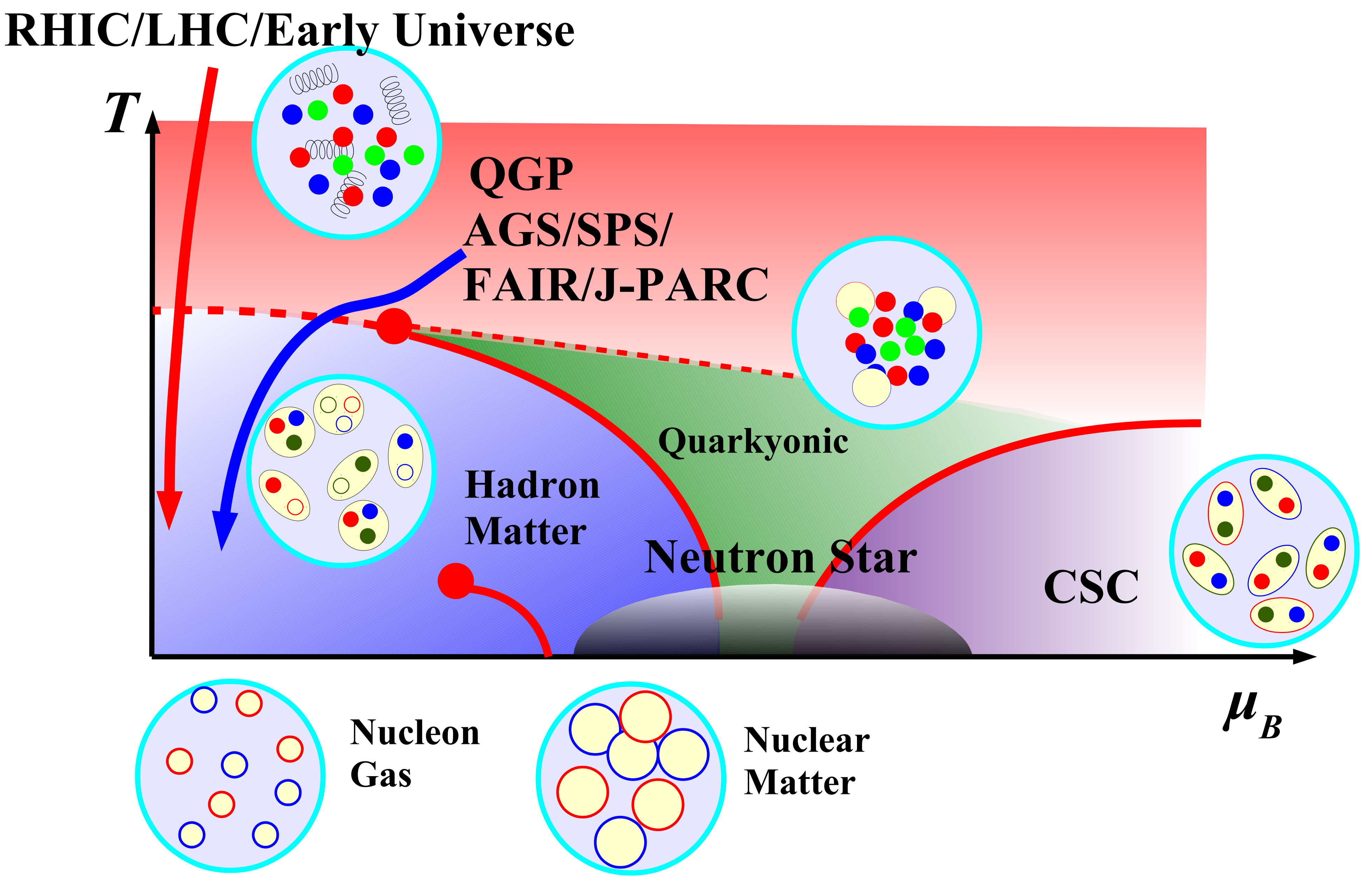
Phase diagram and heavy-ion collisions: Overview

Akira Ohnishi (YITP, Kyoto Univ.)

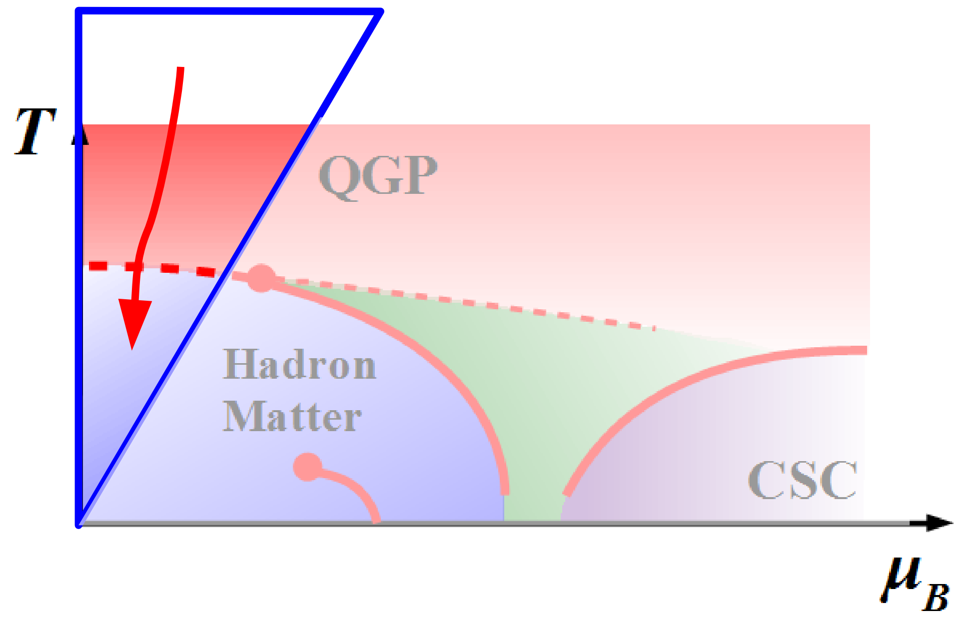
XLI International Symposium on Multiparticle Dynamics (ISMD2011), Sep. 26-30, 2011, Miyajima-Island, Hiroshima, Japan

- **QCD phase diagram**
- **High temperature region**
- **Critical point search**
- **Cold dense matter and phase diagram structure**
- **Exotic hadrons and their formation in heavy-ion collisions**
- **Summary**

QCD Phase Diagram

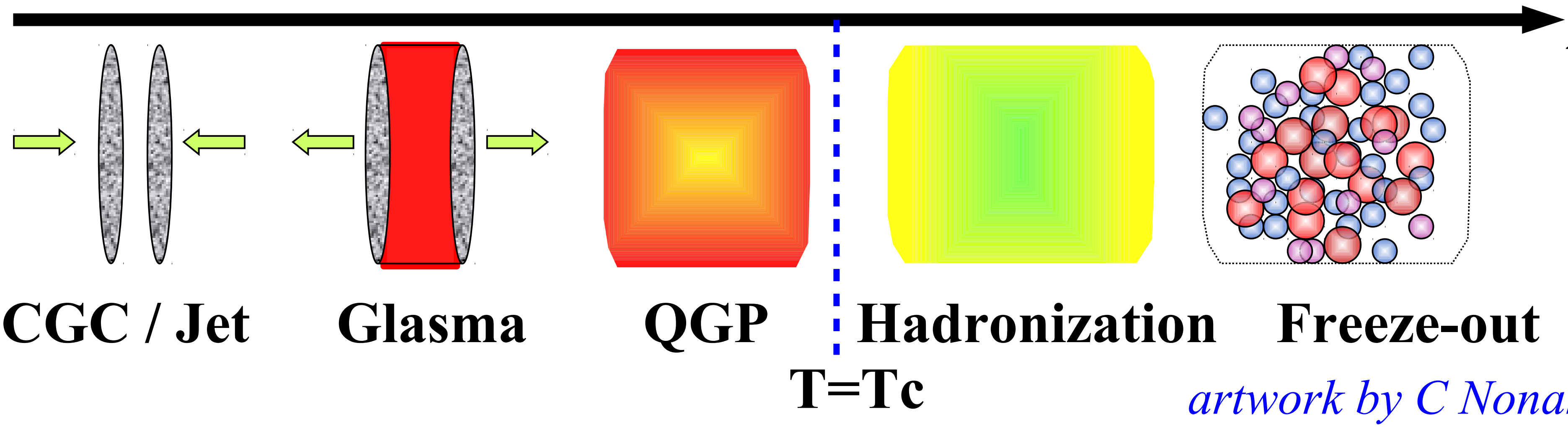


High Temperature Phase Transition



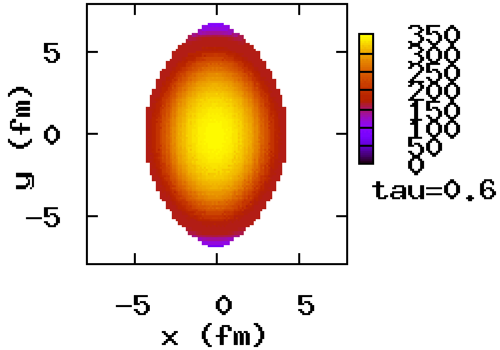
- **What is the value of Tc ?**
  - ***Signposting the phase diagram of QCD, S. Gupta***
- **Can we observe the temperature of QGP ?**
  - ***Photon Measurements in Heavy Ion Collisions, Y. Yamaguchi***
- **Chiral Magnetic Effects**
  - ***Chiral Magnetic Effect -- Impact of the Strong Magnetic Field in the Heavy-Ion Collision, K. Fukushima***

High-Energy Heavy-Ion Collisions



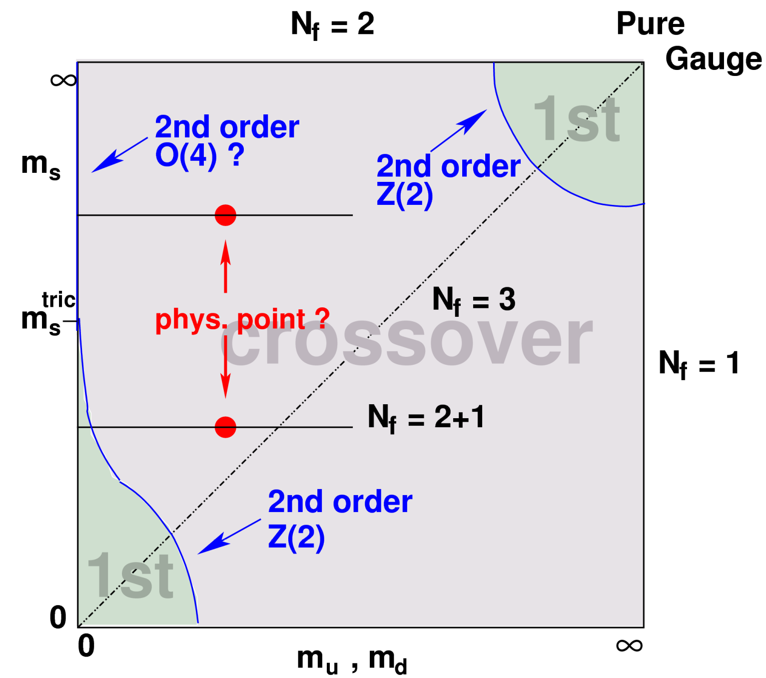
artwork by C Nonaka

- **Chemical Freeze-out and Phase boudnary**
  - **Fluctuation observables and Tc in lattice QCD (Gupta)**
- **Property of Quark Gluon Plasma**
  - **Temperature before Hadronization (Yamaguchi)**
  - **Chiral Magnetic Effect (Fukushima)**



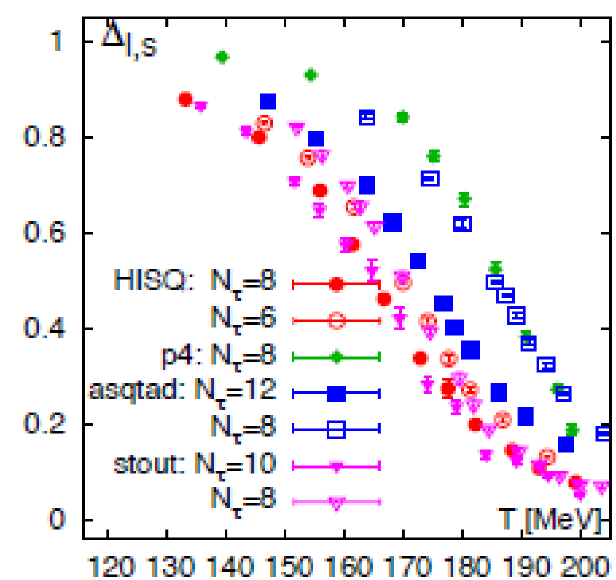
Order and Critical Temperature in Lattice QCD

- **Order of the phase transition at μ=0**
  $SU(N_F)_L x SU(N_F)_R \to SU(N_F)_V$
  - **Cross over at physical point**
    E.g. Y. Aoki et al., Nature 443('06) 675
  - **Scaling at $m_{u,d} \to 0$: 2nd or 1st ?**
    Kaczmarek et al., PRD83('11)014504;
    de Forcrand, Philipsen, PoS(LAT08)208



- **Tc value from lattice QCD**
  K. Kanaya, PoS LATTICE2010 ('10) 012
  Tc=(145-185) MeV
  - **Staggered Fermion: Tc=(145-165) MeV**
    (Problem ="Heavy" pion contamination)
  - **Other Fermions:**
    Tc=160-184 MeV

DW(2+1)Cheng et al. (DW,2+1, HotQCD)0911.3450;
Wilson(N_F=2)Bornyakov (QCDSF-DIK) 0910.2392;
Ejiri et al. (WHOT) 0909.2121.

