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**for the NA49 and NA61 Collaborations**

# Search for the QCD critical point at SPS energies

EPS HEP 2009
Krakow, Poland
July 16th - 22th, 2009

**CERN** (**S**uper **P**roton **S**ynchrotron and
**L**arge **H**adron **C**ollider accelerators)

Circumference of the SPS tunnel – 6 km
Circumference of the LHC tunnel – 27 km

Some theoretical (lattice) calculations locate the **critical point (CP) of strongly interacting matter** in the SPS energy range

**$(T^{CP}, \mu_B^{CP}) = (162 \pm 2,\ 360 \pm 40)$ MeV**

Fodor, Katz, JHEP **0404**, 050 (2004)

**$(T^{CP}/T_c, \mu_B^{CP}/T^{CP}) = (\approx 0.95,\ 1.1 \pm 0.2)$**

$T_c$ – cross-over temperature at $\mu_B = 0$

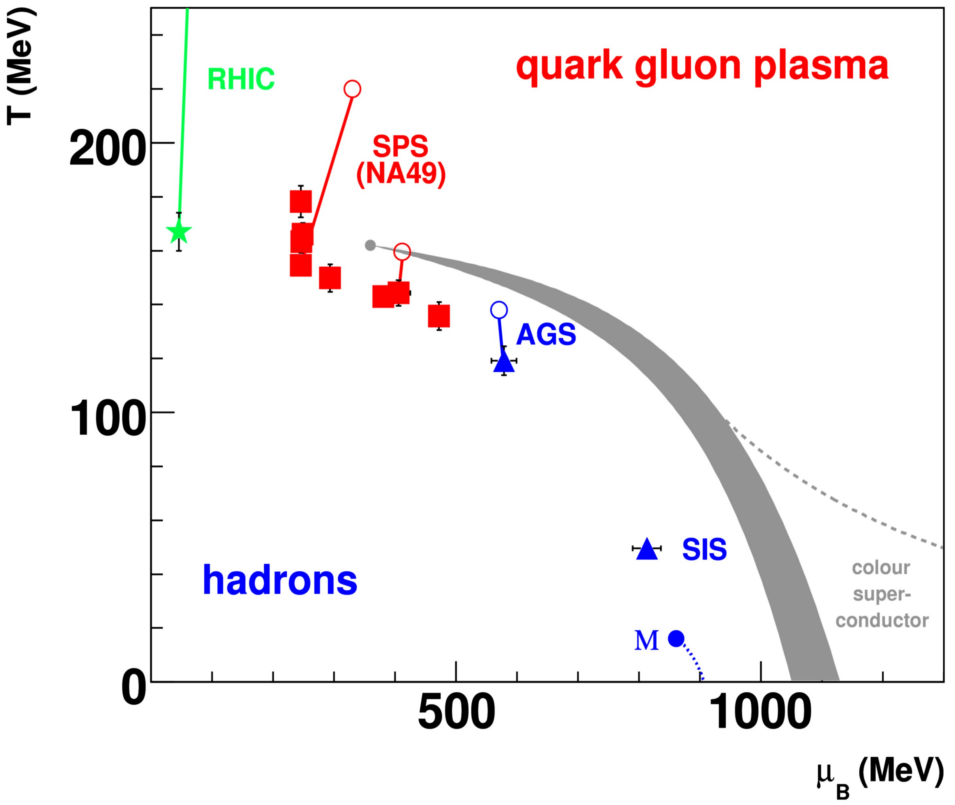
Gavai, Gupta, PR**D71**, 114014 (2005)

**Critical opalescence is observed in most liquids** (including water)

*"As the fluid cools down under conditions such that it passes near the end point of the boiling transition, it goes from transparent to opalescent to transparent as the end point is approached and then passed. This non-monotonic phenomenon is due to scattering of light on critical long wavelength density fluctuations (...)"* Stephanov, Rajagopal, Shuryak, PR**D60**, 114028 (1999)

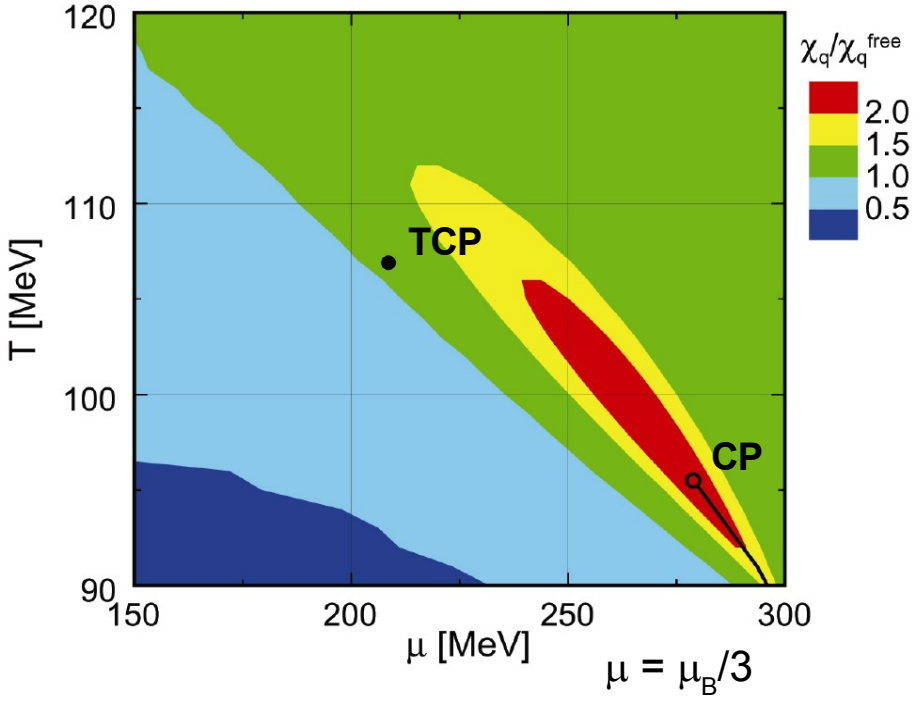
**For strongly interacting matter** maximum of CP signal expected when freeze-out happens near CP

**very interesting region covered by NA49 !**

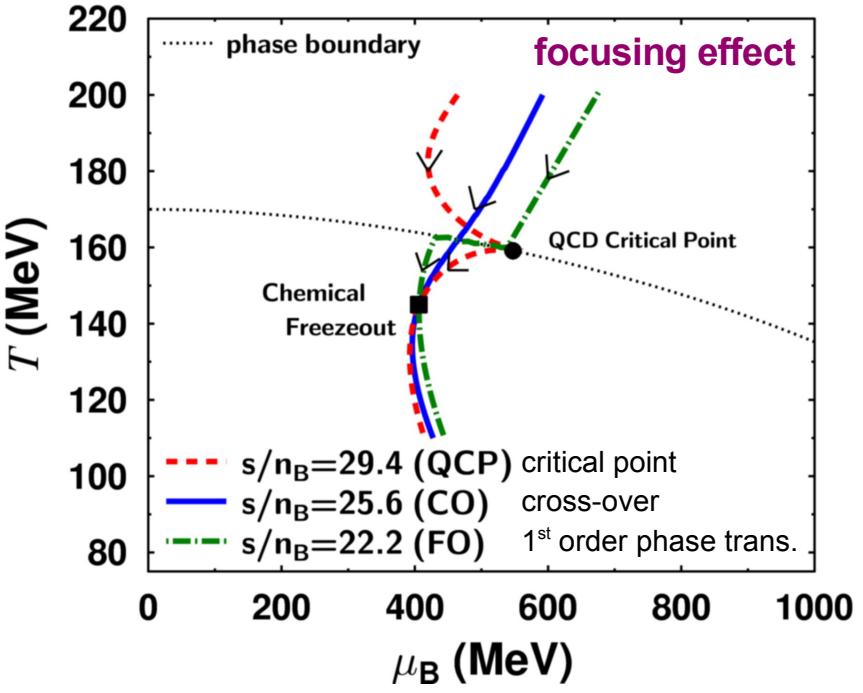



CP should be searched above the energy of the onset of deconfinement. From NA49 data $E_{OD} \cong 30A$ GeV

(C. Alt et al., PR**C77**, 024903 (2008))




Hatta, Ikeda PR**D67**, 014028 (2003)




For a given chemical freeze-out point three isentropic trajectories ($n_B/s$ = const.) are shown

Askawa et al. PRL**101**, 122302 (2008)

**Effect of critical point extends over a critical region** with $\sigma(\mu_B)$ and $\sigma(T)$

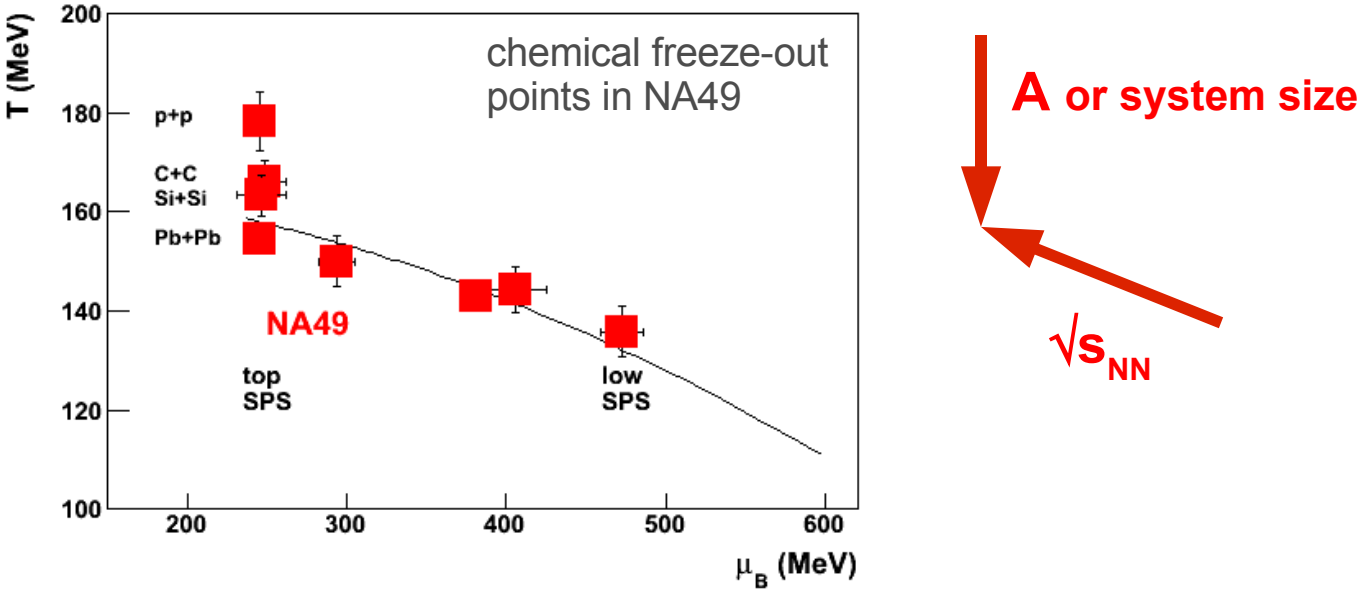
**The presence of the critical point can deform the trajectories** describing the evolution of the expanding fireball in the $(T,\mu_B)$ phase diagram

$\Rightarrow$ We do not need to hit precisely the critical point because **a large region can be affected!**

**At CP enlarged fluctuations of multiplicity and mean transverse momentum**
Stephanov, Rajagopal, Shuryak, PR**D60**, 114028 (1999)

Other signatures of CP also proposed: **transverse mass spectra of baryons and anti-baryons, (elliptic flow of baryons and mesons** and **intermittency in transverse momentum space of di-pions** not discussed here**)**

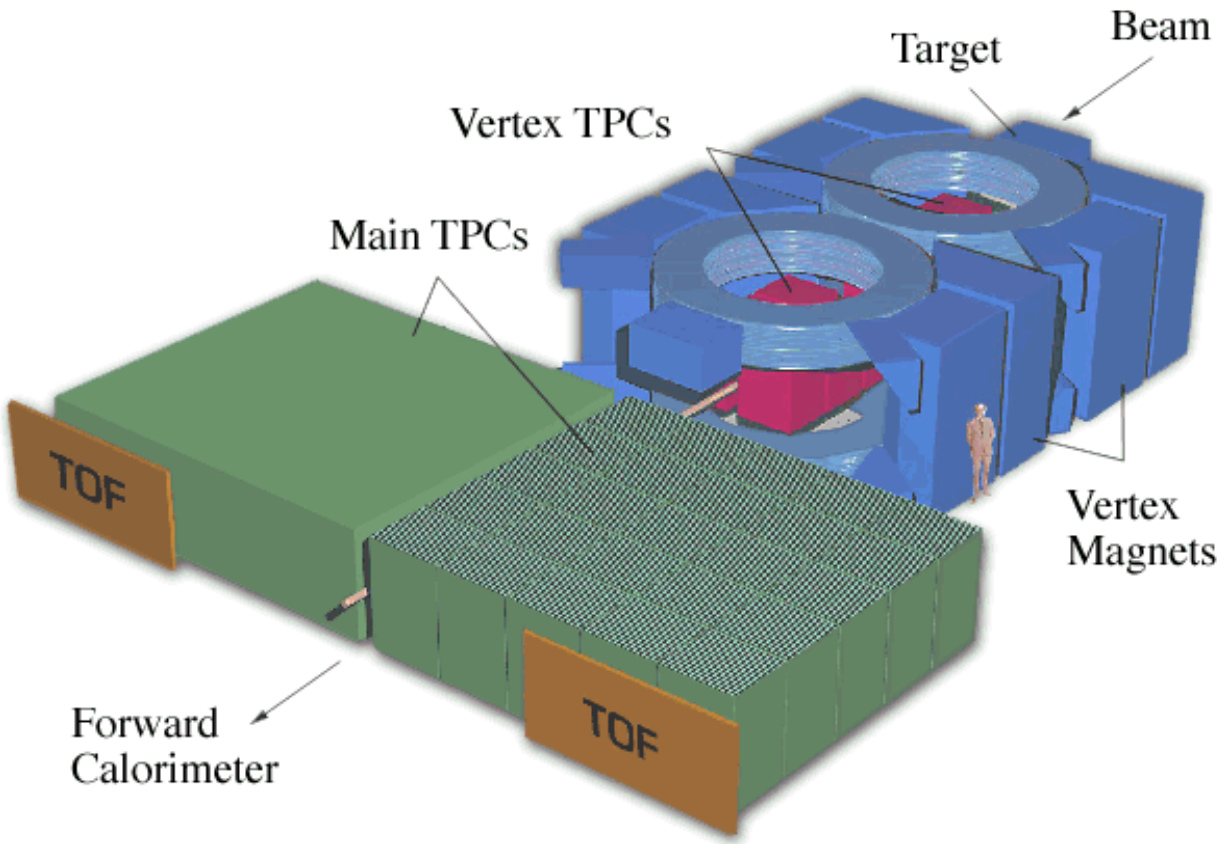
($T$, $\mu_B$) phase diagram can be scanned by varying energy and system size




