

Implementing the universal framework for analysis of anisotropic flow for MPD and BM@N

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The work has been supported by the Ministry of Science and Higher Education of the Russian Federation, Project "Fundamental and applied research at the NICA (JINR) megascience experimental complex" № FSWU-2025-0014



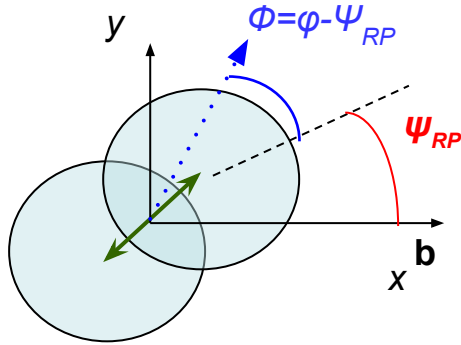
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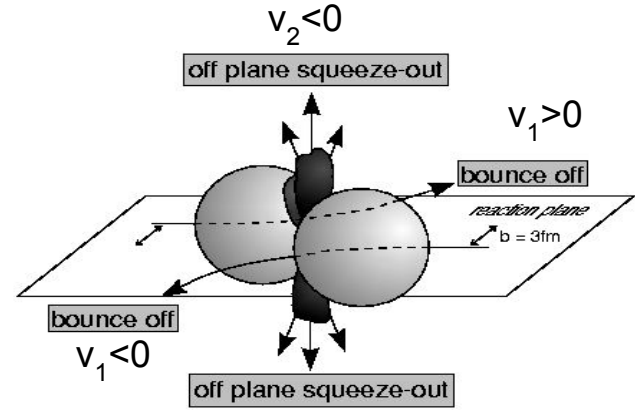
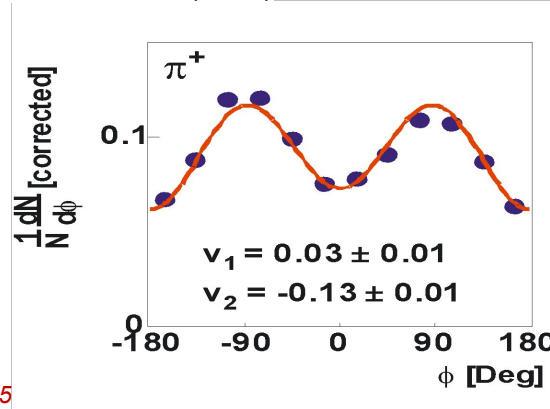


Azimuthal anisotropic flow 1989-2000

Diogene, M. Demoulin et al., Phys. Lett. B241, 476 (1990)
 Plastic Ball, H.H. Gutbrod et al., Phys. Lett. B216, 267 (1989)



S Voloshin, Y. Zhang, Z. Phys. C70,(1996), 665



$$\frac{d^2 N}{d\varphi d\Psi_{RP}} = \frac{N}{2\pi} \left(1 + 2 \sum_{n=1}^{\infty} v_n \cos n(\phi - \Psi_{RP}) \right)$$

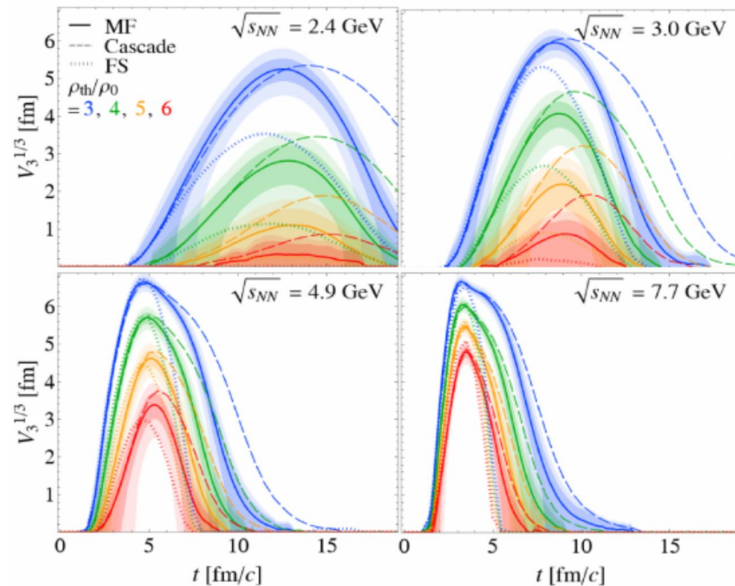
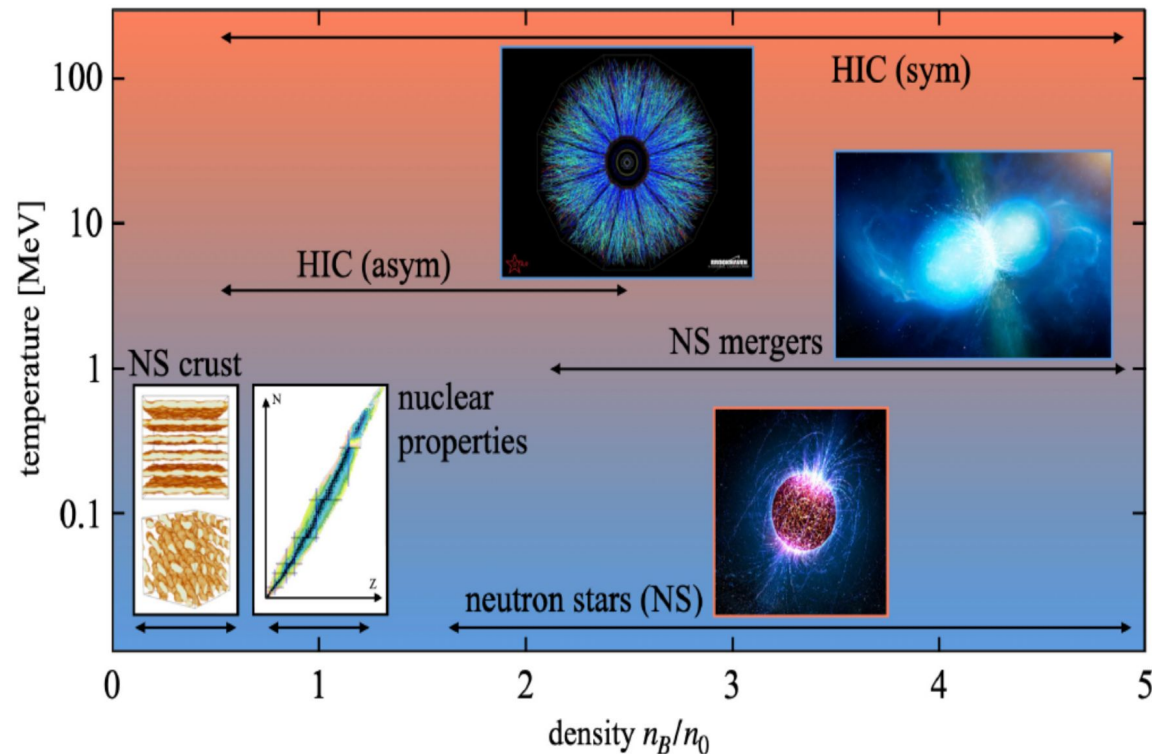
The anisotropy is quantified by decomposing the azimuthal distribution in a Fourier series

$$v_n = \langle \cos n(\phi - \Psi_{RP}) \rangle$$

v_1 is directed flow, v_2 — elliptics and v_3 — triangular

Compressed baryonic matter at the laboratory and in astrophysics

J.Subatomic Part.Cosmol. 3 (2025) 100015



Equation of state (EoS) of compressed baryonic matter

Pressure

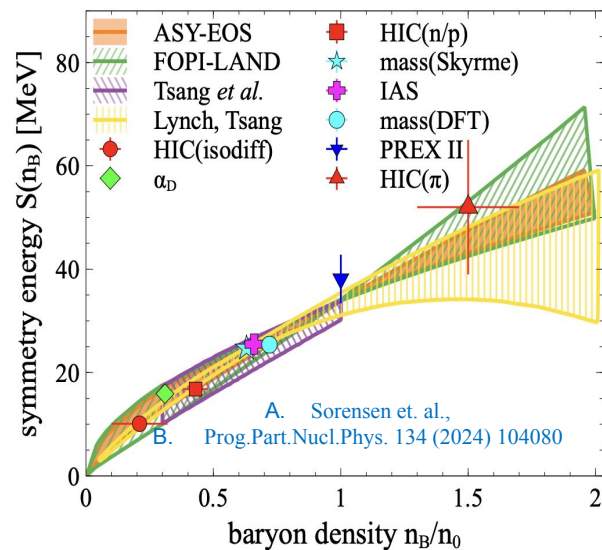
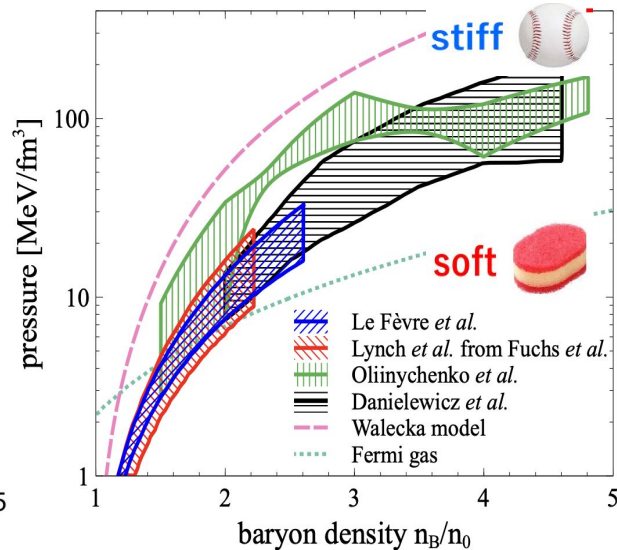
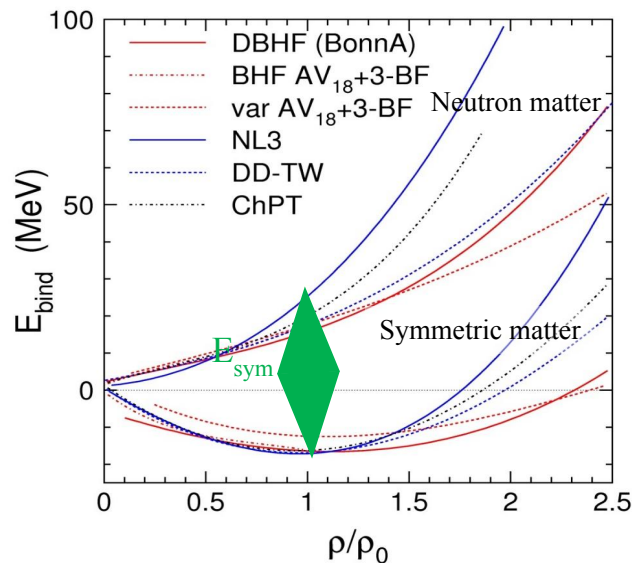
$$P = n^2 \frac{d(E/A)}{dn_b}$$

Energy per nucleon $\rightarrow \frac{E}{A} = m_N + E_A(n_B) + E_{\text{sym}}(n_B) \frac{(n_p - n_n)^2}{n_B^2}$

Isospin asymmetry $n_B = n_p + n_n$

Isospin-symmetric matter

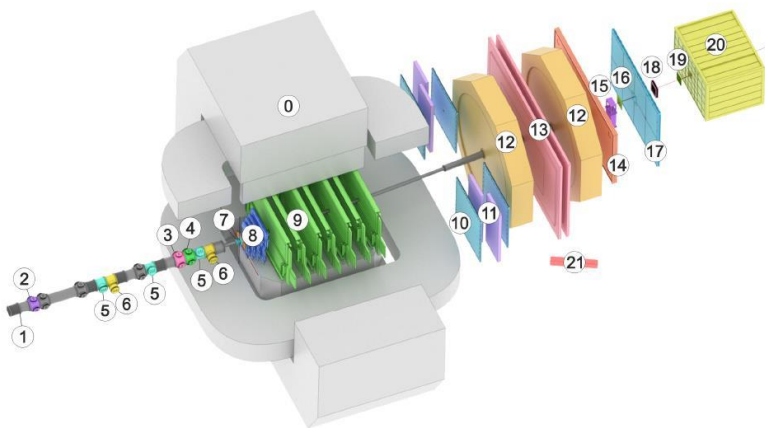
Symmetry energy



EOS relates the density (n_B), pressure (P), temperature (T), energy (E), and isospin asymmetry $(n_p - n_n)/n_B$

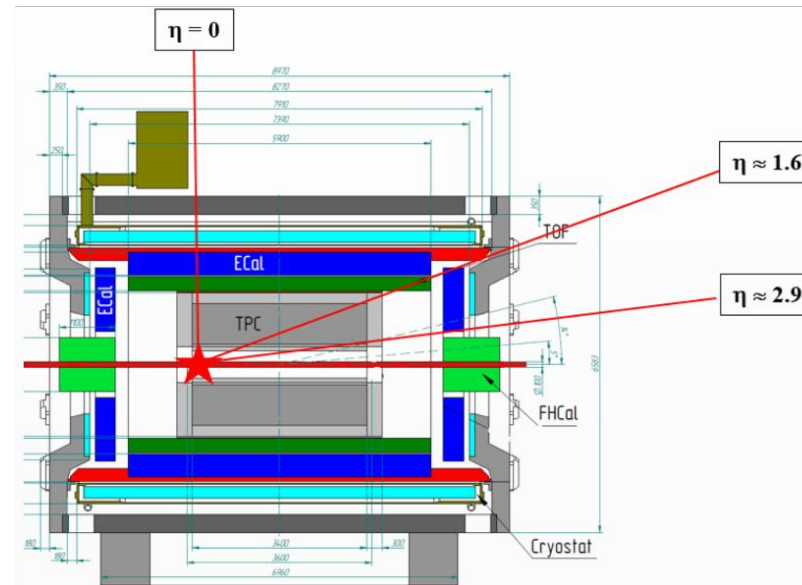
BM@N and MPD experimental setups

BM@N experiment



- Magnet SP-41 (0)
- Vacuum Beam Pipe (1)
- BC1, VC, BC2 (2-4)
- SiBT, SiProf (5, 6)
- Triggers: BD + SiMD (7)
- FSD, GEM (8, 9)
- CSC 1x1 m² (10)
- TOF 400 (11)
- DCH (12)
- TOF 700 (13)
- ScWall (14)
- FD (15)
- Small GEM (16)
- CSC 2x1.5 m² (17)
- Beam Profilometer (18)
- FQH (19)
- FHCAL (20)
- HGN (21)

MPD-FXT



Flow vectors u_n and Q_n

For each particle a unit-vector (u_n) is defined using its azimuthal angle:

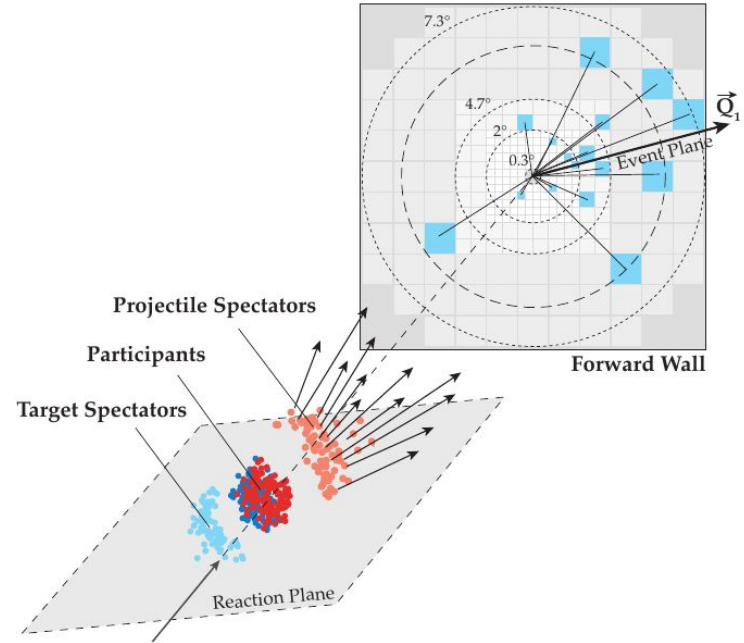
$$\vec{u}_n = (\cos n\varphi, \sin n\varphi)$$

where φ — azimuthal angle

Sum over a group of particles in a single event gives an estimation of reaction plane orientation:

$$\vec{Q}_n = \frac{\sum_{k=1}^M w_k u_n^k}{C} = \frac{|Q|}{C} (\cos n\Psi_n^{EP} \sin n\Psi_n^{EP})$$

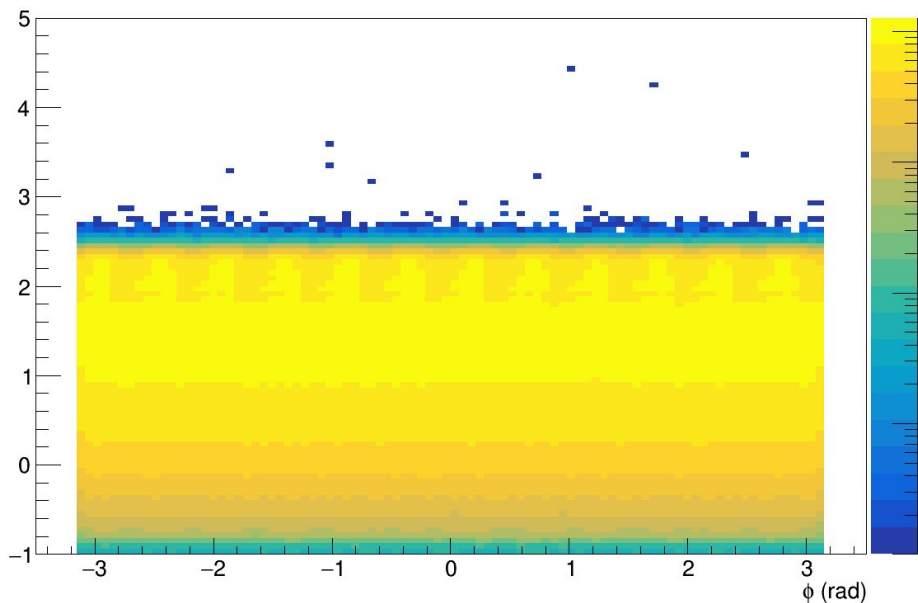
Ψ_n^{EP} — symmetry plane angle
(reaction plane estimation)



- Reaction plane is usually estimated using the spectators in the forward detector

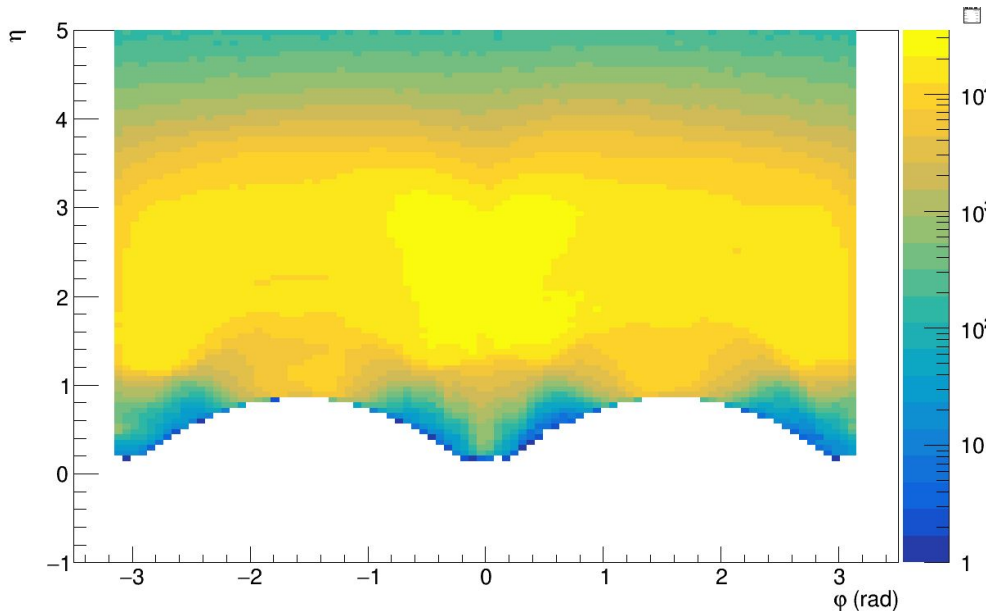
Influence of azimuthal acceptance on v_n

Uniform azimuthal acceptance



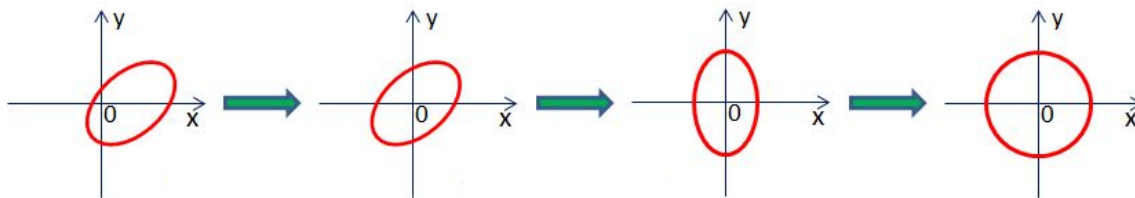
$$\frac{\langle u_n^x Q_n^x \rangle}{R_n^x} = \frac{\langle u_n^y Q_n^y \rangle}{R_n^y}$$

Non-uniform azimuthal acceptance

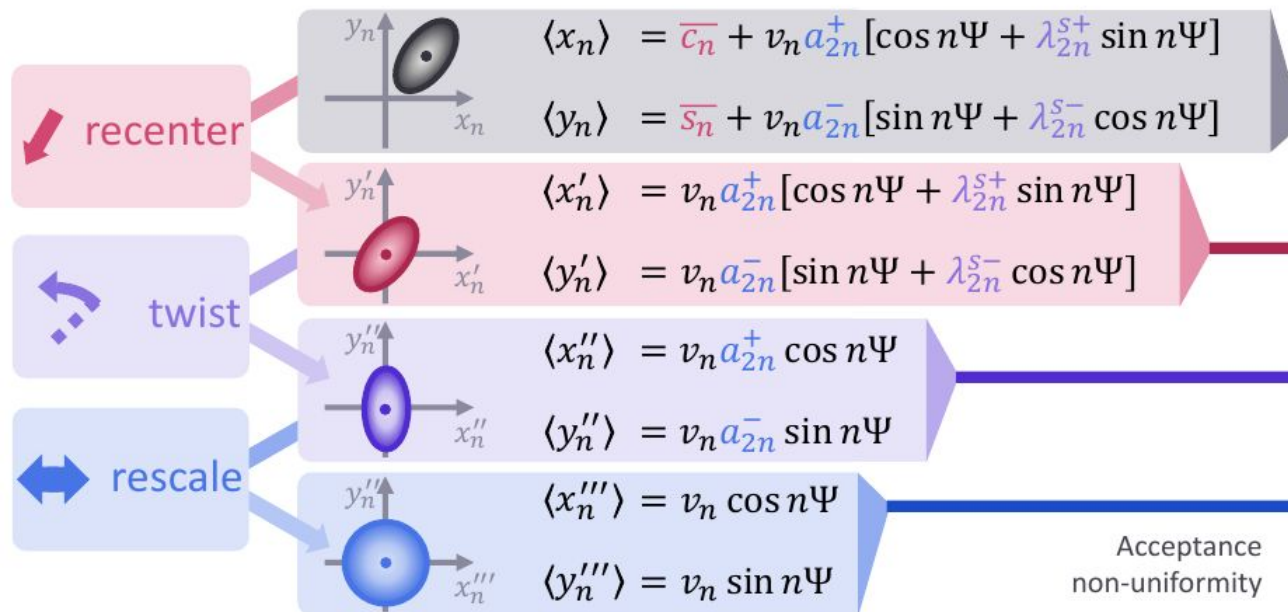


$$\frac{\langle u_n^x Q_n^x \rangle}{R_n^x} \neq \frac{\langle u_n^y Q_n^y \rangle}{R_n^y}$$

