

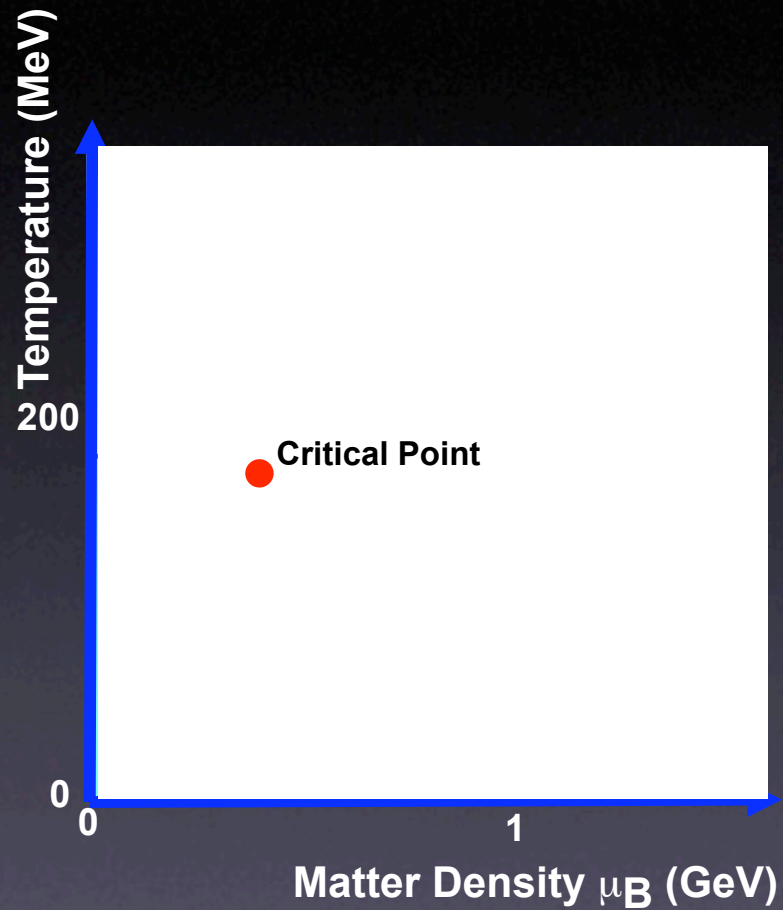
Experimental Search for the Critical Point

(with particular attention to fluctuations of conserved quantities)

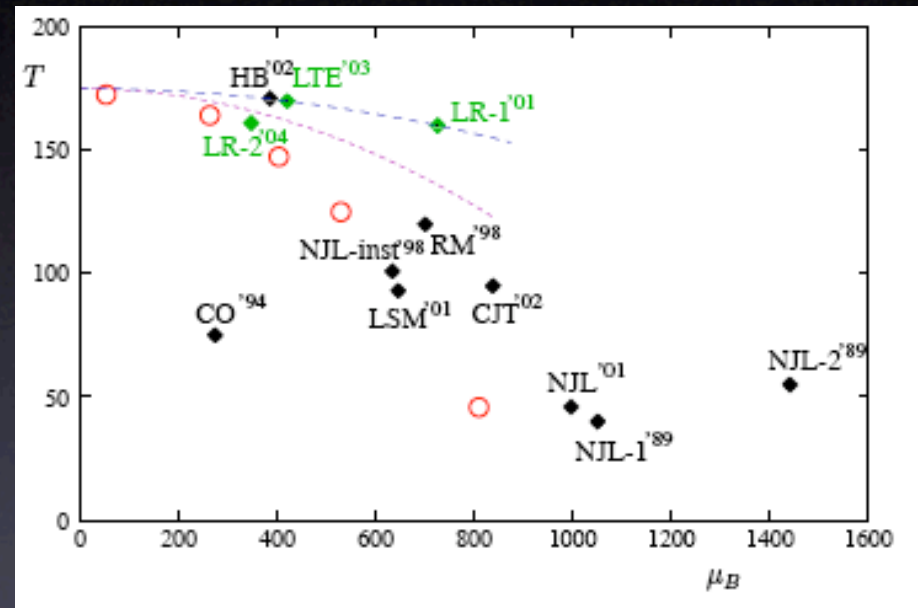
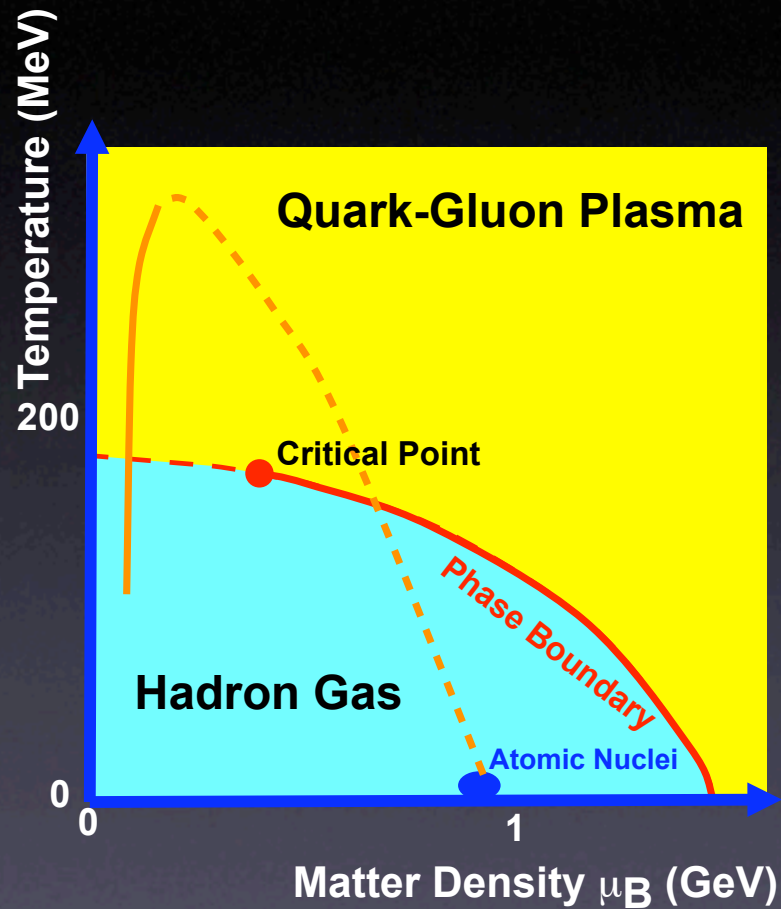
ECT Trento
March 22 2006

Gunther Roland

Experimental Search for the Critical Point



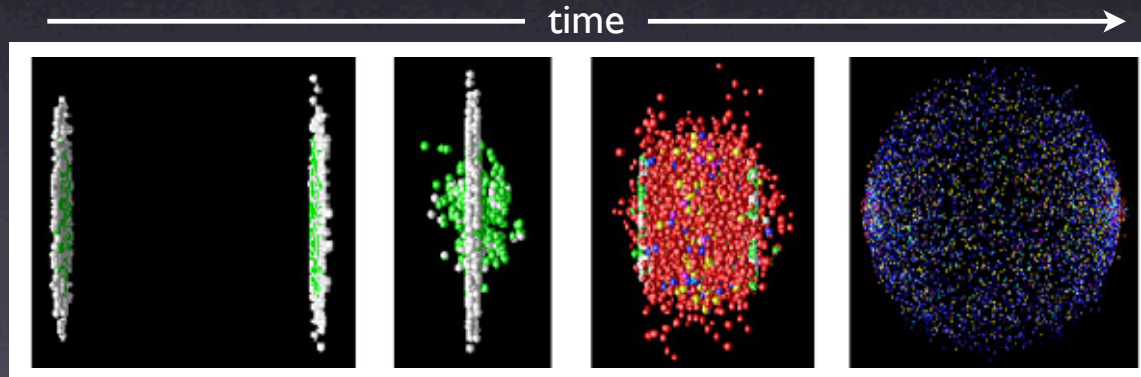
Experimental Search for the Critical Point



Plot from M. Stephanov,
Correlations '05

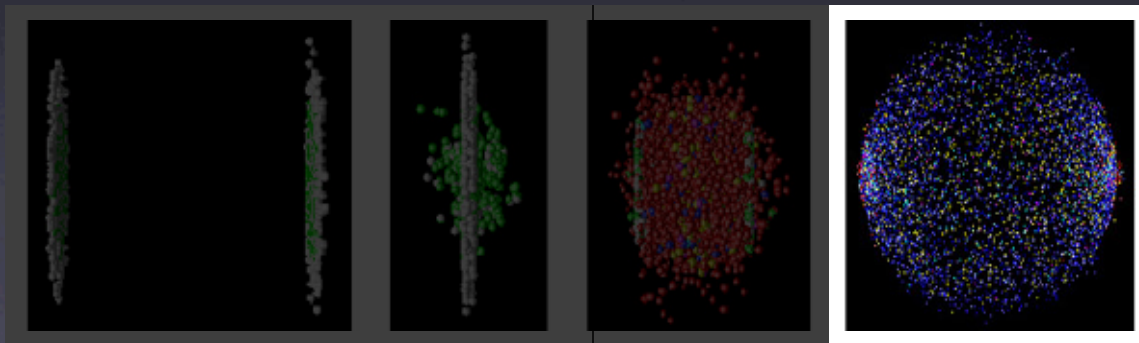
Experimental Search for the Critical Point

- Theoretical guidance is limited
- Experimental strategy:
 - Search in different observables, correlate observables
 - Fine grained exploration of μ_B, T space



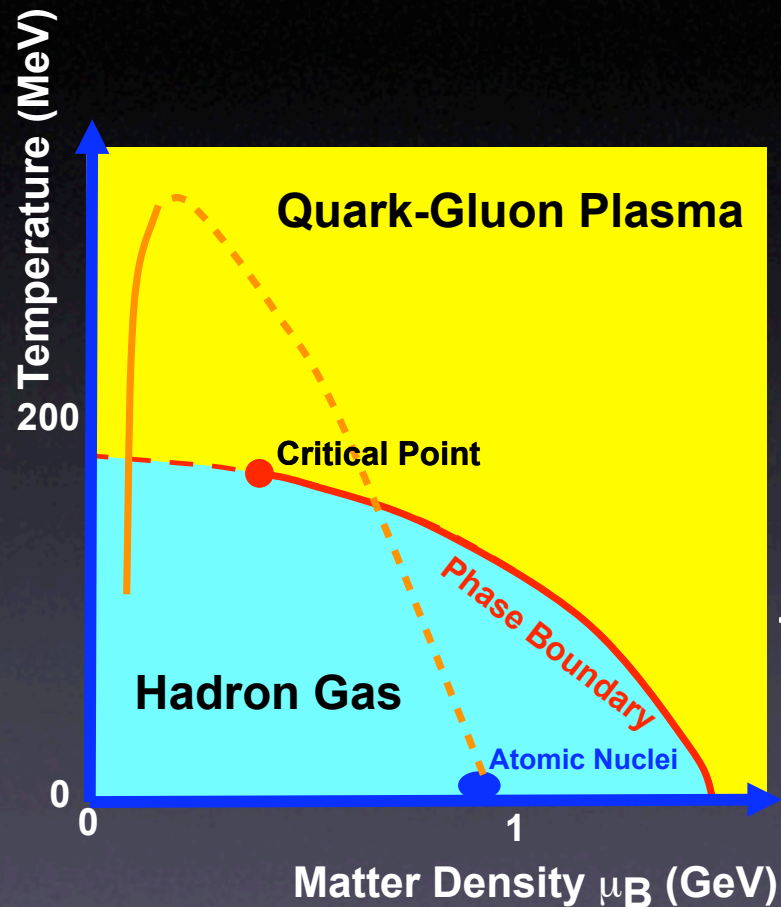
Experimental Search for the Critical Point

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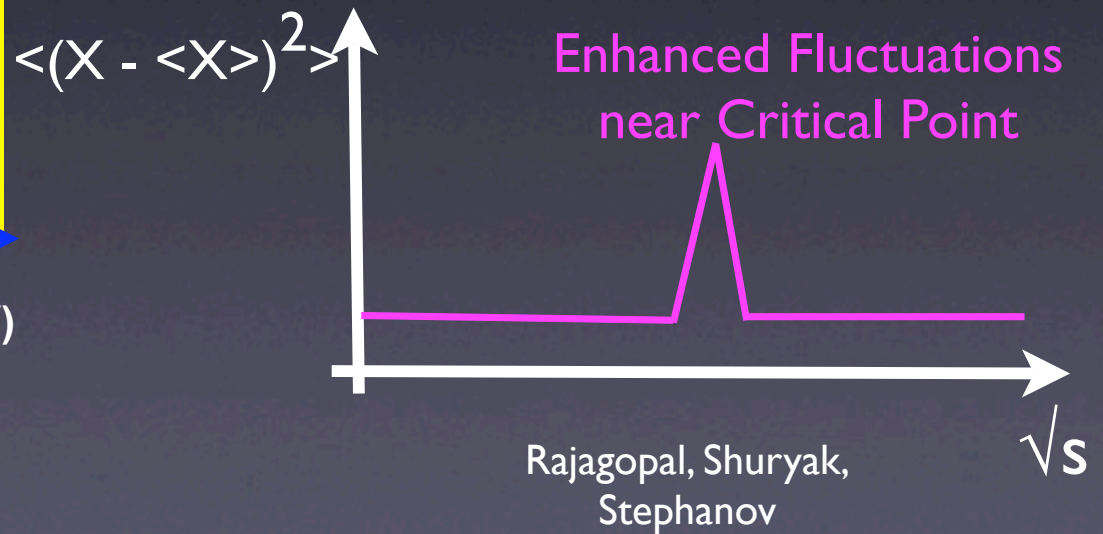
Experiments only see
final state particles

Experimental Search for the Critical Point

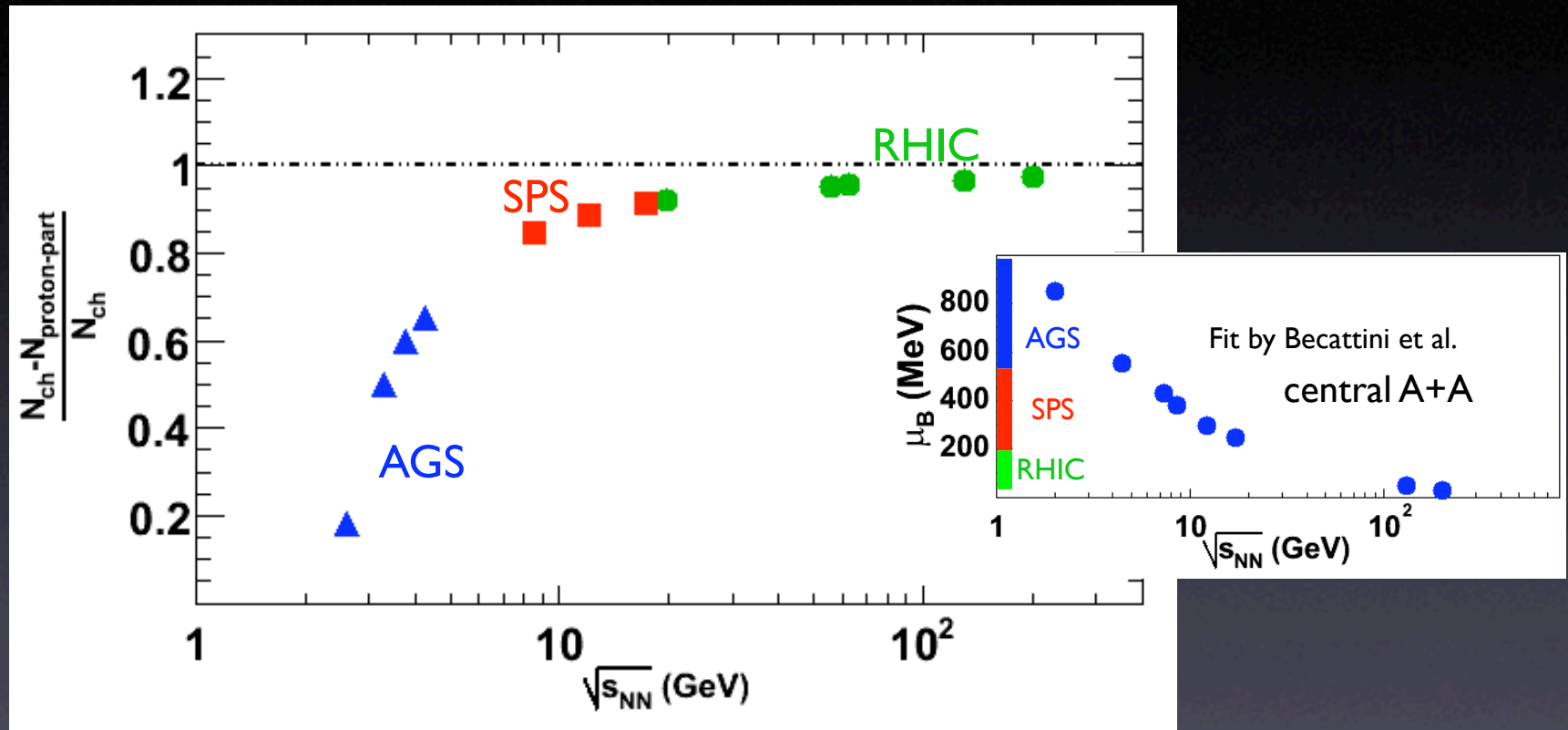


Susceptibilities diverge near critical point

Locate the critical point using correlation/fluctuation measurements



Energy Regimes and Accelerators

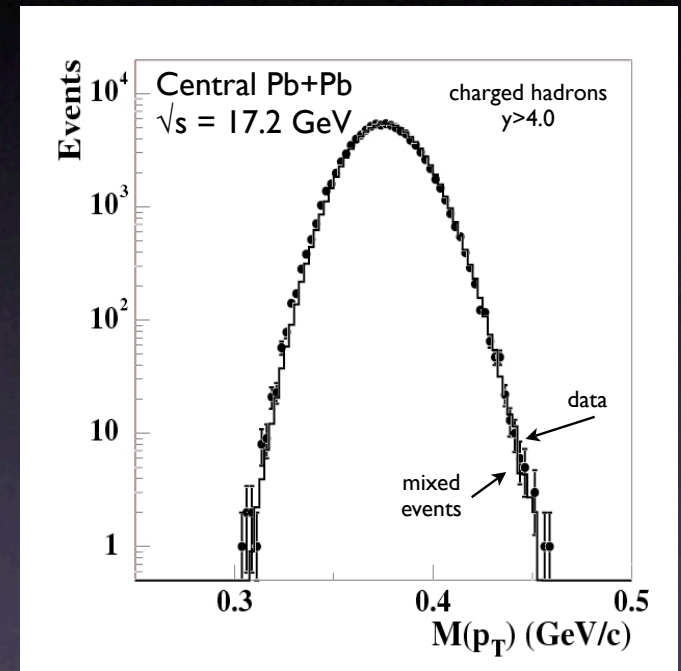


Change from baryon- to meson dominated system

First result on $\langle p_T \rangle$ fluctuations (1999)

