NA49: Fluctuation Results and the Search for the Critical Point

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GOETHE UNIVERSITÄT FRANKFURT AM MAIN

for the NA49 collaboration

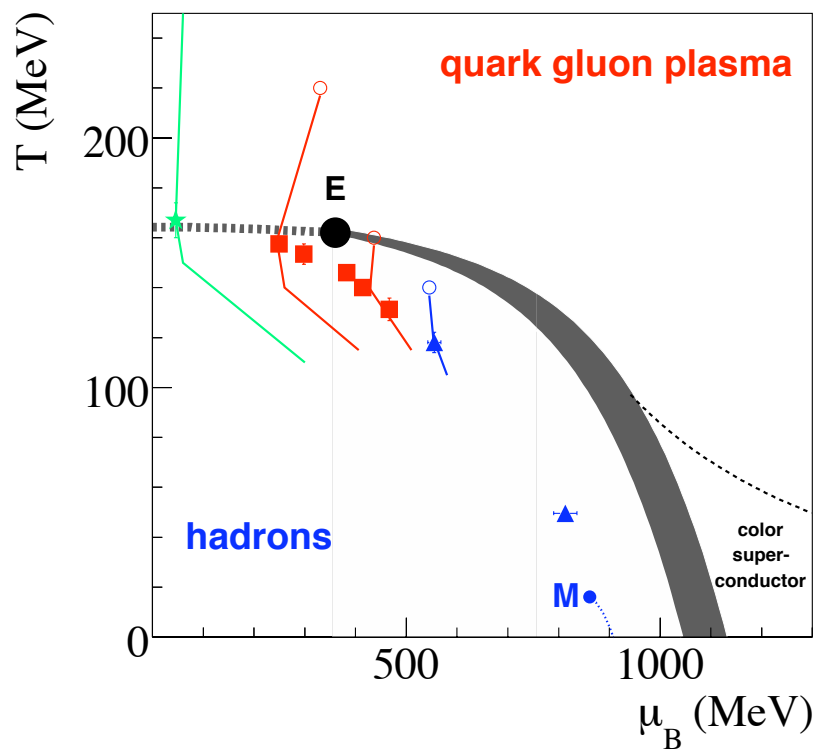
Fluctuations Critical Point and Phase Transition

- Onset of deconfinement indicated in *inclusive* observables at low SPS energies
- Can *fluctuations* convey more information
  - About the onset of deconfinement?

    At the phase transition, 2 distinct event classes or the mixed phase may be reflected in larger event-by-event fluctuations
  - On the nature of the phase transition and in particular about the critical point?

    Diverging susceptibilities near the critical point are directly connected to fluctuations

    (cf. e.g. Stephanov, Rajagopal, Shuryak, Phys.Rev.D60:114028; Gorenstein, Gazdzicki, Zozulya Phys.Lett. B585 237)



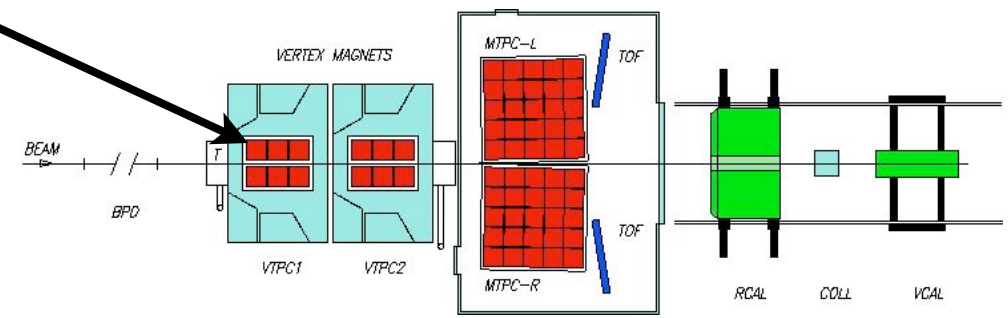
Critical Point and crossover:
Fodor et. al.: JHEP 0404 (2004) 050

Outline

- Experiment: details relevant to fluctuation analysis
  - Acceptance
  - Centrality determination
- Hadron ratio fluctuations
  - Signature for the onset of deconfinement and the critical point?
  - NA49 results on K/π, p/π, and K/p fluctuations
- Critical point effects on fluctuations
  - Multiplicity, $\langle p_T \rangle$ fluctuations at SPS
  - Estimated critical point effect
  - Net baron or proton Kurtosis: Expected effects from phase transition and critical point

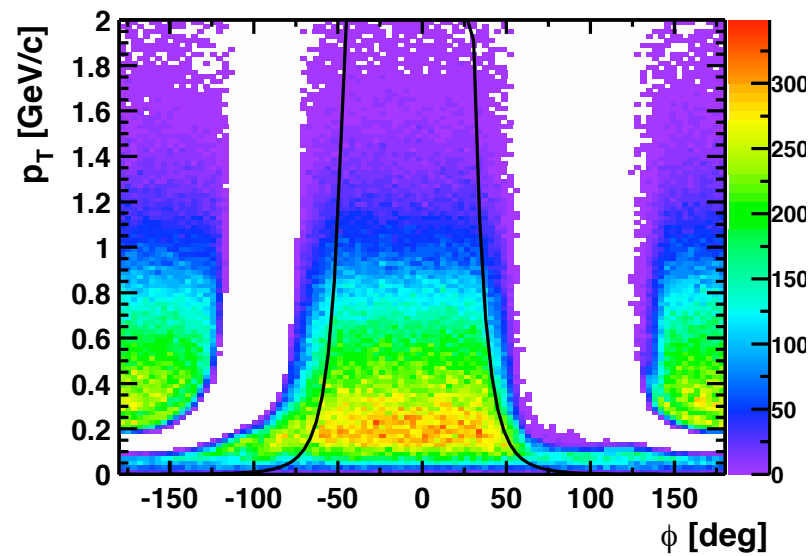
NA49: TPC Acceptance

- Large volume Time Projection Chambers (TPCs):
  - Tracking in magnetic field:
    → momentum, charge
  - Specific energy loss d*E*/d*x*:
    → PID of p, K, π, ... : Resolution 3-4%



  - Acceptance:
    - Mainly $y > 0$
    - Full p_T range
    - Limited φ acceptance; p_T, y dependent
    - Acceptance is changing with energy

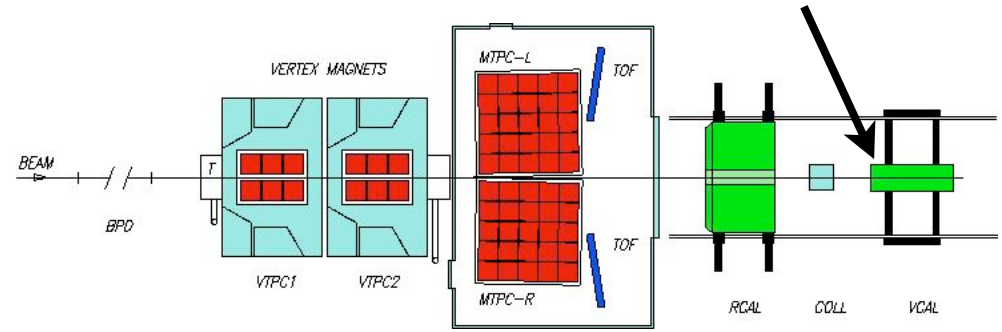
Example plot: acceptance for $1.4 < y < 1.6$



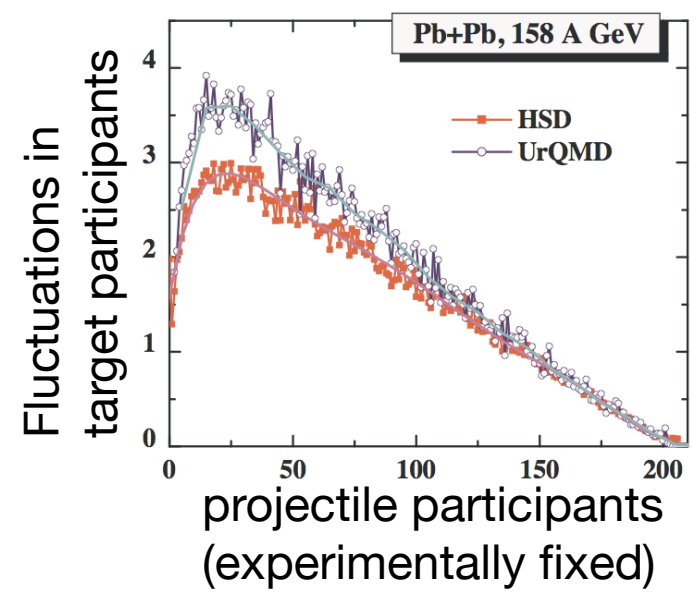
Phys.Rev.C 70, 2004

For inclusive measurements, azimuthal acceptance can be corrected for
Correlations and Fluctuations are affected by acceptance
→ Has to be taken into account in model comparisons!

NA49: Centrality Determination



- Veto Calorimeter (VCAL):
  - Measurement of projectile spectator energy → centrality of collision
  - Number of projectile participants can be derived
  - Number of all participants (N_{part}) can be calculated in Glauber MC model
- Fluctuations in N_{part} must be minimized
  - Fluctuations of extensive quantities (e.g. multiplicity) are directly affected
  - Fluctuations of intensive quantities (e.g. ratios, $\langle p_T \rangle$) are indirectly affected
- In very central collisions
  - The number of projectile participants is fixed
  - Fluctuations of all participants are minimized



Phys.Rev. C73 034902

NA49 Data Sets

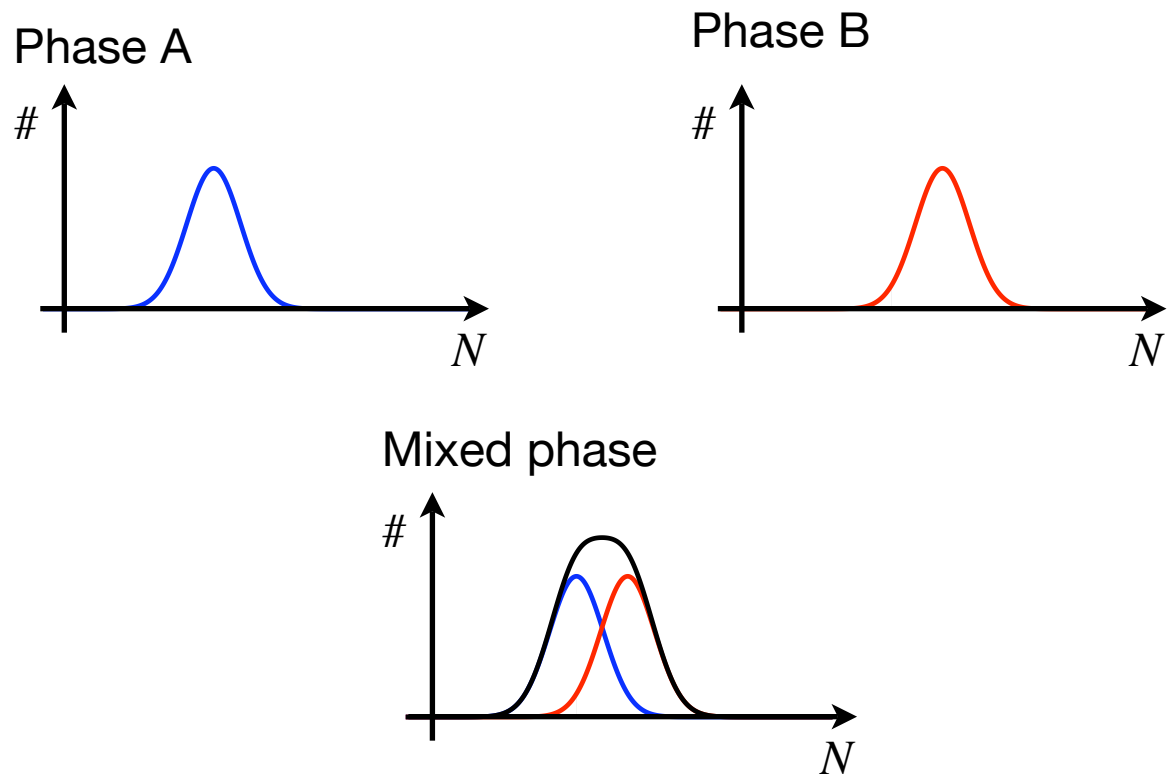
Data sets analyzed for the shown fluctuation results

Energy	$\sqrt{s_{NN}}$	System	Centrality	Statistics
158*A* GeV	17.3	Pb+Pb	10%, 23%	800k, 3M
			min. bias	410k
		C+C, Si+Si	15%, 12%	220k, 300k
		p+p	min. bias	6.8M
80*A* GeV	12.3	Pb+Pb	7%	300k
40*A* GeV	8.7	Pb+Pb	7%	600k
			min. bias	750k
		C+C, Si+Si	66%, 29%	240k, 130k
30*A* GeV	7.6	Pb+Pb	7%, 35%	440k, 230k
20*A* GeV	6.3	Pb+Pb	7%, 35%	360k, 330k

+ stricter centrality selection

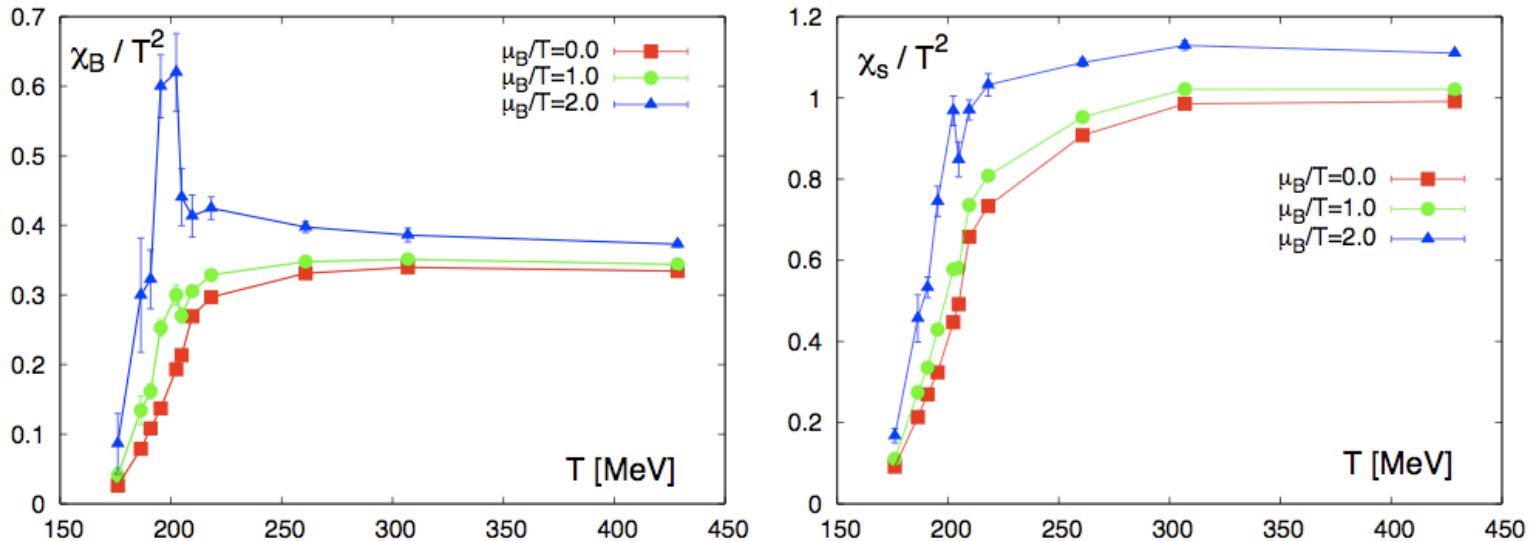
Introduction

- Hadron Ratios ...
  - ... are an intensive quantity
  - ... characterize the chemical composition of the fireball
  - ... not affected by hadronic re-interaction when looking at conserved quantities (baryon number, strangeness)
- Change of particle (e.g. strangeness) production properties at the phase transition
  - Two event classes
  - Larger fluctuations in the mixed phase



Introduction

- Lattice calculations show change in quark number susceptibilities

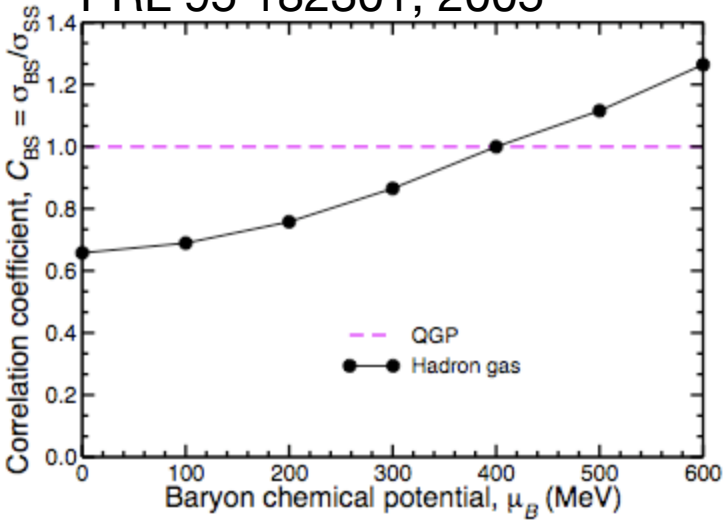


F. Karsch, PoS (CPOD07) 026 and PoS (Lattice 2007) 015

- Direct connection to number fluctuations $\chi \sim \langle N^2 \rangle$
- Step seen for light and strange quarks
- Smooth transition at $\mu_B = 0$
- Light quark number susceptibility diverges at the critical point

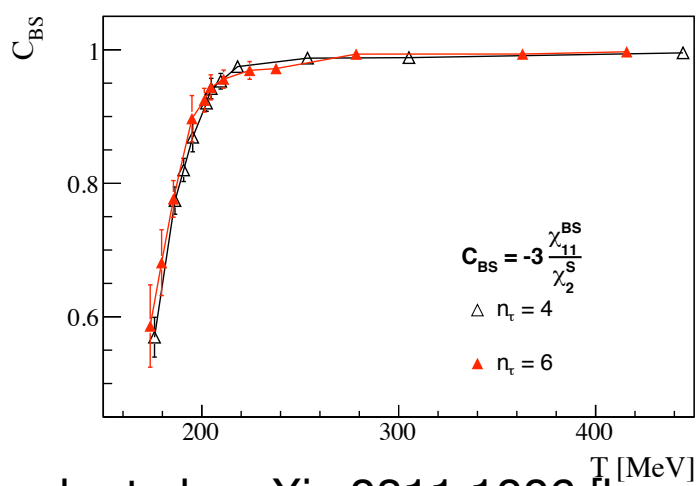
K/p Introduction

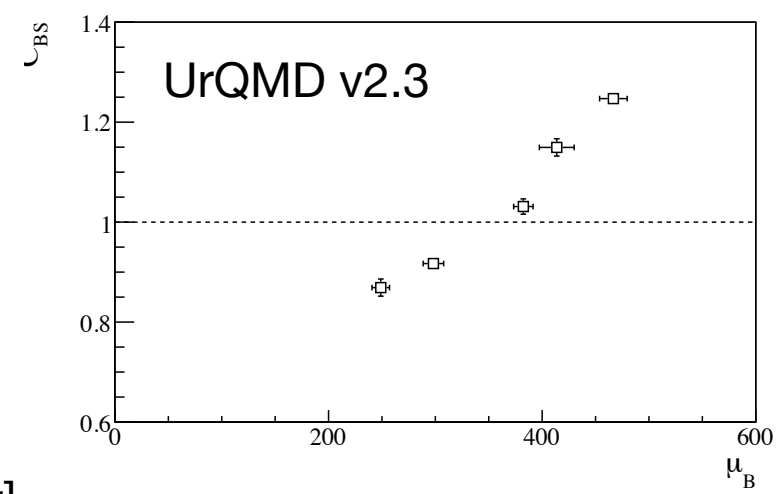
Koch, Majumder, Randrup
PRL 95 182301, 2005



$$C_{\rm BS} = -3\frac{\langle BS\rangle - \langle B\rangle\langle S\rangle}{\langle S^2\rangle - \langle S\rangle^2} = -3\frac{\chi_{11}^{\rm BS}}{\chi_2^{\rm S}}$$

