한국 아이디어

쿼크물질 연구소 (2008 SRC 안)

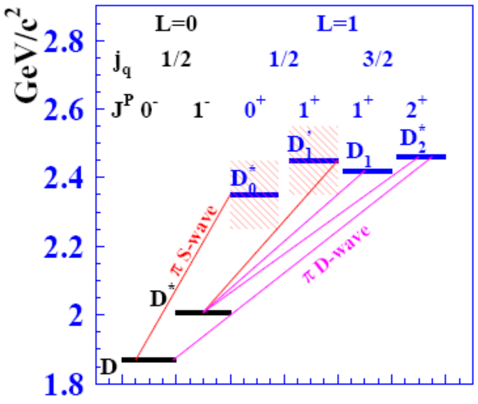
연구주제

- 가벼운 벡터중간자를 활용한 쿼크물질 카이랄 대칭성확인
- 무거운 쿼크계를 활용한 쿼크물질의 탈구속 현상확인
- 중이온 충돌 실험의 특이현상을 통한 쿼크물질 확인

한국아이디어 1

중이온 충돌 실험의 특이현상을 통한 쿼크물질 확인

Recent Highlights in Hadron Physics



Babar: D_{SJ}(2317) 0+

Puzzle in Constituent Quark Model(2400)

1. DK threshold effect
2. Chiral partner of $(0^- 1^-)$
3. Tetraquark

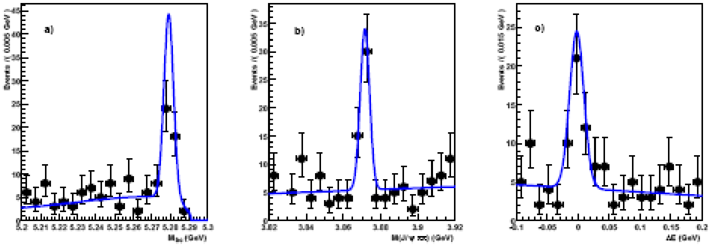
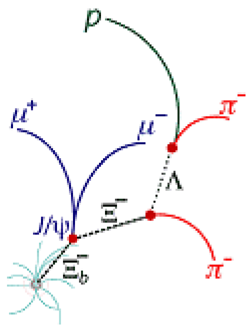


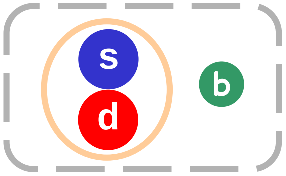
FIG. 17: X(3872) in the $J/\psi\pi^+\pi^-$ channel from Ref. [150].

X(3872), Y(4260), Z(4430) (ψ'π)...
structure

1. DD* molecule
2. c$\underline{c}$ state ?
3. Tetraquark

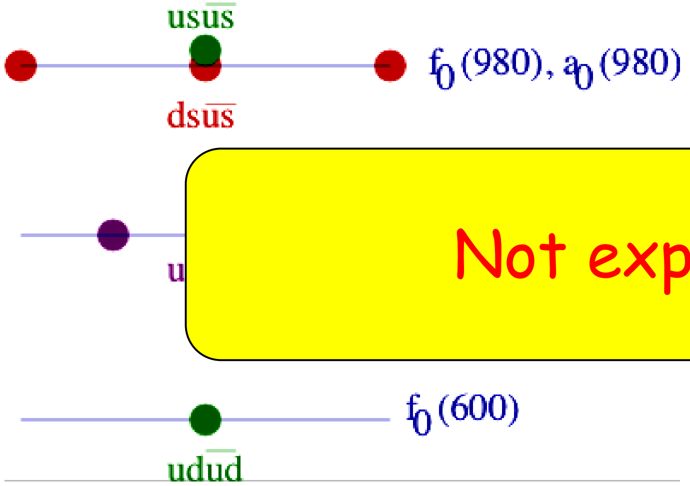
FNAL D0 Ξ(bsd 5774) bayron





1. Λ_b Σ_b Ξ_b available
2. Test of constituent quark model

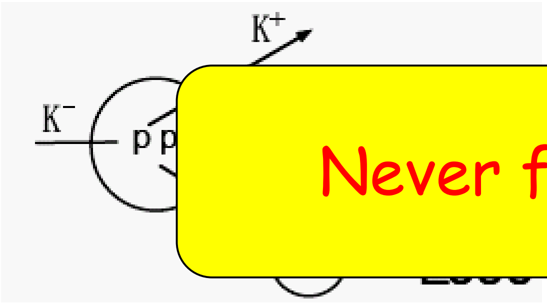
Previous Work on Multiquark Configuration



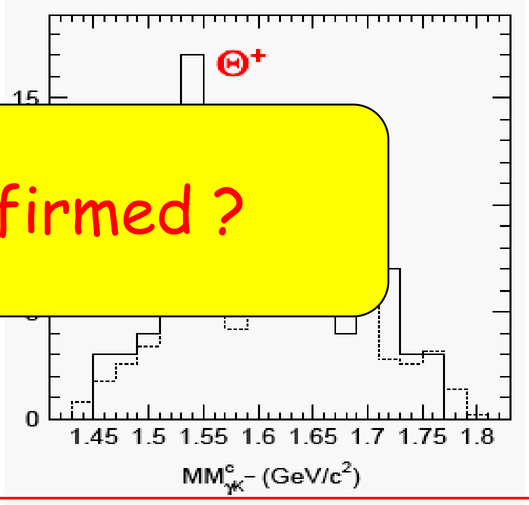
Scalar tetraquark (Jaffe 76)

Not explicitly exotic

Search for H dibaryon



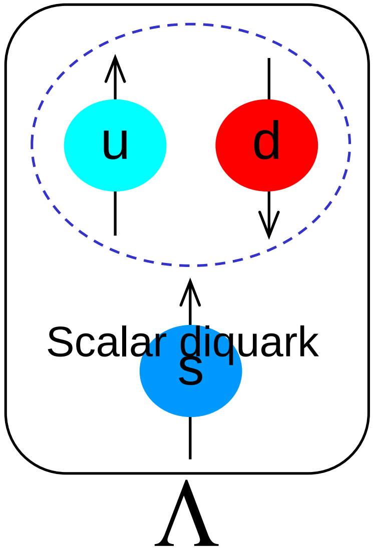
Search for Θ+ pentaquark

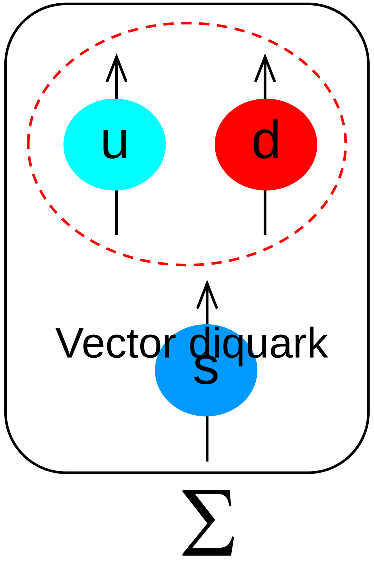


Never found nor confirmed ?

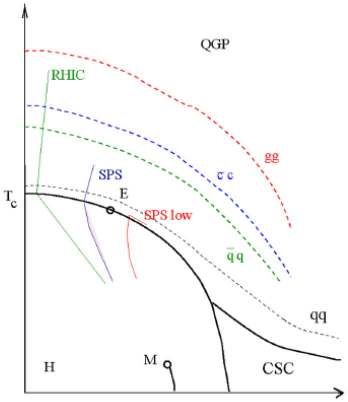
Common feature : attractive scalar Diquark $\langle \varepsilon^{abc} u_a C\gamma^5 d_b \rangle$

Important diquark	qq	qq
Color	Antisym	Antisym
Flavor	Antisym (I=0)	Sym (I=1)
Spin	Antisym (S=0)	Sym (S=1)
Total force	attractive	repulsive

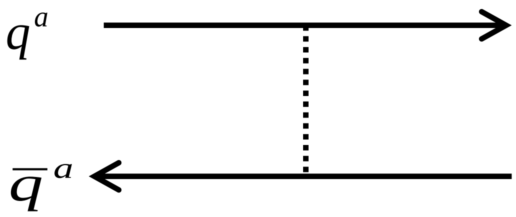


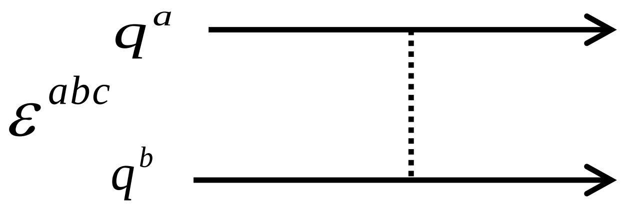


1. Special feature of QCD
2. Long history in Baryon spectrum : example Λ Σ ,,,,
3. Responsible for Exotics (Multiquark configuration)
4. Theoretically: one gluon exchange, Instanton
5. Color superconductivity: 2SC,CFL, BEC
6. sQGP: Shuryak, Zahed (04)



