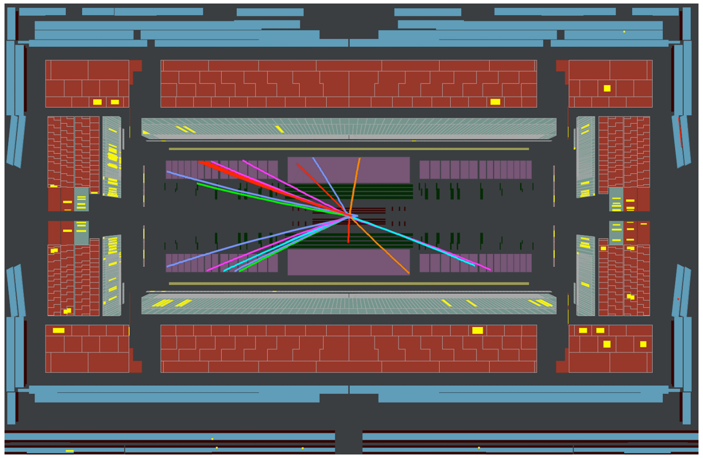
Charm quarks and Lattice QCD

Christine Davies
University of Glasgow

UK HEP Forum,
Cosener's House,
Nov. 2013

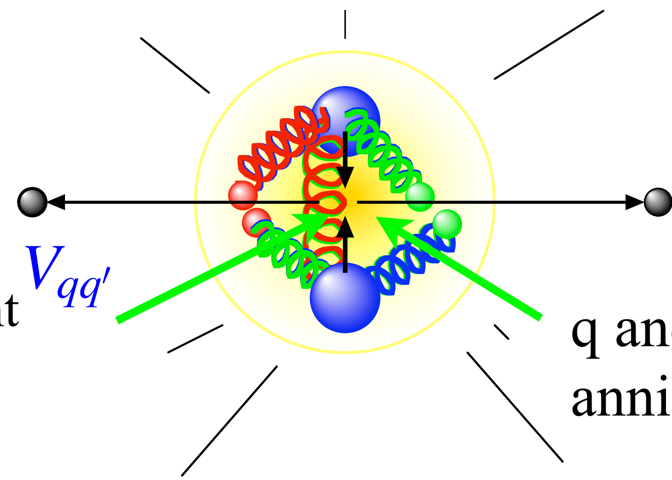
QCD is a key part of the Standard Model but quark confinement is a complication/interesting feature.



ATLAS
@LHC

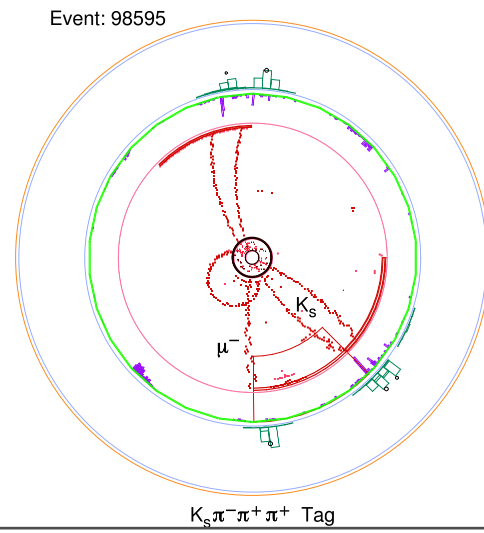
VS

Properties of hadrons calculable from QCD if fully nonperturbative calculation is done - can test QCD/search for new physics and determine parameters (to 1%).



CKM element $V_{qq'}$

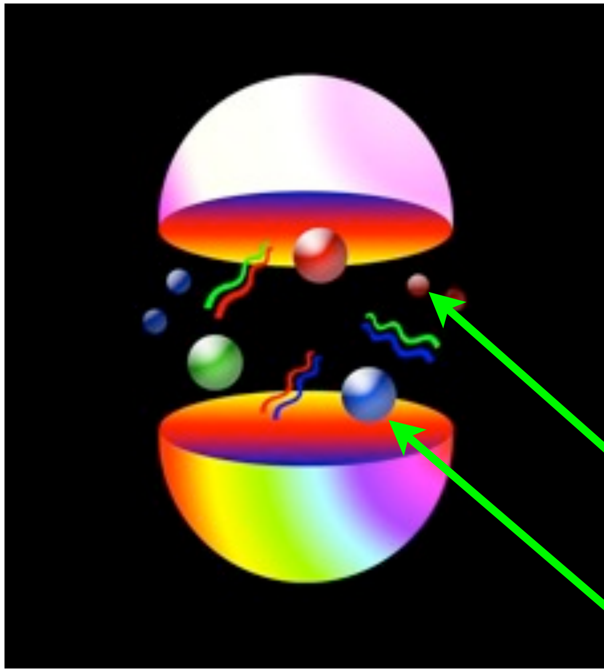
q and $\overline{q}'$ annihilate

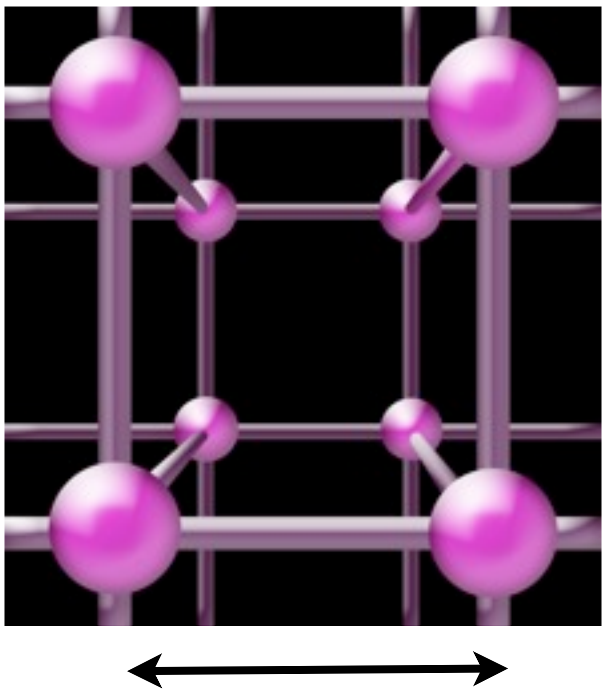


CLEO-c

$D_s \to \mu\nu$

$D_s \to K\pi\pi\pi$





Lattice QCD = fully nonperturbative QCD calculation

RECIPE

- Generate sets of gluon fields for Monte Carlo integrn of Path Integral (inc effect of u, d, s (+ c) sea quarks)
- Calculate averaged “hadron correlators” from valence q props.
- Fit as a function of time to obtain masses and simple matrix elements
- Determine a and fix m_q to get results in physical units.
- extrapolate to $a = 0, m_{u,d} = phys$ for real world. *now have phys $m_{u,d}$*

Issues with handling 'heavy' quarks on the lattice:

$$L_q = \overline{\psi}(\not{D} + m)\psi \rightarrow \overline{\psi}(\gamma \cdot \Delta + ma)\psi$$

Δ is a discrete finite difference with discretisation errors. What sets the scale for these?

For light hadrons the scale is Λ_{QCD} = few hundred MeV

For heavy hadrons the scale can be m_Q

$$E(a) = E(a=0) \times (1 + A(m_Q a)^2 + B(m_Q a)^3 + \ldots)$$

$m_c a \approx 0.4, m_b a \approx 2$ $\qquad a \approx 0.1\text{fm}$

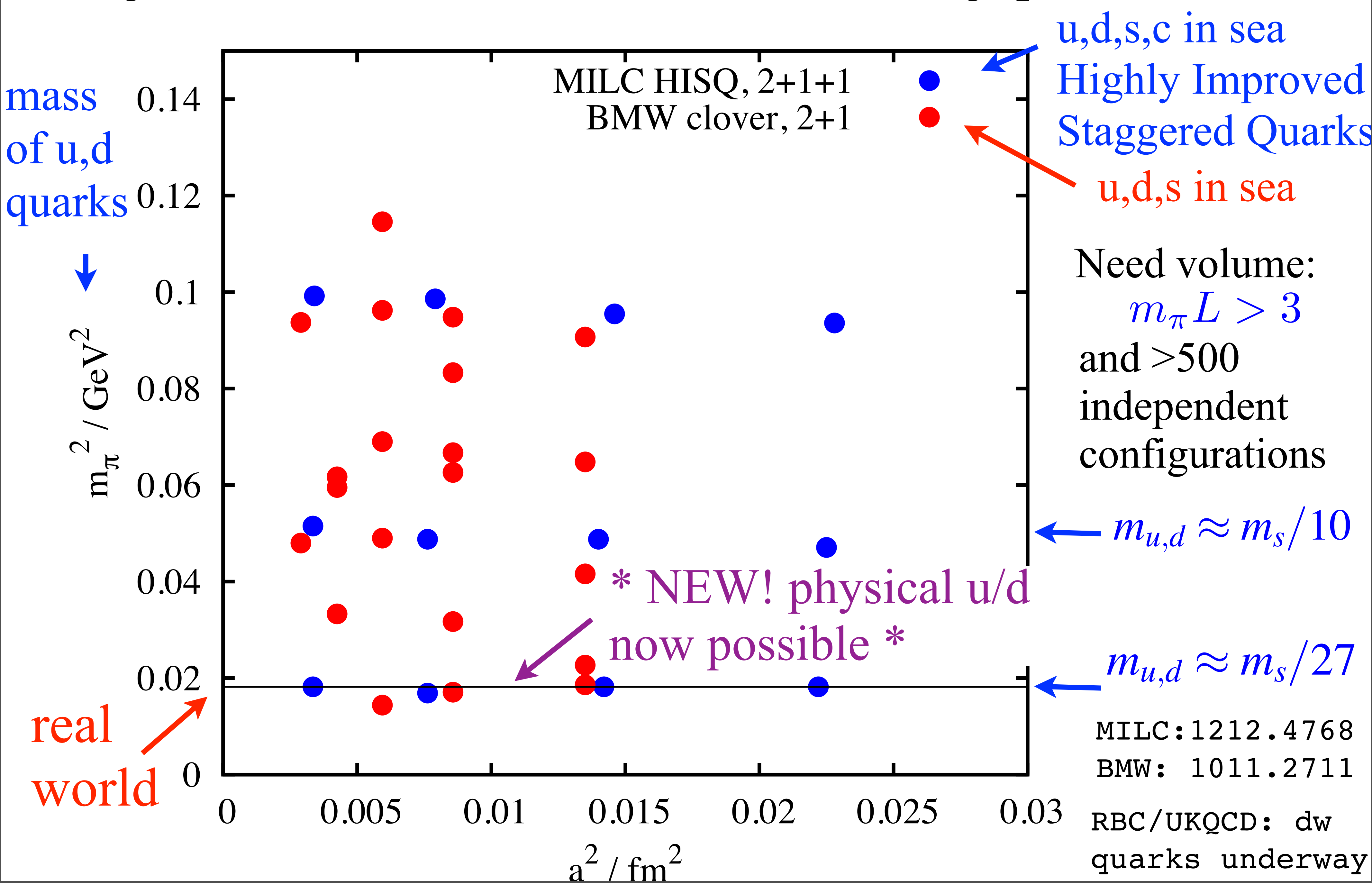
→ charm is between heavy and light

with good discretisation of Dirac equation and multiple values of a can do accurate continuum extrapolation.