- Suggested as "A Diagnostic of Strongly Interacting Matter"
  - QGP: strangeness is carried by strange quarks - Baryon Number and Strangeness are correlated
  - Hadron Gas: strangeness is carried by K and Λ - Baryon-Strangeness correlation changes with μ_B
  - Lattice QCD confirms phase transition effect at μ_B=0
  - Hadron gas behavior reproduced in UrQMD
  - Find measurable proxy: K/p





Cheng, Karsch et al.: arXiv:0811.1006 [hep-lat]

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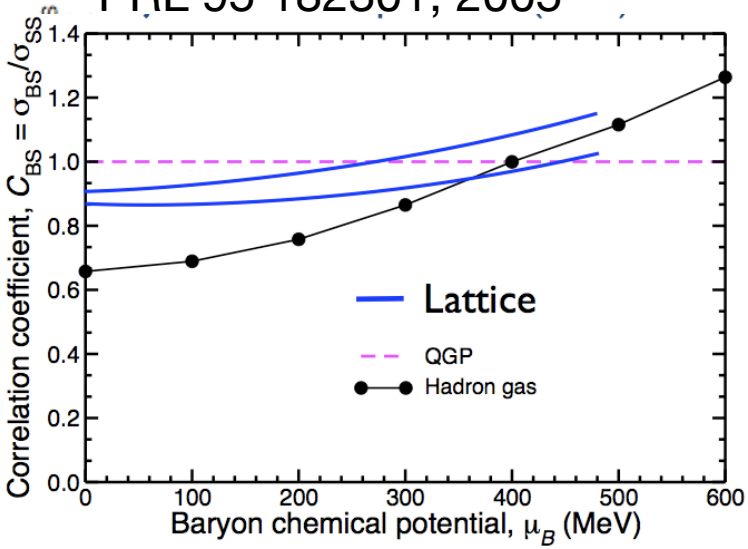

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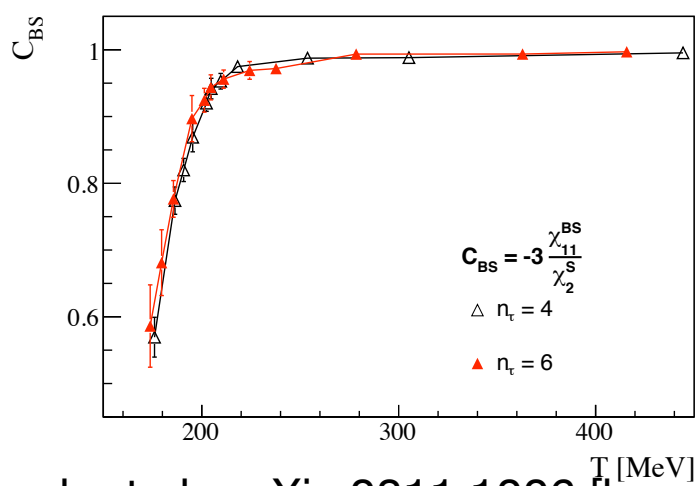

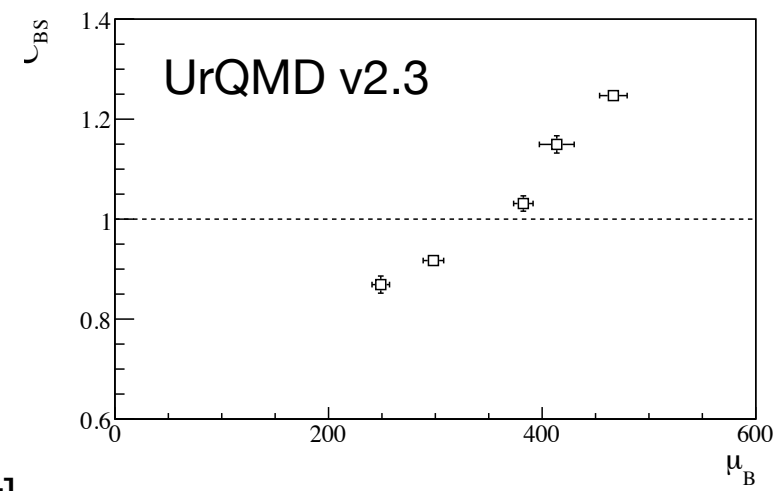

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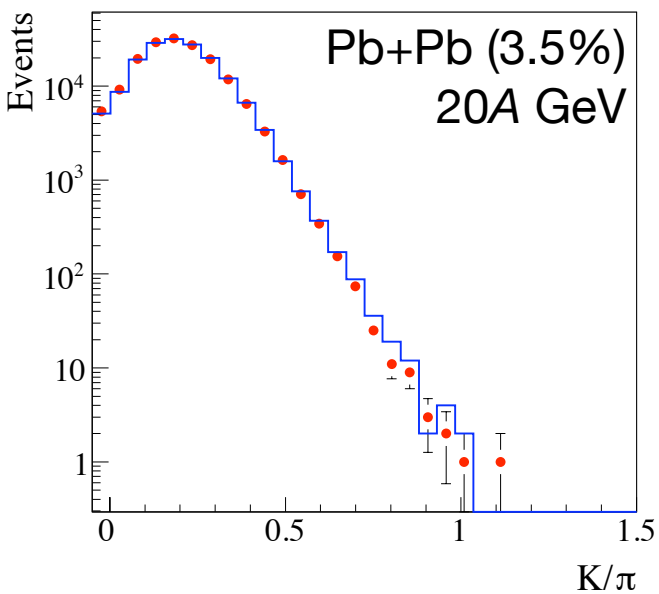
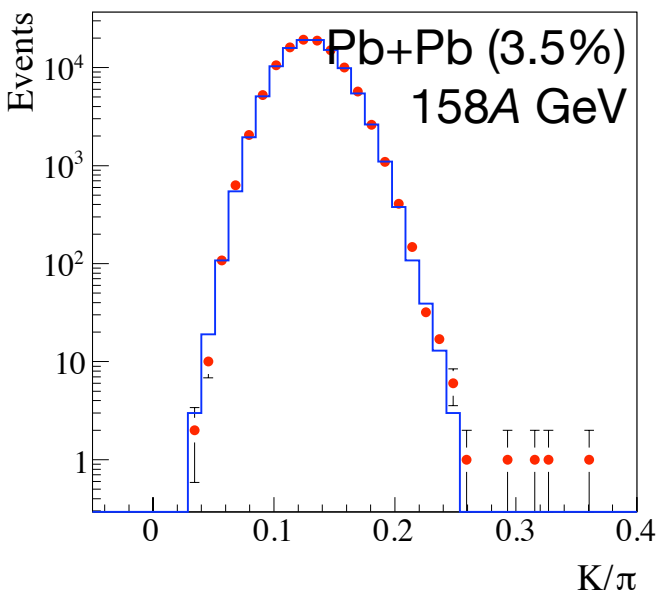
Introduction

- Extract event-by-event hadron ratios (e.g. K/π) from
  - real measured events (●)
  - mixed events (–)

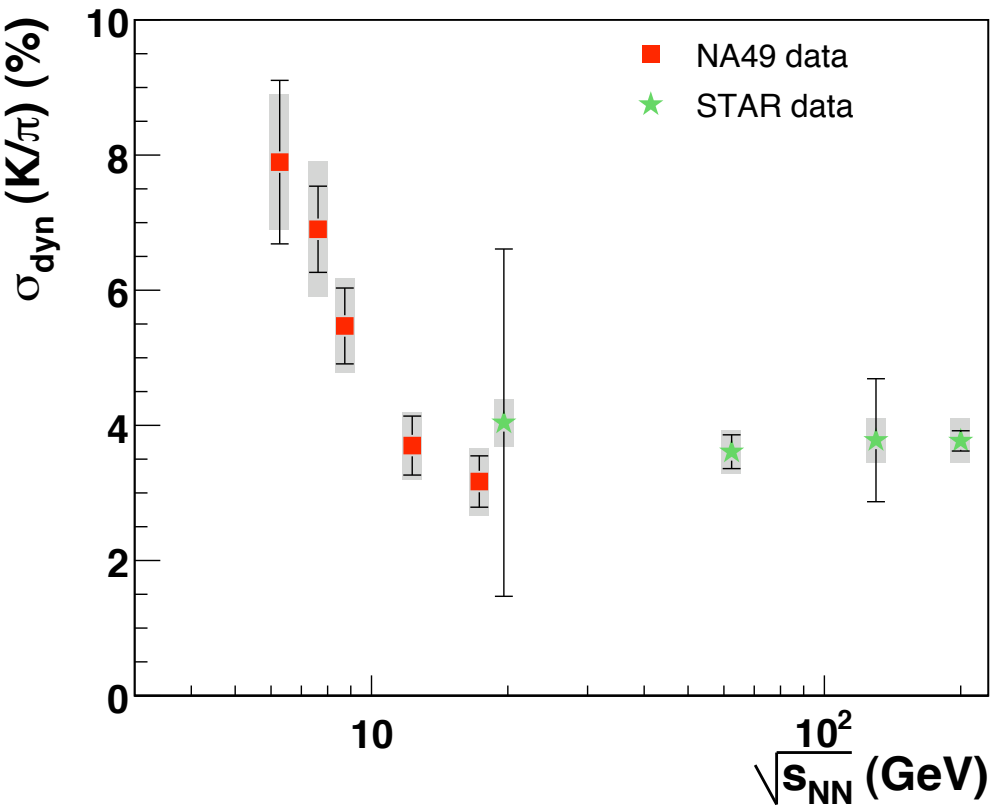




- Extract *dynamical* fluctuations as quadratic difference of relative widths:

$$\sigma^2_{\mathrm{dyn}} = \mathrm{sign}\left(\sigma^2_{\mathrm{data}} - \sigma^2_{\mathrm{mix}}\right)\sqrt{\left|\sigma^2_{\mathrm{data}} - \sigma^2_{\mathrm{mix}}\right|}$$

Ratio Fluctuations K/π Ratio

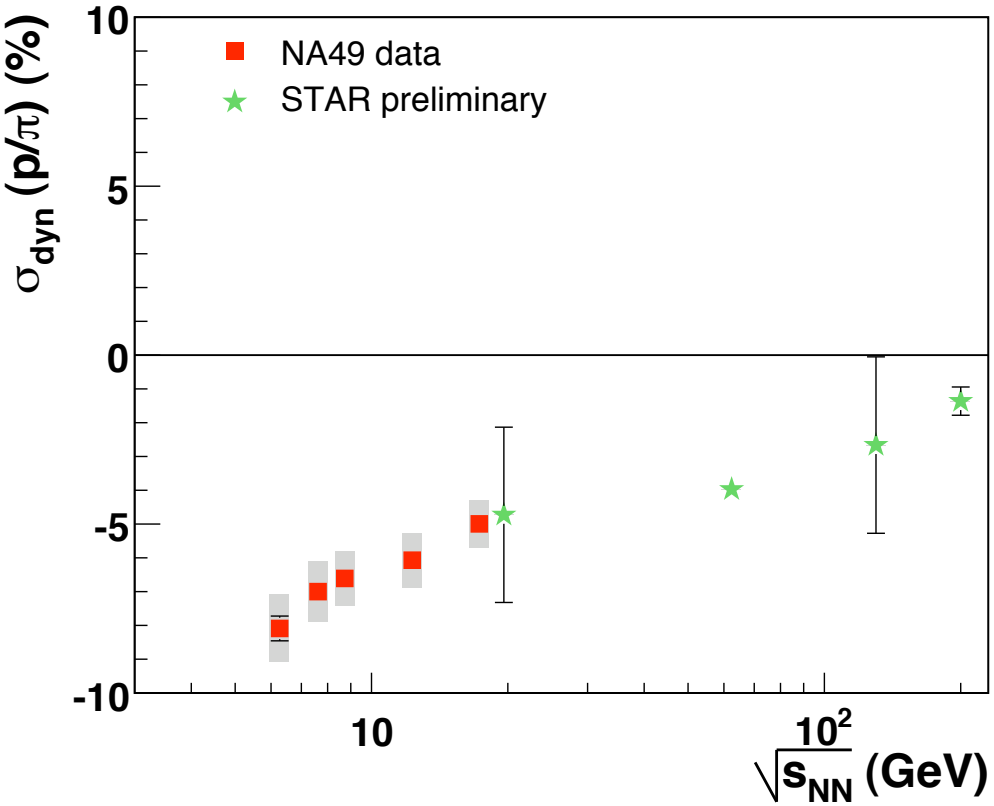


NA49: arXiv:0808.1237 [nucl-ex]
To appear in Phys. Rev. C

STAR: arXiv:0901.1795 [nucl-ex]
Submitted to Phys. Rev. Lett.

- K/π: Positive dynamical fluctuations
  - Dominated by kaon number fluctuations
  - Steep rise towards low SPS energies
  - No variation from top SPS energy to RHIC energy

Ratio Fluctuations p/π Ratio



- p/π: Negative dynamical fluctuations
  - Correlation due to resonance decay is dominant

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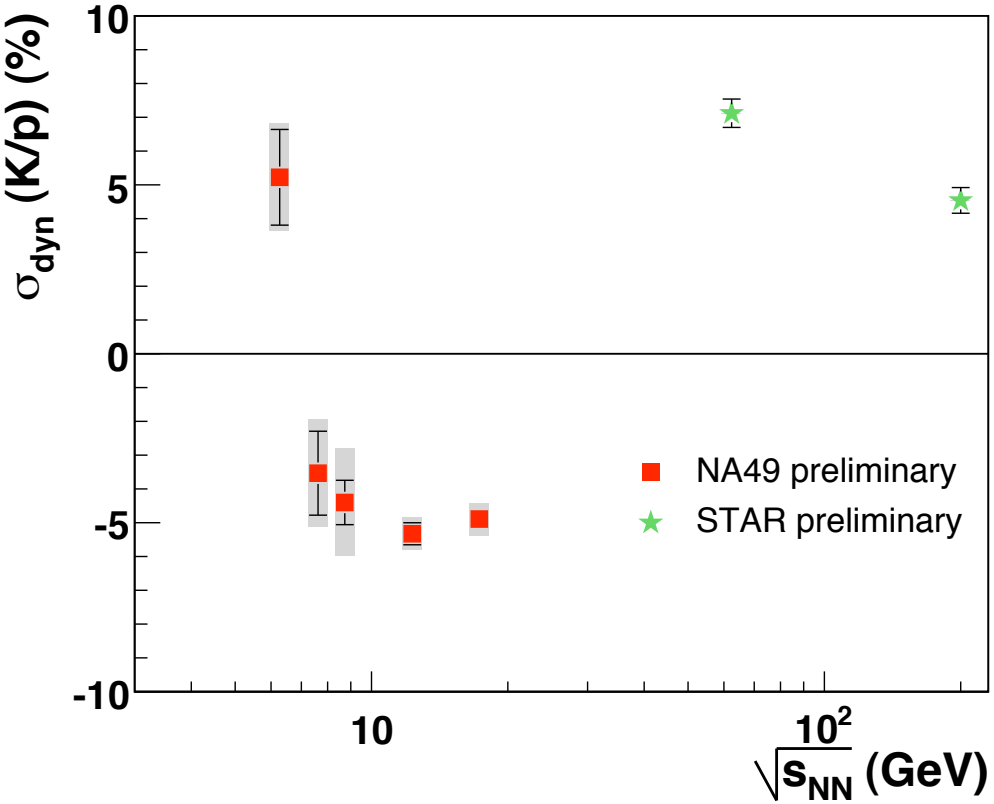
STAR: Quark Matter 2009 Poster

K/p Ratio



- K/p: Two sign changes
  - Negative plateau at higher SPS energies
  - Positive plateau at RHIC
  - Jump to positive values at 20*A* GeV

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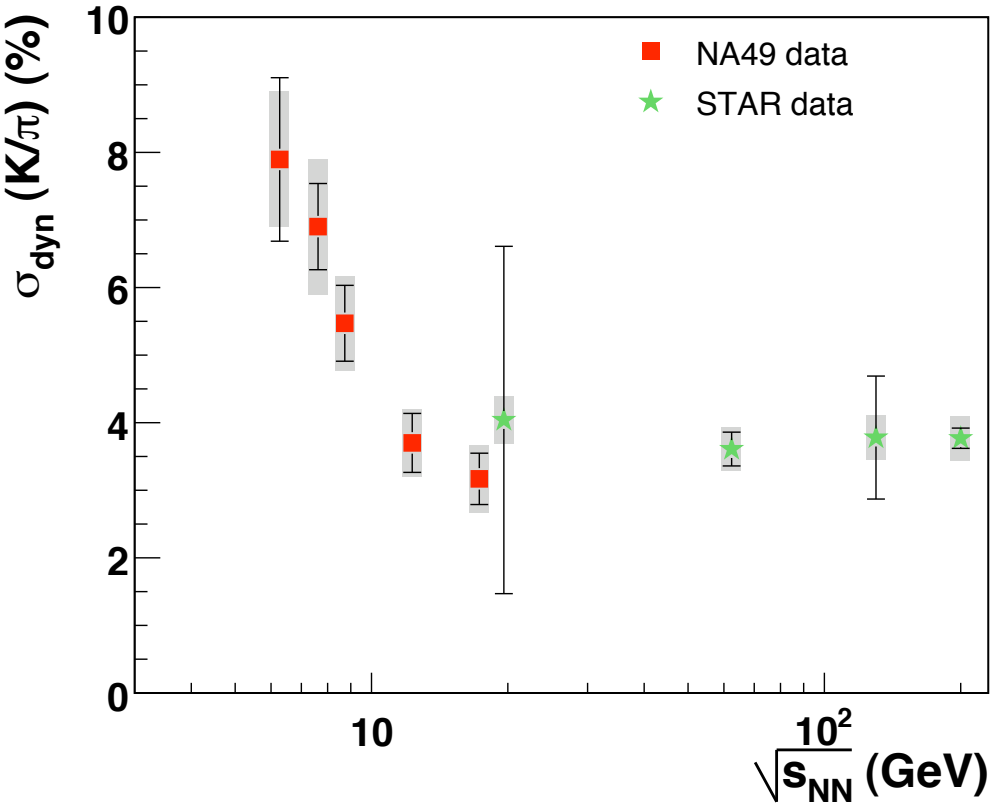
K/π: Transport Models



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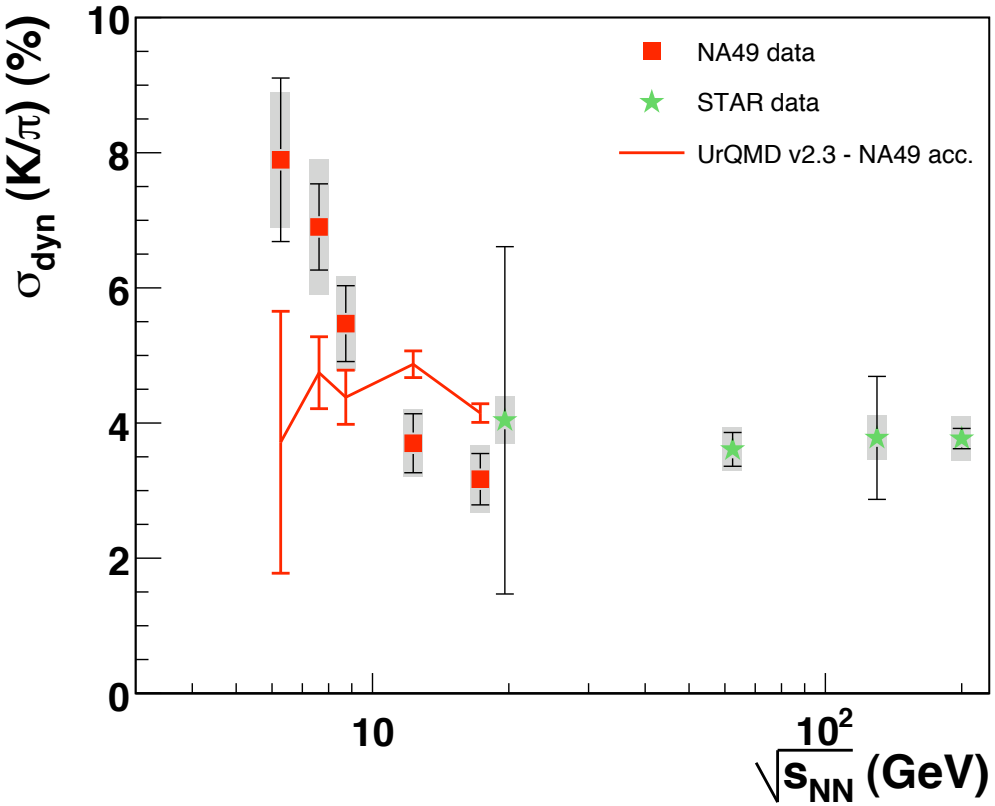

