The exploration of the phase diagram of strongly interacting matter at CERN SPS

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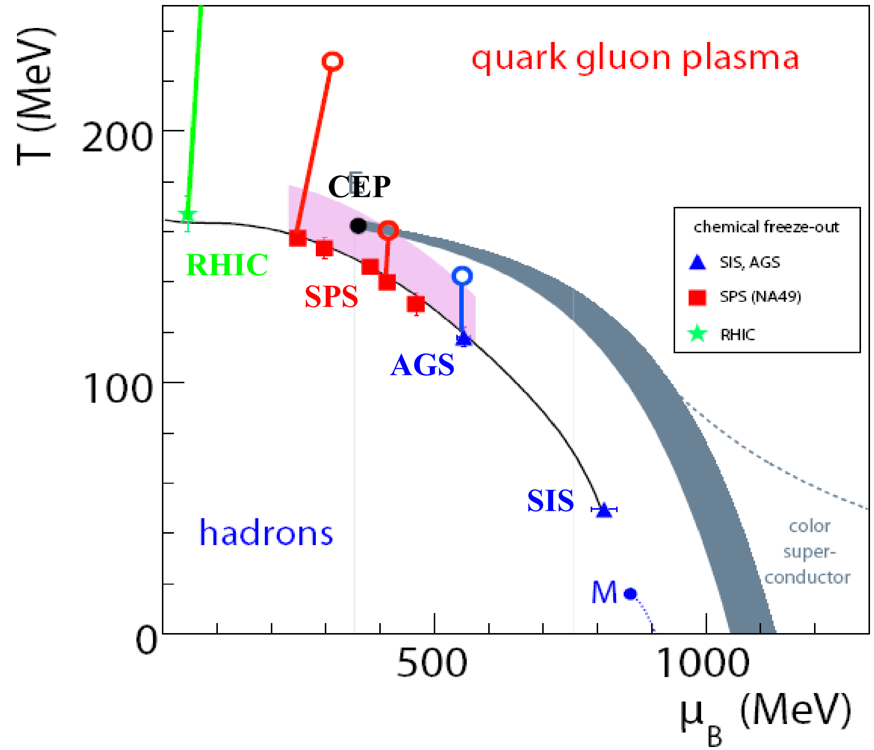
for the NA49 and NA61 Collaborations

Phase diagram of strongly interacting matter



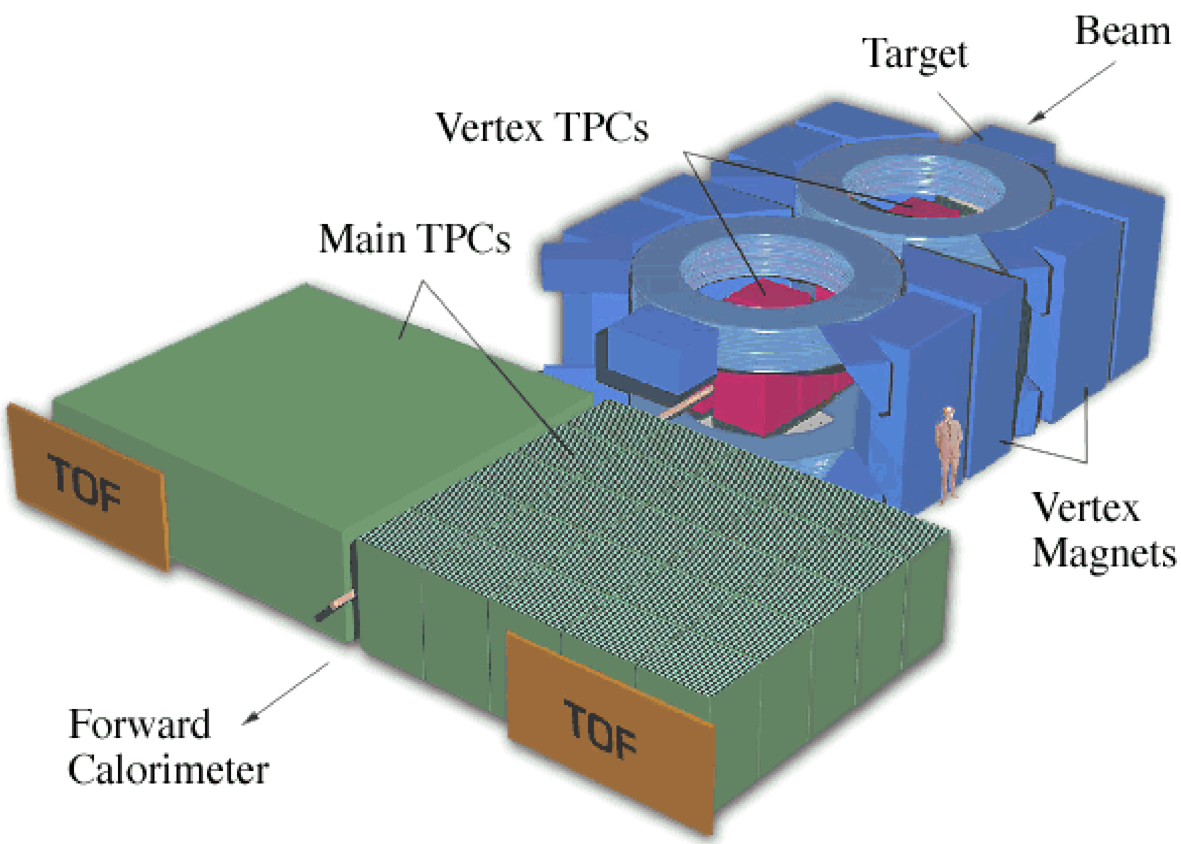
- **QCD considerations suggest a 1st order phase boundary ending in a Critical End Point (CEP)**

- **lattice calculations locate CEP in the SPS energy range**

  Z.Fodor, S.D.Katz,JHEP 0404,050 (04),
  R.V.Gavai, S.Gupta,PRD 71,114014 (05)

- **maximum of Critical End Point signal is expected for freeze-out close to CEP → SPS energy range**

NA49 experiment at CERN SPS



Large acceptance: ≈ 50%

High momentum resolution

Good particle identification

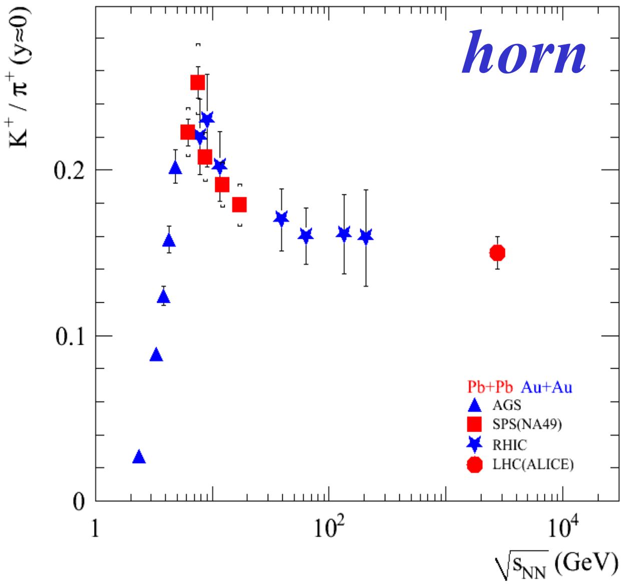
Operating years:
1994 – 2002

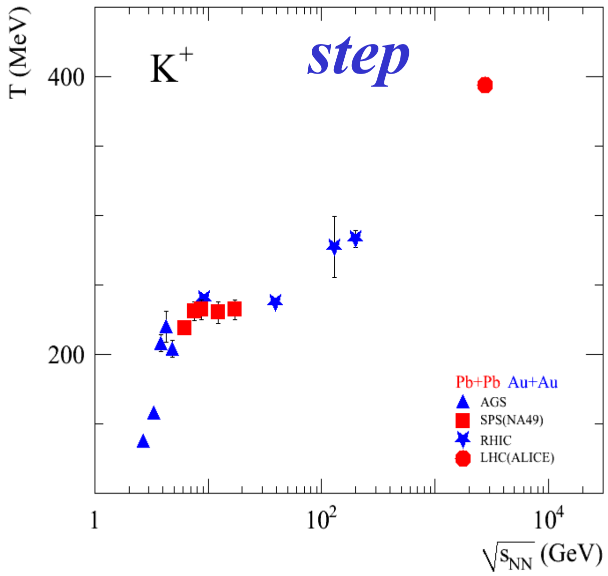
Interactions:
p+p, C+C, Si+Si, Pb+Pb

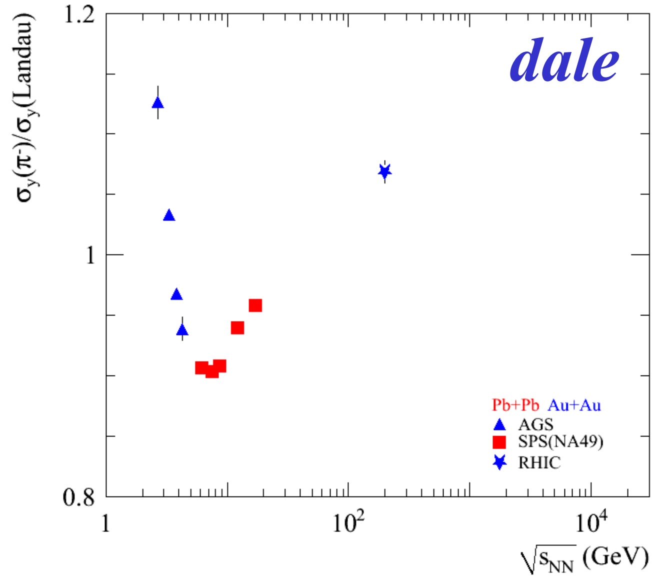
Center of mass energy:
$\sqrt{s_{NN}}$ = 6.3 – 17.3 GeV

S.*Afanasiev et al., NiM A430, 210 (1999)*

Evidence for the onset of deconfinement







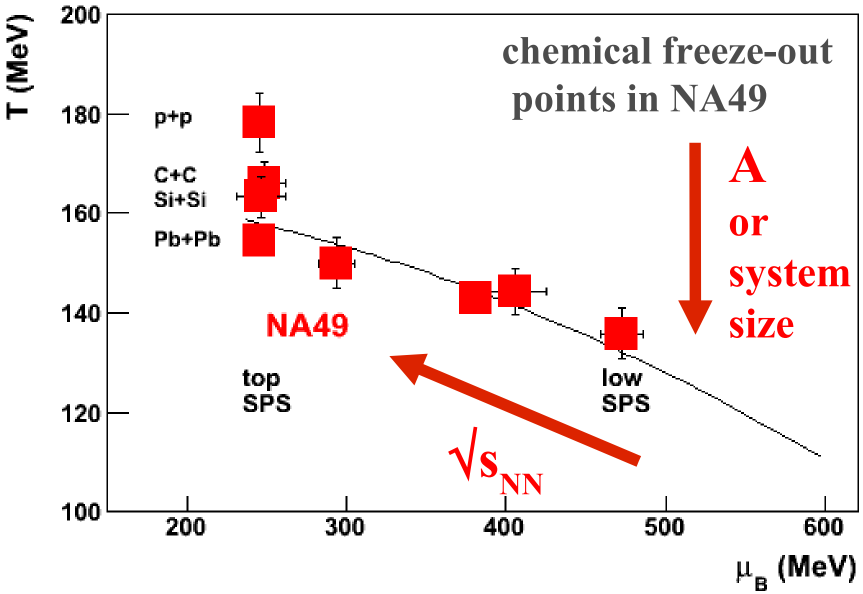
- **rapid changes in energy dependence of hadron production properties provide evidence for the phase transition**
- **the LHC and RHIC BES points confirm NA49 measurements and trends**

Data:
NA49: C.Alt et al., PRC 77, 024903 (2008)
STAR: L.Kumar, arXiv:1106:6071 (2011), B.Mohanty,QM2011
ALICE: J.Schukraft QM2011, M.Floris QM2011, A.Toia QM2011
and
A.Rustamov, arXiv:1201.4520

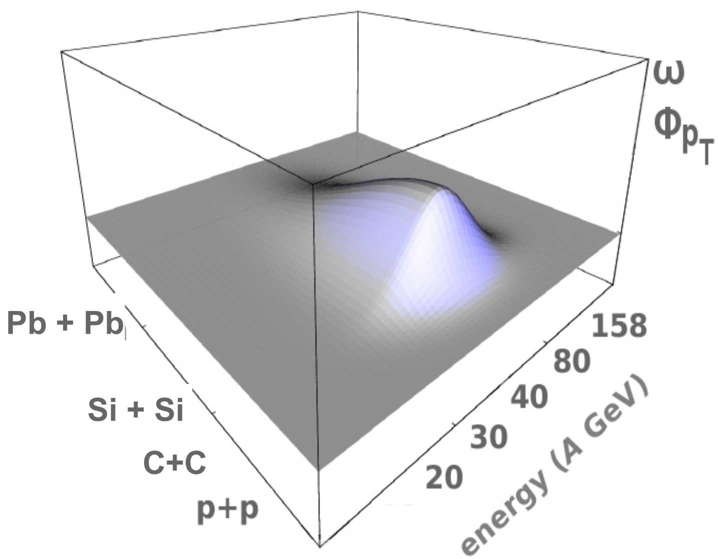
Theoretical predictions:
M.Gazdzicki, M.Gorenstein, APP B30, 2705 (99)

Evidence for the onset of deconfinement in Pb+Pb collisions at $\sqrt{s_{NN}} \approx 8$ GeV

General strategy for the search of the critical point



- **2D scan with energy and system size:**
  - NA49 scan with beam energy 20-158*A* GeV of central Pb+Pb collisions
  - NA49 scan with the system size (p+p, C+C, Si+Si, Pb+Pb) at 158*A* GeV



- If freeze-out is close to critical point and system is large enough a hill in fluctuations and local power-law fluctuations should be observed

Fluctuation measures studied by NA49

M.I.Gorenstein, M.Gazdzicki, Phys. Rev. C84, 014904 (2011)
M.Gazdzicki, St.Mrowczynski, Z.Phys. C54, 127(1992)

- scaled variance ω of the multiplicity distribution P(n)

- intensive fluctuation measure, ω affected by N_W fluctuations

- Φ_x measure of fluctuations of observable x (<p_T>, <φ>, Q)

- Φ_x strongly intensive fluctuation measure independent of N_W and its fluctuations

