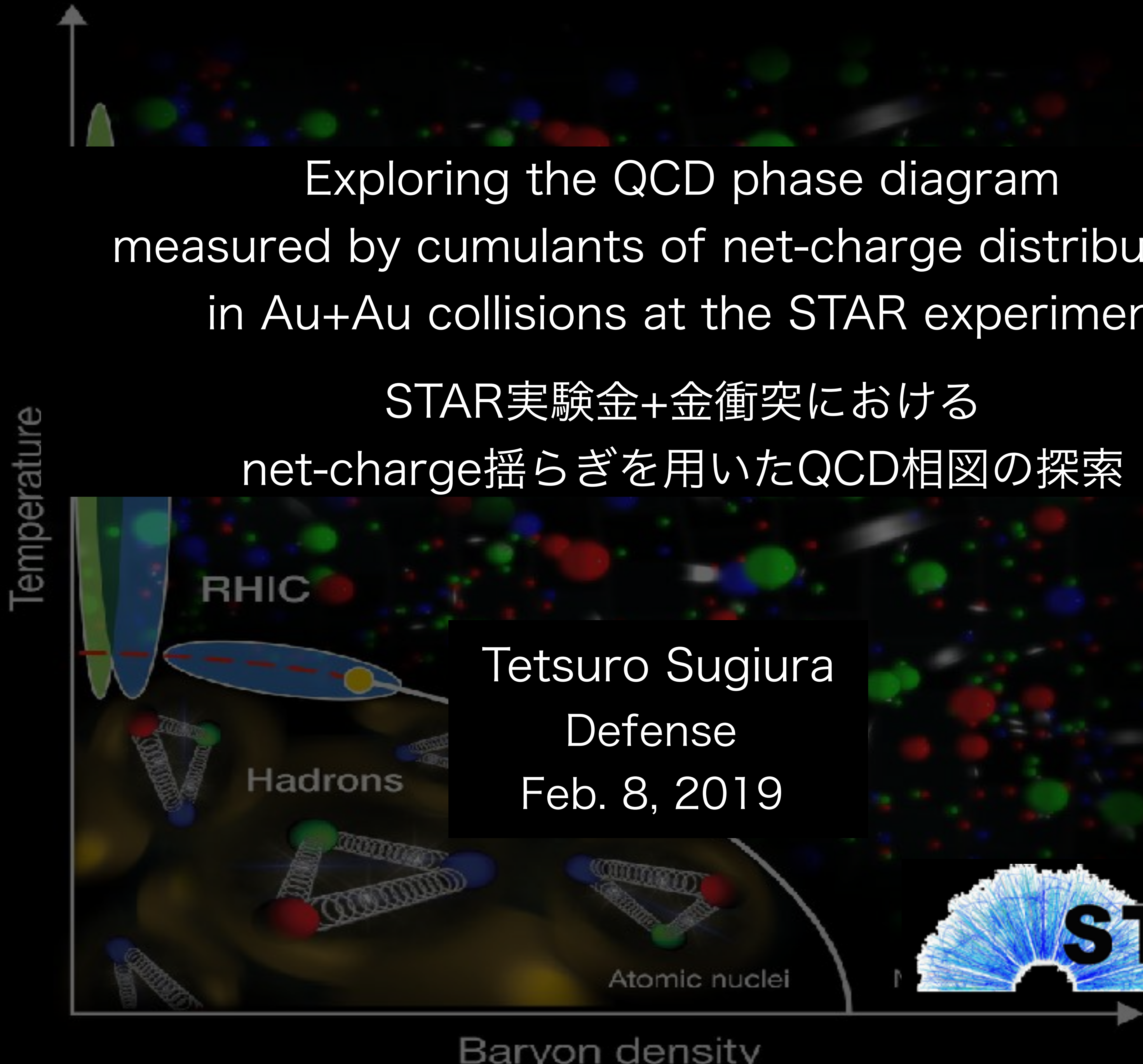
Exploring the QCD phase diagram measured by cumulants of net-charge distributions in Au+Au collisions at the STAR experiment

STAR実験金+金衝突における net-charge揺らぎを用いたQCD相図の探索

Tetsuro Sugiura

Defense

Feb. 8, 2019



My activity

✦ **2014 - 2015** Master course ✦ **2016 - 2019** Ph.D course

Conference and workshop : 10 talk and 2 poster presentations

- CiRfSE workshop, @University of Tsukuba — Mar. 2015 **talk**, Jan. 2016 **talk**
- JPS @University of Miyazaki, — Sep. 2016 **talk**
- ★ QM2017 @Chicago, — Feb. 2017 **poster**
- JPS @Osaka University, — Mar. 2017 **talk**
- JPS @Utsunomiya University, — Sep. 2017 **talk**
- TCHoU workshop, — Mar. 2018 **talk**
- ★ QM2018 @Venice, — May. 2018 **poster**
- HIP/HIC @ Nagoya University — Jun. 2018 **talk**
- ★ APS/JPS joint meeting @Hawaii, — Oct. 2018 **talk**
- ★ QNP2018 @Tsukuba, — Nov. 2018 **talk**
  - arXiv:1901.03639
- TCHoU workshop, — Feb. 2019 **talk**

Blue: $\Delta\eta$ dependence analysis
Red: C_6 net-charge analysis
Green: Correction method
★ **International conference**

Master thesis:

- "$\Delta\eta$ dependence of net-charge fluctuations in Au+Au collisions at RHIC-STAR experiment"

Teaching experience

Summer challenge TA @KEK
- (M2, D1, D2)

Paper: 1 paper contributed as 2nd author

T. Nonaka, <u>T. Sugiura</u>, S. Esumi, H. Masui, X. Luo
"Importance of separated efficiencies between positively and negatively charged particles for cumulant calculations" PRC. 94. 034909, Sep. 2016

STAR shift taking

: (D1, D2)

Outline

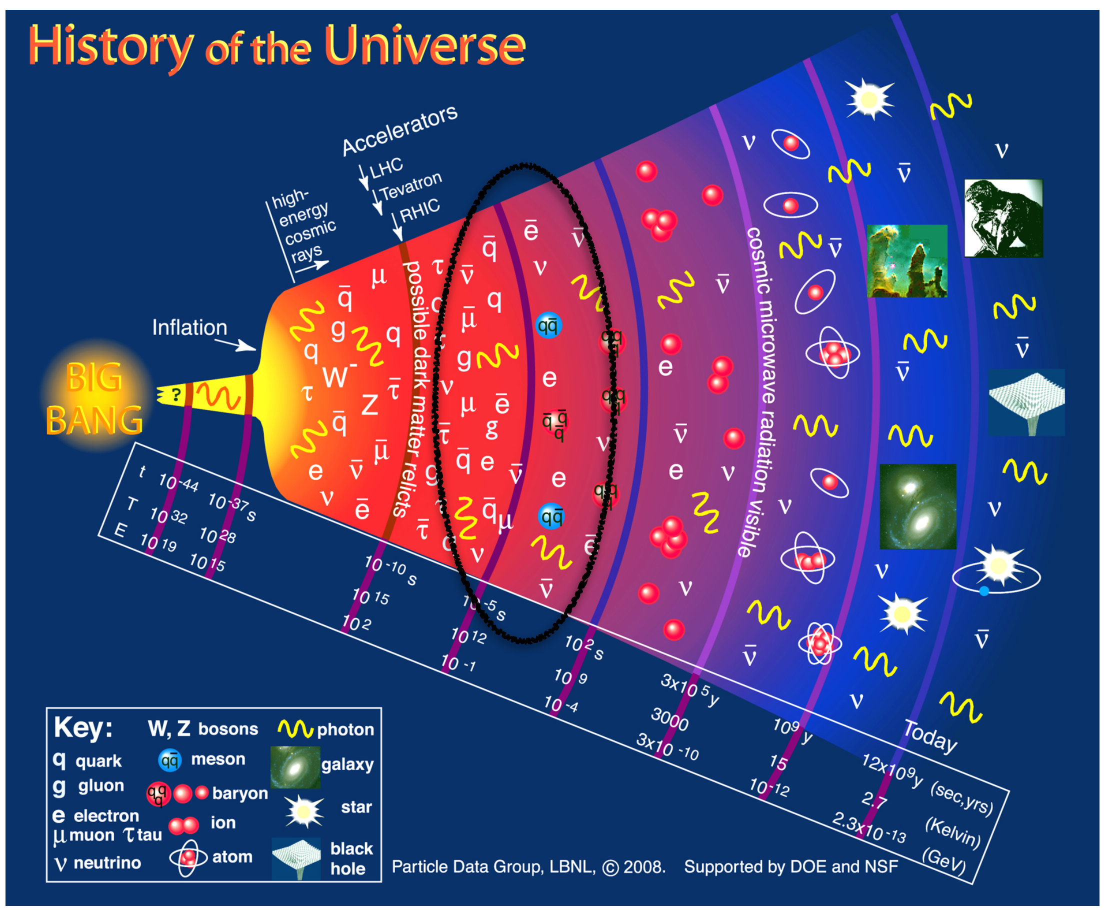
- Introduction
- Motivation
  - Sixth-order cumulants analysis (Experiment)
  - $\Delta\eta$ dependende of net-charge (Experiment)
  - Volume fluctuation study (Simulation)
- Analysis mothod (Experimant)
- Results (Experiment)

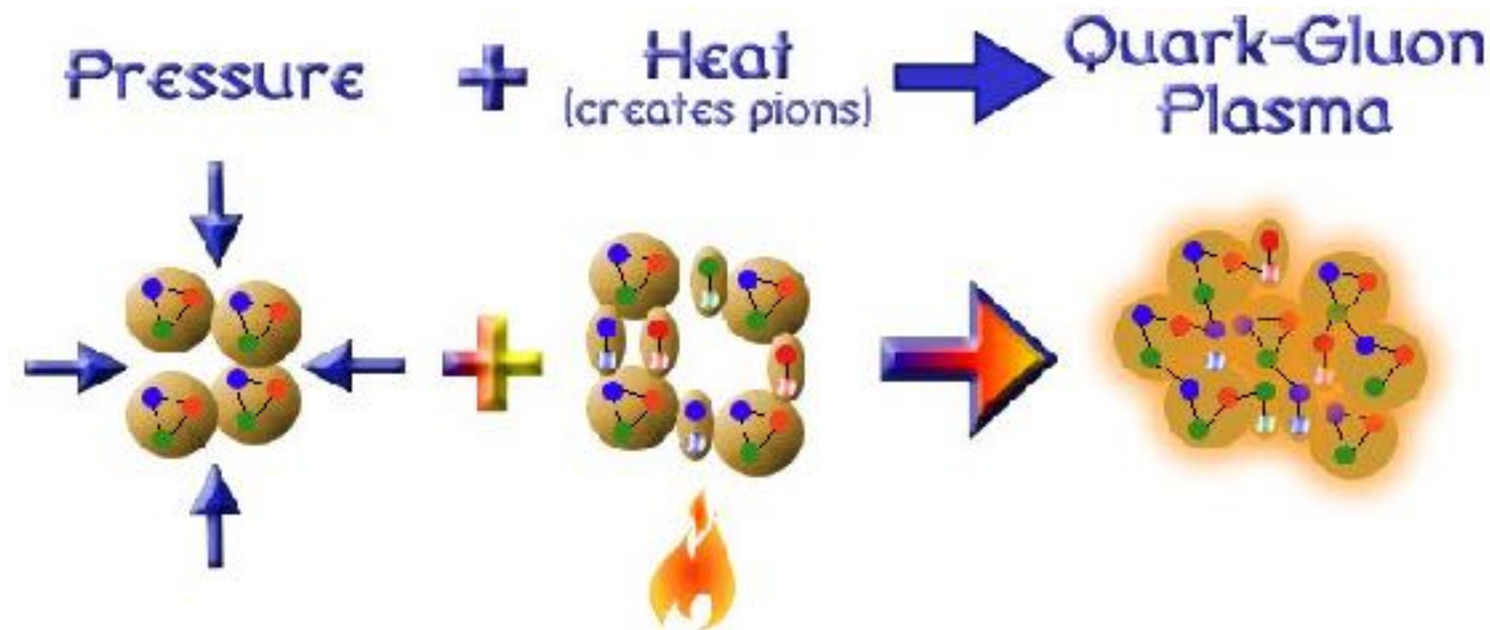
- Analysis mothod (Simulation)
- Results (Simulation)
- Summary and Outlook

Quark-Gluon Plasma (QGP)

- Quarks and gluons are confined inside of nucleons. **(Color confinement)**
- Interactions are very weak inside of nucleons. **(Asymptotic freedom)**

→
- Quarks are de-confined under high density or high temperature. **(Quark-Gluon Plasma ; QGP)**

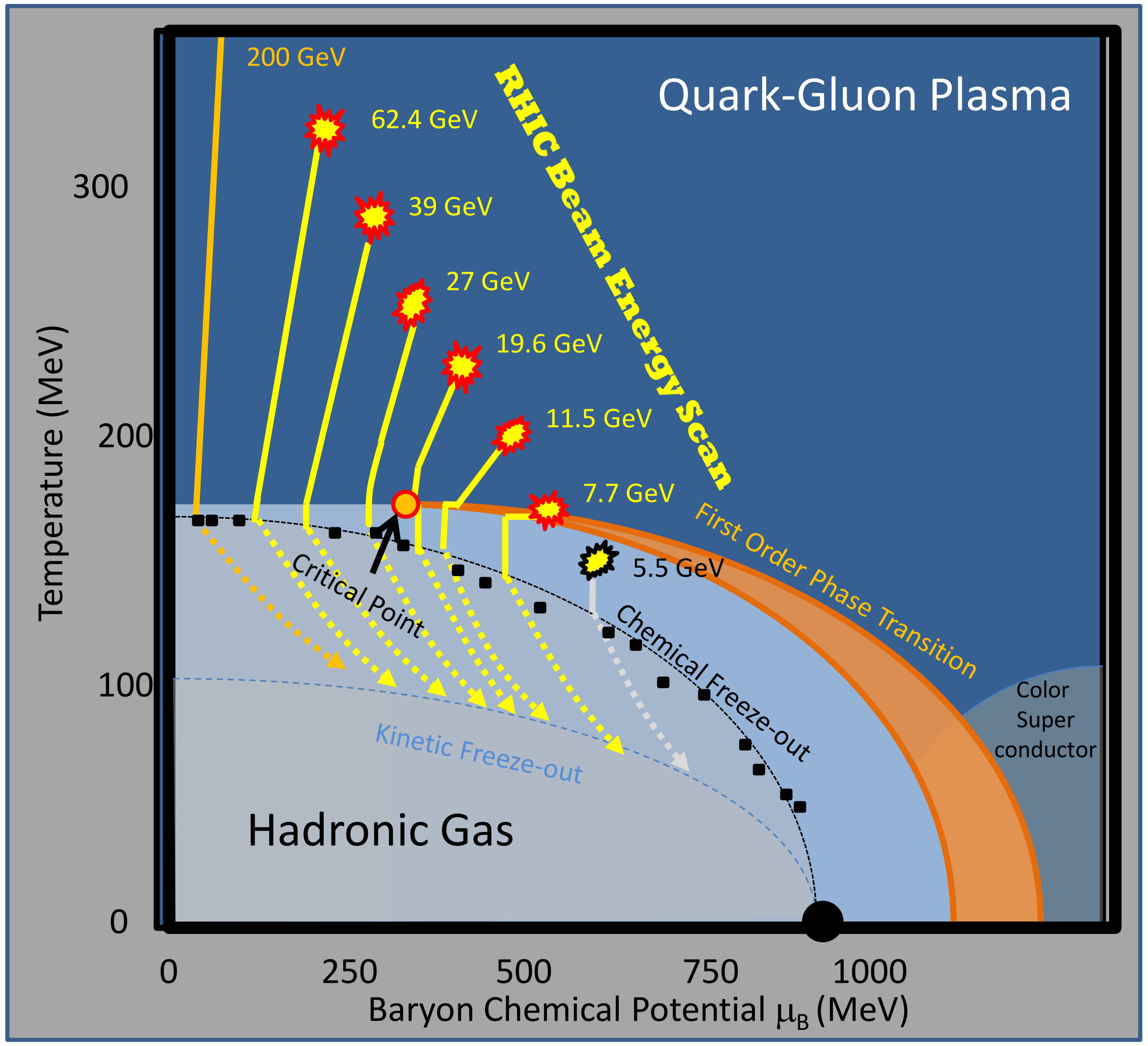




T_C~160 MeV

- QGP is considered to be exist in early universe, μs after big bang.

Phase transition and Beam Energy Scan



- **Cross over transition around μ_B=0** from Lattice QCD but there is no experimental evidence.
- Location of critical point is unknown.

Detail structure of QCD diagram should be discovered experimentally

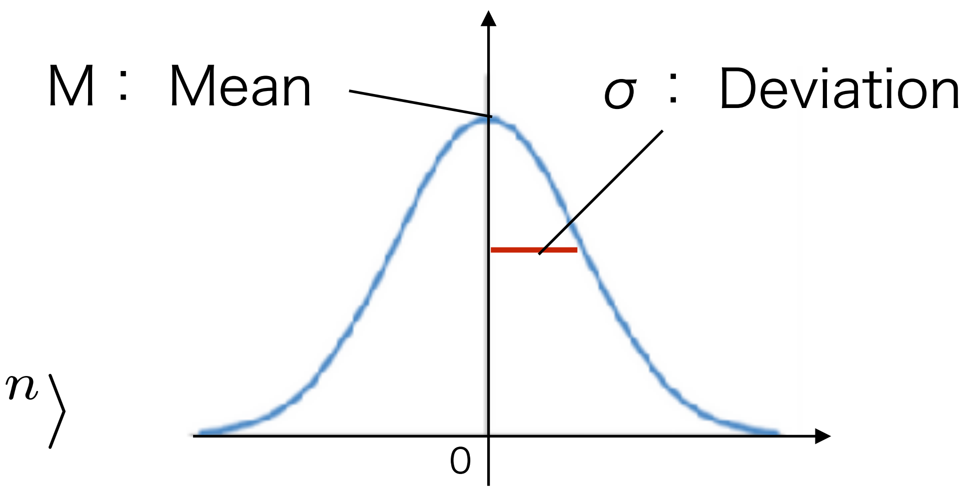
Beam Energy Scan I (BES-I) 2010-2014

- Varying the center of mass energy, $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4 and 200 GeV in Au+Au collisions.
- $\sqrt{s_{NN}}$ = 54 GeV in Au+Au collision data was taken in 2017.
- BES-II will start from 2019.

→ Event by event fluctuations are considered as one of the powerful tool to discover the phase diagram.

Event-by-event fluctuations

Net-charge : $N_+ - N_-$



- nth-order moment is defined by

$$\langle m^n \rangle = \sum_m m^n P(m)\,, \quad \langle \delta m^n \rangle = \langle (m - \langle m \rangle)^n \rangle$$

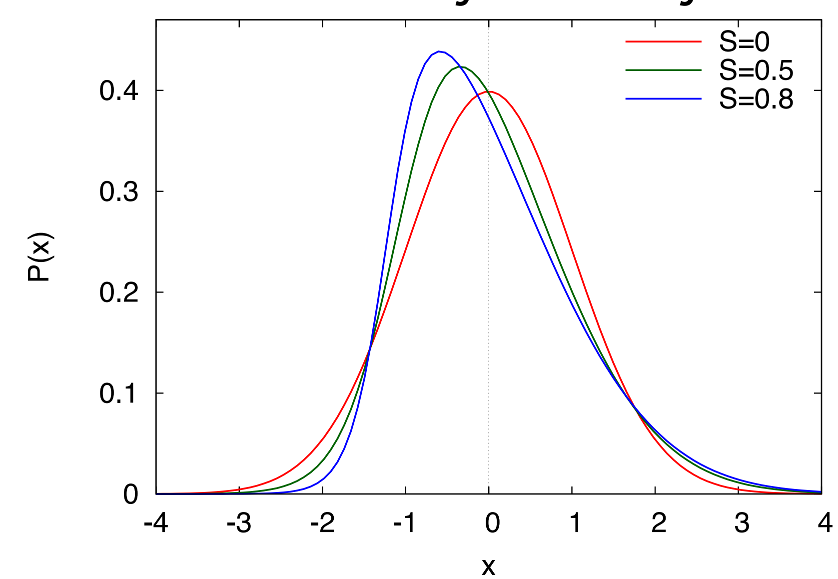
- Cumulants can be written by moments

Cumulants ⟷ Moments

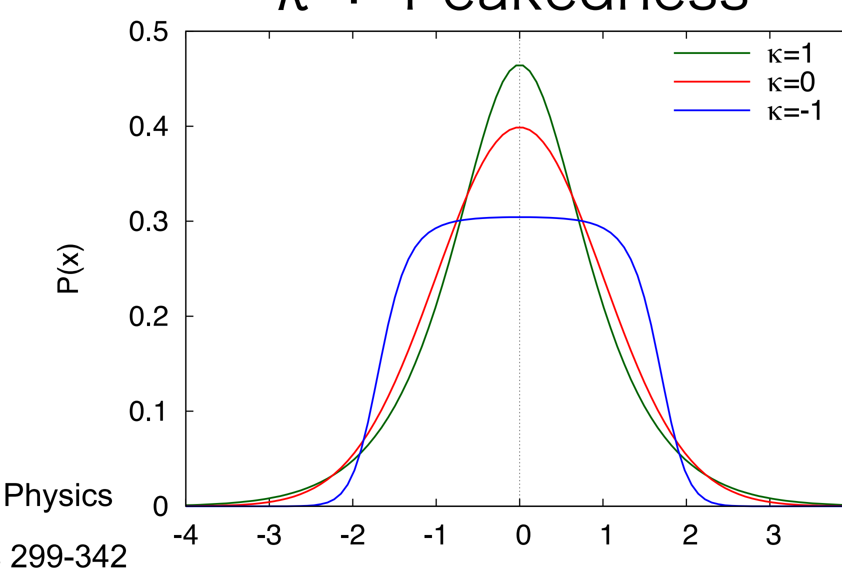
$$C_1 = \langle m \rangle$$
$$C_2 = \langle \delta m^2 \rangle$$
$$C_3 = \langle \delta m^3 \rangle$$
$$C_4 = \langle \delta m^4 \rangle - \langle \delta m^3 \rangle$$

$$M = C_1$$
$$\sigma^2 = C_2$$
$$S = \frac{C_3}{(C_2)^{3/2}}$$
$$\kappa = \frac{C_4}{(C_2)^2}$$

S : Asymmetry



κ : Peakedness



- Cumulants are proportional to the volume (**Additivity**)

Progress in Particle and Nuclear Physics

Volume 90, September 2016, Pages 299-342

Cumulant ratios and Critical behaviour

Cumulant
(can be measured experimentally)

$$C_n = (-T)^{n-1}\frac{\partial^n \Omega}{\partial \mu^n} \equiv \chi_n V$$

Susceptibility
(can NOT be measured experimentally)

- Cumulant ratios **can be directly compared to the ratio of susceptibilities**.
- By measuring the **cumulant ratios**, **effect from the volume can be canceled**.

$$S\sigma = \frac{C_3}{C_2} = \frac{\chi_3}{\chi_2}$$

$$\kappa\sigma^2 = \frac{C_4}{C_2} = \frac{\chi_4}{\chi_2}$$

- Higher order cumulants are more sensitive to the signal from the critical point.
- These relations are only valid for cumulants of **conserved quantities**.

$$C_2 \approx \xi^2 \qquad C_5 \approx \xi^{9.5}$$

$$C_3 \approx \xi^{4.5} \qquad C_6 \approx \xi^{12}$$

$$C_4 \approx \xi^7$$

ξ : Correlation length

Statistical baseline (Skellam distributions)

- If distribution of N_+ and N_- follow the Poisson distributions, net-charge distribution follow the **Skellam distribution.**

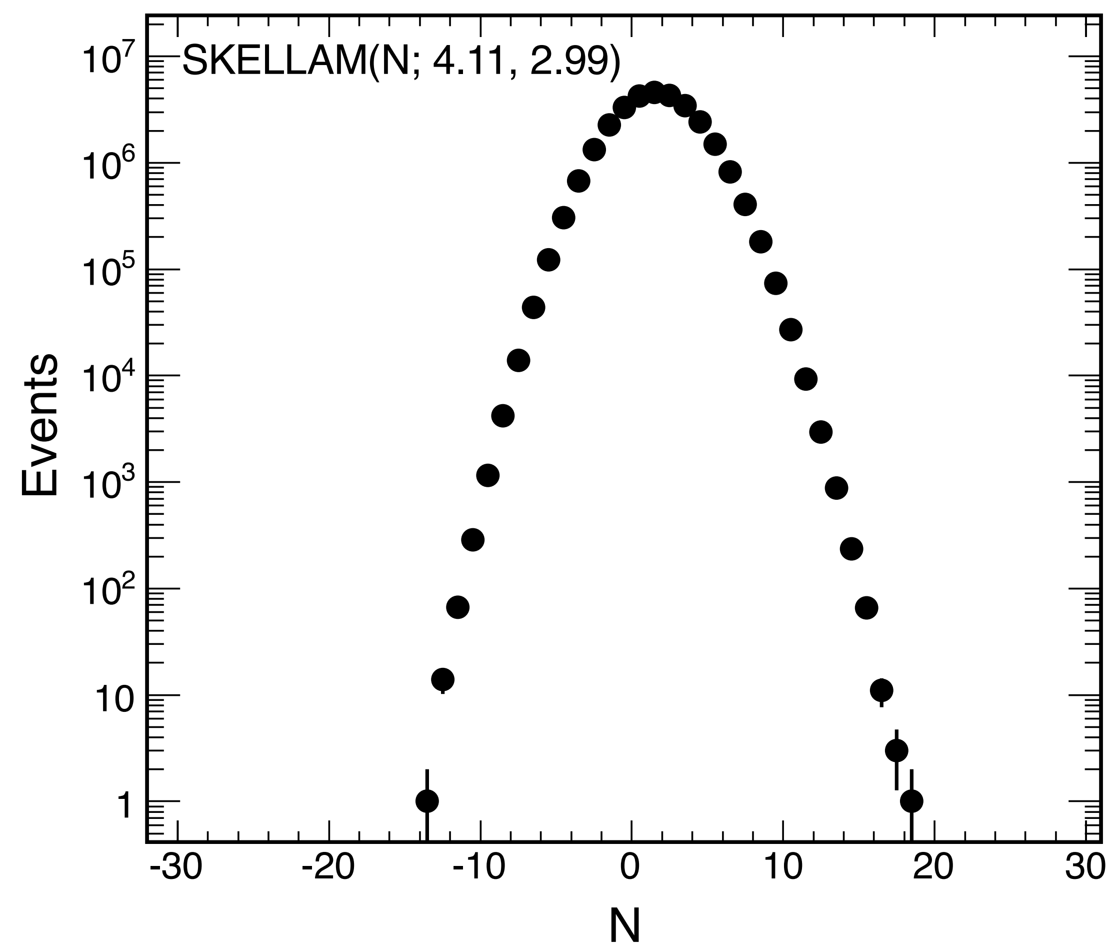
$$C_n = \lambda_1 + (-1)^n \lambda_2$$

λ_1 : Poisson parameter of N_+ distribution

λ_2 : Poisson parameter of N_- distribution

$$\frac{C_{2n}}{C_{2m}} = \frac{C_{2n+1}}{C_{2m+1}} = 1$$

$$\frac{C_{2n+1}}{C_{2m}} = \frac{\lambda_1 - \lambda_2}{\lambda_1 + \lambda_2}$$



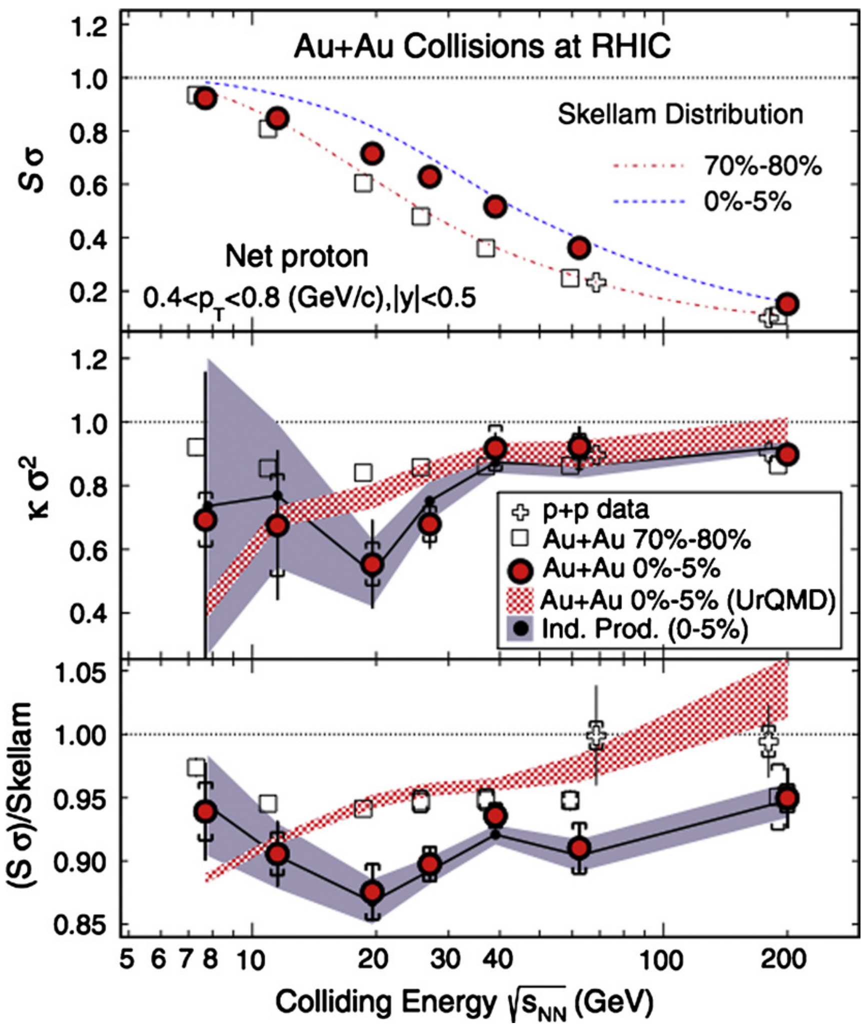
For example

$$\frac{C_6}{C_2} = \frac{C_4}{C_2} = \boxed{1}$$

This values can be used as a statistical baseline.

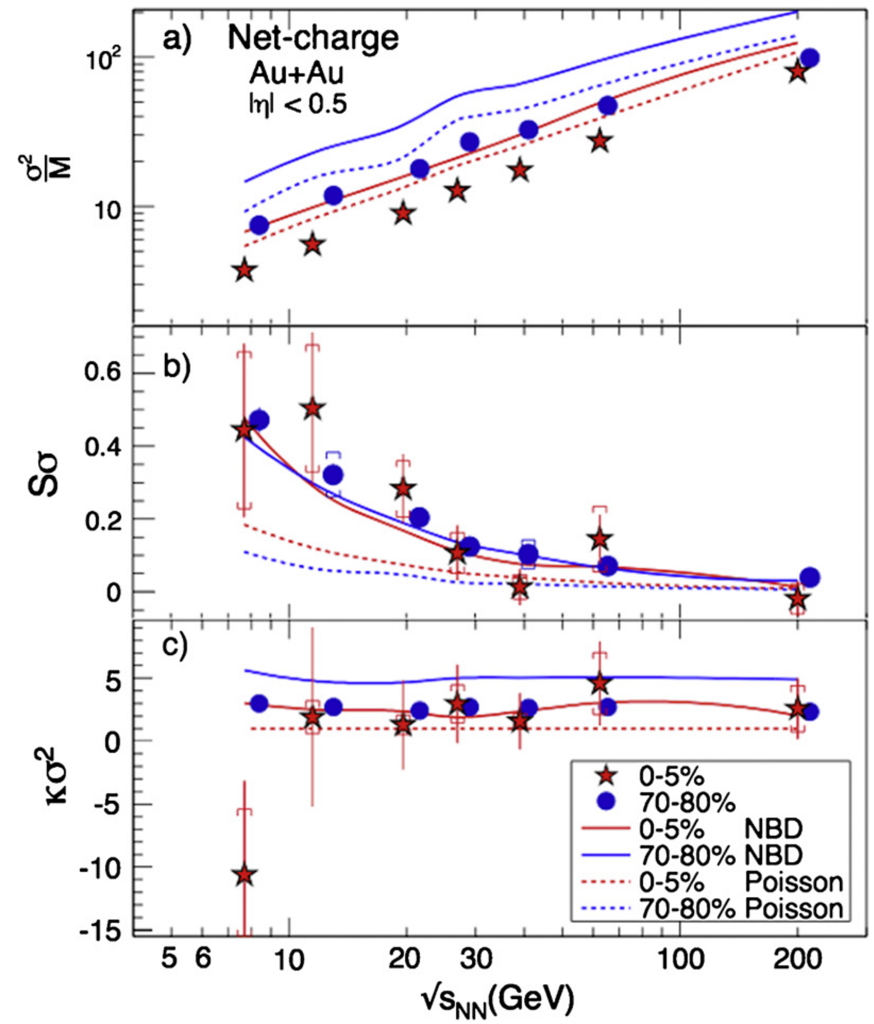
Published results

Net-proton



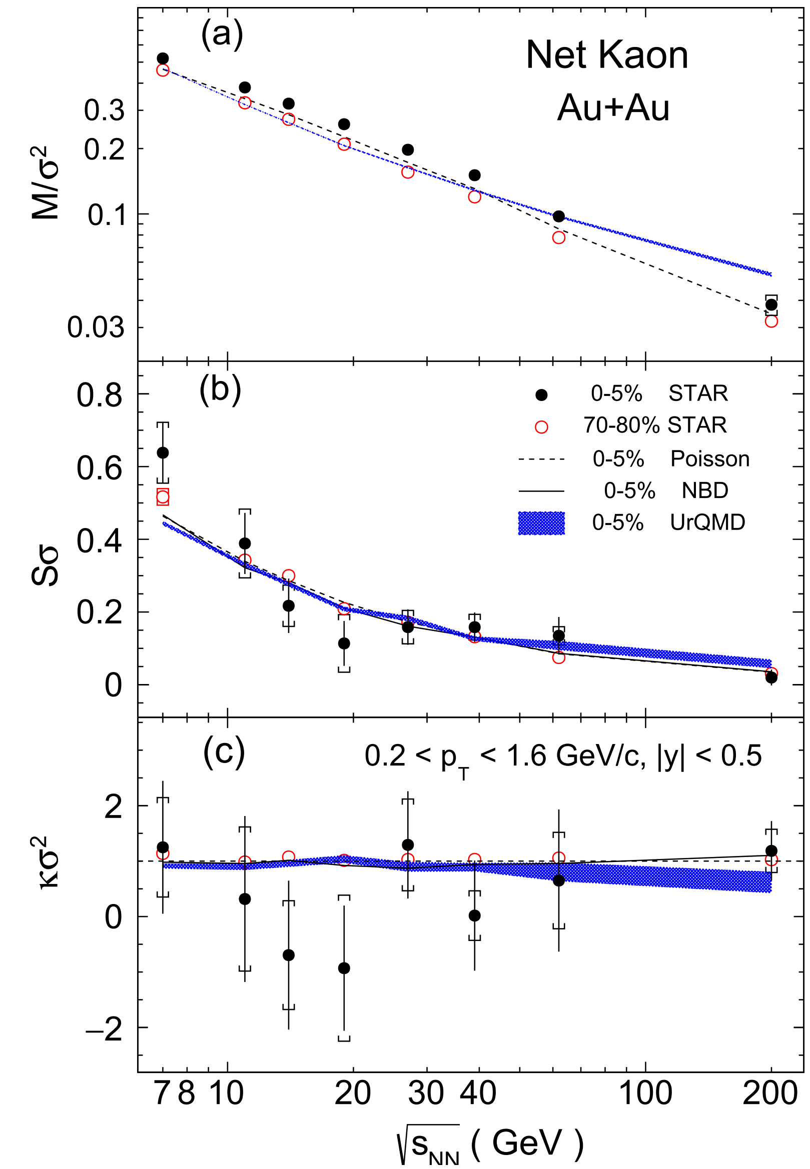
L. Adamczyk *et al.* (STAR Collaboration)
Phys. Rev. Lett. 112, 032302 (2014)

Net-charge



L. Adamczyk *et al.* (STAR Collaboration)
Phys. Rev. Lett. 113, 092301(2014)

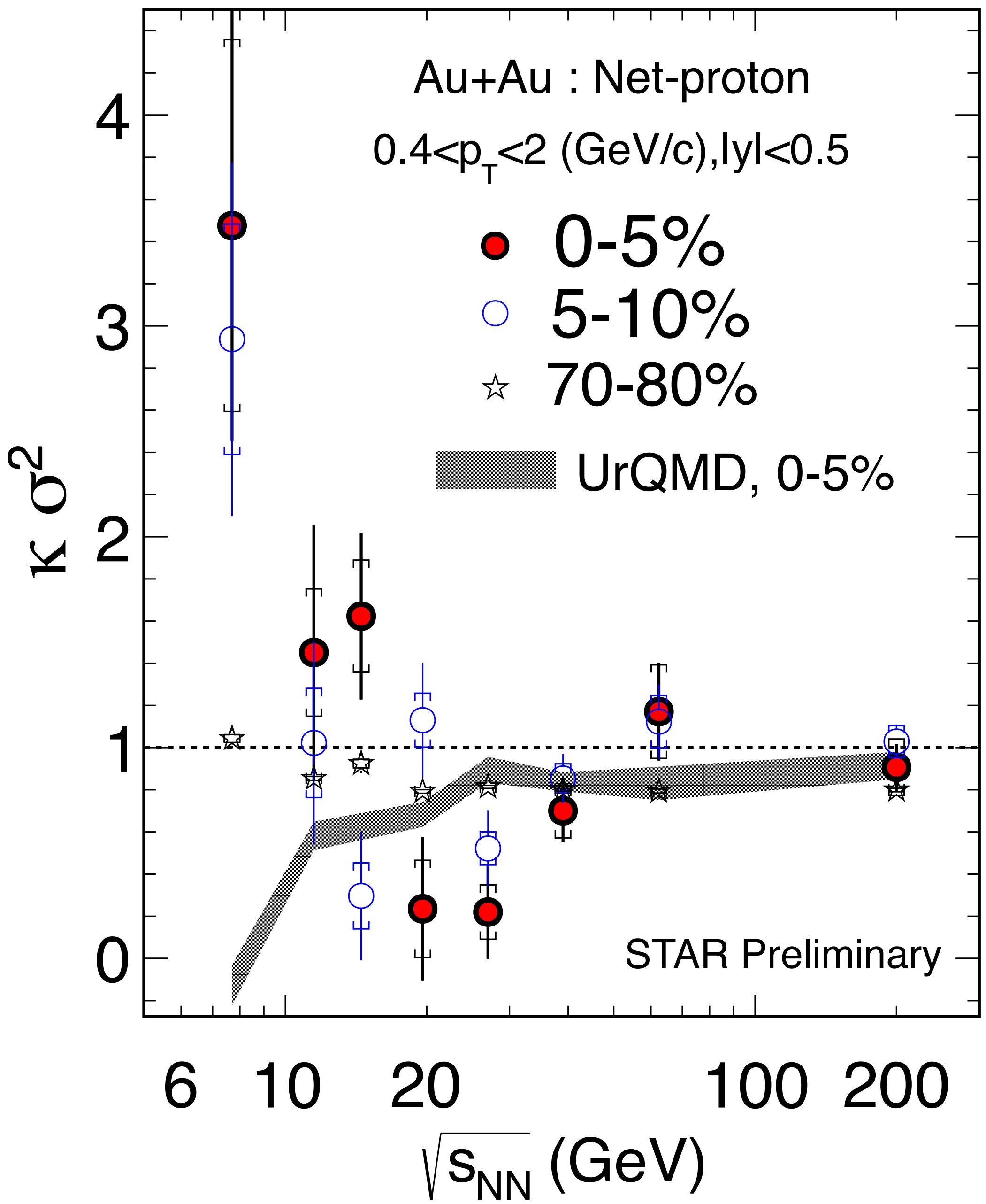
Net-Kaon



Physics Letters B Volume 785,
10 October 2018, Pages 551-560

- **STAR published up to 4-th order fluctuations** of net-proton, net-charge and net-kaon distributions.
- **Critical phenomena have not been observed yet.**

Net-proton preliminary results



X. Luo, Nucl. Phys. A956 (2016) 75–82, [1512.09215].

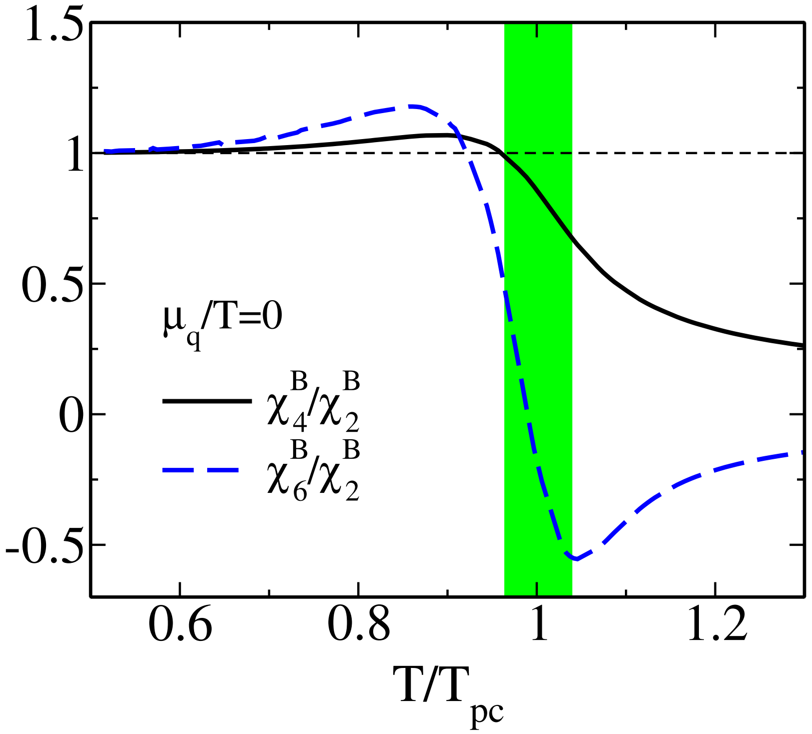
- Interesting energy dependences were observed by **expanding p_T range by using TOF**.
- Minimum around $\sqrt{s_{NN}}$ = 20 GeV
- Larger than unity at $\sqrt{s_{NN}}$ = 7.7 GeV

- Signal from phase transition or critical point?
- More statiscs is necessary.