## Strategy to look for critical point in NA49:

- Energy scan (beam 20A-158A GeV) with central Pb+Pb collisions
- System size dependence (different ions) at 158A GeV (top SPS energy)

## NA49 (fixed target) experiment at CERN SPS




Operating since 1994; p+p, C+C, Si+Si and Pb+Pb interactions at center of mass energy **6.3 – 17.3 GeV** for N+N pair

**Hadron spectrometer**
Four TPCs; two VTPCs (1/2) in the **B** field and two others MTPCs (R/L) outside;
for a precise measurement of **p** and dE/dx

**Large acceptance:** ≈50%
**High momentum resolution:**

$$\sigma(p)/p^2 \approx 10^{-4} \quad ((GeV/c)^{-1})$$

**Good particle identification:**

$$\sigma(TOF) \approx 60\,ps,$$
$$\sigma(dE/dx)/\langle dE/dx \rangle \approx 0.04,$$
$$\sigma(m_{inv}) \approx 5\,MeV$$

**Centrality determination:**
Forward Calorimeter
(energy of projectile spectators)

# Event-by-event transverse momentum and multiplicity fluctuations

$\Phi_{pT}$ - measures transverse momentum fluctuations on event-by-event basis

$\omega$ - measures multiplicity 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)

$$\Phi_{p_T} = \sqrt{\frac{\langle Z^2_{p_T} \rangle}{\langle N \rangle}} - \sqrt{\overline{z^2}_{p_T}}$$

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

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

$\Phi_{pT}$ (A+A) = $\Phi_{pT}$ (N+N)

**$\Phi_{pT}$ is independent of $N_{part}$ fluctuations**

$\omega$ (A+A) = $\omega$ (N+N) + < n > $\omega_{part}$

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

$\omega_{part}$ - fluctuations in $N_{part}$

**$\omega$ is strongly dependent on $N_{part}$ fluctuations**

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

$\Phi_{pT}$ = 0

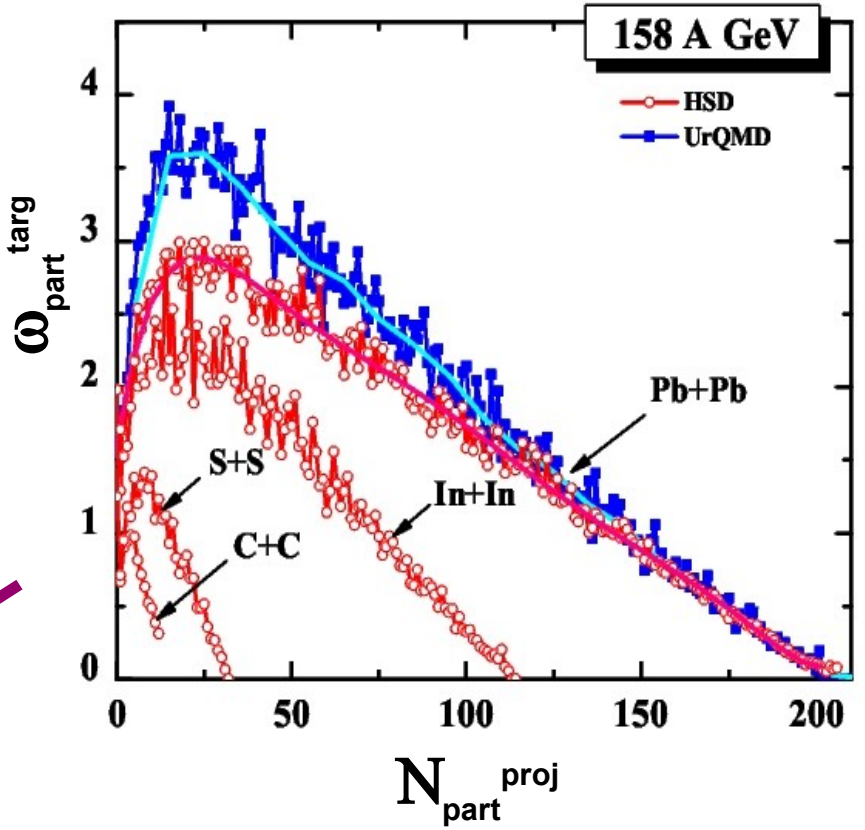
For **Poissonian multiplicity distribution**

$\omega$=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




**$\omega_{part}^{targ}$ - 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 and kinematic cuts** (for $\Phi_{pT}$ and ω measurements):

- p+p, central and semi-central A+A collisions: 1% most centr. for ω and 5-15% for $\Phi_{pT}$
- **forward-rapidity region**
- 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

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

**Width of CP region in (T, $\mu_B$) plane** based on Hatta, Ikeda PR**D67**, 014028 (2003)

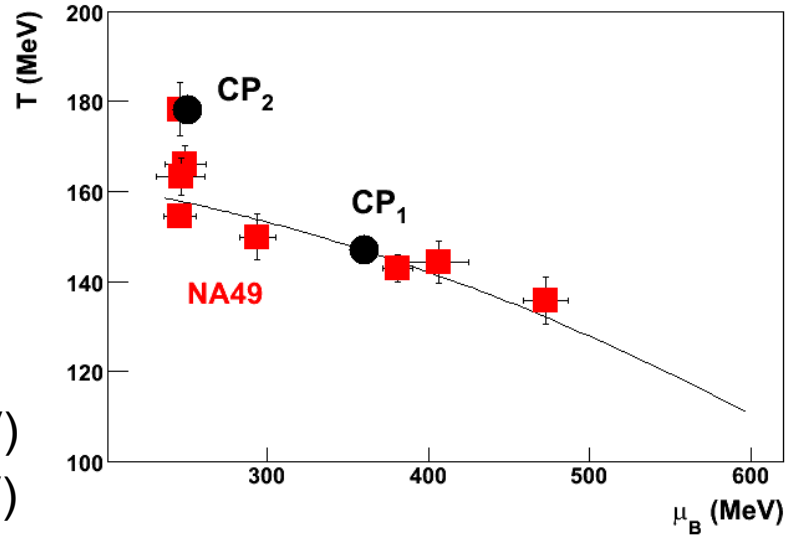
$\sigma(\mu_B) \approx 30$ MeV and $\sigma(T) \approx 10$ MeV

**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)

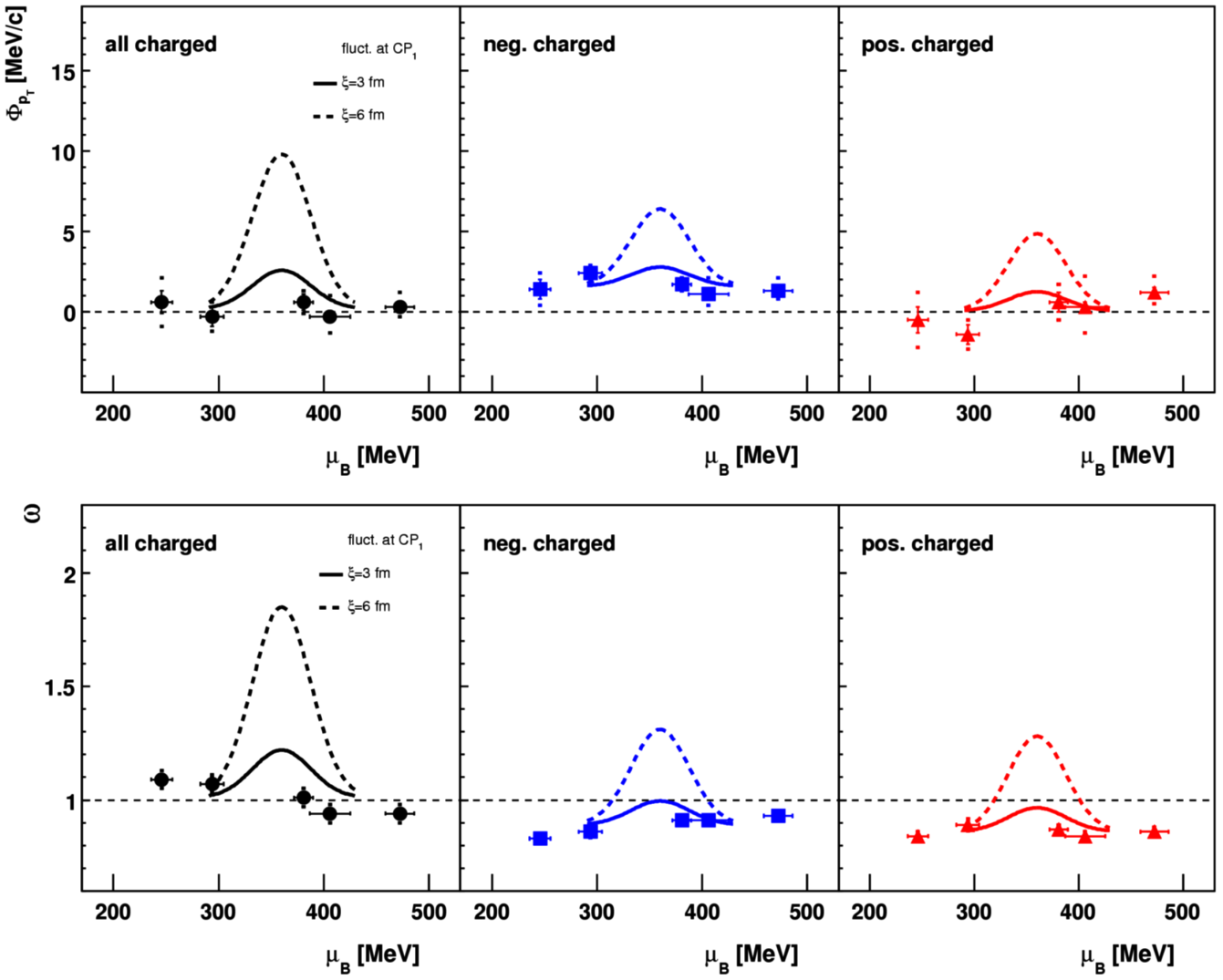
- $\mu_B(CP_2) \cong 250$ MeV ($\mu_B$ for A+A collisions at 158A GeV)
  $T(CP_2) = 178$ MeV ($T_{chem}$ for p+p collisions at 158 GeV)



# Energy dependence for central Pb+Pb

→ Average $p_T$ fluctuations (PR**C79**, 044904 (2009))

→ 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 $\mu_B$ = 360 MeV)

base-lines for $CP_1$ predictions (curves) are mean $\Phi_{pT}$ and $\omega$ values for 5 energies

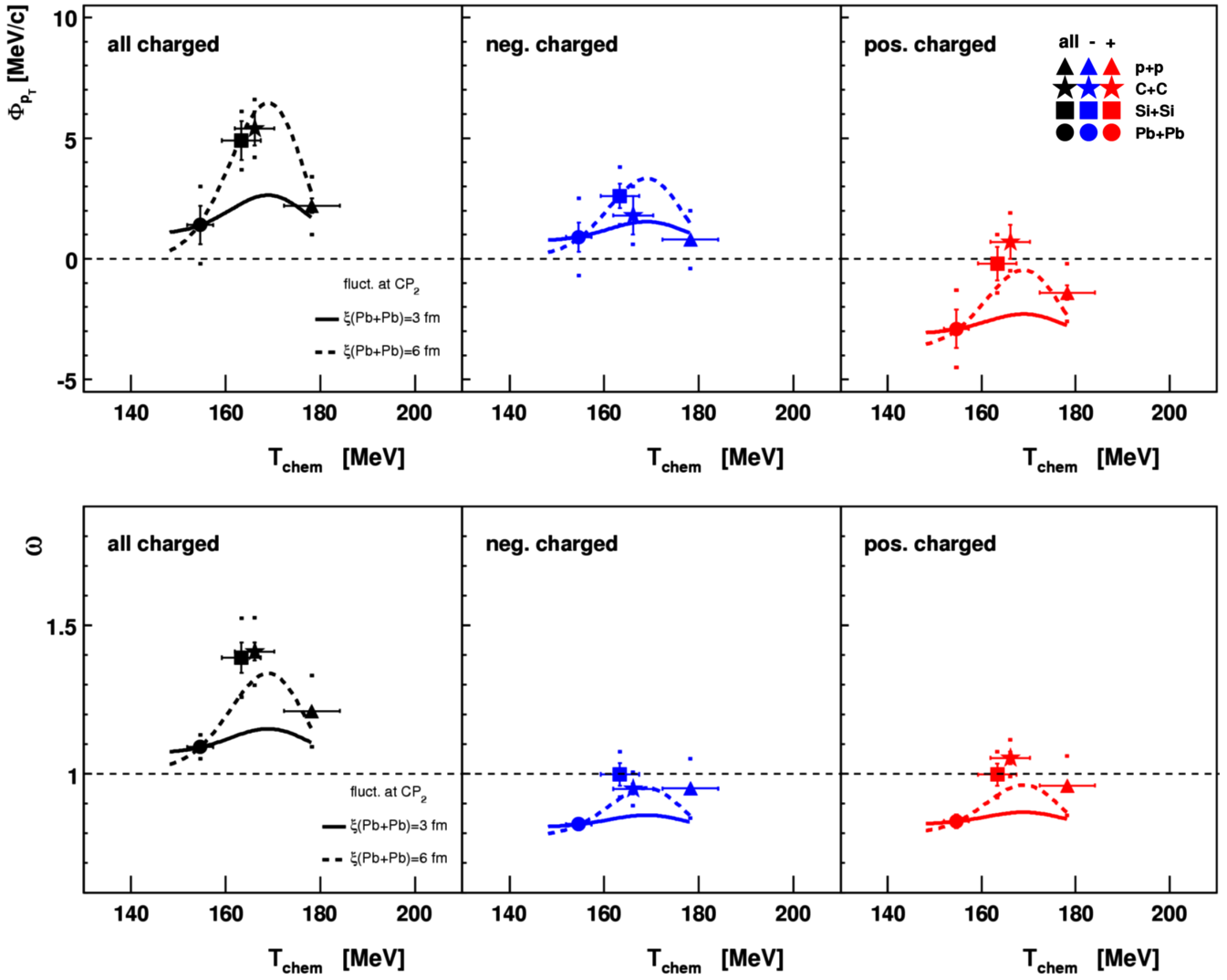
**Data do not provide evidence for critical point fluctuations**

→ **No significant energy dependence at SPS energies**

# System size dependence at 158A GeV

→ Average $p_T$ fluctuations (PR**C70**, 034902, 2004))

→ Multiplicity fluctuations (pp: PR**C75**, 064904 (2007); PbPb: PR**C78**, 034914 (2008); CC, SiSi: B. Lungwitz, PhD)




$CP_2$ location:

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

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

$CP_2$ predictions (curves) normalized to reproduce $\Phi_{pT}$ and $\omega$ value for central Pb+Pb collisions

