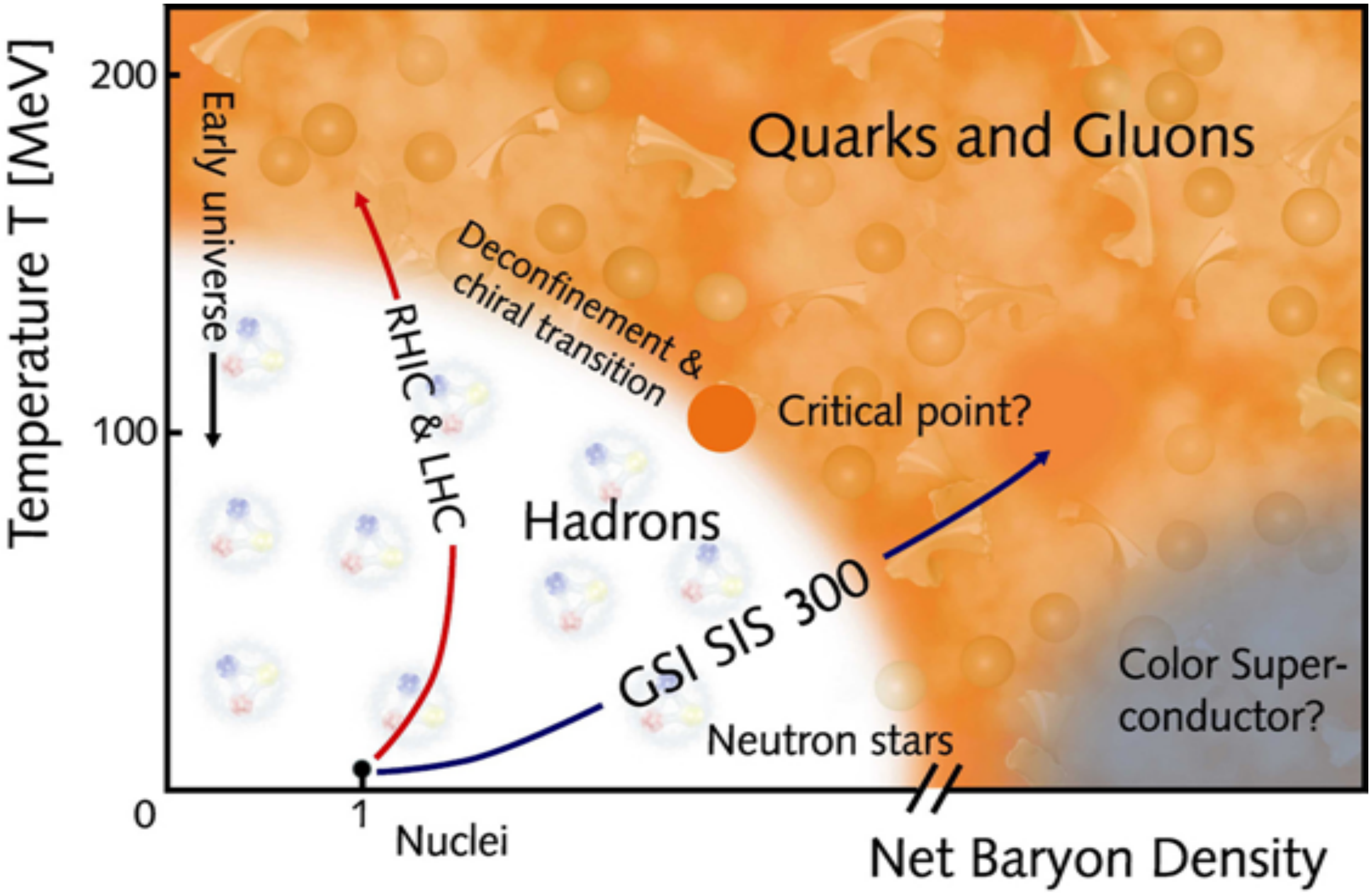
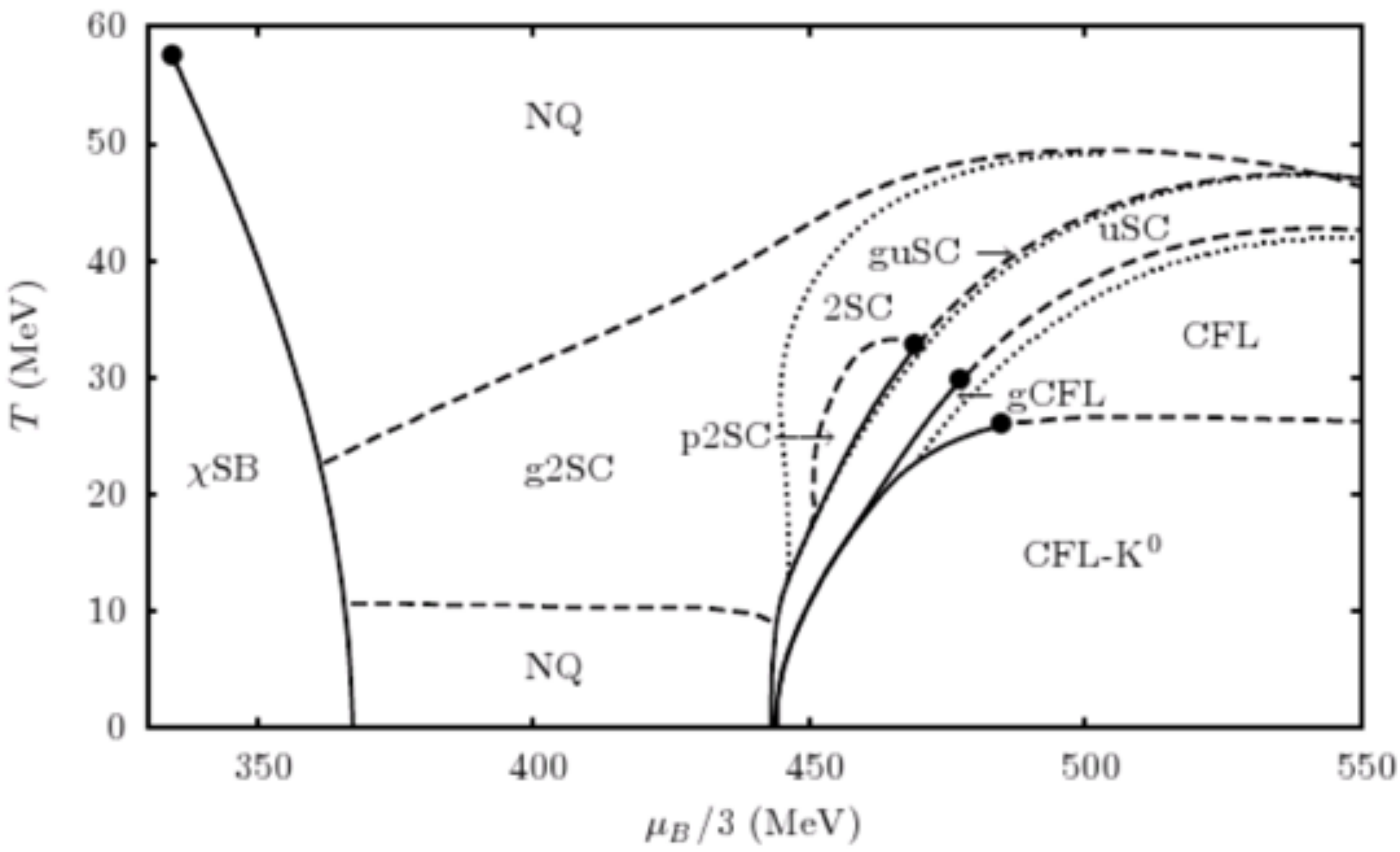
Fishing For the QCD Phase Transition

The QCD Phase diagram



Can be very rich

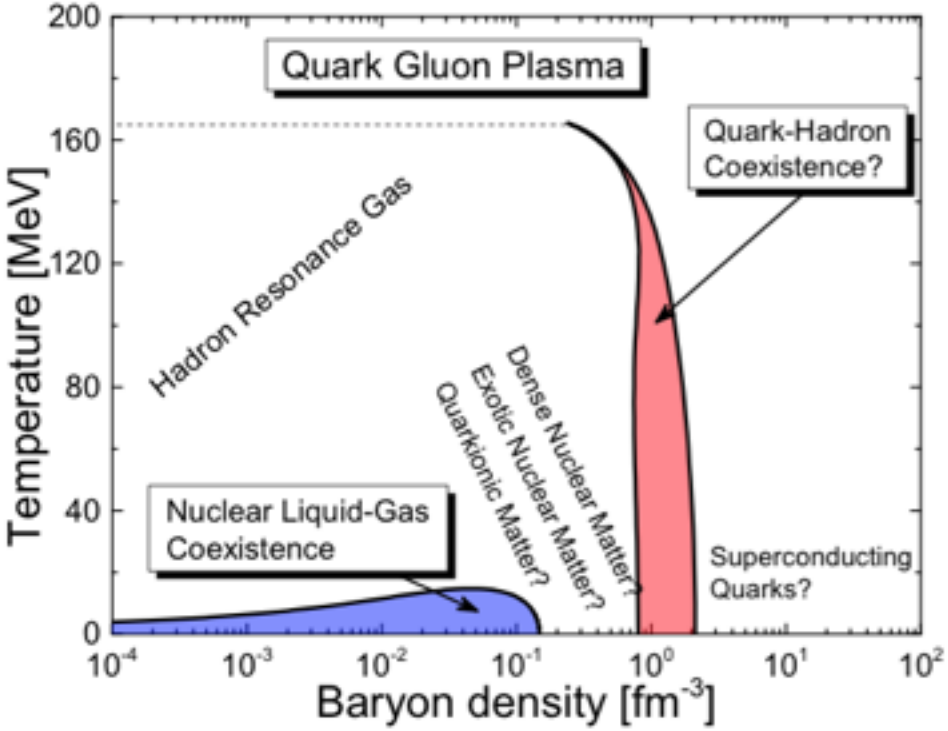


H. Warringa hep-ph/0606063

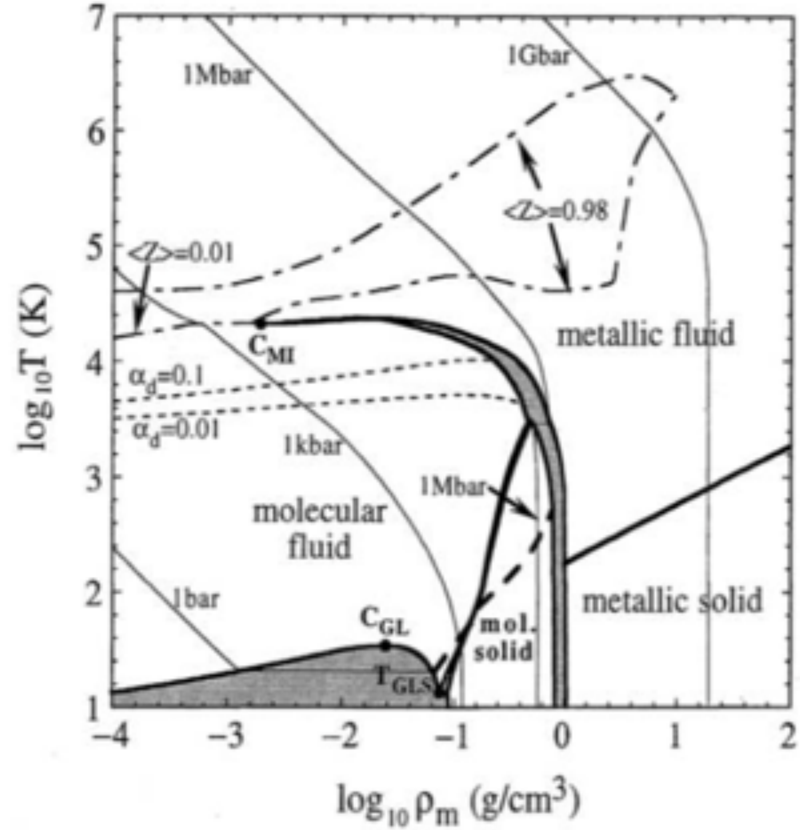
At least theoretically……

Phase Diagrams

Maybe it's better to look at the Phase diagram in density.



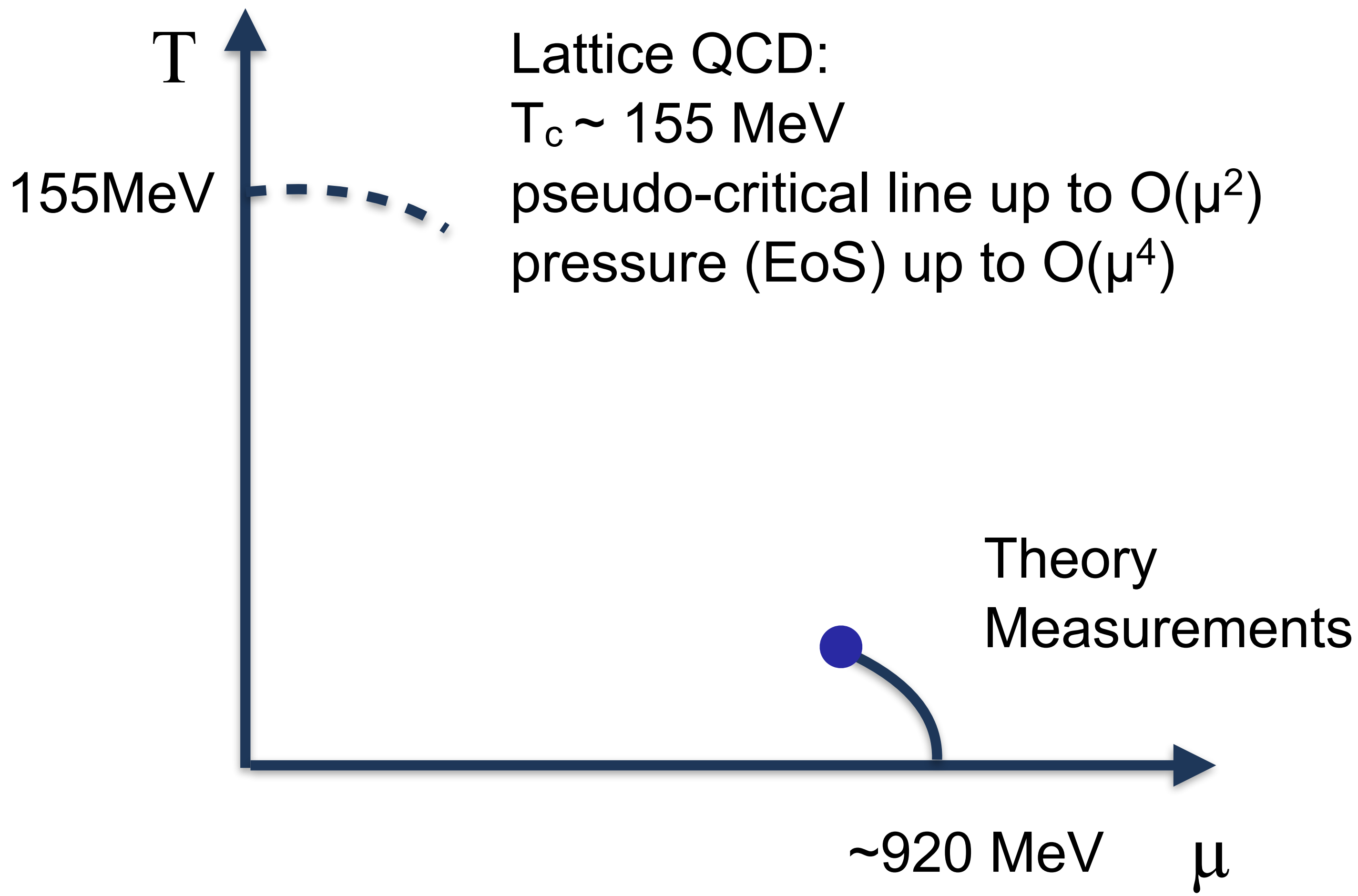
M. Hempel, V. Dexheimer, S. Schramm and I. Iosilevskiy, Phys. Rev. C 88, no. 1, 014906 (2013)



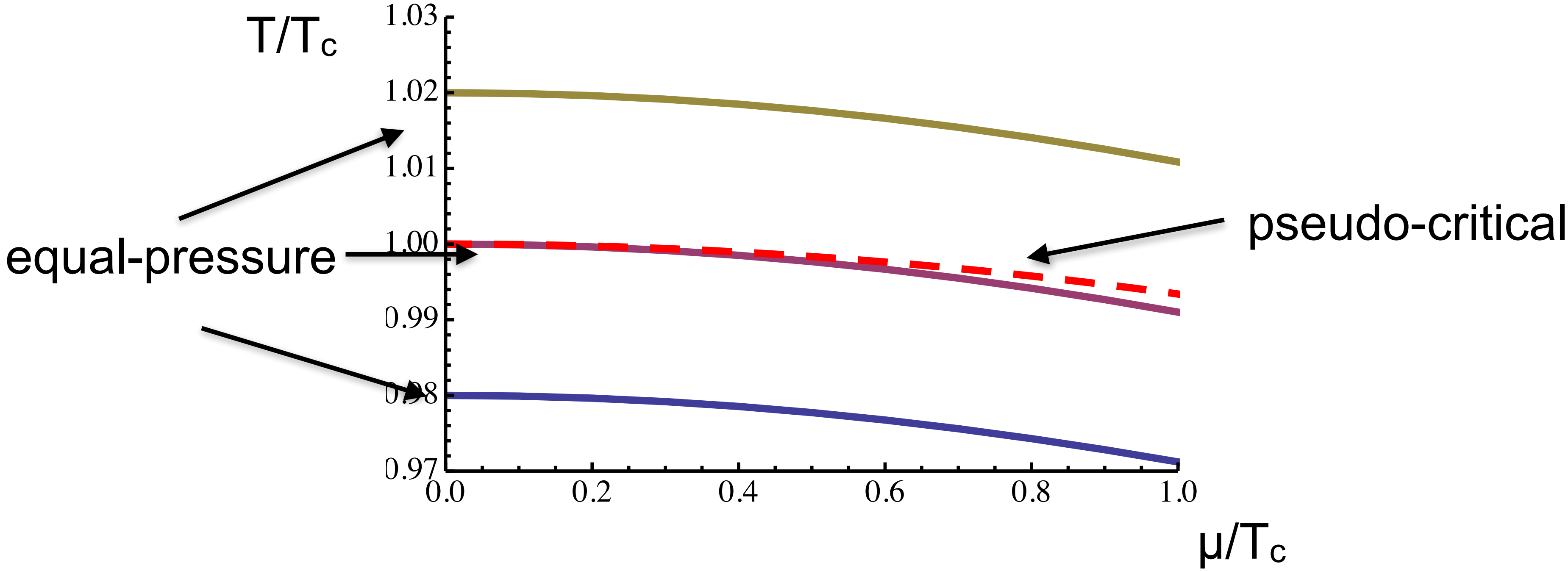
Kitamura H., Ichimaru S., J. Phys. Soc. Japan 67, 950 (1998).

Curious similarity

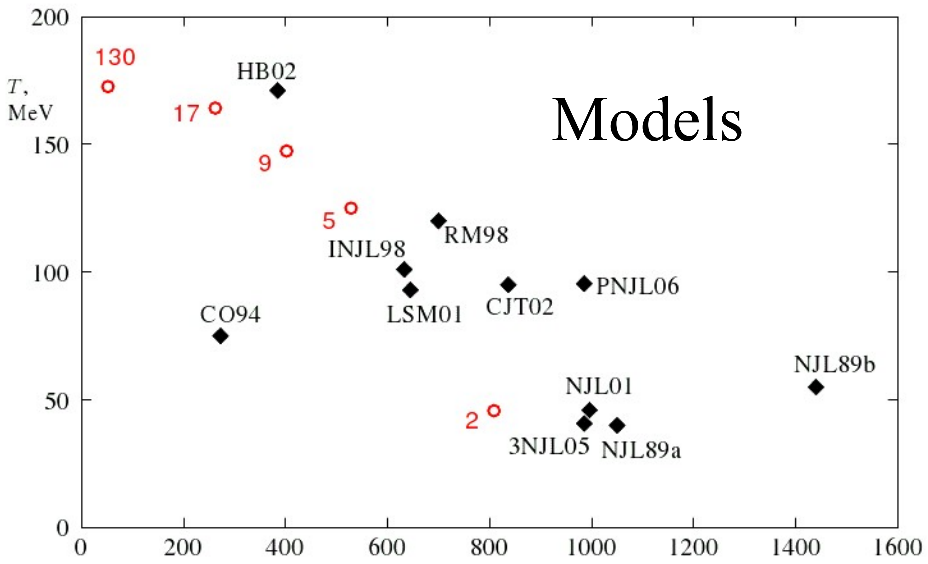
What we know about the Phase Diagram

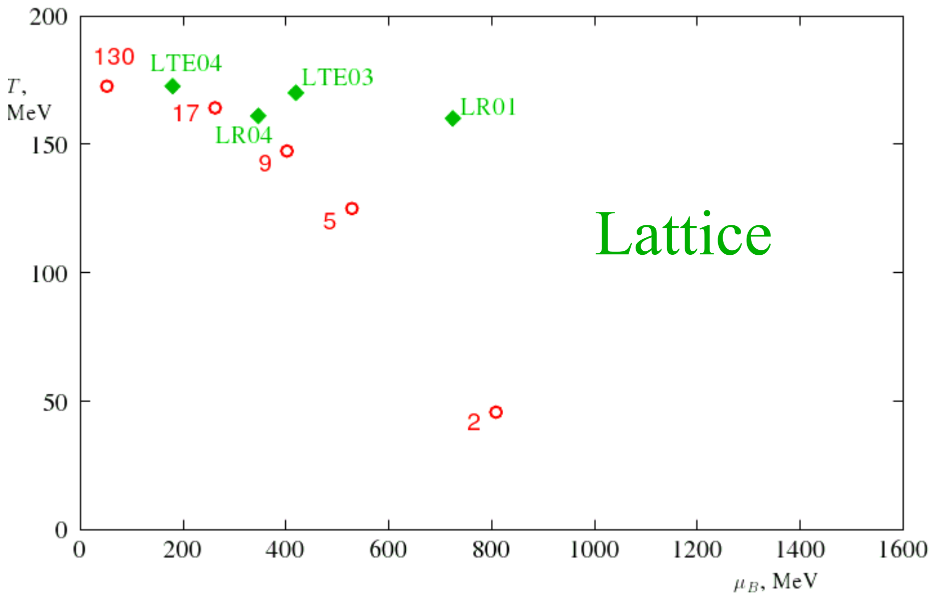


Equal-pressure and Pseudo critical line(s)



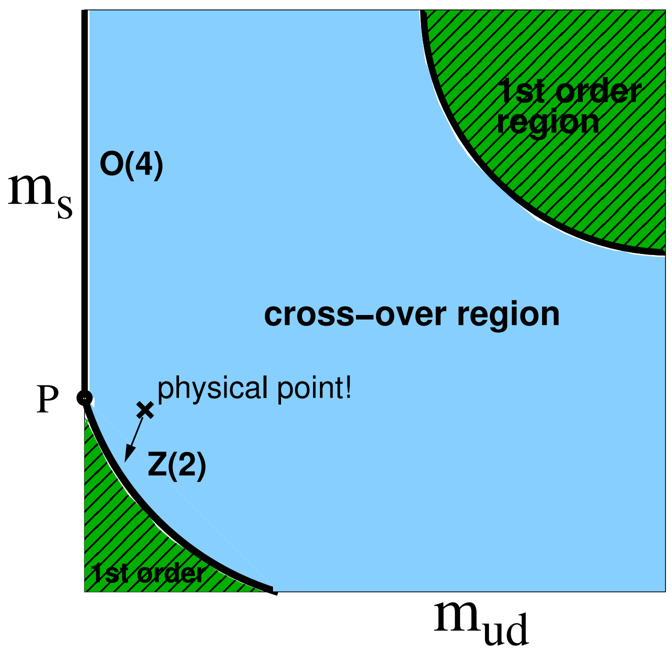
Is there a critical point?