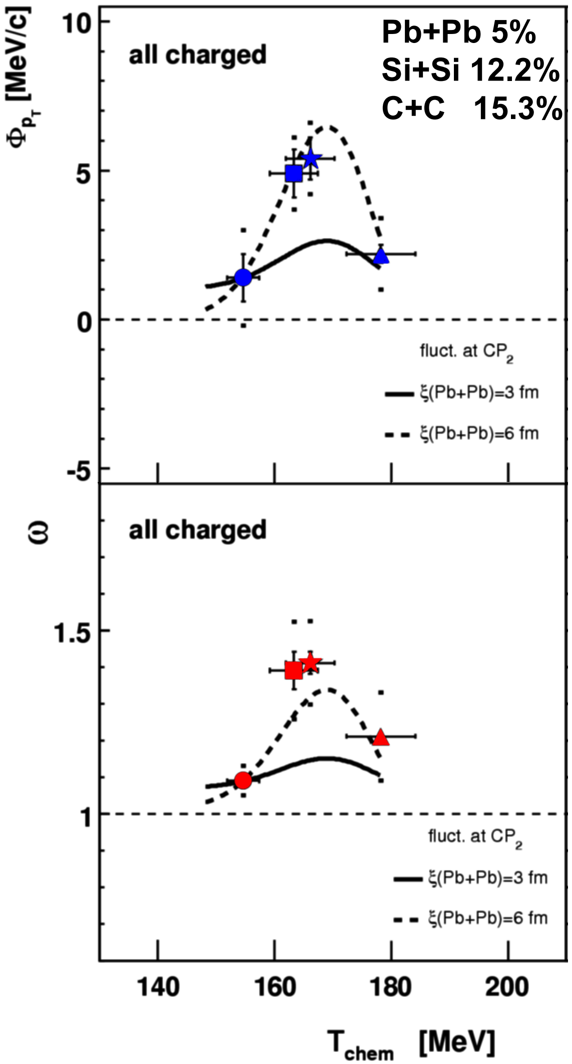
- F_2 factorial moment of low mass $\pi^+\pi^-$ pair number and proton number fluctuations in p_T space

- power-law behavior is expected at the critical point

- σ_{dyn} measure of particle ratio fluctuations (K/π, p/π, K/p)

- $\sigma^2_{dyn} \sim 1/N_W$, not intensive quantity

Φ_{p_T}, ω : fluctuations of $\langle p_T \rangle$ and $\langle N \rangle$



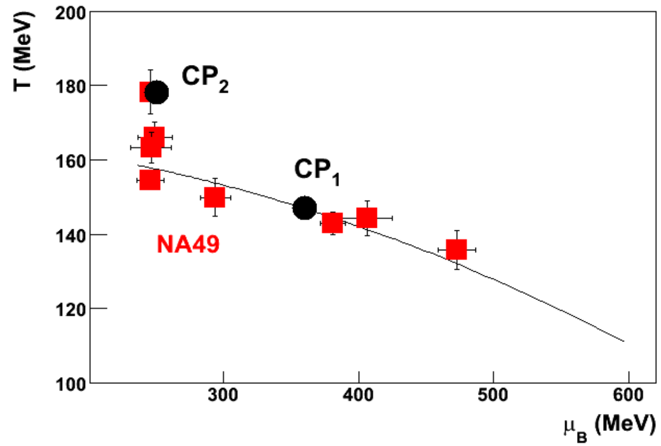
NA49 data:

PRC70, 034902 (2004)

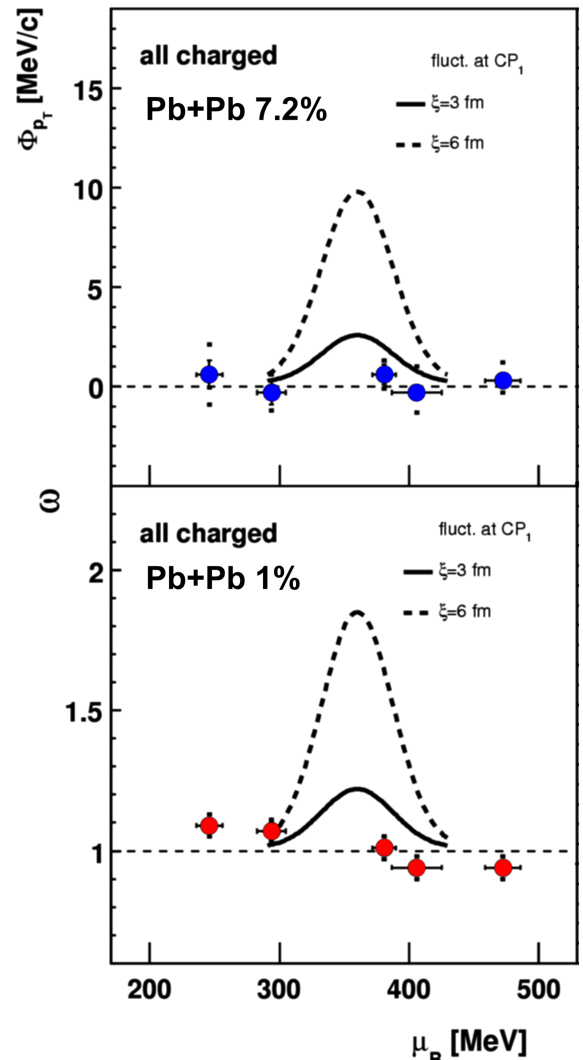
PRC75, 064904 (2007)

PRC78, 034914 (2008)

PRC79, 044904 (2009)



First hint of the hill of fluctuations?



CP2 example:

μ_B= 250 MeV (data at 158A GeV)

T = 178 MeV (fit of p+p data)

Theoretical predictions:

*M.Stephanov, K.Rajagopal, E.V.Shuryak PRD **60**, 114028 (99)*

*Y.Hatta, T.Ikeda PRD **67**, 014028 (03)*

*Z.Fodor, S.D.Katz, JHEP **0404**,50 (04)*

CP1 example:

μ_B= 360 MeV (lattice QCD),

T = 147 MeV (freeze-out line)

Low mass $\pi^+\pi^-$ pairs and protons number fluctuations

- critical point predicted to lead to power-law density fluctuations of σ field
- observation via low mass $\pi^+\pi^-$ pairs number fluctuations in p_T space

- mixing between the chiral condensate and the baryon density
  → power-law baryon density fluctuations
- observation via protons number fluctuations in p_T space

- power law behavior of second factorial moment

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

is expected (intermittency) $F_2(M) = \sim (M^2)^{\varphi_2}$

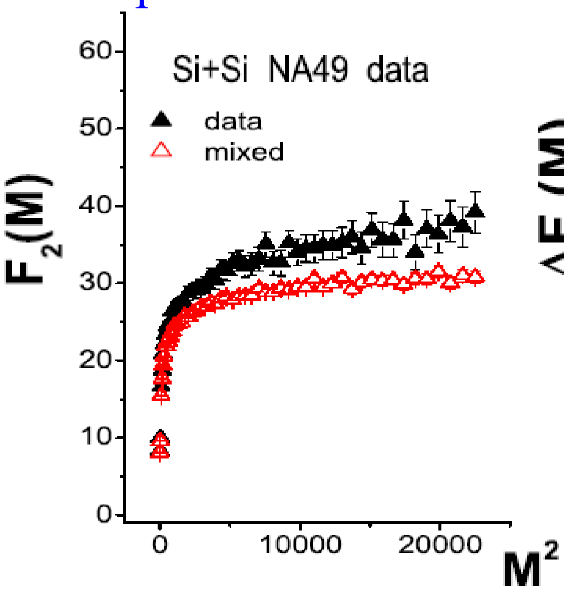
- combinatorial background is estimated by mixed events and subtracted

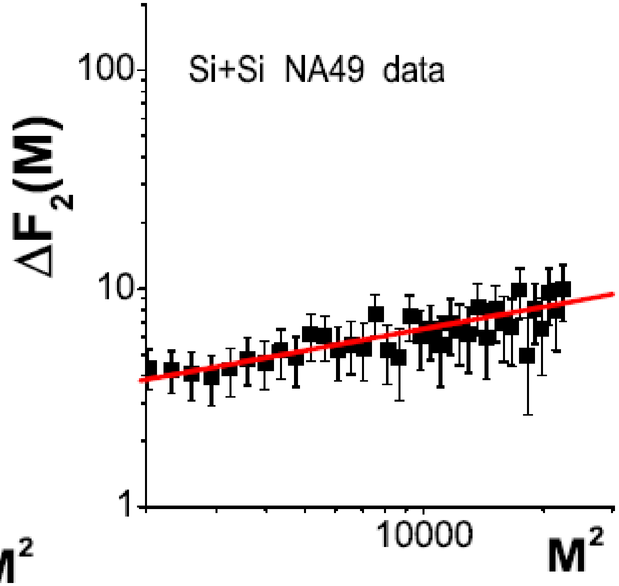
<u>Theory:</u> N.Antoniou et al.,
Nucl.Phys. A693,799(2001); A761, 149(2005)

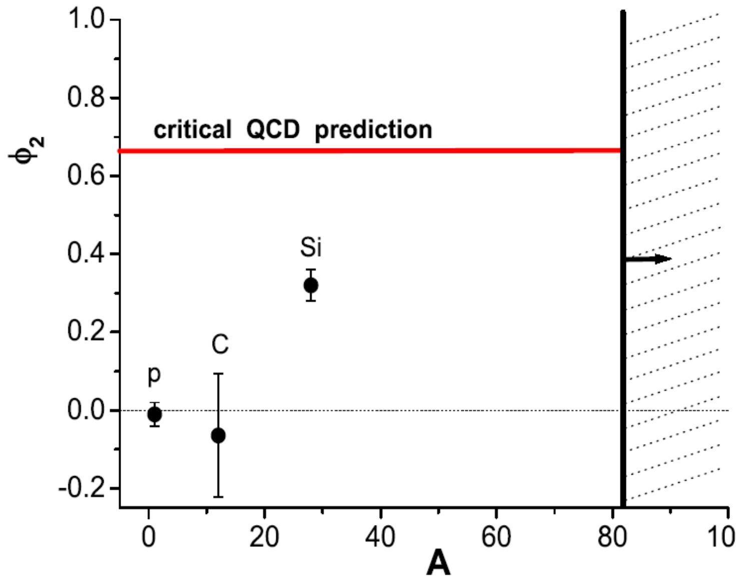
Low mass $\pi^+\pi^-$ pairs and protons number fluctuations

$\pi^+\pi^-$ pairs

NA49 data: *T.Anticic et al., PRC 81, 064907(2010)*

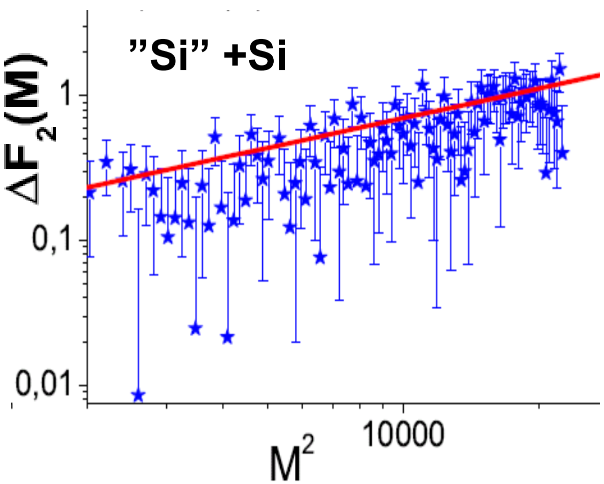


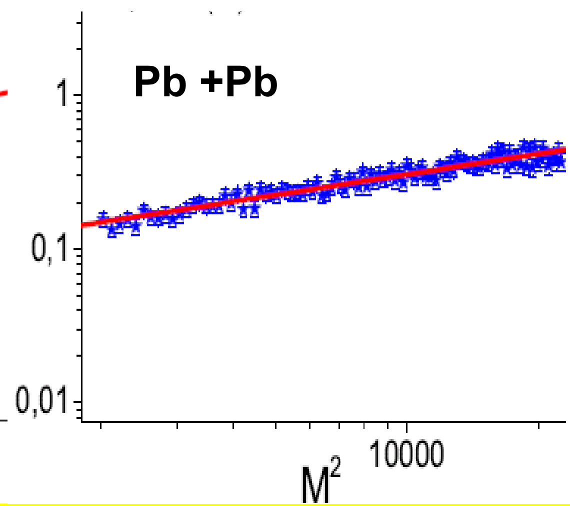


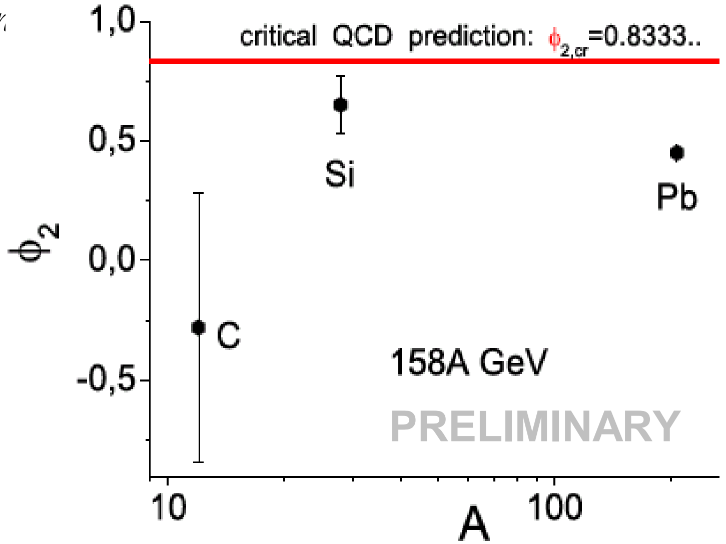


protons

NA49 data: *paper under preparation*

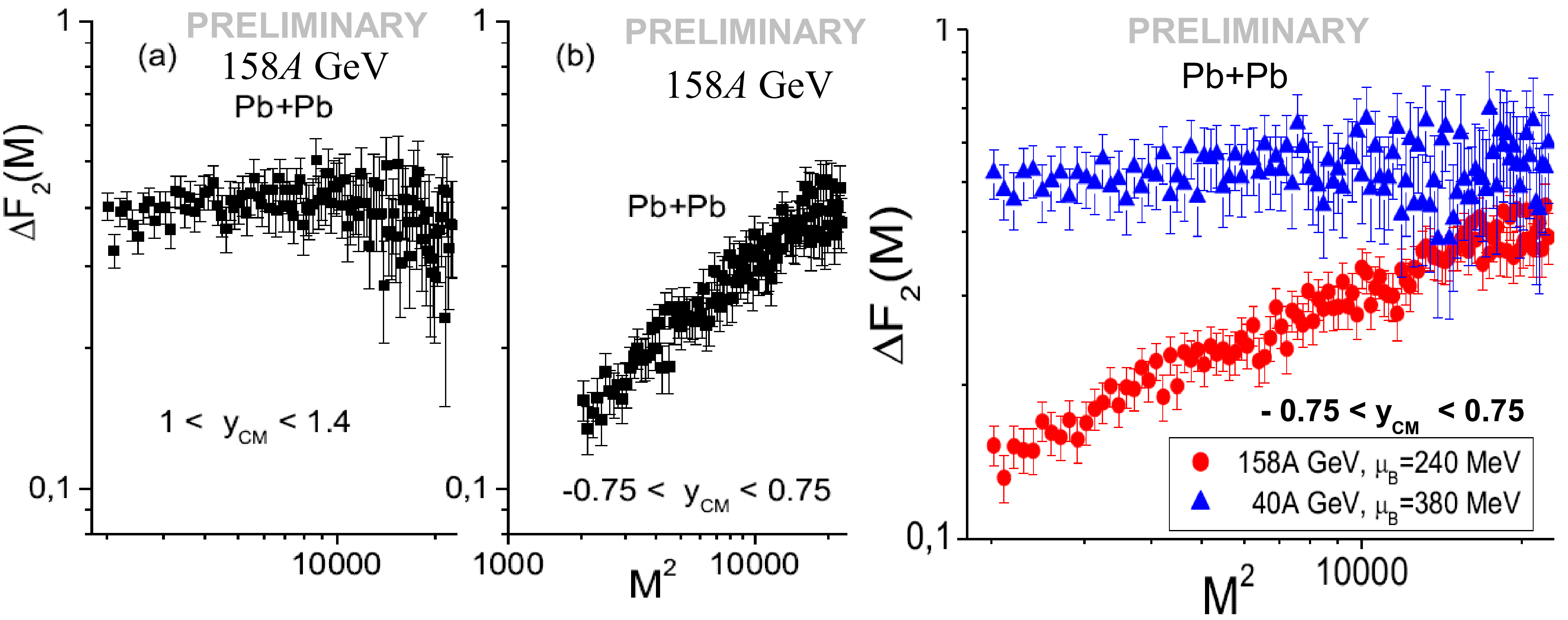






Critical point close to freeze-out points of Si+Si and Pb+Pb system at 158A GeV ?

