# Energy and System Size Dependence of Fluctuations: NA49 results and NA61 plans

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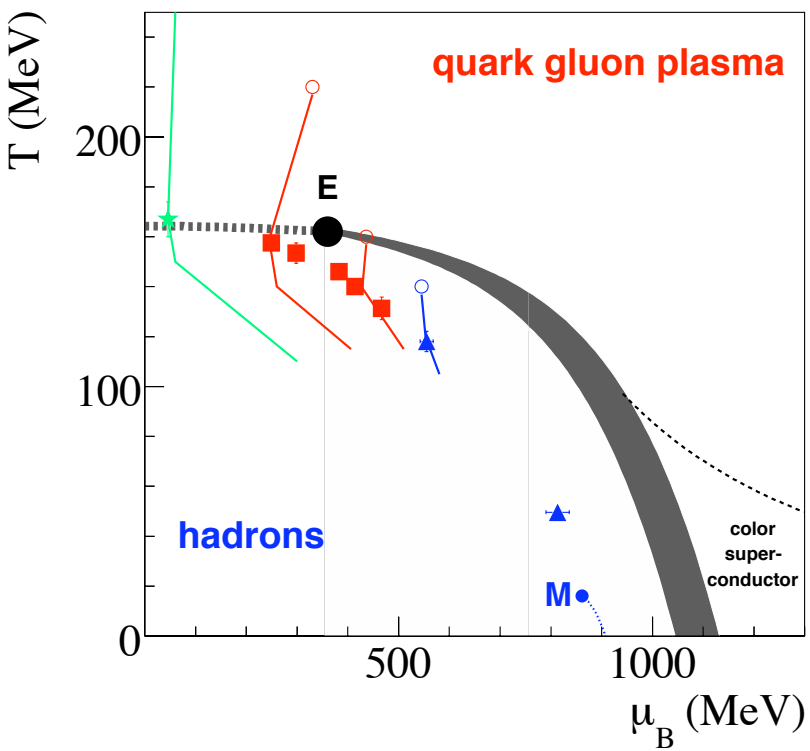
NA49

SHINE NA61

# Outline

- Fluctuations as a Signature of Phase Transition and Critical Point?
- NA49 Results on Energy and System Size Dependence of Fluctuations:
  - Charge Fluctuations
  - $\langle p_T \rangle$ Fluctuations
  - Multiplicity Fluctuations
  - Hadron Ratio Fluctuations
- Search for the Critical Point at SPS: The NA61/SHINE Experiment
  - Plans
  - Status

# Introduction




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

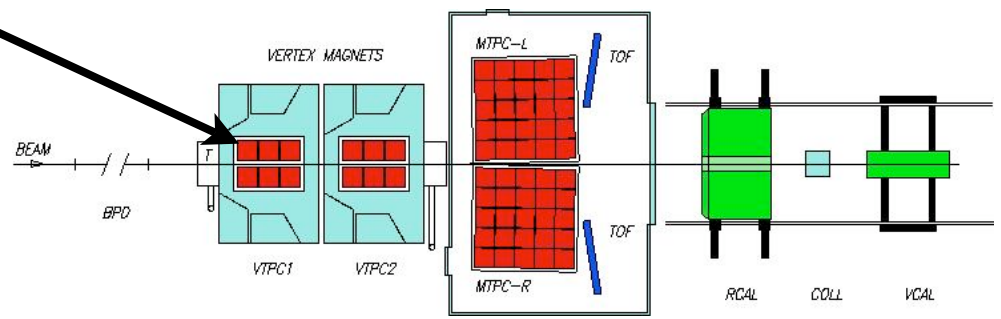
- Inclusive observables at SPS energies indicate the onset of deconfinement
- Can fluctuations convey more information
  - About the onset of deconfinement?
    - At the phase transition, 2 distinct event classes or mixed phase may be reflected in larger event-by-event fluctuations
  - On the nature 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)

# NA49: TPC Acceptance

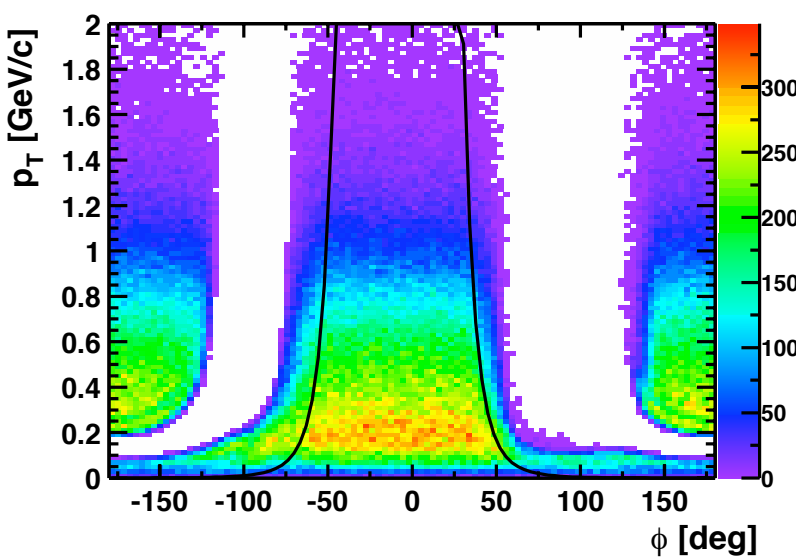
Setup details relevant to fluctuation analysis:

- 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 $1.4 < y < 1.6$



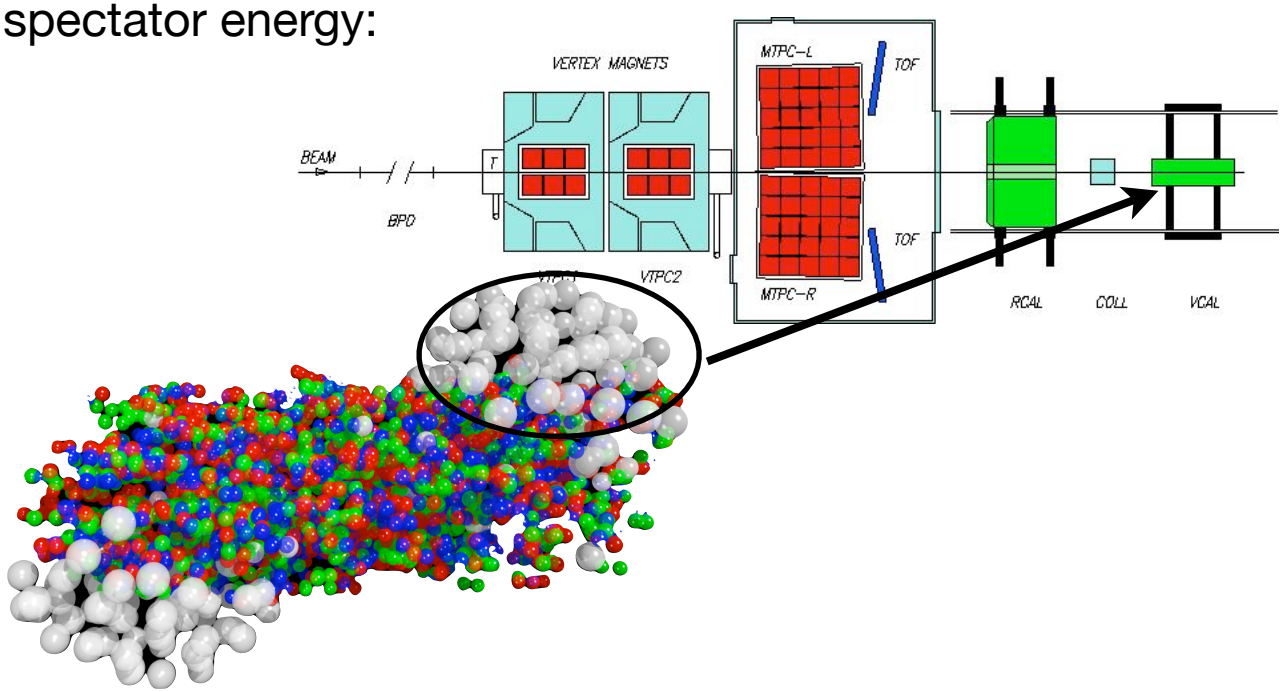

Phys.Rev.C 70, 2004

→ Has to be taken into account in model comparisons!

