THE QUEST FOR PHASE TRANSITIONS IN STRONGLY INTERACTING MATTER

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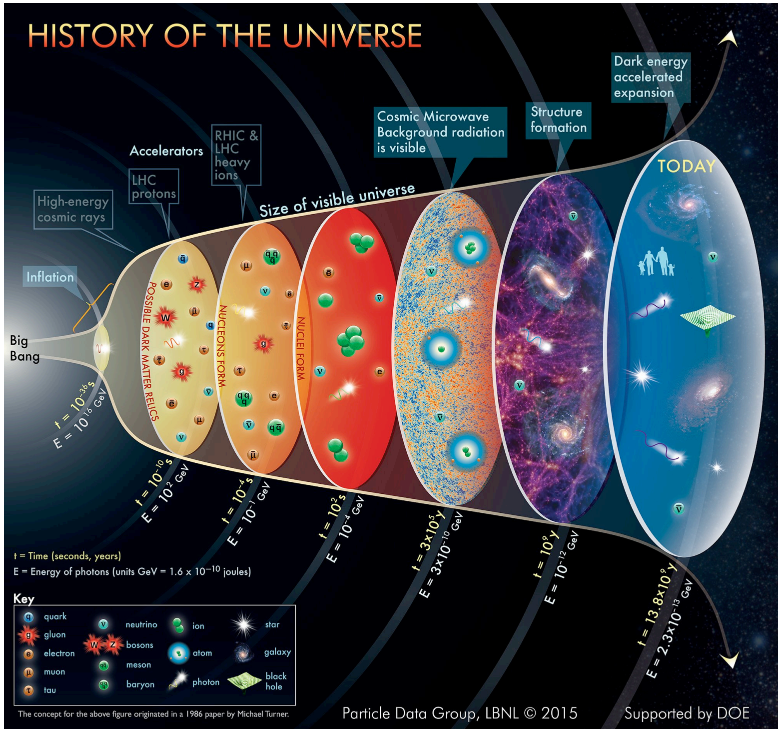
JINR Scientific Council

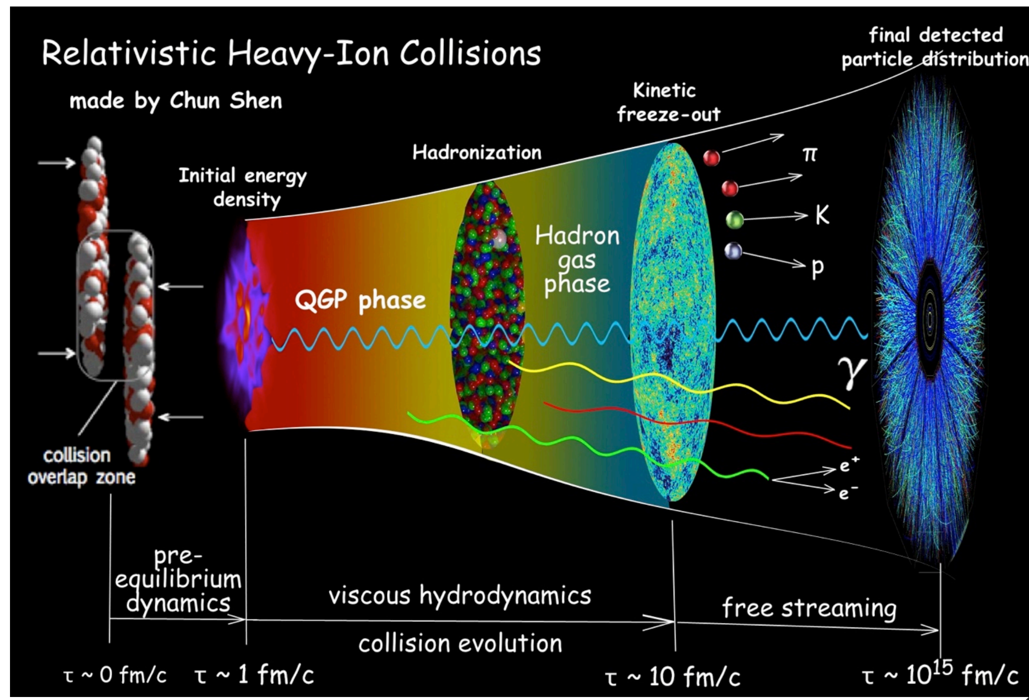
- Phase transitions then and now
- Phases of EM interacting matter
- Phases of strongly interacting matter
- Experimental programs
  - Obtained results
- Summary
- Outlook

Phase transitions then and now



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

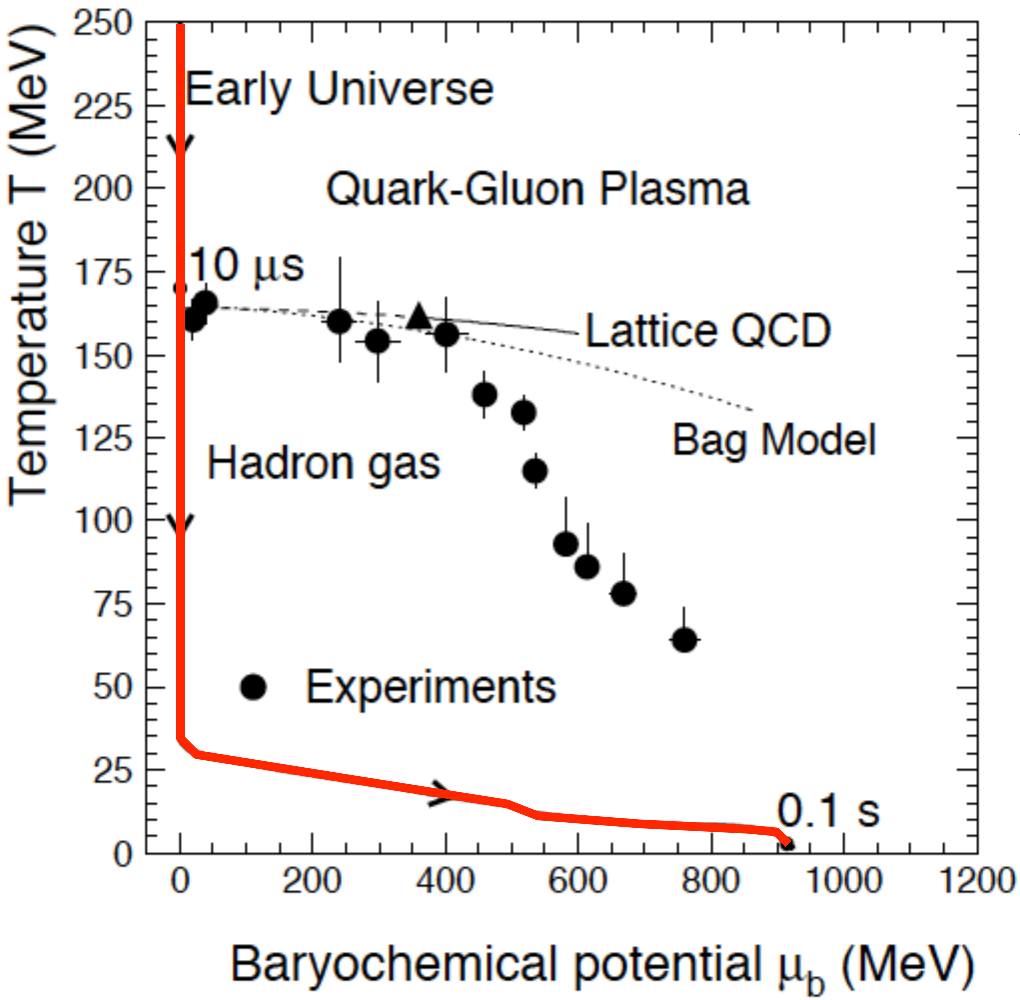
- recreating the Universe in laboratories
- exploring phase transitions



$m_p \approx 937$ MeV
$2m_u + m_d \approx 10$ MeV
(broken Chiral symmetry)

no isolated quarks seen thus far
(confinement)

Bing Bang vs. Little Bangs



Ansatz:

- charge neutrality
- net-lepton number = net baryon number
- constant entropy per-baryon

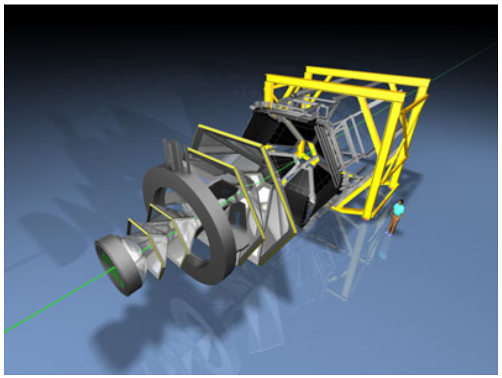
P. Braun-Munzinger, J. Wambach,
Rev. Mod. Phys. 81, (2009) , 1031

H. Schade, B. Kämpfer,
Phys. Rev. C79 (2009), 044909

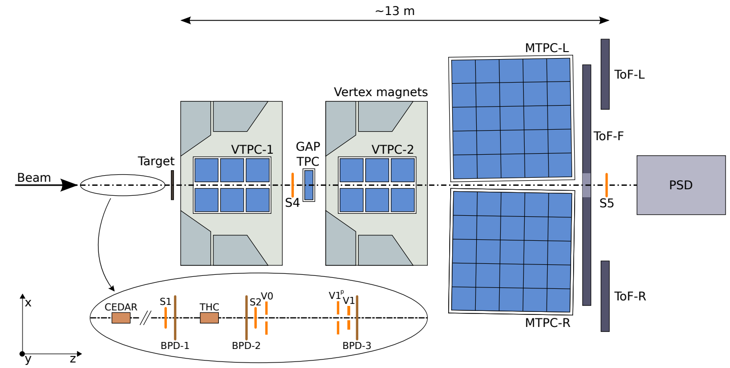
The Universe follows a different path!

Experimental campaigns in a wide energy range

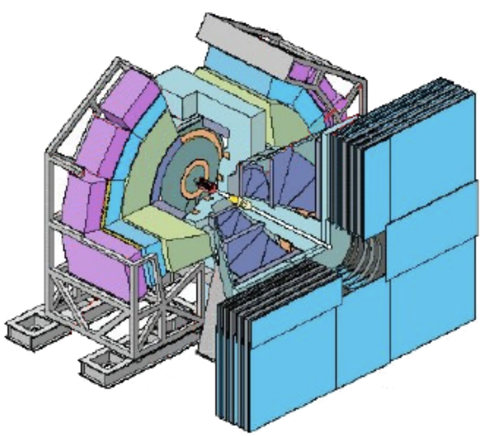
HADES (few GeV)



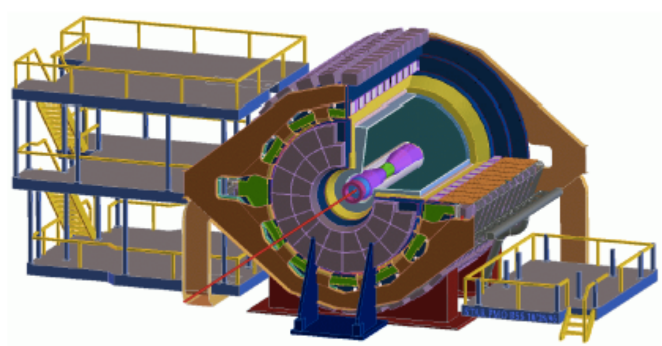
NA61/SHINE (5- 17 GeV)



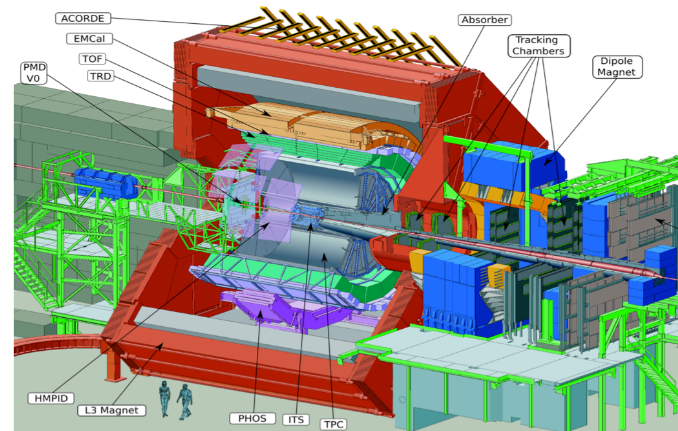
PHENIX (7.7- 62.4 GeV)