Protons number fluctuations



NA49 data: *paper under preparation.*

The intermittency effect observed for Pb+Pb at top SPS is confined to protons at midrapidity and disappears at lower energy.

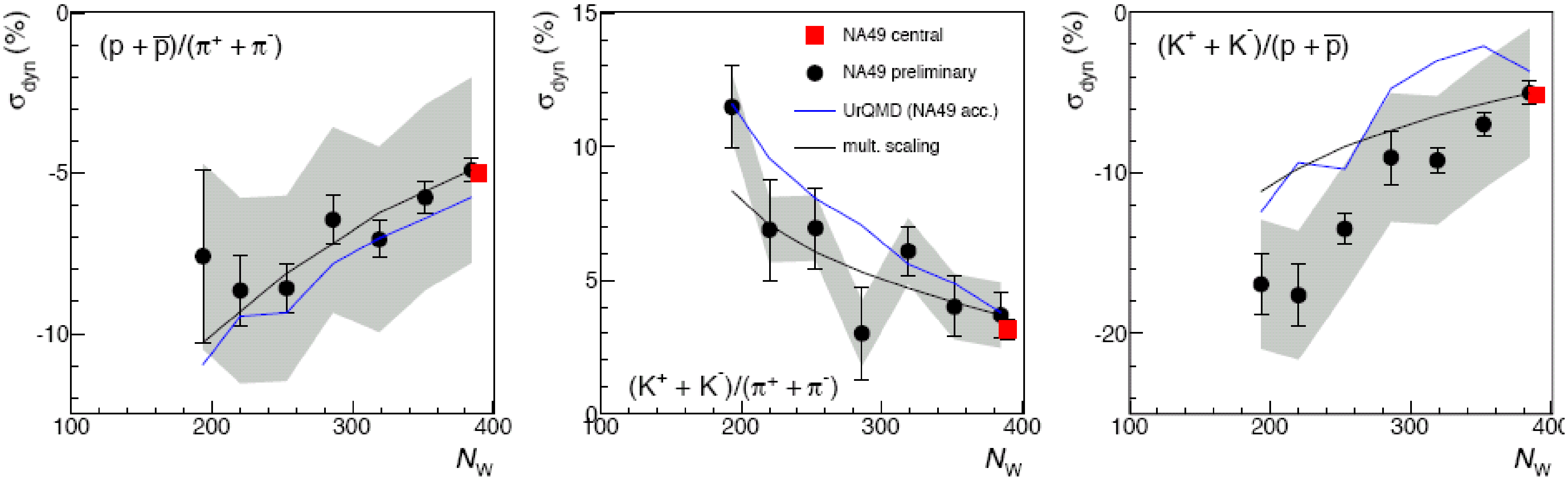
Theory: *N.Antoniou et al., Nucl.Phys. A693,799(2001); A761, 149(2005)*

Critical baryochemical potential is closer to $\mu_B \approx 240$ MeV than to $\mu_B \approx 380$ MeV ?

Particle ratio fluctuations

<u>NA49 data:</u> T.Schuster QM2011, arXiv:1204.2130

Pb+Pb 17.3 GeV



- Increase of $|\sigma_{dyn}|$ $\left(\sigma_{dyn} = \text{sign}(\sigma^2_{data} - \sigma^2_{mix})\sqrt{|\sigma^2_{data} - \sigma^2_{mix}|}\ ; \quad \sigma^2_{dyn} = |\nu_{dyn}|\right)$ towards peripheral collisions for all three ratios
- Similar trend in RHIC STAR data for $(K^+ + K^-)/(\pi^+ + \pi^-)$ at $\sqrt{s_{NN}}$ = 62 and 200 GeV

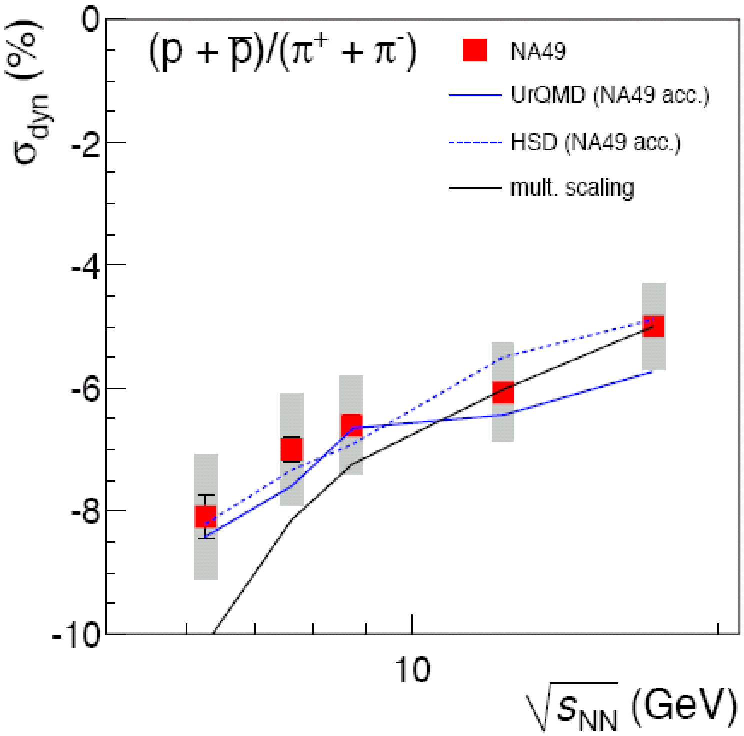
  B.I.Abelev et al., PRL 103, 092301 (2009)

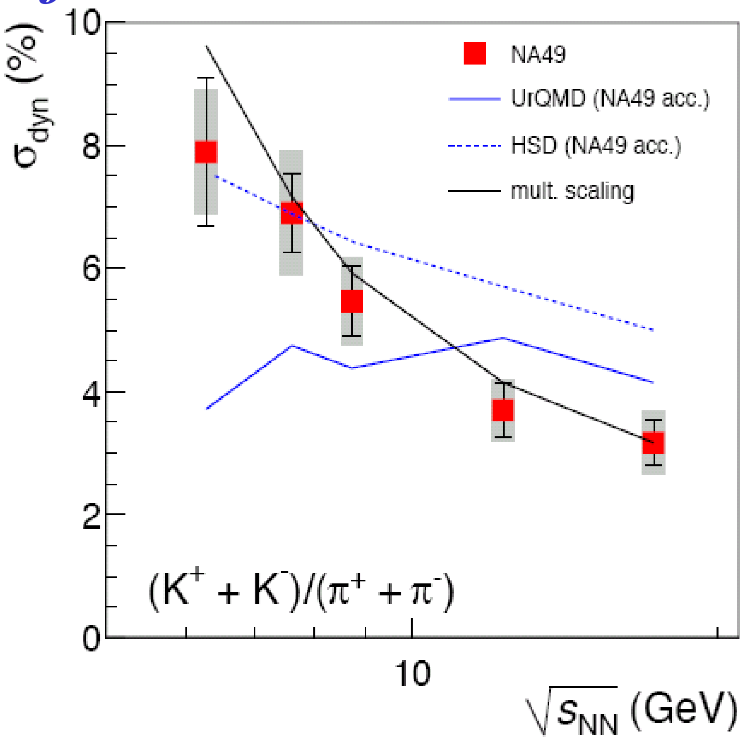
- UrQMD predicts similar behavior with N_w
- Scaling with multiplicities, $\sigma_{\text{dyn}} \propto \sqrt{\frac{1}{\langle A\rangle} + \frac{1}{\langle B\rangle}}$ works for all three ratios

  V.Koch, T.Schuster PRC 81, 034910 (2010)

Unchanged correlation strength (same physics) with system size ?

Particle ratio fluctuations





NA49 data: *T.Schuster QM2011*

- p/π: $\sigma_{dyn} < 0$ correlation due to resonance decay *S.Jeon, V.Koch PRL 83, 5435 (99)*
- reproduced by hadronic transport models (UrQMD, HSD)

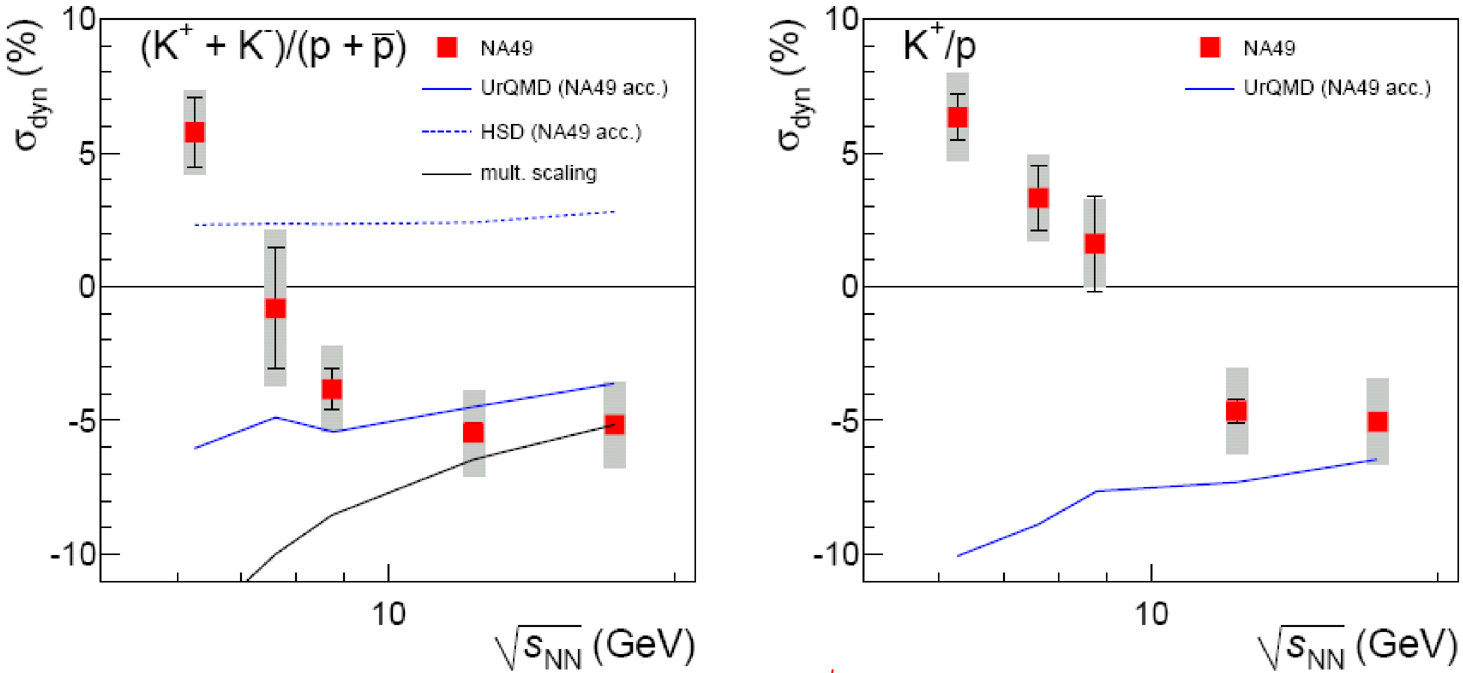
- K/π: $\sigma_{dyn} > 0$ anti-correlation
- UrQMD and HSD models are contradictory; neither describes data well

Scaling with multiplicities: $\sigma_{\rm dyn} \propto \sqrt{\frac{1}{\langle A \rangle} + \frac{1}{\langle B \rangle}}$

Scaling:
V.Koch, T.Schuster PRC 81, 034910 (2010)

Unchanged correlation strength (same physics) with energy ?

