Net-proton C_4 measurement at $\sqrt{s_{NN}} = 54.4$ GeV in Au+Au collisions at the RHIC-STAR experiment

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STAR
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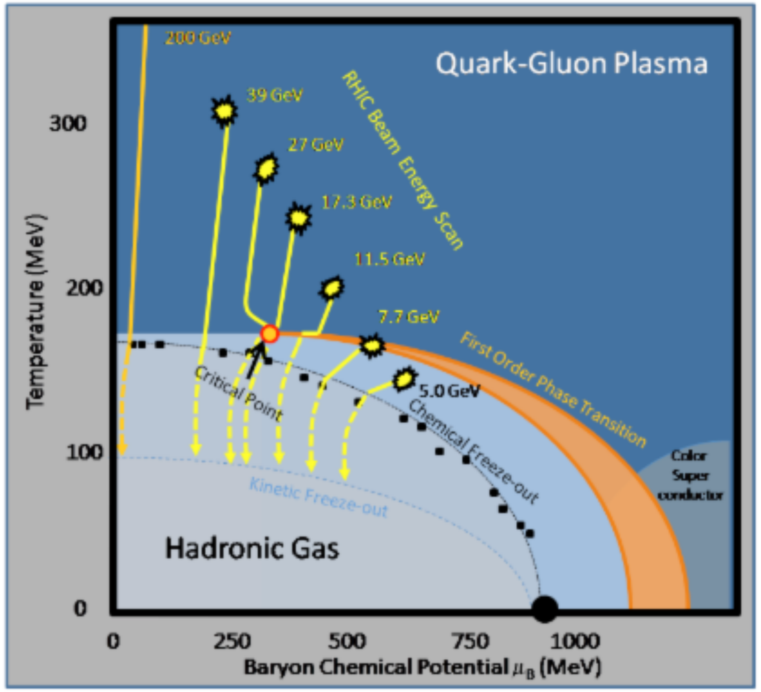
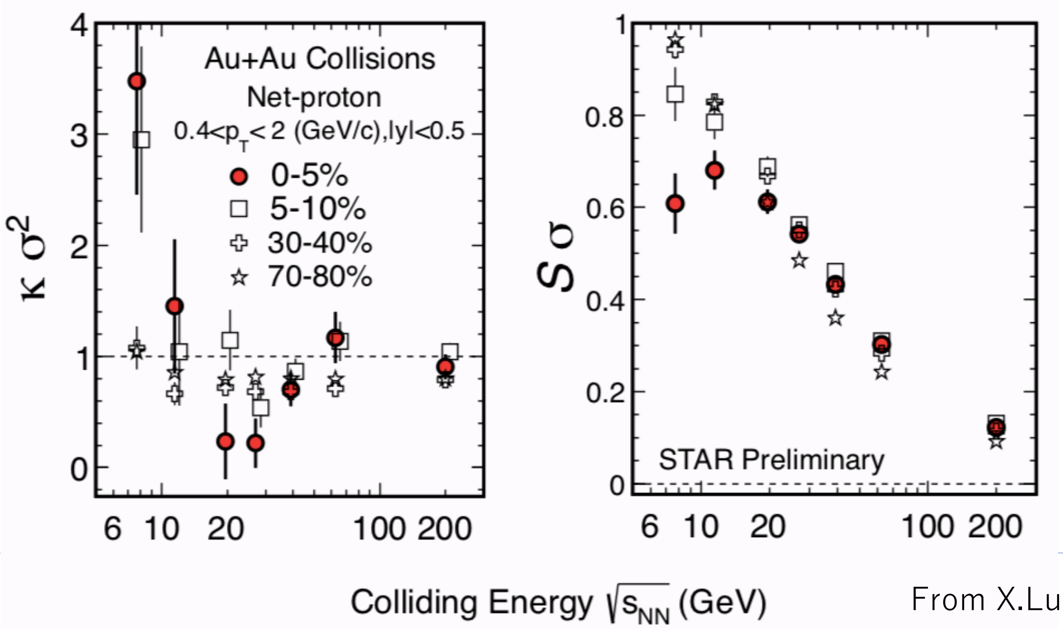
Physics Motivation

- ✓Lattice QCD calculation has predicted that phase transition around μ_B=0 is "**smooth crossover**". From Y.Aoki et al., Nature, 443, 675 (2006)
- ✓We search for the 1st-order phase transition and the **Critical Point**.
- ✓Fluctuations of conserved quantities are considered to be a powerful tool to search for the critical point.



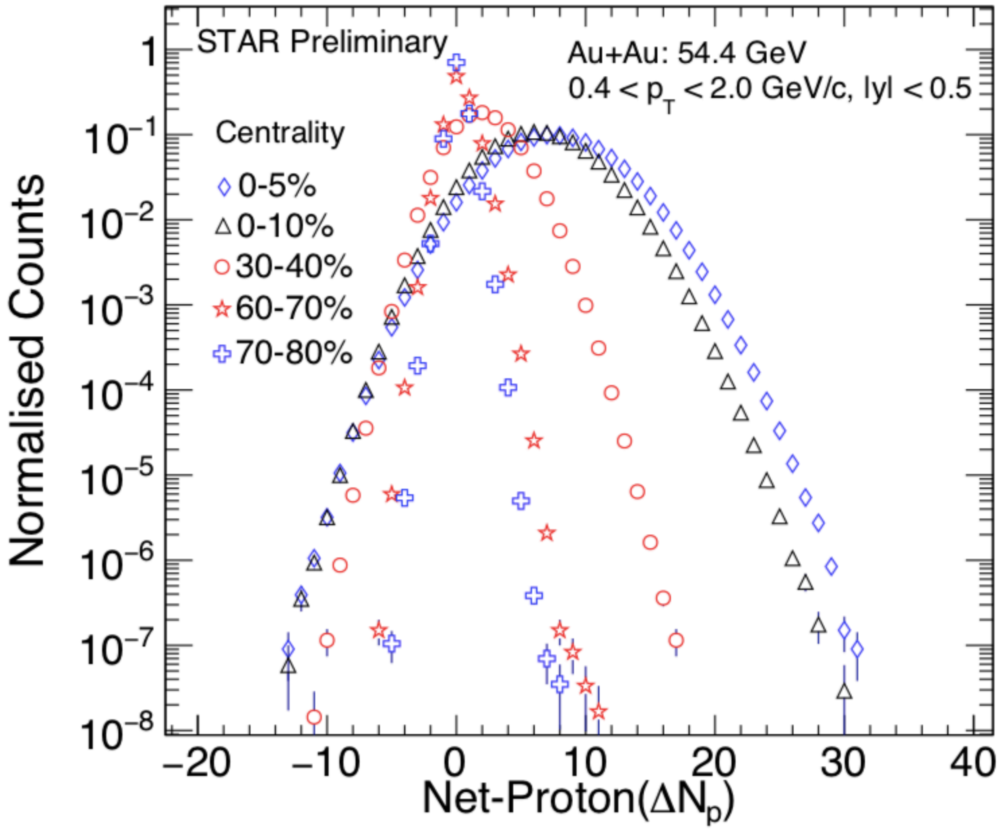
<u>Beam Energy Scan@STAR</u> <u>(~2014, 7.7-200 GeV)</u>

Non-monotonic behavior of net-p $\kappa\sigma^2$ at low energy appeared, which could be a signature of the critical point.