- p_T - simple observable (supposedly...)
- High statistical precision:
 - $\sigma_{p_T}/\langle p_T \rangle_{inc} < 0.1\%$
- Sensitive to many interesting scenarios
 - Critical Point
 - DCC production
 - Droplet formation
 - **Any non-statistical, momentum-localized process**

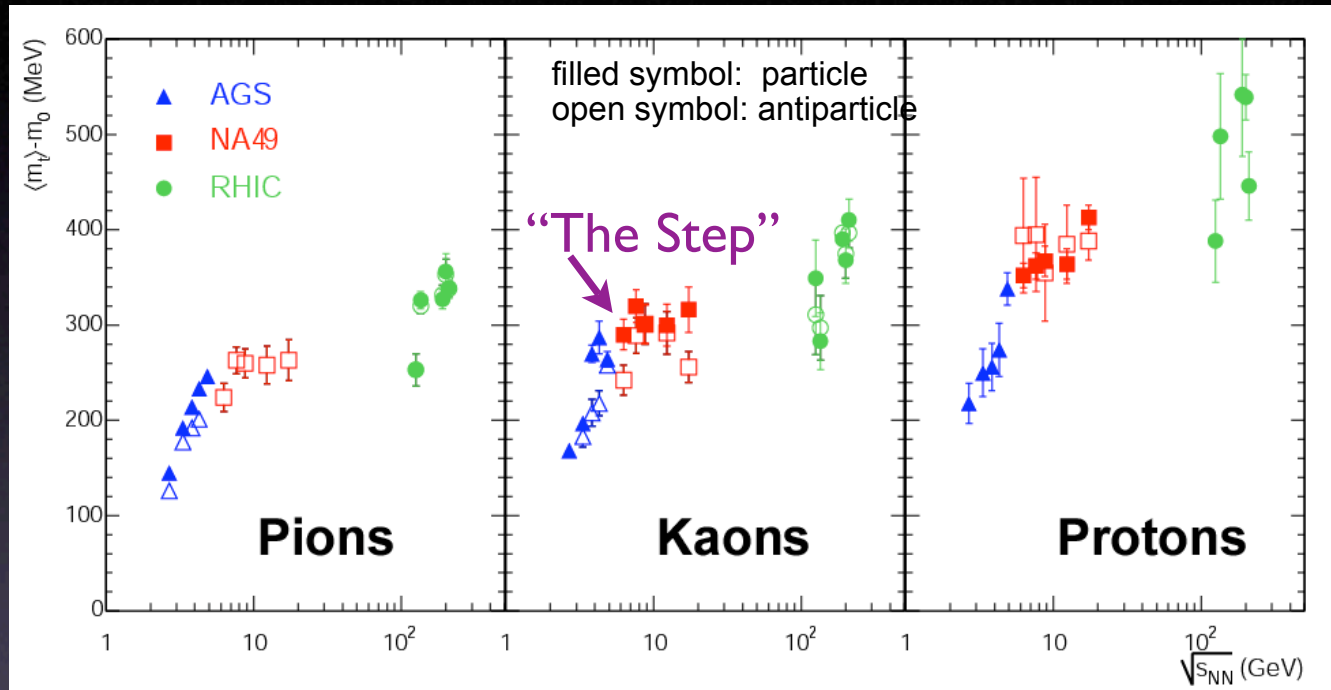
NA49, Phys Lett B459 (1999) 679



Event-by-event $\langle p_T \rangle$ compared to stochastic reference (mixed events)

Excitation Function: Momentum Spectra

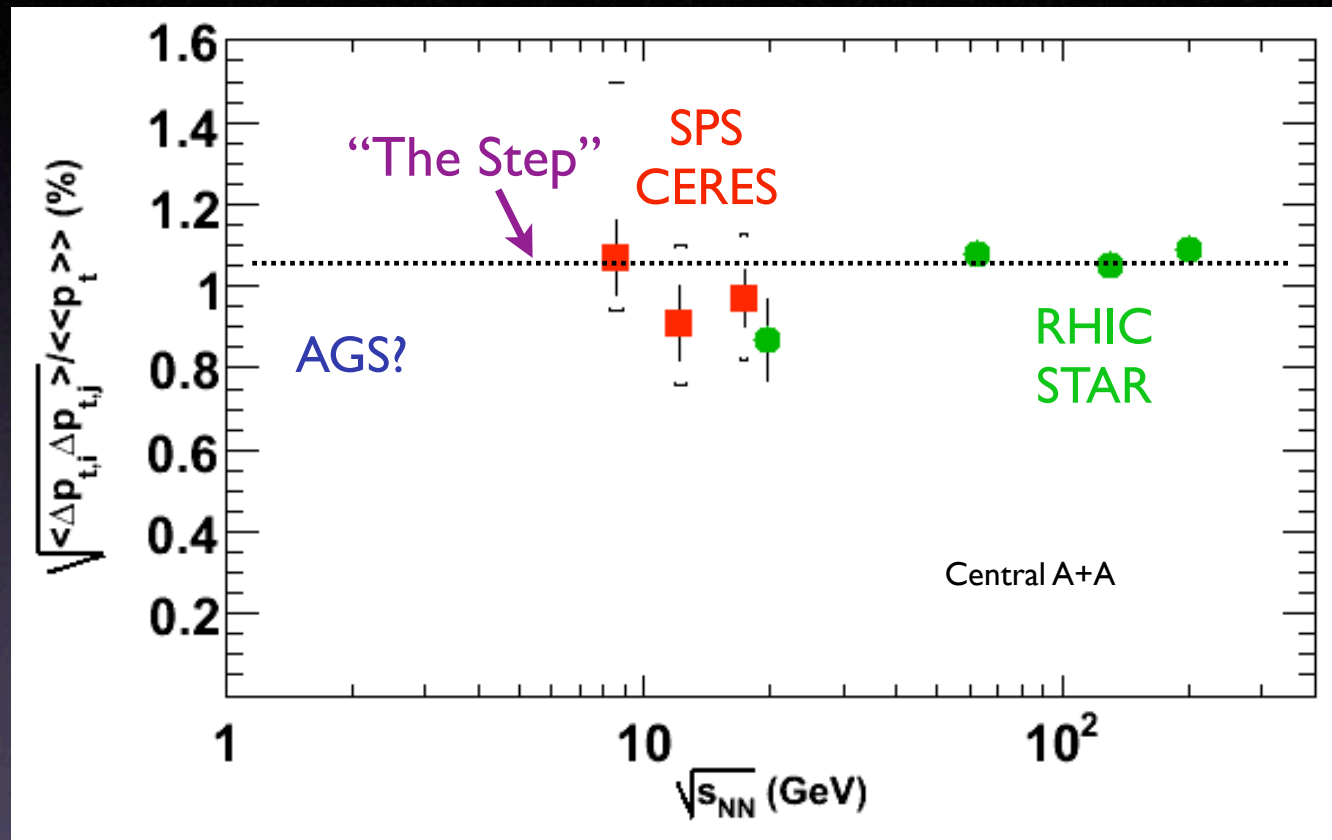
Compilation by NA49
Plot from Claudia Hoehne, QM'05



- Structure in energy dependence of $\langle m_T \rangle$
- Reminiscent of Van Hove's T vs ϵ prediction (1982)
- Surprisingly difficult measurement
 - Decay corrections, PID acceptance

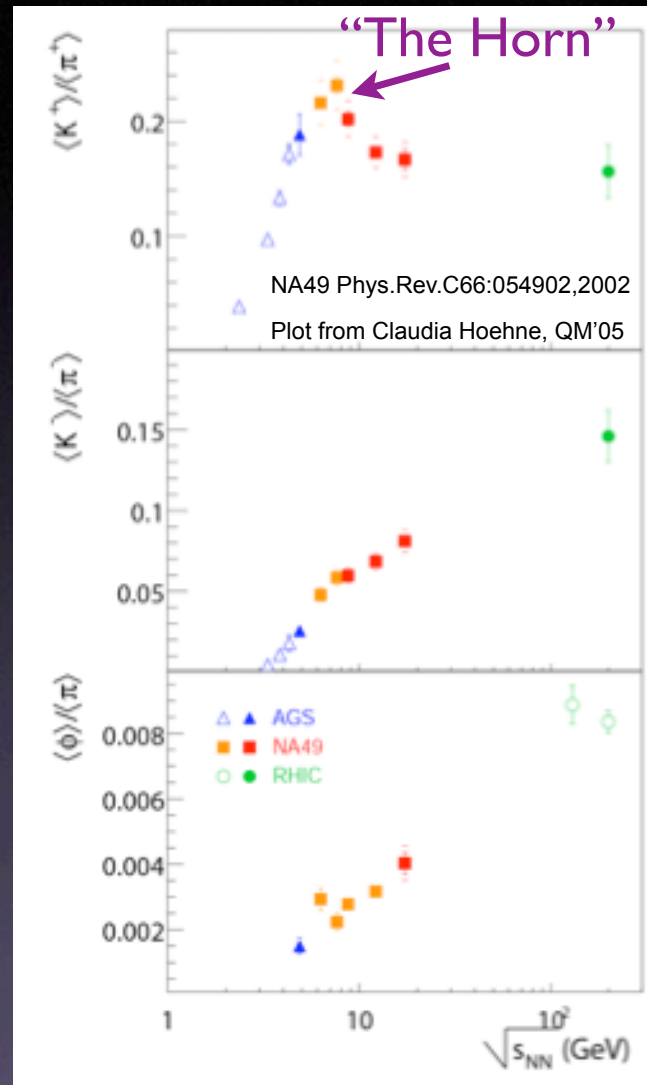
Excitation Function: Momentum Fluctuations

Compilation by STAR
STAR PRC 72 044902 (2005)



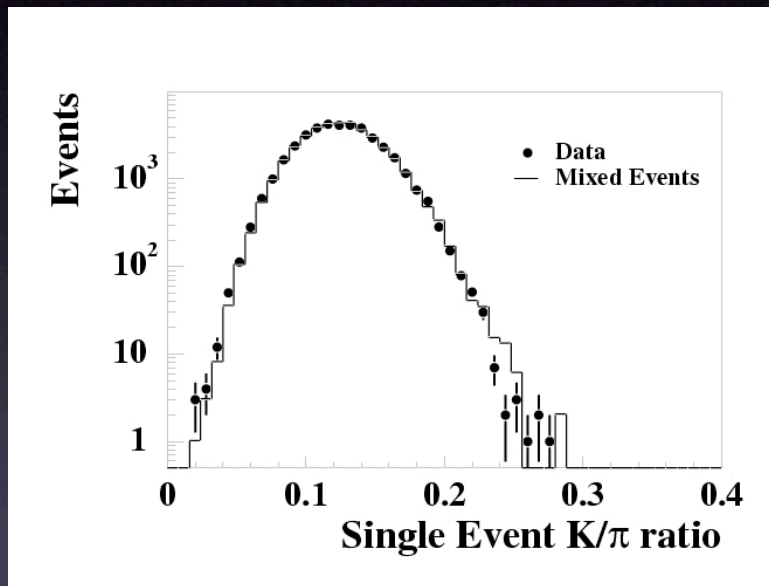
Monotonic energy dependence over measured range
No results near “step” region

Particle Ratios

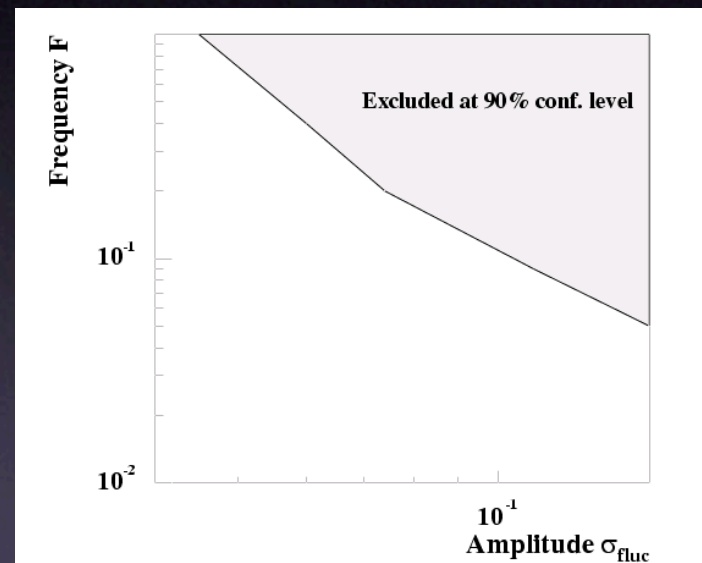


Non-monotonic behavior at AGS/SPS boundary

First result on ratio fluctuations (2000)



Pb+Pb, 17.2 GeV
NA49, PRL 86 (2001) 1965



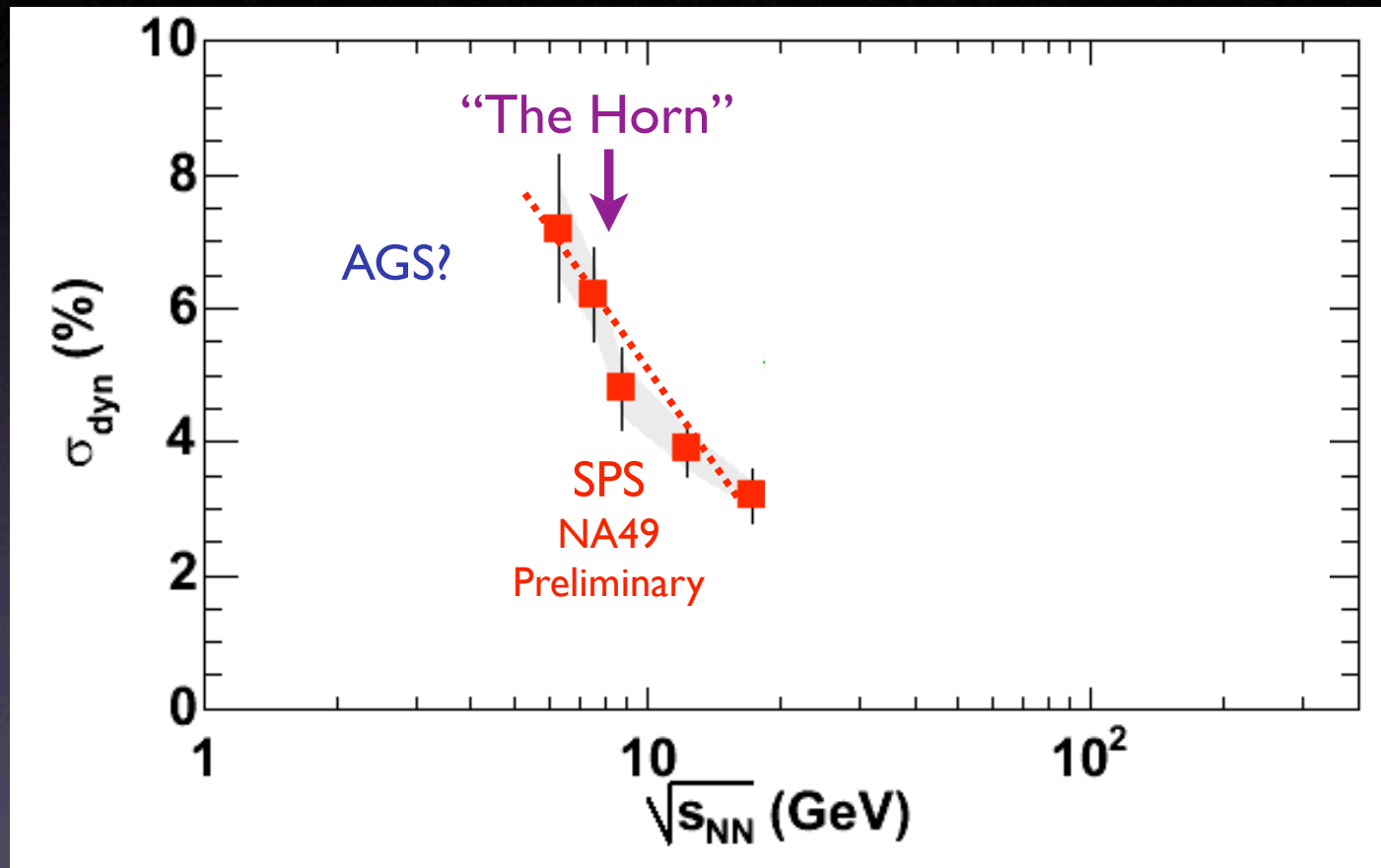
PhD thesis Christof Roland, 2000

- Dynamical fluctuations are small ($< \sim 5\%$)
- Compatible with resonance gas (Jeon, Koch; nucl-th/9906074)
- Strangeness enhancement in every event
- Chemical freeze-out at same T in every event