Attraction in quark-antiquark vs. scalar diquark





$$-\frac{4\alpha}{3}\frac{1}{r}$$

One gluon exchange

$$-\frac{1}{2}\frac{4\alpha}{3}\frac{1}{r}$$

$$\sigma \times r$$

Lattice calculation

(Nakamura, Saito 05)

$$\frac{1}{2}\sigma \times r$$

$$\frac{C}{m_i m_k}\sum S_i \cdot S_k$$

Phenomenological fit of

color spin interaction

to hadron spectrum

$$\frac{1}{3}\frac{C}{m_i m_k}\sum S_i \cdot S_k$$

Baryon Mass difference

$$\sum \frac{C_B}{m_i m_k}\left[s_i \cdot s_k\right]$$

Mass Diff.	$M_\Delta - M_N$	$M_\Sigma - M_\Lambda$	$M_{\Sigma_c} - M_{\Lambda_c}$	$M_{\Sigma_b} - M_{\Lambda_b}$
Formula	$\frac{3C_B}{2m_u^2}$	$\frac{C_B}{m_u^2}(1-\frac{m_u}{m_s})$	$\frac{C_B}{m_u^2}(1-\frac{m_u}{m_c})$	$\frac{C_B}{m_u^2}(1-\frac{m_u}{m_b})$
Fit	290 MeV	77 MeV	154 MeV	180 MeV
Experiment	290 MeV	75 MeV	170 MeV	192 MeV

$$m_u = m_d = 300\text{ MeV}$$

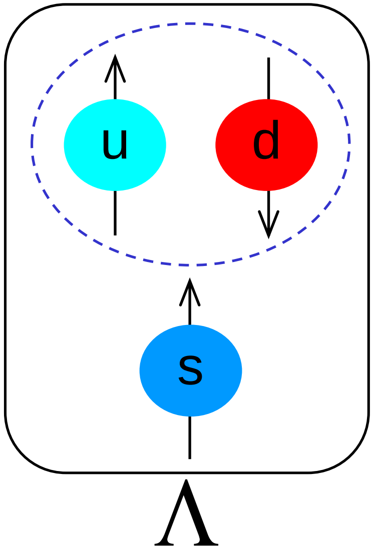
$$m_s = 500\text{ MeV}$$

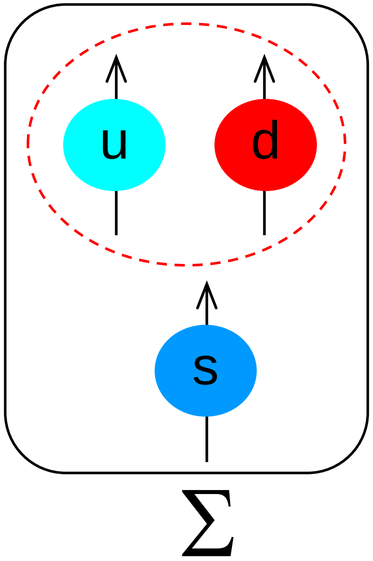
$$m_c = 1500\text{ MeV}$$

$$m_b = 4700\text{ MeV}$$

Example

$$\text{Mass} = \text{Kinetic } + .. + \frac{C_B}{m_u m_d}\left[s_u \cdot s_d\right] + \frac{C_B}{m_u m_s}\left[(s_u + s_d)\cdot s_s\right]$$

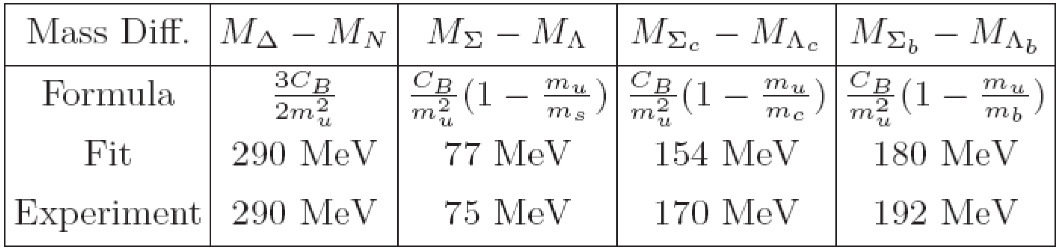




$$\Lambda_c \text{ Mass} = \text{Kinetic } + .. - \frac{3}{4}\frac{C_B}{m_u m_d}$$

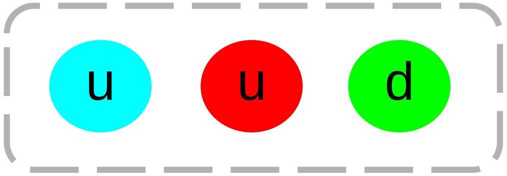
$$\Sigma_c \text{ Mass} = \text{Kinetic } + .. + \frac{1}{4}\frac{C_B}{m_u m_d} - \frac{C_B}{m_u m_c}$$

Baryon Mass difference



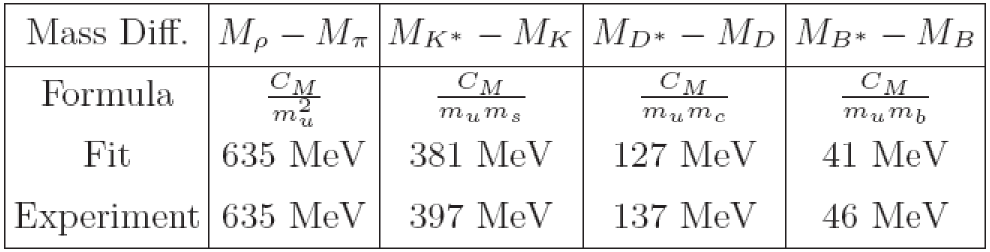
Mass Diff.	$M_\Delta - M_N$	$M_\Sigma - M_\Lambda$	$M_{\Sigma_c} - M_{\Lambda_c}$	$M_{\Sigma_b} - M_{\Lambda_b}$
Formula	$\frac{3C_B}{2m_u^2}$	$\frac{C_B}{m_u^2}(1-\frac{m_u}{m_s})$	$\frac{C_B}{m_u^2}(1-\frac{m_u}{m_c})$	$\frac{C_B}{m_u^2}(1-\frac{m_u}{m_b})$
Fit	290 MeV	77 MeV	154 MeV	180 MeV
Experiment	290 MeV	75 MeV	170 MeV	192 MeV

$$\sum \frac{C_B}{m_i m_k}\left[s_i \cdot s_k\right]$$



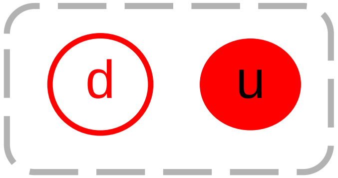
$$m_u = m_d = 300\text{ MeV},\;\; m_s = 500\text{ MeV},\;\; m_c = 1500\text{ MeV},\;\; m_b = 4700\text{ MeV}$$

Meson Mass difference



Mass Diff.	$M_\rho - M_\pi$	$M_{K^*} - M_K$	$M_{D^*} - M_D$	$M_{B^*} - M_B$
Formula	$\frac{C_M}{m_u^2}$	$\frac{C_M}{m_u m_s}$	$\frac{C_M}{m_u m_c}$	$\frac{C_M}{m_u m_b}$
Fit	635 MeV	381 MeV	127 MeV	41 MeV
Experiment	635 MeV	397 MeV	137 MeV	46 MeV

$$\sum \frac{C_M}{m_i m_k}\left[s_i \cdot s_k\right]$$

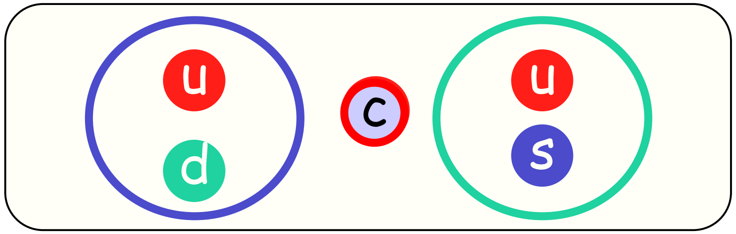


Works very well with **$3\times C_B = C_M = 635\, m_u^2$**

Why heavy pentaquarks $\Theta_{cs}(udus\underline{c})$

For a Pentaquark

For a charmed Pentaquark

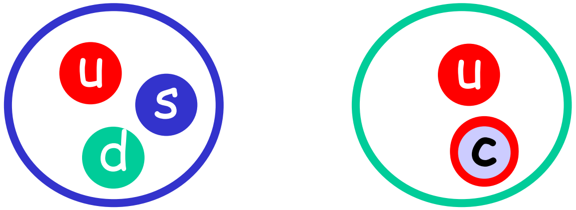


$$-232\ \text{MeV} = -\frac{3C_B}{4m_u^2} \qquad -\frac{3C_B}{4m_u m_s}$$

= −232 MeV

For a Nucleon and a Kaon

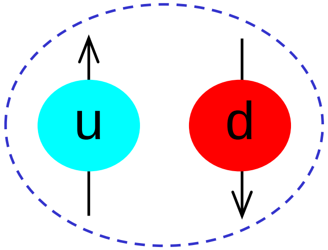
For a Nucleon and a D-meson



$$-430\ \text{MeV} = -\frac{3C_B}{4m_u^2} \qquad -\frac{3C_M}{4m_u \cancel{m_s}}$$ □ m_c

