Hybrid Model with the QCD Critical Point

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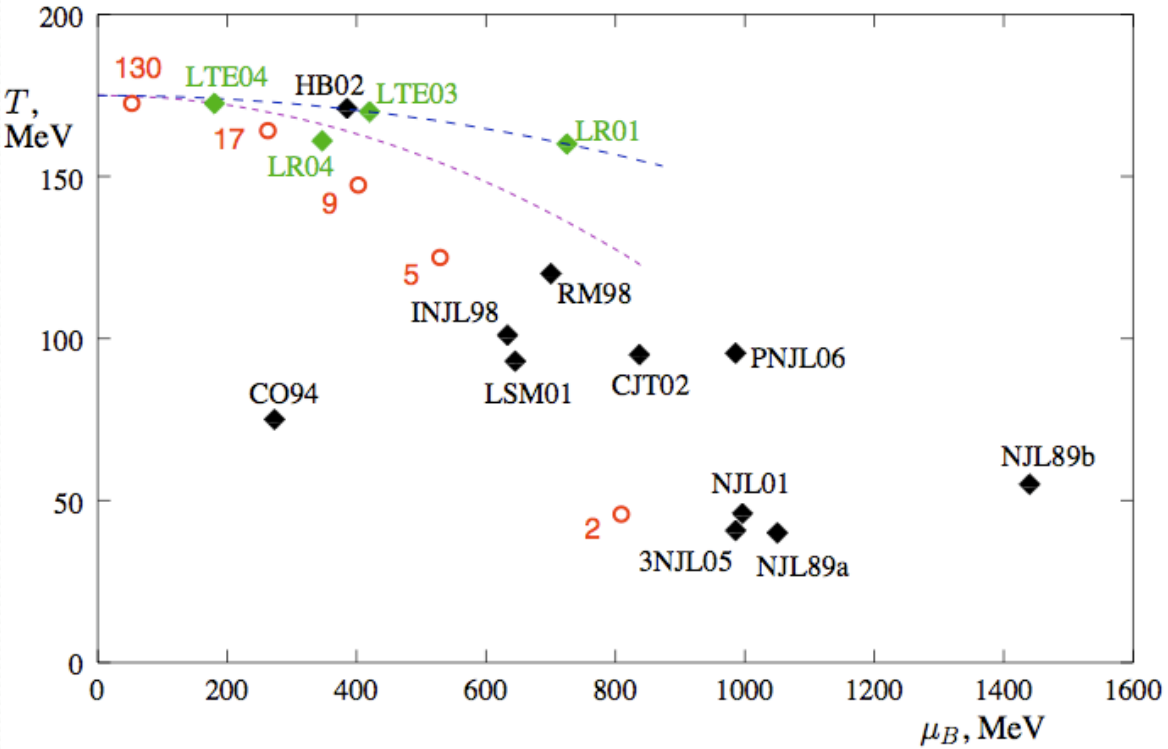
In collaboration with Asakawa, Bass, and Mueller

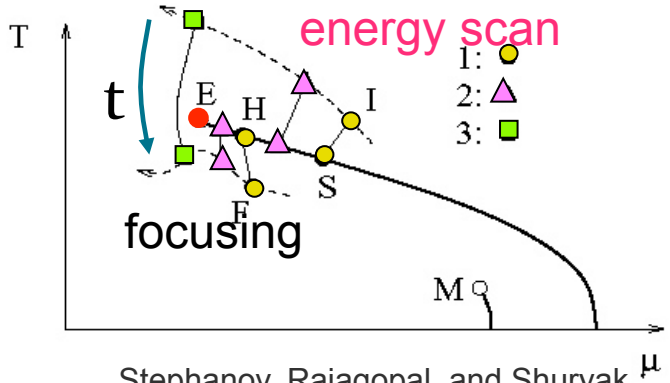
September 17, 2009@ECT*

Where is the QCD Critical Point?

- Lattice QCD, Effective theories....

Stephanov,hep-lat/0701002





Stephanov, Rajagopal, and Shuryak, PRL81 (1998) 4816

- QCP search in heavy ion collisions
  -Energy scan
  -Experiments and phenomenology

Towards Quantitative Analyses

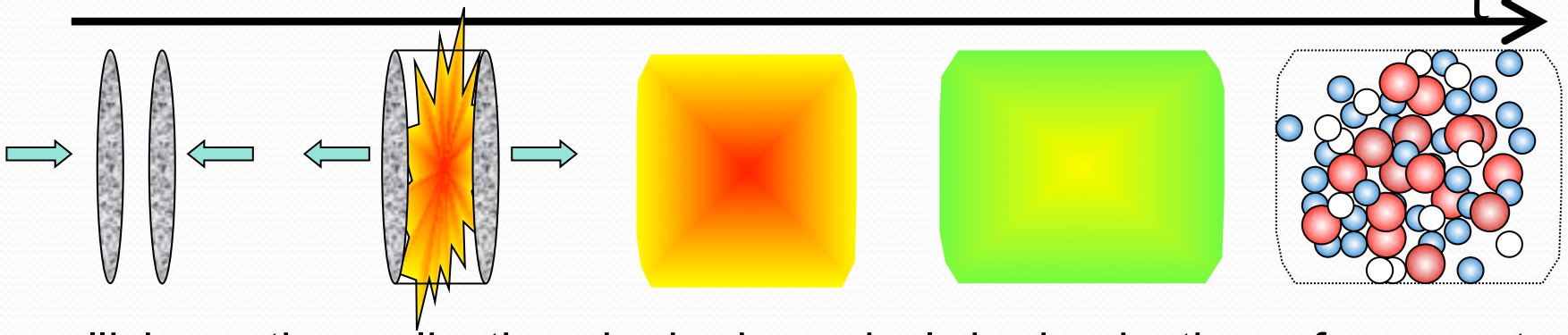
- Realistic dynamical model
  - 3D Hydro + UrQMD (hadron base event generator)
- Equation of state with QCD critical point
- Physical observables

  Signals of QCP should survive after freezeout process.
  - Fluctuations
  - Hadron ratios

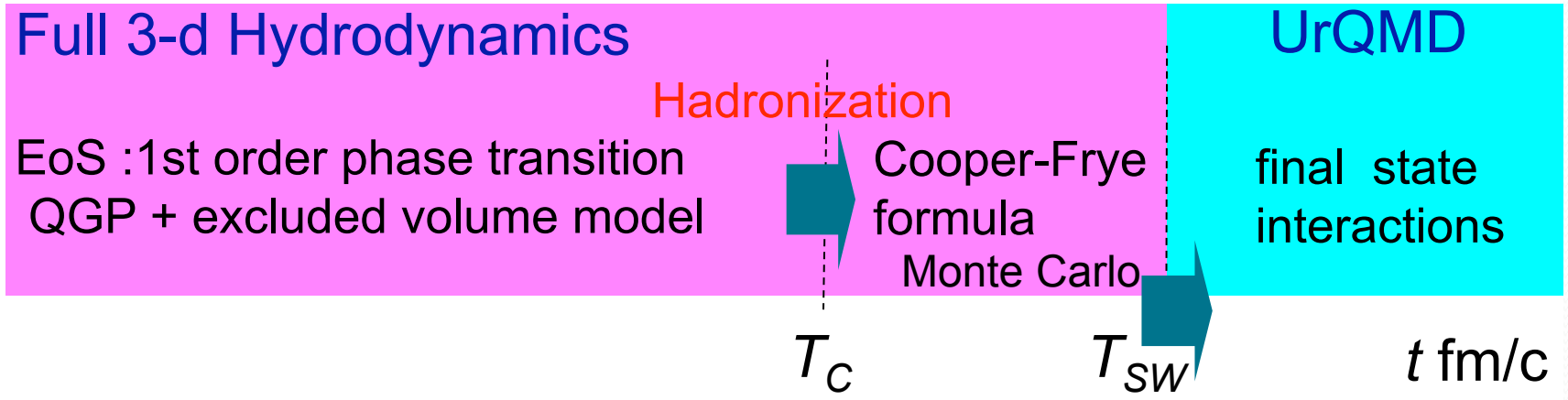
3D Hydro+UrQMD Model

- Schematic sketch

Nonaka and Bass PRC75:014902(2007)



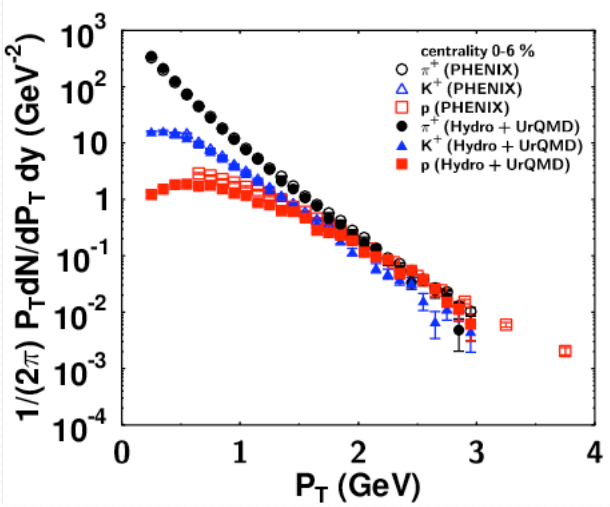
- 3D Hydro + UrQMD

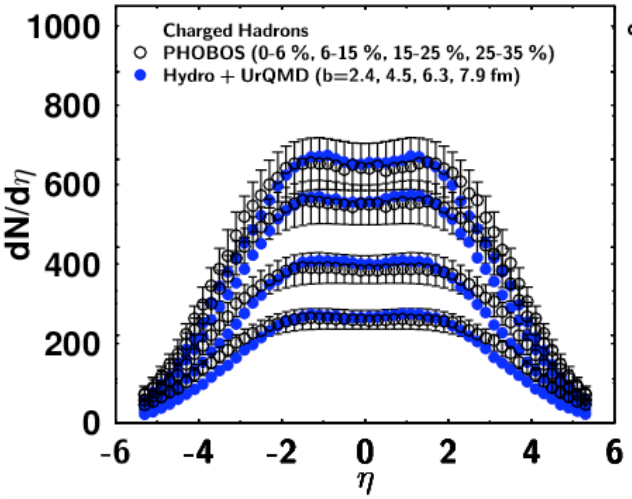


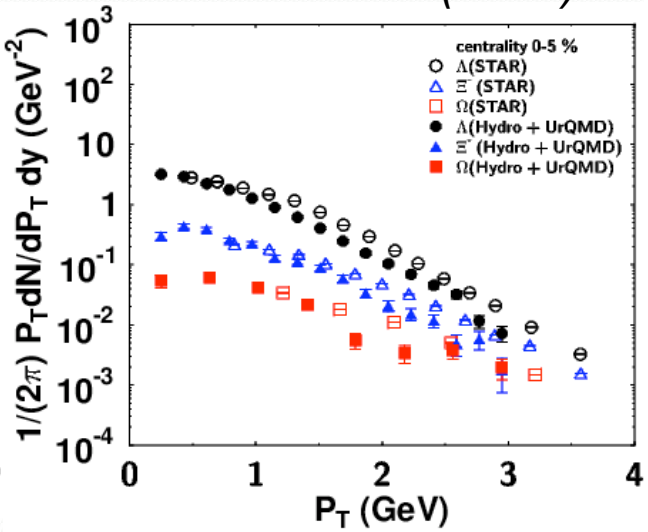
T_C:critical temperature > T_{SW}: Hydro ➔ UrQMD

