Recent Results from the Search for the Critical Point of Strongly Interacting Matter at the CERN SPS

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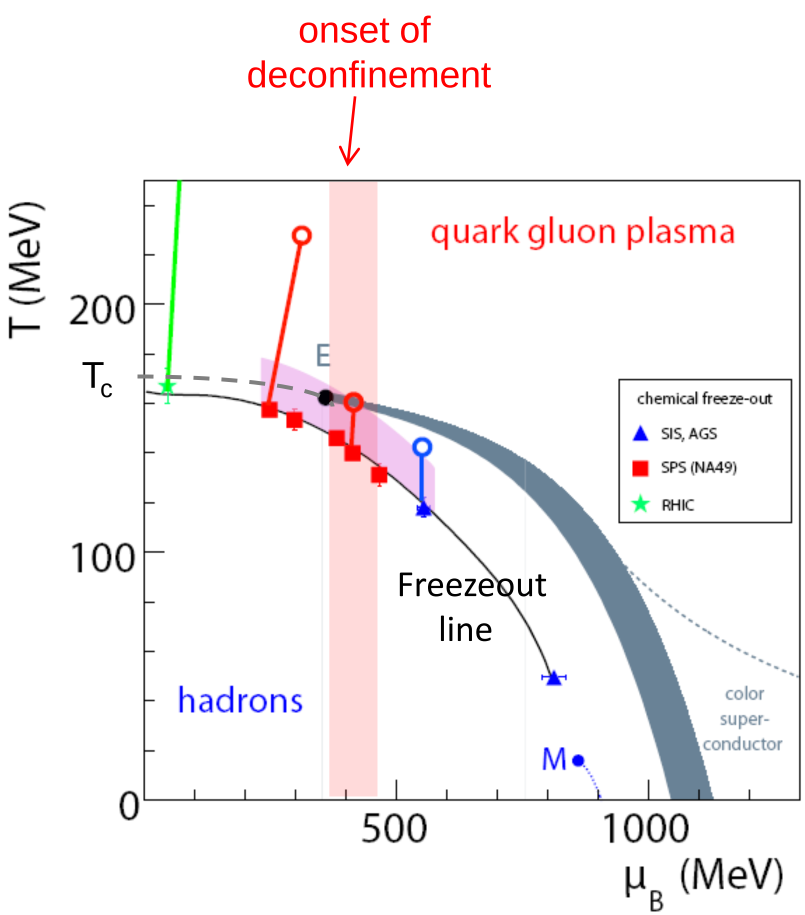
for the NA49 and NA61/SHINE collaborations

Phase diagram of strongly interacting matter

strongly interacting matter expected in the state of

hadrons at low energy density ε

quasi-free quarks and gluons at high ε



standard QCD considerations suggest 1st order phase boundary ending in a critical endpoint E

experimental study of A+A collisions found:

onset of deconfinement at ≅ 30A GeV

(NA49,C.Alt et al.,PRC77,024903(2008))

LQCD can provide quantitative predictions in the non-perturbative region of QCD

- indicates crossover transition for zero net baryon density ($\mu_B = 0$)
- not yet able to make firm predictions for the experimental case of $\mu_B > 0$

→ search for critical point via fluctuations above energy of onset of deconfinement

recent LQCD based estimates of critical point location :

- critical point potentially accessible:
  - Z.Fodor, S.Katz JHEP 04,50(2004)
    $T = 147$ MeV, $\mu_B = 360$ MeV
  - S.Datta, R.Gavai, S.Gupta Nucl.Phys.A905-905,883c(2013)
    $T = 0.96\ T_c$, $\mu_B / T = 1.8$ $\rightarrow \mu_B \approx 290$ MeV

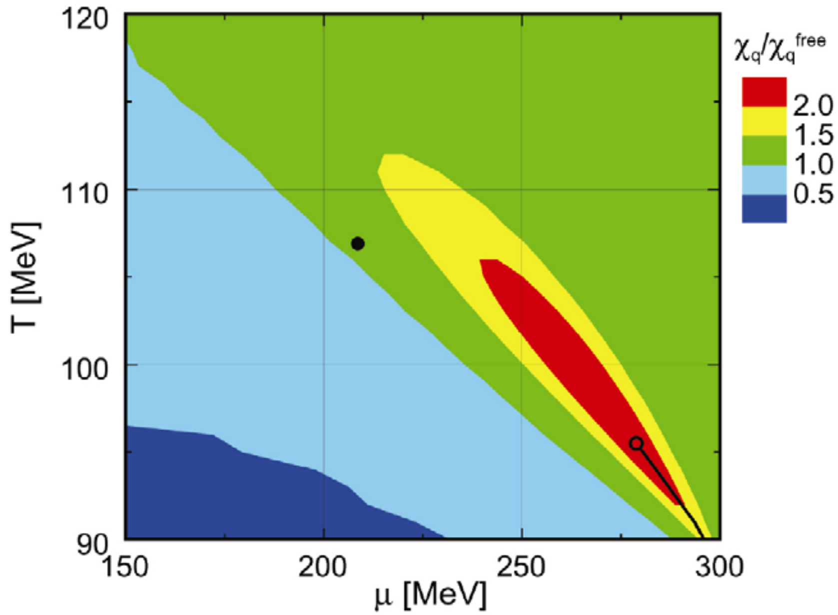
- unobservable in A+A collisions ?
  - A.Li, A.Alexandru, K.-F.Liu PRC D84,071503(2011)
    $T = 157$ MeV, $\mu_B = 441$ MeV
    system does not reach deconfinement !

- critical point does not exist
  - Ph.de Forcrand, O.Philipsen JHEP 11,012(2008)
    G.Endrödi, Z.Fodor, S.Katz, K.Szabo JHEP 1104,001(2011)
    extrapolation (Taylor expansion) to finite $\mu_B > 0$ leads to a weakening of the phase transition and a crossover

potentially observable signatures of the critical point

- enhanced event-to-event fluctuations of integrated quantities e.g. N, <p_T>, …
- strong local particle density fluctuations (intermittency)

