Stress-testing the Standard Model with Lattice QCD

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HPQCD collaboration

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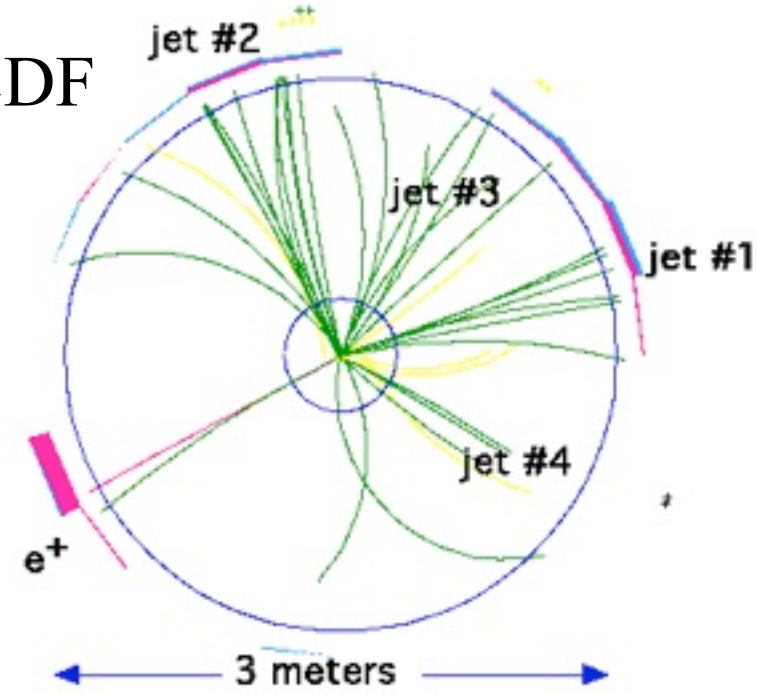
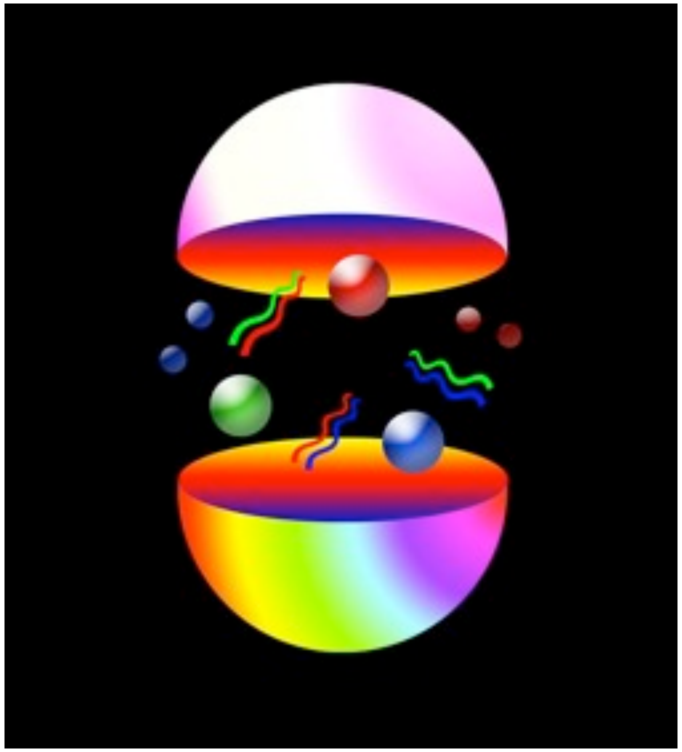
QCD is a key part of the Standard Model but quark confinement is a complication/interesting feature.

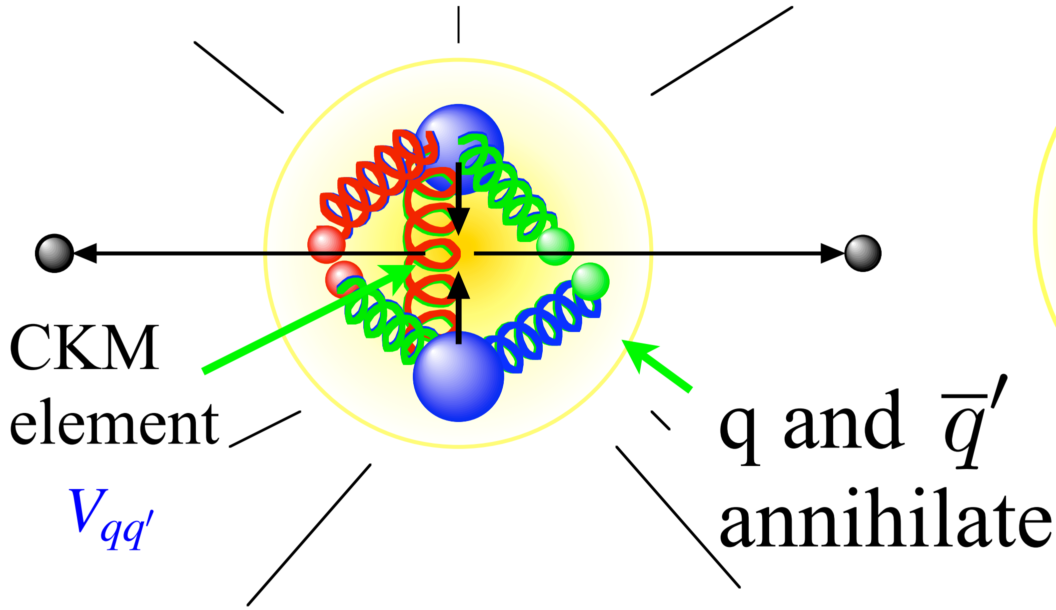
CDF

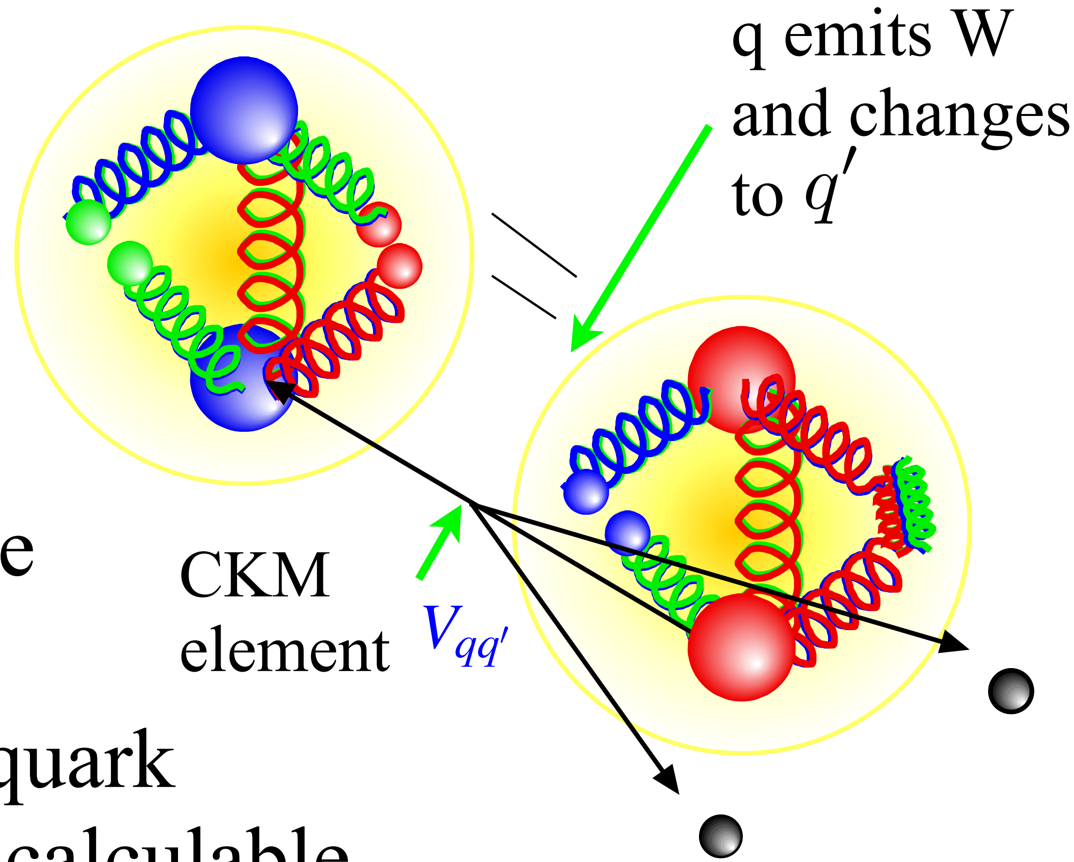


Cross-sections calculated at high energy using QCD pert. th. NLO have ~5% errors. Also parton distribution function and hadronisation uncertainties

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

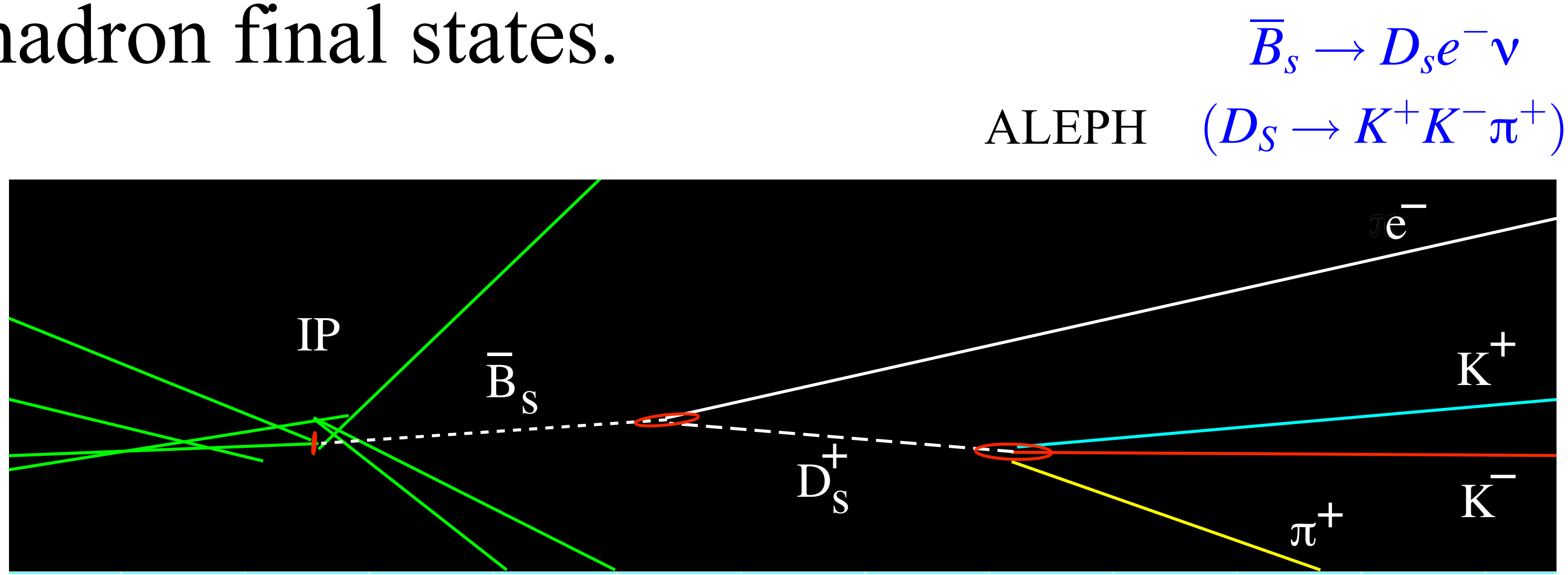


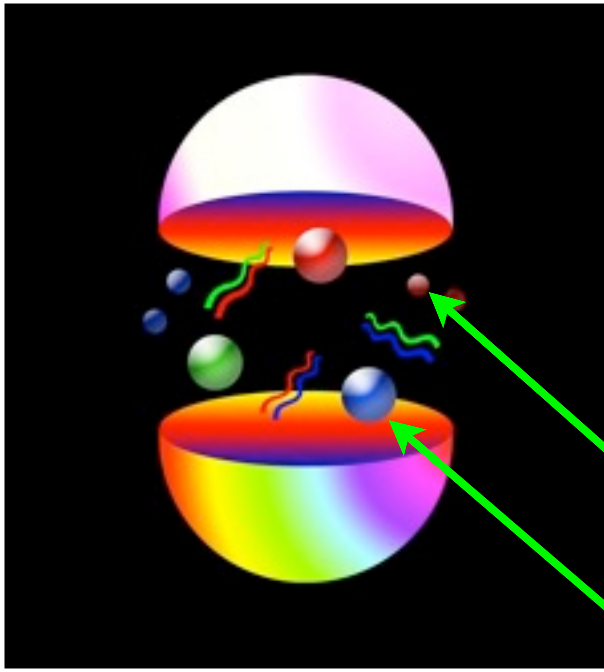




Rates for simple weak or em quark processes inside hadrons also calculable, but *not* multi-hadron final states.