Particle ratio fluctuations



NA49 data:
T.Anticic et al., PRC 83 061902 (2011);
T.Schuster QM2011

- σ_{dyn} shows a strong dependence on $\sqrt{s_{NN}}$, going from positive values at low energies to $\sigma_{dyn} < 0$ at high energies
- ratio for positive charges K^+/p^+, has no resonance contribution
- neither hadronic models (UrQMD, HSD) nor scaling with multiplicities

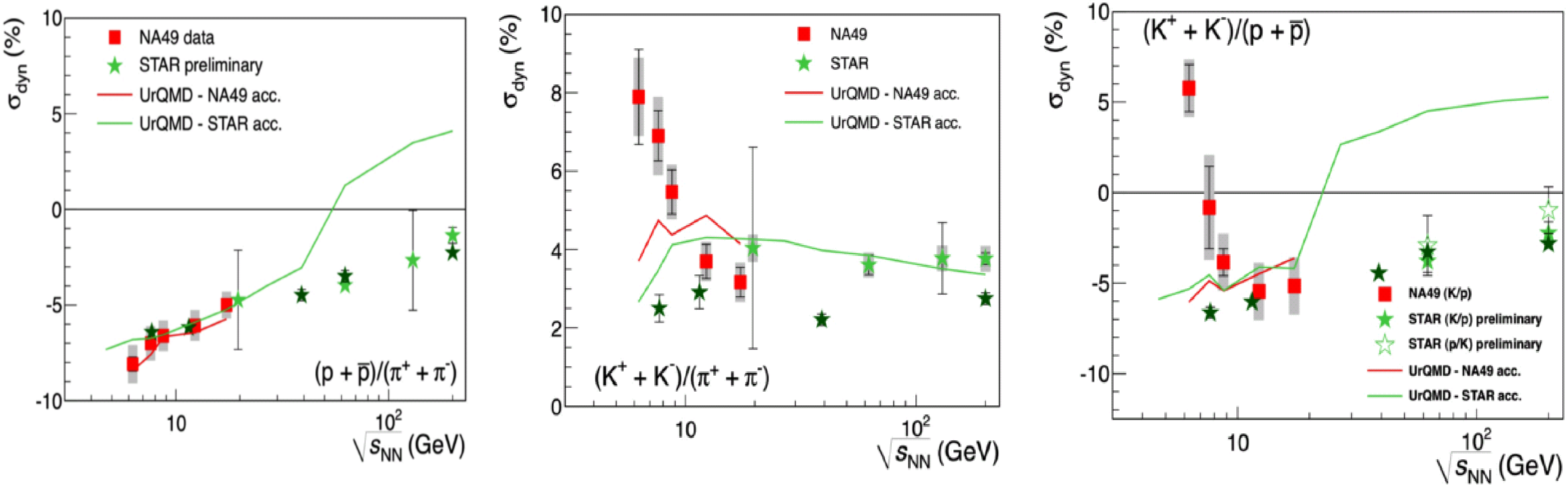
$$\sigma_{\rm dyn} \propto \sqrt{\frac{1}{\langle A \rangle} + \frac{1}{\langle B \rangle}}$$

(*V.Koch, T.Schuster PRC 81, 034910 (2010)*) describe data

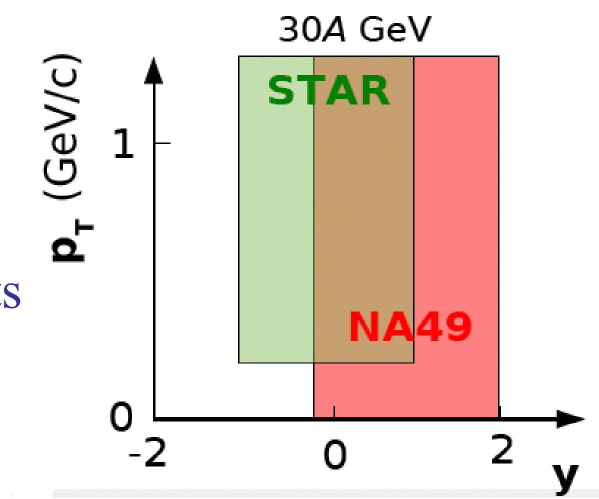
Theory:
V.Koch, A.Majumder, J.Randrup PRL 95, 182301 (05)

Is the underlying correlation physics (baryon-strangeness) changing with energy ?

Particle ratio fluctuations
NA49 SPS – STAR RHIC (BES)



- p/π: agreement between NA49 and STAR BES
- K/π, K/p: differences between NA49 and STAR at lower SPS energies

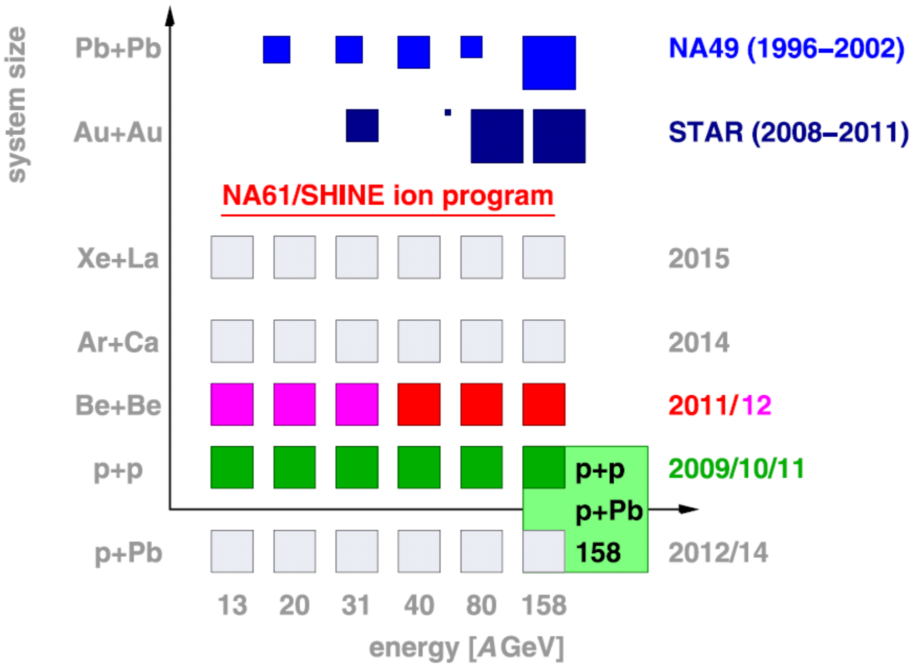


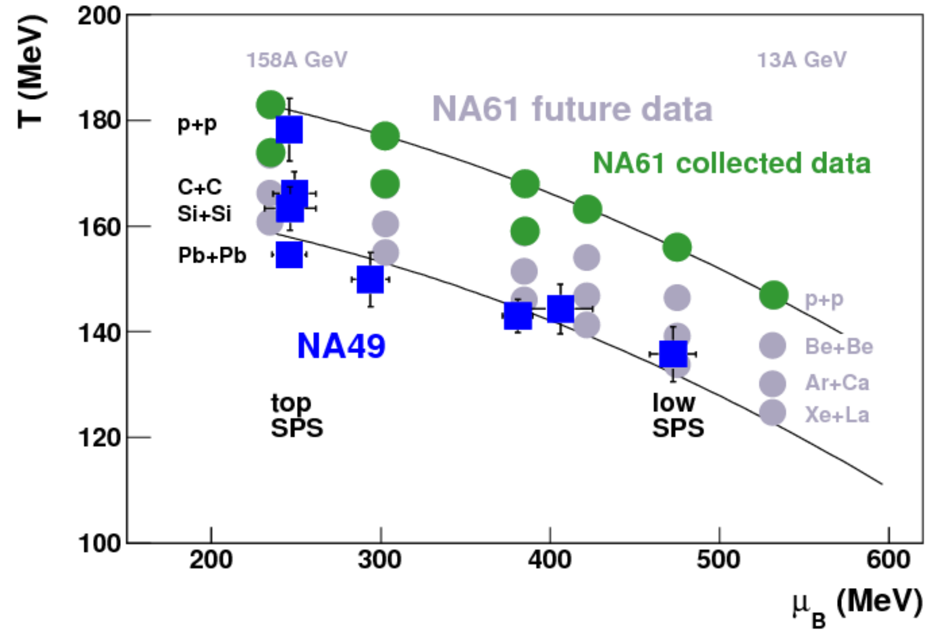
Search for the sources of discrepancies is ongoing
- new "identity method" seems to confirm NA49 results

<u>STAR data:</u>
p/π : QM2009 + QM2011(BES, dark green)
K/π : PRL 103, 092301 (2009), QM2011 (BES, dark green)
K/p, p/K at 62A, 200A GeV: SQM2009 (light green)
K/p: QM2011 (BES, dark green)

NA61/SHINE experiment

http://na61.web.cern.ch/na61/xc/index.html

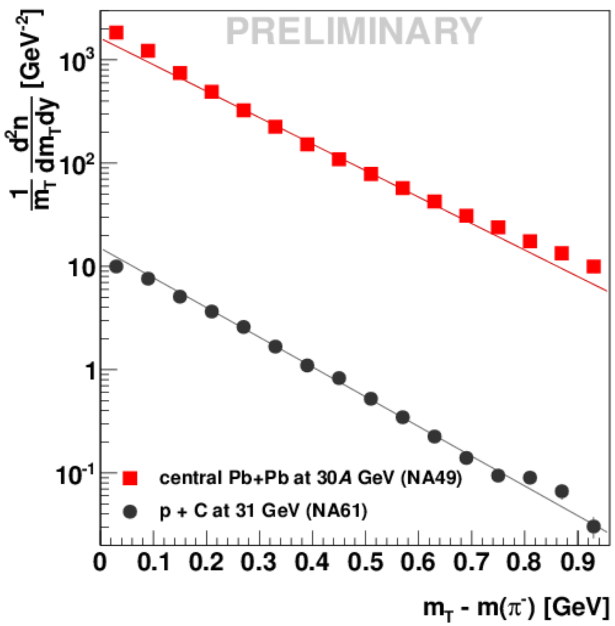


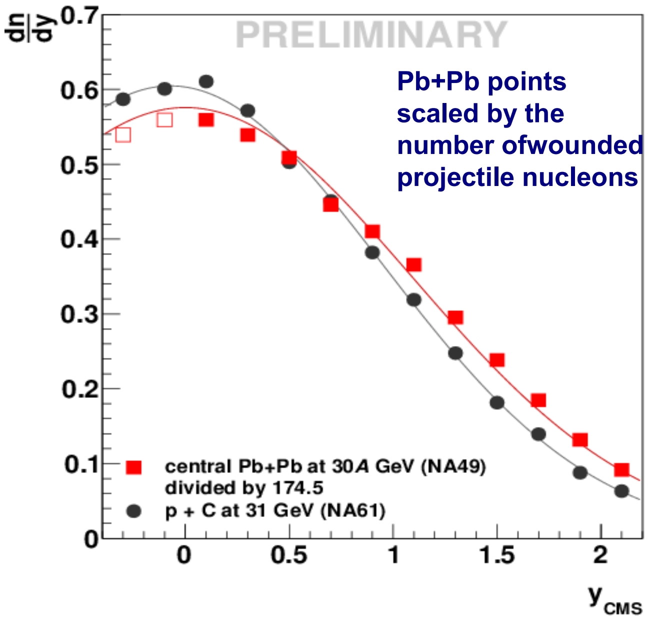


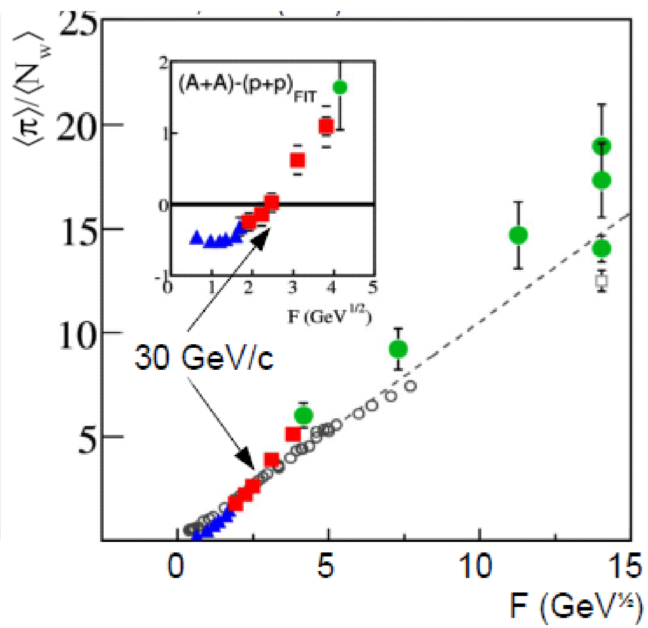
- 2D scan (T, μ_B) with six SPS beam energies 13*A*, 20*A*, 30*A*, 40*A*, 80*A*, 158*A* GeV and five different systems p+p, p+Pb, Be+Be, Ar+Ca, Xe+La
- higher statistics – at least 10^6 events per energy and per reaction
- better centrality selection (PSD detector) and reduction of interactions in the gas inside VTPCs (Helium beam pipe)
- similar analysis like in NA49 with better precision

NA61/SHINE experiment
π^- results for ion physics

<u>*NA49 data*</u>: *PRC77*, 024903(2008)







A·exp (m_T/T) fitted in 0.2<m_T<0.7 GeV

p+C at 31 GeV/c → T = 151 ± 3 MeV

Pb+Pb at 30*A* GeV/c → T = 157 ± 2 MeV

Pion multiplicity scales with the number of projectile wounded nucleons at 30 GeV/c

Inverse slope parameter increases with the number of wounded projectile nucleons

Summary

- **Onset of deconfinement: NA49 measurements are confirmed**
  - first LHC data confirm the interpretation
  - results from RHIC agree with relevant NA49 data

- **Critical point: fluctuations of:**
  - <N> measured by scaled variance ω
  - $\langle p_T \rangle$ measured by Φ_{pT}
  - number of low-mass $\pi^+\pi^-$ pairs measured by factorial moment F_2

  are enhanced in Si+Si collisions at 158A GeV which are consistent with expectations for critical point

  - number of protons measured by factorial moment F_2

  exhibit power law for Si+Si and Pb+Pb systems at 158GeV; Pb+Pb data suggest the critical baryochemical potential is closer to $\mu_B \approx$ 240 MeV than to $\mu_B \approx$ 380 MeV

- **Particle ratio fluctuations:**
  - K/π and p/π fluctuations as a function of energy and system size can be described by a simple multiplicity scaling model
  - K/p fluctuations show a deviation from multiplicity scaling which can be a hint of changing of underlying correlation physics

There is no convincing evidence for the critical point as yet but there are several indications which motivate further search by NA61 and other experiments

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

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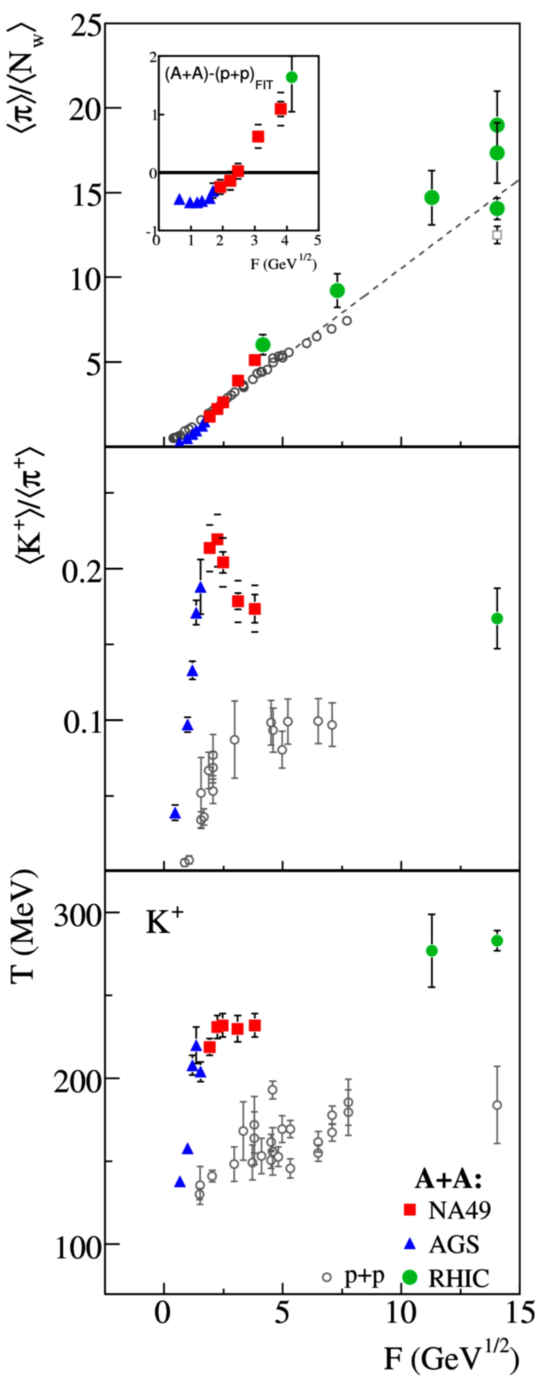
University of Geneva, Geneva, Switzerland
University of Warsaw, Warsaw, Poland
Warsaw University of Technology, Warsaw, Poland
The Universidad Tecnica, Valparaiso, Chile