From X.Luo,PoS(CPOD2014)019

Fluctuation Analysis



- ✓Net quantities are defined by

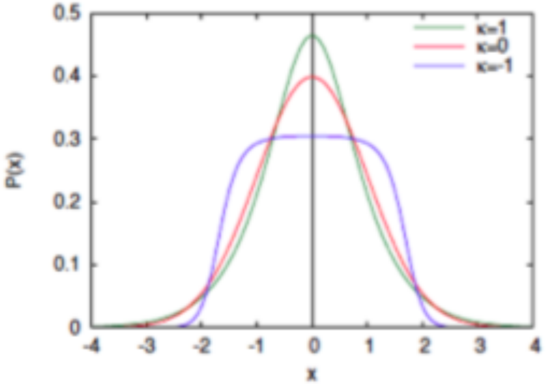
$$\Delta N_p = N_p - N_{\bar{p}}$$

- ✓Cumulants up to the 4th-order are written by

$$C_1 = \langle N \rangle$$
$$C_2 = \langle \delta N^2 \rangle$$
$$C_3 = \langle \delta N^3 \rangle$$
$$C_4 = \langle \delta N^4 \rangle - 3\langle \delta N^2 \rangle^2,$$

where

$$\delta N = N - \langle N \rangle$$



- ✓Cumulant ratios are related to thermodynamic susceptibilities as,

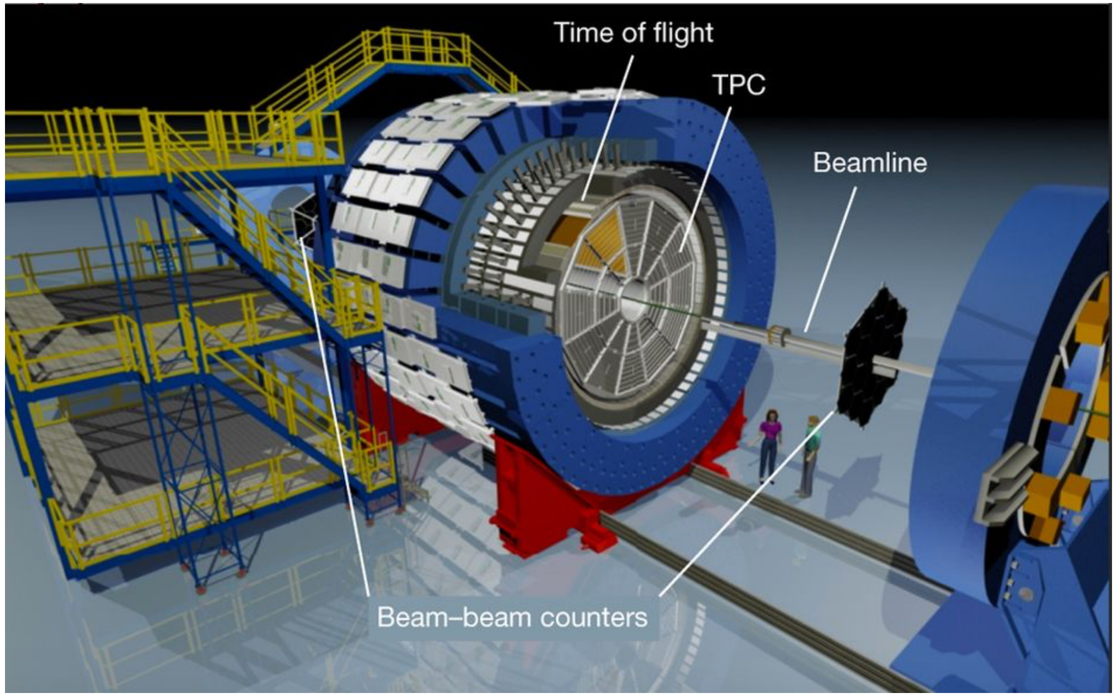
$$C_3/C_2 = S\sigma = \chi^3/\chi^2$$
$$C_4/C_2 = \kappa\sigma^2 = \chi^4/\chi^2$$

- ✓Higher order moments are more sensitive to correlation length.

From M.A.Stephanov, Phys. Rev. Lett. 102, 032301

Data Analysis

- ✓Dataset = Au+Au 54.4 GeV year 2017
- ✓# of Events = 553 M
- ✓Event Selection
  - |Vz|<30 cm
  - |Vr|<2cm
  - Pile-up events were removed.
- ✓Collision centrality is determined by Refmult3* to avoid autocorrelation effect.
- ✓Track cut
  - nHitsFit>20, nHitDedx>5
  - dca<1 cm
  - 0.4<p_T<2.0 GeV/c
  - |y|<0.5
- ✓Proton identification was done using TPC and TOF**.



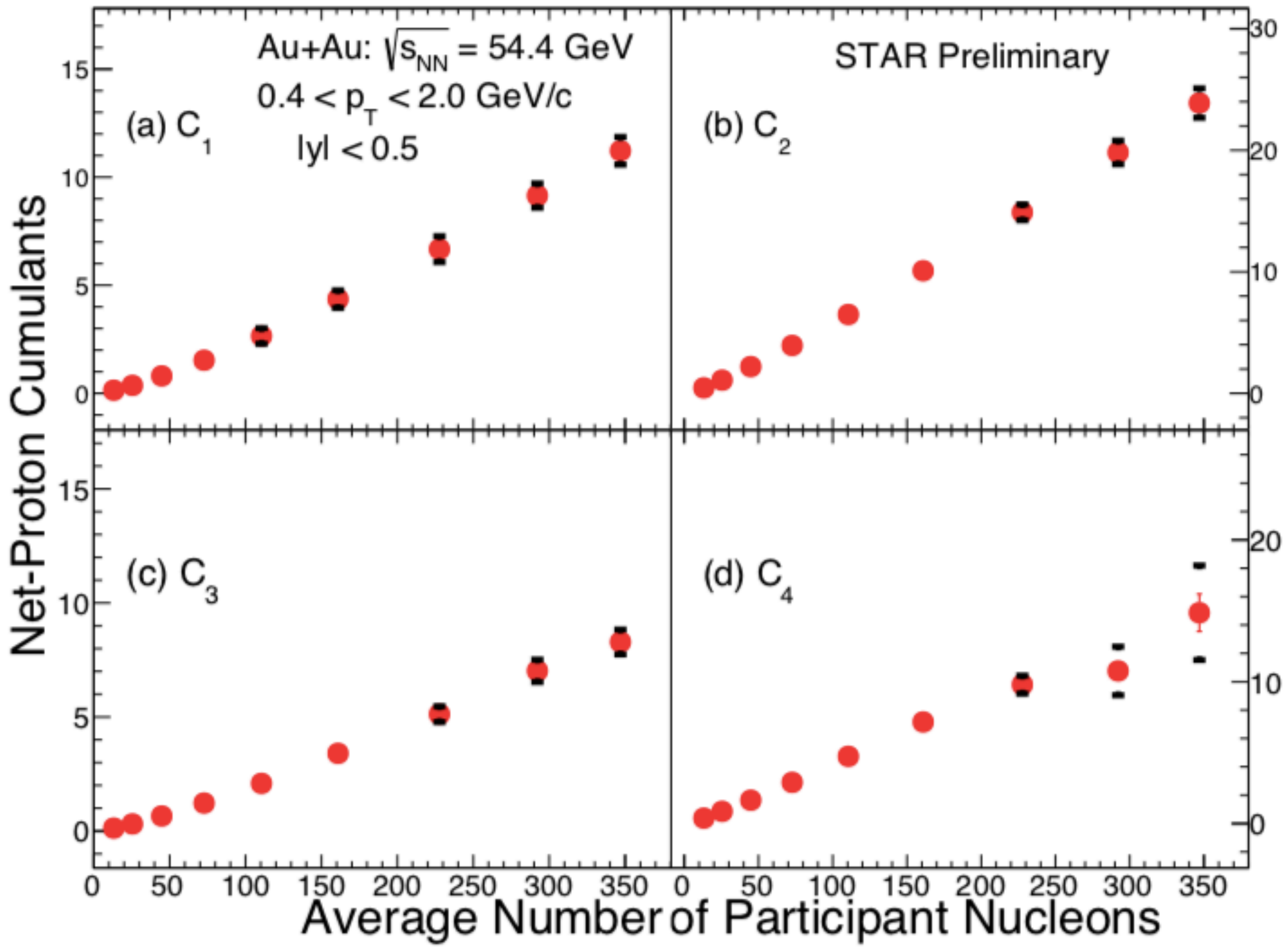
*Refmult3 ··· charged particle multiplicity excluding protons and antiprotons measured in $|\eta| < 1$

