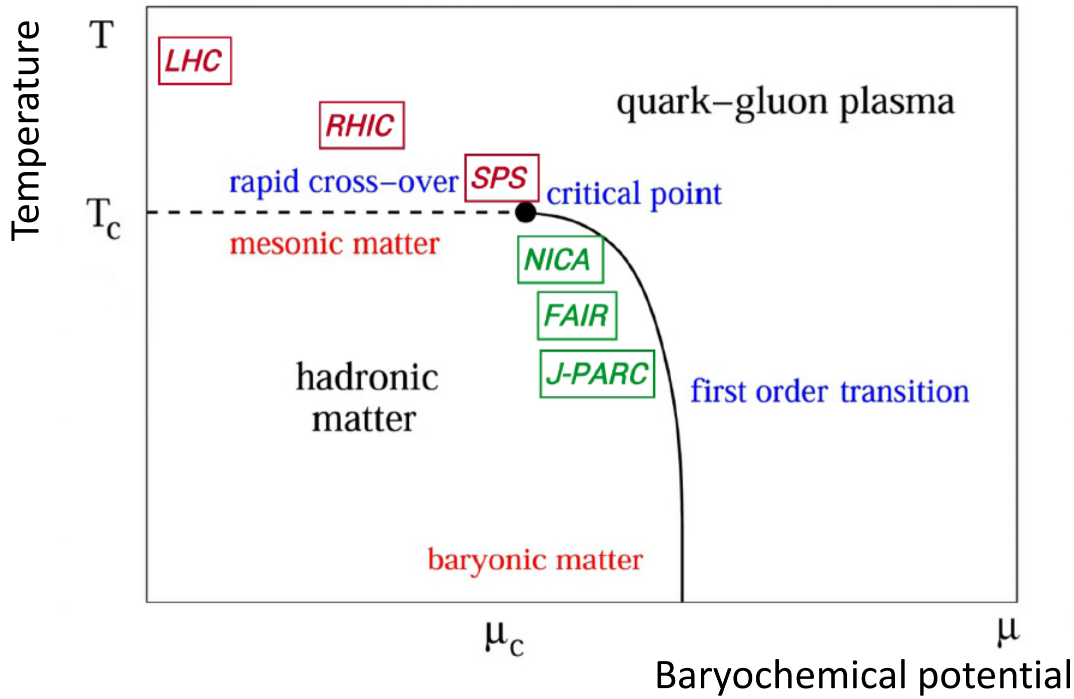
Search for the Critical Point of Strongly Interacting Matter in Heavy-Ion collisions

P. Seyboth
Max-Planck-Institut für Physik, München
and
Jan Kochanowski University, Kielce

results obtained at the CERN SPS and RHIC Beam Energy Scan by the NA49, NA61/SHINE, STAR and PHENIX collaborations

Phase diagram of strongly interacting matter

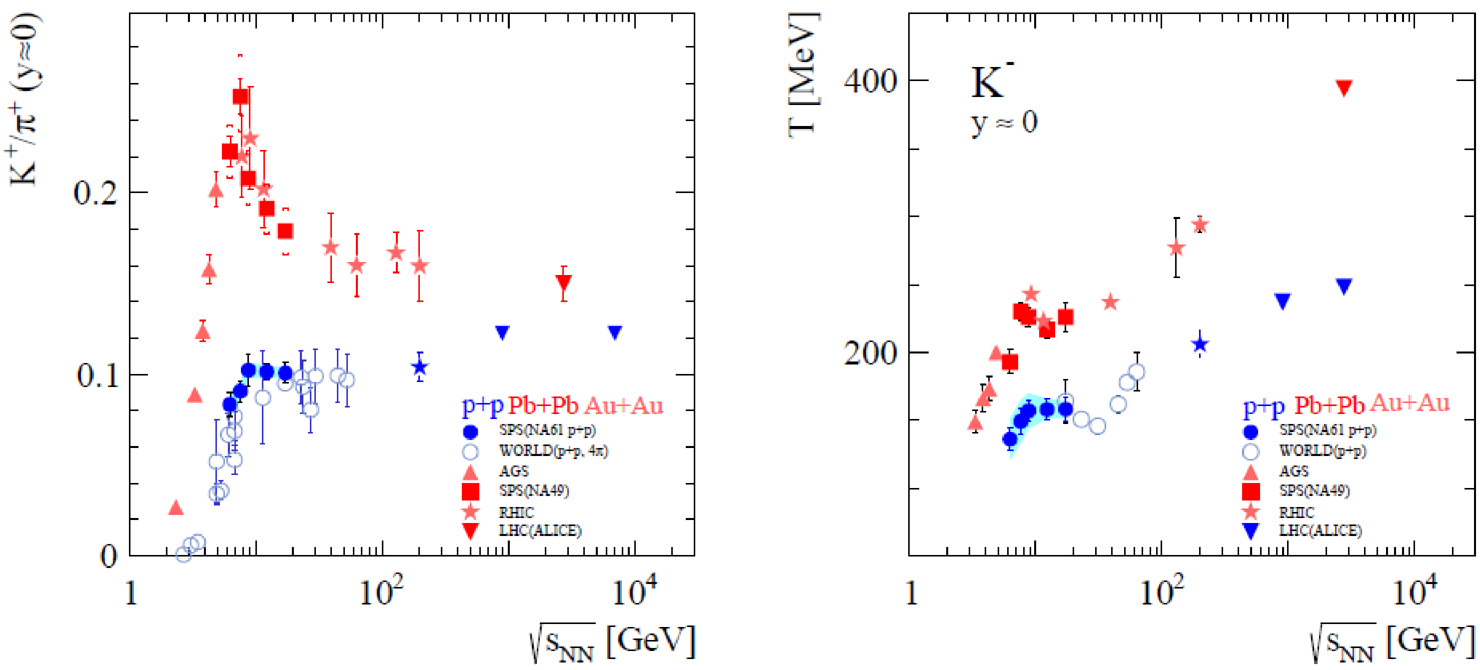
1^{st} order phase transition line ends in a critical point of 2^{nd} order then turns into continuous rapid crossover when μ decreases ($\sqrt{s_{NN}}$ increases)



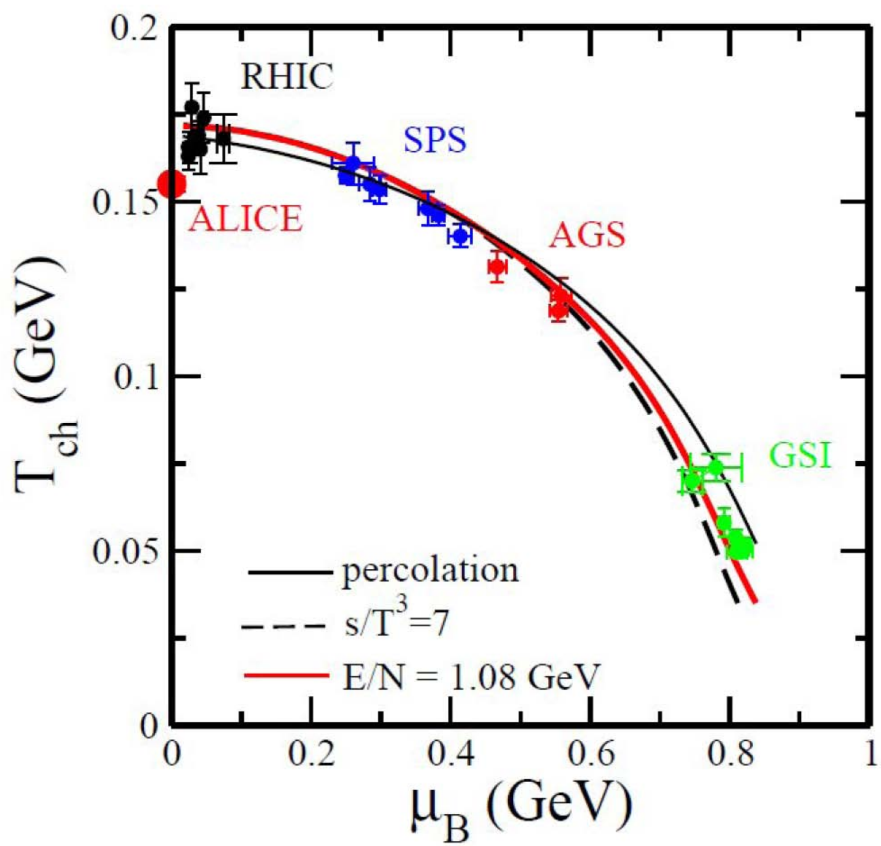
- explored experimentally in relativistic nucleus-nucleus collisions
- onset of deconfinement in central Pb+Pb collisions at about 30A GeV
- critical point effects potentially observable above $\sqrt{s_{NN}} = 7.7$ GeV

rapid changes of K and π production properties
signal the onset of deconfinement at $\sqrt{s_{NN}} \approx$ 7.7 GeV

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



Statistical model fits to measured particle yields provide location T_{ch} , μ_B in the phase diagram of the colliding system at freezeout



J.Cleymans, EPJ Web Conf. 95, 03004 (2015)

Does the CP exist, where is it located ?

Lattice QCD estimates contradictory for finite μ_B, extrapolations required

- 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

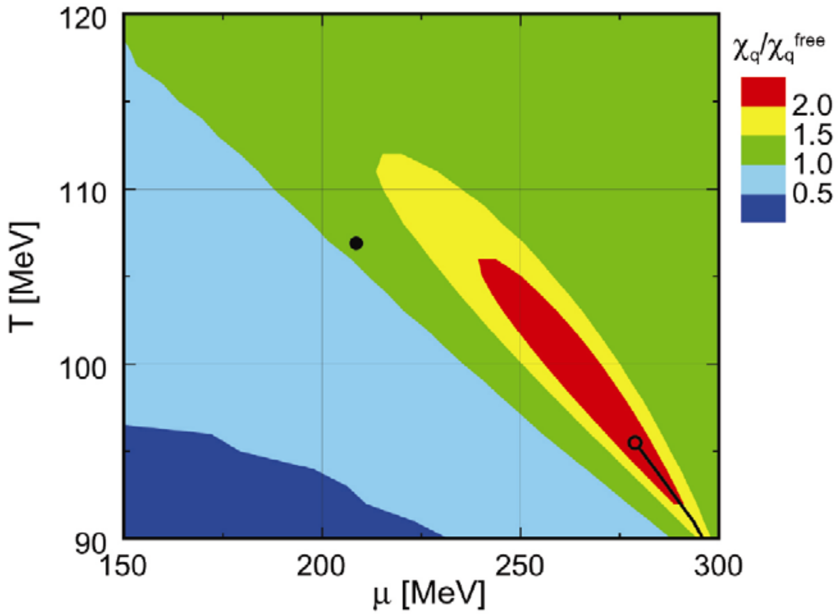
- unobservable in A+A collisions ?
  - A.Li, A.Alexandru, K.-F.Liu: PRC D84,071503(2011)
    $T = 157$ MeV, $\mu_B = 441$ MeV
    system does not reach deconfinement !