Excitation Function: K/ π Fluctuations

NA49, Christof Roland, QM'04

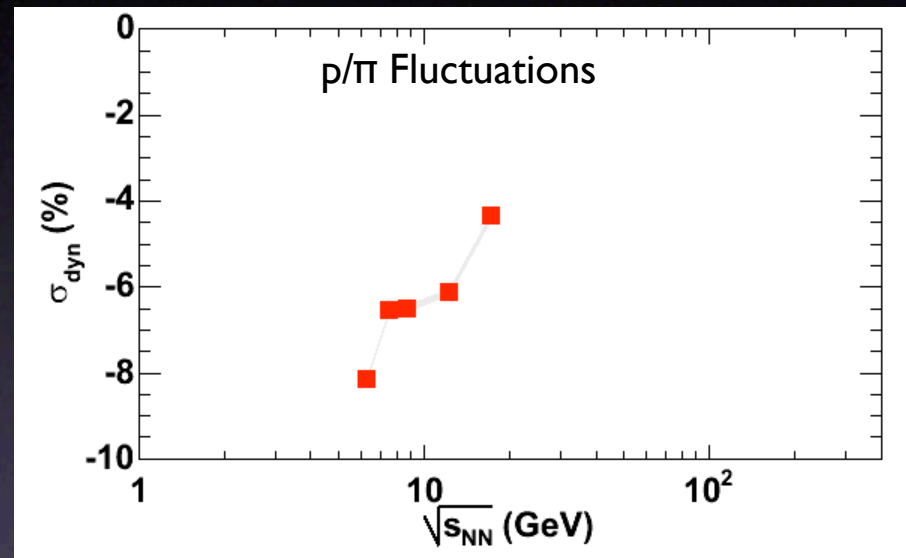
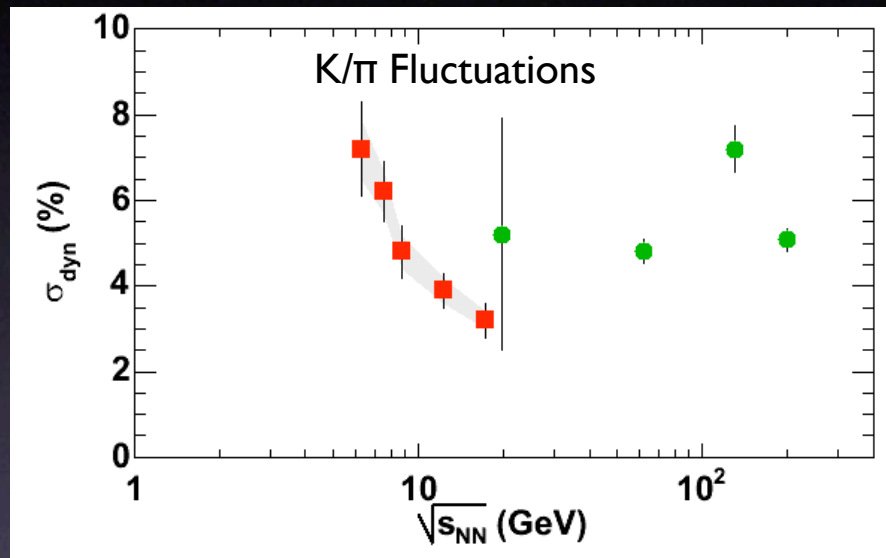
STAR, Supriya Das, VI Workshop '05



Strong increase towards low energy
Comparison between experiments difficult

Proton-number fluctuations?

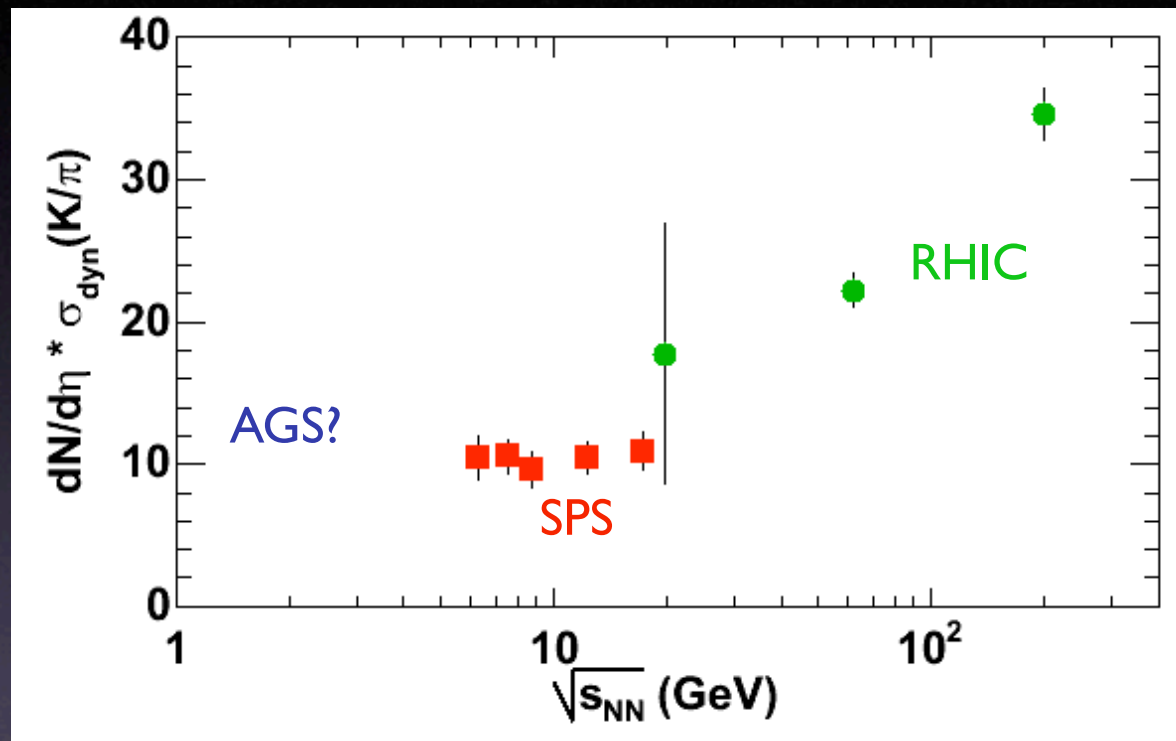
NA49, Christof Roland, QM'04



Proton/ π fluctuations negative
→ Correlated production of protons and pions

Excitation Function: K/ π Fluctuations

Normalized by dN/dy



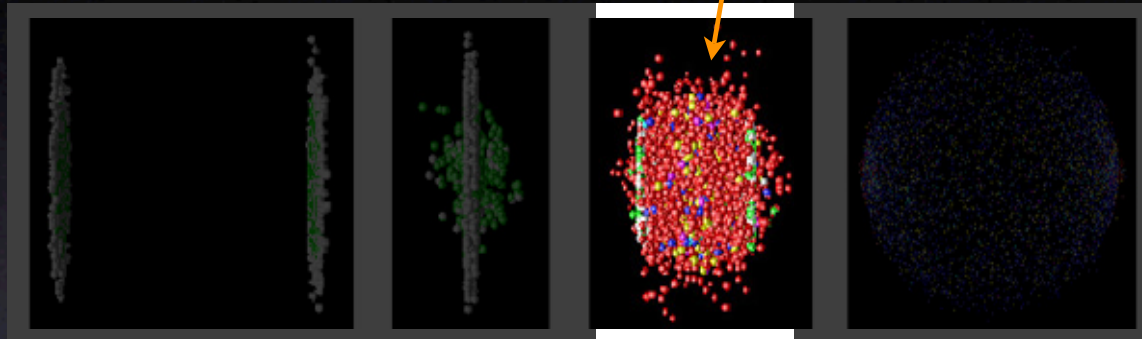
Scaling by dN/dy or $(dN/dy)^{1/2}$ does not work over full energy range

Net Charge Fluctuations and the QGP

DoF of Medium?

Jeon, Koch PRL (2000) hep-ph/0003168

Asakawa, Heinz, Mueller PRL (2000) hep-ph/0003169



- **Net Charge/ Δy Fluctuations \Leftrightarrow Charge/DoF**
 - Fluc's change from **1-2 (QGP)** to **4 (Pion Gas)**
- **Fluctuations frozen b/c charge conservation**
 - Diffusion vs Expansion timescale

Note:

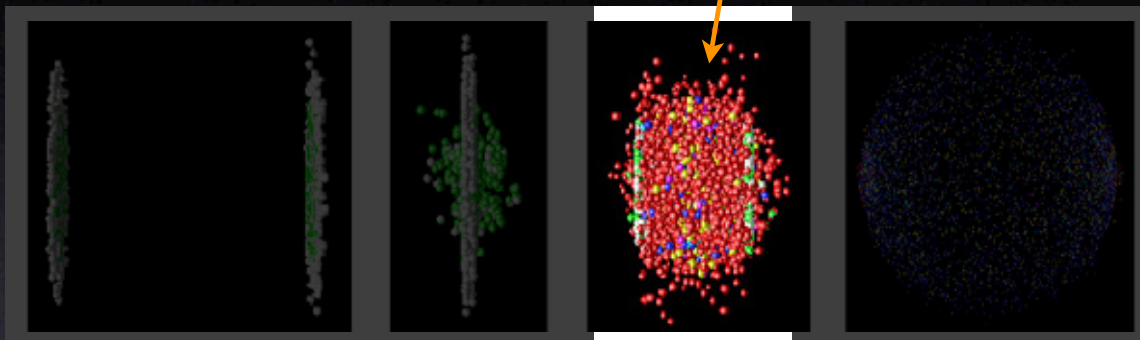
- * Similar for net baryon number
- * Connection to quark number susceptibilities
- * Connection to Critical point

Net Charge Fluctuations and the QGP

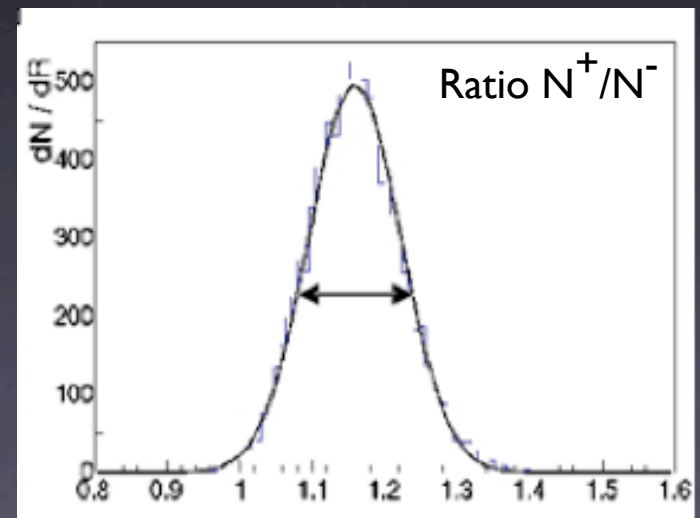
DoF of Medium?

Jeon, Koch PRL (2000) hep-ph/0003168

Asakawa, Heinz, Mueller PRL (2000) hep-ph/0003169



- **Net Charge/ Δy Fluctuations \Leftrightarrow Charge/DoF**
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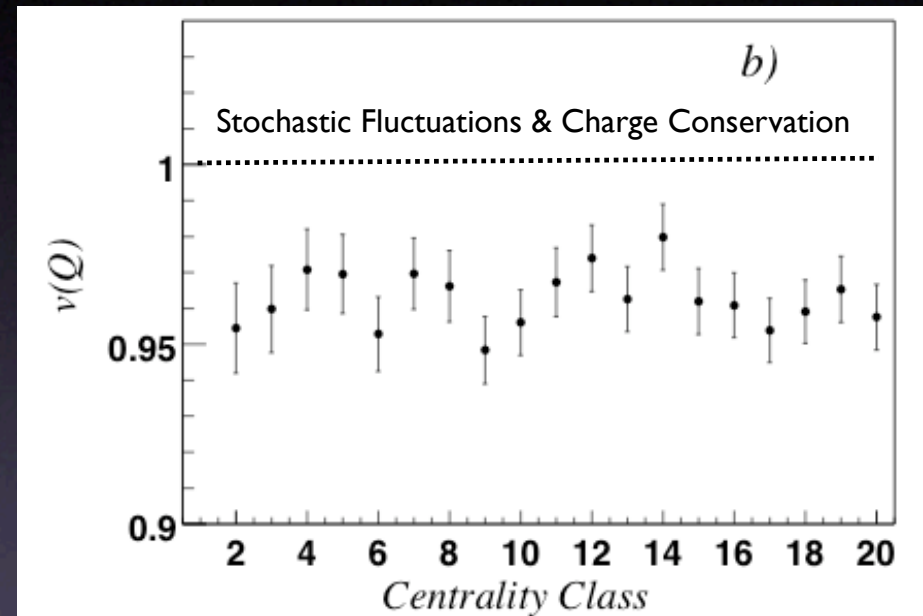
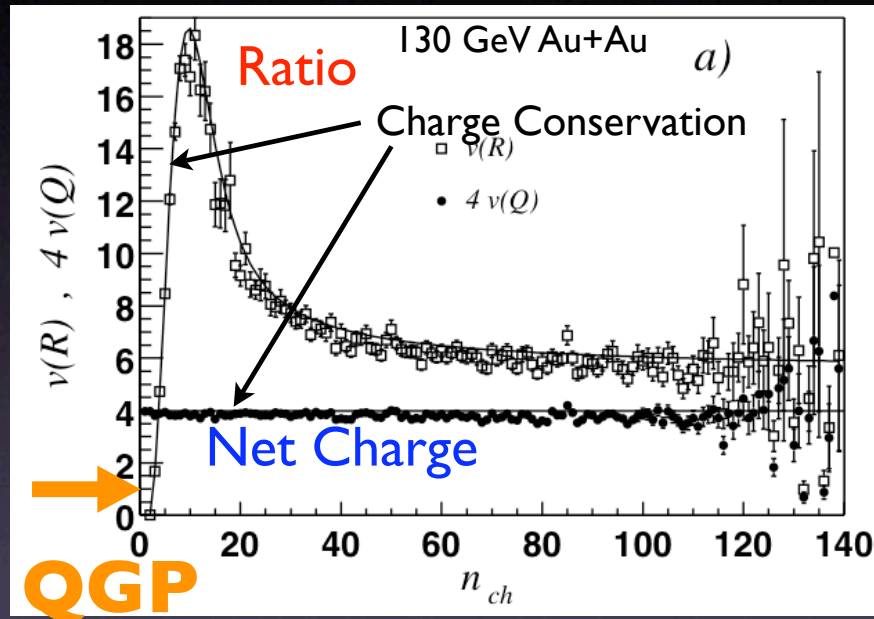


Event-by-event distribution of net charge ratio

First results on net-charge fluctuations

Acceptance: $\Delta y \approx 0.7$, $\Delta\Phi = \pi$

PHENIX PRL 89 (2002)



Centrality \longrightarrow

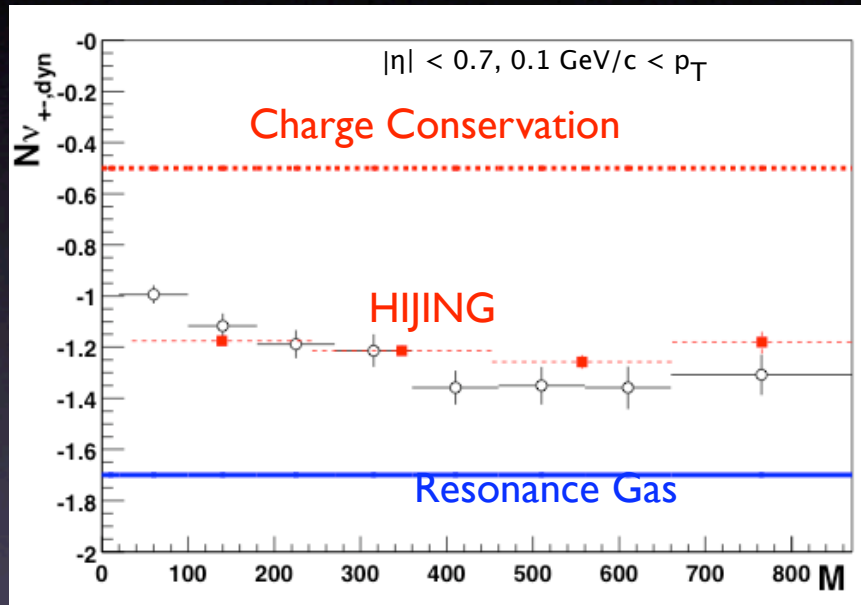
Centrality \longrightarrow

Fluctuations agree with stochastic distributions of Hadrons

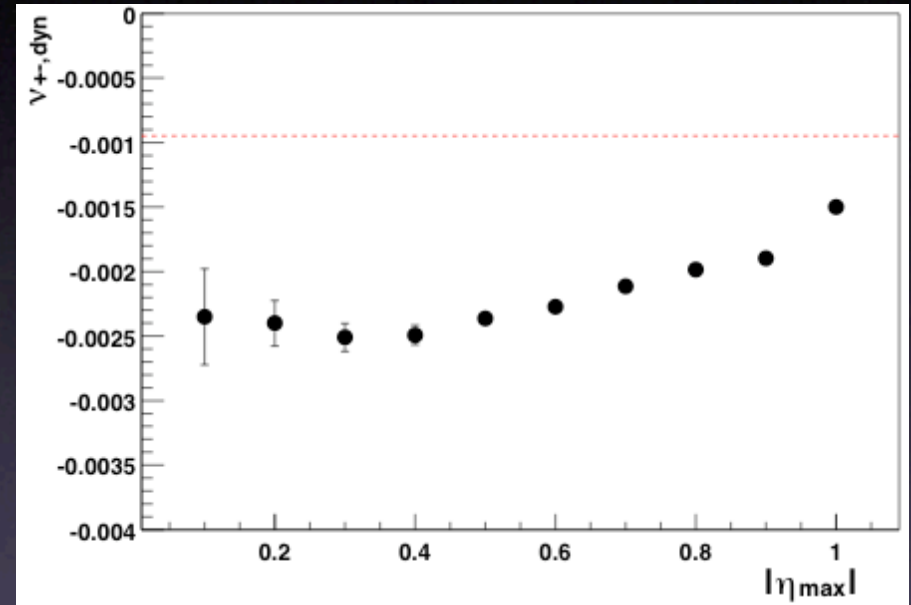
Results from STAR

Acceptance: $\Delta y \approx 2$, $\Delta\Phi = 2\pi$

STAR PRC 68 (2003)



