# EXPLORING THE STRUCTURE OF STRONGLY INTERACTING MATTER WITH FLUCTUATION SIGNALS

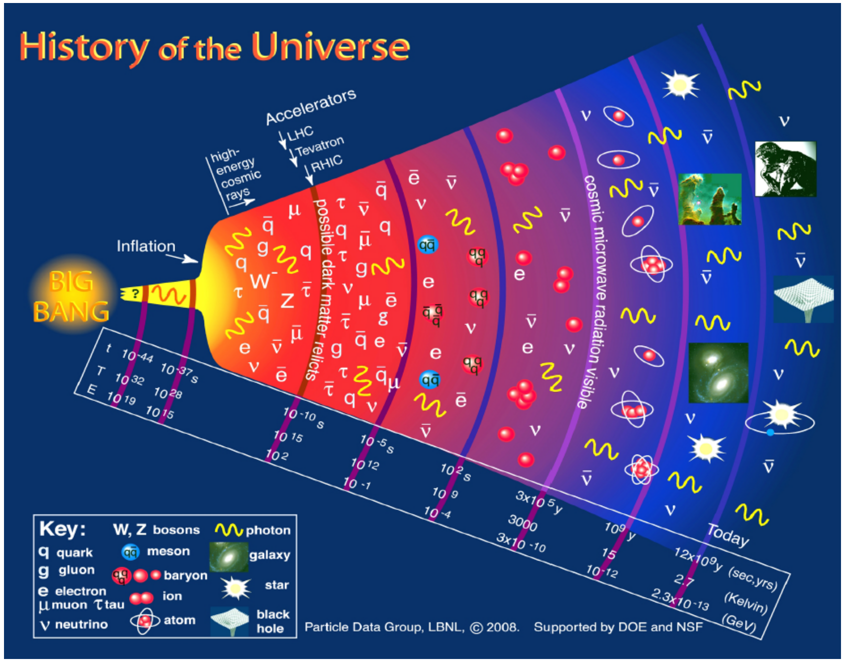


Anar Rustamov
a.rustamov@cern.ch

Universität Heidelberg & GSI

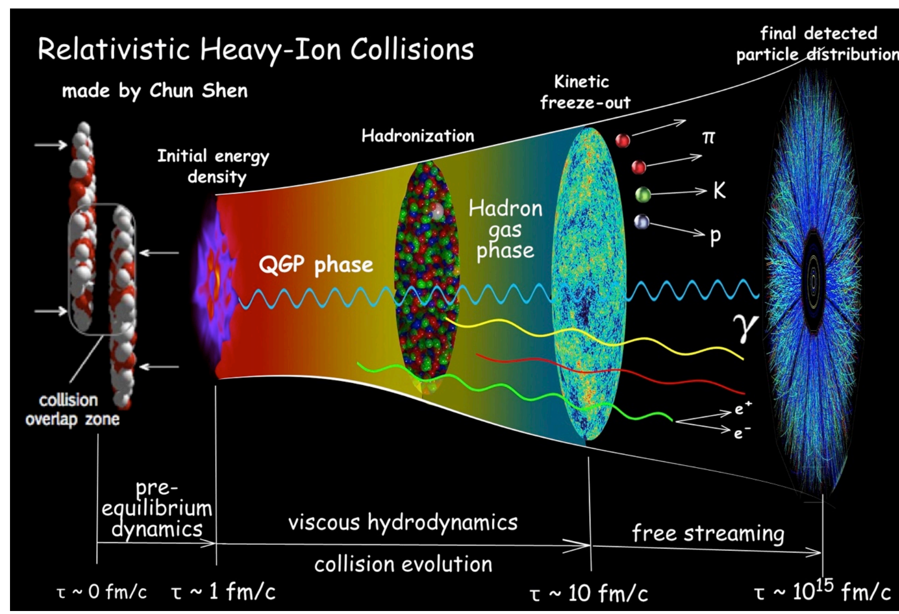
- Phase transitions
- E-by-E fluctuations
  - Net-charge fluctuations
  - Chemical fluctuations
  - Experimental results
- Summary

