Theory: Critical Point Search from RHIC Beam Energy Scan: fluctuations of conserved charge

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2012 RHIC & AGS Annual Users' Meeting

OUTLINE

1) Introduction

2) QCD phase diagram: facts and expectations

3) Fluctuations of conserved charges as a probe of QCD phase diagram

4) Conclusions and outlook

Not a point, but any critical behavior?

STRUCTURE OF QCD PHASE DIAGRAM

What do we really know about QCD phase diagram from first principles?

0) Perturbative QCD at high T and μ: deconfinement: liberation of quarks and gluons

1) Zero chemical potential μ: analytic crossover. Lattice QCD at physical quark masses: Bernard et al '05, Cheng et al '06, Aoki et al '06

Recent developments at μ=0:

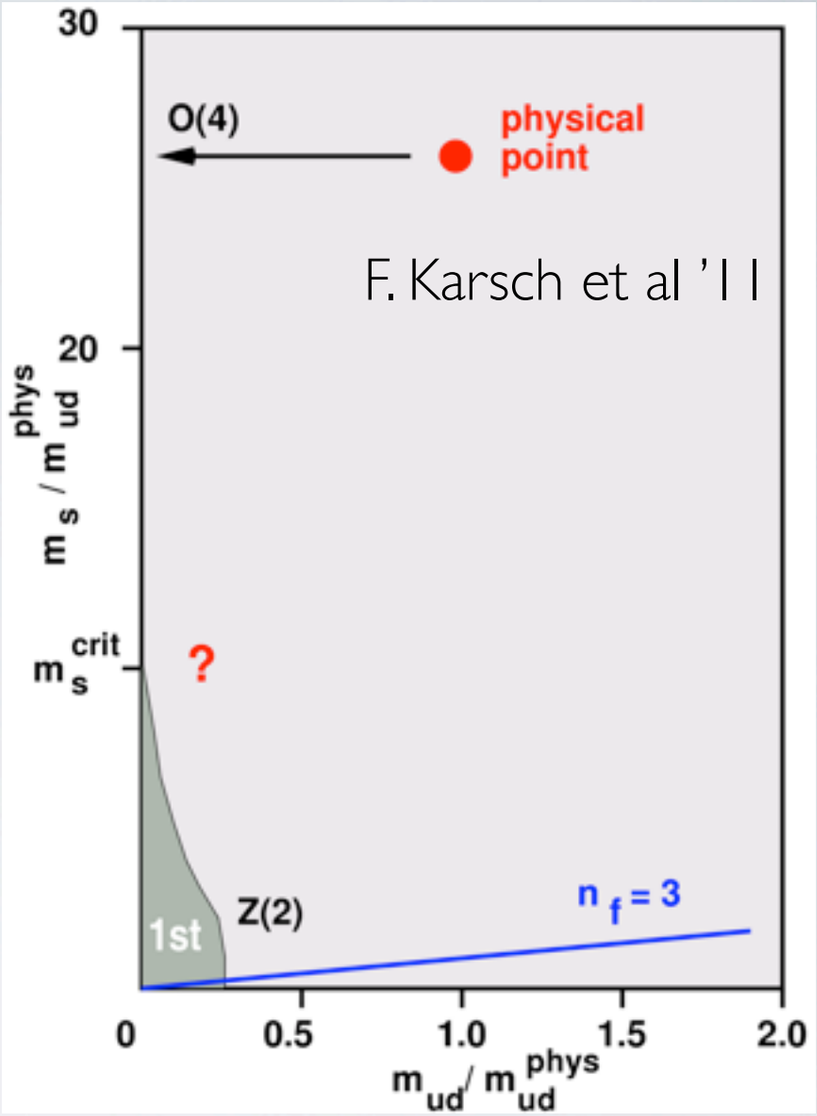
2) At physical pion mass QCD is in scaling regime of O(4) chiral dynamics.

Recent developments at μ=0:

2) What is the order of the phase transition at physical strange mass and zero light quark masses?

Why is this question relevant?

At physical pion mass QCD is in scaling regime of O(4) chiral dynamics.



Chiral properties strongly affects QCD physical m_π.

3) Pseudo-critical phase transition temperature at zero baryon chemical potential

T_c=154±9 MeV (HOTQCD collaboration)

This temperature reflects chiral properties of the transition

4) Curvature of transition at zero chemical potential

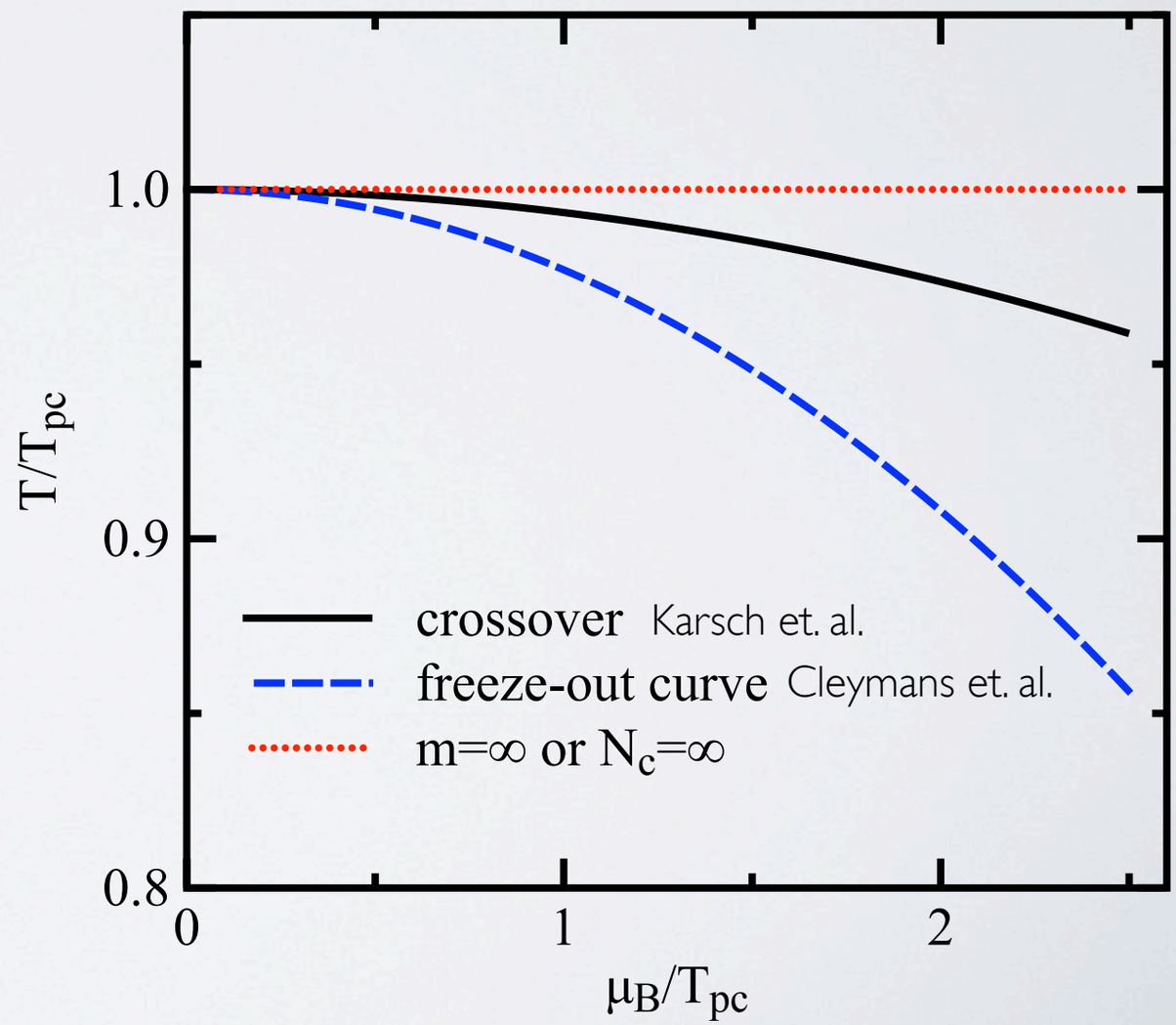
$$T/T_c \approx 1 - 0.0066(\mu_B/T)^2$$

BNL-Bielefeld collaboration '11

Freeze-out curve:

$$T/T_{fr} \approx 1 - 0.023(\mu_B/T)^2$$

Cleymans et al



3) Pse

baryo

T_c=15

This te

Deconfinement is very gradual. There is no good observable to define a precise temperature.

4) Curvature of transition at zero chemical potential

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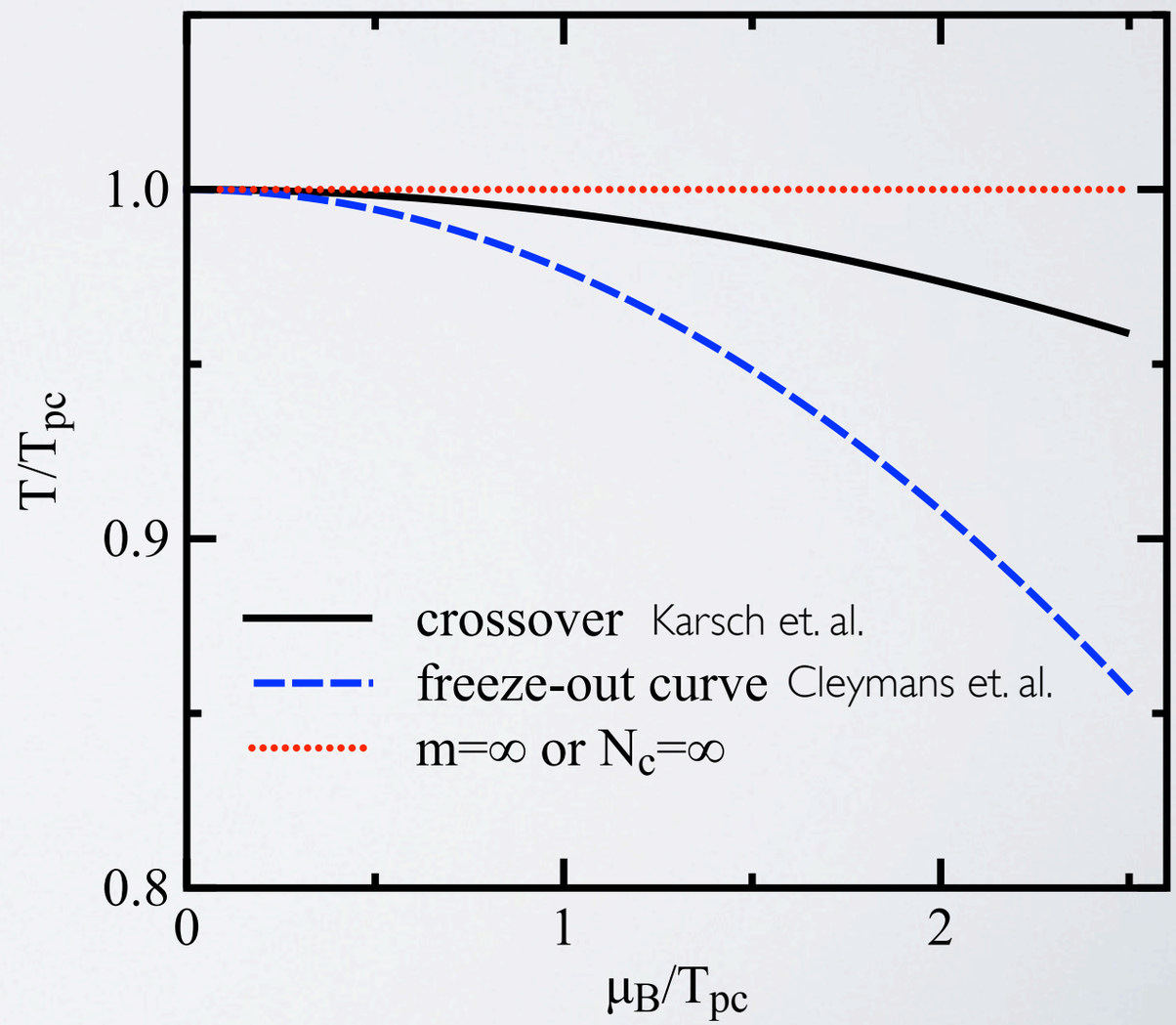

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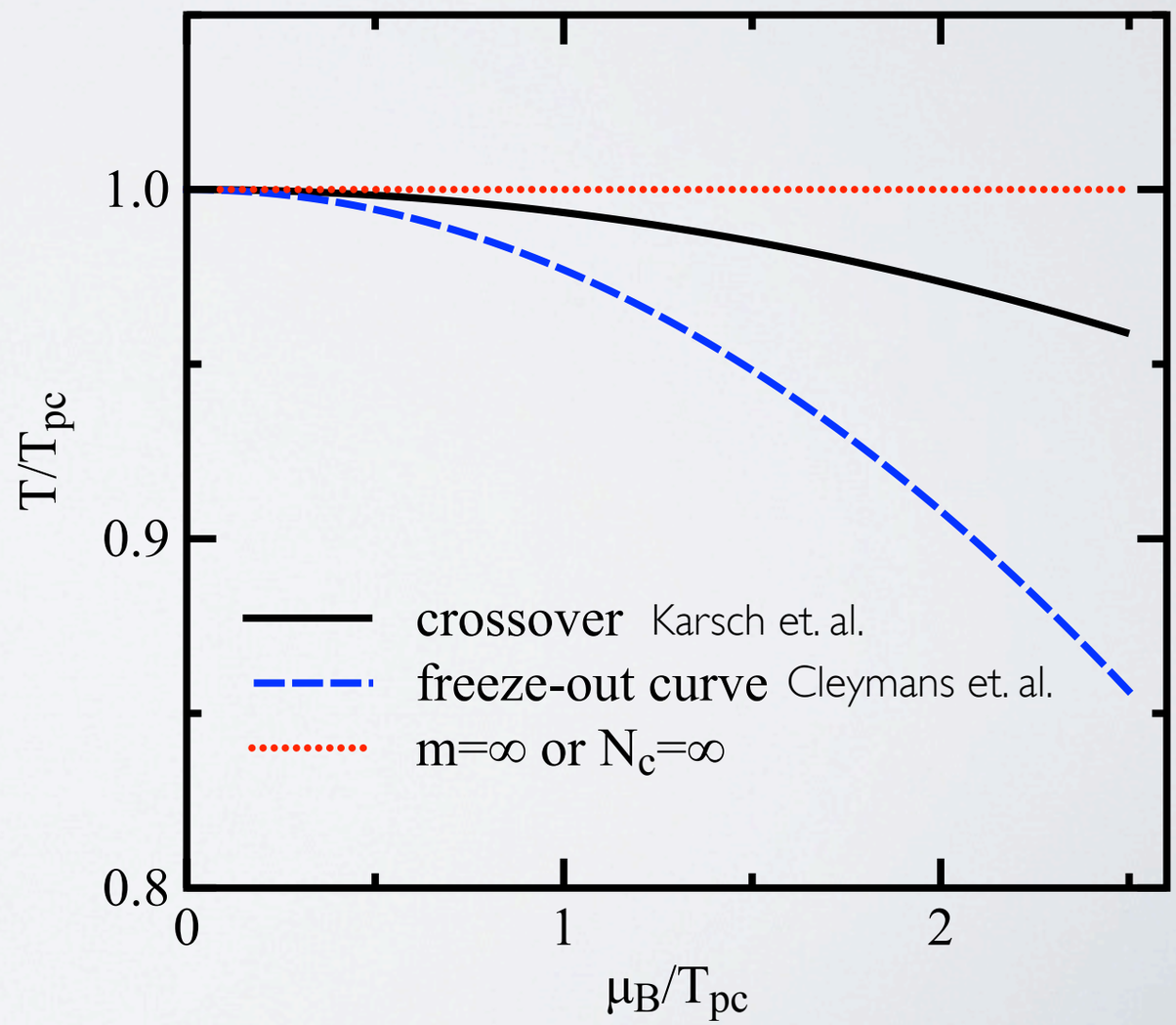
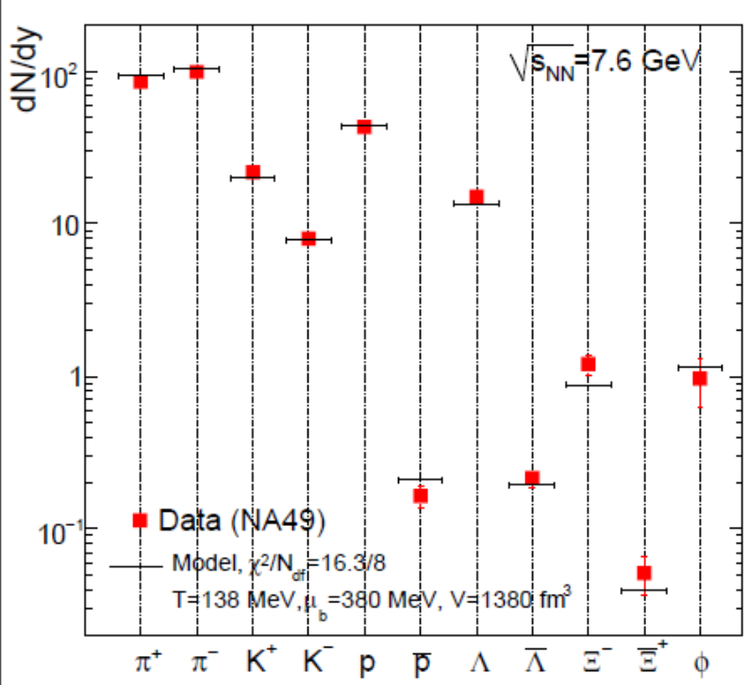


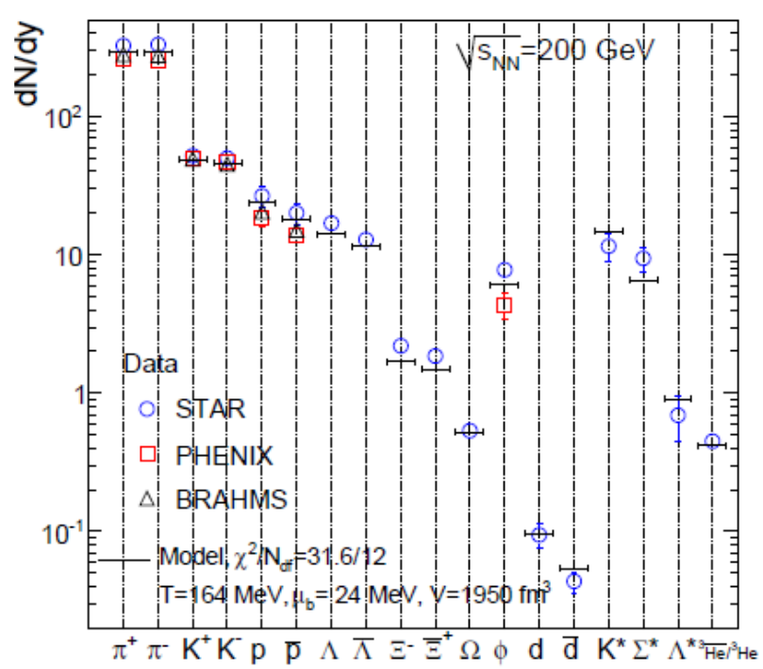
FREEZE-OUT CURVE

1) based on analysis of experimental data via hadron resonance gas model (HRG).

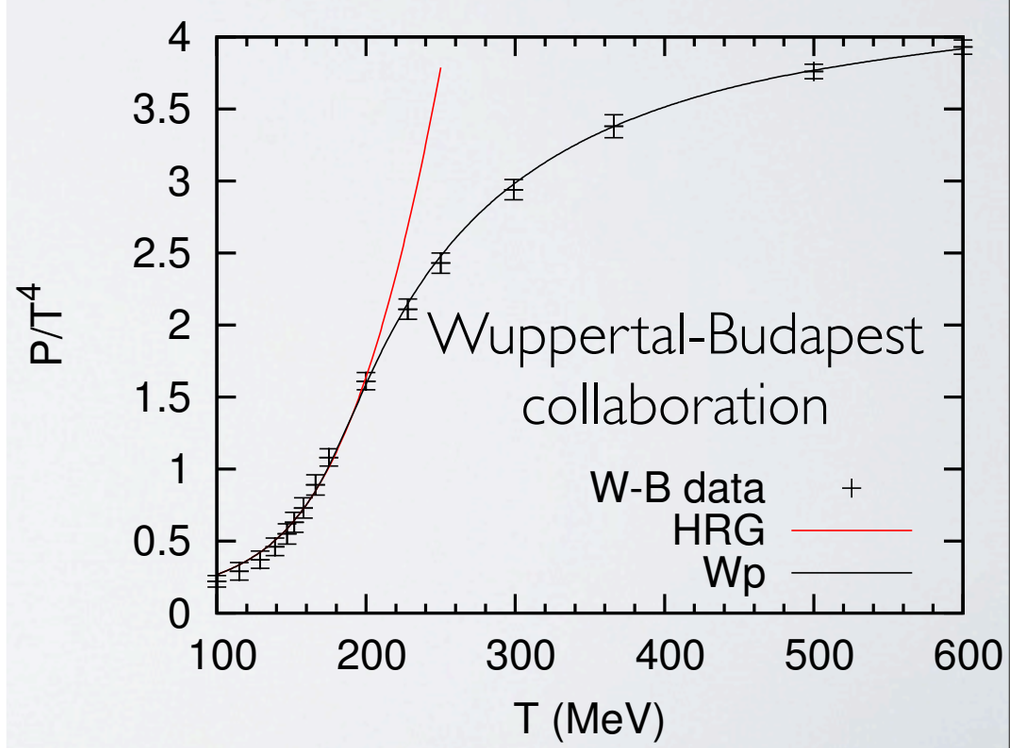
2) HRG

- non-interacting hadrons and their resonances
- unique T and μ for a given $\sqrt{s}$ and centrality

