Roundtable discussion on the charmed sea

Panel

- Craig McNeile
- Carsten Urbach
- Antonio Vairo
- Jianwei Qiu
- Mariapaola Lombardo

Moderator

- Estia Eichten (forAndreas Kronfeld)

Charge

Presently lattice QCD simulations with 2+1+1 flavors of sea quark are being computed. The new feature, compared with the familiar MILC ensembles with 2+1 flavors of sea quark, is the charmed quark sea.

Interactions with the lattice community suggest a wide range of views whether this can have a big effect, and whether it is predictable. Some claim it is completely negligible (in the context of error budgets at the 1% level), while others state that it is completely unpredictable.

This contrasts with views from phenomenologists, who imagine that—after a leading effect on renormalization—the effects can be estimated in perturbation theory. This raises the possibility that we can anticipate which quantities have a truly negligible shift, say 0.1%, and which have a noticeable effect, say a 1–2%. There is also the matter of intrinsic charm. In principle, careful analysis (of suitable quantities) could shed light on this topic.

Issues for this roundtable:

(1) Explore what can be expected from the inclusion of the charmed sea.

(2) How big are the effects of charmed quarks in quarkonium systems? Heavy-light systems?

(3) Are there places where the inclusion of charm quarks might be very sugnificant?

(a) Intrinsic charm ?

(b) Physics in medium?

(4) Cross-talk between lattice and phenomenlogy

Craig (1), Carsten (1), Antotio (2), Jianwei (3a), Maria (3b)

Craig McNeile

Is $2+1 \approx 2+1+1$?

Lattice QCD results with 2+1 flavors of sea quarks crucial for determining many CKM matrix elements.
The Flavour Lattice Average Group (FLAG) (arXiv:1011.4408) use

$$M_{\Xi} - M_{\Lambda} \propto m_s - m_{ud}$$

from a $2+1$ lattice QCD calculation agreeing with experiment (BMW-c, arXiv:0906.3599) at 2% level to claim that missing charm in the sea is under 2%. FLAG will average results from 2+1 and 2+1+1 lattice QCD calculations, but not results from $n_f = 2$ calculations.
Christine Davies, compared mass of η_s (fictitious strange- strange pseudoscalar meson) computed with 2+1+1 and 2+1 from MILC simulations.

$$(m_{\eta_s}^{2+1+1})^2 - (m_{\eta_s}^{2+1})^2 \propto m_s \sim 1\%$$

Estimating missing sea charm effects

hep-lat/9211046, El-Khadra used Richardson's potential that depends on n_f to estimate wave-function at origin in charmonuim, between nf=3 and nf=0.
HPQCD paper on Bs spectroscopy (1010.3848), Massive quark loop in the gluon propagator

$$V(r) = -\frac{C_f \alpha_s}{r} \to -C_f \alpha_s \left(\frac{1}{r} + \frac{\alpha_s}{10 m_c^2} \delta^3(r) \right) .$$

Quoted a shift of around 5 MeV to masses of both Υ and η_b. Apply with 50% errors.
It is possible to expand the fermion determinant in heavy quark masses and Wilson loops. See hep-lat/0501009, Matthew Nobes.

Possible future paper title: 2+1 != 2+1+1

I believe that for T=0 physics we can only compare lattice calculations with 2+1+1 and 2+1 sea quarks after a careful continuum limit.

MILC collaboration et al. plans (from Paul Mackenize)

a fm	m_s/m_l	Vol	M core hours	Comment
0.12	1/5	24^3 64	3	
	1/10	32^3 64	8	
	1/27	48^3 64	24	
0.09	1/5	32^3 64	10	
	1/10	48^3 96	35	
	1/27	64^3 96	48	above almost done
0.06	1/5	48^3 144	38	
	1/10	64^3 144	128	
	1/27	96^3 144	218	
0.045	1/5	64^3 192	135	
	1/10	88^3 192	352	
	1/27	128^3 192	1083	new Argonne computer 2012
0.03	1/5	96^3 288	685	new Argonne computer 2012

Time scale a few years. With the configurations with lattice spacing 0.03 fm, the bottom quark can be included via relativistic formalism – ideally (in my view) compute f_B decay constant before start of super B factories

ETMC plans

From latest International lattice data (ILDG) grid workshop. The European Twisted Mass Collaboration plan on generating gauge configurations with parameters:

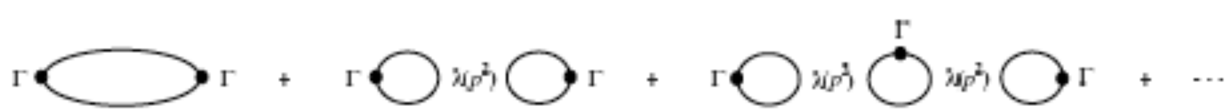
- Nf $= 2 + 1 + 1$
- Lattice volumes $= 24^3 \times 48$ to $96^3 \times 192$
- $m_\pi = 160$ .. 500 MeV
- a $= 0.055$ to 0.085 fm

Big/interesting/amusing dynmical charm effects

There has been a lot of recent work on looking at the strangeness content of the nucleon (arXiv:1012.0562, arXiv:0911.2407). Replace strange quark with charm quark to look for “hidden charmonium” (for example: hep-ph/9704379, rho pi Puzzle)

$$\langle P \mid \overline{c}\Gamma c \mid P\rangle$$

where $\Gamma = 1$, γ_μ or $\gamma_\mu\gamma_5$
Disconnected valence charm loops for η_c, $\eta_c(2S)$, .. need charm loops in the sea.

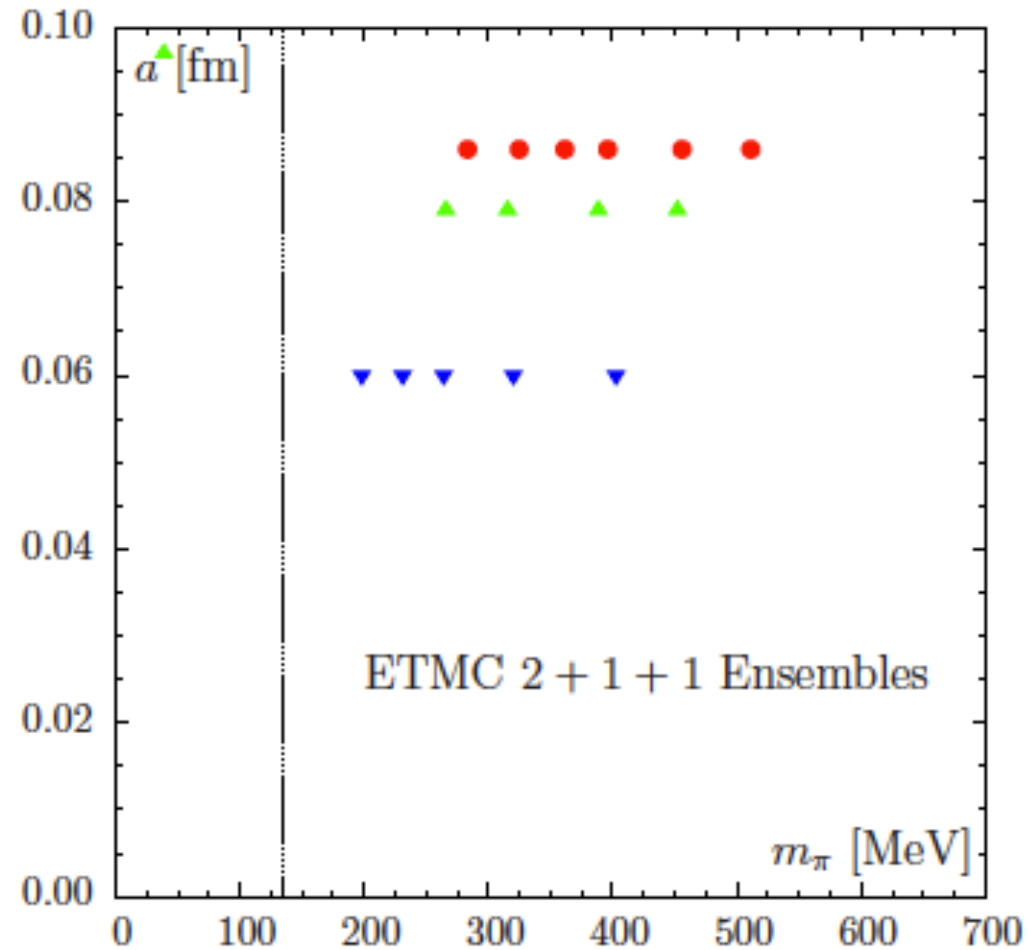


Also η_c - η' - η mixing (Feldmann hep-ph/9907491).
Unquenched lattice calculations of heavy glueballs (for PANDA) probably need charm quarks in the sea

