The Ideal Liquid Discovered by RHIC

Infrared Slavery Above and Hadronic Freedom Below Tc

in collaboration with

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(partly, H.-J. Park, E. Shuryak)

NPA 740 (2004) 171; 747 (2005) 530
hep-ph/0503016
nucl-th/0507011; nucl-th/0507073

Chang-Hwan Lee @ PUSAN NATIONAL UNIVERSITY

Plan of Talk

Below Tc : Chiral Symmetry Restoration

- Brown/Rho Scaling
- Vector Manifestation a la Harada/Yamawaki

Above Tc: colorless Mesonic Bound States

- What can we learn from lattice calculations ?
- Implications for RHIC:
  Scaling decay width & Delayed-decay of mesons

Below Tc: Chiral Symmetry Restoration

- Dropping Masses a la Brown/Rho Scaling
- Harada/Yamawaki & Harada/Sasaki/Rho

Vector Manifestation.

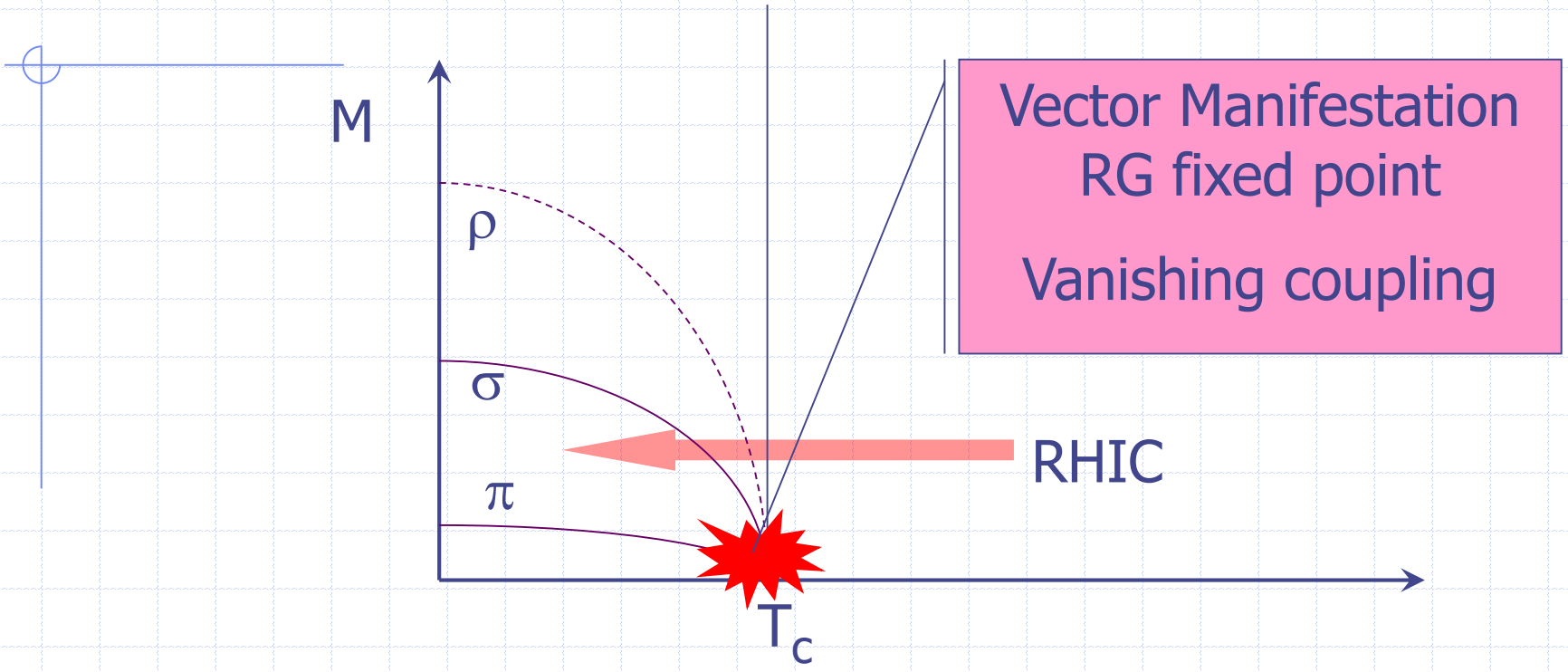
Fixed Point of RG approach gives

vanishing coupling, vanishing mass

towards chiral symmetry restoration point.

both mass & decay-width scale !

below Tc
Chiral Symmetry Restoration



Vector Manifestation
RG fixed point

Vanishing coupling

Q) What happens above Tc ?

Hadronization ?

Above Tc:

Ideal Liquid at RHIC (Shuryak's talk)

- Matter formed at RHIC is not weakly interacting quasi-particle gas.

Question

- Can hadronic modes survive after phase transition ?
- How can these modes connected with chiral symmetry restoration below Tc ?

Mesonic bound states above Tc:

- Hatsuda & Kunihiro, PRL 55 (1985) 158
  (para pion & sigma)
  Asakawa, Hatsuda, & Nakahara, NPA 715 (2003) 863c
  Brown, Lee, Rho, & Shuryak, NPA 740 (2004) 171

  Quark-antiquark bound states exists above Tc.