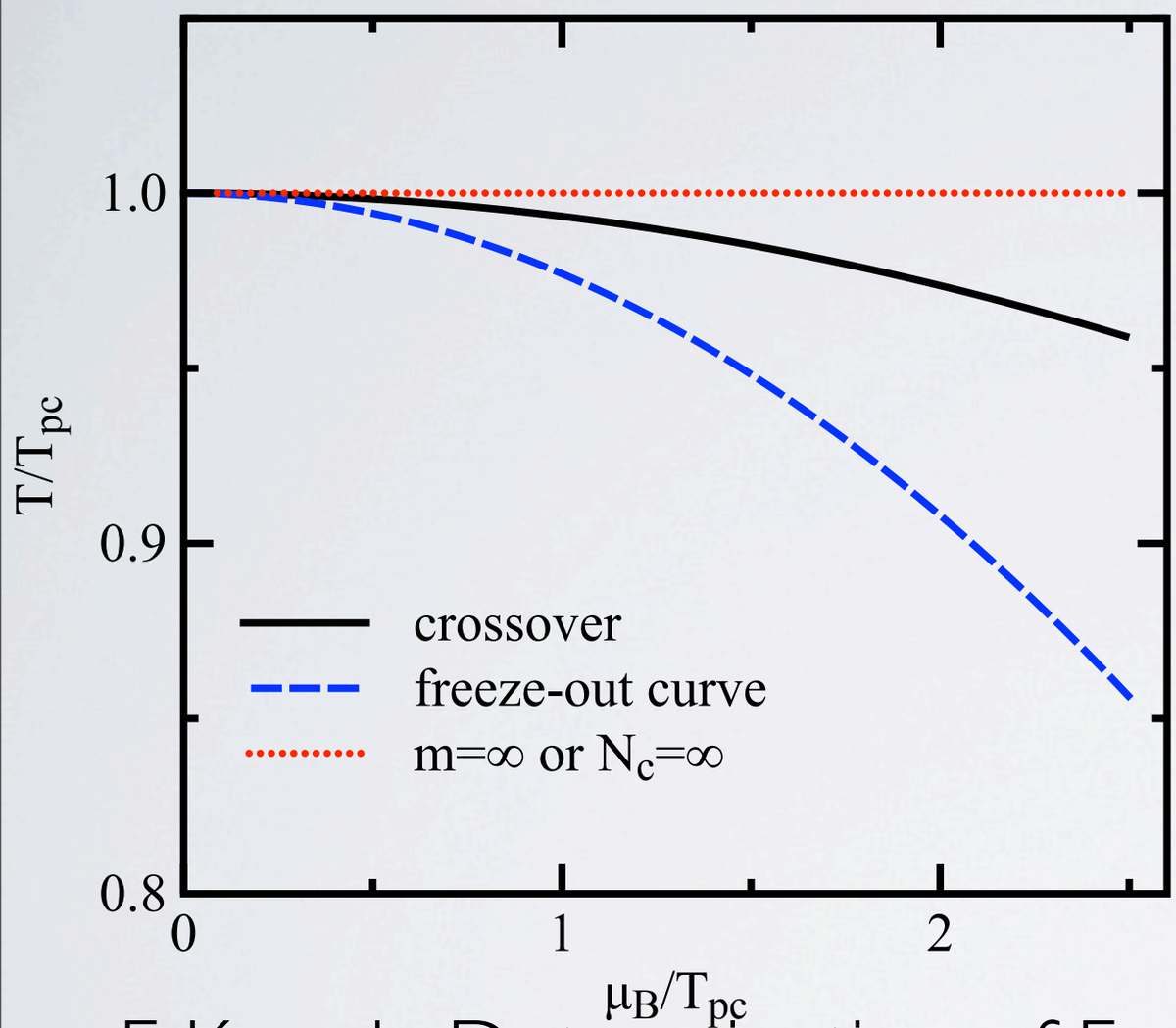




A. Andronic et al



FREEZE-OUT CURVE AND PHASE TRANSITION



- F. Karsch: Determination of Freeze-out Conditions from Lattice QCD Calculations: arXiv:1202.4173
- Dynamical models with a realistic EoS (P. Huovinen and P. Petreczky)

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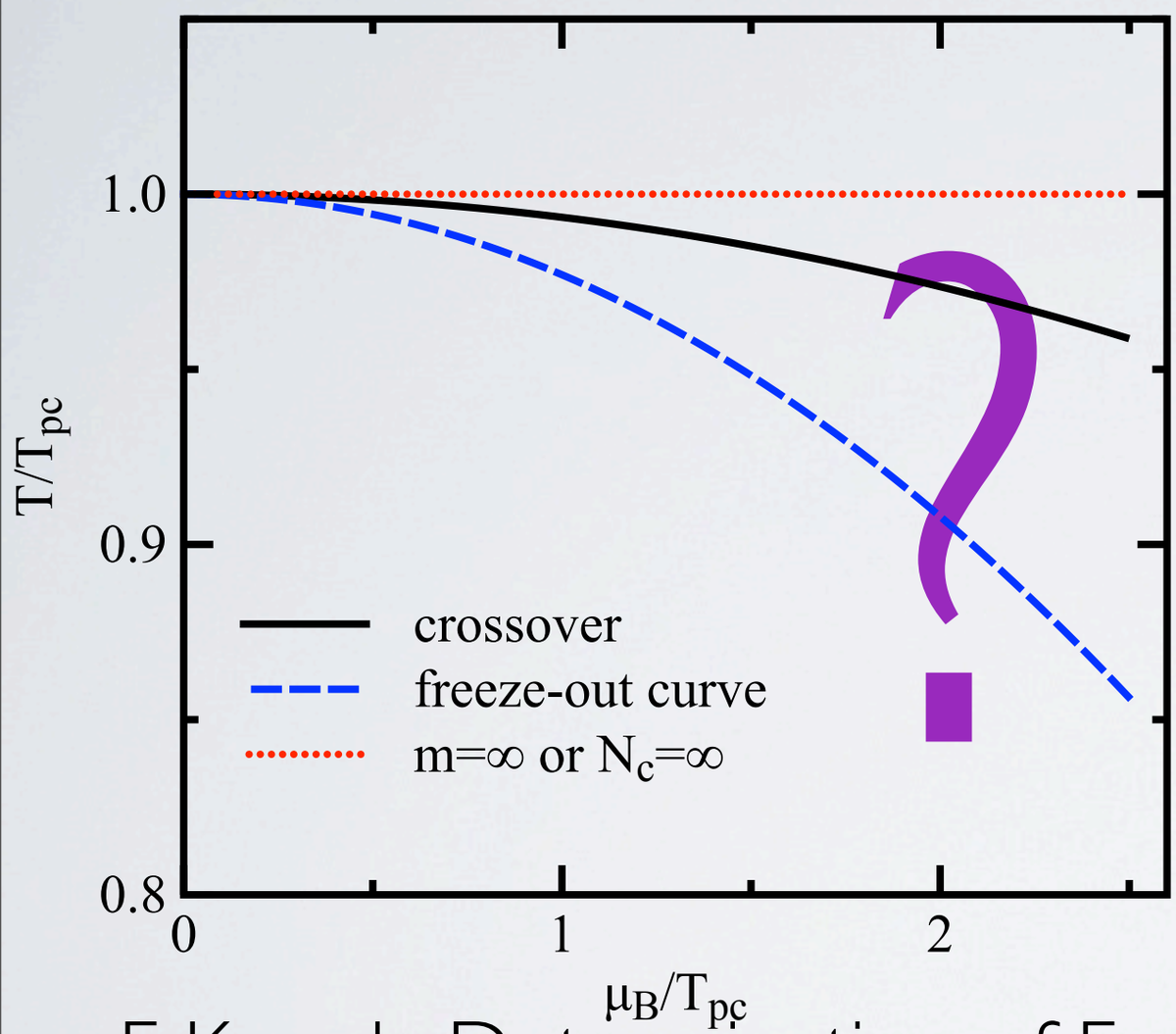

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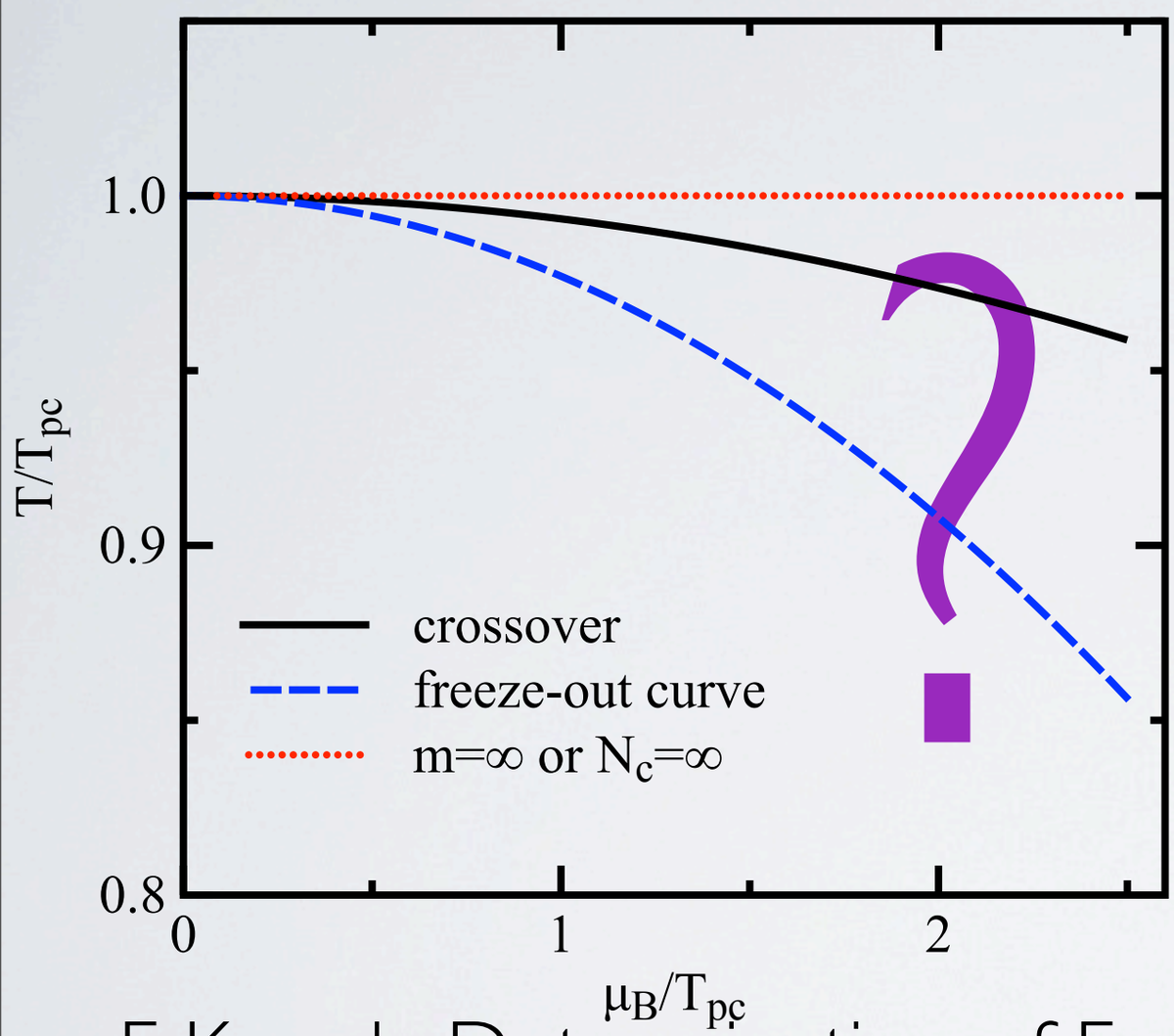

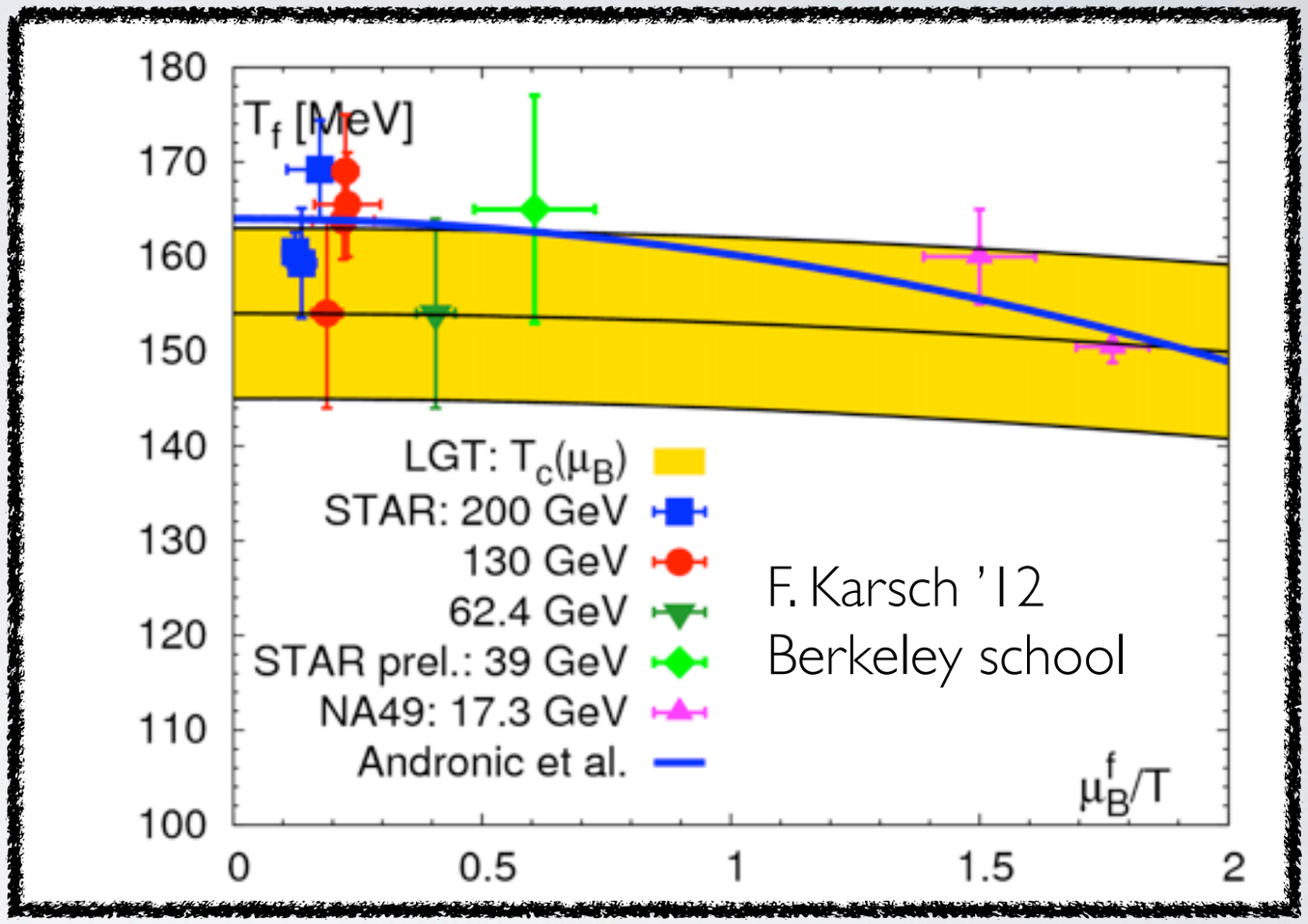

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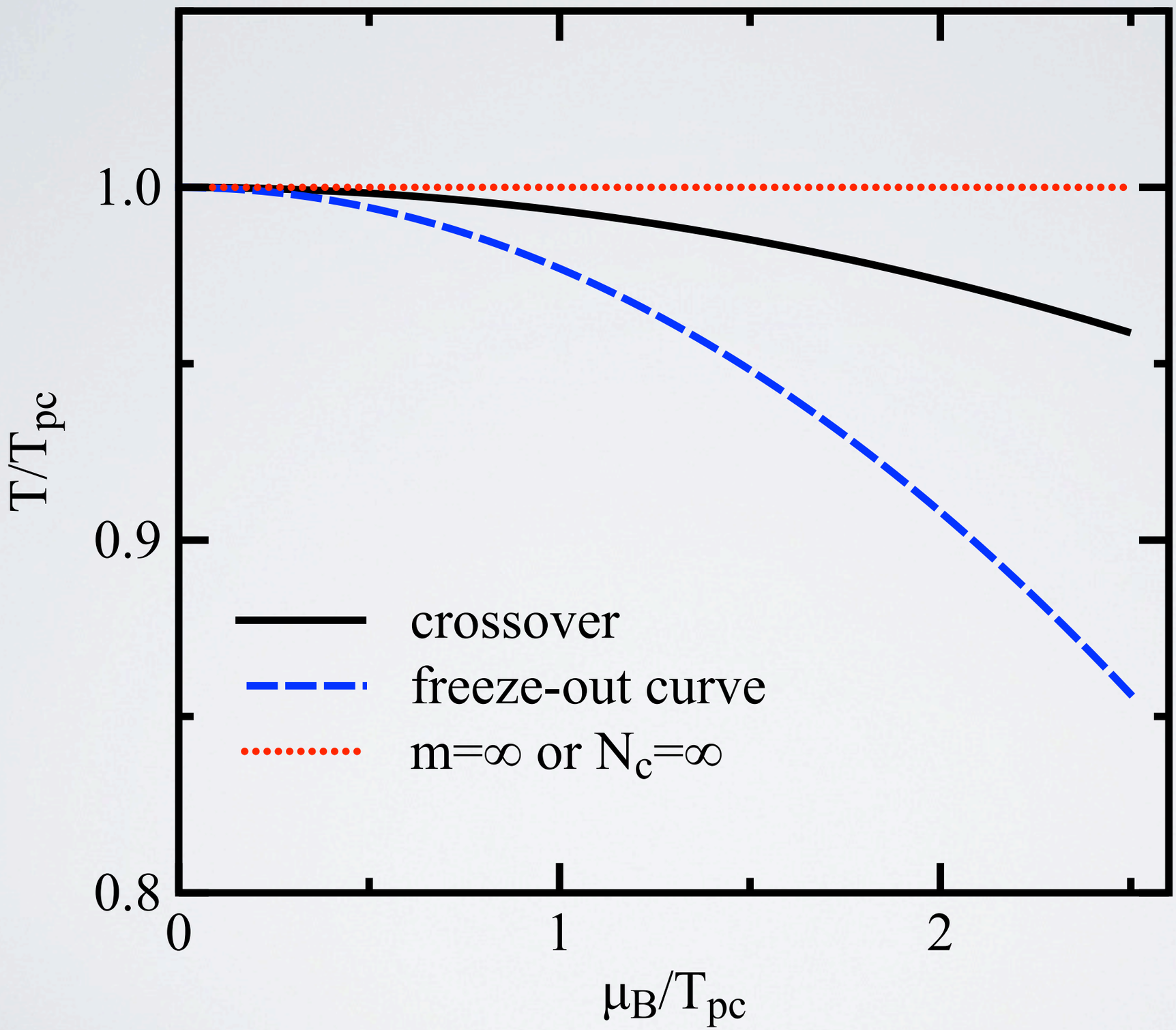

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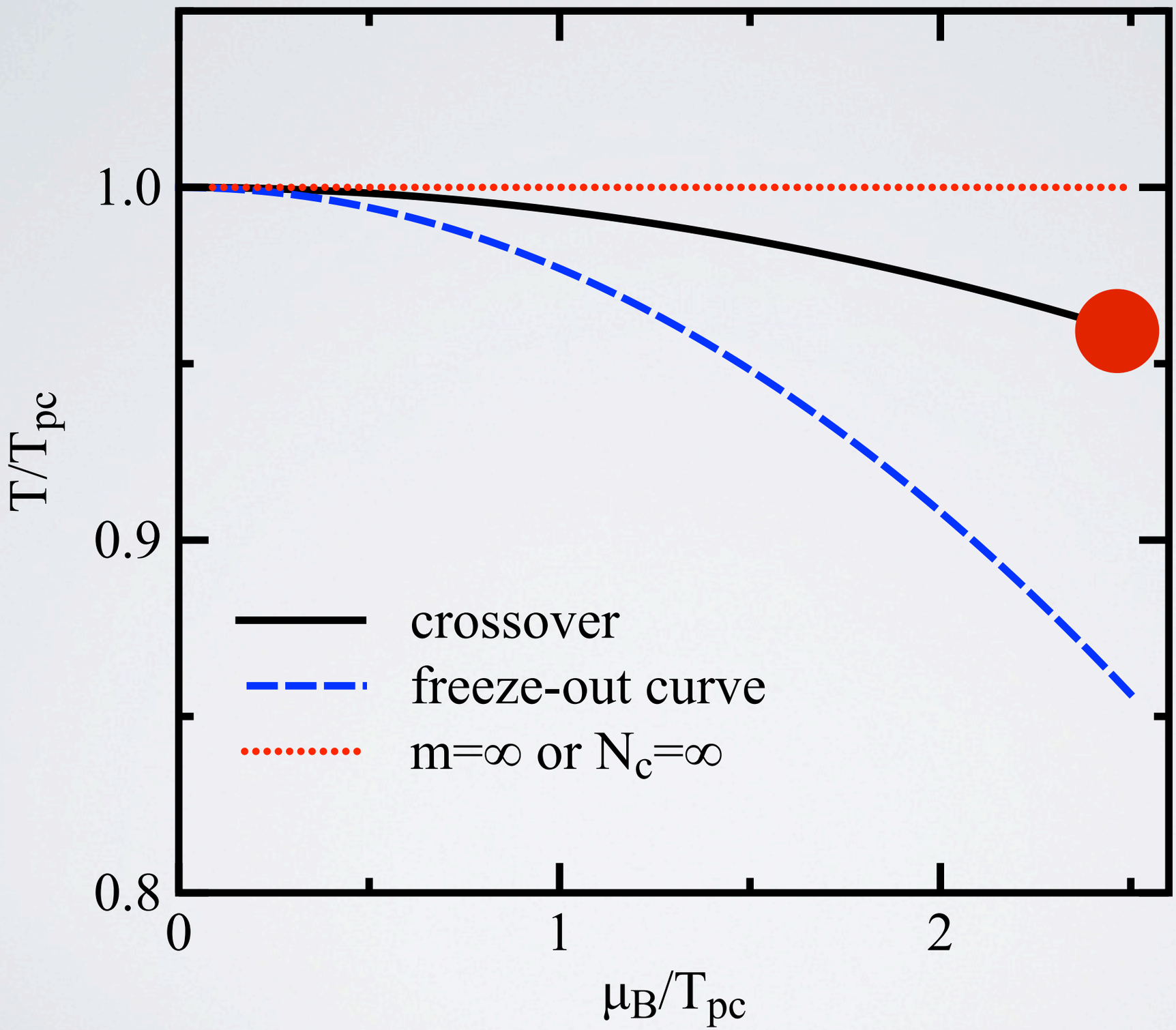

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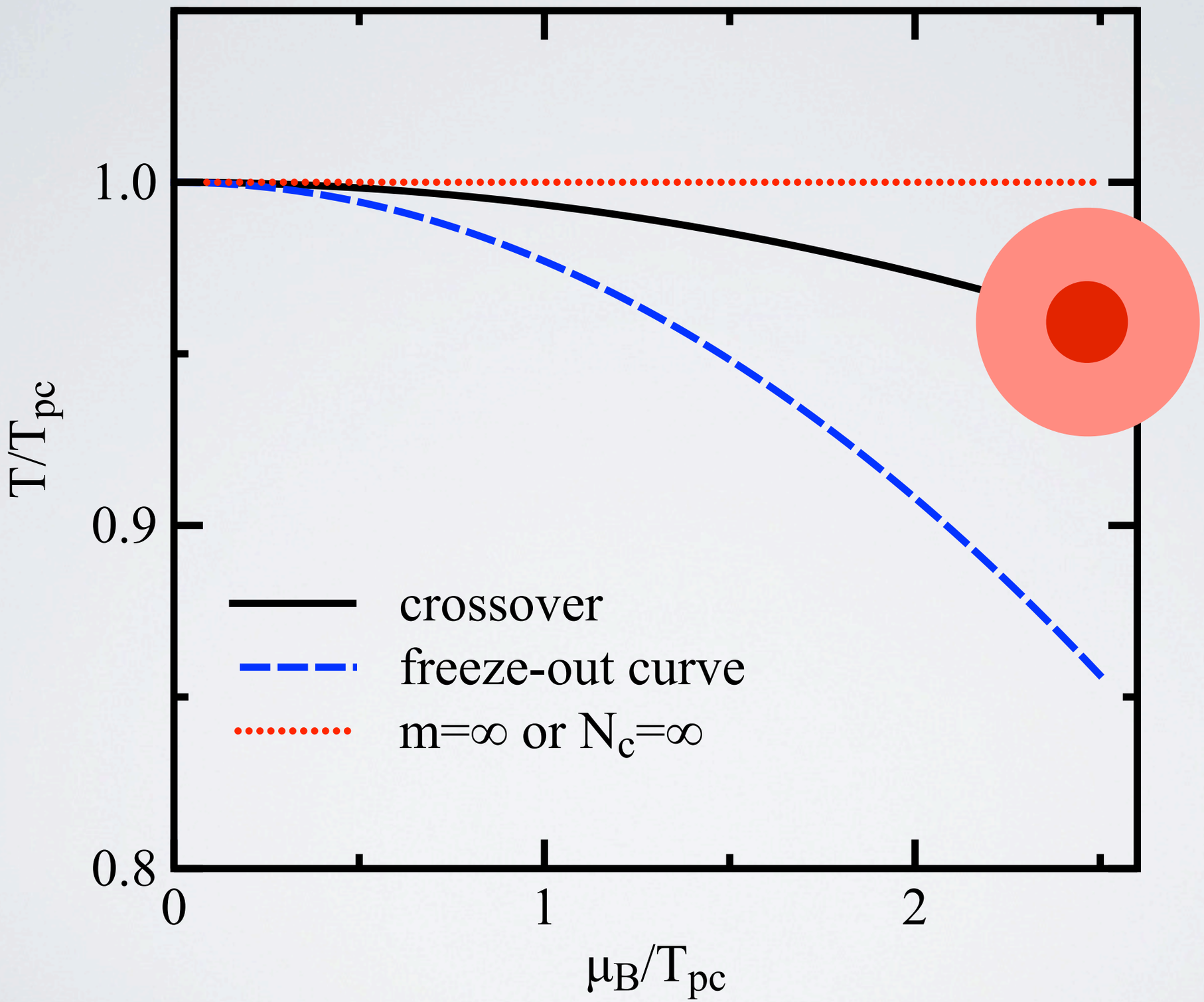


LATTICE ON CRITICAL END POINT

Is there CEP?

