Flavour physics with Lattice QCD

Christine Davies
University of Glasgow
HPQCD collaboration

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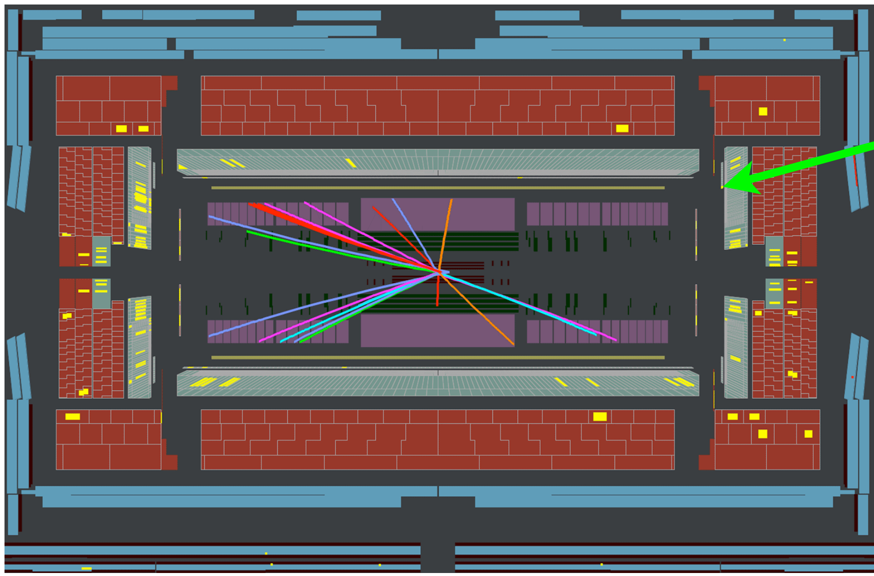
QCD is a key part of the Standard Model but quark confinement is a complication/interesting feature.

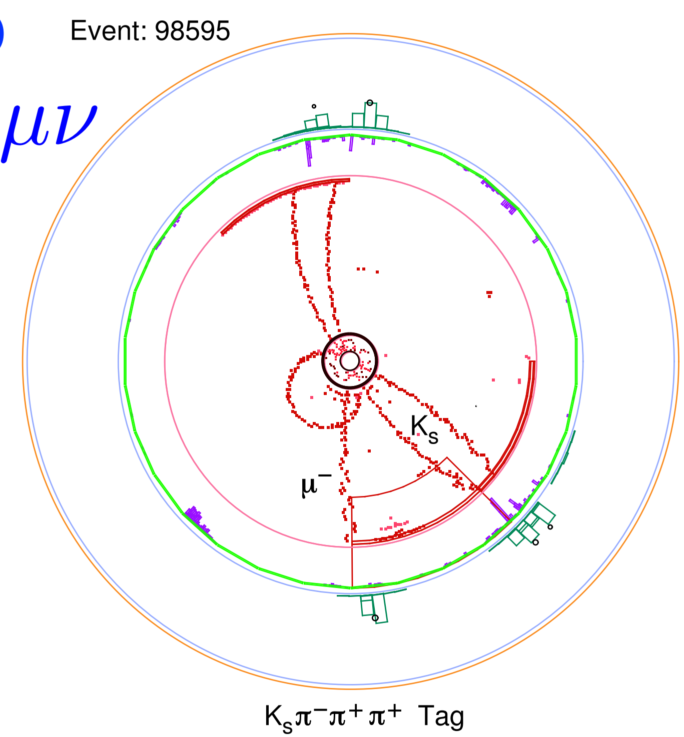


ATLAS@LHC

Connecting observed hadron properties to those of quarks requires full nonperturbative treatment of Quantum Chromodynamics.

CLEO

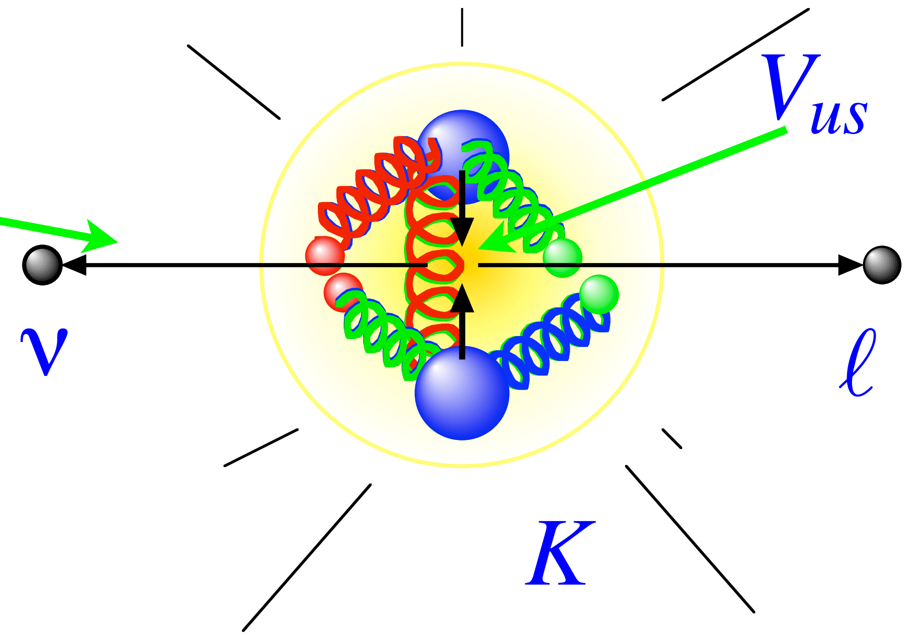
$D \to \mu\nu$



Some properties of hadrons can be very accurately measured and are calculable in lattice QCD - can test SM and determine parameters very accurately (1%).

Weak decays probe meson structure and quark couplings

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



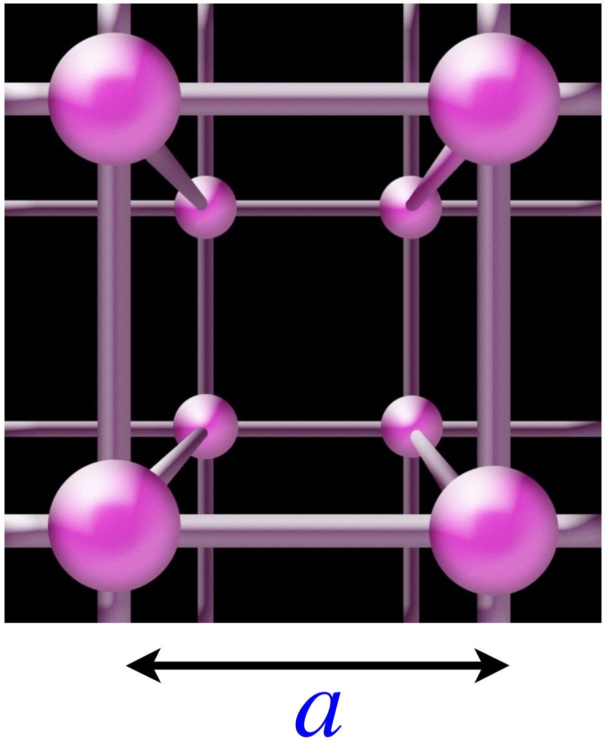
CKM matrix

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

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

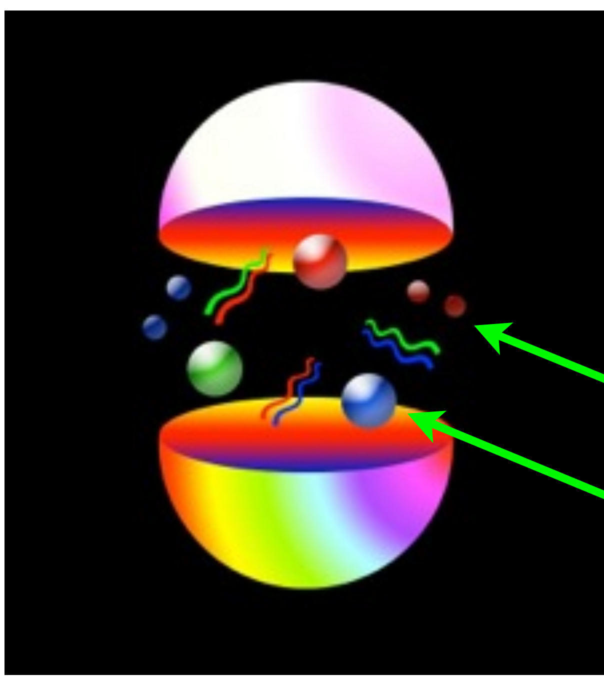


Lattice QCD = fully nonperturbative, based on Path Integral formalism

basic integral $\int \mathcal{D}U\mathcal{D}\psi\mathcal{D}\overline{\psi}\exp(-\int \mathcal{L}_{QCD}d^4x)$

discretise quark and gluon fields in a 4-d space-(Euclidean)time volume

a=0.1fm, N = 50^4, gives multi-million dimensional integral

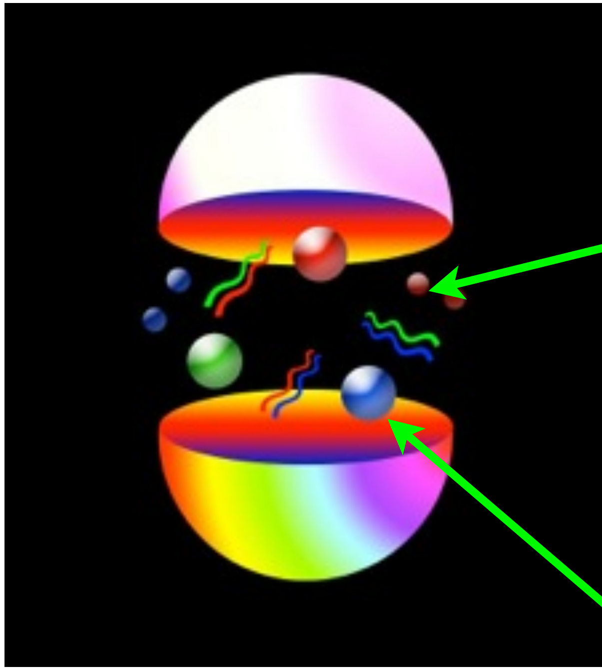


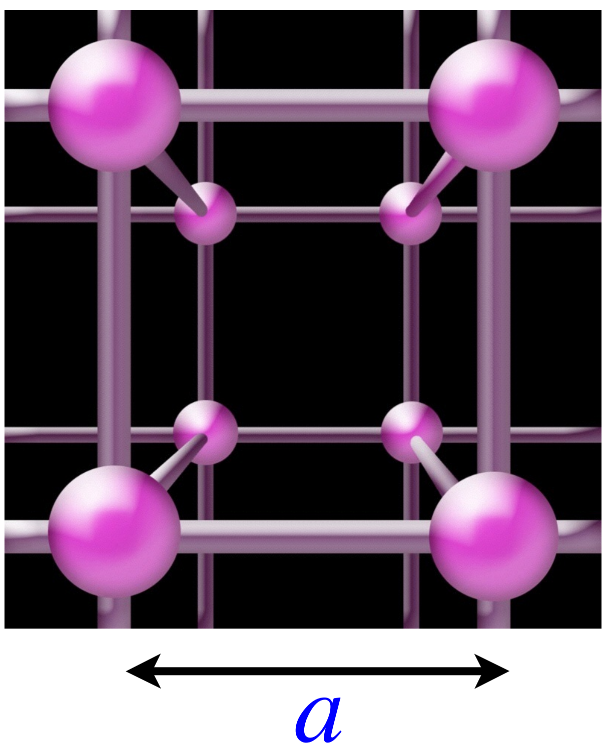
Integrating over quark fields leaves gluon field integral.

