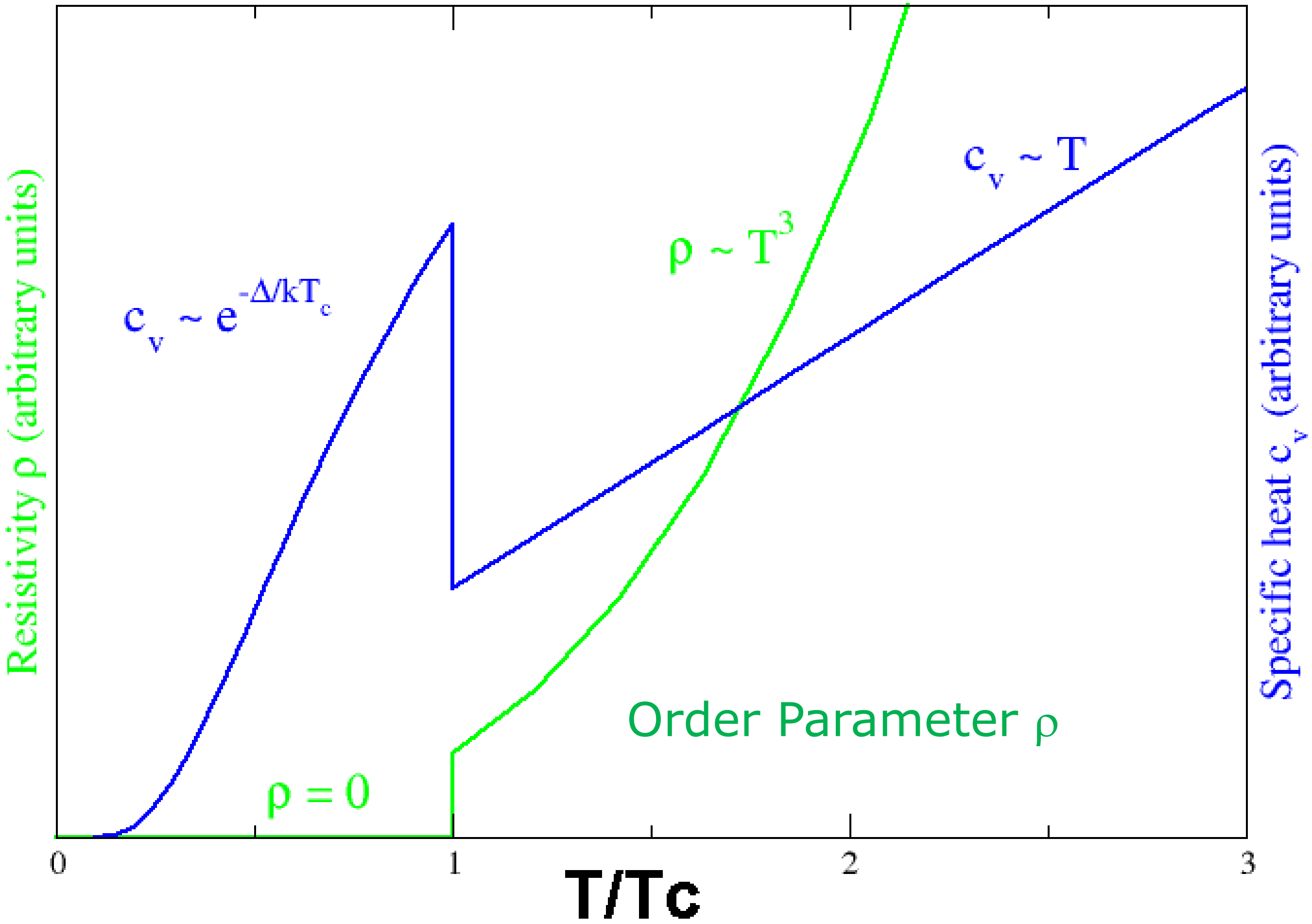
J/ψ suppression and QGP

Su Houng Lee

Thanks to Dr. Kenji Morita(GSI), Dr. Taesoo Song(Texas)
and present group members
김경일, 박우성, 정기상, 박효진, 김혜진,+ Dr. 조성태

YONSEI UNIVERSITY

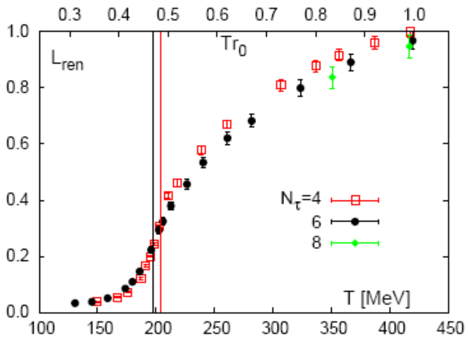
Superconductivity



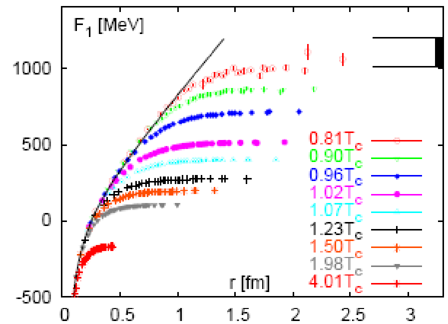
Order parameter in QCD?

Lattice results for phase transition in QCD *(from Karsch's review)*

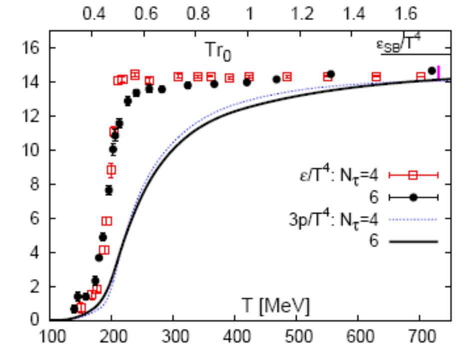
Confinement: $L=e^{-F}$



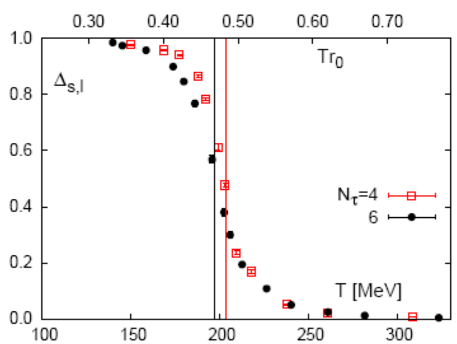
Heavy quark V(r)



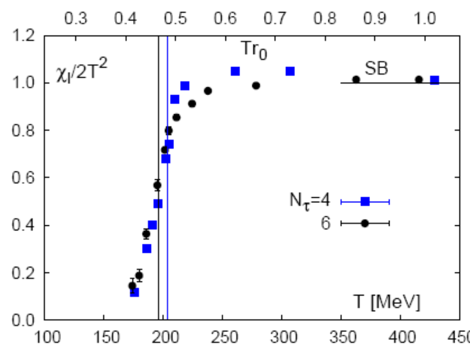
EOS: e , p



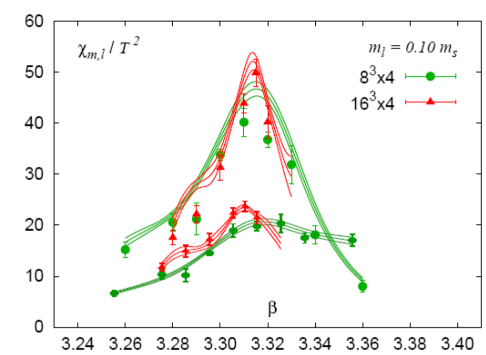
Chiral sym: $\langle\bar{q}q\rangle$



Quark number χ_q



Susceptibility χ_{mq} χ_L



QCD phase transition, heavy quark system and nuclear matter

K.Morita, SHL: PRL 100, 022301 (08)

K.Morita, SHL: PRC 77, 064904 (08)

SHL, K. Morita: PRD 79, 011501 (09)

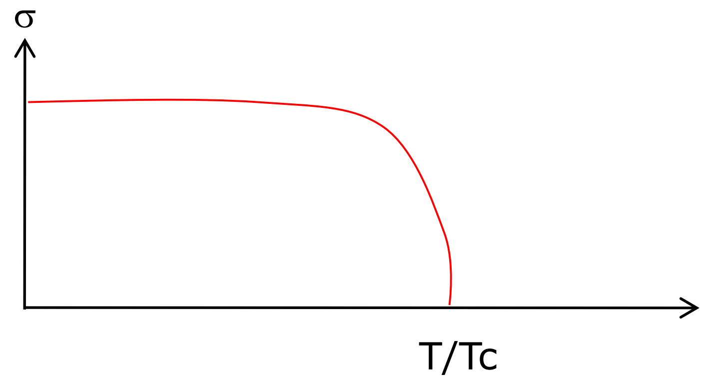
Y.Song, SHL, K.Morita: PRC 79, 014907 (09)

Early work on J/ψ at finite T (Hashimoto, Miyamura, Hirose, Kanki)

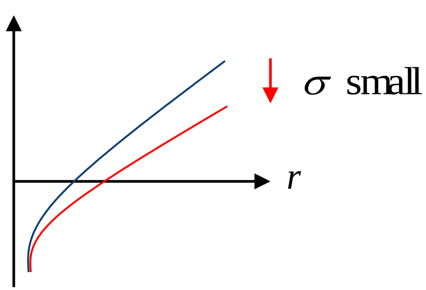
VOLUME 57, NUMBER 17 PHYSICAL REVIEW LETTERS 27 OCTOBER 1986

Mass Shift of Charmonium near Deconfining Temperature and Possible Detection in Lepton-Pair Production

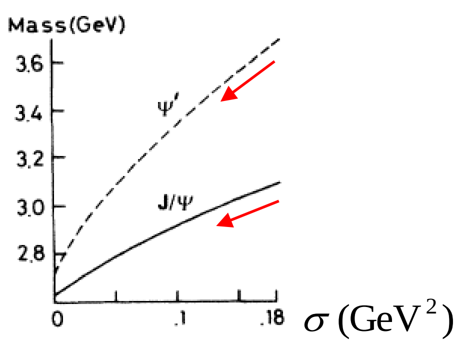
QCD order parameter

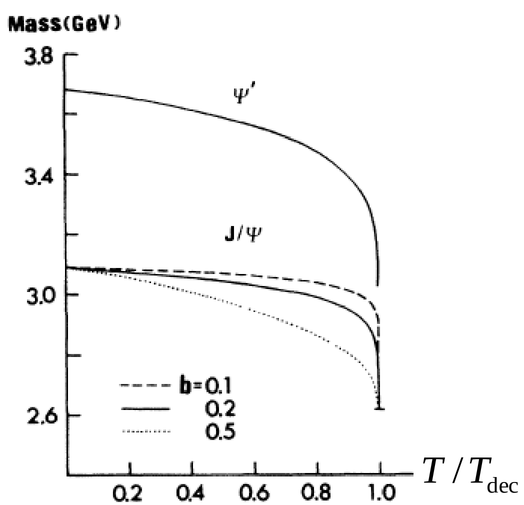


$$\sigma(T) = \sigma(0) \times \left[\left(T_{\text{dec}} - T\right)/T_{\text{dec}}\right]^{b}$$



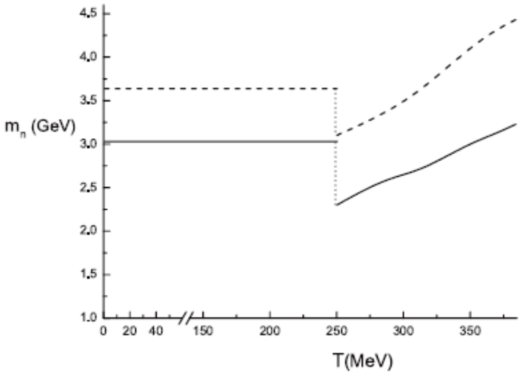
$$V(r) = -\frac{4}{3}\frac{\alpha_s(r)}{r} + \sigma \times r$$