**Data are consistent with the $CP_2$ predictions**

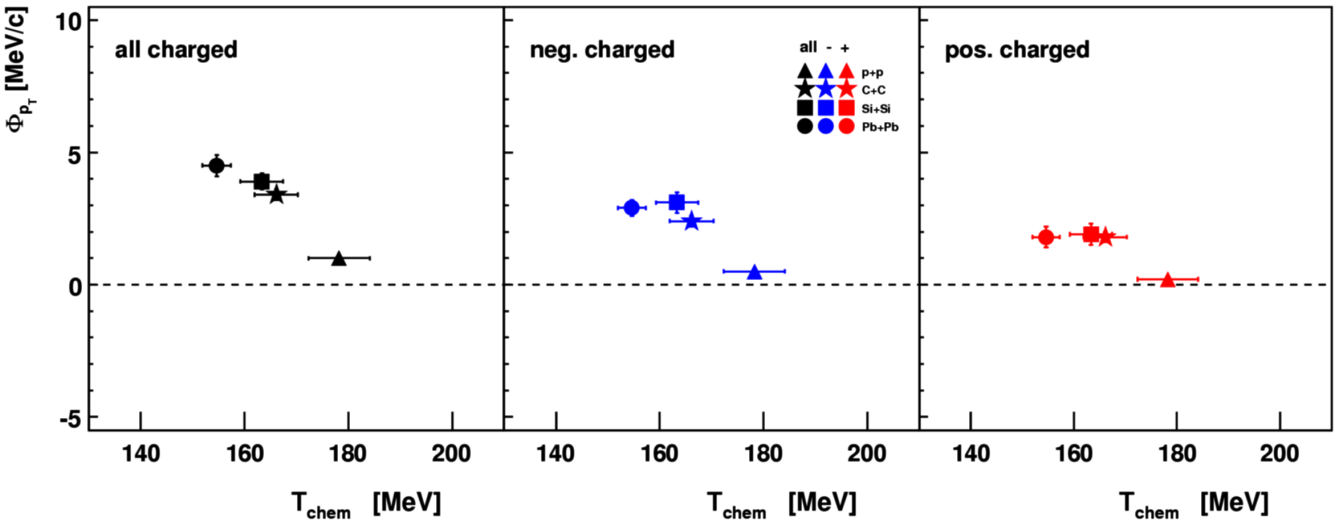
→ **Maximum of $\Phi_{pT}$ and $\omega$ observed for C+C and Si+Si**

→ **Increase ~ two times larger for all charged than for negatively charged particles**

**Expectations:** fluctuations due to the critical point originate mainly from low $p_T$ pions

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

**NA49 results** for low and high $p_T$ regions:

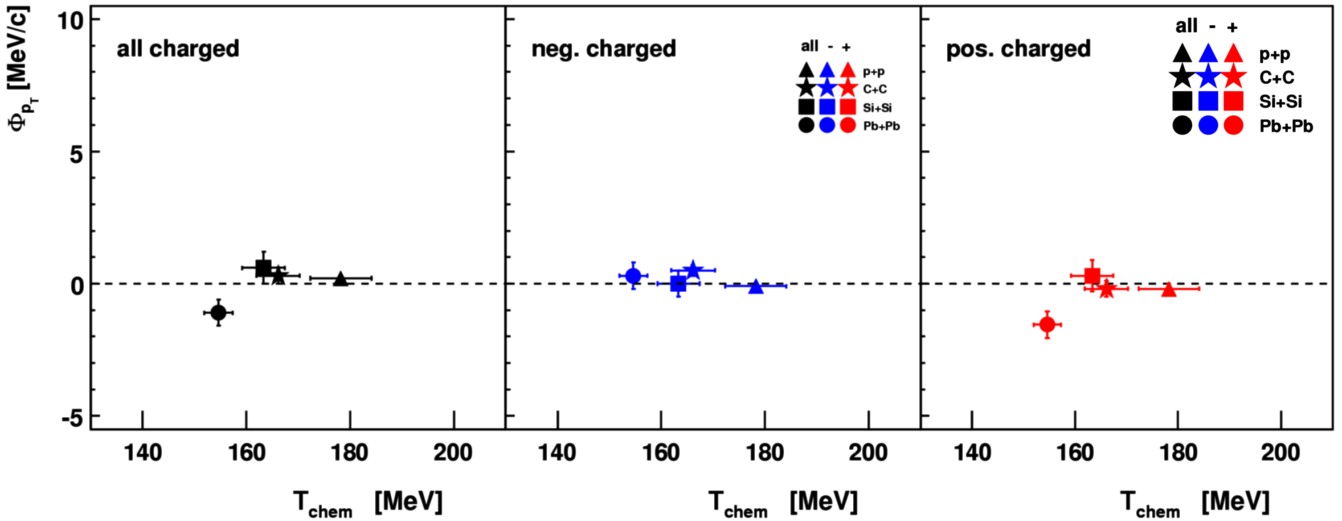



low $p_T$ region

**$p_T$ < 0.5 GeV/c**

**signal observed**

*NA49 preliminary*




high $p_T$ region

**$p_T$ > 0.5 GeV/c**

**fluctuations consistent with zero**

→ **Correlations observed predominantly at low $p_T$**

→ **No more maximum of $\Phi_{pT}$ due to large correlations in Pb+Pb; their origin currently analyzed** (short range correlations considered)

# Transverse mass spectra of baryons and anti-baryons

**The presence of a critical point can deform the trajectories** describing the evolution of the expanding fireball in the (T - $\mu_B$) phase diagram. The critical point serves as an attractor of the hydrodynamical trajectories. Askawa et. al. PRL**101**, 122302 (2008):

If the average emission time of hadrons is a function of transverse velocity ($\beta_T$) **this deformation will change the $\beta_T$ dependence of $\bar{p}/p$ ratio** provided that the fireball passes **in the vicinity of the critical point**

Expected observable: the **$\bar{p}/p$ ratio should fall with increasing transverse momentum** instead of a rise ($\bar{p}$ anihilation) or flat behavior in a scenario without the critical point

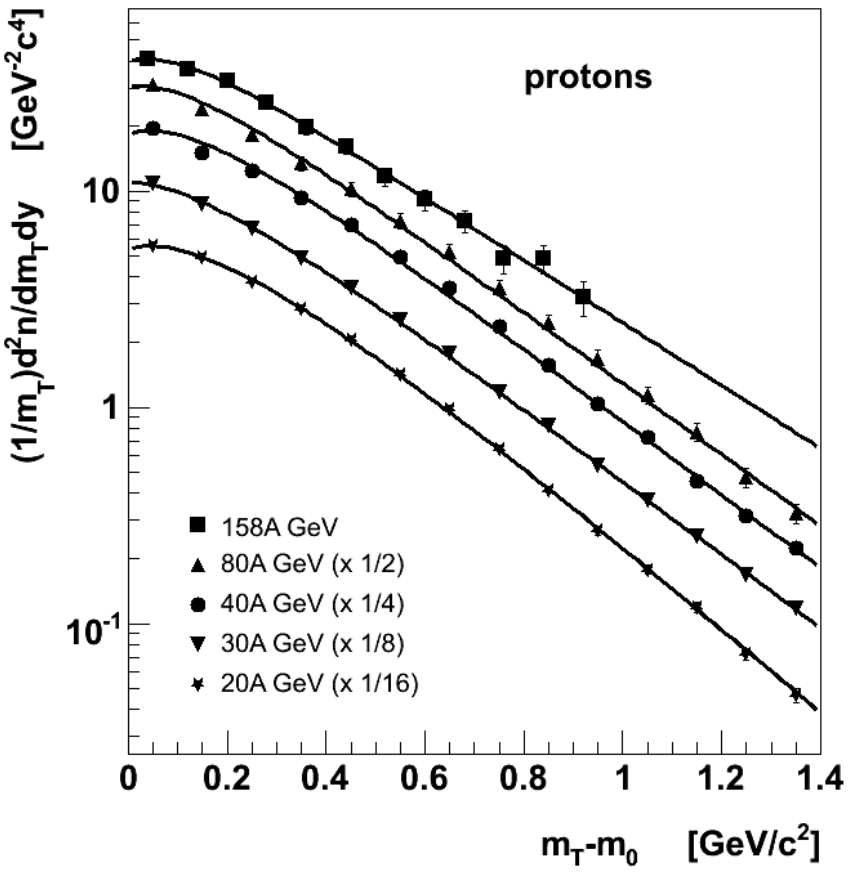
(For UrQMD+THERMINATOR predictions see also Luo et al. arXiv:0903.0024)

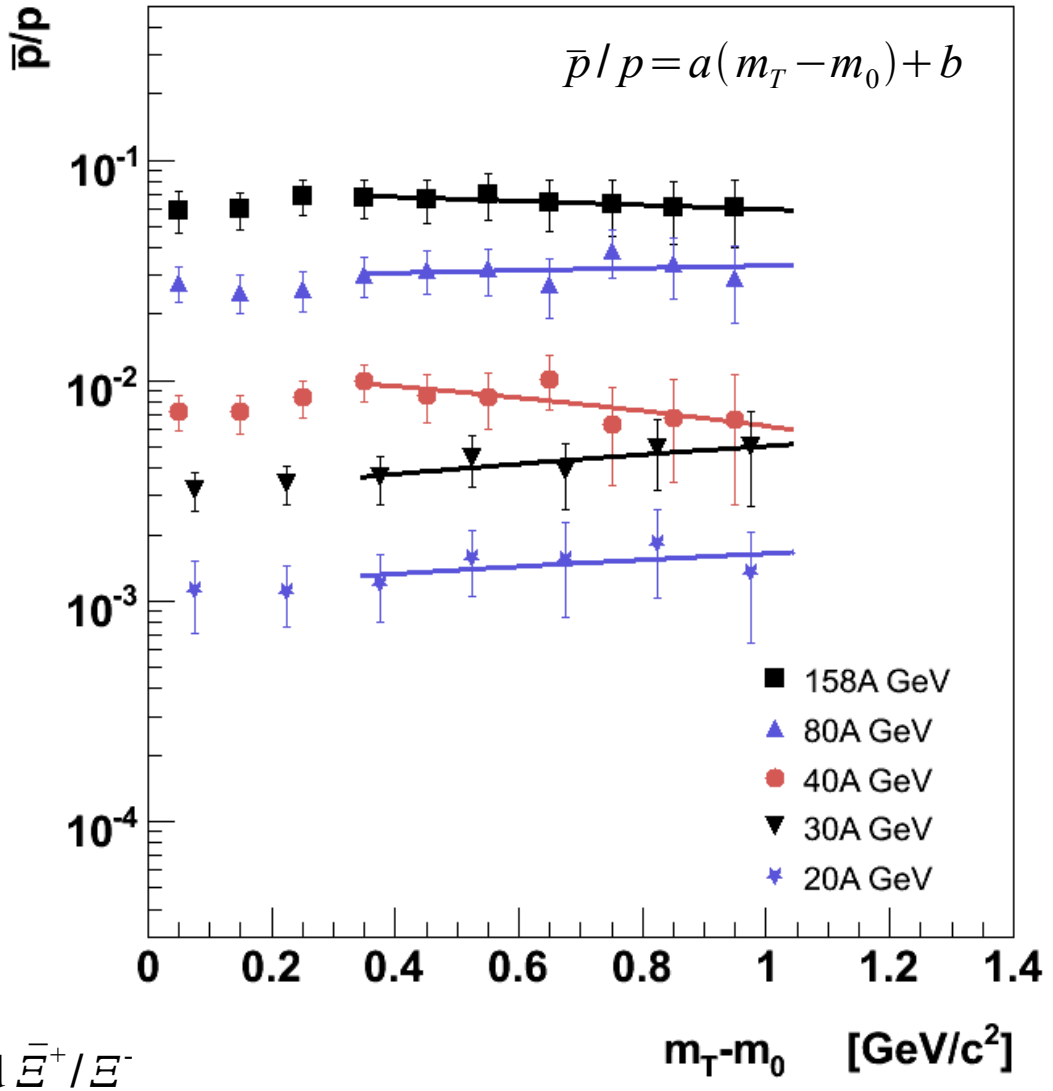
# Energy dependence for central Pb+Pb
## → $\bar{p}/p$ ratio versus $m_T$ (PR**C73**, 044910 (2006))

$$\frac{1}{m_T}\frac{d^2n}{dm_T\,dy} = C_1 \exp\left(-(m_T - m_0)/T_{slope}\right) + C_2 \exp\left(-(m_T - m_0)/T'\right)$$

Points for $\bar{p}$ divided by fitted curves (left) for protons

fit to data in the range $0.0 < m_T - m_0 < 1.5$



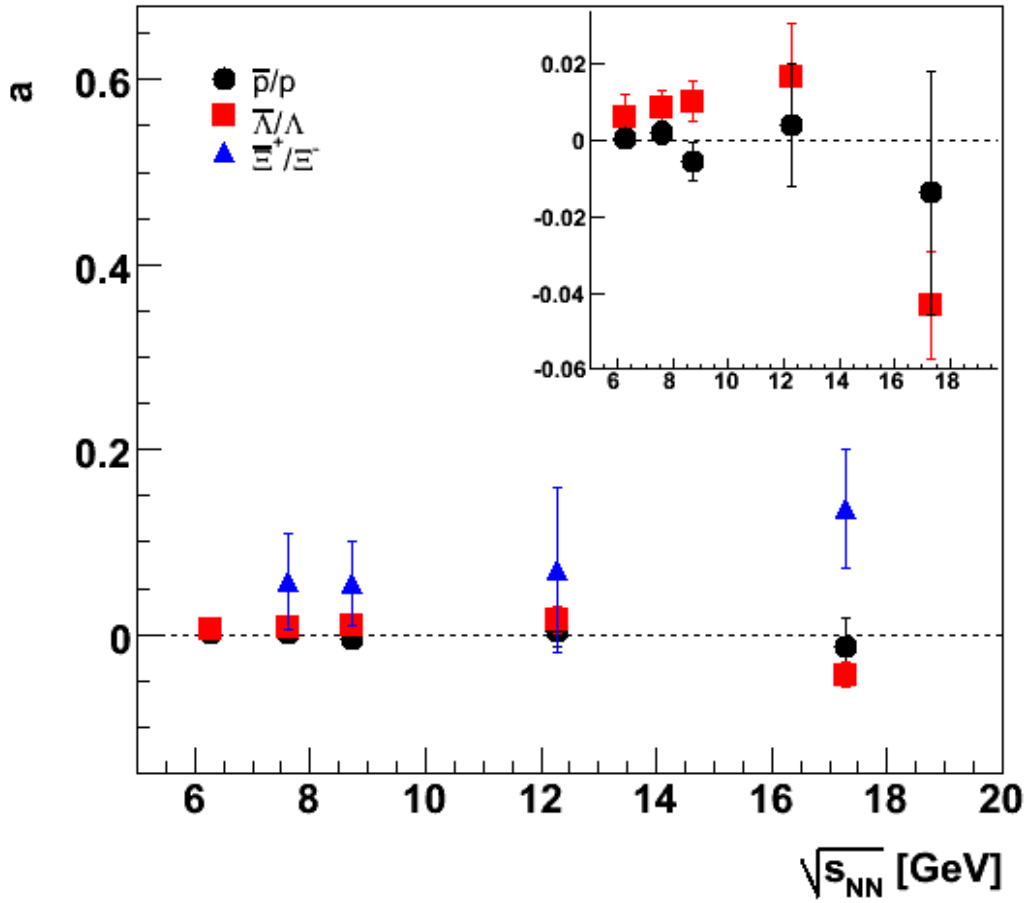




Similar procedure applied also for $\bar{\Lambda}/\Lambda$ and $\bar{\Xi}^+/\Xi^-$