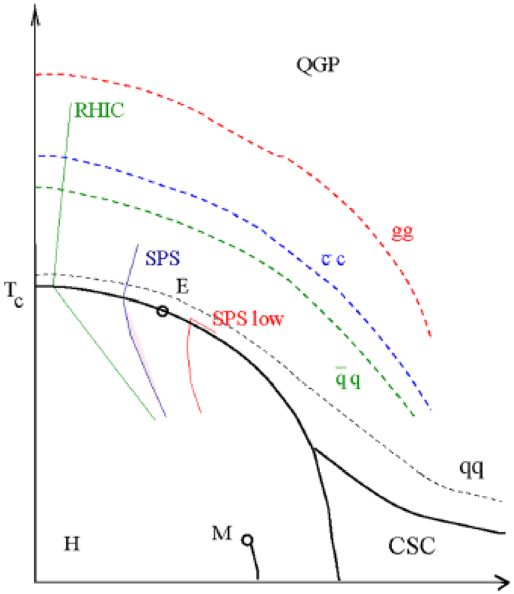
= −240 MeV

Possible diquarks in sQGP



$$\text{Scalar diquark Mass} = \text{Kinetic} + .. - \frac{3}{4}\frac{C_B}{m_u m_d}$$

$$\rightarrow \quad -145 \ \text{ MeV Binding}$$

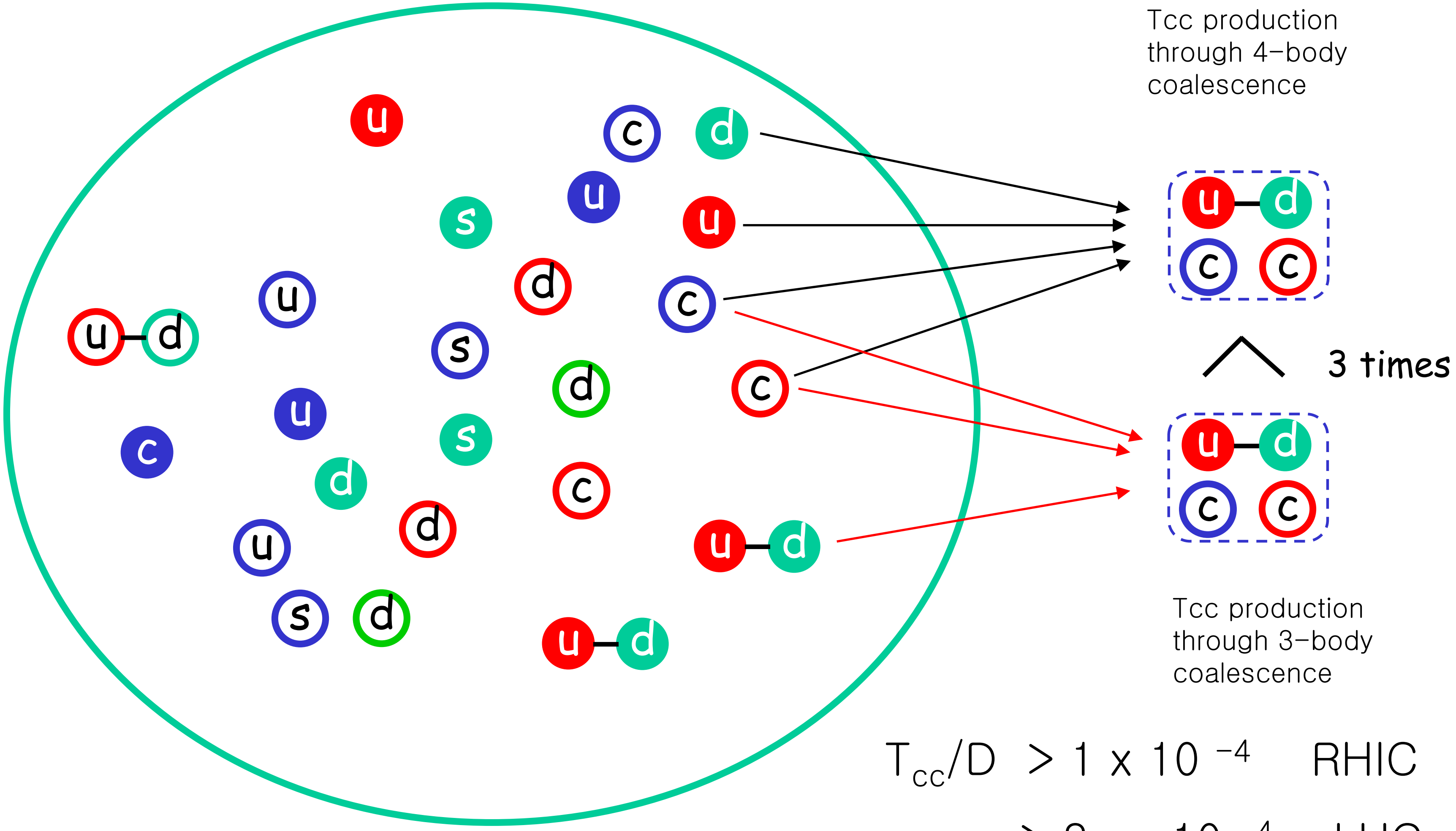


sQGP: Shuryak, Zahed (04) argued that

scalar diquarks might exist in sQGP

Additional Production of multiquark states from Diquarks in sQGP

Additional production of T_{cc}(ud<u>cc</u>) through 2-body coalescence



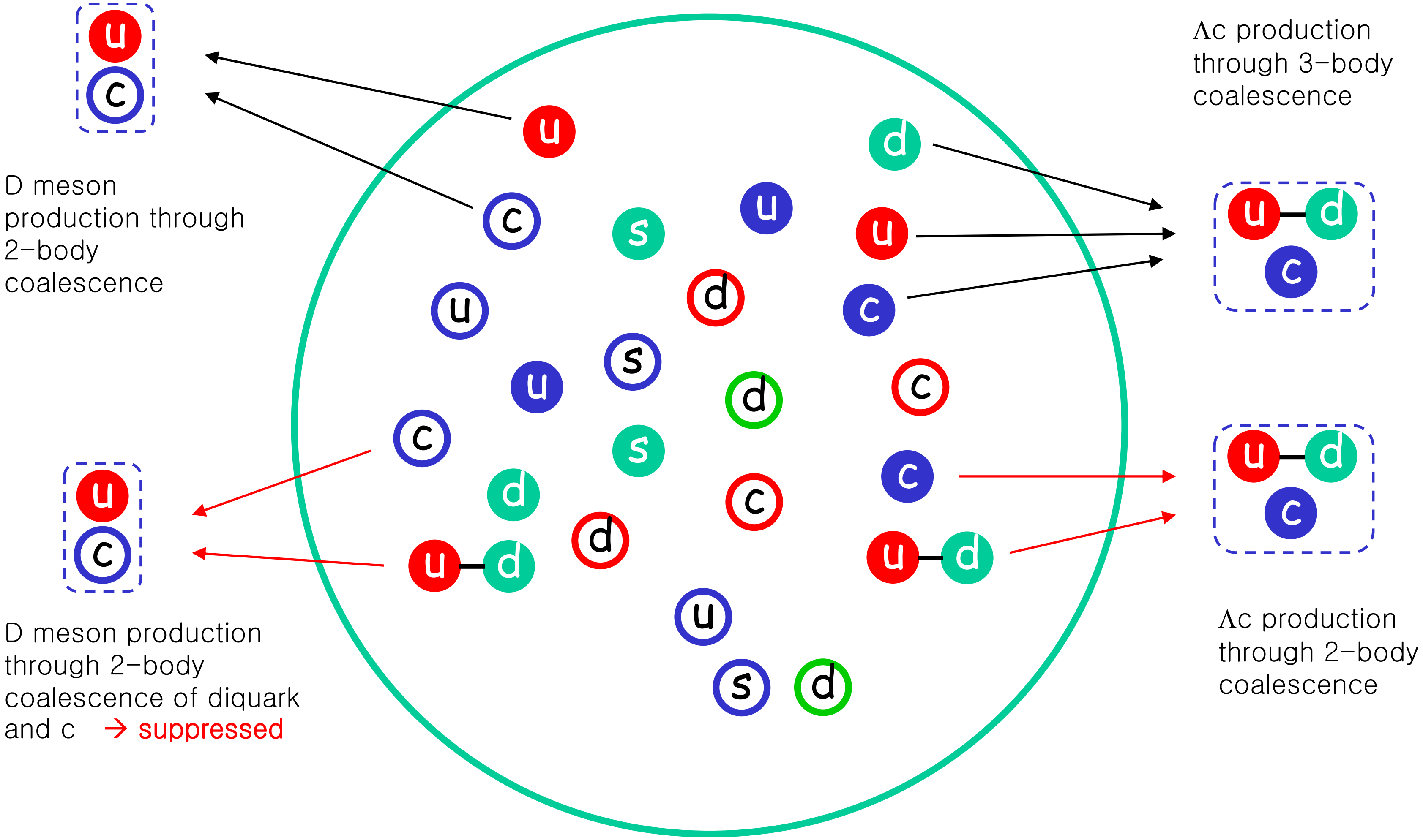
Tcc production through 4−body coalescence