Some indications:

- Reweighing from $\mu=0$

Z. Fodor and S. Katz, '04:

$T_E=162\pm2$ MeV, $\mu_E=360\pm40$ MeV.

- Taylor expansion at $\mu=0$:

F. Karsch et al,

R. Gavai and S. Gupta

Radius of convergence → CEP

$T_E/T_c = 0.94\pm0.01$, $\mu_E/T_c=1.8\pm0.1$

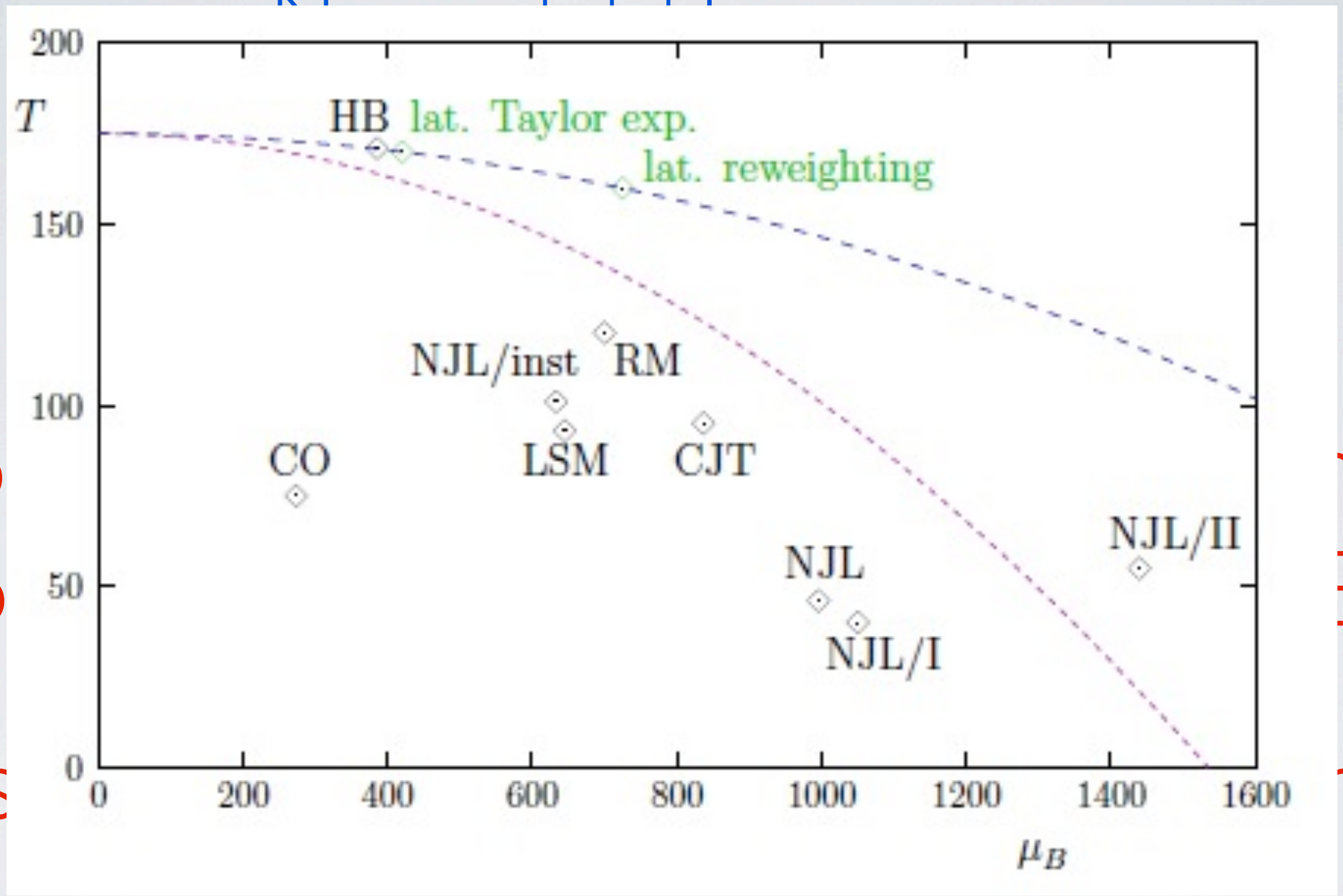
EFFECTIVE MODELS ON CRITICAL END POINT

No predictable power:
location is very sensitive to
parametrization and
physical inputs

Models are still useful to understand
properties of the transition and CEP

based on the Universality argument

EFFECTIVE MODELS ON CRITICAL END POINT



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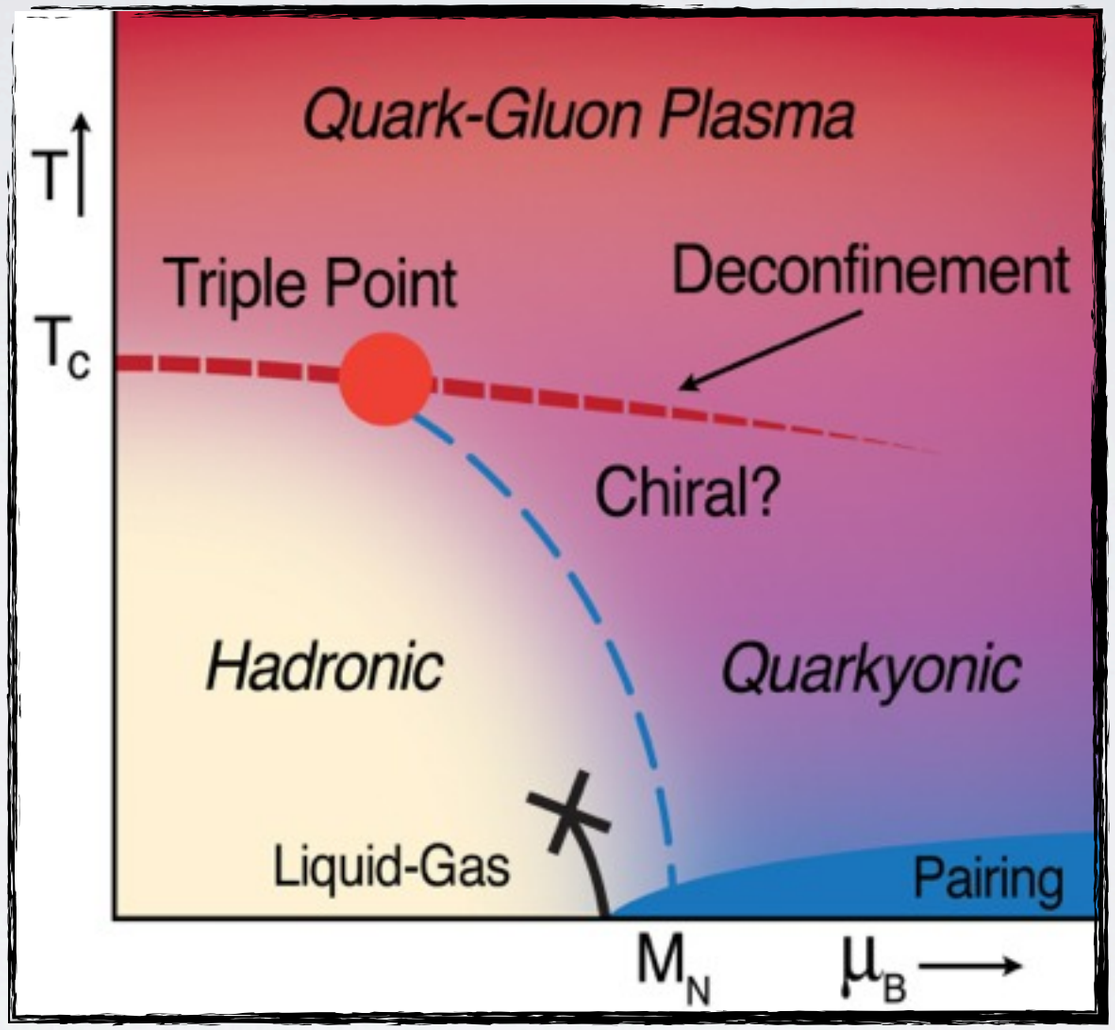
QUARKYONIC MATTER

L. McLerran and R. Pisarski: large N_c argument; non-homogenous chiral condensate



Quarkyonic phase could hide CEP, resulting in completely different behavior of observables

THEORY VS EXPERIMENT

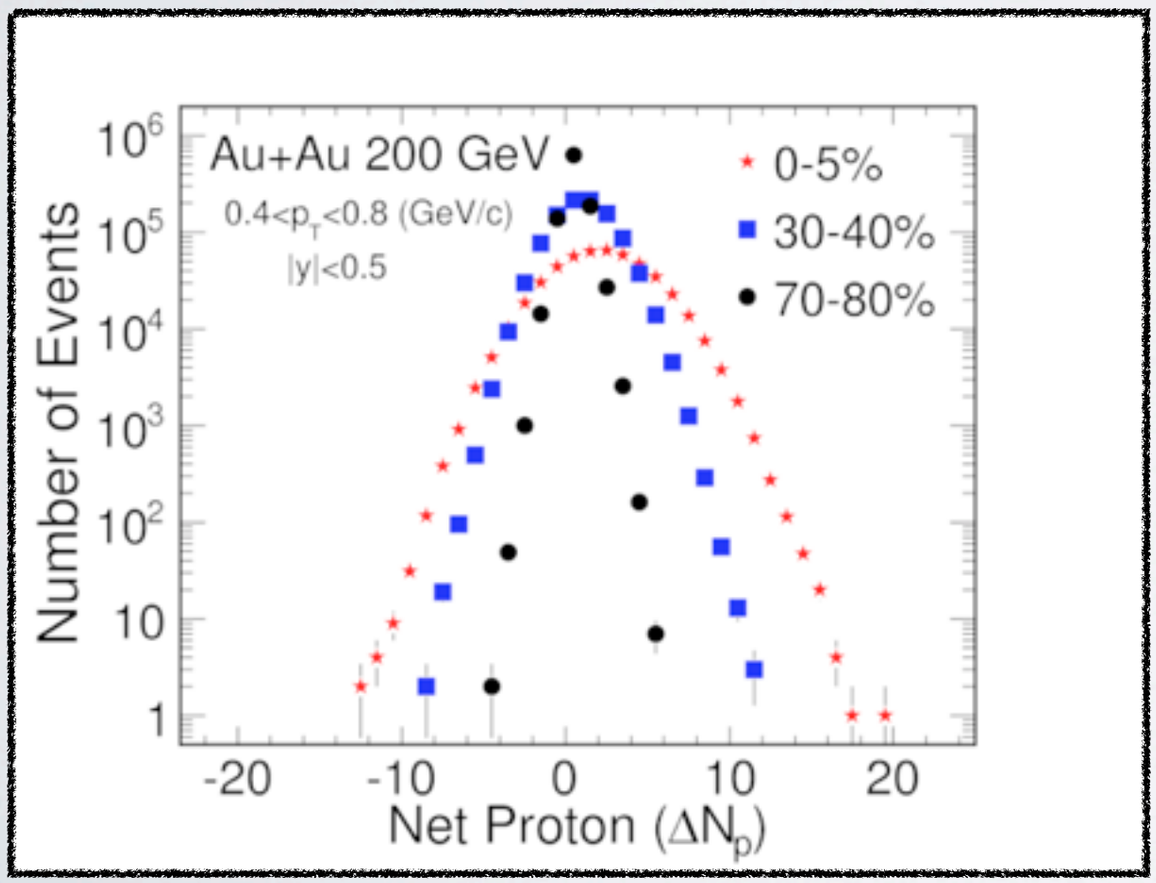
Experiment can help to answer many questions on QCD diagram, which are not accessible to theory at present.

Using predictions from models and universal properties

FLUCTUATIONS OF CONSERVED CHARGES
HRG PREDICTIONS

Experiment:

$$P(N) \to m_i = \sum_N N^i P(N) \to \chi_i$$



Theory:

$$p(\mu) \to \chi_i \propto \frac{\partial^i p(\mu)}{\partial \mu^i}$$

Hadron resonance gas:

$T \ll m_p \to$ Boltzmann appr.:

Pressure:

$$p = T^4 \sum_i f(m_i/T) \cosh(\mu_B/T) + g(T)$$

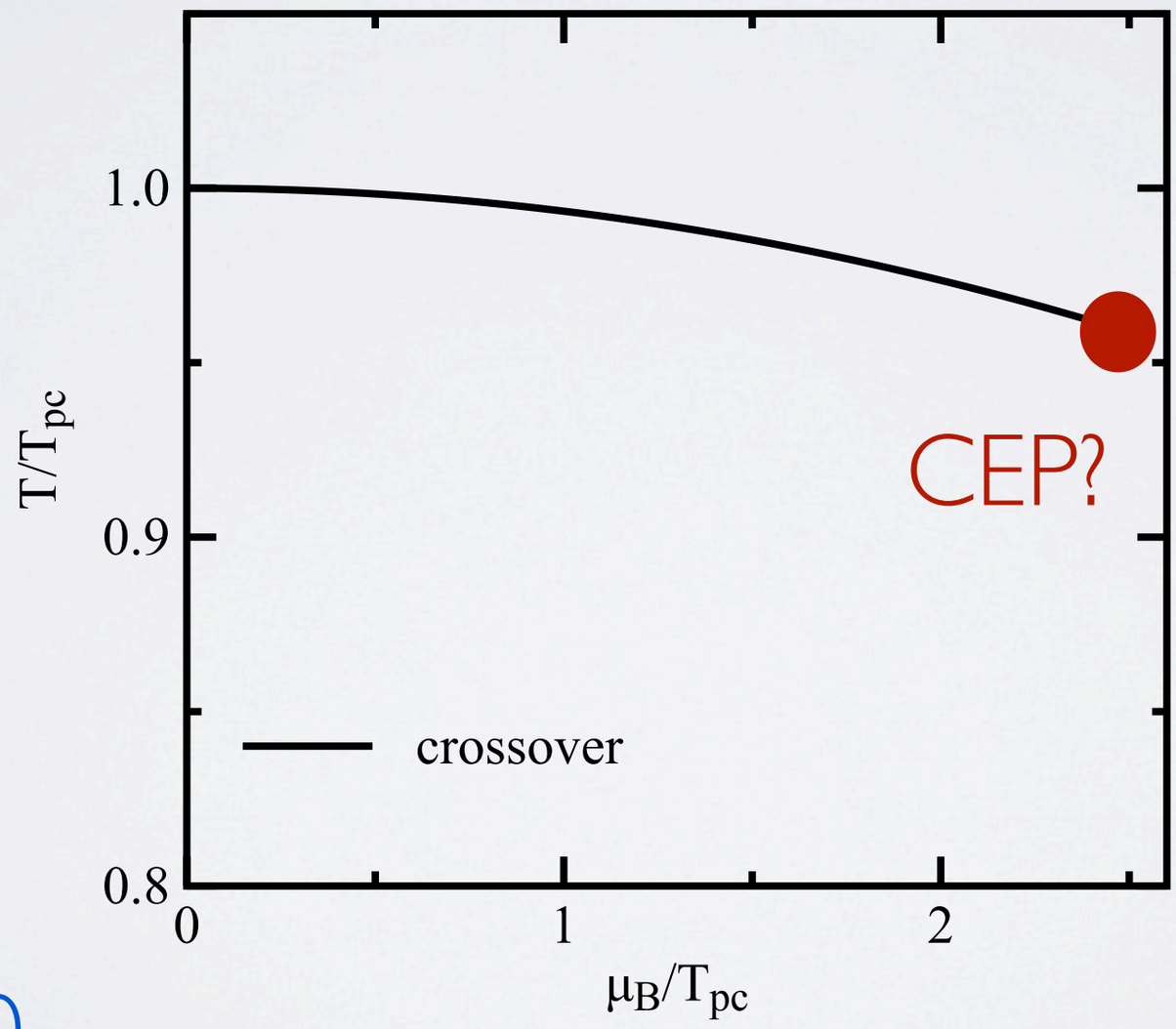
Cumulants and their ratios:

$$\chi_{2n} \propto \cosh(\mu_B/T)$$

$$\chi_{2n+1} \propto \sinh(\mu_B/T)$$

$$\chi_{2n}/\chi_2 = 1 \text{ and } \chi_{2n+1}/\chi_1 = 1$$

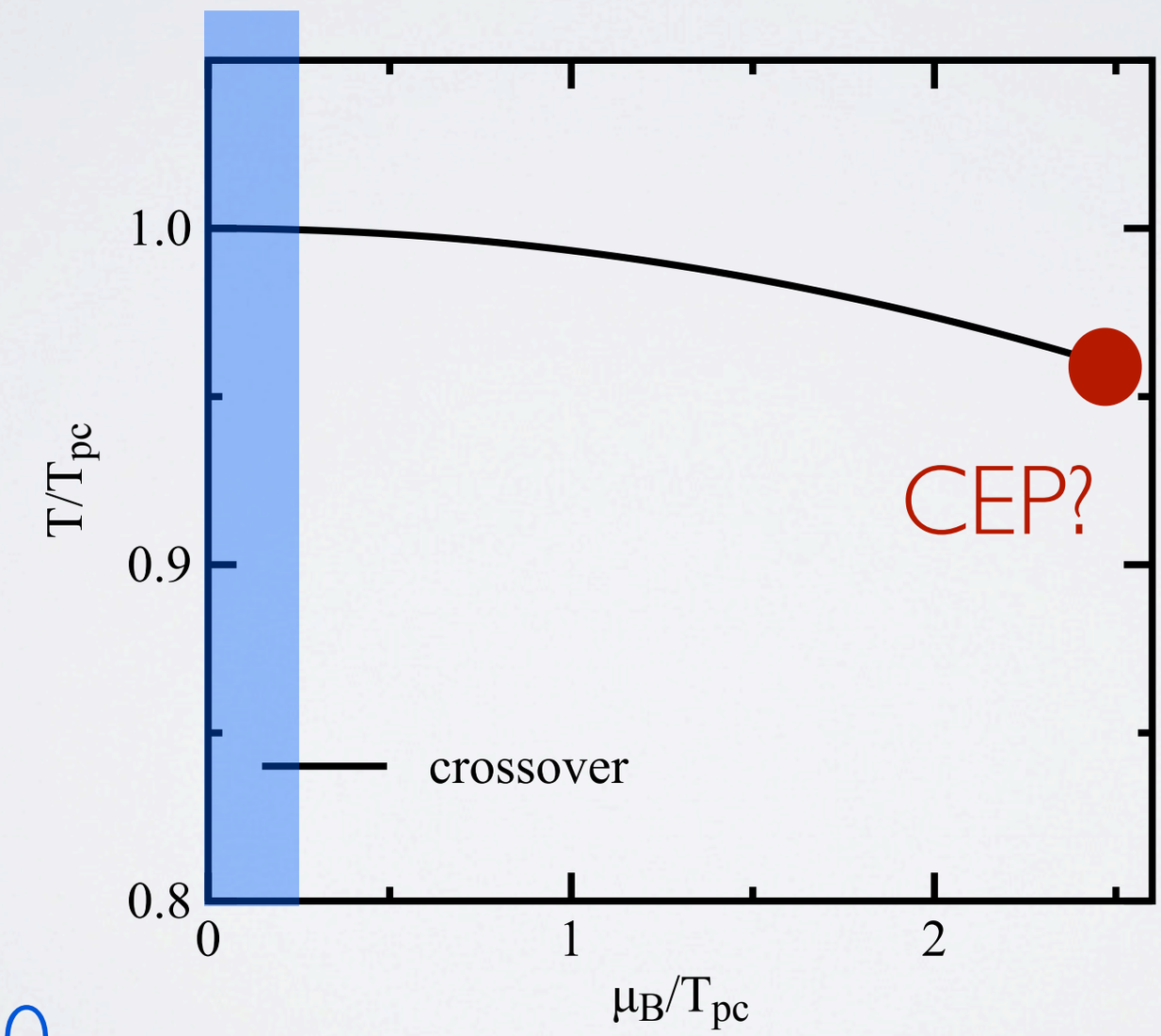
REVIEW OF THE SIGNALS



μ/T=0 → μ/T≳1

REVIEW OF THE SIGNALS

$\sqrt{s}$ = 200 ÷ 64 GeV



μ/T=0

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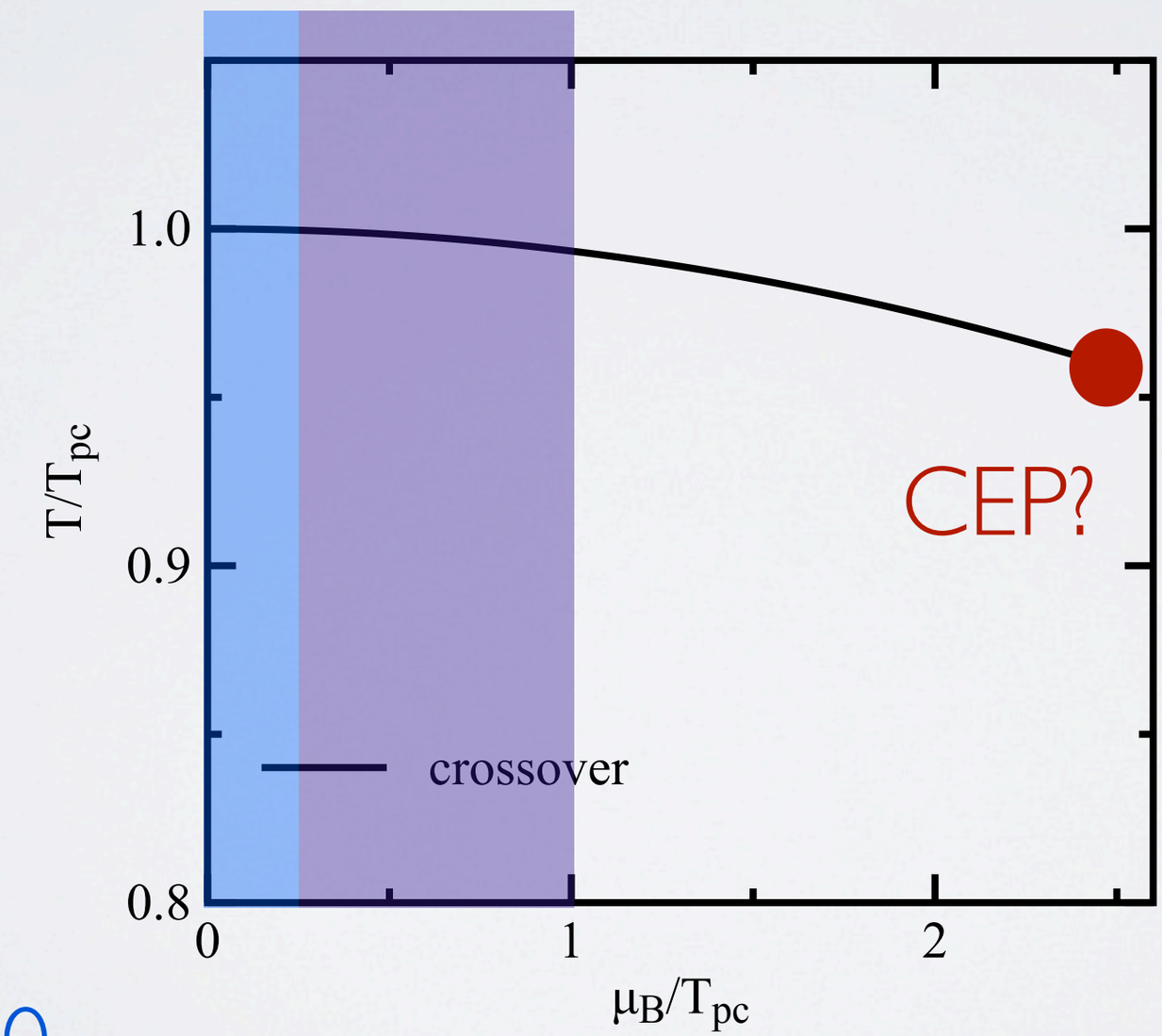
REVIEW OF THE SIGNALS

$\sqrt{s}$ = 200 ÷ 64 GeV 64 ÷ 25 GeV

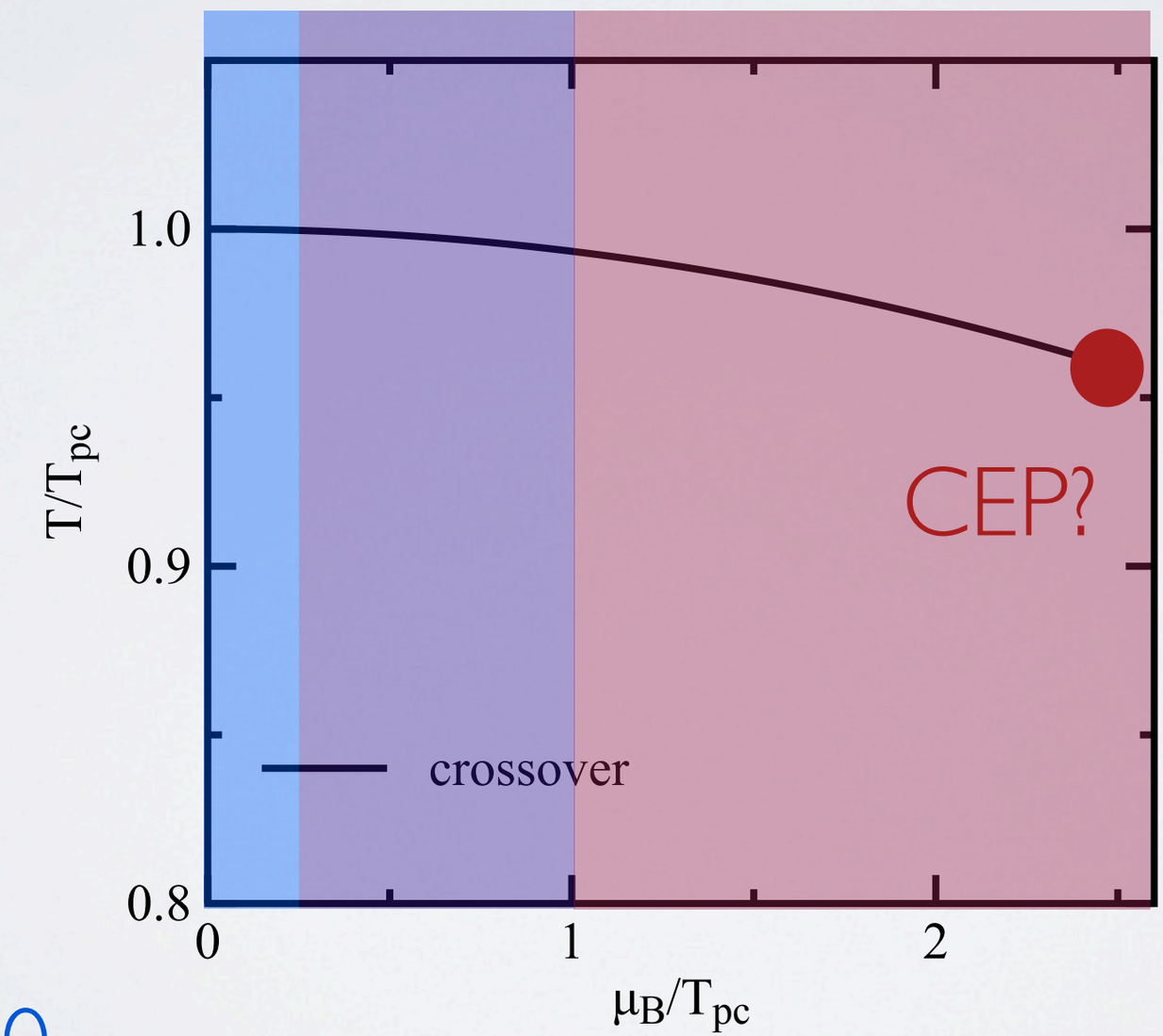


μ/T=0

μ/T≳1

REVIEW OF THE SIGNALS

$\sqrt{s}$ = 200 ÷ 64 GeV 64 ÷ 25 GeV 25÷ 7 GeV



μ/T=0 μ/T≳1

PREDICTIONS: CROSSOVER AND REMNANTS OF O(4) CHIRAL DYNAMICS

Chiral limit, $m_{u,d}=0$.

Close to transition, t=0, pressure is defined by scaling laws with critical exponent $\boldsymbol{\alpha}$ = - 0.21

Pressure: $p \sim t^{(2-\alpha)}$ $\qquad t \sim \frac{T}{T_c} - 1 + \kappa \left(\frac{\mu}{T_c}\right)^2$

Cumulants at μ=0:

-- divergent χ_6

Cumulants at μ≠0:

-- negative and divergent χ_4

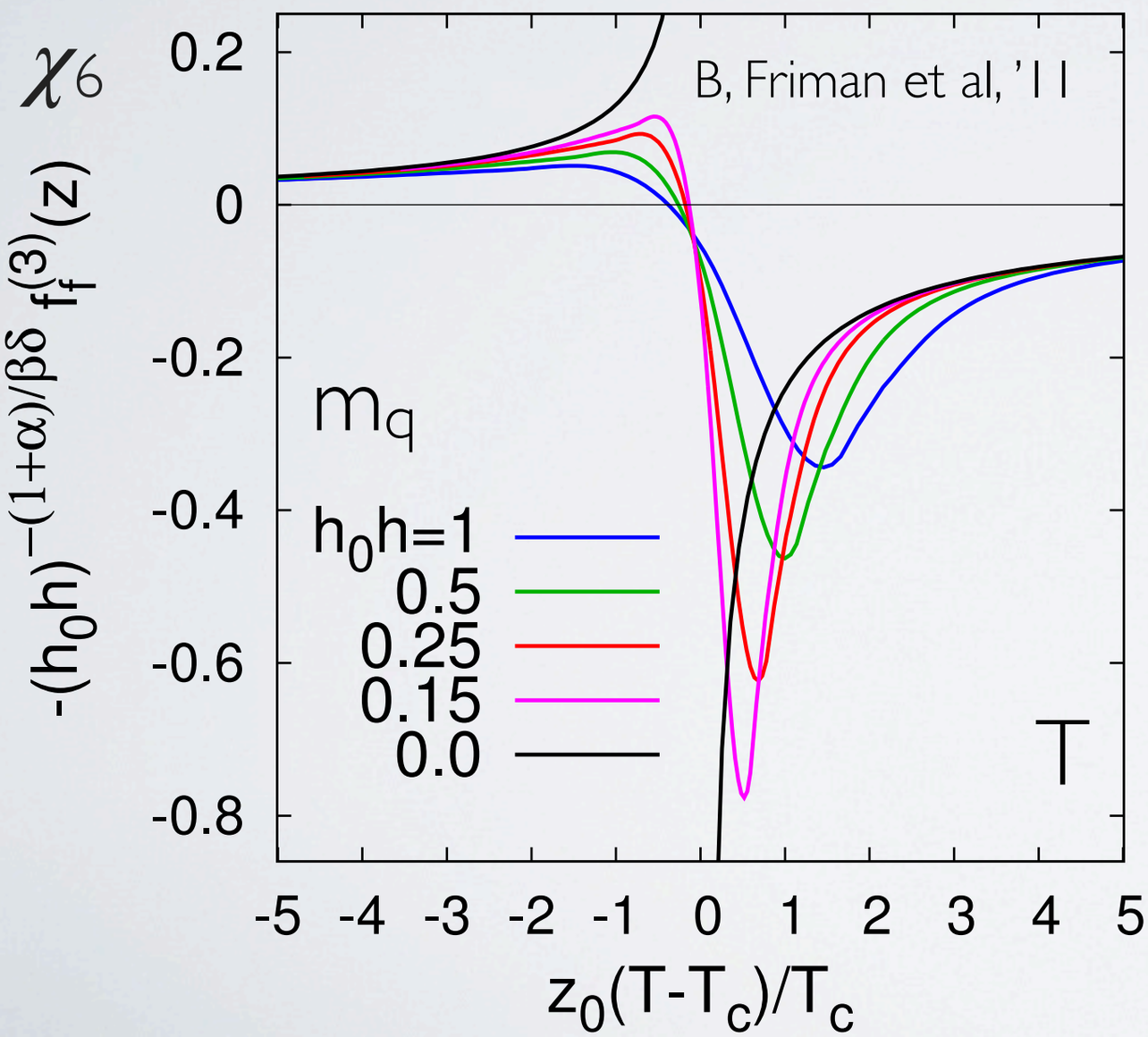
-- divergent χ_6

Physical pion mass, $m_{u,d} \neq 0$.

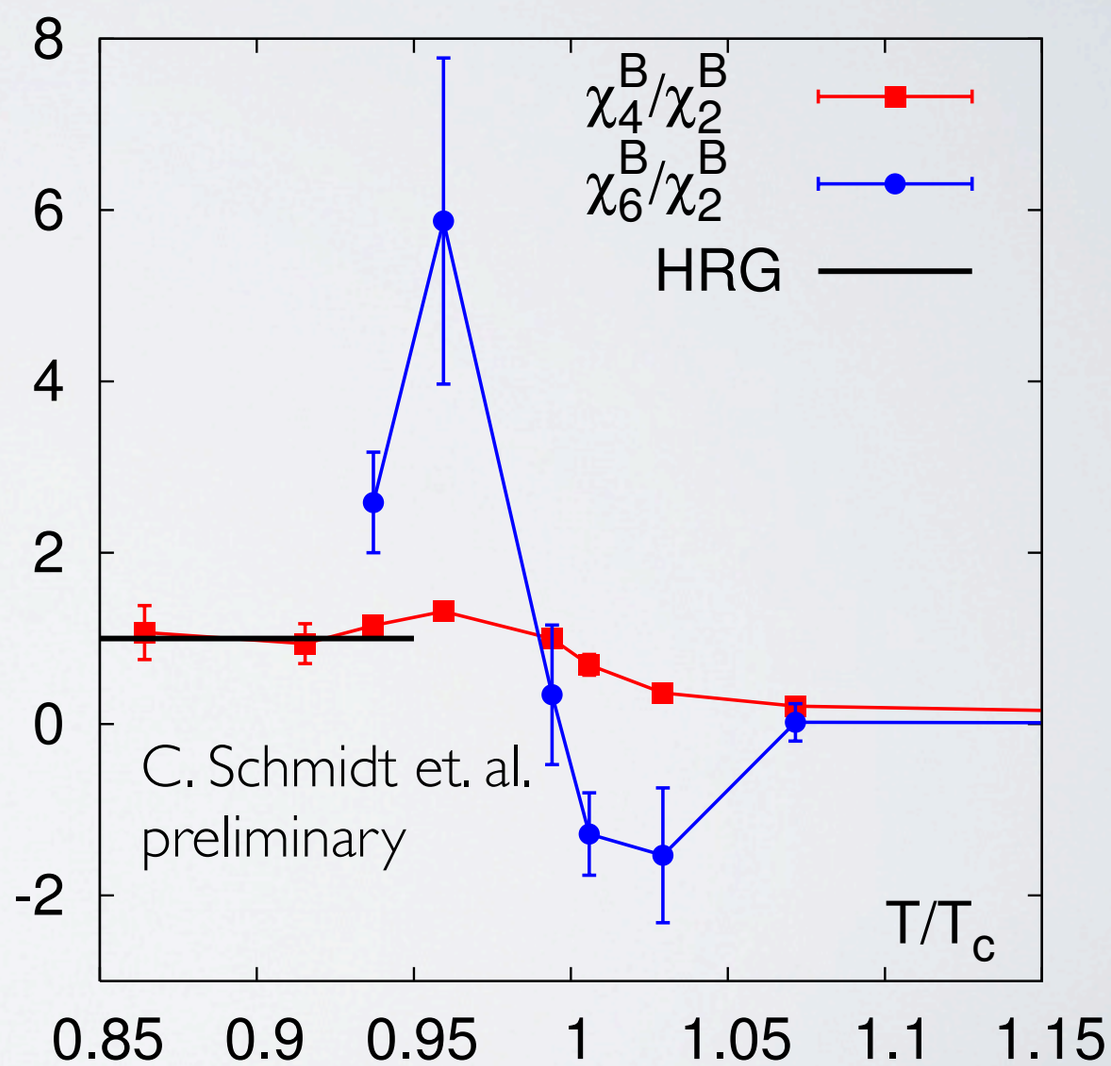
Cumulants at μ=0:

-- negative χ_6

O(4) scaling function:



Lattice QCD:

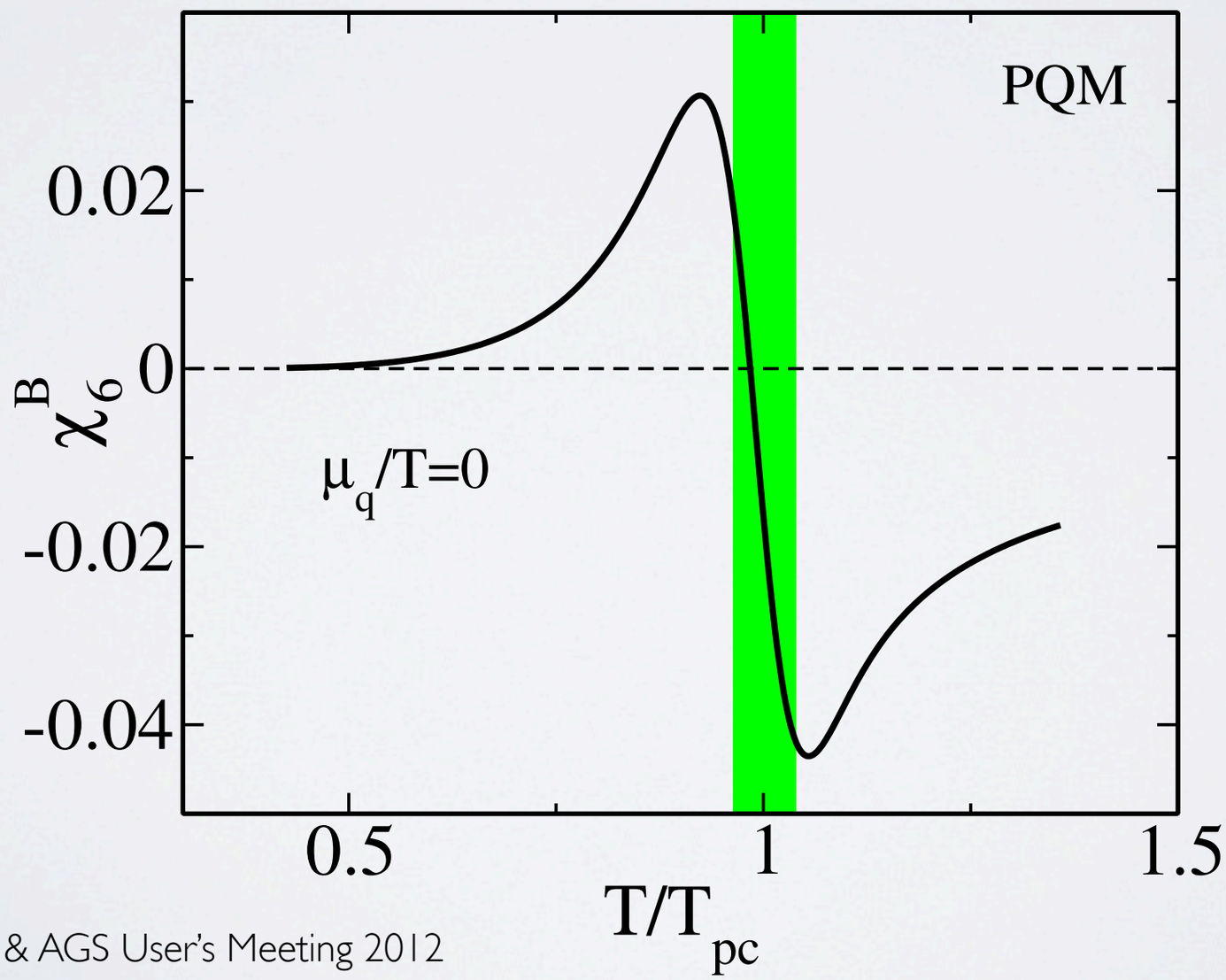


Physical pion mass, $m_{u,d} \neq 0$.