QM2005

- Poster by Kitazawa (with Kunihiro, Nemoto)
  hep-ph/0505070, …
- talk by Mannarelli (with Rapp)

Potential from Bielefeld Lattice Results

$$V_1(r,T) = F_1(r,T) - T\frac{\partial F_1(r,T)}{\partial T}$$

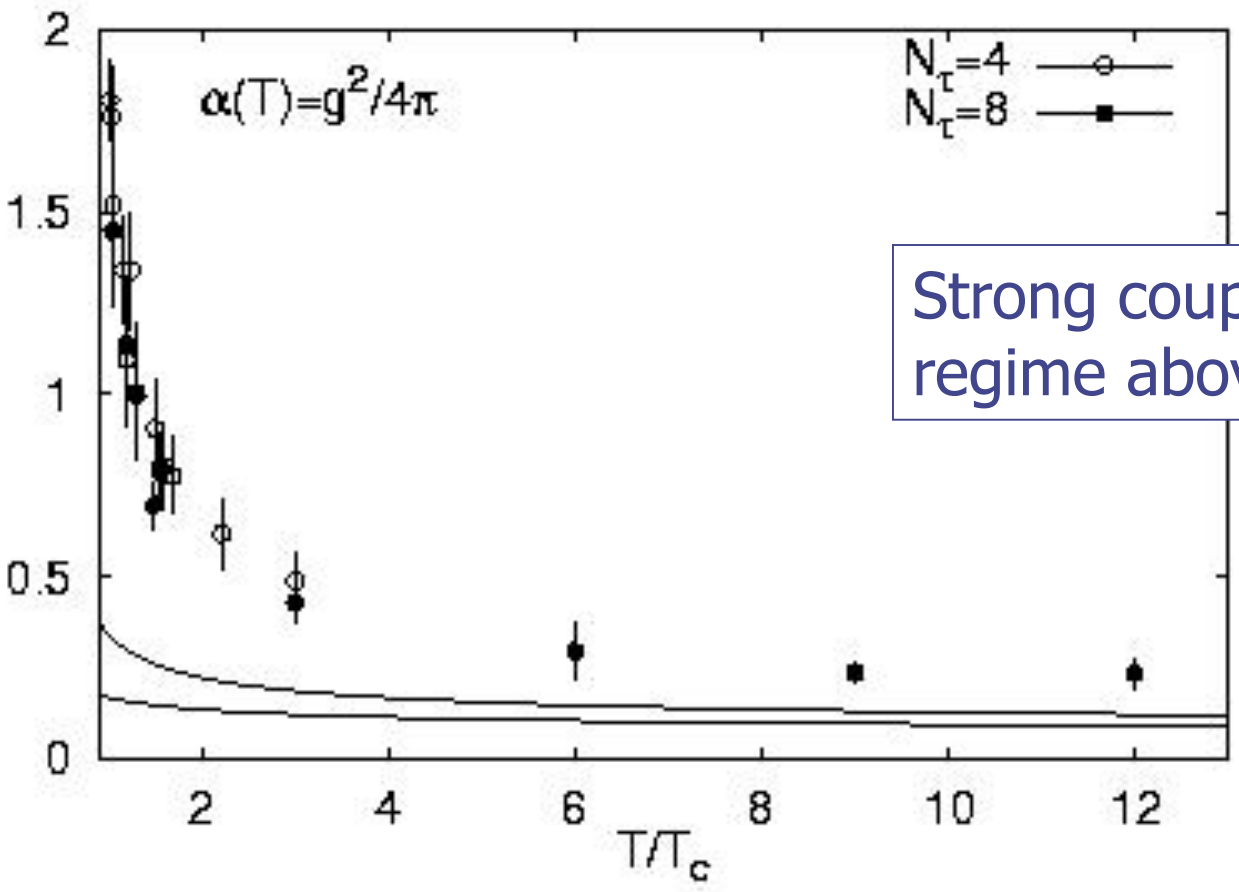
cf) Wong, hep-ph/0408020; combination of V & F

What is the binding energy if we take the potential extracted from lattice free energy ?

Assumption:

finite value of V_1 at $r=\infty$ is absorbed into the renormalized thermal mass of quarks.

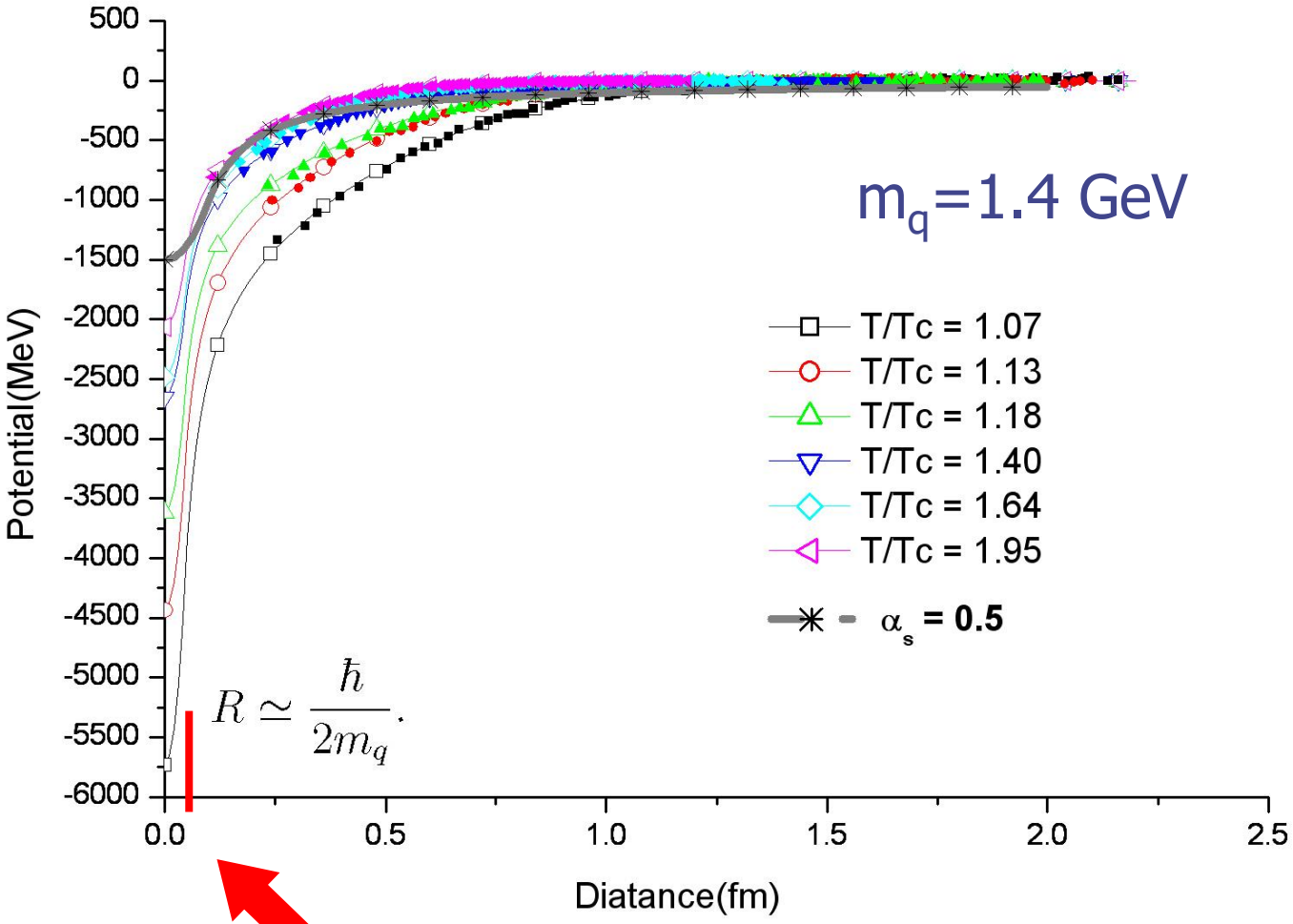
Above Tc: Running coupling at large diatance



