Searching for the QCD Critical End Point

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1410.5454, 1509.04968

Schematic QCD Phase Diagram

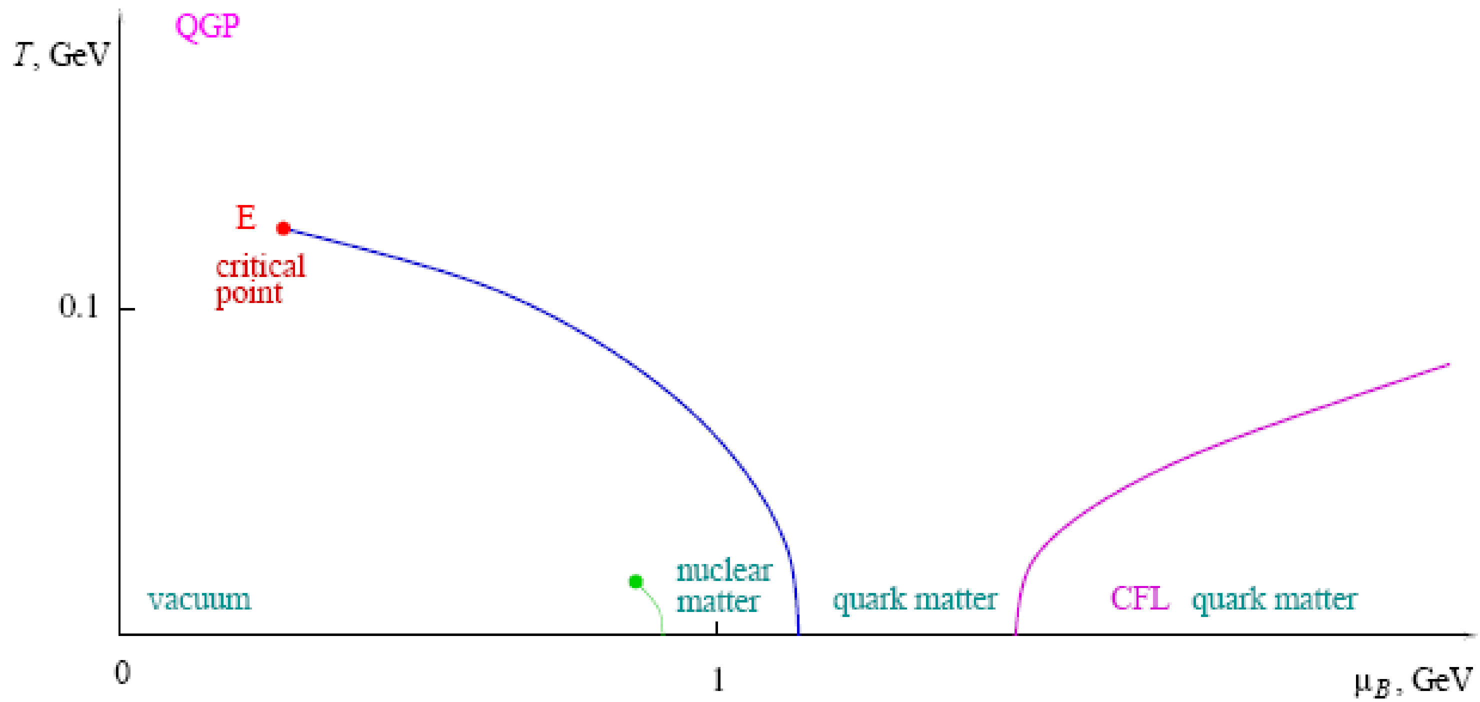
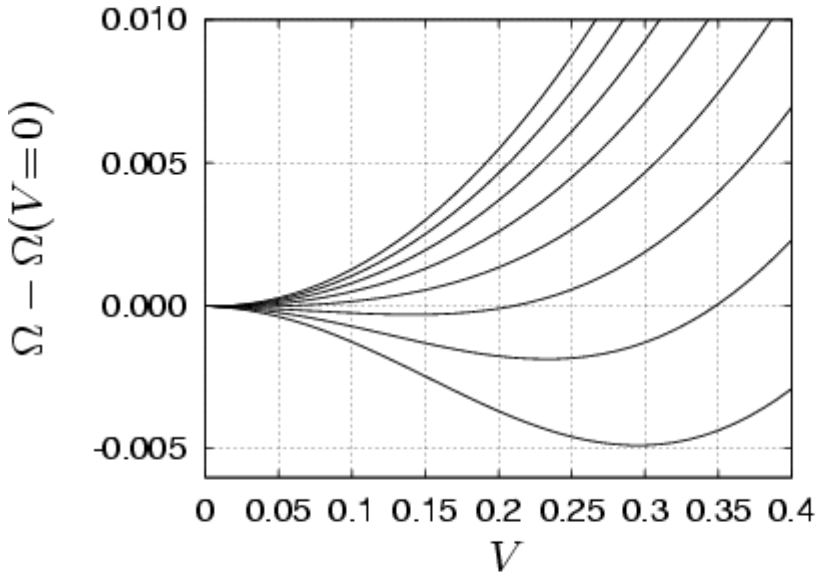


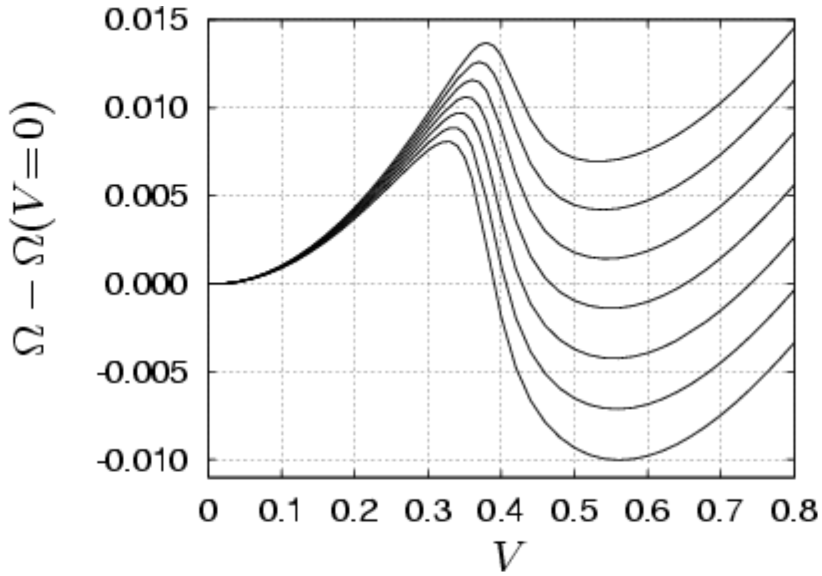
Fig. 1. QCD phase diagram

The location of the critical point (CEP)is still unknown.
Th: Difficult to apply LQCD to the low T / high chemical potential region.

Phase Transitions

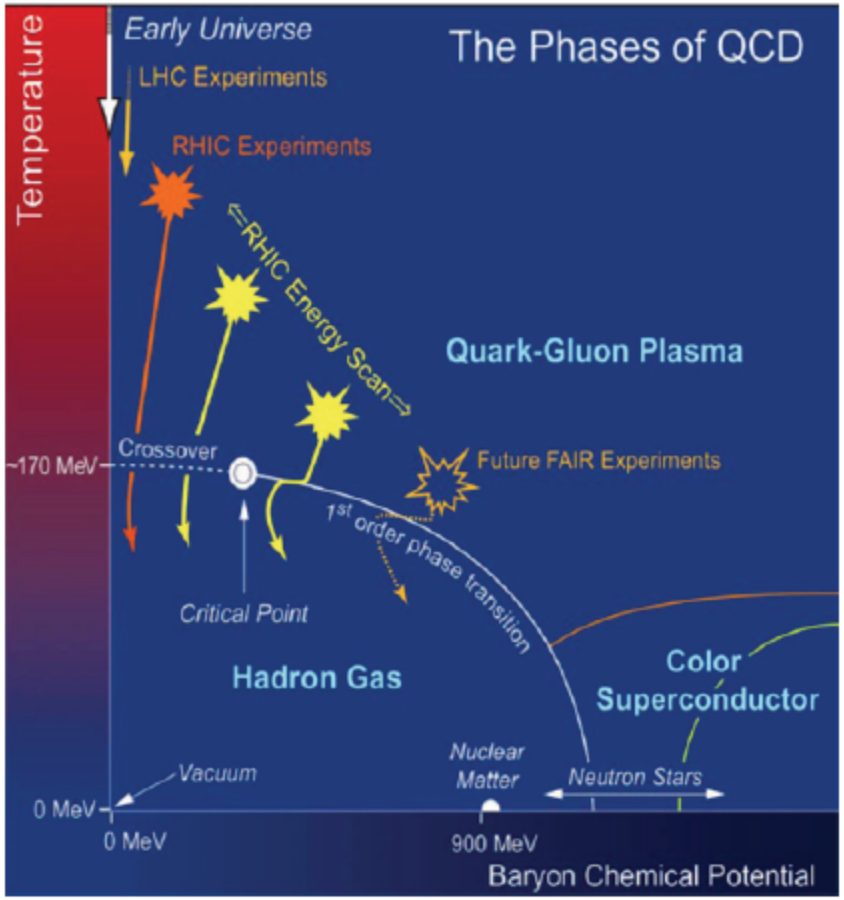


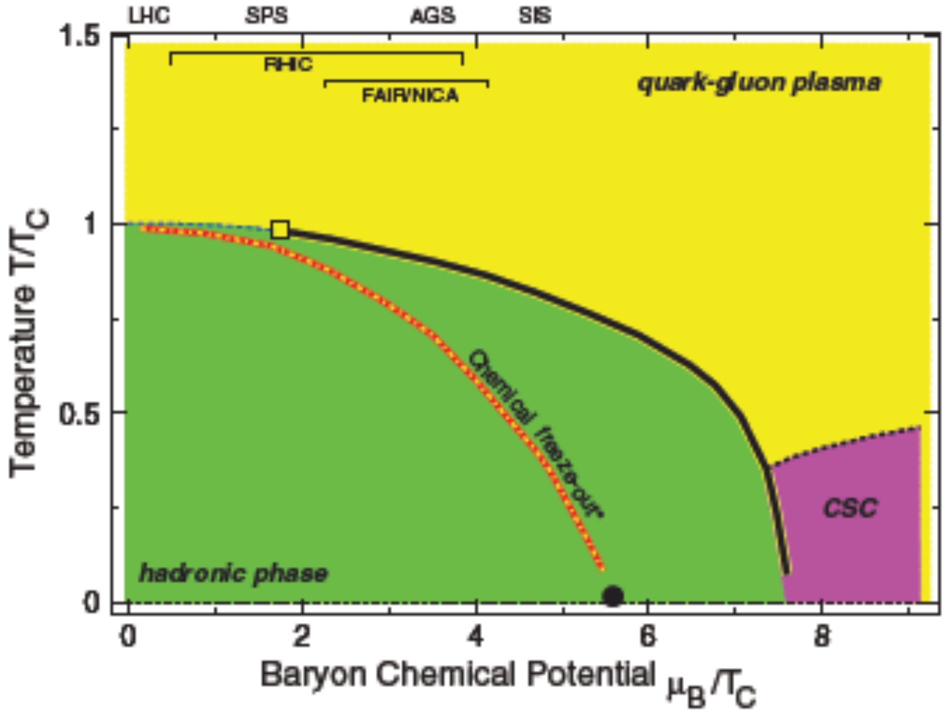
2nd-order phase transition



1st-order phase transition

Exp: Energy Scan





Fire ball expansion, fast or slow?

Signatures of CEP

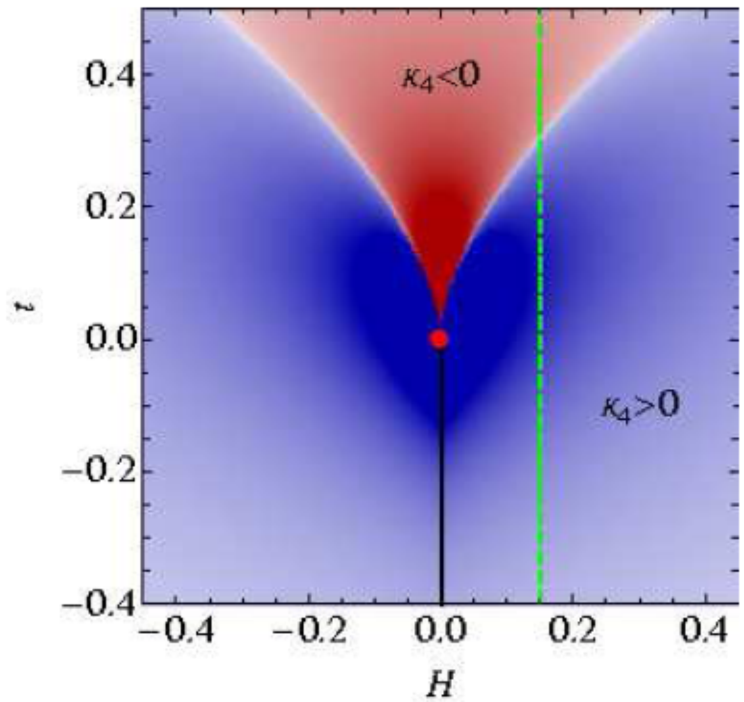
- Assuming slow expansion (thermal equilibrium)
- Correlation length diverges at the CEP, so are fluctuations, e.g. event by event variations of baryon number $\left\langle (\delta N)^2 \right\rangle, \delta N = N - \langle N \rangle$
- If correlation length is finite at freeze out, higher (nongaussian) moments could be useful:

$$\kappa_3 \propto \left\langle (\delta N)^3 \right\rangle,$$

$$\kappa_4 \propto \left\langle (\delta N)^4 \right\rangle - 3 \left\langle (\delta N)^2 \right\rangle^2$$

Universality

- In the scaling region, physics is the same within the same universality class---an effective field theory argument.
- QCD near CEP ~ Ising model



(Stephanov)