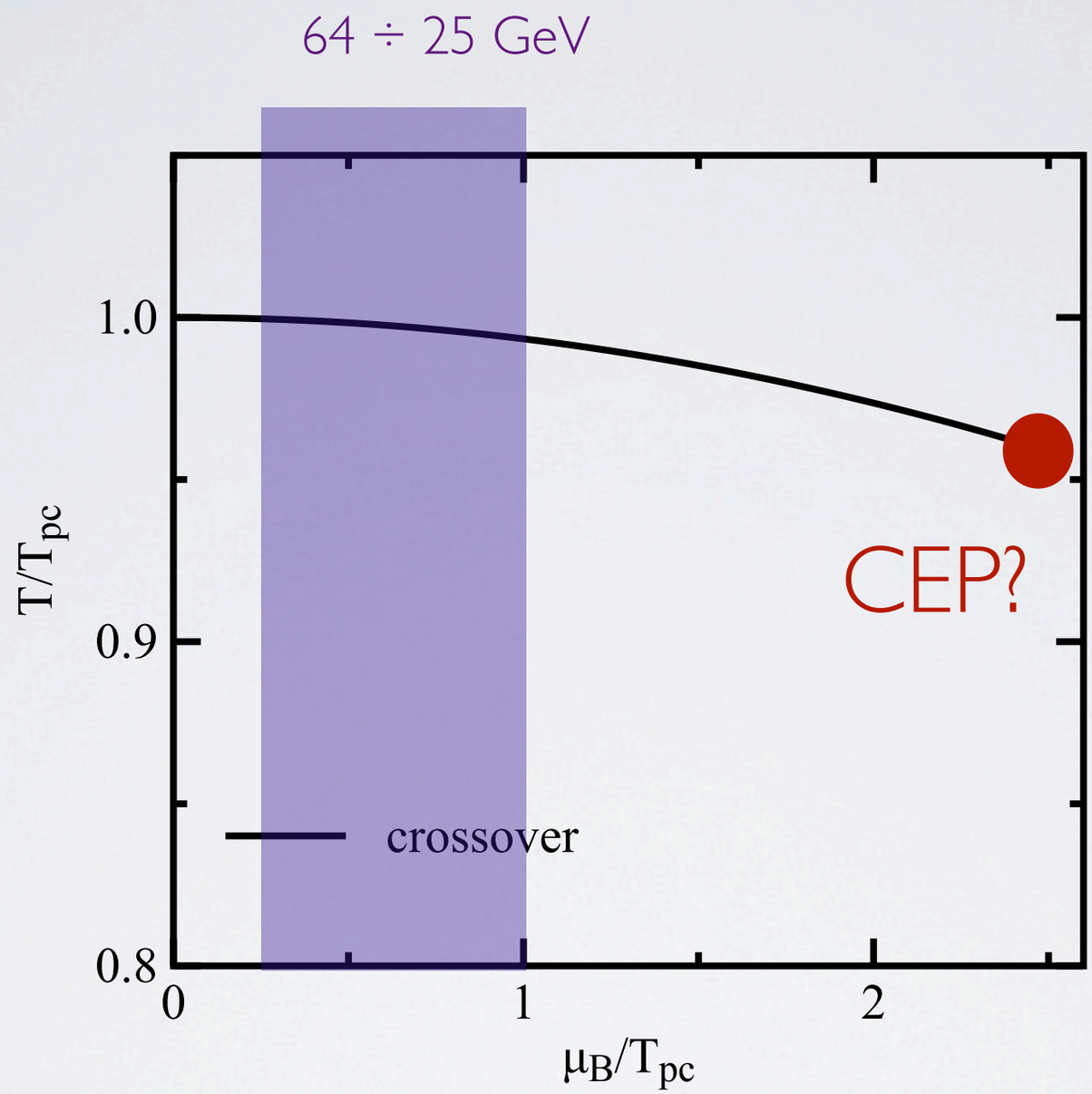
Cumulants at $\mu=0$:

-- negative χ_6

Polyakov-loop extended quark-meson model:



μ≠0, but away from CEP



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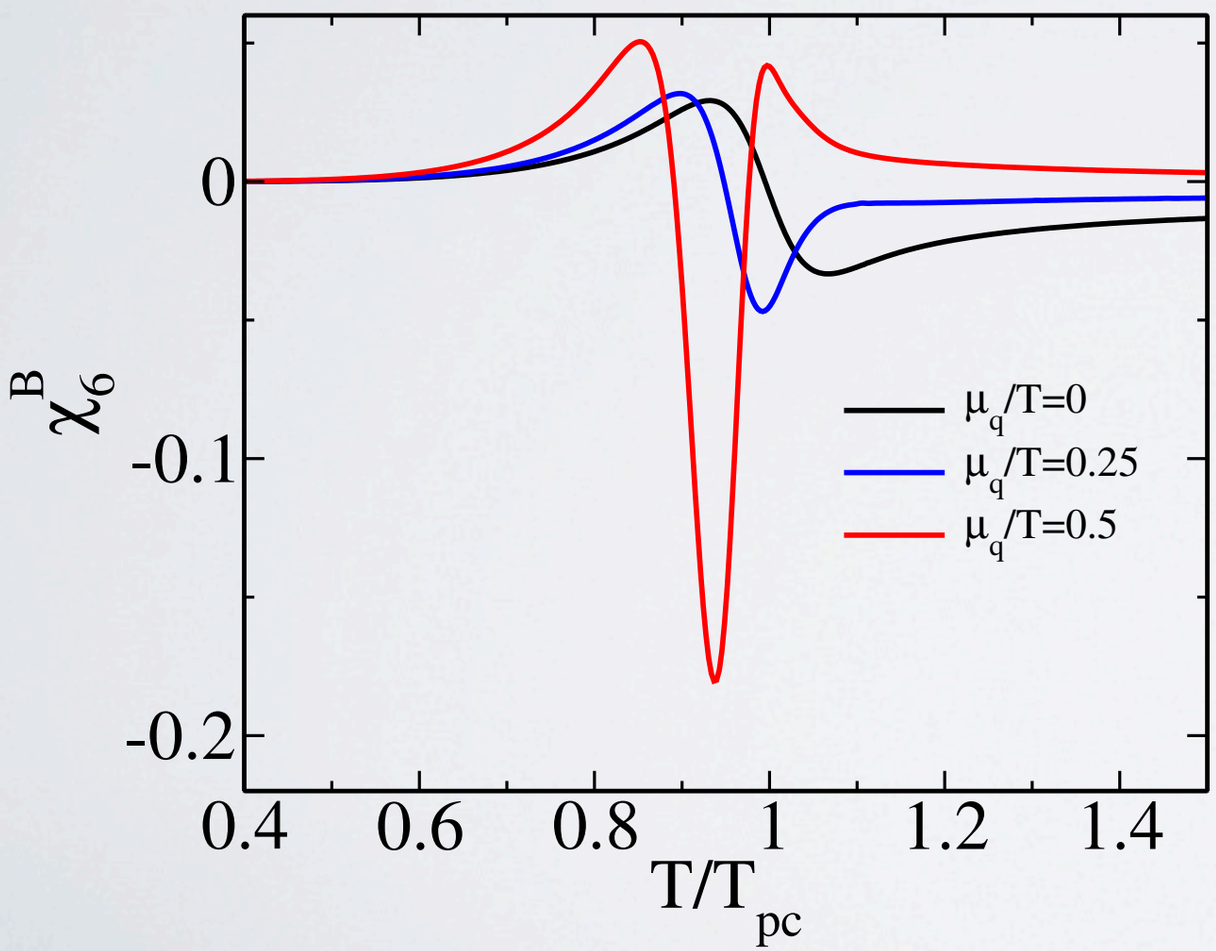
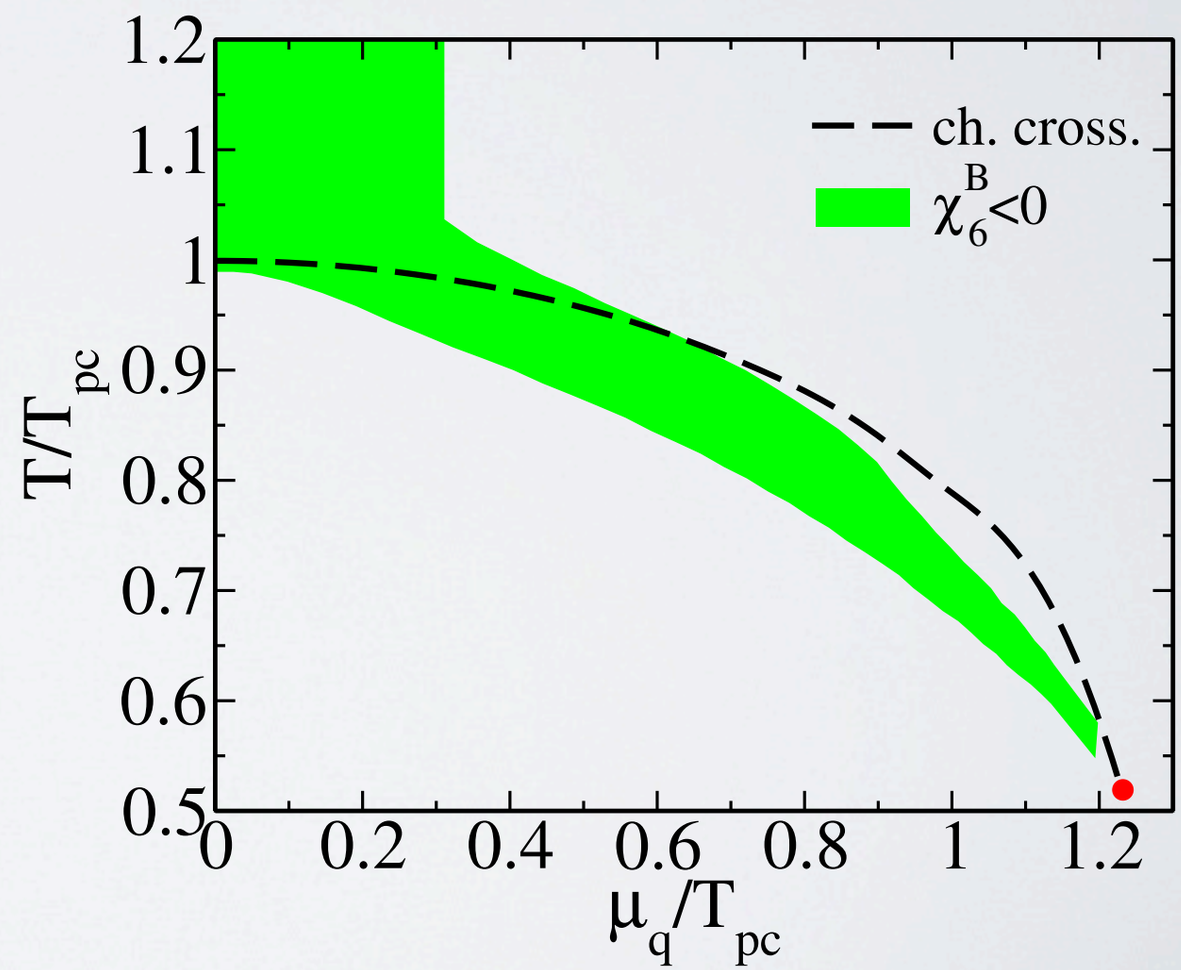


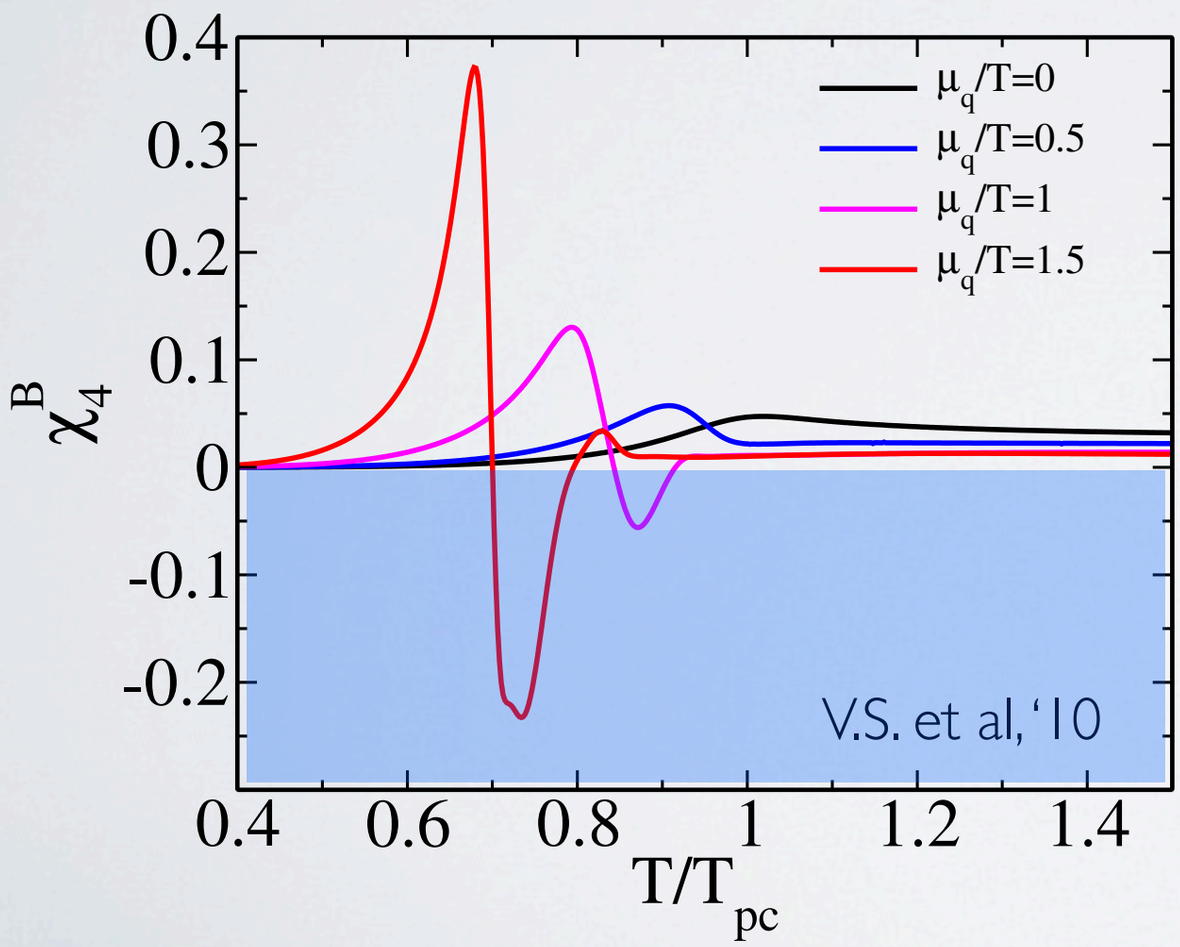


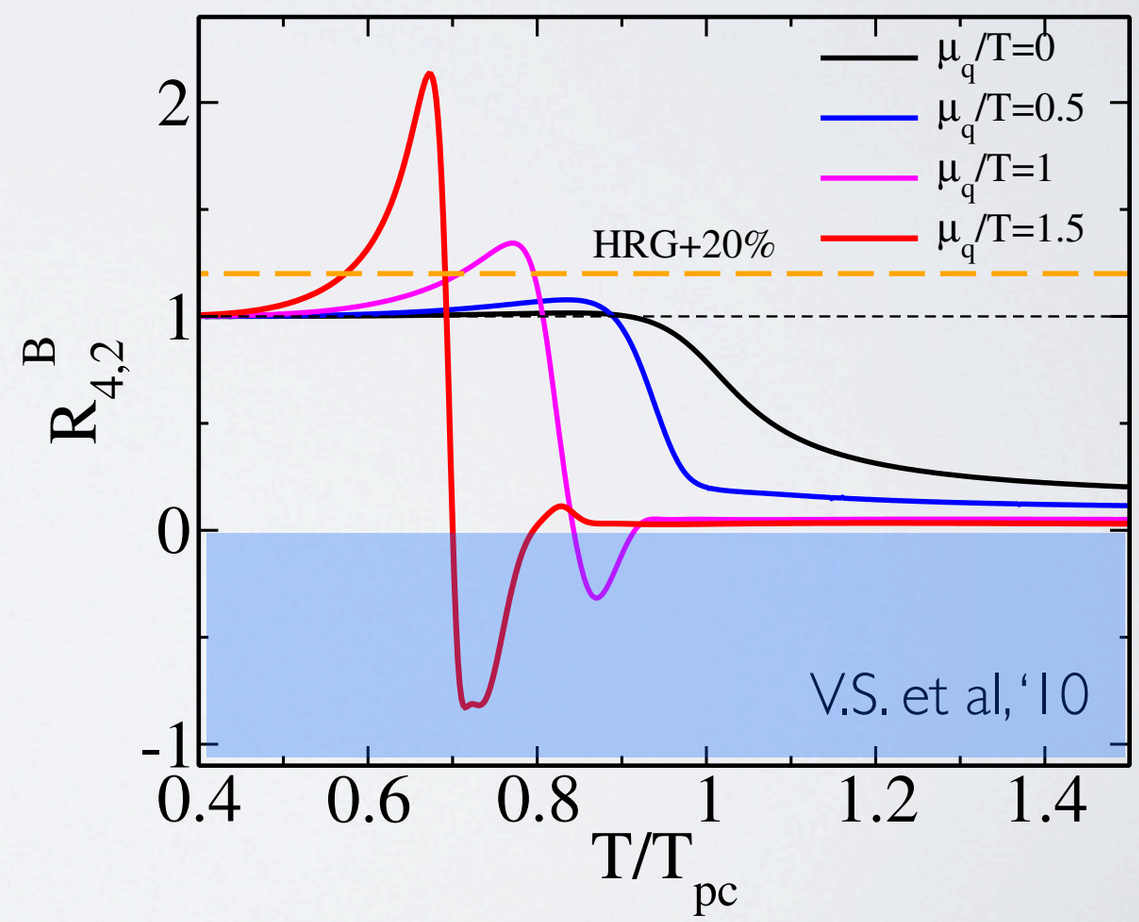
Cumulants at μ≠0:

-- negative χ_4

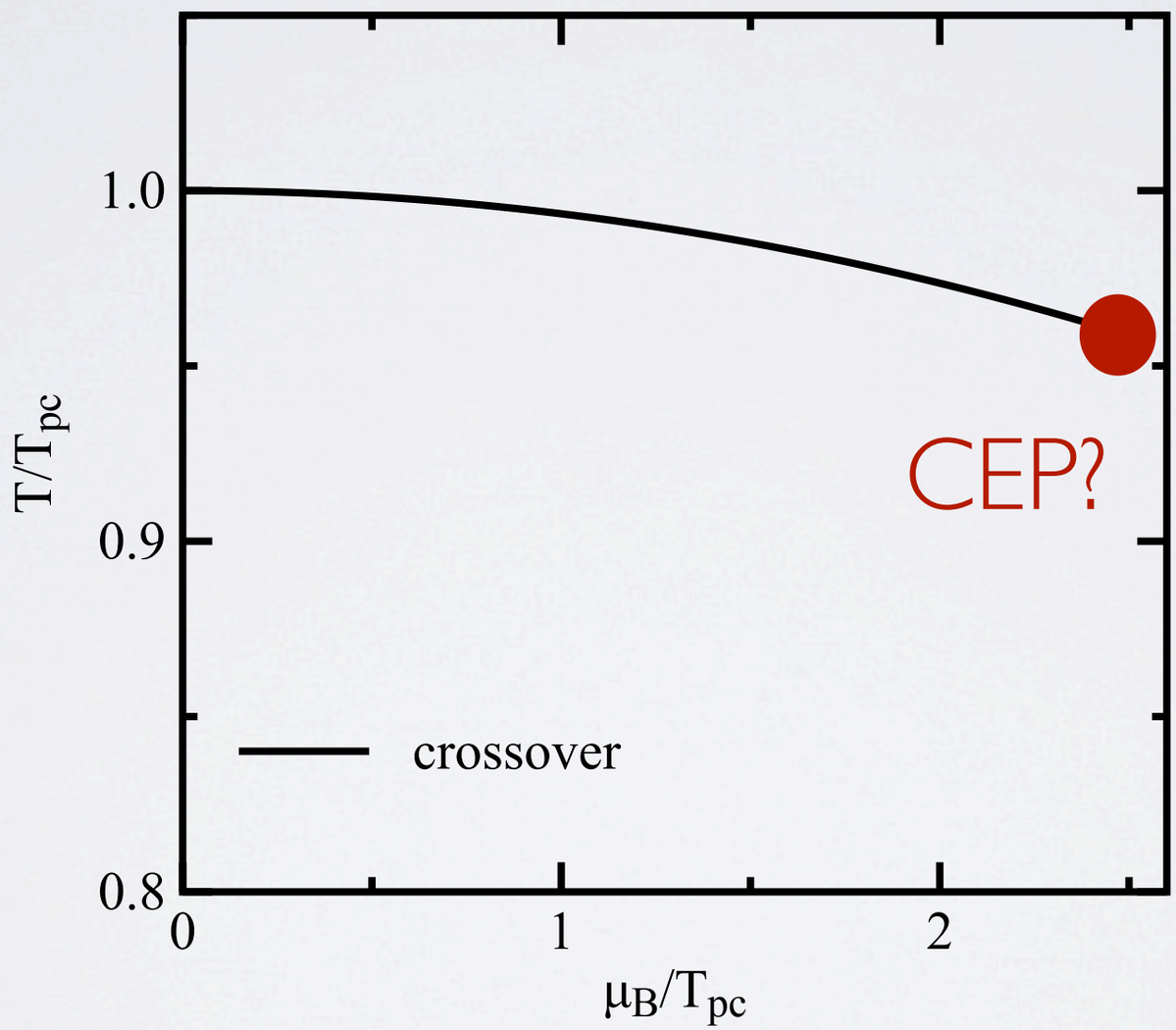
Polyakov-loop extended quark-meson model:

Kurtosis: $R_{4,2} = \chi_4 / \chi_2$





Vicinity of CEP critical region



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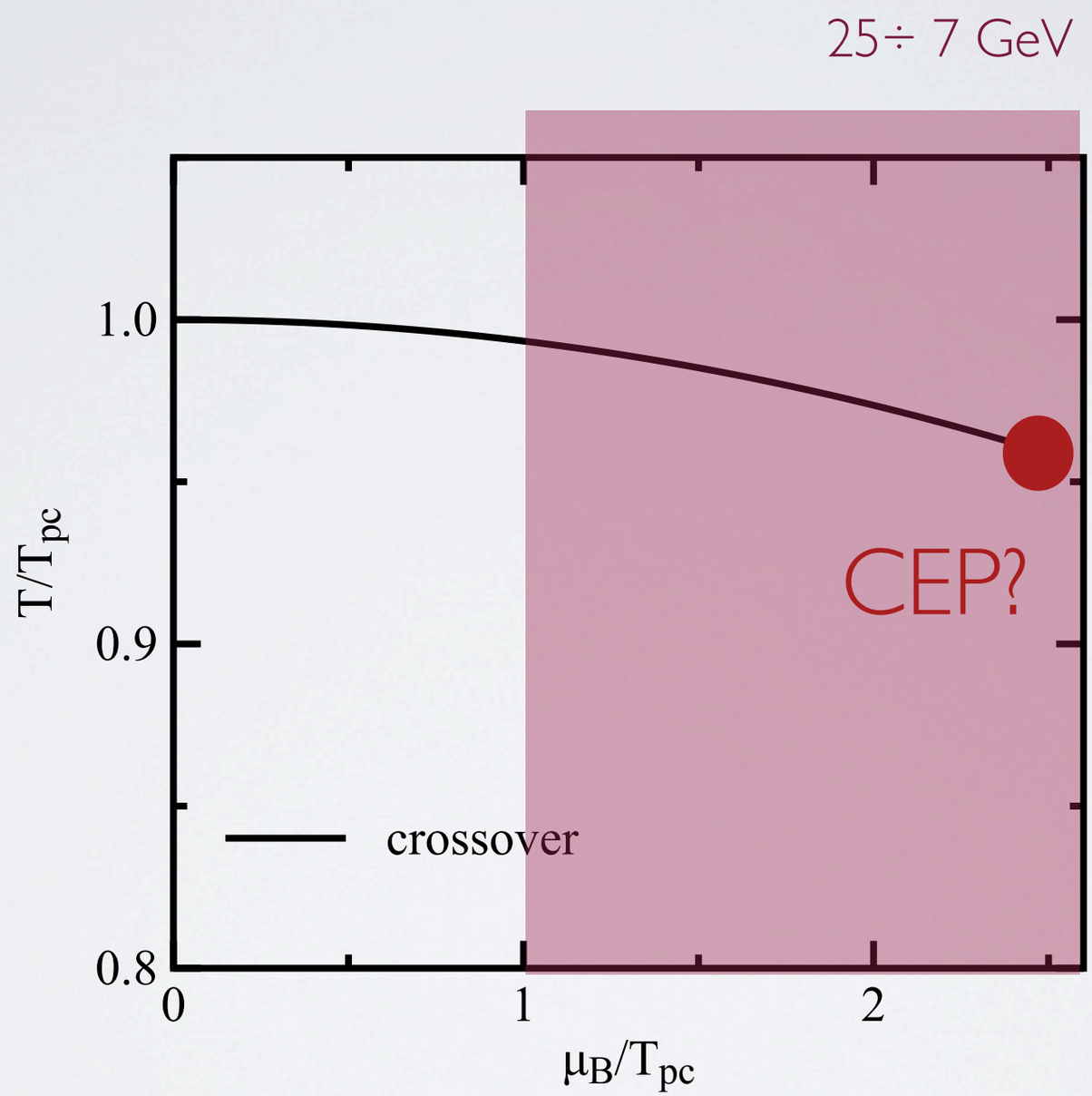