- K/π: Positive dynamical fluctuations
  - Rise towards low energies not reproduced by UrQMD

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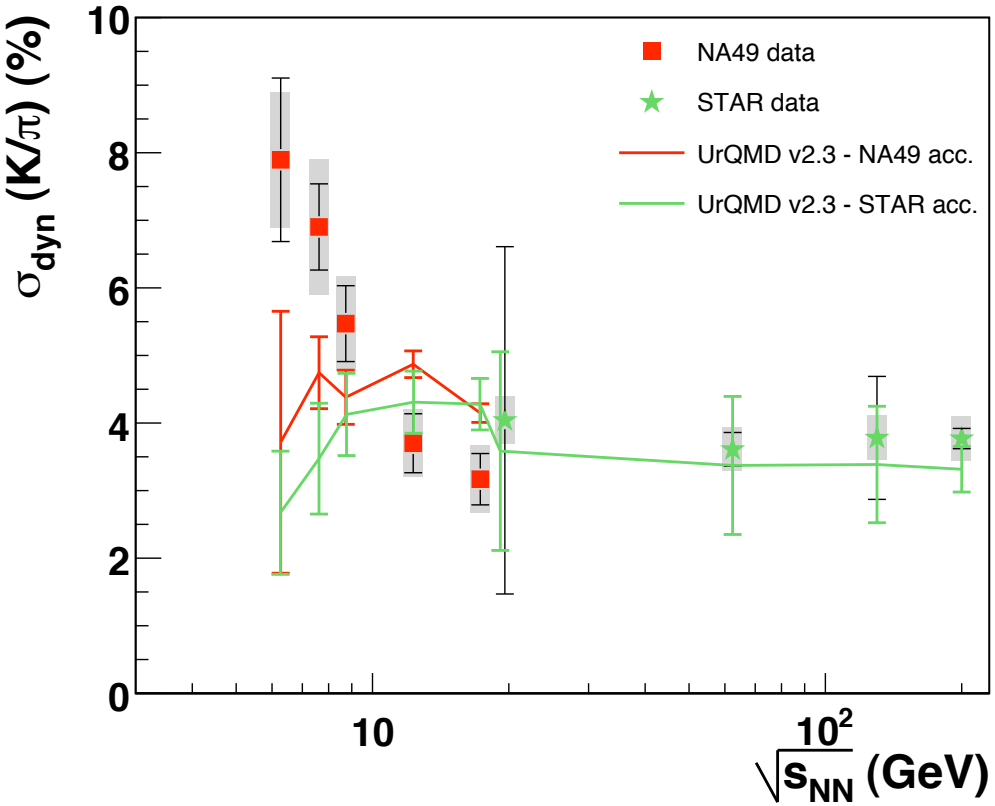

- K/π: Positive dynamical fluctuations
  - Rise towards low energies not reproduced by UrQMD
  - No large acceptance effect

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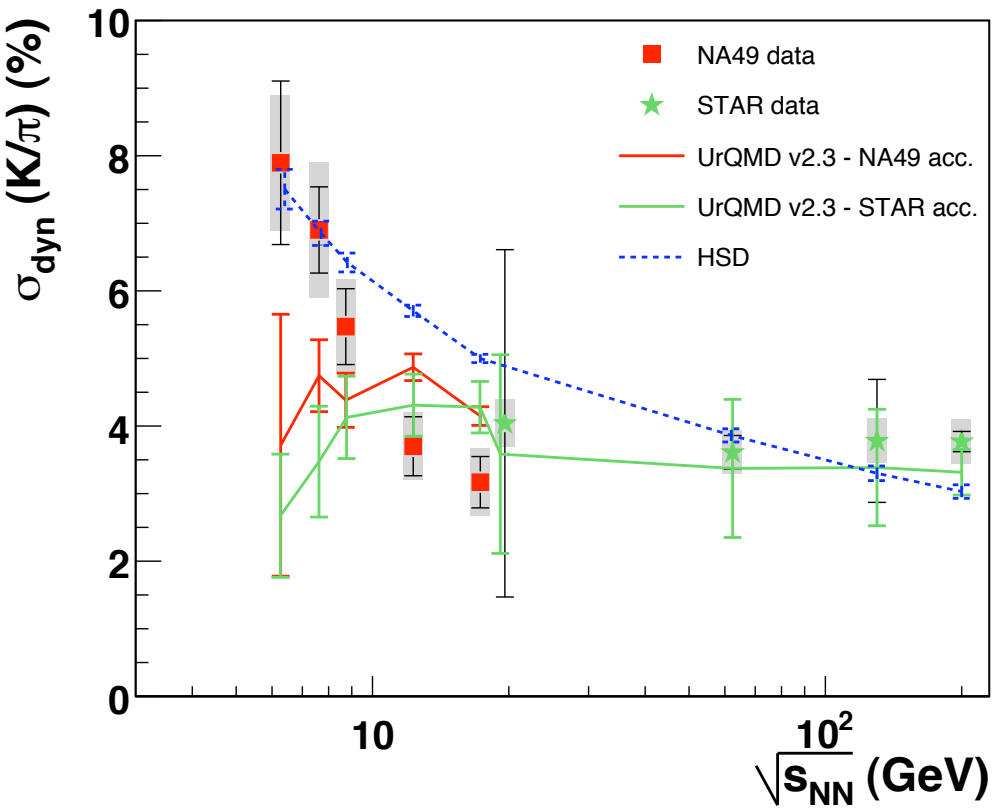

- K/π: Positive dynamical fluctuations
  - Rise towards low energies not reproduced by UrQMD
  - No large acceptance effect
  - HSD catches trend, fails high SPS data see talk by V. Konchakovski for details

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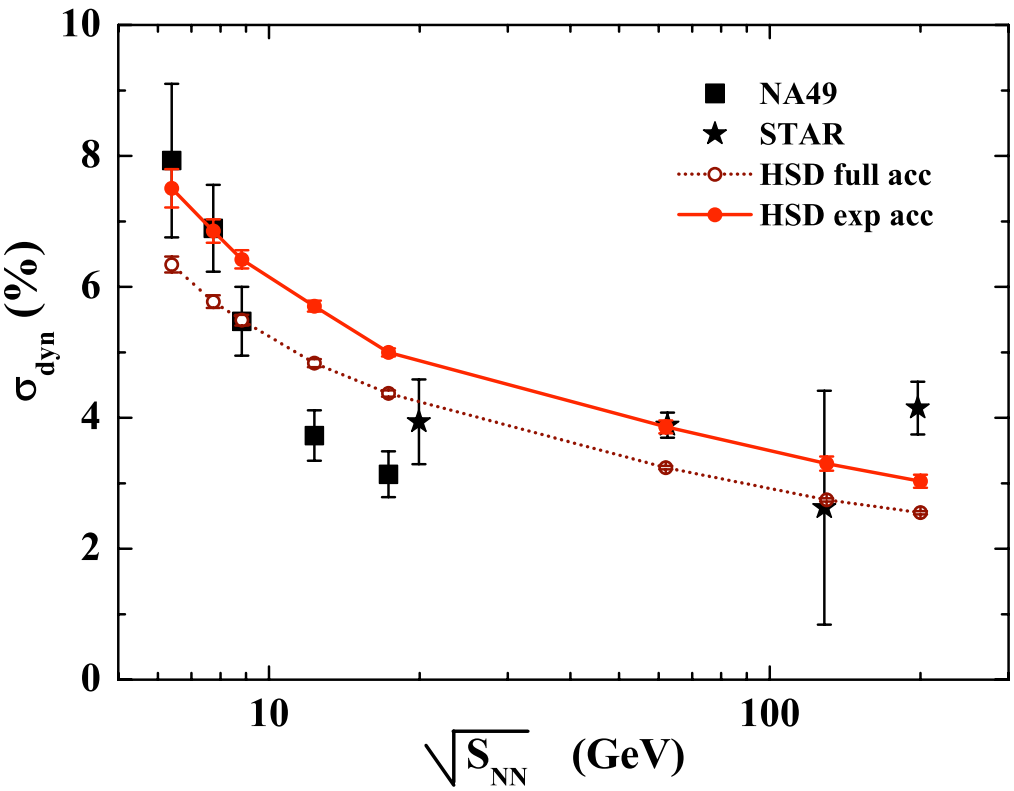
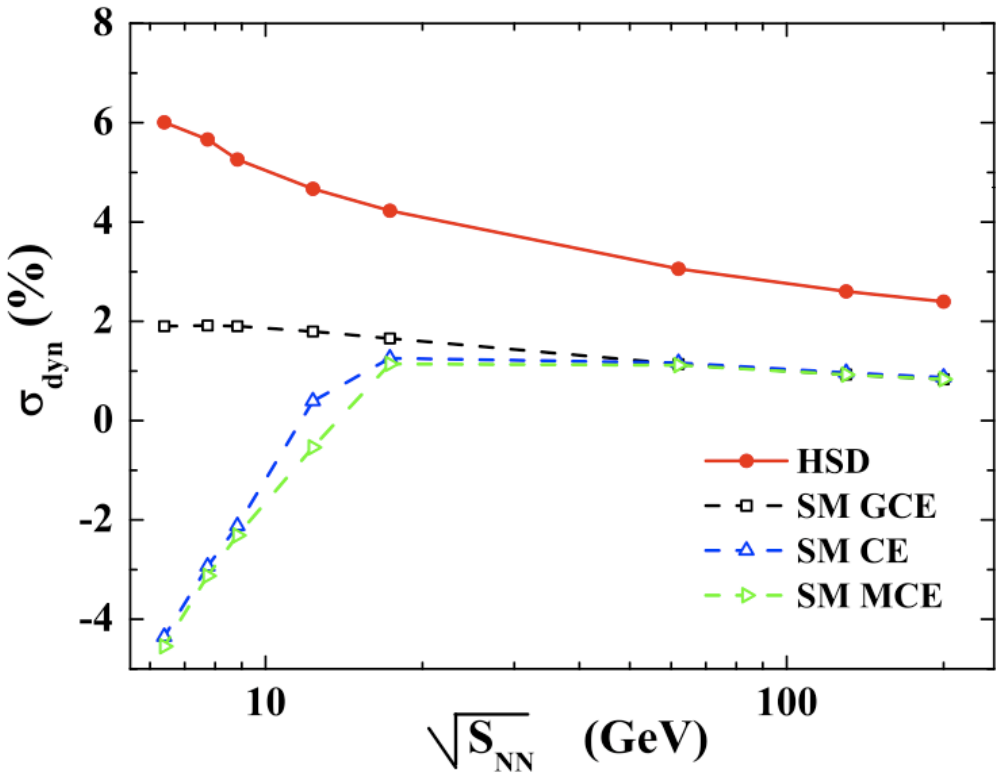
K/π: Discussion

- Statistical model and HSD comparison
  → see talk by V. Konchakovski for details





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K/π: Discussion

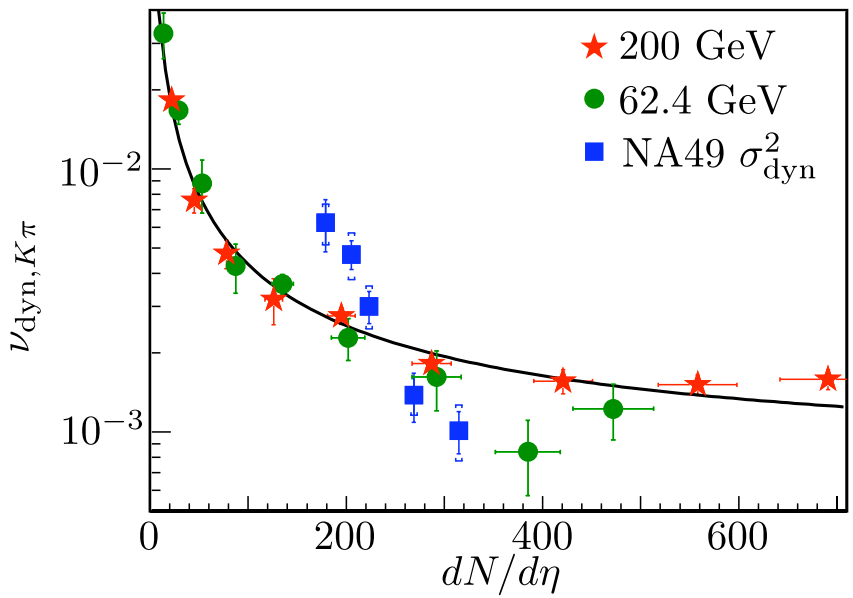
- Scaling behaviours?
  - Different energies show a common dN/dη scaling at RHIC

$$\nu_{\mathrm{dyn}} = \sigma^2_{\mathrm{dyn}} \propto 1/\frac{\mathrm{d}N}{\mathrm{d}\eta}$$

  - Central NA49 data still show a deviation from this scaling - Effect of changing acceptance?
  - NA49 data scales when using multiplicities *in acceptance*: V. Koch, e.g. kaons

$$\sigma_{\mathrm{dyn}} \propto \frac{1}{\sqrt{\langle K \rangle}}$$

  - UrQMD results don't scale



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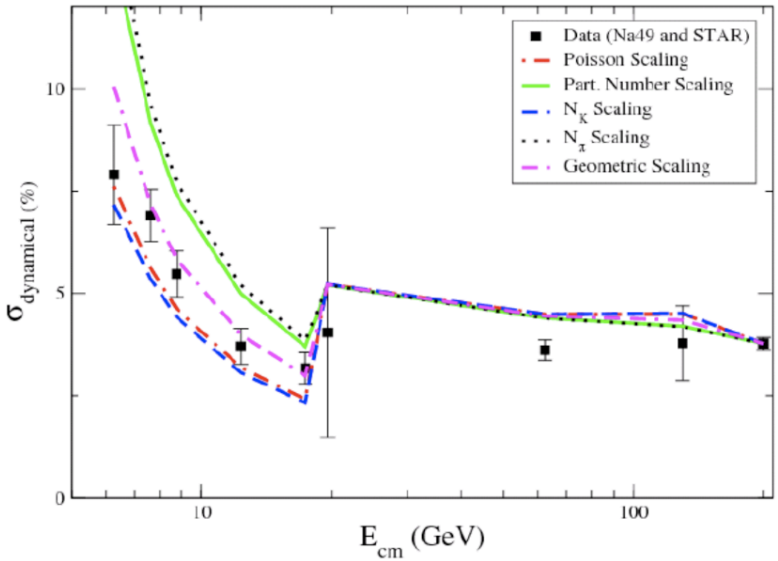
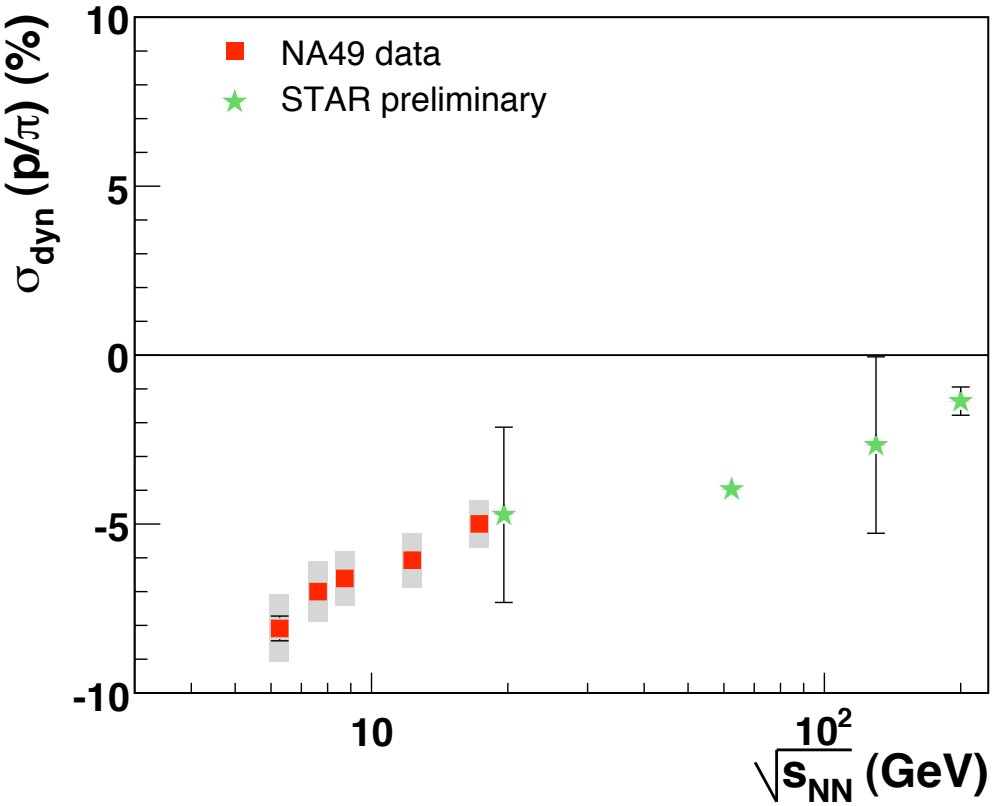


V. Koch: this workshop

- Contradicting interpretations - K/π fluctuations remain interesting!