# Phase transitions

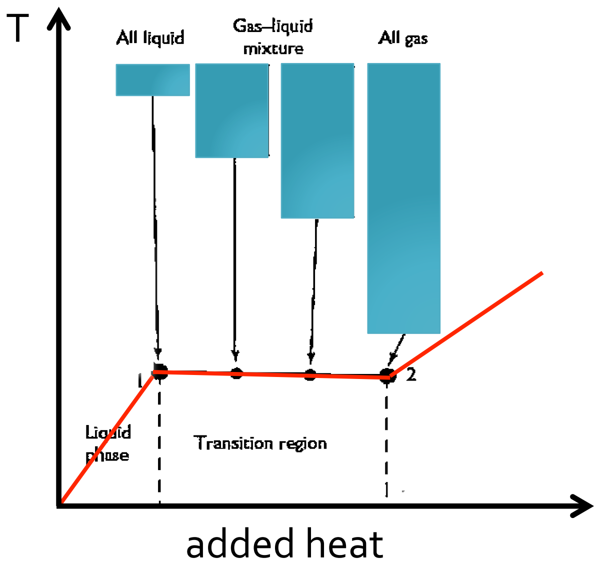


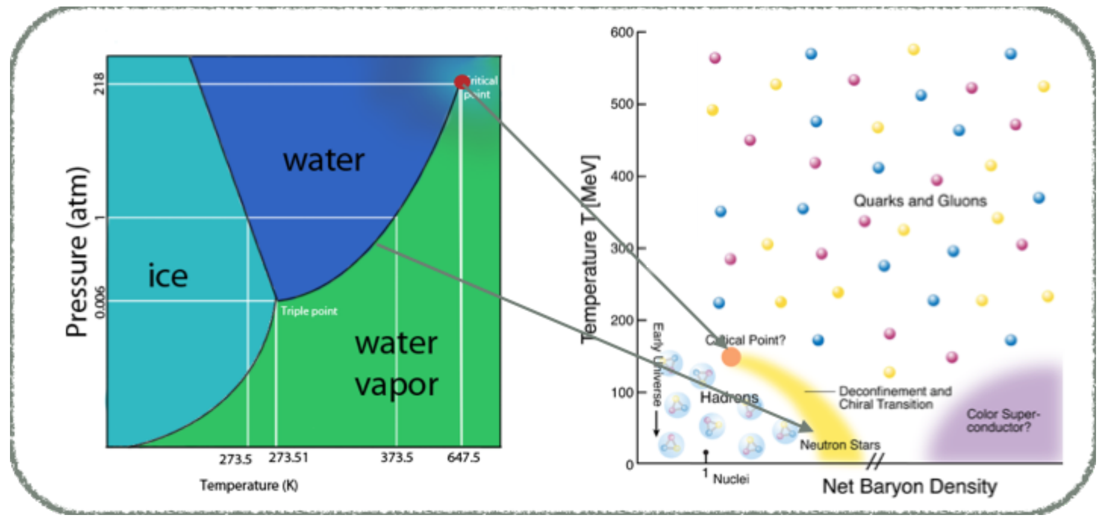

1/100.000 seconds after the Big Bang
quarks and gluons recombine to hadrons

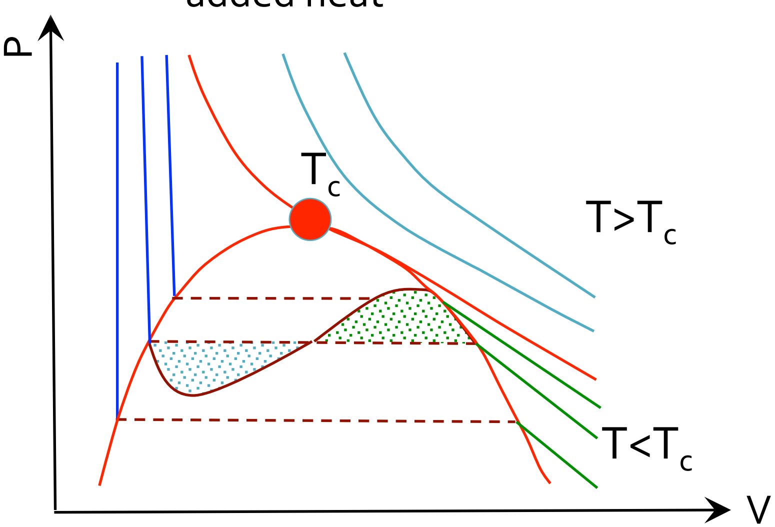
recreating that stage in laboratories



# Critical phenomena



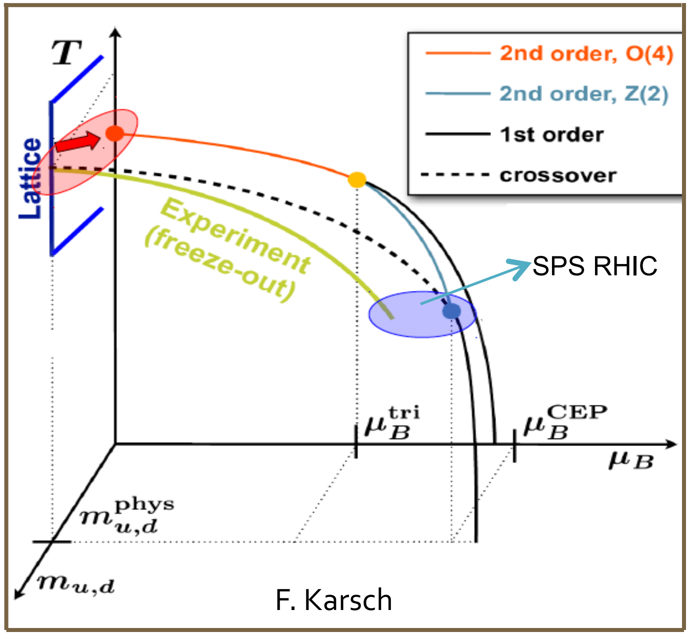



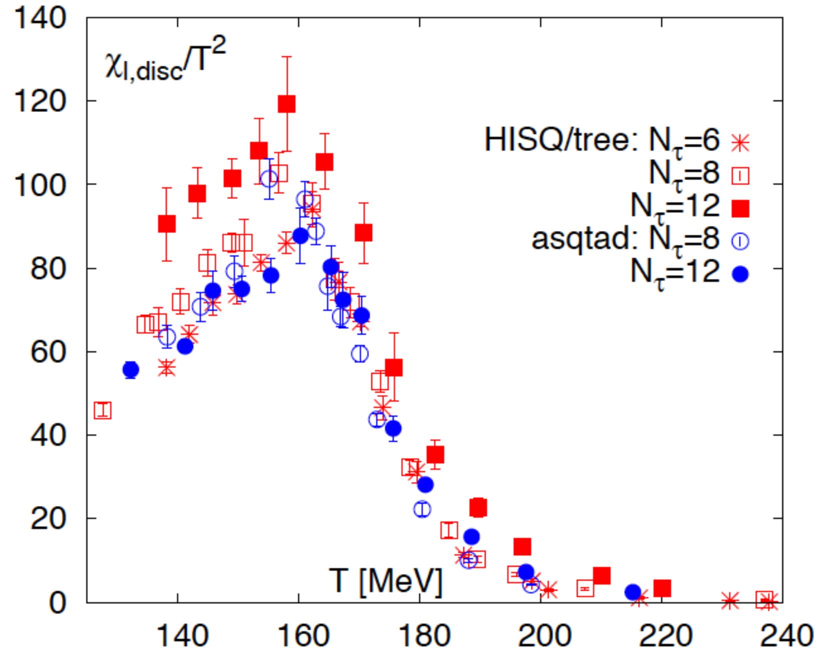

$$\frac{\left\langle \left(N-\langle N\rangle\right)^2\right\rangle}{\langle N\rangle^2}=\frac{Tk_T}{V} \qquad k_T=-\frac{1}{V\left(-\partial P/\partial V\right)}$$

compressibility

- Interactions are important for phase transitions
- Large fluctuations close to the critical point

# Current status, pseudo critical point



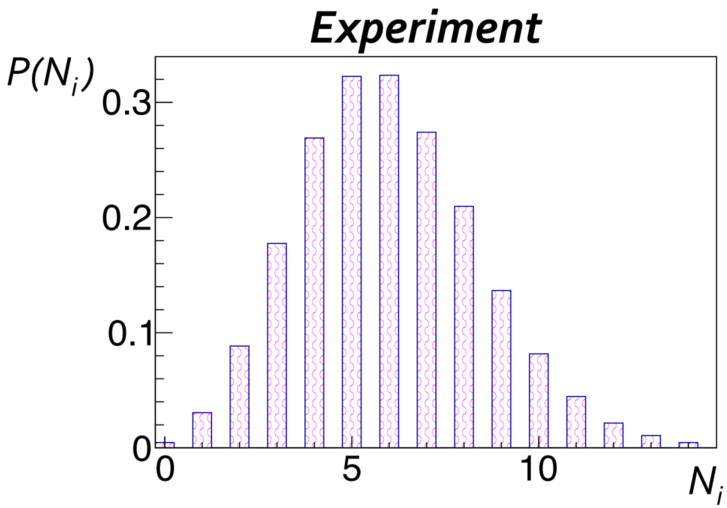

A. Bazavov et al., Phys.Rev. D85 (2012) 054503

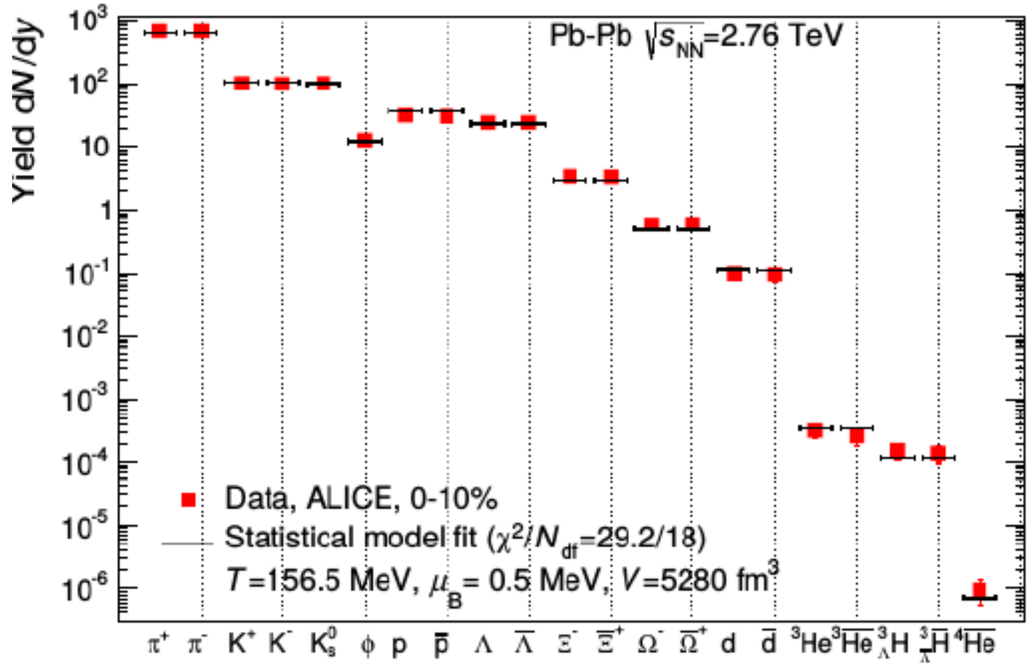
***freeze-out at the phase boundary!***

$$T_c^{lattice} = 154 \pm 9\ MeV, \quad T_{fo}^{ALICE} = 156 \pm 3 MeV$$

- ***E-by-E fluctuations:***
  - To study dynamics of the phase transitions
  - To locate phase boundaries

# Phase boundaries from first moments




$$\langle N_i \rangle = V \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp\left[\left(E_i - \mu_i\right)/T\right] \pm 1}$$

$$\mu_i = \mu_B B_i + \mu_s S_i + \mu_I I_i$$

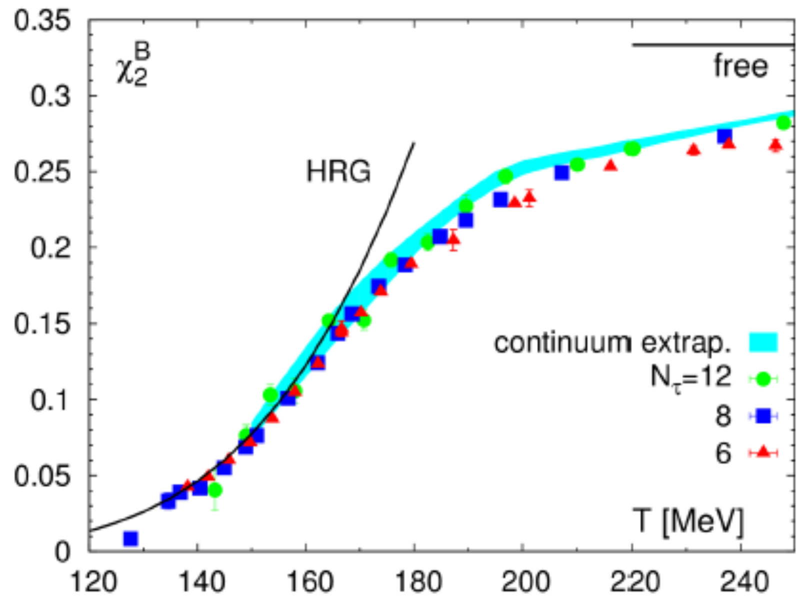
$$\chi^2 = \sum_{k=1}^{n} \frac{\left(\langle N_k^{\exp} \rangle - \langle N_k^{HRG} \rangle\right)^2}{\sigma_k^2}$$