# NA49: Centrality Determination

Setup details relevant to fluctuation analysis:

- Veto Calorimeter (VCAL):
  - Measurement of projectile spectator energy:
    → centrality of collision




- Volume fluctuations must be controlled
  - Fluctuations of extensive quantities (e.g. *N*) are directly affected
  - Fluctuations of intensive quantities are indirectly affected

# NA49 Data Sets

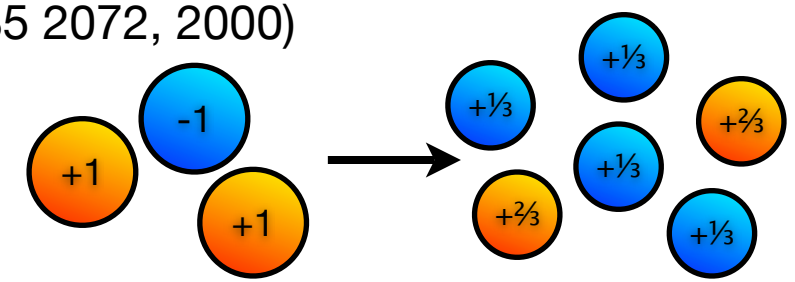
Data sets analyzed for the shown fluctuation results

| 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

# Net-Charge Fluctuations

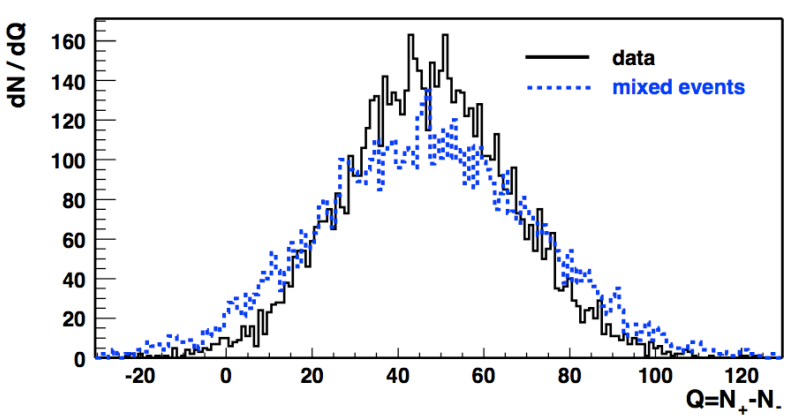
- Original idea: Significantly smaller fluctuations in QGP
  (M. Asakawa, U. Heinz and B. Müller, Phys. Rev. Lett. 85 2072, 2000)
  (S. Jeon and V. Koch, Phys. Rev. Lett. 85 2076, 2000)

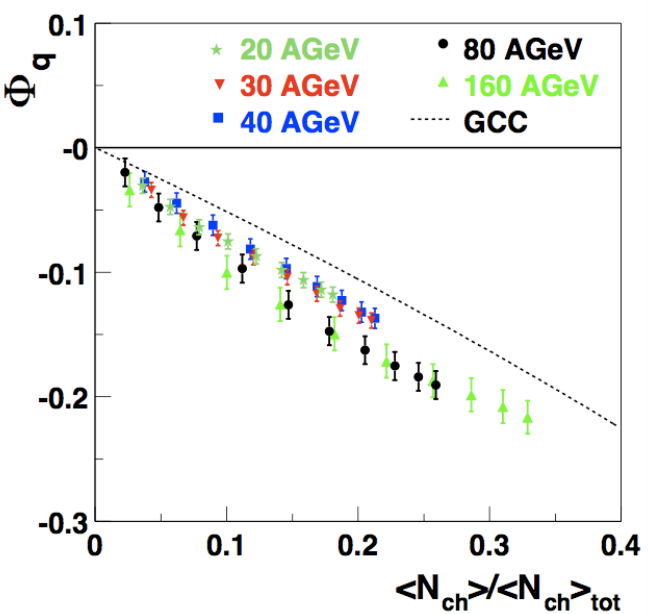



- Fluctuation measure

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

  - $\Phi = 0$ for independent particle production
  - independent of volume and multiplicity fluctuations




NA49 Phys. Rev. C 70 064903, 2004

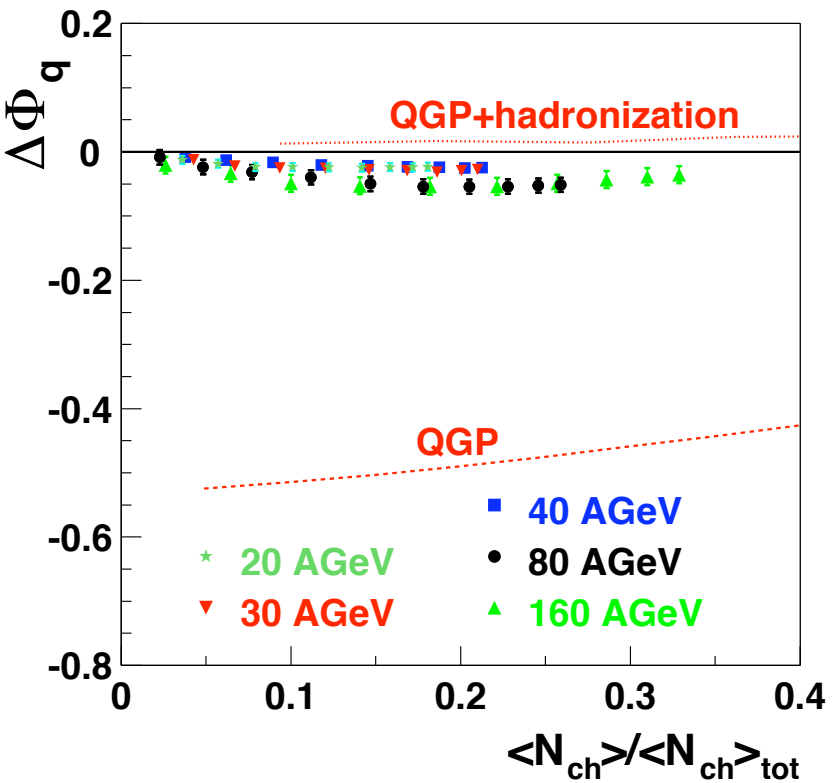
# Net-Charge Fluctuations

- Subtract influence of global charge conservation (acceptance dependence)

$$\Delta\Phi_q = \Phi_q - \Phi_{q,\mathrm{GCC}}$$

- NA49 data: Predicted suppression not observed
- No strong energy or acceptance dependence of $\Delta\Phi_q$
- QGP signatures may be shadowed by rescattering in the hadronic stage and resonance decay

(E. Shuryak, M. Stephanov, Phys. Rev. C 63 064903, 2001)
(J. Zaranek, Phys. Rev. C 66 024905, 2002)



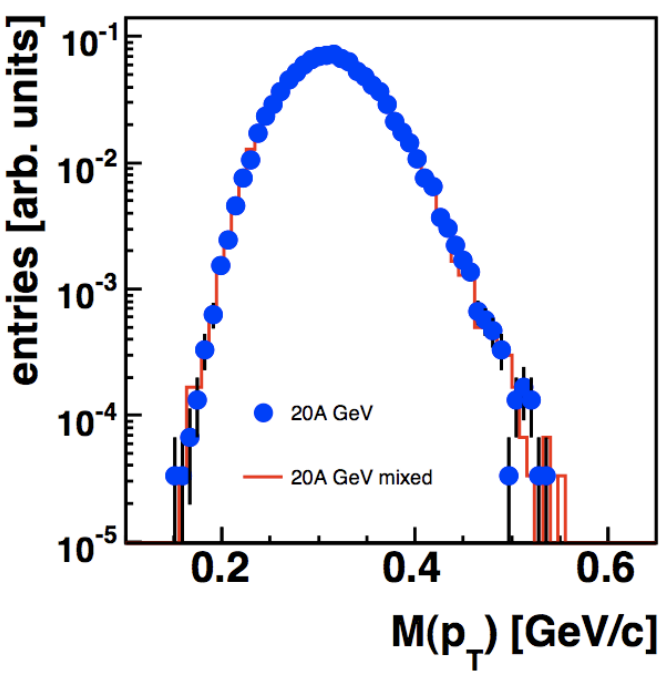

NA49 Phys. Rev. C 70 064903, 2004

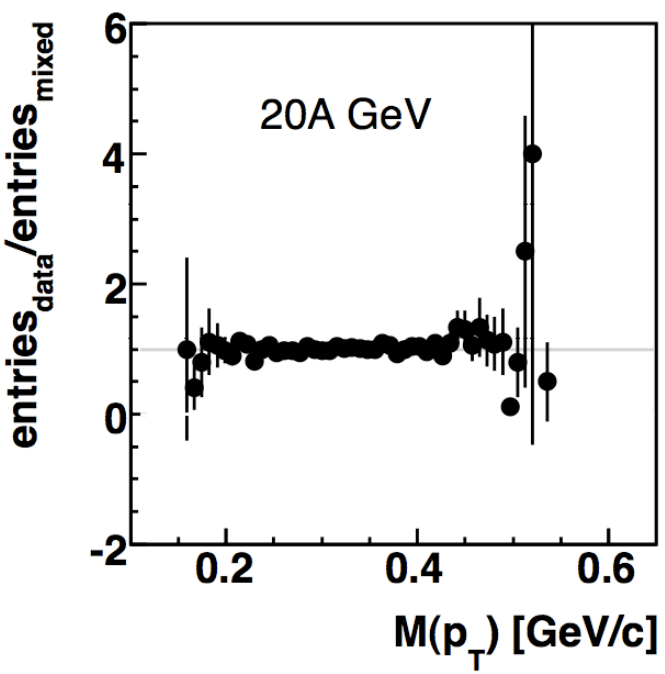
| | |
|---|---|
| Onset of deconfinement? | No sensitivity |
| Critical point? | No predictions |

# $\langle p_T \rangle$ Fluctuations

- Enhanced fluctuations in $\langle p_T \rangle$ expected near the critical point
  (e.g. Stephanov, Rajagopal, Shuryak Phys.Rev.D60:114028)