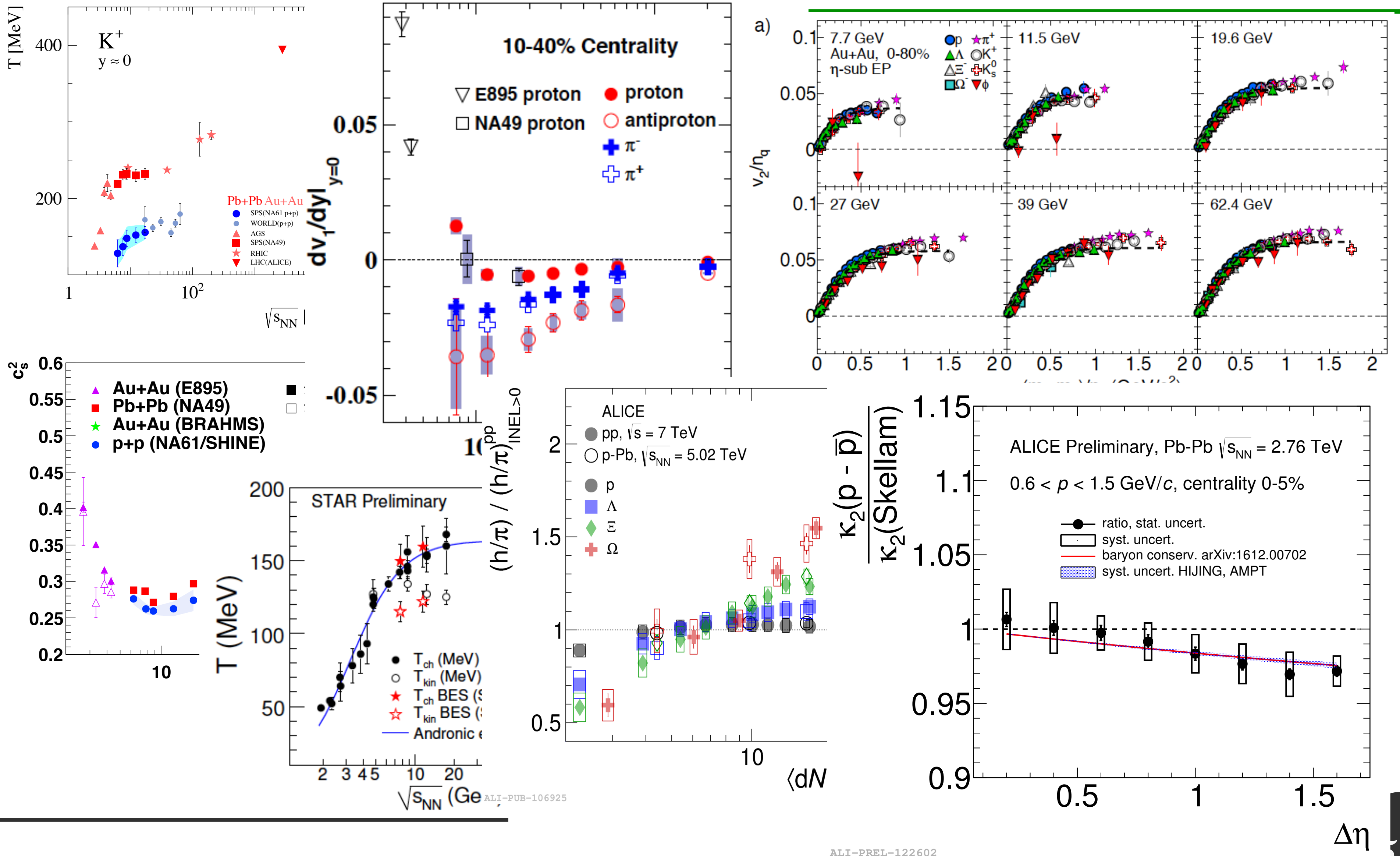
STAR (7.7- 62.4 GeV)



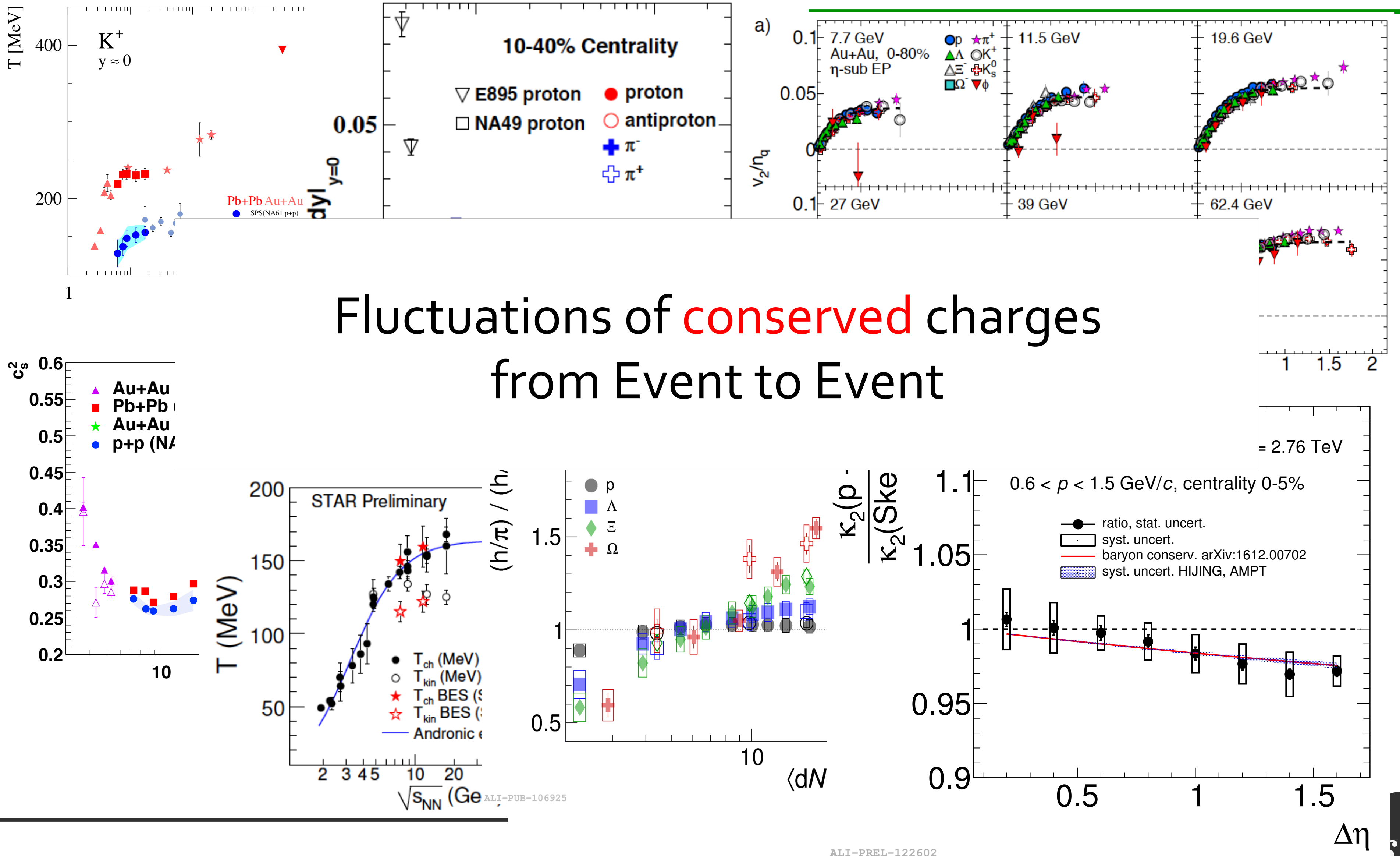
ALICE (few TeV)



Measured signals

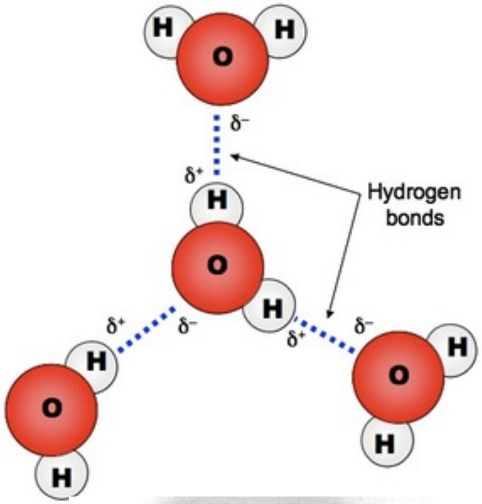


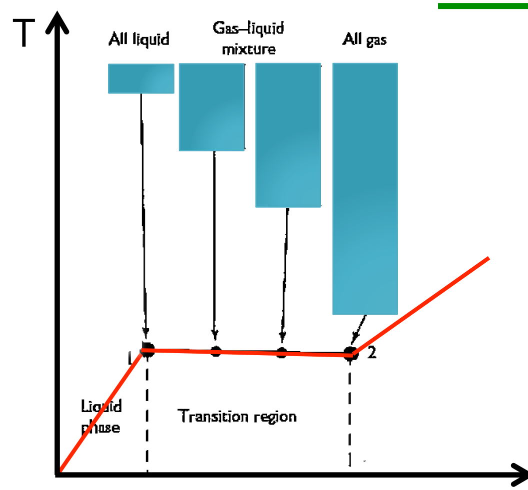
Exposed in this talk

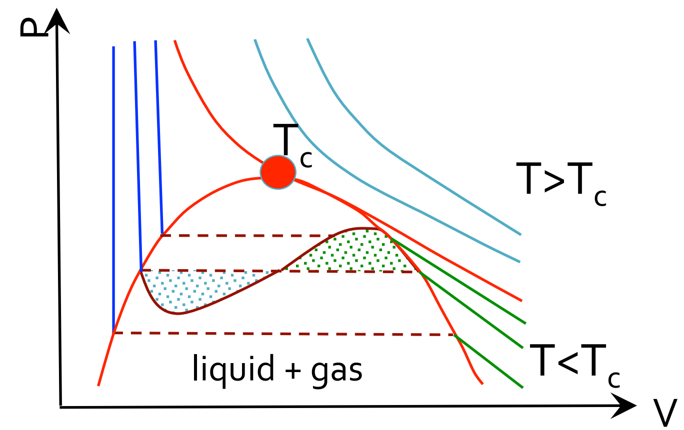


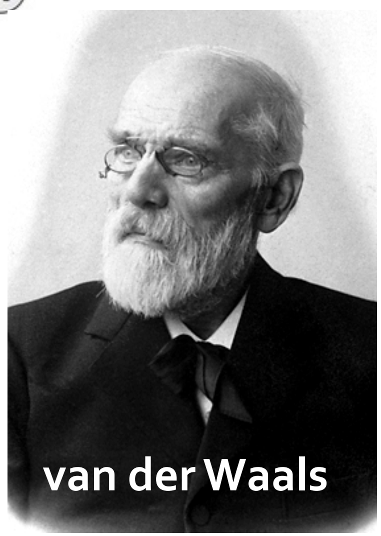
Fluctuations of conserved charges
from Event to Event

Phase transitions, importance of interactions









The Nobel Prize in Physics, 1910

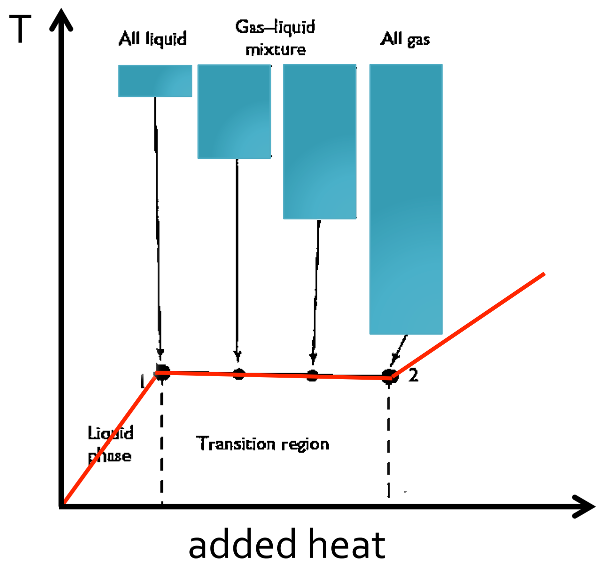
$$(V - Nb)\left(P + \frac{N^2 a}{V^2}\right) = NT$$

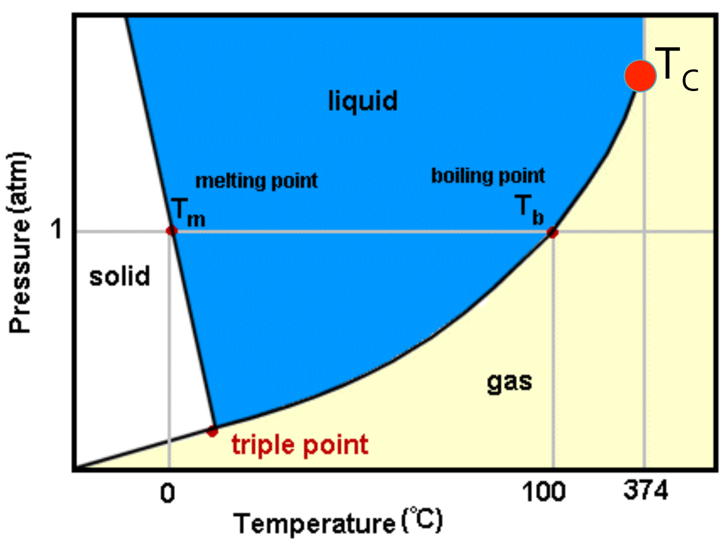
$$\frac{\left\langle (N - \langle N \rangle)^2 \right\rangle}{\langle N \rangle^2} = \frac{T k_T}{V} \qquad k_T = -\frac{1}{V\left(\partial P / \partial V\right)}$$

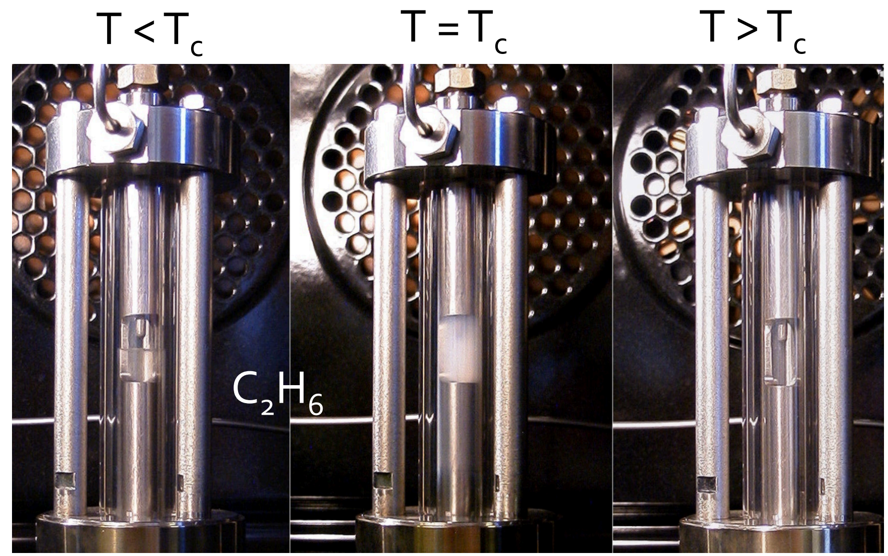
- Interactions are important for phase transitions
- Large fluctuations close to the critical point

$$\text{Ideal gas:} \left\langle (N - \langle N \rangle)^2 \right\rangle \xrightarrow{PV=NT} \langle N \rangle \ \text{(Poisson)}$$