**PID ···

0.4<pT<0.8 GeV/c ⇒ Only TPC

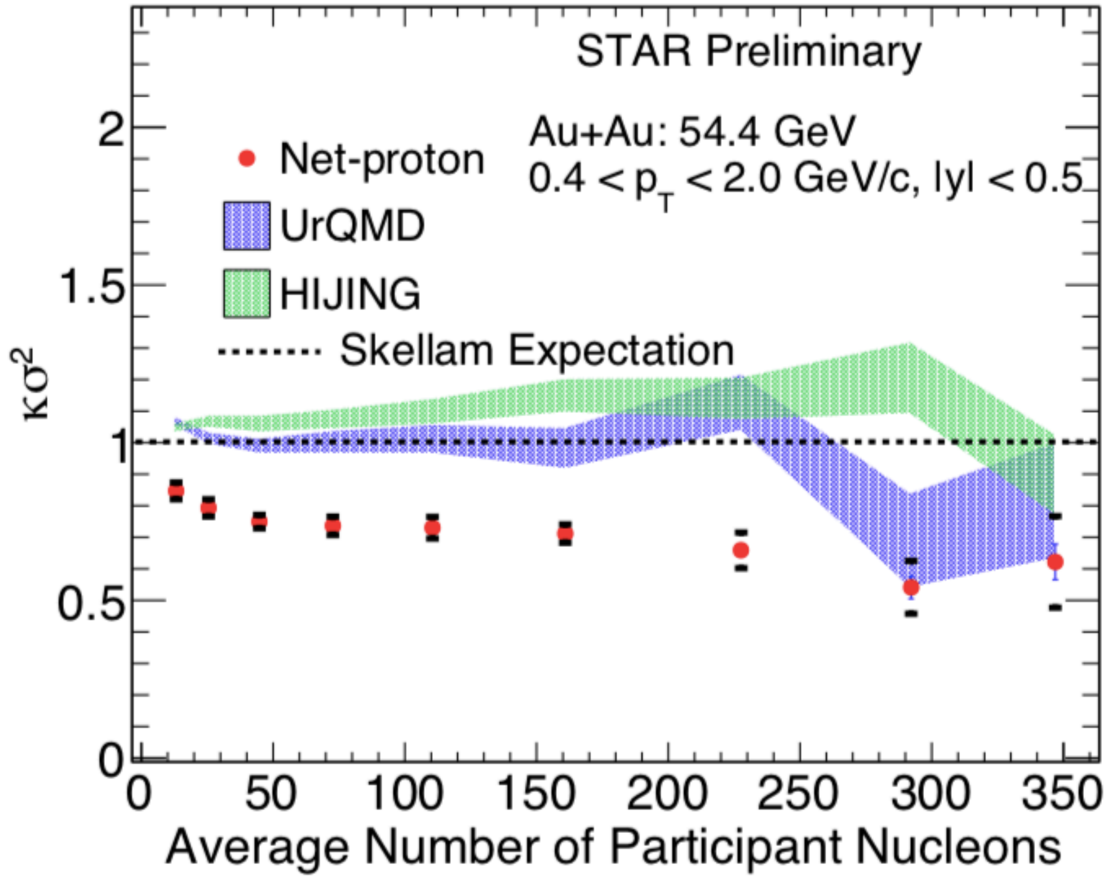
0.8<pT<2.0 GeV/c ⇒ TPC and TOF

Centrality dependence of Cumulants



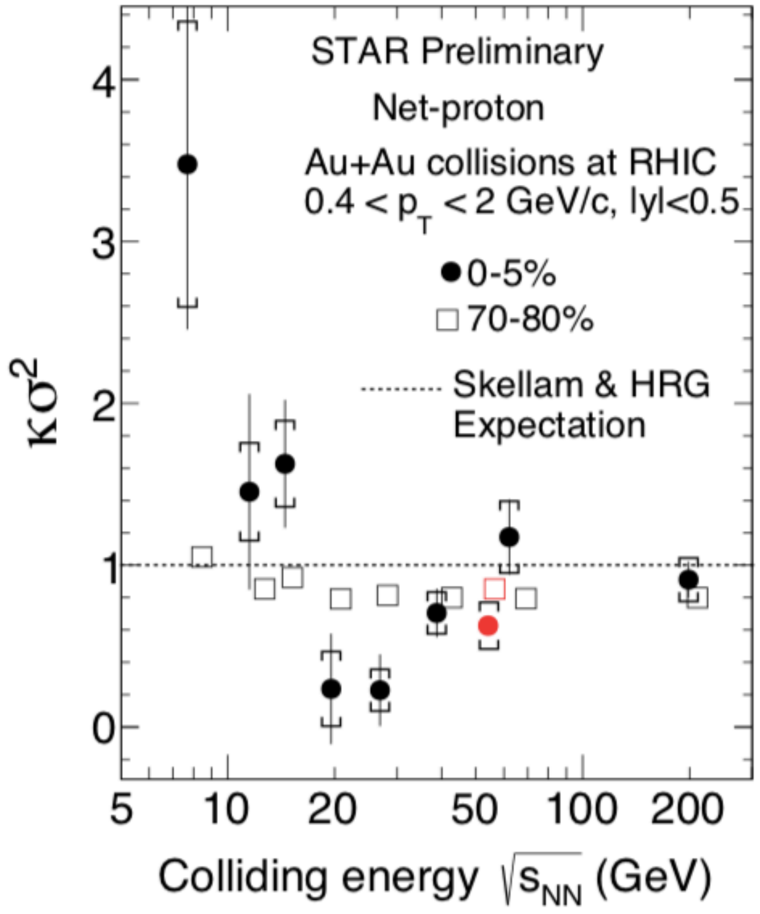
✓Cumulants up to the 4th-oreder increases with number of participants.

Centrality dependence of $\kappa\sigma^2$



✓Experimental results are below Skellam expectation (=1) and hadron transport models.

Energy Dependence of $\kappa\sigma^2$



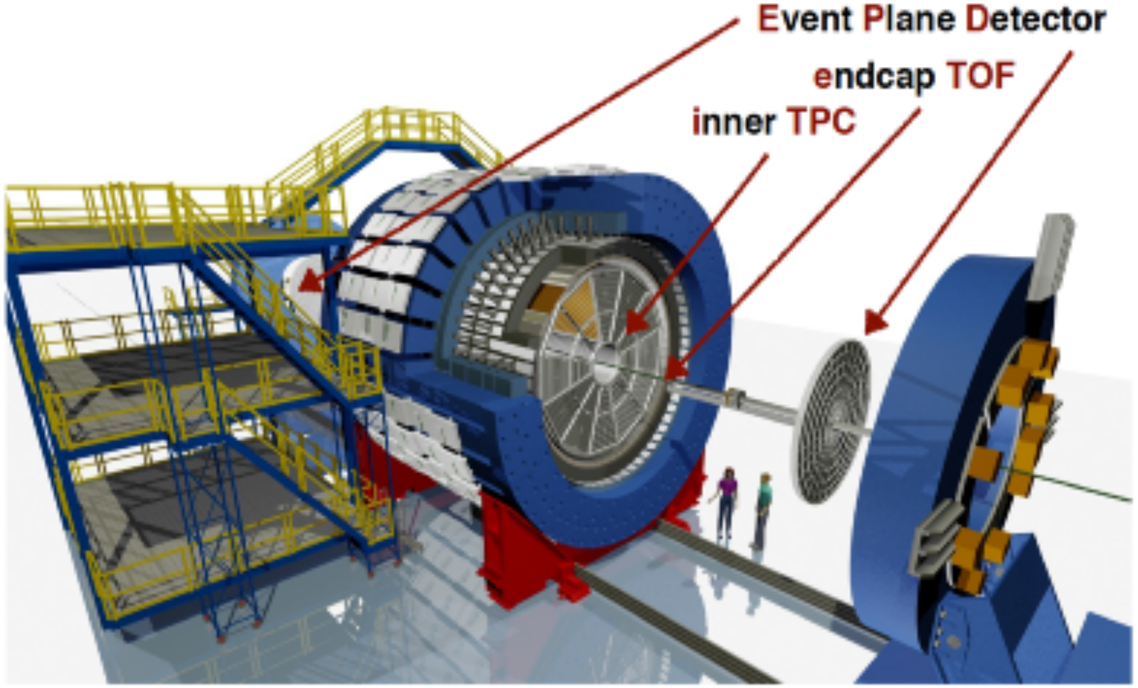
- C_4/C_2 values at 54.4 GeV follows the energy dependence observed in other energies.