- New NA49 results on centrality dependence of K/π fluctuations → see talk by D. Kresan for details

p/π: Transport Models



- p/π: Negative dynamical fluctuations
  - SPS energies explained in UrQMD
  - Discrepancy at RHIC

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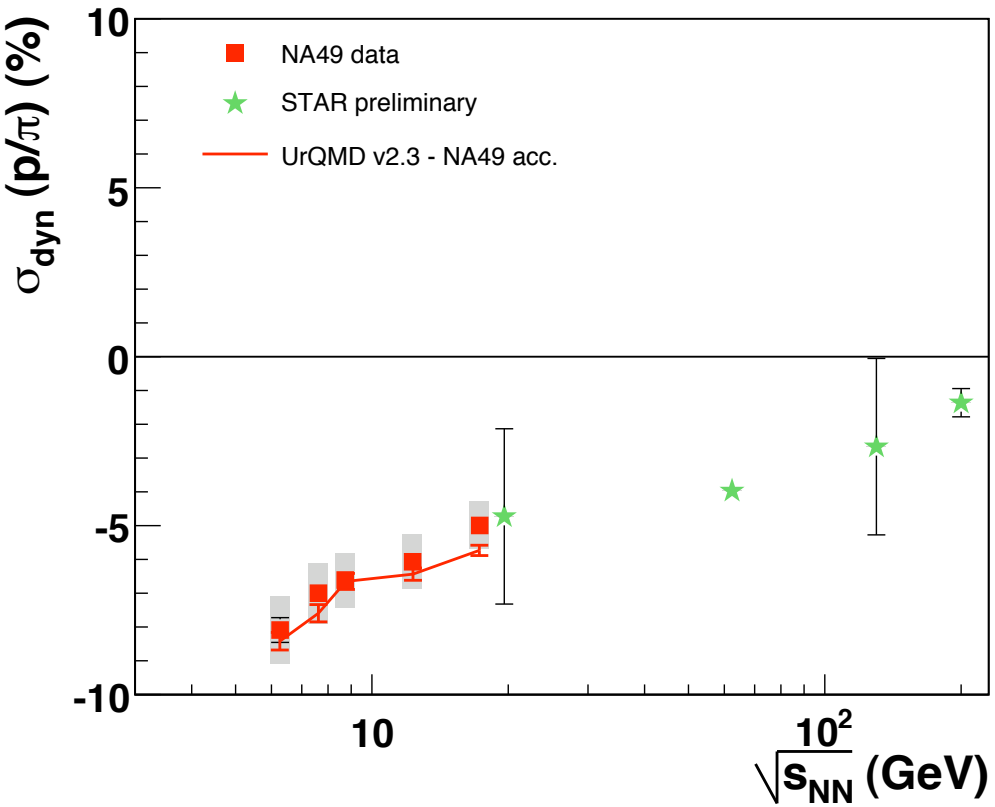

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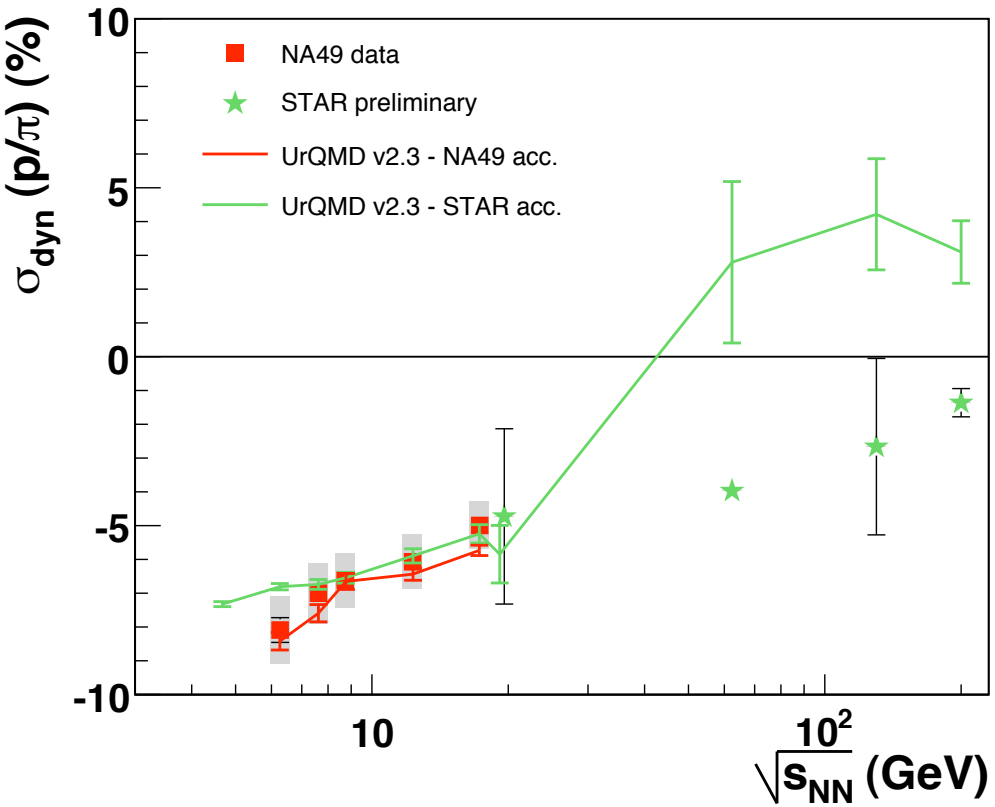

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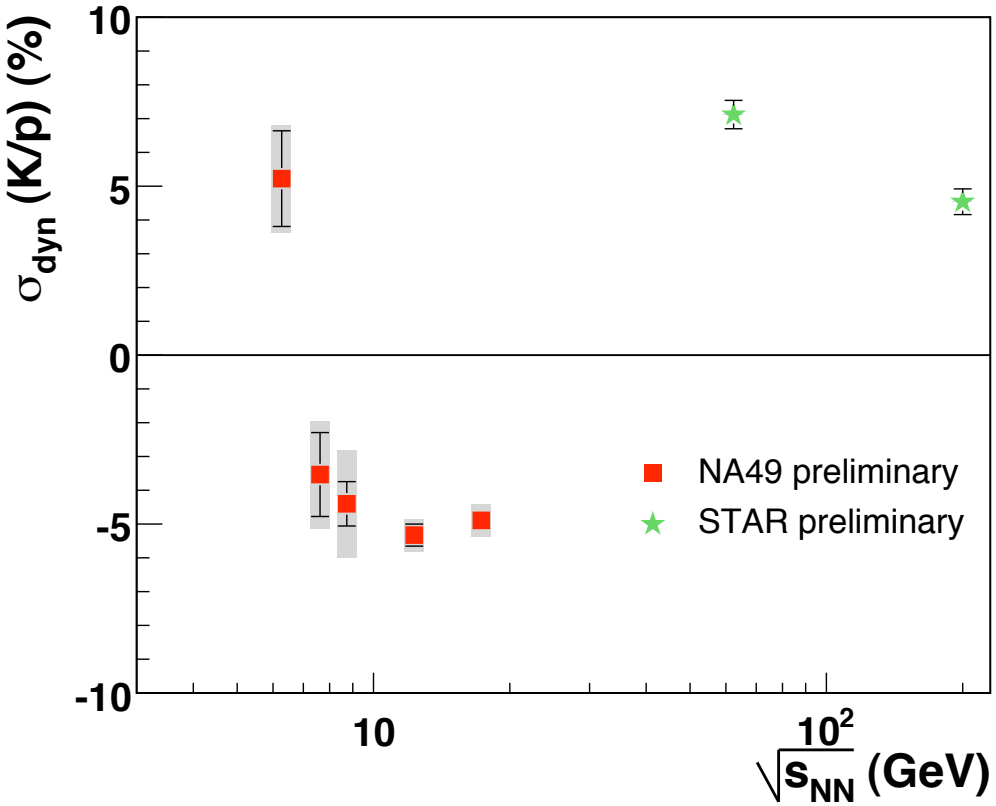

- K/p: Two sign changes
  - High SPS data reproduced in model
  - RHIC data as well
  - Jump between SPS and RHIC is not due to acceptance!
  - Jump at 20*A* GeV not described

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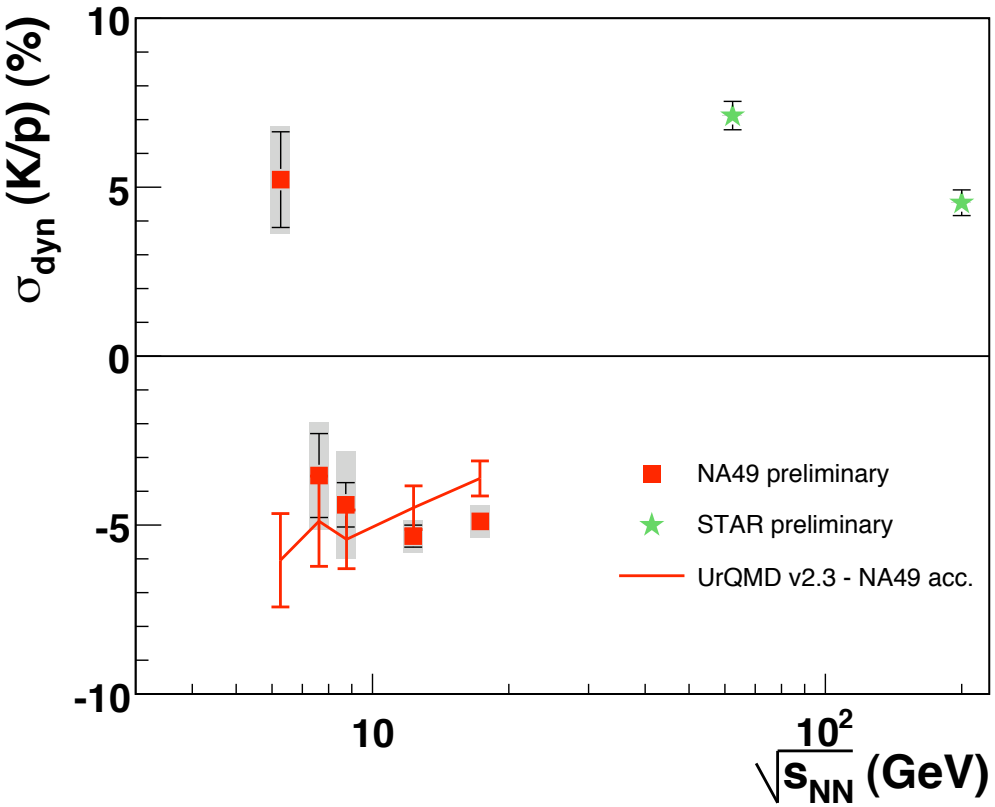

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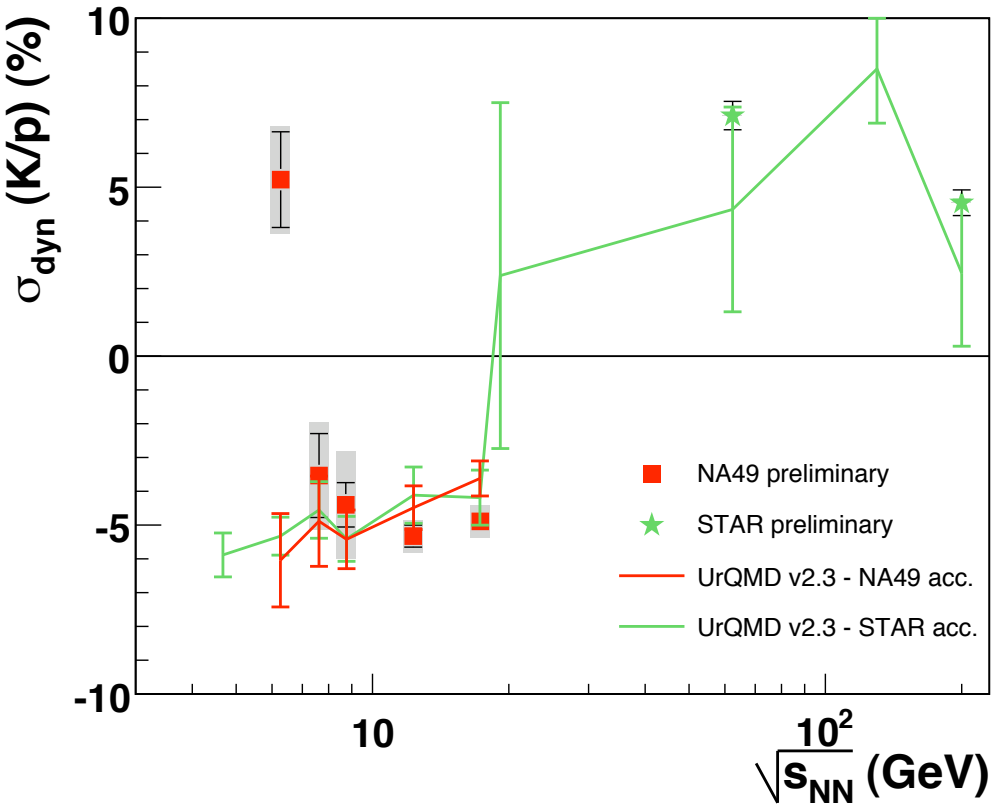

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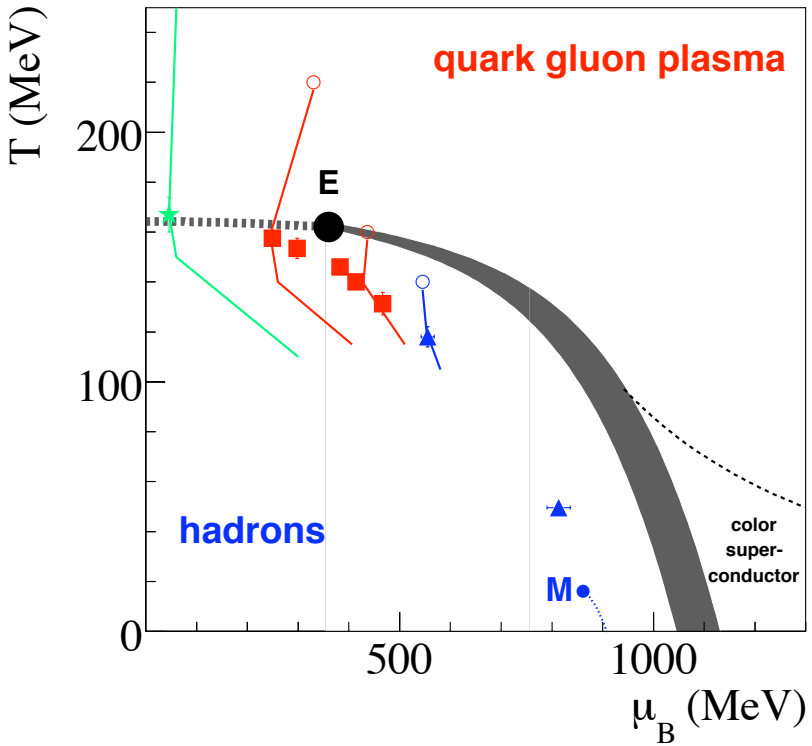
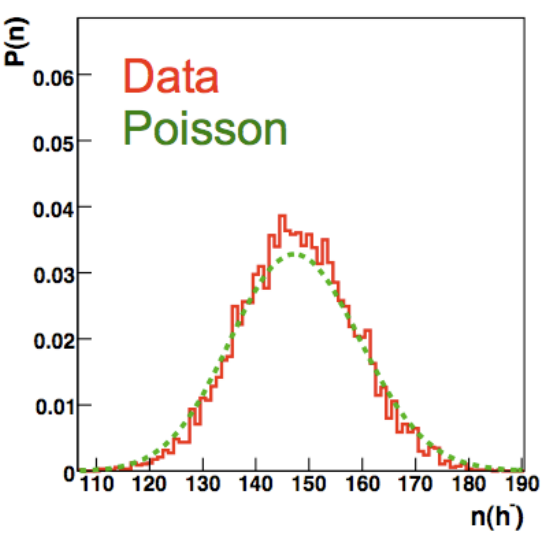
Introduction

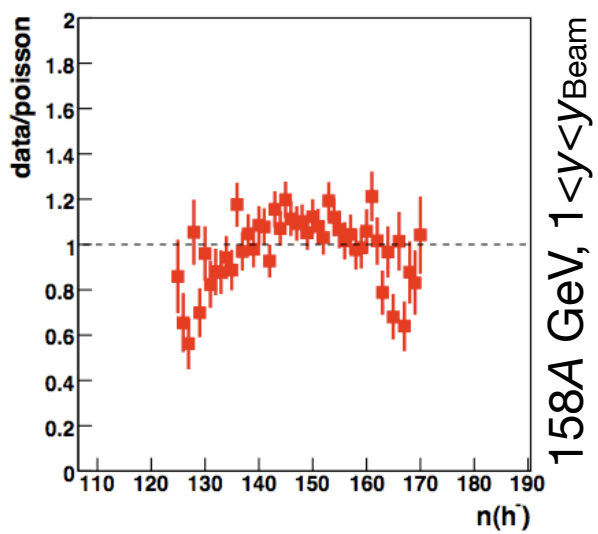
- SPS energies: Freeze-out close to conjectured phase boundary and critical point
- Strong fluctuations of the chiral condensate at the critical point should be reflected in the pion number and $\langle p_T \rangle$ fluctuations
  (Stephanov, Rajagopal, Shuryak, Phys. Rev. D60: 114028, 1999)
- Compare fluctuation measures to the estimated critical point effect

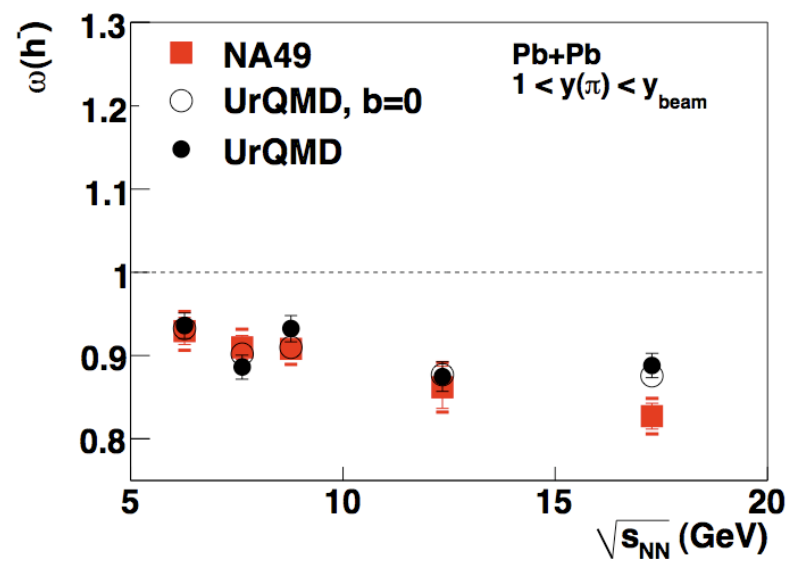


N Fluctuations

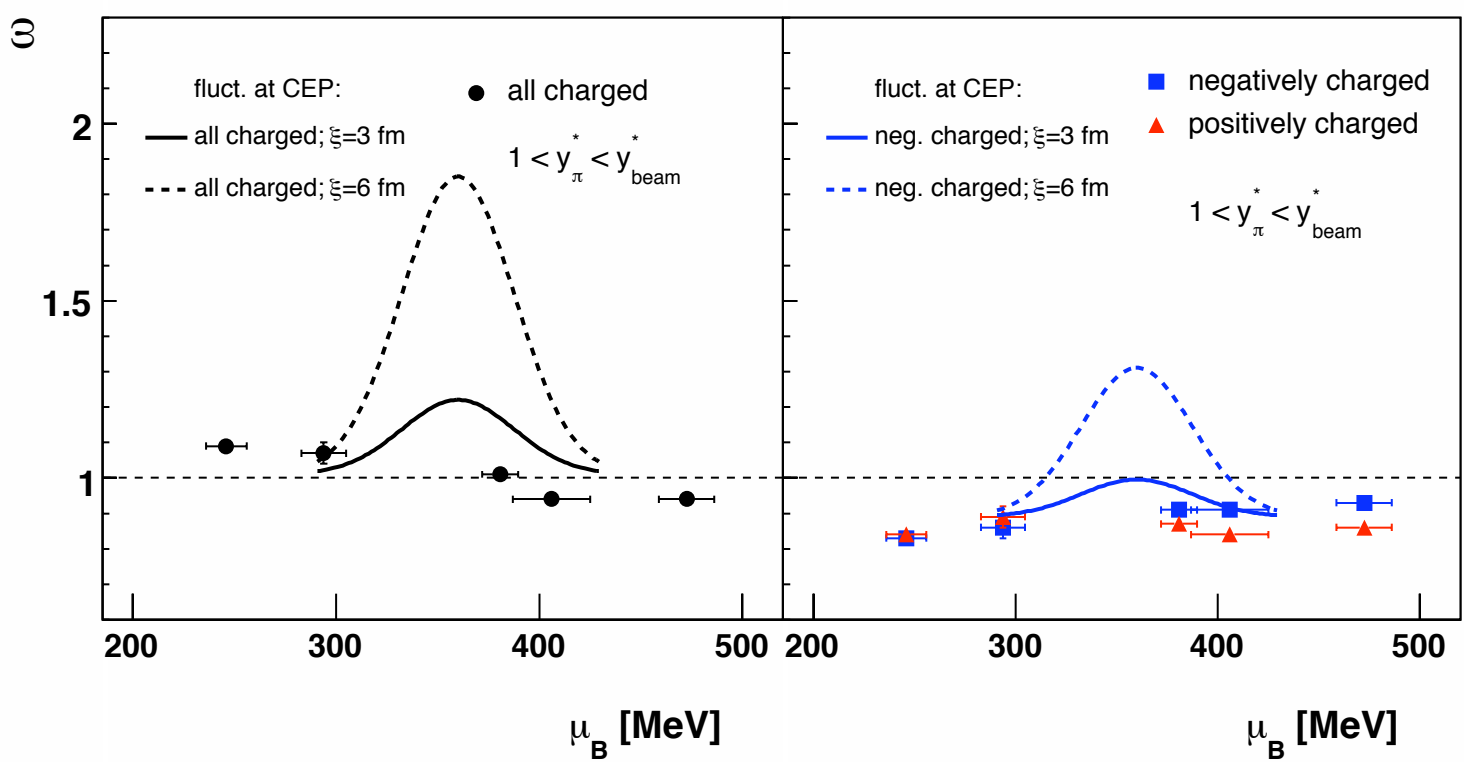
- *N* is an extensive quantity!
  - Avoid volume fluctuations: Strict centrality selection: 1%
- Measure used in NA49: scaled variance, $\omega = \frac{\mathrm{Var}(n)}{\langle n \rangle} = \frac{\langle n^2 \rangle - \langle n \rangle^2}{\langle n \rangle}$
  - Measured width compared to Poissonian
  - h-: data narrower than Poisson, ω < 1
  - Energy dependence: Trend reproduced by UrQMD