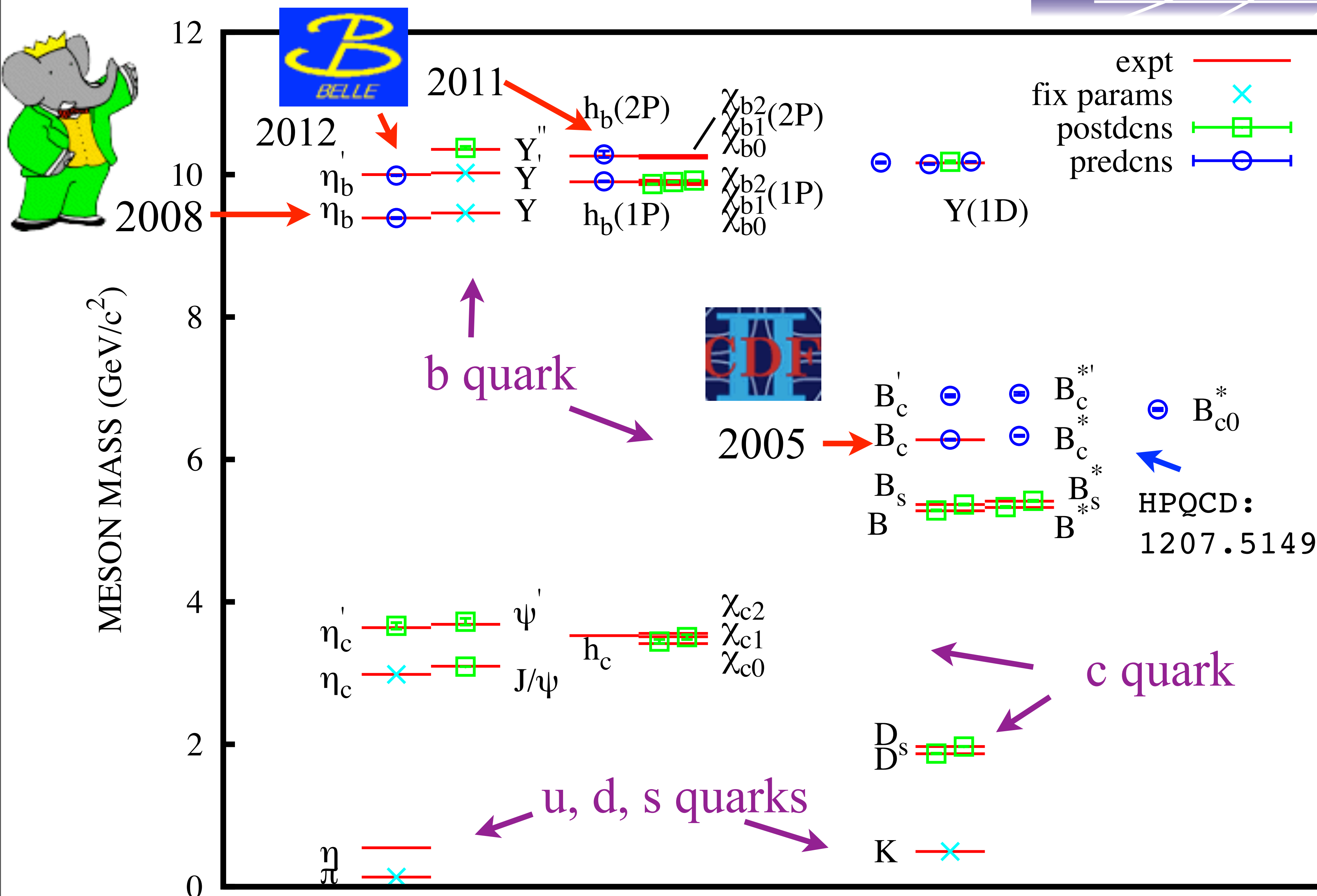
Highly Improved Staggered Quarks (HISQ) formalism has errors improved to $\alpha_s(am)^2, (am)^4$ HPQCD, hep-lat/0610092

Now also using for b quarks ....

Example parameters for gluon configurations being made using two different formalisms for handling quarks.



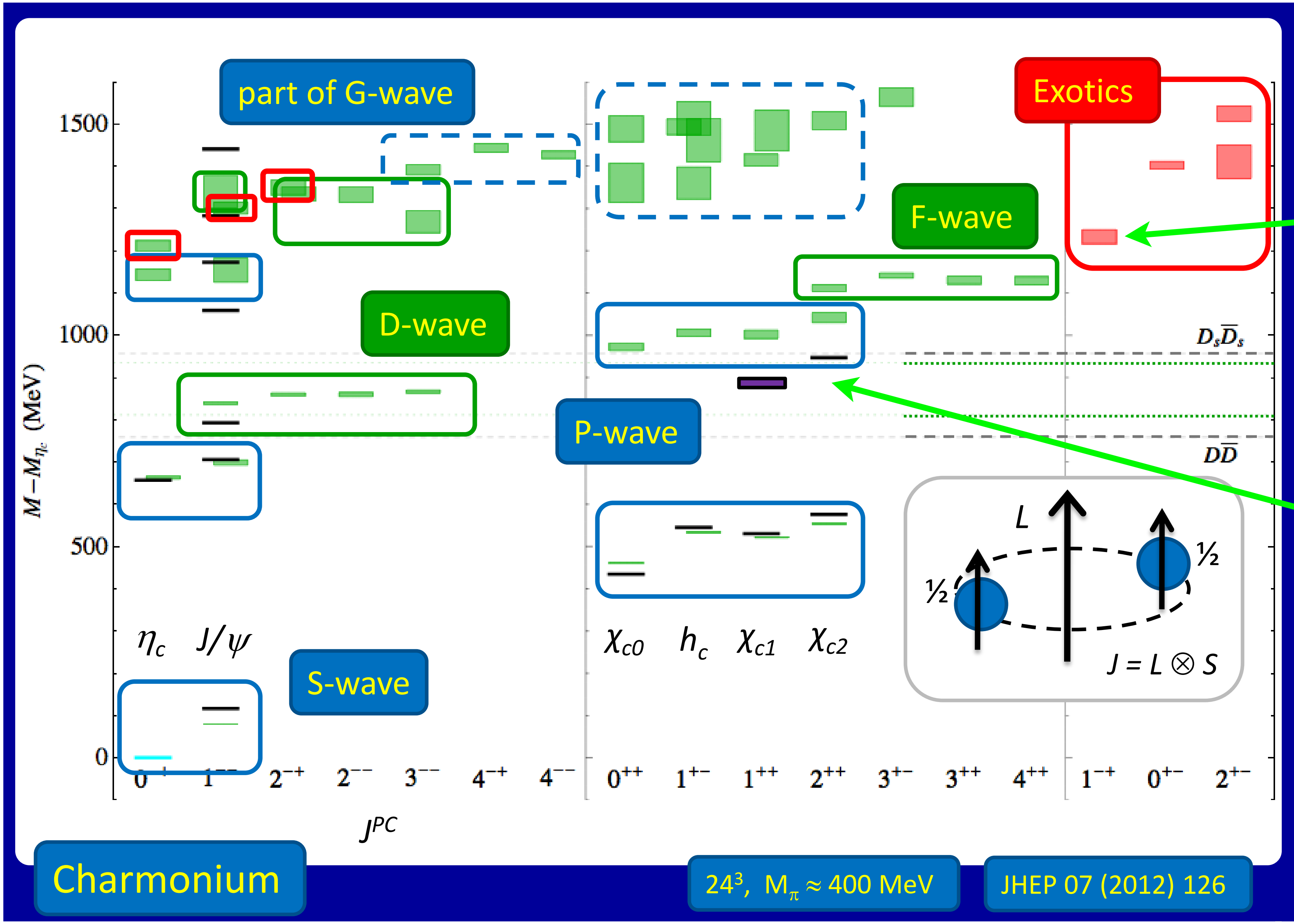
Results for the masses of mesons that are long-lived and so can be well-characterised in experiment



Agreement very good - errors typically a few MeV, need to worry about em, mu-md ..

Mapping excited states is harder but important ...

Hadron Spectrum Collaborn: 1204.5425



lightest multiplet $(0, 1, 2)^{-+}$ 1^{--}

X(3872)

uses aniso-tropic clover c quarks

No extrapolation to physical point and only 'single particle' operators so systematic errors still significant

Lattice QCD is best method to determine quark masses

$m_{q,latt}$ determined very accurately by fixing a meson mass to be correct. e.g. for m_c fix M_{η_c}

The issue is conversion to the $\overline{MS}$ scheme

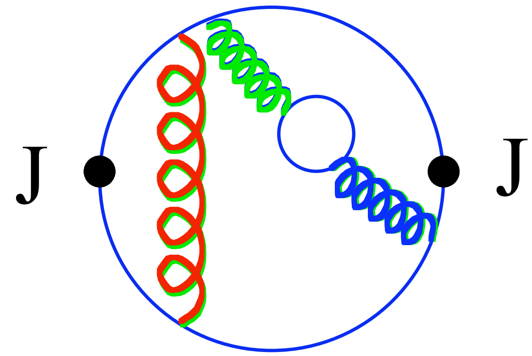
- Direct method

$$m_{\overline{MS}}(\mu) = Z(\mu a) m_{latt}$$

Calculate Z perturbatively or partly nonperturbatively.

- Indirect methods: (after tuning m_{latt}) match a quantity calculated in lattice QCD to continuum pert. th. in terms of $\overline{MS}$ quark mass

e.g. Moments of current-current correlators for heavy quarks known through α_s^3.

