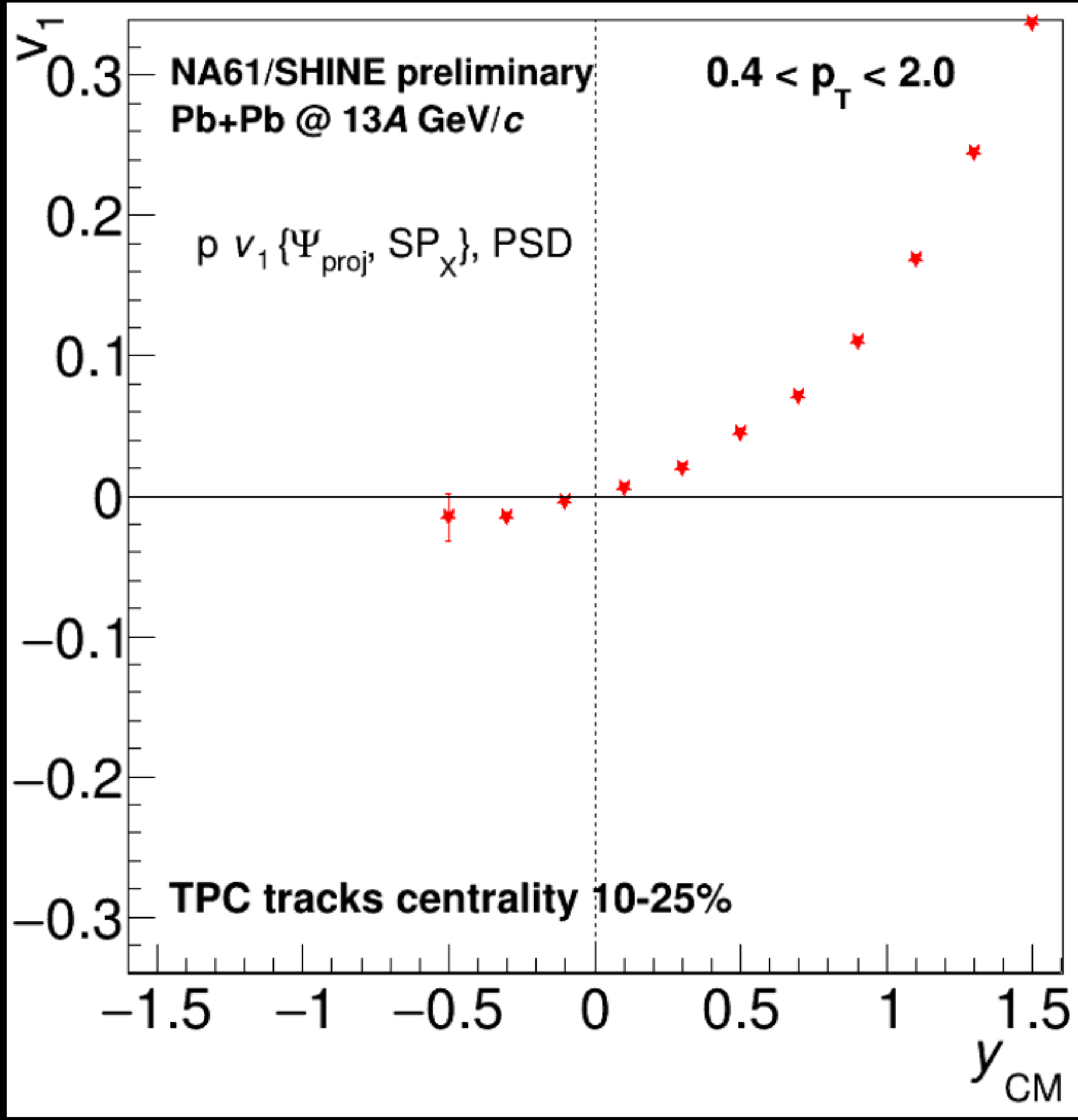
- elliptic flow of π− and p is different but it does not show any energy dependence