Perspective for BES-II

Beam Energy Scan II (2019~)

- Lower collision energies (<20 GeV)
- New detectors (EPD, eTOF, iTPC)
- 10-20 larger statistics than BES-I

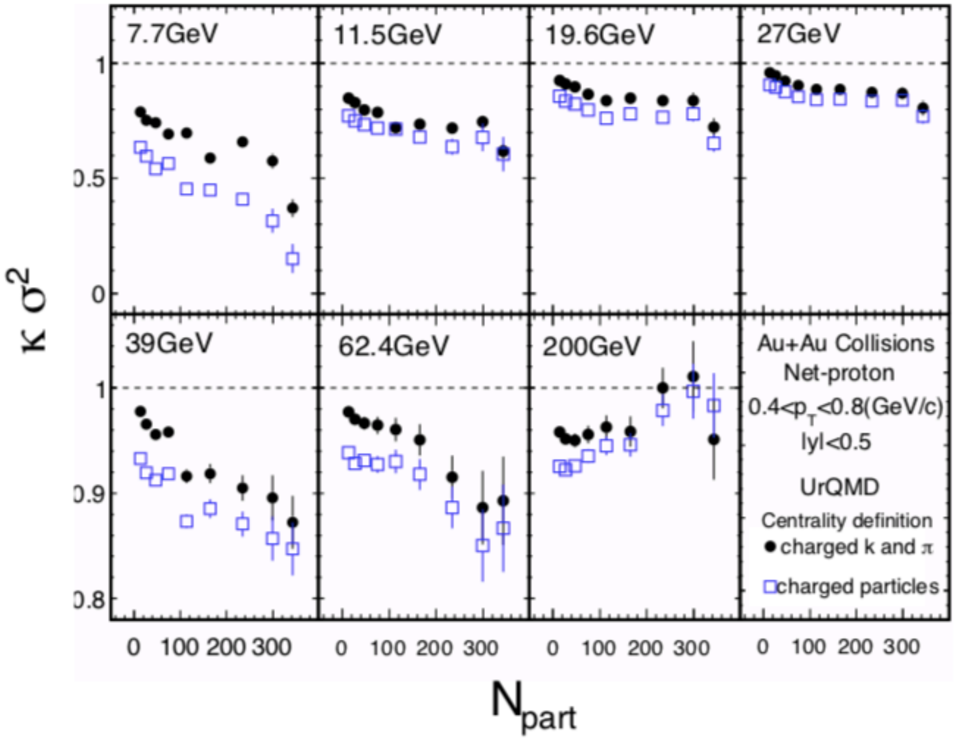
- ✓ The Event Plane Detector (EPD) was installed in 2018 in forward rapidity region $(2.1 < |\eta| < 5.1)$.
- ✓ When collision centrality is determined by EPD, autocorrelation effect is thought to be reduced because of η-gap between EPD and TPC.

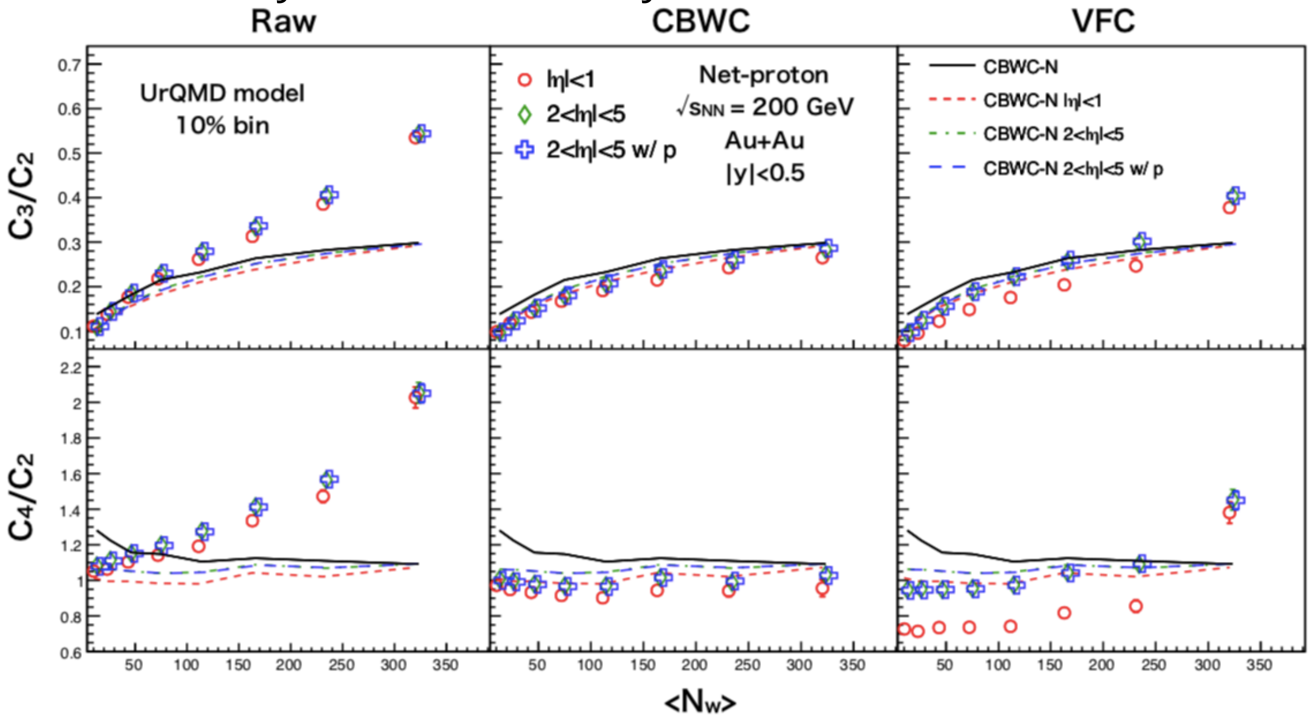


Autocorrelation Effect

✓According to previous UrQMD studies, auto-correlation effect is considered to make fluctuations smaller.

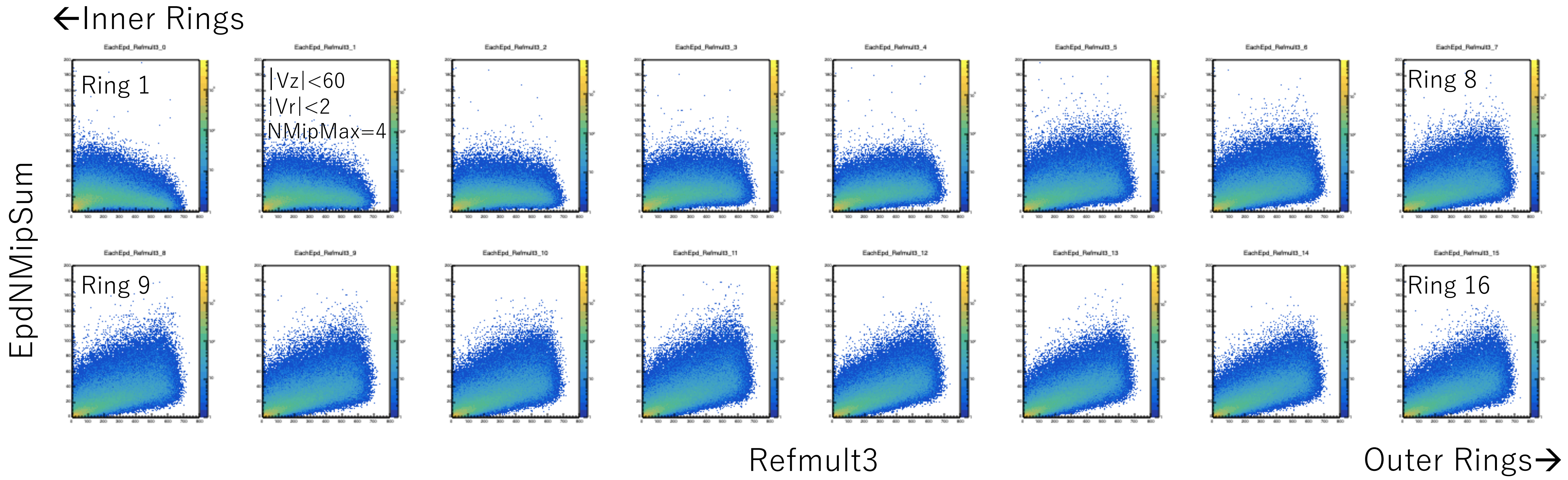
- Fluctuations with centrality determined by multiplicity including protons are below the results by excluding protons.
- When centrality is determined by particles in forward rapidity region (corresponds to EPD), fluctuations are larger than results by TPC centrality.





