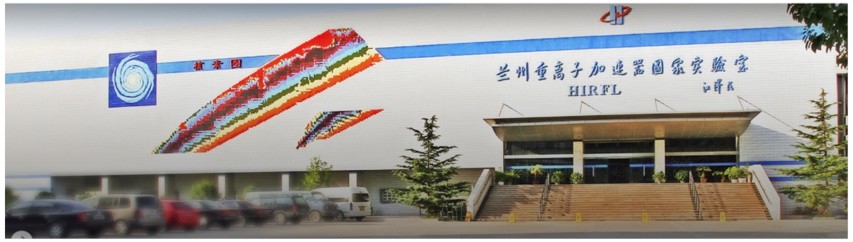

46th CBM Collaboration meeting (19-24/Oct/2025), PIFI-day

STAR measurements and outlook for future experiments

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Div. of Physics, Inst. of Pure and Applied Sciences,
Tomonaga Center for the History of the Universe (TCHoU)

Contents

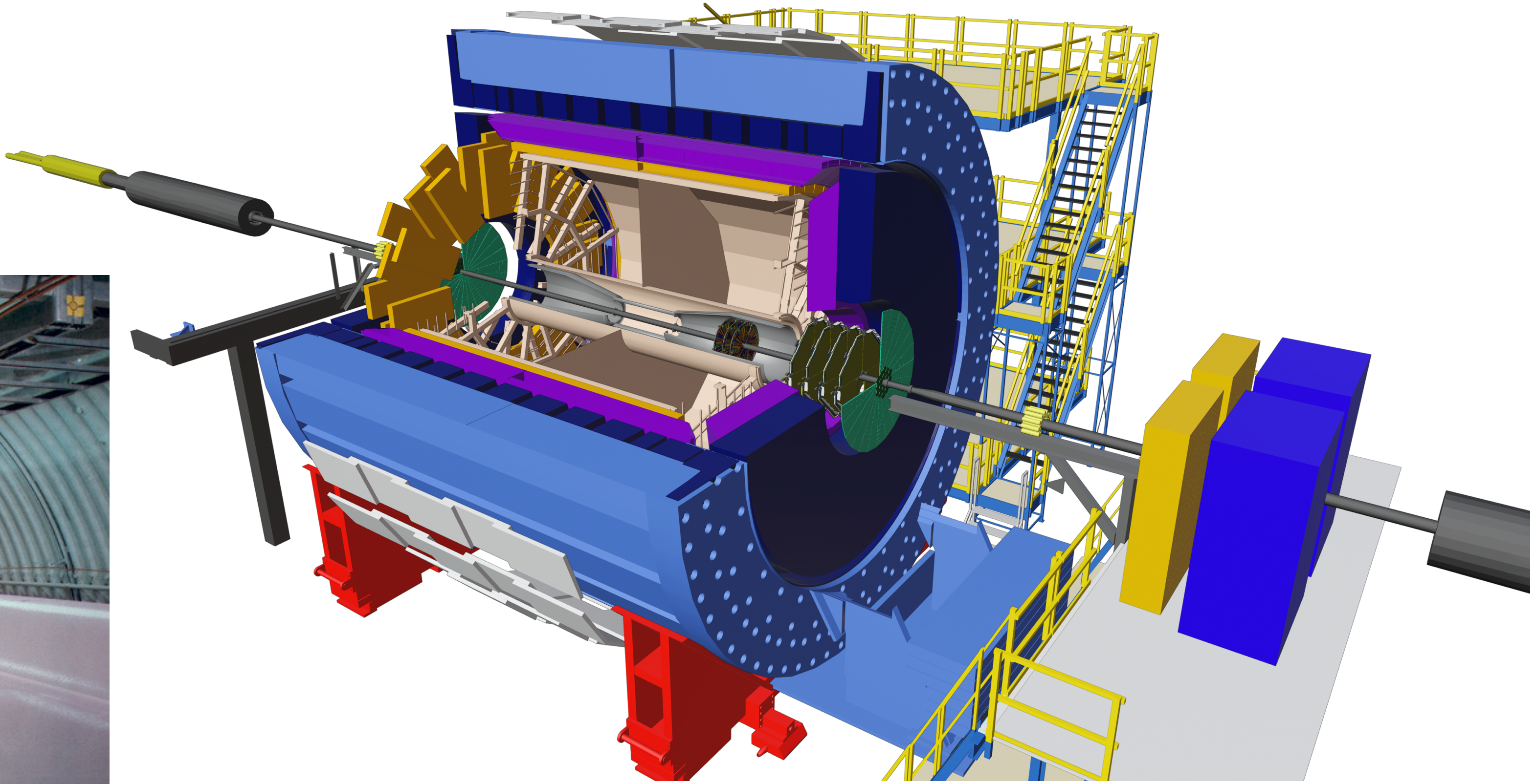
- STAR experiment and detectors
- Tracking, particle identification, reaction plane and centrality
- Temperature measurements and Freeze-out
- Anisotropic flow, correlation, fluctuation
- Next plan and Outlook

The STAR experiment at the Relativistic Heavy Ion Collider, Brookhaven National Laboratory

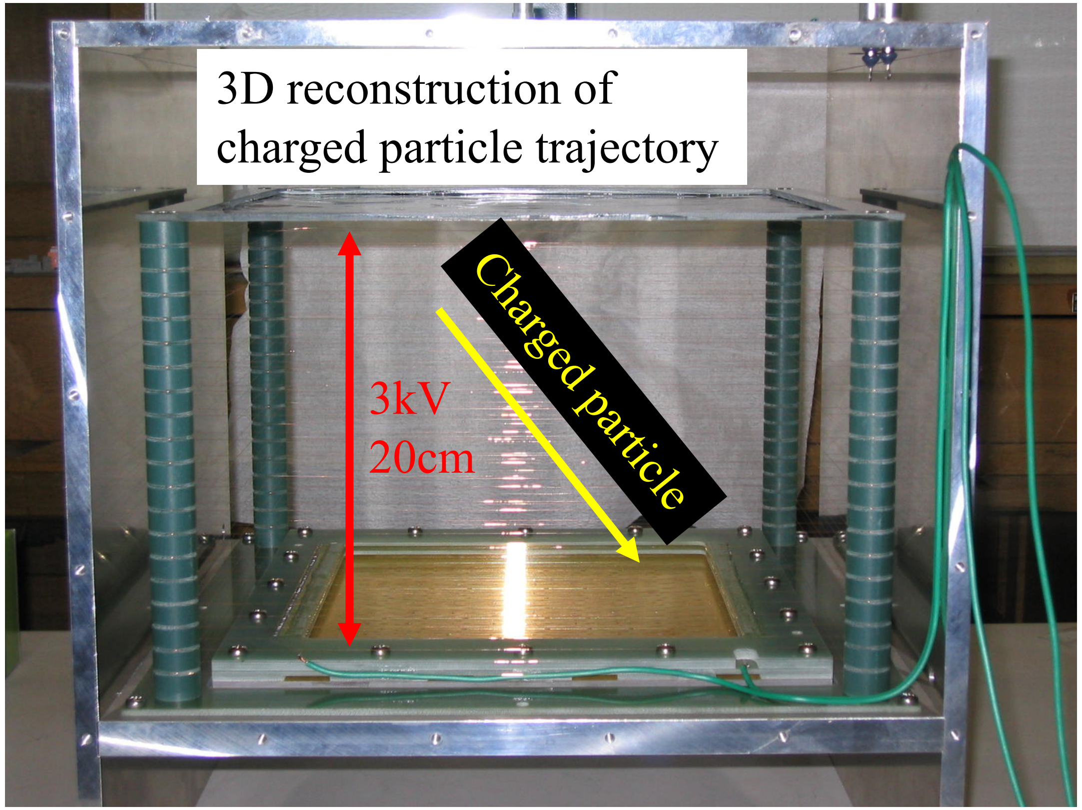
筑波大学 宇宙史研究センター Tomonaga Center for the History of the Universe

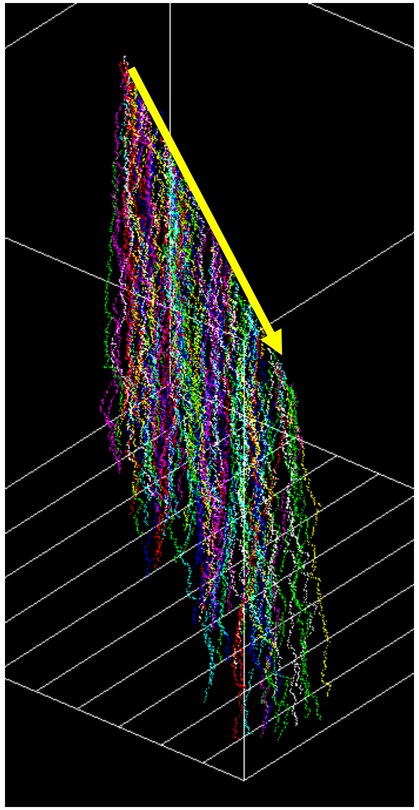
筑波大学 University of Tsukuba

STAR experiment (Solenoidal Tracker at RHIC)
with Relativistic Heavy-Ion Collider (RHIC)
at Brookhaven National Laboratory (BNL)



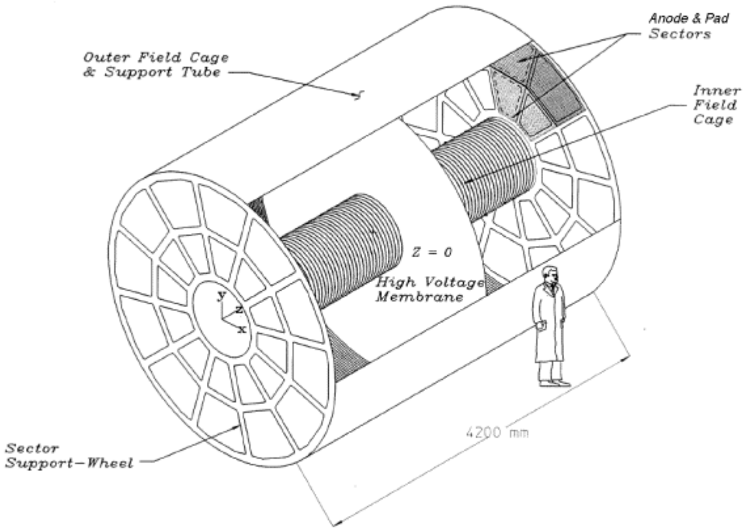
TPC (Time Projection Chamber)
for 3D tracking of charged particles

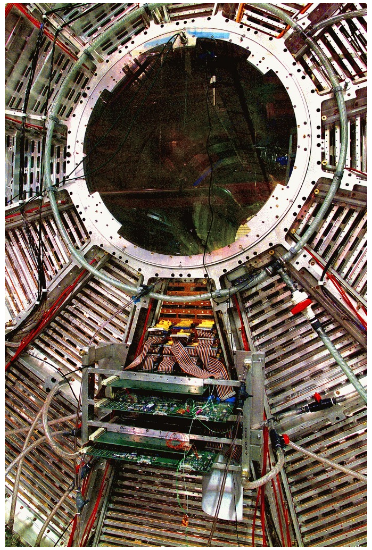


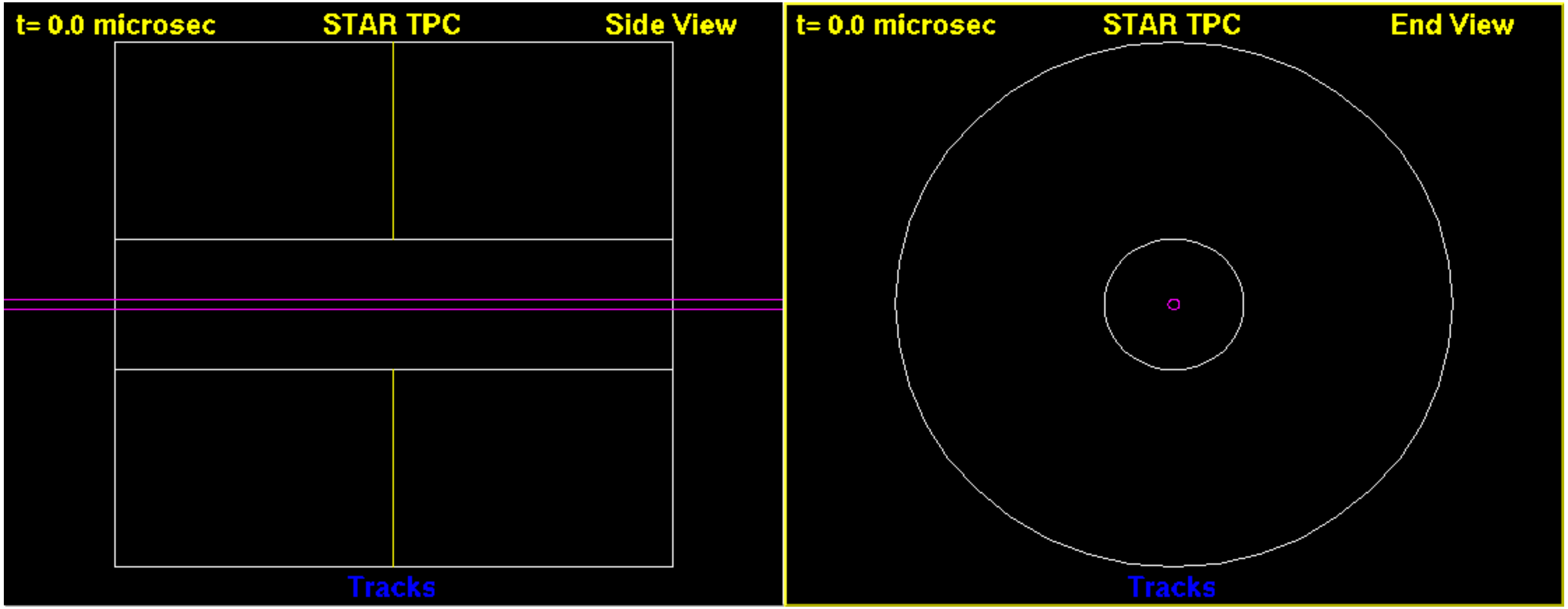


STAR TPC

charged particle trajectory

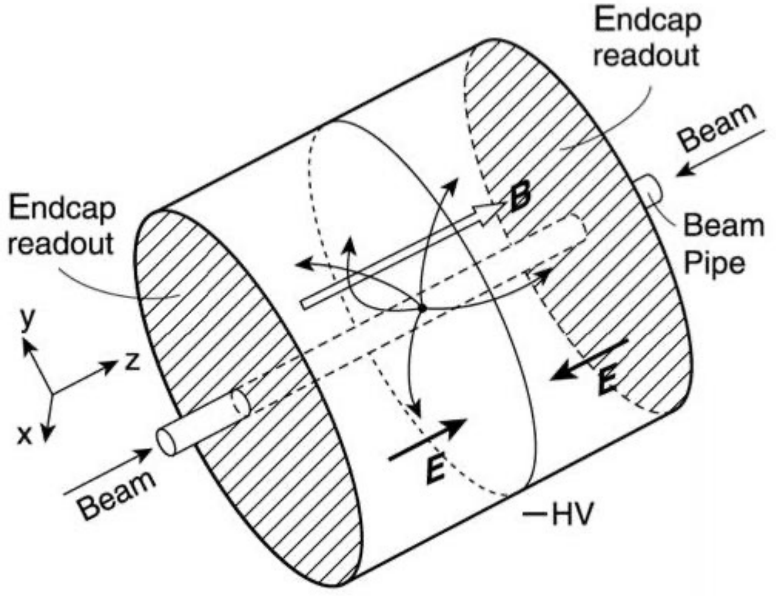


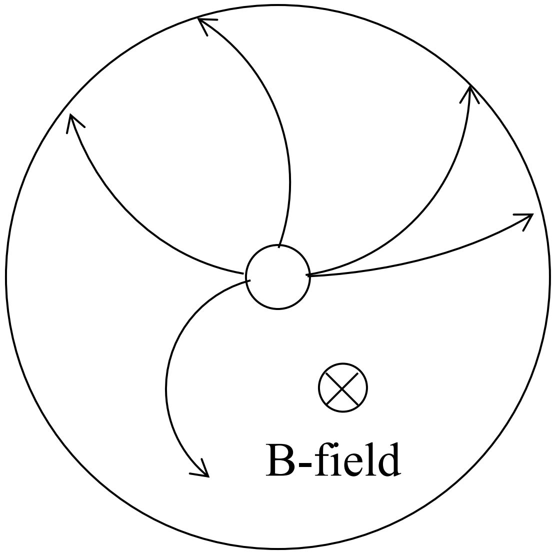


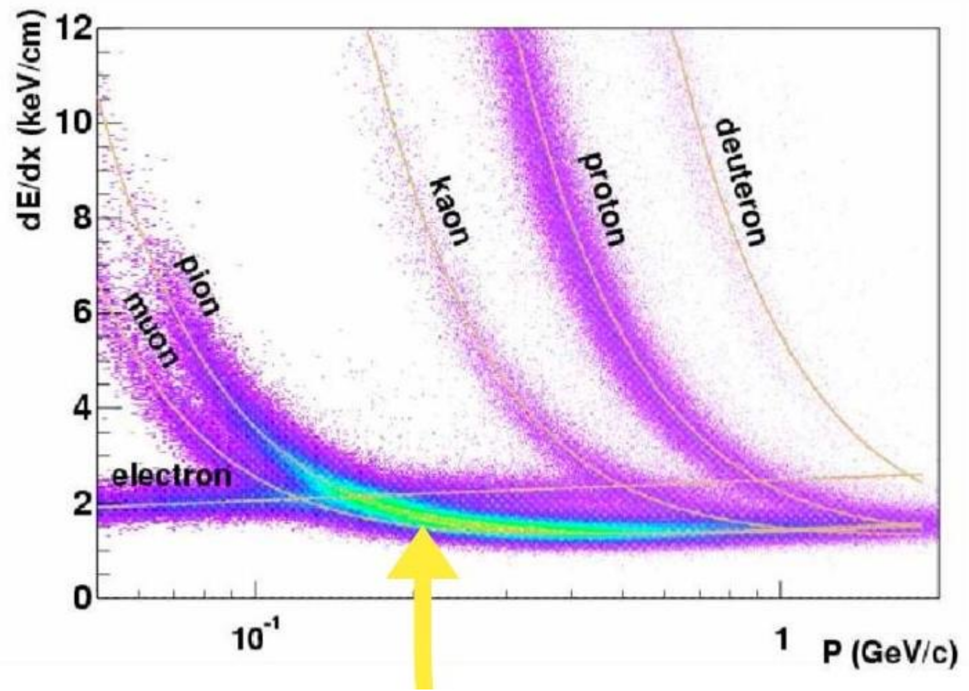


STAR TPC

Momentum (pT) measurement
Particle identification (dE/dx)