effects of the critical point are expected over a range of T,μ_B

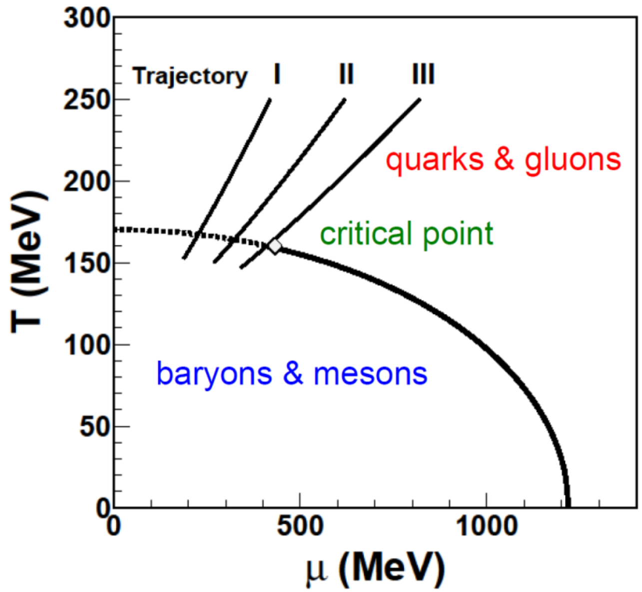


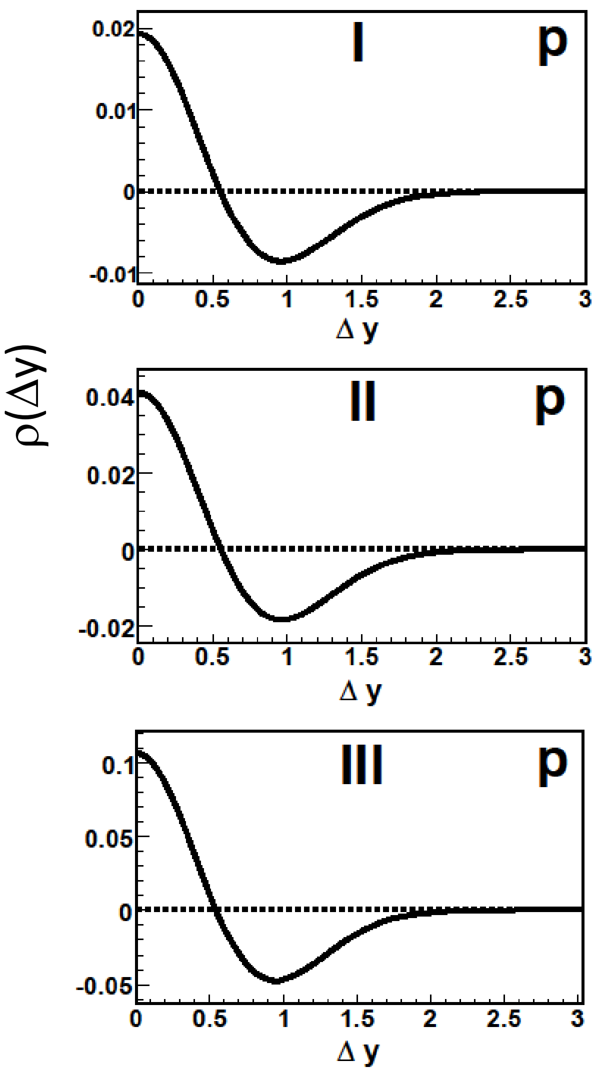
Y.Hatta and T.Ikeda,
PRD67,014028 (2003)

hydrodynamical evolution of fluctuations

J.Kapusta QM2012

Nucl.Phys.A904-905,887c(2013)





proton correlation function:

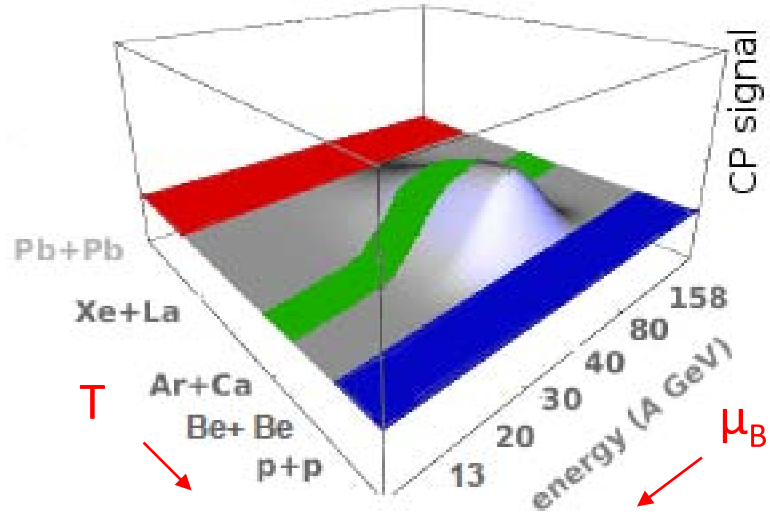
$$\rho(y_1, y_2) = \left\langle \frac{dN(y_2)}{dy_2}\frac{dN(y_1)}{dy_1} - \left\langle \frac{dN}{dy} \right\rangle^2 \right\rangle \left\langle \frac{dN}{dy} \right\rangle^{-1}$$

magnitude decreases with the distance at which the trajectory passes by the critical point

search strategy: 2-d scan in A,E ($\rightarrow T,\mu_B$) of phase diagram

expect “hill” of fluctuations

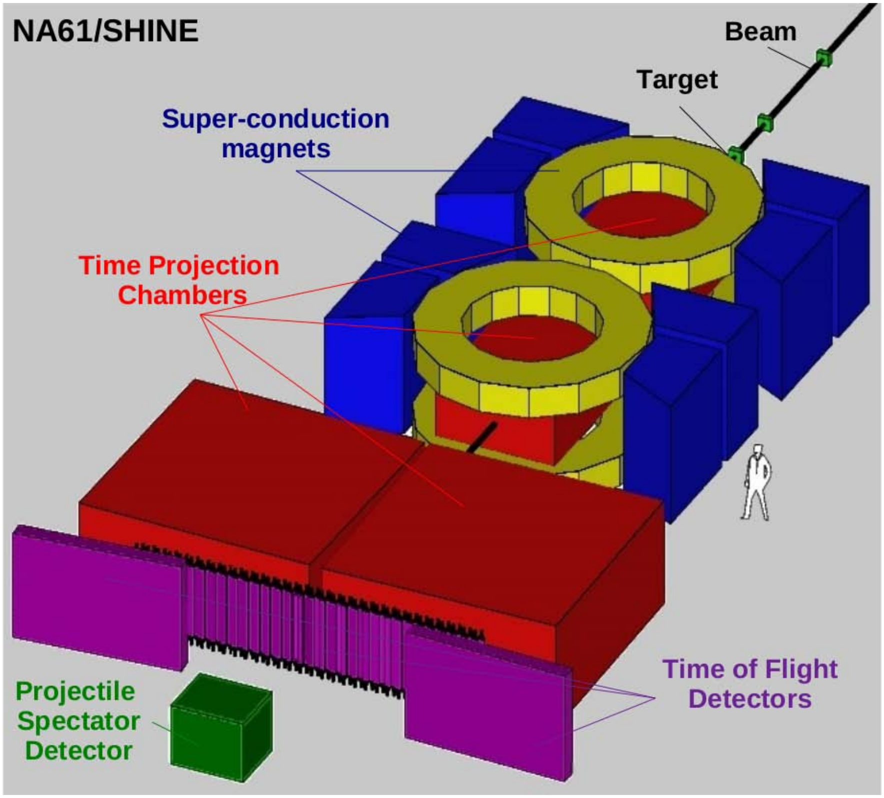
experimental control parameters:
- collision energy $\rightarrow \mu_B$
- size A of colliding nuclei
  - $\rightarrow$ duration of evolution after hadrochemical freezeout
  - $\rightarrow$ slight change of T ?



- expected size of fluctuation signals (ω, Φ_x ,…) $\propto \xi^2$ limited by short lifetime and size of collision system (correlation lengths ξ ~ 3 – 6 fm for Pb+Pb)

(M.Stephanov, K.Rajagopal,E.Shuryak, PRD60,114028(1999))

- deconfinement necessary for observing CP effect (E $\geq$ 30A GeV)
- can fluctuation signals survive later fireball evolution ??



