Hadron Production in Nucleus-Nucleus Collisions at the CERN SPS

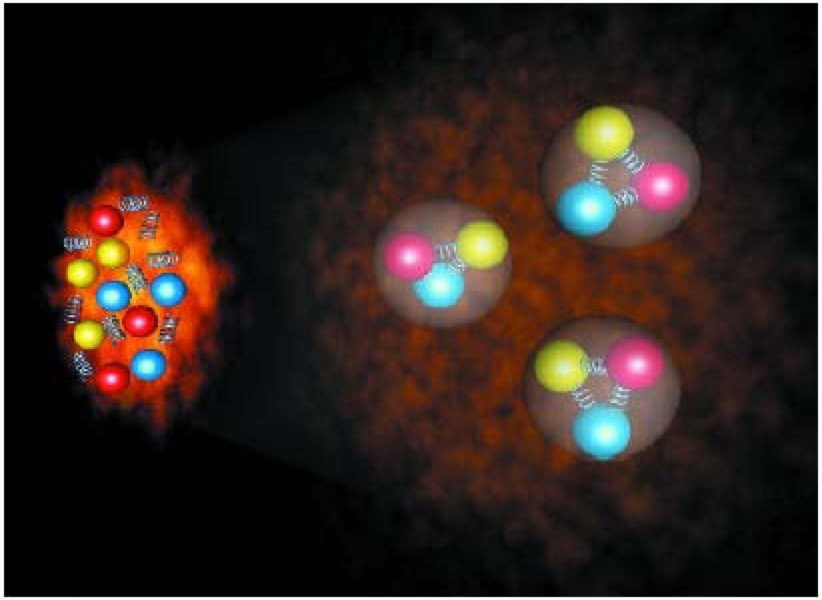
(Search for the Quark-Gluon-Plasma and Critical Point)

P. Seyboth
Max-Planck-Institut für Physik, München
and
Jan Kochanowski University, Kielce
(for NA49/NA61 collaborations)

- early results: energy density, thermalisation, flow
- onset of deconfinement
- search for the critical point in fluctuations
- future programs

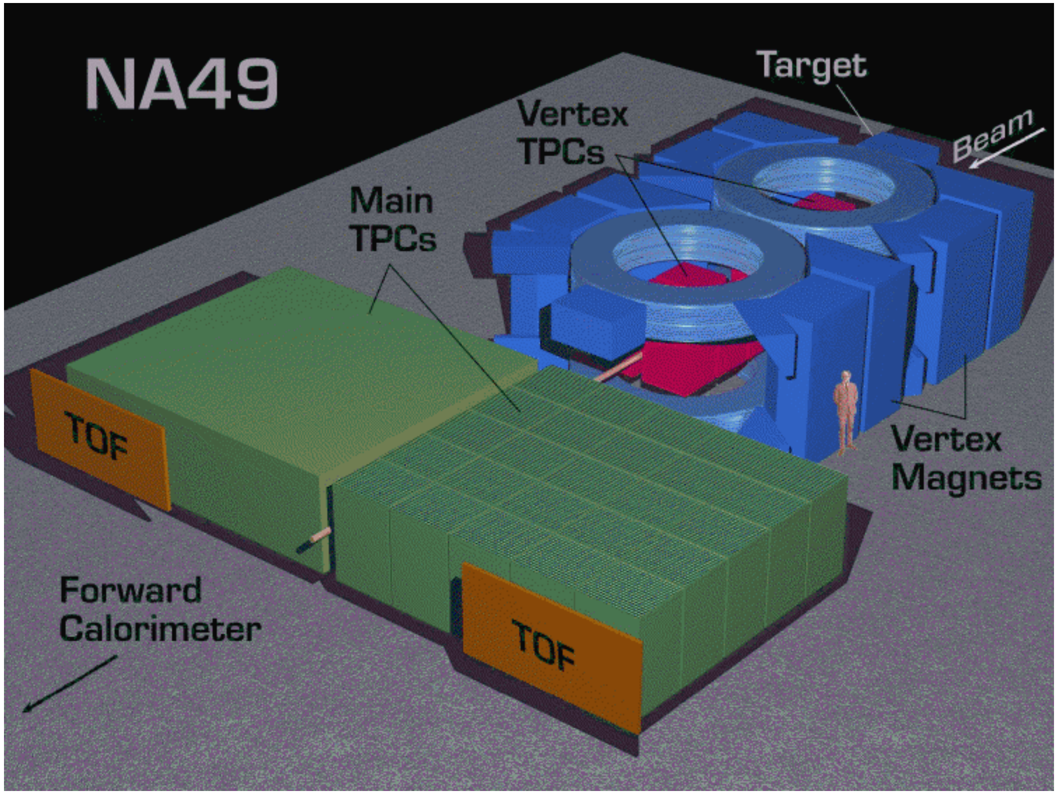
search for deconfinement (Quark-Gluon-Plasma)

quasi-free
quarks and gluons



hadrons

- more effective degrees of freedom → enhanced pion production
- smaller mass of strangeness carriers → strangeness enhancement
- screening of color force → suppression of charmonium production
- stronger energy loss of propagating partons → jet quenching



NA49 Detector

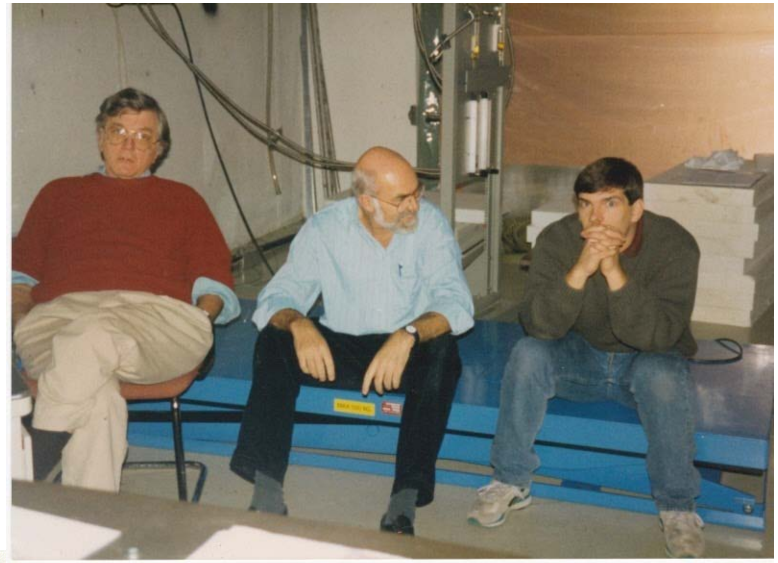
search for the QGP

data taking 1994-2002

(reactivated 2007 for NA61)

- two superconducting magnets (1.5 T, 7 Tm bending power)
- four time projection chambers (180k channels, $\sigma_{dE/dx} \approx 4\%$)
- two time-of-flight walls (1800 pixels, $\sigma_{TOF} \approx 60ps$)
- mid-rapidity ring calorimeter (240 cells)
- zero degree calorimeter

NA49 collaboration 1996



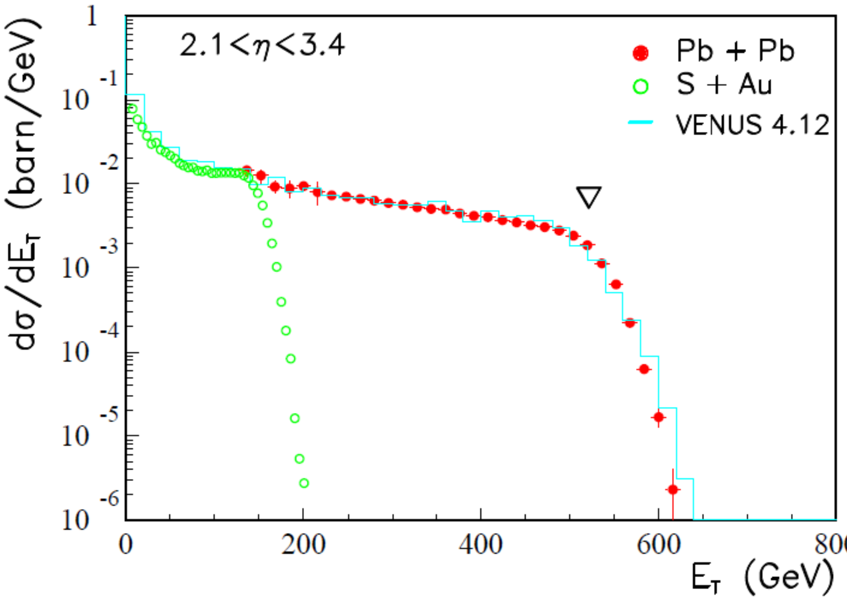
Chuck Whitten
Volker Eckardt
Ian Ferguson

MTPC field cage

early NA49 results (Pb+Pb at 158A GeV)

energy density

Phys.Rev.Lett. 75,3814(1995)

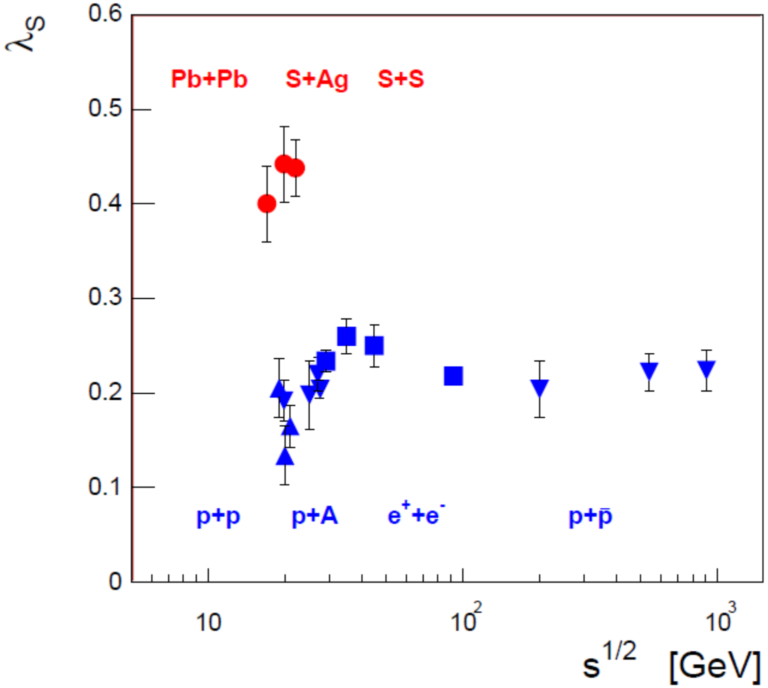


$$\epsilon = (dE_T/d\eta)/(\pi \cdot R^2 \cdot \tau_0)$$

$$\tau_0 = 1[fm/c],\ R = 1.12 \cdot A^{1/3}[fm]$$

reaction	ϵ [GeV/fm^3]	ref
S+S	1.3	NA35
S+Au	2.6	NA35
Pb+Pb	3.2	NA49

strangeness enhancement



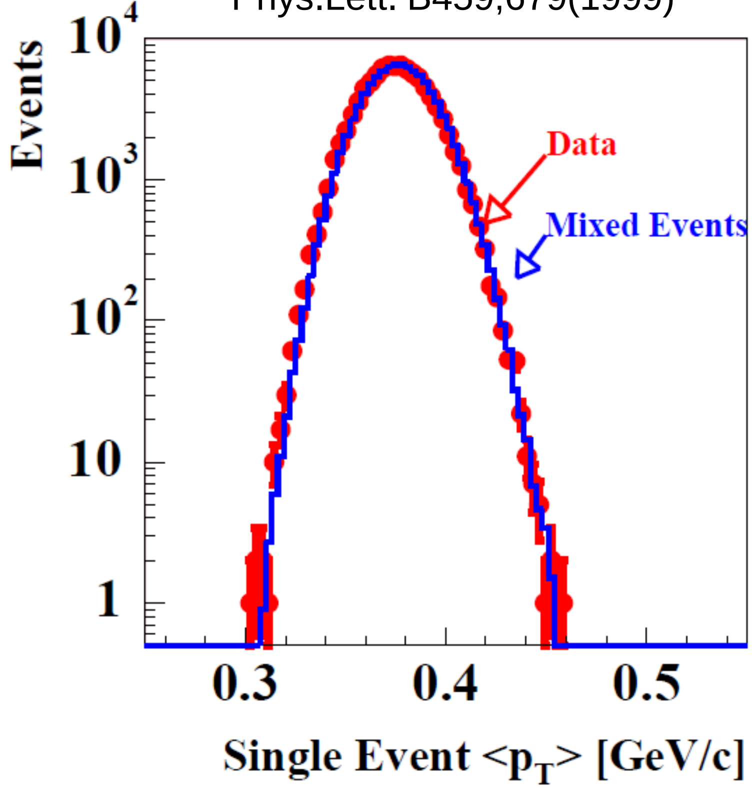
$$\lambda_S = \frac{2\langle s+\bar{s}\rangle}{\langle u+\bar{u}\rangle + \langle d+\bar{d}\rangle}$$