Tcc production through 3−body coalescence

$T_{cc}/D > 1 \times 10^{-4}$ RHIC

$> 2 \times 10^{-4}$ LHC

Additional production of Λ_c(udc) through 2-body coalescence, and Λ_c/D ratio



D meson production through 2−body coalescence

Λc production through 3−body coalescence

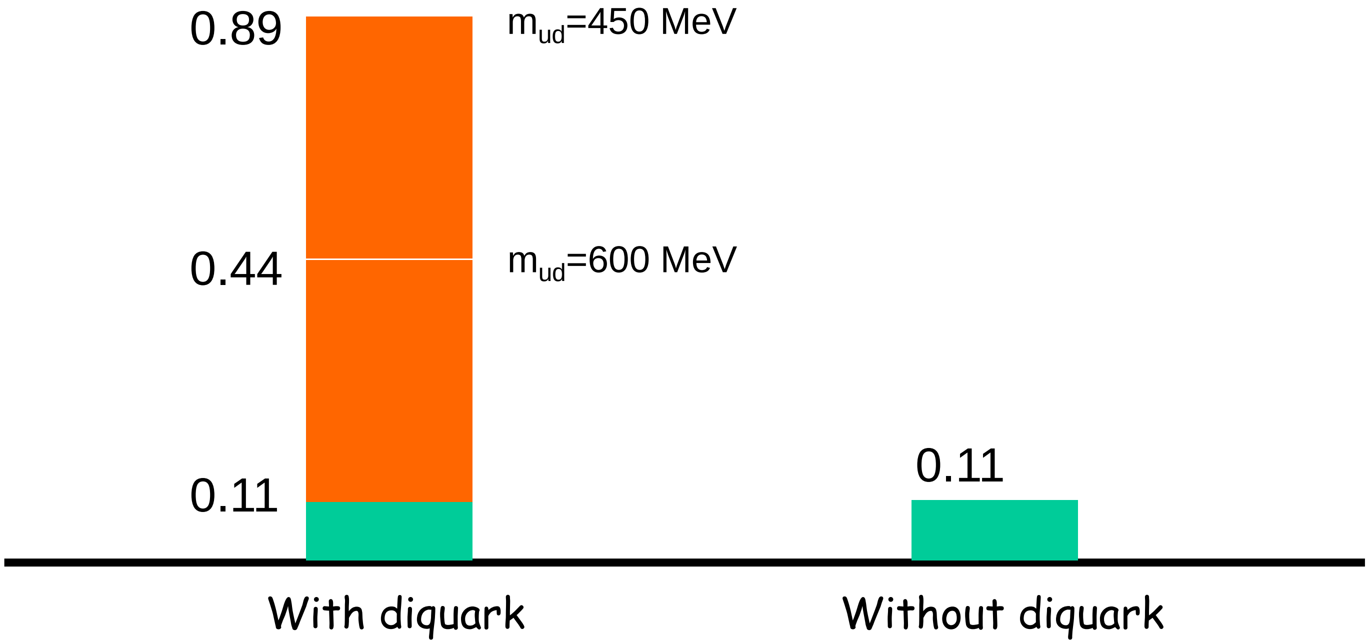
D meson production through 2−body coalescence of diquark and c → suppressed

Λc production through 2−body coalescence

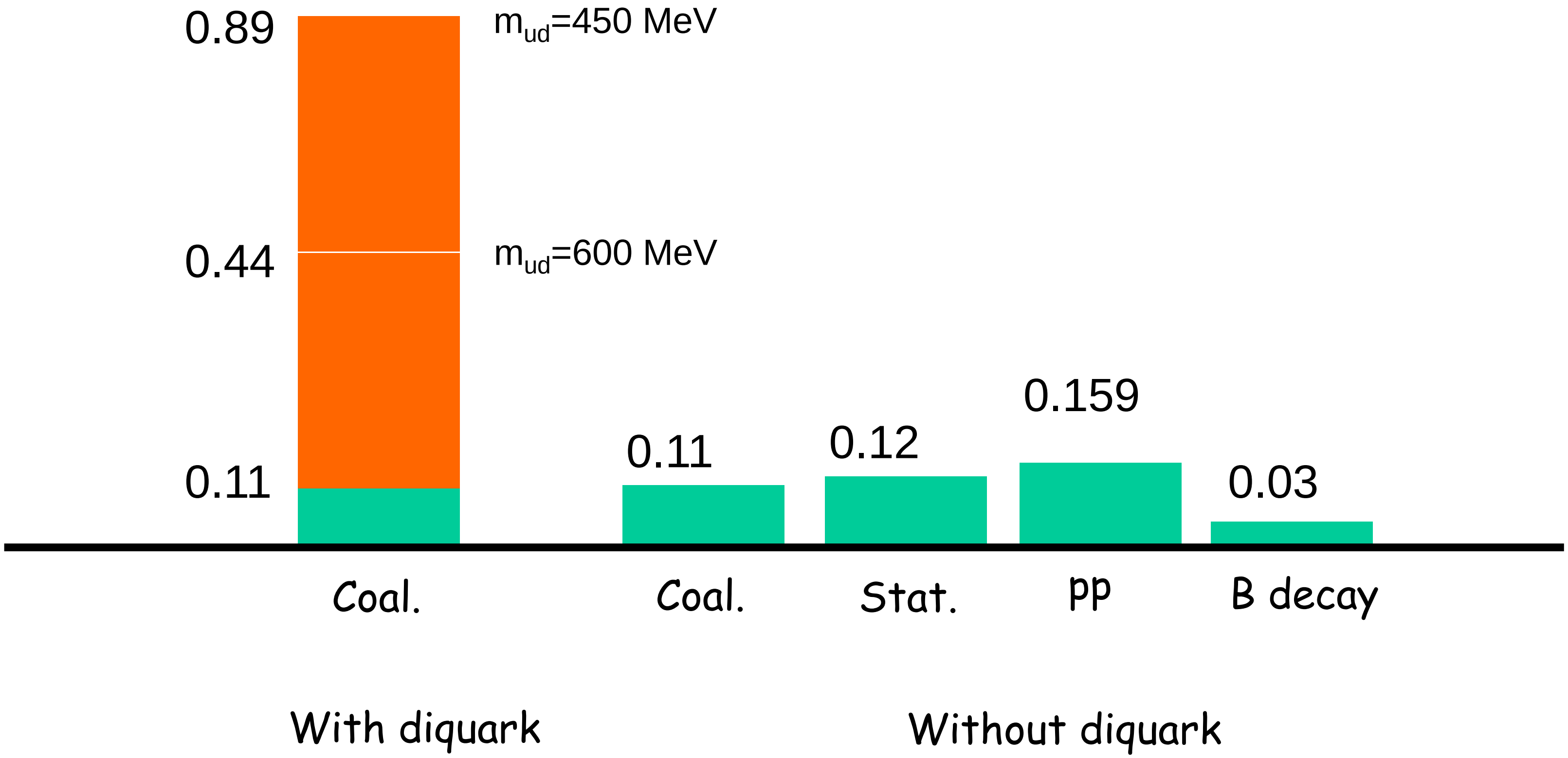
Λ_c/D ratio in coalescence model (same in RHIC and LHC)

Parameters：

T_c=170 MeV, m_u=m_d=300 MeV, m_{ud}=450 MeV to 600 MeV



Λ_c/D ratio in other processes



Summary of Korean idea 1

1. Diquark are unique in QCD

2. Mutltiquark states will exits in Heavy sector, due to diquark structure T_{cc} (ud $\bar{c}\bar{c}$) Θ_{cs} (udus$\bar{c}$)…

   LHC can be a very useful heavy exotic factory

   - ☐ If found, it will be the first exotic ever,
   - ☐ will tell us about QCD, q-q interaction and dense matter
   - ☐ great step forward in QCD

3. If diquarks exists near Tc, additional production of T_{cc} and Θ_{cs}. Λc/D enhancement can be a signature of sQGP

   - ☐ LHC plans to measure Λc and D → Korean idea 1 (I.K.Yoo, SHLee, PRL08)

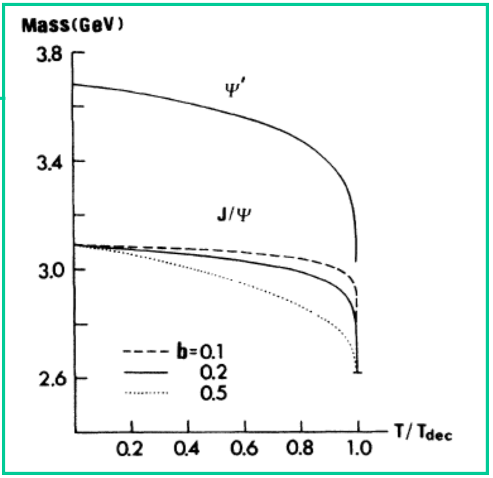
4. H dibaryon could be found at LHC?