Corrections for azimuthal non-uniformity

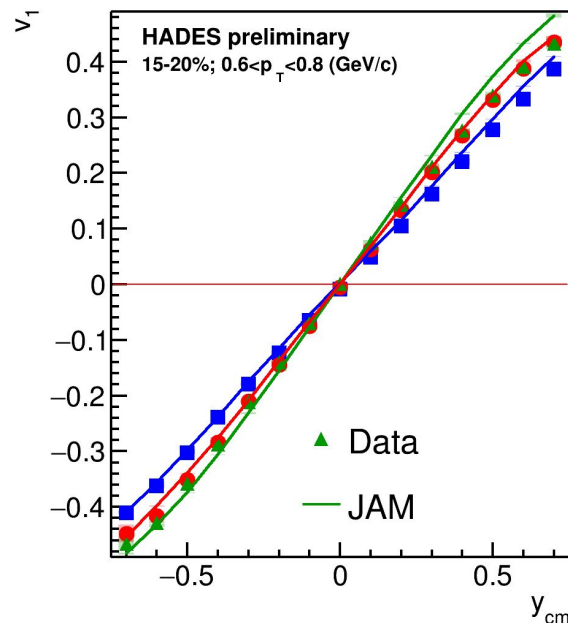
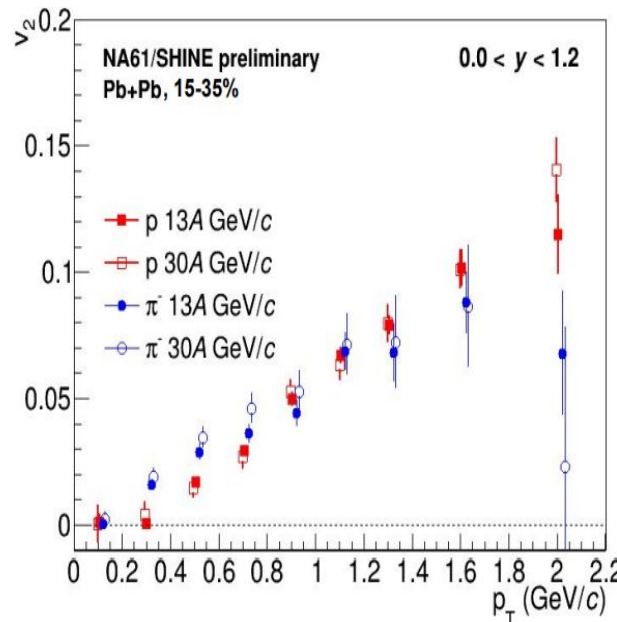
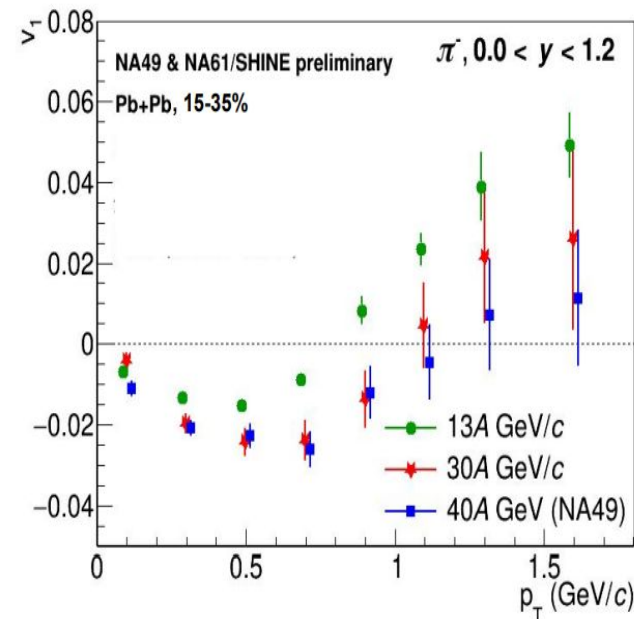
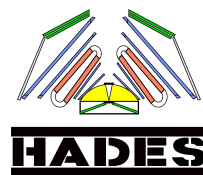
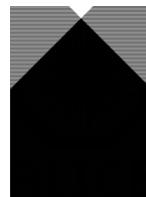


Bias in the single particle / flow vector ($n=m$)



Method for correcting the azimuthal non-uniformity was suggested in Phys.Rev.C77:034904,2008

QnTools framework



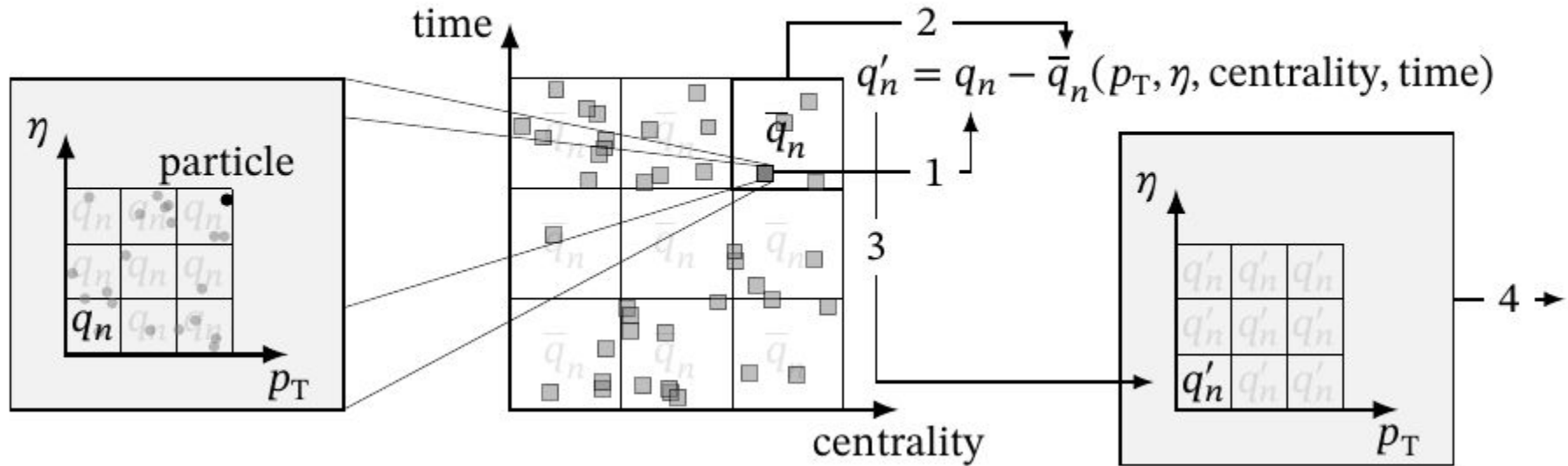
- All the methods used for performance study were carried out using QnTools framework: <https://github.com/HeavyIonAnalysis/QnTools> (well documented and well-tested)
- Methods for flow measurements in fixed-target experiments were tested on experimental data from NA61/SHINE, HADES and ALICE
- Tested and implemented in MPD root

Applying the corrections on azimuthal non-uniformity

Create Flow Vectors
in each collision

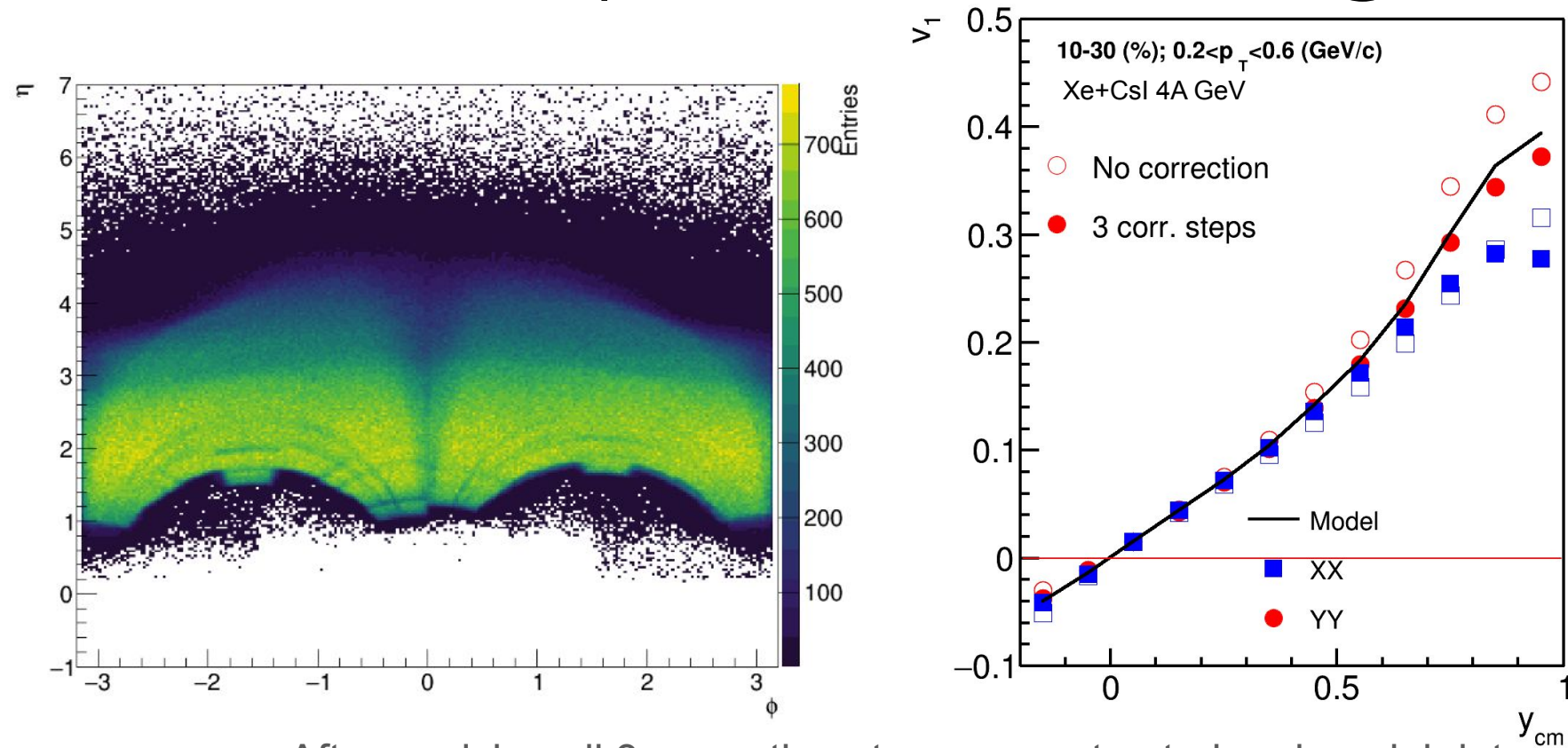
Calculate Corrections
using all collisions

Apply Corrections
in each collision



QnTools allows for applying corrections multidifferentially. For example for BM@N for 3 axis: 10 bins in p_T , 16 bins in y_{cm} and 8 bins in centrality

Non-uniform acceptance corrections in BM@N



After applying all 3 correction steps reconstructed and model data are in agreement

Flow methods for v_n calculation

Tested in HADES:

M Mamaev et al 2020 PPNuclei 53, 277–281

M Mamaev et al 2020 J. Phys.: Conf. Ser. 1690 012122

Scalar product (SP) method:

$$v_1 = \frac{\langle u_1 Q_1^{F1} \rangle}{R_1^{F1}} \quad v_2 = \frac{\langle u_2 Q_1^{F1} Q_1^{F3} \rangle}{R_1^{F1} R_1^{F3}}$$

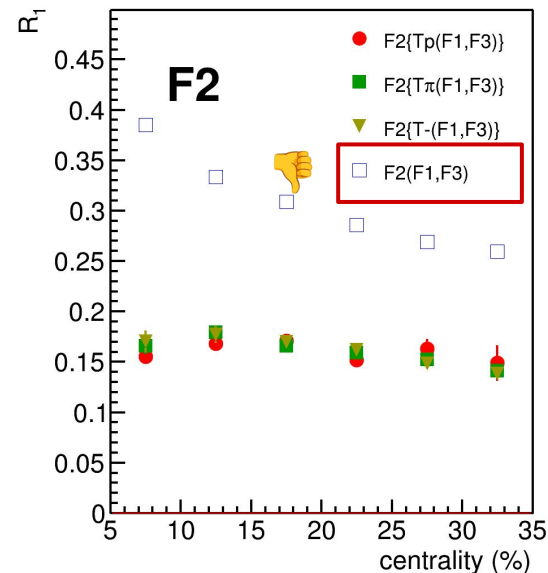
Where R_1 is the resolution correction factor

$$R_1^{F1} = \langle \cos(\Psi_1^{F1} - \Psi_1^{RP}) \rangle$$

Symbol “F2(F1,F3)” means R_1 calculated via (3S resolution):

$$R_1^{F2(F1,F3)} = \frac{\sqrt{\langle Q_1^{F2} Q_1^{F1} \rangle \langle Q_1^{F2} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}$$

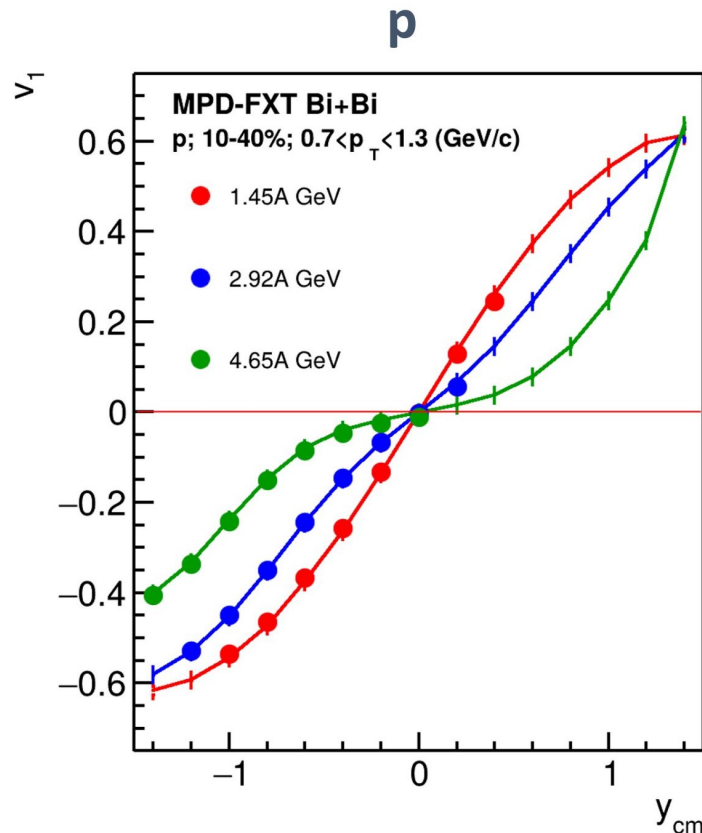
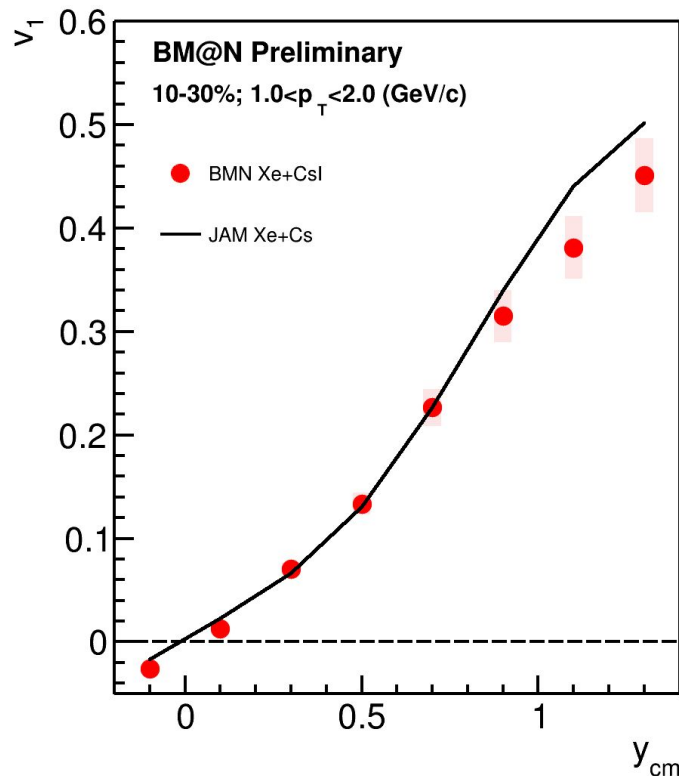
Method helps to eliminate non-flow
Using 2-subevents doesn't



Symbol “F2{Tp}(F1,F3)” means R_1 calculated via (4S resolution):

$$R_1^{F2\{Tp\}(F1,F3)} = \langle Q_1^{F2} Q_1^{Tp} \rangle \frac{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{Tp} Q_1^{F1} \rangle \langle Q_1^{Tp} Q_1^{F3} \rangle}}$$

Collective flow measurements using QnTools in BM@N and MPD



Using QnTools allows for performing the robust v_n estimation independently on experimental setup

Auxiliary packages

QnTools interface for simple ROOT-trees:

https://github.com/mam-mih-val/qntools_macros

Package for arithmetics with QnTools-correlations:

<https://github.com/mam-mih-val/calc2>

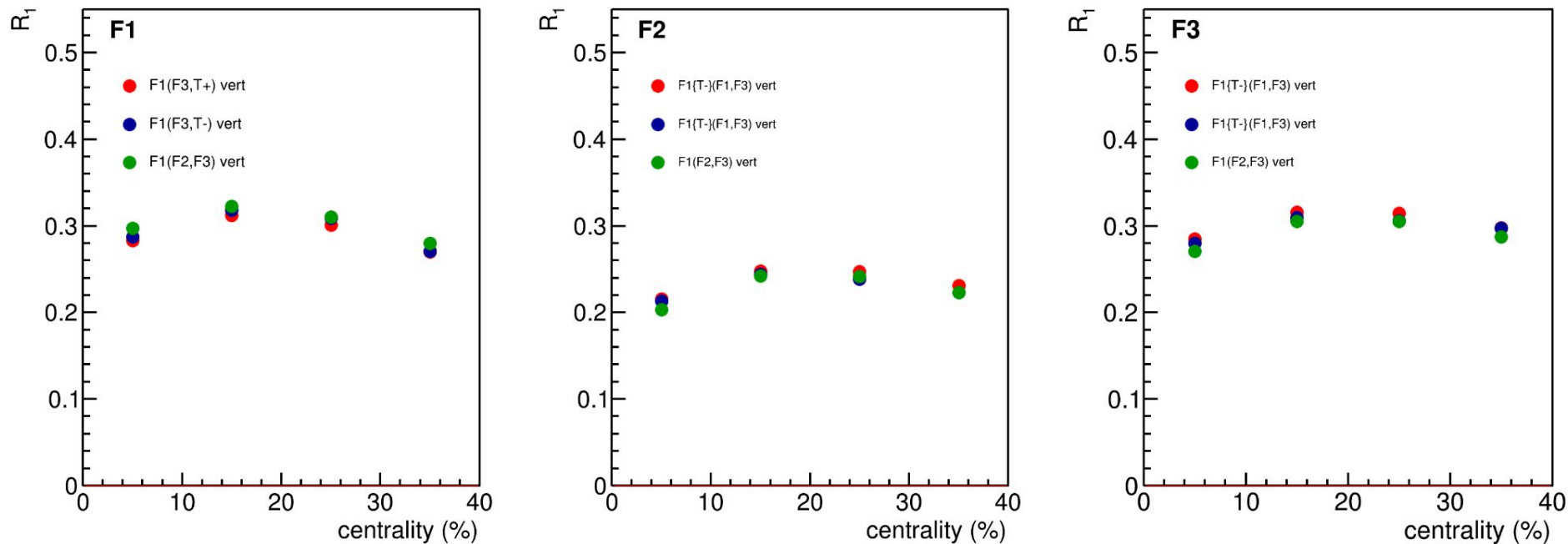
Package simplifying drawing graphs out of QnTools-correlations:

<https://github.com/mam-mih-val/ris2>

Summary

- Directed flow of protons is measured multidifferentially as a function of p_T , y and centrality
- The JAM model describes the $v_1(y)$ reasonably well in high transverse momentum region
- The directed flow slope at midrapidity $dv_1/dy|_{y=0}$ was extracted
- The results for directed flow slope dv_1/dy of protons are in a good agreement with the world data

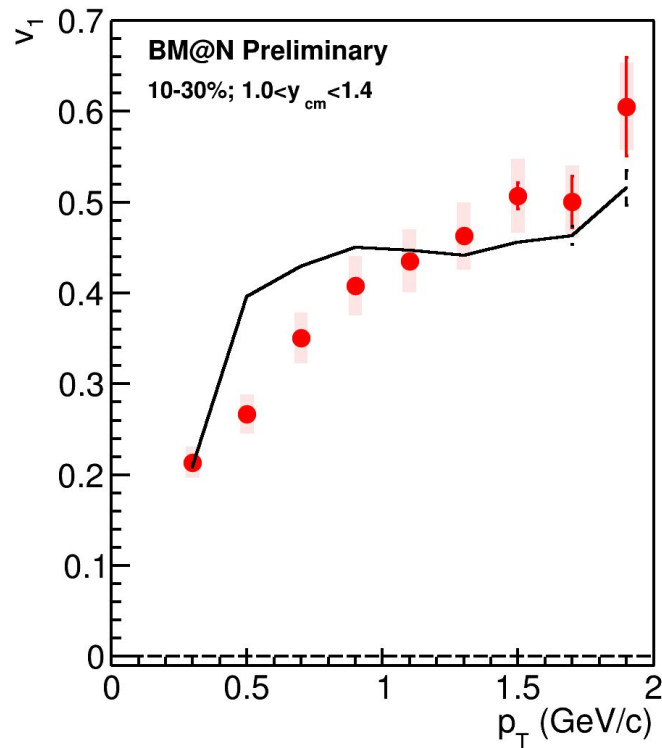
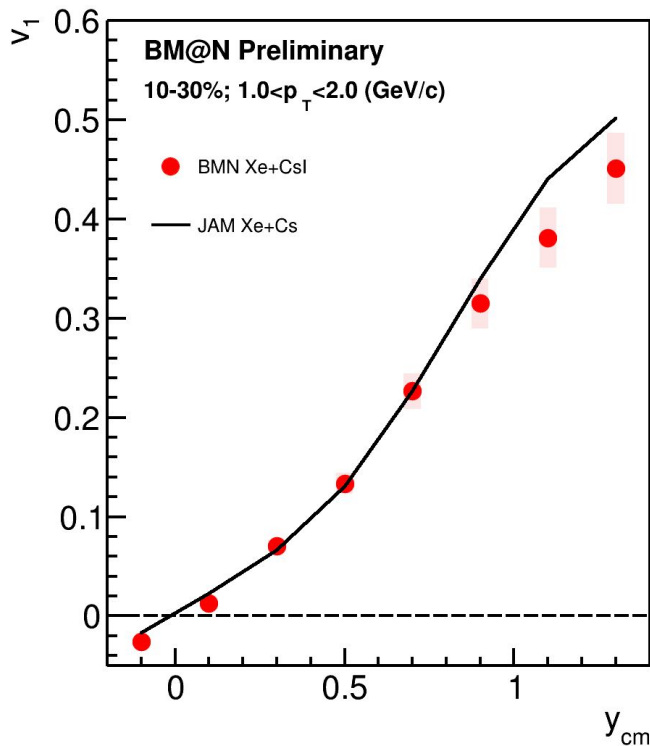
Symmetry plane resolution in Xe+CsI at $E_{\text{kin}}=3.8A$ GeV



All the R_1 estimations are in a good agreement which suggests low non-flow contribution

Proton v_1 vs rapidity and transverse momentum

Mamaev M. Int. J. Mod. Phys. E. — 2024. — T. 33, №11. — C. 2441009.