Universality

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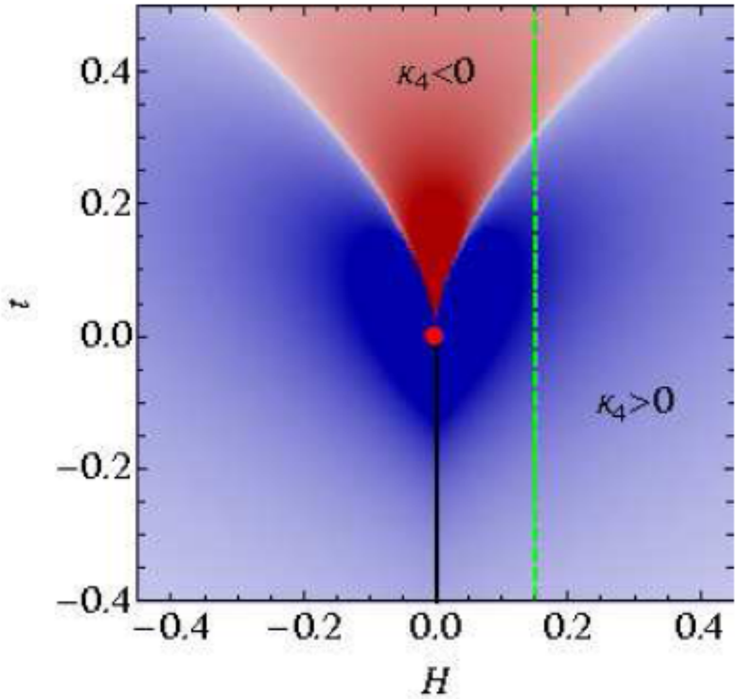
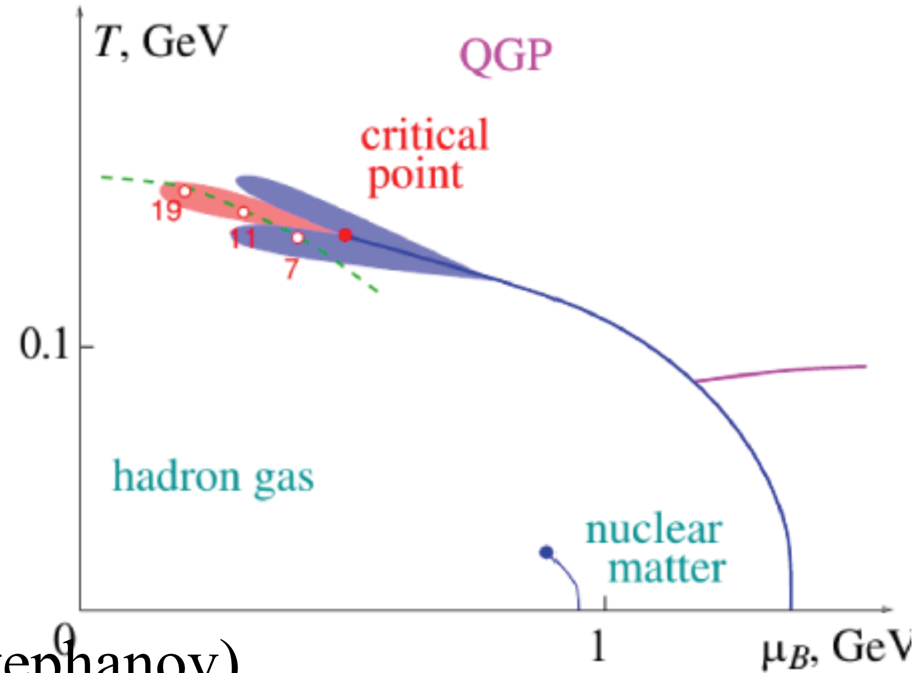
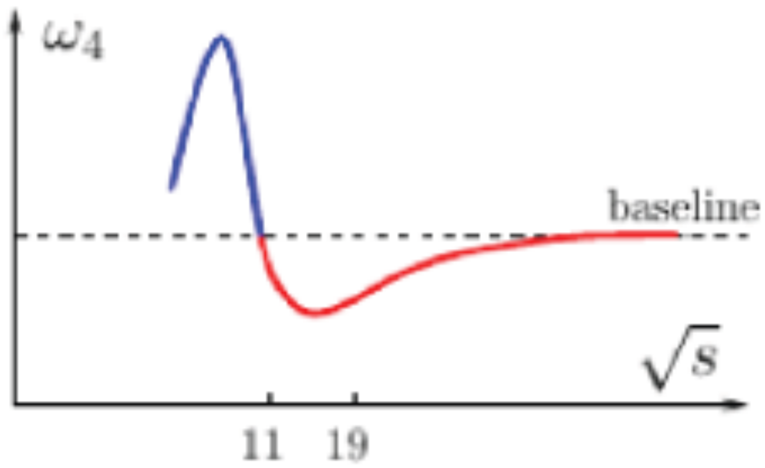
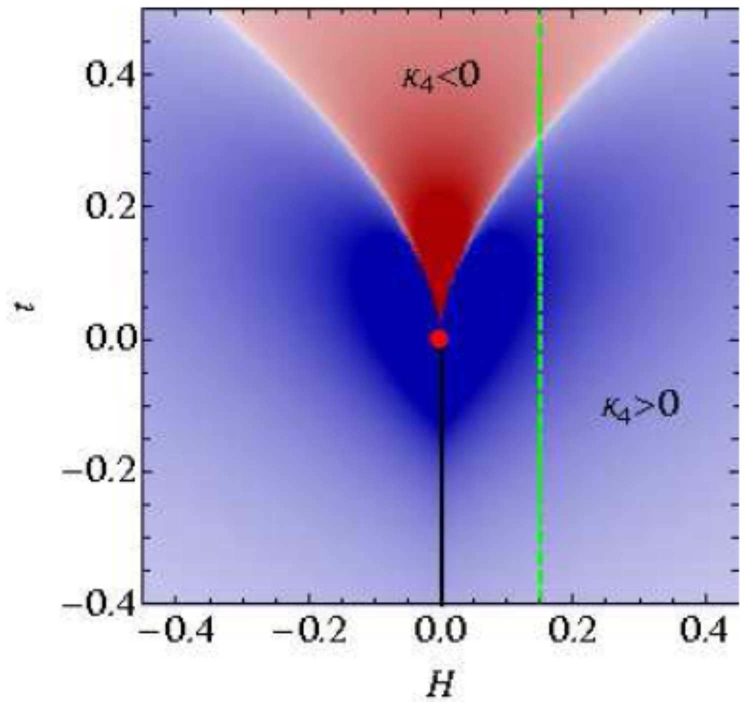




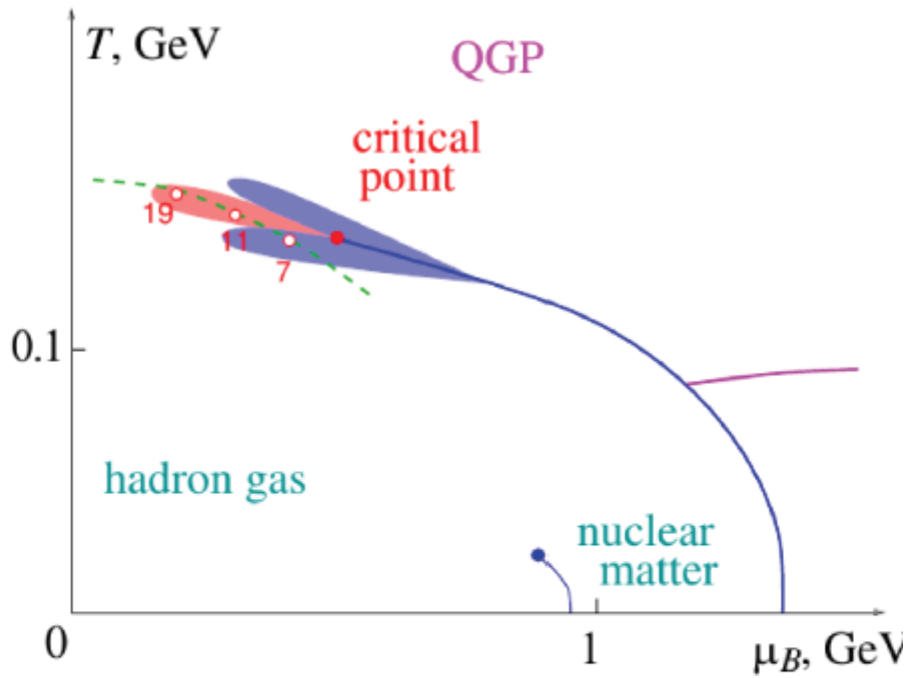
(Stephanov)



ω_4
baseline
$\sqrt{s}$
11
19

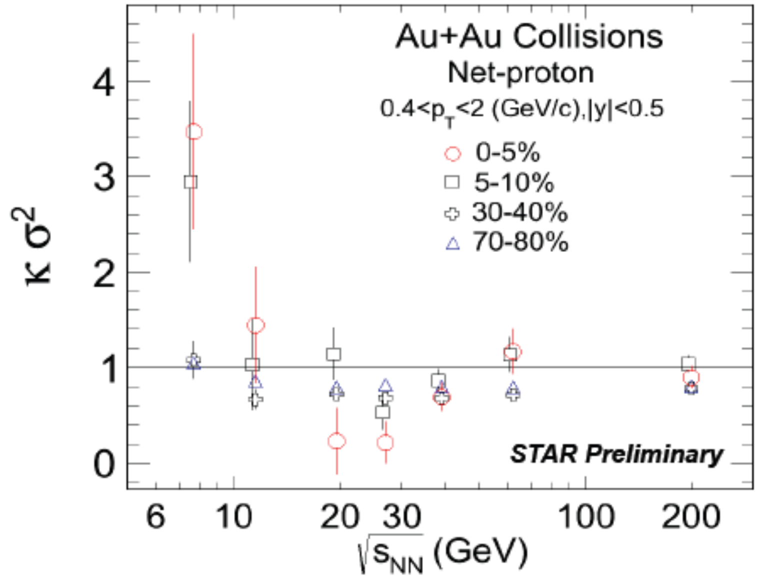


$\kappa_4<0$
$\kappa_4>0$
0.4
0.2
0.0
−0.2
−0.4
t
−0.4
−0.2
0.0
0.2
0.4
H

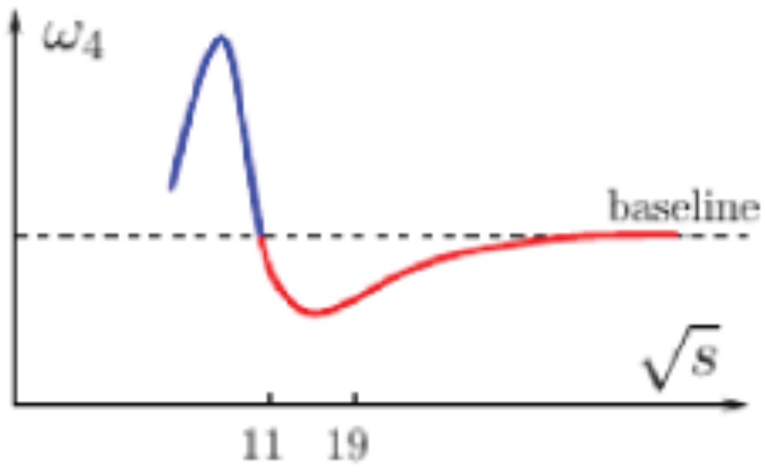


T, GeV
QGP
critical
point
19
11
7
0.1
hadron gas
nuclear
matter
0
1
μ_B, GeV

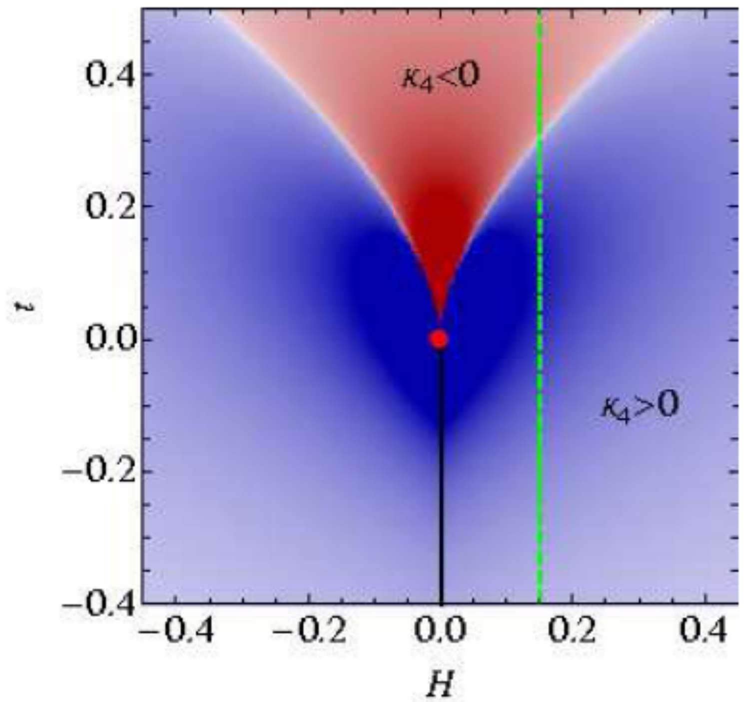
CPOD 2014



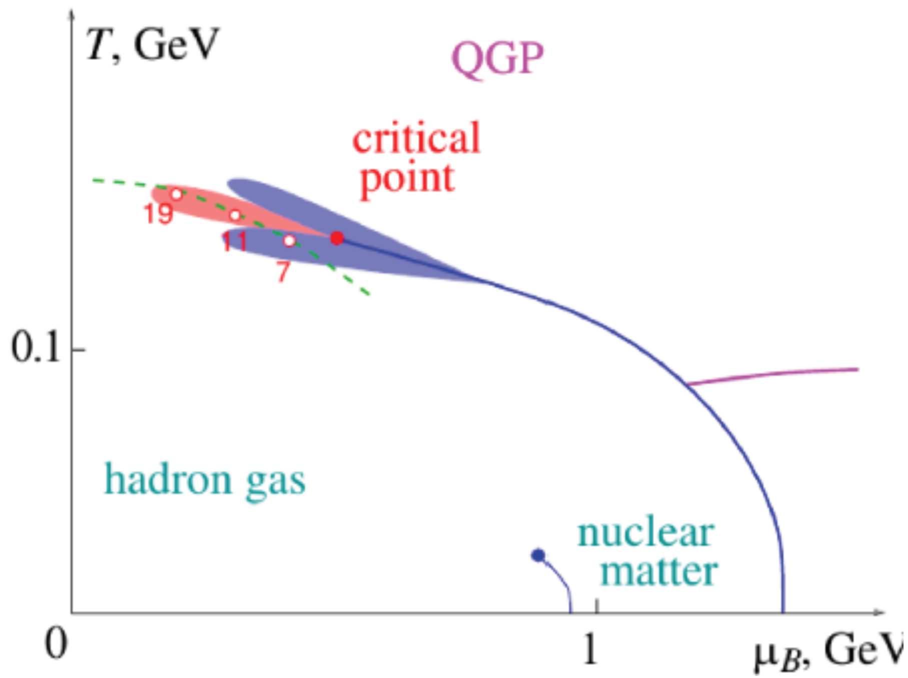
Au+Au Collisions
Net-proton
0.4<p_T<2 (GeV/c),|y|<0.5
0-5%
5-10%
30-40%
70-80%
STAR Preliminary
$\kappa\sigma^2$
$\sqrt{s_{NN}}$ (GeV)



ω_4
baseline
$\sqrt{s}$
11
19

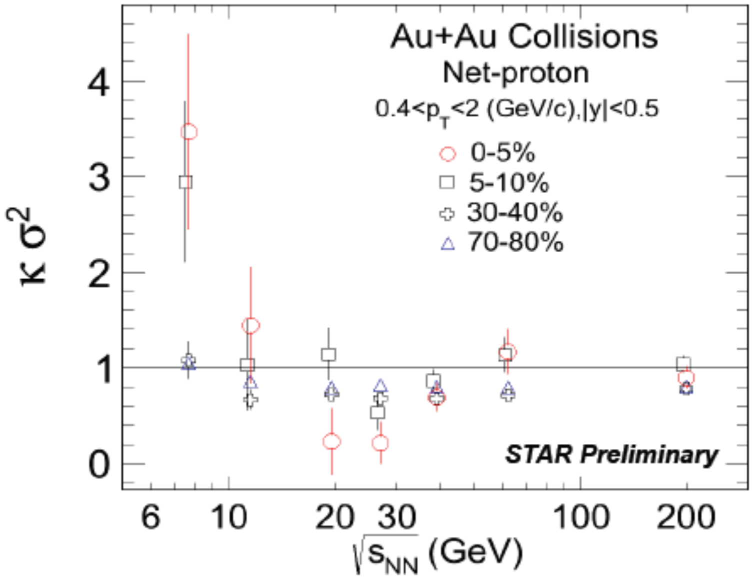


κ_4<0
κ_4>0
t
H

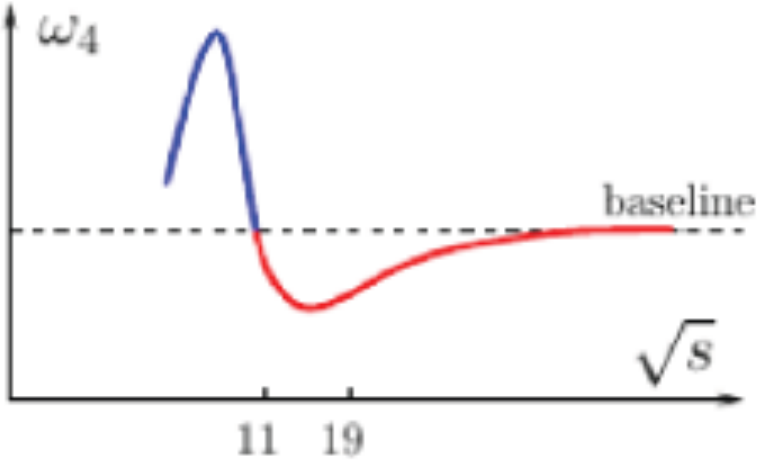


T, GeV
QGP
critical
point
19
11
7
0.1
hadron gas
nuclear
matter
0
1
μ_B, GeV

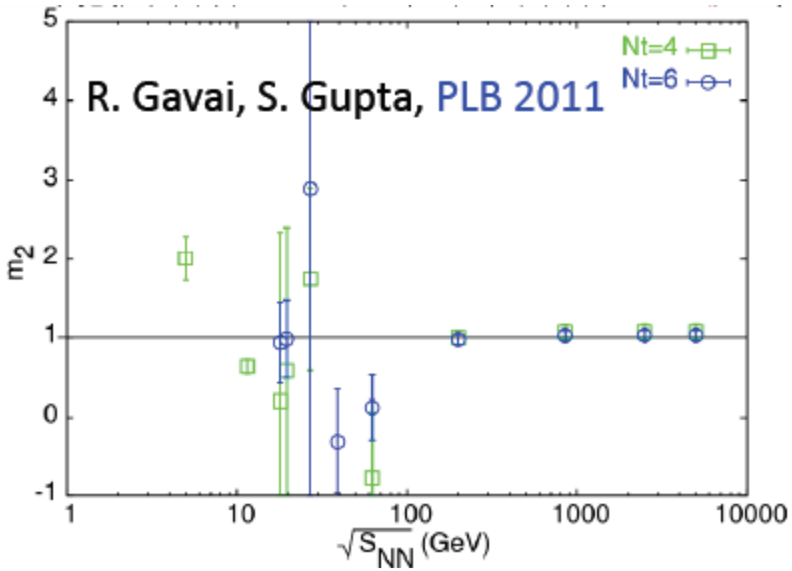
CPOD 2014



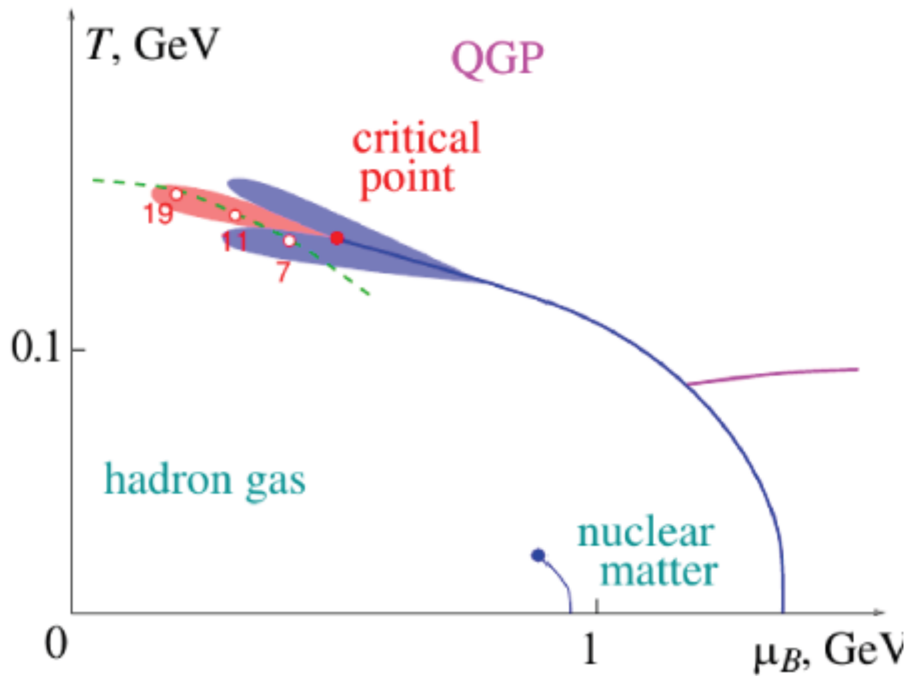
Au+Au Collisions
Net-proton
0.4<p_T<2 (GeV/c),|y|<0.5
0-5%
5-10%
30-40%
70-80%
STAR Preliminary
κ σ²
√s_NN (GeV)