J/ψ in Quark-gluon plasma

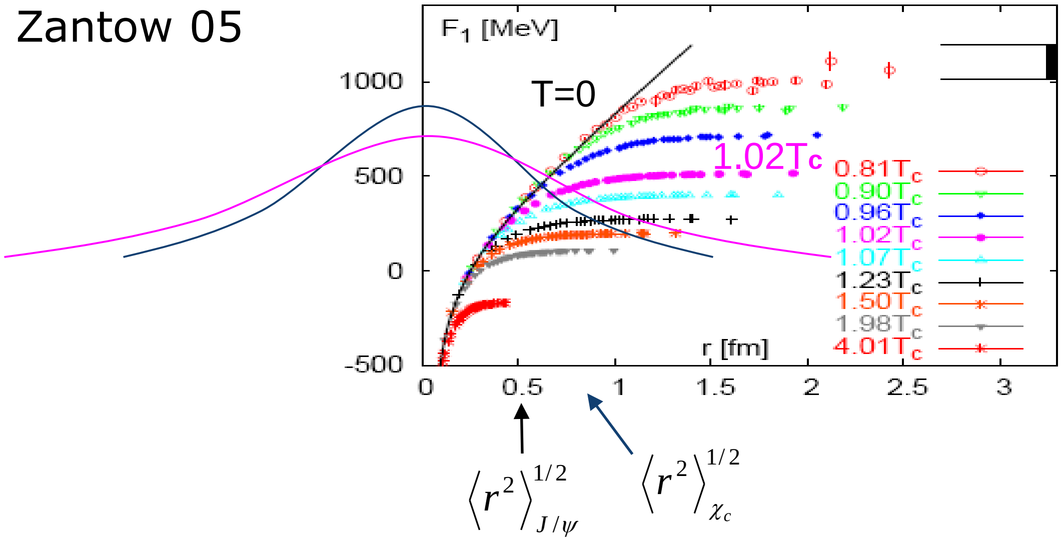
- Matsui and Satz: J/ψ will dissolve at Tc due to color screening
- Lattice MEM : Asakawa, Hatsuda, Karsch, Petreczky ….
  J/ψ will survive Tc and dissolve at 2 Tc
- Potential models (Wong …) :
  Consistent with MEM Wong.
- Refined Potential models with lattice (Mocsy, Petreczky…)
  : J/ψ will dissolve slightly above Tc
- Perturbative approaches: Blaizot et al… Imaginary potential
- pNRQCD: N. Brambial et al.
- Lattice after zero mode subtraction (WHOT-QCD)
  : J/ψ wave function hardly changes at 2.3 Tc
- AdS/QCD (Kim, Lee, Fukushima ..)
  : J/ψ mass change by Y. Kim, J. Lee, SHLee



- Wiki page …https://wiki.bnl.gov/qpg/index.php/Quarkonia.

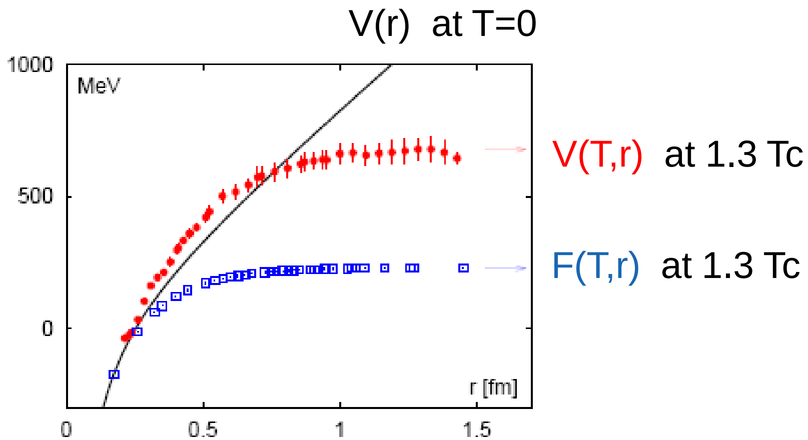
Lattice result on singlet potential

- Kaczmarek, Zantow 05



- What should one use? $F(T,r) = V(T,r) - TS(T,r)$

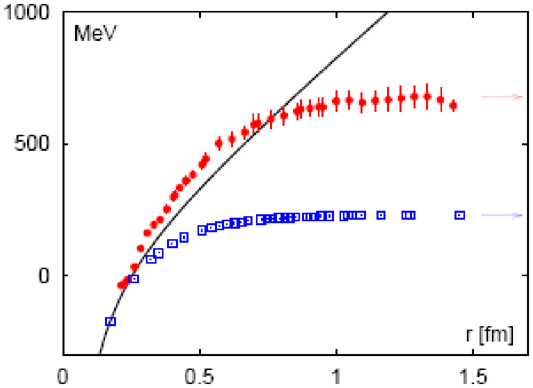
Kaczmarek , Zantow hep-lat/0510094



J/ψ from potential models

- F(T,r) =V(T,r) -TS(T,r)

V(r) at T=0



V(T,r) at 1.3 Tc

F(T,r) at 1.3 Tc

Kaczmarek , Zantow hep-lat/0510094

- Quarkonium dissociation temperature for different potentials

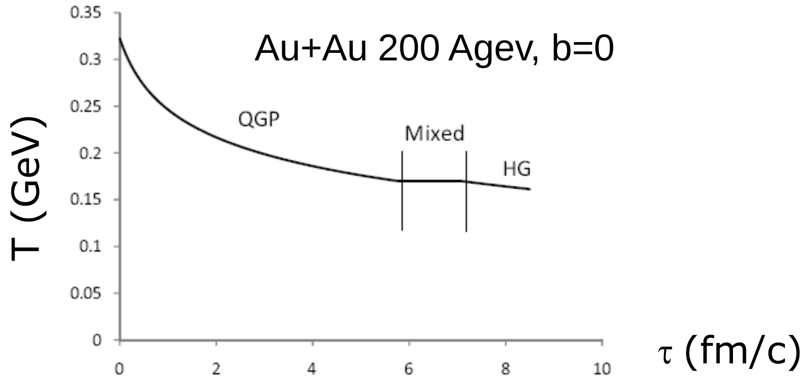
state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
$E_s^i[GeV]$	0.64	0.20	0.005	1.10	0.67	0.54	0.31	0.20
T_d/T_c	1.1	0.74	0.1-0.2	2.31	1.13	1.1	0.83	0.75
T_d/T_c	~ 1.42	~ 1.05	unbound	~ 3.3	~ 1.22	~ 1.18	-	-
T_d/T_c	1.78-1.92	1.14-1.15	1.11-1.12	$\gtrsim 4.4$	1.60-1.65	1.4-1.5	~ 1.2	~ 1.2

Using F(T,r)
Wong 04
Using V(T,r)

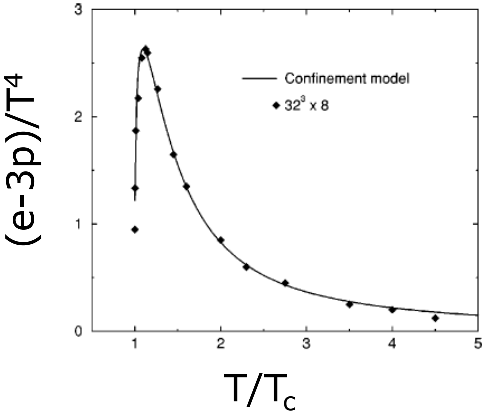
Another model independent approach ?

Few things to note about J/ψ near Tc

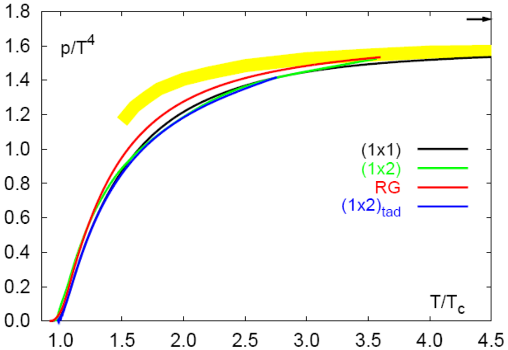
- Tc region is important in HIC



- Large non-perturbative change at Tc



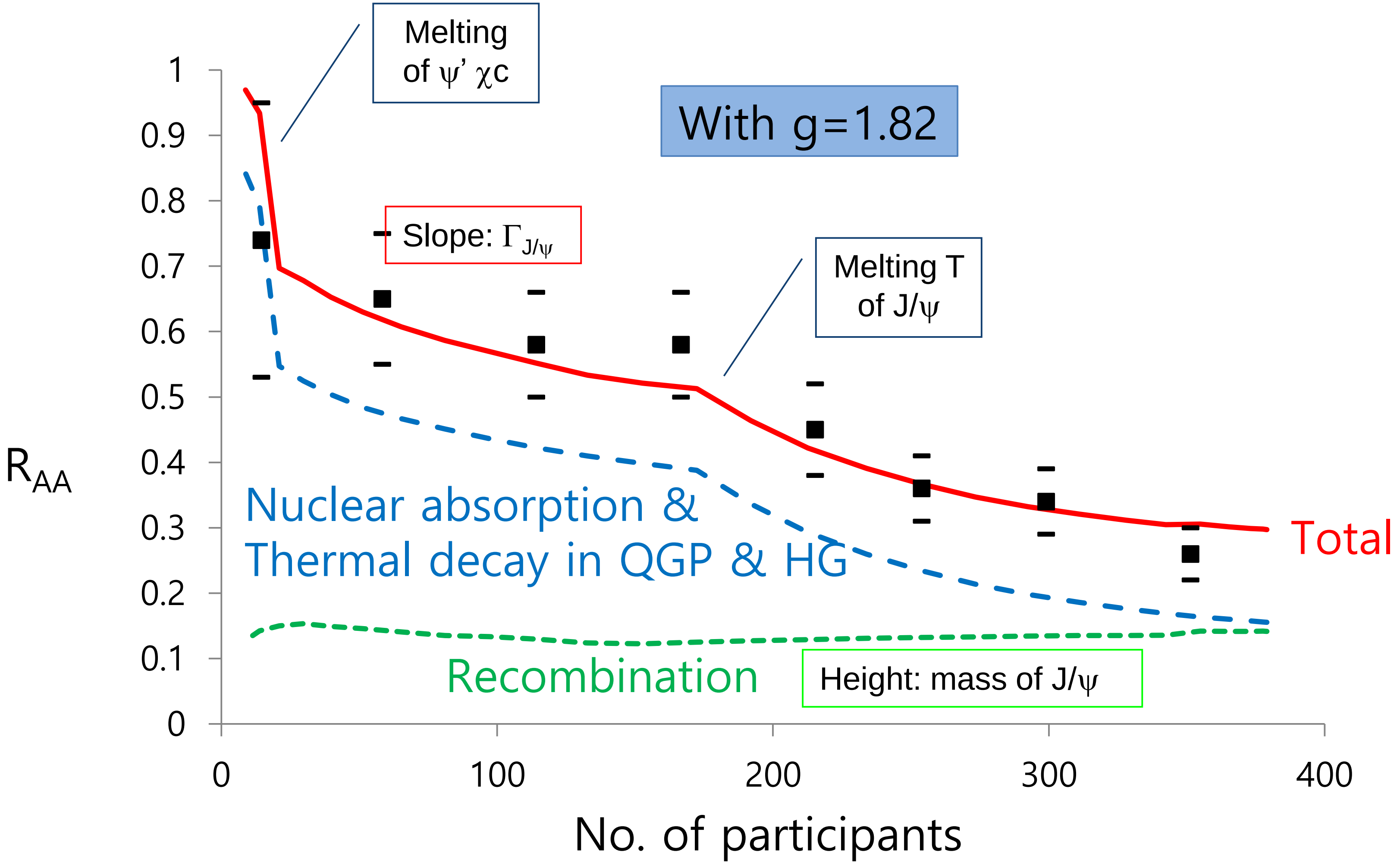
- Resumed perturbation fails



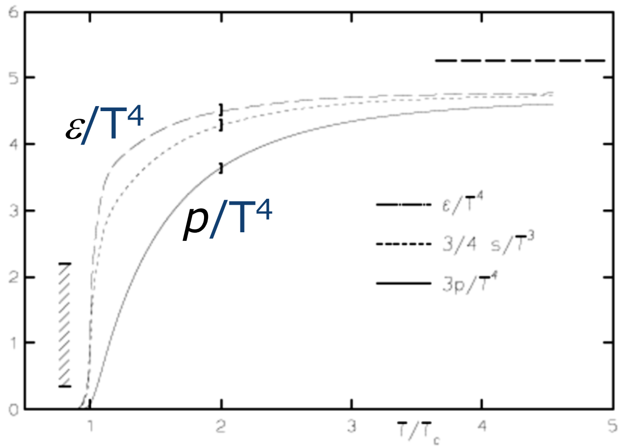
Karsch hep-lat/0106019

Comparison with experimental data of RHIC (√s=200 GeV at midrapidity)