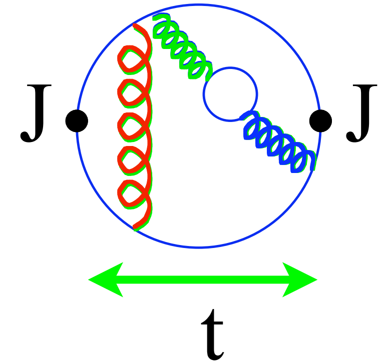


Chetyrkin et al, 0907.2110

HPQCD + Chetyrkin et al, 0805.2999, C. Mcneile et al, HPQCD,1004.4285

Most accurate to use pseudoscalar correlator time-moments:

$$G(t) = a^6 \sum_{\vec{x}} (am_c)^2 < 0|j_5(\vec{x},t) j_5(0,0)|0 >$$

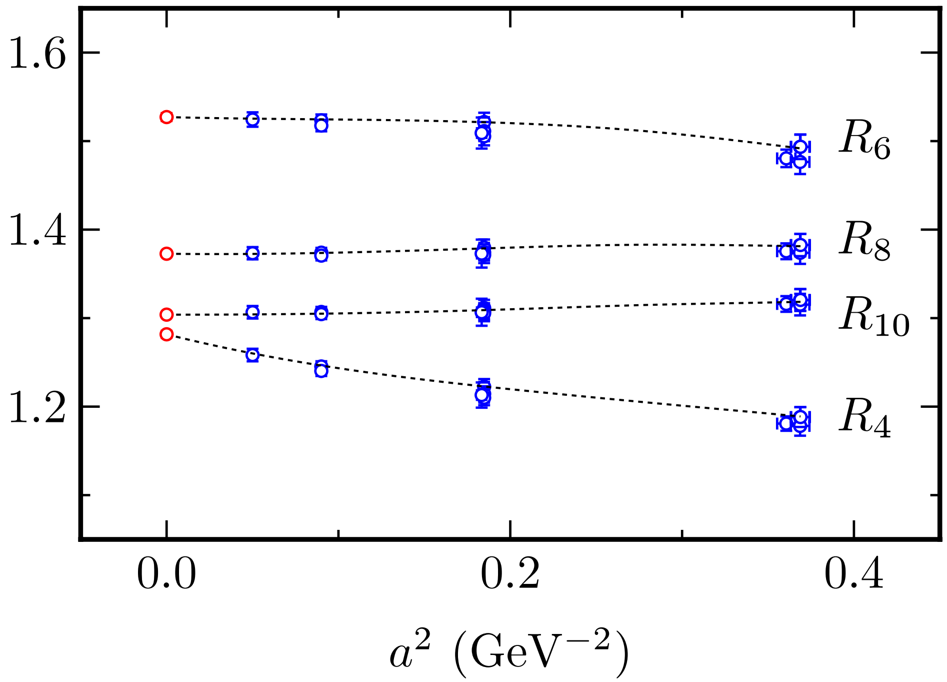


$$G_n = \sum_t (t/a)^n G(t)$$

$$R_{n,latt} = G_4/G_4^{(0)} \quad n = 4$$

ratio to results with no gluon field improves disc. errors

$$= \frac{am_{\eta_c}}{2am_c} (G_n/G_n^{(0)})^{1/(n-4)} \quad n = 6, 8, 10 \ldots$$



extrapolate to a=0 and compare to contnm pert. th.

Fit first 4 moments simultaneously, gives $M_{\eta_c}/2m_c(\mu)$ AND $\alpha_s(\mu)$

RESULT: NOTE 0.5% error

$$m_c(m_c) = 1.273(6)\text{GeV}$$

input for $H \to c\overline{c}$

Quark mass ratios

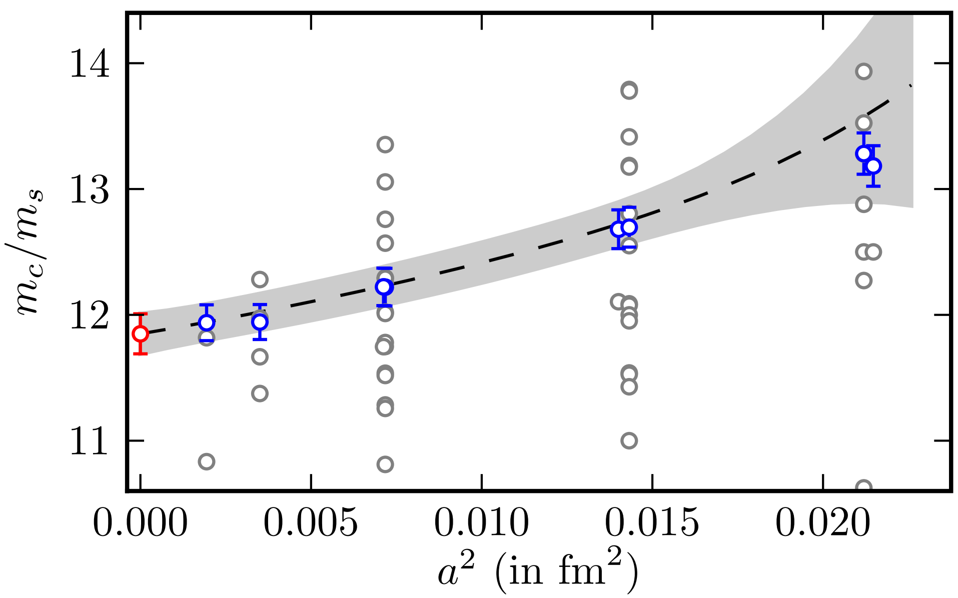
Obtained directly from lattice QCD if same quark formalism is used for both quarks.

Ratio is at same μ and for same n_f.

$$\left(\frac{m_{q1,latt}}{m_{q2,latt}}\right)_{a=0} = \frac{m_{q1,\overline{MS}}(\mu)}{m_{q2,\overline{MS}}(\mu)}$$

Not possible any other way ...

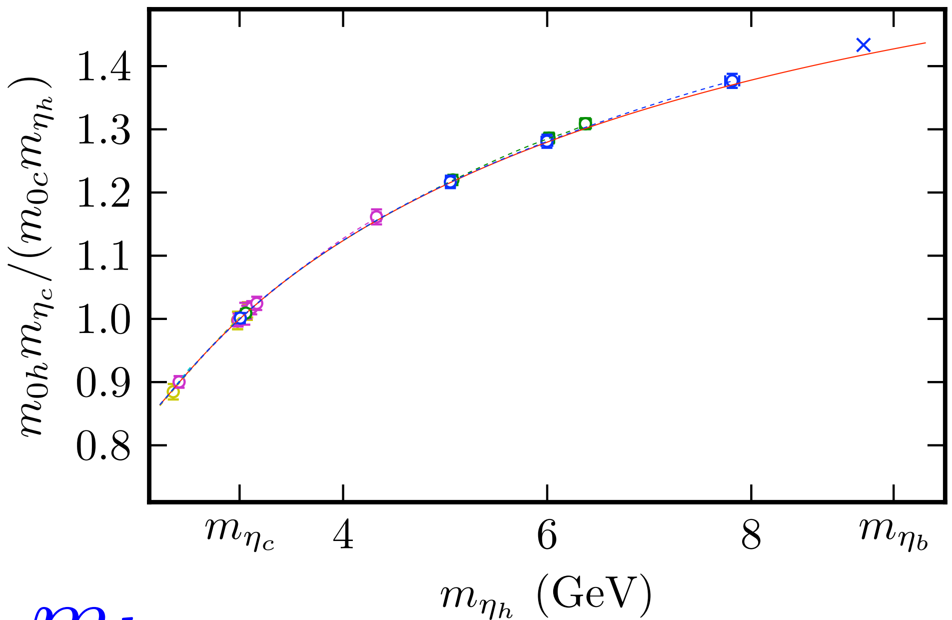
m_c/m_s



$$\frac{m_c}{m_s} = 11.85(16)$$

allows 1% accuracy in m_s

m_b/m_c



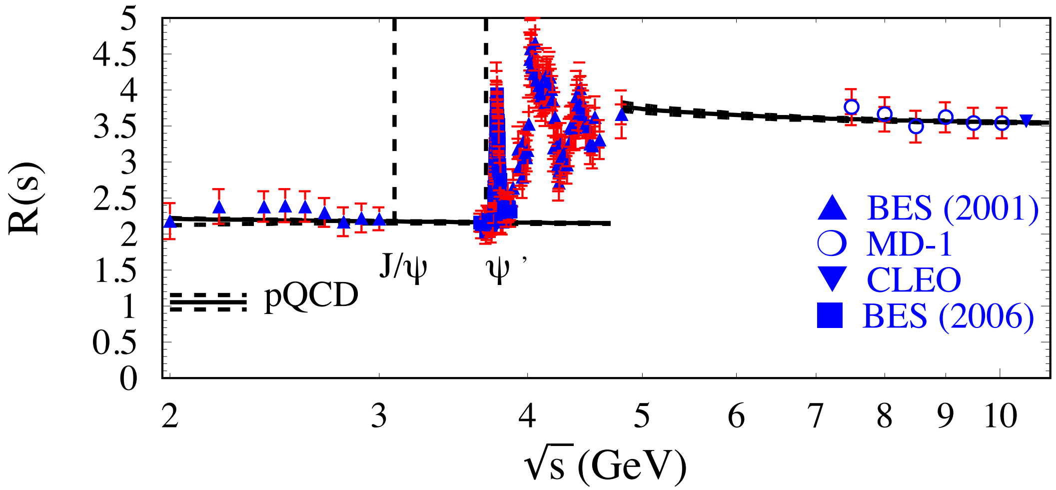
$$\frac{m_b}{m_c} = 4.51(4)$$

HPQCD, 0910.3102; 1004.4285

Can also extract charm piece of:

e.g. Kuhn et al, hep-ph/0702103

$$R_{e^+e^-}(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{4\pi\alpha^2/(3s)}$$ from experiment,