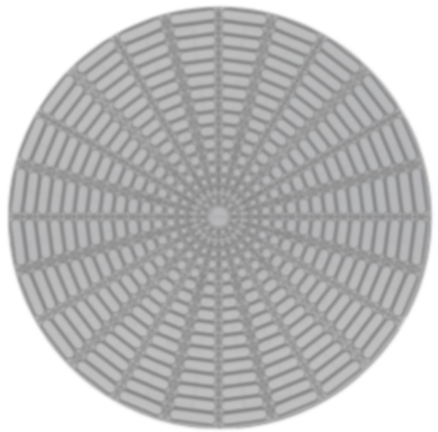
X.Luo et al. , J. Phys. G: Nucl. Part. Phys. 40 105104 (2013)
T.Sugiura et al., arXiv:1903.02314(2019)

Performance of EPD in Au+Au 27 GeV



✓Although positive correlation between EPD and TPC appeared in outer rings, anticorrelation was seen in inner rings because of spectators.

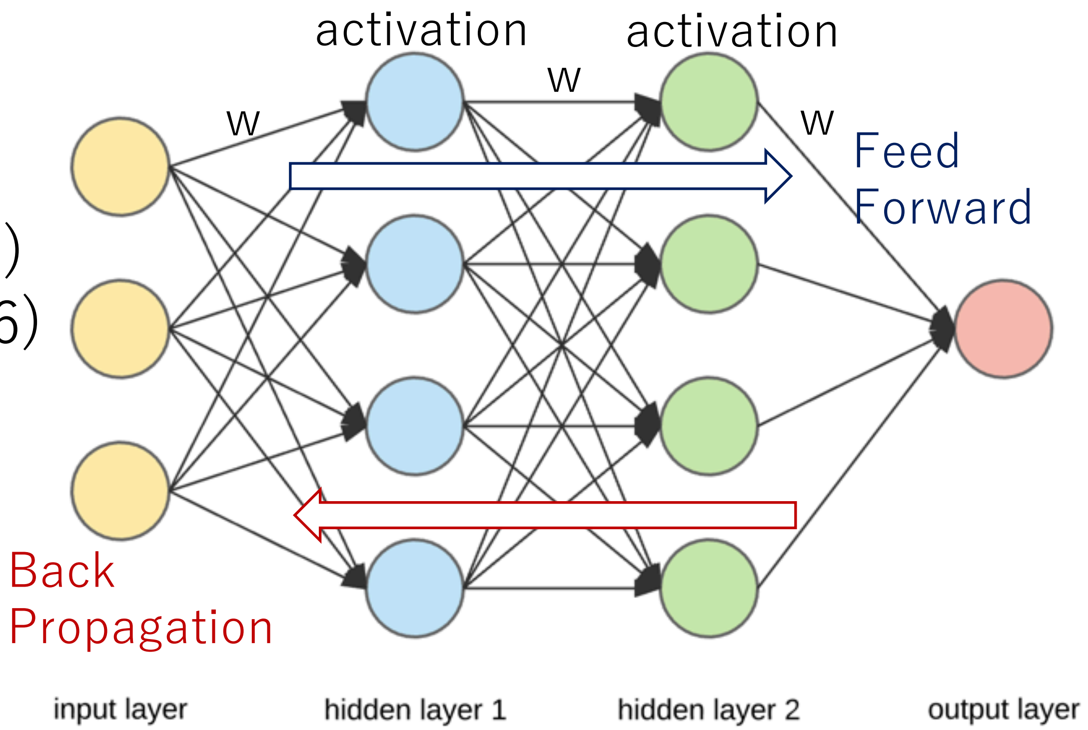
✓When centrality is determined by EPD, less selfcorrelation effect is expected.



Neural Network Approach to Centrality Determination

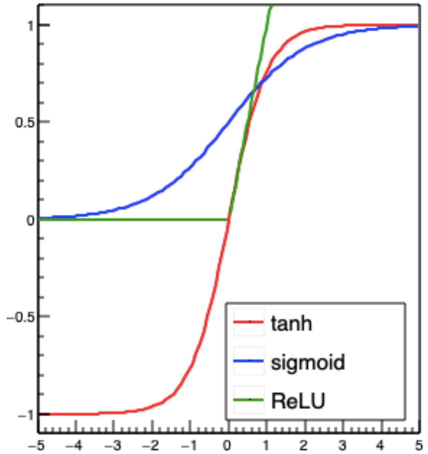
✓Artificial Neural Network is a method of Machine Learning, inspired by biological neural network. It "learns" by updating weights and biases between each neuron.

EastEpdNMip (Ring;1-16)
WestEpdNMip (Ring;1-16)
Vertex position
→33 input

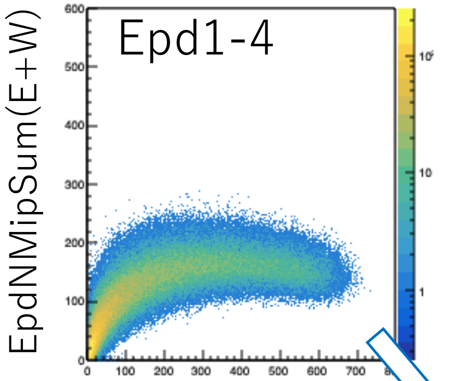


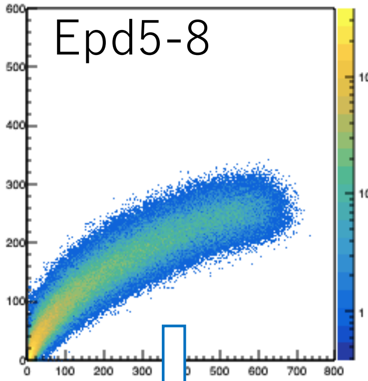
Refmult3
(previous centrality)

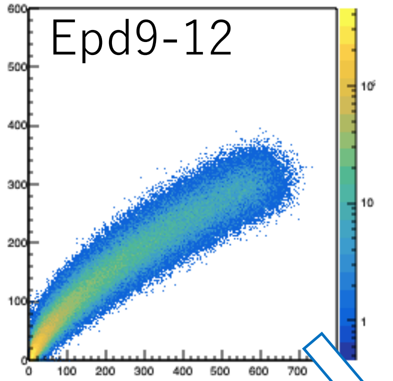
Activation func.