한국아이디어 2

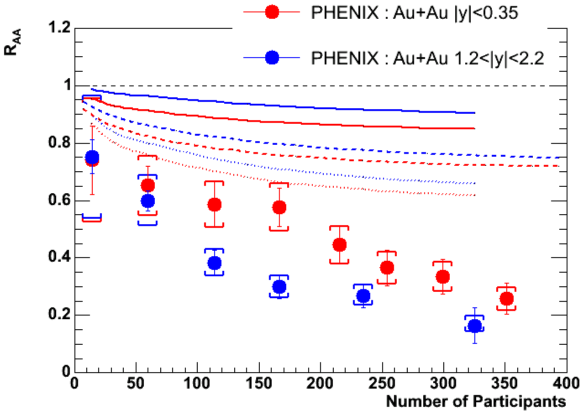
무거운 쿼크계를 활용한 탈구속 현상 확인

J/ψ in Quark Gluon Plasma

1986: Hashimoto, Miyamura,..: Mass shift of J/ψ Near Tc

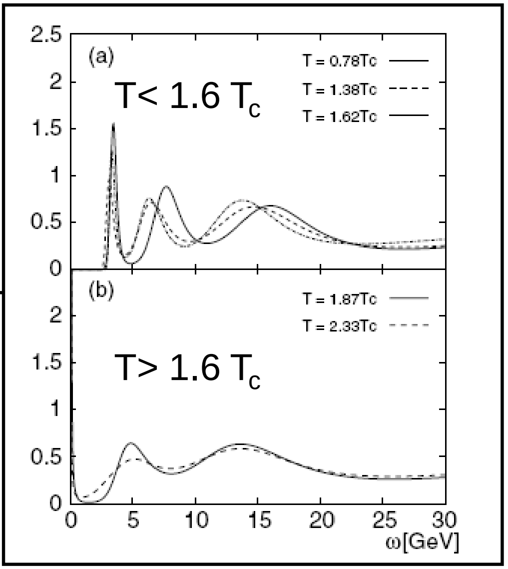


1986: Matsui, Satz: J/ψ will dissolve at Tc



1988: Hansson, Lee, Zahed: J/ψ states in QGP

2004: Asakawa, Hatsuda: J/ψ will survive up to 2 Tc

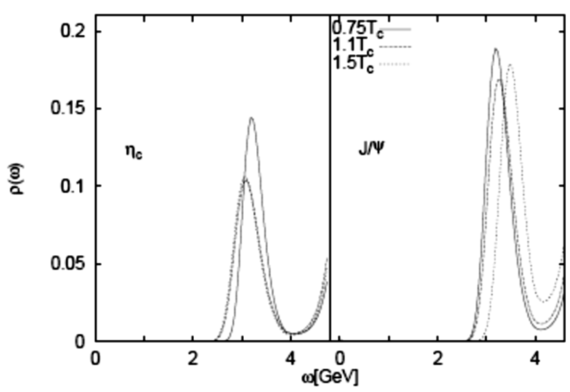


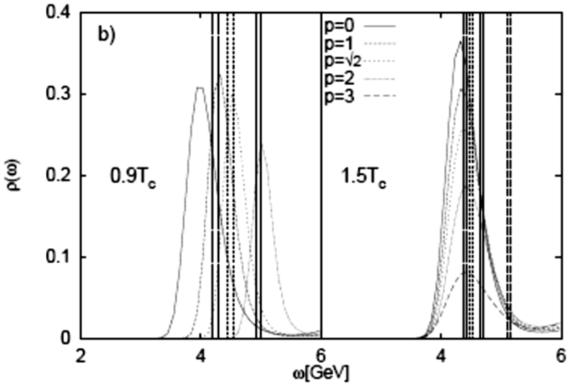
Confirmed by other lattice calculations: Datta etal.

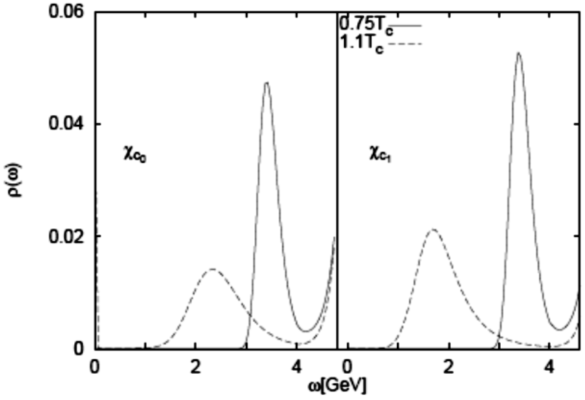
and potential model: Wong. ..

MEM Lattice Results for Charmonium

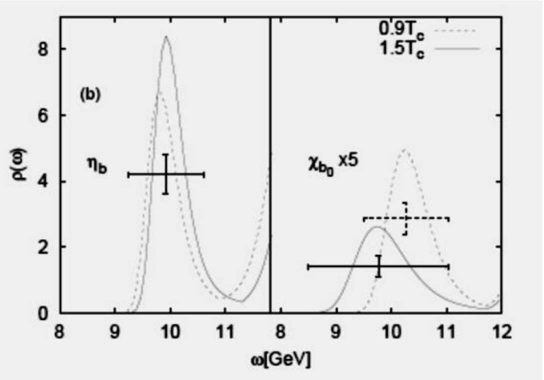
- Datta et al. (04)

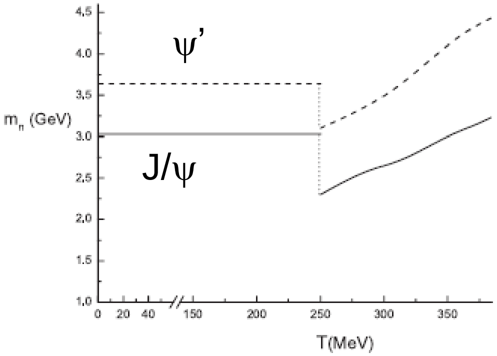






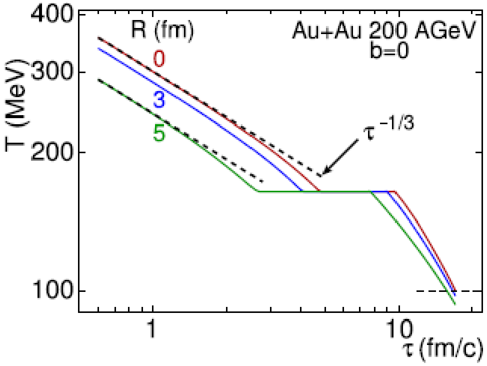
- Datta Karsch , ..(06) Υ χ_b
- Y. Kim, J. Lee, SHL 07 (ADS/QCD)





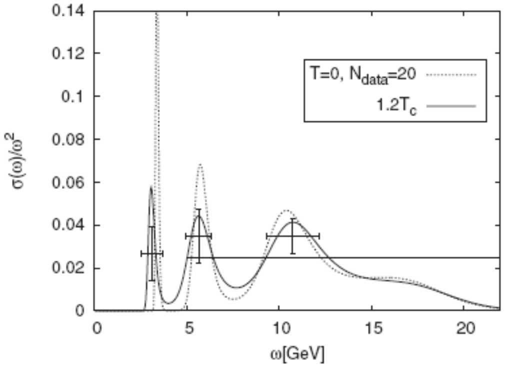
J/ψ in Quark Gluon Plasma

- Tc<T<2Tc is important in RHIC



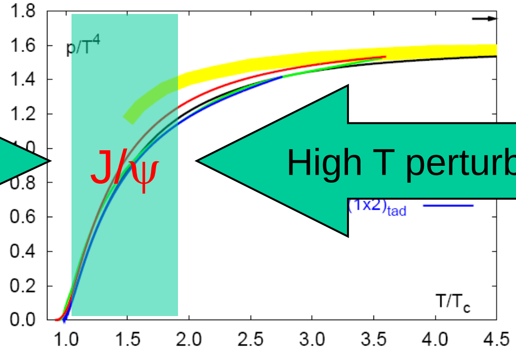
Kolb, Heinz, nucl-th/0305084

- Large uncertainty in lattice MEM



Jakovac et al. hep-lat/0611017

- Tc<T<2Tc is non perturbative region



T=0 phenomenological approach?

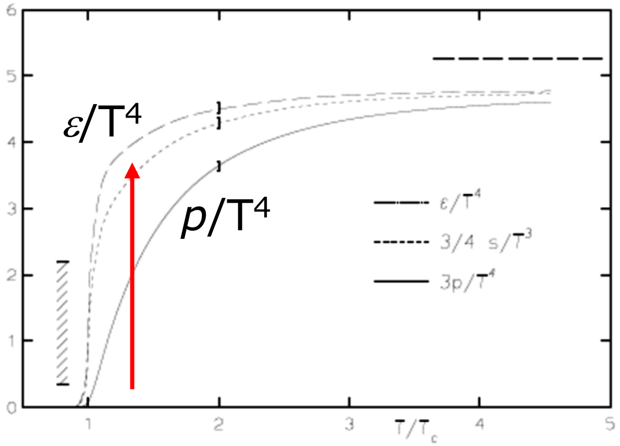
High T perturbative approach?

Karsch hep-lat/0106019

How can we treat heavy quark system in QCD ?

Properties of QGP from lattice

G^2, E^2 and B^2 across T_c -- (quenched case)



Lattice result for purge gauge (Boyd et al 96)

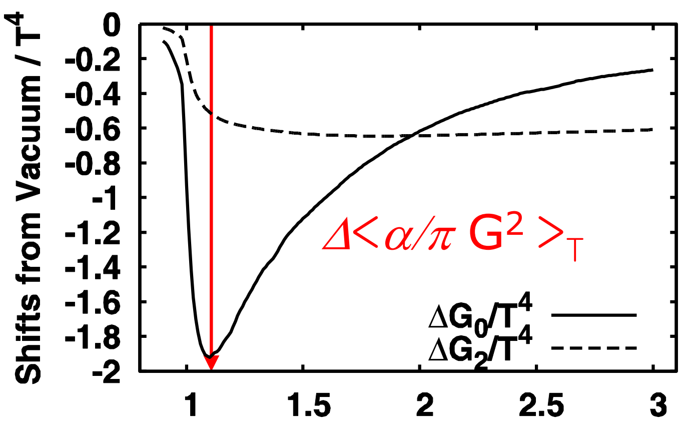
Using energy momentum tensor

p and ε → local operators

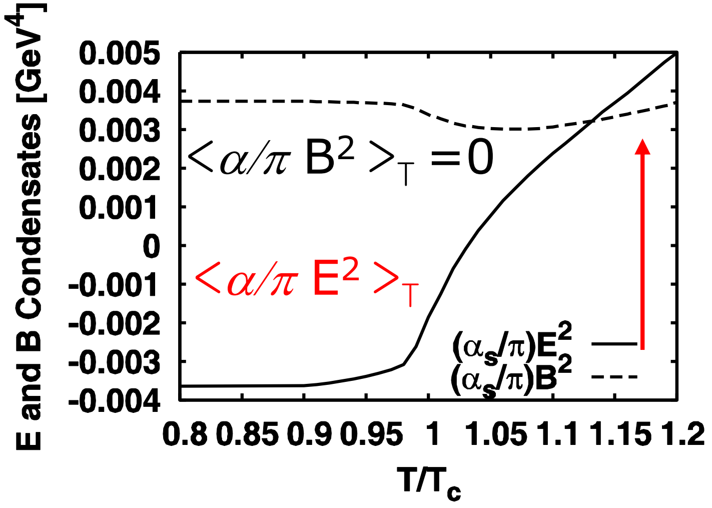
$$T^{\alpha\beta} = -G^{\alpha\mu}G^{\beta\mu} + g^{\alpha\beta}\frac{\beta(g)}{2g}G^2$$

$$\text{operators} \rightarrow \quad \langle T^{\alpha\beta}\rangle = -\left(u^\alpha u^\beta - \frac{1}{4}g^{\alpha\beta}\right)G_2 + \frac{1}{4}g^{\alpha\beta}G_0$$

$$\text{Lattice} \rightarrow \quad \langle T^{\alpha\beta}\rangle = \left(u^\alpha u^\beta - \frac{1}{4}g^{\alpha\beta}\right)(\varepsilon + p) + \frac{1}{4}g^{\alpha\beta}(\varepsilon - 3p)$$