Critical End Point

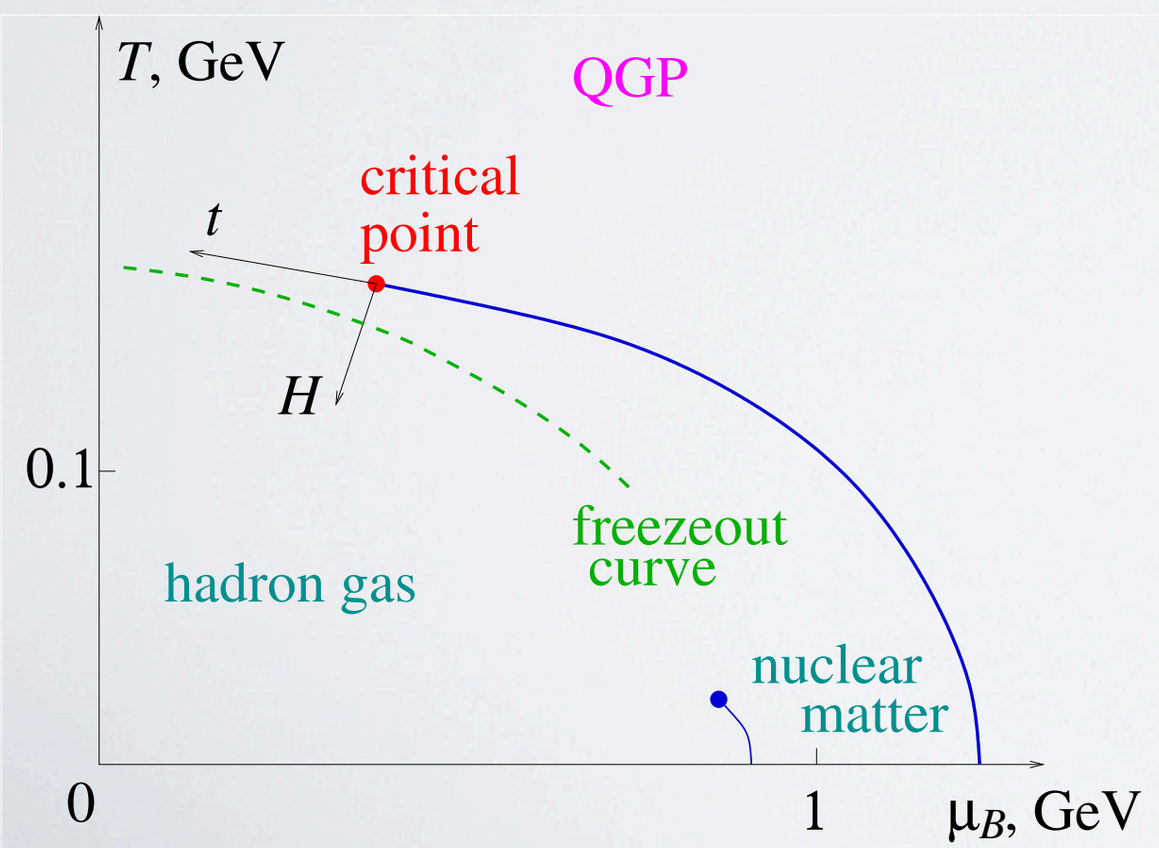
-- divergent $\chi_2 \sim \xi^2$ (K. Rajagopal et al '98)

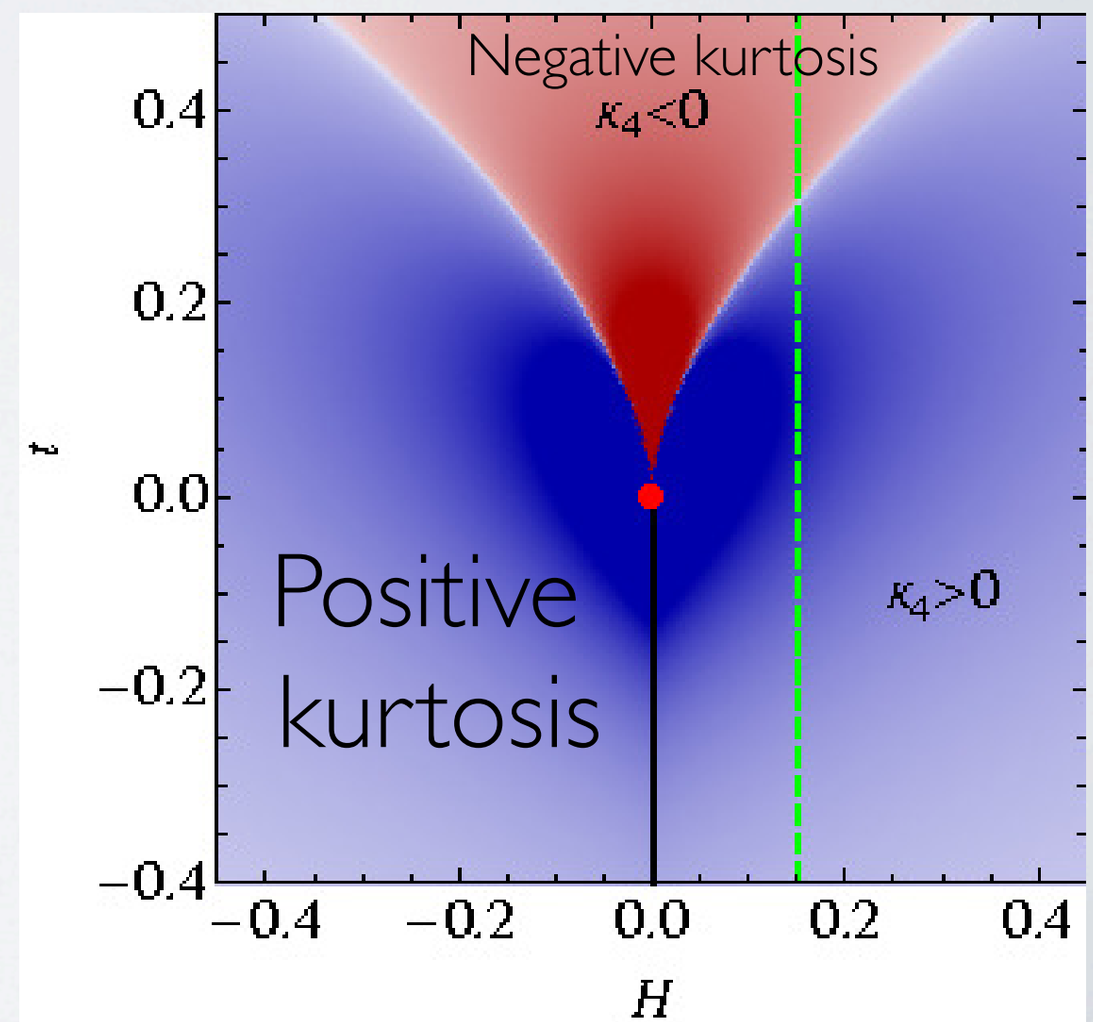
higher cumulants $\chi_n \sim \xi^{5n/2-3}$, $\chi_4 \sim \xi^7$ (M. Stephanov '09)

-- owing to finite size/finite lifetime effects, ξ is finite

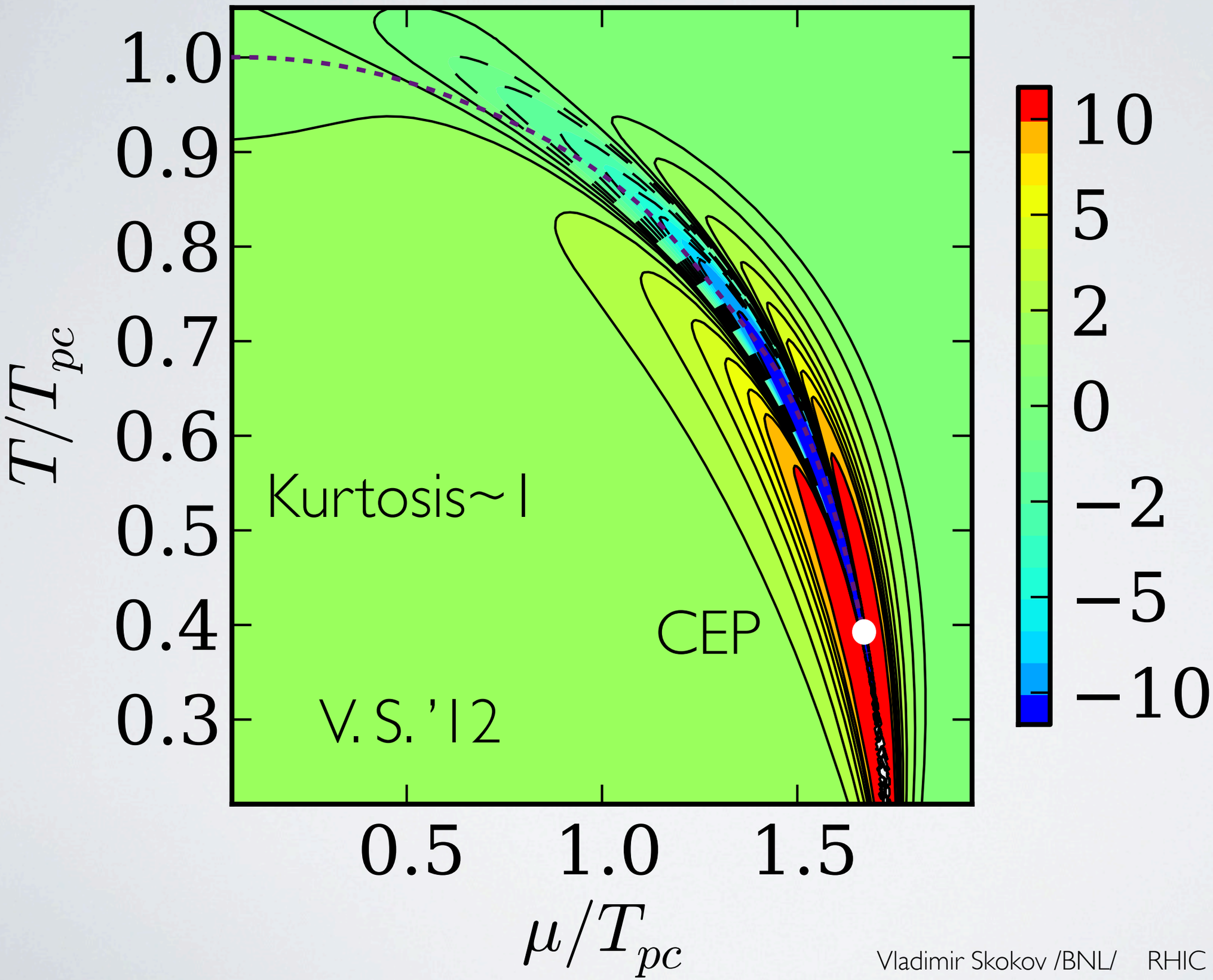
-- universal properties close to CEP result special pattern in sign of kurtosis (M. Stephanov '11)

Mapping 3d Ising model:





Polyakov-loop extended quark-meson model and negative kurtosis:



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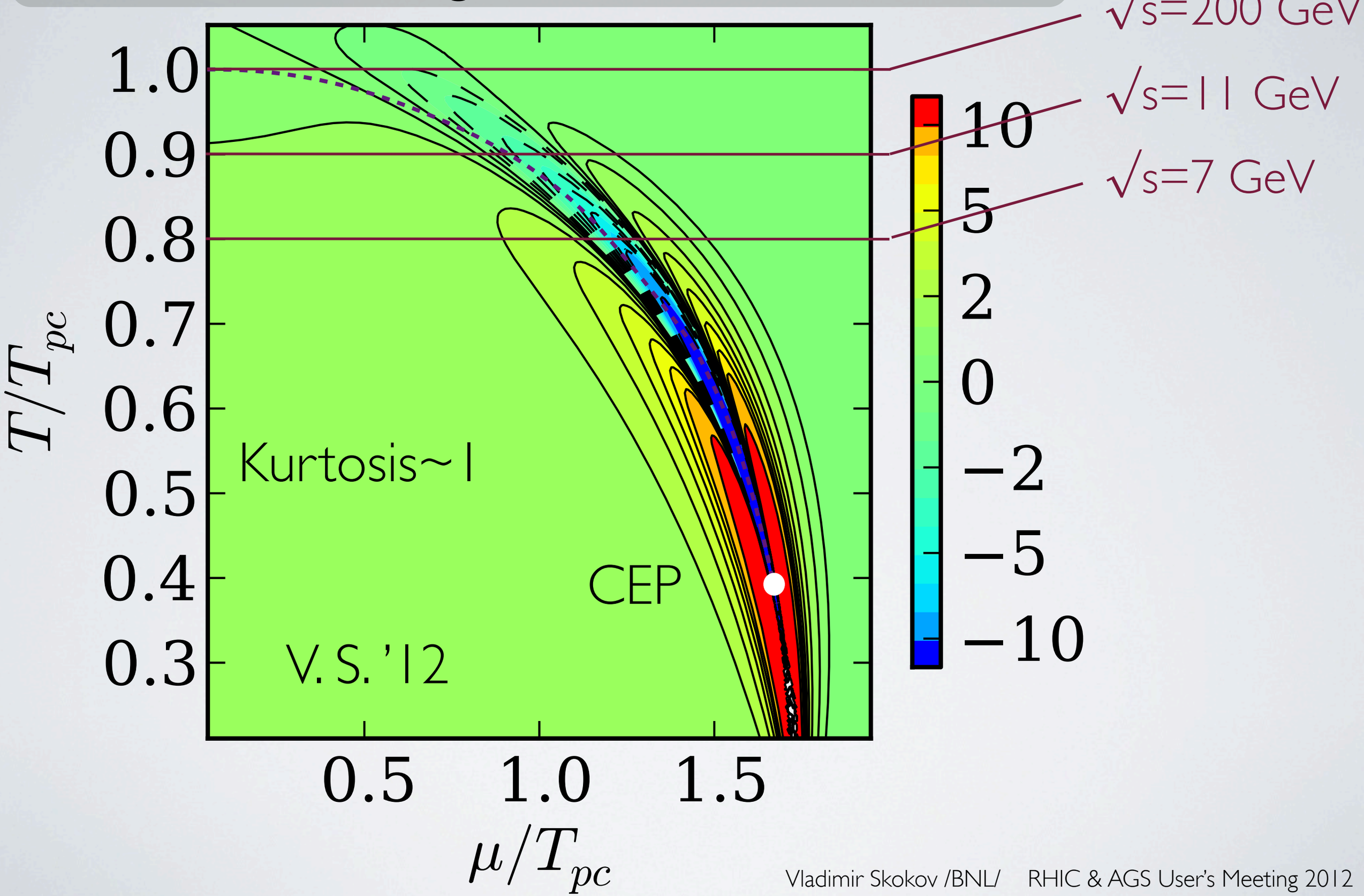

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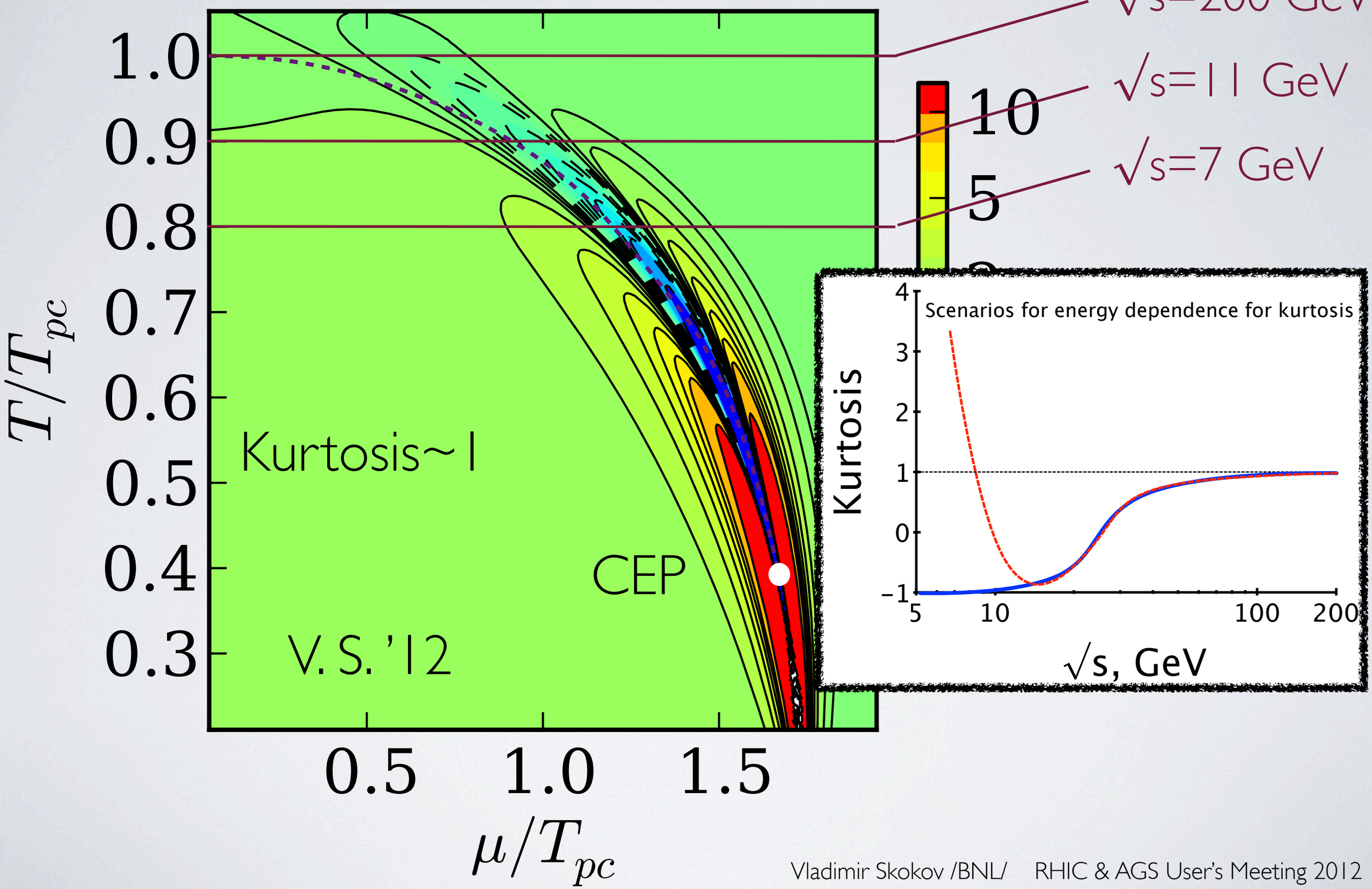
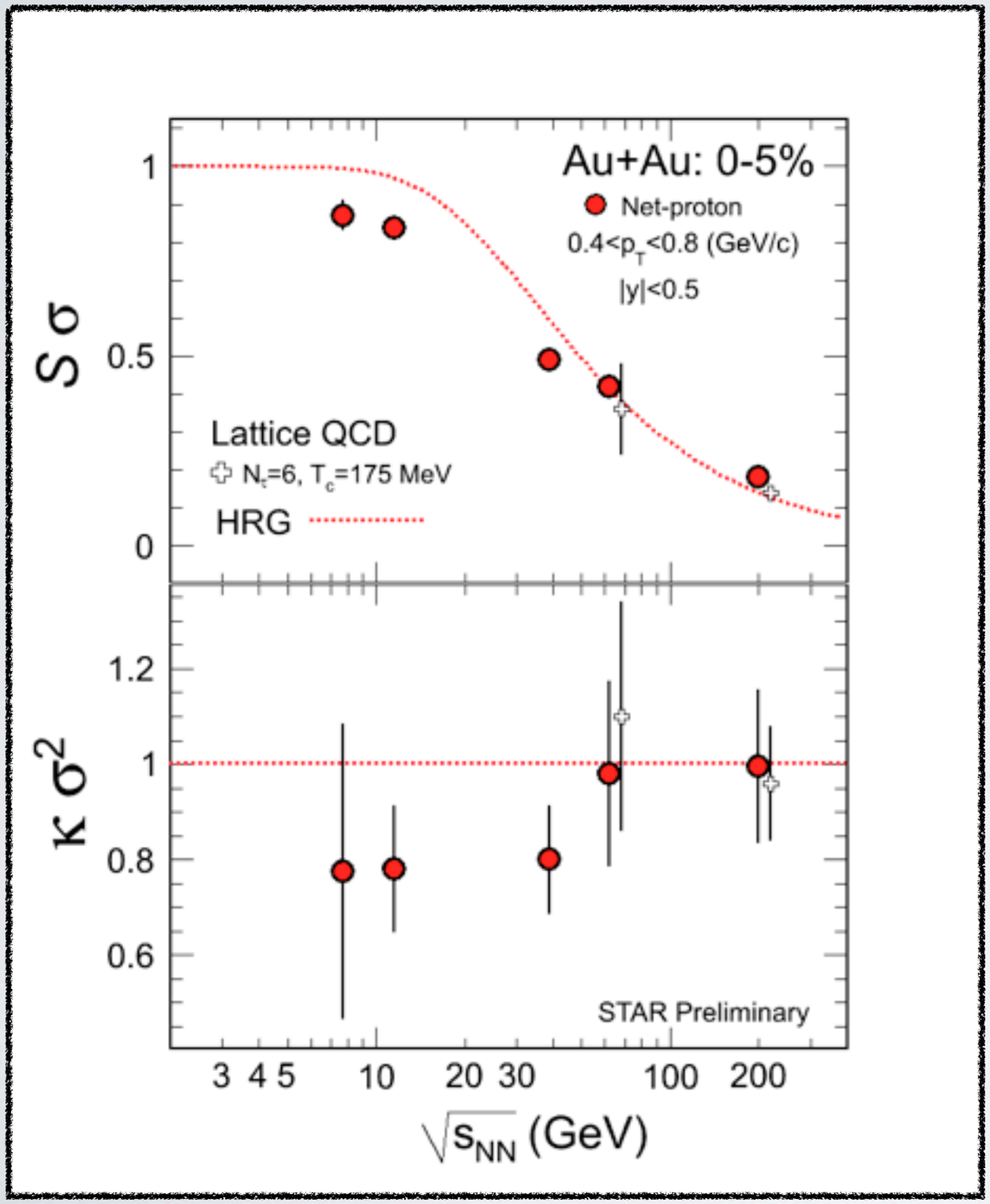
Just for fun