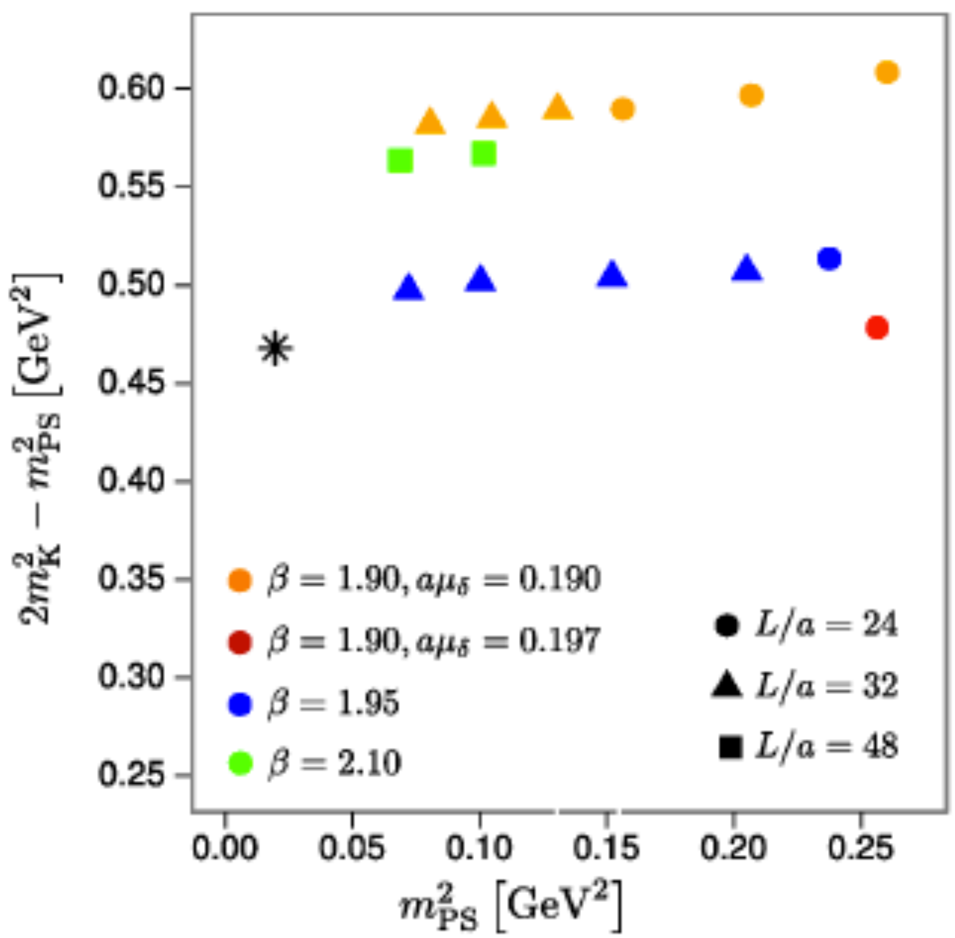
Carsten Urbach

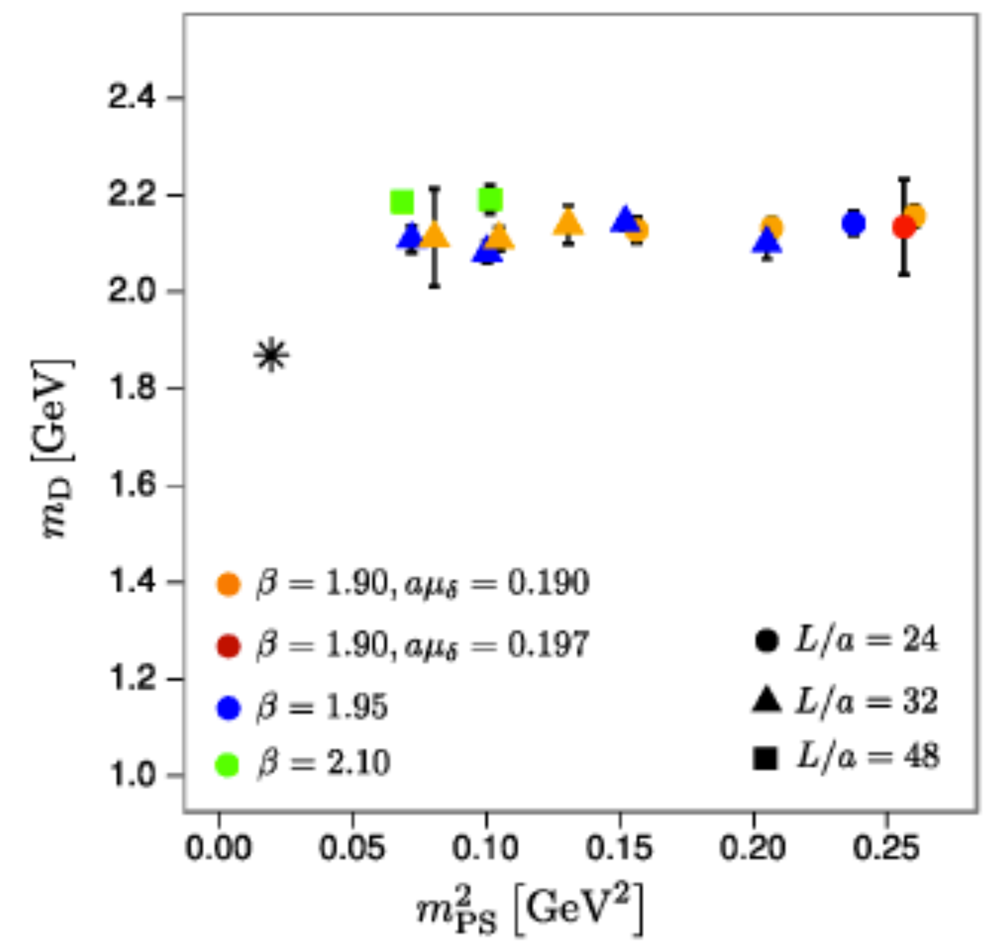
ETMC $N_f = 2 + 1 + 1$ Current Simulation Landscape

- Maximally Twisted Mass fermions
- $\mathcal{O}(a)$ improved observables
- 5000 to 10000 trajectories
- $m_\pi \cdot L \geq 4$ (some exceptions)
- am_c roughly 0.25 at finest latice spacing and 0.5 coarsest



Kaon and D-meson Masses





ETMC Future Plans

if computer resources permit...