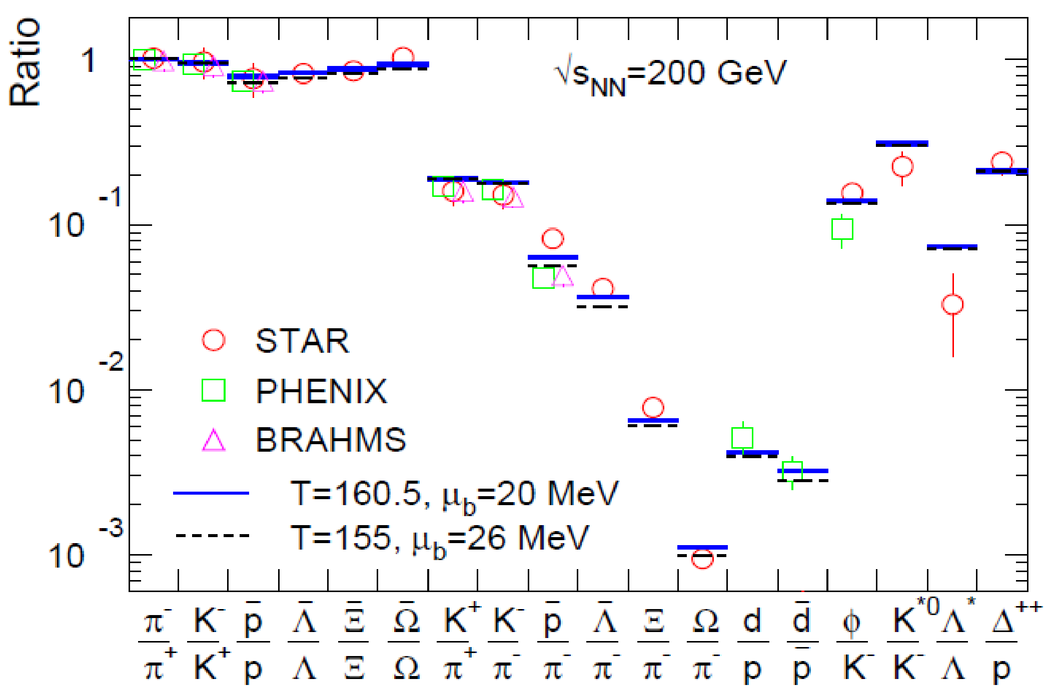


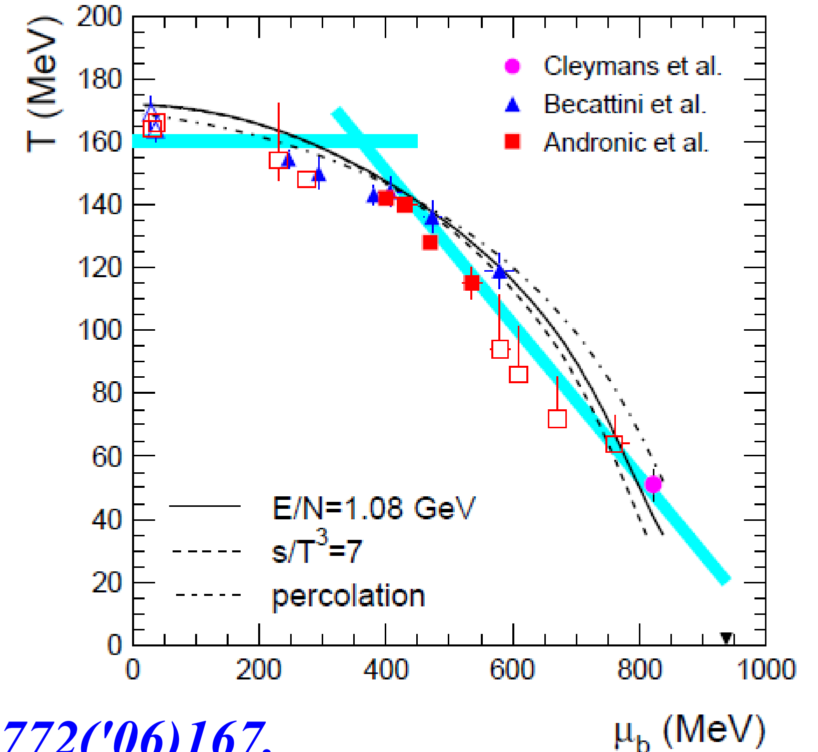
Statistical Model

- **Statistical model**

$$N_h^{\text{stat}} = V_H \frac{g_h}{2\pi^2} \int_0^\infty \frac{p^2\,dp}{\gamma_h^{-1}\exp(E_h/T_H) \pm 1} \quad (\gamma_h : \text{fugacity})$$

  - **Successful explanation of hadron yields at RHIC**
  - **Chem. Freeze-out line may reflect the phase boundary**

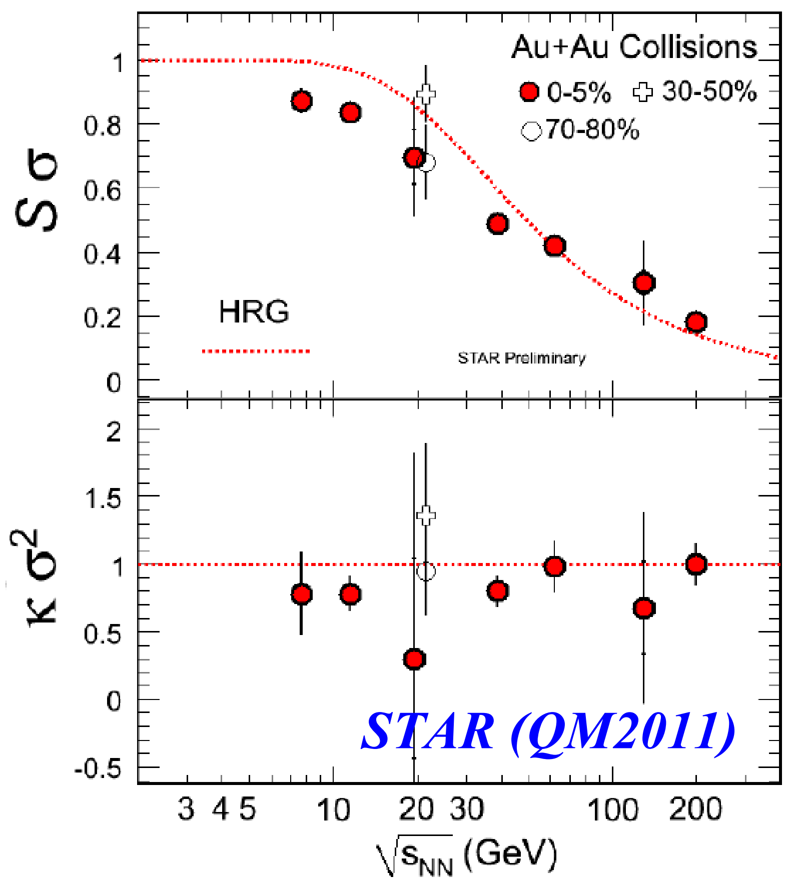


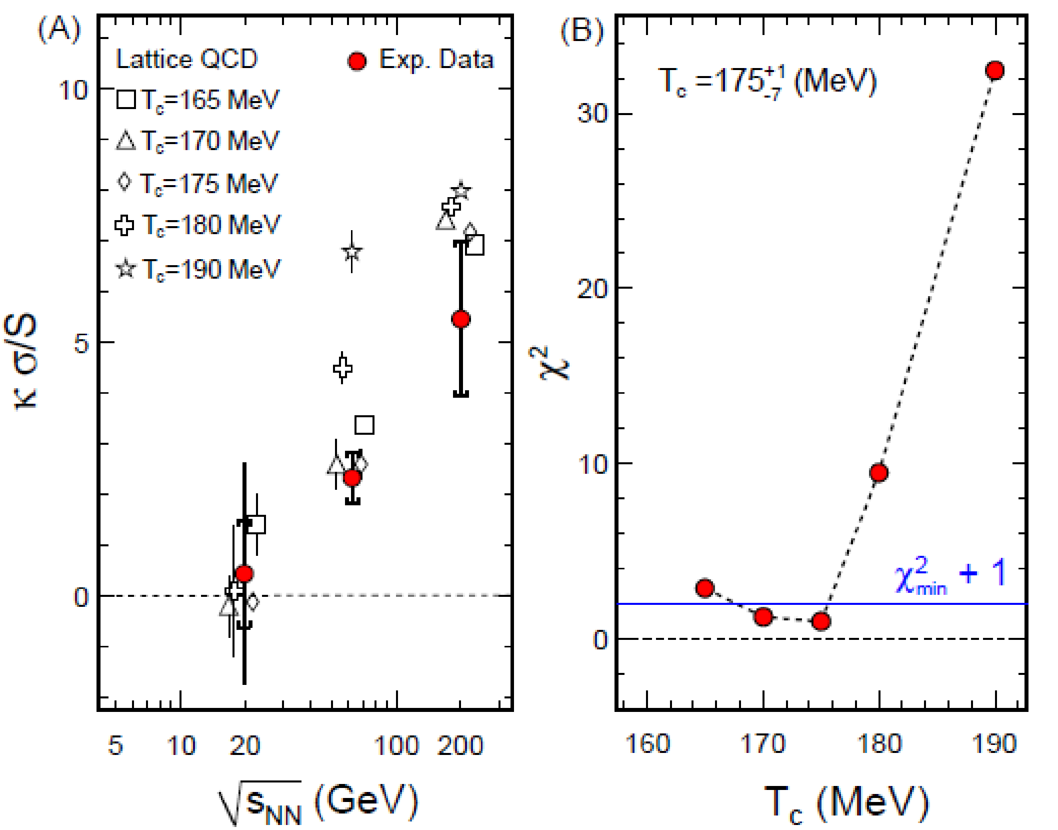


A. Andronic, P. Braun-Munzinger, J. Stachel, NPA772('06)167.

Can we guess Tc from data ?

- Can we connect two temperatures ?
  - Statistical model results → *Hadronic* Chemical Freeze-out *T*
  - Lattice QCD results → Cross over Tc (145-185 MeV)
- Challenge to relate Lattice Tc and Hadronic fluctuation observables
  Talk by S. Gupta (Sep.26, 9:15-)



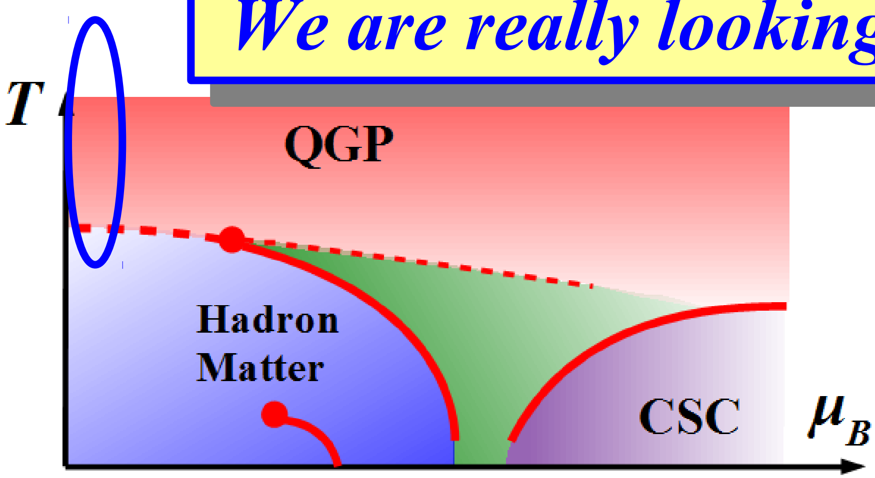


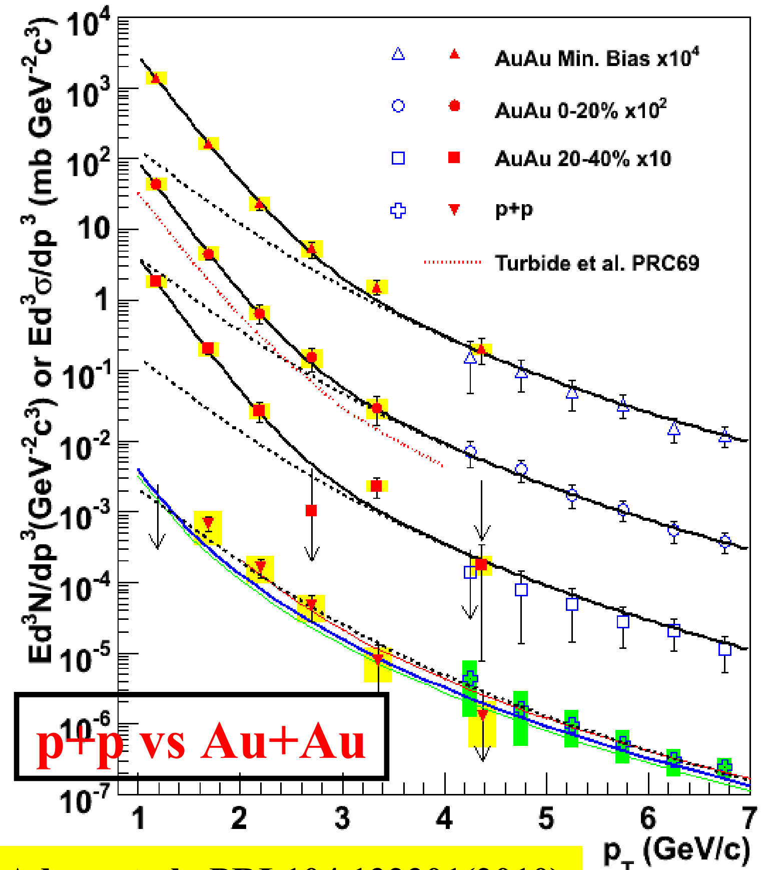
Gupta, Luo, Mohanty, Ritter, Xu, Science 332 ('11)1525.