NA 49

SHINE
NA61

Thank
You

Backup slides



Onset of deconfinement in NA49

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

Kink: increased entropy

Pions measure early stage entropy. In **S**tatistical **M**odel of the **E**arly **S**tage (APP **B30**, 2705 (1999)) **: $\langle\pi\rangle/N_w \sim (ndf)^{1/4}$**

Change of slope around 30*A* GeV;

no change of slope in p+p data

$$\langle\pi\rangle = 1.5(\langle\pi^+\rangle + \langle\pi^-\rangle) \qquad F \simeq \sqrt{\sqrt{s_{NN}}}$$

Horn: decrease of strangeness carrier masses (rise → saturation) and of strangeness to entropy ratio (step down)

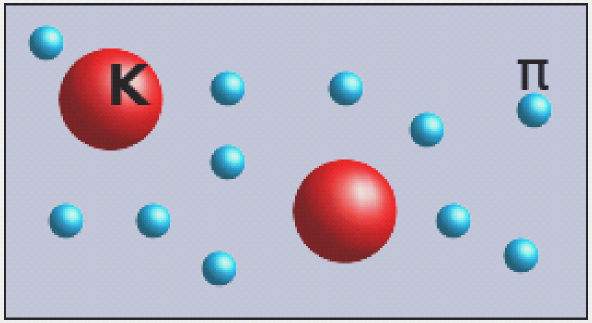
Sharp peak observed at 30*A* GeV (not seen in p+p);

Step: constant T and p in mixed phase

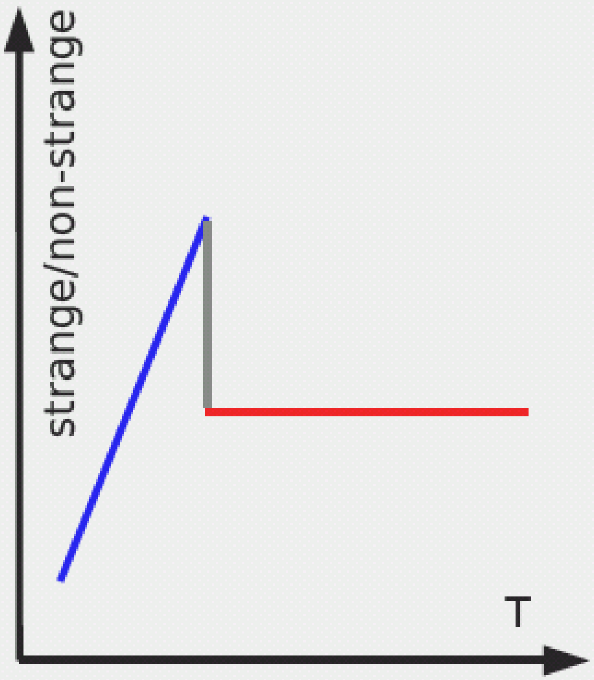
Inverse slope of m_T spectra: strong rise at AGS, plateau at SPS, rise towards RHIC (not seen in p+p). Consistent with constant temperature and pressure in mixed phase (latent heat) – SMES; Gorenstein et al., PL **B567**, 175 (2003)

Onset of deconfinement: the toy model of the horn

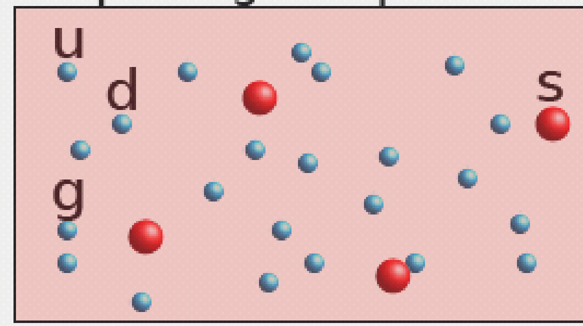
hadron gas



$$\frac{\langle K \rangle}{\langle \pi \rangle} \propto \frac{M T^{3/2}}{T^3} \cdot e^{-M/T}$$



quark-gluon plasma



$$\frac{\langle s \rangle}{\langle u+d+g \rangle} \propto \frac{T^3}{T^3} = const(T)$$

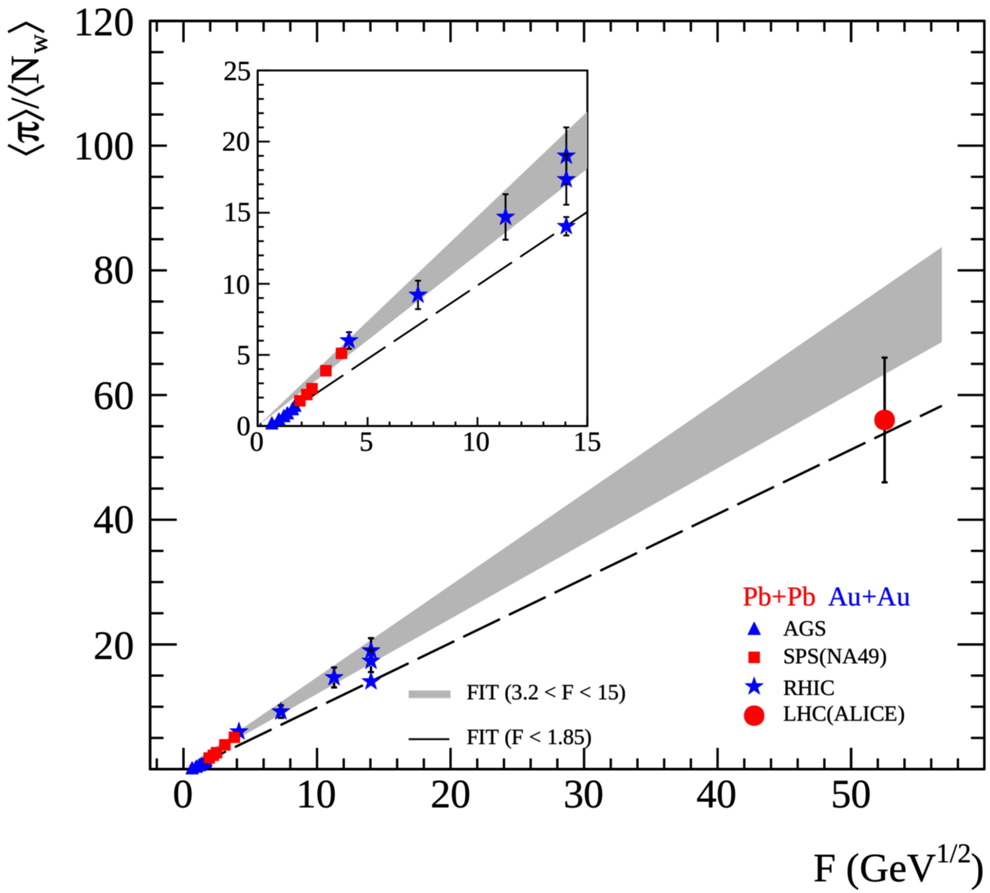
$$\langle n \rangle = \frac{g V}{(2\pi)^3} \int d^3 p \, \frac{1}{e^{E/T} \pm 1}$$

$$\approx g V \frac{2\pi^2}{4 \cdot 45} T^3$$ for light particles

$$\approx g V \left(\frac{M T}{2\pi}\right)^{3/2} e^{-M/T}$$ for heavy particles

Verification of NA49 results and interpretation by STAR and ALICE

Up to recently the evidence of the onset of deconfinement (kink, horn, step) was based on the results of a single experiment (NA49)



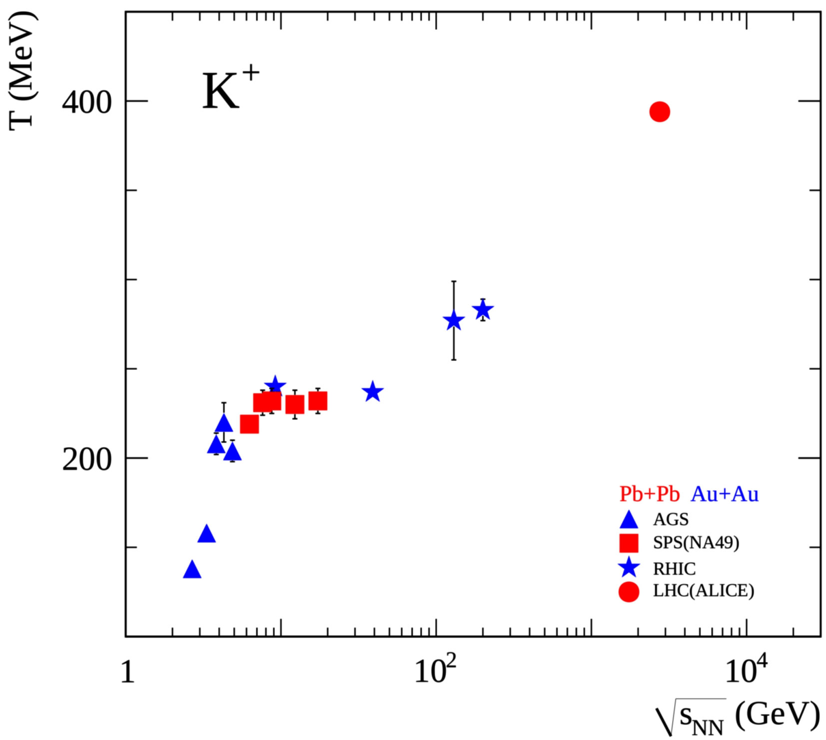
Mean pion multiplicity per participant nucleon

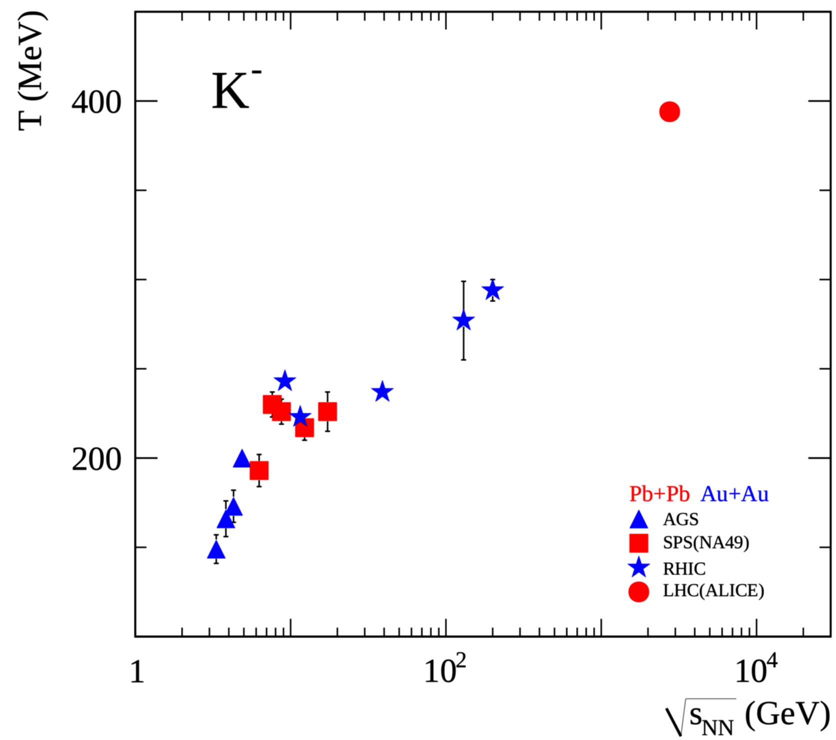
$$\frac{\langle \pi \rangle}{\langle N_W \rangle} \sim (ndf)^{1/4} F$$

- The LHC point, within a large systematic error, does not contradict extrapolations from high SPS and RHIC energies

Rustamov, https://indico.cern.ch/conferenceDisplay.py?confId=144745

Inverse slope parameter of transverse mass spectra





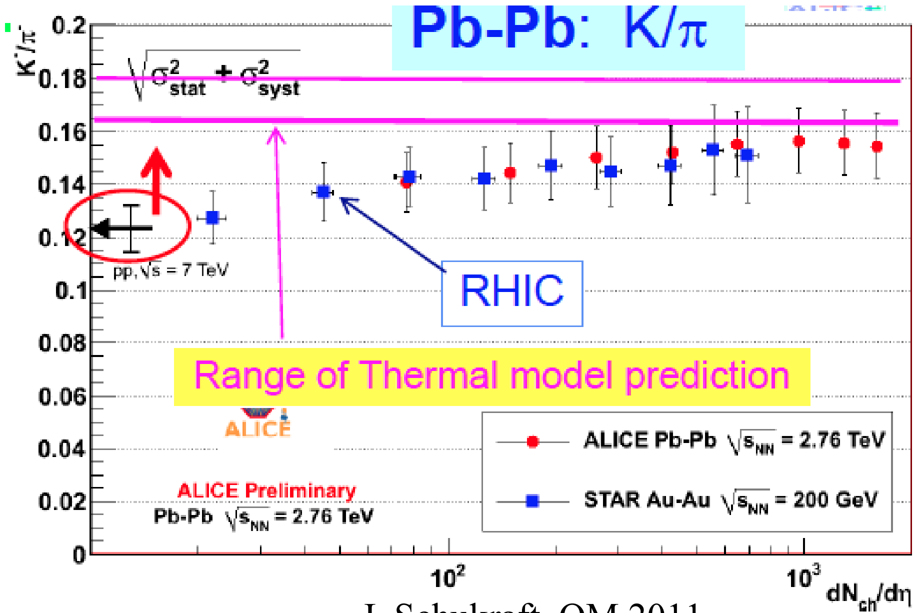
- The LHC point and the RHIC BES (Beam Energy Scan) points confirm the step structure expected for the onset of deconfinement