- reduce pion mass towards physical point
- additional ensembles to bracket the strange and possibly charm quark mass
- reducing the lattice spacing towards 0.055 fm
- large statistics runs $\Rightarrow$ flavour singlet physics
- large volume runs $\Rightarrow$ resonance parameters and small lattice momenta

QWG11: charm-sea round table

Antonio Vairo

Technische Universität München

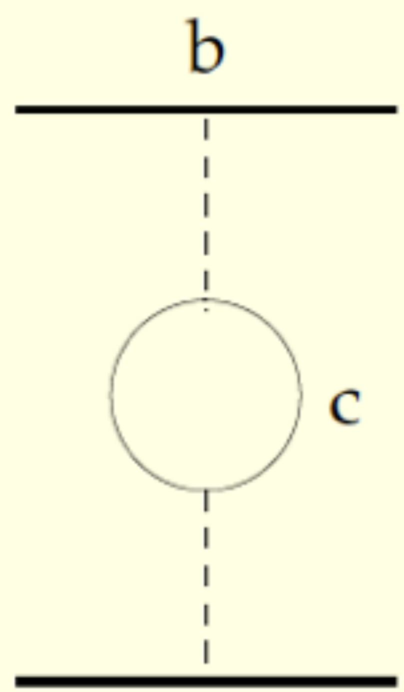
c-mass effects

- $m_c \gg \Lambda_{\mathrm{QCD}}$
  Charm-mass effects happen at a perturbative scale.
- If $m_c \gg 1/r \sim m_b v_b$
  the charm quark contributes through local NRQCD operators. The charm quark decouples at the momentum-transfer scale.
- If $m_c \sim 1/r \sim m_b v_b$
  charm-quark effects have to be taken into account dynamically at the momentum transfer scale. This may be the relevant situation for the bottomonium system:

$$m_c \sim m_b v_b \sim 5 \text{ GeV} \times 0.3$$

Note that this situation requires $m_b v_b \gg \Lambda_{\mathrm{QCD}}$.

c-mass effects in the static potential

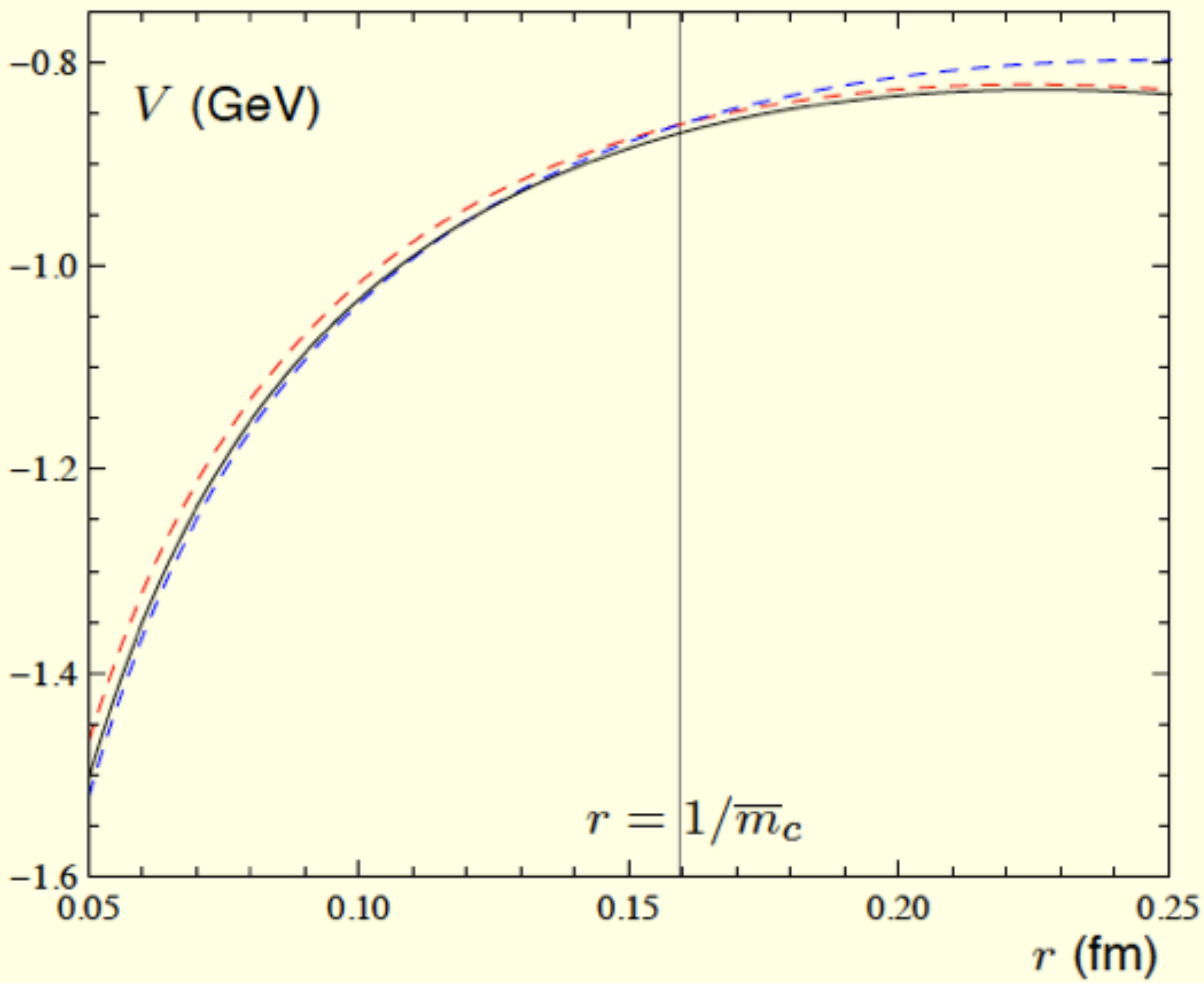


$$\delta V(r) \;=\; -\frac{C_F}{2}\frac{\alpha_s}{\pi}\frac{\alpha_s}{r}\left\{\int_0^1 dx\,\frac{x^2(1-x^2/3)}{1-x^2}e^{-m_c r/\sqrt{1-x^2}}+\frac{1}{3}\ln(rm_c)^2\right\}$$

where $\alpha_s = \alpha_s^{(4)}(1/r)$.

- **Eiras Soto PLB 491 (2000) 101**

c-mass effects in the static potential



blue dashed: c massless ($n_l = 4$)

red dashed: c infinitely heavy ($n_l = 3$)

black: $V^{(n_l=4)} + \delta V$

$\overline{m}_c = 1.237$ GeV

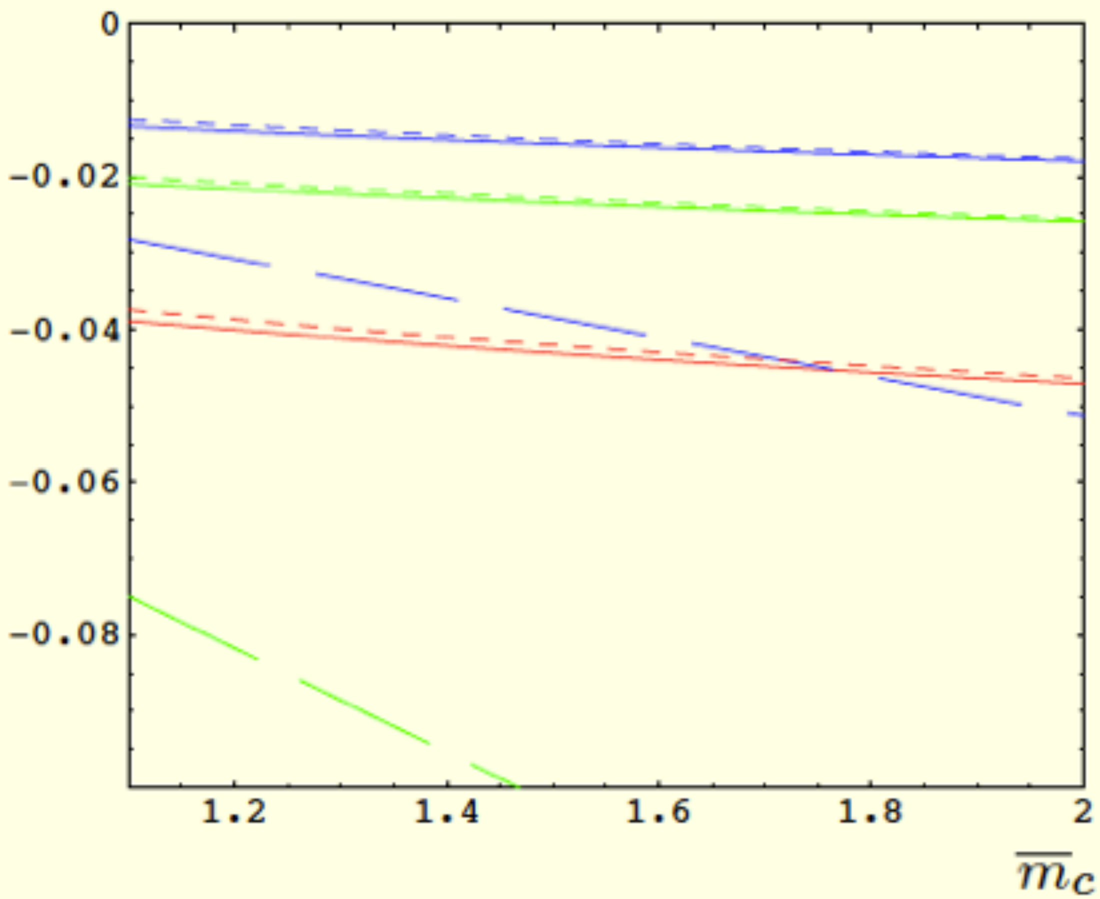
c-mass effects in the (weakly coupled) bottomonium spectrum