Strangeness Enhancement Unique Feature of Nucleus - Nucleus Collisions

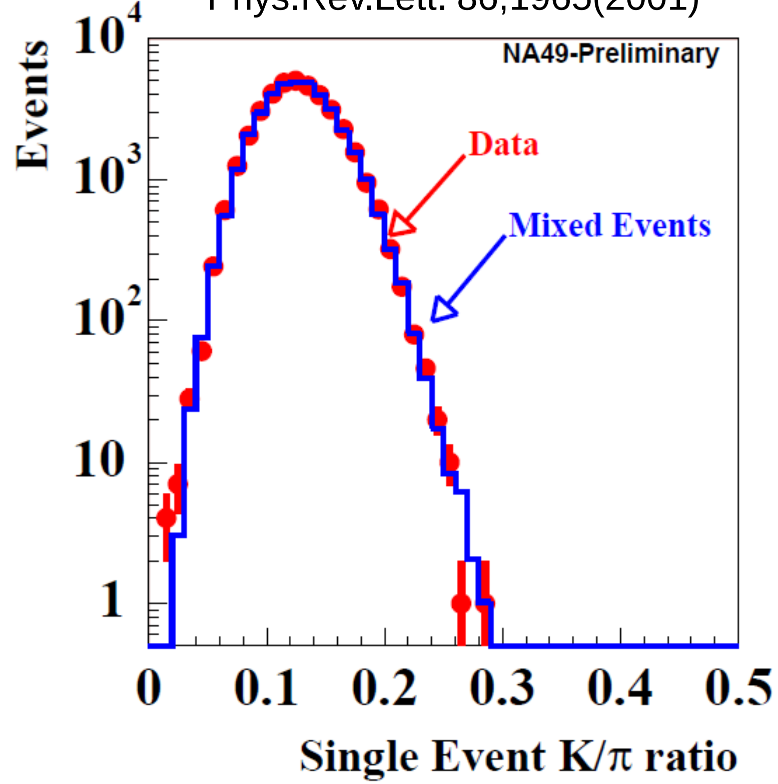
early NA49 results (Pb+Pb at 158A GeV)

event-to-event fluctuations (central collisions)

Phys.Lett. B459,679(1999)



Phys.Rev.Lett. 86,1965(2001)



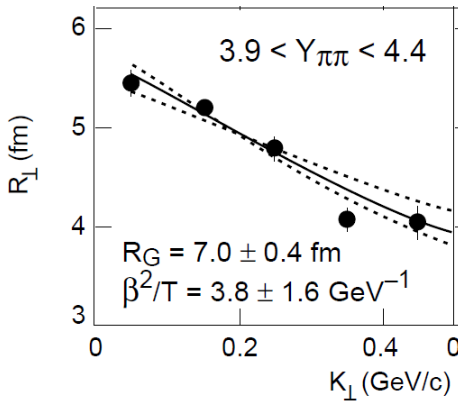
events are rather uniform, no unusual event classes

early NA49 results (Pb+Pb at 158A GeV)

analysis of $\pi\pi$ BE correlations (3d Yano-Koonin formalism)

Eur.Phys.J. C2, 661 (1998)

fireball properties – size, lifetime



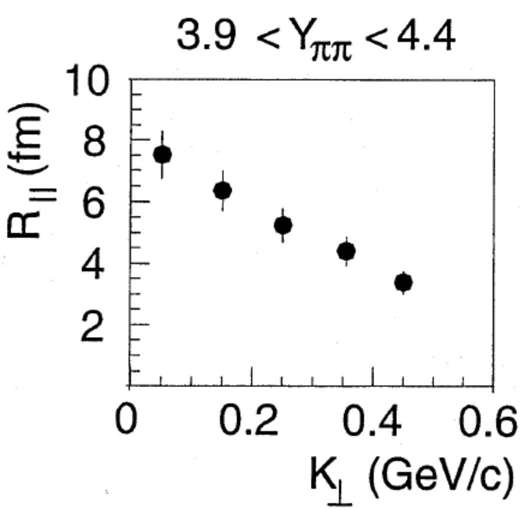
R_{fo} = $R_\perp$ = 7.5 fm

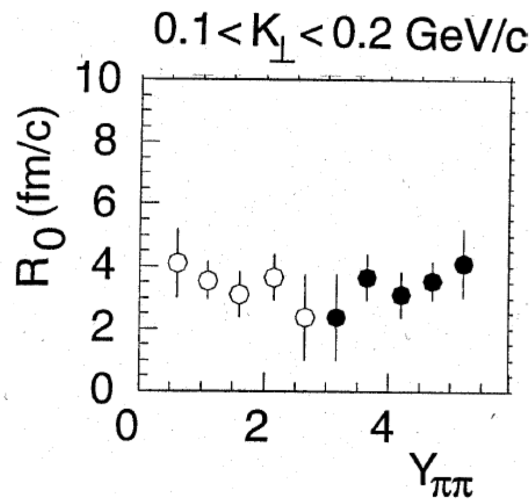
≈ 2 times R_{Pb} (rms)

liftetime $\tau \approx R_\parallel$ = 8 fm/c

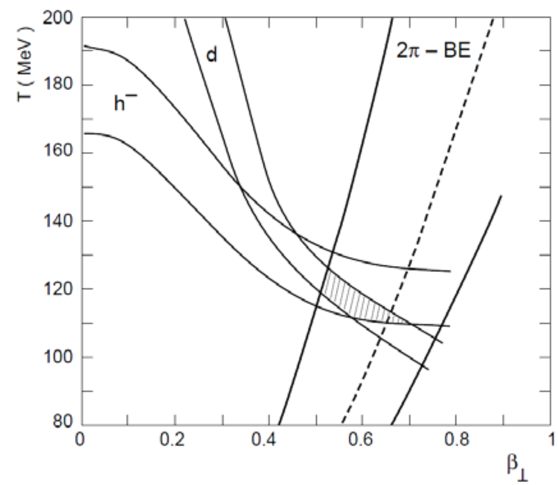
emission duration

$\Delta\tau = R_0 \approx 3.5$ fm/c





collective expansion

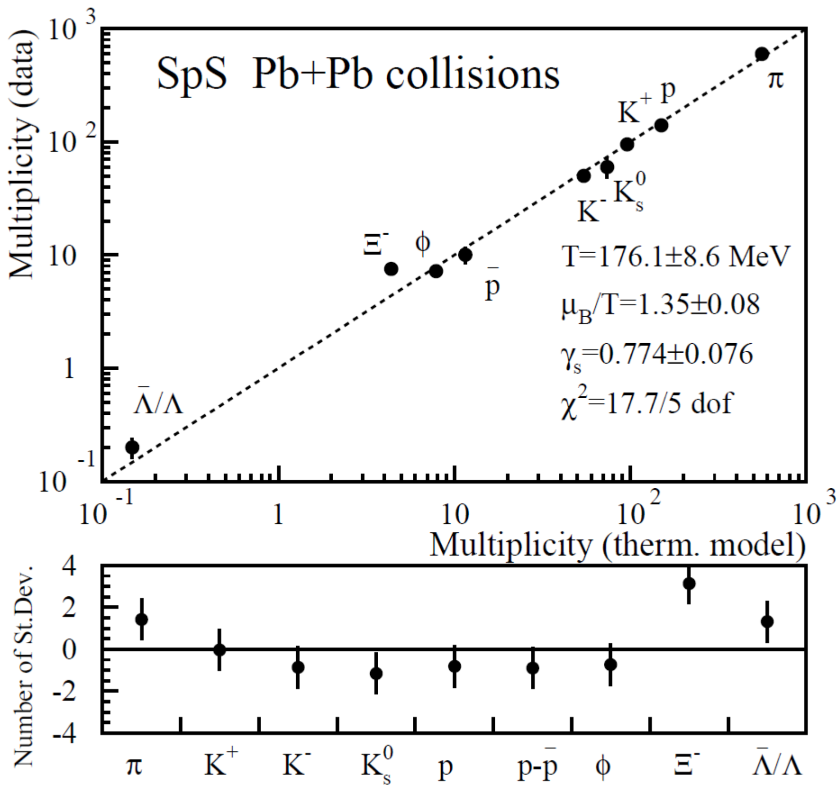


$T_{fo,kin} \approx 120$ MeV

$\beta_T \approx 0.55$

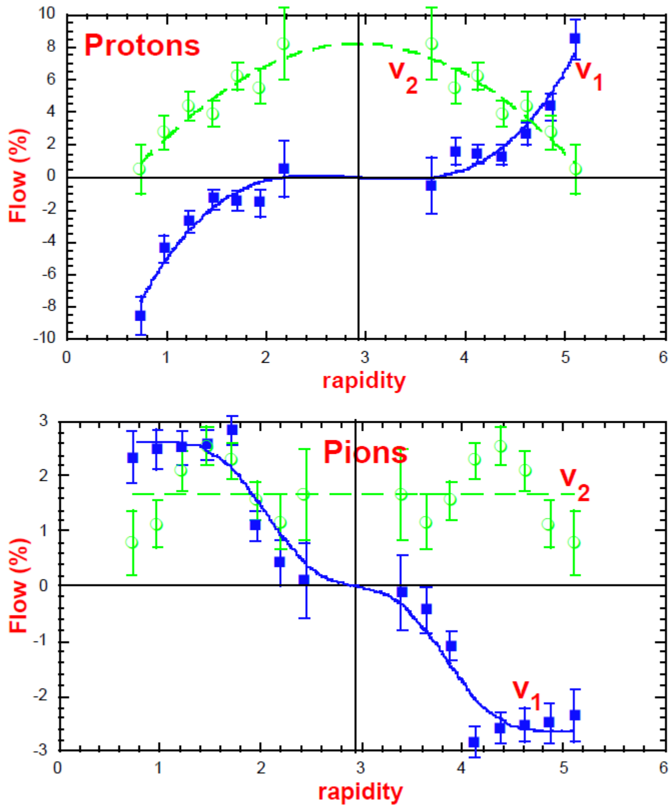
early NA49 results (Pb+Pb at 158A GeV)

statistical particle ratios → $T_{fo,chem}$, μ_B



elliptic and directed flow

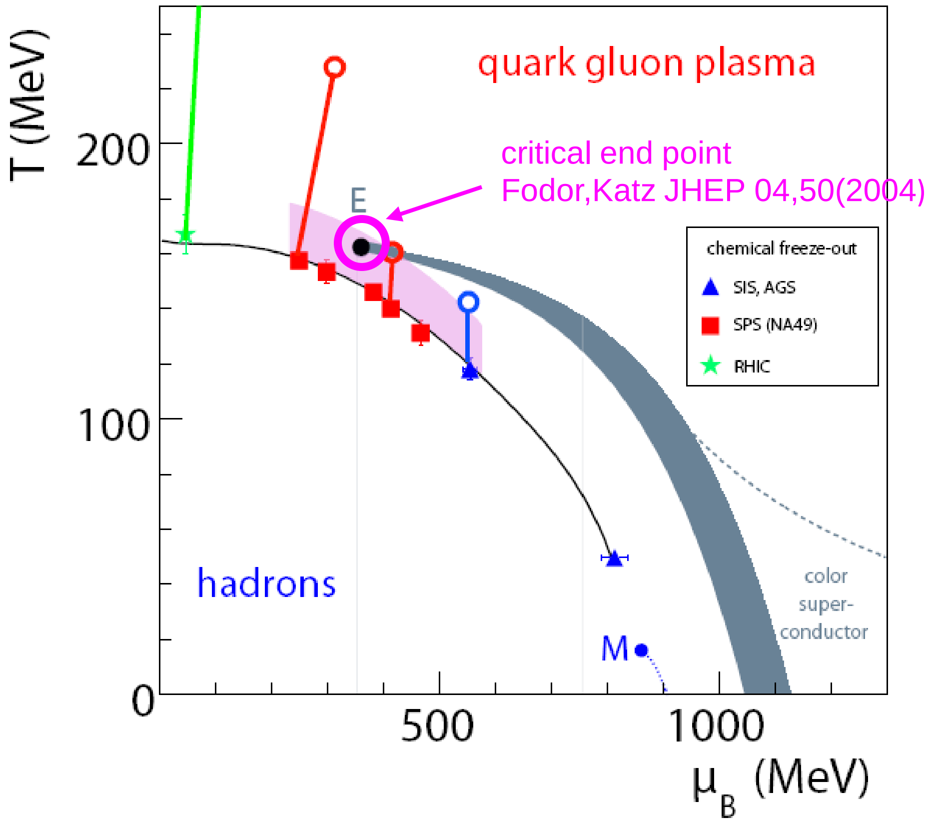
Phys.Rev.Lett. 80,4136(1998)