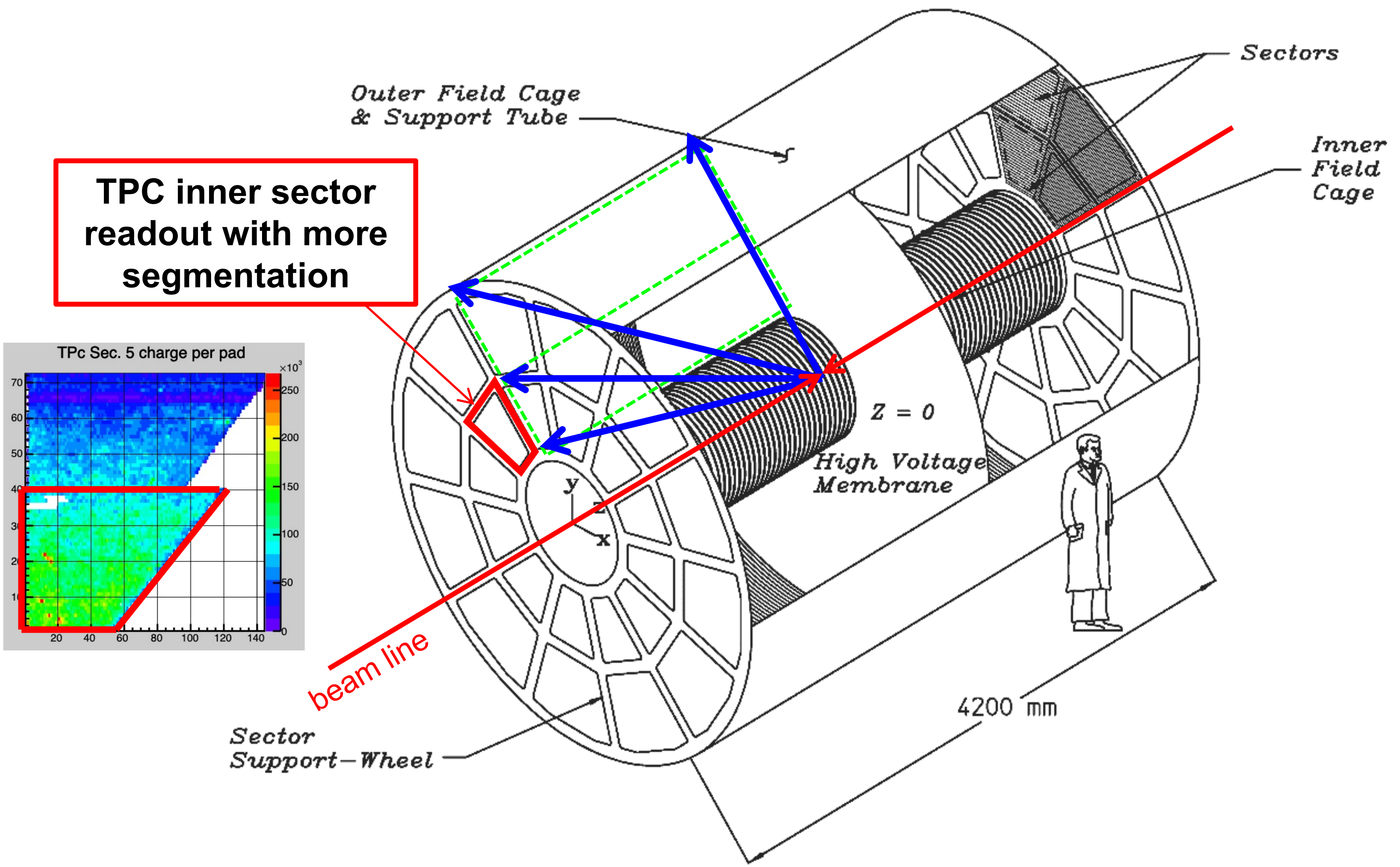


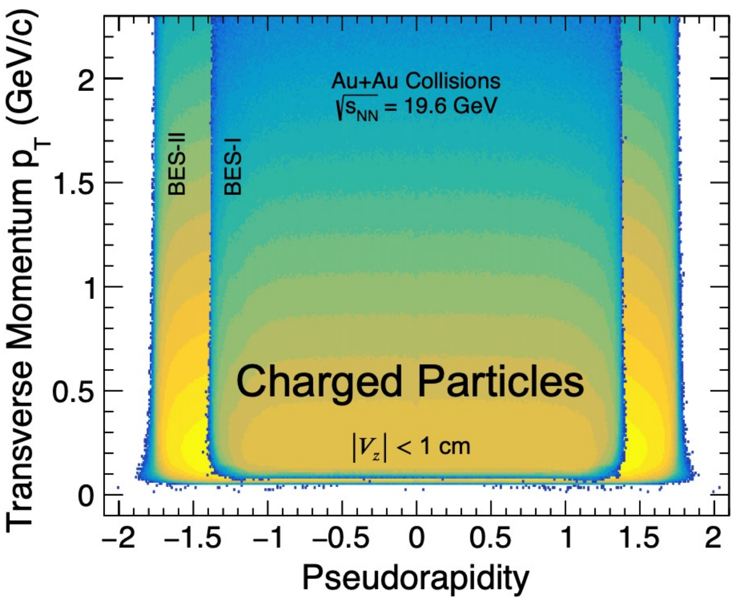


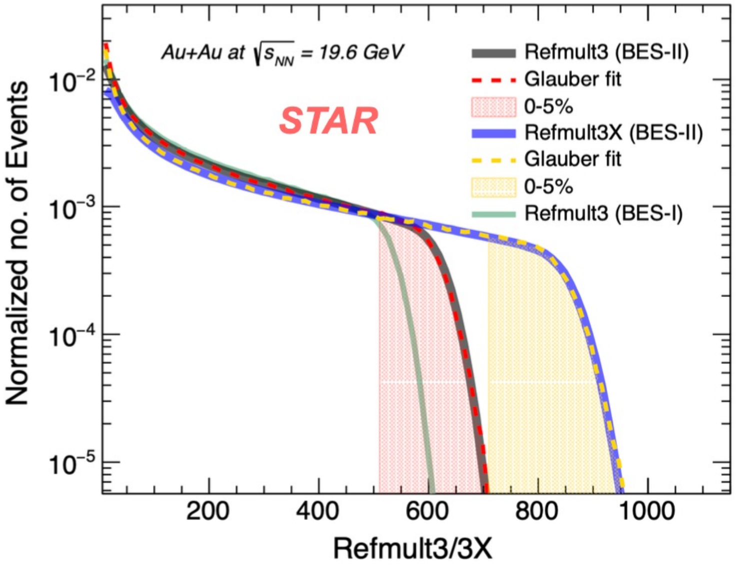


minimum ionization
(Bethe-Bloch) velocity and charge

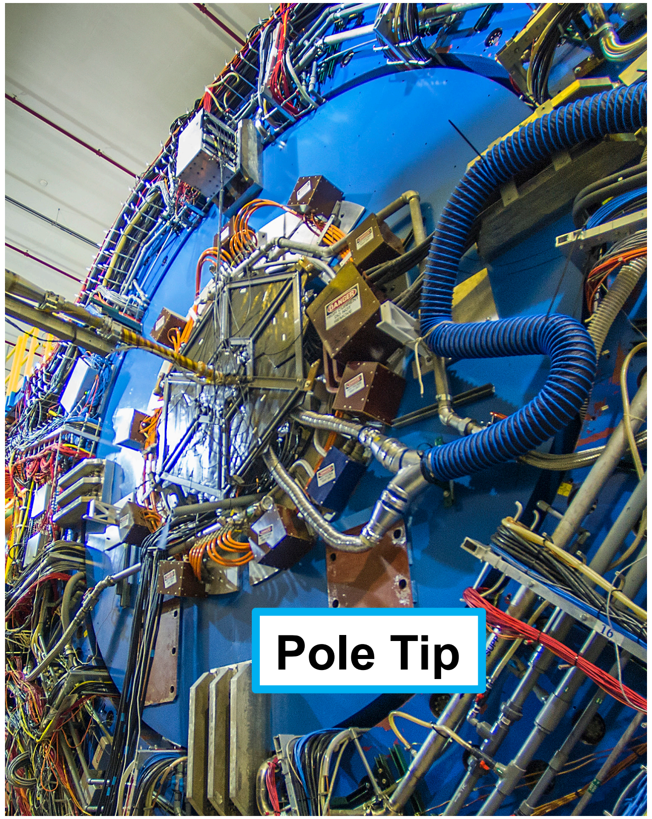
STAR TPC upgrade for BES2

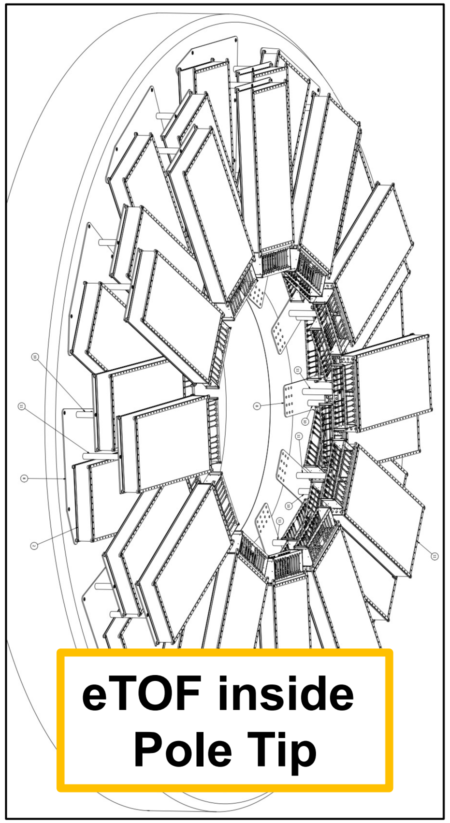


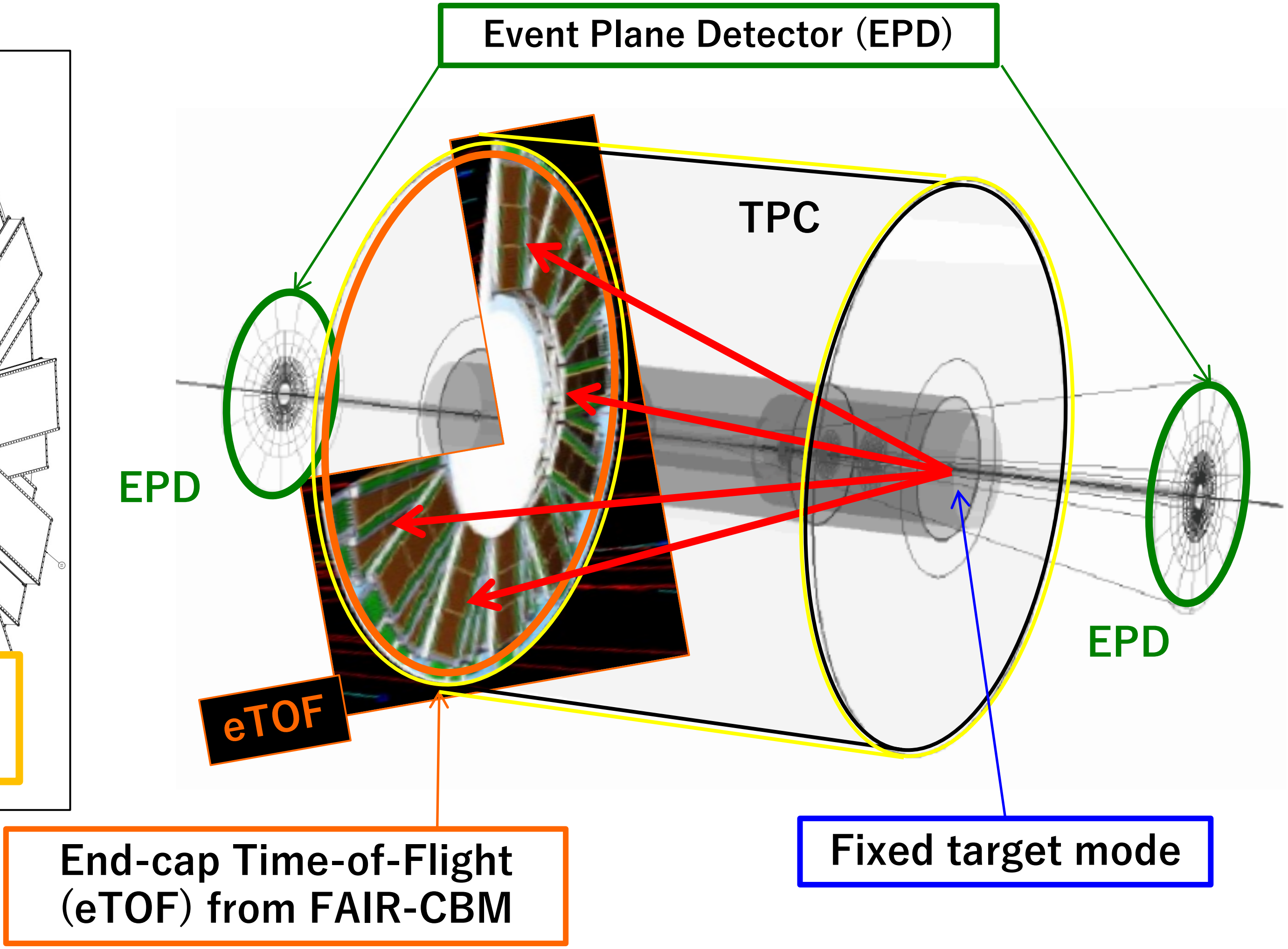




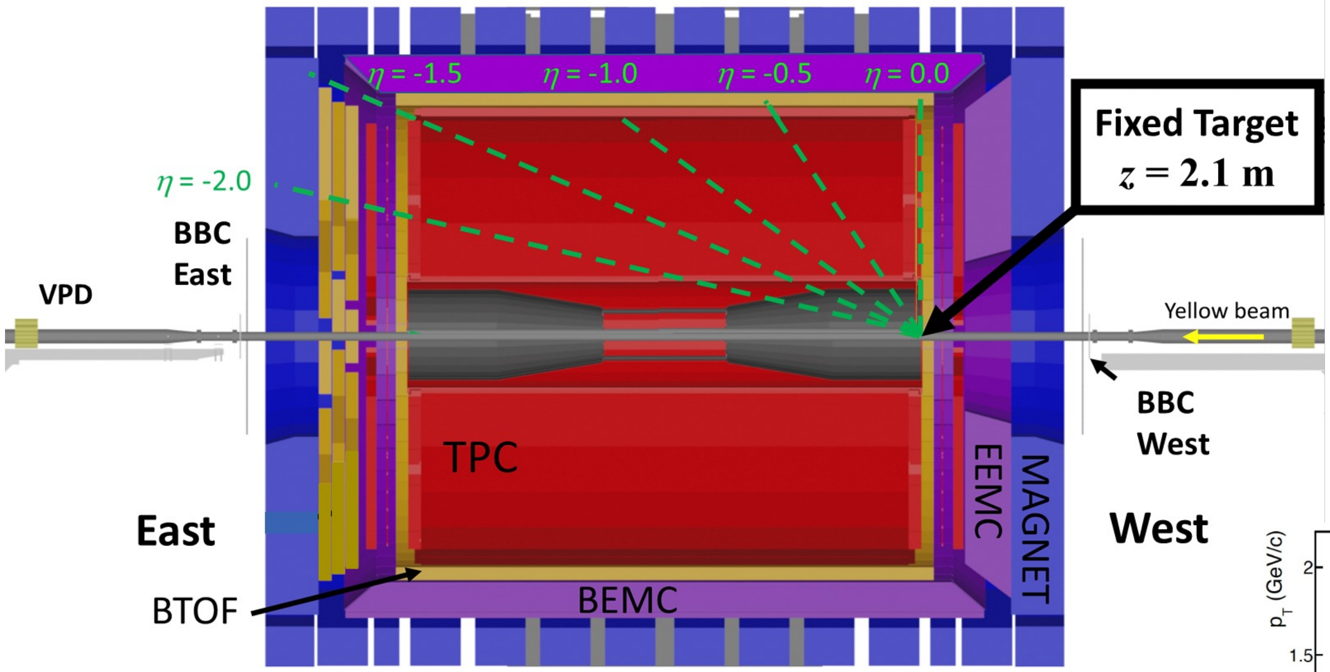
STAR eTOF (end-cap TOF, MRPC)

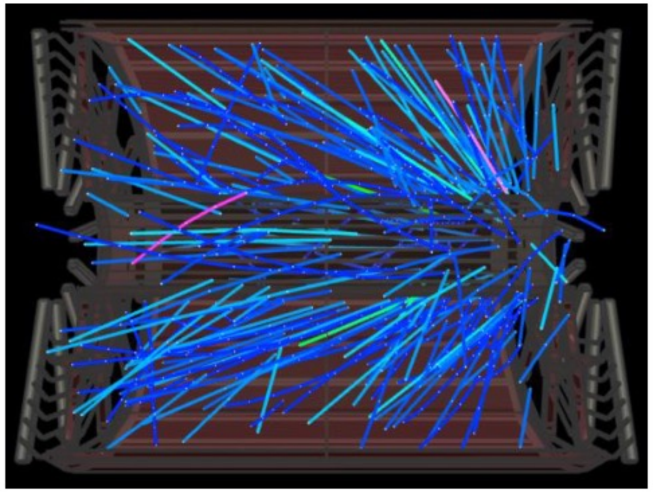


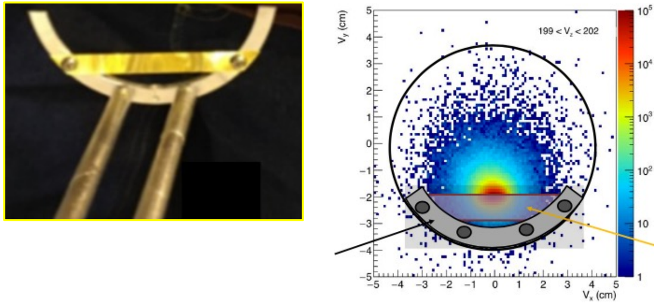


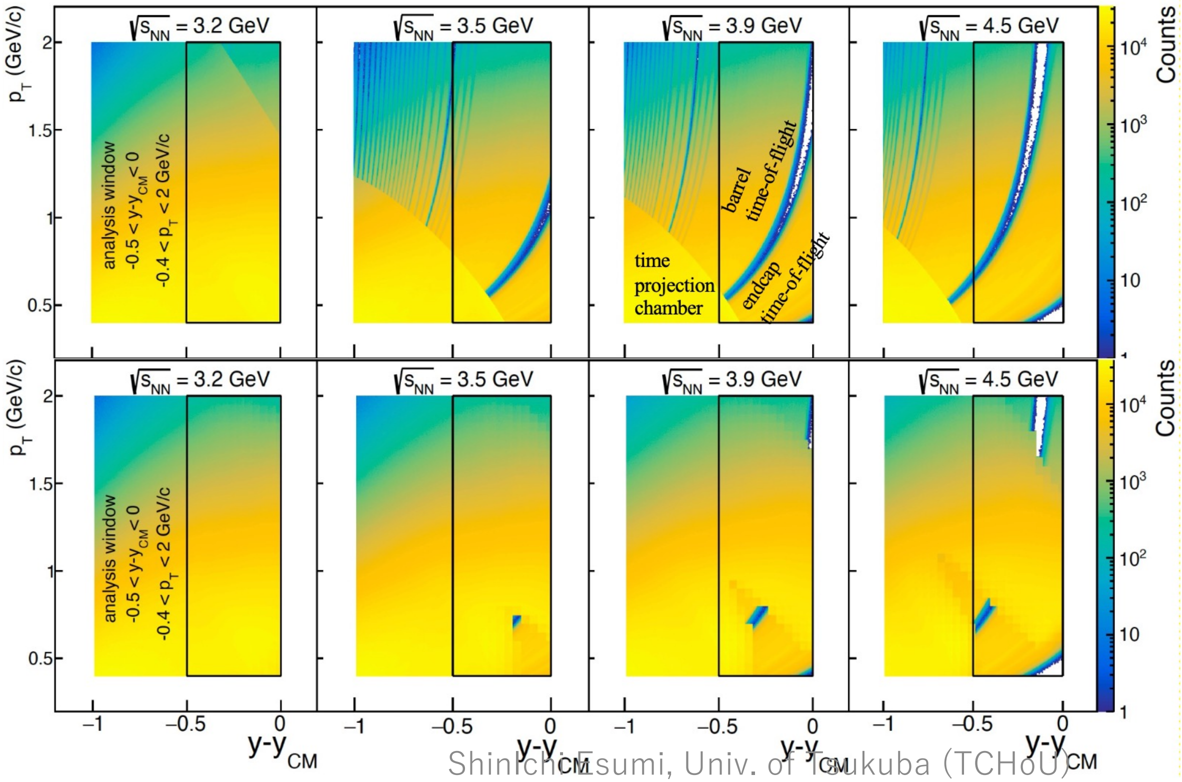


STAR Fixed Target setup

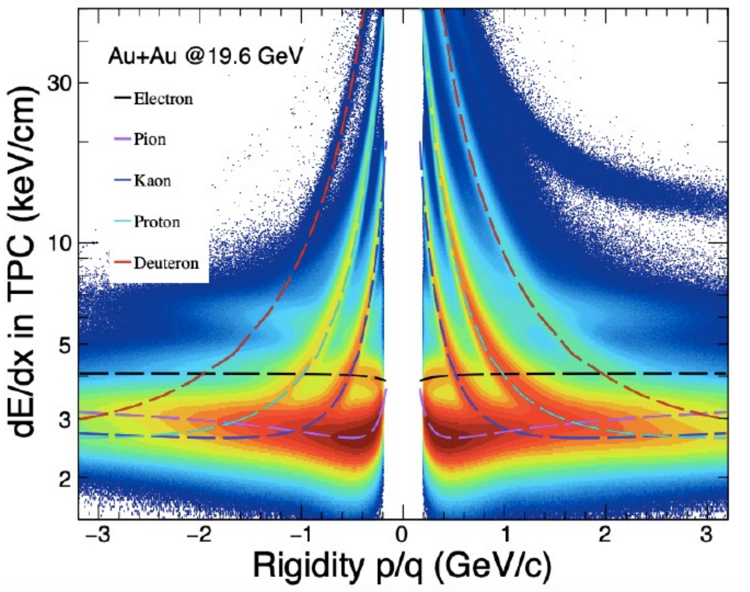


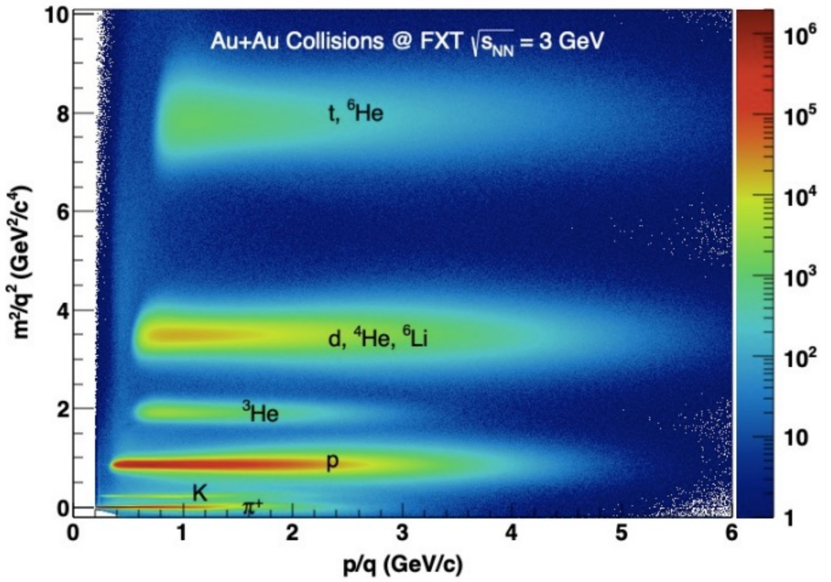


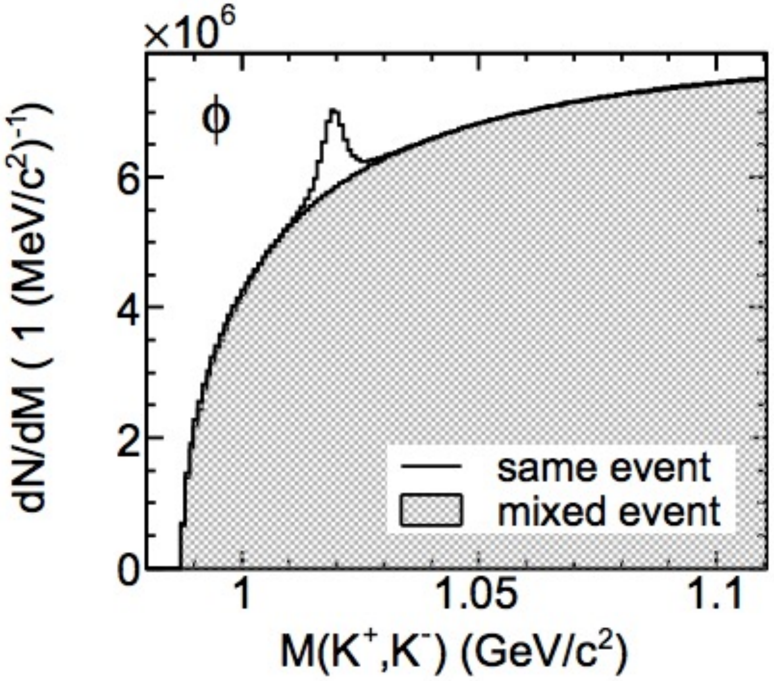


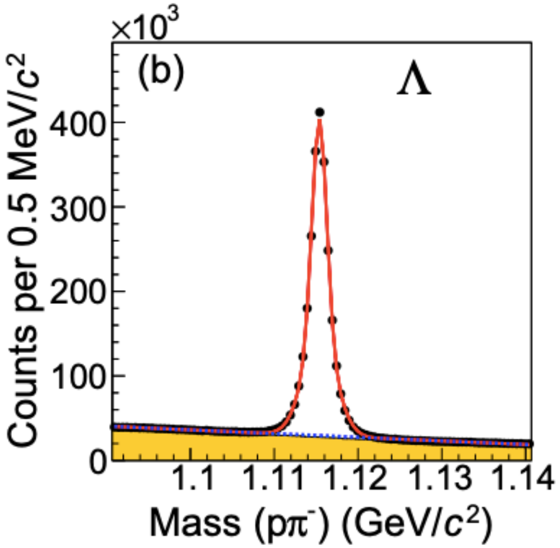


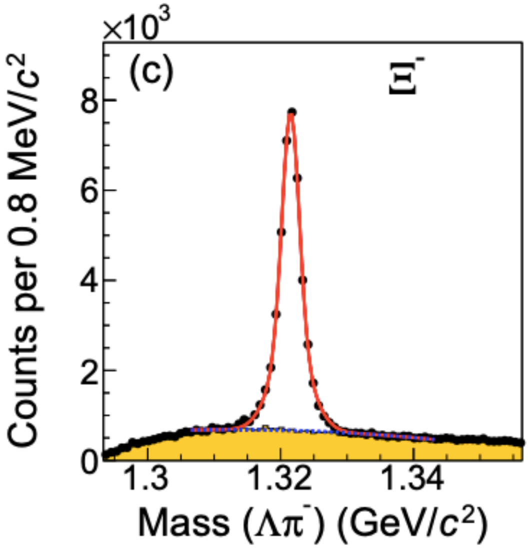
Particle identification in STAR

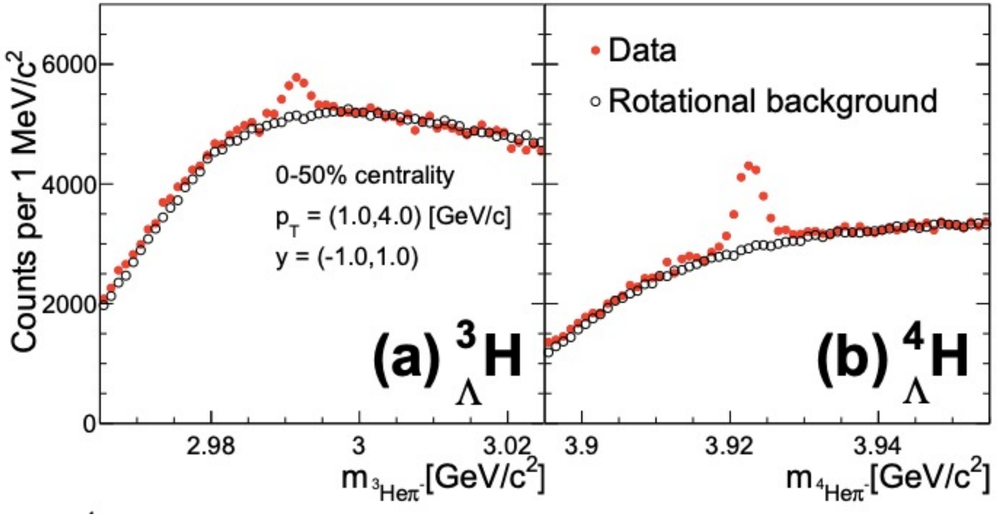




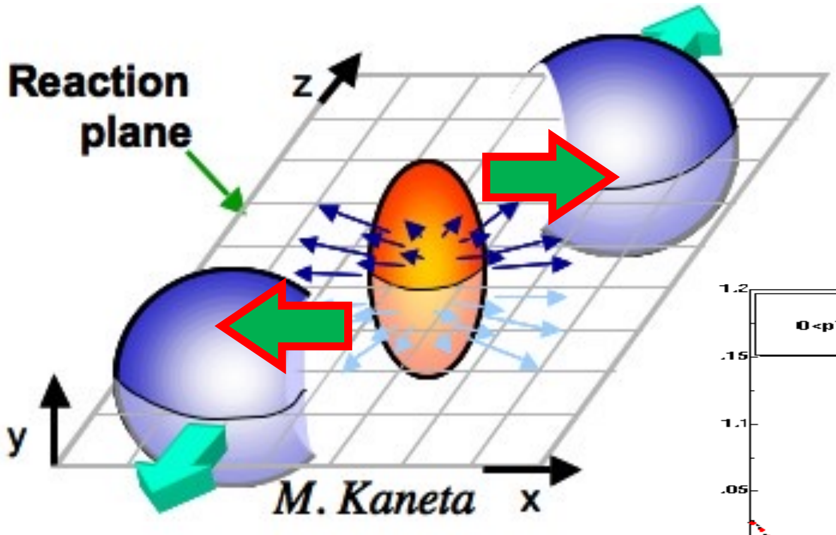


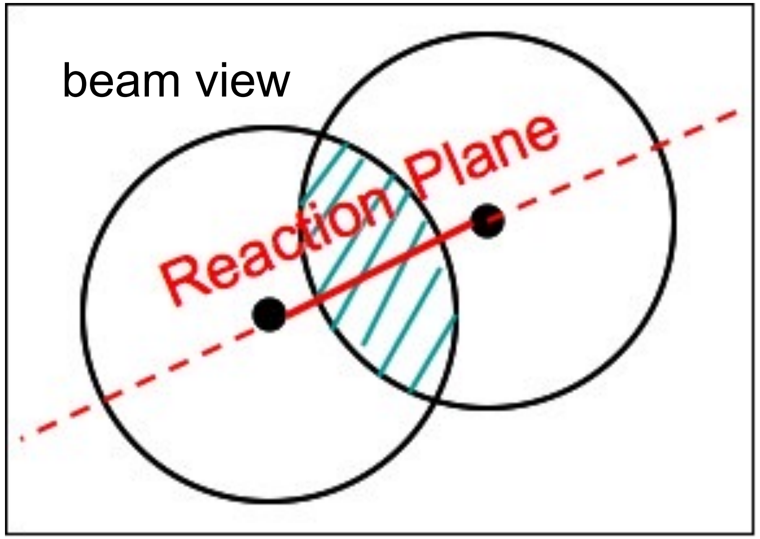


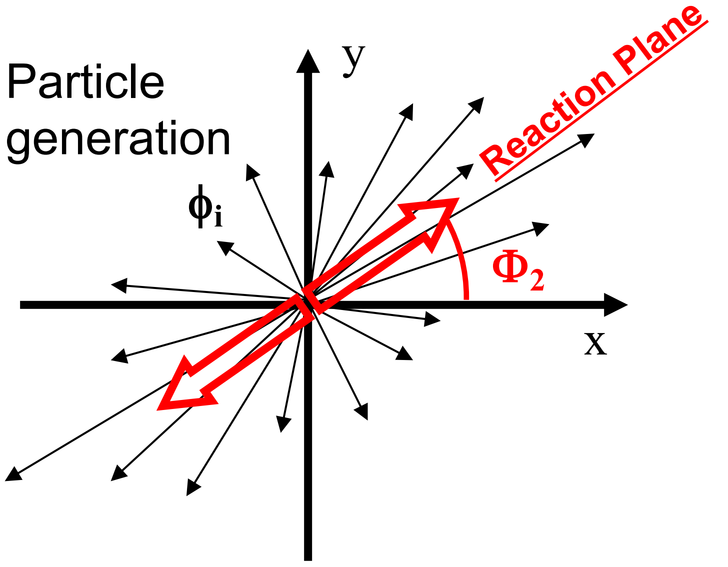




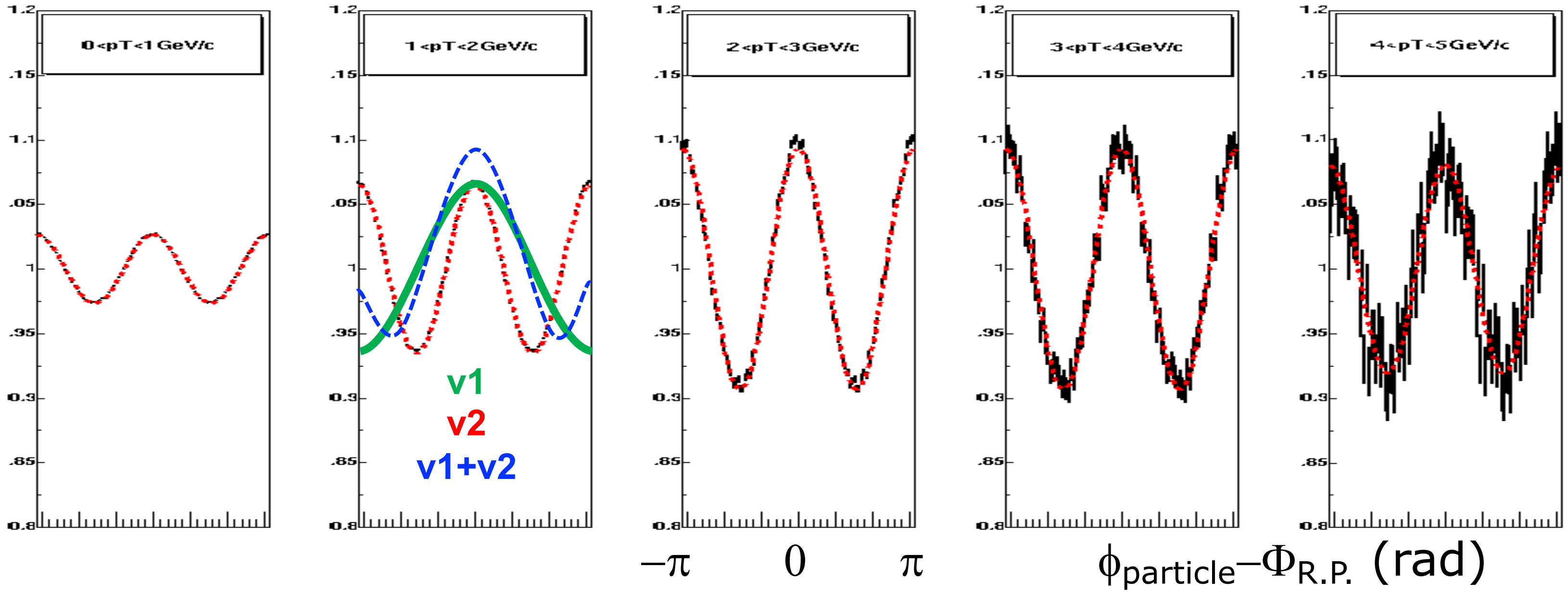
Reaction plane, Event plane, Event anisotropy





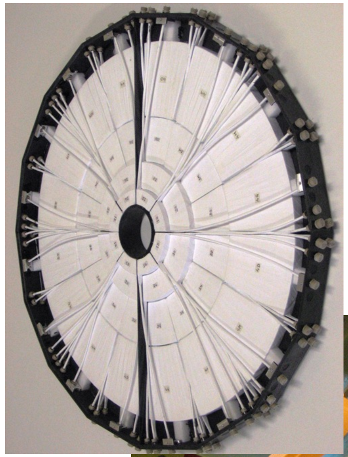


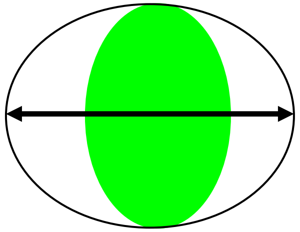
$Q_{nx} = \Sigma_i\{w_i \cos n\phi_i\}$
$Q_{ny} = \Sigma_i\{w_i \sin n\phi_i\}$
$\Phi_n = \mathrm{atan2}(Q_{ny},Q_{nx})/n$
$Q_{nvec} = |Q_n| / \mathrm{sqrt}(\Sigma_i\{w_i\})$



Reaction plane detectors

V0 (ALICE)

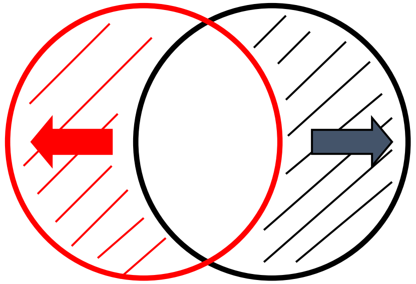




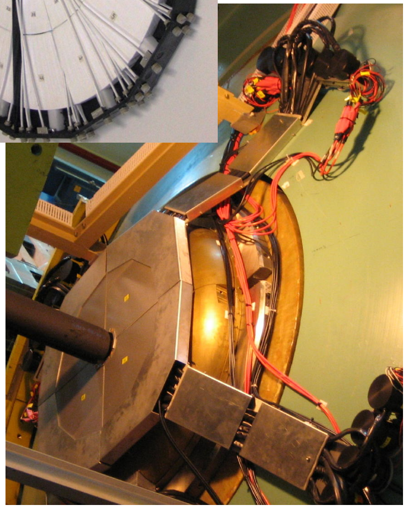
participant elliptic R.P.