PR**C73**, 044910 (2006); PR**C78**, 034918 (2008)

# Energy dependence for central Pb+Pb
## → Anti-baryon/baryon ratio versus $m_T$

**anti-baryon/baryon=a ($m_T$ – $m_0$) + b**




**→ No significant energy dependence** of slope parameter (a) in anti-baryon to baryon ratio.

**No evidence for the critical point**

# Summary of NA49 results

- Results on hadron production in A+A collisions at the CERN SPS energies related to the search for the critical point of strongly interacting matter have been presented

- **There are no indications of the critical point in the energy dependence** of multiplicity and mean transverse momentum fluctuations, and ratios of the anti-baryon/baryon transverse mass spectra **in central Pb+Pb collisions**

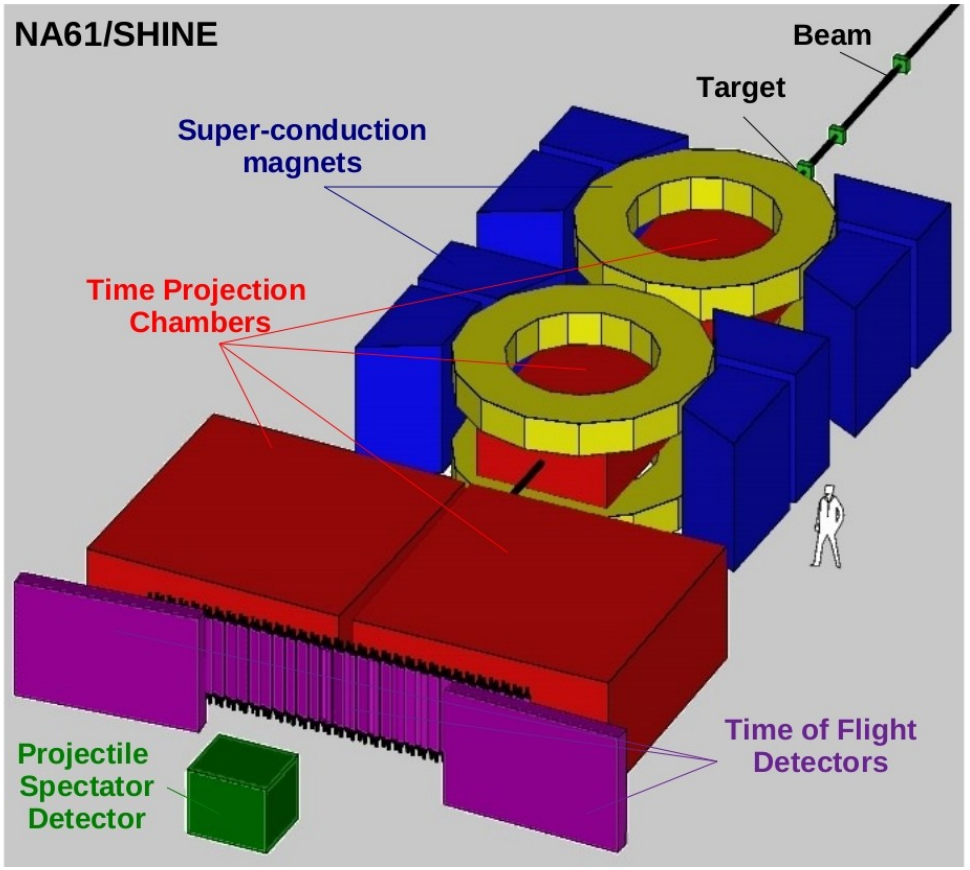
- **The system size dependence at 158A GeV shows:**
  - a **maximum of mean $p_T$ and multiplicity fluctuations** in the complete $p_T$ range $\rightarrow$ **consistent with $CP_2$ predictions**
  - an **increase** (from p+p up to Pb+Pb) **of mean $p_T$ fluctuations in the low $p_T$ region (reason currently under study)**; high $p_T$ particles show no fluctuation signal

- The low $p_T$ region will be carefully analyzed for the effects of short range correlations on $\Phi_{pT}$ and $\omega$

- A detailed energy and system-size scan is necessary to establish the existence of the critical point $\rightarrow$ NA61/SHINE

# Search for the critical point in NA61/SHINE

## SHINE (fixed target) experiment at CERN SPS



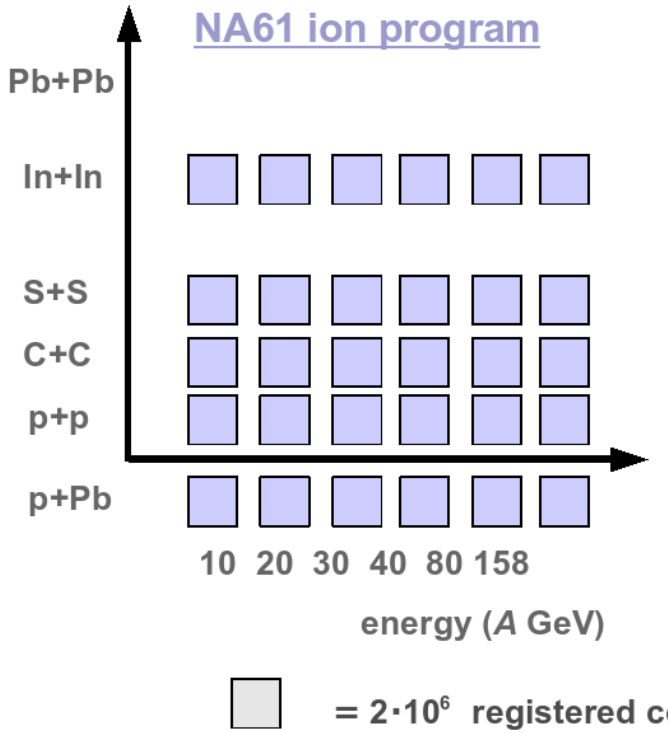

NA61/SHINE physics program:

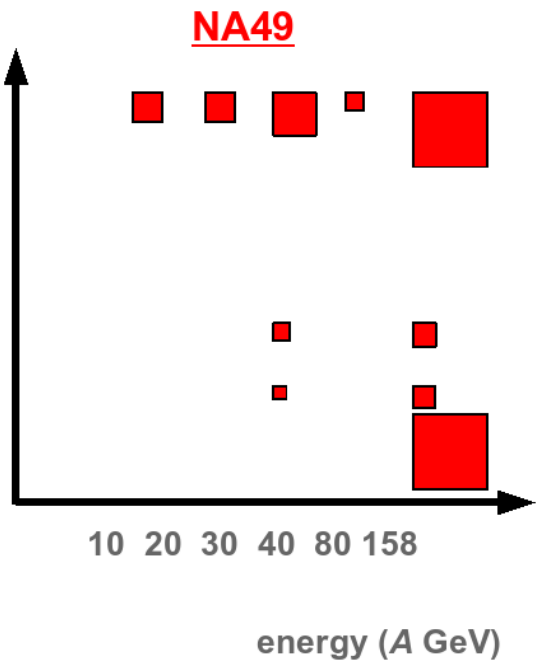
- **Critical Point and Onset of Deconfinement,**
- High $p_T$ physics
- Neutrino physics
- Cosmic-ray physics

Main upgrades:

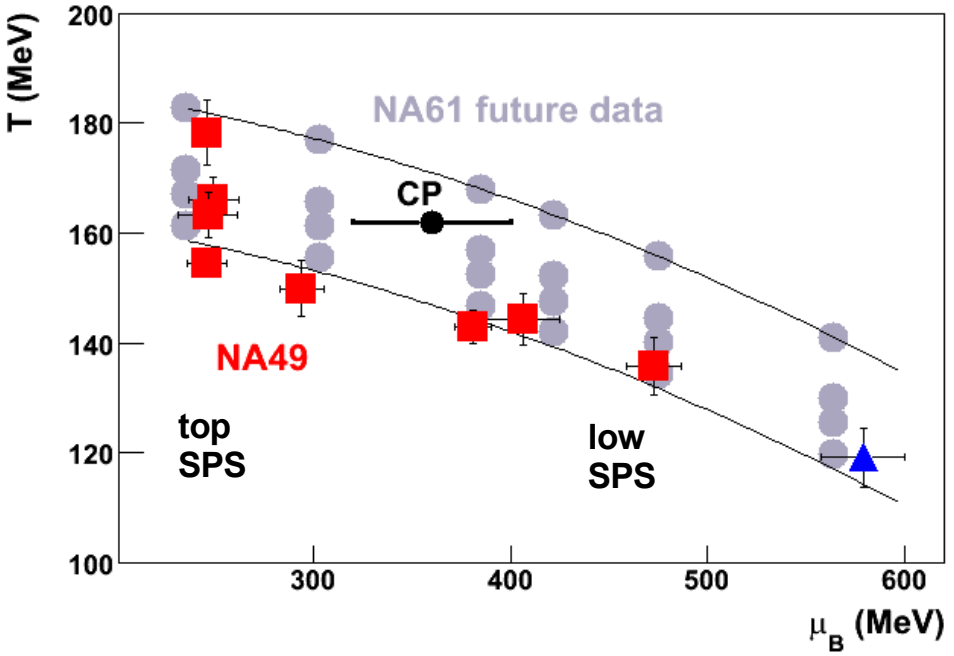
- 2007: Construction of the **forward ToF wall**
- 2008: Replacement of the TPC digital **read-out** and **DAQ** (increase of the event rate by a factor of ≈ 10)
- Planned: Replacement of Forward Calorimeter (VETO) by **Projectile Spectator Detector**

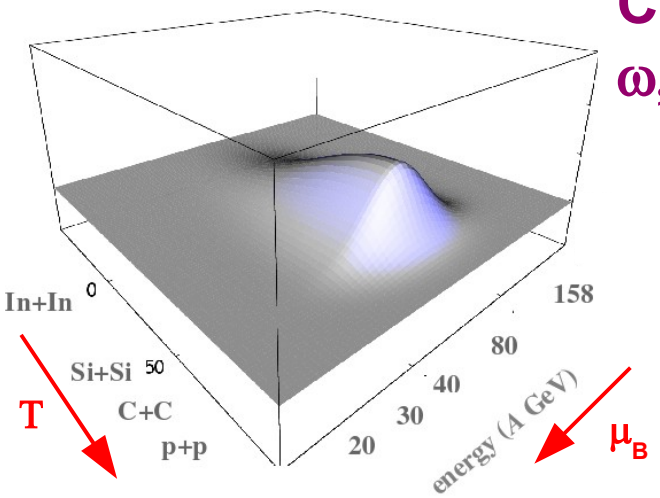
**NA61 upgrades:** CERN-SPSC-2006-034, SPSC-P-330




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




**CP signal**

$\omega$, $\Phi_{pT}$, ...

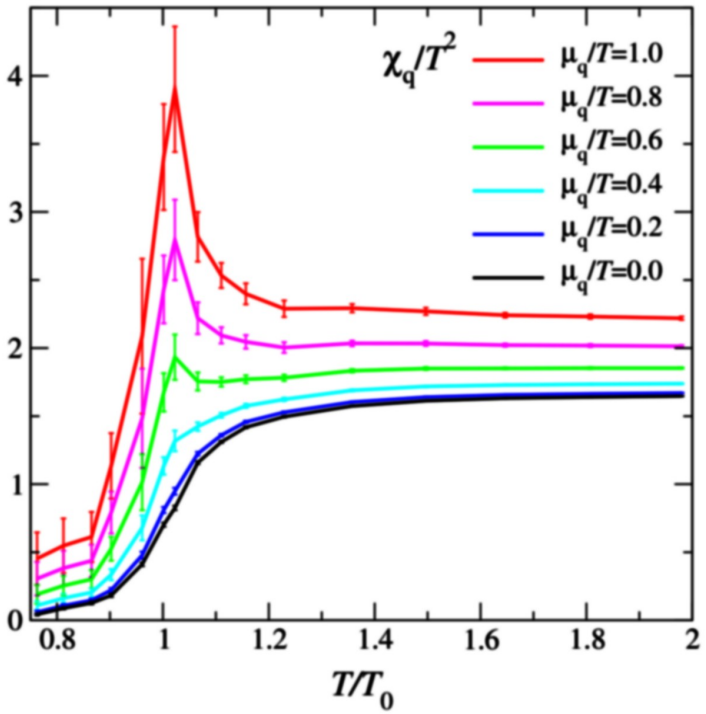
# NA49 Collaboration:

T. Anticic, B. Baatar,D.Barna, J. Bartke, L. Betev, H. Białkowska, C. Blume, B. Boimska, M. Botje, J. Bracinik, P. Buncic, V. Cerny, P. Christakoglou, P. Chung, O. Chvala, J. G. Cramer, P. Csato, P. Dinkelaker, V. Eckardt, Z. Fodor, P. Foka, V. Friese, J. Gal, M. Gaździcki, V. Genchev, E. Gładysz, K. Grebieszkow, S. Hegyi, C. Hohne, K.Kadija, A. Karev, D. Kikola, V. I. Kolesnikov, E. Kornas, R. Korus, M. Kowalski, M. Kreps, D. Kresan, A. Laszlo, R. Lacey, M. van Leeuwen, P. Levai, L. Litov, B. Lungwitz, M. Makariev, A. I. Malakhov, M. Mateev, G. L. Melkumov, A. Mischke, M. Mitrovski, J. Molnar, St. Mrówczyński, V. Nicolic, G. Palla, A. D. Panagiotou, D. Panayotov, A. Petridis, W. Peryt, M. Pikna, J. Pluta, D. Prindle, F. Puhlhofer, R. Renfordt, C. Roland, G. Roland, M. Rybczyński, A. Rybicki, A. Sandoval, N. Schmitz, T. Schuster, P. Seyboth, F. Sikler, B. Sitar, E. Skrzypczak, M. Slodkowski, G. Stefanek, R. Stock, C. Strabel, H. Strobele, T. Susa, I. Szentpetery, J. Sziklai, M. Szuba, P. Szymanski, V. Trubnikov, M. Utvic, D. Varga, M. Vassiliou, G. I. Veres, G. Vesztergombi, D. Vranic, Z. Włodarczyk, A. Wojtaszek-Szwarc, I. K. Yoo

