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

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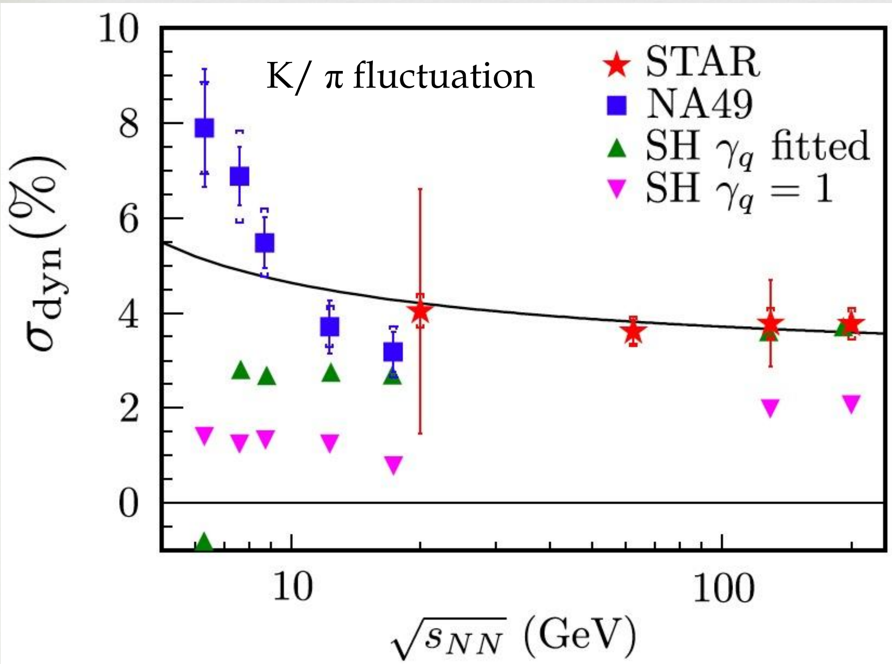
Motivation



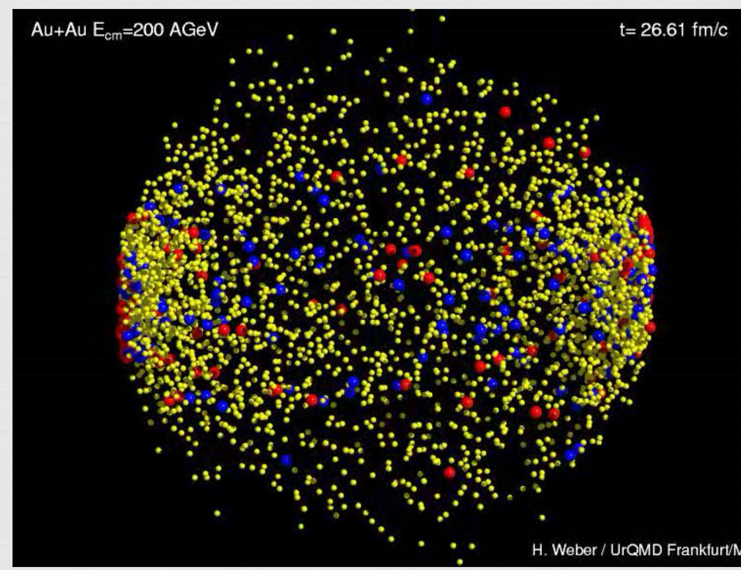
B. I. Abelev *et al,* Phys. Rev. Lett. 103, 092301 (2009)

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 $\nu_{\mathrm{dyn},K\pi}$, which measures how correlated the event-by-event distributions are