Motivation1 -C_6 analysis-

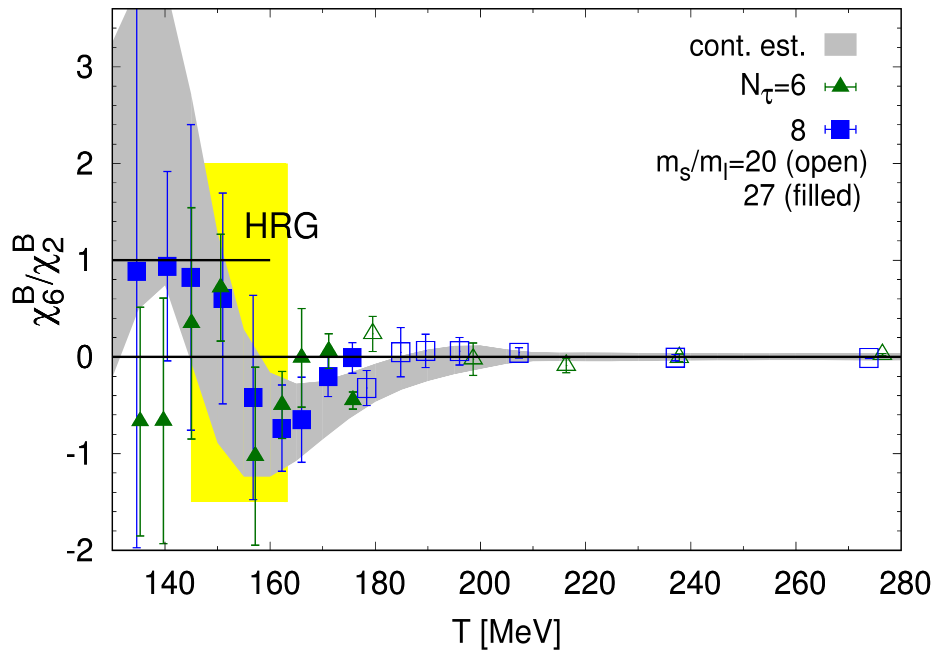
PQM model prediction

Friman et al, Eur. Phys. J. C(2011) 71:1694

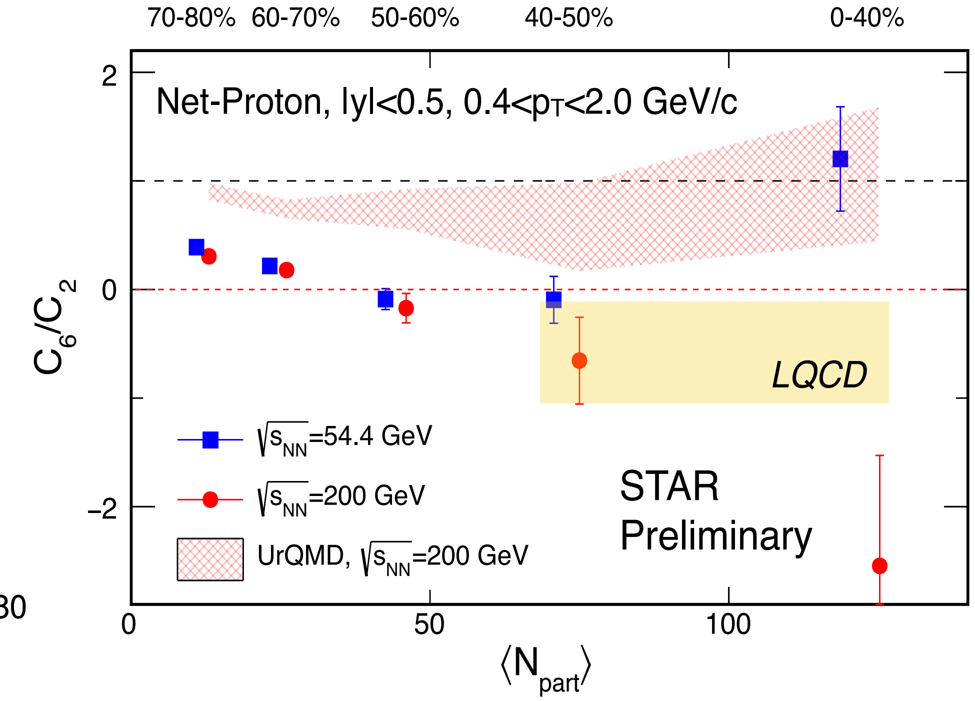


Lattice QCD prediction

A. Bazavov et al, Phys.Rev. D95 (2017) no.5, 054504.



T.Nonaka (STAR Collaboration), QNP2018



freeze-out conditions	χ_4^B/χ_2^B	χ_6^B/χ_2^B	χ_4^Q/χ_2^Q	χ_6^Q/χ_2^Q
HRG	1	1	~ 2	~ 10
QCD: $T^{freeze}/T_{pc} \lesssim 0.9$	$\gtrsim 1$	$\gtrsim 1$	~ 2	~ 10
QCD: $T^{freeze}/T_{pc} \simeq 1$	~ 0.5	< 0	~ 1	< 0

- **Negative C_6** of conserved quantities are predicted to be the signal of **cross-over phase transition**.
- C_6 of net-proton is measured at $\sqrt{s_{NN}}$ = 200 and 54 GeV in Au+Au collisions.
- **C_6 of net-charge** should be measured to compare net-proton results and theoretical predictions.
- 54 GeV net-charge results have not been reported yet.

Motivation2 -Δη dependence-

D-measure (D)

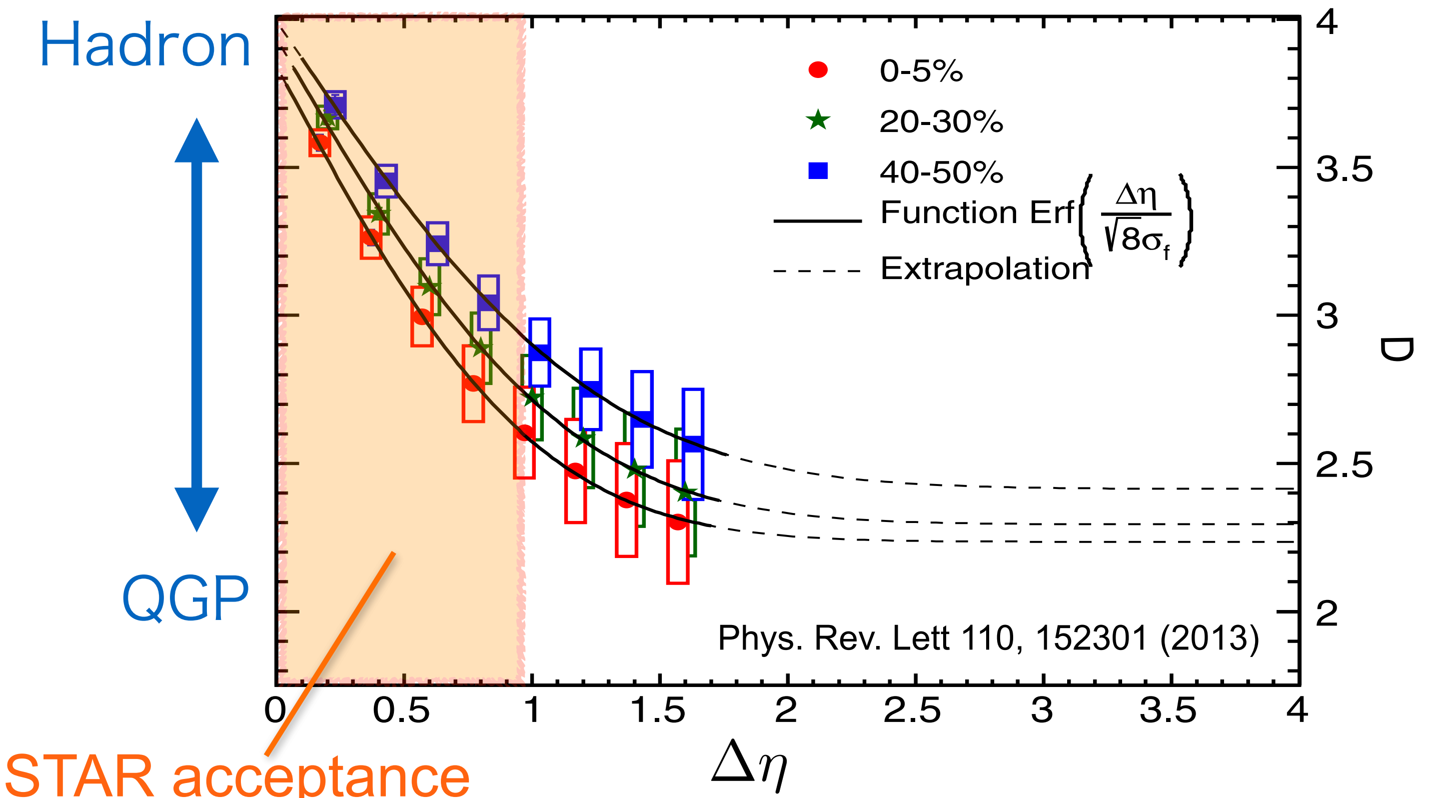
$$D = 4\frac{C_2}{\langle N_{ch} \rangle} \qquad N_{ch} = N^+ + N^-$$

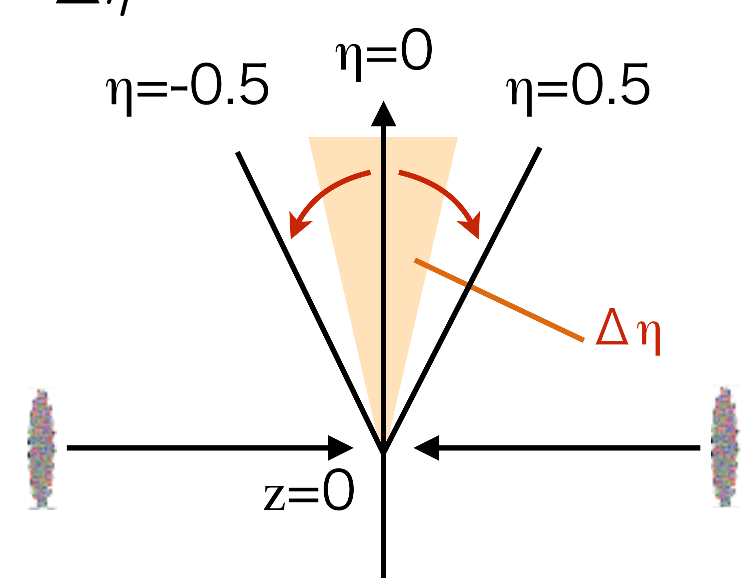
Theoretical predictions

(HRG model, Lattice QCD, etc)

QGP fluctuation :
D =1-1.5
Hadron fluctuation :
D= 3-4

ALICE (2.76TeV Pb+Pb)



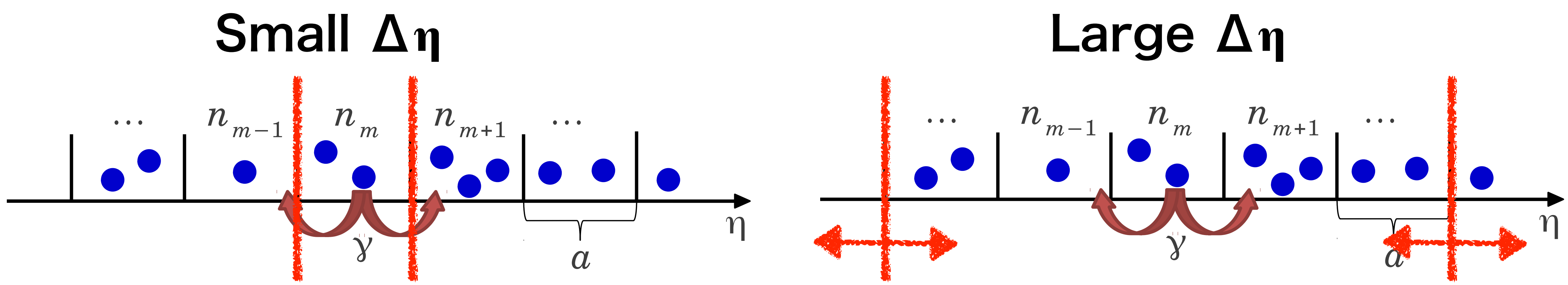


- **D-measure is ovserved to decreace with expanding Δη** in Pb-Pb collisions at 2.76 TeV at ALICE.
- D-measure also decreace from peripheral to central collisions.

Expanding Δη : The signal of QCD transition might been observed

<u>It is important to measure Δη dependence of D-measure in lower energies.</u>

Motivation2 -Δη dependence-

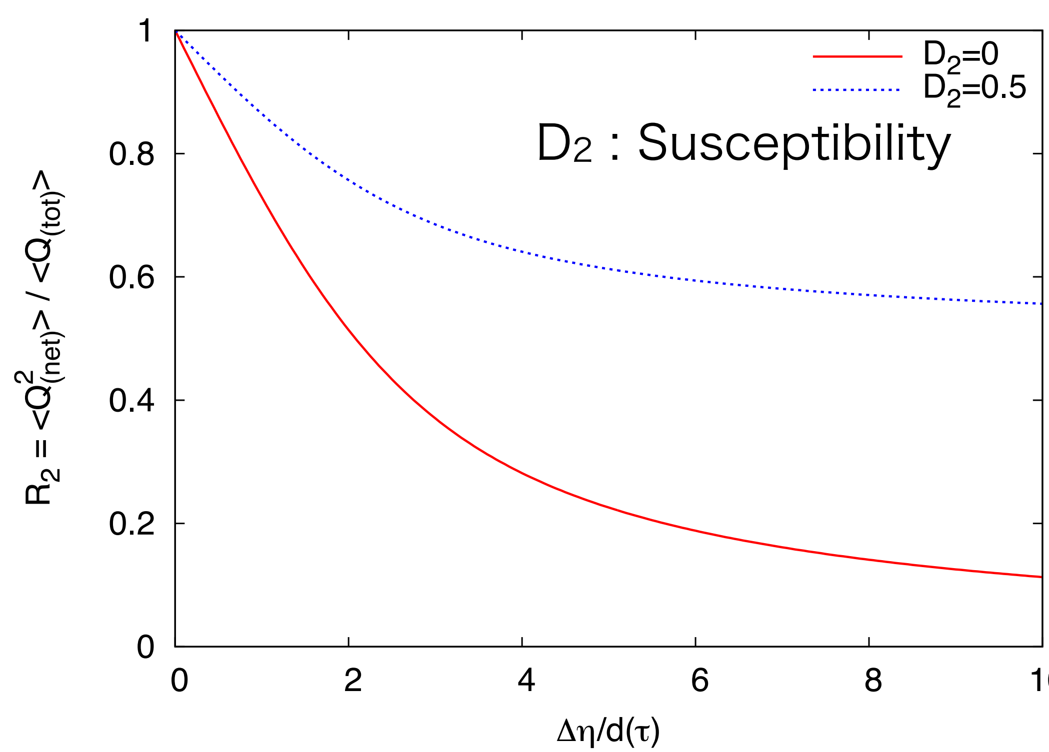


$$\partial_\tau P(\boldsymbol{n},\tau) = \gamma(t)\sum_m \left[(n_m+1)\left\{P\left(\boldsymbol{n}+\boldsymbol{e}_m-\boldsymbol{e}_{m+1},\tau\right)+P\left(\boldsymbol{n}+\boldsymbol{e}_m-\boldsymbol{e}_{m-1},\tau\right)\right\} - 2n_m P(\boldsymbol{n},\tau)\right]$$

$$\boldsymbol{n} = (\cdots, n_{m-1}, n_m, n_{m+1}, \cdots)$$

$$a \to 0$$

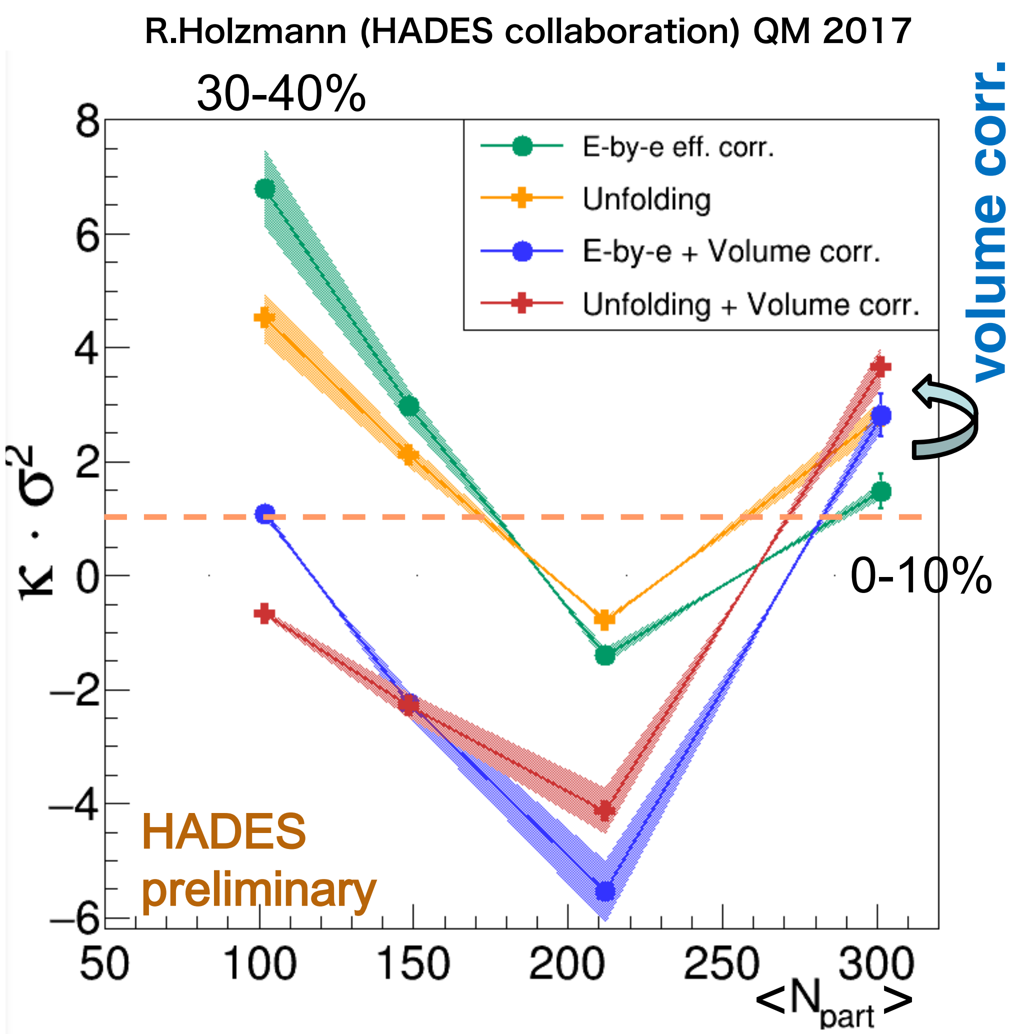
M.Asakawa, M.Kitazaw, Progress in Particle and Nuclear Physics Volume 90, September 2016, Pages 299-342



- Decreasing D-measure with Δη **can be descrived by diffusion** model.
- **Third and fourth-order** cumulants by this model are implemented.

Experimental measurement are necessary up to 4th-order

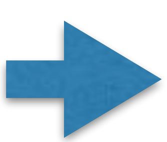
Motivation3 - Volume Fluctuation study-



- **Initial volume fluctuation (VF)** which correspond to the e-by-e fluctuation of number participant nucleons (N_{part}=Nw) artificially enhance cumulants and **should be subtracted from measured cumulants**
- STAR applied **Centrality Bin Width Correction (CBWC)** to eliminate VF.
- New correction Volume fluctuation Correction (VFC) was proposed and HADES experiment have already applied VFC to experimental data.

However…

- **VFC is model dependent** correction whereas **CBWC is data driven** correction.



Inportance of subtracting VF and validity of VFC are studied by using toy model and UrQMD in both net-charge and net-proton cases.

Why net-charge?

- It is importent to measure **both net-proton and net-charge** cumulants and compare the results in order to understand the phase transition.
- **Net-charge is conserved quantity** whereas net-proton and net-Kaon are measured as a proxy of net-baryon and net-strangeness.

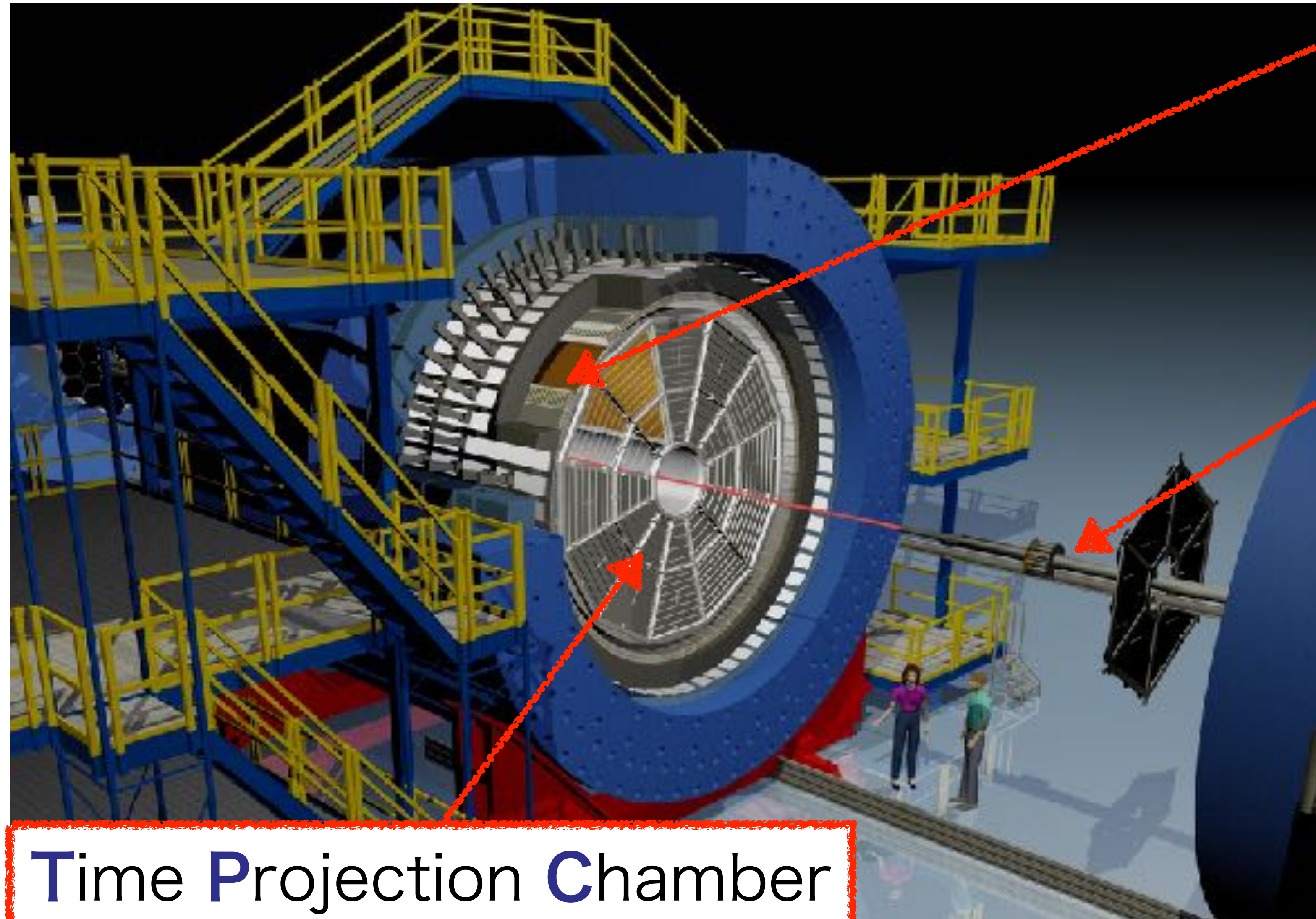
  - My PhD. thesis, University of Tsukuba (2019)
  - T.Nonaka's PhD. thesis, University of Tsukuba (2018)

	net-charge	net-proton	net-Kaon
Conserved quantitiy	**net-charge**	net-baryon	net-strangeness
up to C_4	published (7.7-200 GeV)	published (7.7-200 GeV)	published (7.7-200 GeV)
up to C_6	**200GeV, 54GeV**	**200GeV**, 54GeV	-
$\Delta\eta$ dependence	**7.7-200 GeV (STAR)** 2.76 TeV (ALICE)	-	-

- In **C_6 analysis**, analysis and correction **methods are improved**.
- **$\Delta\eta$ dependence** of D-measure (**2nd order** fluctuation) is reported **by ALICE** whereas **up to 4th-order** cumulants are measured **in this thesis**.
- VFC is studied by T.Nonaka's Doctoral thesis but more studies are necessary.

Analysis mothod (Experiment)

The STAR Detector



Time-Of-Flight

- PID in a broad p_T region.
- Used to remove pile-up events.

Vertex Position Detector

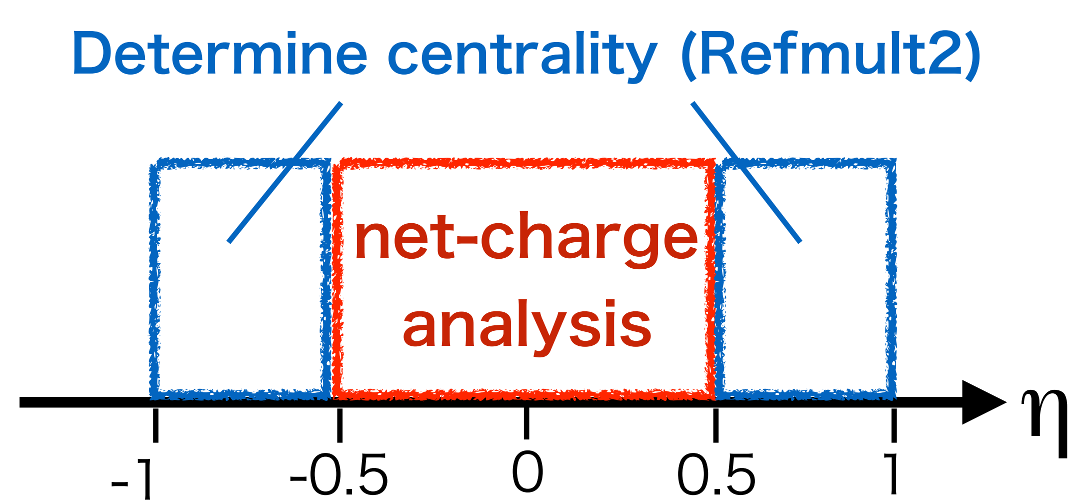
Zero Degree Calorimeter

- Minimum bias trigger
- Used for start time (VPD)
- Collision vertex (VPD)
- Luminosity monitor (ZDC)

ZDC : 18m from vertex

Time Projection Chamber

- Used for tracking, momentum determination and PID.
- Used to determine centrality and to calculate net-charge cumulants.
  - using different kinematic window to avoid auto-correlation



Data set

$\sqrt{s_{NN}}$= 200 GeV	Run11(0-80%)	Run10(10-80%)	Run10(0-10%)	UrQMD
NEvent	485M	211M	196M	45M

$\sqrt{s_{NN}}$= 54 GeV	Run17
NEvent	543M

$\Delta\eta$ analysis

$\sqrt{s_{NN}}$	NEvent (Million)
7.7	1.55
11.5	2.57
14.5	12
19.6	15.5
27	27.5
39	85.3
62.4	50.4
200	97.8

C_6 analysis

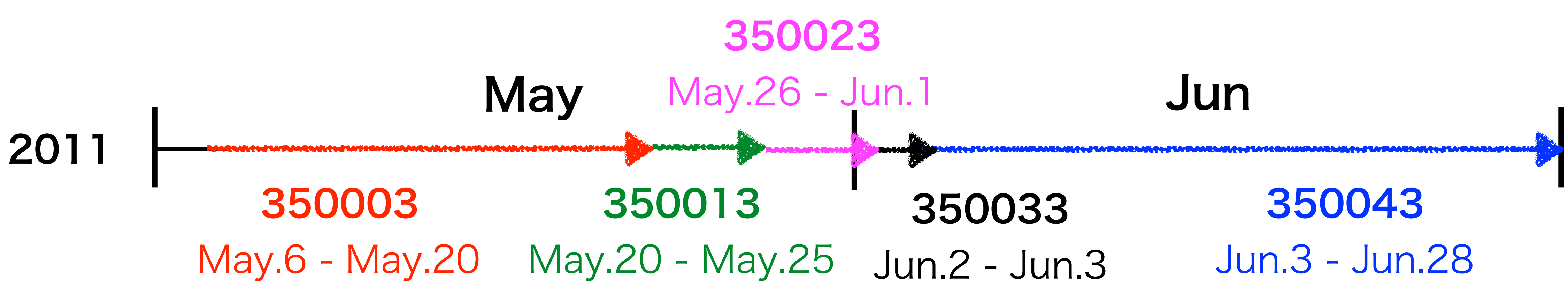
- **C_6 anlysis needs large statistics compared to up to 4th order fluctuation analysis**
  - 200 GeV data was taken from 2010 to 2011 and 54 GeV data was taken in 2017.
  - Statistics of both of them are larger than 100M.
  - Some analysis and correction method are improved compared to published results.

- **All BES-I data were used for $\Delta\eta$.**
  - analysis method and cuts are almost same as published results (up to 4th order).

Trigger ID

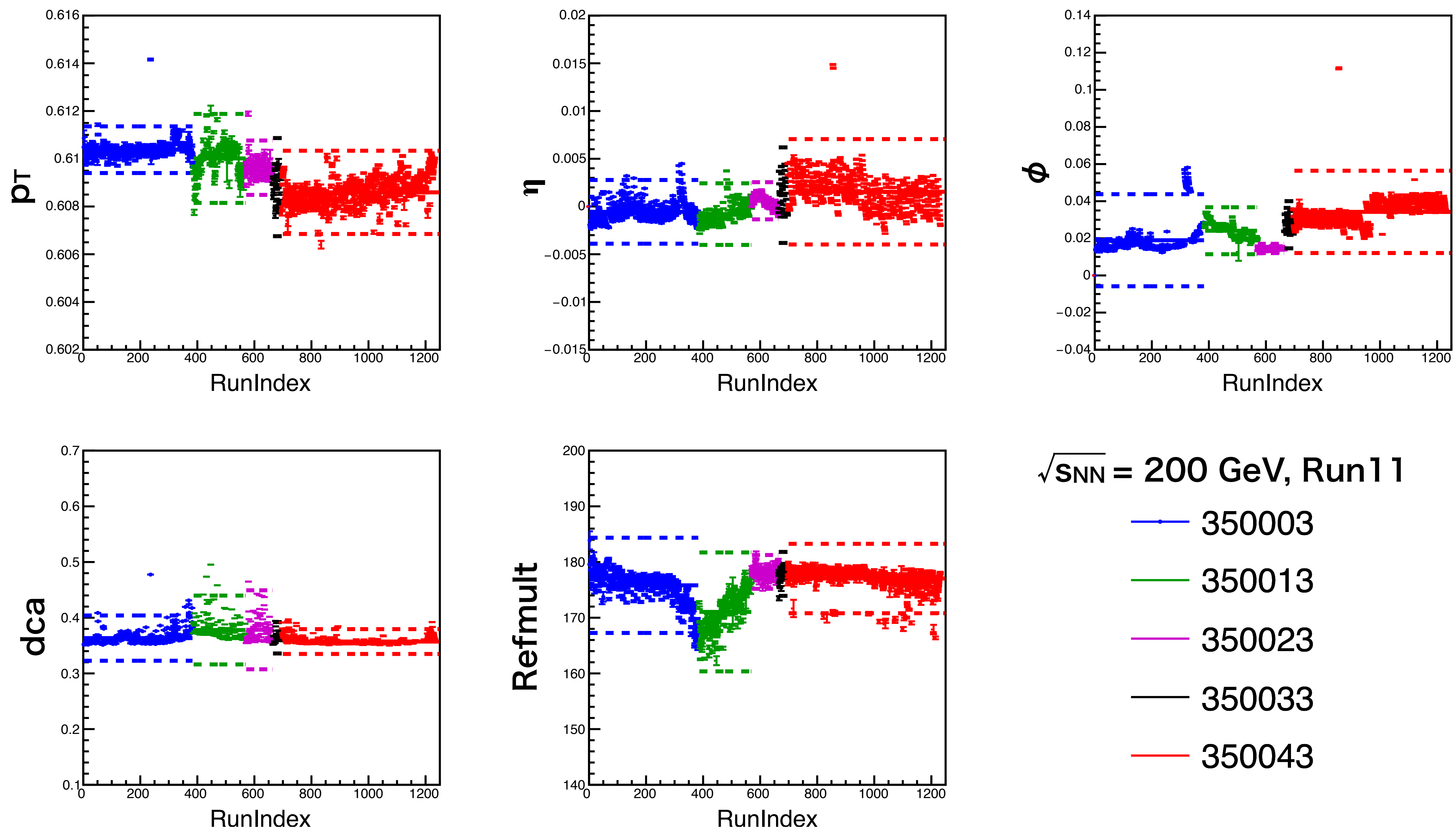
- Run11 data correspond to the data taken in 2011.
- There are several trigger ID. (Minimul bias trigger)
- Trigger ID changed when detector conditions were changed.

$\sqrt{s_{NN}}$= 200 GeV	350003	350013	350023	350033	350043
Run11	200M	74M	15M	12M	187M



- For consistensy check, cumulants are calculated for each trigger ID once and then merged at 200GeV.

Run by run QA

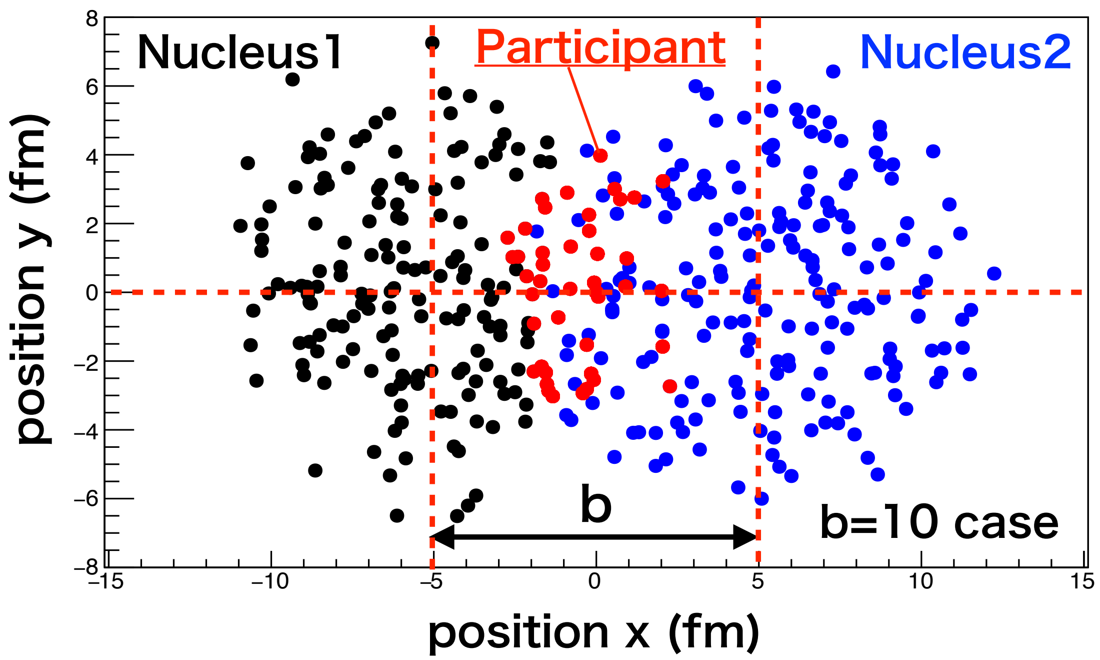


- Run by run <p_T>, <η>, <ϕ>, <dca>, and <Refmult> are measured
- The outlier runs of 3σ were rejected as bad runs for each trigger ID

Glauber model

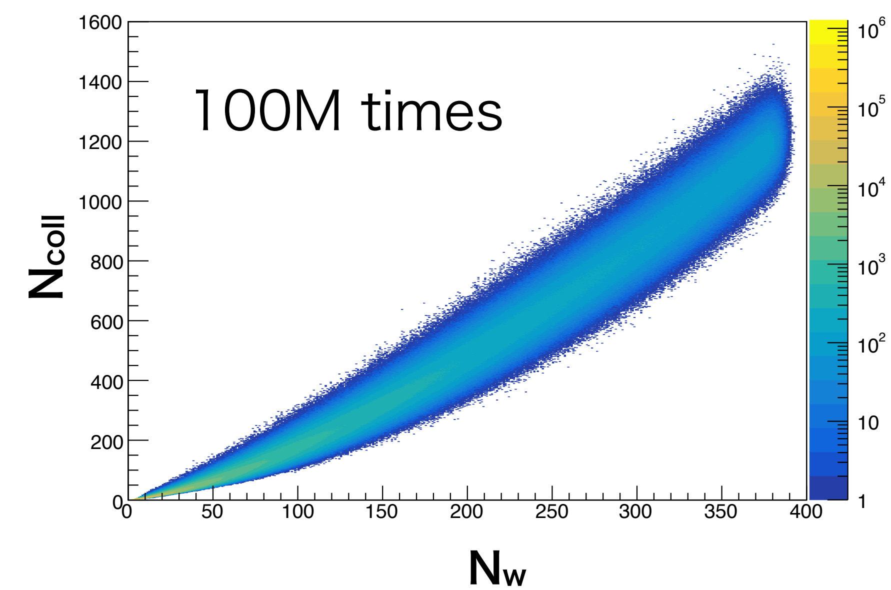
- N_W can't be measured directly by experiment so estimated by Glauber model.

1. Calculate N_W and N_{coll} by Monte Carlo simulation.



- Width : **0.535**
- Radius : **6.4**
- σ : **42** (mb)

Repeat



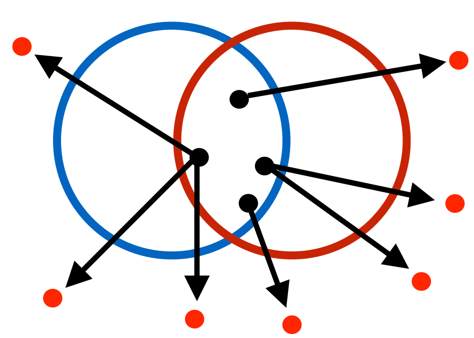
2. Calculate multiplicity by two component model and NBD.

Two component model

Number of source :
$(1-x)*(N_W/2.)+x*N_{coll}$

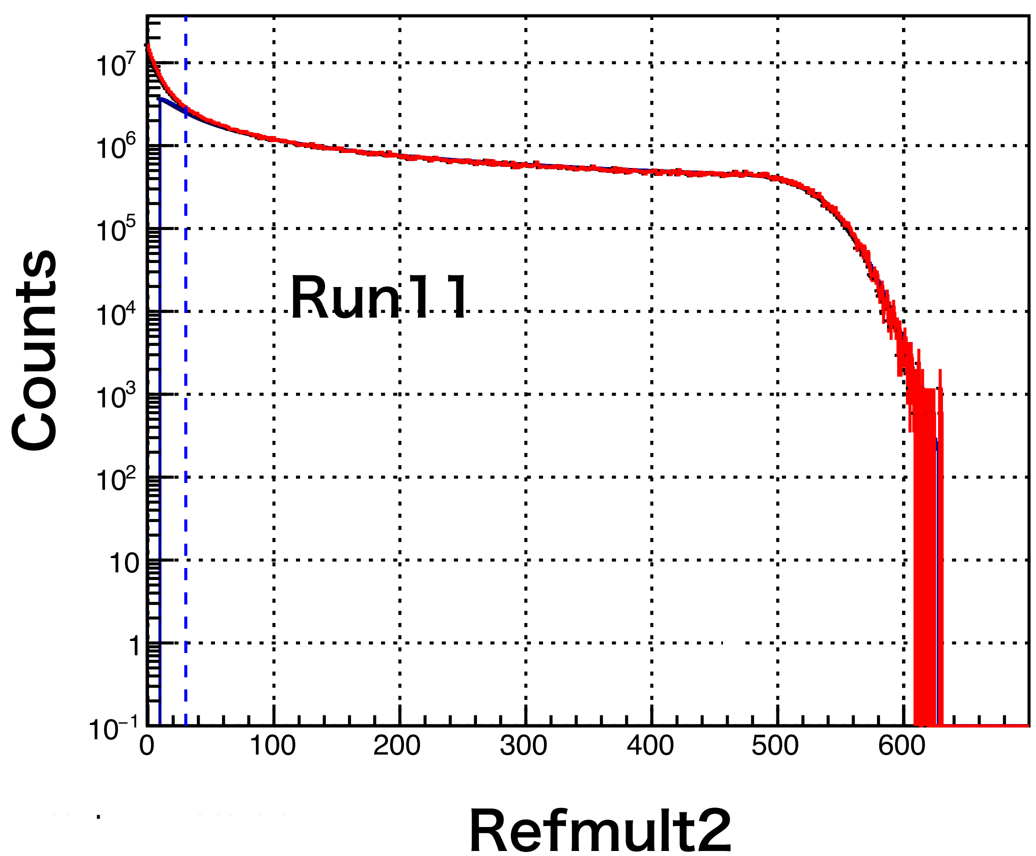
x=0.13

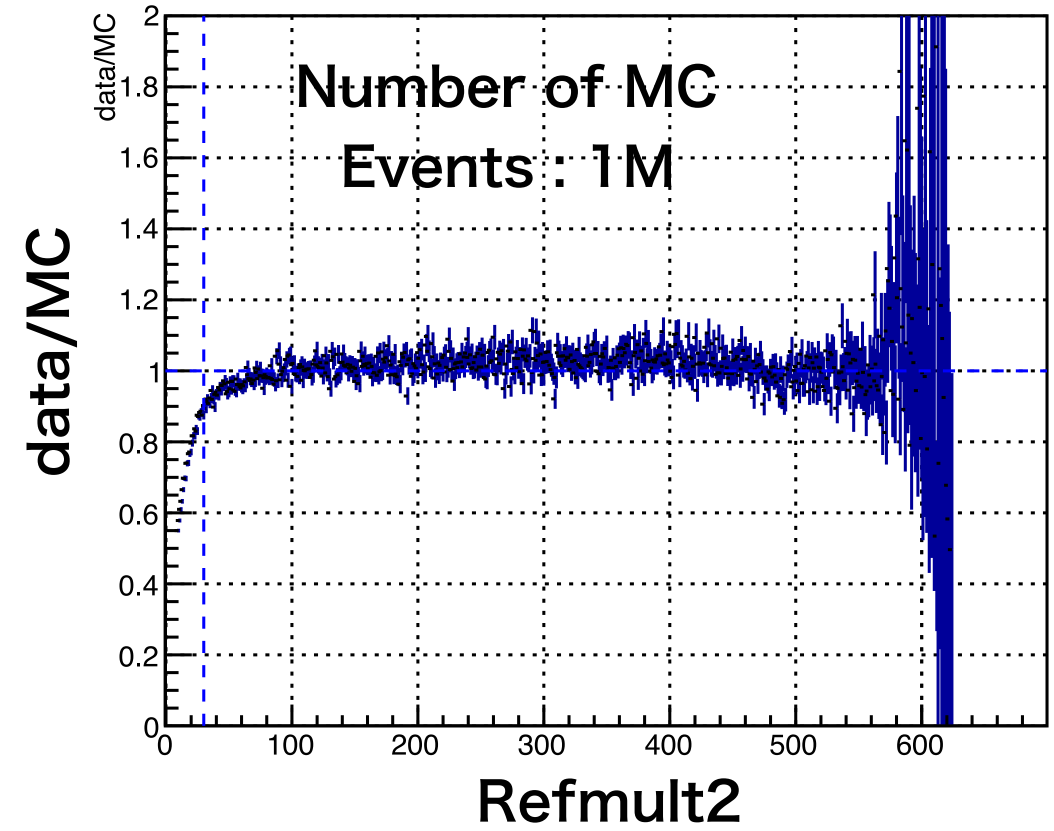
- : initial source
- : final state multiplicity

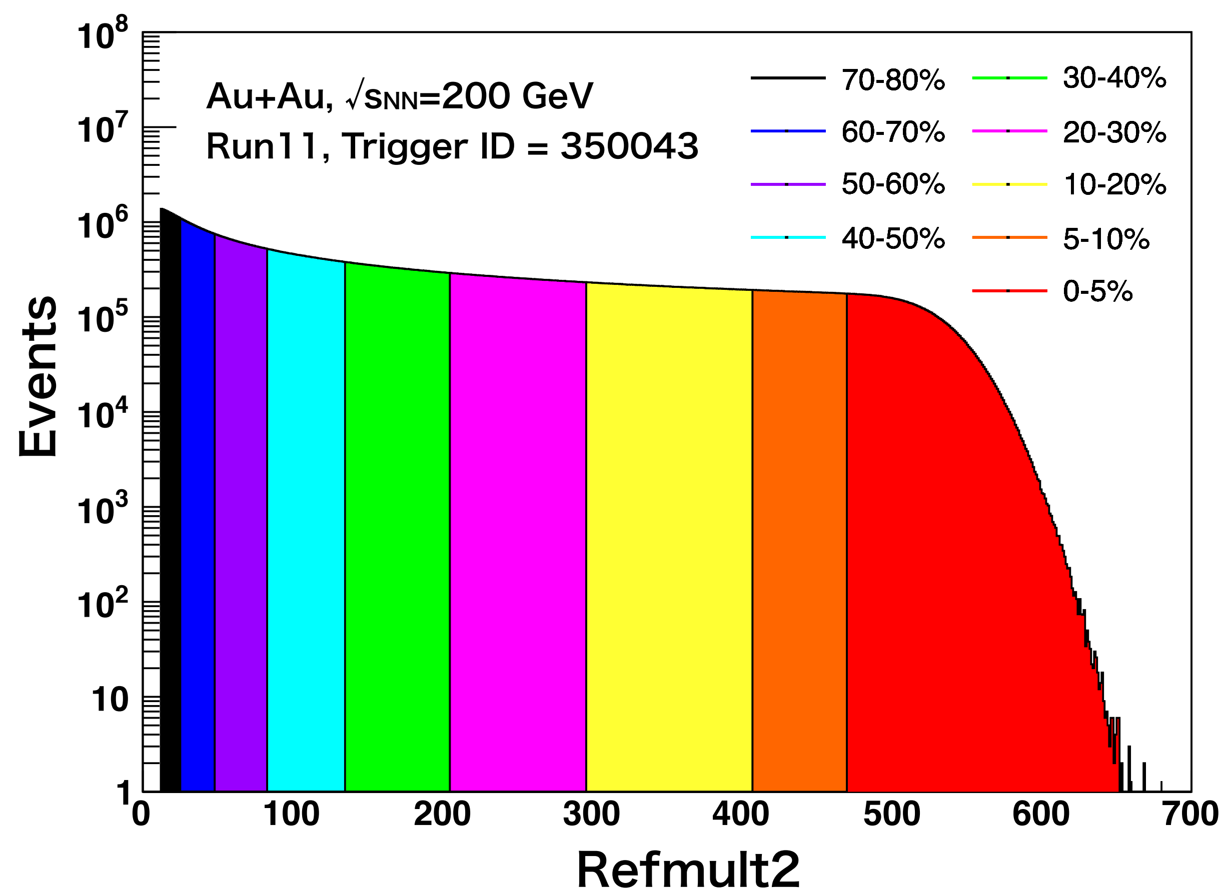


- Final state particles are generated from each source independently. (IPP)
- Number of particles from each source is fluctuating under the NBD.