Rustamov, https://indico.cern.ch/conferenceDisplay.py?confId=144745

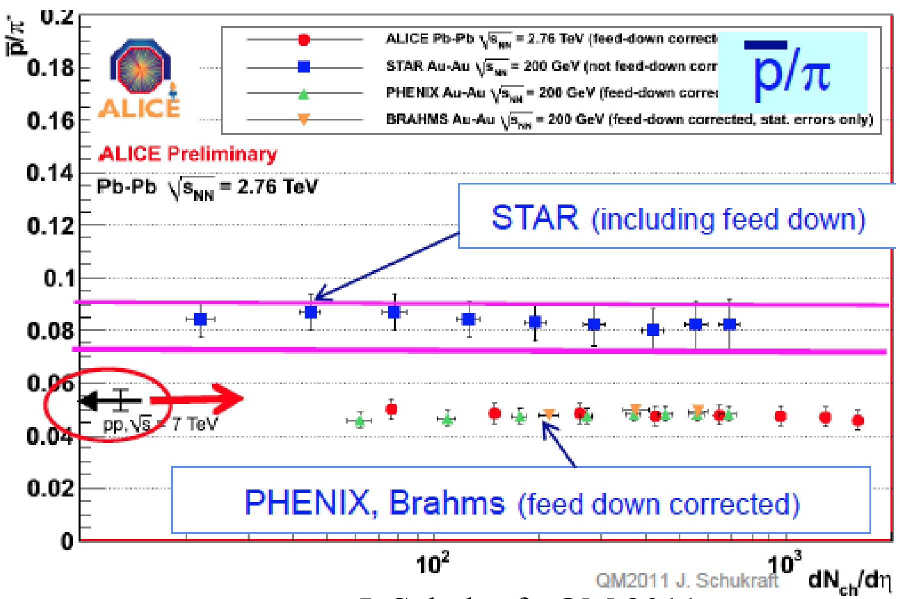
Particle ratios from ALICE

$$\frac{K^-}{\pi^-} \approx 0.15 \pm 0.01$$

$$\frac{K^-}{\pi^-} \approx \frac{K^+}{\pi^+} = 0.15$$



J. Schukraft, QM 2011

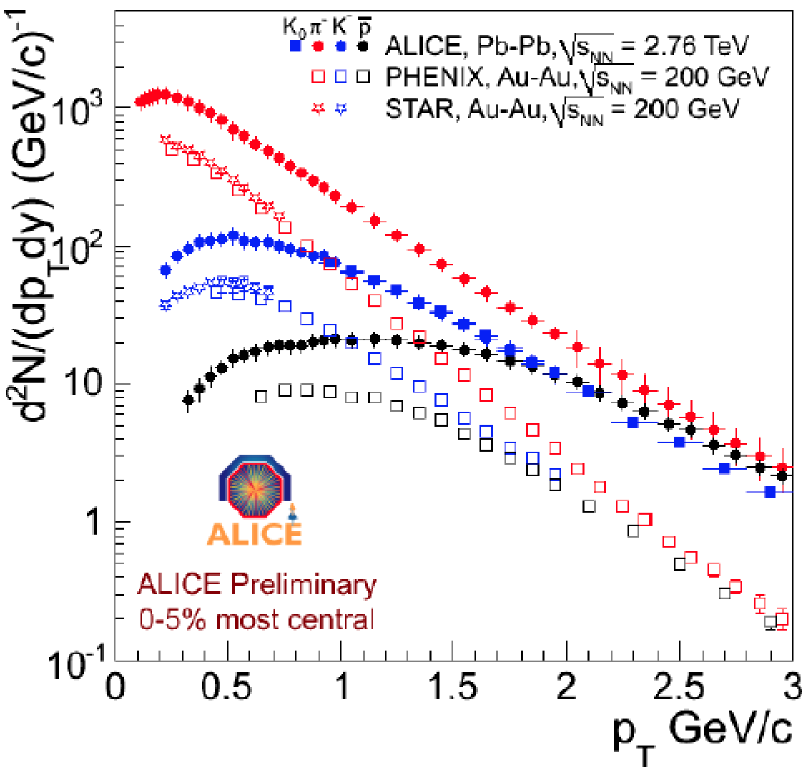


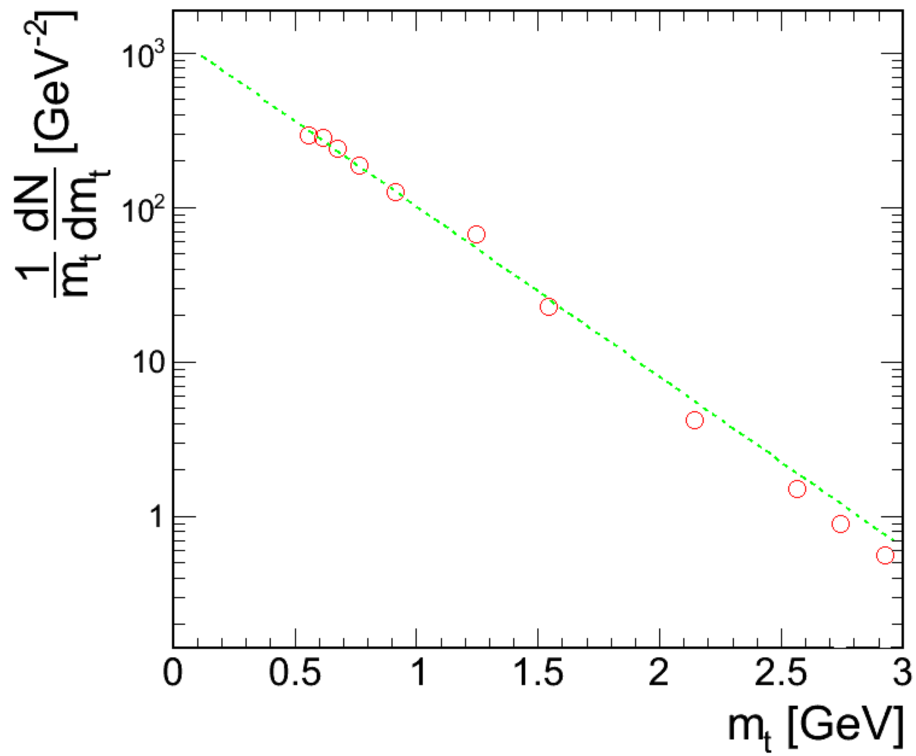
J. Schukraft, QM 2011

$$\frac{\bar{p}}{\pi^-} \approx 0.045$$

Inverse slopes, ALICE

A. Toia, QM 2011



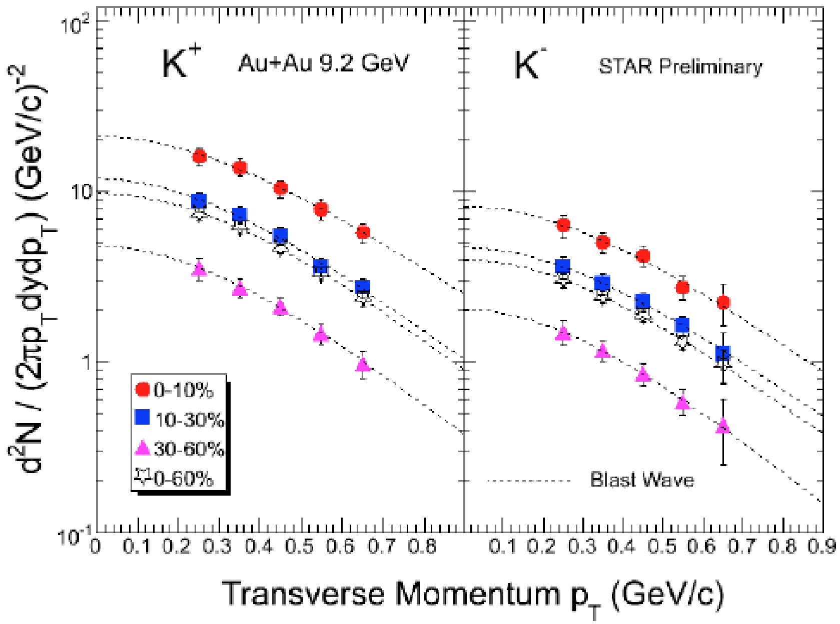


$$\frac{1}{p_\perp}\frac{dN}{dp_\perp} = \frac{1}{m_\perp}\frac{dN}{dm_\perp}$$

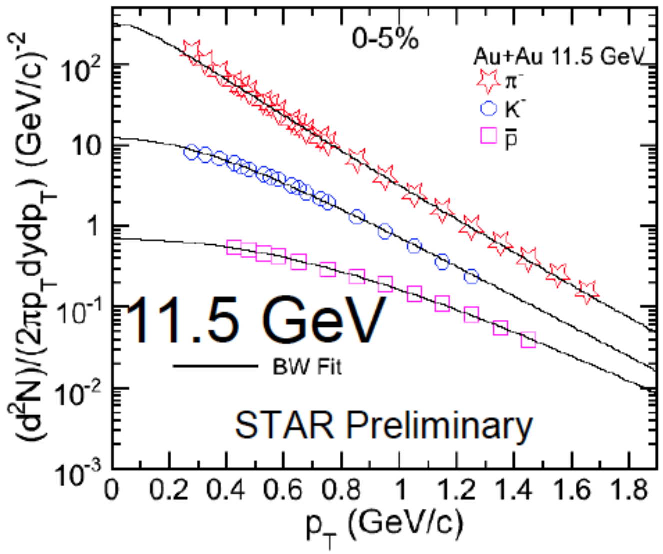
$$\frac{1}{m_\perp}\frac{dN}{dm_\perp} = \text{const}\cdot e^{-\frac{m_t}{T}}$$

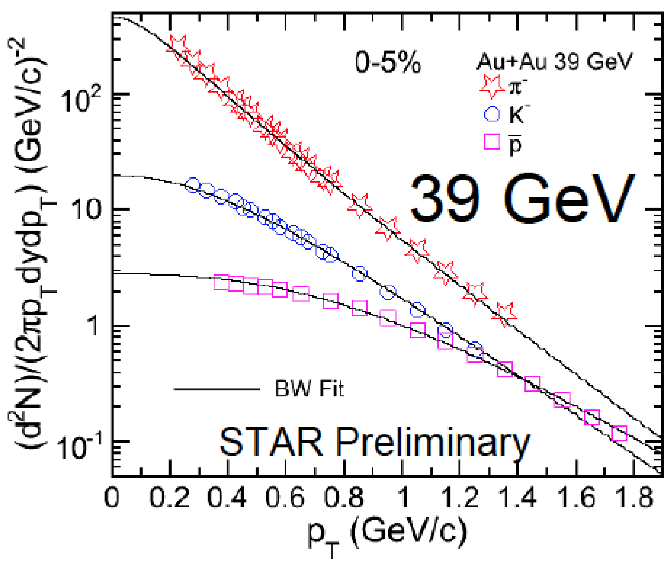
Inverse slopes, STAR

Similar to previous slide, the inverse mt slopes for these distributions have been obtained

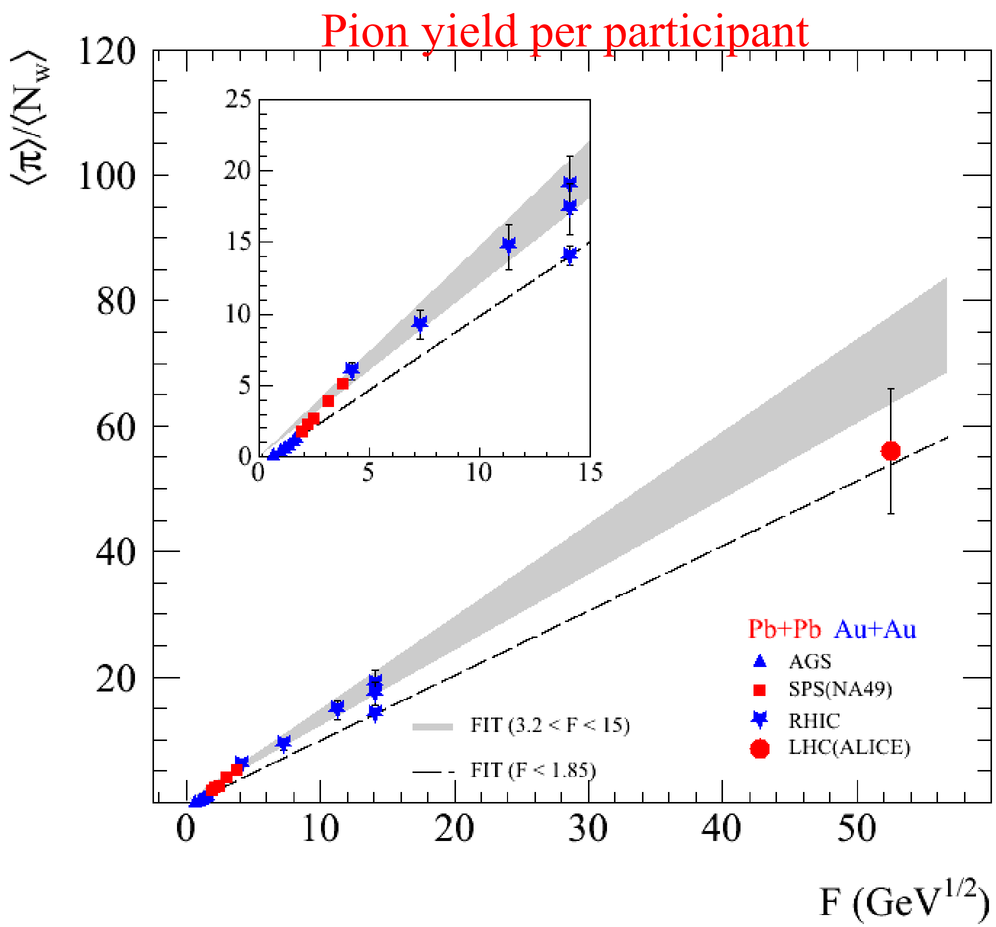


B. Mohanty, QM 2011, L. Kumar SQM 2008





The kink and the new LHC data



The LHC point within a large systematic error consistent with both extrapolations, from high SPS and RHIC energies and from the AGS energies