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

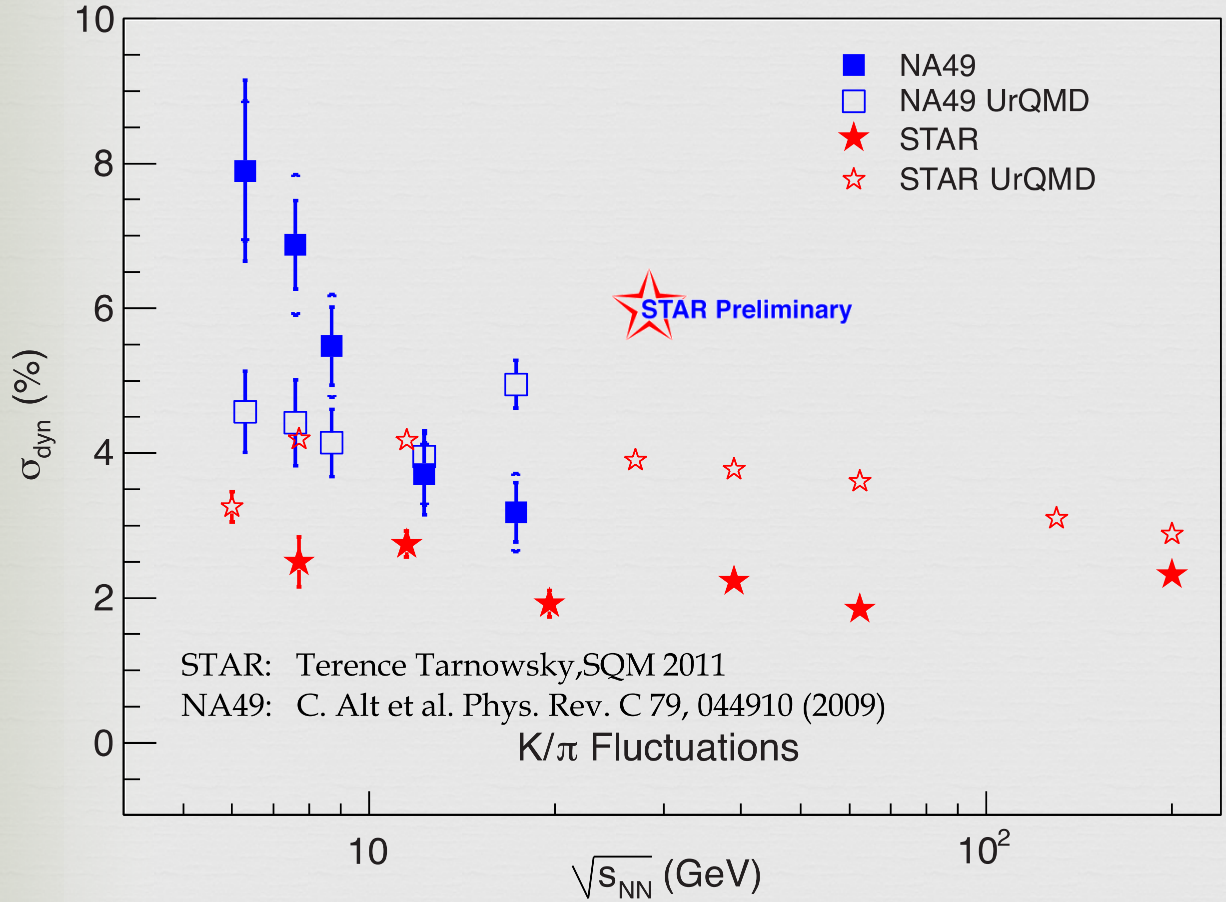
- NA49 uses σ_{dyn}

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

- With enough statistics and large denominator

$$\sigma^2_{\mathrm{dyn}} \approx \nu_{\mathrm{dyn},K\pi}$$

K/π Fluctuations

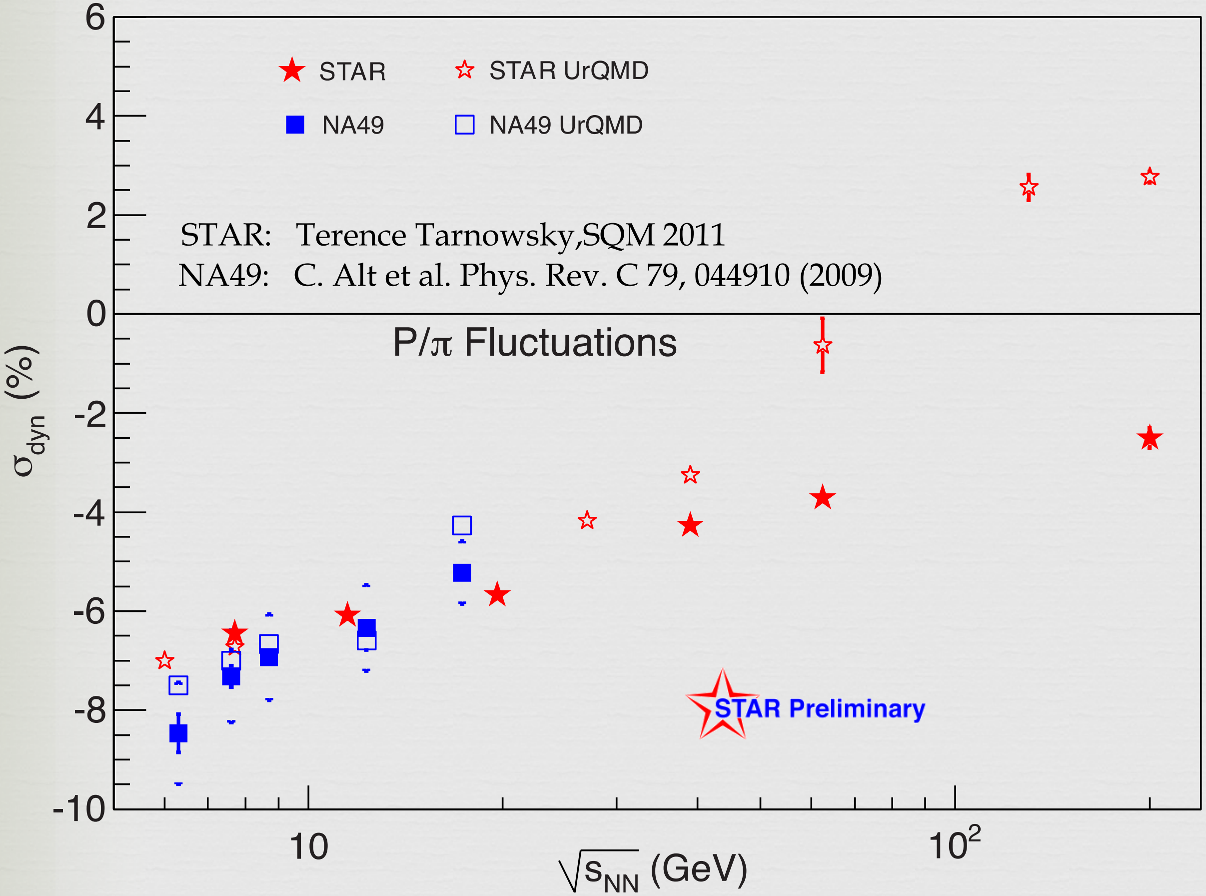


$$\nu_{\mathrm{dyn},K\pi} = \frac{\langle N_K(N_K-1)\rangle}{\langle N_K\rangle^2} + \frac{\langle N_\pi(N_\pi-1)\rangle}{\langle N_\pi\rangle^2} - 2\frac{\langle N_K N_\pi\rangle}{\langle N_K\rangle\langle N_\pi\rangle}$$

$$\sigma_{\mathrm{dyn}} \approx \sqrt{\nu_{\mathrm{dyn}}}$$

- $(K^+ + K^-)/(\pi^+ + \pi^-)$
- STAR results are calculated via $\nu_{\mathrm{dyn},K\pi}$ 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

p/π Fluctuations

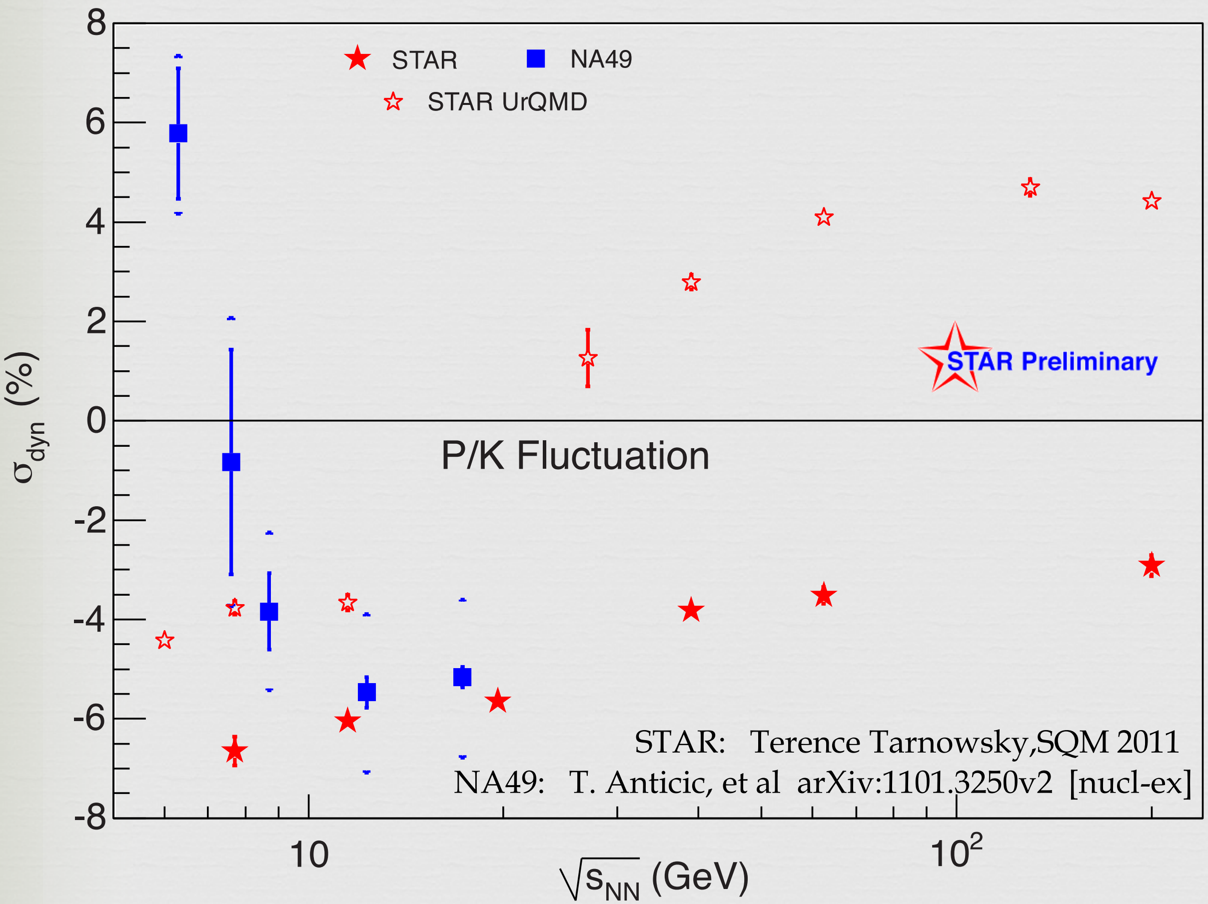


$$\nu_{\mathrm{dyn},p\pi} = \frac{\langle N_p(N_p-1)\rangle}{\langle N_p\rangle^2} + \frac{\langle N_\pi(N_\pi-1)\rangle}{\langle N_\pi\rangle^2} - 2\frac{\langle N_p N_\pi\rangle}{\langle N_p\rangle\langle N_\pi\rangle}$$

$$\sigma_{\mathrm{dyn}} \approx \sqrt{\nu_{\mathrm{dyn}}}$$

- $(p+\bar{p})/(\pi^+ + \pi^-)$
- STAR results are calculated via $\nu_{\mathrm{dyn},p\pi}$ 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