ALICE, PLB 726 (2013) 610

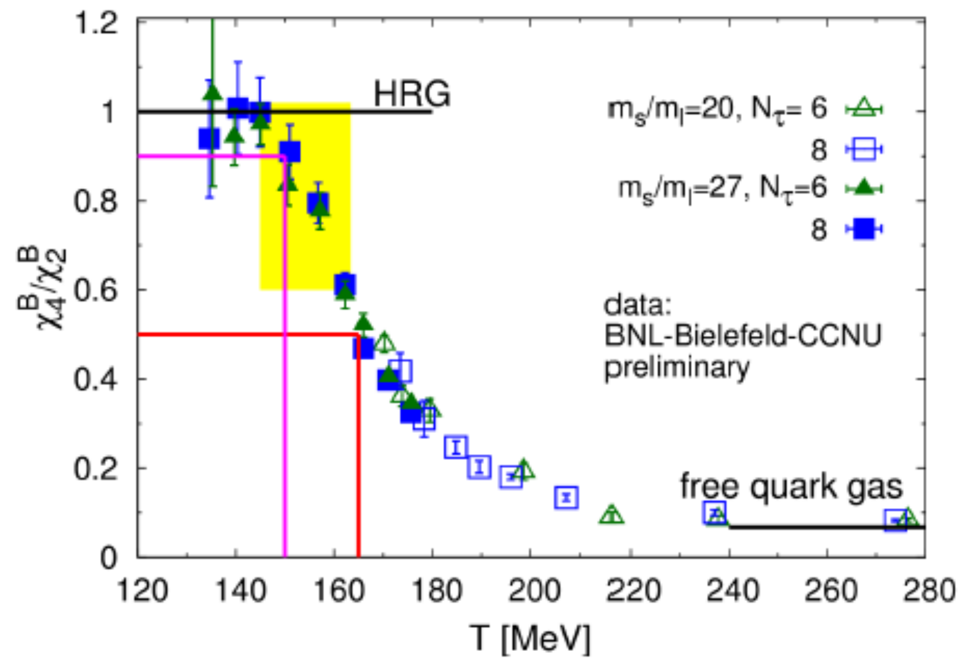
J. Stachel, A. Andronic, P. Braun-Munzinger and K. Redlich
J. Phys. Conf. Ser. 509 (2014) 012019

***works in the energy range spanning by 3 orders of magnitude! y axis: 9 orders of magnitude!***

# LQCD calculations




Consistent with HRG results

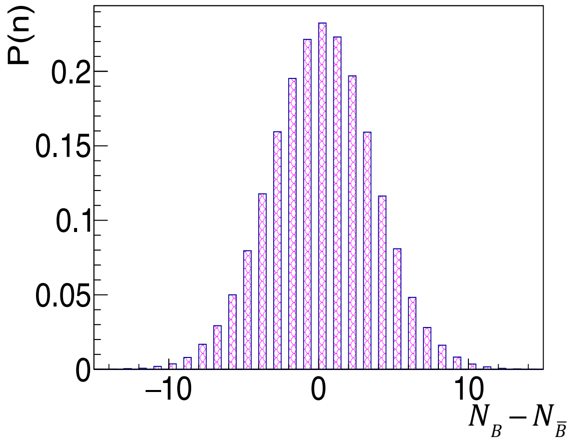



Deviations are visible

F. Karsch, CPOD 2016

How to compare to experimental results?

# Exploring the structure of matter




reconstructing cumulants of this distribution

$$\Delta N = N_B - N_{\bar{B}}$$

$$c_2(\Delta N) = \left\langle \left(\Delta N - \langle \Delta N \rangle\right)^2 \right\rangle$$

$$c_3(\Delta N) = \left\langle \left(\Delta N - \langle \Delta N \rangle\right)^3 \right\rangle$$

$$c_4(\Delta N) = \left\langle \left(\Delta N - \langle \Delta N \rangle\right)^4 \right\rangle - 3c_2^2$$

$$\hat{\chi}_n^{N=B,S,Q} = \frac{\partial^n P/T^4}{\partial\left(\mu_N/T\right)^n} \qquad \frac{P}{T^4} = \frac{1}{VT^3}\ln Z\left(V,T,\mu_{B,Q,S}\right)$$

$$VT^3\,\hat{\chi}_2^N = \left\langle \left(\Delta N\right)^2 \right\rangle - \left\langle \Delta N \right\rangle^2 \equiv c_2(\Delta N)$$

$$\frac{c_4(\Delta N)}{c_2(\Delta N)} \equiv k\sigma^2 = \frac{\hat{\chi}_4^N}{\hat{\chi}_2^N} \qquad \frac{c_3(\Delta N)}{c_2(\Delta N)} \equiv S\sigma = \frac{\hat{\chi}_3^N}{\hat{\chi}_2^N}$$

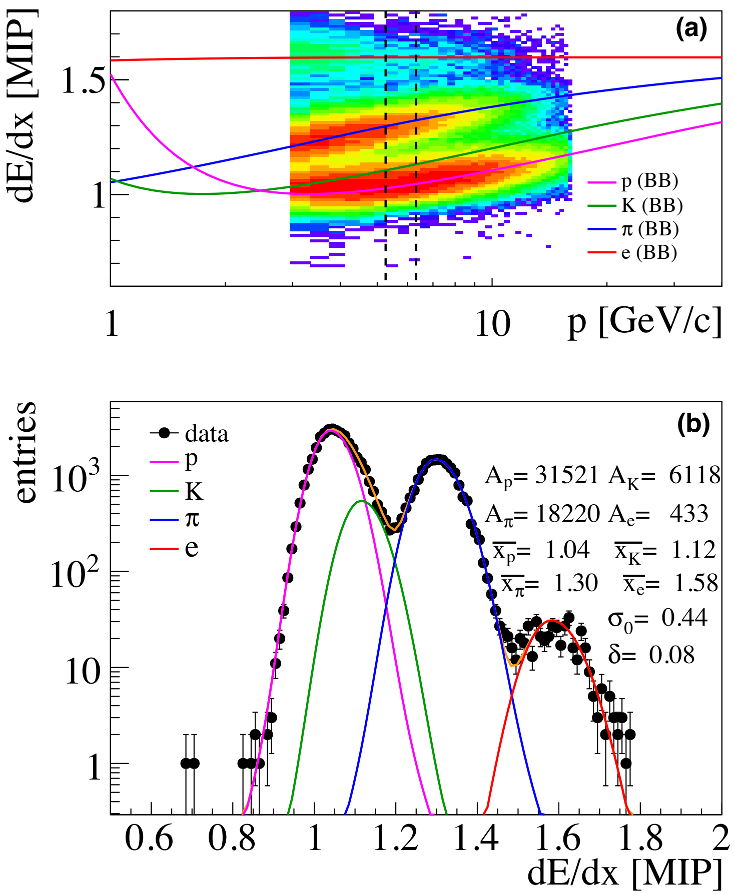
Centrality determination is crucial!

- ***Assumptions:***
  - *Volume is fixed in each event*
  - *Conservations are imposed on the averages*

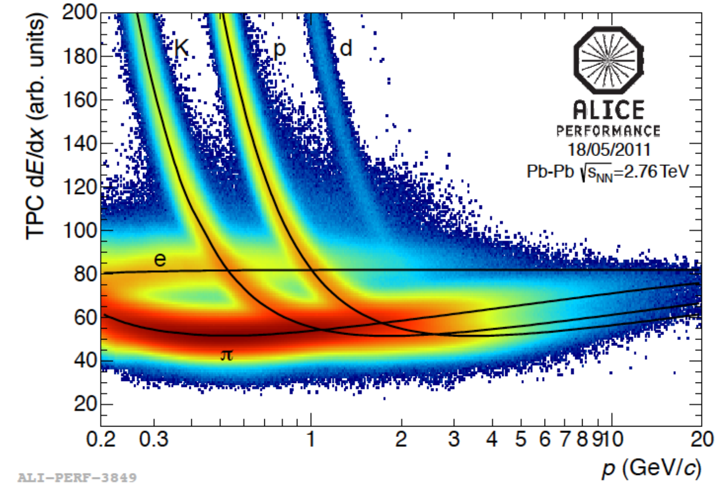
correlation term matters

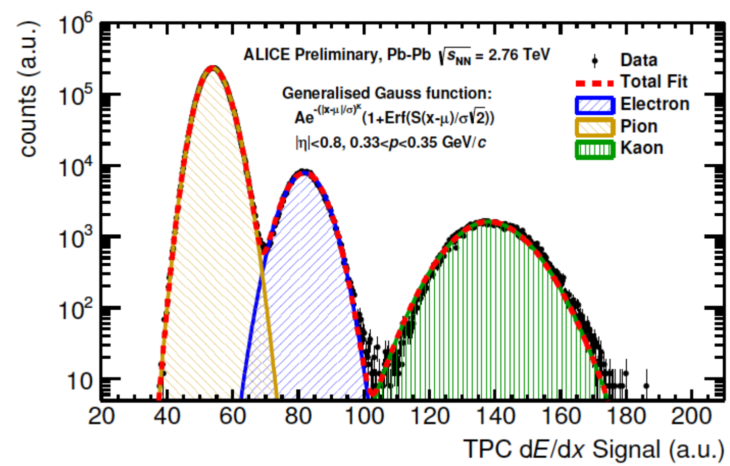
$$c_2(\Delta N) = c_2(N_B) + c_2(N_{\bar{B}}) - 2\left(\langle N_B N_{\bar{B}}\rangle - \langle N_B\rangle\langle N_{\bar{B}}\rangle\right)$$