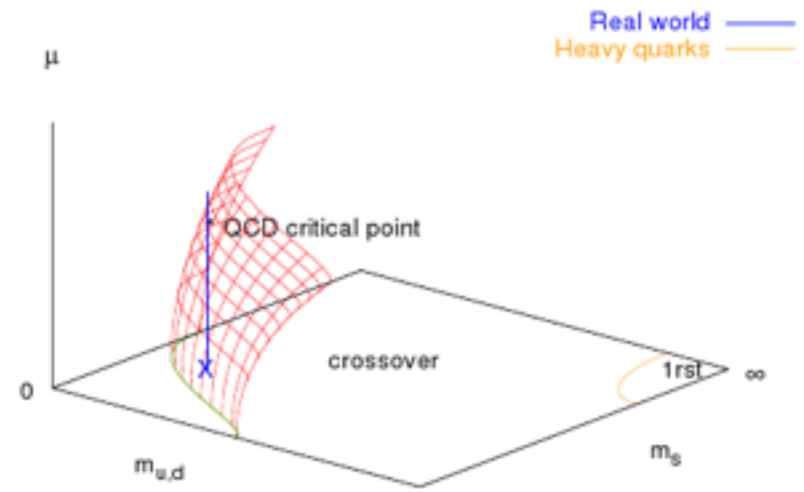




Lots of them!

Is there a critical point?

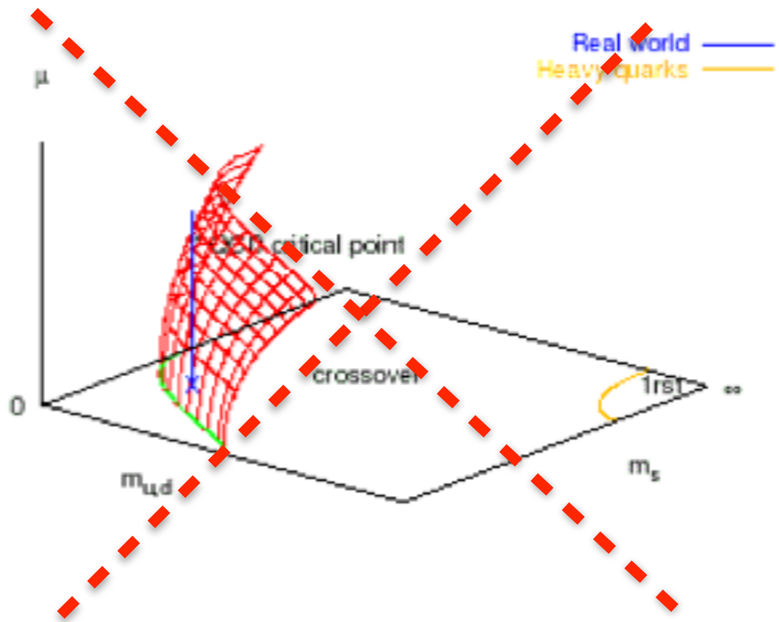




Is there a critical point?

A non-standard scenario: no critical point?

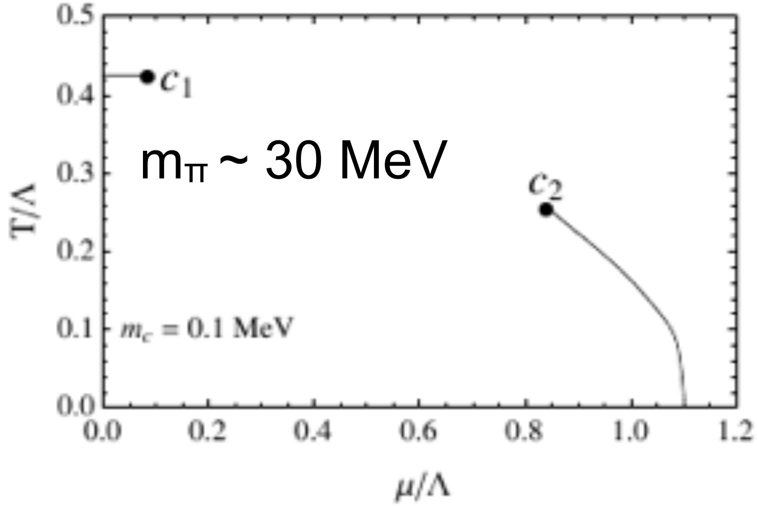
sign of $c_1 = \frac{dm_c(\mu)}{d\mu^2}|_{\mu=0}$

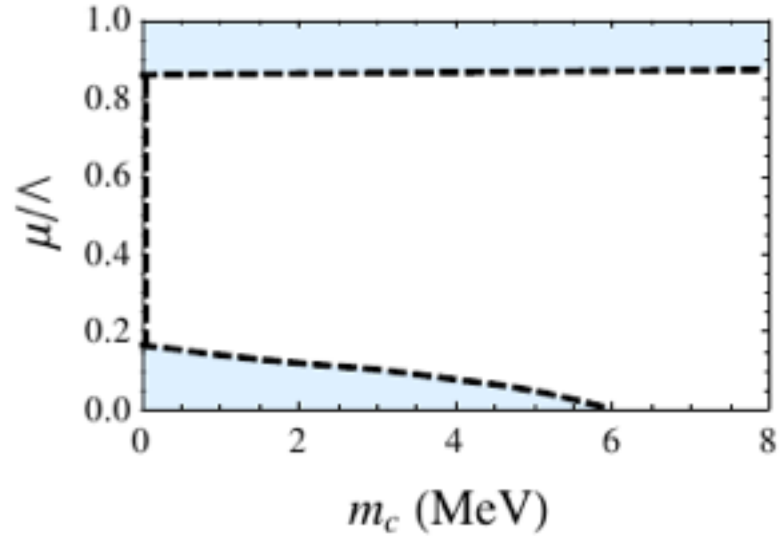


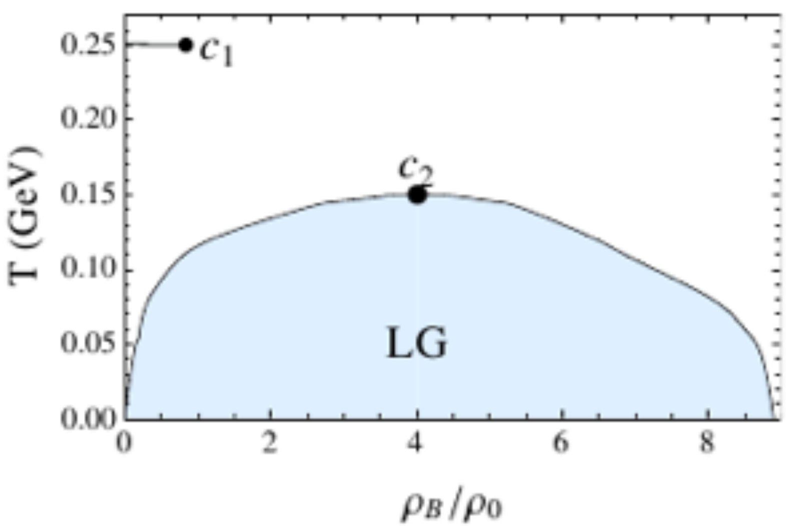
Note: Surface may bend back!

Two critical points?

M. Pinto et al, Phys.Rev. C82 (2010) 055205

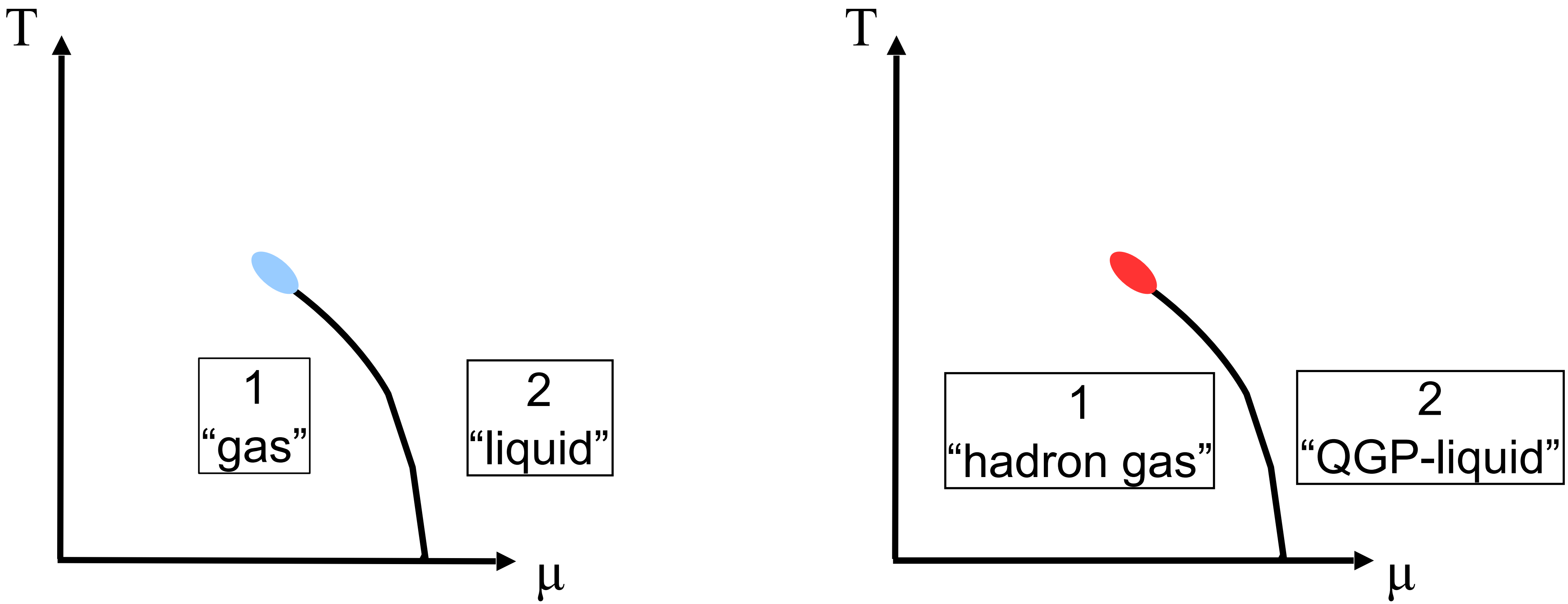






Seen in both Nambu and Linear Sigma Model

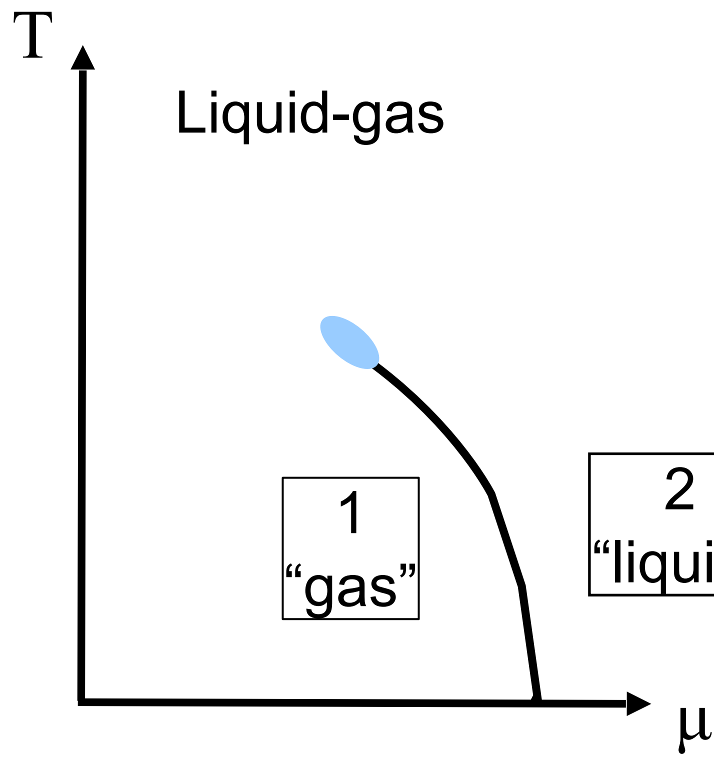
Remarks on Phase diagram

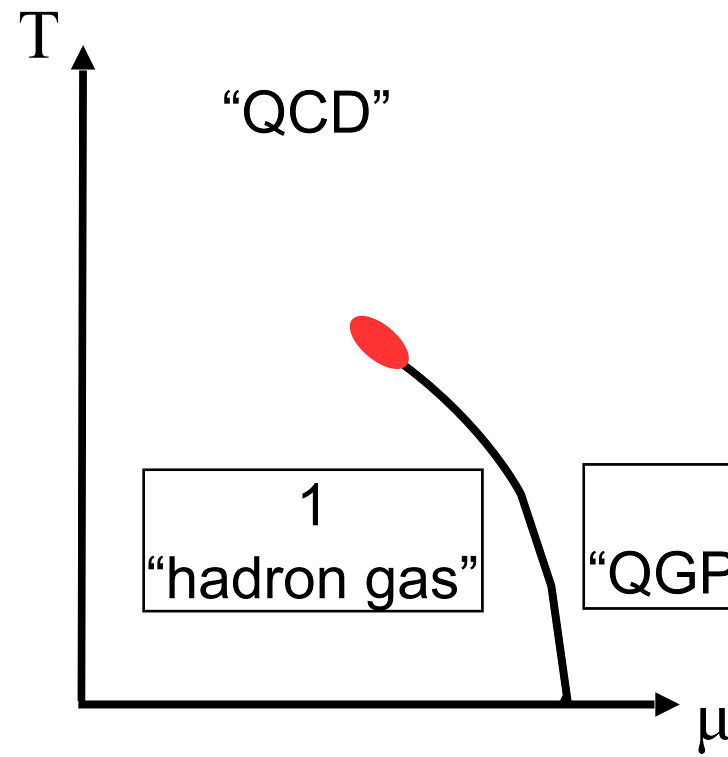


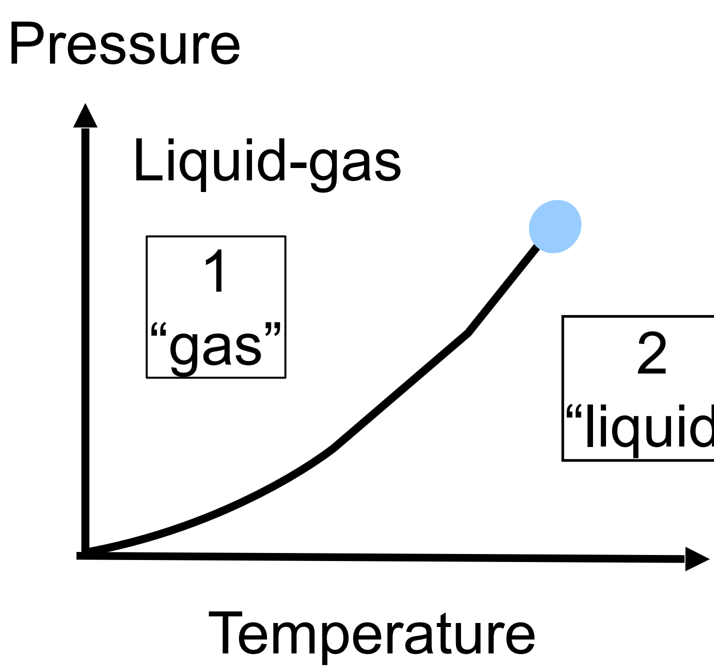
Liquid-Gas
Water, nuclear matter, ...

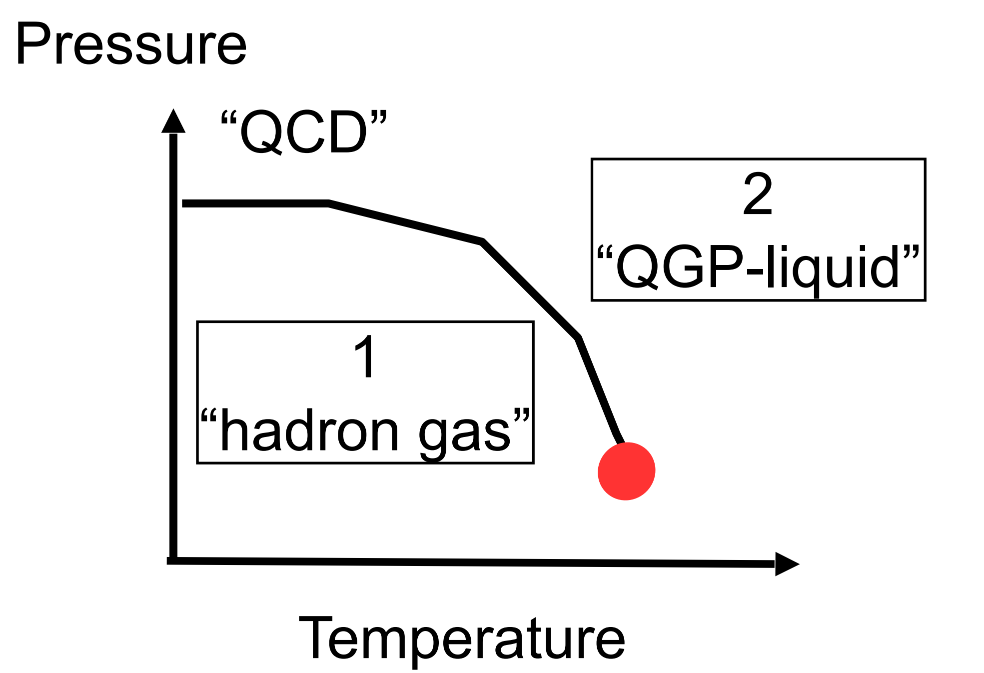
"QCD"

Steinheimer et al, Phys.Rev. C89 (2014) 034901

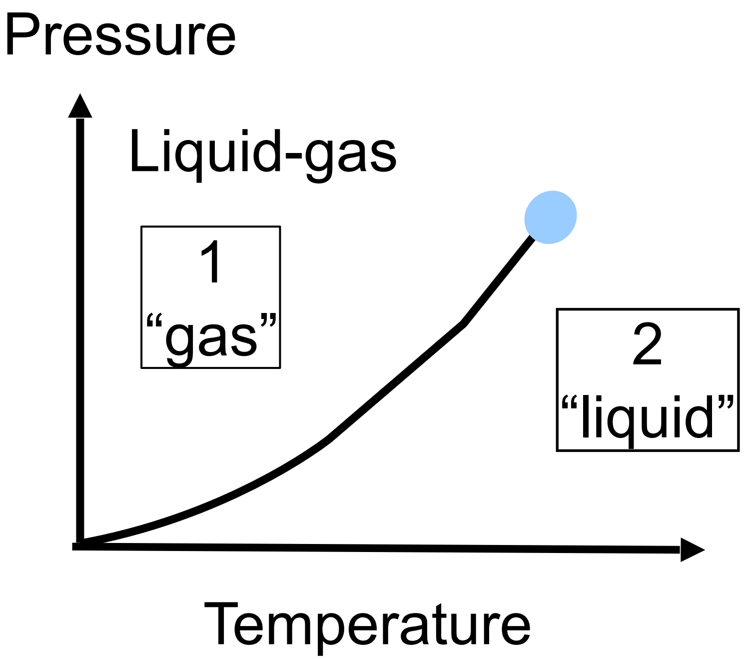

T
Liquid-gas
1
"gas"
2
"liquid"
μ

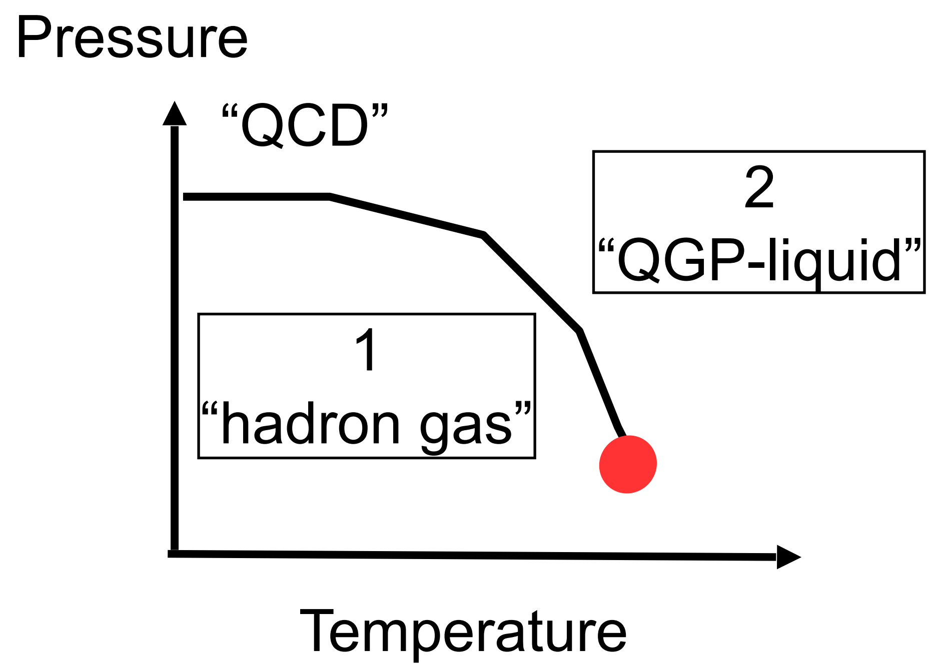

T
"QCD"
1
"hadron gas"
2
"QGP-liquid"
μ


Pressure
Liquid-gas
1
"gas"
2
"liquid"
Temperature


Pressure
"QCD"
2
"QGP-liquid"
1
"hadron gas"
Temperature

Liquid Gas vs QCD PT





Clausius-Clapeyron: $\frac{dP}{dT} = \frac{S_1/B_1 - S_2/B_2}{1/\rho_1 - 1/\rho_2}$ $\quad \rho_2 > \rho_1 \rightarrow (1/\rho_1 - 1/\rho_2) > 0$

$$\frac{dP}{dT} > 0 \rightarrow S_1/B_1 > S_2/B_2$$

$$\frac{dP}{dT} < 0 \rightarrow S_1/B_1 < S_2/B_2$$

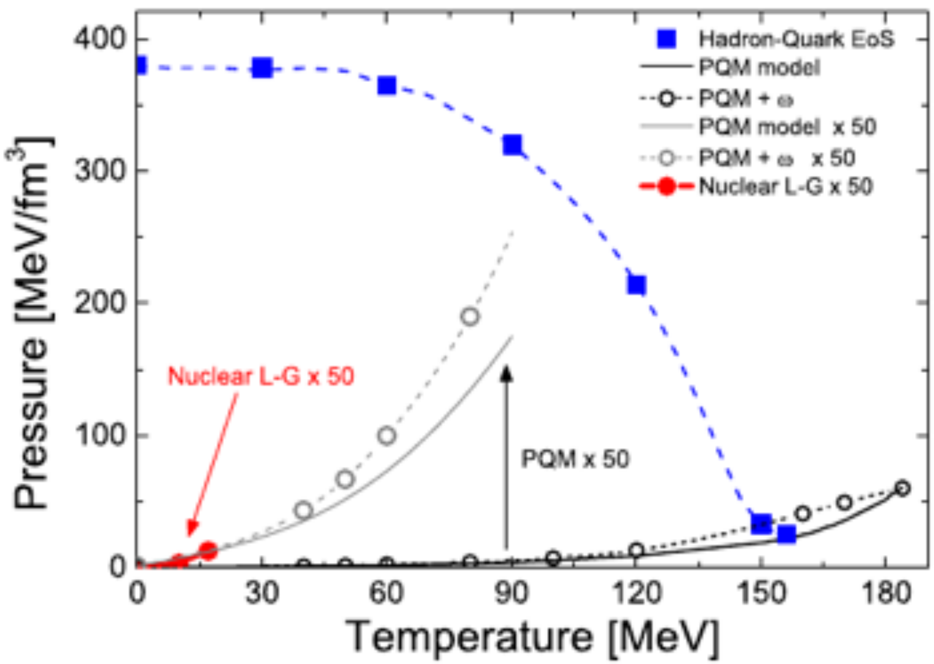
$$\left(\frac{S}{B}\right)_{gas} > \left(\frac{S}{B}\right)_{liquid}$$

$$\left(\frac{S}{B}\right)_{hadron-gas} > \left(\frac{S}{B}\right)_{QGP-liquid}$$