Strong coupling regime above Tc

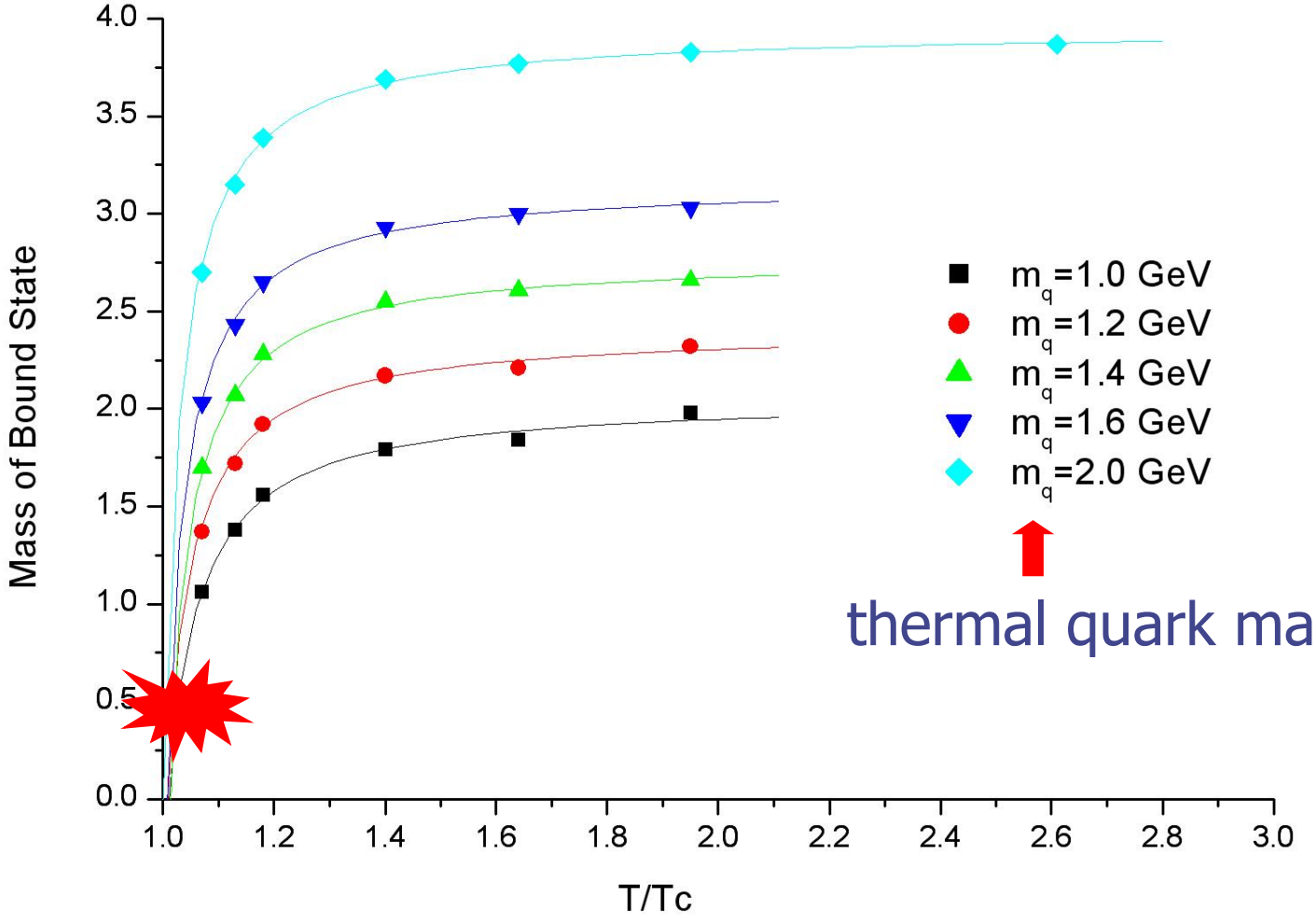
Lattice Calculation by F. Zantow et al. (Bielefeld)

Heavy quark potential (renormalized) from Bielefeld lattice



$$V(r,T) = -\frac{\alpha_s^{\text{eff}}(R,T)}{2R}\left(3 - \frac{r^2}{R^2}\right) \quad \text{for } r < R,$$

Mass of Bound States (with heavy quark potential)



thermal quark mass

Solid lines are just to guide you.