$$\frac{\langle \pi \rangle}{\langle N_W \rangle} \sim g^{1/4} F$$

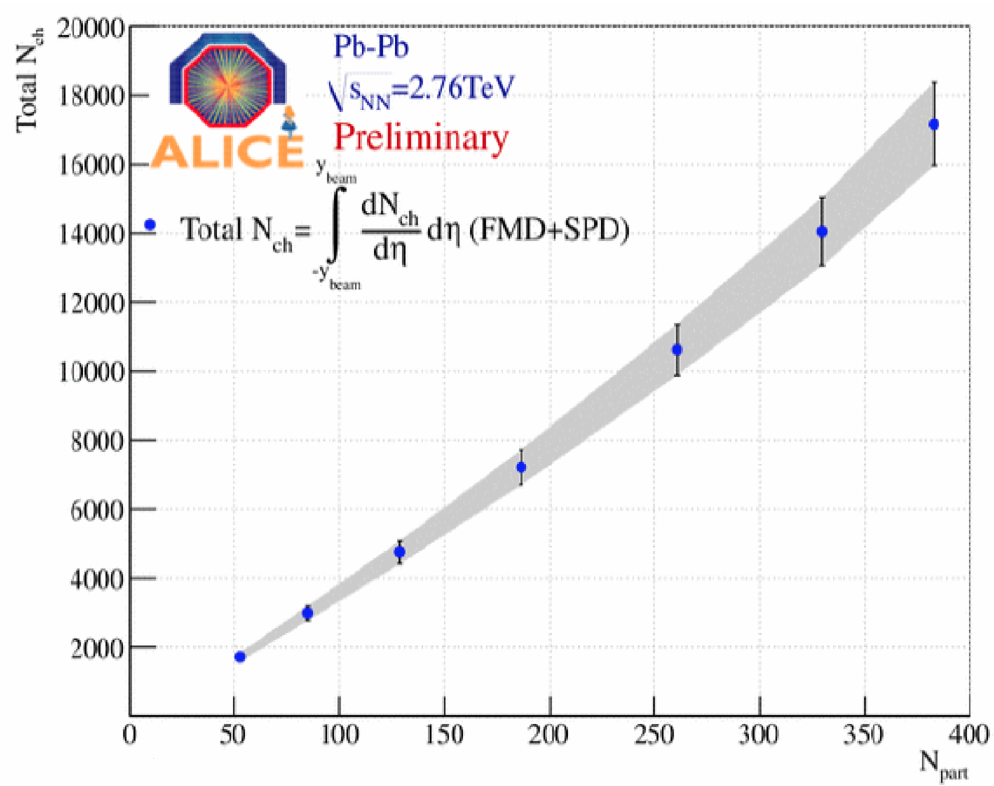
$$F \approx s_{NN}^{1/4}$$

- π yield related to entropy production
- steeper increase in A+A suggests 3-fold increase of early stage d.o.f

For details on plots with LHC points see A. Rustamov, https://indico.cern.ch/conferenceDisplay.py?confId=144745

Particle multiplicities in 4π

A. Toia, QM 2011



Assumptions:

from slide #2

$$\frac{K^- + K^+}{p^- + p^+} = \frac{K^-}{p^-} = 0.15 \pm 0.01$$

$$\frac{p + \bar{p}}{p^- + p^+} = \frac{\bar{p}}{p^-} = 0.045$$

$$\langle N_{\mathrm{ch}}^{\mathrm{total}} \rangle = \langle p^+ + p^- \rangle + \langle K^+ + K^- \rangle + \langle p + \bar{p} \rangle + \frac{N_{\mathrm{part}}}{2} = 1.195 \langle p^+ + p^- \rangle + 192$$

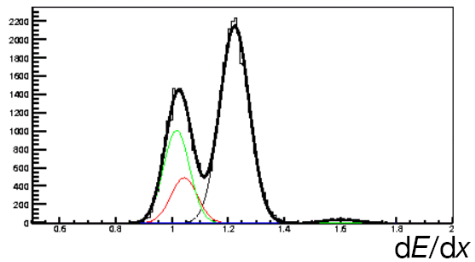
$$\frac{\langle \pi \rangle}{\langle N_{\mathrm{w}} \rangle} = \frac{1.5 \langle p^+ + p^- \rangle}{384} = 55.26 \pm \sqrt{4.1^2 + 8.3^2}$$

additional 15% due to assumption above

Particle ratio fluctuations (method)

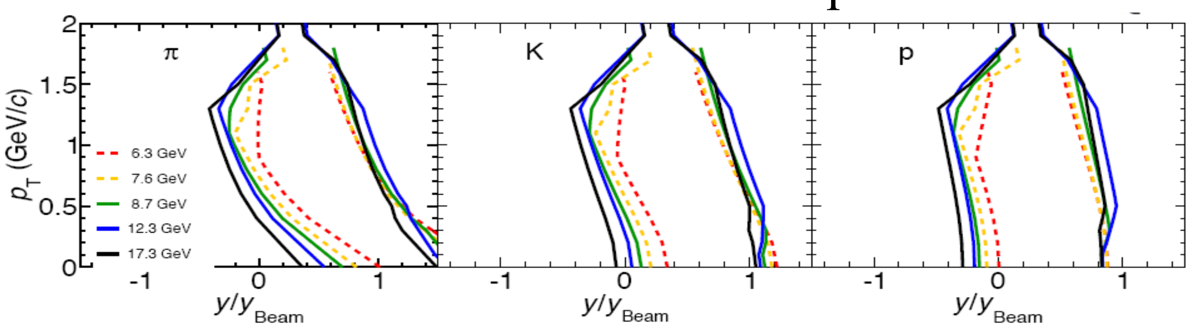
- event-by-event PID based on energy loss dE/dx in MTPCs
- inclusive probability density function + event-by-event maximum likelihood fit to extact relative species abundaces Θ_m

Method: C.*Alt et al., PRC 79, 044910 (2009)*

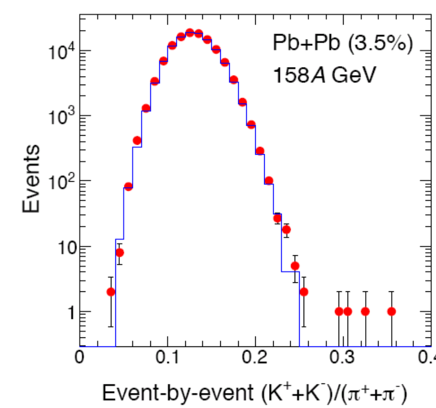


$$\rightarrow \quad L = \prod_{i=1}^{n} \left\{ \sum_{m} \Theta_m F_m(\vec{p}_i) f_m[\vec{p}_i, (dE/dx)_i] \right\}$$

- acceptance different for different species and depends on beam energy; it has to be taken into account for model comparisons



- reference sample of mixed events which preserve multiplicity distribution quantify effect of finite-number statistics and dE/dx resolution



- dynamical fluctuations:

$$\sigma_{\mathrm{dyn}} = \mathrm{sign}\left(\sigma^2_{\mathrm{data}} - \sigma^2_{\mathrm{mix}}\right) \sqrt{\left|\sigma^2_{\mathrm{data}} - \sigma^2_{\mathrm{mix}}\right|}, \; \sigma^2 = \frac{\mathrm{Var}\,(K/\pi)}{\langle K/\pi \rangle^2}$$

- **Intermittency in low mass $\pi^+\pi^-$ pair density fluctuations in p_T space**
  - Proper mass window and multiplicity required
  - Mixed events used as reference
  - **Power-law behavior** from σ mode expected: $\Delta F_2 \sim (M^2)^{\phi_2}$
  - Critical QCD prediction $\phi_2 = 2/3$

2D transv. momentum factorial moments:

$$F_p(M) = \frac{\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i(n_i-1)\ldots(n_i-p+1)\rangle}{\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i \rangle^p}$$

M^2 - number of cells in p_T space of di-pion

$\vec{p}_{T,\pi\pi} = \vec{p}_{T,\pi^+} + \vec{p}_{T,\pi^-}$

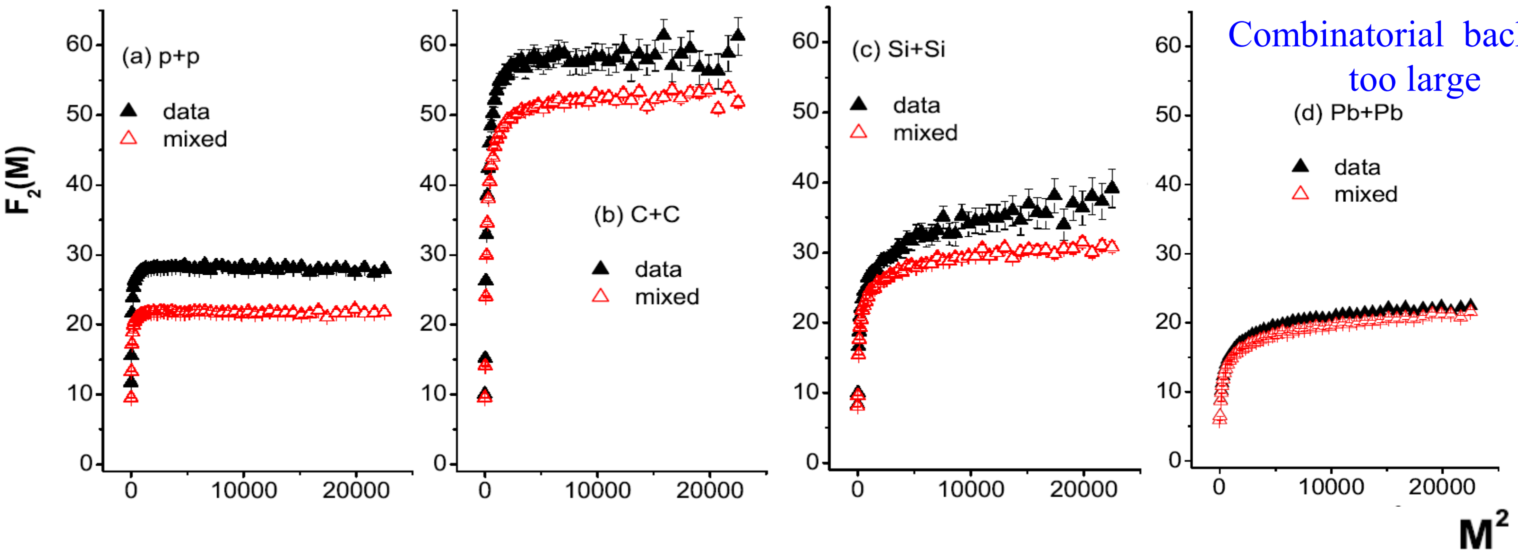
n_i - number of reconstruc. di-pions in i-th cell

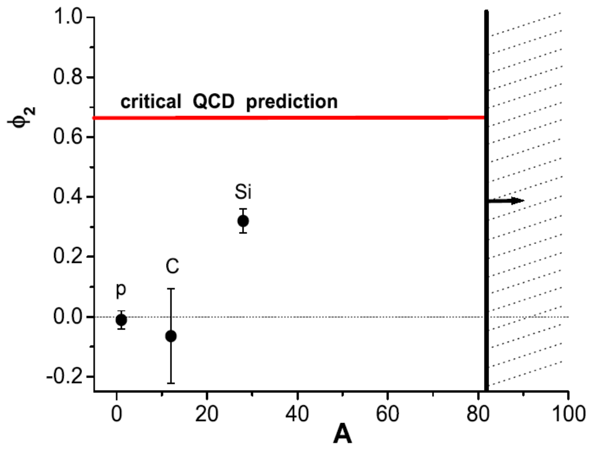
$\Delta F_2(M)$ - combinatorial background subtracted (by use of mixed events) second factorial moment

Critical point: NA49 pilot result

Intermittency of low-mass pion pairs at 158*A* GeV

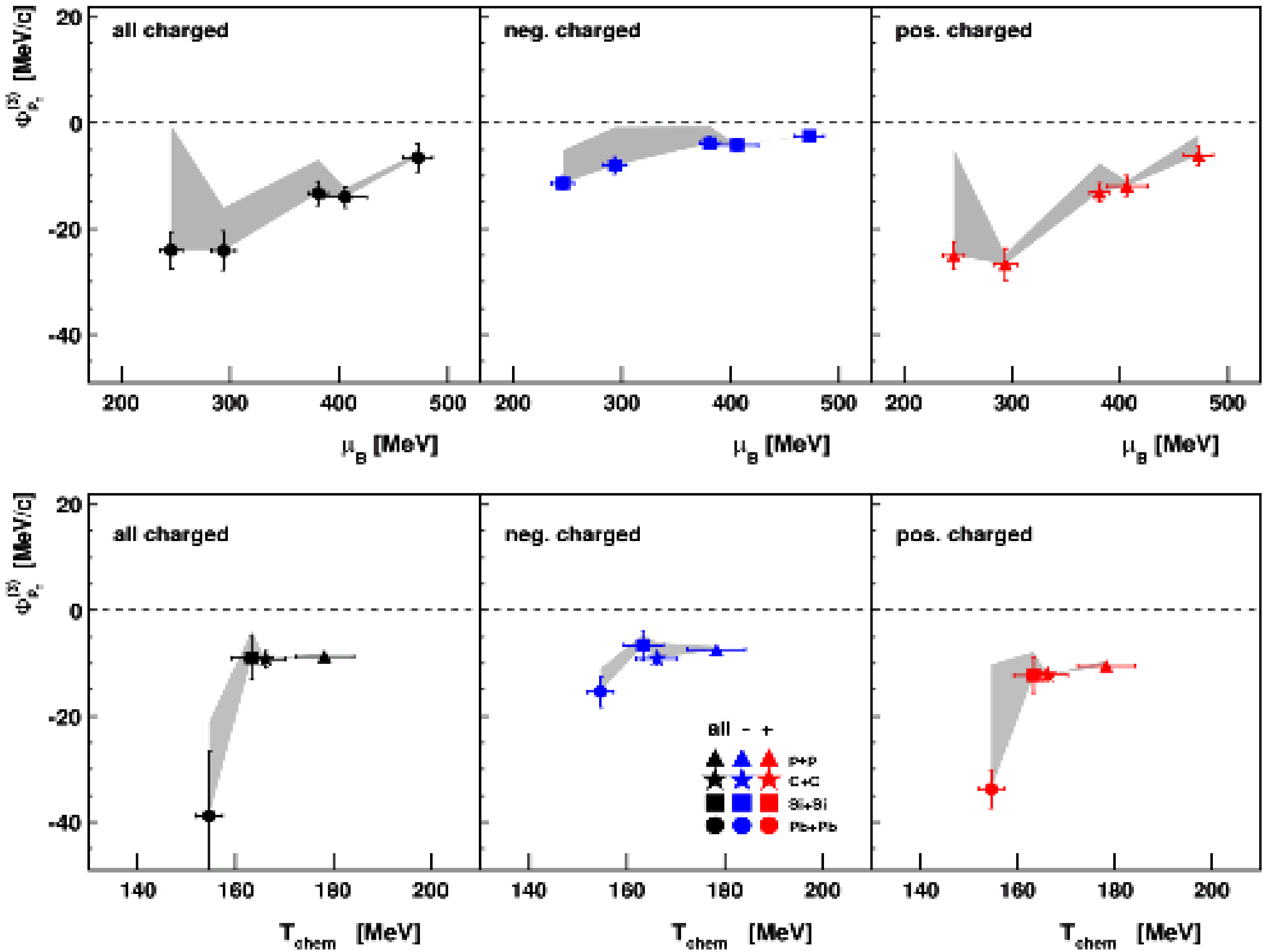
(*PR C81:064907*)





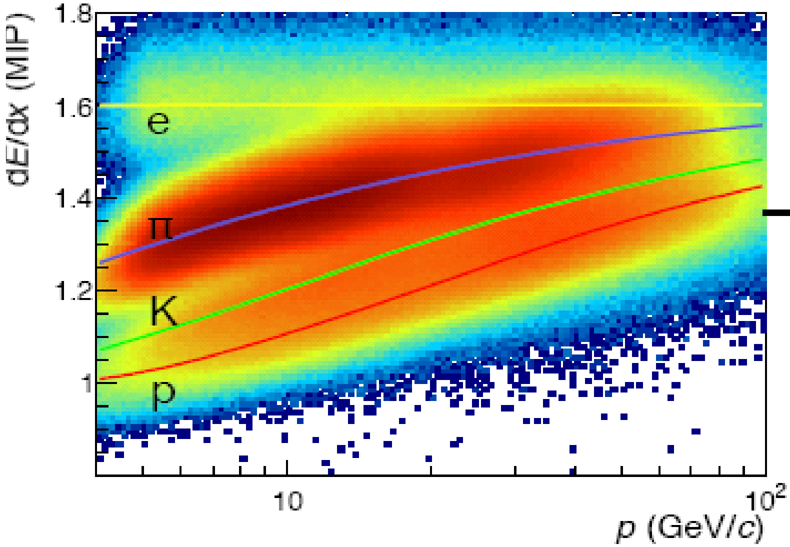
Indications for the intermittency signal for sigma candidates in central Si+Si collisions at 158*A* GeV.