NA49/NA61 Detector

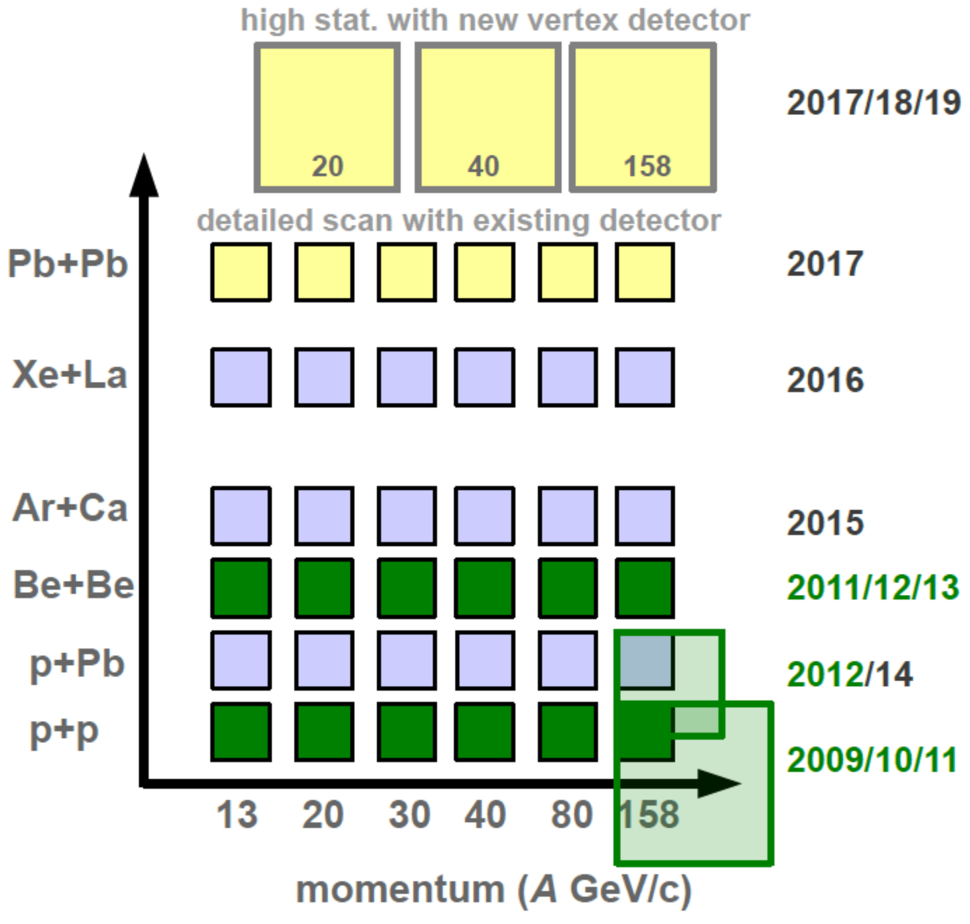
NA49 data taking 1994-2002

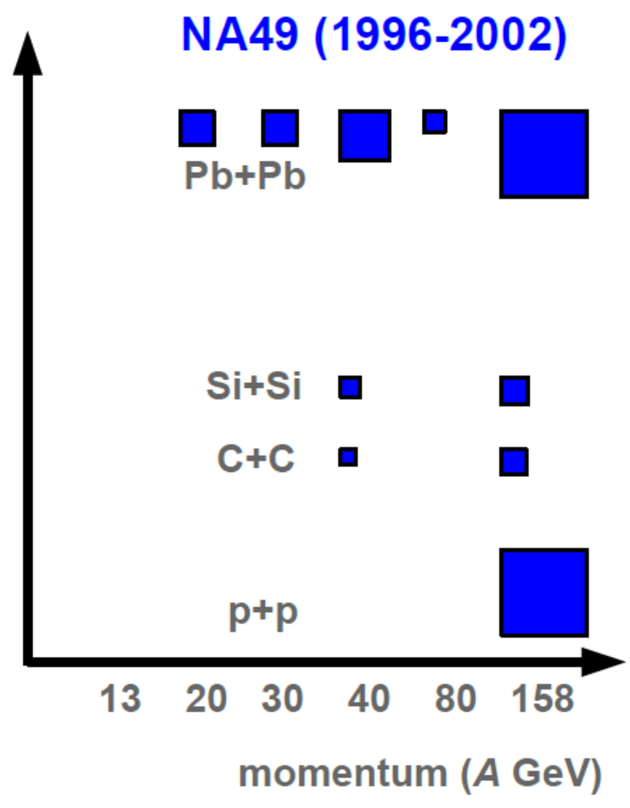
Pb+Pb at
20A,30A,40A,80A,158A GeV
($\sqrt{s_{NN}}$ =6.3, 7.6, 8.7,12.2,17.3 GeV)
+ some C+C, Si+Si at 158A GeV

reactivated in 2007 for NA61
A ,E scan in progress

- two superconducting magnets (1.5 T, 9 Tm bending power)
- four time projection chambers (180k channels, $\sigma_{dE/dx} \approx 4\%$)
- time-of-flight walls (1800 pixels, $\sigma_{TOF} \approx 60$ps)
- PSD replaced old NA49 zero degree calorimeter
- He filled beam pipe in TPCs reduces δ-ray background
- data acquisition system speeded up by factor 10
- acceptance: all p_T , forward cms rapidity

recorded and planned data of NA49 and NA61/SHINE (ion program)





event-to-event fluctuation measures studied by NA49/NA61

- scan in nuclear size A $\rightarrow$
  comparisons require "intensive" measures independent of volume
- unavoidable impact parameter fluctuations $\rightarrow$
  use "strongly intensive" measures independent also of volume fluctuations

scaled variance of the multiplicity distribution P(N) $\rightarrow$ ω, intensive

$$\omega = \frac{Var(N)}{<N>} = \frac{<N^2> - <N>^2}{<N>}$$

fluctuations of $<p_T>$ $\rightarrow$ Φ_{pT}, strongly intensive M.Gazdzicki, S.Mrowczyski, Z.Phys.C54,127(1992)

$$\Phi_{p_T} = \sqrt{\frac{<Z^2>}{<N>}} - \sqrt{\overline{z^2}} \; ; \; z = p_T - \overline{p_T} \; , \; Z = \sum_{i=1}^{N} (p_T^i - \overline{p_T})$$

strongly intensive measures can be constructed from 1st and 2nd moments of extensive event observables , e.g. P_T and N: M.Gorenstein,M.Gazdzicki, PRC84,014904(2011) M.Gazdzicki et al.,arXiv:1303.0871(2013)

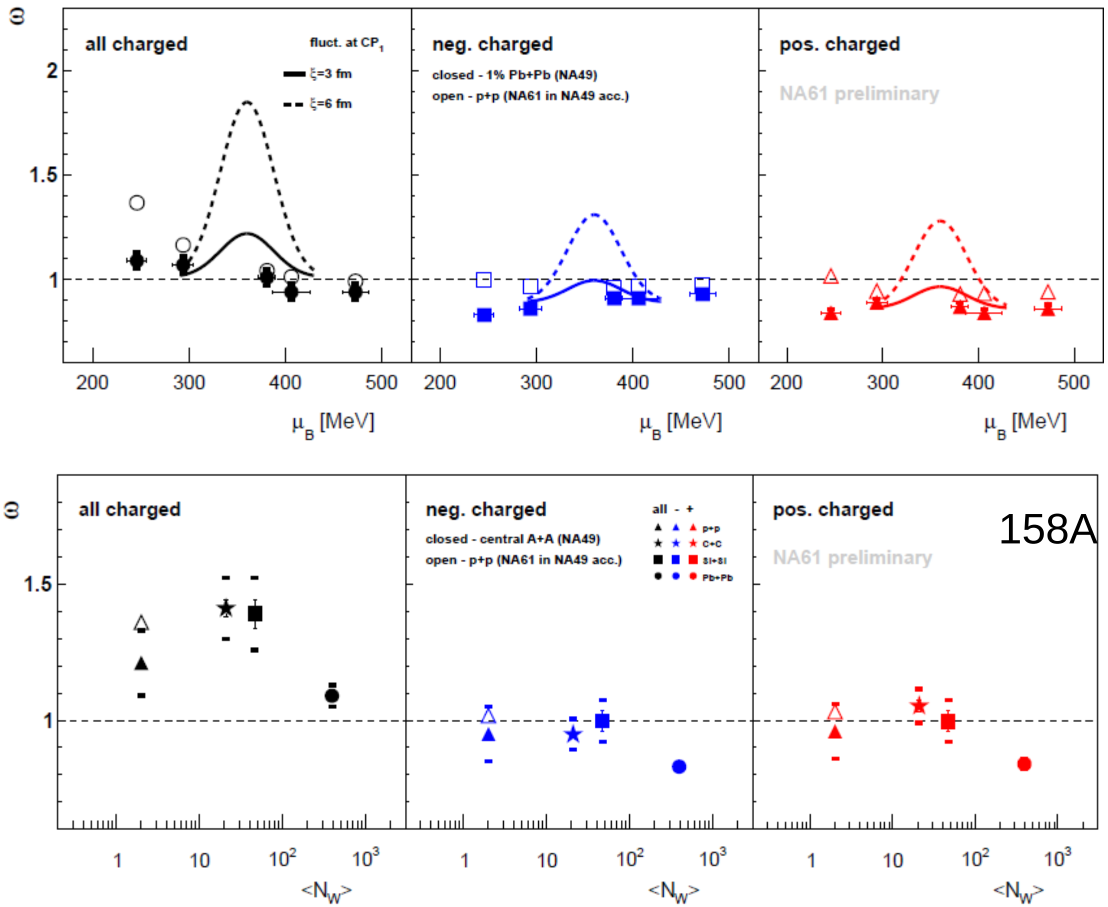
$$\Sigma^{P_T,N} = \frac{1}{C_\Sigma}\left[\langle P_T \rangle \omega(N) - \langle N \rangle \omega(P_T)\right]$$

$$\Delta^{P_T,N} = \frac{1}{C_\Delta}\left[\langle P_T \rangle \omega(N) + \langle N \rangle \omega(P_T) - 2\left(\langle N \cdot P_T \rangle - \langle N \rangle \langle P_T \rangle\right)\right] \; , \qquad P_T = \sum_{i=1}^{N} p_T^i$$

independent particle production: $\omega = 1 \; , \quad \Phi_{p_T} = 0 \; , \quad \Sigma^{P_T,N} = \Delta^{P_T,N} = 1$

fluctuations of the multiplicity of charged particles

NA49 results for 1% most central Pb+Pb collisions (PRC78,034914(2008))
NA61 results for inelastic p+p collisions (preliminary)