Sea quarks appear through det M

Valence quarks through M^{-1}

$$M = \gamma \cdot D + m_q$$





Lattice QCD = two-step procedure

1) Generate sets of gluon fields for Monte Carlo integrn of Path Integral (inc effect of u, d, s, (c) sea quarks)

numerically extremely challenging

2) Calculate valence quark propagators and combine for "hadron correlators"

numerically costly, data intensive

- Fit for masses and matrix elements
- Determine a and fix m_q to get results in physical units.
- cost increases as $a \to 0, m_l \to phys$ and with statistics, volume.

UK landscape - people

8 university teams in UKQCD consortium.

Key members of international collaborations e.g Fastsum, Hadspec, HPQCD, QCDSF, RBC-UKQCD, strongBSM

Different methods for handling quarks, optimised for different physics, but crosschecks important. Results impact:

LHC, BES, KEK, FNAL, JLAB, J-PARC, DAFNE, RHIC, FAIR ...

STFC's HPC facility

DiRAC

www.dirac.ac.uk

Blue Gene/Q @Edinburgh: 98000 cores, 5D Torus Interconnect, 1.3 Pflops 23 in Top500 list 2012

Darwin@Cambridge: State-of-the-art commodity cluster: 9600 Intel Sandybridge cores, infiniband interconnect, fast switch and 2 Pbytes storage

Upgrade needed in 2016!

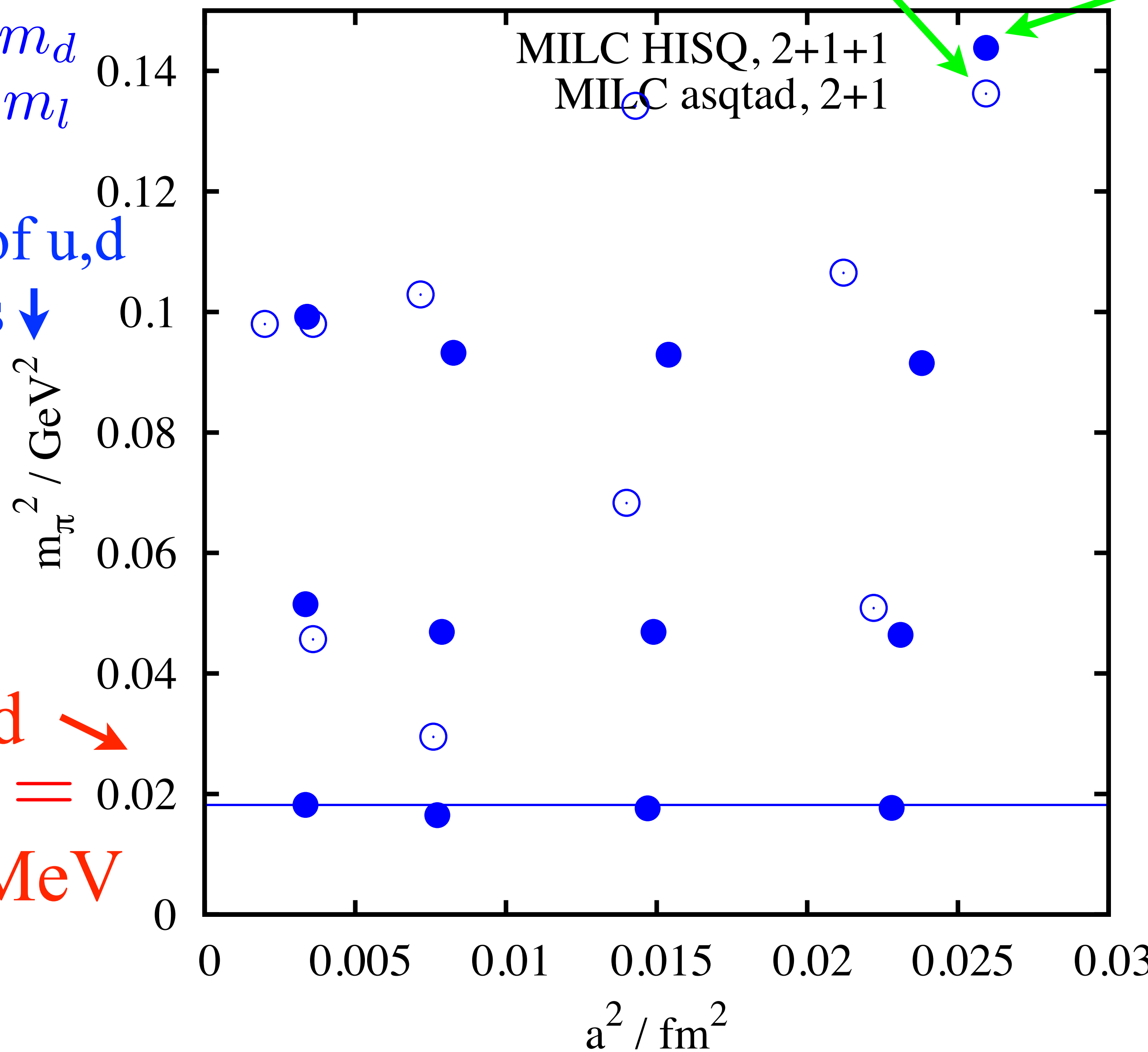
Example parameters for calculations now being done with 'staggered' quarks.

C.Davies et al, HPQCD/FNAL/MILC, hep-lat/0304004.

"2nd generation" lattices inc. c quarks in sea

$m_u = m_d = m_l$

mass of u,d quarks



real world $m_{\pi^0} = 135$ MeV

HISQ = Highly improved staggered quarks - very accurate discretisation

E.Follana et al, HPQCD, hep-lat/0610092.

$m_{u,d} \approx m_s/10$

$m_{u,d} \approx m_s/27$

Volume:

$m_\pi L > 3$

also: 'domain-wall' RBC/UKQCD, 'clover' QCDSF, Hadspec

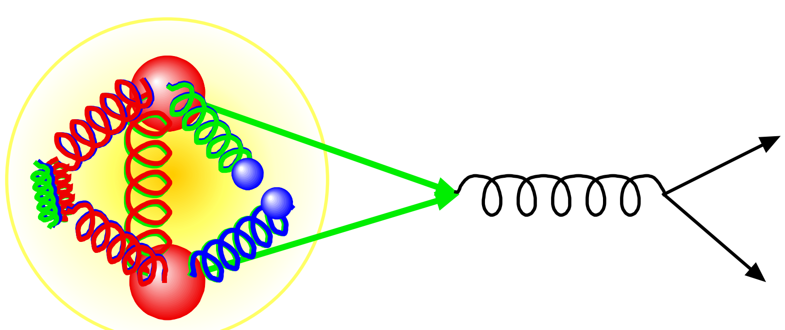
Hadron correlation functions ('2point functions') give masses and decay constants.

$$\langle 0|H^\dagger(T)H(0)|0\rangle = \sum_n A_n e^{-m_n T} \xrightarrow[T]{\text{large}} A_0 e^{-m_0 T}$$

masses of all hadrons with quantum numbers of H

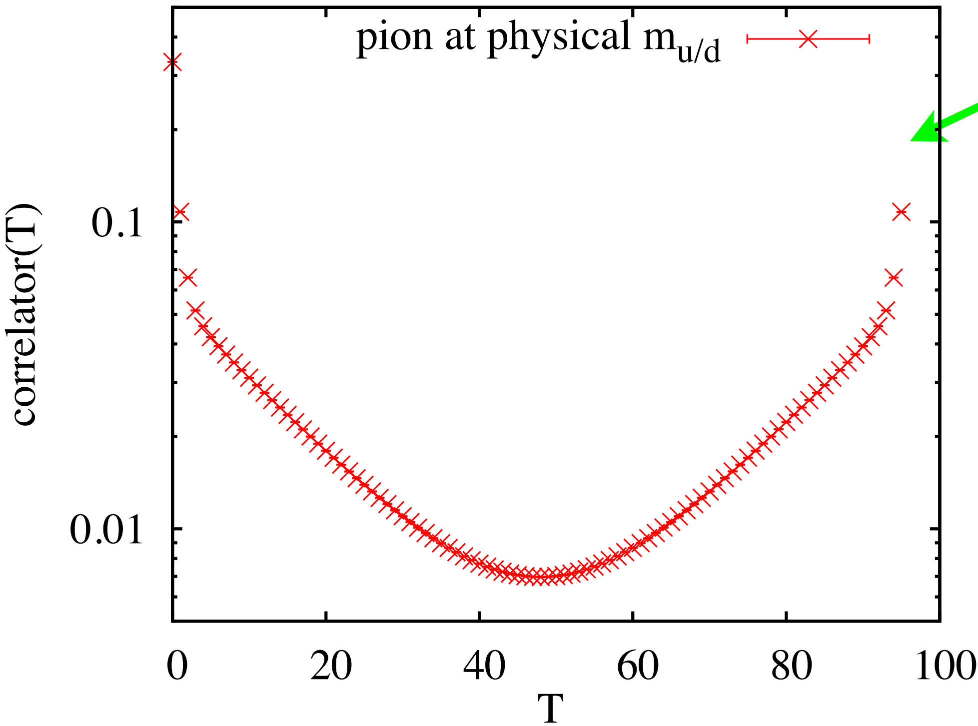
$$A_n = \frac{|\langle 0|H|n\rangle|^2}{2m_n} = \frac{f_n^2 m_n}{2}$$

decay constant parameterises amplitude to annihilate - a property of the meson calculable in QCD. Relate to experimental decay rate.



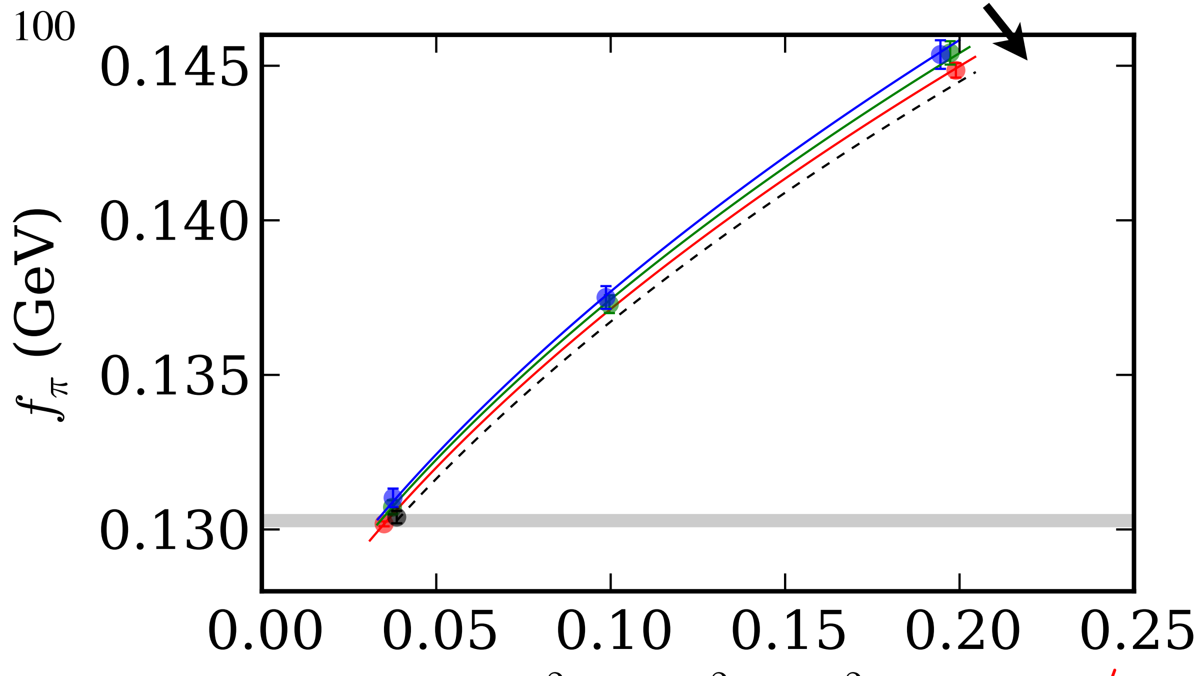
1% accurate experimental info. for f and m for many mesons! Need accurate determination from lattice QCD to match