p/K Fluctuations

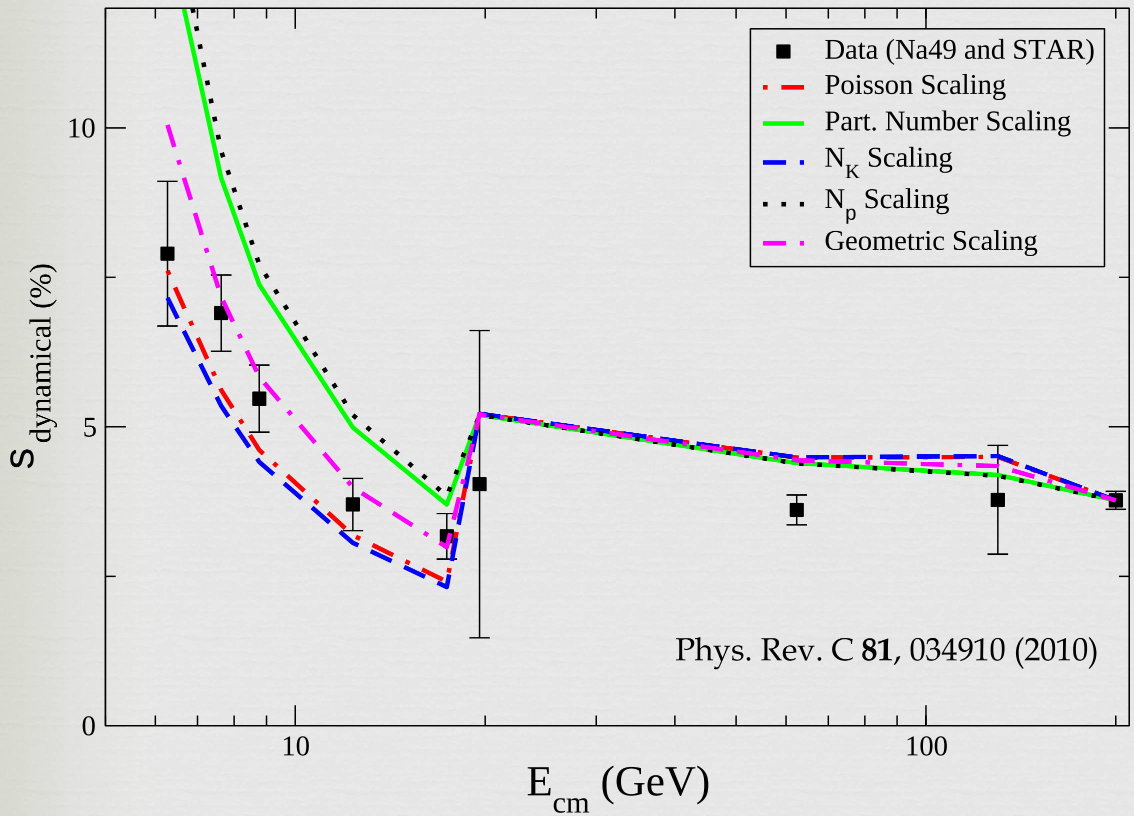


$$\nu_{\mathrm{dyn},pK} = \frac{\langle N_p (N_p - 1)\rangle}{\langle N_p\rangle^2} + \frac{\langle N_K (N_K - 1)\rangle}{\langle N_K\rangle^2} - 2\frac{\langle N_K N_p\rangle}{\langle N_K\rangle\langle N_p\rangle}$$

$$\sigma_{\mathrm{dyn}} \approx \sqrt{\nu_{\mathrm{dyn}}}$$

- $(p+\bar{p})/(K^{+}+K^{-})$
- STAR results are calculated via $v_{dyn,pK}$ using the most central events (0 - 5%)
- STAR results decrease smoothly with decreasing incident energy
- The seems to be disagreement between STAR and NA49 results at 7.7 GeV
- The UrQMD model over-predicts the fluctuations and changes sign at high energy

Scaling properties of fluctuation



√s (GeV)	<π>	<K>
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

$$\sigma_{dyn}(\sqrt{s}) = \sigma_{dyn}(200GeV) \times \frac{\sqrt{\frac{1}{<K>} + \frac{1}{<\pi>}}\Big|_{\sqrt{s}}}{\sqrt{\frac{1}{<K>} + \frac{1}{<\pi>}}\Big|_{200GeV}}$$

Particle number scaling

$$\sigma_{dyn}(\sqrt{s}) = \sigma_{dyn}(200GeV) \times \frac{\sqrt{<K> + <\pi>}\Big|_{200GeV}}{\sqrt{<K> + <\pi>}\Big|_{\sqrt{s}}}$$

N_K scaling

$$\sigma_{dyn}(\sqrt{s}) = \sigma_{dyn}(200GeV) \times \frac{\sqrt{<K>}\Big|_{200GeV}}{\sqrt{<K>}\Big|_{\sqrt{s}}}$$

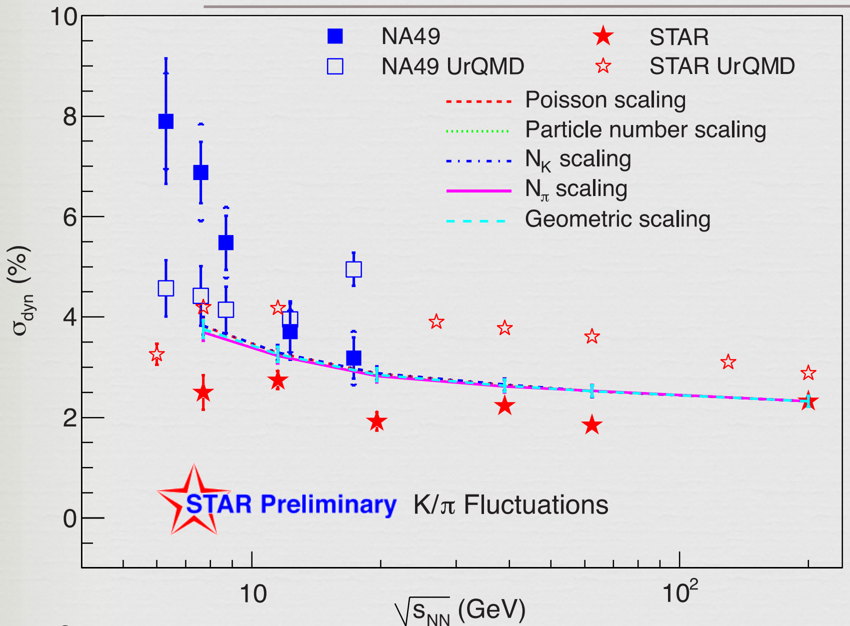
N_π scaling

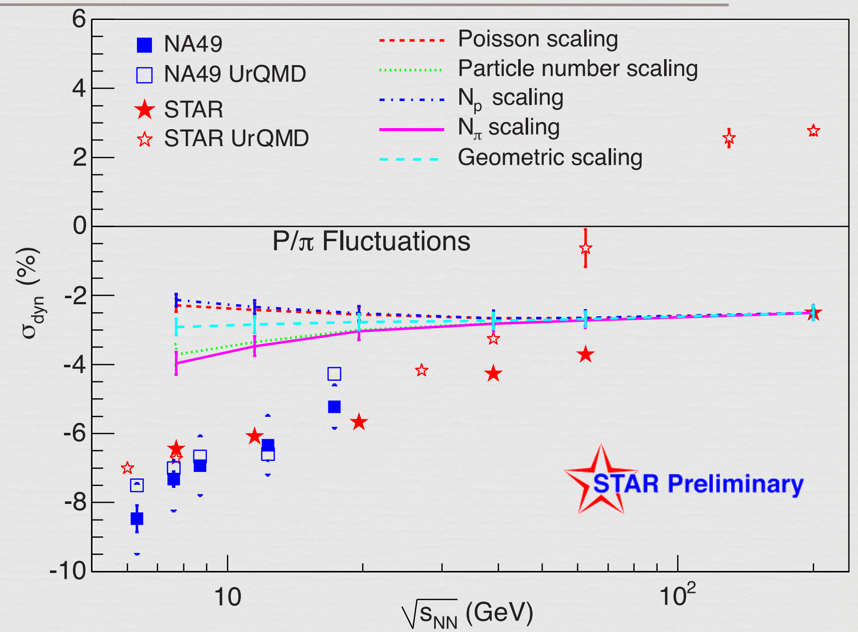
$$\sigma_{dyn}(\sqrt{s}) = \sigma_{dyn}(200GeV) \times \frac{\sqrt{<\pi>}\Big|_{200GeV}}{\sqrt{<\pi>}\Big|_{\sqrt{s}}}$$

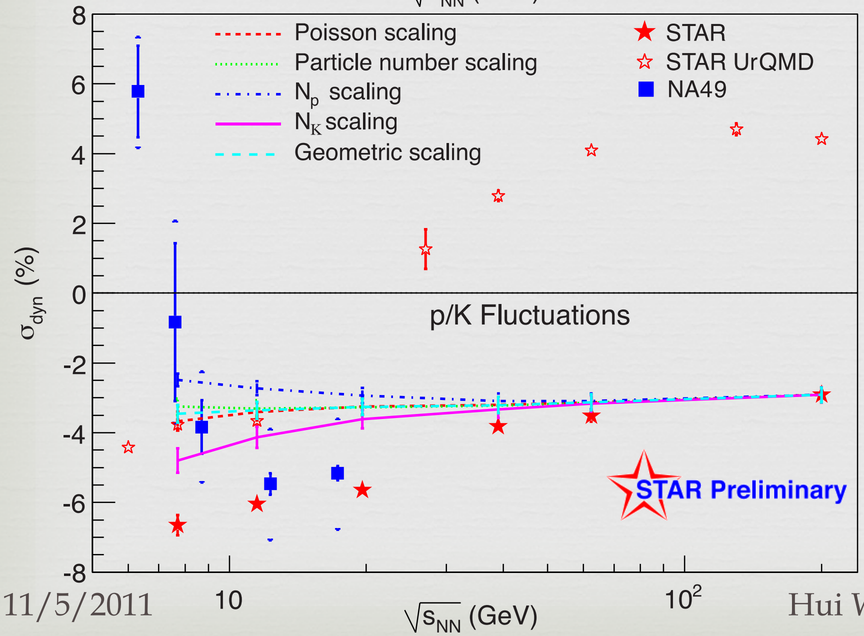
Geometric scaling

$$\sigma_{dyn}(\sqrt{s}) = \sigma_{dyn}(200GeV) \times \frac{(<K><\pi>)^{1/4}\Big|_{200GeV}}{(<K><\pi>)^{1/4}\Big|_{\sqrt{s}}}$$