ω₄
baseline
√s
11
19

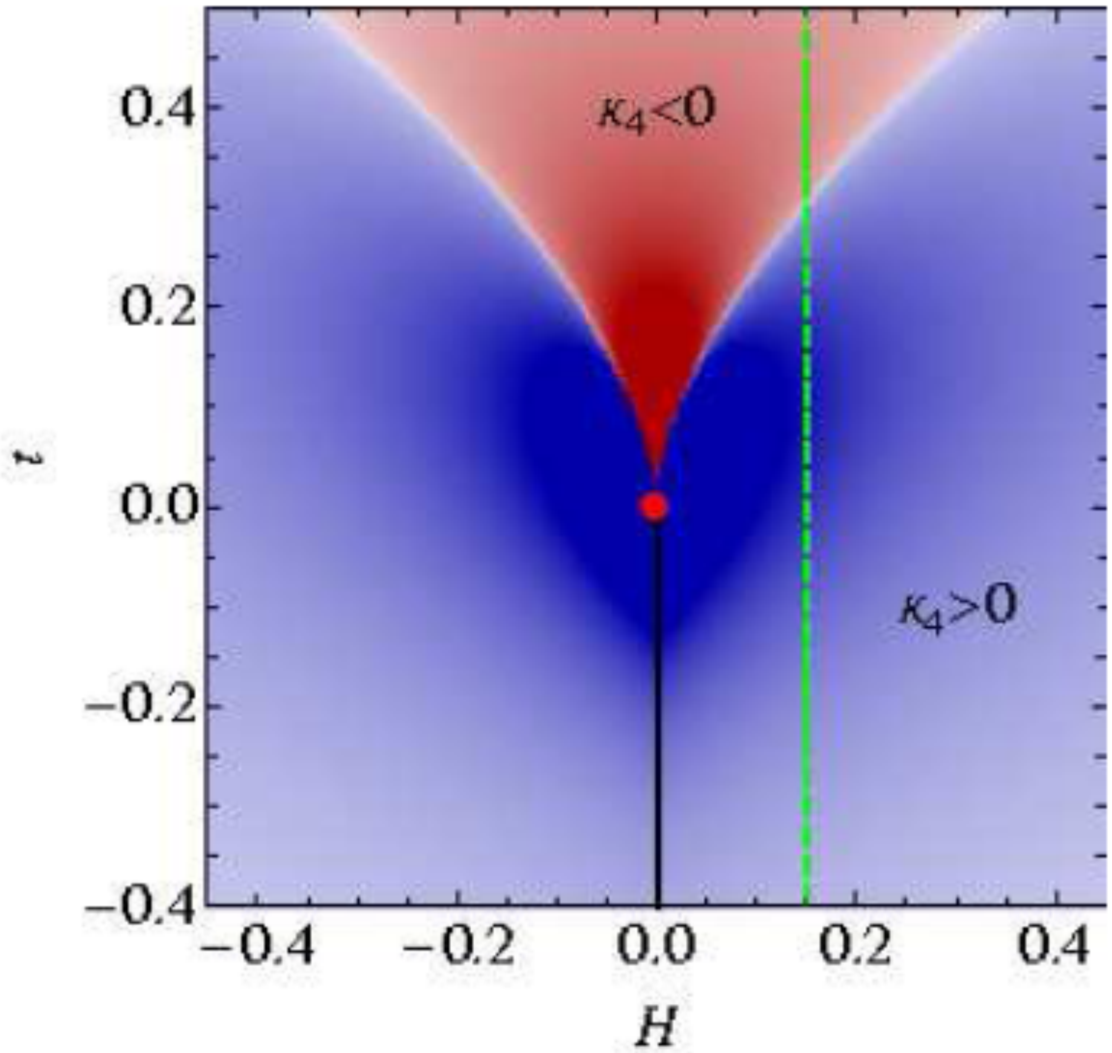


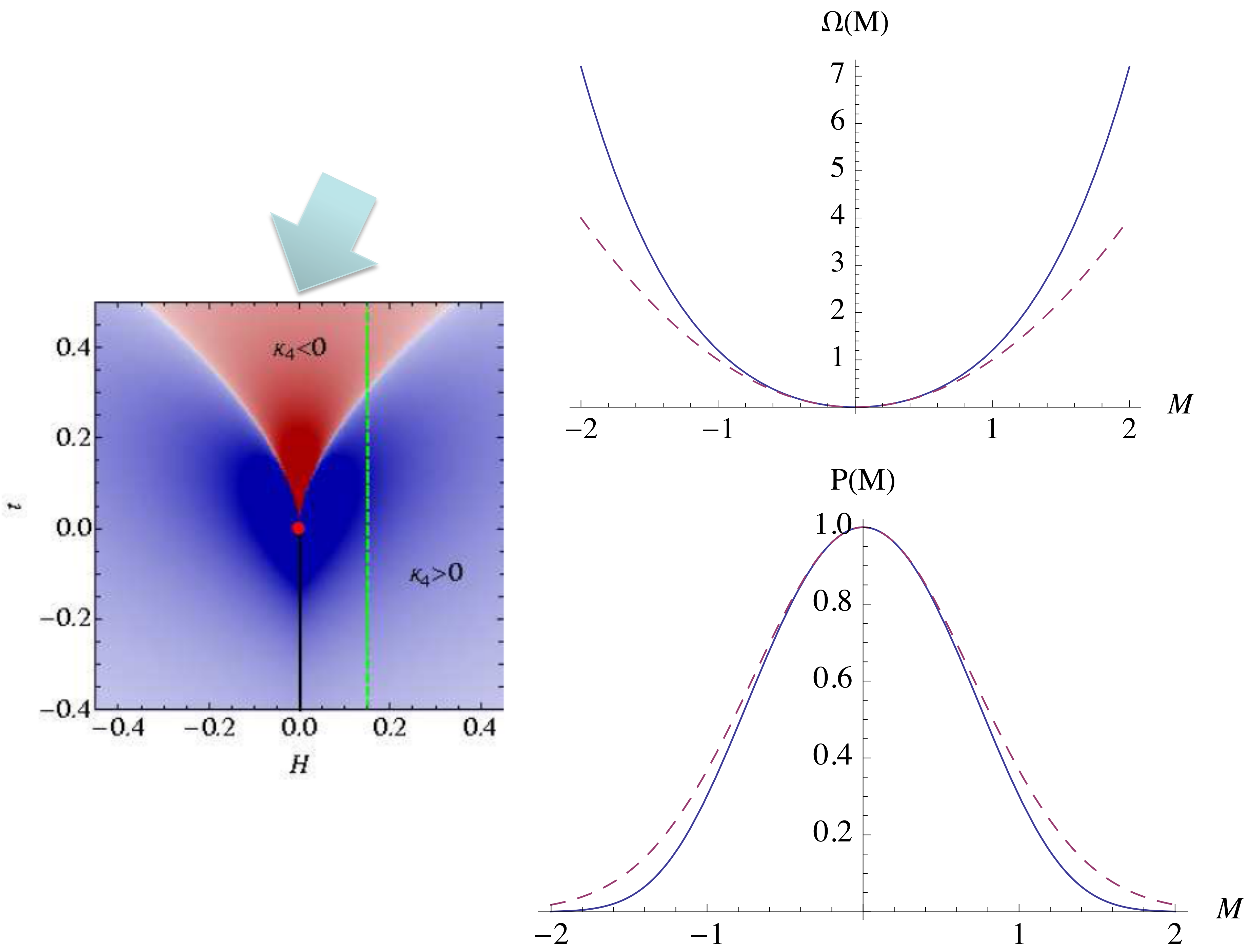
R. Gavai, S. Gupta, PLB 2011
Nt=4
Nt=6
m₂
√S_NN (GeV)



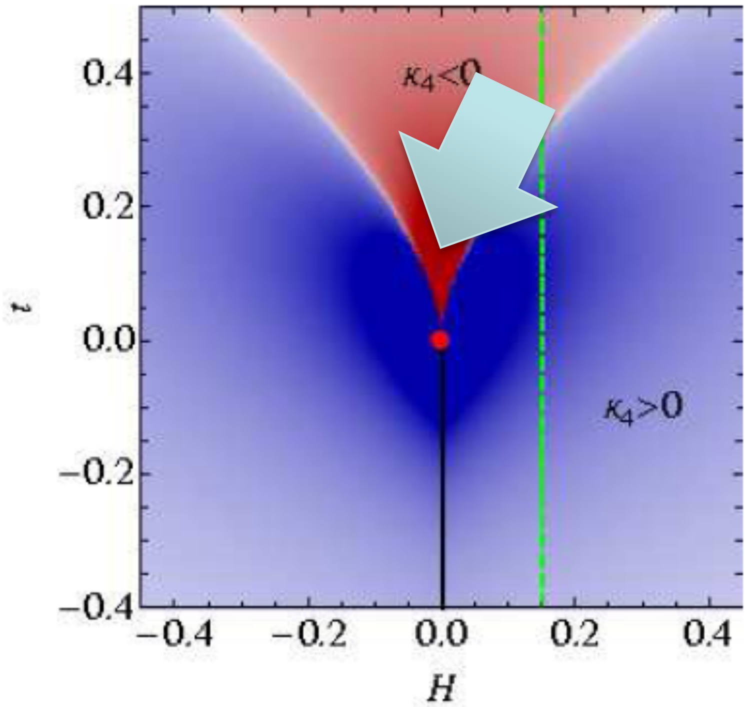
T, GeV
QGP
critical point
19
11
7
0.1
hadron gas
nuclear matter
0
1
μ_B, GeV

What is going on?