Maximum at 1.1Tc

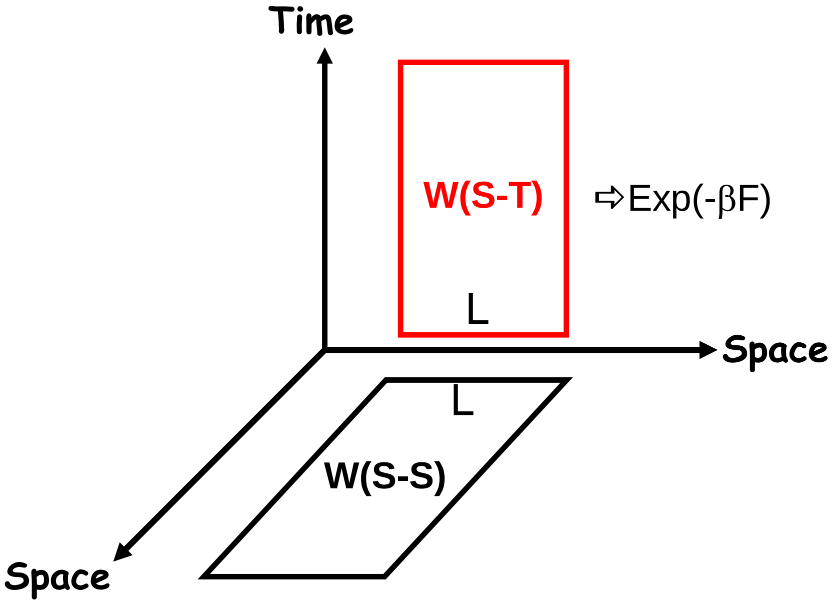


Extraction from lattice: Morita, Lee (08)

E^2 and B^2 across T_c -- (relation to potentials ?)

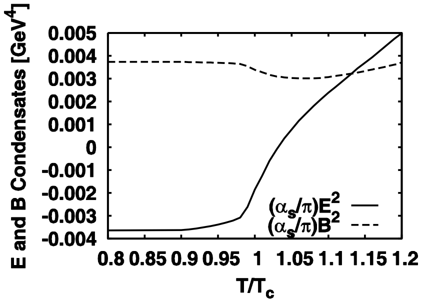
Manousakis, Polonyi, PRL 58 (87) 847
“Nonperturbative length scale in high T QCD”

Shifman NPB73 (80)



$W(S\text{-}T) = 1 - \langle \alpha/\pi\, E^2 \rangle\, (ST)^2 + \ldots$

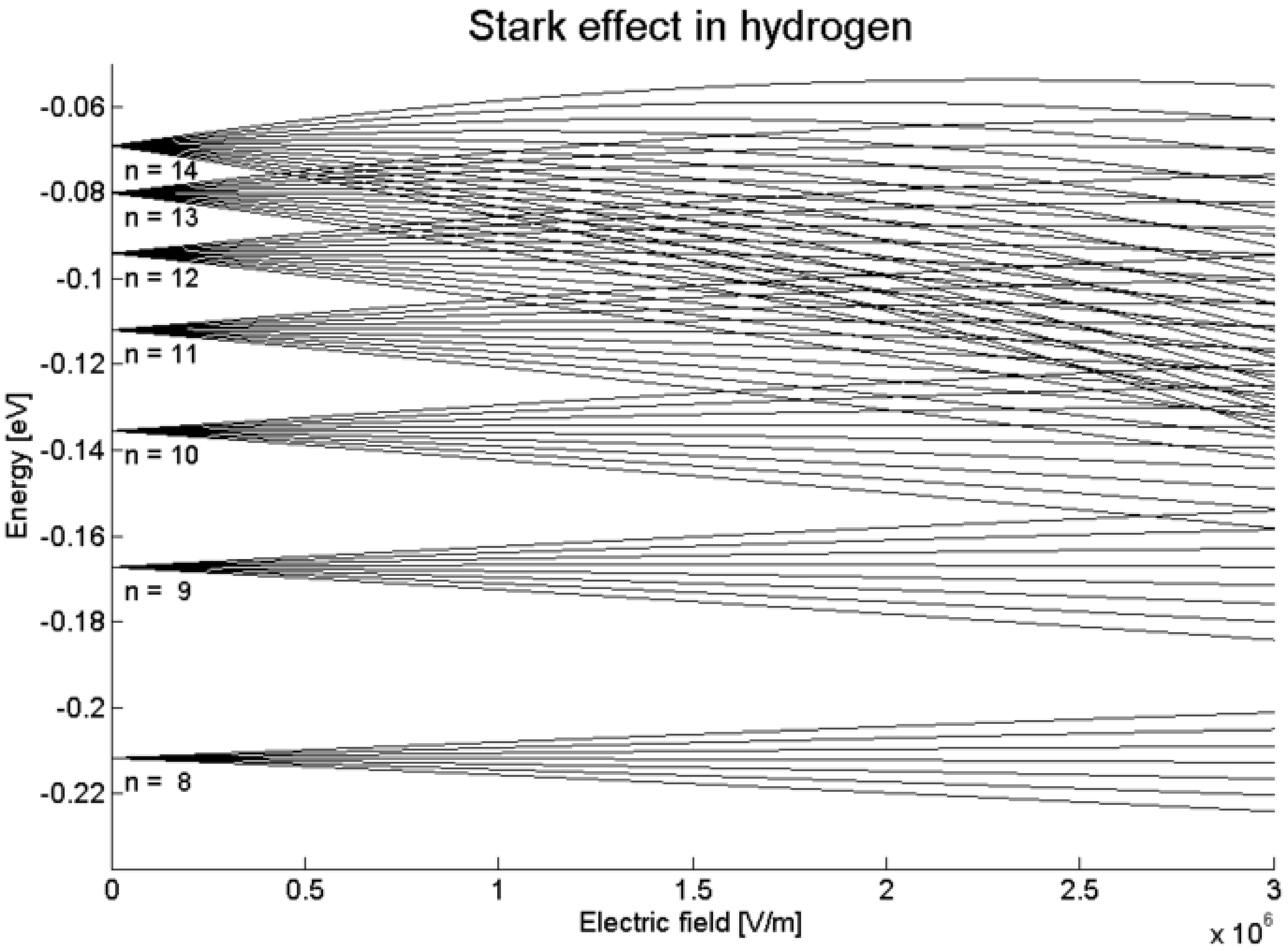
$W(S\text{-}S) = 1 - \langle \alpha/\pi\, B^2 \rangle\, (SS)^2 + \ldots$



	W(S−T)	$\langle \alpha/\pi E^2 \rangle$	W(S−S)	$\langle \alpha/\pi B^2 \rangle$
T<Tc	Area	change	Area	no change
T>Tc	Perimeter	↓	Area	↓

If $\langle E^2 \rangle$ suddenly increases across T_c, what will happen to J/ψ immersed in it ?

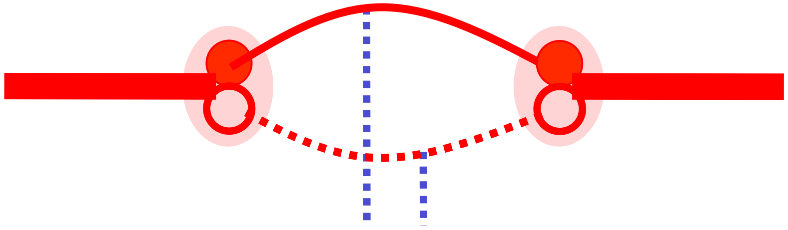
Hydrogen Atom in an external E field



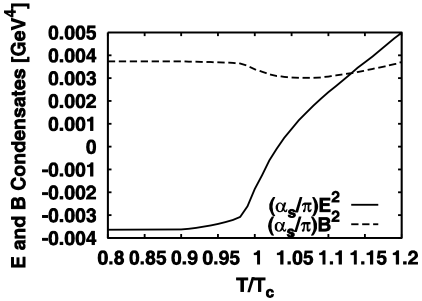
$\langle E \rangle_{\text{external}} \rightarrow \langle E^2 \rangle_T$

QCD 2^{nd} order Stark Effect (Peskin, Luke, Manohar, SHL, CMKo)

$$q^2 = m_{J/\psi}^2$$



$\Delta \langle \alpha/\pi \, E^2 \rangle_T$



Attractive for ground state

$$\Delta M_i = \sum_n \frac{|\langle i|zE|n\rangle|^2}{E_i - E_n}$$

$$\Delta m_{J/\psi} = -\frac{128}{9\pi^2} \boxed{\frac{a_0^2}{\varepsilon_0}} \int dx \frac{x^{3/2}}{(1+x)^6} \frac{1}{x + a_0^2 \varepsilon m} \times \boxed{\left\langle \frac{\alpha}{\pi} E^2 \right\rangle_T}$$

T/Tc	1.0	1.05	ε_0
$\Delta m_{J/\psi}$	-44 MeV	-105 MeV	311 MeV
Δm_{Υ}	-4.3 MeV	-10 MeV	580 MeV

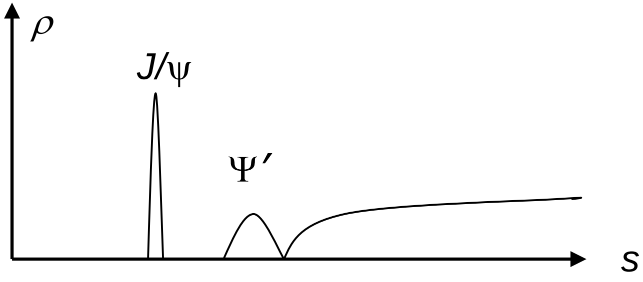
A non-perturbative method ?