Compare to exptl rate gives $V_{qq'}$, tests Standard Model

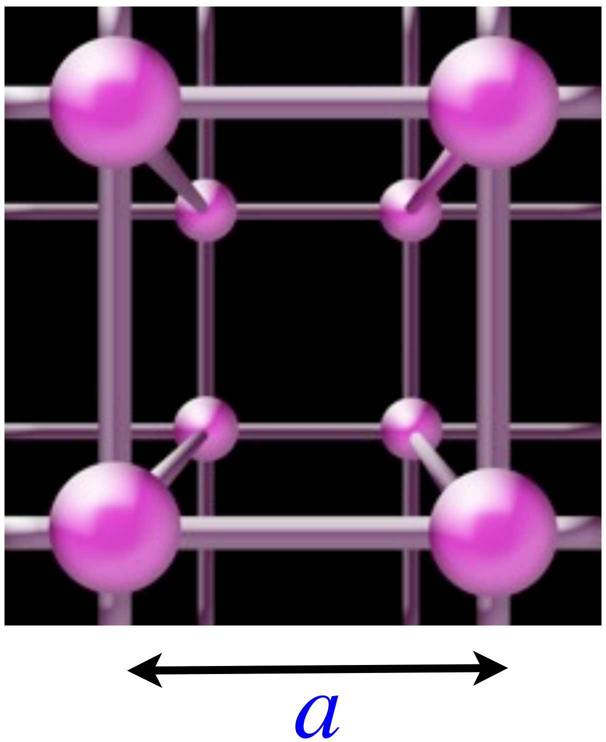




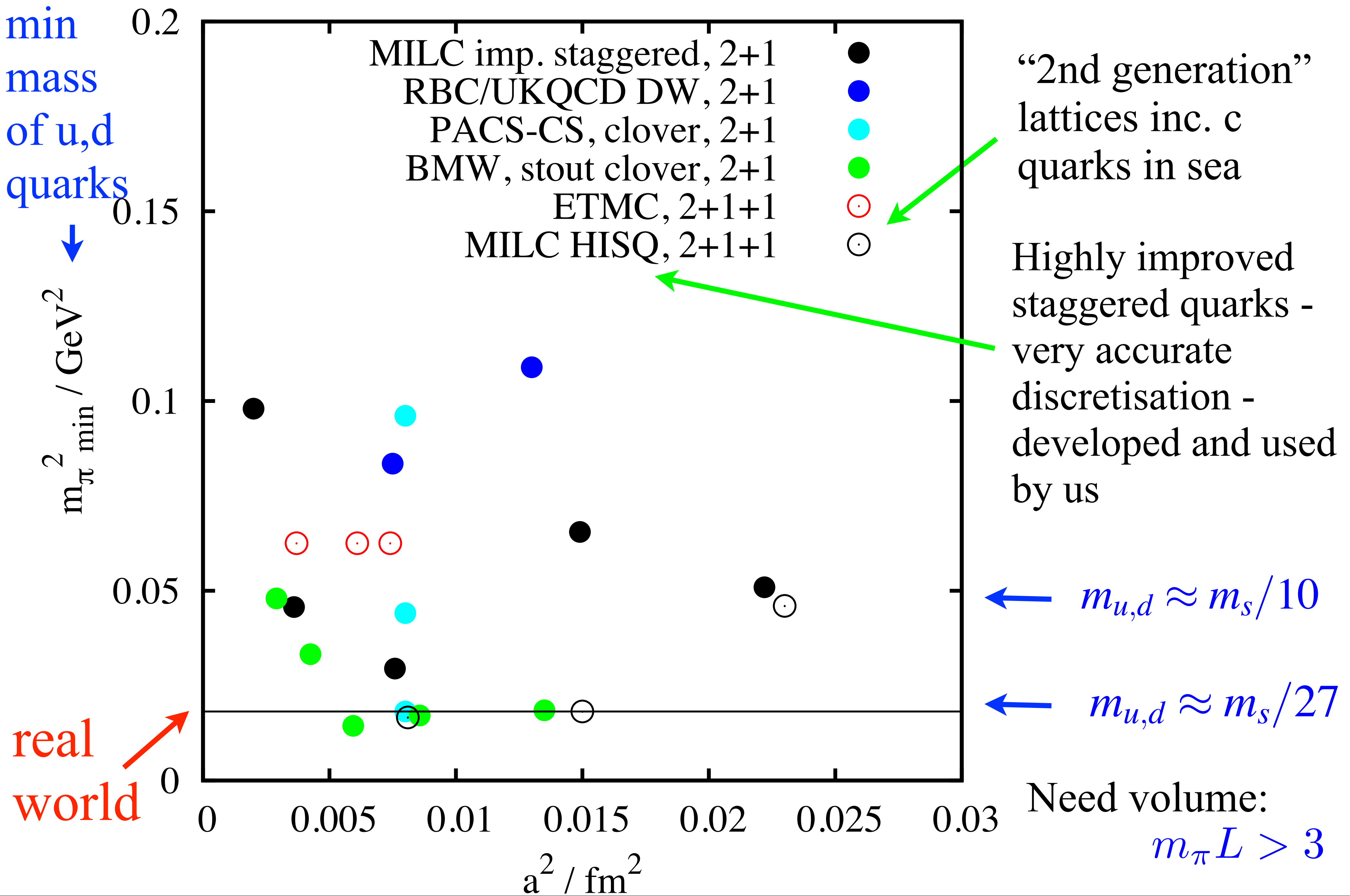
Lattice QCD = fully nonperturbative QCD calculation

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



Example parameters for calculations now being done.
Lots of different formalisms for handling quarks.



Hadron correlation functions (‘2point functions’) give masses and decay constants.

$$\langle 0|H^\dagger(T)H(0)|0\rangle = \sum_n A_n e^{-m_n T}$$

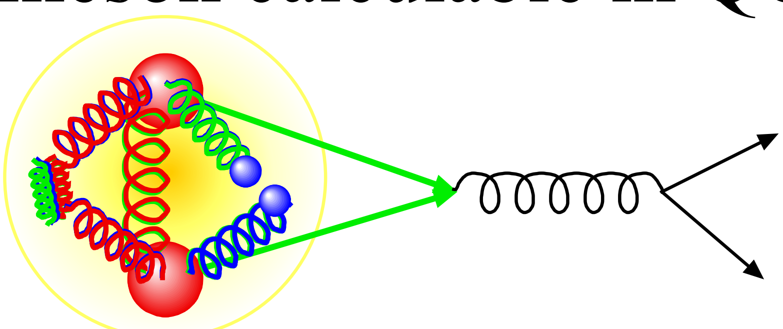
hadron masses (m_n)

$$A_n = \frac{|\langle 0|H|n\rangle|^2}{2m_n}$$

For charged pseudoscalars

$$\langle 0|\overline{\psi}\gamma_0\gamma_5\psi|M\rangle = f_M m_M$$

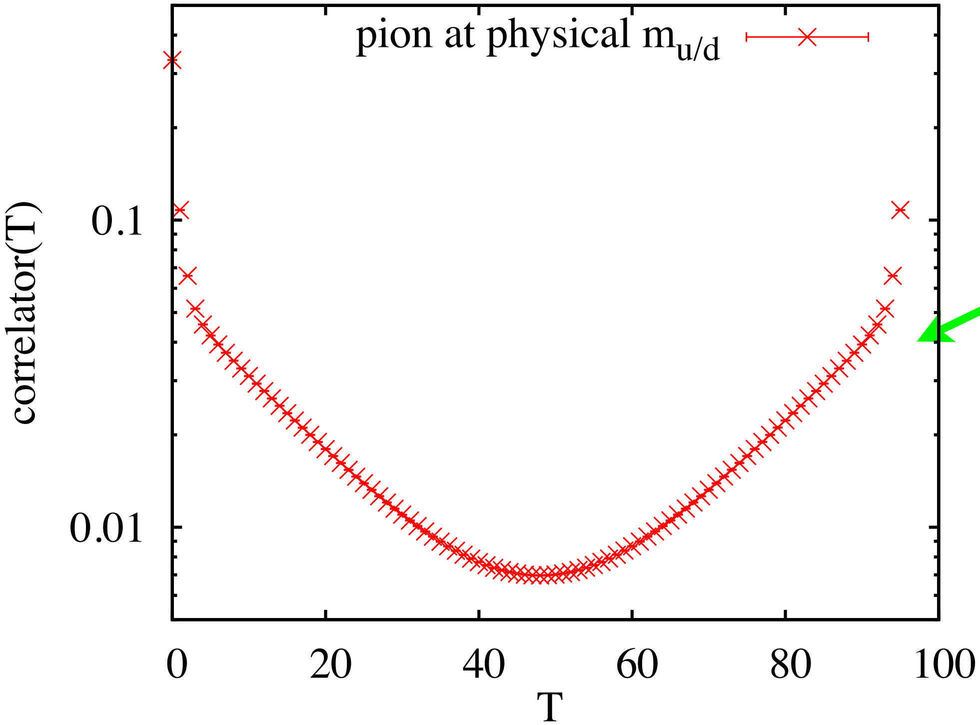
decay constant parameterises amplitude to annihilate to a W in leptonic decay - a property of the meson calculable in QCD



Vector mesons have similar decay constant parameterising annihilation to a photon.

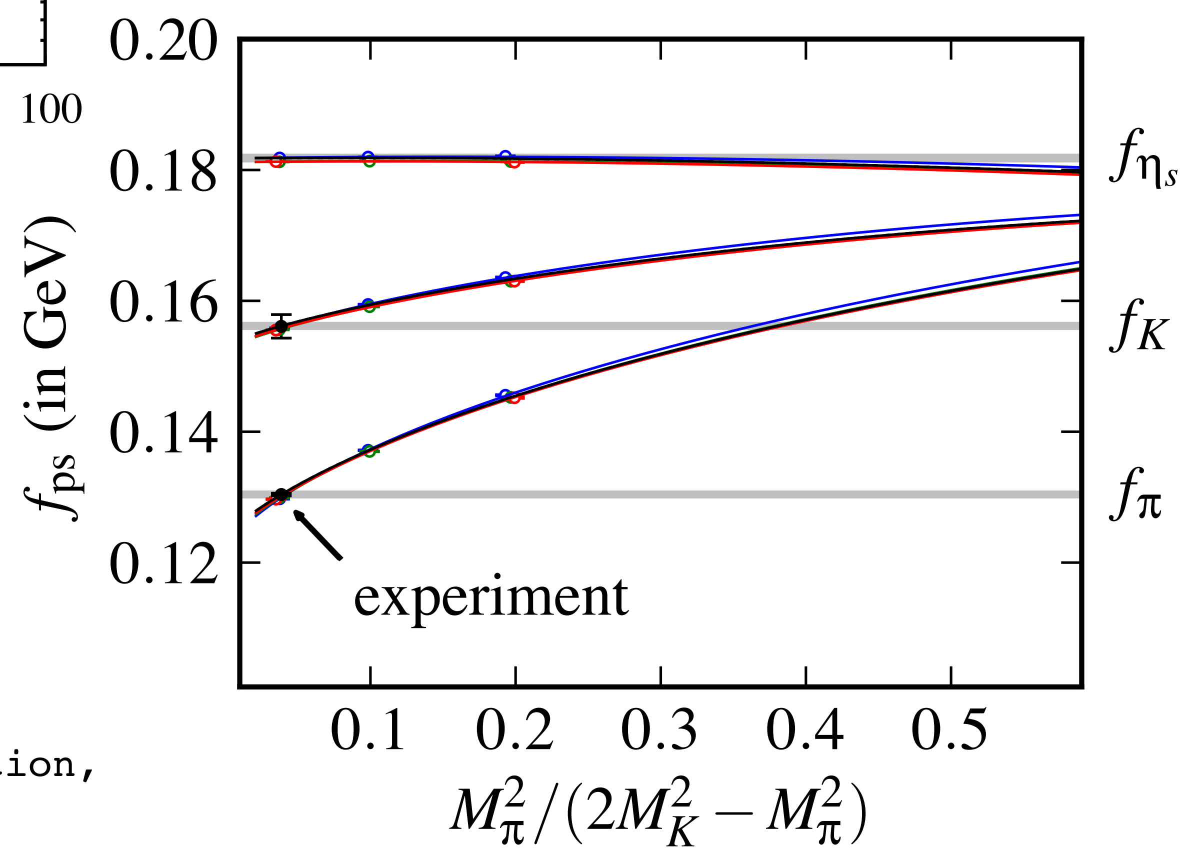
Accurate experimental info. for f and m for gold-plated mesons!

Example (state-of-the-art) calculation



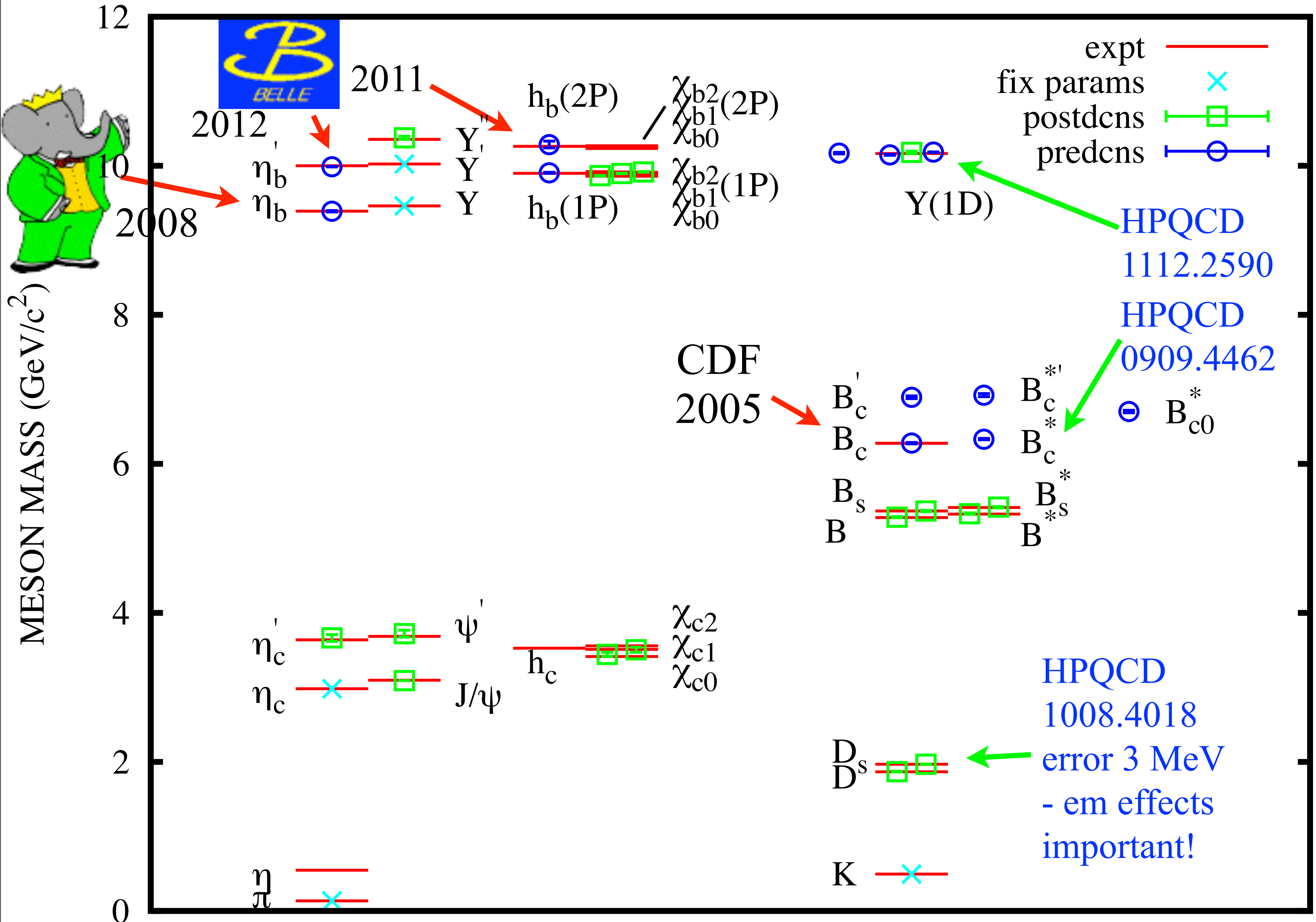
Extract meson mass and amplitude=decay constant from correlator for multiple lattice spacings and $m_{u/d}$

Convert decay constant to GeV units using a. Fit as a function of meson mass and a to obtain continuum physical result.