CP predictions based on M.Stephanov

NA61 p+p: statistical errors only

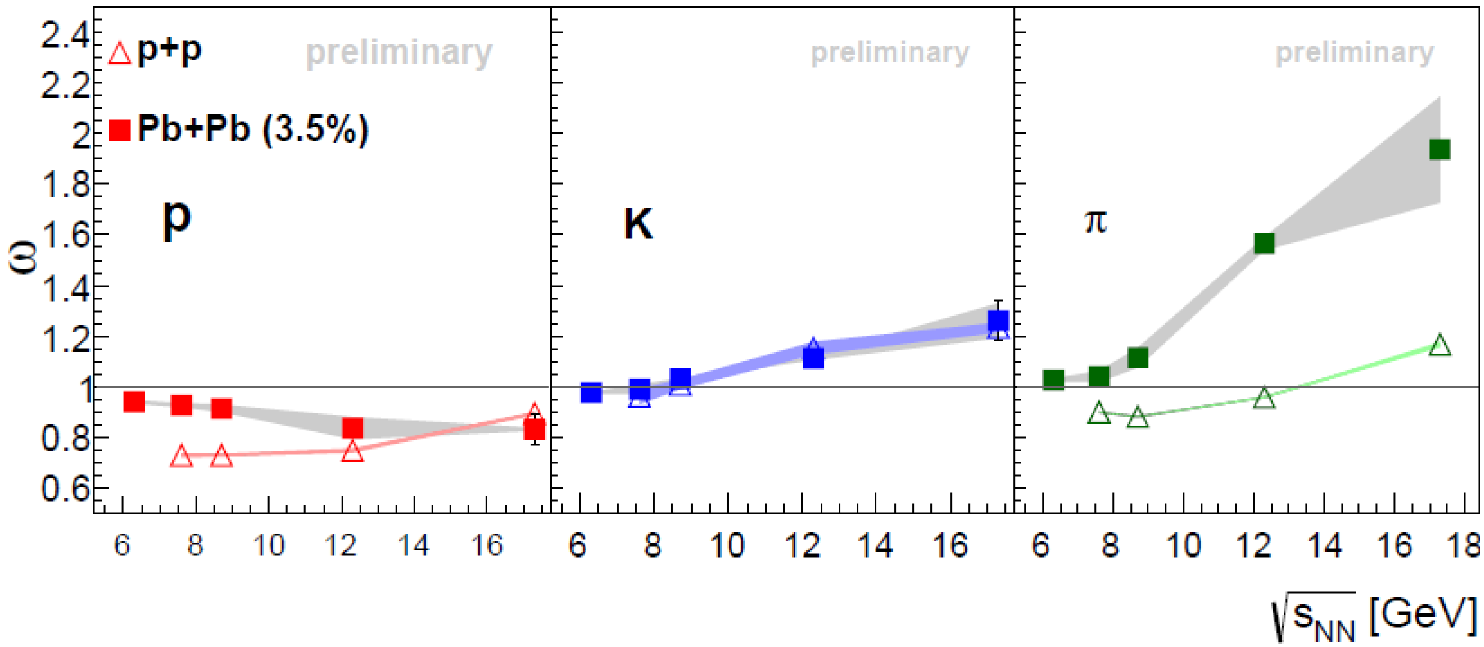
158A GeV

rapidity $y_\pi > 1.0$

- no indication of a bump in the μ_B (energy) dependence of ω
- indication of a maximum for collisions of medium size nuclei

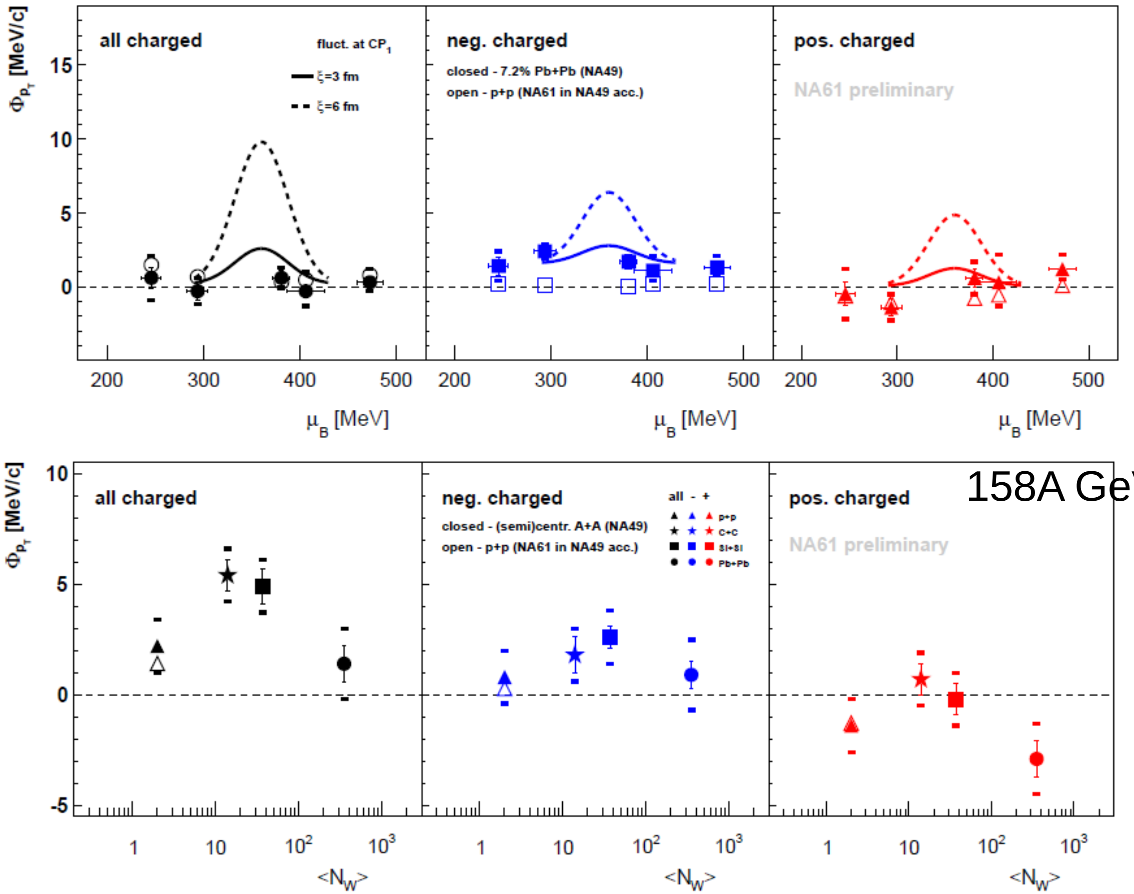
fluctuations of the multiplicity of identified p, K, π

preliminary NA61/NA49 results from identity analysis



- no indication of a bump in the energy dependence of ω
- higher moments more sensitive (M.Stephanov: PRL102,032301(2009))
- systematic uncertainties too large in NA49 data