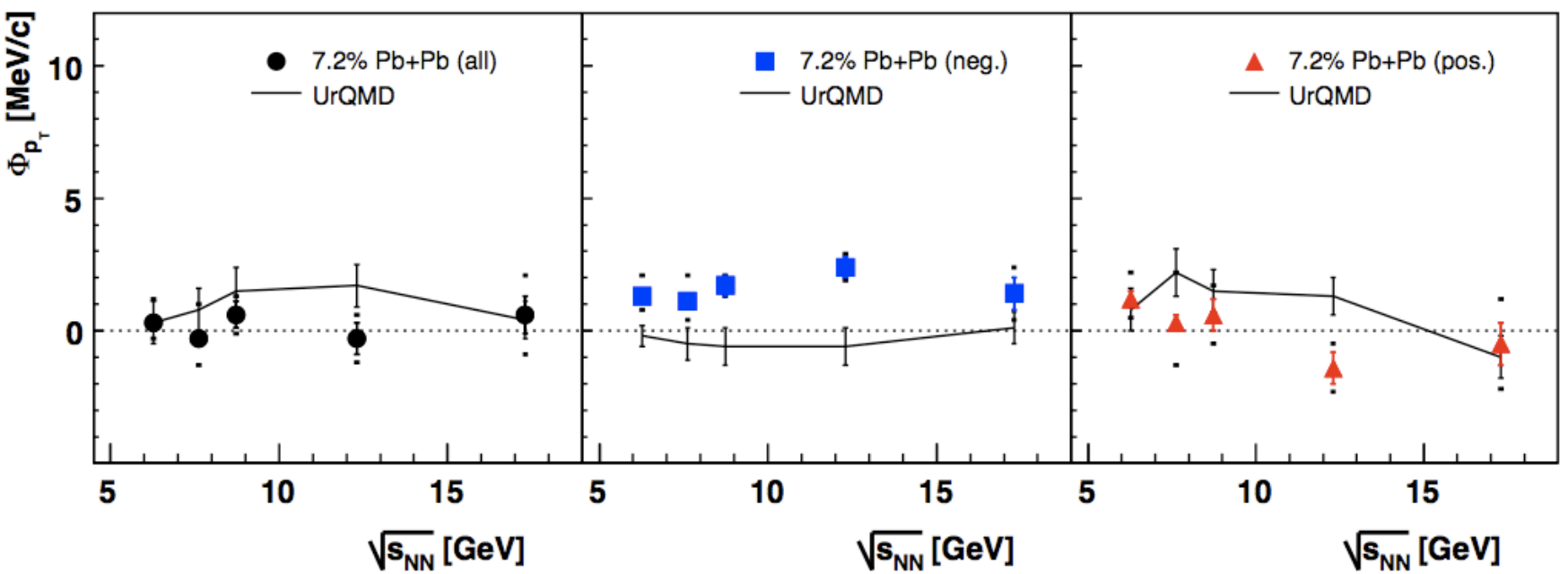
- Measure studied in NA49: $\Phi_{pT}$
  - defined as in $\Phi_q$, but for $x = p_T$



# $\langle p_T \rangle$ Fluctuations

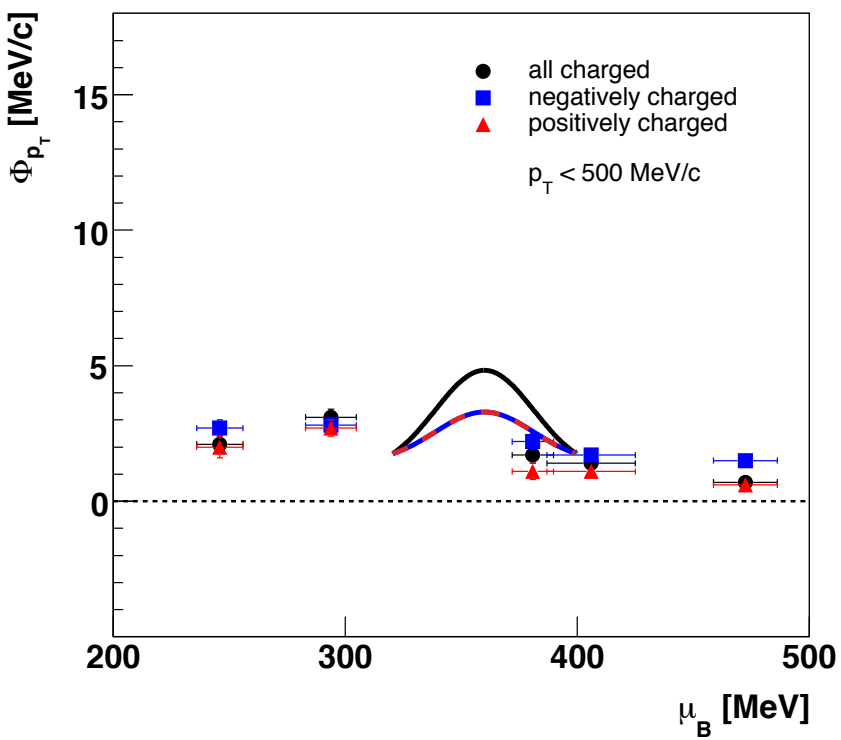
- No significant energy dependence
- Trend reproduced by hadronic model (UrQMD, v1.3)




NA49, arXiv:0805.2245 [nucl-ex]

# $\langle p_T \rangle$ Fluctuations

- Anticipated effect of critical point in NA49 acceptance:
  (large systematic error on prediction)
  - $\Delta\Phi_{pT} \approx 1.5$ MeV/$c$ (for negative/positive particles separately)
  - $\Delta\Phi_{pT} \approx 3$ MeV/$c$ (for all charged particles)




NA49 data:
arXiv:0805.2245 [nucl-ex]

$\mu_B$ from hadron gas fit:
F. Becattini et al,
Phys. Rev. C 73 (2006) 044905

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

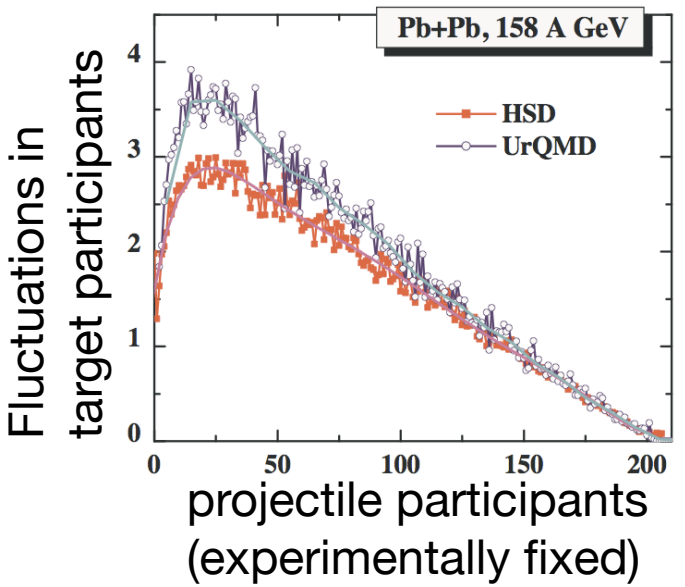
Position of critical point:
Z. Fodor and S. Katz,
JHEP 0404, 050, 2004

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

| | |
|---|---|
| Onset of deconfinement? | No predictions |
| Critical point? | No signal observed |

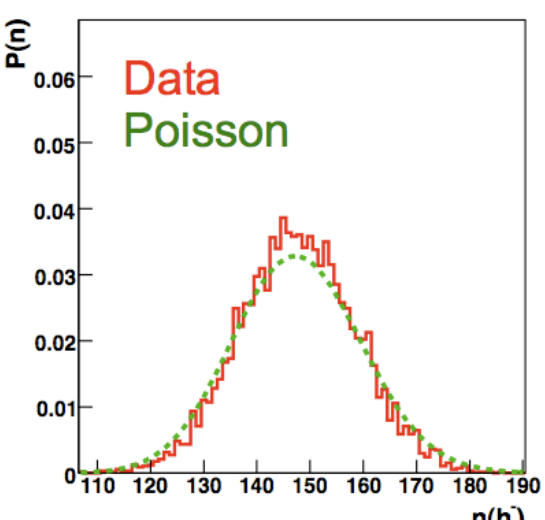
# Multiplicity Fluctuations

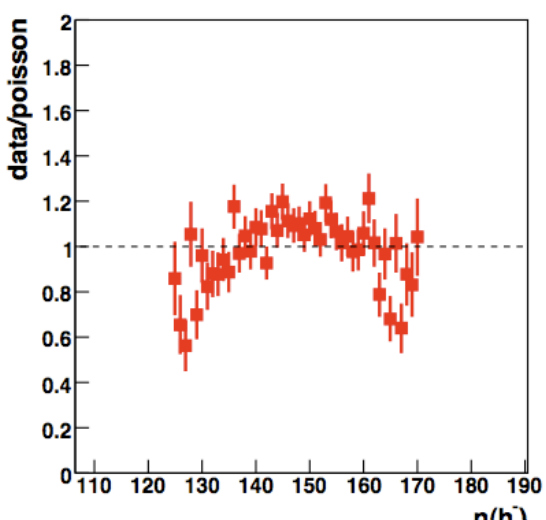
- *n* is an extensive quantity!
  - Avoid volume fluctuations
  - → Strict centrality selection: 1%