- 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

theoretical studies do not yet agree on the existence of the CP

potentially observable signatures of the critical point

- order parameter of QCD is chiral condensate $q\bar{q}$
- large fluctuations of $q\bar{q}$ and susceptibility χ_q develop near CP
- effects of the CP are expected over a considerable range of T,μ_B



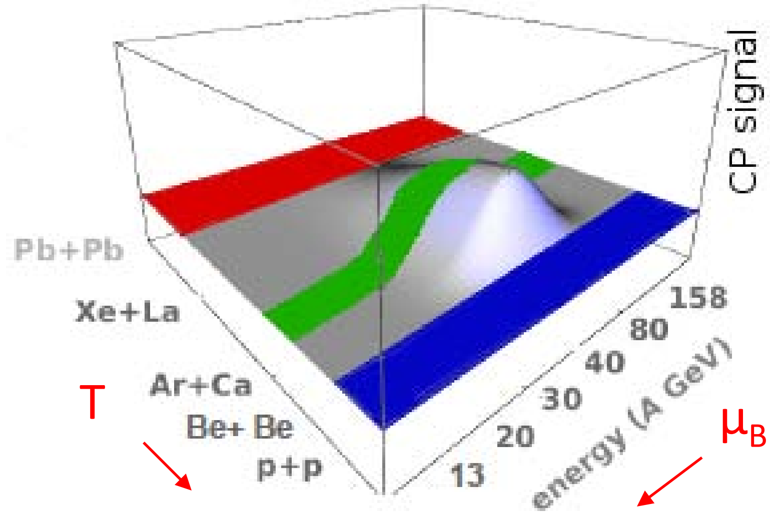
Y.Hatta and T.Ikeda,
PRD67,014028 (2003)

- approach to CP leads to divergence of correlation length ξ
  - $\rightarrow$ system becomes scale invariant leading to intermittency and finite size scaling effects of the compressibility
  - $\rightarrow$ fluctuations of integrated multiplicities of produced particles increase observable in moments (ω, Φ_x etc.) and cumulants (S, κ)

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

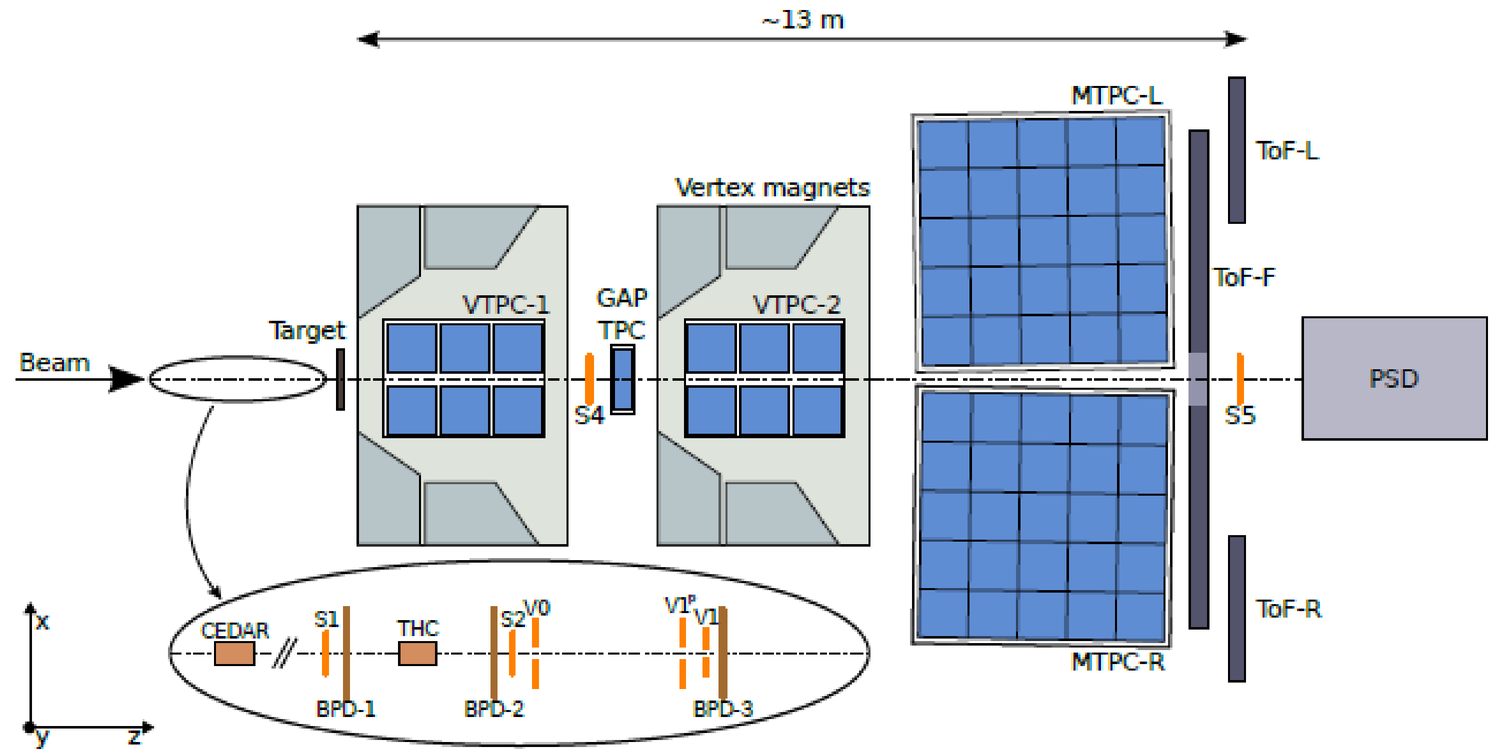
expect "hill" of fluctuations

experimental control parameters:
- collision energy $\rightarrow$ μ_B, T
- size A of colliding nuclei, and/or centrality of collision
  $\rightarrow$ duration of evolution after phase transition
  $\rightarrow$ slight change of T



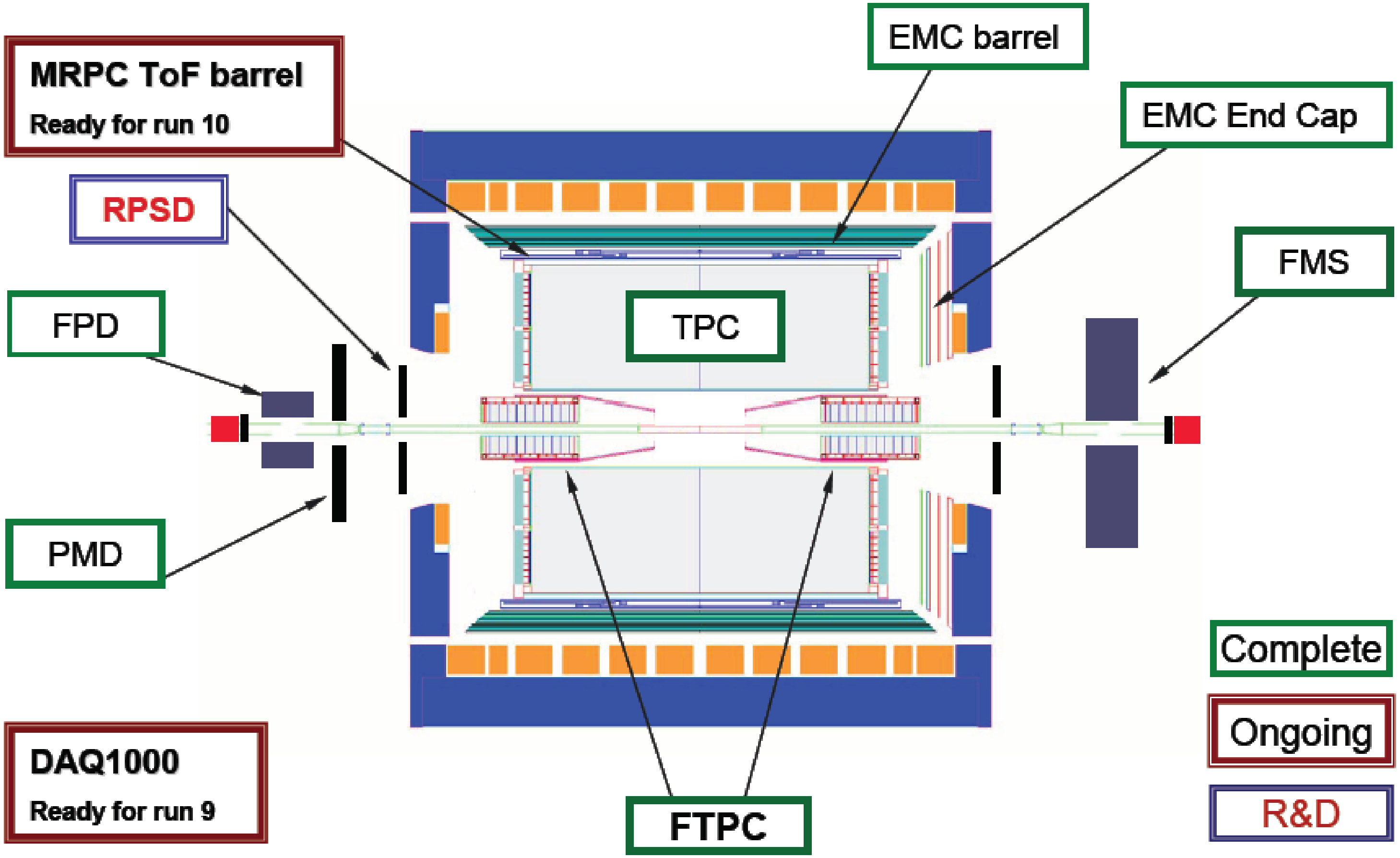
- expected size of fluctuation signals (ω, Φ_x ,... $\propto \xi^2$) is limited by short lifetime and size of collision system (M.Stephanov, et al., PRD60,114028(1999))
- correlation lengths ξ estimated to increase from 0.5 fm in hadron matter to only 1.5 - 3 fm in central Pb+Pb collisions near the CP
- evolution of collision system after phase transition may erase CP signals
  $\rightarrow$ collisions of medium size nuclei may be the best reactions for the search

