

# Particle Ratio Fluctuations and Charge Balance Functions in Heavy Ion Collisions at RHIC



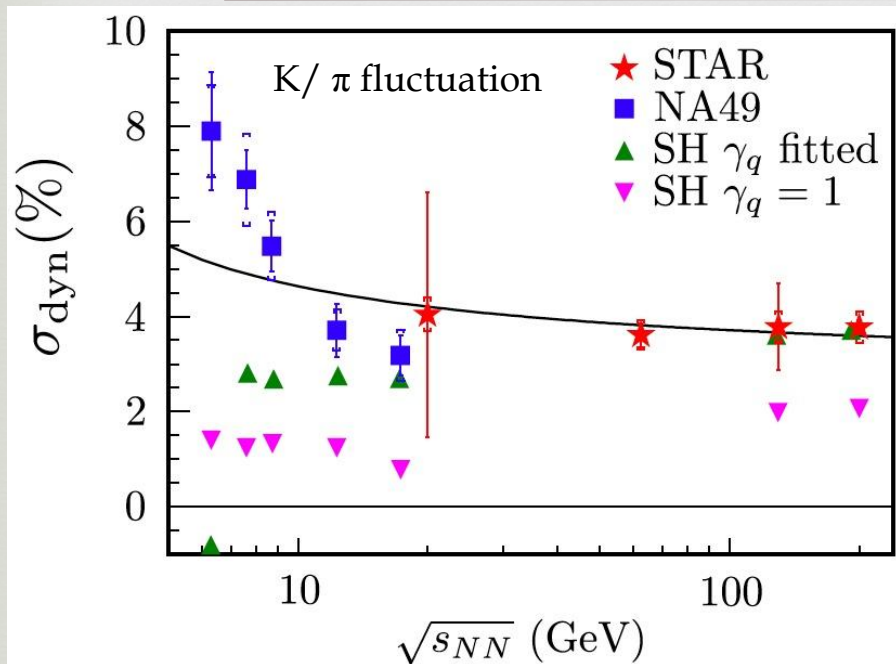
Hui Wang

For the STAR Collaboration



MICHIGAN STATE  
UNIVERSITY

# Motivation



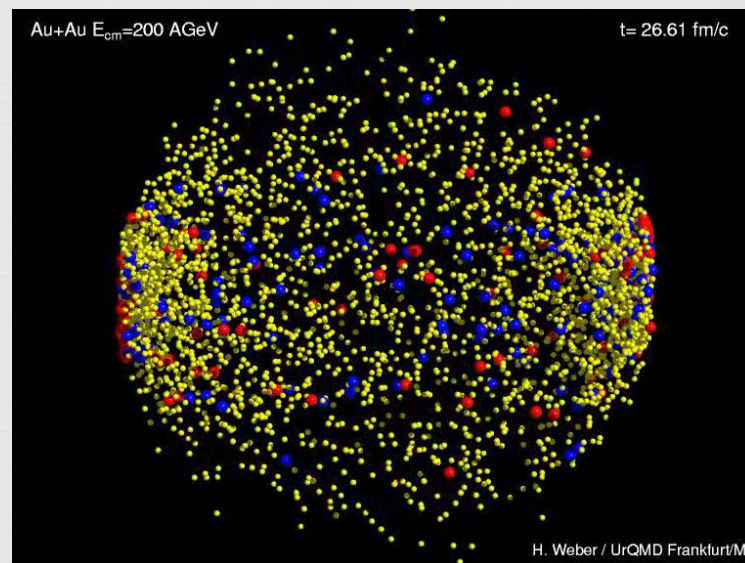
B. I. Abelev *et al*, Phys. Rev. Lett. 103, 092301 (2009)

## Particle Ratio Fluctuations

- Related to strangeness and baryon number fluctuations
- Look for non-monotonic behavior of the fluctuations near critical point

## Charge Balance Function

- Sensitive to the charge formation time and relative diffusion
- A probe for charge production mechanism



# Observable - Fluctuations

Our observable is  $V_{\text{dyn},K\pi}$ , which measures how correlated the event-by-event distributions are

$$V_{\text{dyn},K\pi} = \frac{\langle N_K (N_K - 1) \rangle}{\langle N_K \rangle^2} + \frac{\langle N_\pi (N_\pi - 1) \rangle}{\langle N_\pi \rangle^2} - 2 \frac{\langle N_K N_\pi \rangle}{\langle N_K \rangle \langle N_\pi \rangle}$$

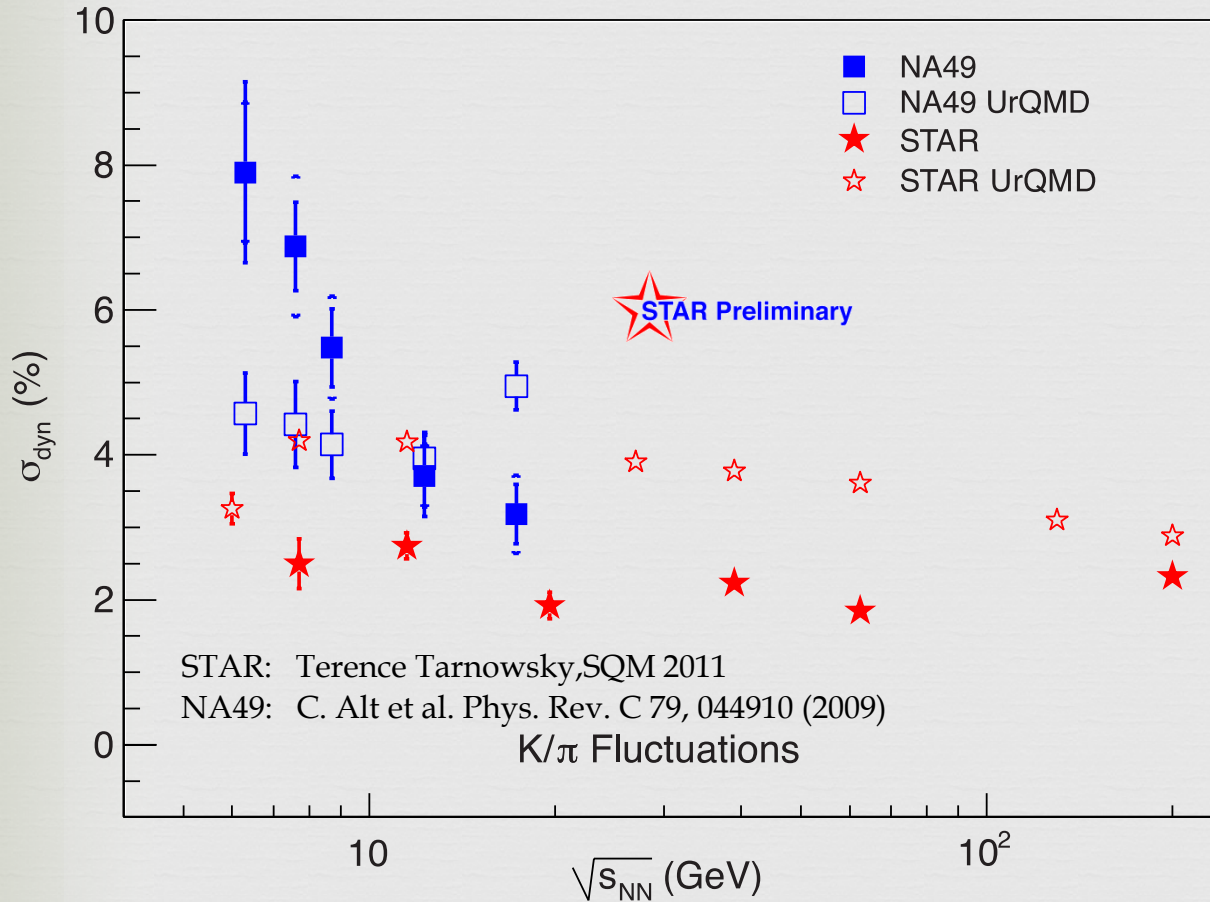
NA49 uses  $\sigma_{\text{dyn}}$

$$\sigma_{\text{dyn}} = \text{sgn}(\sigma_{\text{data}}^2 - \sigma_{\text{mixed}}^2) \sqrt{|\sigma_{\text{data}}^2 - \sigma_{\text{mixed}}^2|}$$

With enough statistics and large denominator

$$\sigma_{\text{dyn}}^2 \approx V_{\text{dyn},K\pi}$$

# K/π Fluctuations



$$\propto (K^+ + K^-) / (\pi^+ + \pi^-)$$

STAR results are calculated via  $v_{\text{dyn}, K\pi}$  using the most central events (0 - 5%)