Example (state-of-the-art) calculation



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

Extrapolation in a

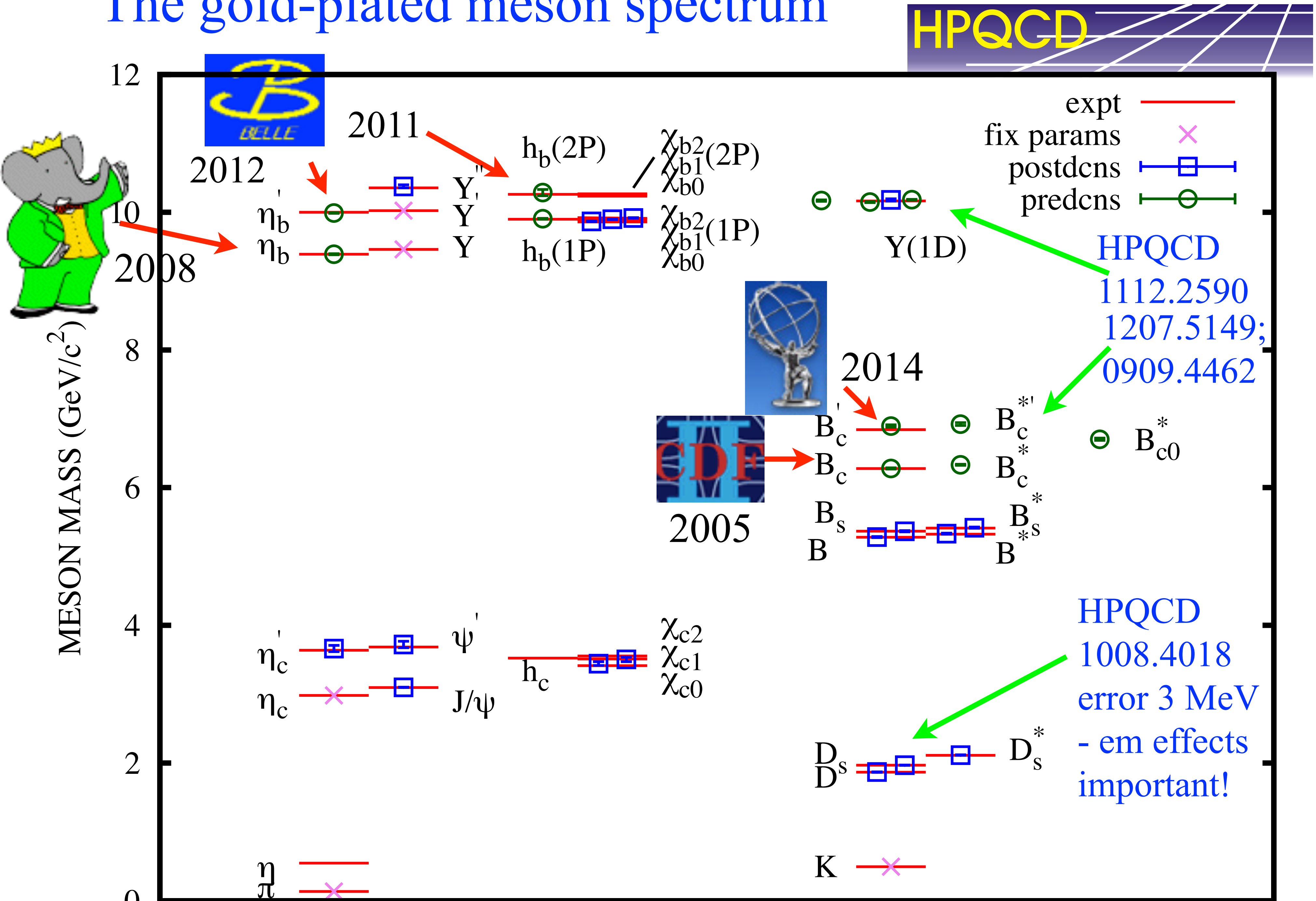


$= m_l/m_s$

Convert decay constant to GeV units using w_0 to fix relative scale. Very small discretisation errors.

R. Dowdall et al, HPQCD, 1303.1670.

The gold-plated meson spectrum

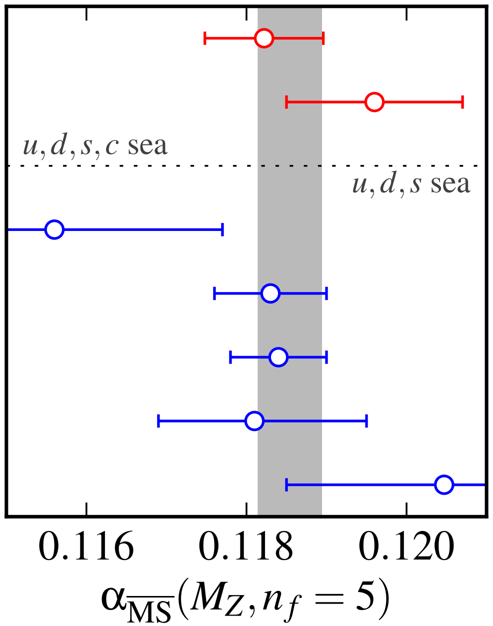


Future: inc QED and $m_u \neq m_d$, see BMW 1406.4088

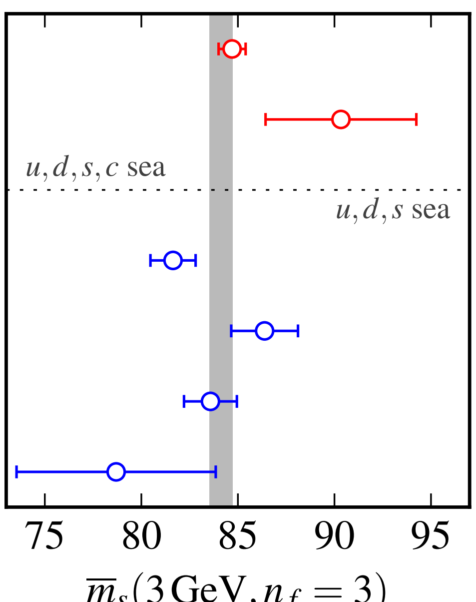
Quark masses and strong coupling constant

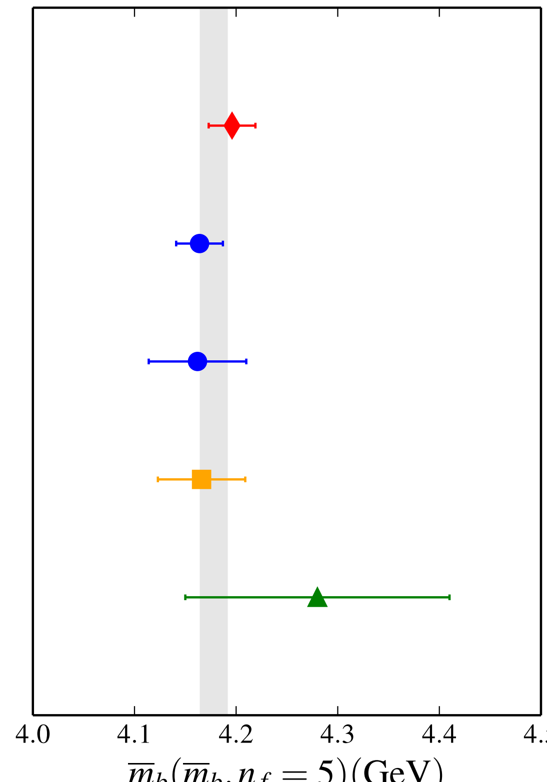
Lattice QCD results have transformed accuracy possible

DiRAC



1408.4169



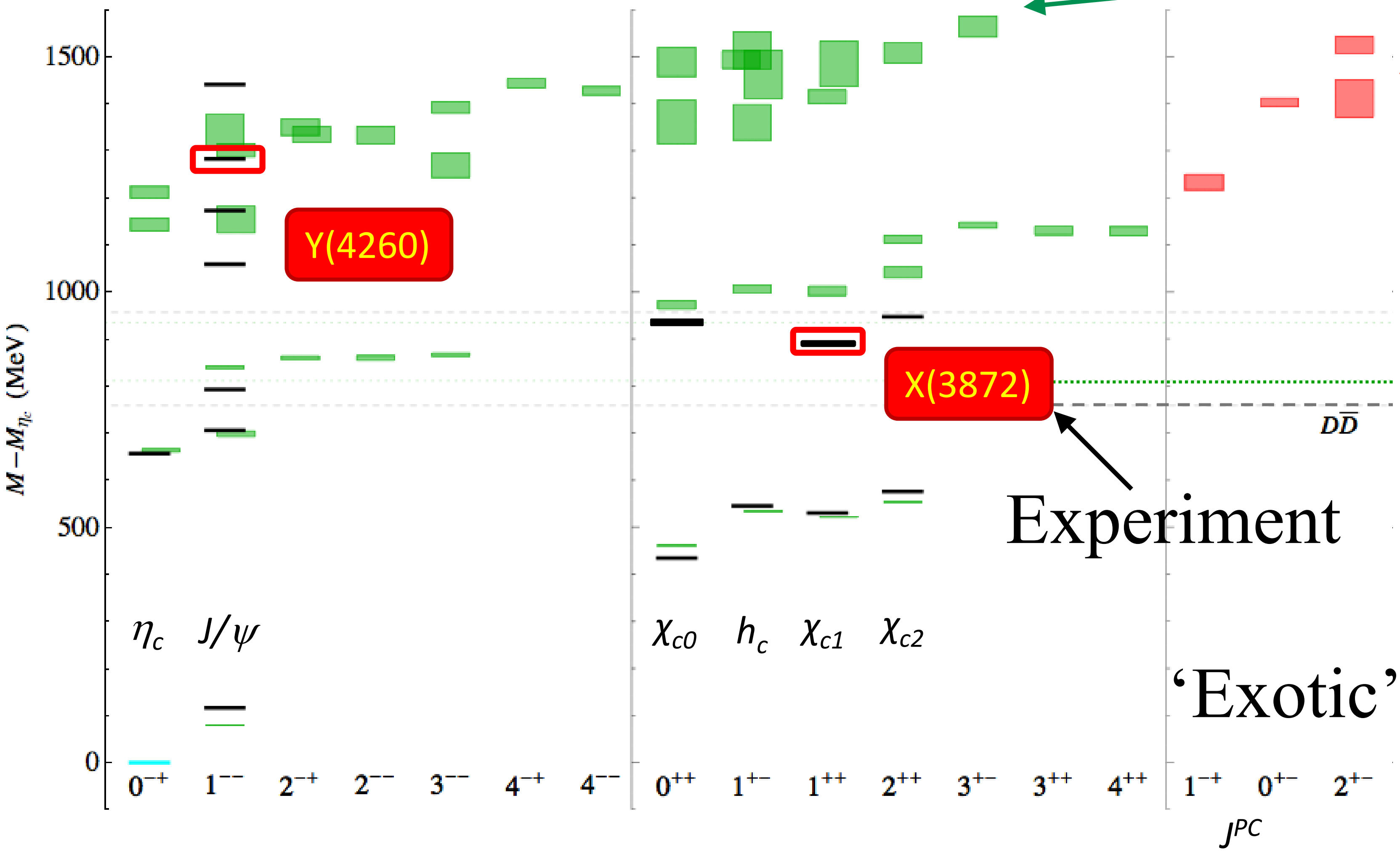


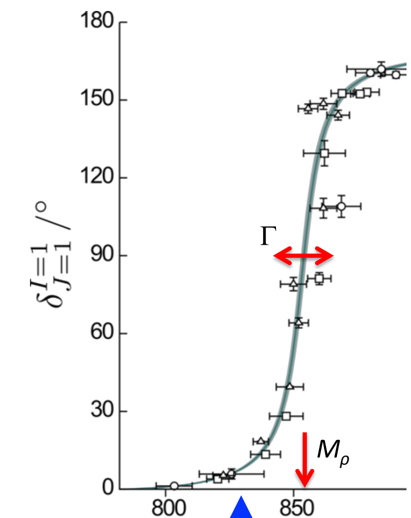
Future: Accurate tests of Higgs $\rightarrow b\bar{b}$ require halving uncertainty on m_b and α_s .....