Glauber fit results







Fitting parameters

n_{pp} : Mean number of generated particles from each source.

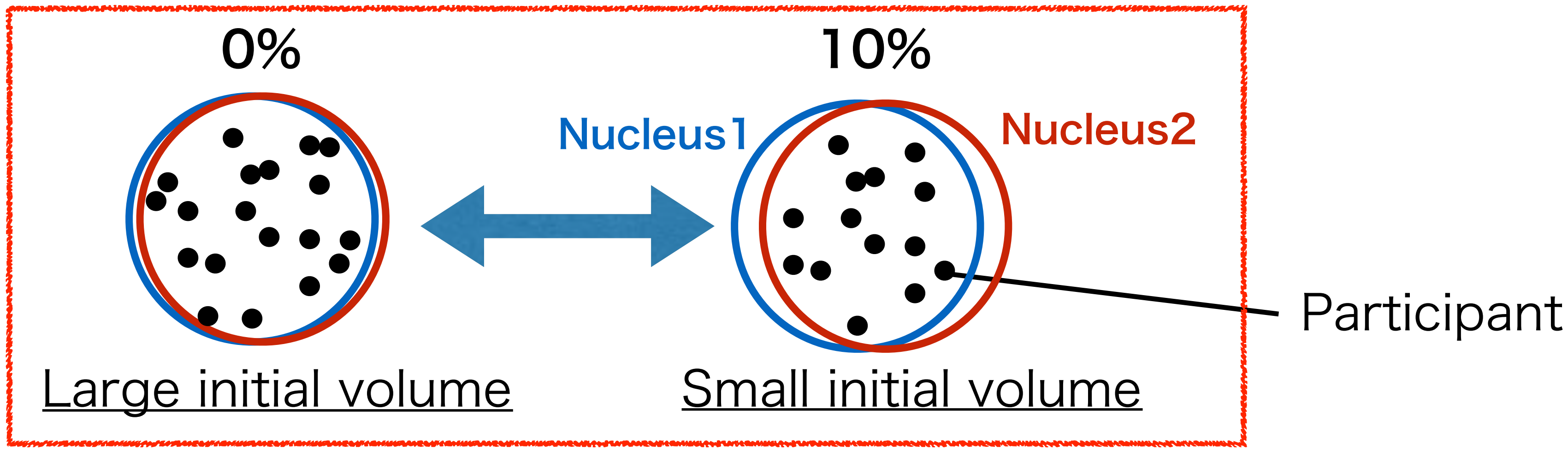
k : Parameters of NBD.

eff : tracking efficiency

Centrality Bin Width Correction

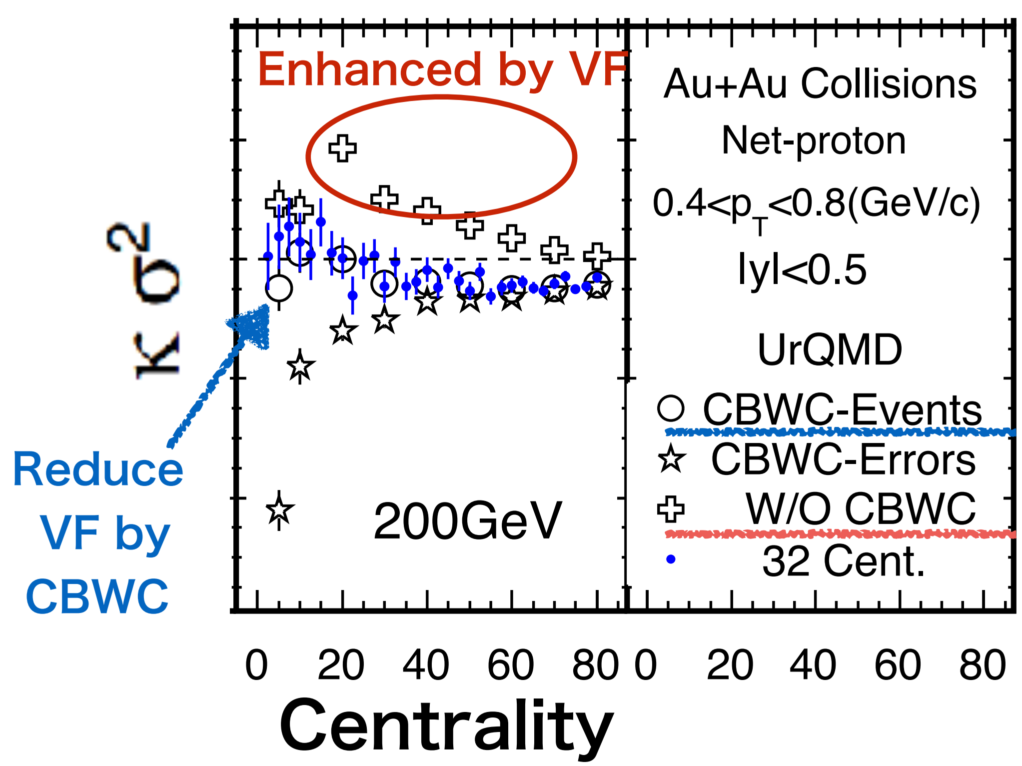
- **Initial volume** which correspond to **number participant nucleons (Nw) are different** even in the same centrality bins.

0-10% centrality bin



- Because of VF, cumulants are **artificially enhanced** which would be the background which should be eliminated.

Xiaofeng Luo, J. Phys. G: Nucl. Part. Phys. 40 105104 (2013)



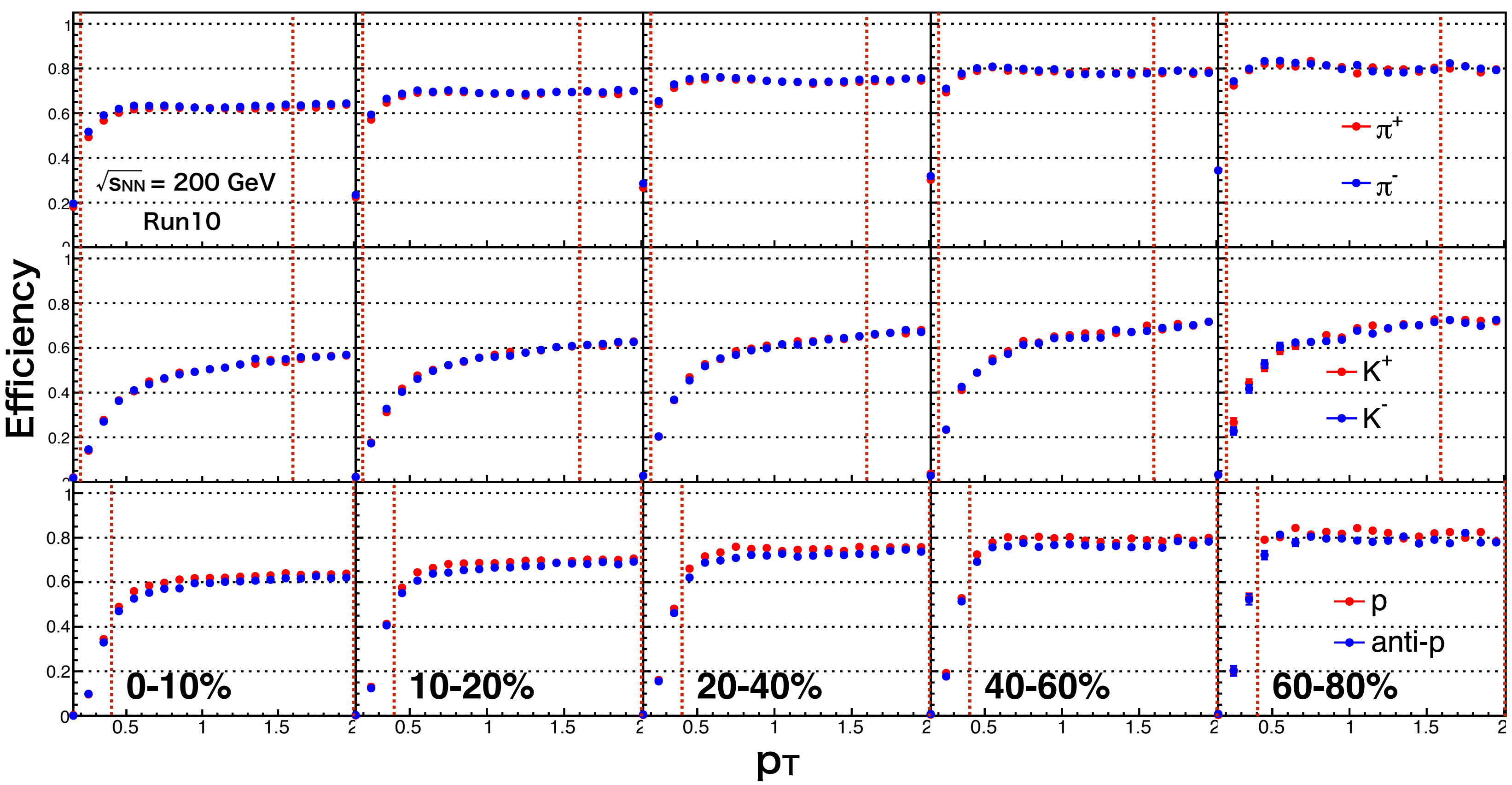
- STAR applied **Centrality Bin Width Correction (CBWC)**.
- In this correction, cumulants are **calculated for each multiplicity bins**.

$$C_n = \sum_r w_r C_{(n,r)} \qquad w_r = \frac{N_r}{\sum_r N_r}$$

Cumulants for each centrality bins — Weight — Cumulants in r-th multiplicity bins

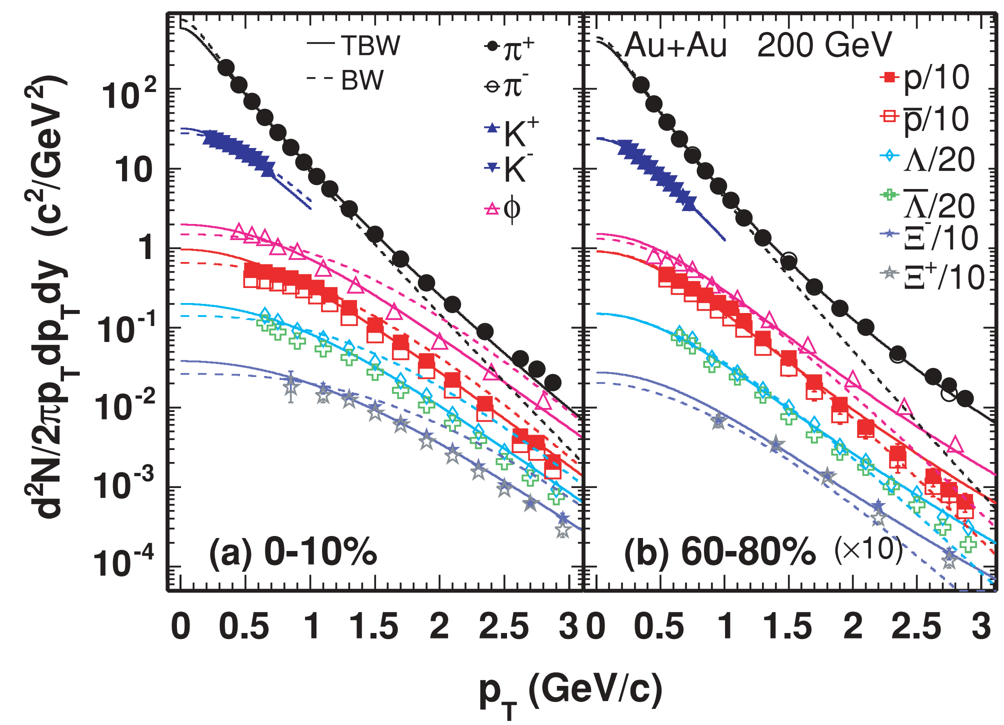
Efficiency estimation

①p_T dependent efficiencies were estimated for each centrality using embedding method. $|\eta| < 0.5$

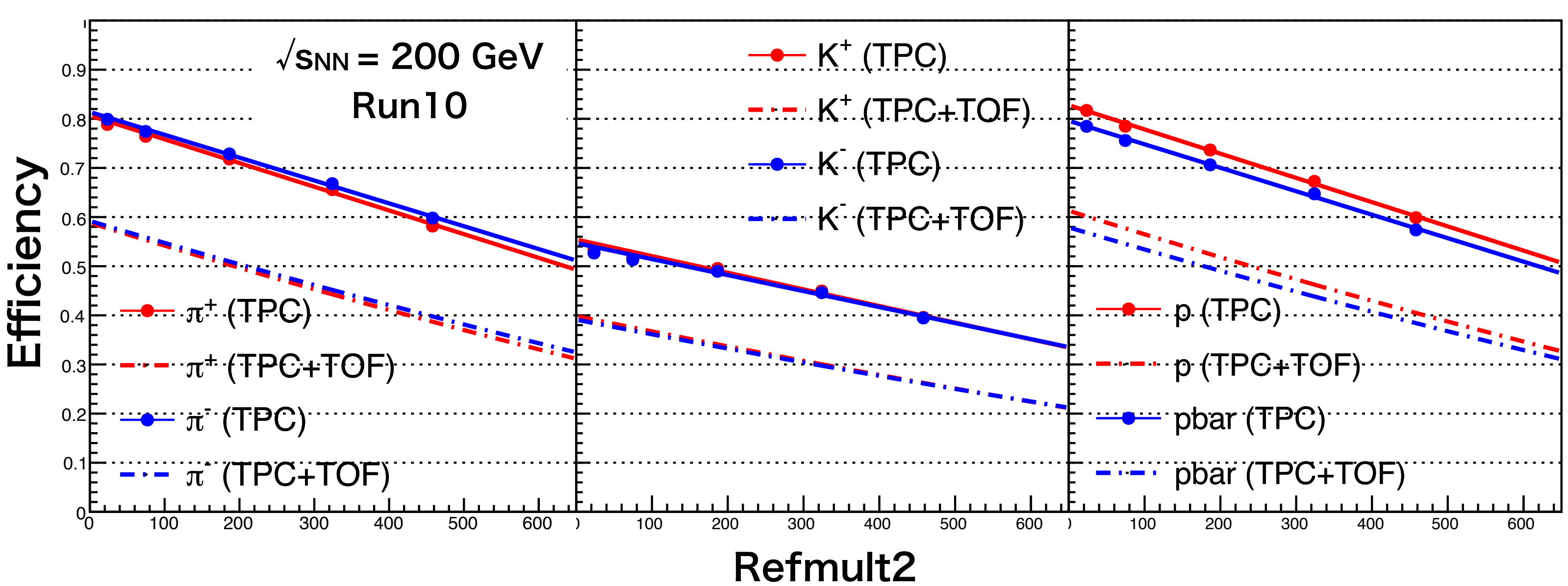


② p_T integrated efficiencies were estimated using results of ① and spectra data.

PHYSICAL REVIEW C 79, 051901(R) (2009)

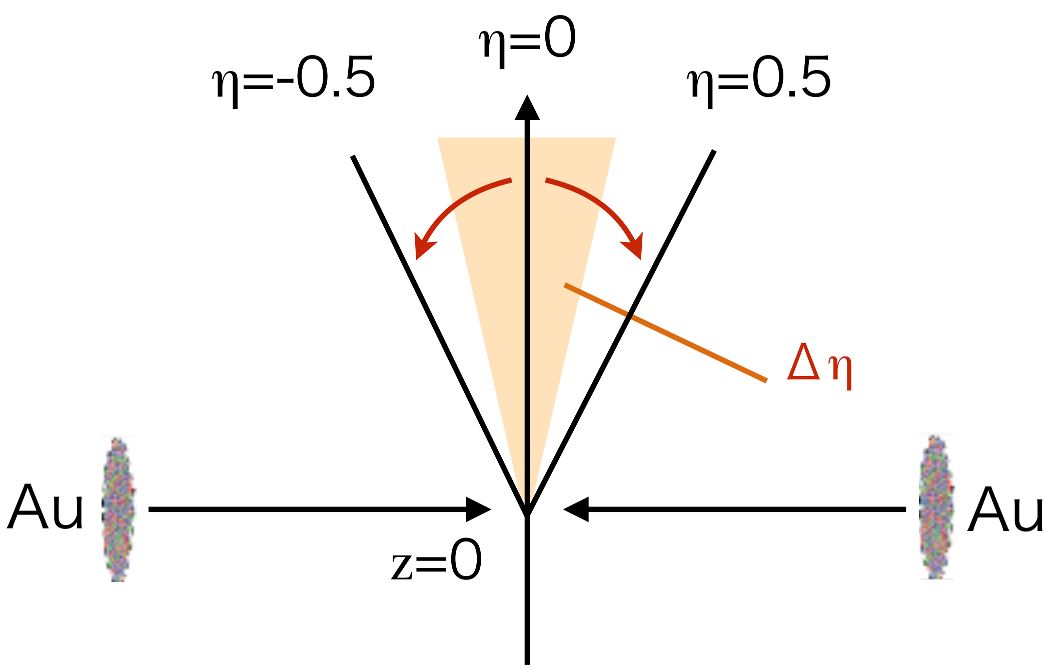


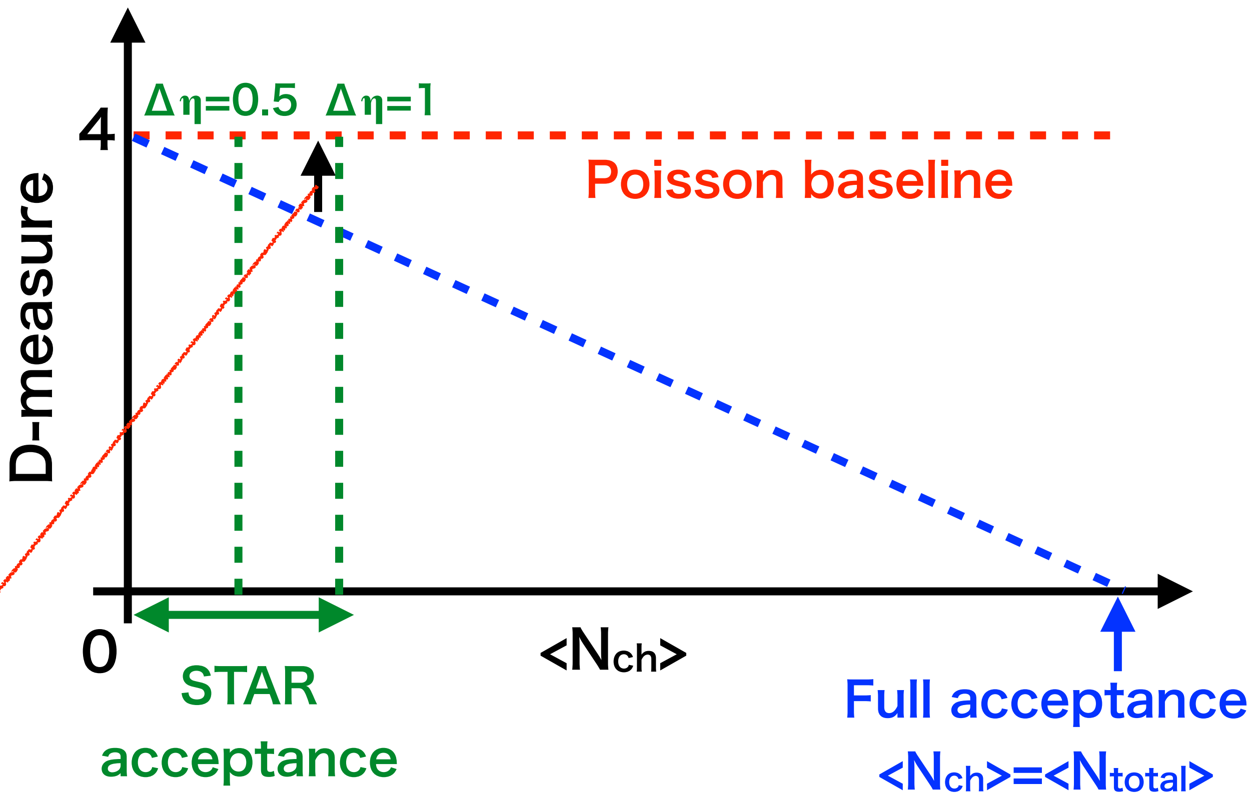
$$\epsilon_i = \frac{\int \epsilon_i(p_T) p_T f(p_T) dp_T}{\int p_T f(p_T) dp_T}$$



③ pol1 fit and estimate tracking efficiencies for each multiplicity bin.

Charge conservation correction on D



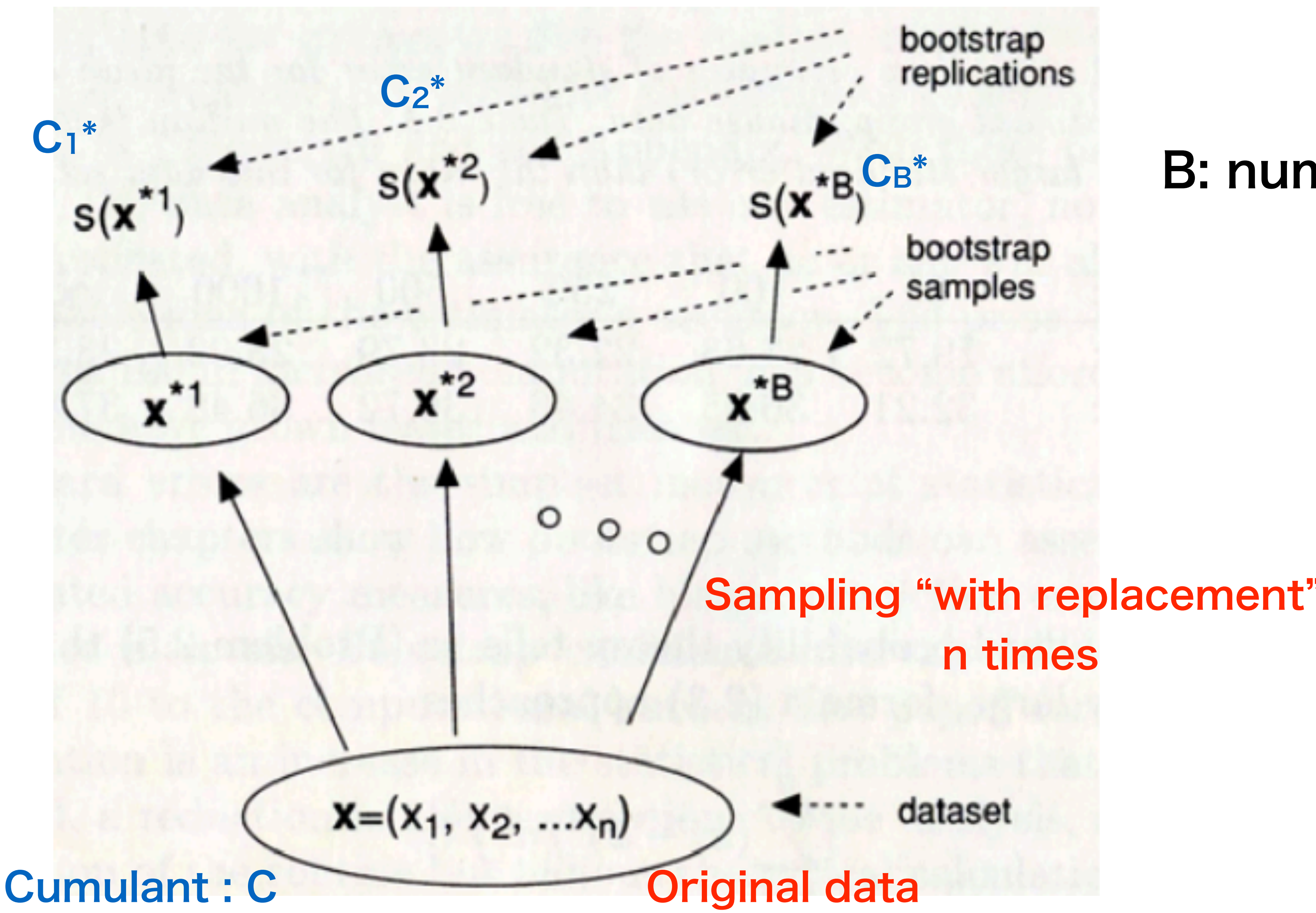


$$D_{corr} = D + 4\frac{\langle N_{ch} \rangle}{\langle N_{total} \rangle}$$

- D-measure decrease with expanding Δη due to charge conservation.
- This effect is critical to measure Δη dependence of D-measure
- Corrected by adding correction term.
- N_{total} is total multiplicity in full acceptance and estimated from PHOBOS experiment results.

Statistical error estimation

- Statistical errors are estimated by **Bootstrap** method.



B: number of bootstrap

- Error of C_n is estimated by calculating **standard error of C_n*** distribution.
- Number of bootstrap is more than 100 times in this anlaysis.

How to estimate Systematic uncertainty?

$$RMS = \sqrt{\frac{1}{n}\sum_i \left(\frac{Y_i - Y_{st.cut}}{Y_{st.cut}}\right)^2}$$

$$Sys.Err = Y_{st.cut}\sqrt{\sum_j (RMS)^2}$$

Net-charge (published)

dca	0.8, 1.0(default), 1.2
nFitPoints	-18, 20(default), 22
nhitsdedx	8, 10(default), 12
efficiency	±5% $+\alpha$?

- Efficiency of positively charged particle and negatively charged particle are changed ±5% at published results.
  (pos,neg) = (+5%, +5%) and (-5%, -5%)
- In this analysis, efficiencies are changed 0.3% separately in addition to conventional method.
  (pos,neg) =(+5%, +5%), (-5%, -5%), (+0.3%, -0.3%), (+0.3%, -0.3%)

Analysis and correction method improvement (C_6 analysis)

Difference between published and current method

- Earlier method

high p_T ↕ low p_T

All positive charged particles | $|\eta|<0.5$ | All negative charged particles

All positive charged particles	All negative charged particles
N_1, ε_1	N_2, ε_2
$(w_{\pi^+}\epsilon_{\pi^+}) + (w_{K^+}\epsilon_{K^+}) + (w_p\epsilon_p)$	$(w_{\pi^-}\epsilon_{\pi^-}) + (w_{K^-}\epsilon_{K^-}) + (w_{\bar{p}}\epsilon_{\bar{p}})$

Net-charge : N_1-N_2 **Efficiency : $(\varepsilon_1+\varepsilon_2)/2$**

- Current method

	π^+	K^+	p	π^-	K^-	pbar
high-p_T	n_1, ε_1	n_2, ε_2	n_3, ε_3	n_4, ε_4	n_5, ε_5	n_6, ε_6
low-p_T	n_7, ε_7	n_8, ε_8	n_9, ε_9	n_{10}, ε_{10}	n_{11}, ε_{11}	n_{12}, ε_{12}

Net-charge : $(n_1 + n_2 + n_3 + n_7 + n_8 + n_9) - (n_4 + n_5 + n_6 + n_{10} + n_{11} + n_{12})$

Efficiency : $\epsilon_1 \quad \epsilon_2 \quad \epsilon_3 \quad \cdots$

12 efficiency bins were used

- **Earlier method** : Count all charged particle with averaged efficiency.
- **Current method** : Count π, K, p with separated efficiencies.

Efficiency correction for different phase space

It was suggested that efficiency correction using the average efficiency for different region of the phase space (different p_T bins for different particle species) would give artificial results when distributions do not follow Poisson.

2 distribution model

5% smaller than Poisson | cumulants Poisson

n_A, ε_A | n_B, ε_B

$$\Delta\epsilon = \epsilon_A - \epsilon_B$$

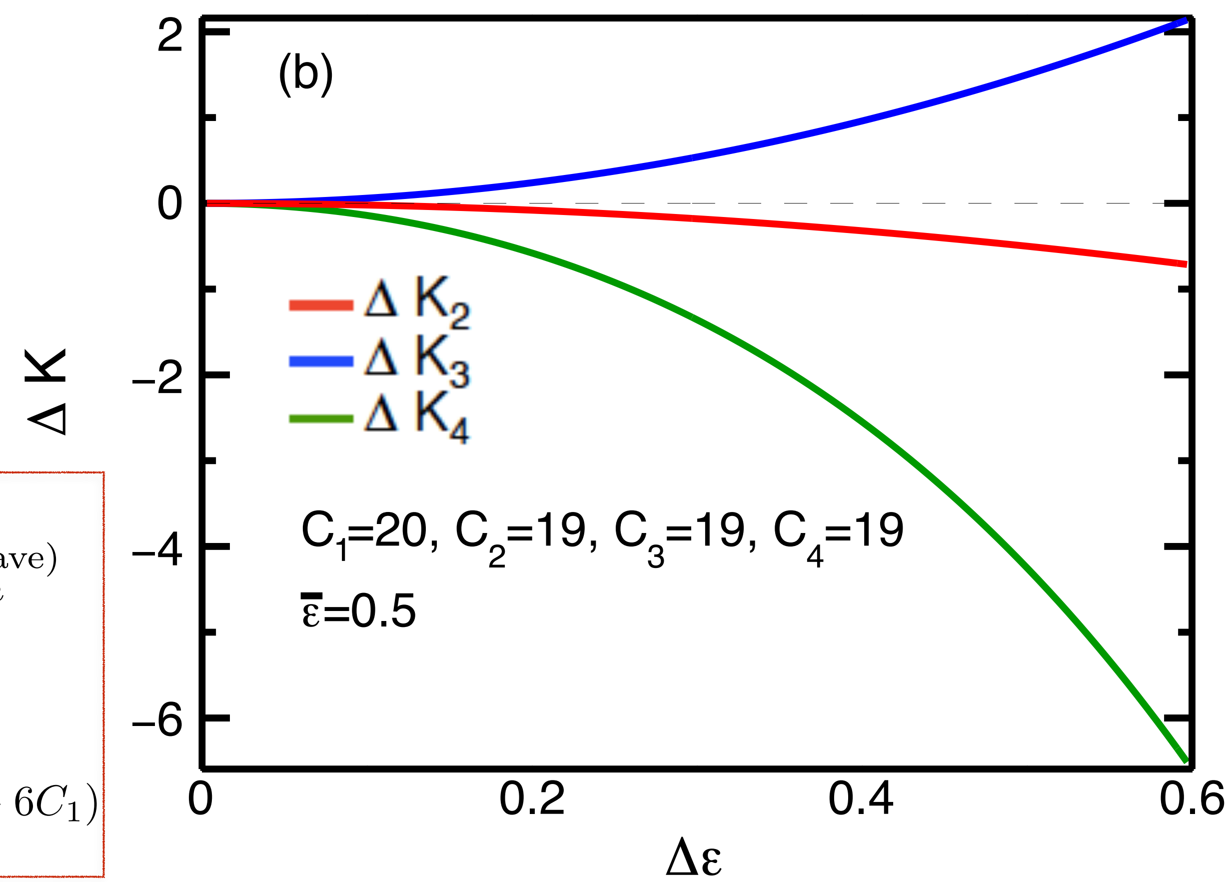
$$\Delta K_2 = \frac{1}{2}\left(\frac{\Delta\varepsilon}{\bar{\varepsilon}}\right)^2 (C_2 - C_1),$$

$$\Delta K_m = K_m - K_m^{(\mathrm{ave})} = 2C_m - K_m^{(\mathrm{ave})}$$

$$\Delta K_3 = \frac{3}{2}\left(\frac{\Delta\varepsilon}{\bar{\varepsilon}}\right)^2 (C_3 - 2C_2 + C_1),$$

$$\Delta K_4 = \frac{1}{2}\left(\frac{\Delta\varepsilon}{\bar{\varepsilon}}\right)^2 (6C_4 - 18C_3 + 19C_2 - 7C_1) + \frac{1}{8}\left(\frac{\Delta\varepsilon}{\bar{\varepsilon}}\right)^4 (C_4 - 6C_3 + 11C_2 - 6C_1)$$

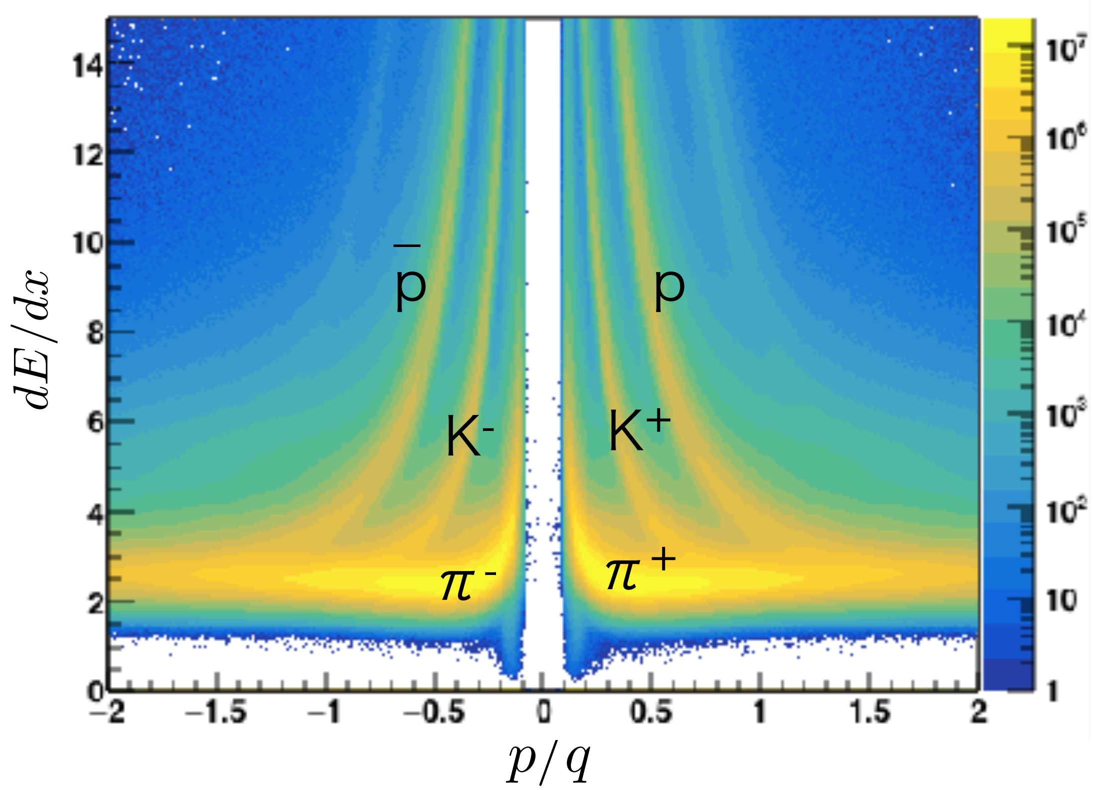
Phys. Rev. C **95**, 064912 T.Nonaka, M.Kitazawa and S.Esumi

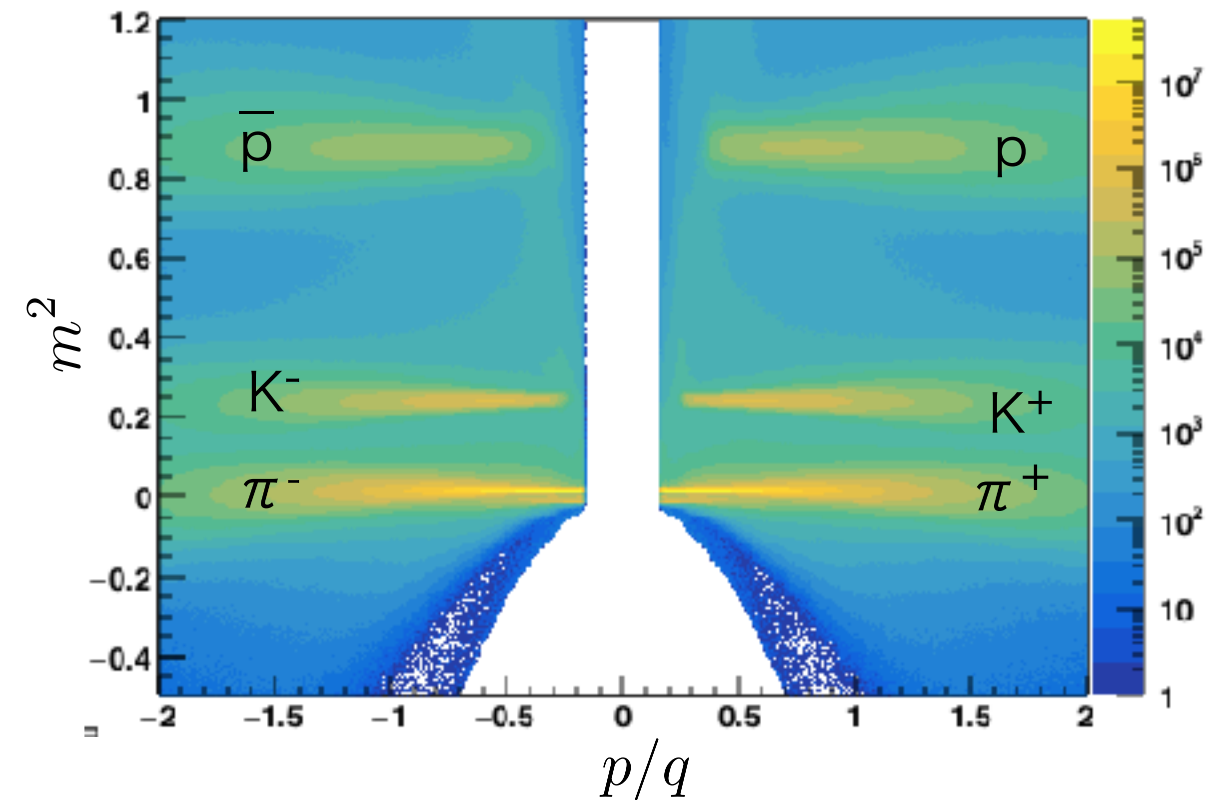


<u>We can't estimate true corrected cumulant when uses average efficiencies if Δ ε is large.</u>

Particle Identification

Au+Au,$\sqrt{s_{NN}}$ = 200GeV
STAR Preliminary





- PID have been done by using dE/dx of TPC
- TOF is also used for PID at high p_T region

Track cut	π	K	p
p_T (TPC only)	0.2 - 0.5 GeV/c	0.2 - 0.4 GeV/c	0.4 - 0.8 GeV/c
p_T (TPC+TOF)	0.5 - 1.6 GeV/c	0.4 - 1.6 GeV/c	0.8 - 2. GeV/c

Factorial cumulant method

Cumulant (measured) → Factorial Cumulant (measured)

↓ Efficiency correction

Cumulant (true) ← Factorial Cumulant (true)

1-4th-order cumulants (factorial cumulant formula)

Phys. Rev. C **95**, 064912

T.Nonaka, M.Kitazawa and S.Esumi

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

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

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

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

Cumulant (true)

Cumulant (measured)

$$q_{(r,s)} = q_{(a^r/p^s)} = \sum_{i=1}^{M}(a_i^r/p_i^s)n_i.$$

M: Number of phase space

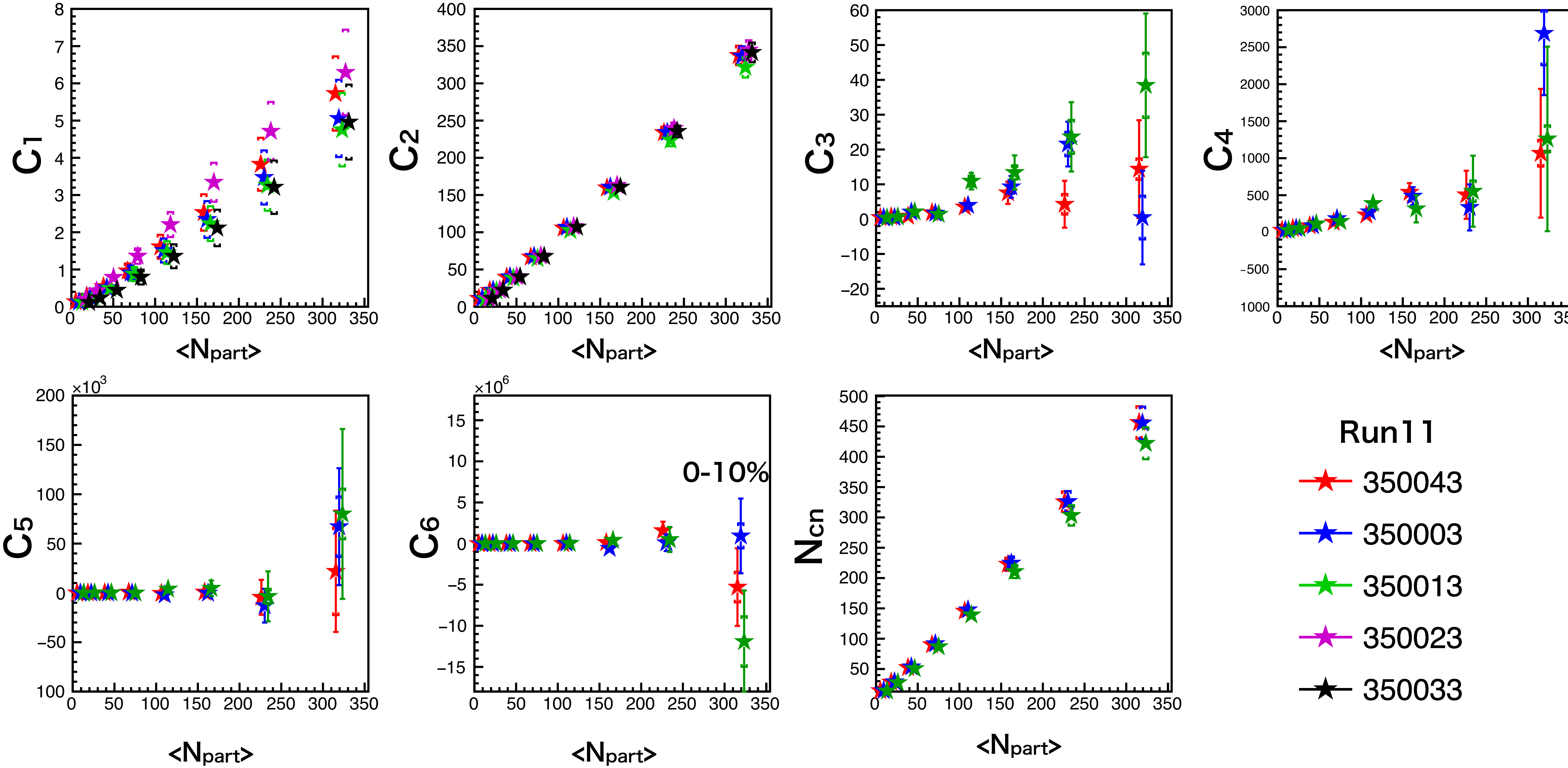
n_i: Number of particle

p_i: Efficiency

a_i: +1 (positive charge) or -1 (negative charge)

