Charm physics from Lattice QCD

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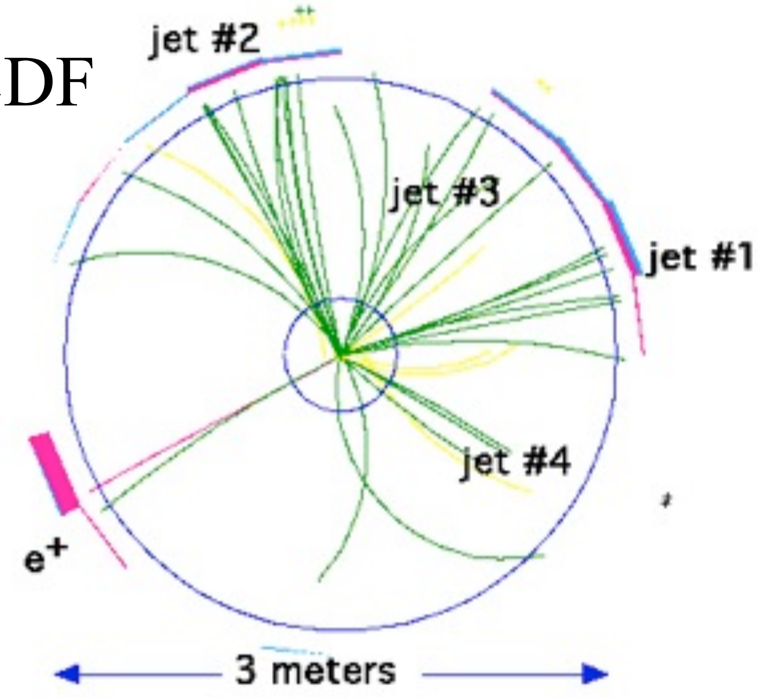
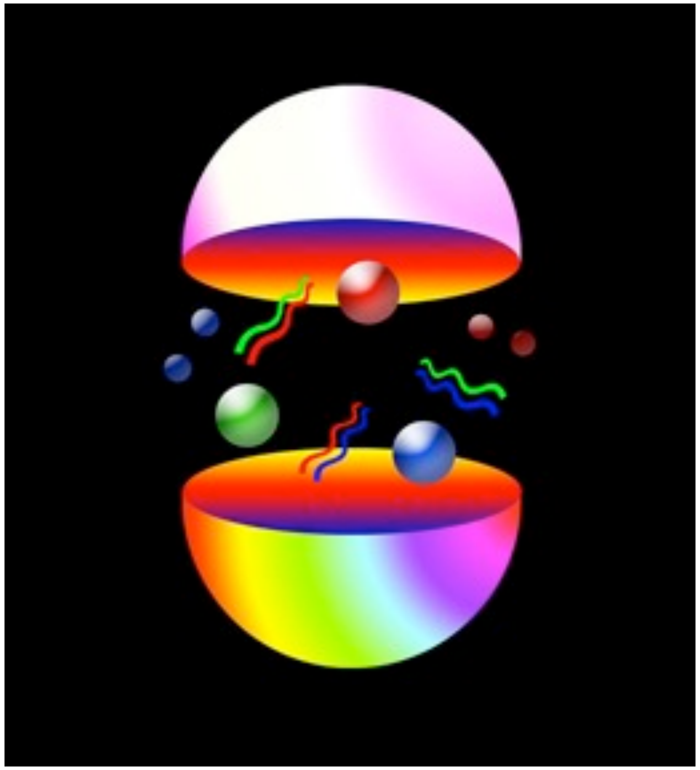
Lattice QCD meets phenomenology
Durham, Sept.2010

QCD is a key part of the Standard Model but quark confinement complicates things.

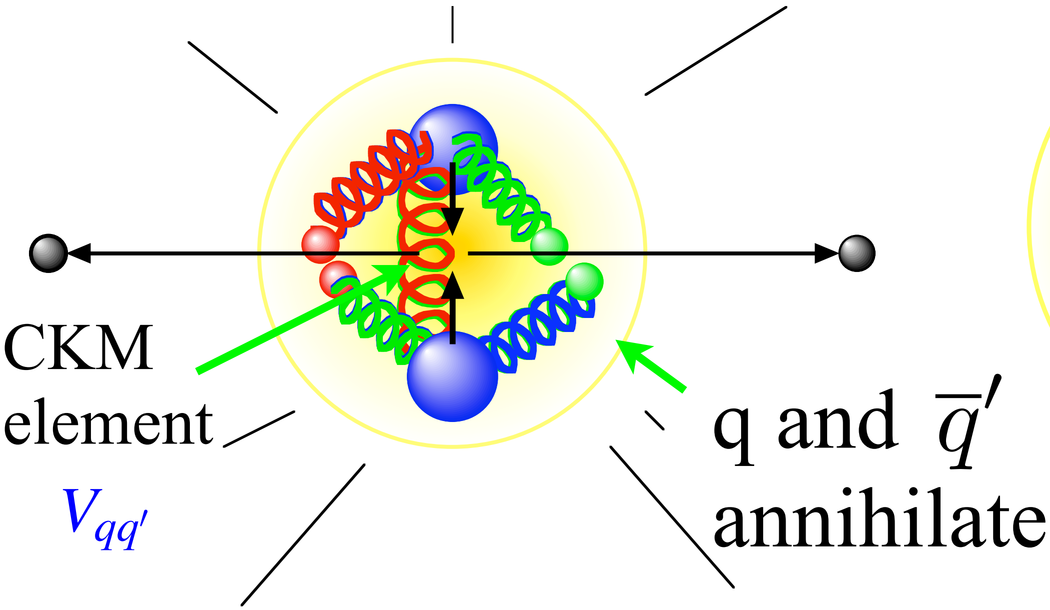
CDF

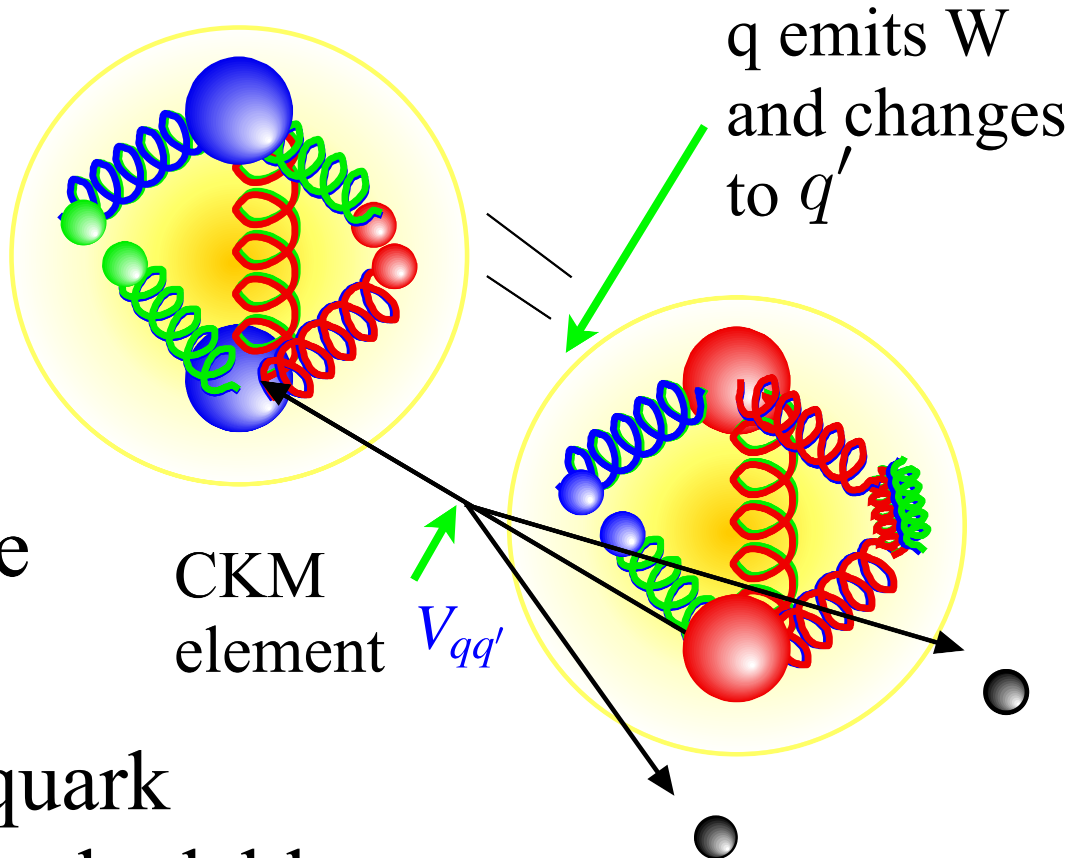


QCD only tested to 5-10% level at high energies from comparison of e.g. jet phenomena to pert.th.



But properties of hadrons calculable from QCD if fully nonperturbative calc. is done - can test QCD and determine parameters very accurately (1%).



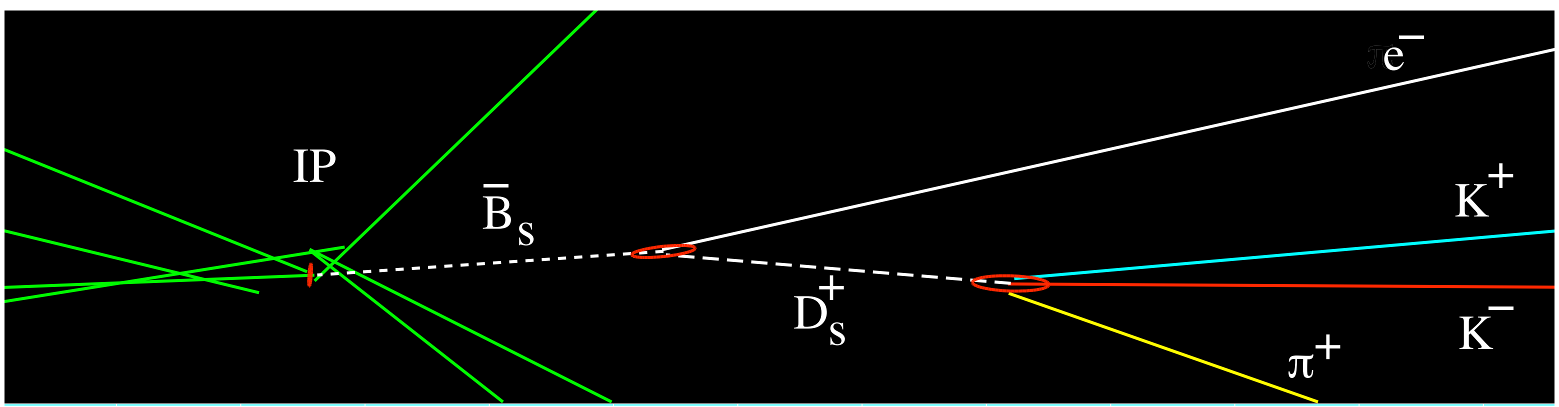


Rates for simple weak or em quark processes inside hadrons also calculable, but *not* multi-hadron final states.