Modification for light quarks in chiral limit

color-magnetic effects (cf K-electron)

$$H_{int} = \frac{e^2}{r}(1 - \vec{\alpha}_1 \cdot \vec{\alpha}_2),$$

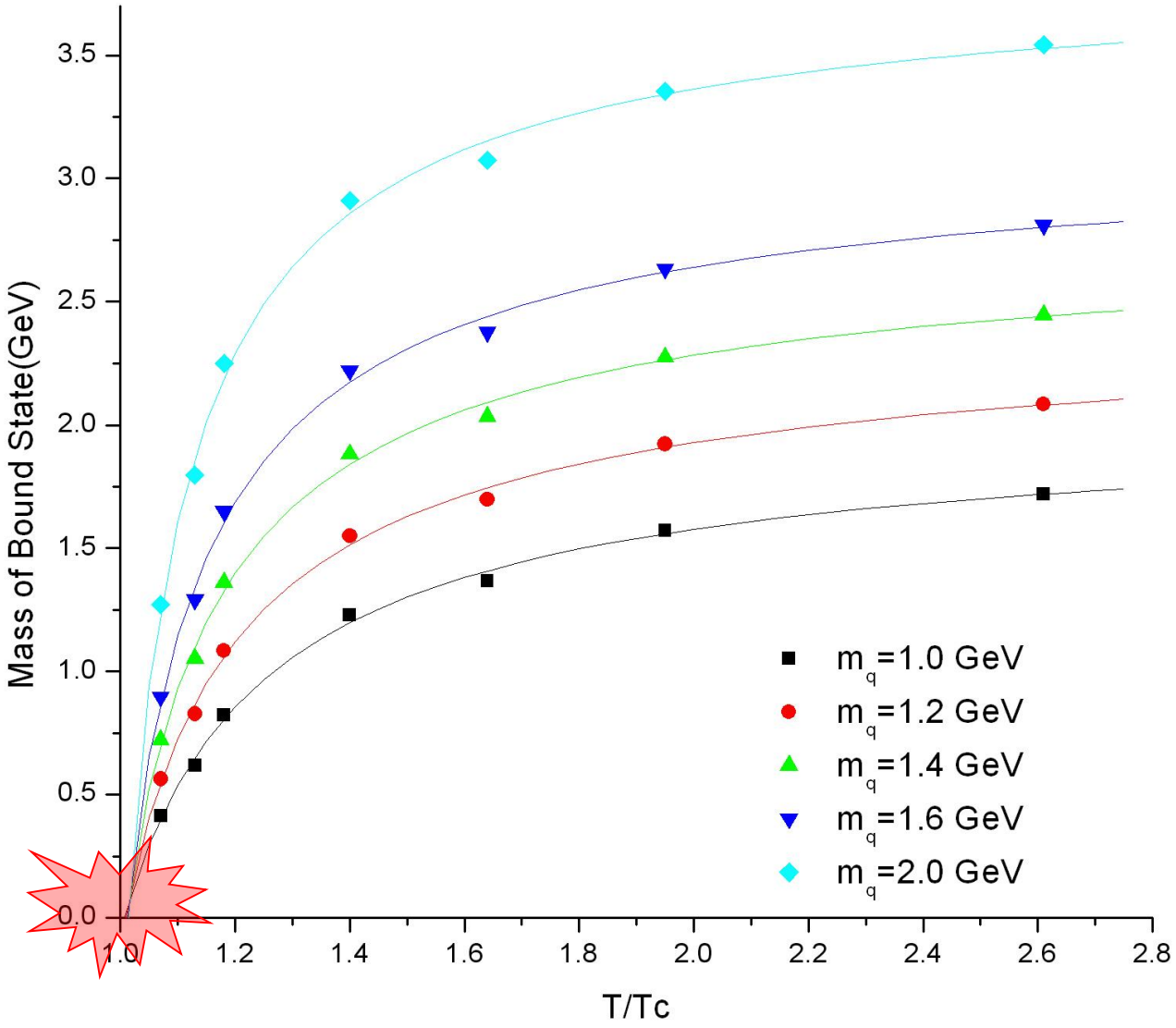
alpha =
velocity of particles (c=1 unit)