# PID examples




NA49: Phys.Rev. C89 (2014) no.5, 054902



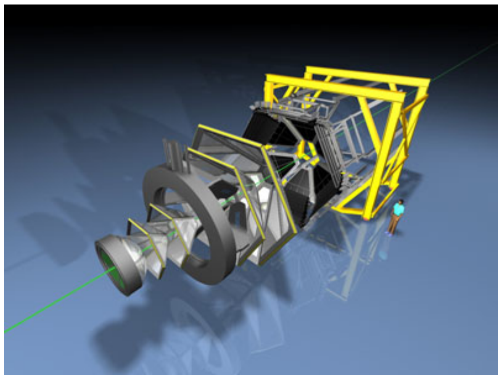




ALICE: Int.J.Mod.Phys. A29 (2014) 1430044

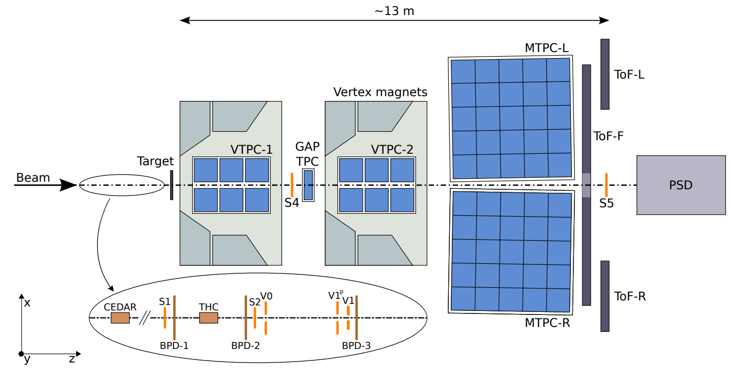
M. Arslandok, QM2015

# Probing the matter in a wide energy range

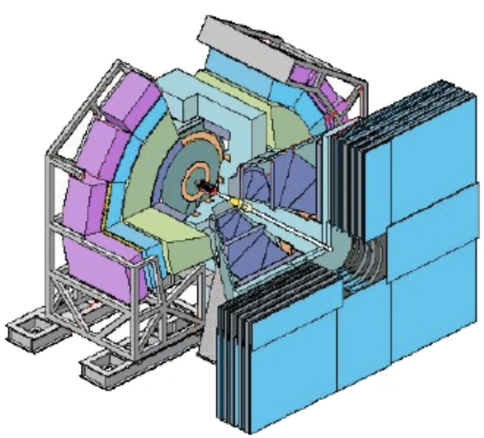
## HADES (few GeV)



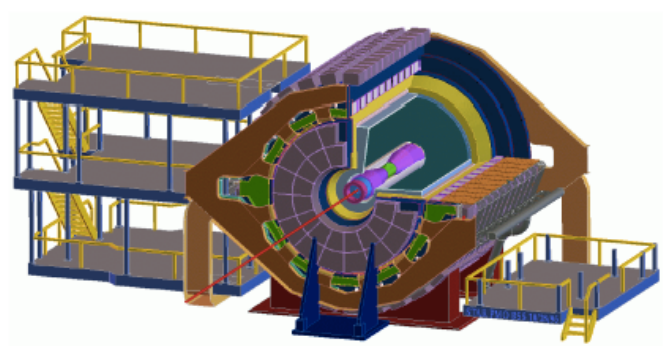
## NA61/SHINE (5- 17 GeV)



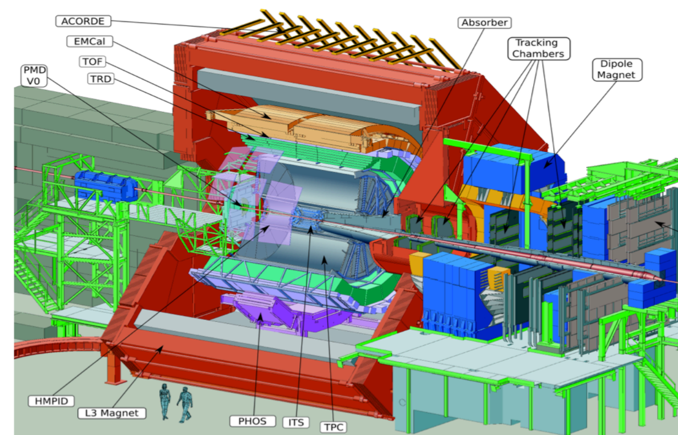

## PHENIX (7.7- 62.4 GeV)



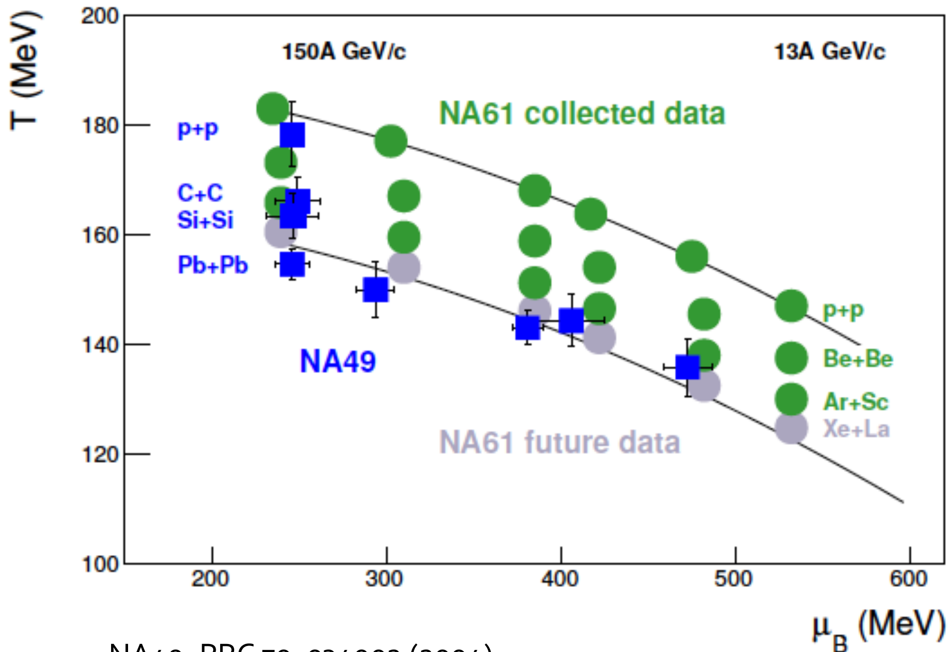
## STAR (7.7- 62.4 GeV)



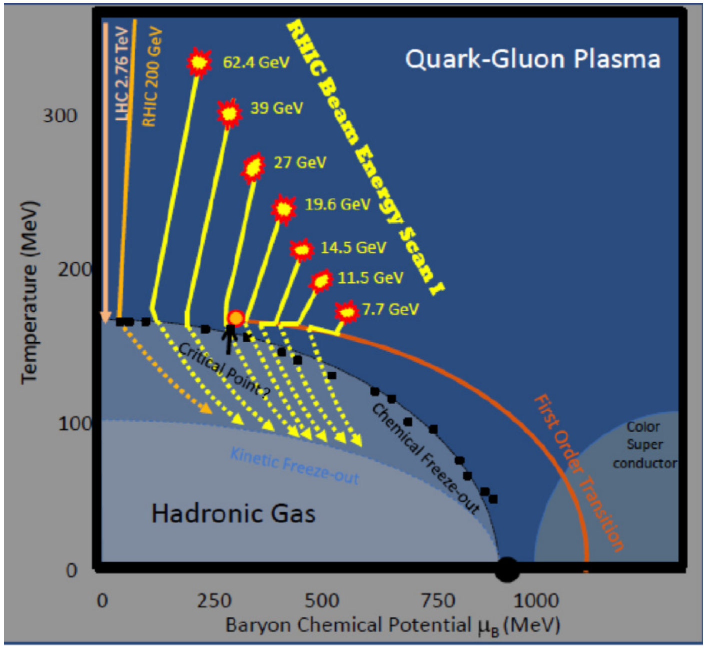
## ALICE (few TeV)