See e.g. Hempel et al, arXiv:1302.2835

Liquid-gas vs QCD

QCD: pressure at T=Tc and μ=0 same as at T=0 and ρ ~ 2.5 ρ0

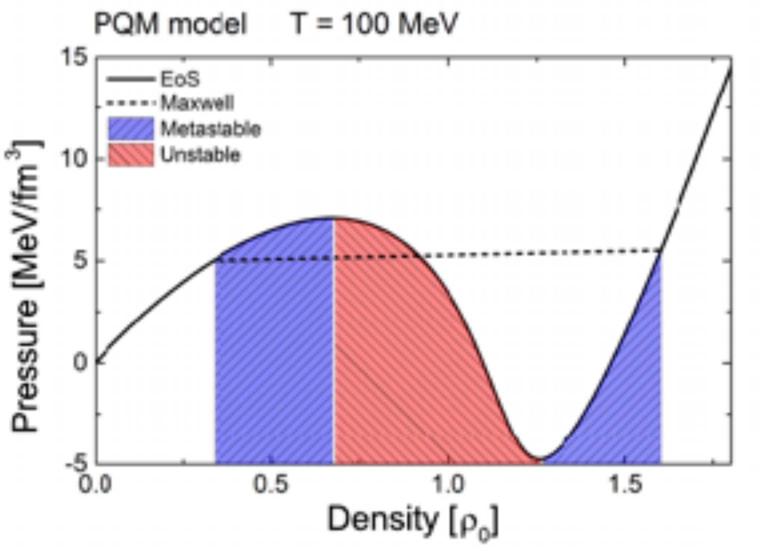


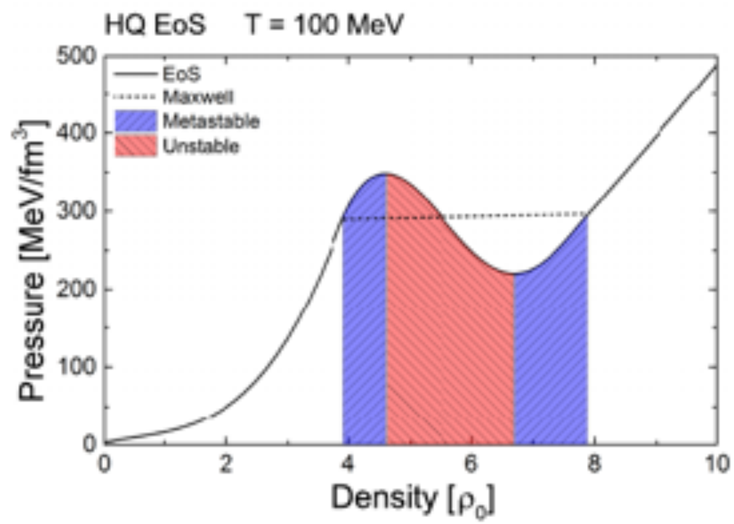
Steinheimer et al,
Phys.Rev. C89 (2014) 034901

If T=0 phase transition happens above 2.5 ρ_0 → $\frac{dP}{dt} < 0$

Note: virtually ALL models predicting a QCD critical point have $\frac{dP}{dt} > 0$

Liquid-gas vs QCD



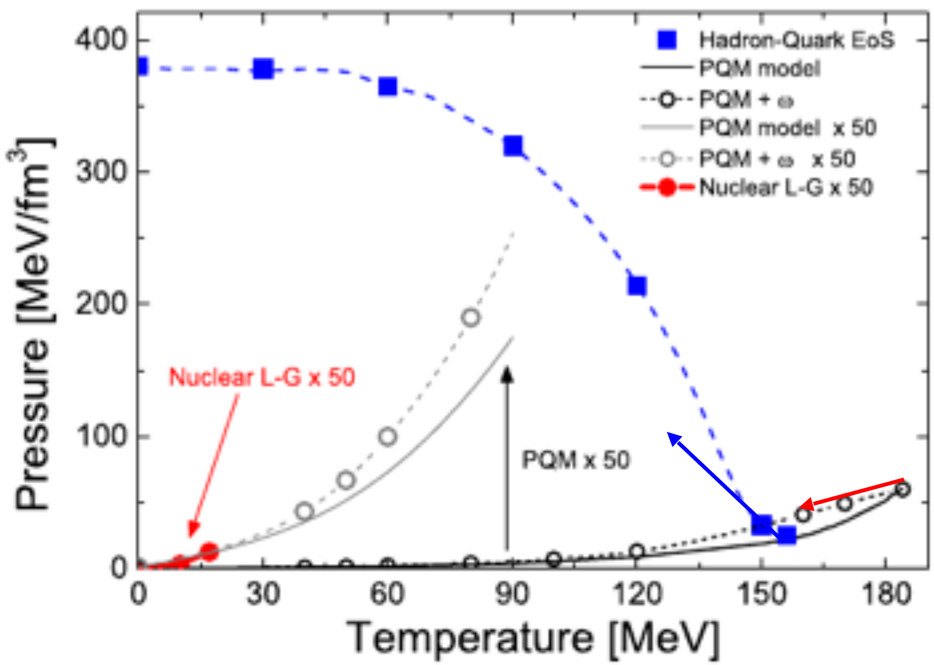


Liquid Gas:
T=0: Liquid co-exists with vacuum

QCD:
T=0: Liquid co-exists with nuclear matter

Steinheimer et al,
Phys.Rev. C89 (2014) 034901

Lattice to the rescue?



Slope of pressure along pseudo-critical line

$$\frac{\partial}{\partial T} p_{\rm pc}(T, \mu = 0)|_{T=T_\times} = s(T_\times, \mu = 0) - \frac{T_\times^3}{2\kappa} \chi_2(T_\times) \,. \quad (18)$$

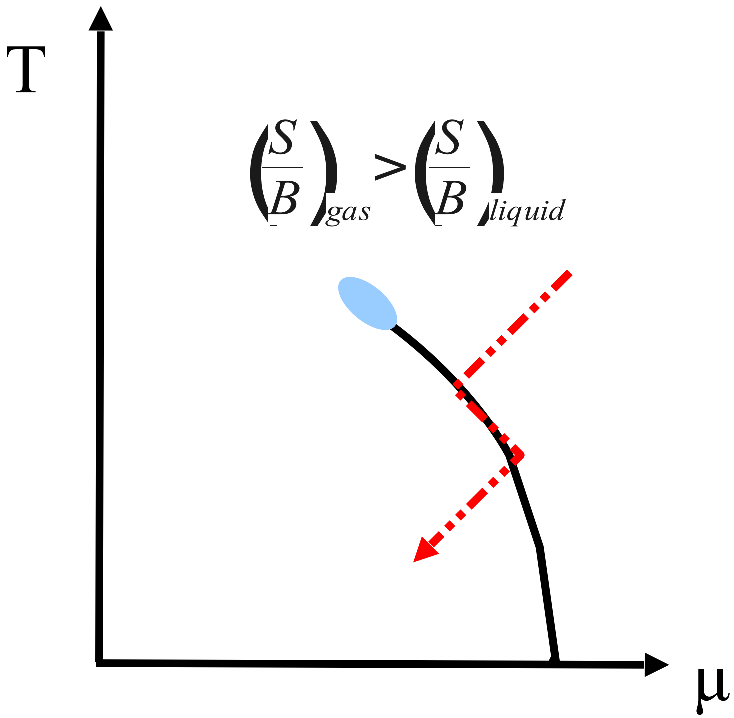
Lattice data from Wuppertal/Budapest:

Sign depends on definition of pseudo-critical line

Liquid-gas vs QCD

Liquid-Gas

P(T)co-exist = 0

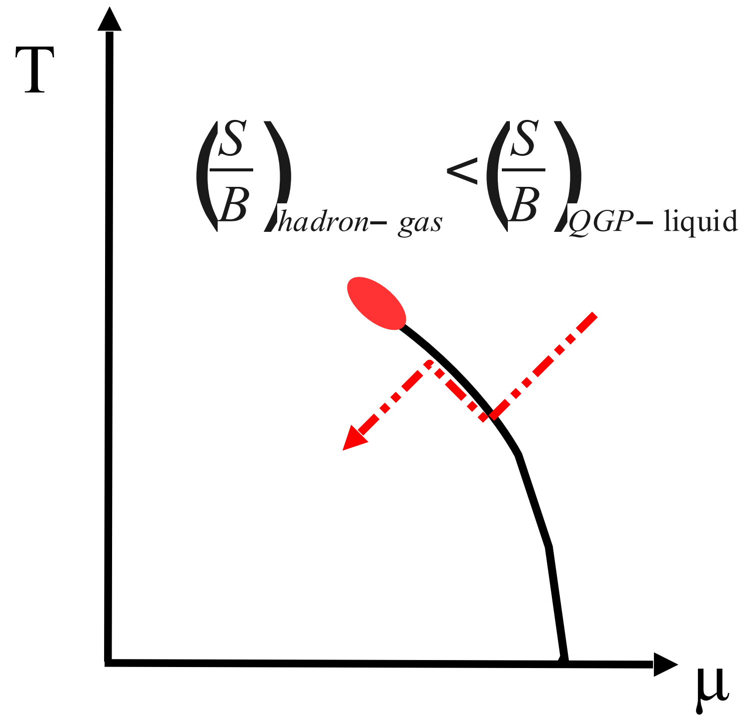


Droplets are stable in vacuum

$$\frac{dP}{dt} > 0$$

"QCD"

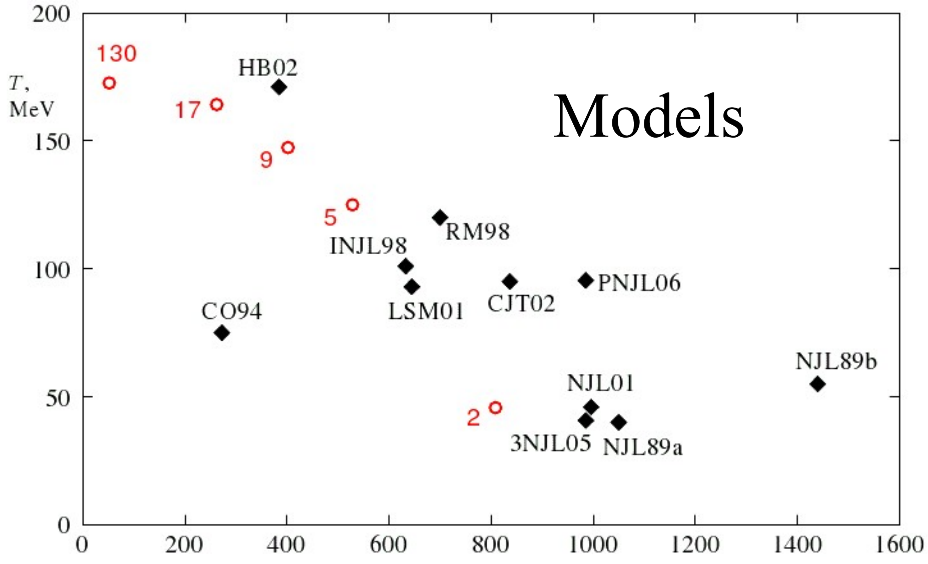
P(T)co-exist > 0!!!

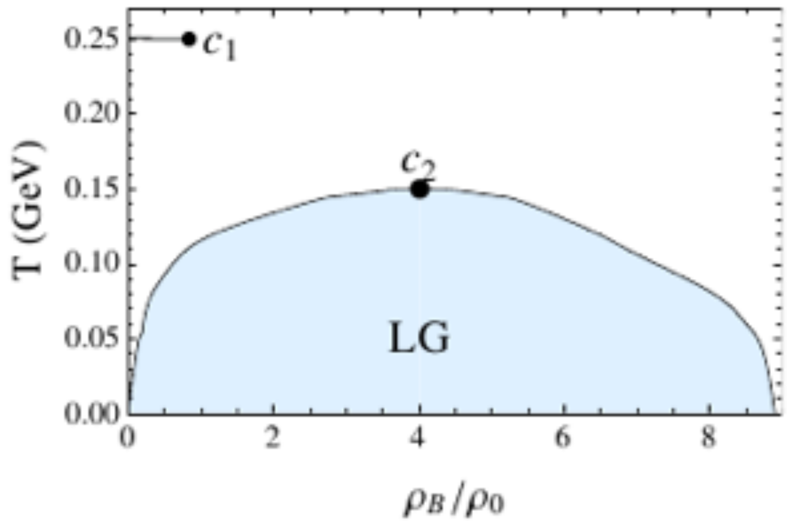


No stable droplets in vacuum

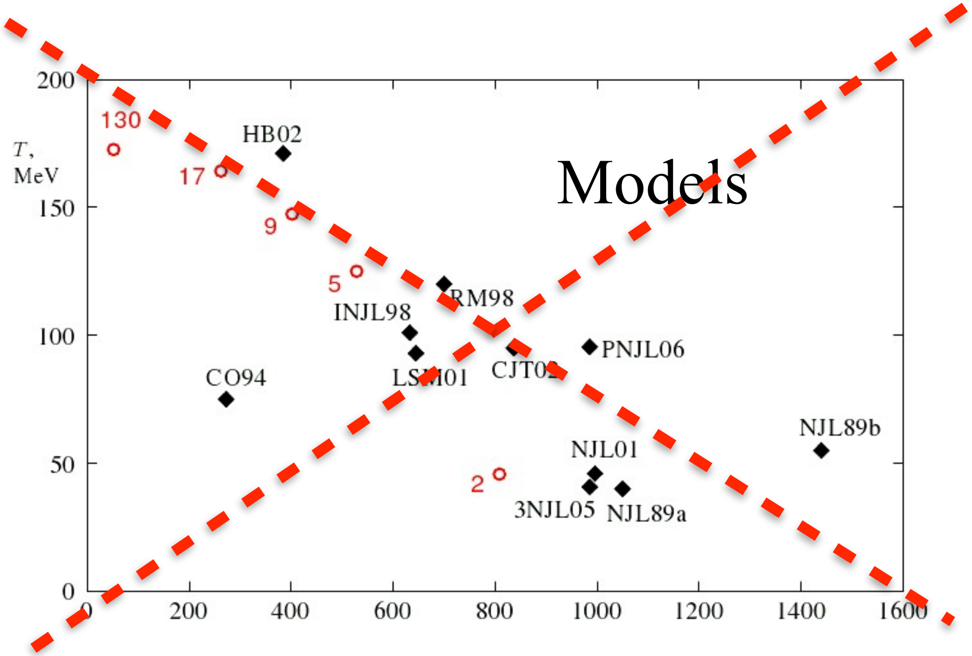
$$\frac{dP}{dt} < 0$$

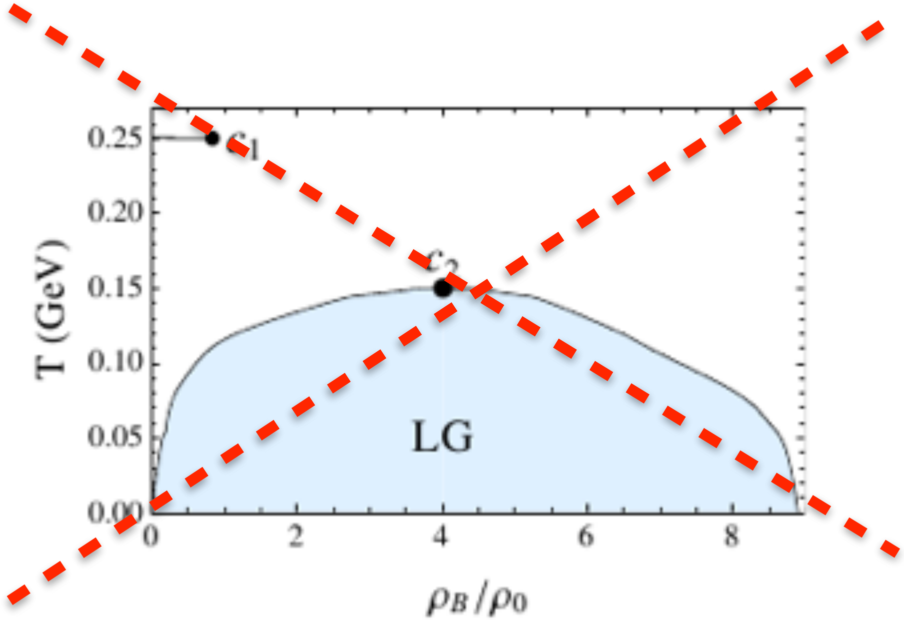
Most models are of liquid-gas type





Most models are of liquid-gas type





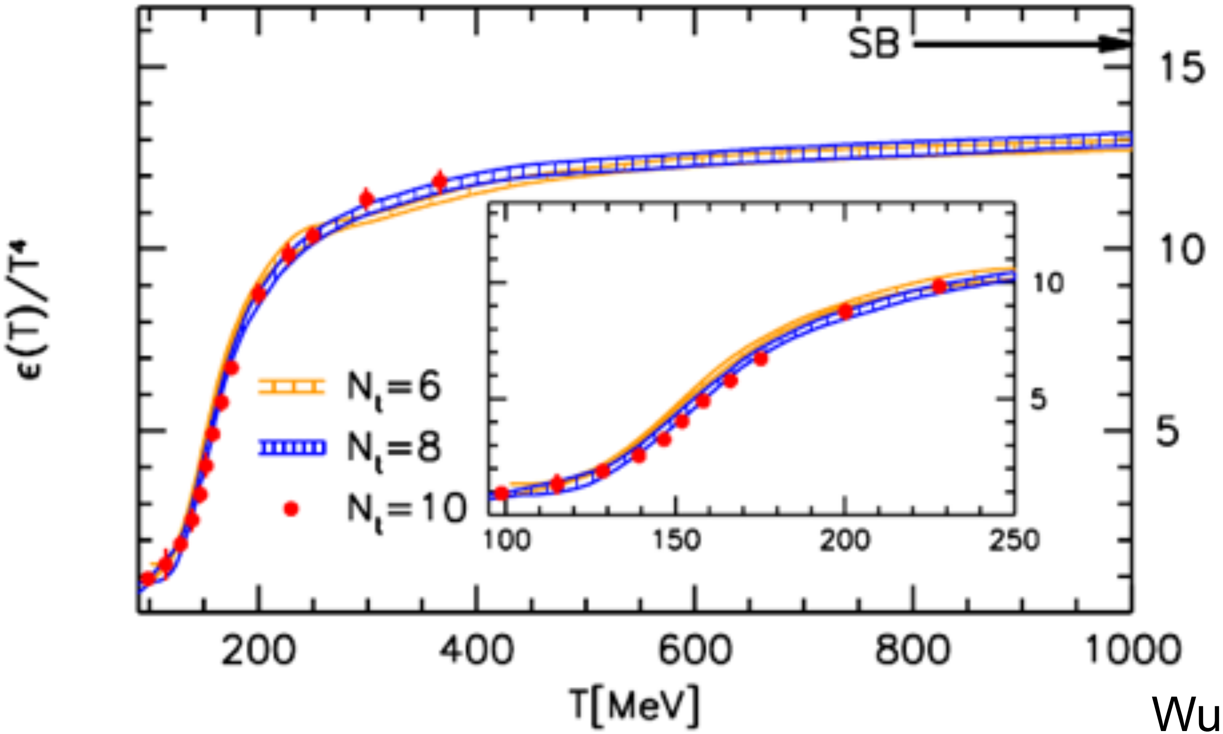
Not clear how useful the are

Guidance from Theory

Guidance from Theory
The critical Point

Back to Lattice

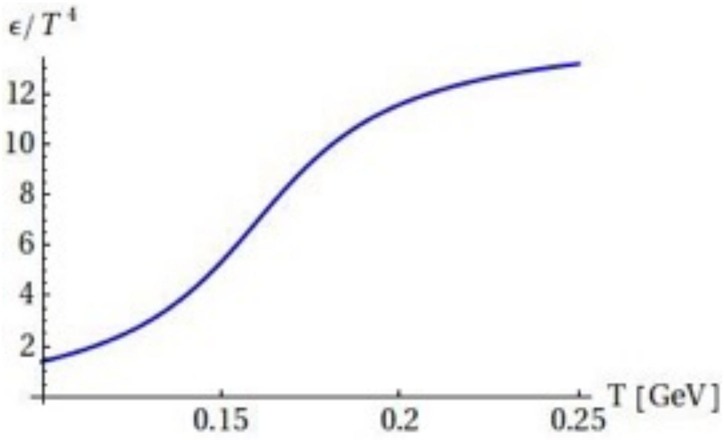
μ=0 only

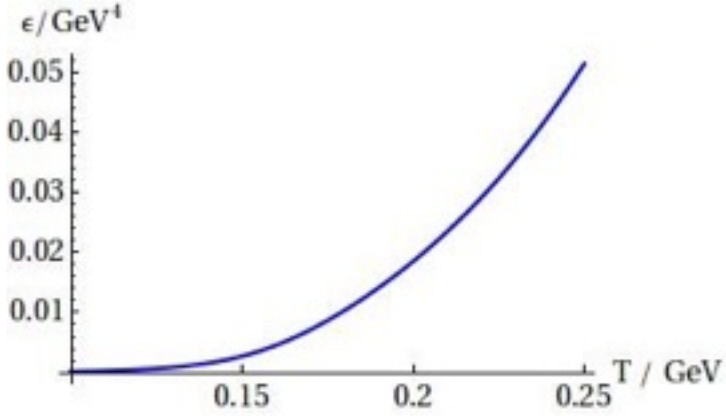


Wuppertal/Budapest

+ Cross over transition at zero net baryon density

The Lattice EOS



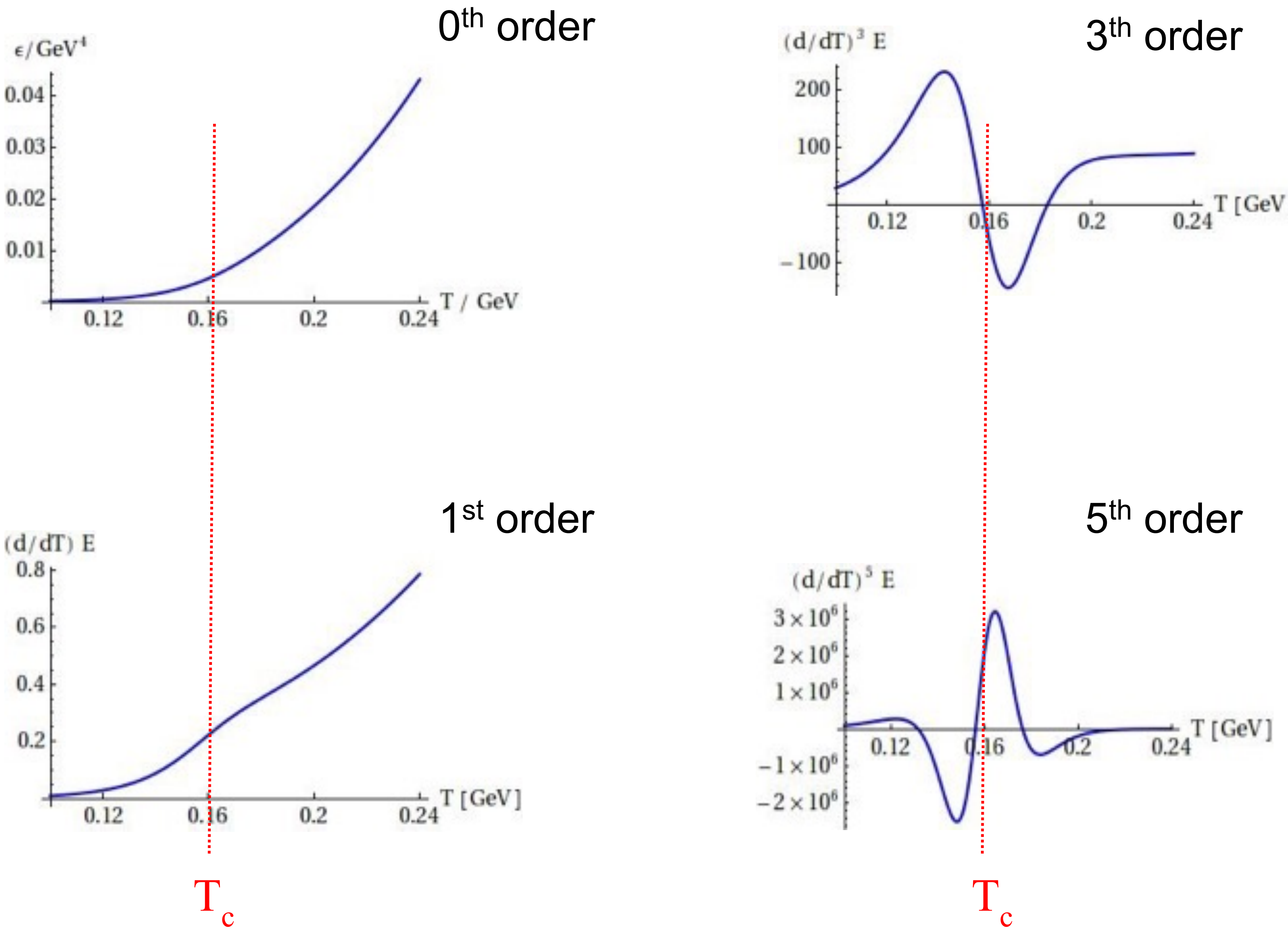


What we always see....