$\overline{B}_s \longrightarrow D_s e^- \nu$

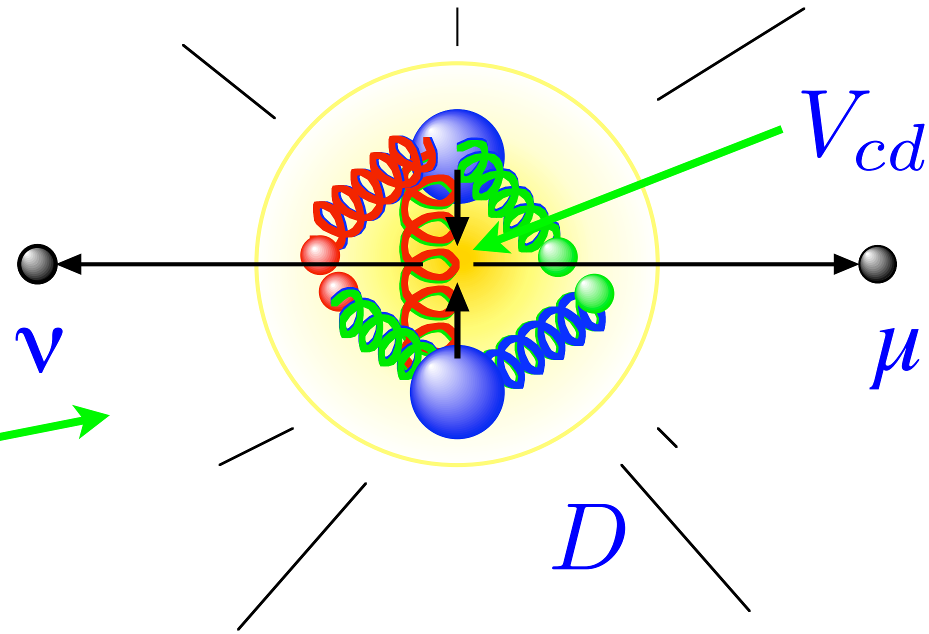
ALEPH $(D_S \longrightarrow K^+ K^- \pi^+)$

Compare to exptl rate gives $V_{qq'}$ accurately



charm physics important component of this as sits between light and bottom physics

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ \pi \to l\nu & K \to l\nu & B \to \pi l\nu \\ & K \to \pi l\nu & \\ V_{cd} & V_{cs} & V_{cb} \\ D \to l\nu & D_s \to l\nu & B \to D l\nu \\ D \to \pi l\nu & D \to K l\nu & \\ V_{td} & V_{ts} & V_{tb} \\ \langle B_d|\overline{B}_d\rangle & \langle B_s|\overline{B}_s\rangle & \end{pmatrix}$$



Expt = CKM x theory(QCD)

Also, lots of interesting new hadrons being discovered in charmonium and charm-light sectors raising QCD issues ..

Lattice QCD: solving a path integral

Path integral over gluon and quark fields on a 4-d space-time lattice - quarks anticommute so do by hand.

$$\mathcal{L}_{QCD} = \frac{1}{2} Tr F_{\mu\nu}^2 + \overline{\psi}(\gamma \cdot D + m)\psi$$

= a huge matrix, M

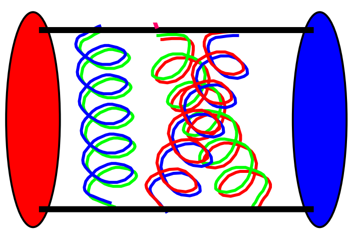
$$\int \mathcal{D}U \mathcal{D}\psi \mathcal{D}\overline{\psi} O(\psi, \overline{\psi}) e^{-S_{QCD}} \rightarrow$$

Integral over gluon fields only

$$\int \mathcal{D}U O(M^{-1}) e^{-(S_g - \ln(\det M))}$$

valence quarks inc. in operator

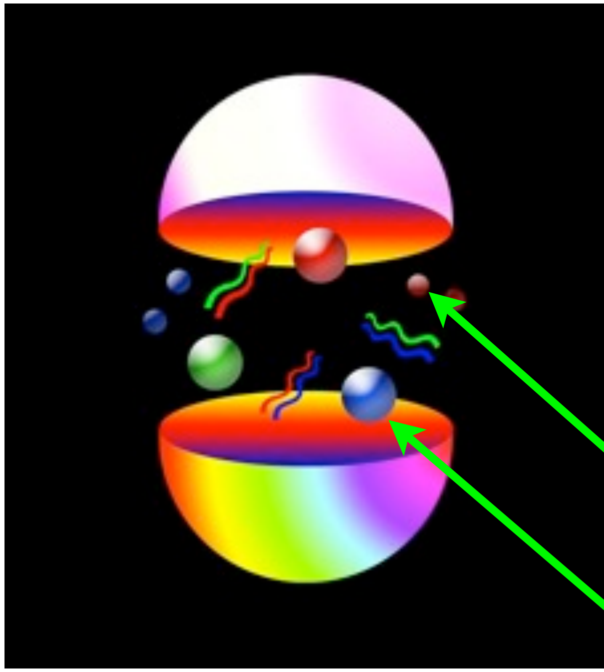
complicated prob, distn for gluons - inc. effects of sea quarks



$$< O > = < H(t) H^\dagger(0) > = \sum_n A_n e^{-E_n t}$$

ensemble average

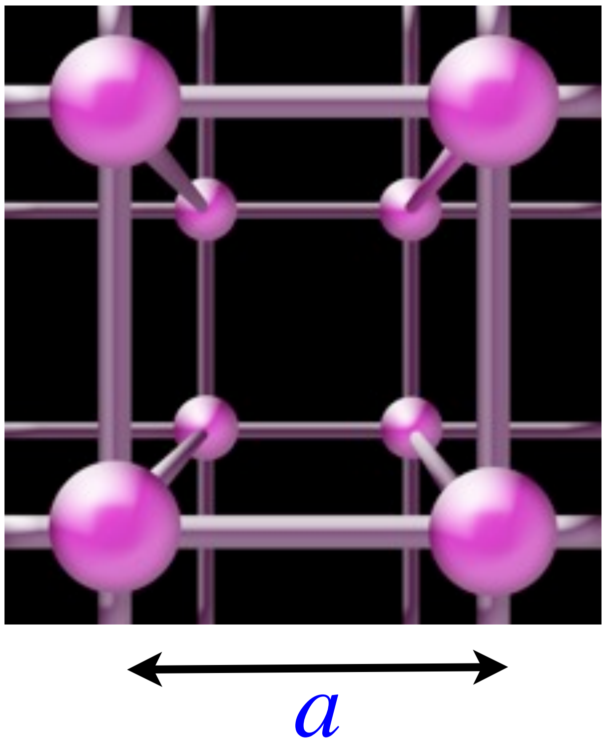
Fit as fn of t to get hadron mass. A_n gives e.g. decay constant



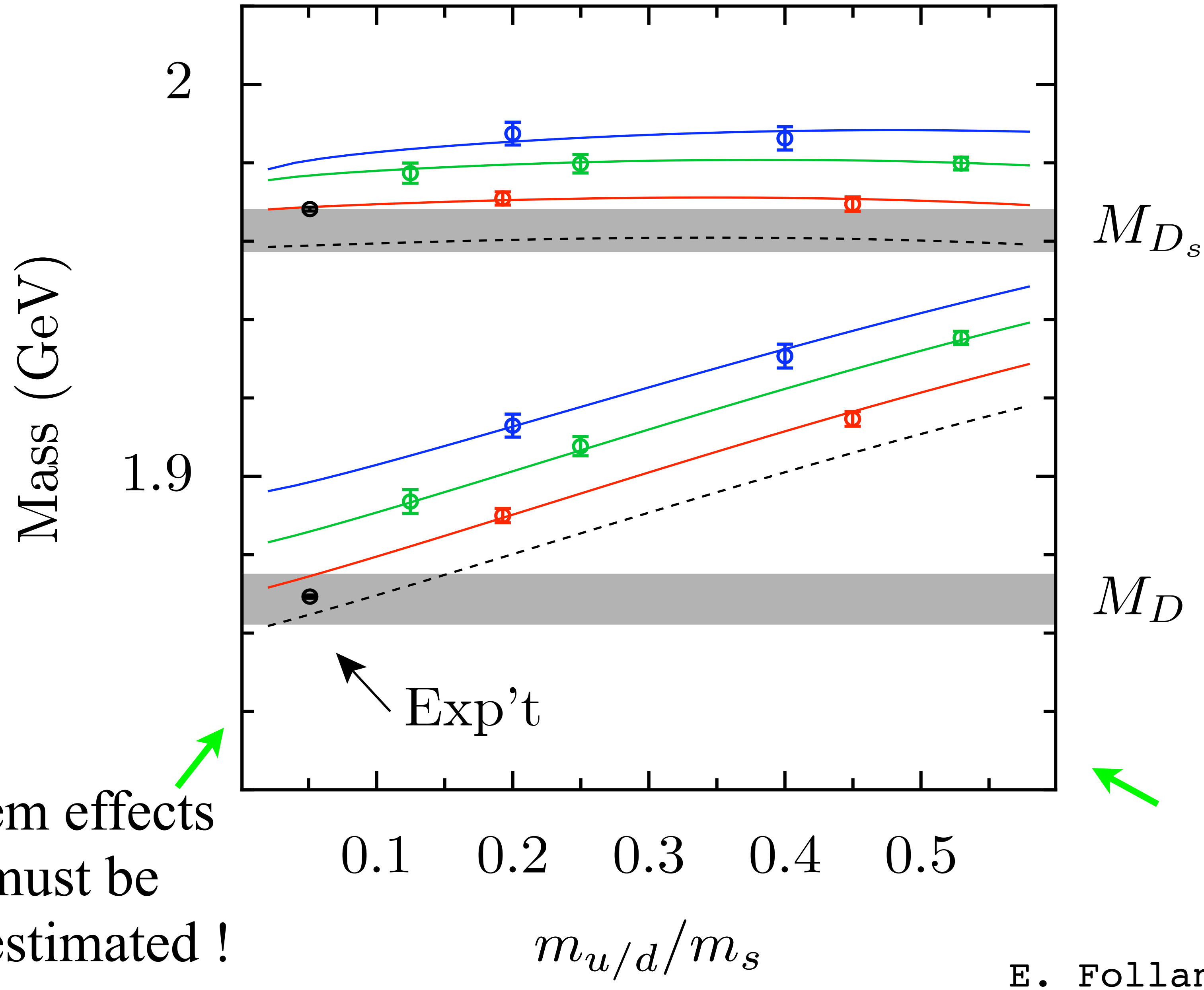
Lattice QCD = fully nonperturbative QCD calculation

RECIPE

- Generate sets of gluon fields for Monte Carlo integrn of Path Integral (inc effect of u, d and s sea quarks)
- Calculate averaged "hadron correlators" from valence q props.
- Fit for masses and simple matrix elements
- Fix m_q and determine a to get results in physical units.
- extrapolate to $a = 0, m_{u,d} = phys$ for real world



Lattice results need to be extrapolated to the real world where a=0 and $m_{u/d}$ = small.