Centrality \longrightarrow

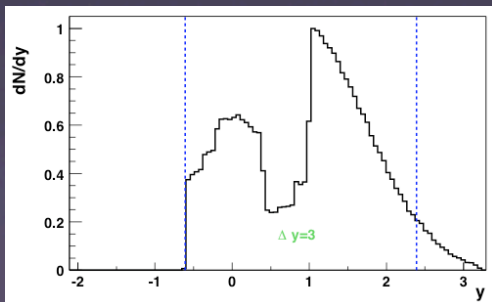
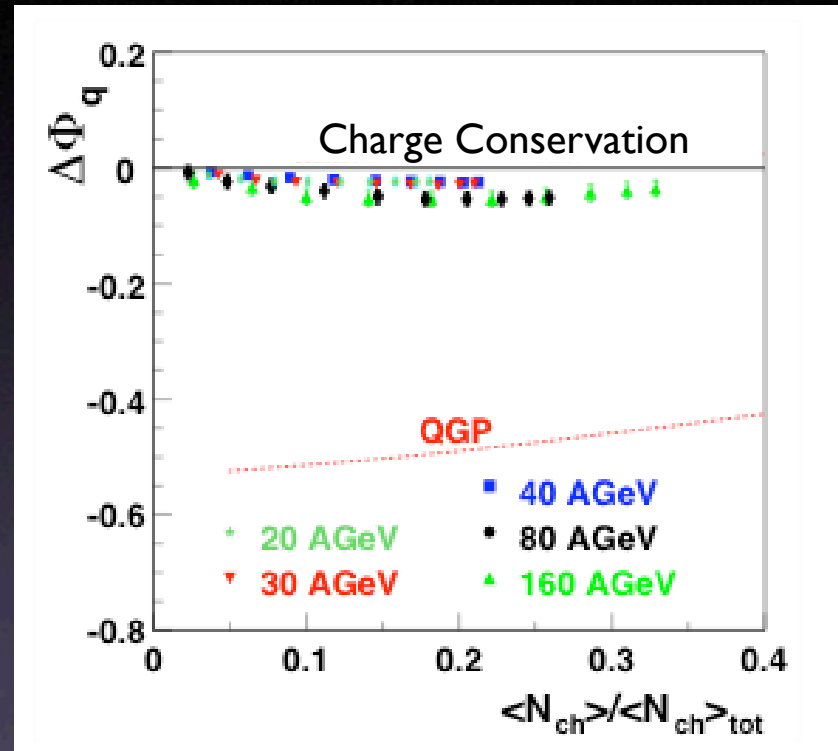
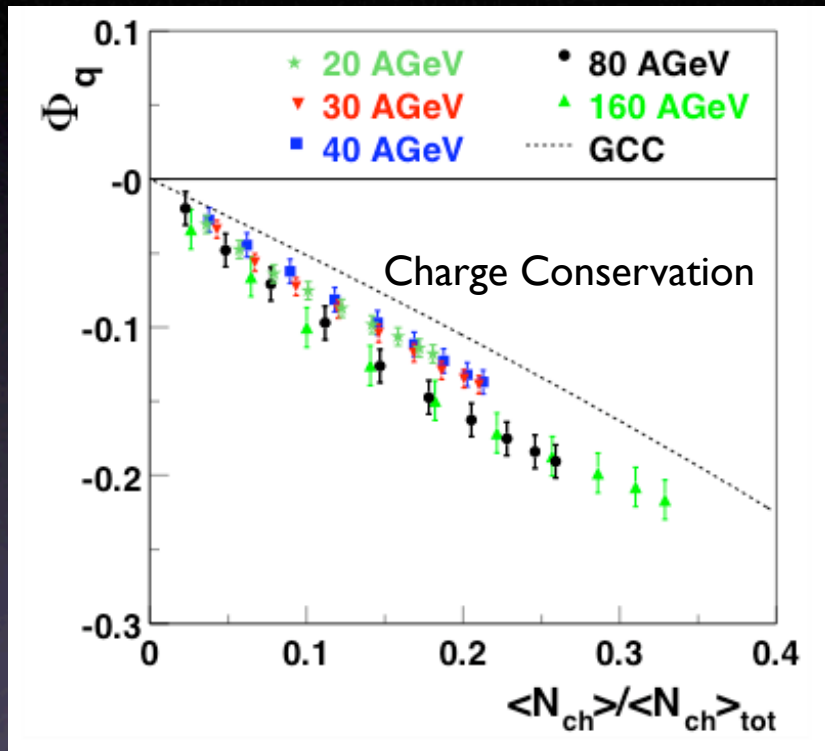


Rapidity range \longrightarrow

Fluctuations agree with stochastic distributions of Hadrons

Results at lower energies: NA49

NA49, PRC 70 064903 (2004)

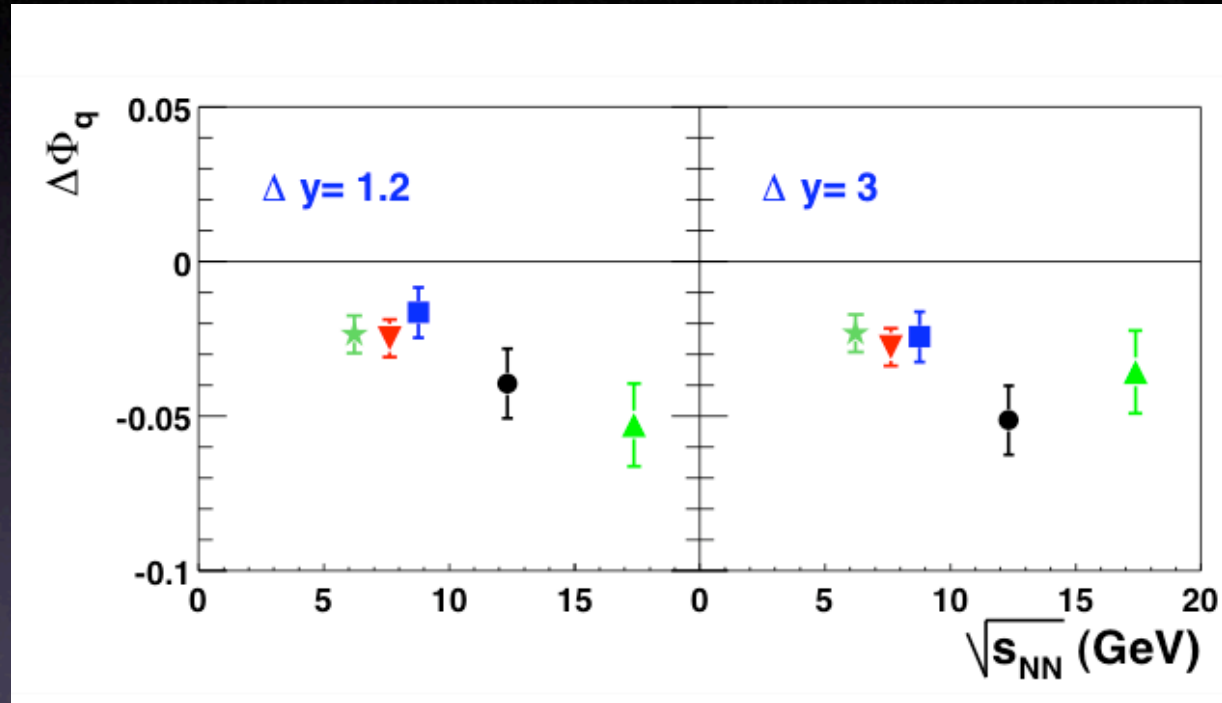


Rapidity range \rightarrow

Rapidity range \rightarrow

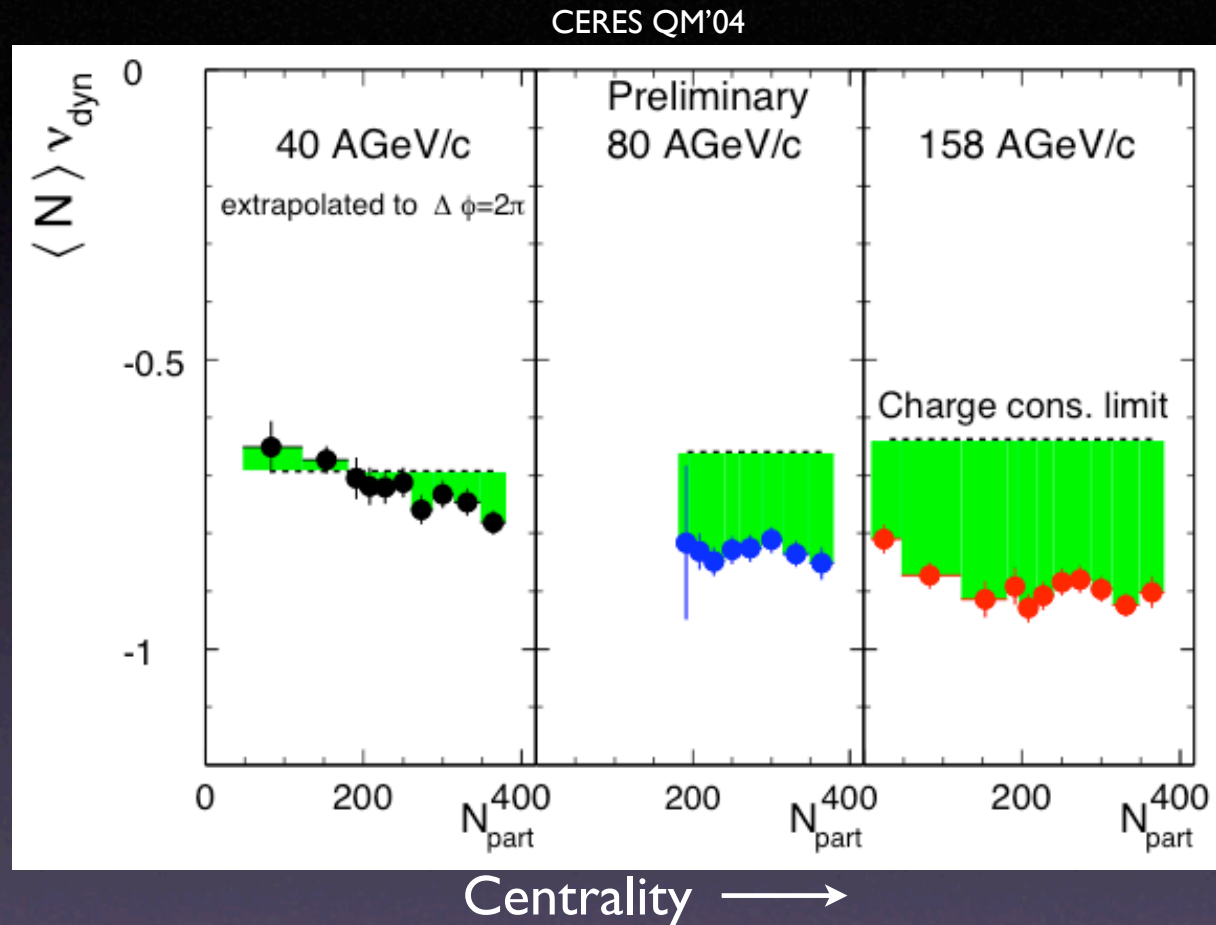
Energy-Dependence at lower energies

NA49, PRC 70 064903 (2004)



Some energy dependence at low energies?

CERES charge fluctuations data

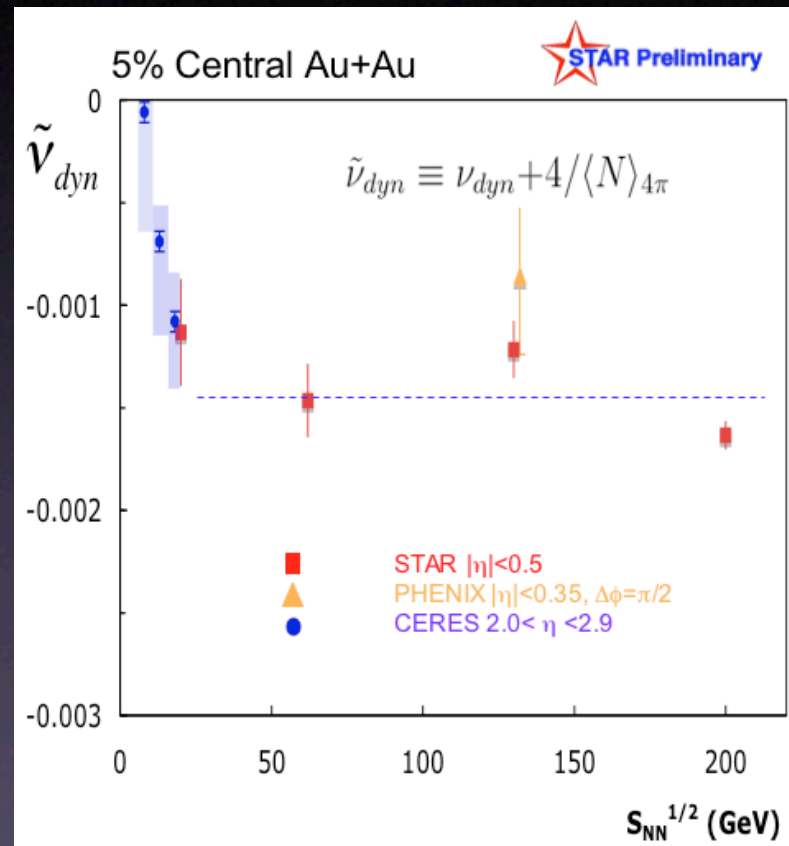


Some energy dependence at low energies?

Excitation Function: Charge Fluctuations

NA49, PRC 70 064903 (2004)

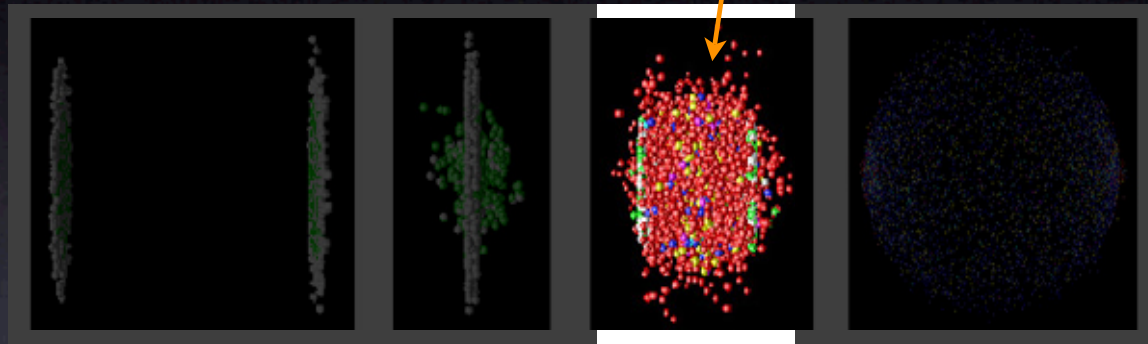
Plot from Claude Pruneau
RHIC Users meeting workshop '04
PHENIX: PRL 89 082301 (2002)



Little (no) \sqrt{s} dependence of charge fluctuations

What have we learned from Charge fluctuations?

DoF of Medium?