T. Song (preliminary)



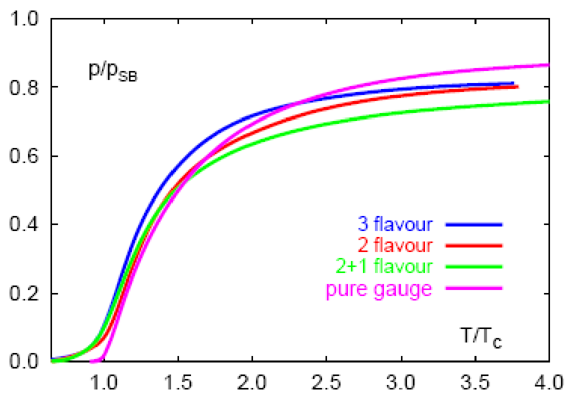
Lattice data on (ε , p)



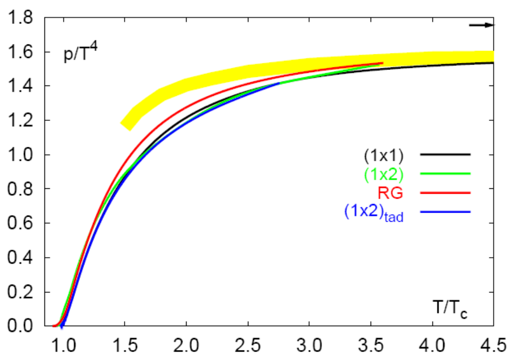
Lattice result for purge gauge (Boyd et al 96)

Sudden increase in ε

Slow increase in p



Rescaled pressure (Karsch 01)



Karsch hep-lat/0106019

Local operator related to confinement? Gluon Operators near Tc

- Two independent operators

Gluon condensate $\left\langle \frac{\alpha}{\pi} G^2 \right\rangle = G_0$

Twist-2 Gluon $\left\langle \frac{\alpha_s}{\pi} G^{\alpha\mu} G^{\beta\mu} \right\rangle = \left(u^\alpha u^\beta - \frac{1}{4} g^{\alpha\beta} \right) G_2$

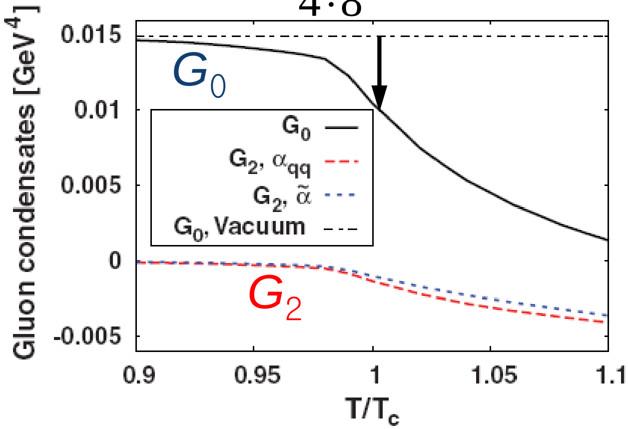
or

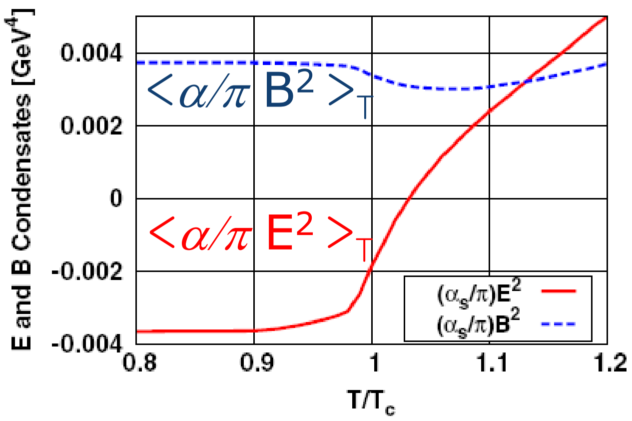
$\left\langle \frac{\alpha}{\pi} E^2 \right\rangle$

$\left\langle \frac{\alpha_s}{\pi} B^2 \right\rangle$

- At finite temperature: from $G_0 = -\frac{8}{9}(\varepsilon - 3p), \quad G_2 = \frac{\alpha}{\pi}(\varepsilon + p)$

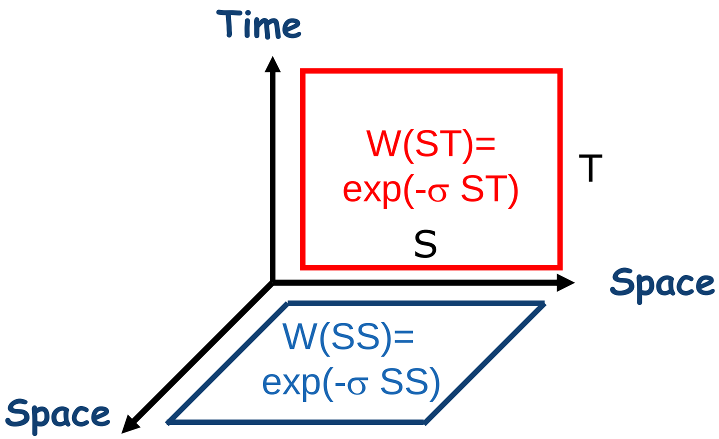
$$\mathrm{B} = -\frac{9}{4 \cdot 8}\left(G_0(T_c) - G_0\right) \approx (189\ \mathrm{MeV})^4$$





$\langle E^2 \rangle$, $\langle B^2 \rangle$ vs confinement potential

- Local vs non local behavior



OPE for Wilson lines: Shifman NPB73 (80)

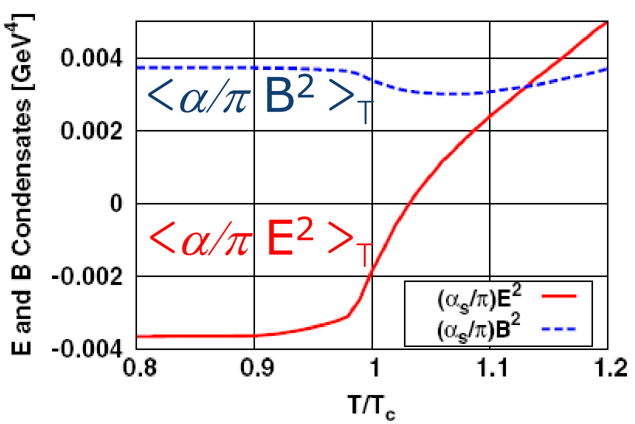
$W(S\text{-}T) = 1 - \langle \alpha/\pi\, E^2 \rangle (ST)^2 + \ldots$

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

- Behavior at T>Tc

$W(SS) = \exp(-\sigma\, SS)$

$W(ST) = \exp(-\, g(1/S)\, S)$



Local operators in Nuclear Medium

- Linear density approximation

$$\langle \mathrm{Op} \rangle_\rho = \langle \mathrm{Op} \rangle_0 + \frac{\rho_N}{2m_N} \langle \mathrm{N} | \mathrm{Op} | \mathrm{N} \rangle,$$

$$\Delta G_0 \propto \langle \mathrm{N} | \mathrm{T}^\mu_\mu (\mathrm{Chiral}) \, | \mathrm{N} \rangle = m_N^0 \rightarrow 750 \, \mathrm{MeV}$$

$$G_2 \propto 2m_N \int dx x G(x, \mu^2) \quad \rightarrow \quad 0.9 \, m_N$$

$$\Delta \langle \bar{\psi} \psi \rangle \propto \Sigma_{\pi \mathrm{N}} \quad \rightarrow 45 \, \mathrm{MeV}$$

- Condensate at finite density

$$G_0(\rho) = G_0 - \frac{8}{9} m_N^0 \rho = G_0 \left(1\text{-}0.061 \frac{\rho}{\rho_{\mathrm{n.m}}} \right)$$

$$G_2(\rho) = -\frac{\alpha_s}{\pi} 0.9 \rho$$

$$\Delta \left\langle \frac{\alpha}{\pi} E^2 \right\rangle_\rho = (\alpha_s \times 0.2 + 0.167) \rho$$

$$\Delta \left\langle \frac{\alpha}{\pi} B^2 \right\rangle_\rho = (\alpha_s \times 0.2 - 0.167) \rho$$

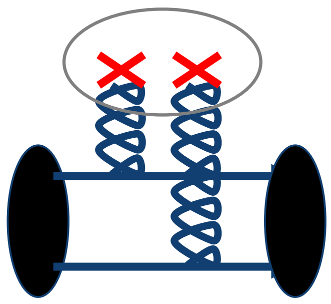
$$\langle \bar{\psi} \psi \rangle_\rho = \langle \bar{\psi} \psi \rangle_0 \left(1 - 0.2 \frac{\rho}{\rho_{\mathrm{n.m}}} \right)$$

- At $\rho = 5 \times \rho_{\mathrm{n.m.}}$

$$\left\langle \frac{\alpha}{\pi} G^2 \right\rangle_{5\rho_{n.m.}} = 0.7 \times \left\langle \frac{\alpha}{\pi} G^2 \right\rangle_0 \approx \left\langle \frac{\alpha}{\pi} G^2 \right\rangle_{\mathrm{Tc}}$$

$$\langle \bar{\psi} \psi \rangle_{5\rho_{n.m.}} \approx 0 \qquad = \langle \bar{\psi} \psi \rangle_{\mathrm{Tc}}$$

- Vacuum



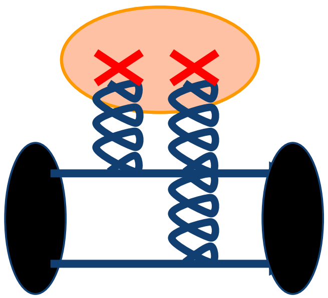
$$\left\langle \frac{\alpha}{\pi} G^2 \right\rangle, \quad \left\langle \frac{\alpha}{\pi} GDDG \right\rangle$$

- Medium corrections

+

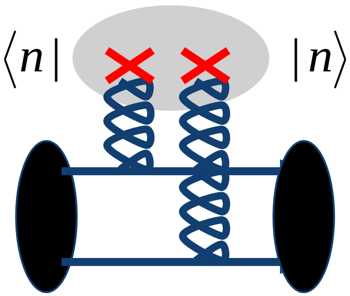
Finite temperature

Lattice calculation



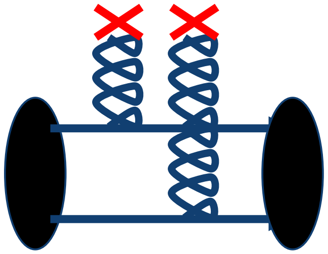
Finite density

Nucleon expectation value

$\langle n |$  $| n \rangle \times \rho_n$

J/ψ near T_c

QCD vacuum $$\left\langle \frac{\alpha}{\pi} G^2 \right\rangle_0 = 2\left\langle \frac{\alpha}{\pi} B^2 \right\rangle_0 = 2\left\langle \frac{\alpha}{\pi} E^2 \right\rangle_0 = \left(0.35\,\mathrm{GeV}\right)^4$$