To do this well needs:

- statistical precision
- small disc. errors and several values of a
- small $m_{u/d}$, < $m_s/2$

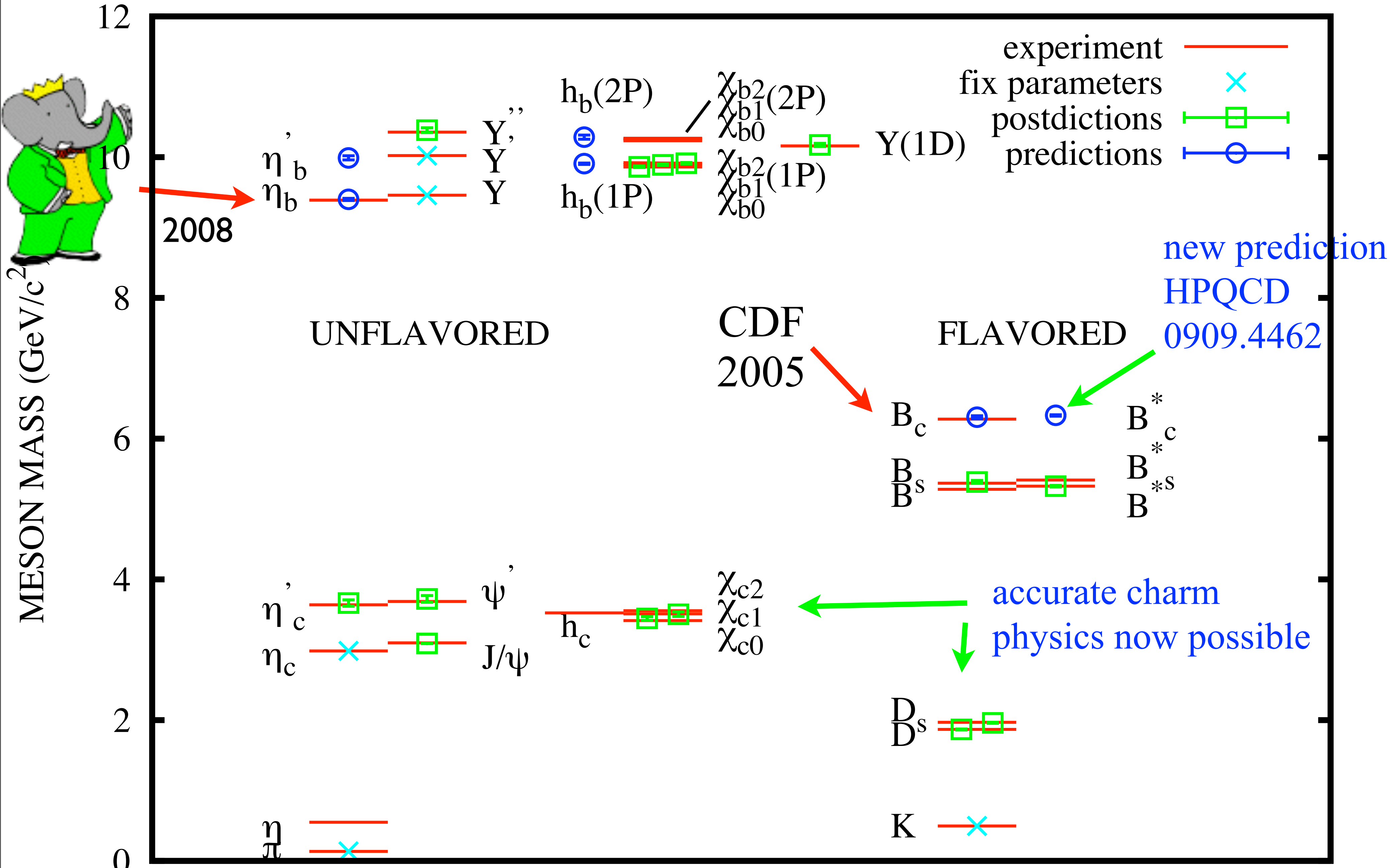
em effects must be estimated !

using HISQ charm quarks

E. Follana et al, 0706.1726

The gold-plated meson spectrum - HPQCD 2009

inc u, d and s sea quarks critical for agreement with expt. across the board



I. Allison et al, hep-lat/0411027, A. Gray et al, hep-lat/0507013

Charm quarks in lattice QCD - heavy or light?

Advantages of relativistic quark formalism:

- $E_{sim} = m$
- PCAC relation (if enough chiral symmetry) gives $Z = 1$
- same action as for u, d, s, so cancellation in ratios

Key issue is discretisation errors:

$$E = E_{a=0}(1 + A(m_c a)^2 + B(m_c a)^4 + \ldots)$$

$$m_c a \approx 0.4,\ (m_c a)^2 \approx 0.2,\ \alpha_s (m_c a)^2 \approx 0.06,\ (m_c a)^4 \approx 0.04$$

for $a \approx 0.1 fm$

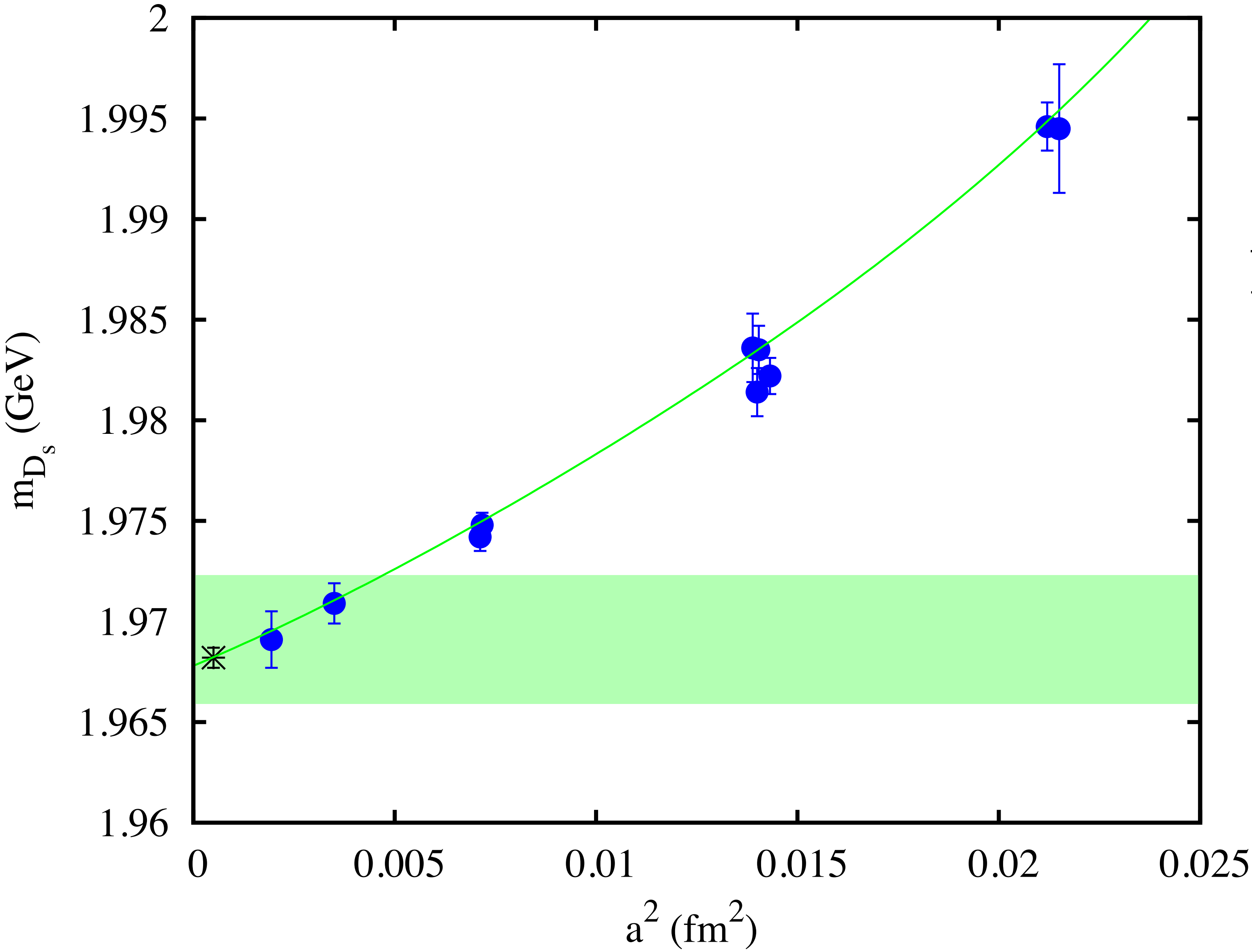
Need to remove *all* of these errors for precision results

Highly Improved Staggered Quarks (HISQ) formalism does this, twisted mass formalism has a^2 errors. HPQCD