Scaling Properties of Fluctuations

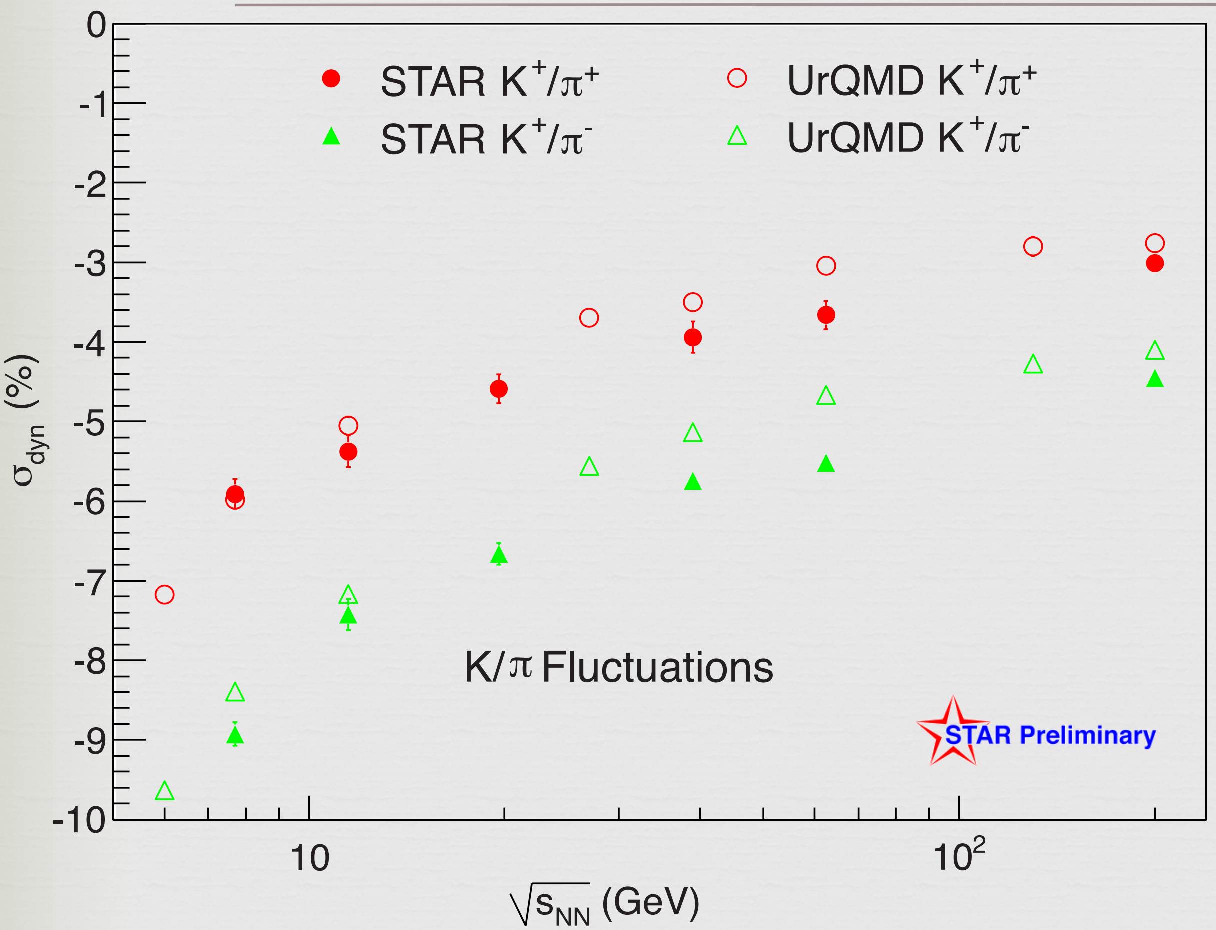






- Scale STAR results by actual number of particles used by STAR in the ν_{dyn} calculations
- The energy dependence of p/π and p/K fluctuation can't be explained by simple multiplicity scaling

Charge Dependent K/π Fluctuation



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

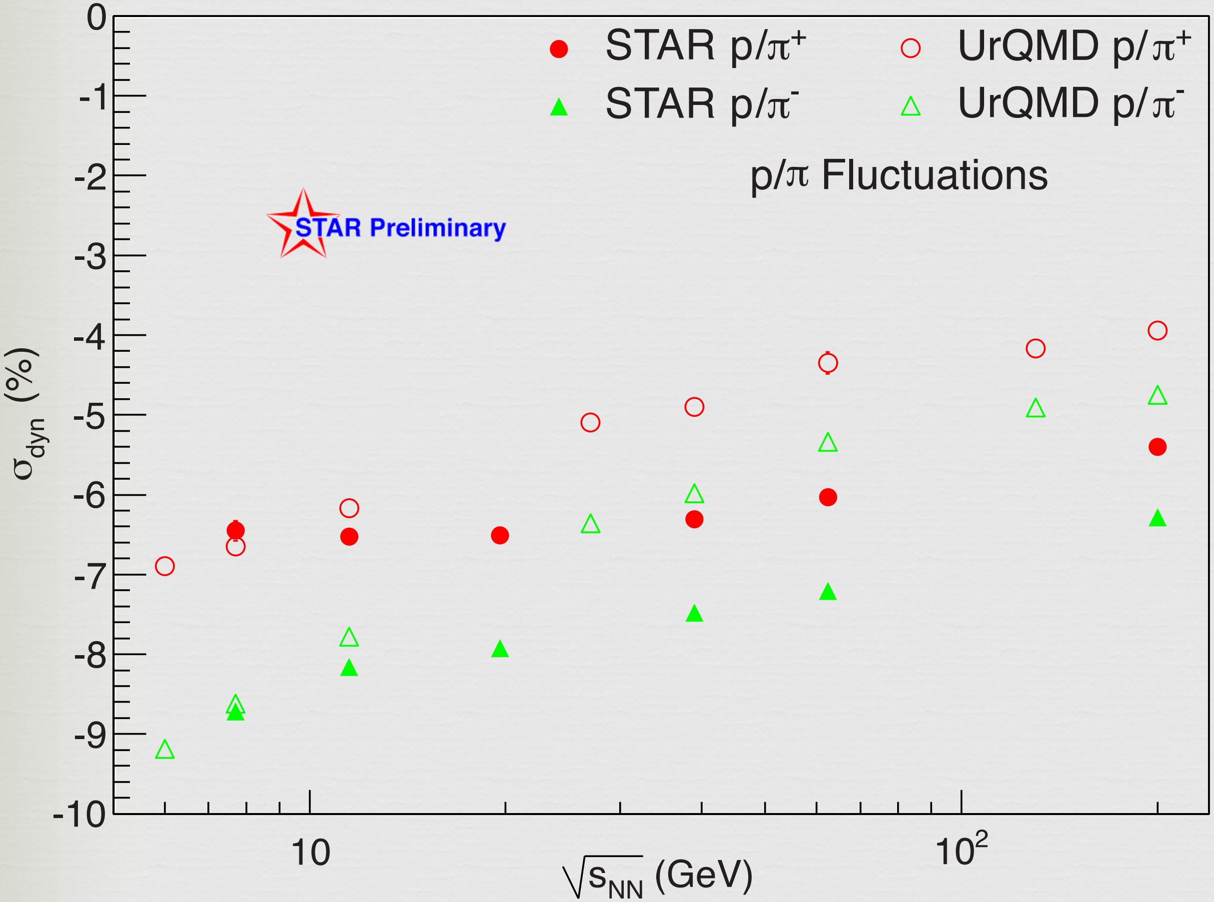
$$\sigma_{\text{dyn}} \approx \sqrt{\nu_{\text{dyn}}}$$

- STAR results are calculated via ν_{dyn}
- K^+/π^- is strongly negative due to decays, possible candidate is

$$K^*(892) \rightarrow K^+ + \pi^-$$

- K^+/π^+ is also negative, needs further study to investigate the origin
- UrQMD qualitatively agrees with the data