STAR data show no significant energy dependence

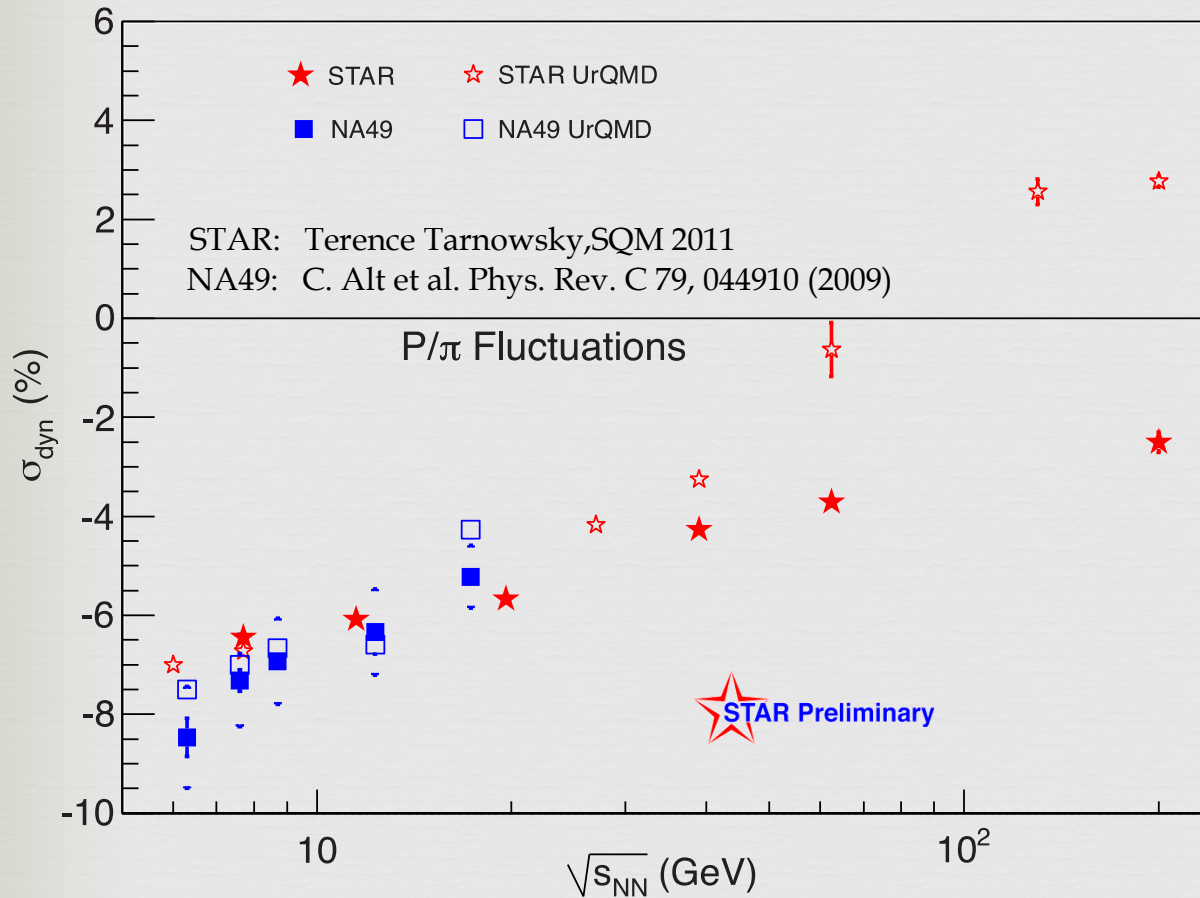
There appears to be a disagreement between STAR and NA49 results below 19.6 GeV

The UrQMD model shows little energy dependence and over-predicts the fluctuations

$$v_{\text{dyn}, K\pi} = \frac{\langle N_K (N_K - 1) \rangle}{\langle N_K \rangle^2} + \frac{\langle N_\pi (N_\pi - 1) \rangle}{\langle N_\pi \rangle^2} - 2 \frac{\langle N_K N_\pi \rangle}{\langle N_K \rangle \langle N_\pi \rangle}$$

$$\sigma_{\text{dyn}} \approx \sqrt{v_{\text{dyn}}}$$

# p/π Fluctuations



$$\propto (p + \bar{p}) / (\pi^+ + \pi^-)$$

STAR results are calculated via  $v_{\text{dyn}, p\pi}$  using the most central events (0 - 5%)

STAR results show a smooth decrease with decreasing incident energy

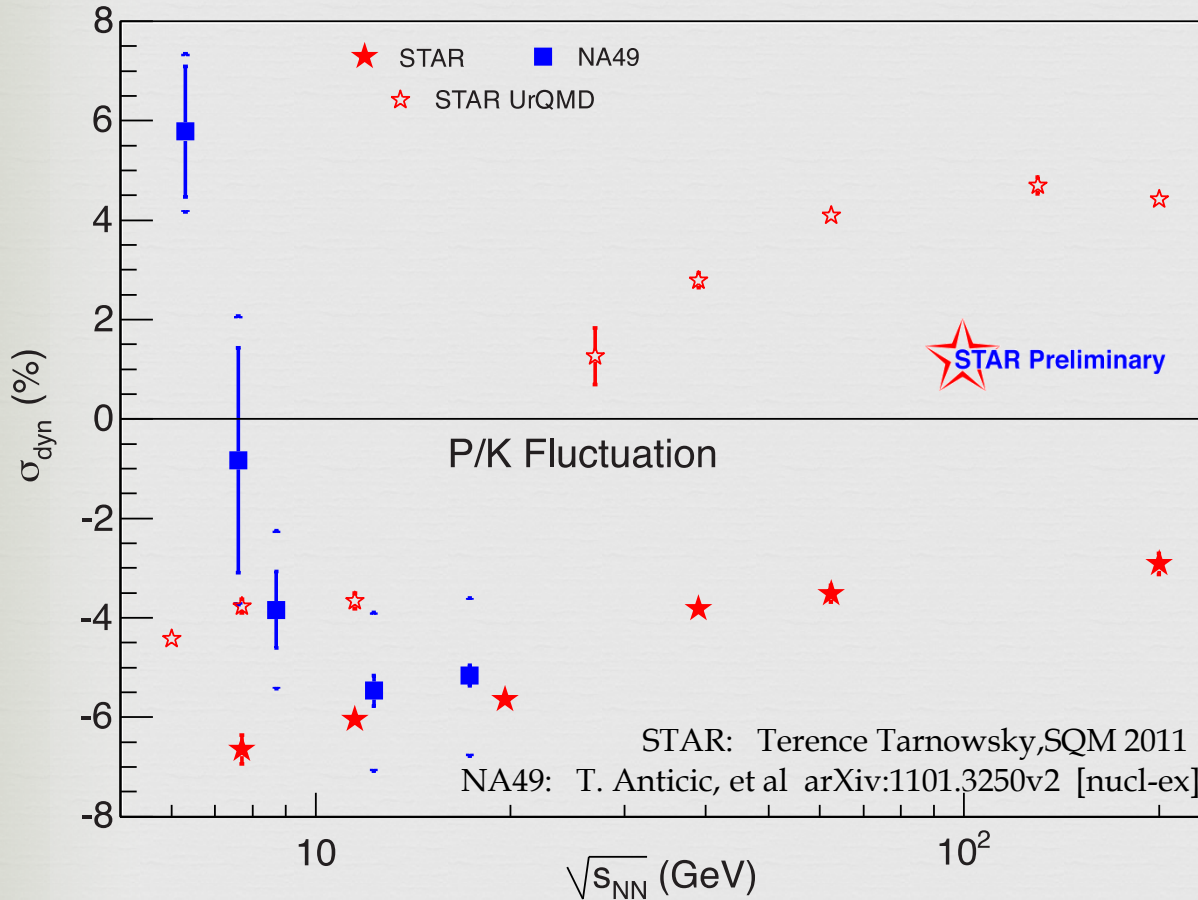
There is good agreement between STAR and NA49 results

The UrQMD model agrees with the data at low energy, but changes sign at high energy

$$v_{\text{dyn}, p\pi} = \frac{\langle N_p (N_p - 1) \rangle}{\langle N_p \rangle^2} + \frac{\langle N_\pi (N_\pi - 1) \rangle}{\langle N_\pi \rangle^2} - 2 \frac{\langle N_p N_\pi \rangle}{\langle N_p \rangle \langle N_\pi \rangle}$$

$$\sigma_{\text{dyn}} \approx \sqrt{v_{\text{dyn}}}$$

# p/K Fluctuations



☞  $(p + \bar{p}) / (K^+ + K^-)$

☞ STAR results are calculated via  $v_{\text{dyn}, pK}$  using the most central events (0 - 5%)

☞ STAR results decrease smoothly with decreasing incident energy

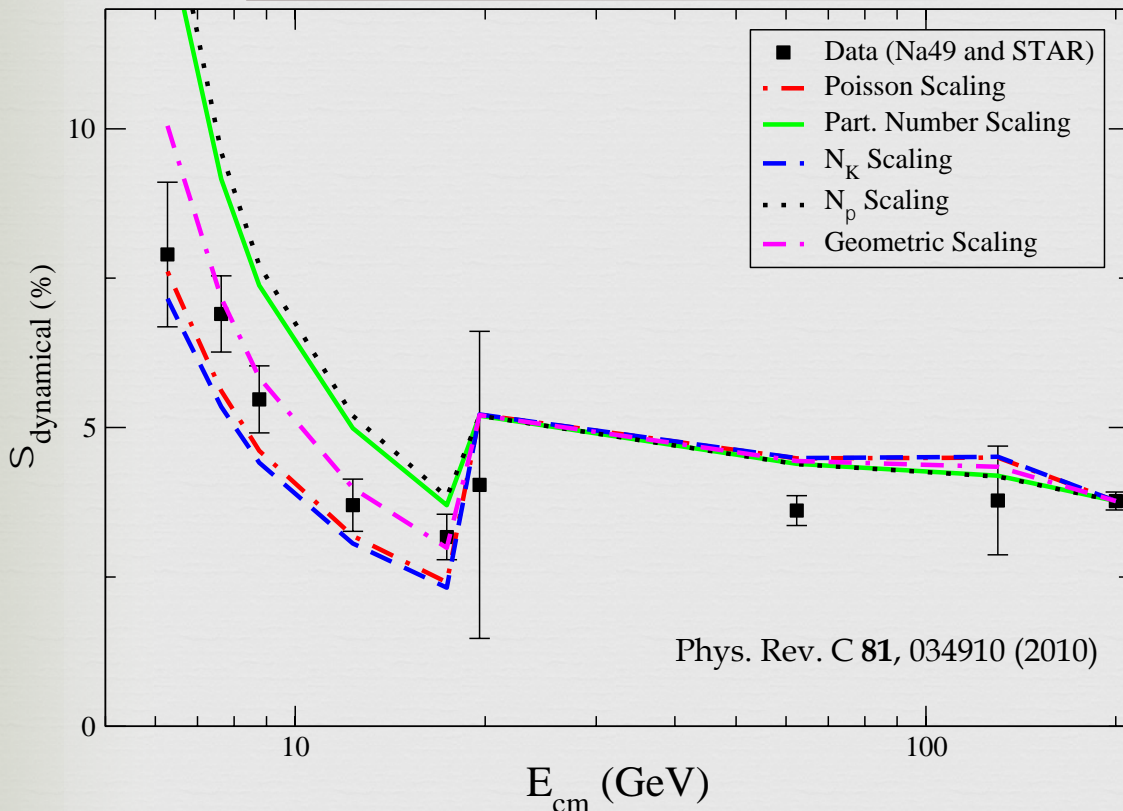
☞ There seems to be disagreement between STAR and NA49 results at 7.7 GeV