3-rd moment of <p_T> fluctuations

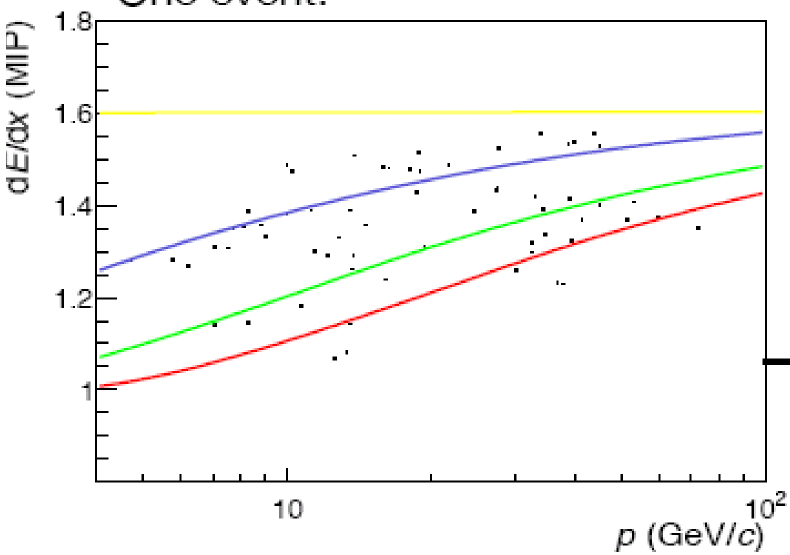


Event-by-event PID using dE/dx

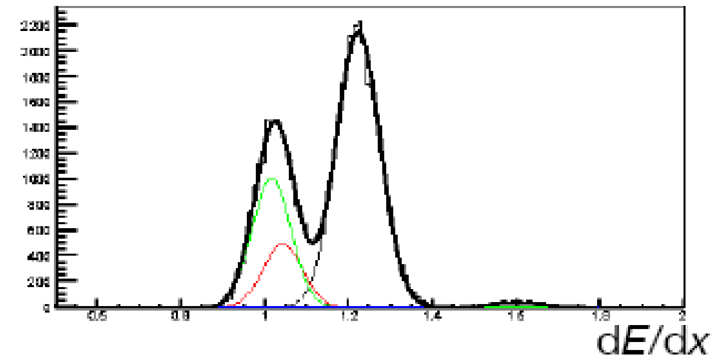
~100k events:



One event:



Fit d*E*/dx spectra in phase space bins



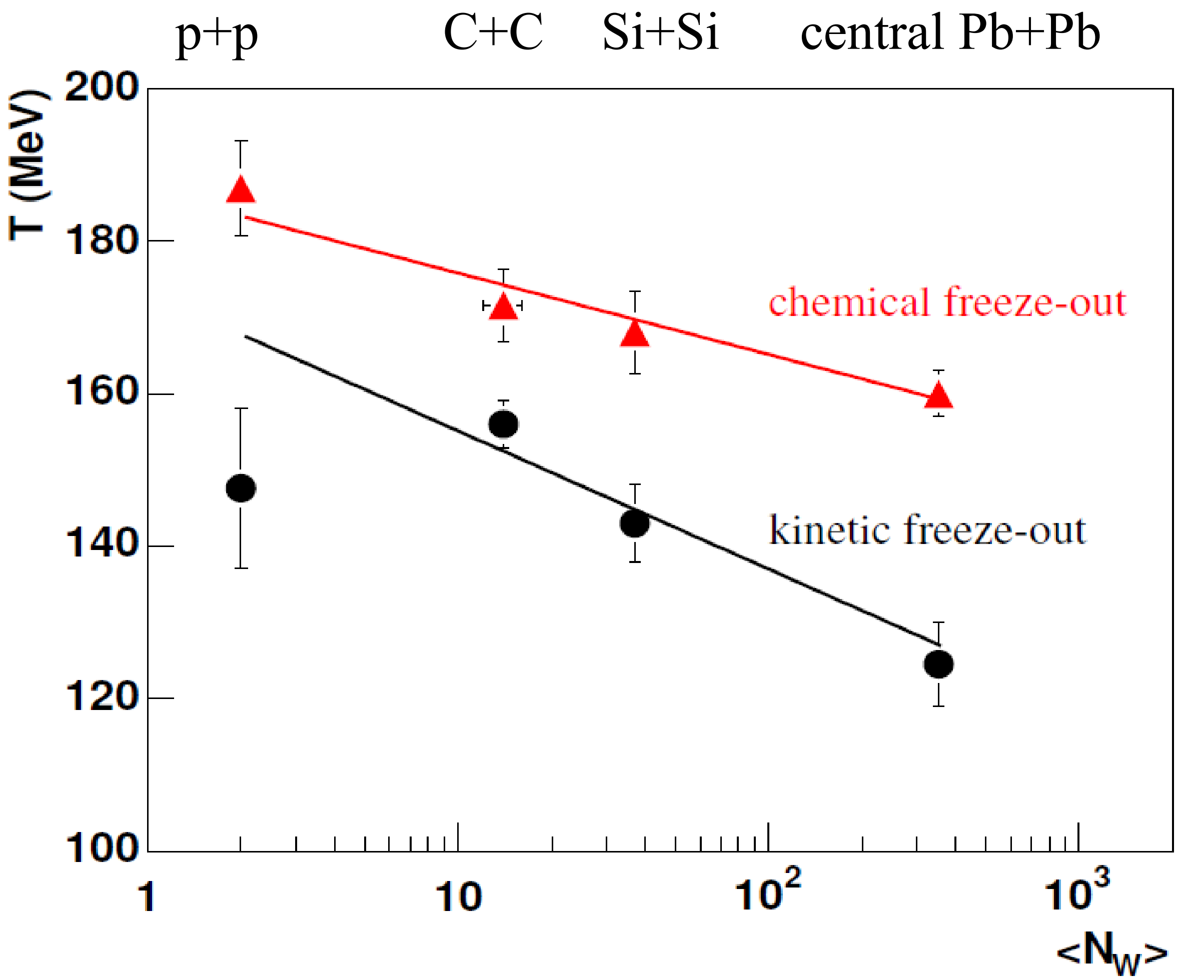
Inclusive probability density function (*p*,d*E*/dx)

$$F\left(\vec{p},(\mathrm{d}E/\mathrm{d}x)\,|\Theta\right)$$
$$= \Sigma_{(m)} r^{(m)}\left(\vec{p}|\Theta^{(m)}\right) f_{p}^{(m)}\left(\mathrm{d}E/\mathrm{d}x\right.$$

(*m* = π,K,p,...)

Extract hadron multiplicities with maximum likelihood from each event

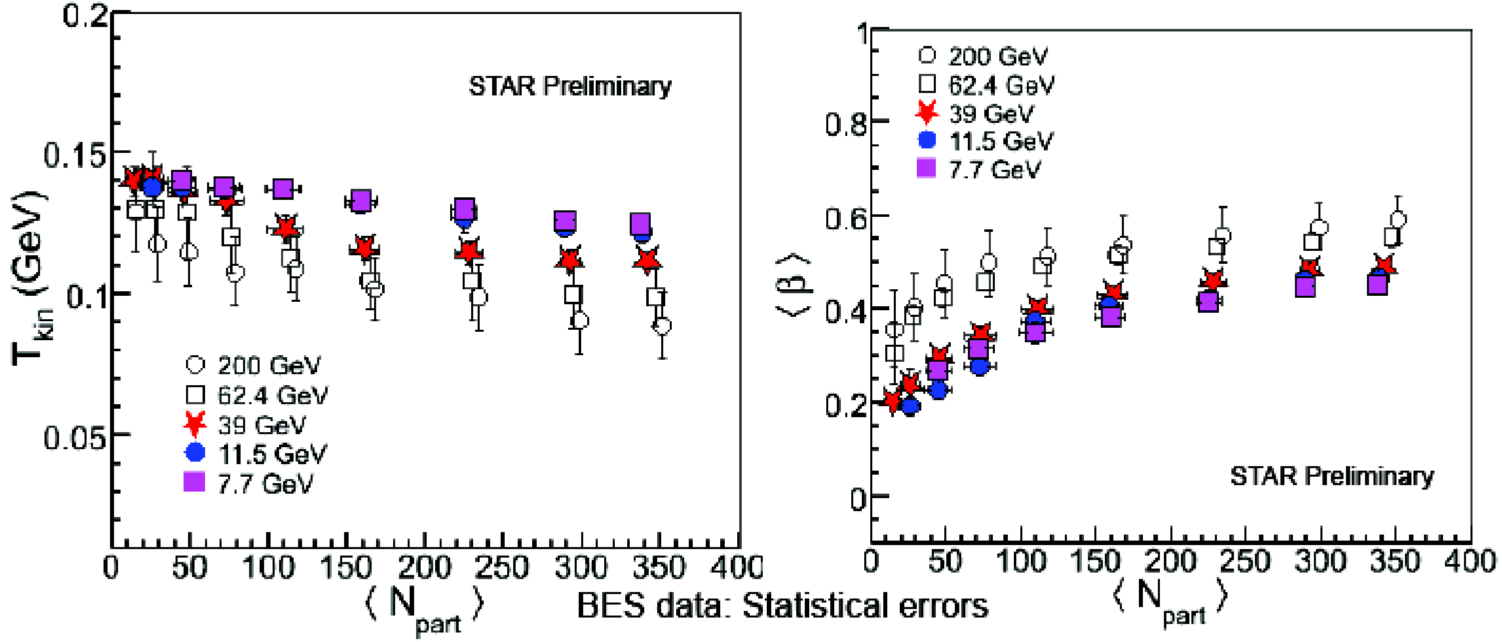
NA49: System size dependence at 158*A* GeV



Becattini, Manninen, MG, PR C73, 04495 (06)

Kraus, JP G31, S147 (05)

Centrality Dependence: T_{kin} and $\langle\beta\rangle$



- ✧ Kinetic freeze-out temperature decreases with increase in energy and centrality
- ✧ Average flow velocity increases with increase in energy and centrality

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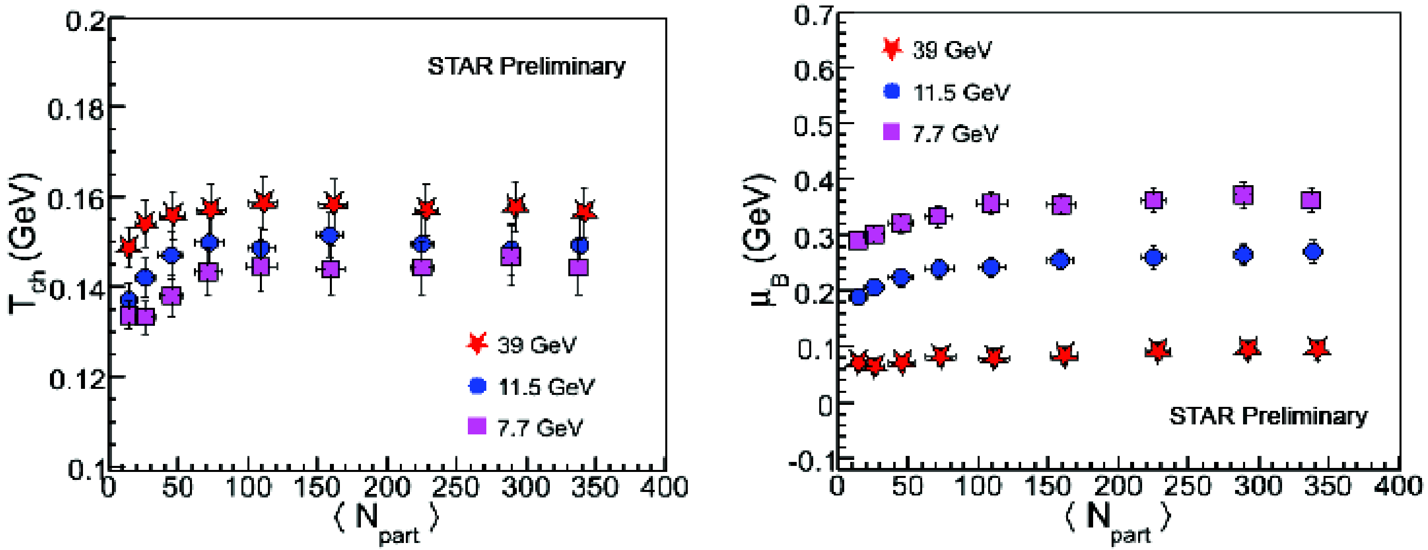
consistent with the NA49 findings

STAR: Centrality dependence for Au+Au

Centrality Dependence: T_{ch} and μ_B



- ✧ The chemical freeze-out temperature increases slightly with increase in energy
- ✧ Baryon chemical potential decreases with increase in energy

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Seems to contradict the NA49 findings: possible reasons:

- STAR limited acceptance, limited set of yields,
- strangeness enhancement not taken into account in the STAR fits (neither CE nor γ_s)