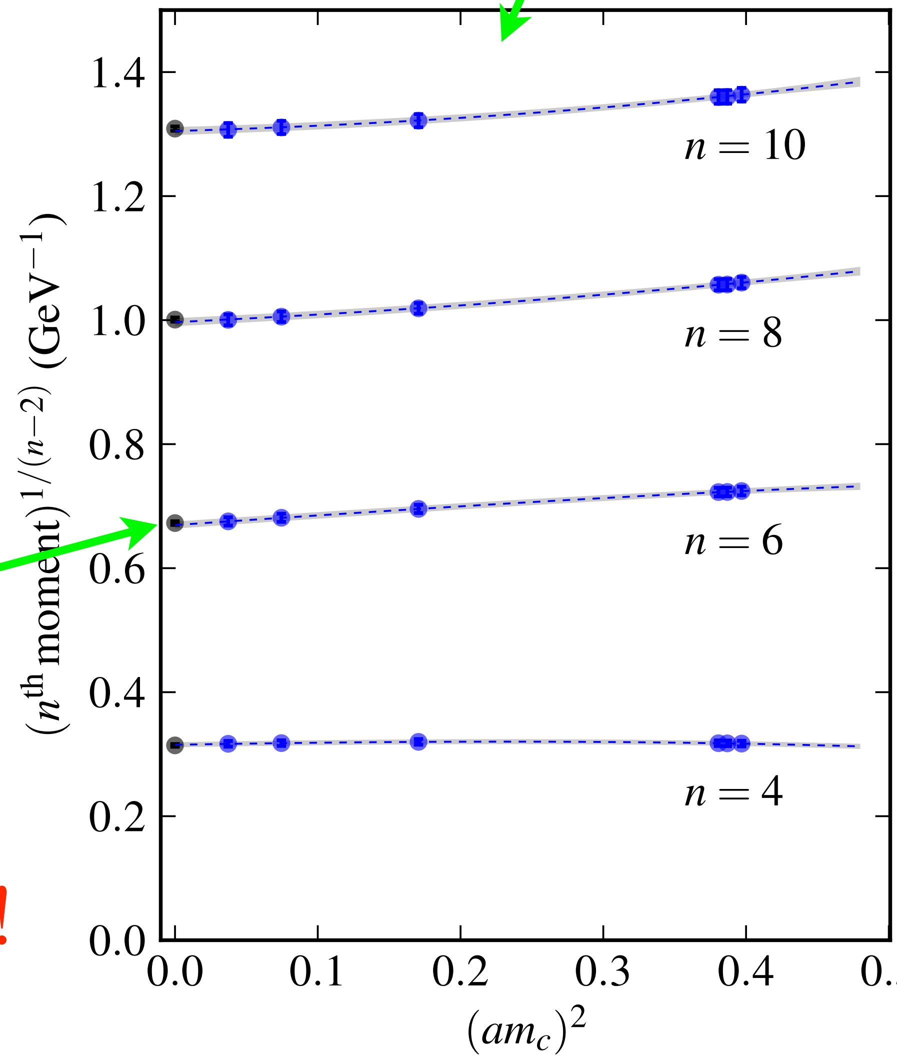


and compare moments

$$\mathcal{M}_k \equiv \int \frac{ds}{s^{k+1}} R_{e^+e^-}(s)$$

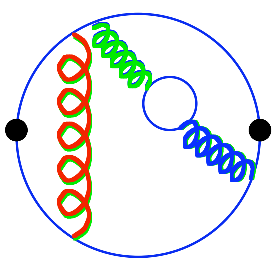
to lattice QCD for vector case

lattice and expt errors both ~1%



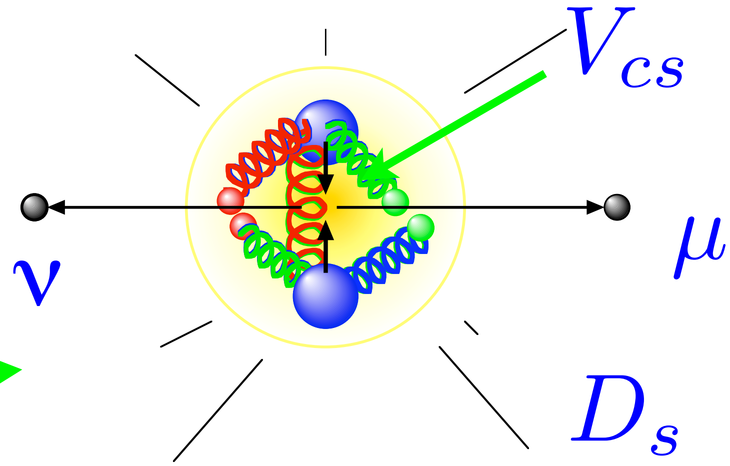
G. Donald et al, HPQCD, 1208.2855

good agreement!

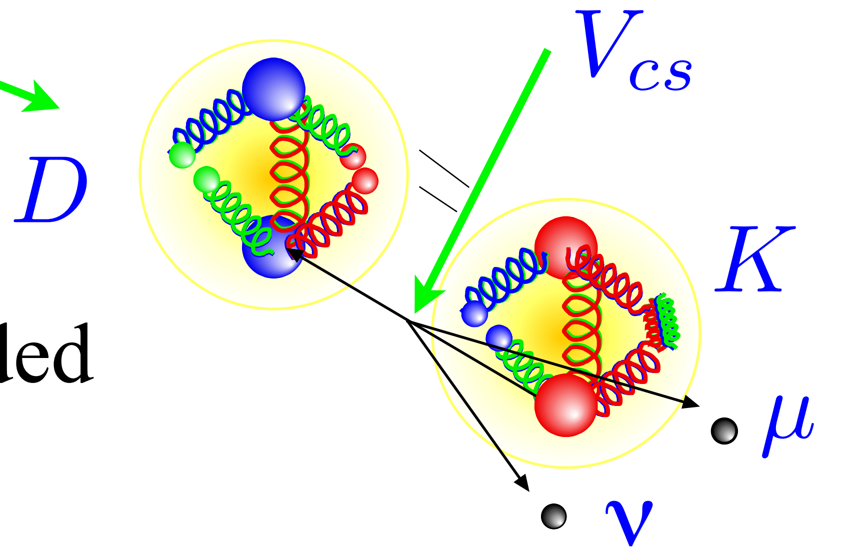
J  J ← vector coupling to photon

Weak decays probe meson structure and quark couplings

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



$Br(M \to \mu\nu) \propto V_{ab}^2 f_M^2$



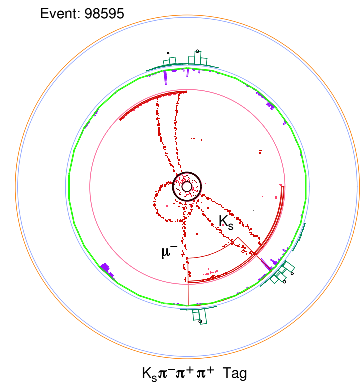
Expt = CKM x theory(QCD)

Precision lattice QCD + expt needed for accurate CKM elements.

If V_{ab} known, compare lattice to expt to test QCD

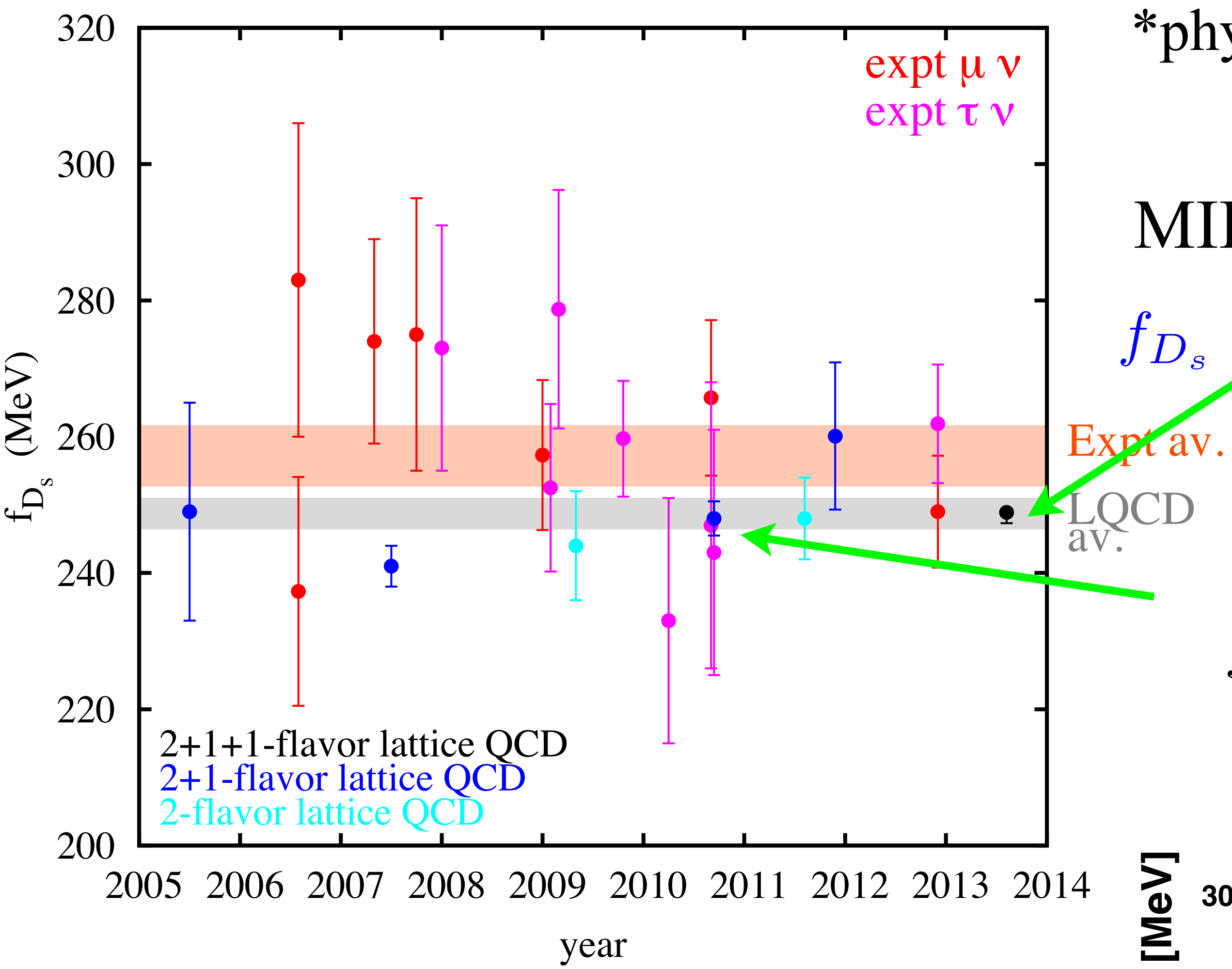
$Br(M \to M'\mu\nu) \propto V_{ab}^2 f_+^2(q^2)$