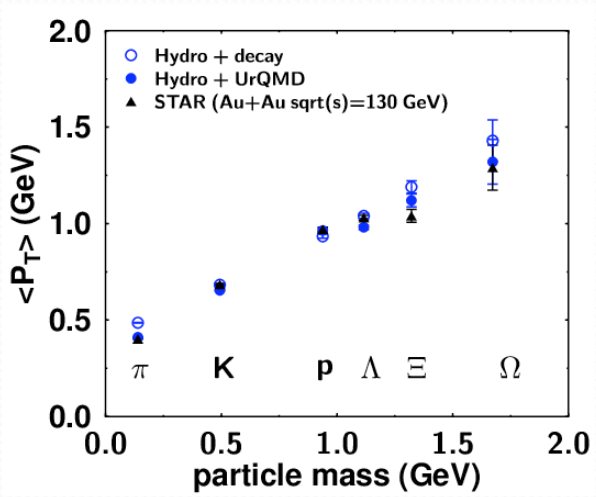
Highlights of 3D Hydro+UrQMD

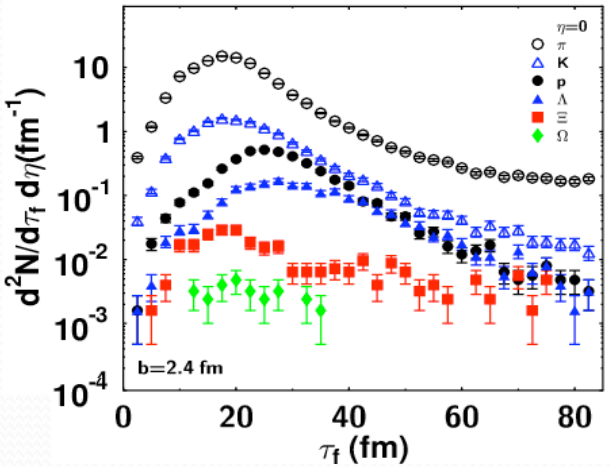
Nonaka and Bass PRC75:014902(2007)

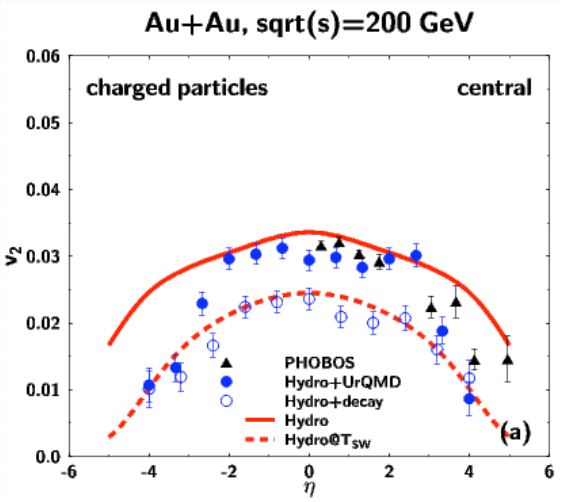












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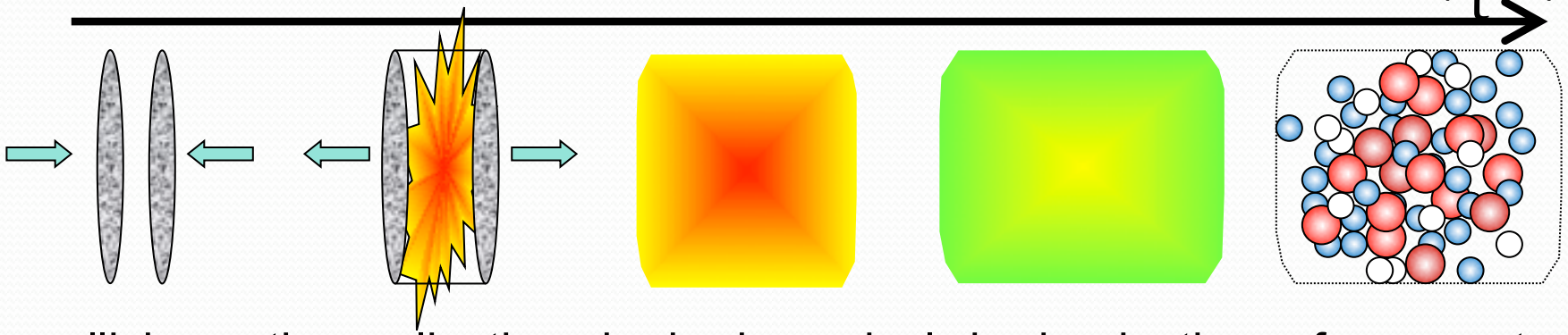
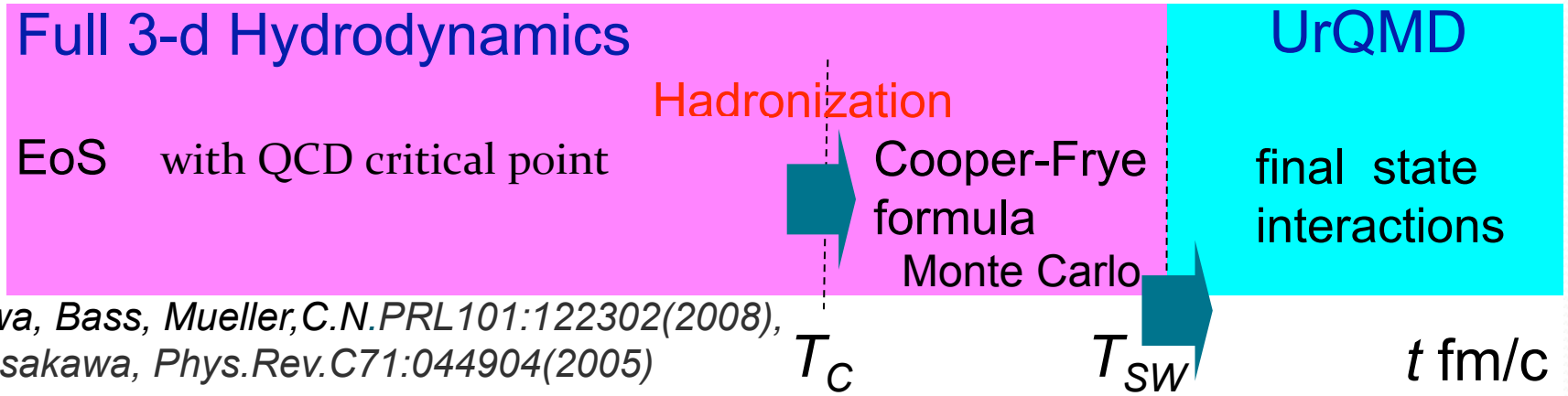
3D Hydro+UrQMD Model

- Schematic sketch

C.N. and Bass PRC75:014902(2007)



- 3D Hydro + UrQMD



Asakawa, Bass, Mueller,C.N.PRL101:122302(2008),
C.N., Asakawa, Phys.Rev.C71:044904(2005)

T_C:critical temperature > T_{SW}: Hydro ➔ UrQMD

EOS with QCD Critical Point

C.N. and Asakawa, PRC71,044904(2005)

- Singular part near QCD critical point + Non-singular part
  - Singular part

3d Ising Model ⟷ QCD

Same Universality Class

$r = \dfrac{T - T_C}{T_C}$

h : extermal magnetic field

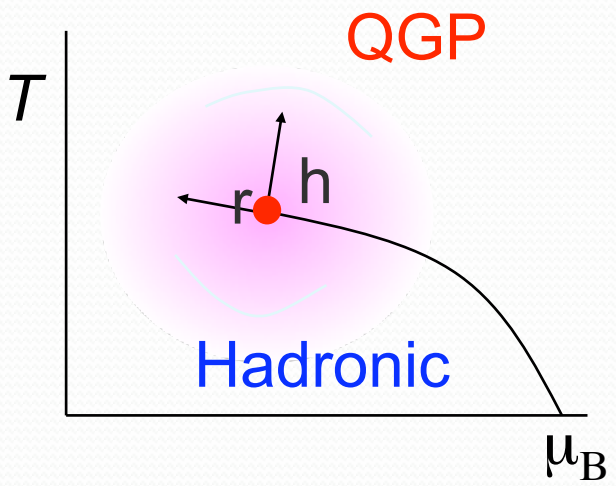
$(r, h) \longleftrightarrow (T, \mu_B)$

T , μ_B

- Mapping : (r, h) 3-d Ising Model

↓

(T, μ_B) QCD



EOS of 3-d Ising Model

- Parametric Representation of EOS

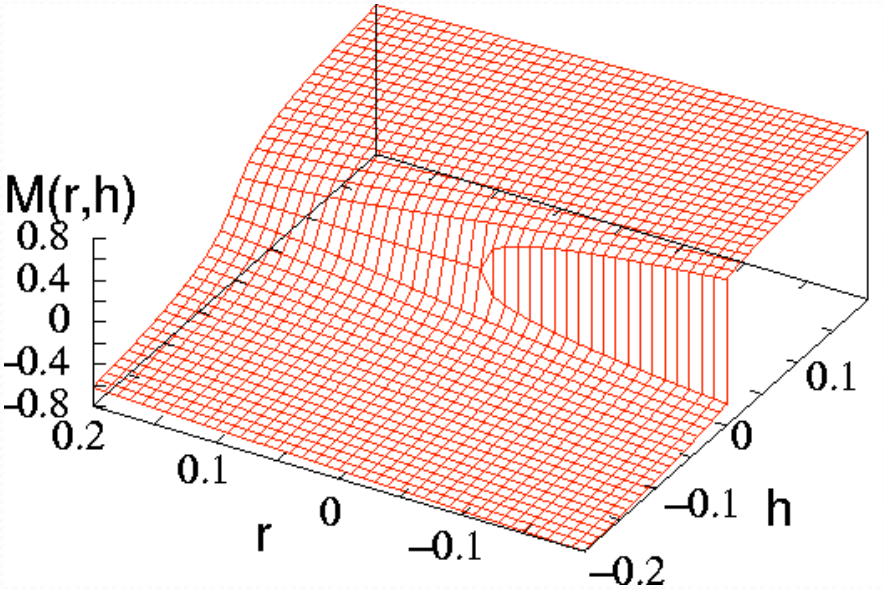
$$\begin{cases} M = M_0 R^{\beta}\theta \\ h = h_0 R^{\beta}\tilde{h}(\theta) = hR_0^{\beta\delta}(\theta - 0.76201\theta^3 + 0.00804\theta^5) \\ r = R(1-\theta^2) \qquad (R \geq 0,\ -1.154 \leq \theta \leq 1.154) \end{cases}$$

$$r = \frac{T - T_C}{T_C}$$

h : external magnetic field

$$\beta = 0.326$$

$$\delta = 4.8$$

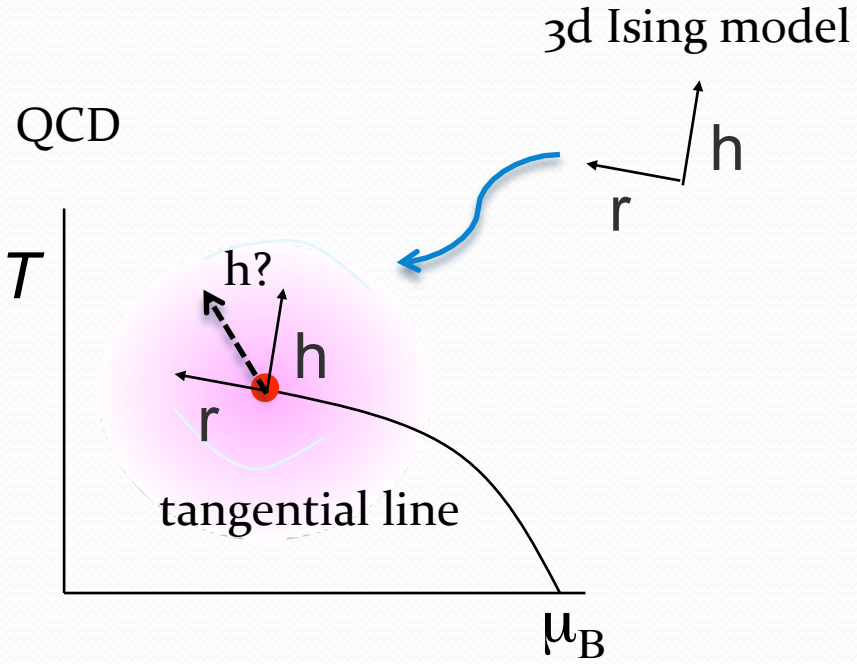


Guida and Zinn-Justin NPB486(97)626

Mapping : 3D Ising Model ➔ QCD

No Universality

- h axis ?