☞ The UrQMD model overpredicts the fluctuations and changes sign at high energy

$$v_{\text{dyn}, pK} = \frac{\langle N_p (N_p - 1) \rangle}{\langle N_p \rangle^2} + \frac{\langle N_K (N_K - 1) \rangle}{\langle N_K \rangle^2} - 2 \frac{\langle N_K N_p \rangle}{\langle N_K \rangle \langle N_p \rangle}$$

$$\sigma_{\text{dyn}} \approx \sqrt{v_{\text{dyn}}}$$

# Scaling properties of fluctuation



$\sqrt{s}$ (GeV)	$\langle \pi \rangle$	$\langle K \rangle$
6.27	30.9	5.7
7.63	66.6	10.2
8.77	103.3	15.0
12.3	227.6	31.2
17.3	416.6	54.2
19.6	227.6	10.7
62.4	319.2	14.5
130	351.9	14.4
200	432.6	20.6

Poisson scaling

$$\sigma_{dyn}(\sqrt{s}) = \sigma_{dyn}(200\text{GeV}) \times \frac{\sqrt{\frac{1}{\langle K \rangle} + \frac{1}{\langle \pi \rangle}}_{\sqrt{s}}}{\sqrt{\frac{1}{\langle K \rangle} + \frac{1}{\langle \pi \rangle}}_{200\text{GeV}}}$$

$N_K$  scaling

$$\sigma_{dyn}(\sqrt{s}) = \sigma_{dyn}(200\text{GeV}) \times \frac{\sqrt{\langle K \rangle}_{200\text{GeV}}}{\sqrt{\langle K \rangle}_{\sqrt{s}}}$$

$N_\pi$  scaling

$$\sigma_{dyn}(\sqrt{s}) = \sigma_{dyn}(200\text{GeV}) \times \frac{\sqrt{\langle \pi \rangle}_{200\text{GeV}}}{\sqrt{\langle \pi \rangle}_{\sqrt{s}}}$$

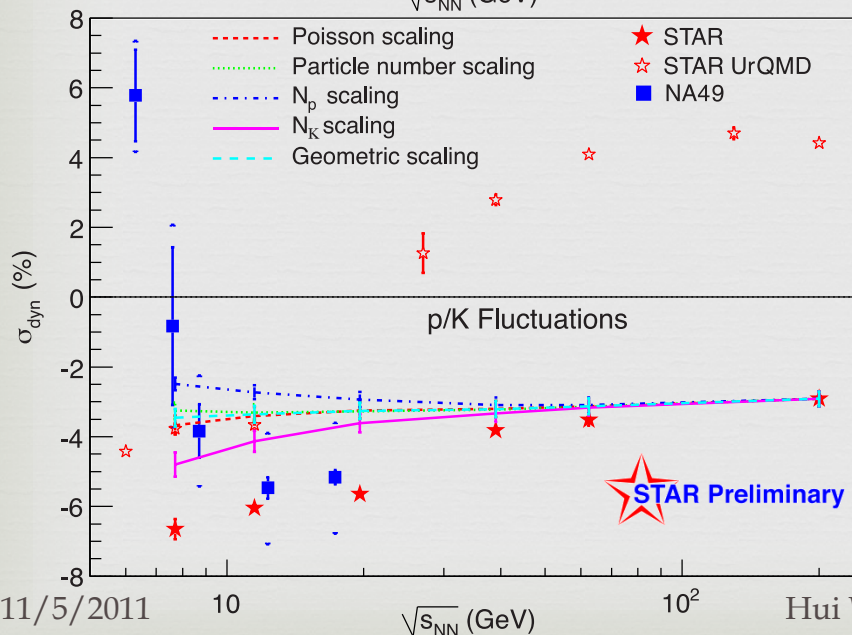
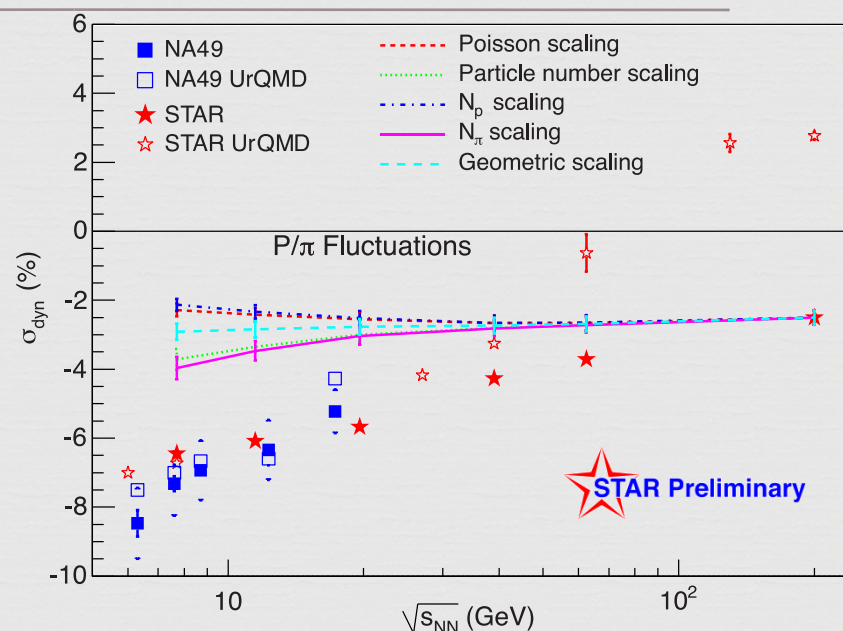
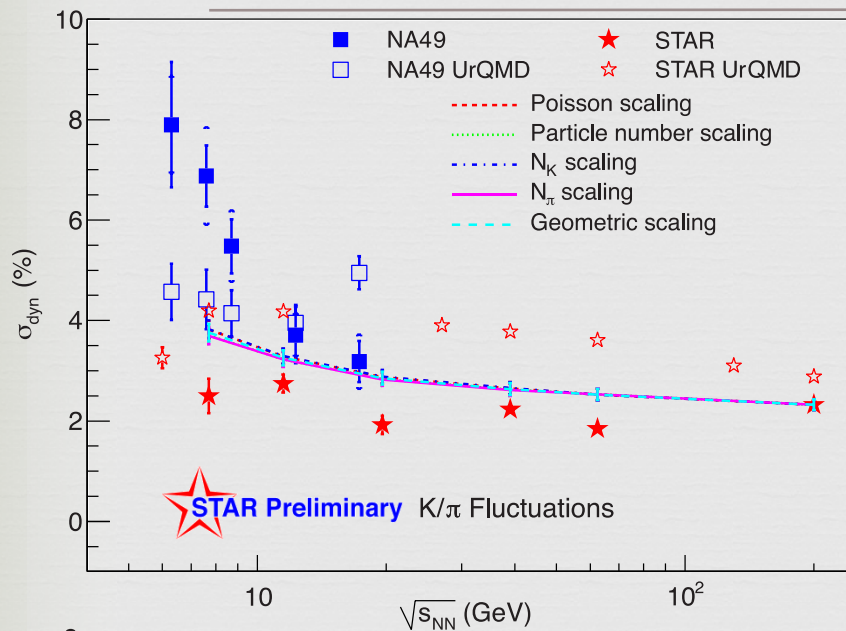
Particle number scaling

$$\sigma_{dyn}(\sqrt{s}) = \sigma_{dyn}(200\text{GeV}) \times \frac{\sqrt{\langle K \rangle + \langle \pi \rangle}_{200\text{GeV}}}{\sqrt{\langle K \rangle + \langle \pi \rangle}_{\sqrt{s}}}$$

Geometric scaling

$$\sigma_{dyn}(\sqrt{s}) = \sigma_{dyn}(200\text{GeV}) \times \frac{(\langle K \rangle \langle \pi \rangle)^{1/4}_{200\text{GeV}}}{(\langle K \rangle \langle \pi \rangle)^{1/4}_{\sqrt{s}}}$$