Net charge fluctuations
large (\sim hadron gas)

Small/no \sqrt{s} dependence

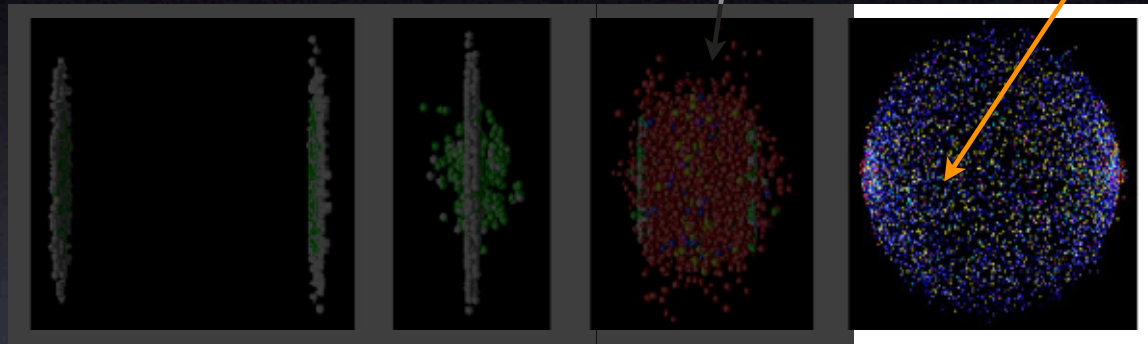


Quark coalescence?
Property of Hadronization?
Diffusion?
Bound states?

What have we learned from Charge fluctuations?

DoF of Medium?

How are hadrons made?



Net charge fluctuations
large (\sim hadron gas)

Small/no \sqrt{s} dependence



Quark coalescence?

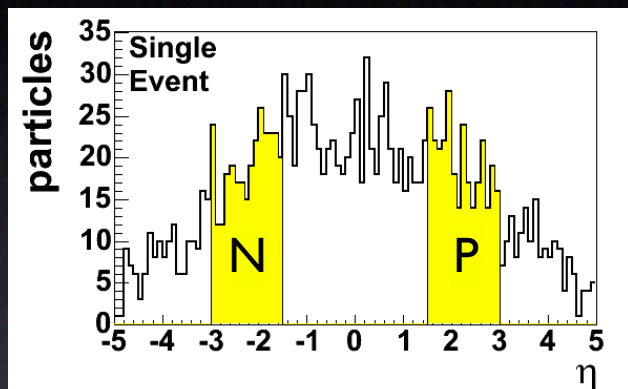
Property of Hadronization?

Diffusion?

Bound states?

The importance of hadronization

Forward/backward multiplicity correlations



$$C = \frac{P - N}{\sqrt{P + N}}$$

Use variance σ_C^2

Particles produced independently:

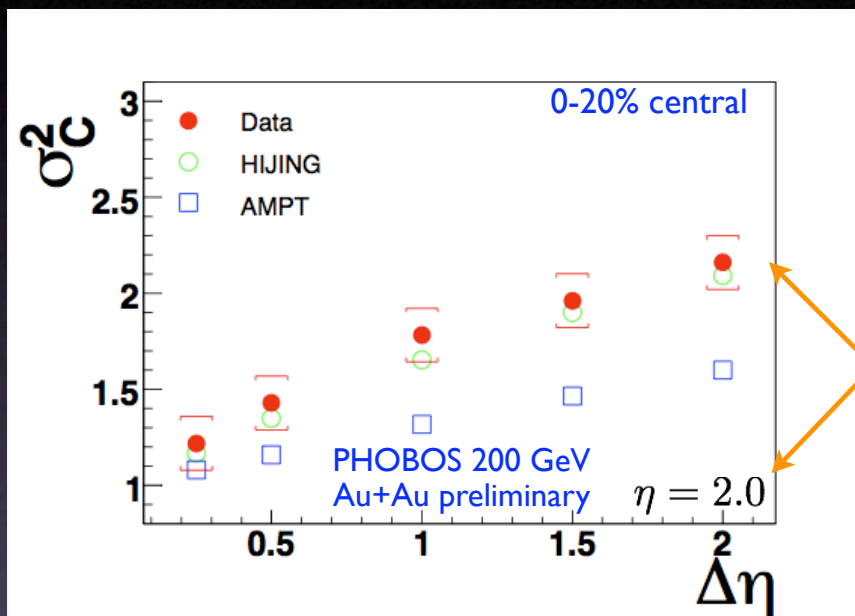
$$\sigma_C^2 = 1$$

Particles produced in clusters of size K :

$$C \rightarrow \sqrt{K} C$$
$$\sigma_C^2 \rightarrow K \sigma_C^2$$

The importance of hadronization

Forward/backward multiplicity correlations



Particles produced independently:

$$\sigma_C^2 = 1$$

Particles produced in clusters of size K :

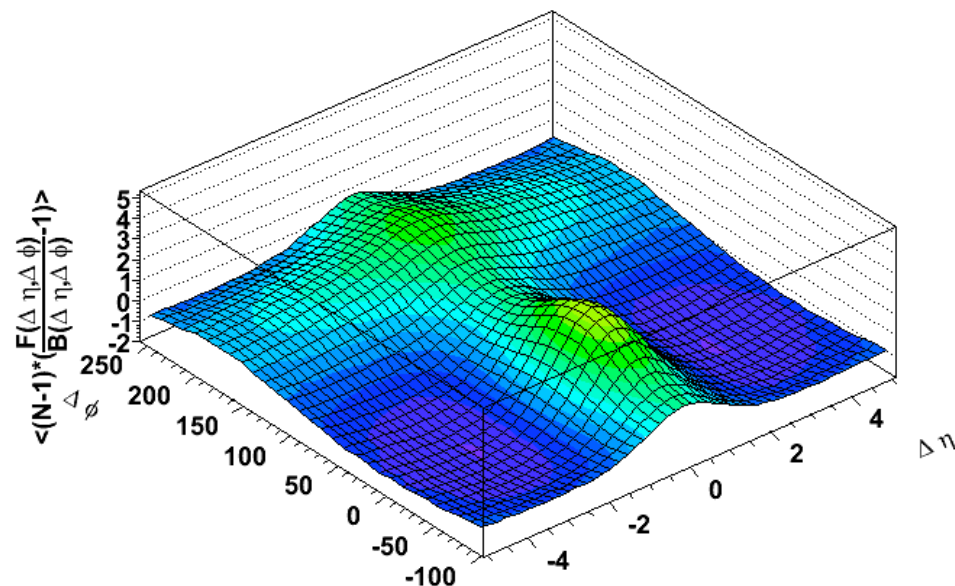
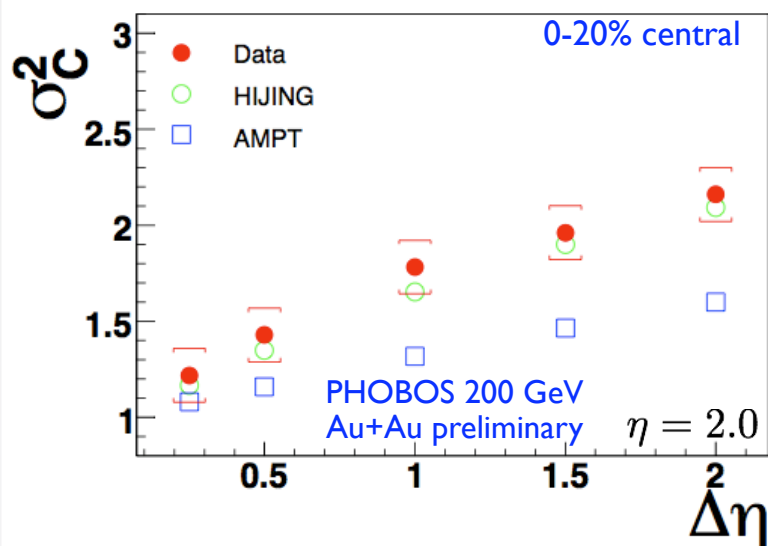
$$C \rightarrow \sqrt{K} C$$
$$\sigma_C^2 \rightarrow K \sigma_C^2$$

effective cluster size $\approx 2-2.5$
for 200 GeV Au+Au

The importance of hadronization

“Clusters” in A+A (and p+p) collisions

PHOBOS QM'05

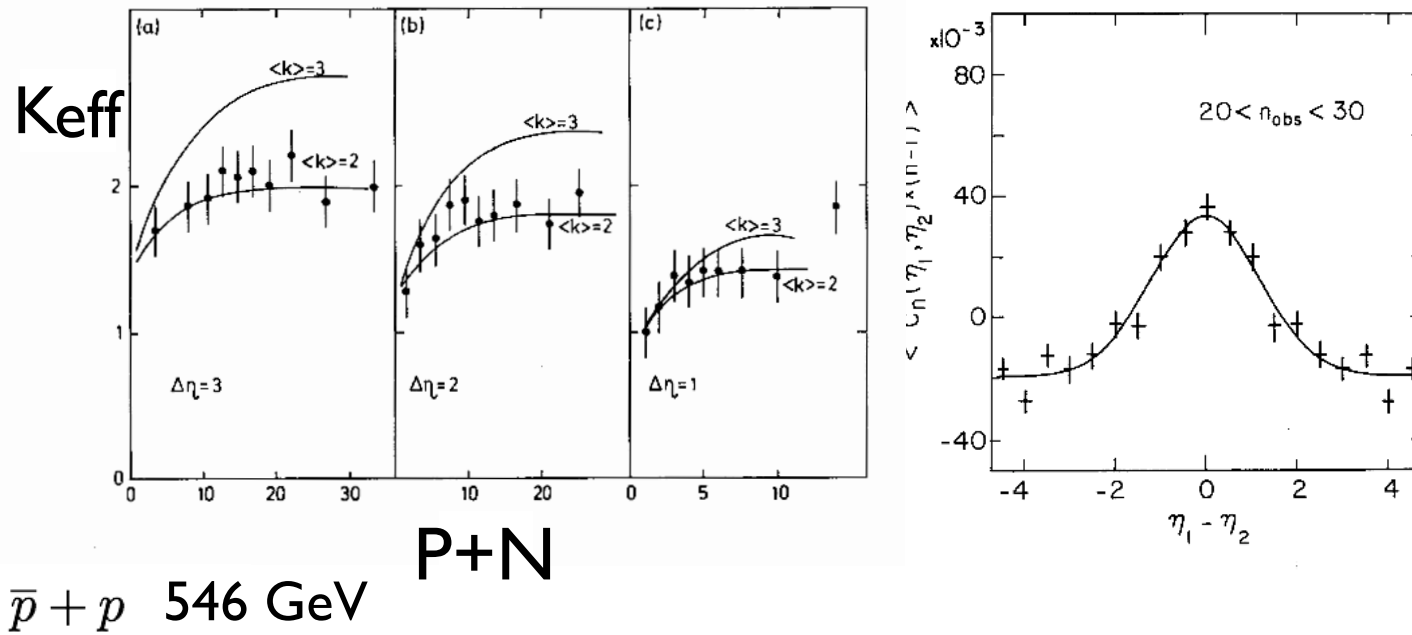


effective cluster size $\approx 2-2.5$
for 200 GeV Au+Au

“Cluster” in $\Delta\eta, \Delta\phi$ space via
2-particle correlations
(pythia p+p @200 GeV, $\eta < 3$)

Clusters in $p+p$

UA5: Phys.Lett.B123:361,1983



Clusters in Au+Au reminiscent
of results from $p+\bar{p}$

Measuring global charge fluctuations

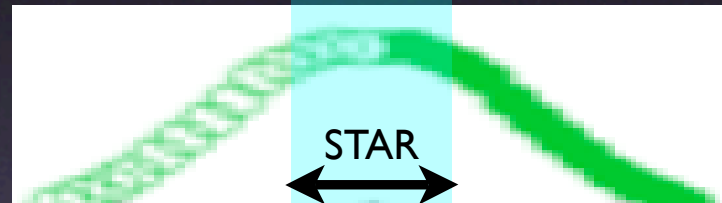
“Clustersize” $\Delta y \approx 2$

SPS



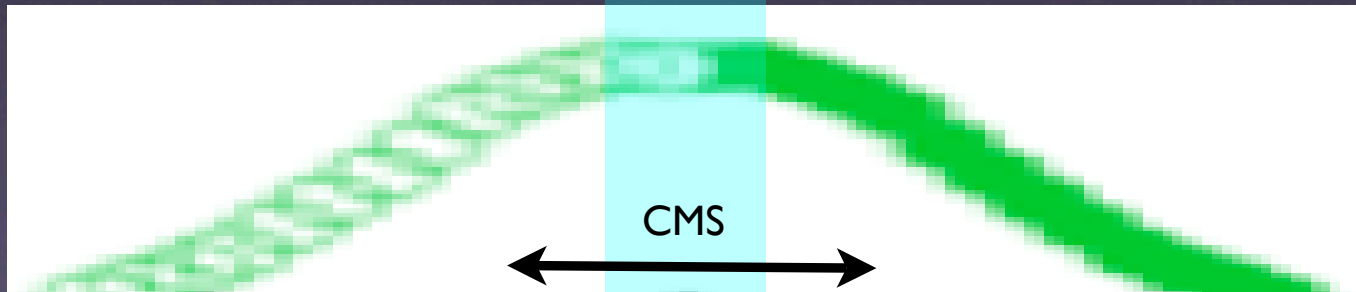
Acc. \approx Clustersize \approx Rapidity gap

RHIC



Acc. \approx Clustersize $<$ Rapidity gap

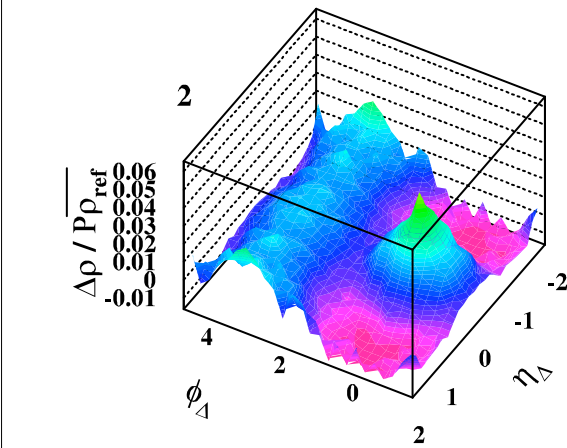
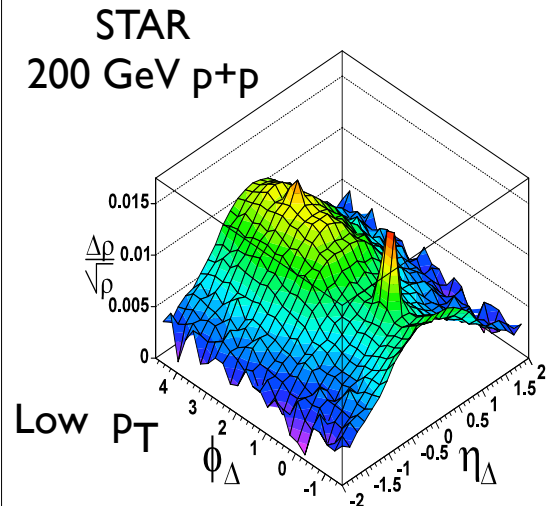
LHC



Acc. $>$ Clustersize \ll Rapidity gap

Beyond global charge fluctuations

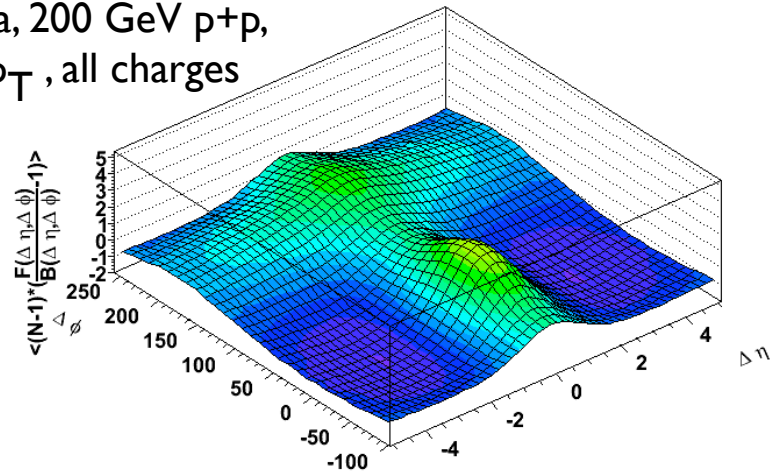
Beyond global charge fluctuations



High p_T

Tom Trainor et al (STAR)

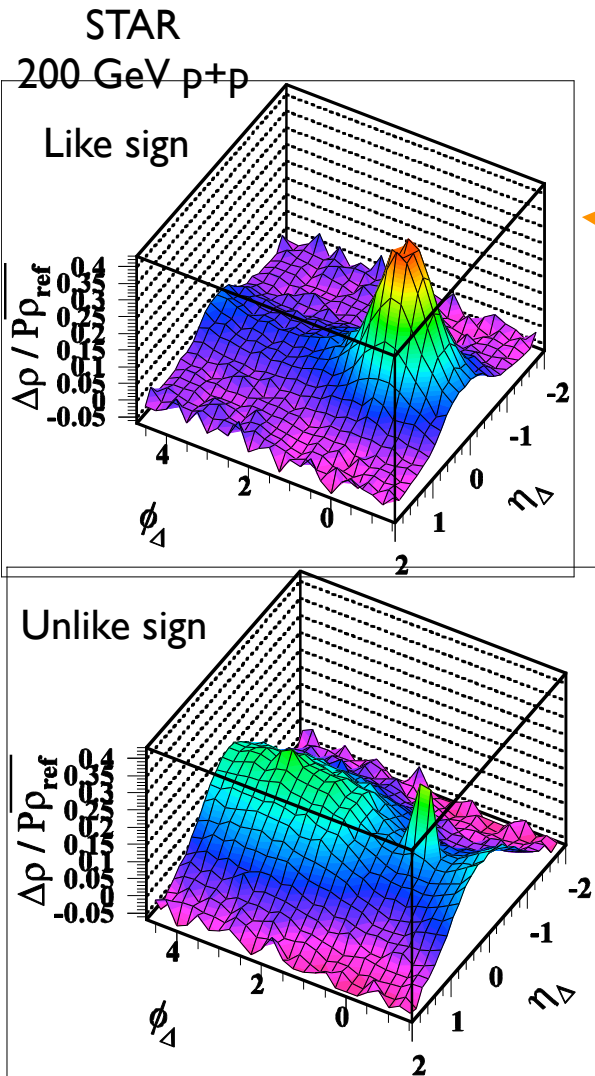
Pythia, 200 GeV p+p,
all p_T , all charges