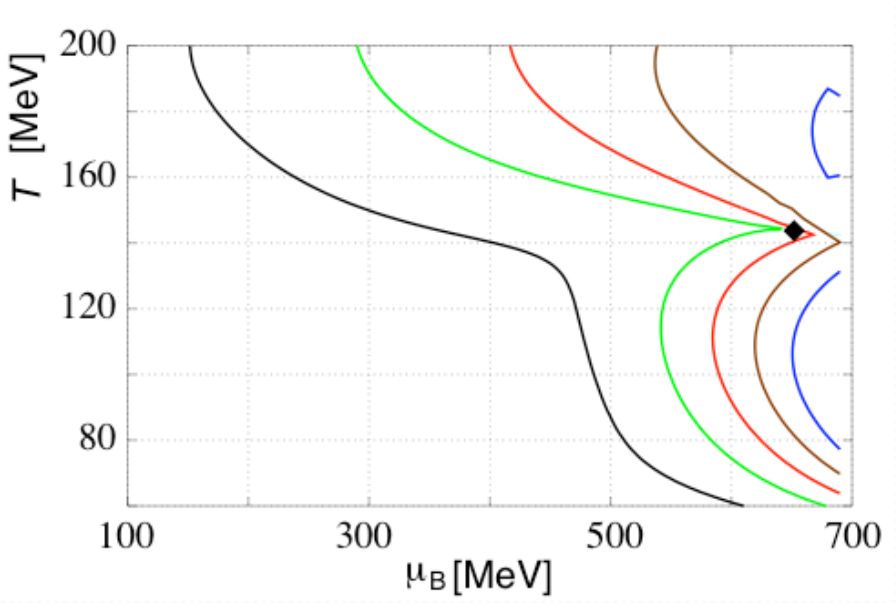
- Critical Region?
  - Lattice QCD
  - Effective theory
  - Experiments

inputs in our model

Focusing Effect

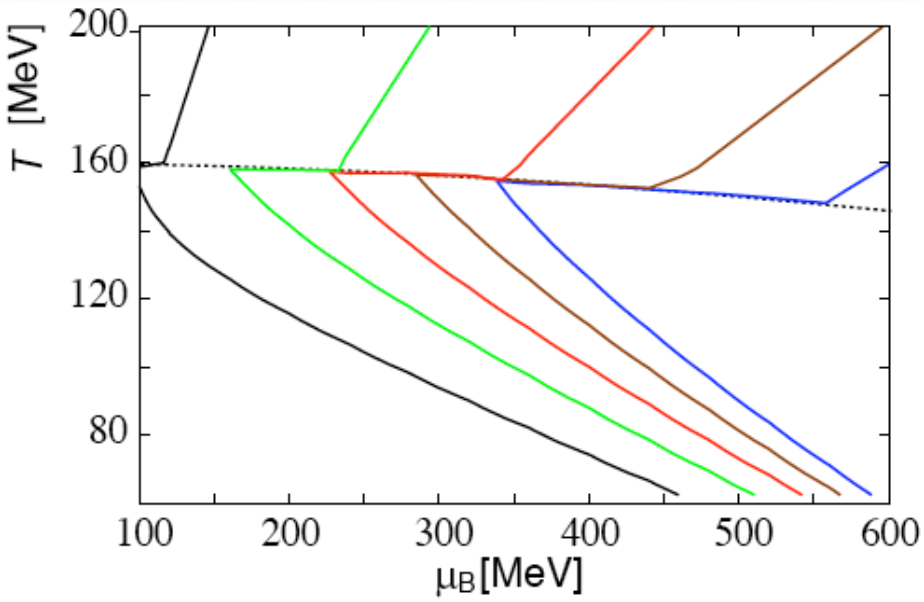
- Isentropic Trajectories on QCD phase diagram

With QCD critical point



Focused

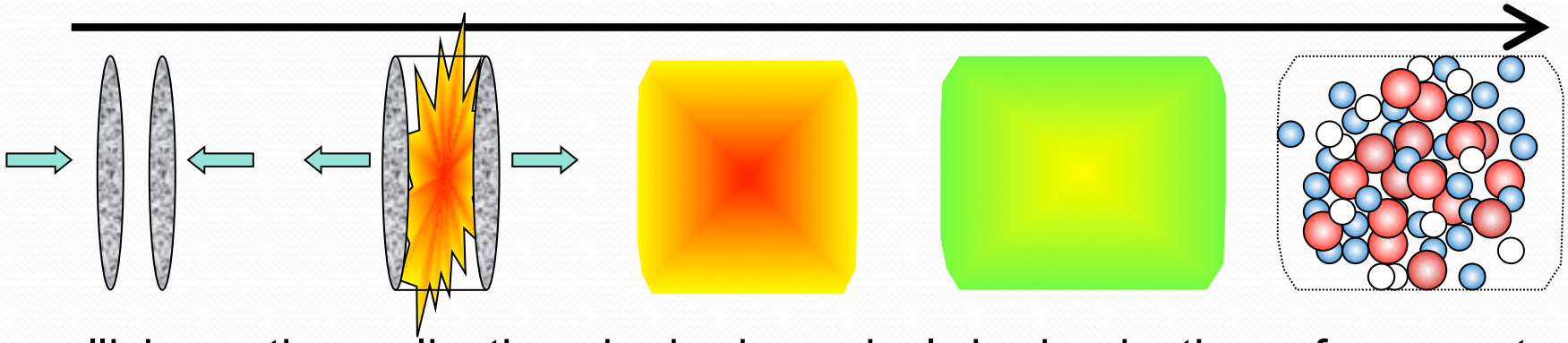
Bag Model +
Excluded Volume Approximation
(No Critical Point)



Not Focused

Signal of QCP

- Signal of QCD critical point should survive even after freezeout process.

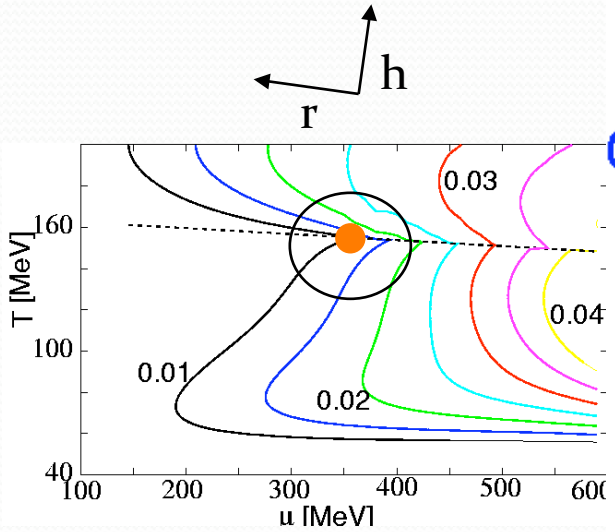


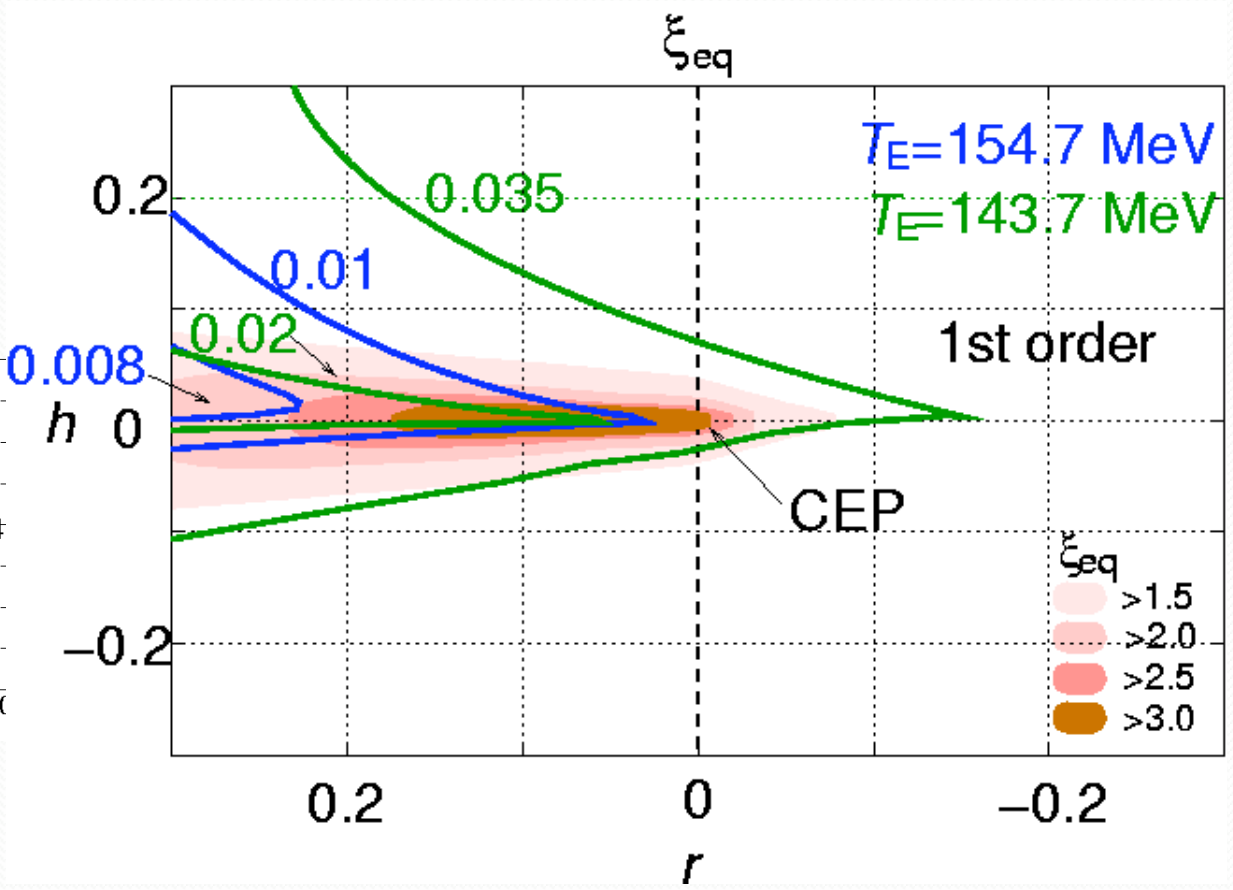
- Fluctuations: conserved values ex. charge, baryon number
- Hadron ratios: fixed at chemical freezeout temperature T_{ch}