fluctuations of the average transverse momentum: Φ_{p_T}



CP predictions based on M.Stephanov

rapidity $y_\pi > 1.1$

158A GeV

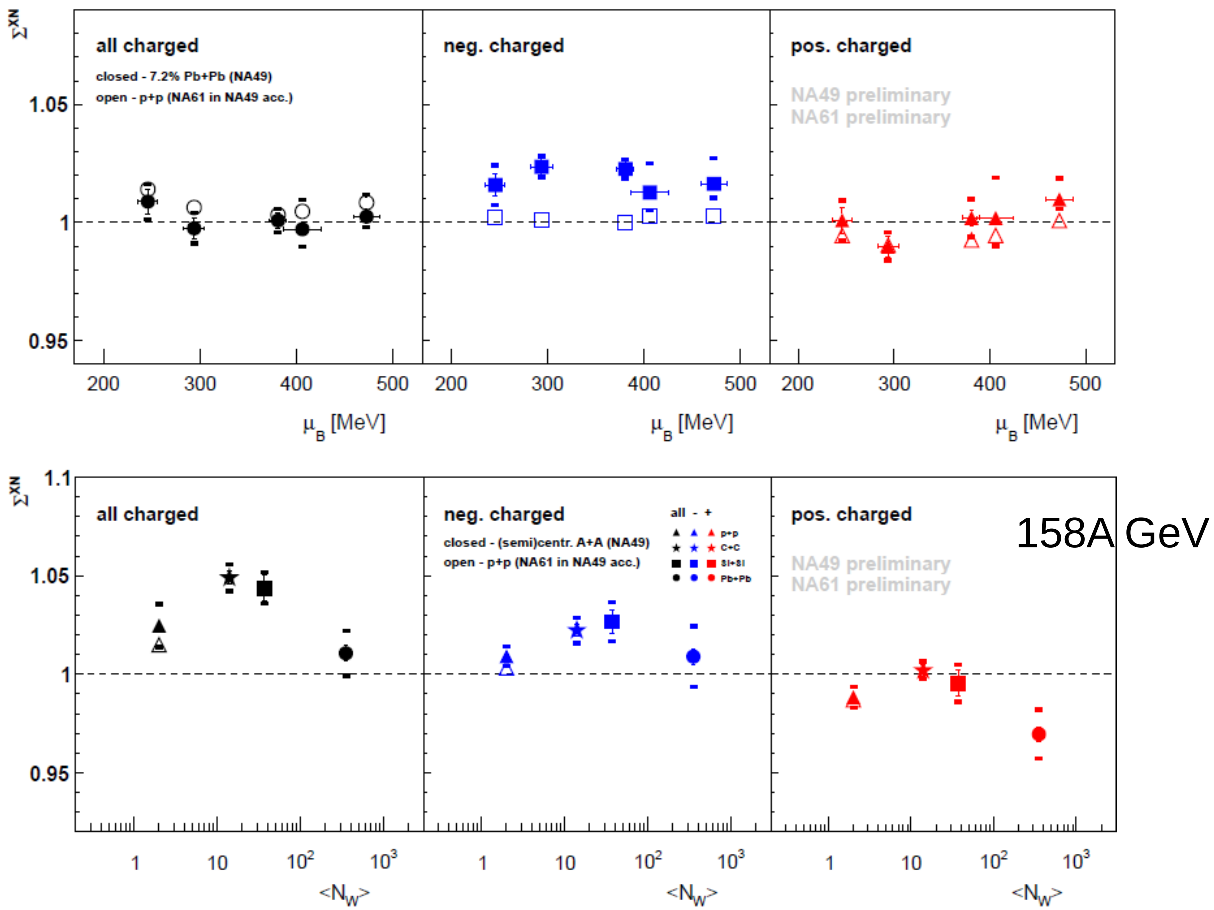
NA49:
Pb+Pb 5% central
PRC79,044904(2009)
PRC70,034902(2004)

NA61:
p+p preliminary

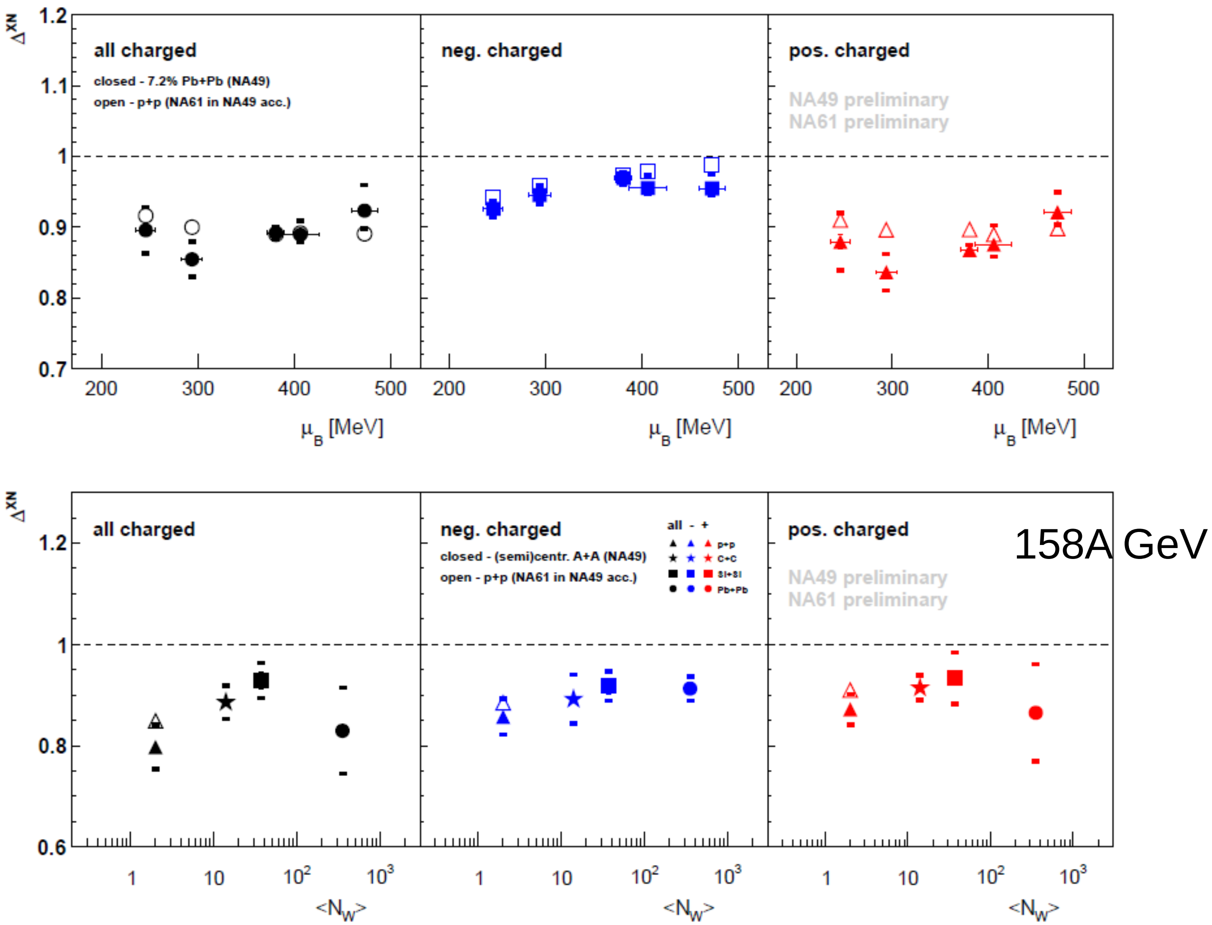
- no indication of a bump in the μ_B (energy) dependence of Φ_{pT}
- indication of maximum for collisions of medium size nuclei

fluctuations of transverse momentum: $\Sigma^{P_T,N}$

Φ_{p_T} and $\Sigma^{P_T,N}$ are related $\rightarrow$ $\Phi_{p_T} = \sqrt{\overline{p_T} \cdot \omega(p_T)} \cdot \left[\sqrt{\Sigma^{P_T,N}} - 1 \right]$



fluctuations of transverse momentum: $\Delta^{P_T,N}$



similar conclusion from new strongly intensive measures $\Sigma^{P_T,N}$, $\Delta^{P_T,N}$

search for critical point fluctuations via factorial moment analysis

N.Antoniou et al., NPA693,799(2001); PRL97,032002(2006)

- at the critical point local density fluctuations with power-law singularity are expected both in configuration and momentum space
  - σ field: density of σ particles, related to low-mass $\pi^+\pi^-$ pairs
  - baryonic density: related to net baryon density (≈ protons)