NA49/NA61 detector at the CERN SPS



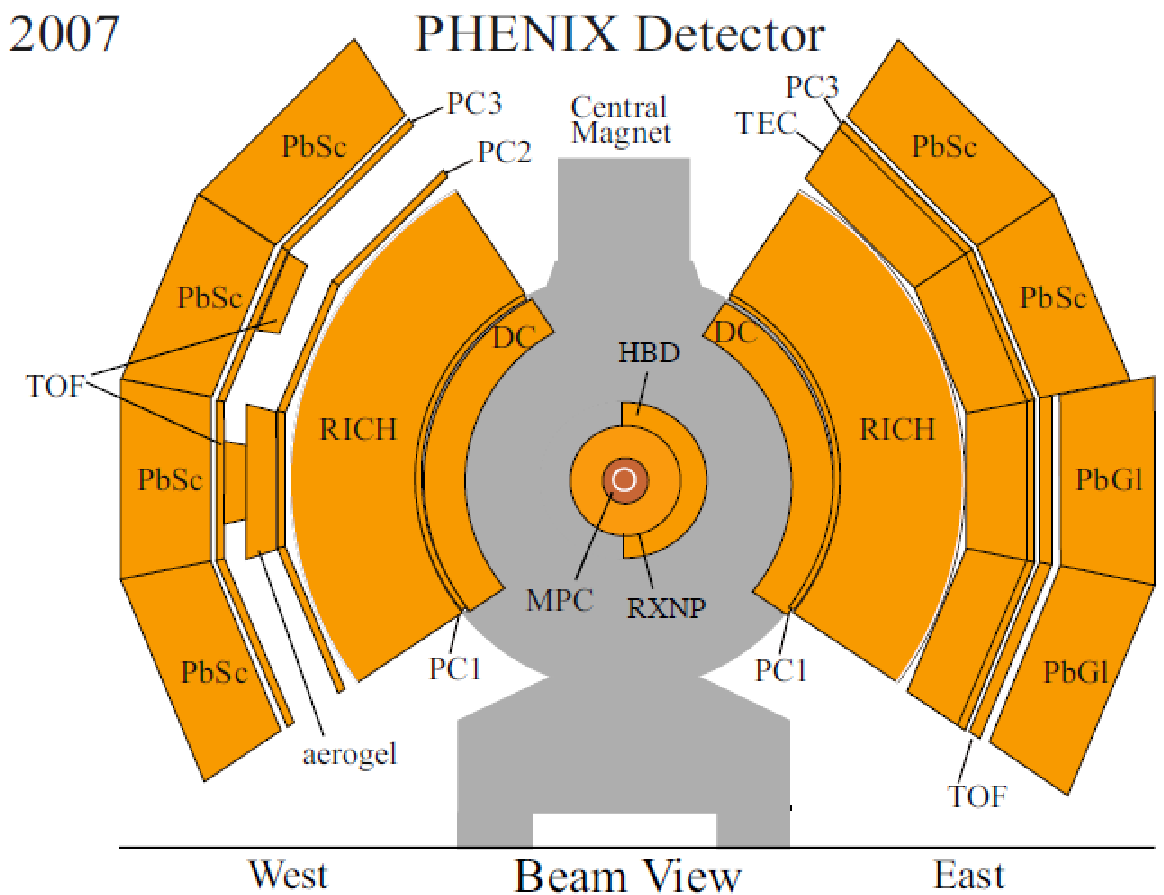
- fixed target spectrometer at CERN SPS with particle identification
- acceptance mainly in forward rapidity region $y_{cms} > 0$, no low p_T restriction
- particle mass dependent acceptance, large track density
- collision centrality (volume) selection via energy of projectile spectators

STAR detector (2010) at BNL-RHIC



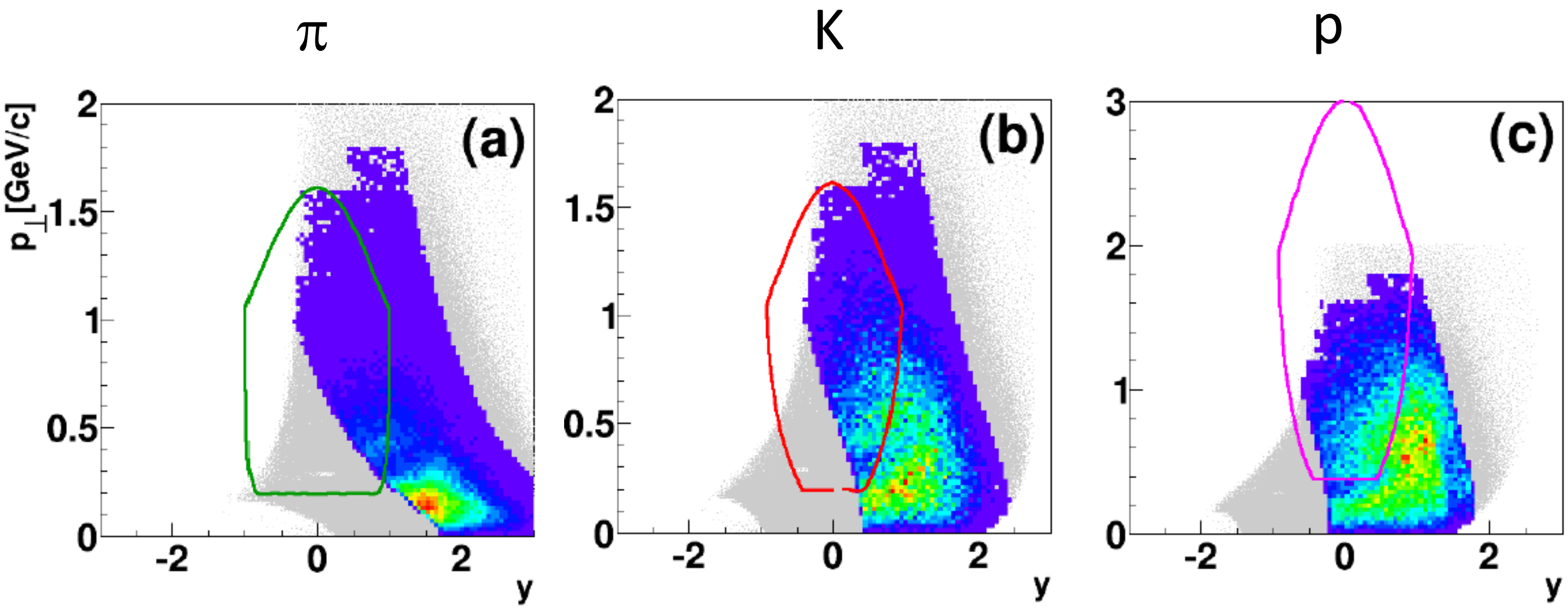
- solenoid detector, uniform azimuthal acceptance, excellent identification
- acceptance $|\eta_{cms}| < 1$, independent of particle type and collision energy
- small p_T region not accessible, centrality selection via spectators not possible

PHENIX detector (2007) at BNL-RHIC



- 2-arm spectrometer with particle identification
- charged particle acceptance $|\eta| < 0.35$, ~ 50% in azimuthal angle

detector acceptance for NA49/NA61 and STAR at $\sqrt{s_{NN}}$ = 7.7 GeV



STAR: areas within curves

NA49/NA61: shaded region with identification (colored)
without identification (grey)

2nd order phase transition and intermittency

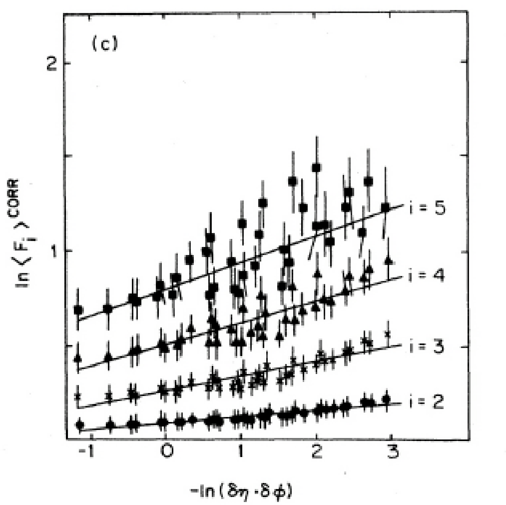
J.Wosiek,Acta Phys.Pol.B19,863(1988); H.Satz,NPB326613(1989); A.Bialas,R.Hwa,PLB253,436(1991)

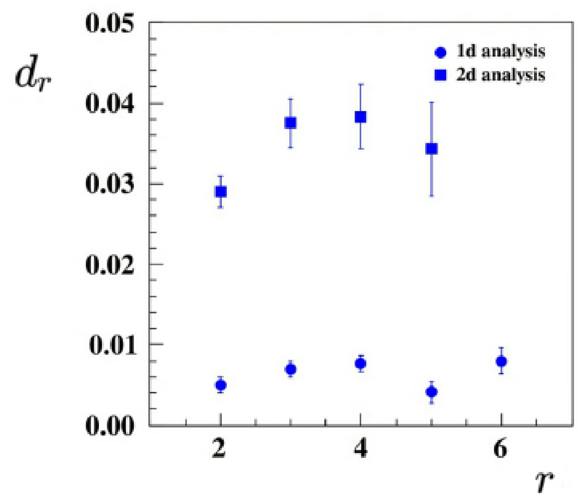
- 2nd order phase transition or CP lead to the divergence of the correlation length ξ resulting in scale invariance and the phenomenon of intermittency
- manifested in a power-law behavior of scaled factorial moments F_r of the particle multiplicity on the subdivision cell size δ of momentum phase space Δ (M=Δ/δ)

$$F_r(\delta) = \left\langle \frac{1}{M}\sum_{i=1}^{M} N_i(N_i-1)\cdots(N_i-r+1)\right\rangle \Big/ \left\langle \frac{1}{M}\sum_{i=1}^{M} N_i \right\rangle^r = F_r(\Delta)\cdot(\Delta/\delta)^{\Phi_r}$$

- and $\Phi_r = (r-1)\cdot d_r$ with rank independent fractal dimensions d_r

KLM emulsion experiment S+(Ag Br): R.Holynski et al.PRC40,2449(1989)





- charged particle analysis in azimuthal angle ϕ and pseudorapidity η seemed to show scale invariance
- unfortunately analysis in momentum space did not find confirmation (NA35)

search for the critical point via factorial moment analysis

N.Antoniou et al., NPA693,799(2001)

- the order parameter of QCD is the chiral condensate $q\bar{q}$
- the quantum state carrying its quantum numbers and critical properties is the σ field which decays after the phase transition into low-mass $\pi^+ \pi^-$ pairs
- the chiral condensate mixes with the net-baryon density (providing an equivalent order parameter) and transfers its critical properties to the net-baryon as well as net-proton or proton multiplicity

Y.Hatta,M.Stephanov, PRL91,102003(2003)

- experimental observation of critical fluctuations via scale invariance of scaled factorial moments (power law behaviour) in transverse momentum space

predicted intermittency index based on universality class arguments:

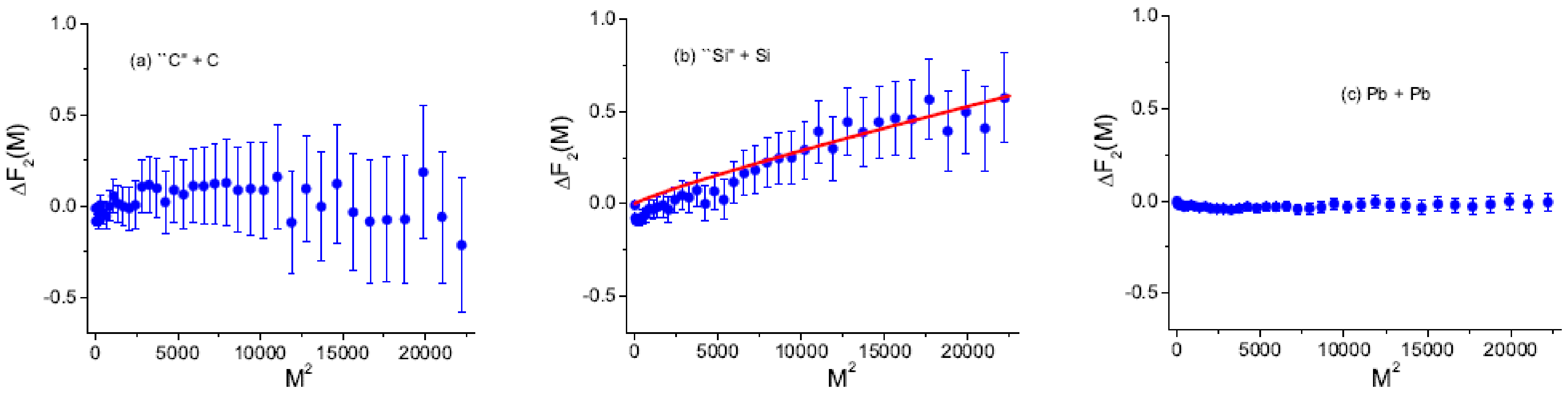
low-mass $\pi^+ \pi^-$ pairs:	$\Phi_2 = 2/3$	N.Antoniou et al., NPA693,799(2001)
protons:	$\Phi_2 = 5/6$	N.Antoniou et al., PRL97,032002(2006)

- in the analysis of real data the unavoidable background is simulated by mixed events and subtracted: $\Delta F_2(M) = F_2^{data}(M) - F_2^{mix}(M)$

NA49: proton factorial moments analysis at 158*A* GeV

- 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



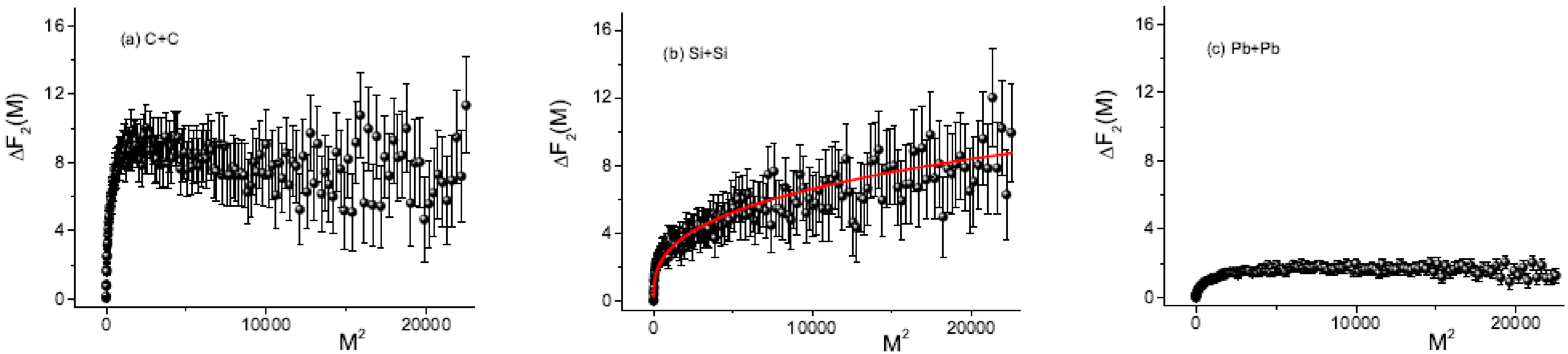
- $\Delta F_2(M)$ fluctuates around zero for "C"+C and Pb+Pb collisions
- power law observed in "Si"+Si collisions $\Phi_2 = 0.96 \pm 0.3$ (stat) $\pm$ 0.16 (syst)

intermittency behavior for protons in "Si"+Si consistent with CP expectation

NA49: $\sigma \to \pi^+\pi^-$ factorial moments analysis at 158*A* GeV

- 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}
- centrality 0 – 12.5 %

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



- $\Delta F_2(M)$ fluctuates around constant value for "C"+C and Pb+Pb collisions
- power law observed in "Si"+Si collisions $\Phi_2 = 0.33 \pm 0.04$ (stat)

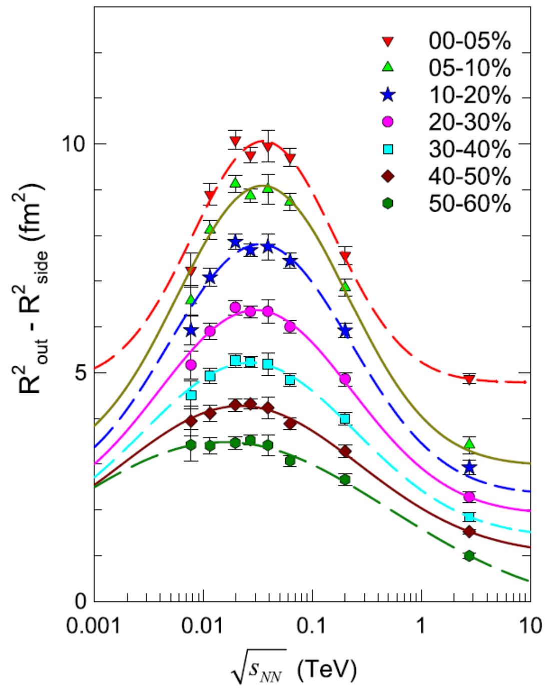
intermittency for low-mass $\pi^+\pi^-$ pairs in central "Si"+Si collisions exponent below CP expectation. Residual background ?

R.Lacey, PRL114,142301(2015)

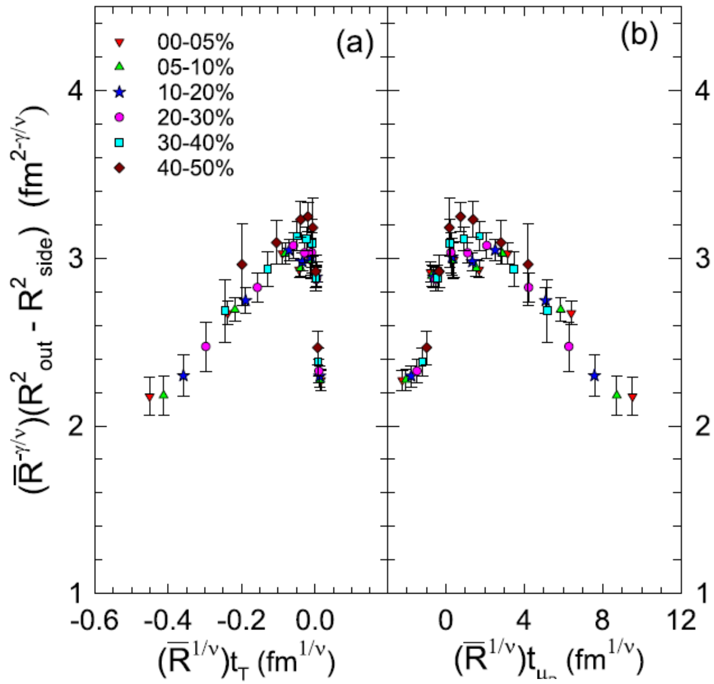
finite size scaling in Au+Au/Pb+Pb collisions

$R^2_{\text{out}} - R^2_{\text{side}}$ from 2-pion BE correlations is linked to emission duration and compressibility, expect maximum (minimum) in the vicinity of CP

non-monotonic energy dependence



finite size scaling



centrality of the collision related to the volume: $1/\bar{R} = \sqrt{(1/\sigma_x^2 + 1/\sigma_y^2)}$

finite-size scaling: $(R^2_{\text{out}} - R^2_{\text{side}})^{\max} \propto \bar{R}^{\gamma/\nu}$

$\sqrt{s_{NN}}(V) = \sqrt{s_{NN}}(\infty) - k \times \bar{R}^{-(1/\nu)}$

M.Ladrem,A.Ait-El-Djoudi EPJC44,257(2005)

fitted parameters suggest existence of CP at $\mu_B \sim 95$ MeV, T ~ 165 MeV

fluctuation studies using distributions of integrated event quantities

e.g. distribution of conserved charges (net-charge, net-baryons, net-strangeness) or multiplicity, average transverse momentum

expected to show non-monotonic behaviour (peak, dip) in the vicinity of the CP

cumulants κ of the distribution P(N):

$\kappa_2 = <(\delta N)^2>$ $\quad \kappa_3 = <(\delta N)^3>$ $\quad \kappa_4 = <(\delta N)^4> - 3<(\delta N)^2>^2$ with $\delta N := N - <N>$

extensive observables, proportional to volume (size) of system

normalized cumulants: $\omega_k = \kappa_k / <N>$

intensive observables, independent of volume <u>but not of volume fluctuations</u>

reference IPM $\rightarrow$ P(N) Poisson, $\omega_\kappa = 1$ for $\kappa \geq 2$

$P(N_A - N_B)$ Skellam, $\kappa_3/\kappa_2 = (<N_A> - <N_B>)/(<N_A> + <N_B>)$; $\kappa_4/\kappa_2 = 1$

cumulant ratios of special interest:

$\kappa_3/\kappa_2 = S\sigma$ $\quad \kappa_4/\kappa_2 = \kappa\sigma^2$ $\quad$ (σ^2 = variance, S =skewness, κ = kurtosis)

for conserved charges related to susceptibilities calculable in lattice QCD

$S\sigma \sim \chi^{(3)}/\chi^{(2)}$ $\quad \kappa\sigma^2 \sim \chi^{(4)}/\chi^{(2)}$

power of divergence at CP:

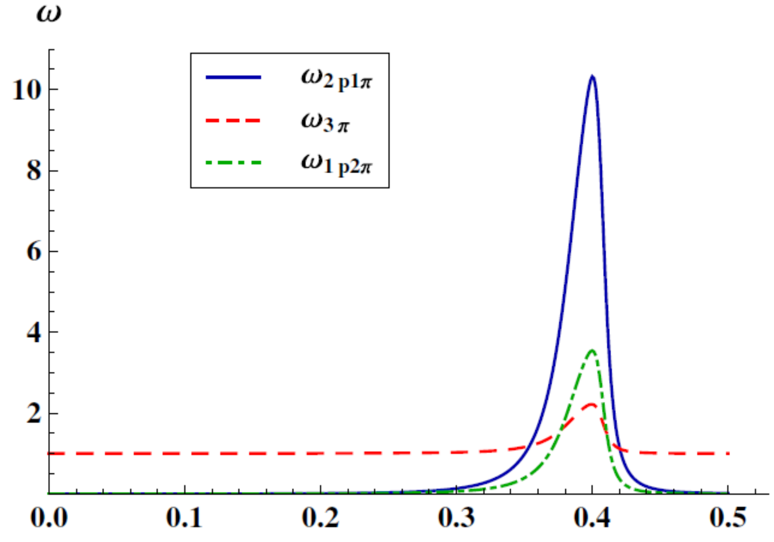
M.Stephanov,PRL102,032301(2009)