NA61/SHINE RESULTS

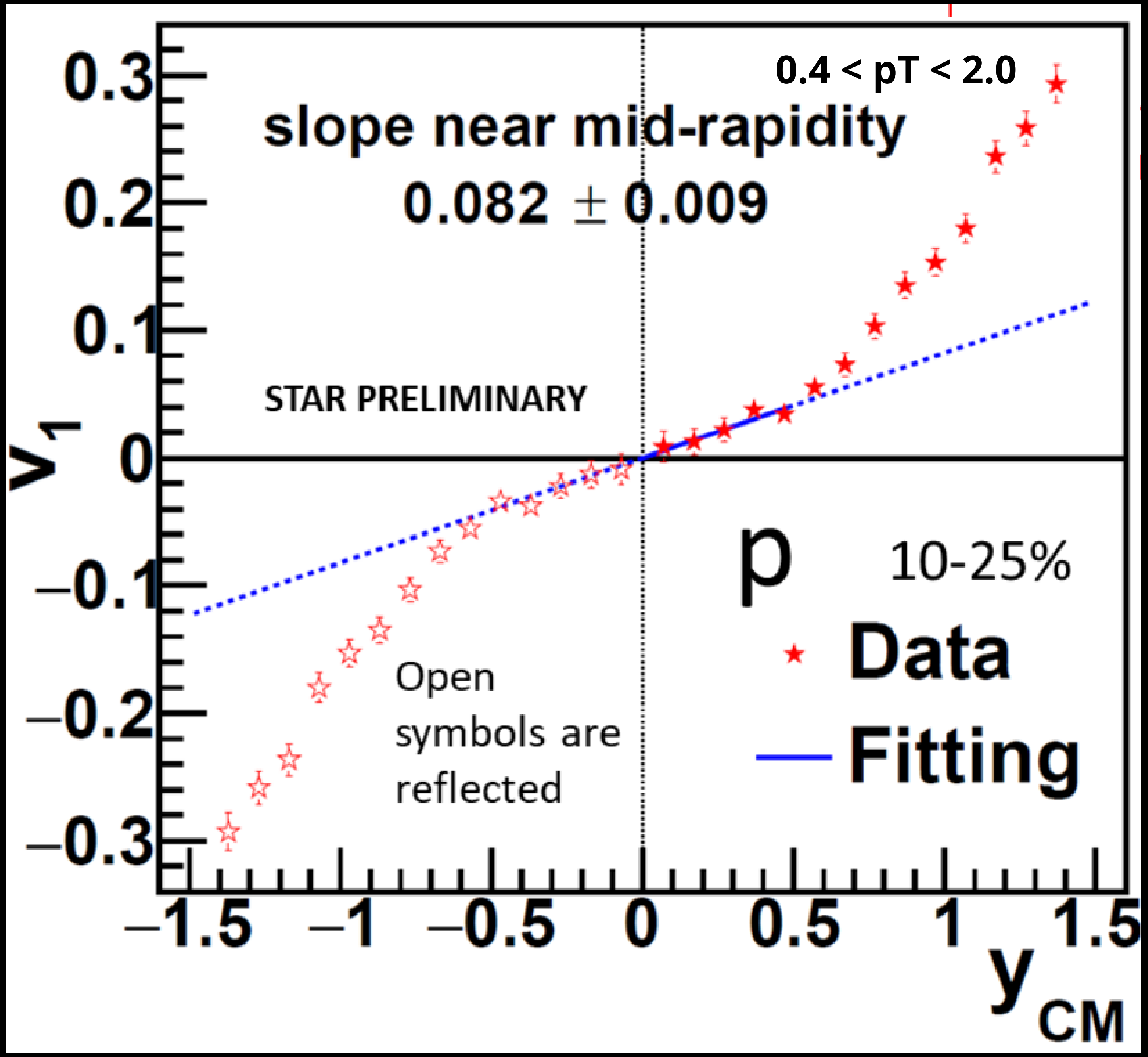
Flow: Comparison with STAR

protons

NA61/SHINE



STAR Au+Au @ 4.5 GeV FXT



D.Cebra, EMMI Workshop 2019, GSI

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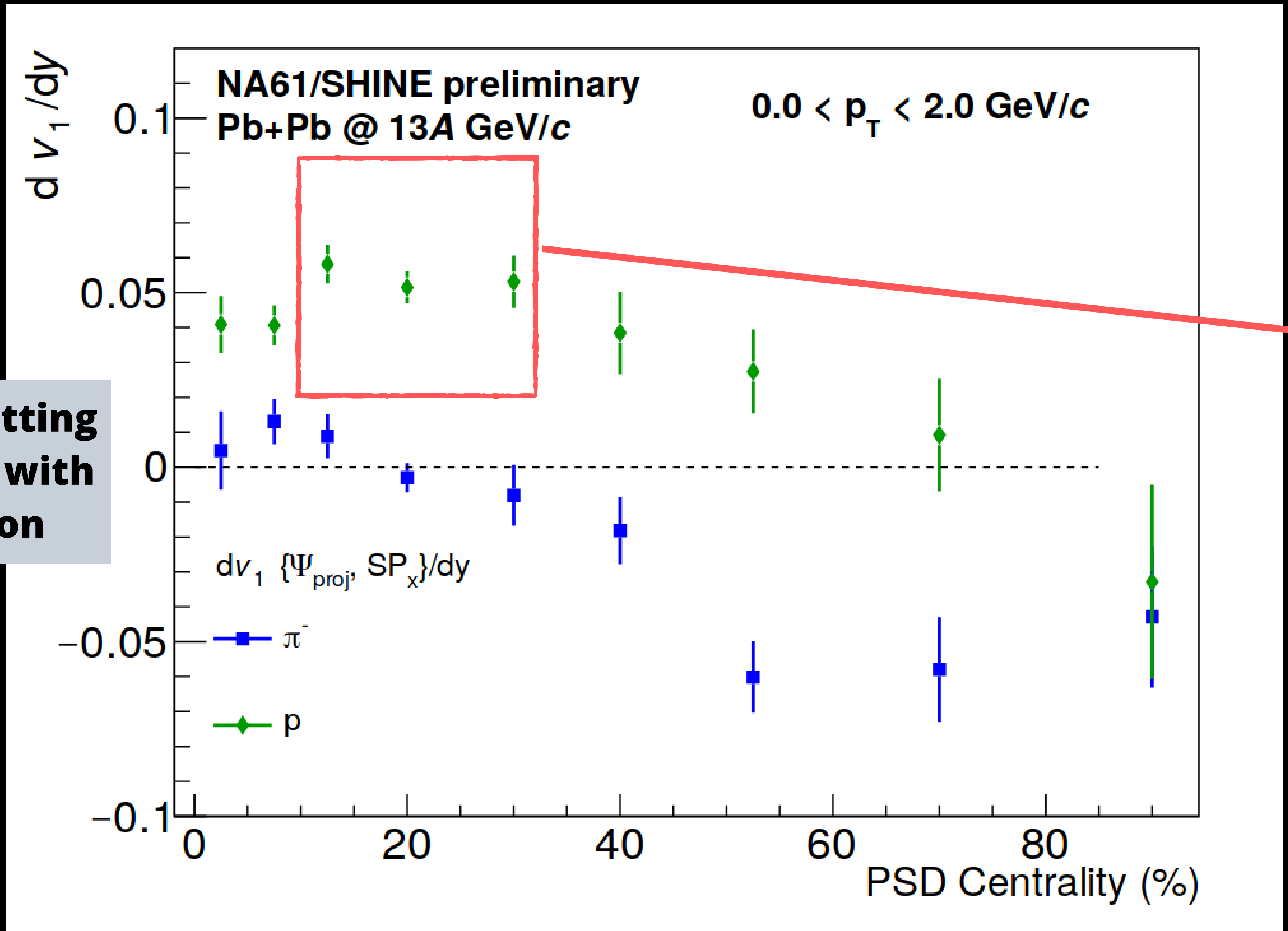
NA61/SHINE RESULTS