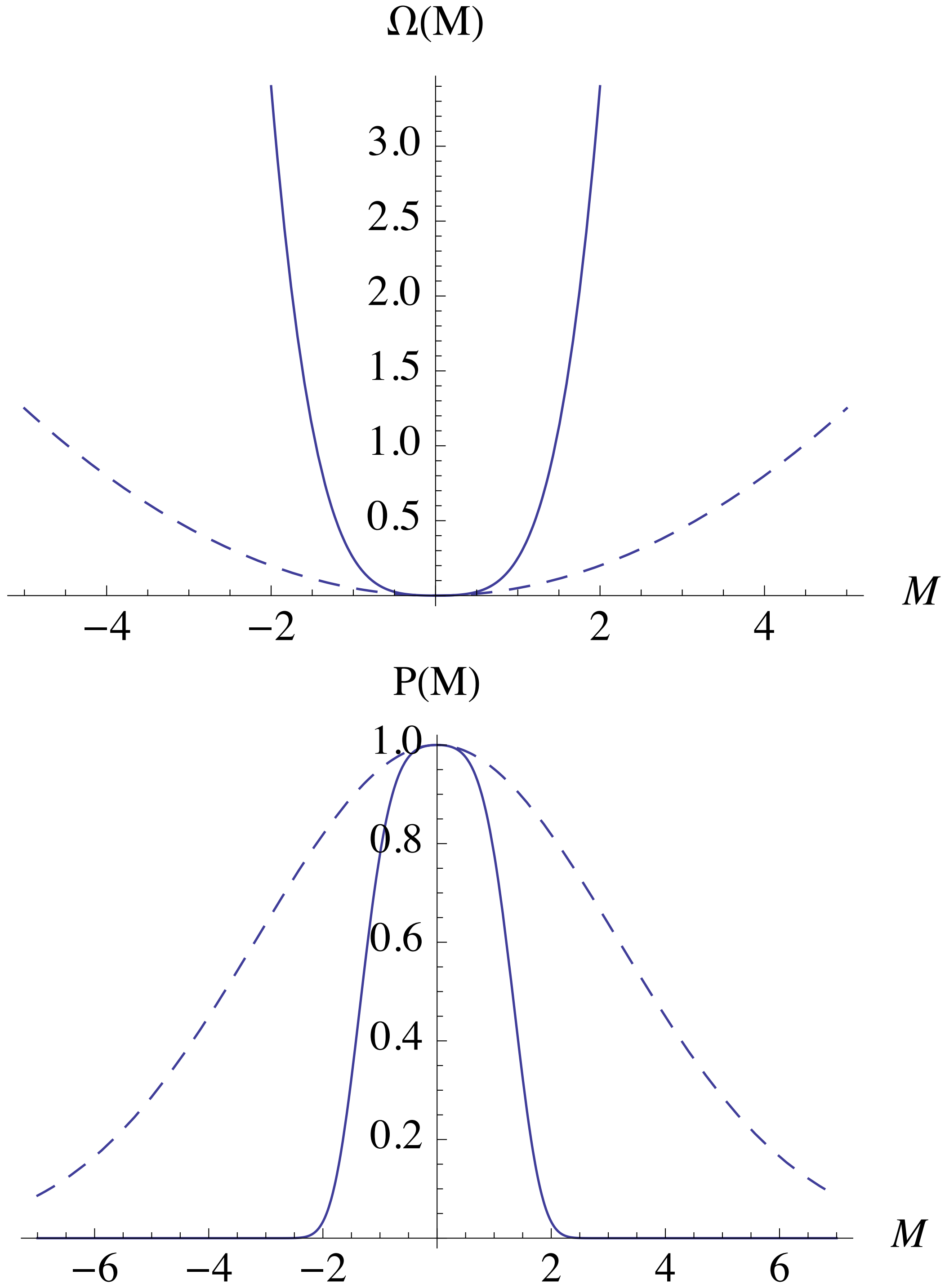




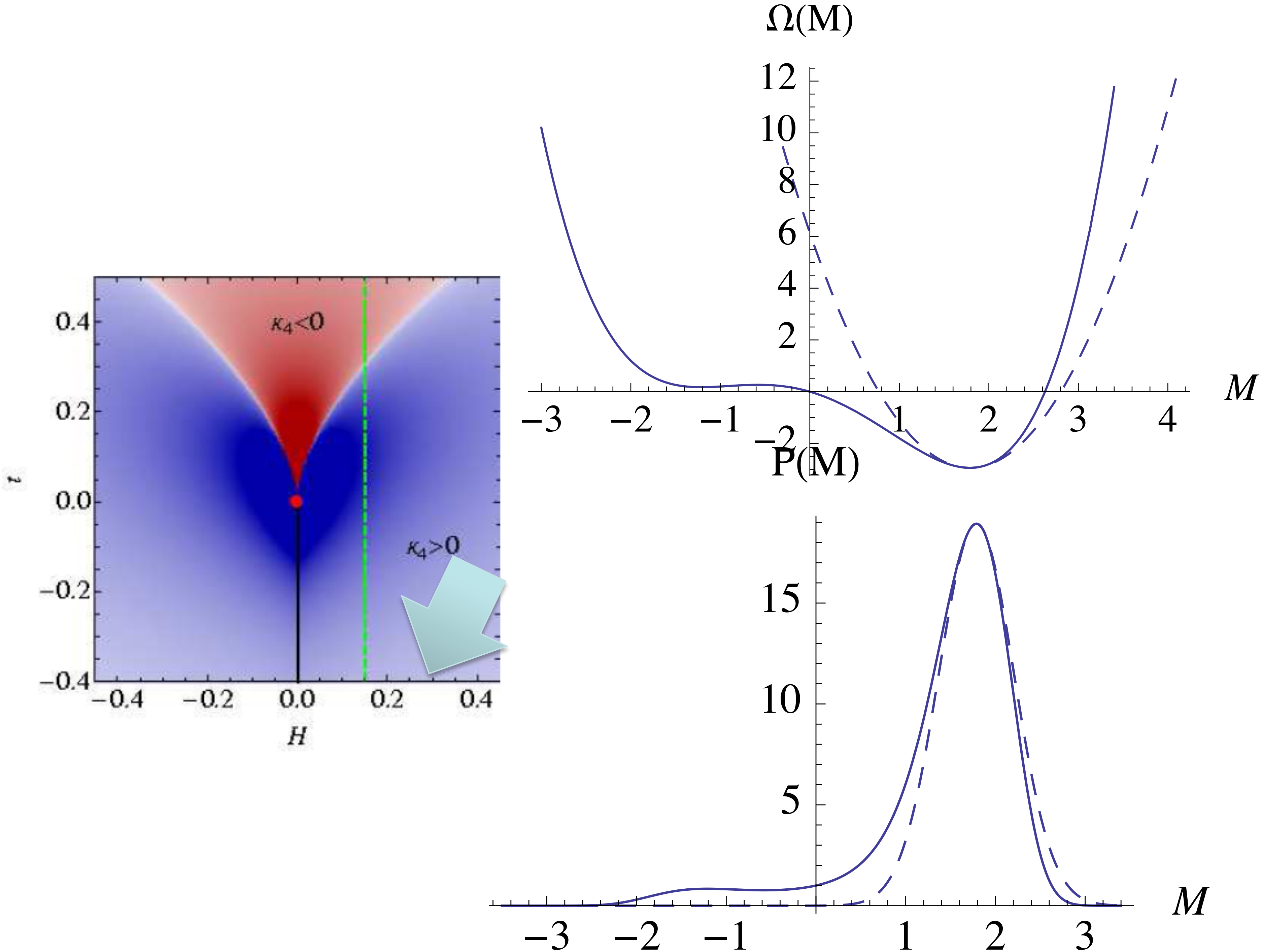
Ω(M)
P(M)
M
κ4<0
κ4>0
t
H



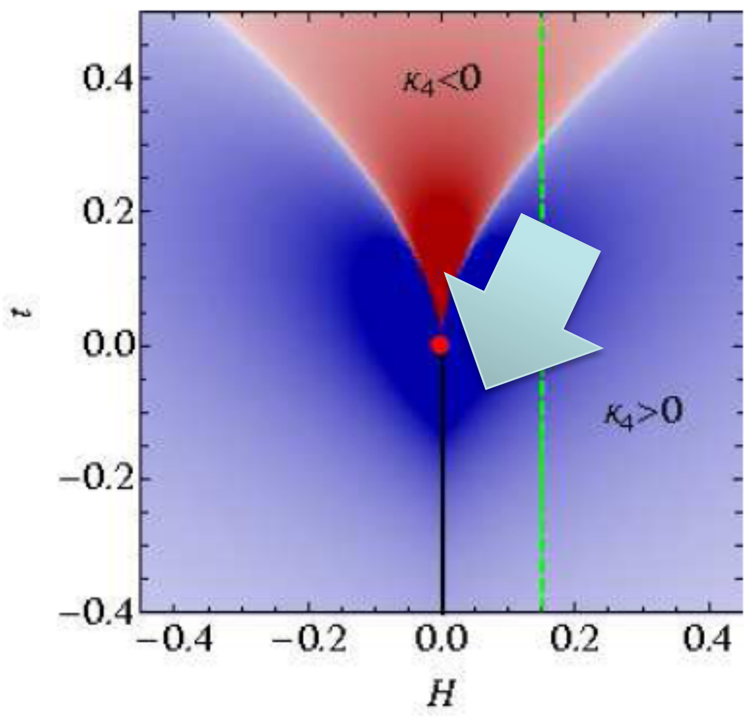
$\kappa_4<0$
$\kappa_4>0$
t
H



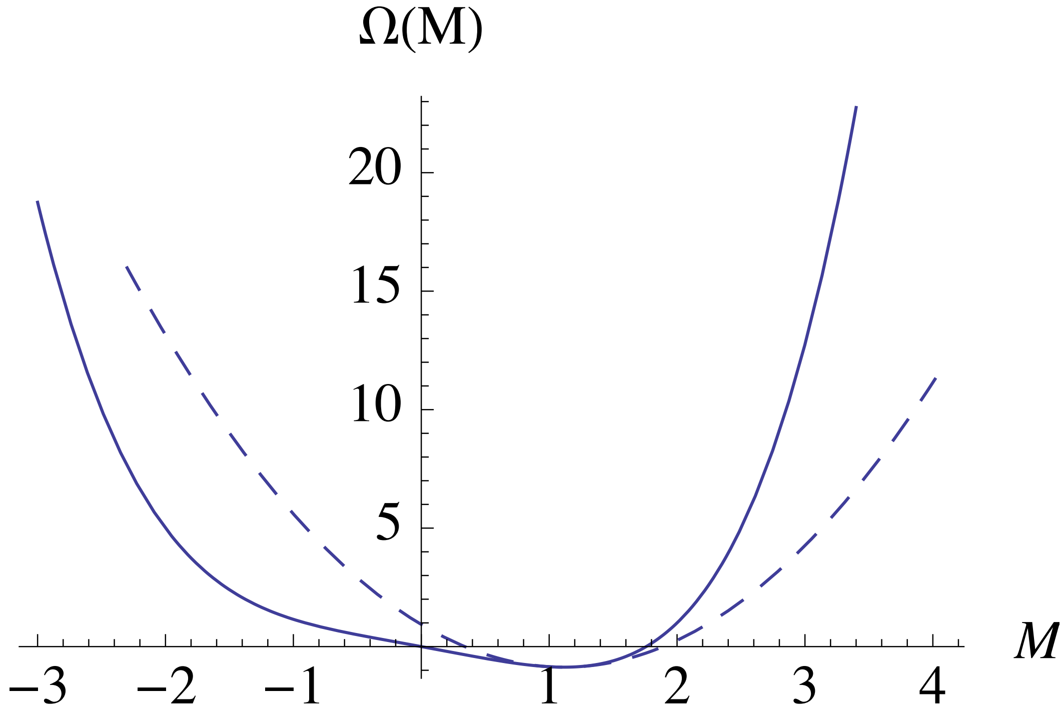
Ω(M)
P(M)
M



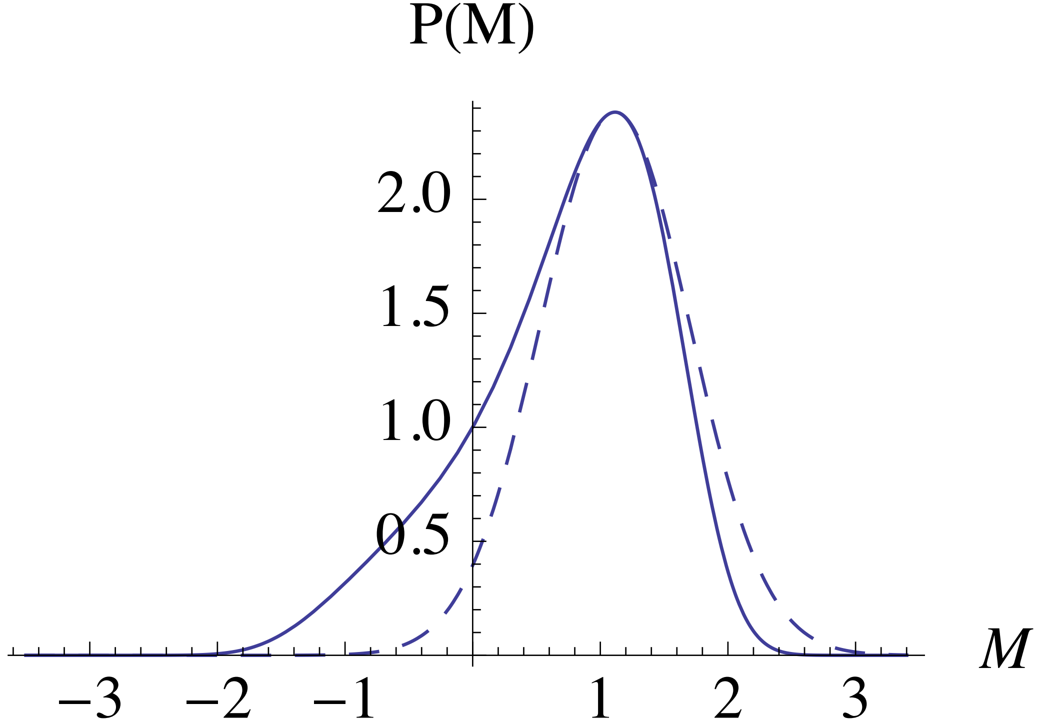
κ₄<0
κ₄>0
t
H
Ω(M)
M
P(M)
M



$\kappa_4<0$
$\kappa_4>0$
0.4
0.2
0.0
−0.2
−0.4
−0.4 −0.2 0.0 0.2 0.4
t
H

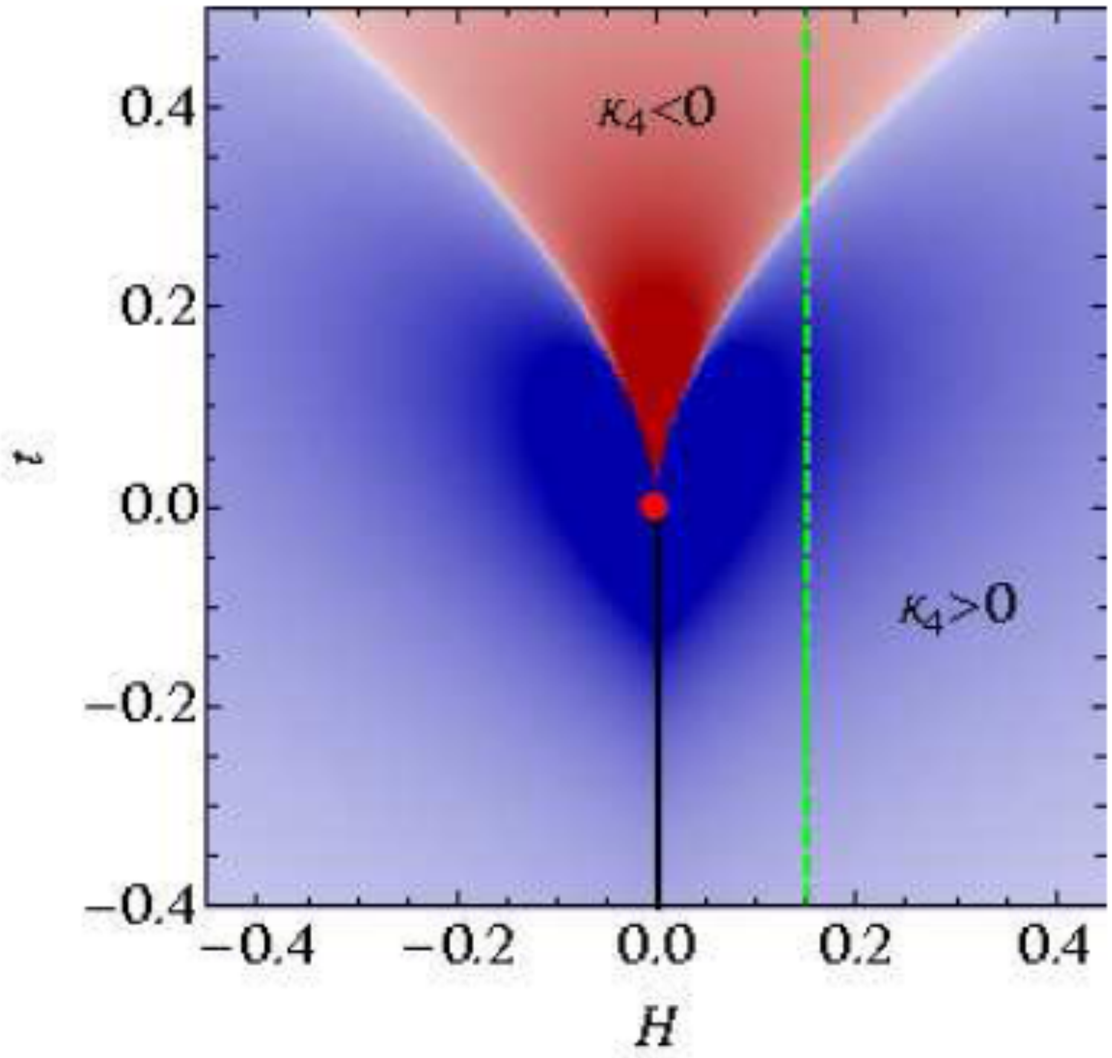


Ω(M)
20
15
10
5
M
−3 −2 −1 1 2 3 4



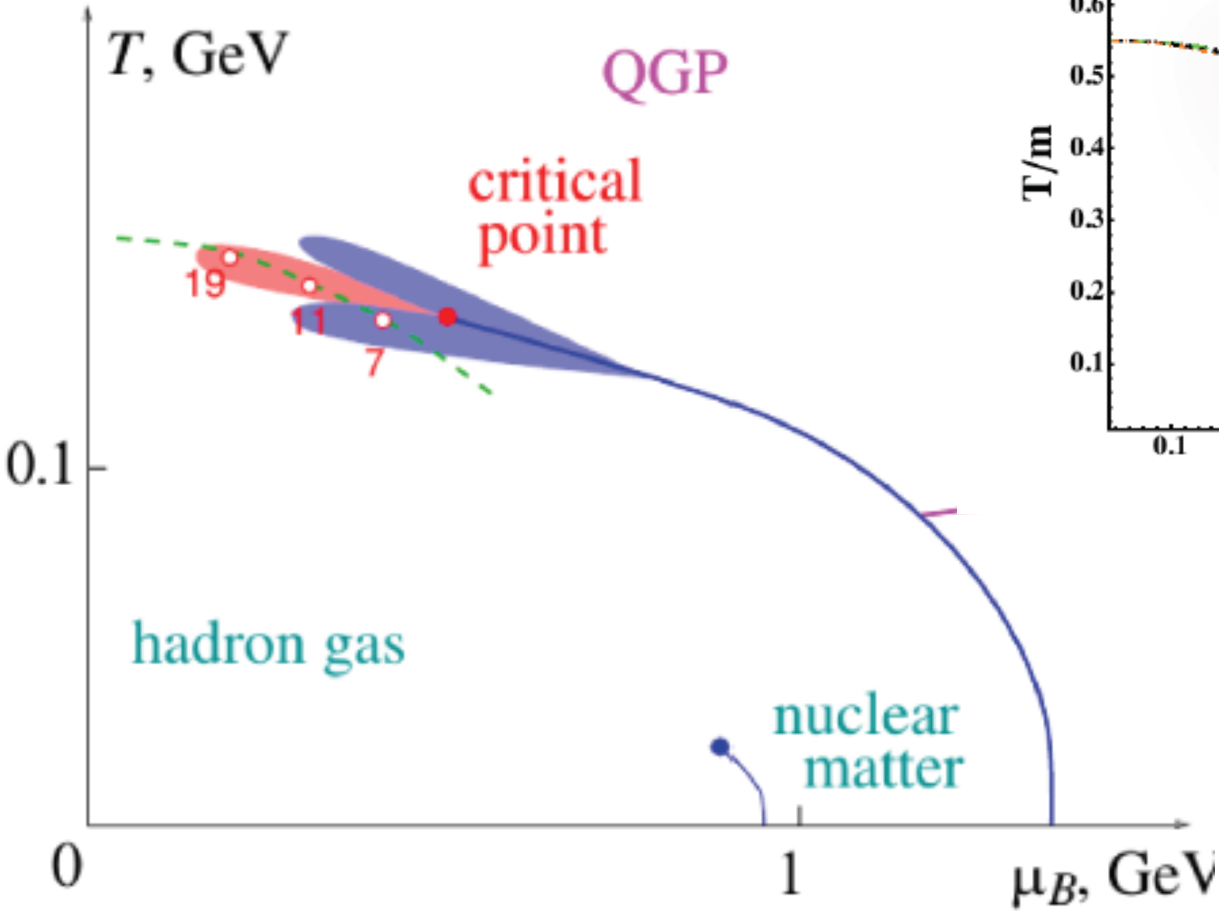
P(M)
2.0
1.5
1.0
0.5
M
−3 −2 −1 1 2 3

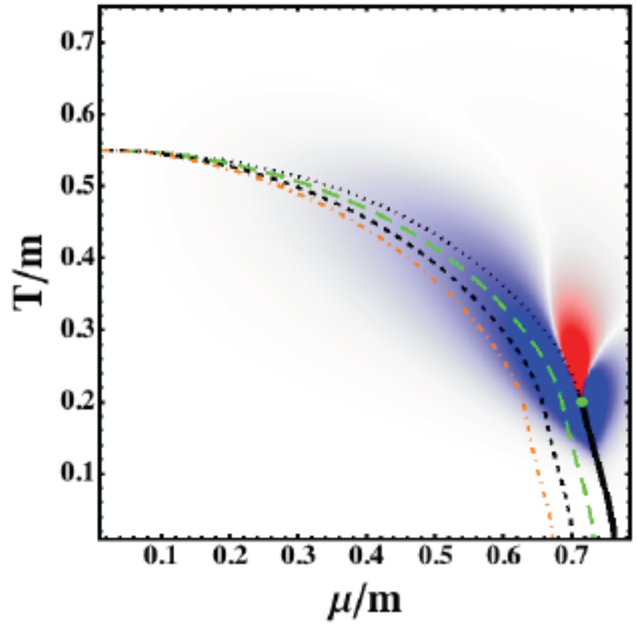
What is going on?