# Dedicated Beam energy scan programs



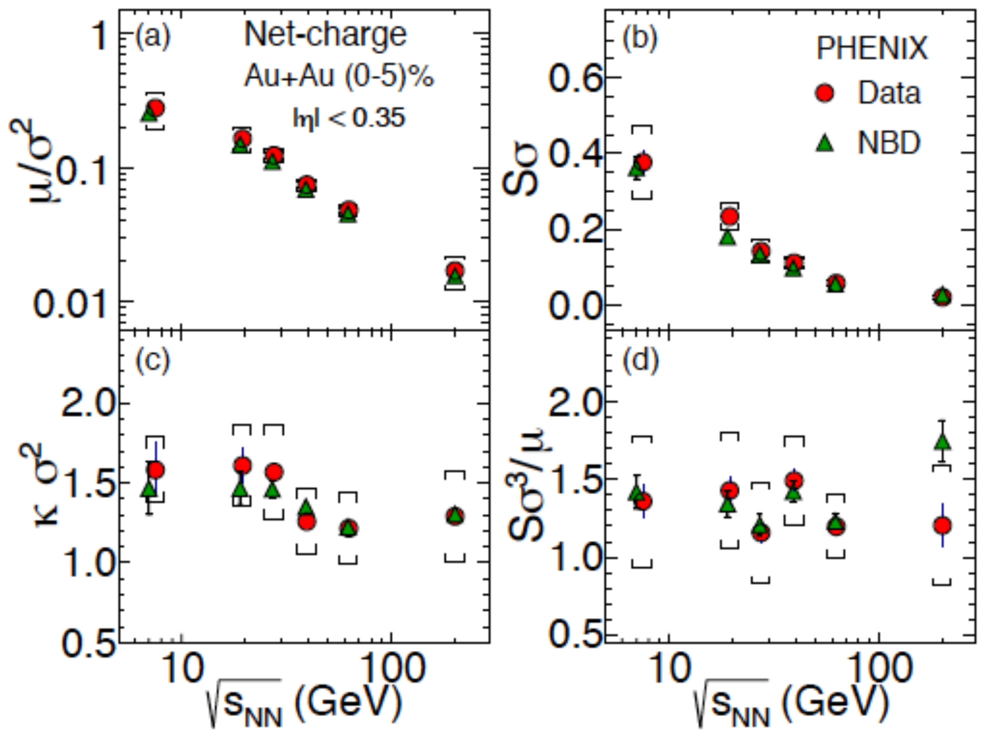

NA49: PRC 70, 034902 (2004)
NA61: Predicted based on PRC 73, 044905 (2006)




- Onset of deconfinement
- Search for the critical point
- Locating phase boundaries

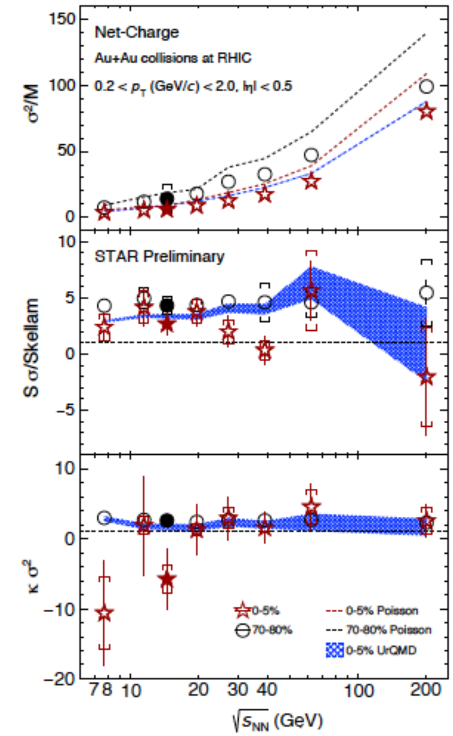
# Net-charge

PHENIX




PRC93 (2016) 011901(R)

STAR




PRL 112 32302 (2014) + QM15

No direct comparison due to different acceptances

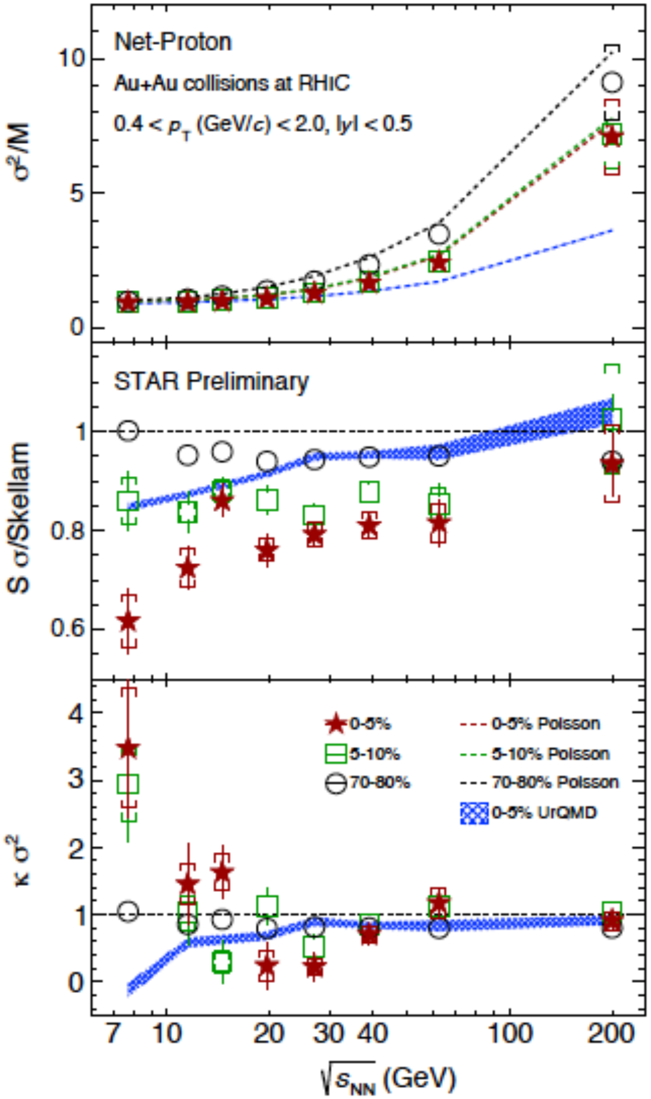
Data matches with the difference of two Negative Binomial densities fitted to the single multiplicity distributions

Consistent with the Skellam Baseline

Larger error bars for $k\sigma^2$

# Net-proton

PRL 112 32302 (2014) + QM15



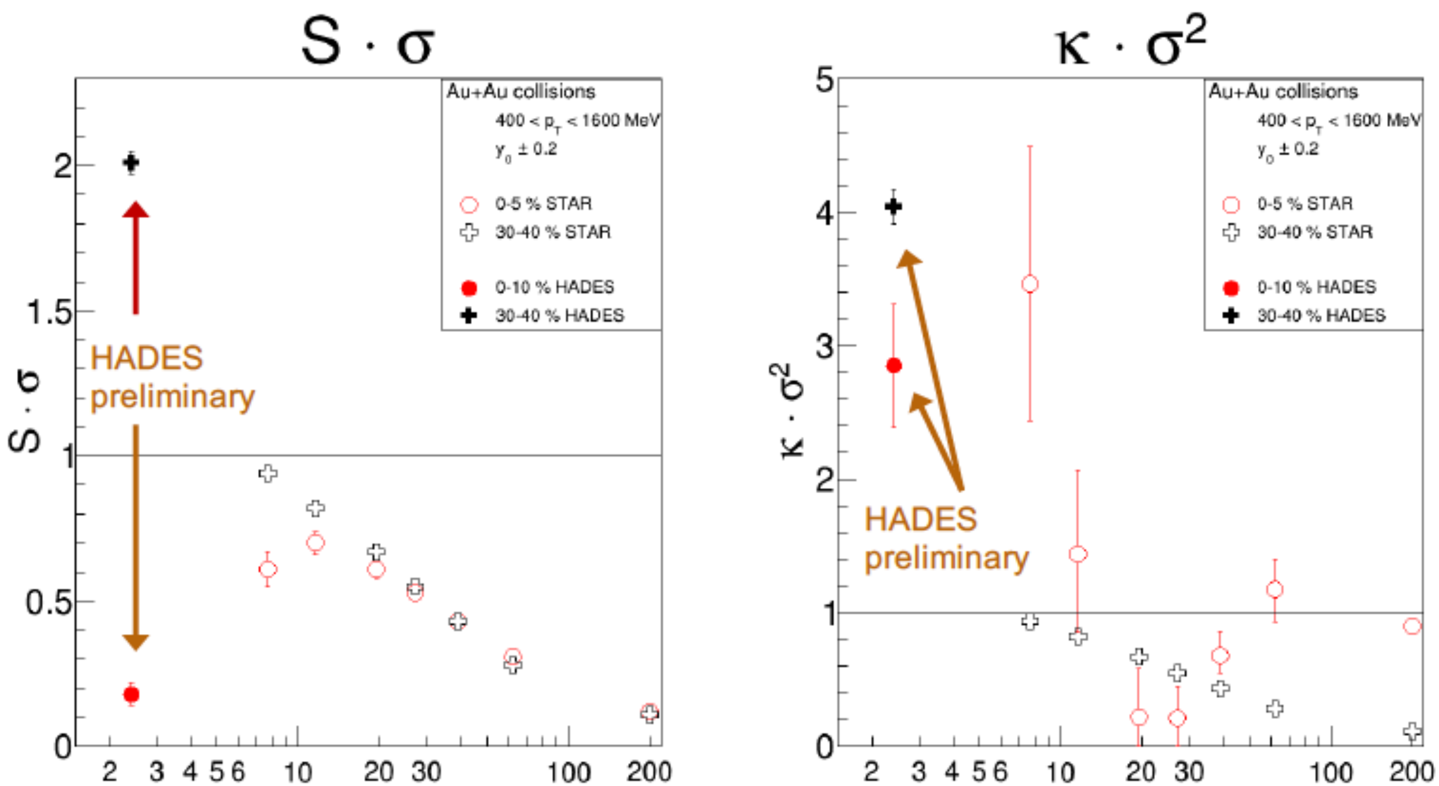

Non-monotonic behavior for third and fourth cumulants!