QCD sum rules for Heavy quark system T=0

$$M_n = \left(\frac{d}{dQ^2}\right)^n < J(Q), J(0) >= \int ds \frac{\rho(s)}{(s+Q^2)^n}$$

Phenomenological side

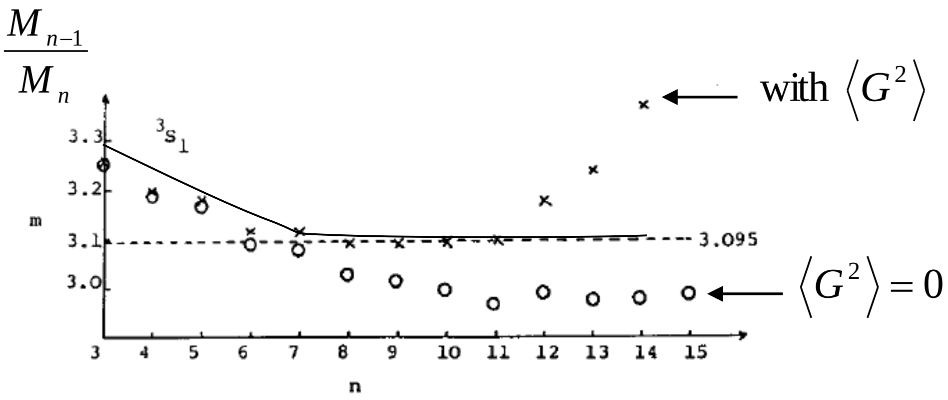
OPE



$$M_n = \frac{1}{\left(m^2_{J/\psi}\right)^n}\left(f_{J/\psi} + c\left(\frac{m^2_{J/\psi}}{m^2_{\psi'}}\right)^n .. \right)$$

$$\frac{M_{n-1}}{M_n} = m^2_{J/\psi} + \frac{\left(m^2_{\psi'} - m^2_{J/\psi}\right)}{f_{J/\psi}}\left(\frac{m^2_{J/\psi}}{m^2_{\psi'}}\right)^n$$

$$M_n = a_n\left(1 + \alpha + \frac{(n+4)!}{n!}\frac{\langle G^2\rangle}{\left(4m_c^2\right)^2} ..\right)$$

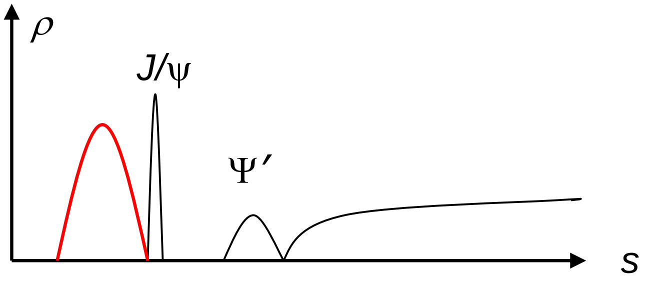


→ predicted $M_{\eta c} < M_{J/\psi}$ before experiment

QCD sum rules for Heavy quark system T near Tc

Phenomenological side

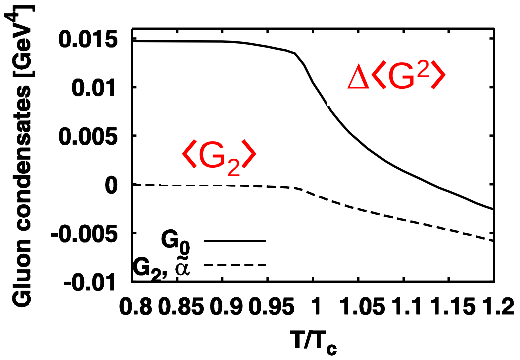
OPE

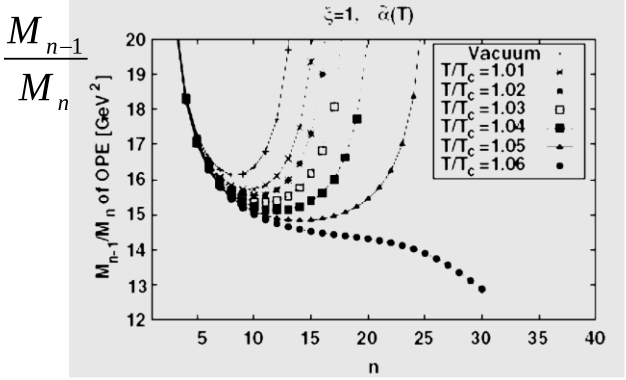


$$\rho(s)=\frac{f\sqrt{s}\Gamma}{\left(s-m_{J/\psi}^2\right)^2+s\Gamma^2}$$

$$M_n=\int ds\,\frac{\rho(s)}{(s+Q^2)^n}$$

$$M_n=a_n\left(1+\alpha+\frac{(n+4)!}{n!}\frac{\Delta\langle G^2\rangle+c\langle G_2\rangle}{\left(4m_c^2\right)^2}\ldots\ldots\ldots\ldots\ldots\ldots\right)$$

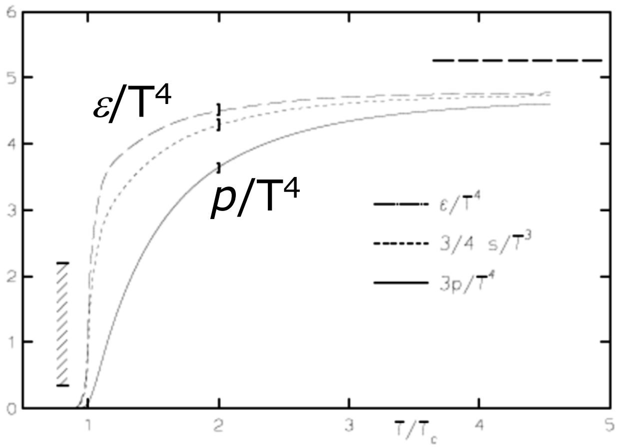




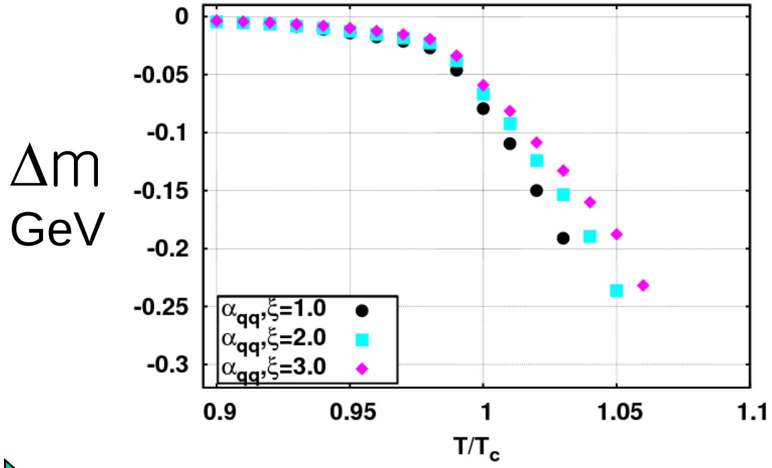
Matching M_{n-1}/M_n from Phen to OPE

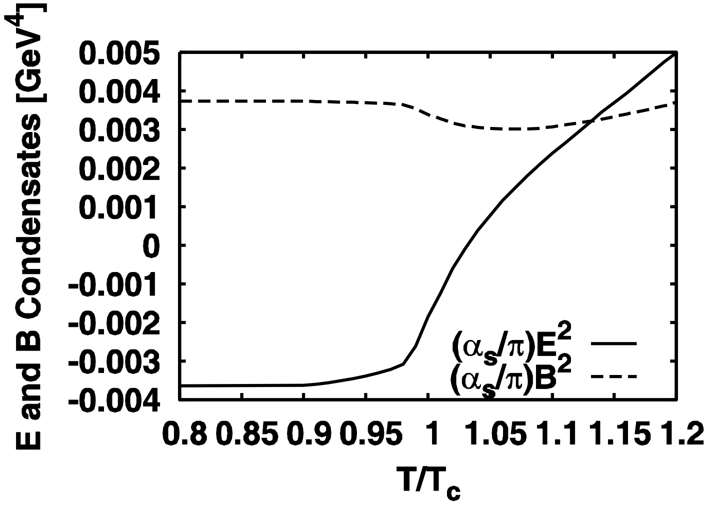
→ Obtain constraint for $\Delta m_{J/\psi}$ and Γ