Can we measure QGP temperature ?

- **Temperature measured via hadrons < Tc**
  → How can we measure QGP temperature ?
- **Direct photon spectrum in Au+Au at RHIC**
  Talk by Y. Yamaguchi (Sep.26, 15:15-)
  - **Significant excess in p_T<3GeV/c**
  - **Exponential fit (Central): T = 221 MeV**
  - **Initial temperature: T_i =(300-600) MeV (depending on thermalization time)**

T_{photon}, T_i > T_c (LQCD)
We are really looking QGP !





A. Adare et al., PRL104,132301(2010)

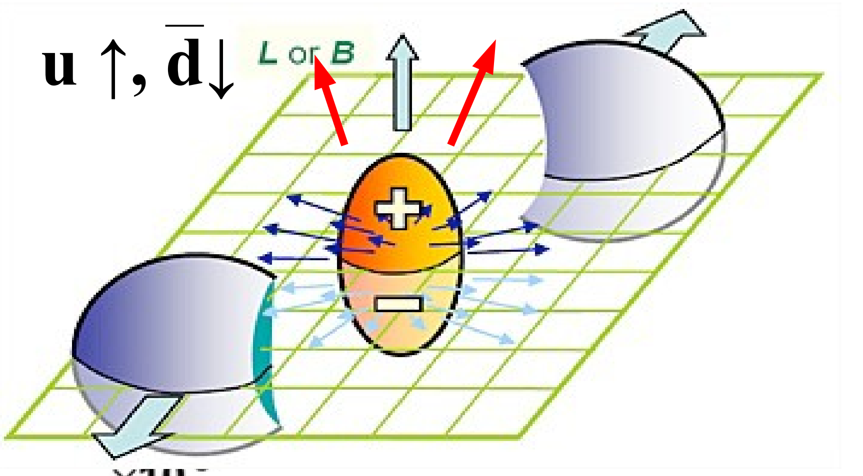
Chiral Magnetic Effects

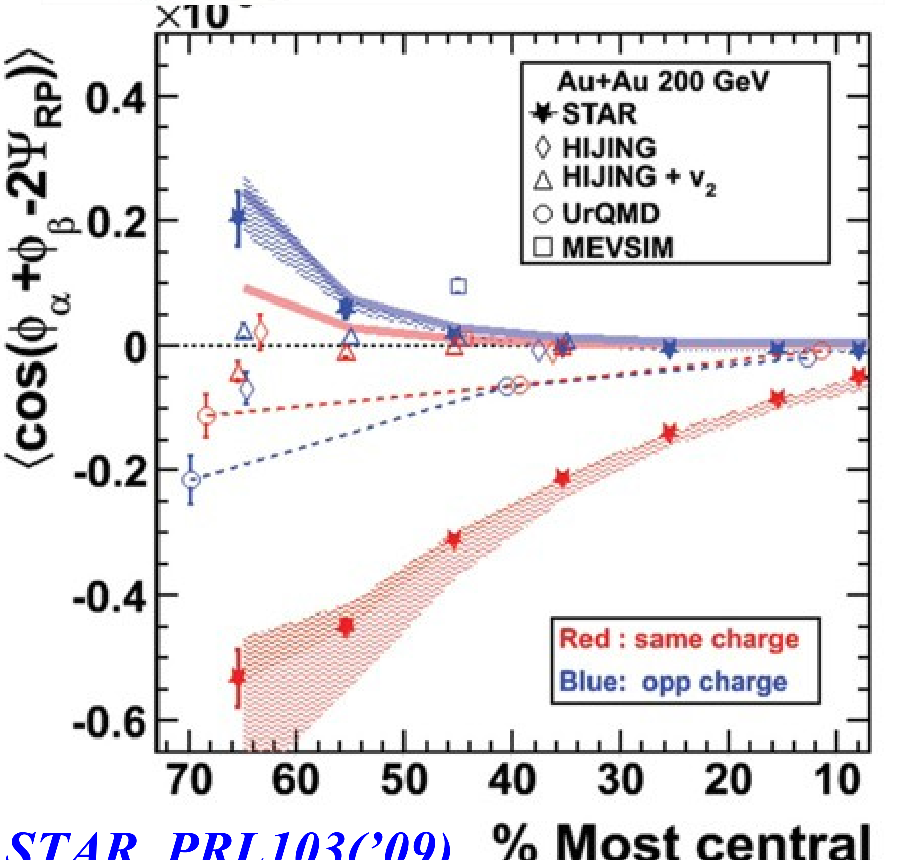
- **Enhanced same charge pairs in y-direction in peripheral collisions**
- **Chiral Magnetic Effects**
  Talk by K. Fukushima, Sep.26, 9:40-
  Strong magnetic field
  + chirally imbalanced plasma ($\mu_5 \neq 0$)
  → EM current is generated !
  (local parity violation)

$$J = \frac{e^2}{2\pi^2} \mu_5 B \quad (\text{vector} \propto \text{axial})$$

Fzukushima, Kharzeev, Warring, PRD78('08)074033

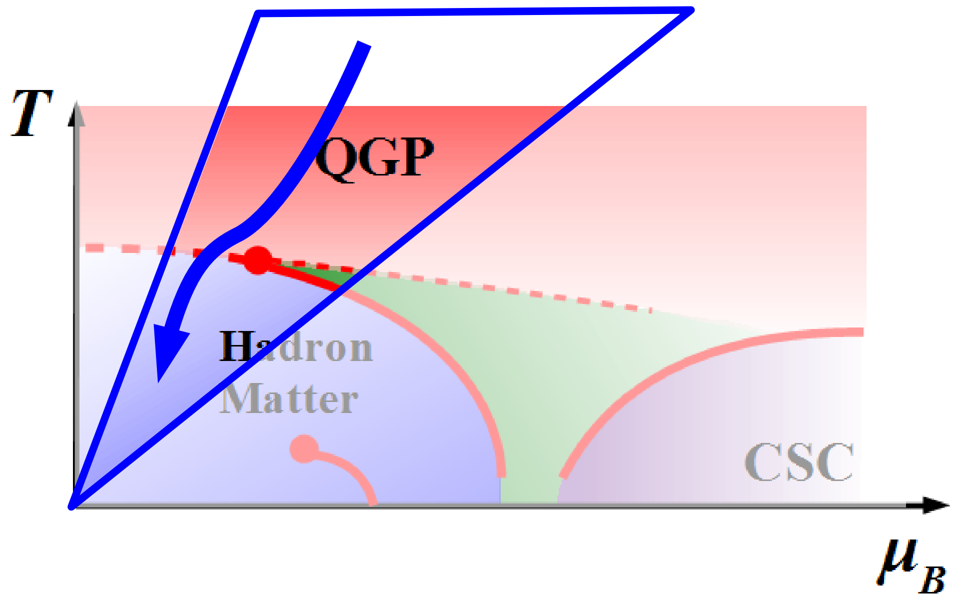
- **Other interpretation**
  E.g. Propagation of conserved chages
  S. Schlichting, S. Pratt, PRC83('11)014913





STAR, PRL103('09)