In this connected to the critical point?

Can these results be directly compared with HRG and or LQCD results?

How to interpret consistencies and/or deviations?

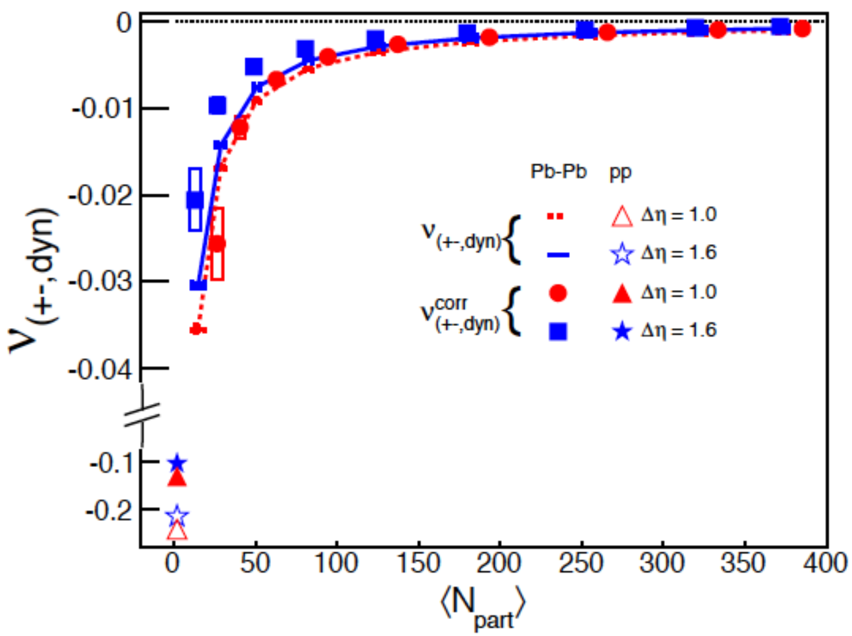
# Excitation functions

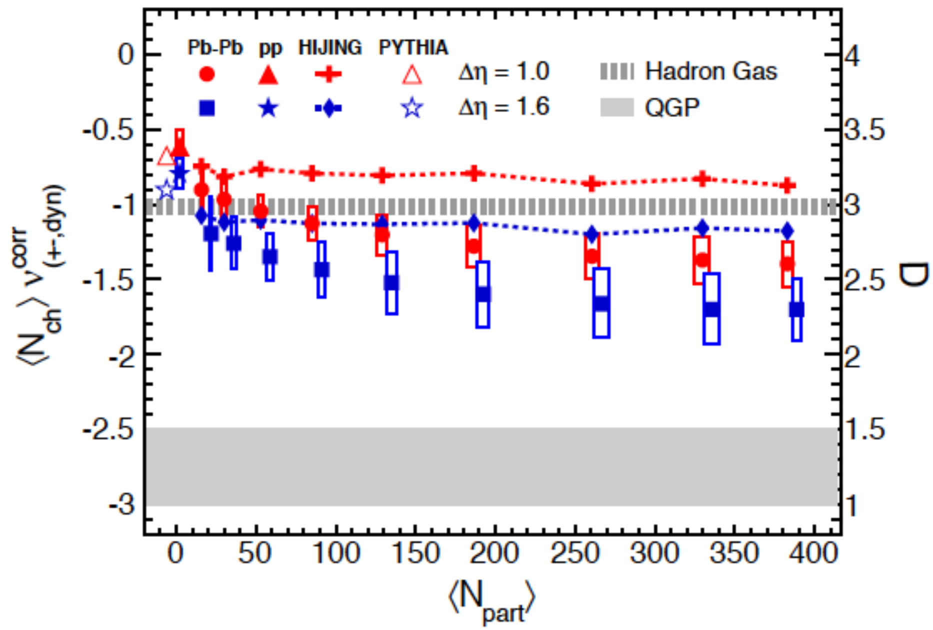



- How to interpret energy dependence?
  - Baryon number conservation is not corrected for
  - Volume fluctuations are not accounted for
  - Isospin effects are important at lower energies

R. Holzmann, SQM 2016

# ALICE RESULTS




ALICE: Phys.Rev.Lett. 110 (2013) no.15, 152301

$$\langle N_{ch} \rangle = \langle N_- + N_+ \rangle, \quad \Delta N = N_+ - N_-$$

$$\langle N_{ch} \rangle \nu_{(+-,dyn)} \xrightarrow{\langle N_+ \rangle = \langle N_- \rangle} 4\frac{\left\langle \left(\Delta N - \langle \Delta N \rangle\right)^2 \right\rangle}{\langle N_{ch} \rangle} - 4, \quad \langle N_{ch} \rangle \nu^{corr}_{(+-,dyn)} = \langle N_{ch} \rangle \nu_{(+-,dyn)} + 4\frac{\langle N_{ch} \rangle}{\langle N_{ch} \rangle_{4\pi}}$$

- **New results on net-proton, net-kaon and net-pion fluctuations from ALICE will be released soon**

# Chemical fluctuations

# Fluctuation measures

$$\omega_A = \frac{\langle A^2\rangle - \langle A\rangle^2}{\langle A\rangle}$$ Poisson case: $\langle A^2\rangle = \langle A\rangle^2 + \langle A\rangle, \quad \omega_A = 1$

$$\nu_{dyn} = \frac{\langle A^2\rangle - \langle A\rangle}{\langle A\rangle^2} + \frac{\langle B^2\rangle - \langle B\rangle}{\langle B\rangle^2} - 2\frac{\langle AB\rangle}{\langle A\rangle\langle B\rangle}$$

C. Pruneau, S. Gavin, S. Voloshin, Phys. Rev. C 66, 044904 (2002)

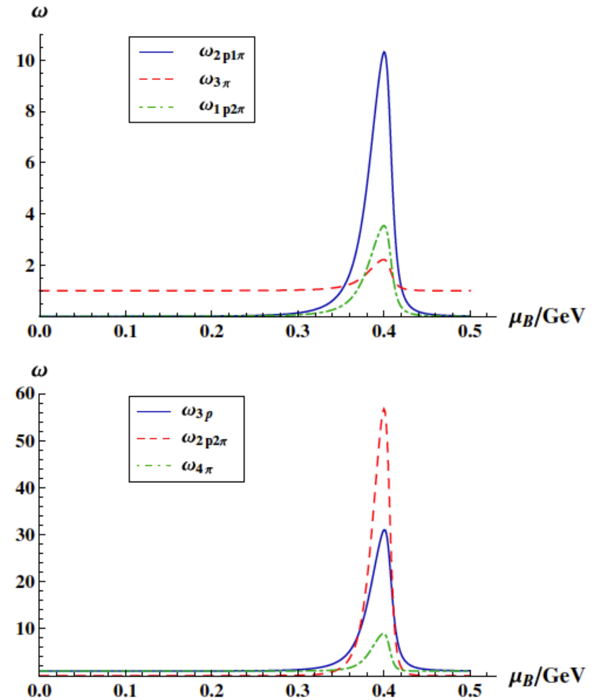
$$\Sigma[A,B] = \frac{\langle B\rangle\omega_A + \langle A\rangle\omega_B - 2\left(\langle AB\rangle - \langle A\rangle\langle B\rangle\right)}{\langle A+B\rangle}$$

$$\Phi[A,B] = \frac{\sqrt{\langle A\rangle\langle B\rangle}}{\langle A+B\rangle}\left[\sqrt{\Sigma[A,B]} - 1\right]$$

M. I. Gorenstein, M. Gazdzicki, Phys.Rev. C84 (2011) 014904

Independent Poisson distributions: $\nu_{dyn} = 0, \quad \Sigma = 1, \quad \Phi = 0$