- experimental observation via 2nd factorial moments of the multiplicity in p_T space, subdivided into M bins in $p_{T,x}$ and $p_{T,y}$

$$F_2(M) = \left\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i(n_i - 1) \right\rangle / \left\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i \right\rangle^2 \quad \propto \quad M^{2\Phi_2}$$

- estimate the background by mixed events and subtract

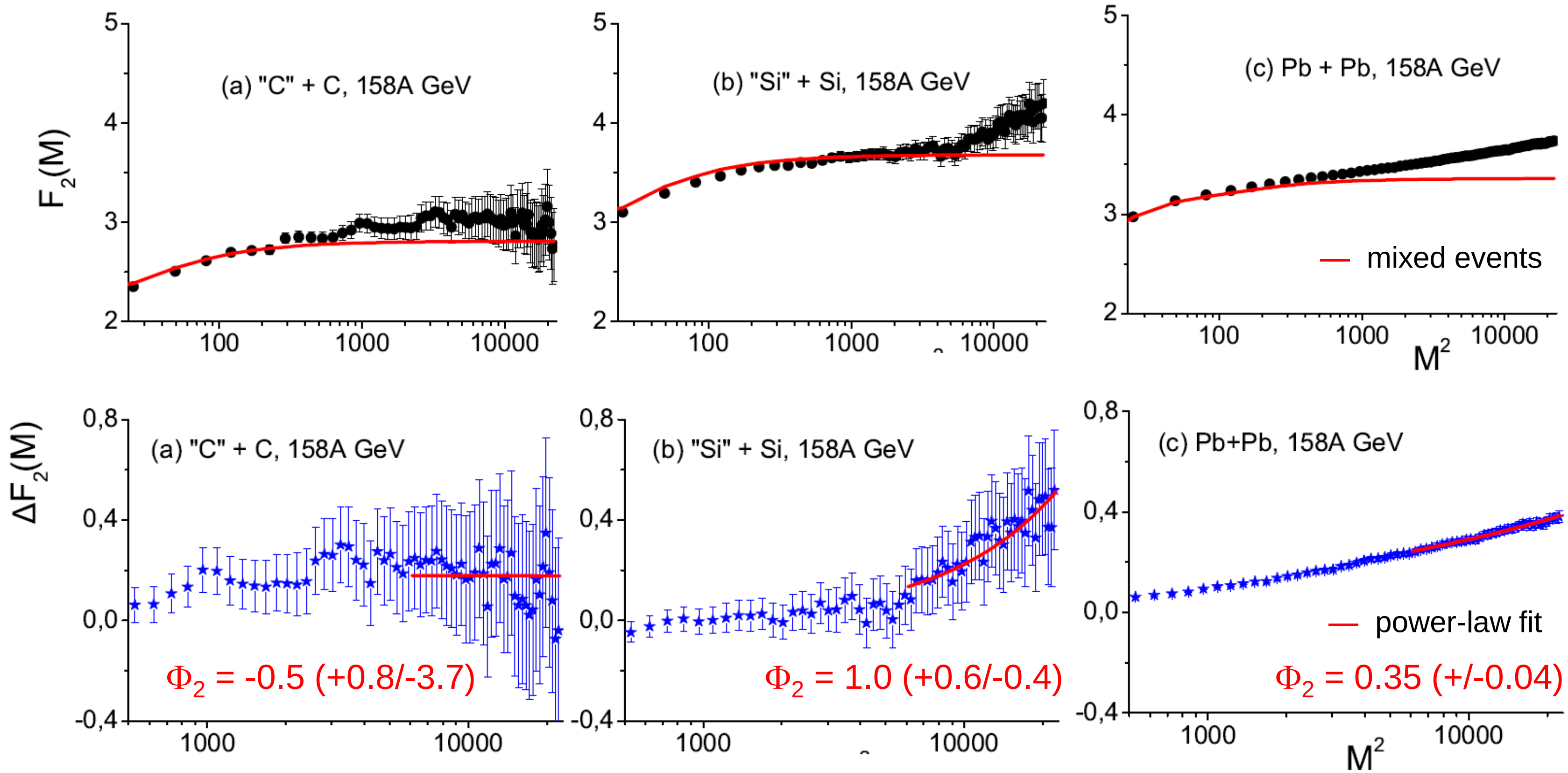
$$\Delta F_2(M) = F_2^{data} - F_2^{mix} \propto M^{2\Phi_2}$$

- predicted power-law index ϕ_2 - low-mass $\pi^+ \pi^-$ pairs 2/3
  - protons 5/6

proton factorial moments analysis

- protons identified by dE/dx measured in the TPCs, purity > 80 %
- cms rapidity $|y_{cms}| < 0.75$ (singularity expected at midrapidity)
- centrality 0 – 12.5 %

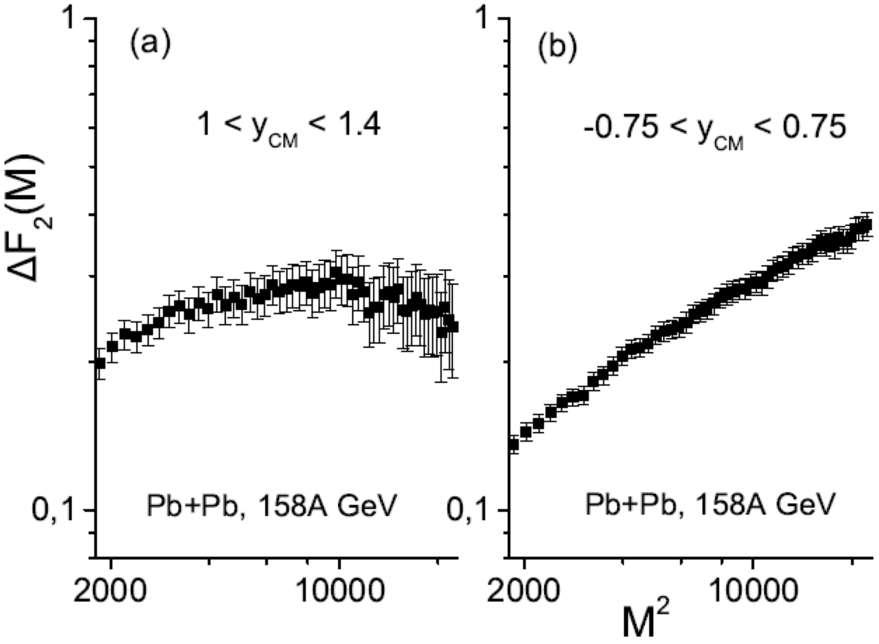
T.Anticic et al., arXiv:1208.5292



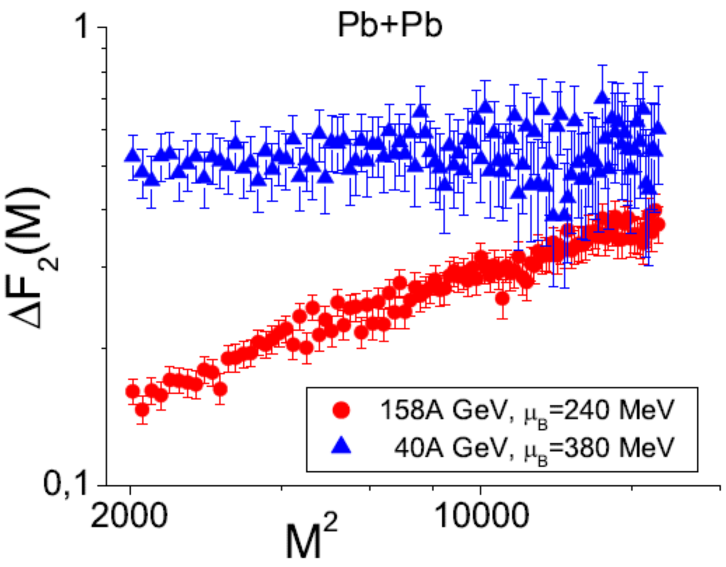
power-law behavior for protons in "Si"+Si and Pb+Pb at 158A GeV