RXN · V0 · EPD

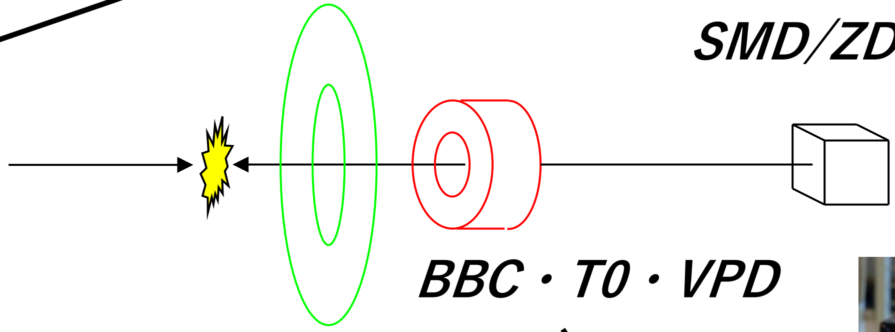
spectator directed R.P.



ZDC/SMD
(PHENIX/STAR)



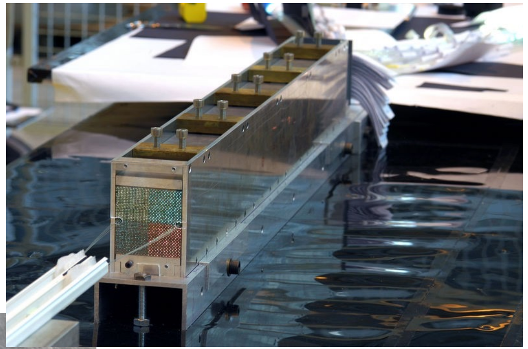
RXN
(PHENIX)

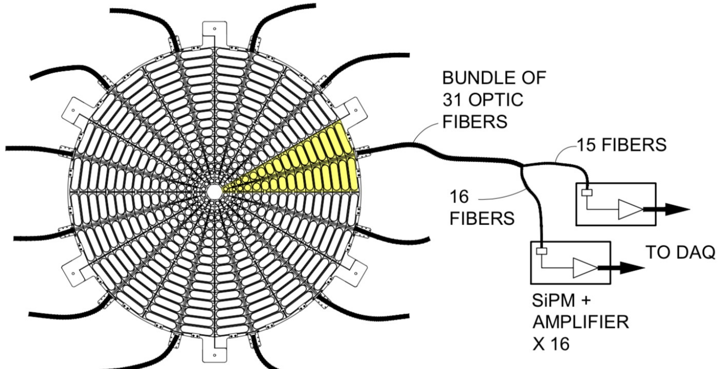


SMD/ZDC

BBC · T0 · VPD

ZDC (ALICE)

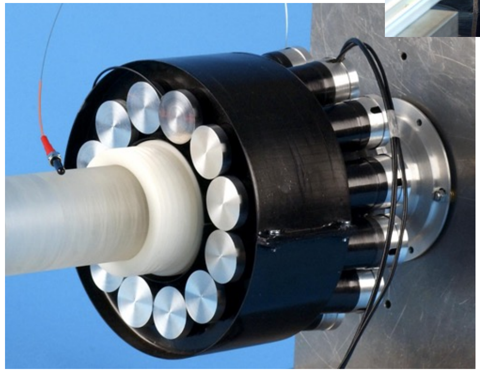




EPD (STAR)

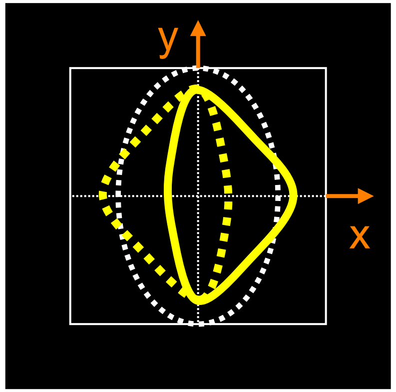
BBC (PHENIX)

T0 (ALICE)



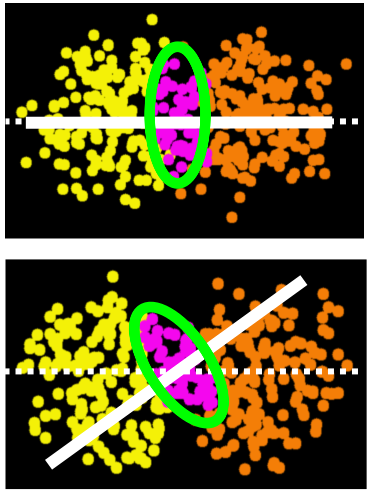
Higher order event anisotropy --- v_3 ---

black-disk collision, sign-flipping v_3 like v_1
initial geometrical fluctuation, no-sign-flipping v_3



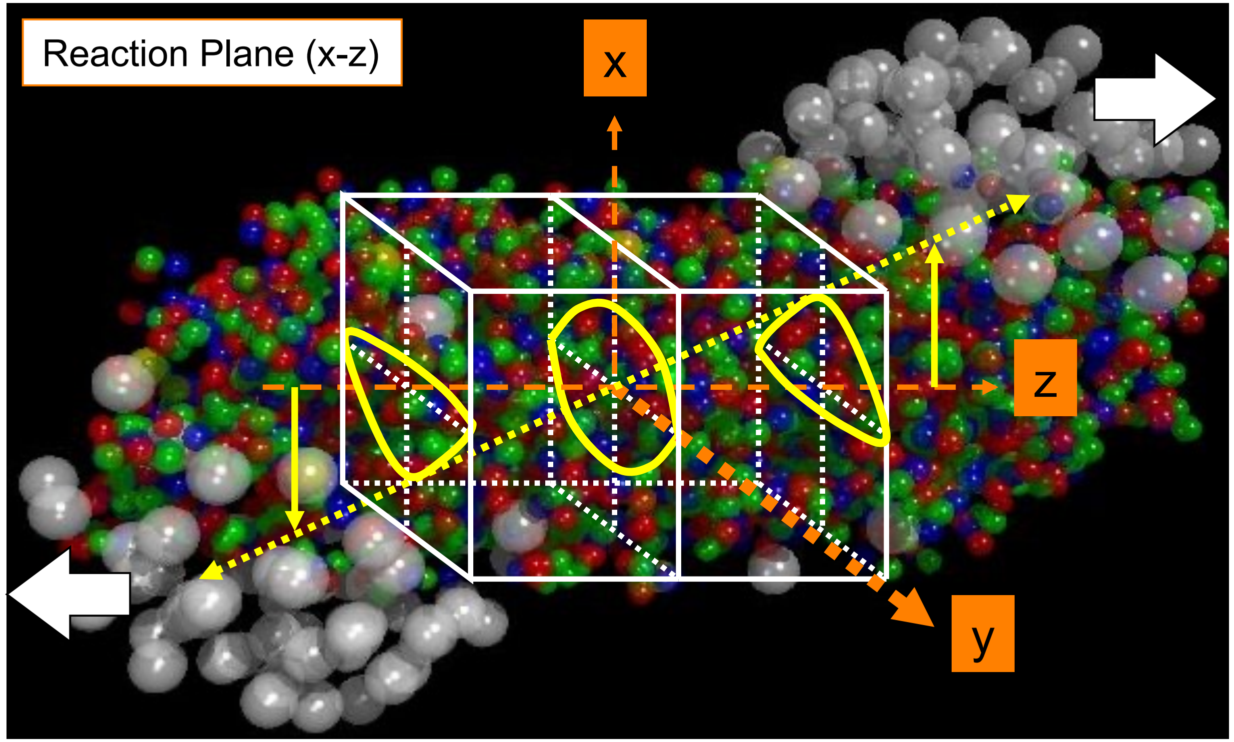
standard eccentricity

ε_{std}

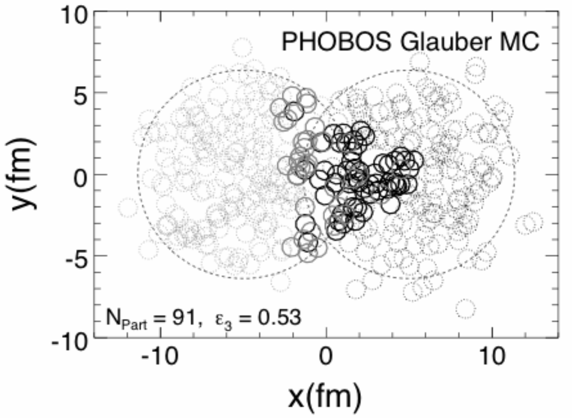


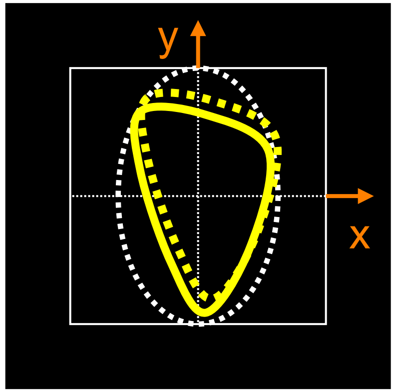
participant eccentricity

ε_{part}

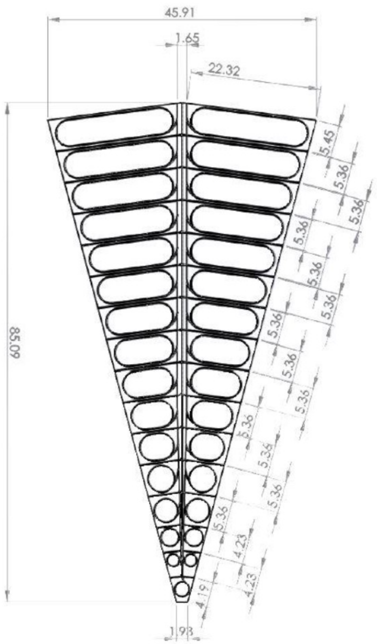


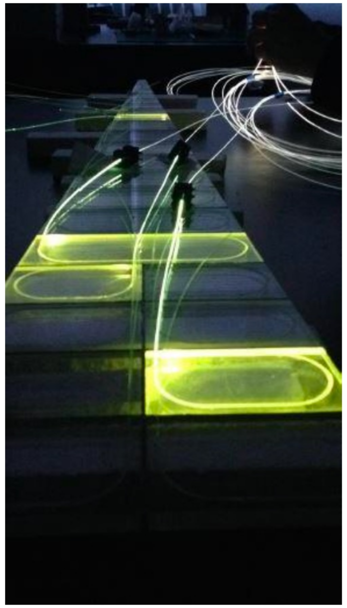
arXiv:1003.0194

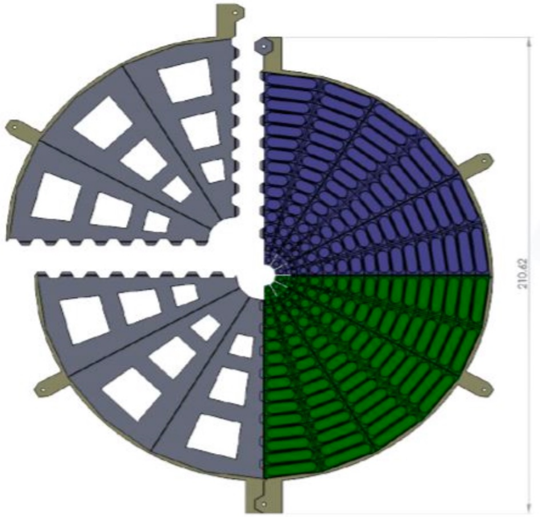


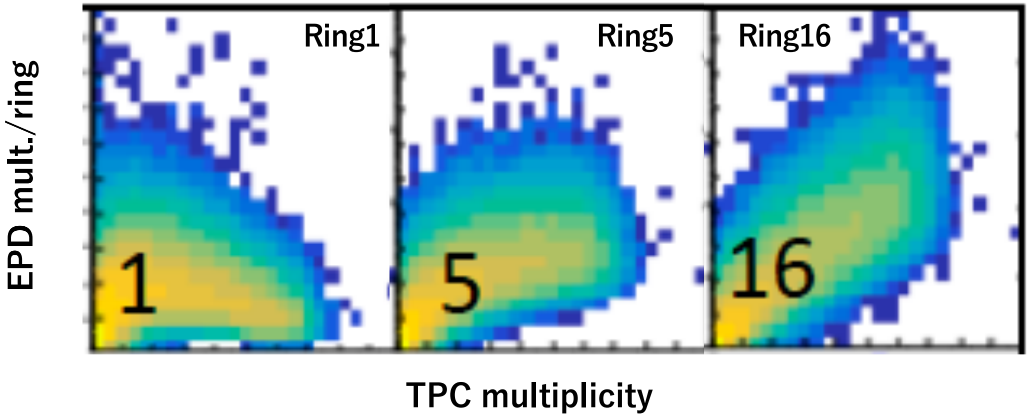


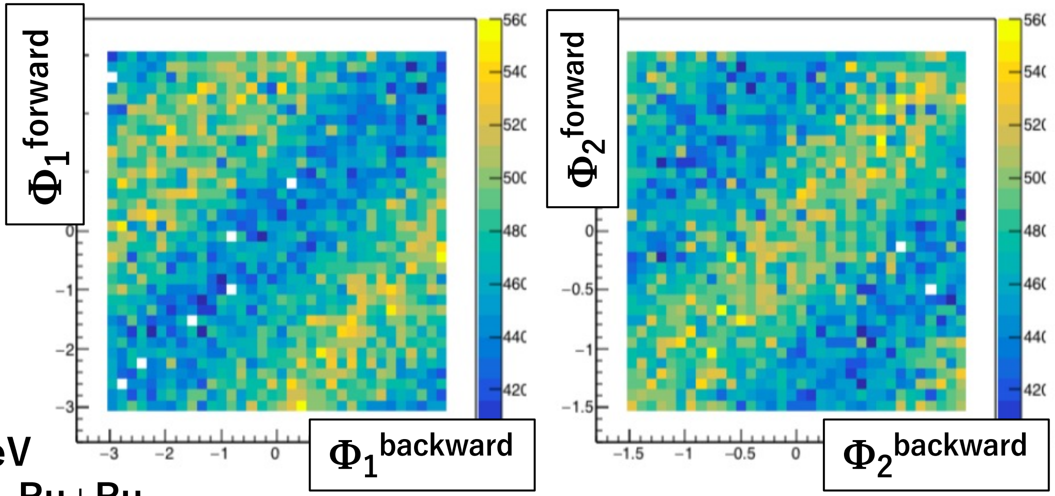
Event Plane Detector (EPD) |η|=2 - 5







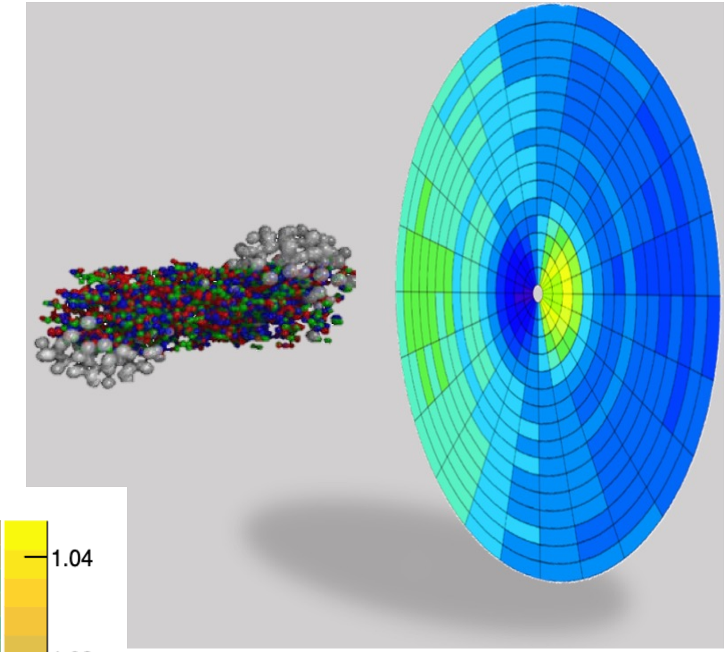


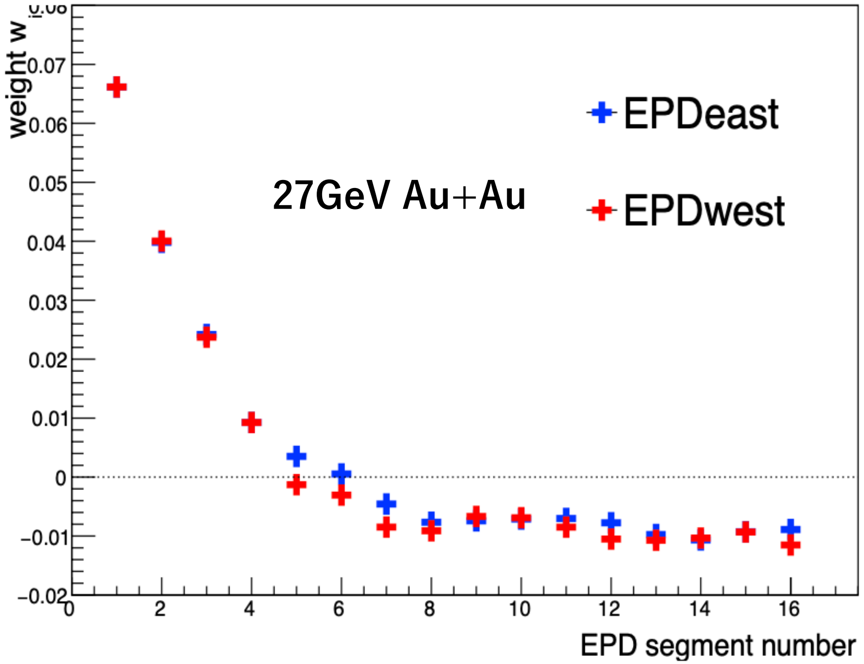


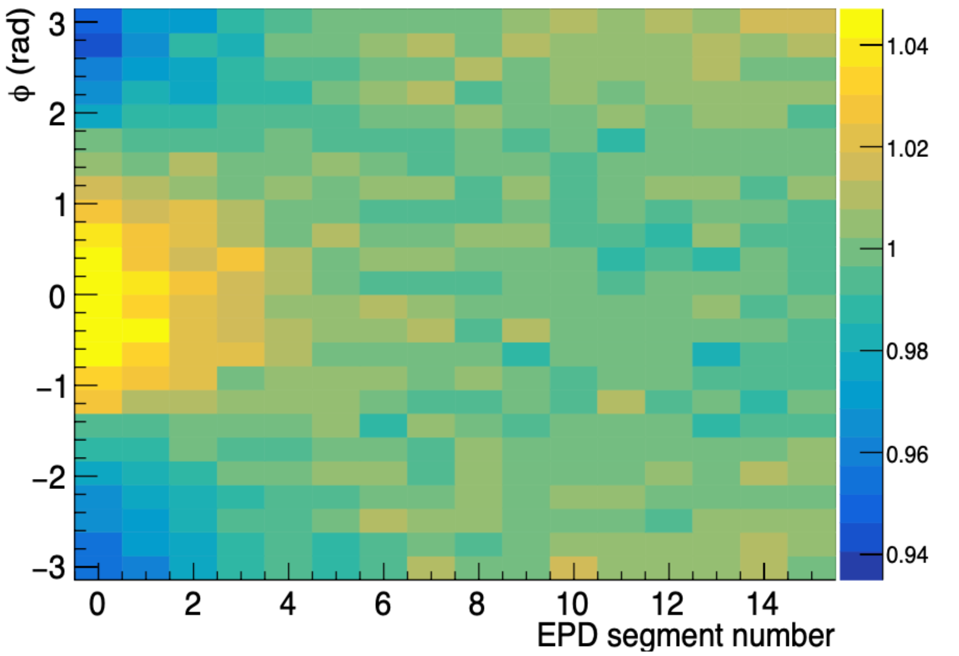
200GeV
Zr+Zr, Ru+Ru

Event Plane Detector (EPD)

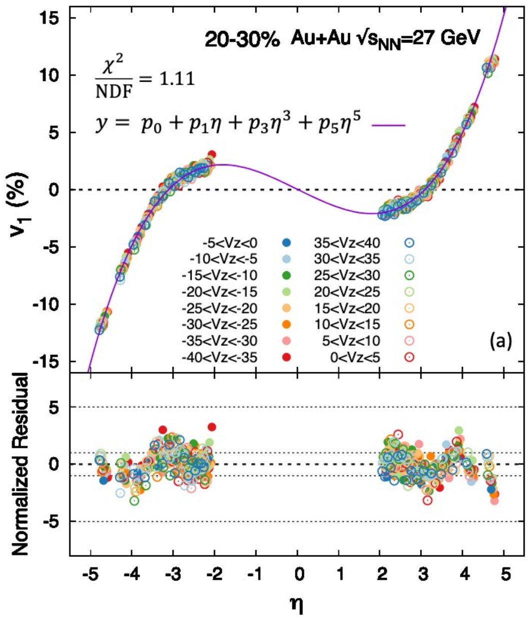
~50% of signal from secondaries
flow measurements with EPD with Geant simulation







inner ring ⟷ outer ring



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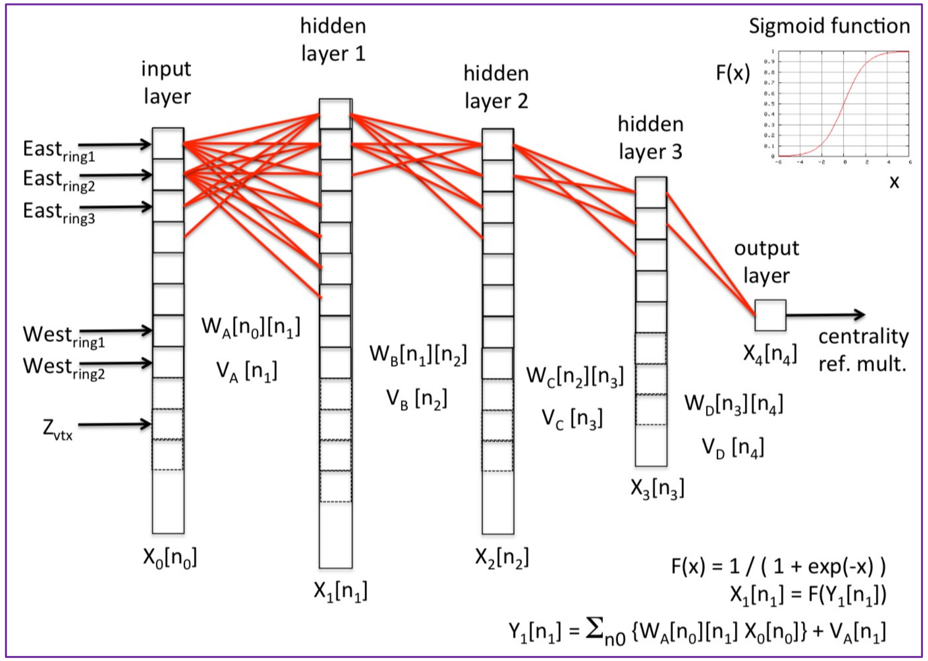
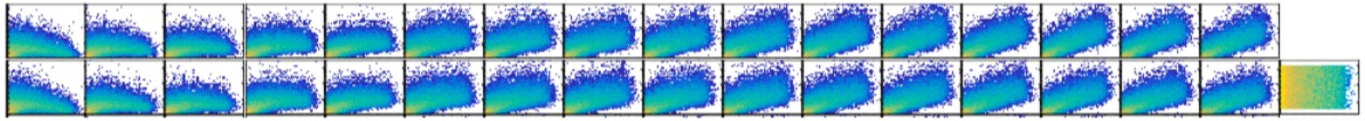
Centrality determination with Event Plane Detector (EPD)

Machine learning approach



27GeV Au+Au 50k education events and 50k test events (EPD+TPC)

16 ADC sum values from 2 arms + zvertex = 33 input neurons



3 hidden layers (n1=66, n2=30, n3=10 neurons)

back-propagation to modify weight W and bias V

Error (target-output) : $E = 0.5\,(X_T[n_4] - X_4[n_4])^2$

$dE/dX_4 = X_T - X_4$, $dX_4/dY_4 = F'(X_4)$, $dY_4/dW_D = X_3$

$dE/dW_D = (dE/dX_4)\,(dX_4/dY_4)\,(dY_4/dW_D)$

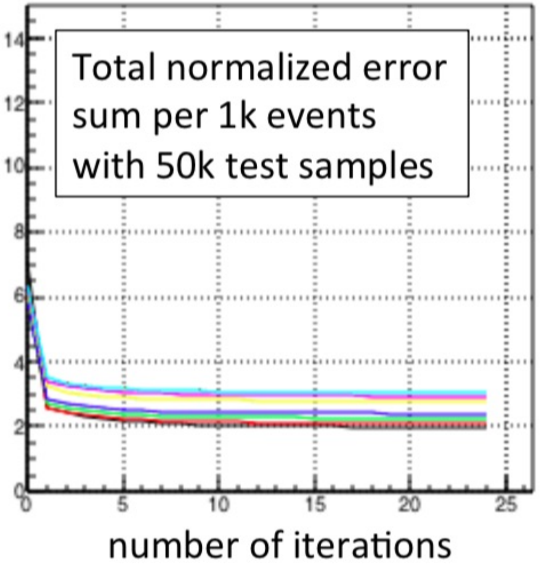
$W_D = W_D + \alpha\,(X_T - X_4)\,F'(X_4)\,X_3$