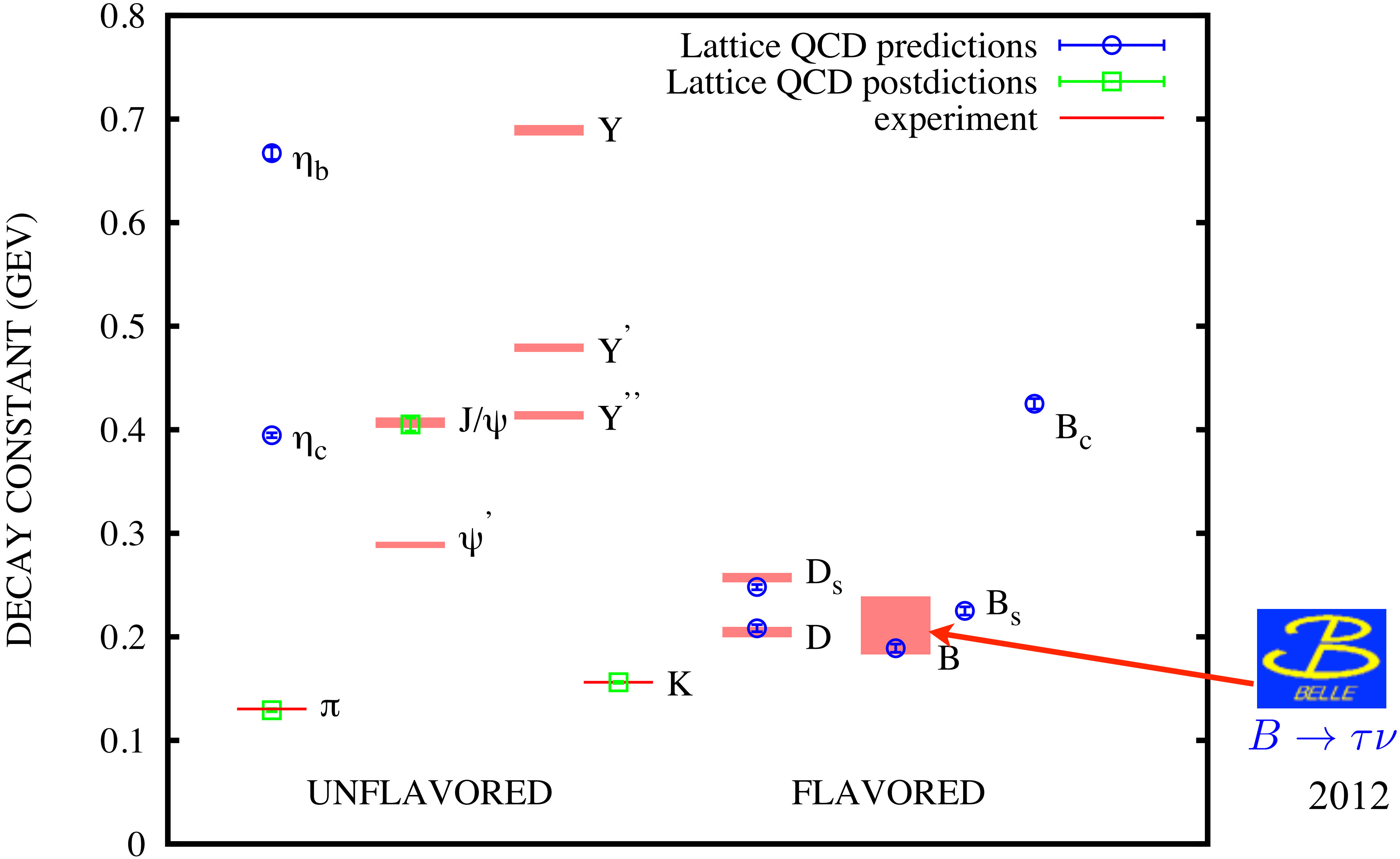
R. Dowdall et al, HPQCD in preparation, used DiRAC phase 2.

The gold-plated meson spectrum - HPQCD



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

Summary of results on decay constants - HPQCD

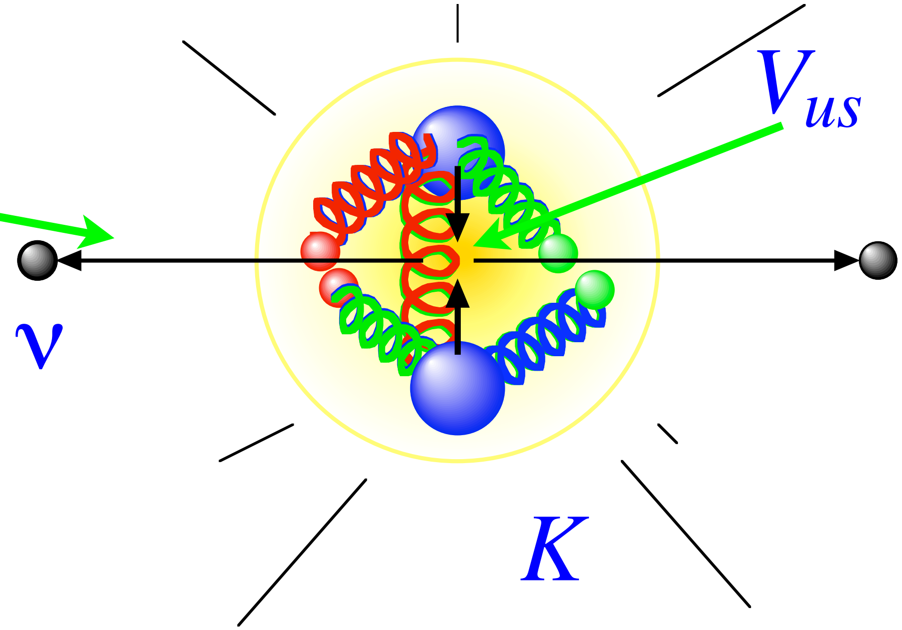


More work needed on vector (electromagnetic) decay constants

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 matrix



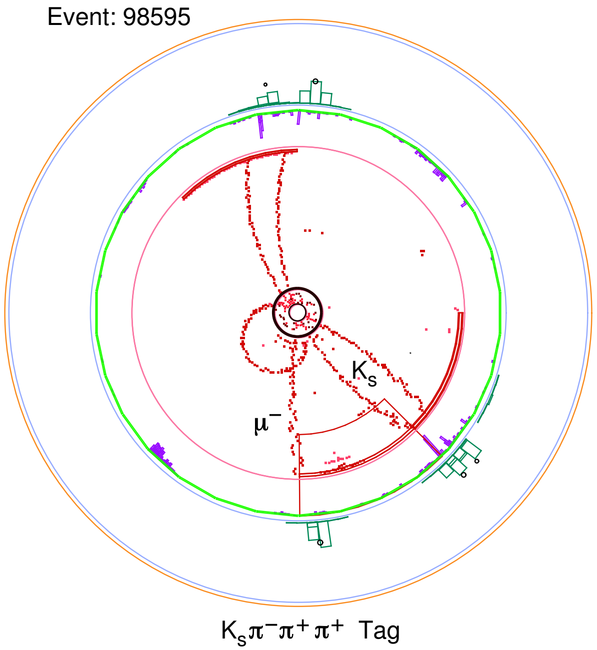
$$Br(M \to \mu\nu) \propto V_{ab}^2 f_M^2$$

Expt = CKM x theory(QCD)

Need precision lattice QCD to get accurate CKM elements to test Standard Model.

If V_{ab} known, compare lattice to expt to test QCD (as on previous slide)