+ J/Ψ suppression (NA38,NA50), low mass di-lepton enhancement (NA45)

signatures not unique for QGP -> look for threshold in energy scan

Exploration of phase diagram of strongly interacting matter



only central collisions are considered here

- QCD considerations suggest a 1st order phase boundary ending in a critical point

- hadro-chemical freeze-out points are obtained from statistical model fits to measured particle yields
- T and μ_B approach phase boundary and estimated critical point at SPS

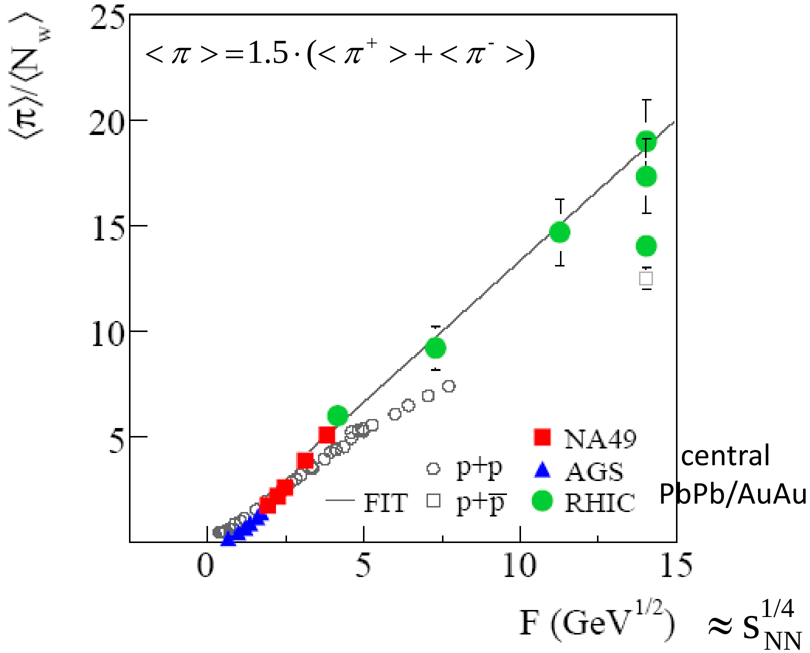
- evidence of onset of deconfinement from rapid changes of hadron production properties
- search for a maximum of fluctuations as indication of the critical point

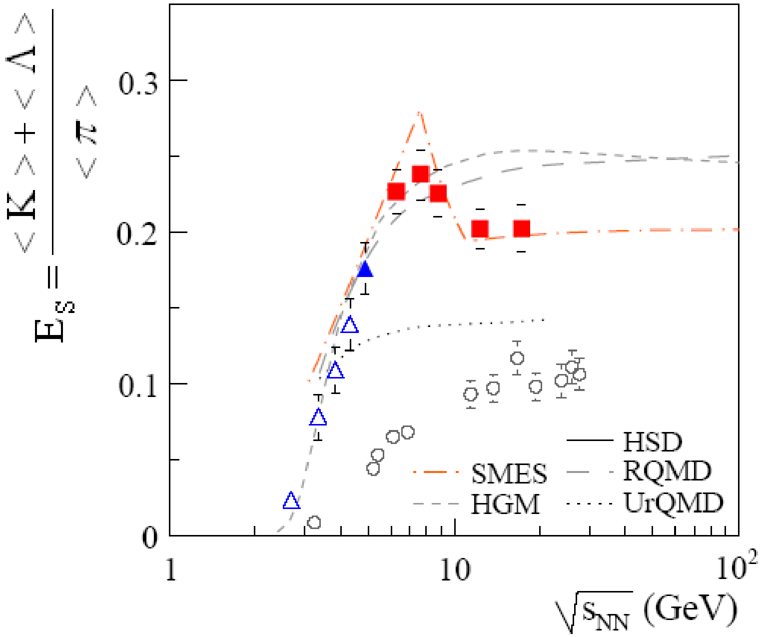
evidence for the onset of deconfinement (1)

the kink — pion yield per participant

the horn — ratio of strange particle to pion yield

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





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

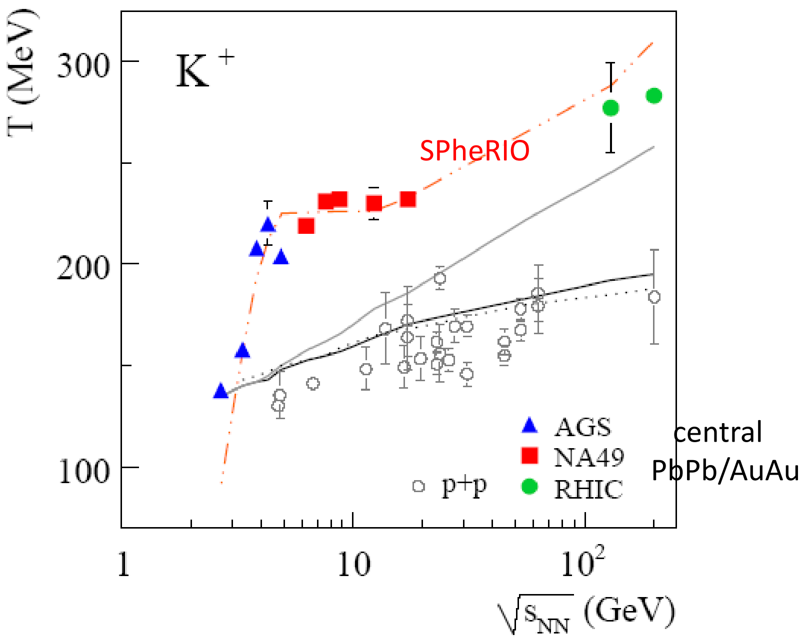
- E_s related to strangeness/entropy ratio
- plateau consistent with prediction for deconfinement

evidence for the onset of deconfinement (2)

the step

shape of transverse mass spectra

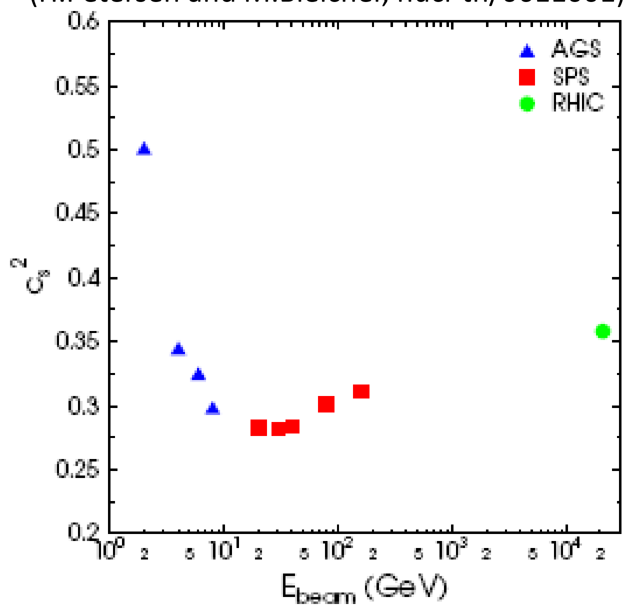
NA49,C.Alt et al., PRC77,024903 (2008)



the dale

estimate of sound velocity

(H.Petersen and M.Bleicher, nucl-th/0611001)



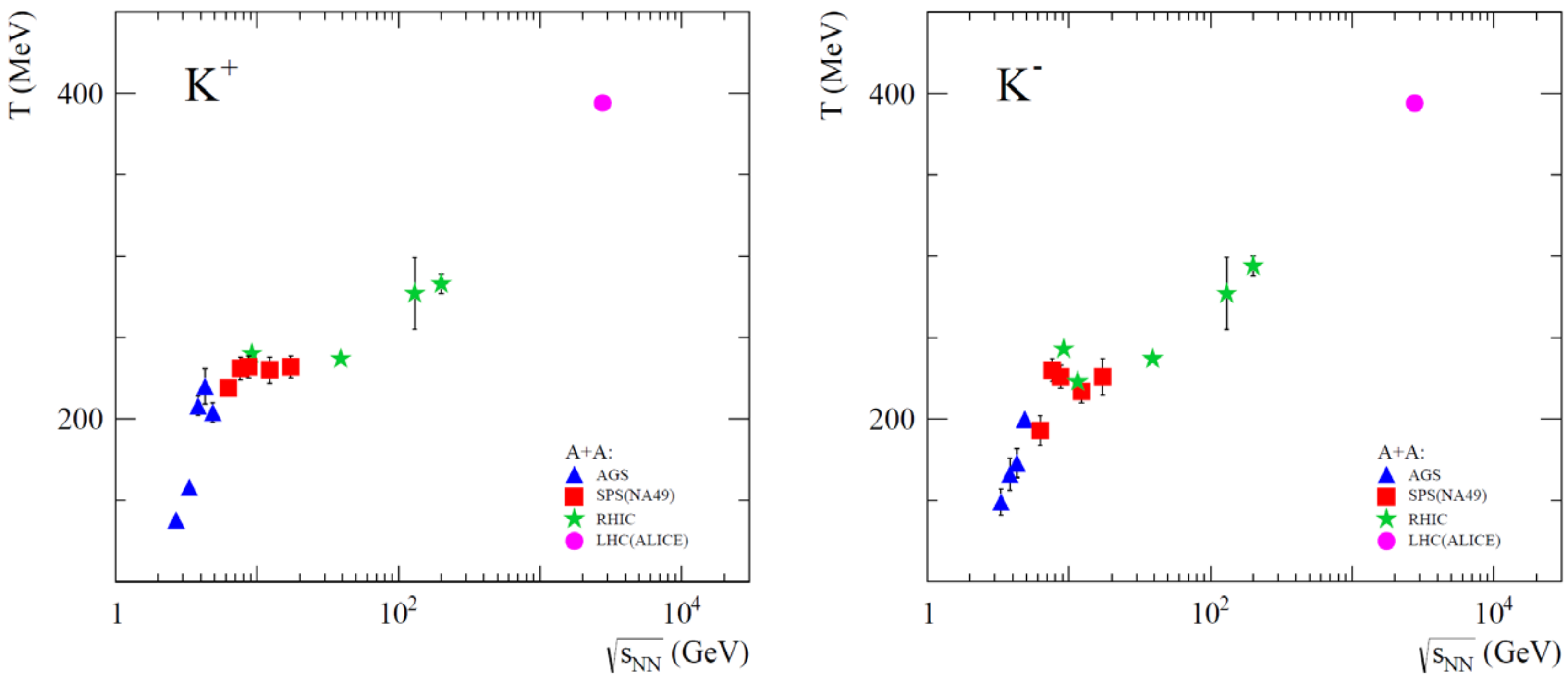
softening of transverse (step) and longitudinal (minimum of c_s) features of EoS due to mixed phase (soft point of EoS)

rapid changes of hadron production properties at low SPS energy most naturally explained by onset of deconfinement