$V_D = V_D + \alpha\,(X_T - X_4)\,F'(X_4)$

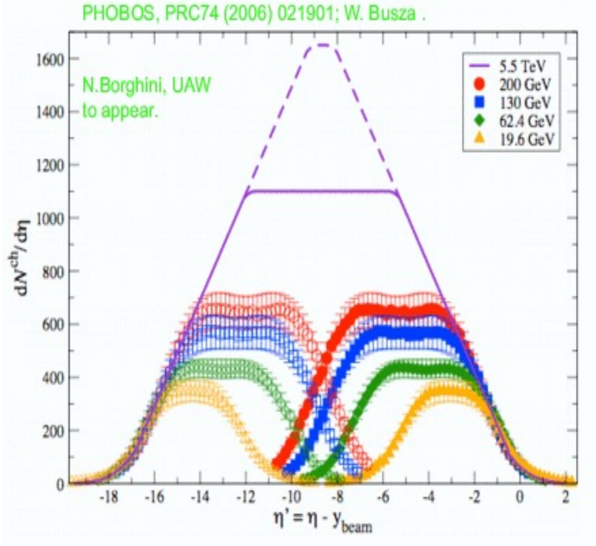
$dE/dX_3 = (X_T - X_4)\,F'(X_4)\,W_D$

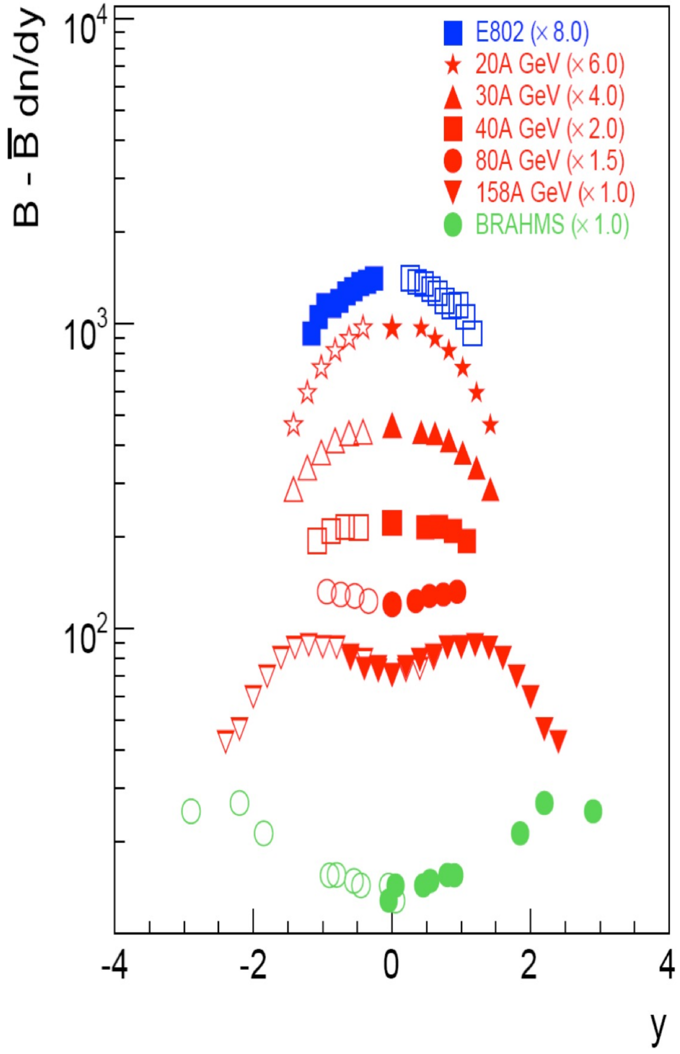
.....

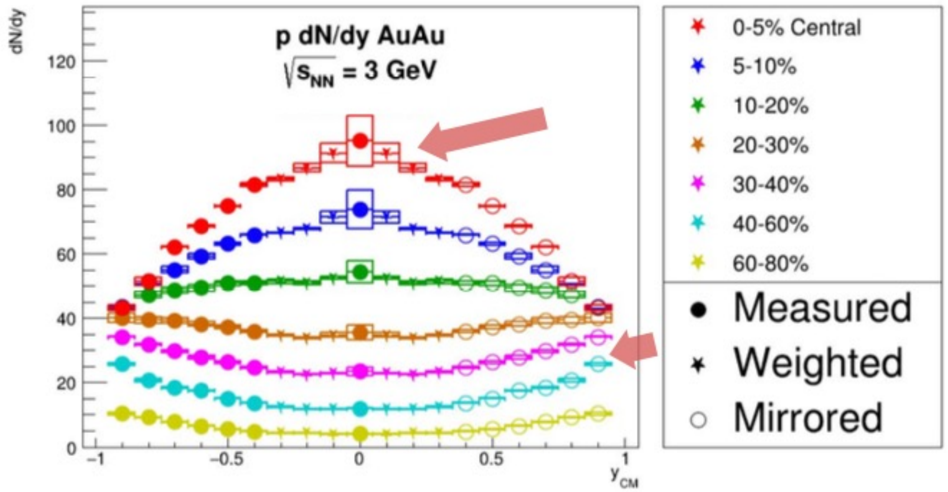
1 output layer with 1 neuron (as refmult)

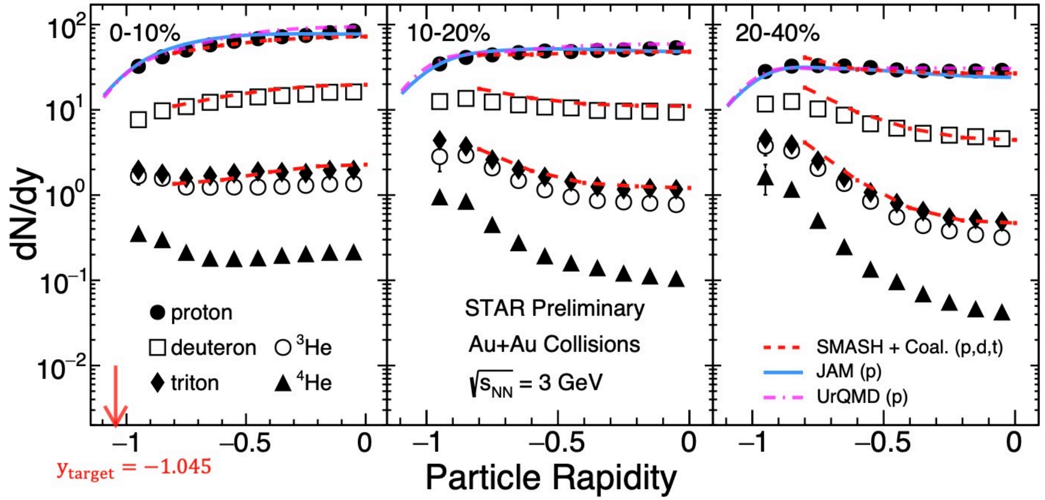


Baryon stopping and rapidity distribution

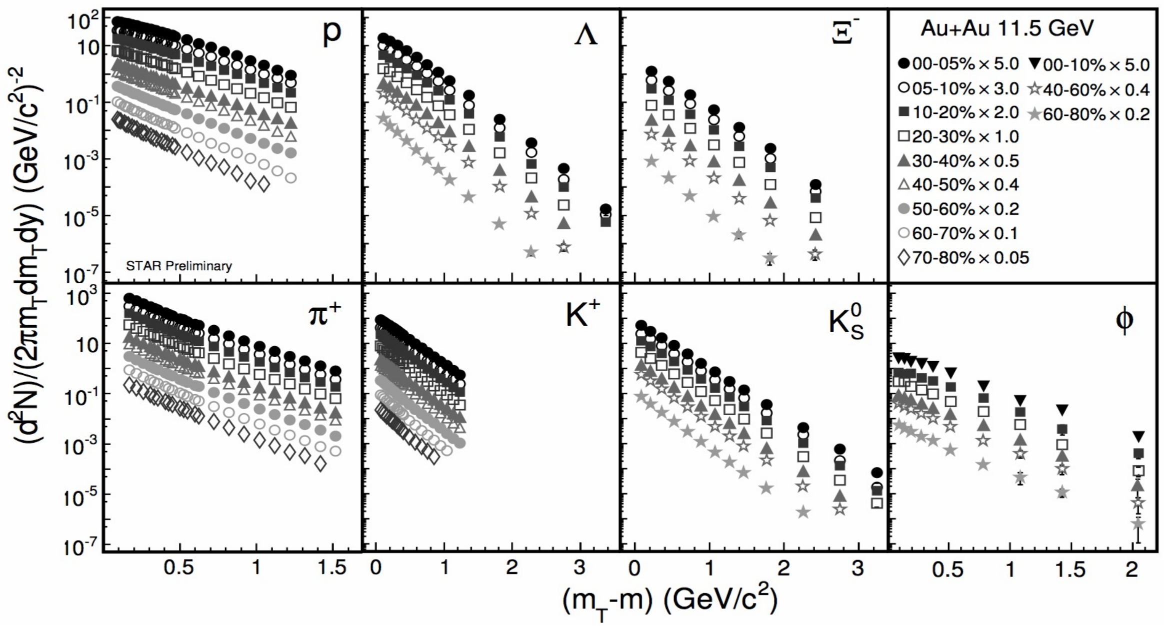


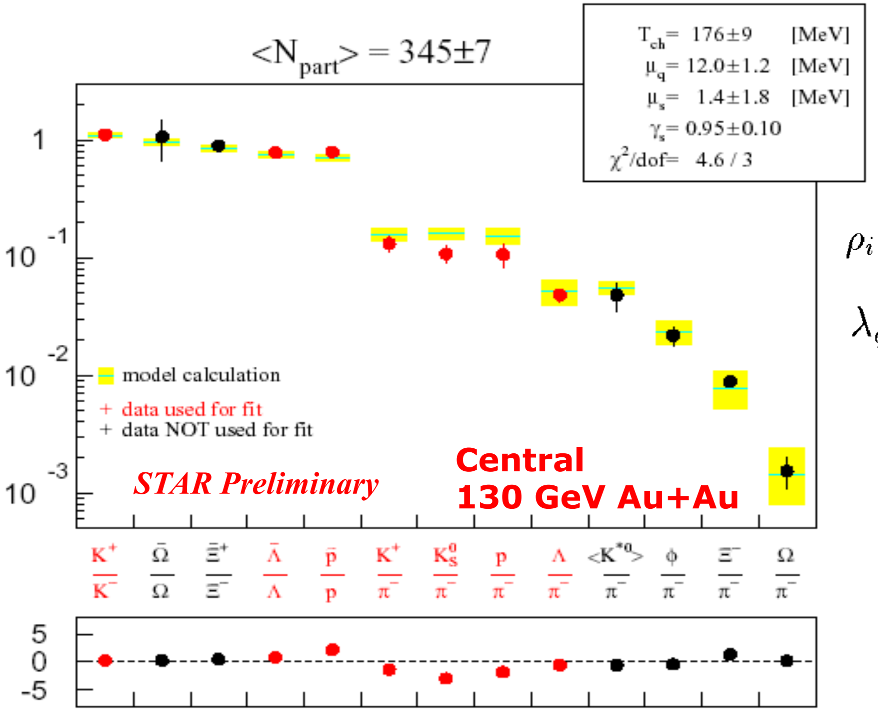






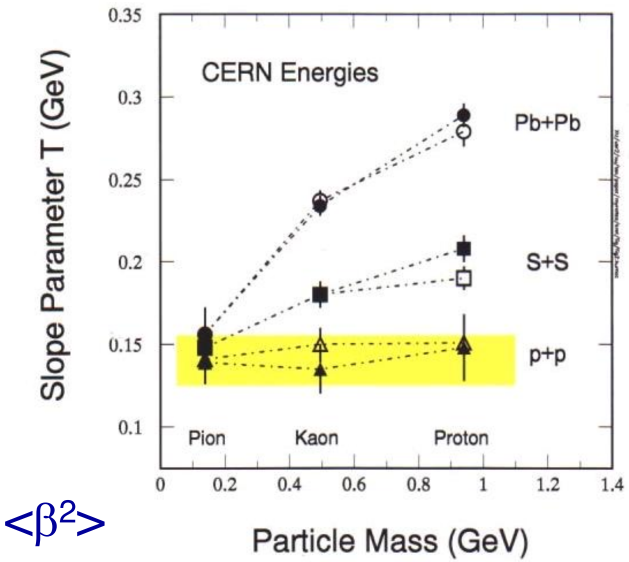
Particle yields and
Transverse momentum distributions





$$\rho_i = \gamma_s^{|s_i|} \frac{g_i}{2\pi^2} T_{ch}^3 \left(\frac{m_i}{T_{ch}}\right)^2 K_2(m_i/T_{ch})\ \lambda_q^{Q_i}\ \lambda_s^{s_i}$$

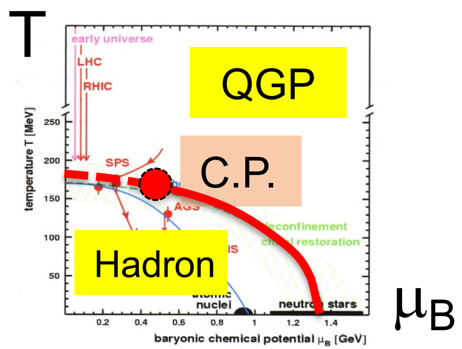
$$\lambda_q = \exp(\mu_q/T_{ch}), \quad \lambda_s = \exp(\mu_s/T_{ch})$$

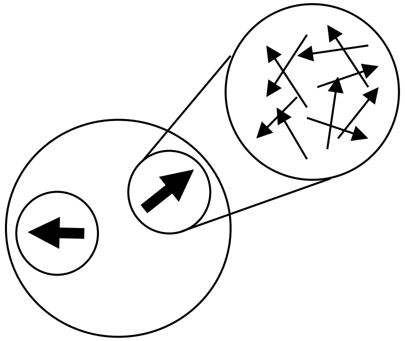


$T \sim T_0 + m \langle\beta^2\rangle$

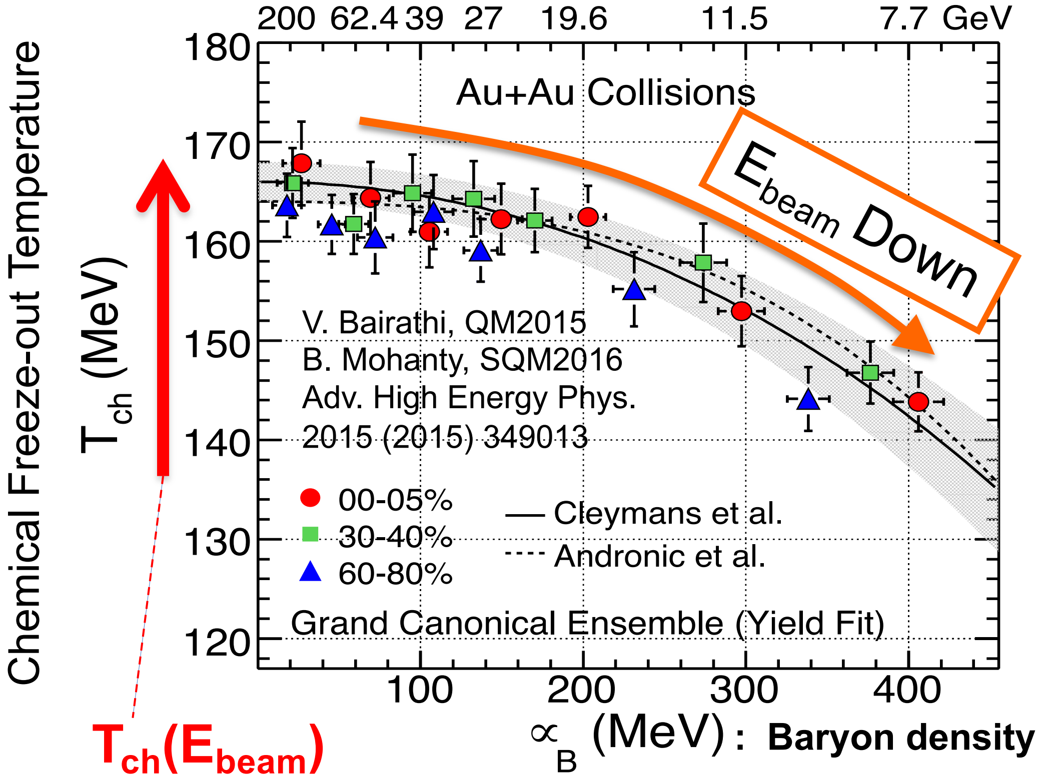
$E = E_{thermal} + E_{collective}$

Chemical and Thermal model fitting

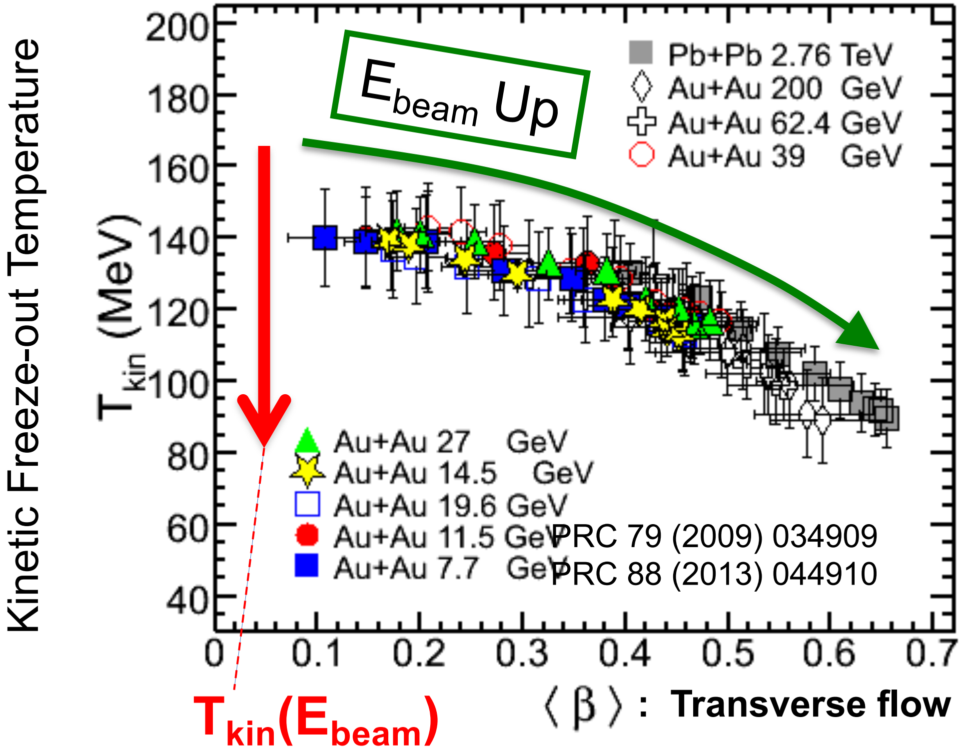


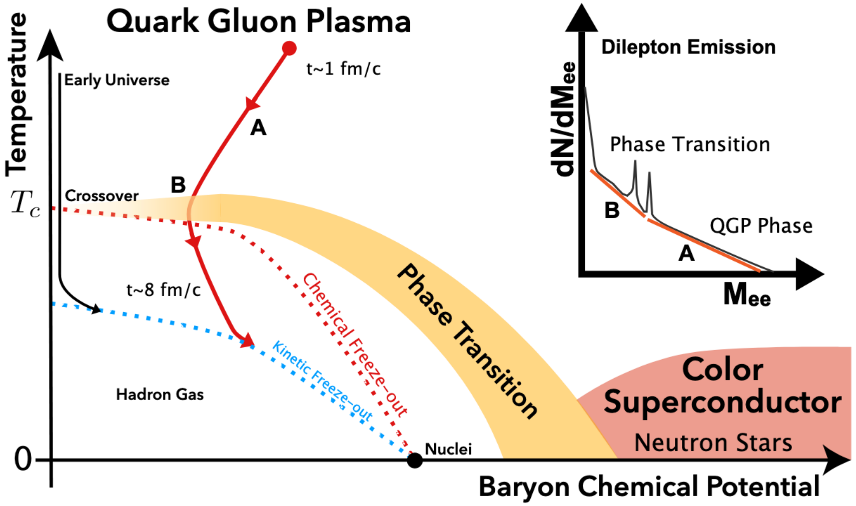


From the hadron yields and ratios
Chemical Freeze-out at the end of inelastic interaction



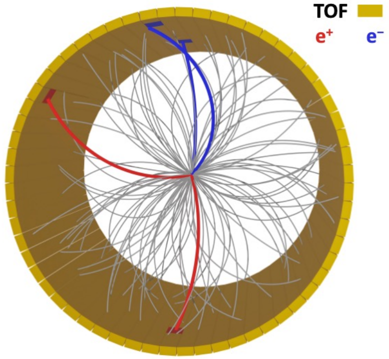
From the hadron transverse momentum spectra
Kinetic Thermal Freeze-out at the end of elastic interactions

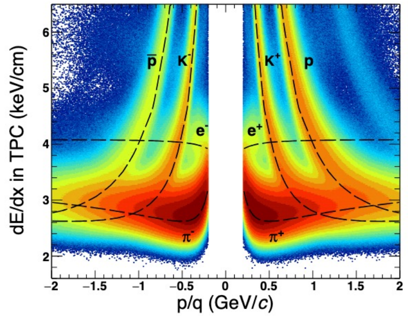


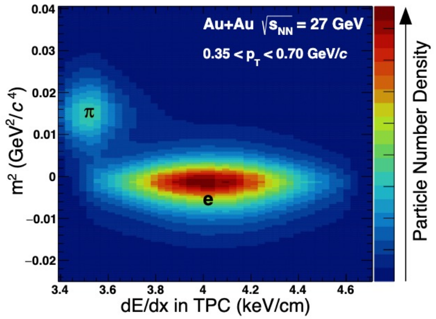


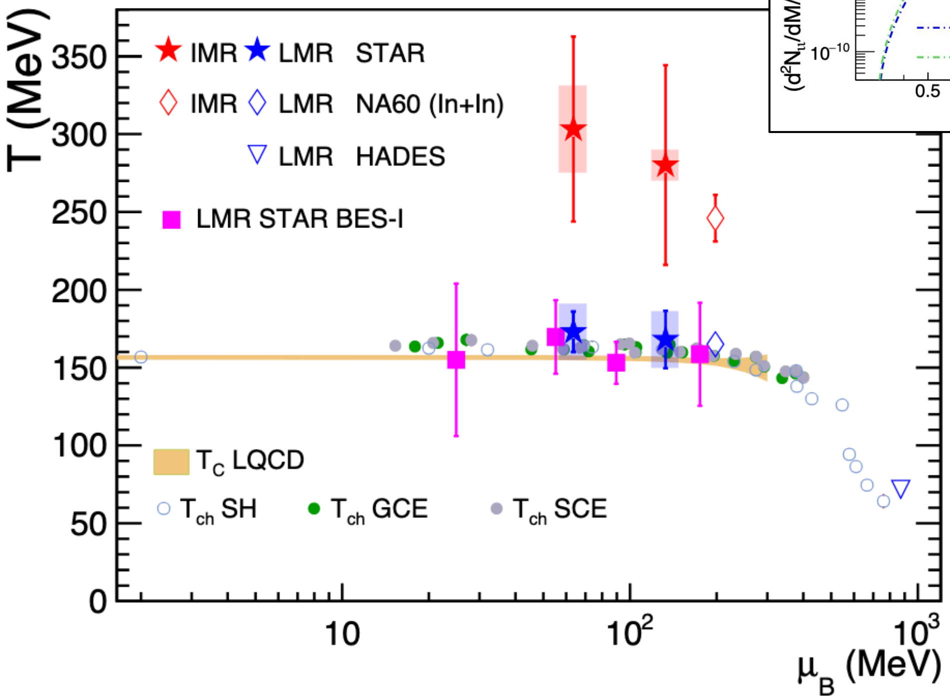
Earlier temperature of QGP with di-lepton

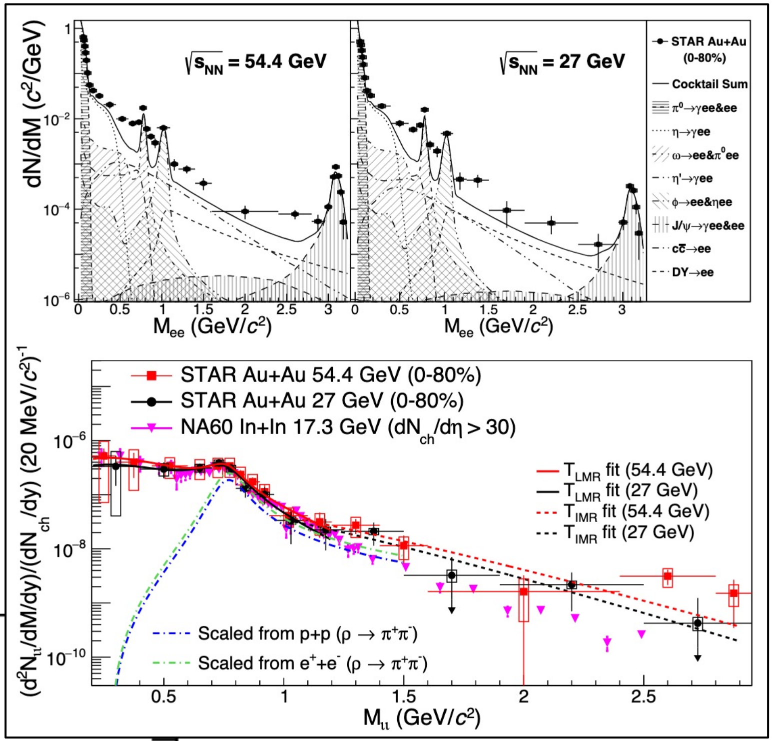
arXiv:2402.01998
accepted in Nature Communications