statistics in central Pb+Pb collisions allows study of dependence on

rapidity



collision energy



no signal at higher rapidity as expected from theory

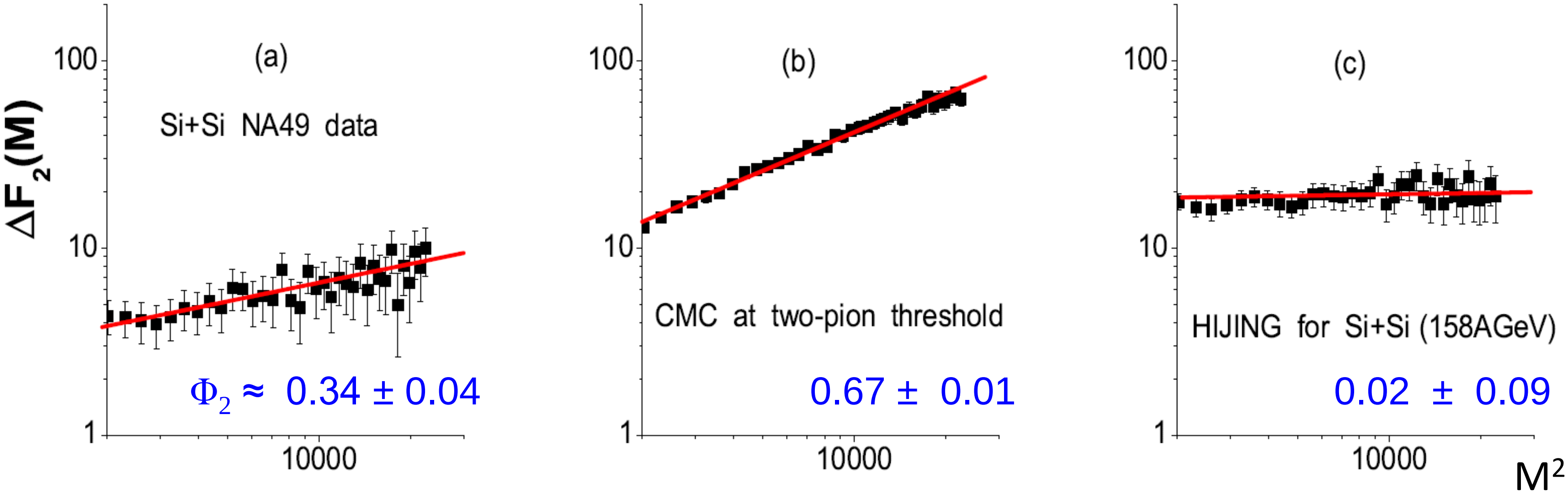
power-law signal disappears at lower collision energy

$\sigma \rightarrow \pi^+\pi^-$ factorial moments analysis

- pions identified by dE/dx measured in the TPCs
- select $\pi^+\pi^-$ pairs near threshold to reduce combinatorial background
- exclude Coulomb correlation region at very small Q_{inv}

NA49 results for central collisions at 158A GeV (centrality 0 – 12.5 %):

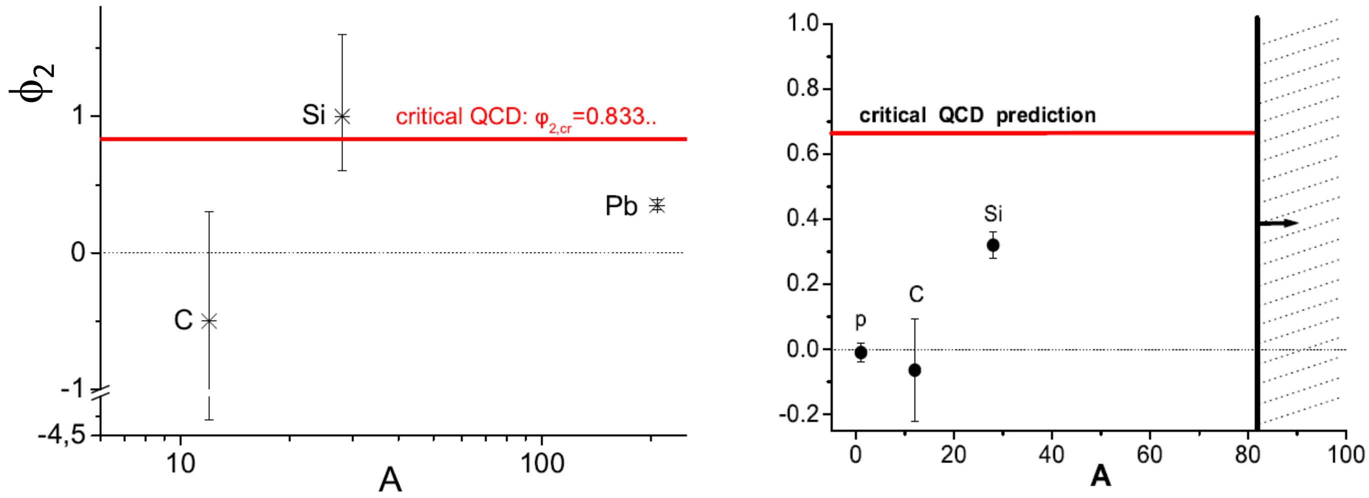
T.Anticic et al, PRC81,064907(2010)



power-law behavior observed for low-mass $\pi^+\pi^-$ pairs in central "Si"+Si collisions at 158A GeV

power law exponents fitted to background corrected factorial moments ΔF_2

protons | low-mass $\pi^+\pi^-$ pairs

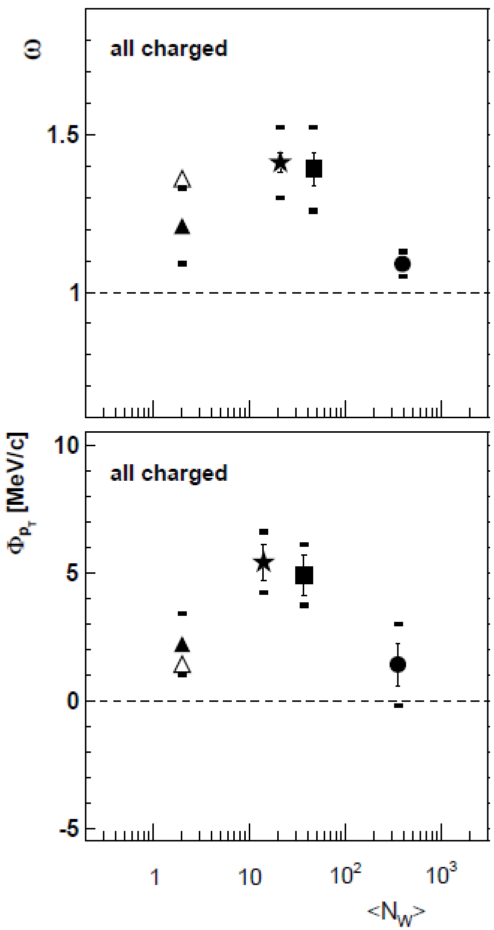


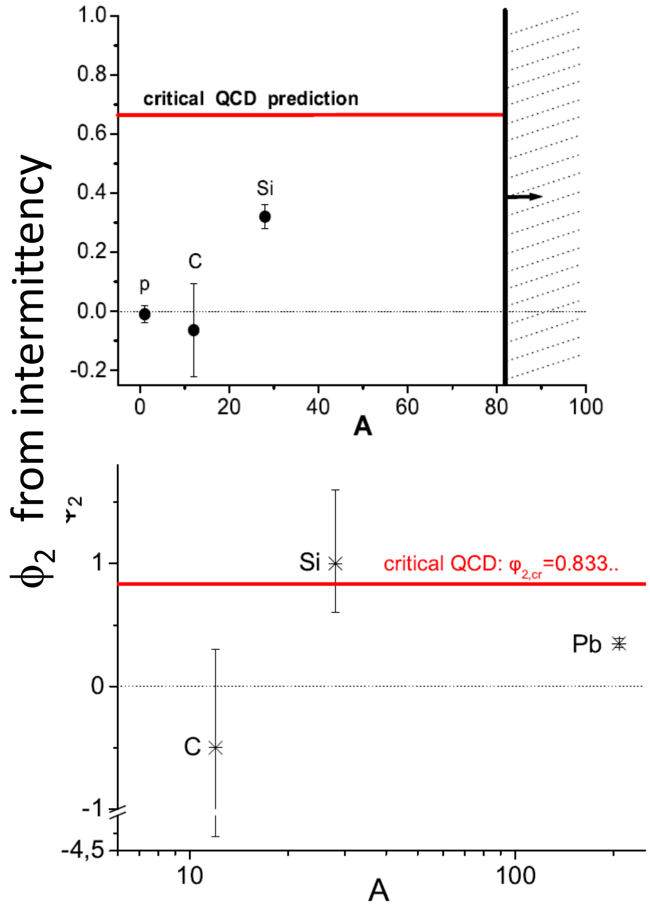
suggestive of maximum of power-law exponent ϕ_2 for central "Si"+Si collisions at 158A GeV

unfortunately NA49 statistics in Si+Si are marginal at 158A GeV and too small at other energies $\rightarrow$ we need the NA61 scan of A and $\sqrt{s_{NN}}$

fluctuations in NA49 possibly related to the critical point

(central collisions at 158A GeV)