What it really means....

"T_c" ~ 160 MeV

Derivatives



How to measure derivatives

At μ = 0:

$$Z = tr\, e^{-\hat{E}/T + \mu/T \hat{N}_B}$$

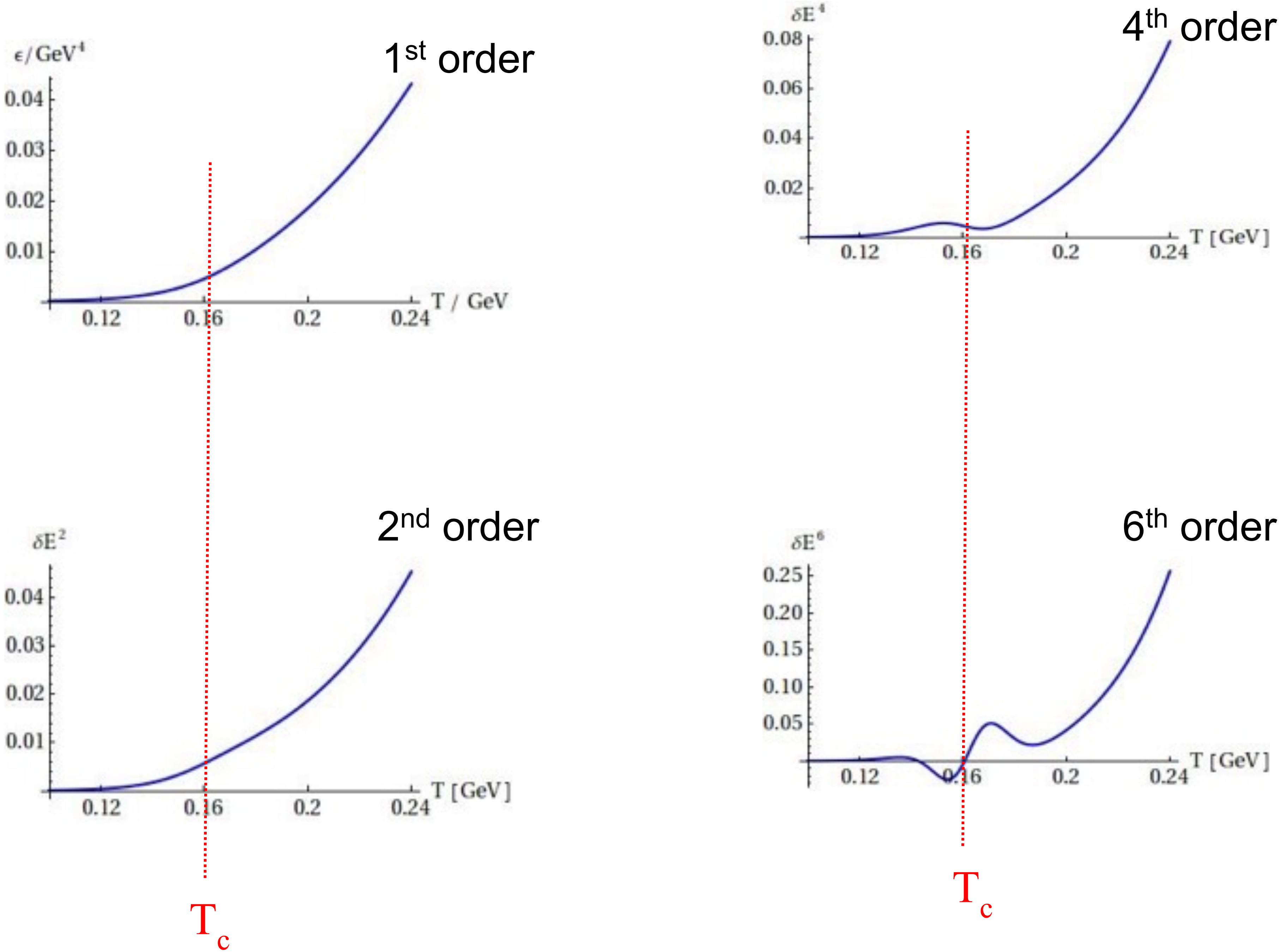
$$\langle E \rangle = \frac{1}{Z}\, tr\, \hat{E}\, e^{-\hat{E}/T + \mu/T \hat{N}_B} = -\frac{\partial}{\partial 1/T} \ln(Z)$$

$$\langle (\delta E)^2 \rangle = \langle E^2 \rangle - \langle E \rangle^2 = \left(-\frac{\partial}{\partial 1/T} \right)^2 \ln(Z) = \left(-\frac{\partial}{\partial 1/T} \right) \langle E \rangle$$

$$\langle (\delta E)^n \rangle = \left(-\frac{\partial}{\partial 1/T} \right)^{n-1} \langle E \rangle$$

Cumulants of Energy measure the temperature derivatives of the EOS

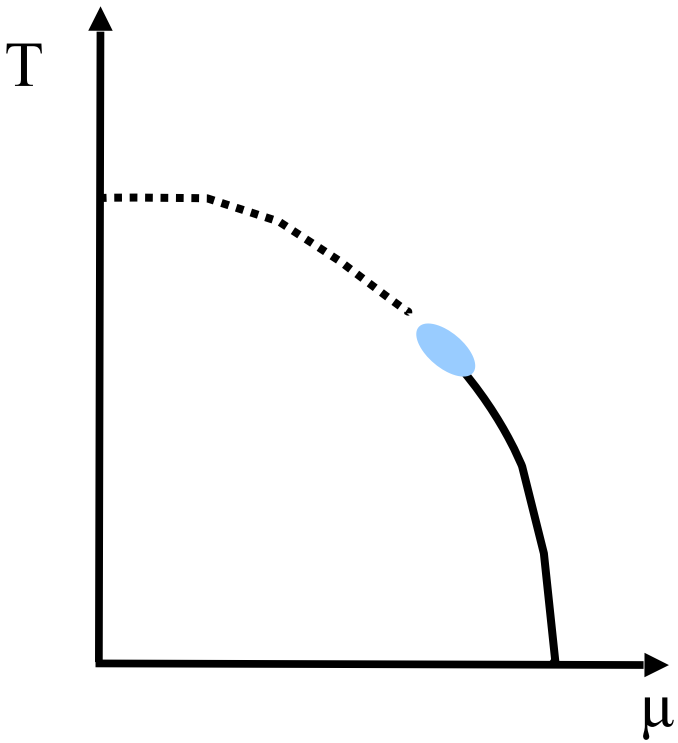
Fluctuations/Cumulants



Another way

$$F = F(r), \quad r = \sqrt{T^2 + a\mu^2}$$

a ~ curvature of critical line



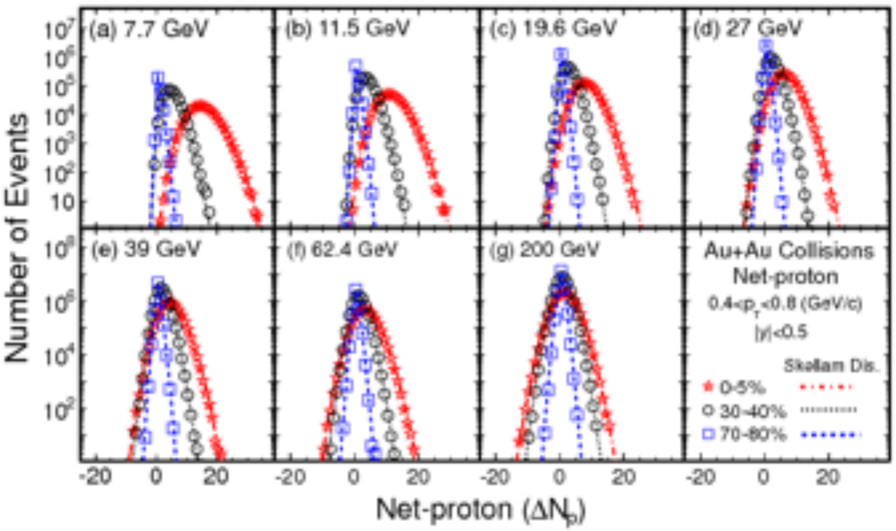
$$\partial_\mu^2 F(T,\mu)_{\mu=0} = \frac{a}{T}\partial_T F(T,0)$$

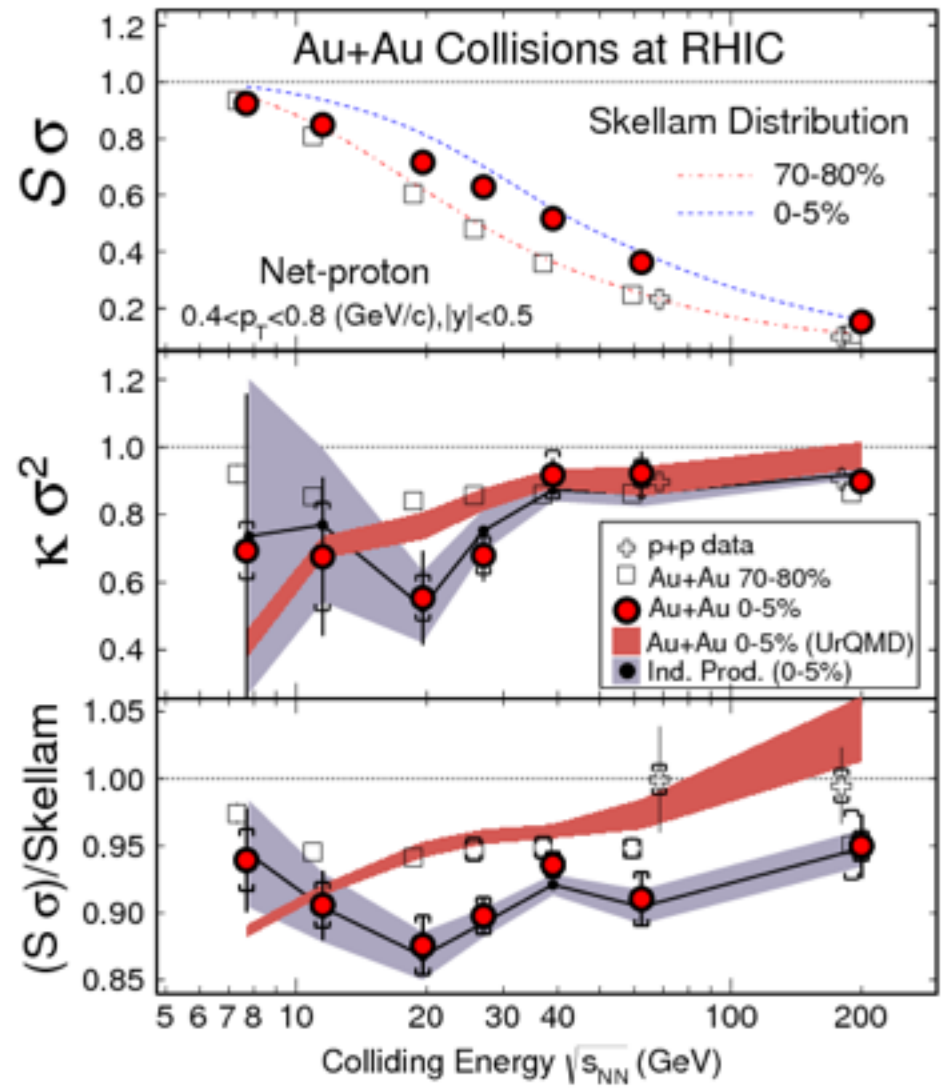
$$\partial_\mu^2 F(T,\mu)_{\mu=0} = 3\frac{a^3}{T}\left(T\partial_T^2 - \partial_T\right) F(T,0)$$

Baryon number cumulants give same info.
Less problem with flow etc.
Needs higher order cumulants (derivatives)
at μ ~ 0

STAR net-proton cumulants

(Phys.Rev.Lett. 112 (2014) 032302)

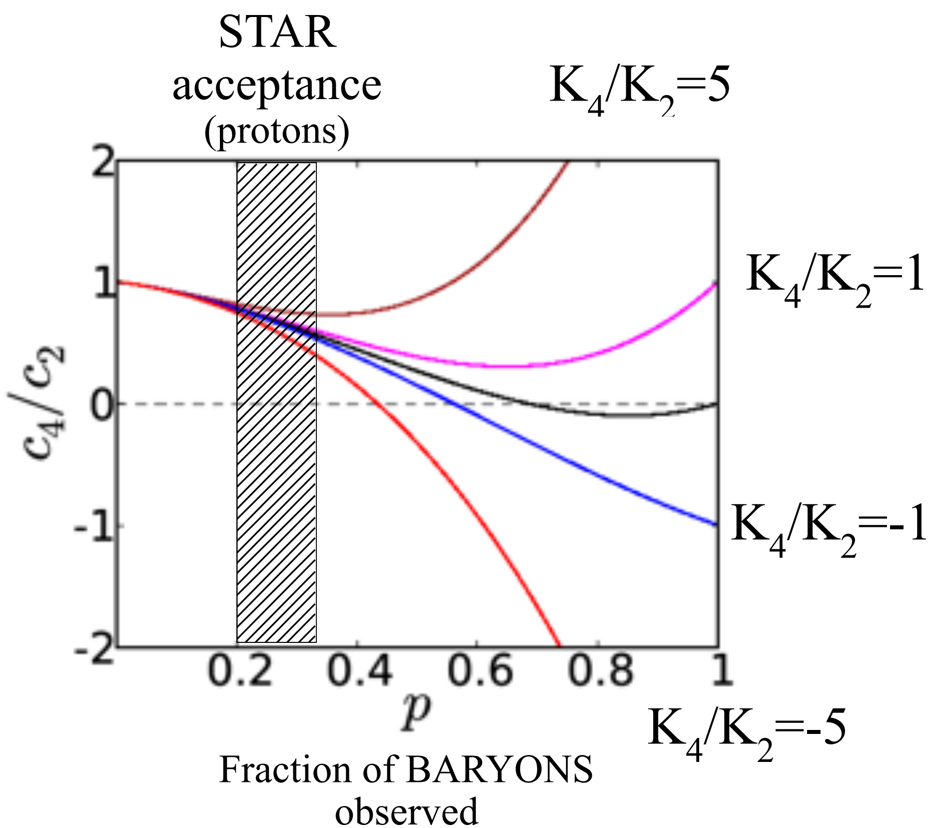


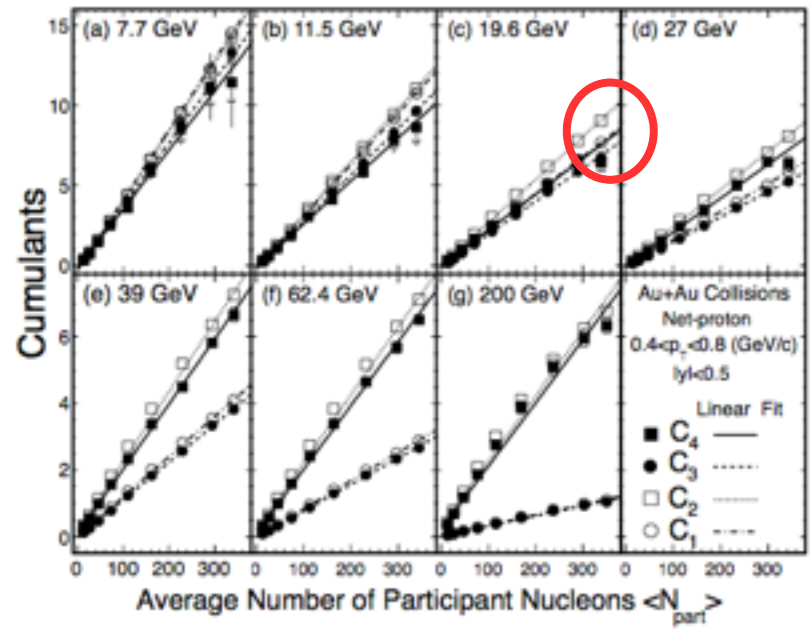


Things to consider

- Fluctuations of conserved charges ?!
- Higher cumulants probe the tails. Statistics!
- The detector “fluctuates” !
- Net-protons different from net-baryons
  - Isospin fluctuations
- Beware of the “Poissonizer”
- Auto-correlations
- “Stopping” Fluctuations

The "Poissonizer"





NA49: 32 protons per unit rapidity at top SPS energies!!!
STAR "sees" 8

N.B. This also affects comparison of Lattice with data to e.g. extract freeze out parameters

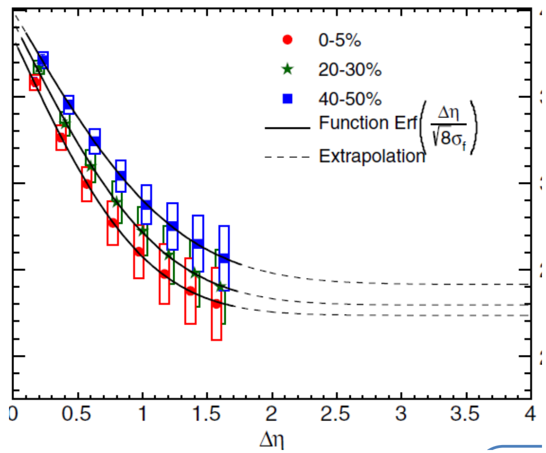
Correlations: Lattice vs Data

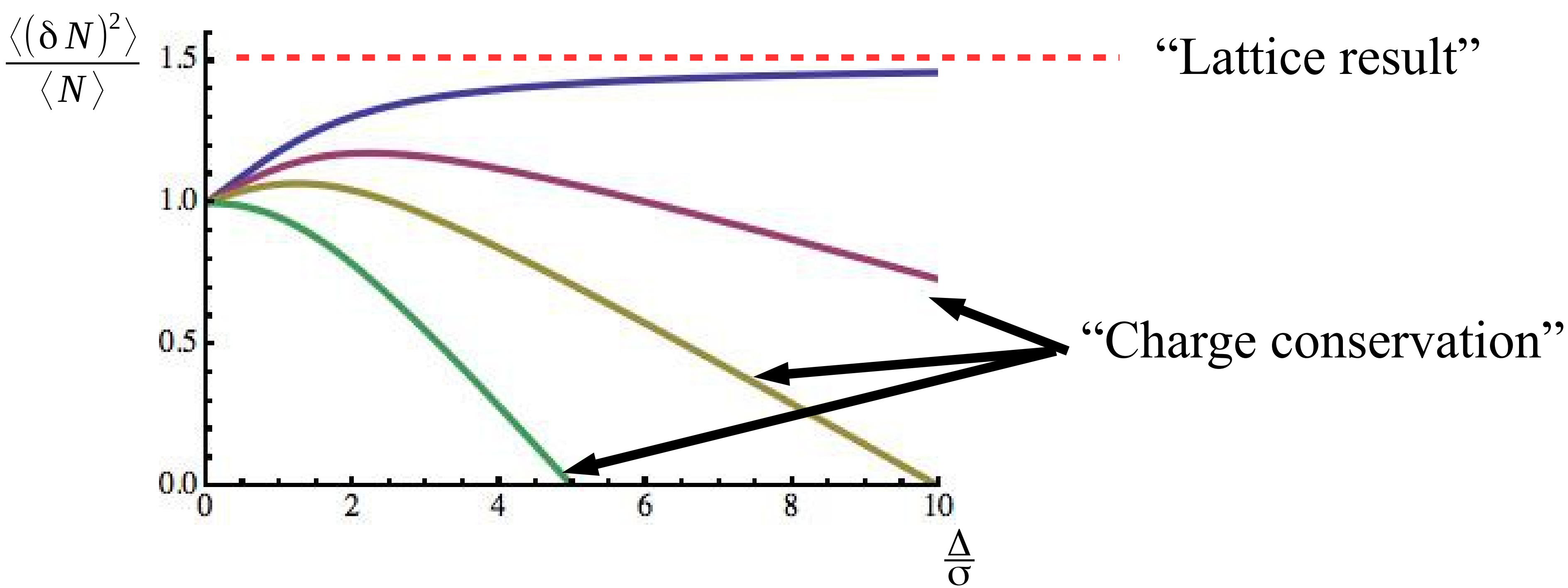
$$\langle n(y_1)(\,n(y_2)-\delta(y_1-y_2)\,)\rangle=\langle n(y_1)\rangle\langle n(y_2)\rangle\left(1+C(y_1,y_2)\right)$$

$$C(y_{1,}\,y_2)\sim\exp\left(\frac{-(y_1-y_2)^2}{2\sigma^2}\right)$$

$$\frac{\langle(\delta N)^2\rangle}{\langle N\rangle}=1+\langle N\rangle\int_{\Delta/2}^{\Delta/2}C(y1,y2)\,dy1\;dy_2$$

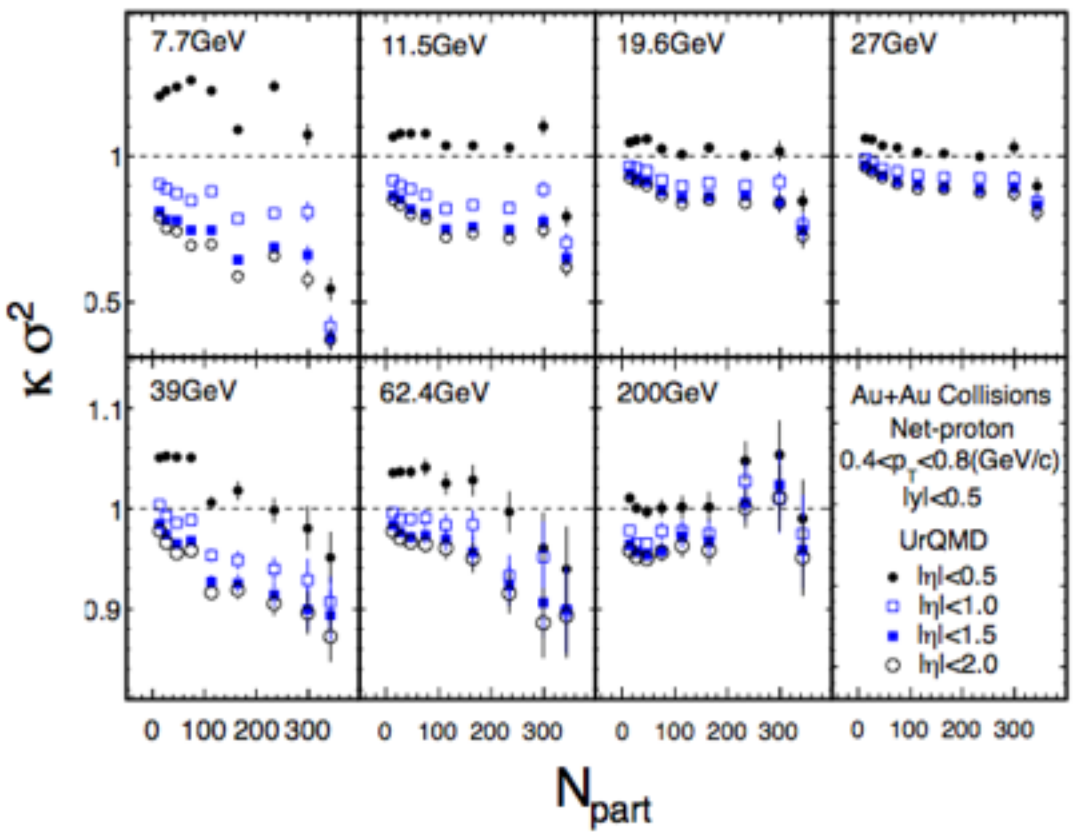
Alice Charge Flucts

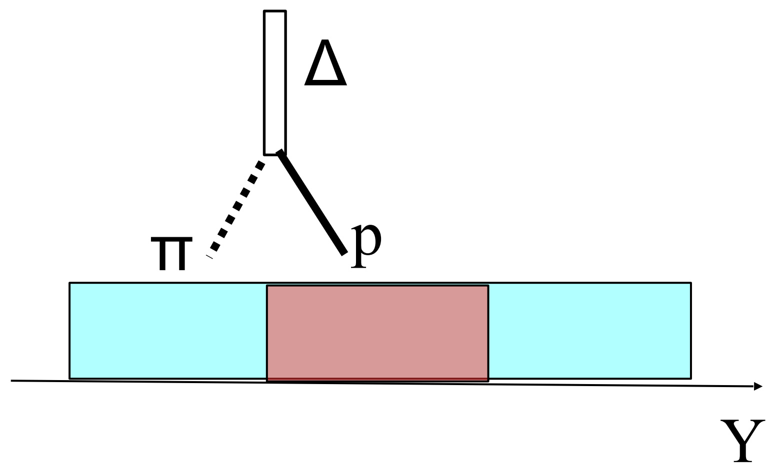




Auto Correlations

Luo et al, arXiv:1303.2332





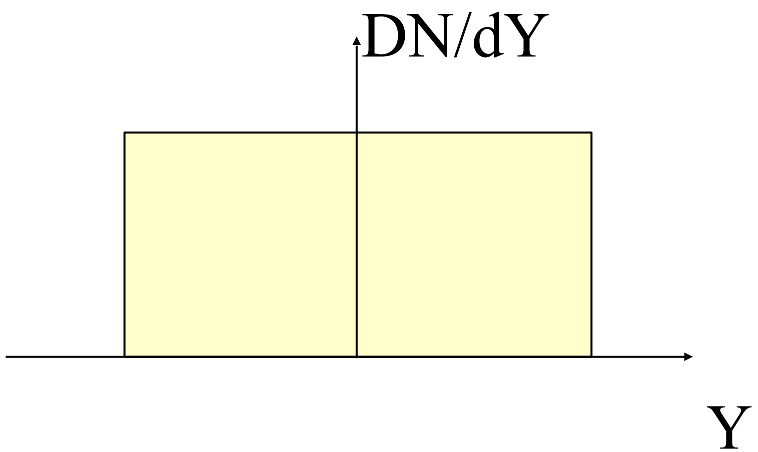
Strong correlation between multiplicity determination and proton cumulants due to baryon resonances

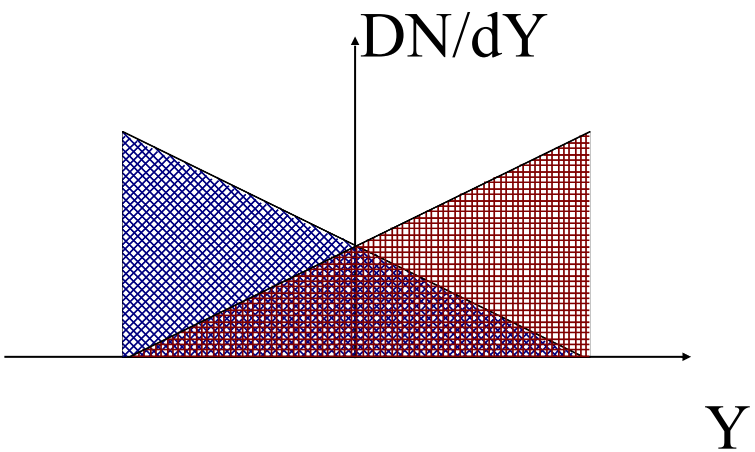
Need to determine multiplicity far away in rapidity from cumulants

"Stopping" Fluctuations

At low energy most of the baryon number (isospin) is brought in from the colliding nuclei.