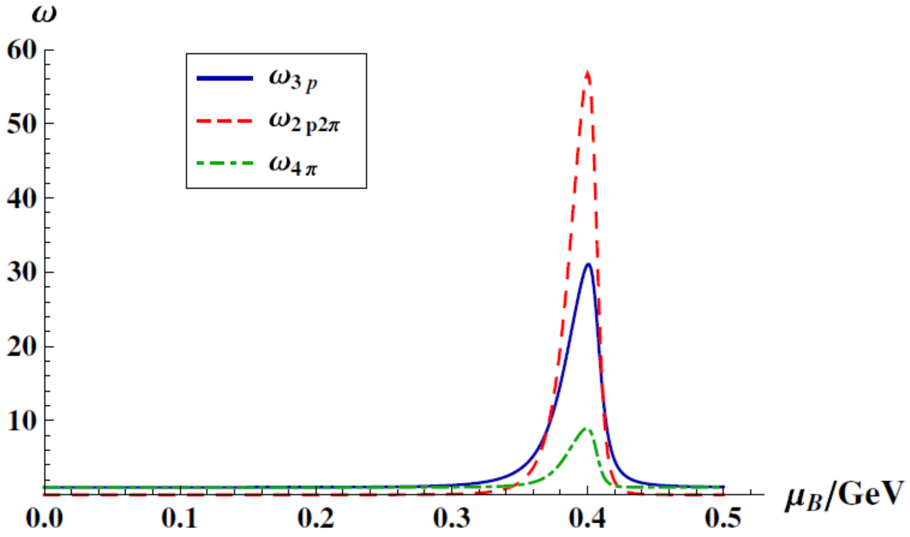
scaled variance $\omega_2 \sim \xi^2$ $\quad$ skewness $S \sim \xi^{4.5}$ $\quad$ kurtosis $\kappa \sim \xi^7$

QCD based calculations predict large effects in the vicinity of the CP

C.Athanasiou et al., PRD82,074008(2010)

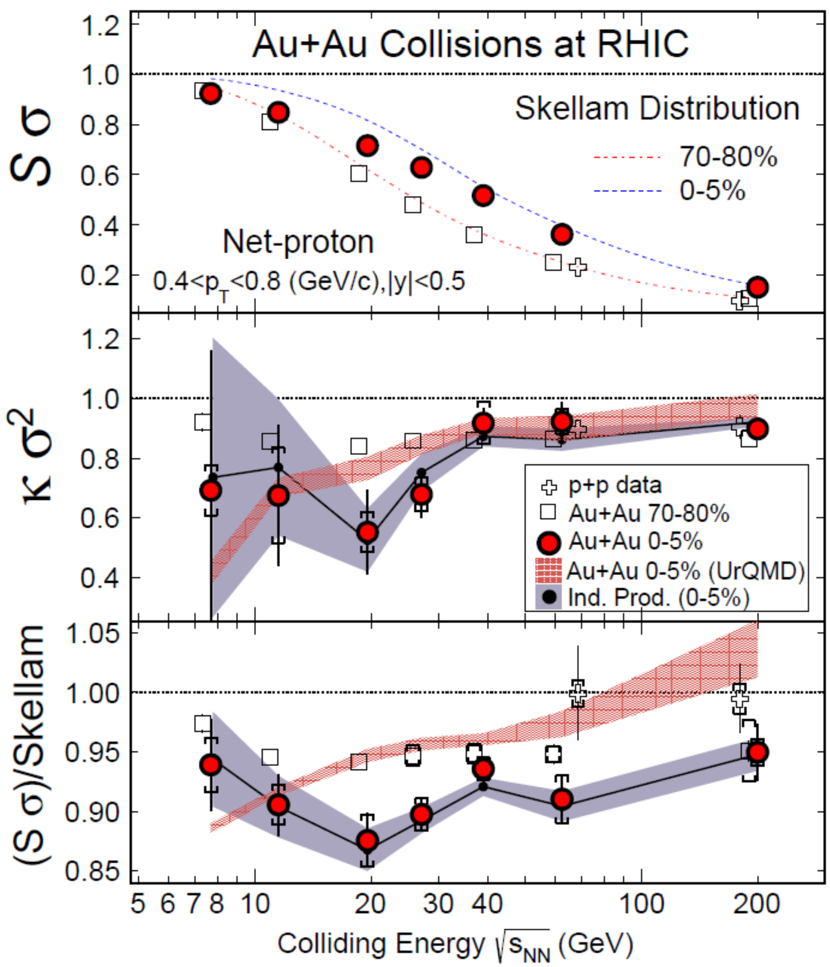
- assumptions on CP: ξ_{max} = 2 fm, μ_B = 400 MeV,
  100 MeV for width of region with ξ > 1 fm





strong increase of normalized cumulants for 3 or 4 pion and proton multiplicity fluctuations, in particular when protons are involved

STAR: moments of the net-proton multiplicity distribution



$|y| < 0.5$, $0.4 < p_T < 0.8$ GeV/c

L.Adamczyk et al.,Phys.Rev.Lett.,112,032302(2014)

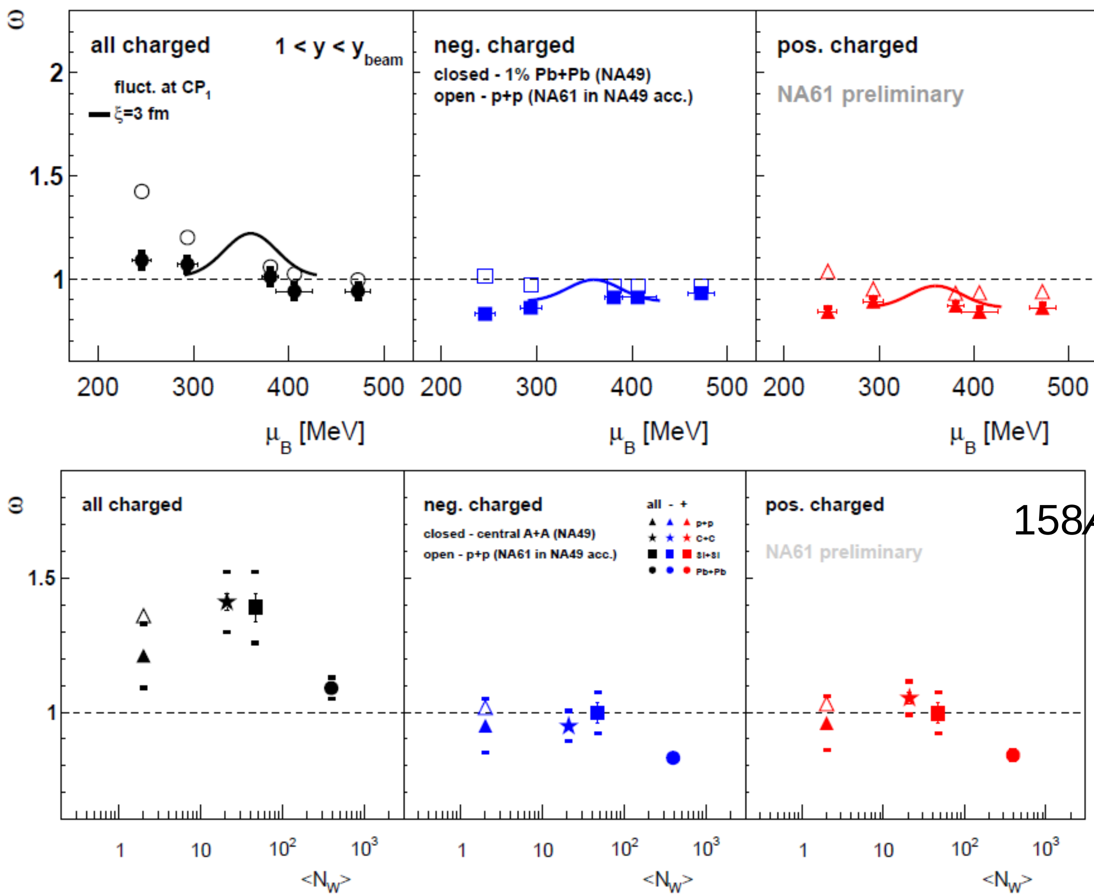
moments of $N_p - N_{pbar}$ distribution (mostly protons for $\sqrt{s_{NN}} \leq 20$ GeV)

- measurements close to expectation from independent particle production (Skellam distribution)
- hadronic model UrQMD follows the trend of the results

no clear evidence for structure attributable to the CP

NA49/NA61: scaled variance of the multiplicity distribution

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



predicted curves based on M.Stephanov for CP at μ_B=360 MeV

rapidity $y_\pi > 1.0$

158*A* GeV

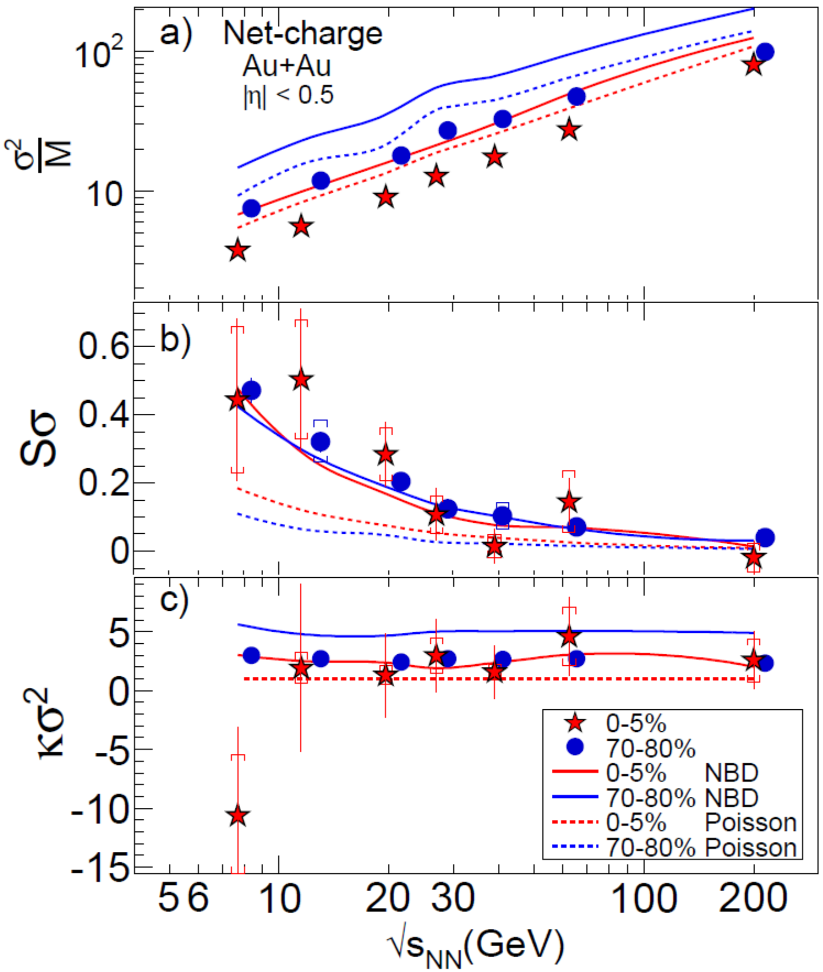
NA61 p+p:
statistical errors only

- no significant peak in the μ_B (energy) dependence of scaled variance ω
- indication of a maximum for collisions of medium size nuclei at 158*A* GeV