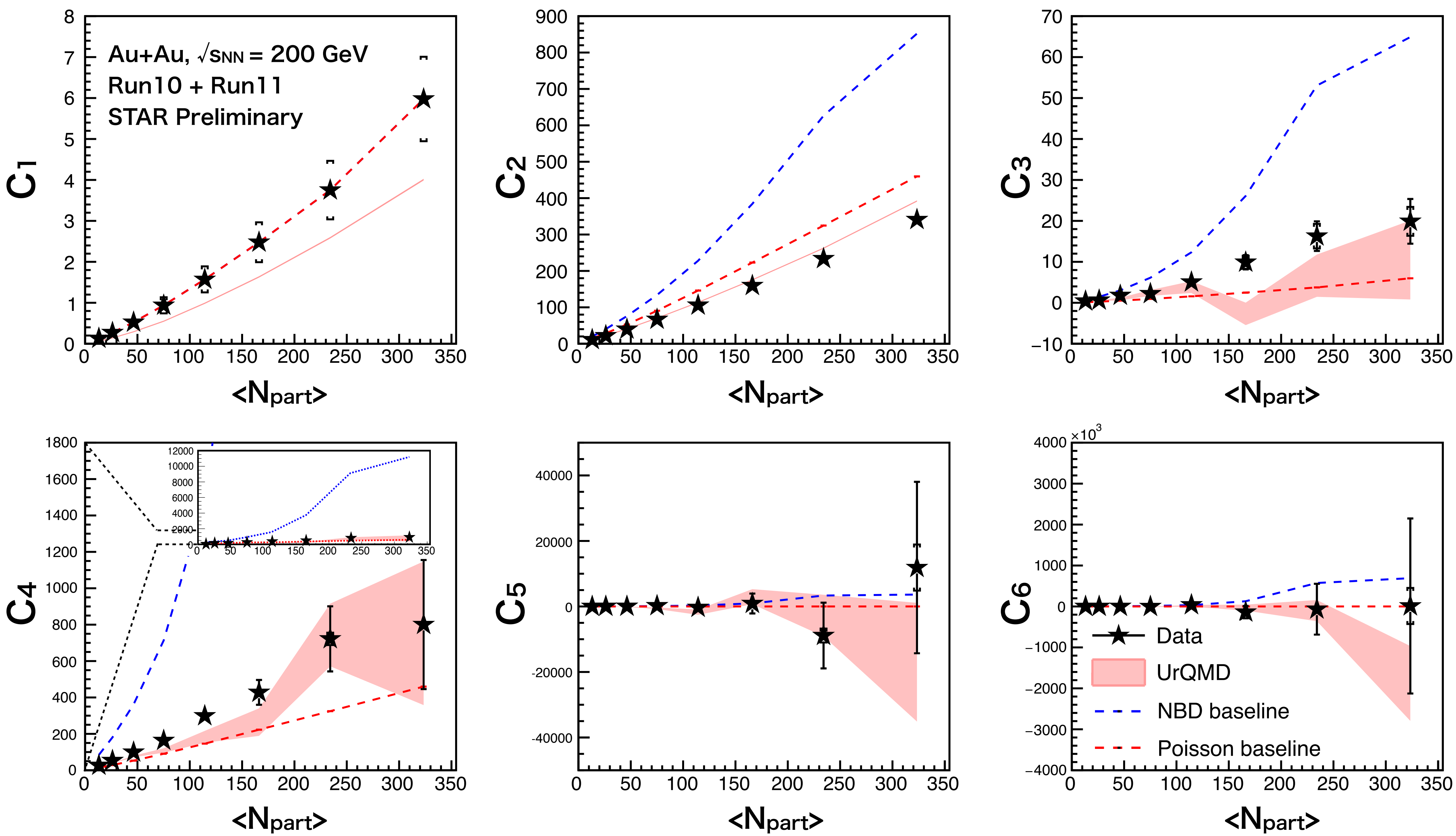
Results (C_6 analysis)

Cumulants (200GeV, Run11)



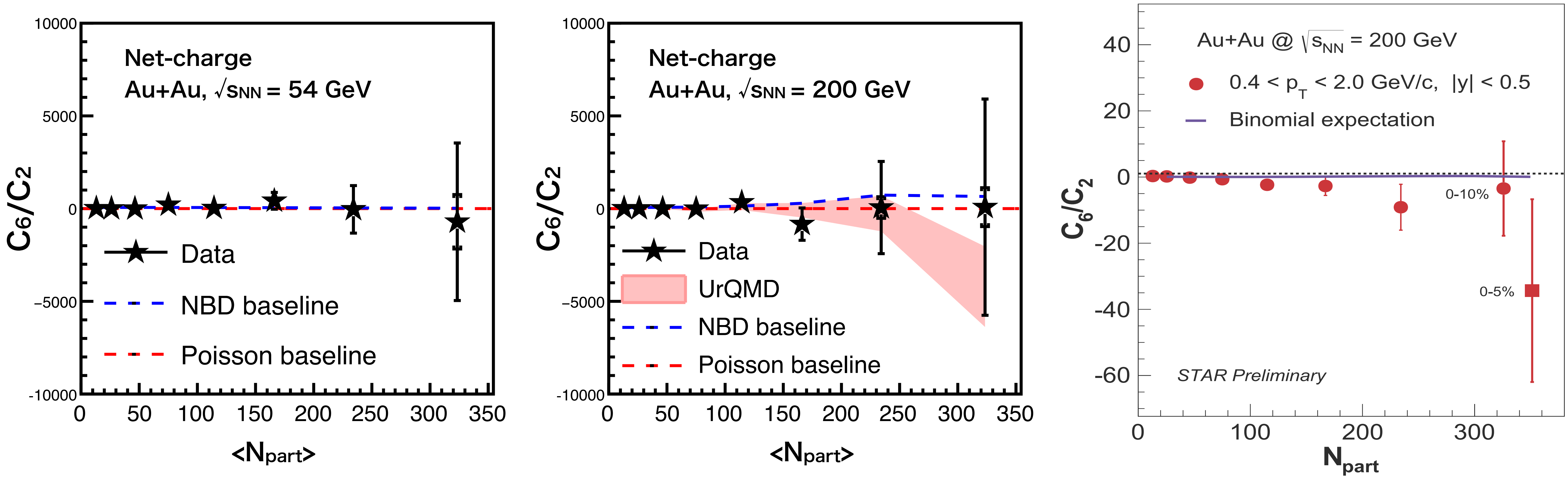
- Cumulants of all trigger ID are consistent within statistical or systematic errors.

Cumulants (200GeV, Run10+Run11)



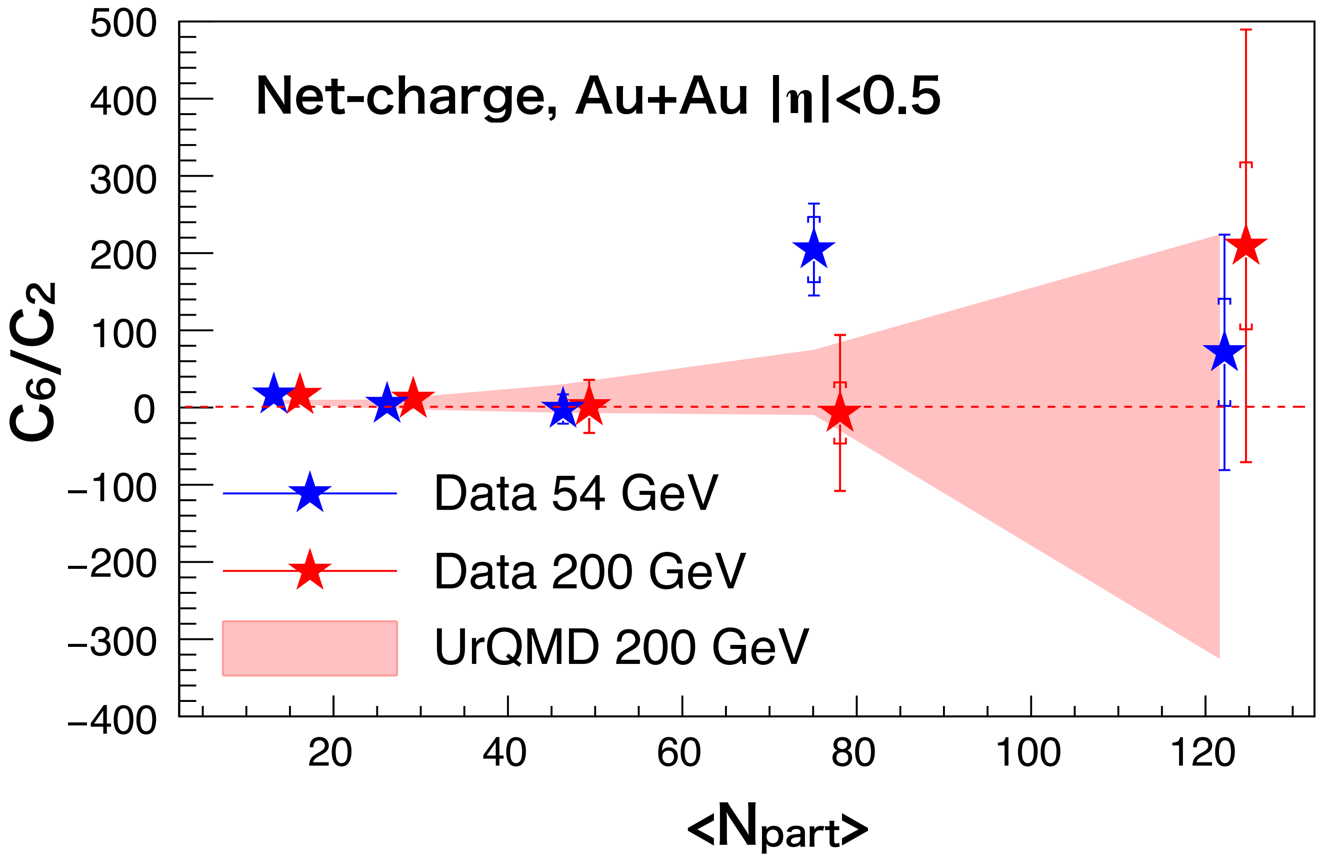
- From 1st- to 6th-order cumulants were measured as a function of <N_{part}>
- Linear trend can be seen.
- For higher-order cumulants, statistical uncertainties are larger than the systematic ones.
- NBD baseline becomes larger than experimental values especially at C_4.

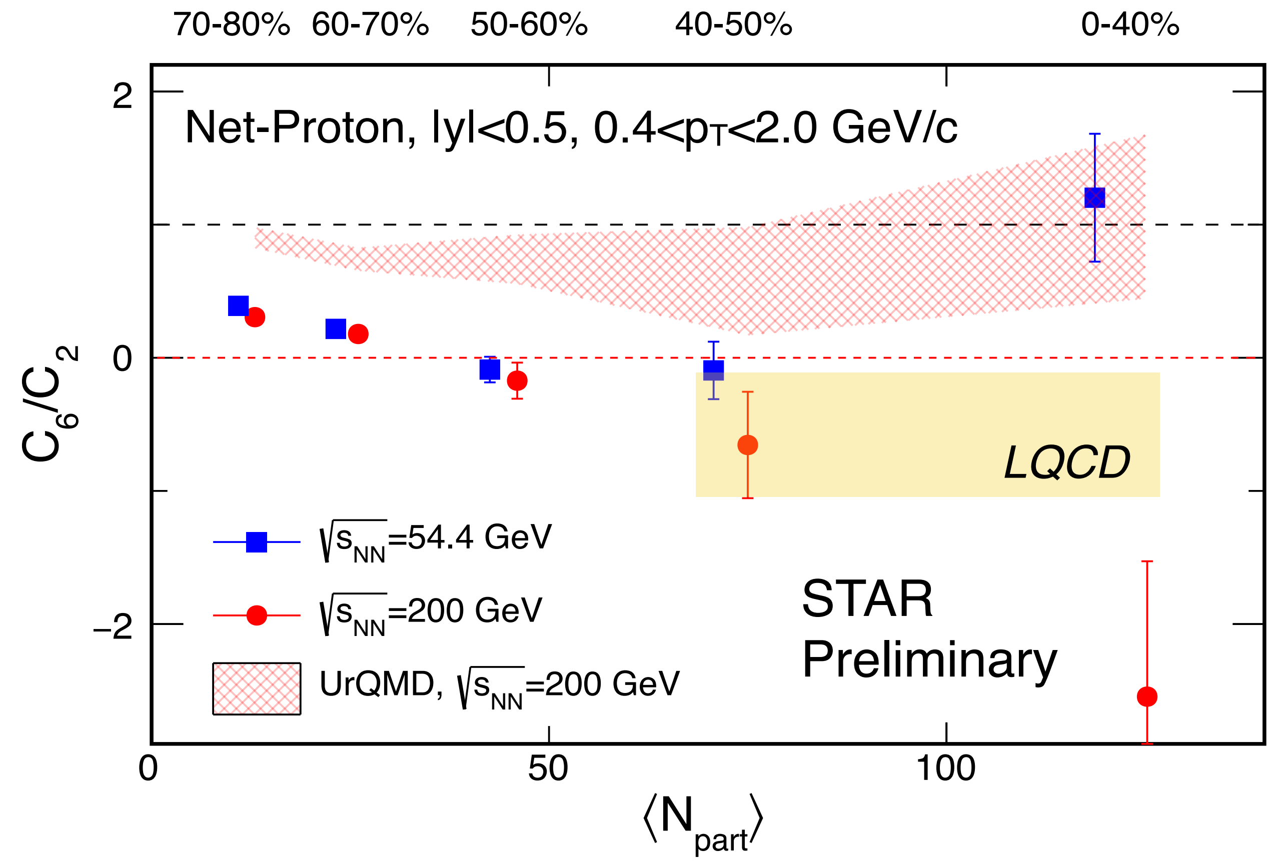
C_6/C_2 at 200 GeV and 54GeV



- Centrality dependecne of C_6/C_2 of net-charge at 200 GeV and 54 GeV are compared to that of net-proton at 200 GeV.
- Compared to Poisson, NBD, and UrQMD.
- All statistical baseline and UrQMD results of C_6/C_2 are consistent within statistical uncertainties and large deviations are not observed.

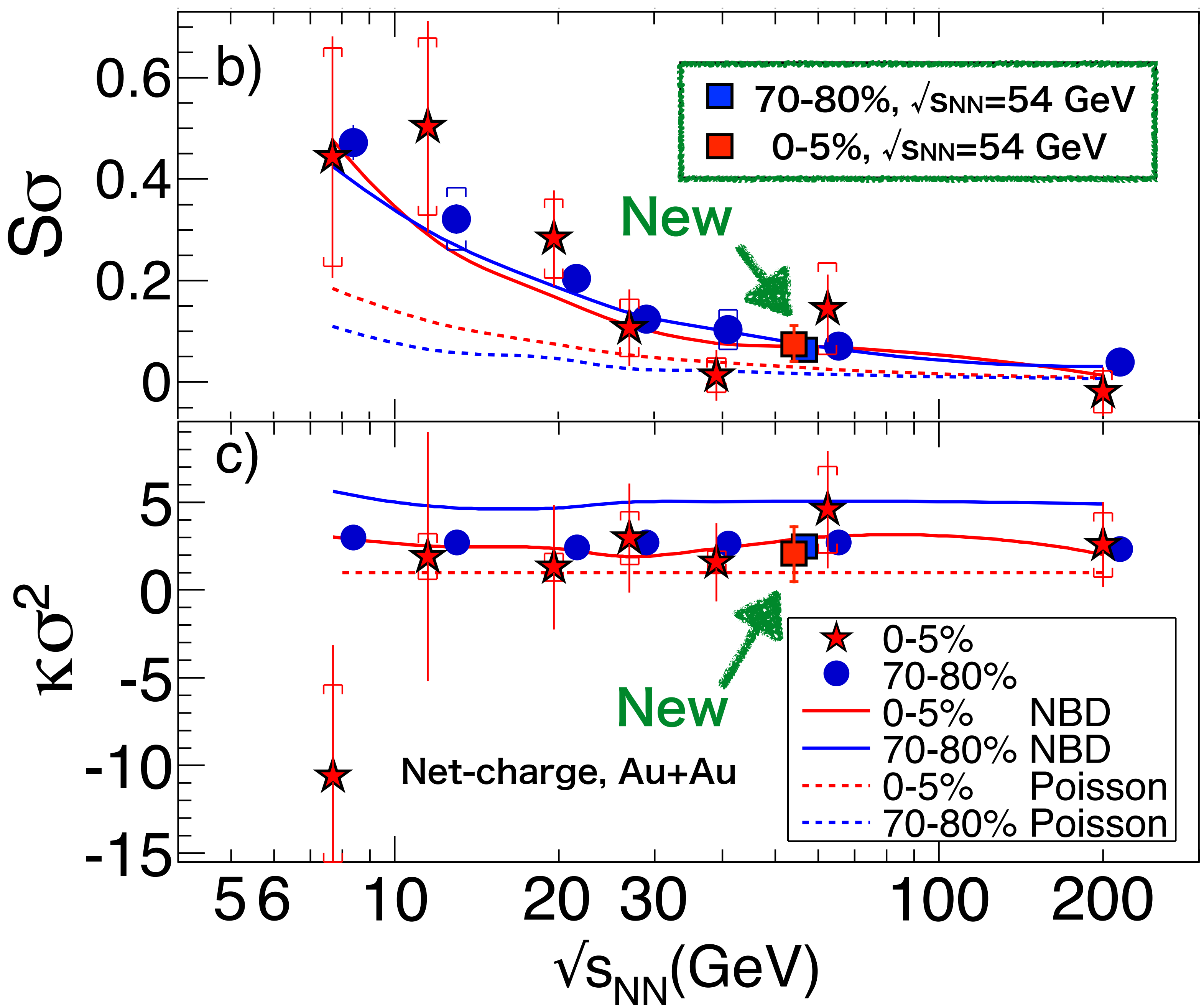
C_6/C_2 (0-40% merged)





- 0-40% centralities are merged.
- Deviation between 200 GeV and 54 GeV is ovserved in 0-40% centrality at net-proton and 40-50% at net-charge.
  → Signal from cross-over??
- Statistical errors are large and which results should be compare to lower energies in future.

C_3/C_2 and C_4/C_2 at 54 GeV



$$S\sigma = \frac{C_3}{C_2} = \frac{\chi_3}{\chi_2}$$

$$\kappa\sigma^2 = \frac{C_4}{C_2} = \frac{\chi_4}{\chi_2}$$

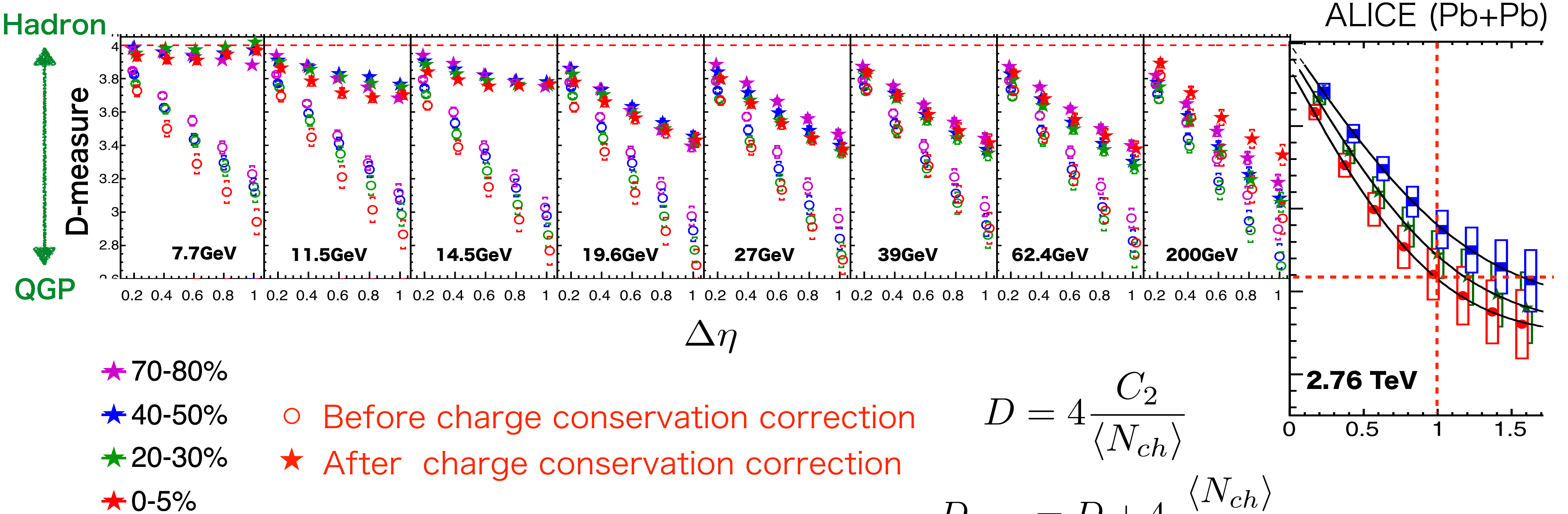
L. Adamczyk *et al.* (STAR Collaboration)
Phys. Rev. Lett. 113, 092301(2014)

- C_3/C_2 and C_4/C_2 of net-charge at 54 GeV are newly measured in addition to BES energies.
- Close to 39 GeV and 62.4 GeV results.

→ Results at 54 GeV are not conflict with publisehd BES-I results.

Results (Δη dependence)

Δη dependence of D-measure

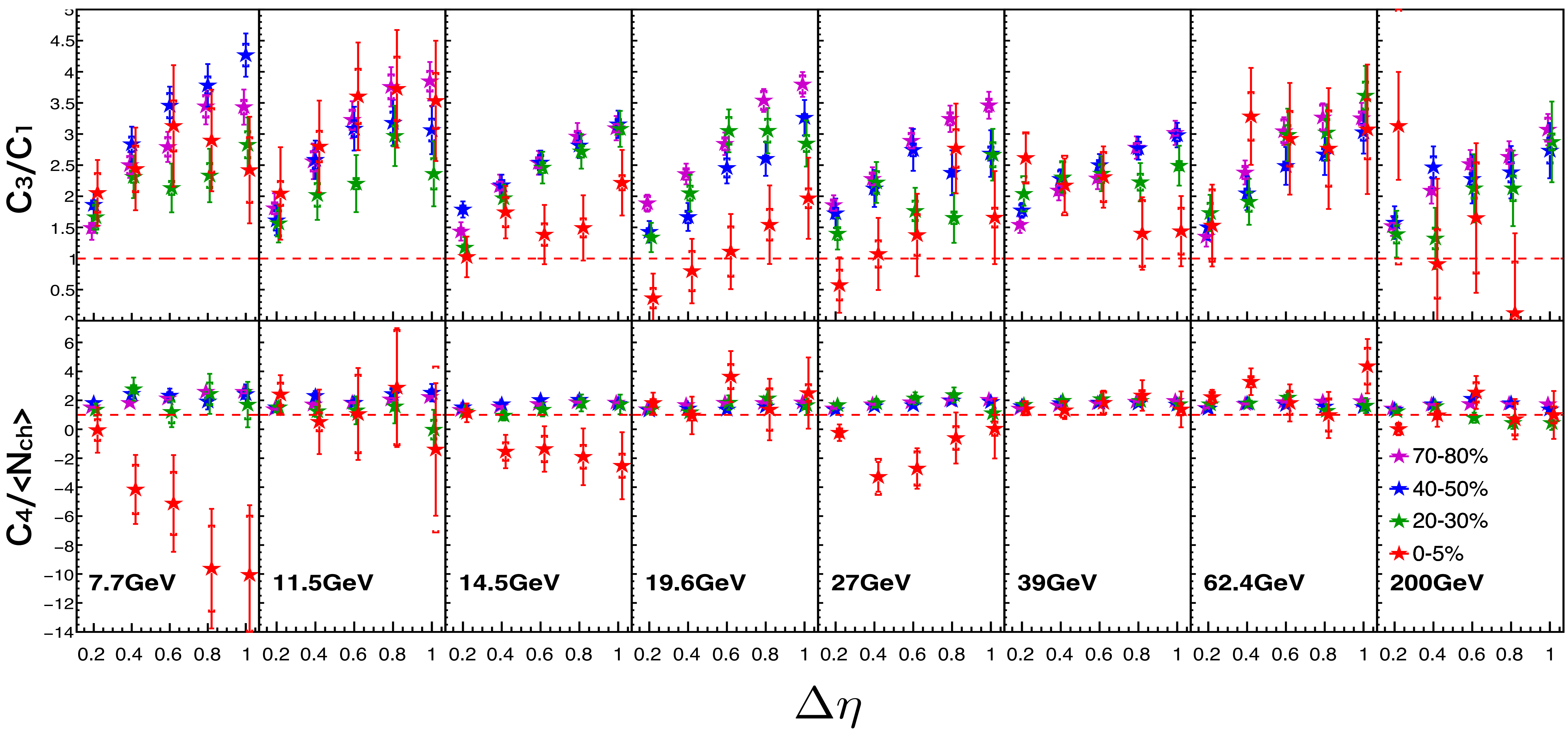


$$D = 4\frac{C_2}{\langle N_{ch} \rangle}$$

$$D_{corr} = D + 4\frac{\langle N_{ch} \rangle}{\langle N_{total} \rangle}$$

- D-measure are observed to decreace with Δη.
- Even tough charge conservations are applied, D-measure is decreace with Δη and this trend is stronger with collision energies.
- These results do not conflict with ALICE and the trends of Δη dependence might represent the time evolution of phase transition.

Experimental results of C_3/C_1 and $C_4/\langle N_{ch}\rangle$



- At C_3/C_1 and $C_4/\langle N_{ch}\rangle$, most of the results are observed to increase with $\Delta\eta$ without most central collision at $C_4/\langle N_{ch}\rangle$.
- These treands can not be descrived by diffusion process whereas the treands of D-measure can be explained by this model.

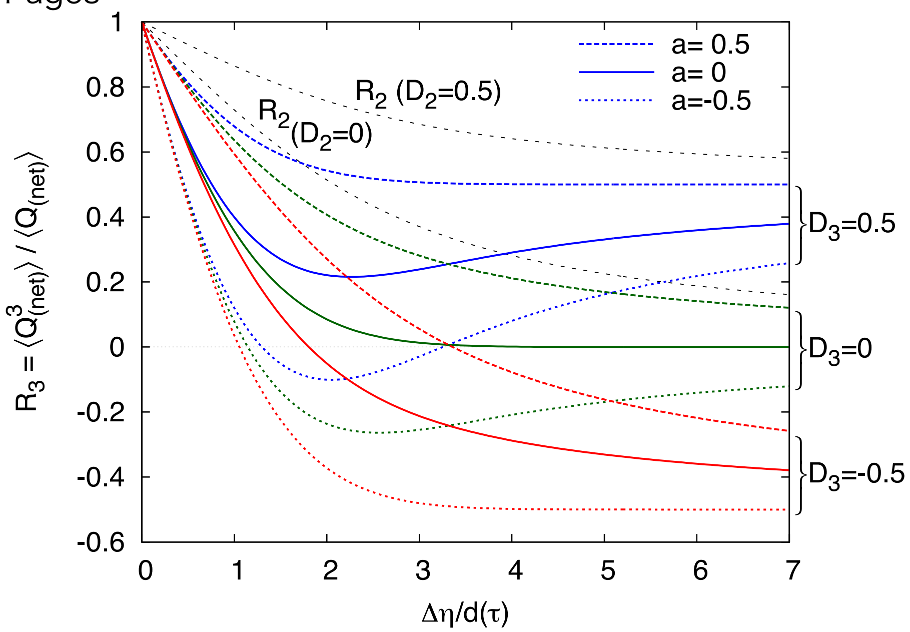
Theoretical predictions of C_3/C_1 and $C_4/$<N_{ch}>

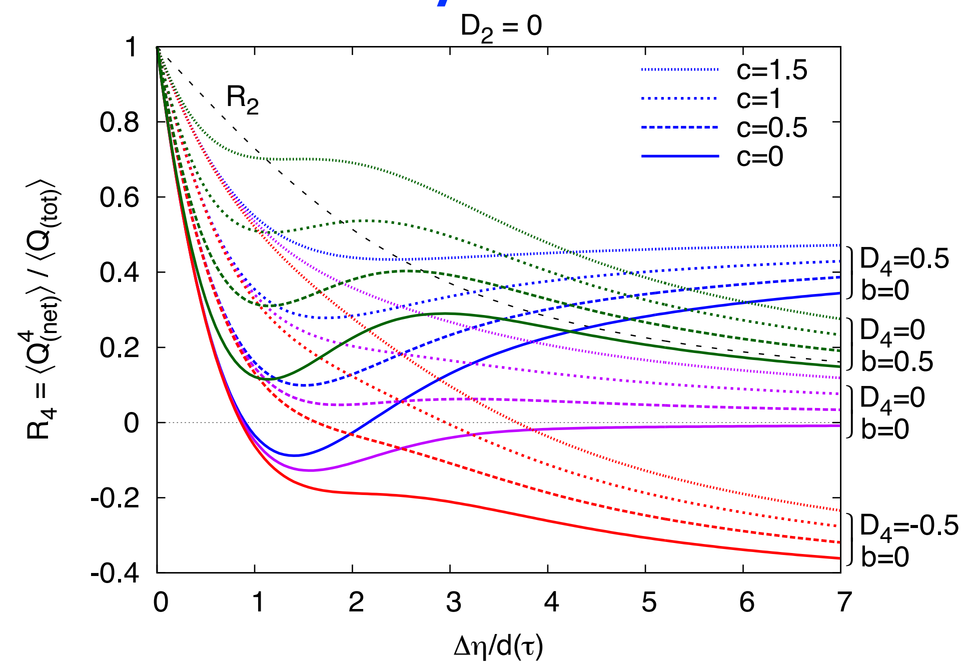
M.Asakawa, M.Kitazaw,
Progress in Particle and Nuclear Physics
Volume 90, September 2016, Pages
299-342

C_3/C_1

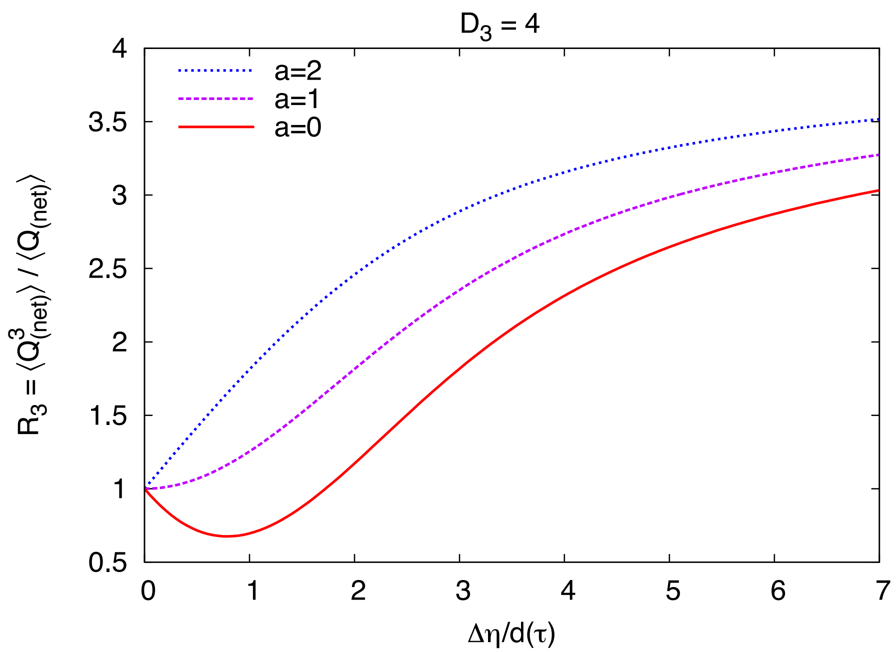
$C_4/$<N_{cn}>

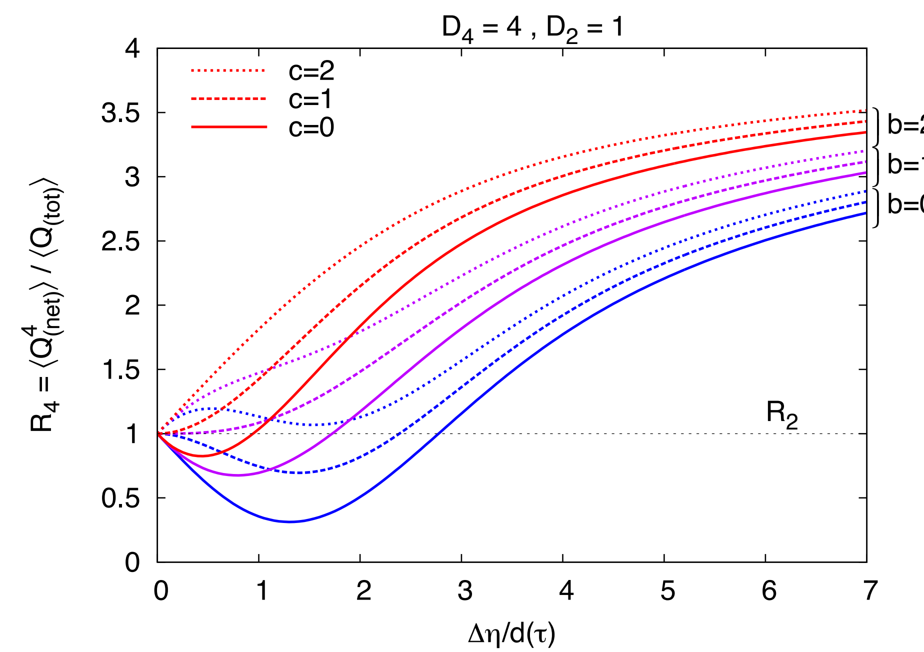
Small susceptibilities





Large susceptibilities





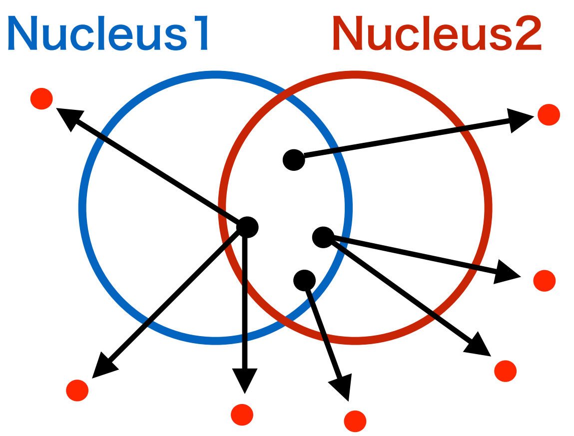
- Δη dependence of **third and fourth-order cumulant ratios are also predicted** by the model but there are a lot of parameters and depend on initial condition.
- Experimental results are close to theoretical expectation with large susceptibilitiy reults.

Volume fluctuation correction

Volume fluctuation correction (VFC)

Nuclear Physics A Volume 960, April 2017, Pages 114-130

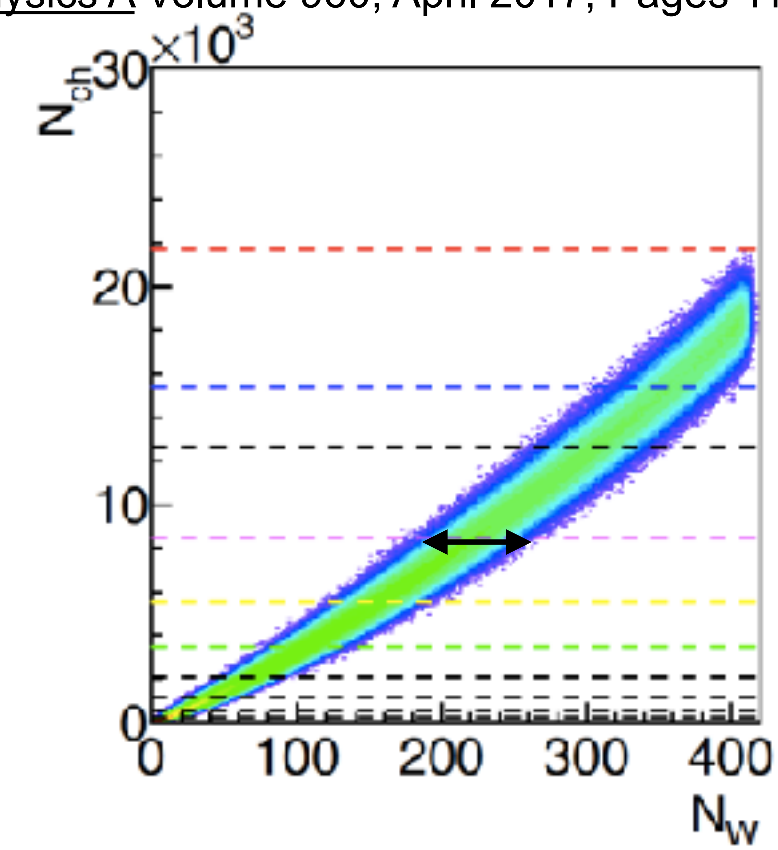
- Nw is fluctuating even if final state multiplicity is fixed.
  →**CBWC may not be enough to eliminate VF**



Independent particle production (IPP) model

● : initial source

● : final state multiplicity



- Under the IPP model, measured cumulants include additional term from VF which can be written by Nw cumulants.
- We can know **true cumulants by subtracting additional terms (VFC)**

Measured cumulant | True cumulant

Δn : number of net-particle

Additional term caused from N_W fluctuation

$$\kappa_1(\Delta N) = \langle N_W \rangle \kappa_1(\Delta n)$$

$$\kappa_2(\Delta N) = \langle N_W \rangle \kappa_2(\Delta n) + \langle \Delta n \rangle^2 \kappa_2(N_W)$$

$$\kappa_3(\Delta N) = \langle N_W \rangle \kappa_3(\Delta n) + 3\langle \Delta n \rangle \kappa_2(\Delta n) \kappa_2(N_W) + \langle \Delta n \rangle^3 \kappa_3(N_W)$$

$$\kappa_4(\Delta N) = \langle N_W \rangle \kappa_4(\Delta n) + 4\langle \Delta n \rangle \kappa_3(\Delta n) \kappa_2(N_W) + 3\kappa_2^2(\Delta n)\kappa_2(N_W) + 6\langle \Delta n \rangle^2 \kappa_2(\Delta n) \kappa_3(N_W) + \langle \Delta n \rangle^4 \kappa_4(N_W)$$

Toy model method

- Generate 2 independent Poisson distribution
- Parameter : λ_+, λ_-

Glauber : 500M events
Poisson : 100M events

$$\lambda_+ * \langle N_W \rangle = N_+$$
$$\lambda_- * \langle N_W \rangle = N_-$$
$$(\lambda_+ - \lambda_-) * \langle N_W \rangle = (N_+ - N_-)$$

Nw Calculated from Glauber

Number of particles

- λ_+ and λ_- are determined to N_+ and N_- describe the real experiment.

Nw fixed : Generate Poisson <Nw> times.
…No Nw fluctuation

Nw fluc : Generate Poisson Nw times.
…Nw fluctuation

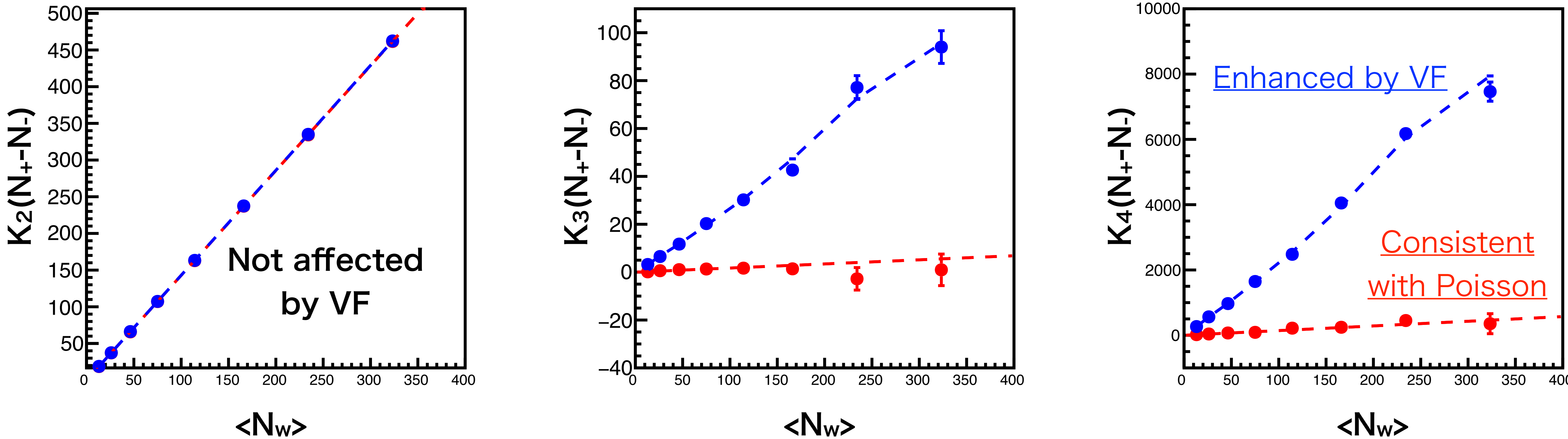
VFC : Subtract Nw fluctuation

Should be same

- Nw fixed
- Poisson
- Nw fluc **VF(large)**
- Nw fluc Exp
- VFC
- CBWC+Nw fluc **VF(small)**

- **Nw fixed** and **VFC** results should be same.
- Results from CBWC are also compared.