Need to control the fluctuations to due baryon stopping

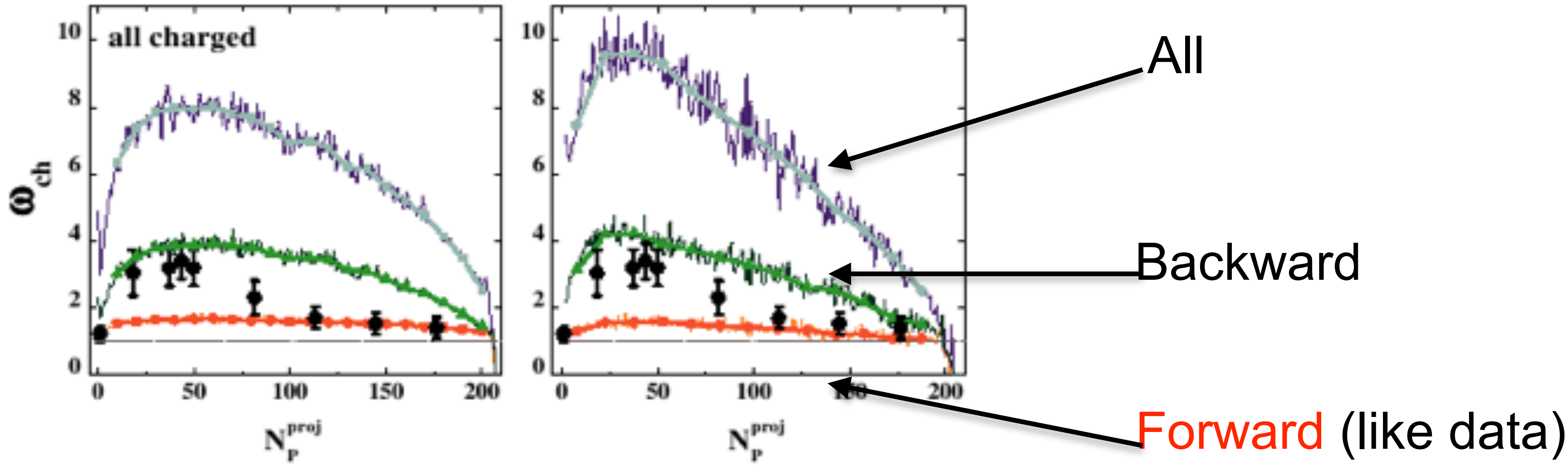




These fluctuations may also be biased by multiplicity selection.

Dynamics, event selection ...
(or why a symmetric detectors are good)

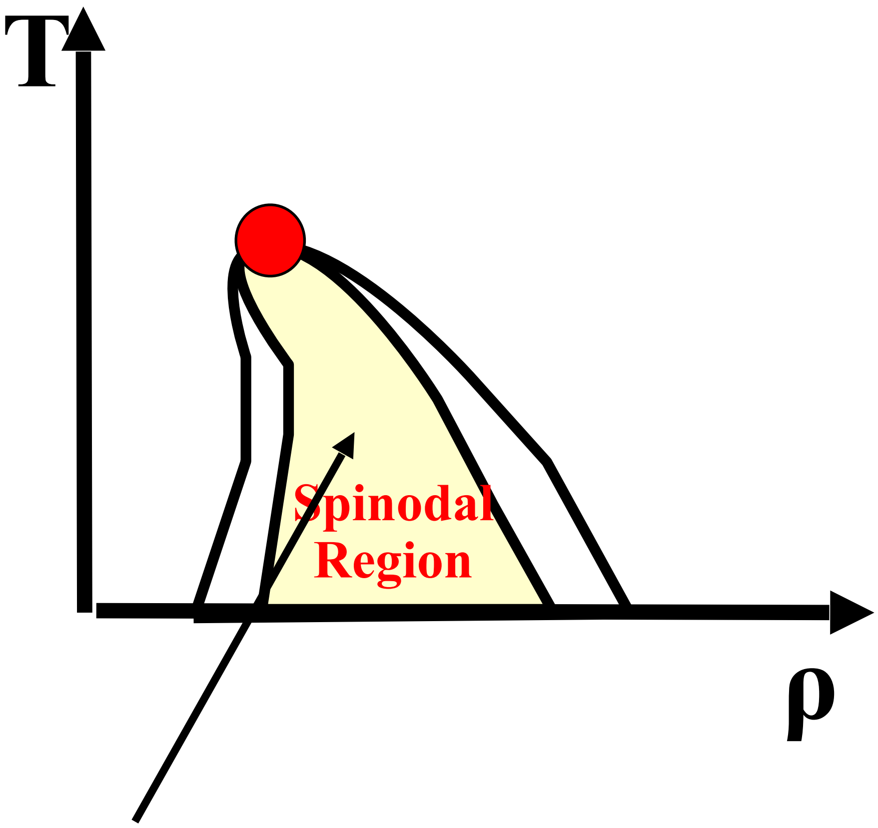
Konchakovski et al, nucl-th/0511083



Fluctuations are sensitive to dynamics (mixing of projectile and target material?)

Event selection/trigger affects fluctuations → large Acceptance!
Need backward and forward multiplicity detectors!
Need Backward and forward particle ID (protons) !

Co-existence region



Spinodal instability:
Mechanical instability

$$\frac{\partial p}{\partial \epsilon} < 0$$

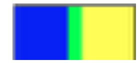
Exponential growth of clumping

Non-equilibrium phenomenon!

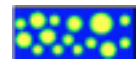
System should spent long time
in spinodal region

Phase-transition dynamics: Density clumping

Phase transition => { Phase coexistence: surface *tension*



Phase separation: *instabilities*



} Introduce a *gradient* term:

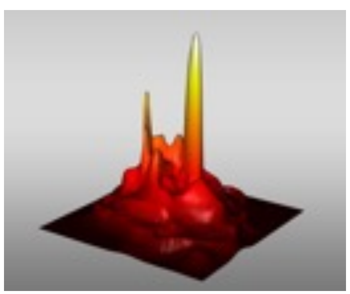
$$p(\mathbf{r}) = p_0(\varepsilon(\mathbf{r}), \rho(\mathbf{r})) - C\rho(\mathbf{r})\nabla^2\rho(\mathbf{r})$$

Insert the modified pressure into existing ideal finite-density fluid dynamics code

Use UrQMD for pre-equilibrium stage to obtain fluctuating initial conditions

Simulate central Pb+Pb collisions at ≈3 GeV/A beam kinetic energy on fixed target, using an Equation of State either ***with*** a phase transition or ***without*** (Maxwell partner):

With phase transition:



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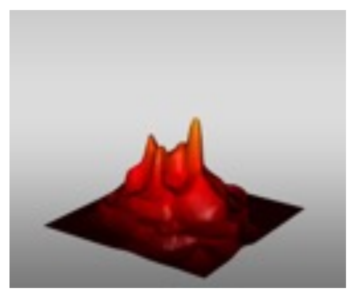
Without phase transition:



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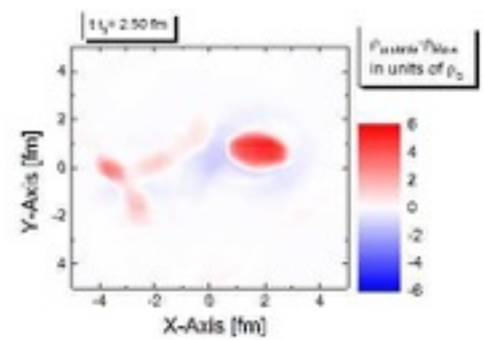
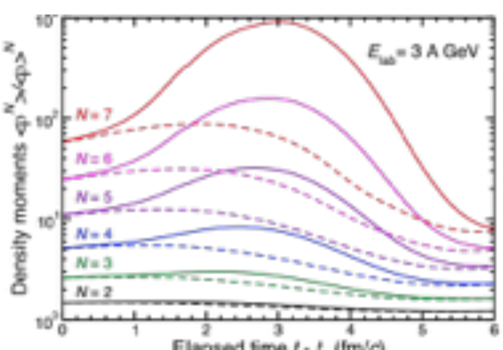
Density enhancement:

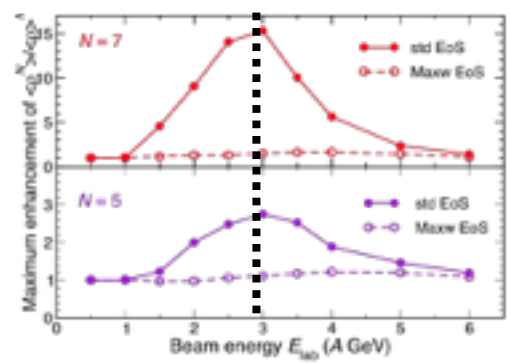




Evolution of density moments

$$\langle \rho^N \rangle \equiv \frac{1}{A}\int \rho(\mathbf{r})^N \rho(\mathbf{r}) d^3\mathbf{r}$$

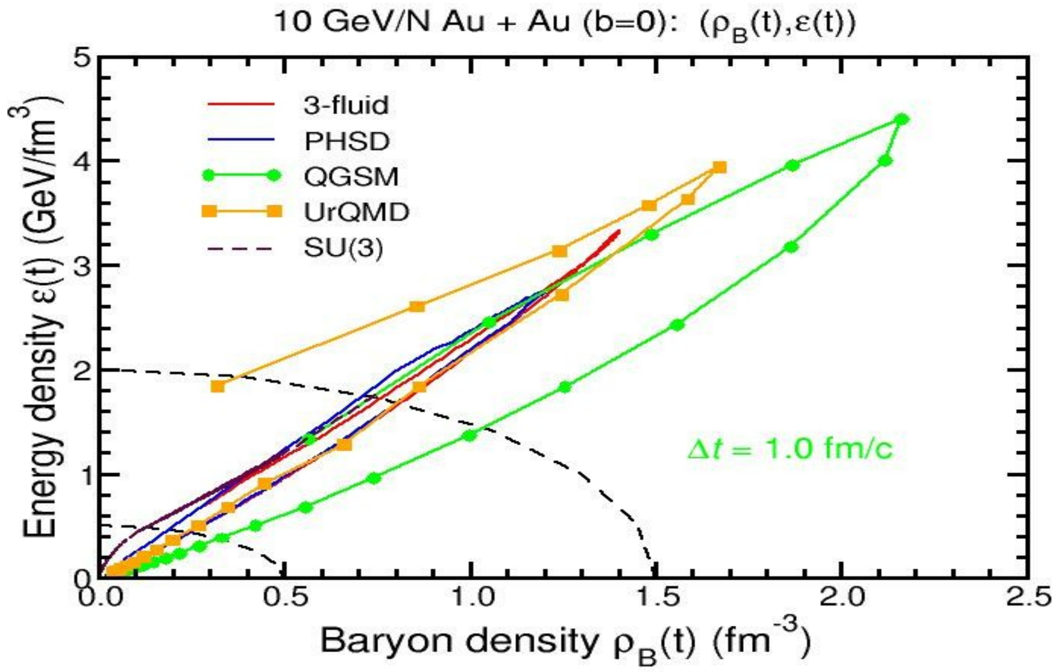
J. Steinheimer & J. Randrup,
PRL 109, 212301(2012)
PRC 87, 054903 (2013)



E_{Lab}=3 GeV

Phase trajectories

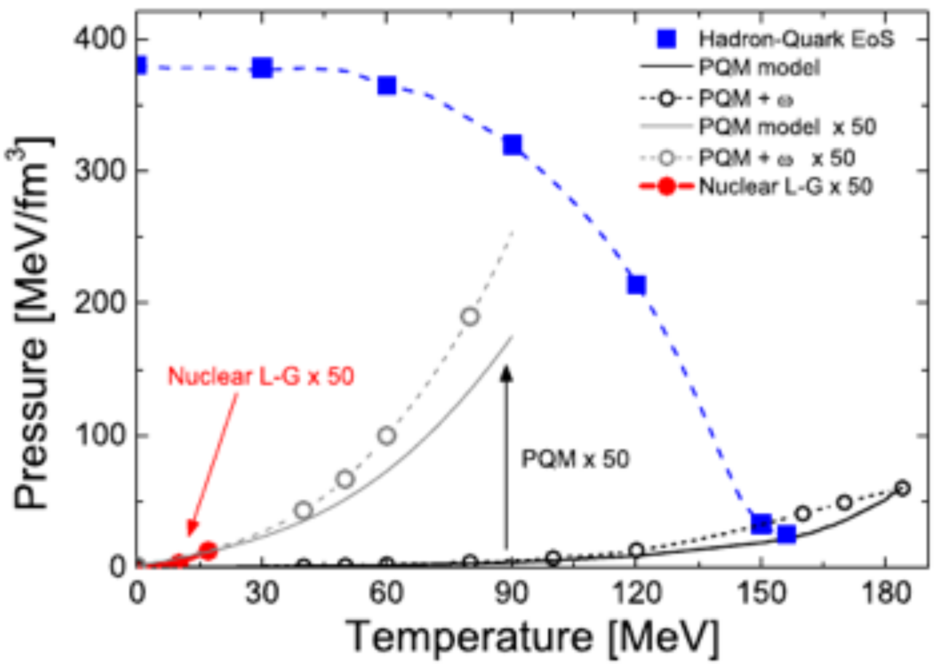
(J. Randrup et al)



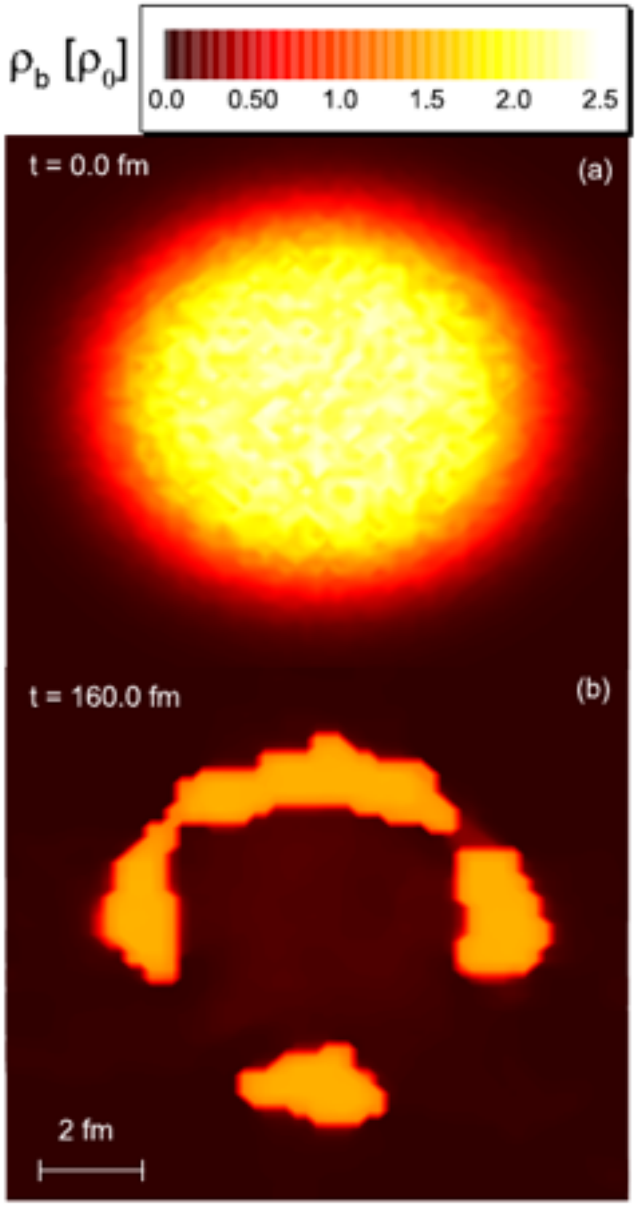
10 AGeV!!!!!

SIS 100 territory

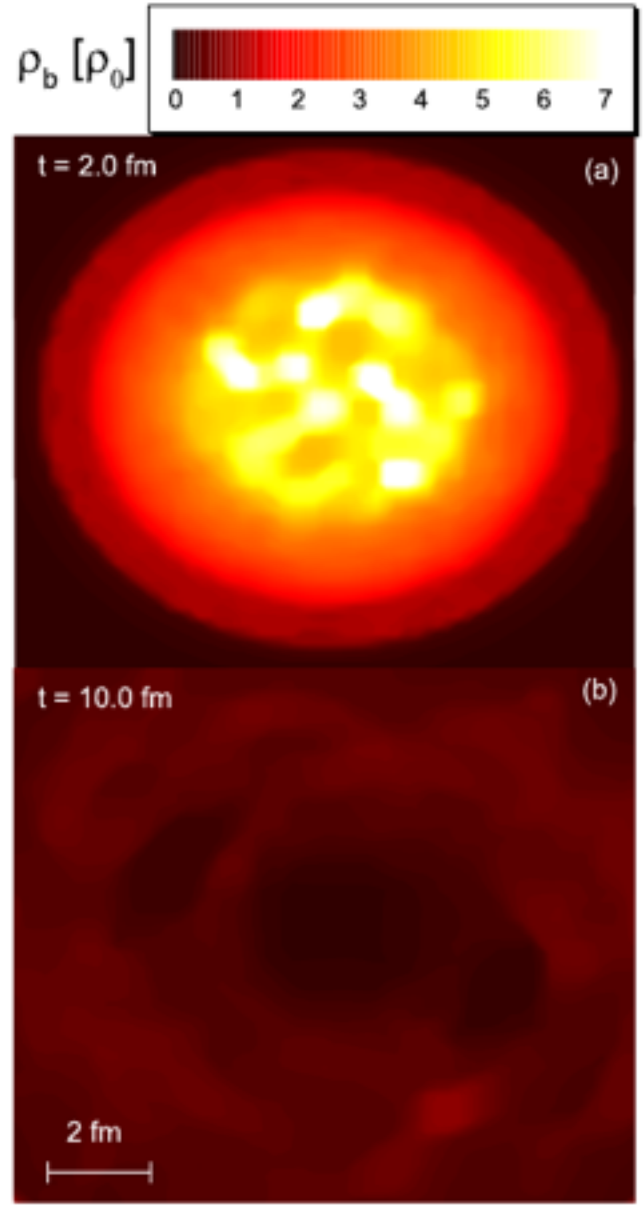
Consider two Equations of State



Steinheimer et al,
Phys.Rev. C89 (2014) 034901

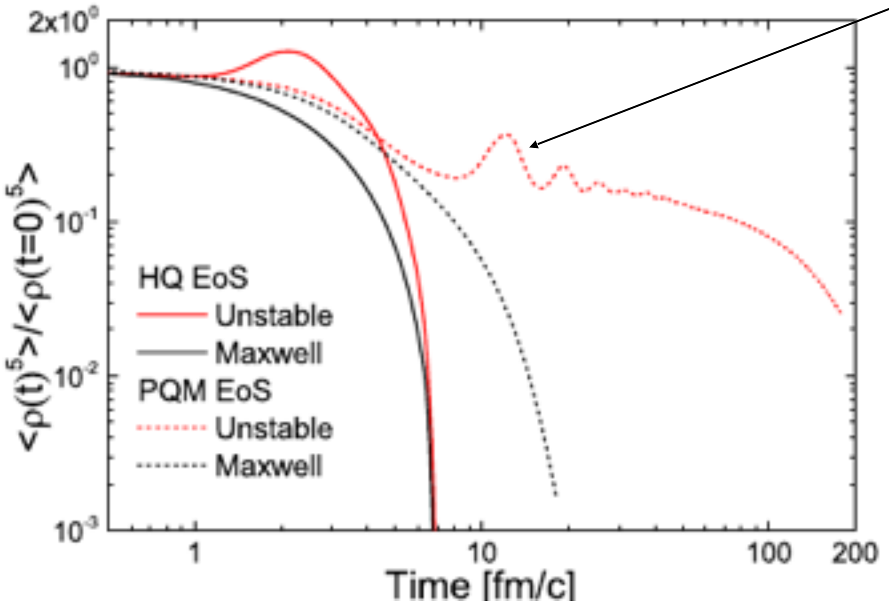


PQM ("liquid-gas")



"QCD"

Time evolution

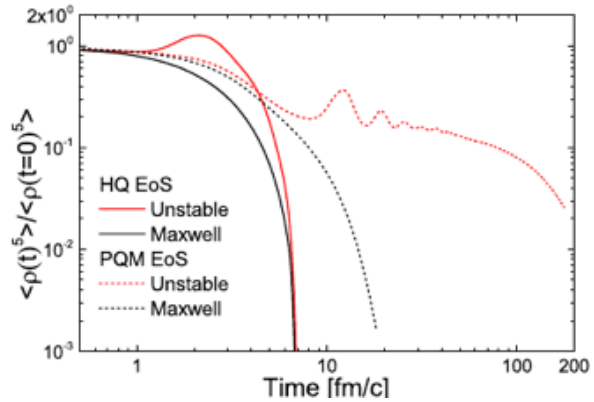


Oscillation of nearly stable droplets for "liquid-gas" EoS

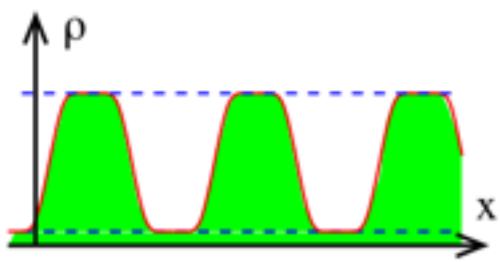
Higher pressure leads to faster evolution of "QCD" EoS.

Steinheimer et al,
Phys.Rev. C89 (2014) 034901

Cluster a.k.a. nuclei



Even if total baryon number does not fluctuate the baryon **density** does



Therefore measure production of NUCLEI: d, ^{3}He, ^{4}He, ^{7}Li....