$\Sigma[A,B]$, $\Phi[A,B]$ } depend neither on volume ($N_W$) nor on its fluctuations

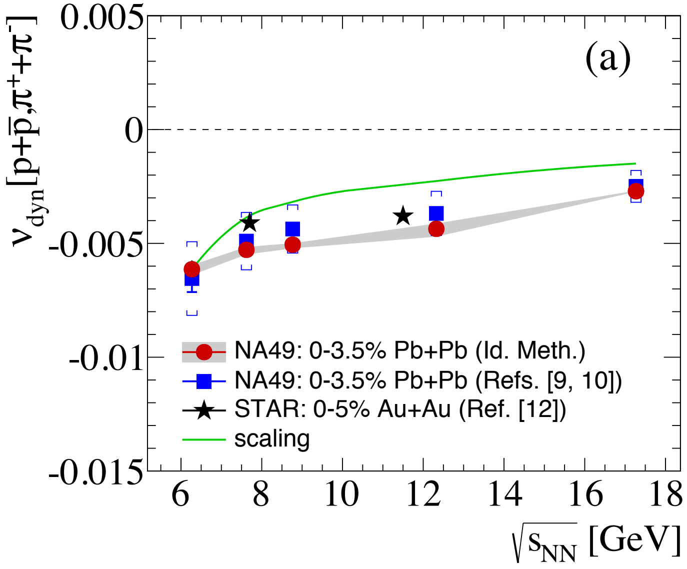


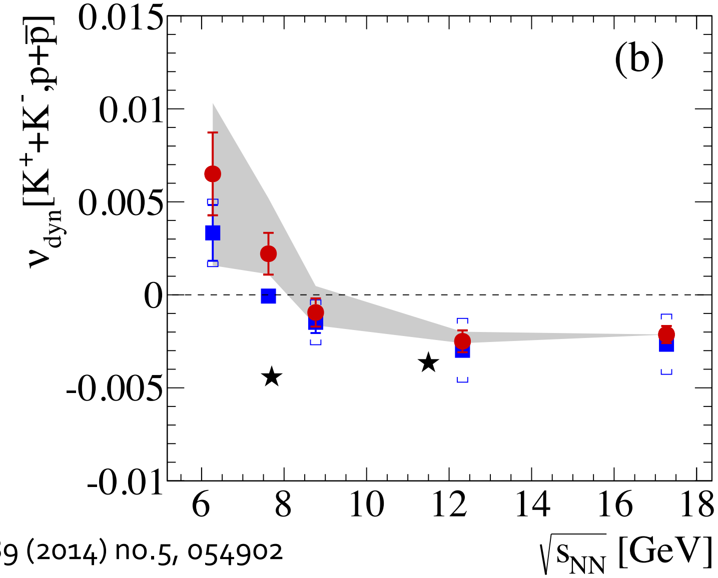

Phys. Rev. D 82, 074008 (2010)

$$\omega_{2A} = \frac{\overline{\left(A - \langle A\rangle\right)^2}}{\langle A\rangle} = \frac{\langle A^2\rangle - \langle A\rangle^2}{\langle A\rangle} = \frac{Var(A)}{\langle A\rangle}$$

$$\omega_{1A2B} = \frac{\overline{\left(A - \langle A\rangle\right)\left(B - \langle B\rangle\right)^2}}{\langle A\rangle^{1/3}\langle B\rangle^{2/3}}$$

# NA49/STAR Puzzle



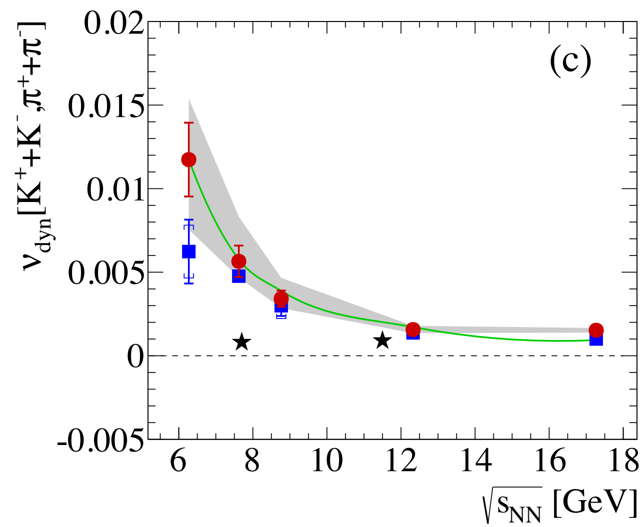




NA49: Phys.Rev. C89 (2014) no.5, 054902

[p,π]: agreement with both, published results of NA49, and STAR

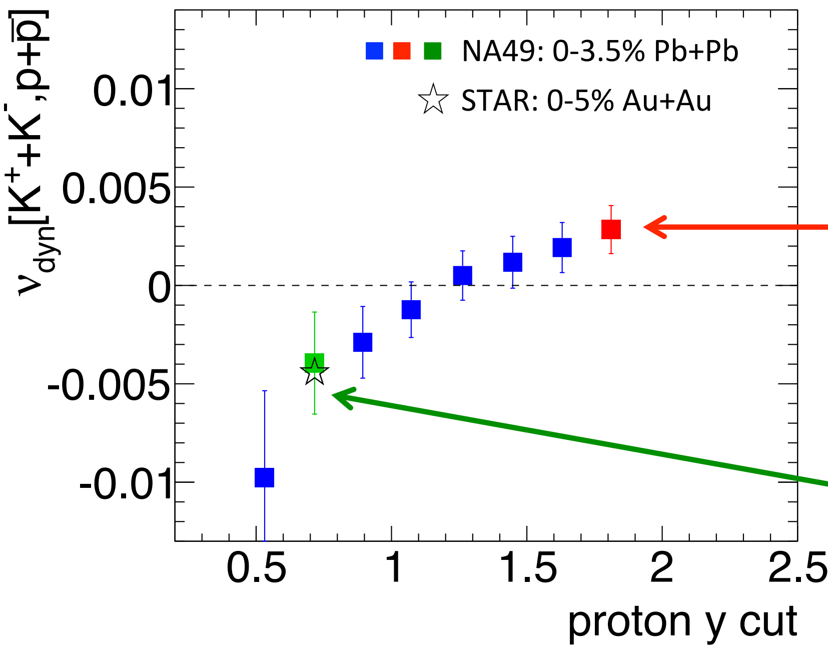
[K,π]: increasing trend at low energy published by NA49 is reproduced. Difference with STAR remains!

[K,p]: increasing trend at low energy published by NA49 is reproduced. Difference with STAR remains!



# NA49/STAR Puzzle resolved

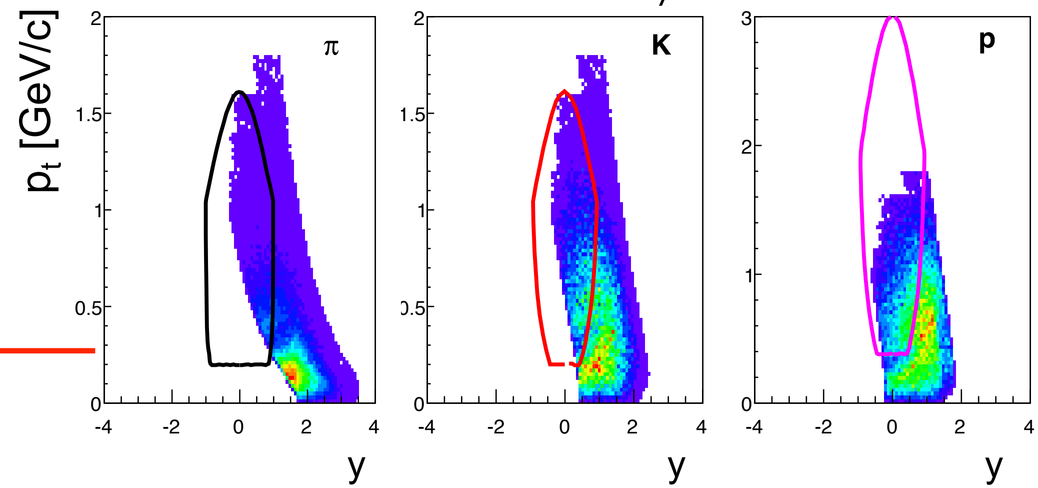
NA49 central Pb+Pb data at 30*A* GeV/c




fluctuation measures are acceptance dependent
Compare experimental results in a common acceptance