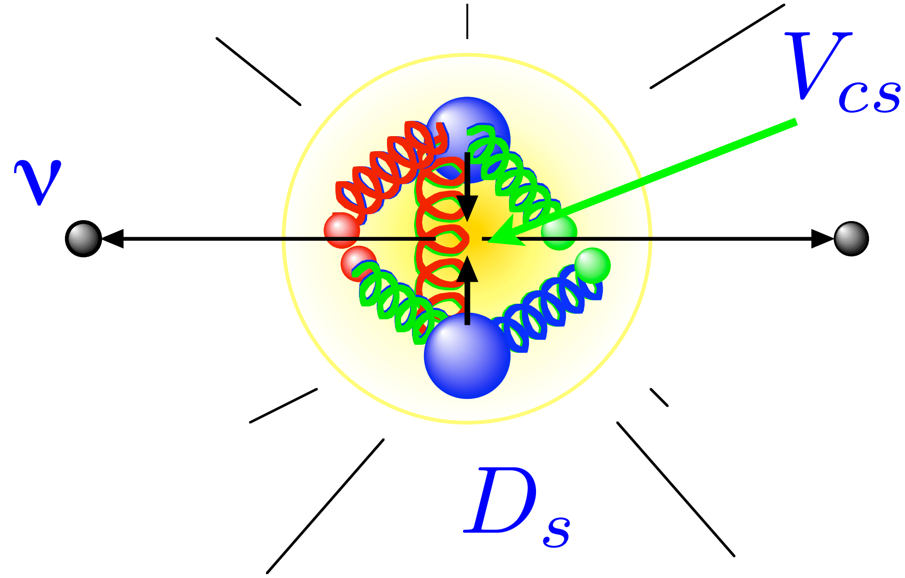
Results for D_s meson



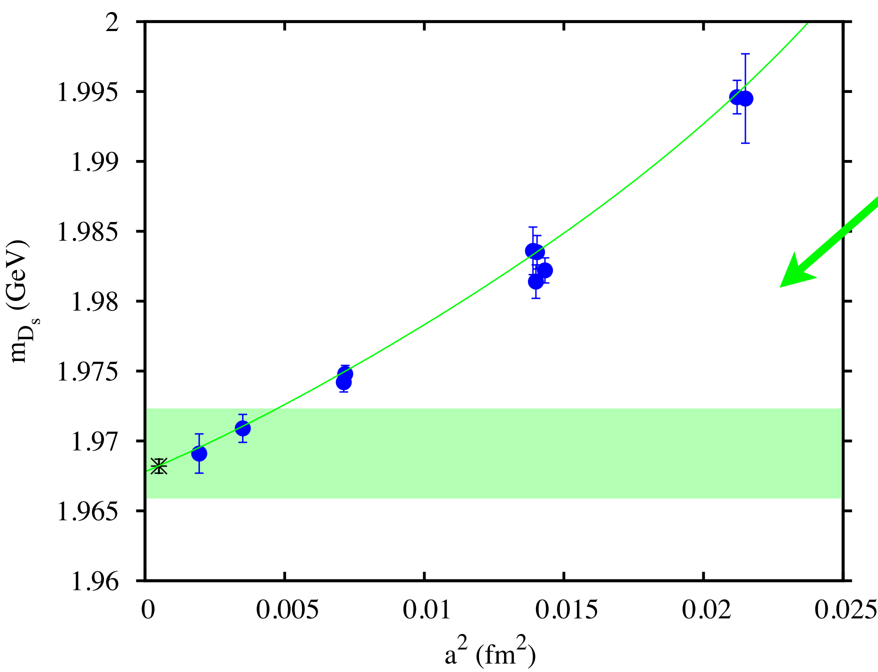
CLEO-c

$D_s \to \mu\nu$

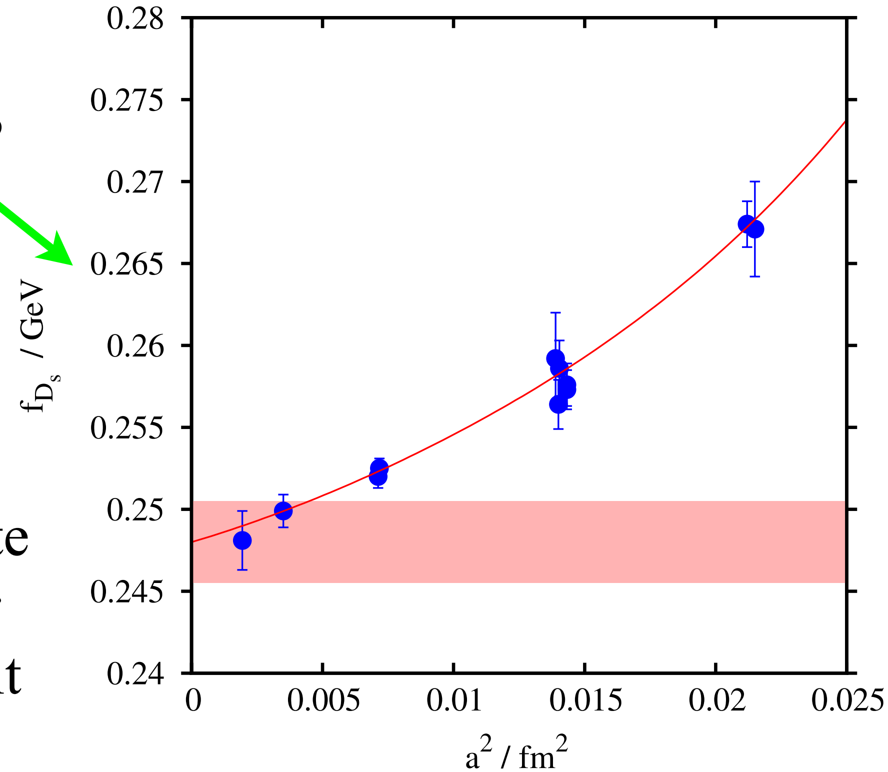
$D_s \to K\pi\pi\pi$



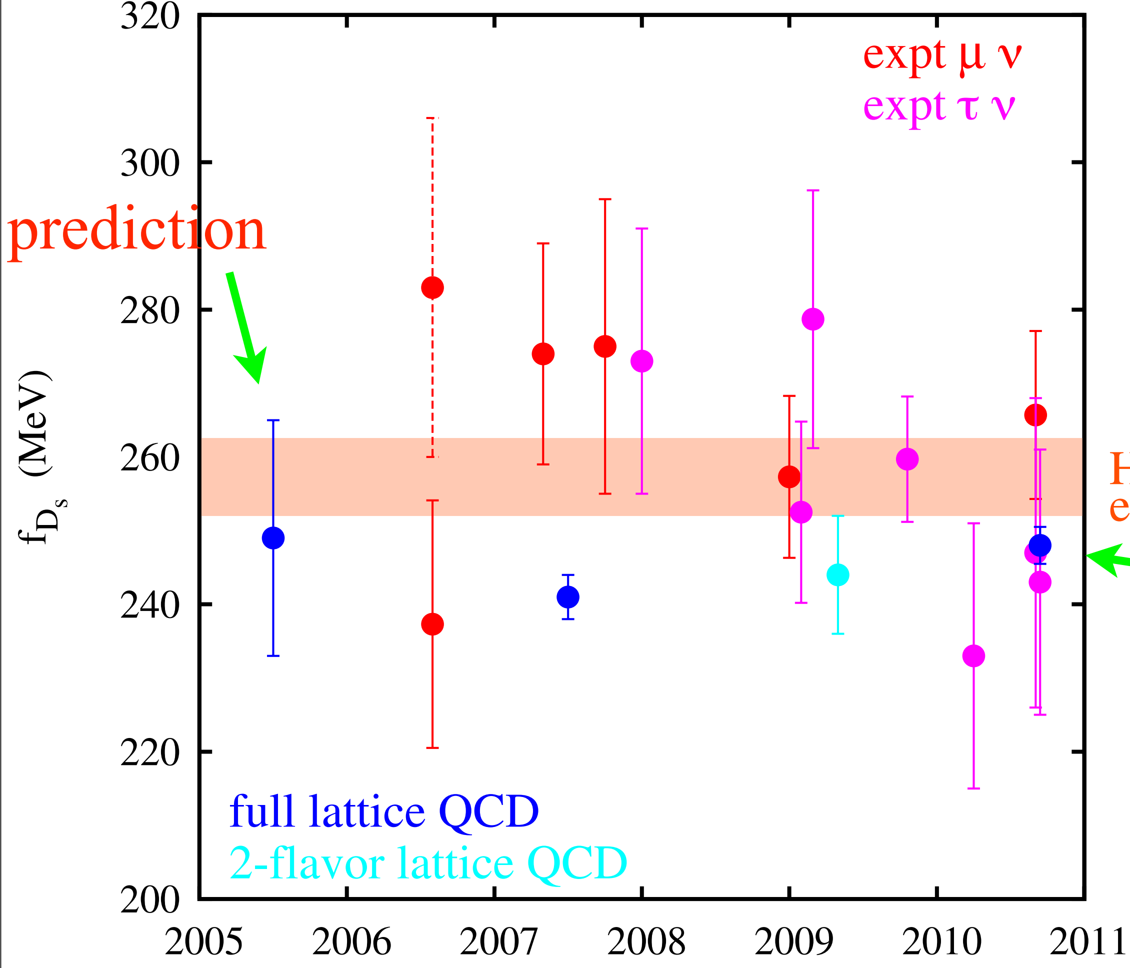
using HISQ quarks



Must extrapolate to a=0 for final result



HPQCD:CTH Davies et al,1008.4018.

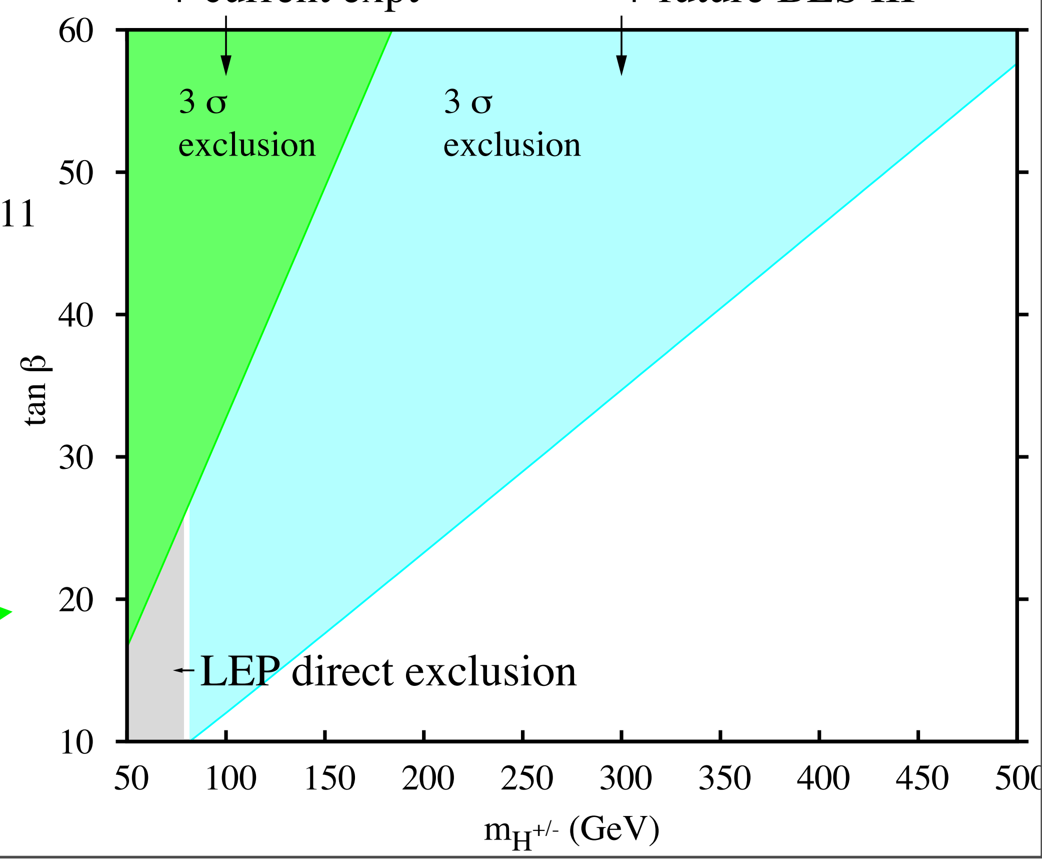


Compare lattice to expt for D_s decay constant - take Vcs from unitarity

exciting history!

HFAG expt av. 257(5) MeV

248.0(2.5) MeV HPQCD/HISQ

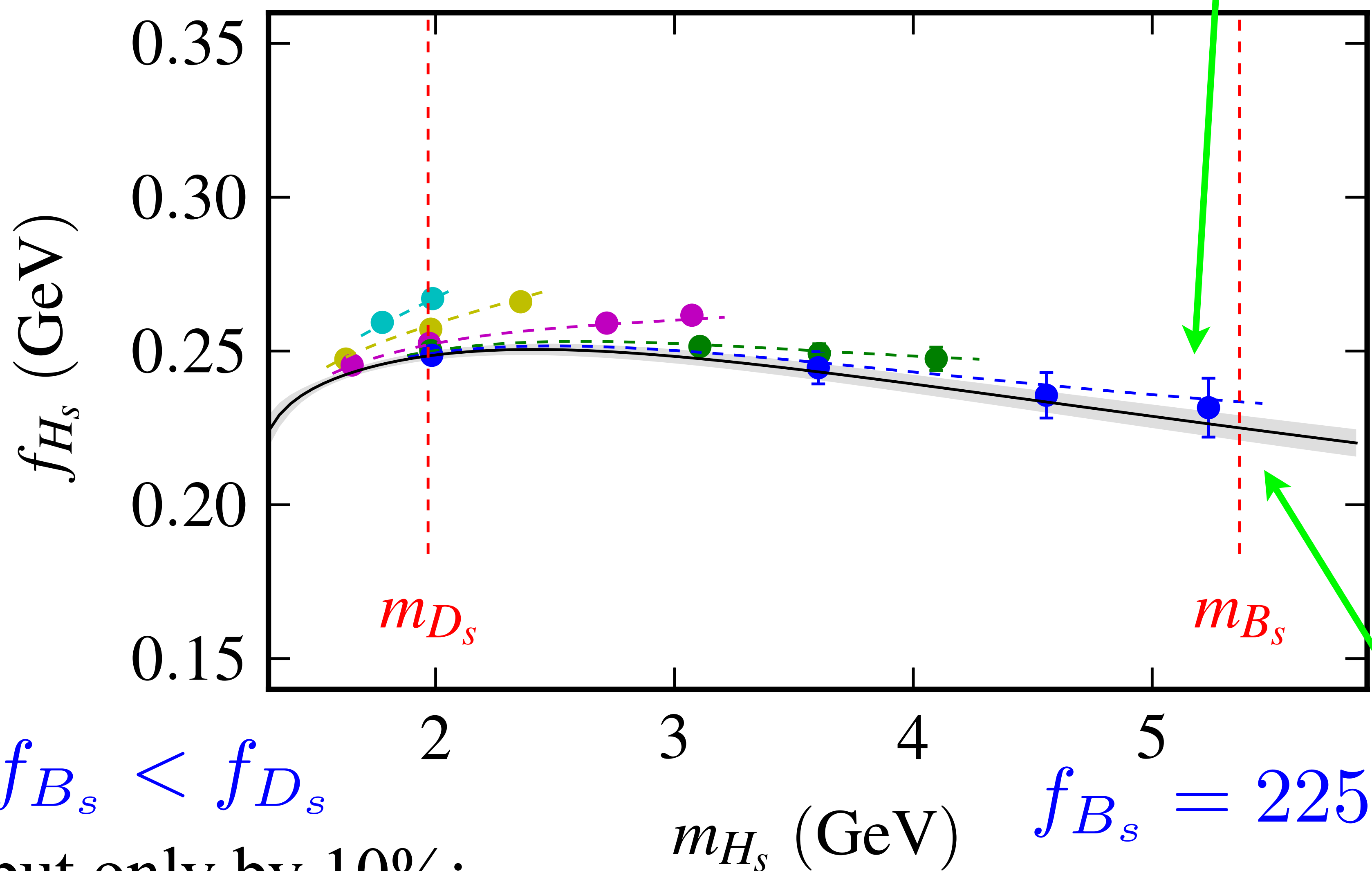


allows Beyond the Standard Model constraints - charged Higgs would reduce leptonic rate.

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%:

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

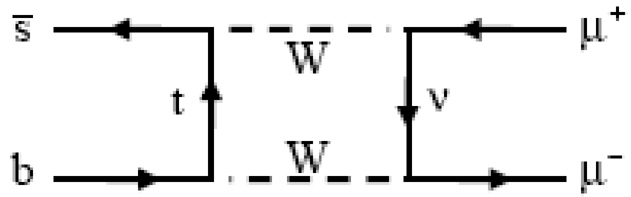
$f_{B_s} = 225(4)\mathrm{MeV}$

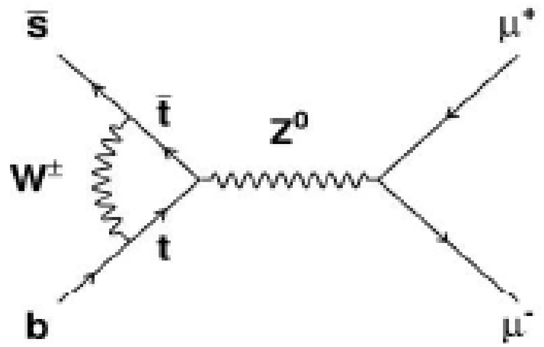
expt: $f_B = 211(28)\mathrm{MeV}$

(Belle 2012 using unitarity Vub)

Enables SM branching fraction to be determined for:

$$\mathrm{Br}(B_s \to \mu^+\mu^-) = A f_{B_s}^2 M_{B_s} |V_{tb}^* V_{ts}|^2 \tau(B_s)$$



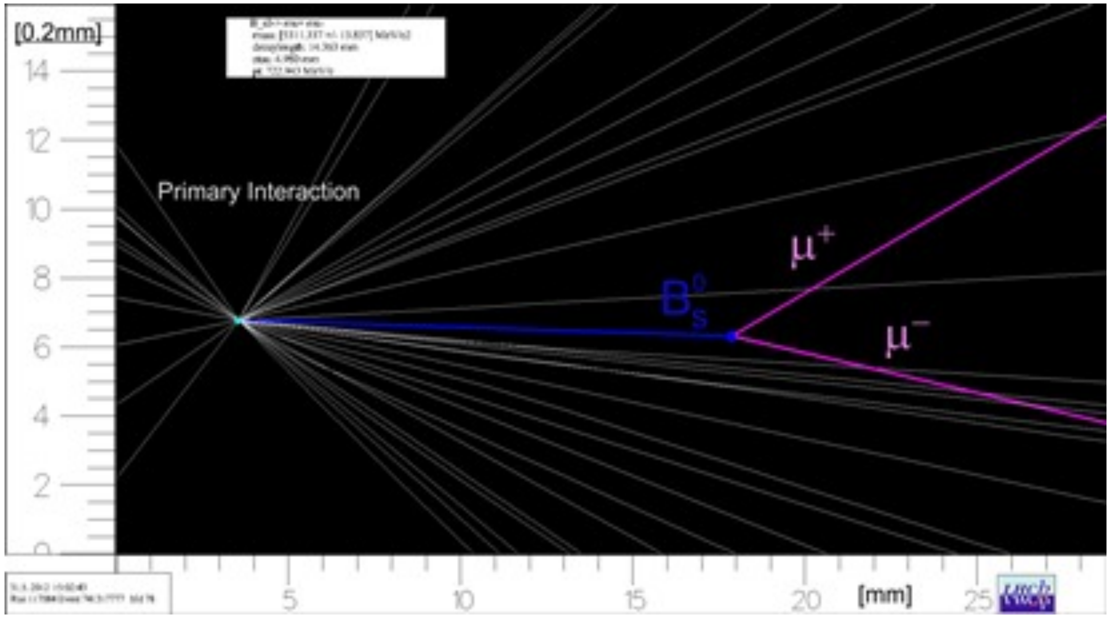


Result from lattice QCD f_{Bs}:

$$3.64(23) \times 10^{-9}$$

(very similar result using lattice QCD mixing rate ratio) E. Gamiz: CKM 2012

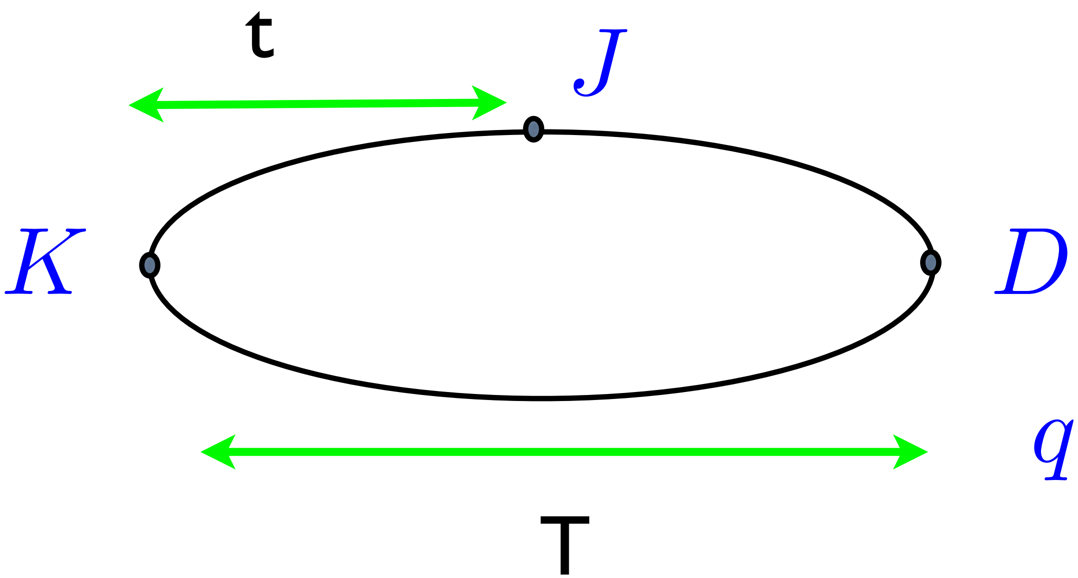
LHCb: November 2012

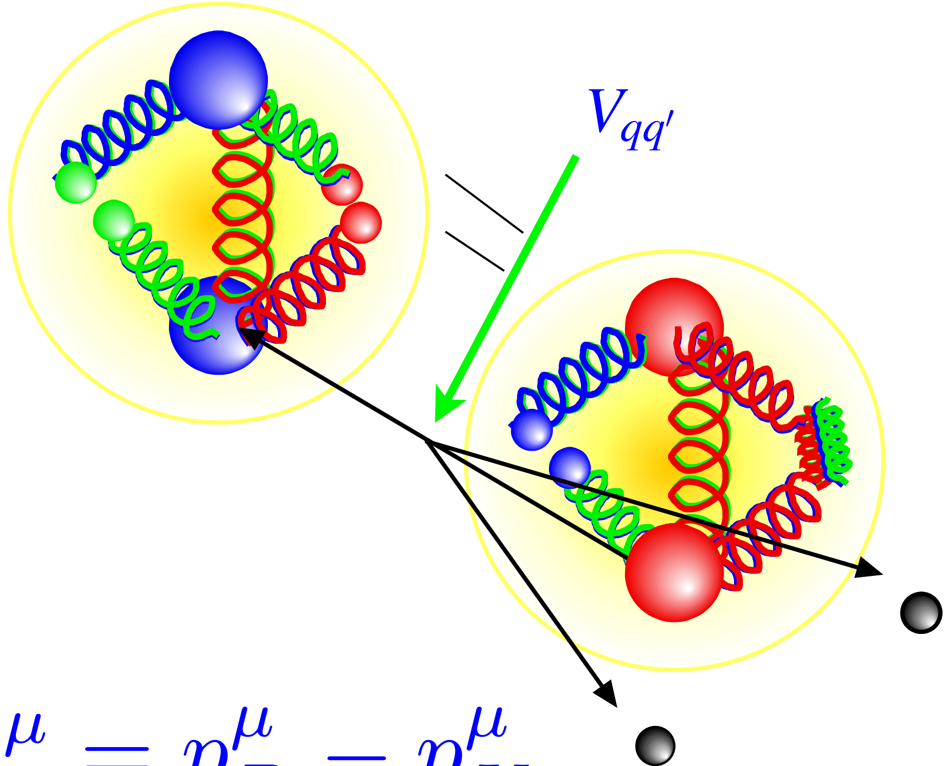


Now seen by LHCb at around the SM rate. Improved accuracy will allow strong test against SM.

Semileptonic form factors

'3point function' - amplitude





$$q^\mu = p_D^\mu - p_K^\mu$$

$$< K|V^\mu|D >= f_+(q^2)\left[p_D^\mu + p_K^\mu - \frac{M_D^2 - M_K^2}{q^2}q^\mu\right]$$

$$+f_0(q^2)\frac{M_D^2 - M_K^2}{q^2}q^\mu$$

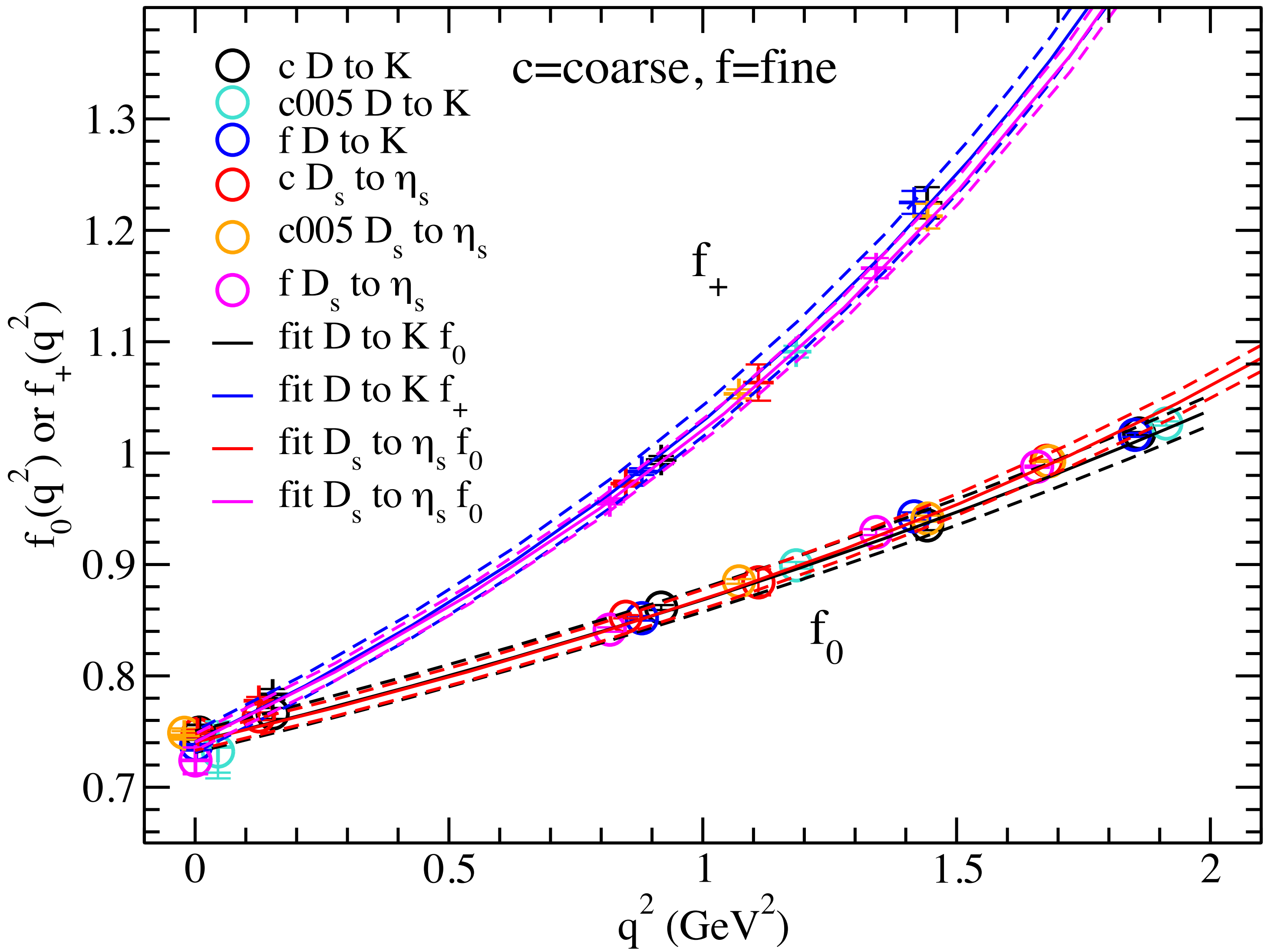
measured by expt through rate for e.g $D \to K l \nu$

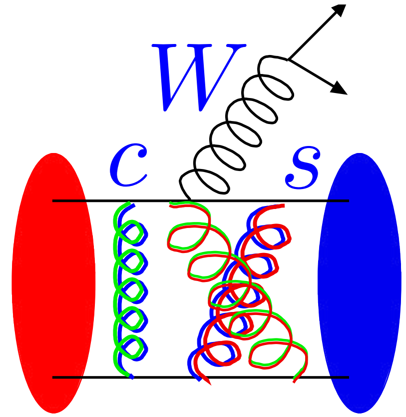
$$f_0(0) = f_+(0)$$

$$< K|S|D >= \frac{M_D^2 - M_K^2}{m_{0c} - m_{0s}}f_0(q^2)$$

abs. norm. for same c/s action HPQCD: 1008.4562

Semileptonic form factors for charmed mesons:





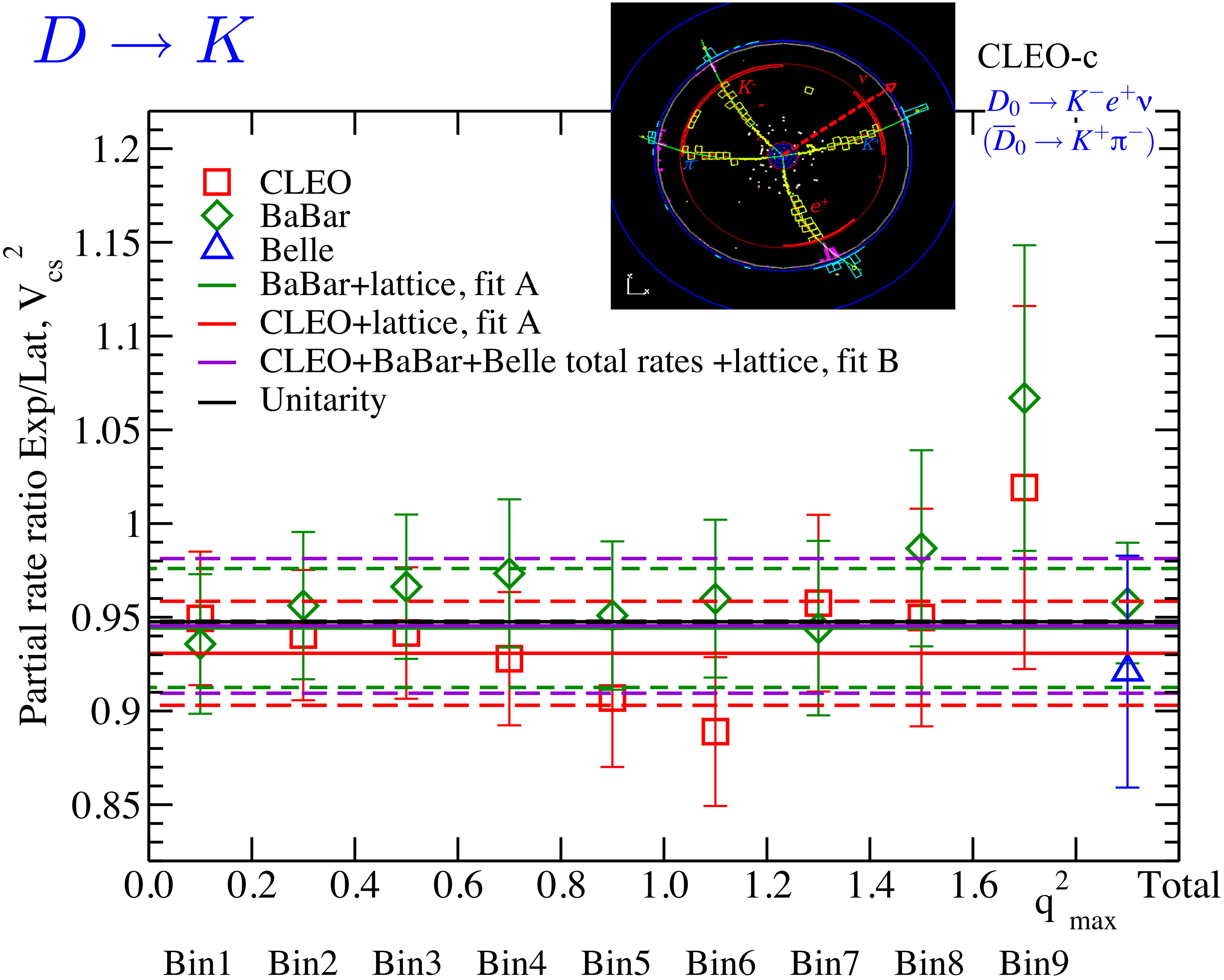
J. Koponen et al, HPQCD, CHARM2012

q^2 is 4-mom transfer between D and outgoing meson

Comparison to expt gives more detailed test of QCD.
Note: form factor seems to be independent of spectator quark in decay. (not predicted by QCD sum rules ....)