Phys.Rev. C73 034902

- 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, $\omega < 1$

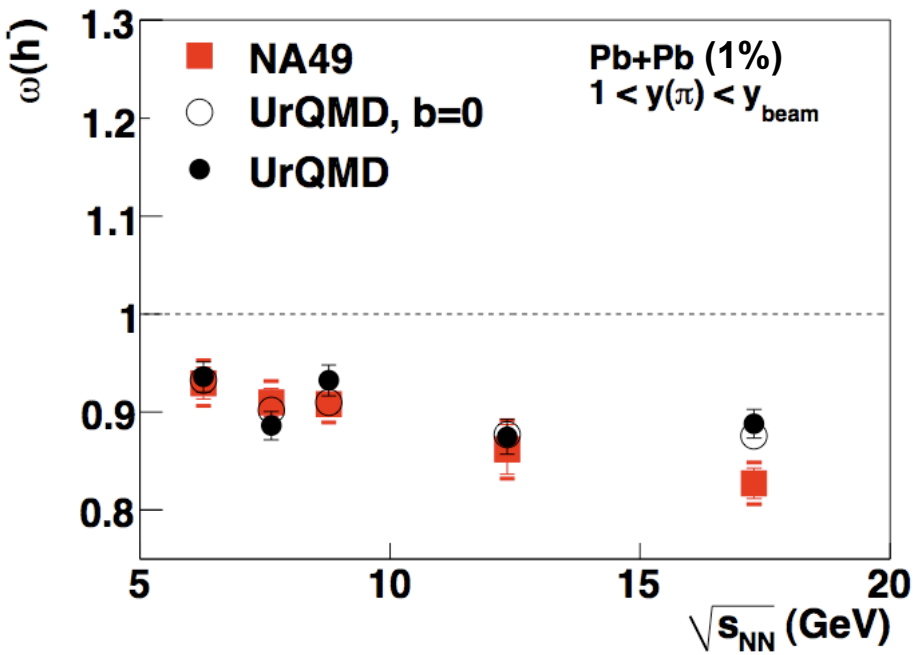



158*A* GeV, 1<*y*<$y_{Beam}$

# Multiplicity Fluctuations

- Energy dependence: Trend reproduced by the hadronic transport model UrQMD v1.3



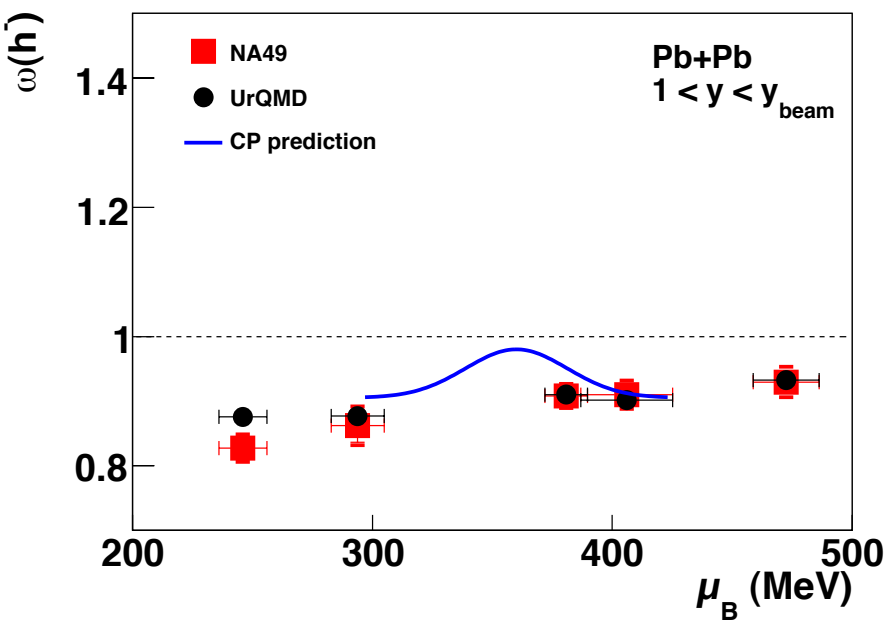

NA49 Data:
arXiv:0712.3216 [nucl-ex]
(submitted to Phys. Rev. C)

UrQMD:
B. Lungwitz and M. Bleicher,
arXiv:0707.1788 [nucl-th]

- Predicted increase due to onset of deconfinement: 0.02 (smaller than systematic errors)
  (M. Gazdzicki, M. Gorenstein, St. Mrowczynski Phys.Lett.B585: 115, 2004)

# Multiplicity Fluctuations

- Predicted increase due to critical point:
  $\Delta\omega\ (h^-) \approx 0.25$ in $4\pi$ and $\Delta\omega\ (h^-) \approx 0.075$ in NA49 acceptance
  (large systematic error of prediction)

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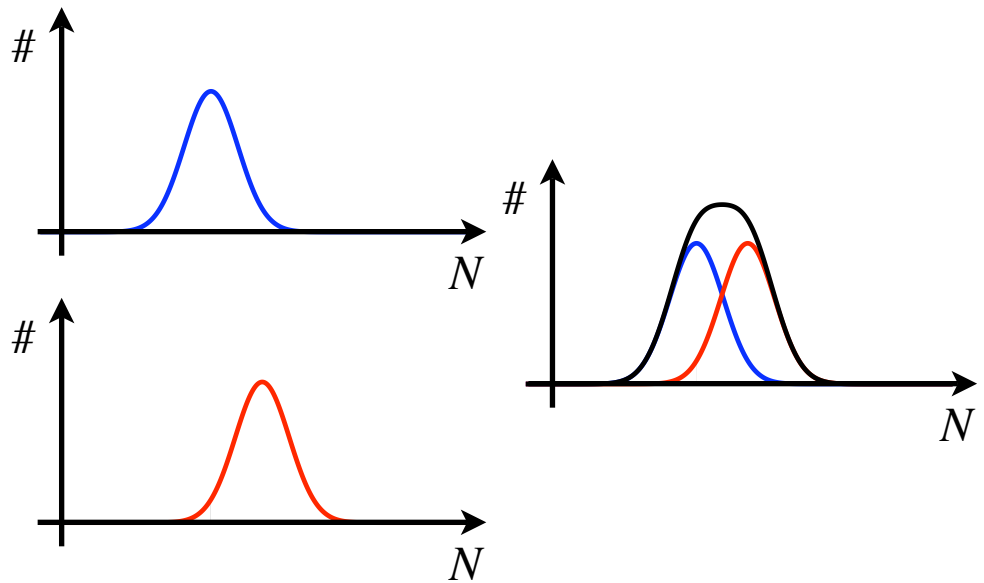
Critical point effect:
M. Stephanov, K. Rajagopal, E. Shuryak,
Phys.Rev.D60:114028,1999
and private communication

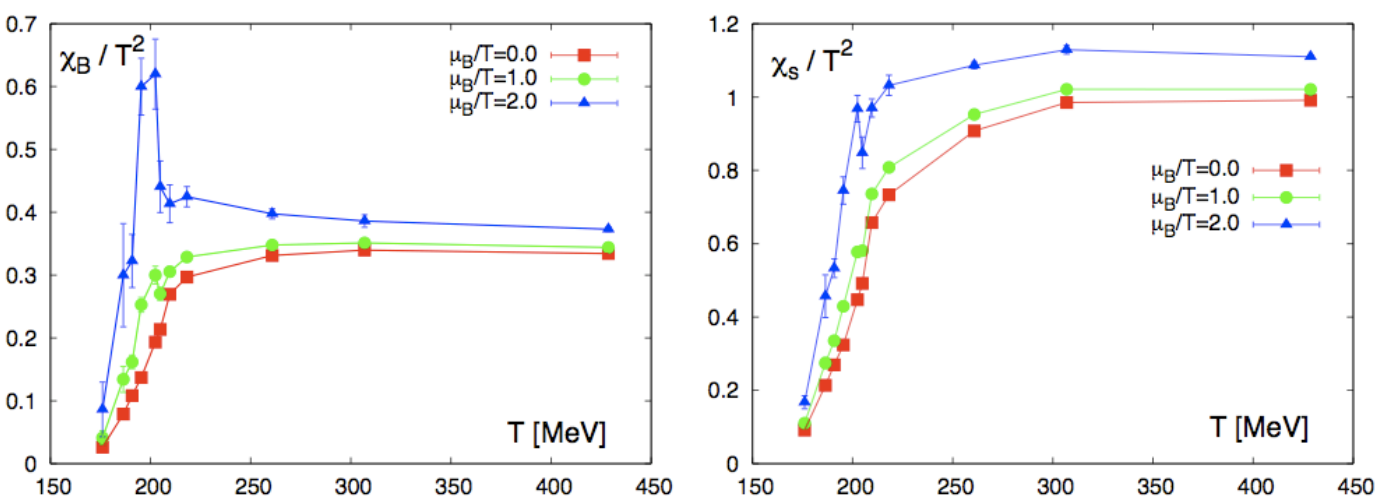
| | |
|---|---|
| Onset of deconfinement? | No sensitivity |
| Critical point? | No signal observed |

# Strangeness Fluctuations

- Original idea:
  - Change of strangeness production at the phase transition
  - Two event classes
  - Larger fluctuations in the mixed phase