$$
\begin{aligned}
(\delta E_{b\bar{b}})^{(1)}_{m_c} = & \frac{\overline{m}_b (C_F \alpha_s^{(4)}(\mu))^2}{4n^2} \frac{\alpha_s^{(4)}(\mu)}{3\pi} \left\{ -\frac{3\pi}{2} n\bar{\rho} + \Big(n(2n+1) + (n+l)(n-l-1) \Big) \bar{\rho}^2 \right. \\
& -\pi n \left(\frac{1}{3}(n+1)(2n+1) + (n+l)(n-l-1) \right) \bar{\rho}^3 \\
& +2 \ln \left(\frac{2}{\bar{\rho}} \right) - 2 \Big(\psi(n+l+1) - \psi(1) \Big) \\
& -\frac{2}{(2n-1)!} \sum_{k=0}^{n-l-1} \left(\begin{array}{c} n-l-1 \\ k \end{array} \right) \left(\begin{array}{c} n+l \\ 2l+1+k \end{array} \right) \bar{\rho}^{2(n-l-1-k)} \\
& \left. \times \frac{d^{2n-1}}{d\bar{\rho}^{2n-1}} \left[\bar{\rho}^{2k+2l+1} \frac{(2-\bar{\rho}^2-\bar{\rho}^4)}{\sqrt{\bar{\rho}^2-1}} \mathrm{Atan} \left(\frac{\sqrt{\bar{\rho}-1}}{\sqrt{\bar{\rho}+1}} \right) \right] \right\},
\end{aligned}
$$

where $\bar{\rho} = 2n\overline{m}_c / (\overline{m}_b C_F \alpha_s^{(4)}(\mu))$.

- Eiras Soto PLB 491 (2000) 101

c-mass effects in the (weakly coupled) bottomonium spectrum



$(\delta E)^{(1)}_{m_c}$: continuous line
$(\delta E)^{(1)}_{m_c \to 0}$: dashed line
$(\delta E)^{(1)}_{m_c \to \infty}$: dotted line

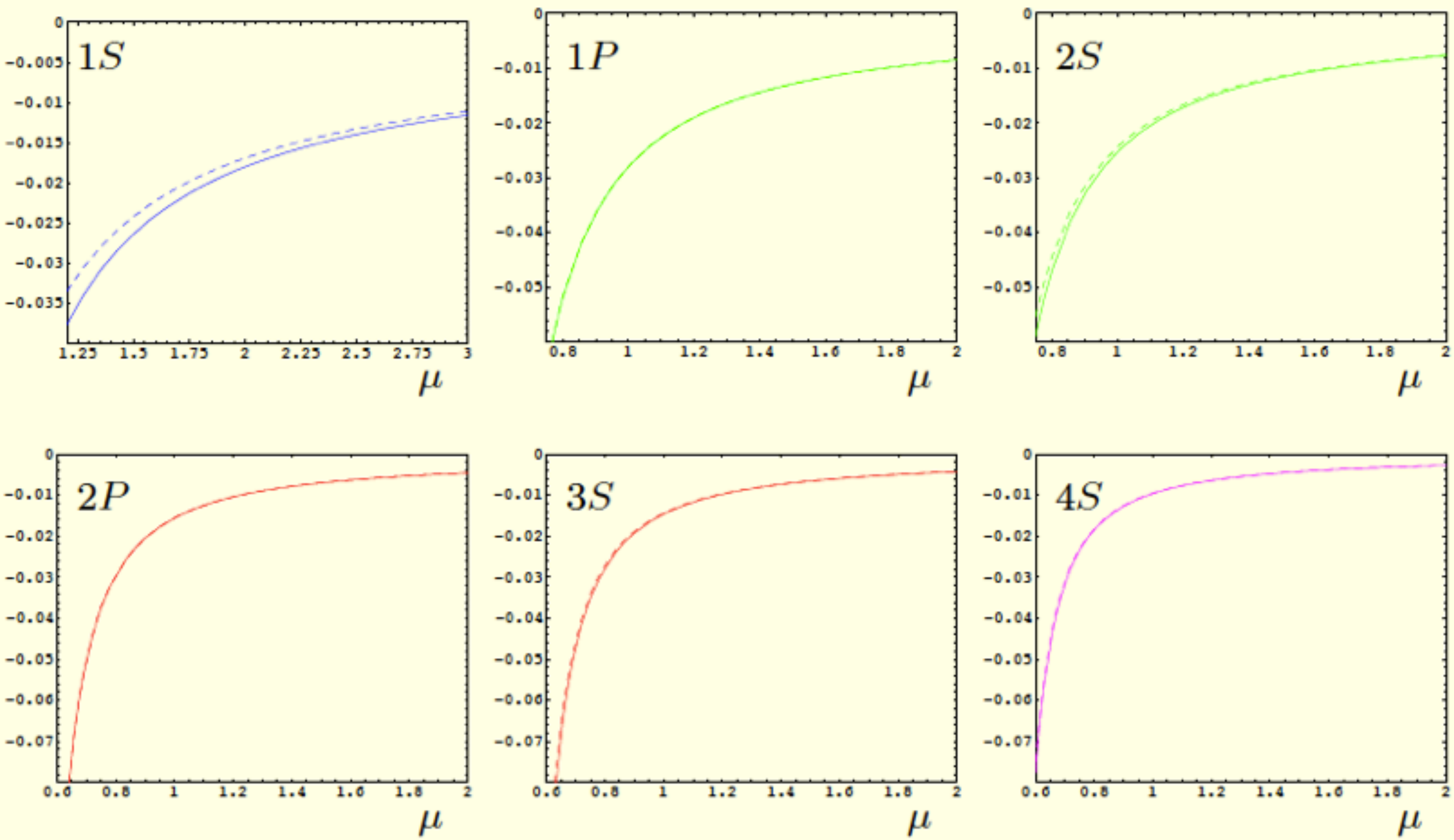
$\overline{m}_b = 4.201$ GeV

blue: 1S for $\mu = 2.446$ GeV
green: 2S for $\mu = 1.065$ GeV
red: 3S for $\mu = 0.724$ GeV

$(\delta E_{b\bar{b}})^{(1)}_{m_c}$ is well approximated by the large charm-mass limit $(\delta E_{b\bar{b}})^{(1)}_{m_c \to \infty}$.
In the "worst" situation (the $1S$ level), the difference is about 5% (less than 1 MeV).

- Brambilla Sumino Vairo PRD 65 (2002) 034001

c-mass effects in the (weakly coupled) bottomonium spectrum



for $\overline{m}_b = 4.201$ GeV and $\overline{m}_c = 1.237$ GeV.