Constraining new physics with lattice QCD: f_{D_s}



New results using HISQ quarks on MILC 2+1+1 configs with

physical u/d quarks



MILC (Lattice2013):

$$f_{D_s} = 248.9 \pm 0.2_{stat} \, {}^{+0.5}_{-1.6}{}_{syst} \text{ MeV}$$

agrees well with previous HPQCD with 2+1 sea quarks:

$$f_{D_s} = 248.0(2.5)\text{MeV}$$

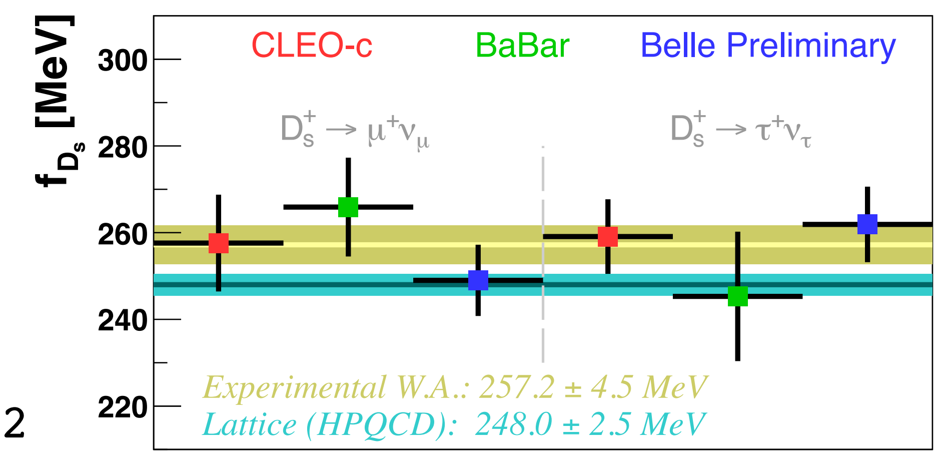
HPQCD:1008.4018

experimental update: new Belle results

World av: $f_{D_s} = 257.2(4.5)\text{MeV}$

2σ above theory

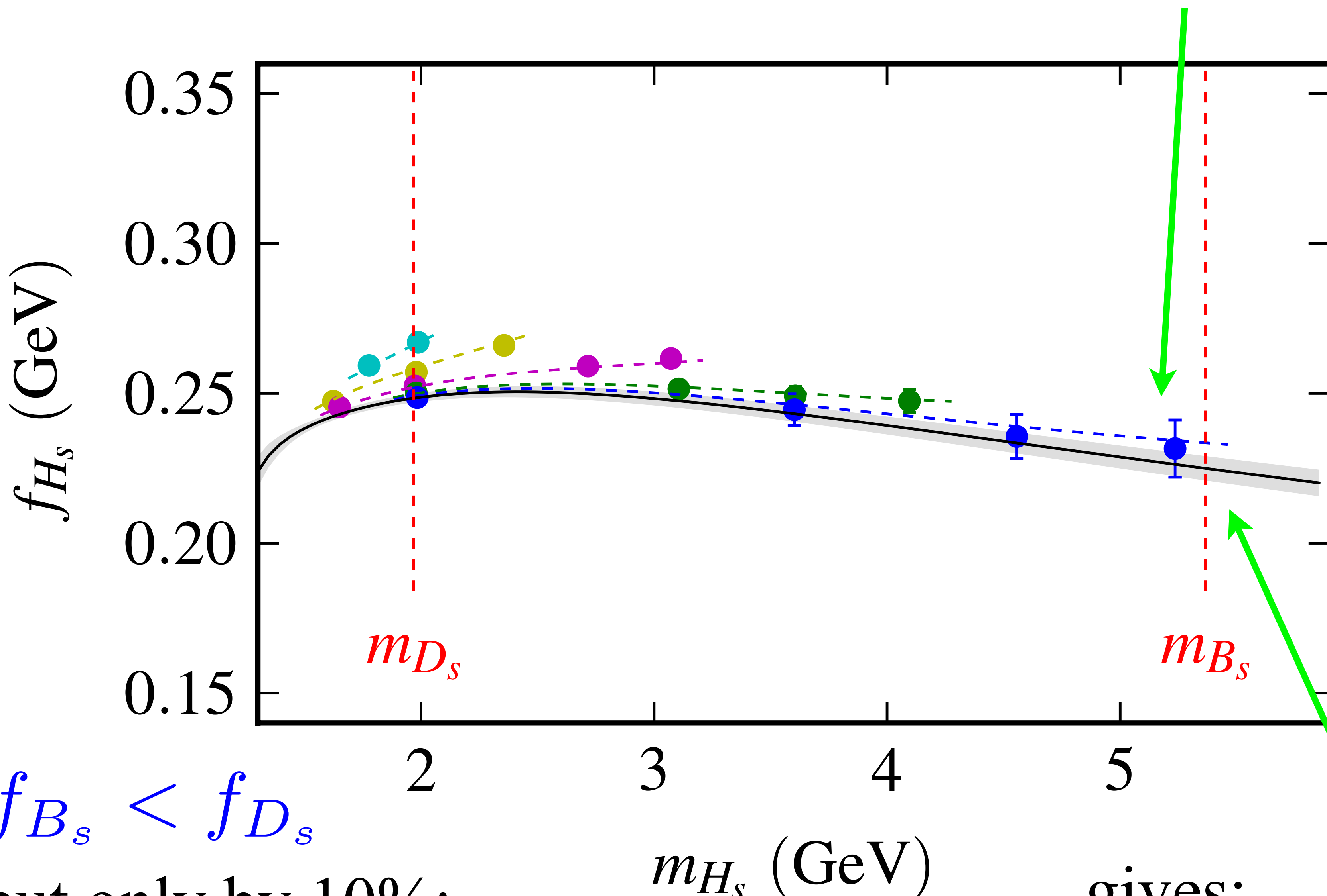
Zupanc:charm2012



Mapping out dependence on heavy quark mass ...

uses HISQ and multiple m and a. Finest: a=0.045fm

HPQCD:
C McNeile
et al,
1110.4510.



Tests HQET

$f_{B_s} < f_{D_s}$

but only by 10%:

$f_{B_s}/f_{D_s} = 0.906(14)$

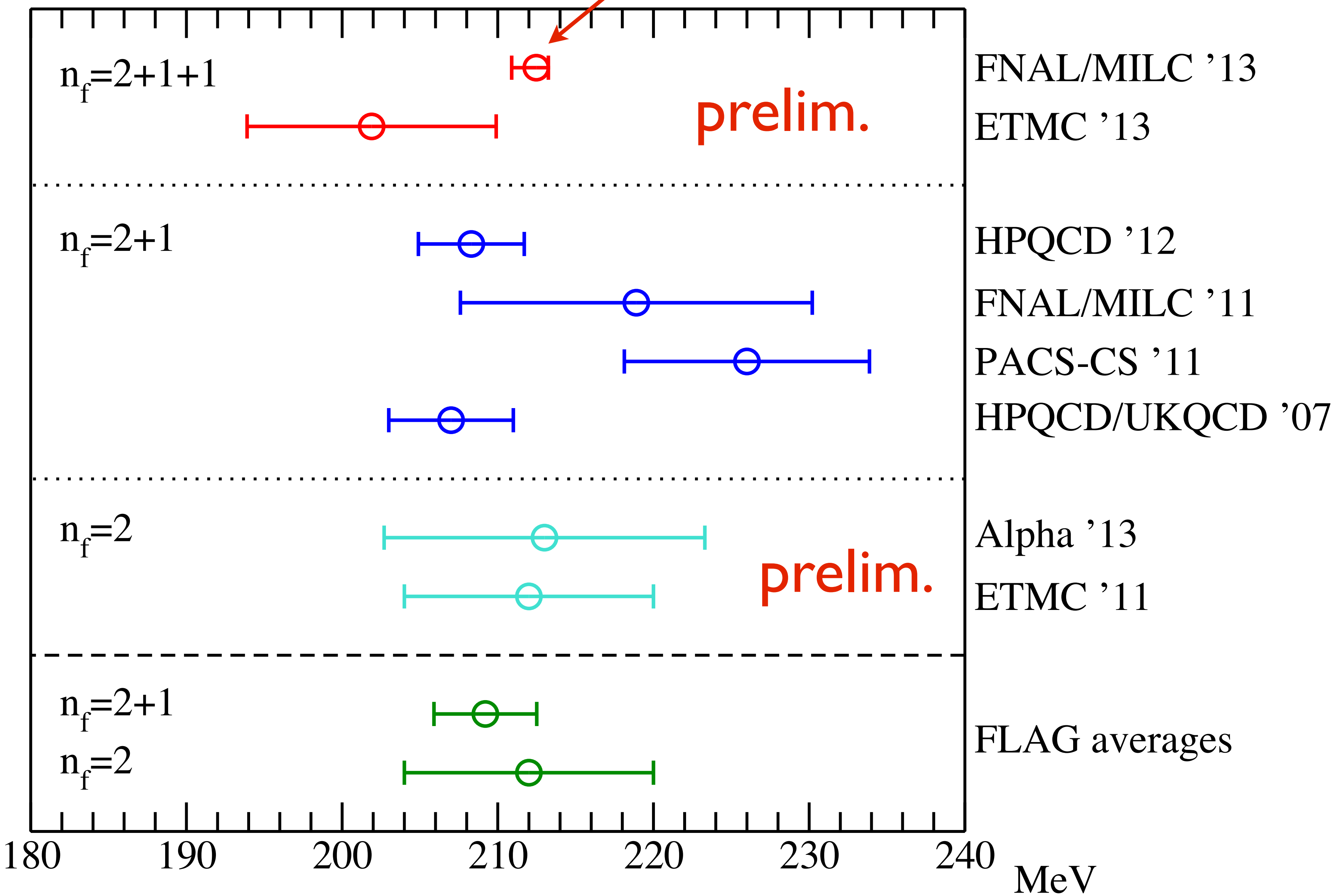
gives:

$f_{B_s} = 225(4)\mathrm{MeV}$

Current status: f_D

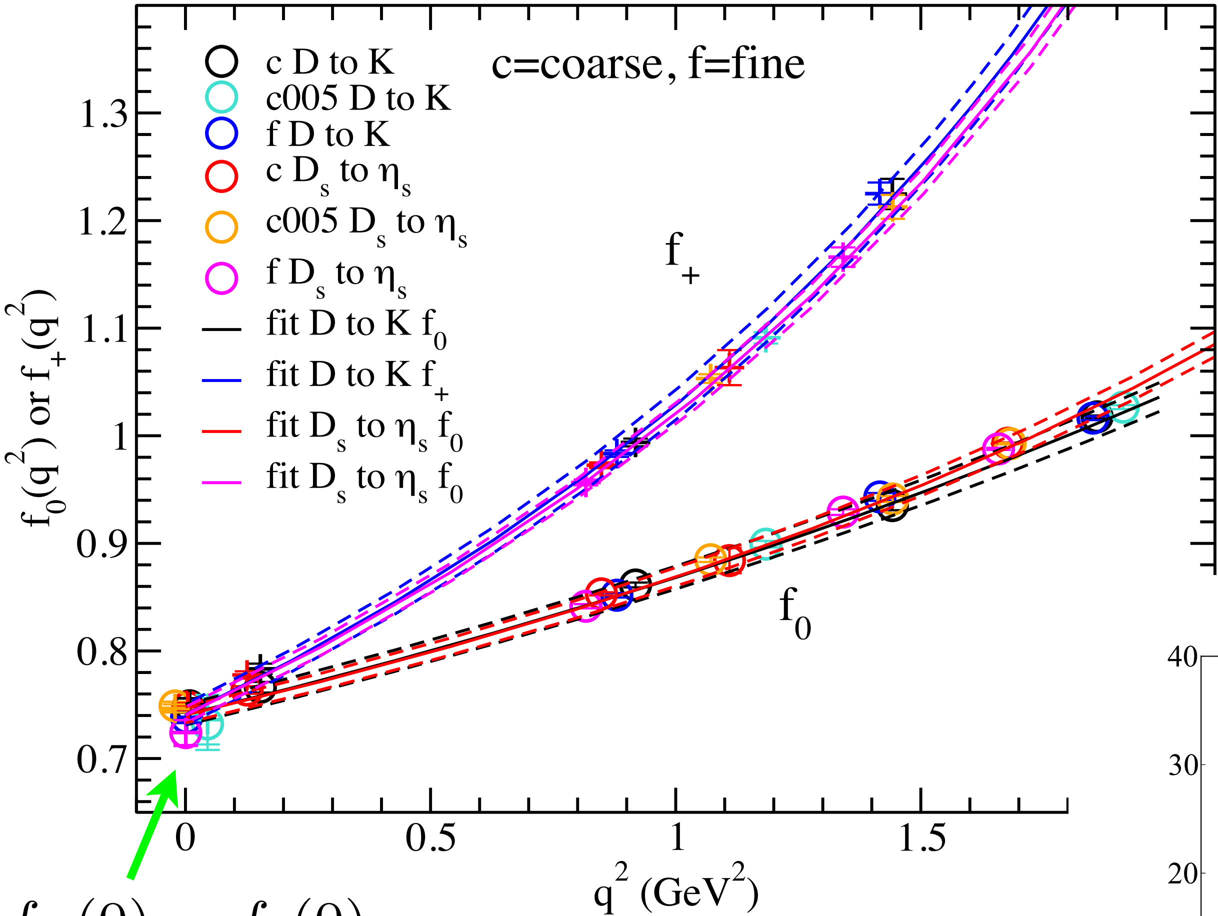
Jonna Koponen, Charm2013

$$f_D = 212.5 \pm 0.5_{\rm stat}{}^{+0.6}_{-1.5}|_{\rm syst}\ \mathrm{MeV}$$



CLEO-c result f_D = 207(9) MeV assuming V_{cd} known

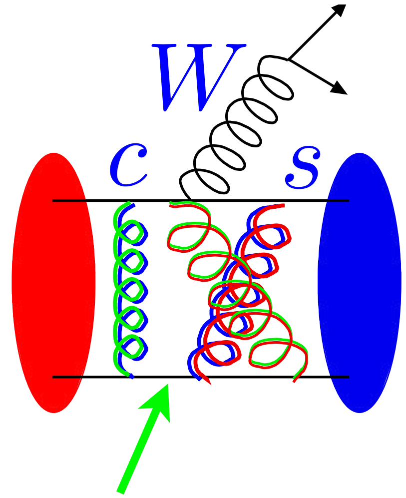
Semileptonic form factors for charmed mesons: $c \to s$



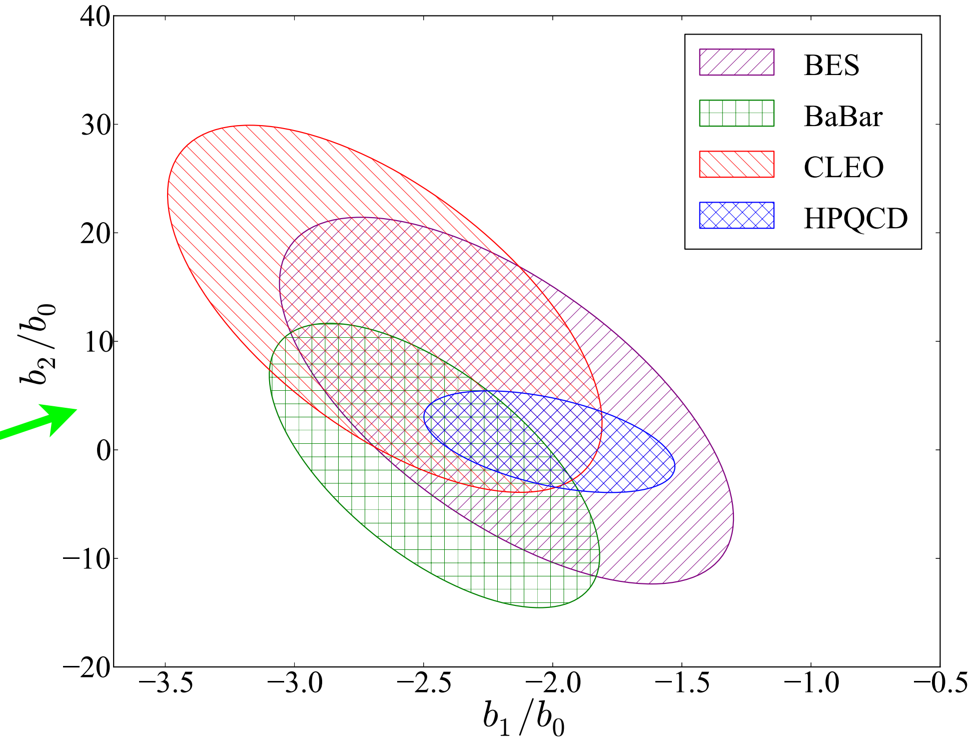
$f_+(0) = f_0(0)$

4-mom transfer

HPQCD,
1305.1462



spectator

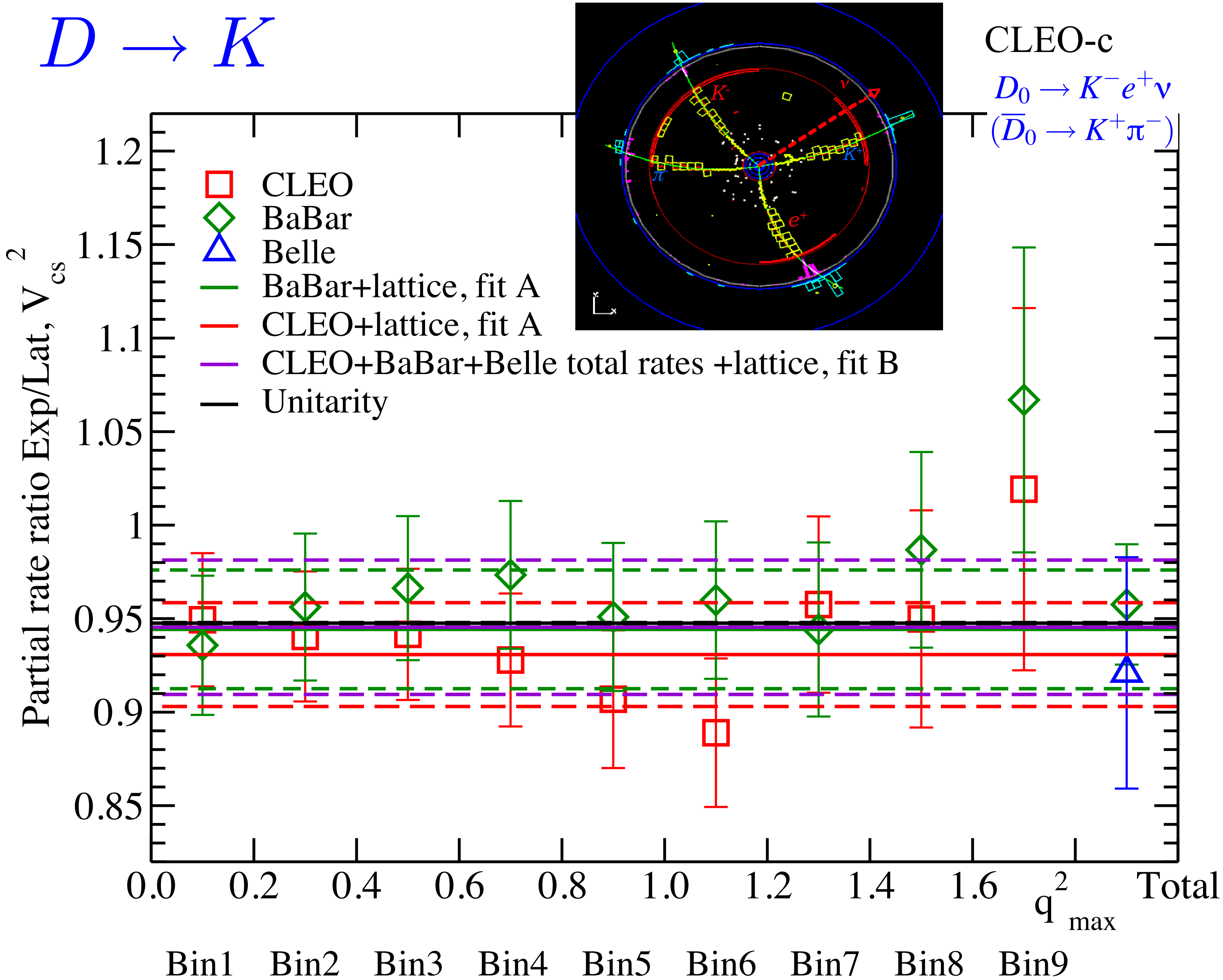


Shape agrees well with expt.