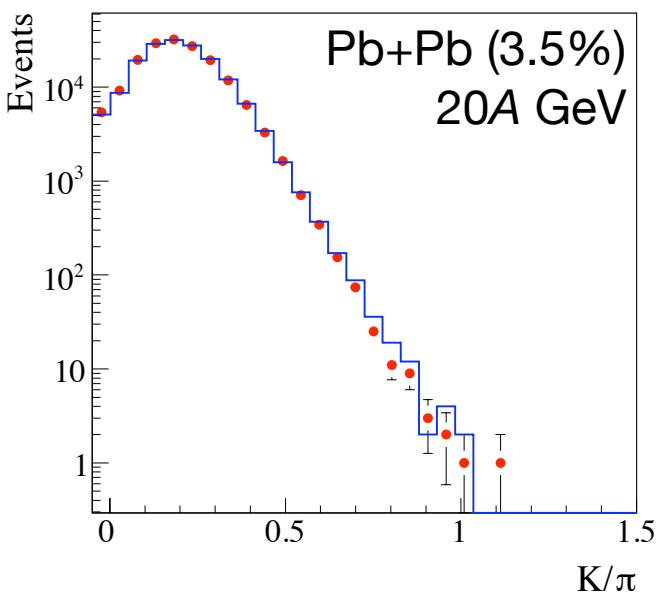

- Lattice calculations show change in quark number susceptibilities
  - For light and strange quarks
  - Smooth transition at $\mu_B = 0$
  - Divergence at the critical point

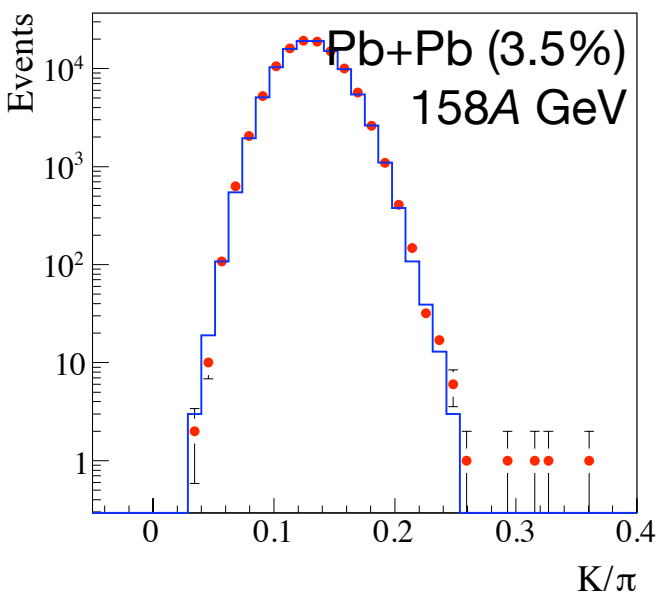



F. Karsch, PoS (CPOD07) 026

# Particle Ratio Fluctuations

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

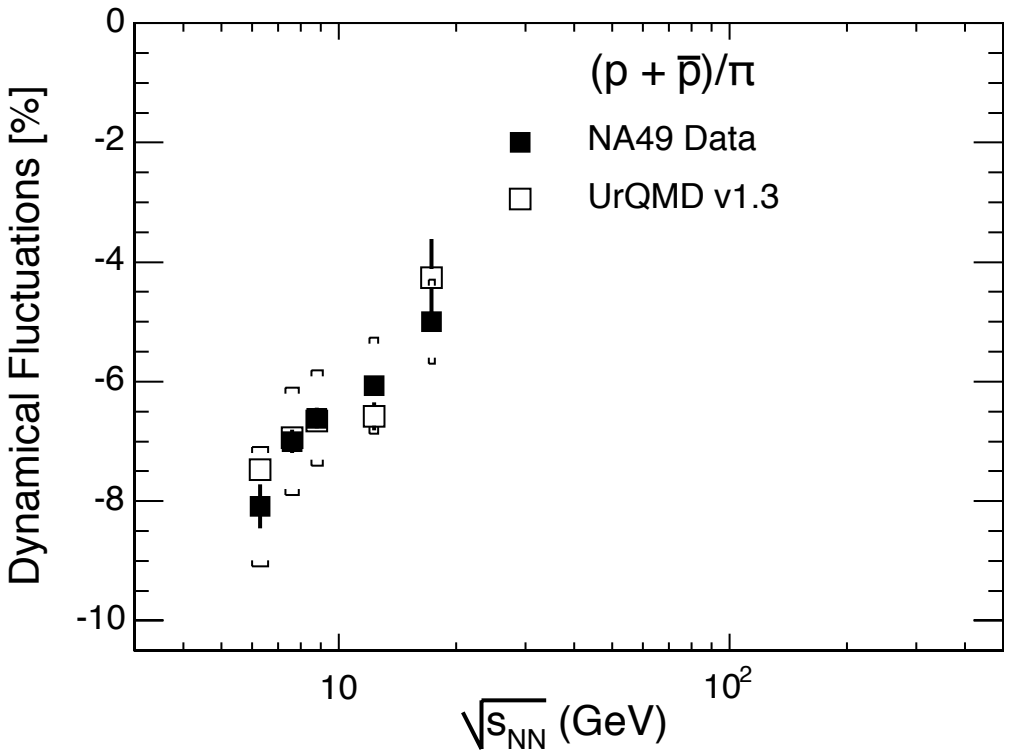



- Extract *dynamical* fluctuations as quadratic difference of relative widths:

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

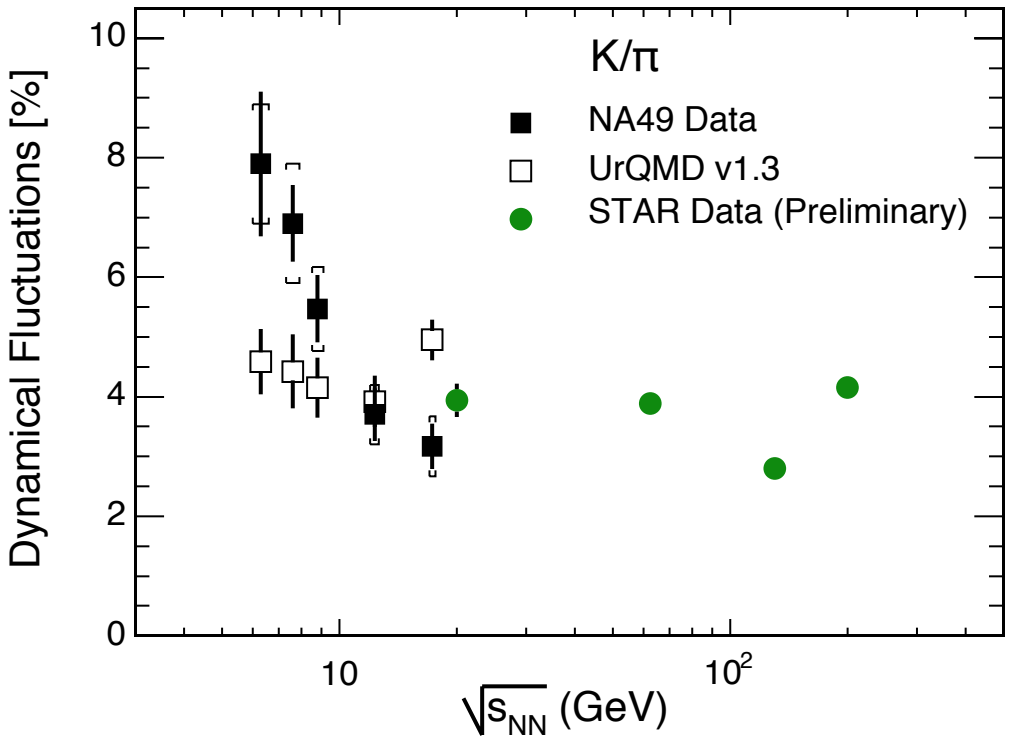
# Particle Ratio Fluctuations




- p/π: Negative dynamical fluctuations
  - Can be understood in terms of resonance decay
  - Energy dependence reproduced in hadronic model (UrQMD)

arXiv:0808.1237 [nucl-ex]
Submitted to Phys. Rev. C

# Particle Ratio Fluctuations




- K/π: Positive dynamical fluctuations
  - Steep rise towards low SPS energies
  - Cannot be reproduced in hadronic model (UrQMD)
  - No variation from top SPS energy to RHIC energy

NA49: arXiv:0808.1237 [nucl-ex]
Submitted to Phys. Rev. C

STAR data: S. Das, J. Phys. G32 S541

Onset of deconfinement?

Critical point?