STAR: moments of the net-charge multiplicity distribution

Au+Au collisions at RHIC

L.Adamczyk et al.,Phys.Rev.Lett.,113,092301(2014)



$|\eta| < 0.5,\ 0.2 < p_T < 2.0$ GeV/c

moments of the $N^+ - N^-$ distribution
(protons with p < 400 MeV removed)

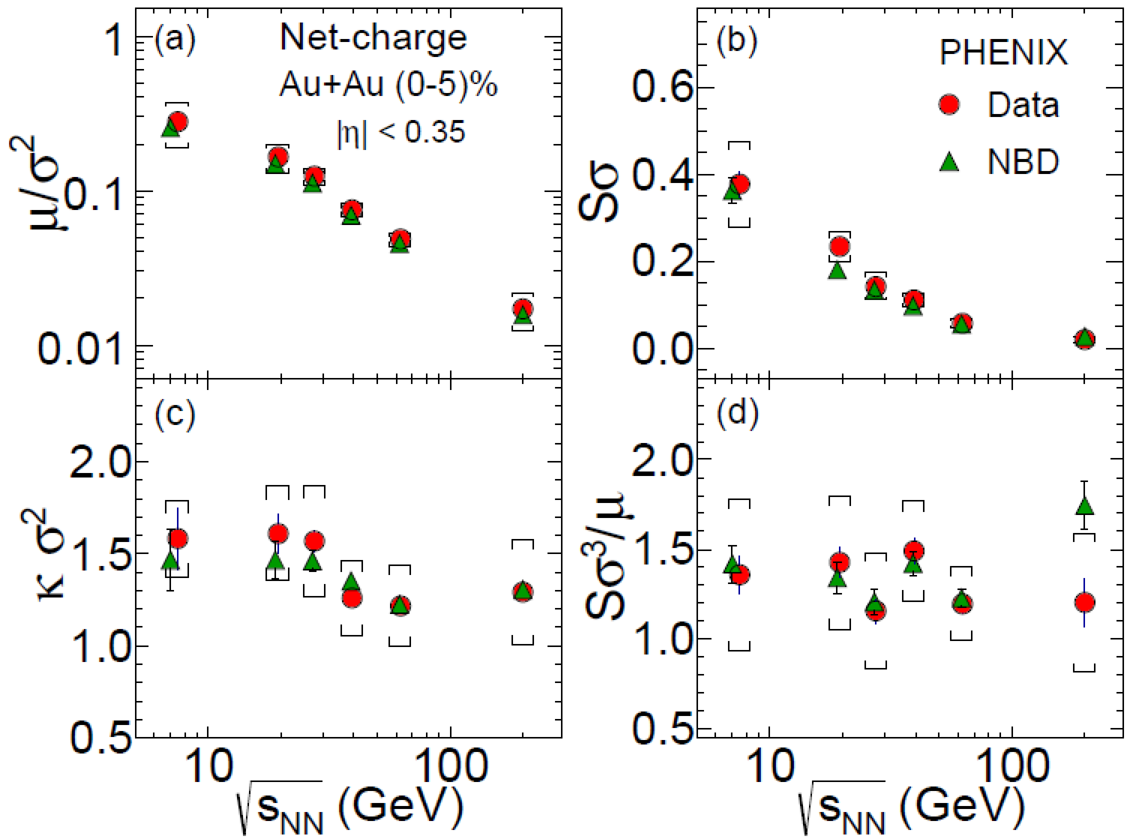
- σ^2/Mean below Poisson and NBD prediction; trace of global charge conservation ?
- $S\sigma$ shows smooth decrease
- $\kappa\sigma^2$ consistent with energy independence

no clear evidence for structure attributable to the CP

PHENIX: moments of the net-charge multiplicity distribution

A.Adare et al.,arXiv:1506.07834(2015)

0 – 5 % most central Au+Au collisions



|η| < 0.35
0.2 < p_T < 2.0 GeV/c

• convolution of NBD fitted to N^+ and N^- distributions describes the data

no clear evidence for structure attributable to the CP

strongly intensive event-by-event fluctuation measures

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

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.,PRC88,024907(2013)

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

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

measure Φ_x often used in the past, related to Σ :

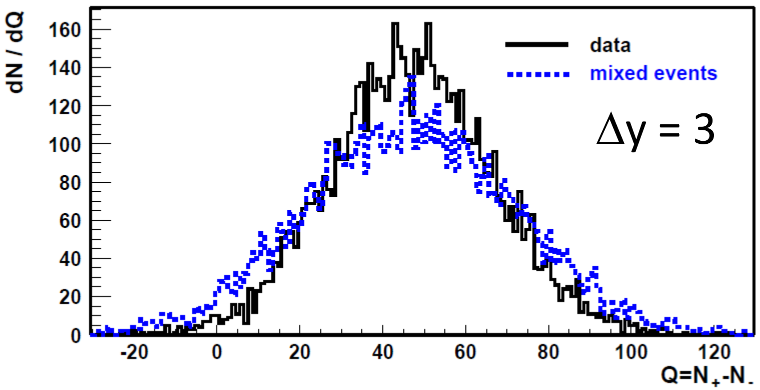
M.Gazdzicki, S.Mrowczyski, Z.Phys.C54,127(1992)

$$\Phi_x \equiv \sqrt{\overline{x}\cdot\omega[x]}\left[\Sigma[X,N]-1\right] \qquad \text{with } X = \sum_{i=1}^{N} x_i$$

independent particle production, ideal Boltzmann gas GCE:

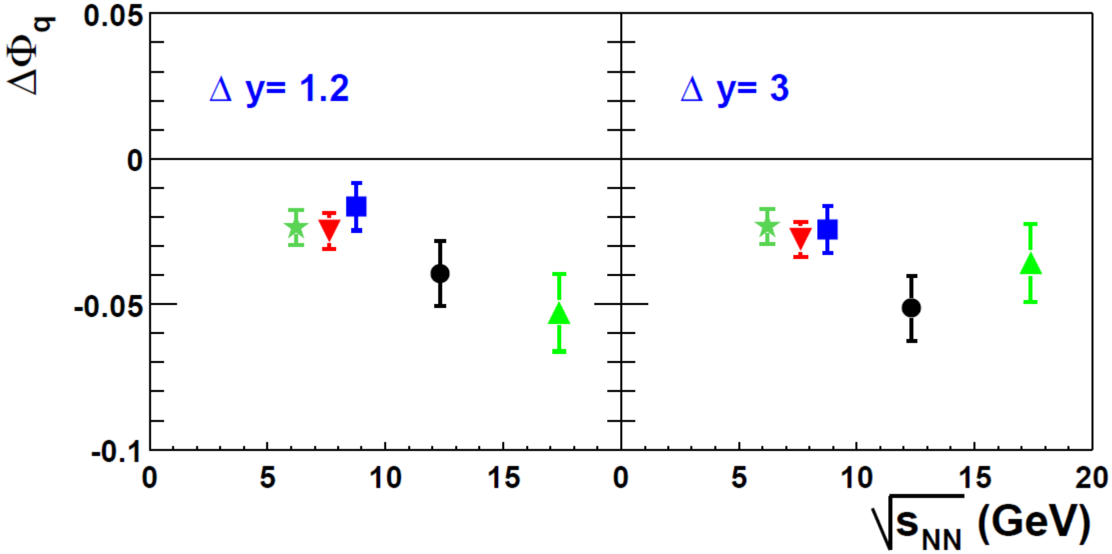
$$\omega = 1\,, \quad \Phi_{p_T} = 0\,, \quad \Sigma^{P_T,N} = \Delta^{P_T,N} = 1 \quad (\text{with suitable normalization})$$

NA49: net-charge fluctuations in central Pb+Pb collisions



- clear effect of global charge conservation needs to be corrected
- study of observable Φ_q with q = $\pm$1
- effect of global charge conservation (GCC) calculated and subtracted:

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

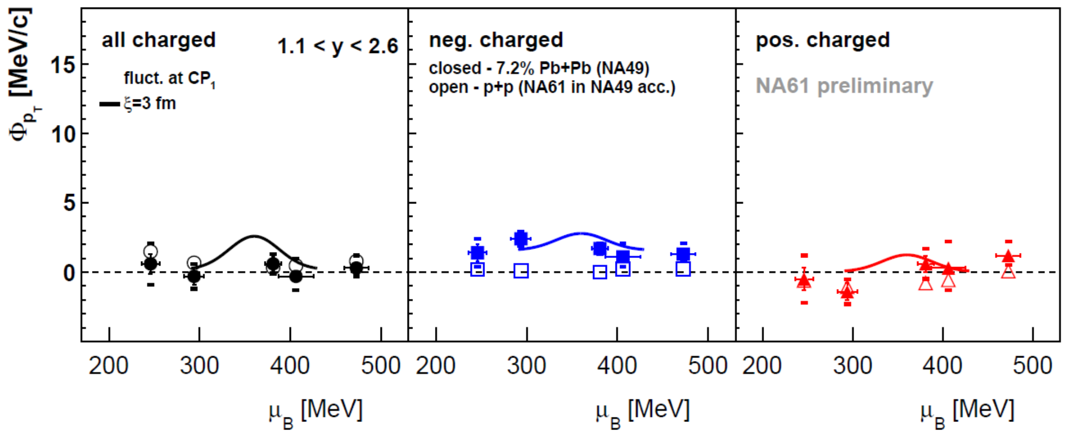


genuine charge fluctuations small at all SPS energies

no clear evidence for structure attributable to the CP

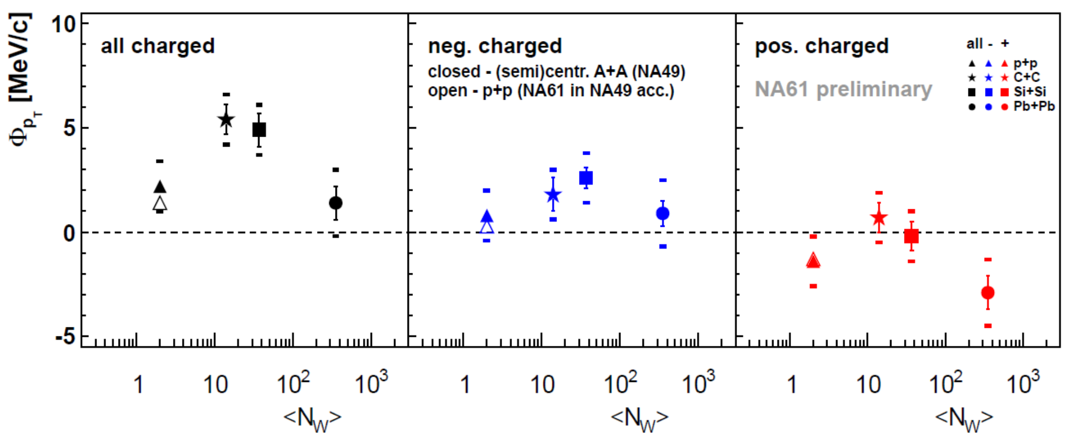
NA49: P_T – multiplicity fluctuations

NA49 results for 3.5 % most central Pb+Pb collisions (C.Alt et al.,PRC78,034914(2008))
NA61 results for inelastic p+p collisions (preliminary, T.Czopowicz, arXiv:1503.01619)