$\langle d\rangle \sim \langle \rho_B^2\rangle$ $\langle {}^3He\rangle \sim \langle \rho_B^3\rangle$ $\langle {}^7Li\rangle \sim \langle \rho_B^7\rangle$

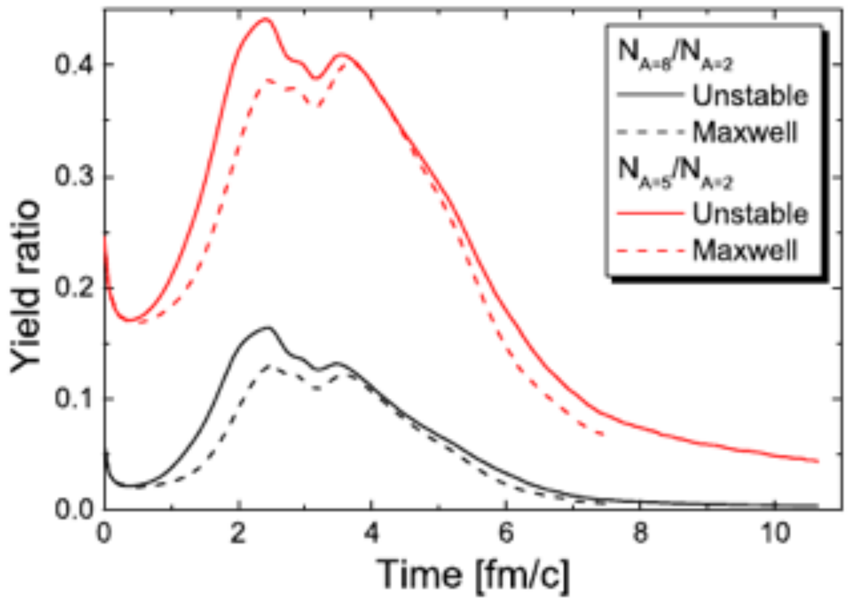
Extracts higher moments of the baryon **density** at freeze out

Nice Idea, but...

“Cluster” formation

“QCD” EoS

$$\left(\frac{S}{B}\right)_{hadron-gas} < \left(\frac{S}{B}\right)_{QGP-\text{liquid}}$$



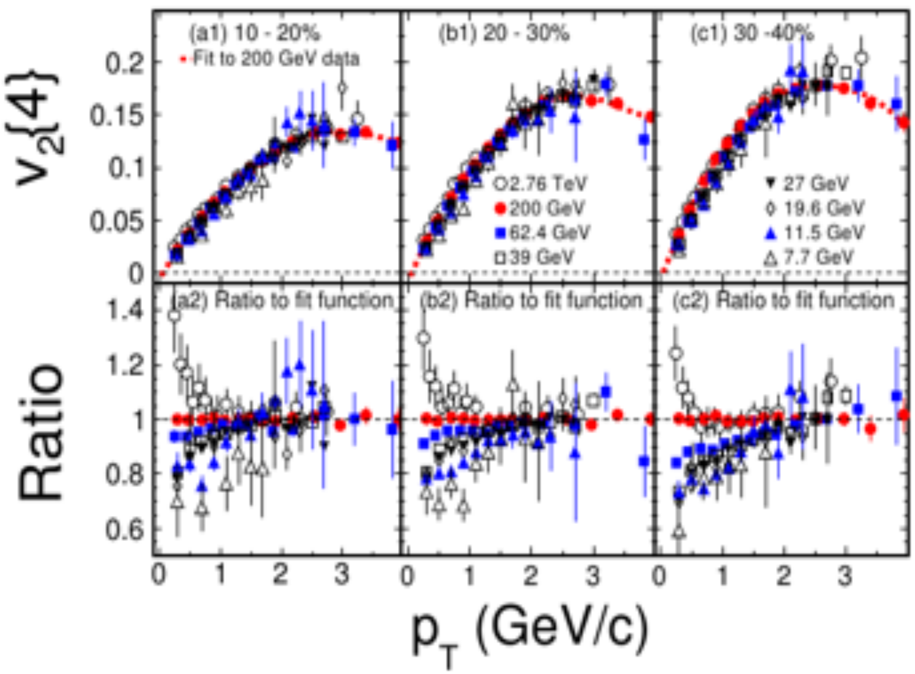
Clumping in coordinate space is compensated by dilution in momentum space → tiny effect

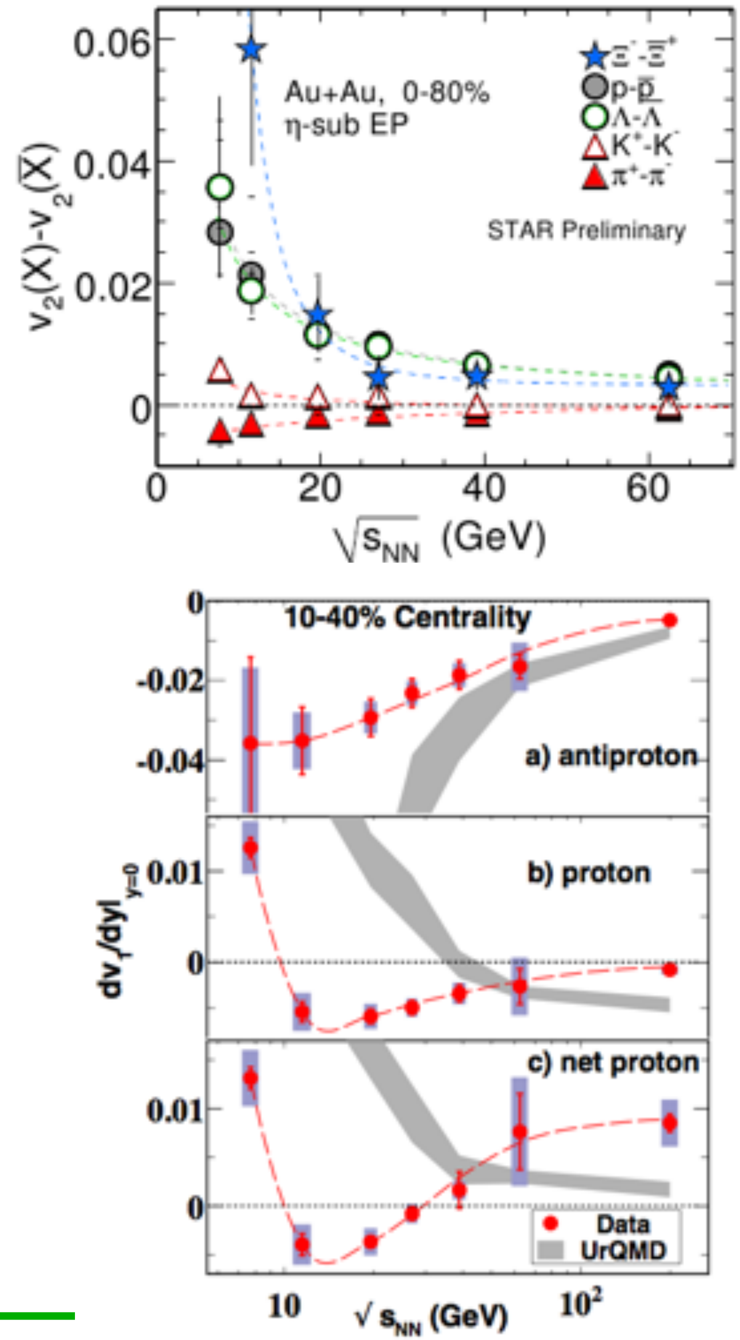
Steinheimer et al,
Phys.Rev. C89 (2014) 034901

Other Fishing Ponds

- Flow
- Dileptons
- exotica such as Chiral Magnetic effect

Flow



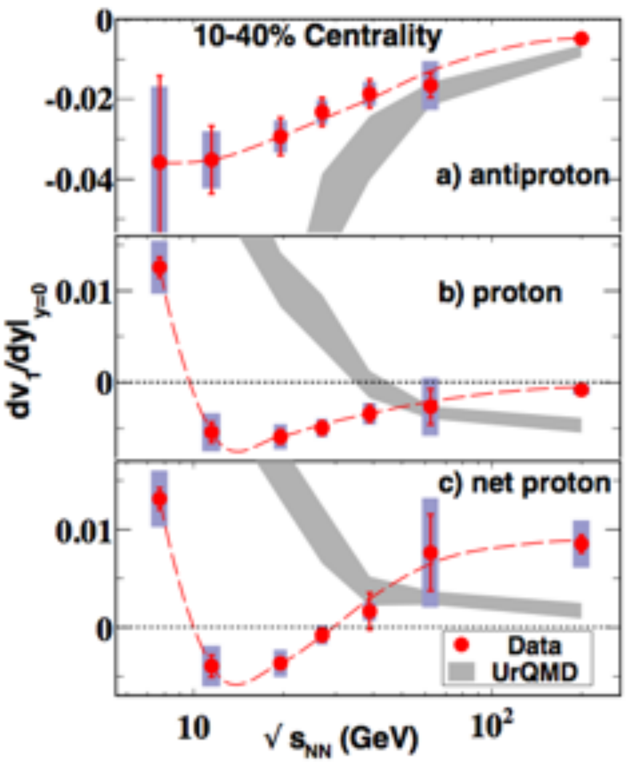


Elliptic flow:

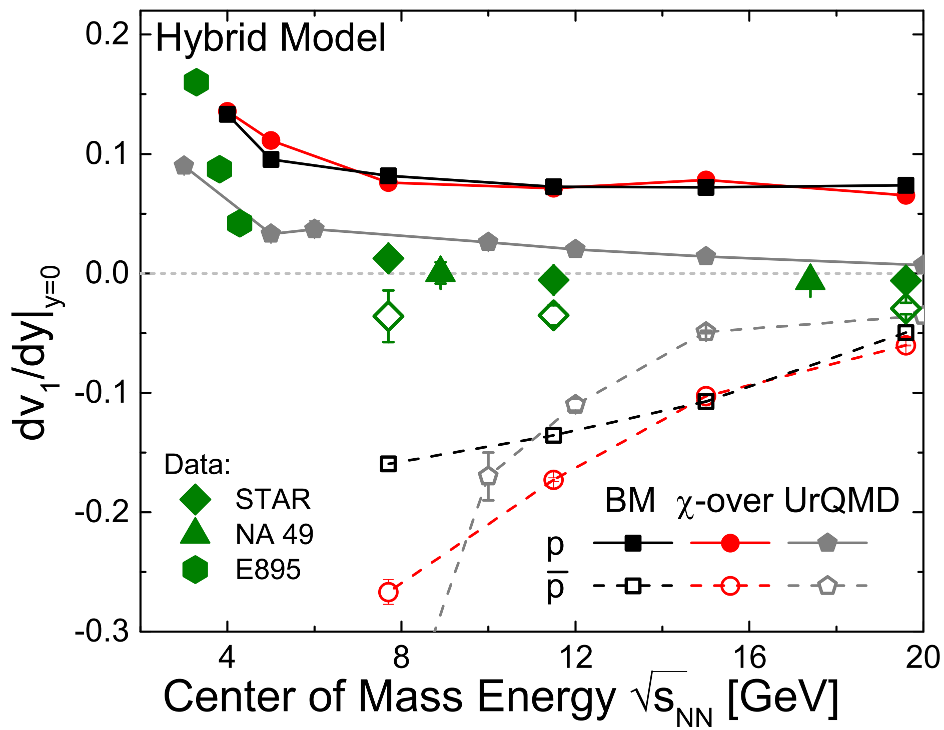
- Little change from top RHIC/LHC energy!
- Quark number scaling still works
- Stopping of baryon number and isospin splits v_2 between particles and antiparticles
- Directed flow (v_1)
  Minimum in directed flow. But tiny effect

Directed Flow (v_1)

STAR Data

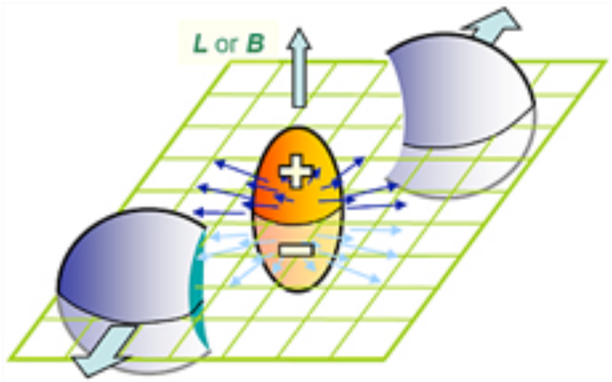


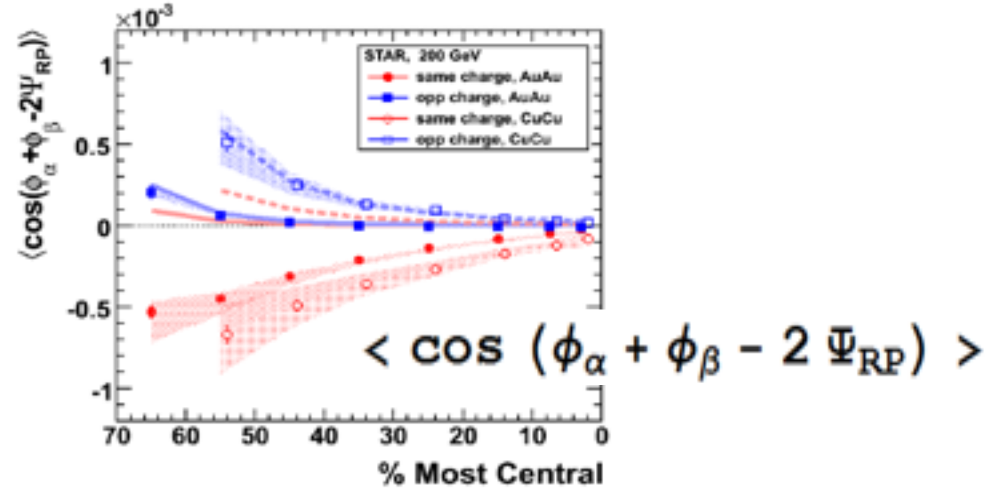
Calulation J. Auvinen et al

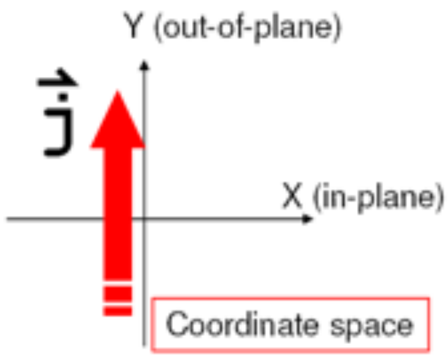


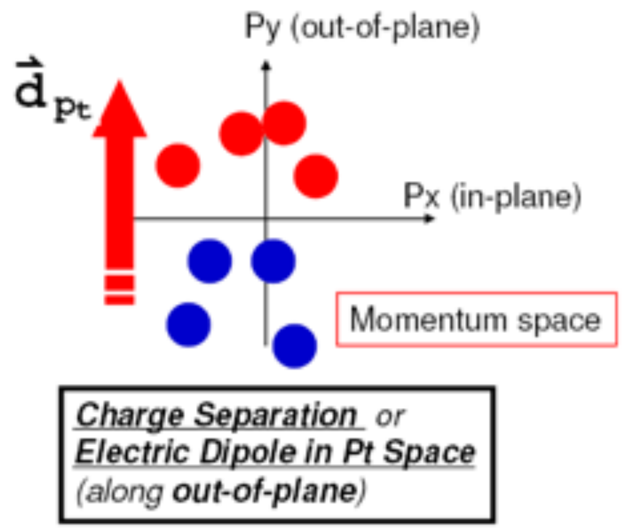
TINY effect! First make sure that v_1 in models is ~ 0

CME & Charge Dipole









A dipole charge distribution along out-of-plane direction

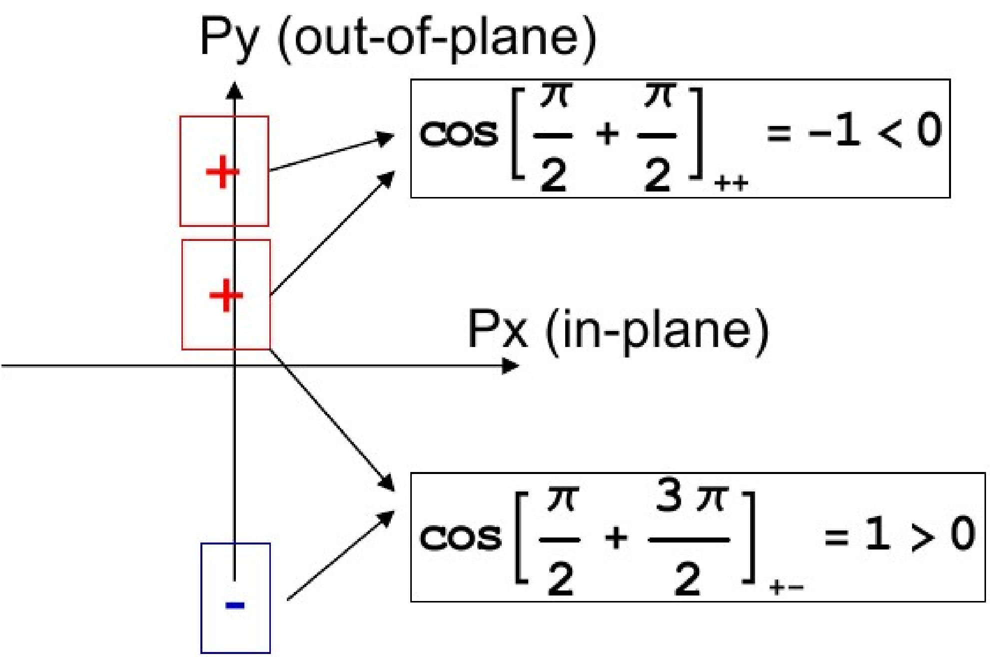
14

J. Liao, BES II workshop, Berkeley, Sept 2014

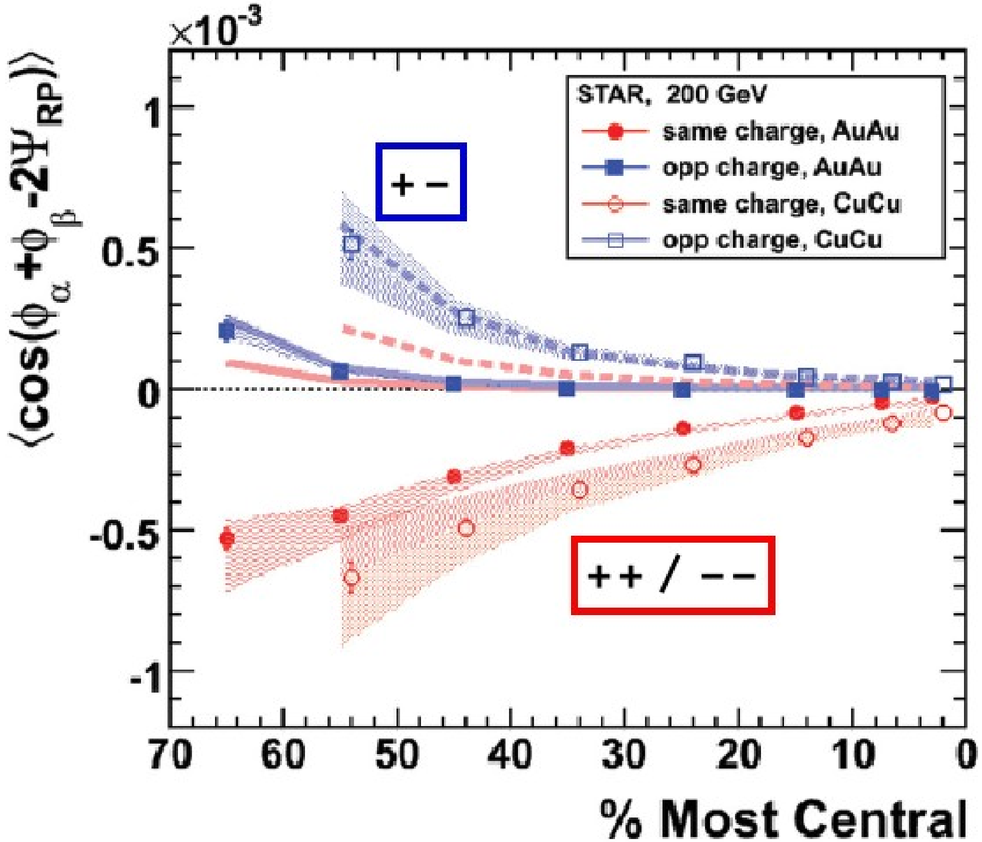
The STAR measurement
(which everybody discusses)

3P correlations: *Voloshin (04)*

$$\langle \cos(\phi_a + \phi_\beta - 2\Psi_{RP}) \rangle = \langle \cos(\phi_a + \phi_\beta - 2\phi_c) \rangle / v_{2,c}.$$



CME expectation



STAR (09)

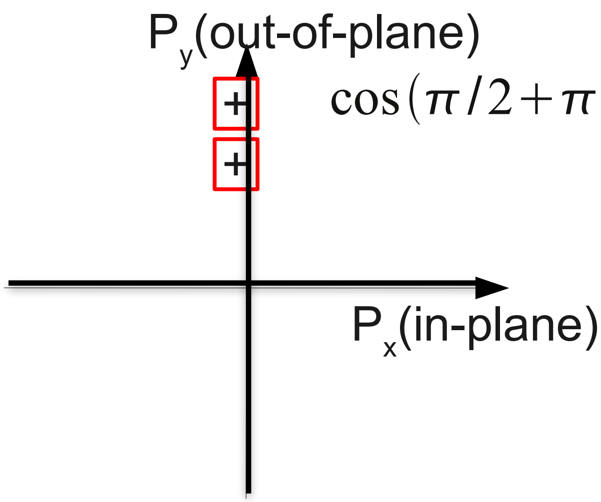
The STAR measurement

(a closer look)

Concentrate on same sign pairs for the moment

Set $\Psi_{R.P.} = 0$

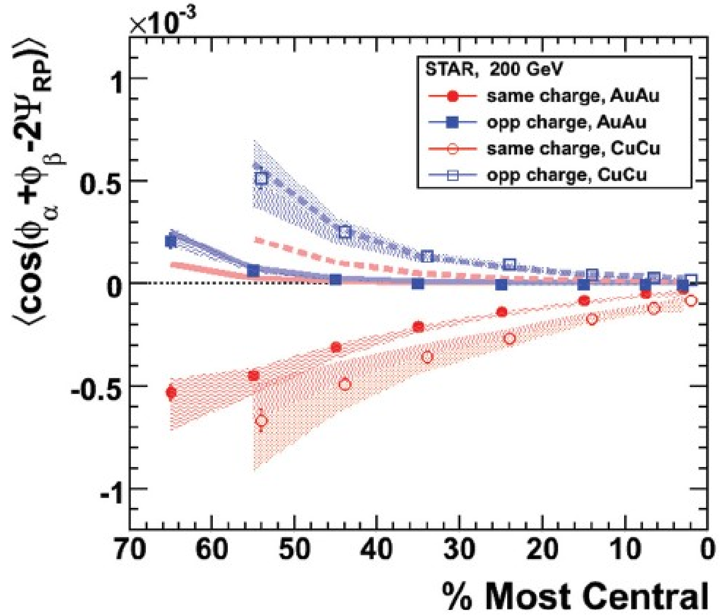
$$\langle \cos(\phi_1 + \phi_2 - \Psi_{R.P}) \rangle_{++} = \langle \cos(\phi_1 + \phi_2) \rangle_{++}$$

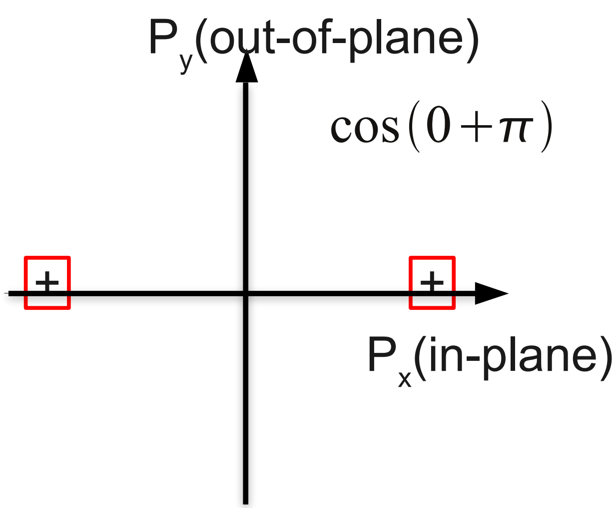


$\cos(\pi/2 + \pi/2)$

$$\langle \cos(\phi_1 + \phi_2 - 2\Psi_{R.P.}) \rangle_{++} < 0$$

for **both** configurations





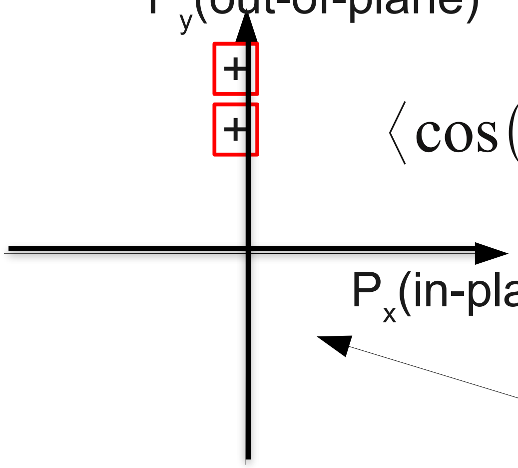
$\cos(0 + \pi)$

How to distinguish?