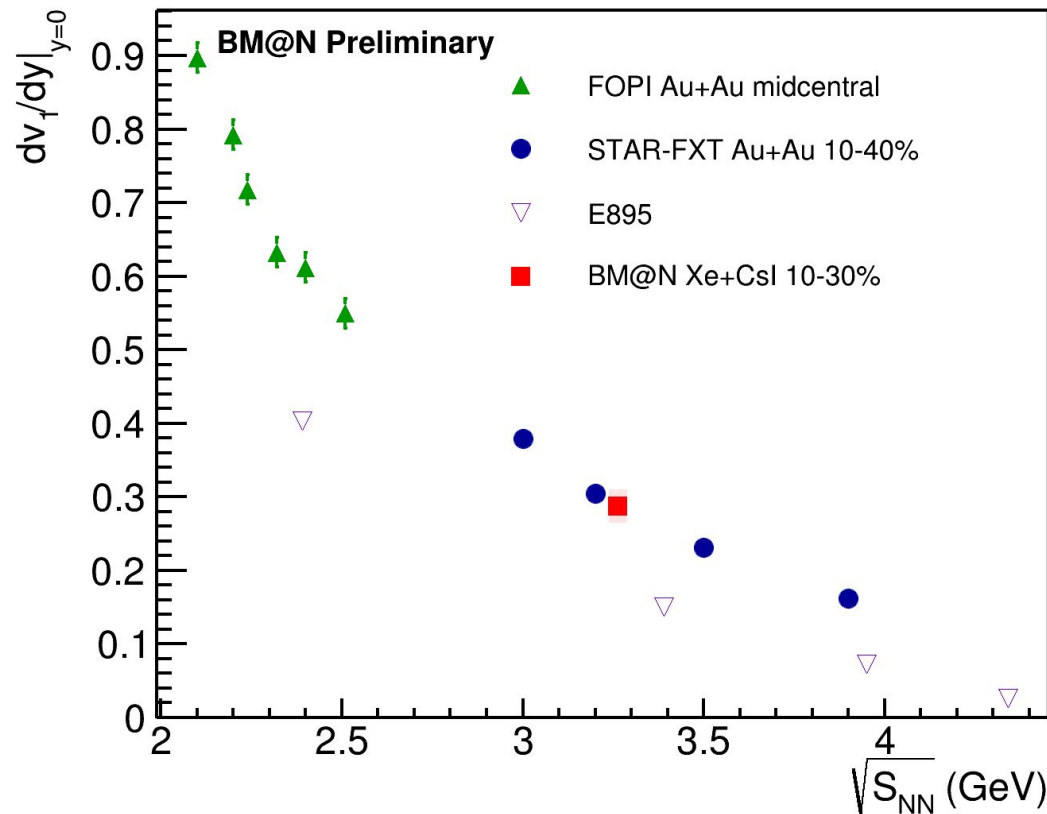
JAM agrees with experimental data within 8% at rapidities $y_{cm} < 1$

$dv_1/dy|_{y=0}$ vs collision energy

FOPI: Nucl.Phys.A 876 (2012)

STAR: Phys.Lett.B 827 (2022)

E895: Phys.Rev.Lett. 84 (2000)



- Proton data from BM@N agree with STAR measurements
- Higher directed flow of proton in BM@N and STAR data suggests more hard equation of state

BACKUP

Flow vectors

From momentum of each measured particle
define a u_n -vector in transverse plane:

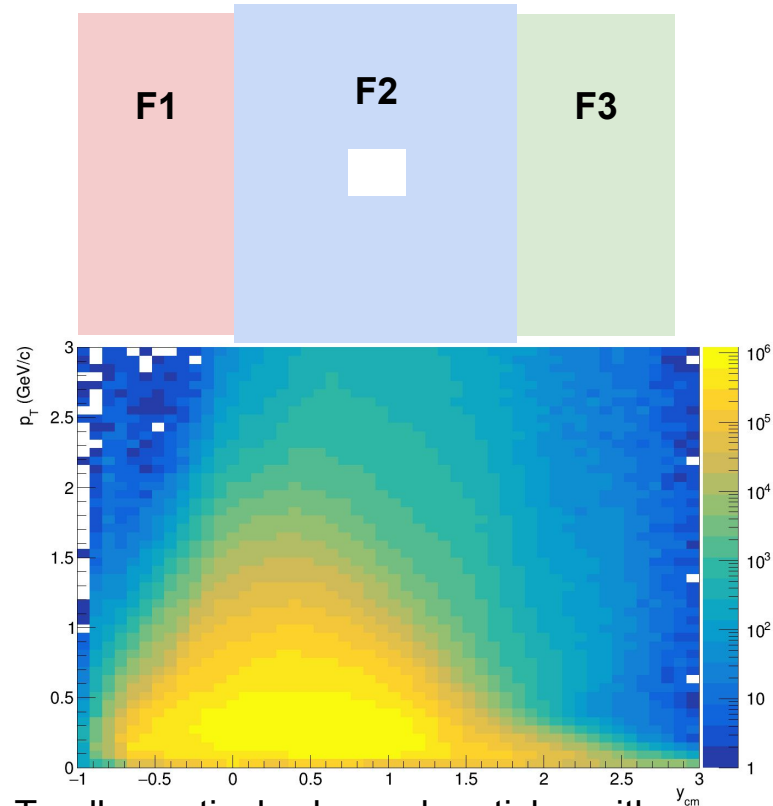
$$u_n = e^{in\phi}$$

where ϕ is the azimuthal angle

Sum over a group of u_n -vectors in
one event forms Q_n -vector:

$$Q_n = \frac{\sum_{k=1}^N w_n^k u_n^k}{\sum_{k=1}^N w_n^k} = |Q_n| e^{in\Psi_n^{EP}}$$

Ψ_n^{EP} is the event plane angle



T-: all negatively charged particles with:

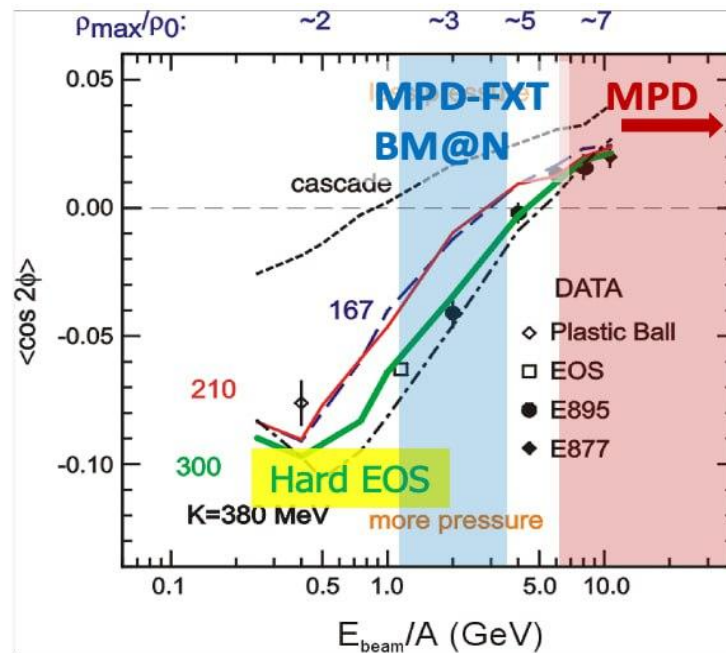
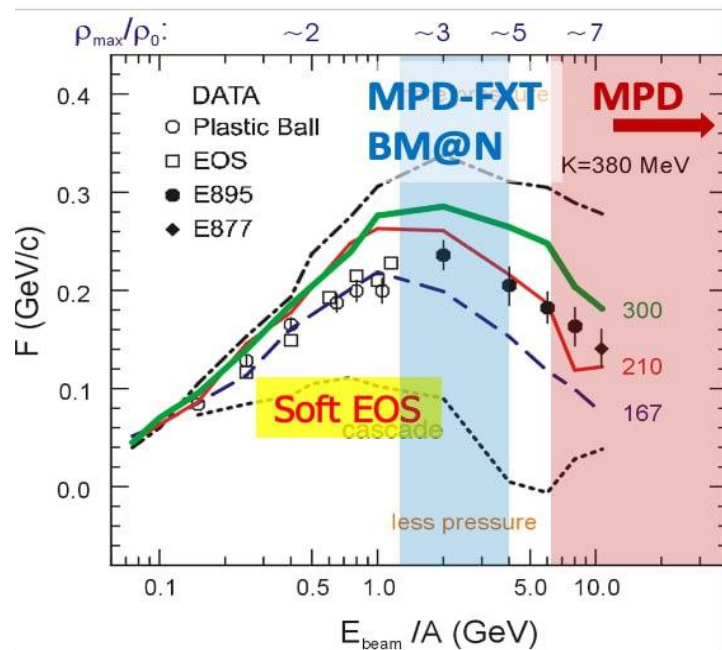
- $1.5 < \eta < 4$
- $p_T > 0.2 \text{ GeV/c}$

T+: all positively charged particles with:

- $2.0 < \eta < 3$
- $p_T > 0.2 \text{ GeV/c}$

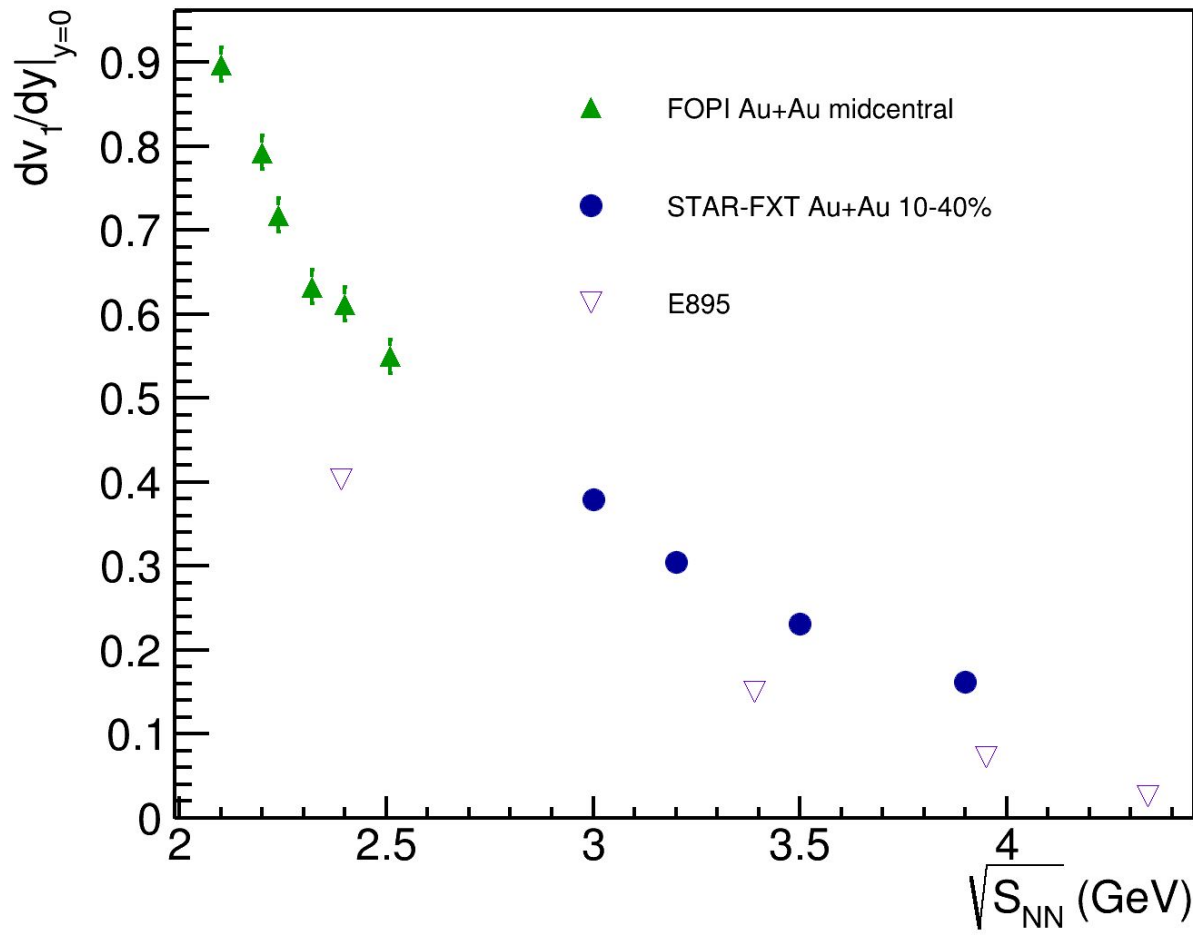
v_n at the energy of NUCLOTRON-NICA

P. DANIELEWICZ, R. LACEY, W. LYNCH
10.1126/science.1078070



- **Ambiguity of comparing experimental v_n with theoretical predictions:**
 - v_1 suggests $K_{\text{nm}} \sim 210$ MeV and v_2 suggests $K_{\text{nm}} \sim 300$ MeV
- **Additional measurements are needed to address the discrepancy of K_{nm}**

Need for a new measurements for ν_1



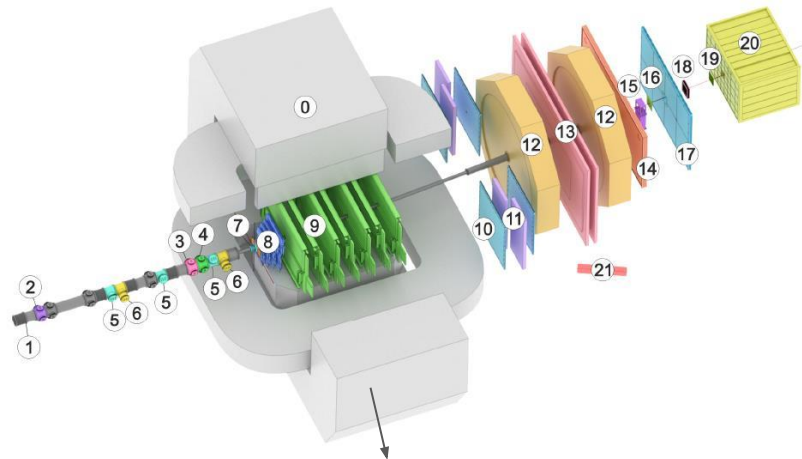
The new results are needed to address the discrepancy of dv_1/dy measured by E895 and STAR

FOPI: Nucl.Phys.A 876 (2012)
STAR: Phys.Lett.B 827 (2022)
E895: Phys.Rev.Lett. 84 (2000)

The BM@N experiment (“Baryonic matter at Nuclotron”)

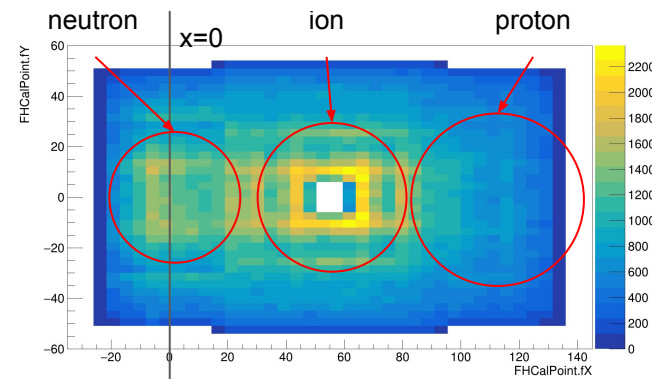
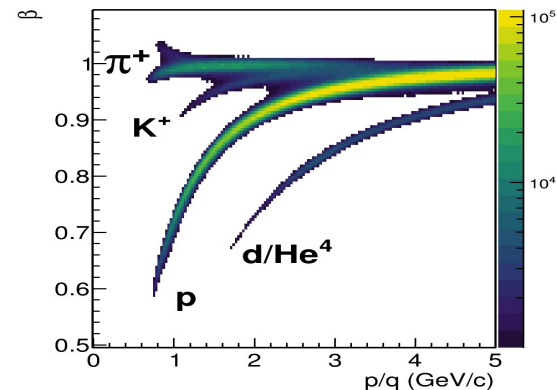
500M of Xe+Csl at $E_{\text{kin}}=3.8A$ GeV were collected in the early 2023

Nucl.Instrum.Meth.A 1065 (2024)



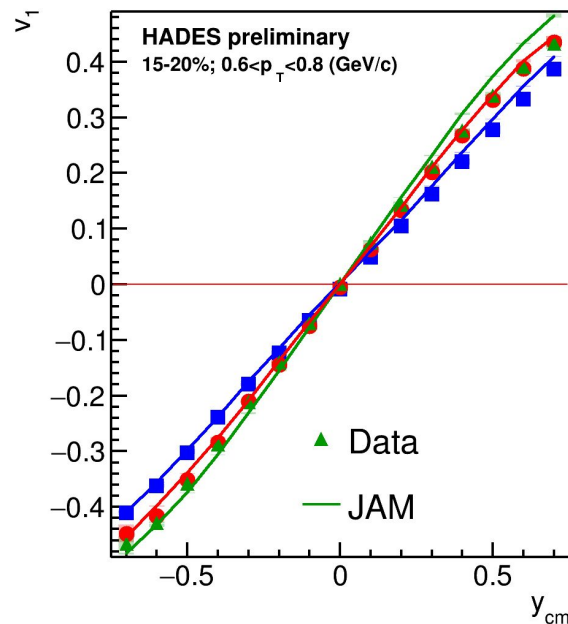
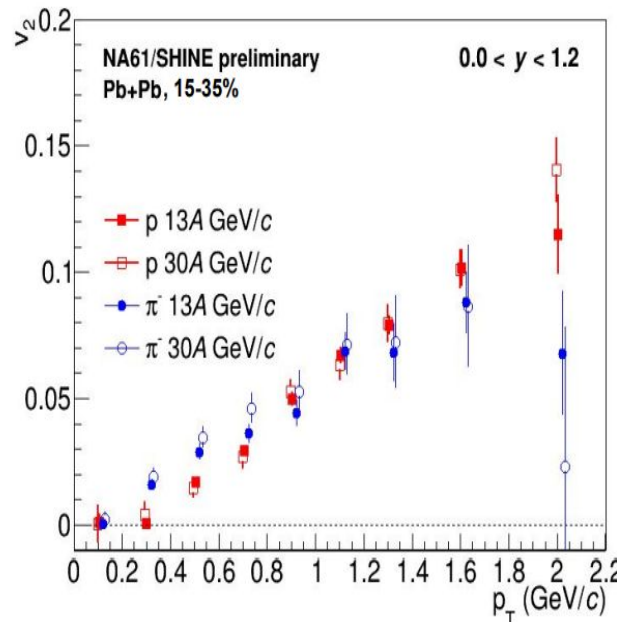
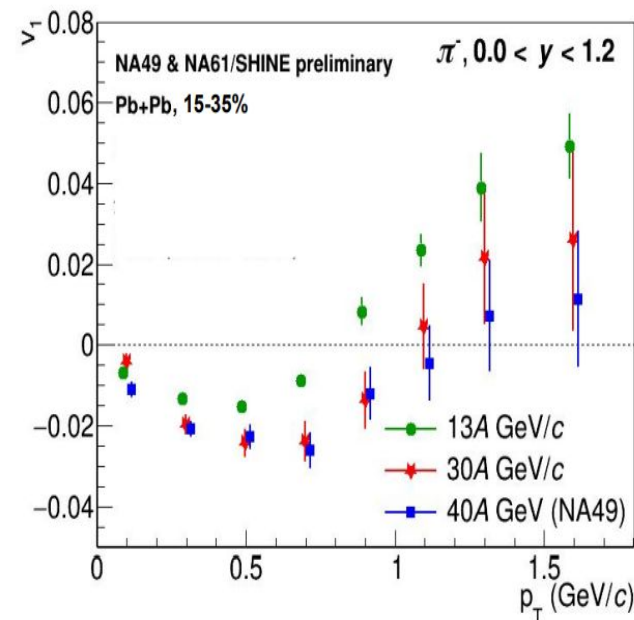
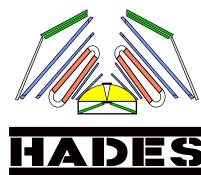
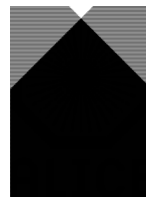
Central tracked inside the analysing magnet

- Magnet SP-41 (0)
- Vacuum Beam Pipe (1)
- BC1, VC, BC2 (2-4)
- SiBT, SiProf (5, 6)
- Triggers: BD + SiMD (7)
- FSD, GEM (8, 9)
- CSC 1x1 m² (10)
- TOF 400 (11)
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- Small GEM (16)
- CSC 2x1.5 m² (17)
- Beam Profilometer (18)
- FQH (19)
- FHCAL (20)
- HGN (21)



The symmetry plane is estimated using the azimuthal asymmetry of the spectator fragment energy deposition in FHCAL

QnTools framework



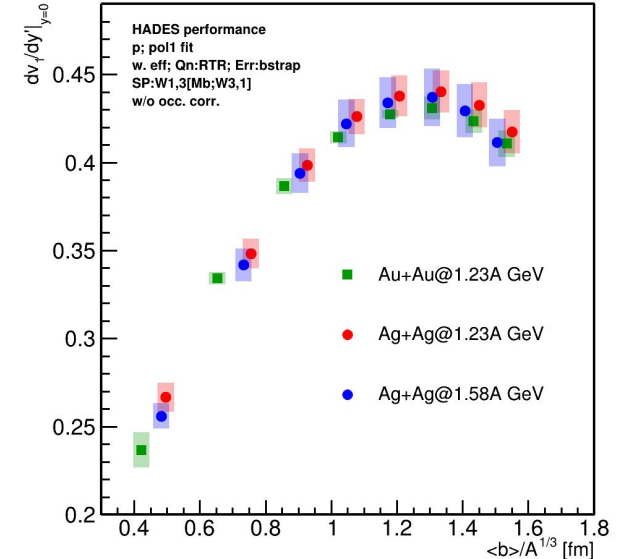
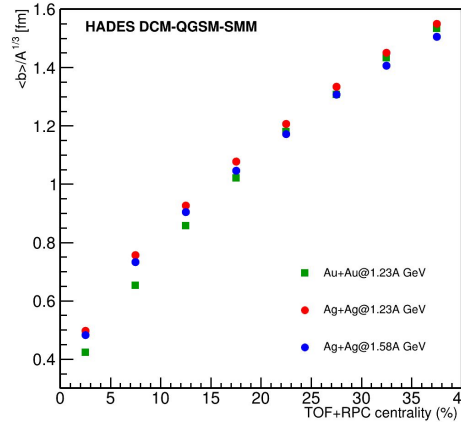
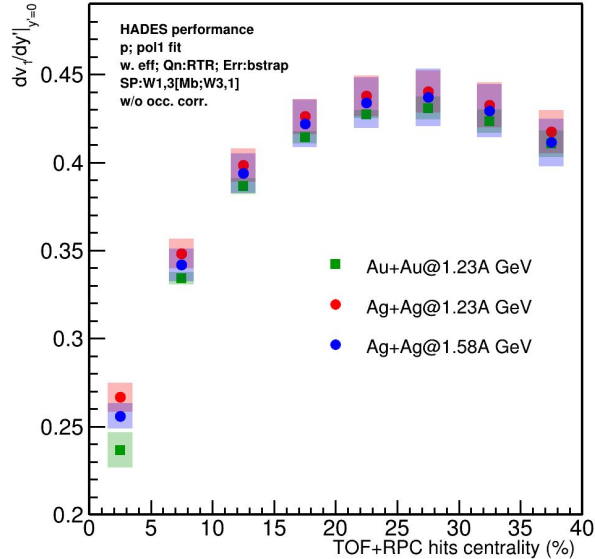
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- Tested and implemented in MPD root

Масштабирование dv_1/dy с энергией столкновения и размером системы

$$y_{CM} \rightarrow y' = y_{CM} / y_{beam}$$

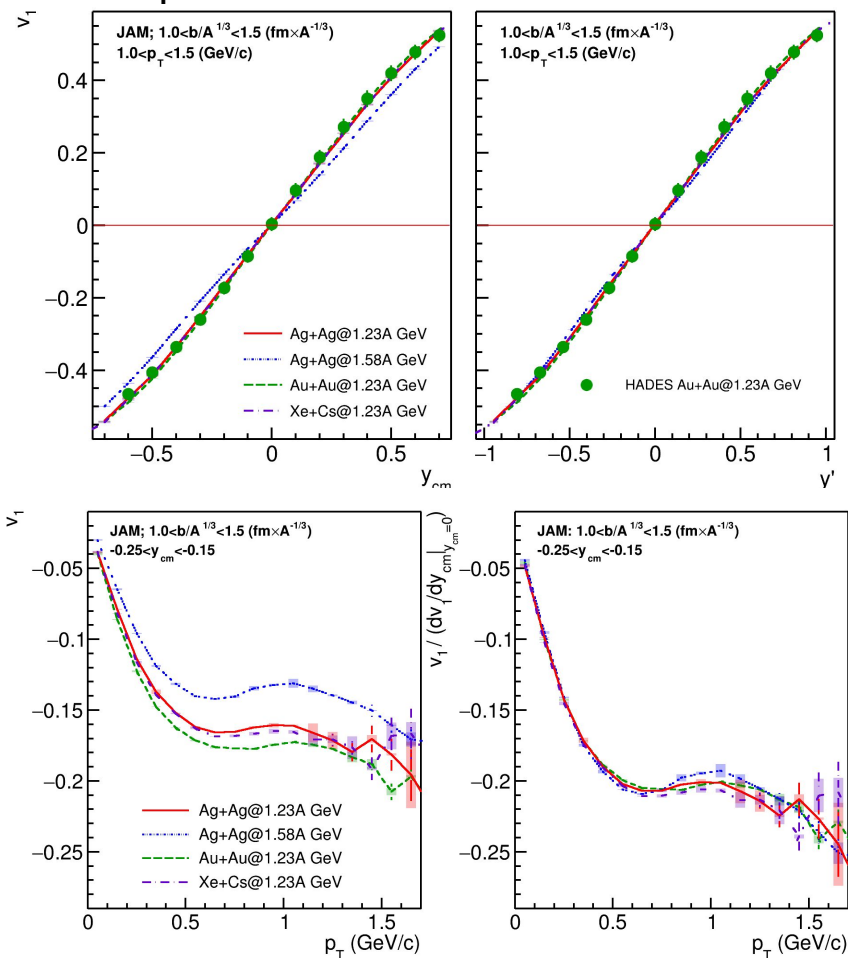
$$\text{центральность} \rightarrow \langle b \rangle / A^{1/3}$$

$$y' = y_{CM} / y_{beam} + \langle b \rangle / A^{1/3}$$



- После корректировки зависимости от времени пролета (y_{beam}) dv_1/dy' не зависит от размера сталкивающихся ядер и энергии столкновения, а зависит только от относительного прицельного параметра ($\langle b \rangle / A^{1/3}$)
- Замена центральности на $\langle b \rangle / A^{1/3}$ улучшает масштабирование dv_1/dy' в центральных столкновениях

dv_1/dy scaling with collision energy and system size



- Scaling with collision energy is observed in model and experimental data
- Scaling with system size is observed in model and experimental data
- We can compare the results with HIC-data from other experiments (e.g. STAR-FXT Au+Au)

Flow vectors

From momentum of each measured particle define a u_n -vector in transverse plane:

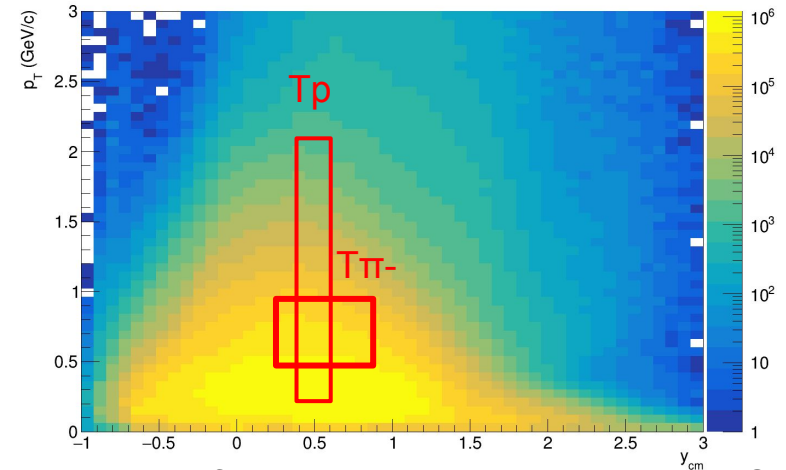
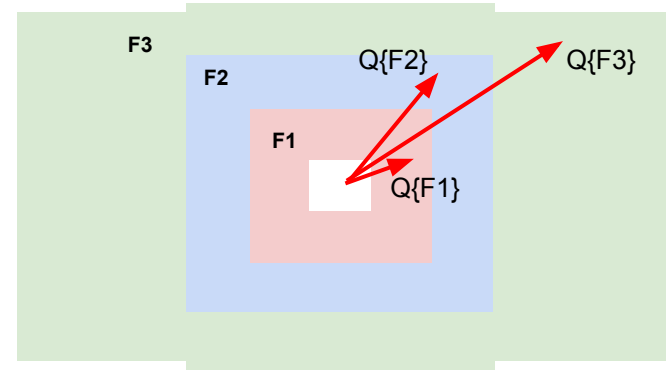
$$u_n = e^{in\phi}$$

where ϕ is the azimuthal angle

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Ψ_n^{EP} is the event plane angle



Additional subevents from tracks not pointing at FHCAL:

Tp: p; $0.4 < y < 0.6$; $0.2 < p_T < 2$ GeV/c; $w=1/\text{eff}$

T π^- : π^- ; $0.2 < y < 0.8$; $0.1 < p_T < 0.5$ GeV/c; $w=1/\text{eff}$

T-: all negative; $1.0 < \eta < 2.0$; $0.1 < p_T < 0.5$ GeV/c; $w=1/\text{eff}$ ²⁸

Flow methods for v_n calculation

Tested in HADES:

M Mamaev et al 2020 PPNuclei 53, 277–281

M Mamaev et al 2020 J. Phys.: Conf. Ser. 1690 012122

Scalar product (SP) method:

$$v_1 = \frac{\langle u_1 Q_1^{F1} \rangle}{R_1^{F1}} \quad v_2 = \frac{\langle u_2 Q_1^{F1} Q_1^{F3} \rangle}{R_1^{F1} R_1^{F3}}$$

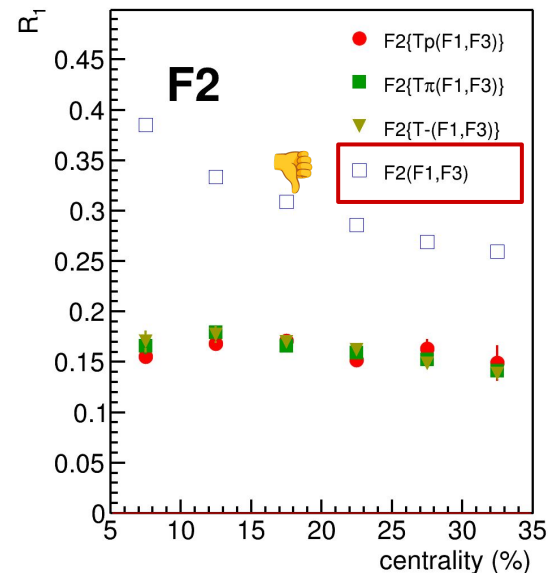
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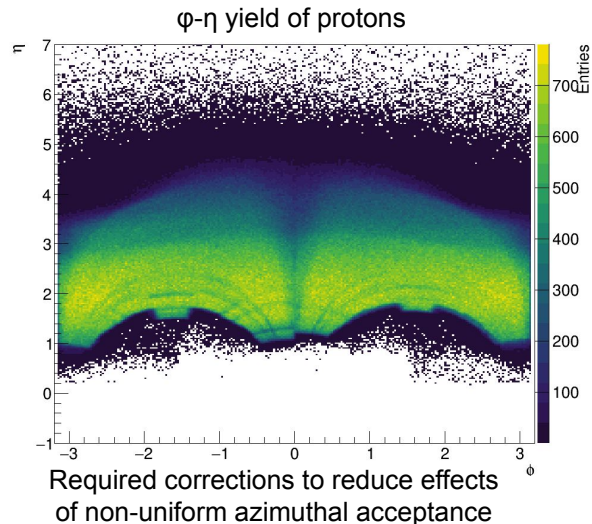
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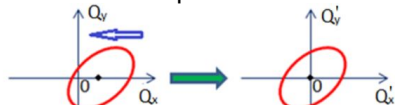
Symbol “F2{Tp}(F1,F3)” means R_1 calculated via (4S resolution):

$$R_1^{F2\{Tp\}(F1,F3)} = \langle Q_1^{F2} Q_1^{Tp} \rangle \frac{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{Tp} Q_1^{F1} \rangle \langle Q_1^{Tp} Q_1^{F3} \rangle}}$$

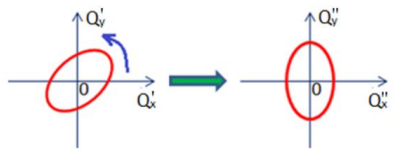
Azimuthal asymmetry of the BM@N acceptance



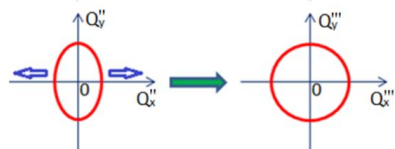
1. Recentering



2. Twist

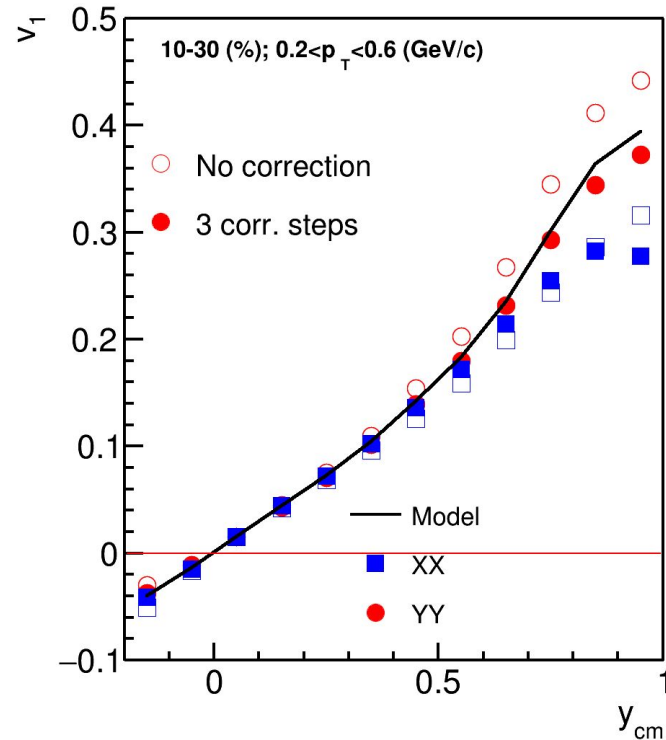


3. Rescaling



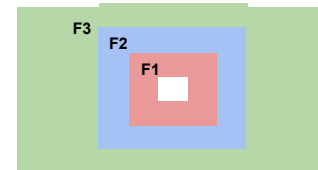
Corrections are based on method in:

I. Selyuzhenkov and S. Voloshin PRC77, 034904 (2008)



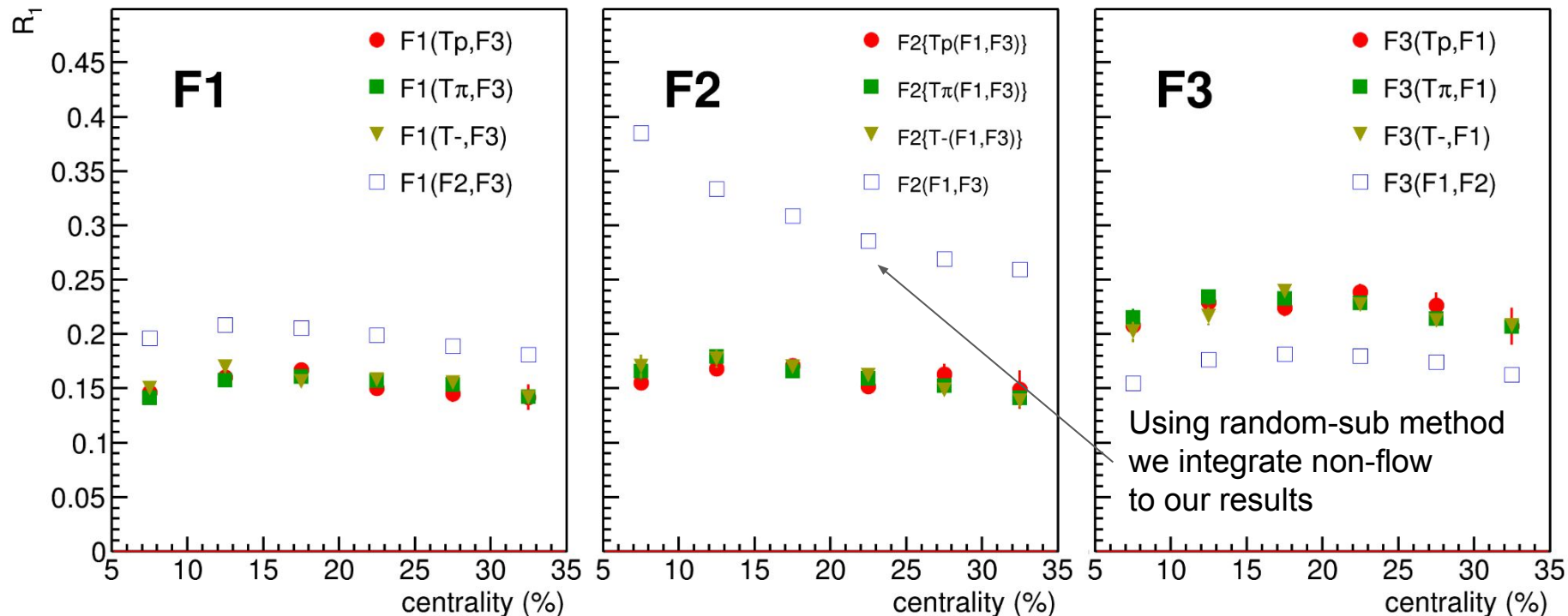
- Better agreement after rescaling for YY
- XX component has a large bias (due to magnetic field)

SP R1: DCMQGCM-SMM Xe+Cs@4A GeV



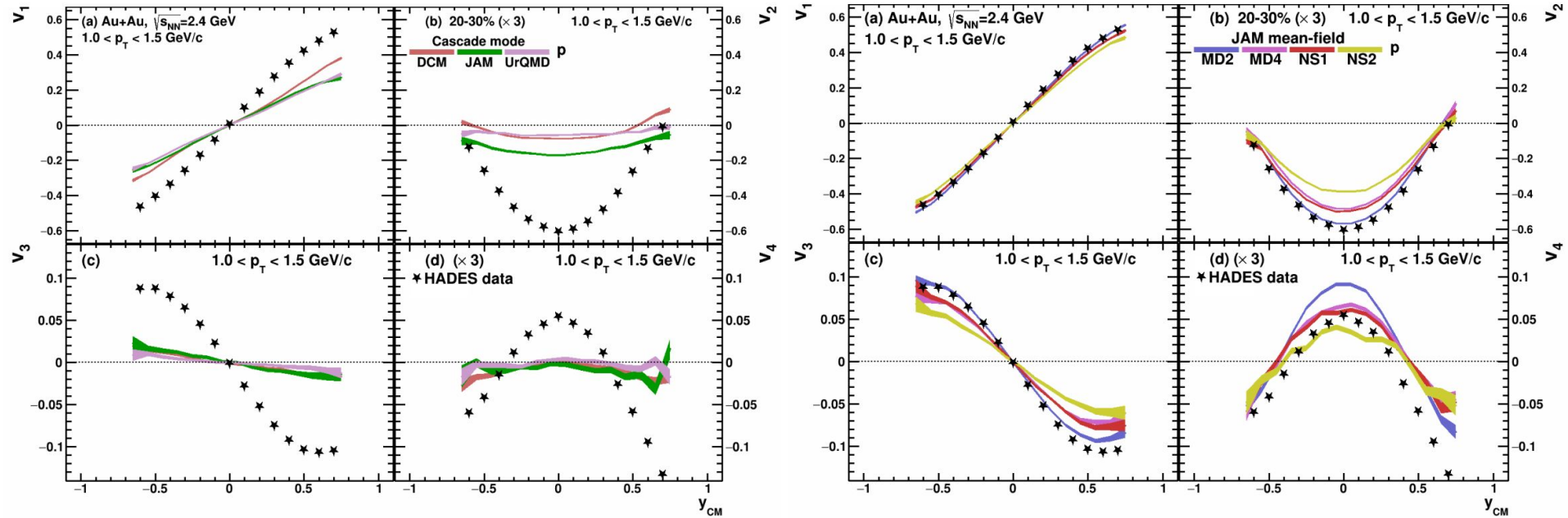
SP gives unbiased estimation of v_n (root-mean-square)

EP gives biased estimation (somewhere between mean and RMS)



Using the additional sub-events from tracking provides a robust combination to calculate resolution ³¹

Models



- Cascade mode fail to reproduce flow signal
- Mean-Field models reproduce flow signal up to 4th harmonic

Simulation datasample

- Xe+Cs nuclei collisions
- DCMQGSM-SMM model (realistic yields of spectator fragments), describes flow poorly
- JAM model (realistic flow signal)
- Geant4 transport code (important for simulation of hadronic showers in the forward calorimeter)
- Realistic reconstruction

	2A GeV	3A GeV	4A GeV
DCMQGSM-SMM	6M	6M	2M
JAM MD2	3M	3M	5M

Flow vectors

From momentum of each measured particle define a u_n -vector in transverse plane:

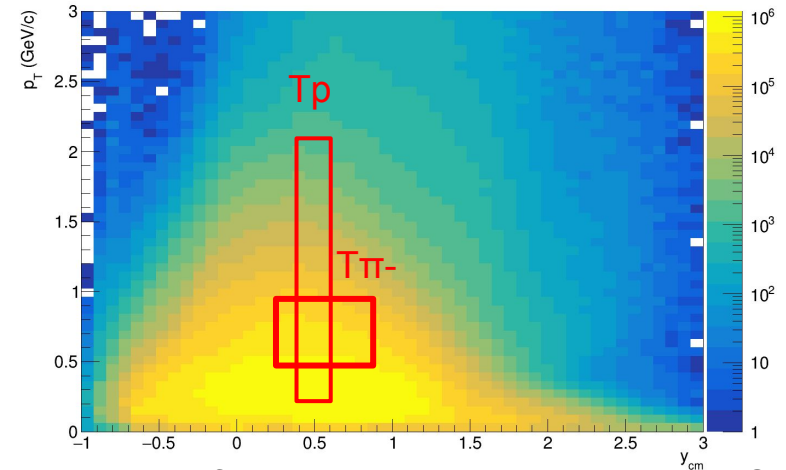
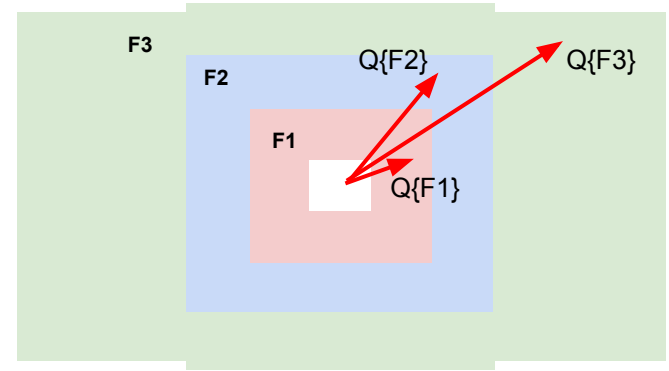
$$u_n = e^{in\phi}$$

where ϕ is the azimuthal angle

Sum over a group of u_n -vectors in one event forms Q_n -vector:

$$Q_n = \frac{\sum_{k=1}^N w_n^k u_n^k}{\sum_{k=1}^N w_n^k} = |Q_n| e^{in\Psi_n^{EP}}$$

Ψ_n^{EP} is the event plane angle



Additional subevents from tracks not pointing at FHCAL:

Tp: p; $0.4 < y < 0.6$; $0.2 < p_T < 2$ GeV/c; $w=1/\text{eff}$

Tπ-: π-; $0.2 < y < 0.8$; $0.1 < p_T < 0.5$ GeV/c; $w=1/\text{eff}$

T-: all negative; $1.0 < \eta < 2.0$; $0.1 < p_T < 0.5$ GeV/c; $w=1/\text{eff}$ ³⁴

Flow methods for v_n calculation

Tested in HADES:

M Mamaev et al 2020 PPNuclei 53, 277–281

M Mamaev et al 2020 J. Phys.: Conf. Ser. 1690 012122

Scalar product (SP) method:

$$v_1 = \frac{\langle u_1 Q_1^{F1} \rangle}{R_1^{F1}} \quad v_2 = \frac{\langle u_2 Q_1^{F1} Q_1^{F3} \rangle}{R_1^{F1} R_1^{F3}}$$

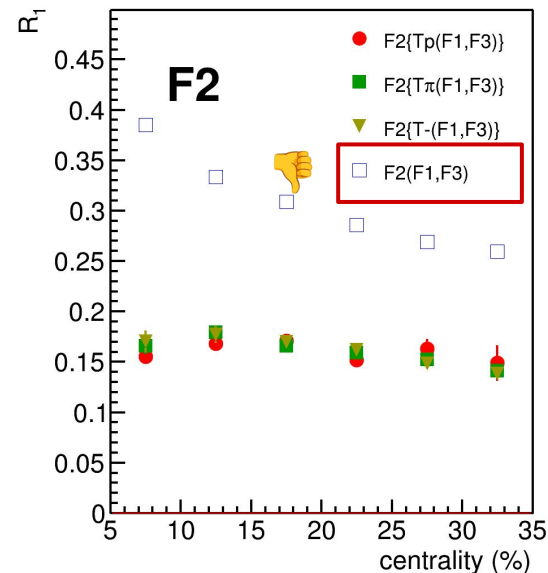
Where R_1 is the resolution correction factor

$$R_1^{F1} = \langle \cos(\Psi_1^{F1} - \Psi_1^{RP}) \rangle$$

Symbol “F2(F1,F3)” means R_1 calculated via (3S resolution):

$$R_1^{F2(F1,F3)} = \frac{\sqrt{\langle Q_1^{F2} Q_1^{F1} \rangle \langle Q_1^{F2} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}$$

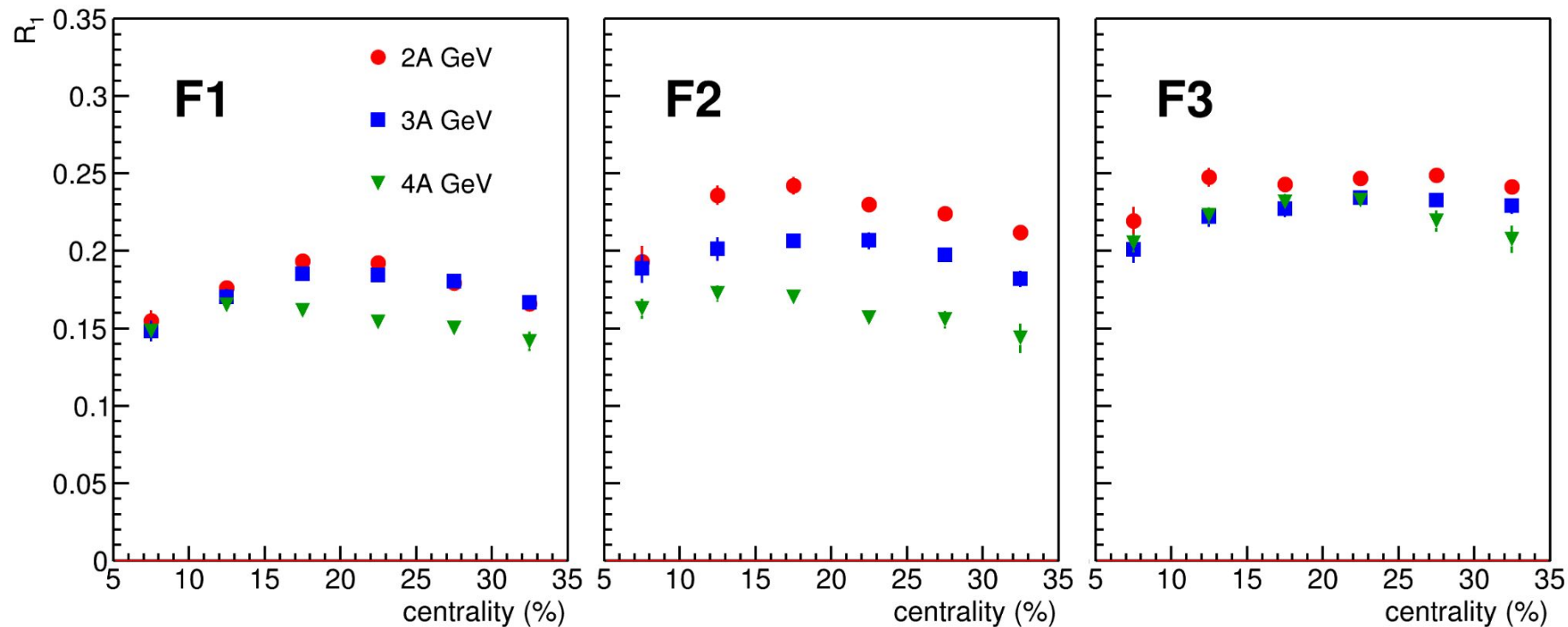
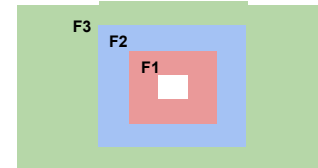
Method helps to eliminate non-flow
Using 2-subevents doesn't



Symbol “F2{Tp}(F1,F3)” means R_1 calculated via (4S resolution):

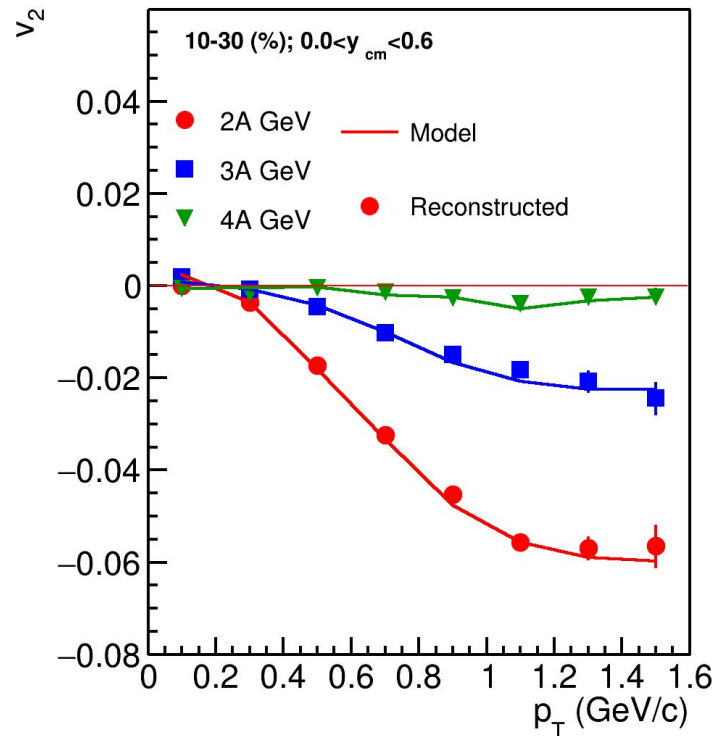
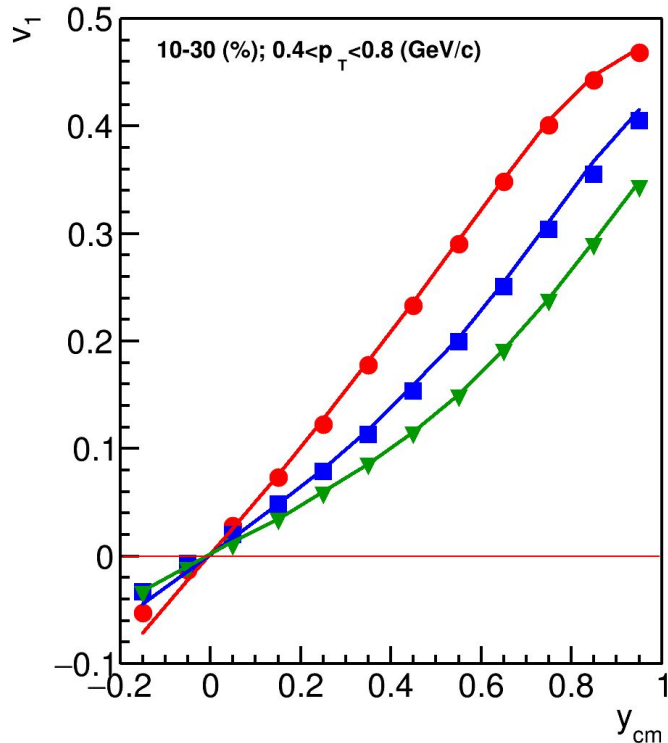
$$R_1^{F2\{Tp\}(F1,F3)} = \langle Q_1^{F2} Q_1^{Tp} \rangle \frac{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{Tp} Q_1^{F1} \rangle \langle Q_1^{Tp} Q_1^{F3} \rangle}}$$