Robust!

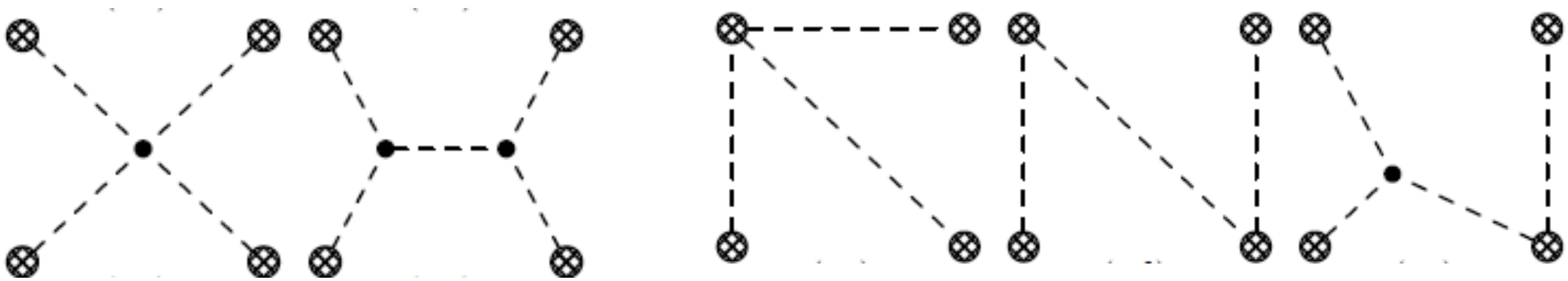
Mapping: model dependent





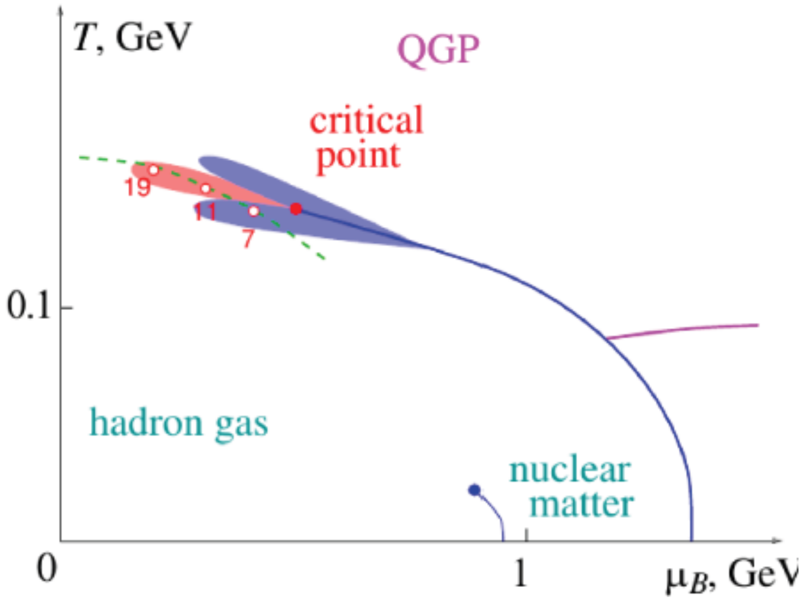
Our Works

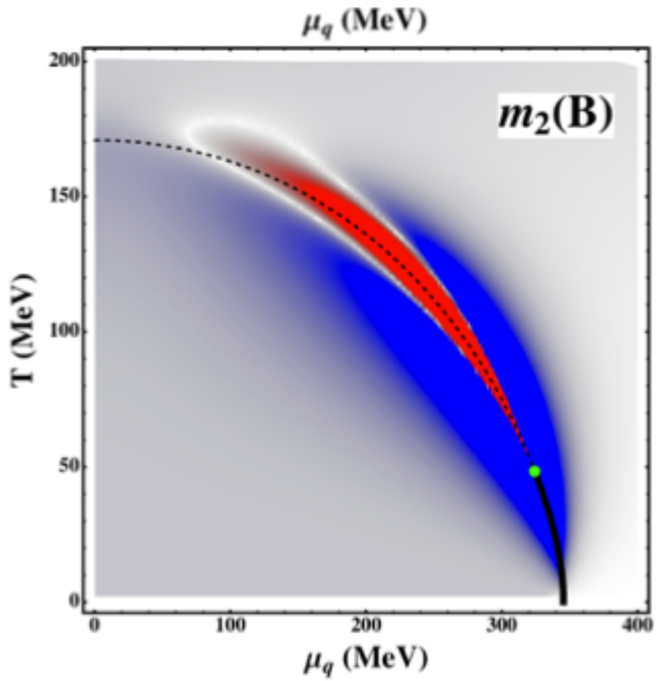
- Mapping and diagram power counting w/ effective potential: more diagrams equally important



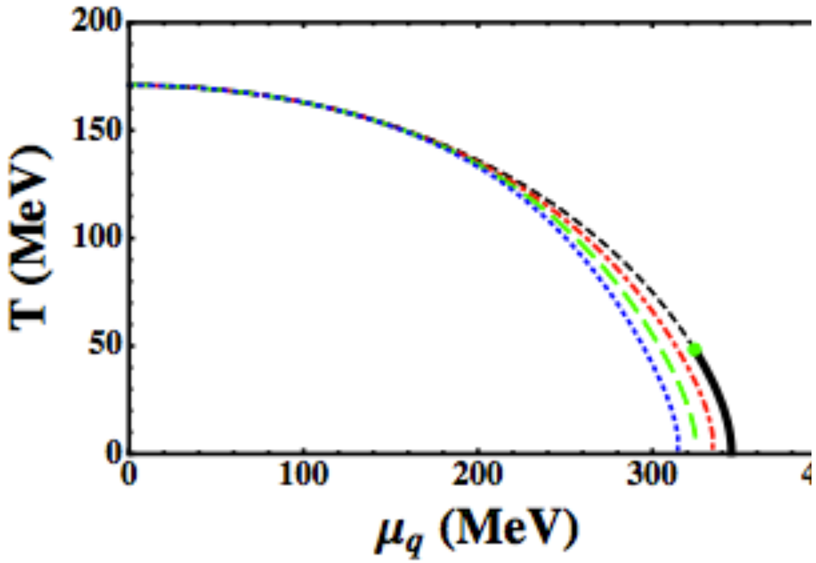
- Explicit model calculations: (a) 1+1 dim Gross-Neveu model in the large N limit (b) 3+1 dim 3 flavor NJL model ($\mu_s = \mu_I = 0$), complete set of susceptibilities up to 4 derivatives.

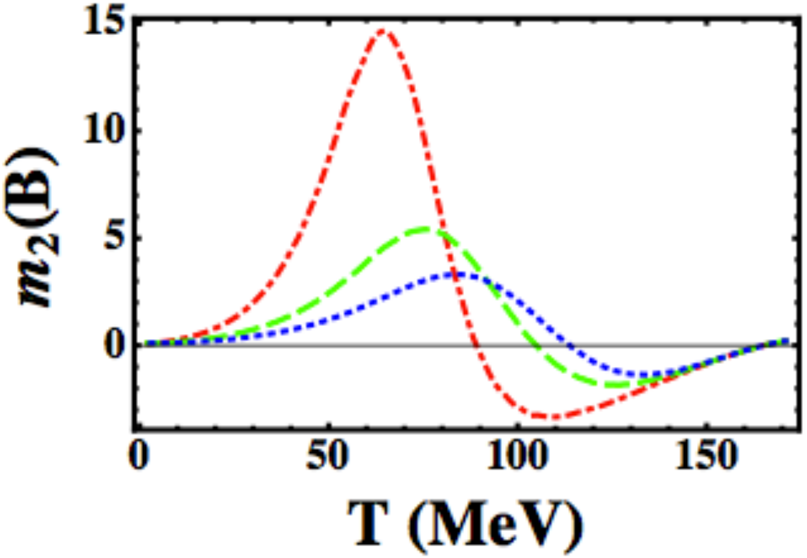
m2 = 4th moment/2nd moment

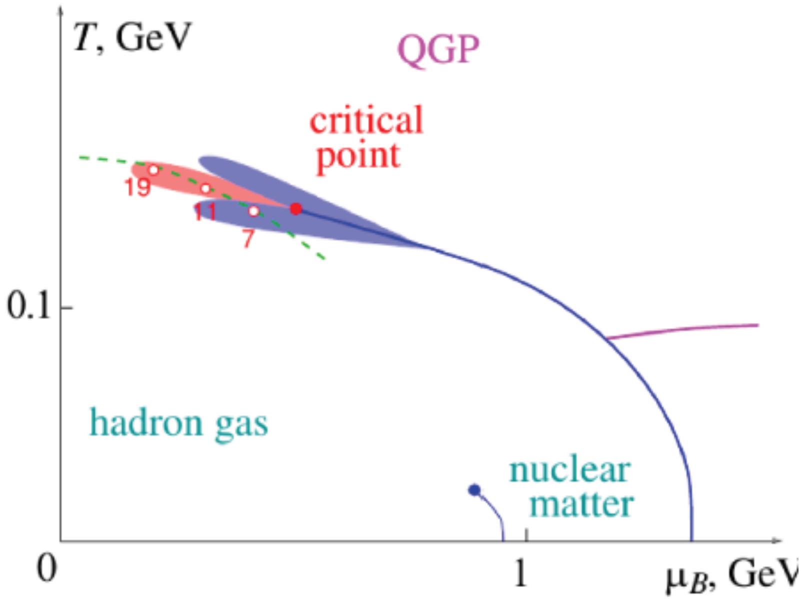


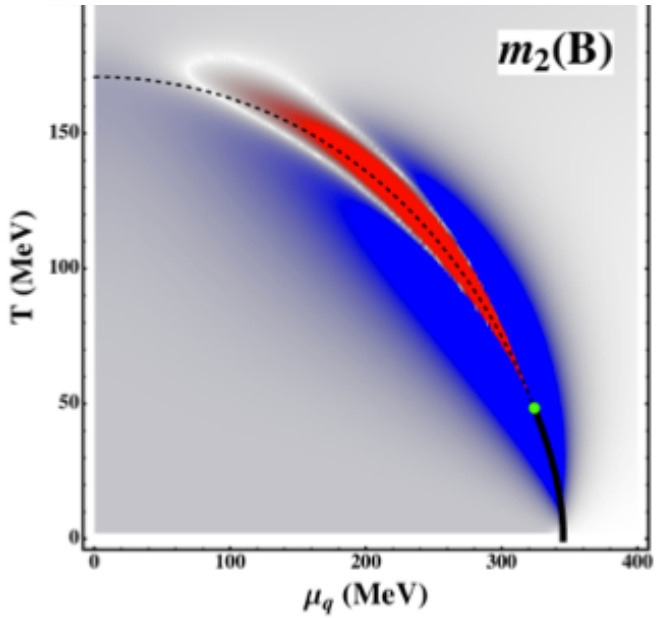


m2 = 4th moment/2nd moment









m2 = 4th moment/2nd moment

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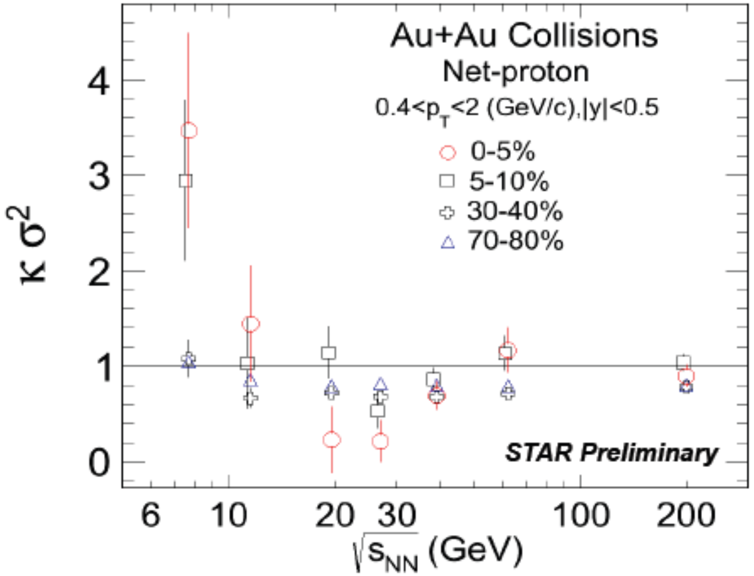