Flow: Comparison with STAR

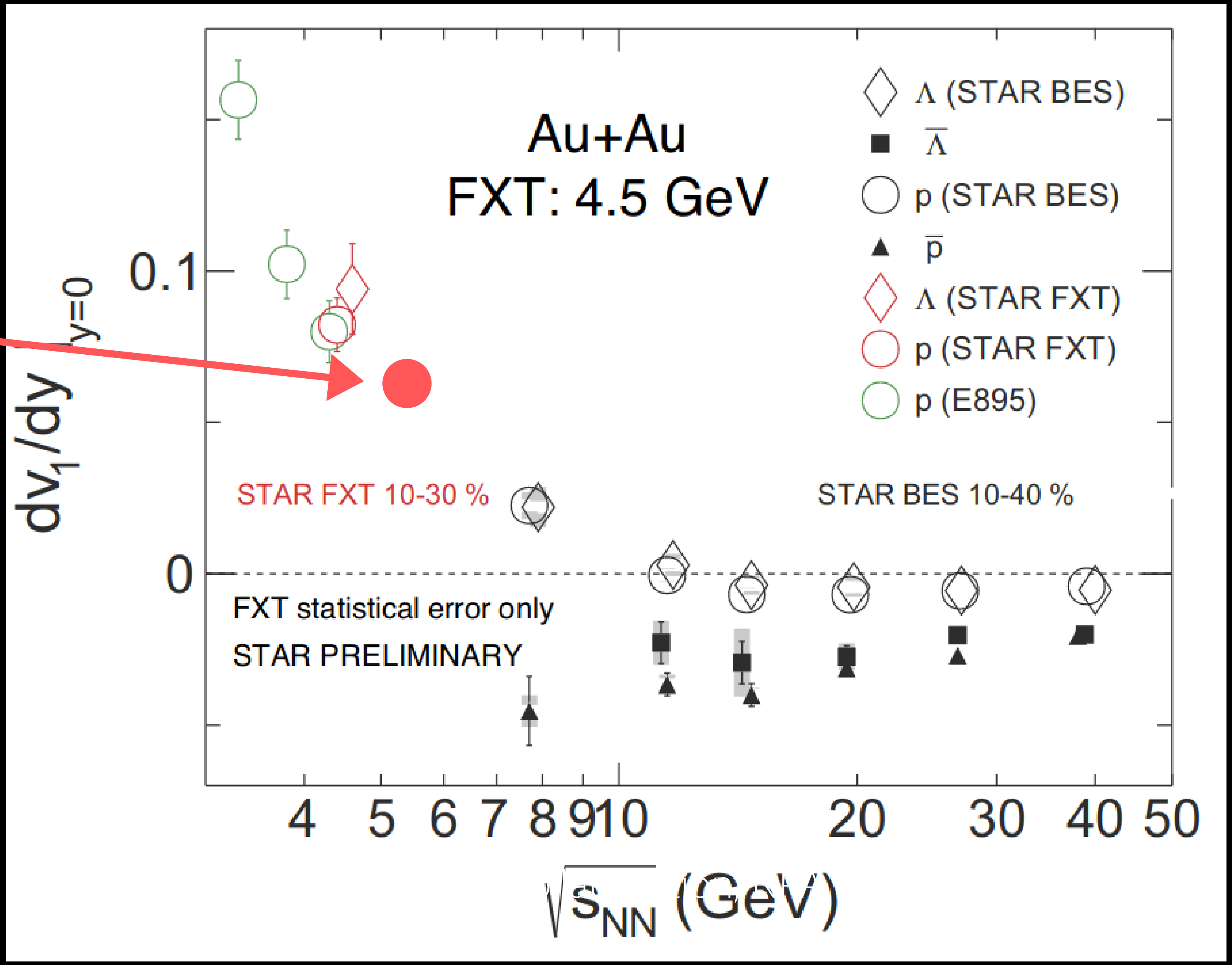
dv_1/dy

calculated by fitting $v_1(y)$ for $|y|<0.4$ with linear function

NA61/SHINE



STAR



STAR Collaboration, NPA 982, 899 (2019)