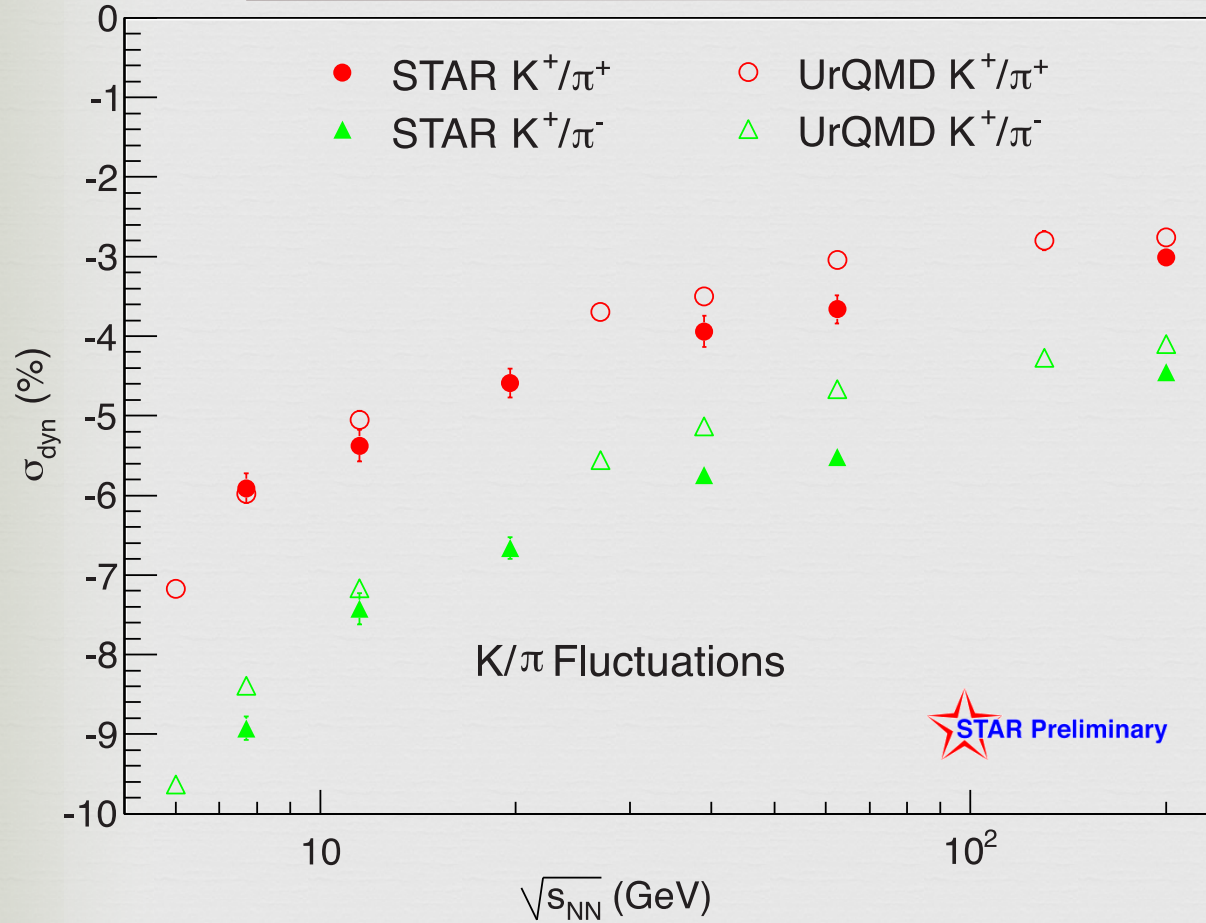
# Scaling Properties of Fluctuations



☞ Scale STAR results by actual number of particles used by STAR in the  $v_{\text{dyn}}$  calculations

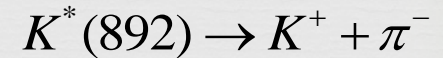
☞ The energy dependence of p/ $\pi$  and p/K fluctuation can't be explained by simple multiplicity scaling

# Charge Dependent K/ $\pi$ Fluctuation



STAR results are calculated via  $v_{\text{dyn}}$

$K^+/\pi^-$  is strongly negative due to decays, possible candidate is



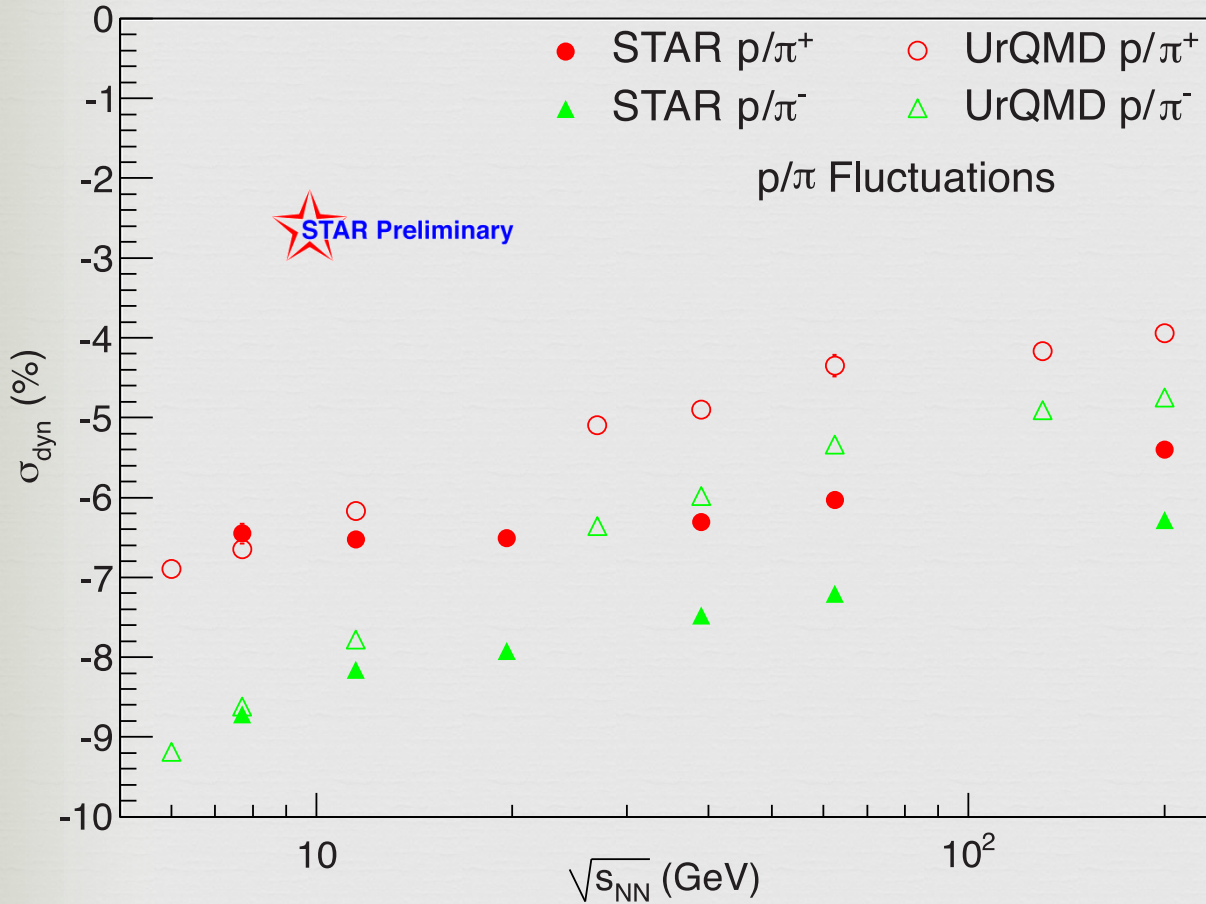
$K^+/\pi^+$  is also negative, needs further study to investigate the origin

UrQMD qualitatively agrees with the data

$$v_{\text{dyn}, K\pi} = \frac{\langle N_K (N_K - 1) \rangle}{\langle N_K \rangle^2} + \frac{\langle N_\pi (N_\pi - 1) \rangle}{\langle N_\pi \rangle^2} - 2 \frac{\langle N_K N_\pi \rangle}{\langle N_K \rangle \langle N_\pi \rangle}$$

$$\sigma_{\text{dyn}} \approx \sqrt{v_{\text{dyn}}}$$

# Charge Dependent $p/\pi$ Fluctuation



☞ STAR results are calculated via  $v_{\text{dyn}}$

☞ Both same and opposite sign fluctuations are negative

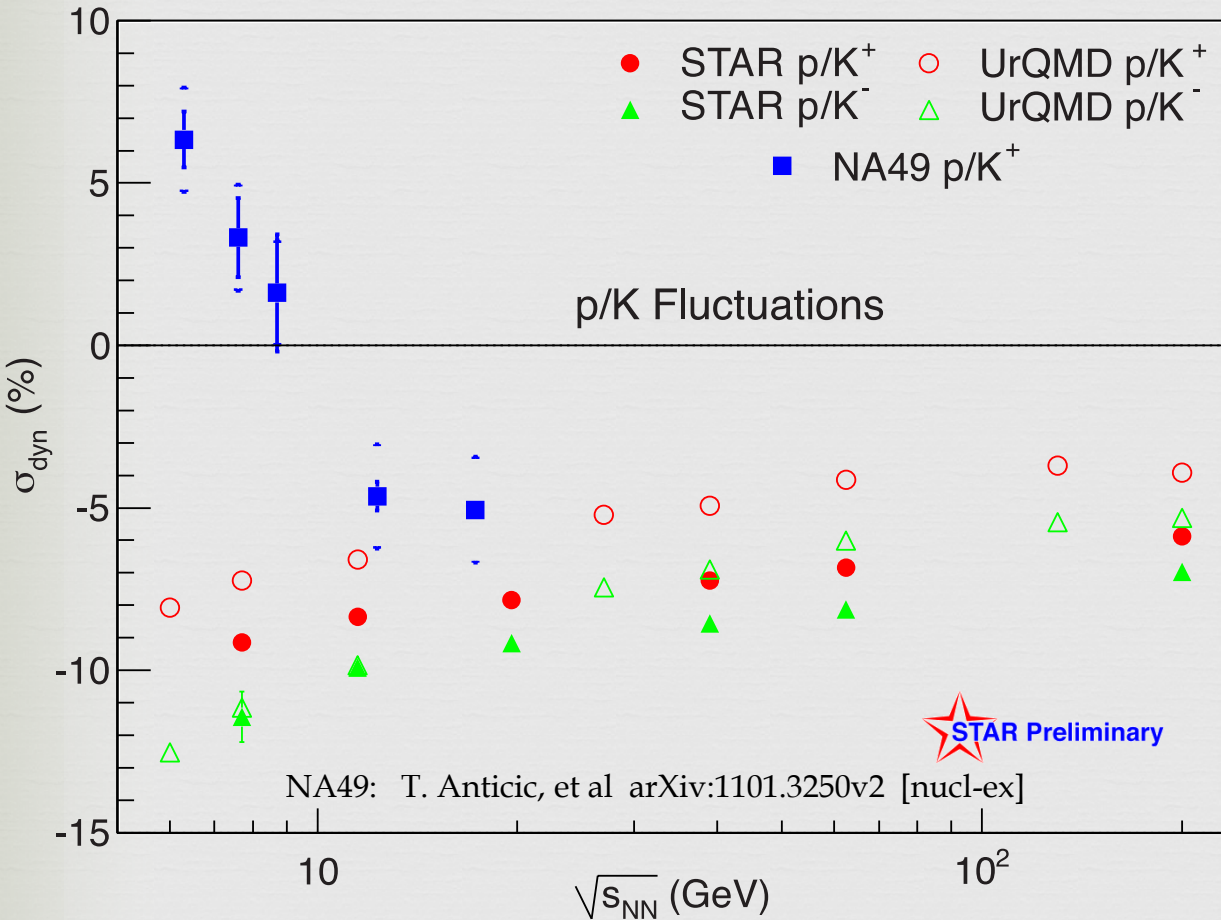
☞ Unstable particle decays like  $\Delta$  might introduce more correlations for opposite signs