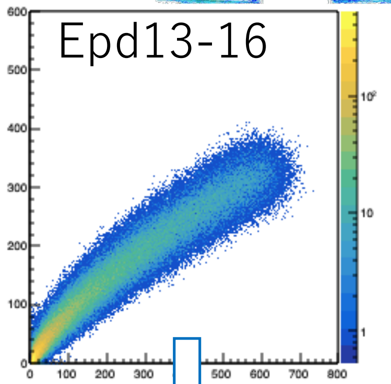


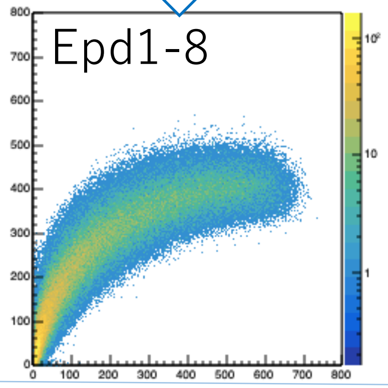
Prospective for Centrality determination by EPD

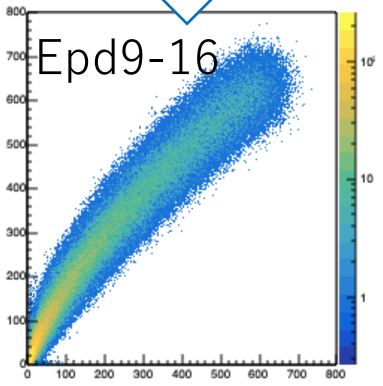




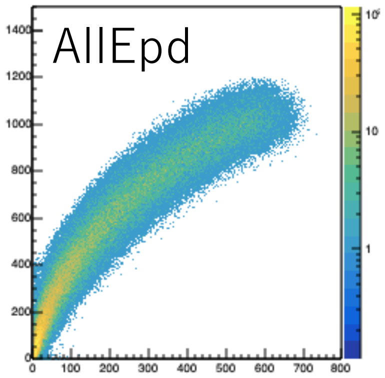






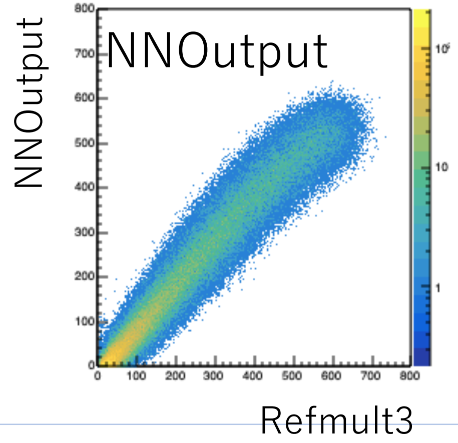


Expected linear correlation is broken in inner rings due to spectators.



Neural Network

Recovering linear correlation between NMip and Refmult3!



Summary & Outlook

- <u>Summary</u>
  - ✓Net-proton cumulants up to 4th-order at Au+Au 54.4 GeV was presented.
  - ✓Perspective for centrality determination using EPD was shown.

- <u>Outlook</u>
  - ☐Neural network approach will be used to determine collision centrality with EPD NMip.
  - ☐Fluctuations of conserved quantities will be measured with new centrality determination, and compared to the previous results.

Back Up

Efficiency Correction

- Efficiency correction for cumulants are applied with track-by-track method.

$$\langle Q \rangle_c = \langle q_{(1,1)} \rangle_c,$$

$$\langle Q^2 \rangle_c = \langle q_{(1,1)}^2 \rangle_c + \langle q_{(2,1)} \rangle_c - \langle q_{(2,2)} \rangle_c,$$

$$\langle Q^3 \rangle_c = \langle q_{(1,1)}^3 \rangle_c + 3\langle q_{(1,1)} q_{(2,1)} \rangle_c - 3\langle q_{(1,1)} q_{(2,2)} \rangle_c + \langle q_{(3,1)} \rangle_c - 3\langle q_{(3,2)} \rangle_c + 2\langle q_{(3,3)} \rangle_c,$$

$$\begin{aligned}\langle Q^4 \rangle_c = {} & \langle q_{(1,1)}^4 \rangle_c + 6\langle q_{(1,1)}^2 q_{(2,1)} \rangle_c - 6\langle q_{(1,1)}^2 q_{(2,2)} \rangle_c + 4\langle q_{(1,1)} q_{(3,1)} \rangle_c + 3\langle q_{(2,1)}^2 \rangle_c \\ & +3\langle q_{(2,2)}^2 \rangle_c - 12\langle q_{(1,1)} q_{(3,2)} \rangle_c + 8\langle q_{(1,1)} q_{(3,3)} \rangle_c - 6\langle q_{(2,1)} q_{(2,2)} \rangle_c \\ & +\langle q_{(4,1)} \rangle_c - 7\langle q_{(4,2)} \rangle_c + 12\langle q_{(4,3)} \rangle_c - 6\langle q_{(4,4)} \rangle_c,\end{aligned}$$

- q(r,s) is defined by

$$q_{(r,s)} = \sum_{j=1}^{n_{\mathrm{tot}}} \frac{a_j^r}{\varepsilon_j^s},$$

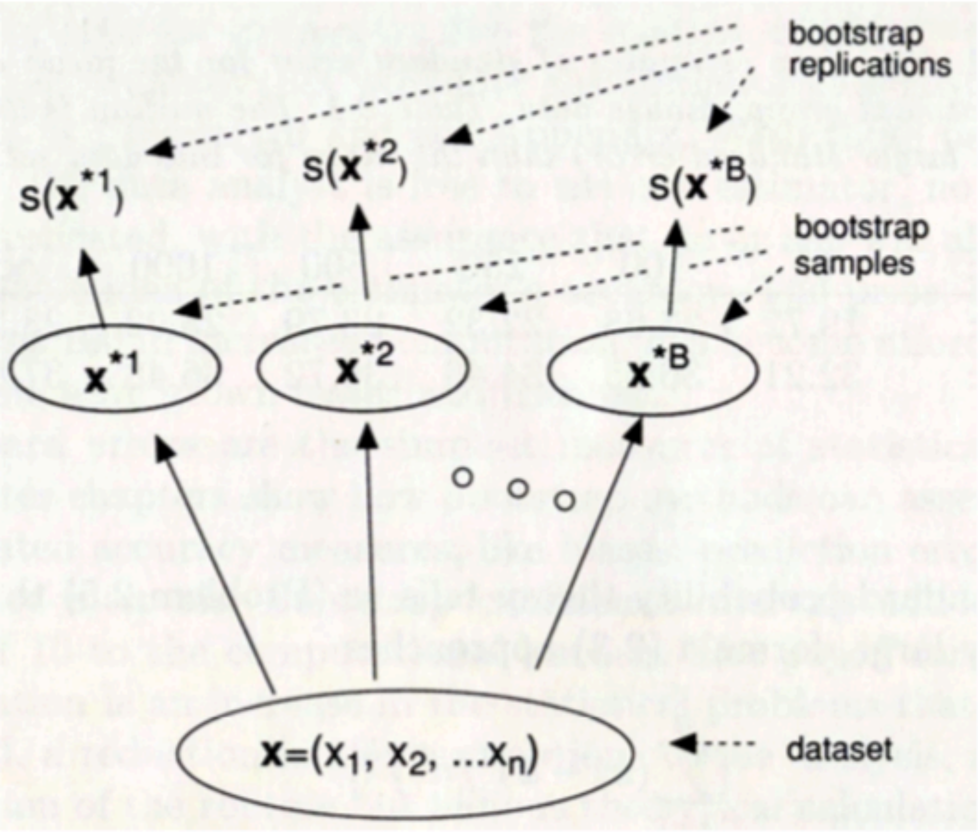
From X.Luo and T.Nonaka, "Efficiency correction for cumulants of multiplicity distributions based on track-by-track efficiency", Phys. Rev. C 99, 044917 (2019)

Estimation of Uncertainties

✓In order to estimate systematic errors, some cuts below were varied.

- dca
- Track quality (nHitsFit, nHitDedx)
- Particle Identification
- Tracking efficiecy

✓Statistical errors were estimated by Bootstrap method.