No quantitative predictions for $\sigma_{dyn}$

# Summary Energy Dependence

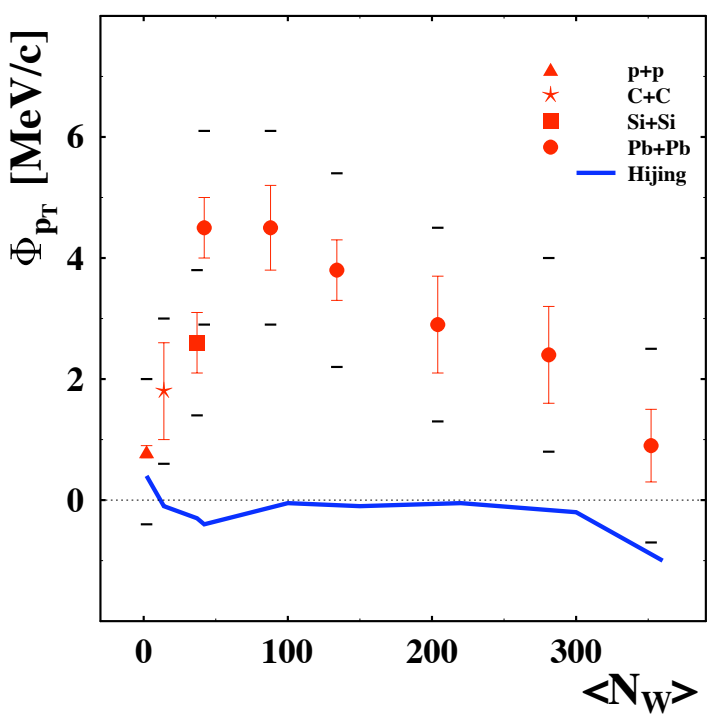
- NA49 Results on the energy dependence of fluctuations:

| | *Onset of deconfinement* | *Critical Point* |
|---|---|---|
| – Charge Fluctuations: | No sensitivity | No predictions |
| – $\langle p_T \rangle$ Fluctuations: | No predictions | No signal observed |
| – Multiplicity Fluctuations: | No sensitivity | No signal observed |
| – Hadron Ratio Fluctuations: | No quantitative predictions | |

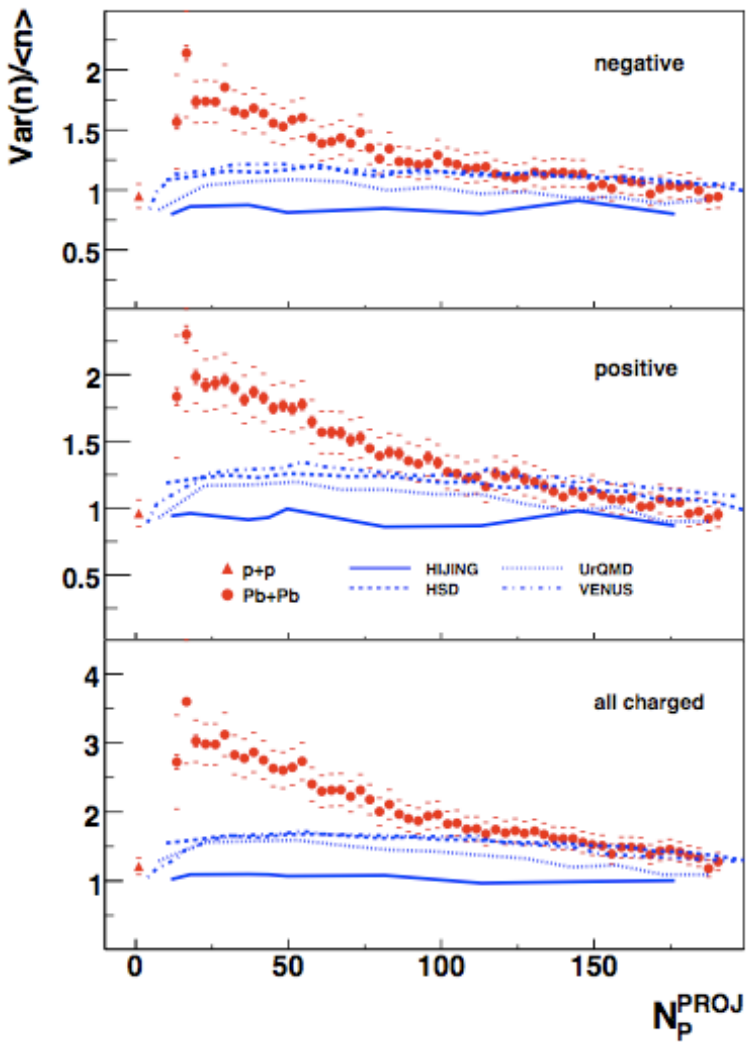
but the structure seen in the energy dependence of K/π fluctuations cannot be explained in a hadronic scenario!

# Centrality Dependence

- Centrality dependence at $E_{Beam}$ = 158*A* GeV:
  - Enhanced fluctuations in peripheral collisions not reproduced by transport models

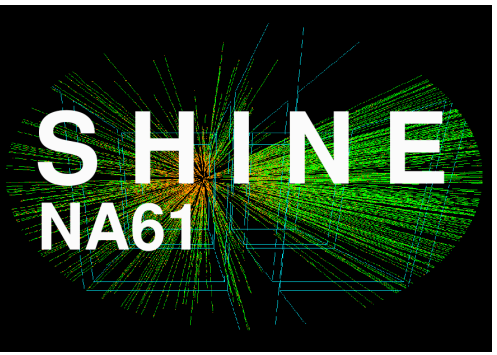



Phys.Rev. C70 034902, 2004




Phys. Rev. C75 064904, 2007

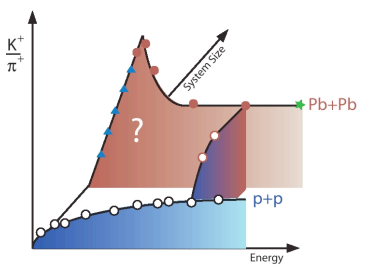
# Future SPS Ion Program

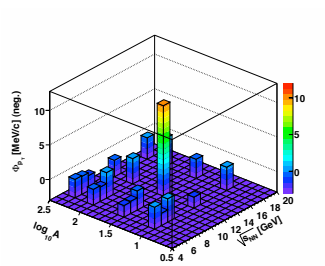



NA61 / SHINE:
A new SPS Ion Program based on NA49 detector

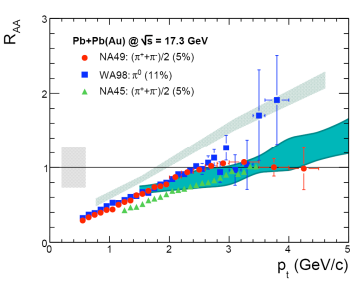
## 5 Main Physics Goals:

Study the properties of the *Onset of Deconfinement*

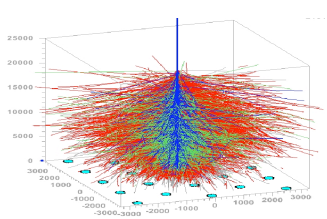


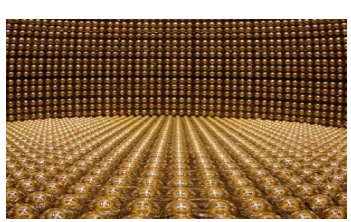



Discover the QCD *Critical Point*



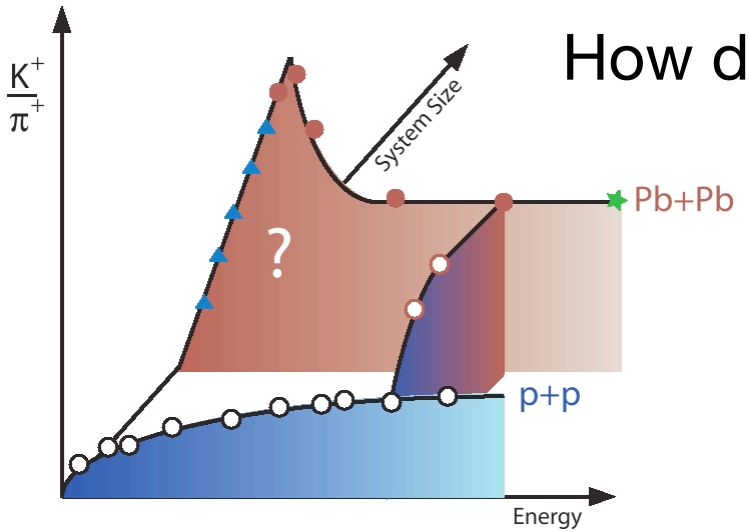

Increase range for *High* $p_T$ measurements at SPS





Provide important input for
*Cosmic Ray* and *Neutrino* physics

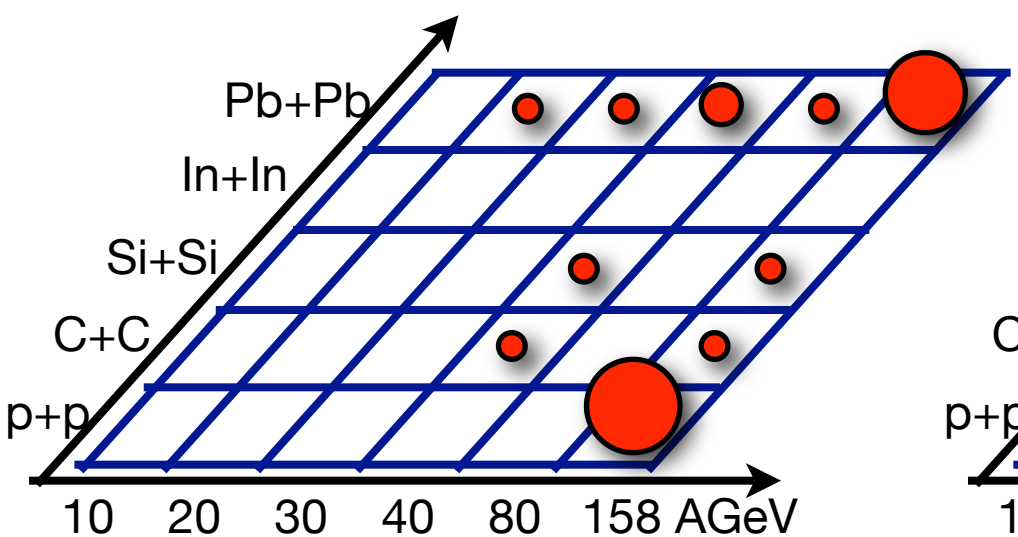
# Onset of Deconfinement



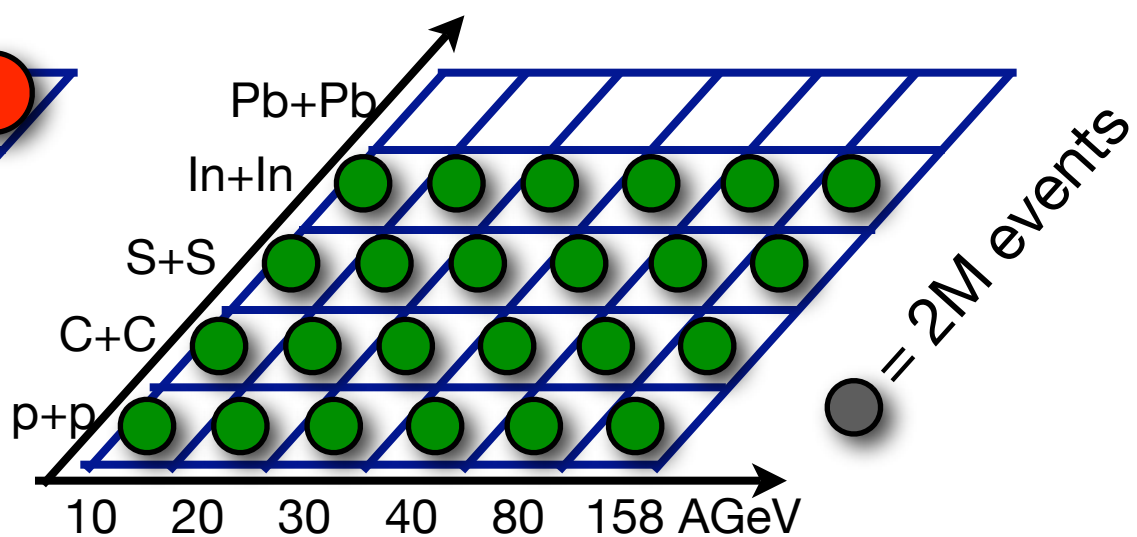

How do “horn” position and amplitude vary with system size?

→ Extend the original SPS energy and system size scan

NA49 energy and system size scan

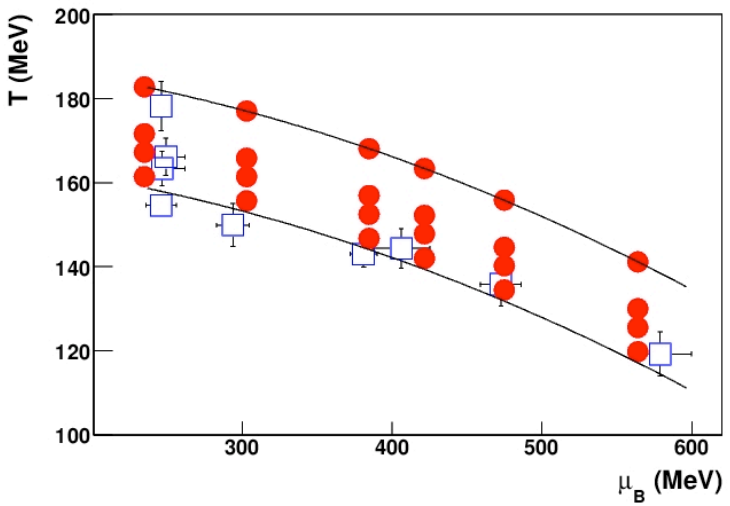



NA61/SHINE plan



# Critical Point

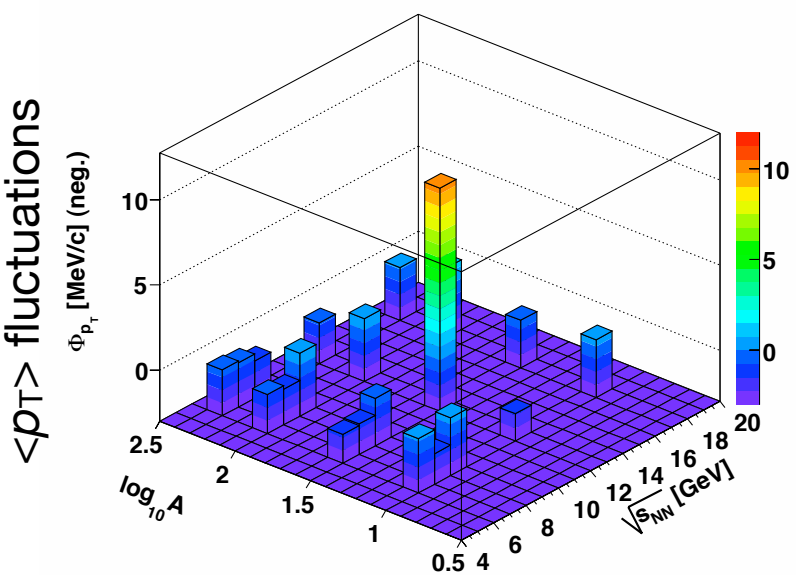
- Small systems freeze out at higher temperatures:
  - A 2-D scan ($T$,$\mu_B$) is possible by varying ($A$,$\sqrt{s}$)




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

- UrQMD simulation of fluctuations visible in the NA49 acceptance
- Anticipated critical fluctuations:
  ≈ 8 MeV/$c$
  (Stephanov, Rajagopal, Shuryak
  Phys.Rev.D60:114028 and Stephanov priv. comm.)

  Added to the S+S @ 80A GeV point



# Status and Schedule

| | | |
|---|---|---|
| 2006 | p+Pb | Test run |
| 2007 | p+C | Neutrino physics<br>detector R&D |

*1 month p beam successfully completed, results are coming*

| | | |
|---|---|---|
| 2008 | p+C, p+p | high $p_T$, cosmic ray & neutrino physics |

*Approved, will start end of August*

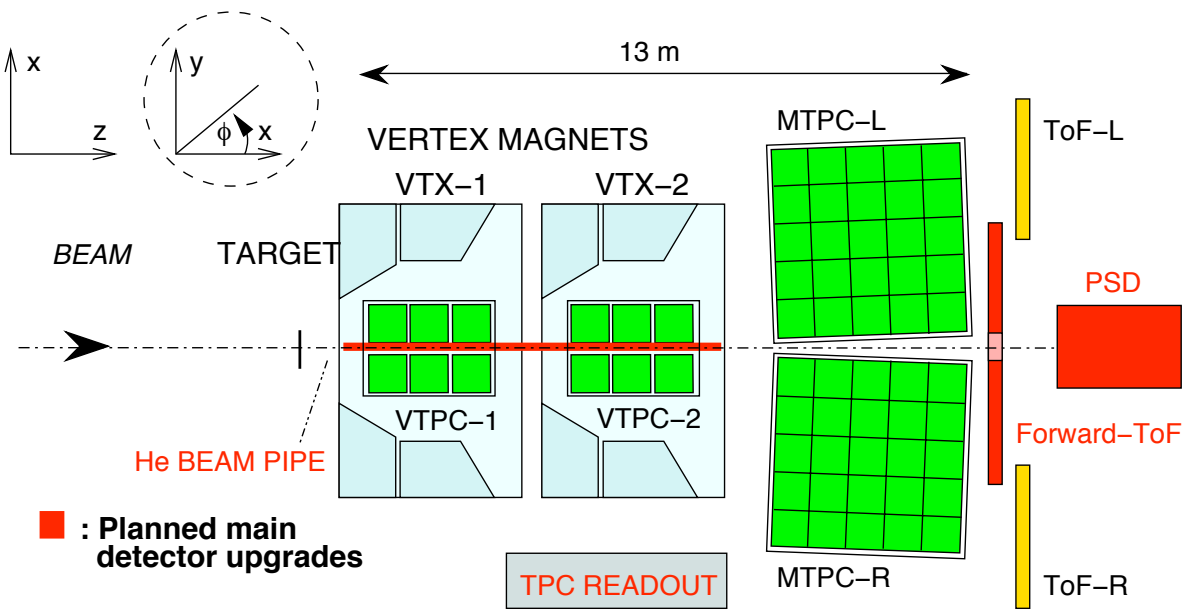
*proposed future runs:*

| | | |
|---|---|---|
| 2009 | p+Pb at 158A GeV | high $p_T$ |
| | p+p at 6 energies | |
| 2010 | p+Pb at 6 energies | |
| 2011 | S+S at 6 energies | |
| 2012 | C+C at 6 energies | |
| 2013 | In+In at 6 energies | |

Energy and system size scan for onset of deconfinement and critical point

# Detector Upgrade

- 2007: Installation of forward TOF detector complete
- 2008: Replacement of the TPC readout and DAQ by an ALICE-like system: Increase event rate to ≈ 100 Hz (= 10 * NA49)
- 2011: Replacement of the Veto Calorimeter by a Projectile Spectator Detector (PSD):
  - Increase the resolution to $\Delta E/E \approx 50\%/\sqrt{(E/1\text{GeV})}$
  - Possibly determine the reaction plane
- 2011: Installation of He beam pipe in Vertex TPCs:
  - Reduce background from δ electrons