QCD at T_c $$\left\langle \frac{\alpha}{\pi} G^2 \right\rangle_{\mathrm{Tc}} = 0.75 \times \left\langle \frac{\alpha}{\pi} G^2 \right\rangle_0 \qquad \left\langle \frac{\alpha}{\pi} E^2 \right\rangle_{\mathrm{Tc}} = 0.5 \times \left\langle \frac{\alpha}{\pi} E^2 \right\rangle_0$$

$$\left\langle \frac{\alpha}{\pi} B^2 \right\rangle_{\mathrm{Tc}} = \left\langle \frac{\alpha}{\pi} B^2 \right\rangle_0$$

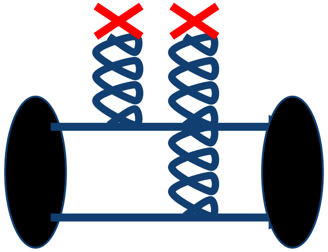
Nuclear medium: 20% deconfinement

QCD vacuum $$\left\langle \frac{\alpha}{\pi} G^2 \right\rangle_0 = 2\left\langle \frac{\alpha}{\pi} B^2 \right\rangle_0 = 2\left\langle \frac{\alpha}{\pi} E^2 \right\rangle_0 = (0.35\,\mathrm{GeV})^4$$

$$\left\langle \frac{\alpha}{\pi} G^2 \right\rangle_{\mathrm{Medium}} = \left\langle \frac{\alpha}{\pi} G^2 \right\rangle_0 \left(1 - 0.061 \frac{\rho}{\rho_{\mathrm{n.m.}}}\right)$$

$$\Delta\left\langle \frac{\alpha}{\pi} E^2 \right\rangle_{\mathrm{Medium}} = (\alpha_s \times 0.2 + 0.167)\rho$$

$$\Delta\left\langle \frac{\alpha}{\pi} B^2 \right\rangle_{\mathrm{Medium}} = (\alpha_s \times 0.2 - 0.167)\rho$$



Approaches to Heavy quark system in medium

OPE, QCD Stark Effect, and

QCD sum rules

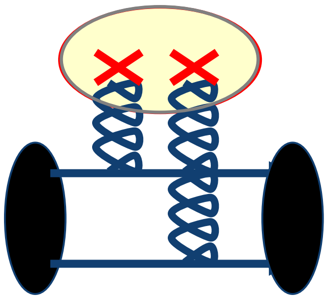
Approach based on OPE

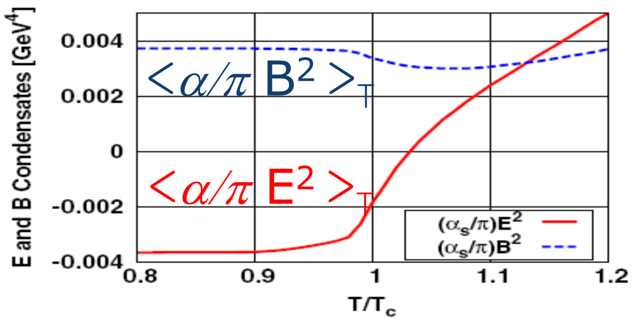
- Separation of scale in this approach

Non perturbative $\langle G^n \rangle + \Delta \langle G^n \rangle_{T,\rho}$

μ

perturbative





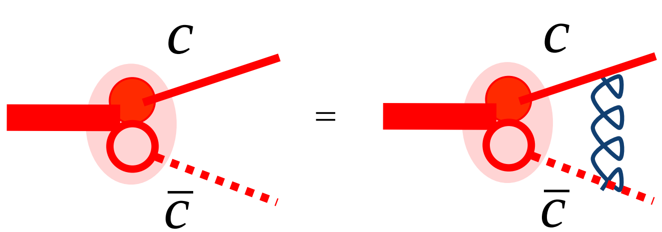
- In this work,

1. J/ψ mass shift (Δm) near Tc: QCD 2nd order Stark effect
2. J/ψ width (Γ) near Tc : perturbative QCD + lattice
3. check consistency of Δm , Γ at Tc :QCD sum rules
4. Application to nuclear matter

Mass shift: QCD 2nd order Stark Effect : Peskin 79 $\varepsilon > \Lambda_{qcd}$

- OPE for bound state: m→ infinity

$$\varepsilon_0 = m\left(N_c g^2/16\pi\right)^2 \rightarrow O(mg^4), \qquad |\vec{k}| \rightarrow O(mg^2)$$



$$g^2 \frac{mg^4(mg^2)^3}{(mg^4)(mg^4)(mg^2)^2} \rightarrow O(1)$$

- Attractive for ground state

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

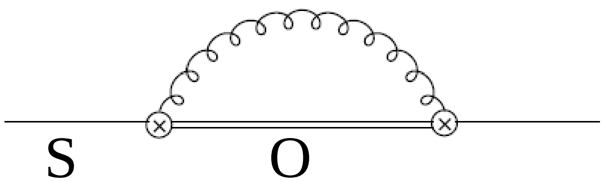
$$\Delta m_{J/\psi} = -\frac{128}{9\pi^2} \boxed{\frac{a_0^2}{\varepsilon_0}} \int dx \frac{x^{3/2}}{(1+x)^6} \frac{1}{x + a_0^2 \varepsilon m} \times \boxed{\left\langle \frac{\alpha}{\pi} E^2 \right\rangle_{\text{Medium}}}$$

2nd order Stark effect from pNRQCD

- LO Singlet potential from pNRQCD : Brambilla et al. 1/r > Binding > Λ_{QCD},

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\,\mu\nu} + \sum_{i=1}^{n_f}\bar{q}_i\, i\not{D} q_i + \int d^3r\ \mathrm{Tr}\left\{\mathrm{S}^\dagger\left[i\partial_0 + C_F\frac{\alpha_{V_s}}{r}\right]\mathrm{S} + \mathrm{O}^\dagger\left[iD_0 - \frac{1}{2N_c}\frac{\alpha_{V_o}}{r}\right]\mathrm{O}\right\}$$
$$+V_A\,\mathrm{Tr}\left\{\mathrm{O}^\dagger\vec{r}\cdot g\vec{E}\,\mathrm{S} + \mathrm{S}^\dagger\vec{r}\cdot g\vec{E}\,\mathrm{O}\right\} + \frac{V_B}{2}\mathrm{Tr}\left\{\mathrm{O}^\dagger\vec{r}\cdot g\vec{E}\,\mathrm{O} + \mathrm{O}^\dagger\mathrm{O}\vec{r}\cdot g\vec{E}\right\} + \dots \quad (55)$$

$$[\delta V_S(r)]_{11} = -ig^2\frac{T_F}{N_c}\frac{r^2}{d-1}\int_0^\infty dt\, e^{-it\Delta V}\left[\left\langle \vec{E}^a(t)\phi(t,0)_{ab}\vec{E}^b(0)\right\rangle_T\right]_{11},$$

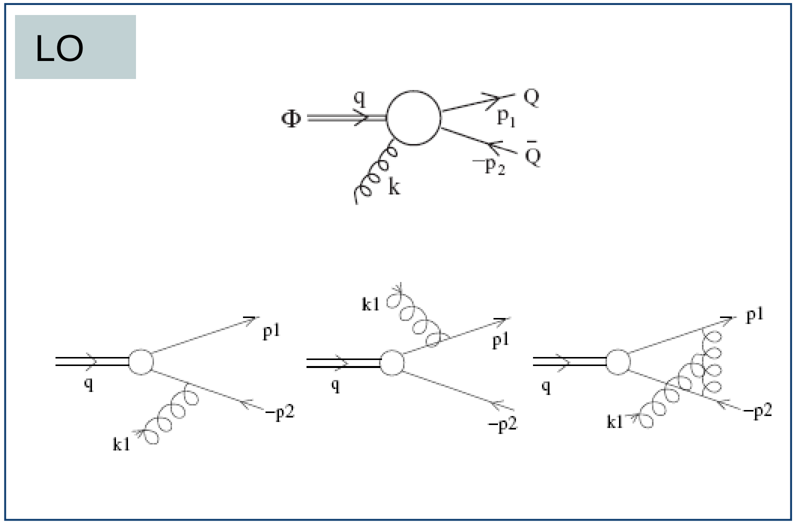


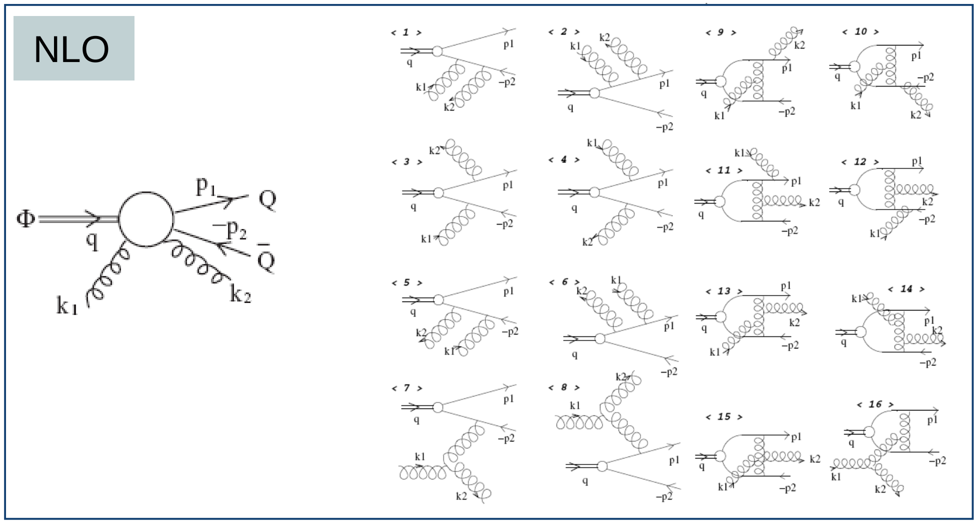
- Derivation

  - Take expectation value $\delta E_{J/\psi} = -ig^2\frac{T_F}{N_c}\frac{-i}{d-1}\int\frac{d^3p}{(2\pi)^3}\frac{r^2}{E_O - E_{J/\psi}}|\psi(p)|^2\left[\left\langle \vec{E}^a(t)\phi(t,0)_{ab}\vec{E}^b(0)\right\rangle_T\right]_{11}$
  - Large Nc limit $\Delta V = \frac{1}{r}\left(\frac{\alpha_{V_O}}{2N_c} + C_F\alpha_{V_S}\right) \approx \frac{N_c\alpha_s}{2r}$
  - Static condensate $\left[\left\langle \vec{E}^a(t)\phi(t,0)_{ab}\vec{E}^b(0)\right\rangle_T\right]_{11} \to \left[\left\langle \vec{E}^a(0)\vec{E}^a(0)\right\rangle_T\right]_{11}$
  - Energy
$$E_{J/\psi} = 2m_c - \epsilon$$
$$E_O = 2m_c + p^2/m_c,$$
  - → $= -\frac{1}{18}\int_0^\infty dk^2\left|\frac{\partial\psi(k)}{\partial k}\right|^2\frac{k}{k^2/m_h + \epsilon_0}\left\langle\frac{\alpha_s}{\pi}\Delta E^2\right\rangle_T$

Thermal width from NLO QCD + confinement model

- Elementary $\sigma_{J/\psi}$ in pert QCD, LO (Peskin + others) and NLO (Song, Lee 05)