Toy model VFC check (10%step)

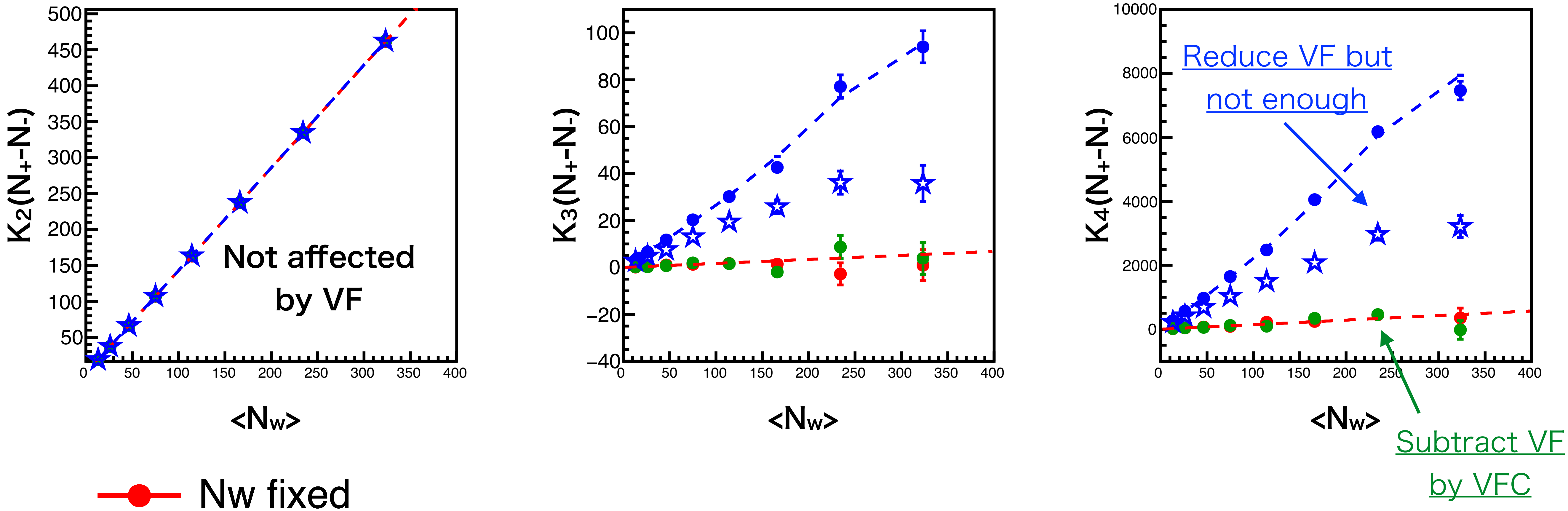


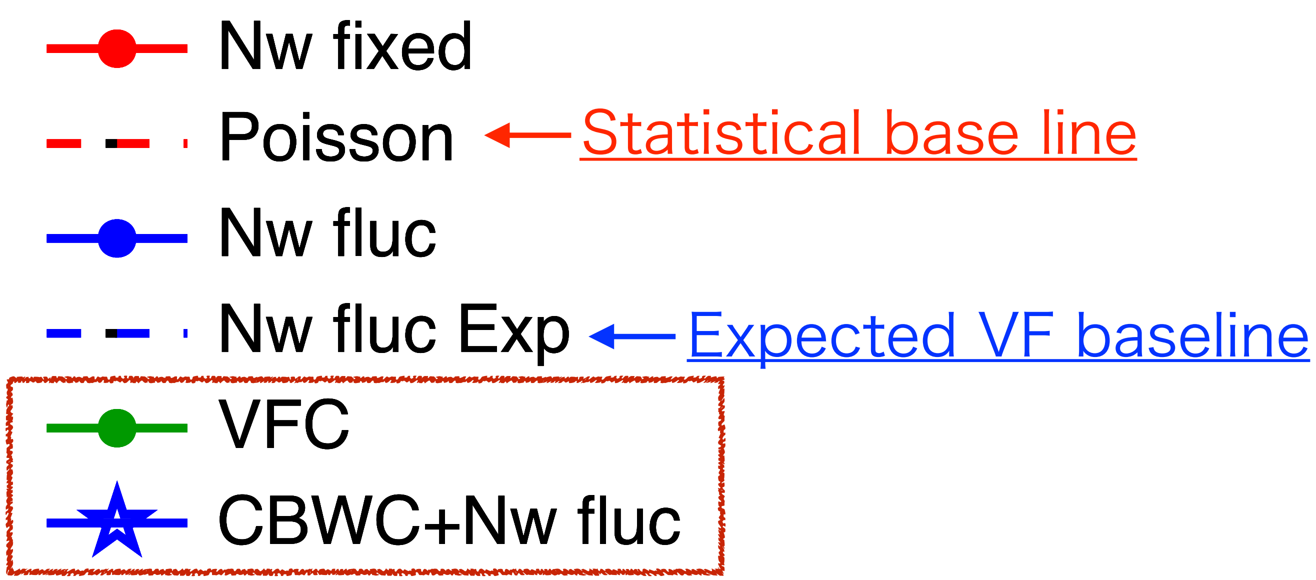
- Nw fixed
- Poisson ← Statistical base line
- Nw fluc
- Nw fluc Exp ← Expected VF baseline

Glauber : 500M
Poisson : 100M
bootstrap=100

- K_2 does not largely affected by participant fluctuation.
- Nw fixed cumulants are consistent with Poisson baseline.
- Nw fluc cumulants are enhanced by VF.

Toy model VFC check (10%step)





Glauber : 500M
Poisson : 100M
bootstrap=100

- VFC works well up to 4-th order cumulants.
- CBWC can reduce VF but not enough.

UrQMD model

- **VFC will be done by using UrQMD** model in which **IPP model might be broken**.
- In this model, **we can directly know N_w without Glauber fit**.

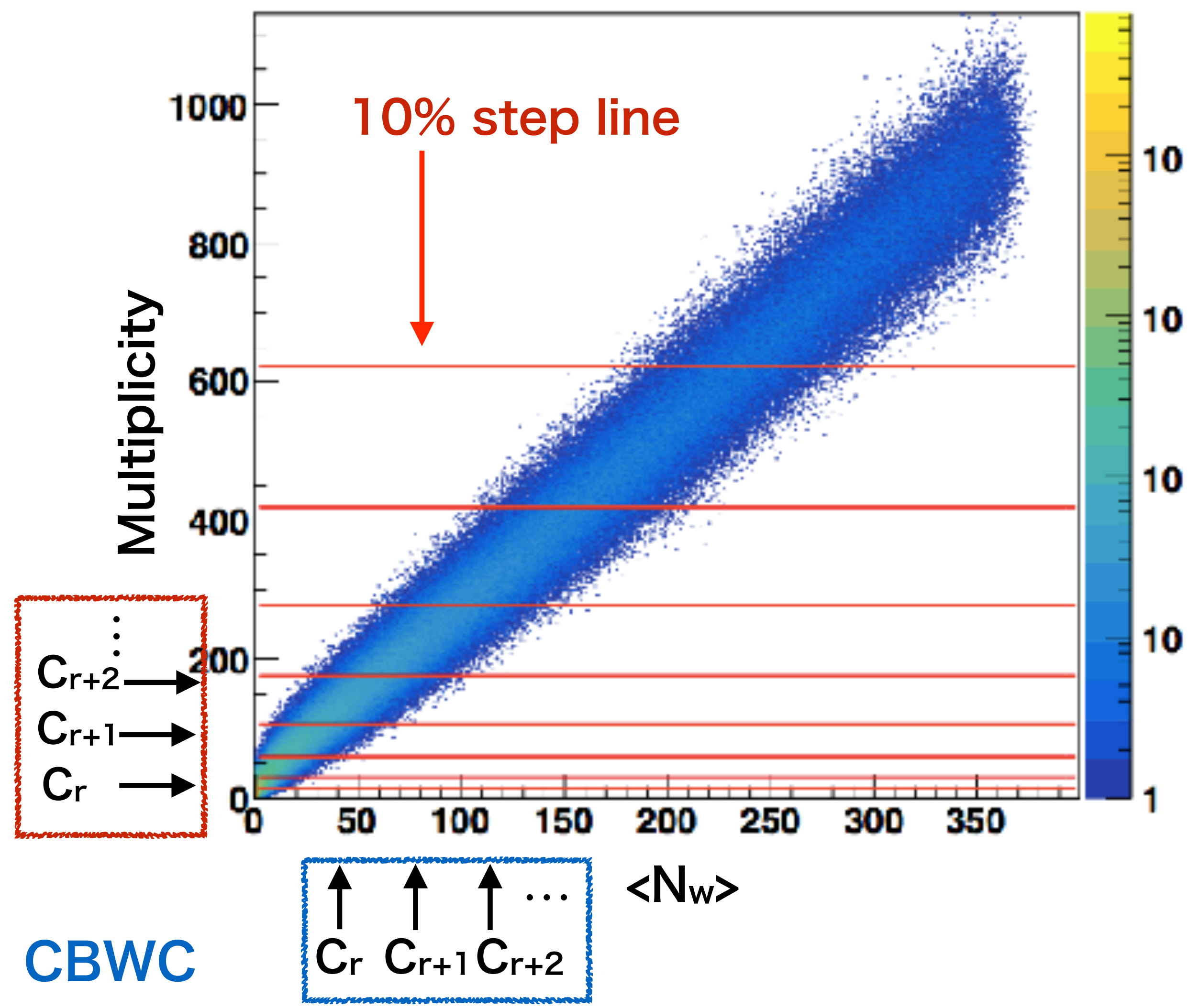
How to know “true” cumulants?

- In order to compare to CBWC and VFC results, we want to know “true” (no VF) cumulants.
- “True” cumulants can be calculated by CBWC using **N_w instead of multiplicities.**

$$C_n = \sum_{r} w_r C_{(n,r)}$$

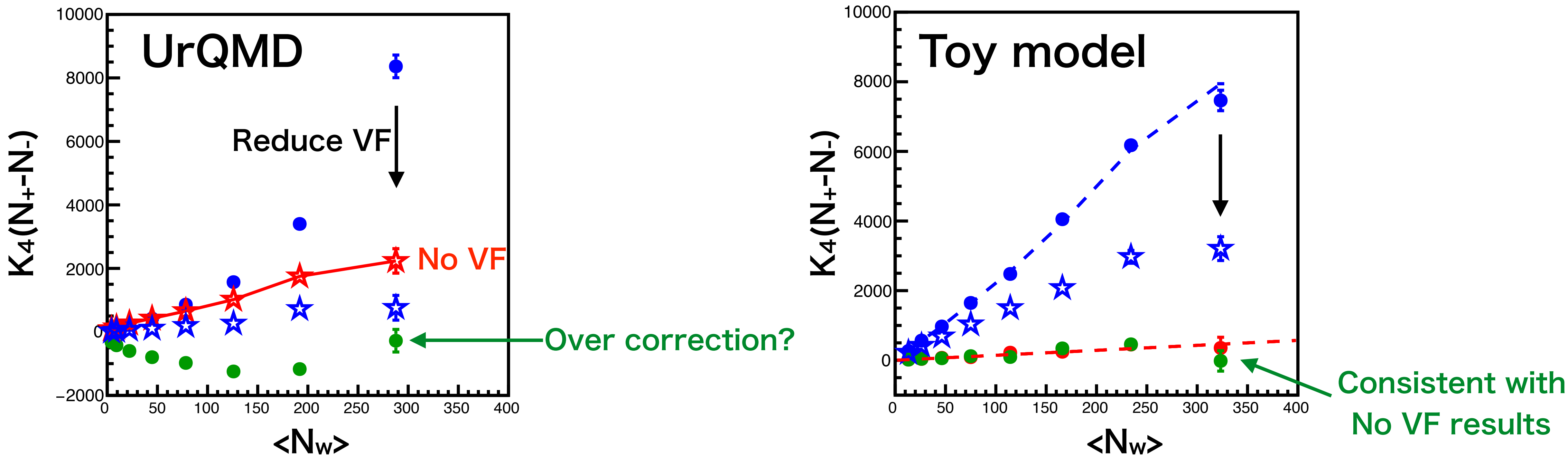
Cumulants in r-th Nw bins

Standatd CBWC



CBWC by Nw (no VF)

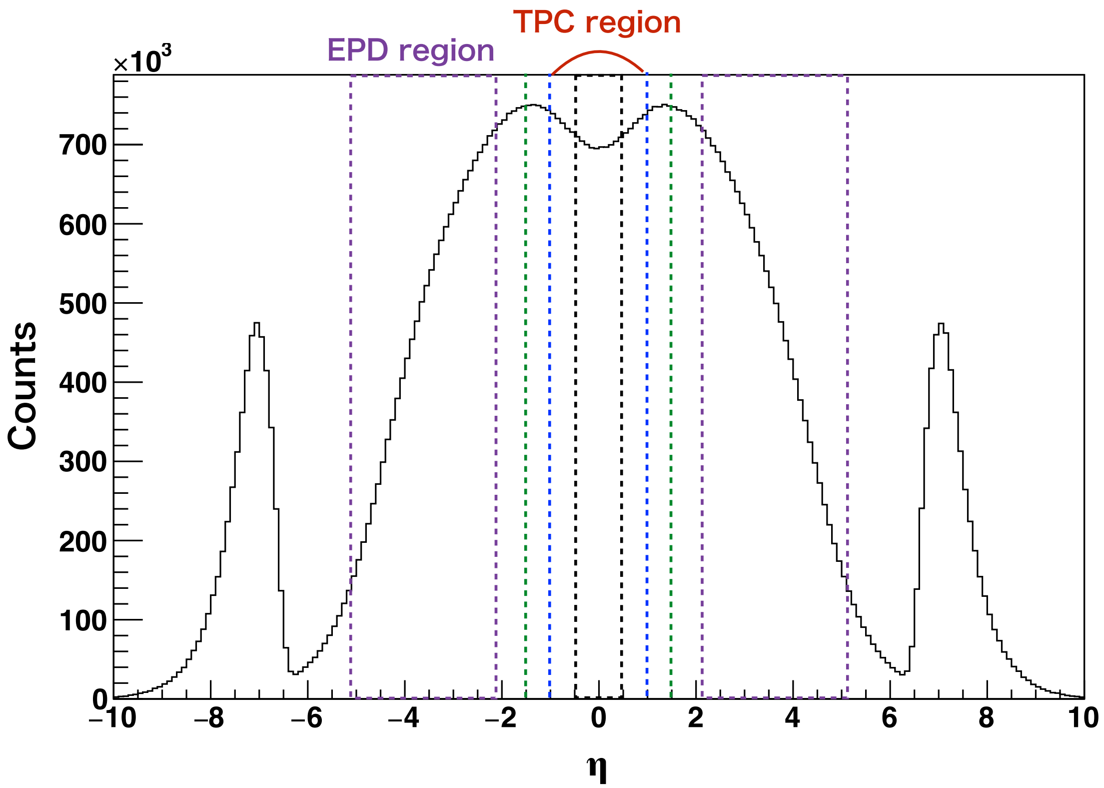
UrQMD results (Net-charge)



Raw	: No correction
VFC	: VFC was applied
CBWC-Nw (no VF)	: CBWC by Nw (true)
CBWC	: CBWC by multiplicity (experimental CBWC)

- CBWC-Nw (no VF, true) cumulants are larger than CBWC results even though CBWC results include VF.
  - IPP assumption is expected to be broken in UrQMD.
- CBWC results are larger than VFC results and close to CBWC-Nw cumulants.
  - CBWC is better than VFC?

Correlation in UrQMD



- In Toy model, particles used for centrality determination and particles used for the net-charge calculation are produced independently.
- On the other hand, cumulants in UrQMD may include auto-correlation effect.

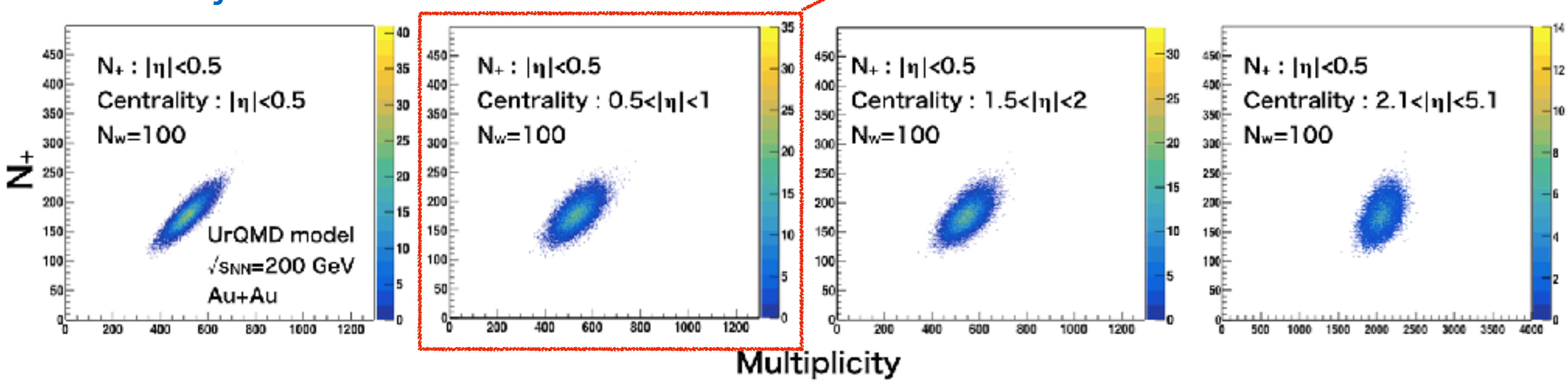
① |η|<0.5 (Refmult)

② 0.5<|η|<1 (Refmult2)
 - experimentally used for net-c analysis

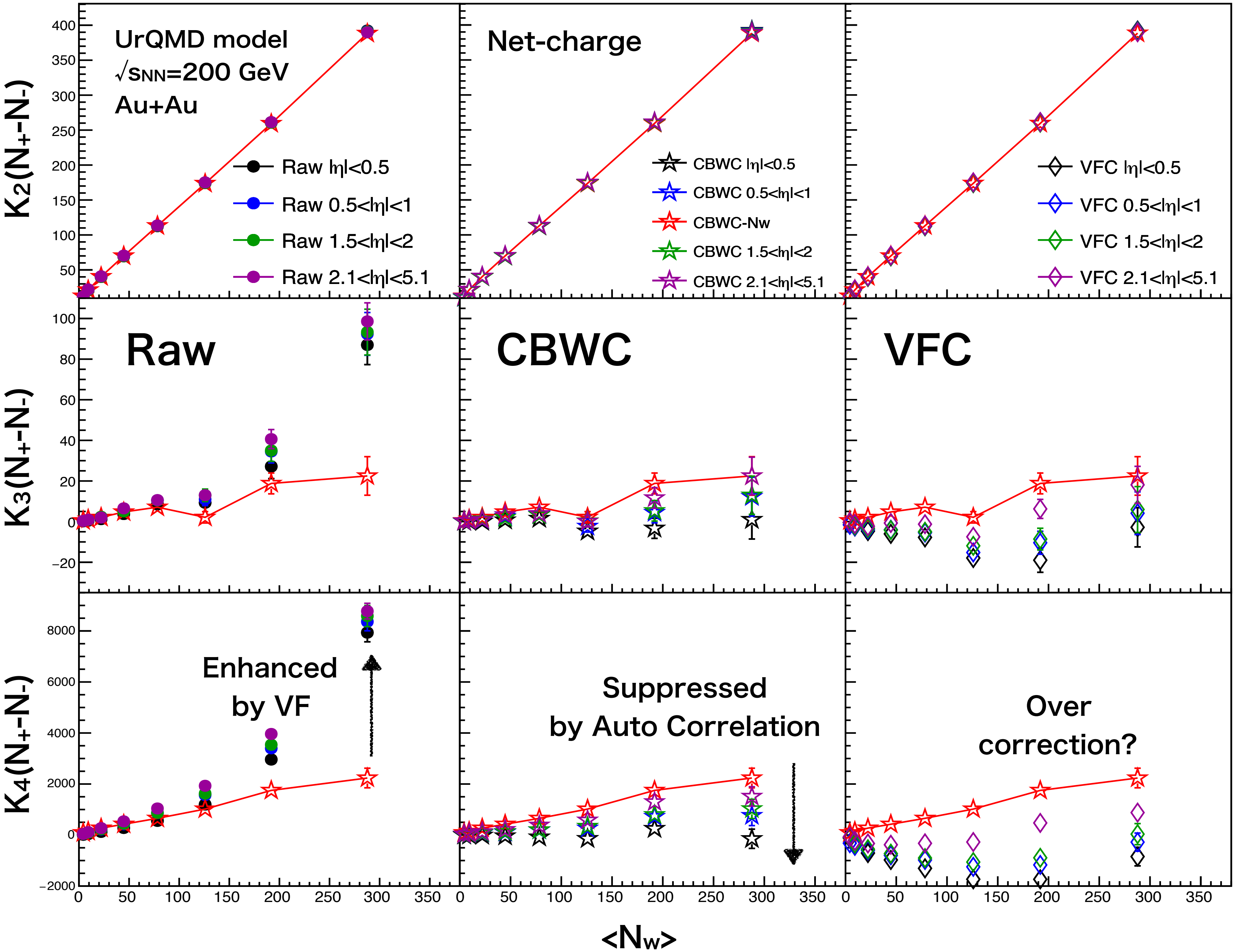
③ 1<|η|<1.5

④ 2.1<|η|<5.1 (EPD region)
 - centrality determination from BES II

<u>Correlation remain even though different eta regions were used for centrality determination and particles net-charge calculations</u>



UrQMD with different centrality determination (Net-charge)

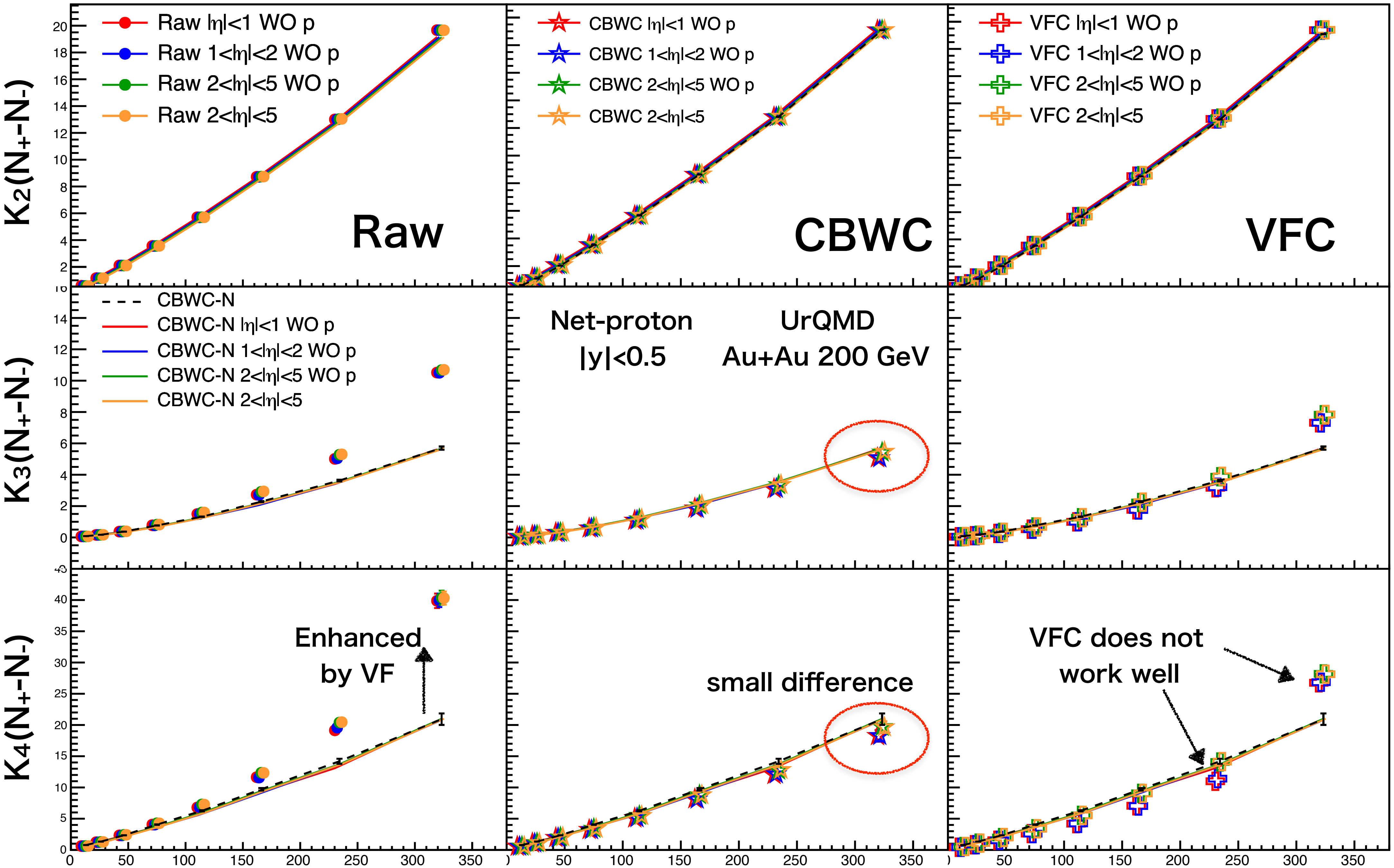


|η|<0.5
0.5<|η|<1
1<|η|<1.5
2.1<|η|<5.1

CBWC-Nw :
No VF and written in all plot

- Suppressions are observed because of the correlation
  - Largest in |η|<0.5 and smallest in EPD region (2.1<|η|<5.1)
- VF are observed in raw results but not observed in CBWC results
  - NOT consistent with Toy model. IPP is broken?
- If CBWC-Nw results are “true”, VFC results are over correction

UrQMD with different centrality determination (Net-proton)



- Similar studies have been done by net-proton case
- Similar behaviour has been observed as net-charge case but magnitude is smaller than net-charge results.

Summary

C_6 net-charge analysis

- Net-charge cumulants **up to 6th-order** at $\sqrt{s_{NN}}$**=200 GeV and 54 GeV** in Au+Au collisions were reported.
- C_6/C_2 were compared to Poisson, NBD, UrQMD and net-proton results.
- **Deviation** are ovserved between **200 GeV and 54 GeV** in **0-40%** centrality at **net-proton** and **40-50%** at **net-charge**.
  - These results are **not conflict with the theoretical prediction** of cross-over
  transition but **statistical errors are large**.
  - Results of the other centralities are consistent with statistical baseline within the statistical error.
- C_3/C_2 and C_4/C_2 of **net-charge** at $\sqrt{s_{NN}}$**=54 GeV** are newly measured in addition to BES energies and results were **not conflict with publisehd BES-I results**.

Summary

Δη dependence analysis

- **Δη dependence of net-charge cumulants and D-measure** were measured in Au+Au collisions at $\sqrt{s_{NN}}$**=7.7, 11.5, 14.5, 19.6, 27, 39, 62.4 and 200 GeV**.
- D-measure **decreace with Δη** and this trend is **stronger with collision energies**.

  - These results **do not conflict with ALICE** and the trends of Δη dependence **might represent the time evolution of phase transition**.
- $C_4/\langle N_{ch}\rangle$ and $C_3/\langle N_{ch}\rangle$ are observed to increase with Δη in most of centralities which may be the hint of the signal from phase transition.

Summary

VFC

- The validity of the VFC on higher-order net-charge and net-proton cumulants have been studied by using toy model and UrQMD model in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV.
- **Even though CBWC has applied, we can't completely remove participant fluctuation under the IPP models**.
- However, **VFC does not works well in UrQMD model so IPP model is expected to be broken** in UrQMD.
- The values of cumulants are also depend on how determine centrality because an correlation between net-quantities and the multiplicity which is used for centrality determination is different.
- EPD is installed from BES-II, and the cumulants **may become larger** than current results when we determine the centrality by EPD instead of TPC.

Ouklook

- BES-II will start from 2019
  - High statistics at lower energy region
  - Access more forward rapidity with new detector (iTPC, eTOF and EPD).
- Sixth-order cumulants can be measured at lower energy region and can be compare to the results at 200 GeV and 54GeV.
- $\Delta\eta$ dependence can be measured from 0 to 1.5 by iTPC and eTOF ($0<\Delta\eta<1$ in currect analysis).
- It is important to study whether we should apply VFC to experimental results or not for future analysis.

back up

Statistical errors of cumulants

Generally…

- ✓ Statistical error of **net-charge cumulant** is larger than **net-proton cumulants**
- ✓ Statistical error of cumulant **in central** is larger than cumualnt in **peripheral**

Why?

➡ Cumulants depend on the width of the distribution (**σ**).

For example

Mean value : $\mathbf{C_1 \pm \sigma/\sqrt{N}}$ → Standard Error

➡
- Statistical error of C_1 is proportional to σ.
- Statistical error of nth-order cumulant is written by

$$\mathbf{Err(C_n) \sim \sigma^n/\sqrt{N}}$$

Rough estimation of statistical errors

Efficiency Uncorrected

$$\mathrm{Err}\left(\frac{C_3}{C_2}\right) \propto \frac{\sigma}{\sqrt{n}}$$

$$\mathrm{Err}\left(\frac{C_4}{C_2}\right) \propto \frac{\sigma^2}{\sqrt{n}}$$

$$\mathrm{Err}\left(\frac{C_6}{C_2}\right) \propto \frac{\sigma^4}{\sqrt{n}}$$

Efficiency Corrected

$$\mathrm{Err}\left(\frac{C_3}{C_2}\right) \propto \frac{\sigma}{\epsilon\sqrt{n}}$$

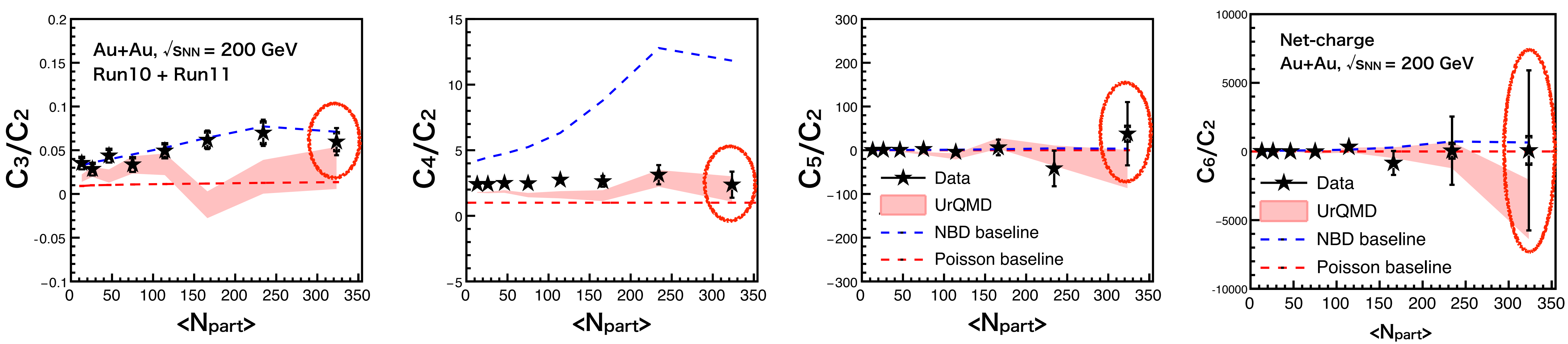
$$\mathrm{Err}\left(\frac{C_4}{C_2}\right) \propto \frac{\sigma^2}{\epsilon^2\sqrt{n}}$$

$$\mathrm{Err}\left(\frac{C_6}{C_2}\right) \propto \frac{\sigma^4}{\epsilon^4\sqrt{n}}$$

For example: σ^2=350, ε =0.4~0.5
(0-10%, 200GeV, Eff corr)

σ / ε =40~100

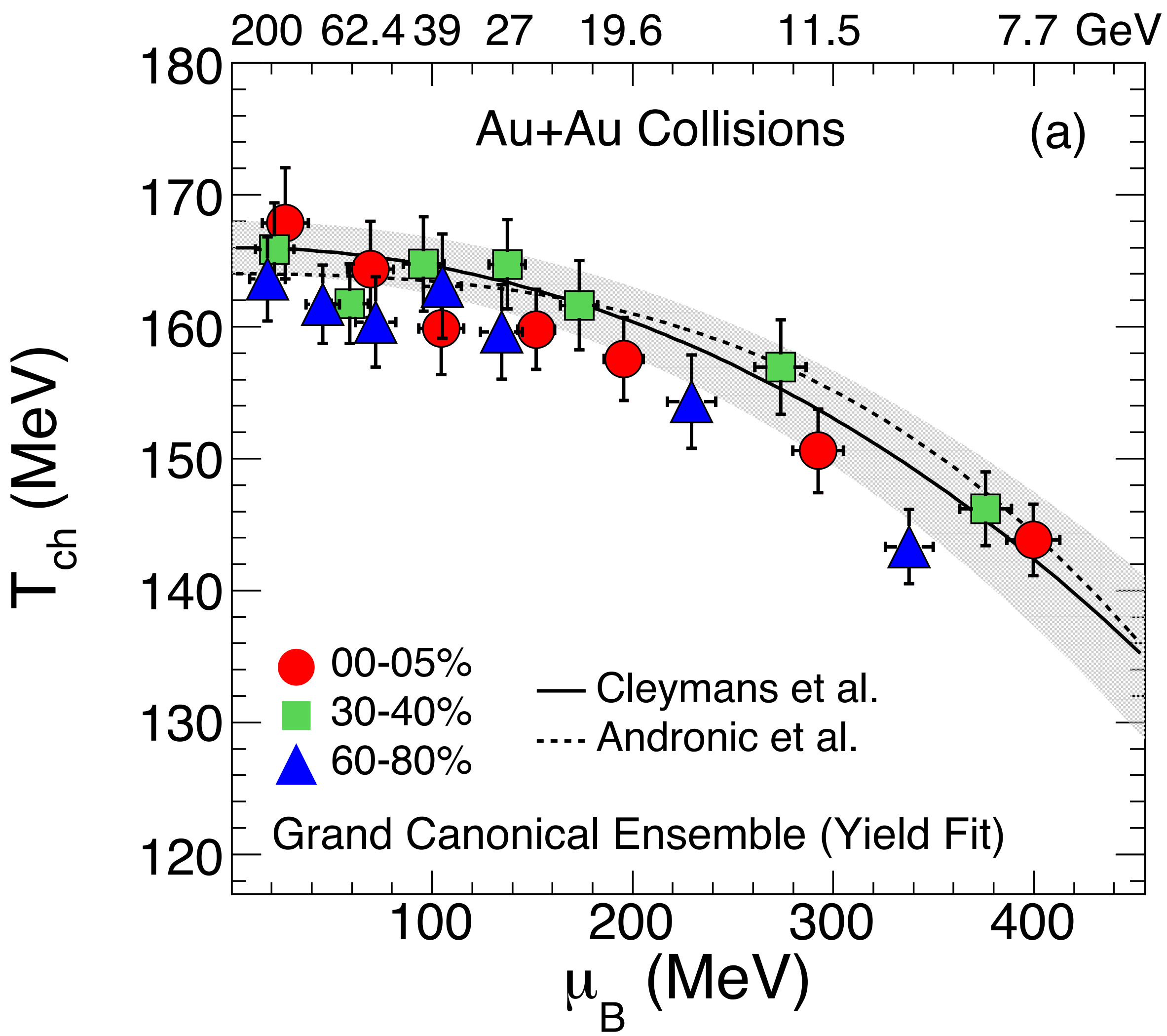
- Error of C_6/C_2 is more than 1000 time large than that of C_4/C_2.

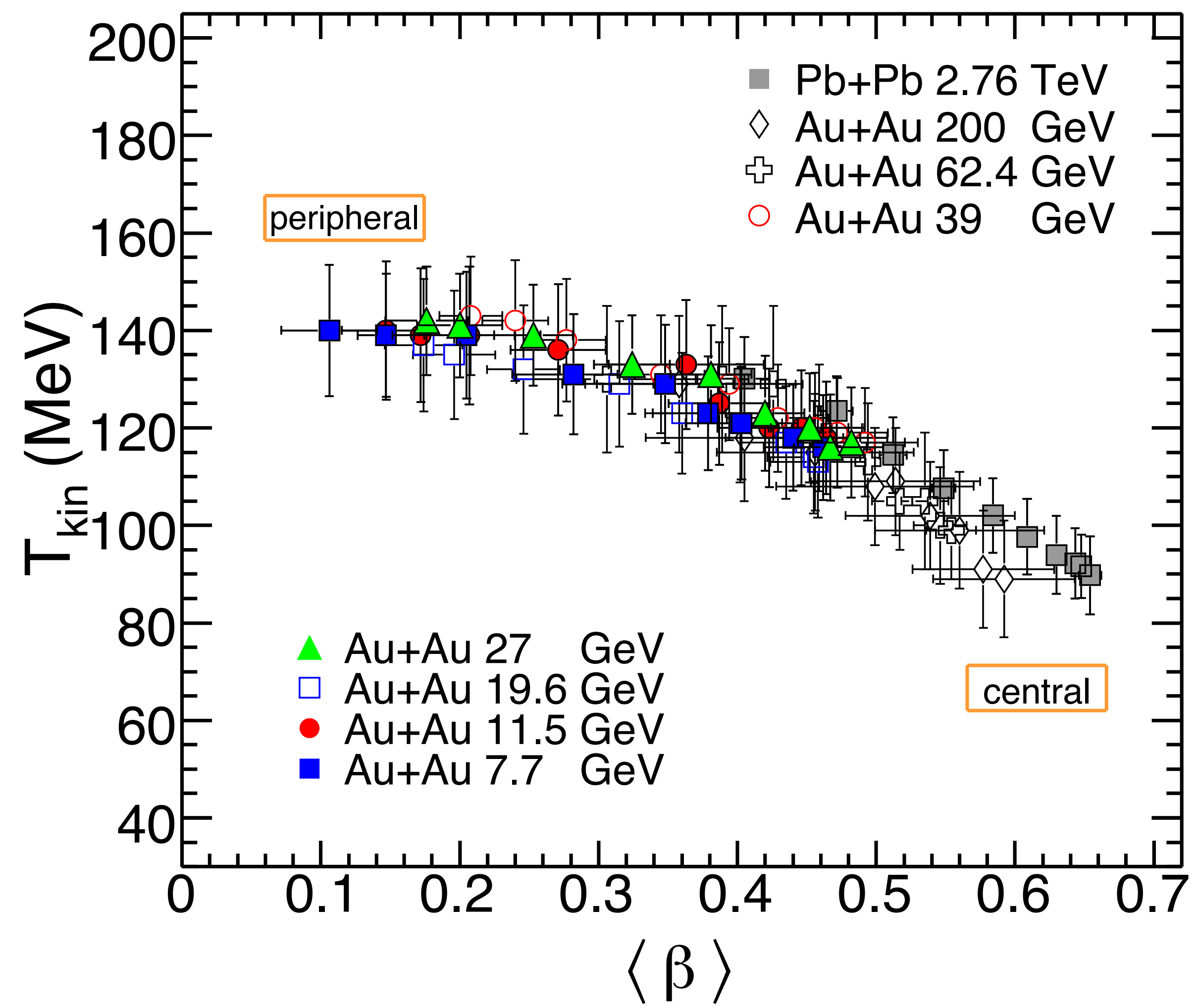


	C3/C2	C4/C2	C5/C2	C6/C2
St.Err	~0.014	~1	~70	~5600

*σ / ε *σ / ε *σ / ε

Freeze-out parameters



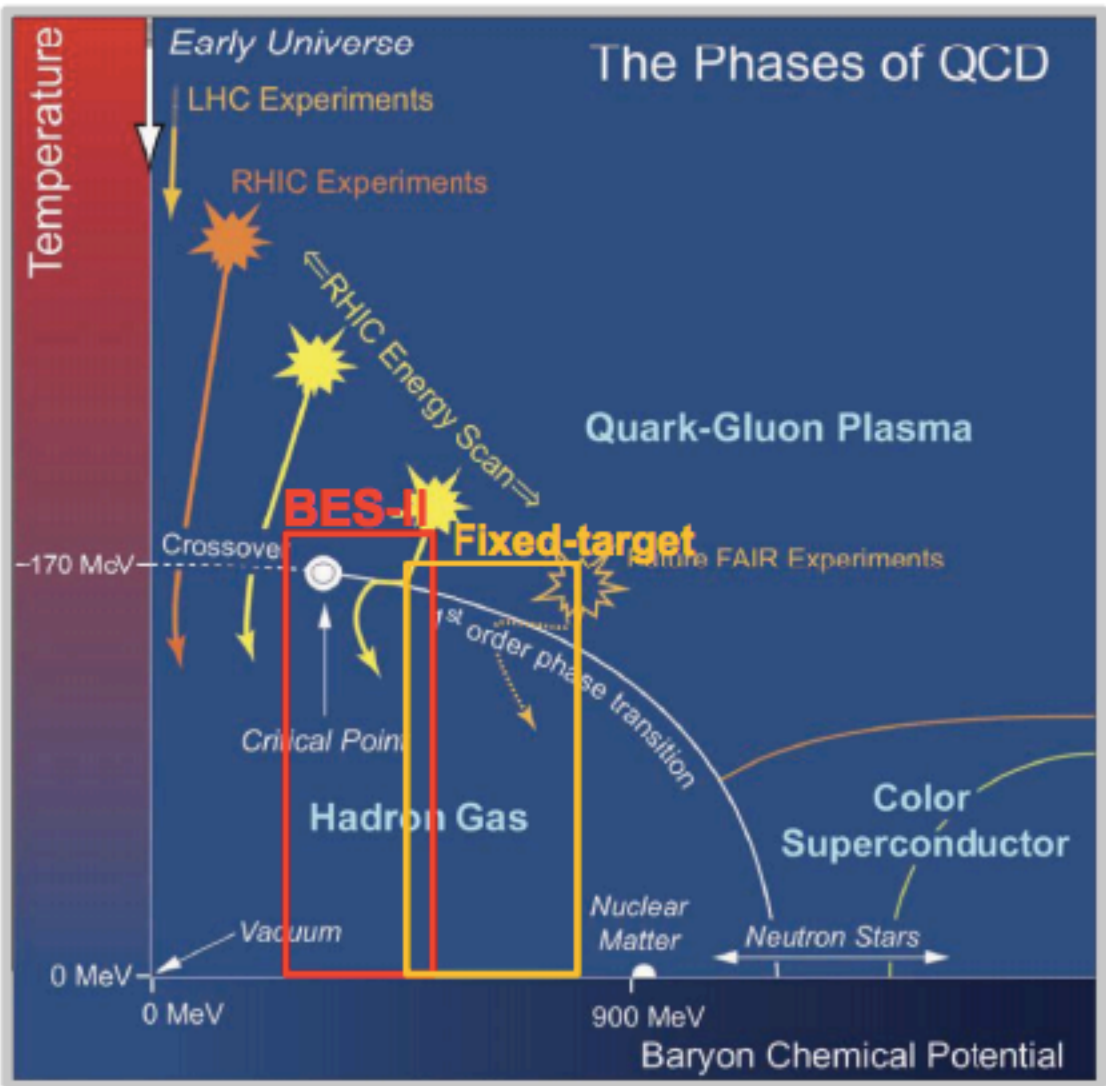


- Chemical and kinetic freeze-out and parameters are obtained from particles yield and spectra.

What is the good observables which is sensitive to the phase transition?

→ Event by event fluctuations are considered as one of the powerful tool to discover the phase diagram.