Charge Dependent p/π Fluctuation

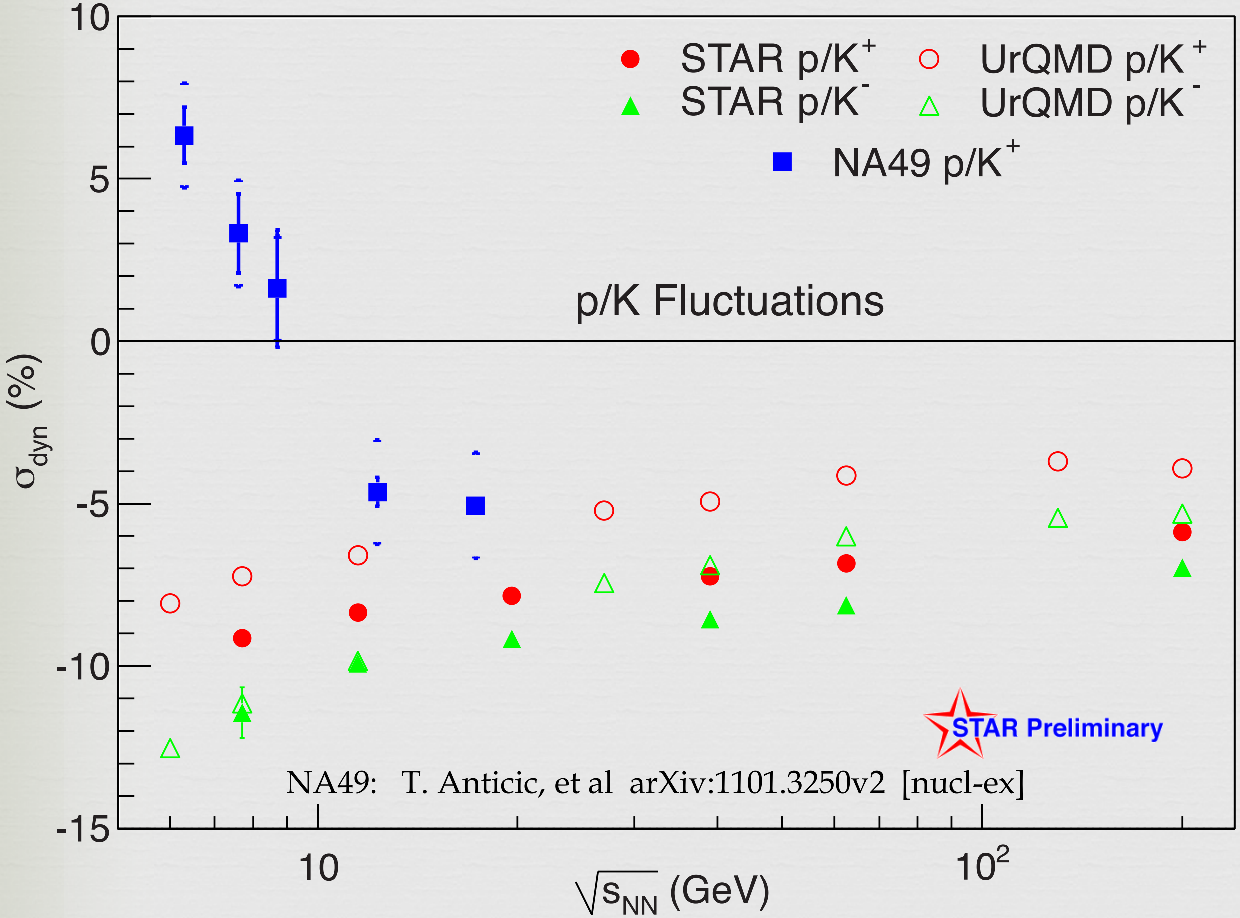


$$\nu_{\mathrm{dyn},p\pi} = \frac{\langle N_p (N_p - 1)\rangle}{\langle N_p \rangle^2} + \frac{\langle N_\pi (N_\pi - 1)\rangle}{\langle N_\pi \rangle^2} - 2\frac{\langle N_p N_\pi \rangle}{\langle N_p \rangle \langle N_\pi \rangle}$$

$$\sigma_{\mathrm{dyn}} \approx \sqrt{\nu_{\mathrm{dyn}}}$$

- STAR results are calculated via v_{dyn}
- Both same and opposite sign fluctuations are negative
- Unstable particle decays like Δ might introduce more correlations for opposite signs
- UrQMD over-predicts the fluctuations

Charge Dependent p/K Fluctuations



$$\nu_{\mathrm{dyn},Kp} = \frac{\langle N_K (N_K - 1)\rangle}{\langle N_K \rangle^2} + \frac{\langle N_p (N_p - 1)\rangle}{\langle N_p \rangle^2} - 2\frac{\langle N_K N_p \rangle}{\langle N_K \rangle \langle N_p \rangle}$$

$$\sigma_{\mathrm{dyn}} \approx \sqrt{\nu_{\mathrm{dyn}}}$$

- STAR results are calculated via v_{dyn}
- Both same and opposite sign fluctuations are negative
- Disagreement between STAR and NA49 p/K^+ results

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

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

- It can be written as

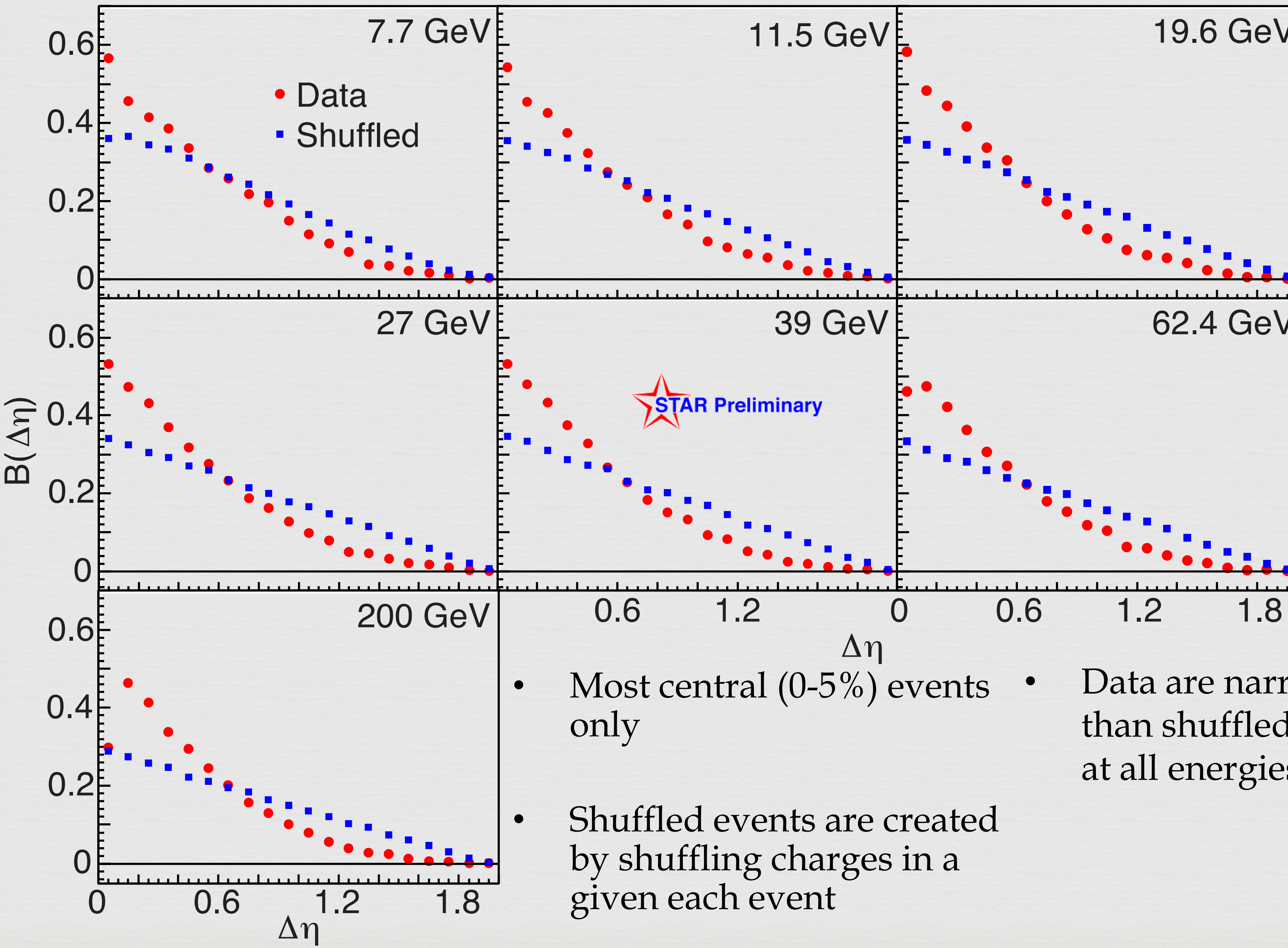
$$B(\Delta\eta)=\frac{1}{2}\left\{\frac{N_{+-}(\Delta\eta)-N_{++}(\Delta\eta)}{N_+}+\frac{N_{-+}(\Delta\eta)-N_{--}(\Delta\eta)}{N_-}\right\}$$

- The width of balance function is calculated via weighted average

$$\langle\Delta\eta\rangle=\frac{\sum_{\text{all }\Delta\eta} B\left(\Delta\eta_i\right)\Delta\eta_i}{\sum_{\text{all }\Delta\eta} B\left(\Delta\eta_i\right)}$$