Electromagnetically Interacting matter







$$\frac{\langle \rho^2 \rangle - \langle \rho \rangle^2}{\langle \rho \rangle^2} = \frac{T\chi}{V}, \quad \chi = -\frac{1}{V}\frac{\partial V}{\partial P}$$

Einstein, 1910

$$Rayleigh\,Ratio \propto \chi$$

probing phase transitions
with fluctuations

Strongly Interacting matter, ultimate temperature

1965: Hagedorn’s mass spectrum

$$\rho(m) \propto e^{m/T_H}$$

partition sum for a resonance gas
in equilibrium

$$Z(T,V) \simeq \exp\left[\frac{VT}{2\pi^2}\int_0^\infty m^2 K_2\left(\frac{m}{T}\right)\rho(m)\,dm\right]$$

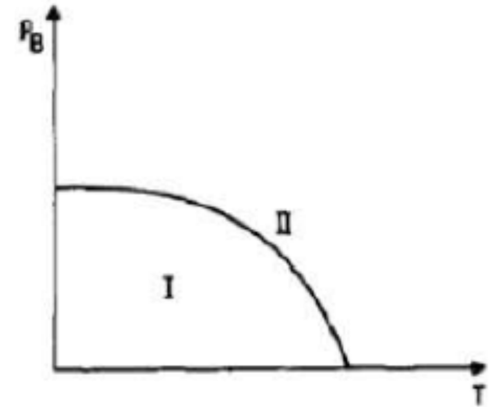
$$K_2(m/T) \sim (T/m)^{1/2}\exp(-m/T)$$

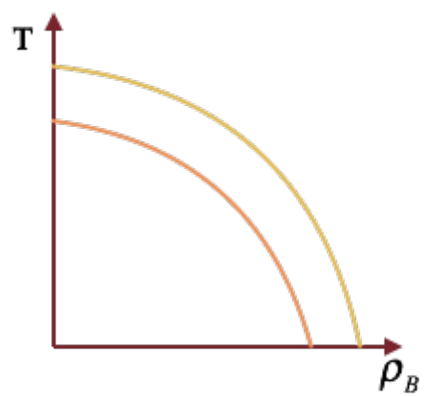
in the hadronic phase (m/T >> 1)

$$Z(V,T) \to \infty, \quad T \to T_H$$

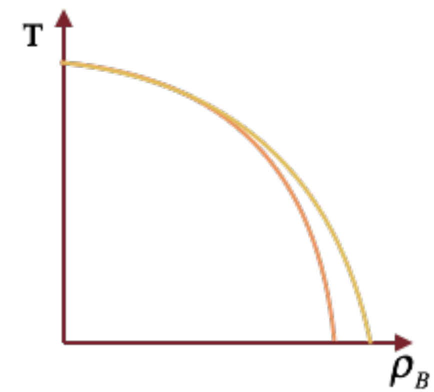
1970: *K. Huang and S. Weinberg;*
Our present theoretical apparatus is really inadequate to deal with much earlier times, say when T > 100 MeV

1975: Cabibbo & Parisi;
exponential hadronic
spectrum and
quark liberation



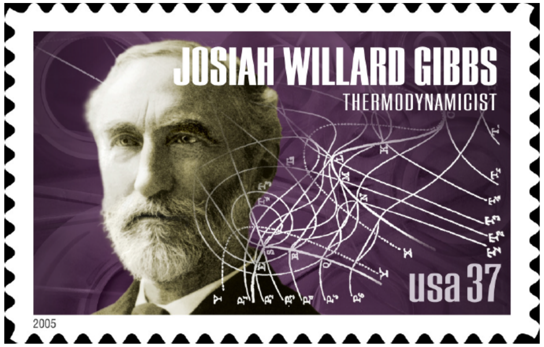


1982: G. Baym;
deconfinement and chiral
phase boundaries



1983: Lattice Monte Carlo;
deconfinement and chiral
phase boundaries coincide

Fluctuations, Ensemble averaging



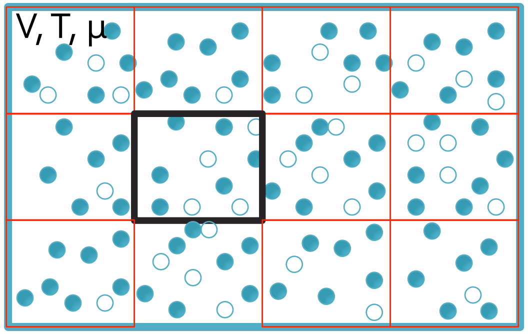
Ergodicity hypothesis: Averaging over time is equivalent to the averaging over ensembles.

Ensemble is an idealisation consisting of a large number of mental copies of a system, considered all at once, each represents a possible state that the real system!

probability of a given state with E_j and N_j

$$p_j = \frac{\exp\left[-\left(E_j - \mu N_j\right)/T\right]}{Z_{GCE}}$$

Grand Canonical Ensemble

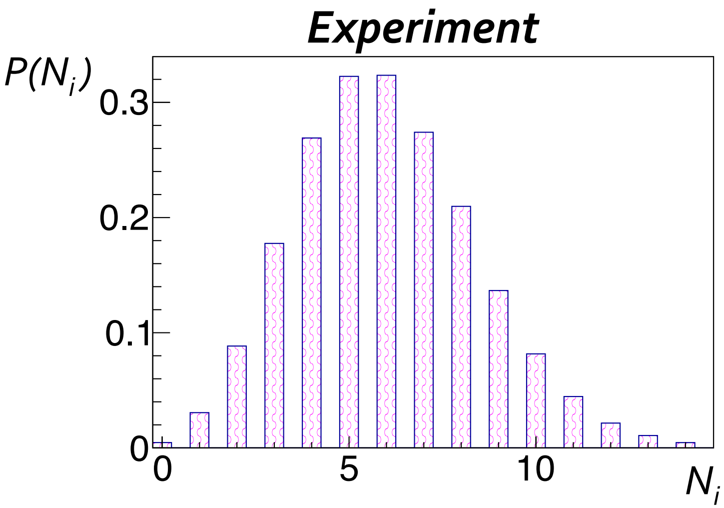


$$Z_{CGE}\left(T,V,\mu\right) = \sum_j \exp\left[-\frac{E_j - \mu N_j}{T}\right]$$ partition function

$$\left\langle N \right\rangle = \sum_j N_j p_j = T \frac{\partial \ln Z_{CGE}}{\partial \mu}\bigg|_V$$

$$k_2 \left\langle N \right\rangle = \left\langle N^2 \right\rangle - \left\langle N \right\rangle^2 = \sum_j N_j^2 p_j = T^2 \frac{\partial^2 \ln Z_{CGE}}{\partial \mu^2}\bigg|_V$$

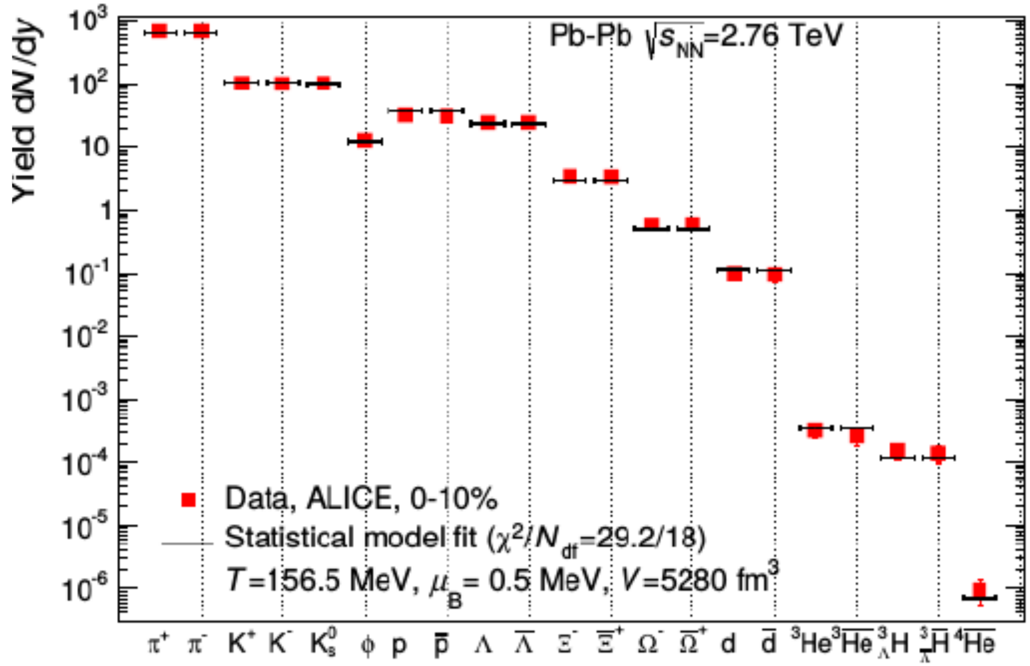
Phase boundaries from first moments



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

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

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

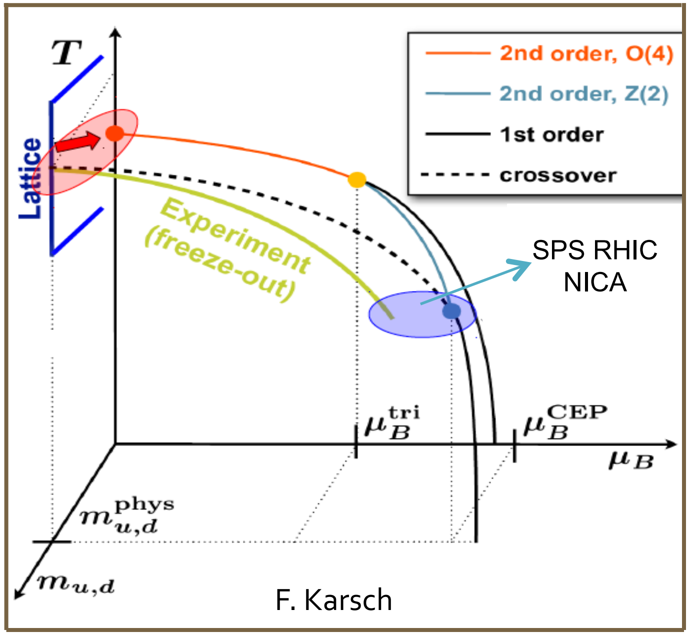


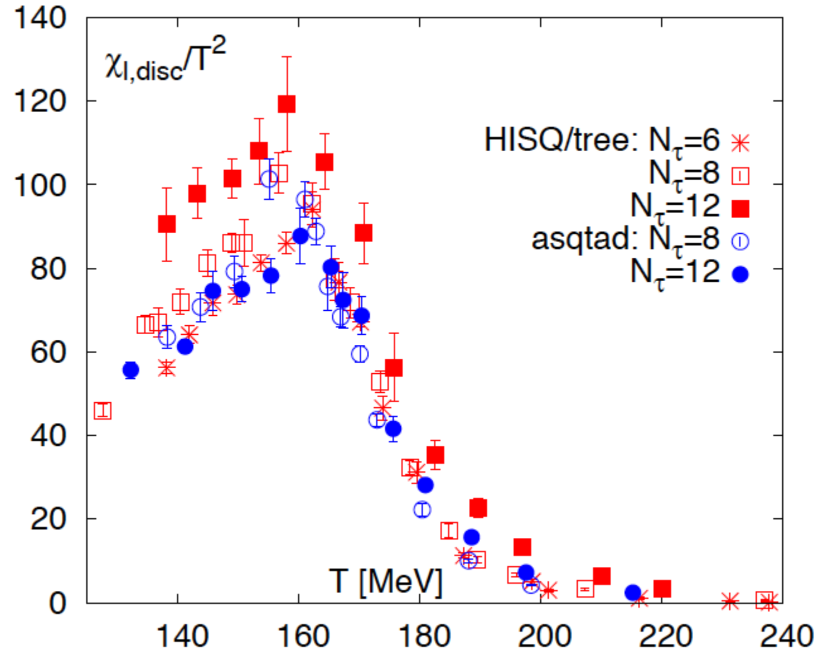
ALICE, PLB 726 (2013) 610

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!