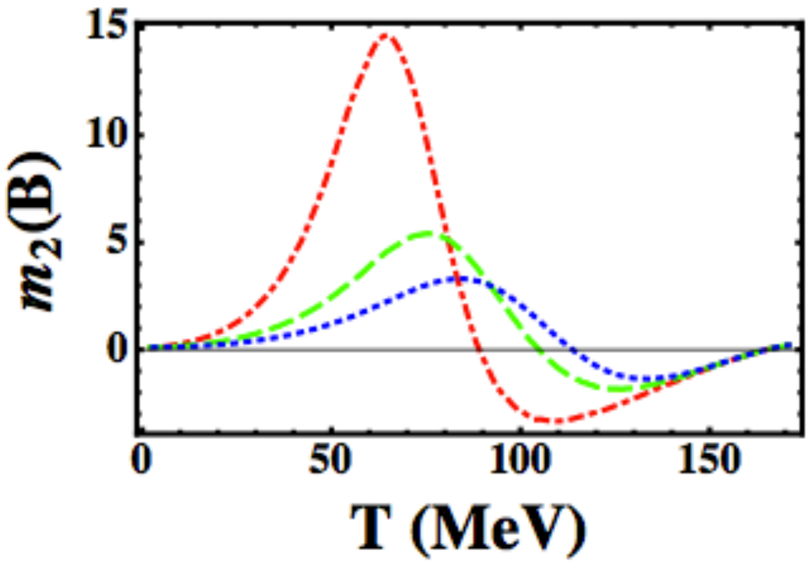

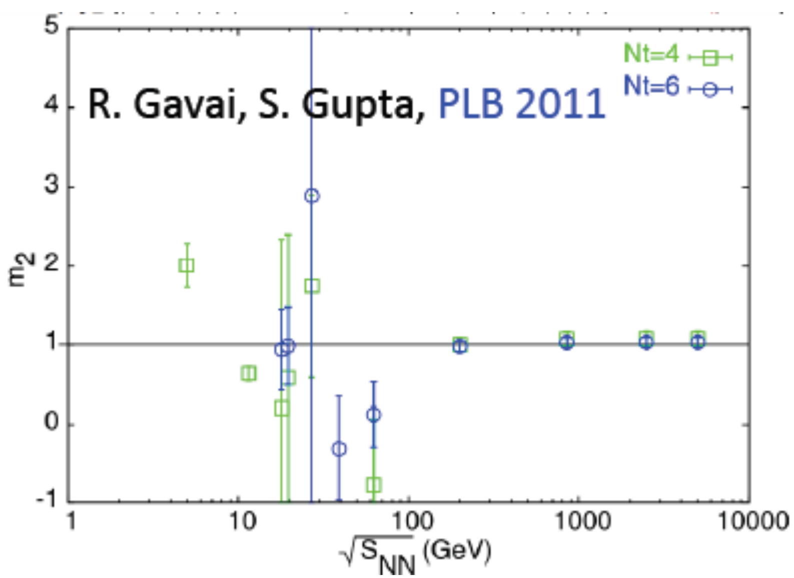

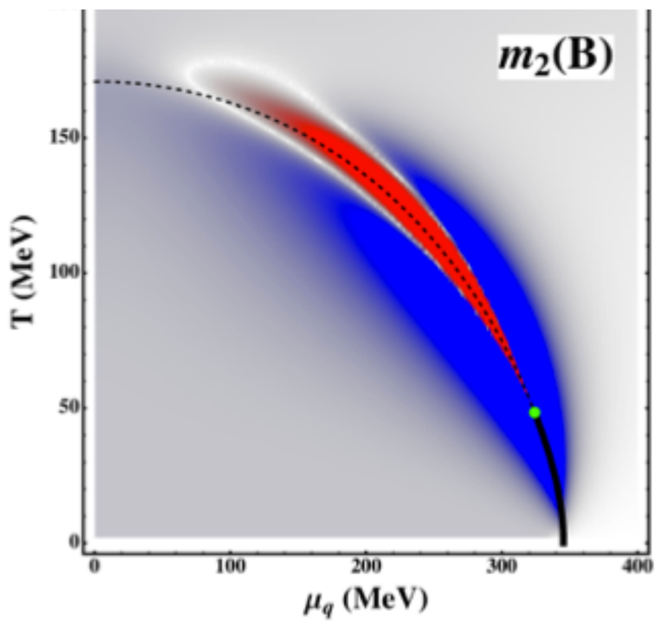

m1 = 3rd moment/2nd moment

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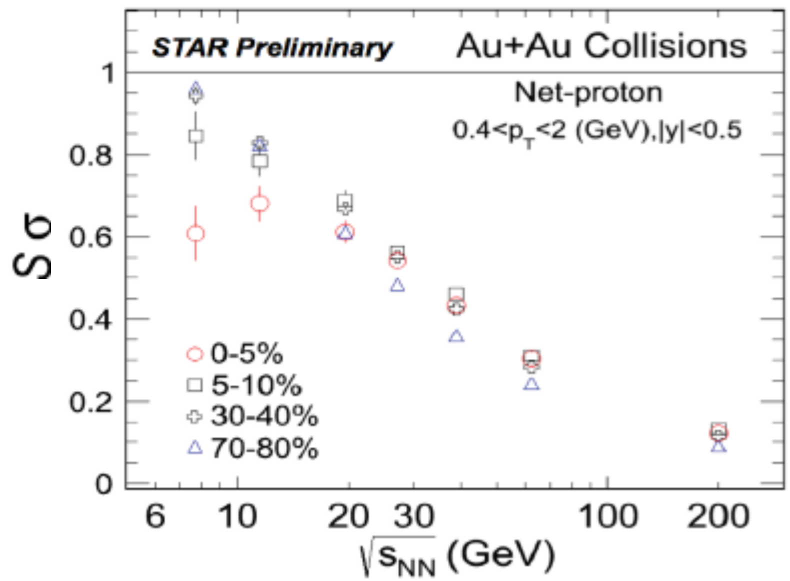
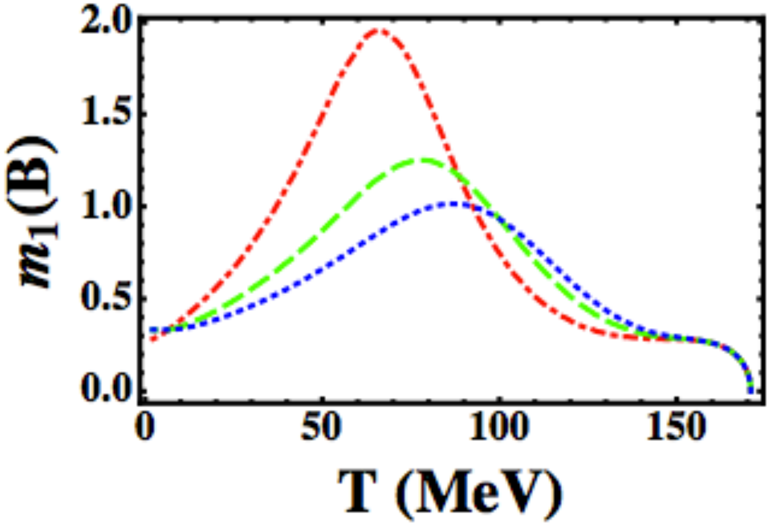
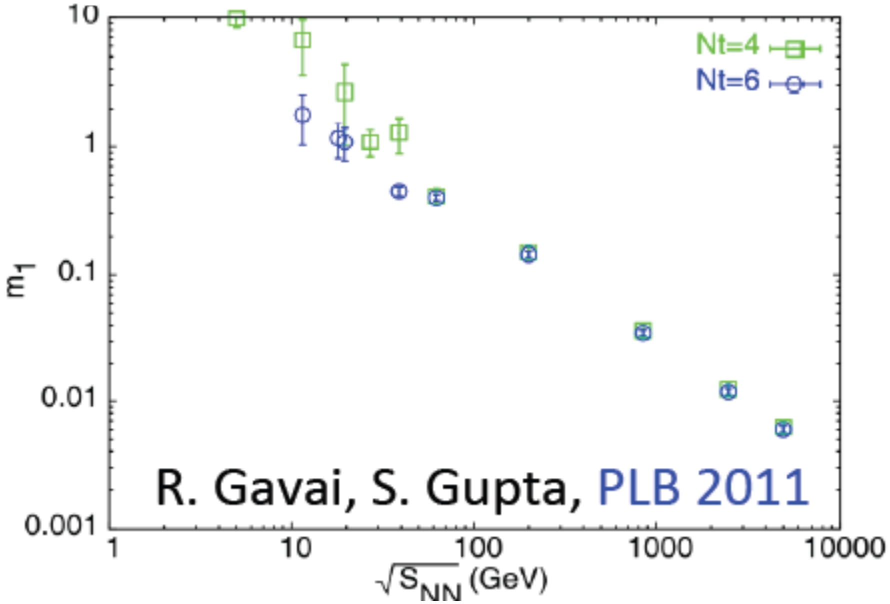
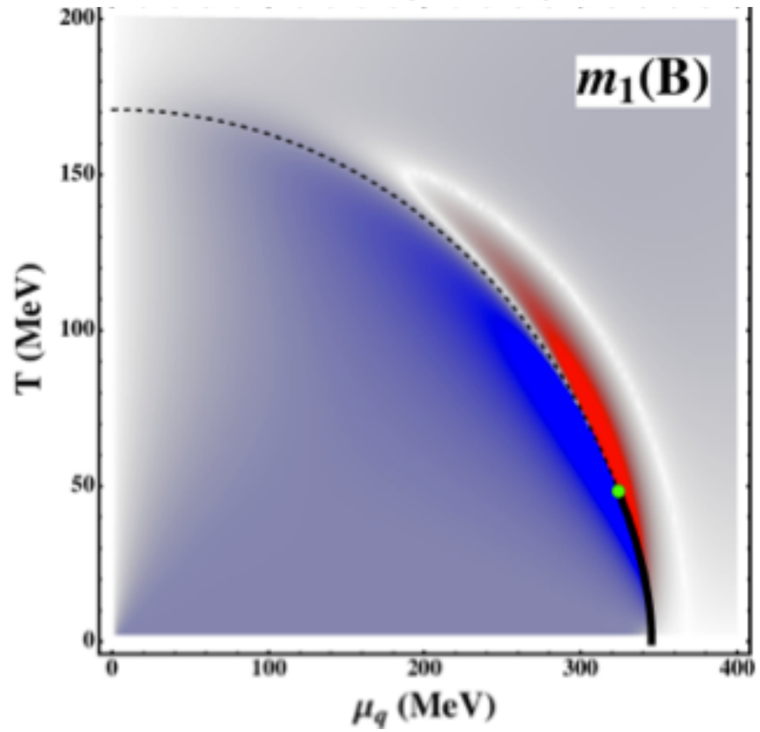
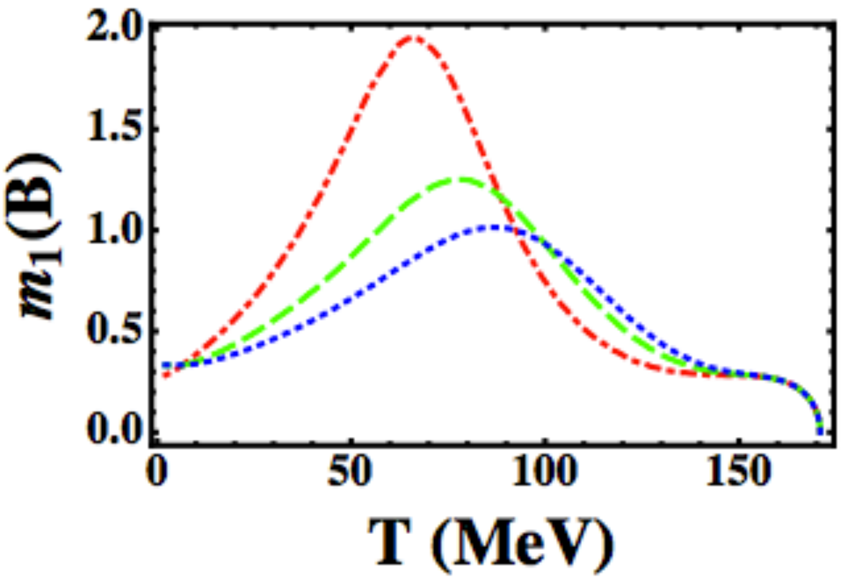




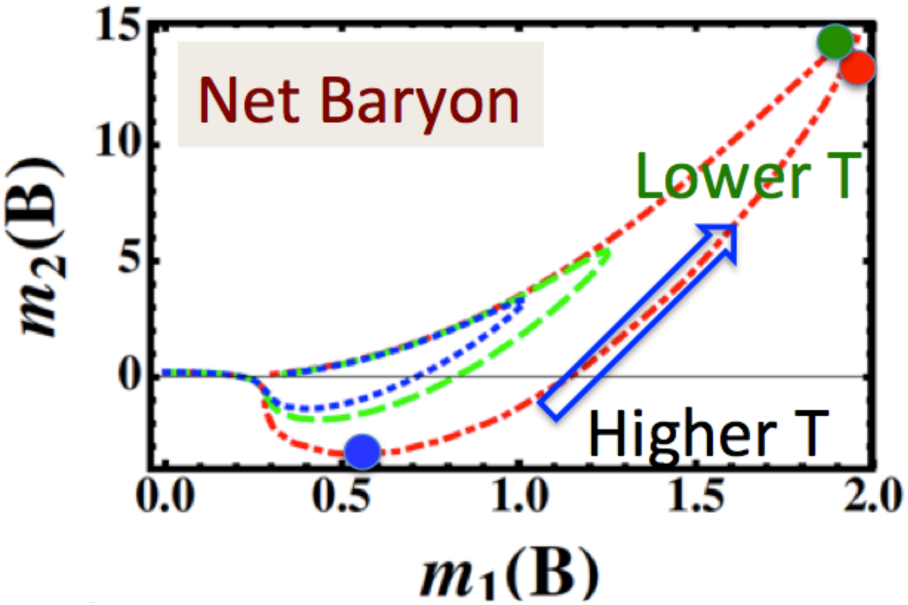




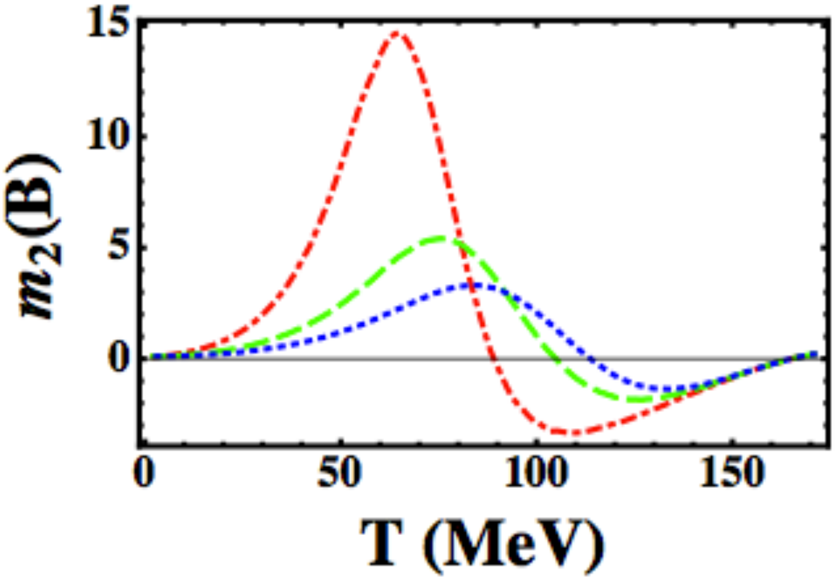
m2 vs m1



2.0
1.5
1.0
0.5
0.0
m_1(B)
0
50
100
150
T (MeV)

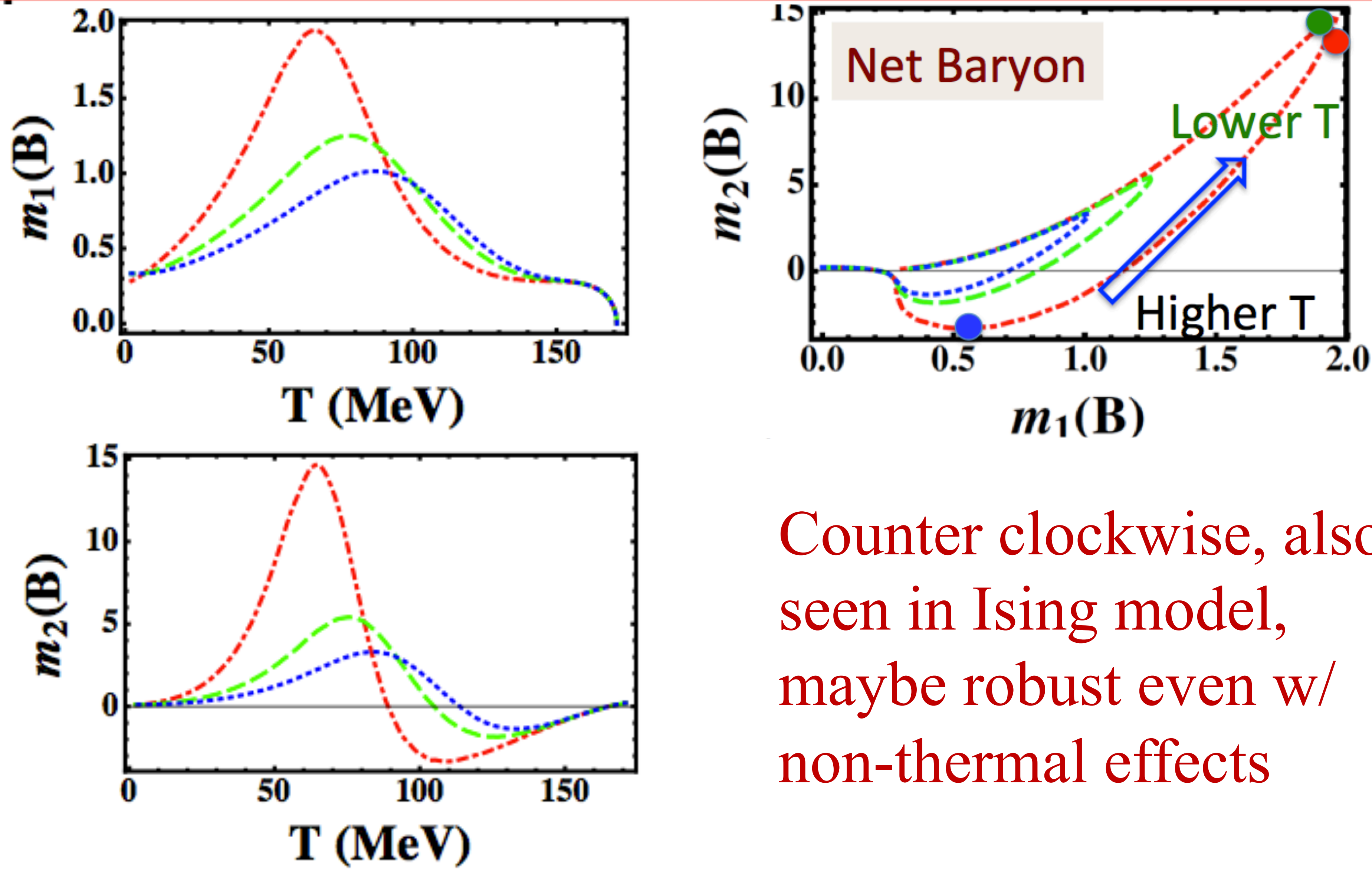


Net Baryon
Lower T
Higher T
15
10
5
0
m_2(B)
0.0
0.5
1.0
1.5
2.0
m_1(B)



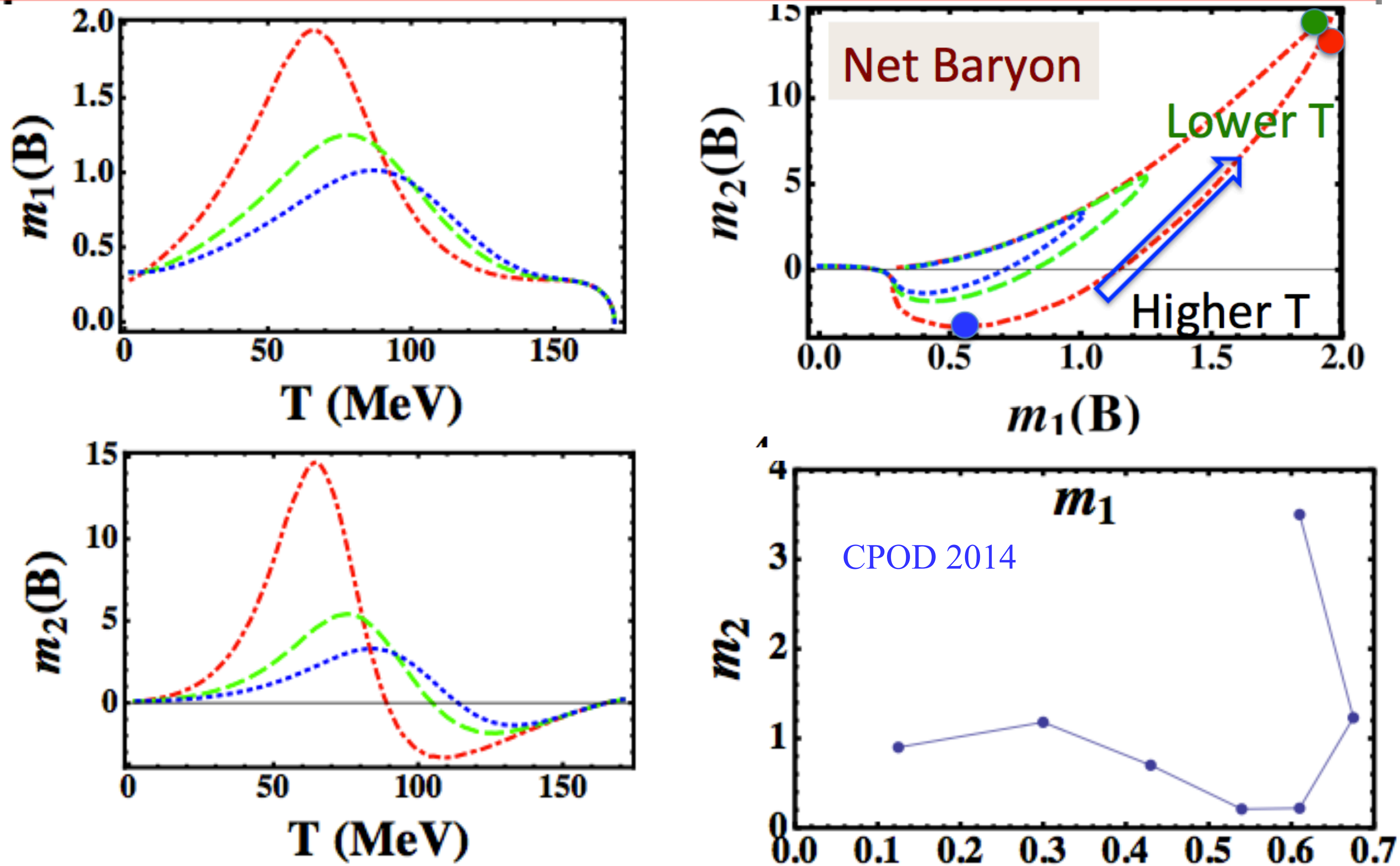
15
10
5
0
m_2(B)
0
50
100
150
T (MeV)

$$\boxed{T_{\min,m_2} > T_{\max,m_1} > T_{\max,m_2} > T_{\rm CEP}}$$



Counter clockwise, also seen in Ising model, maybe robust even w/ non-thermal effects