- Brambilla Sumino Vairo PRD 65 (2002) 034001

c-mass effects in the (weakly coupled) bottomonium spectrum

State	μ	$\alpha_s^{(4)}(\mu)$	$\bar{\rho}$	$(\delta E_{b\bar{b}})^{(1)}_{m_c}$	$(\delta E_{b\bar{b}})^{(1)}_{m_c\to 0}$	$(\delta E_{b\bar{b}})^{(1)}_{m_c\to\infty}$
1^3S_1	2.446	0.277	1.59	-0.0143	-0.032	-0.0136
1^3P_0	1.140	0.428	2.06	-0.0210	-0.076	-0.0210
1^3P_1	1.111	0.437	2.02	-0.0221	-0.079	-0.0221
1^3P_2	1.086	0.445	1.99	-0.0232	-0.082	-0.0232
2^3S_1	1.065	0.452	1.96	-0.0219	-0.084	-0.0211
2^3P_0	0.726	0.695	1.91	-0.0426	-0.199	-0.0424
2^3P_1	0.703	0.733	1.81	-0.0490	-0.222	-0.0488
2^3P_2	0.678	0.782	1.70	-0.0581	-0.252	-0.0579
3^3S_1	0.724	0.698	1.90	-0.0405	-0.201	-0.0392

for $\overline{m}_b = 4.201$ GeV and $\overline{m}_c = 1.237$ GeV; energies are in GeV.

- Brambilla Sumino Vairo PRD 65 (2002) 034001

c-mass effects in the (weakly coupled) bottomonium spectrum

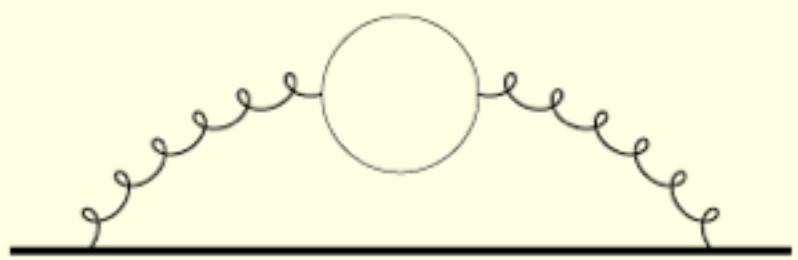
The NLO correction, $(\delta E_{b\bar{b}})^{(2)}_{m_c}$, is known only for the $1S$ state. For $\overline{m}_b = 4.201$ GeV, $\overline{m}_c = 1.237$ GeV and $\mu = 2.446$ GeV

$$(\delta E_{1S})^{(2)}_{m_c} \approx -38.8\,\mathrm{MeV}, \qquad (\delta E_{1S})^{(2)}_{m_c\to\infty} \approx -38.3\,\mathrm{MeV}.$$

- Hoang hep-ph/0008102

This confirms that the error in the large charm-mass limit is very small (about 1%). Considering that the $1S$ state is the state located furthest from the decoupling limit, we may expect that the decoupling works even better for higher states.

c-mass effects in the bottom mass

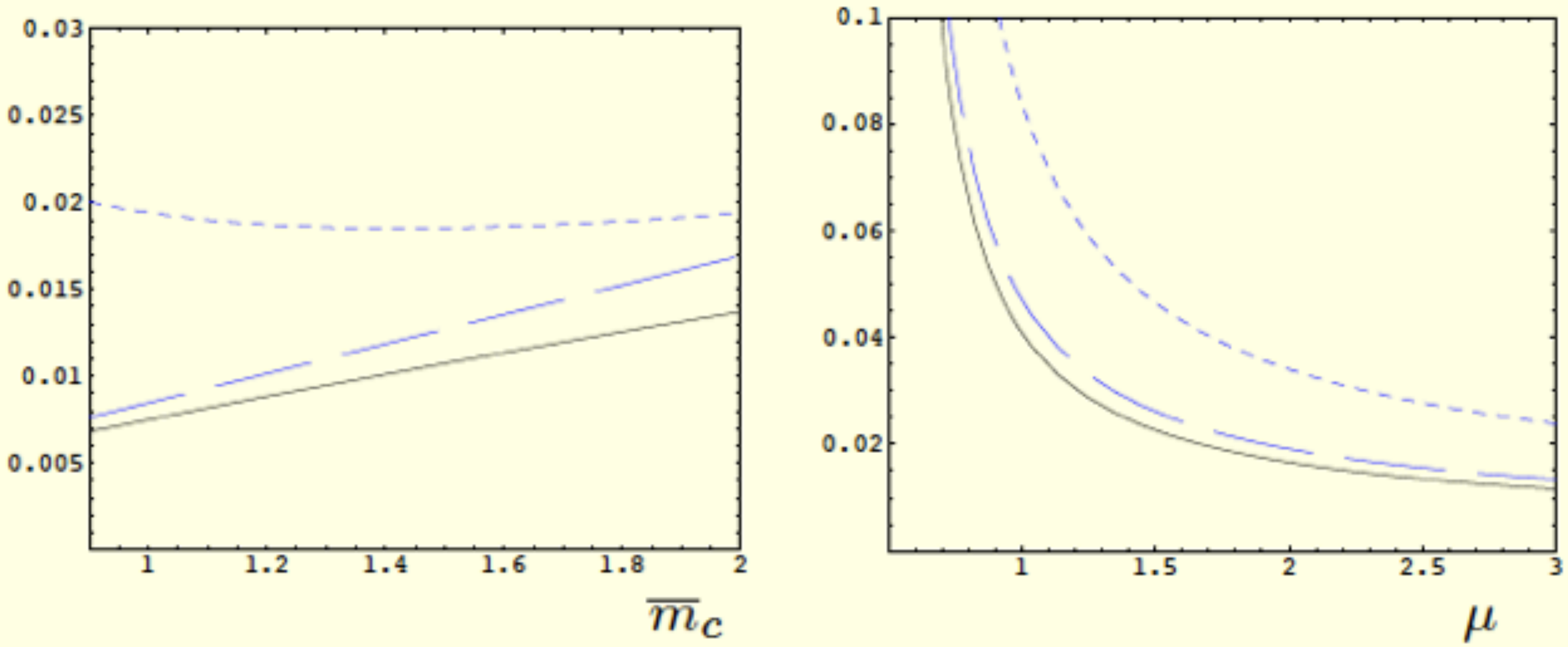


$$
\begin{aligned}
(\delta m_b)^{(1)}_{m_c} \quad = \quad & \frac{\overline{m}_b}{3}\left(\frac{\alpha_s^{(4)}(\overline{m}_b)}{\pi}\right)^2 \Bigg[\ln^2(\xi) + \frac{\pi^2}{6} - \left(\ln(\xi) + \frac{3}{2}\right)\xi^2 \\
& +(1+\xi)(1+\xi^3)\left(\mathrm{Li}_2(-\xi) - \frac{1}{2}\ln^2(\xi) + \ln(\xi)\ln(1+\xi) + \frac{\pi^2}{6}\right) \\
& +(1-\xi)(1-\xi^3)\left(\mathrm{Li}_2(\xi) - \frac{1}{2}\ln^2(\xi) + \ln(\xi)\ln(1-\xi) - \frac{\pi^2}{3}\right)\Bigg]
\end{aligned}
$$

where $\xi = \overline{m}_c/\overline{m}_b$.

- Gray Broadhurst Grafe Schilcher ZPC 48 (1990) 673

c-mass effects in the bottom mass



$(\delta m_b)^{(1)}_{m_c}$: continuous line
$(\delta m_b)^{(1)}_{m_c \to 0}$: dashed line
$(\delta m_b)^{(1)}_{m_c \to \infty}$: dotted line

$\overline{m}_b = 4.201$ GeV
$\overline{m}_c = 1.237$ GeV (2nd figure)

$(\delta m_b)^{(1)}_{m_c}$ is approximated by $(\delta m_b)^{(1)}_{m_c \to 0}$ at the 15% level, while it is far off the decoupling limit $(\delta m_b)^{(1)}_{m_c \to \infty}$; for $\overline{m}_c = 1.237$ GeV, we have

$$(\delta m_b)^{(1)}_{m_c} \approx 9.1\,\mathrm{MeV}, \qquad (\delta m_b)^{(1)}_{m_c \to 0} \approx 10.5\,\mathrm{MeV}, \qquad (\delta m_b)^{(1)}_{m_c \to \infty} \approx 18.7\,\mathrm{MeV}.$$

- Brambilla Sumino Vairo PRD 65 (2002) 034001

c-mass effects in the bottom mass

The NLO correction, $(\delta m_b)^{(2)}_{m_c}$, is unknown. For $\overline{m}_b = 4.201$ GeV and $\overline{m}_c = 1.237$ GeV, it has been estimated

$$(\delta m_b)^{(2)}_{m_c} \approx (\delta m_b)^{(2)}_{m_c \to 0} \approx 17\,\mathrm{MeV}.$$

- `Hoang hep-ph/0008102`
  `Melles PRD 62 (2000) 074019, NPPS 96 (2001) 472`

It may be expected that this value approximates $(\delta m_b)^{(2)}_{m_c}$ with a relative uncertainty smaller than 20%. Note that the series of (δm_b) shows no signals of convergence.