# NA61/SHINE Collaboration:

N. Abgrall, A. Aduszkiewicz, B. Andrieu, T. Anticic, N. Antoniou, A. G. Asryan, B. Baatar, A. Blondel, J. Blumer, L. Boldizsar, A. Bravar, J. Brzychczyk, S. A. Bunyatov, K.-U. Choi, P. Christakoglou, P. Chung, J. Cleymans, D. A. Derkach, F. Diakonos, W. Dominik, J. Dumarchez, R. Engel, A. Ereditato, G. A. Feofilov, Z. Fodor, M. Gaździcki, M. Golubeva, K. Grebieszkow, F. Guber, T. Hasegawa, A. Haungs, M. Hess, S. Igolkin, A. S. Ivanov, A. Ivashkin, K. Kadija, N. Katrynska, D. Kiełczewska, D. Kikoła, J.-H. Kim, T. Kobayashi, V. I. Kolesnikov, D. Kolev, R. S. Kolevatov, V. P. Kondratiev, A. Kurepin, R. Lacey, A. Laszlo, S. Lehmann, B. Lungwitz, V. V. Lyubushkin, A. Maevskaya, Z. Majka, A. I. Malakhov, A. Marchionni, A. Marcinek, M. Di Marco, I. Maris, V. Matveev, G. L. Melkumov, A. Meregaglia, M. Messina, C. Meurer, P. Mijakowski, M. Mitrovski, T. Montaruli, St. Mrówczyński, S. Murphy, T. Nakadaira, P. A. Naumenko, V. Nikolic, K. Nishikawa, T. Palczewski, G. Palla, A. D. Panagiotou, W. Peryt, A. Petridis, R. Planeta, J. Pluta, B. A. Popov, M. Posiadała, P. Przewłocki, W. Rauch, M. Ravonel, R. Renfordt, D. Rohrich, E. Rondio, B. Rossi, M. Roth, A. Rubbia, M. Rybczyński, A. Sadovsky, K. Sakashita, T. Schuster, T. Sekiguchi, P. Seyboth, K. Shileev, A. N. Sissakian, E. Skrzypczak, M. Słodkowski, A. S. Sorin, P. Staszel, G. Stefanek, J. Stepaniak, C. Strabel, H. Stroebele, T. Susa, I. Szentpetery, M. Szuba, A. Taranenko, R. Tsenov, R. Ulrich, M. Unger, M. Vassiliou, V. V. Vechernin, G. Vesztergombi, Z. Włodarczyk, A. Wojtaszek-Szwarc, J. G. Yi, I.-K. Yoo

**back-up slides**




**For strongly interacting matter long range baryon density fluctuations expected**

A picture supported by lattice calculations

Baryon density fluctuations appear to diverge for some critical value of the baryochemical potential

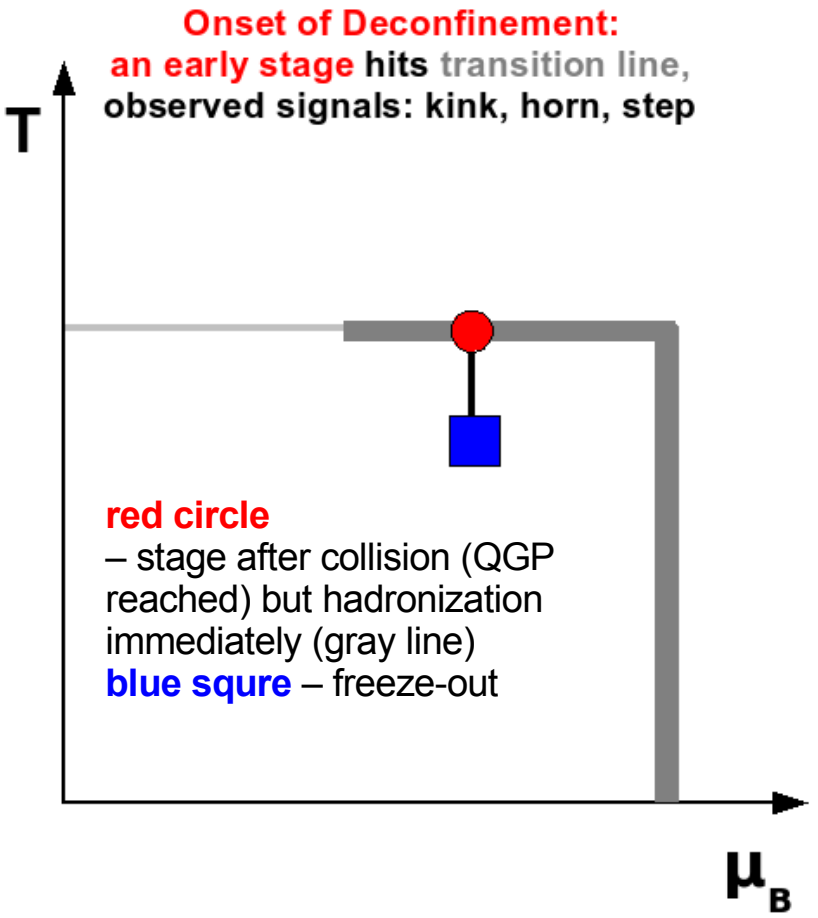
C. R. Allton, Phys. Rev. **D68** (2003), 014507

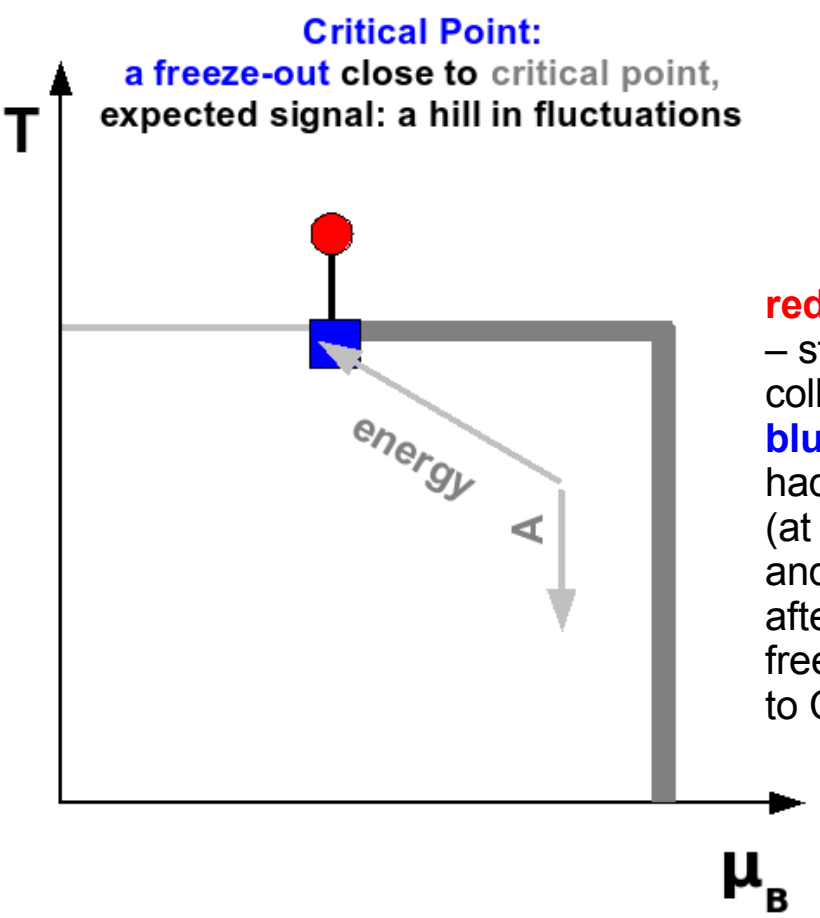
quark number susceptibility: $\chi_q \equiv \partial n_q/\partial \mu_q$,

$T_0$ – critical temperature for $\mu_q = 0$ ($\mu_B = 3\mu_q$)

CP should be searched above the phase transition energy as $E_{CP} > E_{OD}$
From NA49 data $E_{OD} \cong 30$ A GeV

## Reaching the phase transition (left) and hadronization and freeze-out at CP (right)




**red circle**
– stage after collision (QGP),
**blue square** – hadronization point (at gray line) at CP and immediately after hadronization freezeout (also close to CP)

**E(OoD) ≈ 30A GeV ≤ E(OoC)**

# Data sets (for $\Phi_{pT}$ and $\omega$ measurements):

## Energy dependence for central Pb+Pb collisions

- Central Pb+Pb interactions (7.2% most central for $\Phi_{pT}$ and 1% most central for $\omega$)
- kinematic acceptance
  - for $\Phi_{pT}$: 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 $\omega$: 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 $\omega$;
  p+p, semi-central C+C (15.3%) and Si+Si (12.2%), 5% most central Pb+Pb for $\Phi_{pT}$
- kinematic acceptance
  - for $\Phi_{pT}$: forward-rapidity $1.1 < y_{\pi}^{*} < 2.6$ and $0.005 < p_T < 1.5$ GeV/c
  - for $\omega$: 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)

## New (updated in 2008) predictions at CP (values for the energy scan):

### Concerning $\Phi_{pT}$ (additive correction to uncorrelated particle production):

Remark: uncorrelated particle production results in $\Phi_{pT} = 0$

**Assuming correlation length $\xi$ = 6 fm**

$4\pi$ acceptance: 40 MeV/c (all charged)
20 MeV/c (one charge only)

acceptance correction in rapidity: 0.6
acceptance correction in azimuthal angle: 0.4 (common for all energies)

Finally for NA49 acceptance: 40*0.6*0.4 = 9.6 MeV/c (all charged)
4.8 MeV/c (like-sign particles)

*However, the correlation length may not exceed 3 fm...*

**Assuming correlation length $\xi$ = 3 fm**

$4\pi$ acceptance: 10 MeV/c (all charged)
5 MeV/c (one charge only)

acceptance correction in rapidity: 0.6
acceptance correction in azimuthal angle: 0.4

Finally for NA49 acceptance: 2.4 MeV/c (all charged)
1.2 MeV/c (like-sign particles)

## New (updated in 2008) predictions at CP (values for the energy scan):

### Concerning $\omega$ (additive correction to uncorrelated particle production):

Remark: uncorrelated particle production results in $\omega$ =1

**Assuming correlation length $\xi$ = 6 fm**

$4\pi$ acceptance: 2 (all charged)
1 (one charge only)

acceptance correction in rapidity: 0.6
acceptance correction in azimuthal angle: 0.7 (depends on energy; here mean value for 5 energies)

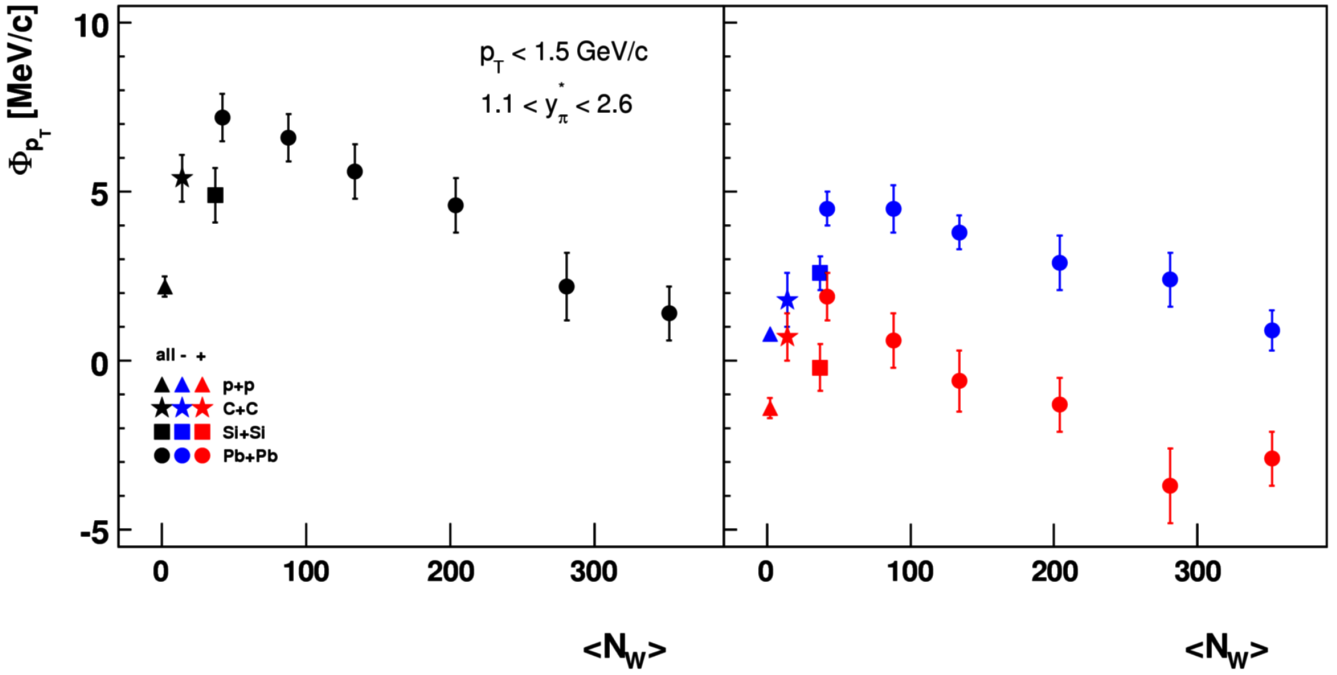
Finally for NA49 acceptance: 2*0.6*0.7 = 0.84 (all charged)
0.42 (like-sign particles)

**Assuming correlation length $\xi$ = 3 fm**

$4\pi$ acceptance: 0.5 (all charged)
0.25 (one charge only)

acceptance correction in rapidity: 0.6
acceptance correction in azimuthal angle: 0.7

Finally for NA49 acceptance: 0.21 (all charged)
0.105 (like-sign particles)