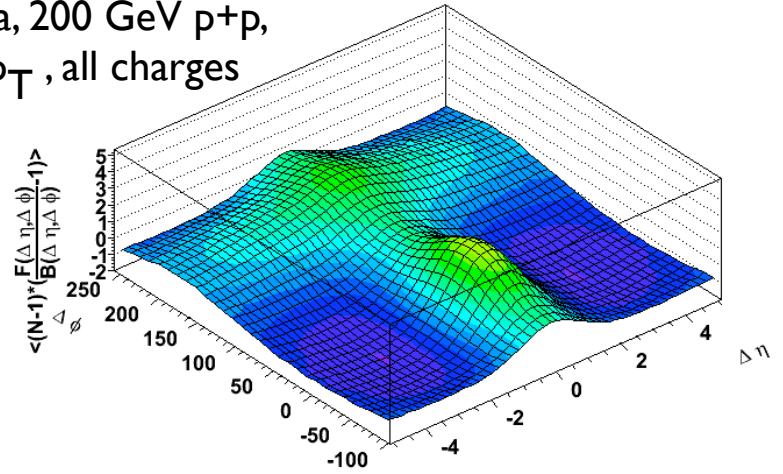
2-D angular correlation function

Split sample

Beyond global charge fluctuations



Pythia, 200 GeV p+p,
all p_T , all charges

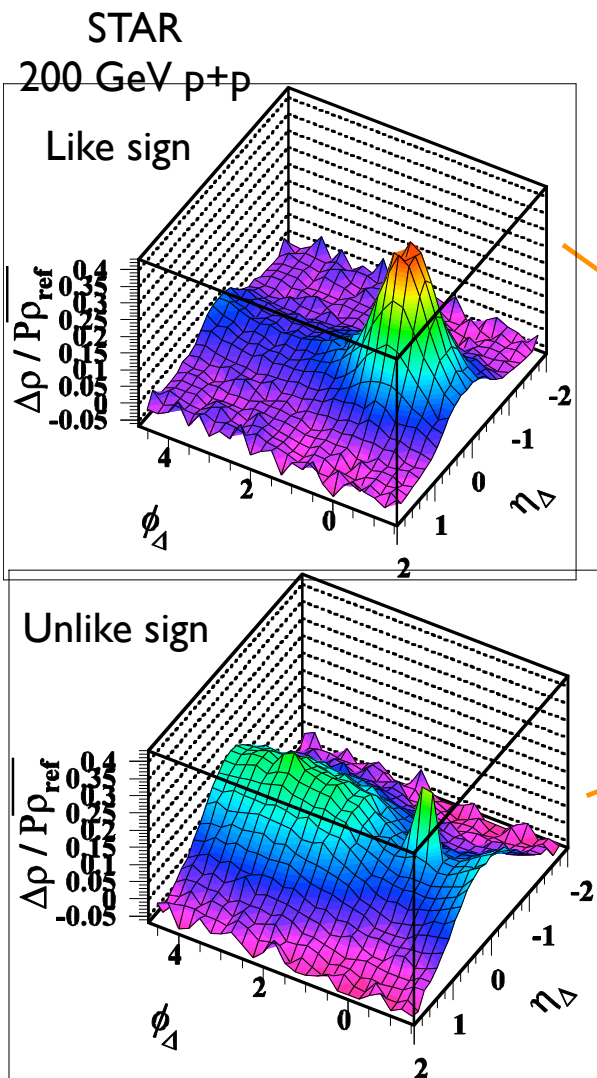


Split sample

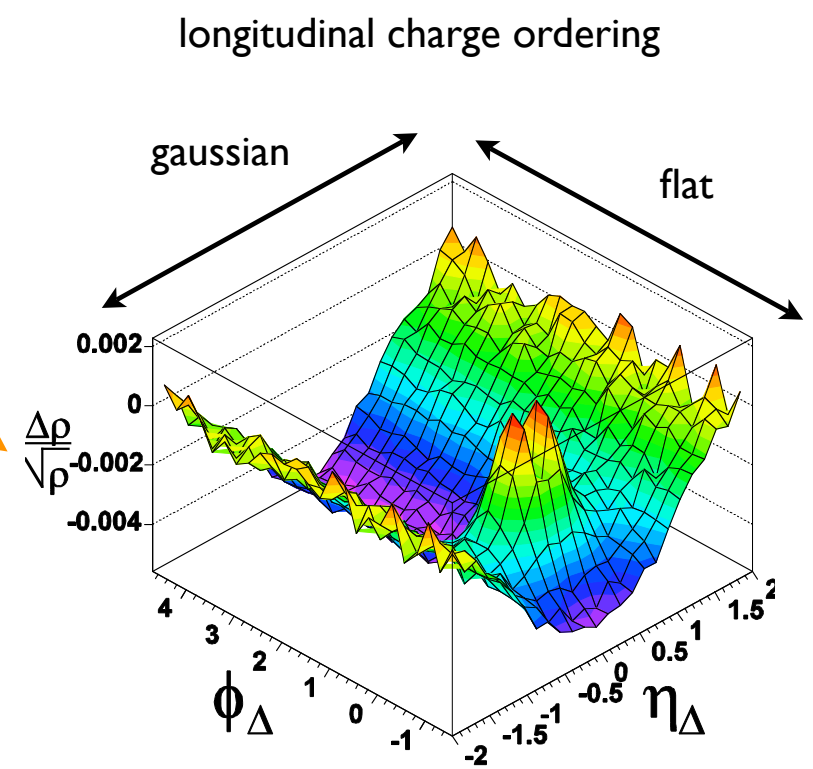
2-D angular correlation function

Tom Trainor et al (STAR)

Charge Dependent Correlations



subtract

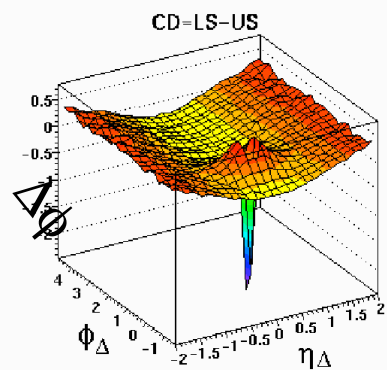


“Charge Dependent (CD)”
correlations
[= like sign - unlike sign]

Tom Trainor et al (STAR)

Charge Dependent Correlations

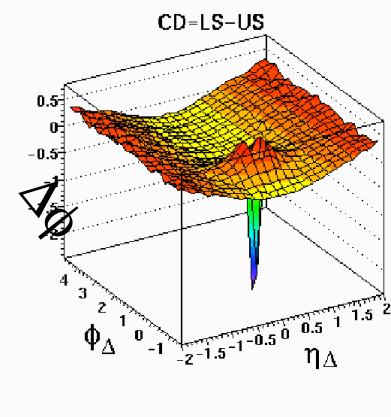
Difference of like-sign and unlike-sign 2-particle correlations:



p+p

Charge Dependent Correlations

Difference of like-sign and unlike-sign 2-particle correlations:

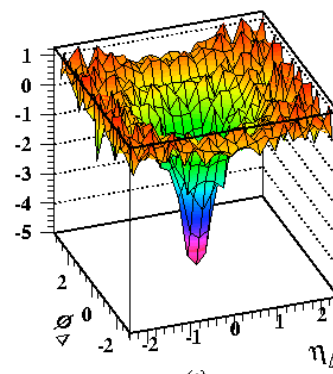
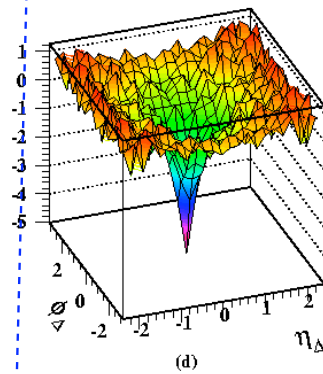


p+p

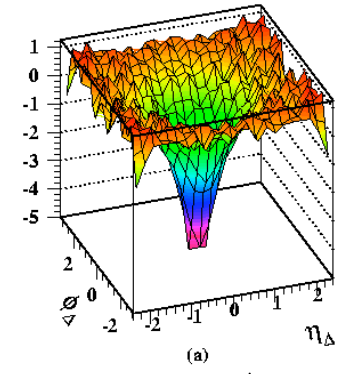
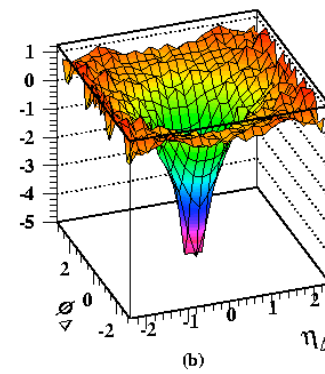
peripheral



central



Au+Au

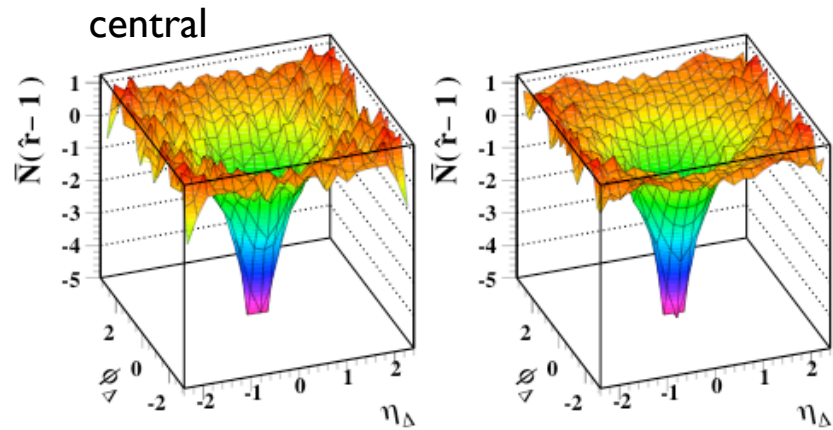


$\Delta\eta$

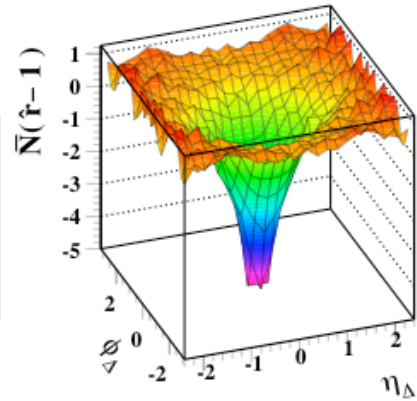
STAR
nucl-ex/0406035

Evolution of “cluster” properties/charge correlations

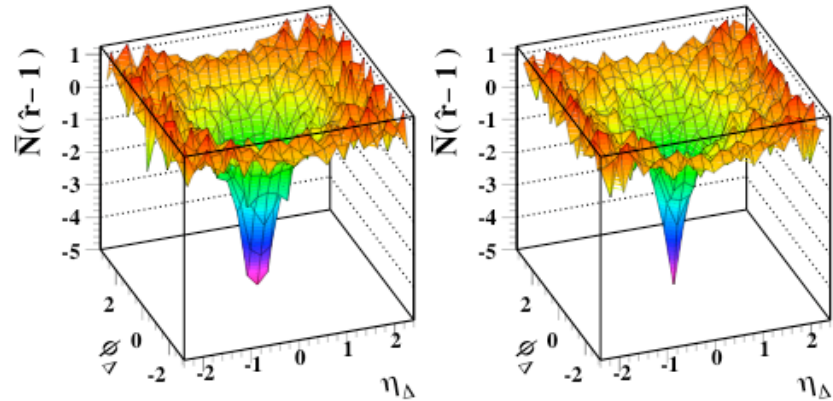
Charge Dependent Correlations



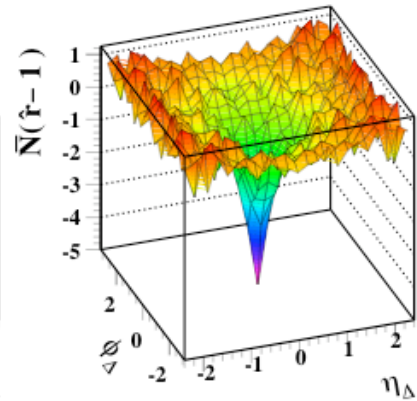
(a)



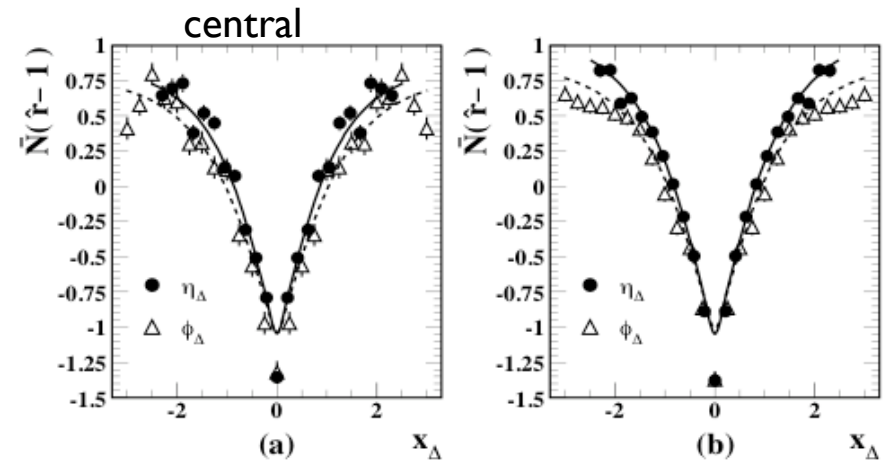
(b)



(c)

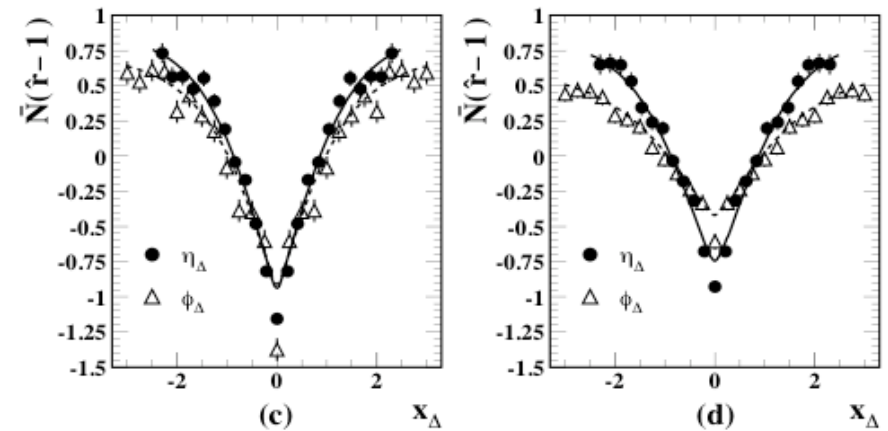


(d)



(a)

(b)



(c)

(d)