Dynamics of phase transitions





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

Bridge from experiment to theory

for a thermal system in a fixed volume V
within the Grand Canonical Ensemble

$$\hat{\chi}_2^B = \frac{\langle \Delta N_B^2 \rangle - \langle \Delta N_B \rangle^2}{VT^3} = \frac{\kappa_2(\Delta N_B)}{VT^3}$$

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

- ***In experiments***
  - *Volume (participants) fluctuates from E-to-E*
  - *Global conservation laws are important*

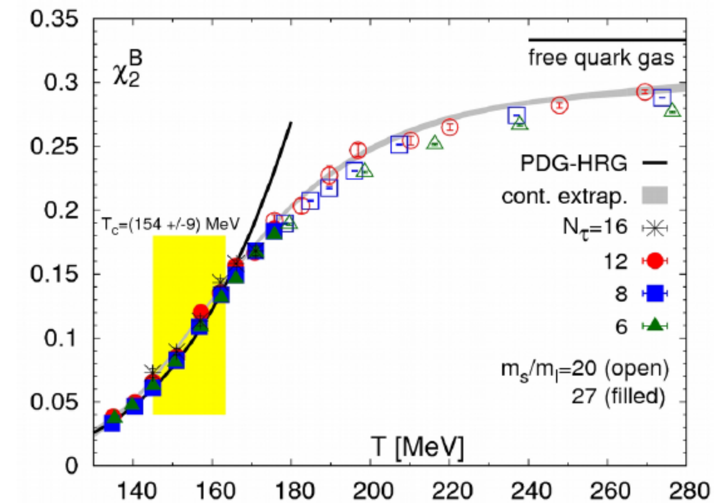
$$\hat{\chi}_n^B \neq \frac{\kappa_n(\Delta N_B)}{VT^3} \qquad \frac{\kappa_4(\Delta N_B)}{\kappa_2(\Delta N_B)} \equiv \gamma_2 \sigma^2 \neq \frac{\hat{\chi}_4^B}{\hat{\chi}_2^B}$$

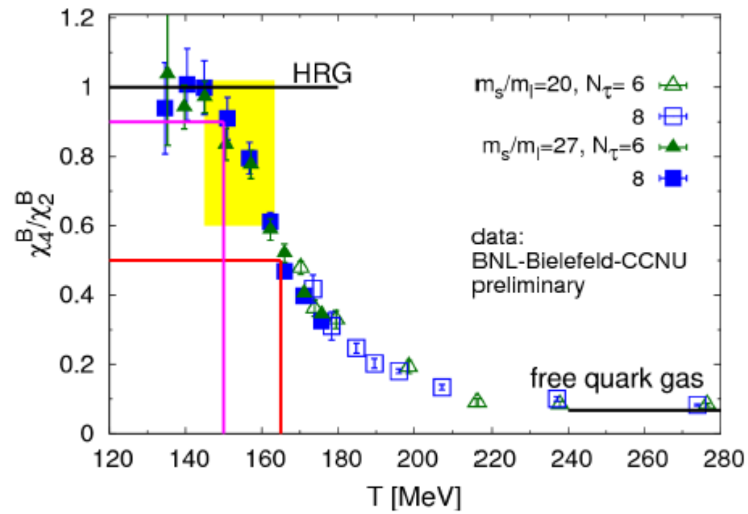
V. Skokov, B. Friman, and K. Redlich, Phys.Rev. C88 (2013) 034911

P. Braun-Munzinger, A. R., J. Stachel, arXiv:1612.00702, NPA 960 (2017) 114

At $s^{1/2}$ > 10 GeV net-proton is a reasonable proxy for the net-baryon

M. Kitazawa, and M. Asakawa, Phys. Rev. C86 (2012) 024904





smaller than in HRG for T > 150 MeV

F. Karsch, QM17, arXiv:1706.01620
O. Kaczmarek, QM17, arXiv:1705.10682

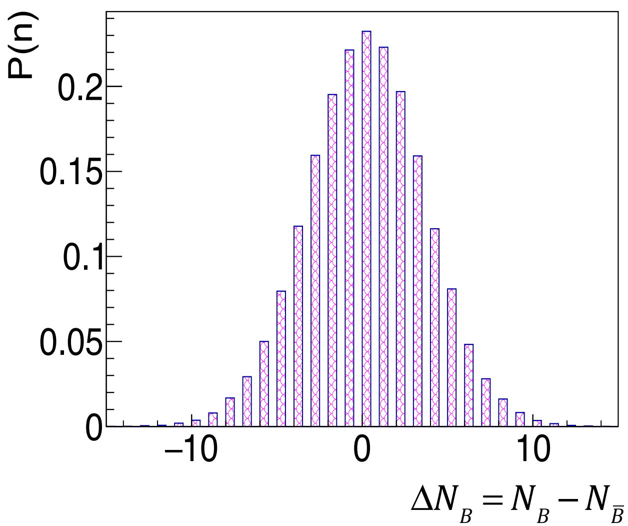
Net-particle cumulants, definitions

$$\kappa_1(X) = \langle X \rangle$$

$$\kappa_2(X) = \left\langle \left(X - \langle X \rangle\right)^2 \right\rangle$$

$$\kappa_3(X) = \left\langle \left(X - \langle X \rangle\right)^3 \right\rangle$$

$$\kappa_4(X) = \left\langle \left(X - \langle X \rangle\right)^4 \right\rangle - 3\kappa_2^2(X)$$



e.g., second cumulant of net-baryons

$$\kappa_2(N_B - N_{\bar{B}}) = \left\langle \left(N_B - N_{\bar{B}}\right)^2 \right\rangle - \left\langle N_B - N_{\bar{B}} \right\rangle^2$$

$$\kappa_2(N_B - N_{\bar{B}}) = \kappa_2(N_B) + \kappa_2(N_{\bar{B}}) - 2\left(\langle N_B N_{\bar{B}} \rangle - \langle N_B \rangle \langle N_{\bar{B}} \rangle\right)$$

Correlation term may arise from:

1. Resonance contributions
2. Global conservation laws

Poisson limit:

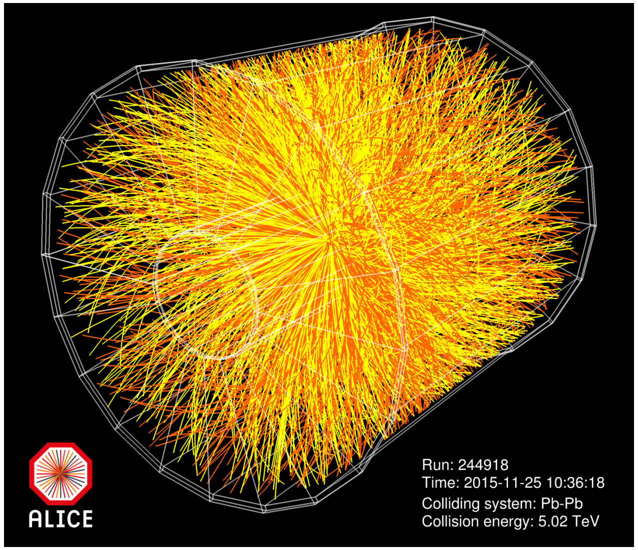
$$\kappa_2(N_B) = \langle N_B \rangle$$

$$\kappa_2(N_{\bar{B}}) = \langle N_{\bar{B}} \rangle$$

$$\kappa_2(N_{\bar{B}} - N_B) \xrightarrow{\langle N_B N_{\bar{B}} \rangle = \langle N_B N_{\bar{B}} \rangle} \langle N_B \rangle + \langle N_{\bar{B}} \rangle$$

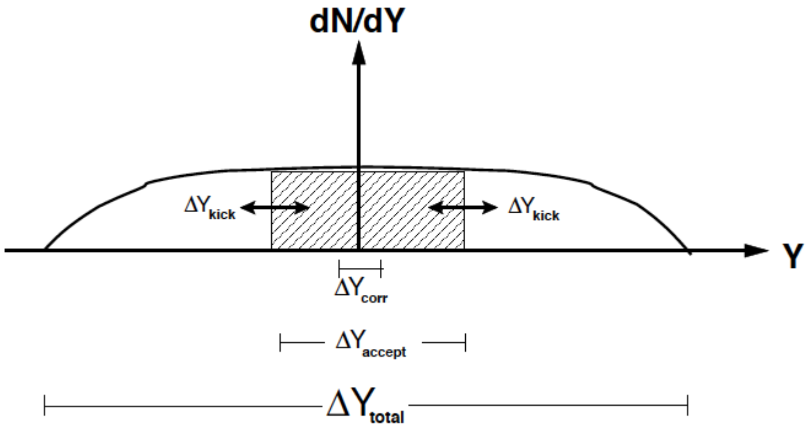
Skellam

Experimental trick: cuts on y and/or p_t



Large $\frac{\Delta y_{accept}}{\Delta y_{total}}$: conservations dominate

Small $\frac{\Delta y_{accept}}{\Delta y_{total}}$: dynamical fluctuations may disappear

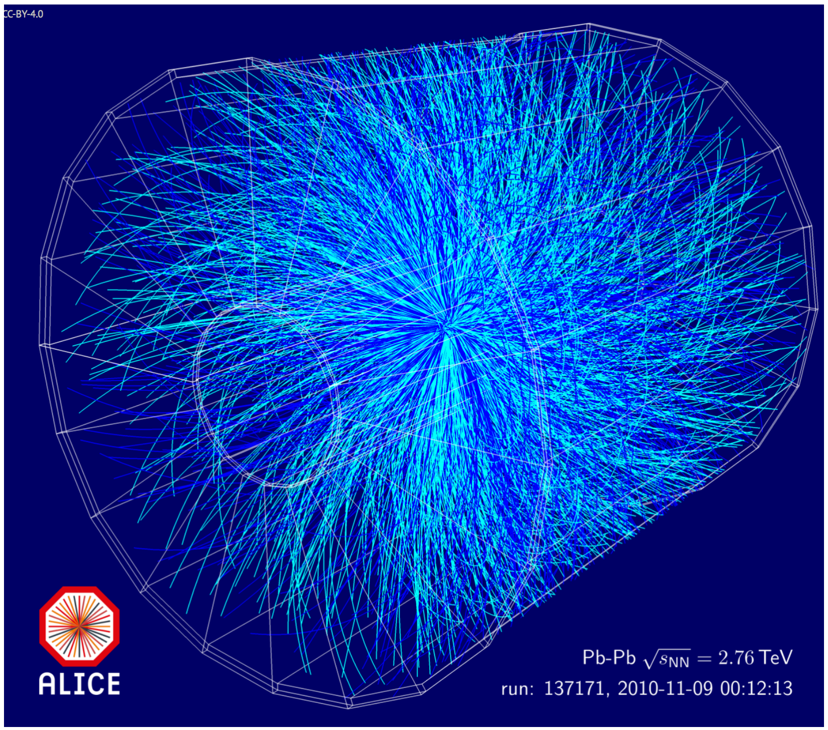


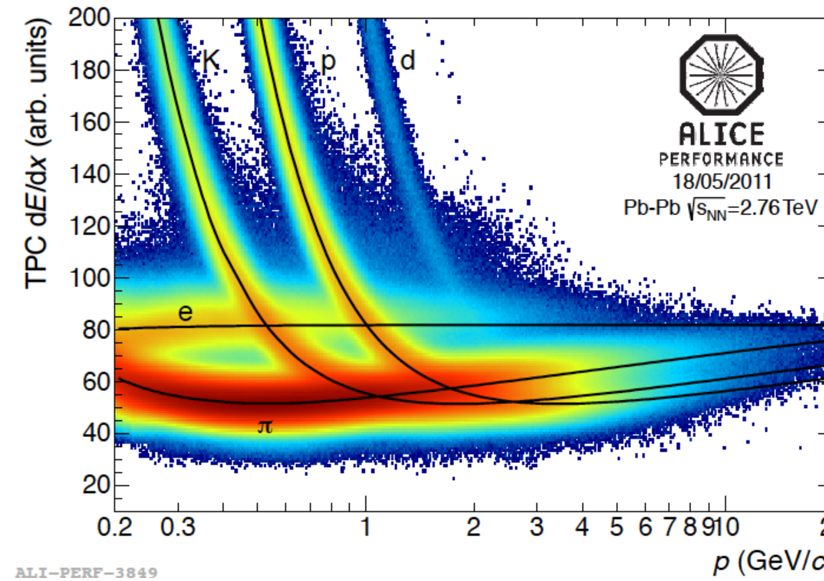
- Our approach:
  - Estimation of non-dynamical fluctuations
  - Selection of optimum acceptance
  - Correction for conservation lows

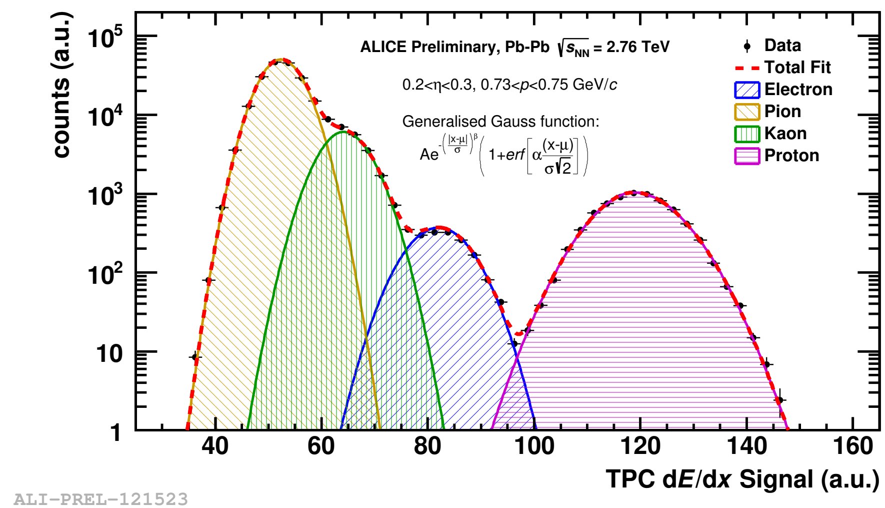
P. Braun-Munzinger, A. R., J. Stachel, in preparation