Summary

- c-quark mass effects in the (weakly-coupled) spectrum satisfy

$$\frac{(\delta E_{b\bar{b}})^{(1)}_{m_c} - (\delta E_{b\bar{b}})^{(1)}_{m_c\to\infty}}{(\delta E_{b\bar{b}})^{(1)}_{m_c}} \sim -\frac{1}{\bar{\rho}^{2l+2}}\frac{1}{2\psi(n+l+1)-2\psi(1)+5/3}.$$

  we are close to the charm-quark decoupling limit, which works even better for high n and l.

- c-quark mass effects in the bottom mass satisfy

$$\frac{(\delta m_b)^{(1)}_{m_c} - (\delta m_b)^{(1)}_{m_c\to 0}}{(\delta m_b)^{(1)}_{m_c}} = -\frac{6}{\pi^2}\xi + \mathcal{O}(\xi^2) \simeq -18\%,$$

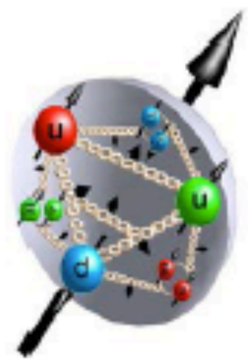
  the charm mass can be considered small and we are close to the situation of four active and massless flavours.

Jianwei Qiu

Intrinsic charm

Brodsky, et al. Phys.Lett. B93, 451 (1980)
Vogt et al, Ingelman et al, Pumplin, ...

- Proton wave function – light-cone:



$$\vec{P} \quad |P,S\rangle = \sum_{\text{Fock states } n} \psi_n(x_i, k_{Ti})\,|x_i, k_{Ti}\rangle_n$$

$$\approx |uud\rangle + |uudg\rangle + |uudq\bar{q}\rangle + |uudc\bar{c}\rangle + \ldots$$

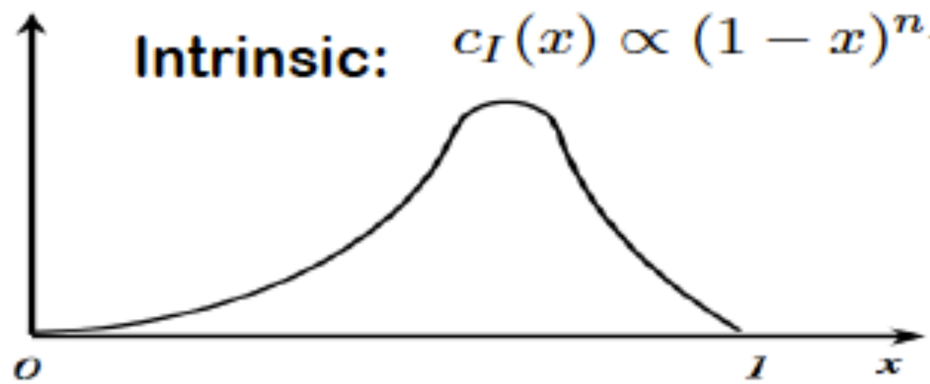
Momentum conservation: $\sum_i x_i = 1, \quad \sum_i \vec{k}_{Ti} = 0$

- Intrinsic charm – quark mass effect:

If all partons have about the same velocity: $\gamma\, m_i\, v \sim x_i P$

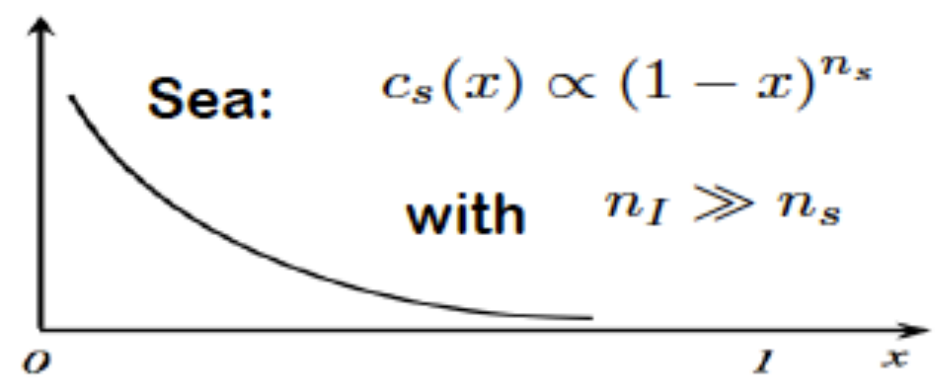
Heavy quarks have an larger averaged $\langle x\rangle$