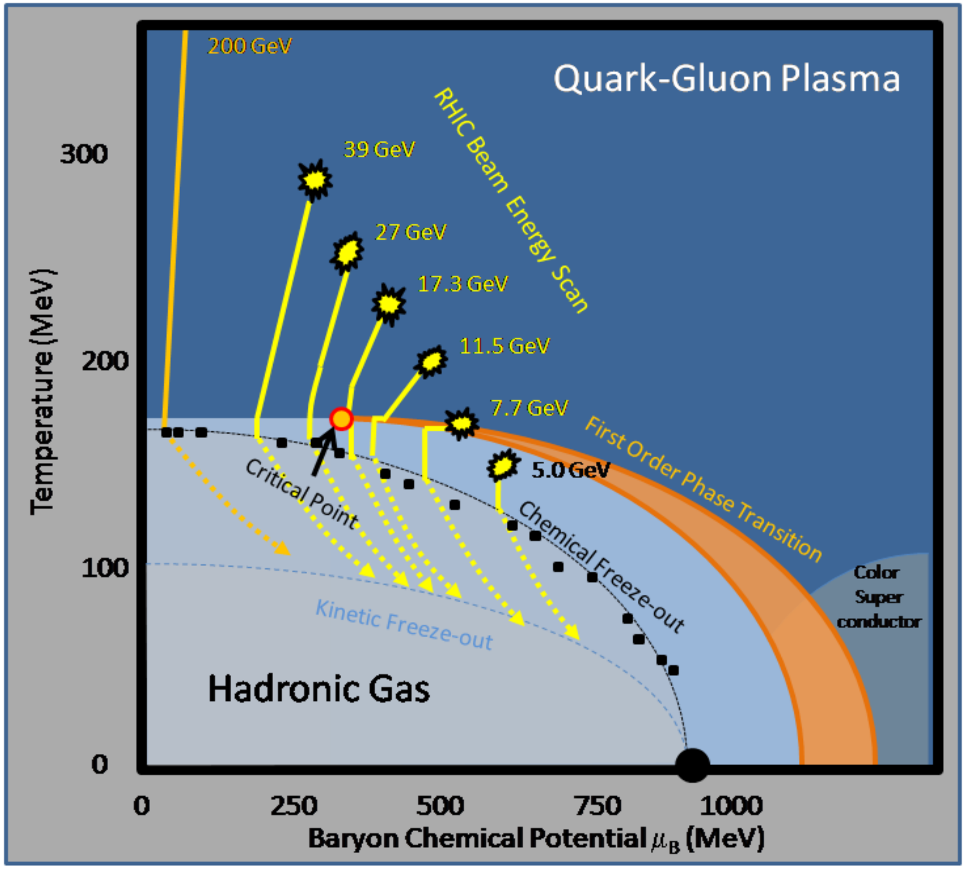
QCD Critical Point



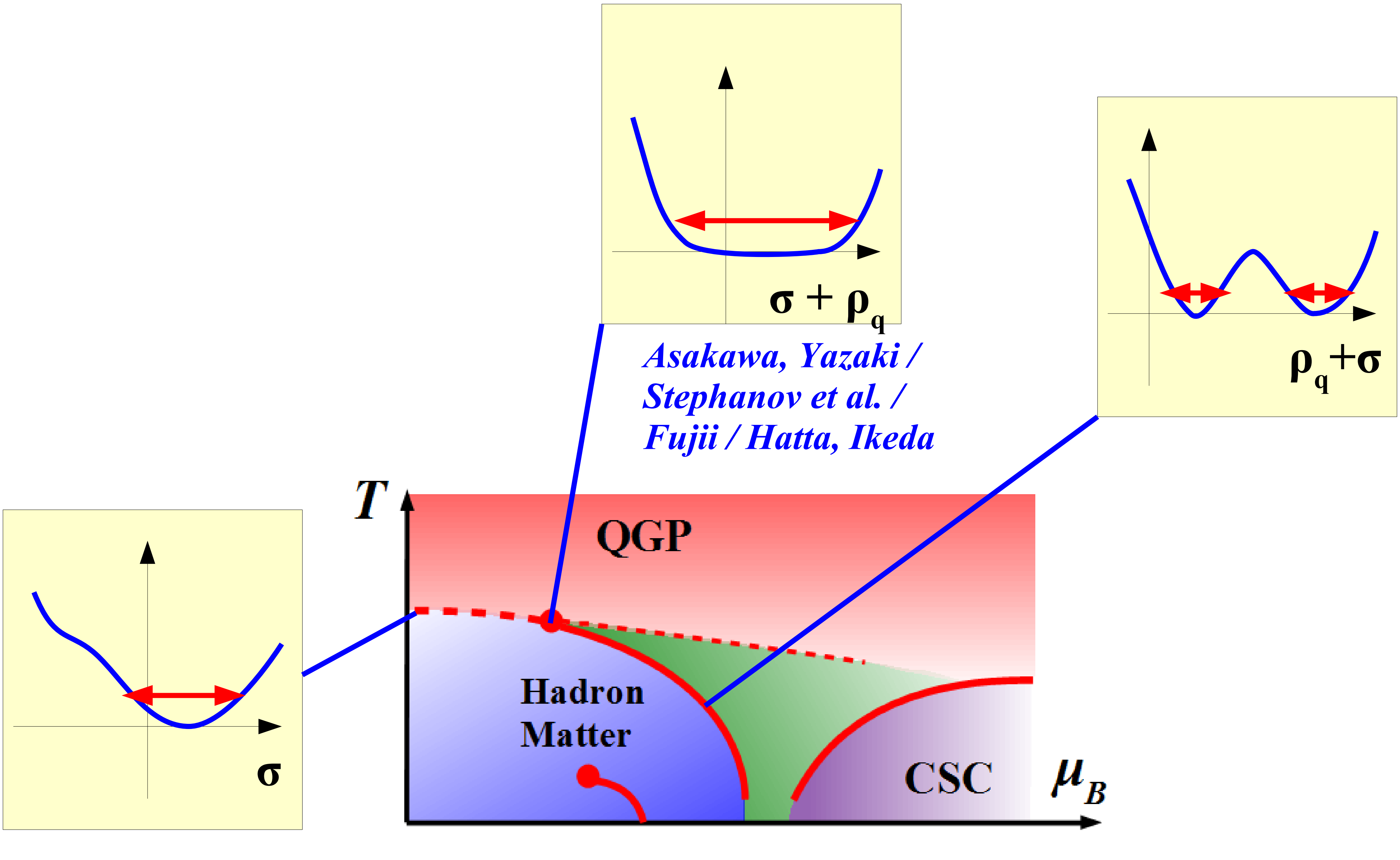
- **Experimental Search of QCD critical point**
  - ***Onset of deconfinement and search for the critical point of strongly interacting matter at CERN SPS energies, G. Stefanek***
  - ***NA61 experiment, critical point search, T. Czopowicz***
  - ***The RHIC Beam Energy Scan: A Study of the QCD Phase Diagram and Search for the Critical Point, D. Cebra***

QCD Critical Point

- We do not observe real (1st or 2nd order) phase transition at top energy of RHIC and LHC. How can we observe it ?
- Critical Point (CP) connects cross over at small μ (lattice QCD) and 1st order transition at low T.
  Asakawa, Yazaki ('89)
- Questions
  - Where is CP ?
  - How can we observe CP ?
  - How many CPs exist ?
  - Where does the 1st order phase transition take place ?
  - What is the signal of 1st ord. p.t. ?
- Basic idea
  → Go to lower energy HIC
  BES @ RHIC, SPS, FAIR,
  (and J-PARC)



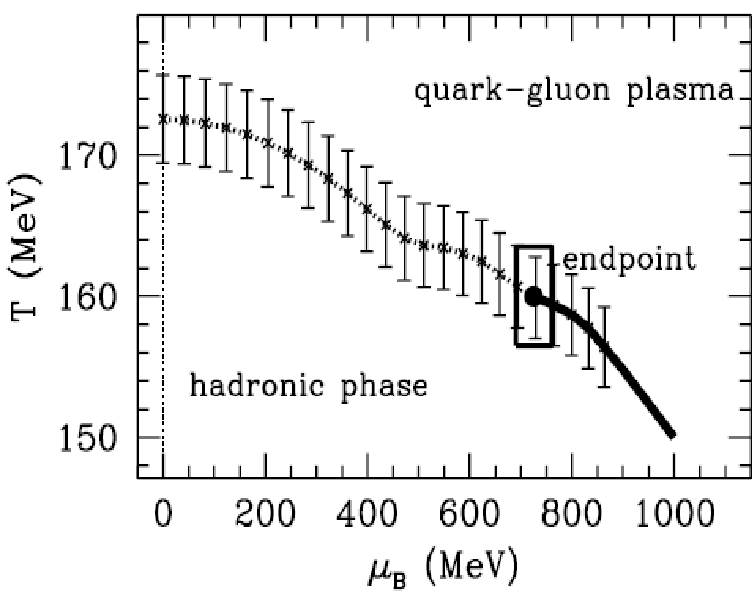
QCD Critical Point (cont.)



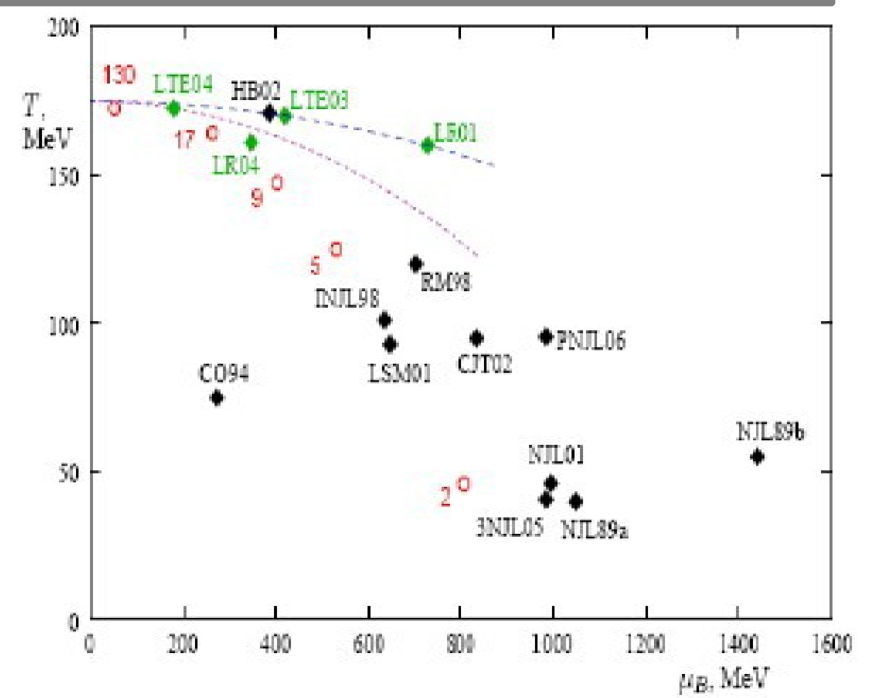
Where is CP ?

- **Theoretical prediction of CP location**
  - **Lattice QCD has the sign problem at finite μ: Fermion det. D*(μ) = D(-μ)**
    → Many attempts to overcome / avoid sign problem
    Reweighting / Taylor expansion / Analytic cont. / Canonical …
    → Consistent results at small μ (μ/T < 1), Not reliable at larger μ.
  - **Effective model predictions strongly depend of model details.**

Experimental / Observational inputs are essential

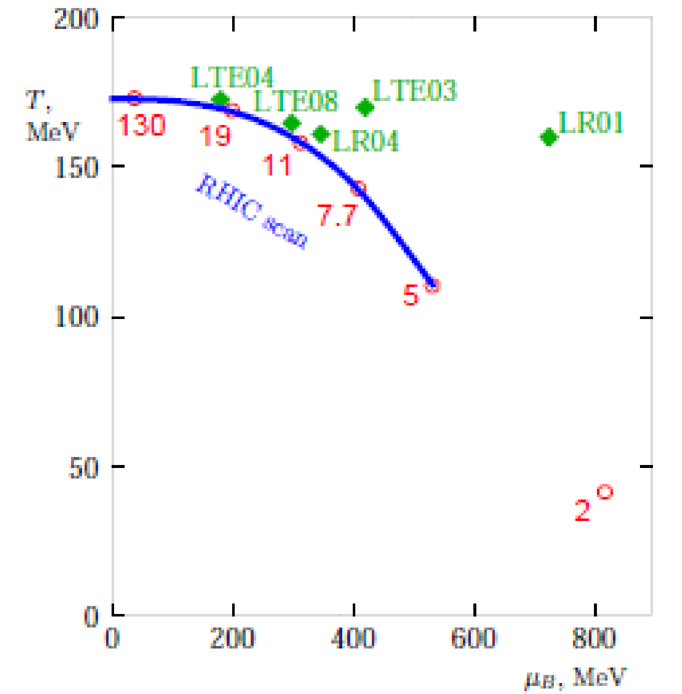


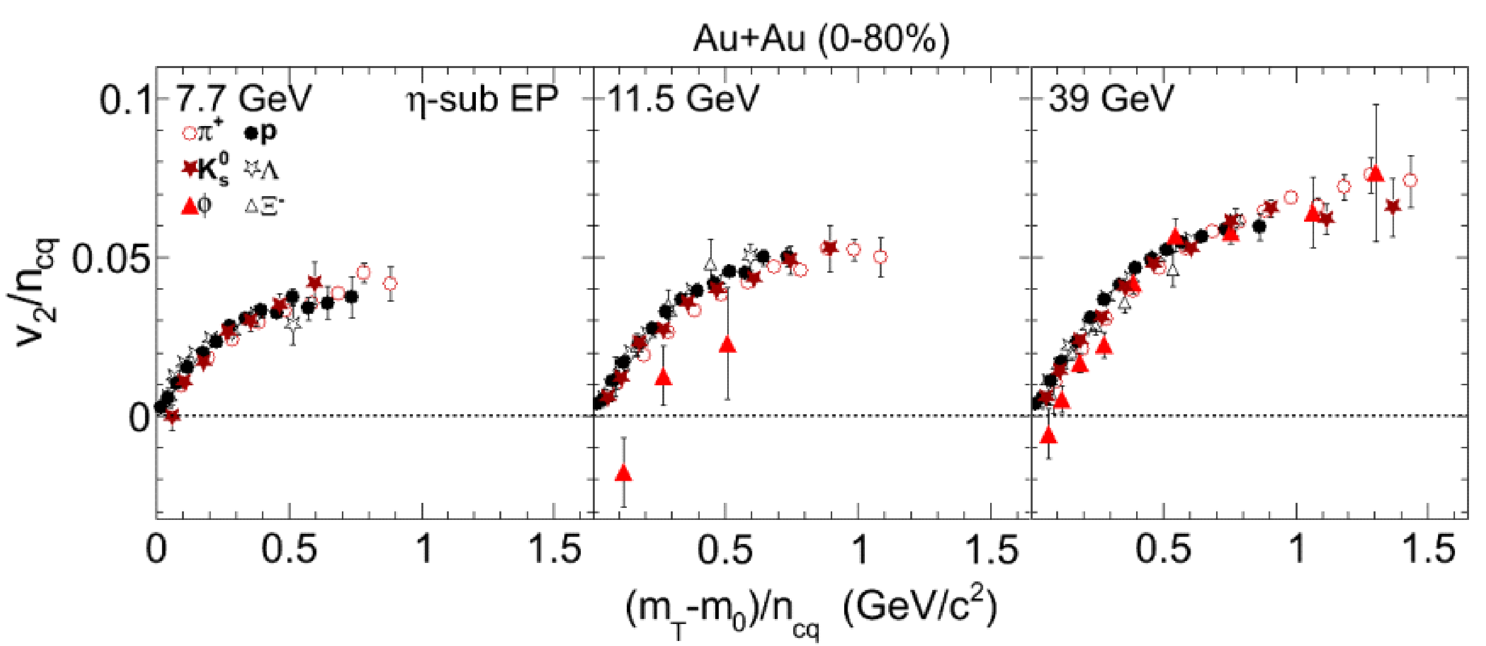
Z.Fodor, S.D.Katz, JHEP 0203, 014



Critical Point Search at RHIC

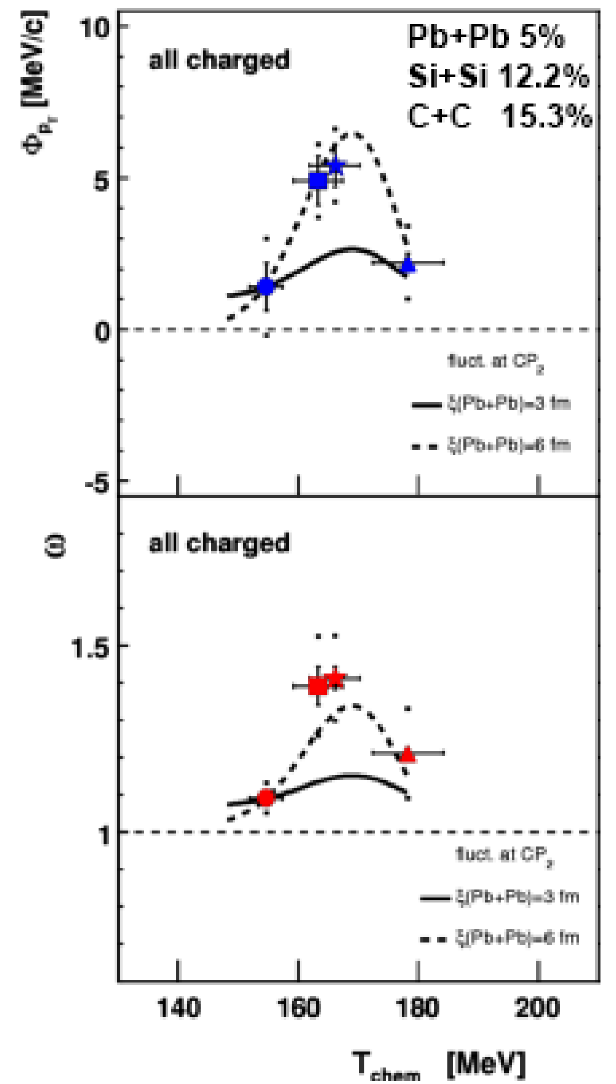
- **Beam Energy Scan (BES) program at RHIC**
  Talk by D. Cebra (STAR, Sep.26, 14:50-)
  - **$\sqrt{s_{NN}}$ = 5-200 GeV**
    → μ_B < 500 MeV at Chemical Freeze-out
  - **First stage results of BES @ RHIC**
    → Quark number scaling of v_2 works and $v_2(p_T)$ saturates for $\sqrt{s_{NN}}$ > 39 GeV