predicted curves based on M.Stephanov for CP at μ_B=360 MeV

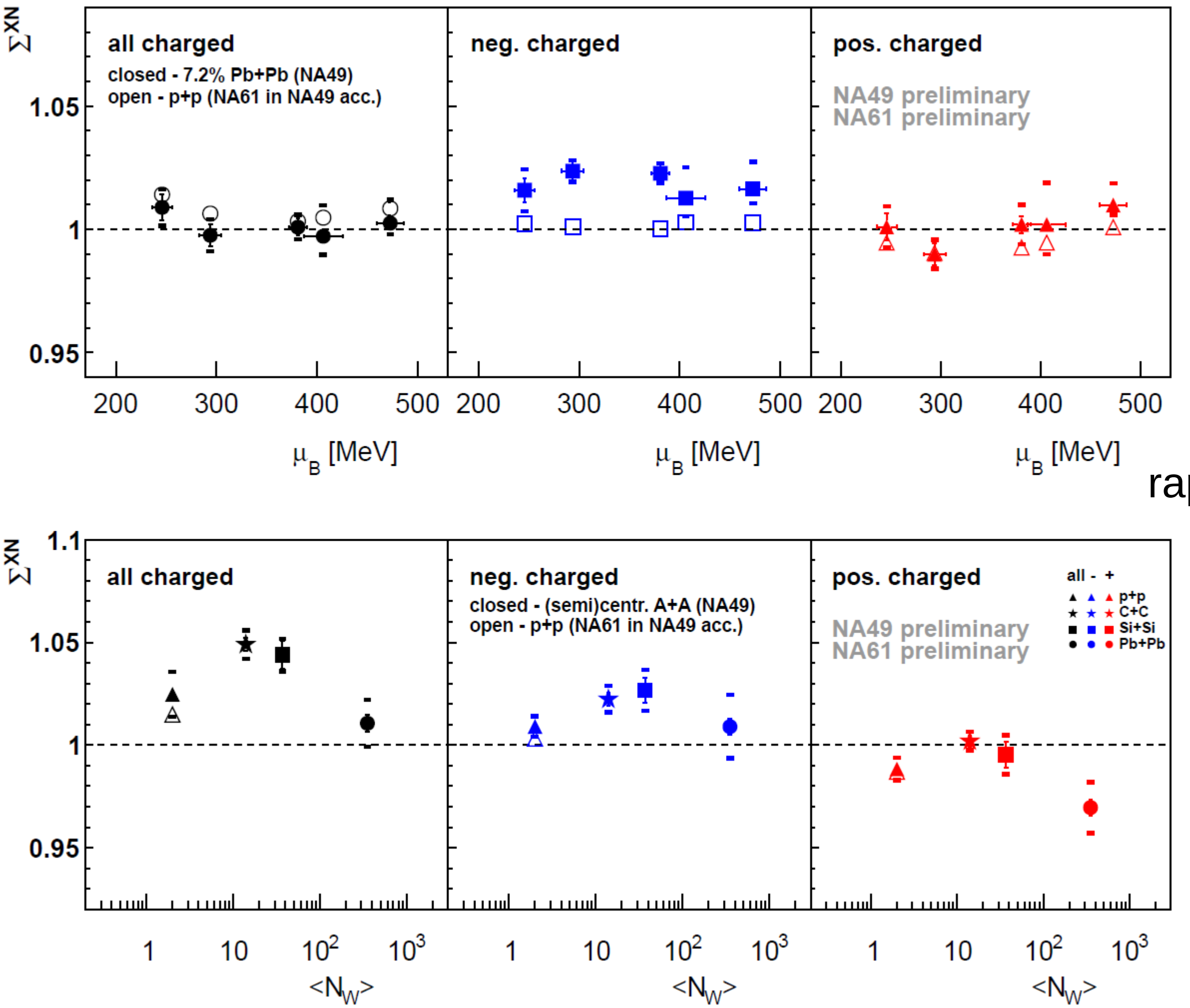
rapidity $y_\pi > 1.0$



158A GeV

- no indication of a peak in the μ_B (energy) dependence of Φ_{P_T}
- indication of a maximum for collisions of medium size nuclei at 158A GeV

NA49: P_T – multiplicity fluctuations, fluctuation measure Σ

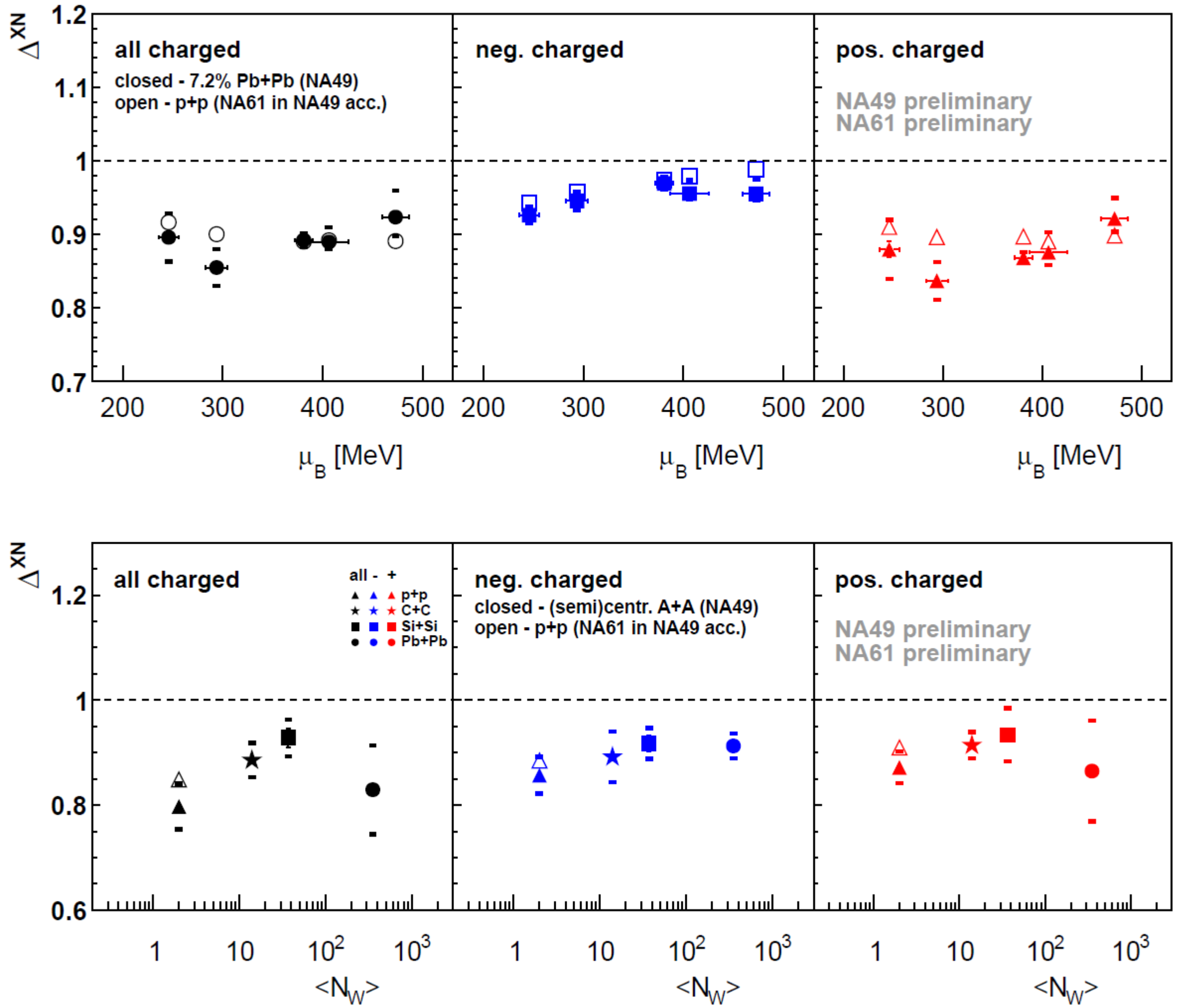


rapidity $y_\pi > 1.0$

158*A* GeV

p_T fluctuation measures Φ and Σ show no μ_B (energy) dependence but indication of maximum for medium size nuclei

NA49: P_T – multiplicity fluctuations, fluctuation measure Δ



rapidity $y_\pi > 1.0$

158A GeV

interpretation of results on Δ less clear

Summary

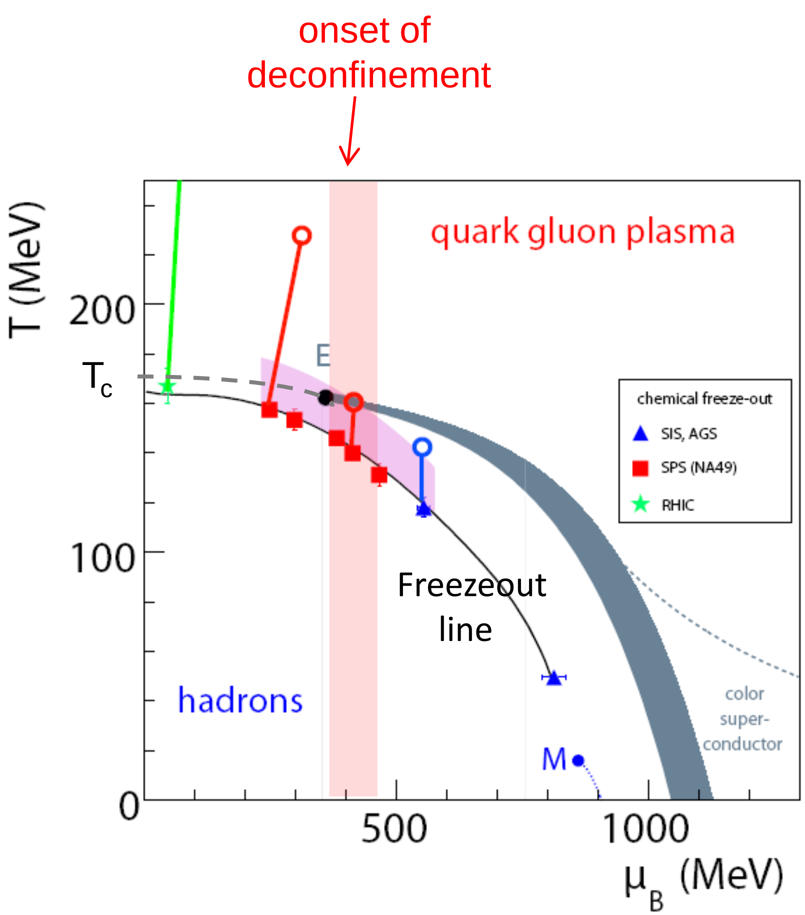
- the structure of the phase diagram of strongly interacting matter is an important aspect of QCD in the non-perturbative sector
- the existence of a critical point of strongly interacting matter and the location in the phase diagram need clarification by theory
- interesting hints were found in the energy and system size dependence of CP sensitive fluctuation observables (intermittency, finite-size scaling, enhanced fluctuations of multiplicity and p_T). Confirmations required.
- a vigorous experimental program searching for evidence of the critical point is in progress at the CERN SPS and RHIC (and soon at NICA)

exploration of the phase diagram of strongly interacting matter
and
discovering the critical point
remain an exciting and challenging enterprise