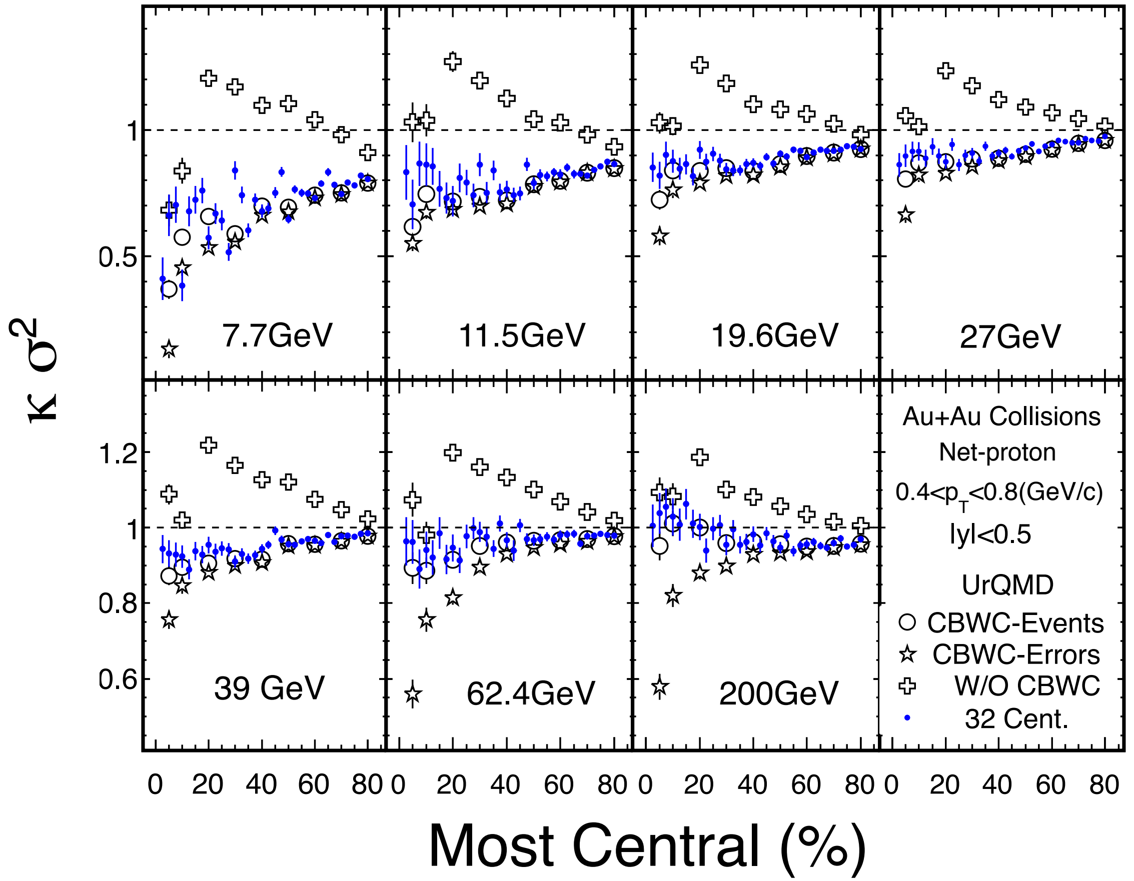
From B. Efron,R. Tibshirani, "An introduction to the bootstrap", Chapman Hall (1993)

Centrality Bin Width Correction

- ✓In order to reduce Volume Fluctuation Effect (VF), Centrality Bin Width Correction has been applied in fluctuation measurements.

$$C_n = \frac{\sum_r n_r C_r}{\sum_r n_r} = \sum_r w_r C_{(n,r)}$$

- ✓VF makes fluctuations larger according to UrQMD model studies.



From X.Luo et al. ,J. Phys. G: Nucl. Part. Phys. 40 105104 (2013)

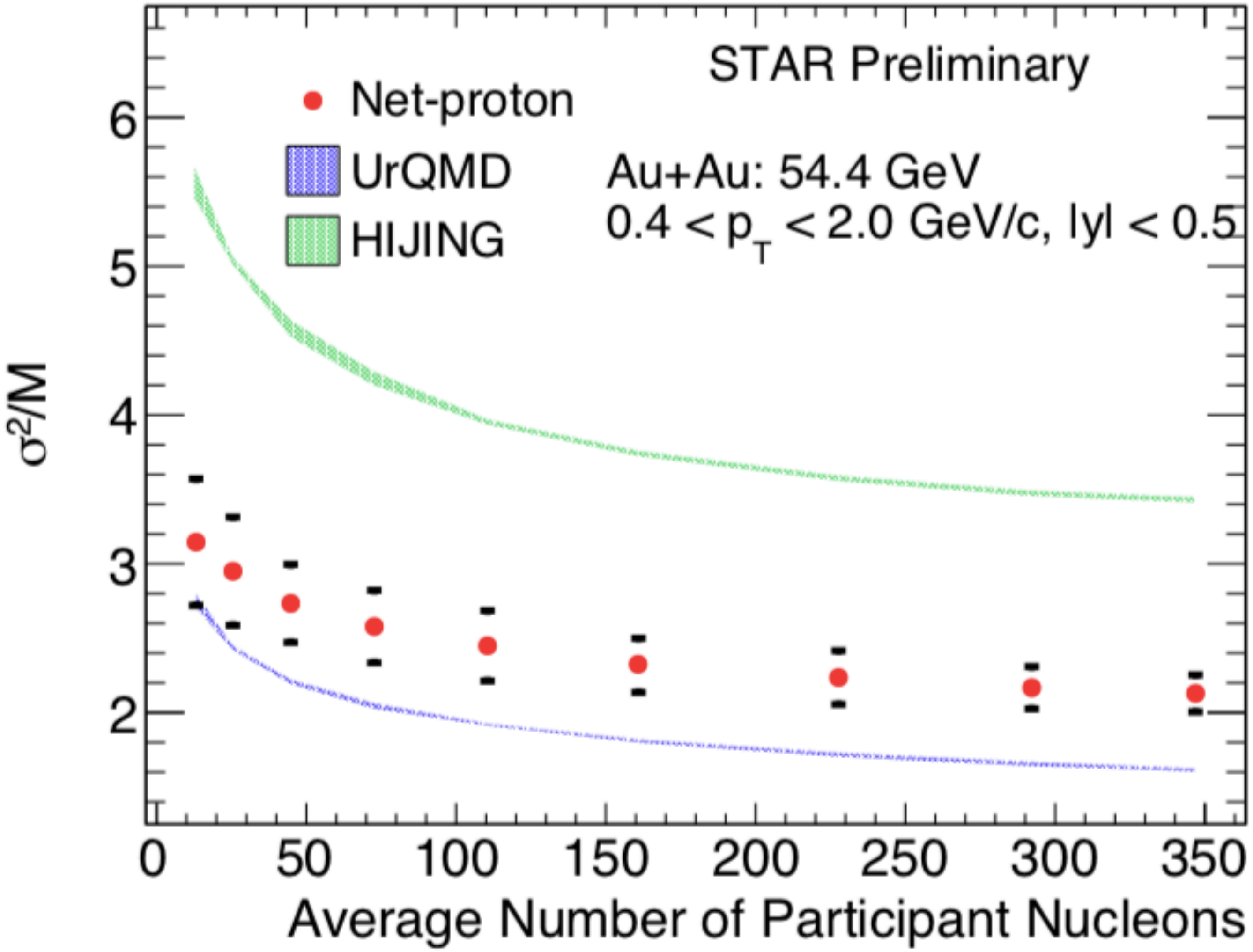
BES-I Summary/Plan for BES-II

$\sqrt{s_{NN}}$	Statistics(M)	Year
7.7	~3	2010
11.5	~6.6	2010
14.5	~10	2014
19.6	~15	2011
27	~32	2011
39	~86	2010
62.4	~45	2010
200	~238	2010