Correlation Length

Widom's scaling low

$$\xi_{eq}^2(r,M) = f^2 M^{-2\nu/\beta} g\left(\frac{|r|}{|M|^{1/\beta}}\right)$$





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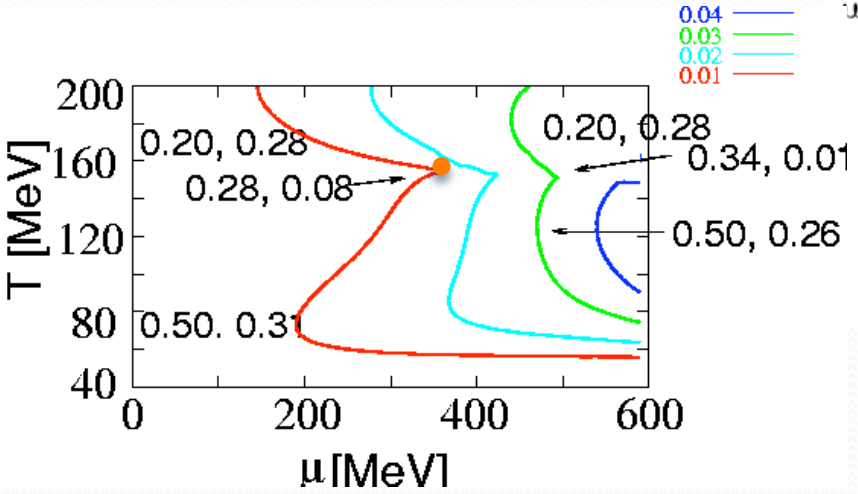
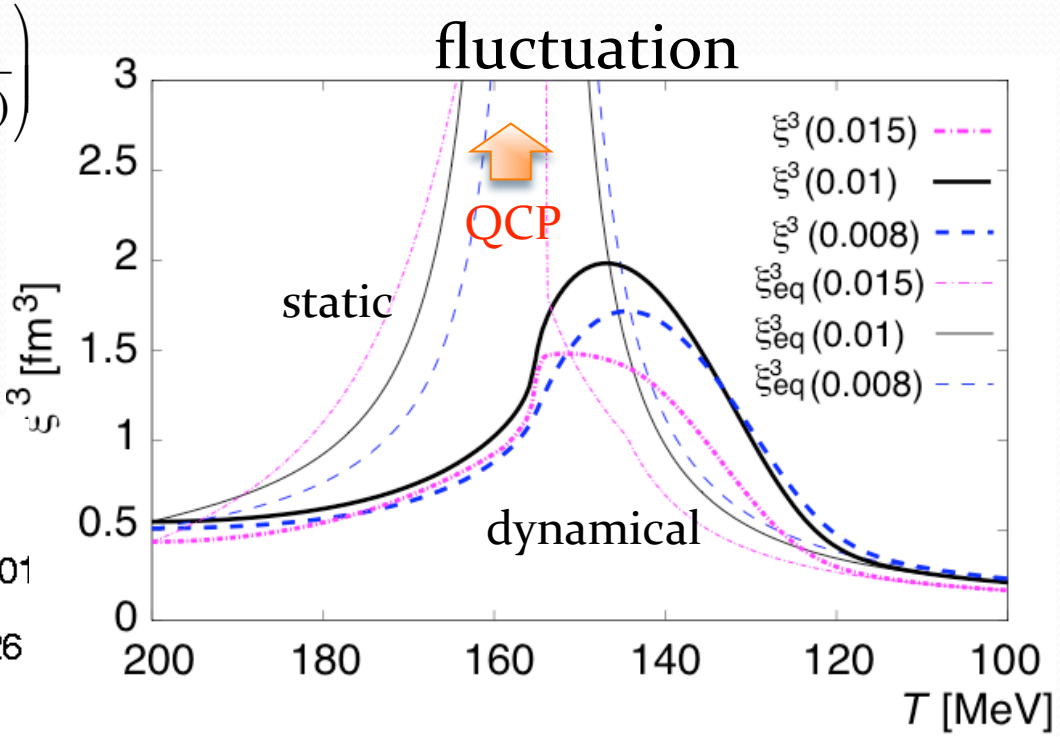
Fluctuation in 1d Hydro.

- $$\frac{d}{d\tau}m_\sigma(\tau) = -\Gamma\left[m_\sigma(\tau)\right]\left(m_\sigma(\tau) - \frac{1}{\xi_{\rm eq}(\tau)}\right)$$

$$\Gamma(m_\sigma) = \frac{a}{\xi_0}(m_\sigma\xi_0)^z, \quad m_\sigma(\tau) = 1/\xi(\tau)$$

$z = 3.0$ Model H
(Halperin RMP49(77)435)





- critical slowing down
- evolution rate

fluctuation : clear signal?

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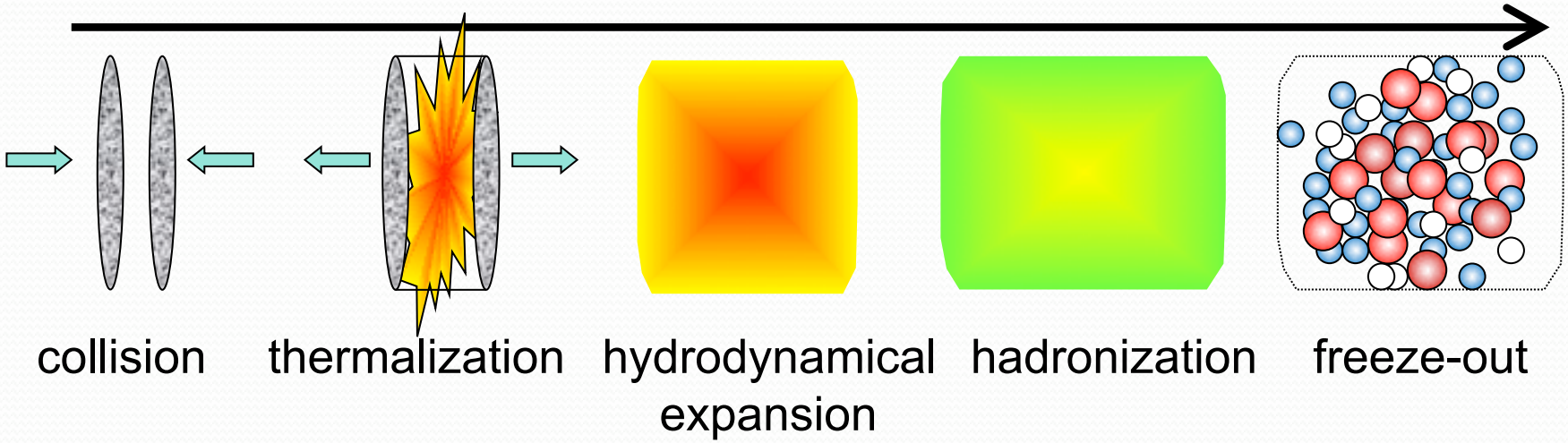
Signal of QCP

- Signal of QCD critical point should survive even after freezeout process.

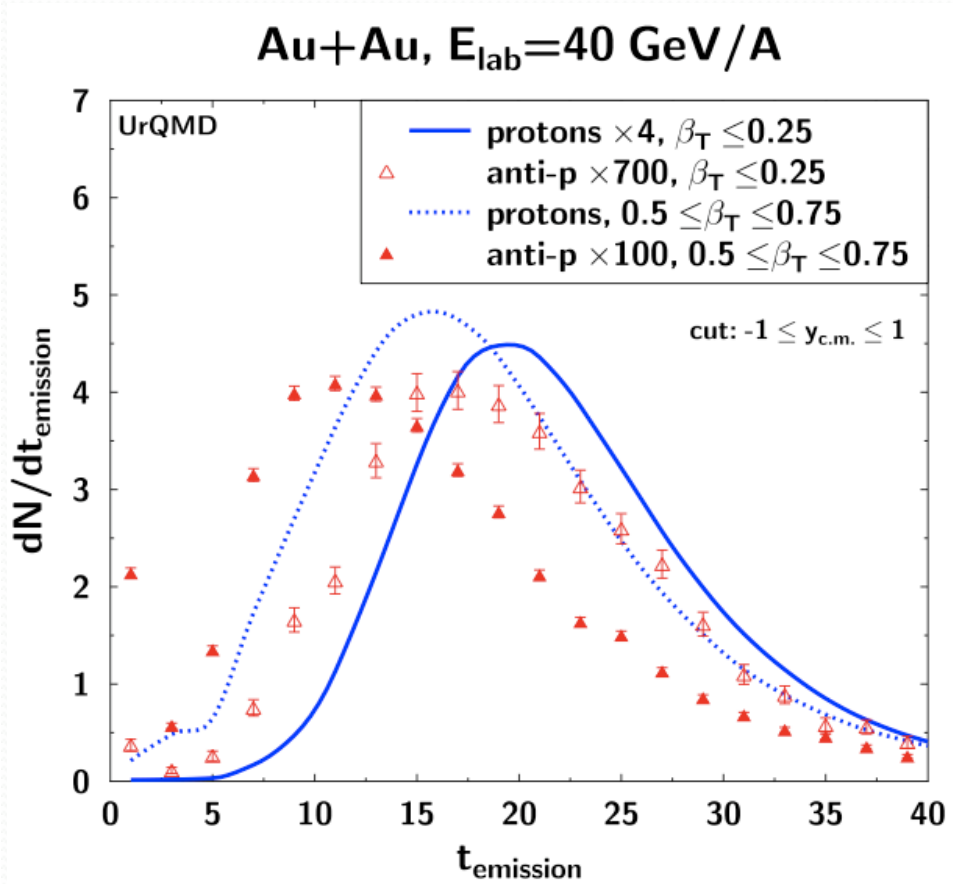


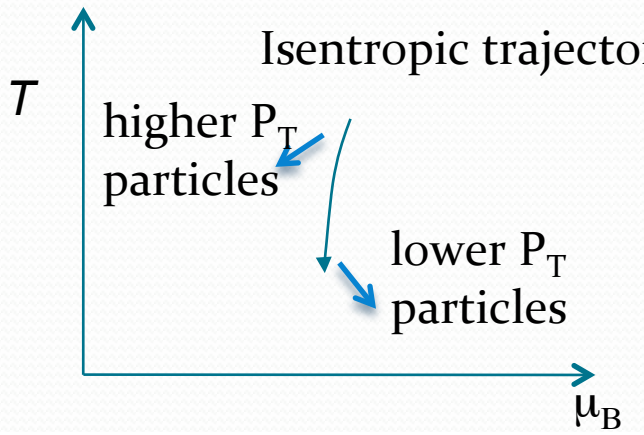
- Fluctuations: conserved values ex. charge, baryon number
- Hadron ratios: fixed at chemical freezeout temperature T_{ch}

  Key: T_{ch} depends on transverse momentum

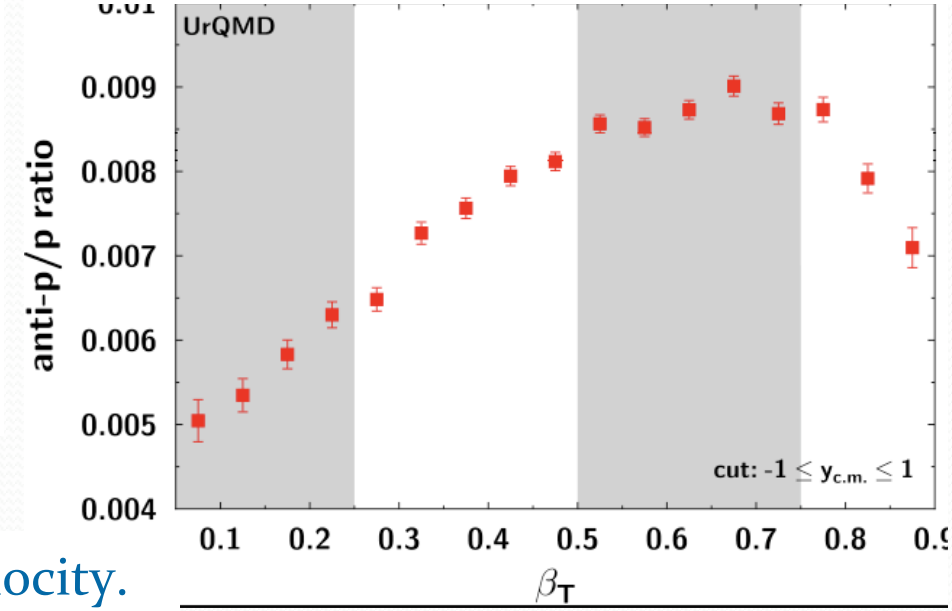
Hadron Production on n_B/s const. line

UrQMD : no QCD critical point





- T_{ch} depends on transverse velocity.