Beam Energy Scan Phase II (BES- II)



STAR, Q.Yang (talk)

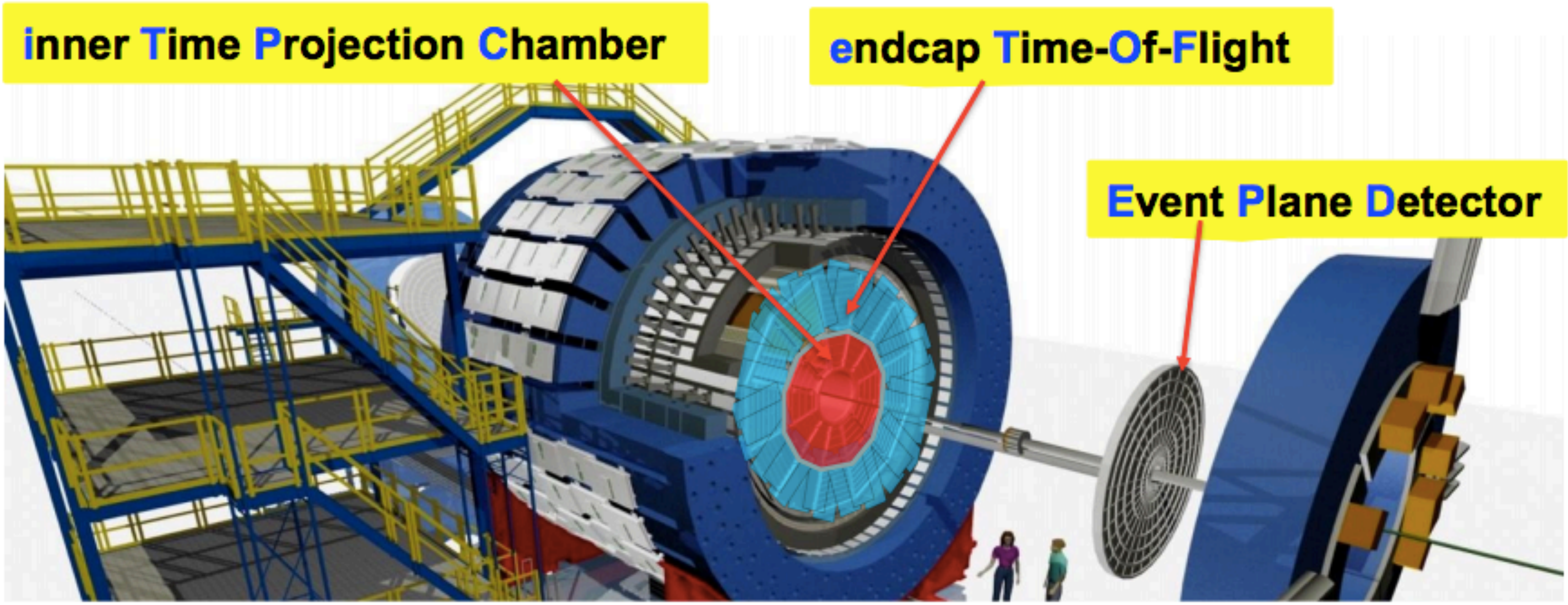
$\sqrt{S_{NN}}$ (GeV)	Proposed Event Goals (M)	BES-I Event (M)
7.7	100	4
9.1	160	N/A
11.5	230	12
14.5	300	20
19.6	400	36
3.0 - 7.7	~100 per energy	N/A

Collider mode

Fixed-target mode

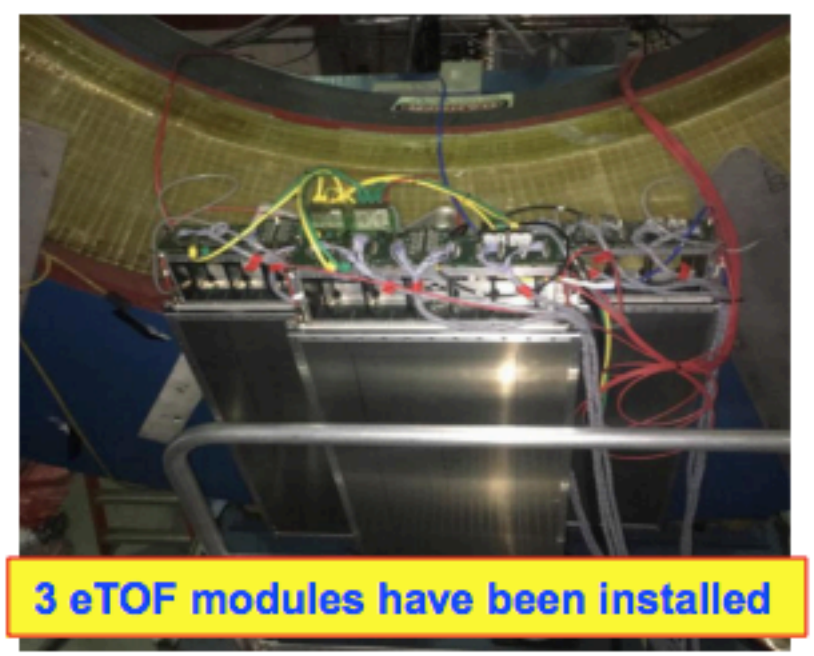
- RHIC BES II :10-25 times more statistics and detector upgrade
  →**Dramatically reduce the uncertainties.**
- Precise map the QCD phase diagram 200<μ_B<720 MeV

Detector upgrades




One iTPC sector has been installed


Full EPD has been installed


3 eTOF modules have been installed

Q.Yang (STAR collaboration) QM2018

Value of D-measure

D-measure (D)

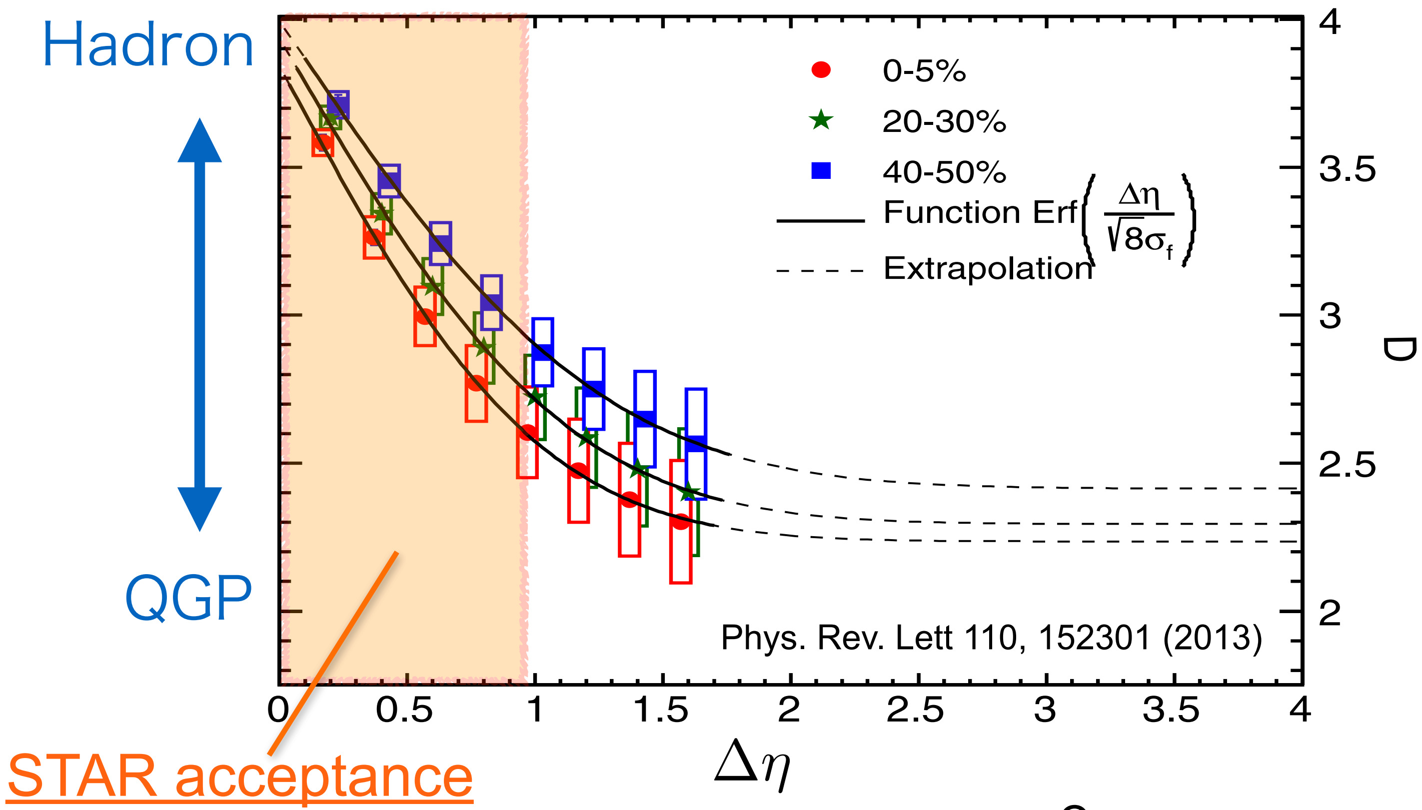
$$D = 4\frac{C_2}{\langle N_{ch} \rangle} \qquad N_{ch} = N^+ + N^-$$

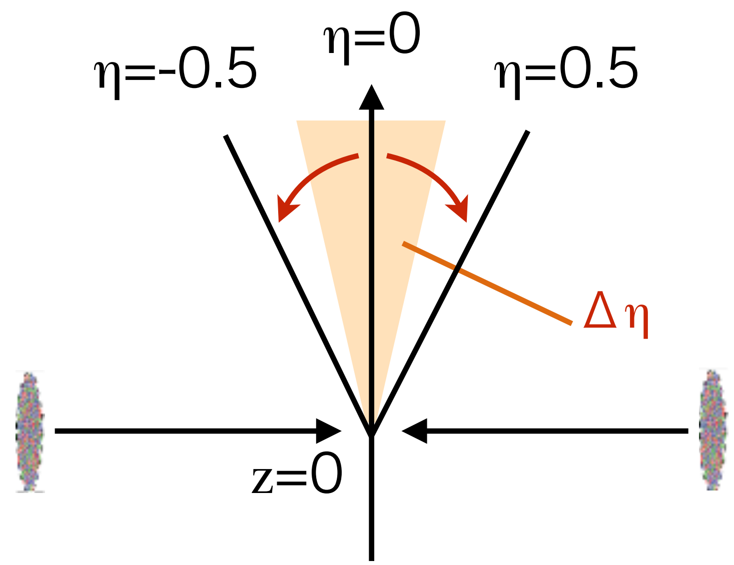
Theoretical predictions

QGP fluctuation : D =1-1.5

Hadron fluctuation : D= 3-4

ALICE (2.76TeV Pb+Pb)

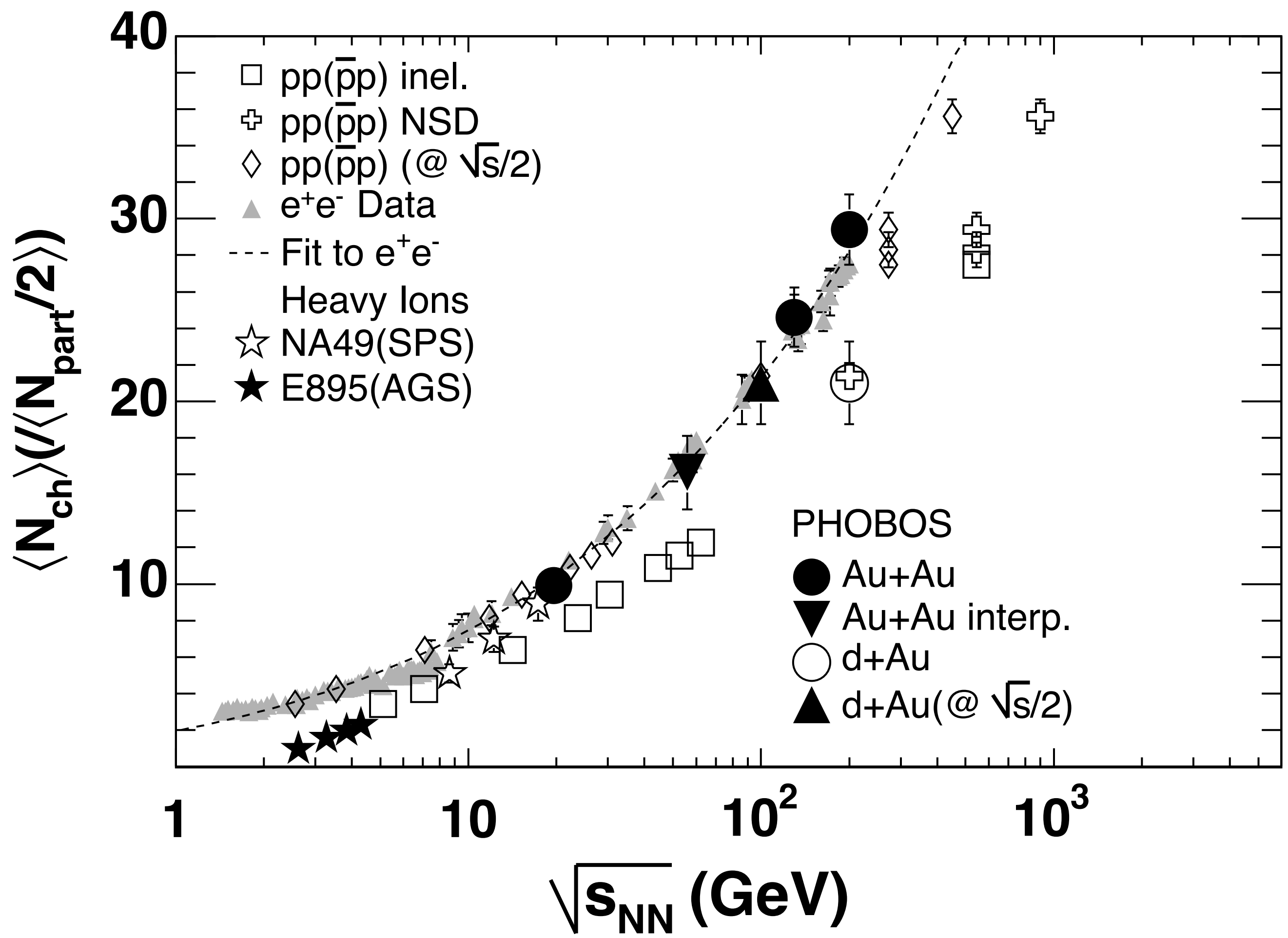




- **D-measure is ovserved to decreace with expanding Δη** in Pb-Pb collisions at 2.76 TeV at ALICE.
- D-measure also decreace from peripheral to central collisions.

Charge conservation correction on D

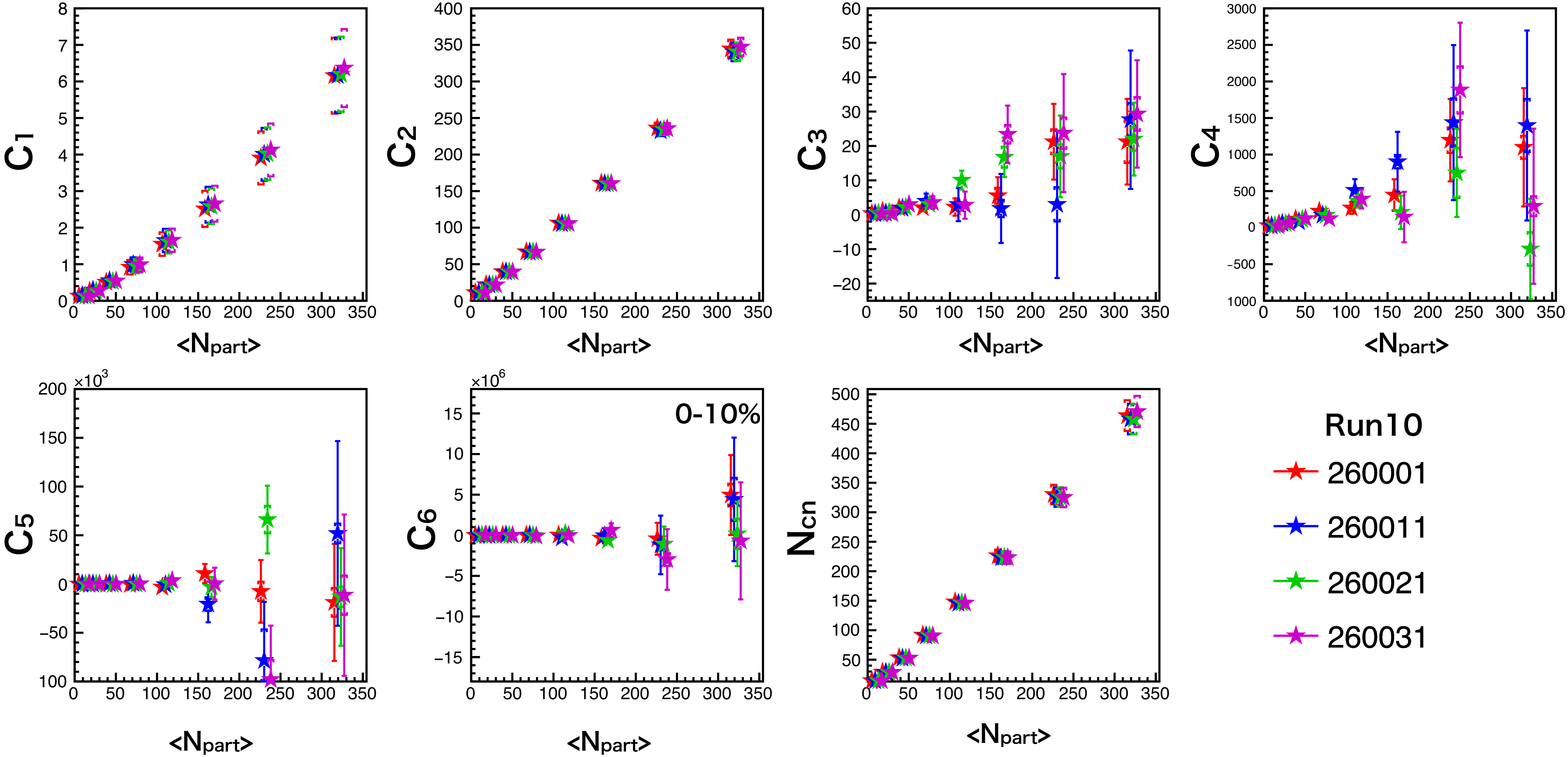
B. B. Back et al. (PHOBOS Collaboration),
Nuclear Physics A Volume 757, Issues 1–2, 8 August 2005, Pages 28-101



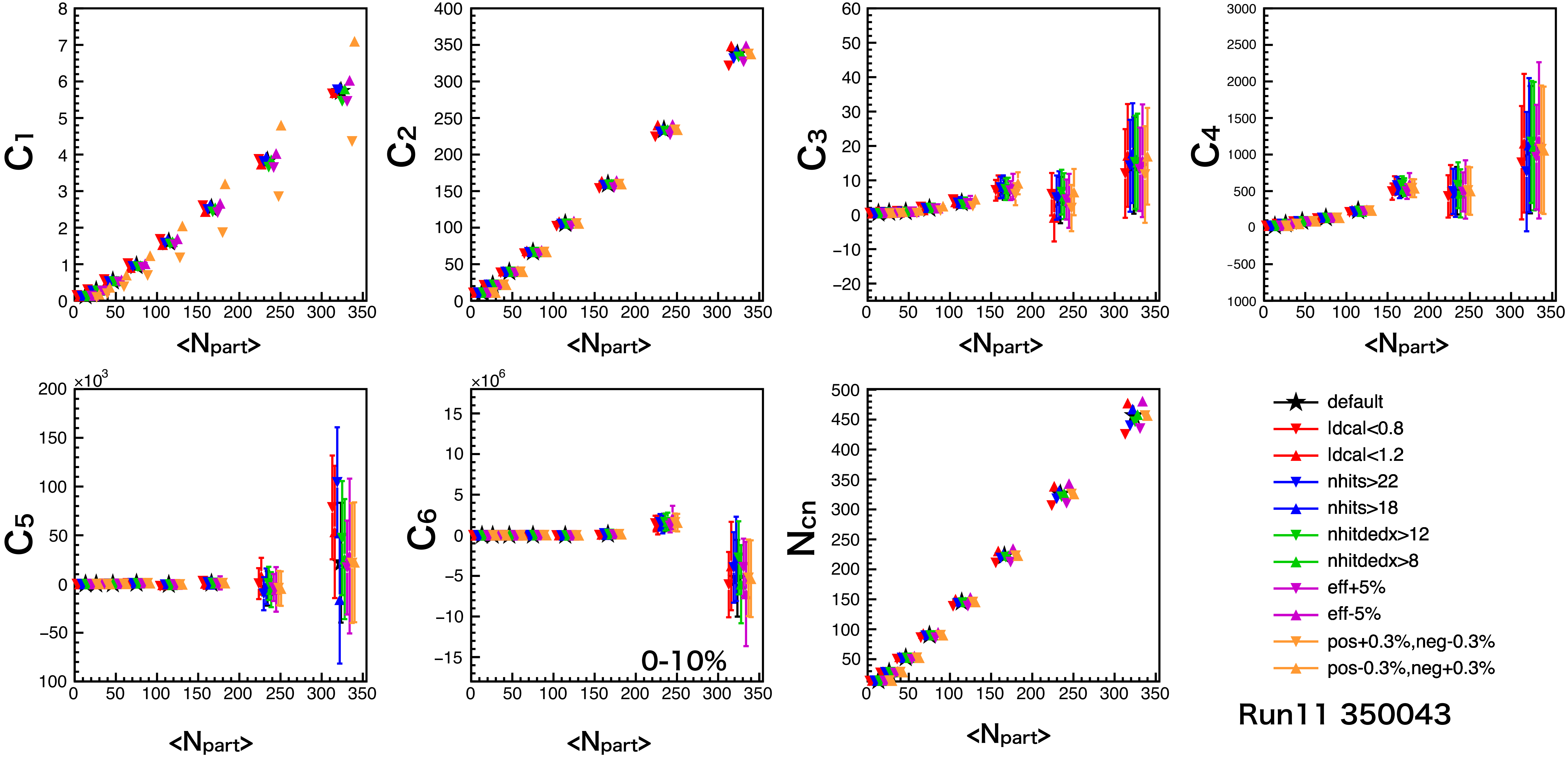
- N_{total} is total multiplicity in full acceptance and estimated from PHOBOS experiment.

back up
(Experimental results)

Cumulants (Run10, trigger by trigger)

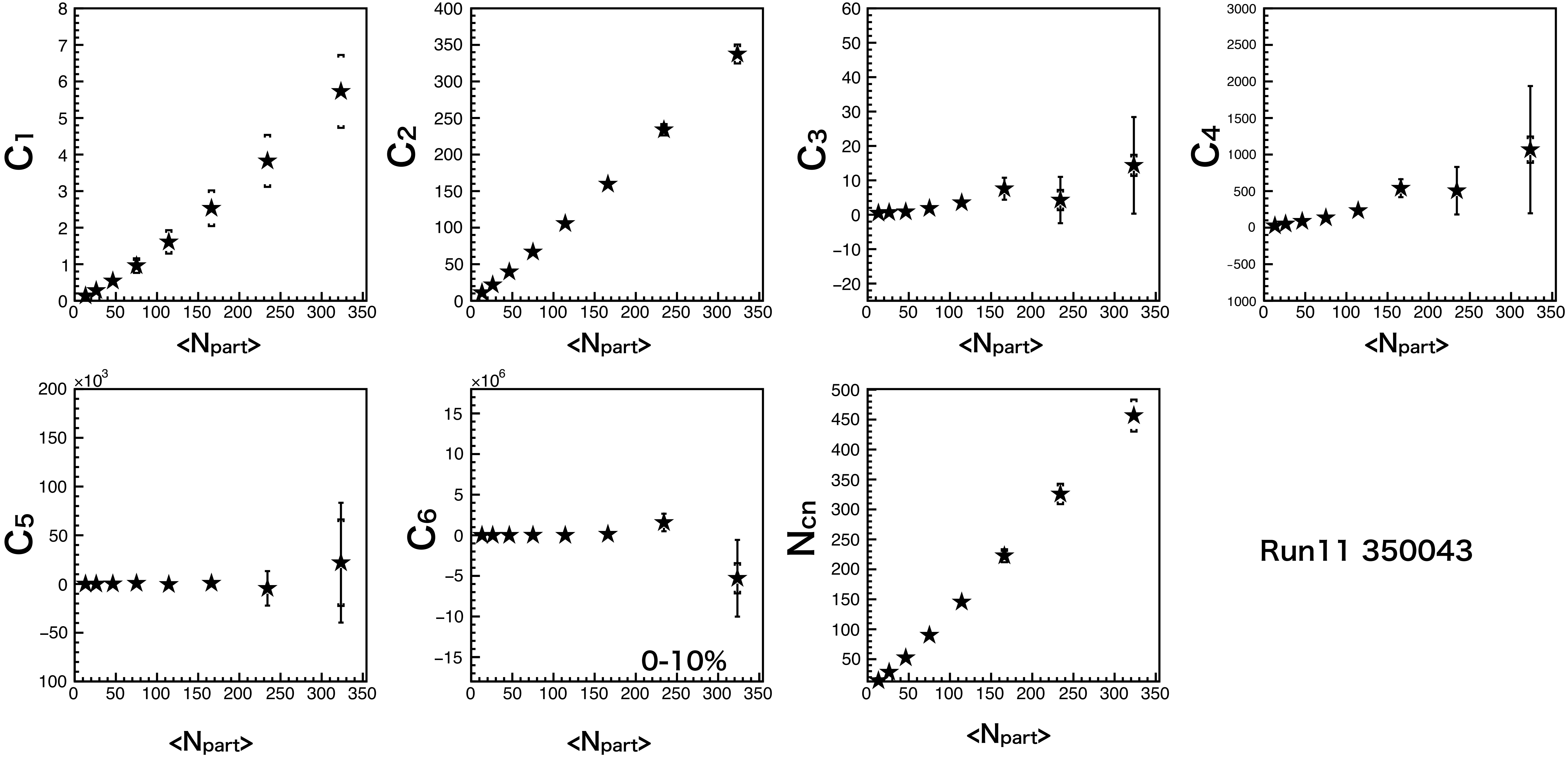


Cumulants (Run11, 350043)

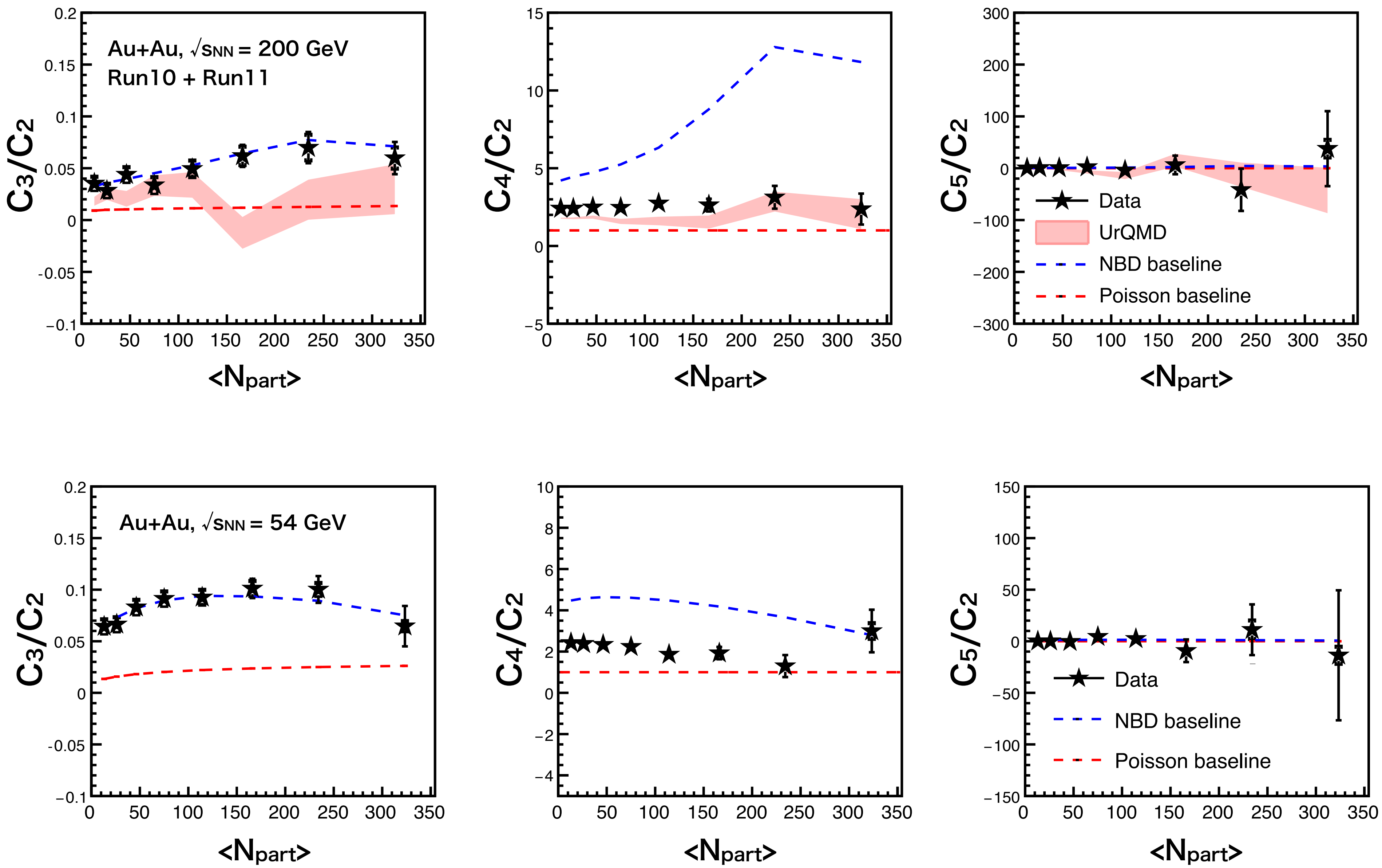


- (Effpos*1.003, Effneg*0.997) and (Effpos*0.997, Effneg*1.003) were calculated to estimate systematic uncertainty of the deviation between positively and negatively charged particle efficiency.

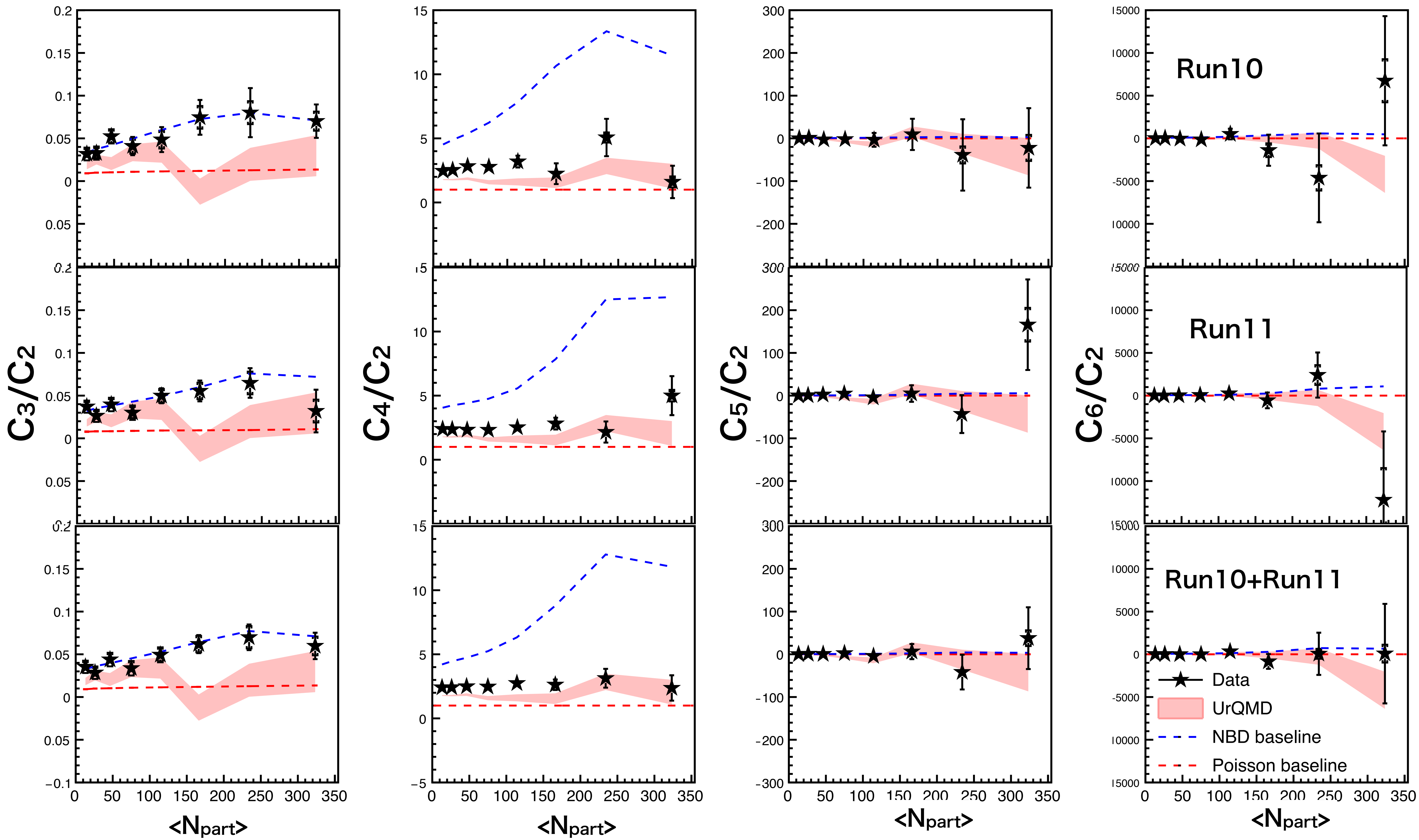
Cumulants (Run11, 350043)



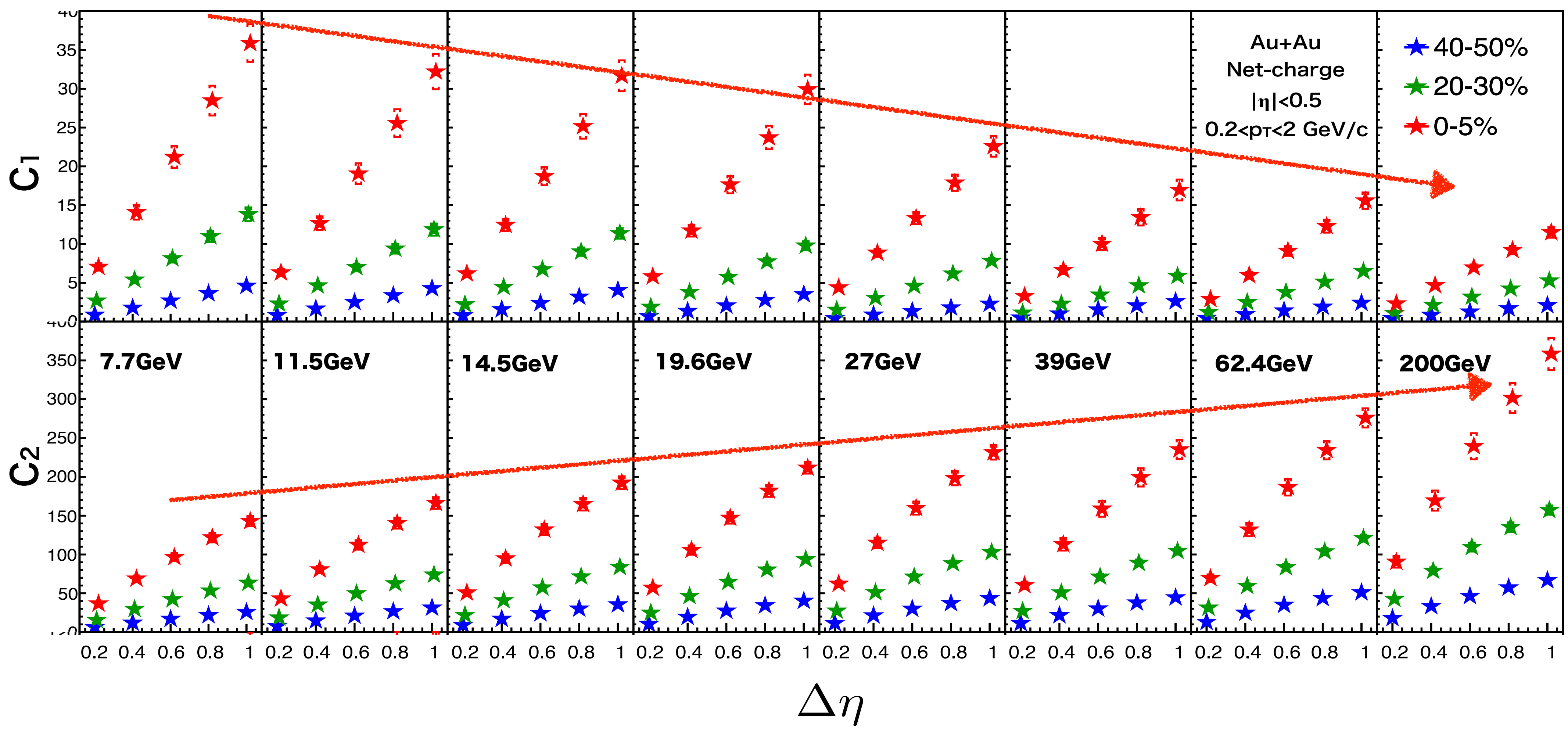
- (Effpos*1.003, Effneg*0.997) and (Effpos*0.997, Effneg*1.003) were calculated to
estimate systematic uncertainty of the deviation between positively and negatively charged particle efficiency.


Au+Au, √sNN = 200 GeV
Run10 + Run11
Au+Au, √sNN = 54 GeV
C3/C2
C4/C2
C5/C2
<Npart>
Data
UrQMD
NBD baseline
Poisson baseline

Cumulant ratio (Run10+Run11)

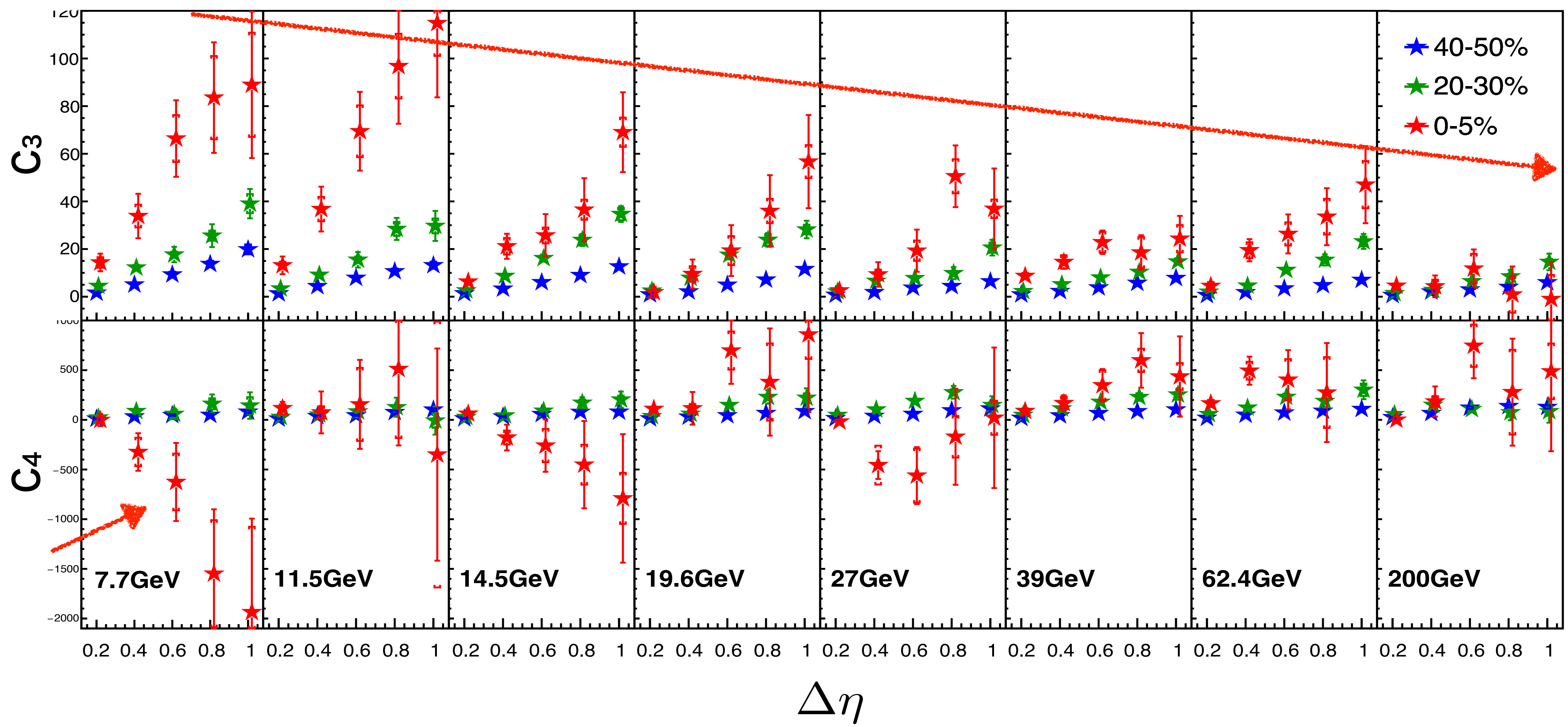


Δη dependence of C_1 and C_2



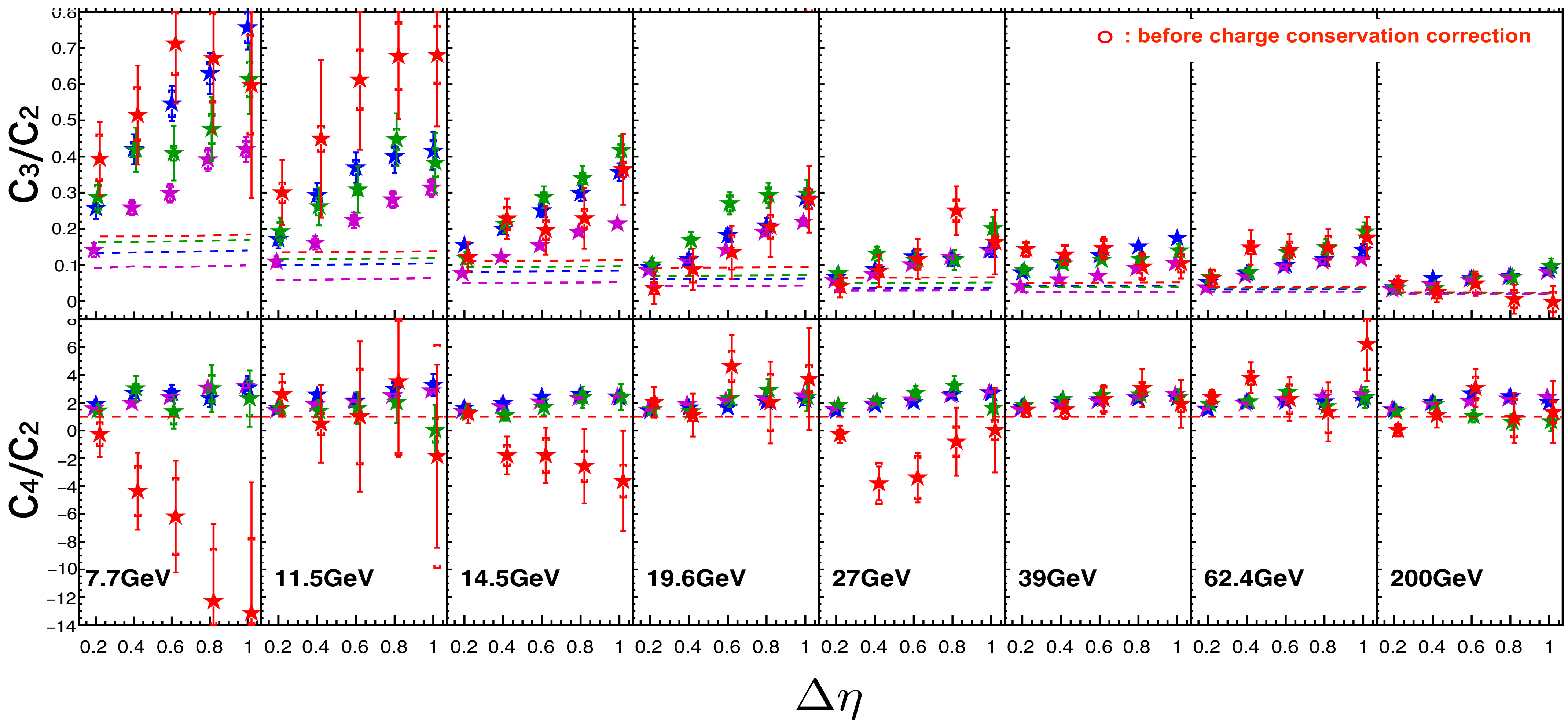
- Cumulants are observed to increace with Δη because of additivity.
- Also cinrease from peripheral to central collisions.
- C_1 is observed to decrease with collision energies because of the baryon stopping.
- C_2 is observed to increase with collision energies because multiplicities are larger with collision energies.