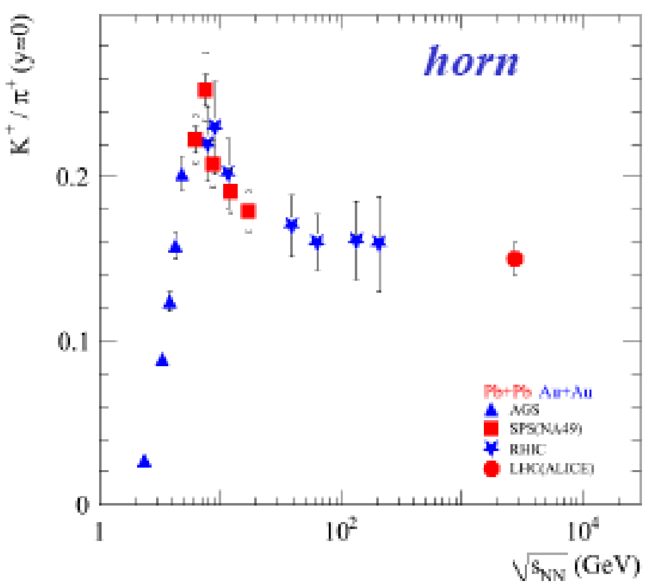


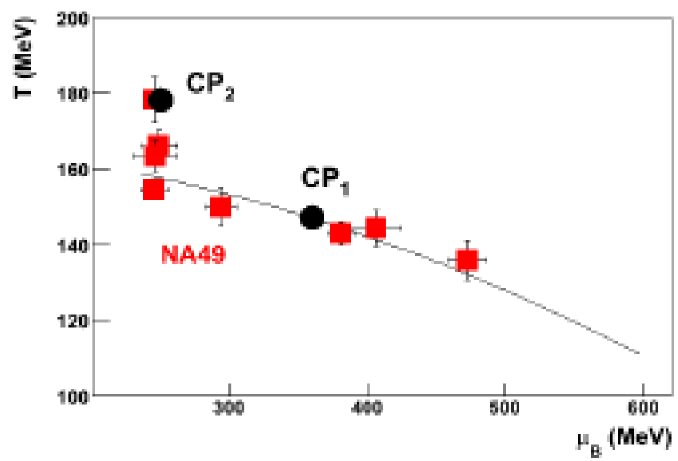


Critical Point / Onset of Deconfinement Search at SPS

- **Non-monotonic incident energy dependence at lower SPS energies**
  → Horn, Step, and Dale around $\sqrt{s_{NN}}$ = 8 GeV
- **Incident energy / System size scan @ SPS**
  → Enhanced fluctuations in Si+Si collisions at E = 158 *A* GeV
  G. Stefanek (Sep.26, 14:10-)
  T. Czopowicz (Sep.26, 14:30-)
- **What do these signals imply ?**







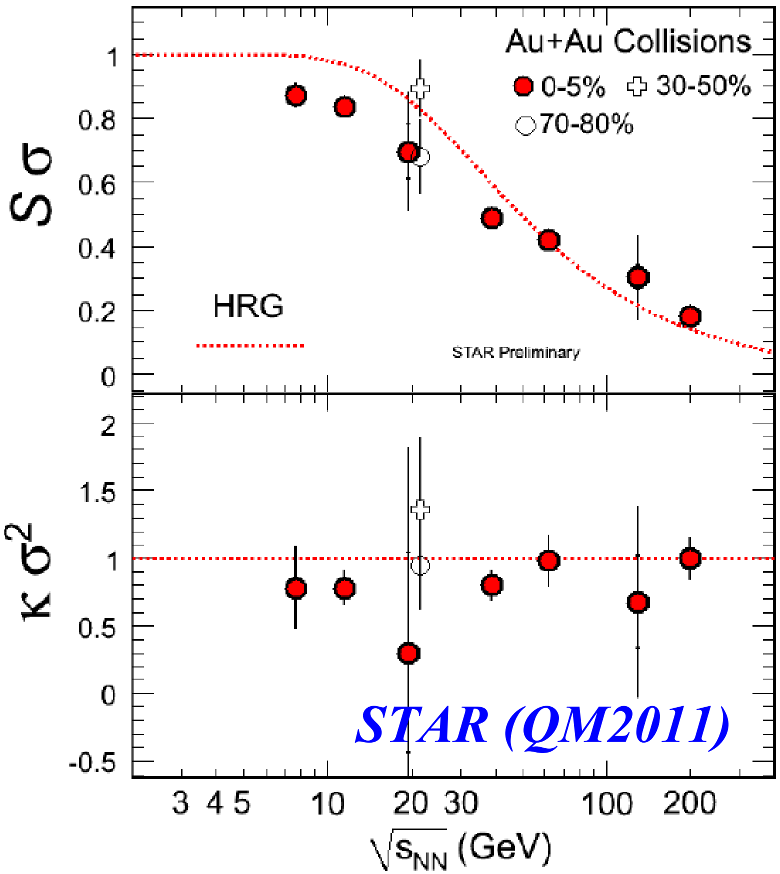
NA49, NA61/SHINE

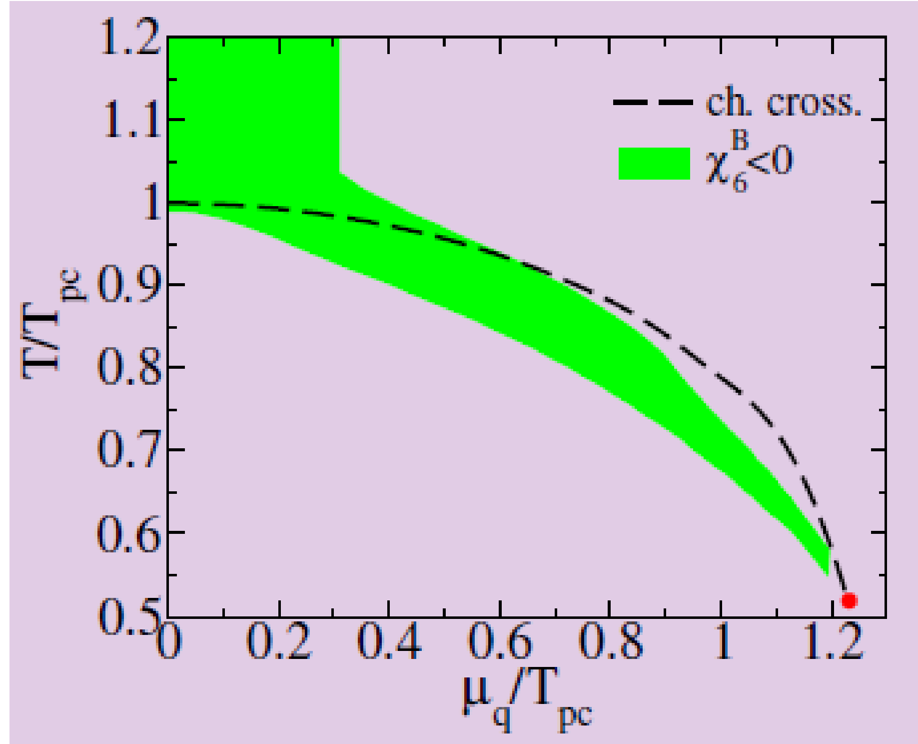
What is the signal of CP ?

- **Skewness sign ?**

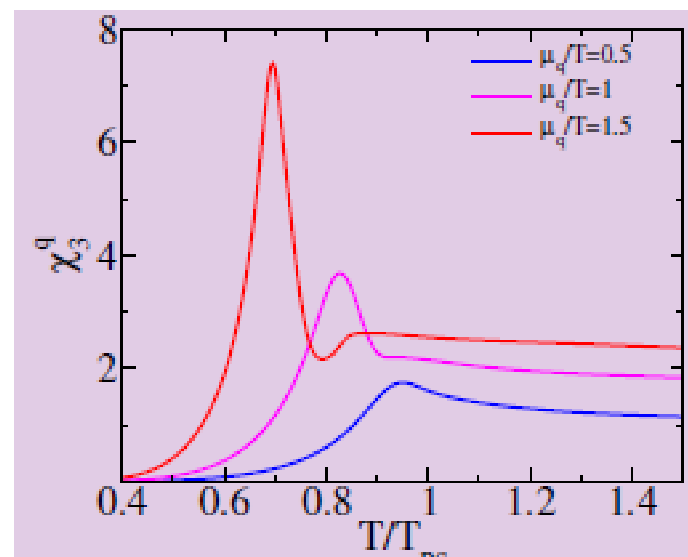
$$\frac{\partial \chi_B}{\partial \mu_B} = -\frac{1}{V}\frac{\partial^3 \Omega}{\partial \mu_B^3} = \frac{\langle (\delta N_B)^3 \rangle}{VT^2}$$