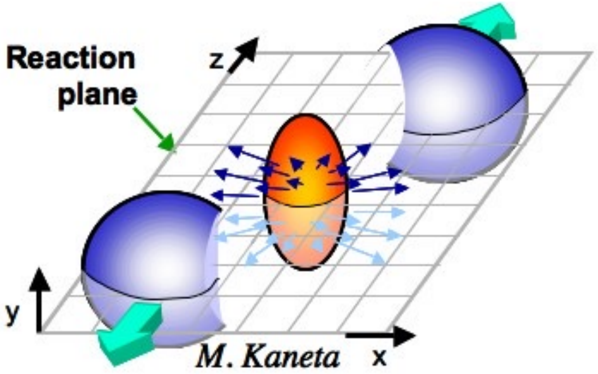






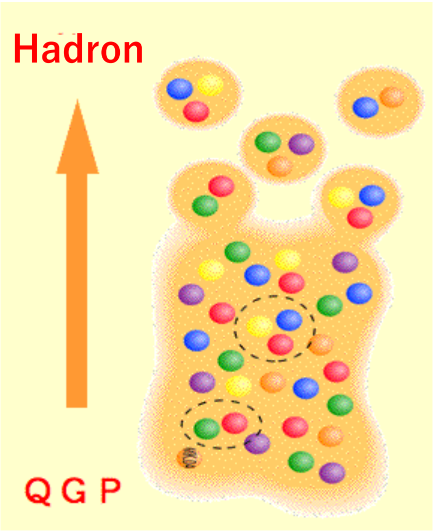


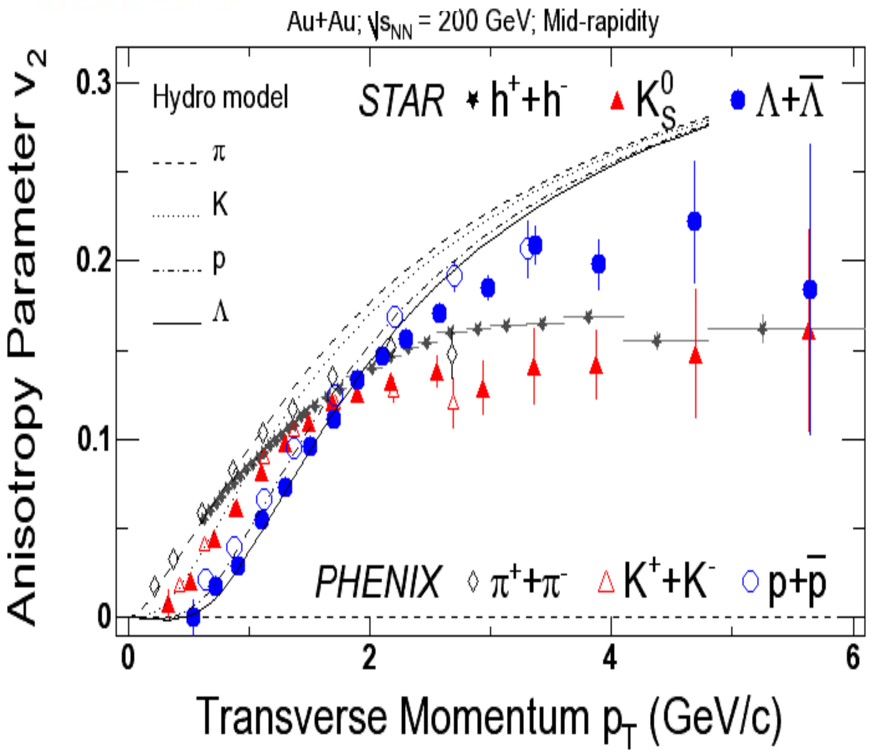


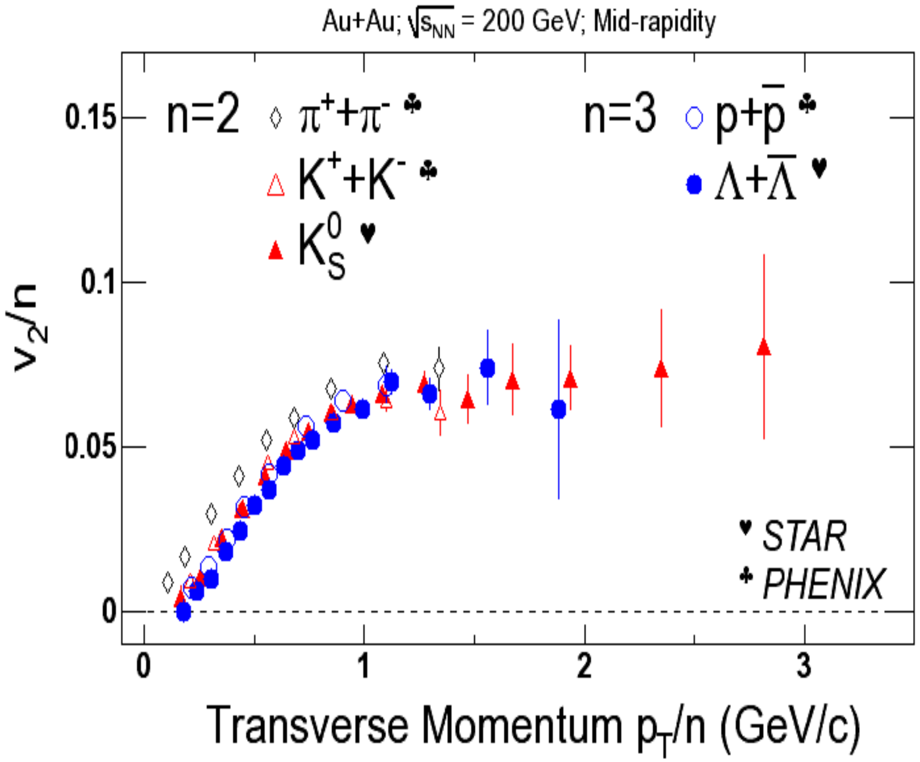


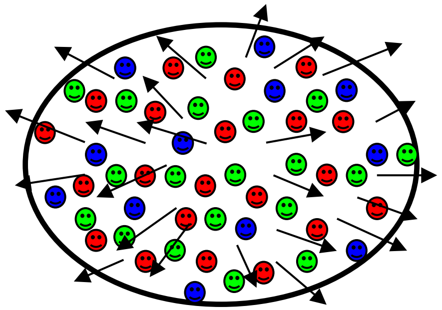
Elliptic flow and NCQ-scaling

(Number of Constituents Quarks : NCQ)



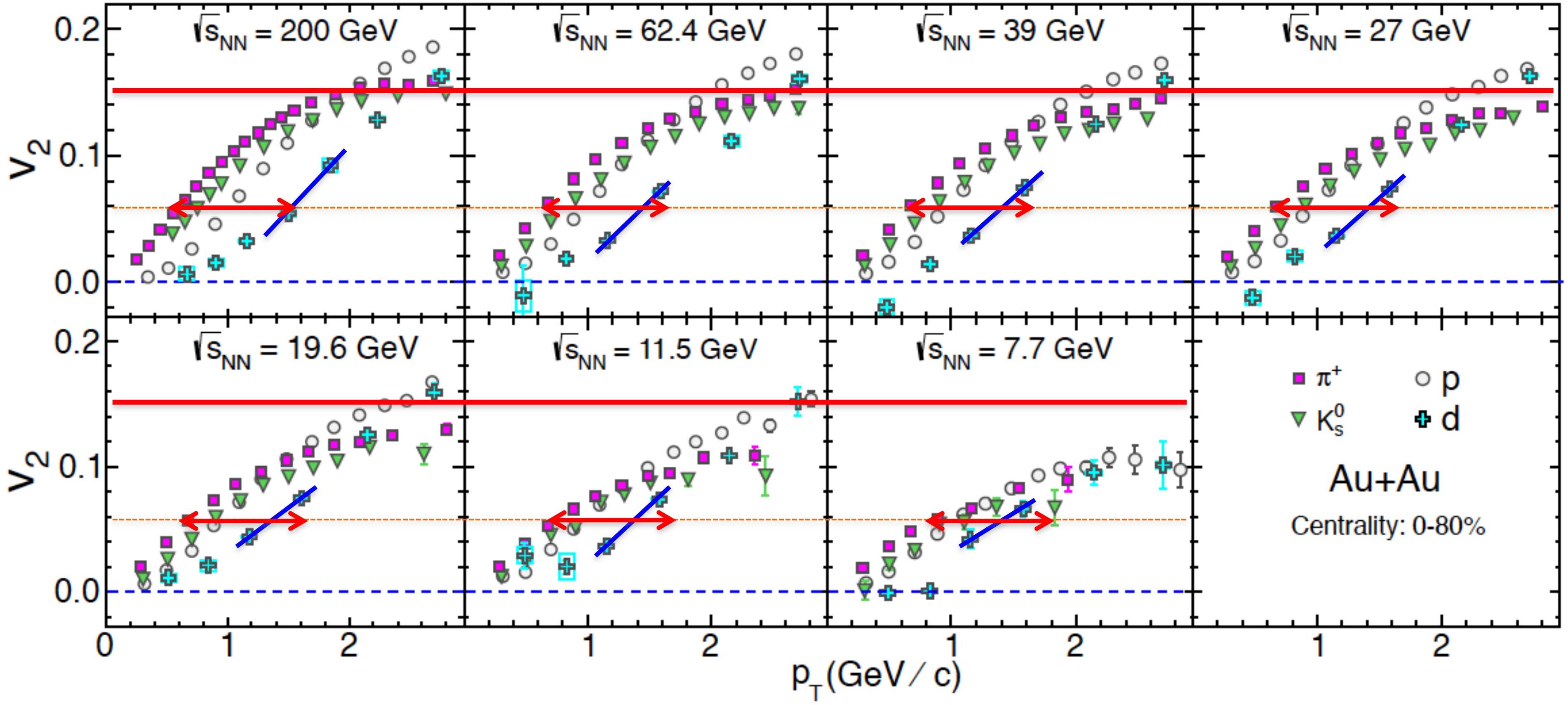






Elliptic flow and radial flow

PRC94 (2016) 34908

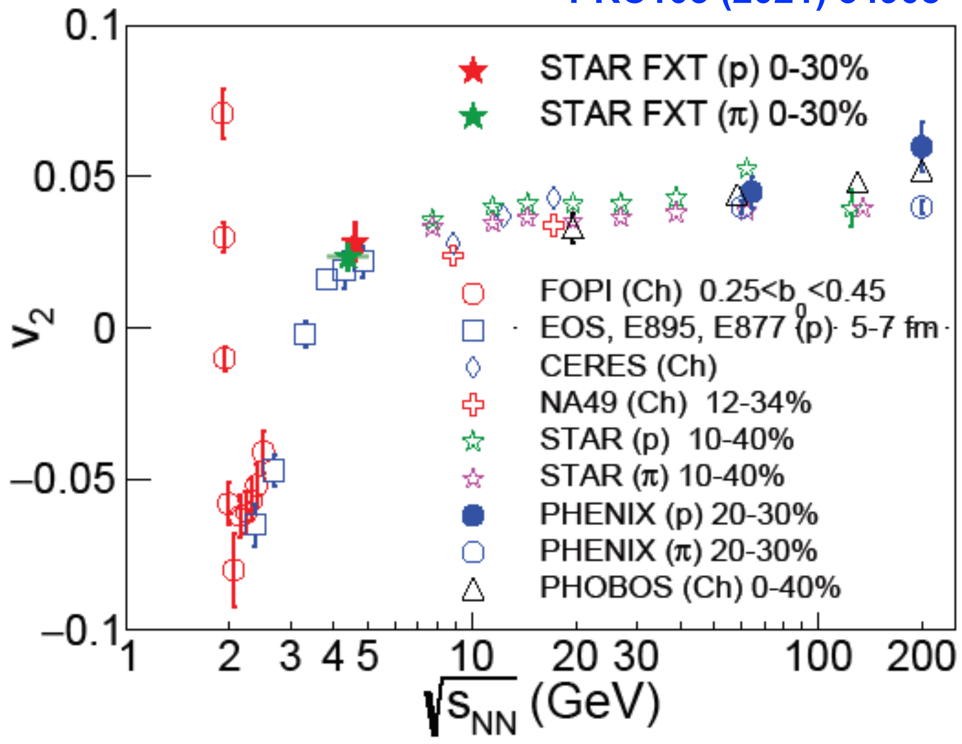


increasing radial and elliptic flow with beam energy

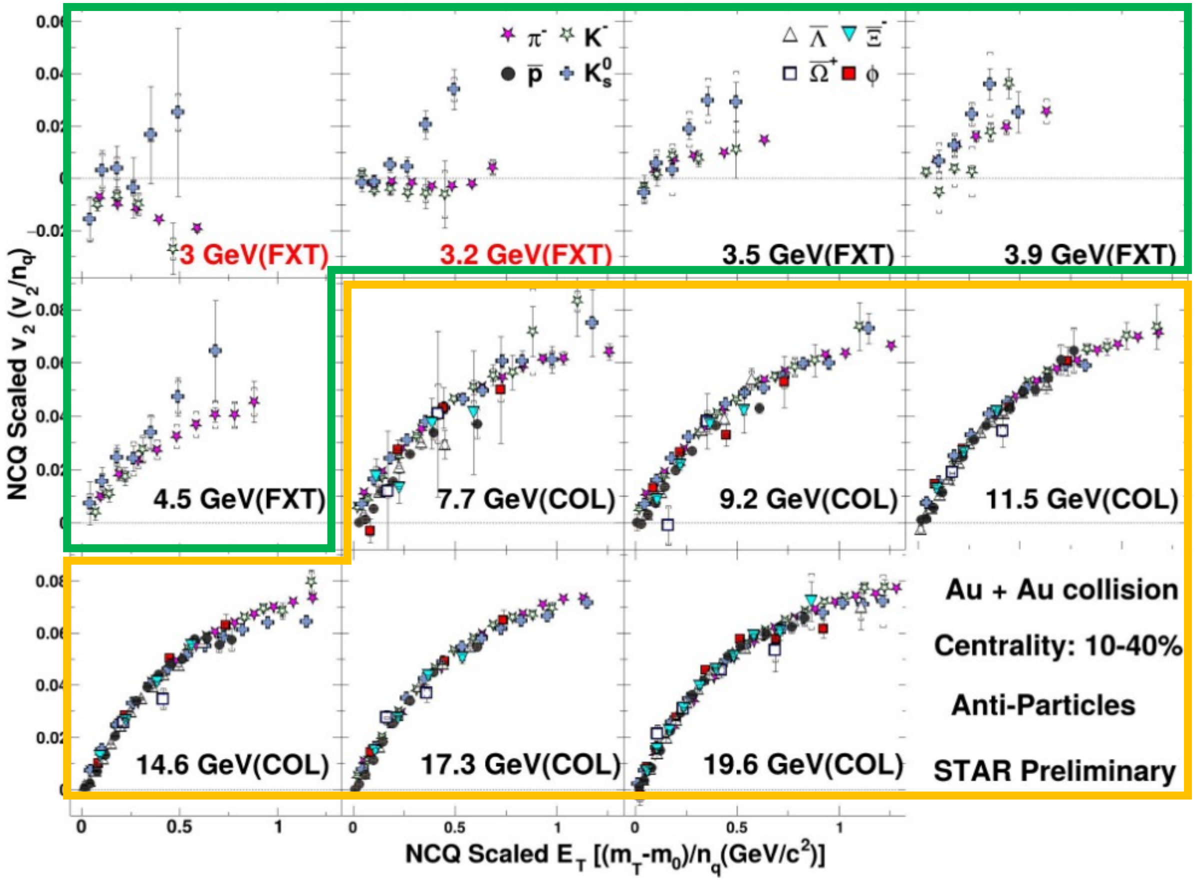
Elliptic flow - energy dependence

from hadronic to partonic system

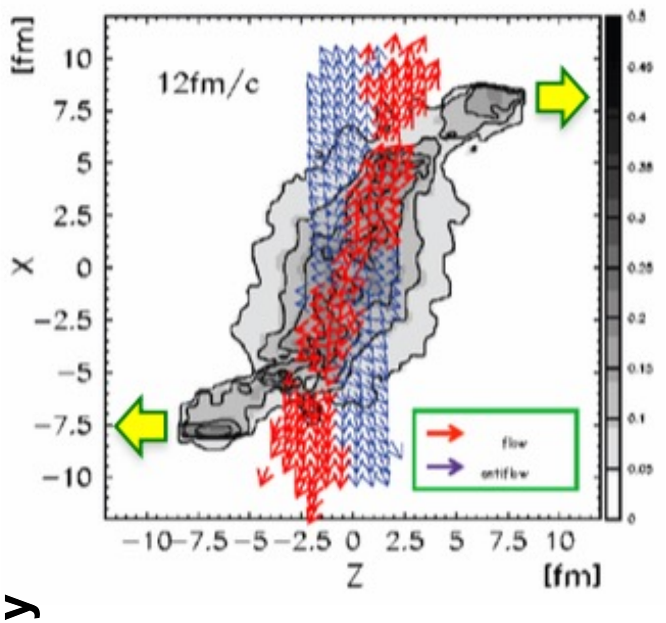
PRC103 (2021) 34908



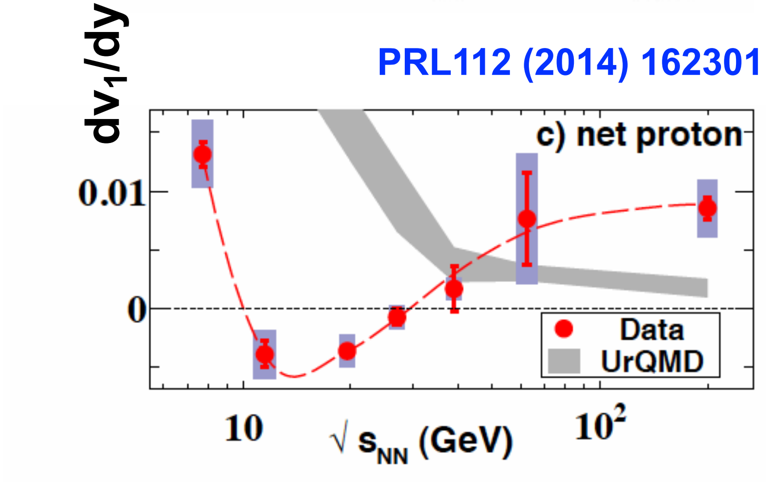
QM25, STAR
PRL135 (2025) 72301



v_2 - N_{CQ} scaling breaks around 3-7 GeV

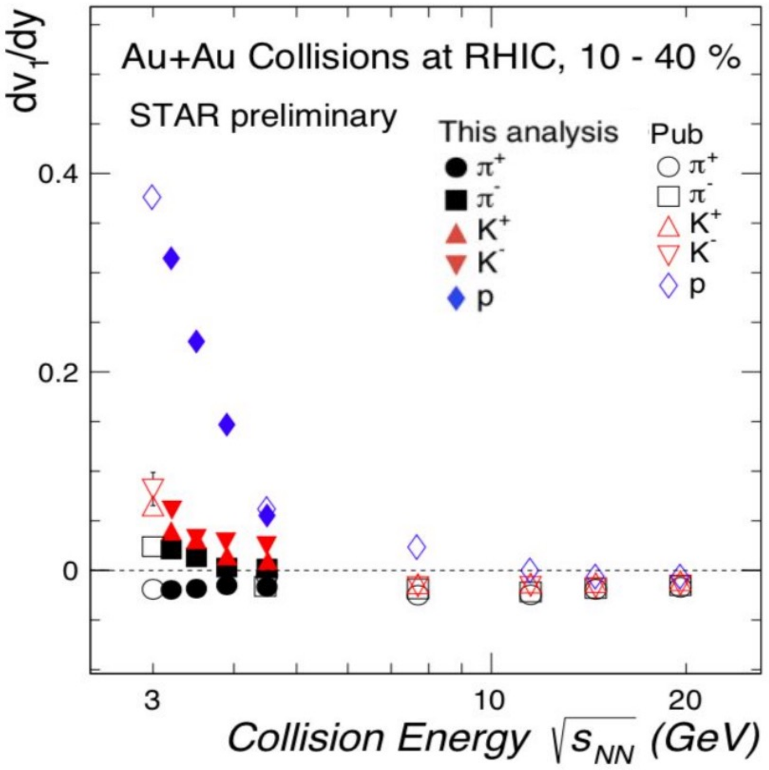


Directed flow (v_1-slope) as a function of energy



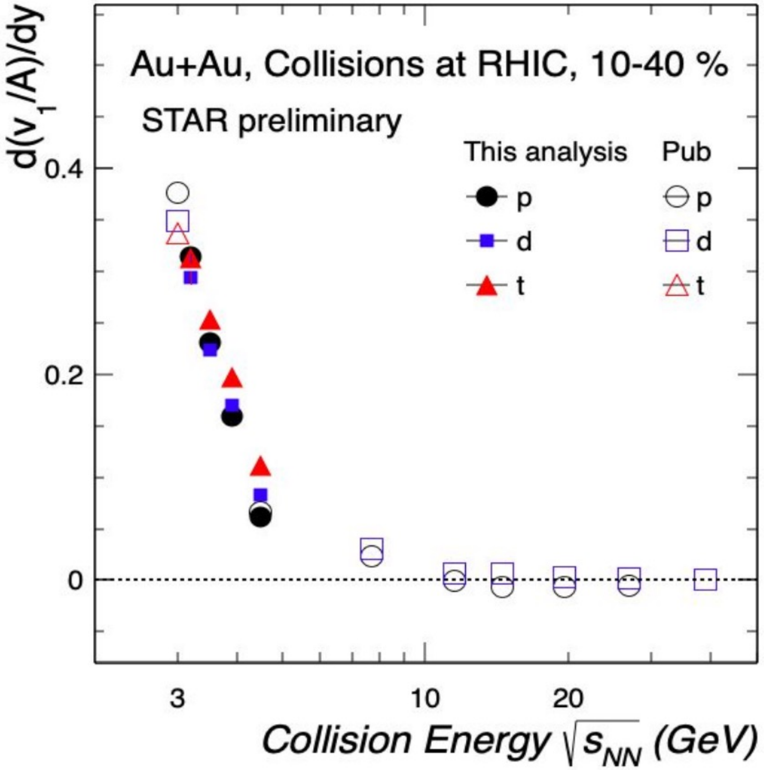
net-proton v_1-slope
(minimum, sign-change)