☞ UrQMD over-predicts the fluctuations

$$v_{\text{dyn}, p\pi} = \frac{\langle N_p (N_p - 1) \rangle}{\langle N_p \rangle^2} + \frac{\langle N_\pi (N_\pi - 1) \rangle}{\langle N_\pi \rangle^2} - 2 \frac{\langle N_p N_\pi \rangle}{\langle N_p \rangle \langle N_\pi \rangle}$$

$$\sigma_{\text{dyn}} \approx \sqrt{v_{\text{dyn}}}$$

# Charge Dependent p/K Fluctuations



- ☞ STAR results are calculated via  $v_{\text{dyn}}$
- ☞ Both same and opposite sign fluctuations are negative
- ☞ Disagreement between STAR and NA49 p/K<sup>+</sup> results

$$v_{\text{dyn},Kp} = \frac{\langle N_K (N_K - 1) \rangle}{\langle N_K \rangle^2} + \frac{\langle N_P (N_P - 1) \rangle}{\langle N_P \rangle^2} - 2 \frac{\langle N_K N_P \rangle}{\langle N_K \rangle \langle N_P \rangle}$$

$$\sigma_{\text{dyn}} \approx \sqrt{v_{\text{dyn}}}$$

# Observable – Balance Function

---

∞ The balance function is a conditional probability that a particle  $a$  in the bin  $p_1$  will be accompanied by a particle  $b$  of opposite charge in the bin  $p_2$

$$B(p_2 | p_1) = \frac{1}{2} \{ \rho(b, p_2 | a, p_1) - \rho(b, p_2 | b, p_1) + \rho(a, p_2 | b, p_1) - \rho(a, p_2 | a, p_1) \}$$

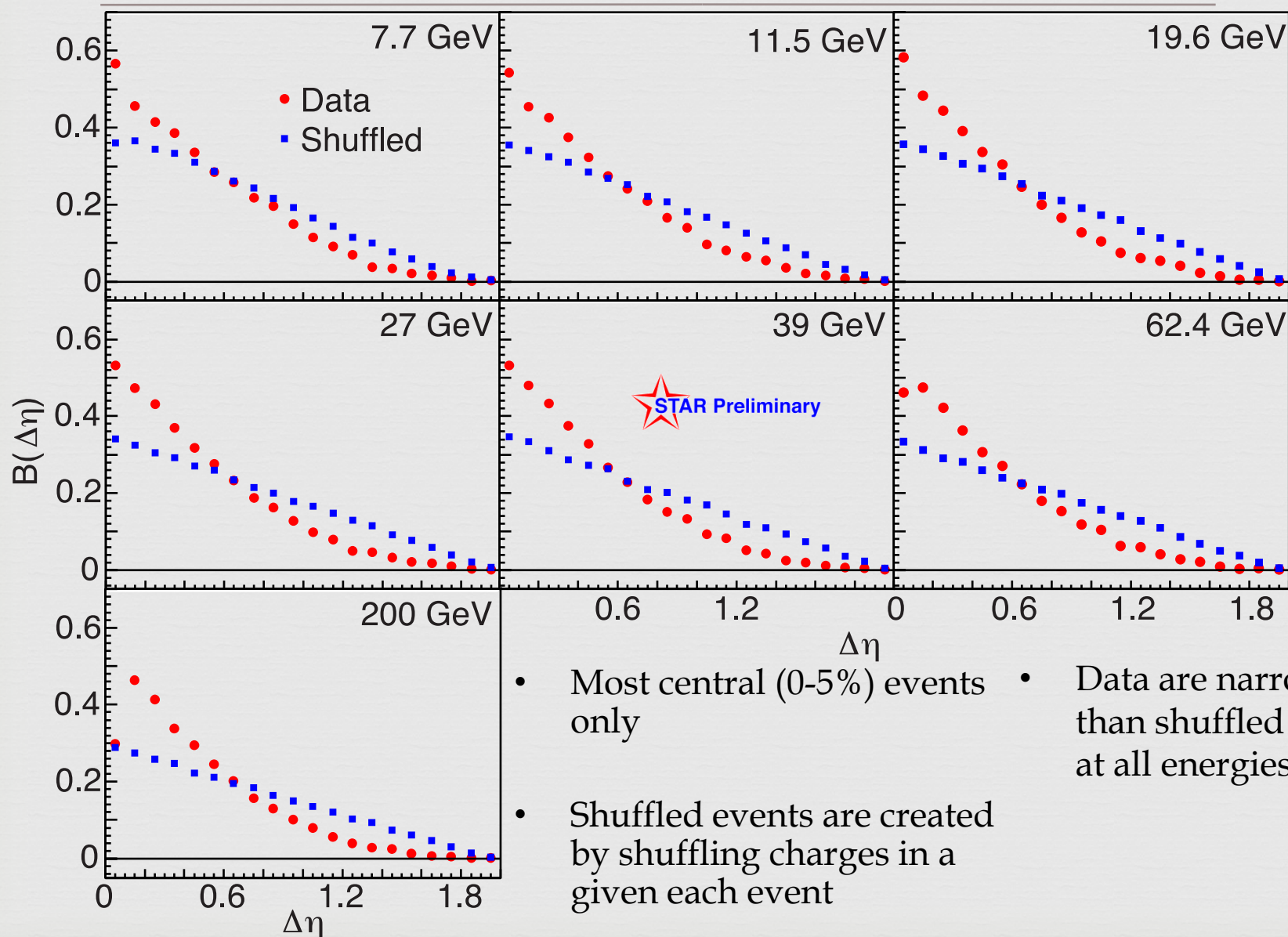
∞ It can be written as

$$B(\Delta\eta) = \frac{1}{2} \left\{ \frac{N_{+-}(\Delta\eta) - N_{++}(\Delta\eta)}{N_+} + \frac{N_{-+}(\Delta\eta) - N_{--}(\Delta\eta)}{N_-} \right\}$$

∞ The width of balance function is calculated via weighted average

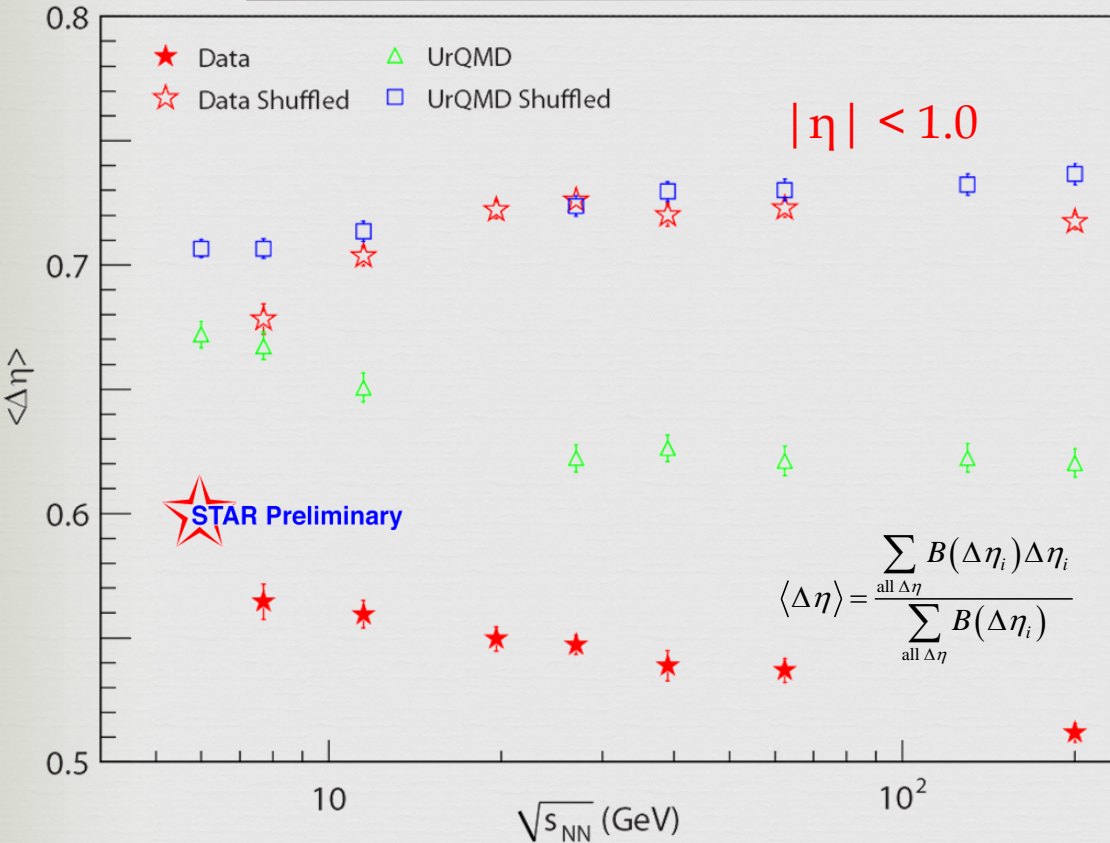
$$\langle \Delta\eta \rangle = \frac{\sum_{\text{all } \Delta\eta} B(\Delta\eta_i) \Delta\eta_i}{\sum_{\text{all } \Delta\eta} B(\Delta\eta_i)}$$
$$W = \frac{100 \cdot (\langle \Delta\eta \rangle_{\text{shuffled}} - \langle \Delta\eta \rangle_{\text{data}})}{\langle \Delta\eta \rangle_{\text{shuffled}}}$$