NA49,C.Alt et al.,PRC77,024903(2008); M.Gazdzicki et al., Acta Phys. Pol. B42, 307 (2011)

confirmation by recent STAR and ALICE results (1)

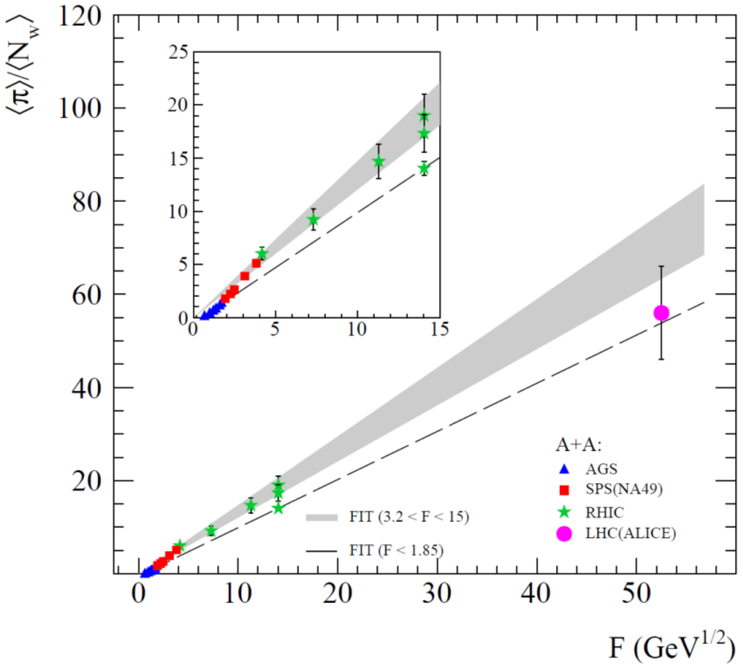
the step



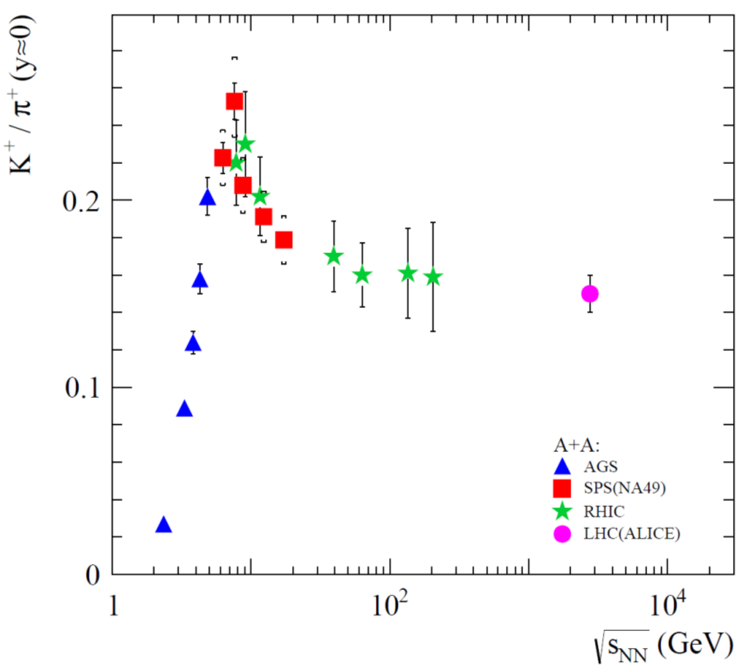
- STAR low energy results confirm the step
- continued rise for ALICE/LHC (increase of radial flow)

confirmation by recent STAR and ALICE results (2)

the kink



the horn



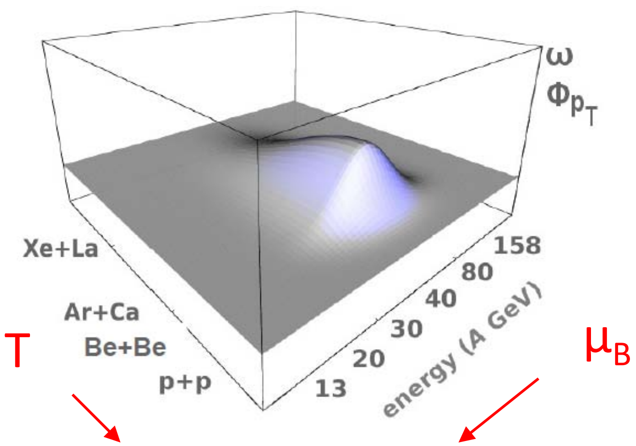
- estimate obtained from ALICE data not inconsistent with extrapolation
- preliminary STAR results confirm horn
- K/π constant above SPS as expected

- key observables evolve smoothly above top SPS energy
- onset of deconfinement at 30A GeV remains the most likely scenario

search for the critical point of strongly interacting matter

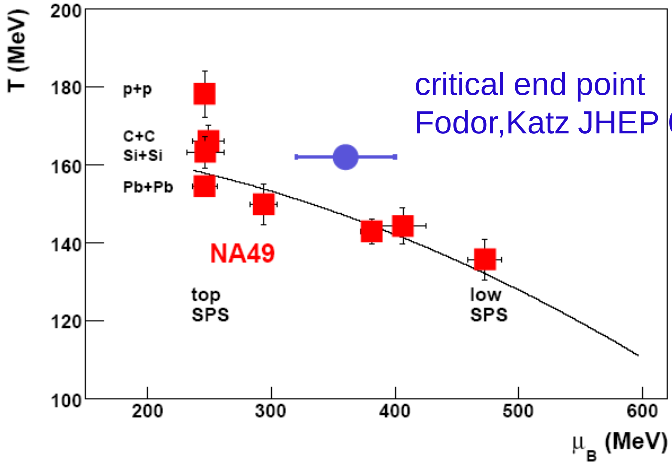
search strategy: 2-dimensional (T,μ_B) scan of phase diagram

expected "hill" of fluctuations



freeze-out points from stat. model

Becattini et al, PRC73, 044905 (2006)



- deconfinement necessary for observing CP effect (above 30A GeV)
- expected size of fluctuation signals ($\sim\xi^2$) limited by short lifetime and size of collision system (correlation lengths ~ 3 – 6 fm for Pb+Pb)

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

- freeze-out close enough to CP ?
- can fluctuation signals survive later fireball evolution ??

fluctuation measures studied by NA49

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

$$\sigma_{dyn} = \text{sign}(\sigma^2_{data} - \sigma^2_{mix})\sqrt{\left|\sigma^2_{data} - \sigma^2_{mix}\right|} \;,\quad \sigma^2 = \frac{Var(A/B)}{\langle A/B\rangle^2} \;,\quad \sigma^2_{dyn} \approx \left|\nu_{dyn}\right|$$

not discussed

- e-by-e fit of dE/dx distribution required in NA49
- mixed events used as reference
- $1/N_W$ dependence V.Koch,T.Schuster PRC81,034910

- Φ_x measure of fluctuations of observable x ($<p_T>$, $<\phi>$, Q, …)

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

$$\Phi_x = \sqrt{\frac{<Z^2>}{<N>}} - \sqrt{<z^2>}\;;$$

$$z = x - <x>\,,\quad Z = \sum_{i=1}^{N}(x_i - <x>)$$

- independent particle emission: $\Phi_x = 0$
- superposition model: $\Phi_x(A+A) = \Phi_x(N+N)$
- Φ_x strongly intensive fluctuation measure independent of $<N_W>$ and its fluctuations

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

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

- independent particle emission: ω = 1
- superposition model: $\omega(A+A) = \omega(N+N) + <N_W>\omega_{NW}$
- ω sensitive to fluctuations of N_W

- intermittency in the production of low mass $\pi^+\pi^-$ pairs and protons

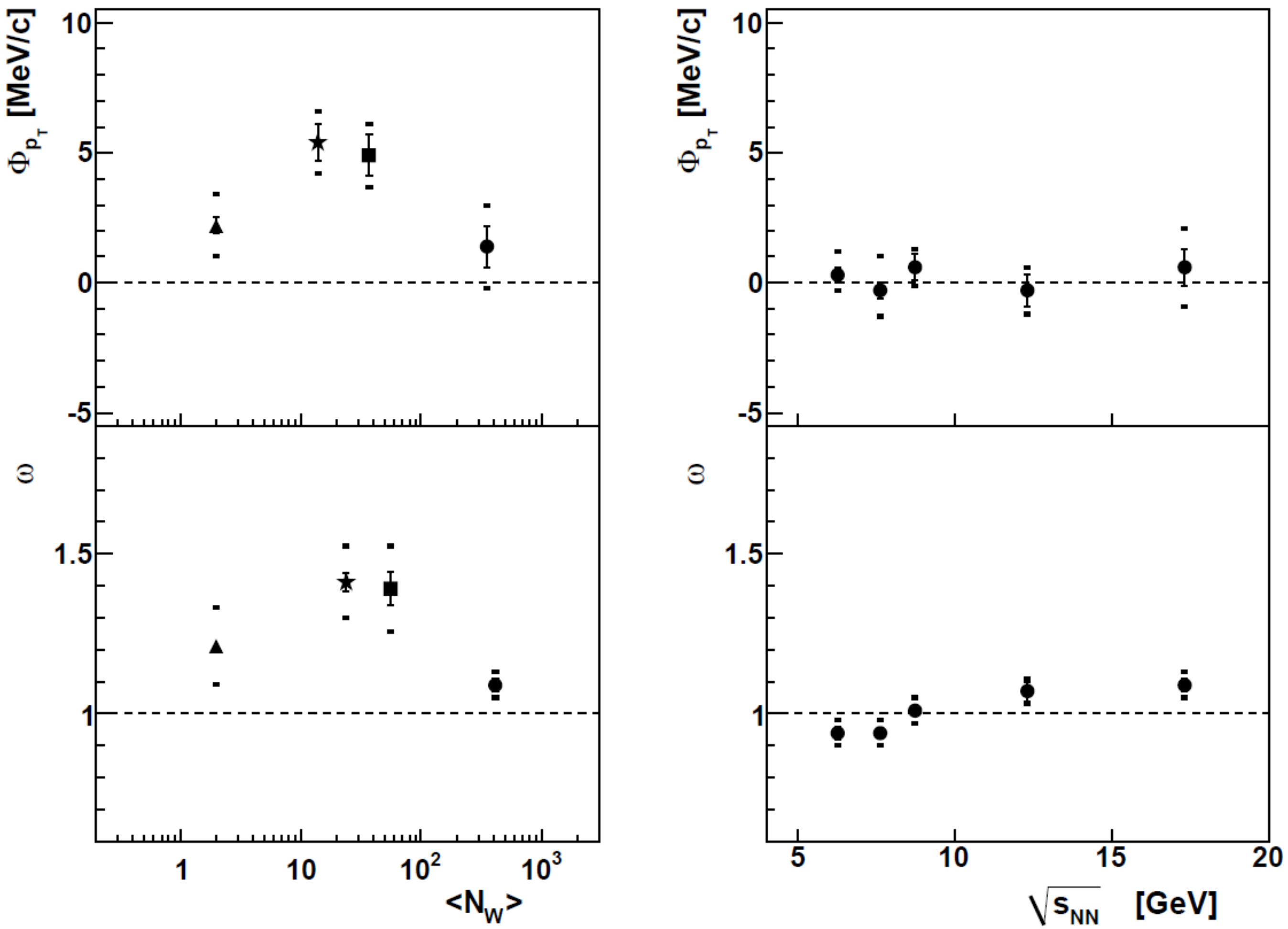
$$F_2(M) = \left\langle \frac{1}{M^2}\sum_{i=1}^{M^2} n_i\cdot(n_i - 1)\right\rangle \Big/ \left\langle \frac{1}{M^2}\sum_{i=1}^{M^2} n_i\right\rangle^2 \propto M^{2\Phi_2}$$