Δη dependence of C_3 and C_4



- Cumulants are observed to increace with Δη because of additivity.
- Also cinrease from peripheral to central collisions.
- C_3 is observed to decrease with collision energies which trend is similar to C_1.
- Statistical error of C_4 in 0-5% centralities are much larger than that in peripheral collisions.

Δη dependence of cumulant ratios



- At C_3/C_2 and C_4/C_2 , most of the results are observed to increase with Δη without most central collision at C_4/C_2 GeV.

back up
(VFC)

Volume fluctuation correction (5,6-th order)

True cumulant

$$\kappa_5(\Delta N) = \langle N_W\rangle\kappa_5(\Delta n) + \{5\kappa_4(\Delta n)\kappa_1(\Delta n) + 10\kappa_3(\Delta n)\kappa_2(\Delta n)\}\,\kappa_2(N_W)$$
$$+\left\{10\kappa_3(\Delta n)\kappa_1^2(\Delta n) + 15\kappa_2^2(\Delta n)\kappa_1(\Delta n)\right\}\kappa_3(N_W) + 10\kappa_2(\Delta n)\kappa_1^3(\Delta n)\kappa_4(N_W)$$
$$+\kappa_1^5(\Delta n)\kappa_5(N_W)$$

Additional term caused from N_W fluctuation

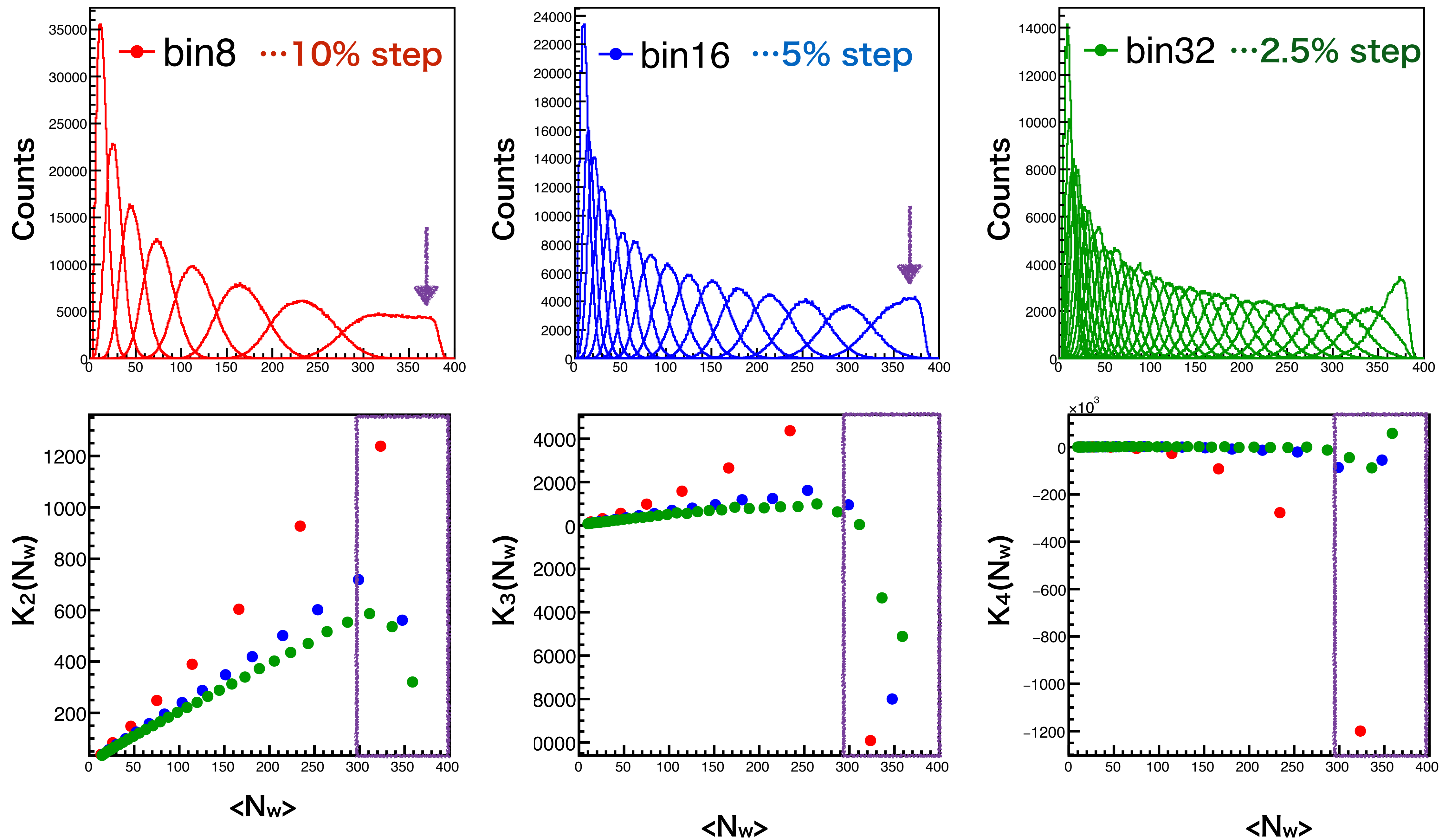
T.Nonaka, Doctoral thesis

$$\kappa_6(\Delta N) = \langle N_W\rangle\kappa_6(\Delta n)$$
$$+\left\{6\kappa_5(\Delta n)\kappa_1(\Delta n) + 15\kappa_4(\Delta n)\kappa_2(\Delta n) + 10\kappa_3^2(\Delta n)\right\}\kappa_2(N_W)$$
$$+\left\{15\kappa_4(\Delta n)\kappa_1^2(\Delta n) + 60\kappa_3(\Delta n)\kappa_2(\Delta n)\kappa_1(\Delta n) + 15\kappa_2^3(\Delta n)\right\}\kappa_3(N_W)$$

Δn : number of net-particle

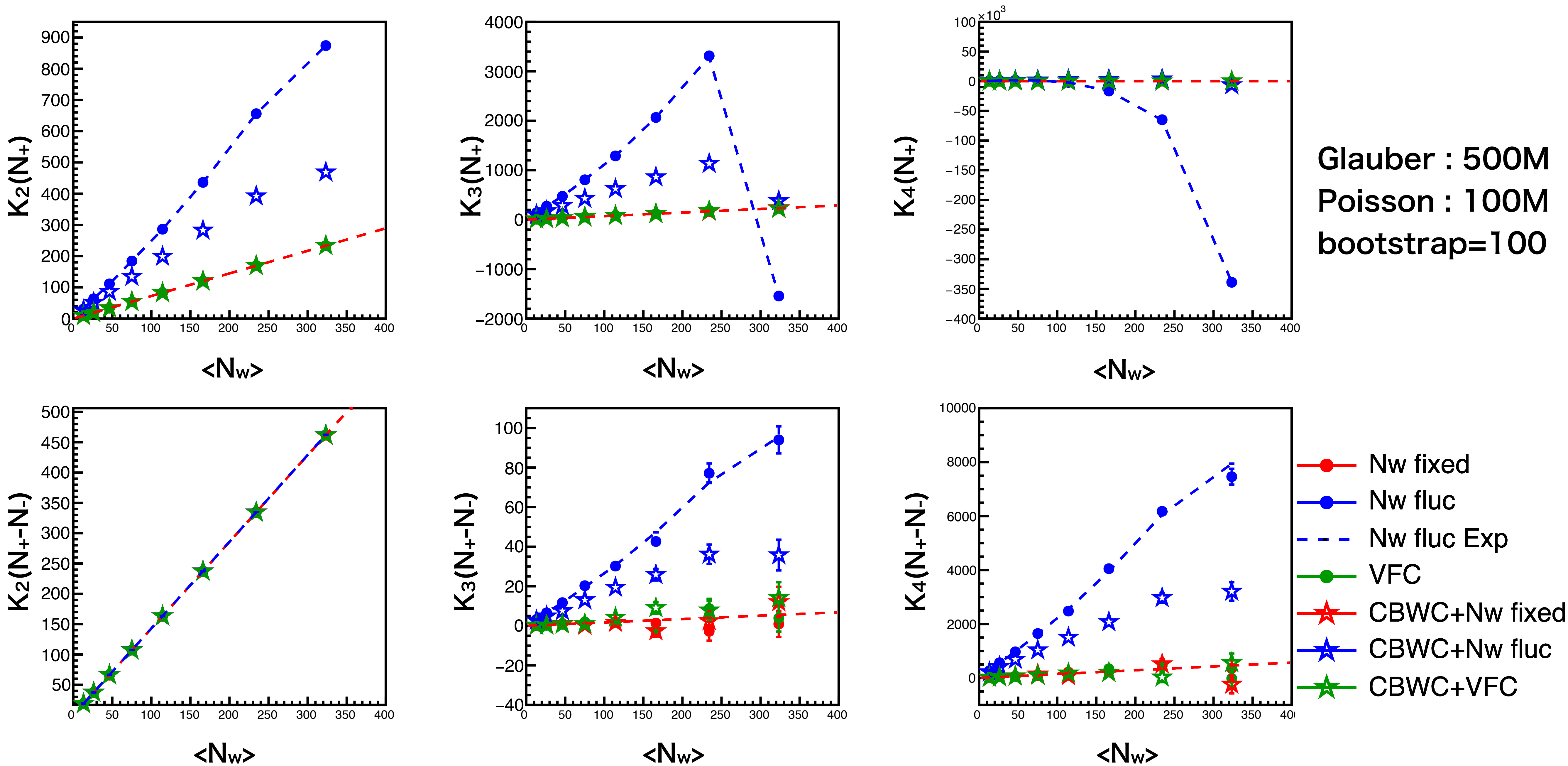
Measured cumulant

Participant fluctuation



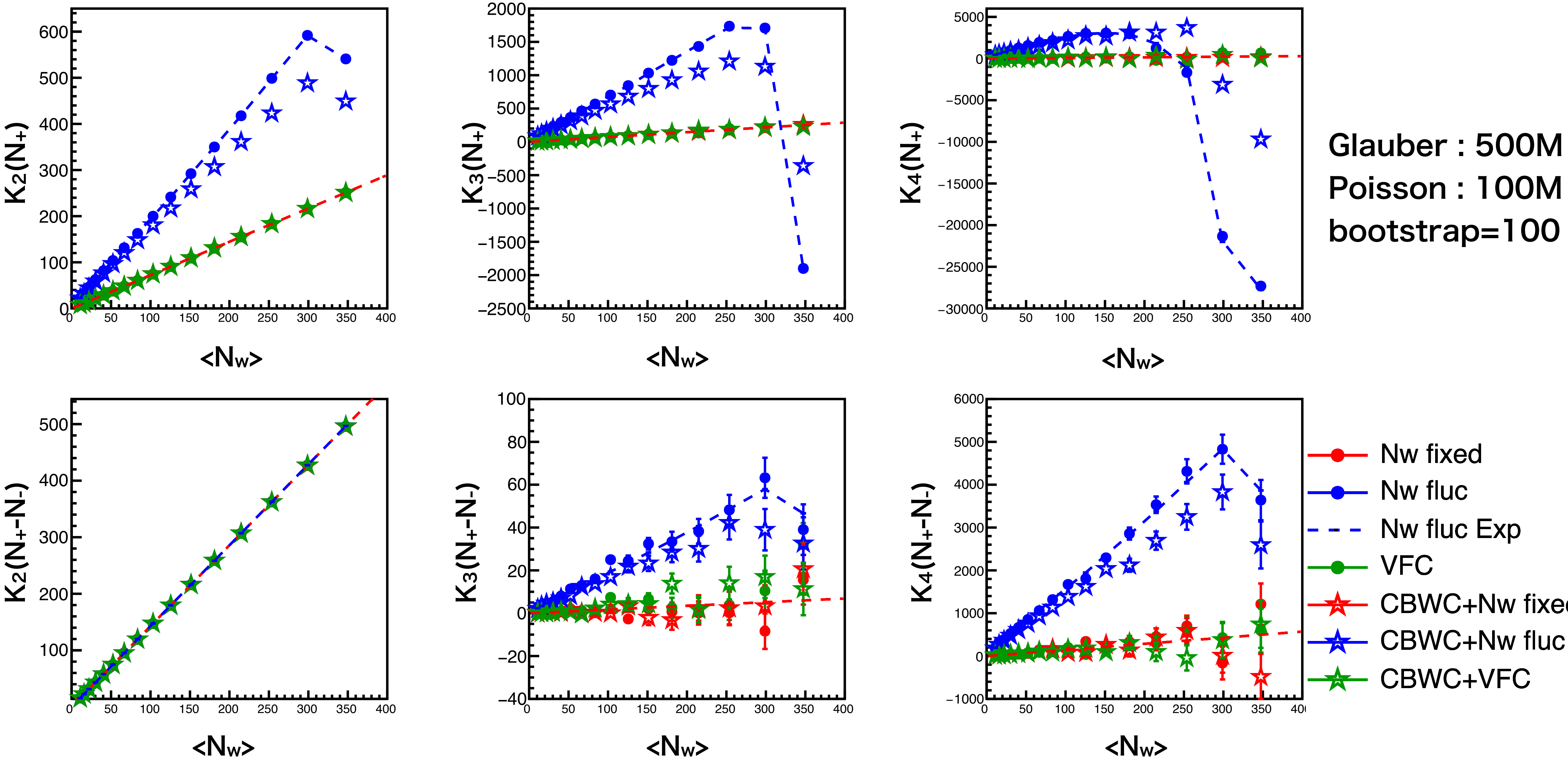
- **<u>Trends are changed around central collision</u>** because maximum value of N_W is fixed.
- Participant fluctuation become larger with number of bin divisions become small.

Toy model VFC check (8bin)



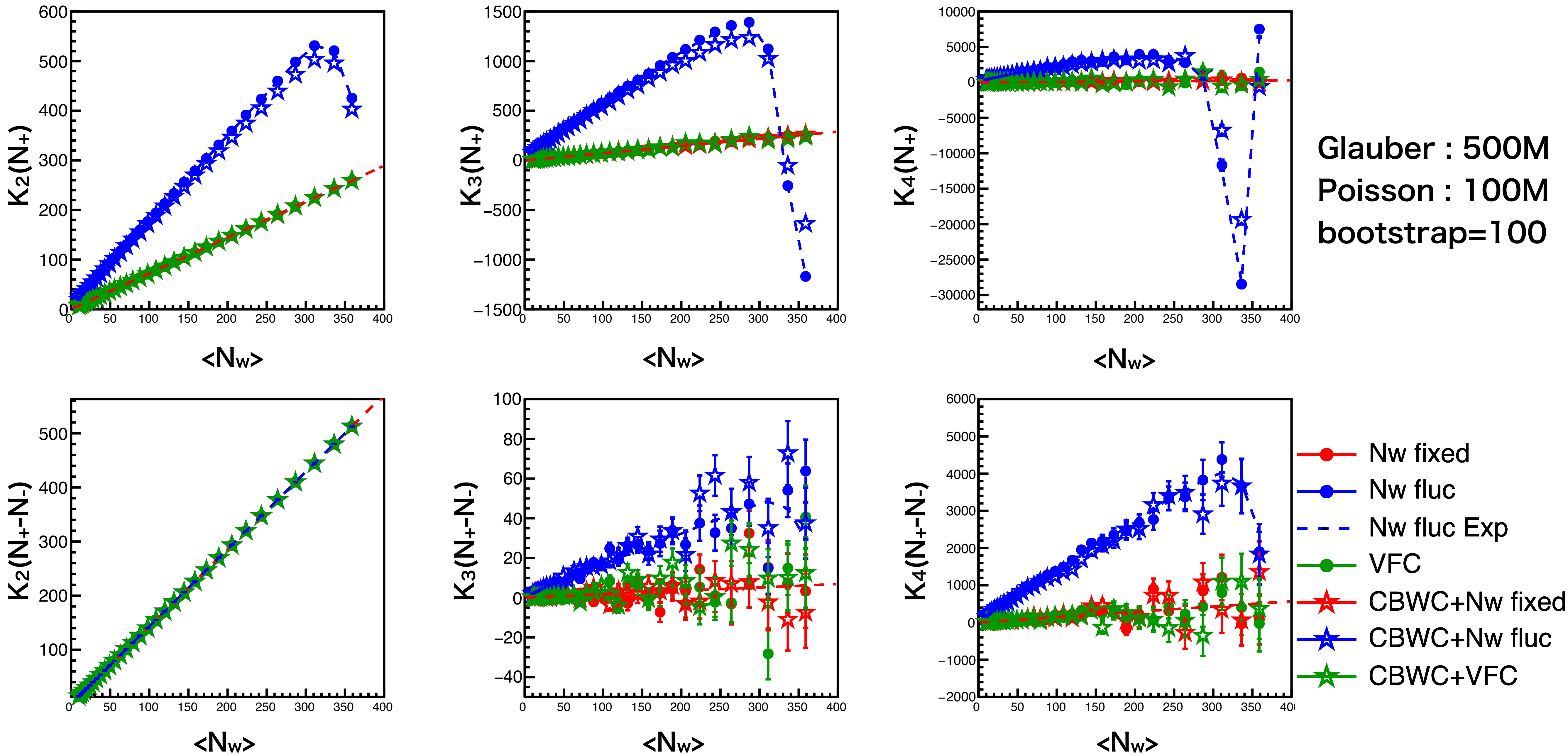
- It seems VFC works well.
- K_1 does not affected by participant fluctuation.
- In net-charge fluctuation, effect from participant fluctuation is smaller than N_+ cumulants because Δn of net-charge is smaller than N_+.

Toy model VFC check (16bin)



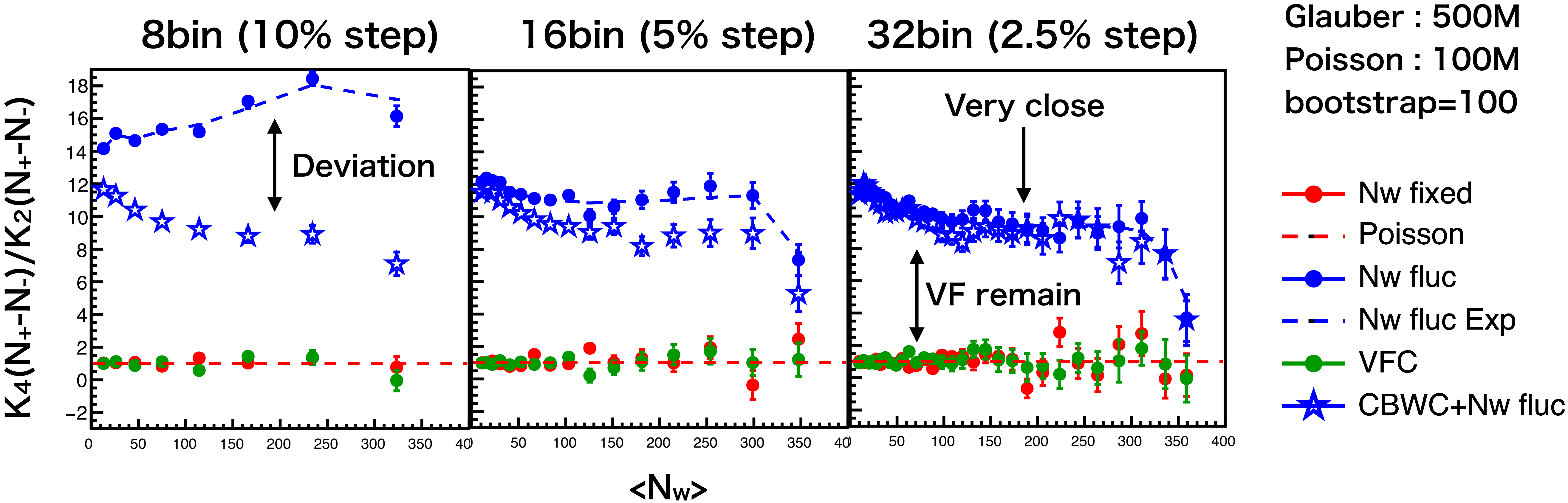
- It seems VFC works well.
- K_1 does not affected by participant fluctuation.
- In net-charge fluctuation, effect from participant fluctuation is smaller than N_+ cumulants because Δn of net-charge is smaller than N_+.

Toy model VFC check (32bin)



- It seems VFC works well.
- K_1 does not affected by participant fluctuation.
- In net-charge fluctuation, effect from participant fluctuation is smaller than N_+ cumulants because Δn of net-charge is smaller than N_+.

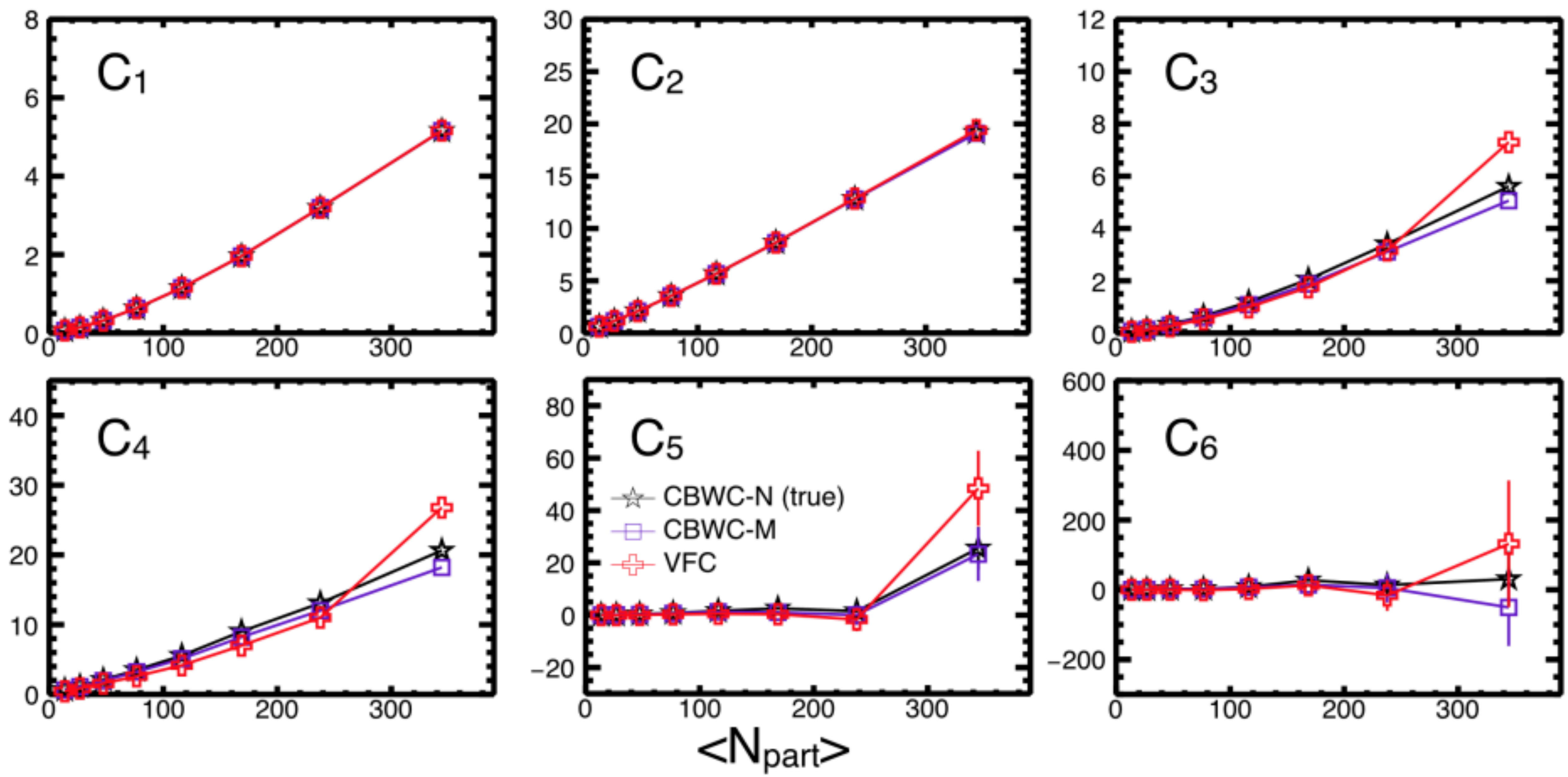
Toy model VFC check (bin dependence)

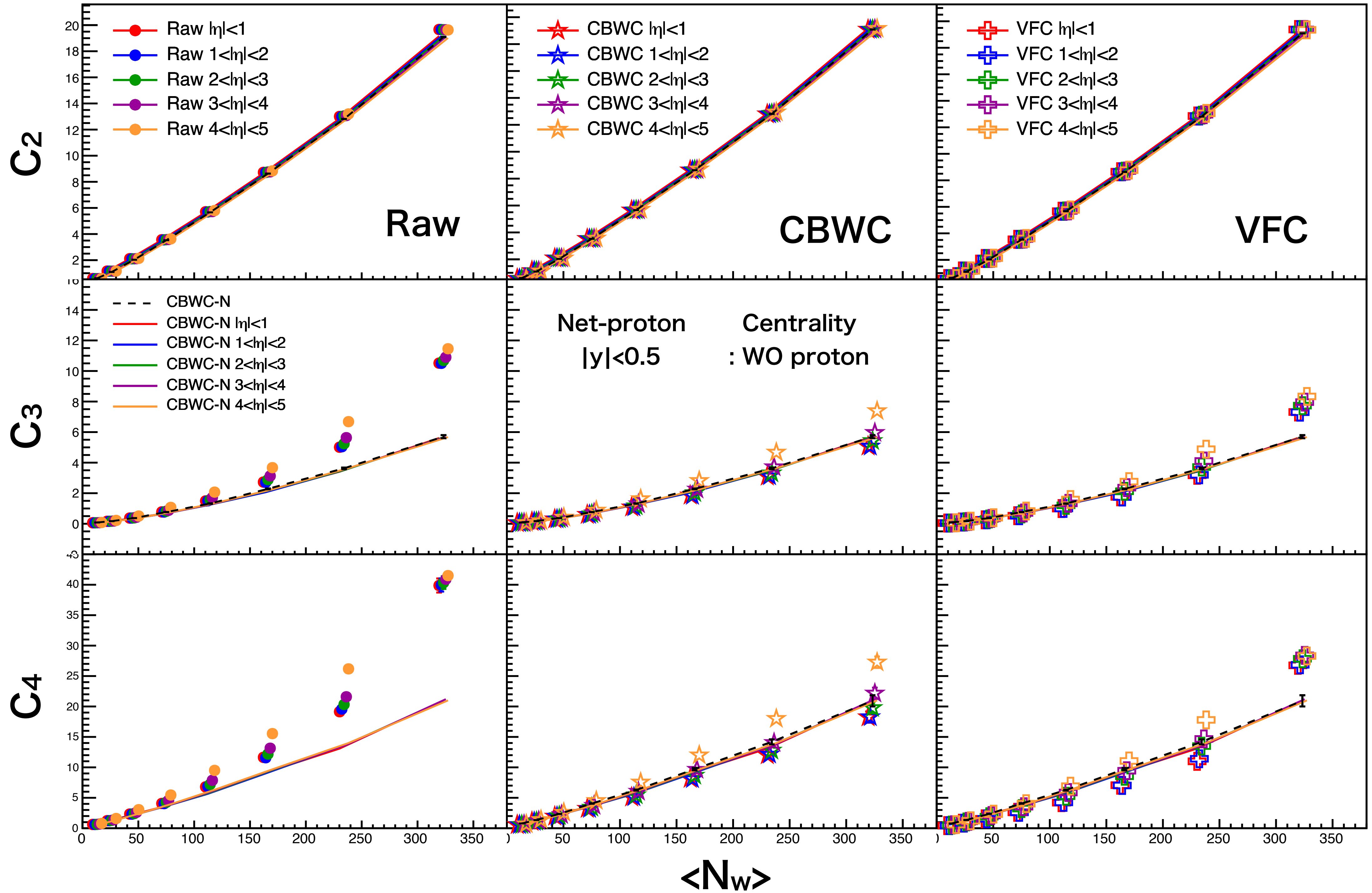


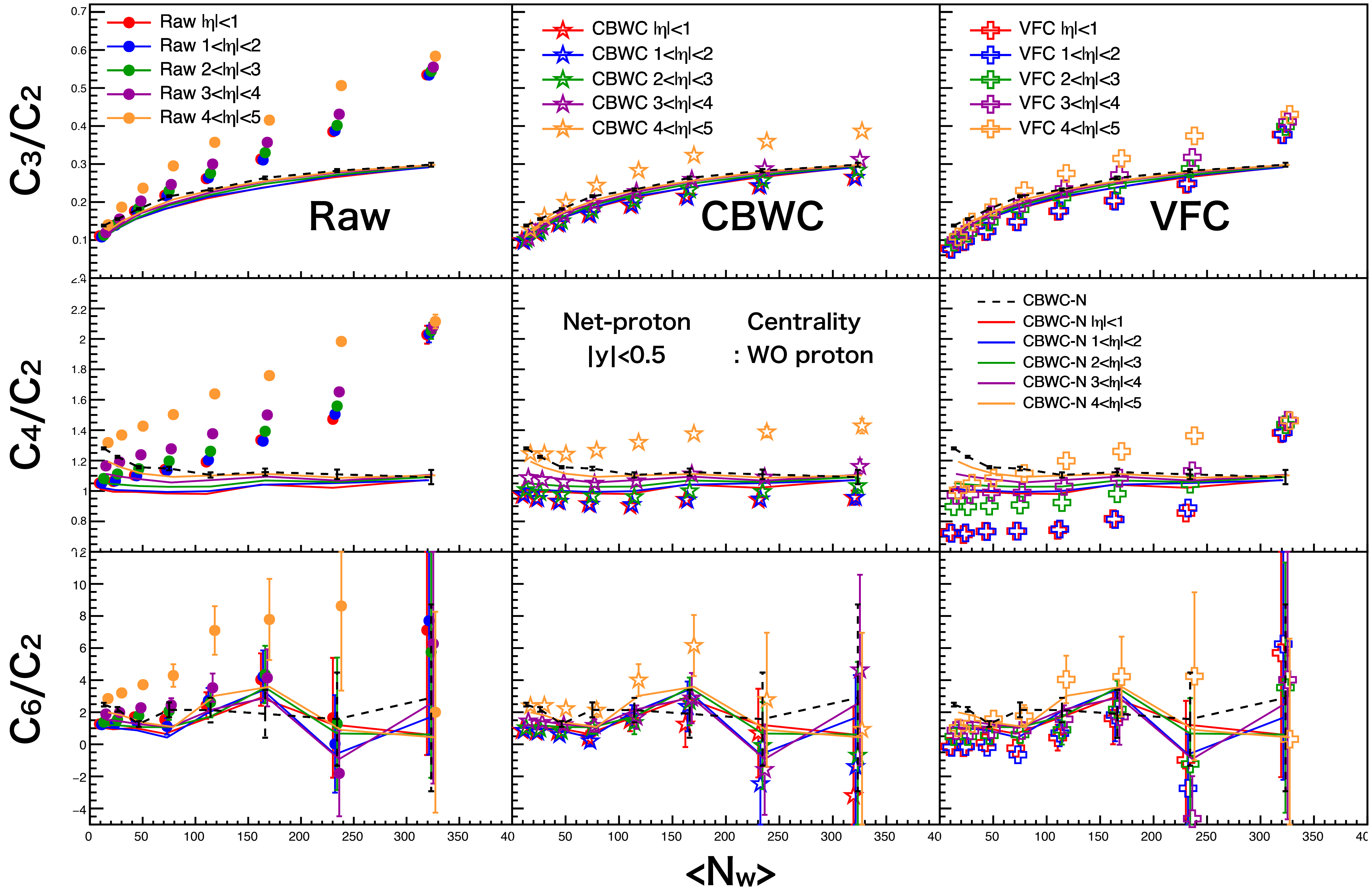
- CBWC cumulants and Without CBWC cumulants become very close if centrality step become 2.5%.

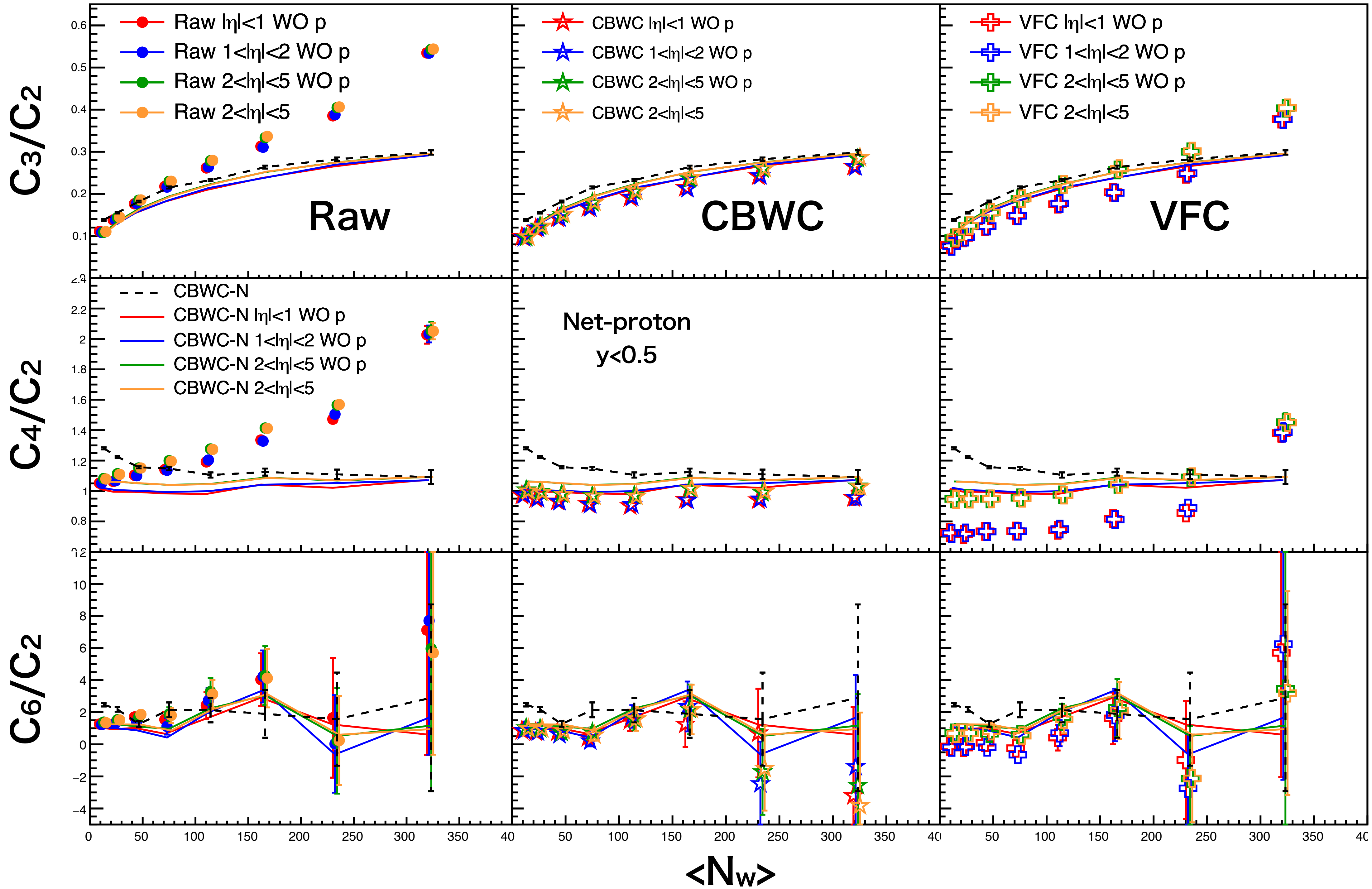
Net-proton case

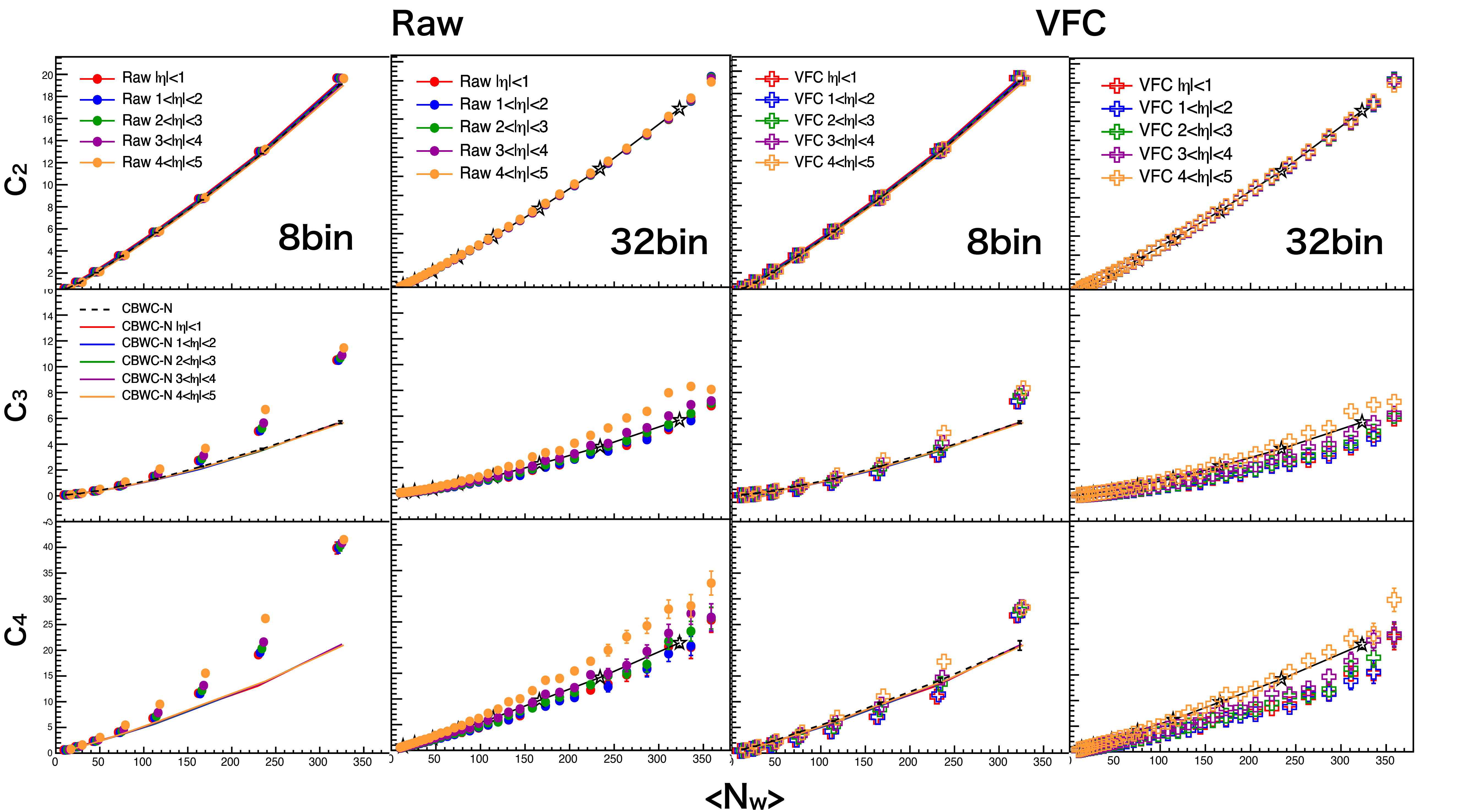
T.Nonaka, Doctoral thesis




Raw |η|<1
Raw 1<|η|<2
Raw 2<|η|<3
Raw 3<|η|<4
Raw 4<|η|<5
Raw
CBWC |η|<1
CBWC 1<|η|<2
CBWC 2<|η|<3
CBWC 3<|η|<4
CBWC 4<|η|<5
CBWC
VFC |η|<1
VFC 1<|η|<2
VFC 2<|η|<3
VFC 3<|η|<4
VFC 4<|η|<5
VFC
CBWC-N
CBWC-N |η|<1
CBWC-N 1<|η|<2
CBWC-N 2<|η|<3
CBWC-N 3<|η|<4
CBWC-N 4<|η|<5
Net-proton
|y|<0.5
Centrality
: WO proton
C2
C3
C4
<Nw>


Raw |η|<1
Raw 1<|η|<2
Raw 2<|η|<3
Raw 3<|η|<4
Raw 4<|η|<5
Raw
CBWC |η|<1
CBWC 1<|η|<2
CBWC 2<|η|<3
CBWC 3<|η|<4
CBWC 4<|η|<5
CBWC
VFC |η|<1
VFC 1<|η|<2
VFC 2<|η|<3
VFC 3<|η|<4
VFC 4<|η|<5
VFC
Net-proton
|y|<0.5
Centrality
: WO proton
CBWC-N
CBWC-N |η|<1
CBWC-N 1<|η|<2
CBWC-N 2<|η|<3
CBWC-N 3<|η|<4
CBWC-N 4<|η|<5
C3/C2
C4/C2
C6/C2
<Nw>

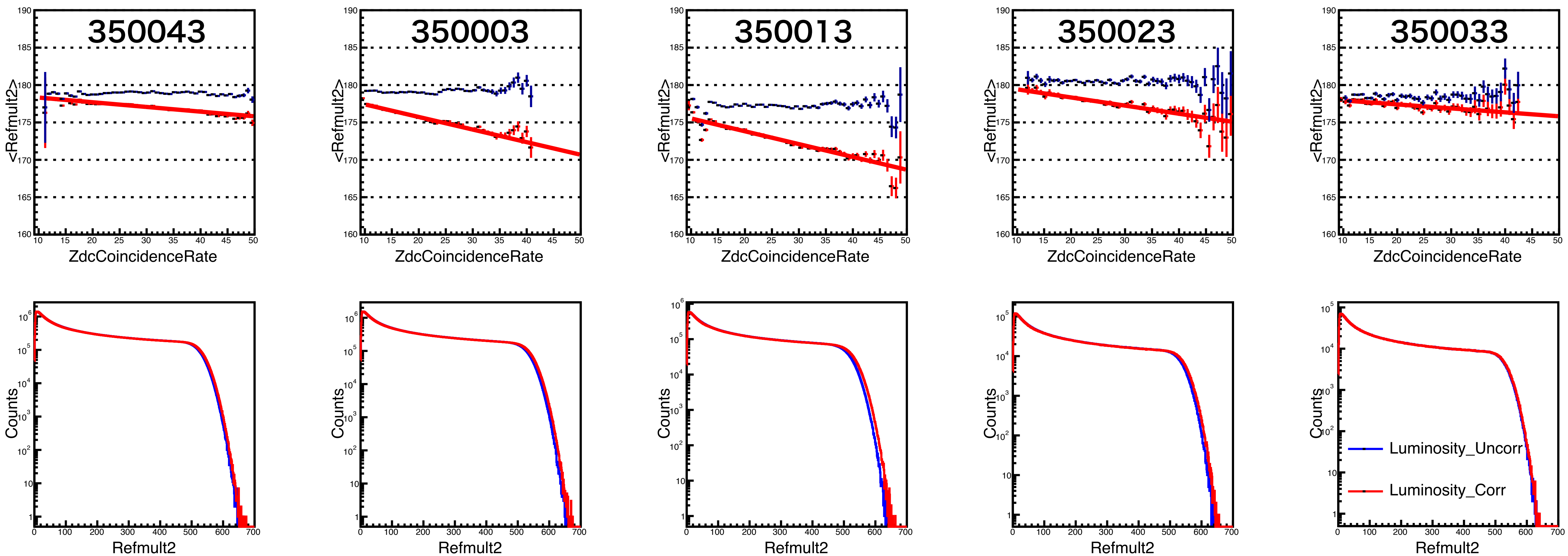

Raw |η|<1 WO p
Raw 1<|η|<2 WO p
Raw 2<|η|<5 WO p
Raw 2<|η|<5
Raw
CBWC |η|<1 WO p
CBWC 1<|η|<2 WO p
CBWC 2<|η|<5 WO p
CBWC 2<|η|<5
CBWC
VFC |η|<1 WO p
VFC 1<|η|<2 WO p
VFC 2<|η|<5 WO p
VFC 2<|η|<5
VFC
CBWC-N
CBWC-N |η|<1 WO p
CBWC-N 1<|η|<2 WO p
CBWC-N 2<|η|<5 WO p
CBWC-N 2<|η|<5
Net-proton
y<0.5
C3/C2
C4/C2
C6/C2
<Nw>


Raw
VFC
C2
C3
C4
Raw |η|<1
Raw 1<|η|<2
Raw 2<|η|<3
Raw 3<|η|<4
Raw 4<|η|<5
8bin
32bin
VFC |η|<1
VFC 1<|η|<2
VFC 2<|η|<3
VFC 3<|η|<4
VFC 4<|η|<5
CBWC-N
CBWC-N |η|<1
CBWC-N 1<|η|<2
CBWC-N 2<|η|<3
CBWC-N 3<|η|<4
CBWC-N 4<|η|<5
<Nw>

back up
(Centrality)

Correction parameter of Refmult2 (Run11)

- Refmult2 was used to determine centrality at net-charge analysis. (multiplicity of $0.5<|\eta|<1$)
- Refmult2 depend on z-vertex and luminosity and trigger ID.
- Calculate z-vertex and luminosity correction parameter for each trigger ID.