STAR
nucl-ex/0406035

peripheral

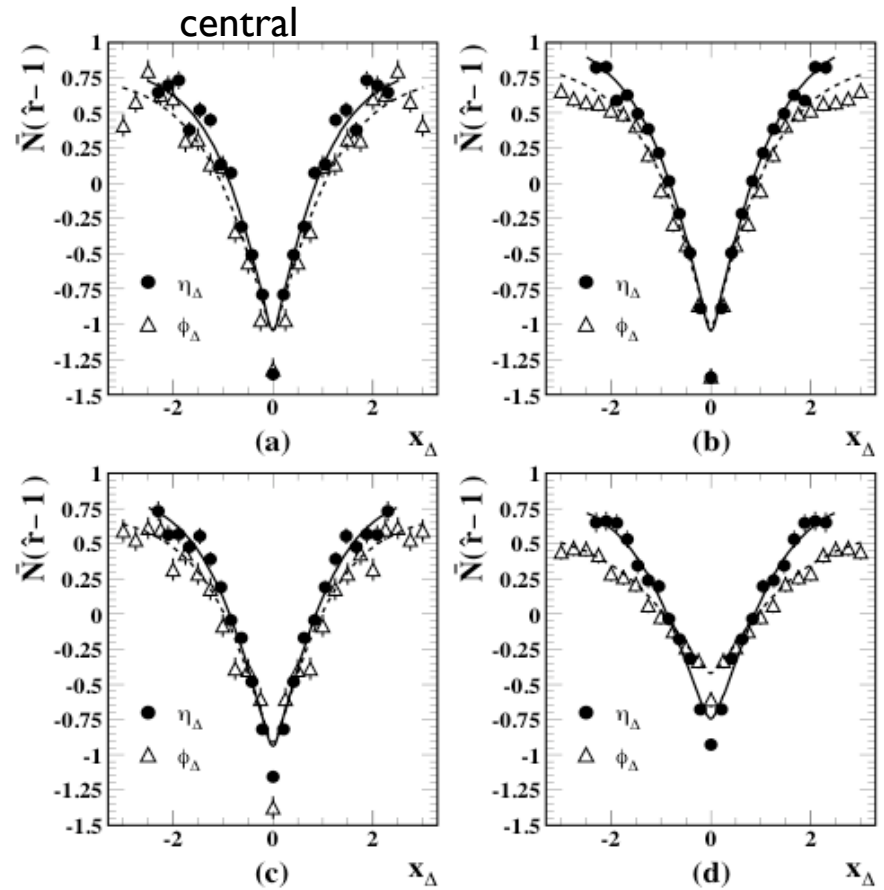
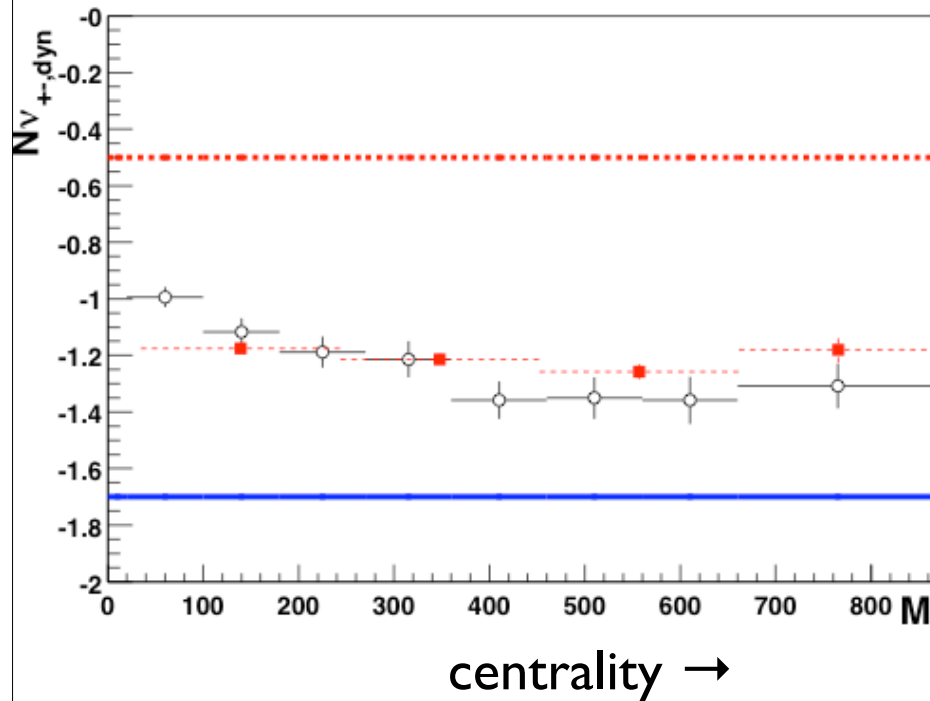
peripheral

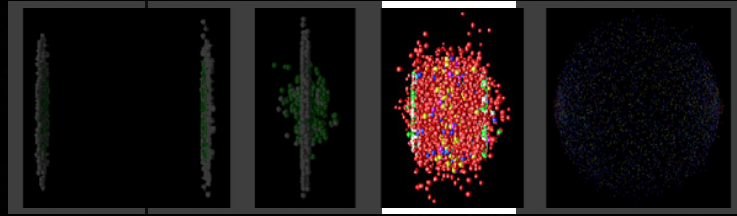
Centrality evolution in Au+Au

Integral measures vs Correlations

STAR Au+Au

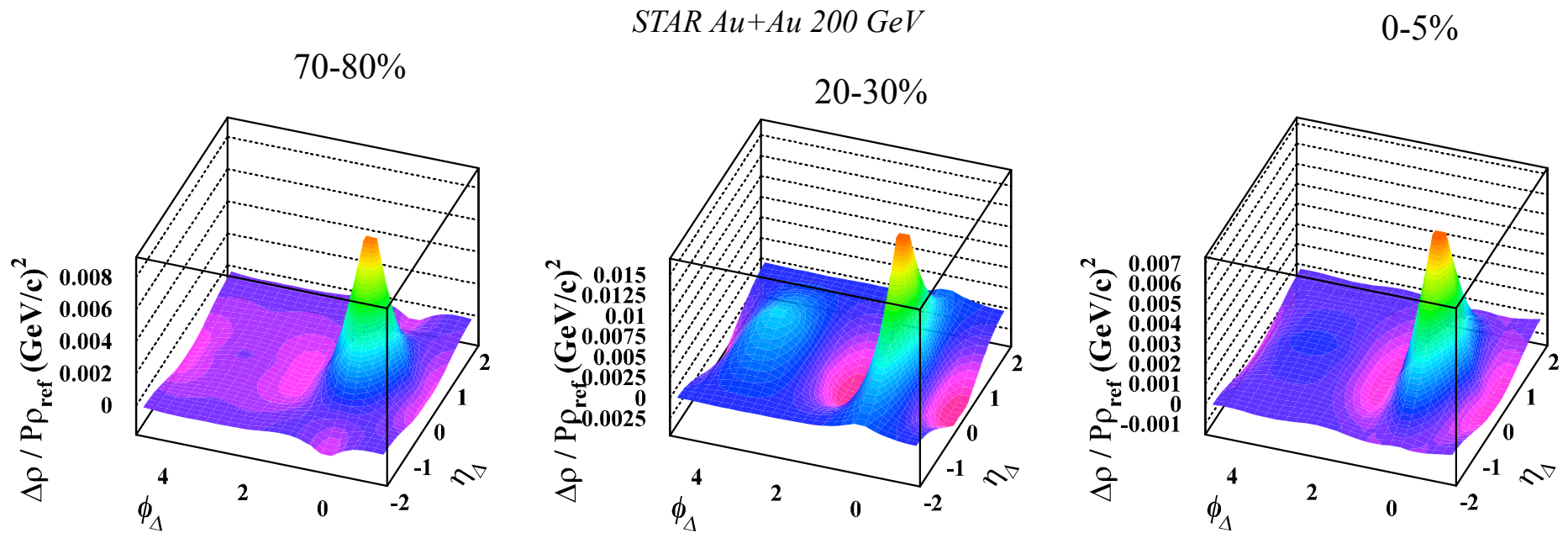
Net-charge Fluctuations



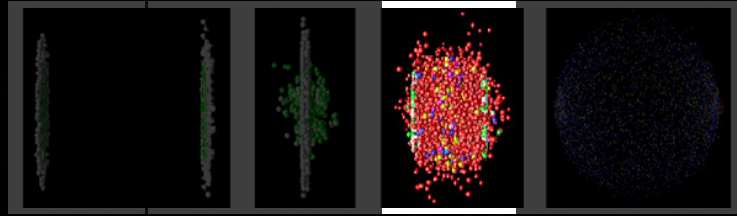


Properties of the Medium

2-particle momentum correlations

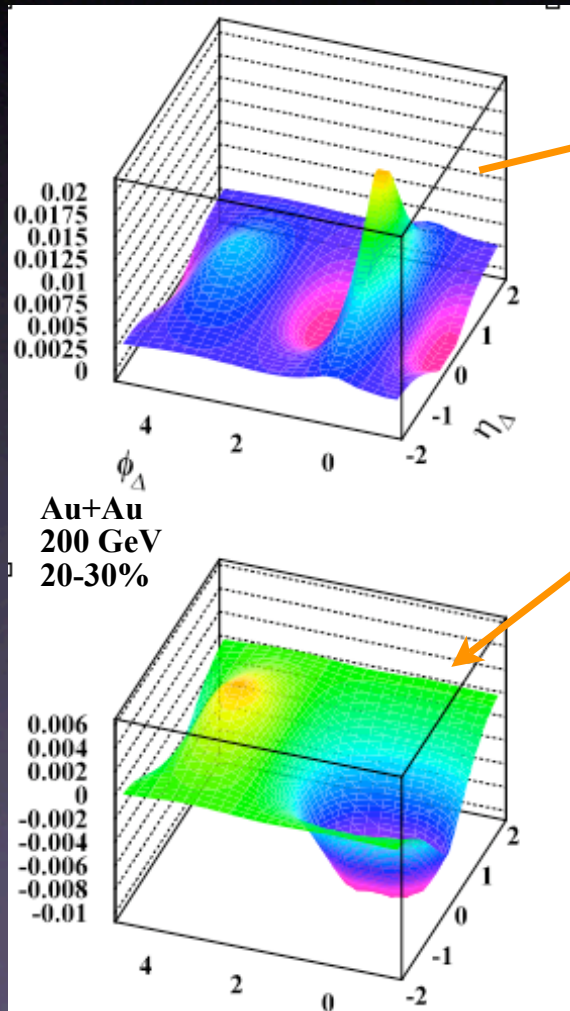


Shape of near-side “parton-fragmentation” peak evolves with centrality



Properties of the Medium

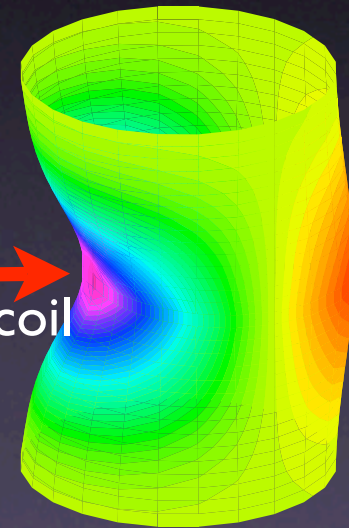
2-particle momentum correlations



Subtract fragmentation peak
to look at medium

Jet

Recoil



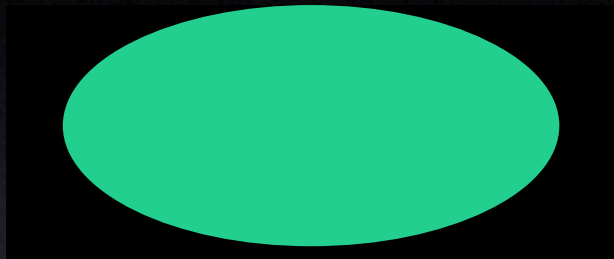
bulk medium

Summary

- Rich existing data set on fluctuations
 - Energy independence of global p_T , charge fluctuations
 - Energy dependence in K/π , p/π fluctuations
 - limited statistical significance
 - Non-trivial structure/change in charge correlations
- Low- \sqrt{s} scan at RHIC could confirm and improve experimental results

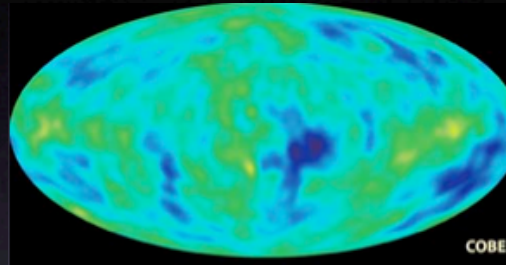
Analogy: Cosmic Microwave Background

Cosmic microwave background



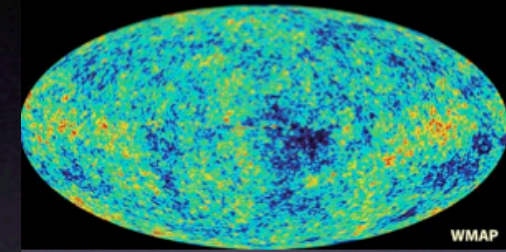
Penzias, Wilson
1964

$$\langle T \rangle = 3\text{K}$$

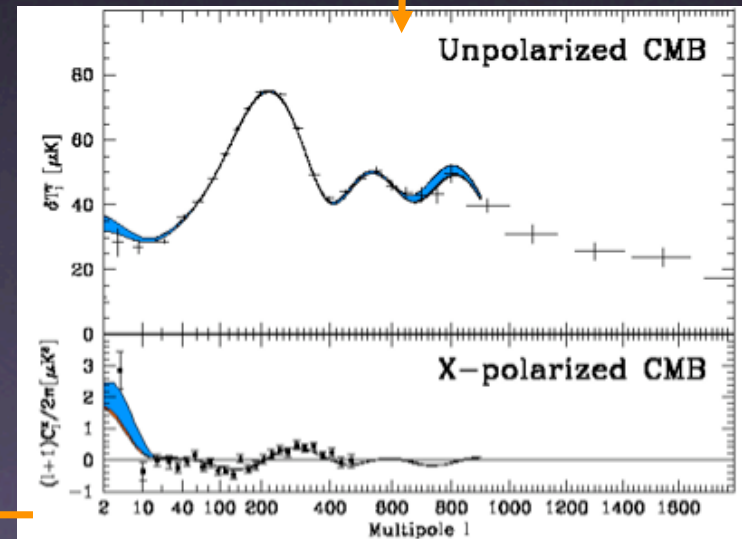


COBE 1992

$$\Delta T/T \sim 10^{-5}$$



WMAP



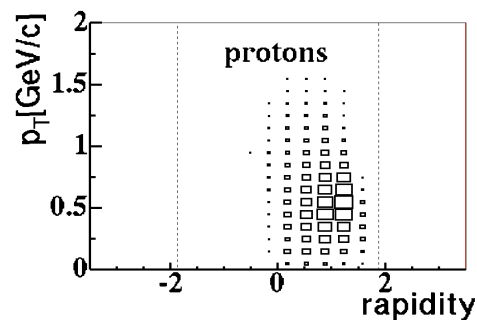
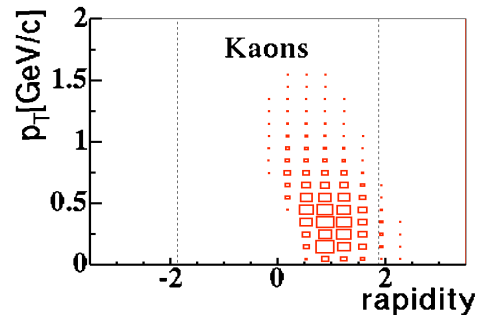
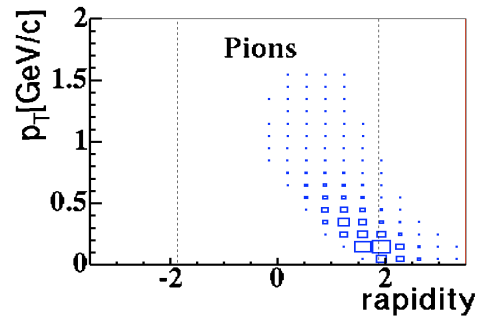
"Best" Cosmological Parameters:
Table 3 from Wilkinson Microwave Anisotropy Probe (WMAP) Observations:
Preliminary Maps and Basic Results,
C. L. Bennett et al. (2003), accepted by the *Astrophysical Journal*,
available at <http://lambda.gsfc.nasa.gov/>

Description	Symbol	Value	+ uncertainty	- uncertainty
Total density	Ω_{tot}	1.02	0.02	0.02
Equation of state of quintessence	w	< -0.78	95% CL	—
Dark energy density	Ω_{Λ}	0.73	0.04	0.04
Baryon density	$\Omega_b h^2$	0.0224	0.0009	0.0009
Baryon density	Ω_b	0.044	0.004	0.004
Baryon density (cm^{-3})	n_b	2.5×10^{-7}	0.1×10^{-7}	0.1×10^{-7}
Matter density	$\Omega_m h^2$	0.135	0.008	0.008
Matter density	Ω_m	0.27	0.04	0.04
Light neutrino density	$\Omega_{\nu} h^2$	< 0.0078	95% CL	—
CMB temperature [K]	T_{mb}	2.725	0.002	0.002
CMB photon density (cm^{-3})	n_{γ}	403.4	0.9	0.9
Baryon-to-photon ratio	η	6.1×10^{-10}	0.3×10^{-10}	0.2×10^{-10}
Baryon-to-matter ratio	$\Omega_b \Omega_m^{-1}$	0.17	0.01	0.01
Fluctuation amplitude in $8h^{-1}$ Mpc spheres	σ_8	0.84	0.04	0.04
Lower cluster abundance scaling	$\sigma_8 \Omega_m^{-0.5}$	0.44	0.04	0.05
Power spectrum normalization (at $k_0 = 0.05 \text{ Mpc}^{-1}$) ^a	A	0.833	0.086	0.253
Scalar spectral index (at $k_0 = 0.05 \text{ Mpc}^{-1}$) ^a	n_s	0.96	0.03	0.03
Running index slope (at $k_0 = 0.05 \text{ Mpc}^{-1}$) ^a	$dn_s/d \ln k$	-0.021	0.016	0.018
Tensor-to-scalar ratio (at $k_0 = 0.002 \text{ Mpc}^{-1}$) ^a	r	< 0.90	95% CL	—
Redshift of decoupling	z_{dec}	1089	1	1
Thickness of decoupling (FWHM)	Δz_{dec}	196	2	2
Hubble constant	h	0.71	0.04	0.03
Age of universe (Gyr)	t_0	13.7	0.2	0.2
Age at decoupling (kyr)	t_{dec}	379	8	7
Age at reionization (Myr, 95% CL)	t_{re}	180	220	80
Decoupling time interval (kyr)	Δt_{dec}	118	9	9
Redshift of matter energy equality	z_{eq}	3233	194	210
Reionization optical depth	τ_{re}	0.17	0.04	0.04
Redshift of reionization (95% CL)	z_{re}	20	10	9
Sound horizon at decoupling (")	θ_A	0.598	0.002	0.002
Angular size distance to decoupling (Gpc)	d_A	14.0	0.2	0.3
Acoustic scale ^b	ℓ_A	323	1	1
Sound horizon at decoupling (Mpc) ^d	r_s	347	2	2