M^2 cells in p_T phase space

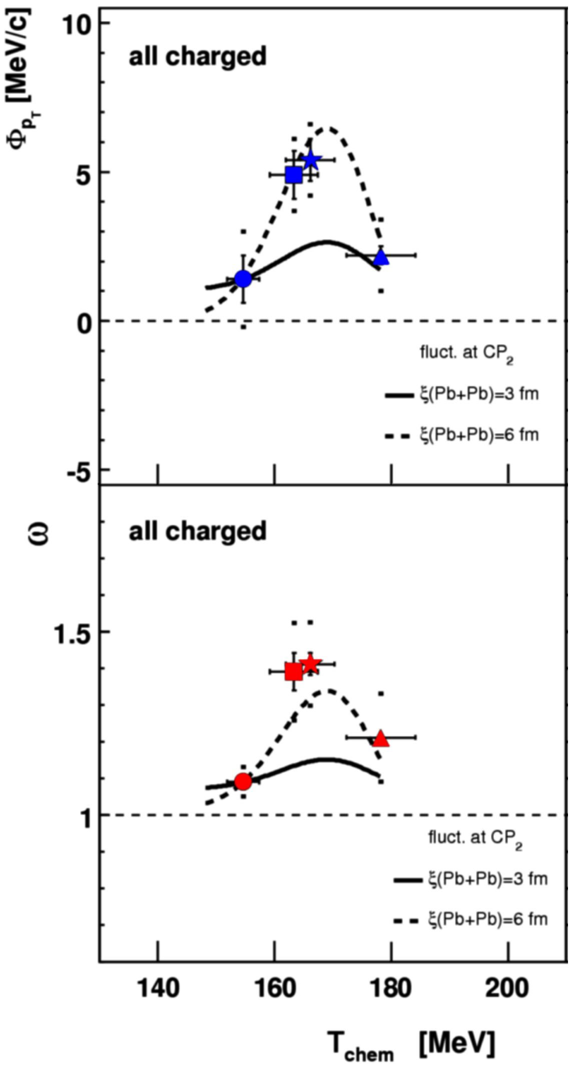
results of critical point search (Φ_{pT} and ω) by NA49

dependence on

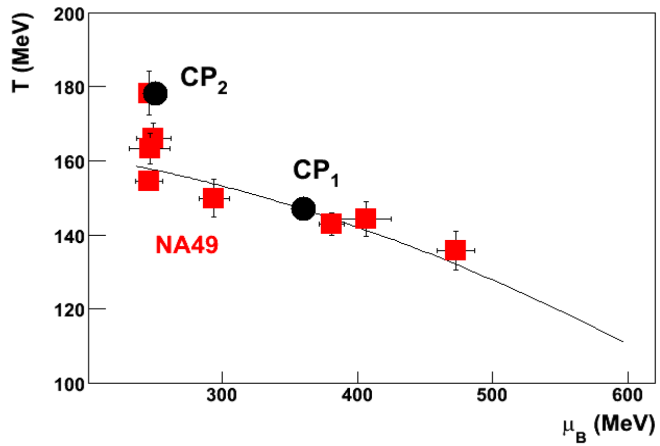
system size: pp, CC, SiSi, PbPb energy (central PbPb)

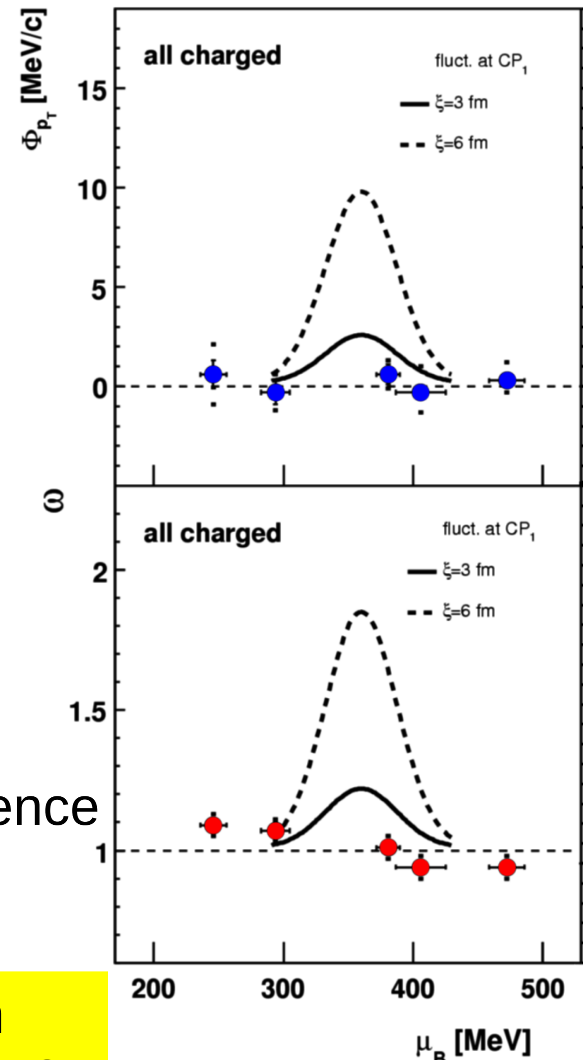


map onto T,μ_B coordinates using statistical model fits



T.Anticic et al., PRC70, 034902 (2004)
C.Alt et al., PRC75, 064904 (2007)
C.Alt et al,. PRC78, 034914 (2008)
T.Anticic et al., PRC79, 044904 (2009)
B.Lungwitz, NA49 thesis (2008)





smooth energy (μ_B) dependence
in central Pb+Pb collisions

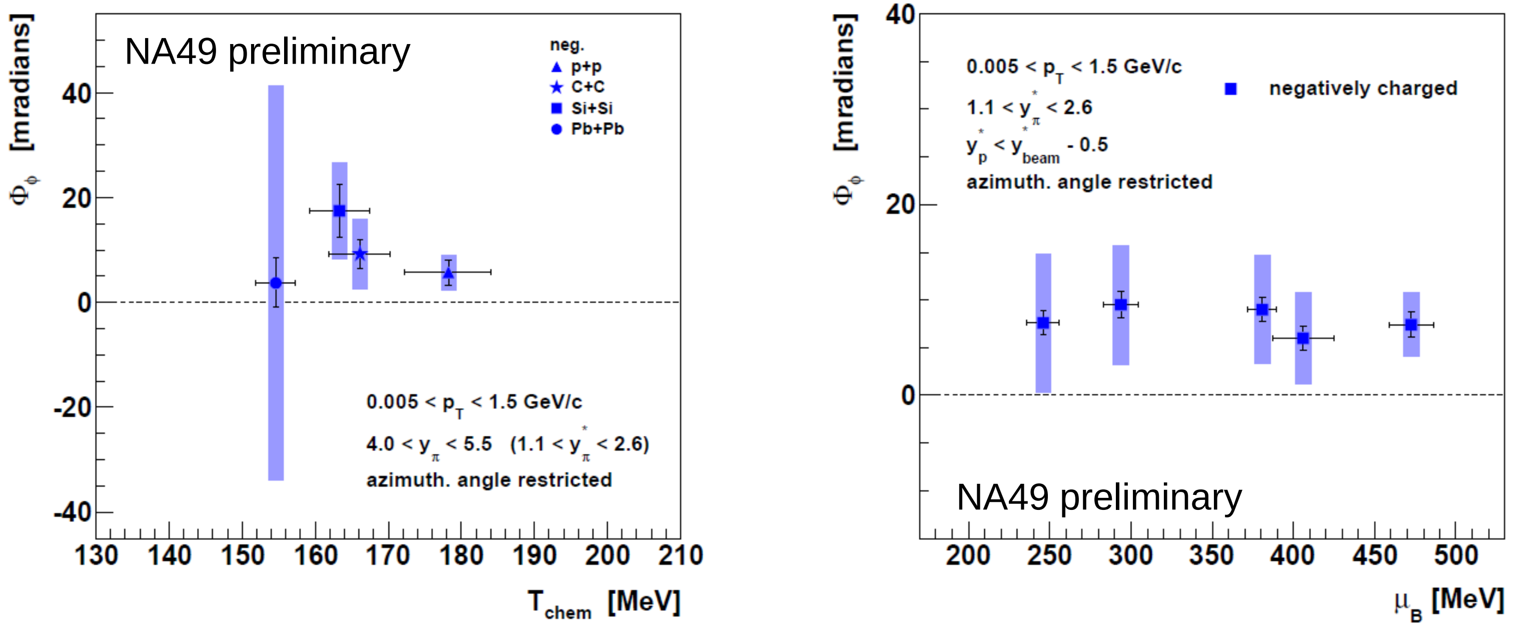
hint of peak at 158A GeV in
nuclear size (T) dependence ?

Φ_ϕ : fluctuations of average azimuthal angle

K.Grebieszkow, NA49 preliminary

- plasma instabilities (S.Mrowczynski, Phys.Lett. B314,118(1993))
- flow fluctuations (S.Mrowczynski,E.Shuryak,Act.Phys.Pol.B34,4241(2003))
- critical point

T,μ_B dependence in central collisions:



- no significant energy (μ_B) dependence in central Pb+Pb collisions
- perhaps hint of maximum in nuclear size (T) dependence

intermittency in particle production as signal of the critical point

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

- at the critical point local density fluctuations with power-law singularity 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 number (≈ protons)

- experimental observation via factorial moments in p_T space:
  (subdivided into M bins in $p_{T,x}$ and $p_{T,y}$)

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

predicted intermittency index at critical point: Φ_2 = 2/3, 5/6

- estimate combinatorial and misidentification background by mixed events and subtract

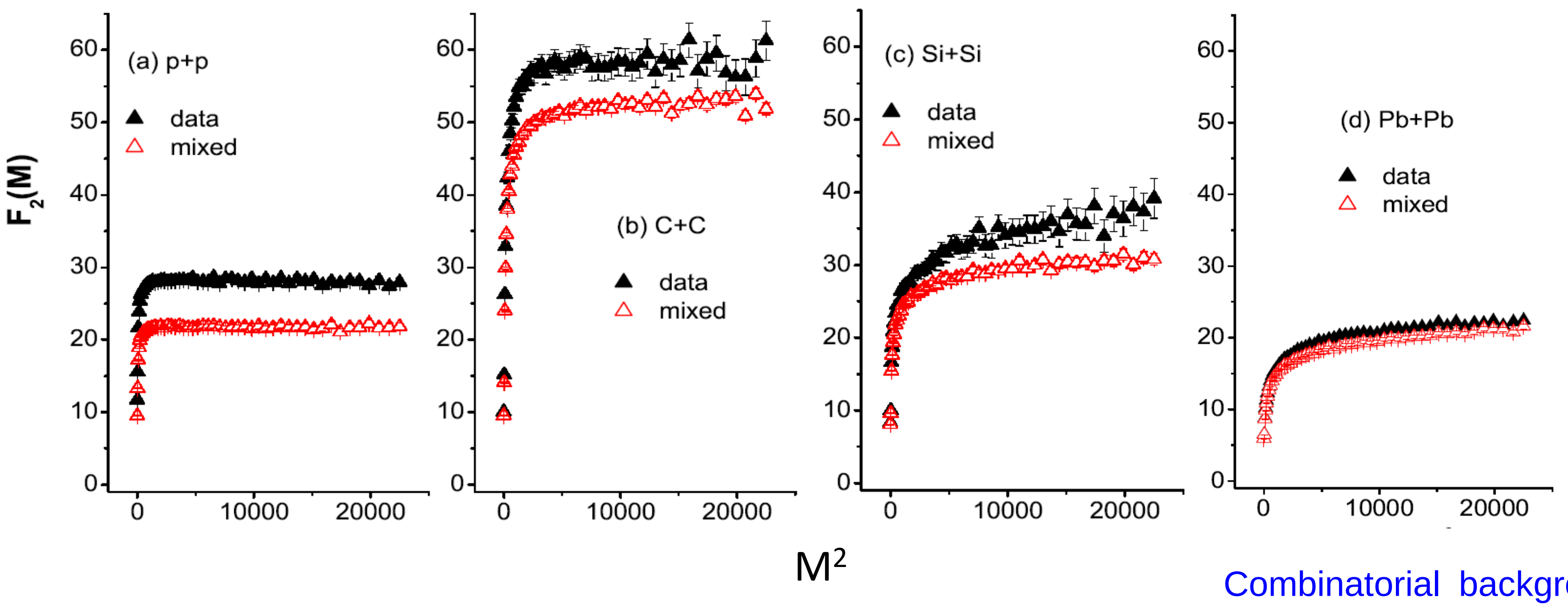
$$\Delta F_2(M) = F_2^{data} - F_2^{mix} \propto M^{2\Phi_2}$$