# Balance Function

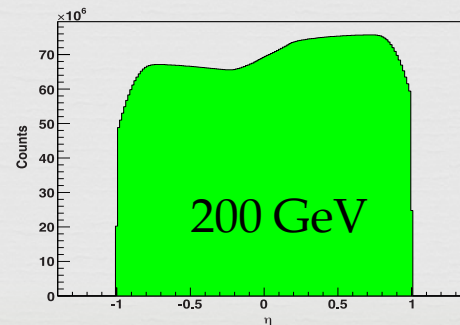
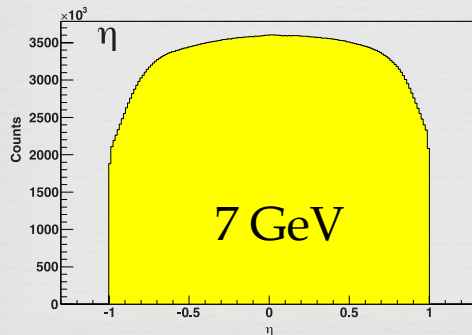


- Most central (0-5%) events only
- Data are narrower than shuffled events at all energies
- Shuffled events are created by shuffling charges in a given each event

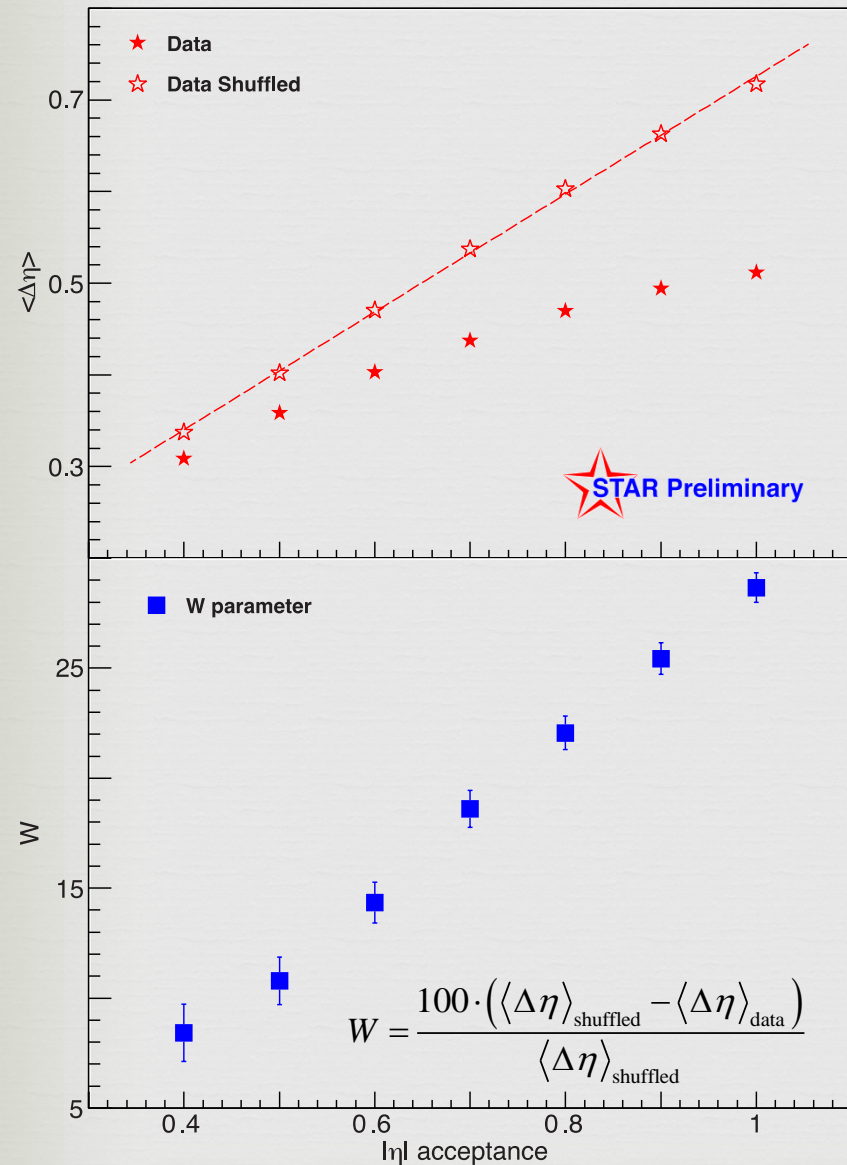
# Weighted Average



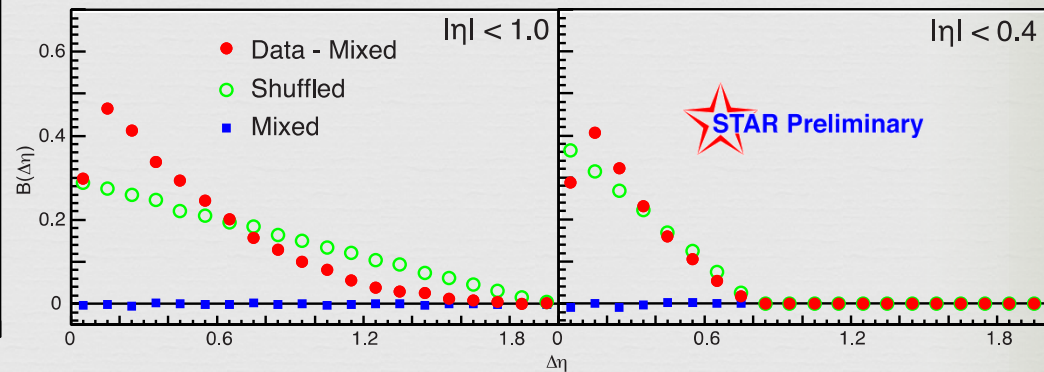
- ☞ Most central (0-5%) events only
- ☞ Remove lowest bin when calculating  $\langle \Delta\eta \rangle$  to reduce HBT/Coulomb effects
- ☞ Both data and UrQMD show a smooth decrease with increasing collision energy, indicating stronger correlations at small  $\Delta\eta$
- ☞ Shuffled event widths also change with energy due to acceptance
- ☞ Balance function width is sensitive to flow and breakup temperature



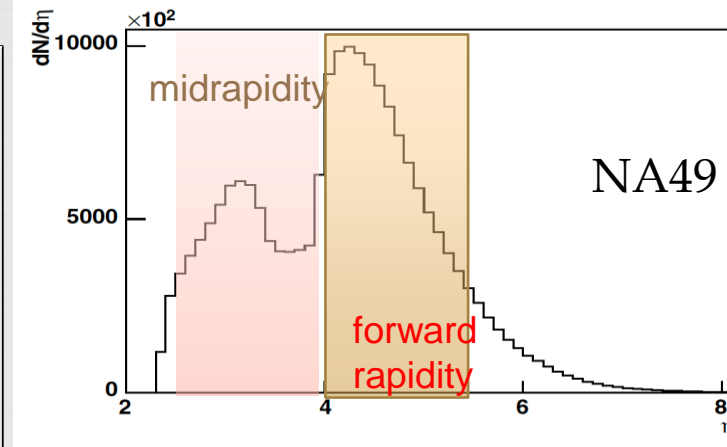
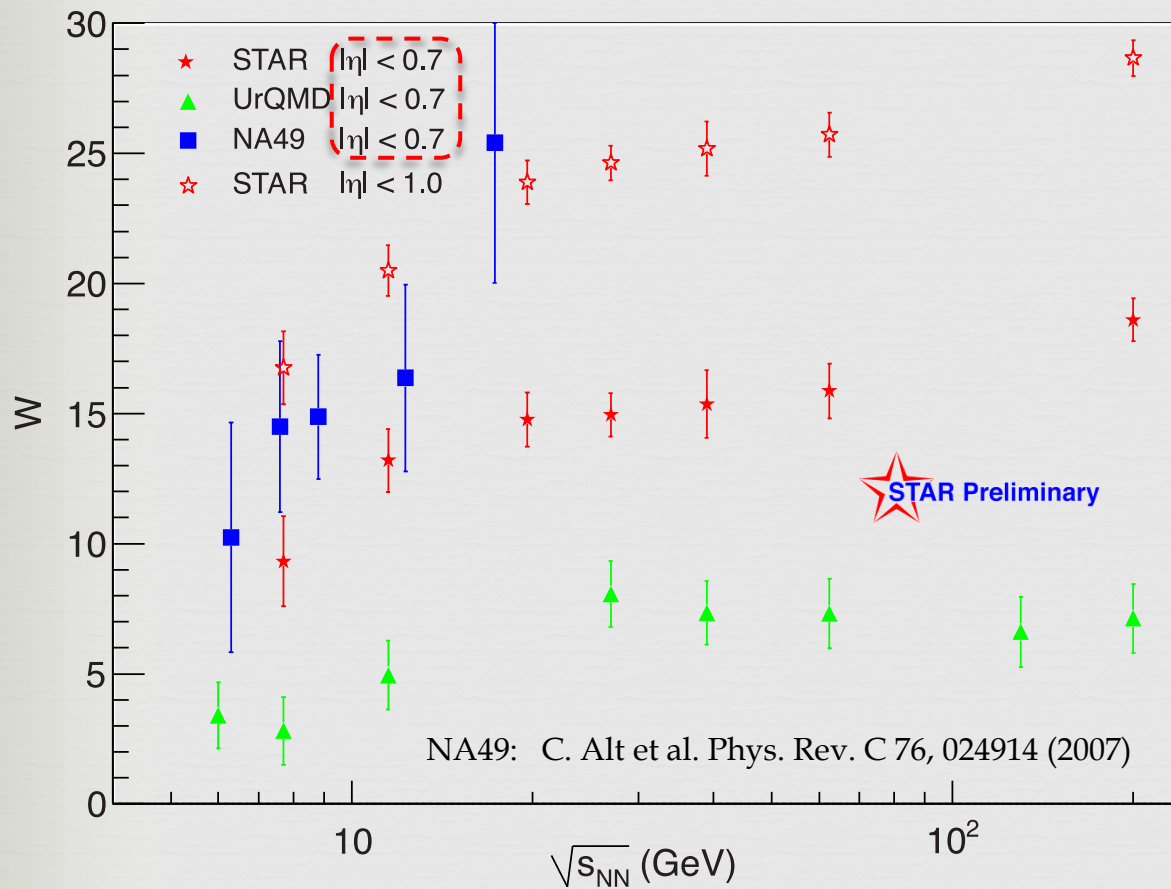
# W Parameter