Constraint for J/ψ Mass and Width above Tc

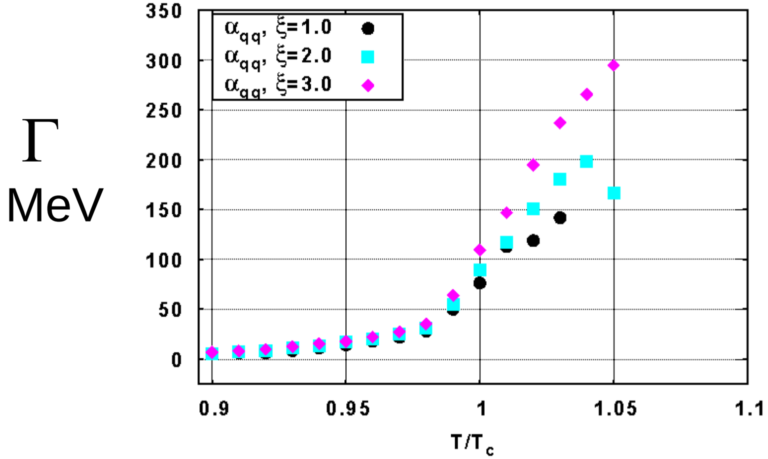


If Γ=0





If Δm=0



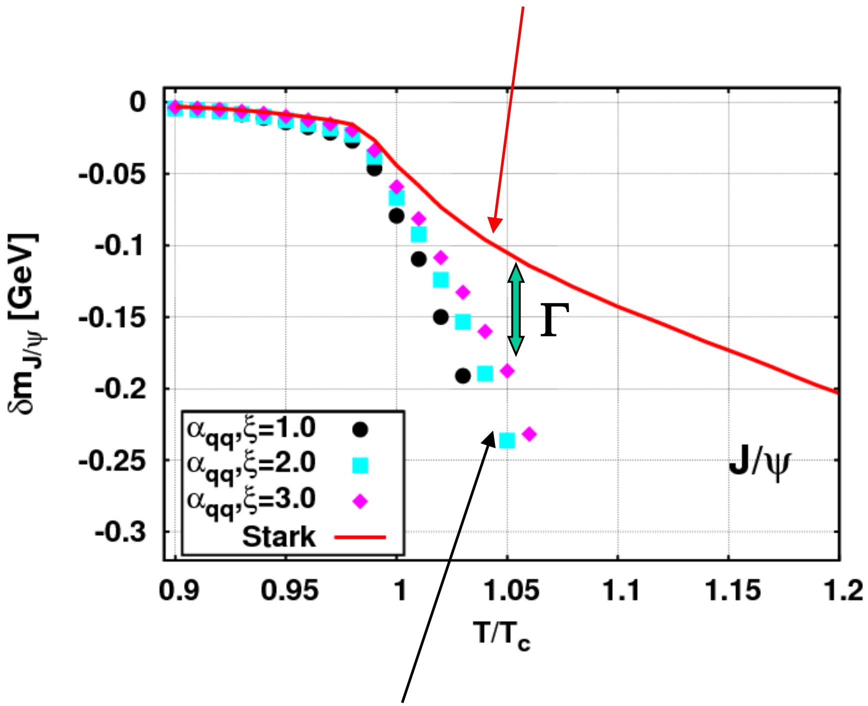
|Δm|+Γ =15xT, near Tc

Due to the sudden change in gluon condensates, there will be a critical behavior of J/ψ near T_c,

$|\Delta m| + \Delta\Gamma$ =150 MeV from Tc to Tc + 10 MeV

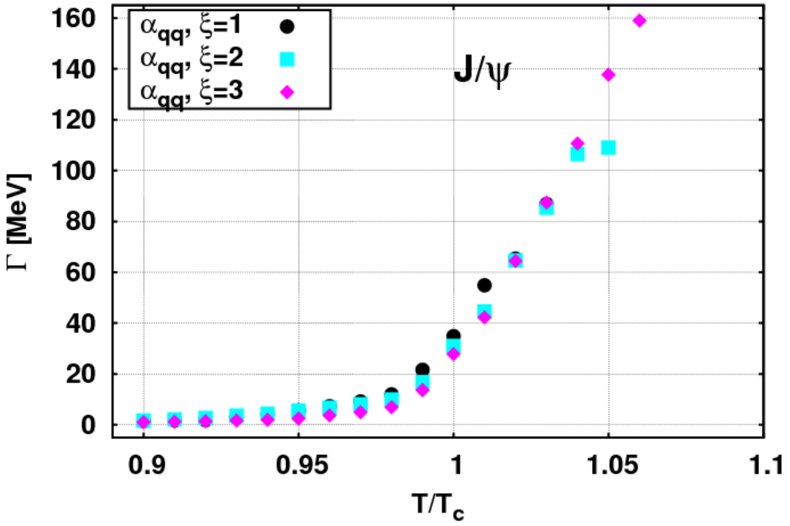
- **Model calculation is needed to get the changes separately,**

  → Use QCD Stark Effect ?



QCD sum rule constraint with ΔΓ=0

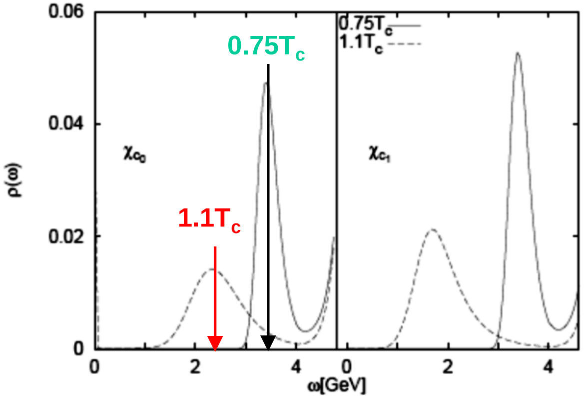
From Γ =constraint−Δm (Stark effect)



Lattice vs. QCD sum rule results

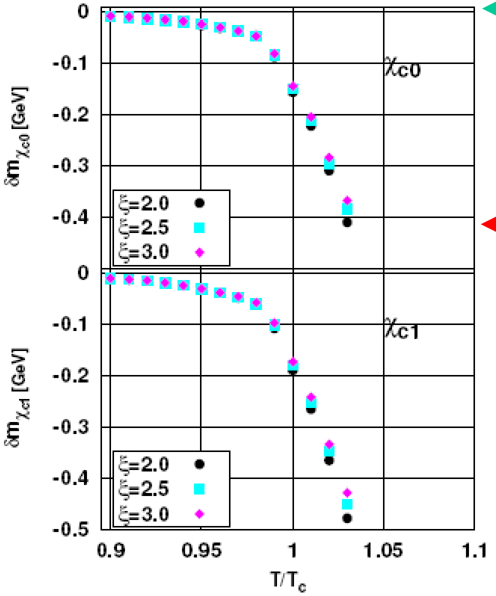
1. χ_c states

Karsch et al.



1 GeV

K.Morita, Y. Song, SHL



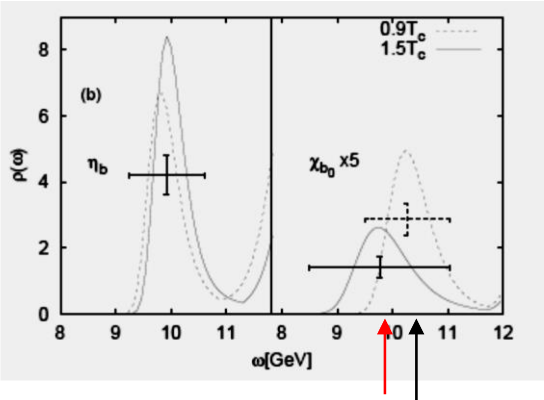
0.9 T_c

400 MeV

1.1T_c

2. χ_b states

Karsch et al.

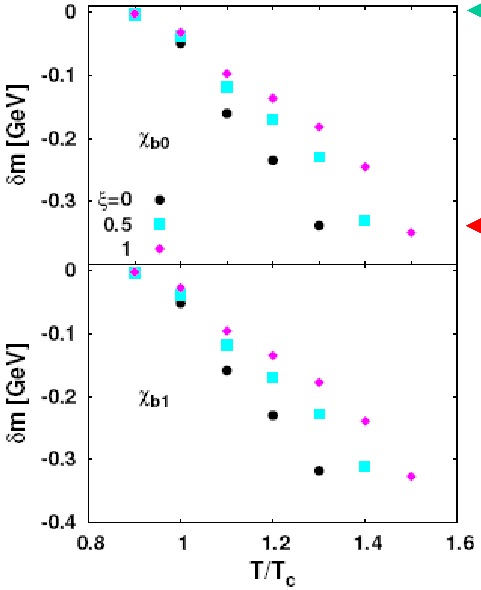


1.5T_c

400 MeV

0.9T_c

K.Morita, Y. Song, SHL



0.9 T_c

400 MeV

1.5T_c

Summary of Korean idea 2

1. **‘Order parameter’ of QCD Phase transition:**

   Critical behavior of heavy quark system near T_c, mass shift and width broadening

2. **A precursor phenomena takes place in nuclear matter**

   → Mass shift could be observed through anti proton project at GSI

3. **Consequences in HIC?. Non trivial effects expected to χ_c , ψ', Y, Y’…**

   → direct measurement of mass shift

   → confirmation through sudden increase in $\chi_c/J/\psi$ or $\psi'/J/\psi$ ratio

*본 실패한 **SRC** 의 성공적 성과*

1. 그 동안 이룩한 **HIM** 의 결집된 노력

2. 앞으로 많이 나올 **Korean Idea** 의 시작

3. 희망을 줌
   → 한국아이디어, **leading role, quark matter** 유치, 노벨상