A. R. SQM 2017

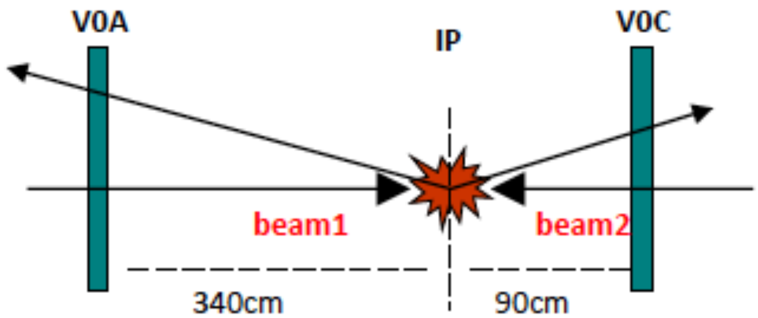
Particle Identification, ALICE example



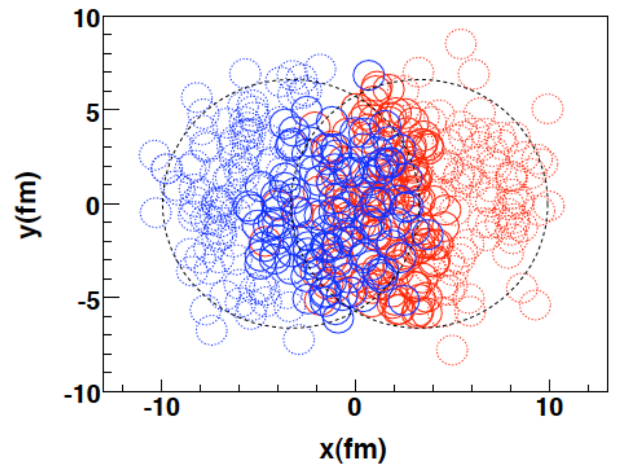


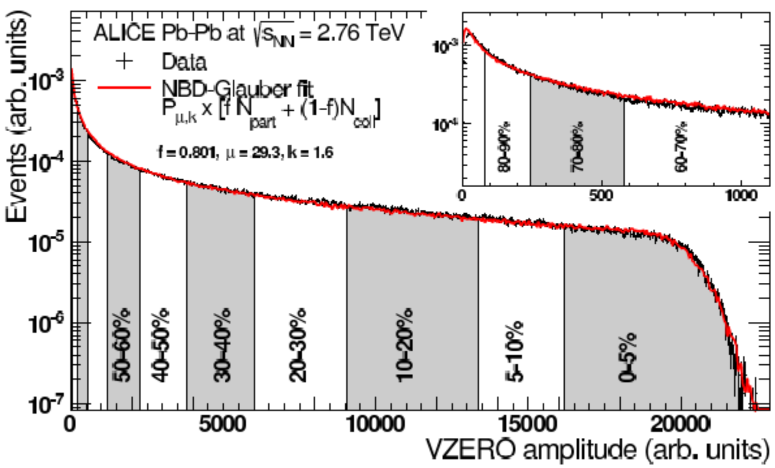


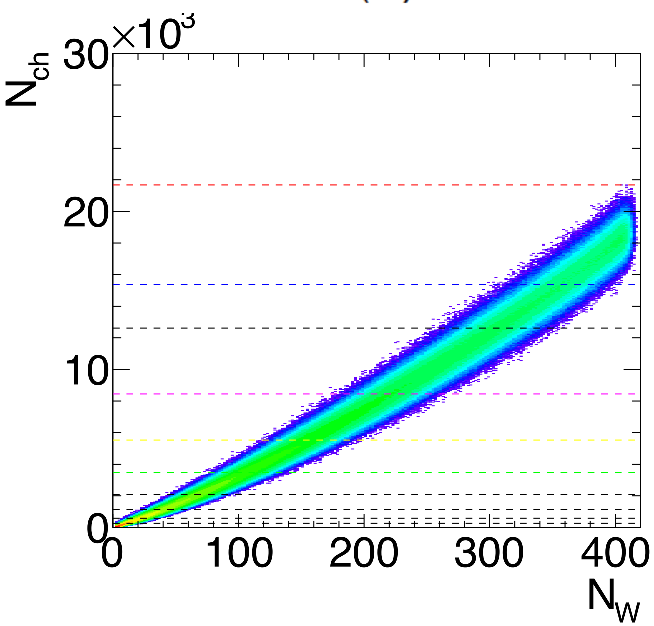
Centrality determination



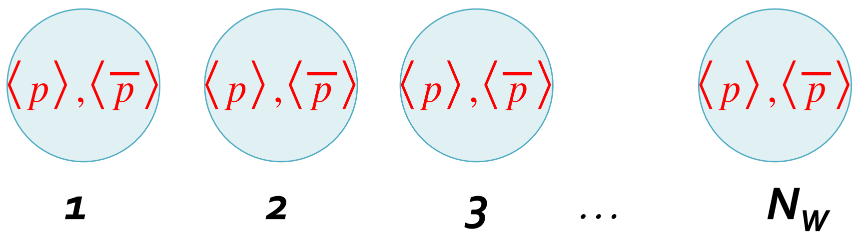
ALICE Phys.Rev. C88 (2013) no.4, 044909



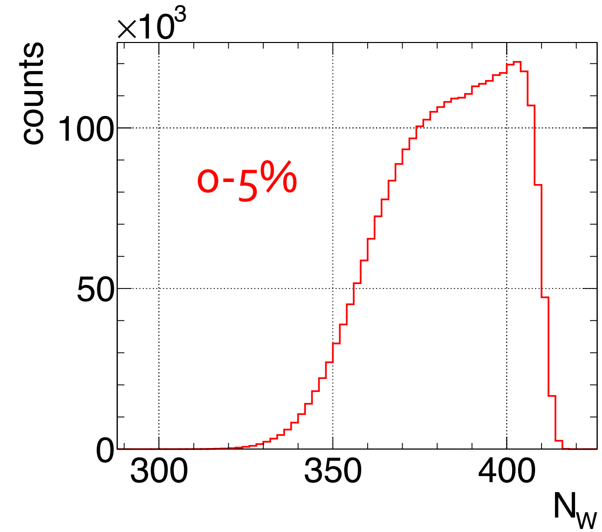


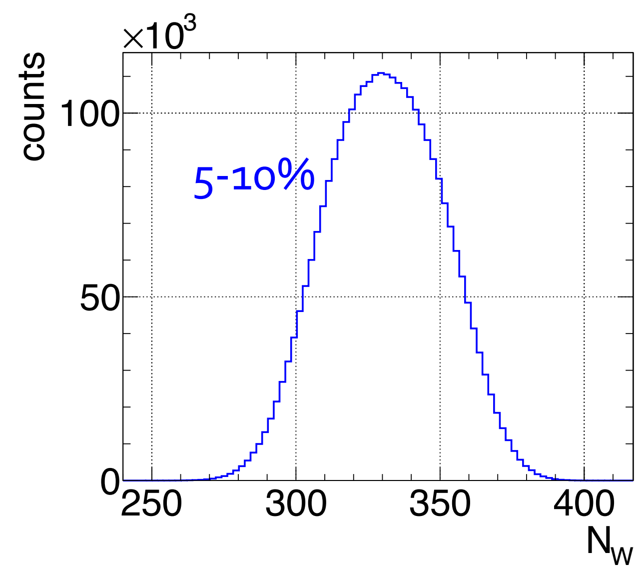


Non-dynamical fluctuations



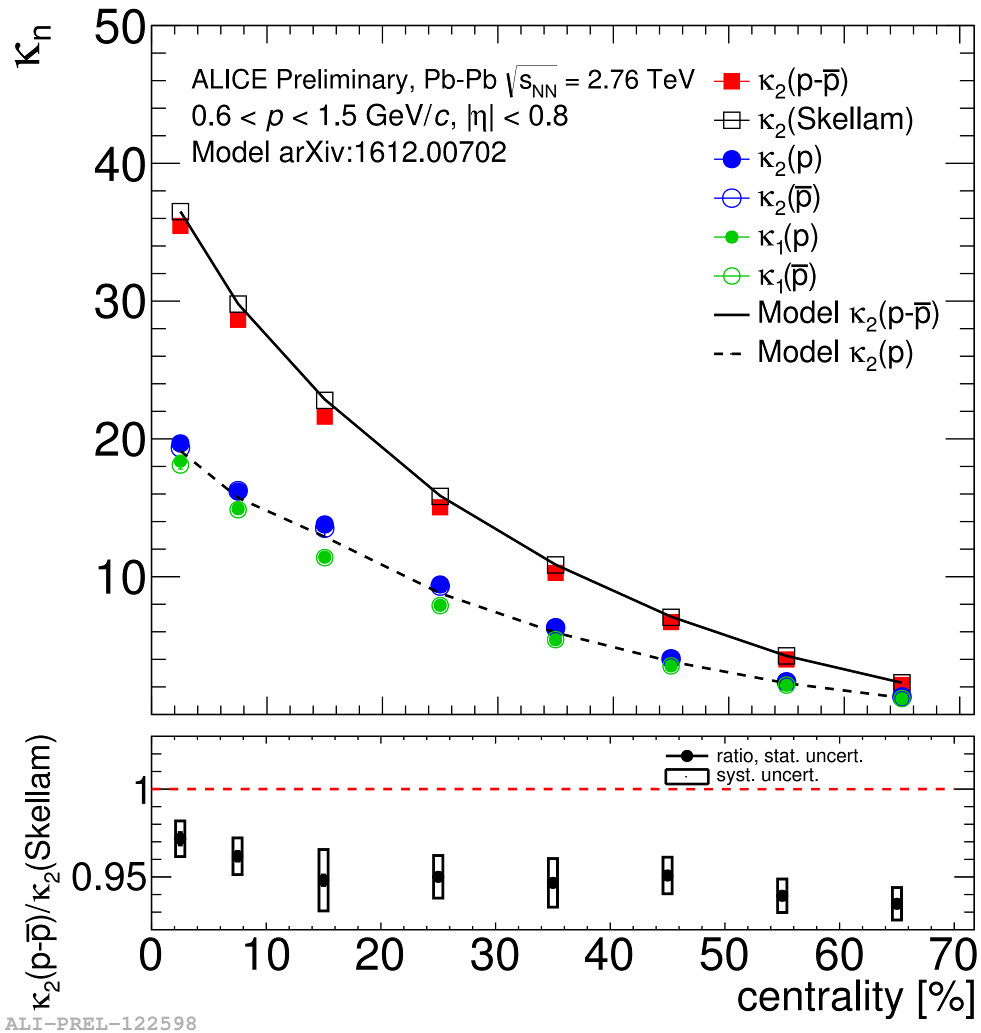
- ***N_W fluctuates with MC Glauber initial conditions***
- ***Particles are produced from each source***
- ***Inputs:***
  - ***Mean proton multiplicities*** $\langle p \rangle$, $\langle \overline{p} \rangle$
  - ***Centrality selection like in experimental data***





P. Braun-Munzinger, A. R., J. Stachel, arXiv:1612.00702, NPA 960 (2017) 114

Results from ALICE



Analysis of higher cumulants is ongoing!

$$\kappa_2(n_B - n_{\bar{B}}) = \kappa_2(n_B) + \kappa_2(n_{\bar{B}}) - 2\left(\langle n_B n_{\bar{B}}\rangle - \langle n_B\rangle\langle n_{\bar{B}}\rangle\right)$$

Input to the Model

$\kappa_1(p),\ \kappa_1(\bar{p})$

centrality selection procedure

Predictions

—— $\kappa_2(p-\bar{p})$

- - - - - $\kappa_2(p)$

participants — vanishes at LHC

$$\kappa_2(N_B - N_{\bar{B}}) = \langle N_W\rangle \kappa_2(n_B - n_{\bar{B}}) + \langle n_B - n_{\bar{B}}\rangle^2 \kappa_2(N_W)$$

from single participant

Second cumulants of net-particles at LHC are not affected by participant fluctuations

easy control of systematics

A. R., QM2017, arXiv:1704.05329

Results from ALICE

Contribution from global baryon number conservation

$$\frac{\kappa_2(p-\bar{p})}{\kappa_2(Skellam)} = 1-\alpha \qquad \alpha = \frac{\langle p \rangle^{measured}}{\langle B \rangle^{4\pi}}$$

P. Braun-Munzinger, A. R., J. Stachel, arXiv:1612.00702, NPA 960 (2017) 114

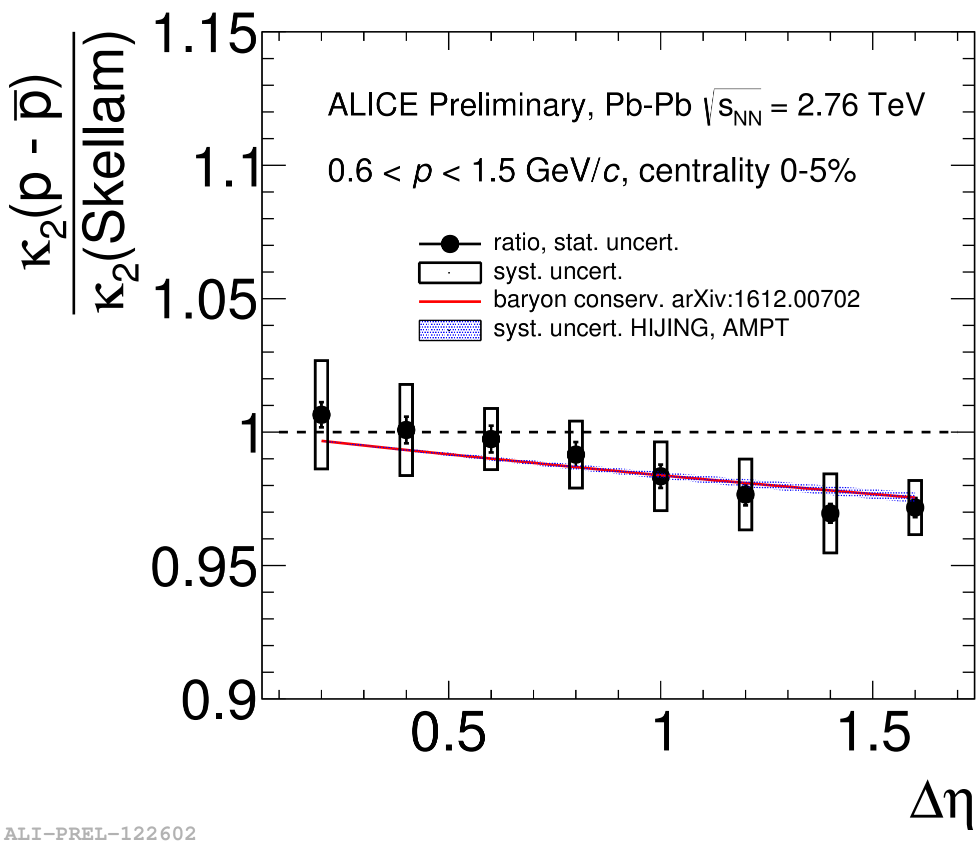
Inputs for $\langle B \rangle^{acc}$ from:

Phys. Lett. B 747, 292 (2015)
P. Braun-Munzinger, A. Kalweit, K. Redlich, J. Stachel

extrapolation from $\langle B \rangle^{acc}$ to $\langle B \rangle^{4\pi}$

using HIJING and AMPT models

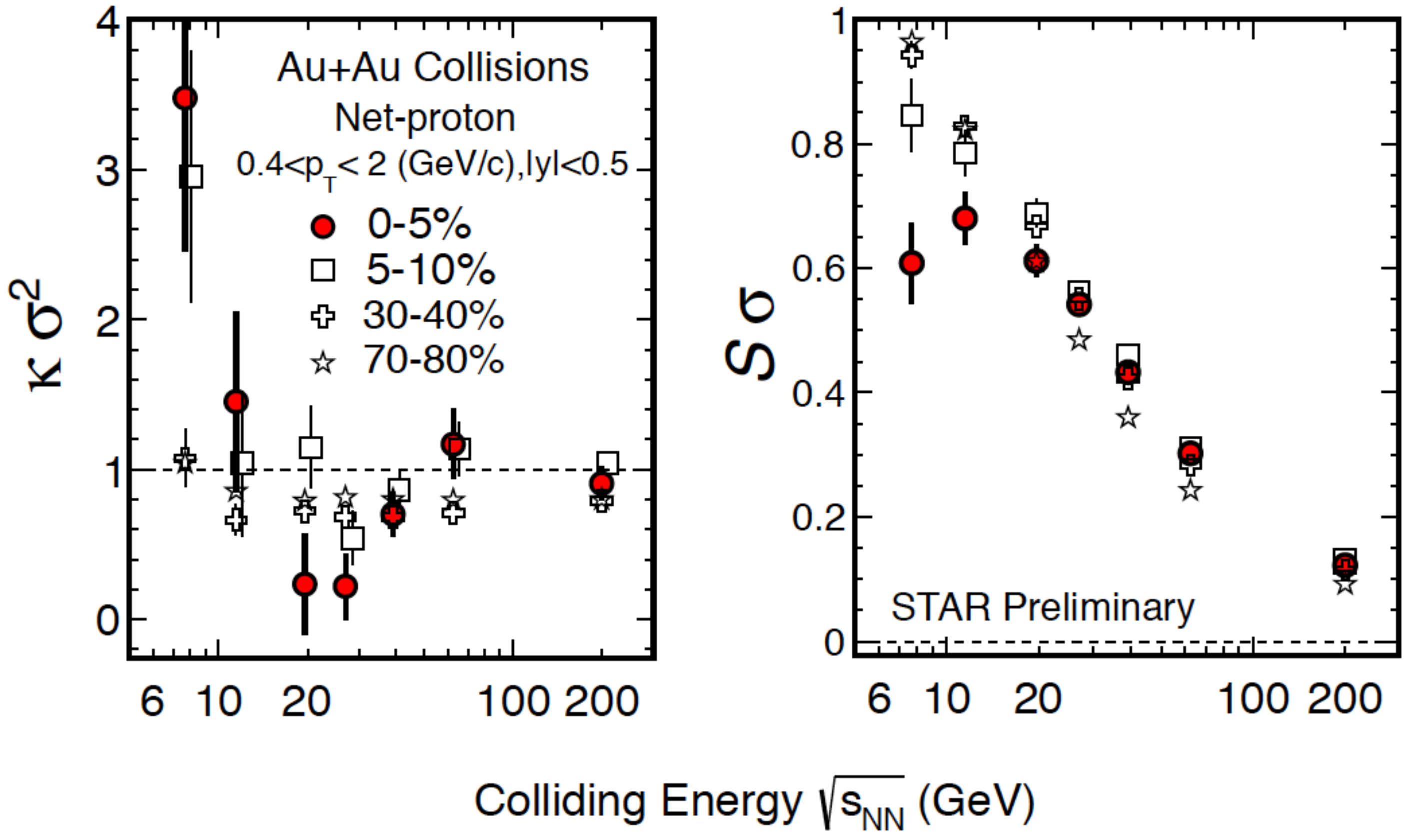
A. R., QM2017, arXiv:1704.05329
A. R., CPOD 2016



The deviation from Skellam is due to the global baryon number conservation.

Analysis of higher cumulants is ongoing!

Results from STAR



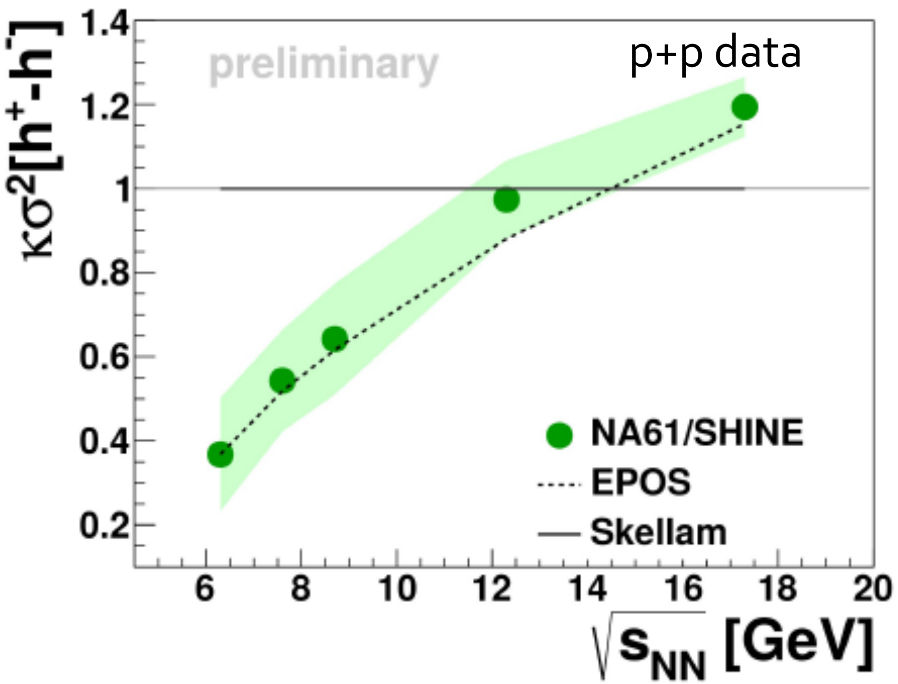
- Close to unity for peripheral collisions
- Below 39 GeV hints for a non-monotonic behavior
- ***More statistics and precise control of systematics are needed to explore this region***

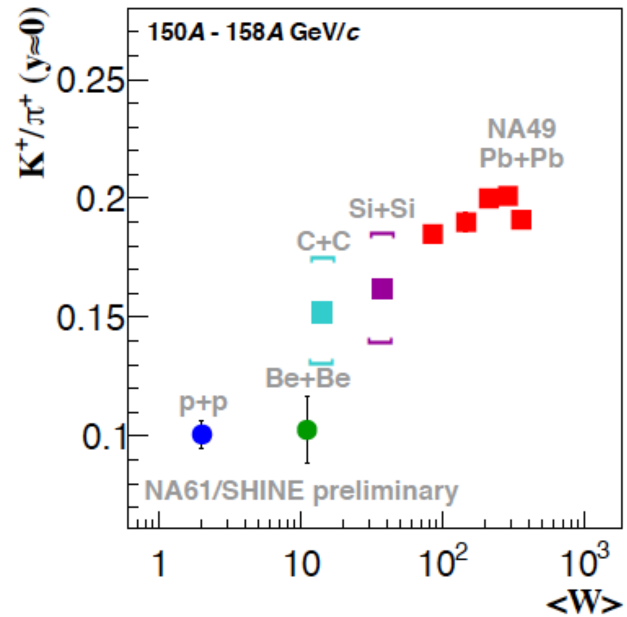
Drop at 7.7 GeV for central events

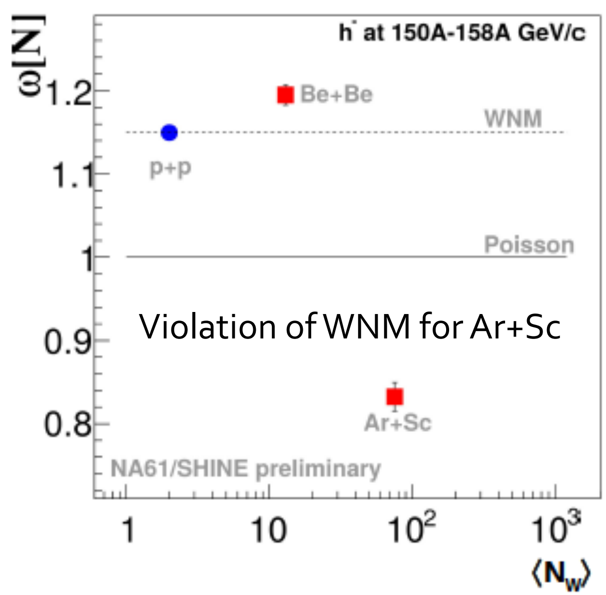
X. Luo, PoS CPOD2014, 019 (2015)
STAR: PRL 112, 032302 (2014)

NOTE: Only statistical uncertainties are presented!

Results from NA61/SHINE/NA49



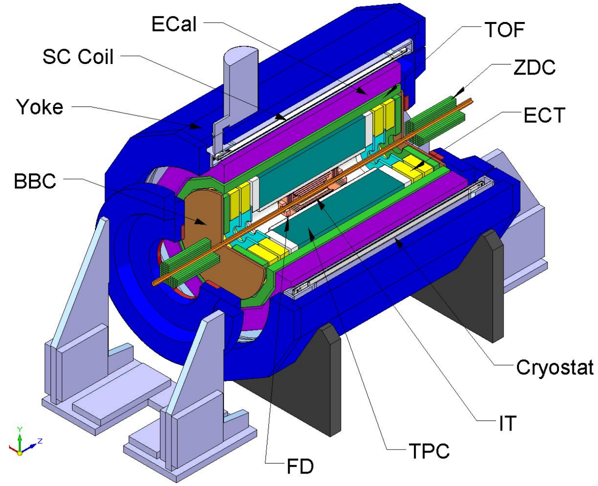


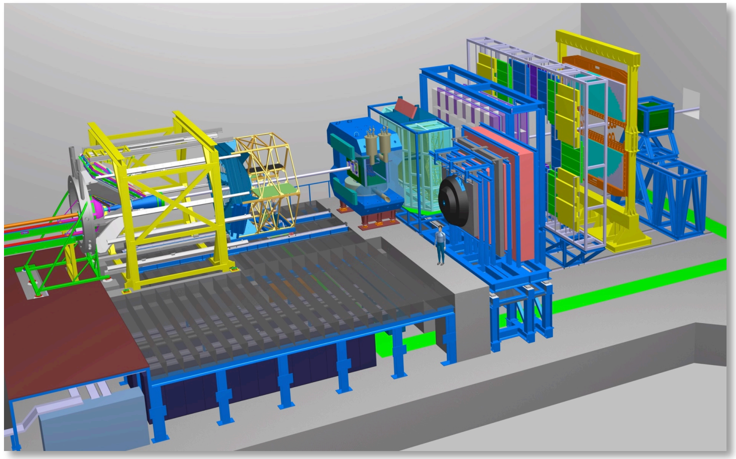


- reproduced by EPOS
- Skellam is not a proper baseline

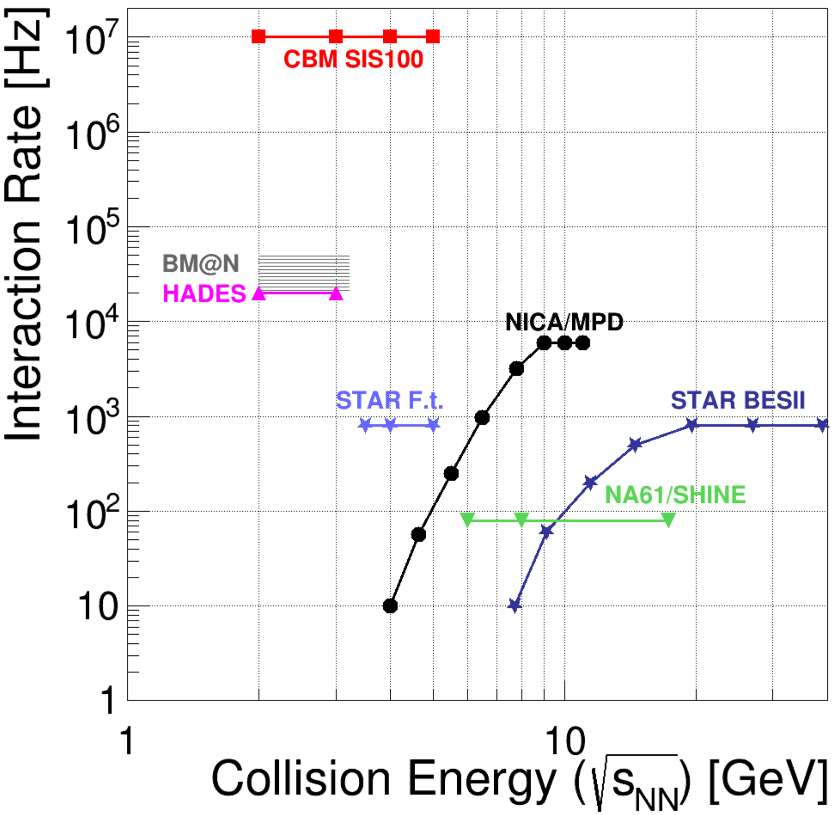
Near Future Experiments

MPD at NICA (collider mode)





CBM at FAIR (fixed target)



V. Kekelidze, QM2017
P. Senger, QM2017

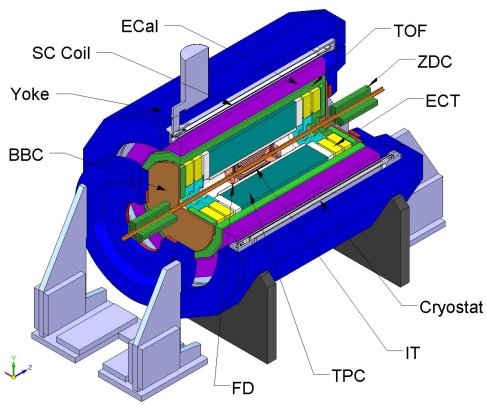
Summary

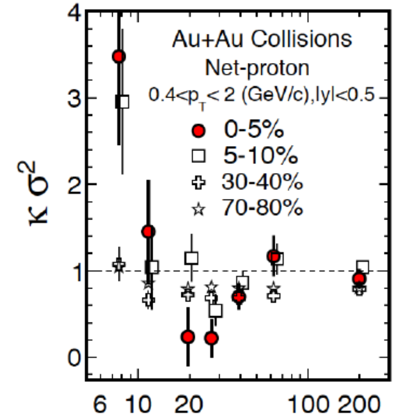
- The measured second cumulants of net-protons at ALICE are, after accounting for baryon number conservation, in agreement with the corresponding second cumulants of the Skellam distribution.
  - LQCD predicts a Skellam behavior for κ_2 of net-baryons at 150 MeV.
- Net-proton measurements from STAR hints for a non-monotonic behavior for energies below 39 GeV. More statistics and control of systematics are needed.
- NA61 data shows violation of the WNM model for Ar+Sc data
- *The analysis of higher cumulants are ongoing in ALICE, which is extremely important for understanding the nature of transition at vanishing μ_B*