More detailed study of unstable and excited states underway first results: charmonium

Hadspec

1204.5425





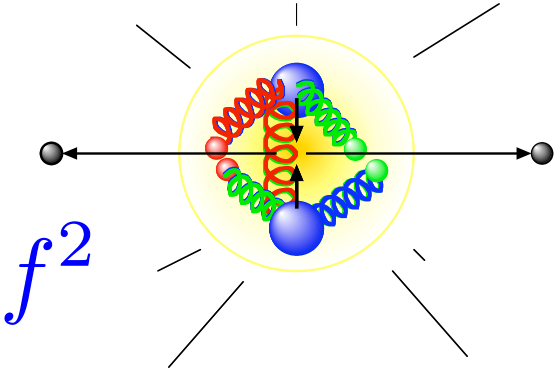
unstable states need multivolume analysis

1411.2004

Future: establish whether tetraquark states, hybrids, glueballs, pentaquarks exist - needs very high stats and large op. basis. Pin down unstable states so they can be included in SM tests

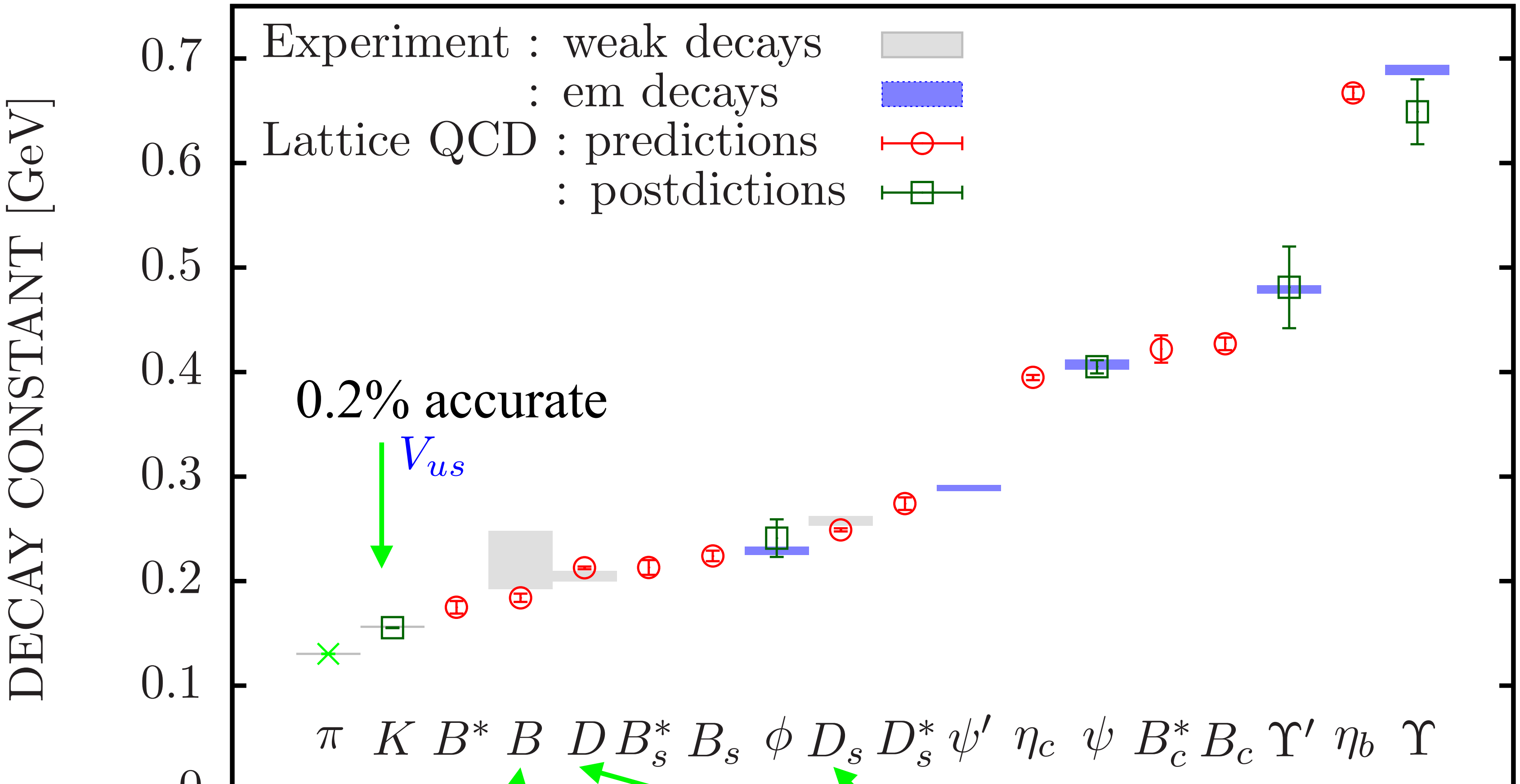
Meson decay constants

Parameterises hadronic information needed for annihilation rate to W or photon:



$$\Gamma \propto f^2$$

HPQCD 1503.05762



2012

$B \to \tau\nu$

V_{ub}

decay constants of vector mesons now being pinned down

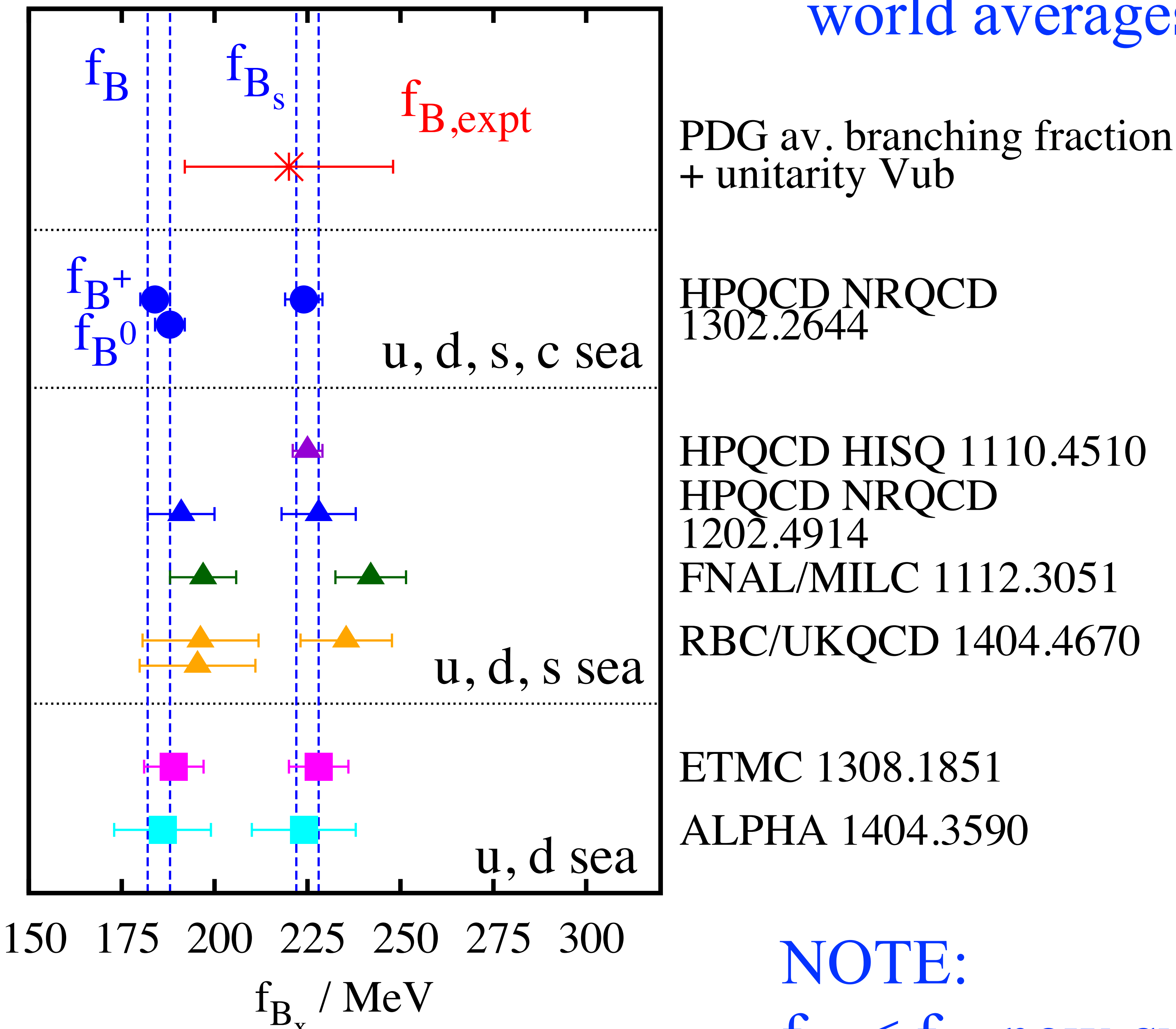
0.5% accuracy from lattice QCD

now : FNAL/MILC 1407.3772

BES will improve expt. V_{cd} V_{cs}

185(3) 225(3) averages

B, B_s decay constant world averages



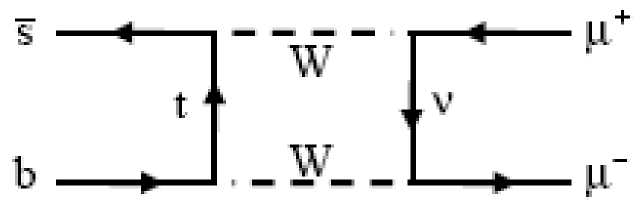
Different approaches to b quark being used and to normalising weak current

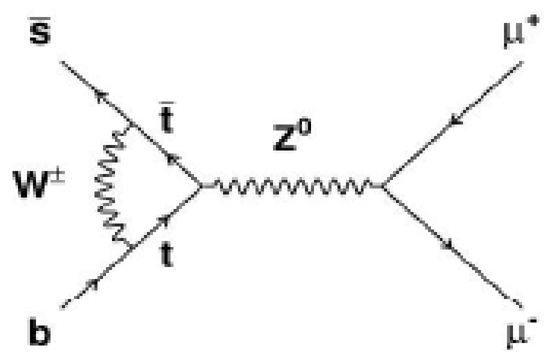
NOTE:

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

Enables SM branching fraction to be determined for:

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



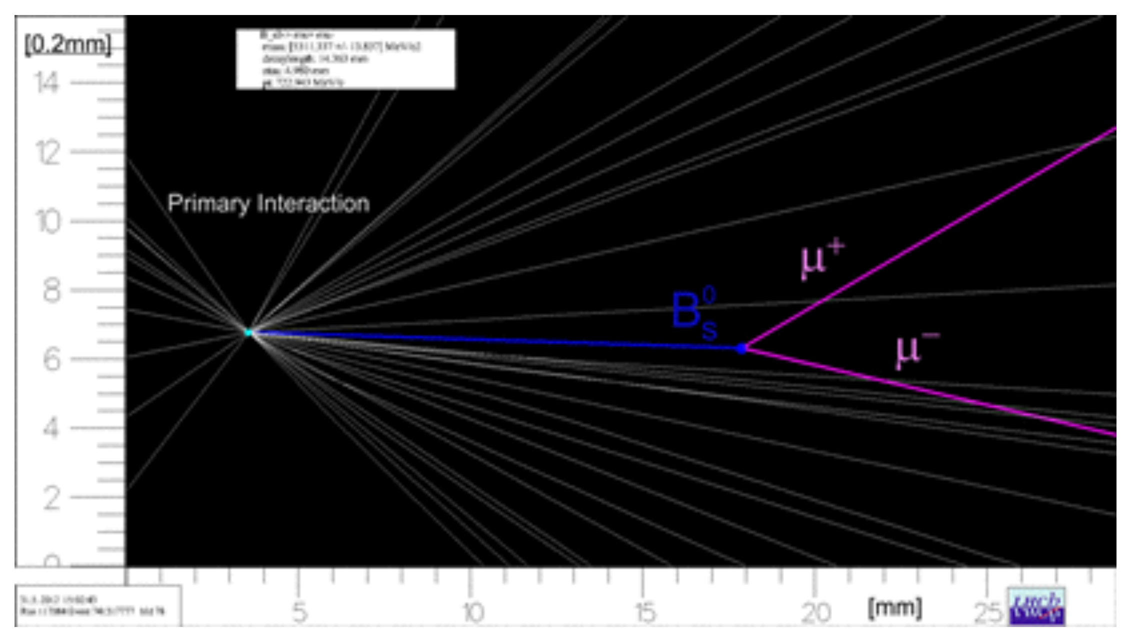


2013: Updated result from lattice QCD f_{Bs}: $3.47(19) \times 10^{-9}$

`HPQCD: R Dowdall et al,1302.2644.`

(including $\Delta\Gamma$ effect in time-integration)

`LHCb: November 2012`



Now seen by LHC (CMS/ LHCb)with 1411.4413

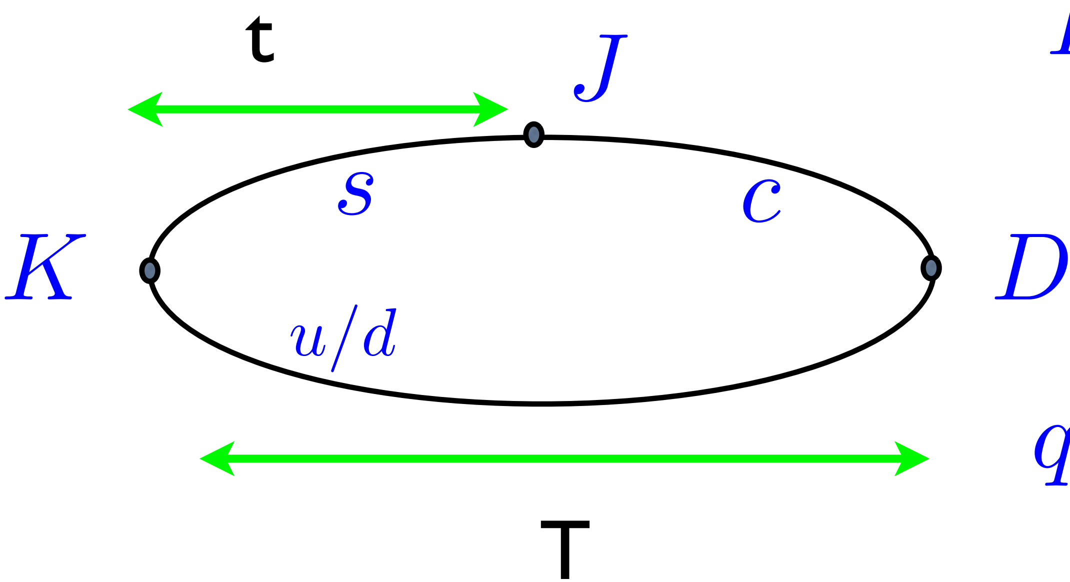
$\mathrm{Br} = 2.8(6) \times 10^{-9}$

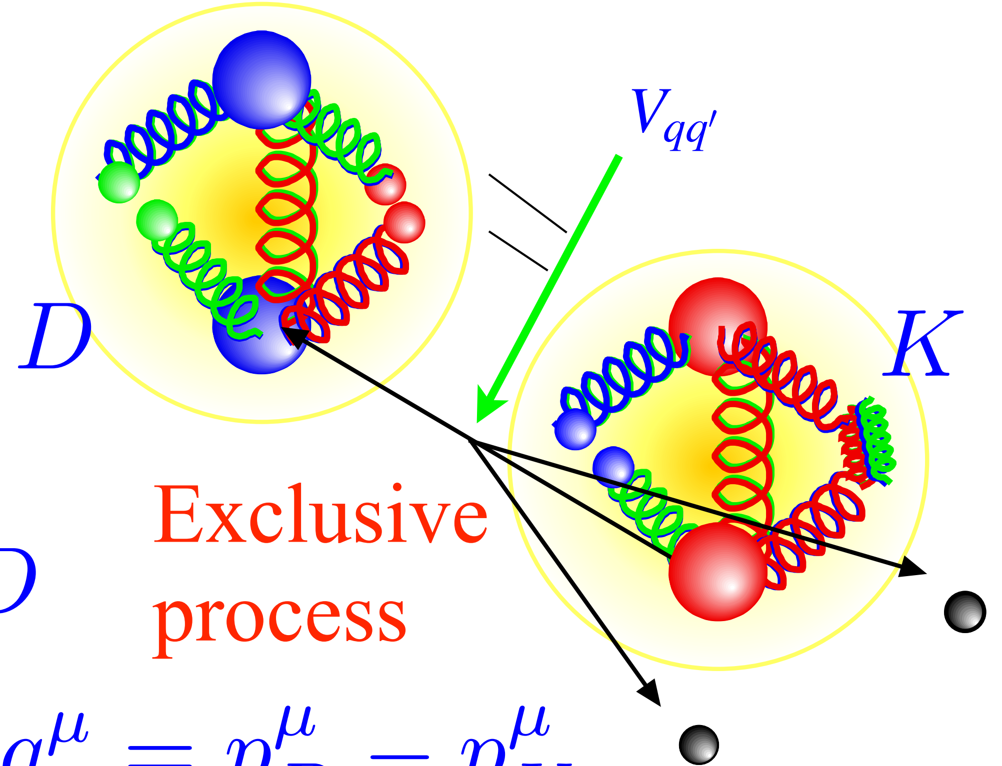
Improved accuracy from Run 2 will allow strong test against SM.

B_d rate a bit high vs SM …

Semileptonic form factors

'3point function' - amplitude





Exclusive process

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

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

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

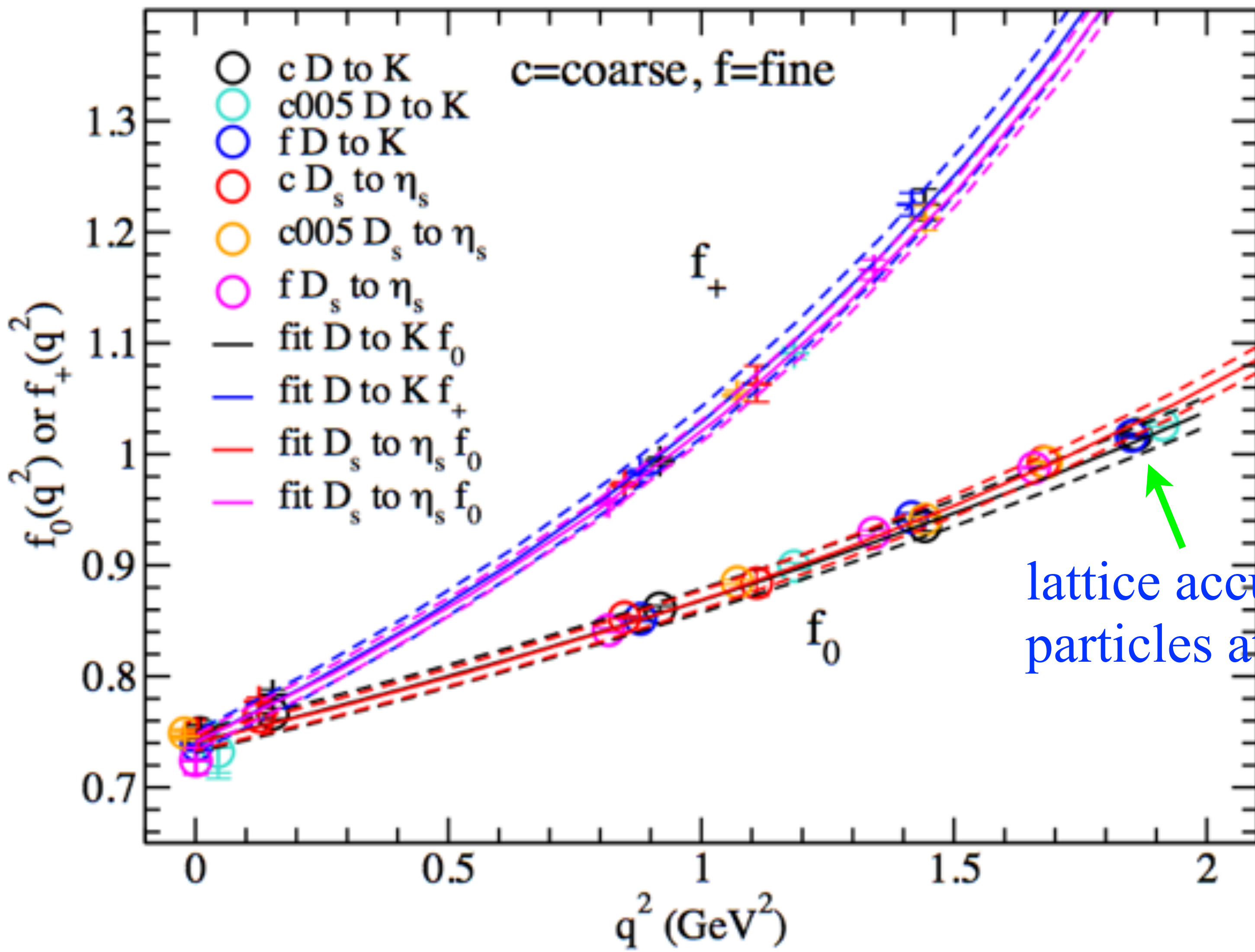
measured by expt through rate for e.g $D \to Kl\nu$

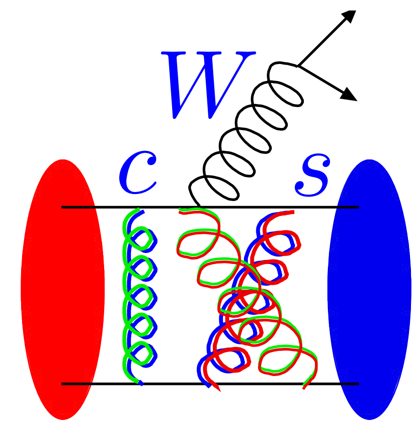
$$f_0(0) = f_+(0)$$

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

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

Semileptonic form factors for charmed mesons:





J. Koponen et al, HPQCD, 1305.1462

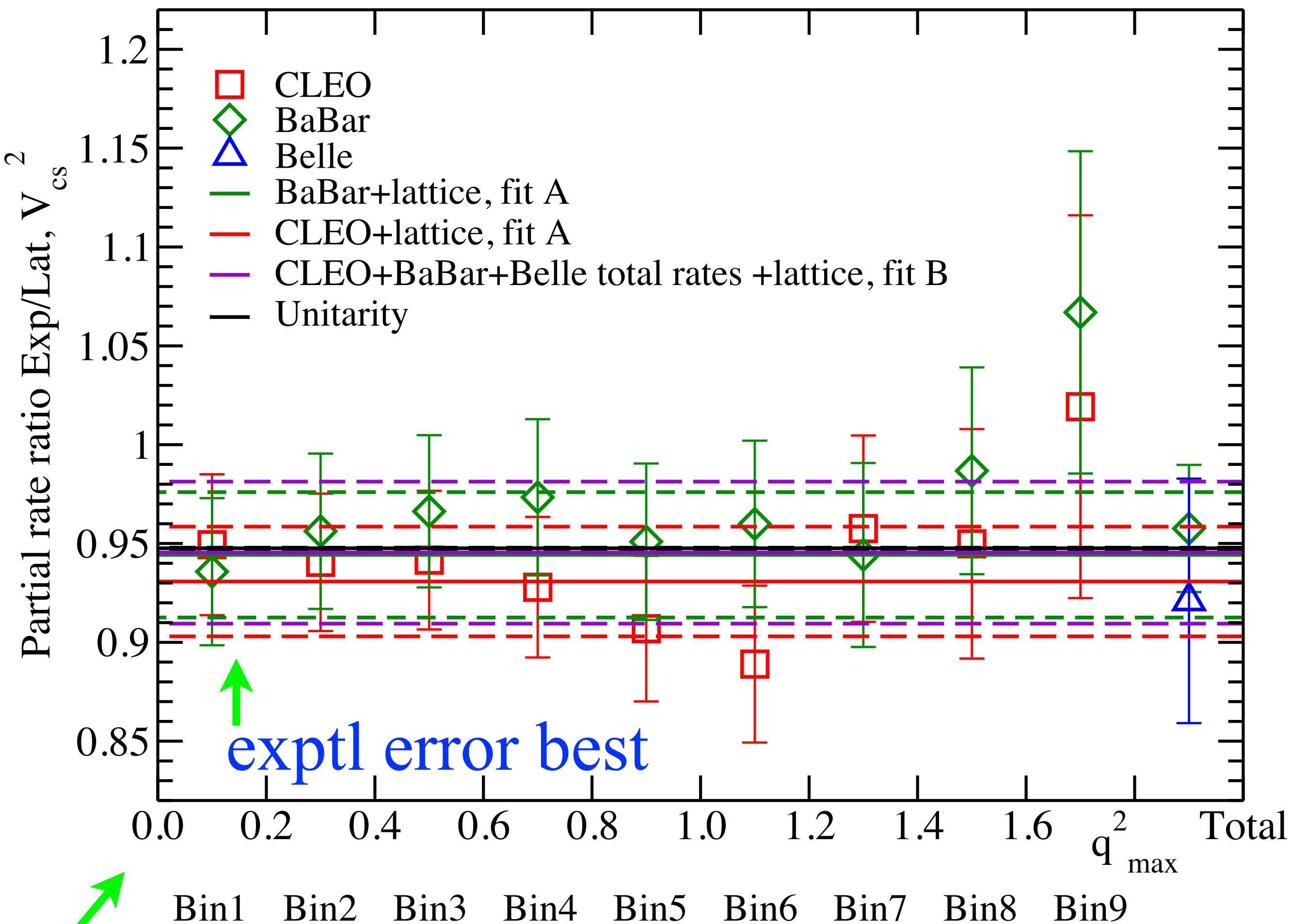
lattice accuracy highest - particles at rest

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 ....)

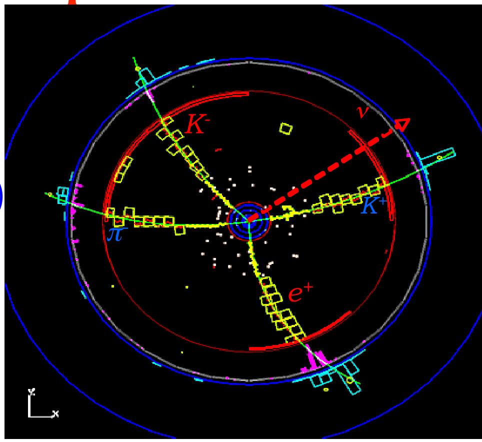
Convert to decay rate in q^2 bins to compare to experiment:

$D \to K$



CLEO-c

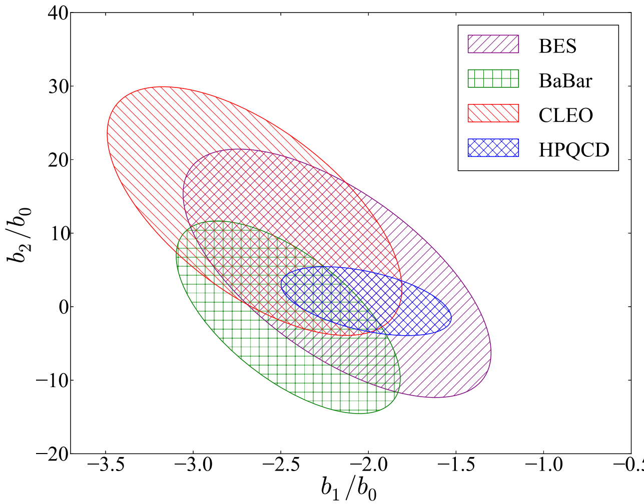
$D_0 \to K^- e^+ \nu$
$(\overline{D}_0 \to K^+ \pi^-)$



J. Koponen et al, HPQCD, 1305.1462

Uses all exptl data in model-indpt way to give Vcs to 1.5%

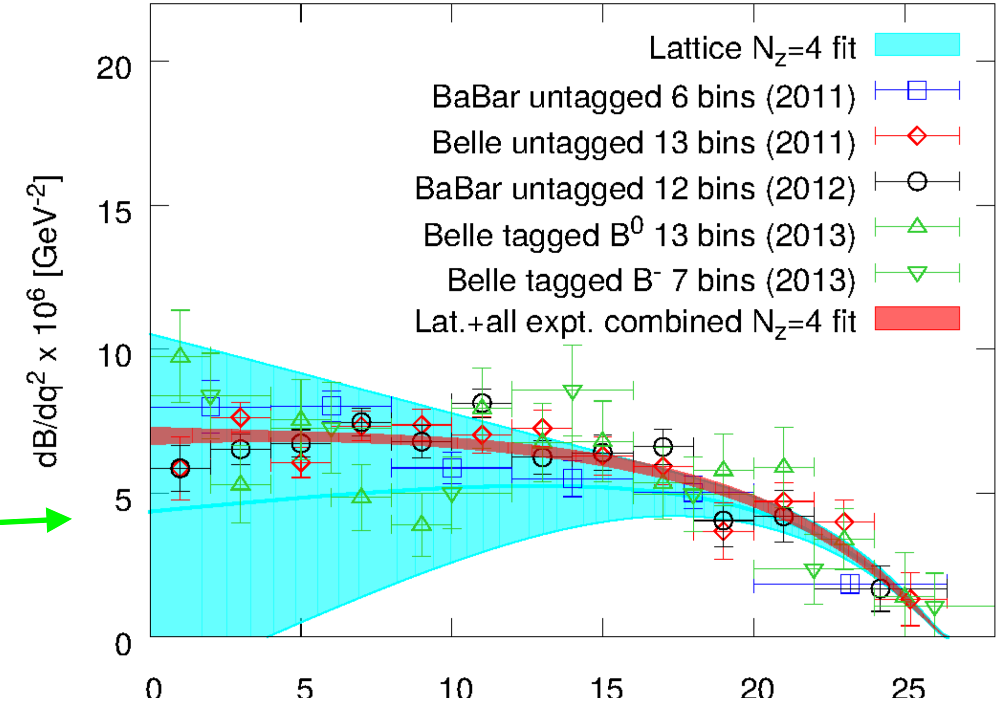
Also tests QCD via form factor shape



$B \to \pi \ell \nu$ and V_{ub}

form factors $m_{u/d}$ -dependent and q^2 range of lattice QCD calculation is limited.

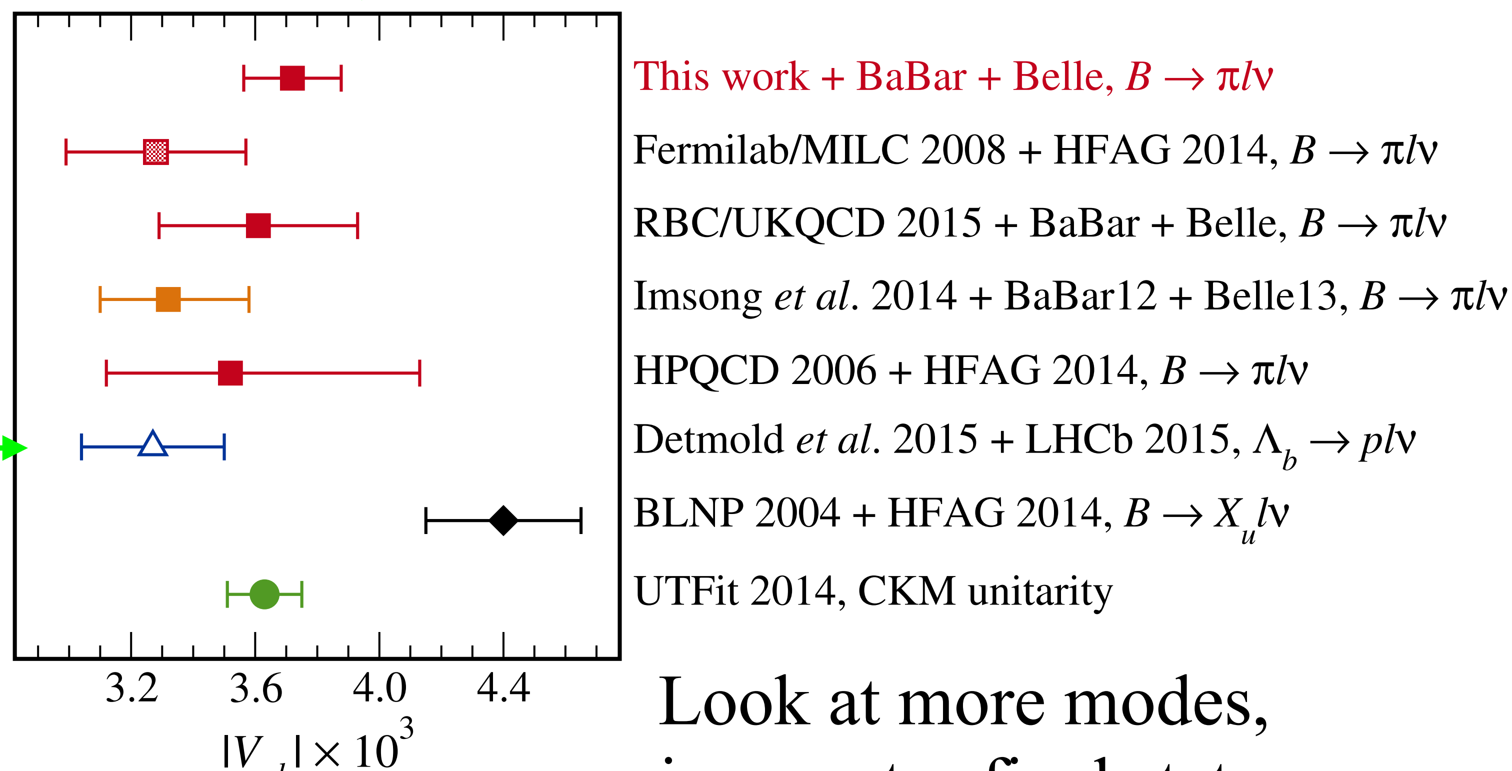
Fermilab/MILC 1503.07839



Long-standing issue of inclusive V_{ub} > exclusive V_{ub} .