π, K, p



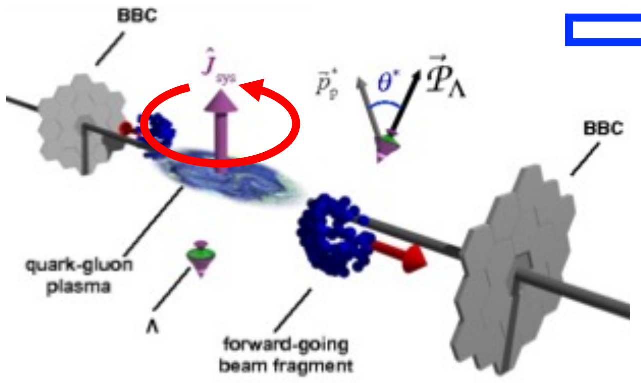
p, d, t

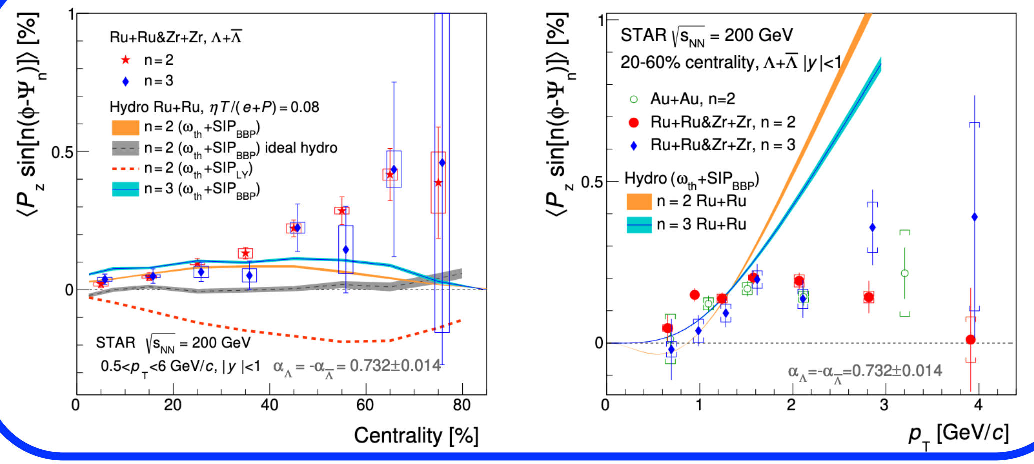
QM25, STAR

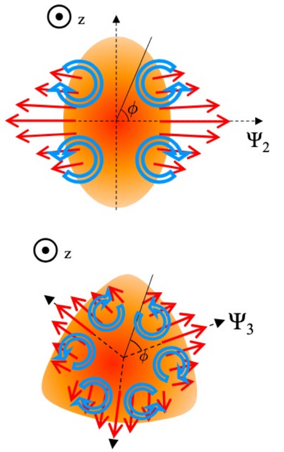


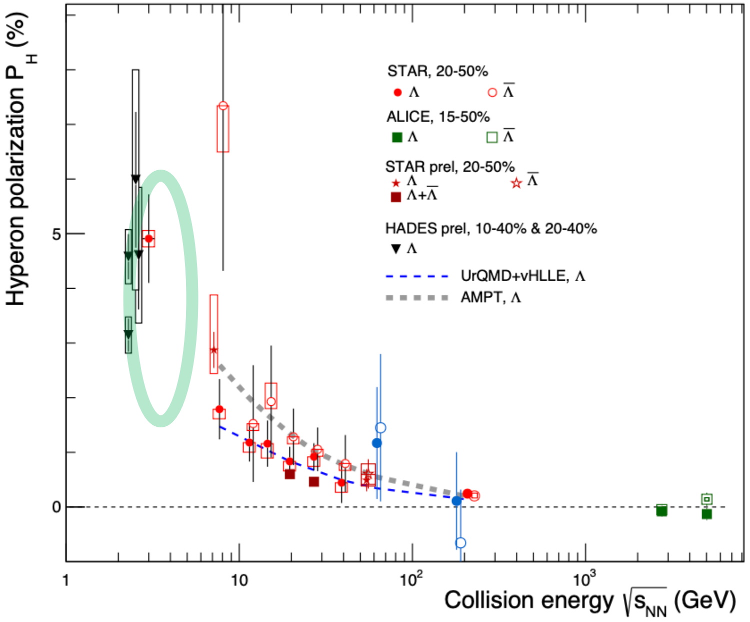
Global and Local polarization

via vorticity, B-field and v_2, v_3 expansion

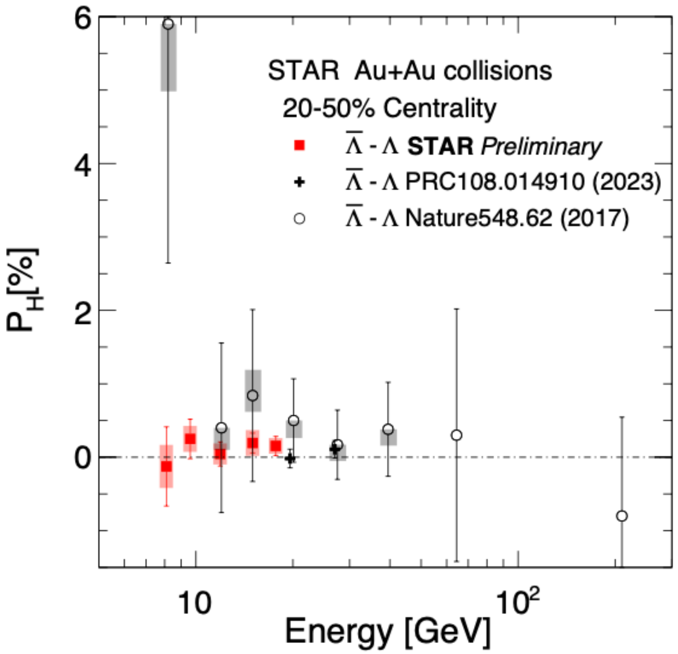


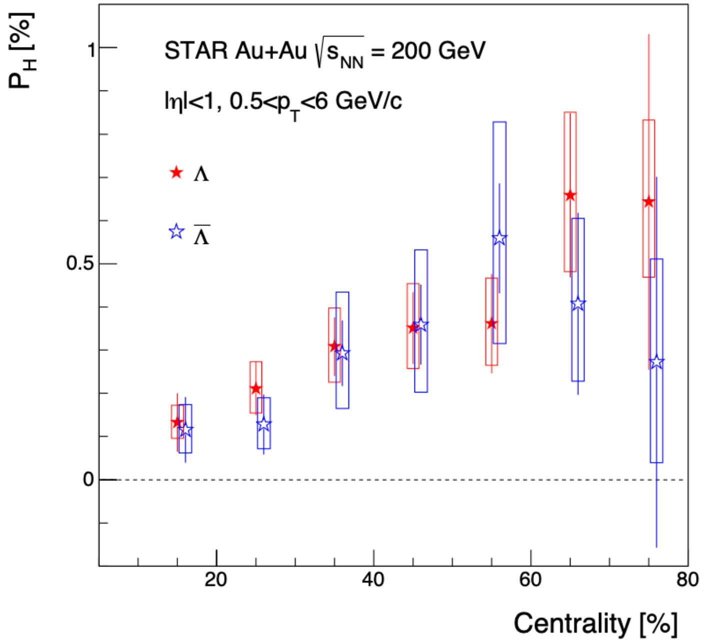






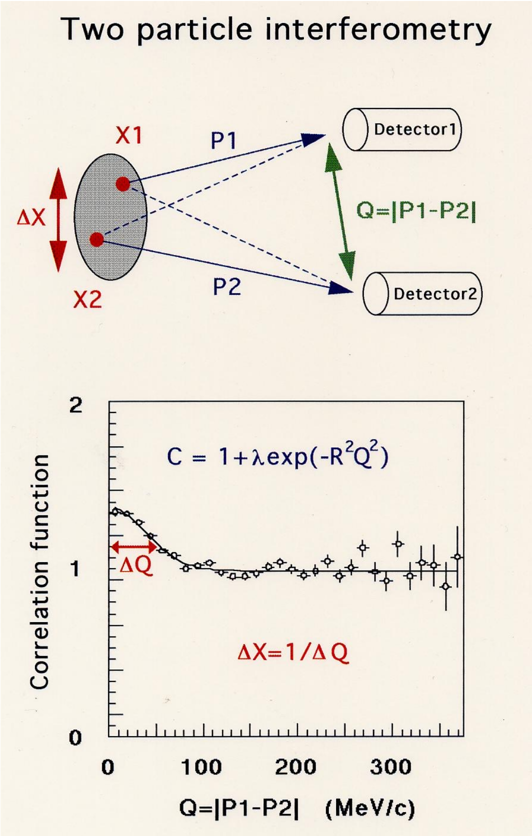
STAR BES-II

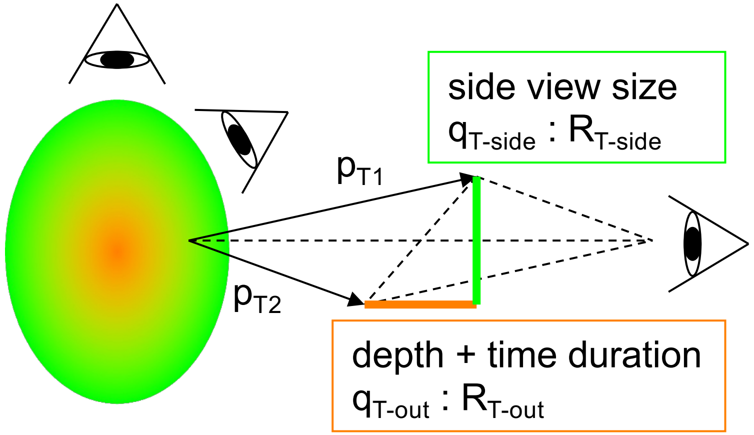


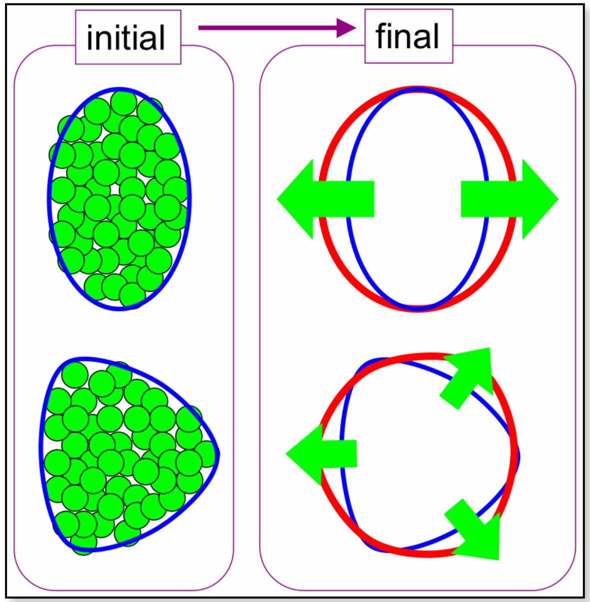


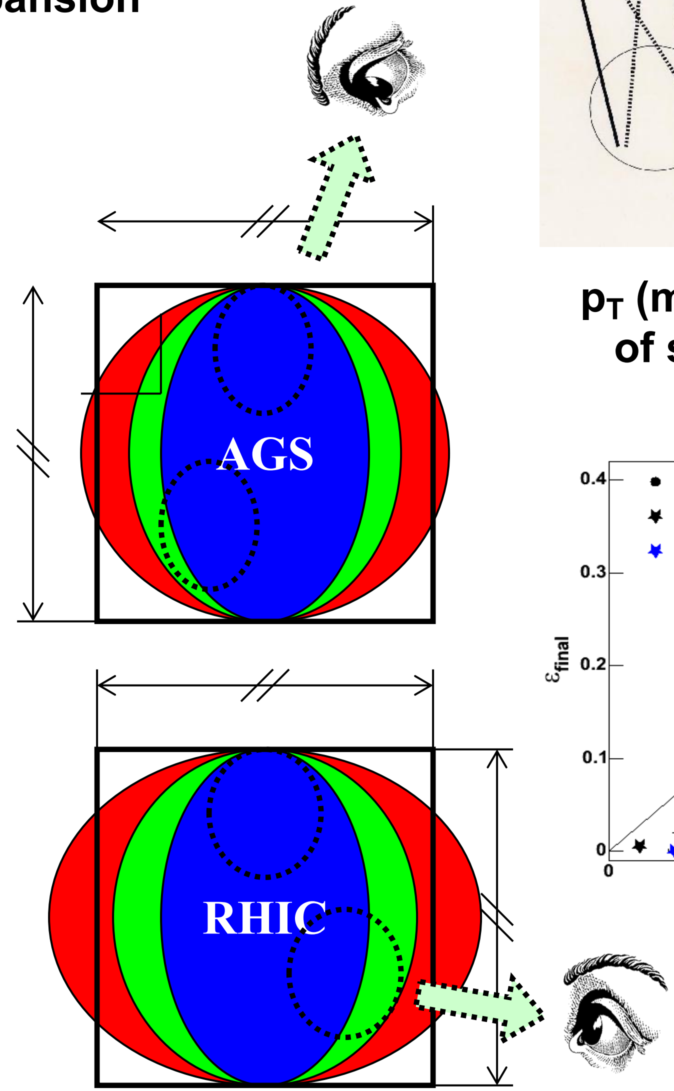
Femto-scopic two-particle correlation (HBT)

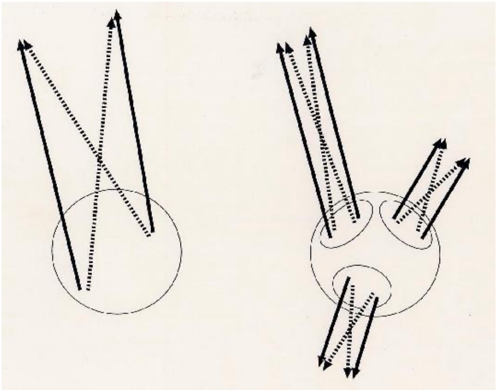
space-time dynamics, transverse source geometry and expansion



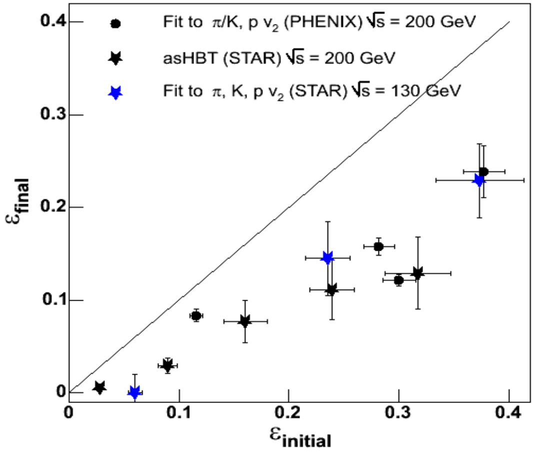








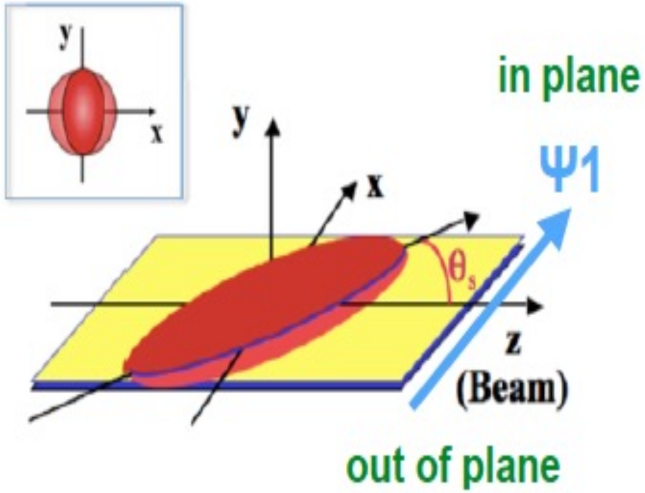
p_T (m_T) dependence of source radius

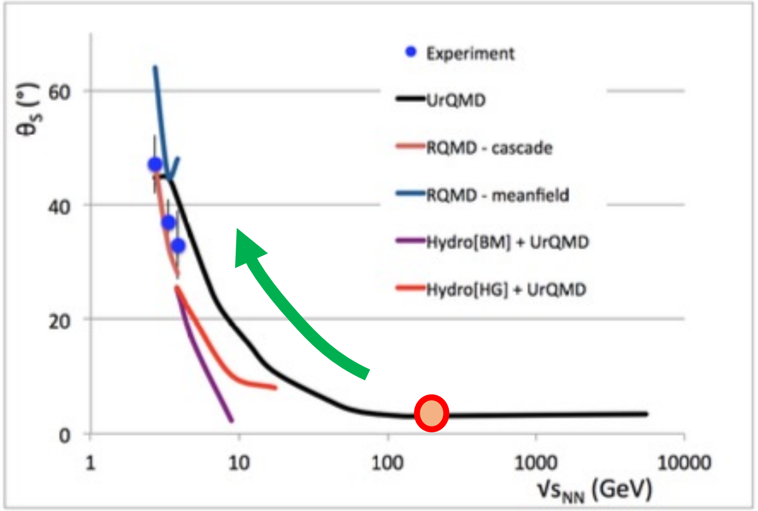


Femto-scopic HBT correlation with Φ_1

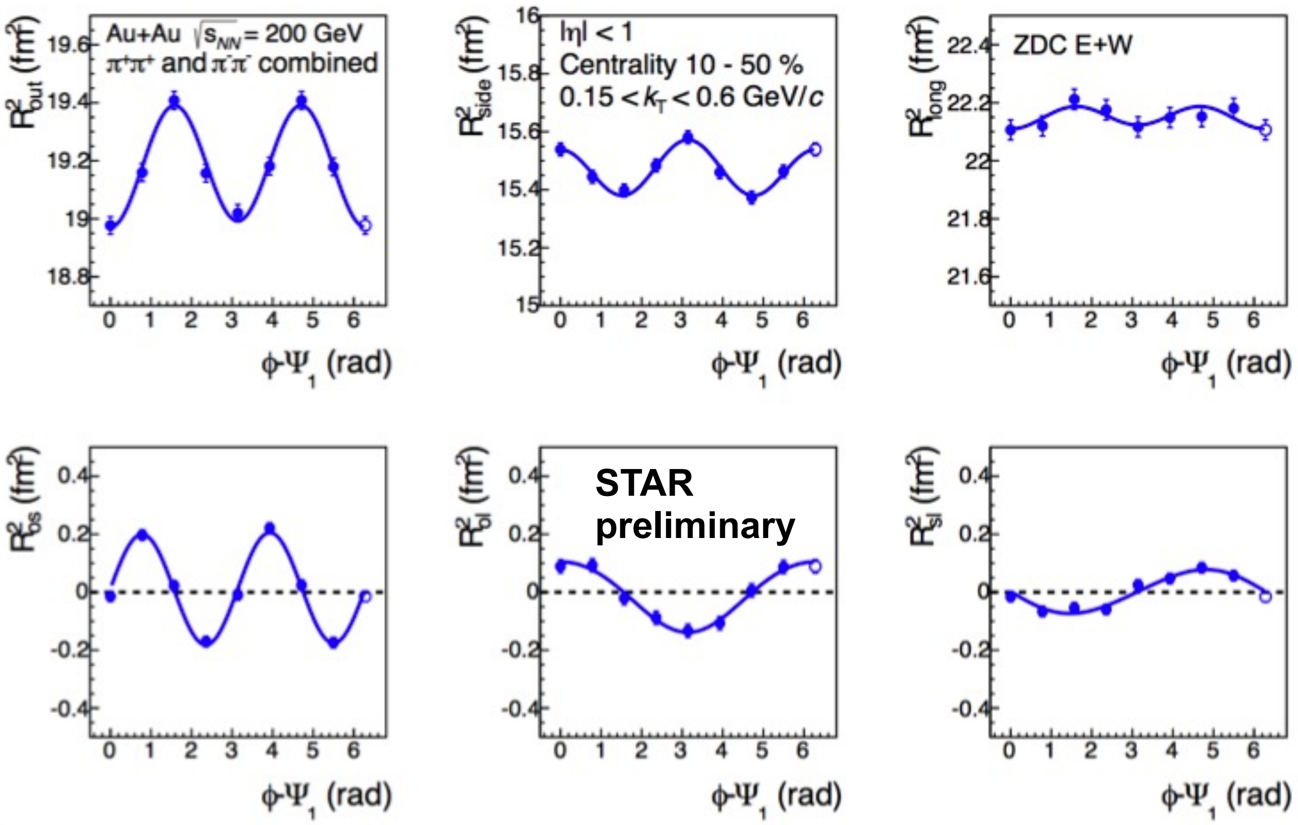
3D source geometry including tilt-angle relation with the directed flow

M A Lisa et al. New J. Phys. 13 (2011) 065006

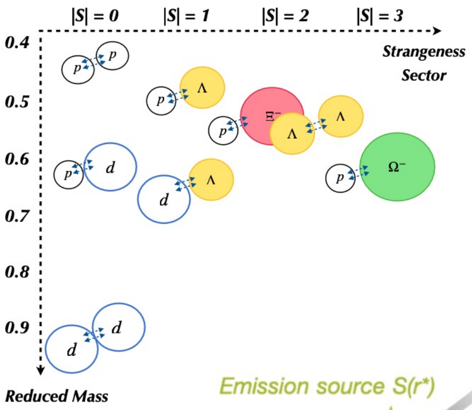


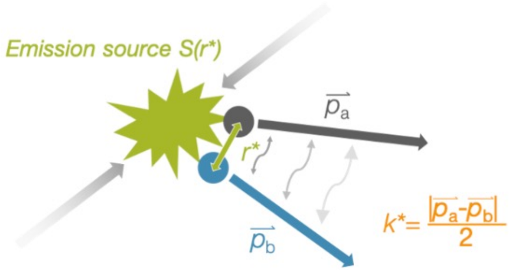


Energy dependence of the tilt angle θ



Femto-scopic two-particle correlation for Baryon-interaction





Source size FSI

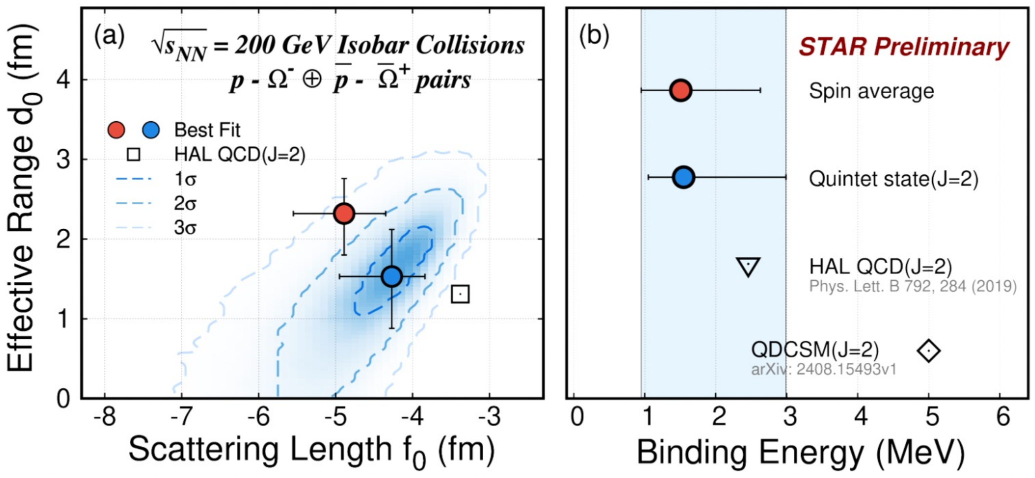
$$C(k^*) = \int S(\vec{r})|\Psi(\vec{k^*},\vec{r})|^2 d^3\vec{r} = \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

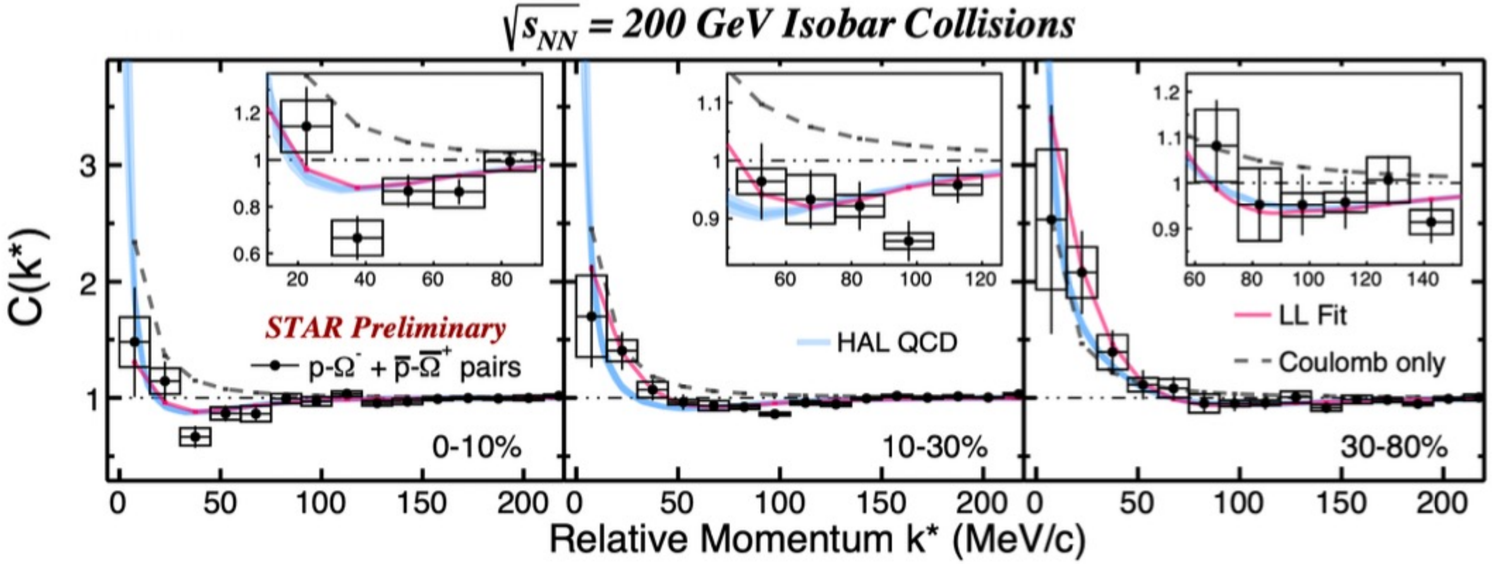
$S(\vec{r})$: Source function

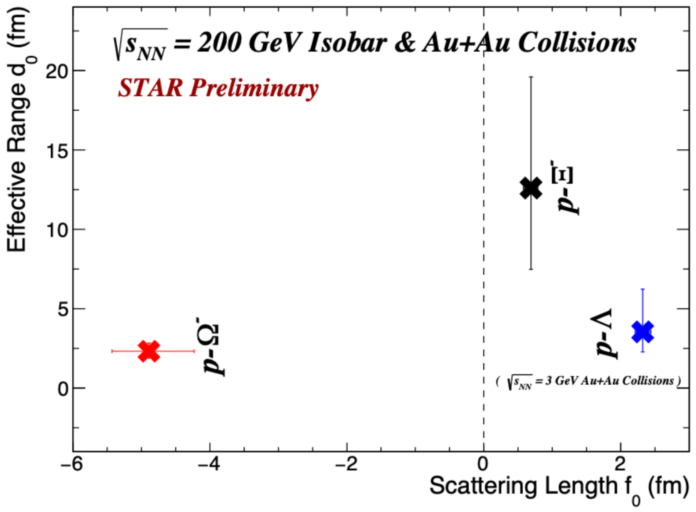
$\Psi(\vec{k^*},\vec{r})$: Pair wave function

$k^* = \frac{1}{2}|\vec{p}_a - \vec{p}_b|$, relative momentum

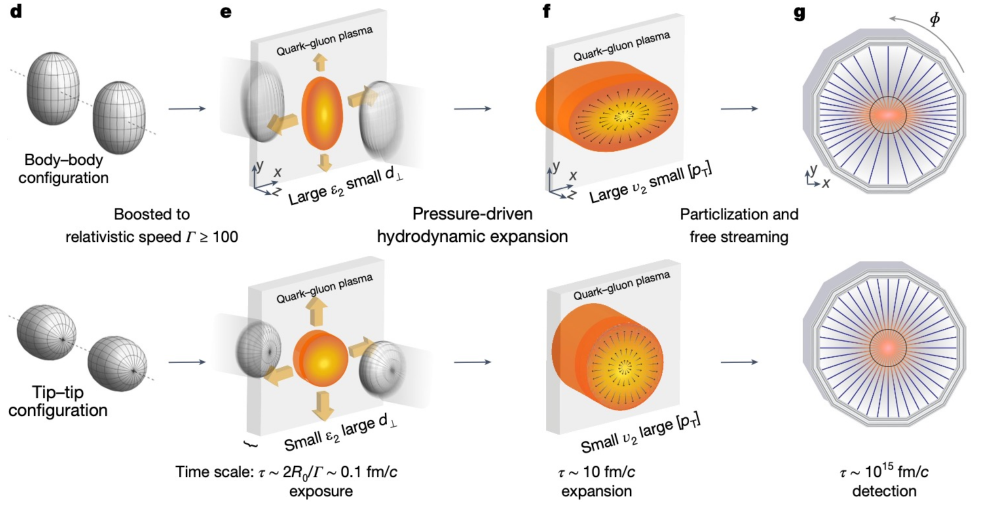
$\vec{r}$: relative distance



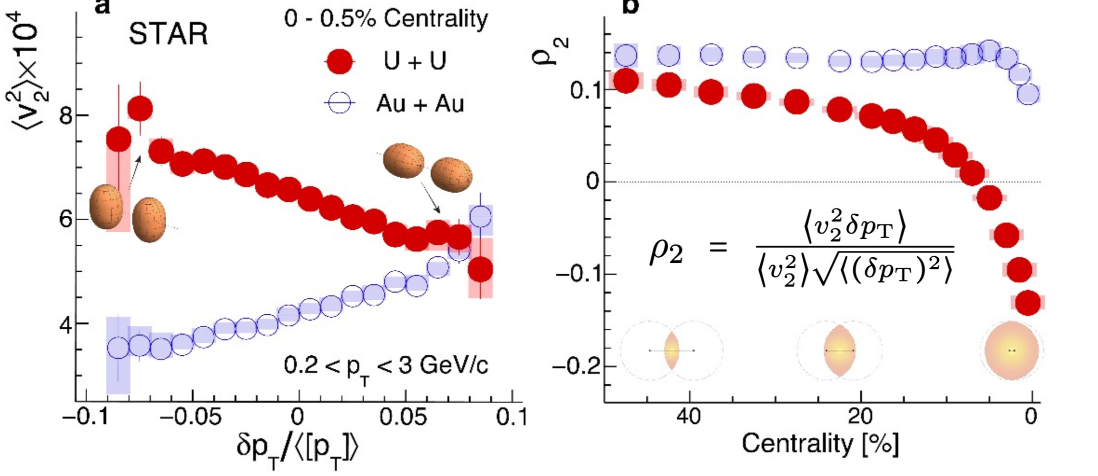




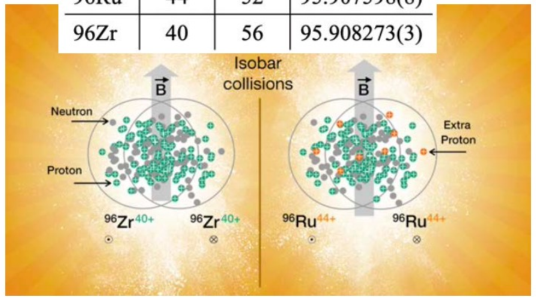
v_2 - Δp_T correlation for Nuclear Imaging

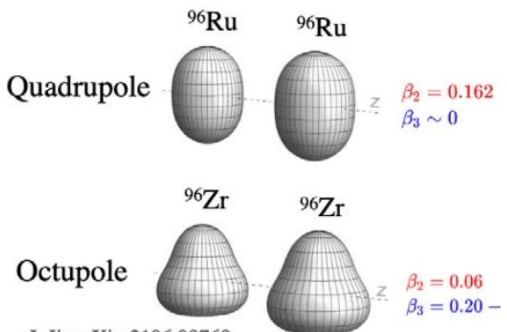


Nature 635 (2024) 67

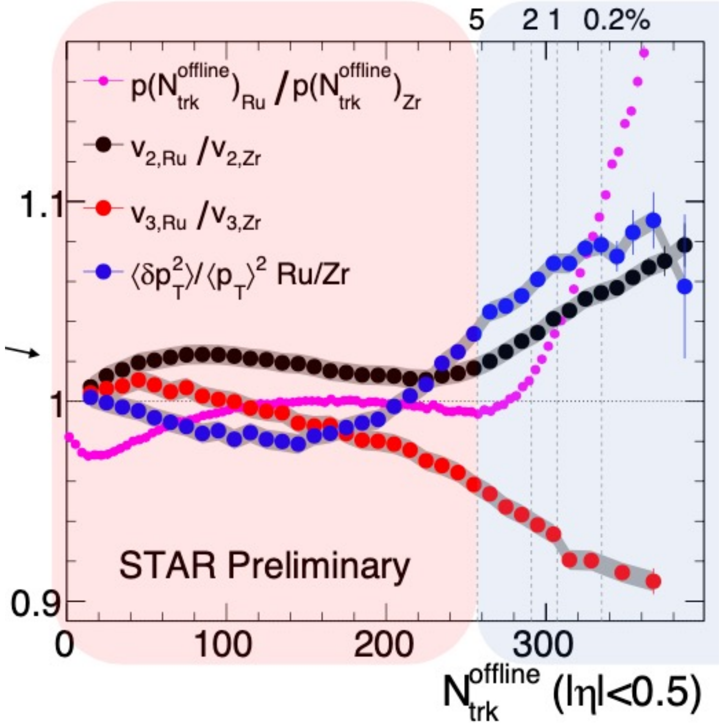


	Z	N	mass
96Ru	44	52	95.907598(8)
96Zr	40	56	95.908273(3)