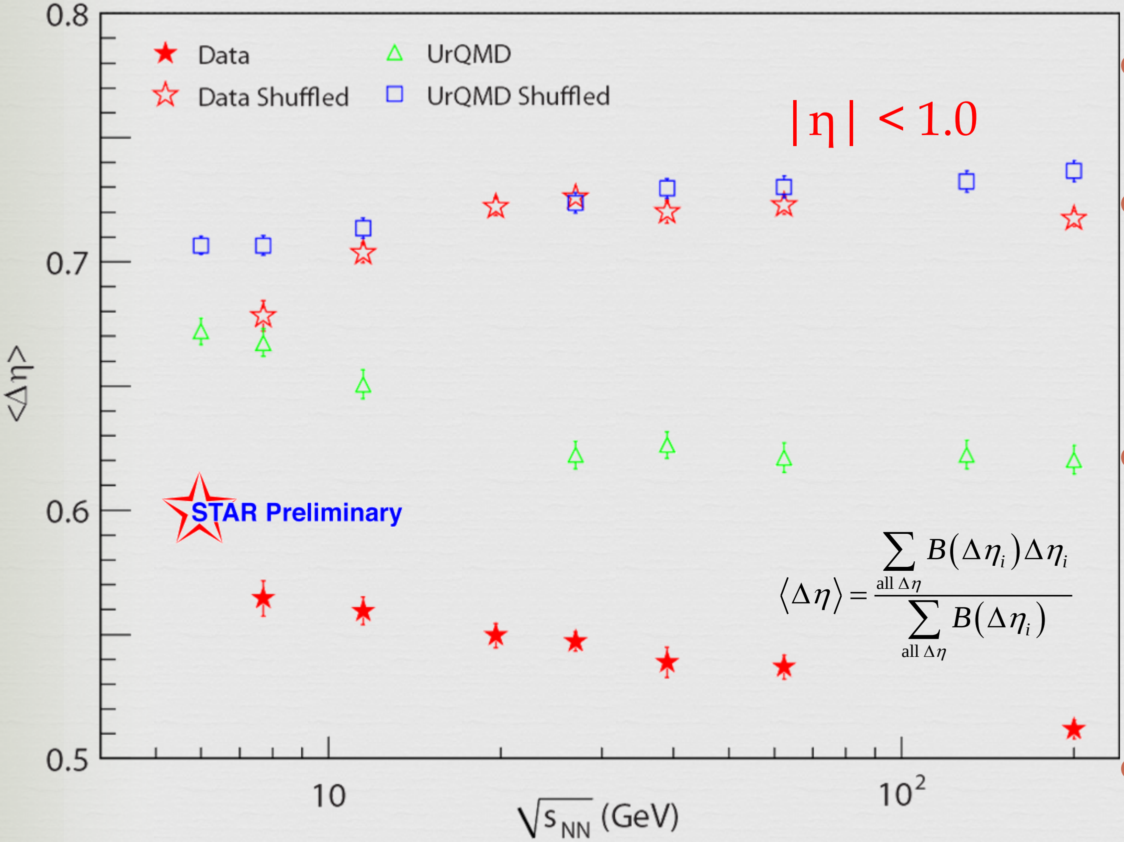
$$W=\frac{100\cdot\left(\langle\Delta\eta\rangle_{\text{shuffled}}-\langle\Delta\eta\rangle_{\text{data}}\right)}{\langle\Delta\eta\rangle_{\text{shuffled}}}$$

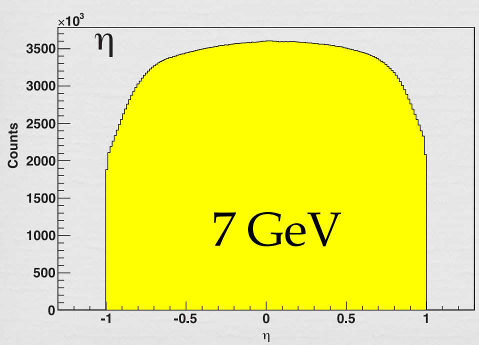
Balance Function

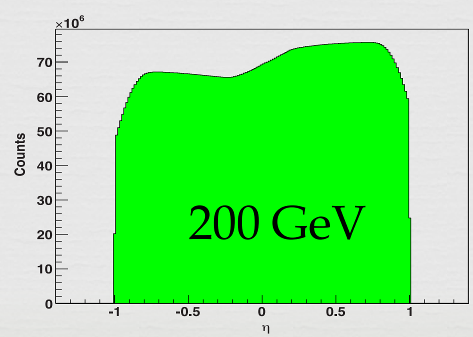


- Most central (0-5%) events only
- Shuffled events are created by shuffling charges in a given each event
- Data are narrower than shuffled events at all energies

Weighted Average

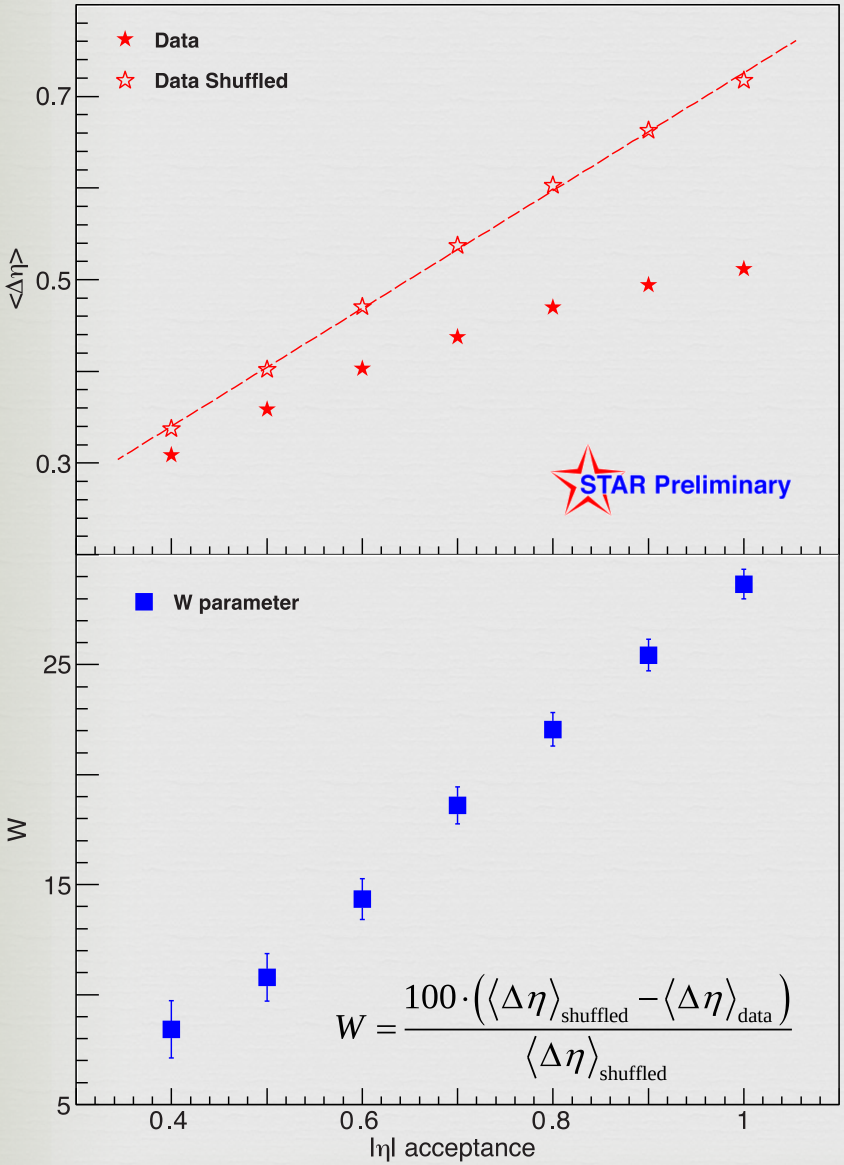




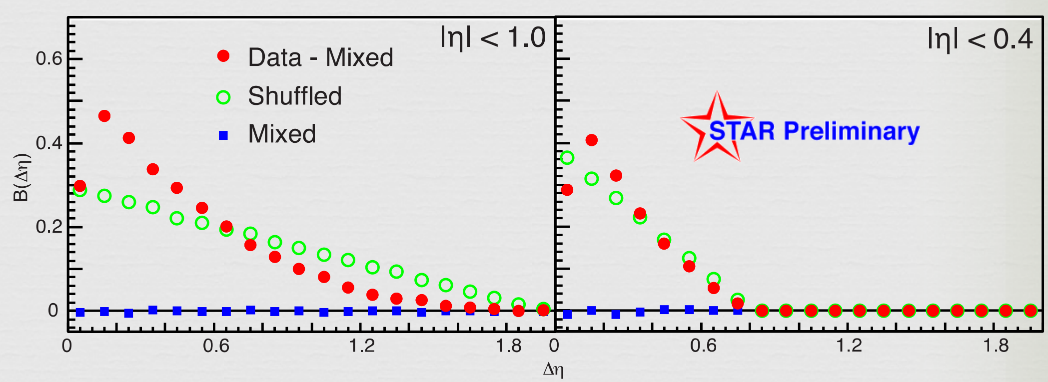


- Most central (0-5%) events only
- Remove lowest bin when calculating <Δη> to reduce HBT/Coulomb effects
- Both data and UrQMD show a smooth decrease with increasing collision energy, indicating stronger correlations at small Δη
- Shuffled event widths also change with energy due to acceptance
- Balance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