- **Kurtosis (4-th order)**
- **6-th order correlation ?**



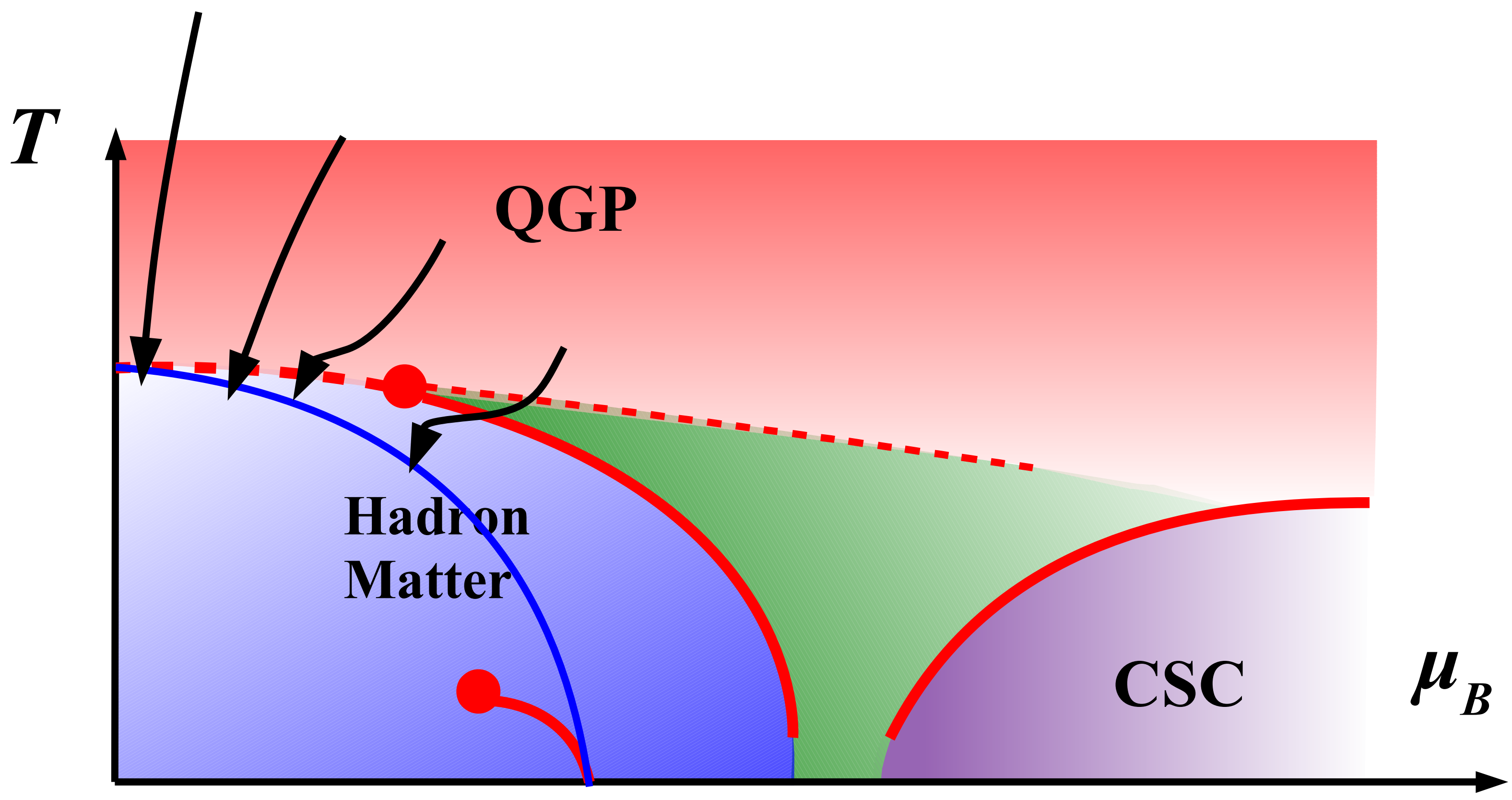


V. Skokov



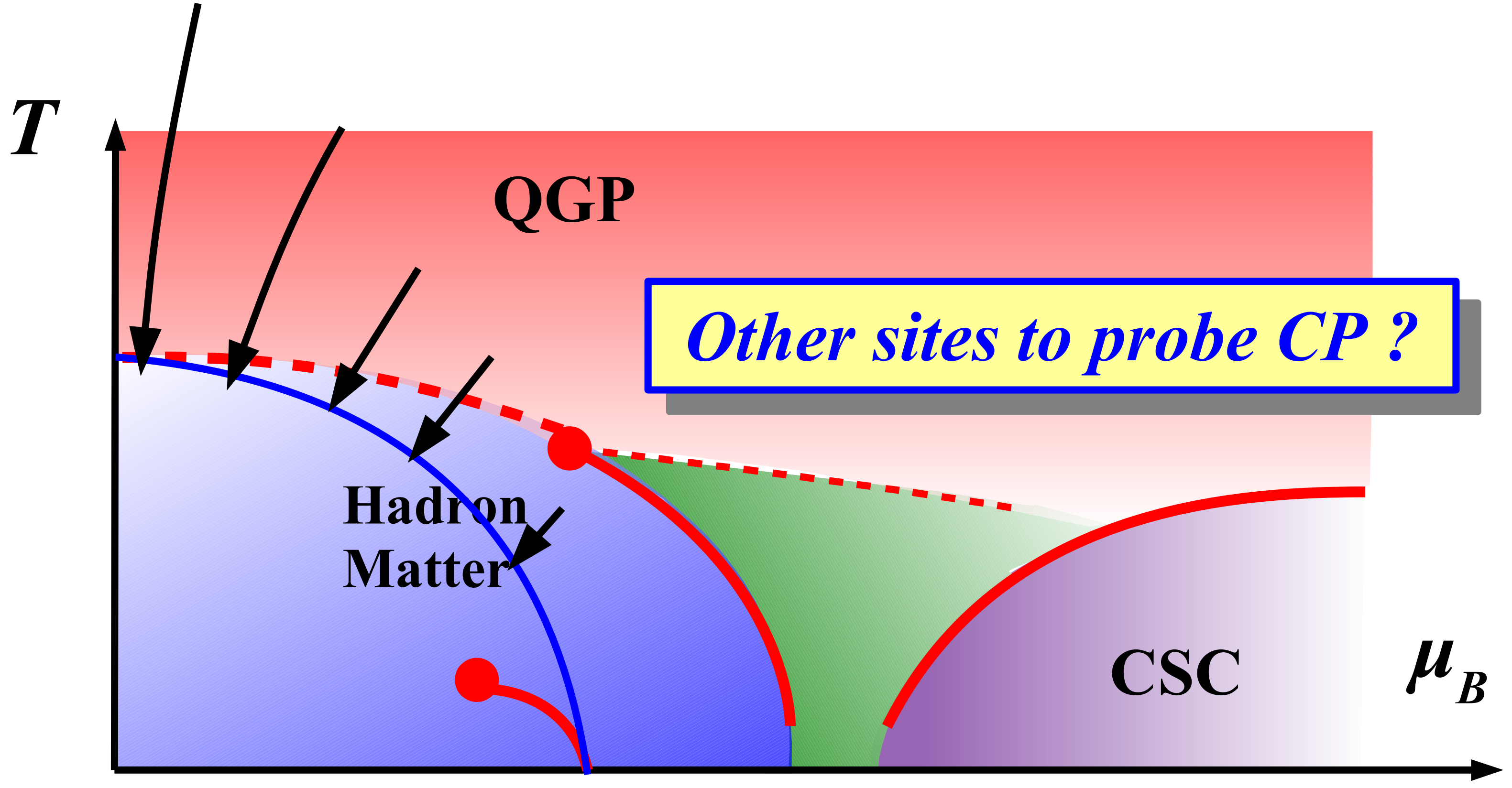
Do we have a luck ?

- **If we have a luck,**
  - **CP is in the region μB < 500 MeV and not far from the freeze-out line.**
    → Observation of CP in HICs



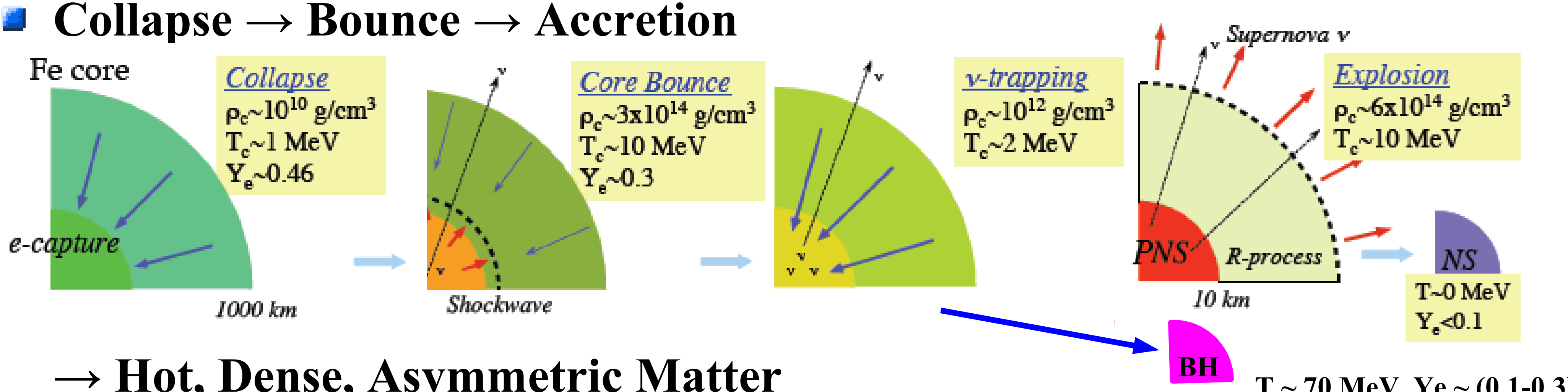
Do we have a luck ?

- **If we have a luck,**
  - **CP is in the region μB < 500 MeV and not far from the freeze-out line.**
    → Observation of CP in HICs
- **If we are unlucky,**
  - **CP has larger chemical potential and not reachable in HICs.**



Dynamical Black Hole Formation

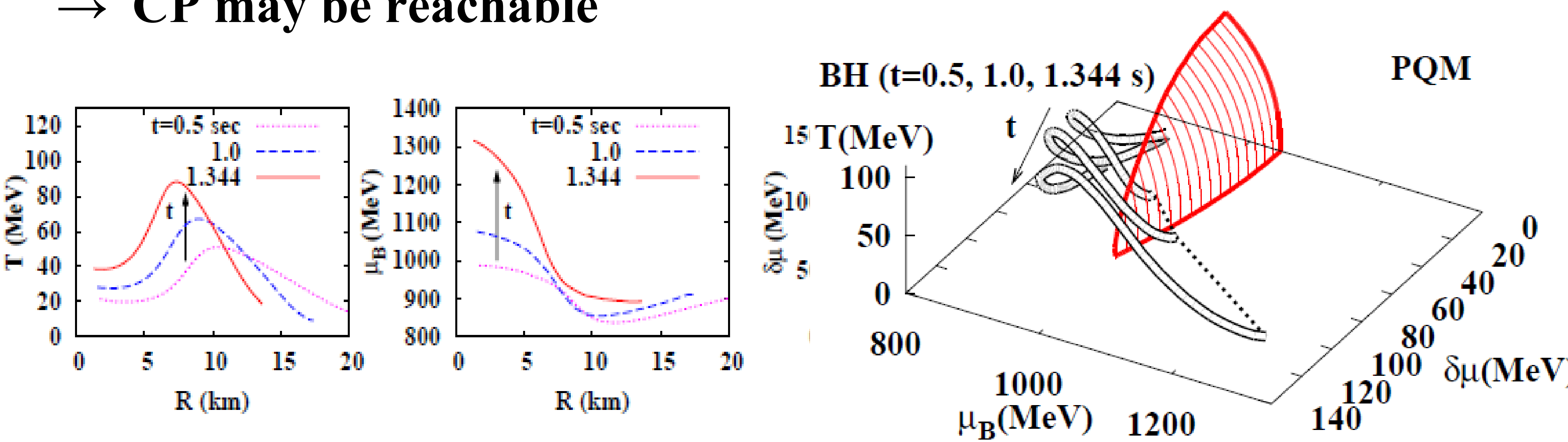
- Collapse → Bounce → Accretion



→ Hot, Dense, Asymmetric Matter

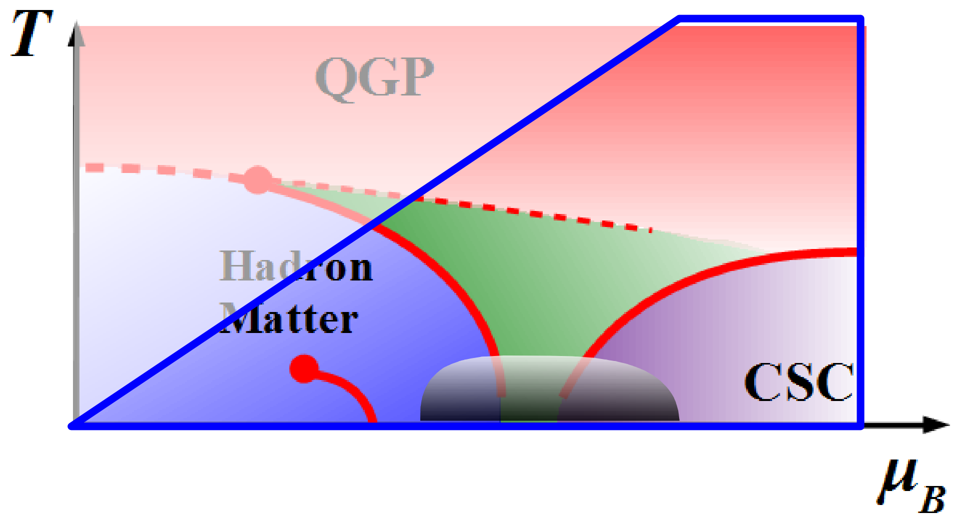
$T \sim 70$ MeV, $\mu_B \sim 1300$ MeV, $\delta\mu=\mu_e/2 \sim 130$ MeV

→ CP may be reachable



K. Sumiyoshi, et al.,('06); K.Sumiyoshi, C.Ishizuka, AO, S.Yamada, H.Suzuki ('09)
AO, H.Ueda, T.Z.Nakano, M. Ruggieri, K. Sumiyoshi, PLB in press.