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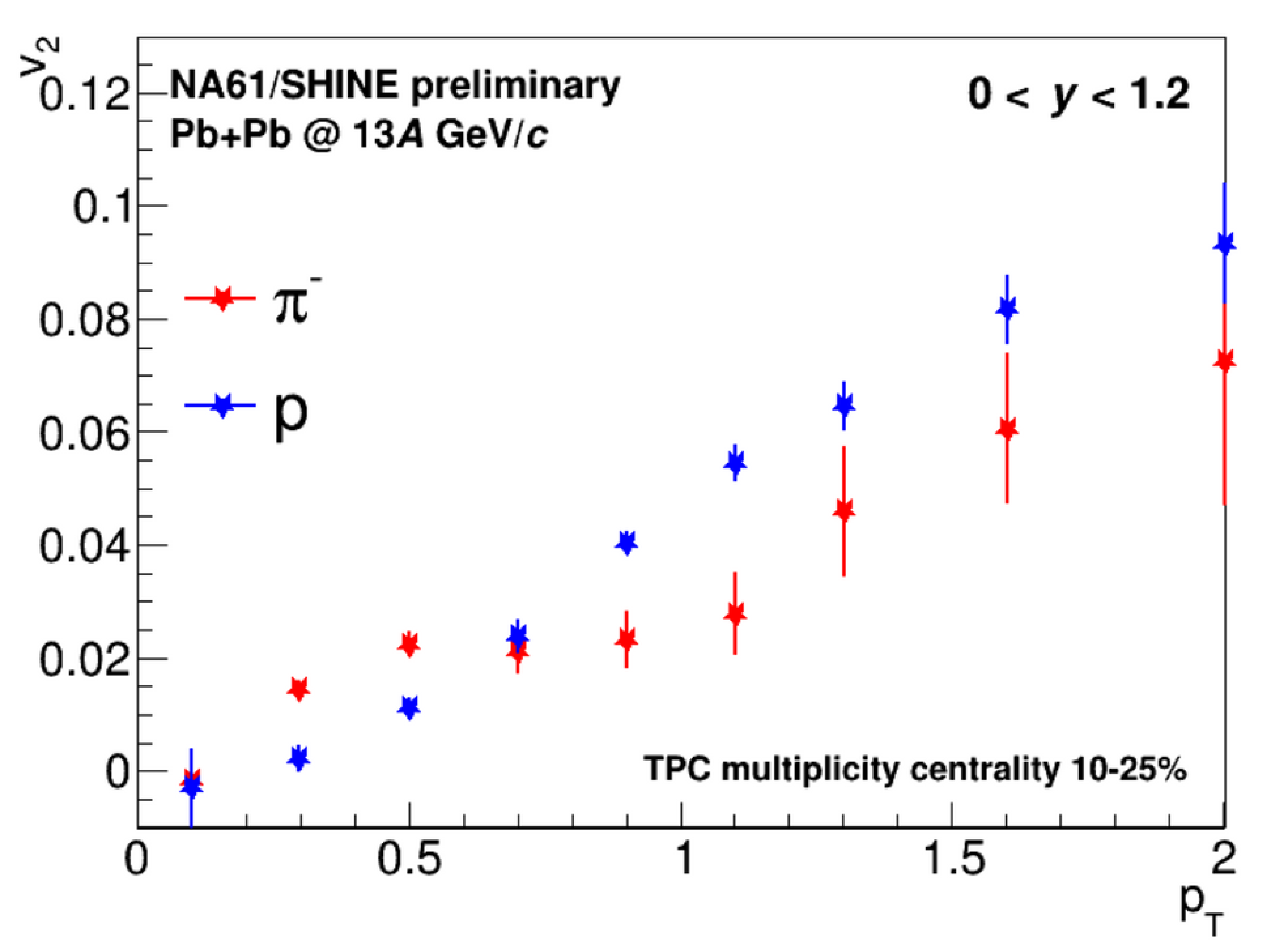
NA61/SHINE RESULTS

Flow: Comparison with STAR

v_2

NA61/SHINE



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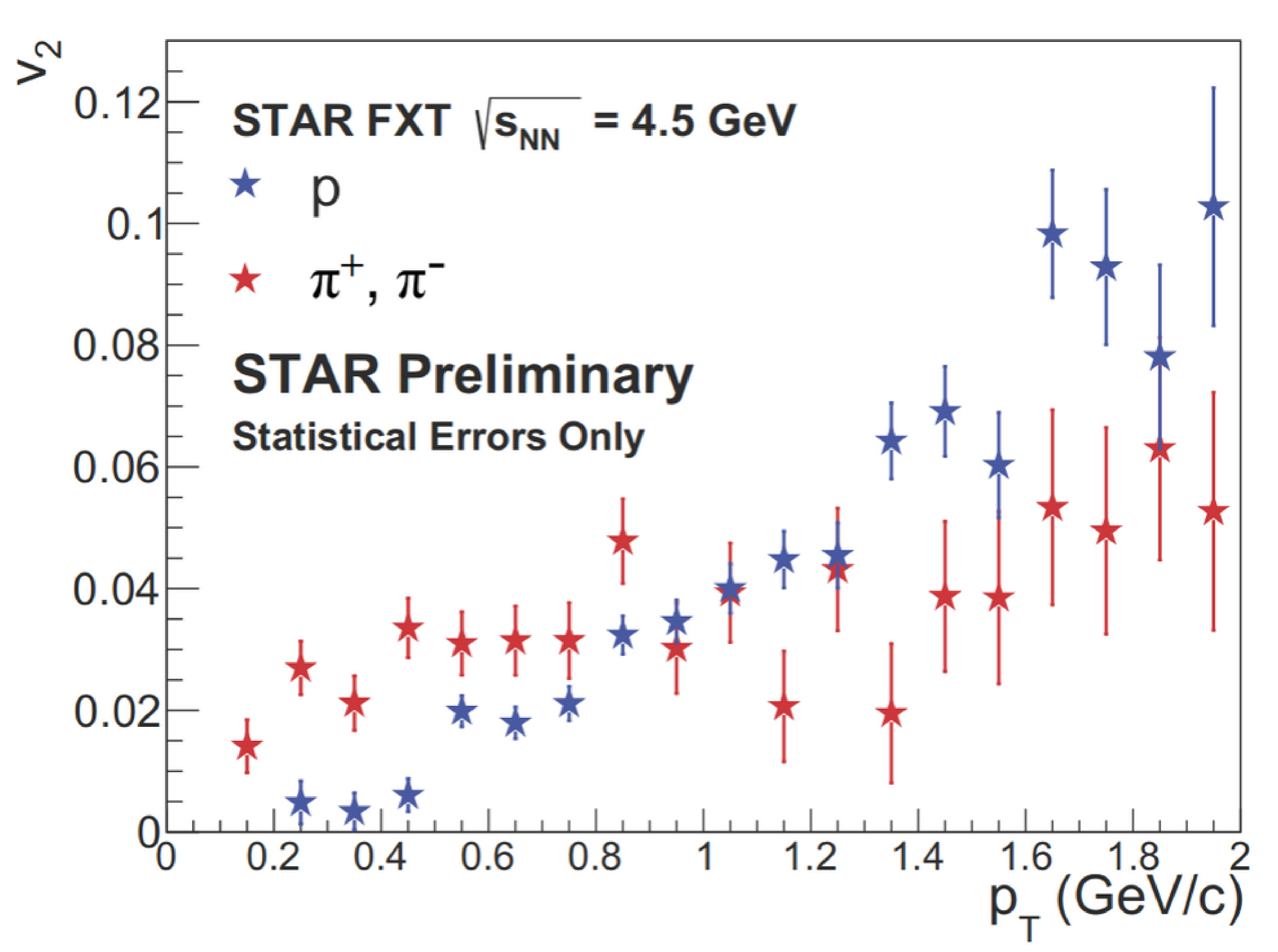

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FLUCTUATIONS AND CORRELATIONS IN NA61/SHINE

CONCLUSIONS

- **multiplicity fluctuations**: interesting behaviour of higher-order moments of different systems at 150/158A GeV/c - further investigation needed
- **net-charge fluctuations**: no indication of critical behaviour is observed
- **flow**: energy dependence in direct flow is observed, while in elliptic flow is not

THANK YOU!