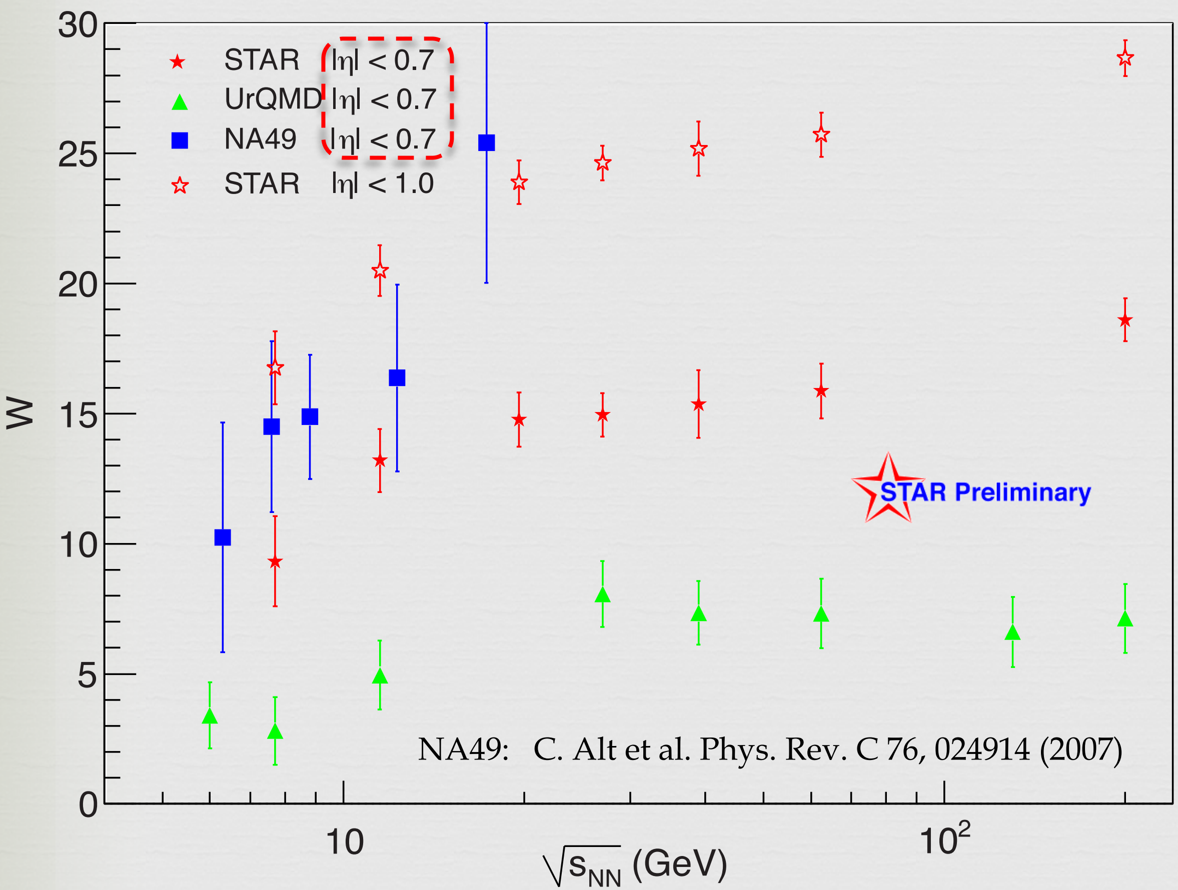
W Parameter

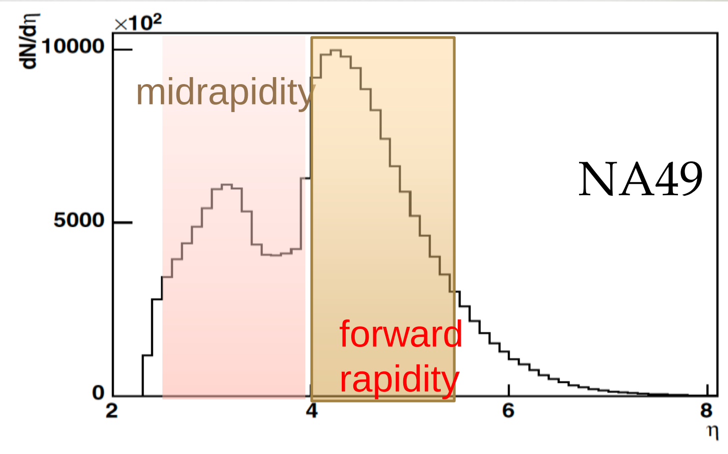


- 200 GeV central (0-5%) events
- Plot <Δη> and W v.s. |η| acceptance
- Data and shuffled events show different |η| acceptance dependence
- W parameter shows a strong acceptance dependence



W Parameter





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

- 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/π fluctuations show no energy dependence, while p/π 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/π 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

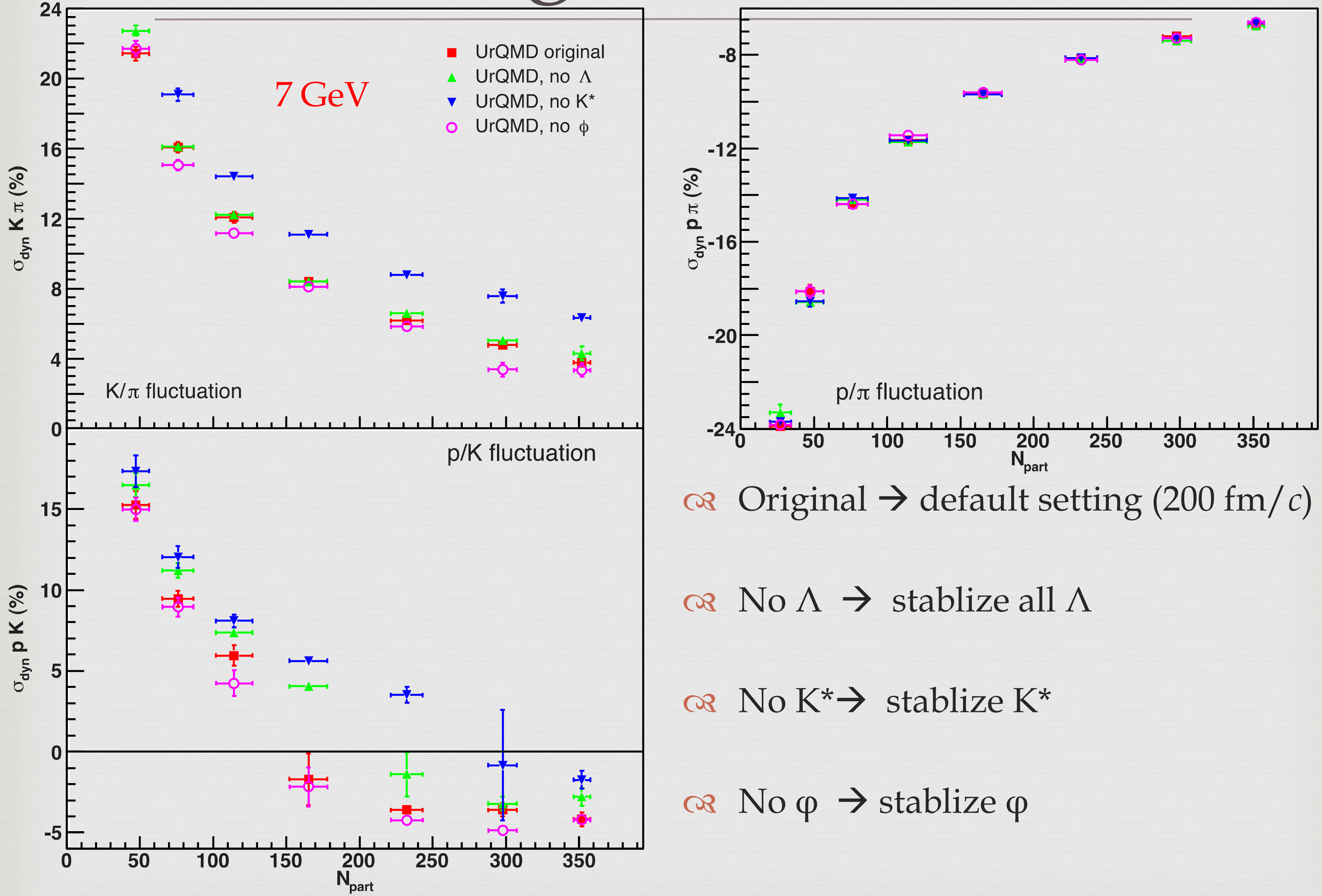
ID	nucleon	ID	delta	ID	lambda	ID	sigma	ID	xi	ID	omega
1	N_{938}	17	Δ_{1232}	27	Λ_{1116}	40	Σ_{1192}	49	Ξ_{1317}	55	Ω_{1672}
2	N_{1440}	18	Δ_{1600}	28	Λ_{1405}	41	Σ_{1385}	50	Ξ_{1530}		
3	N_{1520}	19	Δ_{1620}	29	Λ_{1520}	42	Σ_{1660}	51	Ξ_{1690}		
4	N_{1535}	20	Δ_{1700}	30	Λ_{1600}	43	Σ_{1670}	52	Ξ_{1820}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