The STAR measurement

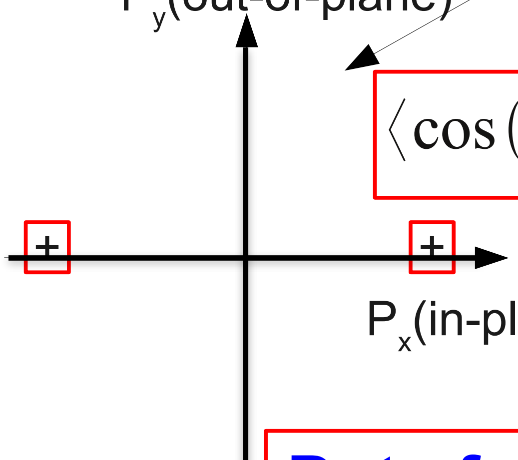
(which not so many discuss)

Add $\langle \cos(\phi_1 - \phi_2) \rangle$ to the mix

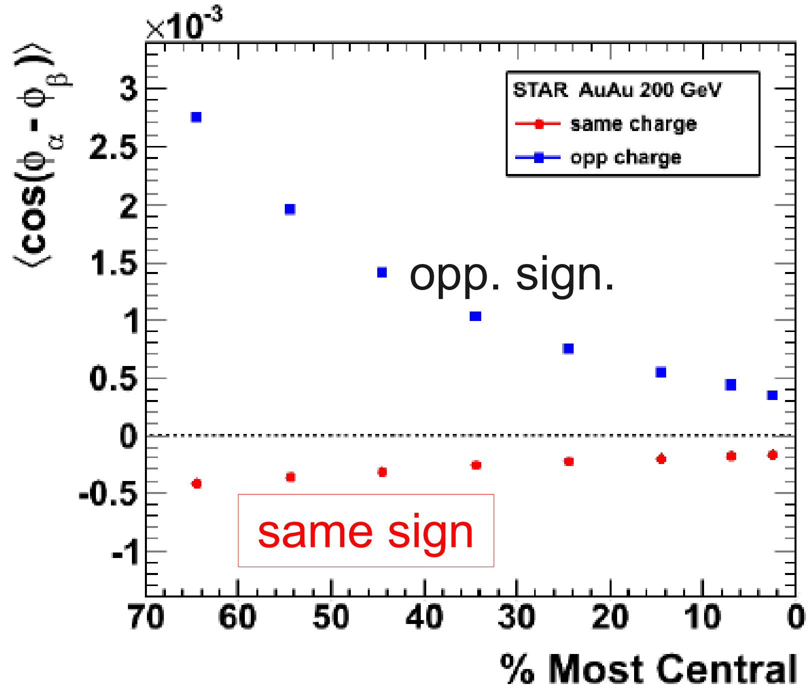


$$\langle \cos(\phi_1 - \phi_2) \rangle_{++} > 0$$

$$\langle \cos(\phi_1 + \phi_2 - 2\Psi_{R.P.}) \rangle_{++} < 0$$

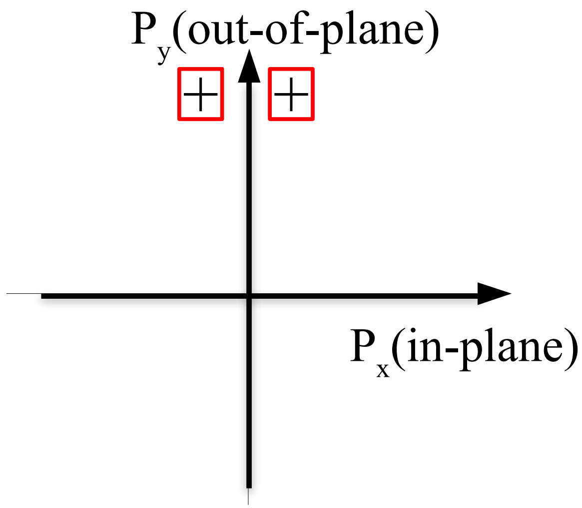


$$\langle \cos(\phi_1 - \phi_2) \rangle_{++} < 0$$

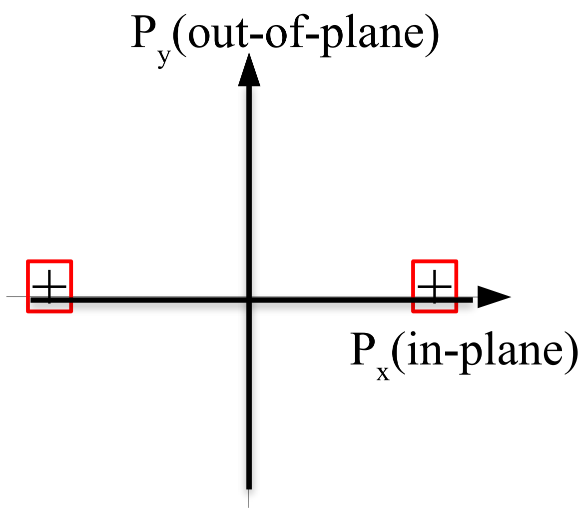


Data favor in-plane back-to-back correlation

The bottom line….

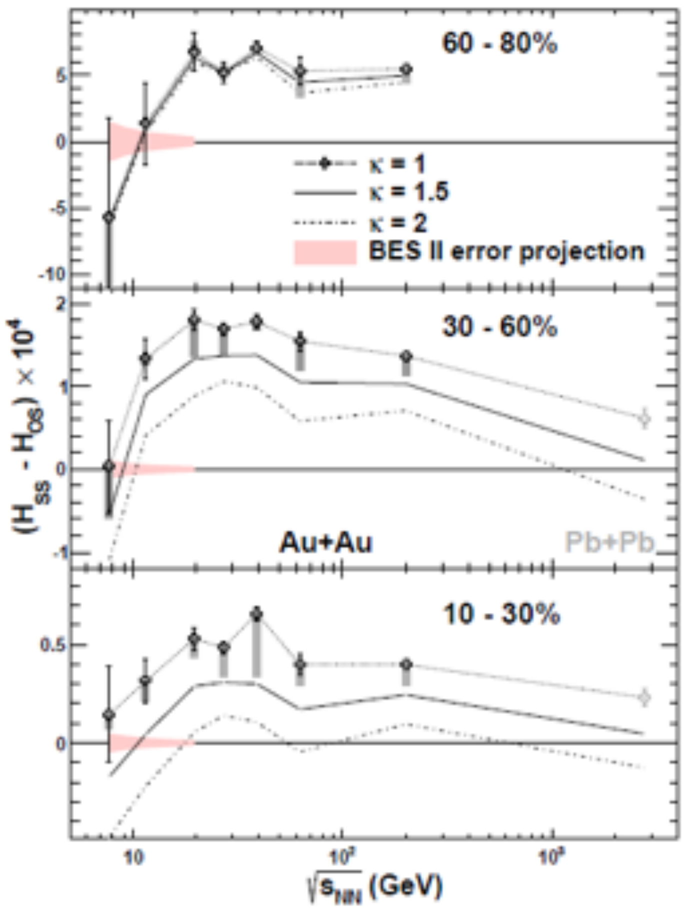


Local Parity violations
Predicts THIS

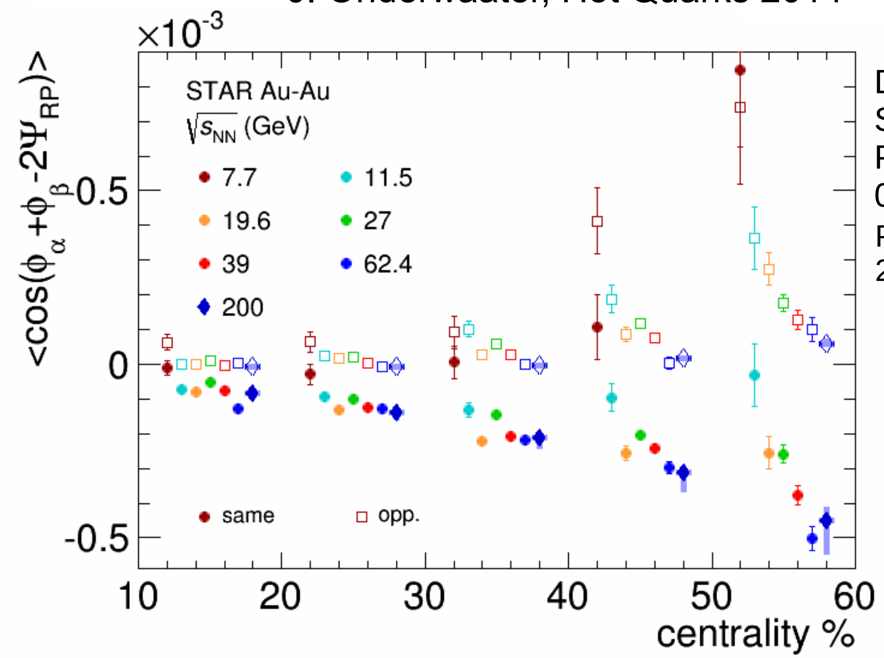


STAR measures THAT

Energy dependence.....



J. Onderwaater, Hot Quarks 2014



Derived from:
STAR
PRL. 113 (2014) 052302
PRL. 103 (2009) 2A51601

...of an un-understood observable.....

Time for systematic approach
(BES Workshop, LBL, Sept 2014)

- Need good simulations for BES similar to top RHIC hydro
- ISSUES:
  - Stopping / baryon transport
  - Equation of state
  - Fluctuations (hydrodynamical, critical, instabilities)
  - Anomaly dynamics

Physically well motivated parameters are better than unphysical models

Things to do

- Factorize the problem!
  - Critical fluctuations, anomaly dynamics are “perturbations”
  - Dynamical framework controlled by “bulk” observables
- Stopping/baryon transport
  - Start from present RHIC/LHC codes and slowly increase μ (39 GeV).
    - EOS known from LQCD
    - Concentrate on initial state, baryon transport, heat conductivity etc
- Equation of state
  - Lattice
  - Nuclear Matter
  - Minimize ignorance, parametrize the rest

Summary

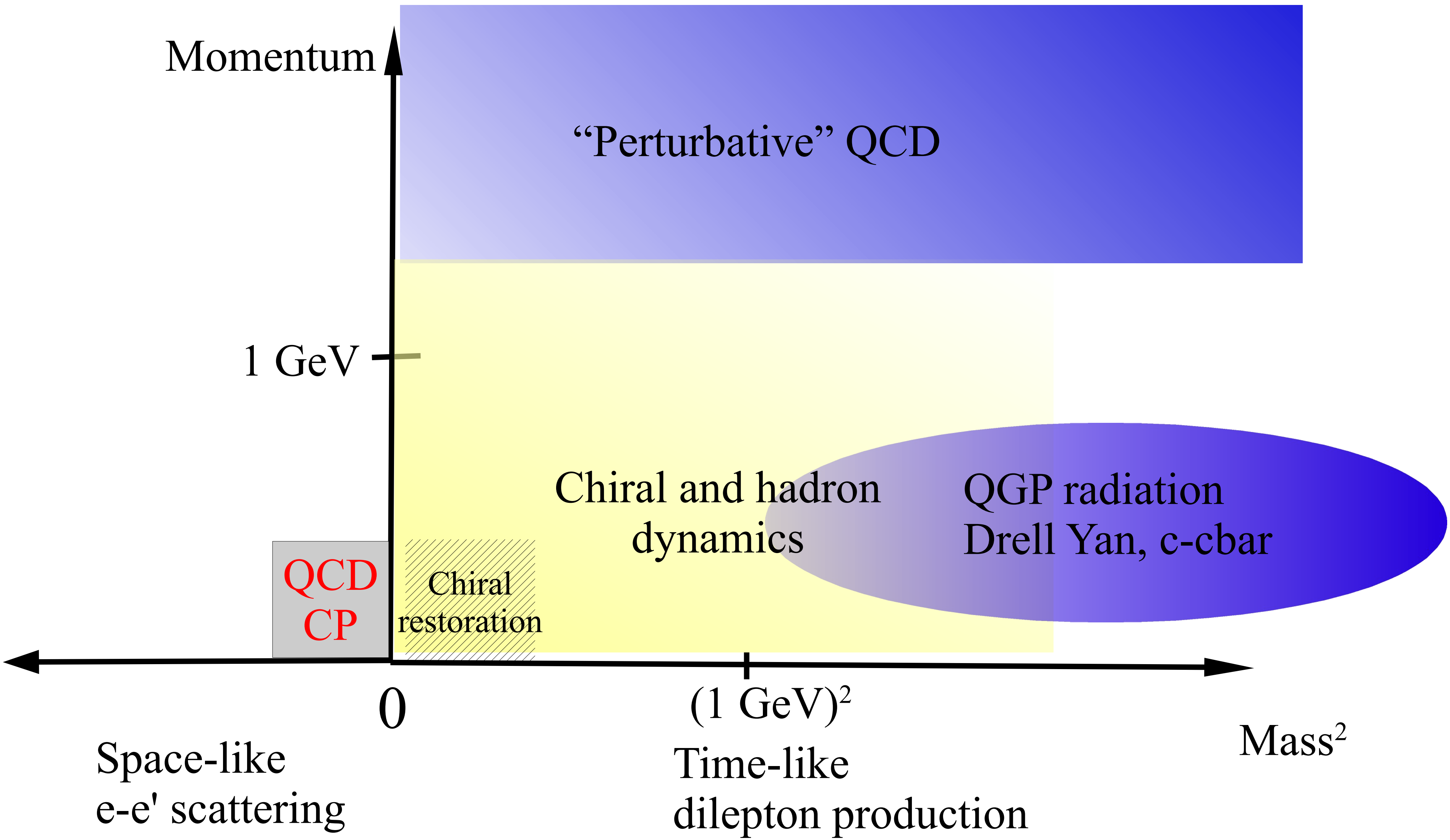
- Phase diagram well known for small μ (Lattice)
  - No sign of phase transition there
- Little guidance from theory for large μ
  - most models predict phase co-existence between QM and vacuum
- BES I shows some interesting results
  - need to systematic modeling
    - stopping
    - EOS (in necessary parametrized)
    - start at high energies and work ourselves down
    - need spectra and rapidity distributions/correlations
    - …..

And with a little luck……….

We will catch the thing

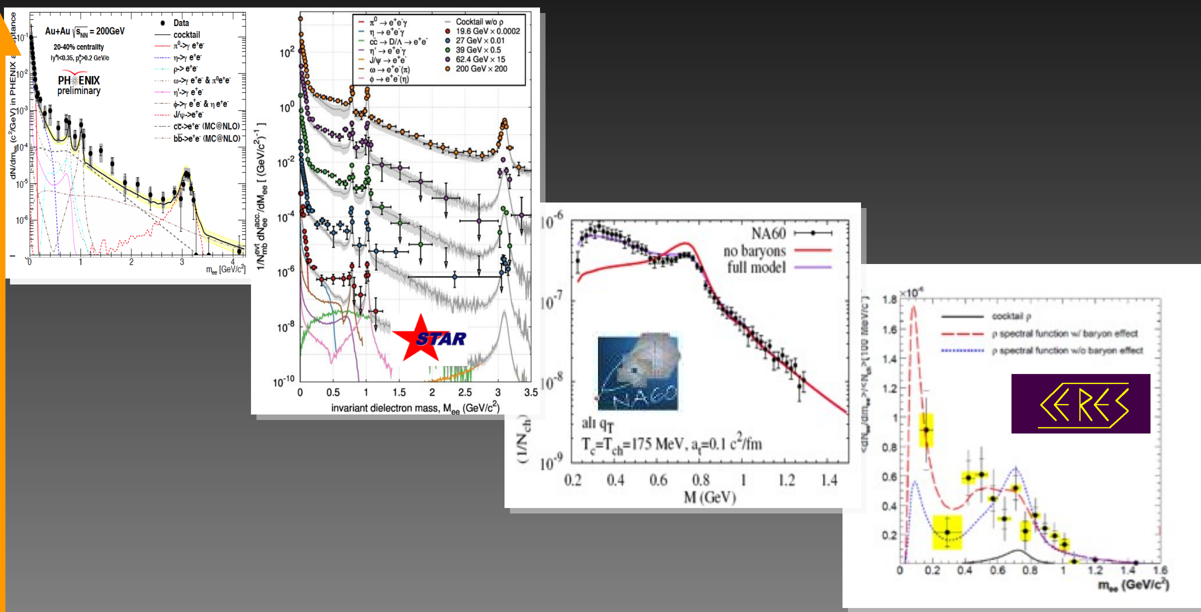
BACKUP

The Dilepton production landscape



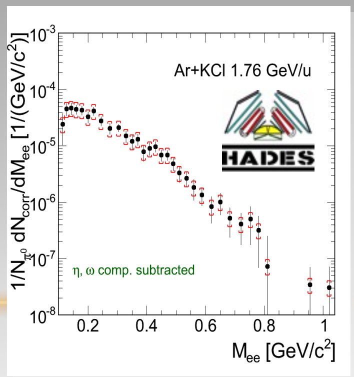
VIRTUAL PHOTON RADIATION FROM HOT AND DENSE QCD MATTER

T



Model: Ralf Rapp
STAR: QM2014,
NA60: EPJC 59 (2009) 607,
CERES: Phys. Lett. B 666 (2006) 425,
HADES: Phys.Rev.C84 (2011) 014902

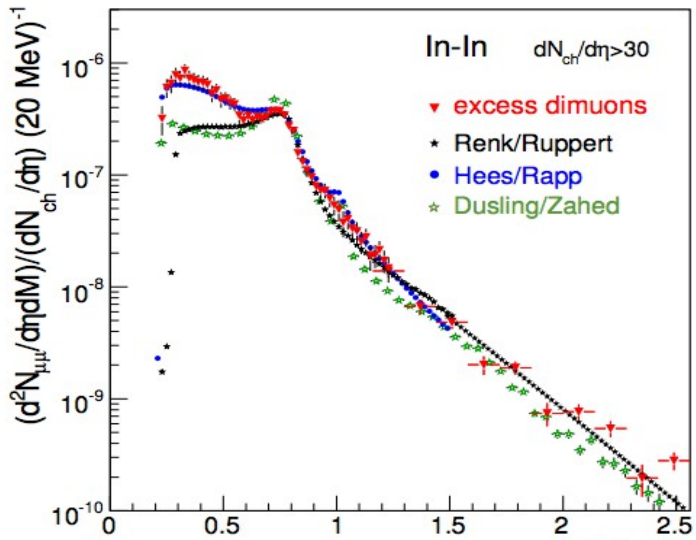
Highly interesting results from RHIC, SPS, SIS18
→ lepton pairs as true messengers
of the dense phase