Critical Point *N* Fluctuations



NA49 data:
Phys. Rev. C79: 044904, 2009

μ_B from hadron gas fit:
F. Becattini et al,
Phys. Rev. C73: 044905, 2006

Amplitude of effect:
Stephanov, Rajagopal, Shuryak,
Phys. Rev. D60: 114028, 1999
and private communication

Position of critical point:
Z. Fodor and S. Katz,
JHEP 0404, 050, 2004

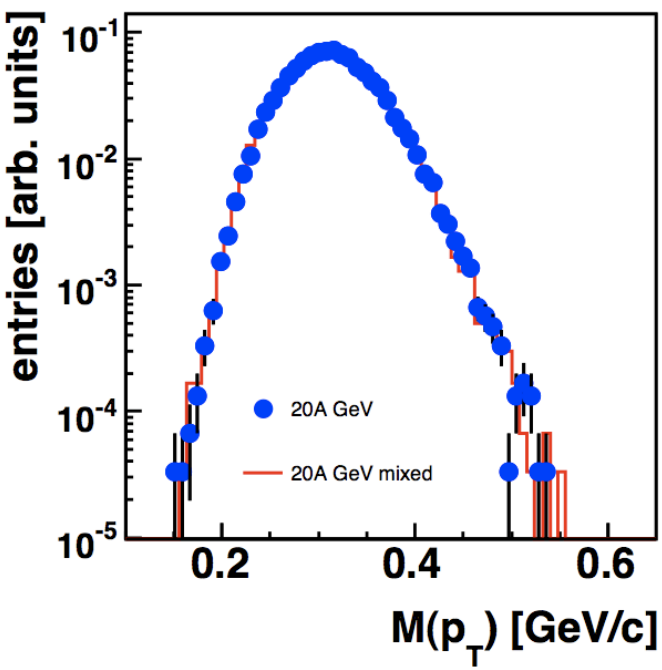
Width of critical point:
Y. Hatta and T. Ikeda,
Phys. Rev. D67: 014028, 2003

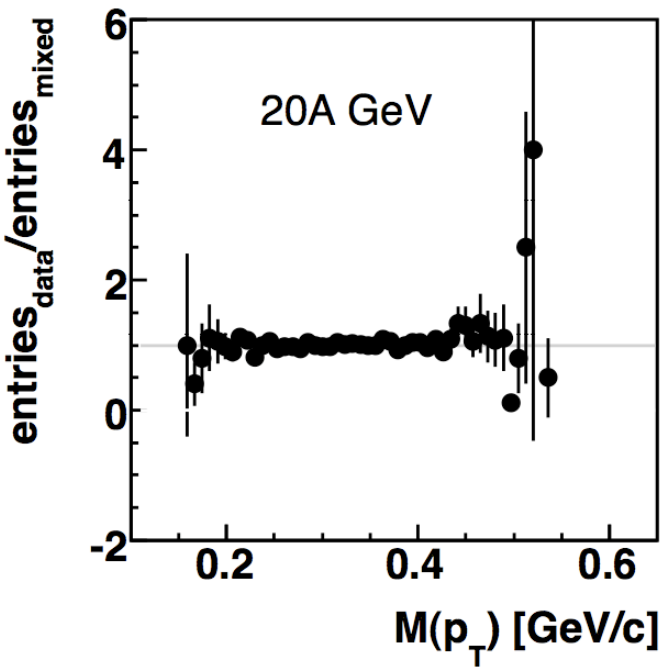
<p_T> Fluctuations

- Fluctuation measure:

$$\Phi = \sqrt{\frac{\langle Z^2 \rangle}{\langle N \rangle}} - \sqrt{\overline{z^2}} \qquad \left(Z = \sum_{i=1}^{N} (x_i - \overline{x}) \, , \qquad z = x - \overline{x} \right)$$

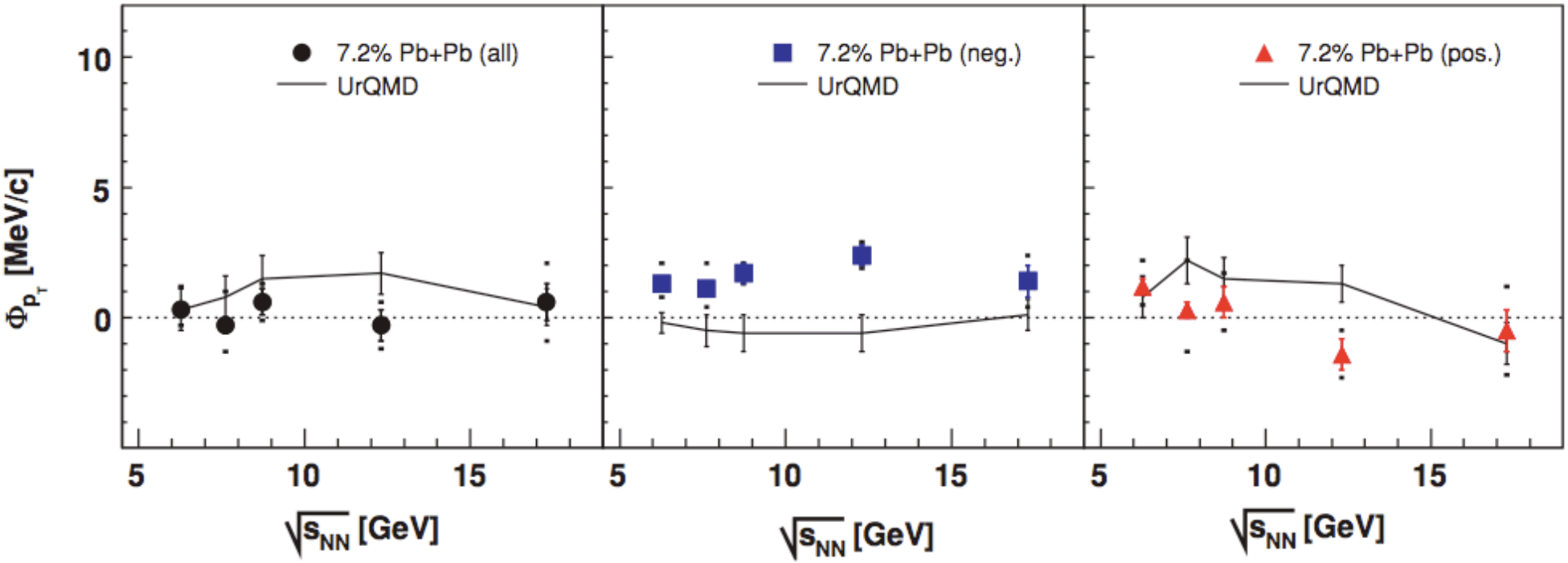
  - Φ = 0 for independent particle production
  - independent of volume and multiplicity fluctuations





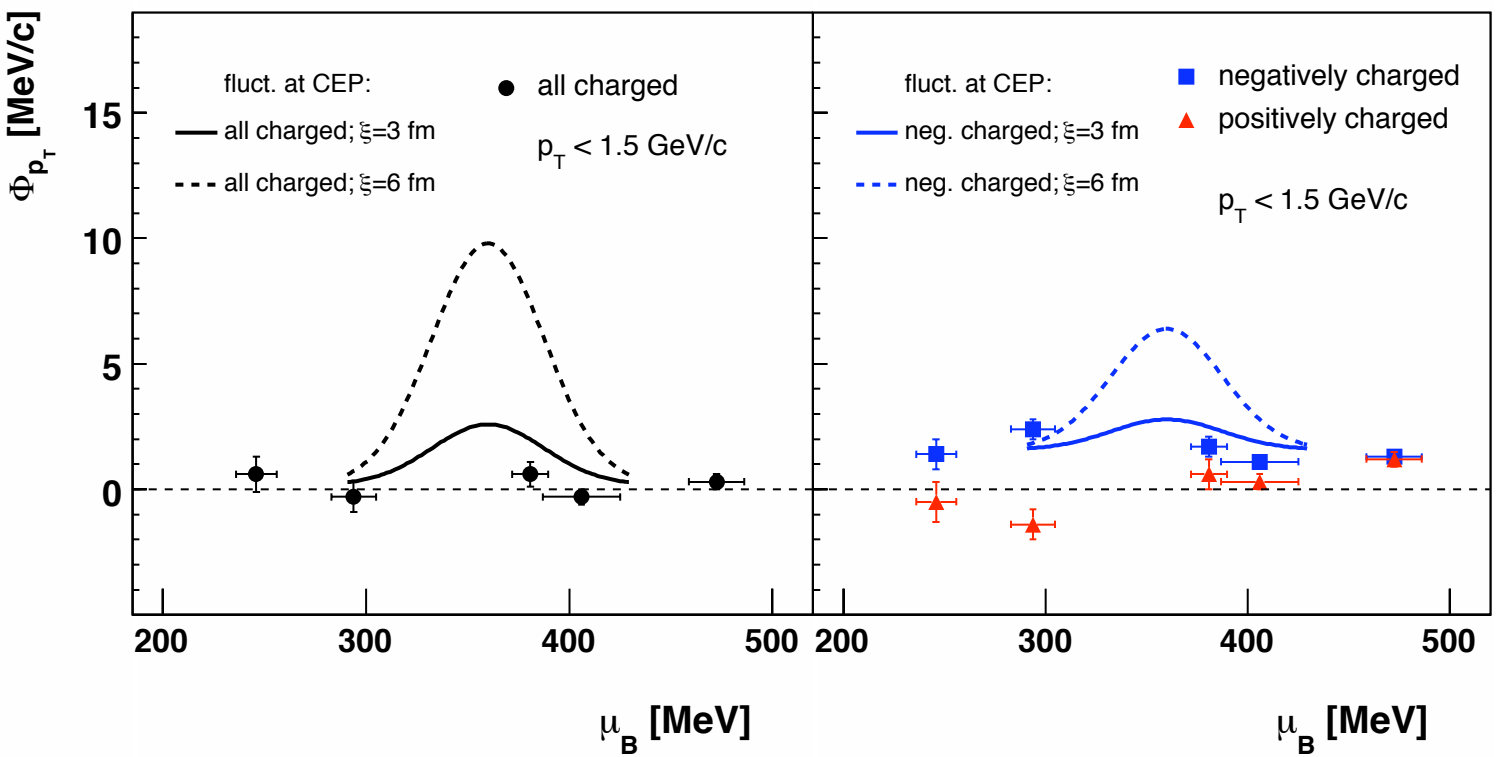
$<p_T>$ Fluctuations

- Flat energy dependence, reproduced by UrQMD



NA49 data:
Phys. Rev. C79: 044904, 2009

Critical Point <p_T> Fluctuations



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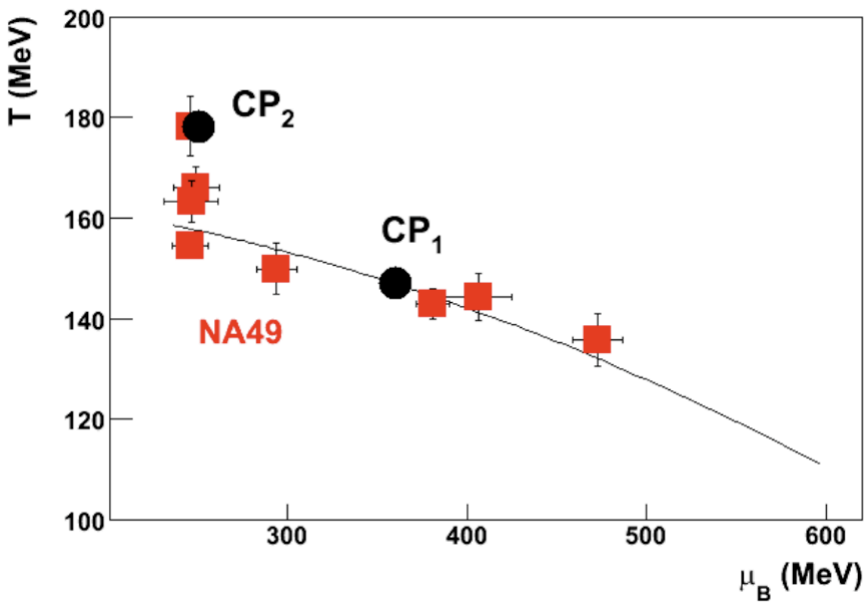
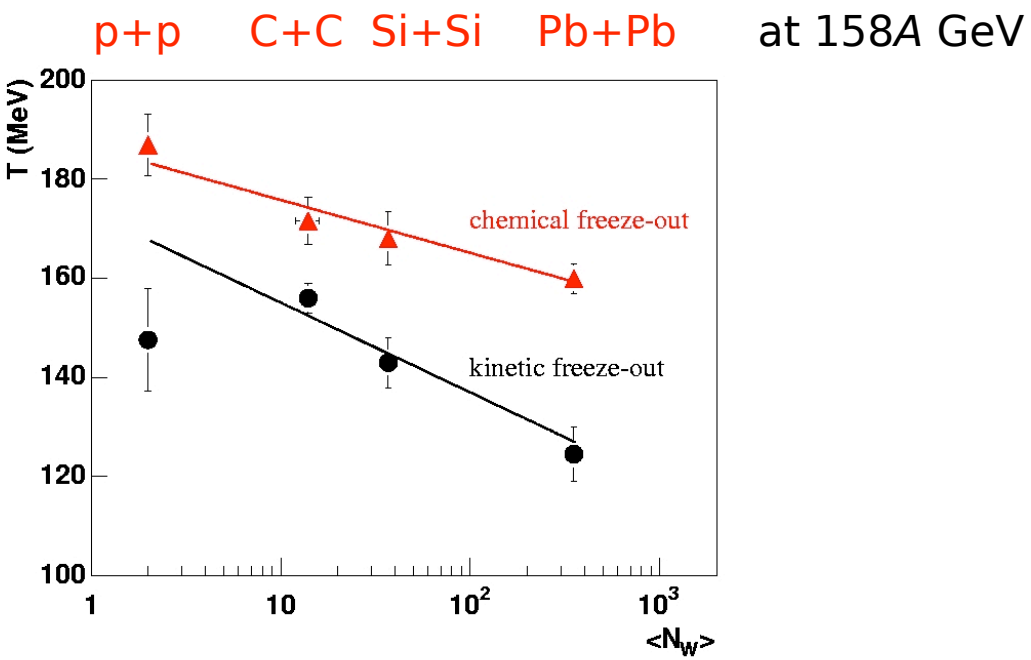
System size dependence



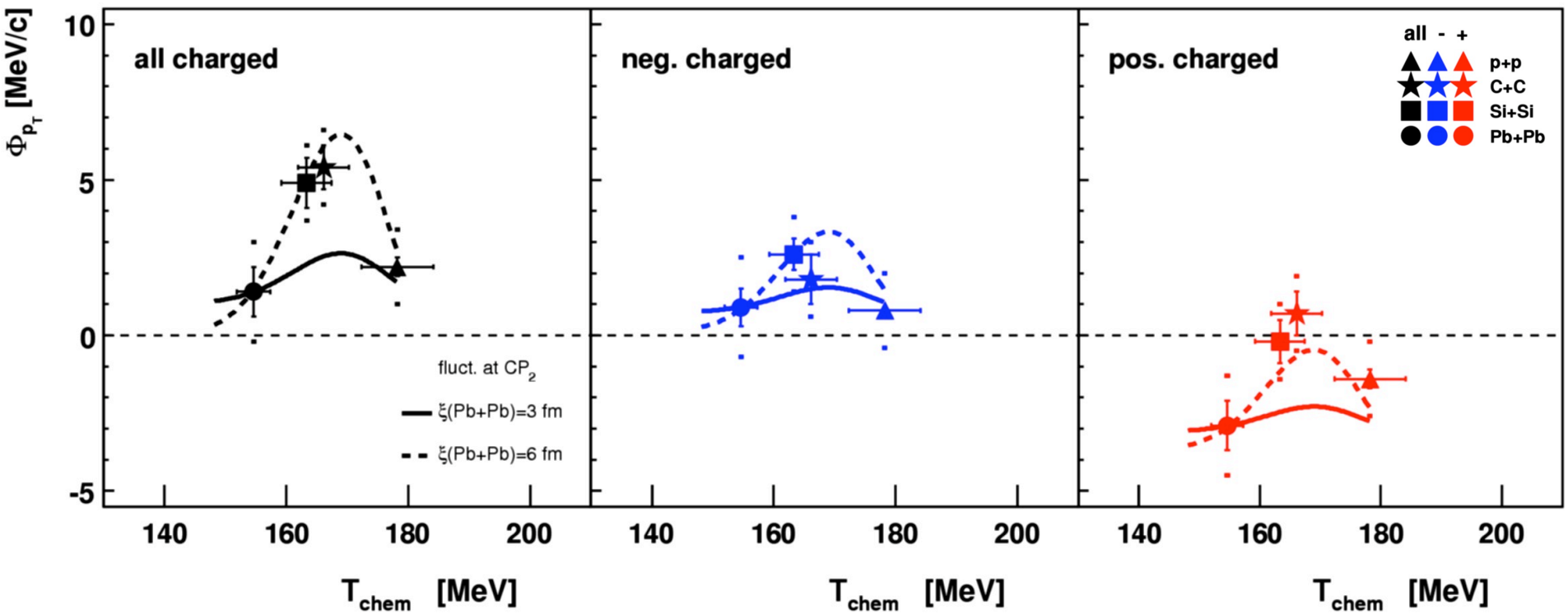


Becattini et al., Phys. Rev. C 73, 044905

- Small systems freeze out at higher temperatures:
  - Chemical and kinetic freeze-out temperatures decrease with increasing system size
- A 2-D scan (T,μ_B) is possible by varying (A,$\sqrt{s}$)
- System size limits correlation length in small systems

System size dependence at 158A GeV
→ Average p_T fluctuations (PR**C70**, 034902, 2004)

CP_2 location:
$\mu_B(CP_2) \cong 250$ MeV = μ_B (A+A at 158A GeV)
$T(CP_2) = 178$ MeV = T_{chem} (p+p)



CP_2 predictions (curves) normalized to reproduce Φ_{PT} value for central Pb+Pb collisions

→ Maximum of Φ_{PT} observed for C+C and Si+Si
→ Increase ~ two times larger for all charged than for negatively charged particles

Data are consistent with the CP_2 predictions

(K. Grebieszkow, QM2009)