- Hadron ratios depend on transverse velocity.

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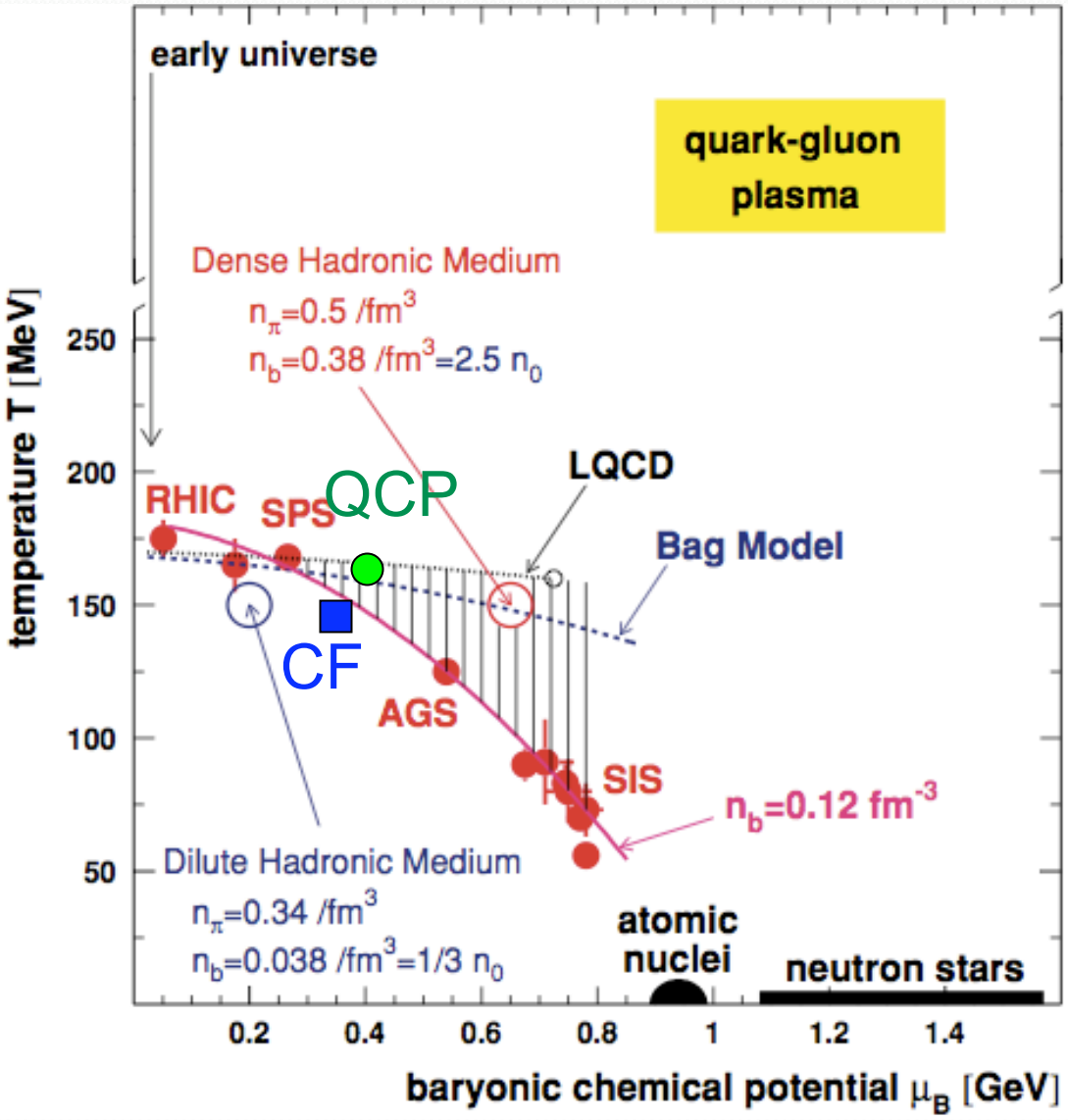
Demonstration

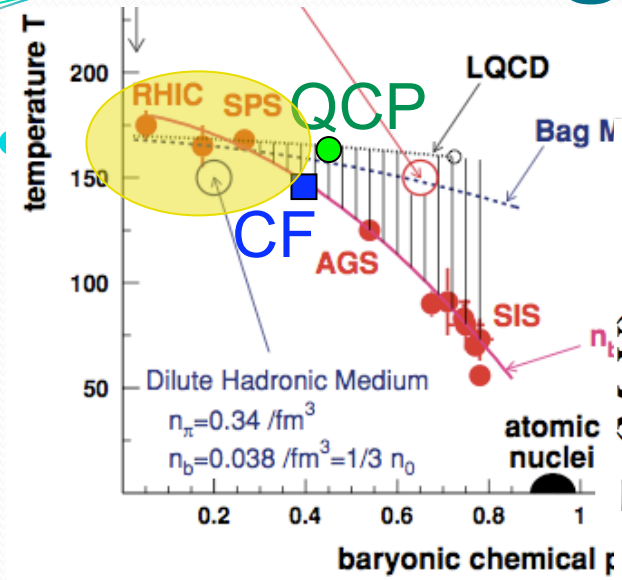


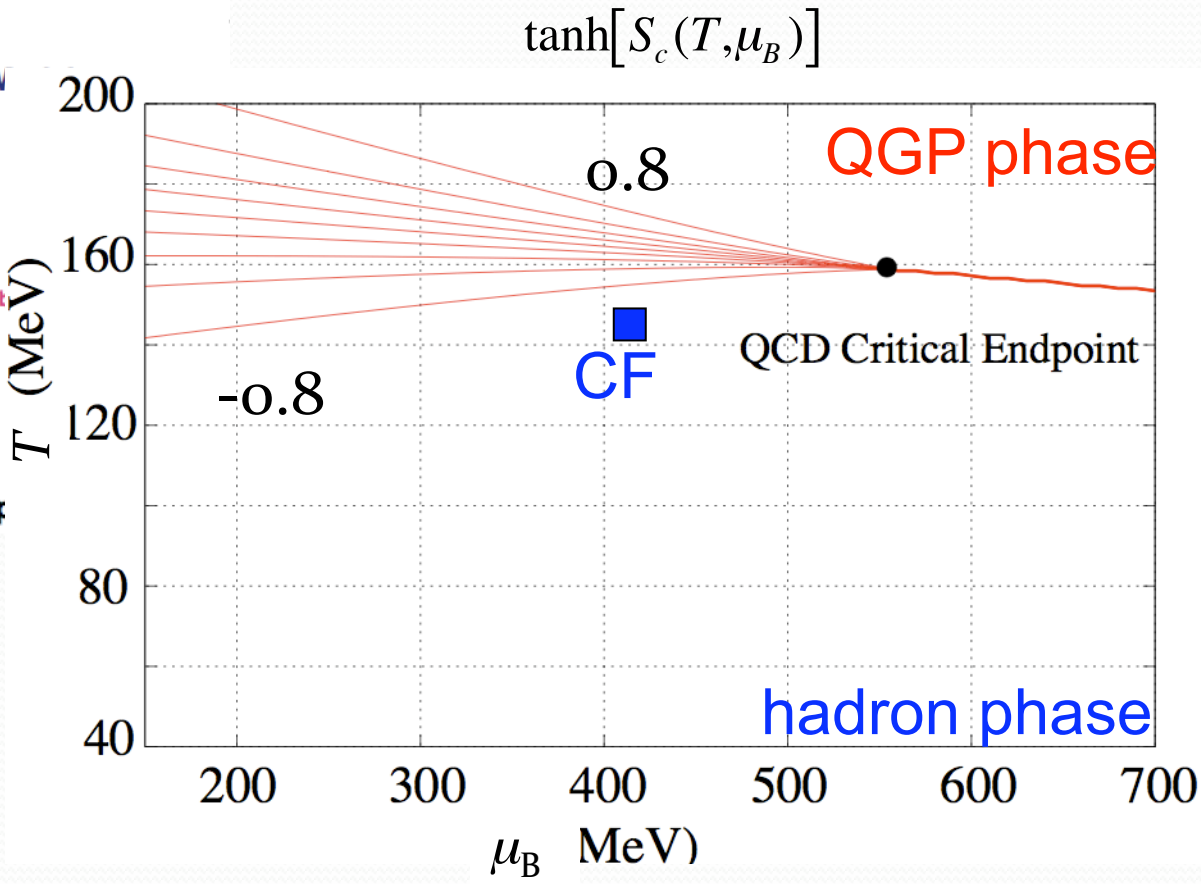
Search of the QCD critical point from experiments

SPS

- Location of QCP
  $(\mu_B, T)=(550,159)$
- Critical Region
  parameter
- Chemical freezeout point
  $(\mu_B, T)=(406,145)$
  from statistical model

Critical Region





QCD critical point
$(\mu_B, T)=(550,159)$

- Entropy density

$$S_{\text{real}}(T,\mu_B)=\frac{1}{2}\{1-\tanh[S_c(T,\mu_B)]\}S_H(T,\mu_B)+\frac{1}{2}\{1+\tanh[S_c(T,\mu_B)]\}S_Q(T,\mu_B)$$