ETMC

Previous method: heavy Fermilab formalism Fermilab/MILC

Results with HISQ charm quarks on MILC 2+1 configs



$$m_{D_s} =$$

$$1.9691(32)\text{GeV}$$

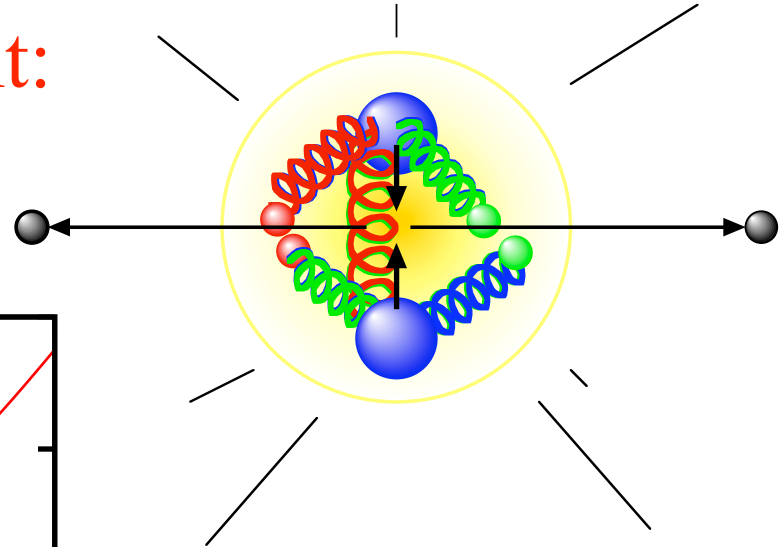
m_c, m_s tuned from m_{η_c}, m_{η_s} so no free parameters

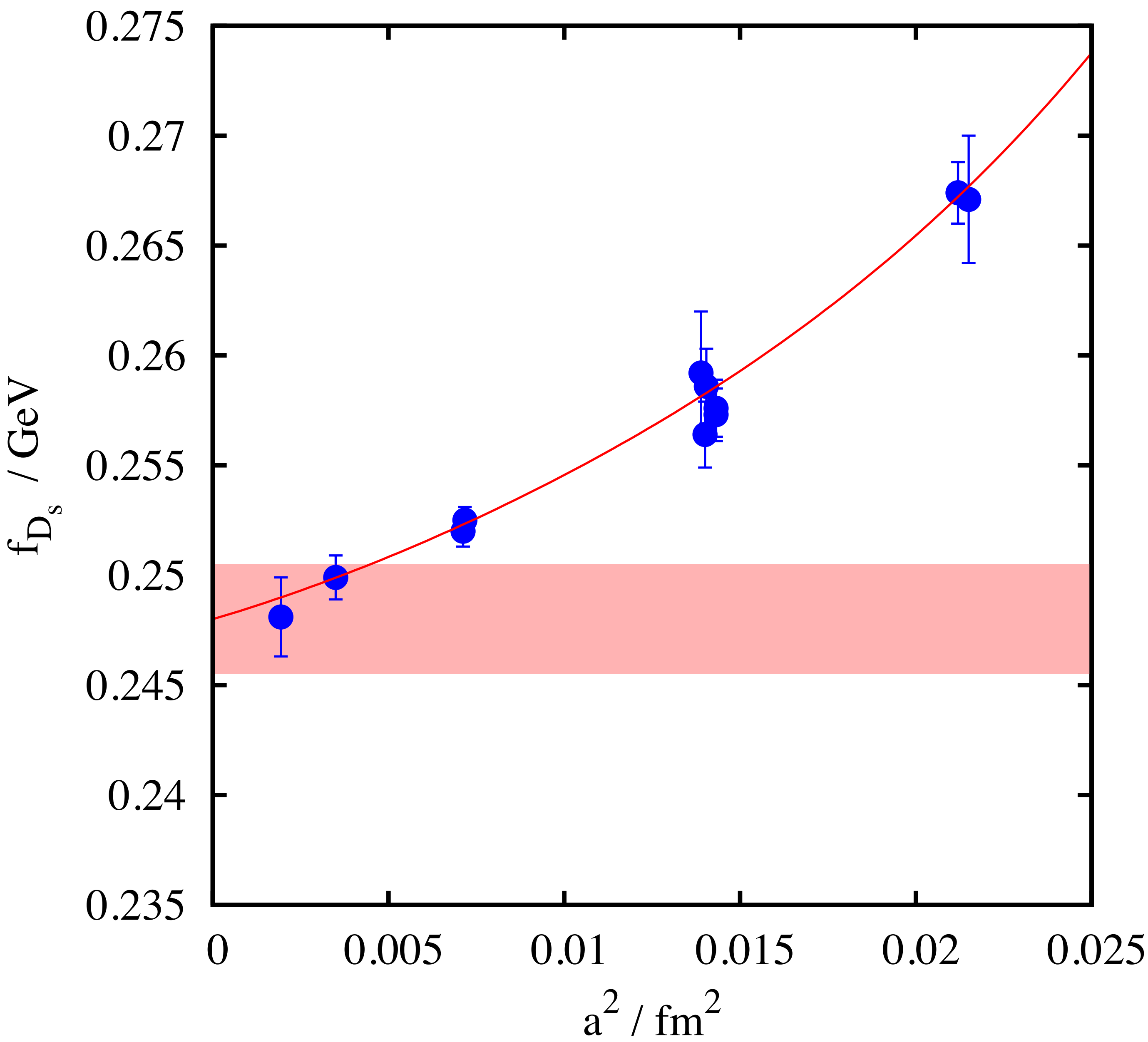
em corrns included

Results at 5 values of a, several sea $m_{u/d}$ and m_s and two volumes

`CTHD, Eduardo Follana, Craig McNeile et al, HPQCD, 1008.4018`

Updated value for D_s decay constant: (since r_1 and r_1/a updated)





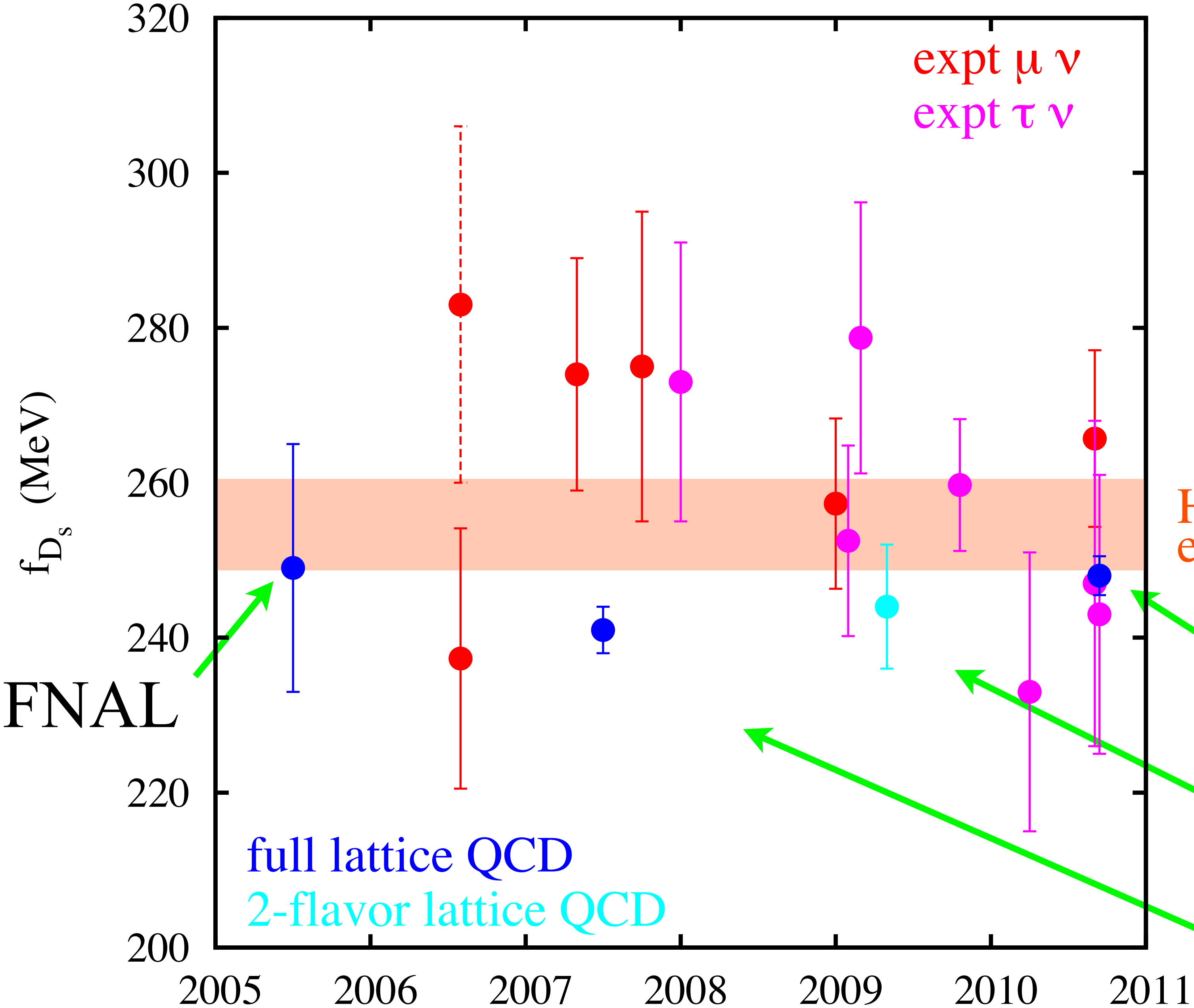
$$D_s \to l\nu$$

$$f_{D_s} = 0.2480(25)\mathrm{GeV}$$

1% error!

Wednesday, 15 September 2010

Compare to recent experimental results (lower than 2008) - no f_{D_s} puzzle remains!?



History of D_s decay constant since 2005

255(6) MeV
update
260(5) MeV?