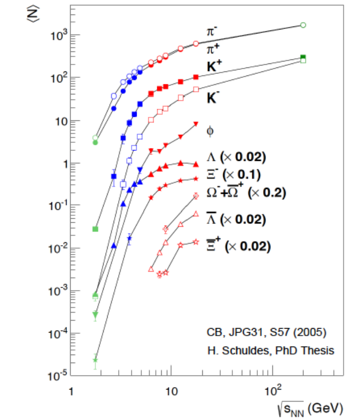
Outlook

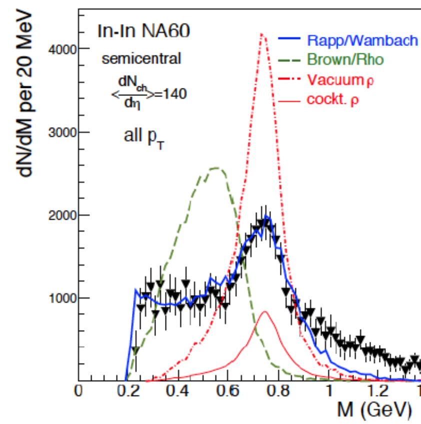
- *No clear signals for critical point*
- *No direct evidence for chiral symmetry restoration*
- *Missing hadron yields and spectra in the NICA energy range*
- *Additional phases at lower baryon chemical potential?*

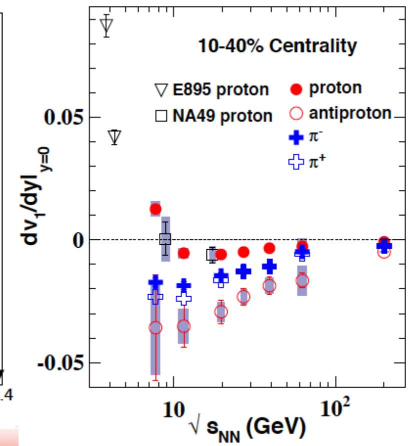
All these and other unresolved issues can and should be explored at the upcoming MPD@NICA

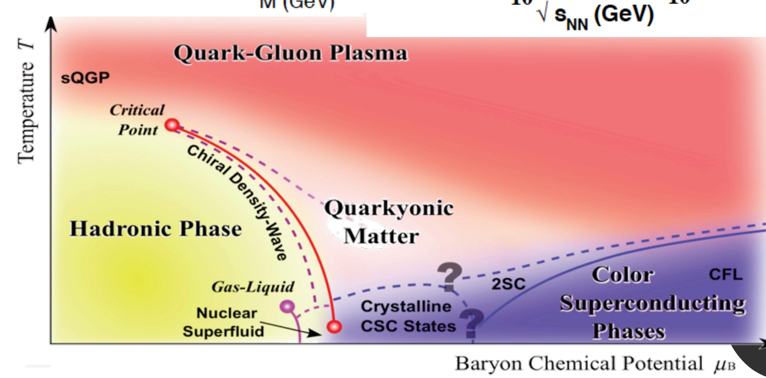






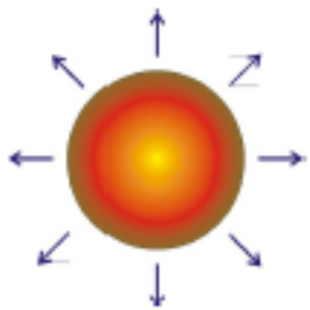






Probing the equation of state

spherical (radial)

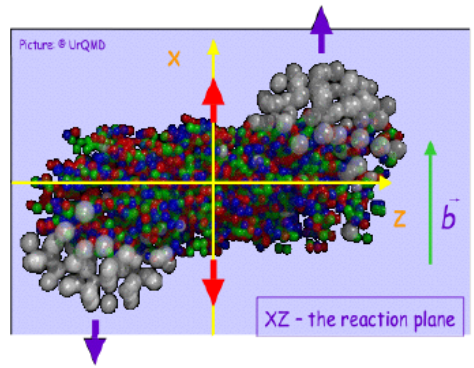


probes EoS

$$\frac{1}{m_T}\frac{d^2n}{dm_T dy} = \alpha e^{-\frac{m_T}{T}}$$

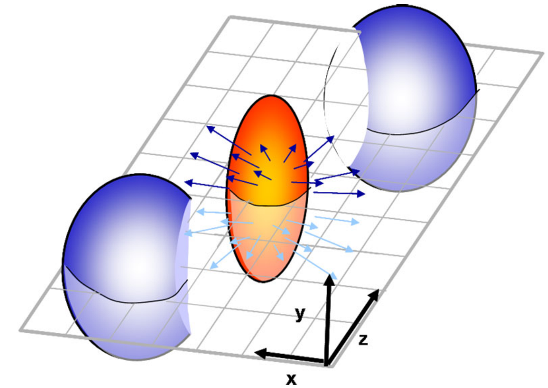
$$T = T_F + m\langle\beta_T\rangle^2, p_T < 2GeV$$

directed



Spectators deflected from dense reaction zone
probes EoS
sensitive to pressure

elliptic

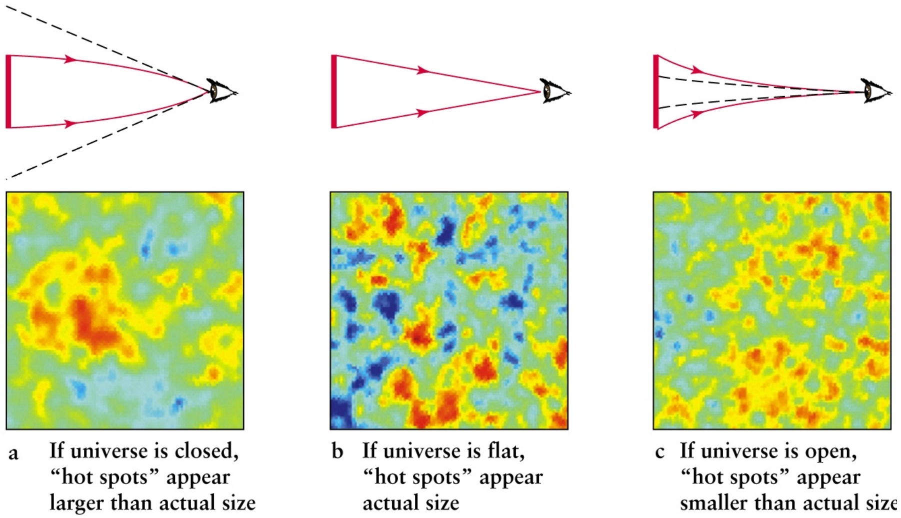


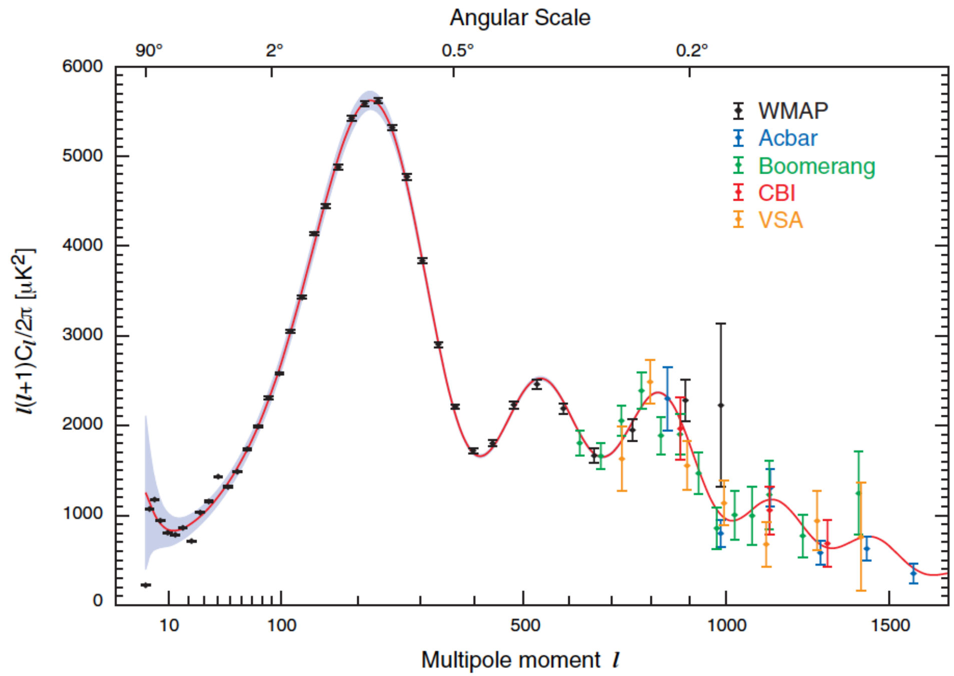
Asymmetry out vs. in-plane
sensitive to EoS
measure of perfect fluid

$$E\frac{d^3N}{d^3\vec{p}} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1 + 2v_1\cos(\phi-\psi_{RP}) + 2v_2\cos(2(\phi-\psi_{RP}))+...\right]$$

$$v_n = \langle\cos(n(\phi-\psi_{RP}))\rangle$$

Fluctuations in the Early Universe





Age of the Universe: 13.77 billion years

The Universe if flat within 0.4 %

Ordinary matter ~ **4.6 %**

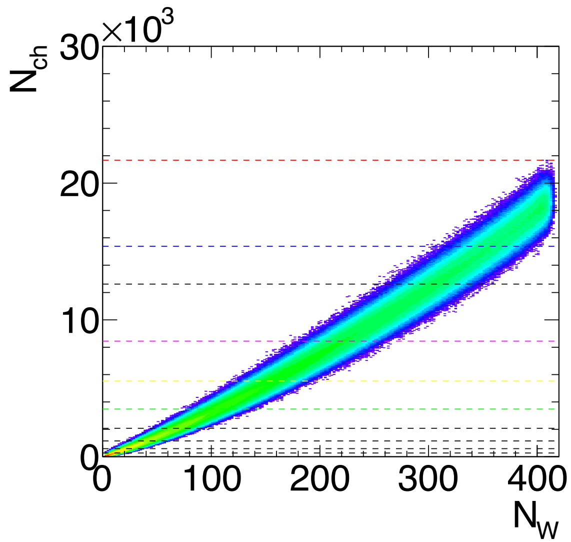
Dark matter ~ **24%**

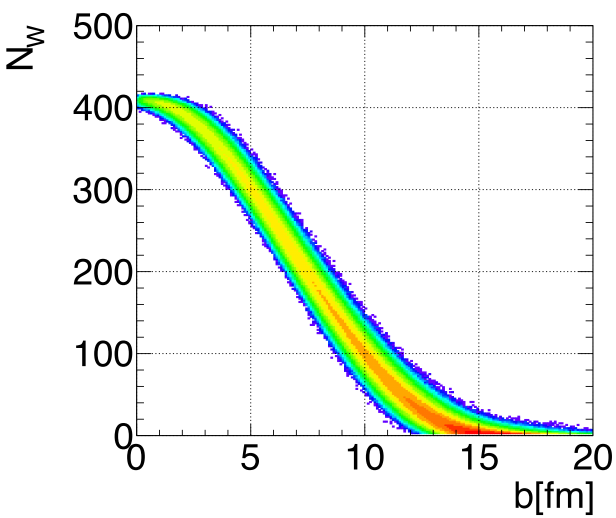
Dark energy ~ **71.4 %**

…

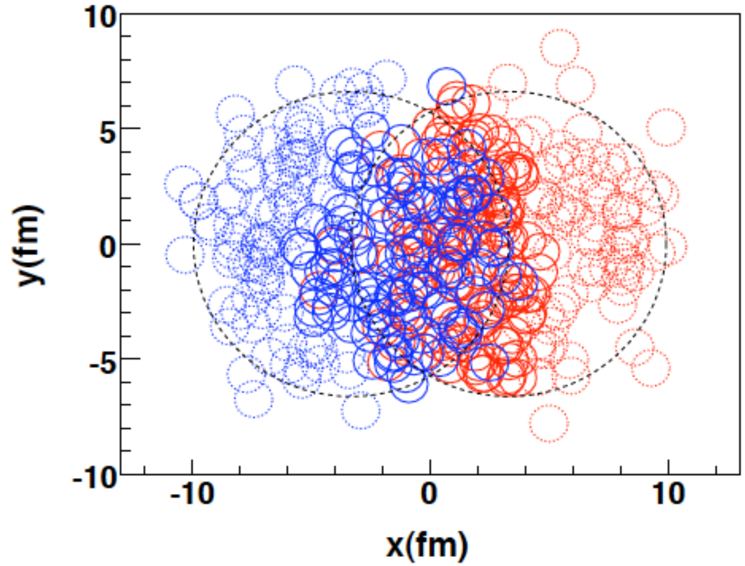
Non-dynamical contributions

Experimental approaches:





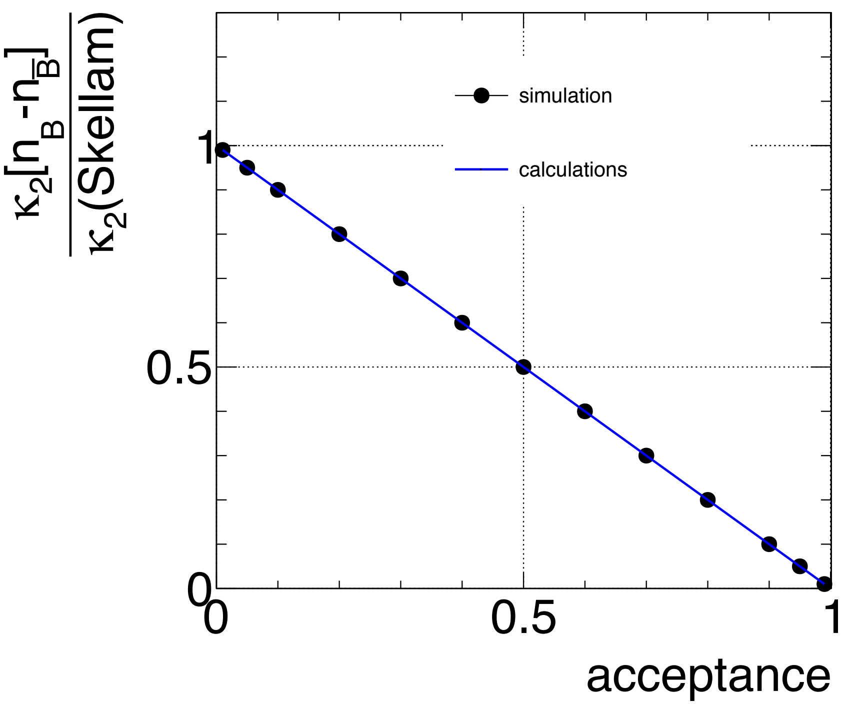
Glauber Model

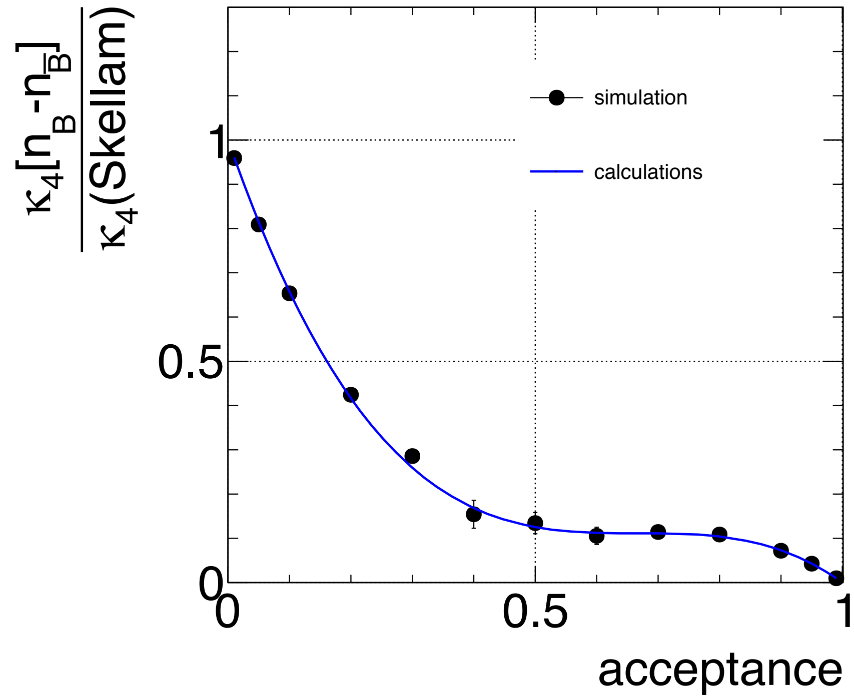


- **Each approach gives:**
  - Similar $\langle N_w \rangle$
  - Very different $\langle N_W^n \rangle$

For higher moments centrality selection is crucial!

Acceptance is crucial



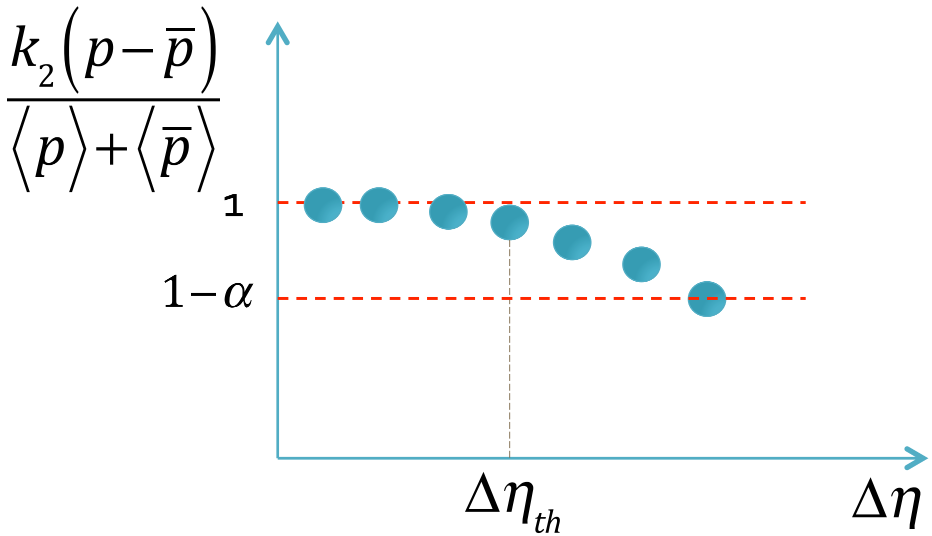


- Model assumption: full correlation in 4 pi (baryon number conservation)
- Approach to independent Poisson (Skellam) for a small acceptance
- Approach to zero for full acceptance
- Acceptance is more crucial for the 4^{th} cumulant
- κ2/Skellam -> 1-acceptance

$$\kappa_2\left(n_B - n_{\bar{B}}\right) = \kappa_2\left(n_B\right) + \kappa_2\left(n_{\bar{B}}\right) - 2\left(\left\langle n_B n_{\bar{B}}\right\rangle - \left\langle n_B\right\rangle\left\langle n_{\bar{B}}\right\rangle\right)$$

P. Braun-Munzinger, A. R., J. Stachel, in preparation

Baryon number conservation



$$\frac{k_2(p-\bar{p})}{\langle p\rangle+\langle\bar{p}\rangle}=1-\alpha$$

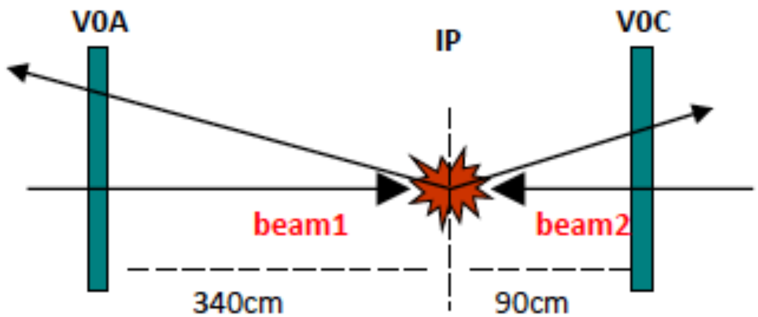
$$\alpha=\frac{\langle n_p^{acc}\rangle}{\langle N_B^{4\pi}\rangle}$$

A. R. talk at CPOD 2016

Proposed comparison procedure:

- Eliminate volume dependence
- Perform analysis for $\Delta\eta>\Delta\eta_{th}$
- Calculate acceptance factors based on experimental data $\alpha(\Delta\eta)=\frac{p^{acc}}{B^{4\pi}}$
- Correct the experimental data
- Compare to LQCD

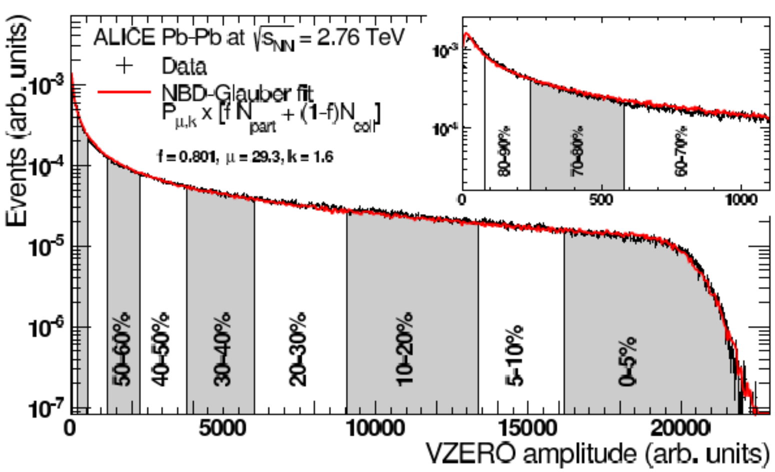
Centrality determination

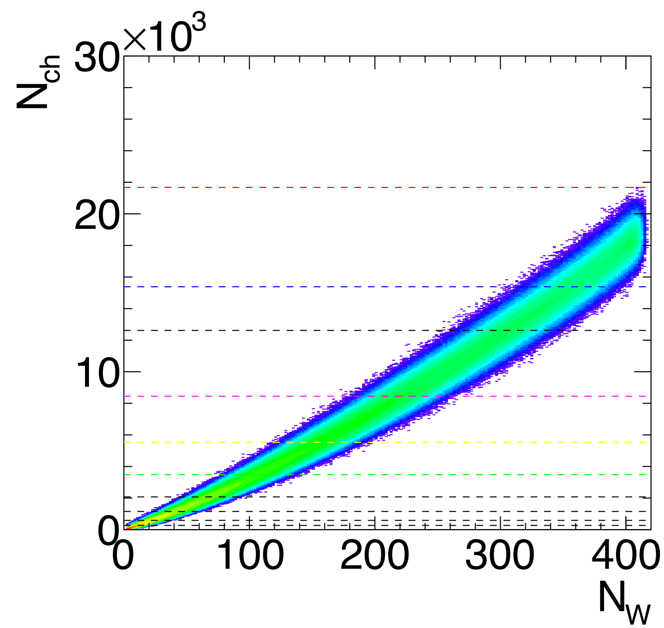


ALICE Phys.Rev. C88 (2013) no.4, 044909

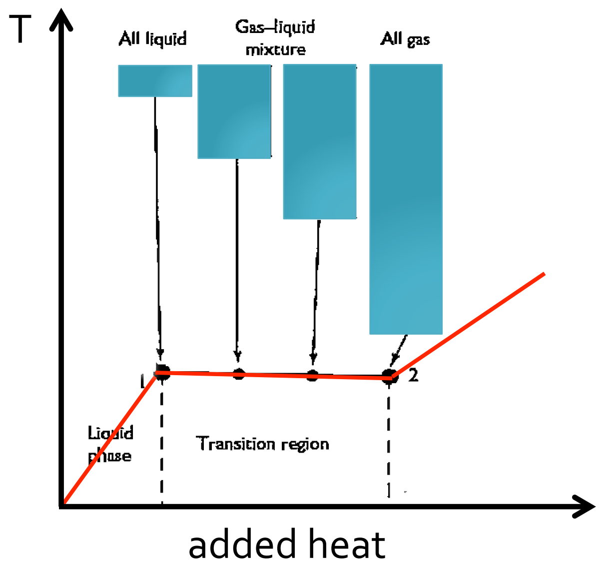
$$P_{\mu,k}(n) = \frac{\Gamma(n+k)}{\Gamma(n+1)\Gamma(k)} \frac{\left(\mu/k\right)^n}{\left(\mu/k+1\right)^{n+k}}$$

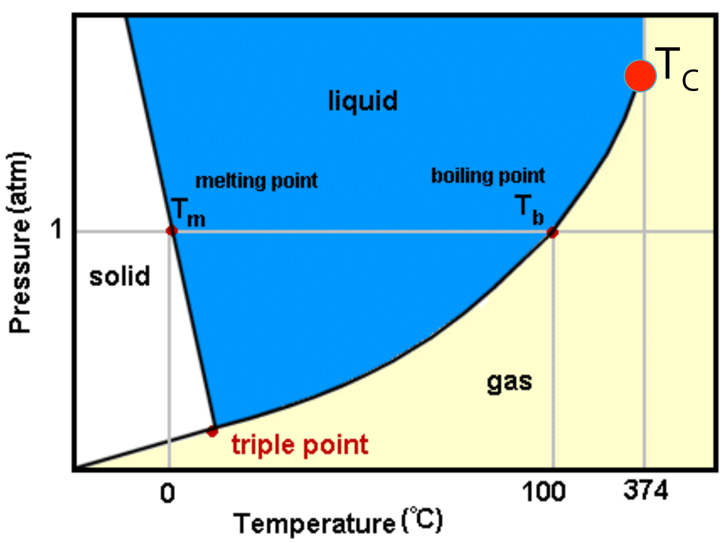
$$N = fN_W + (1-f)N_{coll}$$

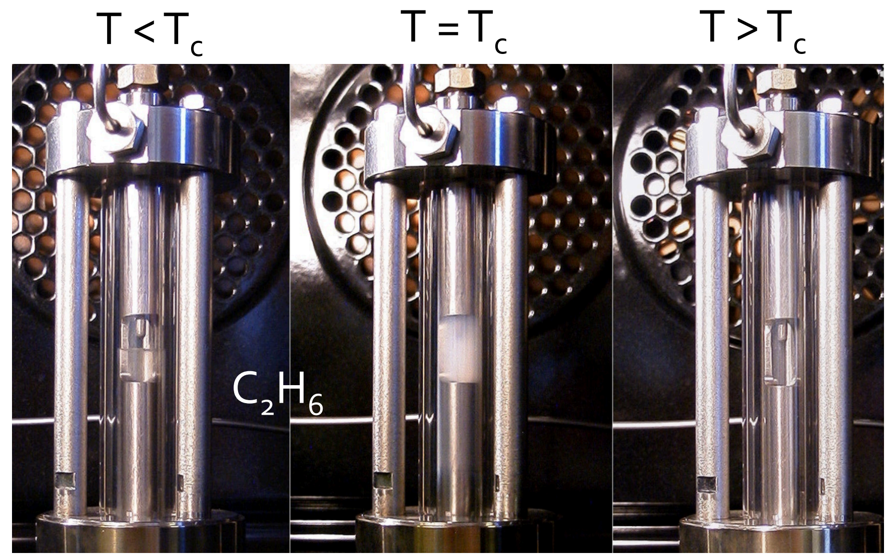




Electromagnetically Interacting matter







$$\frac{\langle \rho^2 \rangle - \langle \rho \rangle^2}{\langle \rho \rangle^2} = \frac{T\chi}{V}, \quad \chi = -\frac{1}{V}\frac{\partial V}{\partial P}$$

Einstein, 1910

$$Rayleigh\,Ratio \propto \chi$$

probing phase transitions
with fluctuations