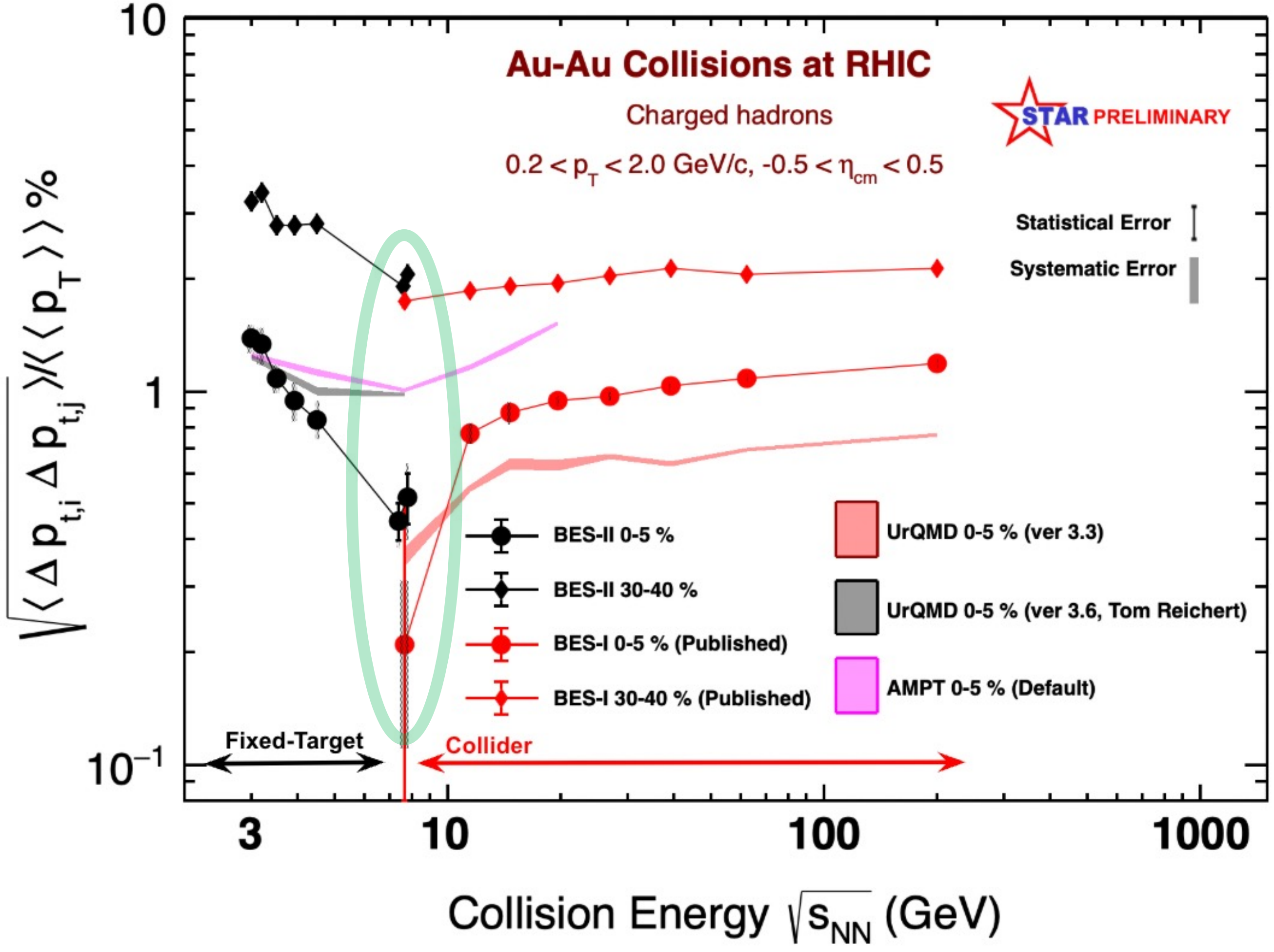
J. Jia, aXiv:2106.08768

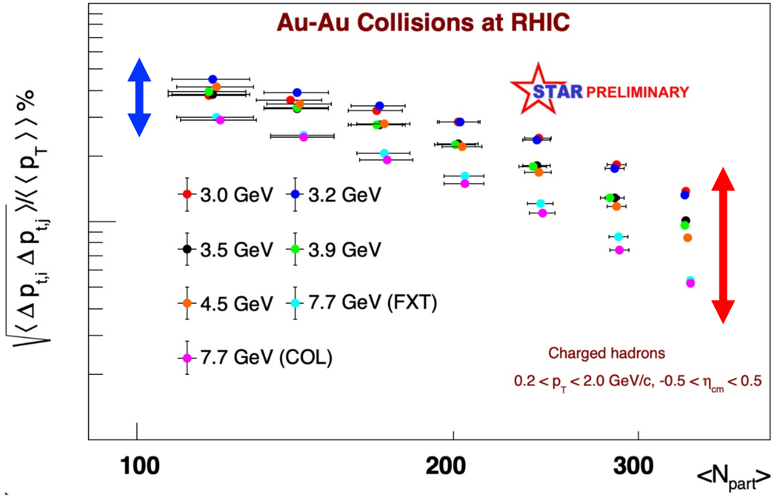


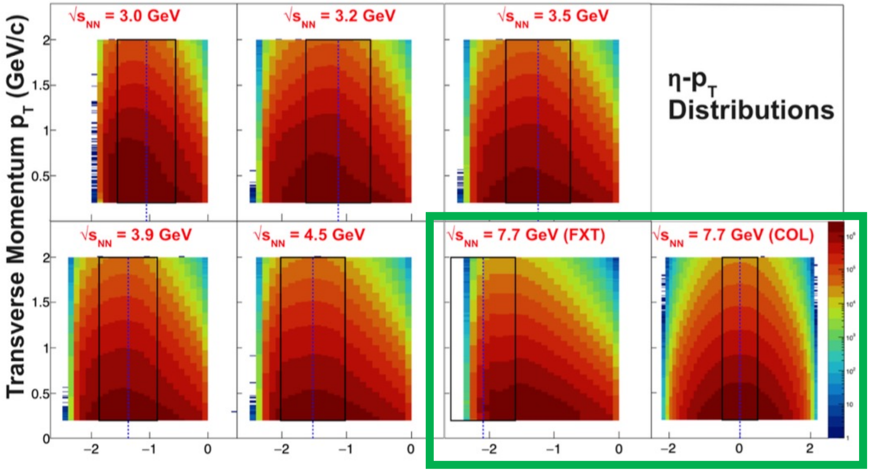
2^{nd} order p_T correlation mean p_T fluctuation

$$<\Delta p_{t,i}\Delta p_{t,j}> = <(p_{t,i} - <p_t>)(p_{t,j} - <p_t>)>_{i\neq j}$$

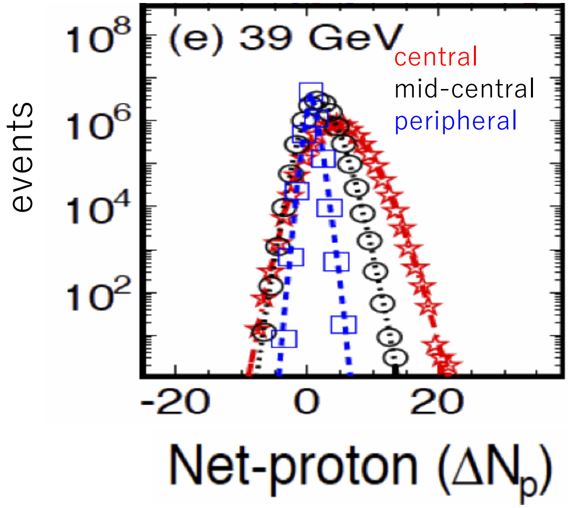
QM25, STAR

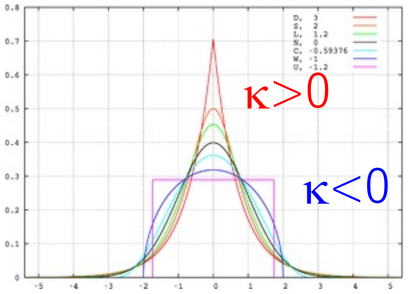




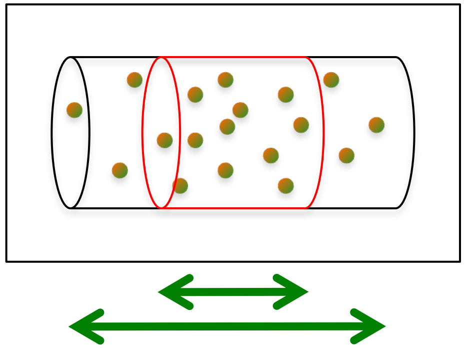


Higher Order Fluctuation of Conserved Quantity (net-Baryon) to look for Critical Point and Phase Transition



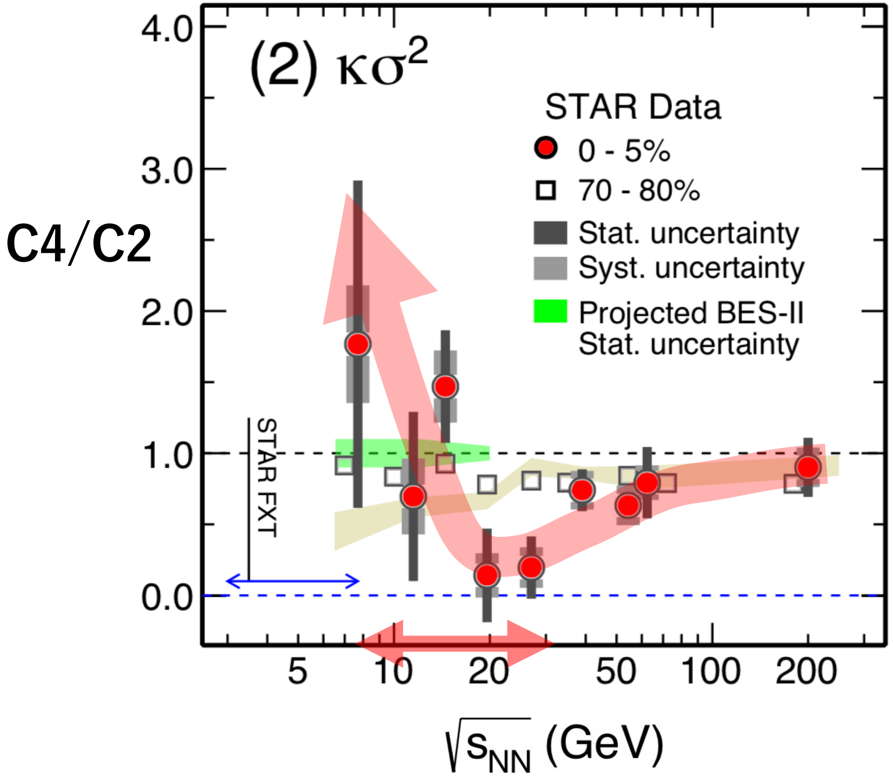


1st (Mean)
2nd (Width)
3rd (Skewness)
4th (Kurtosis, κ)

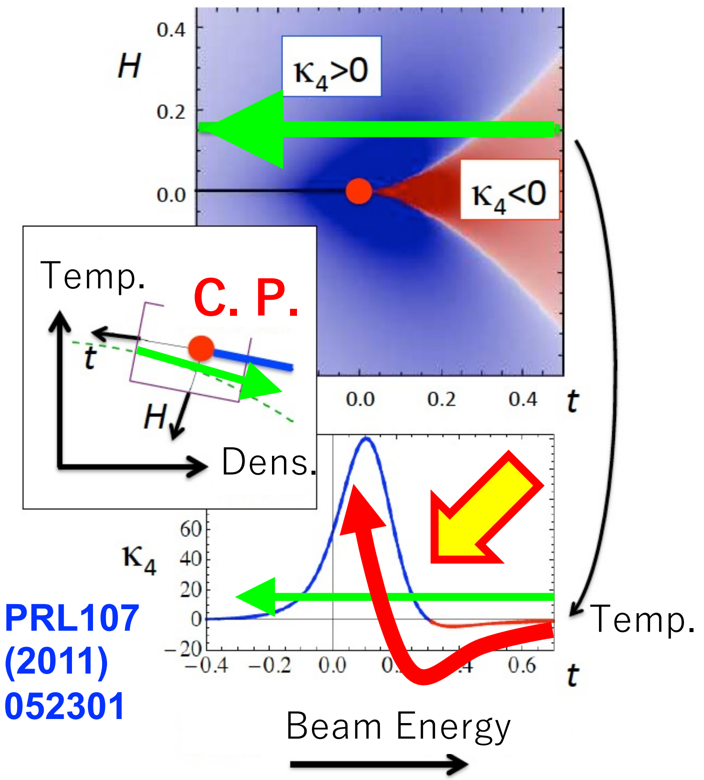


change of correlation length expected at critical point

PRL126 (2021) 092301



Higher order fluctuation (4th order κ_4)



PRL107 (2011) 052301

Non-binomial efficiency correction (Unfolding method)

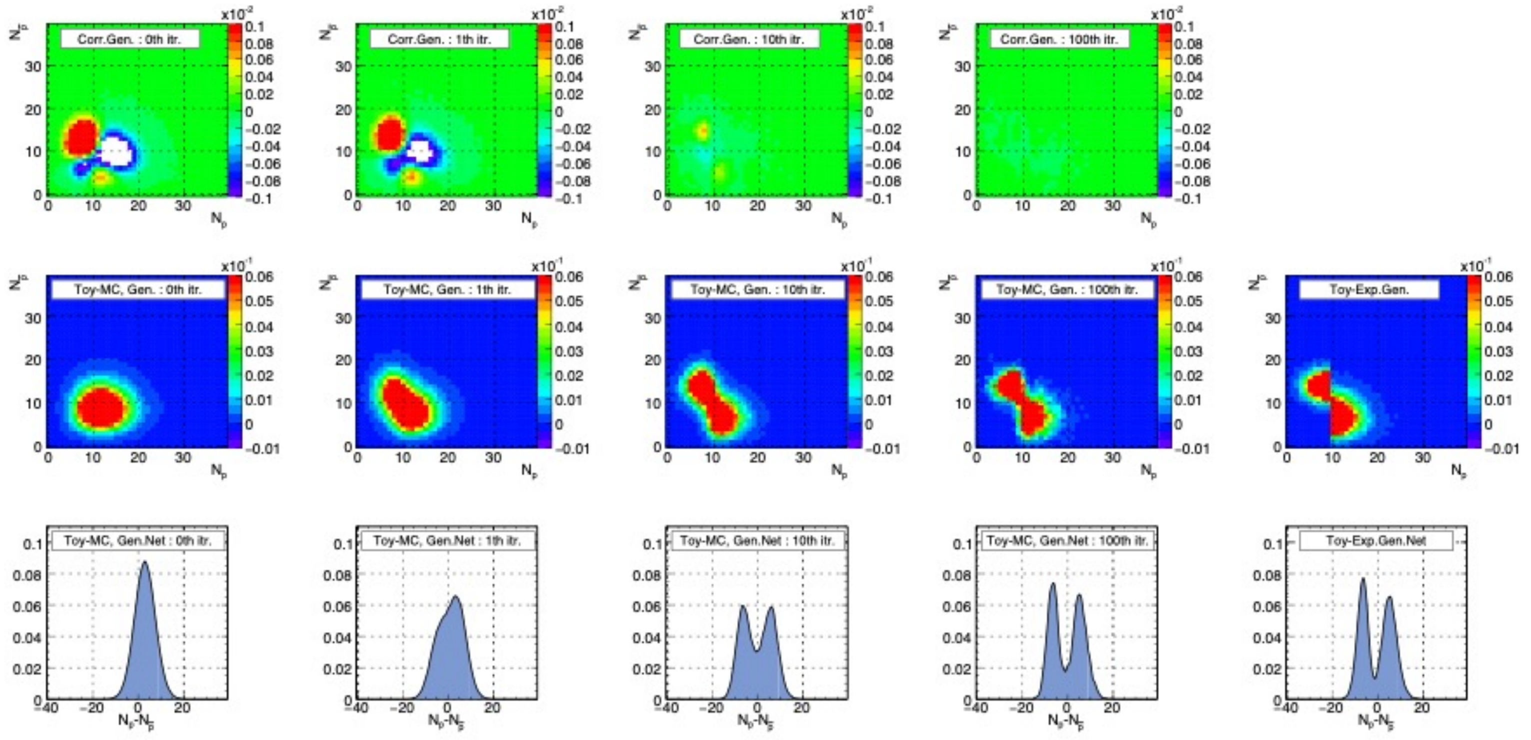


FIG. 4. (Top) Correction functions in the generated coordinates. White-colored bins represent the large negative value outside the z-axis range. (Middle) Toy-MC distributions in the generated coordinates. (Bottom) Toy-MC net-particle distributions in the generated coordinates. The 1st to 4th row from left to right show distributions at the 0th (initial condition), 1st, 10th and 100th iteration. The most right panels show distributions for the toy-experiment sample.

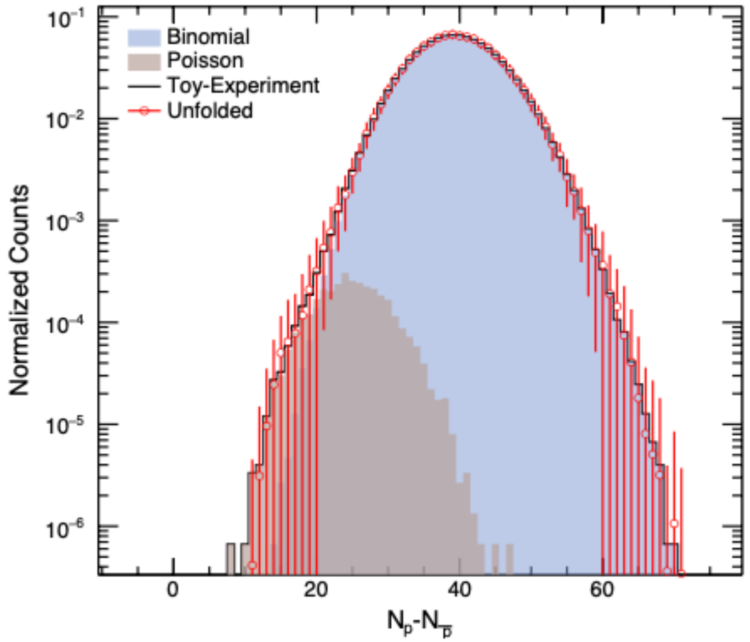
Reconstructing particle number distributions with convoluting volume fluctuations

ShinIchi Esumi,[1,*] Kana Nakagawa,[1] and Toshihiro Nonaka[1,2,†]

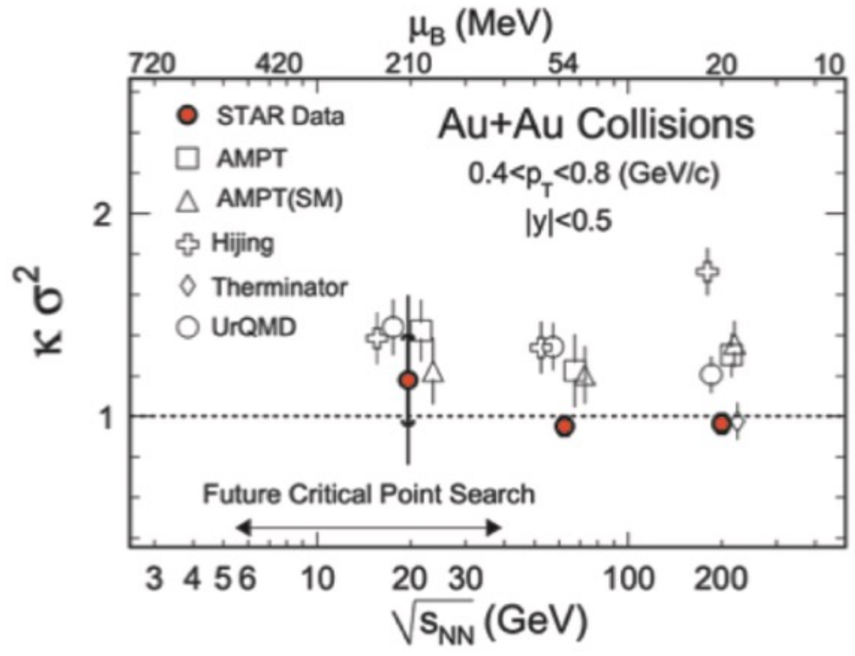
ıonaga Center for the History of the Universe, University of Tsukuba, Tsukuba, Ibaraki 305, Japan

[2] Key Laboratory of Quark & Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, China

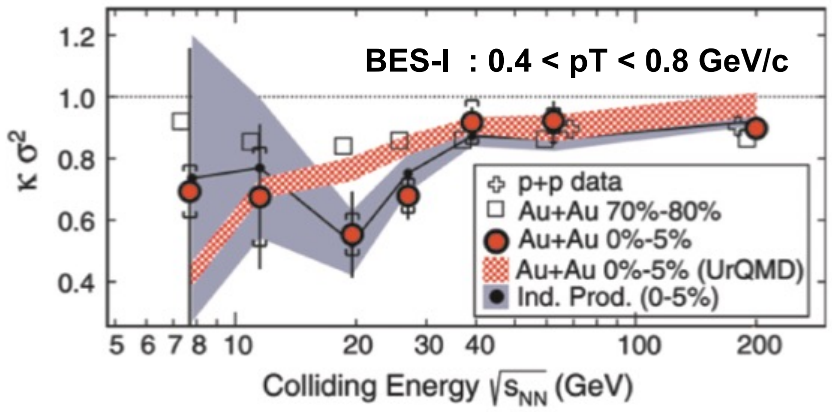
propose methods to reconstruct particle distributions with and without considering initial ıe fluctuations. This approach enables us to correct for detector efficiencies and initial volume ations simultaneously. Our study suggests such a tool could investigate the possible bimodal ure of net-proton distribution in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7 GeV as a signature of ırder phase transition and critical point of hadronic matter [1, 2].



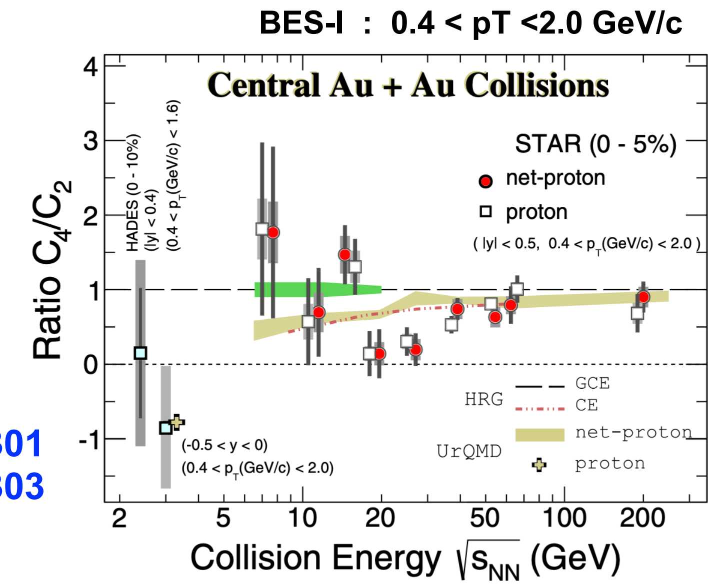
History of net-proton kurtosis results in STAR