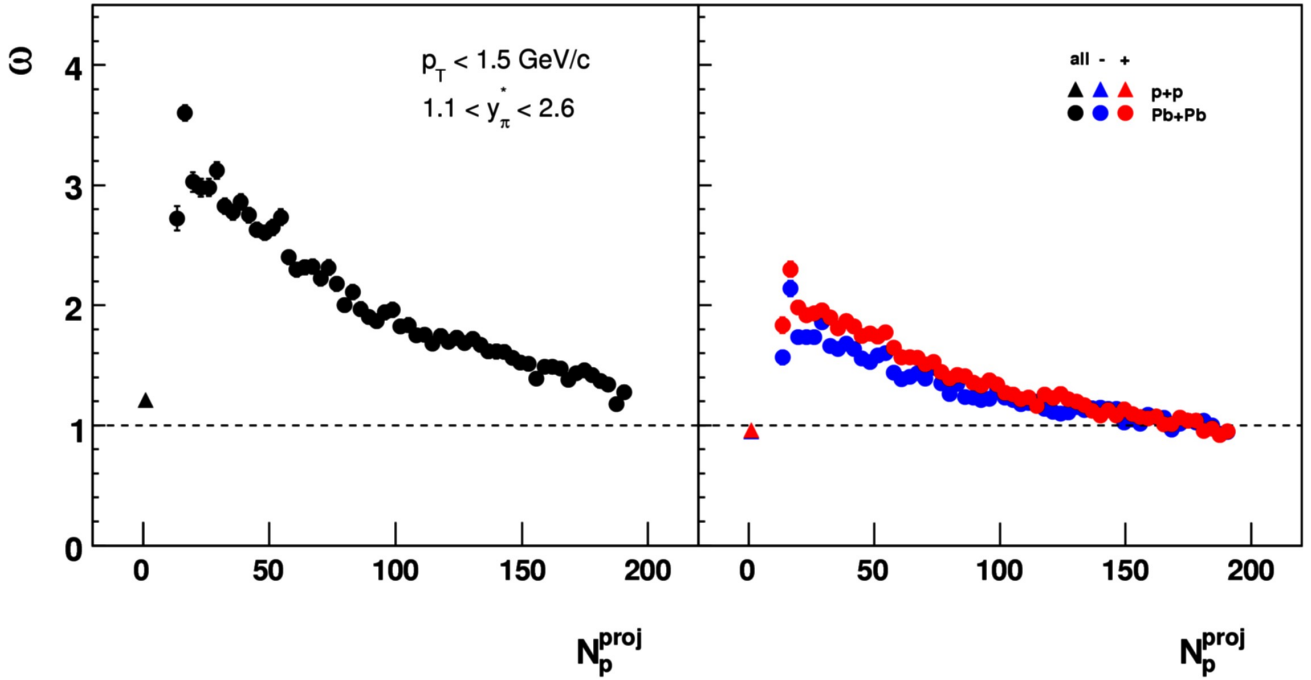

forward rapidity region

$1.1 < y^*_\pi < 2.6$ and

$0.005 < p_T < 1.5$ GeV/c

limited azimuthal acceptance

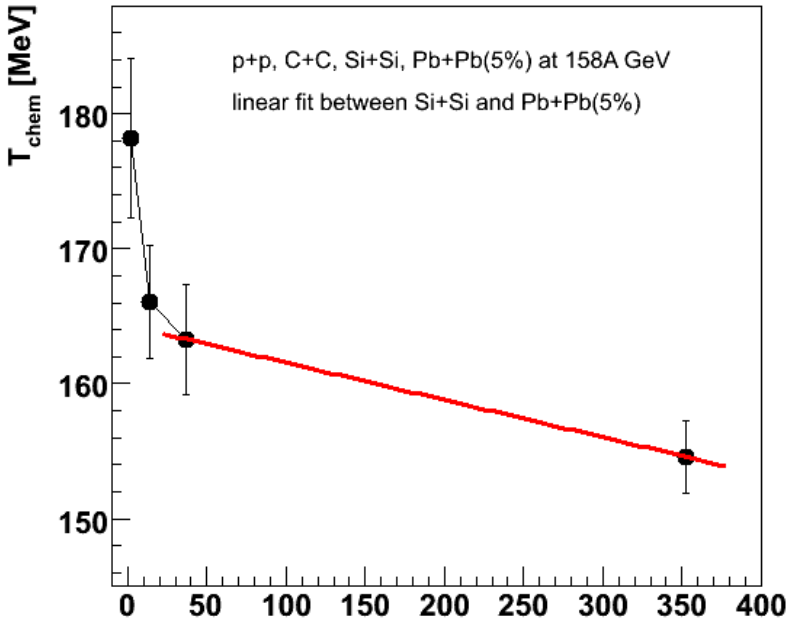
only statistical errors are shown




Very narrow bins in $N_{part}^{proj}$ but $N_{part}^{target}$ not measured in NA49.

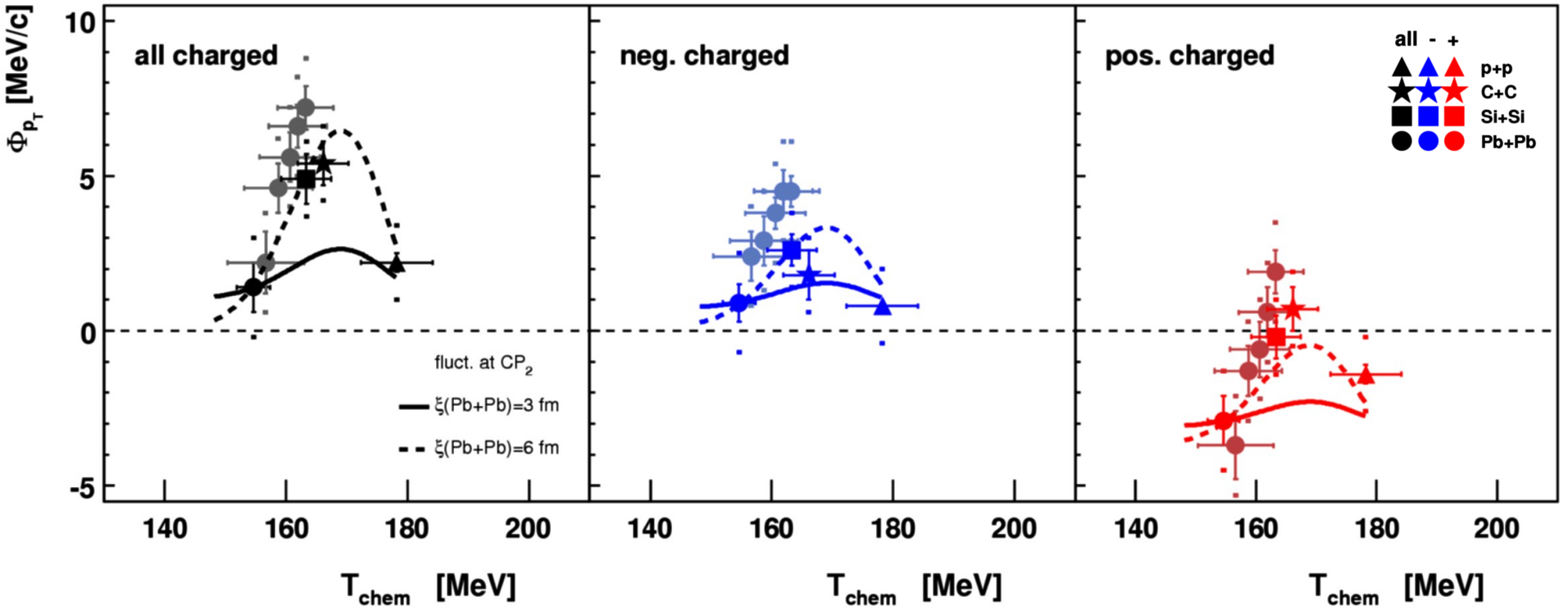
Significant increase of ω for peripheral Pb+Pb; a large effect can still originate from fluctuations of the number of target participants

(see V.P. Konchakovski et al., Phys. Rev C73, 034902 (2006))




## 5 remaining centralities of Pb+Pb also shown

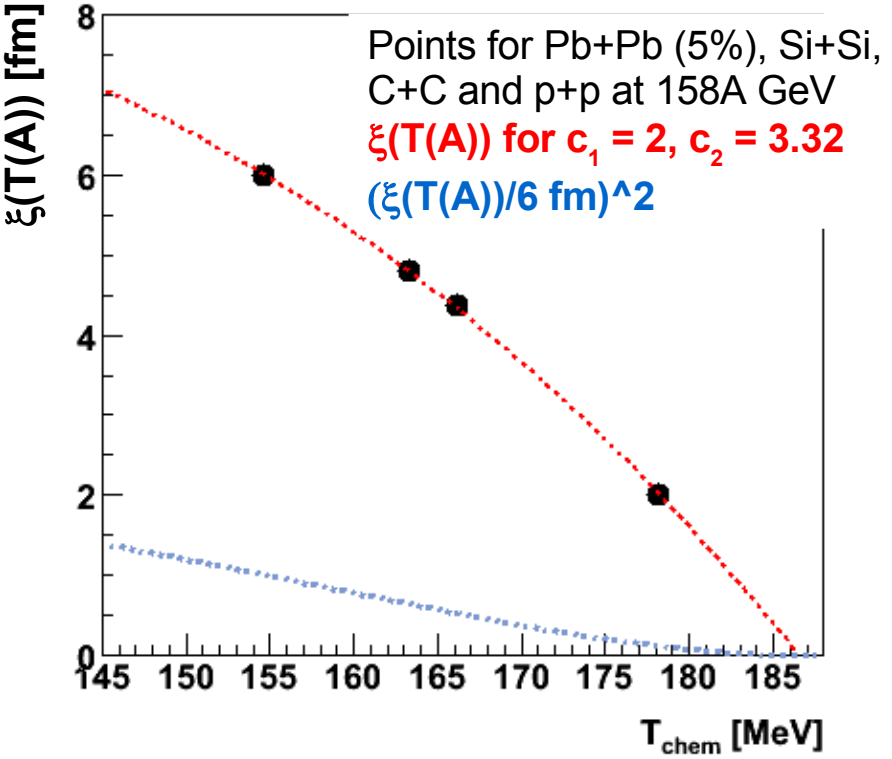
NA49 values of $T_{chem}$ for p+p, C+C, Si+Si, and Pb+Pb (5%) - PR**C73**, 044905 (2006), and for remaining centralities of Pb+Pb (lighter colors) – linear interpolation between two points for Si+Si and Pb+Pb (5%)

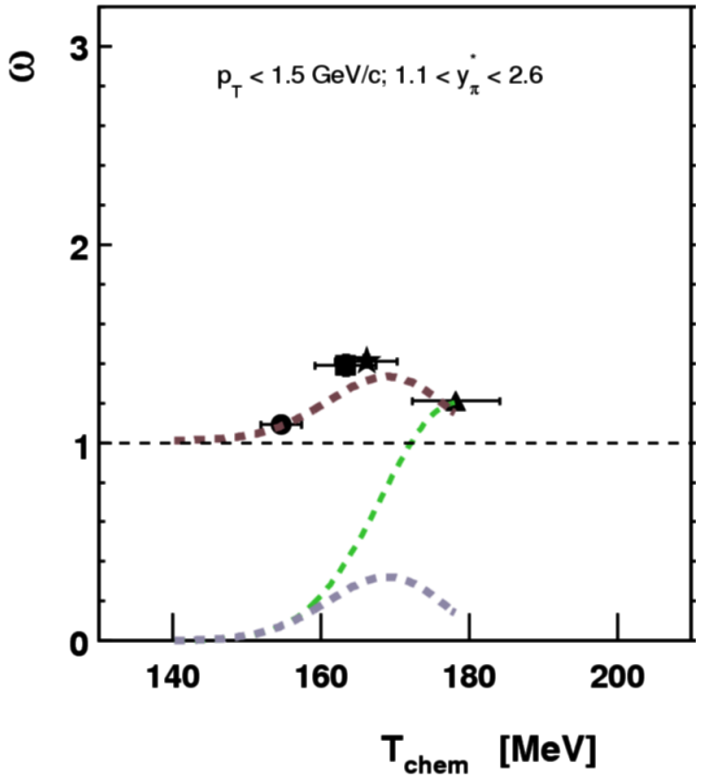


**Correlation length $\xi = \min ( c_1 A^{1/3}, c_2 A^{1/9} )$**

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

Assumed correlation length ξ for Pb+Pb = 6 fm
and for smaller systems ξ decreased