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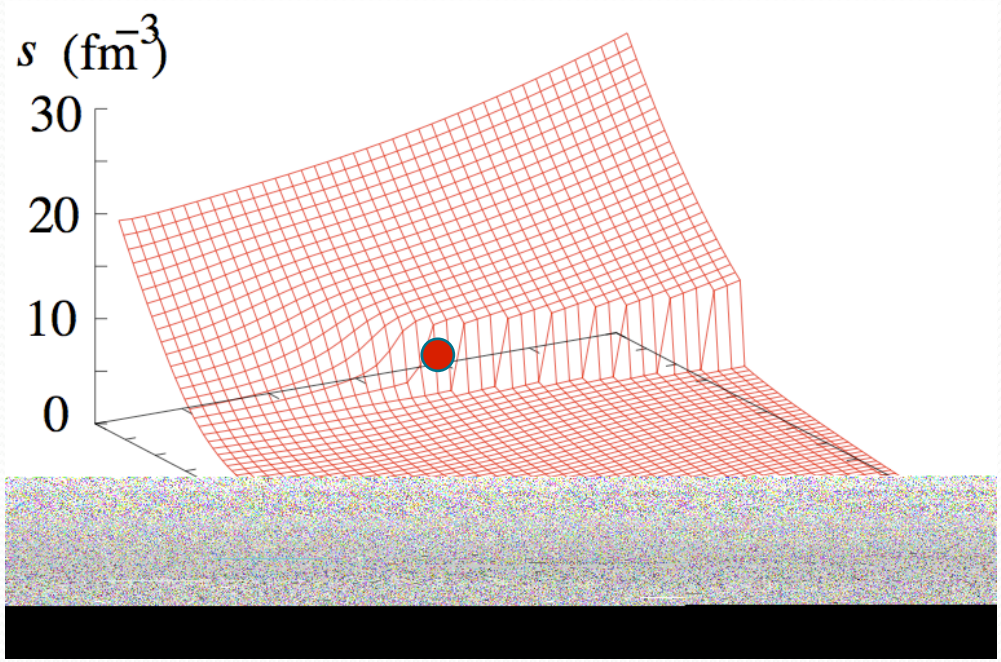
Equation of State

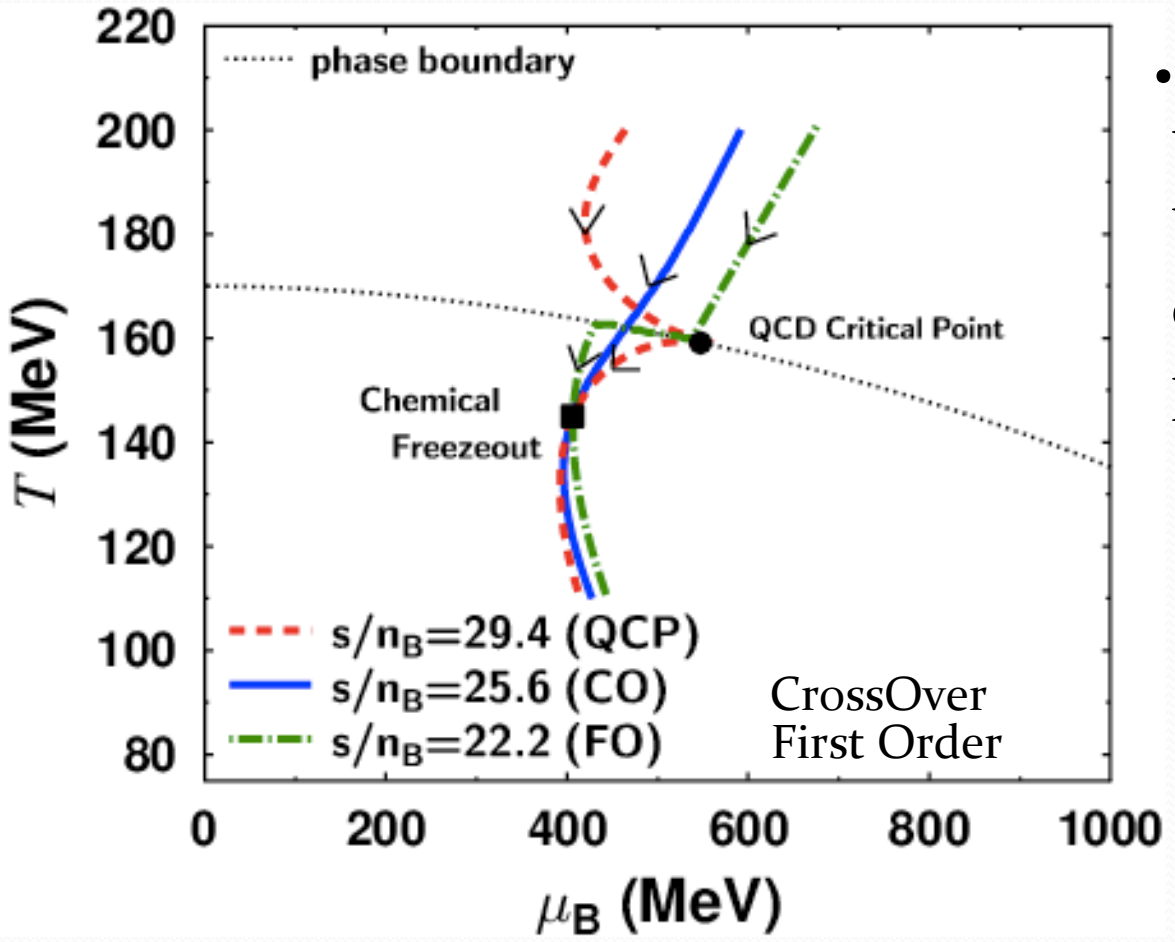
- QCD critical point $(\mu_B, T)=(550,159)$

entropy density



trajectories

Isentropic Trajectories



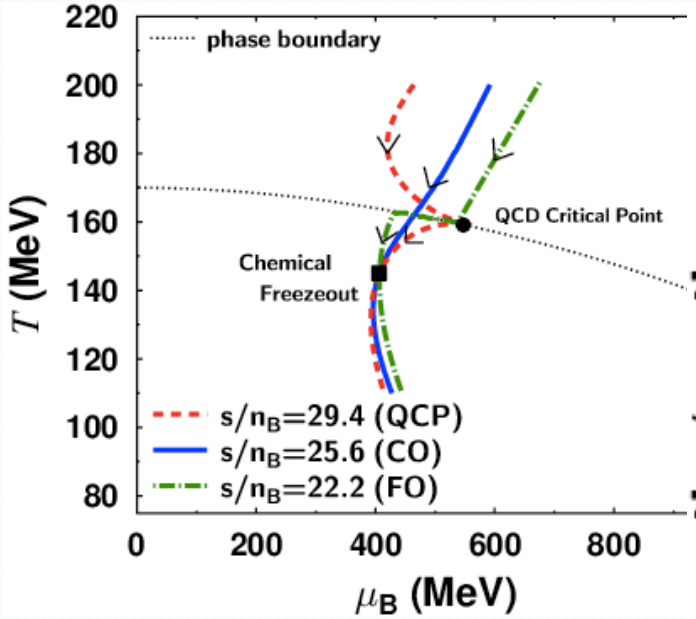
- Hadronization occurs between the phase boundary and chemical freezeout point

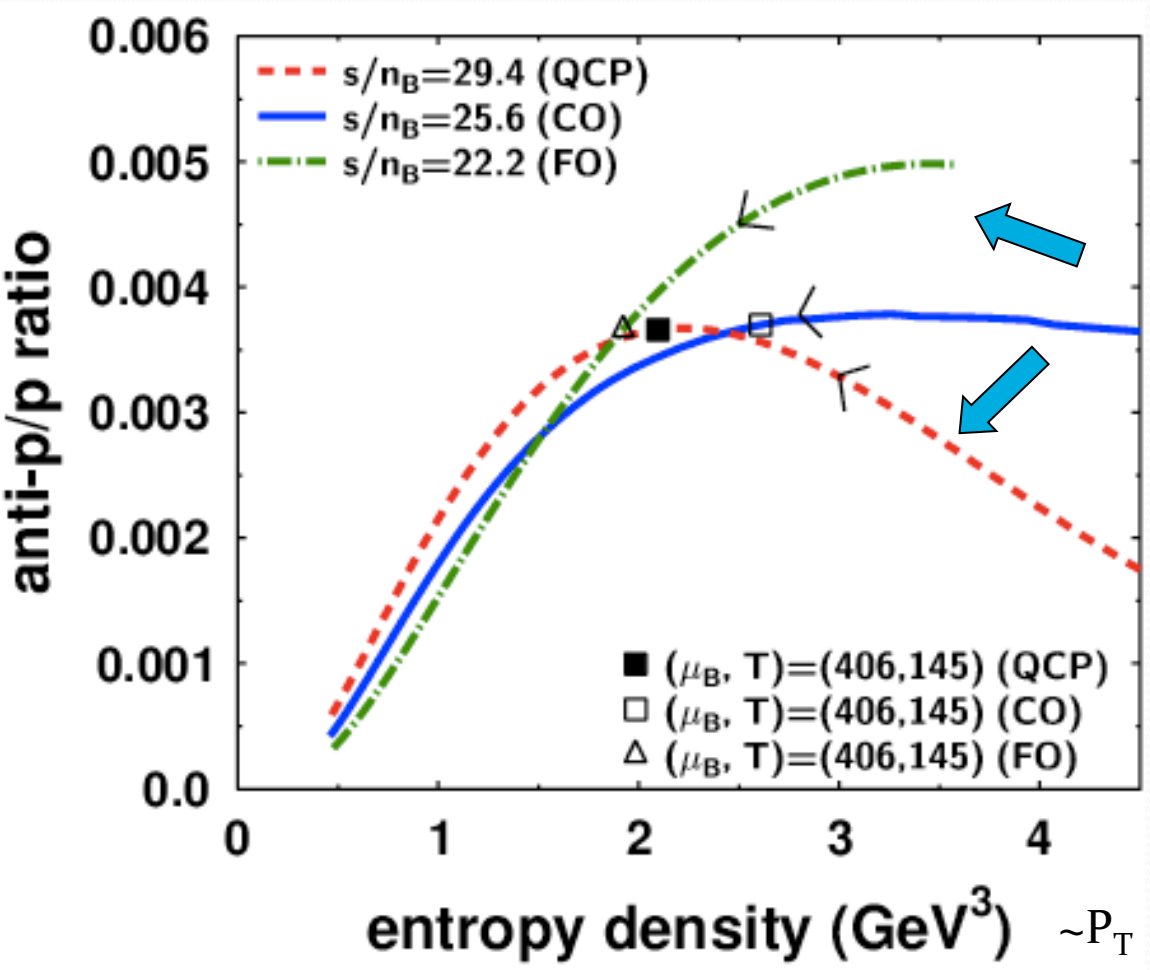
- FO, CO → $\frac{\mu_B}{T}$
- QCP →

→ $\bar{p}/p$ ratio

$$\bar{p}/p \sim \exp\left(-\frac{2\mu_B}{T}\right)$$

Signature of QCP





$$\bar{p}/p \sim \exp\left(-\frac{2\mu_B}{T}\right)$$

- decreases (FO,CO)
- increases (QCP)