Rec R1: DCMQGCM-SMM Xe+Cs



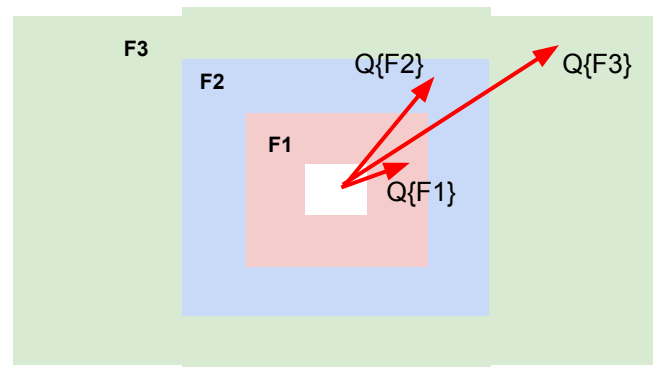
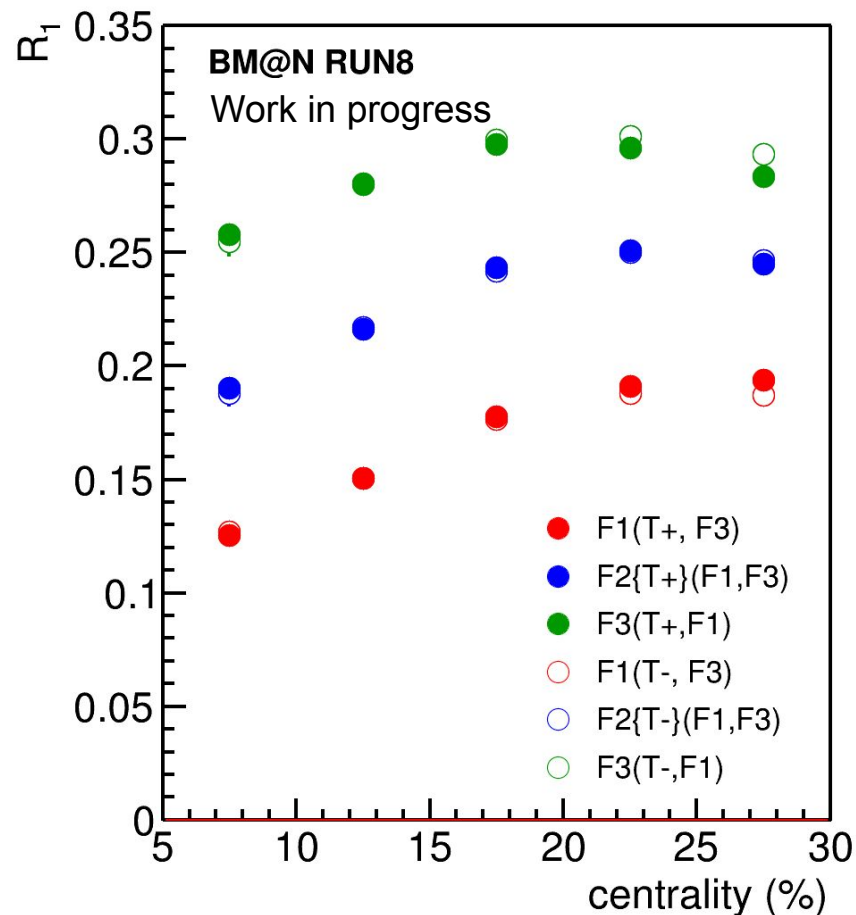
Resolution is lower for higher energies due to lower v_1

Directed and elliptic flow in Xe+Cs (JAM)



- Good agreement between reconstructed and pure model data for all three energies

R1: BM@N Run8 DATA: Xe+Cs@3.8A GeV



T-: all negatively charged particles with:

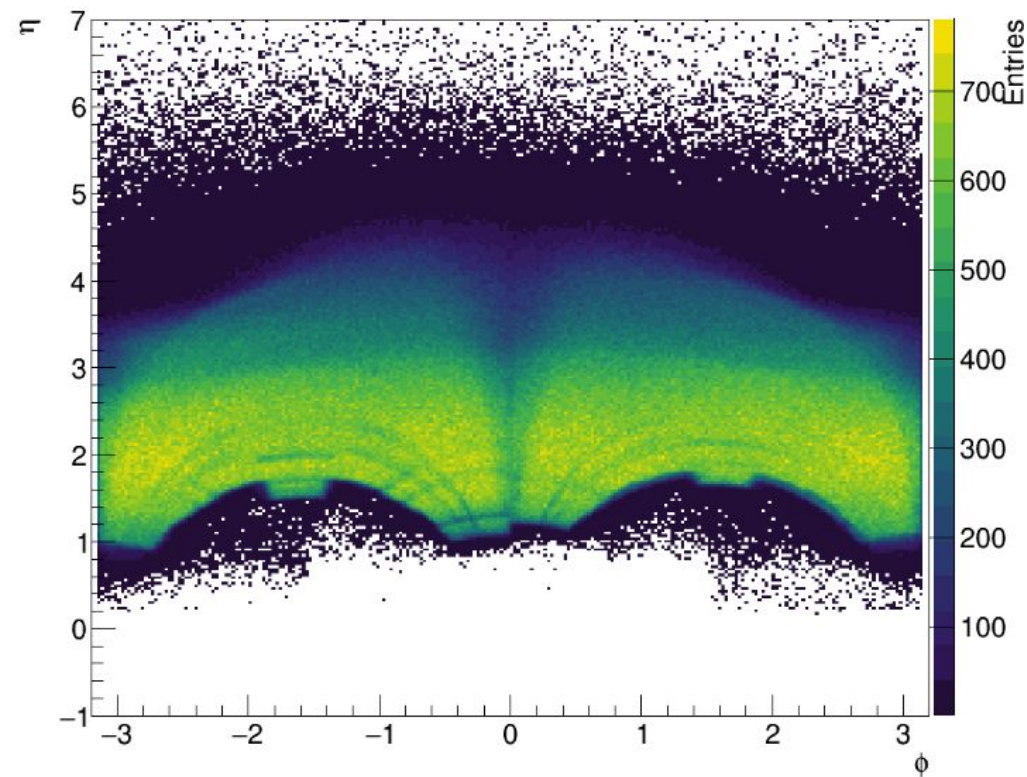
- $1.5 < \eta < 4$
- $p_T > 0.2 \text{ GeV/c}$

T+: all positively charged particles with:

- $2.0 < \eta < 3$
- $p_T > 0.2 \text{ GeV/c}$

Results for v_1 and v_2 are in progress

Влияние азимутального аксептанса



Уравнение состояния сильновзаимодействующей материи

Давление для постоянной температуры:

$$P = n_B^2 \frac{\partial(E/A)}{\partial n_B}$$

где E/A — энергия на нуклон, n_B — число барионов.

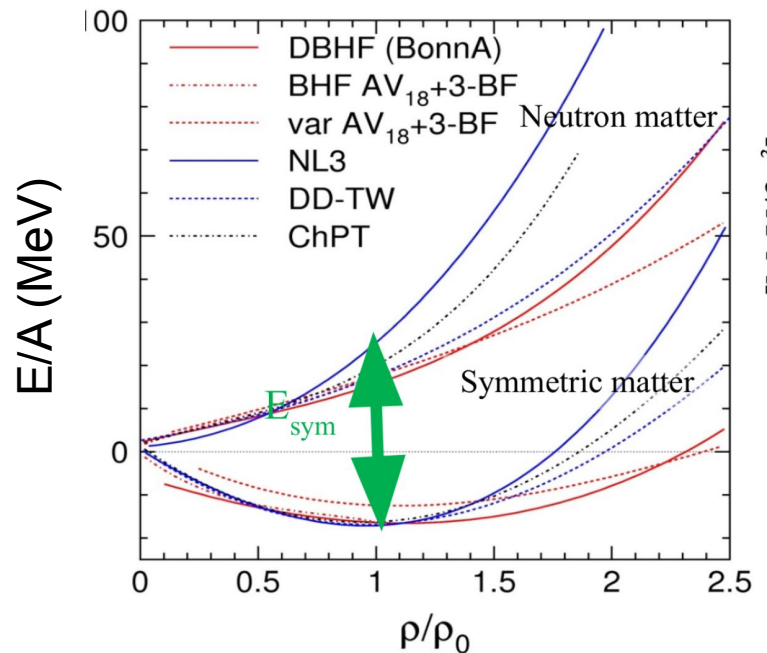
Энергия связи E/A определяется как:

$$E/A = E_A(n_B) + E_{\text{sym}}(n_B) \frac{(n_p - n_n)^2}{n_B^2}$$

где E_A — энергия симметричной материи, E_{sym} — энергия симметрии.

Уравнение состояния ядерной материи может быть охарактеризован коэффициентом несжимаемости:

$$K = 9n_B^2 \frac{\partial^2(E/A)}{\partial n_B^2}$$



Систематические ошибки для данных Au+Au 1.23A ГэВ

Eur.Phys.J.A 59 (2023) 4, 80

Proton, deuteron and triton flow measurements in Au+Au collisions at $\sqrt{s_{\text{NN}}} = 2.4$ GeV

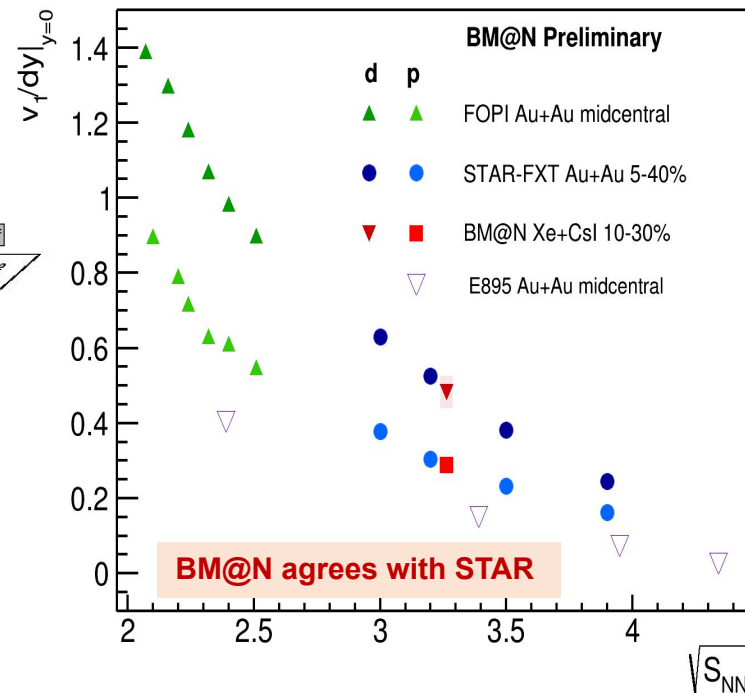
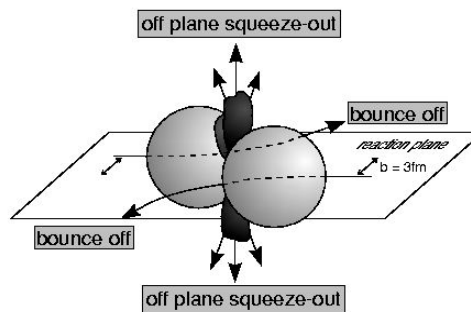
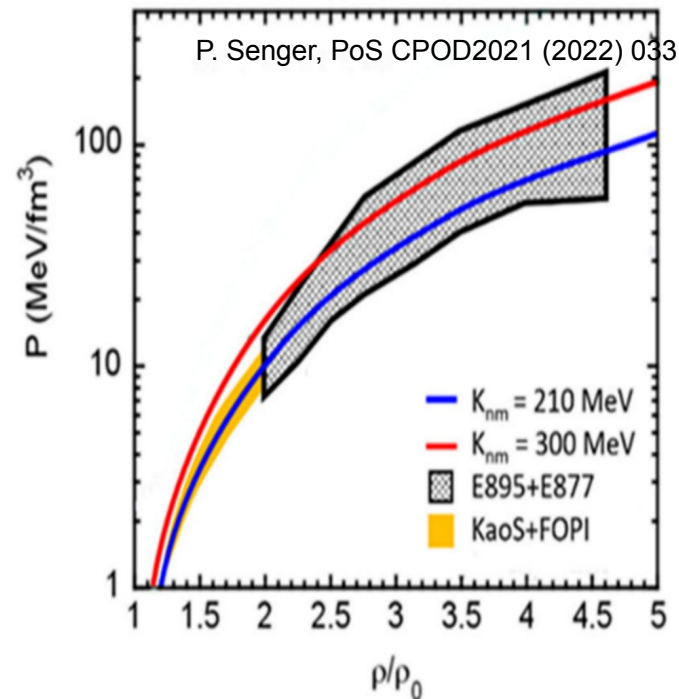
HADES collaboration

J. Adamczewski-Musch⁵, O. Arnold^{10,9}, C. Behnke⁸, A. Belounnas¹³, J.C. Berger-Chen^{10,9}, A. Blanco², C. Blume⁸, M. Böhmer¹⁰, P. Bordalo², L. Chlad¹⁴, I. Ciepal³, C. Deveaux¹¹, J. Dreyer⁷, E. Eppe^{10,9}, L. Fabbietti^{10,9}, P. Filip¹, P. Fonte^{2,a}, C. Franco², J. Friese¹⁰, I. Fröhlich⁸, T. Galatyuk^{6,5}, J.A. Garzón¹⁵, R. Gernhäuser¹⁰, R. Greifehagen^{7,b,i}, M. Gumberidze^{5,6}, S. Harabasz^{6,4}, T. Heinz⁵, T. Hennino¹³, S. Hlavac¹, C. Höhne^{11,5}, R. Holzmann⁵, B. Kämpfer^{7,b}, B. Kardan⁸, I. Koenig⁵, W. Koenig⁵, M. Kohls⁸, B.W. Kolb⁵, G. Korcyl⁴, G. Kornakov⁶, F. Kornas⁶, R. Kotte⁷, A. Kugler¹⁴, T. Kunz¹⁰, R. Lalik⁴, K. Lapidus^{10,9}, L. Lopes², M. Lorenz⁸, T. Mahmoud¹¹, L. Maier¹⁰, A. Malige⁴, A. Mangiarotti², J. Markert⁵, T. Matulewicz¹⁶, S. Maurus¹⁰, V. Metag¹¹, J. Michel⁸, D.M. Mihaylov^{10,9}, C. Müntz⁸, R. Münzer^{10,9}, L. Naumann⁷, K. Nowakowski⁴, Y. Parpottas¹⁸, V. Pechenov⁵, O. Pechenova⁵, K. Piasecki¹⁶, J. Pietraszkowski⁵, W. Przygoda⁴, K. Pysz³, S. Ramos², B. Ramstein¹³, N. Rathod⁴, P. Rodriguez-Ramos¹⁴, P. Rosier¹³, A. Rost⁶, A. Rustamov⁵, P. Salabura⁴, T. Scheib⁸, H. Schuldes⁸, E. Schwab⁵, F. Scozzi^{6,13}, F. Seck⁶, P. Sellheim⁸, I. Selyuzhenkov⁵, J. Siebenson¹⁰, L. Silva², U. Singh⁴, J. Smyrski⁴, Yu.G. Sobolev¹⁴, S. Spataro¹⁷, S. Spies⁸, H. Ströbele⁸, J. Stroth^{8,5}, C. Sturm⁵, O. Svoboda¹⁴, M. Szala⁸, P. Tlusty¹⁴, M. Traxler⁵, H. Tsertos¹², V. Wagner¹⁴, C. Wendisch⁵, M.G. Wiebusch⁵, J. Wirth^{10,9}, D. Wójcik¹⁶, P. Zumbach⁵

The main contribution to the global systematic uncertainty arises from the event-plane resolution. This is mainly caused by so-called “non-flow” correlations which can distort the event-plane determination. The magnitude of these systematic effects is evaluated using the three-sub-event method, i.e. by determining the event-plane resolution for combinations of different sub-events separated in rapidity. It is found to be below 5 % for the centralities 10 – 40 % [36].

36. M. Mamaev, O. Golosov, and I. Selyuzhenkov (HADES), *Phys. Part. Nucl.* **53**, 277 (2022).

Directed flow of protons and EOS of symmetric matter



Nuclear incompressibility from collective proton flow

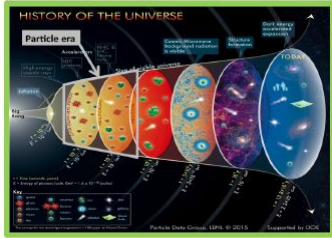
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592

Both STAR and BM@N results for directed flow prefer stiff EOS

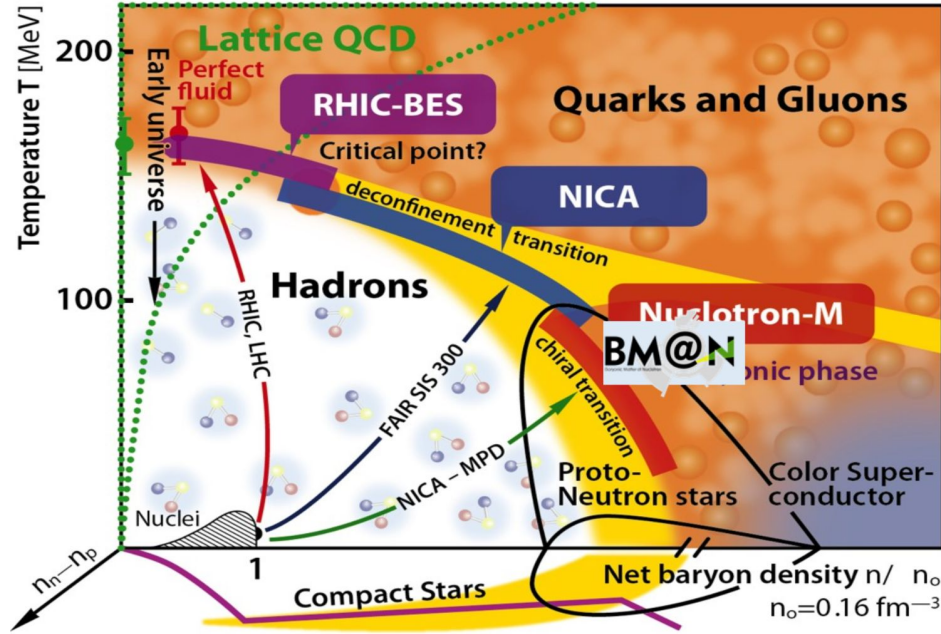
MPD-FXT



Исследование фазовой диаграммы КХД материи



Высокая температура:
эволюция ранней
Вселенной



Высокая барионная
плотность:
столкновения
нейтронных звезд



2005 – Открытие Кварк-Глюонной Материи (КГМ) в столкновениях Au+Au при энергии $\sqrt{s_{NN}} = 200$ ГэВ в экспериментах на коллайдере RHIC (БНЛ). КГМ - сильно взаимодействующую жидкость с очень малой вязкостью

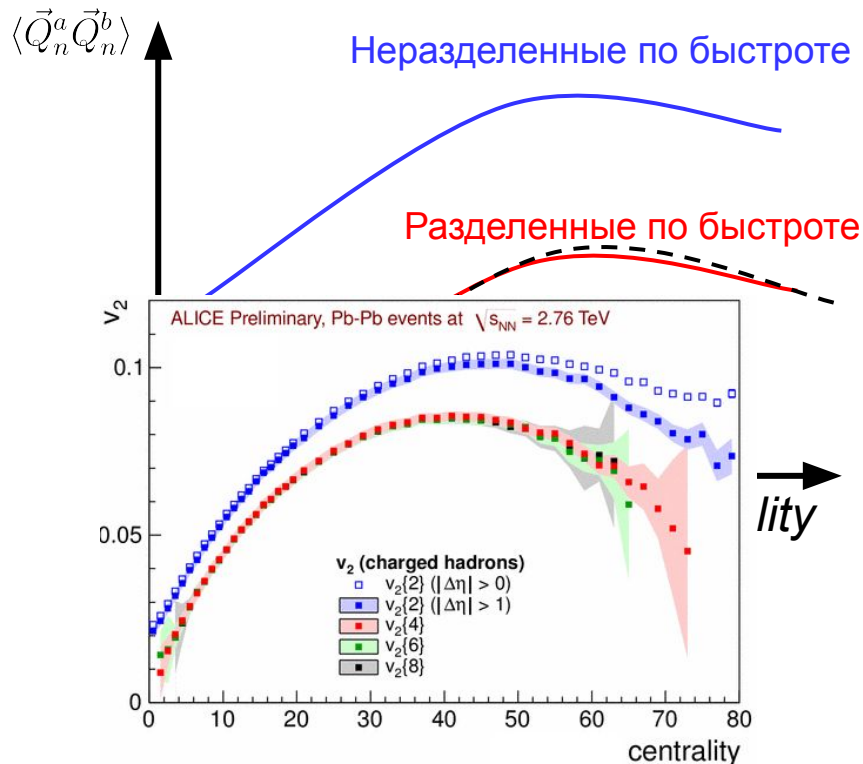
2010 - Поиск сигналов деконфайнмента, фазового перехода первого рода и критической точки КХД материи - основа для программ сканирования по энергии столкновения ядер в современных экспериментах на ускорителях: RHIC, SPS, Nuclotron, SIS18

Непотокковые корреляции

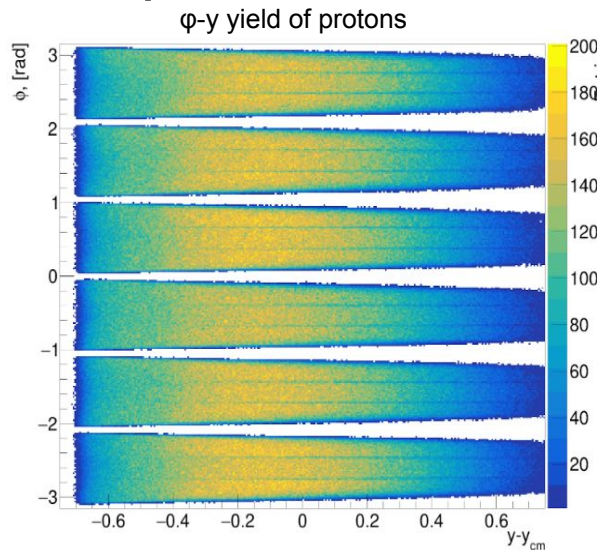
Корреляции не относящиеся к изначальному коллективному движению частиц называют непотокковыми:

- Фемтоскопические корреляции
- Закон сохранения импульса
- Корреляция продуктов распада
- Корреляции возникающие в материале детектора (адронный ливень, магнитное поле)

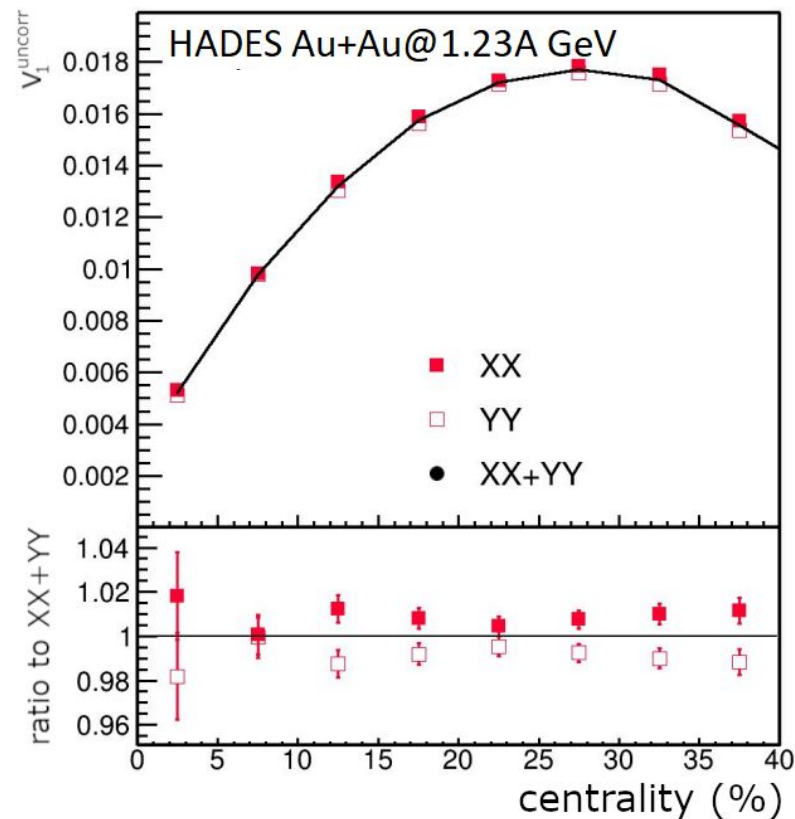
Основной способ подавить непотокковые корреляции — внести разделение по (псевдо-) быстроте между Q_n -векторами