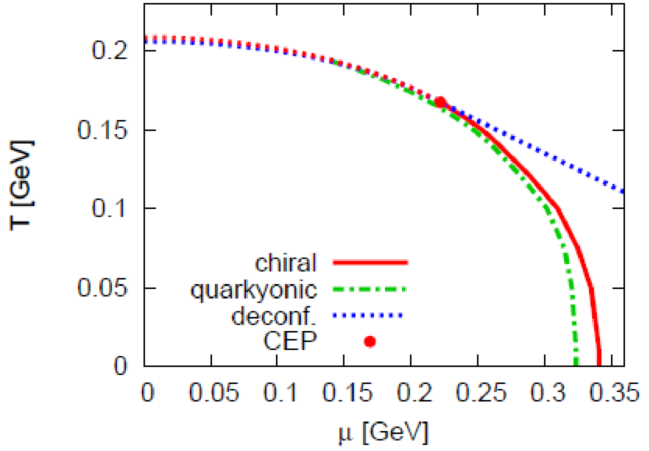
Phase structure in dense matter



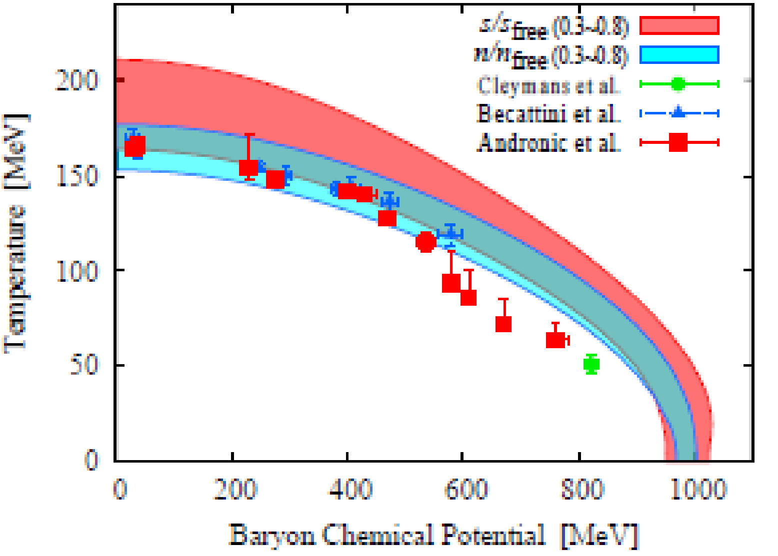
- **Cold dense matter and phase diagram structure**
  - ***Axial Anomaly Mismatched Fermi Surfaces and Vector Interaction in Dense Neutral Quark Matter, T. Kunihiro***
  - ***Multiquark interactions in NJL based model, B. Hiller***

Phase diagram structure

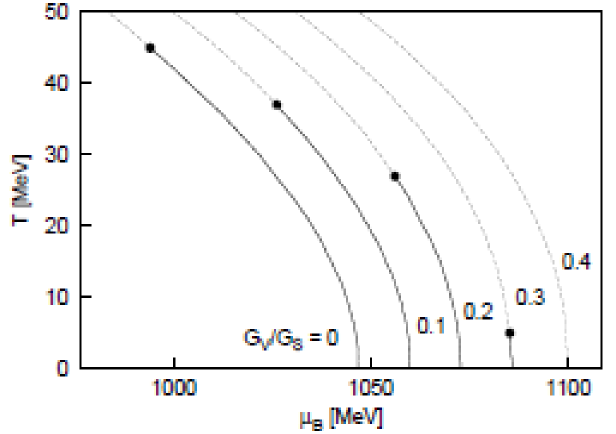
Polyakov loop extended NJL
McLerran, Redlich, Sasaki ('09)
Large Nc: McLerran, Pisarski, NPA796 ('07)83



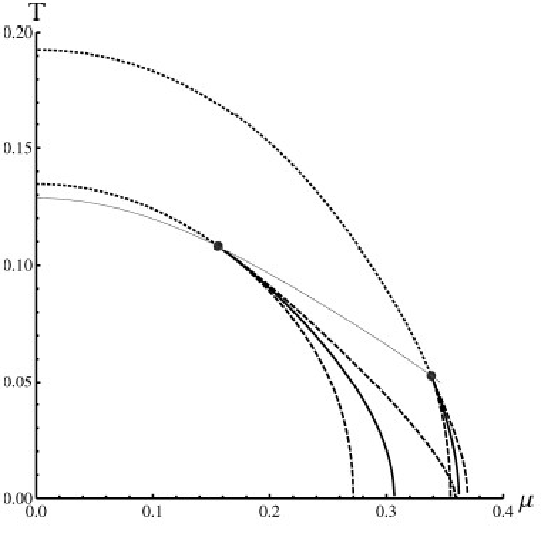
PNJL+Stat.:
K.Fukushima, PLB 695('11)387



NJL with vector int.
Kitazawa,Kunihiro,Nemoto ('02)

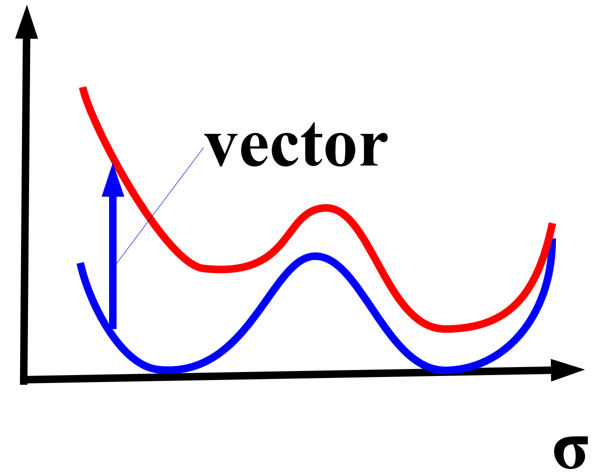


NJL+8q int., Hiller et al.

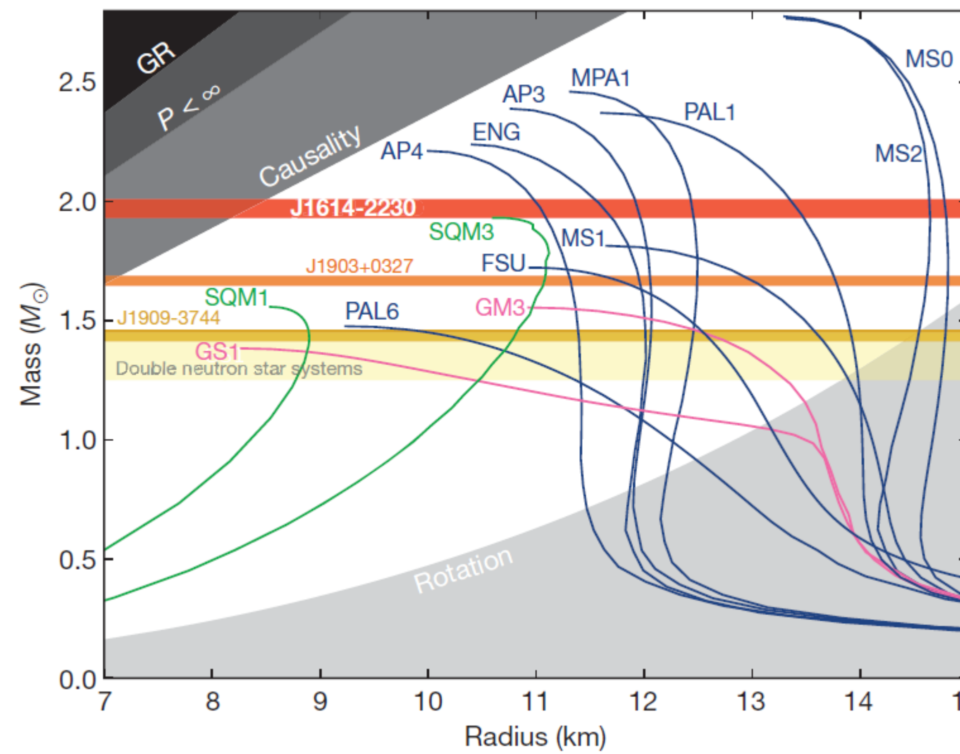


Phase diagram structure (cont.)

- **Phase diagram structure is sensitive to interaction**
  - **Vector interaction → larger μ_{CP}, smaller T_{CP}**
  - **8 quark interaction → shaper transition**
    μ also make p.t. shaper → smaller μ_{CP}
    Talk by B. Hiller (Sep.26, 16:10-)
  - **Number of CPs is also sensitive to interaction and CSC.**
    Talk by T. Kunihiro (Sep.26, 10:05-)



- **Are these academic problems ?**
  → No
  - **When CP is probed in HIC, quarkyonic matter properties affects observables.**
  - **Recently observed 1.97 Msun neutron star would have quark matter core.**

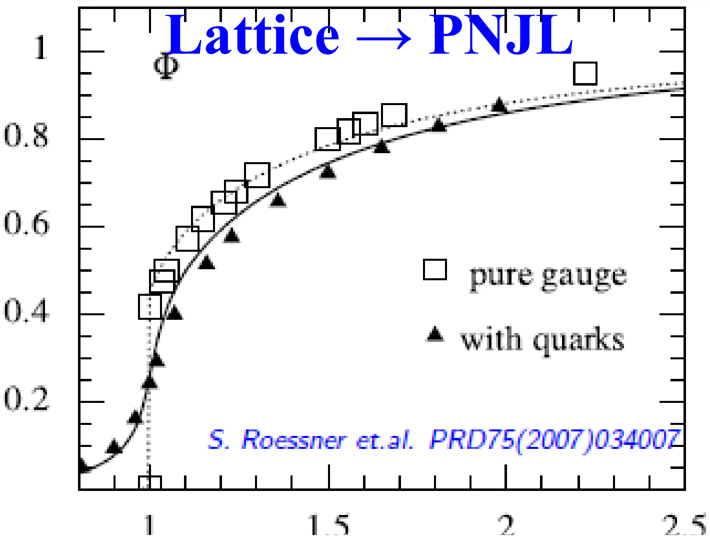


Demorest et al., Nature 467 (2010) 1081

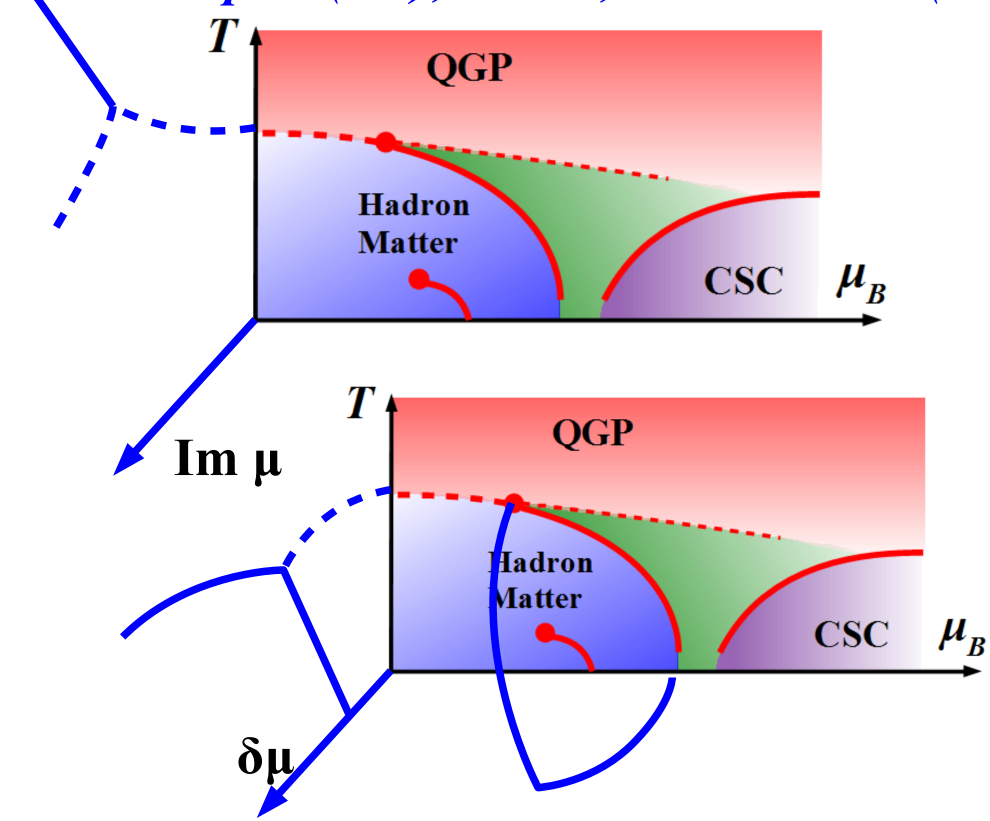
How can we fix model parameters ?

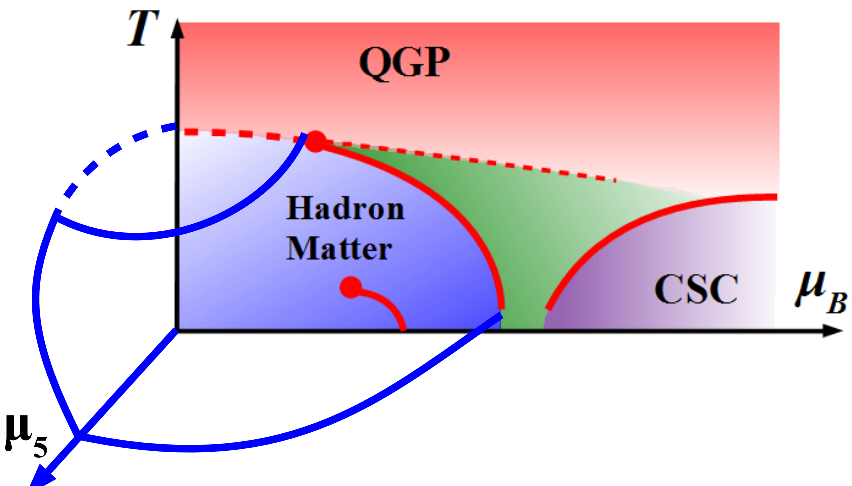
- Vacuum hadron properties + finite T (μ=0) lattice data

  + 3D phase diagram !