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

$D \to K$

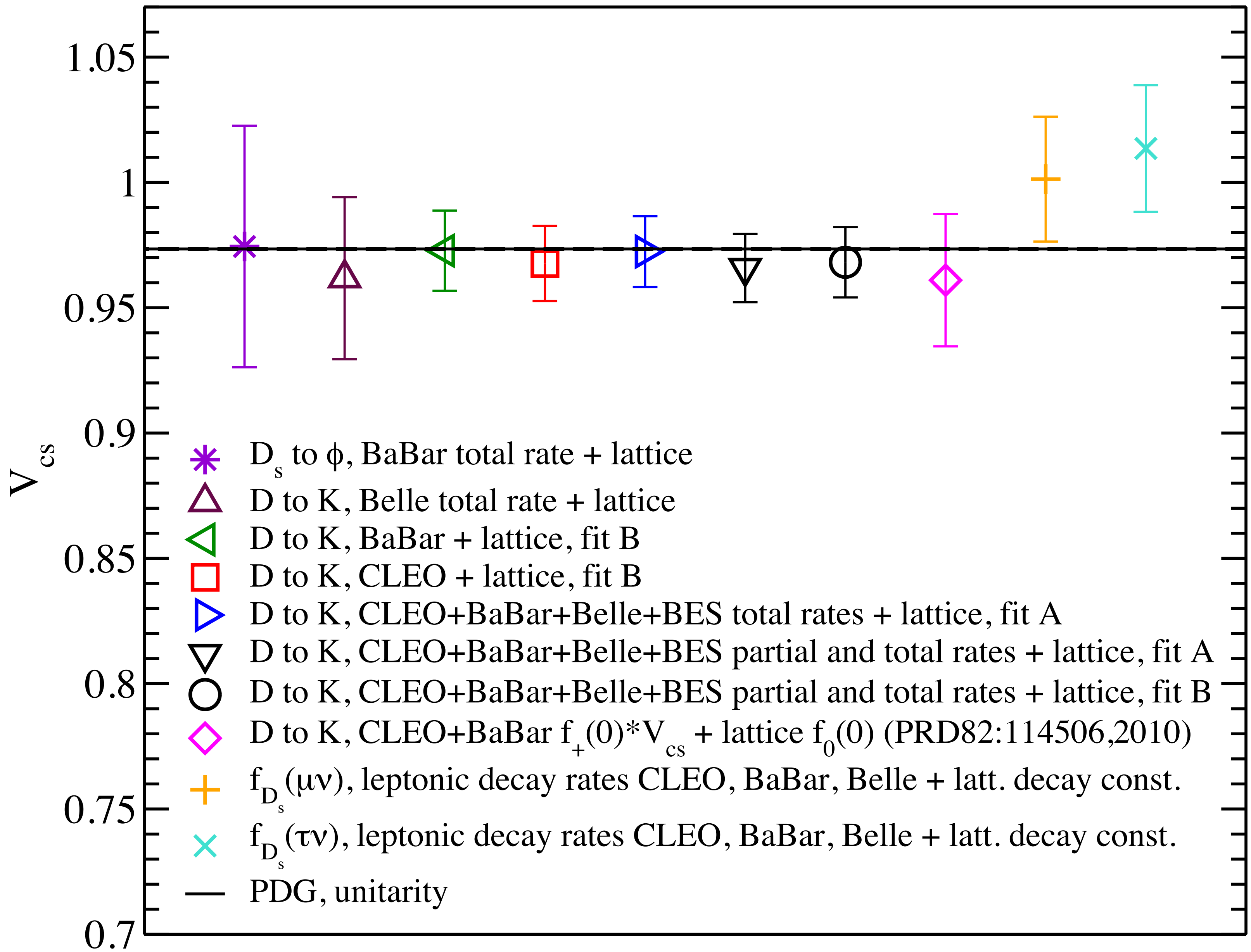


uses all exptl data in model-indpt way

Tests QCD via shape and gives Vcs to 1.5%

J. Koponen et al, HPQCD in preparation

Summary of V_{cs} determinations using lattice + expt



best value:

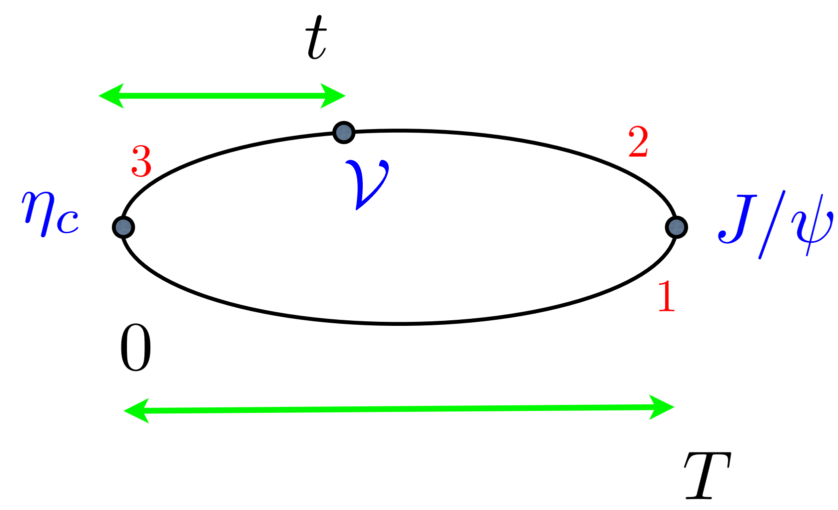
$V_{cs} = 0.965(14)$

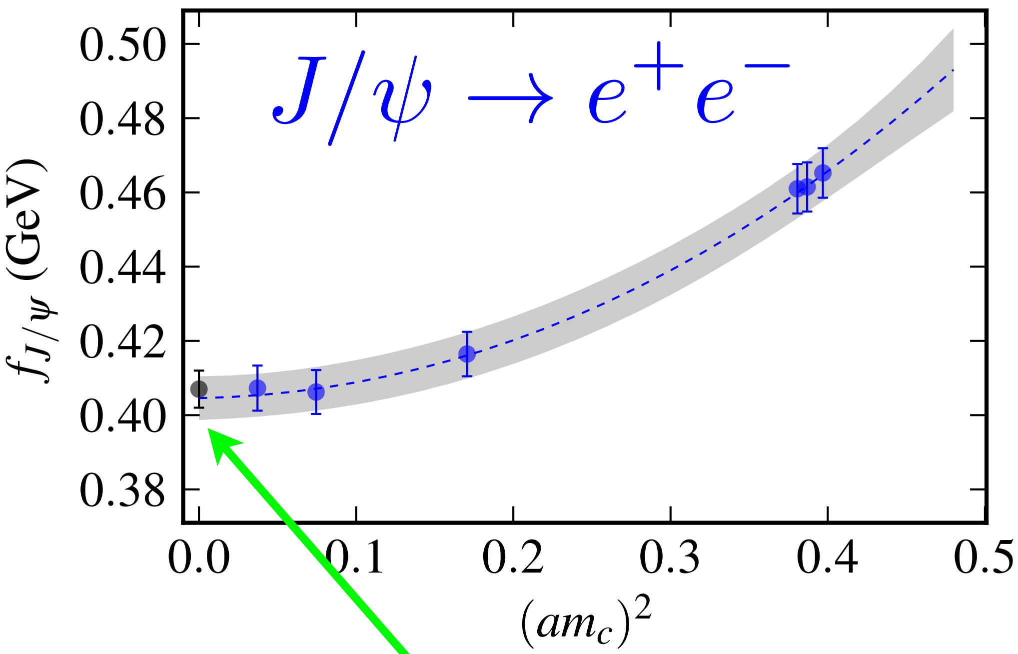
V_{cd} from $D \to \pi l \nu$ in progress ..

J. Koponen et al, HPQCD, CHARM2012 and in preparation

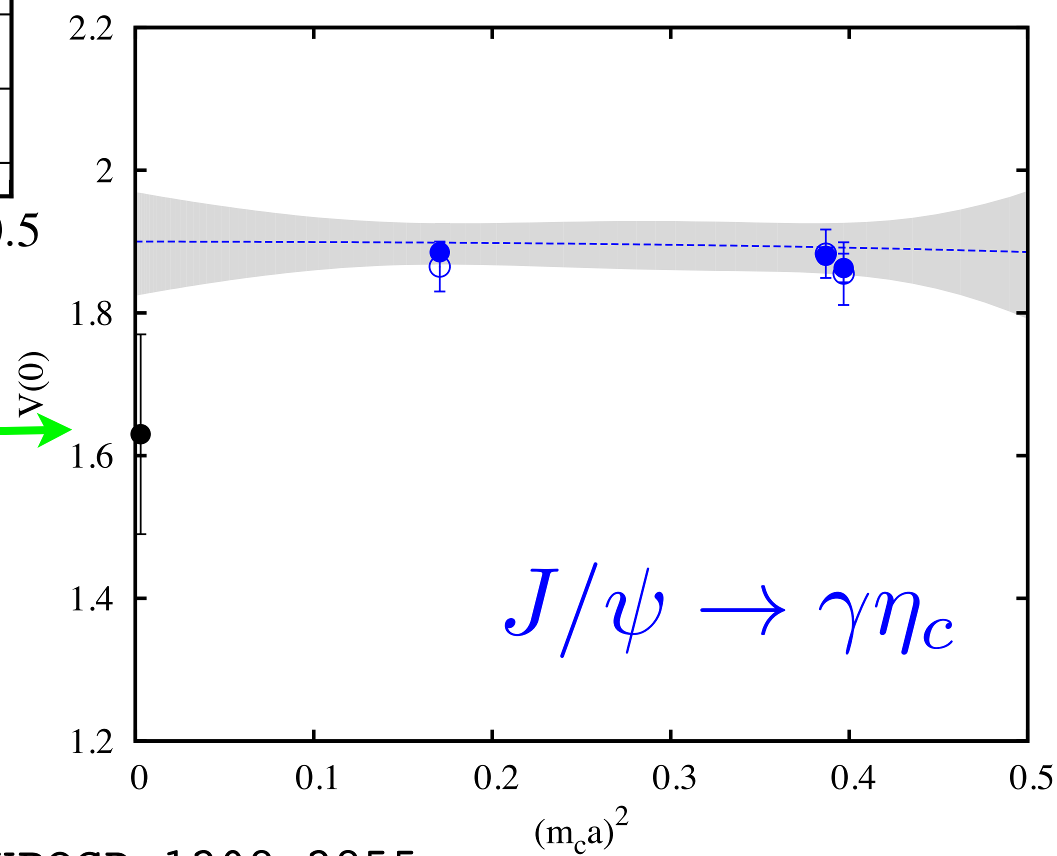
Electromagnetic decays of charmonium

no CKM uncertainties!





experiment

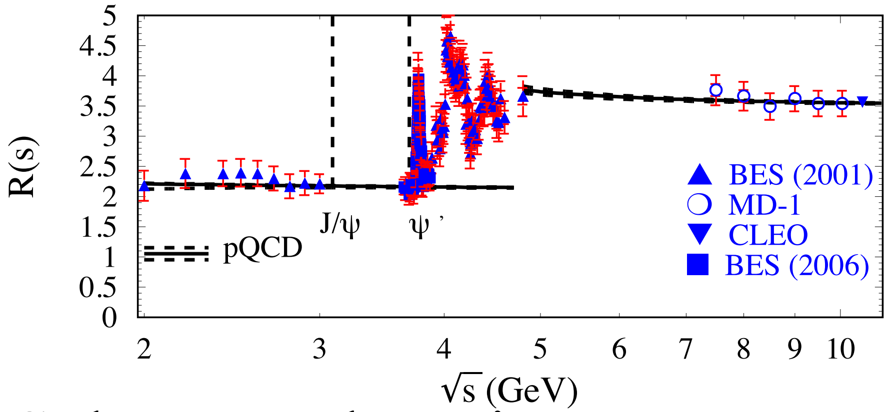


Lattice QCD is only method that can give few% precision

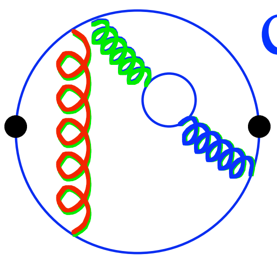
G. Donald et al, HPQCD,1208.2855

Charm contribution to

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma_{\text{pt}}}$$



Subtract u,d,s using pert. th. to get contribn of charm vector correlator



$$\mathcal{M}_n \equiv \int \frac{ds}{s^{n+1}} R_c(s)$$

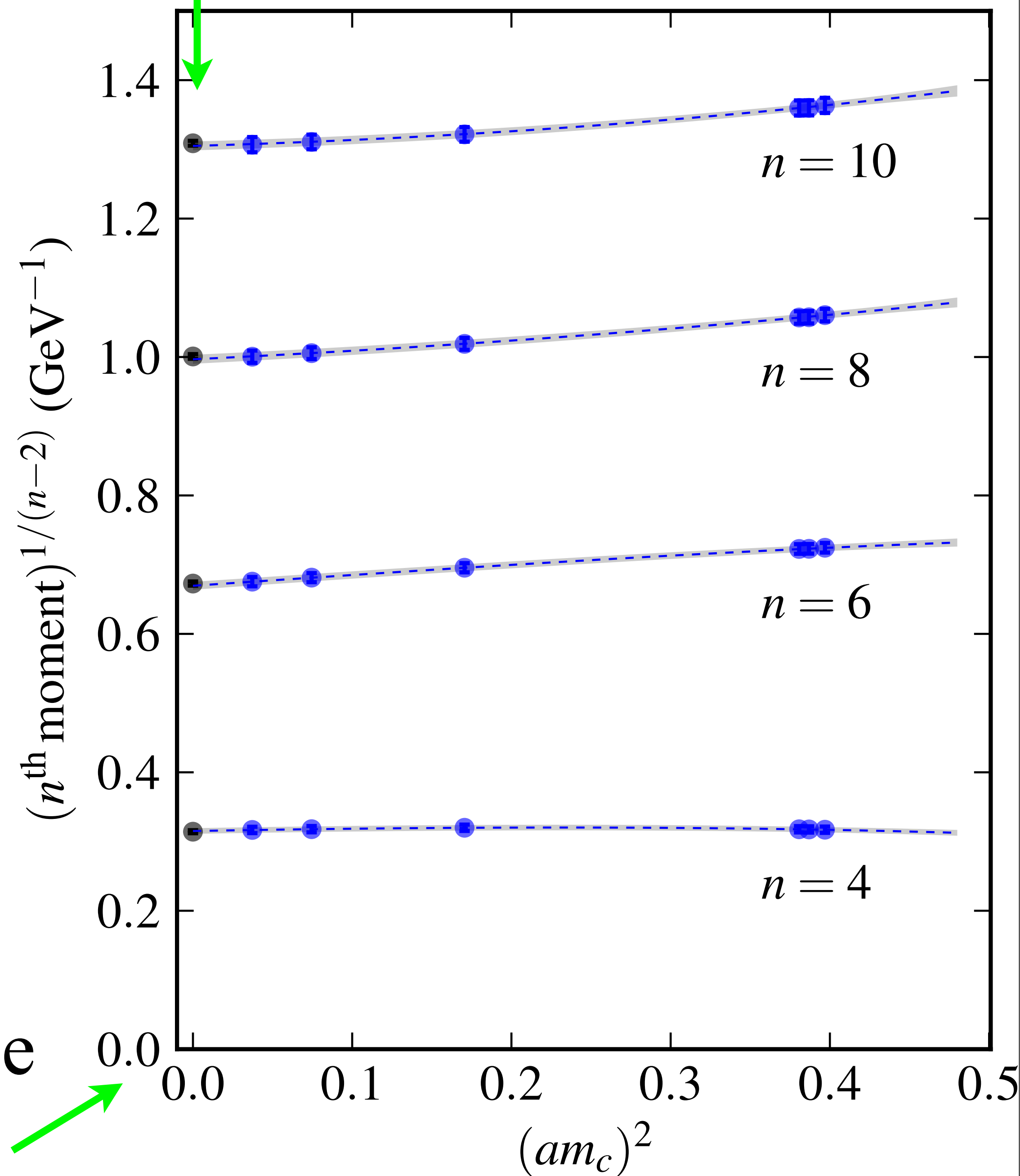
Lattice calcln:

$$M_n = \sum t^n G(t)$$

Agree to 1.5%

'expt'