- ☞ 200 GeV central (0-5%) events
- ☞ Plot  $\langle \Delta\eta \rangle$  and W v.s.  $|\eta|$  acceptance
- ☞ Data and shuffled events show different  $|\eta|$  acceptance dependence
- ☞ W parameter shows a strong acceptance dependence



# W Parameter



$$W = \frac{100 \cdot (\langle \Delta \eta \rangle_{\text{shuffled}} - \langle \Delta \eta \rangle_{\text{data}})}{\langle \Delta \eta \rangle_{\text{shuffled}}}$$

- ☞ The NA49 results agree well with STAR ( $|\eta| < 0.7$ ) at low energies
- ☞ Data show a smooth increase of  $W$  with increasing beam energy, which is consistent with the  $\langle \Delta \eta \rangle$  results
- ☞ UrQMD reproduces the observed trend in  $W$  but predicts a much smaller value of  $W$ , corresponding to a much larger width

# Summary

---

## ❧ Particle Ratio Fluctuations

- ❧ K/ $\pi$  fluctuations show no energy dependence, while p/ $\pi$  and p/K fluctuations show a smooth decrease with energy. Overall, no non-monotonic behavior with energy is observed
- ❧ Simple multiplicity scaling doesn't hold for p/ $\pi$  and p/K fluctuation
- ❧ Opposite sign fluctuations are more negative due to resonance decay contribution

## ❧ Balance Function

- ❧ Balance functions for  $\Delta\eta$  narrow at higher collision energies, which is related to delayed hadronization
- ❧ The W parameter has a trivial acceptance dependence

---

# Back Up

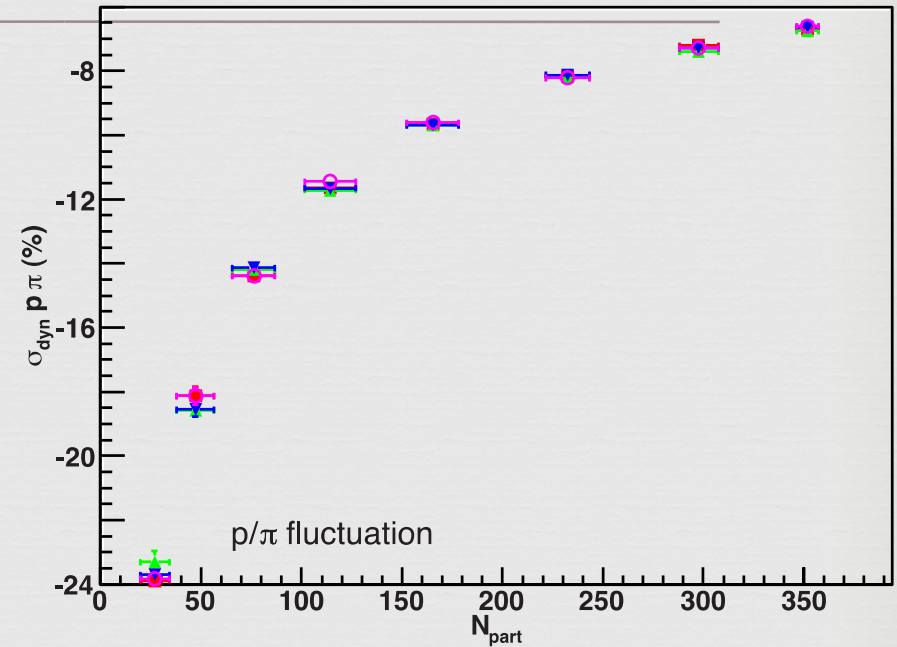
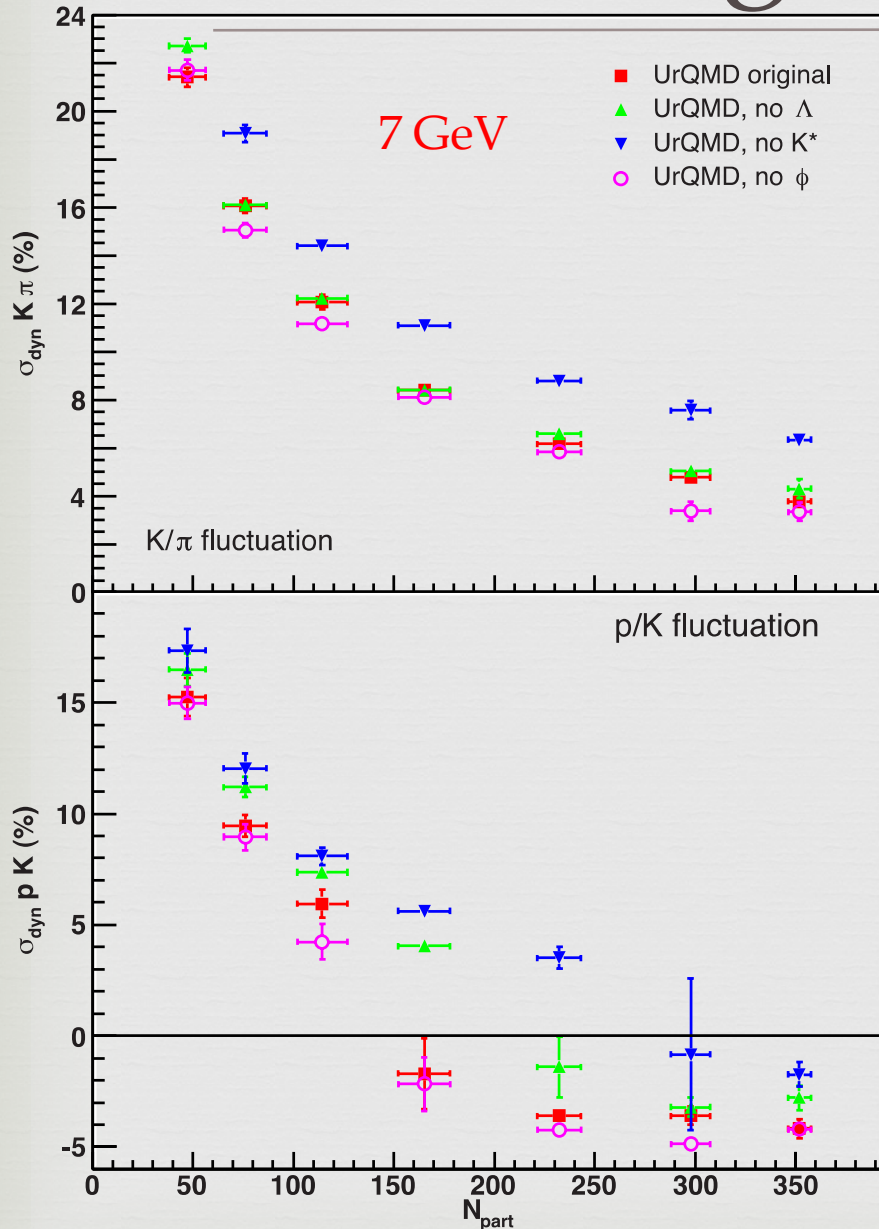
# UrQMD Model

ID	nucleon	ID	delta	ID	lambda	ID	sigma	ID	xi	ID	omega
1	$N_{938}$	17	$\Delta_{1232}$	27	$\Lambda_{1116}$	40	$\Sigma_{1192}$	49	$\Xi_{1317}$	55	$\Omega_{1672}$
2	$N_{1440}$	18	$\Delta_{1600}$	28	$\Lambda_{1405}$	41	$\Sigma_{1385}$	50	$\Xi_{1530}$		
3	$N_{1520}$	19	$\Delta_{1620}$	29	$\Lambda_{1520}$	42	$\Sigma_{1660}$	51	$\Xi_{1690}$		
4	$N_{1535}$	20	$\Delta_{1700}$	30	$\Lambda_{1600}$	43	$\Sigma_{1670}$	52	$\Xi_{1820}$		
5	$N_{1650}$	21	$\Delta_{1900}$	31	$\Lambda_{1670}$	44	$\Sigma_{1775}$	53	$\Xi_{1950}$		
6	$N_{1675}$	22	$\Delta_{1905}$	32	$\Lambda_{1690}$	45	$\Sigma_{1790}$	54	$\Xi_{2025}$		
7	$N_{1680}$	23	$\Delta_{1910}$	33	$\Lambda_{1800}$	46	$\Sigma_{1915}$				
8	$N_{1700}$	24	$\Delta_{1920}$	34	$\Lambda_{1810}$	47	$\Sigma_{1940}$				
9	$N_{1710}$	25	$\Delta_{1930}$	35	$\Lambda_{1820}$	48	$\Sigma_{2030}$				
10	$N_{1720}$	26	$\Delta_{1950}$	36	$\Lambda_{1830}$						
11	$N_{1900}$			37	$\Lambda_{1890}$						
12	$N_{1990}$			38	$\Lambda_{2100}$						
13	$N_{2080}$			39	$\Lambda_{2110}$						
14	$N_{2190}$										
15	$N_{2200}$										
16	$N_{2250}$										