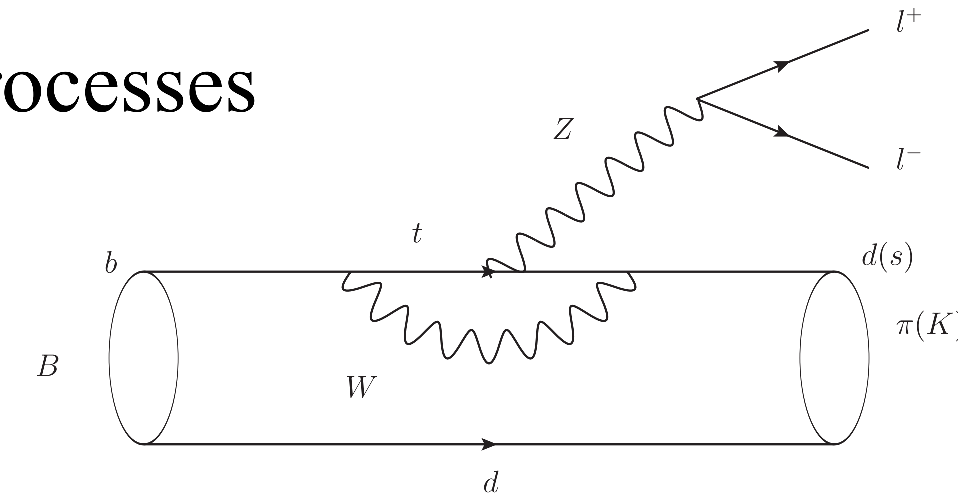
Same for V_{cb}

New LHCb result using baryons+ lattice QCD ff.

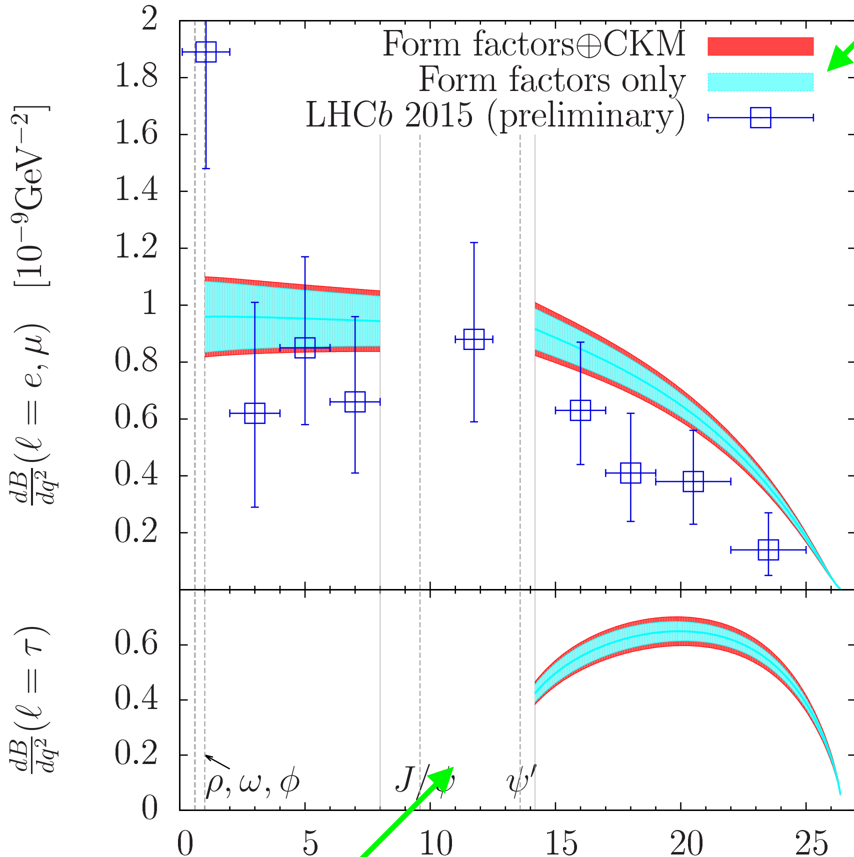


Look at more modes, inc. vector final states ….

$B \to \pi\ell^+\ell^-$ 'penguin' processes

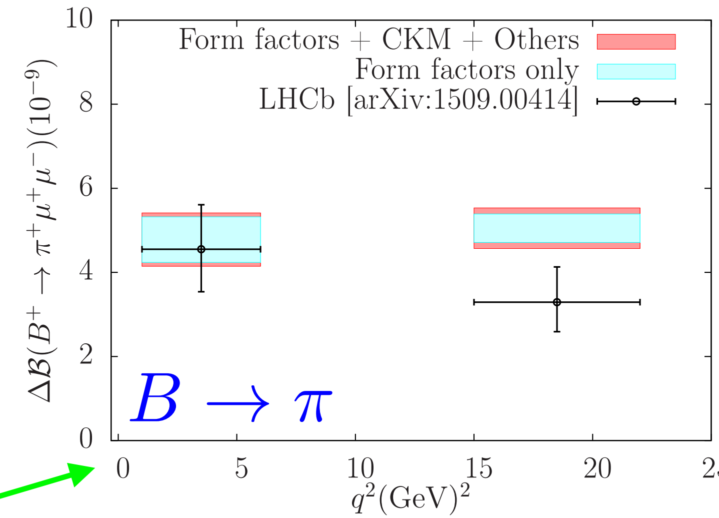


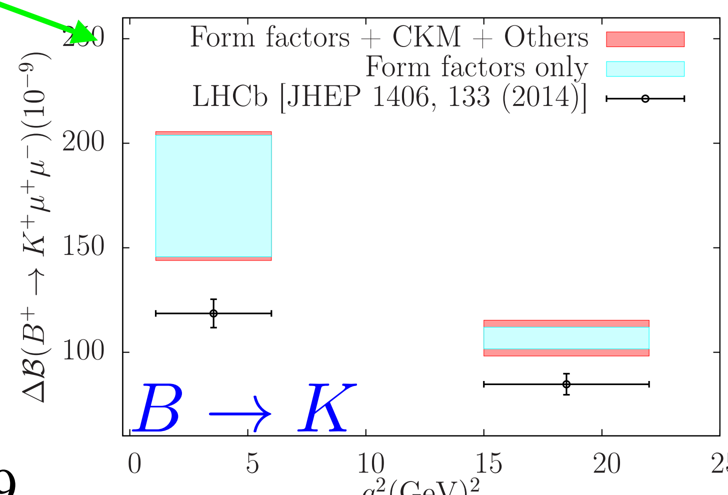
Addnl ops in eff. EW Hamiltonian
give additional tensor form factor + Wilson coeffs.



inc. expt $B \to \pi\ell\nu$

'tension' between expt and SM - Run 2 sort out



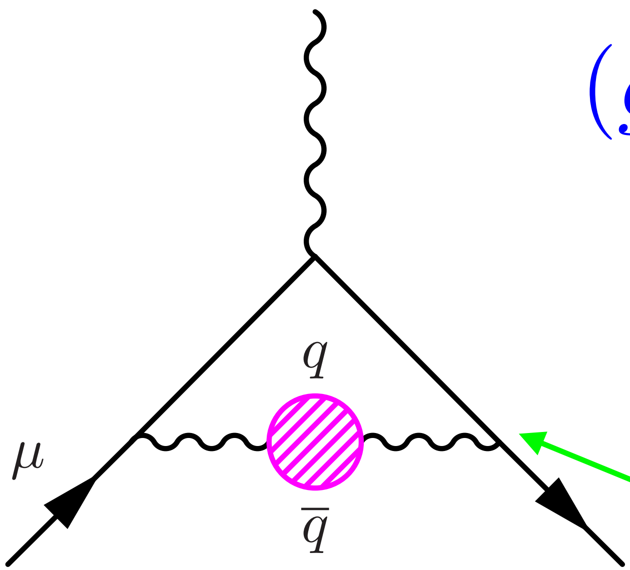


$B \to \pi\psi$

Fermilab/MILC 1510.02349

Lattice QCD can give hadronic contribution to anomalous magnetic moment of muon

B.Chakraborty et al, HPQCD: 1403.1778



$(g-2)_\mu/2$

differs between expt and the SM by $25(9) \times 10^{-10}$ *new physics*?

Error dominated by that from HVP contribution calculated using $R_{e^+e^-}$

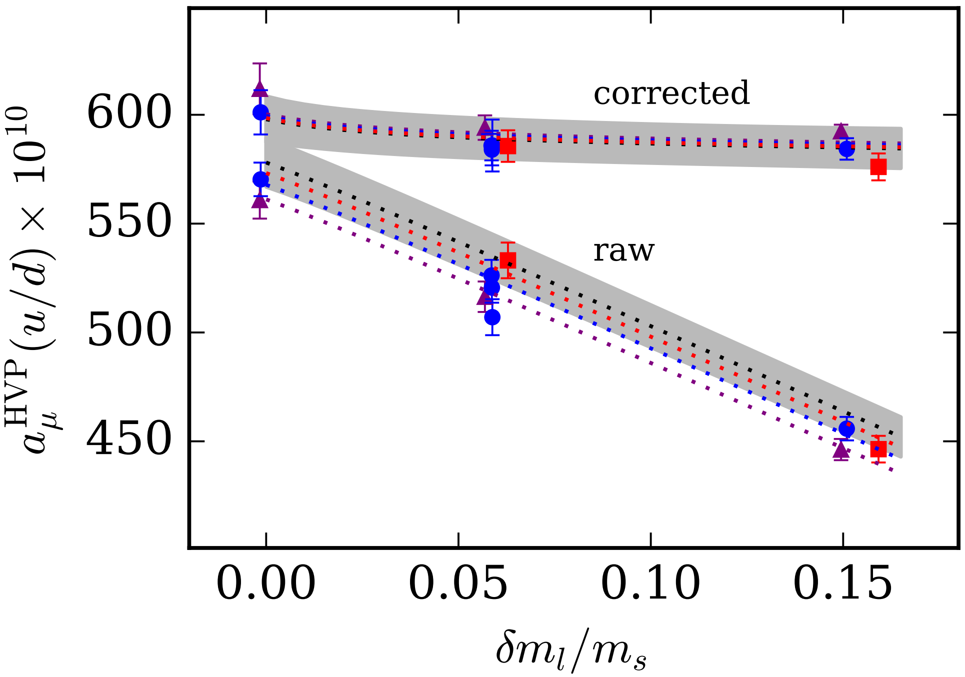
Can we improve ahead of E989 run?