Form factor same whether spectator is u/d or s

Convert to decay rate in q^2 bins to compare to experiment:

$D \to K$



HPQCD
1305.1462

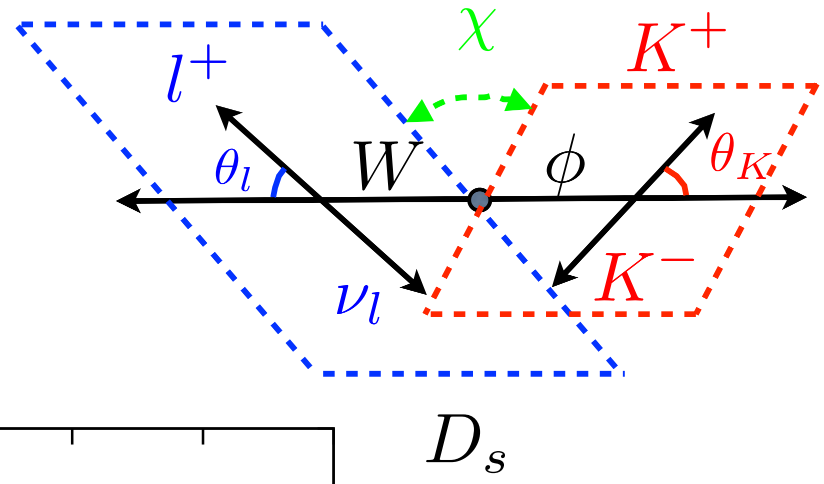
uses all exptl data in model-indpt way

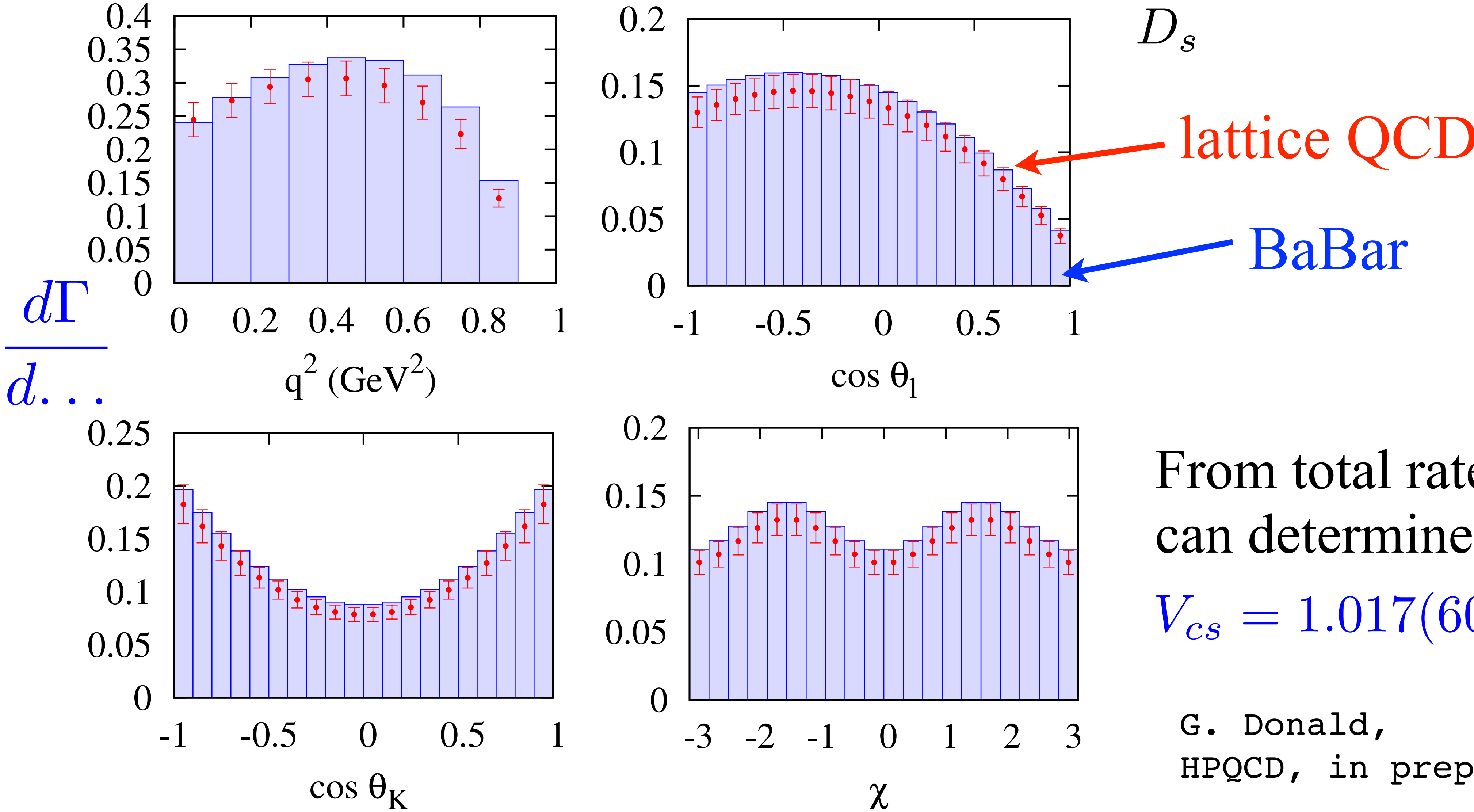
errors of lattice best at large q^2; expt best at small q^2

$$V_{cs} = 0.963(5)_{expt}(14)_{lattice}$$

$D_s \to \phi l \nu$

Vector final state has additional angular information + there are both vector and axial form factors





From total rate can determine:

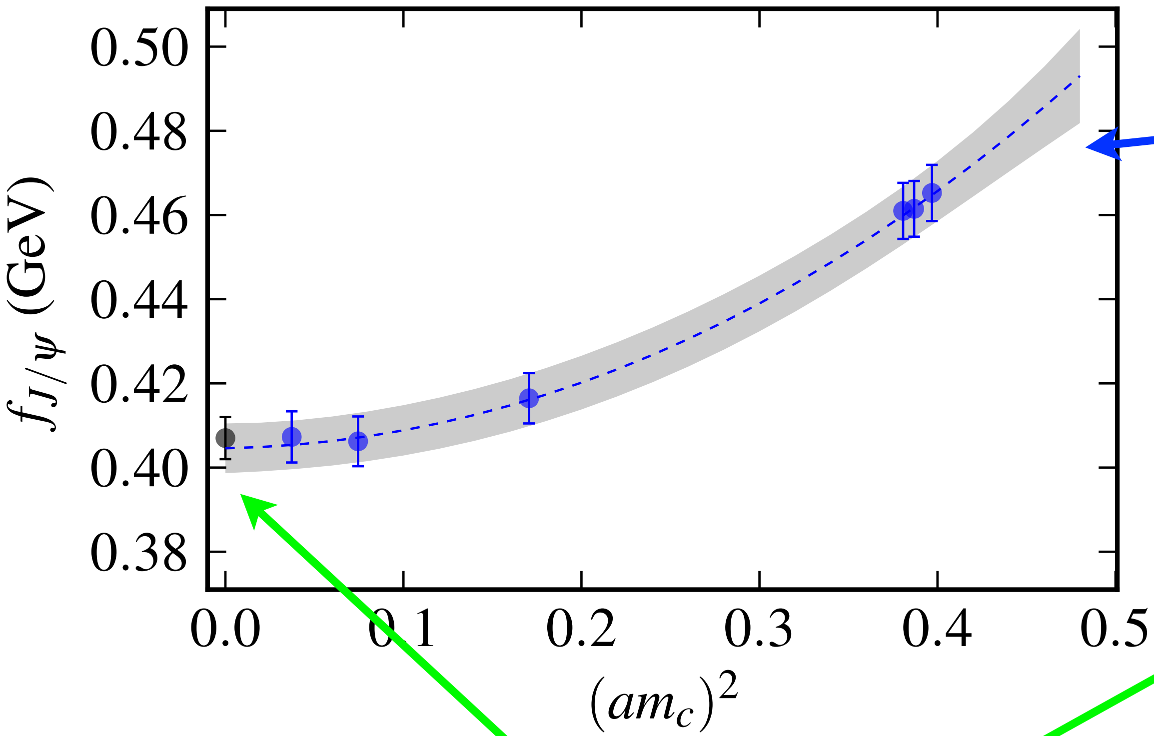
$V_{cs} = 1.017(60)$

G. Donald, HPQCD, in prep

Test with electromagnetic decays of charmonium

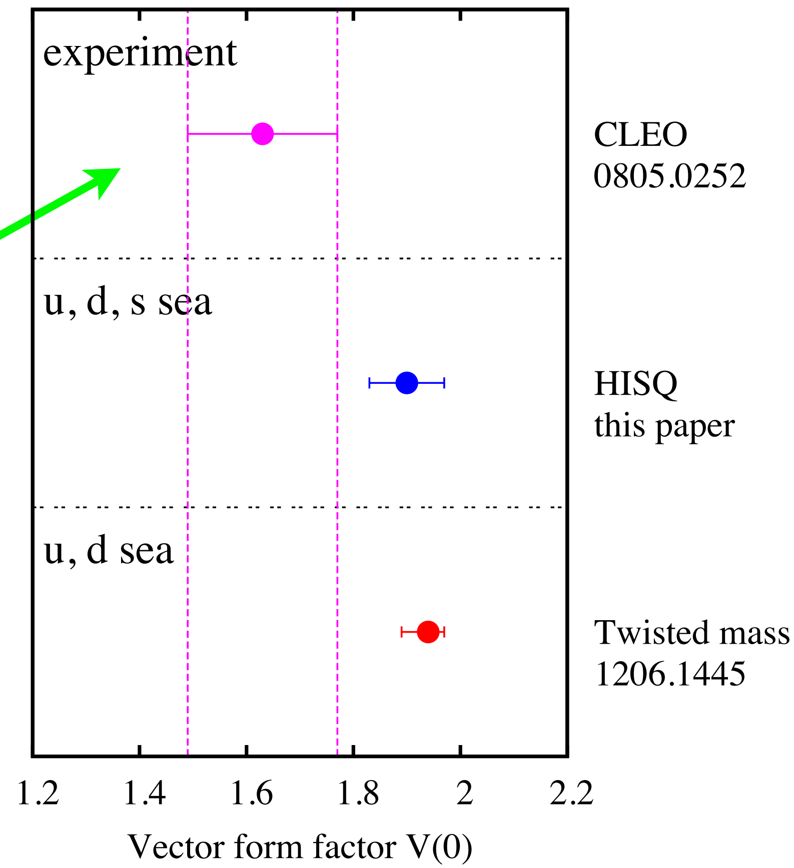
no CKM uncertainties!