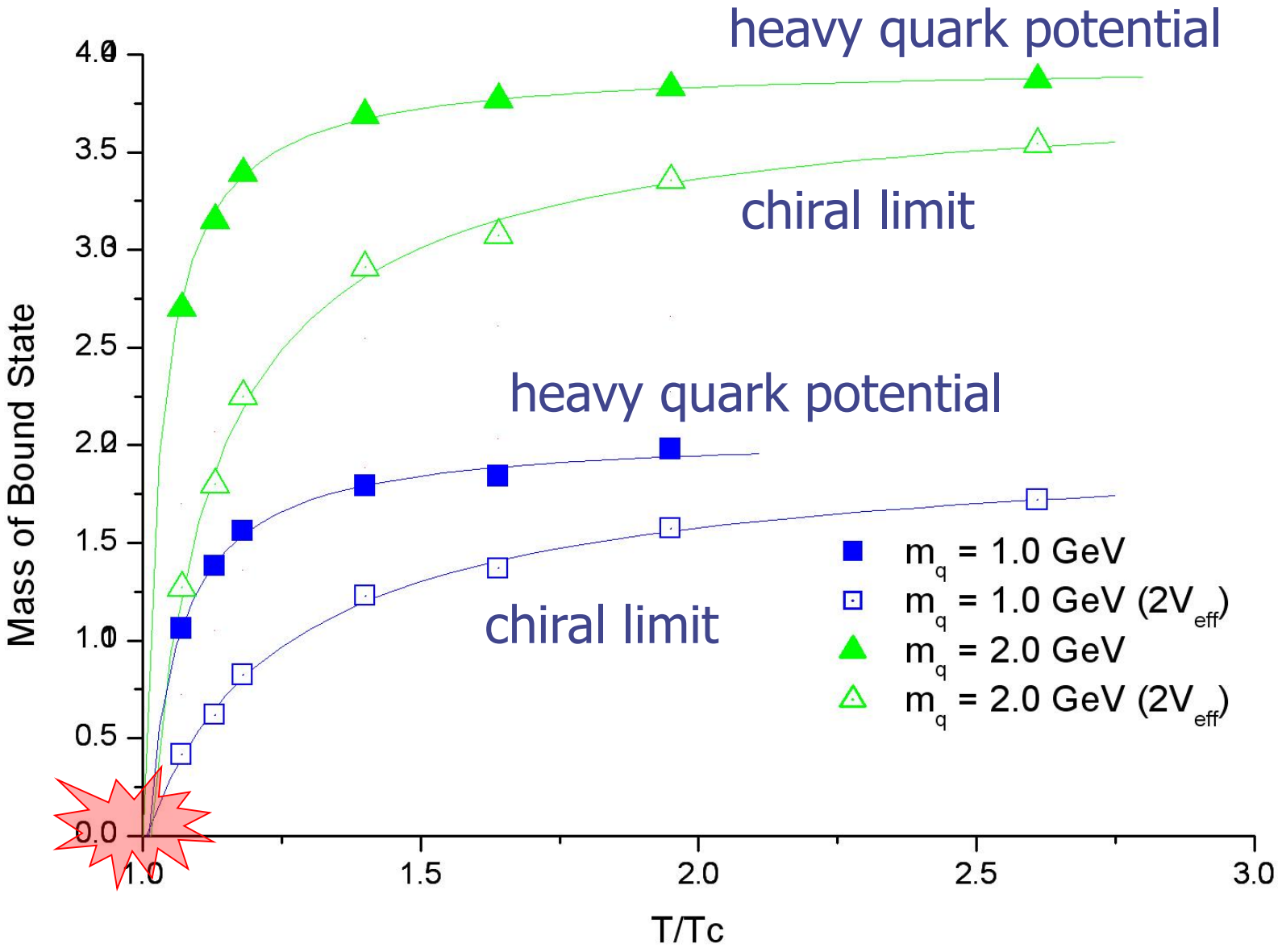
With chirally restored u, d quarks (helicity eigenstates)

$$V^{\rm eff}_{\rm light}(T = T_c) = \begin{cases} 2V^{\rm eff}_{\rm heavy} & for\ \vec{\alpha}_1 \cdot \vec{\alpha}_2 = -1 \\ 0 & for\ \vec{\alpha}_1 \cdot \vec{\alpha}_2 = +1 \end{cases}$$

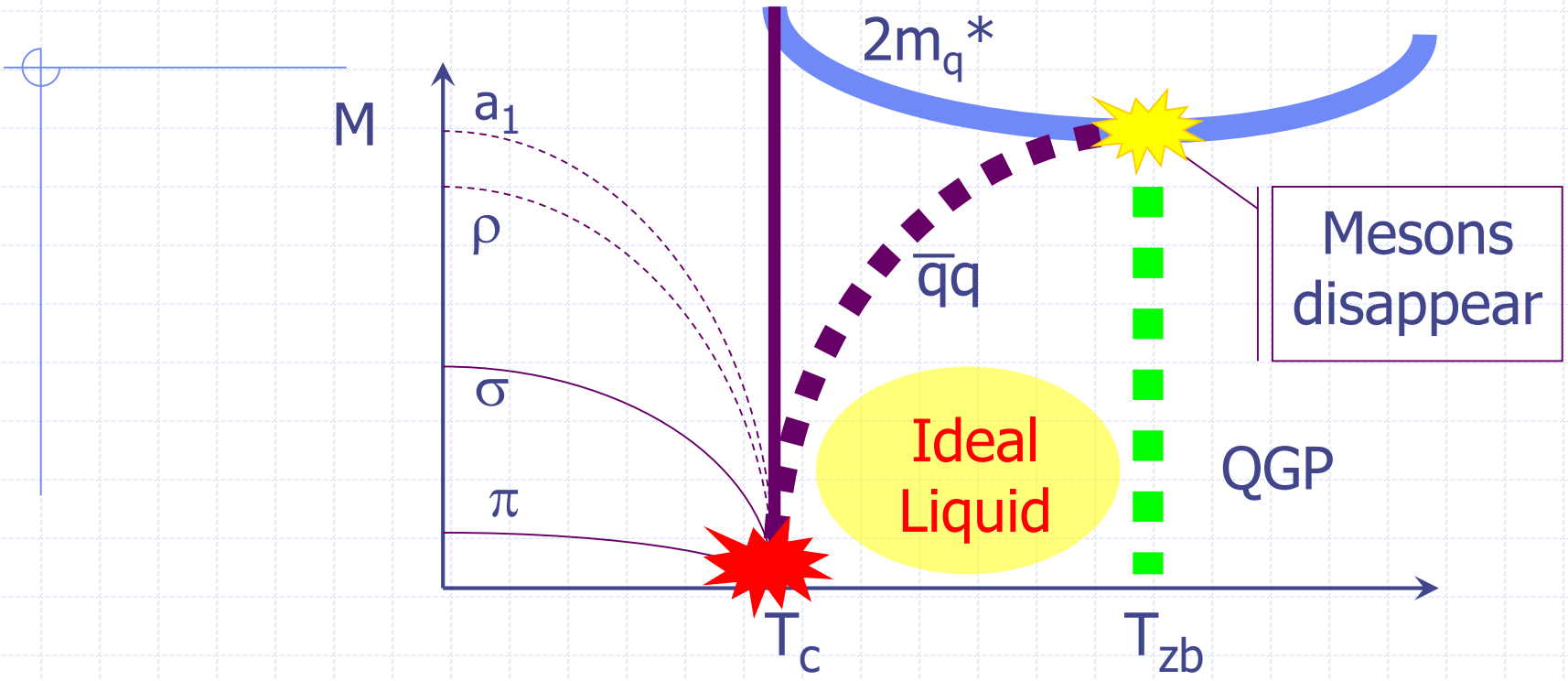
32 degrees of freedom (including plasmino)
= lattice result 32 at Tc !