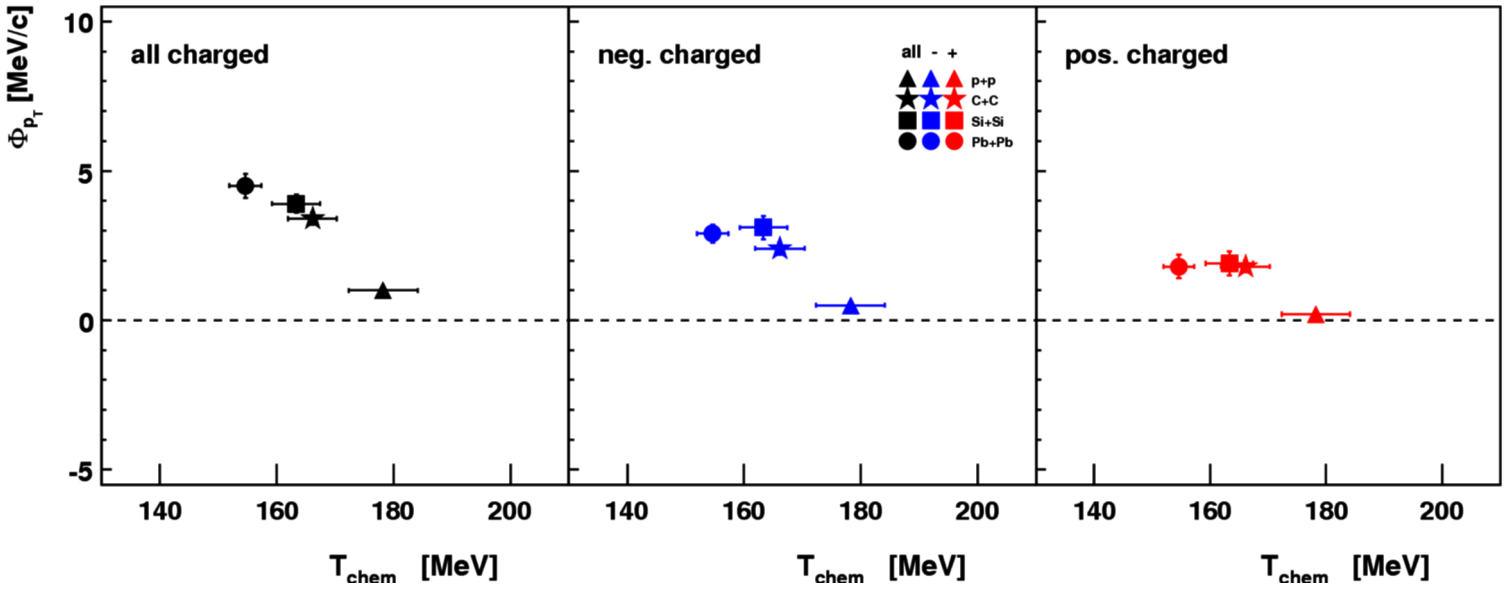




**1. Gaussian curve with maximum predicted by M. Stephanov and position at $T_{chem}$(p+p)**

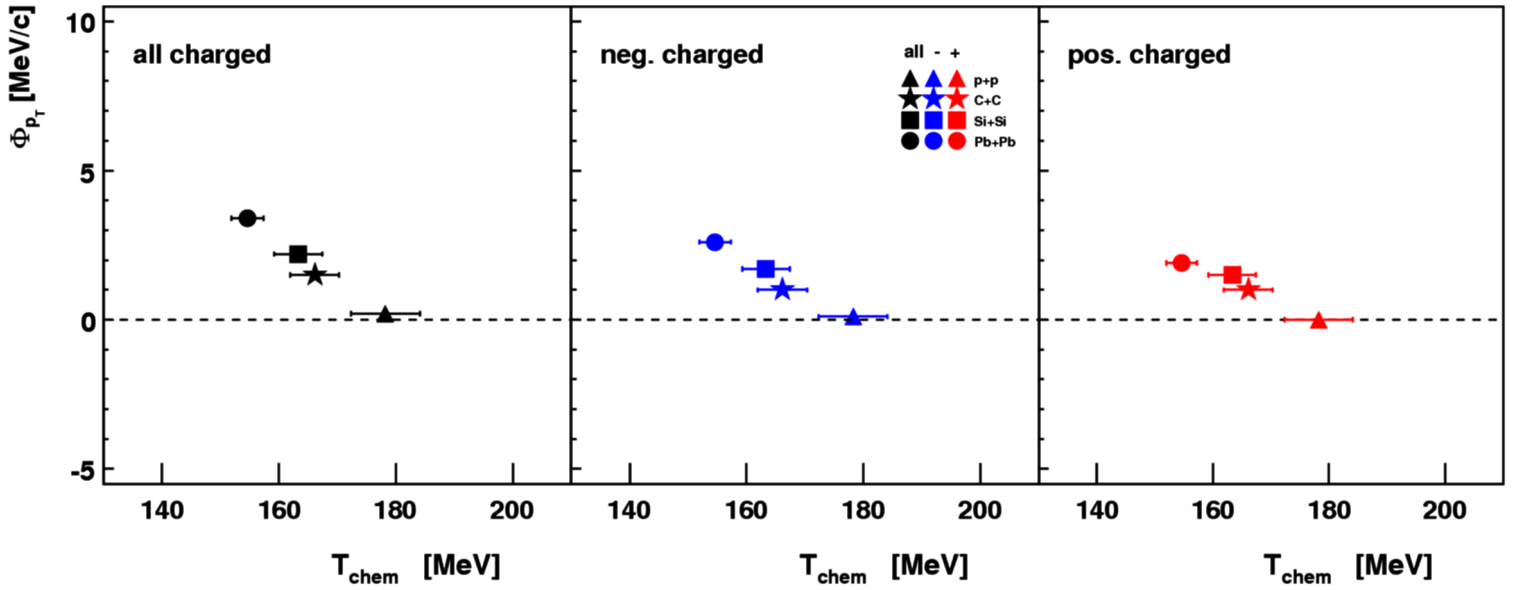
**2. multiplied by (ξ(T(A))/6fm)^2**

**3. Finally curve normalized for central Pb+Pb (it is curve shifted to cross Pb+Pb point)**

Lower $p_T$ regions



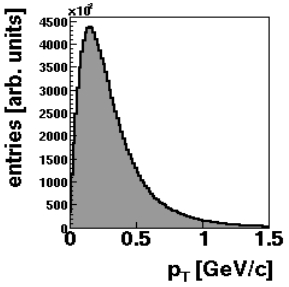

**low $p_T$ region**
**$0.005 < p_T < 0.5$ GeV/c**
**NA49 preliminary**

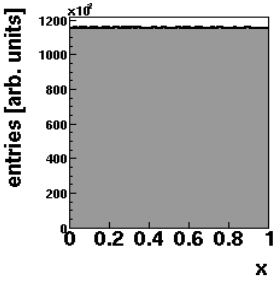


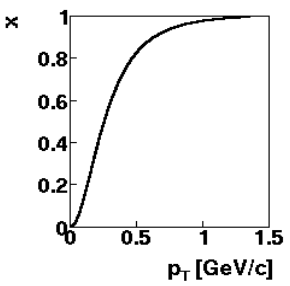

**very low $p_T$ region**
**$0.005 < p_T < 0.25$ GeV/c**
**NA49 preliminary**

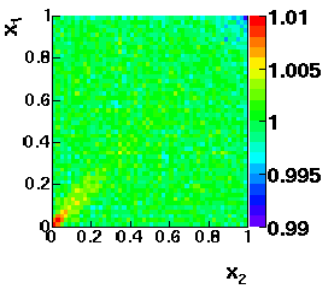
# Two-particle correlations in the cumulative variable x

additional information about the source (nature) of dynamical fluctuations




$$x(i) = \int_0^{p_{Ti}} \rho(p_T)\, dp_T$$

$\rho(p_T)$ - inclusive $p_T$ distribution normalized to unity

$p_T \rightarrow x \rightarrow$ pairs $(x_1, x_2)$ within the same event

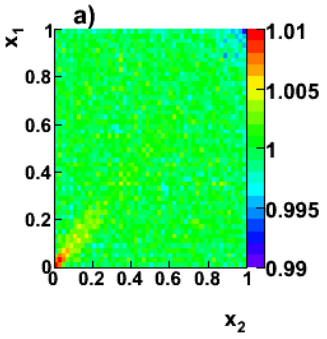
## Examples:

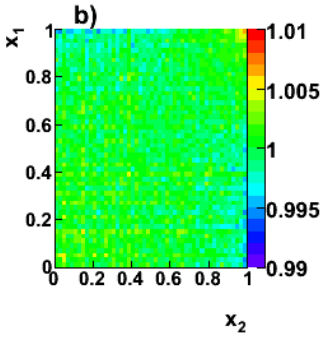
1. Uniform distribution $\rightarrow$ no dynamical fluctuations
2. Structure $\rightarrow$ dynamical fluctuations

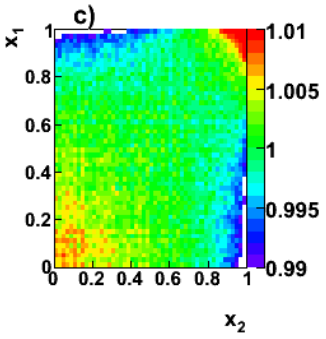
a) Bose-Einstein and Coulomb correlations – along the diagonal

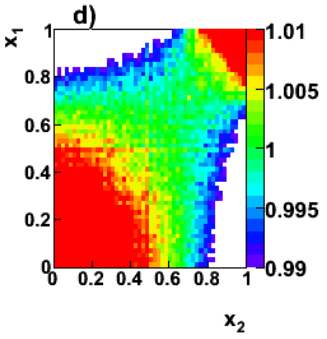
b) E-b-e inverse slope parameter (T) fluctuations – "saddle-shaped" structure

| **Pb+Pb data** | **2.6%, 20 MeV/c Monte Carlo** | **5.3%, 73 MeV/c Monte Carlo** | **10.5%, 224 MeV/c Monte Carlo** |
|---|---|---|---|



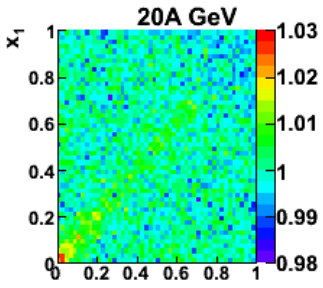



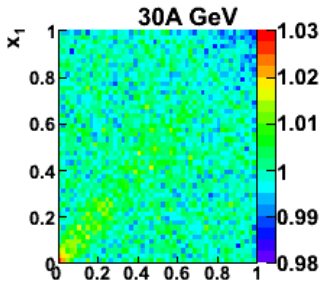



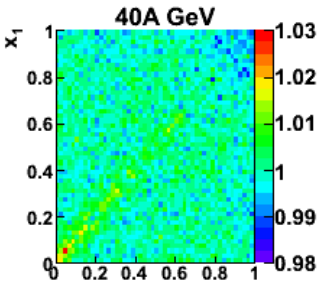



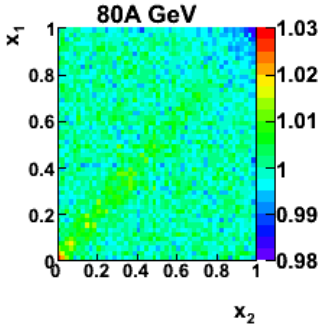

random generator of "T" fluctuations for central Pb+Pb interactions at 158A GeV

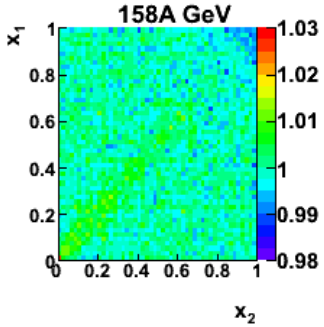
T generated from Gauss with $\sigma_T$. Given in the panel: $\sigma_T/T$ [%] and $\Phi_{PT}$ [MeV/c]



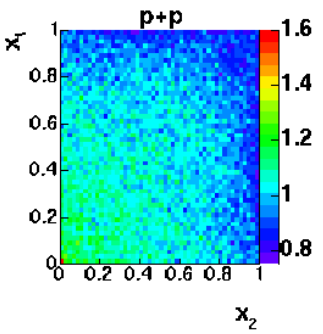



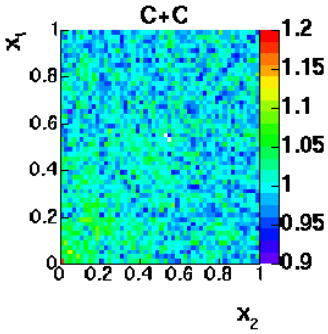



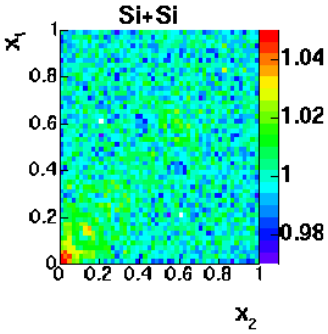



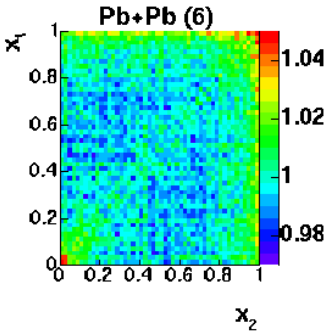



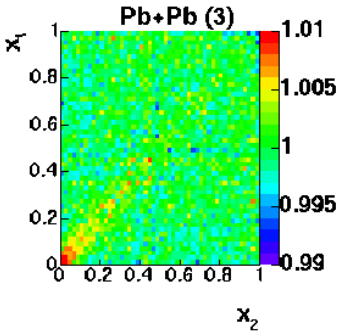

**Energy dependence for central Pb+Pb** (PR**C79**, 044904 (2009)): Short range (Bose-Einstein and Coulomb) correlations - diagonal

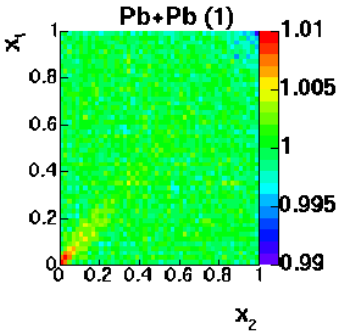



**System size dependence at 158A GeV** (PR**C70**, 034902, 2004): For p+p – structure due to $M(p_T)$ vs. N correlation
Pb+Pb: short range (Bose-Einstein and Coulomb) correlations - diagonal

$0.005 < p_T < 1.5$ GeV/c

# Elliptic flow of baryons and mesons

- N and $p_T$ fluctuations: CP "memory effects" observed at thermal freeze-out
- Collective flow: shows the possible effect accumulated during the whole evolution, rather than just at the freeze-out
- The energy dependence of anisotropic flow is considered to be sensitive to CP

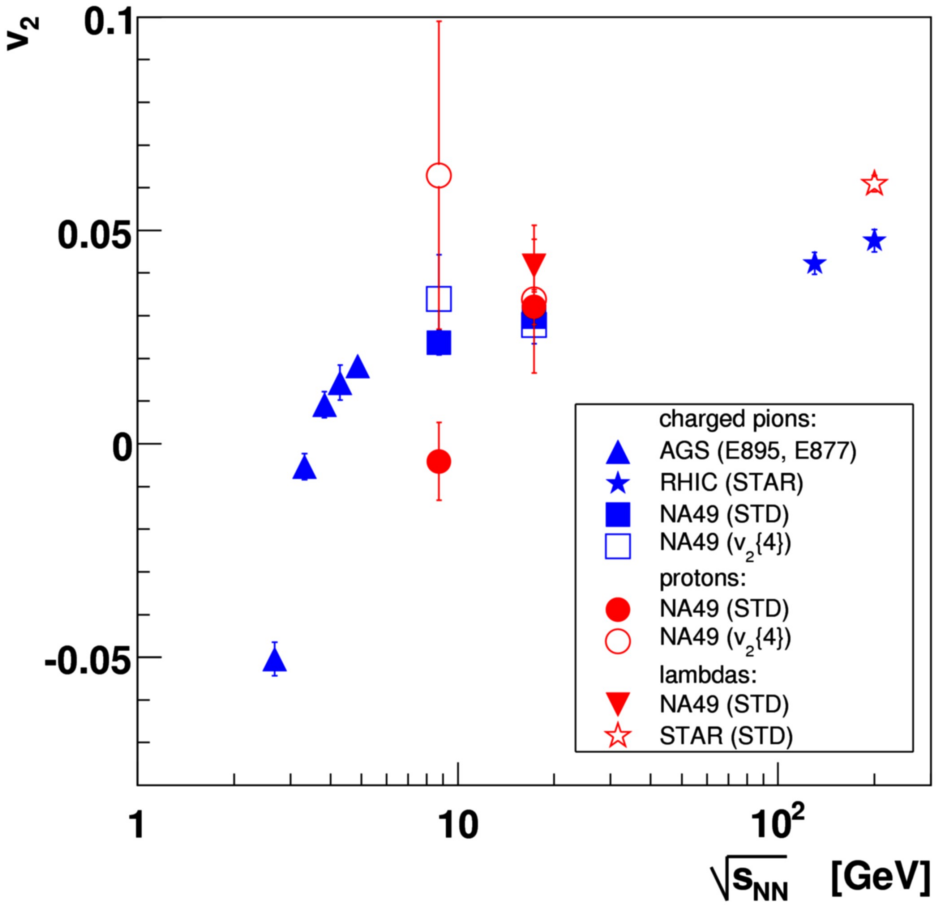
**In the presence of CP** we expect
(E. Shuryak, arXiv:hep-ph/0504048)

- **decrease of the baryon flow**
- **increase of the meson flow**

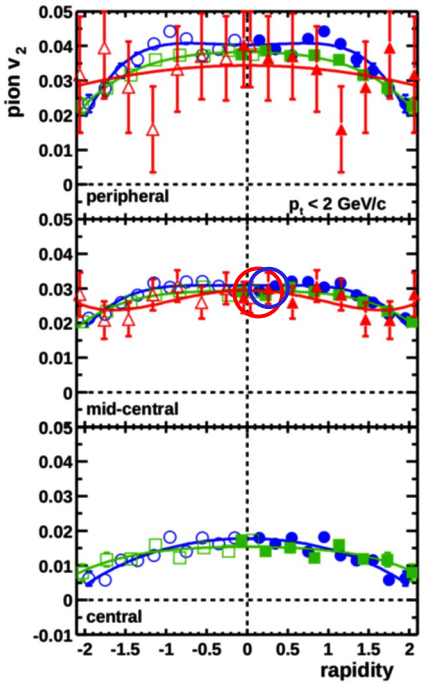
Elliptic flow at mid-rapidity for mid-central Pb+Pb and Au+Au collisions

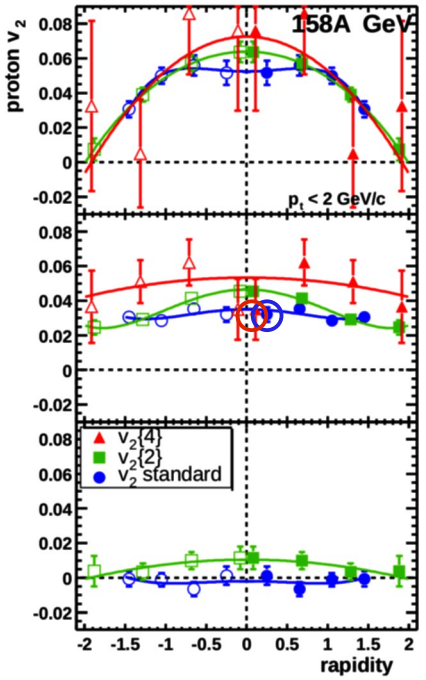
NA49: Alt et al., PRC68, 034903 (2003)
Alt et al., PRC75, 044901 (2007)