G. Donald et al, HPQCD,1208.2855



decay constant for $J/\psi \to e^+e^-$

form factor for $J/\psi \to \gamma\eta_c$



experiment

Lattice QCD is only method that can give O(1%) precision

Conclusion

- Lattice QCD results for gold-plated hadron masses and decay constants now providing stringent tests of QCD/SM.
- Gives QCD parameters and some CKM elements to 1%.
- BSM constraints and tests of sum rules/HQET etc.

Future

- sets of '2nd generation' gluon configs now have $m_{u,d}$ at physical value (so no extrapoln) *or* a down to 0.05fm (so b quarks are 'light')
- Aim for 1% errors for B and B_s physics building on D/D_s
- Harder calculations (excited states, hybrids) will improve

In UK now have access to STFC's DiRAC facility with computers in world's top 100. www.dirac.ac.uk

Summary of latest/best Lattice results

Jonna Koponen,
Charm2013

$$f_D = 212.5 \pm 0.5_{\rm stat} {}^{+0.6}_{-1.5}|_{\rm syst}\ \mathrm{MeV}$$

Preliminary!

$$f_{D_s} = 248.9 \pm 0.2_{\rm stat} {}^{+0.5}_{-1.6}|_{\rm syst}\ \mathrm{MeV}$$

$$f_{D_s}/f_D = 1.1717(20)_{\rm stat}({}^{+0.6}_{-1.5})_{\rm syst}$$

$$V_{cd} = 0.2184 \pm 0.009_{\rm expt} {}^{+0.0008}_{-0.0016}|_{\rm lattice}\ \text{(leptonic)}$$

$$V_{cs} = 1.0169 \pm 0.02_{\rm expt} {}^{+0.002}_{-0.007}|_{\rm lattice}\ \text{(leptonic)}$$

$$V_{cd} = 0.225(6)_{\rm expt}(10)_{\rm lattice}\ \text{(semileptonic)}$$

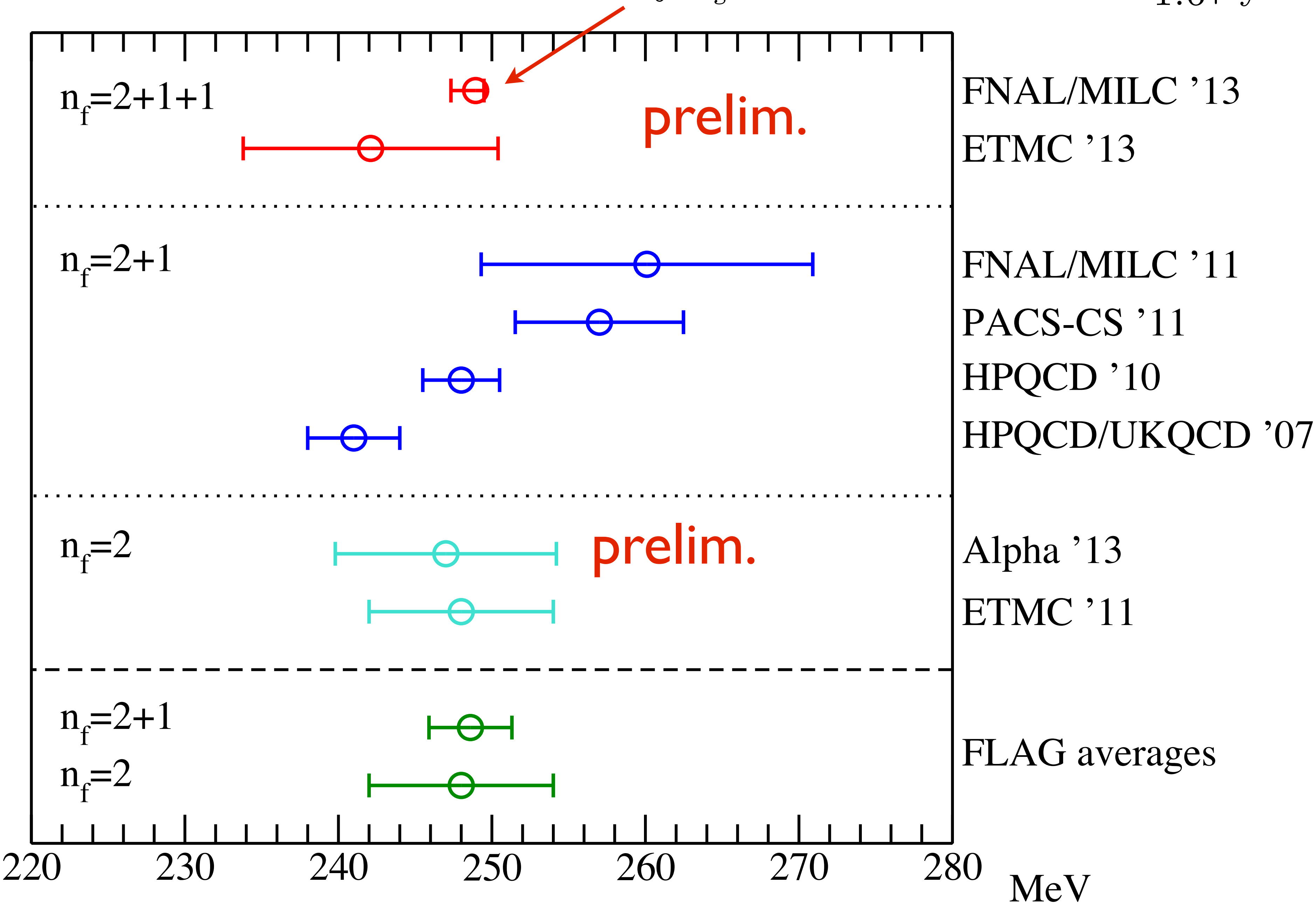
$$V_{cs} = 0.963(5)_{\rm expt}(14)_{\rm lattice}\ \text{(semileptonic)}$$

Decay constants from C. Bernard's talk, Lattice 2013. CKM elements from semileptonic decays taken from PRD84(2011)114505 and arXiv:1305.1462.

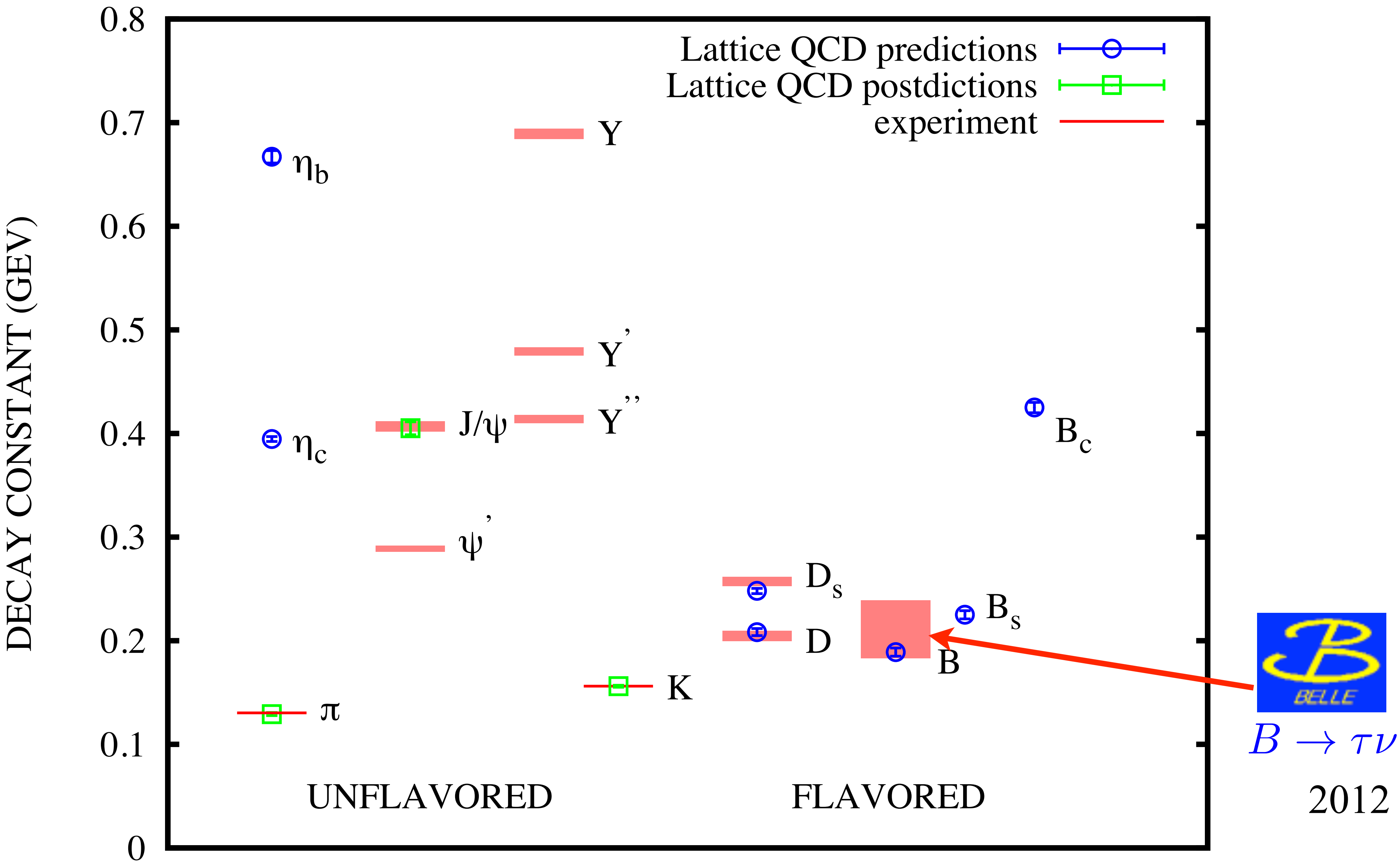
Current status: f_{D_s}

Jonna Koponen, Charm2013

$$f_{D_s} = 248.9 \pm 0.2_{\text{stat}}{}^{+0.5}_{-1.6}|_{\text{syst}}\ \text{MeV}$$



Summary of results on decay constants - HPQCD



More work needed on vector (electromagnetic) decay constants