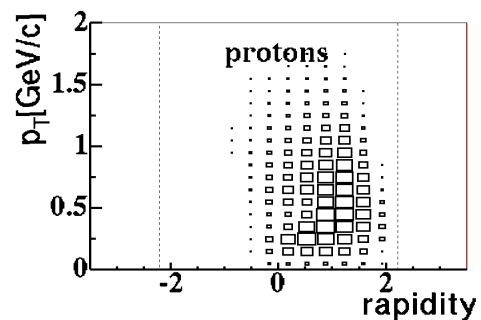
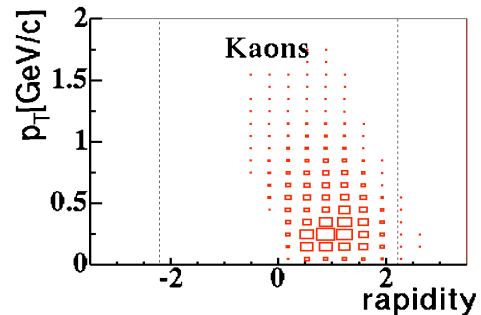
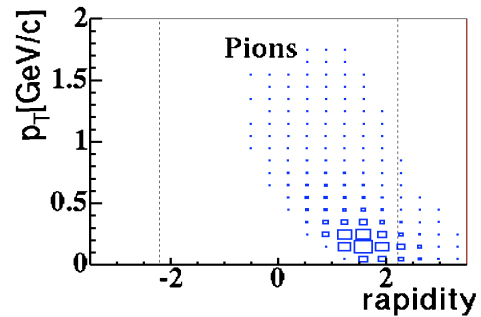
to March 2006

Challenge: Changing acceptance (NA49)

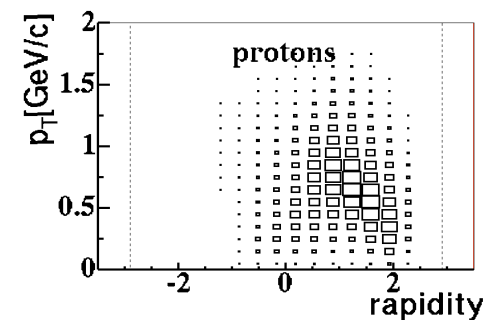
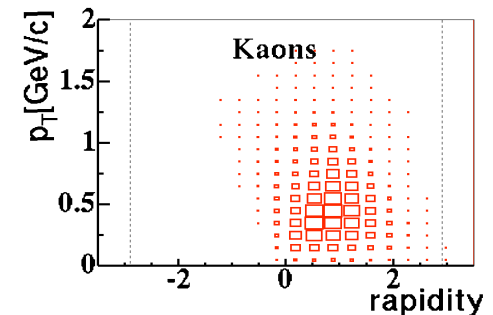
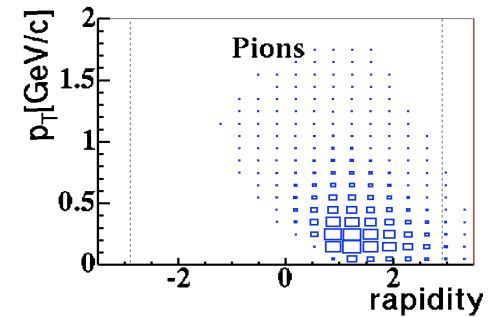
20 GeV:



40 GeV:



160 GeV:

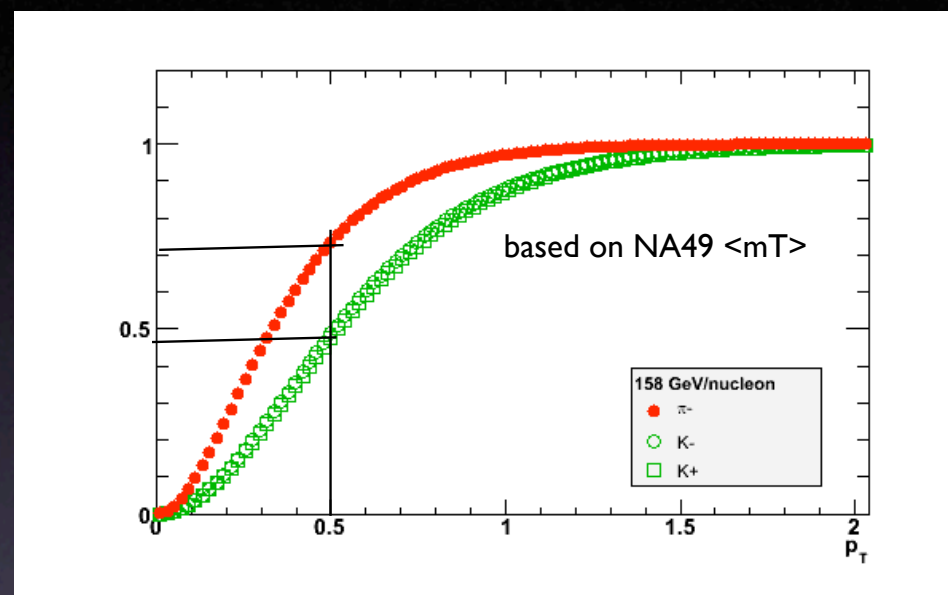


Slide from Christof Roland,
Correlations '05, MIT

What about low p_T ?

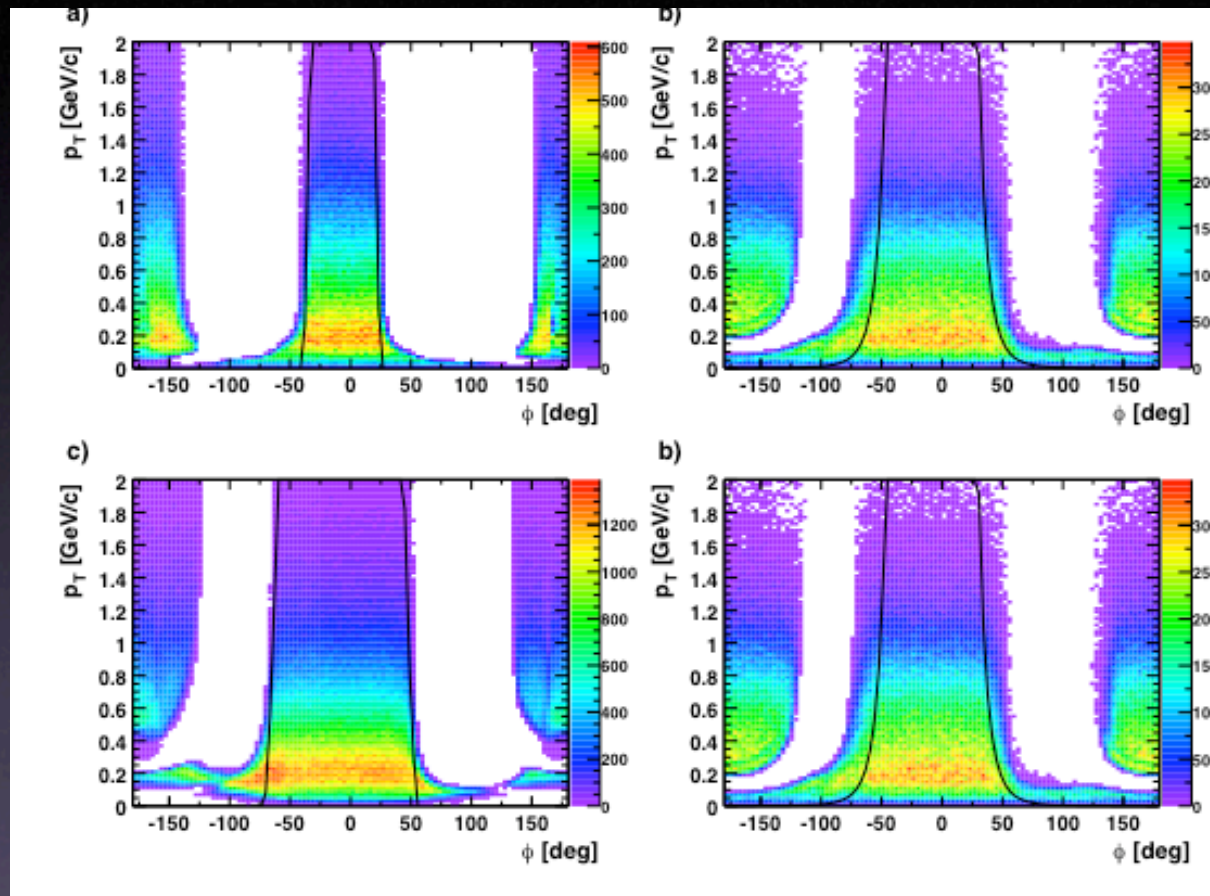
Critical fluctuations:
Long Wavelength
→ look at low p_T

Fraction of particles below p_T



Median Kaon $p_T \sim 0.5$ GeV
(constant over SPS range)

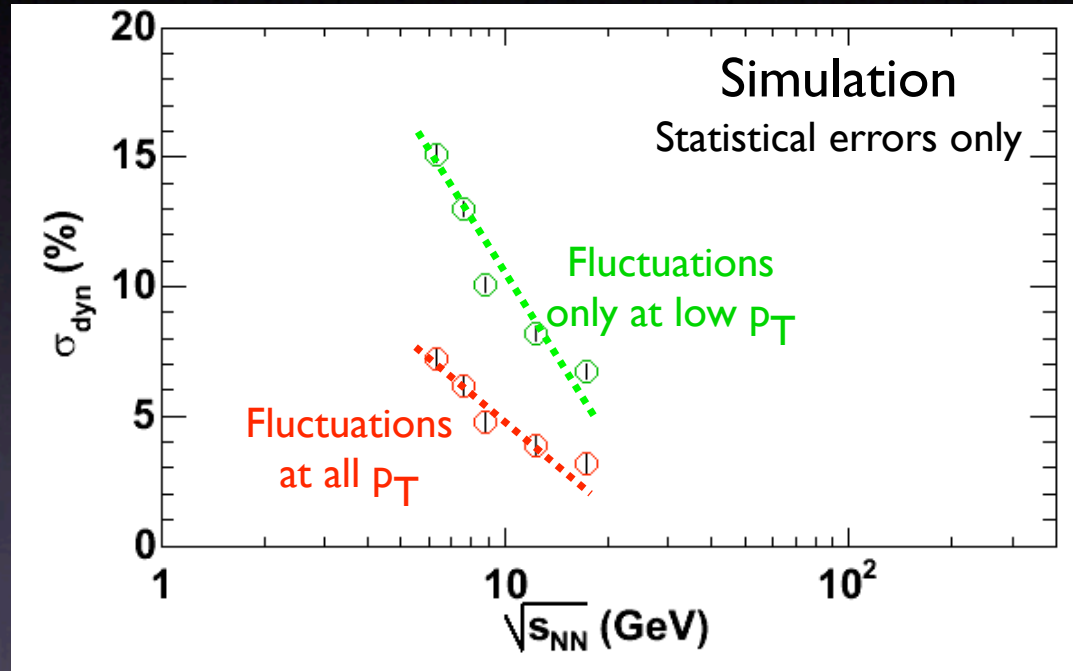
A low p_T measurement (0.1 - 0.5 GeV/c) would
capture $\sim 45\%$ (75%) of all kaons (pions)



Low p_T K/ π Fluctuations at \sqrt{s} RHIC

Assumptions:

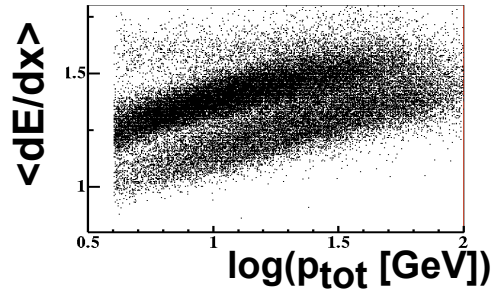
- * Ideal RHIC detector (see above)
- * 100k central Au+Au at each \sqrt{s}
- * K/ π Fluctuations from NA49 are correct
- * $0.1 < p_T < 0.5$ GeV/c



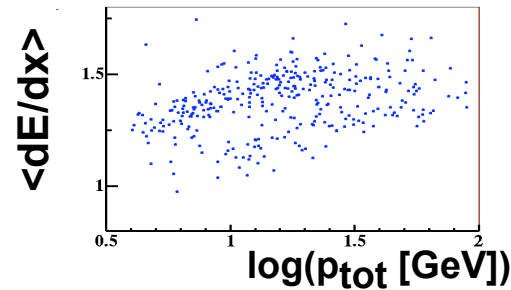
Conclusion:
RHIC low- \sqrt{s} scan should allow precision measurement of (low p_T) K/ π fluctuations

Event-by-event fit of K/ π (NA49)

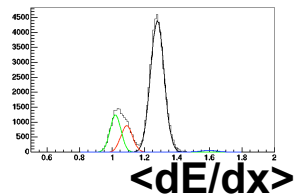
Event Ensemble:



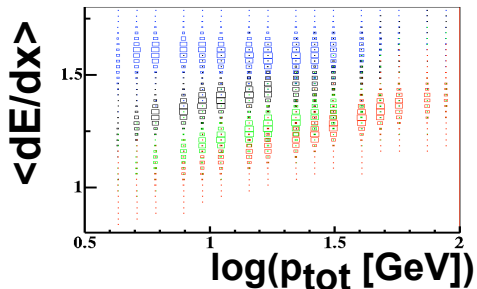
One Event:



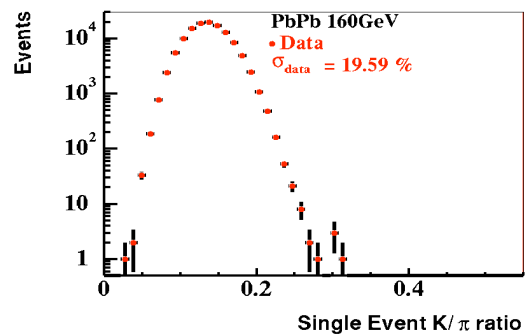
Fit dE/dx spectra in 4D binning



Probability density function:



- Vary relative normalization of the particle species (K/ π , p/ π) in the PDF
- Extract ratios with maximum likelihood fit



Slide from Christof Roland,
Correlations '05, MIT

$$\Phi_{p_T} = \sqrt{\frac{\frac{1}{\varepsilon} \sum_{j=1}^{\varepsilon} (N_j \langle p_T \rangle_j - N_j \hat{p}_T)^2}{\bar{N}}} - \sigma_{\hat{p}_T} \quad (1)$$

$$\simeq \sqrt{\frac{1}{\varepsilon} \sum_{j=1}^{\varepsilon} N_j (\langle p_T \rangle_j - \hat{p}_T)^2} - \sigma_{\hat{p}_T} \quad (2)$$

$$\Sigma_{p_T} = \frac{\sqrt{\sigma_{\langle p_T \rangle, dyn}^2}}{\bar{p}_T} \quad (3)$$

$$\sigma_{\langle p_T \rangle, dyn}^2 = \frac{1}{\varepsilon} \sum_{j=1}^{\varepsilon} \frac{N_j (\langle p_T \rangle_j - \hat{p}_T)^2}{\bar{N}} - \frac{\sigma_{\hat{p}_T}^2}{\bar{N}} \quad (4)$$

The relationship between Φ_{p_T} and Σ_{p_T} when Φ_{p_T} is small and $\Phi_{p_T}^2$ term is neglected:

$$\Phi_{p_T} \simeq \frac{\sigma_{\langle p_T \rangle, dyn}^2 \bar{N}}{2\sqrt{\sigma_{\hat{p}_T}^2}} \quad (5)$$

$$\Sigma_{p_T} \simeq \sqrt{\frac{2\Phi_{p_T} \sqrt{\sigma_{\hat{p}_T}^2}}{\bar{N} \bar{p}_T^2}} \quad (6)$$

Net Charge, and K/ π Fluctuations

Instead of measuring the variance of a yield ratio,

$$r_{12} = \frac{n_1}{n_2} \quad \rightarrow \quad \frac{\langle (\Delta r_{12})^2 \rangle}{\langle r_{12} \rangle^2} \approx \frac{\langle (\Delta n_1)^2 \rangle}{\langle n_1 \rangle^2} + \frac{\langle (\Delta n_2)^2 \rangle}{\langle n_2 \rangle^2} - 2 \frac{\langle \Delta n_1 \Delta n_2 \rangle}{\langle n_1 \rangle \langle n_2 \rangle}$$

Study the “dynamical fluctuations”:

$$v_{12,dyn} = \left\langle \left(\frac{n_1}{\langle n_1 \rangle} - \frac{n_2}{\langle n_2 \rangle} \right)^2 \right\rangle - \frac{1}{\langle n_1 \rangle} - \frac{1}{\langle n_2 \rangle} = \tilde{R}_{11} + \tilde{R}_{22} - 2\tilde{R}_{12}$$

Side Note: $D \equiv \langle n_1 + n_2 \rangle \langle (\Delta r_{12})^2 \rangle$ $\frac{D}{4} \approx 1 + \frac{(\tilde{R}_{++} + \tilde{R}_{--} - 2\tilde{R}_{+-}) \langle n_+ + n_- \rangle}{4}$

$\langle p_t \rangle$ Fluctuations

$$\langle \Delta p_{t,1} \Delta p_{t,2} \rangle = \frac{1}{N_{event}} \sum_{k=1}^{N_{event}} \frac{C_k}{N_k (N_k - 1)}$$

where

$$C_k = \sum_{i=1}^{N_k} \sum_{j=1, i \neq j}^{N_k} (p_{t,i} - \langle \langle p_t \rangle \rangle) (p_{t,j} - \langle \langle p_t \rangle \rangle)$$

$$\langle \langle p_t \rangle \rangle = \left(\sum_{k=1}^{N_{event}} \langle p_t \rangle_k \right) / N_{event}$$

$$\langle p_t \rangle_k = \left(\sum_{i=1}^{N_k} p_{t,i} \right) / N_k$$