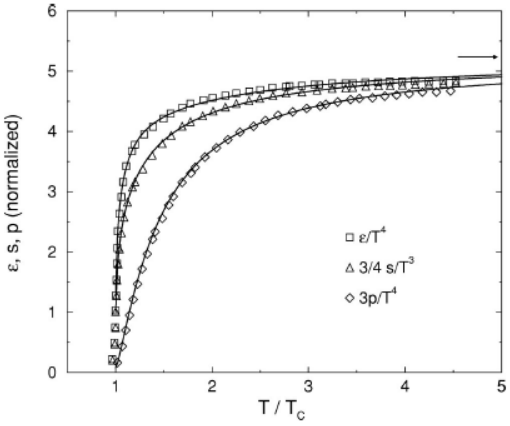
- Thermal width: $\sigma_{J/\psi} \otimes$ thermal gluon (Park, Song, Lee, Wong 08,09)

$$\Gamma^{eff} = d_p \int \frac{d^3 p}{(2\pi)^3} n(p) v_{rel} \sigma_{J/\psi}$$

Confinement model: Schneider, Weise

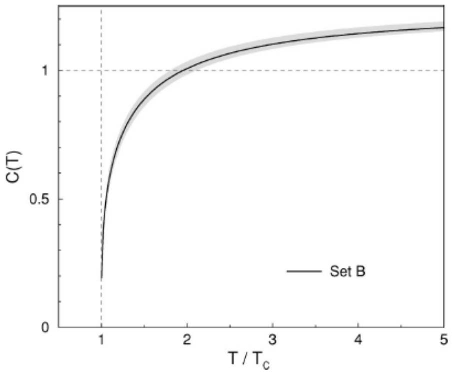
- $$p(T)=\frac{\nu_g}{6\pi^2}\int dk\left[C(T)\,f_B(E_k)\right]\frac{k^4}{E_k}-B(T)$$

  $$\varepsilon(T)=\frac{\nu_g}{2\pi^2}\int dk\left[C(T)\,f_B(E_k)\right]k^2E_k+B(T)$$

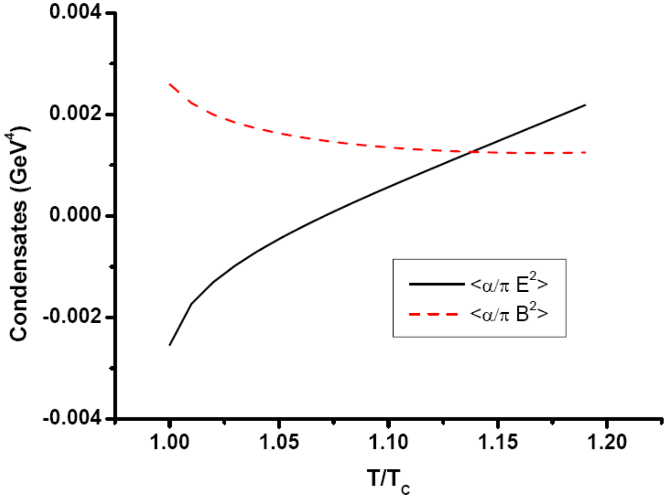


- $$C(T)=C_0\left(\left[1+\delta_c\right]-\frac{T_C}{T}\right)^{\beta_c}$$

  $$m_g(T)=G_0\left(\left[1+\delta\right]-\frac{T_C}{T}\right)^{\beta}T$$



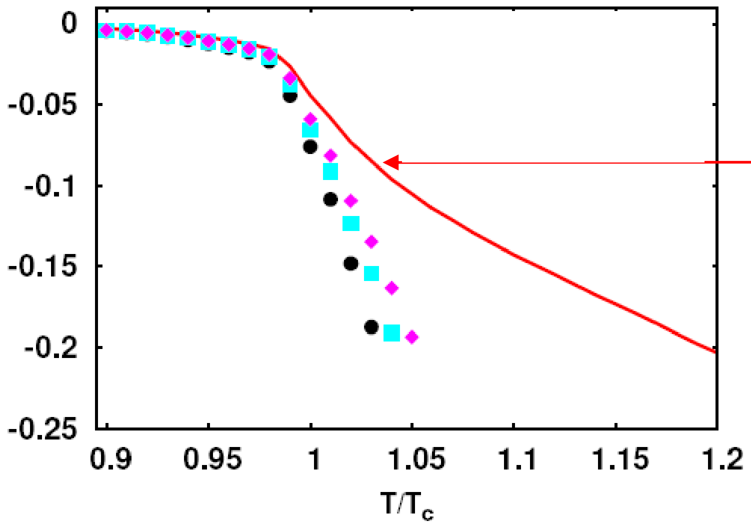
- E,B Condensate



Mass and width of J/ψ near Tc (Morita, Lee 08, M, L & Song 09)

$\Delta M_{J/\psi}$

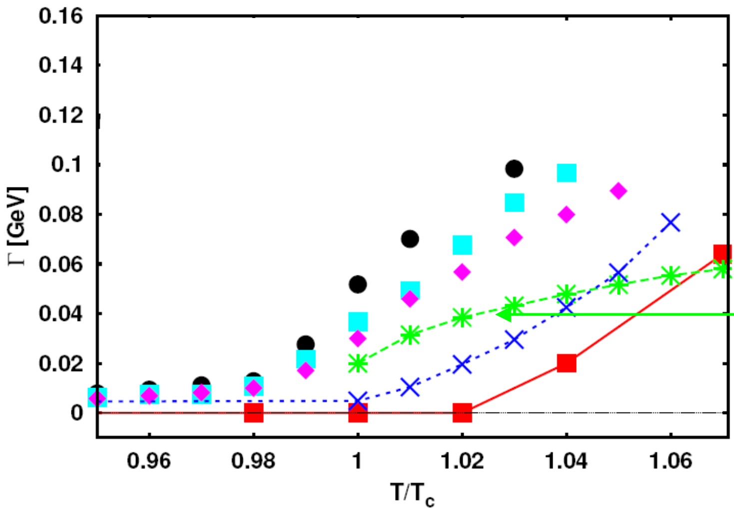
GeV



Δm from QCD Stark Effect

$\Gamma_{J/\psi}$

GeV



Γ =pert QCD + confinement model

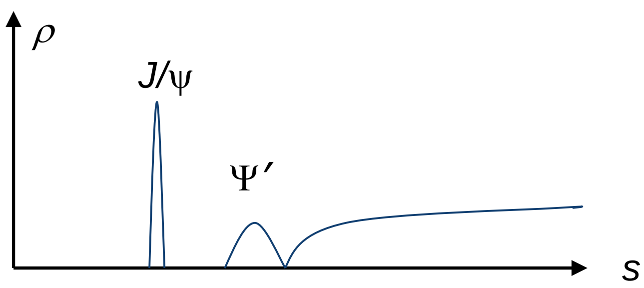
Constraints from QCD sum rules for Heavy quark system

- sum rule at T=0 : can take any Q² >=0, $4m^2 + Q^2 \;>>\; \langle \mathrm{G} \rangle_{\text{vacuum}} = \Lambda^2_{QCD}$

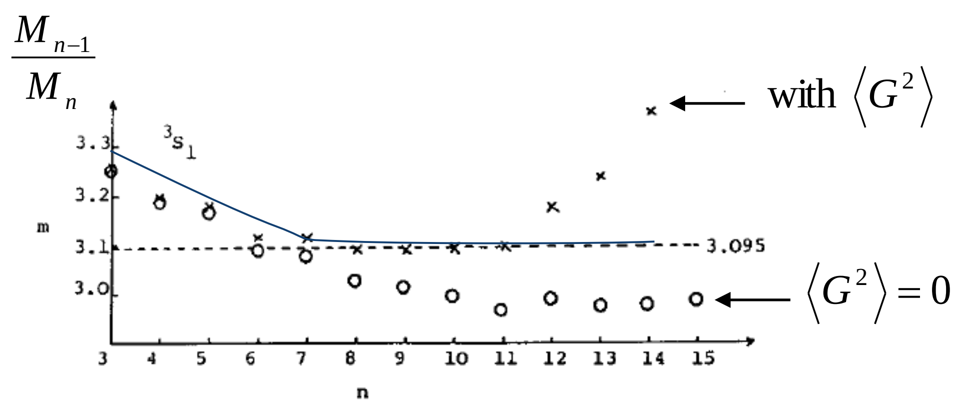
$$M_n = \left(\frac{d}{dQ^2}\right)^n < J(Q), J(0) >= \int ds \frac{\rho(s)}{(s+Q^2)^n}$$

Phenomenological side

OPE



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

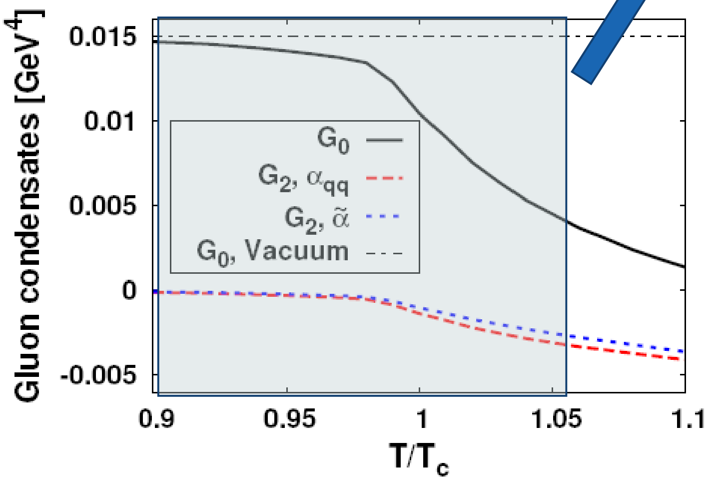


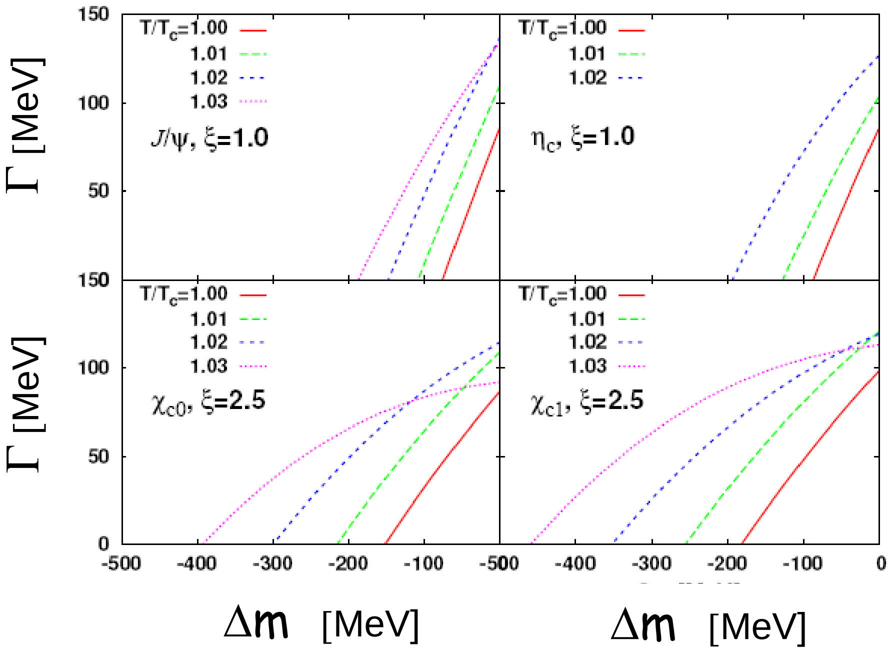
$$M_n = \frac{1}{(m^2_{J/\psi})^n} \left(f_{J/\psi} + c \left(\frac{m^2_{J/\psi}}{m^2_{\psi'}}\right)^n .. \right)$$

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

QCD sum rule constraint (Morita, Lee 08)

$$\frac{1}{n!}\left(-\frac{d}{dQ^2}\right)^n \Pi(Q^2) = \int ds \frac{\rho(s)}{(s+Q^2)^{n+1}}$$