J. Kuhn et al, hep-ph/0702103

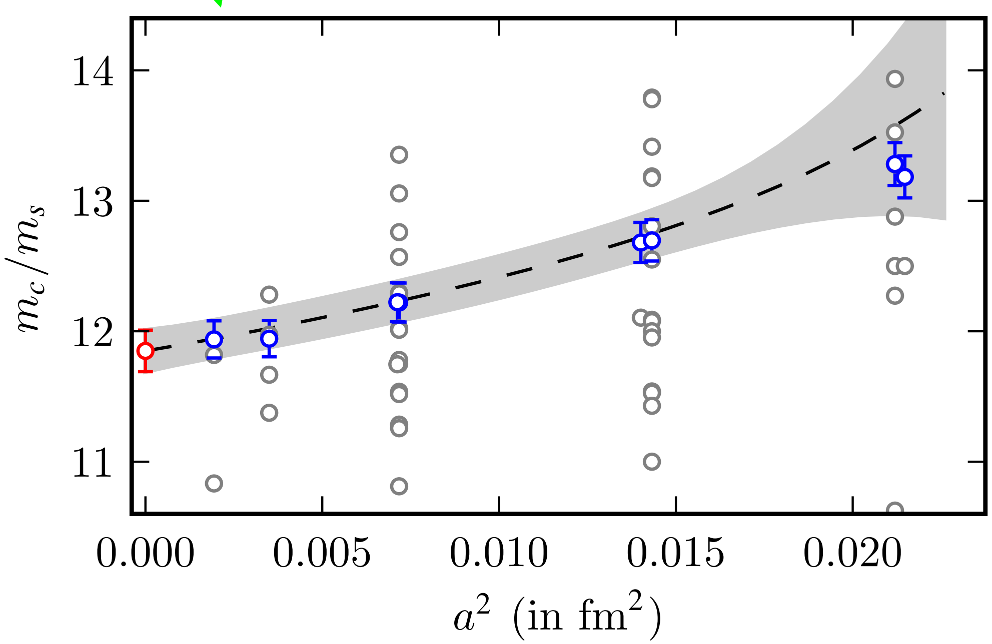


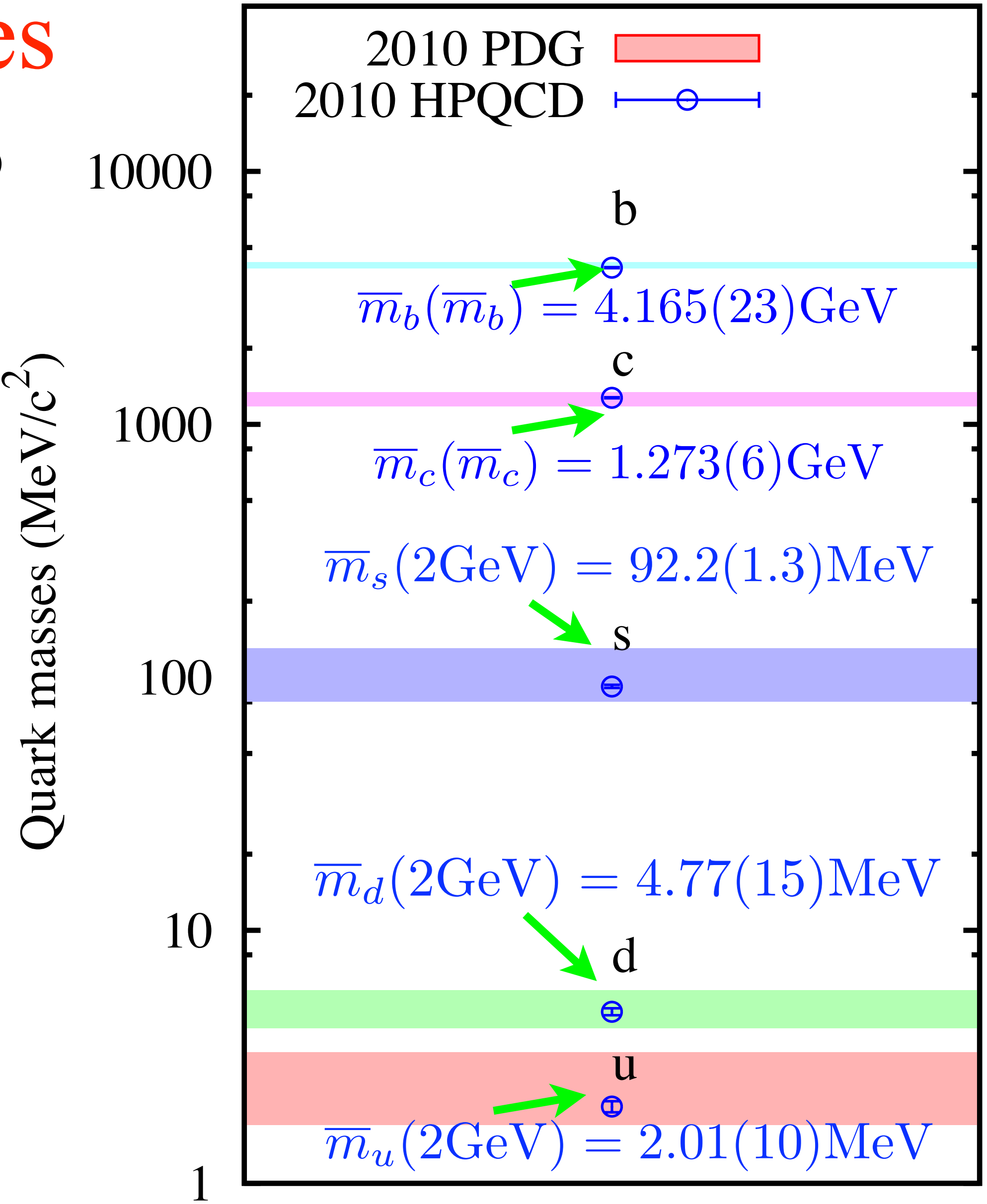
G. Donald et al, HPQCD,1208.2855

Determining quark masses

Lattice QCD has direct access to parameters in Lagrangian for accurate tuning
- issue is converting to contnm schemes such as $\overline{MS}$

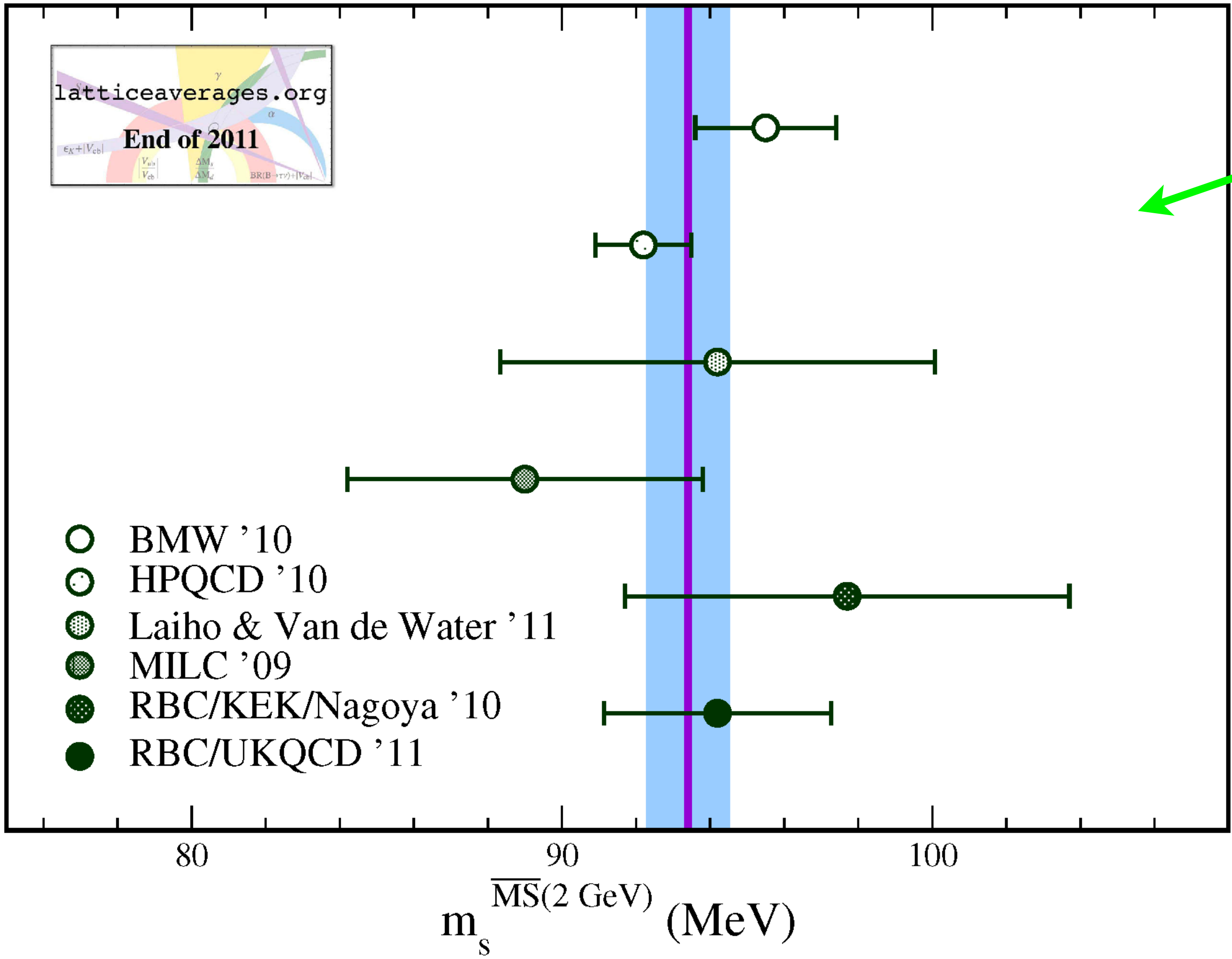
quark mass ratios very accurate:
e.g. m_c/m_s, m_b/m_c, $m_s/m_{u,d}$





C. McNeile, CTHD et al, HPQCD, 0910.3102, 1004.4285

post-2010: Strong convergence of lattice results for strange quark mass



J. Laiho, E. Lunghi, R. Van der Water latticeaverages.org

1% accuracy achieved

Lattice averages:

$$m_s(\overline{MS}, 2\text{GeV}) = 93.4(1.1)\text{MeV}$$

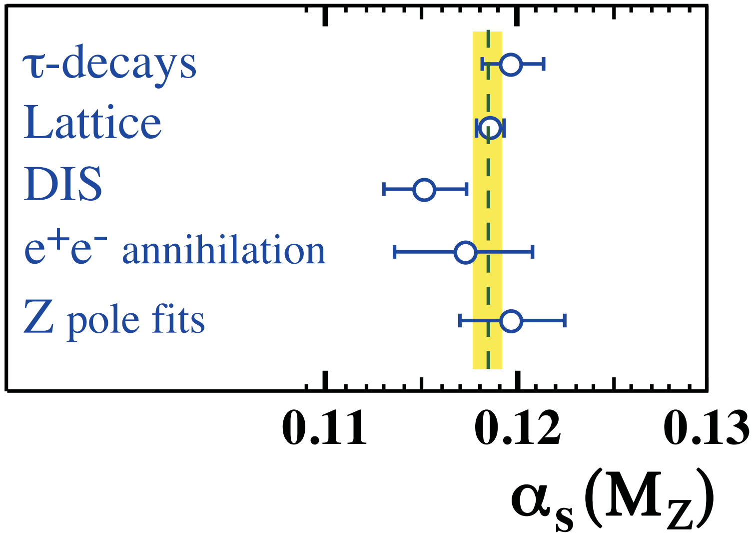
$$\frac{m_s}{m_u + m_d} = 27.56(14)$$

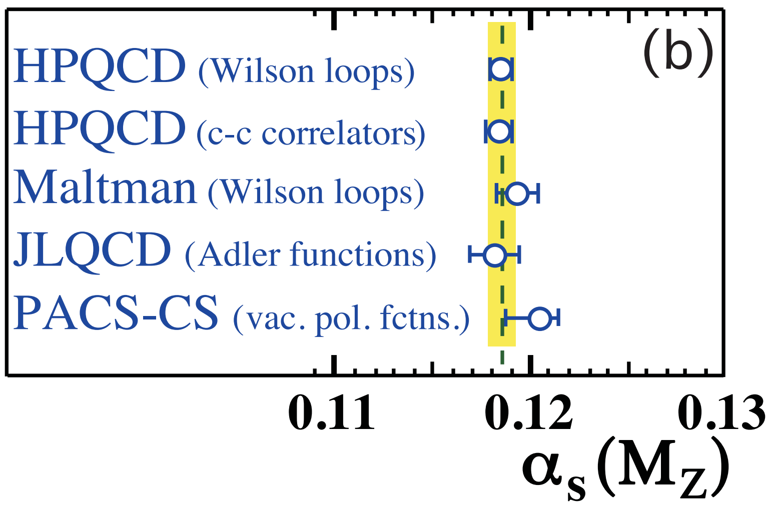
Determining α_s

Lattice QCD now has several determns of α_s to 1%.
Dominate world average : 0.1184(7)

Key points:

- high statistical precision
- high order (NNLO) pert. th. exists and can estimate higher orders
- nonpert. systs. not a significant issue
- approaches very different - good test