with QCP
steeper $\bar{p}$ spectra at high P_T

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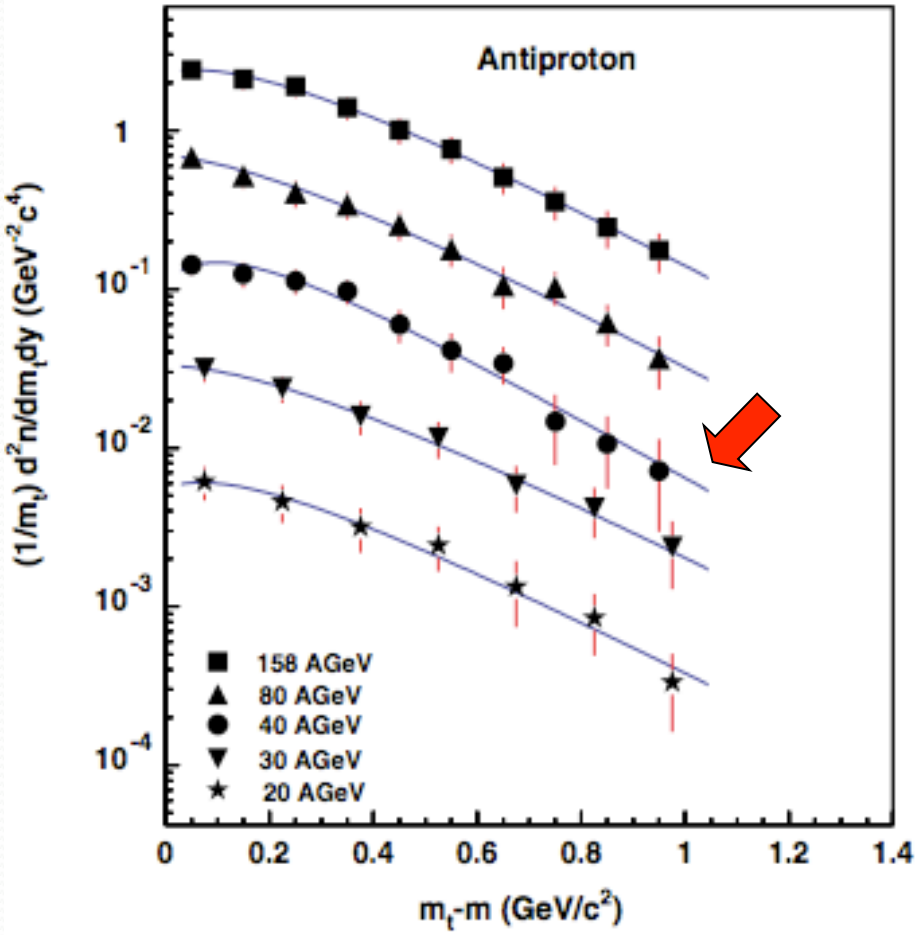
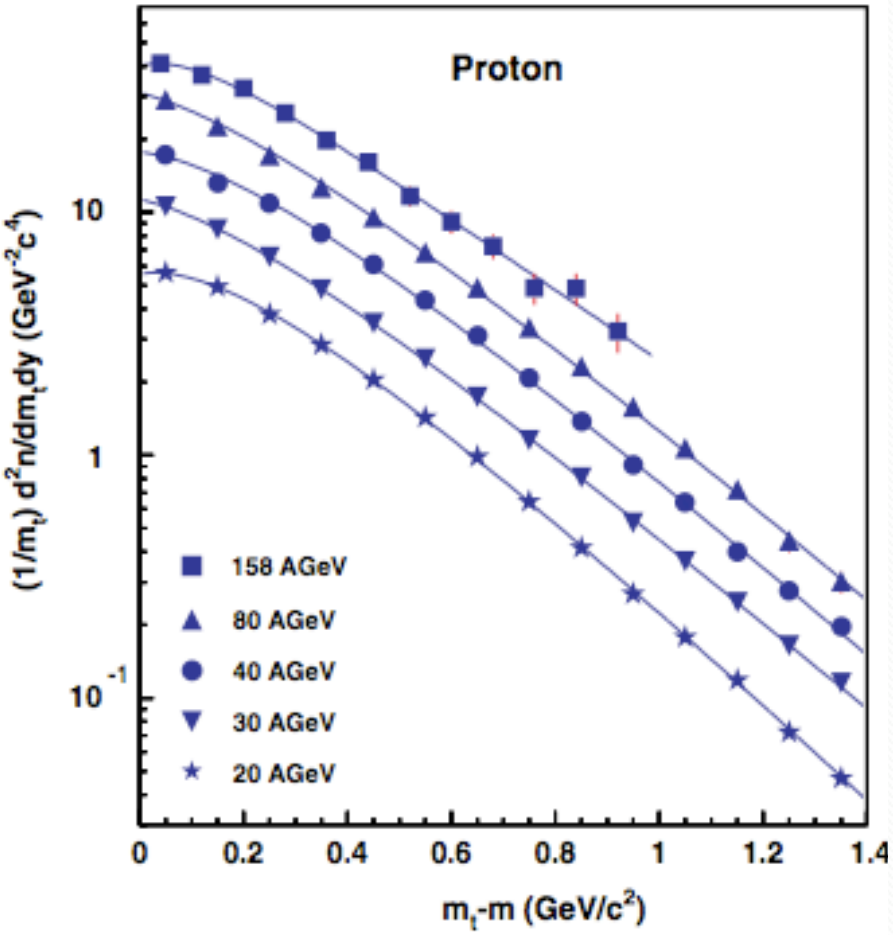
QCD Critical Point?

NA49





steeper $\bar{p}$ spectra at high P_T

NA49, PRC73,044910(2006)

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3D Hydro+UrQMD with QCP

- Initial Conditions
  - Energy density

$$\varepsilon(x,y,\eta) = \varepsilon_{\max} W(x,y;b) H(\eta)$$

  - Baryon number density

$$n_B(x,y,\eta) = n_{B\max} W(x,y;b) H(\eta)$$

  - Parameters

$$\begin{cases} \tau_0 = 0.6 \text{ fm/c} \\ \eta_0 = 0.5 \quad \sigma_\eta = 1.5 \end{cases}$$

  - Flow

$v_L = \eta$ (Bjorken's solution); $v_T = 0$

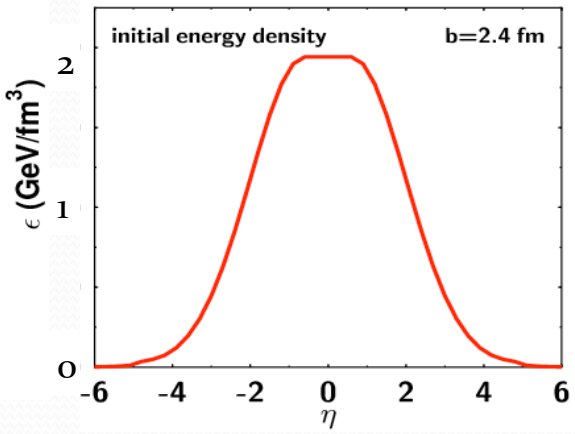
- EOS: QCP, Bag Model
- Switching temperature

T_{SW}=150 [MeV]

QCP: T_E = 159 MeV, μ_E = 550 MeV

T_c=170 MeV at μ_B=0 MeV

•longitudinal direction: $H(\eta)$



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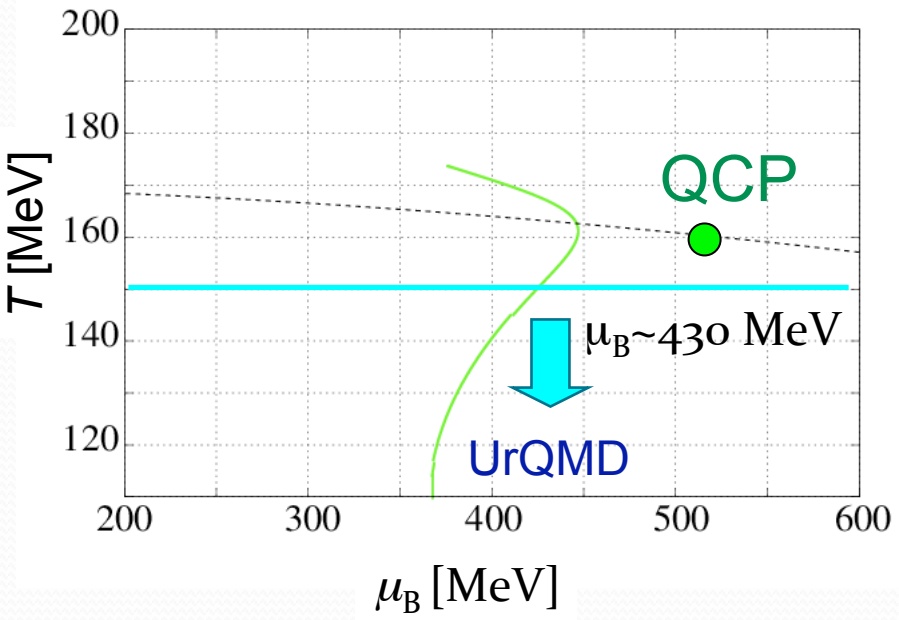
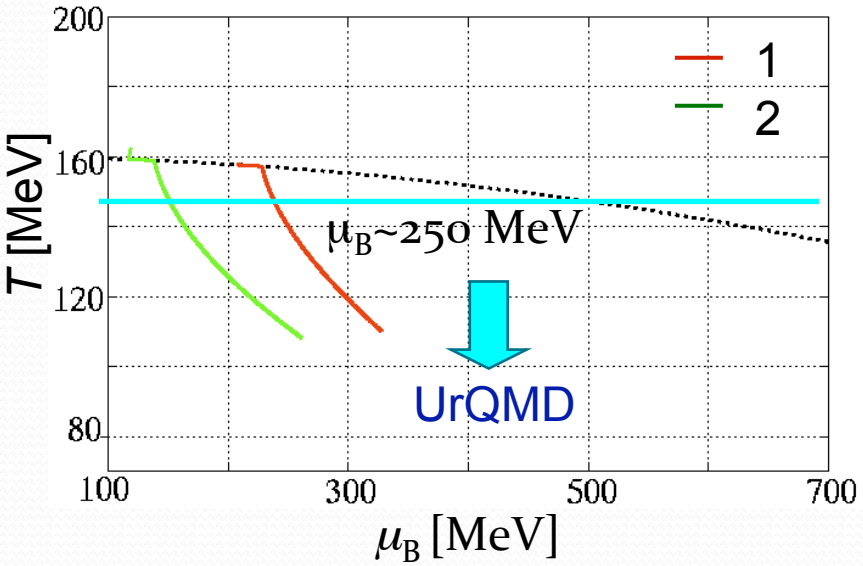
3D Hydro + UrQMD