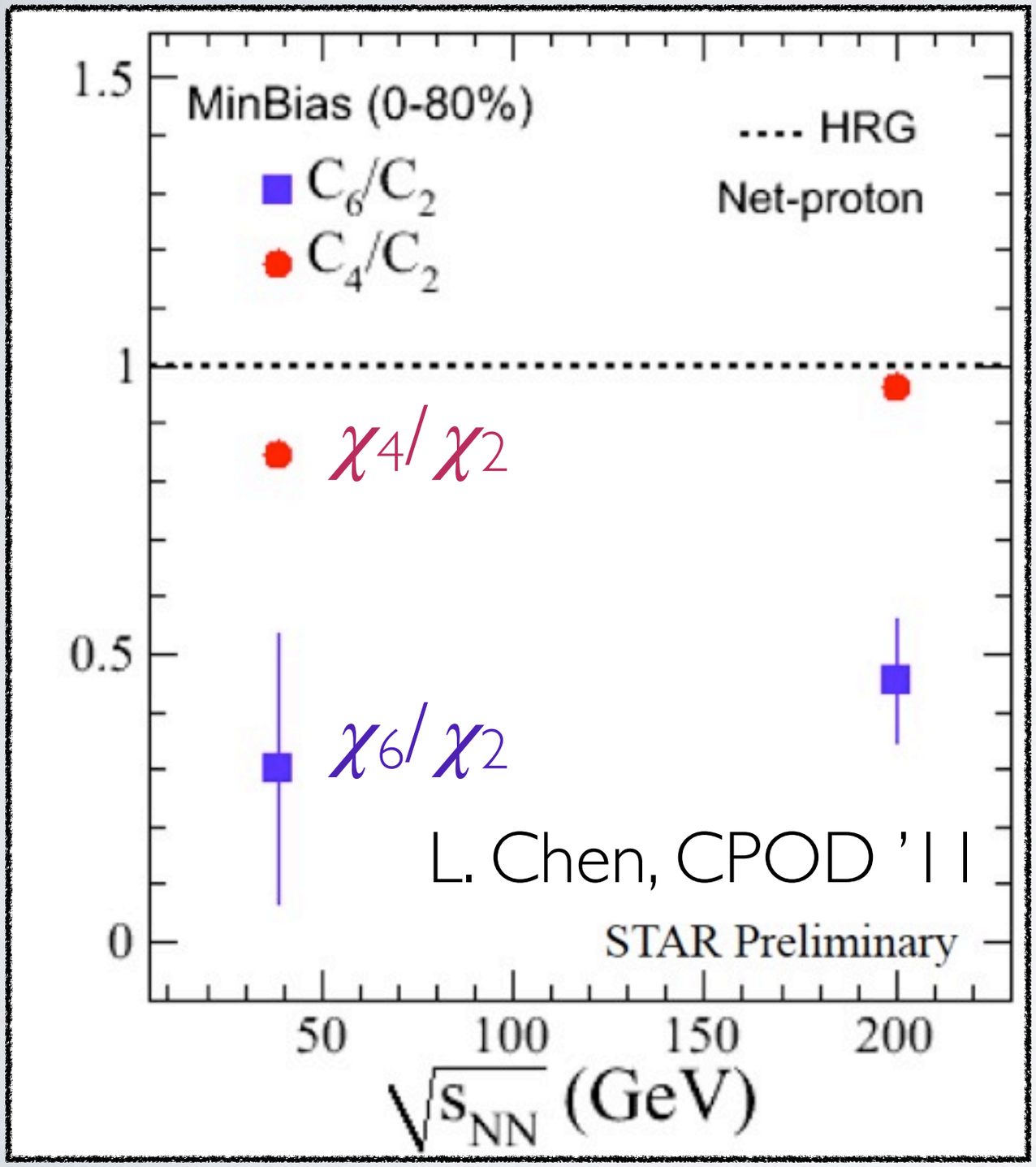


PRELIMINARY EXPERIMENTAL RESULTS: SKEWNESS AND KURTOSIS

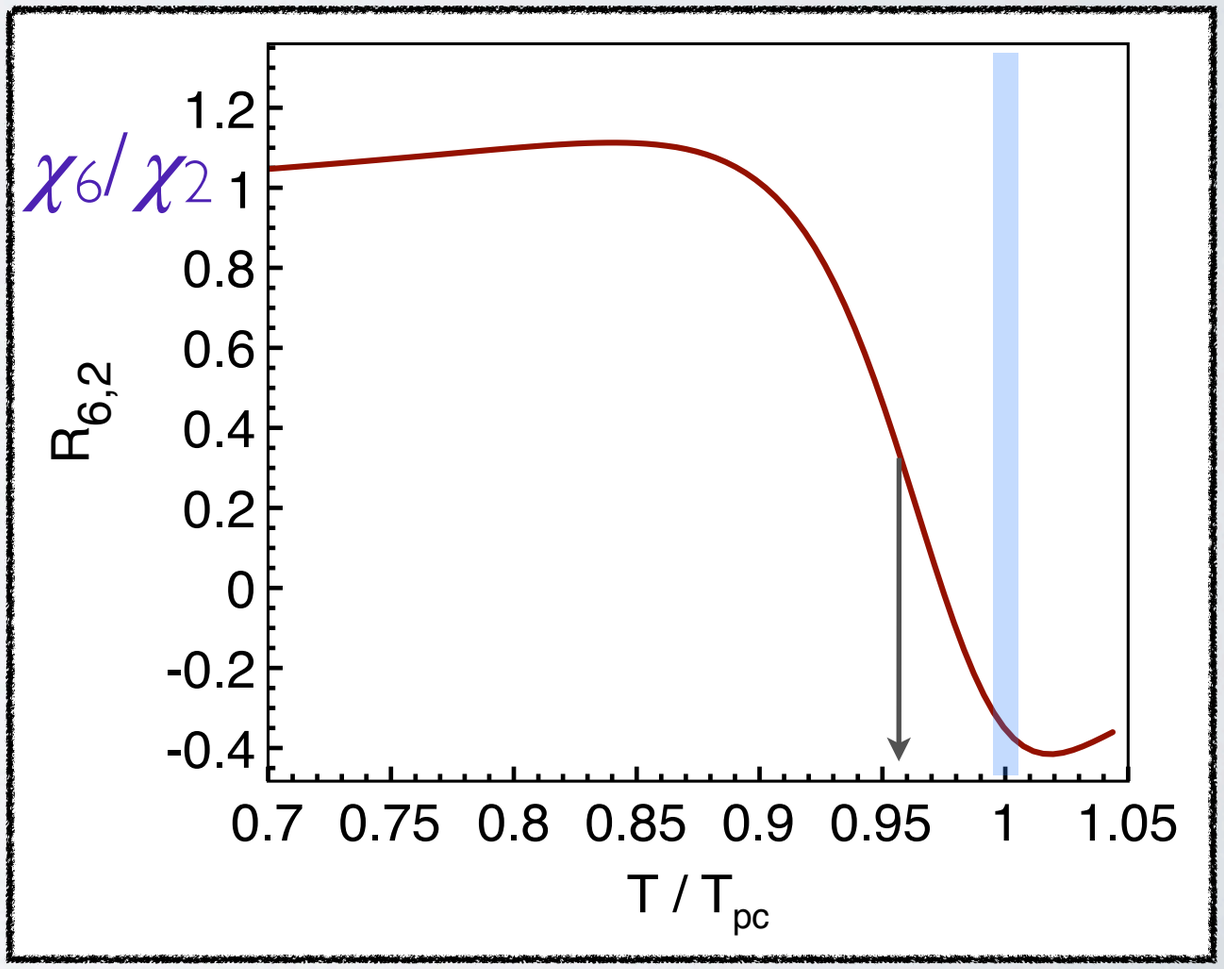


- in line with theory, but not convincing yet
- not a CEP, but quarkyonic phase?! L. McLerran et al
- something else, that is missing in theory predictions?

PRELIMINARY EXPERIMENTAL RESULTS: SIXTH ORDER CUMULANT



- χ_6/χ_2>0, but below HRG
- freeze-out below transition
- other explanations?



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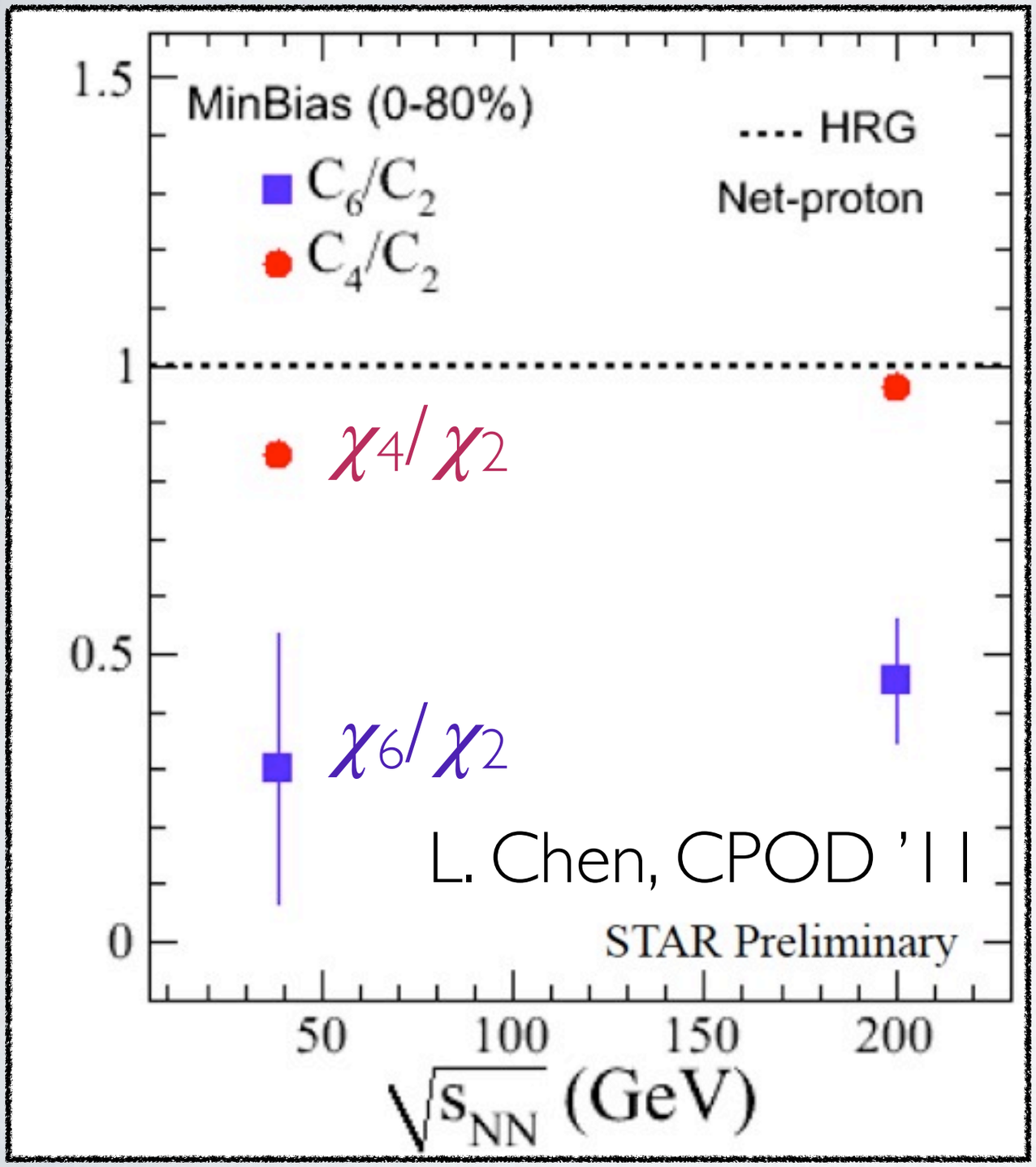

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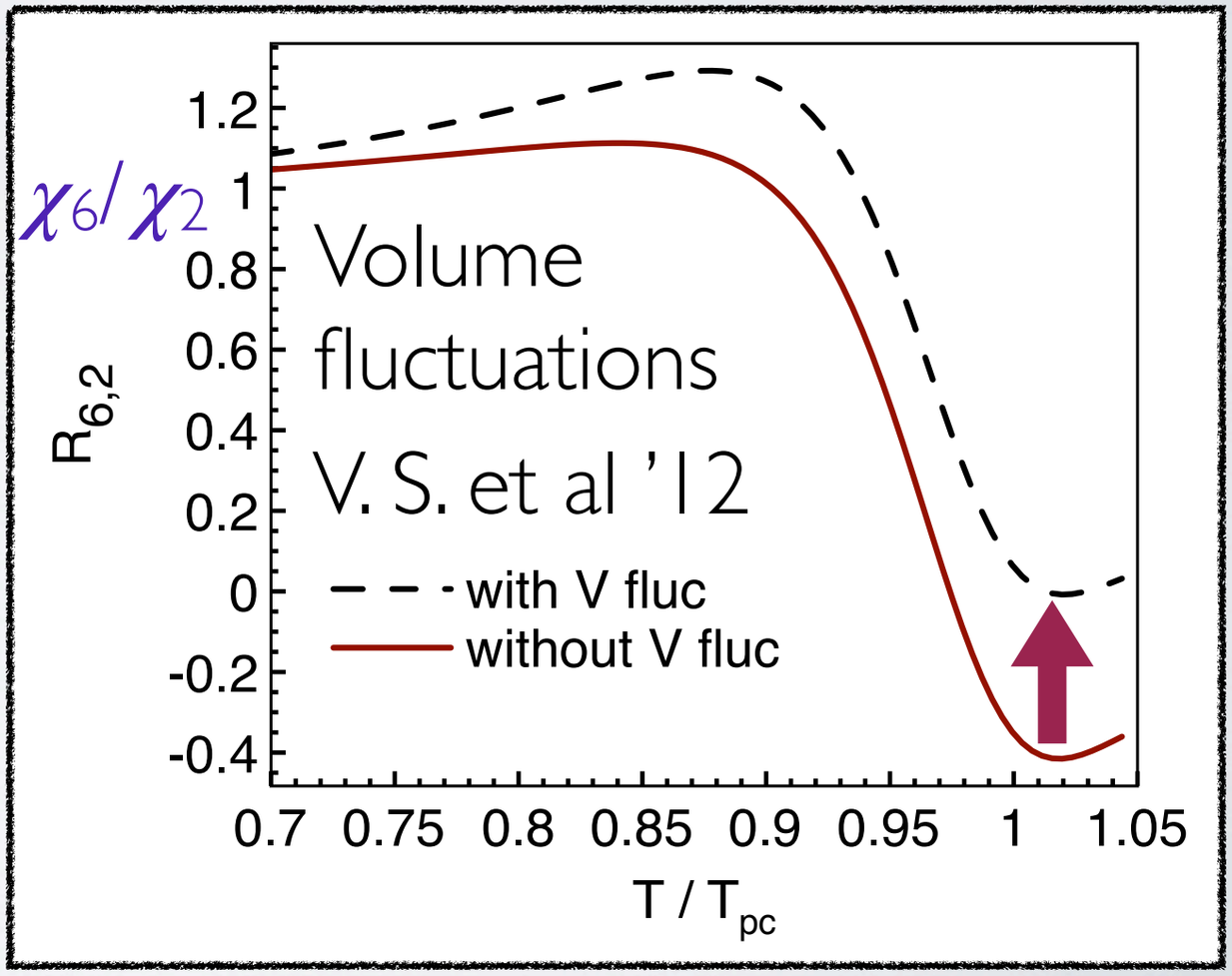


LIMITATIONS OF PREDICTIONS

Cumulants: Direct connection between theory and experiment?!

Issues:

- theory: grand canonical formulation of thermodynamics:

-- conservation laws might be important (M. Nahrgang et al '09, A. Bzdak et al '12)

-- off-equilibrium (B. Berdnikov and K. Rajagopal '00, M. Nahrgang et al '11)

-- theory: subvolume of a system in equilibrium, experiment: momentum cuts

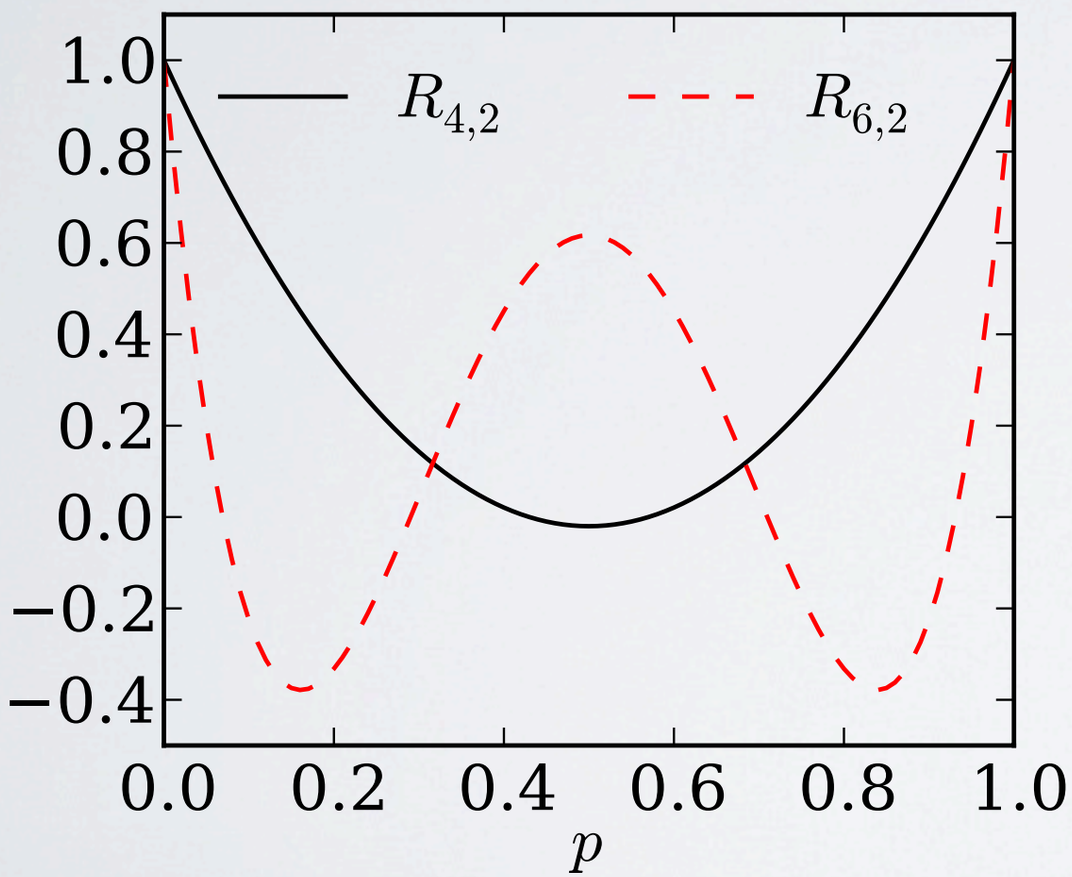
- volume fluctuations, impact parameter fluctuations (see e.g. 1205.4756)
- initial state fluctuations (R. Venugopalan et al, E. Petreska Session 3)

- fluctuations related to experimental acceptance (V. Koch, CPOD '12)

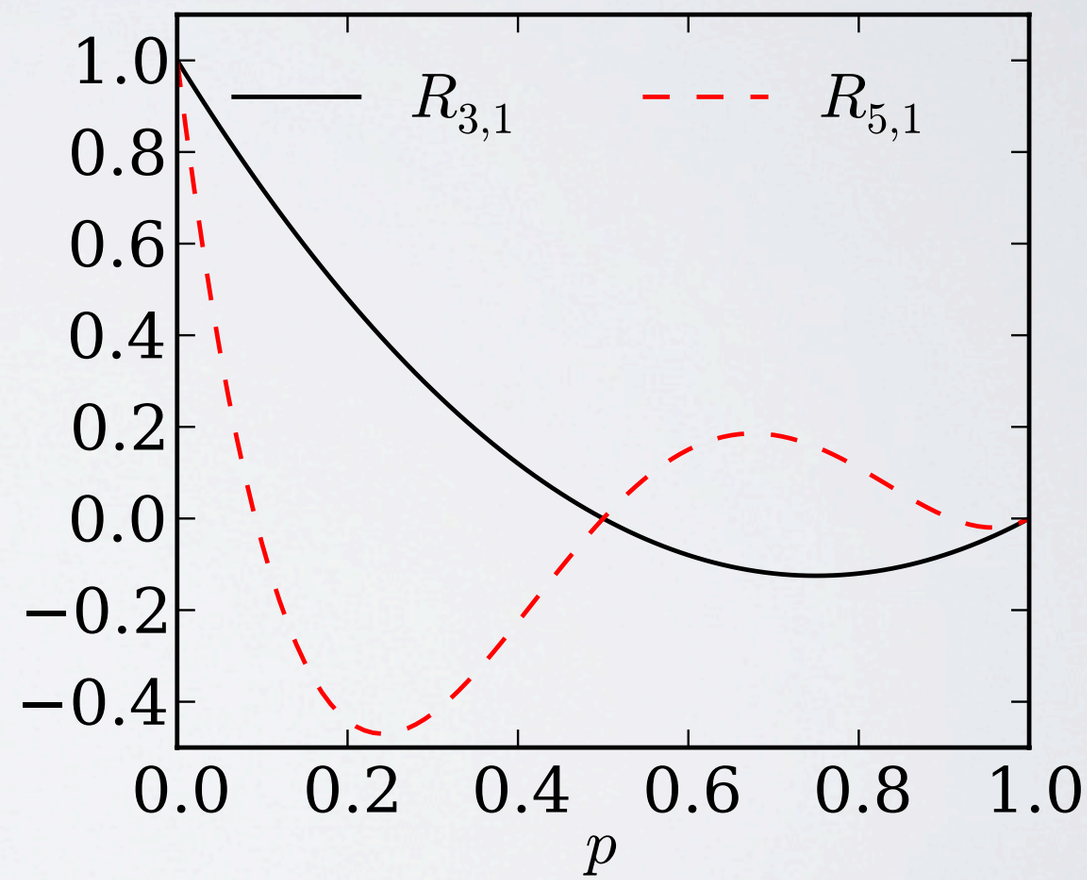
CONSERVATION LAWS

Baryon number conservation in Hadron Resonance Gas
(A. Bzdak, V. Koch and V.S. '12)