With modified potential (chiral limit)



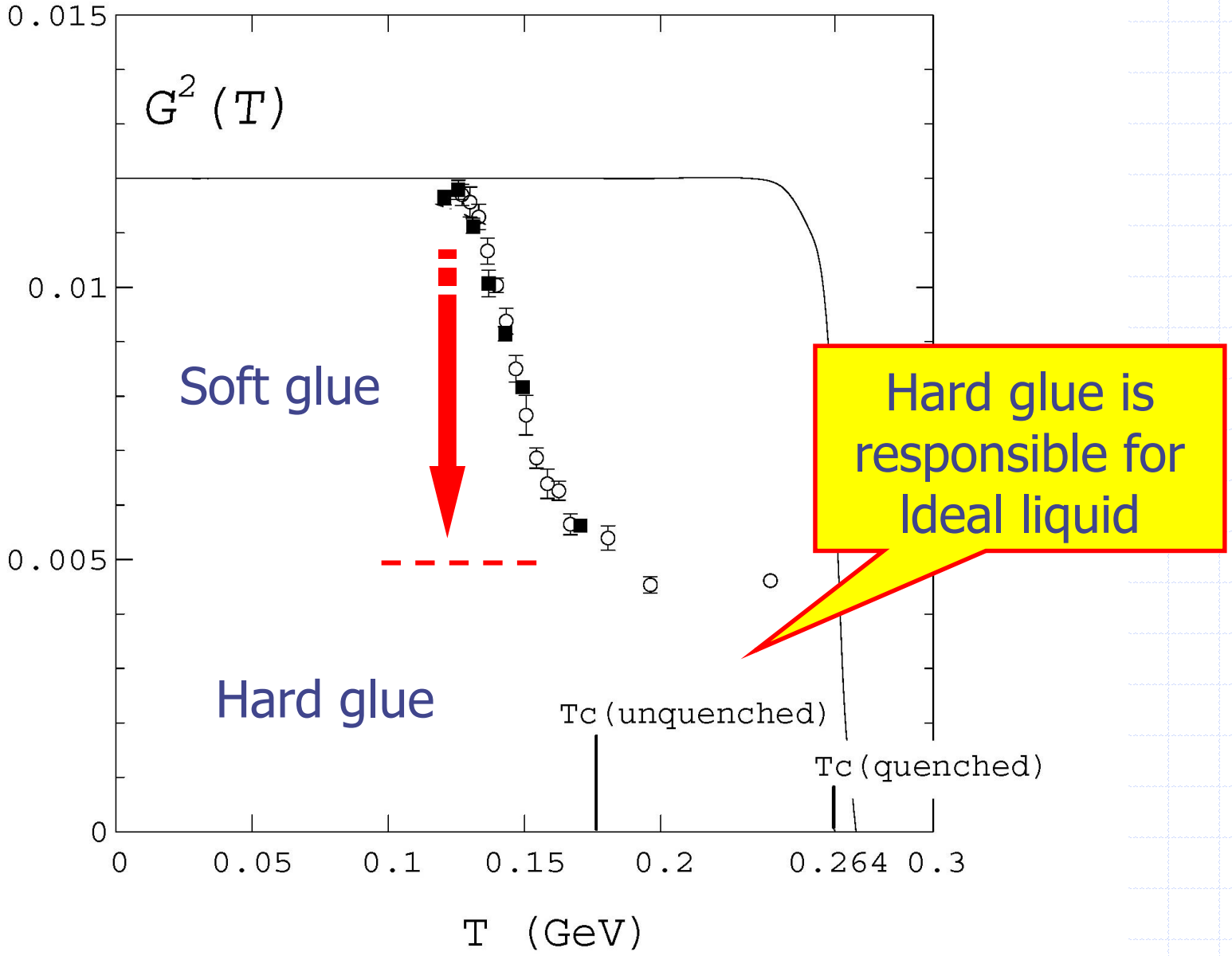

heavy quark potential
chiral limit
heavy quark potential
chiral limit
m_q = 1.0 GeV
m_q = 1.0 GeV ($2V_{eff}$)
m_q = 2.0 GeV
m_q = 2.0 GeV ($2V_{eff}$)
Mass of Bound State
T/Tc
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
1.0
1.5
2.0
2.5
3.0

Unorthodox phase structure (Hypothesis)



- Masses of colorless pion, sigma-like modes above Tc go to zero at T = Tc;+

Lattice Results from Miller: Gluon Condensate



Implications for RHIC

Scaling decay width (nucl-th/0507073)

$$\frac{\Gamma_\rho^\star}{\Gamma_\rho} \sim \left(\frac{m_\rho^\star}{m_\rho}\right)^3 \left(\frac{g^\star}{g}\right)^2 \Rightarrow \left(\frac{m_\rho^\star}{m_\rho}\right)^5$$