Intrinsic: $c_I(x) \propto (1-x)^{n_I}$



Sea: $c_s(x) \propto (1-x)^{n_s}$

with $n_I \gg n_s$

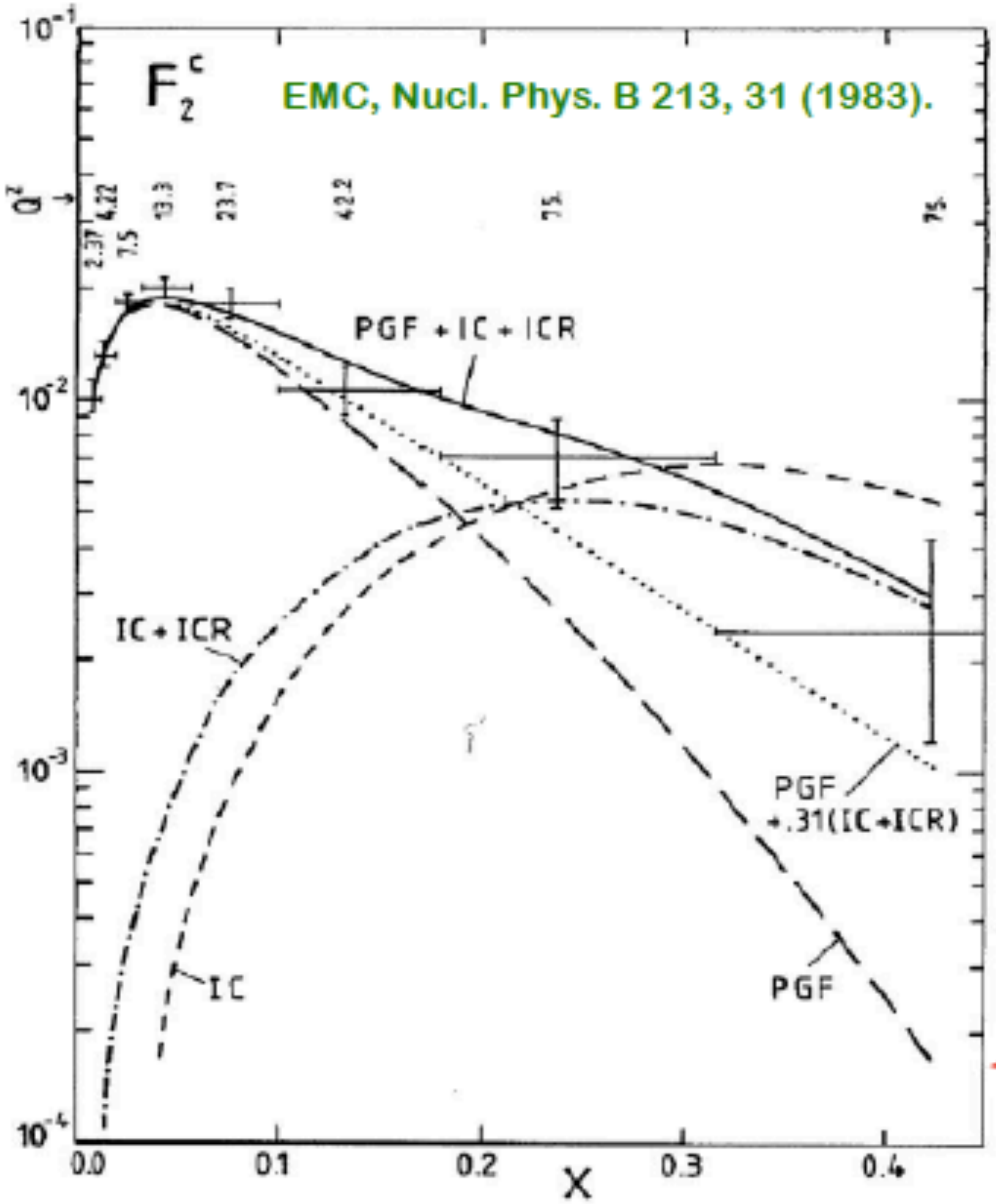


- BHPS model: 1% number probability, < 0.3% momentum fraction

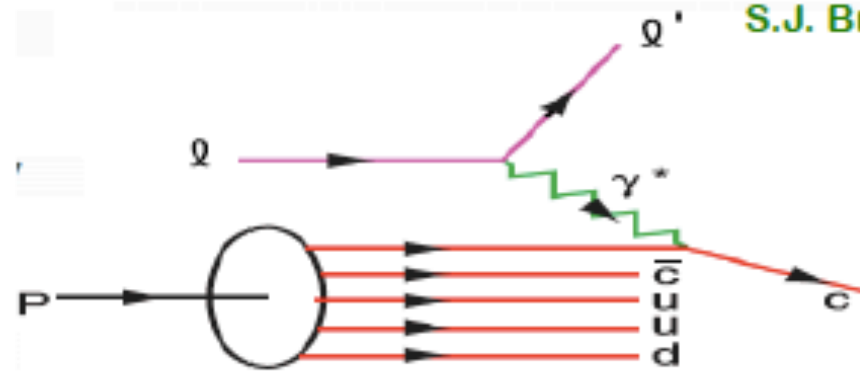
$$f_c(x) = f_{\bar{c}}(x) = 6\,x^2\left[6\,x\,(1+x)\,\ln x + (1-x)(1+10x+x^2)\right]$$

Intrinsic charm – direct search

❑ 1st direct evidence :



S.J. Brodsky, Feb 18, 2008



factor of 30

- EMC data: $c(x, Q^2) > 30 \times$ DGLAP $Q^2 = 75$ GeV^2, $x = 0.42$
- High x_F $pp \to J/\psi X$
- High x_F $pp \to J/\psi J/\psi X$
- High x_F $pp \to \Lambda_c X$
- High x_F $pp \to \Lambda_b X$
- High x_F $pp \to \Xi(ccd) X$ (SELEX)

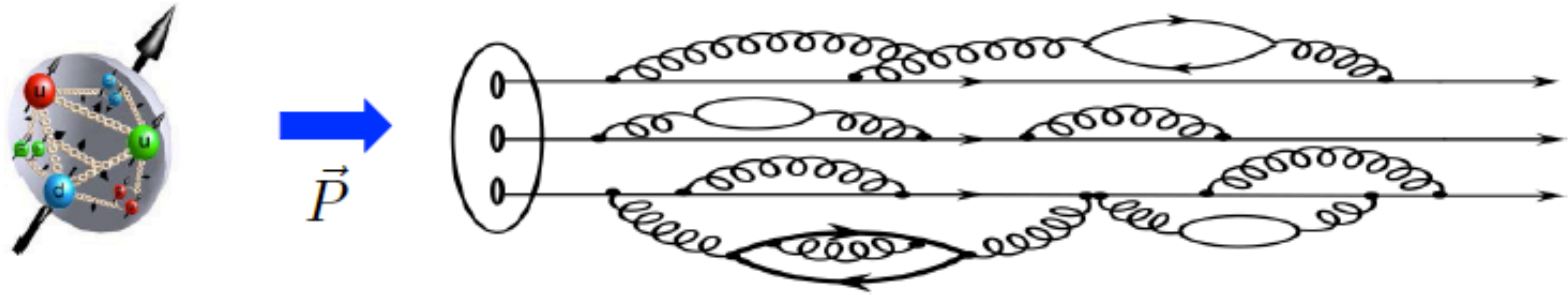
❑ Charm production in hadronic collisions:

Inclusive – convolution of PDFs

Vogt et al, Ingelman et al, Pumplin, ...

Intrinsic charm – indirect effect

- Charm pair fluctuation is always there:



  - PDFs – Leading twist – Hard probe (Q > 2 GeV – CTEQ fits > m_c)

- Questions:
  - What input charm distribution at μ_0 should be used? J. Pumplin, 2005

    $C_I(x,\mu_0)$ or $C_s(x,\mu_0)$ or $C_s(x,\mu_0)+C_I(x,\mu_0)$?

    The difference is smoothed out quickly by DGLAP evolution

  - What impact of the fluctuation on charmless observables?

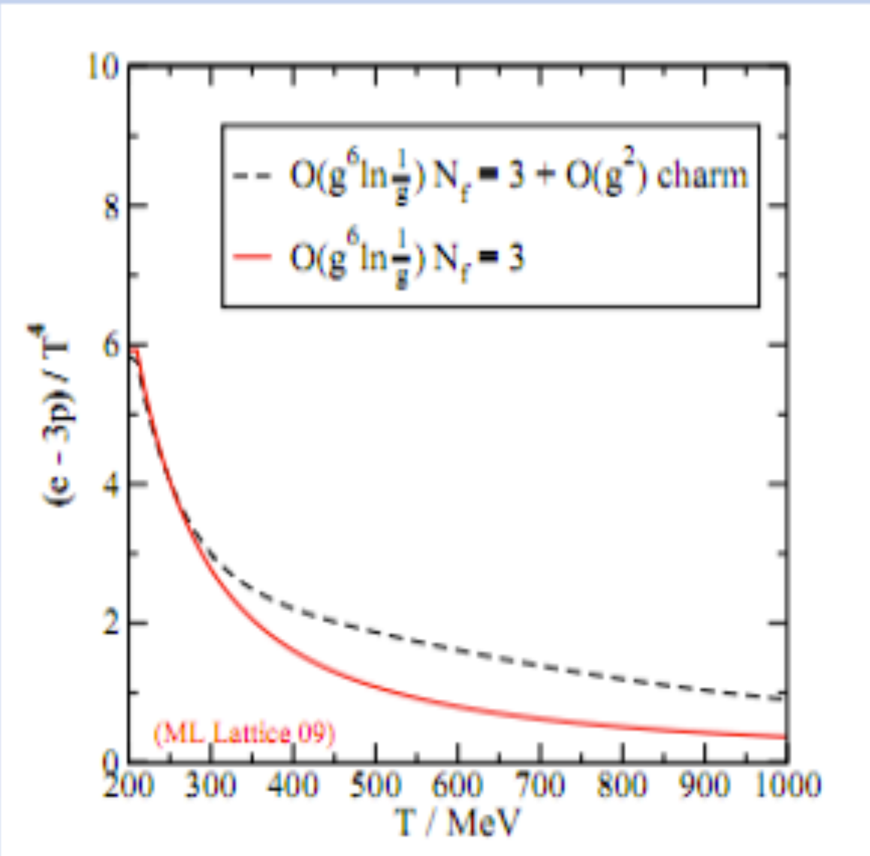
    Very difficult to find out in the direct search

  - Can Lattice QCD calculations with 2+ 1+ (1) show significant differences from that with 2+1 flavors for Lattice measurables?