Hydro with QCD critical point



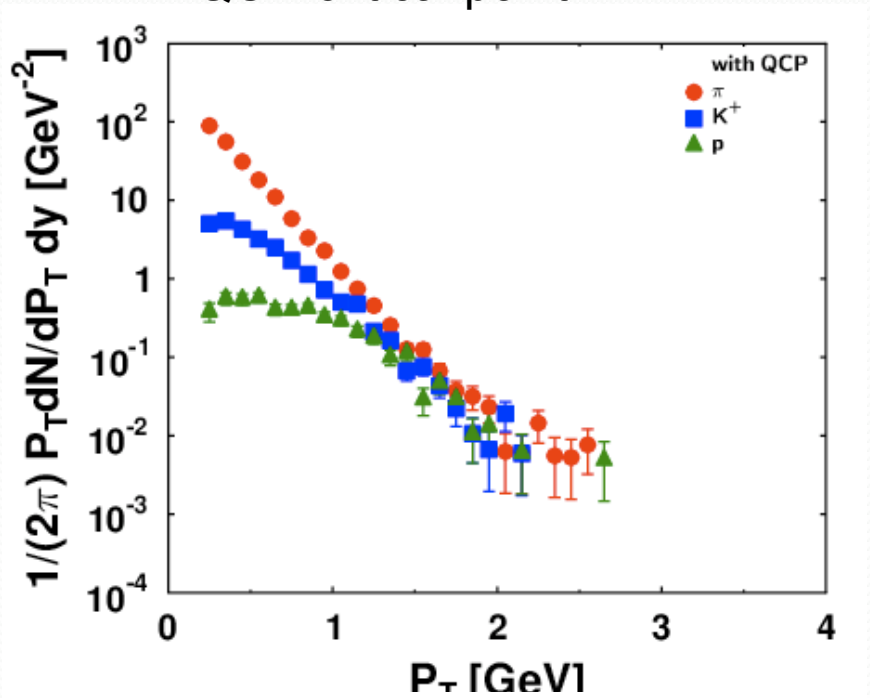
Hydro with Bag Model



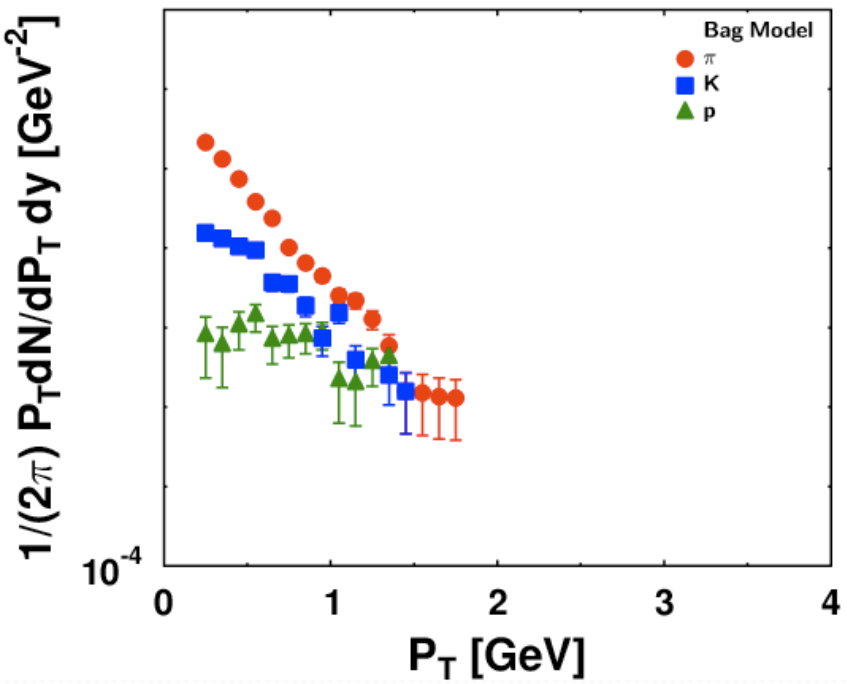
Switching temperature: 150 MeV

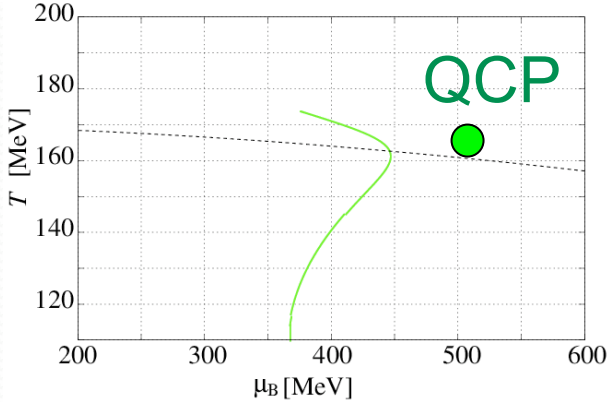
P_T Spectra

QCD critical point



Bag Model





Because of focusing effect

At T_{SW} $\langle \mu_B \rangle_{QCP} > \langle \mu_B \rangle_{BG}$ ⇨ $\frac{p}{\pi}_{QCP} > \frac{p}{\pi}_{BG}$

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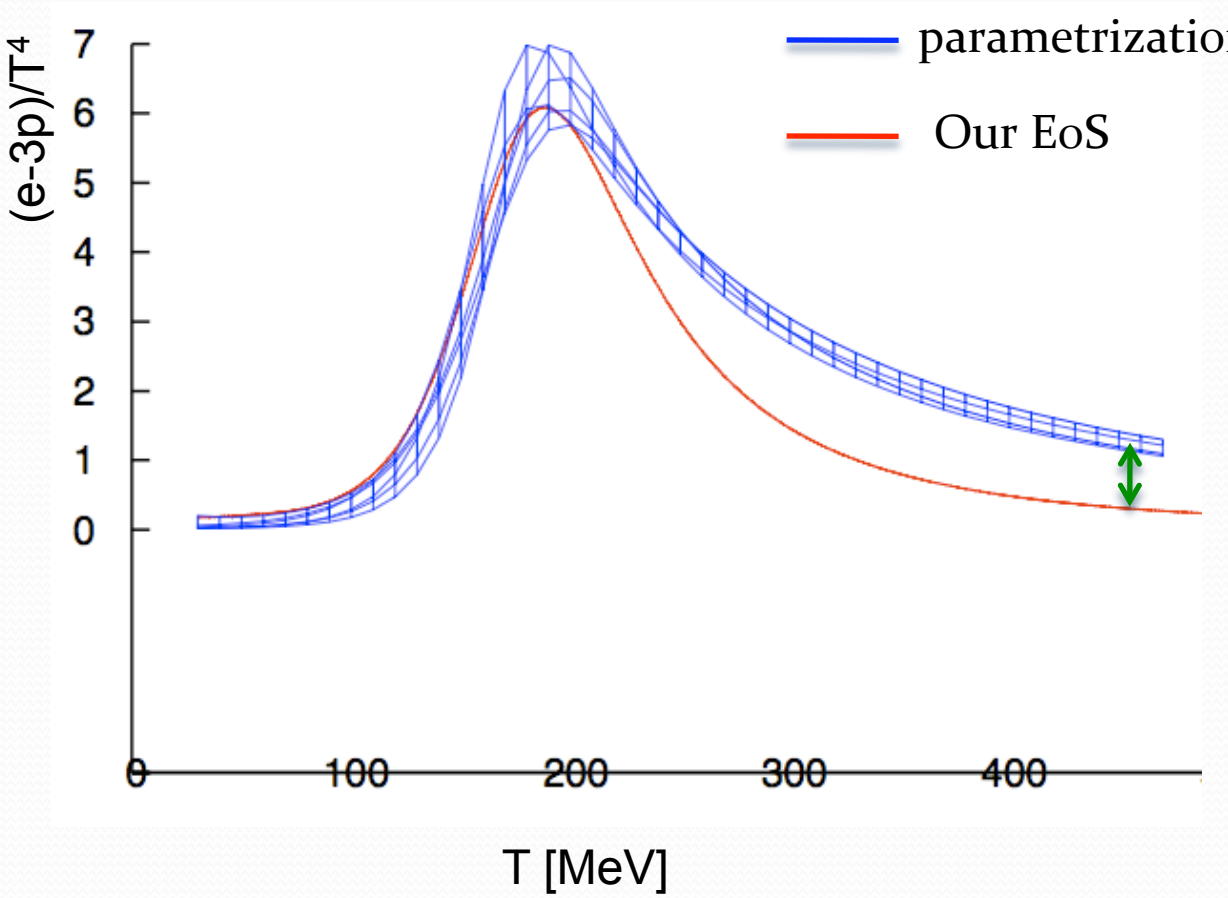
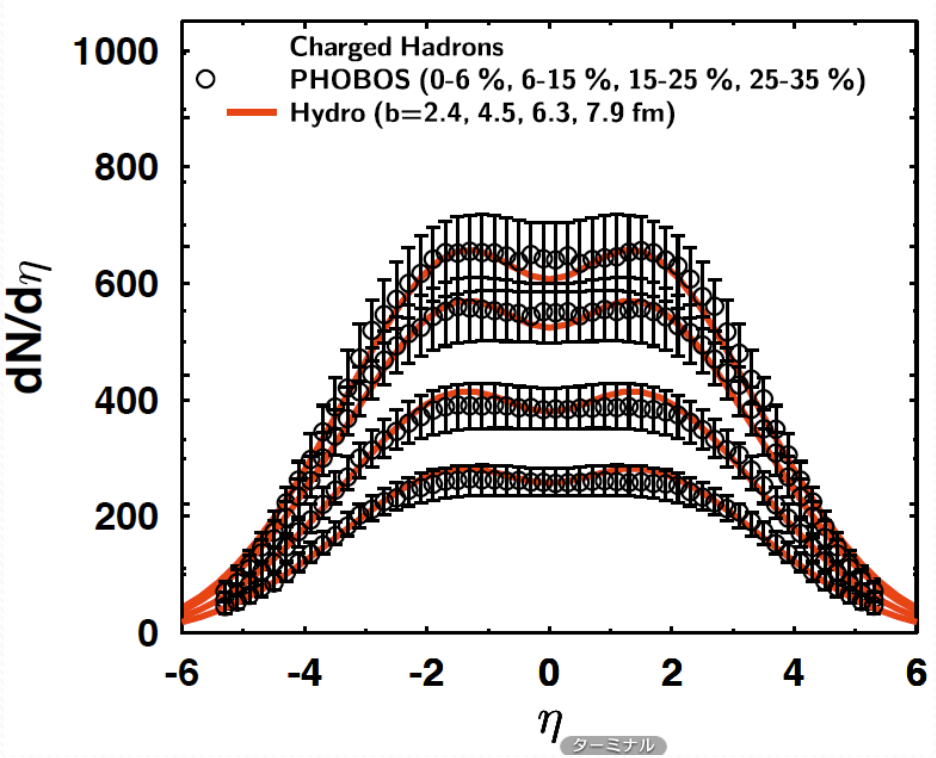
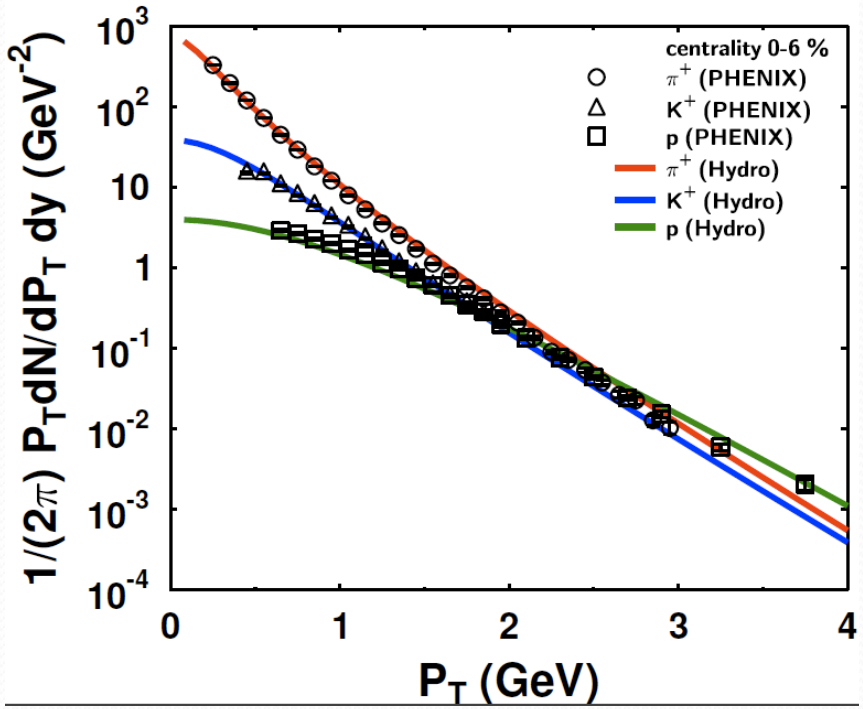
At RHIC

- Smooth connection to lattice data at μ=0



At RHIC





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Summary

Signal of QCD critical point:
$\overline{p}/p$ ratio as a function of transverse momentum

- Towards quantitative analyses
  - EoS with QCP

    Focusing effects in isentropic trajectories
- 3D Hydro + UrQMD model
  - P_T spectra, hadron ratios