D'Elia, Lombardo('03); de Forcrand, Philipsen('03); Sakai, Yahiro et al. ('10),





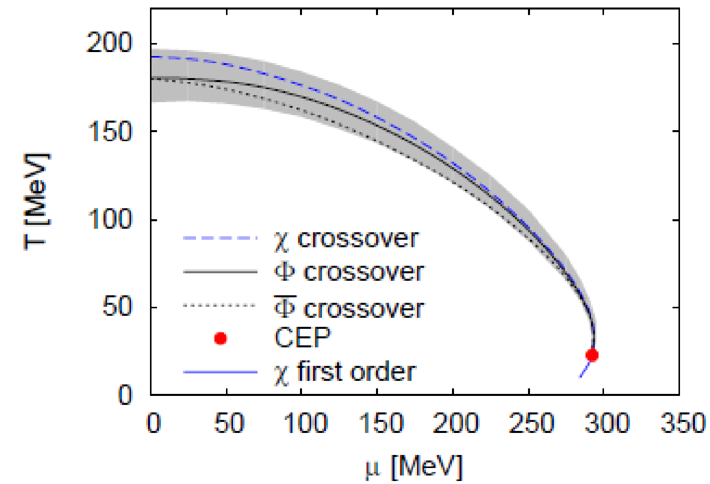
Kogut, Sinclair ('04); Sakai et al.('10); AO, Ueda, Nakano, Ruggieri, Sumiyoshi ('11)

Fukushima et al.('08); Fukushima,Ruggieri,Gatto('10), Ruggieri ('10);Yamamoto('11); Nakano,AO (in prep.)

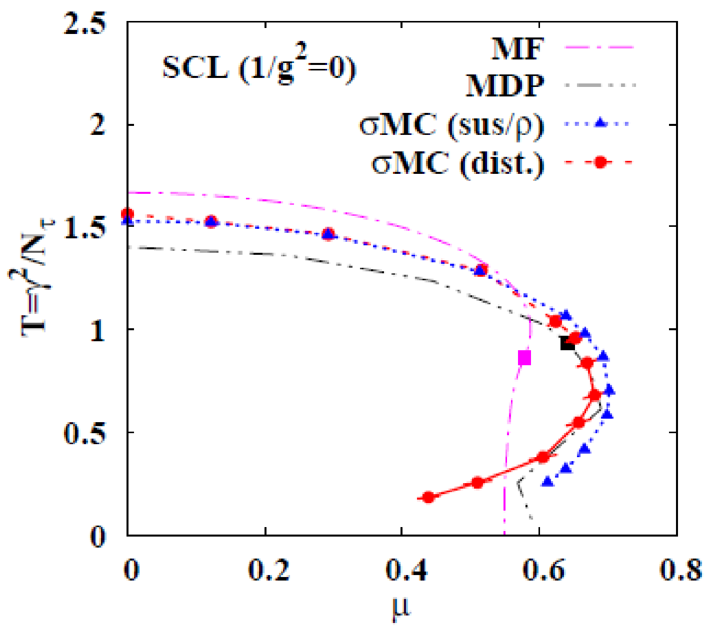
No sign prob. at μ_B=0

"First Principle" Approaches

- **Functional RG method**
  Herbst, Pawlowski, Schafer ('11)
- **Canonical approach in LQCD**
  Ejiri ('08); Nagata, Nakamura('10)
- **Strong Coupling Lattice QCD**
  de Forcrand, Fromm ('09); de Forcrand, Unger ('11) ; Miura,Nakano, AO('11), AO, Nakano, in prep.

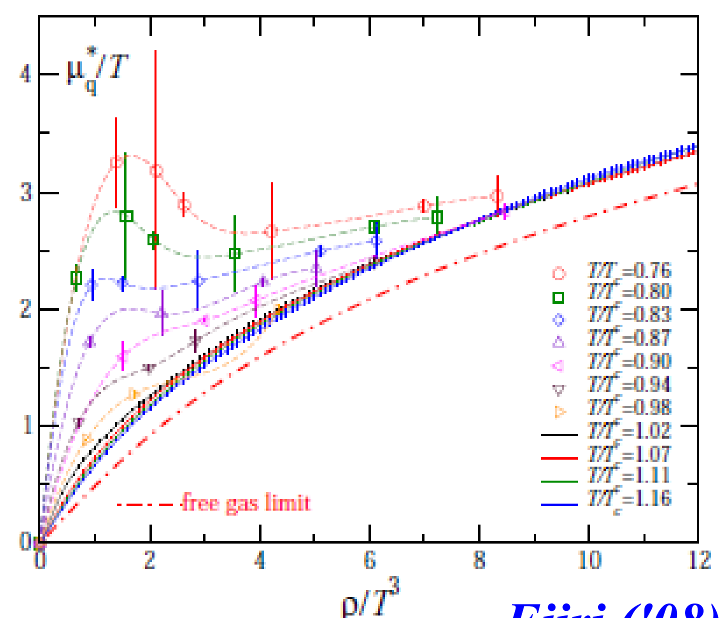


Herbst, Pawlowski, Schafer, ('11)



AO, Nakano

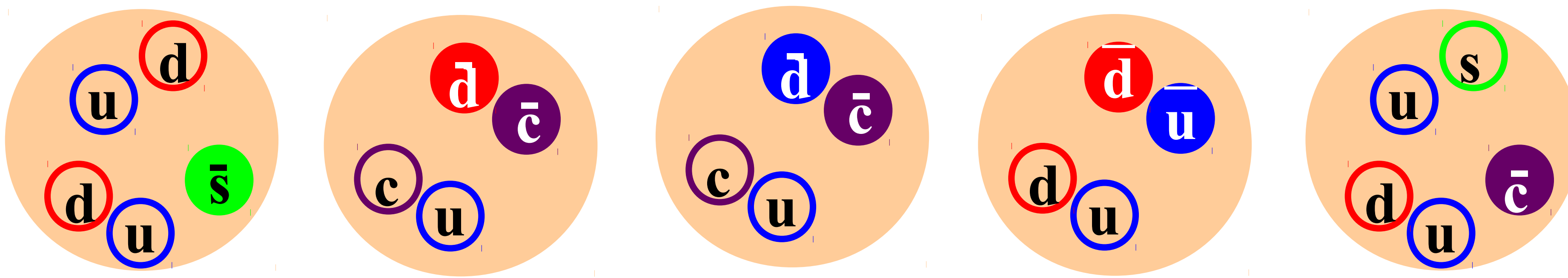
CP ?



Ejiri ('08)

Related Topics: Exotic Hadrons

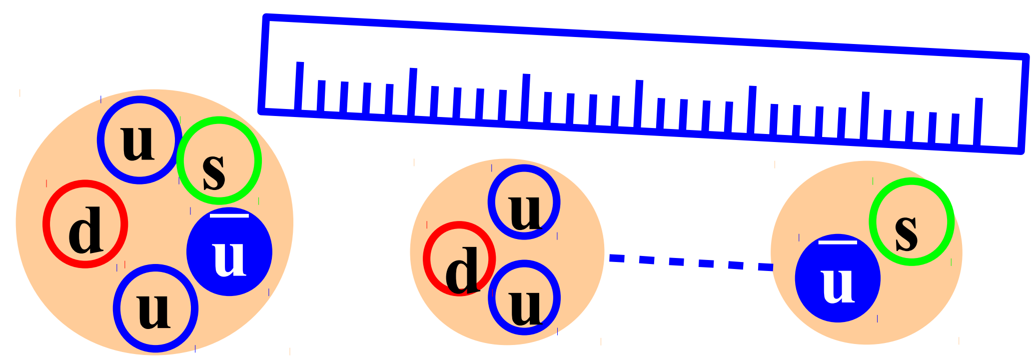
- **Exotic hadrons**
  → Θ⁺, Z, X, Y, ... Discovered/Proposed at LEPS, Belle, BaBar,...



Θ^+ **Z(4430)** **X(3872)** $\mathbf{f_0}$ Θ^+_{cs}

- **X, Y, Z particles from Belle**
  Talk by S. Olsen (Sep.26, 15:35-)

- **Relation to HICs**
  Can we distinguishi various pictures (Di-quark, Hadronic molecule, Tetraquark) ?
  → Production Yields in HIC.



uuds$\bar{u}$ **p** **K⁻**

Λ (1405)

Exotics from Heavy-Ion Collisions

- **Coalescence model**

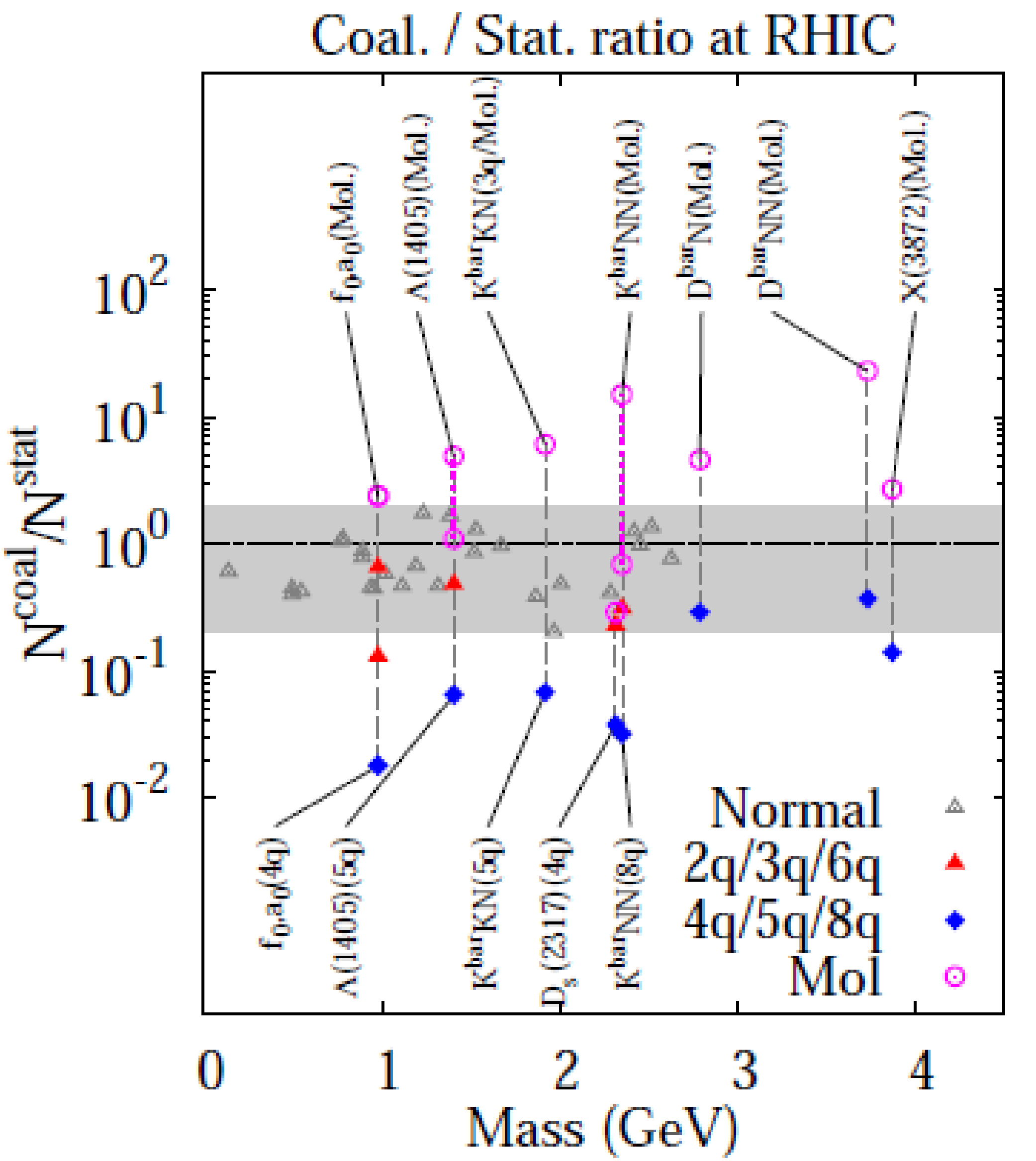
$$N_h^{\text{coal}} \simeq g_h \int \left[\prod_{i=1}^{n} \frac{d^3x\, d^3p}{(2\pi)^3} f(x_i, p_i) \right] \times f^W(x_1, x_2, \dots x_n; p_1, p_2, \dots p_n)$$

Dist. of const. ($f(x_i, p_i)$)

Intrinsic Wigner func. (f^W)

  - **Successful in explaining baryon enhancement, quark number scaling of v_2, .**

- **Assuming that coalescence formation is dominant, we can utilize *Hadron Yield in HIC as a ruler of hadron size*.**



Cho, Furumoto, Hyodo, Jido, Ko, Lee, Nielsen, AO, Sekihara, Yasui, Yazaki (ExHIC Collab.), PRL('11)212001; arXiv:t:1107.1302

Summary

- **For *high T phase transition*, experimental and theoretical progresses are rapid and steady. We wil obtain QCD transition temperature at μ=0 soon, and "initial" temperature of QGP.**
  - **But we have much more to do: Initial condition / Early thermalization / Transport coef. / Dynamics / ….**
- ***QCD critical point is the corner stone* of the phase diagram, and its search is ongoing. Clear signature is not yet obtained, but there are some hints in data. It may be possible to specify its location in ab initio approaches.**
  - **It is very important to find clear signatures of CP or critical region.**
- ***Phase structure at high densities* is also relevant to heavy-ion collision physics, and is closely related to compact star physics. Effective models with the help of ab initio approaches (lattice / Func. RG) would be interesting and useful tools.**
- ***Exotic hadron* formation in HICs is interesting direction; hadron size and formation mechanism.**

Thank you for your attention !