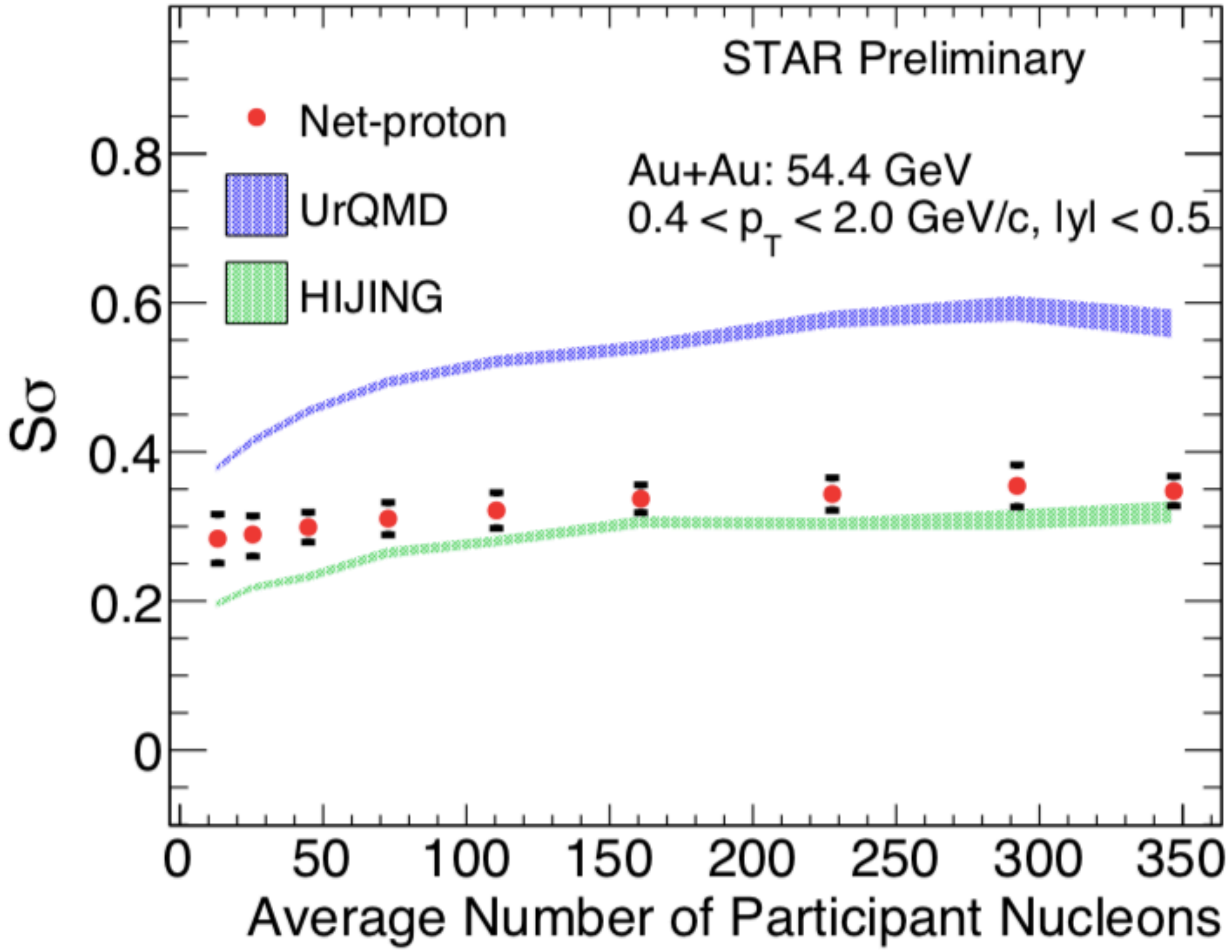
Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time	Number Events
9.8	19.6	205	4.5 weeks	400M
7.3	14.5	260	5.5 weeks	300M
5.75	11.5	315	5 weeks	230M
4.55	9.1	370	9.5 weeks	160M
3.85	7.7	420	12 weeks	100M
31.2	7.7 (FXT)	420	2 days	100M
19.5	6.2 (FXT)	487	2 days	100M
13.5	5.2 (FXT)	541	2 days	100M
9.8	4.5 (FXT)	589	2 days	100M
7.3	3.9 (FXT)	633	2 days	100M
5.75	3.5 (FXT)	666	2 days	100M
4.55	3.2 (FXT)	699	2 days	100M
3.85	3.0 (FXT)	721	2 days	100M

Run 19 Run 20 Run 21

Centrality dependence of Cumulant ratios



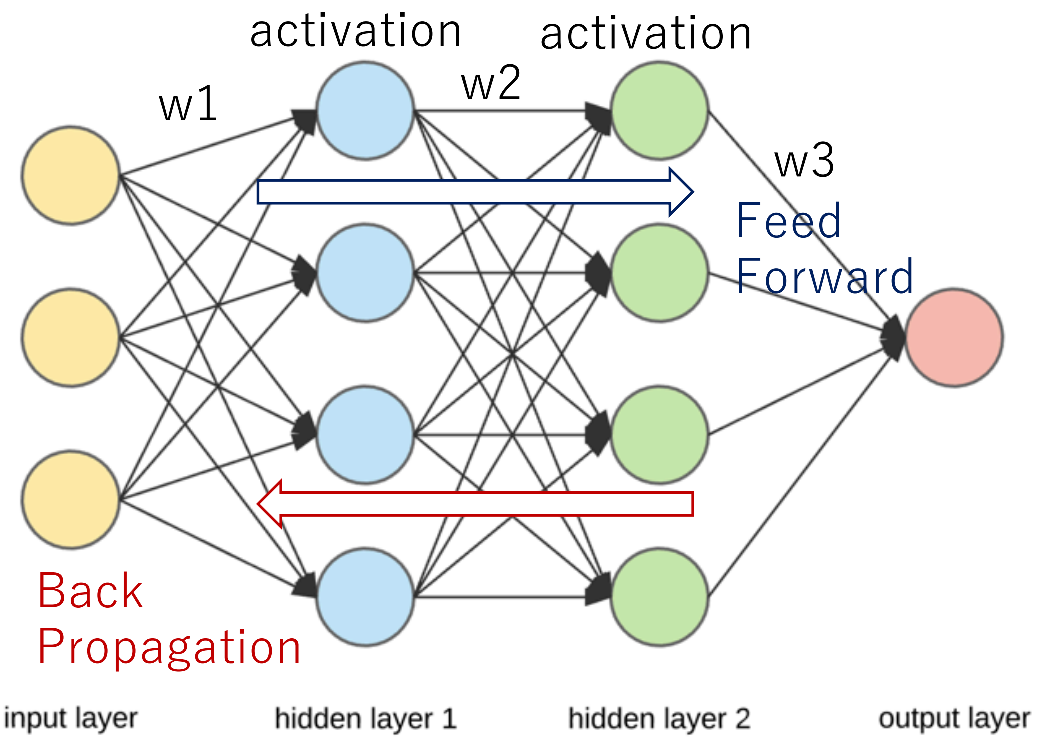
Centrality dependence of Cumulant ratios



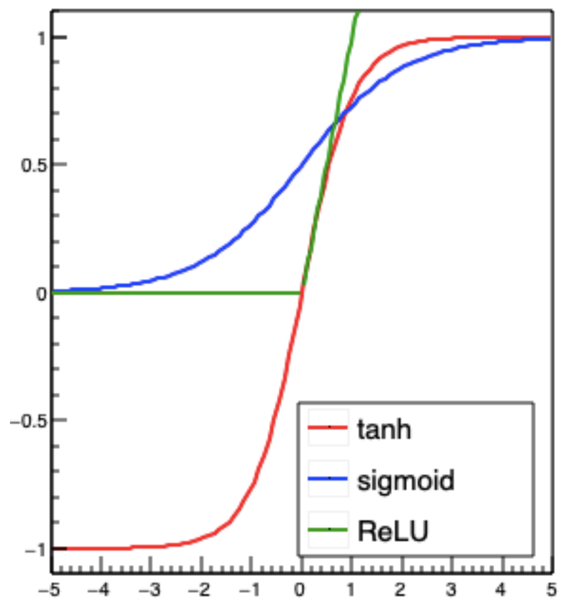
Neural Network

✓Artificial Neural Network is a method of Machine Learning, inspired by biological neural network. It “learns” by updating weights and biases between each neuron.

✓Can we predict collision centrality by EPD information using NN?



activation func.



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✓The Event Plane Detector(EPD) was installed in 2018 in forward rapidity region($2.1 < |\eta| < 5.1$) at STAR detectors.

✓When centrality is determined by EPD, auto-correlation effect is thought to be reduced because of η-gap between EPD and TPC($|\eta| < 1.0$).

✓Previous fluctuation results are possibly biased by the auto-correlation effect.