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 $\cong$ 30A GeV

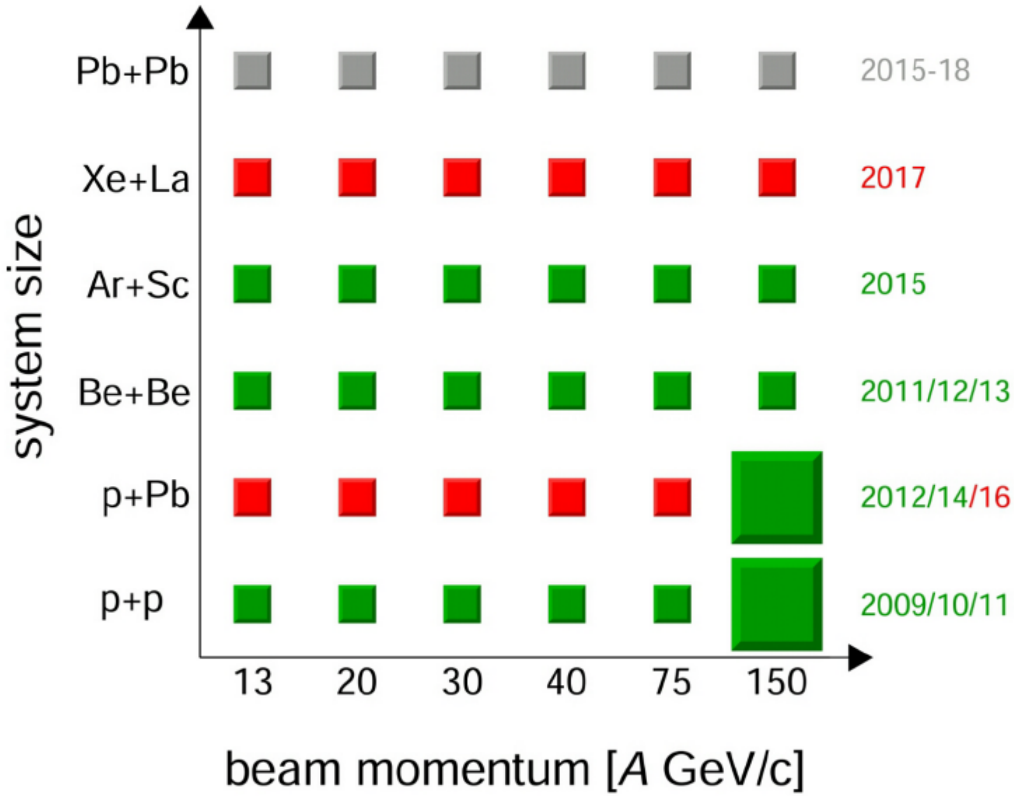
(NA49,C.Alt et al.,PRC77,024903(2008))

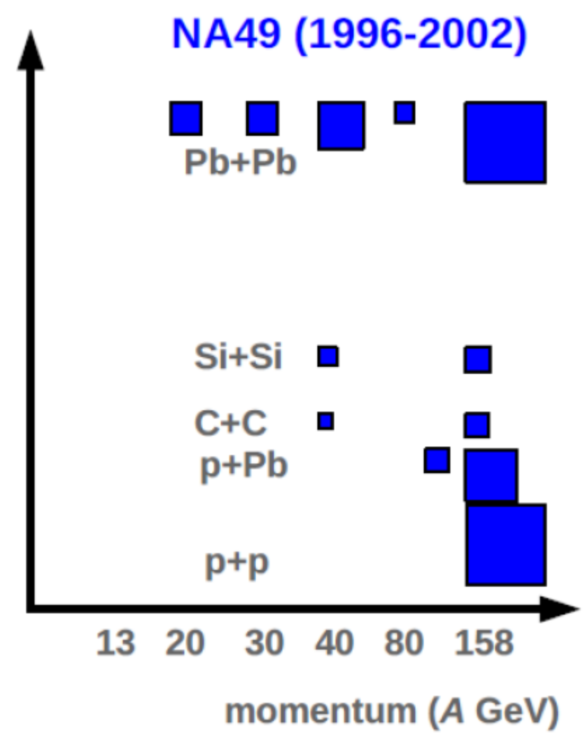
LQCD can provide quantitative predictions in the non-perturbative region of QCD

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

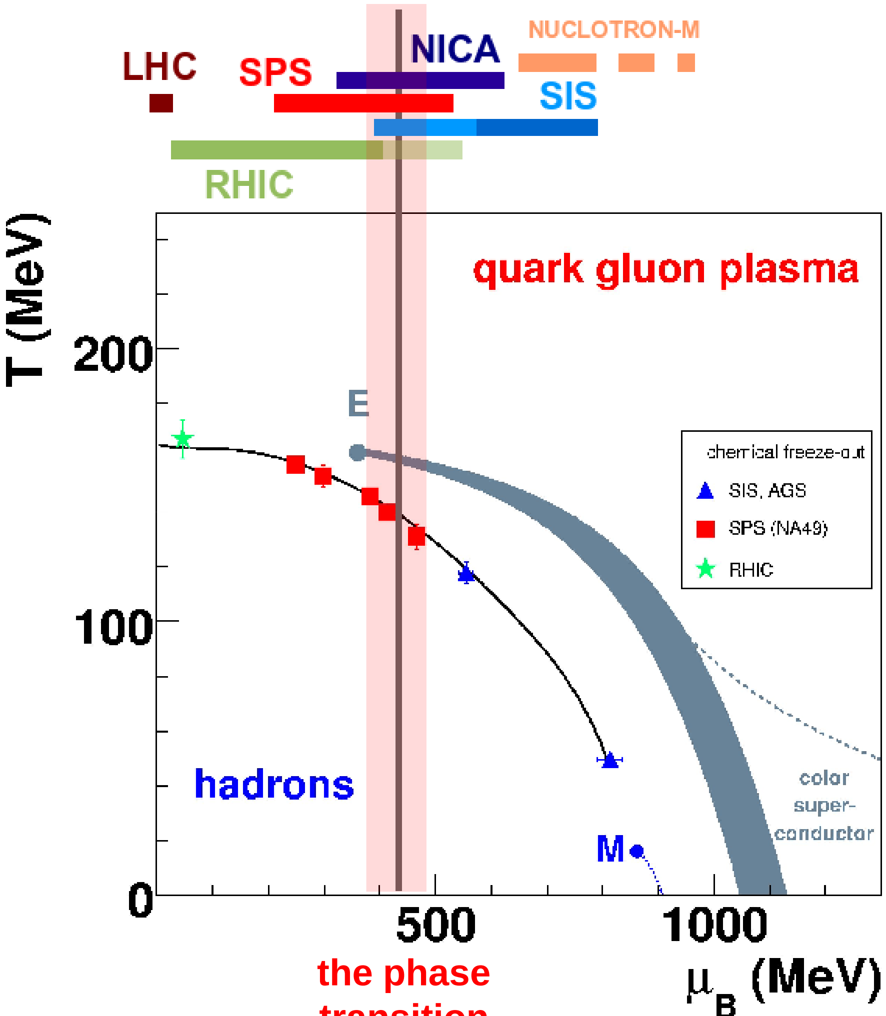
$\rightarrow$ search for critical point via fluctuations above energy of onset of deconfinement

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





relativistic nuclear collisions: future experimental landscape



partly complementary programs

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

BNL RHIC 2010 →
7.7(5 ?) – 200 GeV

JINR Nuclotron 2010 →
< ~ 3.5 GeV

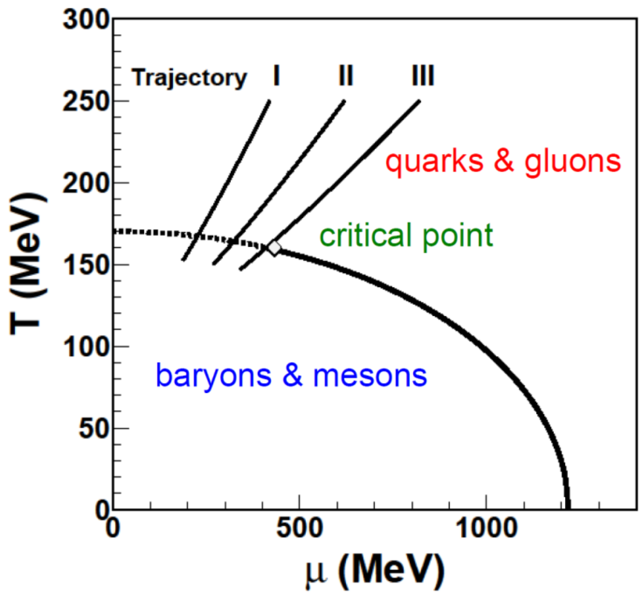
JINR NICA 2019 →
4 – 11 GeV

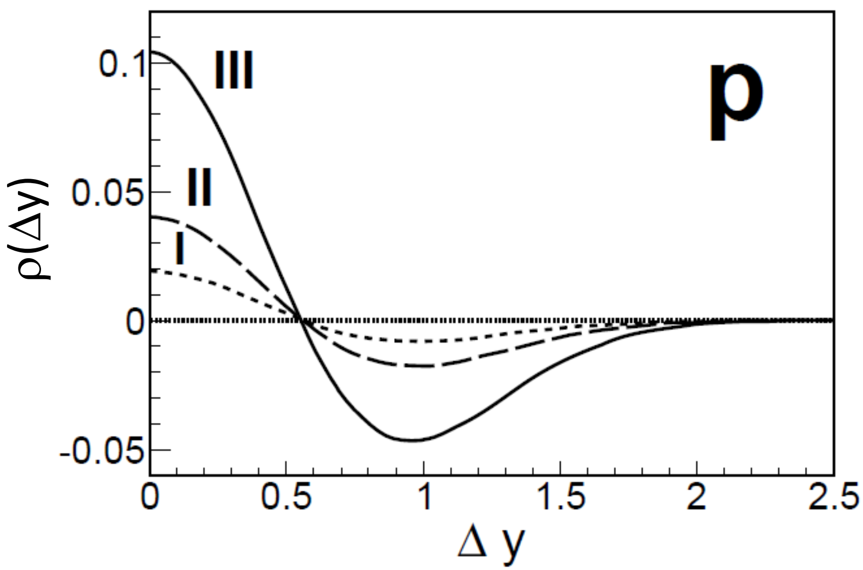
GSI SIS-100 2019 →
2.3 – 4.5 GeV

SIS-300 ??
4.5 – 8.5 GeV

hydrodynamical evolution of critical point fluctuations

J.Kapusta, 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 distance of trajectory from critical point