Justyna Cybowska for the NA61/SHINE Collaboration

2-6 December 2019, Zimanyi School, Budapest

Acknowledgements:

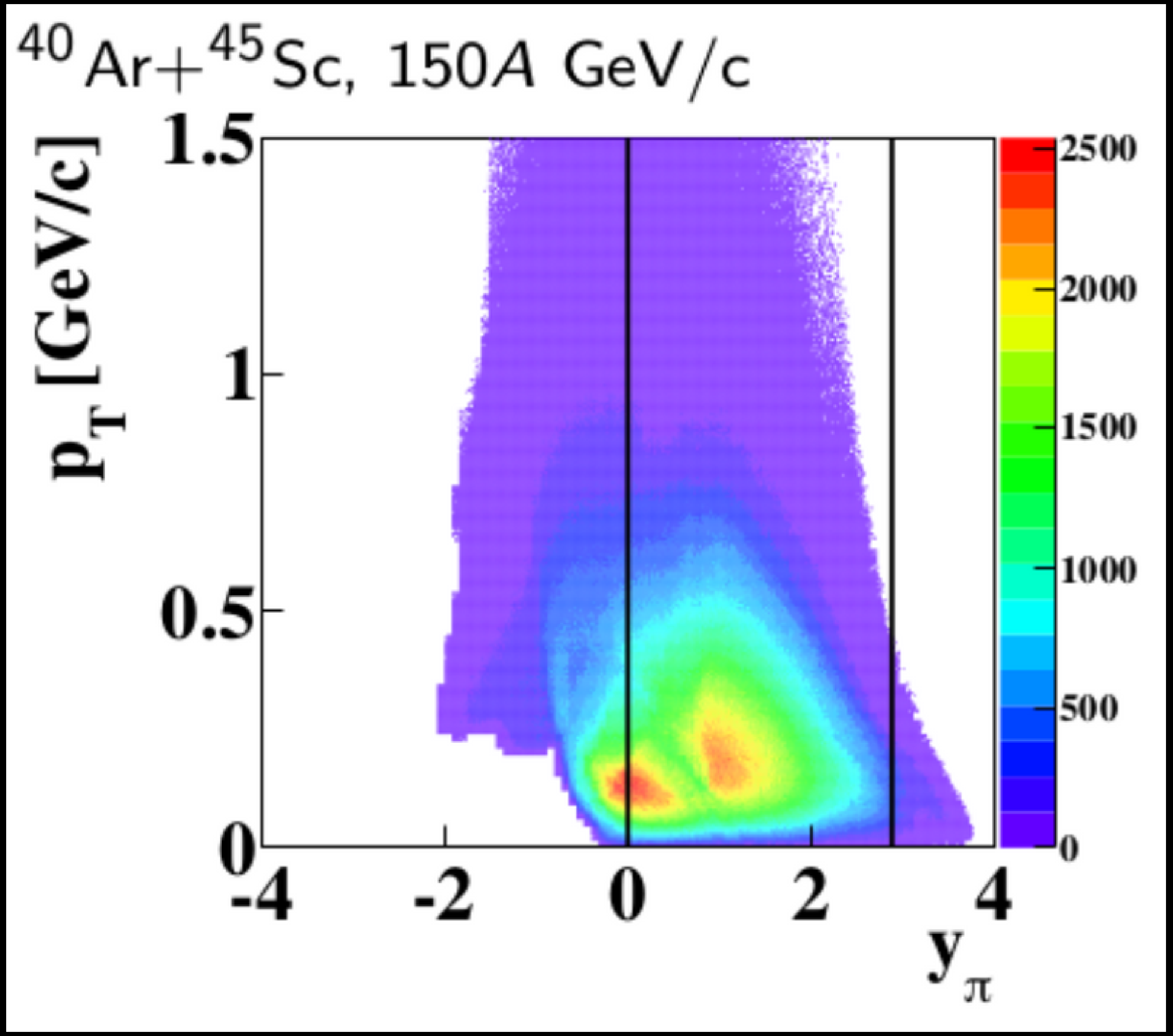
This work was supported by the National Science Centre, Poland under grants no. 2016/21/D/ST2/01983