On lattice, calculate :

$$a^{(\mathrm{f})}_{\mu,\mathrm{HVP}} = \frac{\alpha}{\pi}\int_0^\infty dq^2 f(q^2)(4\pi\alpha Q_\mathrm{f}^2)\hat{\Pi}_\mathrm{f}(q^2)$$

very steep function, so small q^2 dominates

vacuum polarisation function



$$a_\mu^{\mathrm{HVP,LO}} \times 10^{-10}$$

598(11) u/d

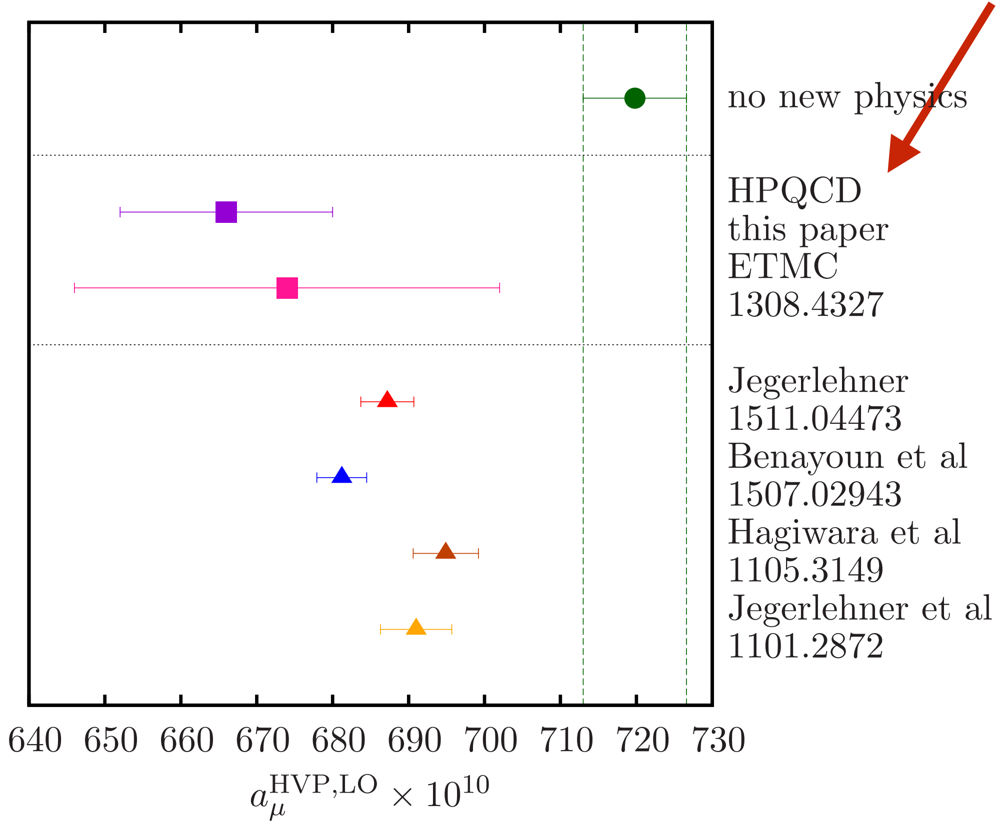
53.4(6) s

14.4(4) c

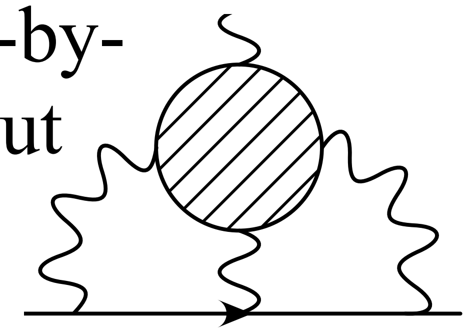
0.27(4) b

Total 666(6)(12)

inc systs from QED, isospin, disc. diags



‘hadronic light-by-light’ smaller but more difficult



see: RBC 1510.01700

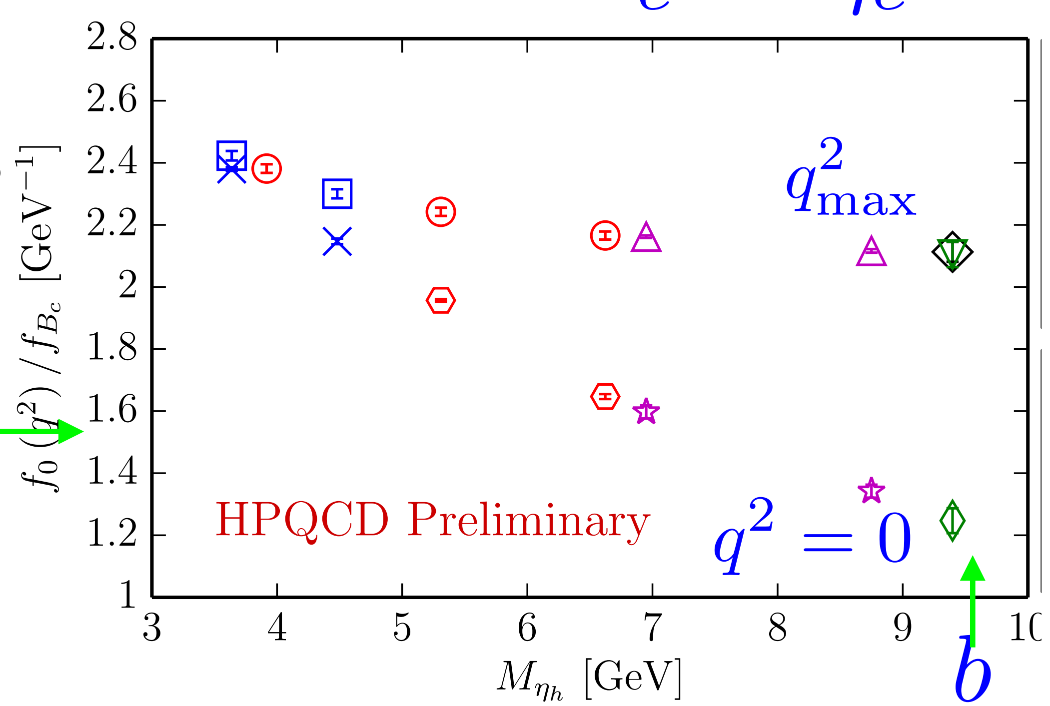
Conclusion

- Lattice QCD results for gold-plated hadron masses, decay constants and form factors now providing stringent tests of QCD/SM.
- Gives QCD parameters and some CKM elements to 1%.
- "Tensions" with expt./inclusive methods to be resolved.

Future

- Aim for 1% errors for B and B_s physics
- Inc. the range of modes studied to inc. vector mesons, baryons etc.
- Inc. the range of q^2 covered by going to finer lattices
- many more calculations …

$B_c \to \eta_c \ell \nu$

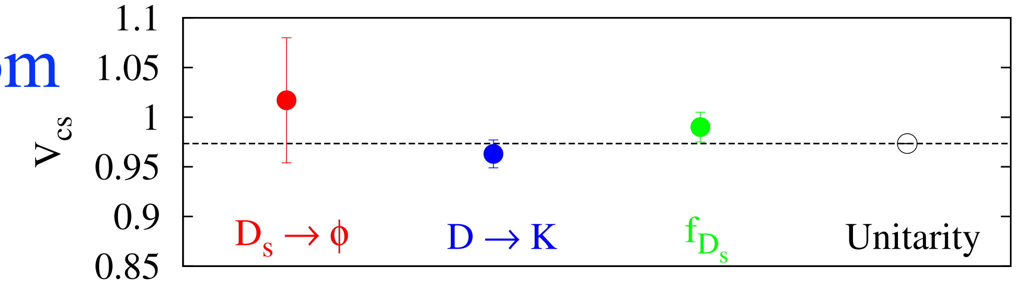


will need faster computers!

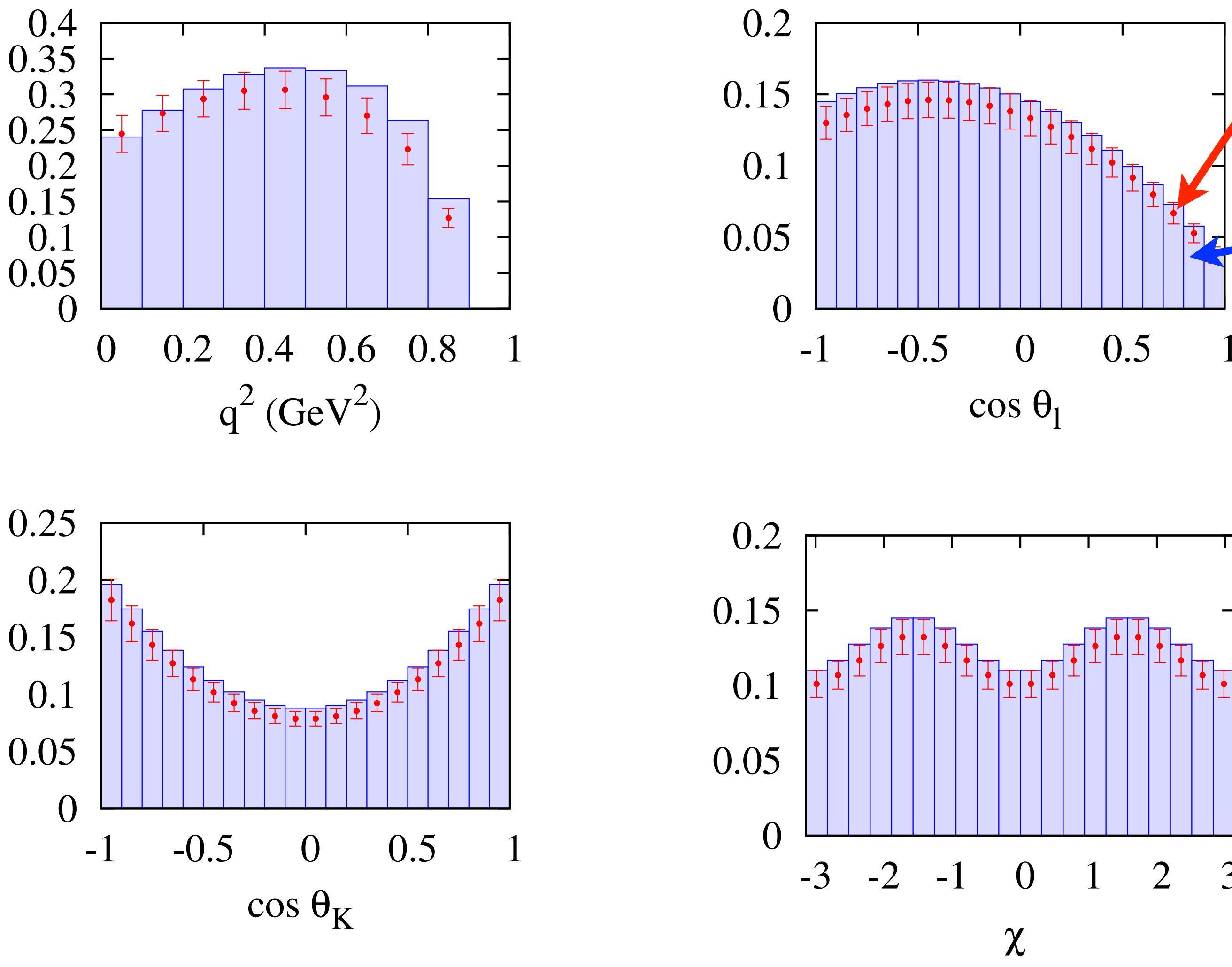
Spares

Independent determination of V_{cs} from

$D_s \to \phi \ell \nu$

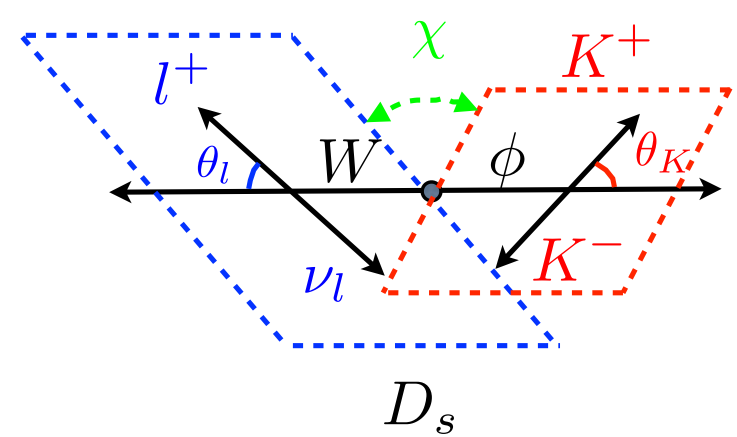


Vector final state means helicity info. is transmitted. Angular and q^2 distributions



Lattice QCD (HISQ on 2+1 asqtad configs)

Experiment (BaBar)



G. Donald et al, HPQCD, 1311.6669

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

1302.2644: calculation of B, B_s masses and decay constants

errors divided into extrapolation and other systematics:

Error %	Φ_{B_s}/Φ_B	$M_{B_s} - M_B$	Φ_{B_s}	Φ_B
EM:	0.0	1.2	0.0	0.0
a dependence:	0.01	0.9	0.7	0.7
chiral:	0.01	0.2	0.05	0.05
g:	0.01	0.1	0.0	0.0
stat/scale:	0.30	1.2	1.1	1.1
operator:	0.0	0.0	1.4	1.4
relativistic:	0.5	0.5	1.0	1.0
total:	0.6	2.0	2.0	2.1

for different quantities different systematics are important