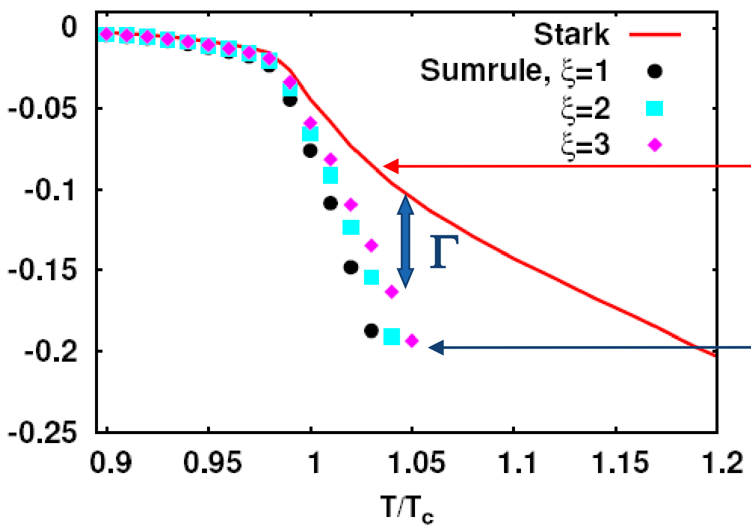


Can also use Borel sum rule

$$B(M) = \int ds \rho(s) \exp\left(-s/M^2\right)$$

Mass and width of J/ψ near Tc (Morita, Lee 08, M, L & Song 09)

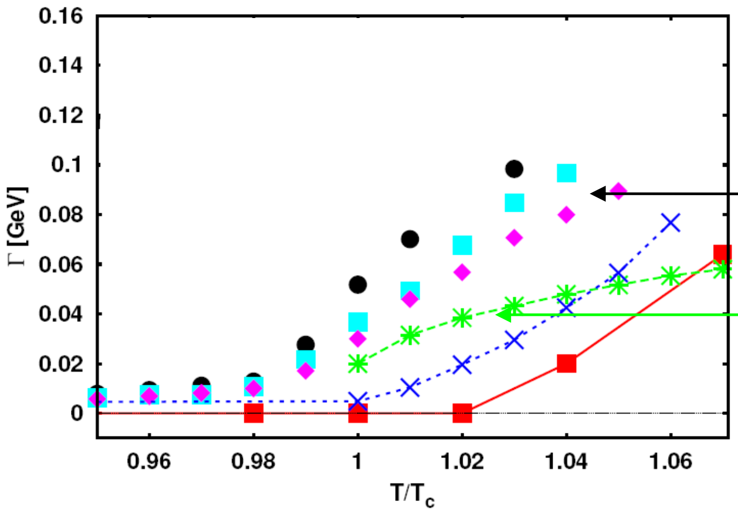
$\Delta M_{J/\psi}$ GeV



Δm from QCD Stark Effect

QCD sum rule limit with ΔΓ =0

$\Gamma_{J/\psi}$ GeV

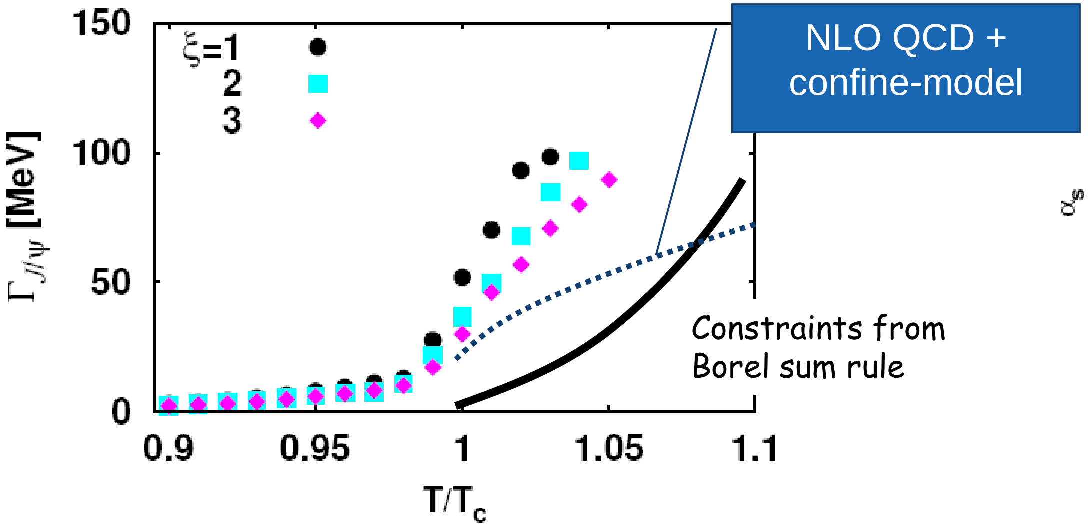


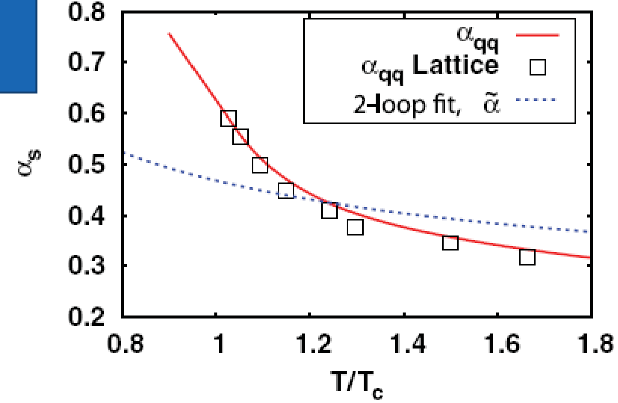
Γ =constraint-Δm (Stark effect)

Γ =pert QCD + confinement model

Γ in NLO QCD + confinement model

- Non perturbative part at Tc: confinement model (m_g(T) C(T))





From Tc to 1.05 Tc mass and width seems to rapidly change by 50 MeV ; to probe higher temperature within this region,

1. For mass, need higher dimensional operators
2. For width, Need higher twist contribution

Three places to look

Reconstruction of Imaginary Correlator

and

R_{AA} from RHIC

and

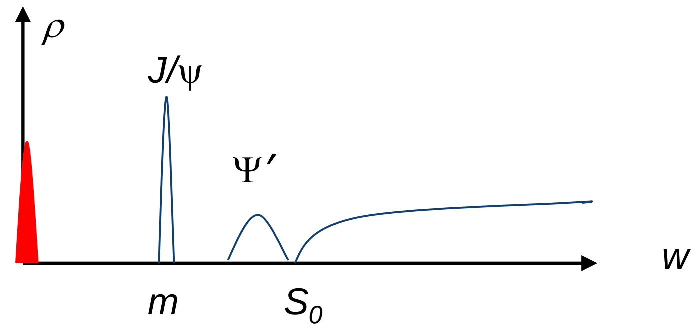
Mass shift at Nuclear matter

Reconstruction of Imaginary correlator

- Imaginary correlator

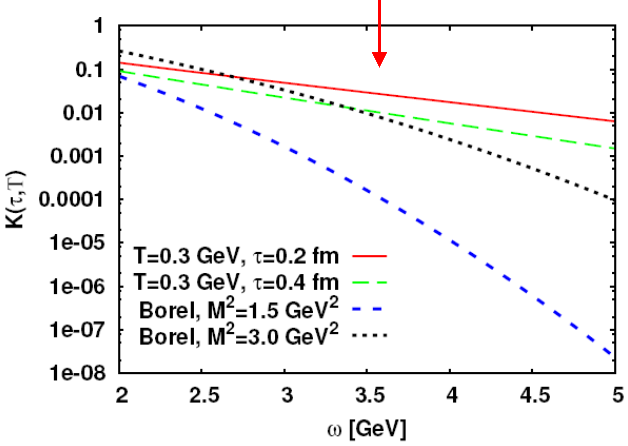
$$G(\tau,T)=\int dw K(w,\tau,T)\rho(w,T)$$

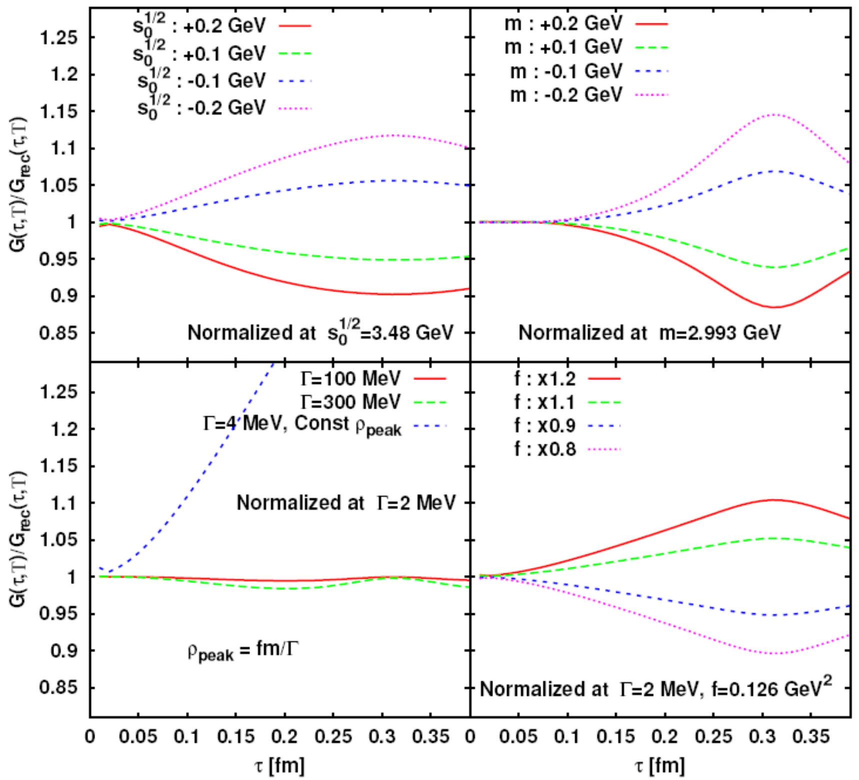
$$K(w,\tau,T)=\frac{\cosh[w(\tau-T/2)]}{\sinh(w/2T)}$$



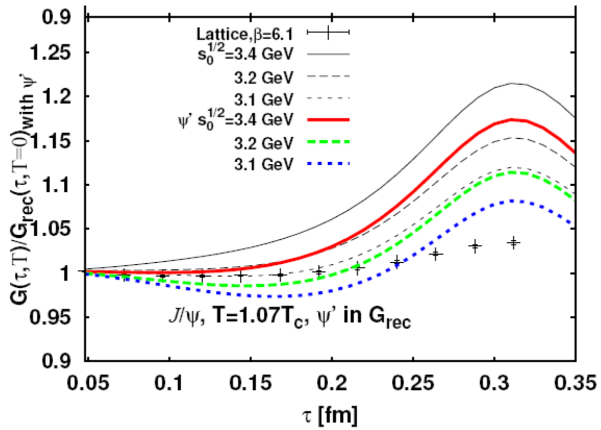
- Reconstructed correlator

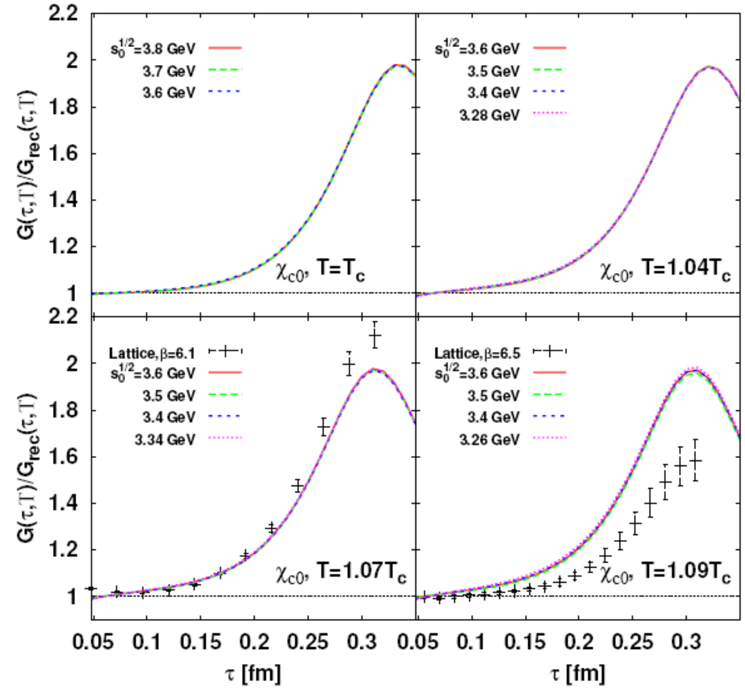
$$G_{rec}(\tau,T)=\int dw K(w,\tau,T)\rho(w,T=0)$$