$\sigma \rightarrow \pi^+\pi^-$ intermittency analysis

- use $\pi^+\pi^-$ pairs near threshold to reduce combinatorial background
- exclude Coulomb correlation region at very small Q_{inv}

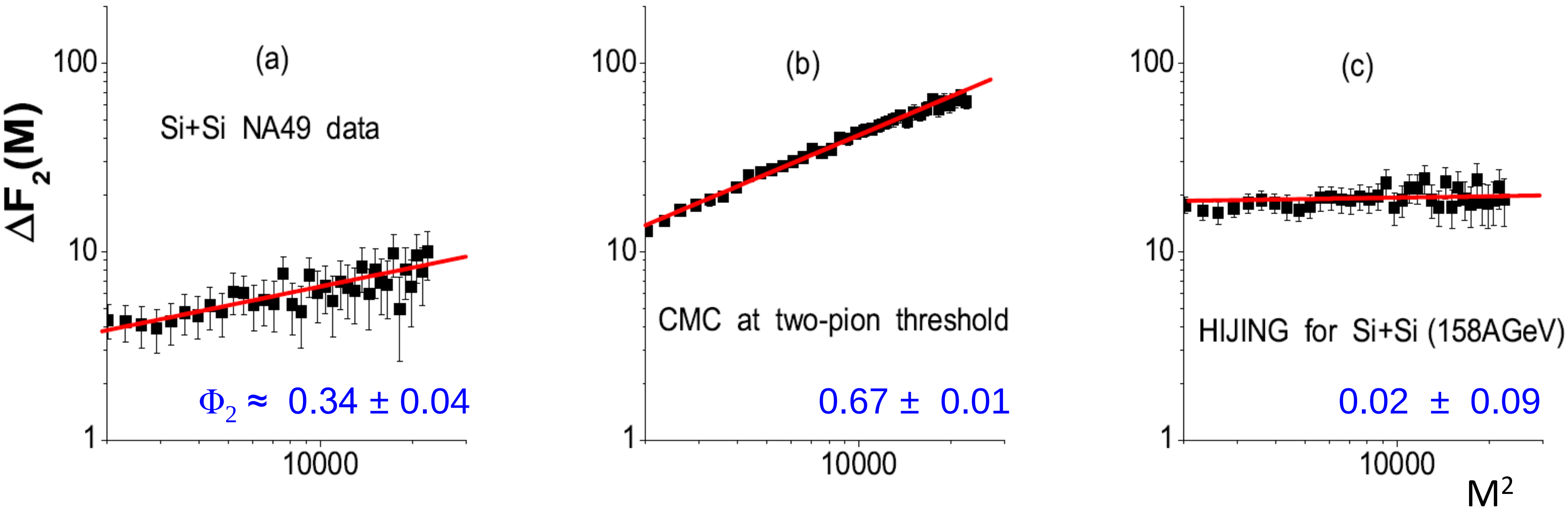
NA49 results for central collisions at 158A GeV:

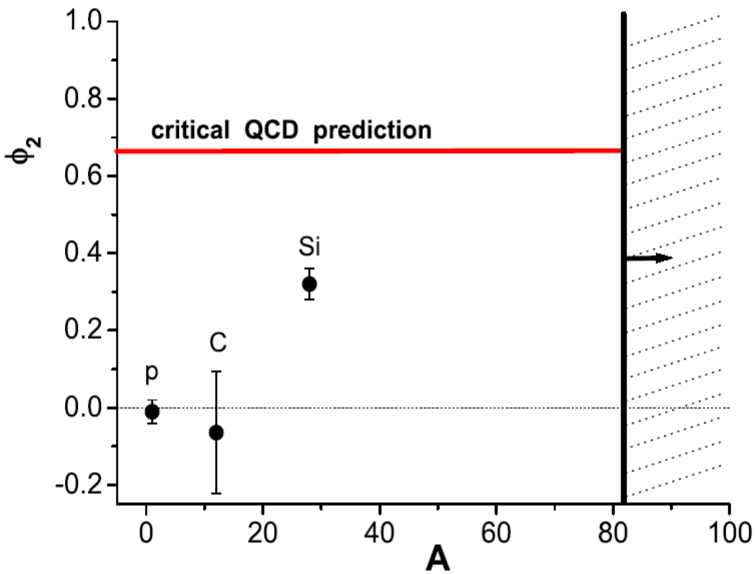
T.Anticic et al, PRC81,064907(2010)



Combinatorial background too large

NA49 results on factorial moment ΔF_2 in central Si+Si collisions



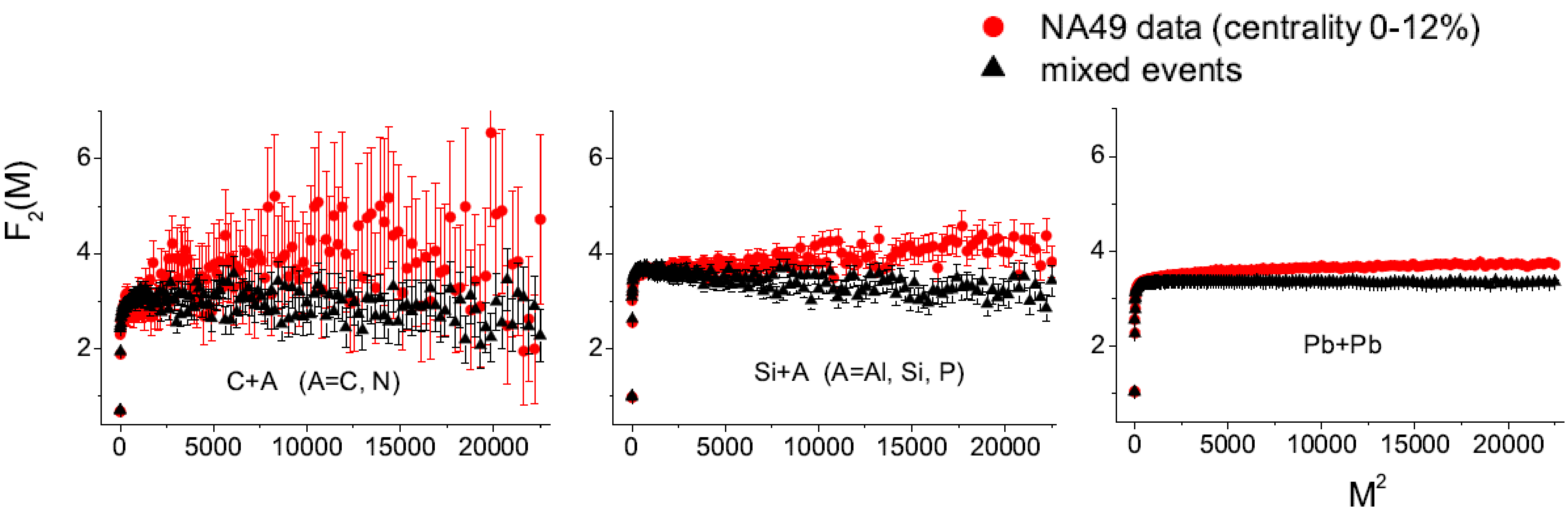


$\pi^+\pi^-$ intermittency seen in central Si+Si collisions at 158A GeV

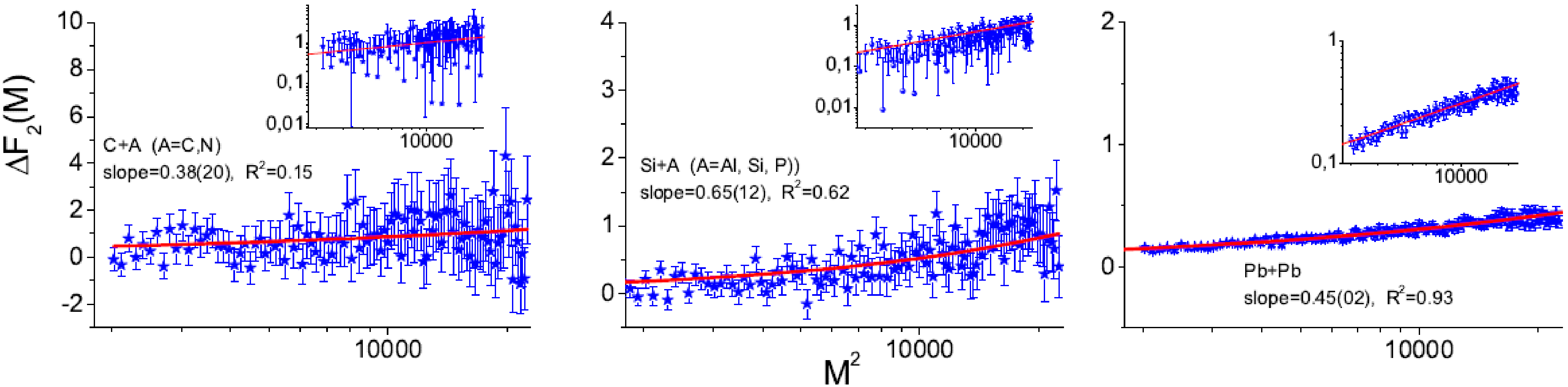
proton intermittency analysis (preliminary results)

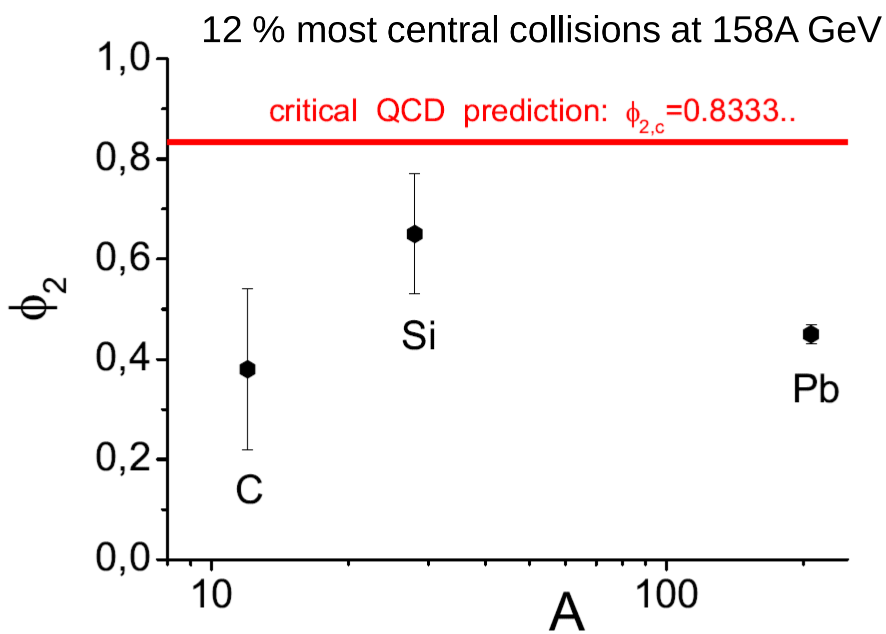
(N.Davis, Univ. of Athens)