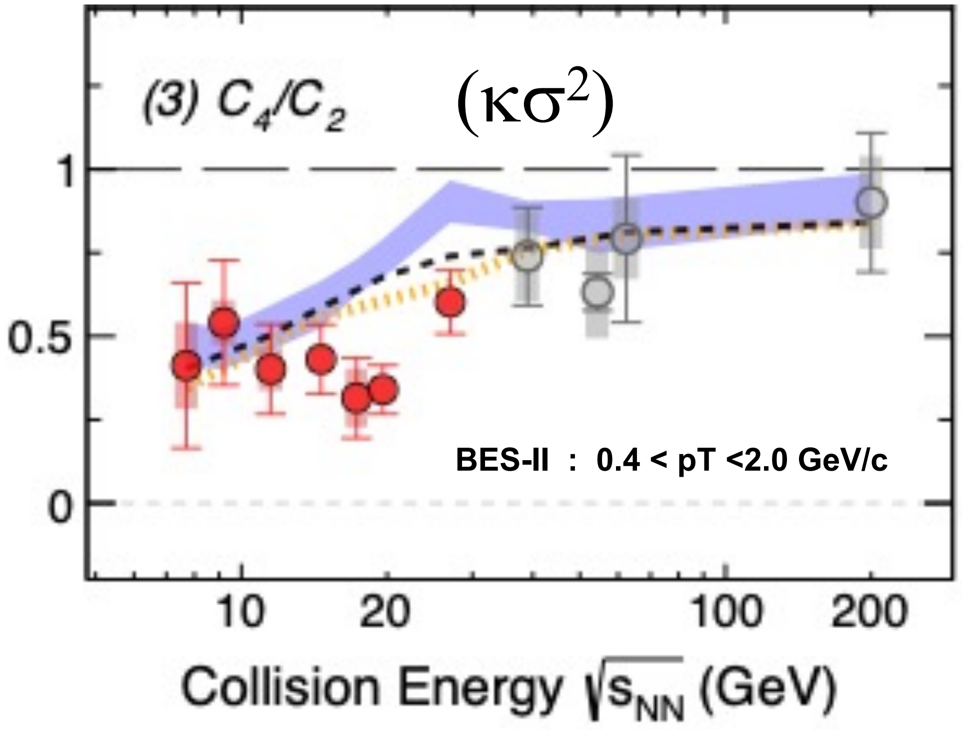
PRL 105 (2010) 022302



PRL 112 (2014) 032302

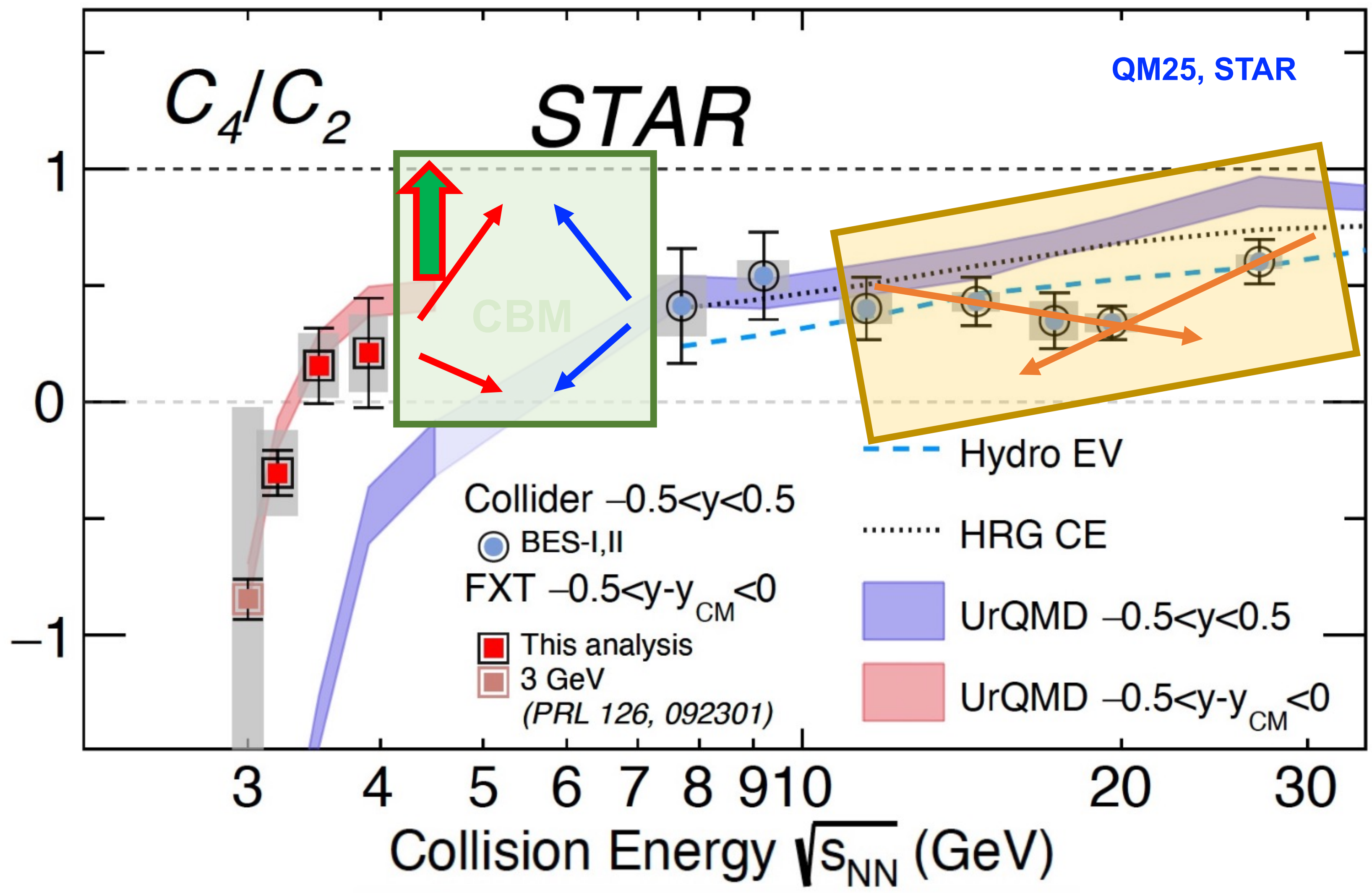


PRL 126 (2021) 092301
PRL 128 (2022) 202303



CPOD2024
SQM2024
PRL135 (2025) 142301

Beam energy dependence of (net-) proton C_4/C_2



RUN25 plan at RHIC

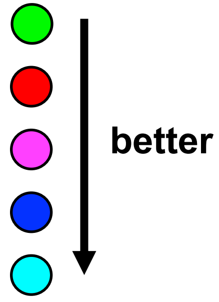
- 200GeV Au+Au

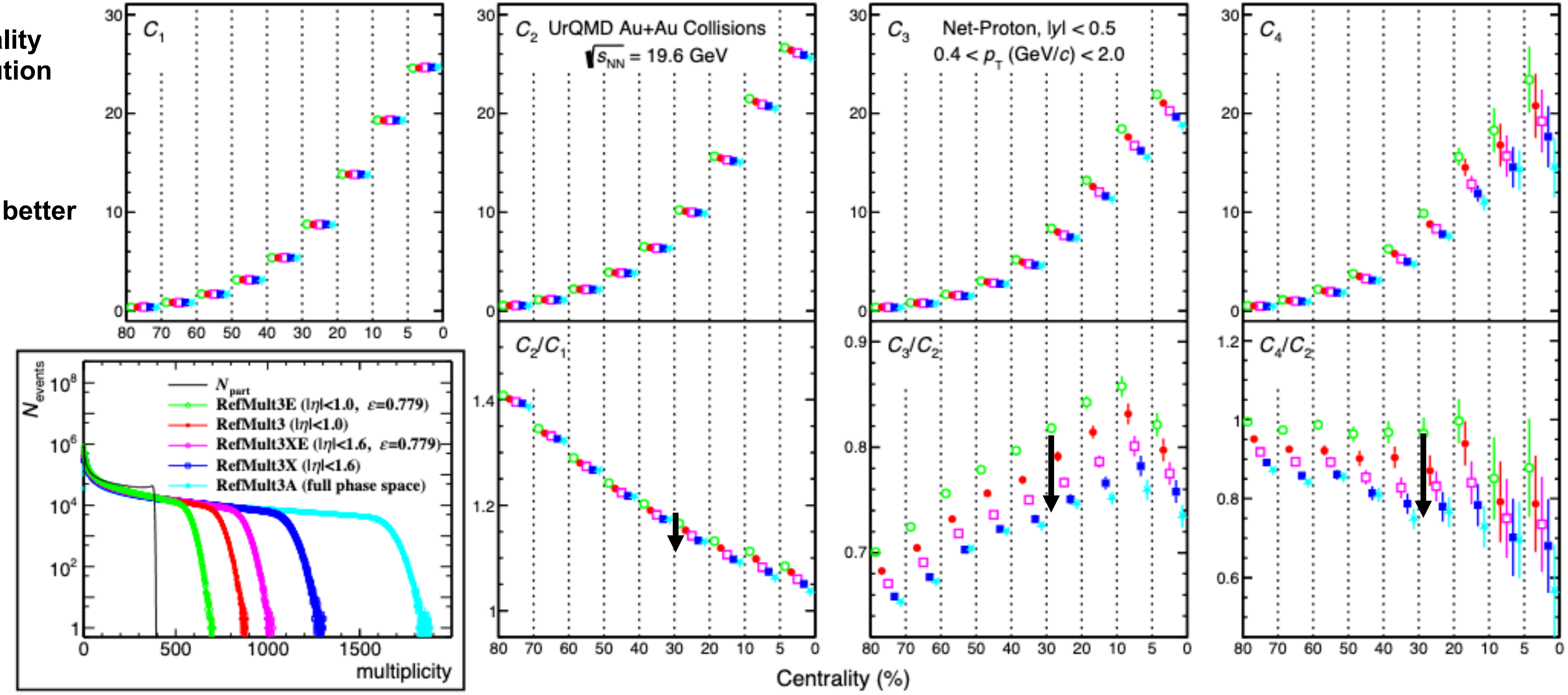
- 200GeV p+p
- 200GeV p+Au
- 4.2/4.5 GeV Au+Au
- 27/62 GeV Isobar (Zr+Zr, Ru+Ru)

$\sqrt{s_{NN}}$ (GeV)	Beam Energy (GeV/nucleon)	Collider or Fixed Target	$y_{center\ of\ mass}$	μ_B (MeV)	Run Time (days)	No. Events Collected (Request)	Date Collected
200	100	C	0	25	2.0	138 M (140 M)	Run-19
27	13.5	C	0	156	24	555 M (700 M)	Run-18
19.6	9.8	C	0	206	36	582 M (400 M)	Run-19
17.3	8.65	C	0	230	14	256 M (250 M)	Run-21
14.6	7.3	C	0	262	60	324 M (310 M)	Run-19
13.7	100	FXT	2.69	276	0.5	52 M (50 M)	Run-21
11.5	5.75	C	0	316	54	235 M (230 M)	Run-20
11.5	70	FXT	2.51	316	0.5	50 M (50 M)	Run-21
9.2	4.59	C	0	372	102	162 M (160 M)	Run-20+20b
9.2	44.5	FXT	2.28	372	0.5	50 M (50 M)	Run-21
7.7	3.85	C	0	420	90	100 M (100 M)	Run-21
7.7	31.2	FXT	2.10	420	0.5+1.0+ scattered	50 M + 112 M + 100 M (100 M)	Run-19+20+21
7.2	26.5	FXT	2.02	443	2+Parasitic with CEC	155 M + 317 M	Run-18+20
6.2	19.5	FXT	1.87	487	1.4	118 M (100 M)	Run-20
5.2	13.5	FXT	1.68	541	1.0	103 M (100 M)	Run-20
4.5	9.8	FXT	1.52	589	0.9	108 M (100 M)	Run-20
3.9	7.3	FXT	1.37	633	1.1	117 M (100 M)	Run-20
3.5	5.75	FXT	1.25	666	0.9	116 M (100 M)	Run-20
3.2	4.59	FXT	1.13	699	2.0	200 M (200 M)	Run-19
3.0	3.85	FXT	1.05	721	4.6	259 M -> 2B(100 M -> 2B)	Run-18+21

Improvement on centrality resolution (volume fluctuation), UrQMD test

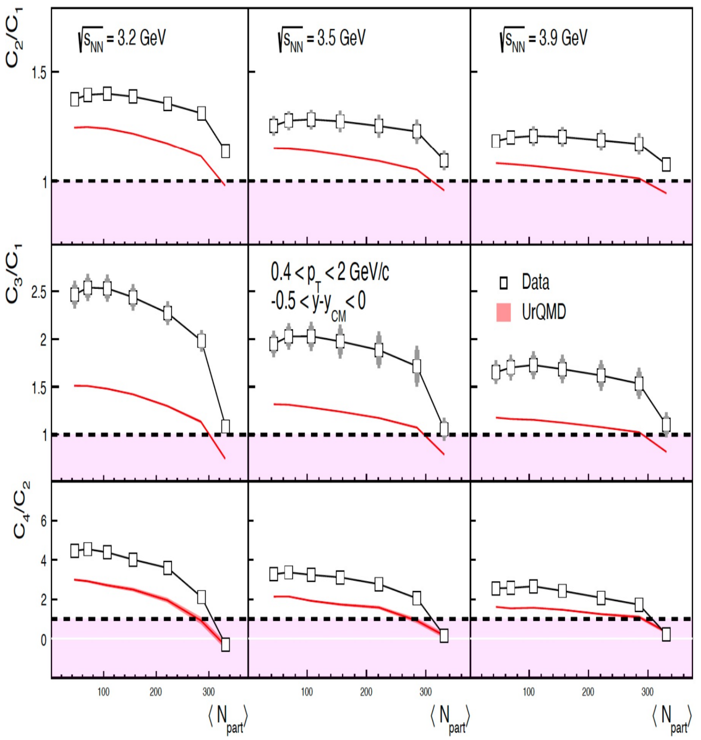
at Au+Au 19.6 GeV





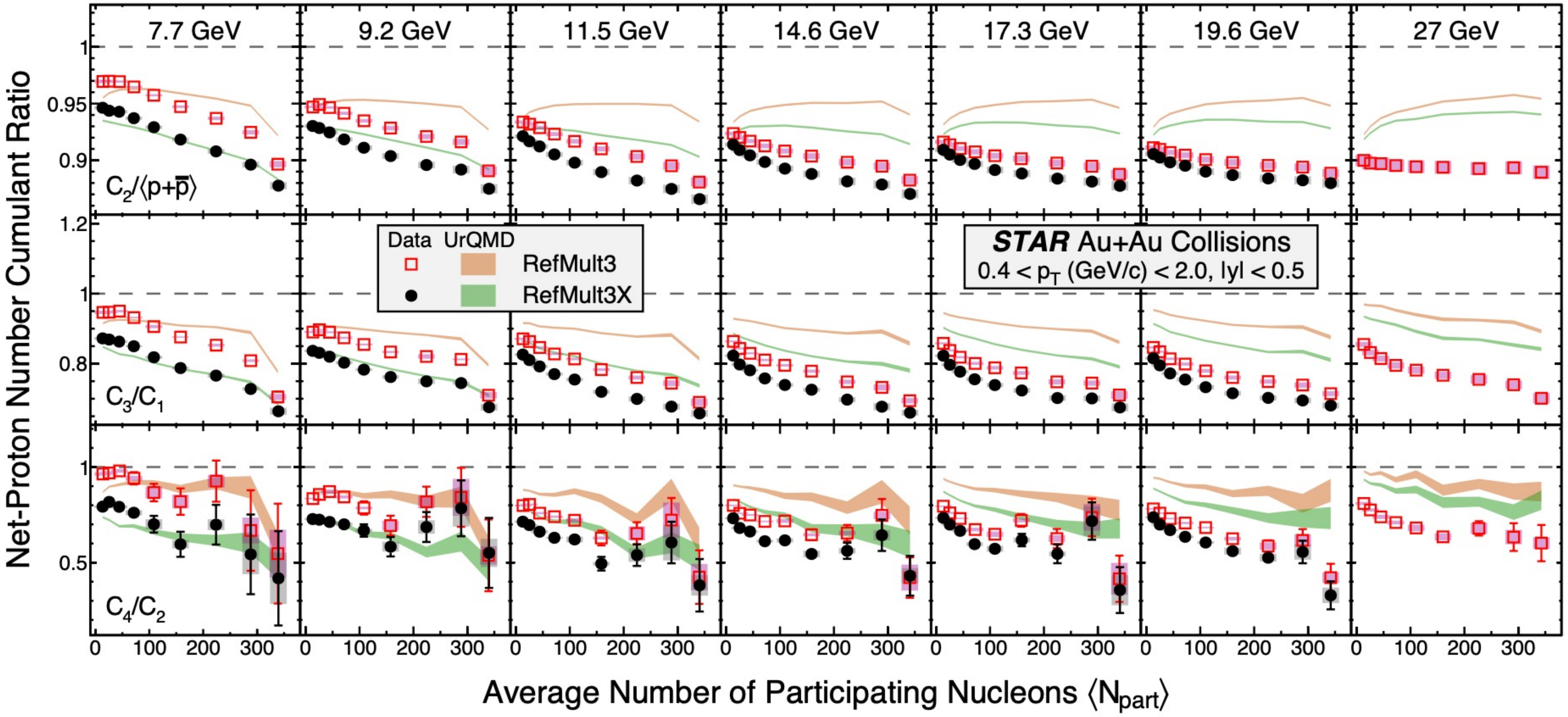
Beam energy and centrality dependence of cumulant ratios

FXT : 3.2 ~ 3.9 GeV

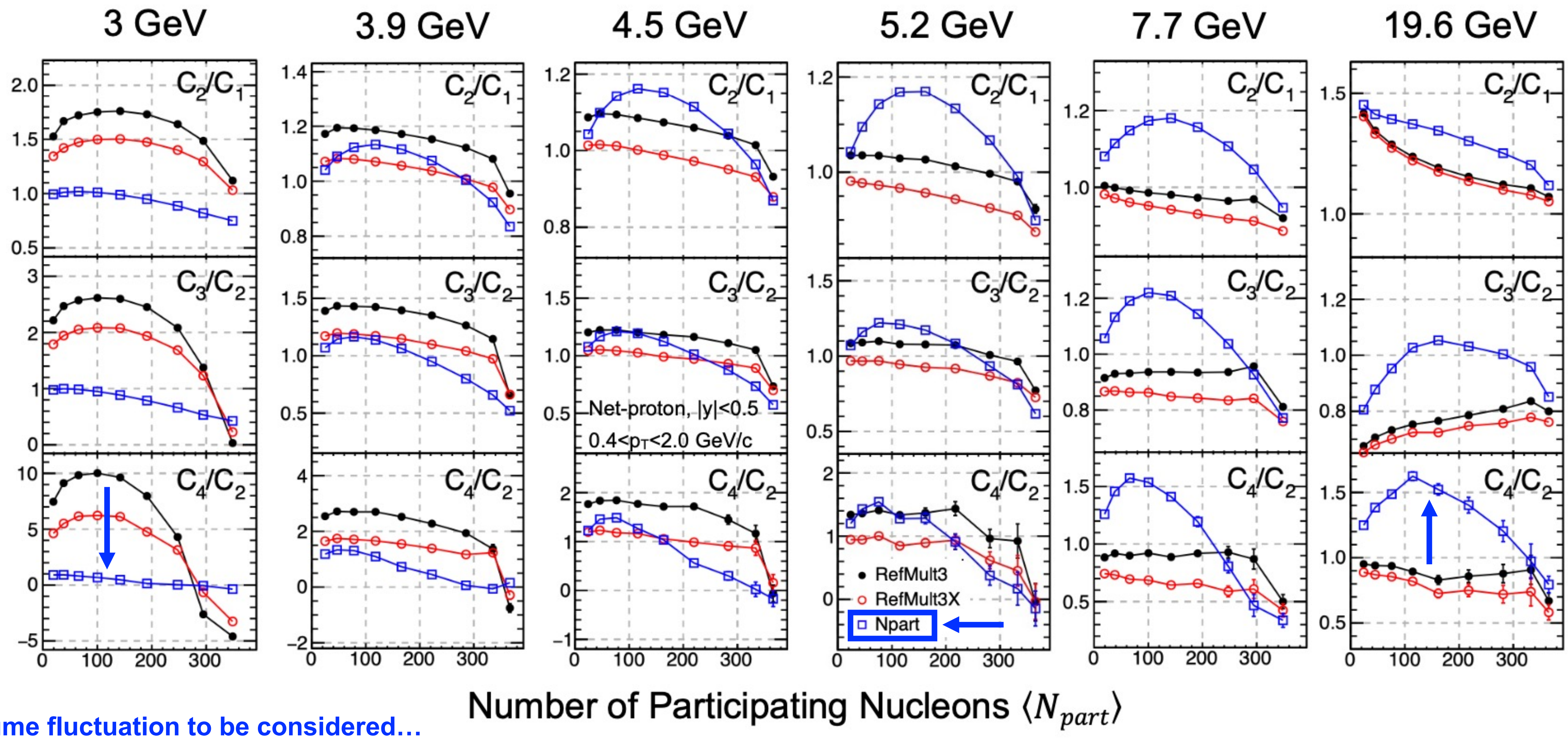


COL : 7.7 ~ 27 GeV

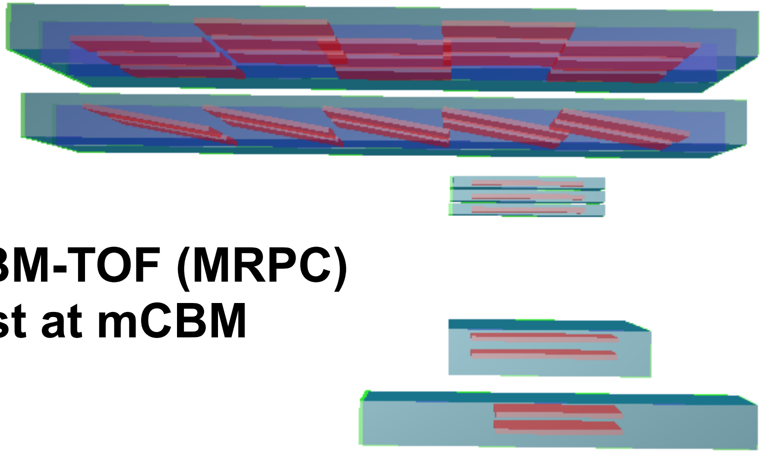
CPOD2024, QM2025



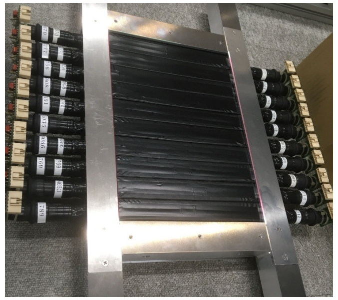
Some more UrQMD tests at different energies

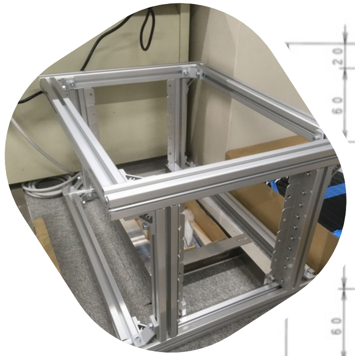


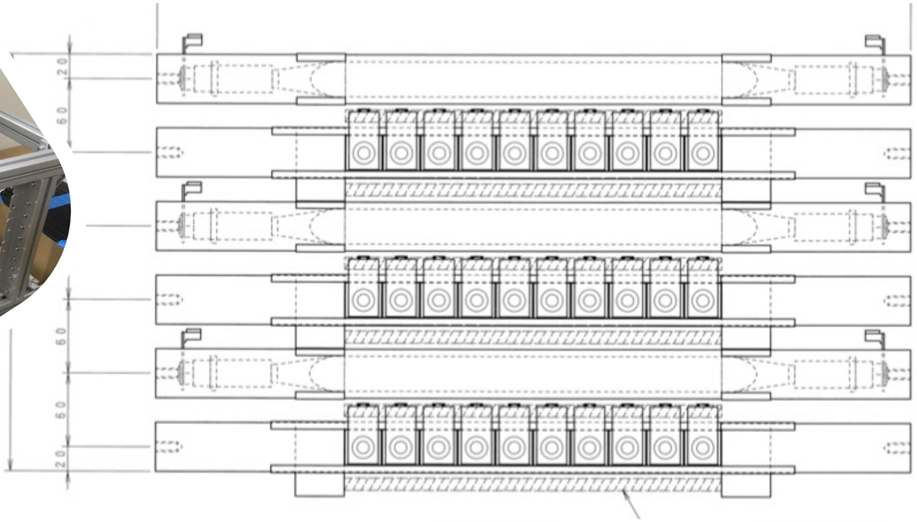
Volume fluctuation to be considered…



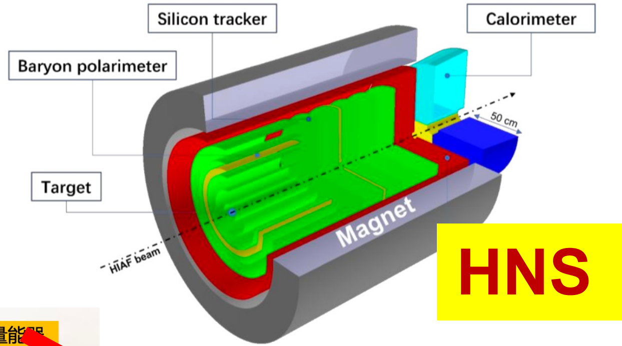
CBM-TOF (MRPC) test at mCBM

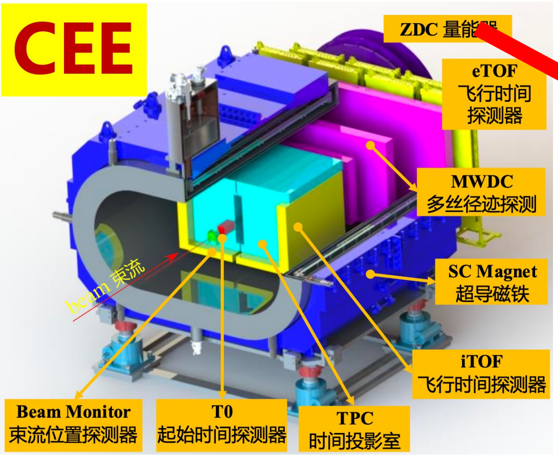


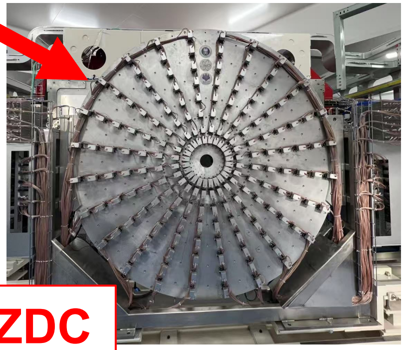




Neutron detector proto-type with scintillator
Stacks of MRPC modules considered as well





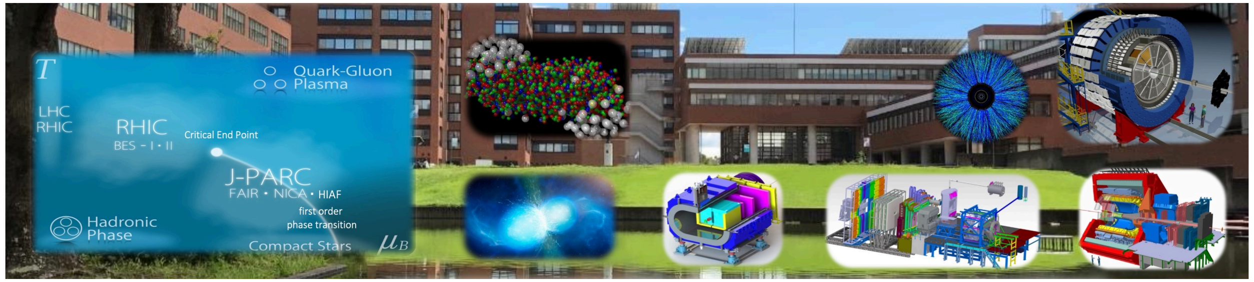


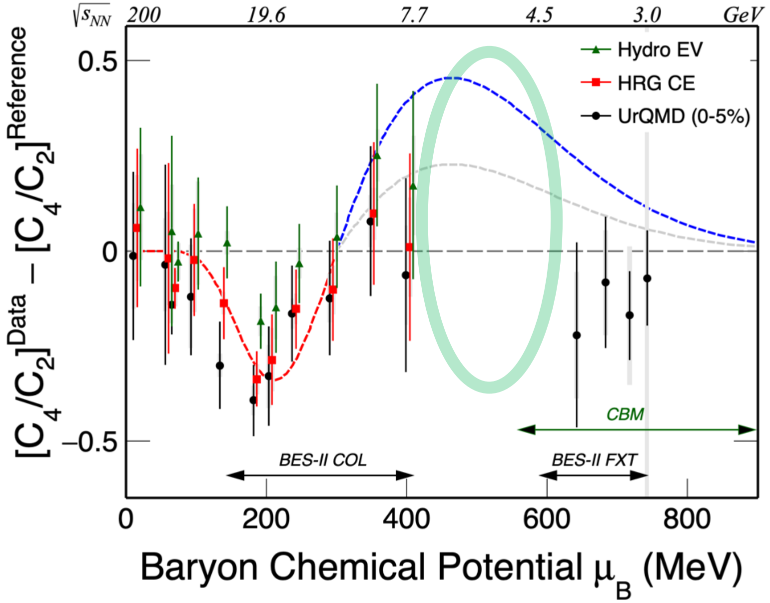
ZDC

Summary

- **STAR experiment and detectors**
- **Tracking, particle identification, reaction plane and centrality**
- **Temperature measurements and Freeze-out**
- **Anisotropic flow, correlation, fluctuation**
- **Next plan and Outlook**

WHBM2023 and WHBM2025 at Tsukuba





Many thanks to :
Daniel Cebra, Xin Dong, Hanwen Feng, Marek Gazdzicki, Norbert Herrmann, Yige Huang, Masakiyo Kitazawa, Volker Koch, Xiaofeng Luo, Rutik Manikandhan, Bedangadas Mohanty, Bappaditya Mondal, Yasushi Nara, Takafumi Niida, Toshihiro Nonaka, Ashish Pandav, Anar Rustamov, Fan Si, Yannick Soehngen, Agnieszka Sorensen, Mikhail Stephanov, Zachary Sweger, Zhaohui Wang, Nu Xu, Yongcong Xu, Xin Zhang, Yifei Zhang, Yu Zhang and the STAR Collaboration and the CBM Collaboration