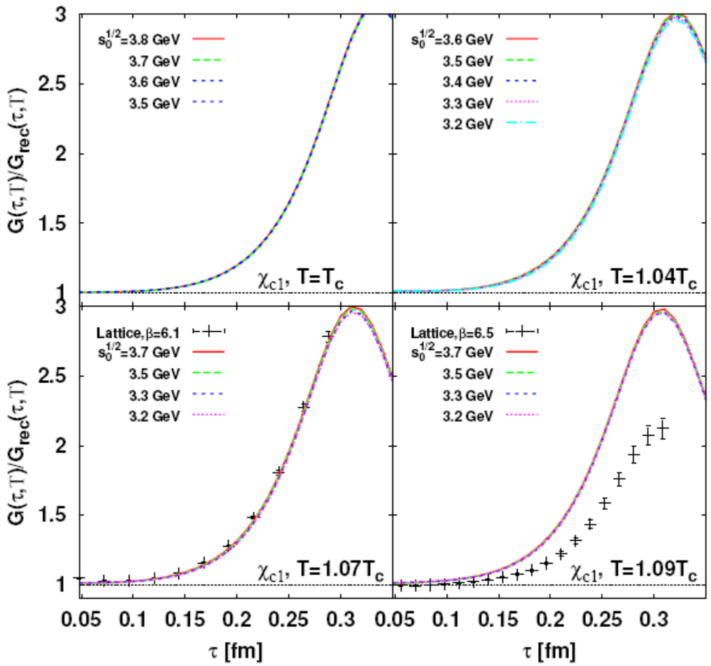


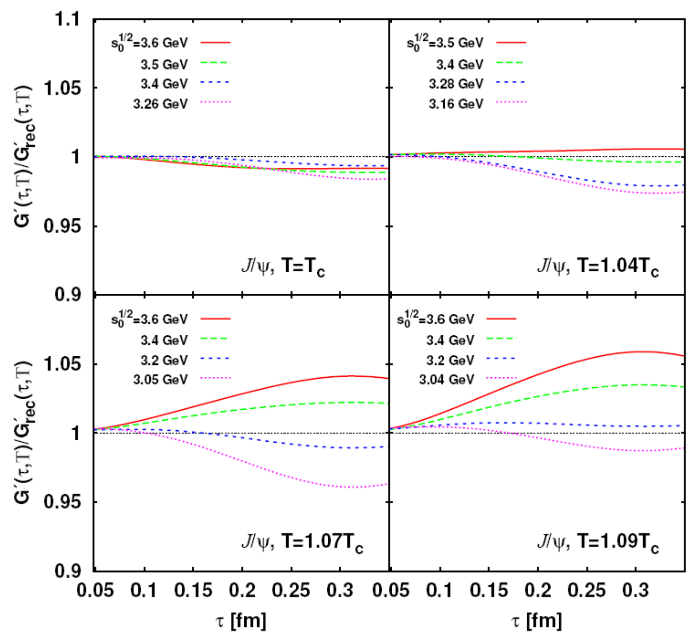


Morita, Lee (09) **arXiv:0908.2856**



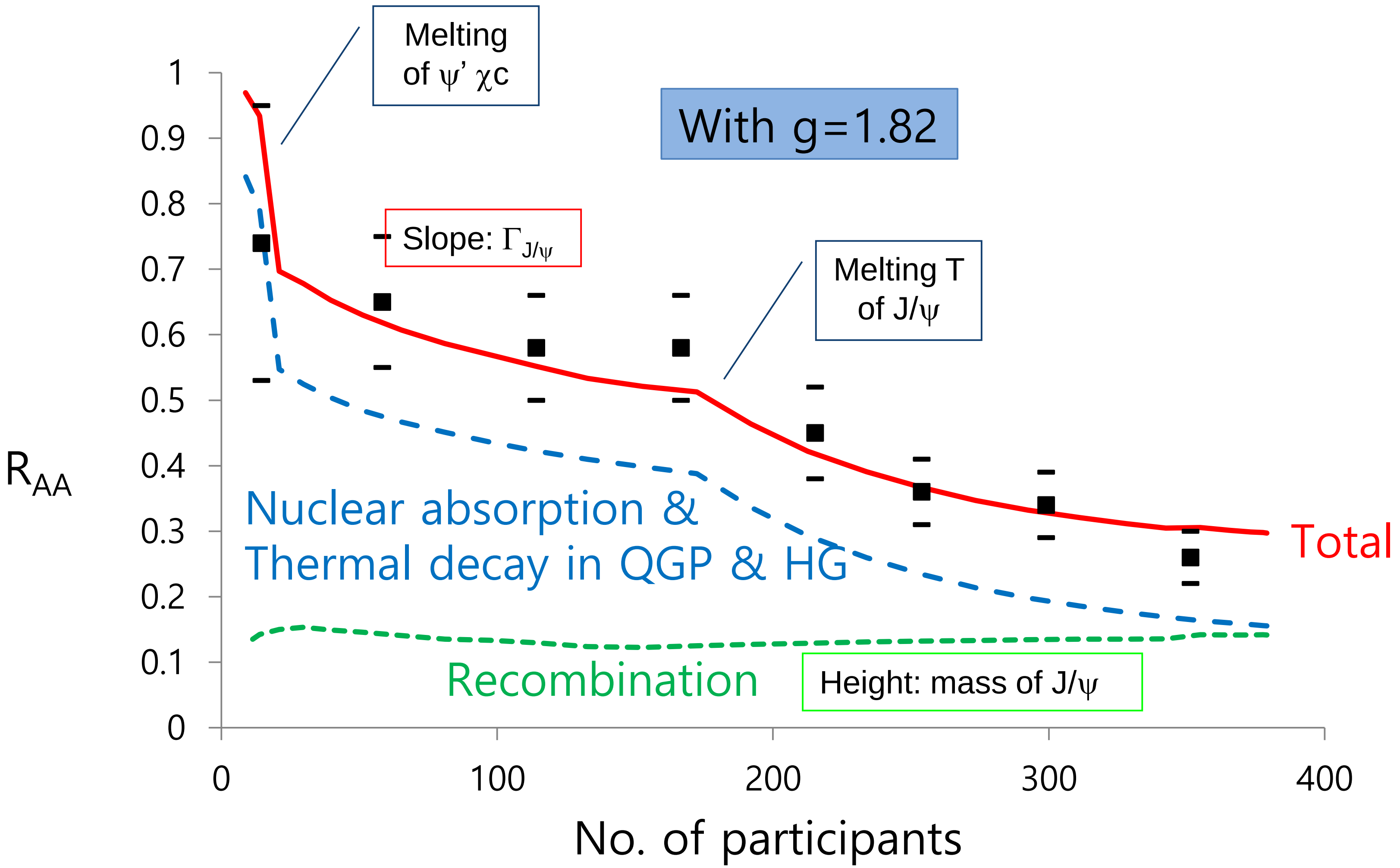






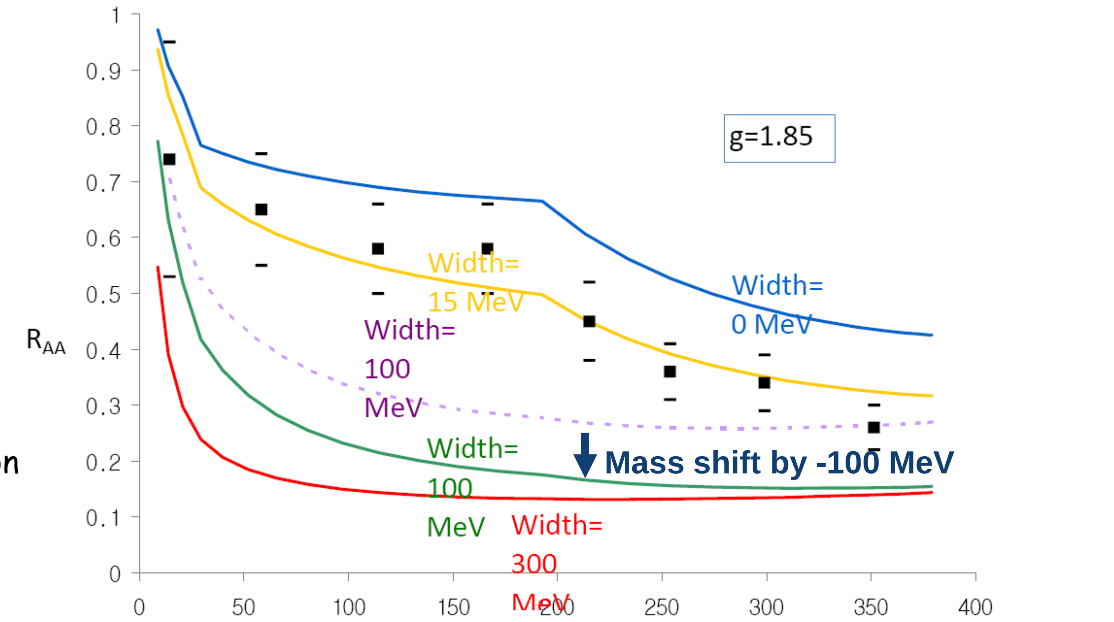
2-comp model (Rapp) Comparison with experimental data of RHIC ($\sqrt{s}$=200 GeV at midrapidity)

T. Song, SHLee (preliminary)

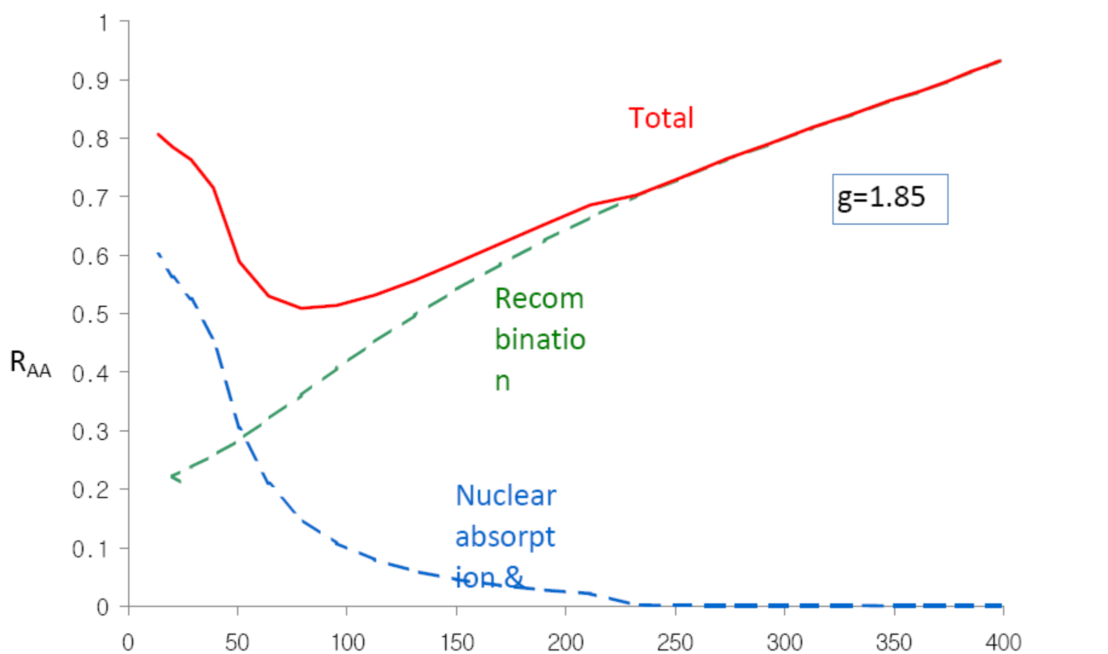


- Effects of width and mass

Assumed recombination effect to be the same

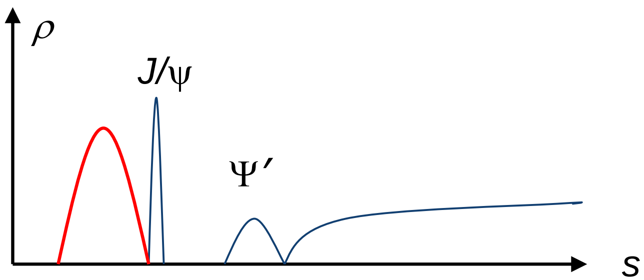


- At LHC



- sum rule in medium $4m^2+Q^2 \gg \langle G\rangle_0 + \Delta\langle G\rangle_{\text{Medium}}$