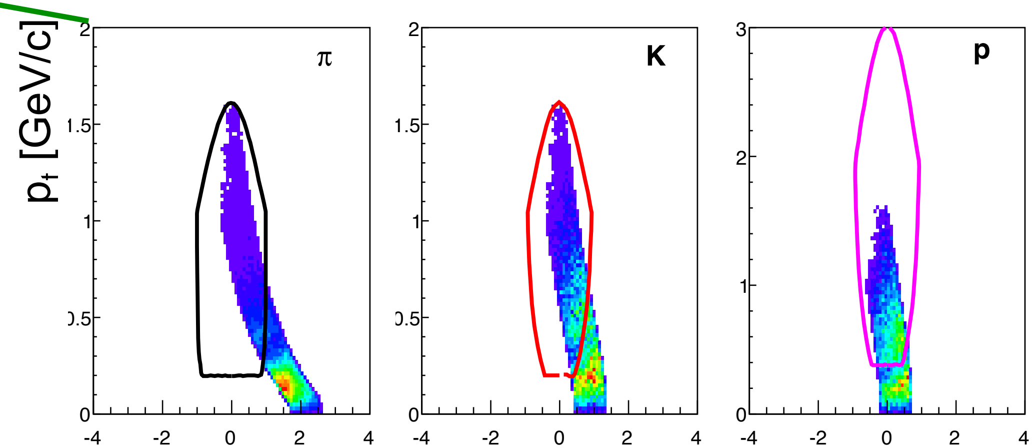
NA49: Phys.Rev. C89 (2014) no.5, 054902

ACCEPTANCE BIN 7



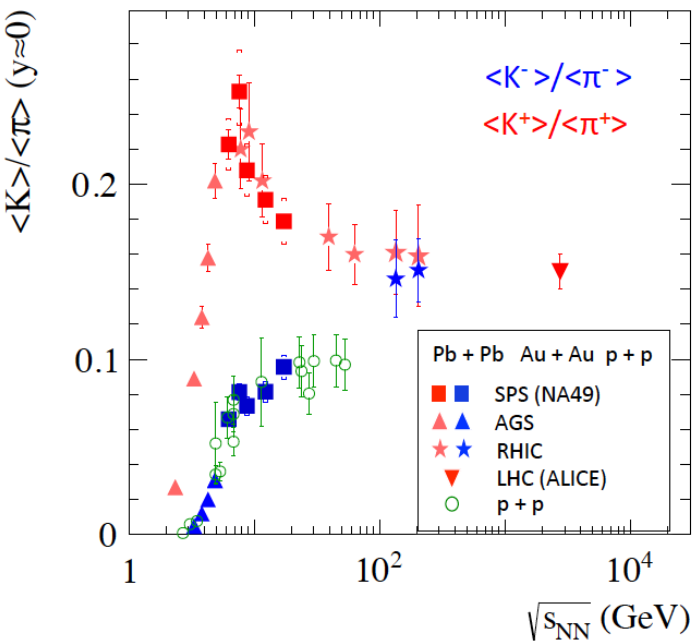

Lines indicate the corresponding STAR acceptance

ACCEPTANCE BIN 1



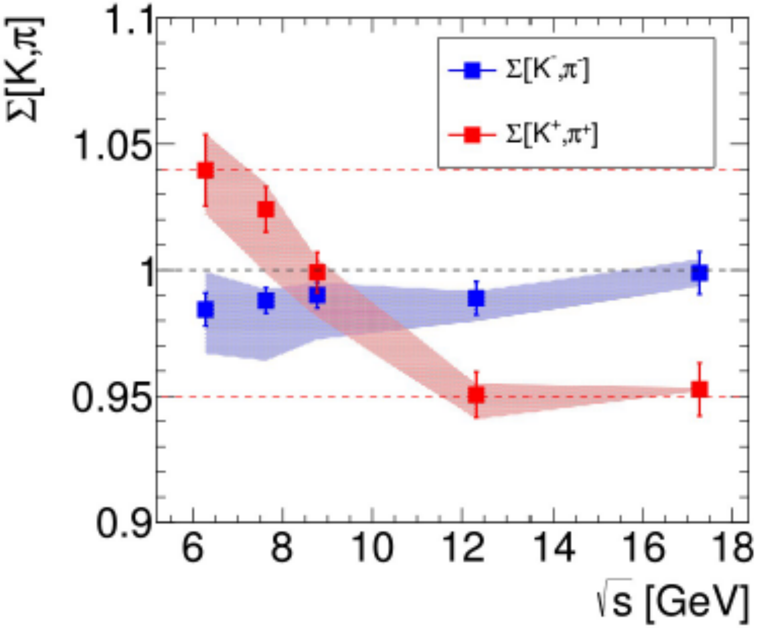
# Recent results from NA49

First moments




structures
only for
positive chargers

Second moments



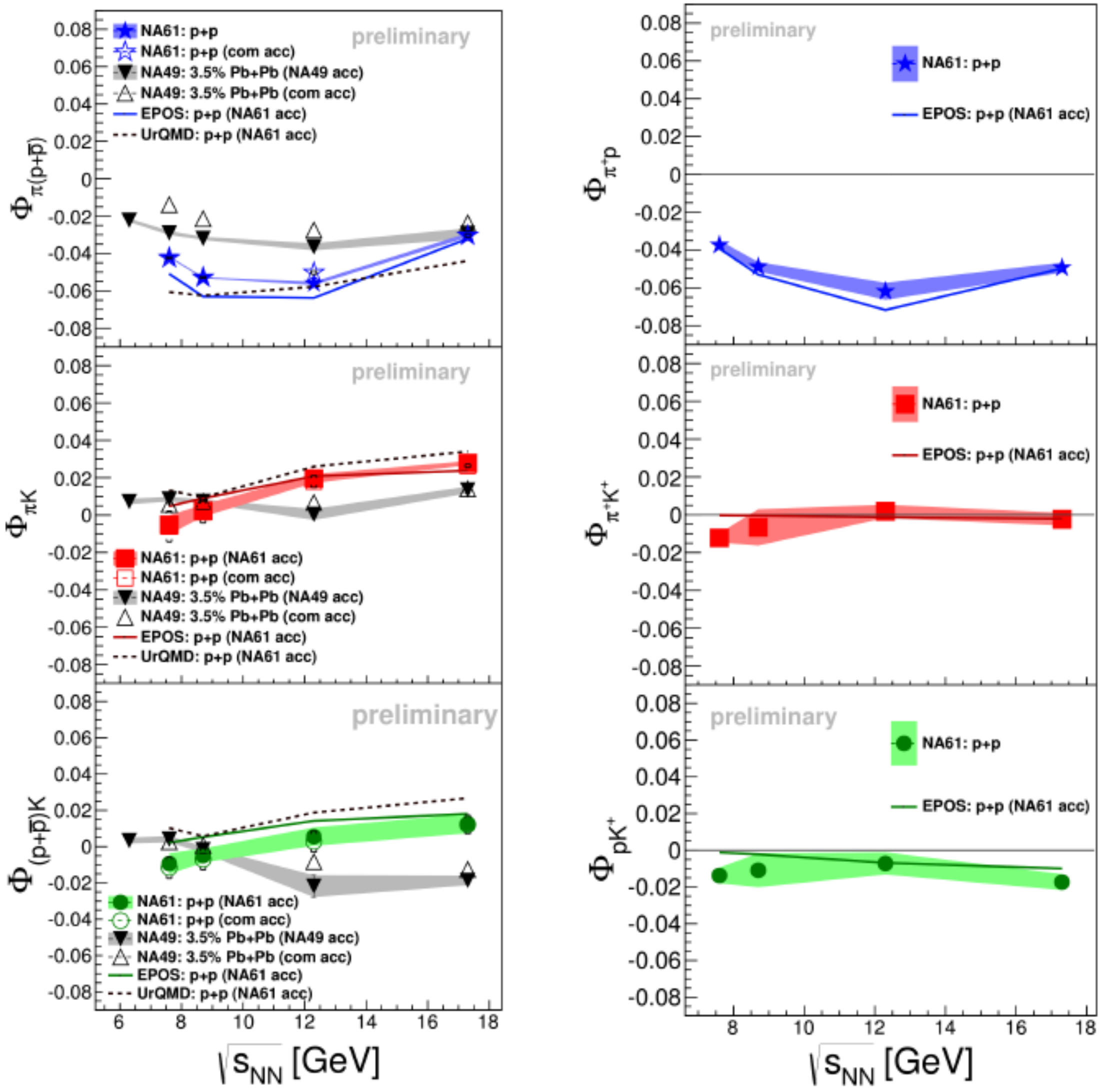

M. Gazdzicki and M. Gorenstein, Acta. Phys. Pol. B30, 2705 (1999)

NA49: PRC77, 024903 (2008)

A. R. CPOD 2016

A. R. Central Eur. J. Phys. 10, 1267-1270 (2012

# Results From NA49/NA61




p+p results are described by models. Energy dependencies are driven by conservation laws and resonance decays.


A. Rustamov, POS (2013) 005
M. Mackowiak-Pawlowska, POS (2013) 048

# Summary

Nor clear signals for the critical point are observed so far

Problems in understanding E-by-E measurements of conserved charges

- How to put acceptance threshold?
- How to compare to model calculations

- **New results on net-proton, net-kaon and net-pion fluctuations from ALICE will be released soon**