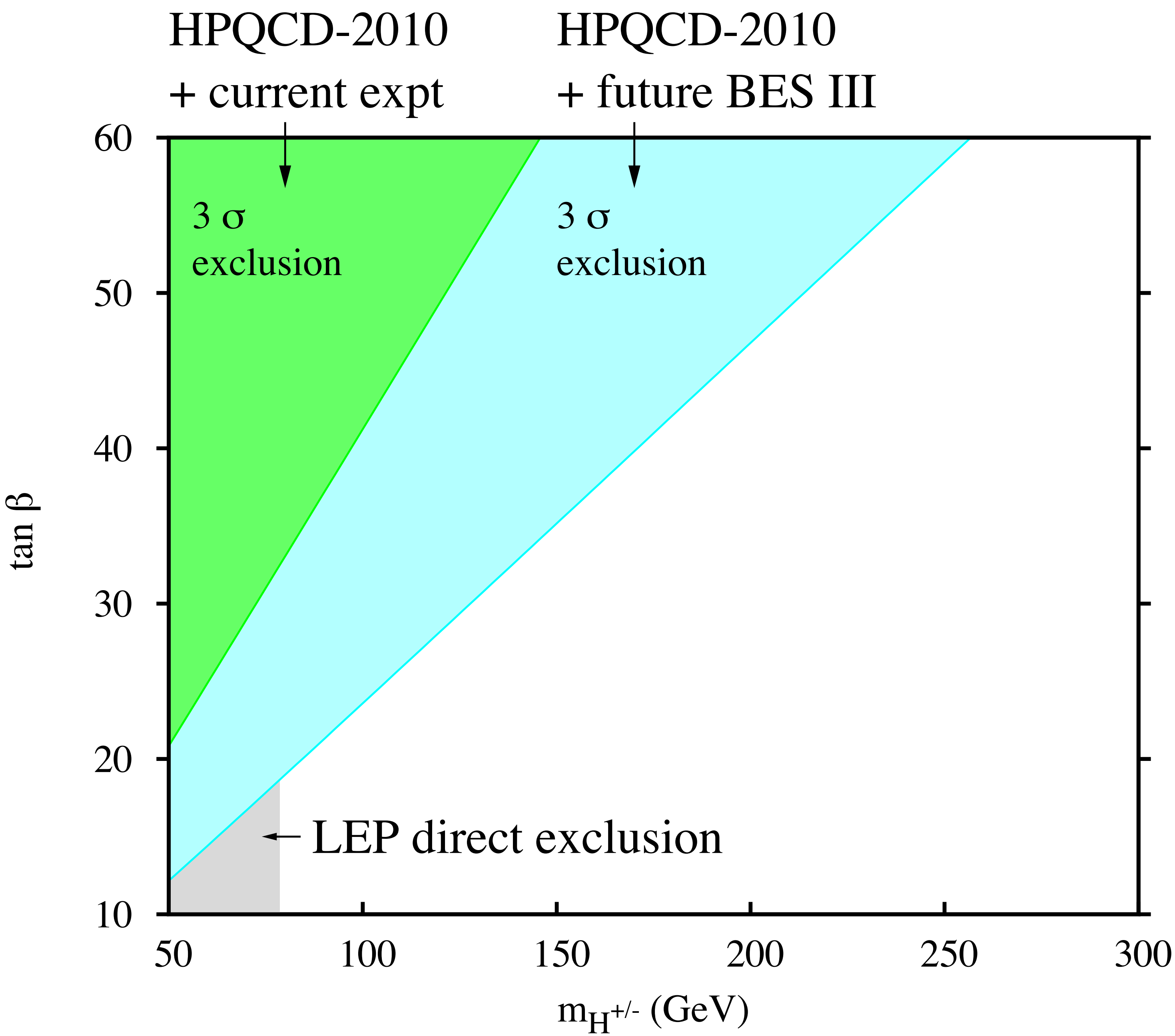
$1\sigma \rightarrow 2\sigma$

new HPQCD

ETMC, u/d sea
now doing u/d/s/c

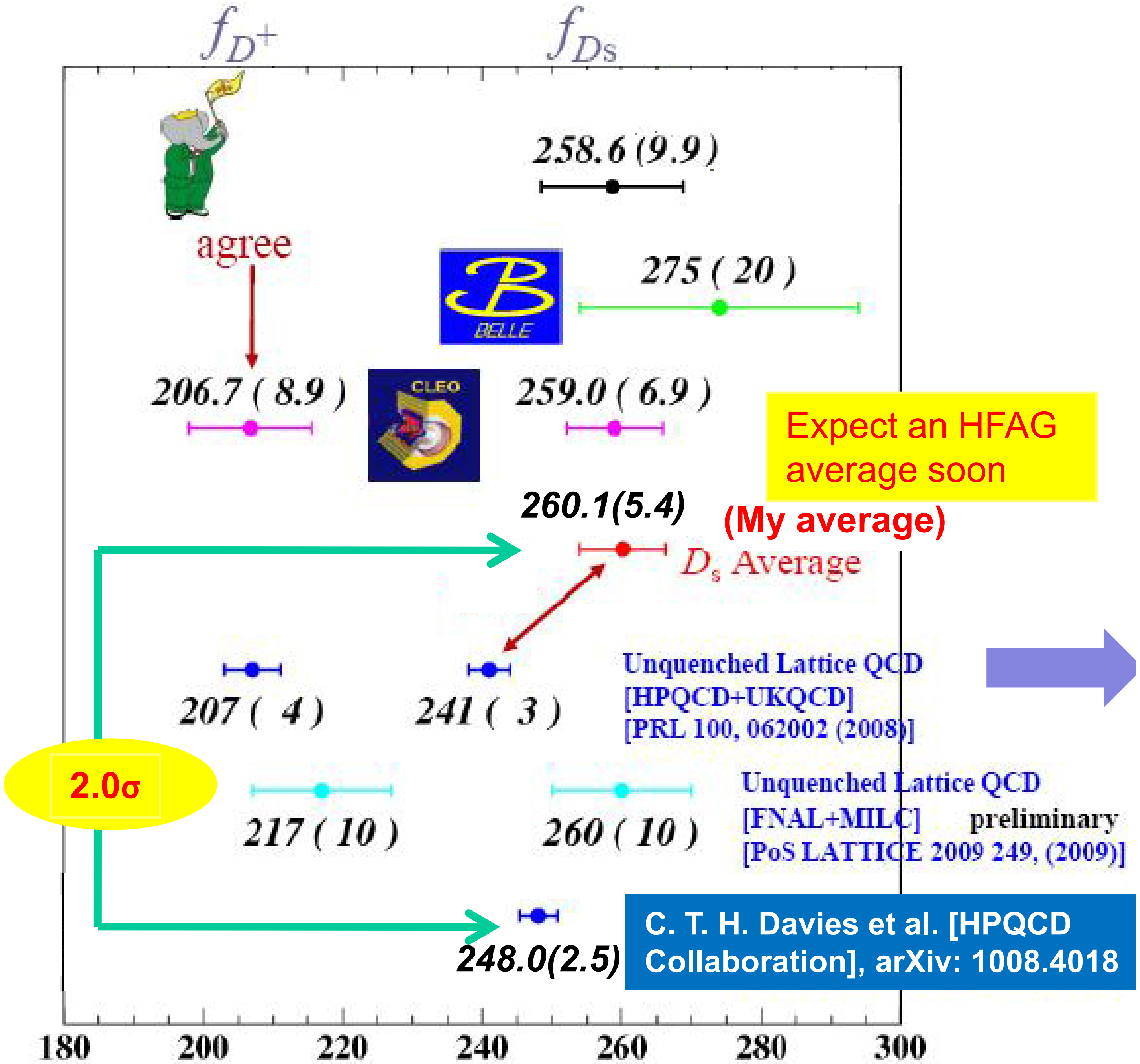
HPQCD 2007

Can use to set limits on charged Higgs in some models



using HFAG/ FPCP10 exptl av.