Phenomenological side

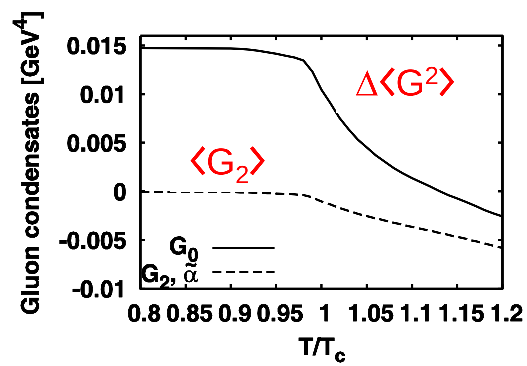


$$\rho(s)=\frac{f\sqrt{s}\Gamma}{\left(s-m_{J/\psi}^2\right)^2+s\Gamma^2}$$

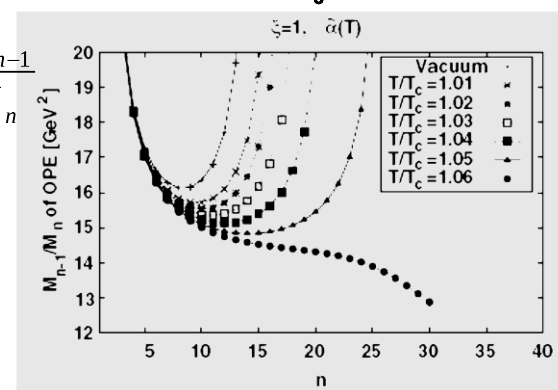
$$M_n=\int ds\,\frac{\rho(s)}{(s+Q^2)^n}$$

OPE

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



$$\frac{M_{n-1}}{M_n}$$



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

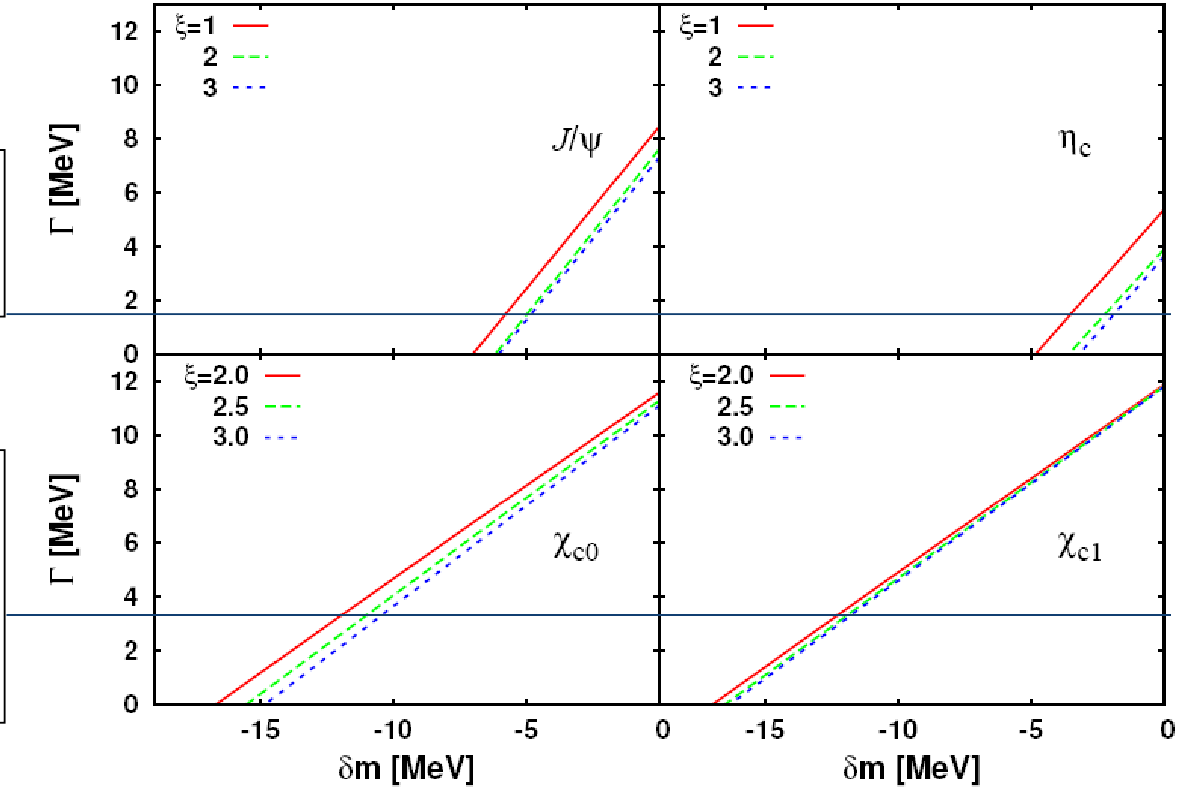
→ Obtain constraint for $\Delta m_{J/\psi}$ and Γ

Mass and width of J/ψ in nuclear Matter (Morita, Lee 08)

- QCD sum rule constraint

$$\Gamma_{J/\psi-N} = \langle \sigma_{J/\psi-N} v_{rel} \rho_N \rangle \approx 1.3\,\mathrm{MeV}$$
$$\text{with} \qquad \sigma_{J/\psi-N} = 2\,\mathrm{mb}$$

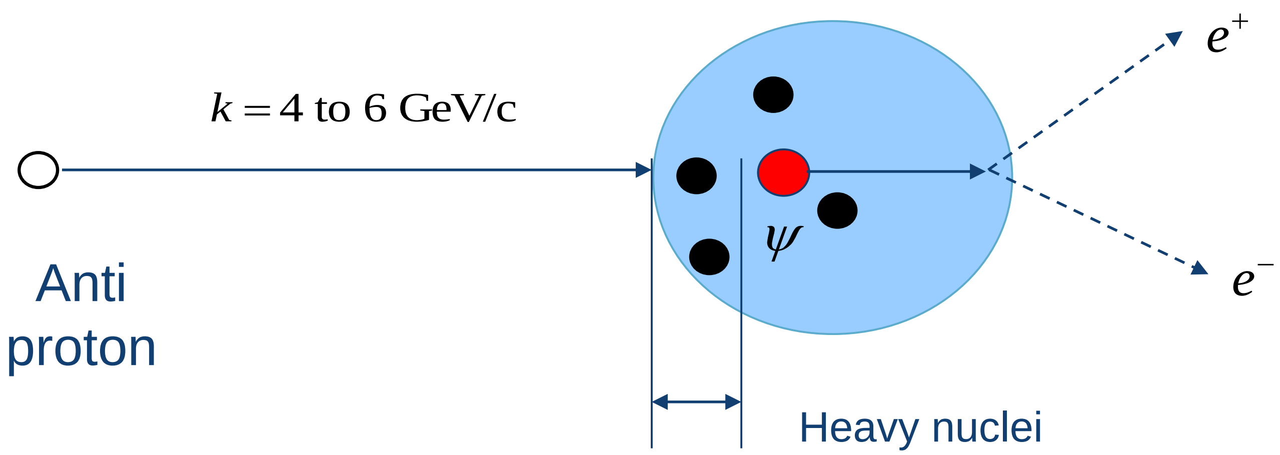
$$\Gamma_{\chi} = \langle \sigma_{\chi_c-N} v_{rel} \rho_N \rangle \approx 3.2\,\mathrm{MeV}$$
$$\sigma_{\chi_c-N} = \sigma_{J/\psi-N} \frac{\langle r^2 \rangle_{\chi_c}}{\langle r^2 \rangle_{J/\psi}}$$



Other approaches for mass shift in nuclear matter

	Quantum numbers	QCD 2nd Stark eff.	Potential model	QCD sum rules	Effects of DD loop
η_c	0^{-+}	**−8 MeV**		**−5 MeV** (Klingl, SHL ,Weise, Morita)	No effect
J/ψ	1^{--}	**−8 MeV** (Peskin, Luke)	**-10 MeV** (Brodsky et al).	**−7 MeV** (Klingl, SHL ,Weise, Morita)	<2 MeV (SHL, Ko)
χ_c	$0,1,2^{++}$	**-20 MeV**		**-15 MeV** (Morita, Lee)	No effect on χ_{c1}
$\psi(3686)$	1^{--}	**-100 MeV**			< 30 MeV
$\psi(3770)$	1^{--}	**-140 MeV**			< 30 MeV

Observation of Δm through p̄-A reaction



$$\frac{1}{0.17\,fm^{-3} \times 5\,fm^2} = 1.2\,fm$$

Can be done at J-PARC

Table 2: Summary of parameters and resultant cross sections.

	J/ψ	η_c	χ_{c0}	χ_{c1}	χ_{c2}
m[MeV]	3097	2980	3415	3511	3556
δm[MeV]	−7	−4	−15	−15	−15
$\Gamma_{\rm tot}$ [MeV]	0.0934	25.5	10.4	0.89	2.05
Final State	e^+e^-	$\gamma\gamma$	$J/\psi\,\gamma$	$J/\psi\,\gamma$	$J/\psi\,\gamma$
$\langle\sigma_{\rm BW}\rangle_{\rm peak}$ [pb]	0.435	10.7	17.0	4.25	18.8
Events/day	7.5	184	294	74	326

Expected luminosity at GSI 2x 10^{32}cm^{-2}s^{-1} → (Events/day)

References

1. Finite temperature lattice: Karsch: arXiv:0711.0661, 0711.0656, 0710.0354, Kaczmarek et al. PRD 70, 074505
2. Sum rule method at finite T: https://wiki.bnl.gov/qpg/index.php/Sum_rule_approach
3. J/psi formal: Hashimoto et al. PRL 57,2123 (1986), Matsui and Satz, PLB 178, 416 (1986), Asakawa, Hatsuda PRL 92, 012001 (2004), Morita, Lee, PRL 100,022301, Mocsy, Petreczky, PRL, 99, 211602 (2007)
4. J/Psi Phenomenology: Gazszicki, Gorenstein, PRL 83, 4009 (1999) , PBM , J. Stachel, PLB490, 196 (2000), Andronic et al. arXiv::nucl-th/0611023, Grandchamp and Rapp, NPA 709, 415 (2002), Yan, Zhuang, Xu, PRL,97,232301 (2006), Song, Park, Lee arXiv: 1002.1884
5. J/psi in medium, Brodsky et al. PRL 64,1011 (1990) , Lee, nucl-th/0310080,