Additional slides

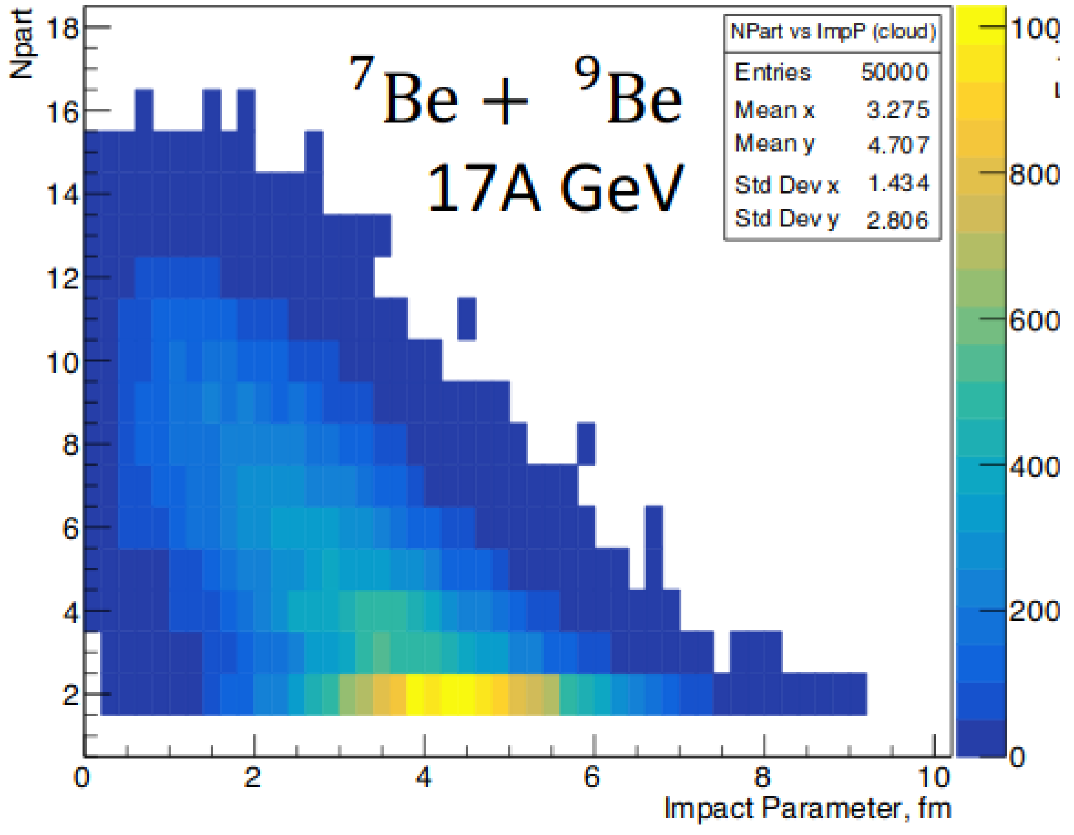
SHINE acceptance in fluctuation study

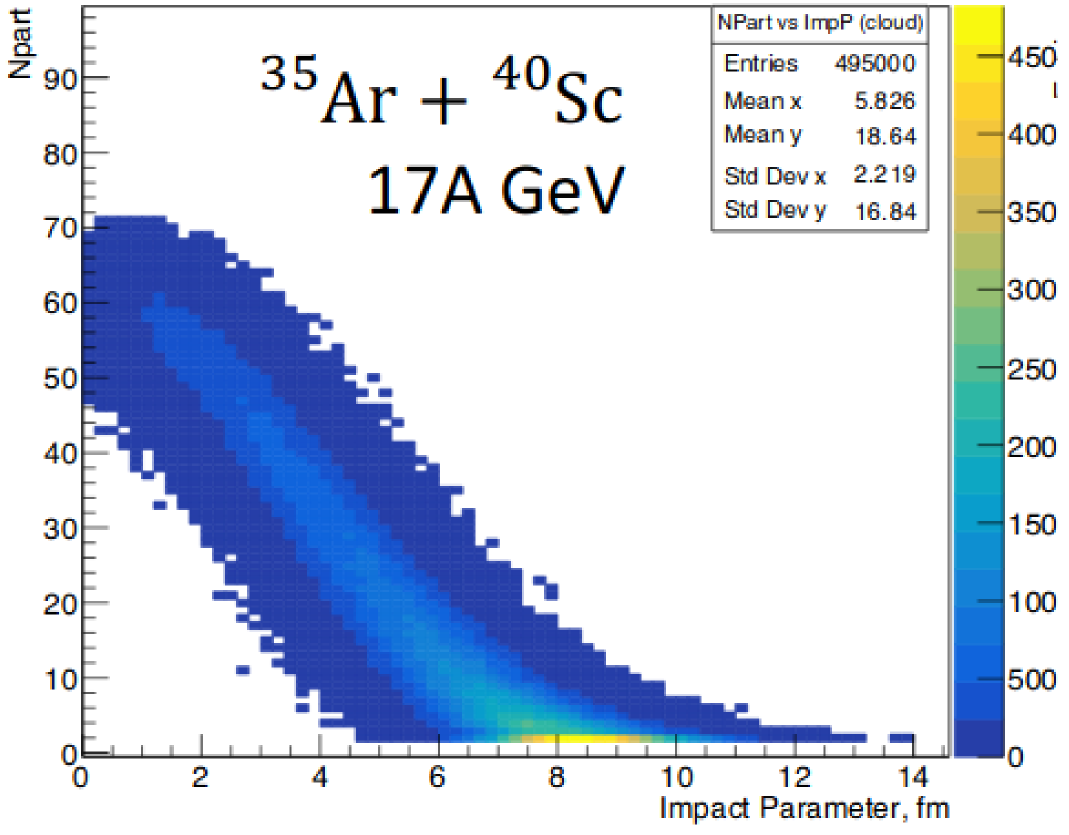
forward rapidity with p_T<1.5

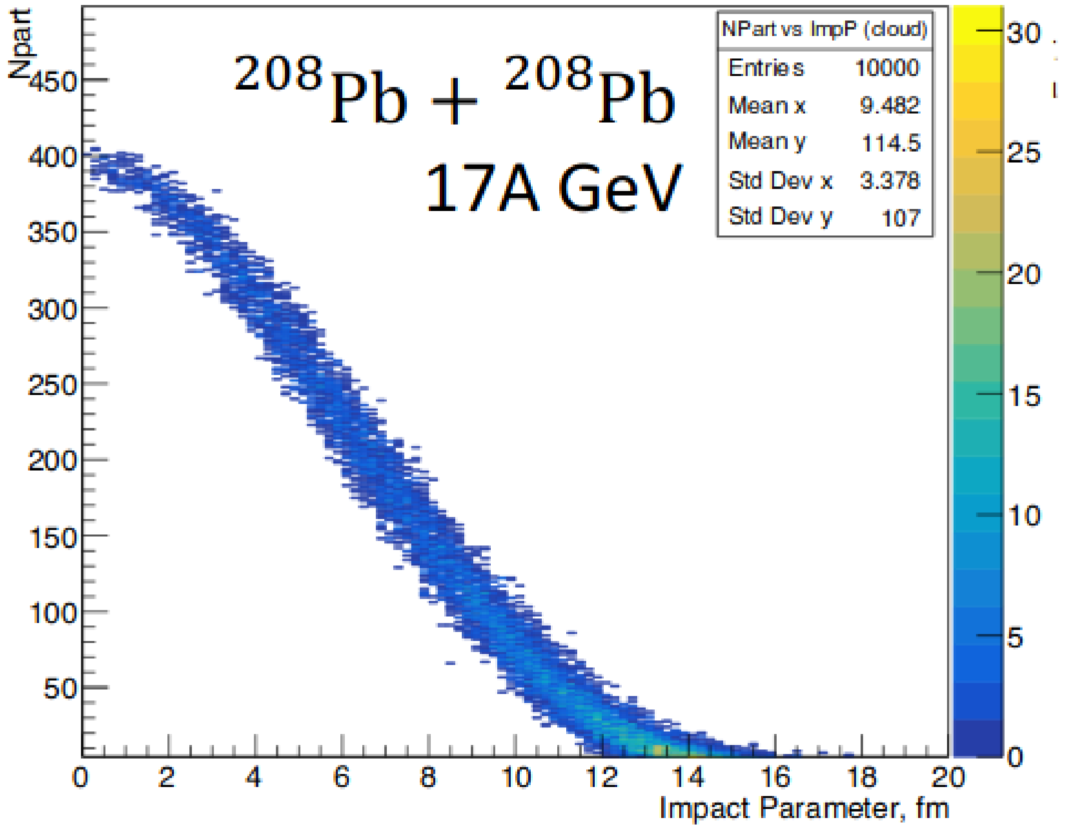
- p+p acceptance - full acceptance of NA61/SHINE (https://edms.cern.ch/document/1549298/1)
- Be+Be/Ar+Sc acceptance: NA61/SHINE p+p acceptance with additional rapidity cut: $0 < y_\pi < y_{beam}$