using Akeroyd and Mahmoudi, 0902.2393

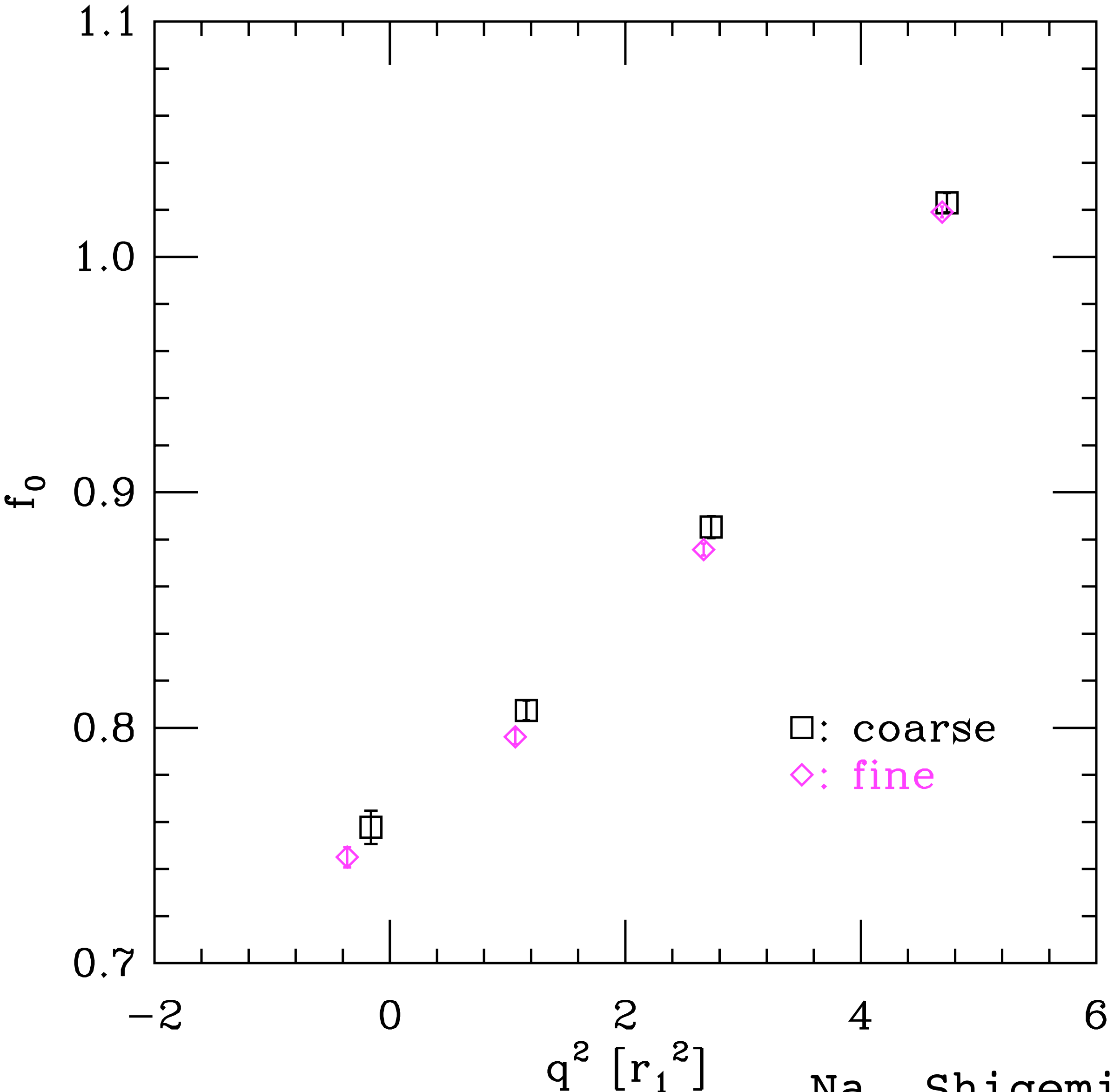


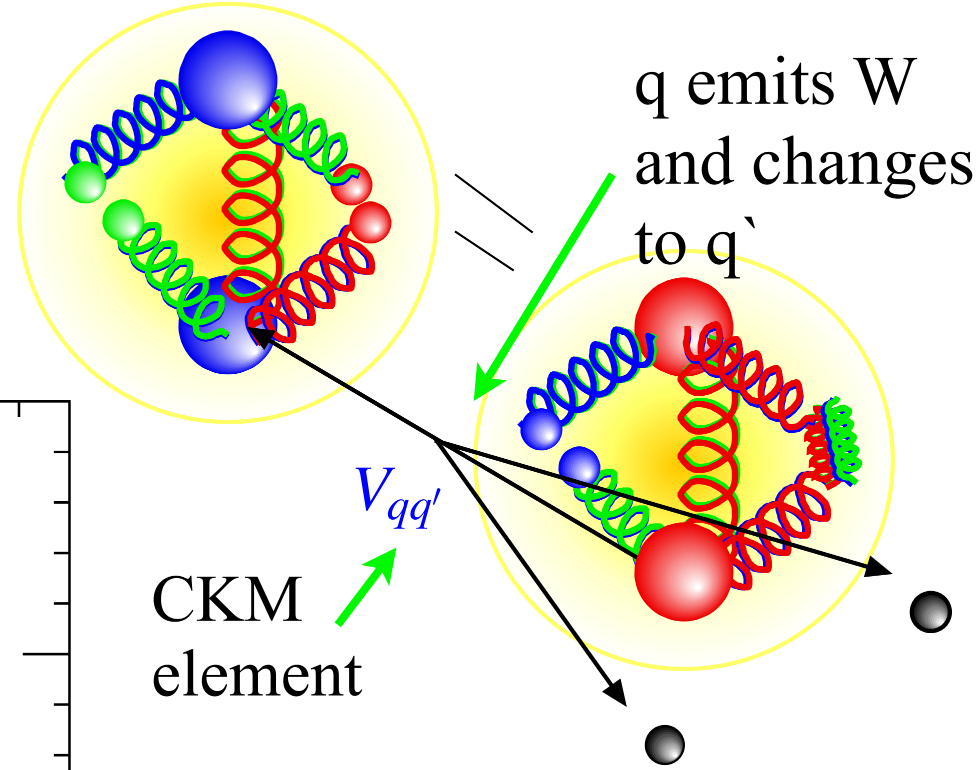
Need also to improve lattice f_D ... work in progress from HPQCD, Fermilab/ MILC, ETMC

Xin,CKM2010

Semileptonic form factors

$D \to K l \nu$





With HISQ quarks
no renormalisation issues
and good statistics
possible

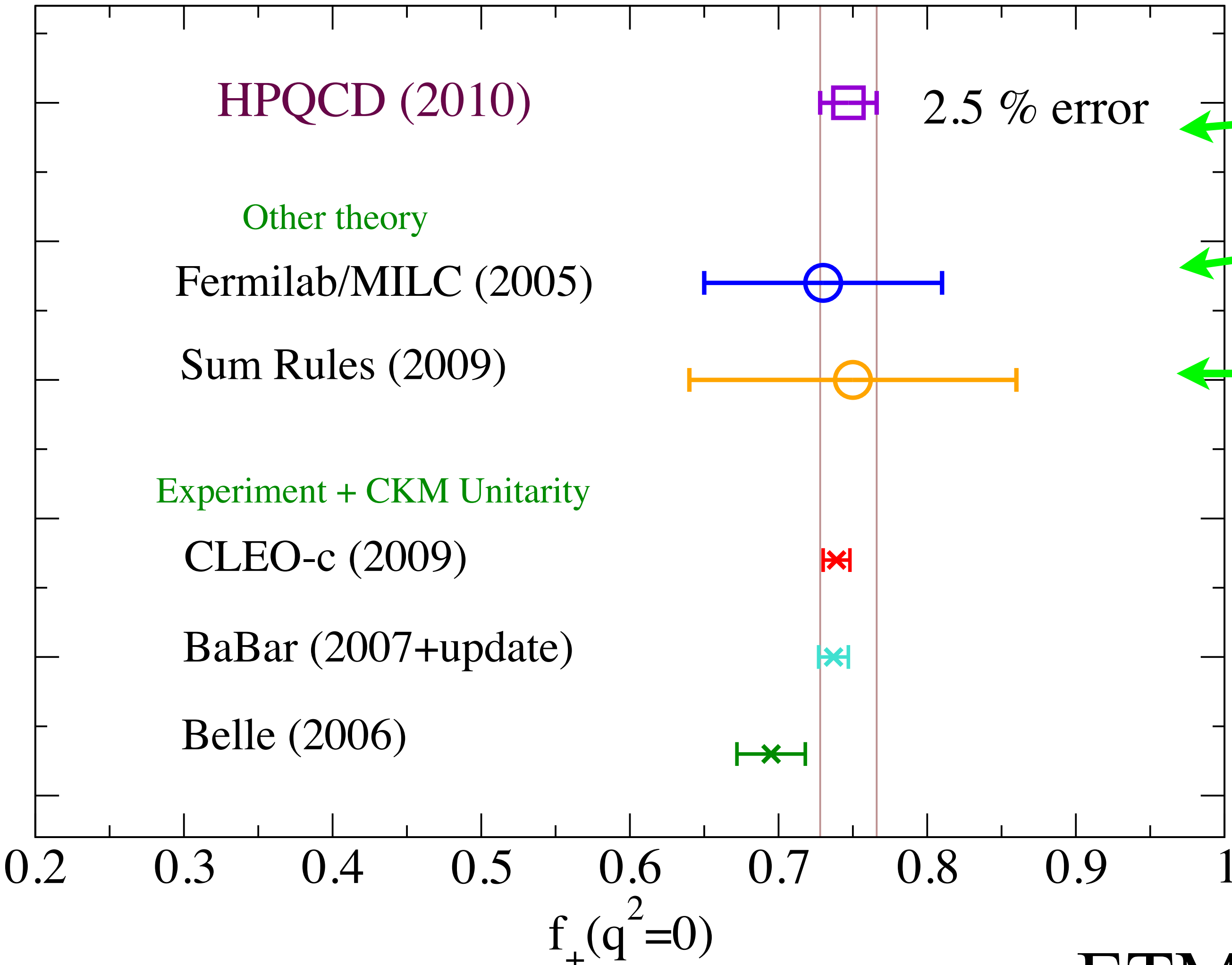
$$f_0(q^2 = 0) = f_+(q^2 = 0) = 0.747(11)(15)$$

2.5% !!