- protons identified by dE/dx measured in the TPCs
- selection by cuts in dE/dx such that purity > 80 %
- cms rapidity $|y_{cms}| < 0.75$



preliminary results from proton intermittency analysis

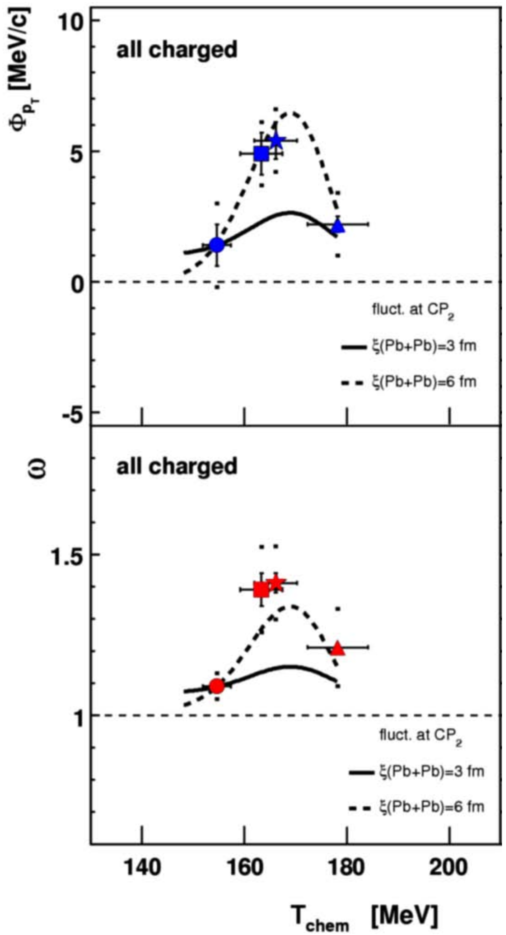




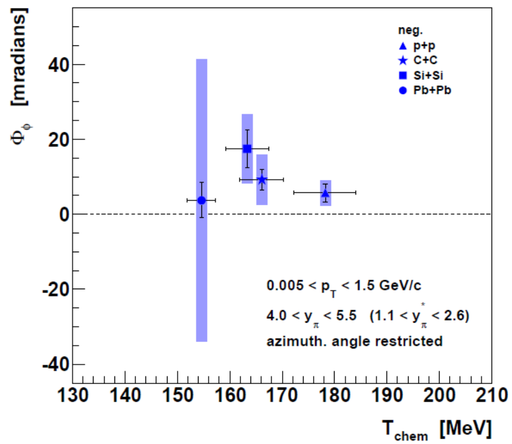
suggestive of maximum in
p intermittency for central
Si+Si collisions at 158A GeV

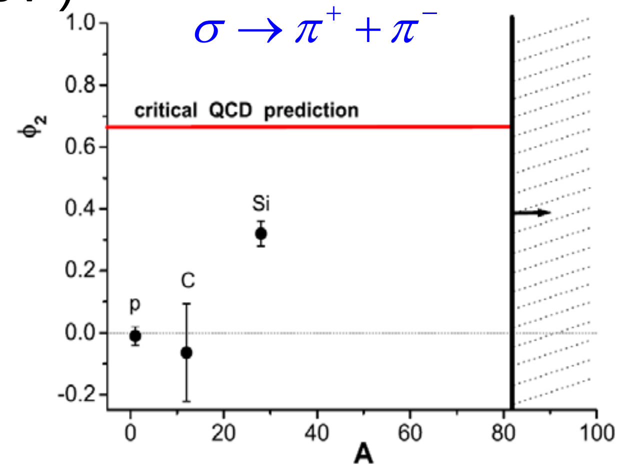
Conclusion from the critical point search in NA49

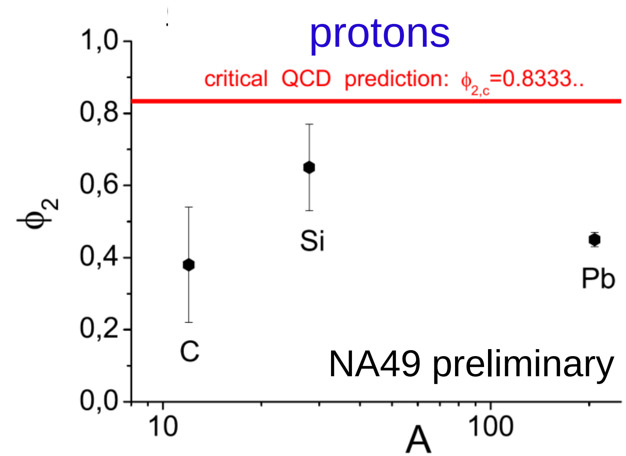
(central collisions at 158A GeV)



NA49 preliminary





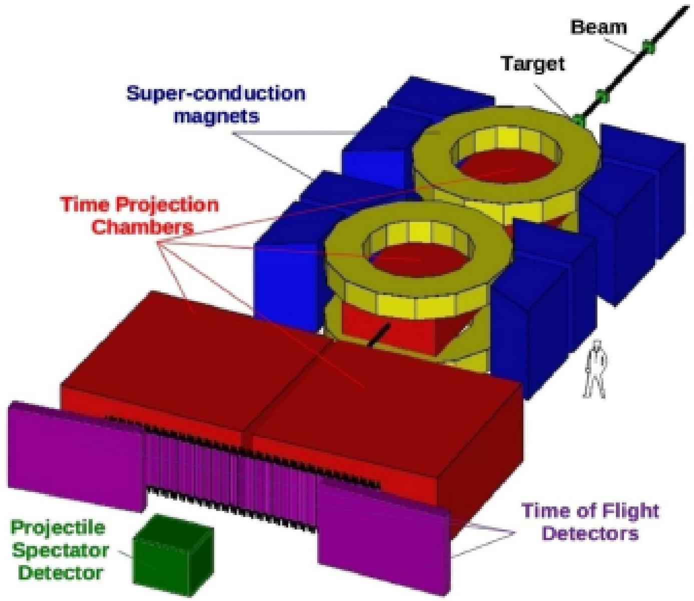


fluctuations of $<p_T>$, n_{ch}, $<\phi>$, intermittency of $\pi^+\pi^-$, p tend to a maximum in Si+Si collisions at 158A GeV

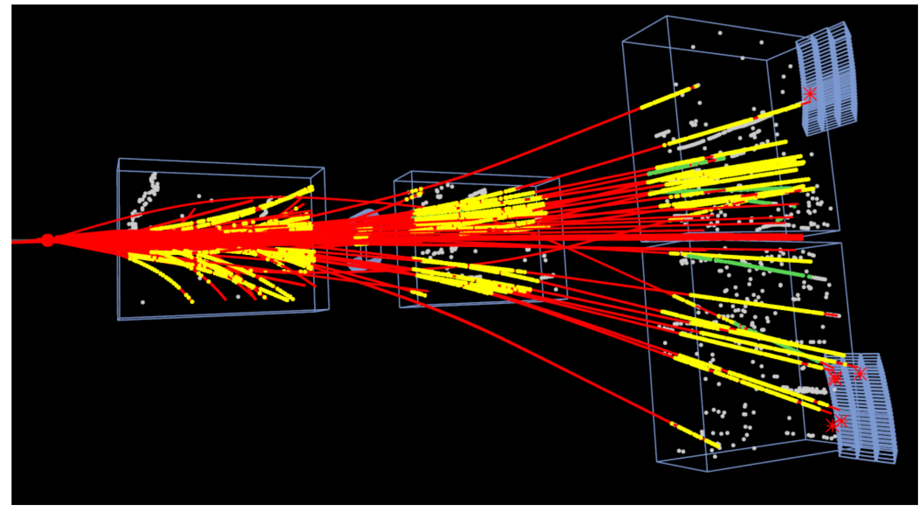
first hint of the hill of fluctuations ??

NA61/SHINE – successor and extension of NA49

(**SHINE – S**PS **H**eavy **I**on and **N**eutrino **E**xperiment)



^{7}Be + ^{9}Be interaction at 158A GeV

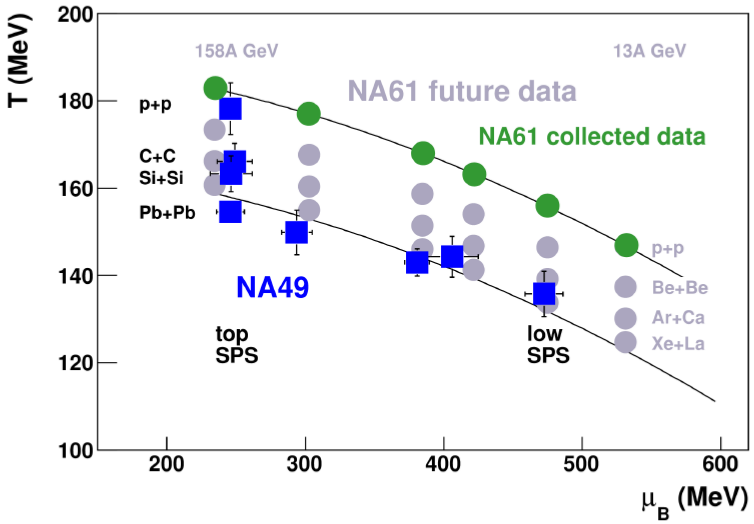


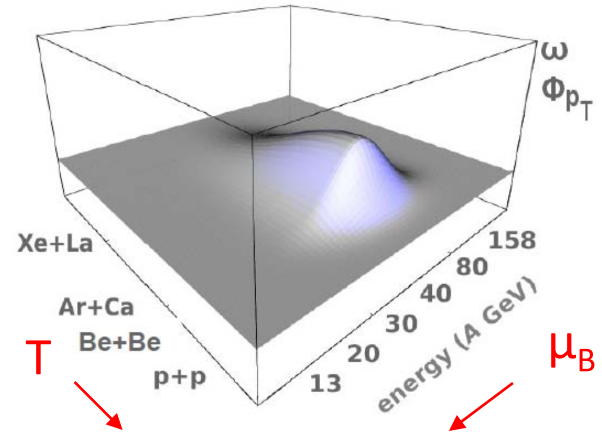
- upgraded NA49 detector (DAQ, TPC readout (x8), PSD, He filled beam pipe)
- study of the onset of deconfinement and search for the critical point
- precision particle production measurement for improving calculations of neutrino beam (T2K) and air shower properties (P. Auger Obs., KASKADE)
- study of nuclear modification factor and Cronin effect using p+p and p+Pb interactions with extended range in $p_T \leq 4.5$ GeV/c