- Dilute system -> impact parameter isn't a meaningful quantity







A. Seryakov, Zimanyi Schoool 2018, Budapest

→ **centrality selection made with use of forward energy**

PSD

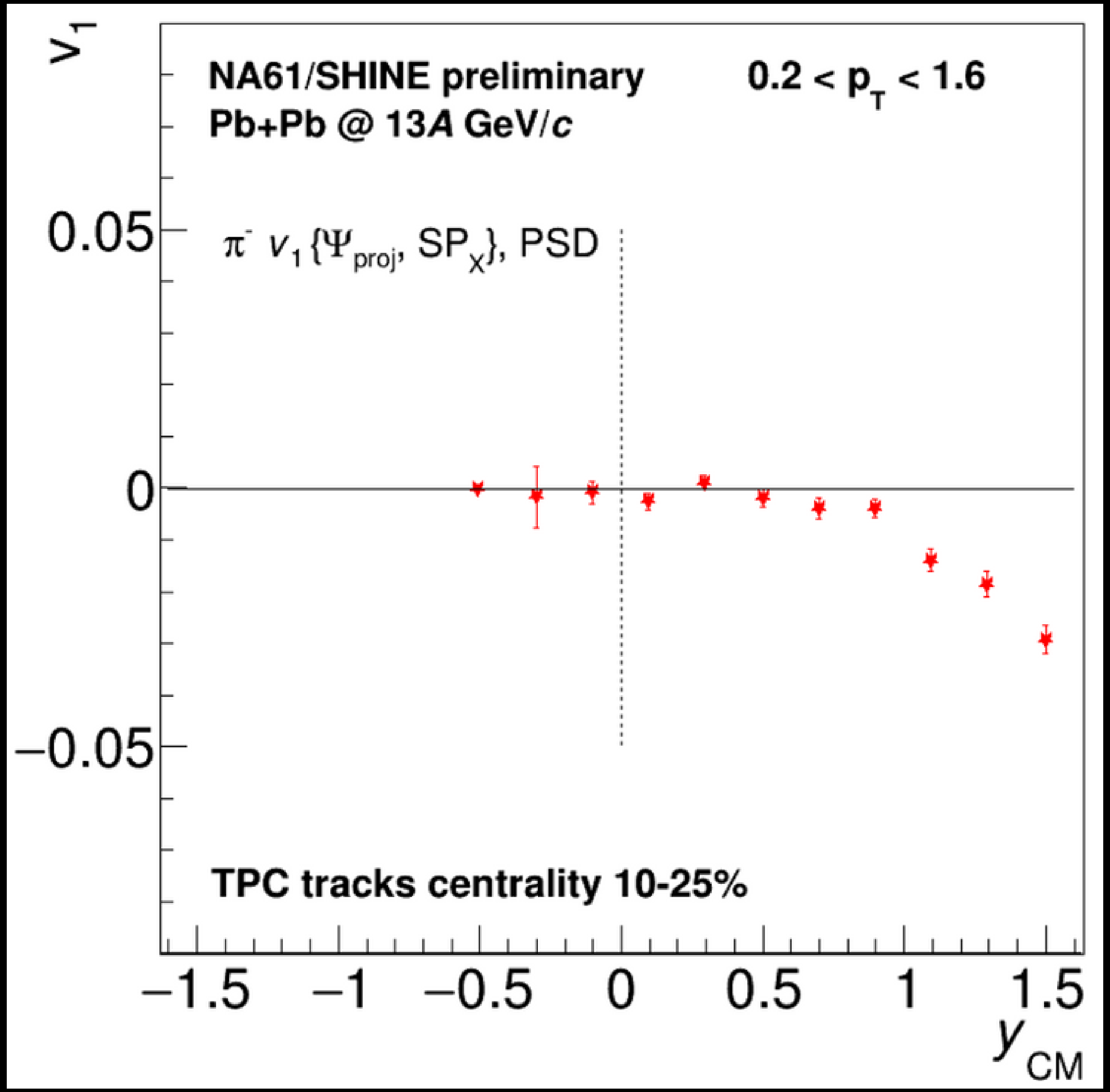
photo: A. Seryakov

NA61/SHINE RESULTS

Flow: Comparison with STAR

π-

NA61/SHINE



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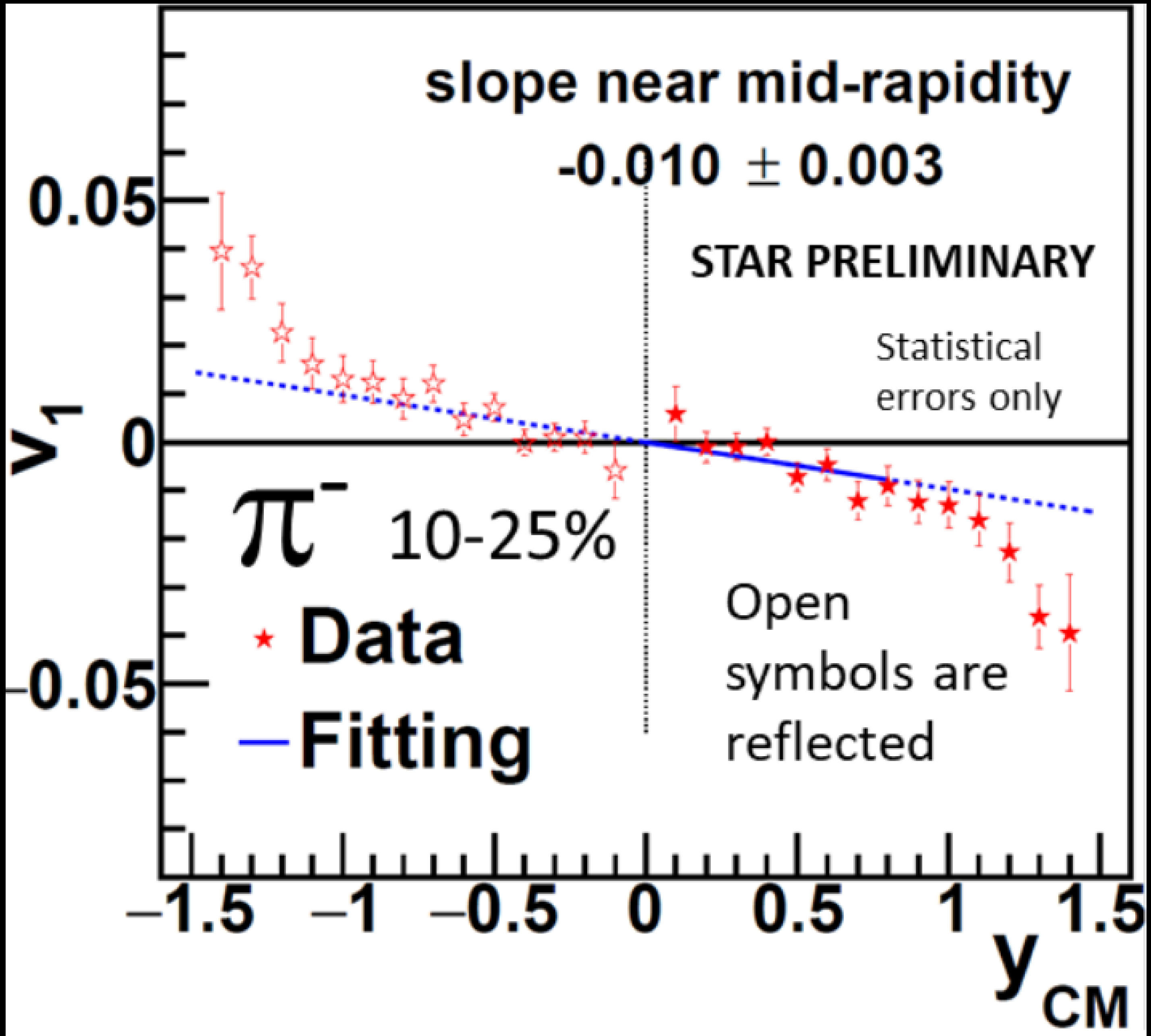

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Analysis technique

Flow coefficients v_n were measured using scalar-product method [9] from correlations of two-dimensional flow vectors $\mathbf{q_n}$ and $\mathbf{Q_n}$. The $\mathbf{q_n}$ is calculated event-by-event from azimuthal angles ϕ_i of the i-th particle's momentum:

$$\mathbf{q_n} = \frac{1}{M}\sum_{i=1}^{M} \mathbf{u_{1,n}}, \tag{2}$$