Vector manifestation by Harada & Yamawaki

T	$m_\rho^\star/m_\rho$	$\Gamma^\star/\Gamma$
175 MeV	0	0
164 MeV	0.18	0
153 MeV	0.36	0.01
142 MeV	0.54	0.05
131 MeV	0.72	0.22
120 MeV	0.90	0.67

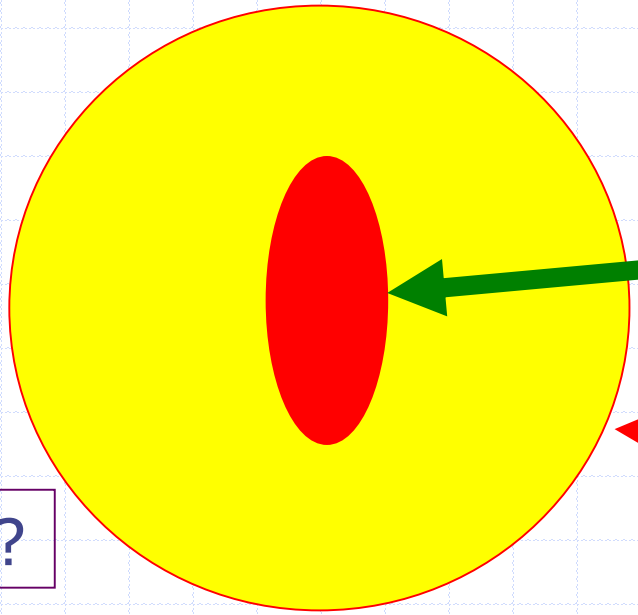
No decay near Tc !

dominant decay is around & below T=120 MeV

STAR: Peripheral collisions: $T_{\text{chemical freeze out}} = Tc$

$$\frac{\rho^0}{\pi^-}|_{STAR} = 0.169 \pm 0.003(\text{stat}) \pm 0.037(\text{syst}),$$

PRL 92 (2004) 092301



Tc : chemical equilibrium

Delayed decay of rho at T=120 MeV

HBT ?

Equilibrium is already established above Tc at RHIC

Peripheral collisions: $T_{\text{chemical freeze out}} = Tc$

$$\frac{\rho^0}{\pi^-}|_{STAR} = 0.169 \pm 0.003(\text{stat}) \pm 0.037(\text{syst}),$$

4×10^{-4} with vacuum mass
(Braun-Munzinger et al.)

With massless mesonic bound states at Tc
this ratio is governed mainly by degrees of freedom