R&D with CERN Gas Detector Development group on GEM detectors for centrality determination in p+A

Successful tests of PSD and GEM prototypes in 2006 test beam

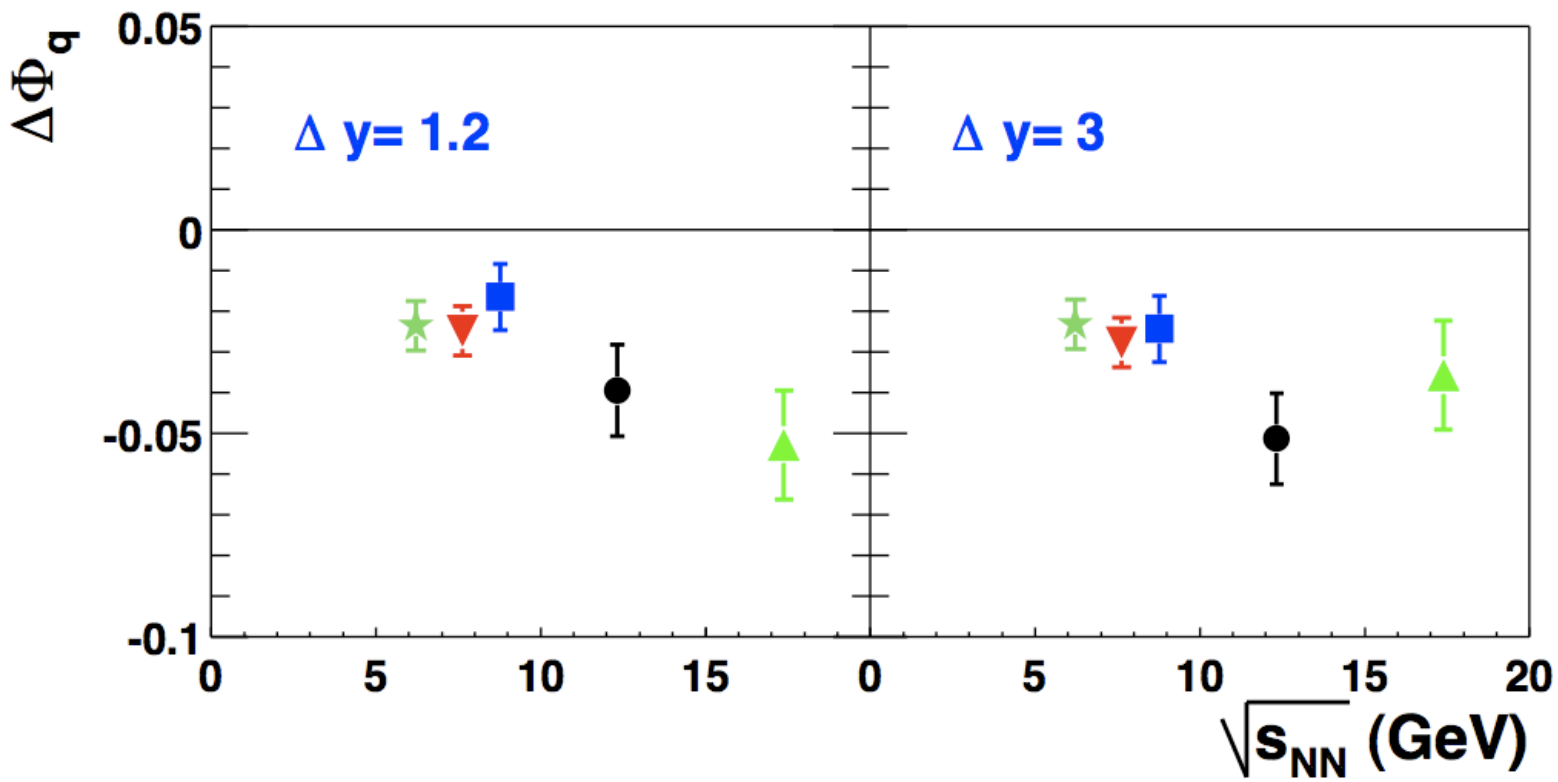
# Summary

- NA49 Results on Fluctuations show interesting results that still await an explanation:
  - Energy dependence of K/π ratio fluctuations
  - Centrality dependence of multiplicity and $\langle p_T \rangle$ fluctuations
- Search for the Critical Point at SPS: NA61/SHINE
  - NA61 will extend the NA49 energy/system size scan to study the onset of deconfinement and search for the critical point
  - Comparison to other worldwide efforts to scan the phase diagram:
    - RHIC energy scan: Systematic study with energy independent acceptance over a wide energy range ($5 < \sqrt{s_{NN}} < 200$ GeV)
    - CBM at FAIR: Measurement of rare probes at lower energies
    - NA61 adds a complementary system size scan and larger rapidity coverage
  - Start of ion beams in SPS in 2011

End.

# Net-Charge Fluctuations

Energy dependence of $\Delta\Phi_q$

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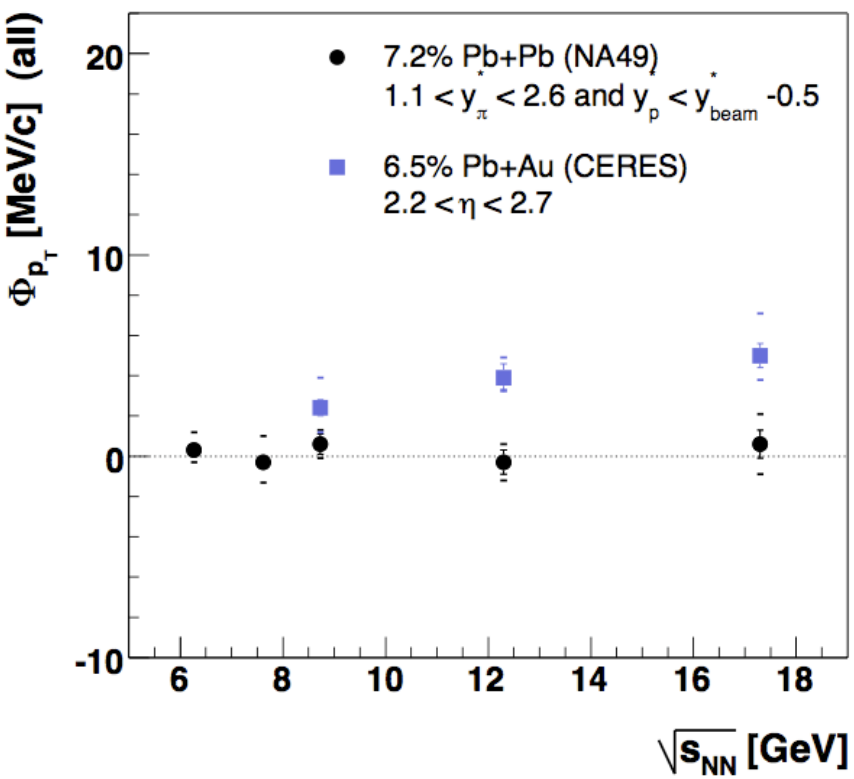
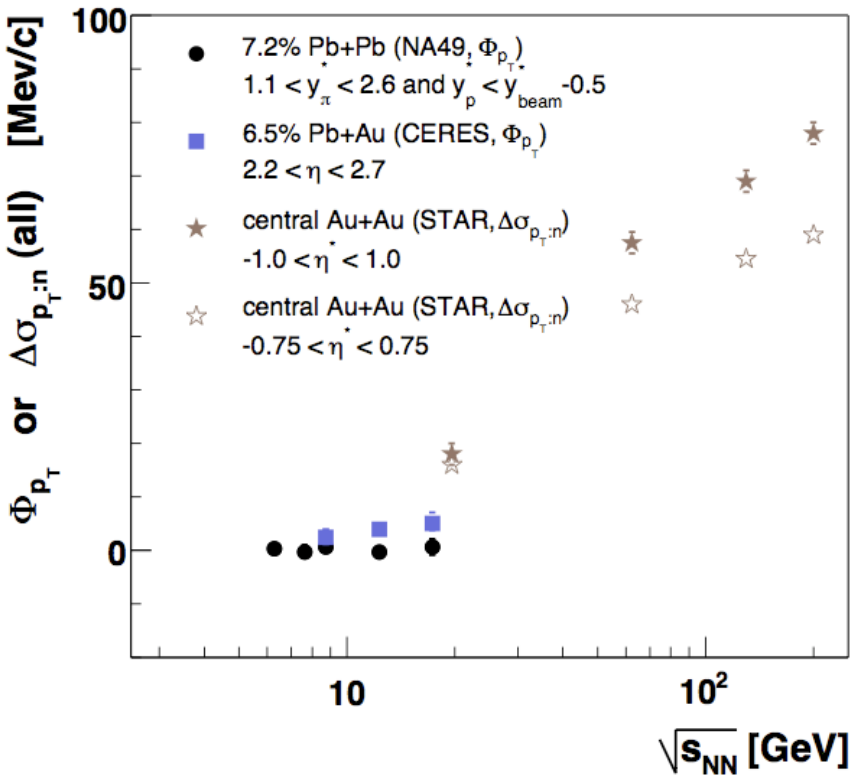
# $\langle p_T \rangle$ Fluctuations

Comparison to CERES and STAR results




NA49 preliminary