Неоднородность азимутального акцептанса HADES



Corrections are based on method in:
I. Selvuzhenkov and S. Voloshin PRC77, 034904 (2008)



$$u_1 = (x_1, y_1) \quad Q_1 = (X_1, Y_1)$$

$$v_1 = \frac{\langle u_1 Q_1 \rangle}{R_1} = 2 \frac{\langle x_1 X_1 \rangle}{R_1^X} = 2 \frac{\langle y_1 Y_1 \rangle}{R_1^Y}$$

$$R_1^X = \frac{\sqrt{\langle X^a X^b \rangle \langle X^a X^c \rangle}}{\sqrt{\langle X^b X^c \rangle}}$$

Векторы потока u_n и Q_n

Из импульса каждой частицы
определяется единичный вектор u_n :

$$\vec{u}_n = (\cos n\varphi, \sin n\varphi)$$

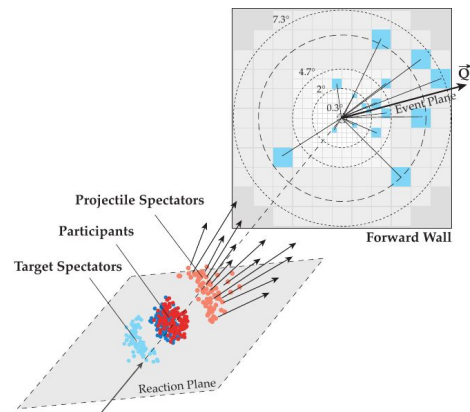
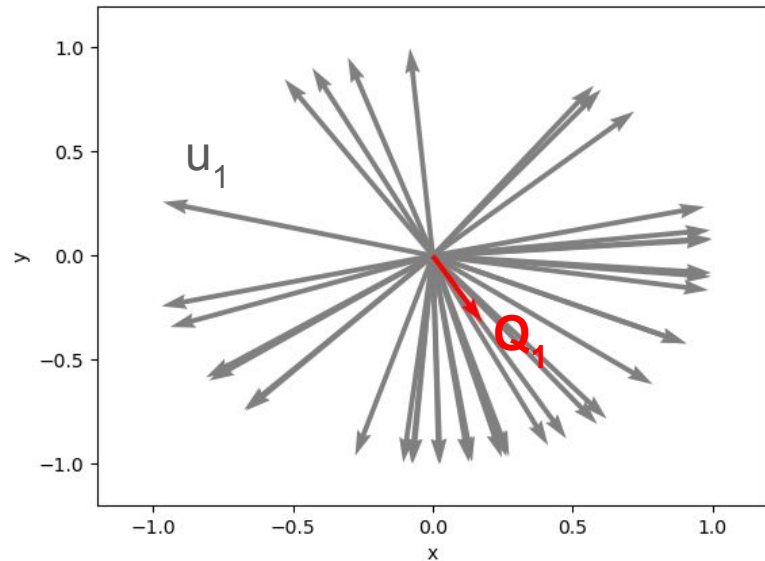
где φ — азимутальный угол импульса

Сумма по группе частиц в одном событии даёт
оценку угла плоскости реакции в событии:

$$\vec{Q}_n = \frac{\sum_{k=1}^M w_k u_n^k}{C} = \frac{|Q|}{C} (\cos n\Psi_n^{EP} \sin n\Psi_n^{EP})$$

Ψ_n^{EP} — угол плоскости симметрии
(оценка угла плоскости реакции)

u_1 -вектора, дающие в сумме Q_1 -вектор



Разрешение плоскости симметрии

$$v_1 = \frac{\langle u_1 Q_1^{F1} \rangle}{R_1^{F1}} \quad v_2 = \frac{\langle u_2 Q_1^{F1} Q_1^{F3} \rangle}{R_1^{F1} R_1^{F3}}$$

Где R_1 — разрешение плоскости симметрии

$$R_1^{F1} = \langle \cos(\Psi_1^{F1} - \Psi_1^{RP}) \rangle$$

Метод трех подсобытий:

$$R_1^{F2(F1,F3)} = \frac{\sqrt{\langle Q_1^{F2} Q_1^{F1} \rangle \langle Q_1^{F2} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}$$

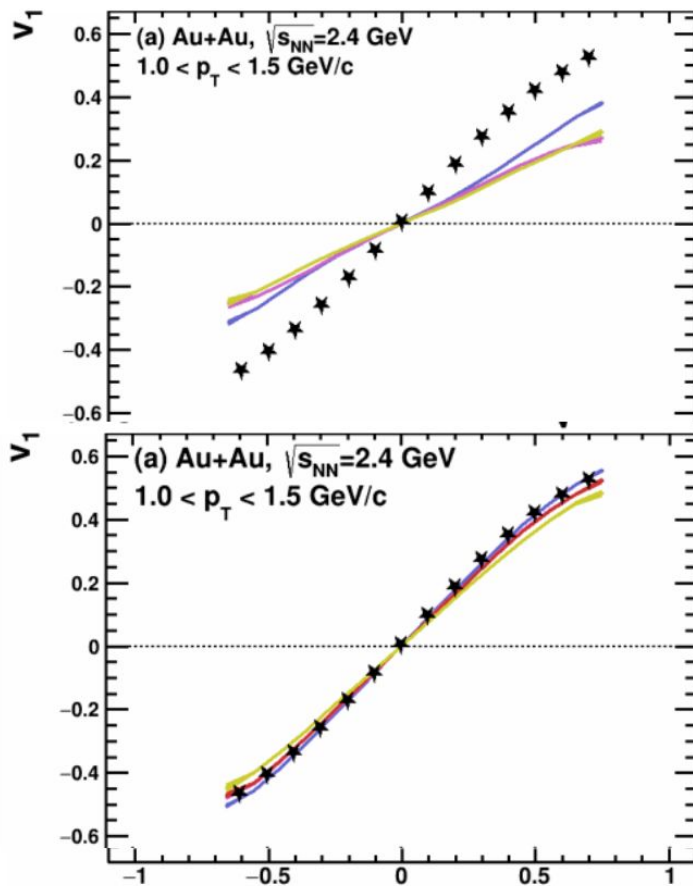
3 оценки для v_n
Можно оценить вклад
непоточковых корреляций

Метод случайных подсобытий:

$$R_1 = \sqrt{\langle Q_1^a Q_1^b \rangle}$$

1 оценка для v_n
Невозможно оценить вклад
непоточковых корреляций

Методика измерения азимутальных потоков



- Направленный поток достигает максимума в кинематической области спектаторов
- Для восстановления плоскости симметрии используются спектаторы, чтобы подавить вклад непотоковых корреляций

Непоточковые корреляции

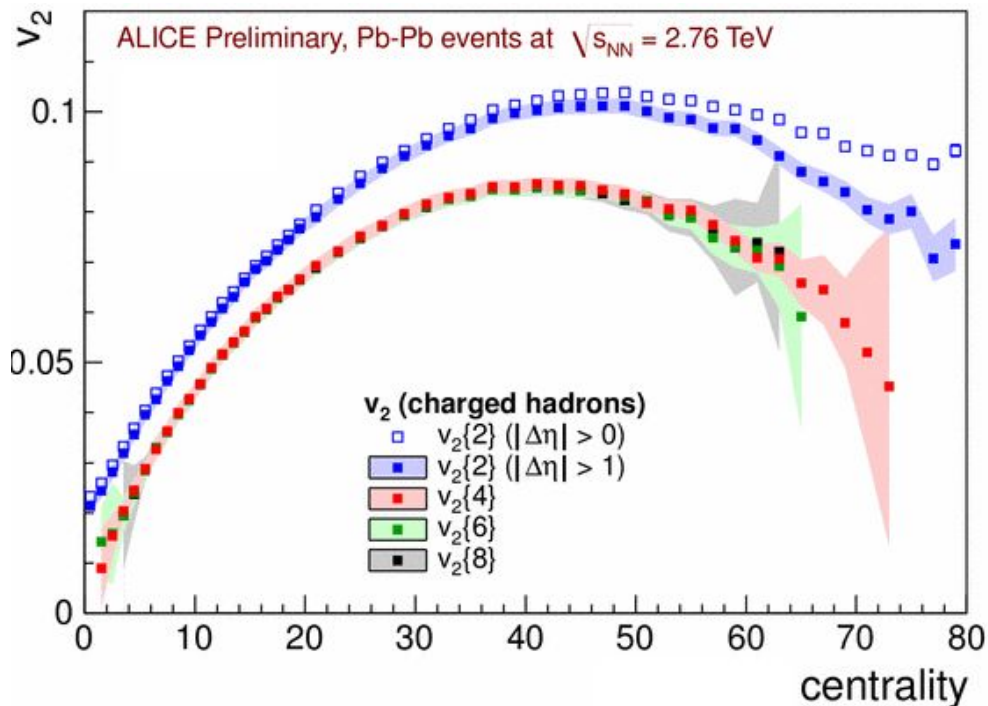
Существуют корреляции между частицами, не связанные с плоскостью реакции. Эти корреляции называются «непоточковыми»

Среди источников корреляций, не связанных с потоком:

- сохранение полного (поперечного) импульса при столкновении;
- распады резонансов в результате слабого взаимодействия
- корреляции ближнего действия (фемтоскопия, распад фрагментов ядер)

Эффекты детектора также могут вносить коррелированную ошибку в измерения потока:

- Разделение траектории одной частицы в результате реконструкции
- Слияние траекторий двух частиц в результате реконструкции
- Сигналы от пролёта одной и той же частицы в соседних модулях сегментированных детекторов



Как правило «непоточковые» корреляции оказывают существенное влияние только на частицы с близкими импульсами, их можно также подавить, увеличив интервал быстроты между частицами.

Векторы потока u_n и Q_n

Из импульса каждой частицы
определяется единичный вектор u_n :

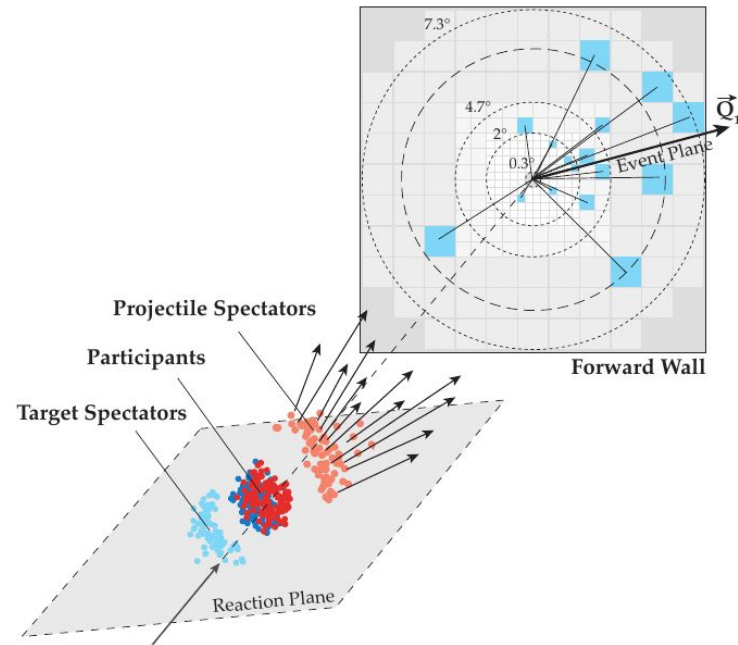
$$\vec{u}_n = (\cos n\varphi, \sin n\varphi)$$

где φ — азимутальный угол импульса

Сумма по группе частиц в одном событии даёт
оценку угла плоскости реакции в событии:

$$\vec{Q}_n = \frac{\sum_{k=1}^M w_k u_n^k}{C} = \frac{|Q|}{C} (\cos n\Psi_n^{EP} \sin n\Psi_n^{EP})$$

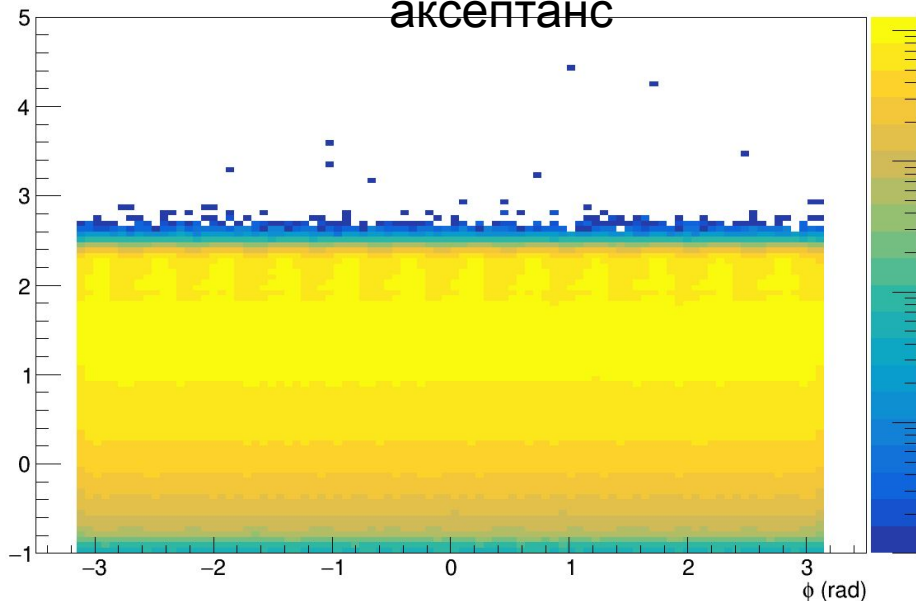
Ψ_n^{EP} — угол плоскости симметрии
(оценка угла плоскости реакции)



- Плоскость симметрии определяется при помощи спектаторов, которые отклоняются в плоскость реакции
- Большое разделение по скорости позволяют минимизировать непотоковые корреляции

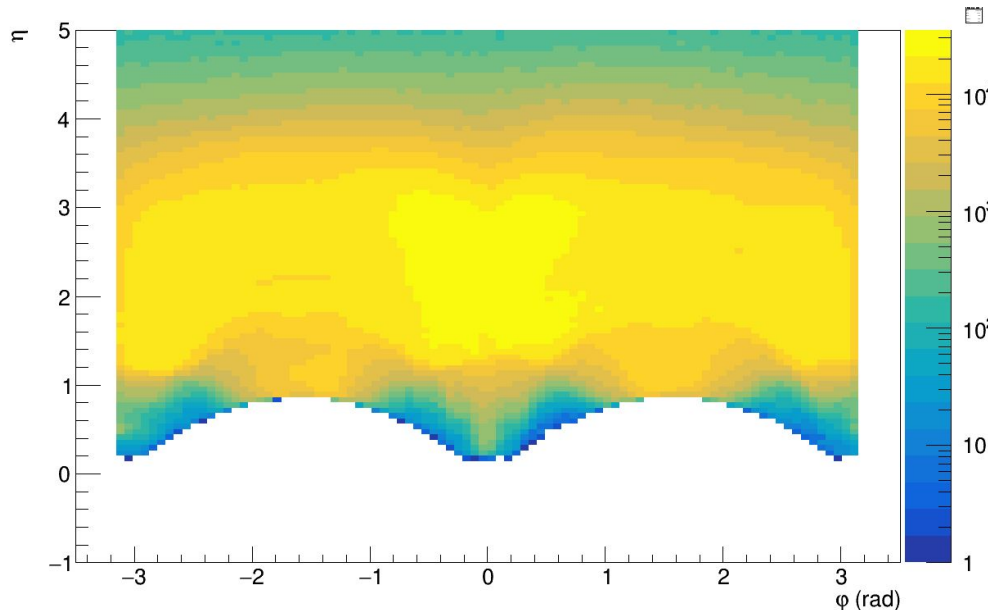
Влияние азимутального акцептанса на v_n

Однородный азимутальный акцептанс



$$\frac{\langle u_n^x Q_n^x \rangle}{R_n^x} = \frac{\langle u_n^y Q_n^y \rangle}{R_n^y}$$

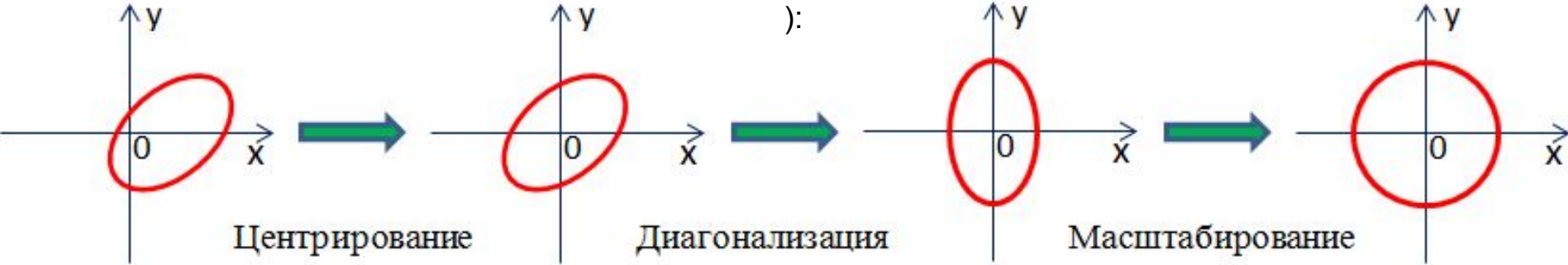
Неоднородный азимутальный акцептанс



$$\frac{\langle u_n^x Q_n^x \rangle}{R_n^x} \neq \frac{\langle u_n^y Q_n^y \rangle}{R_n^y}$$

Коррекция азимутальной неоднородности аксептанса

Коррекции на азимутальную неоднородность аксептанса (Selyuzhenkov I.,
Voloshin S. Phys. Rev. C. — 2008. — Т. 77. — С. 034904)
):



Оригинальный программный код разработанный для коллайдерных экспериментов был адаптирован для экспериментов с фиксированной мишенью:

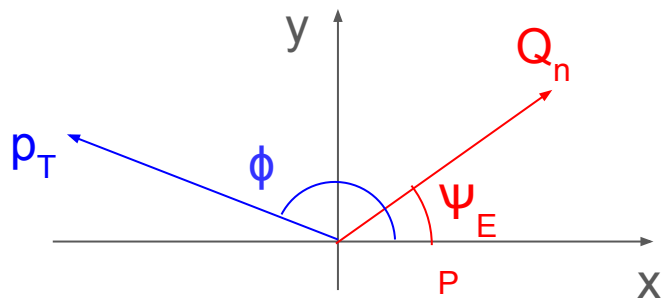
https://github.com/mam-mih-val/qntools_macros

Метод плоскости события

$$\Psi_n^{EP} = \arctan \frac{Q_n^y}{Q_n^x} \quad v_n = \frac{\langle \cos n(\phi - \Psi_n^{EP}) \rangle}{R_n}$$

$$\langle v_n \rangle < v_n < \sqrt{\langle v_n^2 \rangle}$$

Phys. Rev. C. — 2001. — T. 64. — C. 054901



$$R_n = \sqrt{\langle \cos n(\Psi_n^A - \Psi_n^B) \rangle}$$

Ψ_n^A и Ψ_n^B — оценка по двум группам частиц (часто частицы разделяются в группы случайным образом)

Метод подвержен вкладу непотоковых корреляций

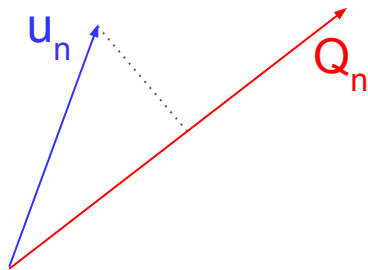
Метод скалярного произведения

Метод скалярного произведения:

$$v_n = \frac{\langle \vec{u}_n \vec{Q}_n \rangle}{R_n}$$

$$v_n \rightarrow \sqrt{\langle v_n^2 \rangle}$$

Phys. Rev. C. — 2001. — Т. 64. — С. 054901



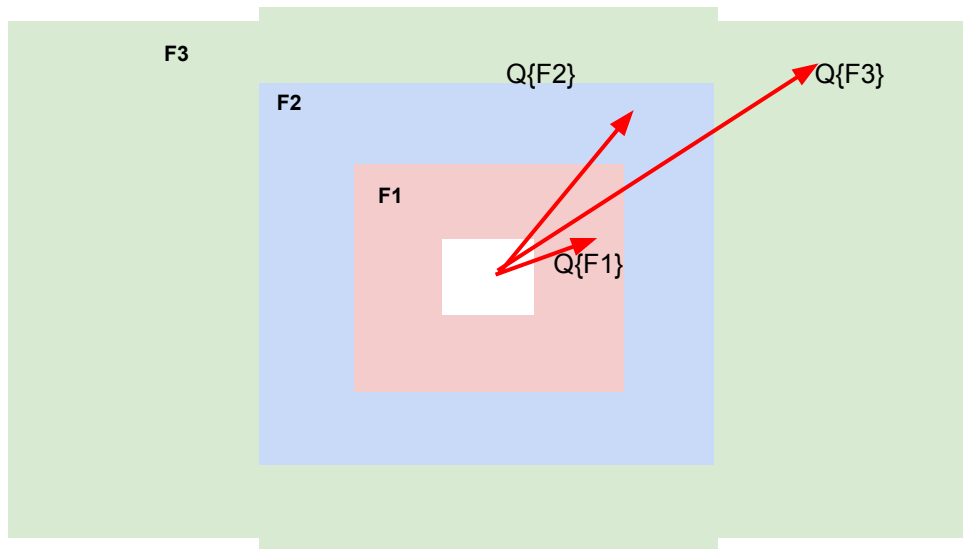
Метод трех подсобытий:

$$R_1^{F2(F1,F3)} = \frac{\sqrt{\langle Q_1^{F2} Q_1^{F1} \rangle \langle Q_1^{F2} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}$$

Метод даёт 3 оценки v_n , что позволяет оценивать вклад непотоковых корреляций

Q-вектора из FHCaI и треков заряженных частиц

Mamaev, M., Taranenko, A. Particles, 2023, 6(2), pp. 622–637

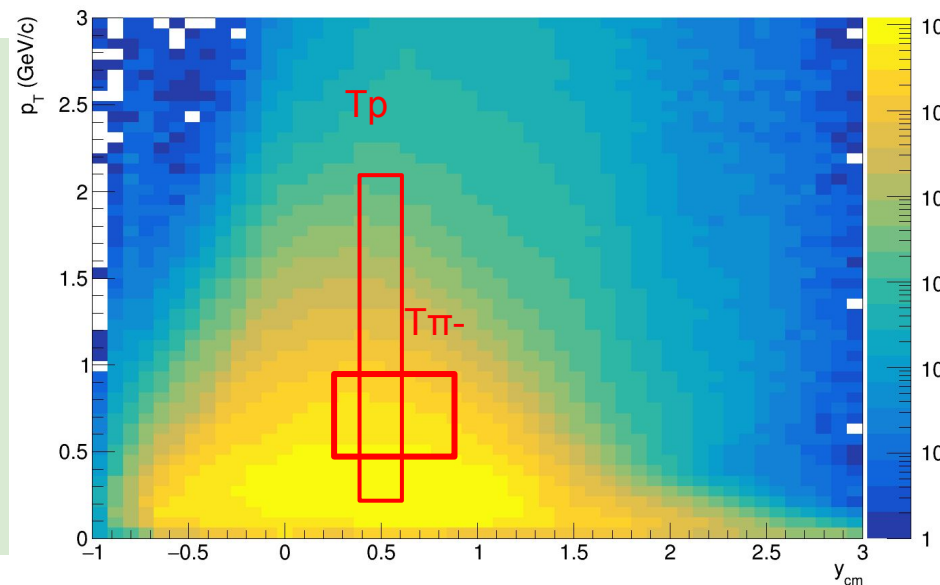


3 вектора из FHCaI:

F1: $4.4 < \eta < 5.5$; $w = E_{\text{kin}}$

F2: $3.9 < \eta < 4.4$; $w = E_{\text{kin}}$

F3: $3.1 < \eta < 3.9$; $w = E_{\text{kin}}$



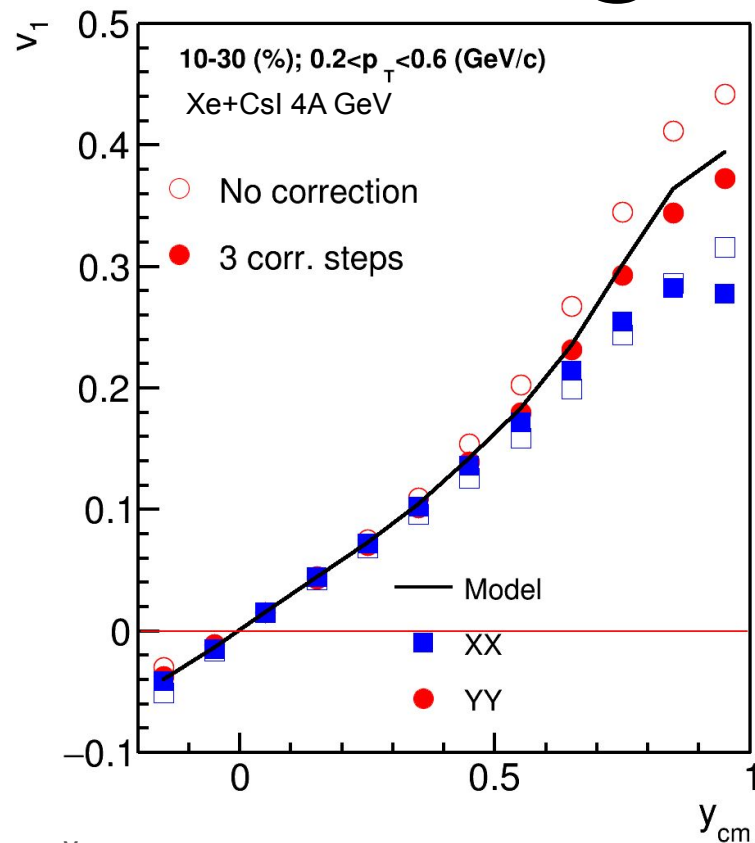
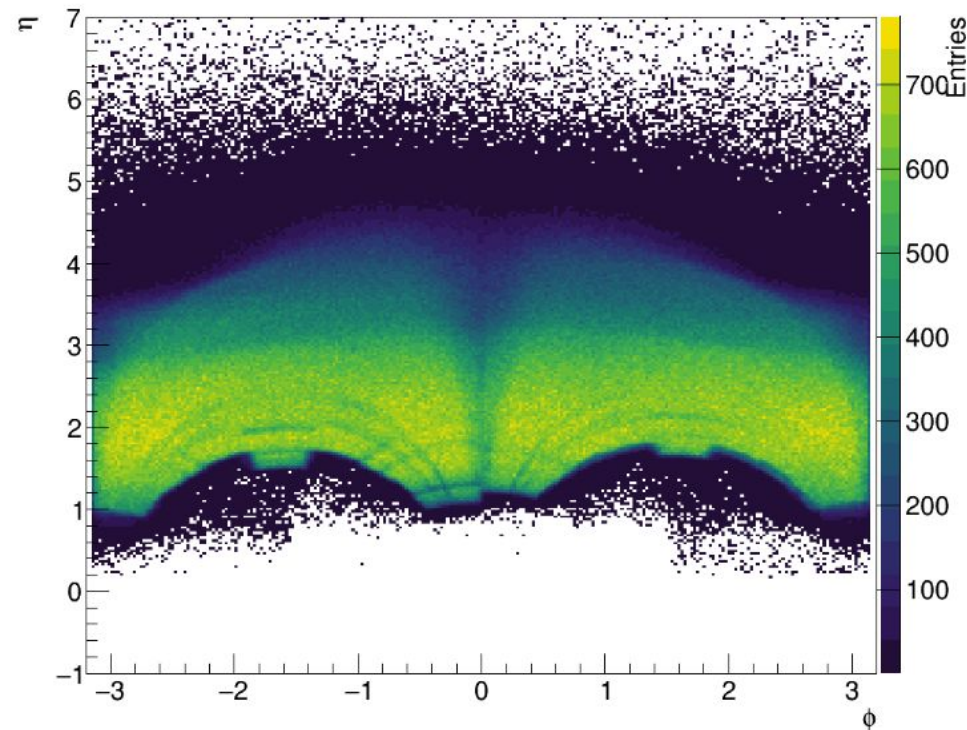
Дополнительные подсобытия из рожденных частиц:

T_p : p ; $0.4 < y < 0.6$; $0.2 < p_T < 2$ GeV/c; $w = 1/\text{eff}$

T_{π^-} : π^- ; $0.2 < y < 0.8$; $0.1 < p_T < 0.5$ GeV/c; $w = 1/\text{eff}$

T^- : all negative; $1.0 < \eta < 2.0$; $0.1 < p_T < 0.5$ GeV/c;

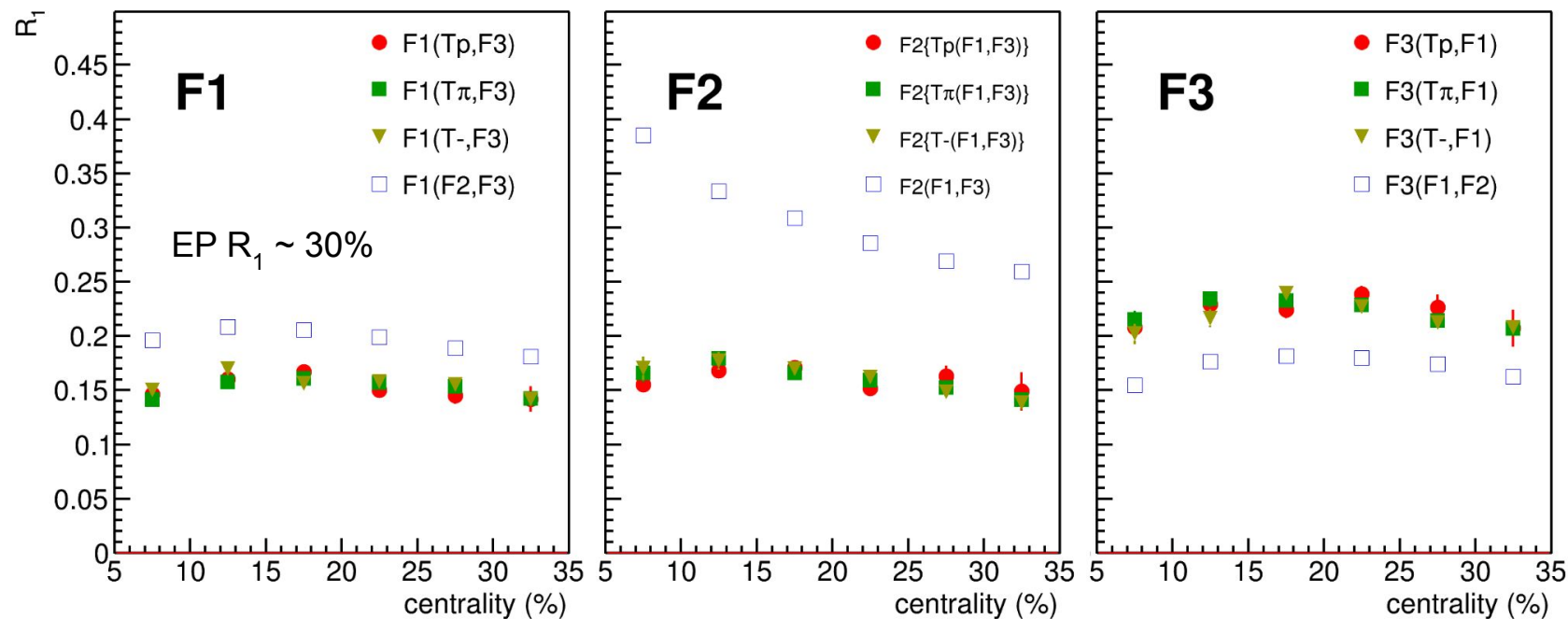
Коррекции на неоднородный аксептанс BM@N



После применения коррекций реконструированные и модельные данные v_1 сходятся

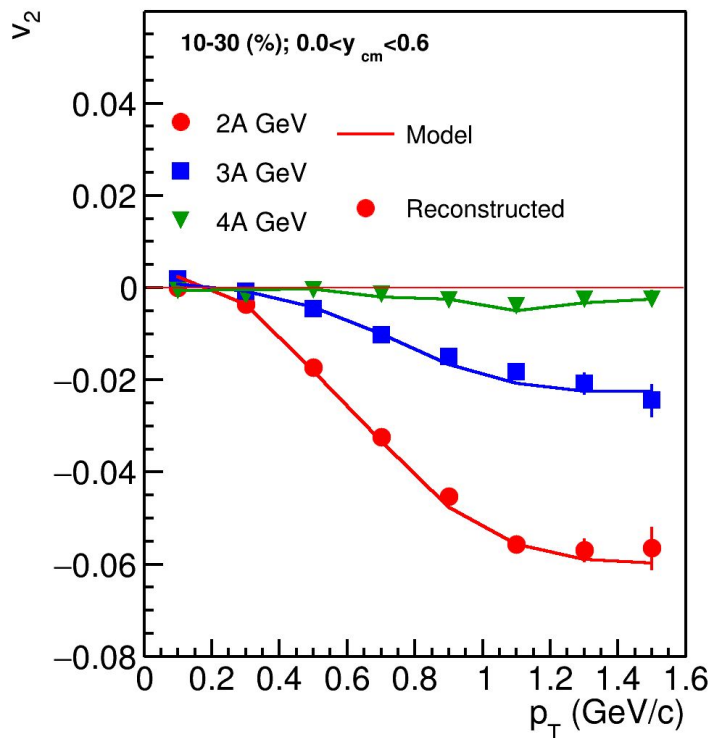
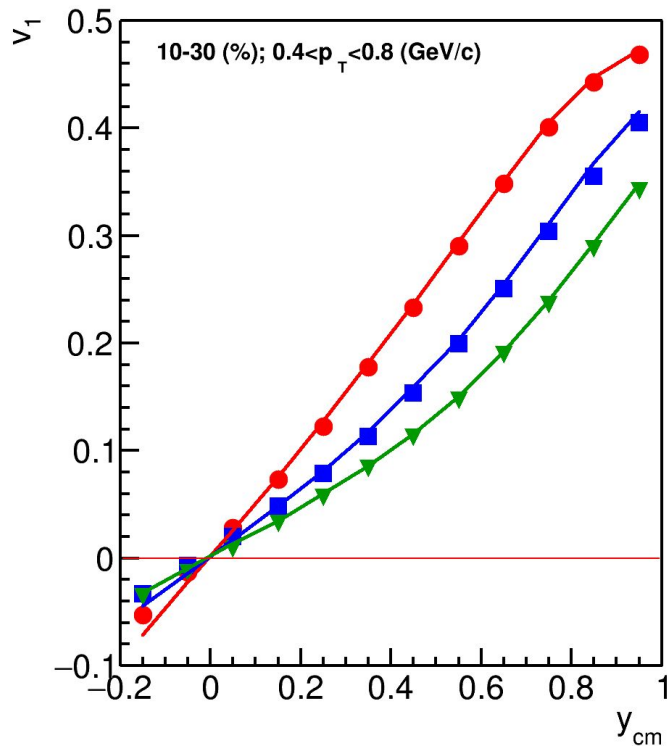
Скалярное произведение: зависимость разрешения плоскости событий R_1 от центральности (модельные данные Xe+Cs(I) $E_{kin} = 3.8$ АГэВ)

Mamaev M. Phys. Part. Nucl. Lett. — 2023. — T. 20, № 5. — С. 1205—1208.



Использование дополнительных подсобытий из треков заряженных частиц даёт согласованные значения для разрешения плоскости симметрии R_1

Оценка эффективности эксперимента BM@N для измерения направленного и эллиптического потоков в столкновениях Xe+CsI



[Mamaev, M.](#)

Physics of Atomic Nuclei,
2023, 86(6), pp. 1346–1353

[Mamaev, M.](#)

Physics of Particles and Nuclei Letters, 2023, 20(5), pp.
1205–1208

[Mamaev, M.](#), [Taranenko, A.](#)

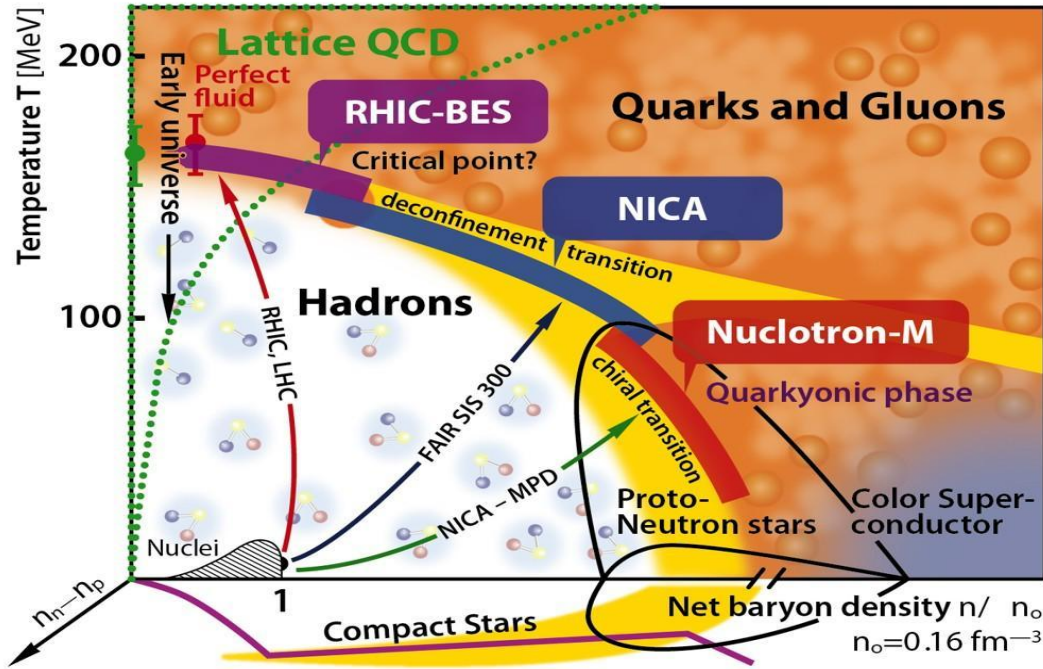
Particles, 2023, 6(2), pp.
622–637

Хорошее согласие между реконструированными и модельными значениями V_n



Critical Temperature
 $T_c \approx 156 \pm 9$ MeV

[PRD 90 094503 (2014)]

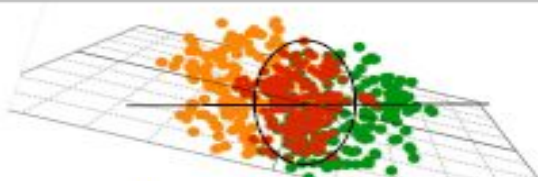


Heavy ion collisions

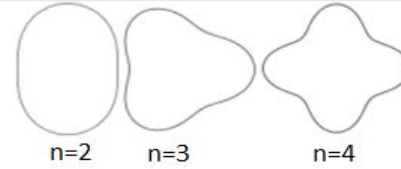
In 2005 4 experiments (STAR, PHENIX, BRAHMS, PHOBOS) at RHIC announced discovery of quark-gluon matter (QGM) with properties of ideal fluid in Au+Au at the energy of $\sqrt{s_{NN}} = 200$ GeV
 In 2010 experiments (ALICE, ATLAS, CMS) at LHC confirmed the observing of QGM in Pb+Pb at $\sqrt{s_{NN}} = 2.76$ TeV

Smooth transition (crossover) to partonic degrees of freedom at zero baryon densities

Anisotropic flow at RHIC and LHC

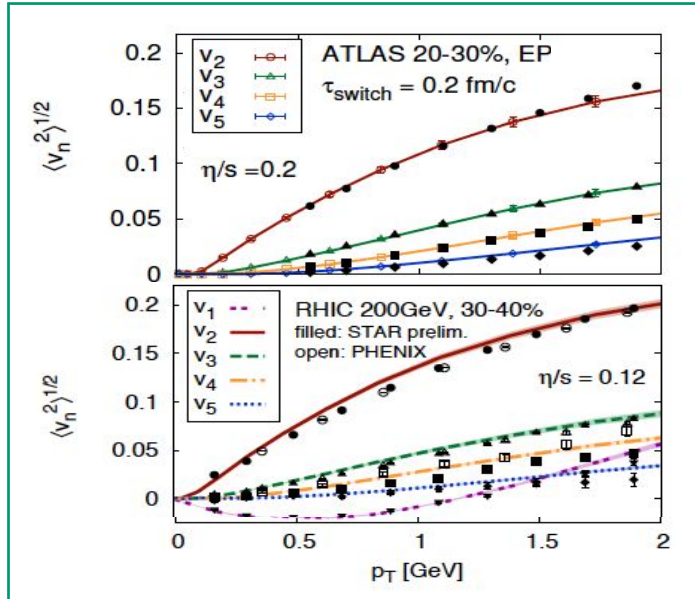


$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}}$$



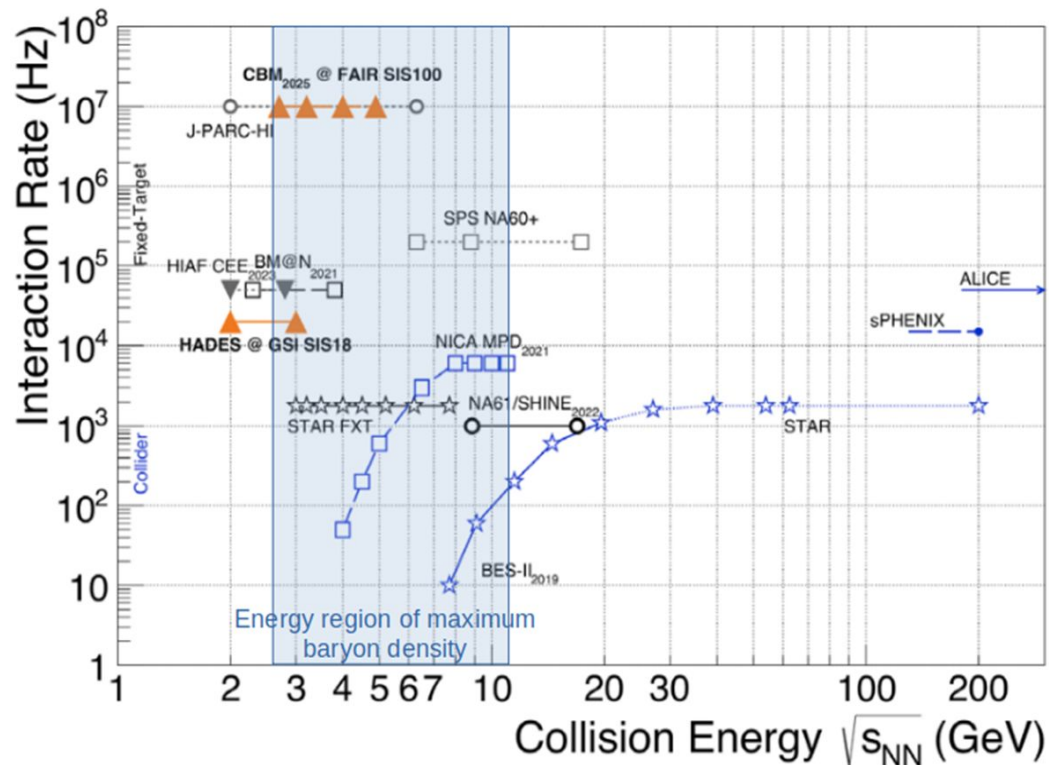
$$\frac{d^2 N}{d\phi d\Psi_{RP}} = \frac{N}{2\pi} \left(1 + 2 \sum_{n=1}^{\infty} v_n \cos n(\phi - \Psi_{RP}) \right)$$

Gale, Jeon, et al., Phys. Rev. Lett. 110, 012302



- The overlap region eccentricity ϵ_n (and corresponding fluctuations) causes azimuthal anisotropy in momentum space v_n with viscous modulations η/s
- For v_2 and v_3 : $v_n \sim k_n \epsilon_n$
- Anisotropic flow at RHIC and LHC are well-described by viscous hydrodynamics with η/s close to the predicted minimum $\eta/s > 1/4\pi$

HIC-experiments at the high-baryon density region



HIC experiments where high-baryon density can be achieved:

Existing:

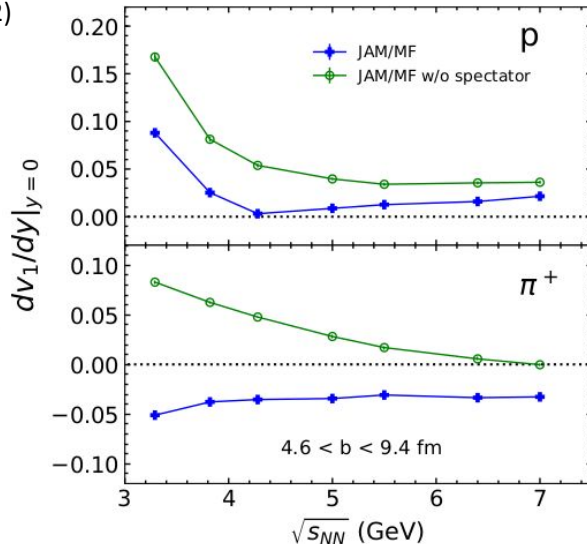
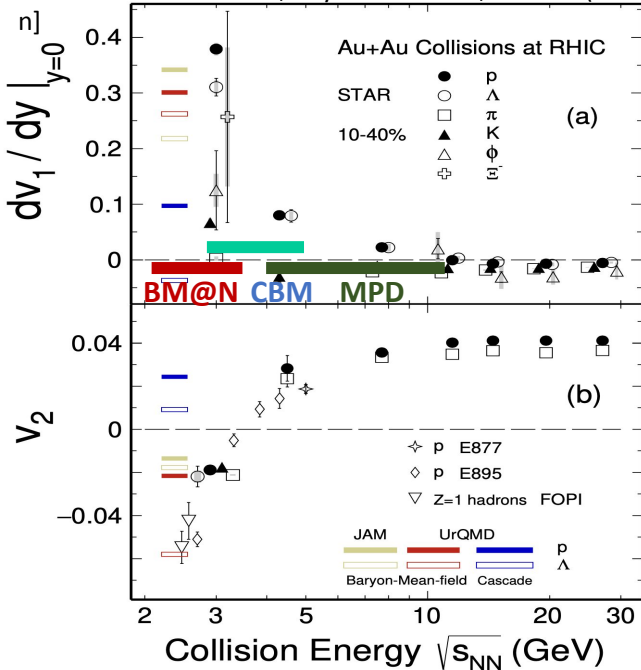
BM@N/NICA — 2.4-3.3 GeV
HADES/SIS18 — 2.4-2.55 GeV
STAR/RHIC — 3-200 GeV

Future:

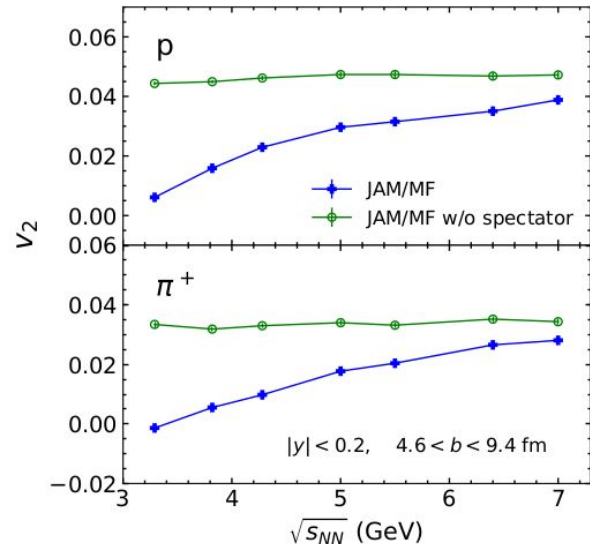
MPD/NICA — 4-11 GeV (2025)
CEE/HIAF — 2.1-4.4 GeV (2026)
CBM/FAIR 2.4-4.9 GeV (2029)

Anisotropic flow in HIC at high-baryon density

M. Abdallah et al. STAR, Phys. Lett. B 827, 137003 (2022)



$$\begin{aligned} \sqrt{s_{NN}} &= 10 \text{ GeV}: t_{\text{pass}} \sim 1 \text{ fm/c} \\ \sqrt{s_{NN}} &= 2, 4 \text{ GeV}: t_{\text{pass}} \sim 20 \text{ fm/c} \end{aligned}$$



Phys. Rev. C 97, 064913 (2018)

At the energies of BM@N anisotropic flow is heavily influenced by:

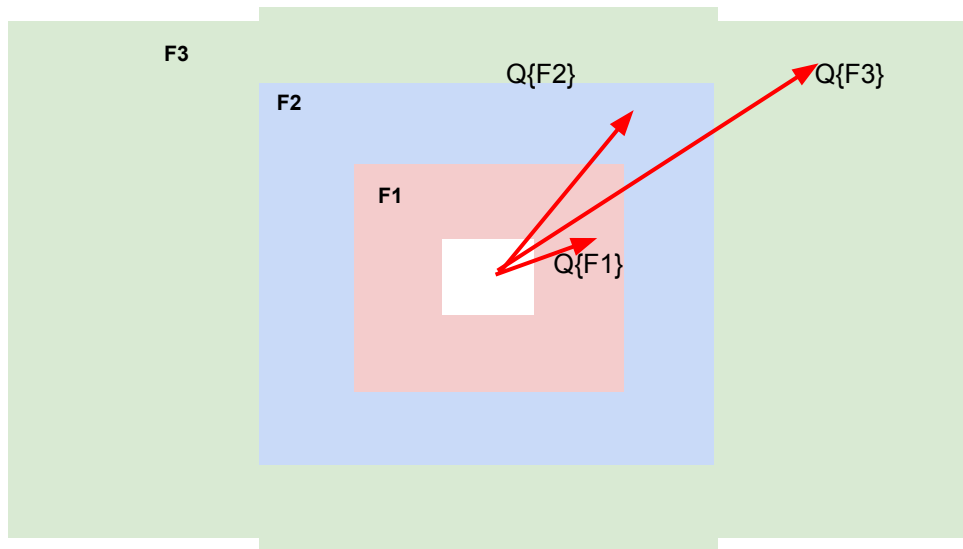
1. Time of expansion of the overlap region:
2. Passing time of colliding nuclei:

$$t_{exp} = R/c_s, c_s = \sqrt{dp/d\varepsilon}$$

$$t_{pass} = 2R/\gamma_{beam}\beta_{beam}$$

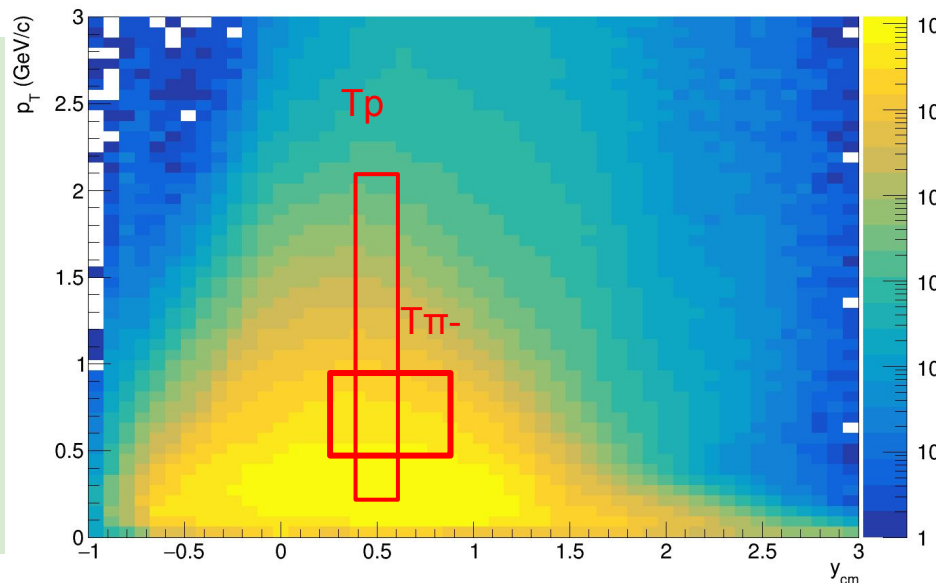
Q-vectors from FHCAL charged particle trajectories

Mamaev, M., Taranenko, A. Particles, 2023, 6(2), pp. 622–637



3 vectors from FHCAL:

F1: $4.4 < \eta < 5.5$; $w = E_{\text{kin}}$
F2: $3.9 < \eta < 4.4$; $w = E_{\text{kin}}$
F3: $3.1 < \eta < 3.9$; $w = E_{\text{kin}}$



Additional subevents from charged particles tracks:

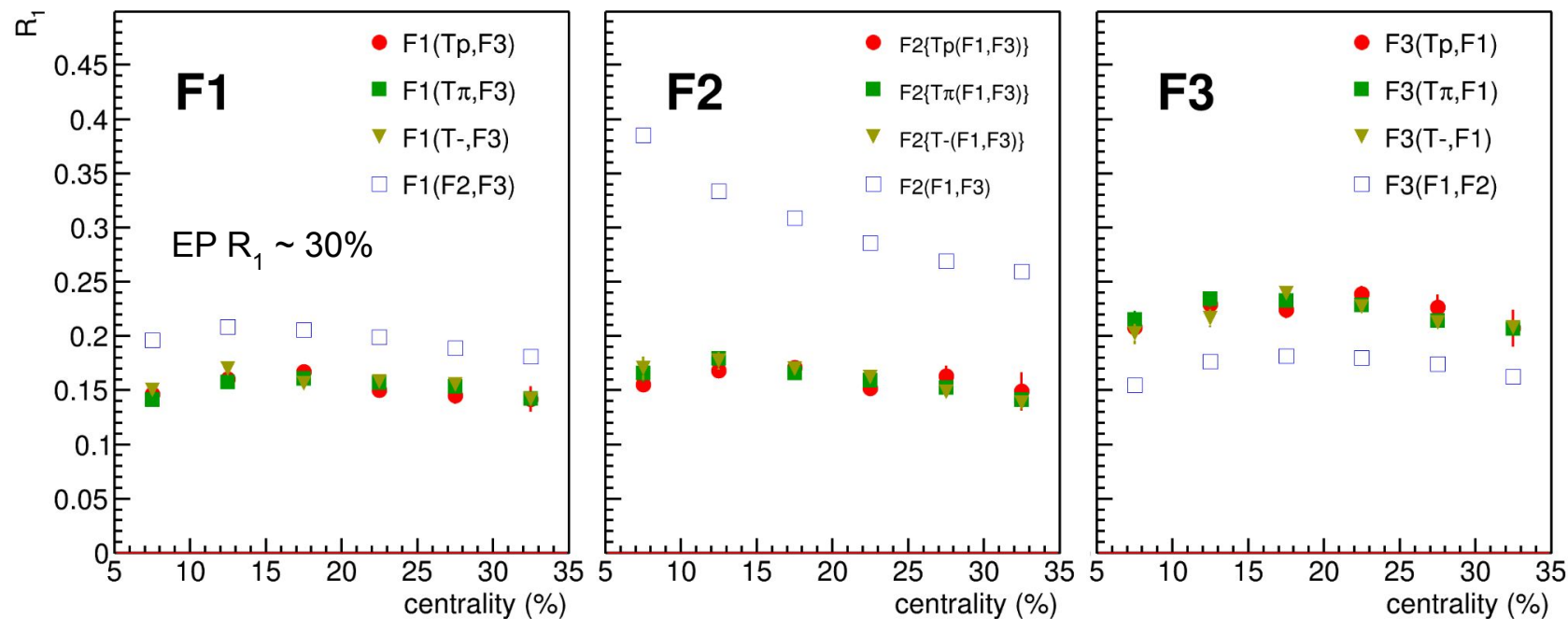
T_p : p ; $0.4 < y < 0.6$; $0.2 < p_T < 2$ GeV/c; $w = 1/\text{eff}$

T_{π^-} : π^- ; $0.2 < y < 0.8$; $0.1 < p_T < 0.5$ GeV/c; $w = 1/\text{eff}$

T_- : all negative; $1.0 < \eta < 2.0$; $0.1 < p_T < 0.5$ GeV/c;

R_1 vs centrality for Xe+Cs(I) at $E_{\text{kin}}=4A$ GeV: MC-simulation

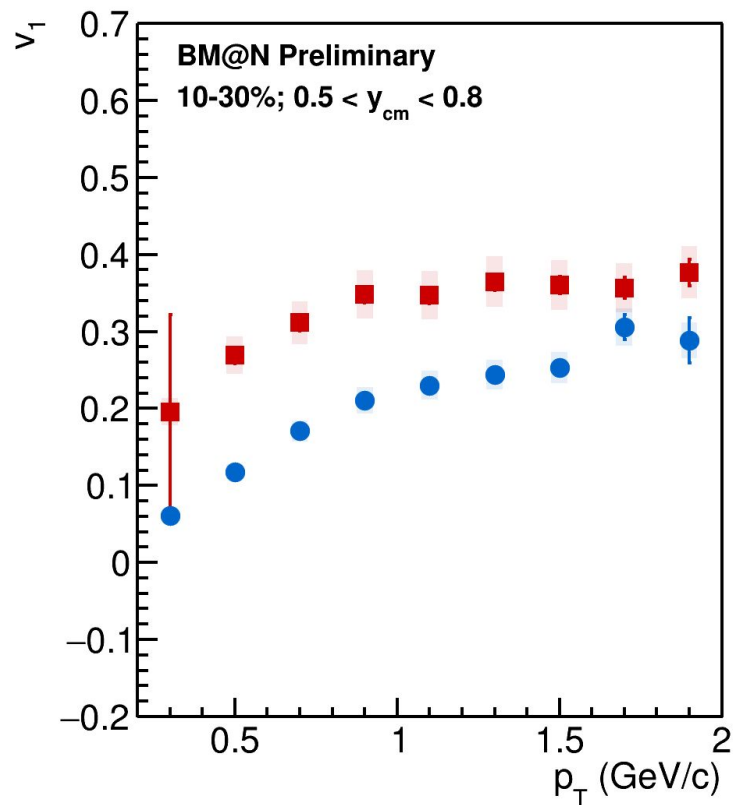
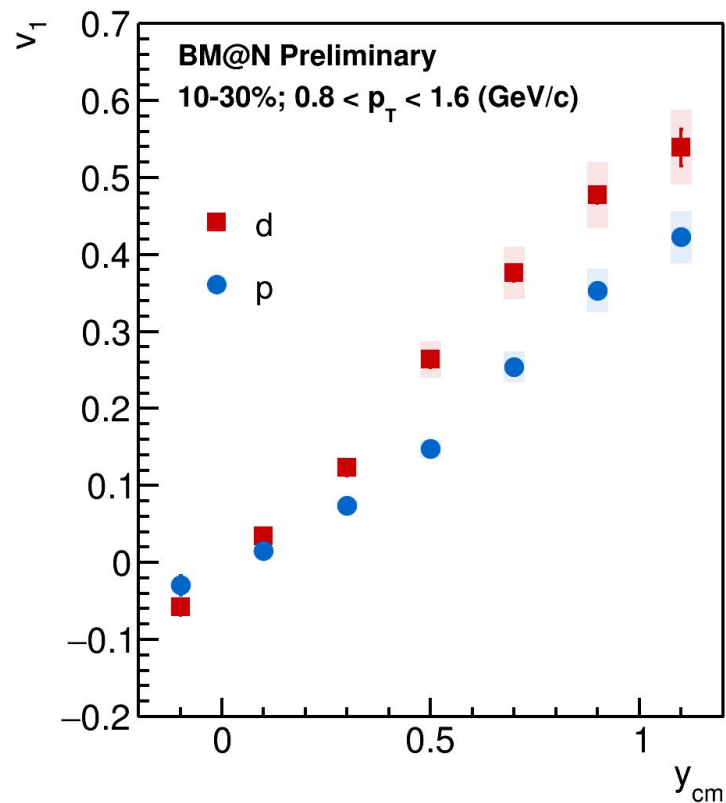
Mamaev M. Phys. Part. Nucl. Lett. — 2023. — T. 20, № 5. — C. 1205—1208.



Использование дополнительных подсобытий из треков заряженных частиц даёт согласованные значения для разрешения плоскости симметрии R_1

Proton and deuteron v_1 vs rapidity and transverse momentum

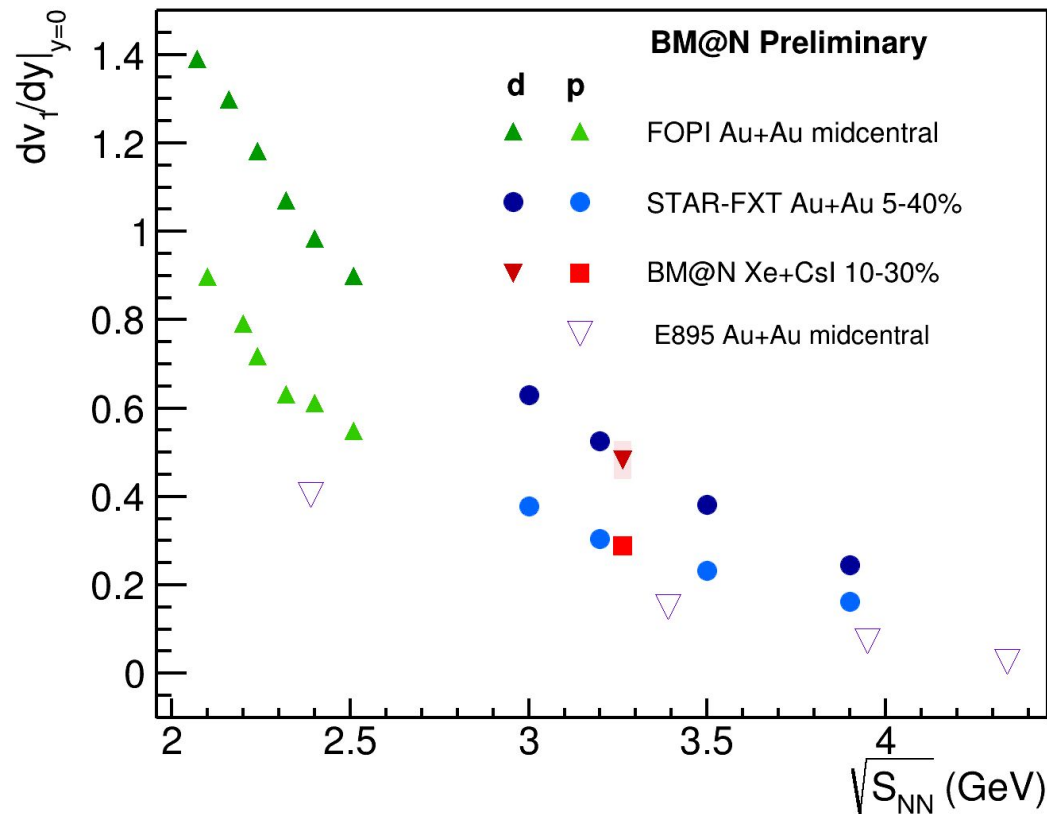
Deuteron data
by I.Zavoronkova



$dv_1/dy|_{y=0}$ vs collision energy

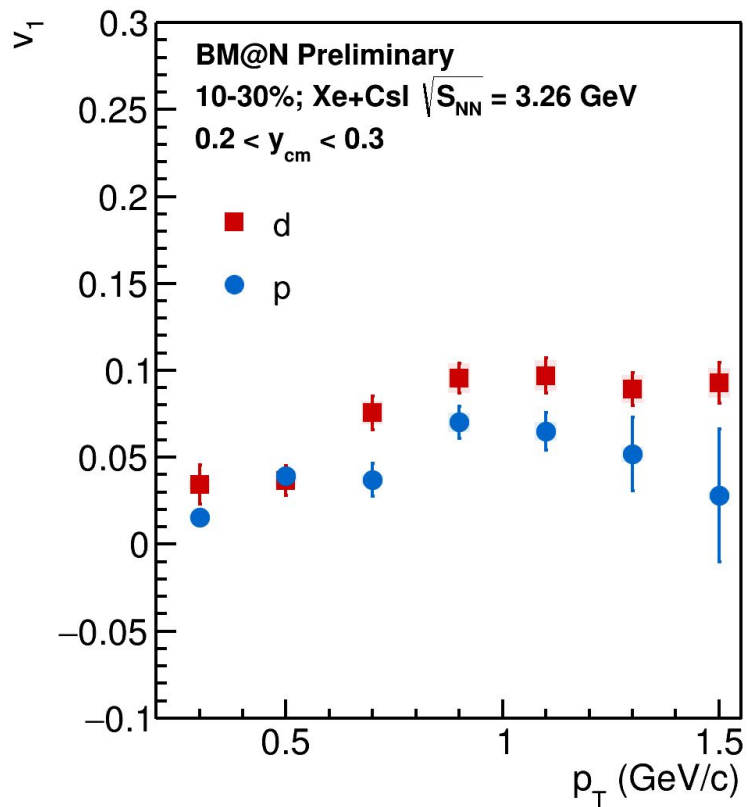
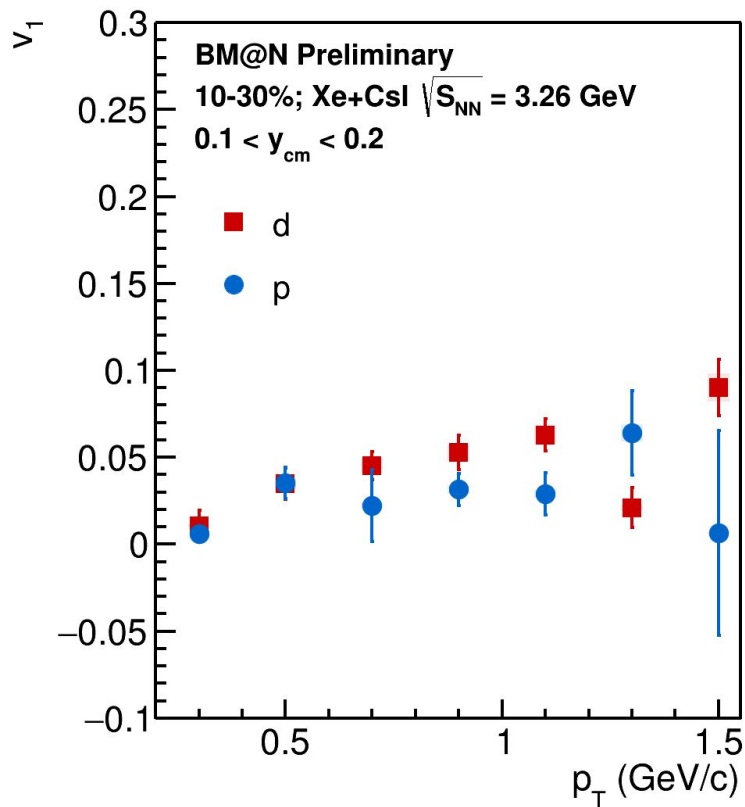
Deuteron data
by I.Zhavoronkova

FOPI: Nucl.Phys.A 876 (2012)
STAR: Phys.Lett.B 827 (2022)
E895: Phys.Rev.Lett. 84 (2000)

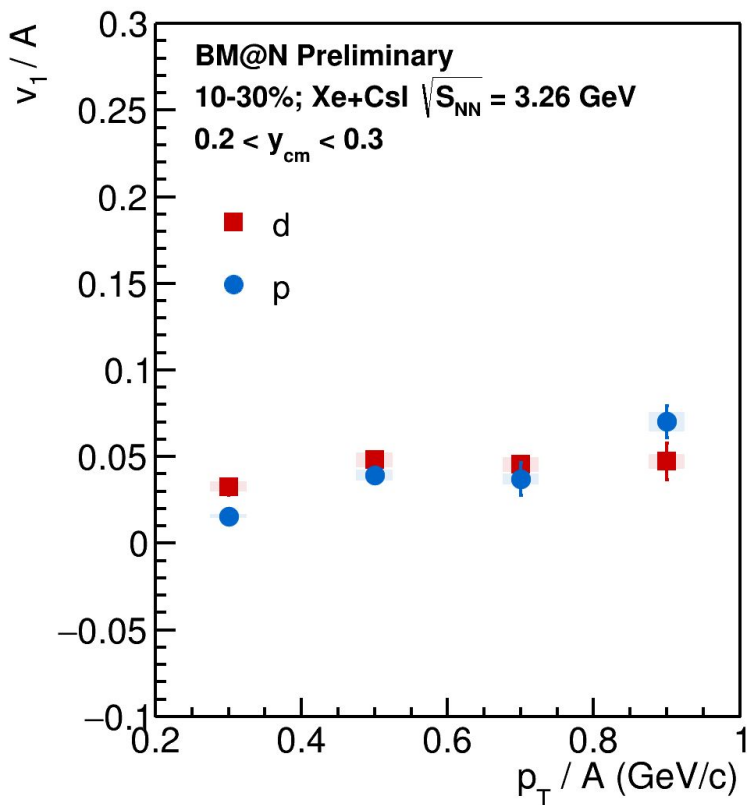
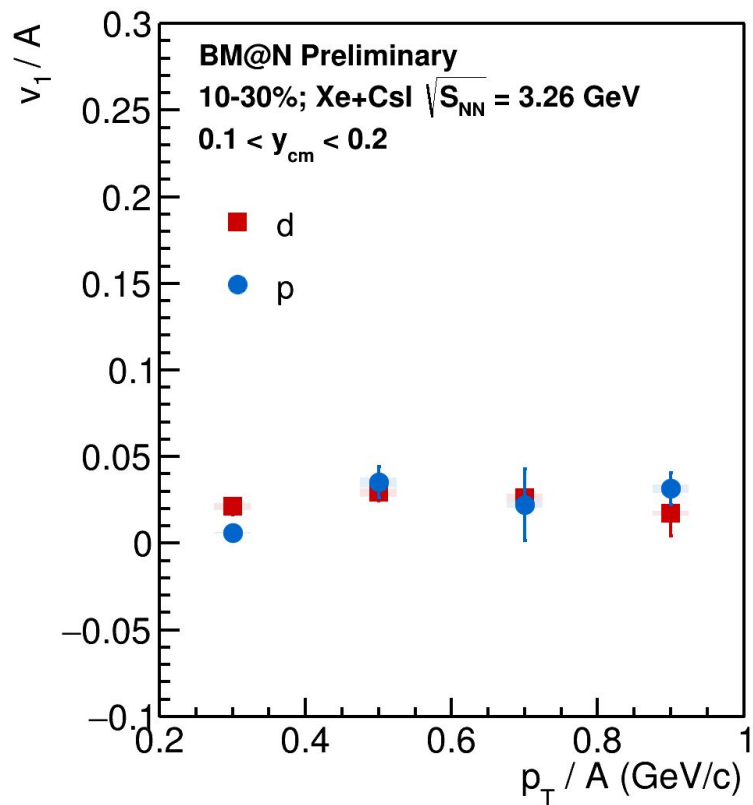


- Both deuteron and proton data from BM@N agree with STAR measurements
- Higher directed flow of proton in BM@N and STAR data suggests more hard equation of state

v_1 of protons and deuterons as a function of p_T



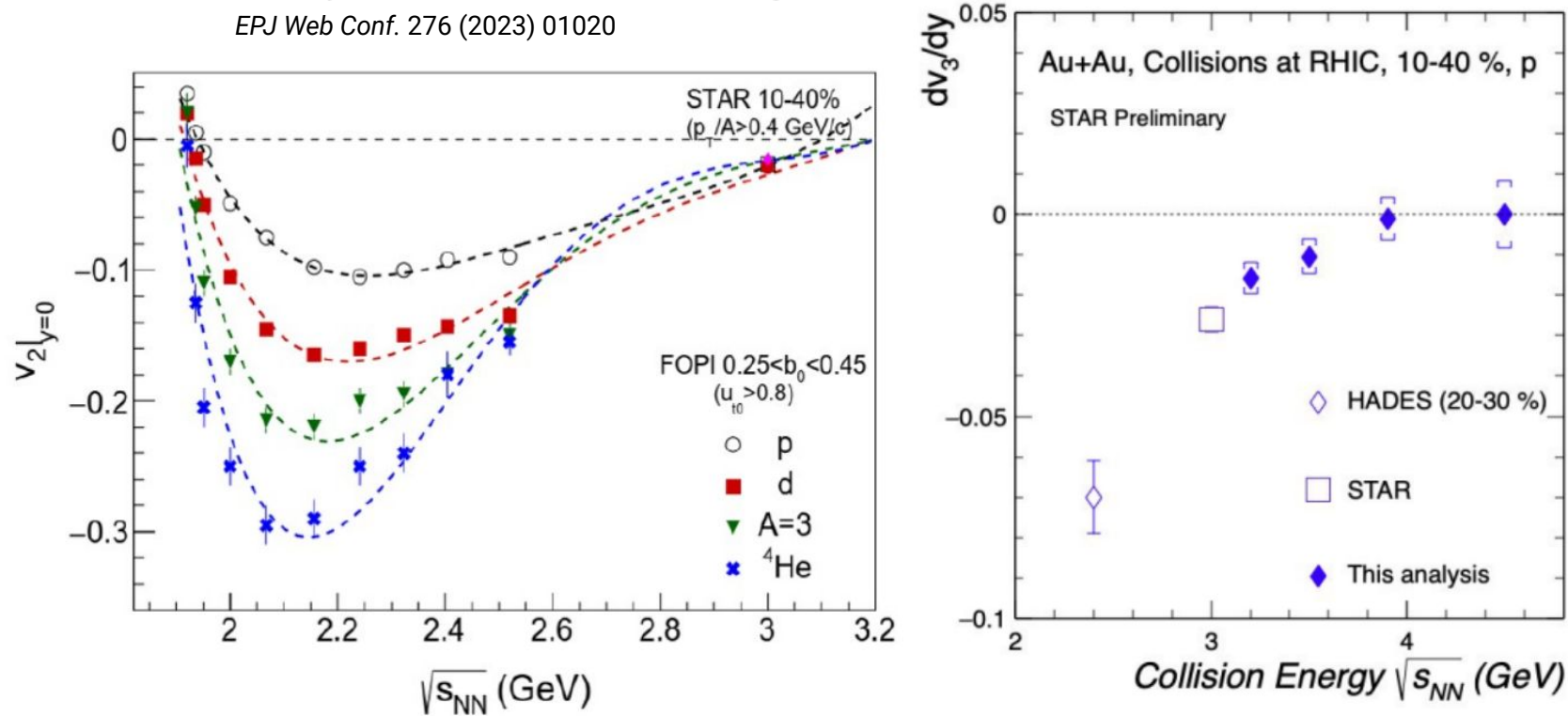
Scaled v_1 of protons and deuterons as a function of scaled p_T/A



v_1 follows the scaling with mass number A .

BES program in the BM@N experiment

EPJ Web Conf. 276 (2023) 01020



- There are no available measurements of v_n in the region $\sqrt{s_{NN}} = 2.5 - 3.0 \text{ GeV}$
 - The upcoming BM@N BES aims to cover this energy range