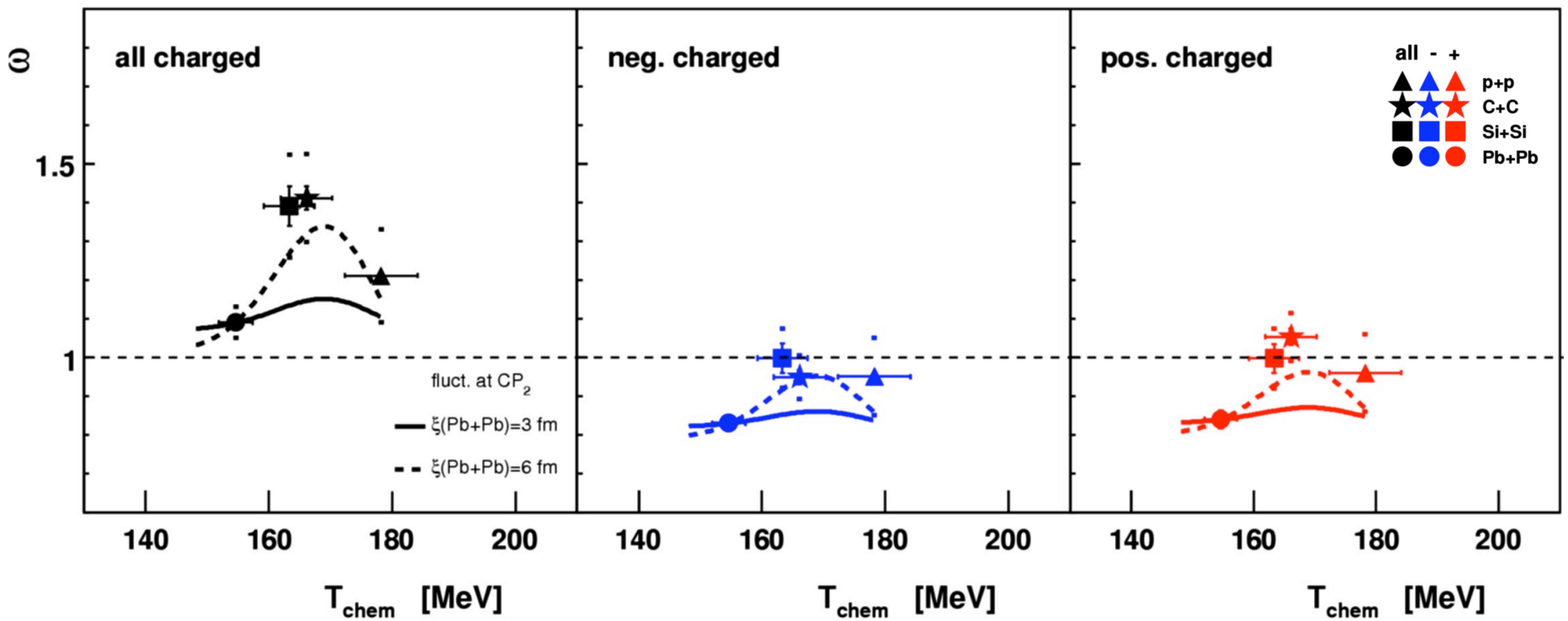
System size dependence at 158A GeV
→ Multiplicity fluctuations

(p+p - PR**C75**, 064904 (2007); Pb+Pb - PR**C78**, 034914 (2008); C+C, Si+Si - B. Lungwitz, PhD thesis)

CP_2 location:

$\mu_B(CP_2) \cong 250$ MeV = μ_B (A+A at 158A GeV)

$T(CP_2) = 178$ MeV = T_{chem} (p+p)



CP_2 predictions (curves) normalized to reproduce ω value for central Pb+Pb collisions

→ Maximum of ω observed for C+C and Si+Si
→ Increase ~ two times larger for all charged than for negatively charged particles

Data are consistent with the CP_2 predictions

(K. Grebieszkow, QM2009)

NA49 Fluctuation Results

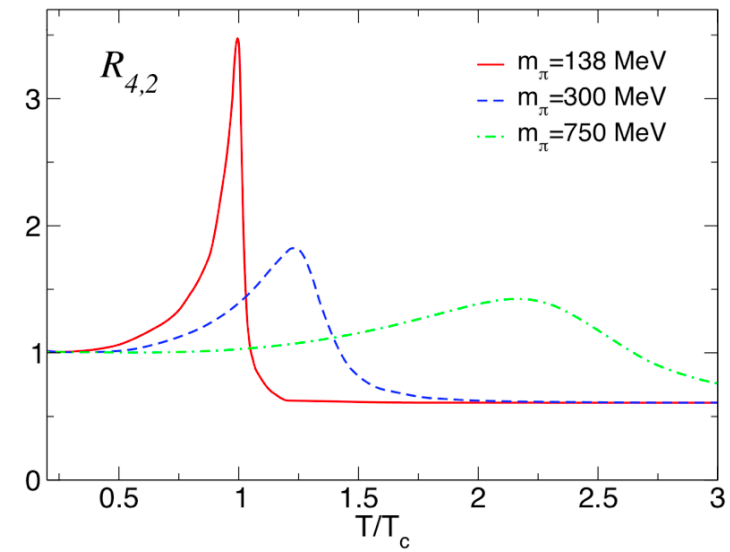
- Energy dependence of hadron ratio fluctuations
  - p/π: Understood in terms of resonance decay and reproduced by hadronic models
  - K/π: Contradicting interpretations - remains interesting!
  - K/p: Non-trivial excitation function - not easy to model
- Critical point effects on fluctuations
  - Central Pb+Pb energy scan:
    Multiplicity and $\langle p_T \rangle$ fluctuations show no enhancement at SPS energies
  - System Size dependence:
    Enhanced fluctuations in smaller systems
  - Estimated critical point effect is parameter dependent

Higher Moments: Kurtosis

- Critical point effect
  - Higher moments are more sensitive to diverging sigma field:

    $$\langle N^2 \rangle \propto \xi^2, \quad \langle N^4 \rangle \propto \xi^7$$

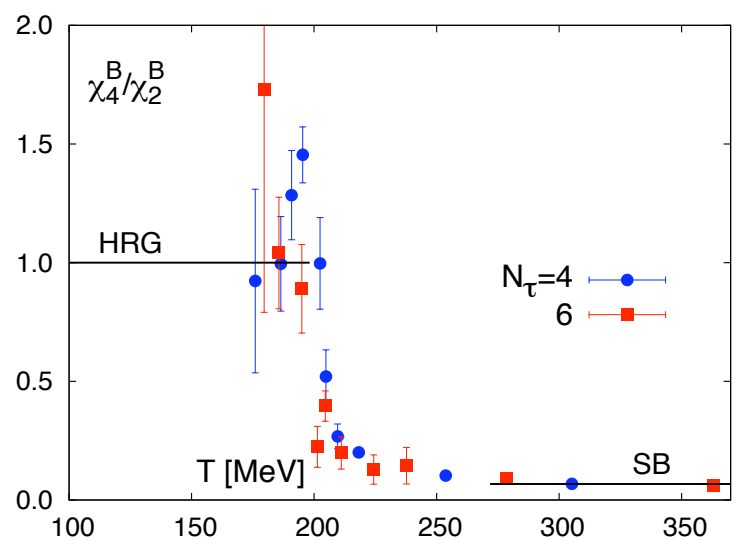
    (Stephanov: PRL 102, 032301 (2009))
  - Divergence should be reflected in net baryon and net proton kurtosis
  - Divergence of kurtosis confirmed in chiral model



arXiv: 0809.3129 [hep-ph]

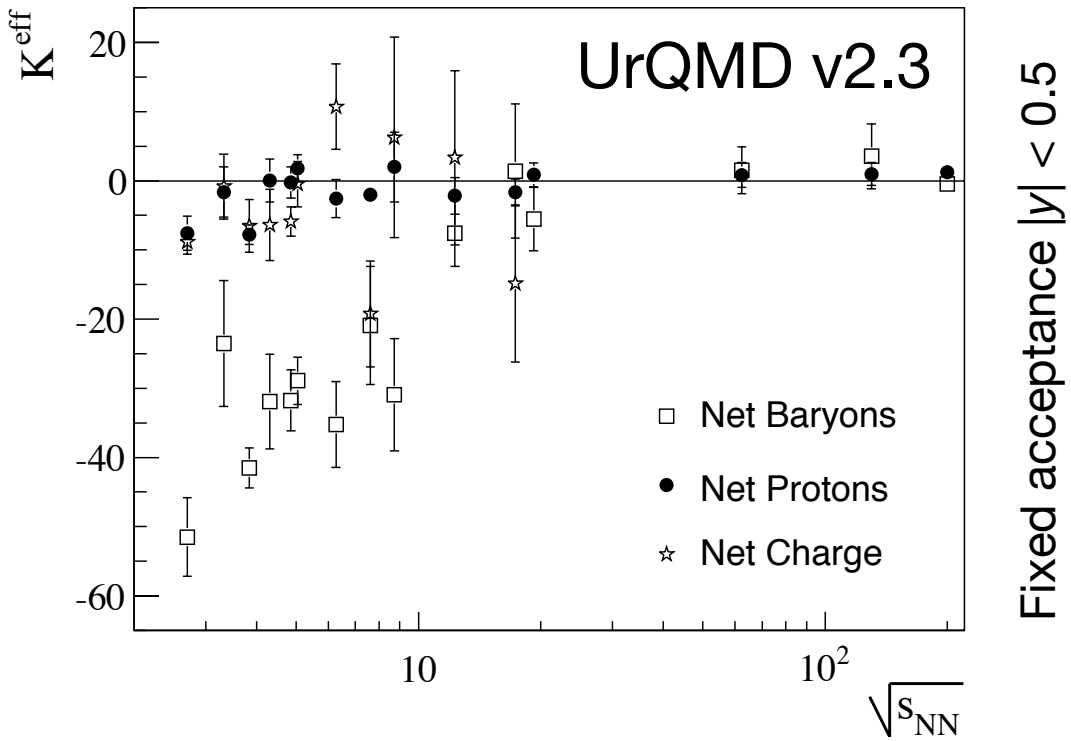
- Phase transition effect
  - In net baryon kurtosis
  - Seen by lattice QCD at μ_B=0
  - Should be measurable via net protons

$$K^{\text{eff}} = K\left(\delta N\right)\langle \delta N^2 \rangle = \frac{\langle \delta N^4 \rangle}{\langle \delta N^2 \rangle} - 3\langle \delta N^2 \rangle = \frac{\chi_4}{\chi_2}$$



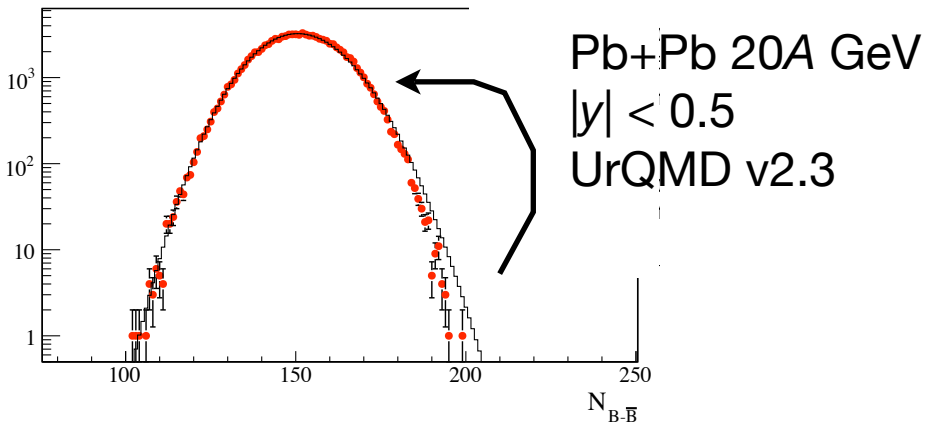
arXiv: 0811.1006 [hep-lat]

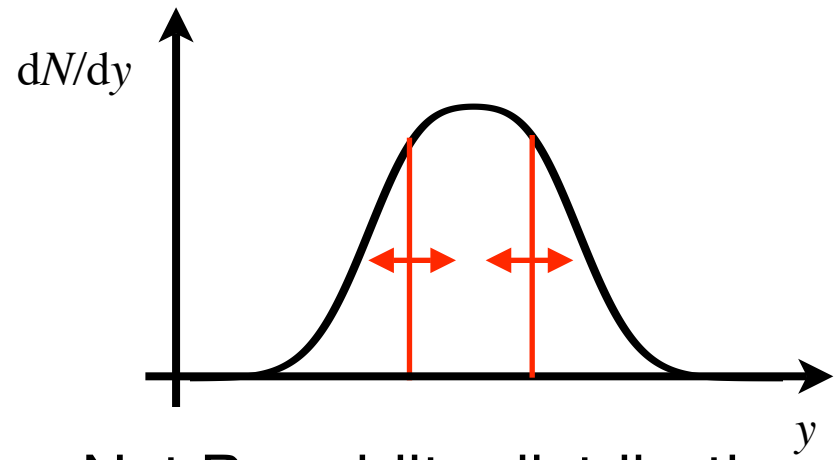
Baseline Effects



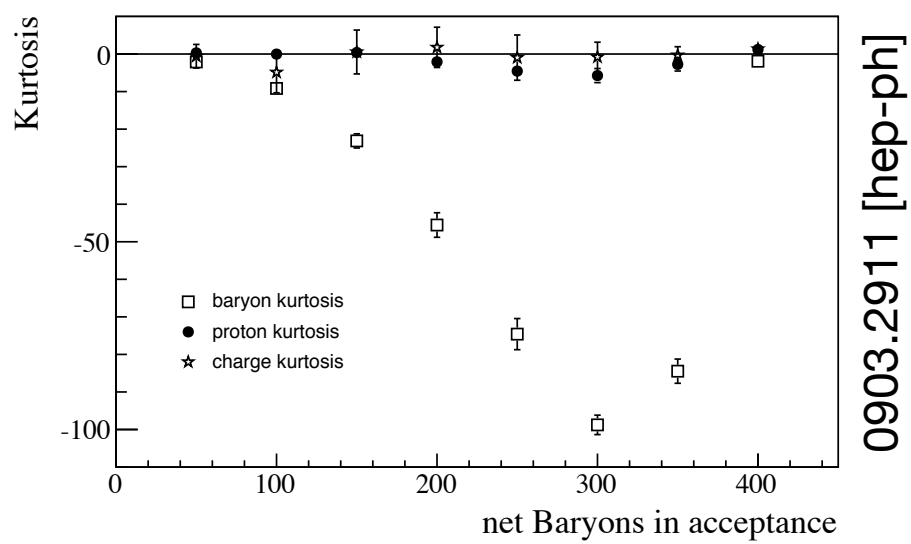
- Calculate a baseline for future measurements in UrQMD:
  - High moments require large, but experimentally achievable statistics (~1M)
  - Results at RHIC energies confirm predictions and are compatible with STAR results
  - Large negative values when going towards interesting energy range:
    For net baryons and (weaker) for net protons

Baseline Effects



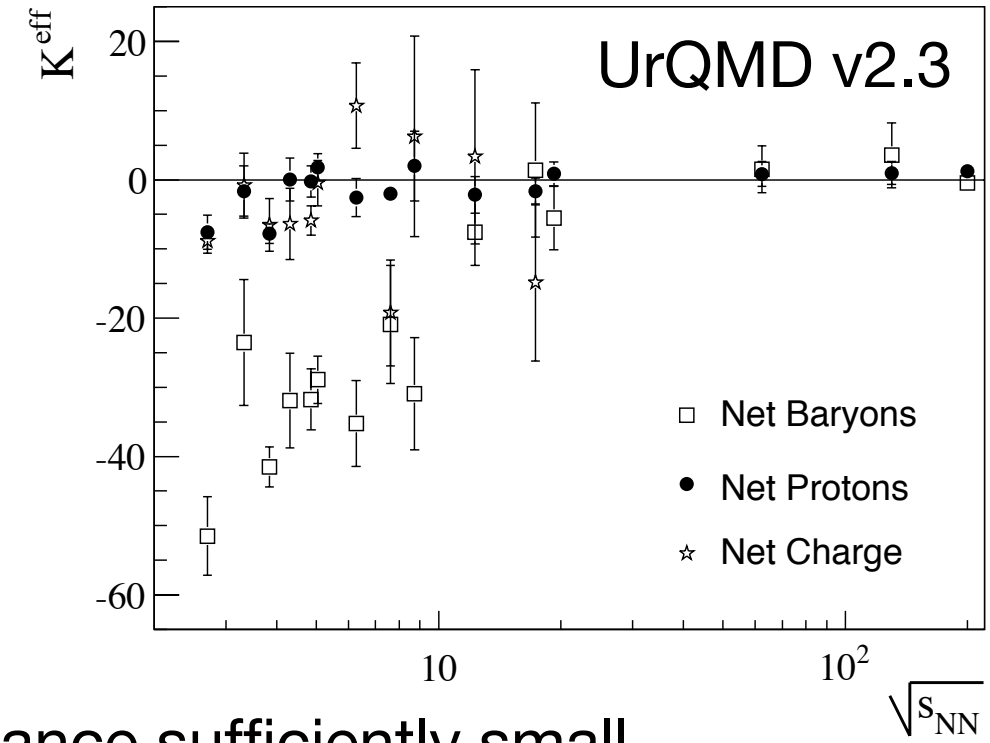


- Net B e-by-e distribution:
  - Compared to Poisson, weight is shifted from tails to flanks
- Net B rapidity distribution
  - 4π integral: constrained to *N*=2*A*
  - in acceptance<<4π: net baryons can fluctuate freely
- Net B kurtosis
  - in acceptance<<4π: K≈0
  - for 4π: K=0 (δ function)
  - for acceptances approaching 4π: large negative values



Baseline Effects

- Exact quantum number conservation affects net baryon and (to less extent) net proton fluctuations

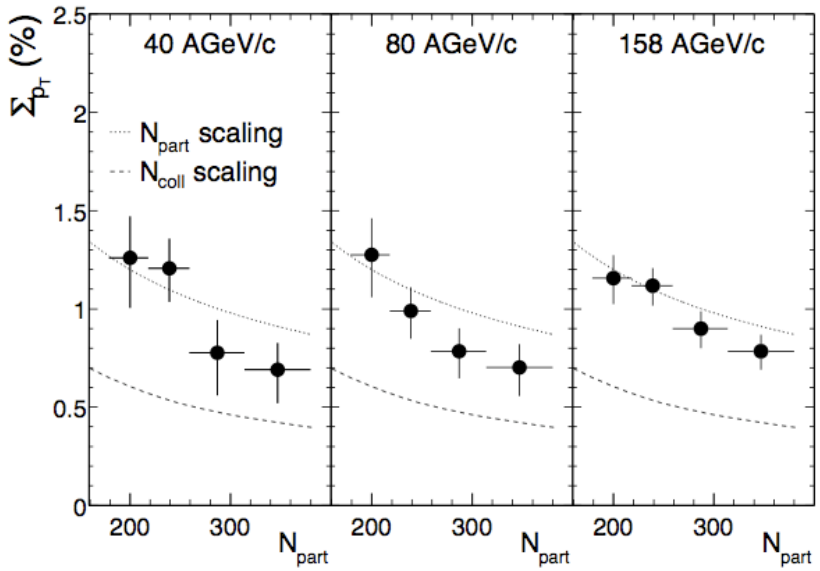


arXiv: 0903.2911 [hep-ph]

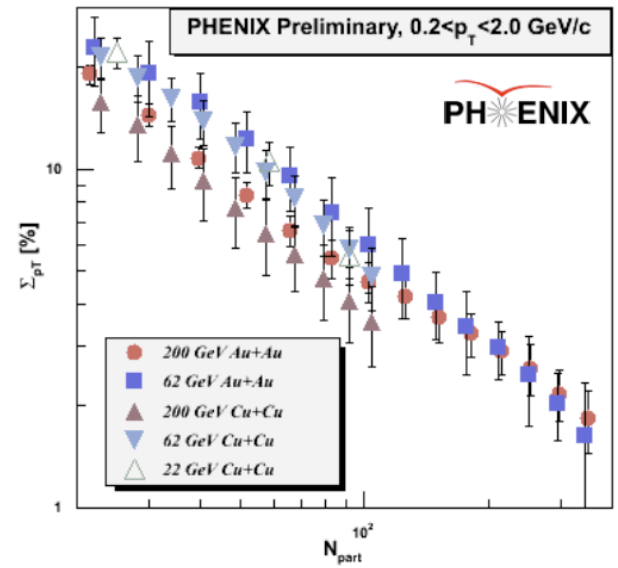
- At high RHIC energies: acceptance sufficiently small
- Lower energies: baryon number conservation in 4π becomes noticeable
- Baseline effects have to be taken into account:
  - Phase transition: background >> signal
  - Critical point effect probably not affected

End.