ID	$0^{-+}$	ID	$1^{--}$	ID	$0^{++}$	ID	$1^{++}$
101	$\pi$	104	$\rho$	111	$a_0$	114	$a_1$
106	$K$	108	$K^*$	110	$K_0^*$	113	$K_1^*$
102	$\eta$	103	$\omega$	105	$f_0$	115	$f_1$
107	$\eta'$	109	$\phi$	112	$f_0^*$	116	$f_1'$
ID	$1^{+-}$	ID	$2^{++}$	ID	$(1^{--})^*$	ID	$(1^{--})^{**}$
122	$b_1$	118	$a_2$	126	$\rho_{1450}$	130	$\rho_{1700}$
121	$K_1$	117	$K_2^*$	125	$K_{1410}^*$	129	$K_{1680}^*$
123	$h_1$	119	$f_2$	127	$\omega_{1420}$	131	$\omega_{1662}$
124	$h_1'$	120	$f_2'$	128	$\phi_{1680}$	132	$\phi_{1900}$

- ✧ Hadronic transport model that include resonance/unstable particle decay
- ✧ Could stabilize one or more particle types from decay
- ✧ UrQMD does not include weak interactions thus no weak decays of particles
- ✧ By default the system would interact for 200 fm/c

# Sum-sign fluctuation



Original  $\rightarrow$  default setting (200 fm/c)

No  $\Lambda \rightarrow$  stabilize all  $\Lambda$

No  $K^* \rightarrow$  stabilize  $K^*$

No  $\phi \rightarrow$  stabilize  $\phi$

# Blast Wave Model

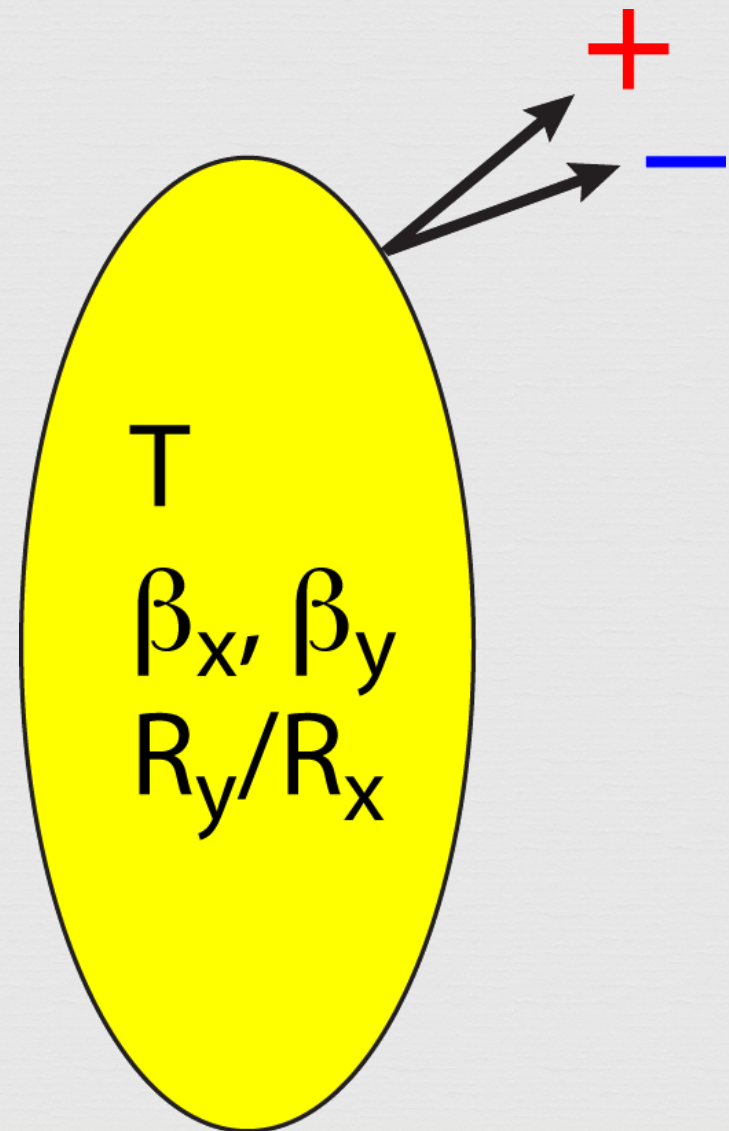
---

STAR

parameterization

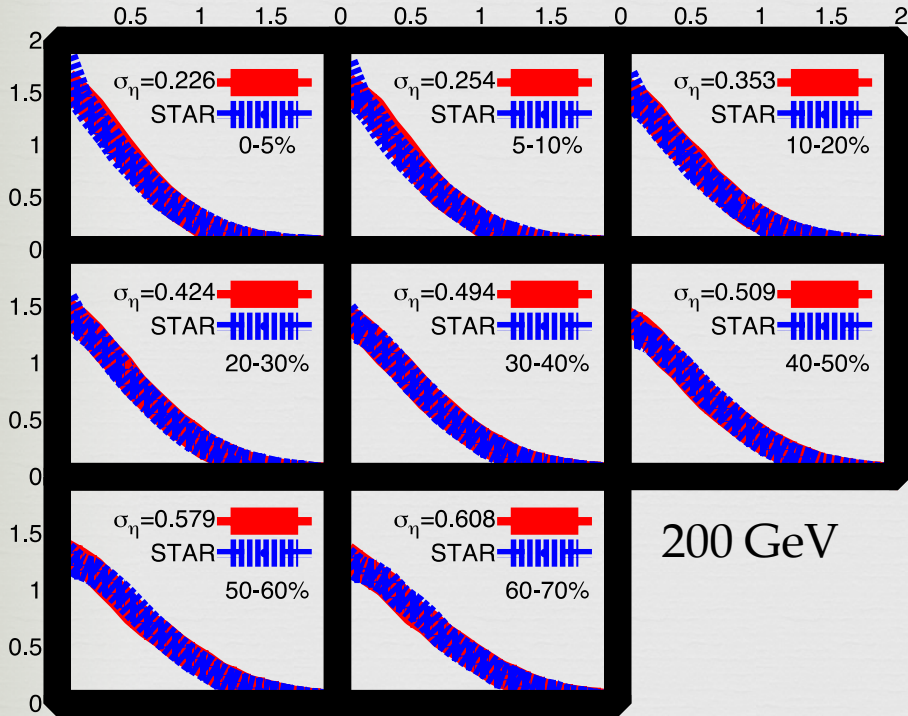
(STAR, PRC, 72, 14904 (2005))

Local charge  
conservation



S. Schlichting and S. Pratt  
Phys. Rev. C 83, 014913 (2011)

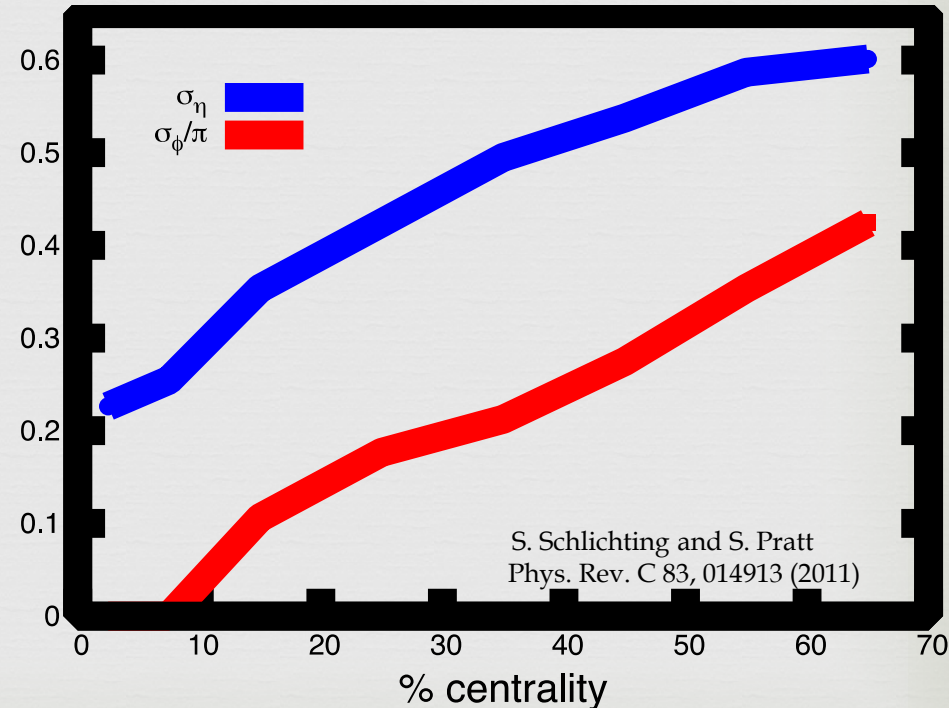
# Blast Wave Model



S. Schlichting and S. Pratt  
Phys. Rev. C 83, 014913 (2011)

Extract the initial separation of balancing charges at time of freeze out by fitting the observed charge balance functions

The narrowing of balance function at central collision can't be explained by changing of kinetic freeze-out temperature and collective flow alone



S. Schlichting and S. Pratt  
Phys. Rev. C 83, 014913 (2011)