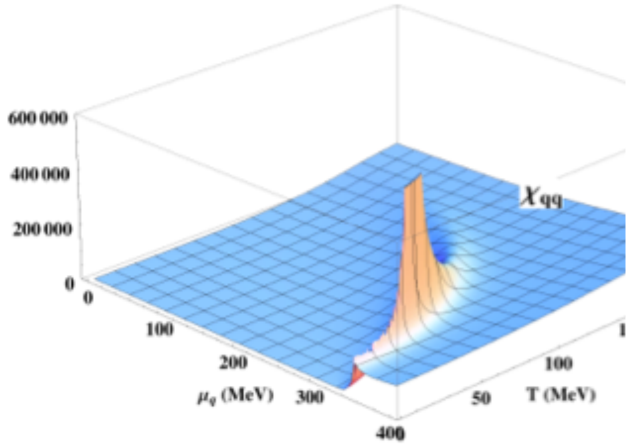
$$\boxed{T_{\min,m_2} > T_{\max,m_1} > T_{\max,m_2} > T_{\mathrm{CEP}}}$$

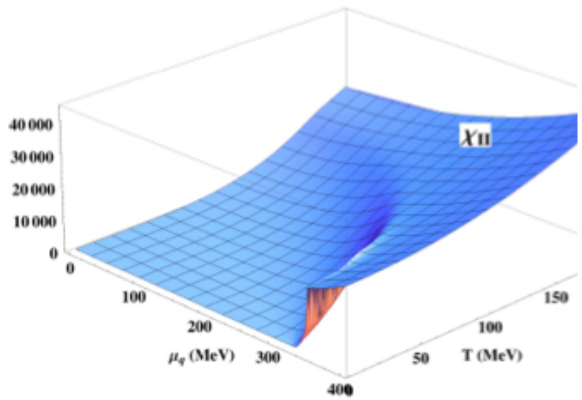


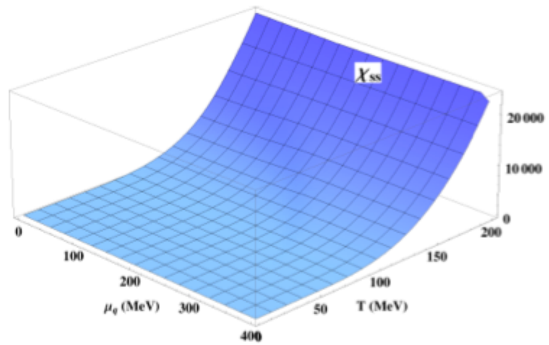
Flavor Dependence

- $\mu_s = \mu_I = 0$, complete set of susceptibilities

$$\chi_{qq}, \chi_{II}, \chi_{ss},$$
$$\chi_q^{(3)}, \chi_{qss}, \chi_{qII},$$
$$\chi_q^{(4)}, \chi_{qqII}, \chi_{qqss}, \chi_I^{(4)}, \chi_{IIss}, \chi_s^{(4)}$$

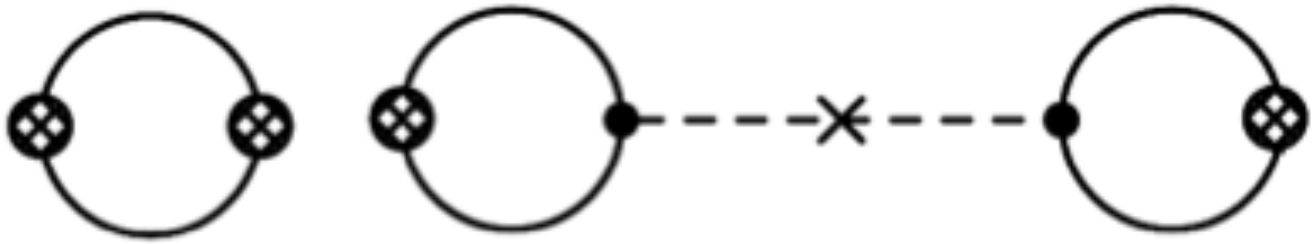


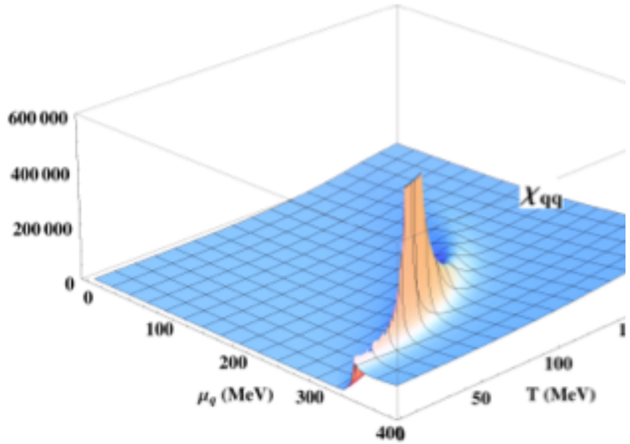


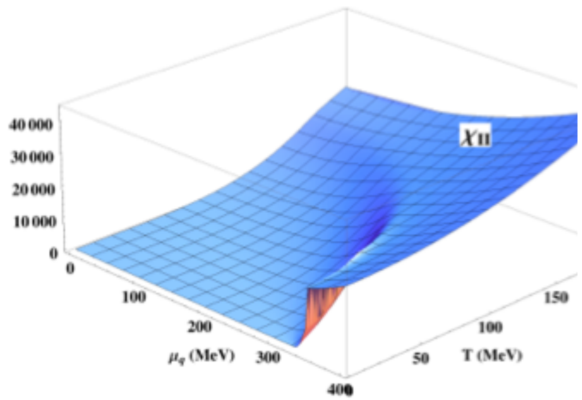


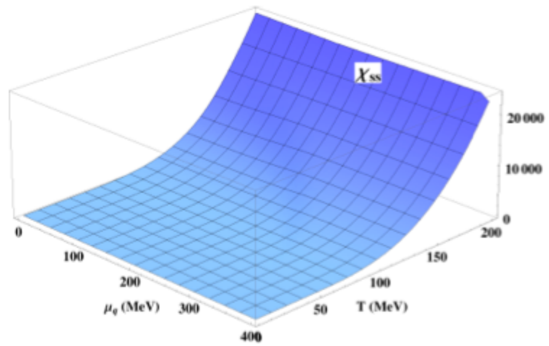
Flavor Dependence

- $\mu_s = \mu_I = 0$



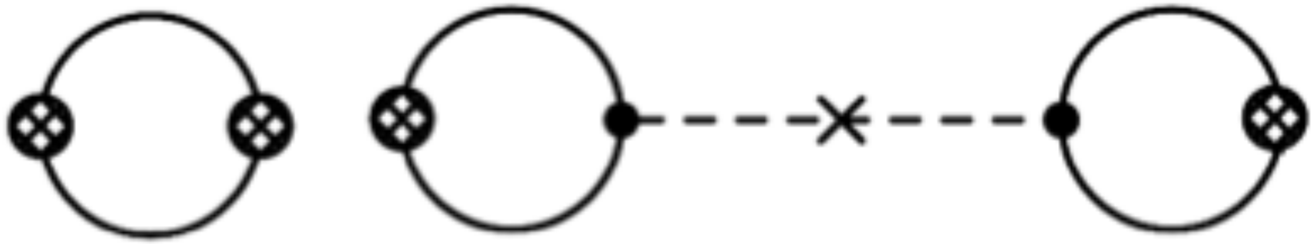




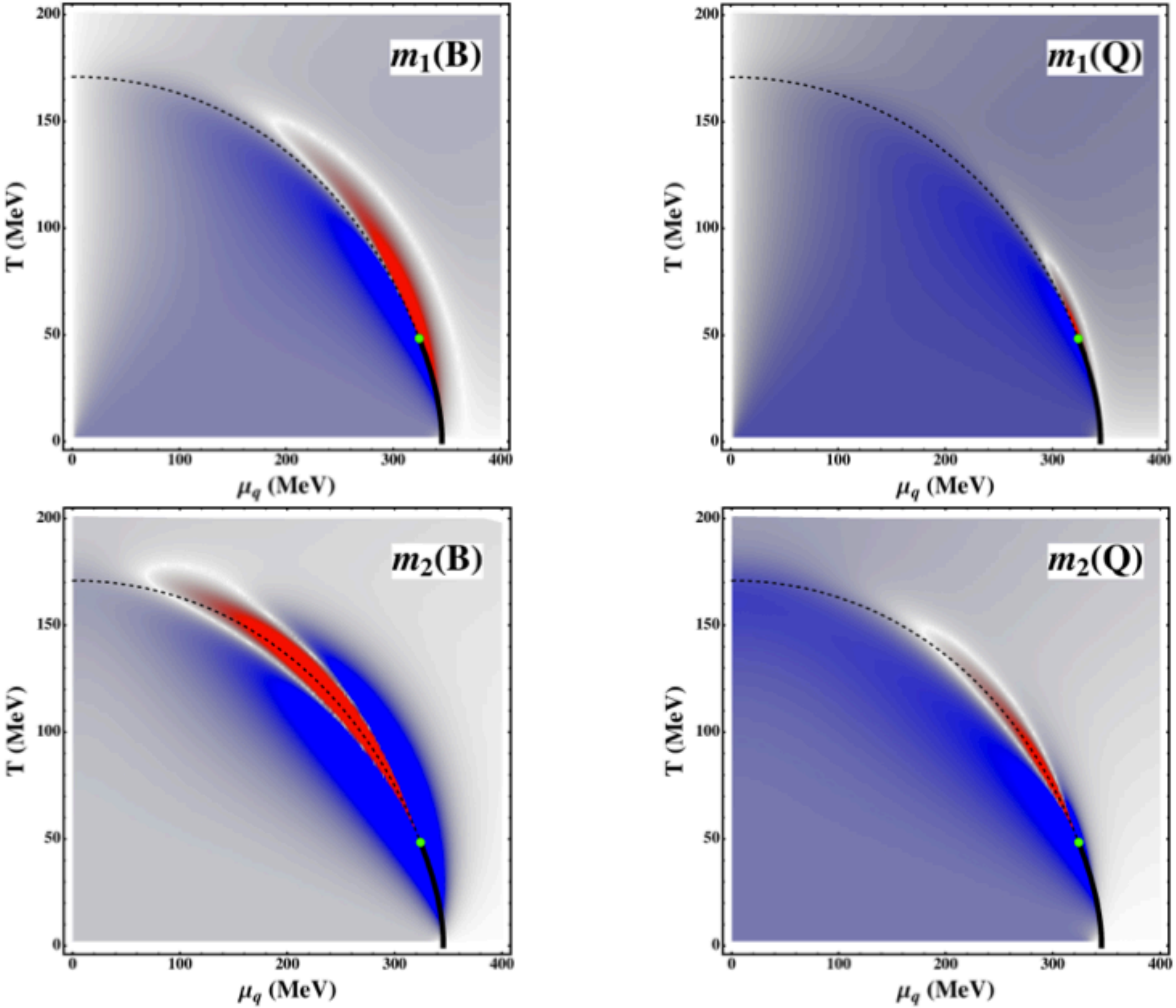


Flavor Dependence

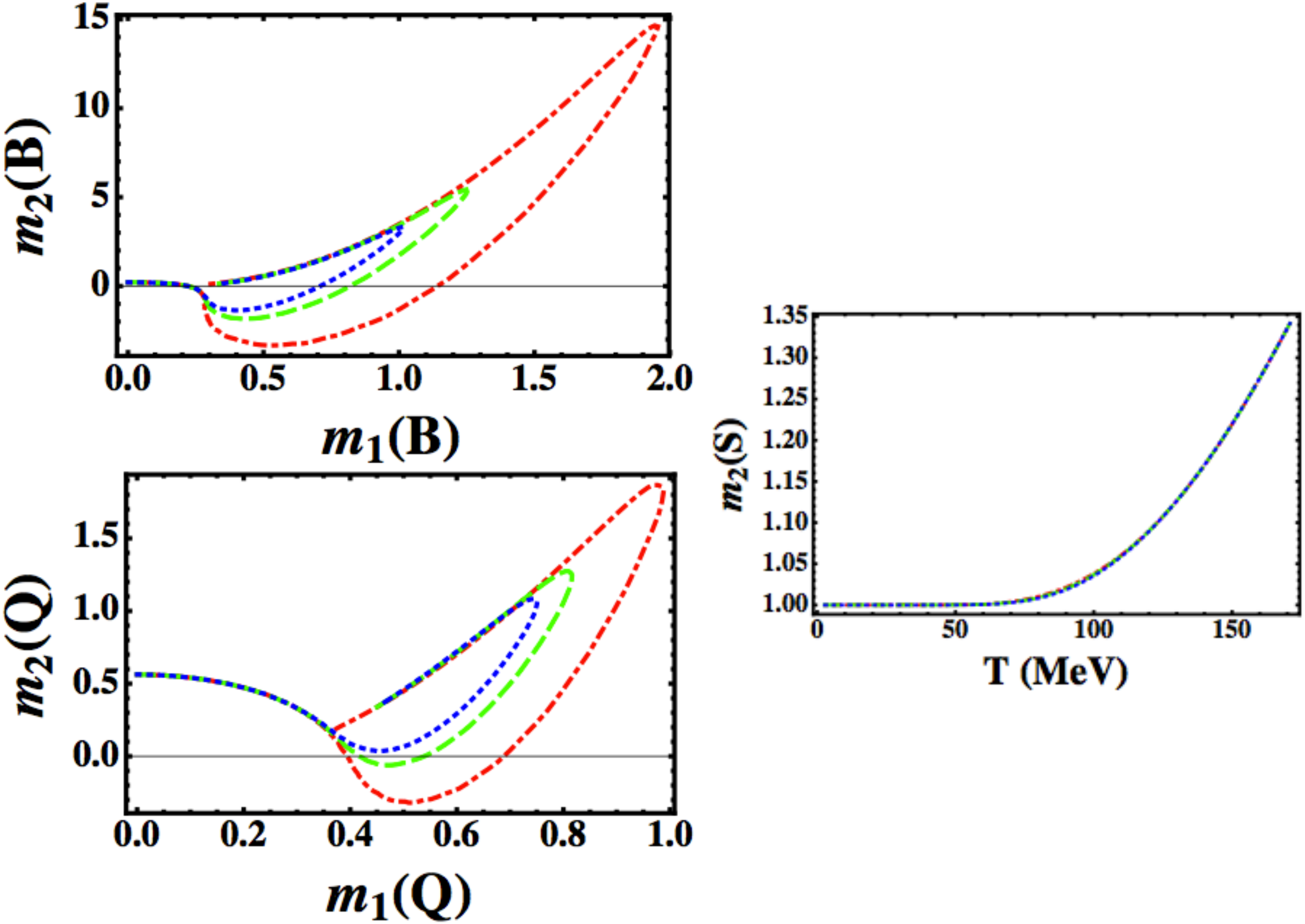
- $\mu_s = \mu_I = 0$



- B, Q, S basis, proton and kaon susceptibilities



m_1(B)
m_1(Q)
m_2(B)
m_2(Q)
T (MeV)
μ_q (MeV)
0
50
100
150
200
0
100
200
300
400

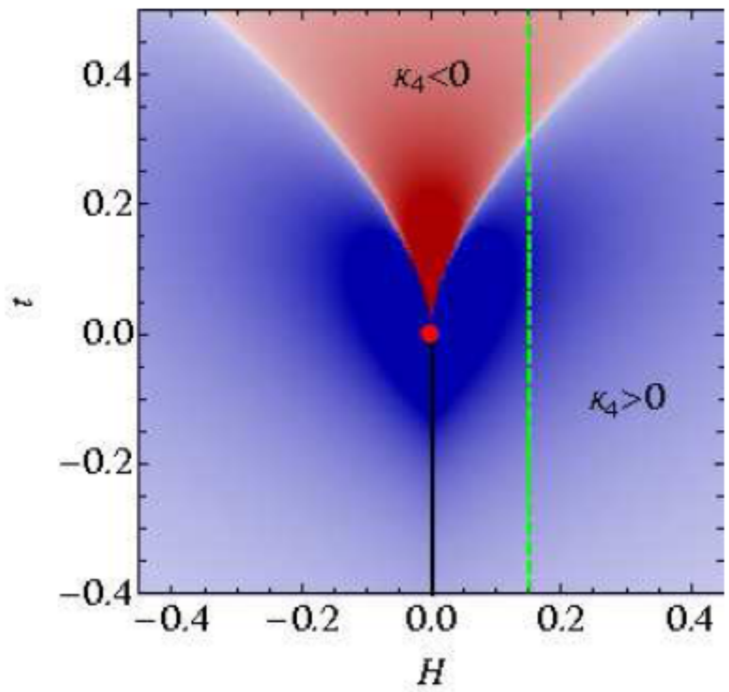


15
10
5
0
m2(B)
0.0
0.5
1.0
1.5
2.0
m1(B)
1.5
1.0
0.5
0.0
m2(Q)
0.0
0.2
0.4
0.6
0.8
1.0
m1(Q)
1.35
1.30
1.25
1.20
1.15
1.10
1.05
1.00
m2(S)
0
50
100
150
T (MeV)