<p_T> Fluctuations Compare to CERES, STAR

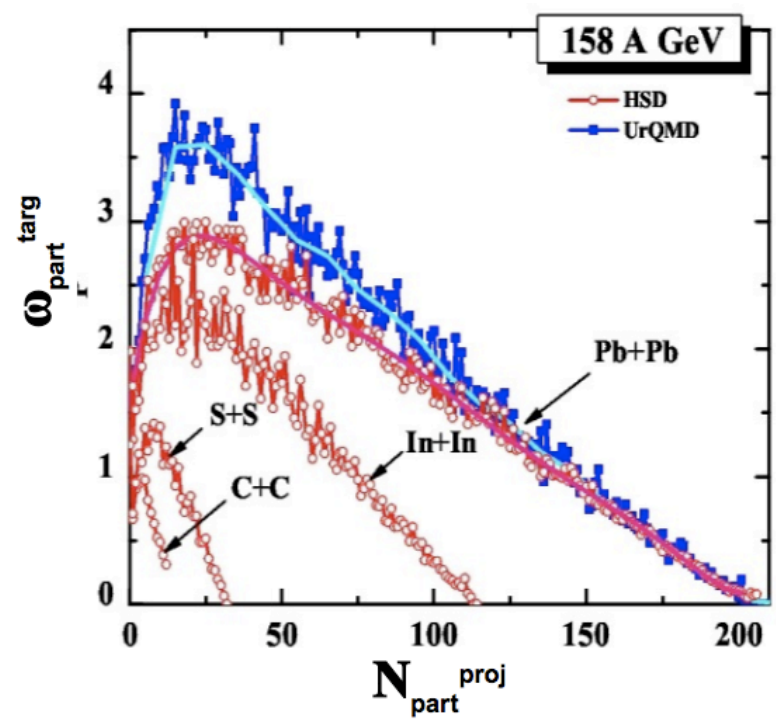


CERES: Nucl.Phys.A727:97-119,2003



PHENIX: J. Mitchell, this workshop

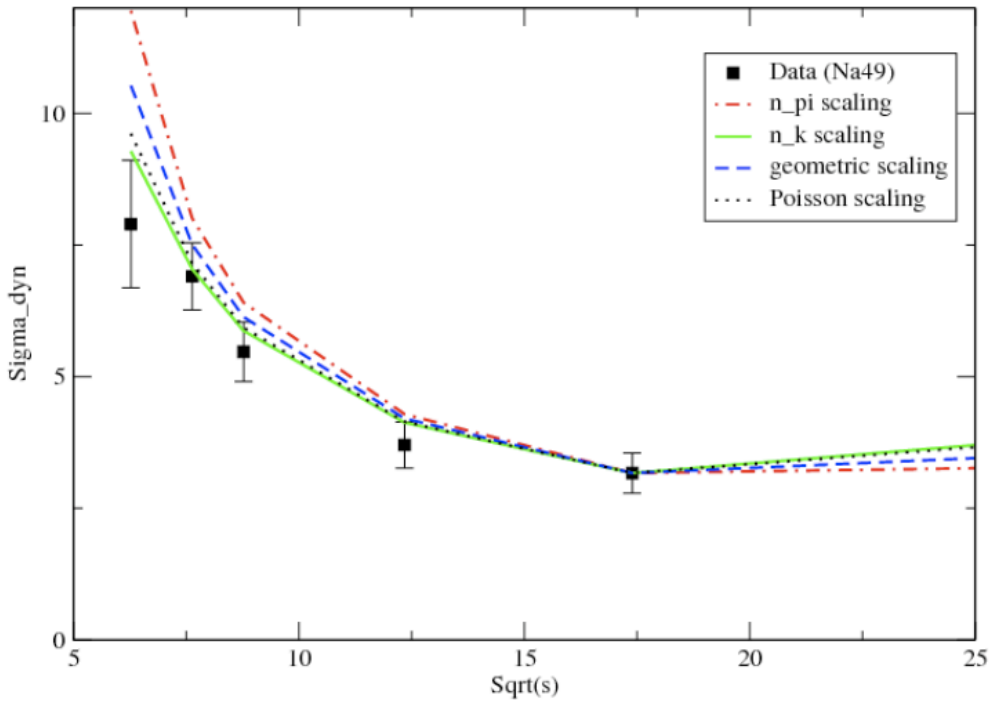
- CERES and PHENIX see enhanced fluctuations in peripheral collisions
- Systematic comparison of different measures is needed
- For fluctuations, peripheral collisions are not like small nuclei collisions!



Phys.Rev. C73 034902

K/π discussion

- Effect of changing acceptance?
- NA49 data scales when using multiplicities *in acceptance*



V. Koch: EMMI workshop 2009, Münster

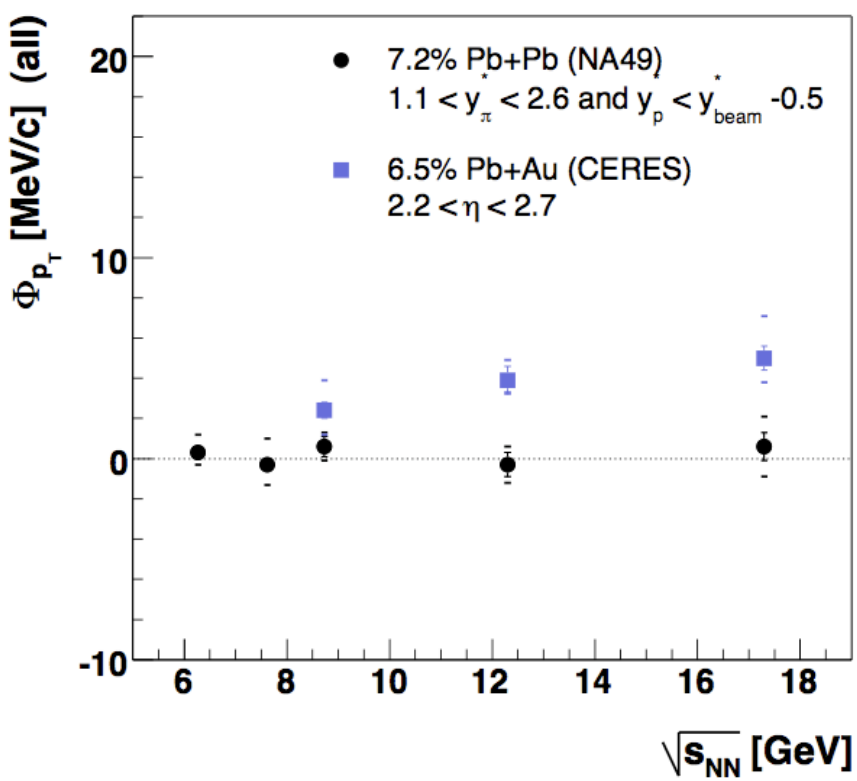
- Contradicting interpretations - K/π fluctuations remain interesting!

Talk to V. Koch if he wants to show it

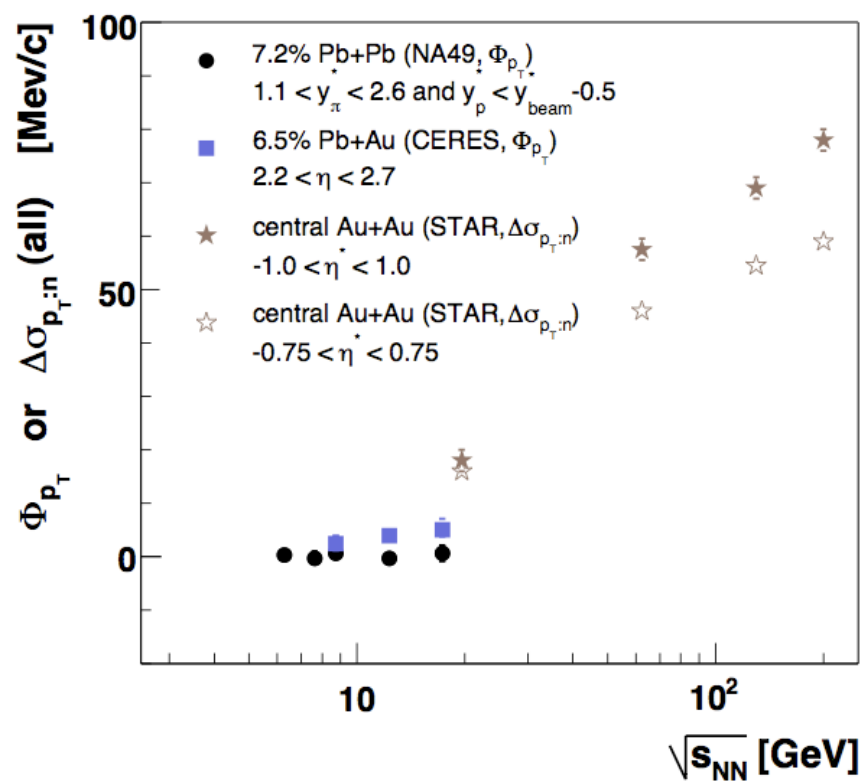
<p_T> Fluctuations Compare to CERES, STAR

- Comparison of NA49, CERES and STAR results - energy dependence

Candiate for being skipped



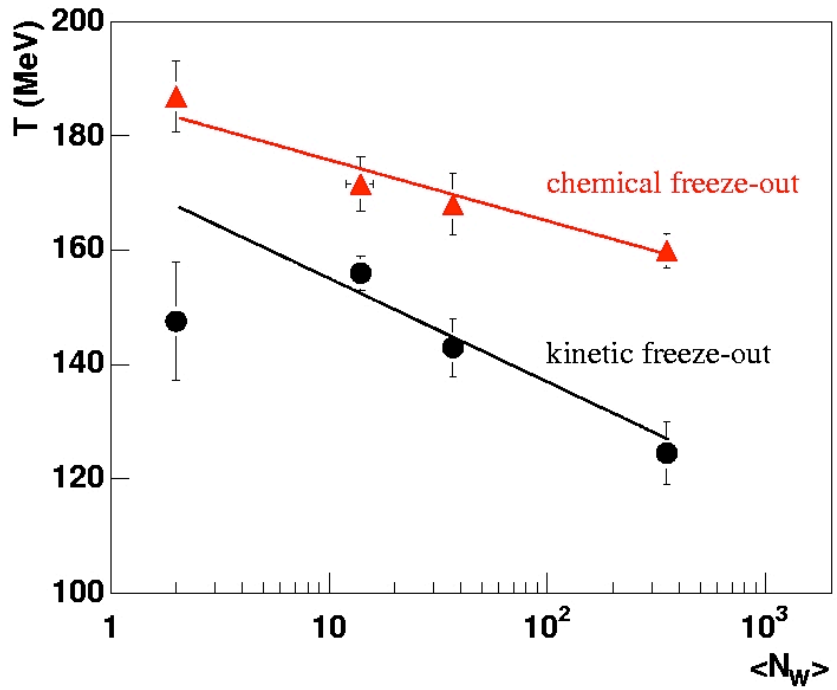
Phys. Rev. C79: 044904, 2009

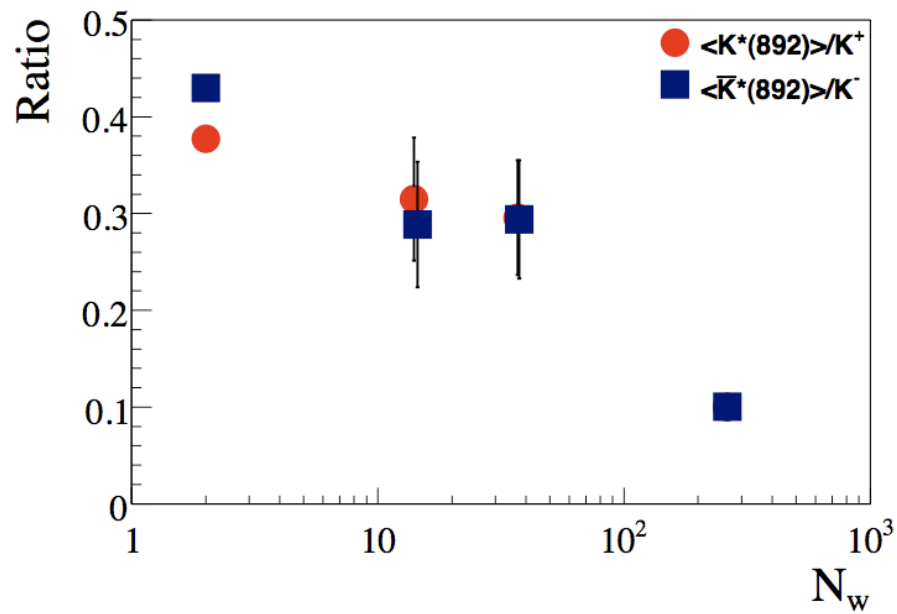


System size dependence

- Thermal freeze-out is also higher in small systems
  - A 2-D scan (T,μ_B) is possible by varying (A,$\sqrt{s}$)
-

p+p C+C Si+Si Pb+Pb at 158*A* G





Introduction

- Critical region
- Estimates for Magnitude of fluctuations

Amplitude of effect:
Stephanov, Rajagopal, Shuryak,
Phys. Rev. D60: 114028, 1999
and private communication

Position of critical point:
Z. Fodor and S. Katz,
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Width of critical point:
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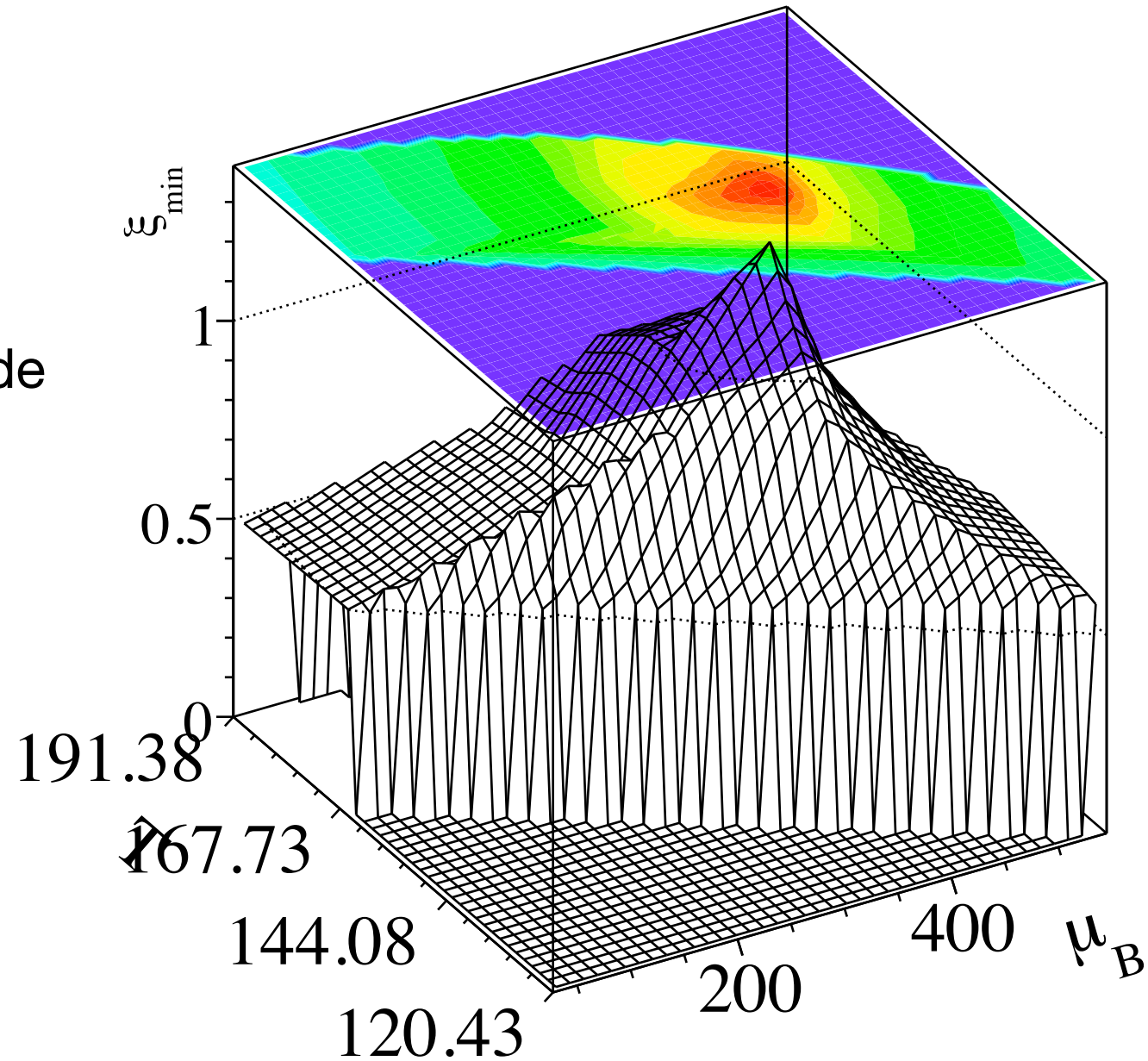
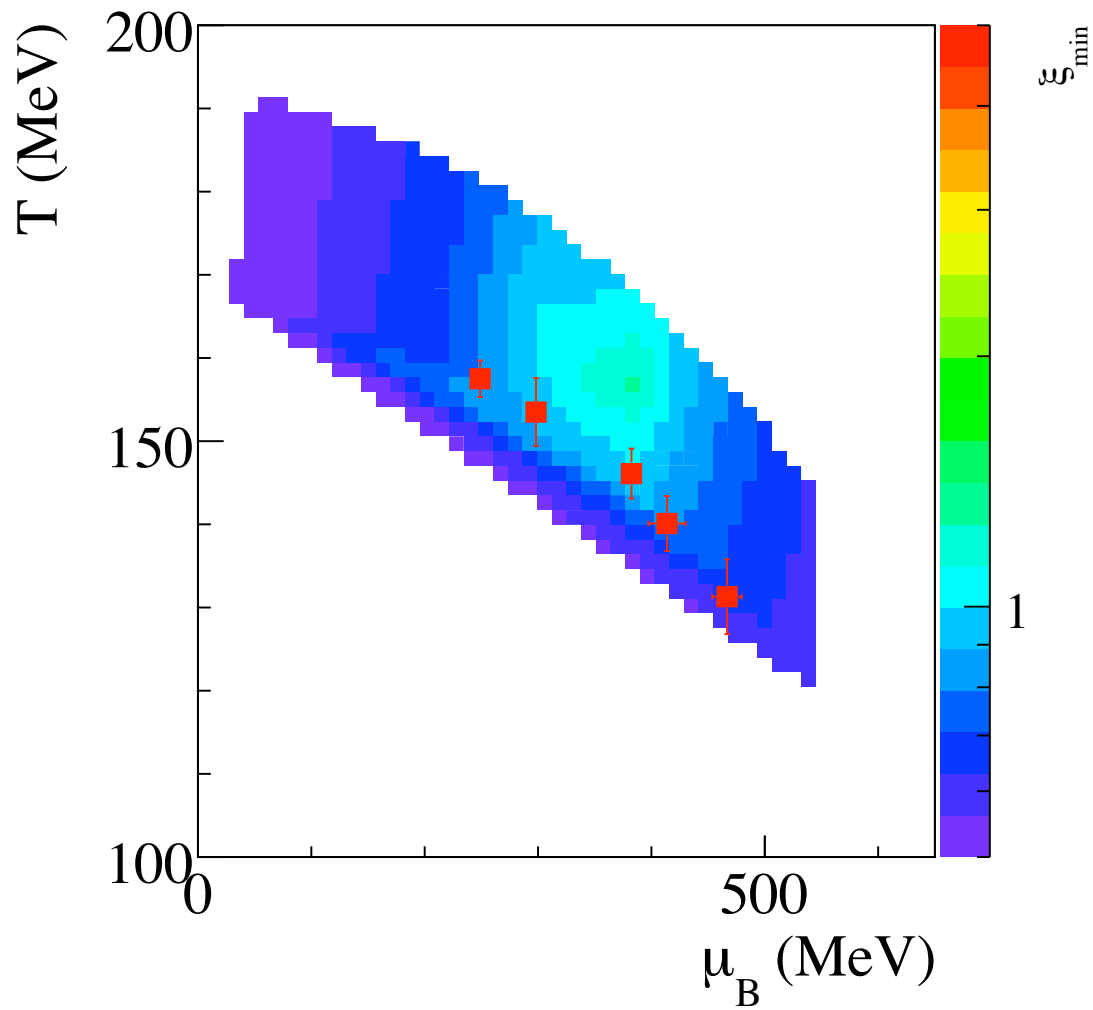


Introduction

- Critical region
- Estimates for Magnitude of fluctuations



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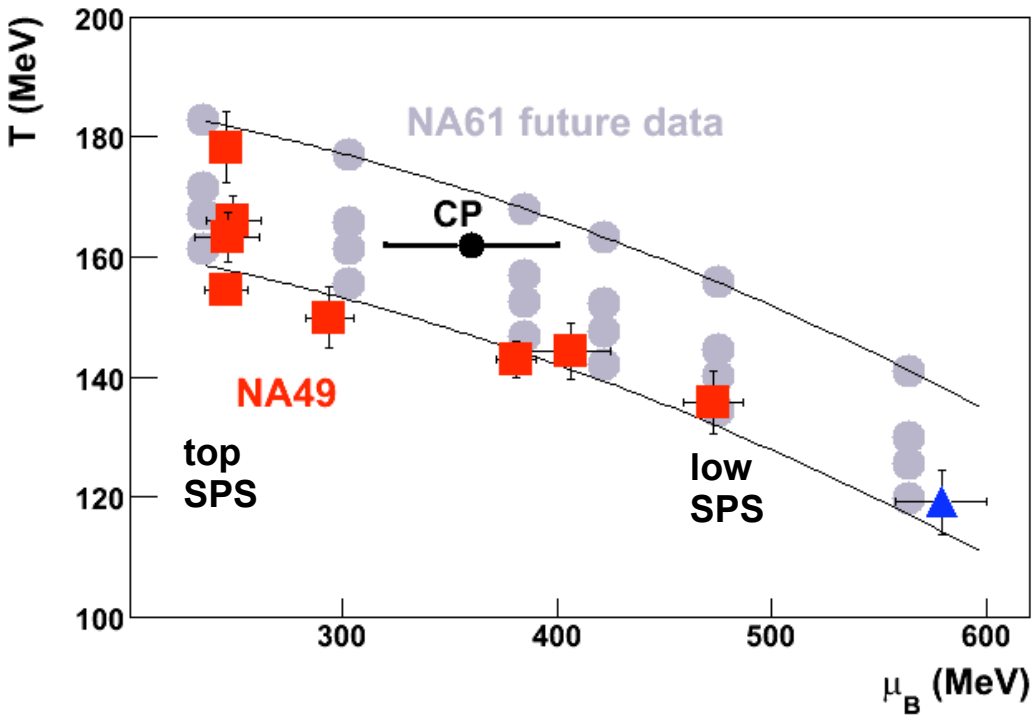
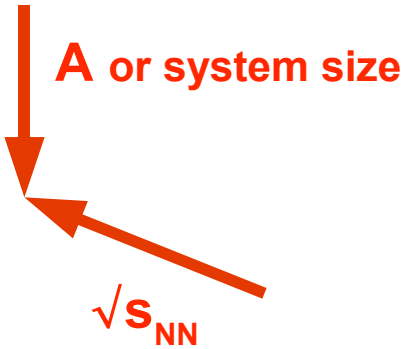
At CP enlarged fluctuations of mean multiplicity and mean transverse momentum

Stephanov, Rajagopal, Shuryak, PR**D60**, 114028 (1999)

(T, μ_B) phase diagram can be scanned by varying energy and system size

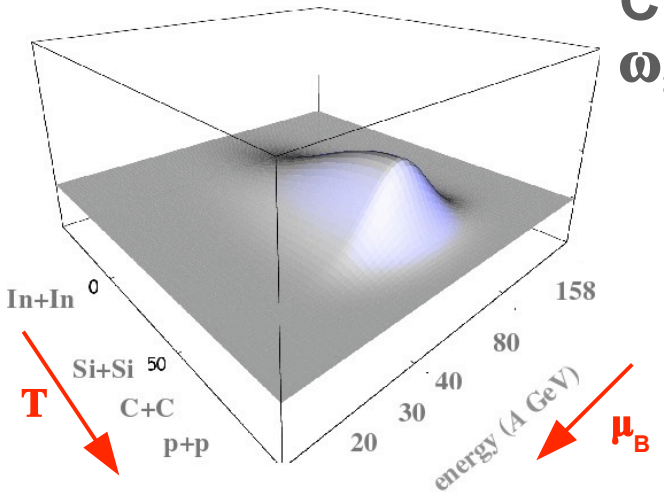




⇒ Non-monotonic dependence of critical point signal on control parameters (energy, centrality, ion size) can help to locate the critical point

CP signal

ω, Φ_{PT}, ...



Event-by-event transverse momentum and multiplicity fluctuations

Φ_{PT} - measures transverse momentum fluctuations on event-by-event basis

single-particle variable $z_{p_T} = p_T - \bar{p}_T$

$\bar{p}_T$ - inclusive average

event variable $Z_{p_T} = \sum_{i=1}^{N} (p_{T_i} - \bar{p}_T)$

(summation runs over particles in a given event)

$$\Phi_{p_T} = \sqrt{\frac{\langle Z_{p_T}^2 \rangle}{\langle N \rangle}} - \sqrt{\overline{z_{p_T}^2}}$$

$\langle ... \rangle$ - averaging over events

ω - measures multiplicity fluctuations on event-by-event basis

Scaled variance of multiplicity distribution

$$\omega = \frac{V(N)}{\langle N \rangle}$$

where variance $V(N) = \langle N^2 \rangle - \langle N \rangle^2$

If A+A is a **superposition** of independent N+N

Φ_{PT} (A+A) = Φ_{PT} (N+N)

Φ_{PT} is independent of N_{part} fluctuations

ω (A+A) = ω (N+N) + < n > ω_{part}

< n > - mean multiplicity of hadrons from a single N+N

ω_{part} - fluctuations in N_{part}

ω is strongly dependent on N_{part} fluctuations

For a system of **independently emitted particles** (no inter-particle correlations)

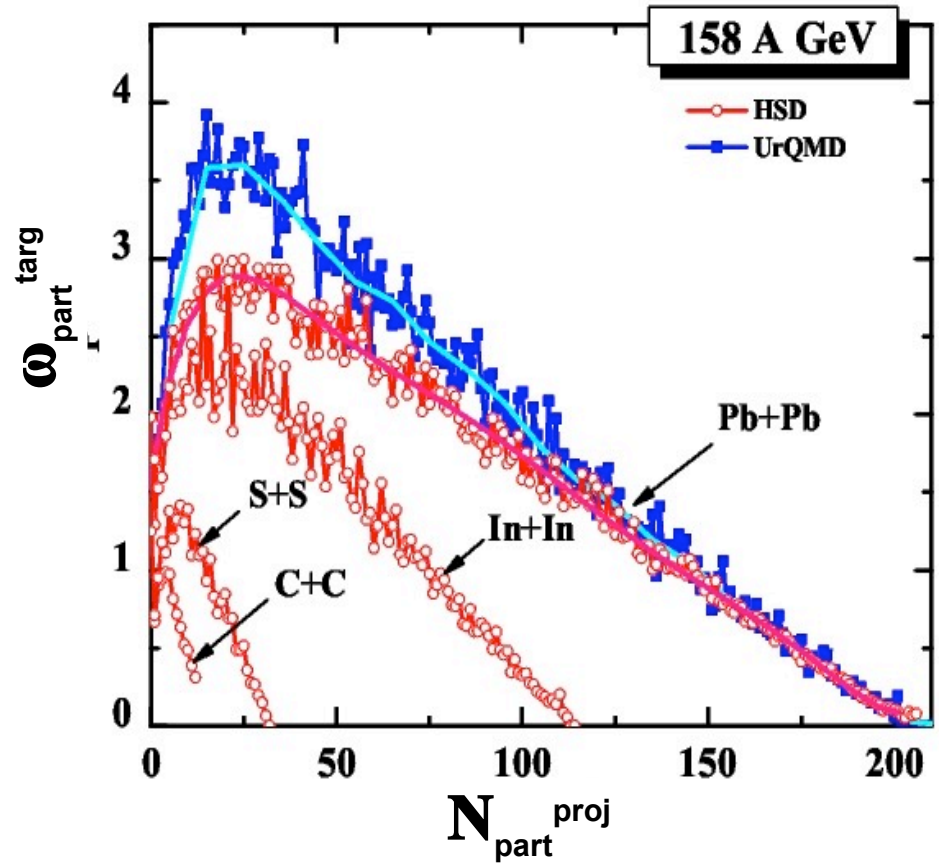
Φ_{PT} = 0

For **Poissonian multiplicity distribution**

ω=1

- **In NA49 fixed target experiment**
  - N_{part}^{proj} can be fixed (spectator energy measured by Forward Calorimeter)
  - N_{part}^{targ} cannot be measured and its fluctuations can be suppressed only by selection of very central collisions

Multiplicity fluctuations (ω) presented here are for very central (1%) collisions



ω_{part}^{targ} - fluctuations in the number of target participants for a fixed N_{part}^{proj}

Konchakovski et al., PR**C73**, 034902 (2006), and private communication

Data sets (for Φ_{PT} and ω measurements):

Energy dependence for central Pb+Pb collisions

- Central Pb+Pb interactions (7.2% most central for Φ_{PT} and 1% most central for ω)
- kinematic acceptance
  - for Φ_{PT}: forward-rapidity $1.1 < y_{\pi}^{*} < 2.6$ and $0.005 < p_T < 1.5$ GeV/c; $y^{*}_{p} < y^{*}_{beam} - 0.5$ (to reject projectile spectator domain)
  - for ω: forward rapidity region $1.1 < y_{\pi}^{*} < y_{beam}$
- limited azimuthal acceptance (for details see corresponding papers)

System size dependence at 158A GeV

- p+p, C+C (1%), Si+Si (1%) and Pb+Pb (1%) for ω;
  p+p, semi-central C+C (15.3%) and Si+Si (12.2%), 5% most central Pb+Pb for Φ_{PT}
- kinematic acceptance
  - for Φ_{PT}: forward-rapidity $1.1 < y_{\pi}^{*} < 2.6$ and $0.005 < p_T < 1.5$ GeV/c
  - for ω: forward rapidity region $1.1 < y_{\pi}^{*} < y_{beam}$ ($1.1 < y_{\pi}^{*} < 2.6$ for p+p points)
- limited azimuthal acceptance (for details see corresponding papers)

Critical point predictions for multiplicity and transverse moment. fluctuations

Magnitude of fluctuations at CP from Stephanov, Rajagopal, Shuryak PR**D60**, 114028 (1999)
with correlation length $\xi = \min(c_1 A^{1/3}, c_2 A^{1/9}) =$

min (limit due to finite system size, limit due to finite life time)

(M. Stephanov, private communication)
where c_1 and c_2 are fixed such that

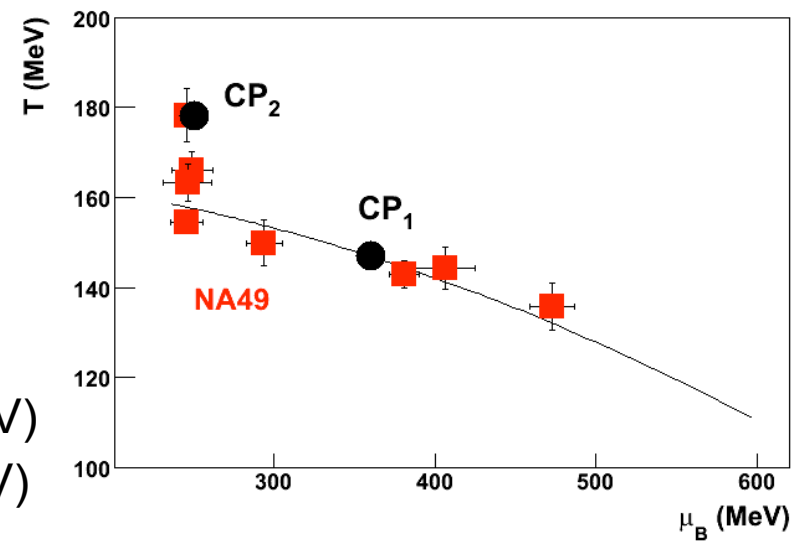
- ξ(Pb+Pb) = 6 fm and ξ(p+p) = 2 fm ($c_1 = 2$, $c_2 = 3.32$)
- ξ(Pb+Pb) = 3 fm and ξ(p+p) = 1 fm ($c_1 = 1$, $c_2 = 1.66$)

Width of CP region in (T, μ_B) plane based on Hatta, Ikeda PR**D67**, 014028 (2003)
$\sigma(\mu_B) \approx 30$ MeV and $\sigma(T) \approx 10$ MeV

Chemical freeze-out parameters, $T(A,\sqrt{s_{NN}})$ and $\mu_B(A,\sqrt{s_{NN}})$ from Beccatini, Manninen, Gaździcki PR**C73**, 044905 (2006)

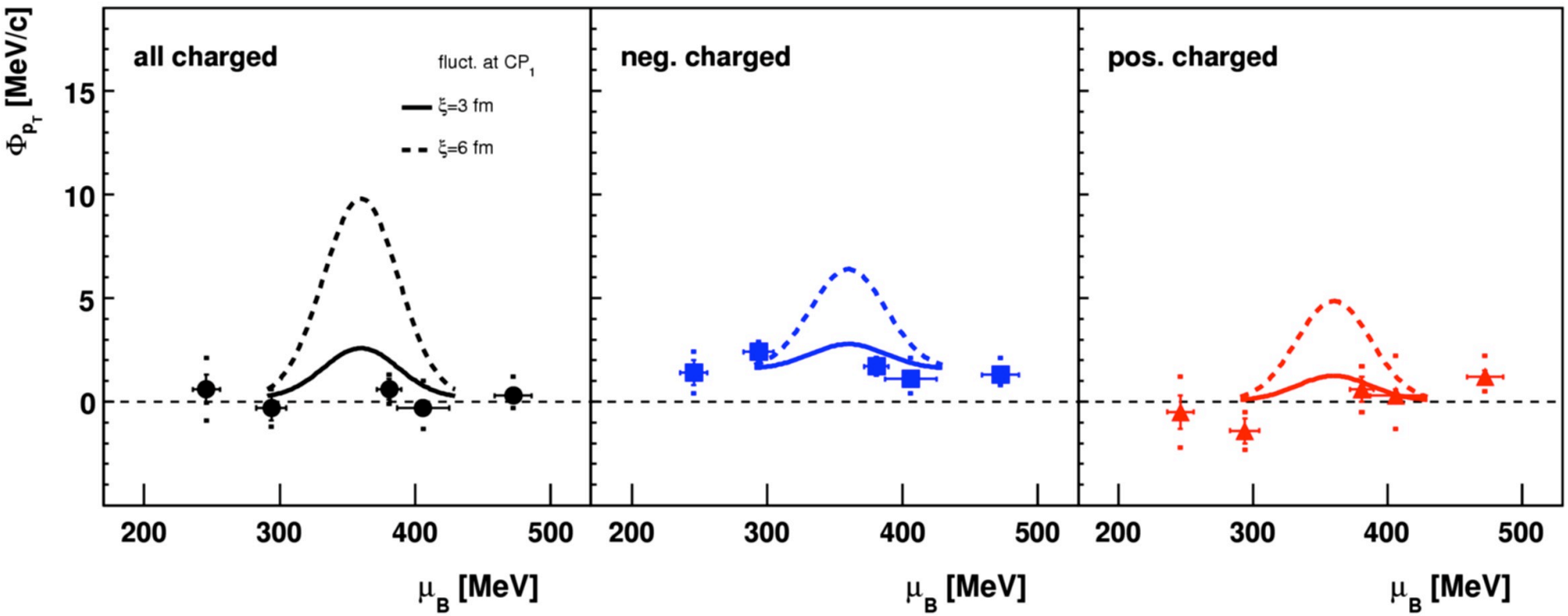
Location of the Critical Point:
two examples considered

- $\mu_B(CP_1) = 360$ MeV (Fodor, Katz JHEP **0404**, 050 (2004))
  $T(CP_1) \approx 147$ (chemical freeze-out temperature T_{chem} for central Pb+Pb at $\mu_B = 360$ MeV)
- $\mu_B(CP_2) \cong 250$ MeV (μ_B for A+A collisions at 158A GeV)
  $T(CP_2) = 178$ MeV (T_{chem} for p+p collisions at 158 GeV)



Energy dependence for central Pb+Pb
→ Average p_T fluctuations (arXiv:0810.5580)

CP_1 location:
$\mu_B(CP_1)$ = 360 MeV
$T(CP_1) \approx 147$ (chemical freeze-out temperature for Pb+Pb at μ_B = 360 MeV)



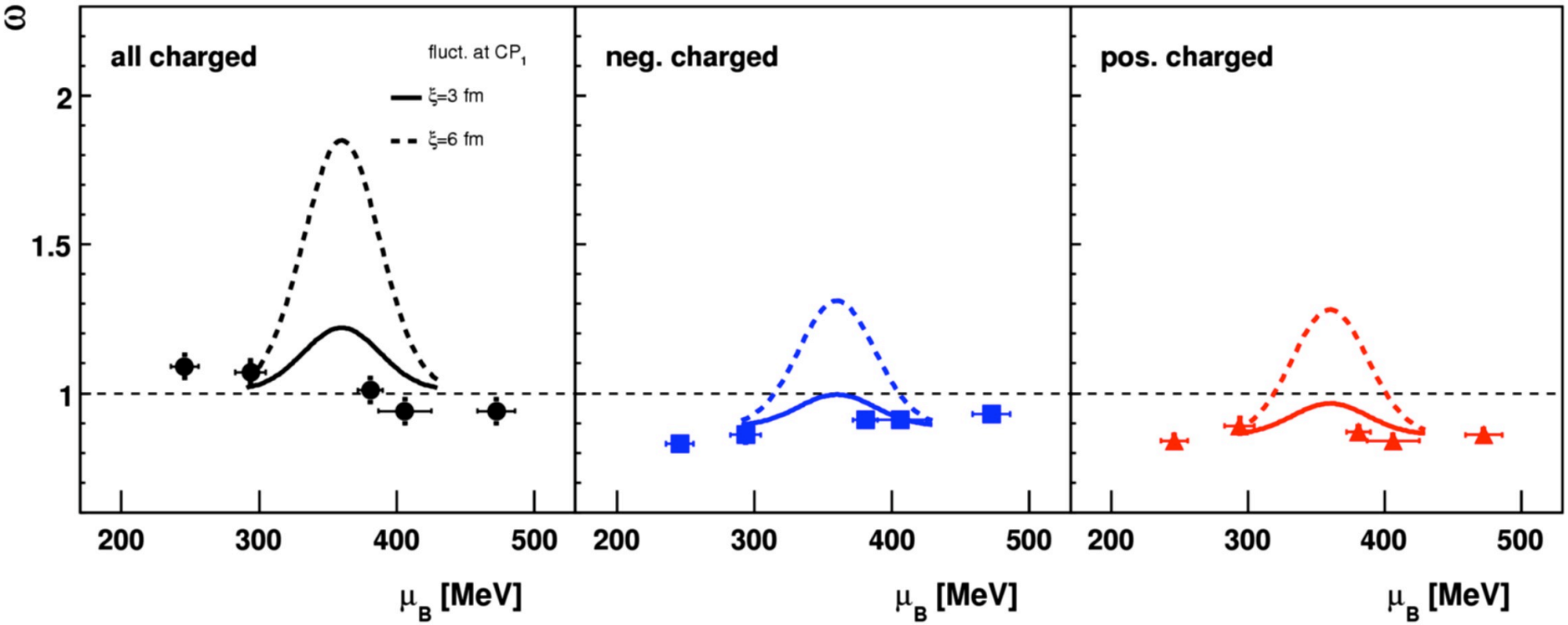
base-lines for CP_1 predictions (curves) are mean Φ_{PT} values for 5 energies

→ No significant energy dependence at SPS energies

Data do not provide evidence for critical point fluctuations

Energy dependence for central Pb+Pb
→ Multiplicity fluctuations (PR**C78**, 034914 (2008))

CP_1 location:
$\mu_B(CP_1)$ = 360 MeV
$T(CP_1) \approx 147$ (chemical freeze-out temperature for Pb+Pb at μ_B = 360 MeV)



base-lines for CP_1 predictions (curves) are mean ω values for 5 energies

→ No significant energy dependence at SPS energies

Data do not provide evidence for critical point fluctuations