ID	0^{-+}	ID	1^{--}	ID	0^{++}	ID	1^{++}
101	π	104	ρ	111	a_0	114	a_1
106	K	108	K^*	110	K_0^*	113	K_1^*
102	η	103	ω	105	f_0	115	f_1
107	η'	109	ϕ	112	f_0^*	116	f_1'

ID	1^{+-}	ID	2^{++}	ID	$(1^{--})^*$	ID	$(1^{--})^{**}$
122	b_1	118	a_2	126	ρ_{1450}	130	ρ_{1700}
121	K_1	117	K_2^*	125	K_{1410}^*	129	K_{1680}^*
123	h_1	119	f_2	127	ω_{1420}	131	ω_{1662}
124	h_1'	120	f_2'	128	ϕ_{1680}	132	ϕ_{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

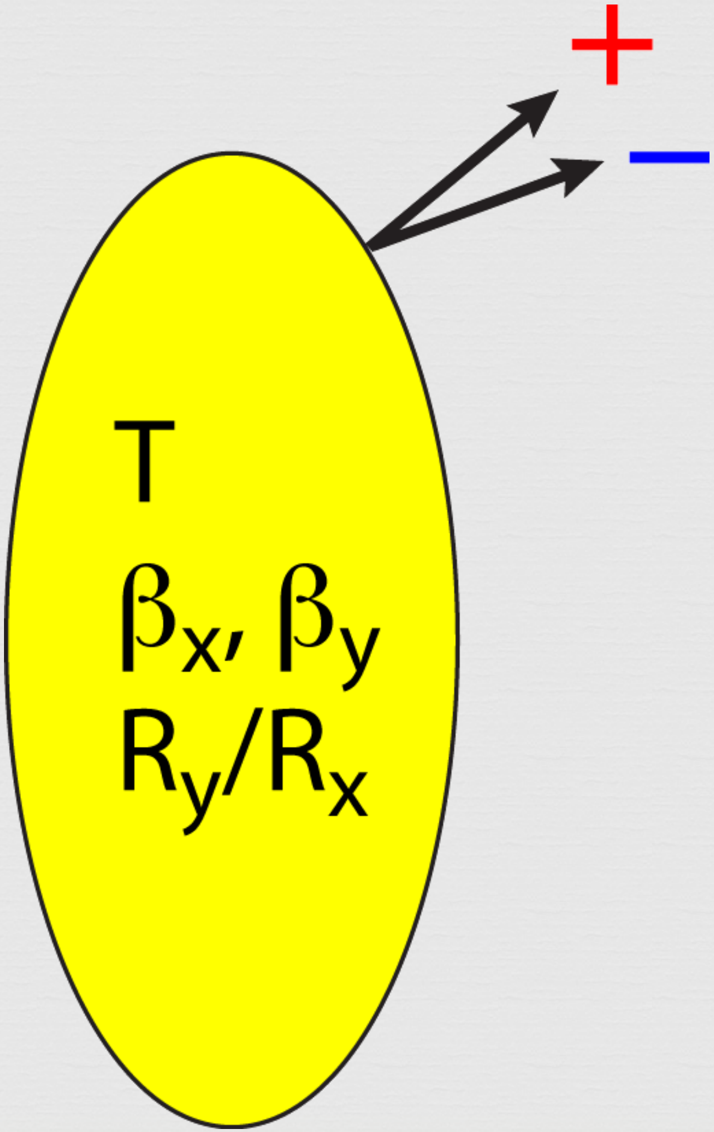
Sum-sign fluctuation



- Original → default setting (200 fm/*c*)
- No Λ → stablize all Λ
- No K*→ stablize K*
- No φ → stablize φ

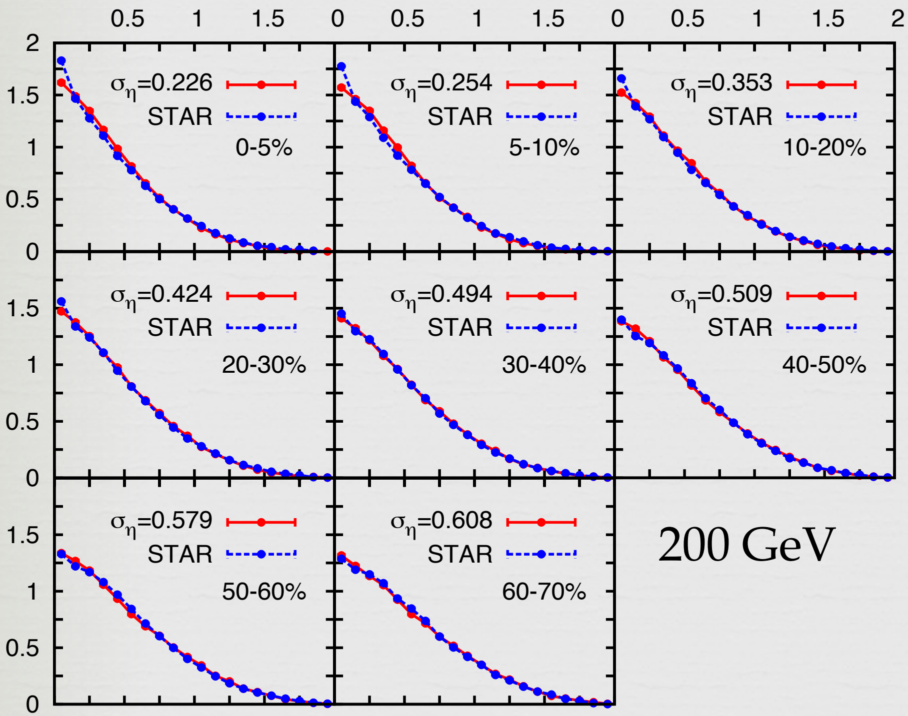
Blast Wave Model

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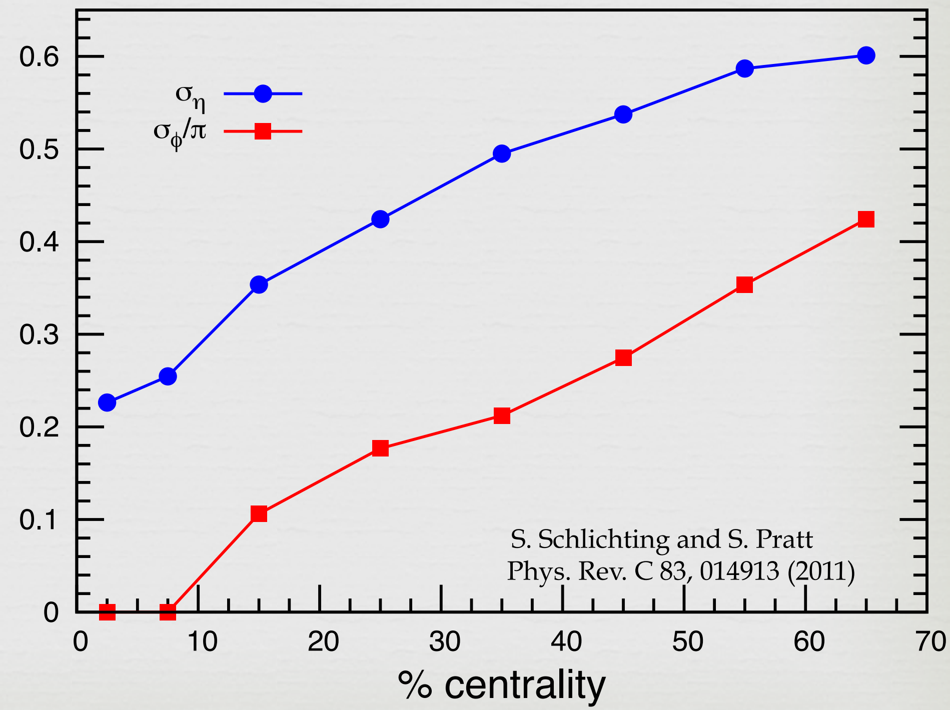
- Extract the initial separation of balancing charges at time of freeze out by fitting the observed charge balance functions



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