Na, Shigemitsu et al, HPQCD, 1008.4562

Semileptonic form factors $D \to K l \nu$

$10\% \to 2.5\%$



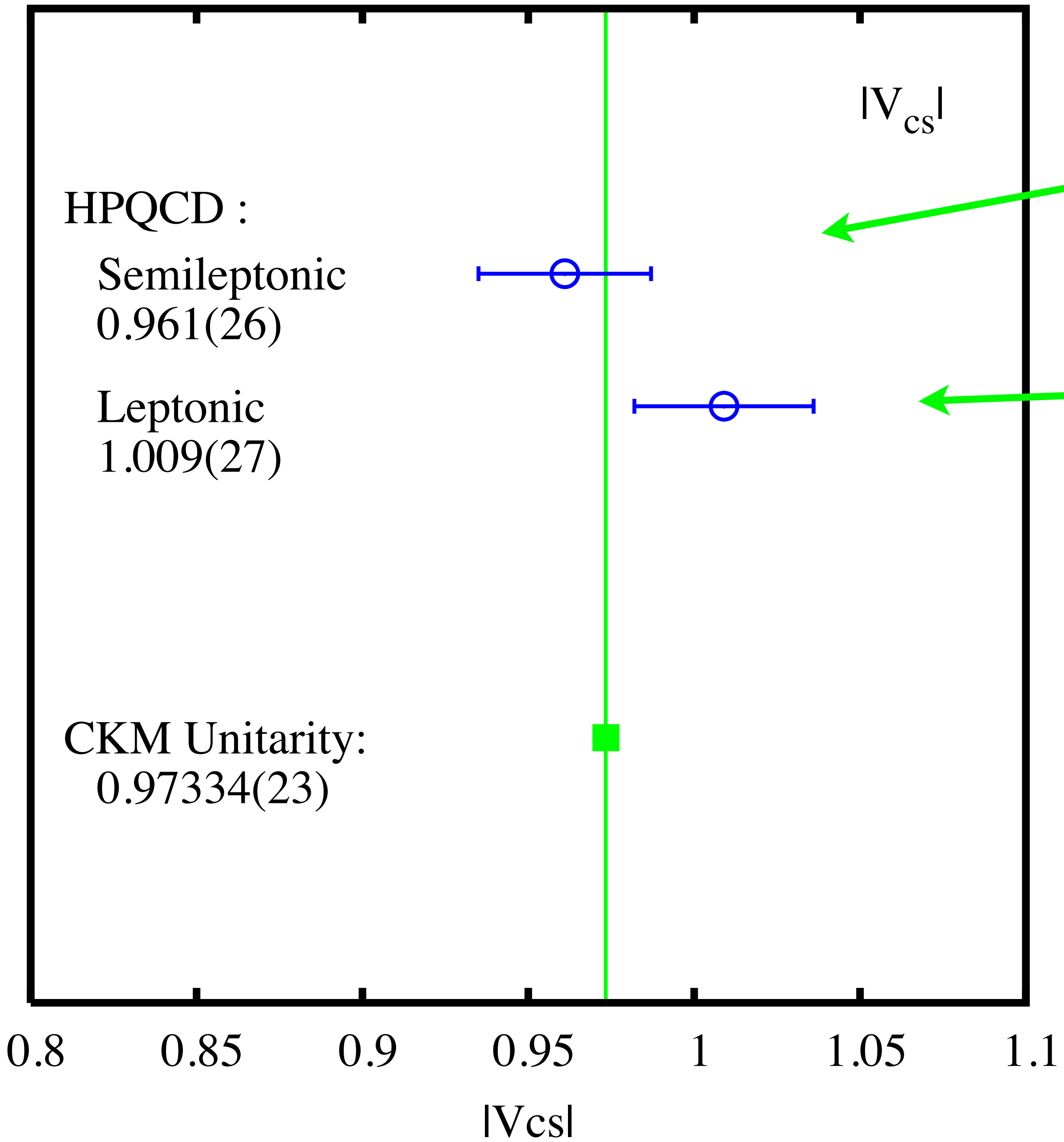
1008.4562

hep-ph/
0408306

Khodjamirian,
PRD80:114005

ETMC prelim. LAT10
0.76(4)(?) u/d sea

Comparison to expt gives direct determination of V_{cs} assuming Standard Model



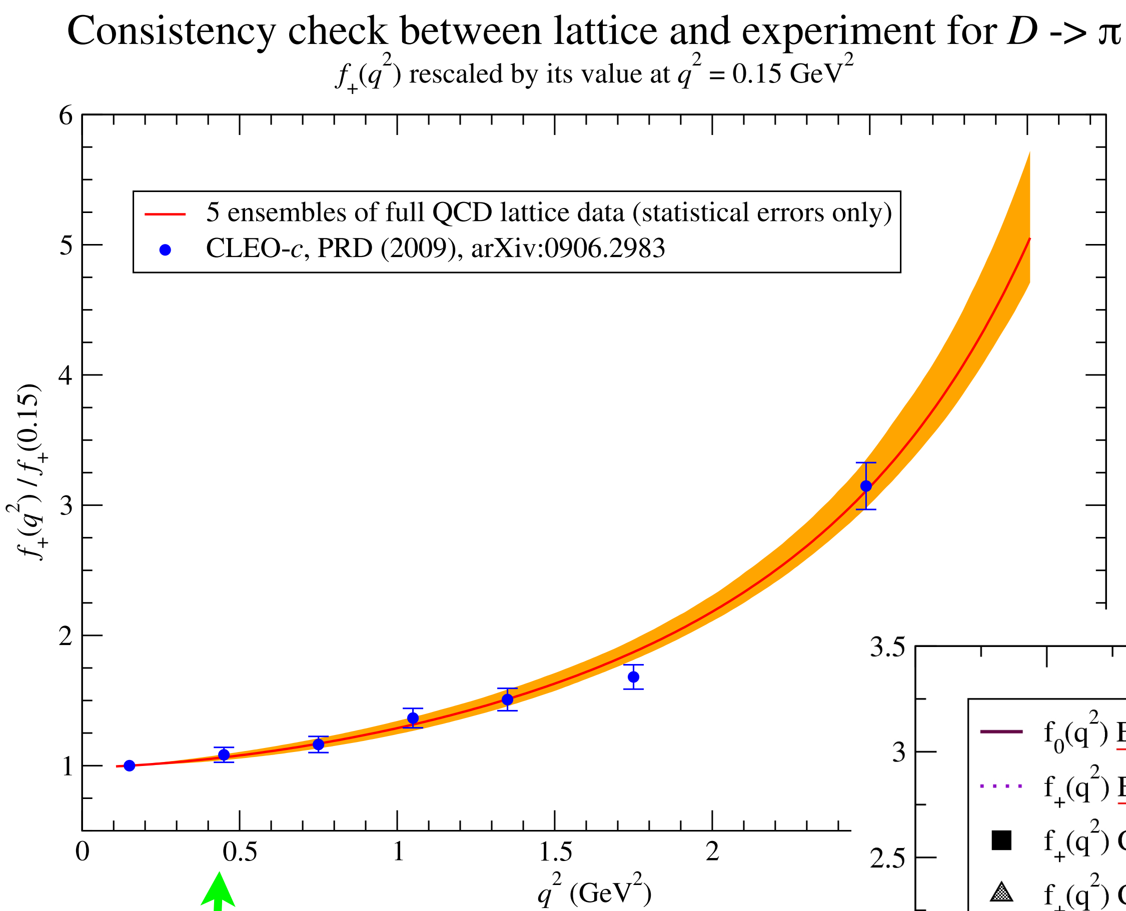
error dominated by theory (now 2.5%)

error dominated by expt (now 2.5%)

Allows 2nd row and 2nd column unitarity tests to 5%

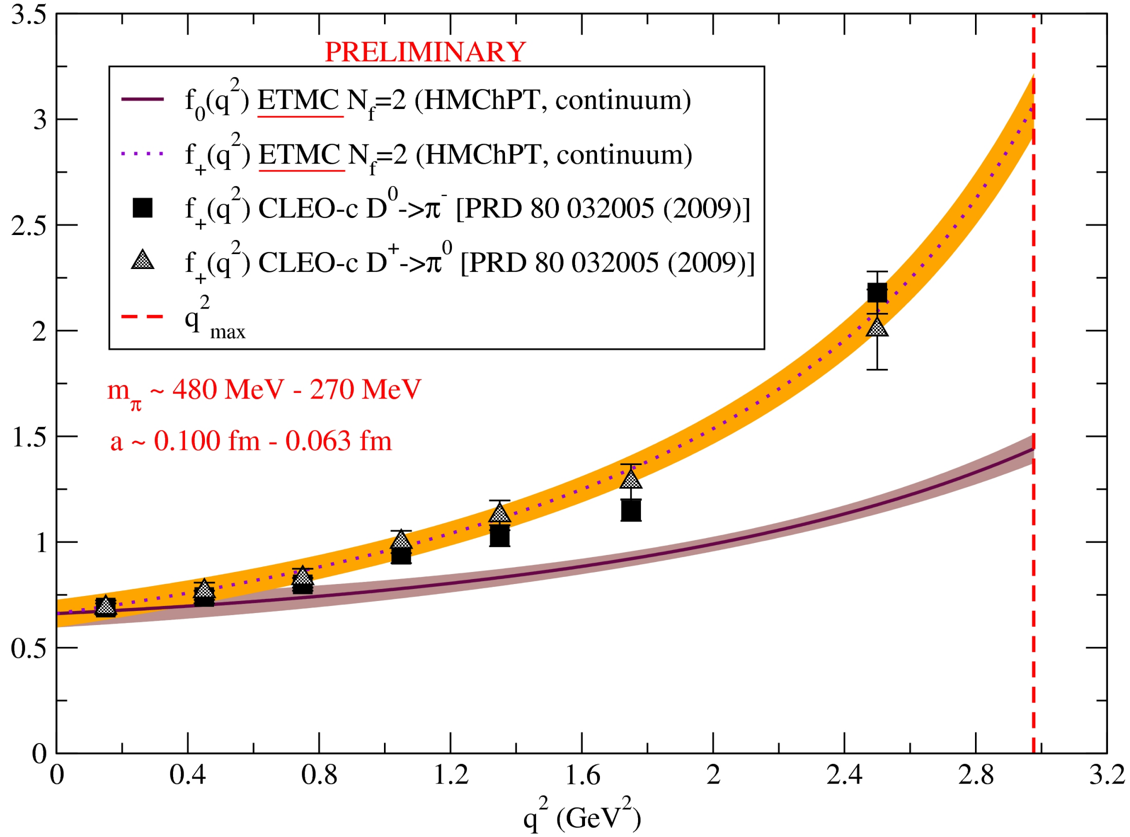
$D \to \pi l \nu$

New preliminary results at LAT2010



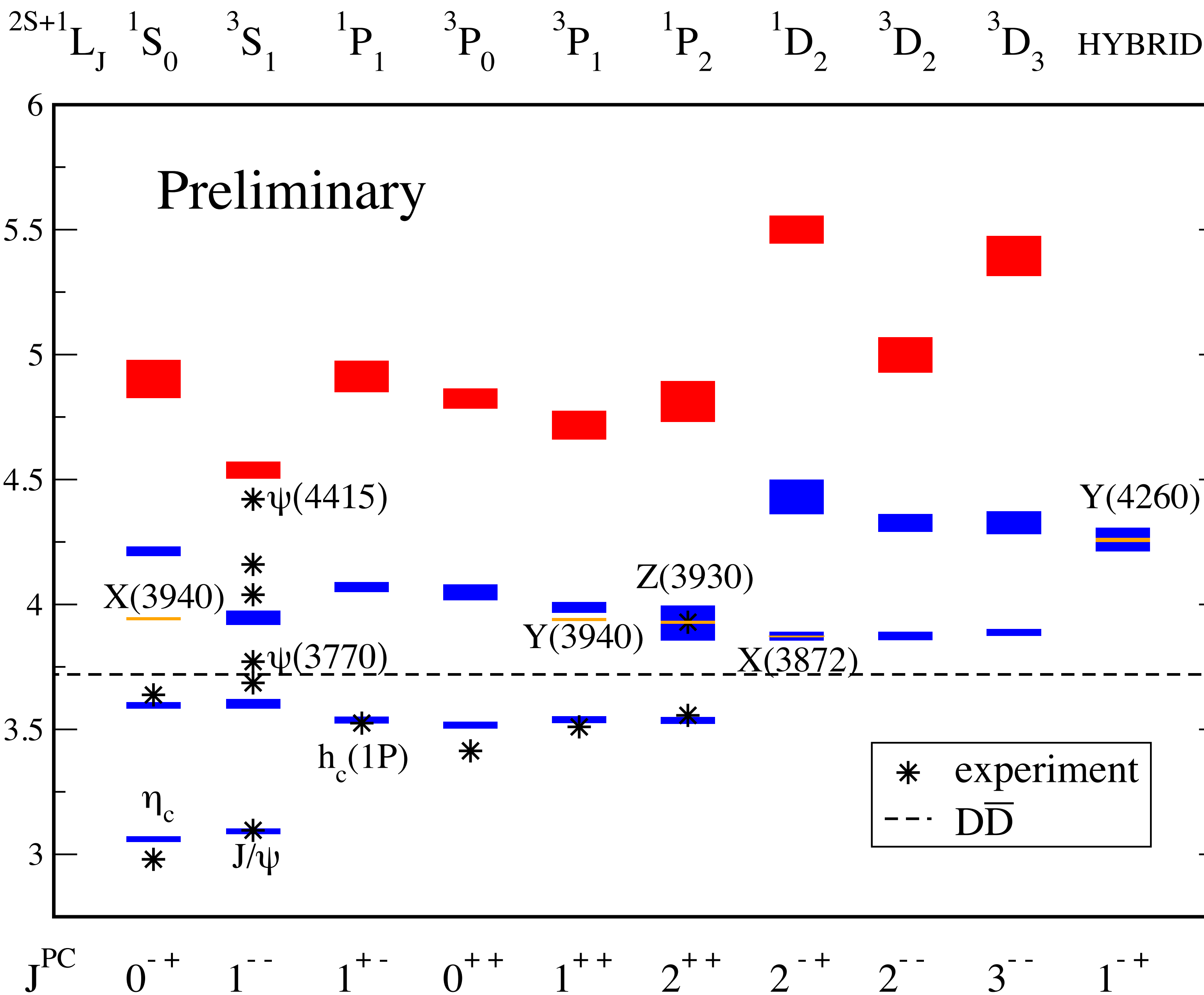
Gamiz et al, Fermilab Lattice/MILC

Di Vita et al, ETMC, u/d sea quarks



expect improved results soon ..