Mariapaola Lombardo

Hot Dynamical Charm

$$p_{SB} = \frac{\pi^2 T^4}{45}\left(N^2 - 1 + \frac{7 N n_f}{4}\right)$$



Theoretical predictions : Charm becomes important for **T > 400 MeV**, within the range of LHC experiments

M. Laine et al. (2006)

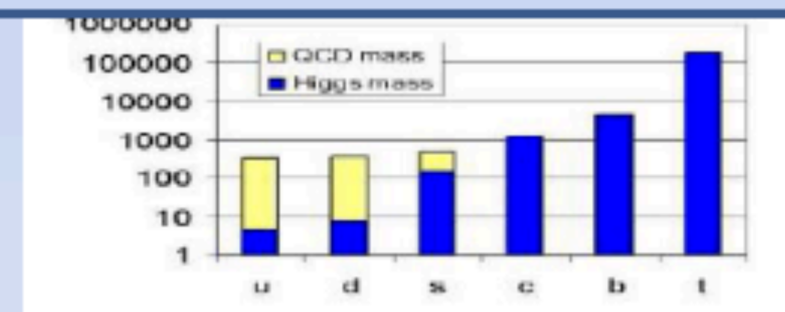
Phenomenological implication: e.g Bulk Viscosity

D.Kharzeev and K. Turkin (2007)

$$\zeta = \frac{1}{9\,\omega_0}\left\{T^5 \frac{\partial}{\partial T}\frac{(\mathcal{E} - 3P)_{\rm LAT}}{T^4} + 16|\epsilon_v|\right\}$$

DK, K.Tuchin, arXiv:0705.4280 [hep-ph]

Common lore : Charm does not contribute to chiral dynamics around Tc (O (200) MeV) – its mass has only EW origin, hence it is not relevant for the Chiral Transition



Speculations: Charm might have an impact on the interplay of chiral symmetry and confinement, hence on the hypothetical Quarkyonic phase

LATTICE RESULTS : CHARM IMPORTANT T > 300 MeV

Levkova, MILC, 2009: Partial Quenched

Effects of the charm quark on the QCD equation of state — Ludmila Levkova

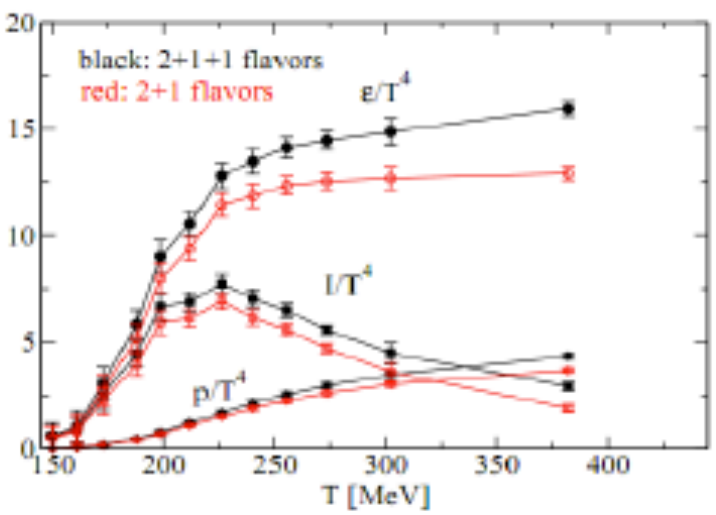


Figure 1: Interaction measure (I), pressure (p) and energy density (ε) divided by the temperature to the fourth power (T^4) for the cases of 2+1 and 2+1+1 flavors.

Charmed EOS starting now. Lattice results confirm theoretical expectations: Charm does make a difference for T > 300 MeV.
Unquenching vs partial quenching not fully established : better invest in understanding charm unquenching effects or just go dynamical?
Twisted Mass Wilson fermions make the decision easy!

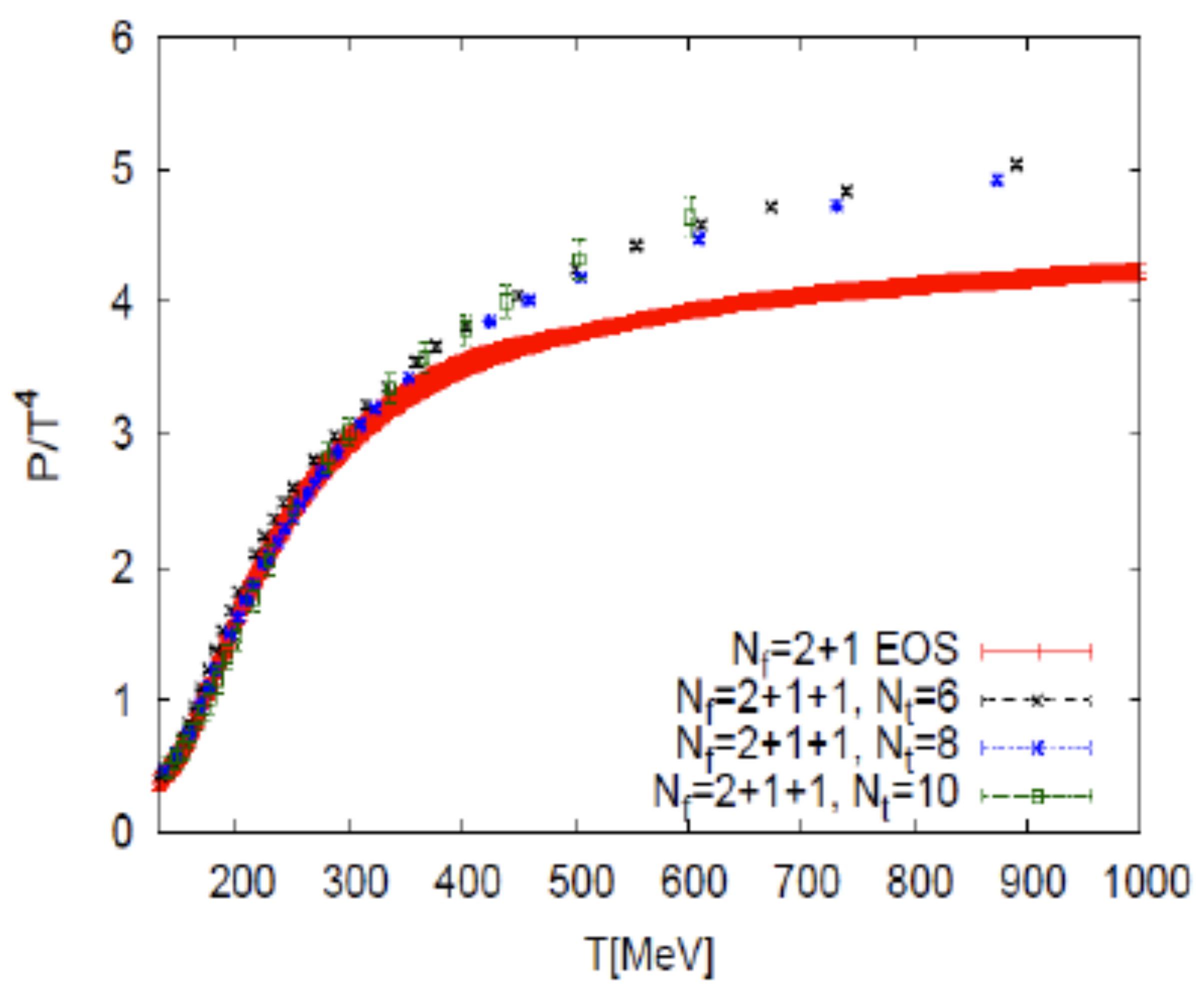
Wuppertal Budapest 2011: Full dynamical charm

The QCD equation of state and the effects of the charm

S. Krieg

University of Wuppertal, Forschungszentrum Juelich
S.Borsanyi, Z.Fodor, S.Katz, C.Ratti, C.Schroeder, K.Szabo

$N_f = 2+1$ continuum vs $N_f = 2+1+1$



FULLY DYNAMICAL RESULTS