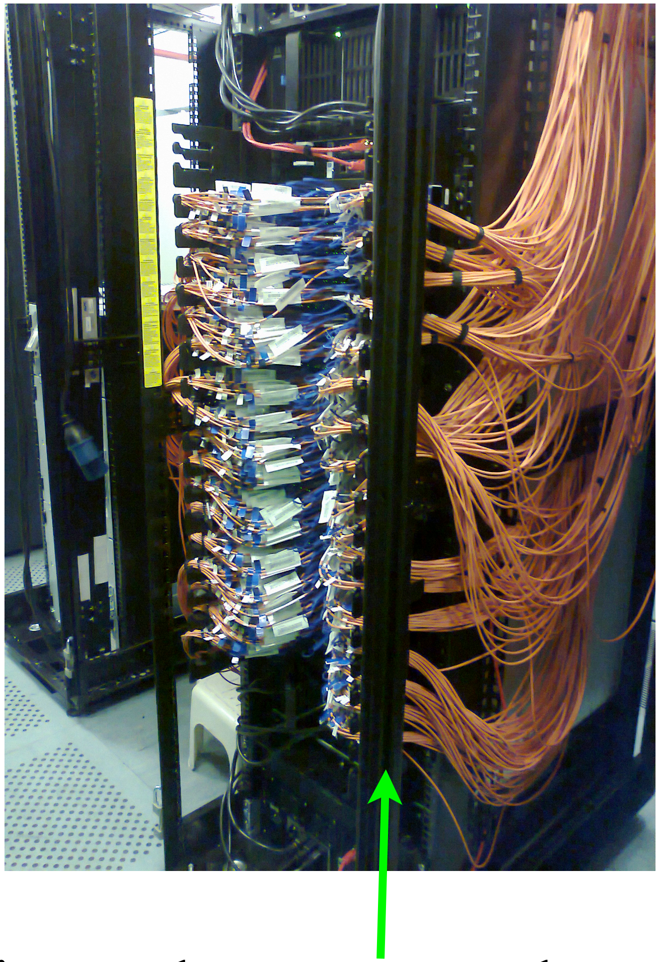


see 2011 Munich alphas workshop Shintani LAT11

CTHD et al,HPQCD 0807.1687; 1004.4285;

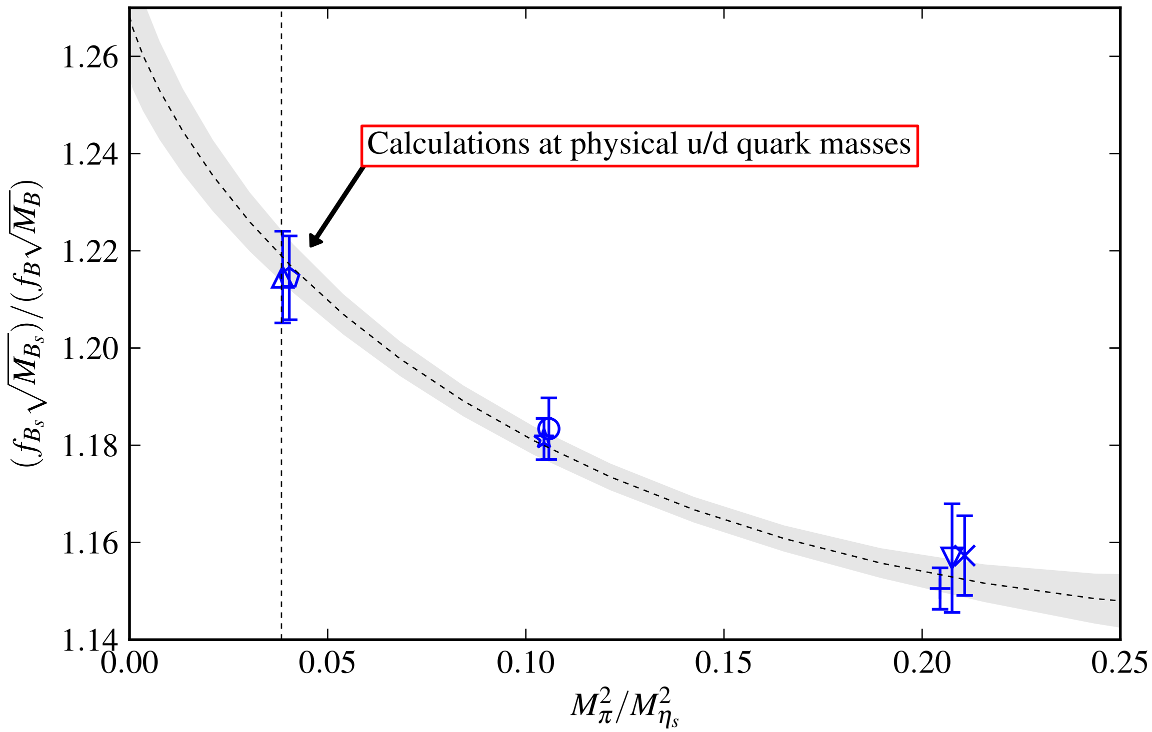
Future with STFC's new £15M DiRAC HPC facility

5 machines at 4 sites, to cover pp, np and astro theory



intra-cluster network switch in Darwin (largest and fastest in UK)

We use Darwin@Cambridge - 9600 core Sandybridge cluster - 93 in top 500. Allows us to work at physical u/d quark masses - no extrapolation needed!



R. Dowdall et al,HPQCD in prep.

In progress: e.m. form factor of the physical pion.

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') *or*

much higher statistics (for e.g. flavour singlet states)

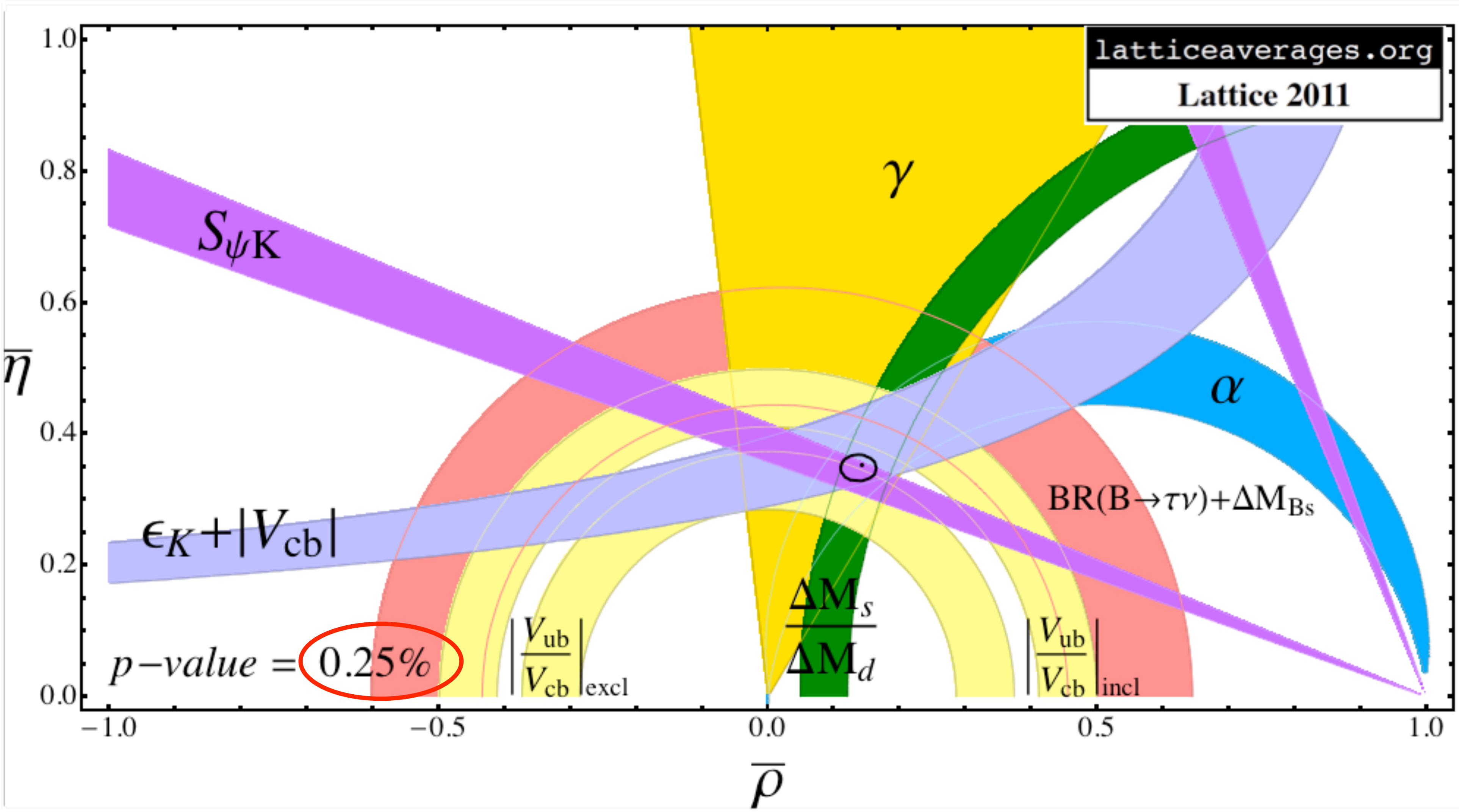
also can include charm in the sea now.

- Aim for 1% errors for B and B_s physics
- Harder calculations (flavor singlet, excited states, nuclear physics) will improve

Spares

Unitarity of CKM matrix tested using lattice QCD results

E. Lunghi, LAT11

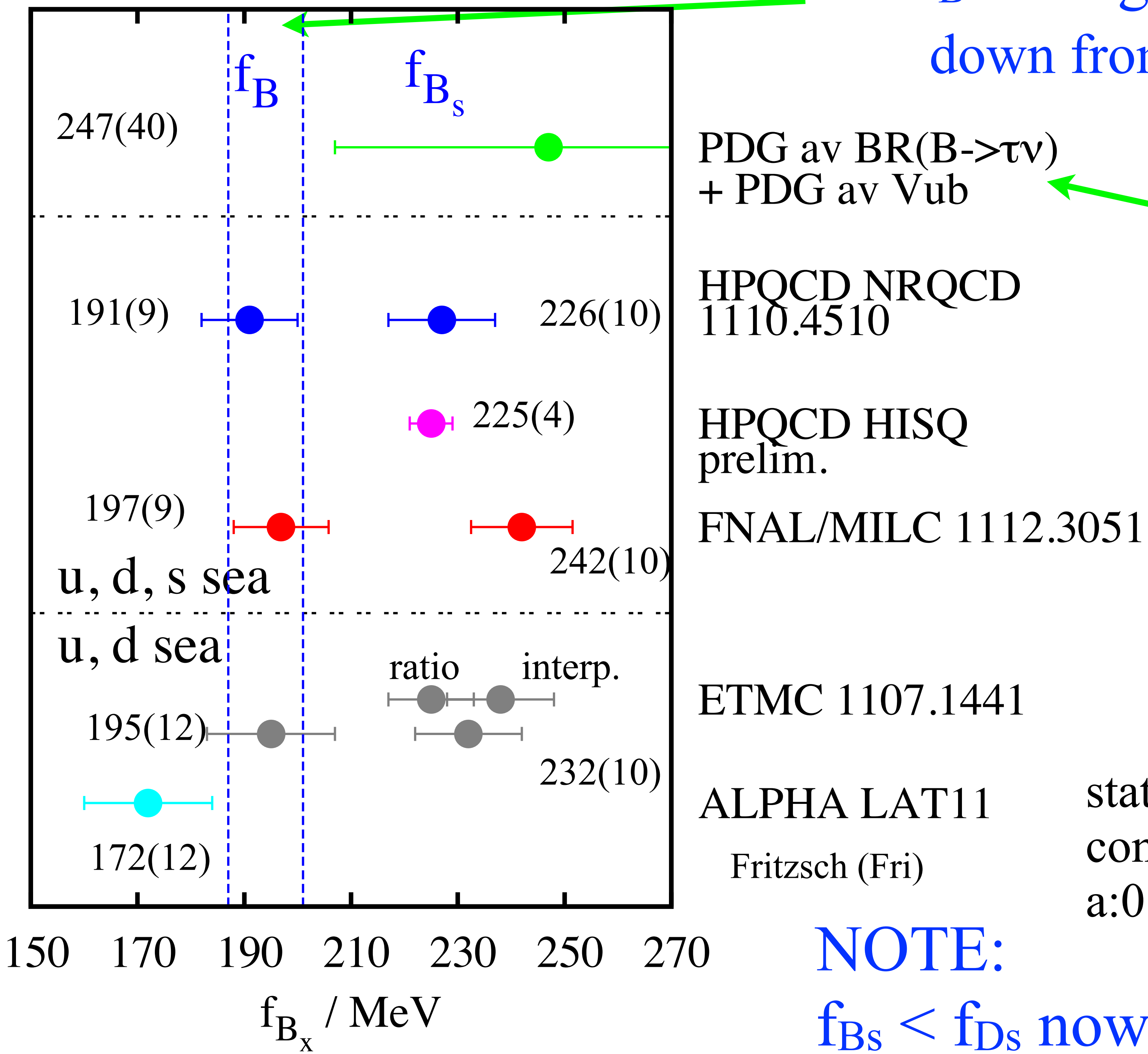


Tensions in UT at 2-3σ level - improve precision further

Problems : $V_{ub,excl.} vs. V_{ub,incl.}$ excl. uses lattice, incl. does not
$\sin(2\beta) vs. \mathcal{B}r(B \to \tau\nu)$

B, B_s decay constant update 2011

f_B average : 194(7) MeV
down from 2010



f_B expt
(B_s has no leptonic decay)

static +1/M
cont. + chiral extrap
a:0.075,0.065,0.048 fm

NOTE:
$f_{Bs} < f_{Ds}$ now quite clear

Look at error budgets to see how things will improve in future ...

stats
tuning
chiral
continuum

$$\Delta_q = 2m_{Dq} - m_{\eta c}$$

	f_K/f_π	f_K	f_π	f_{D_s}/f_D	f_{D_s}	f_D	Δ_s/Δ_d
r_1 uncerty.	0.3	1.1	1.4	0.4	1.0	1.4	0.7
a^2 extrap.	0.2	0.2	0.2	0.4	0.5	0.6	0.5
Finite vol.	0.4	0.4	0.8	0.3	0.1	0.3	0.1
$m_{u/d}$ extrap.	0.2	0.3	0.4	0.2	0.3	0.4	0.2
Stat. errors	0.2	0.4	0.5	0.5	0.6	0.7	0.6
m_s evoln.	0.1	0.1	0.1	0.3	0.3	0.3	0.5
m_d, QED, etc.	0.0	0.0	0.0	0.1	0.0	0.1	0.5
Total %	0.6	1.3	1.7	0.9	1.3	1.8	1.2

for different quantities different systematics are important