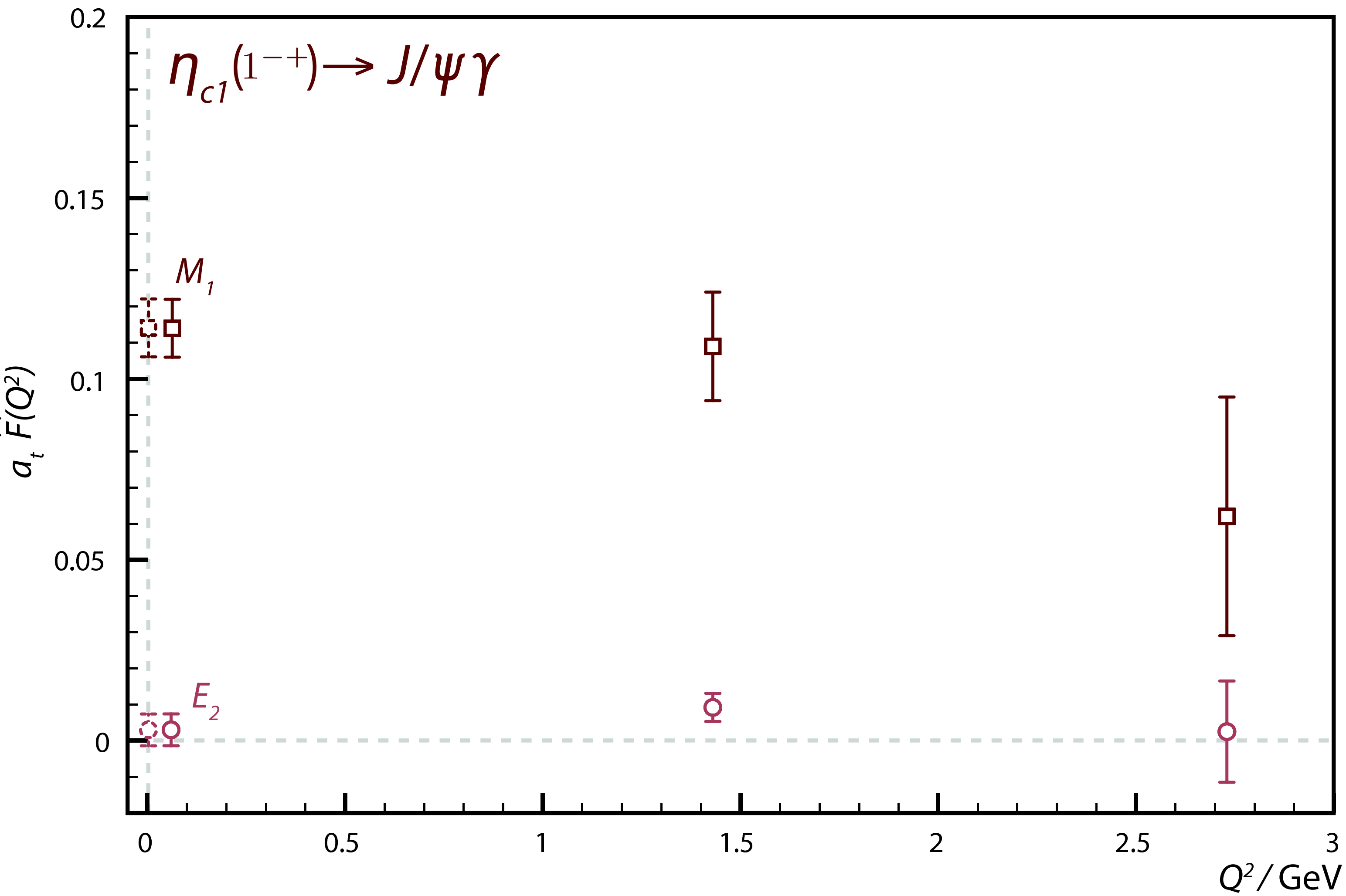
Harder calculations in progress ....



O Cais et al, Trinlat, 0801.1973

v. preliminary excited charmonium spectrum using anisotropic lattices.

Radiative transition rates from exotic charmonia



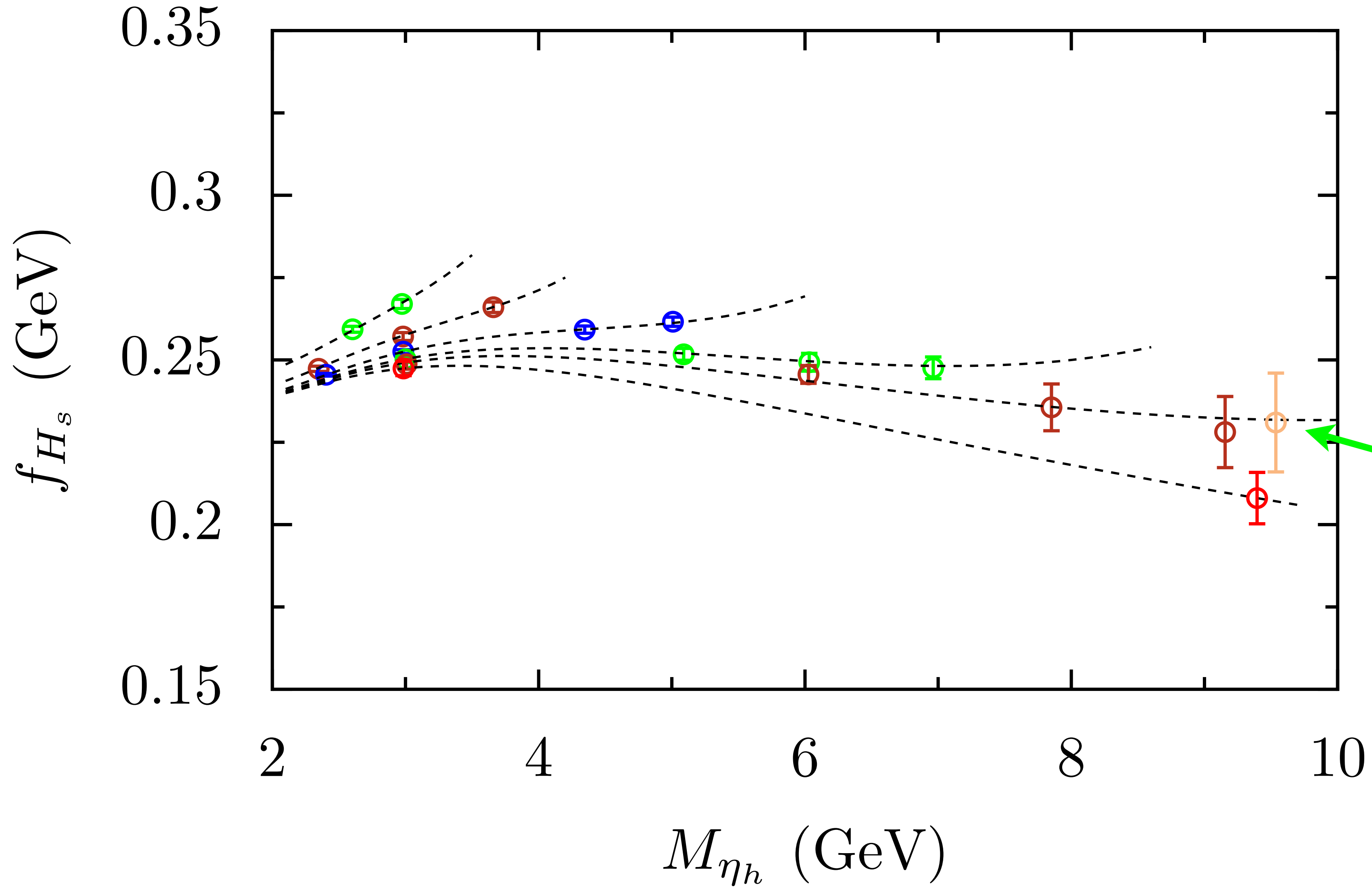
Dudek et al, Hadspec, 0902.2241

$$\eta_{c1} \to J/\psi\gamma \qquad \eta_{c1} = 1^{-+}$$

*quenched approx. at present *

Future - use relativistic formalisms such as HISQ or twisted mass for heavier quarks up to b, i.e. all quarks same method

- Exactly normalised operators, but need very fine lattices



HPQCD, LAT2010, HISQ quarks

NRQCD result

Full error budgets now available for lattice calcs

Error	m_{D_s}	f_{D_s}
statistical/valence tuning	0.094%	0.57%
r_1/a	0.025%	0.15%
r_1	0.051%	0.57%
a^2 extrapoln	0.044%	0.40%
$m_{q,sea}$ extrapoln	0.048%	0.34%
finite volume	0%	0.10%
m_{η_s}	0.056%	0.13%
em effects in D_s	0.036%	0.10%
em and annihln in m_{η_c}	0.076%	0.00%
em effects in η_c	–	–
missing c in sea	0.01%	0%
Total	0.16%	1.0%

→ will tell you what is possible in future
e.g. is error from disc. errors, $m_{u,d}$ extrapoln, stats ...

Conclusions

• relativistic formalisms with absolutely normalised currents are good for gold-plated charm physics - HISQ currently most accurate.

• HPQCD updates give m_{D_s} to 3 MeV and f_{D_s} to 1% - result moved closer to expt - discrepancy now 2 σ
$D \to K$ semileptonic form factors now to 2.5% - gives V_{cs} in agreement with CKM unitarity

• Updates to Fermilab and twisted mass results in progress. Also harder charm calculations ...

• Relativistic techniques have allowed precision for c physics - now applying to b physics - watch this space ..

Future

• sets of 'next generation' gluon configs will have $m_{u,d}$ at physical value (so no extrapoln) *or*
a down to 0.03fm (so b quarks are 'light') *or*
much higher statistics (for harder hadrons)
also can include charm in the sea now.

• Pushing errors down to 1% level will mean em corrections and $m_u \neq m_d$ must be understood.

• some harder calculations (flavor singlet, excited states, nuclear physics) will also become possible