$\sigma \to \pi^+ + \pi^-$

protons

fluctuations of multiplicity,<p_T>
power-law index Φ_2 of $\pi^+\pi^-$ and proton density fluctuations
reach maximum in collisions of medium size nuclei at 158A GeV

Conclusions

- the study of fluctuations in A+A collisions in the SPS and RHIC BES energy range offer the best chance to experimentally observe manifestations of the critical point of strongly interacting matter

- first results of NA49 from a 2d critical point search in A, $\sqrt{s_{NN}}$ ($\rightarrow$ T,μ_B) via fluctuation measurements show perhaps hints of a maximum for Si+Si collisions at 158A GeV

- NA49 results strongly motivate the ongoing NA61/SHINE program which already recorded energy scans of p+p and Be+Be collisions. Ar+Ca and Xe+In energy scans will follow in 2014/2015

- numerous other searches are in progress or planned:
  - analysis and continuation of the RHIC low energy scan
  - future programs at NICA and FAIR

NA49:

78 physicists from 23 institutes and 12 countries:

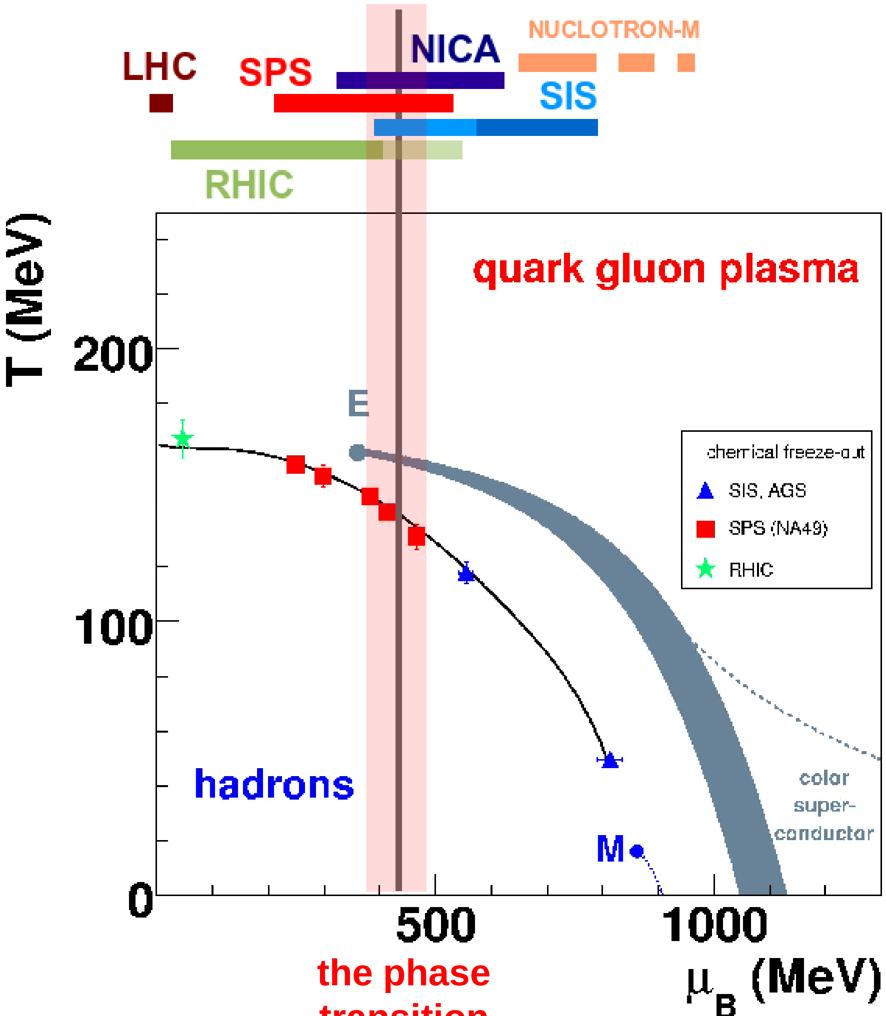
NIKHEF, Amsterdam, Netherlands
University of Athens, Athens, Greece
Comenius University, Bratislava, Slovenia
Eotvos Lorand University, Budapest, Hungary
KFKI IPNP, Budapest, Hungary
MIT, Cambridge, USA
INP, Cracow, Poland
Joint Institute for Nuclear Research, Dubna, Russia
GSI, Darmstadt, Germany
University of Frankfurt, Frankfurt, Germany
CERN, Geneva, Switzerland
Jan Kochanowski Univeristy, Kielce, Poland
University of Marburg, Marburg, Germany
MPI, Munich, Germany
Charles University, Prag, Czech Republic
University of Washington, Seattle, USA
Faculty of Physics, University of Sofia, Sofia, Bulgaria
Sofia University, Sofia, Bulgaria
INR&NE, BAS, Sofia, Bulgaria
State University of New York, Stony Brook, USA
Soltan Institute for Nuclear Studies, Warsaw, Poland
Warsaw University of Technology, Warsaw, Poland
University of Warsaw, Warsaw, Poland
Rudjer Boskovic Institute, Zagreb, Croatia

NA61:

134 physicists from 27 institutes and 15 countries:

University of Athens, Athens, Greece
University of Belgrade, Belgrade, Serbia
University of Bergen, Bergen, Norway
University of Bern, Bern, Switzerland
KFKI IPNP, Budapest, Hungary
Jagiellonian University, Cracow, Poland
Joint Institute for Nuclear Research, Dubna, Russia
Fachhochschule Frankfurt, Frankfurt, Germany
University of Frankfurt, Frankfurt, Germany
University of Geneva, Geneva, Switzerland
Forschungszentrum Karlsruhe, Karlsruhe, Germany
Institute of Physics, University of Silesia, Katowice, Poland
Jan Kochanowski Univeristy, Kielce, Poland
Institute for Nuclear Research, Moscow, Russia
University of Nova Gorica, Nova Gorica, Slovenia
LPNHE, Universites de Paris VI et VII, Paris, France
Faculty of Physics, University of Sofia, Sofia, Bulgaria
St. Petersburg State University, St. Petersburg, Russia
State University of New York, Stony Brook, USA
KEK, Tsukuba, Japan
Soltan Institute for Nuclear Studies, Warsaw, Poland
Warsaw University of Technology, Warsaw, Poland
University of Warsaw, Warsaw, Poland
Univeristy of Wroclaw, Wroclaw, Poland
Universidad Tecnica Federico Santa Maria, Valparaiso, Chile
Rudjer Boskovic Institute, Zagreb, Croatia
ETH Zurich, Zurich, Switzerland

relativistic nuclear collisions: future experimental landscape



the phase
transition
domain

partly complementary programs

CERN SPS 2011 →
$\sqrt{s_{NN}}$ = 5.1 – 17.3 GeV

BNL RHIC 2010 →
7.7(5 ?) – 200 GeV

JINR Nuclotron 2015
< ~ 3.5 GeV

JINR NICA 2017 →
4 – 11 GeV

GSI SIS-100 2017 →
2.3 – 4.5 GeV

SIS-300 ??
4.5 – 8.5 GeV