$$\frac{3\ (\text{rho}^0)}{21\ (\text{pi}^-\ \text{from rho, } \ldots)} = 0.14$$

nucl-th/0507073 : $0.14 \leq (\text{rho}^0/\text{pi}^-) \leq 0.21$

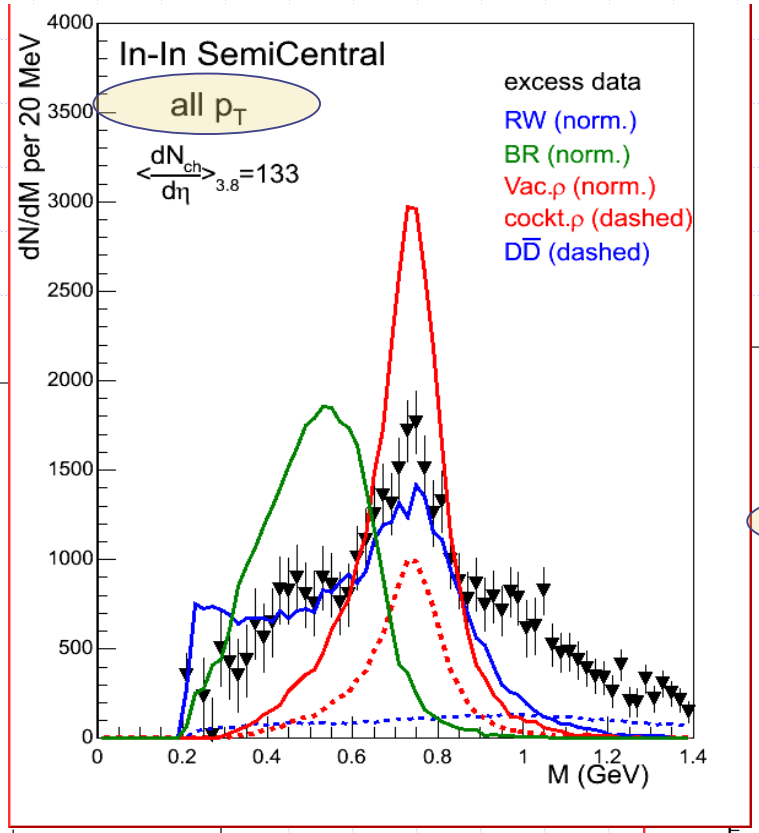
Conclusions

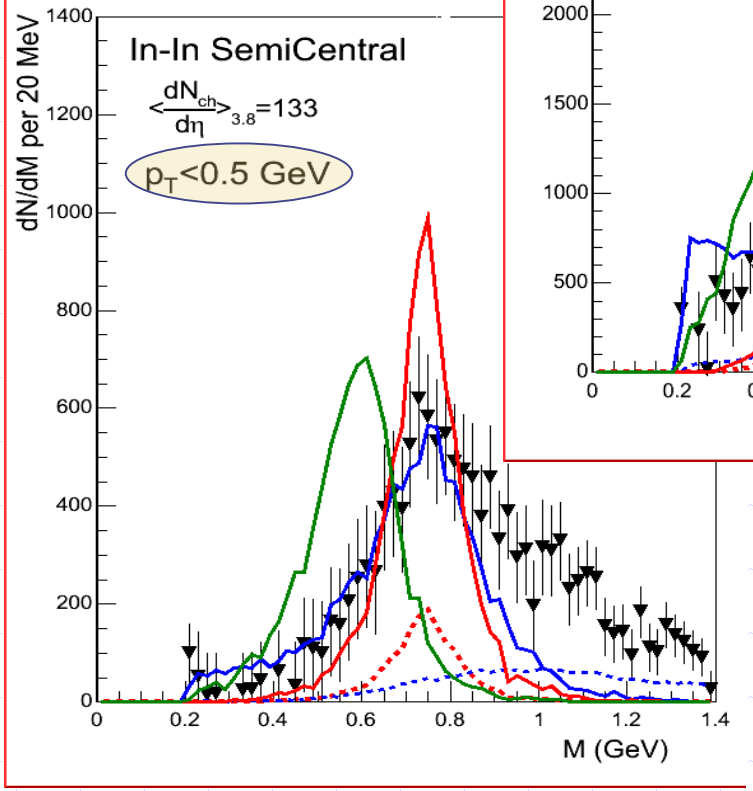
- Our analysis (*chiral symmetry restoration + Bielefeld Lattice Result*) indicates massless *mesonic bound states* at Tc;+.
- *mass & width (simultaneous scaling):* delayed rho decay is consistent with rho/pi ratio in peripheral collisions in STAR.

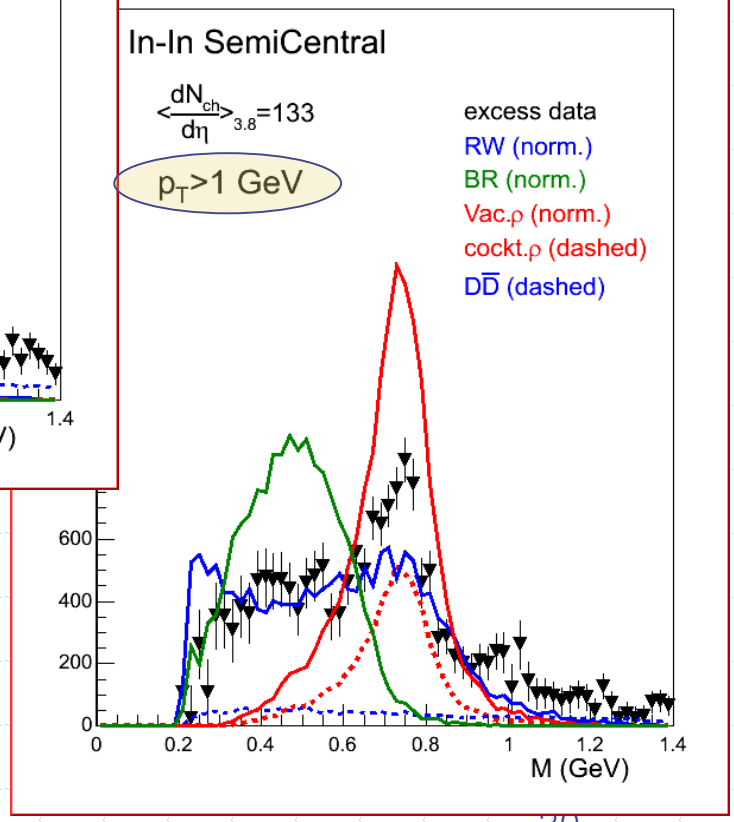
Thanks to Bielefeld Lattice Group (F. Zantow) for providing us their results.

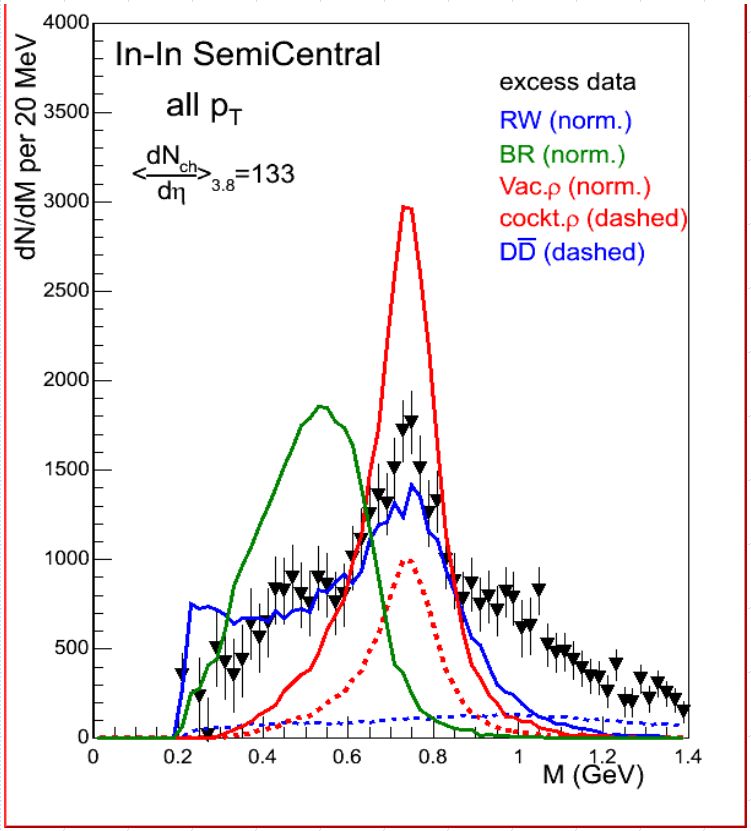
NA60 Comparison of data to RW, BR and Vacuum ρ

p_T dependence









Too early to rule out BR scaling.

Comments on NA60 vs BR

- BR: done by Rapp.
- No consideration on scaling decay width.
- Q) What is bump around 0.5 GeV ?