where $\mathbf{u_{n,i}} = (\cos n\phi_i, \sin n\phi_i)$ and M is selected particle' multiplicity in a given p_{T} and rapidity range. Spectators' symmetry plane is estimated with the $\mathbf{Q_1}$ direction determined from azimuthal asymmetry of energy deposition in PSD subevent A:

$$\mathbf{Q_1^{\mathrm{A}}} = \frac{1}{E_{\mathrm{A}}}\sum_{i=1}^{N_A} E_i \mathbf{n_i} \ , \tag{3}$$

where $E_{\mathrm{A}} = \sum_{i=1}^{N_A} E_i$ is the total energy deposited to PSD subevent A. Unit vector $\mathbf{n_i}$ points in the direction of the center of i-th PSD module and E_i is its measured energy.

Independent estimates of directed flow v_1 an elliptic flow v_2 are given by equations

$$v_1^{\alpha}\{A\} = \frac{2\langle q_{1,\alpha} Q_{1,\alpha}^{A}\rangle}{R_{1,\alpha}^{A}} \quad , \quad v_2^{\alpha\beta\gamma}\{A,B\} = \kappa_{\alpha\beta\gamma}\frac{4\langle q_{2,\alpha} Q_{1,\beta}^{A} Q_{1,\gamma}^{B}\rangle}{R_{1,\beta}^{A} R_{1,\gamma}^{B}}, \tag{4}$$

where $\alpha, \beta, \gamma = x, y$ are q_1 and Q_1 components and A, B - PSD subevents. Only four