- Fit by pol1 ([0]+[1]x)

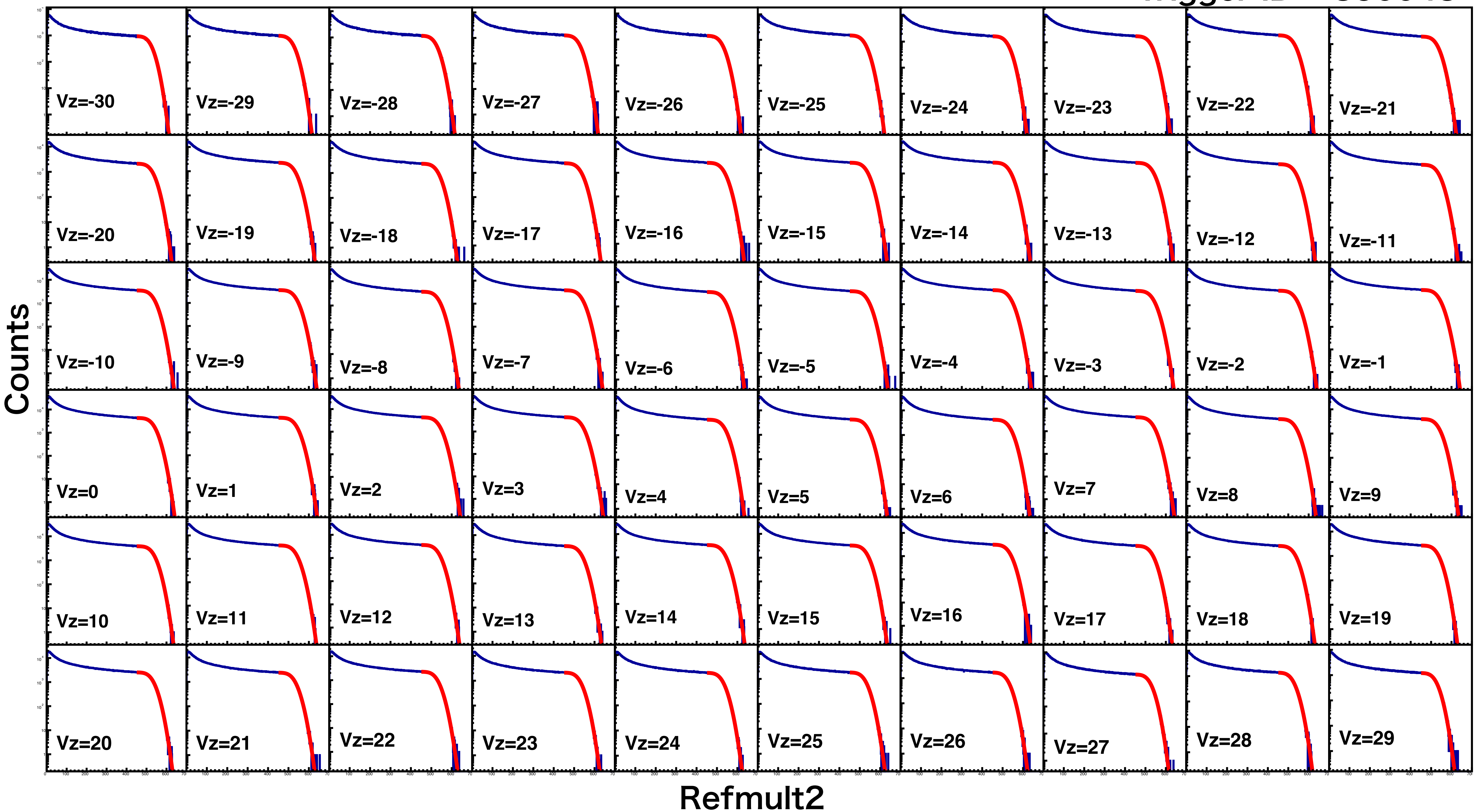
$$\text{correction\_luminosity} = \frac{1}{1 + [1]/[0] * \text{ZdcCoincidenceRate}}$$

luminosity correction factor

Refmult2 distributions of each Vz

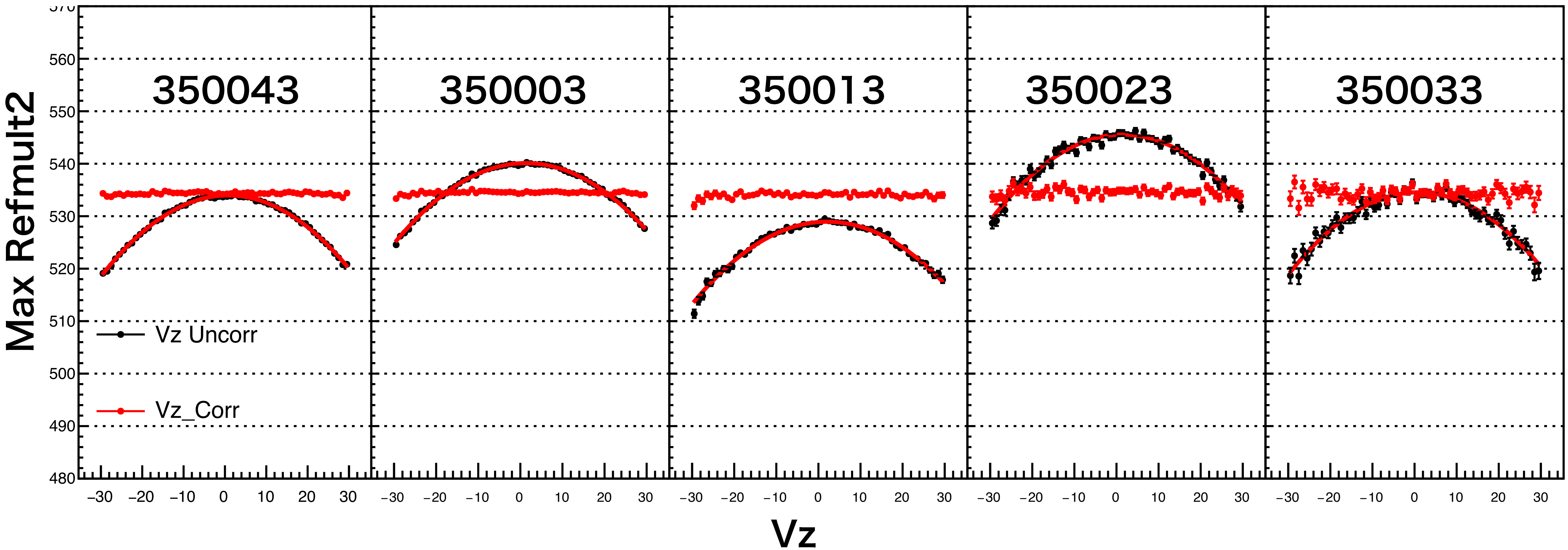
- Maxrefmult2 was measured that is defined by error function for each Vz bins from -30 to 30 after luminosity corrections.

Trigger ID = 350043



- Fit by ([1]*TMath::Erf(-[1]*(x-[2]))+[0]) → **[2] : Maxrefmult2**

Z-vertex correction (Run11)



- Fit by pol2 ([0]+[1]x+[2]x^2)

$$\mathrm{Hovno} = \frac{[0] + \mathrm{par}}{[0] + [1] * x + [2] * x^2}$$

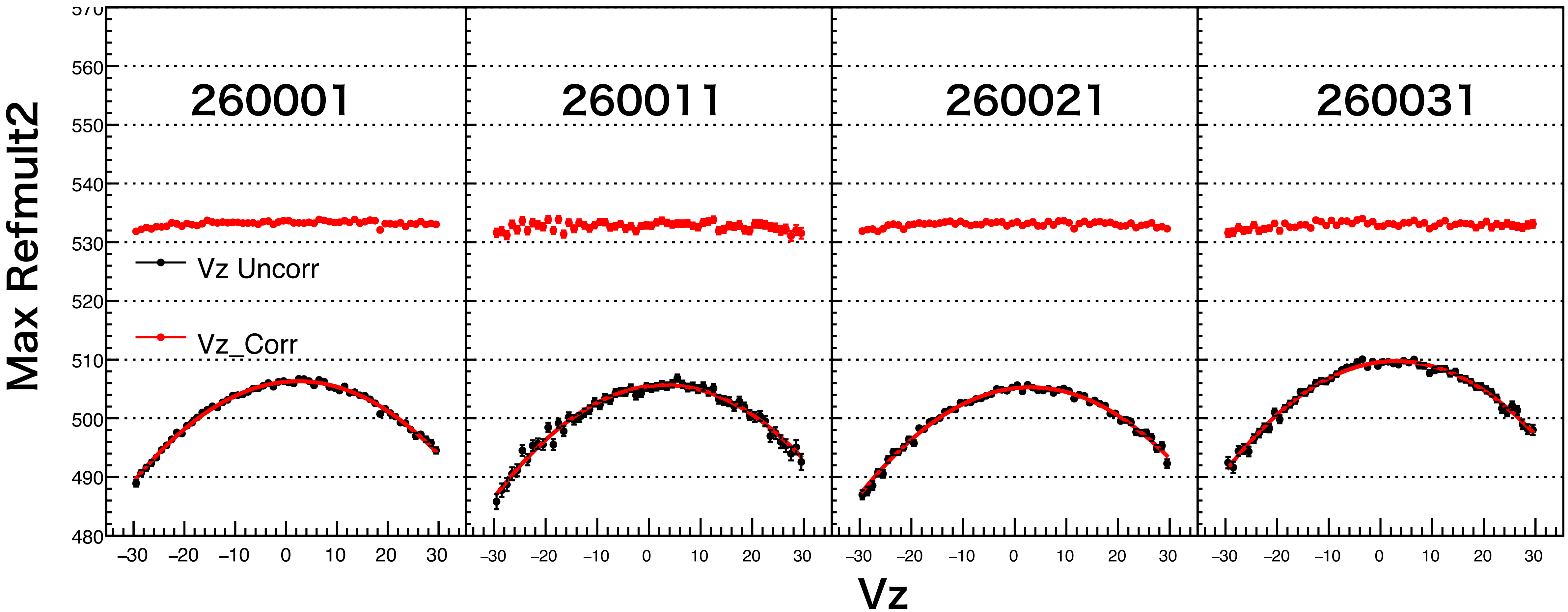
([0] of 350043) - [0] Scaled to 350043

Vz correction factor

Refmult2Corr = (Refmult2+gRandom->Rndm())*correction_lunimosity*Hovno

Corrected Refmult2	**Raw Remult2**	**0 to 1 random number to remove kink structure**	**Luminosity correction factor**

Z-vertex correction (Run10)



- Fit by pol2 ([0]+[1]x+[2]x^2)

$$\mathrm{Hovno} = \frac{[0] + \mathrm{par}}{[0] + [1] * \mathrm{x} + [2] * \mathrm{x}^2}$$

([0] of 350043) - [0] Scaled to 350043

Vz correction factor

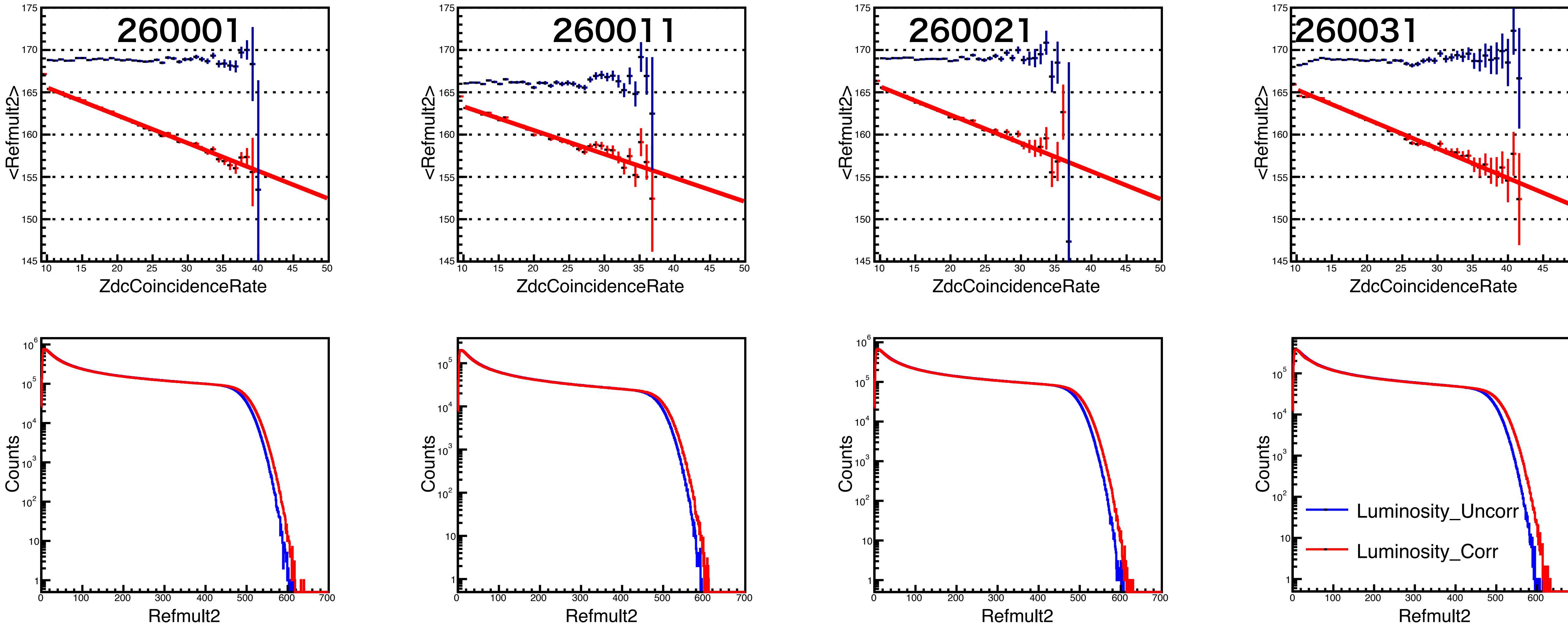
Refmult2Corr = (Refmult2+gRandom->Rndm())*correction_lunimosity*Hovno

Corrected Refmult2	**Raw Remult2**	**0 to 1 random number to remove kink structure**	**Luminosity correction factor**	**Vz correction factor**

Using StRefmultCorr class

Correction parameter of Refmult2 (Run10)

- Refmult2 was used to determine centrality at net-charge analysis. (multiplicity of 0.5<|η|<1)
- Refmult2 depend on z-vertex and luminosity and trigger ID.
- Calculate z-vertex and luminosity correction parameter for each trigger ID.

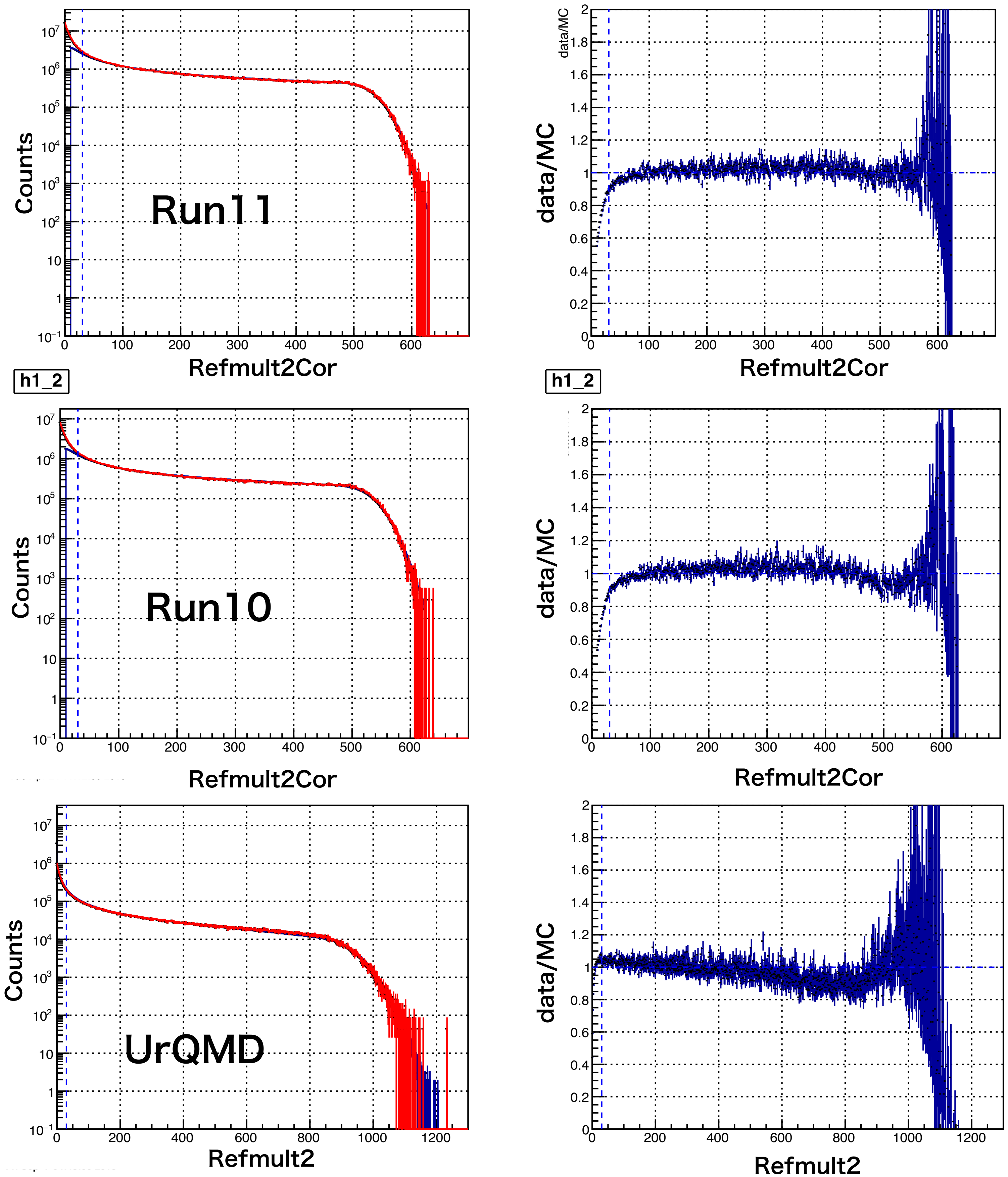


- Fit by pol1 ([0]+[1]x)

$$\text{correction\_luminosity} = \frac{1}{1 + [1]/[0] * \text{ZdcCoincidenceRate}}$$

luminosity correction factor

Glauber fit results



MC : 1M

Experiment

- n_{pp}=2.35
- x=0.13
- k=0.9
- efficiency
  =1-Refmult2Cor*(0.206/560)

n_{pp} : Mean number of generated particles from each source.
k : Parameters of NBD.
x : Parameter of two component model.
Number of source :
$(1-x)*(N_{part}/2.)+x*N_{coll}$

UrQMD

- n_{pp}=**2.90**
- x=0.13
- k=0.9
- efficiency=**1**

Negative binomial distribution

Binomial distribution

r success , given n trials

$$f(r;n,p) = \binom{n}{r} p^r (1-p)^k$$

r : success

k : failures

n : trials

p : probability of success

Negative binomial distribution (NBD)

r success before k failures

$$f(r;k,p) = \binom{r+k-1}{r} p^r (1-p)^k$$

$$\frac{\langle r \rangle}{p} = \frac{k}{1-p} = (k+r)$$

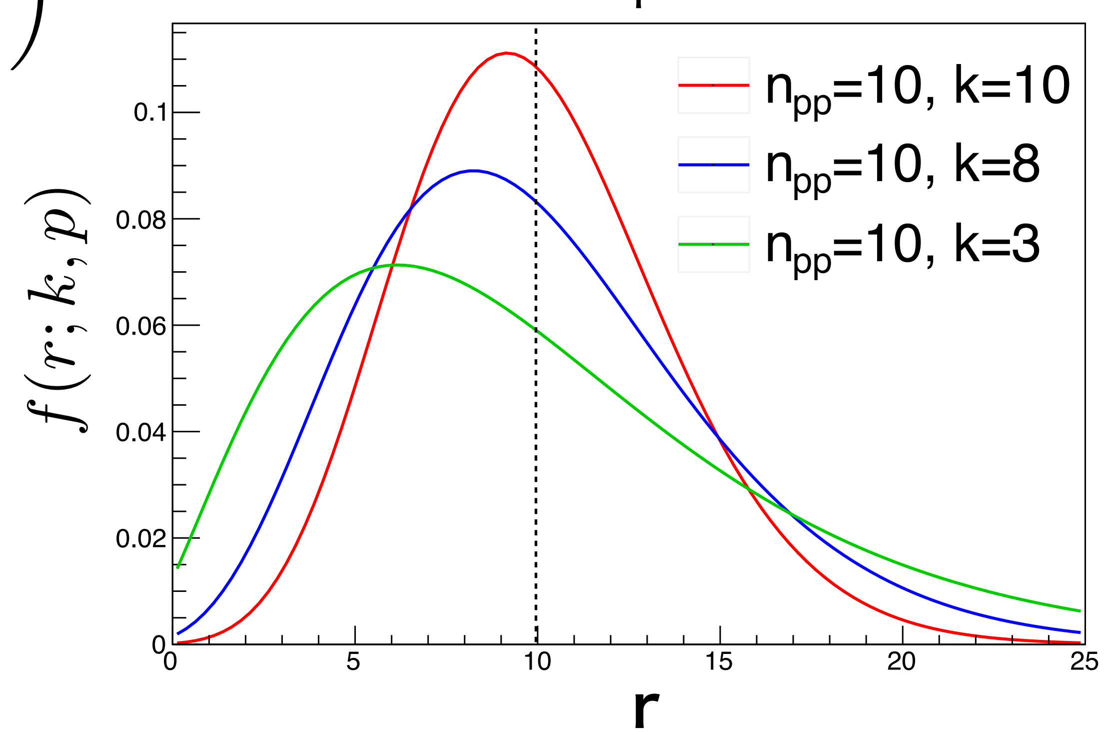
number of trials

$$\rightarrow \langle r \rangle = \frac{pk}{1-p} \equiv n_{pp}$$

Expand k and r to positive real values.

$$f(r;k,p) = \frac{\Gamma(r+k)}{\Gamma(r+1)\Gamma(k)} \left(\frac{n_{pp}}{k+n_{pp}}\right)^r \left(\frac{k}{k+n_{pp}}\right)^k$$

Example



n_{pp} : Mean number of generated particles from each ancestors.

k : Parameters of NBD.

Centrality bins

8 bin

Centrality	bin	<N_{part}>
0-10	406	323.41
10-20	295	234.16
20-30	204	166.14
30-40	134	114.3
40-50	82	75.09
50-60	47	46.32
60-70	24	26.14
70-80	11	13.15

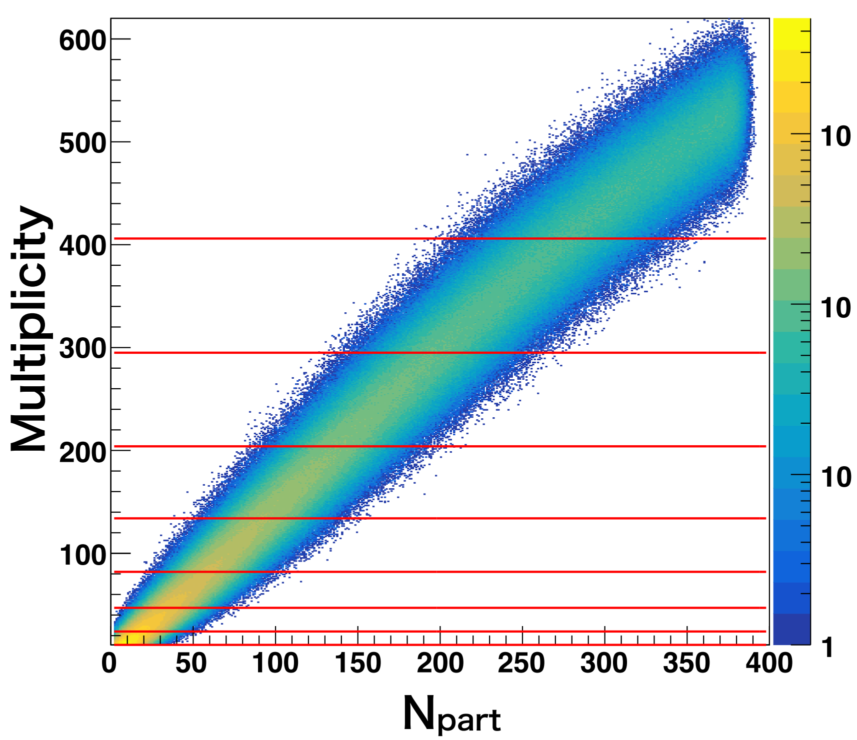
16 bin

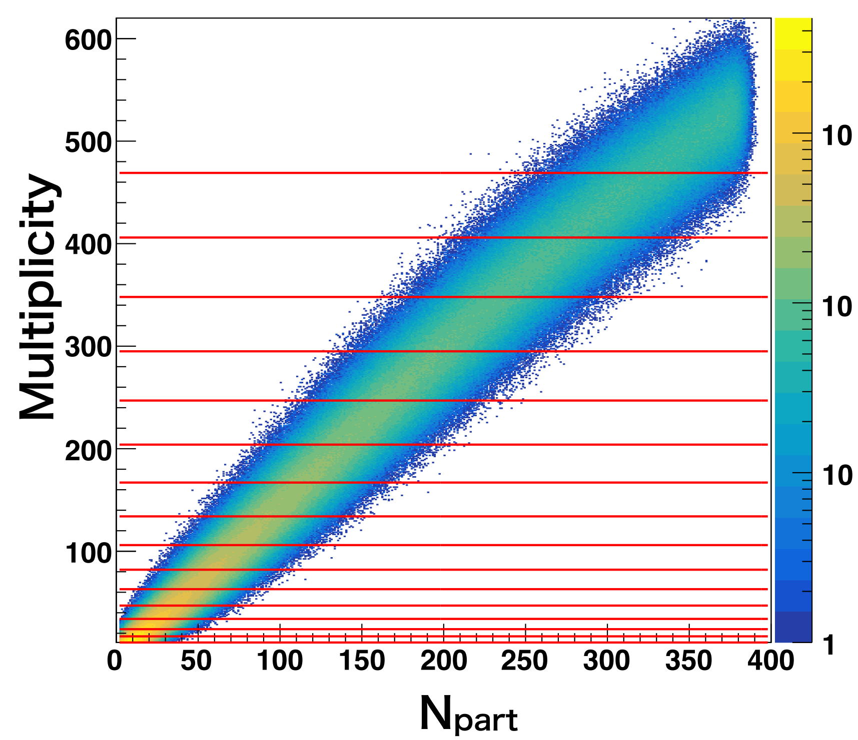
Centrality	bin	<N_{part}>
0-5	469	347.47
5-10	406	298.9
10-15	348	253.64
15-20	295	214.79
20-25	247	180.99
25-30	204	151.34
30-35	167	125.669
35-40	134	103.2
40-45	106	83.61
45-50	82	66.65
50-55	63	52.38
55-60	47	40.46
60-65	34	30.28
65-70	24	22.0
70-75	17	15.73
75-80	11	10.93

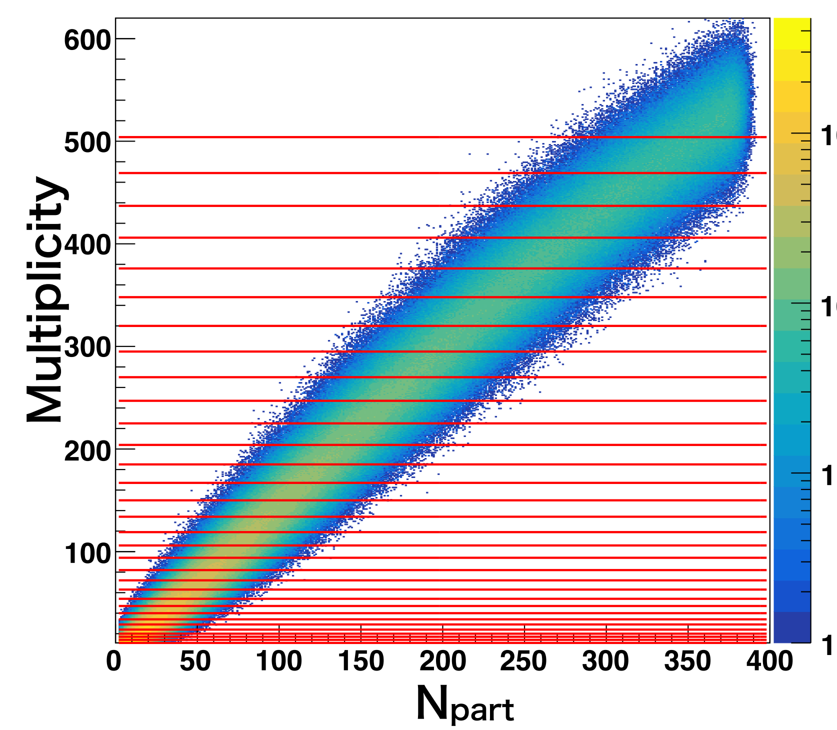
32 bin

Centrality	bin	<N_{part}>
0-2.5	504	358.83
2.5-5	469	336.16
5-7.5	437	311.16
7.5-10	406	286.74
10-12.5	376	263.97
12.5-15	348	243.02
15-17.5	320	223.61
17.5-20	295	205.41
20-22.5	270	188.85
22.5-25	247	172.91
25-27.5	225	158.33
27.5-30	204	144.42
30-32.5	185	131.64
32.5-35	167	119.78
35-37.5	150	108.56
37.5-40	134	97.93
40-42.5	119	88.02

⋮







back up
(Data set, QA, Analysis mothod, etc)

Data set (200 GeV)

	Run11(0-80%)	Run10(10-80%)	Run10(0-10%)	UrQMD
NEvent	485M	211M	196M	45M

Event Selection

$\|v_z\|$	<30
$\|v_r\|$	<2
Pile up event cut	0.46 * nRefMult - 10 < nTOFMatch

Track cut	π	K	p
p_T (TPC only)	0.2 - 0.5 GeV/c	0.2 - 0.4 GeV/c	0.4 - 0.8 GeV/c
p_T (TPC+TOF)	0.5 - 1.6 GeV/c	0.4 - 1.6 GeV/c	0.8 - 2. GeV/c
$\|\eta\|$		< 0.5	
dca		<1	
nhitsfits		>20	
track quality		>0.52	
nhitsdedx		>10	
Centrality		Refmult2 ($\|\eta\|$ >0.5)	
PID (TPC)	nSigmaPion < 2	nSigmaKaon < 2	nSigmaProton < 2
PID (TOF)	-0.15< m^2 <0.14	0.14< $\|m^2\|$ <0.4	0.6 < $\|m^2\|$ <1.2

Same as net-charge published results

Number of Events

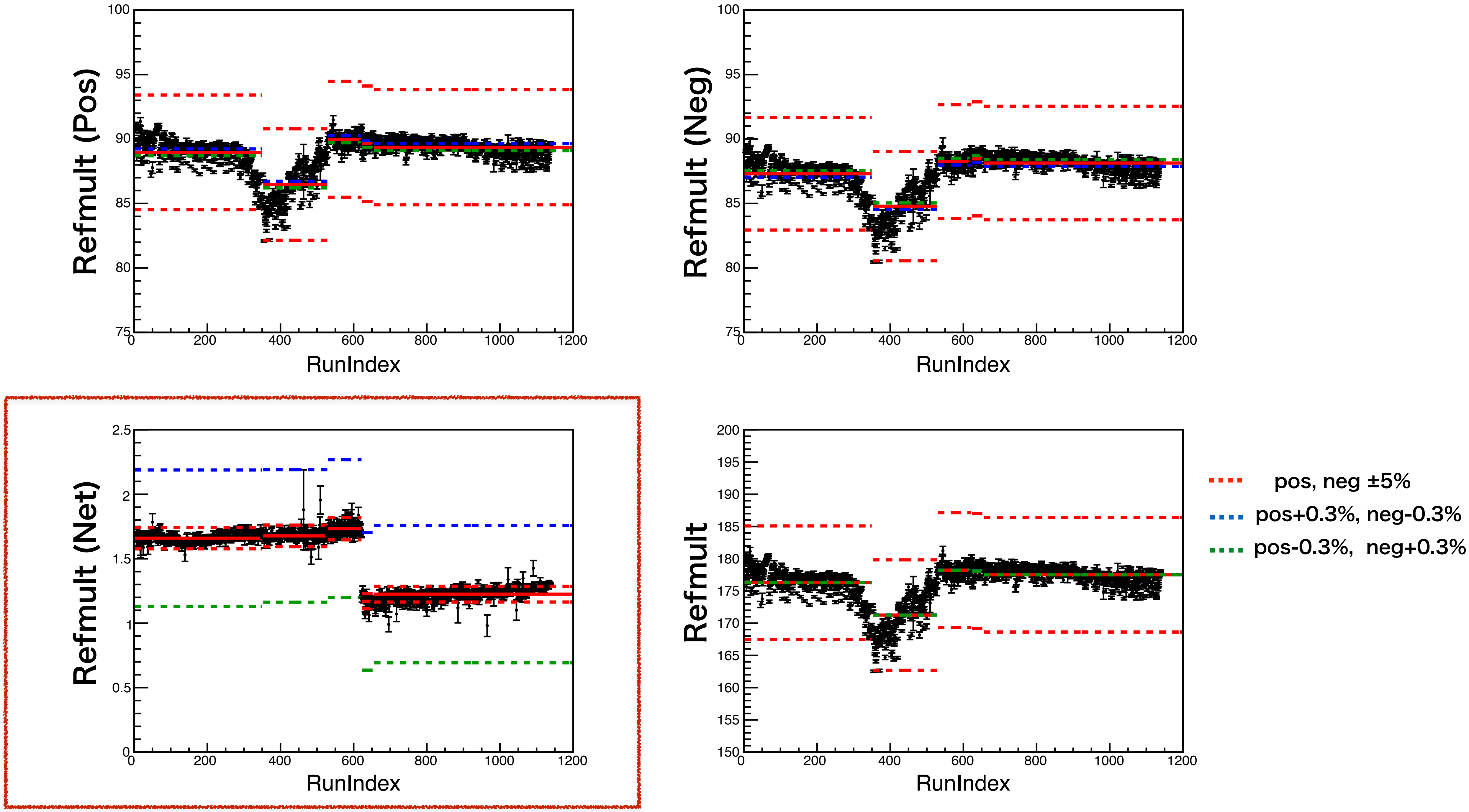
NEvent	350003	350013	350023	350033	350043	Total
Run11 (0-80%)	200M	74M	15M	9M	187M	**485M**

NEvent	260001	260011	260021	260031	Total
Run10 (10-80%)	80M	21M	70M	40M	**211M**
Run10 (0-10%)	53M	20M	76M	47M	**196M**

NEvent	Total
UrQMD	**45M**

Run by run check (Run11, 350043)

Only Good runs are shown   Refmult(Pos)+Refmult(Neg)=Refmult



- When we change (pos,neg)=(+0.3%,-0.3%) and (+0.3%,-0.3%), run by run Refmult (Net) are fluctuate within blue and green line.
- **(pos+0.3%, neg-0.3%) and (pos-0.3%, neg+0.3%) seem enough to estimate systematic uncertainty of net-charge.**

Factorial cumulant method

Example (the 1st-order net-charge fluctuation)

Cumulant (true)

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

$$q_{(r,s)} = q_{(a^r/p^s)} = \sum_{i=1}^{M} (a_i^r/p_i^s) n_i.$$

- M: Number of phase space
- n_i: Number of particle
- p_i: Efficiency
- a_i: +1 (positive charge) or -1 (negative charge)

$$= \frac{n_{(\pi^+,lowpt)}}{p_{(\pi^+,lowpt)}} + \frac{n_{(\pi^+,highpt)}}{p_{(\pi^+,highpt)}} - \frac{n_{(K^+,lowpt)}}{p_{(K^+,lowpt)}} + \frac{n_{(K^-,highpt)}}{p_{(K^+,highpt)}} + \frac{n_{(pbar,lowpt)}}{p_{(pbar,lowpt)}} + \frac{n_{(p,highpt)}}{p_{(p,highpt)}}$$

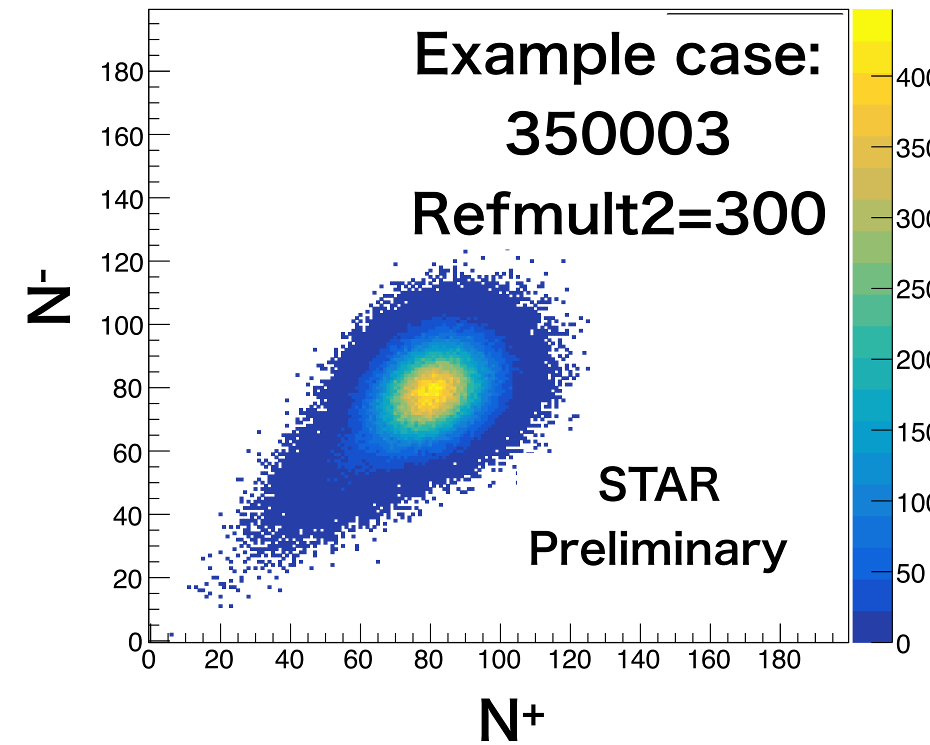
$$- \frac{n_{(\pi^-,lowpt)}}{p_{(\pi^-,lowpt)}} - \frac{n_{(\pi^-,highpt)}}{p_{(\pi^-,highpt)}} - \frac{n_{(K^-,lowpt)}}{p_{(K^-,lowpt)}} - \frac{n_{(K^-,highpt)}}{p_{(K^-,highpt)}} - \frac{n_{(pbar,lowpt)}}{p_{(pbar,lowpt)}} - \frac{n_{(pbar,highpt)}}{p_{(pbar,highpt)}}$$

- 2(charge)*3(πKp)*2(highpt,lowpt)=12 efficiency bins are used at net-charge fluctuation analysis.

NBD check

$$C_1 = \mu$$
$$C_2 = \mu\epsilon$$
$$C_3 = \mu\epsilon(2\epsilon - 1)$$
$$C_4 = \mu\epsilon(6\epsilon^2 - 6\epsilon + 1)$$
$$C_5 = \mu\epsilon(2\epsilon - 1)(12\epsilon^2 - 12\epsilon + 1)$$
$$C_6 = \mu\epsilon(120\epsilon^4 - 240\epsilon^3 + 150\epsilon^2 - 30\epsilon + 1)$$

$$C_n^{net-c} = C_n^{+} + (-1)^n C_n^{-}$$



For example : 350003, Refmult2=300,
Efficiency Uncorrected case

$C_1^+=79.53$	$C_1^-=77.81$
$C_2^+=122.1$	$C_2^-=117.93$
$\varepsilon^+=C_2/C_1=1.53$	$\varepsilon^-=1.51$

used as NBD parameters.

$C_3^+=253$	$C_3^+=240$
$C_4^+=724$	$C_4^+=671$
$C_5^+=2746$	$C_5^+=2486$
$C_6^+=13027$	$C_6^+=11525$

NBD	Poisson
$C_1^{net}=1.72$	$C_1^{net}=1.72$
$C_2^{net}=240$	$C_2^{net}=157$
$C_3^{net}=13.3$	$C_3^{net}=1.72$
$C_4^{net}=1395$	$C_4^{net}=157$
$C_5^{net}=260$	$C_5^{net}=1.72$
$C_6^{net}=24552$	$C_6^{net}=157$

Odd: $C_1^+-C_1^-$
Even: $C_1^++C_1^-$

- **NBD baseline is larger than Poisson because of large ε at 200GeV.**
- **If ε=1, NBD and Poisson baseline are exactly the same.**

NBD check

For example : 350003, Refmult2=300,
Efficiency Corrected case

$C_1^+=139.44$	$C_1^-=136.54$
$C_2^+=265.5$	$C_2^-=256.26$
$\varepsilon^+=C_2/C_1=1.90$	$\varepsilon^-=1.87$

used as NBD parameters.

$C_3^+=745$	$C_3^+=705$
$C_4^+=3007$	$C_4^+=2786$
$C_5^+=16145$	$C_5^+=14640$
$C_6^+=108378$	$C_6^+=96183$

N^+

NBD	Poisson
$C_1^{net}=1.72$	$C_1^{net}=1.72$
$C_2^{net}=521$	$C_2^{net}=157$
$C_3^{net}=40.0$	$C_3^{net}=1.72$
$C_4^{net}=5794$	$C_4^{net}=157$
$C_5^{net}=1505$	$C_5^{net}=1.72$
$C_6^{net}=204561$	$C_6^{net}=157$

Odd: $C_1^+-C_1^-$
Even: $C_1^++C_1^-$

- **NBD baseline is larger than Poisson because of large ε.**
- **If $\varepsilon=1$, NBD and Poisson baseline are exactly the same.**

Tracking efficiency