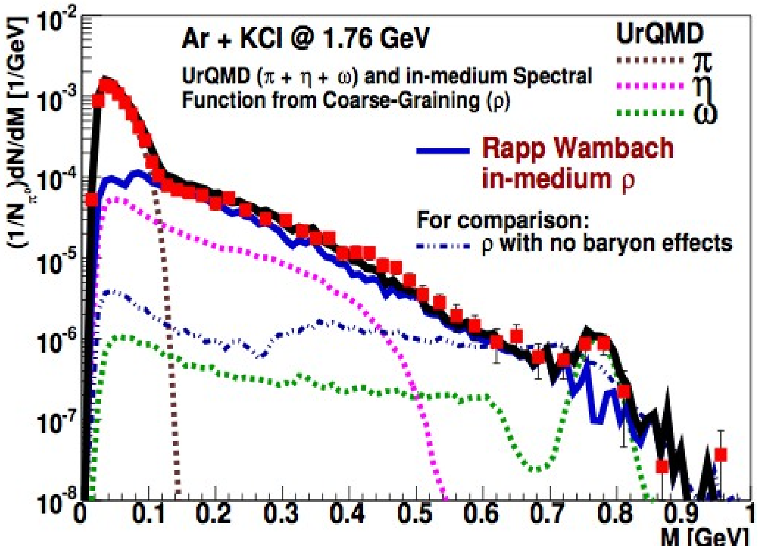


T. Galatyuk, QM14

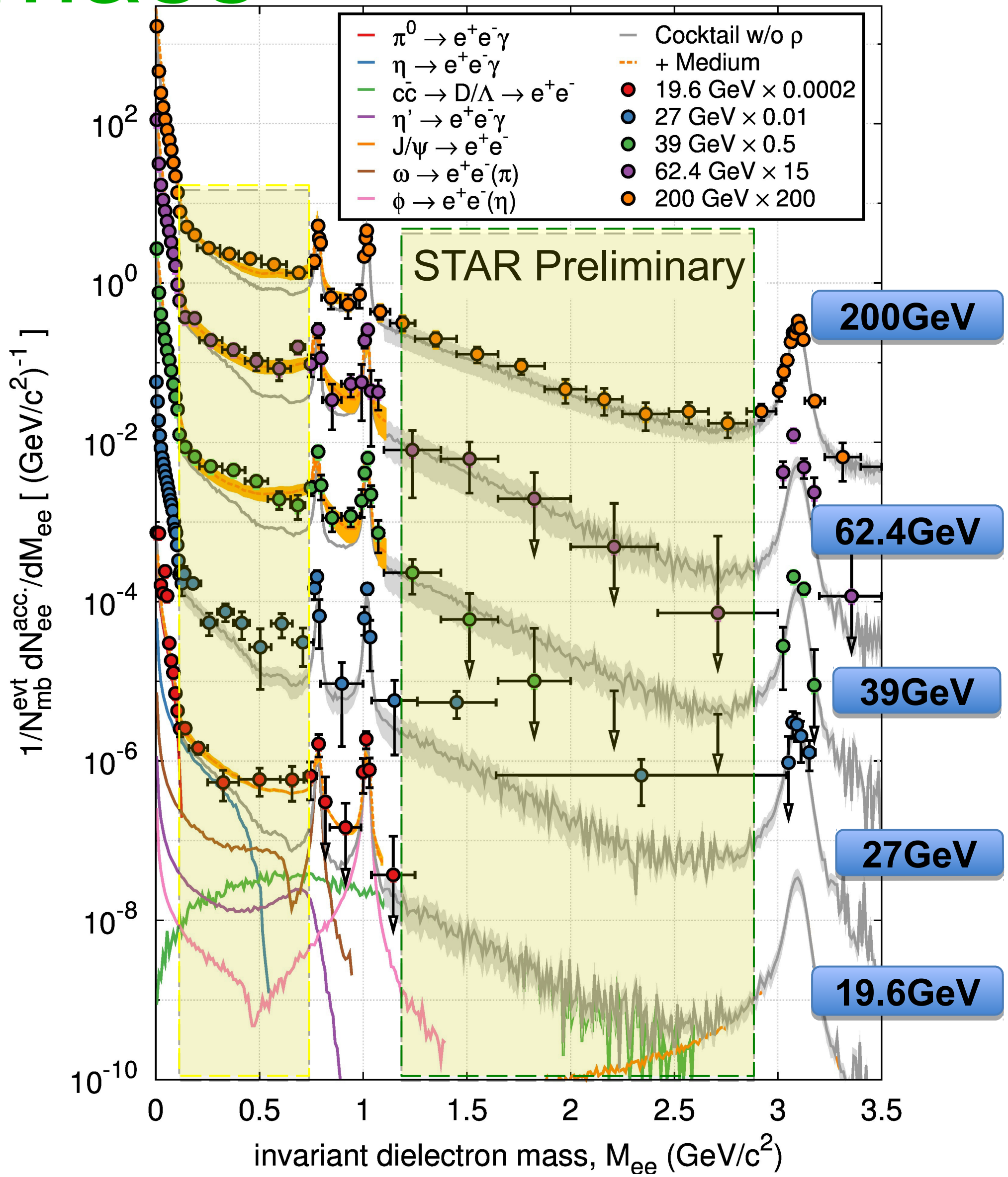
μ_B

Low mass



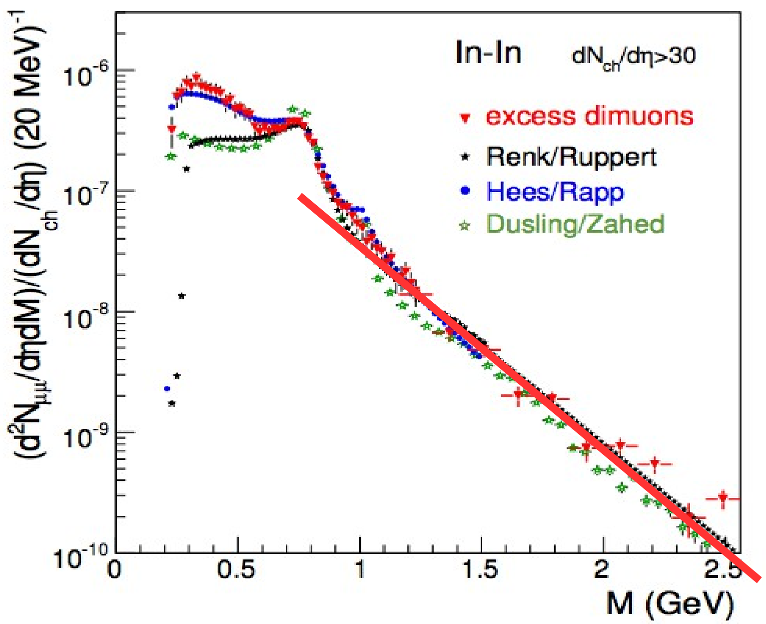


H. van Hees, BNL 14



Low Mass region is understood: Baryon resonances plus broadening through mixing

Intermediate Mass



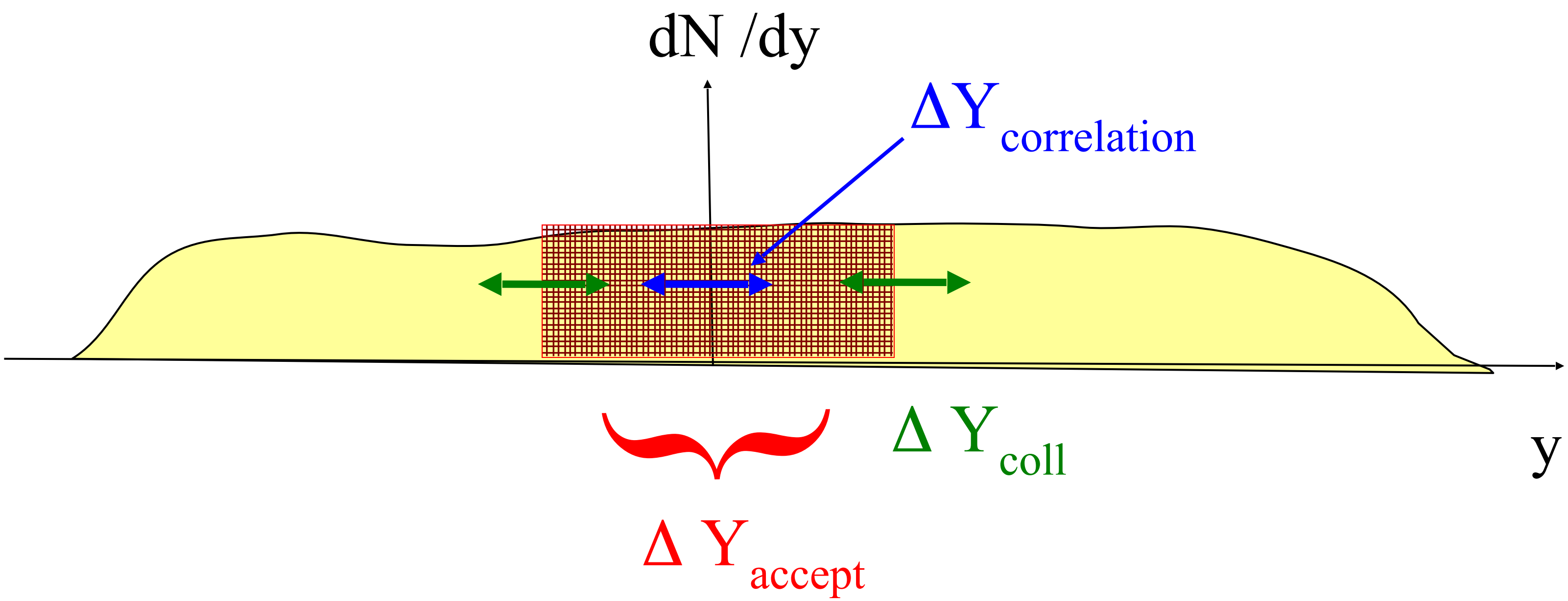
Intermediate mass sensitive to "QGP" radiation. NA60: T_{eff}~ 200 MeV

What to expect at lower energies?

Should we see any radiation if no QGP? YES!

Will we see simply a lower temperature? (Hopefully !)

“Charge” fluctuations

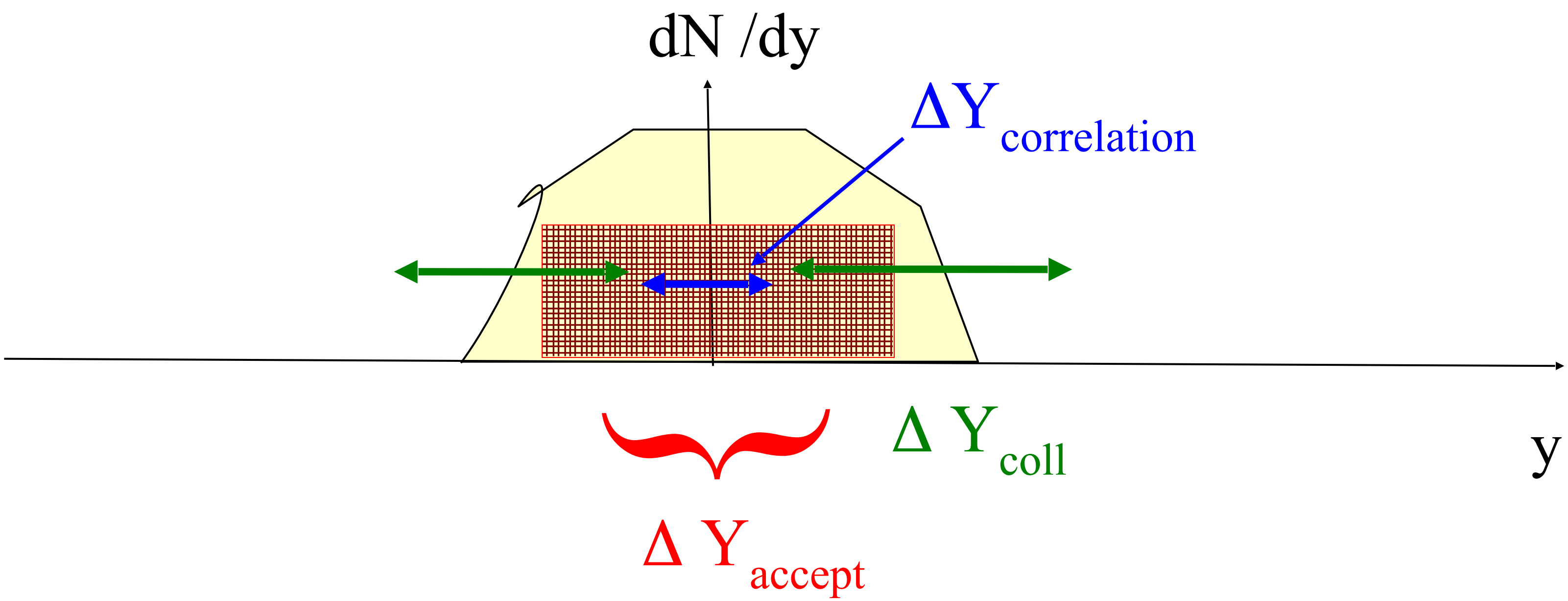


Conditions for “charge” fluctuations:

1)$\Delta Y_{\text{corrrelation}} << \Delta Y_{\text{accept}}$ **(catch the physics)**

1)$\Delta Y_{\text{total}} >> \Delta Y_{\text{accept}} >> \Delta Y_{\text{coll}}$ **(keep the physics)**

“Charge” fluctuations at SPS and below



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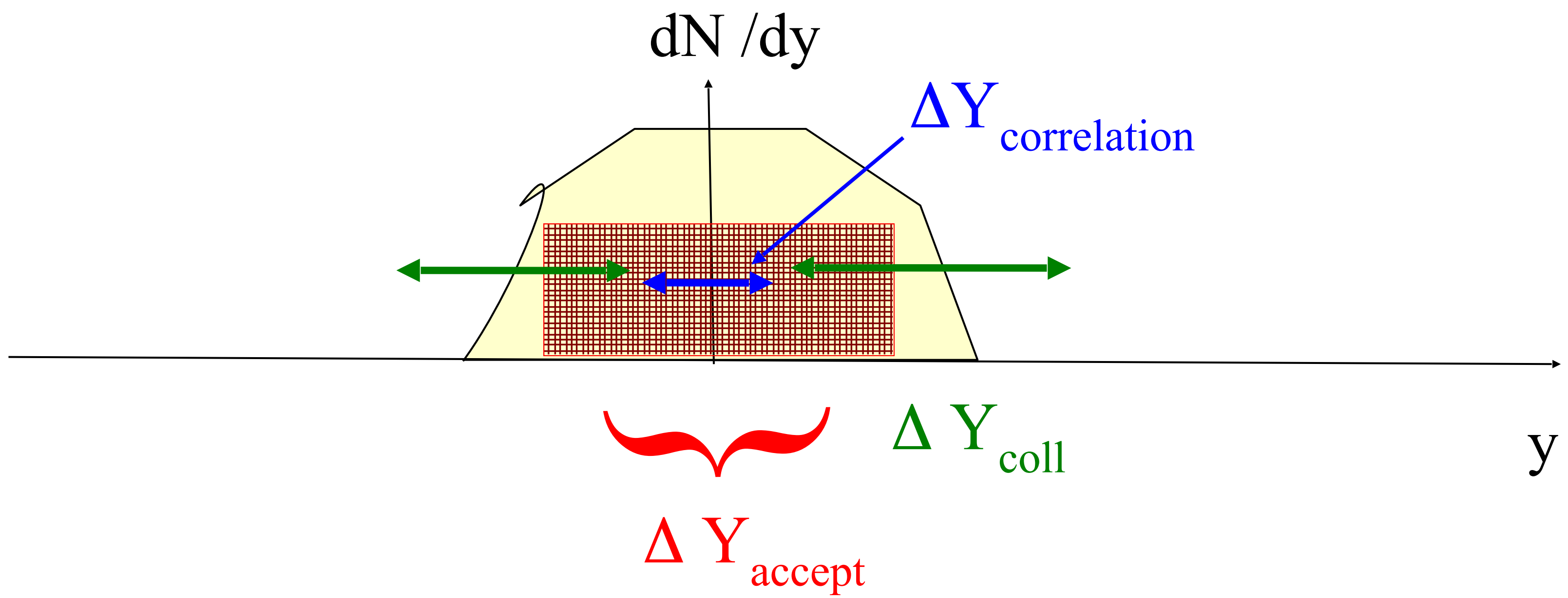
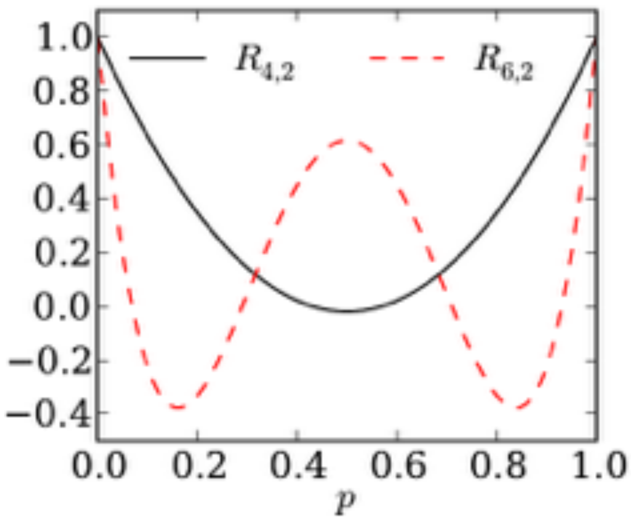


Conditions for “charge” fluctuations:

1) $\Delta Y_{corrrelation} << \Delta Y_{accept}$ **(catch the physics)**

1) $\Delta Y_{total} >> \Delta Y_{accept} >> \Delta Y_{coll}$ **(keep the physics)**

“Avoid” conservation Laws

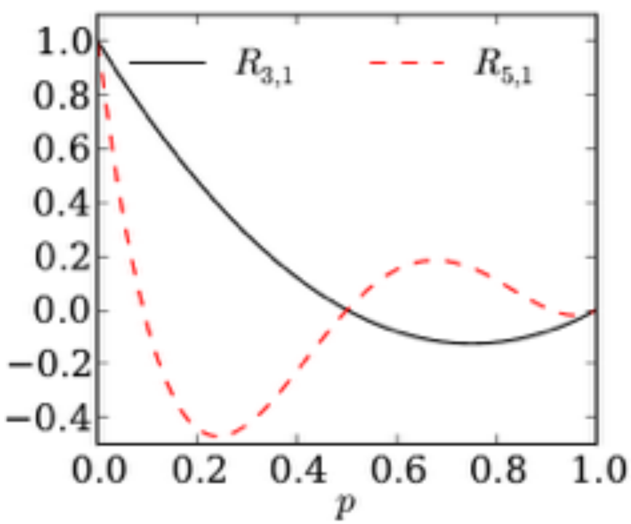


Define: $$R_{m,n} = \frac{C_m}{C_n}$$

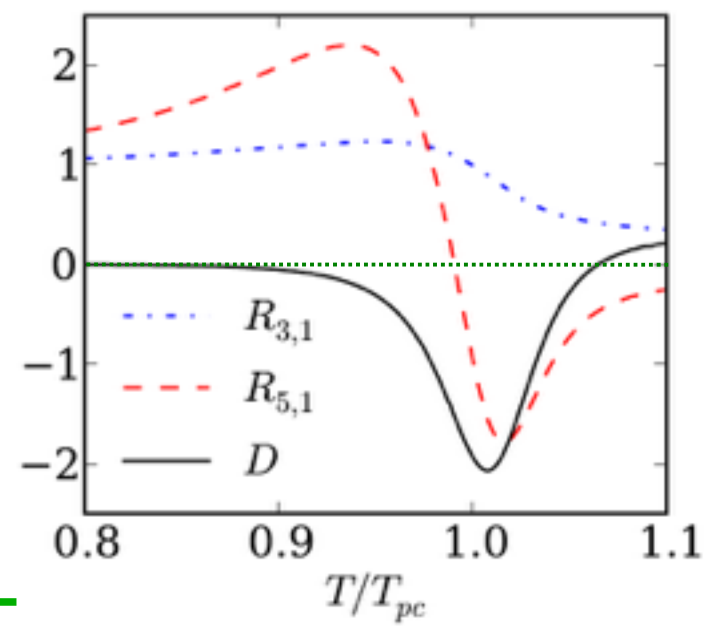
$$D = R_{5,1} - R_{3,1}\left[1 - \frac{3}{4}(1+\gamma)(3-\gamma)\right]$$

$$\gamma = \sqrt{1 + 8R_{3,1}}$$

D = 0 for ALL values of p, B, …
in ABSENCE of any correlations

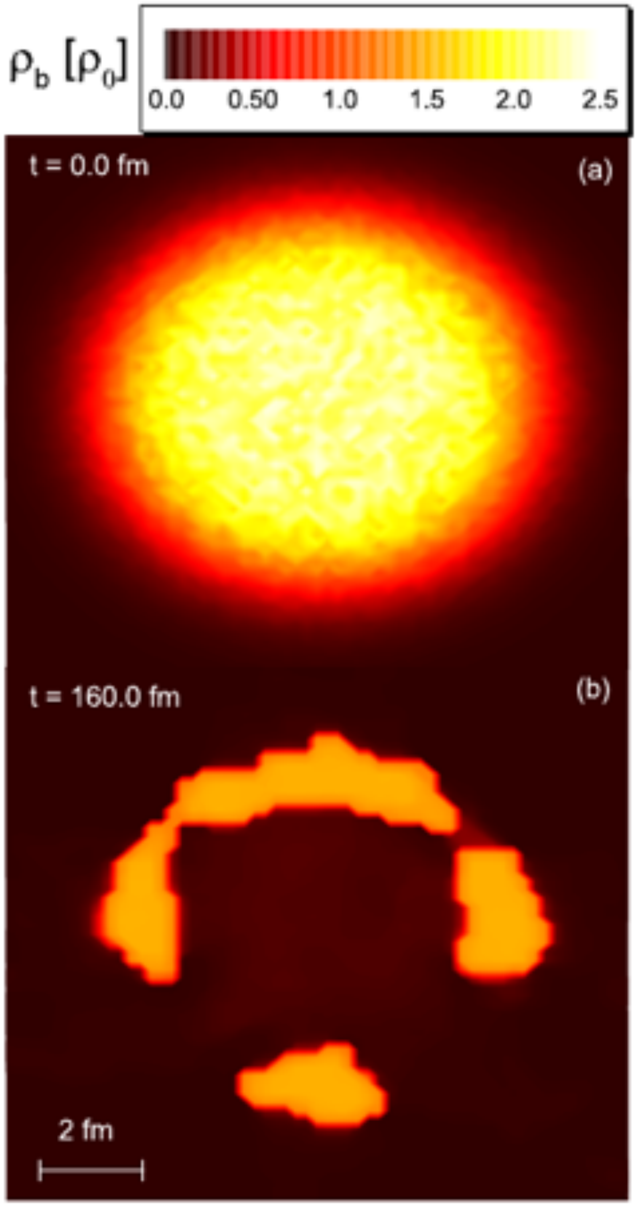


A.Bzdak,VK,V.Skokov arXiv:1203.4529

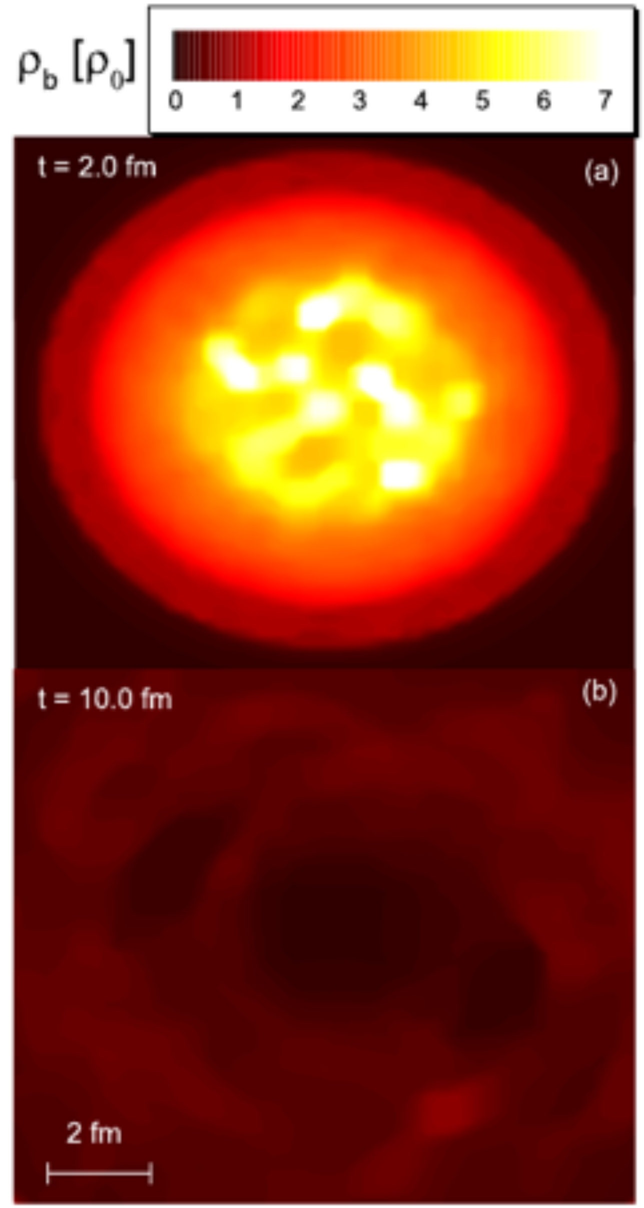


No physics

Flow



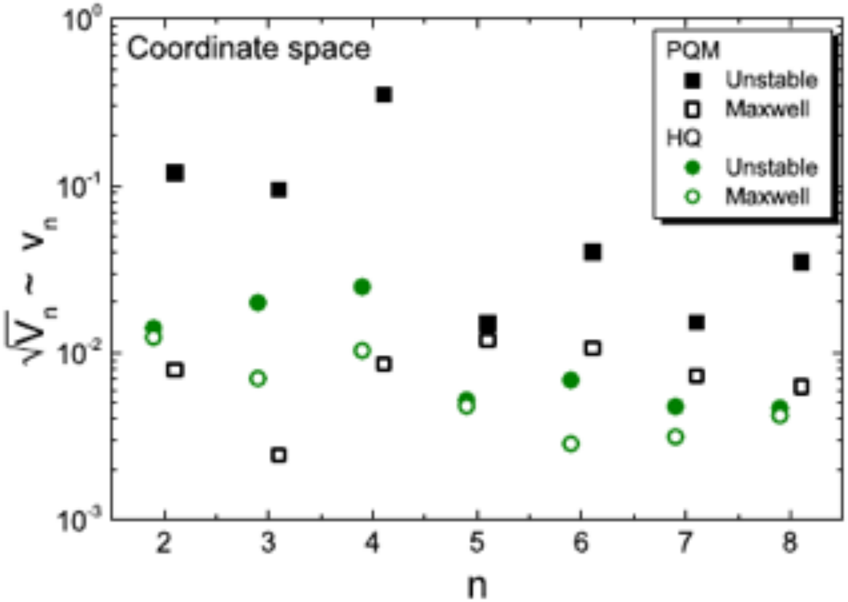
PQM (“liquid-gas”)



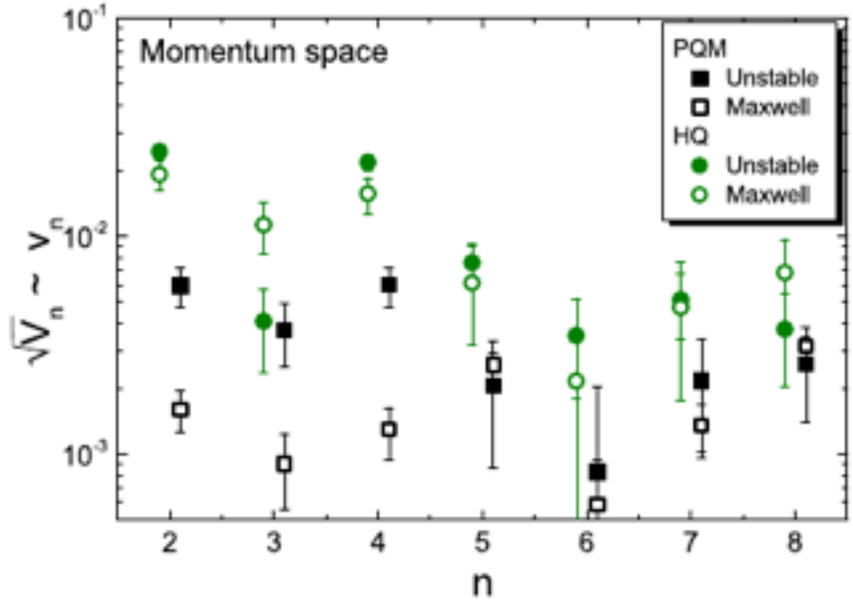
“QCD”

Flow

Coordinate space



Momentum space



Coordinate space asymmetries sensitive to nearly stable droplet formation in "liquid gas" EoS

Small pressure of liquid:
weak mapping into momentum space for liquid-gas
Hardly any effect of instabilities in case of "QCD" EoS

Steinheimer et al,
Phys.Rev. C89 (2014) 034901