$R_{n,m} = \chi_n / \chi_m$



fraction of measured baryons

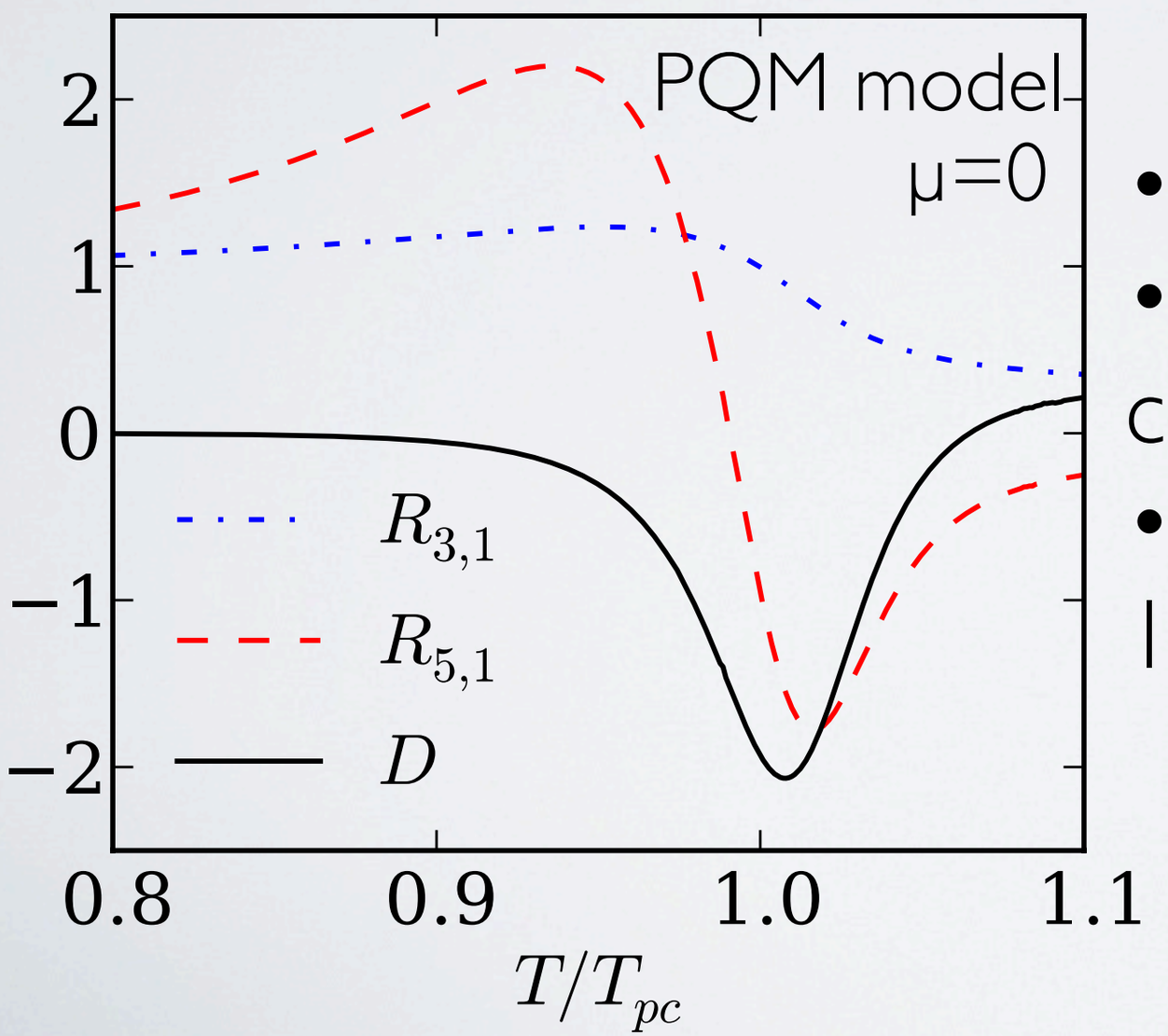


fraction of measured baryons

CONSERVATION LAWS

Observable D that is insensitive to conservation laws, i.e. D=0 for HRG + conservation of baryon number

$$D = R_{5,1} - R_{3,1}\left[1 - \frac{3}{4}(1+\gamma)(3-\gamma)\right], \gamma = \sqrt{1+8R_{3,1}}$$

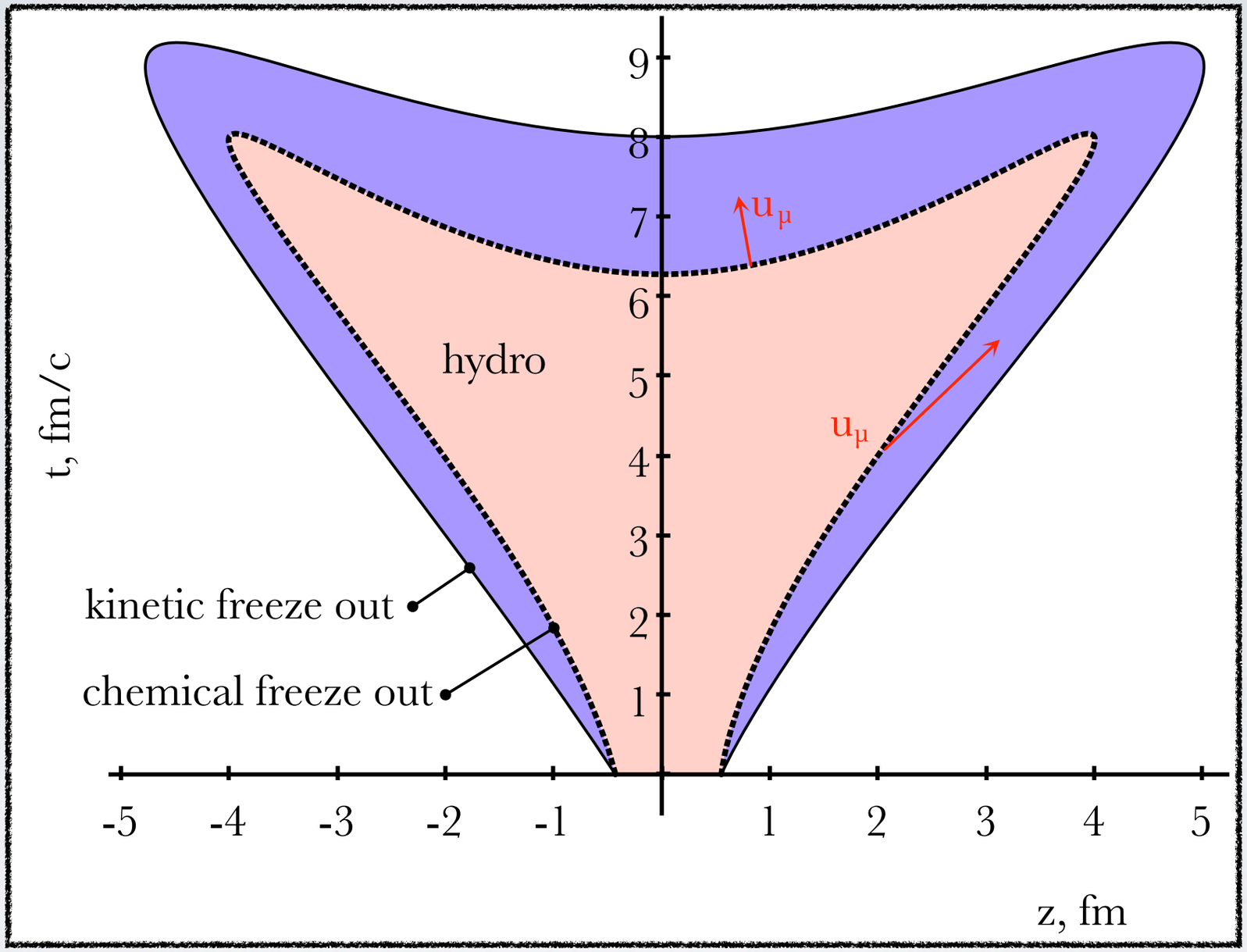


- D<0 at crossover and CEP
- D is not sensitive to conservation laws
- details can be found in 1203.4529

CONCLUSION

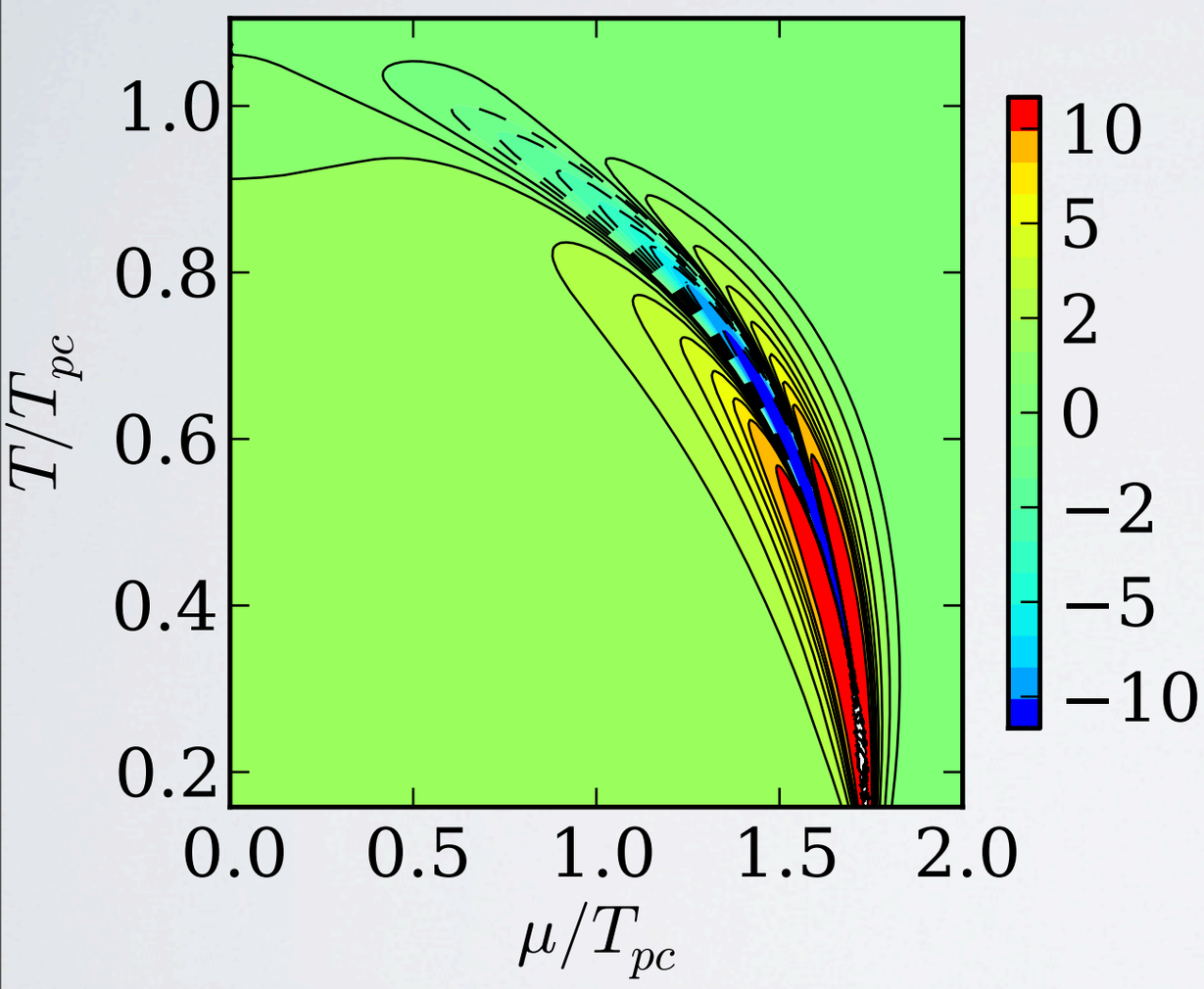
- Chiral dynamics of QCD play key role at crossover: this leads to important observable effects
- Negative sixth order cumulant at crossover transition
- Negative fourth order cumulant at crossover transition for $\mu \neq 0$
- CEP: sensitivity higher order cumulants
- CEP: universal structure of negative kurtosis in the critical region
- Side effects: conservation laws, volume fluctuations, initial state fluctuations, acceptance...
- Present experimental data is very interesting, but not convincing

- How cumulants change as functions of transverse momentum and rapidity cuts? More handle on centrality fluctuations? Electric charge cumulants? Energy fluctuations: is it possible?.....

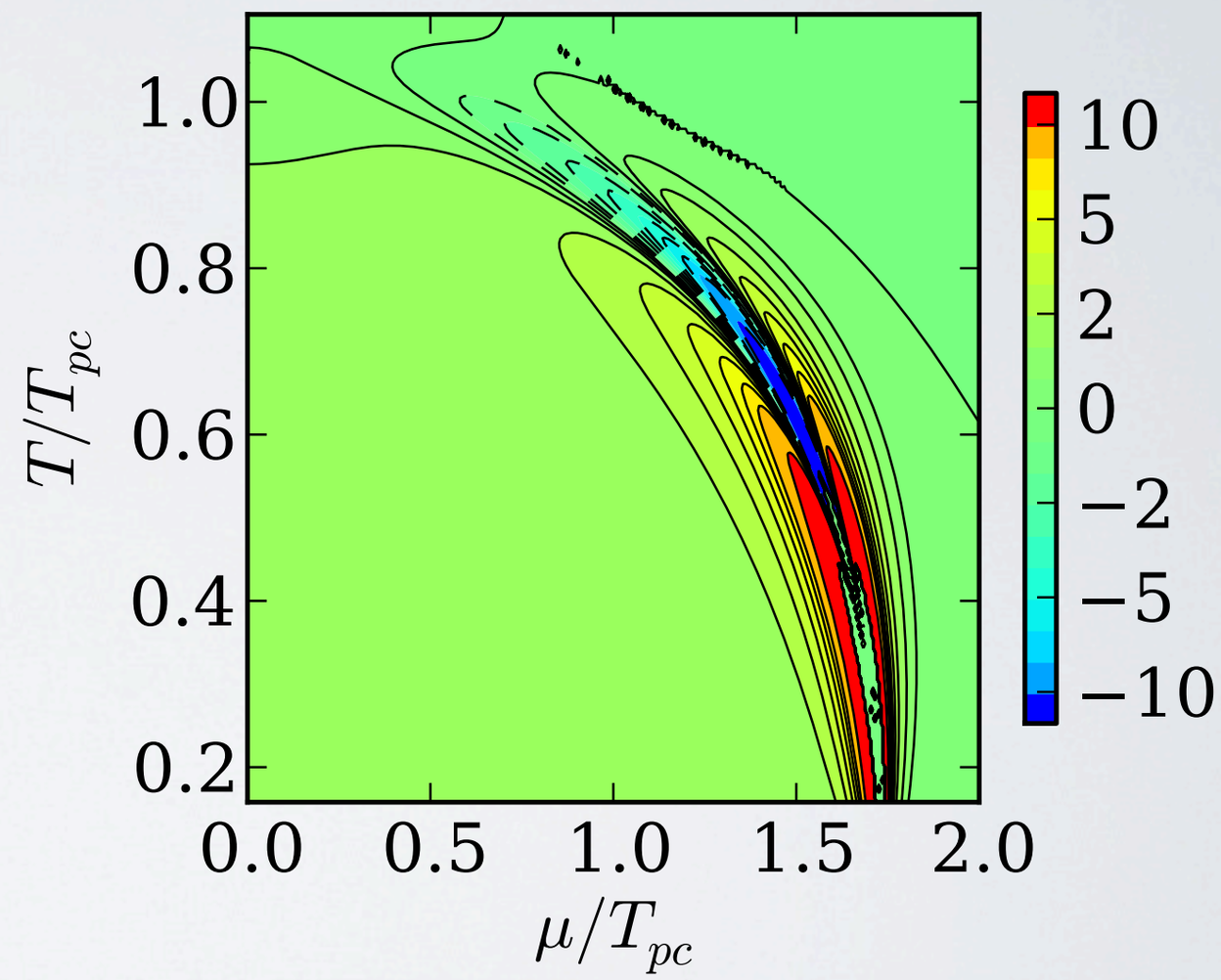

9
8
7
6
5
4
3
2
1
t, fm/c
hydro
u_μ
u_μ
kinetic freeze out
chemical freeze out
-5
-4
-3
-2
-1
1
2
3
4
5
z, fm

MOMENTUM CUTS

Without cuts:

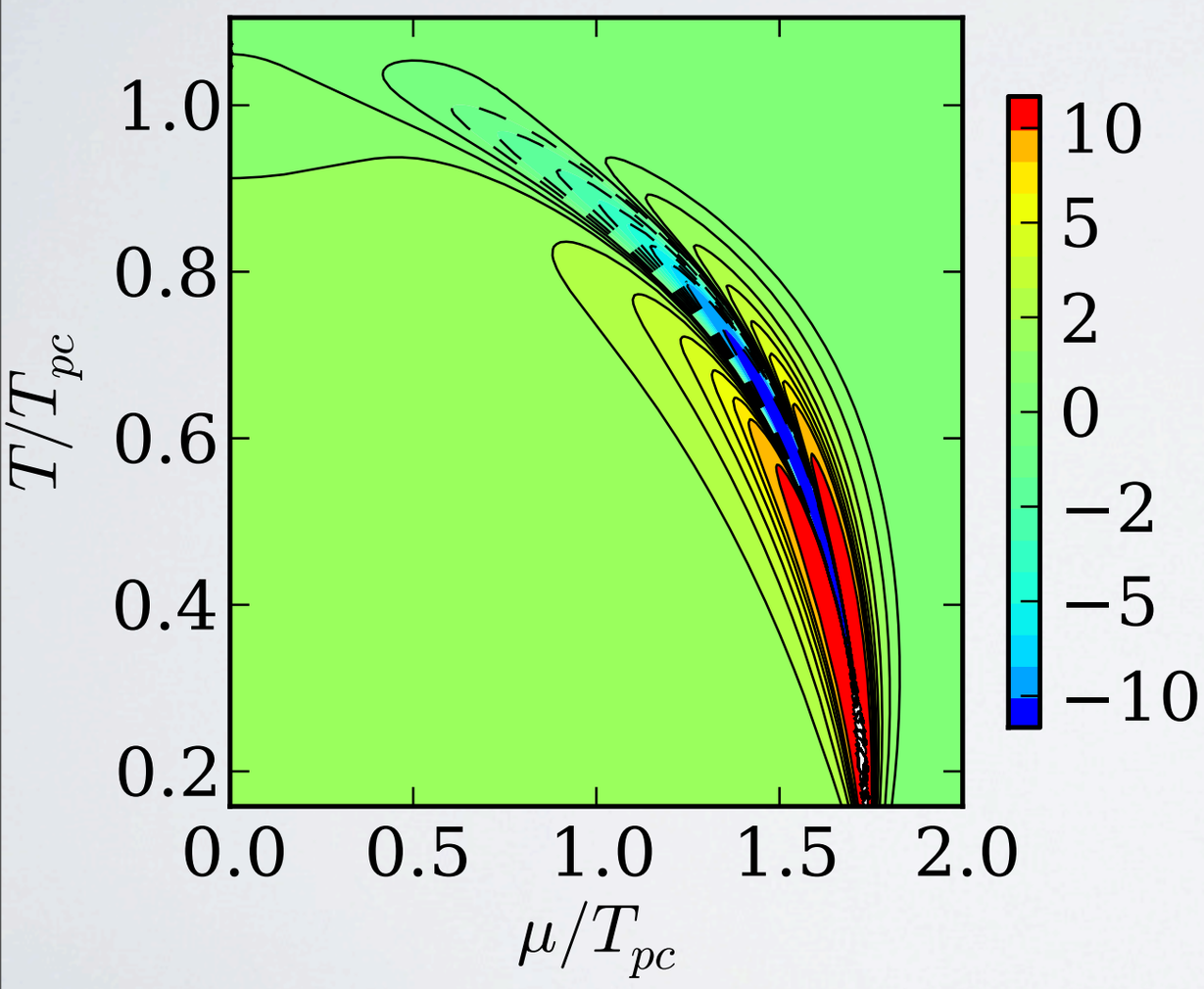
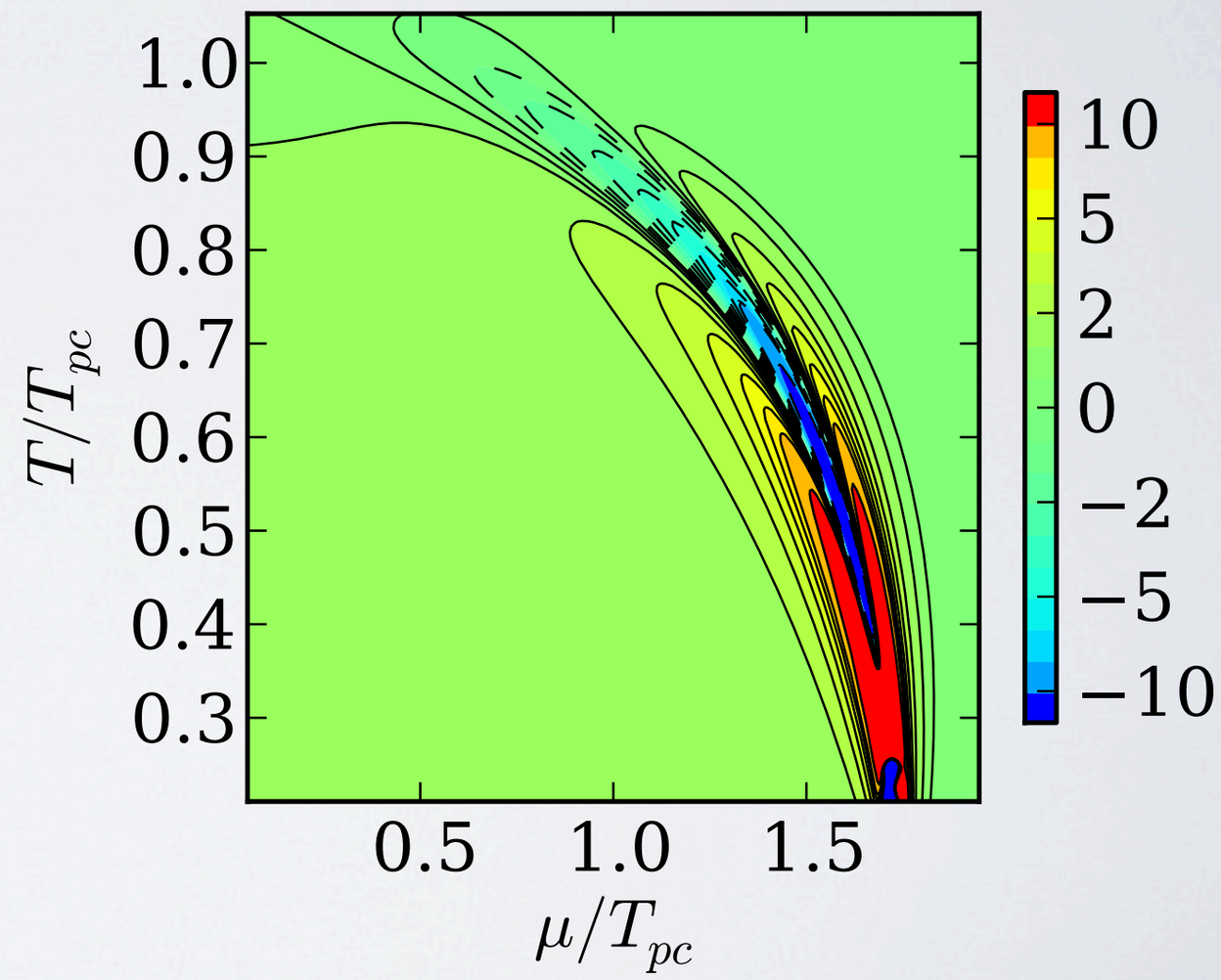


With cuts:



DISTRIBUTION OF T AND μ

Unique T and μ:



Gaussian distribution of T and μ: