Results from Lattice QCD

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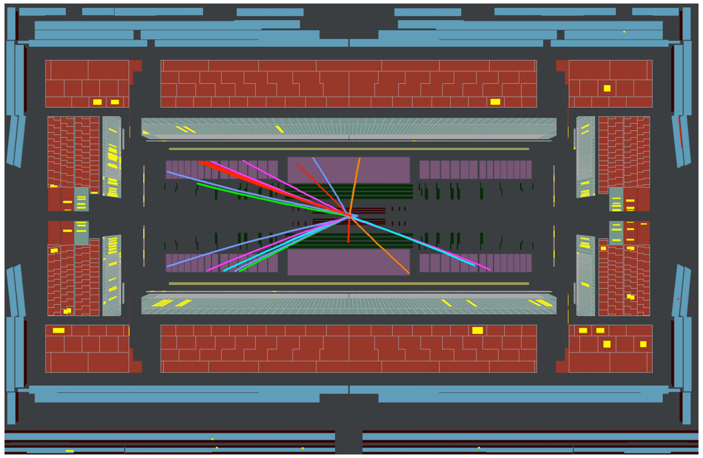
Lepton-Photon 2013
San Francisco, June 2013

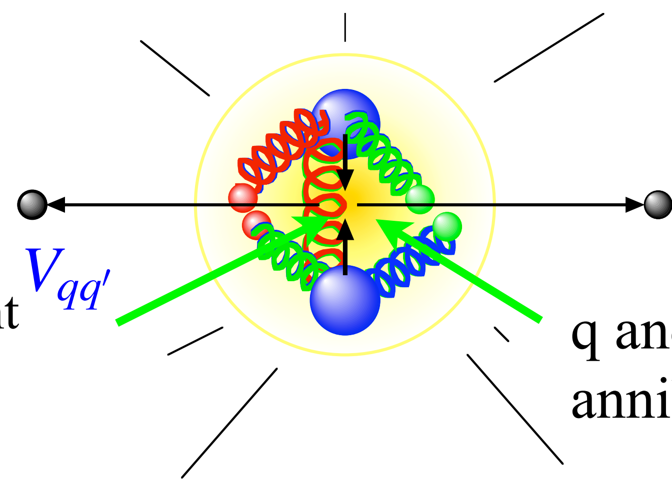
QCD is a key part of the Standard Model but quark confinement is a complication/interesting feature.

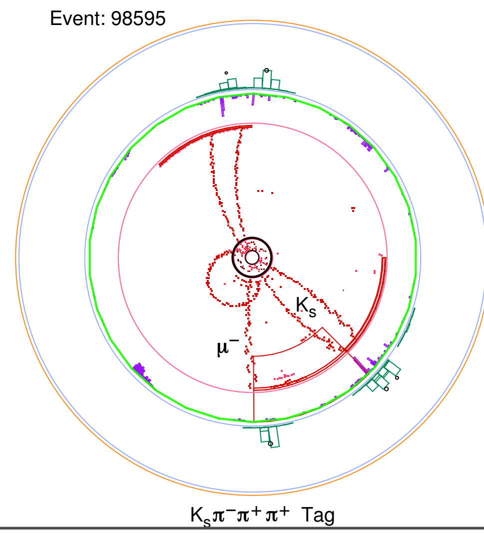


ATLAS
@LHC

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%).





CLEO-c

$D_s \to \mu\nu$

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

Applications of Lattice QCD/Lattice field theory

Annual proceedings of lattice conference: http://pos.sissa.it/

Particle physics

QCD parameters
Shintani: Lat2011

Hadron spectrum
Dudek, Mohler: Lat2012

Hadron structure
Lin: Lat2012

CKM elements
Tarantino: Lat2012

Nuclear physics

Glueballs and exotica

QCD at high temperatures and densities
Lombardo, Aarts: Lat2012;
Satz: Saturday

Nuclear masses and properties
Doi: Lat2012

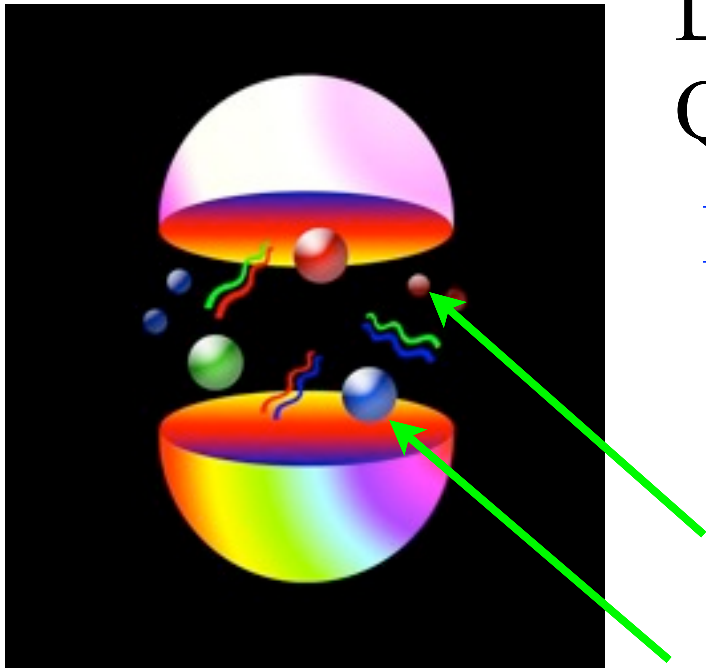
Theories beyond the Standard Model
Giedt, Panero: Lat2012

Quantum gravity
Laiho: Lat2011

Astrophysics
Young: Lat2012

condensed matter physics
computational physics
computer science ...
Boyle: Lat2012

Lattice QCD = fully nonperturbative QCD calculation



RECIPE

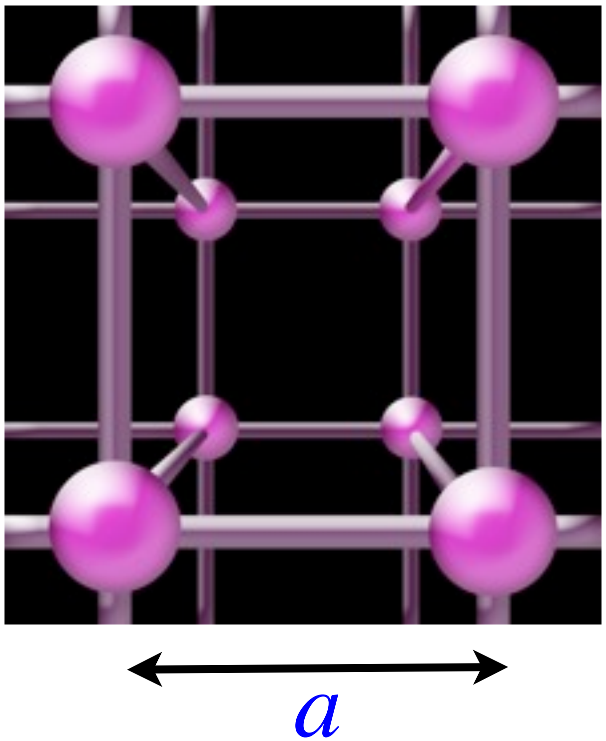
- Generate sets of gluon fields for Monte Carlo integrn of Path Integral (inc effect of u, d, s (+ c) sea quarks)

- Calculate averaged "hadron correlators" from valence q props.

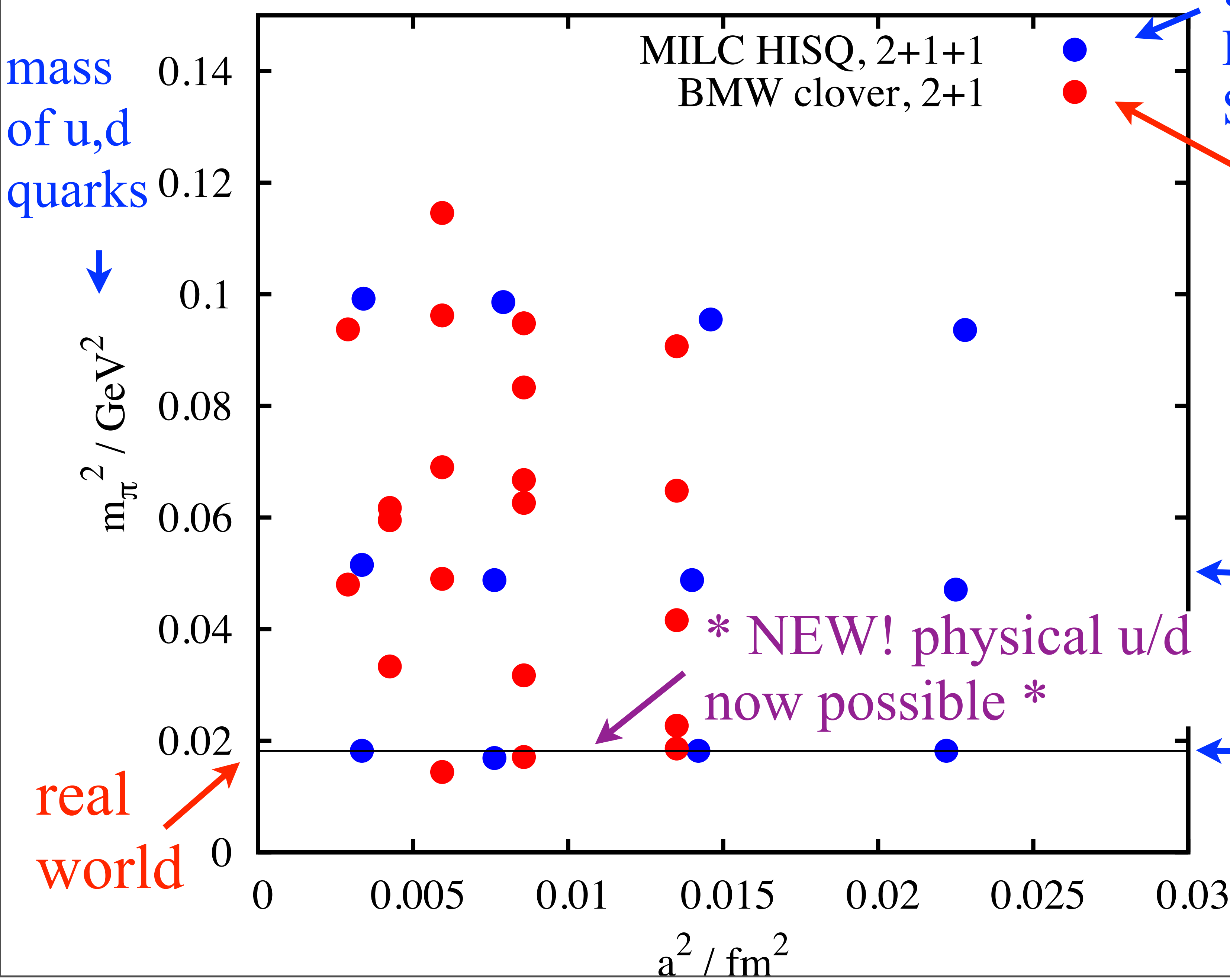
- Fit as a function of time to obtain masses and simple matrix elements

- 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 $m_{u,d}$*



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



u,d,s,c in sea
Highly Improved
Staggered Quarks

u,d,s in sea

Need volume:
$m_\pi L > 3$
and >500
independent
configurations

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

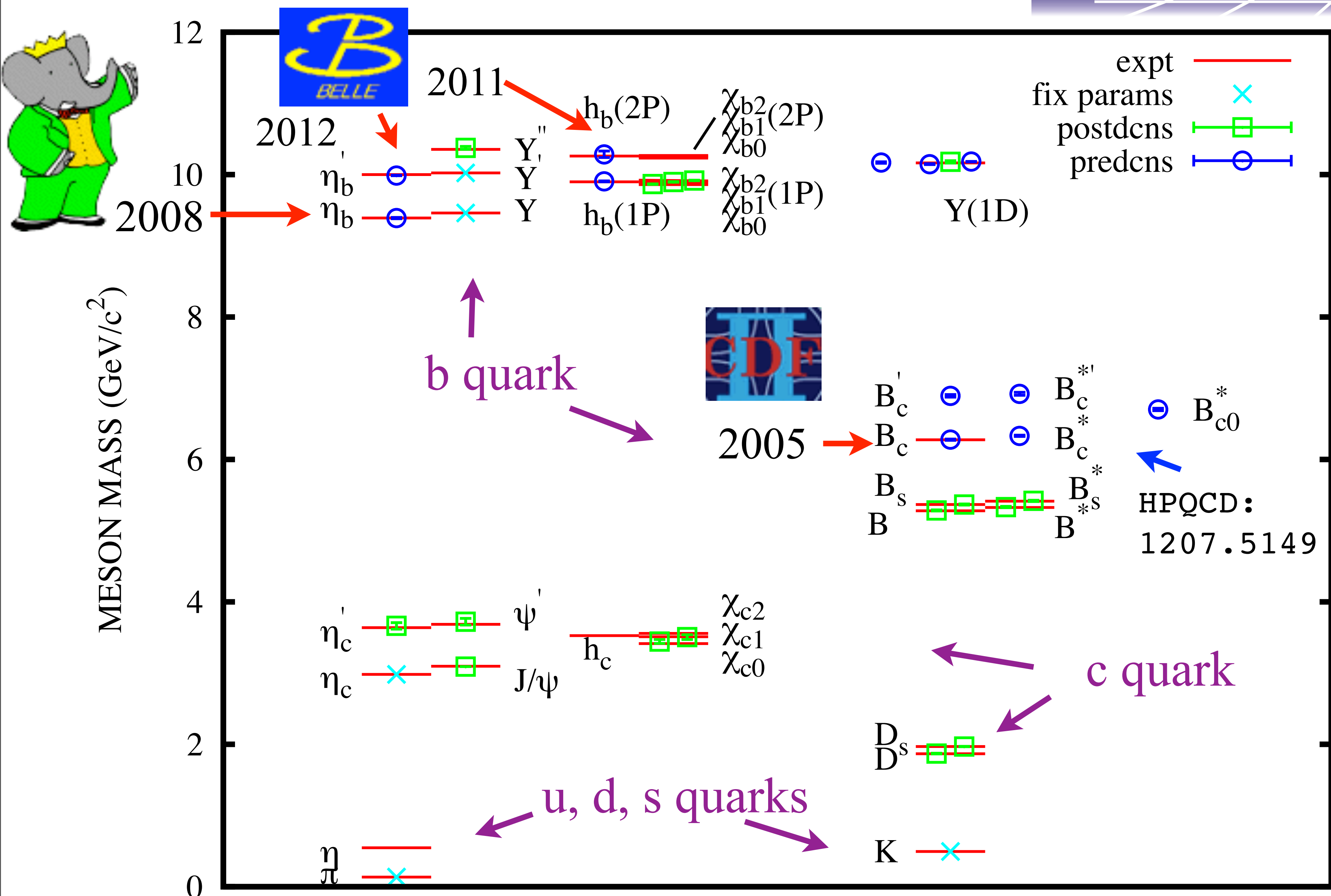
$m_{u,d} \approx m_s/27$

MILC:1212.4768
BMW: 1011.2711

RBC/UKQCD: dw
quarks underway

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

HPQCD



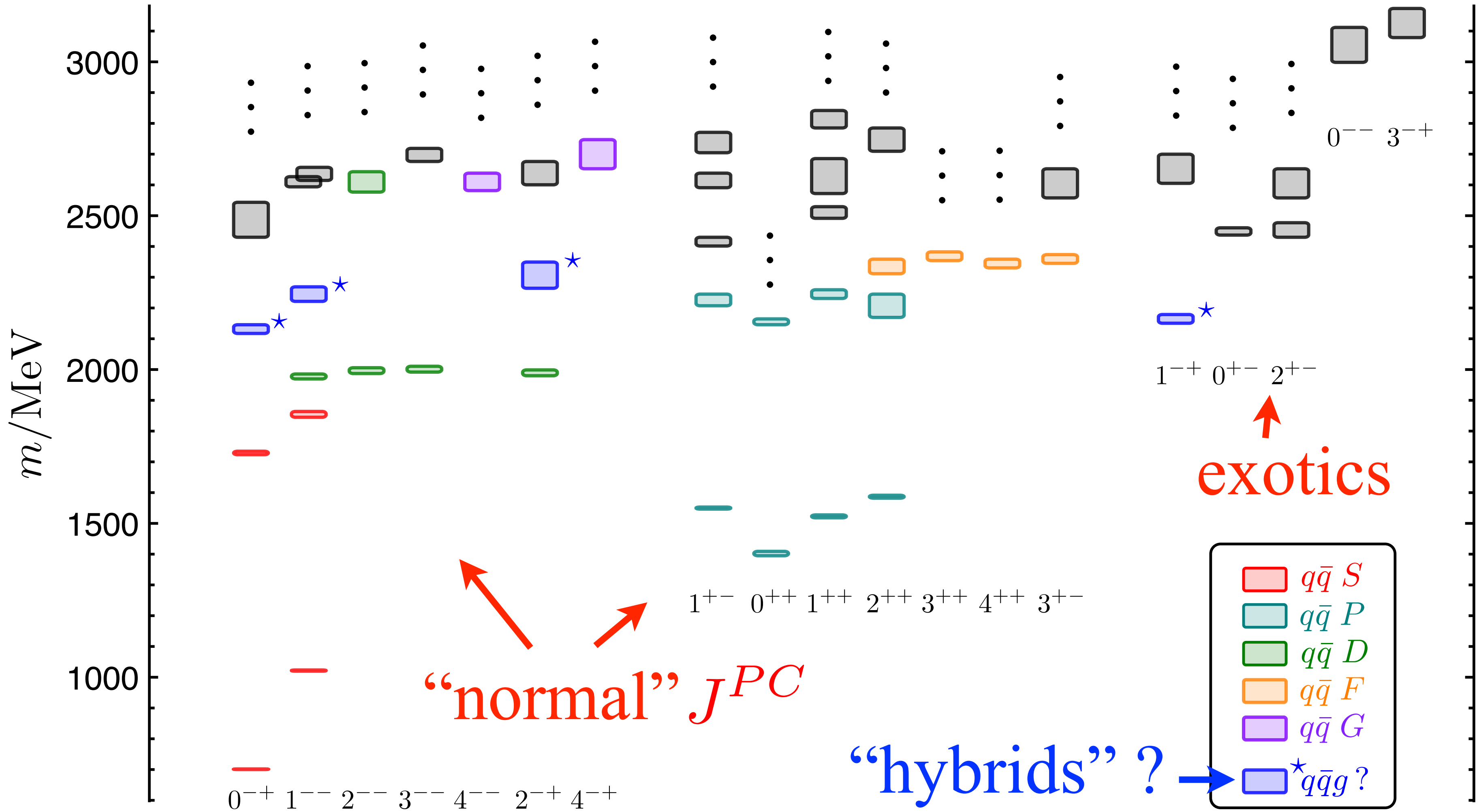
Agreement very good - errors typically a few MeV, need to worry about em, mu-md ..

Mapping excited states is harder ..

Hadron Spectrum:1004.4930
Dudek: Lattice2012
BGR: 1112.1601

Light isovectors: $\pi, \rho, \ldots$

(huge basis of single-hadron operators, but a=0.12 fm (anisotropic), mass π = 700 MeV)



lightest hybrid multiplet $= 1^{--}, (0,1,2)^{-+} = S\text{wave}\, q\bar{q}(0^{-+}, 1^{--}) \times g(1^{+-})$

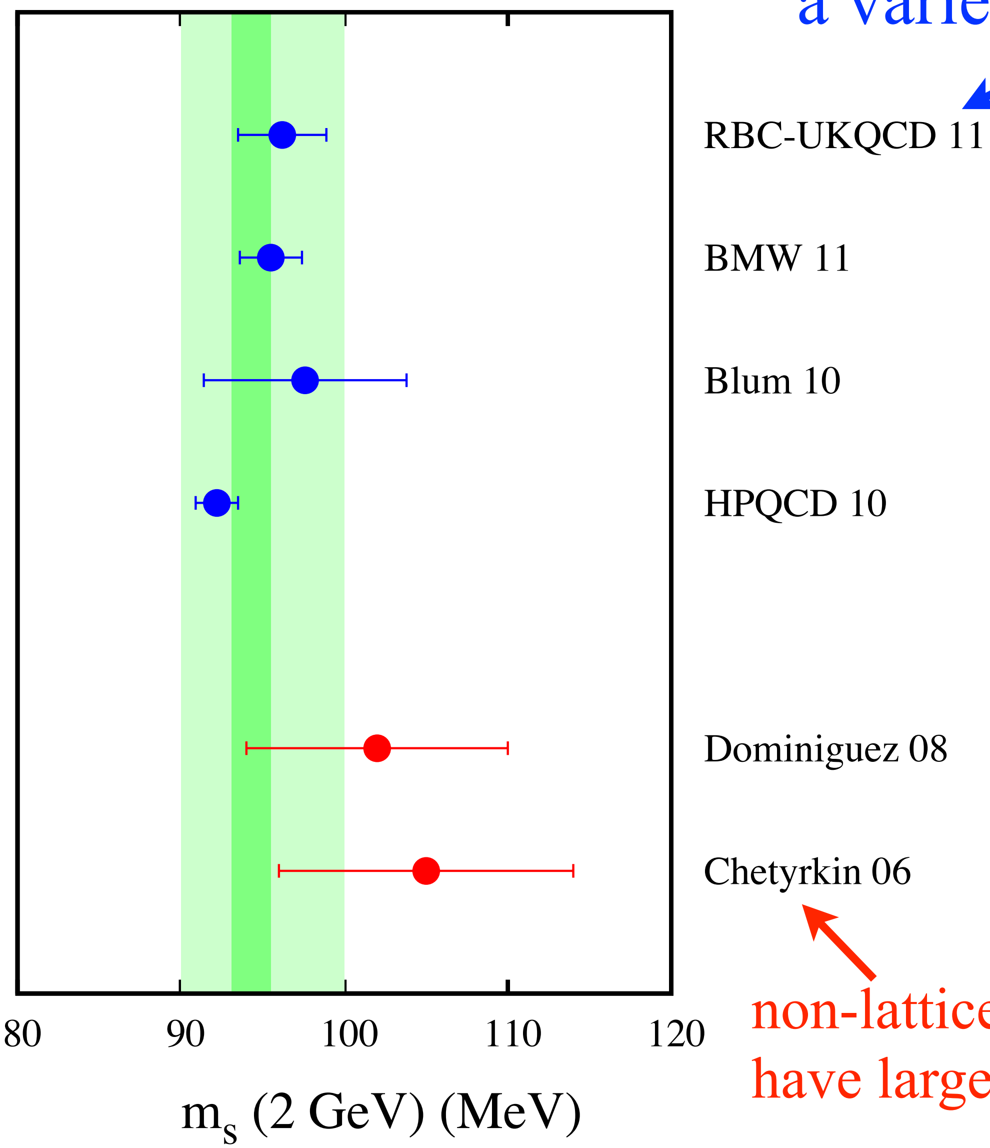
strong overlap with "gluey" operators $\quad \pi_1(1600), \pi(1800), \pi_2(1880) + 1^{--}?$

see also charmonium: Hadron Spectrum:1204.5425

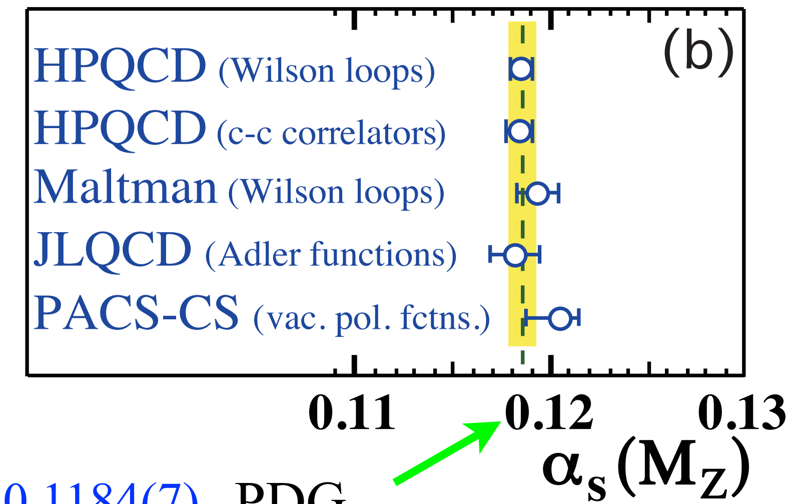
Lattice QCD sets world averages for quark masses and α_s

Direct access to parameters in QCD Lagrangian means systematic errors smaller

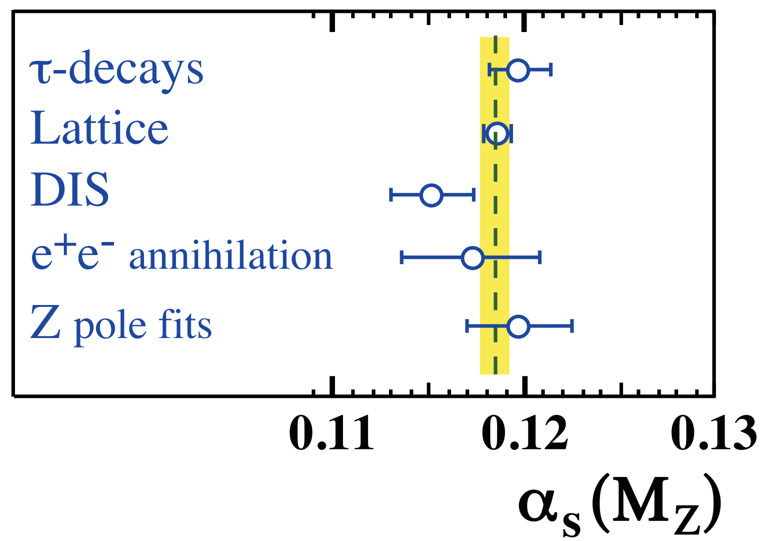
PDG av:94.3(1.2) MeV



a variety of lattice methods agree



av:0.1184(7) PDG



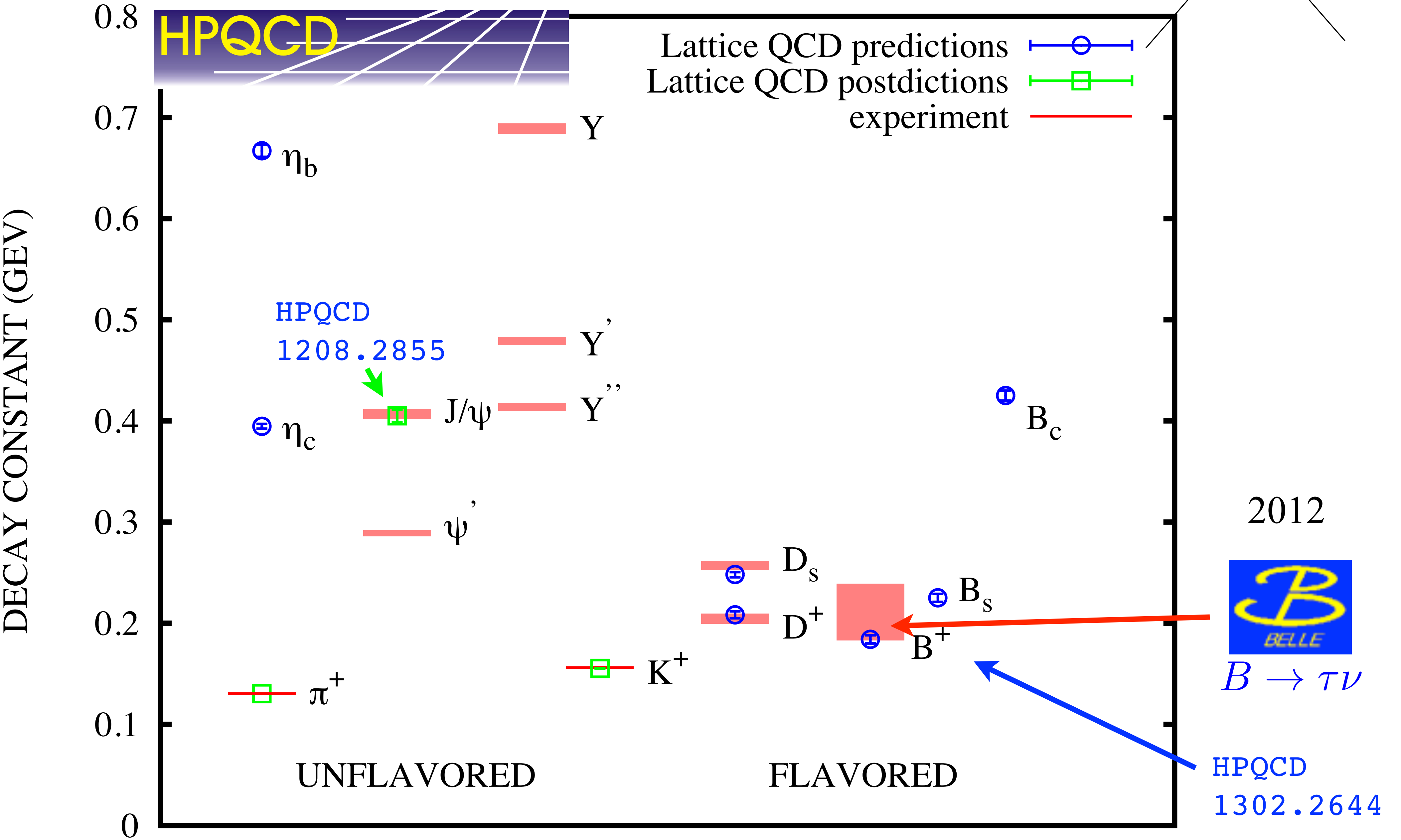
non-lattice methods have larger errors

Lattice calcs now adding QED for accurate m_u/m_d

`Izubuchi:Lattice2012; RM123: 1303.4896`

Meson decay constants

Parameterises hadronic information needed for annihilation rate to W or photon: $\Gamma \propto f^2$

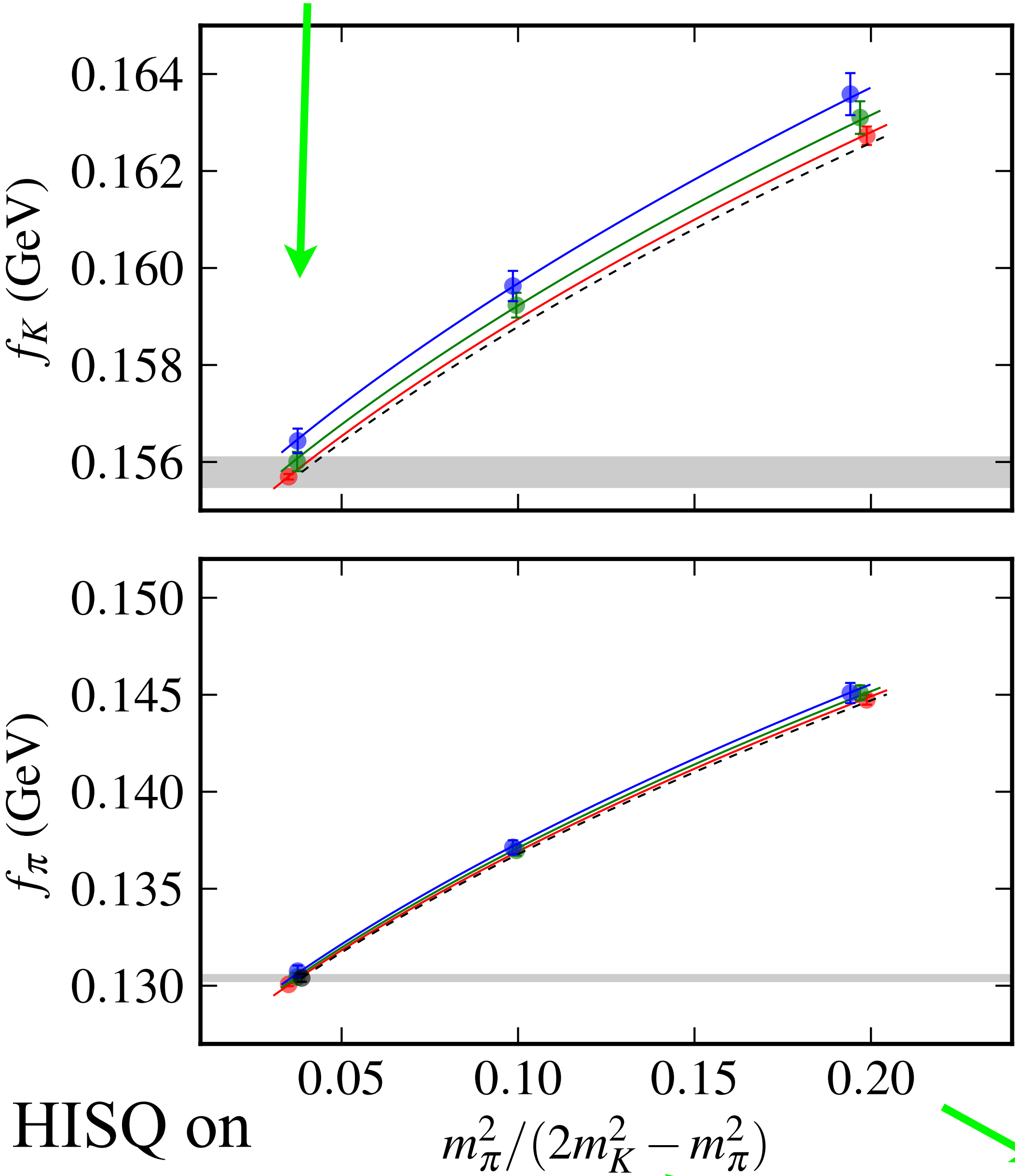


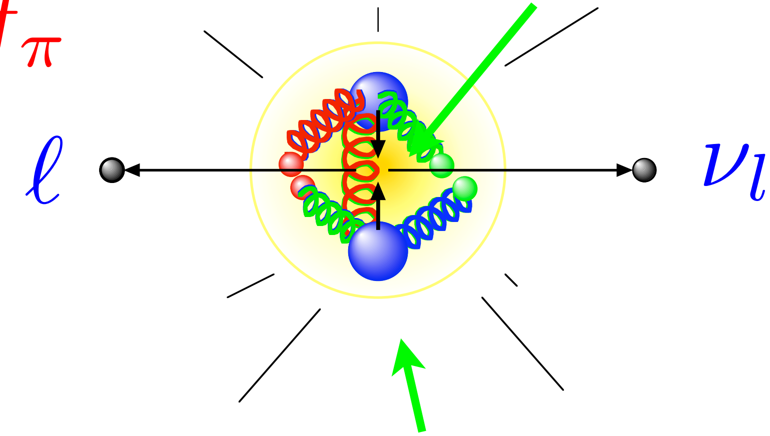
Constraining new physics with lattice QCD

V_{us}/V_{ud}

* results at physical u/d quark masses*

f_K/f_π





Annihilation of K/π to W allows CKM element determination given decay constants from lattice QCD

expt for $\dfrac{\Gamma(K^+ \to \ell\nu)}{\Gamma(\pi^+ \to \ell\nu)}$

$$\frac{|V_{us}|f_{K^+}}{|V_{ud}|f_{\pi^+}} = 0.27598(35)_{\mathrm{Br}(K^+)}(25)_{EM}$$

HISQ on MILC configs

HPQCD:1301.1670

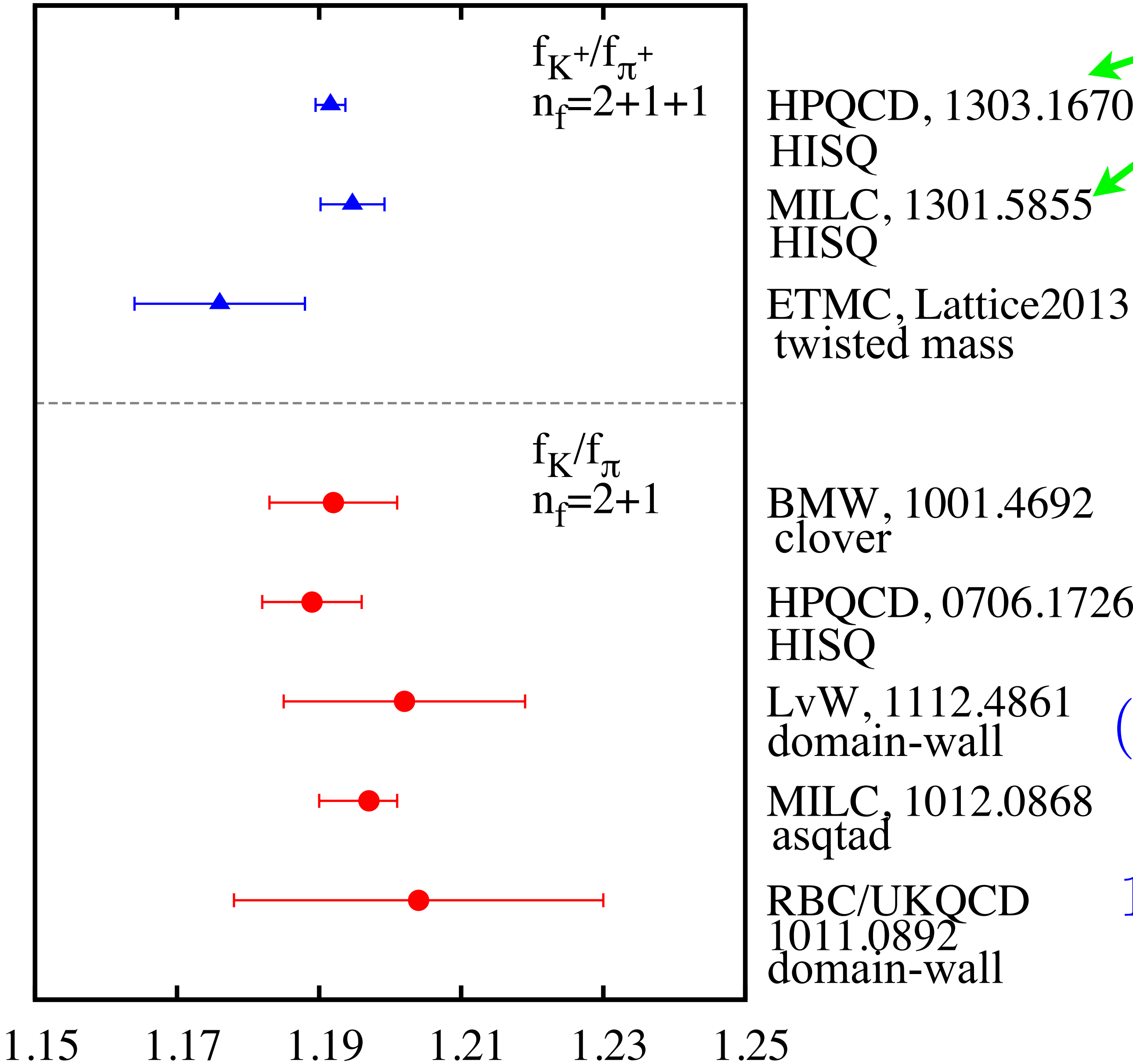
$= m_{u,d}/m_s$

$\dfrac{f_{K^+}}{f_{\pi^+}}$ from lattice gives CKM

Comparison of results (note: $f_{K^+} < f_K$)

RM123:1303.4896 gives by 0.40(4)%

good agreement from different formalisms



* results at physical u/d quark masses*

$$\frac{f_{K^+}}{f_{\pi^+}} = 1.1916(21)$$

$$\frac{|V_{us}|}{|V_{ud}|} = 0.23160(29)_{expt}(21)_{EM}(41)_{latt}$$

$$|V_{us}| = 0.22564$$

$$(28)_{\mathrm{Br}}(20)_{EM}(40)_{latt}(5)_{V_{ud}}$$

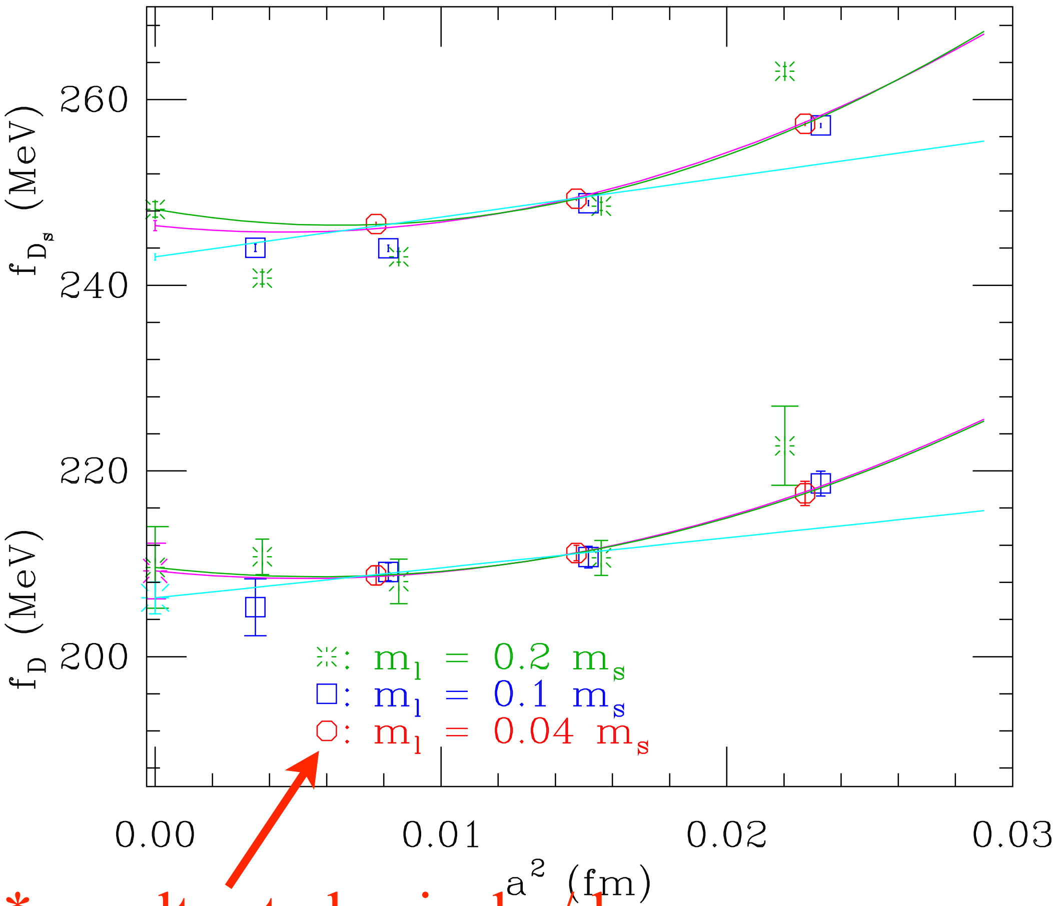
$$1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2$$

$$= -0.00009(51)$$

V_{ud} from nuclear β decay now needs improvement for unitarity test!

Constraining new physics with lattice QCD: f_{D_s}, f_D

MILC:1210.8431 new results using HISQ quarks on MILC 2+1+1 configs



MILC (Lattice2013):

$$f_{D_s} = 247.2(2.2)\text{MeV}$$

$$f_D = 211.4(1.6)\text{MeV}$$

agree well with previous HPQCD:

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

HPQCD:1008.4018

$$f_D = 208.3(3.4)\text{MeV}$$

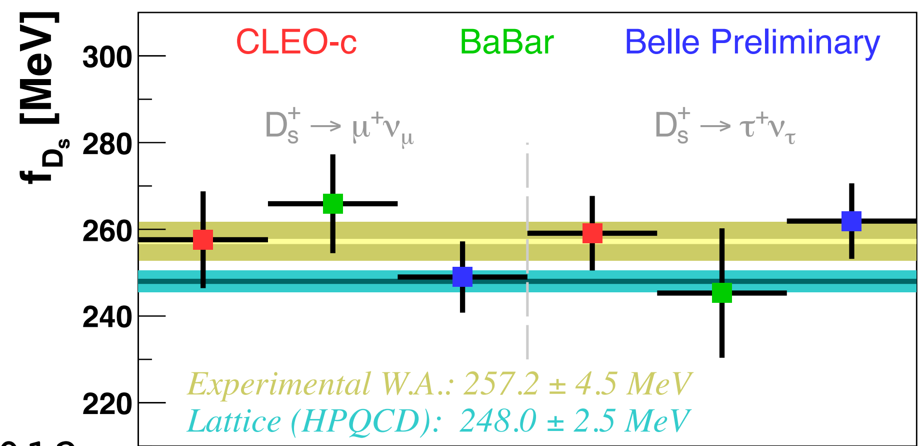
HPQCD:1206.4936

* results at physical u/d quark masses*

experimental update: new Belle results

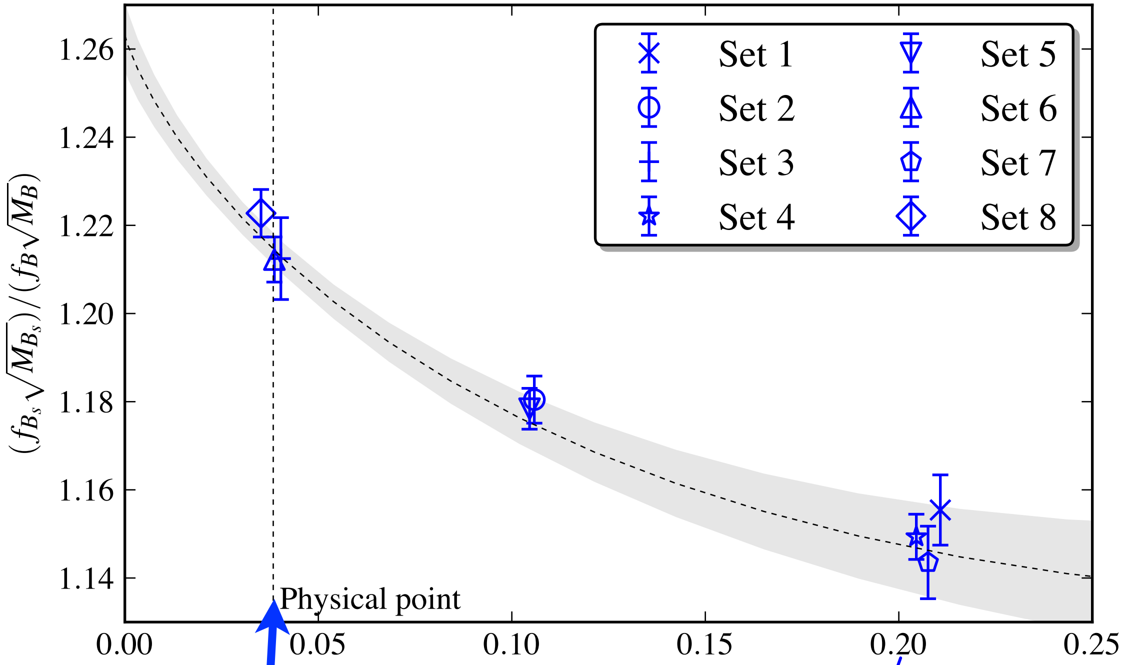
World av: $f_{D_s} = 257.2(4.5)\text{MeV}$

2σ above theory



Zupanc:charm2012

Constraining new physics with lattice QCD: f_{B_s}, f_B



$= m_l/m_s$

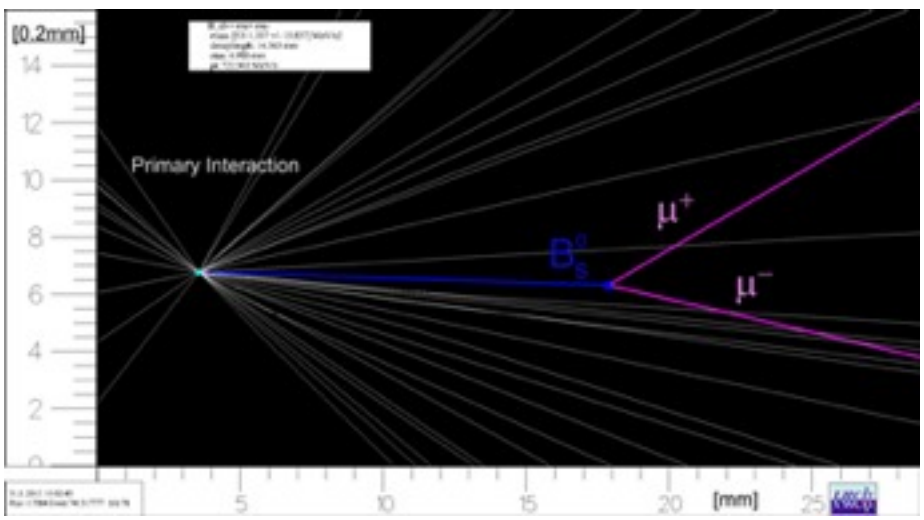
* results at physical u/d quark masses*

HPQCD: 1302.2644.

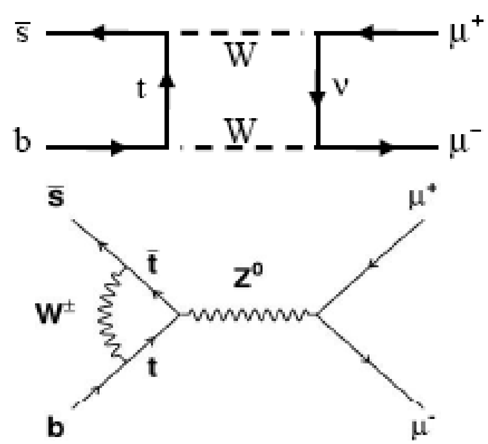
Uses improved NRQCD for b quark and HISQ u/d and s quarks on HISQ 2+1+1 gluon configs

$$f_{B_s} = 224(5)\text{MeV}$$

$$\text{Br}(B_s \to \mu^+\mu^-) = 3.47(19)\times 10^{-9}$$

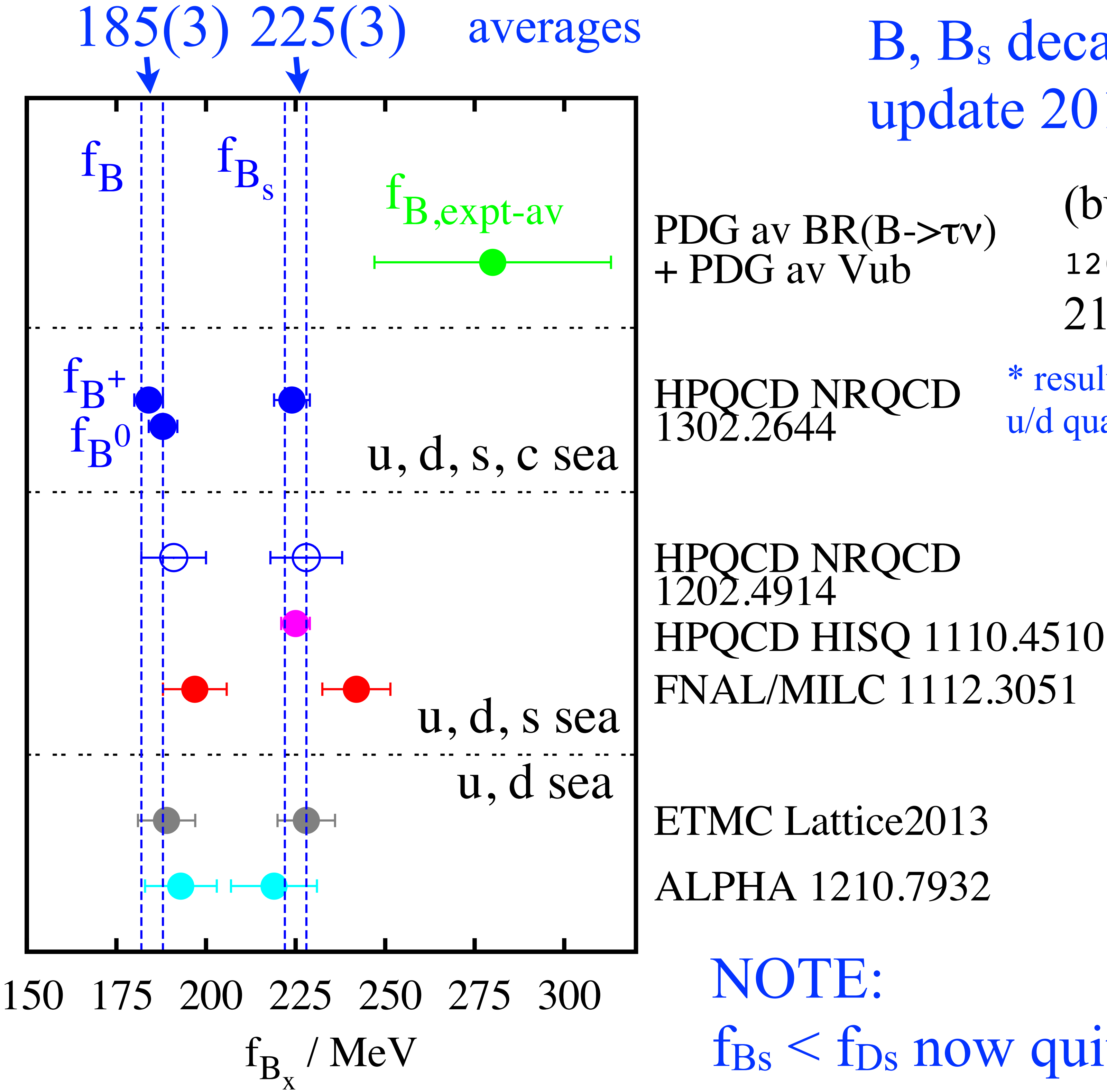


Standard Model processes:



Nov. 2012

B, B_s decay constant update 2013



(but Belle 1208.4678 = 211(28) MeV)

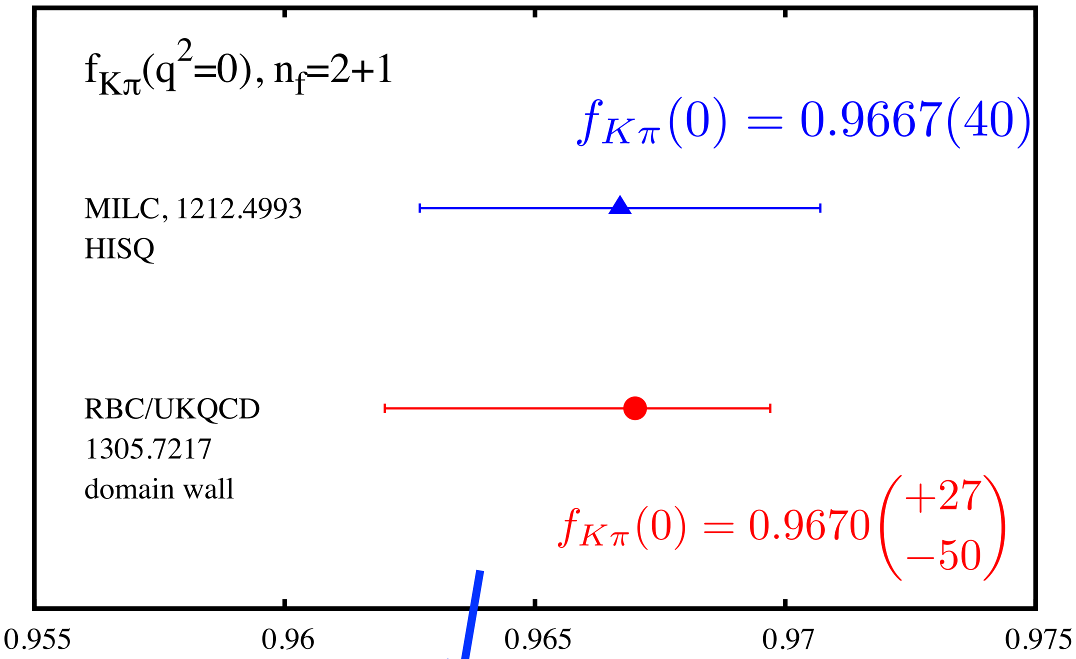
* results at physical u/d quark masses*

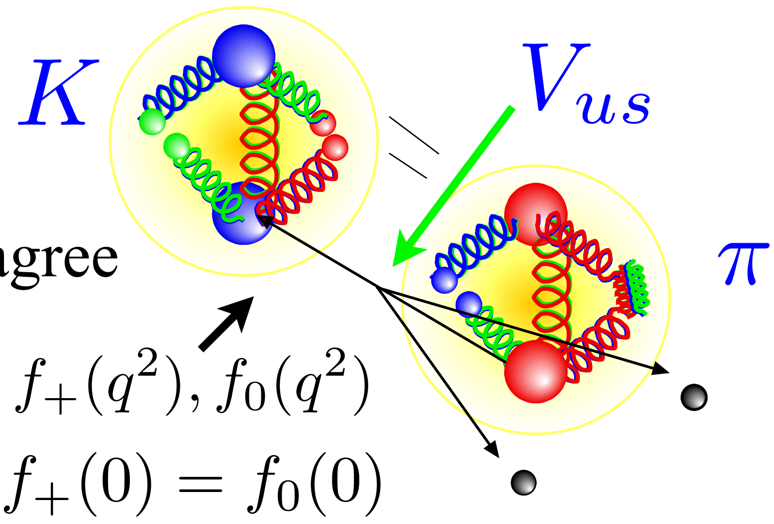
NOTE:
$f_{Bs} < f_{Ds}$ now quite clear

Constraining new physics with lattice QCD: form factors

$K \to \pi \ell \nu$

NEW - now results with full continuum and chiral extrapolation. Different formalisms agree





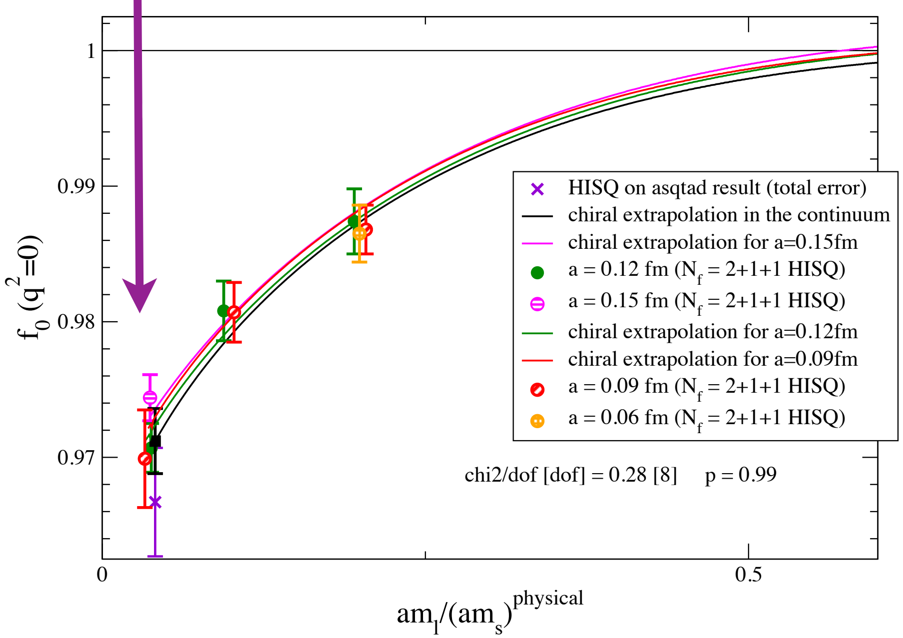
with experiment:

$$|V_{us}| f_{K\pi}(0) = 0.2163(5)$$

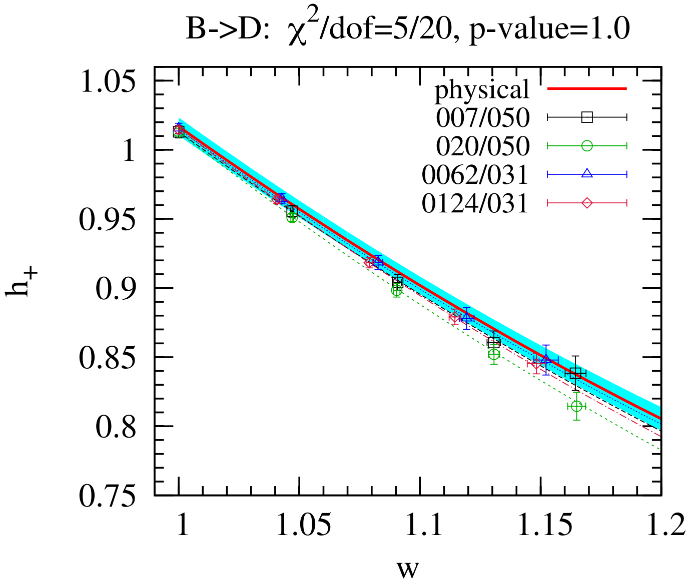
1005.2323

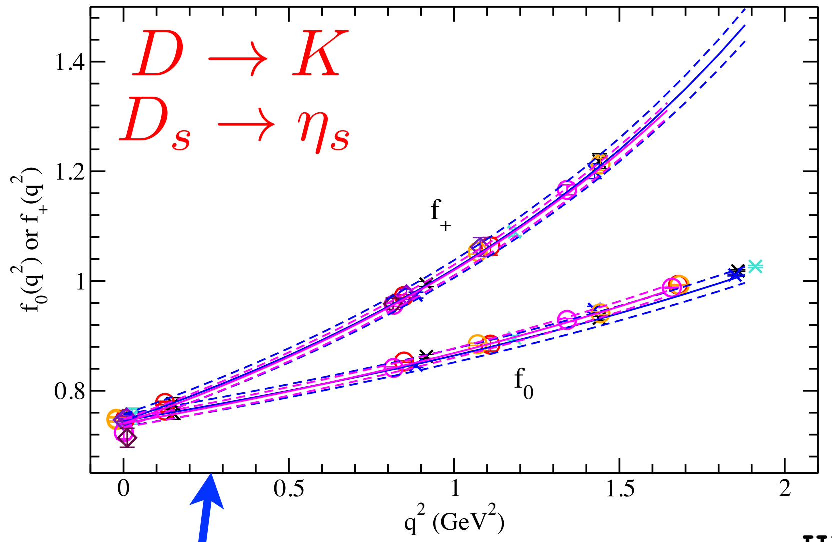
$$|V_{us}| = 0.2238(11)$$

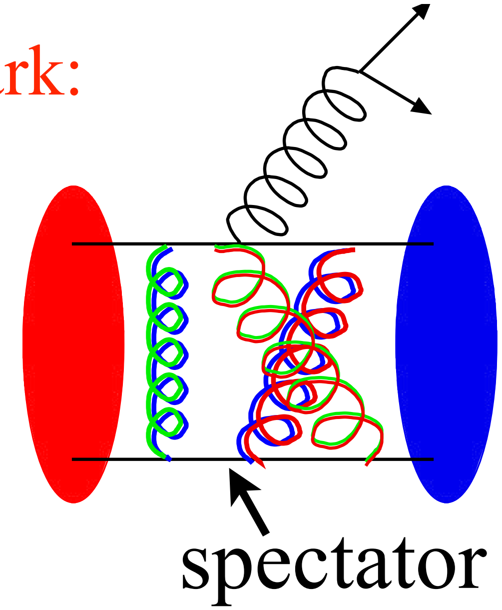
MILC in progress: HISQ results with physical u/d quarks - expect ~0.3% error



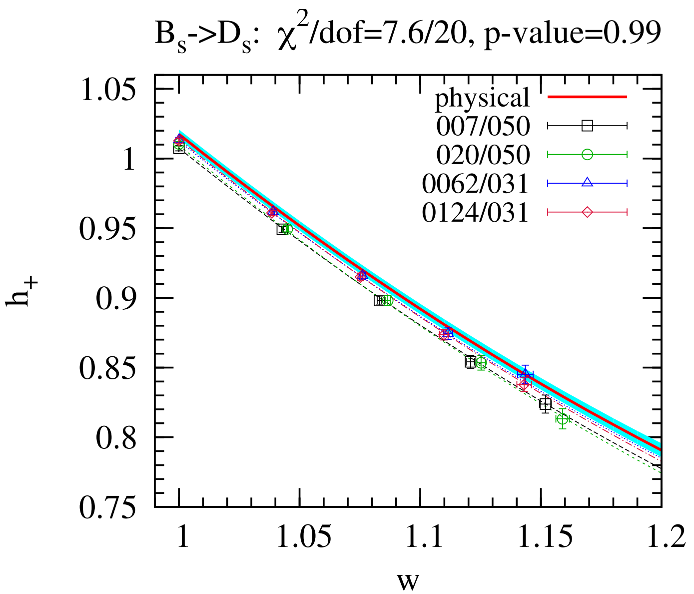
Form factor shapes and dependence on spectator quark:







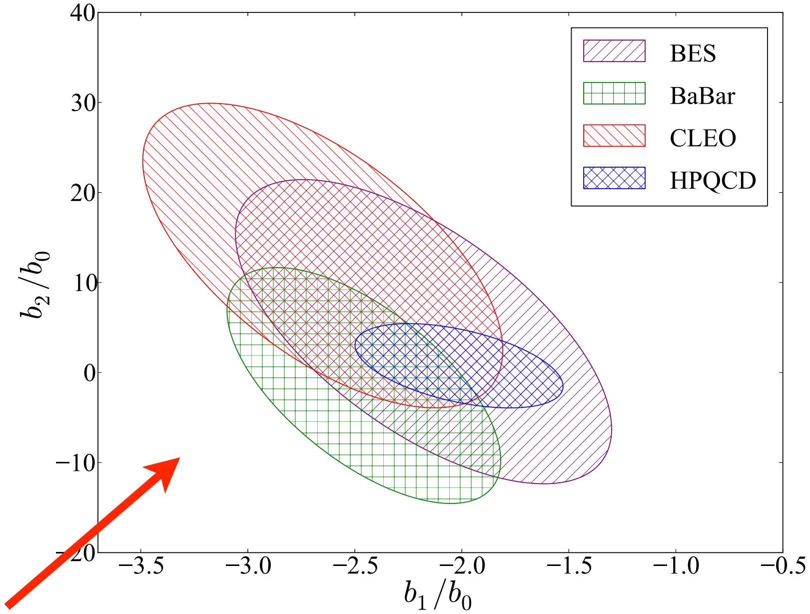
HPQCD: 1305.1462.



$c \to s$

$b \to c$

form factors same for light or strange spectator



Fermilab/MILC:1202.6346. determined ff ratio to use in normln of $B_s \to \mu^+\mu^-$

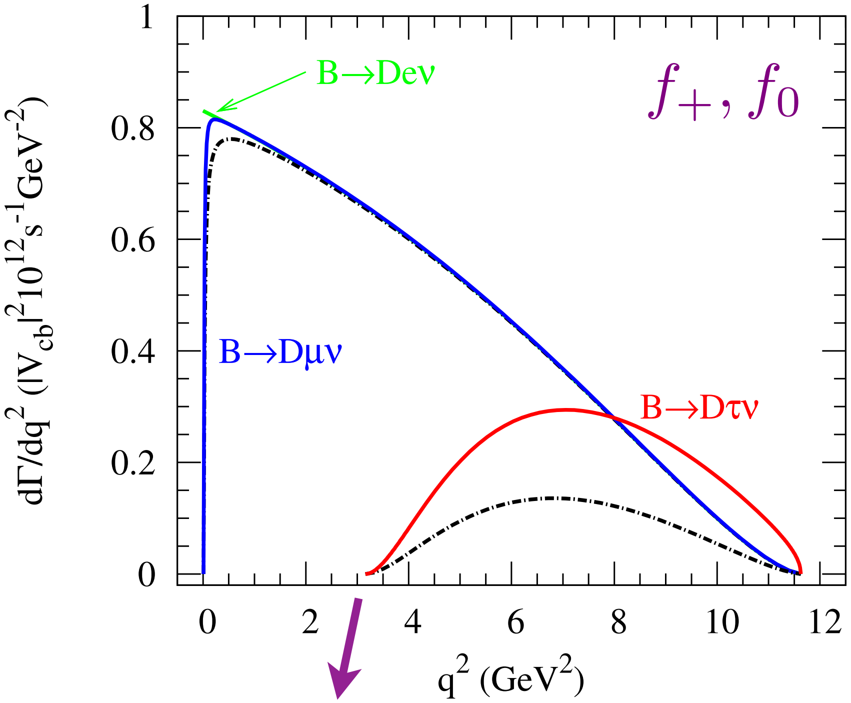
compare f+ shape parameters: lattice and expt.

$D \to K\ell\nu$

B semi-leptonic decays and constraints on new physics

B decays with τ in final state are sensitive to form factors suppressed by lepton masses for e, μ so may see new physics.

$B \to D\ell\nu$ Fermilab/MILC: 1206.4992.

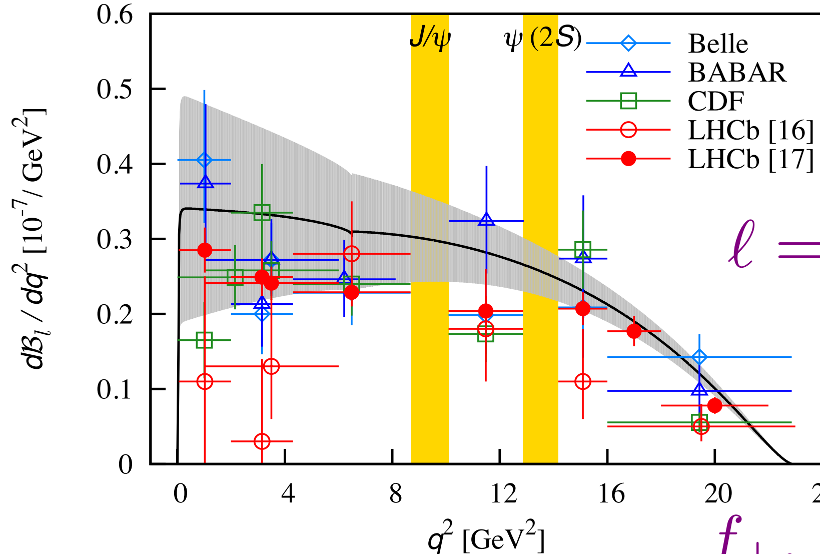


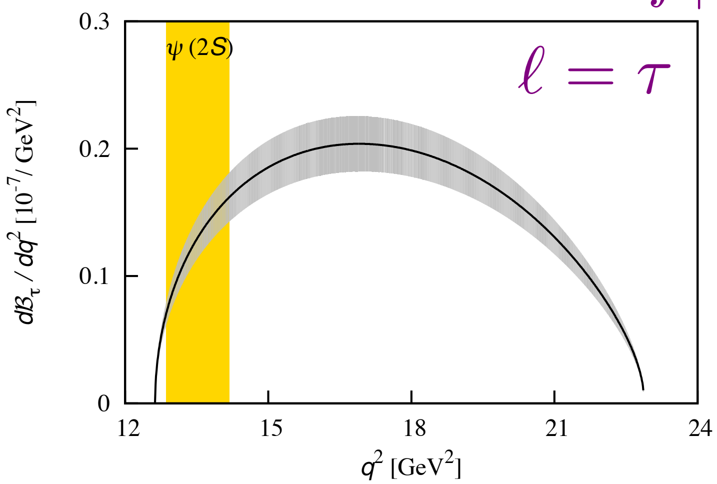
$$\frac{\text{Br}(B \to D\tau\nu)}{\text{Br}(B \to D\ell\nu)} = 0.316(14)$$

$\ell = e, \mu$

BaBar:1205.5442; 1303.0571 $= 0.440(72)$

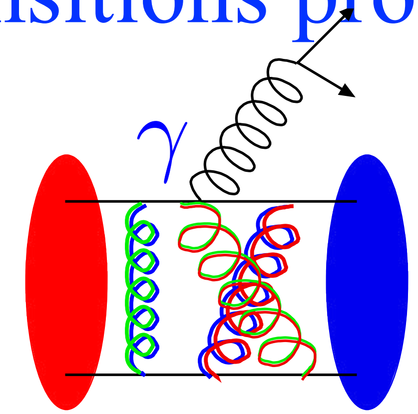
$B \to K\ell^+\ell^-$ HPQCD: 1306.0434; 1306.2384.



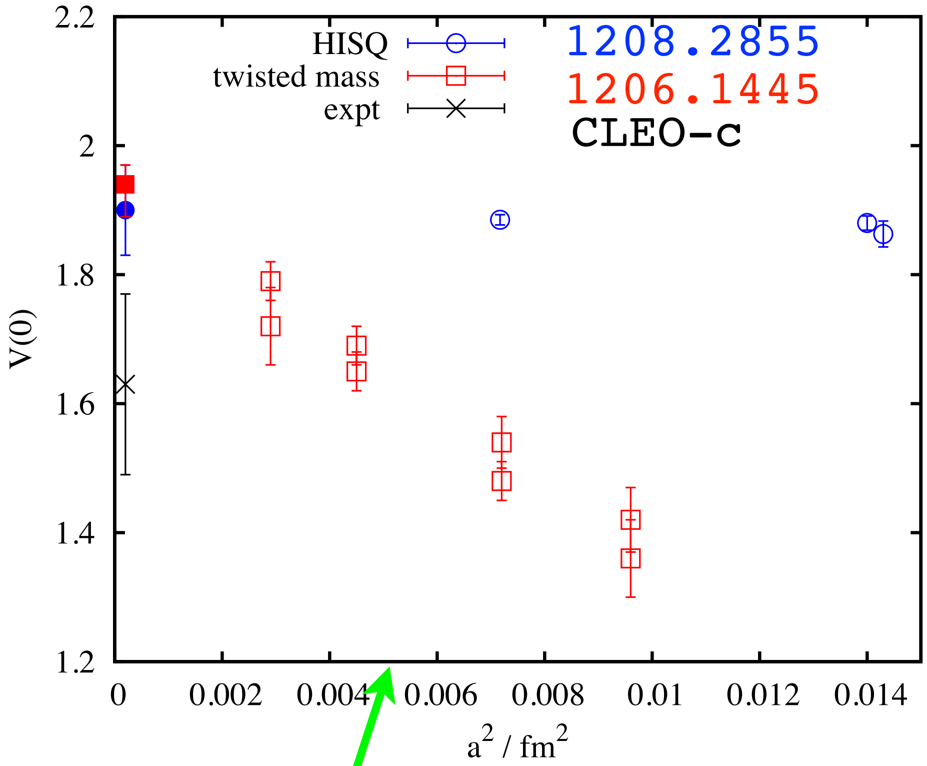


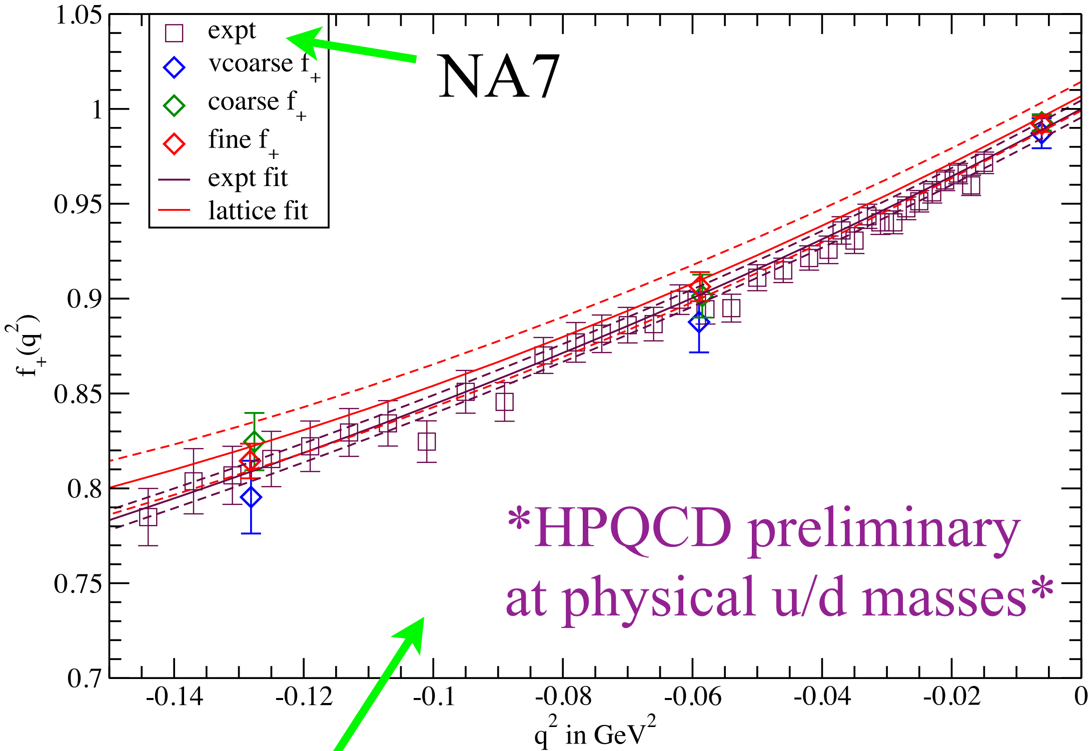
Electromagnetic transitions provide important tests

$$J/\psi \to \gamma \eta_c$$



pion electromagnetic form factor





Different quark formalisms agree. Lattice more accurate than experiment.

Test lattice QCD vs direct experiment at low spacelike q^2 ; $<r^2>$ sensitive to light quark mass

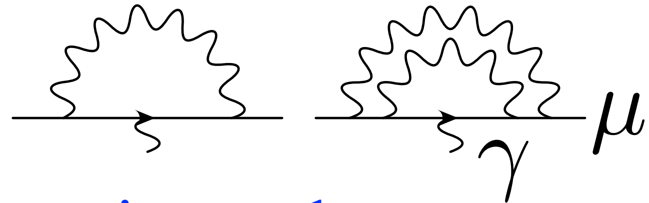
ETMC: 0812.4042; JLQCD:0810.2590; Mainz:1306.2916

Muon anomalous magnetic moment

$$\vec{\mu} = g\frac{e}{2m}\vec{S}$$

anomaly $a_\mu = \dfrac{g-2}{2} = \mathcal{O}(10^{-3})$

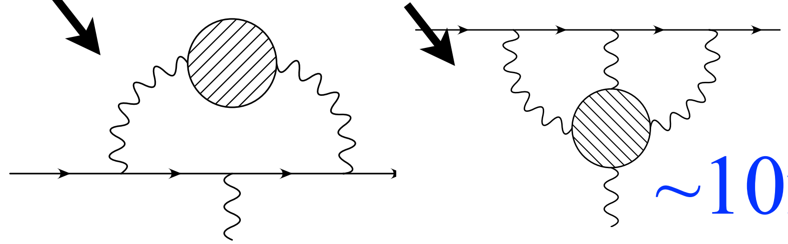
e.g. from QED:



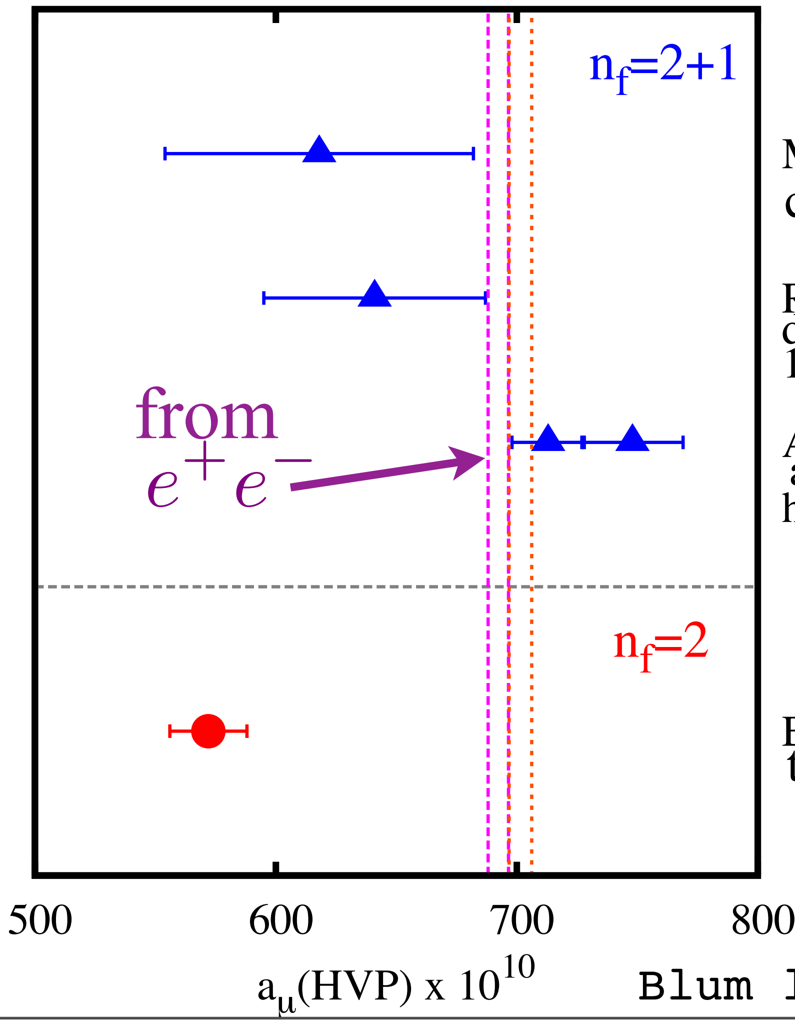
$a_\mu^{expt} - a_\mu^{SM} \approx 29(8)\times 10^{-10} = 3\sigma$ mismatch

BNL, to be improved at FNAL and J-PARC

QCD contribn from hadronic vac. pol and 'light-by-light'.



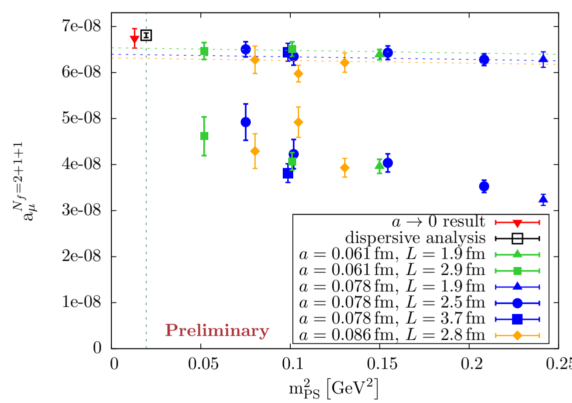
~10x 10^{-10}



Progress on HVP

HLBL needs QCD+QED

ETM underway : nf=2+1+1



Blum lattice2012:1301.2607

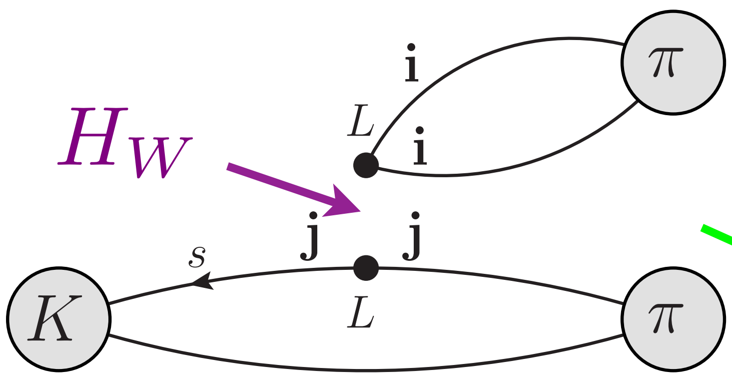
Tuesday, 25 June 2013

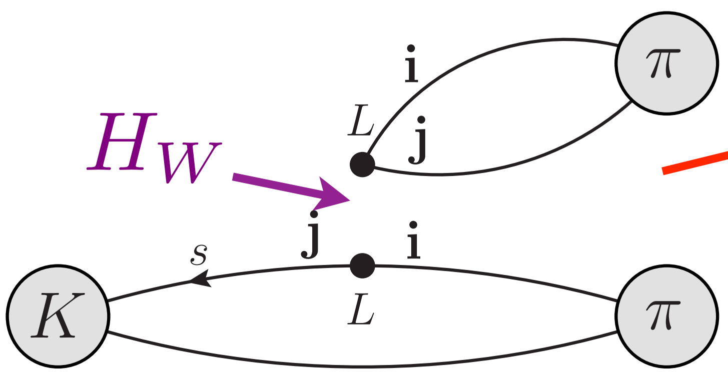
$K \to \pi\pi$ and the $\Delta I = 1/2$ rule

$K \to \pi\pi_{I=2}$ 450 times more likely than $K \to \pi\pi_{I=0}$

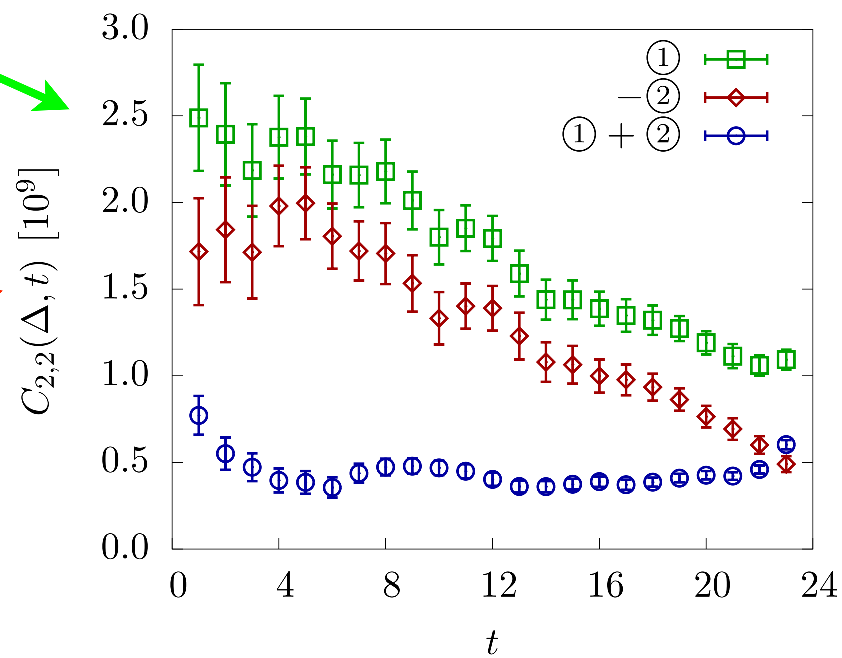
→ nonperturbative enhancement of matrix elements of 4-quark operators from weak Hamiltonian

I=2 amplitude now calculated directly in lattice QCD; I=0 underway





Find cancellation in A_2 between different color contractions of key operator (same effect will enhance A_0) .



naive expectn: (ME2)=(ME1)/3

`Christ: Lattice2012;`
`RBC/UKQCD: 1212.1474; 1111.1699`

Ken Wilson

1936-2013

Originator of Lattice QCD

Conclusion

• Lattice QCD results for gold-plated meson masses, decay constants and form factors provide stringent tests of QCD/ Standard Model.

• Gives QCD parameters and some CKM elements to 1-2% and constrains Beyond the Standard Model physics.

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')

also can include charm in the sea now.

• v. high statistics/large volumes needed for harder calculations (precision baryon physics, flavor singlet /glueball spectroscopy, excited states, nuclear physics) will become available with increased computer power...

Lattice 2013: Mainz, July 29th www.lattice2013.uni-mainz.de