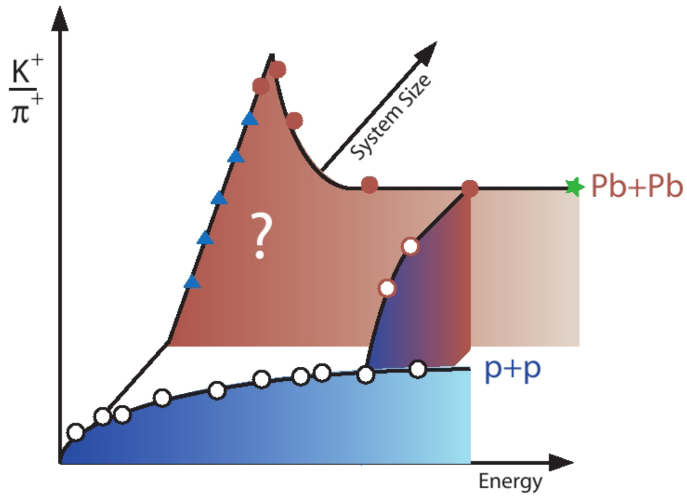
SHINE NA61

Ion physics program of NA61/SHINE: scan in energy and system size A

search for hill of fluctuations as signature of critical point

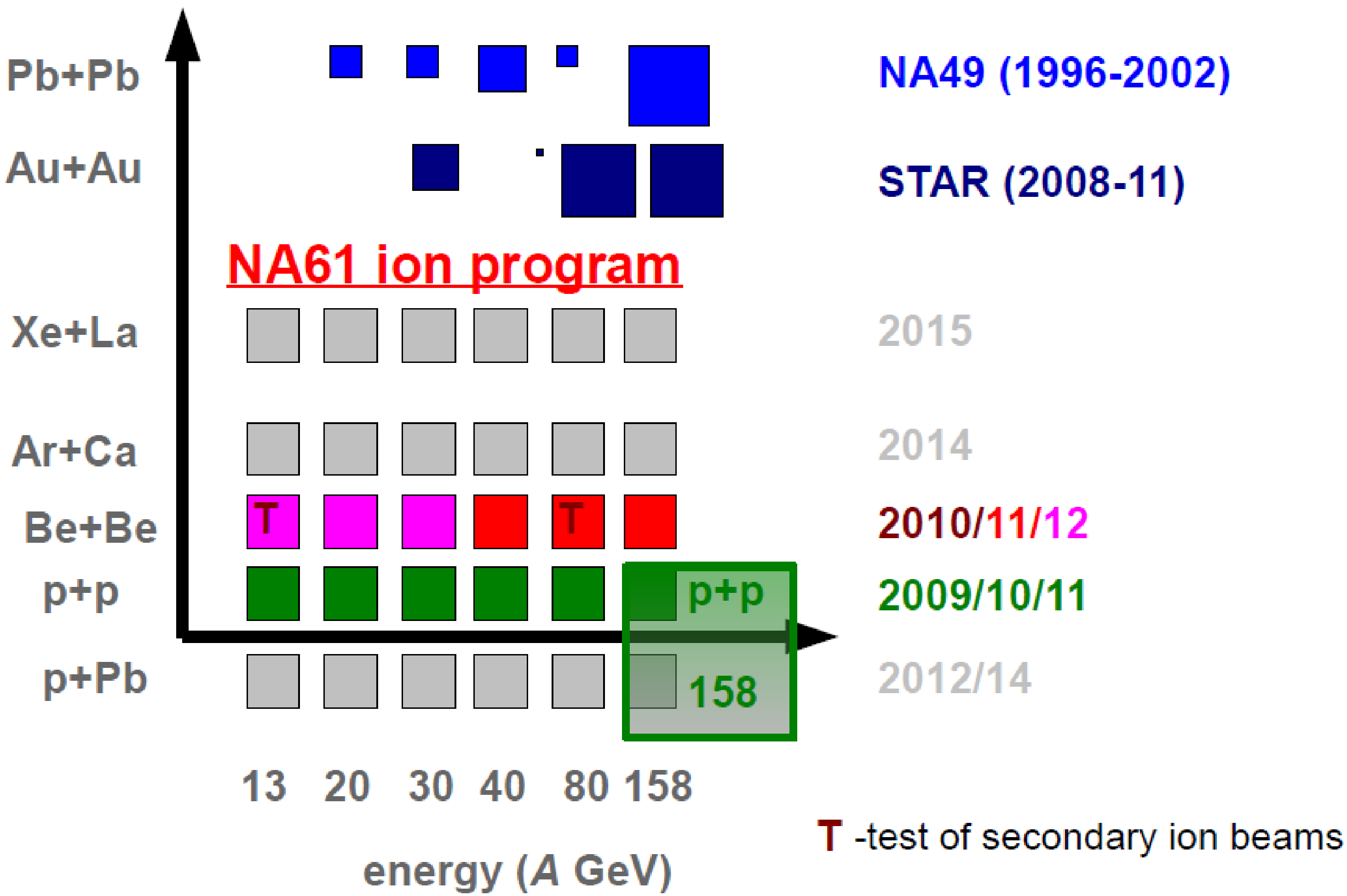




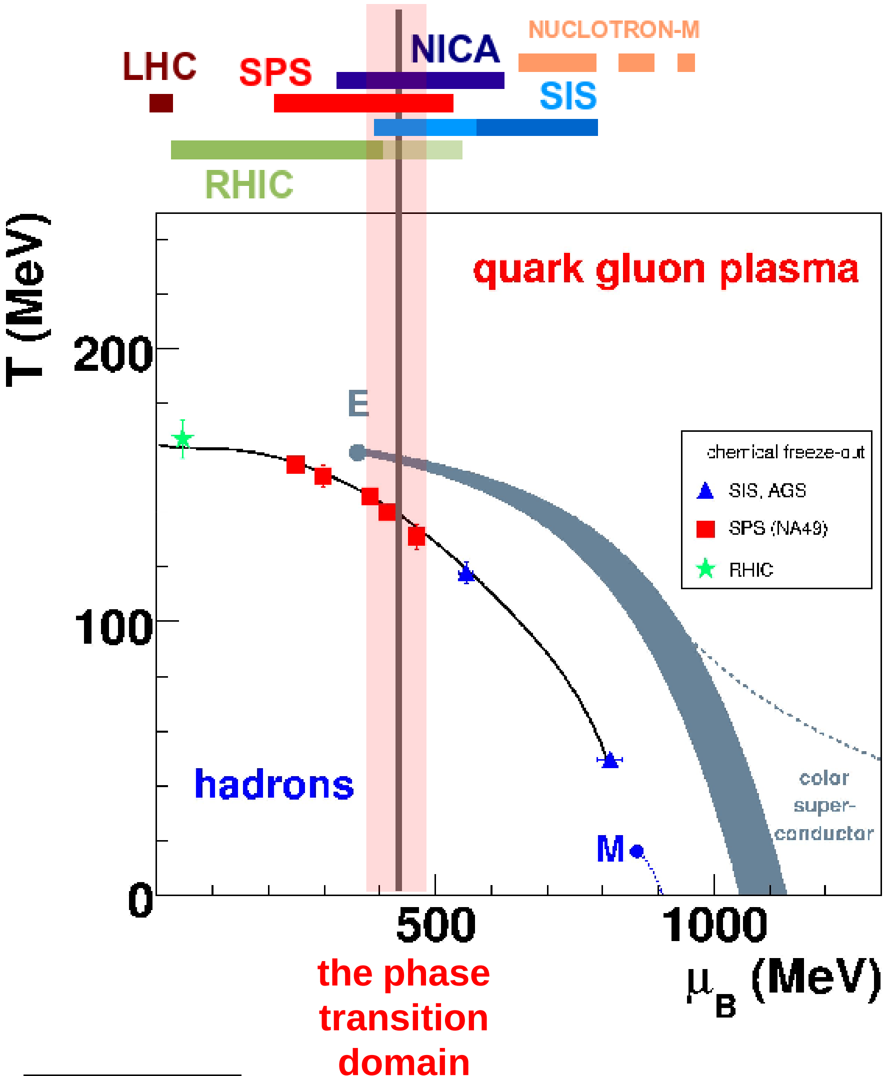


study onset of deconfinement: disappearance of horn etc.

Status and plans for ion collisions at SPS energies



QCD critical point searches – future experimental landscape



partly complementary programs

CERN SPS 2011 →
BNL RHIC 2010 →
DUBNA Nuclotron 2015
NICA 2017
GSI SIS-100 2017

<u>strong points of NA61:</u>

- tight constraint on spectators
- high event rate at all SPS energies
- flexibility to change A and energy
- overlap with AGS energy
- coverage of full forward hemisphere

<u>strong points of BNL/STAR:</u>

- full azimuthal acceptance
- acceptance |y|<1 at all energies
- excellent TOF identification
- low track density

SHINE NA61

Summary

- NA49 evidence for the onset of deconfinement at SPS energies – confirmed by STAR low energy scan at RHIC
- interpretation supported by LHC results
- critical point search of NA49 in the μ_B,T phase diagram hints at a maximum of fluctuations in Si+Si collisions at 158A GeV
- NA49 results provide strong motivation for NA61/SHINE to perform a systematic μ_B,T scan by varying energy and system size
- looking forward to:
  more STAR results from the RHIC low energy scan
  and the future programs at the Nuclotron, NICA and SIS

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

$\Phi_{p_T}^{(3)}$: 3rd moment of <p_T> fluctuations

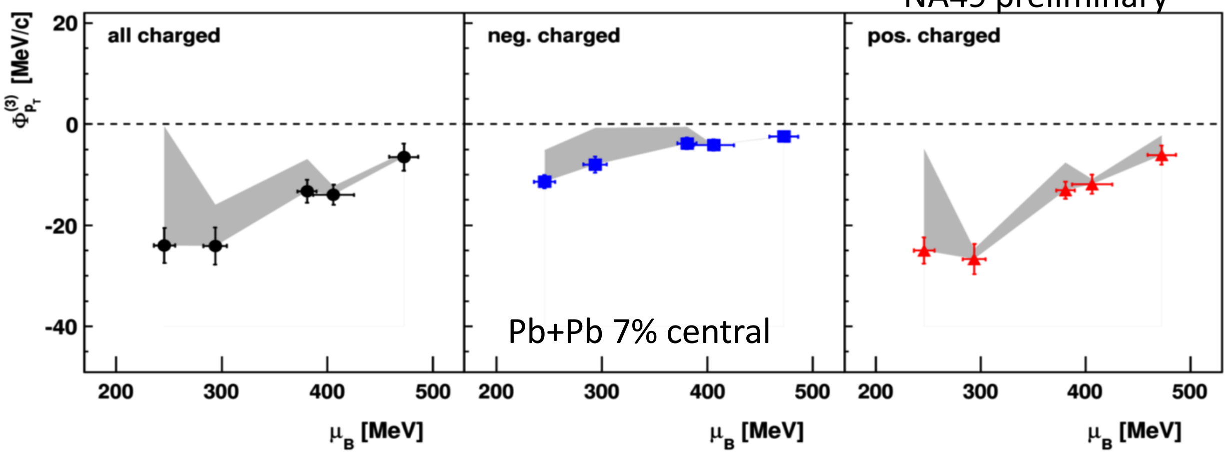
K.Grebieszkow and M.Bogusz, NA49 preliminary

$$\Phi_{p_T}^{(n)} = \left(\frac{\langle Z_{p_T}^2 \rangle}{\langle N \rangle} \right)^{1/n} - \left(\overline{z_{p_T}^{n}} \right)^{1/n}$$

$\Phi_{p_T}^{(3)}$ has strongly intensive property like Φ_{p_T}

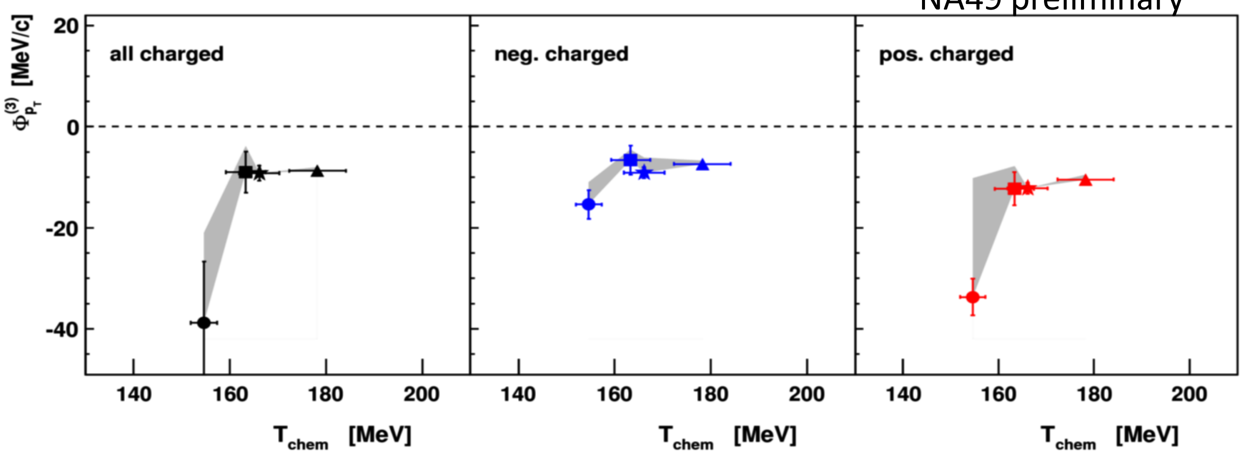
(S.Mrowczynski,Phys.Lett.B465,8(1999))

NA49 preliminary



higher moments are expected to be more sensitive to fluctuations

NA49 preliminary



systematic errors are large

no theoretical predictions yet

Landscape of experimental program on nucleus-nucleus reactions

Facility	SPS	RHIC	NUCLOTRON-M	NICA	SIS-100/300	LHC
Laboratory	CERN Geneva	BNL Brookhaven	JINR Dubna	JINR Dubna	FAIR GSI Darmstadt	CERN Geneva
Experiment	NA61/SHINE	STAR PHENIX	BM@N	MPD	HADES + CBM CBM	ALICE ATLAS CMS
Start of data taking	2009(11)	2010	2015	2017	2017/18 (2019/20)	2009
cms energy [GeV/(N+N)]	5.1 – 17.3	7.7 (5?) – 200	< ~ 3.5	4 – 11	2.3 – ~4.5 ~4.5 – ~8.5	up to 5500 14000 (p+p)
Physics	CP & OD	CP & OD	HDM	OD & HDM	HDM, OD & CP	PDM