**At SPS energies the energy dependence of $v_2$ for baryons is not established**



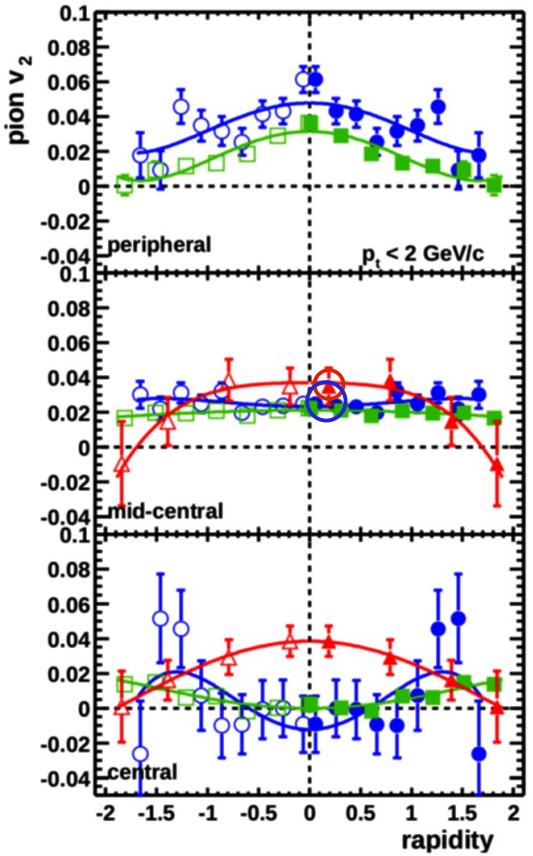

**Data are not conclusive; better experiments required for SPS energy range**

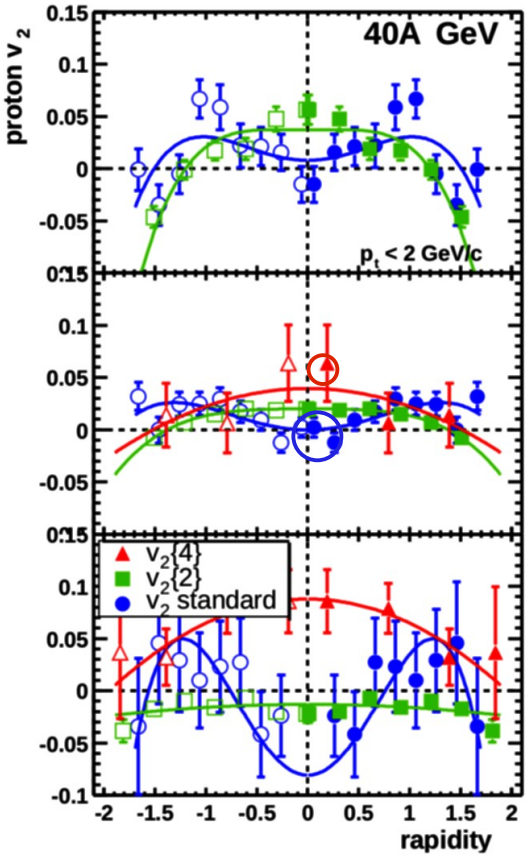



mean values from two red and two blue points close to mid-rapidity

one red and one blue point close to mid-rapidity




mean values from two blue points and one red point at mid-rapidity

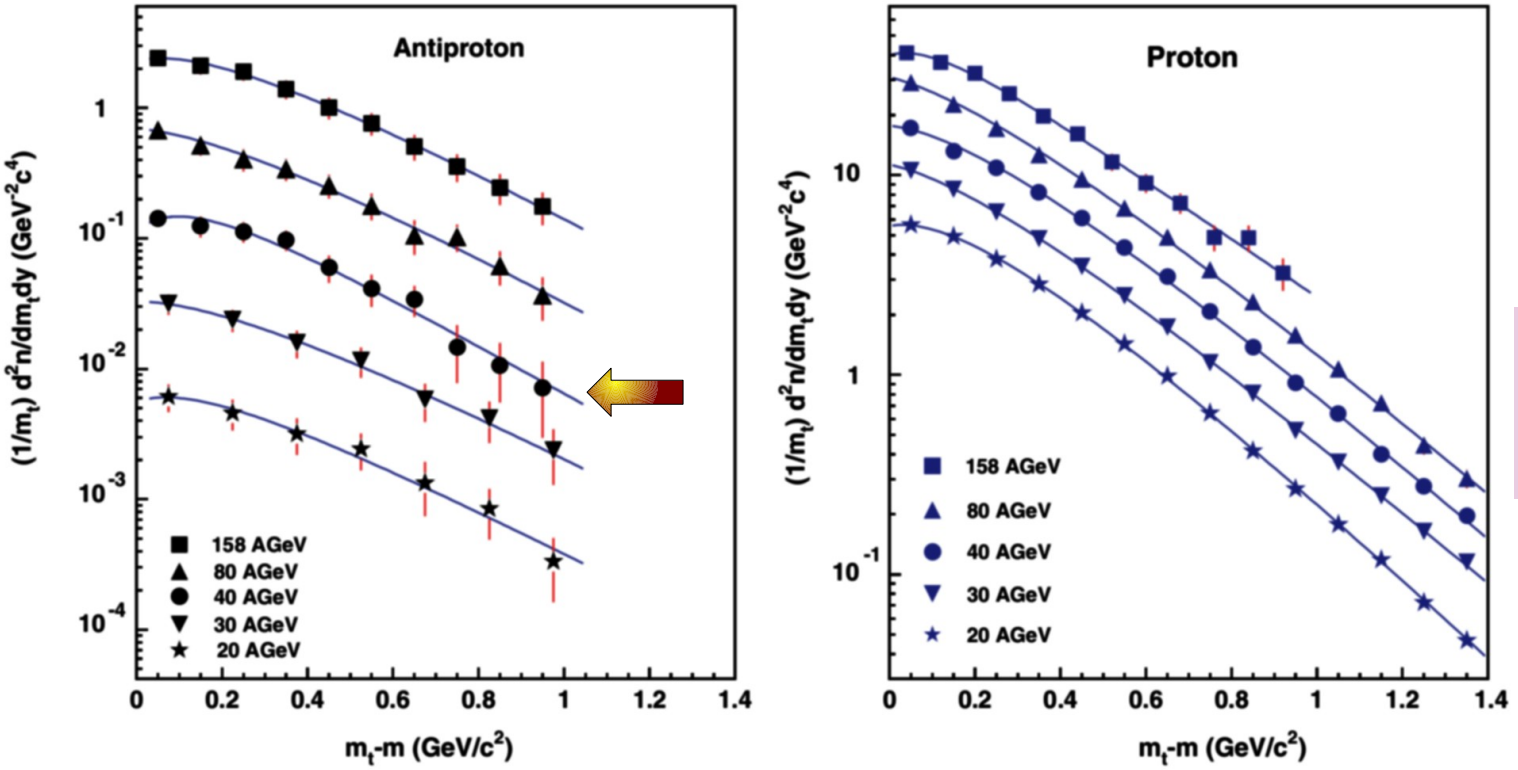
mean values from two blue points and one red point at mid-rapidity

points shown in excitation function are at mid-rapidity $|y^*|<0.2$-$0.3$

C. Alt et al. (NA49 Collab.), Phys. Rev. **C68**, 034903 (2003)

Phys. Rev. C73, 044910 (2006)

$$\frac{1}{m_T}\frac{d^2n}{dm_T\,dy} = C_1 \exp\left(-(m_T - m_0)/T_{slope}\right) + C_2 \exp\left(-(m_T - m_0)/T'\right)$$



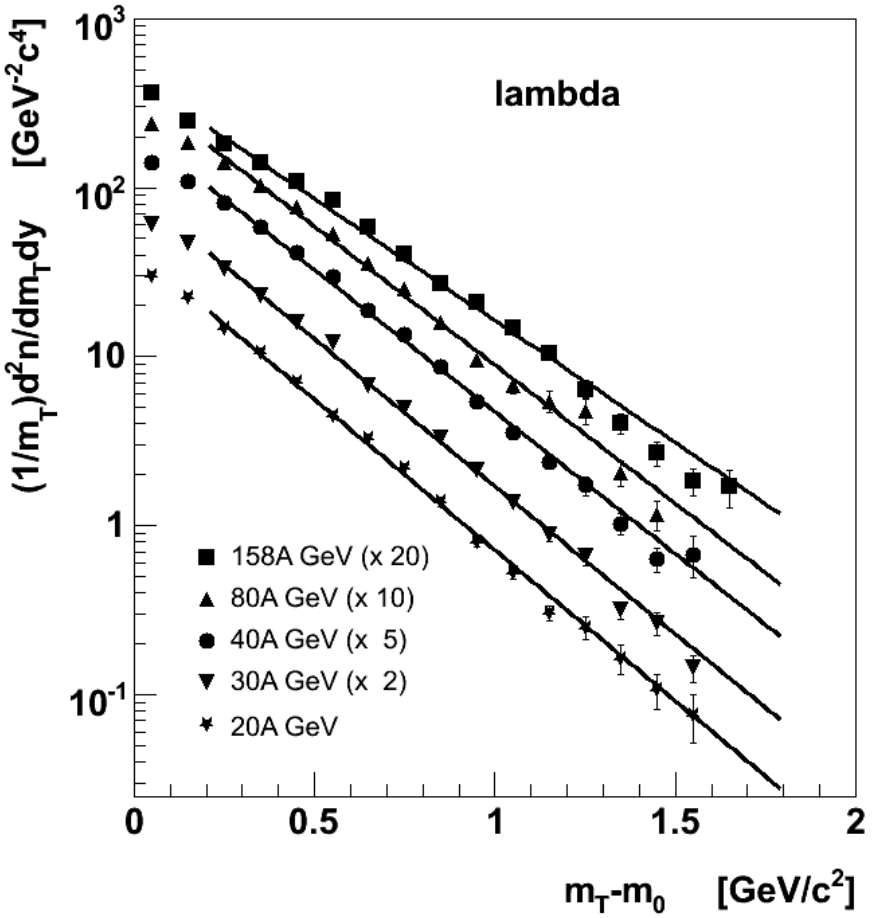

At 40A GeV steeper anti-p spectra at high $p_T$?

FIG. 3. (Color online) Transverse mass distributions for antiprotons and protons at midrapidity in central Pb+Pb collisions at 20*A*, 30*A*, 40*A*, 80*A*, and 158*A* GeV. Errors are statistical. Solid lines illustrate the two-exponential fit of Eq. (1) to the data. For clarity, the spectra are scaled down by a factor of 2 successively from the uppermost data.

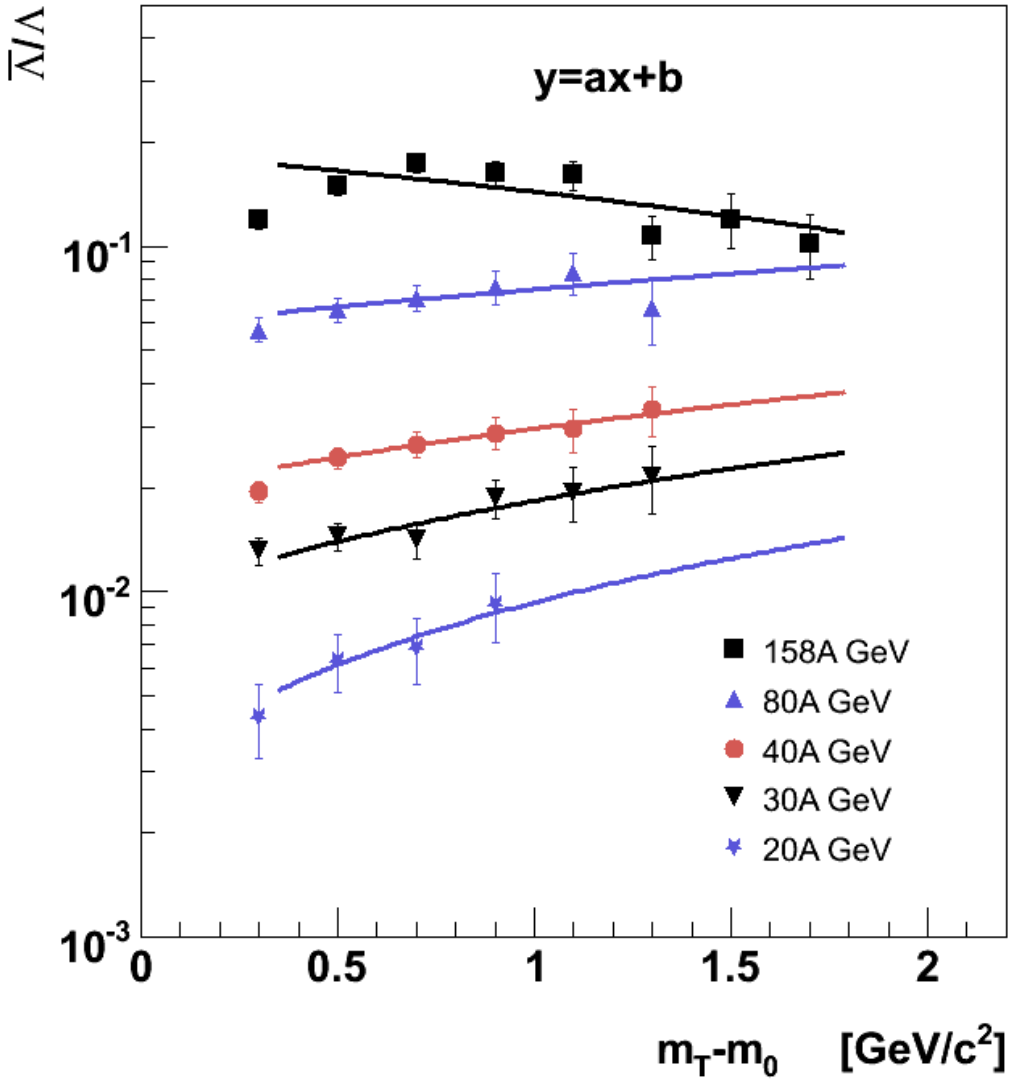
# anti-lambda/lambda ratio versus $m_T - m_0$

$$\frac{1}{m_T}\frac{d^2 n}{dm_T\, dy} \propto \exp\left(\frac{-(m_T - m_0)}{T_{slope}}\right)$$

fit to data in the range $0.2 < m_T - m_0 < 1.8$




Points for anti-lambdas divided by fitted (left) curves for lambdas



## anti-cascades/cascades ratio versus $m_T - m_0$

$$\frac{1}{m_T}\frac{d^2n}{dm_T\,dy} \propto \exp\left(\frac{-(m_T - m_0)}{T_{slope}}\right)$$

fit to data in the range $0.25 < m_T - m_0 < 1.8$

Points for anti-cascades divided by fitted (left) curves for cascades