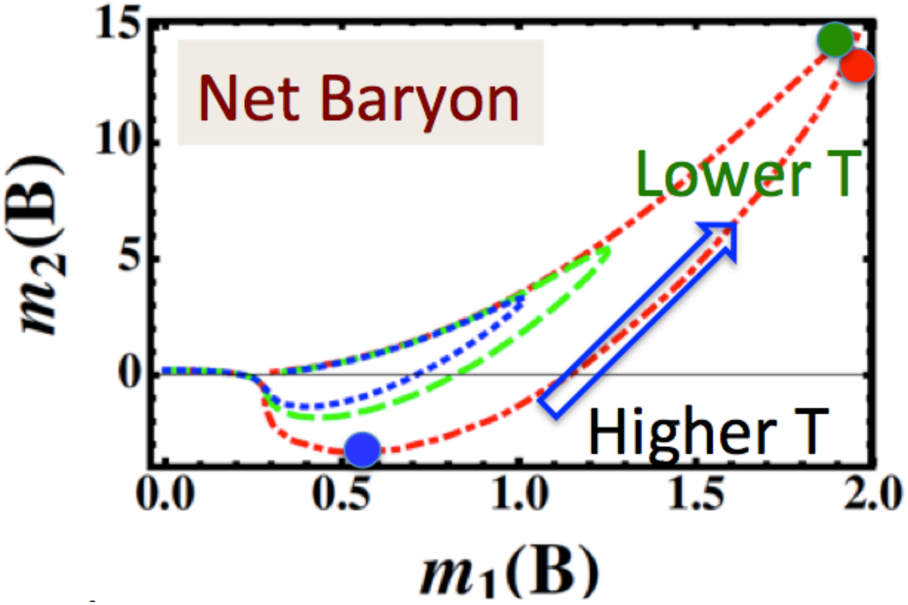
Summary

- It is encouraging to see non-monotonic m1 and m2 at RHIC.

Robust!



Robust?



When the Imaginary is a Real Alternative

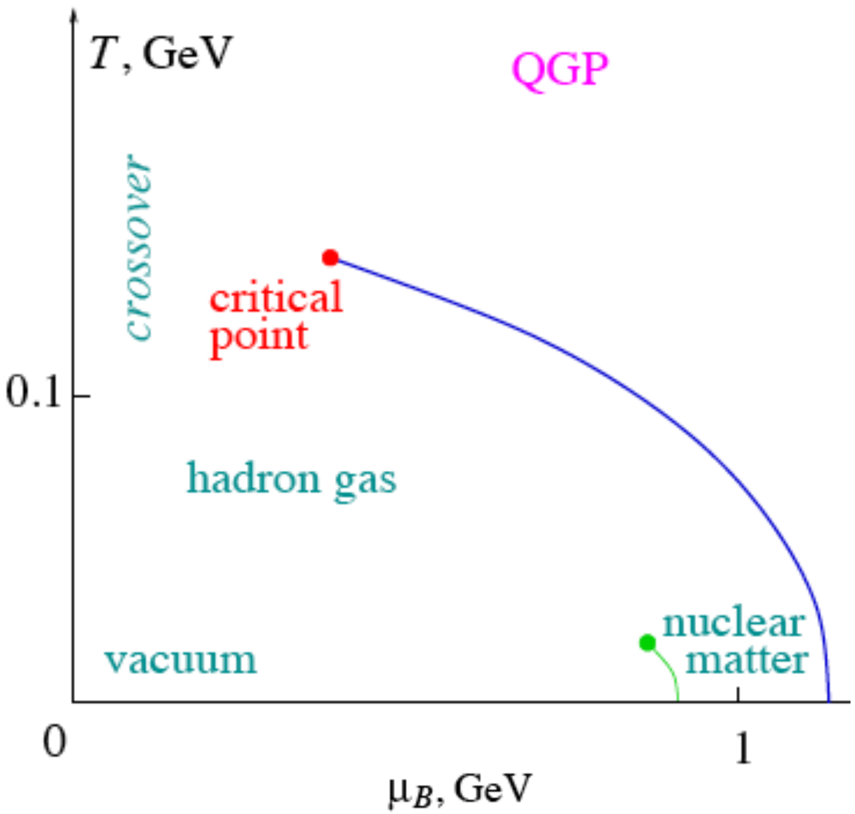
Jiunn-Wei Chen

National Taiwan U.

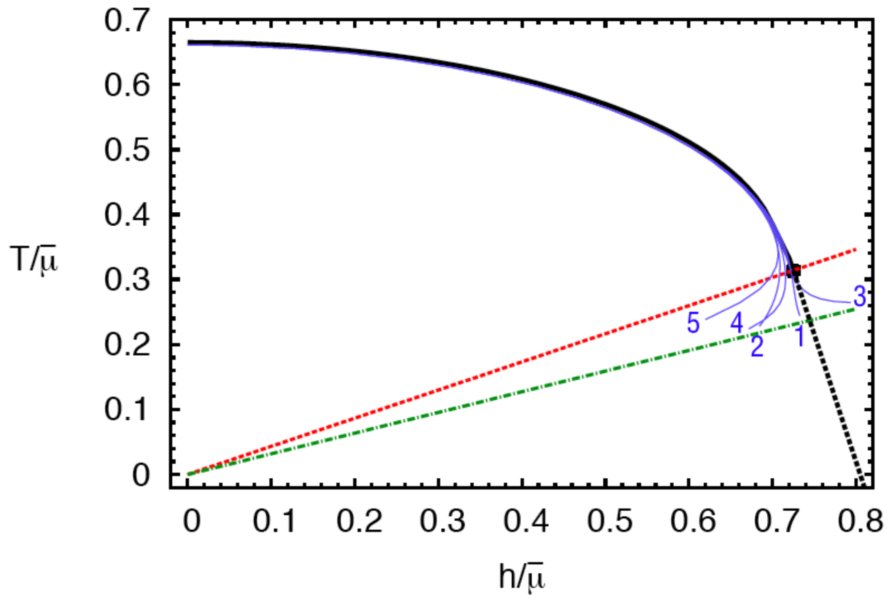
Phys.Rev.Lett. 110 (2013) 262301

Collaborators: Jens Braun, Jian Deng, Joaquin E. Drut, Bengt Friman, Chen-Te Ma, Yu-Dai Tsai

From the hottest to the coolest, and back?



$$h = (\mu_\uparrow - \mu_\downarrow)/2$$
$$\bar{\mu} = (\mu_\uparrow + \mu_\downarrow)/2$$



When Mr. Berry Meets Mr. Wigner

Jiunn-Wei Chen

National Taiwan U.

JWC, Shi Pu, Qun Wang, Xin-Nian Wang

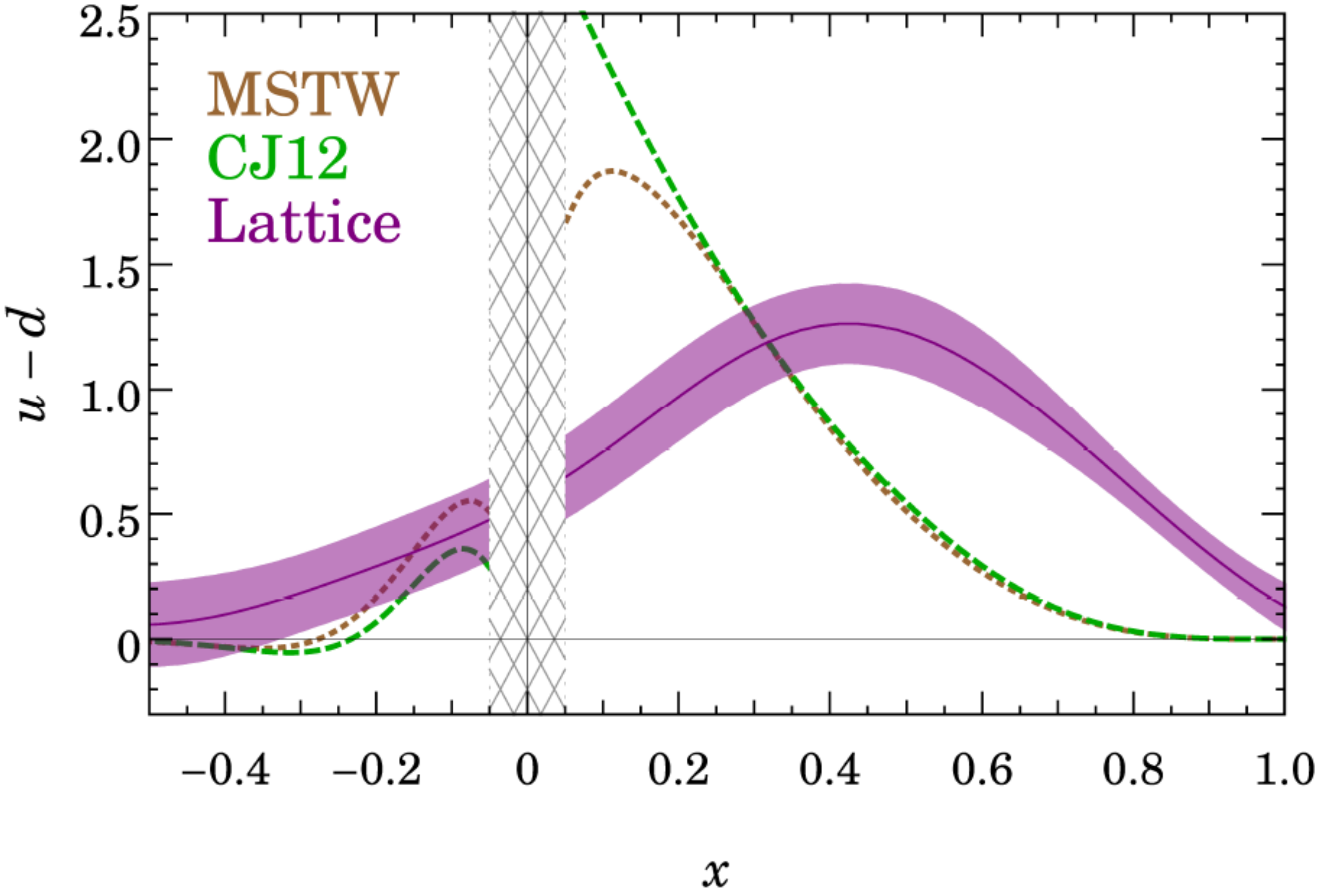
Phys.Rev.Lett. 110 (2013) 262301

Flavor Structure of the Nucleon Sea from Lattice QCD

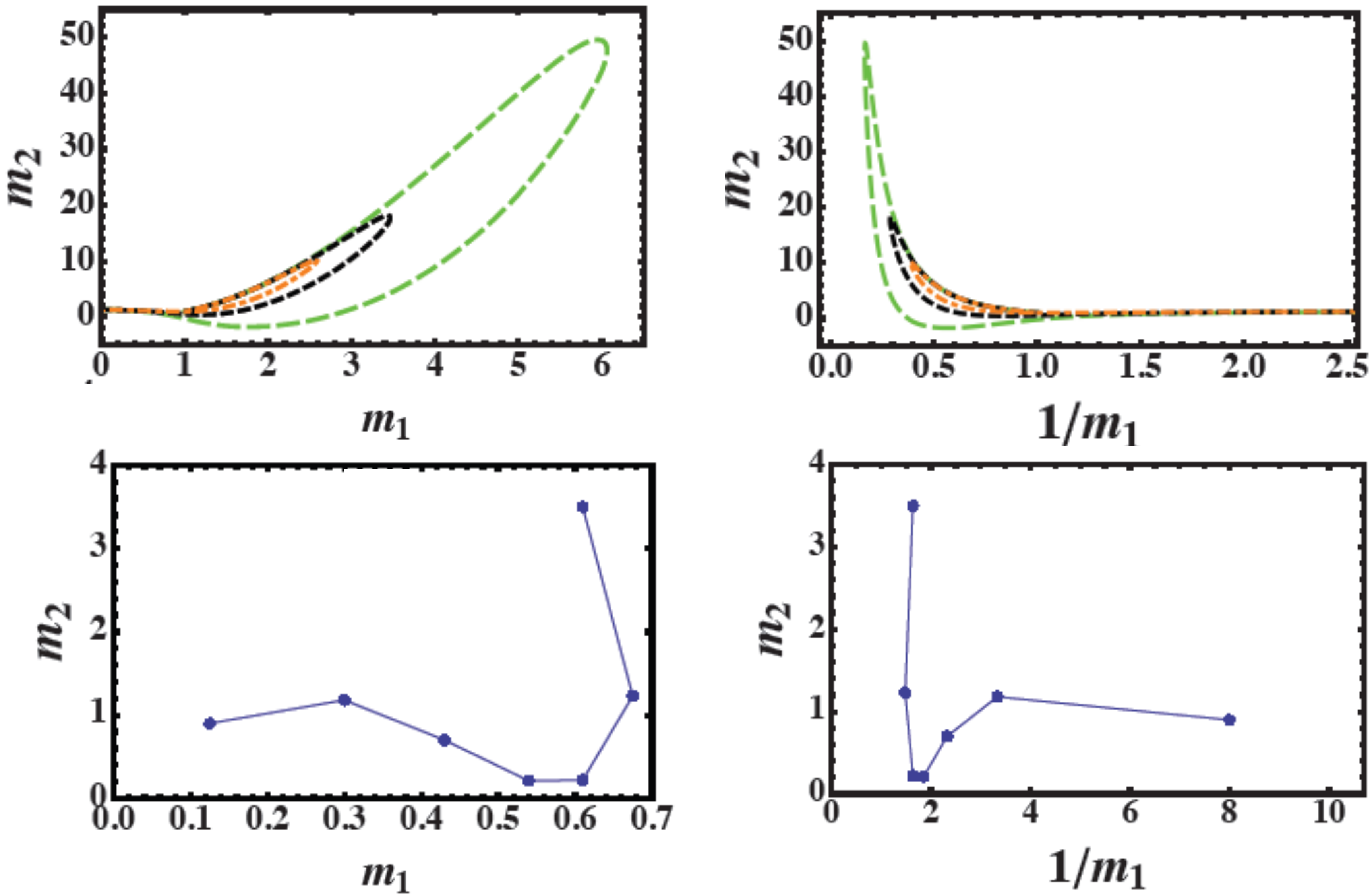
Jiunn-Wei Chen
National Taiwan U.

arXiv:1402.1462 [hep-ph]

Collaborators: Huey-Wen Lin, Saul D. Cohen, Xiangdong Ji


MSTW
CJ12
Lattice
2.5
2.0
1.5
1.0
0.5
0
$u-d$
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1.0
x

Backup slides



m_2
m_1
m_2
$1/m_1$
m_2
m_1
m_2
$1/m_1$

Parton Physics on a Euclidean Lattice
X. Ji, PRL, 2013

$$q(x,\mu^2) = \int \frac{d\xi^-}{4\pi} e^{-ix\xi^- P^+} \langle P|\overline{\psi}(\xi^-)\gamma^+ \times \exp\left(-ig\int_0^{\xi^-} d\eta^- A^+(\eta^-)\right)\psi(0)|P\rangle$$

$$q(x,\mu^2,P^z) = \int \frac{dz}{4\pi} e^{izk^z} \langle P|\overline{\psi}(z)\gamma^z \times \exp\left(-ig\int_0^{z} dz' A^z(z')\right)\psi(0)|P\rangle + \mathcal{O}\left(\Lambda^2/(P^z)^2, M^2/(P^z)^2\right) ,$$