Hadron physics from Lattice QCD

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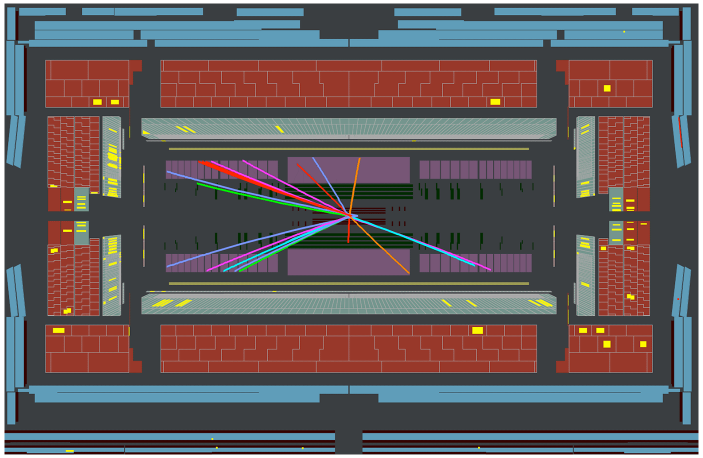
HPQCD collaboration

INPC2013
Florence, June 2013

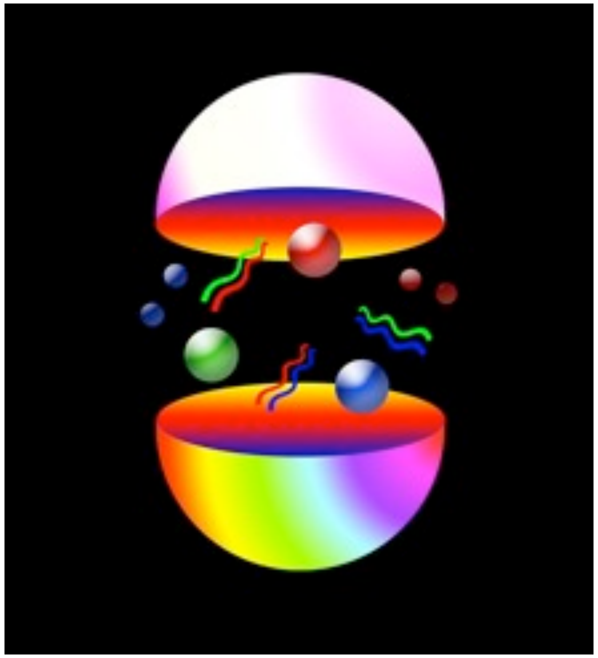
QCD is a key part of the Standard Model but quark confinement is a complication/interesting feature.

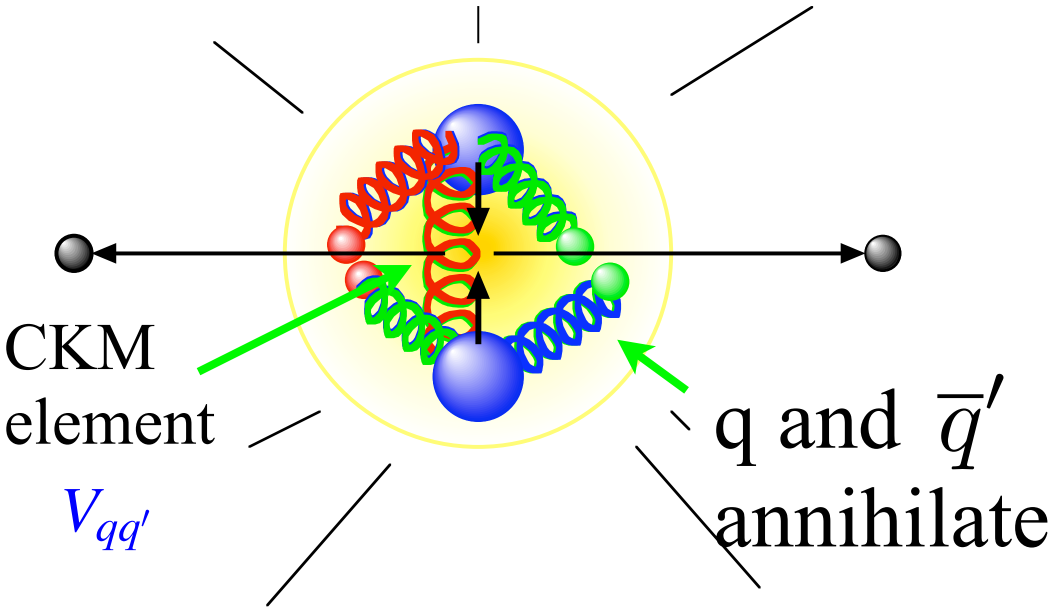


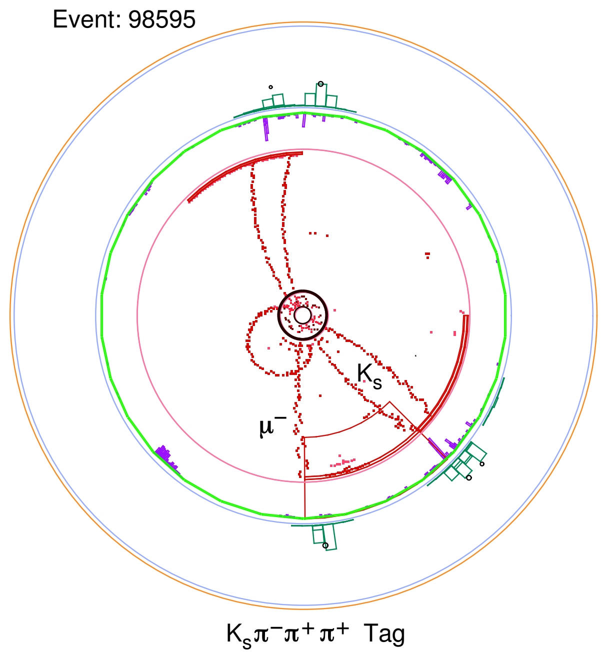
vs

ATLAS@LHC

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



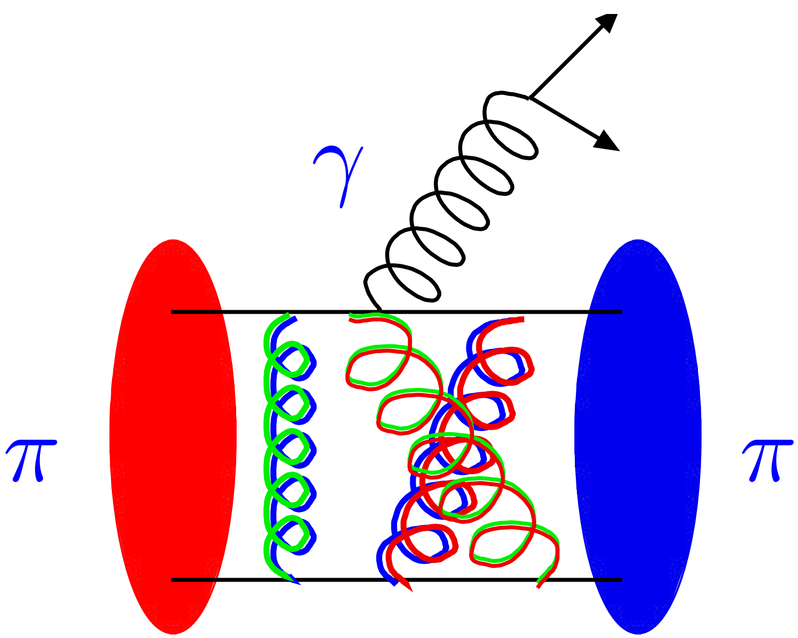




CLEO-c

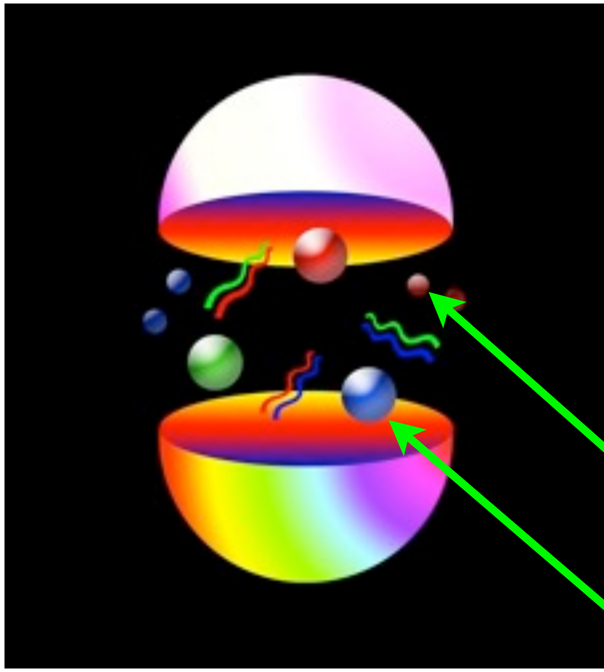
$D_s \to \mu\nu$

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



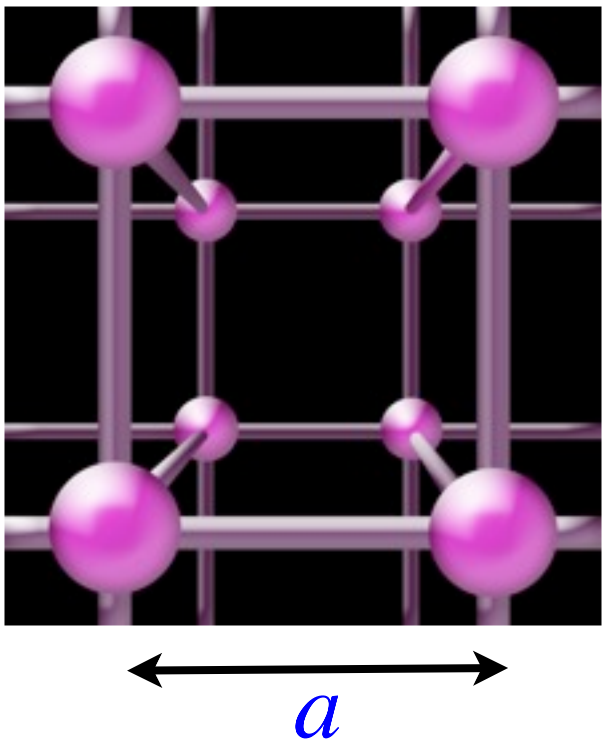
Rates for simple weak or em quark processes inside hadrons also calculable,
but *not* multi-hadron final states in general.

Lattice QCD = fully nonperturbative QCD calculation

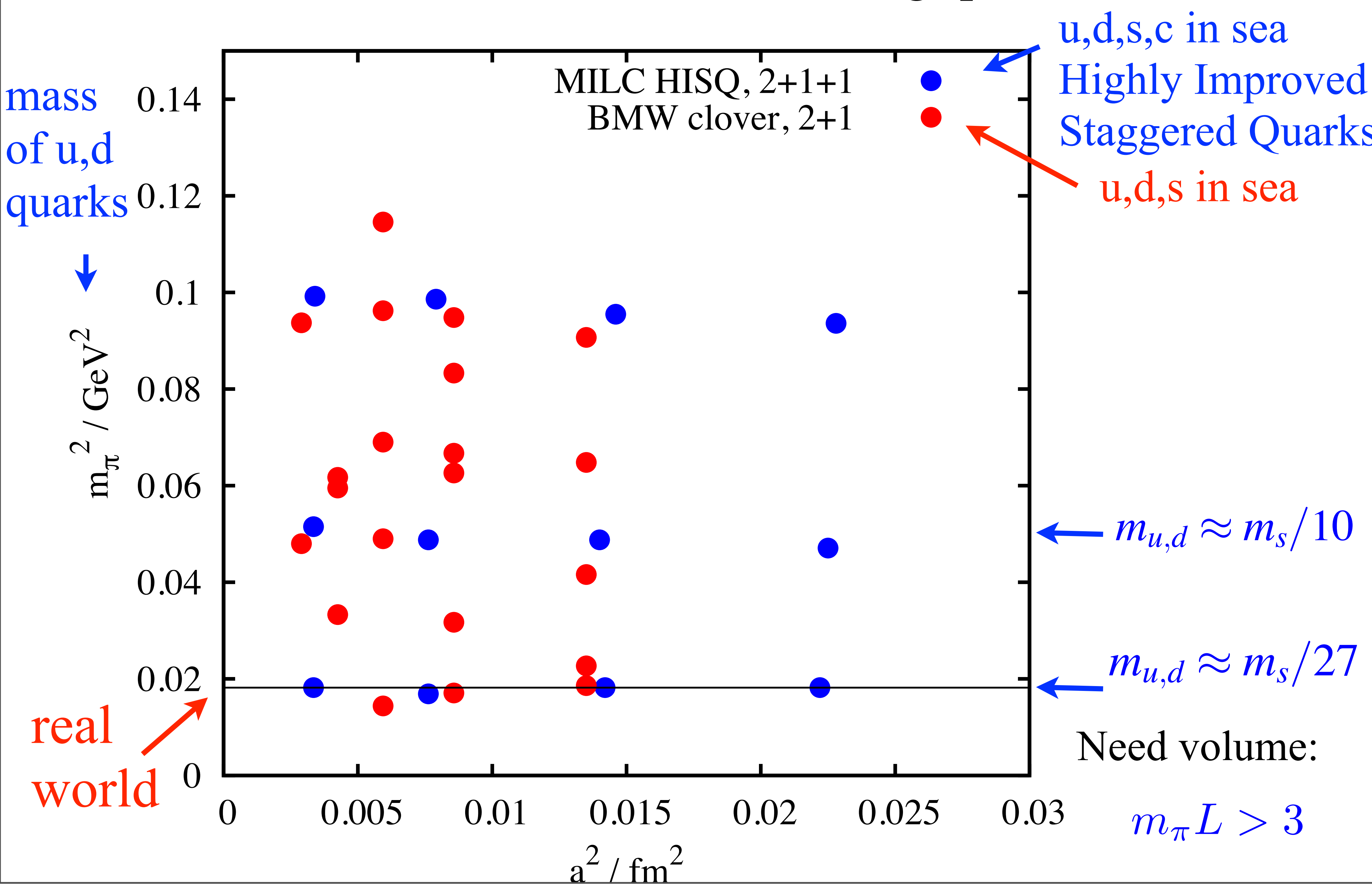


RECIPE

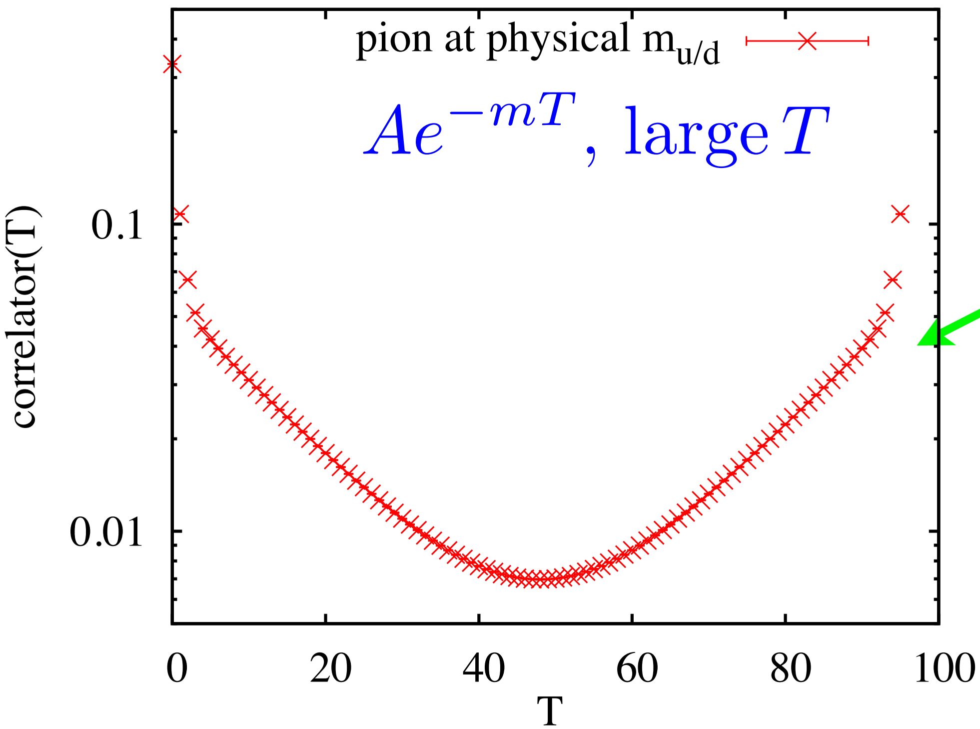
- Generate sets of gluon fields for Monte Carlo integrn of Path Integral (inc effect of u, d, s (+ c) sea quarks)
- Calculate averaged "hadron correlators" from valence q props.
- Fit as a function of time to obtain masses and simple matrix elements
- Determine a and fix m_q to get results in physical 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.



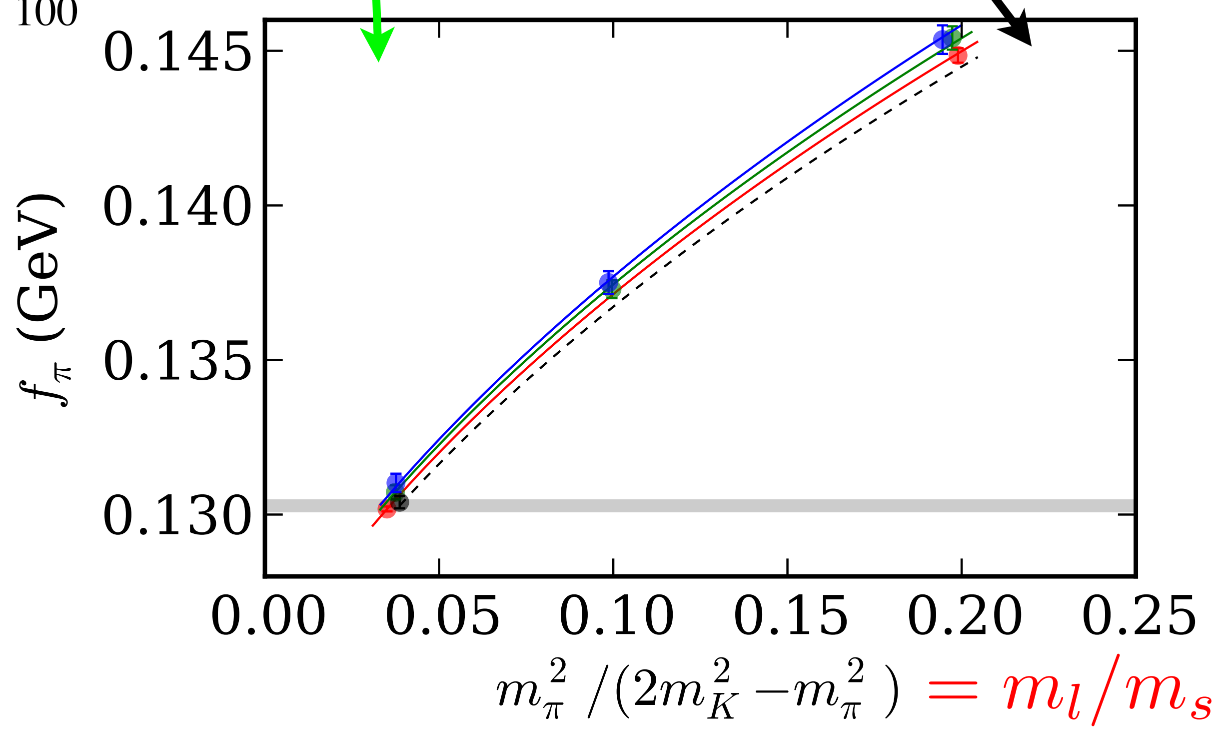
Example (state-of-the-art) calculation



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

NEW results at physical $m_{u/d}$

Extrapolation in a

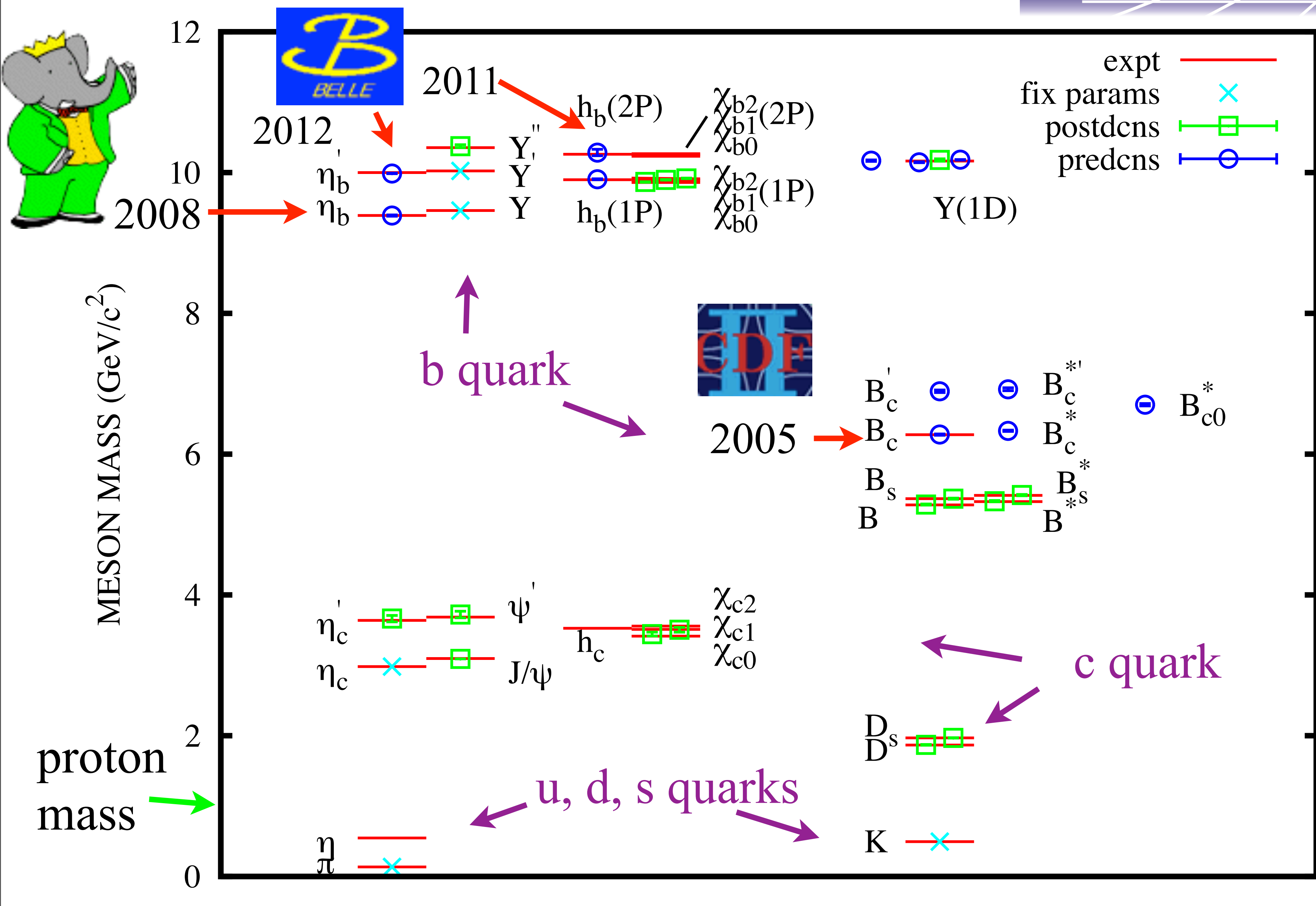


Convert decay constant to GeV units using a. Fit as a function of meson mass and a to obtain continuum physical result.

R. Dowdall et al, HPQCD, 1303.1670

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

HPQCD

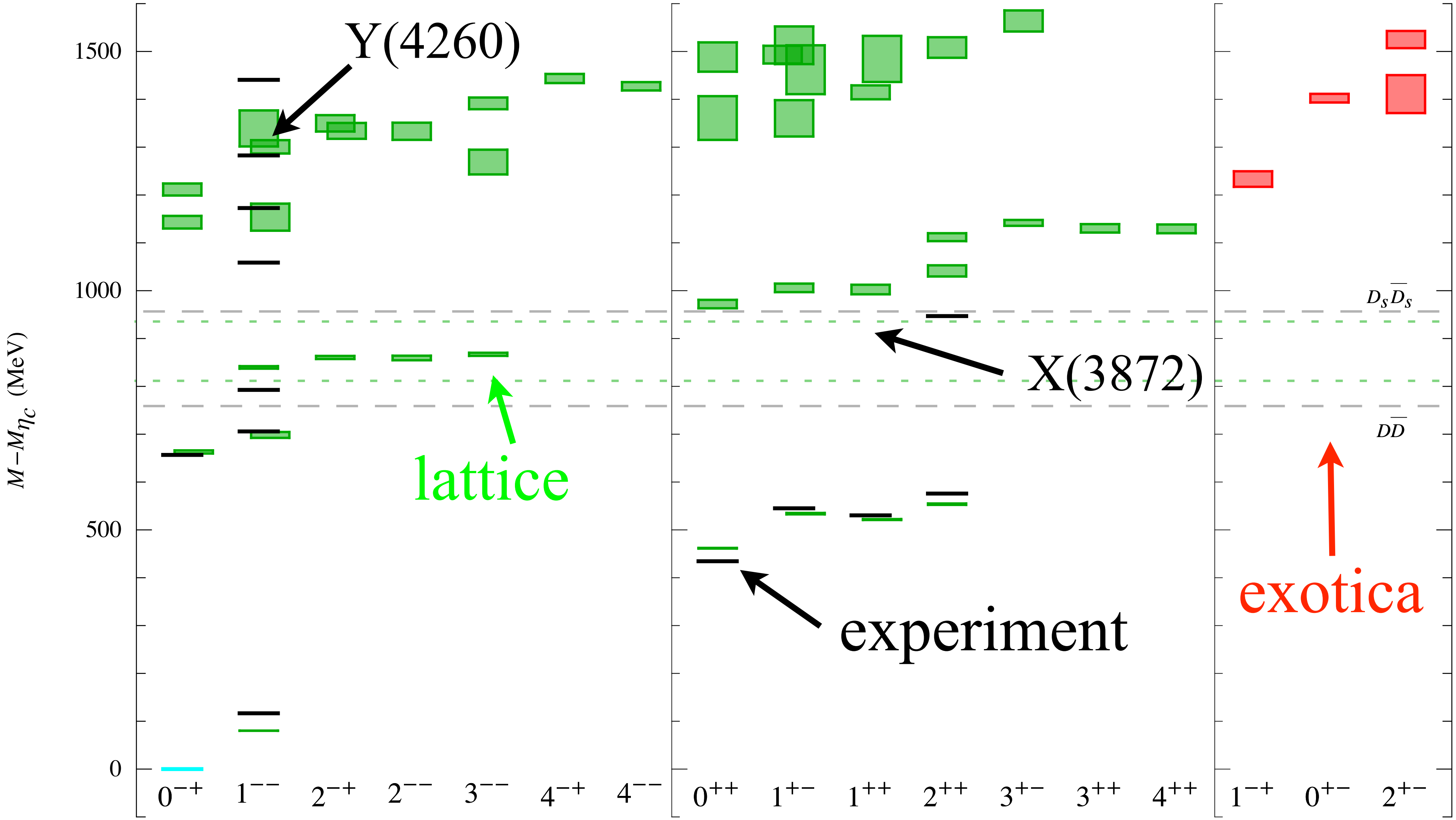


Agreement very good - errors typically a few MeV, need to worry about em, mu-md ..

Mapping excited states is harder ..

Hadspec:1204.5425

Charmonium spectrum:

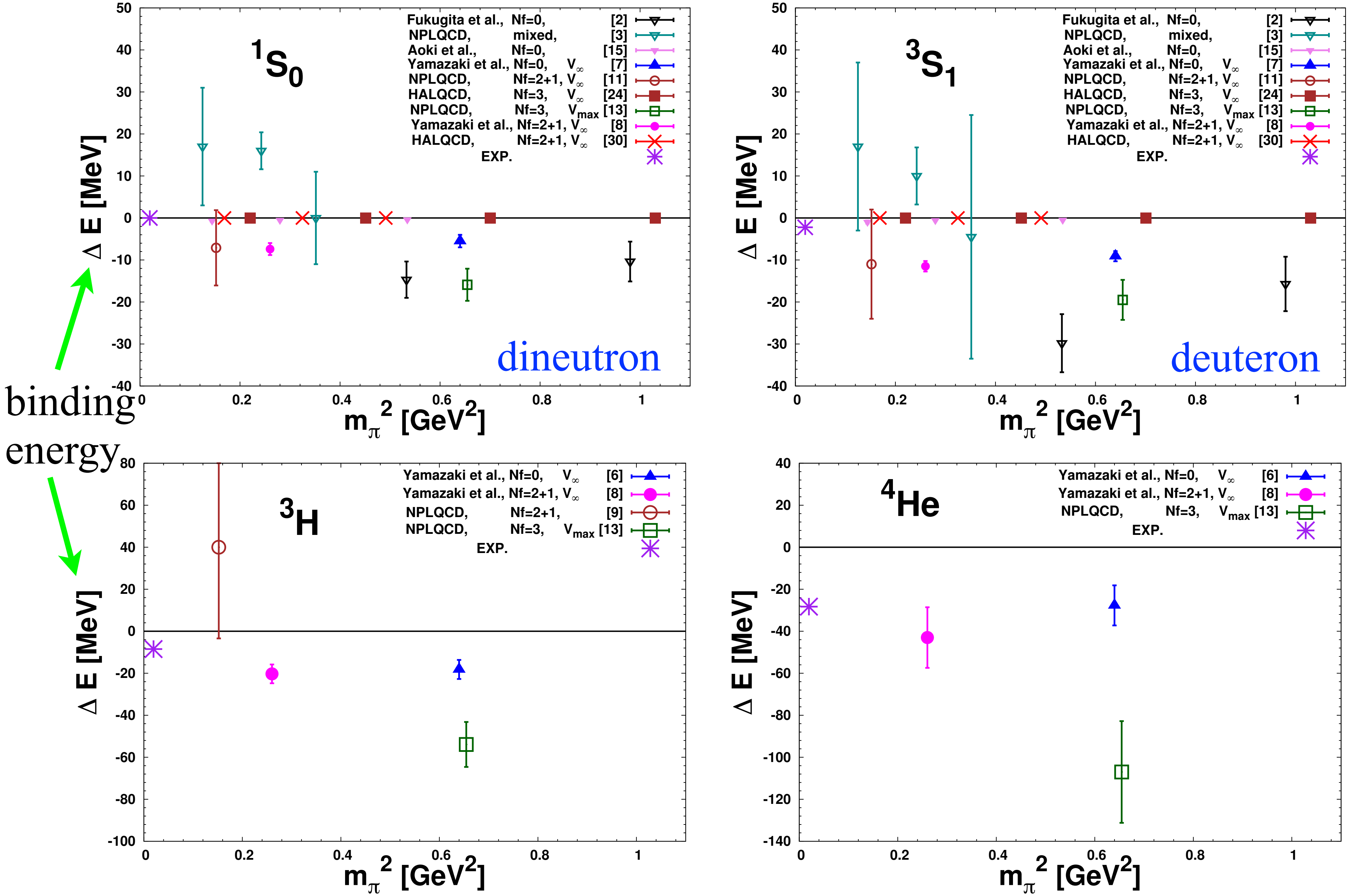


1 value of lattice spacing and heavy u/d quarks : more work needed!

Small nuclei are harder still ..

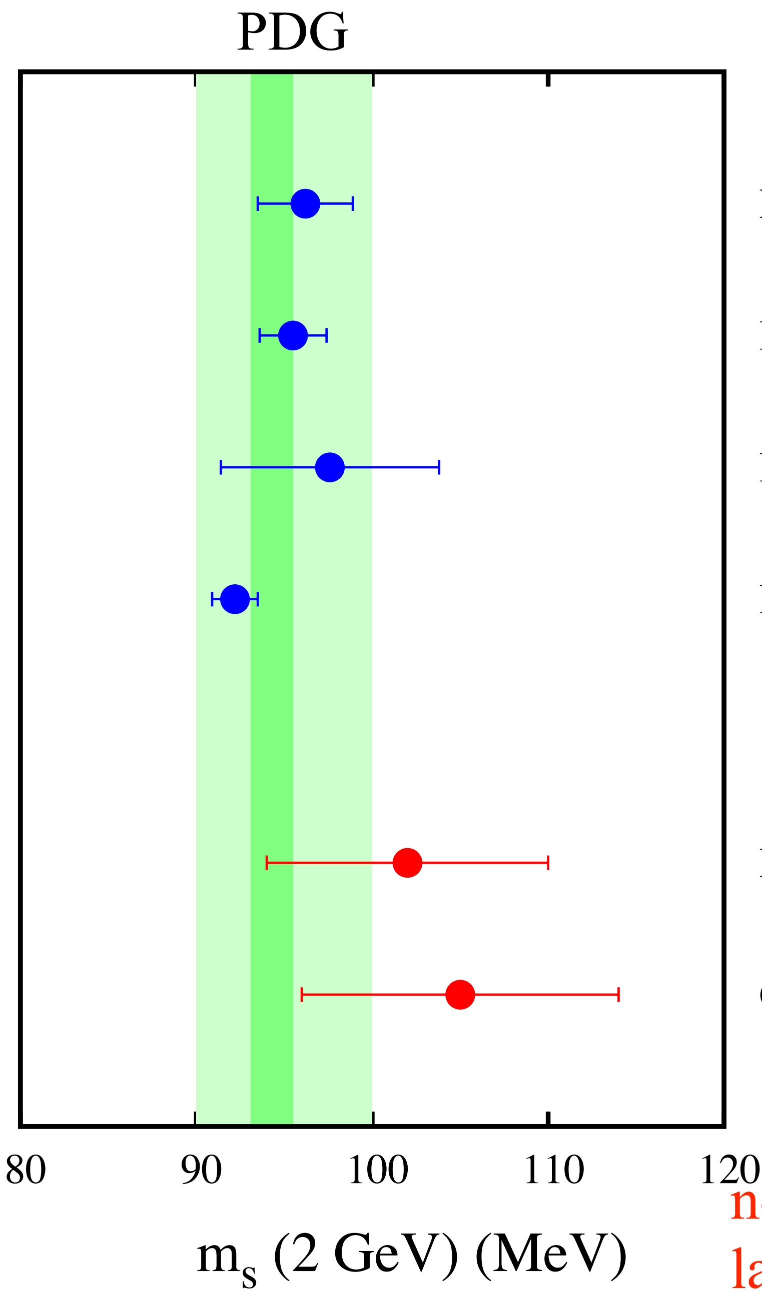
Doi:1212.1572

A lot of variation between calculations, but still at relatively heavy u/d masses ...
Need large volumes to check for real binding.

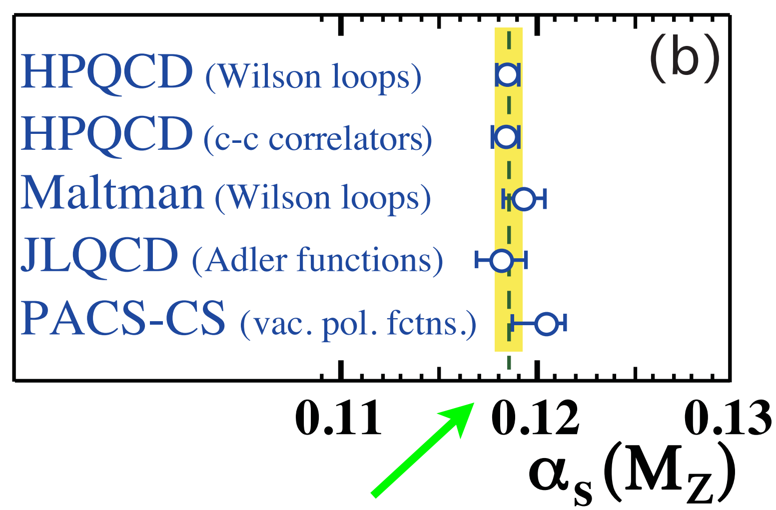


Lattice QCD sets world averages for quark masses and α_s

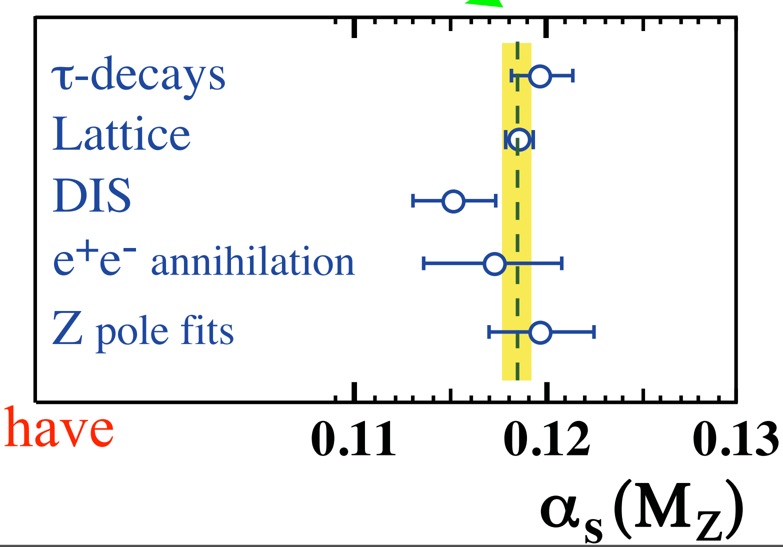
Direct access to parameters in QCD Lagrangian means systematic errors smaller



a variety of lattice methods agree



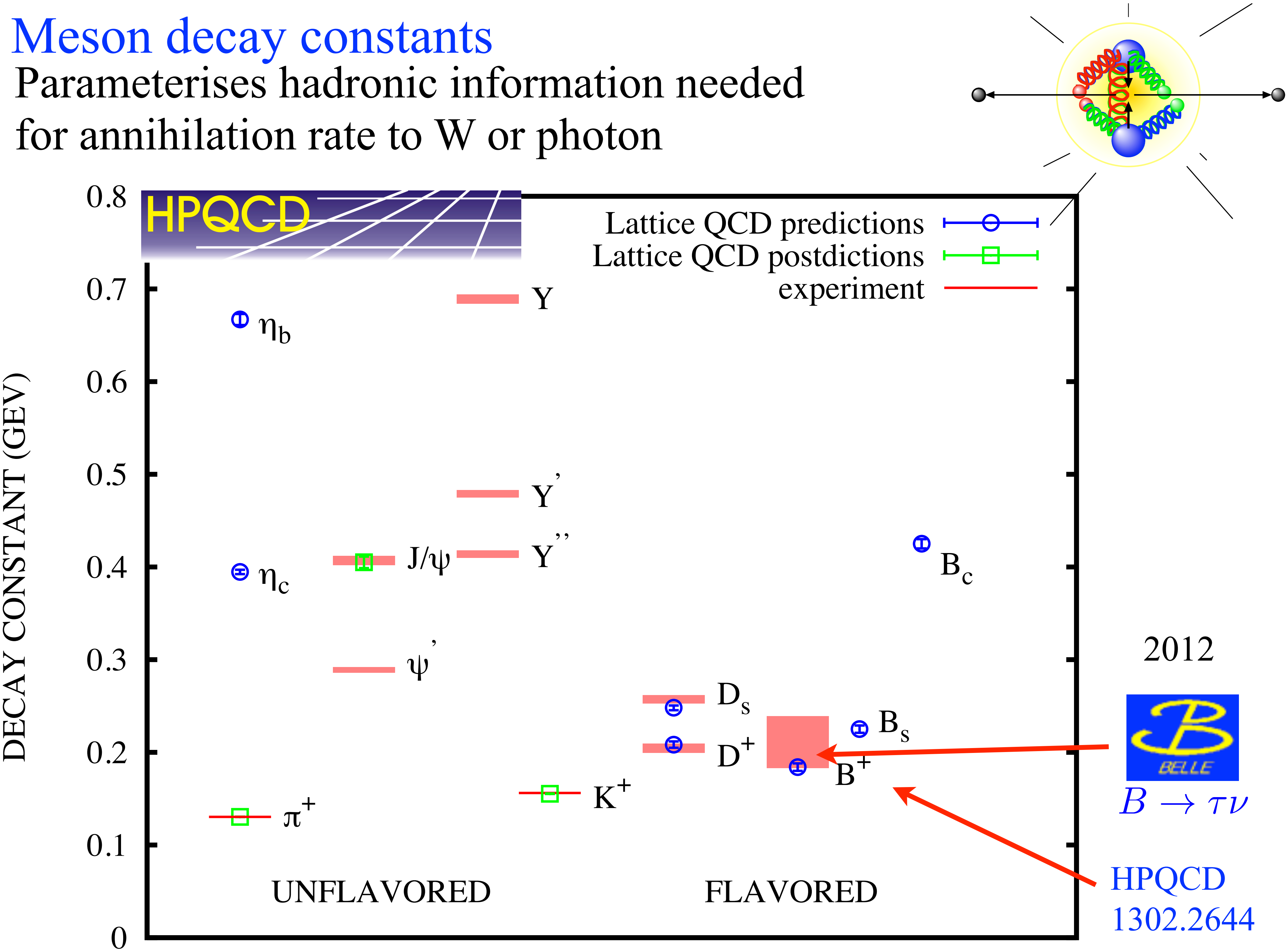
PDG



non-lattice methods have larger errors

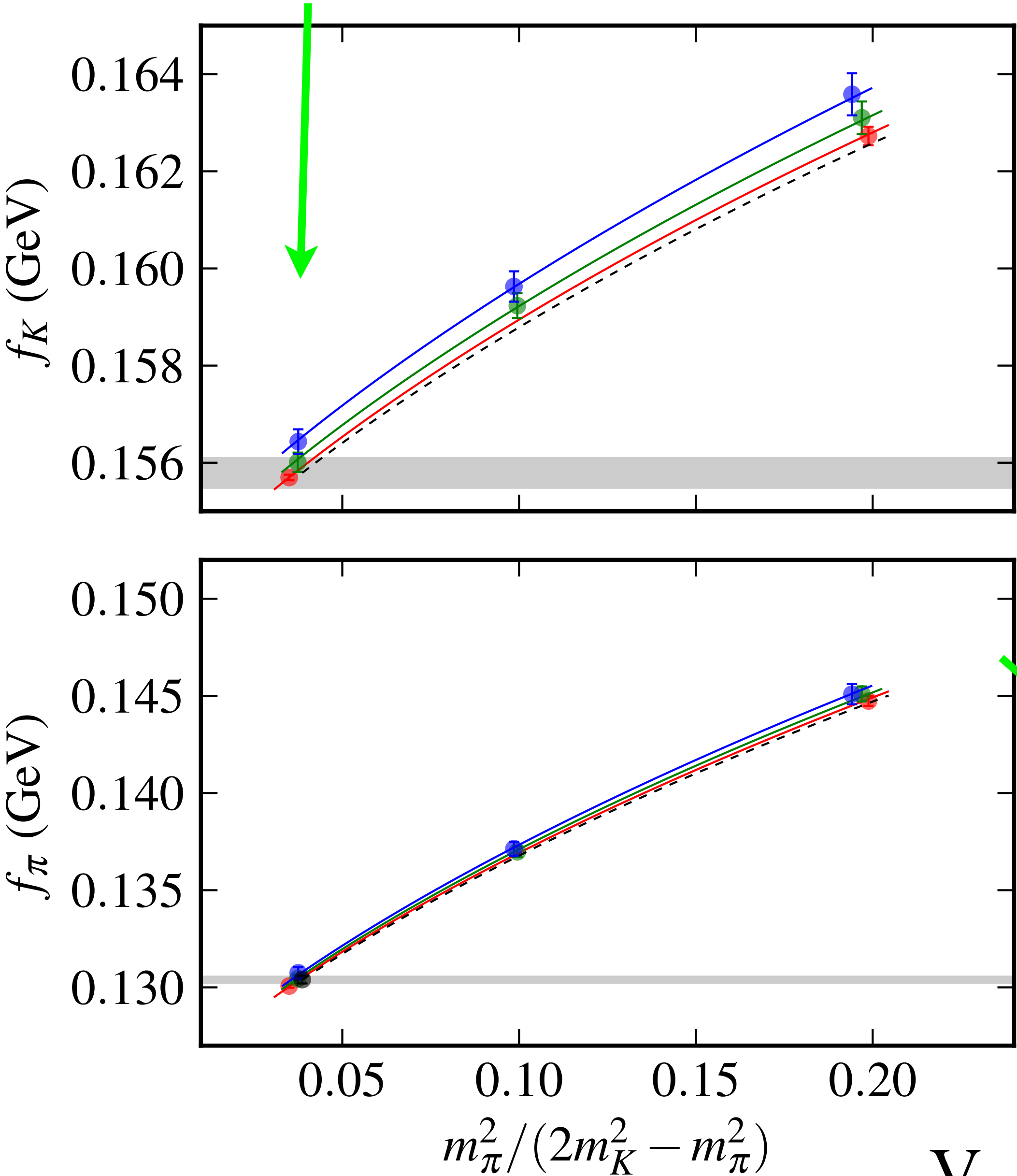
Meson decay constants

Parameterises hadronic information needed for annihilation rate to W or photon

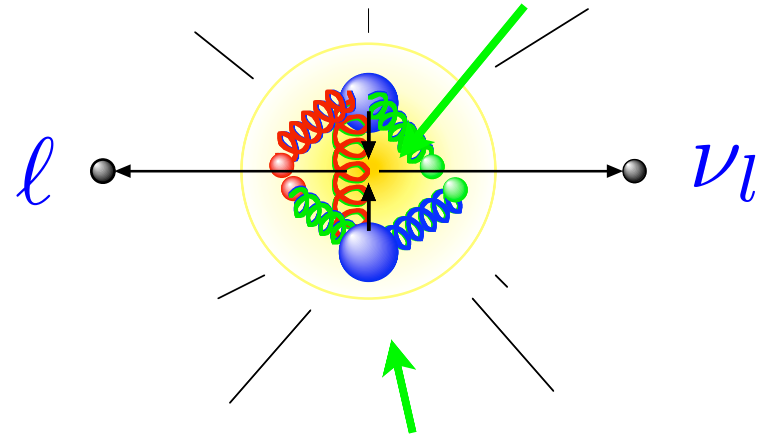


Constraining new physics with lattice QCD

physical u/d quarks



V_{us}/V_{ud}



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

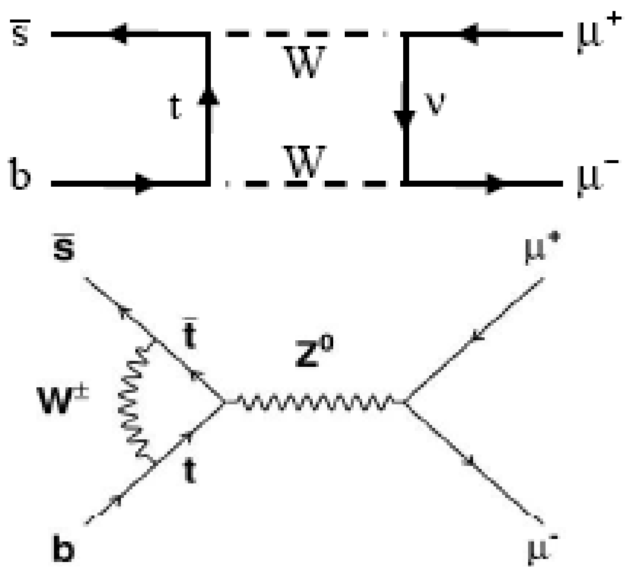
$$\frac{f_{K^+}}{f_{\pi^+}} = 1.1916(21)$$

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

HPQCD: 1303.1670

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

Constraining new physics with lattice QCD



Decay process $$B_s \to \mu^+\mu^-$$

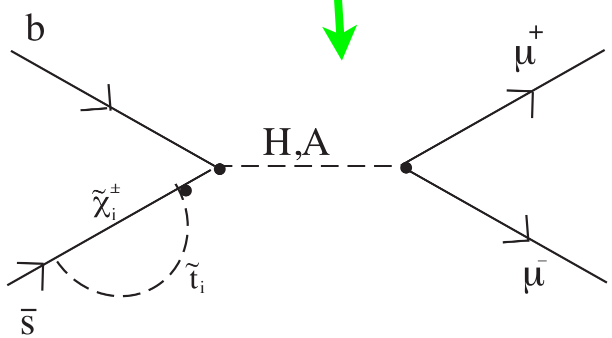
is rare in Standard Model. Rate depends on B_s decay constant. Lattice QCD gives fraction of B_s decays to muons:

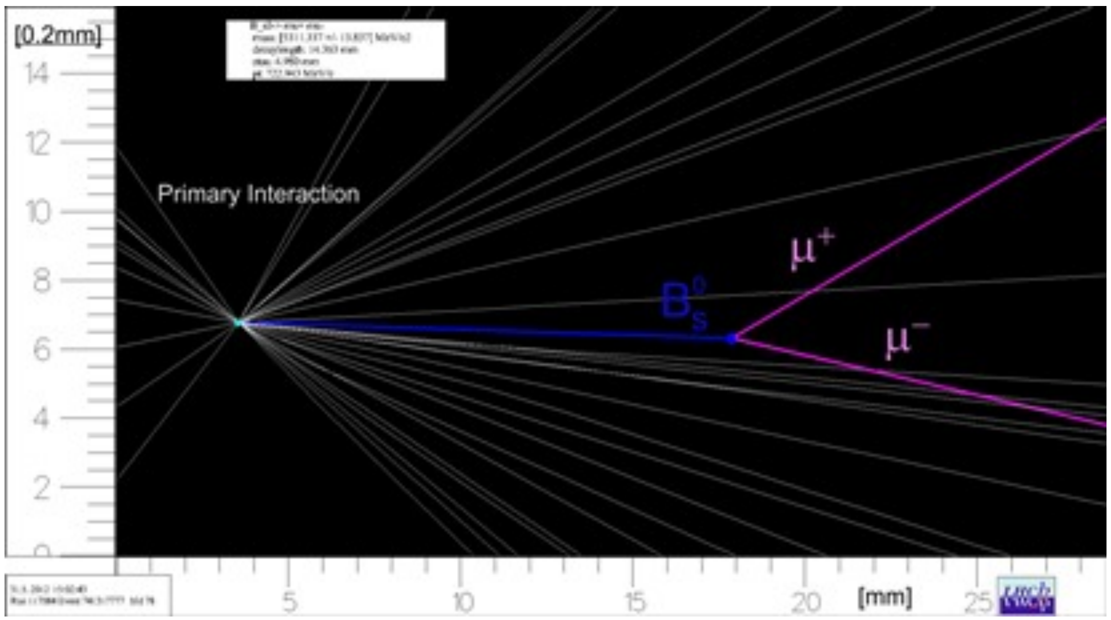
$$3.47 \pm 0.19 \times 10^{-9}$$ HPQCD 1302.2644

LHCb : Nov. 2012 observed decay with rate

$$3.2 \pm 1.5 \times 10^{-9}$$

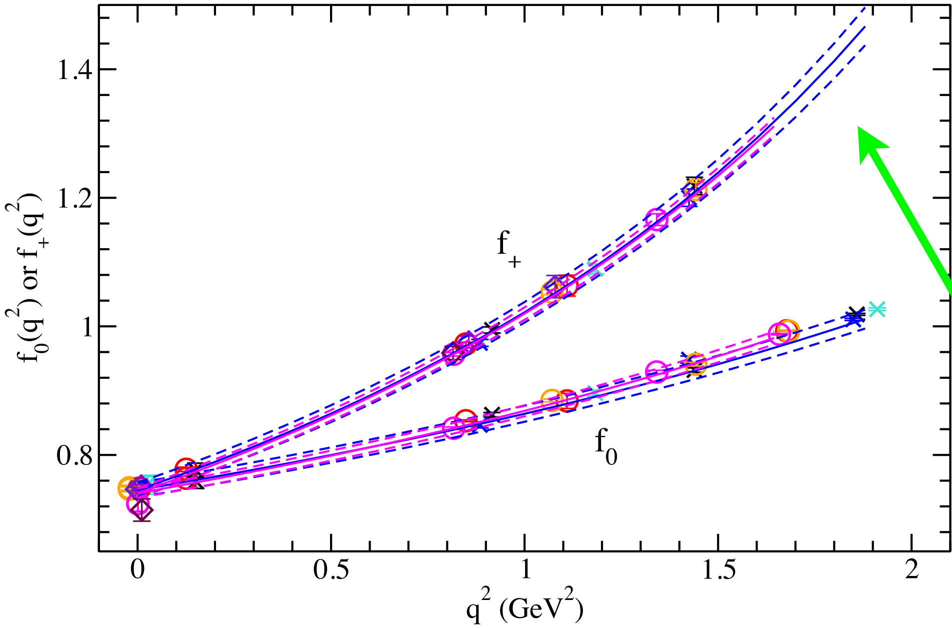
If new particles exist the rate could be very different.





More detailed hadron structure: form factors

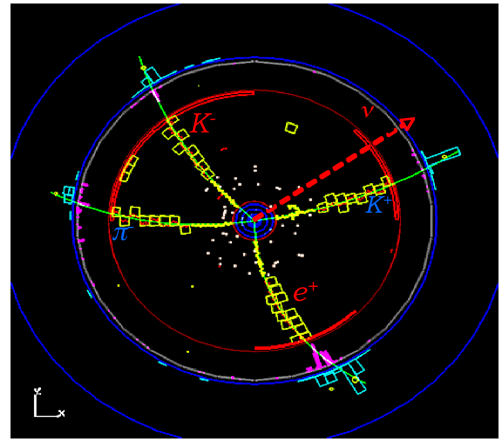
$D \to K \ell \nu$

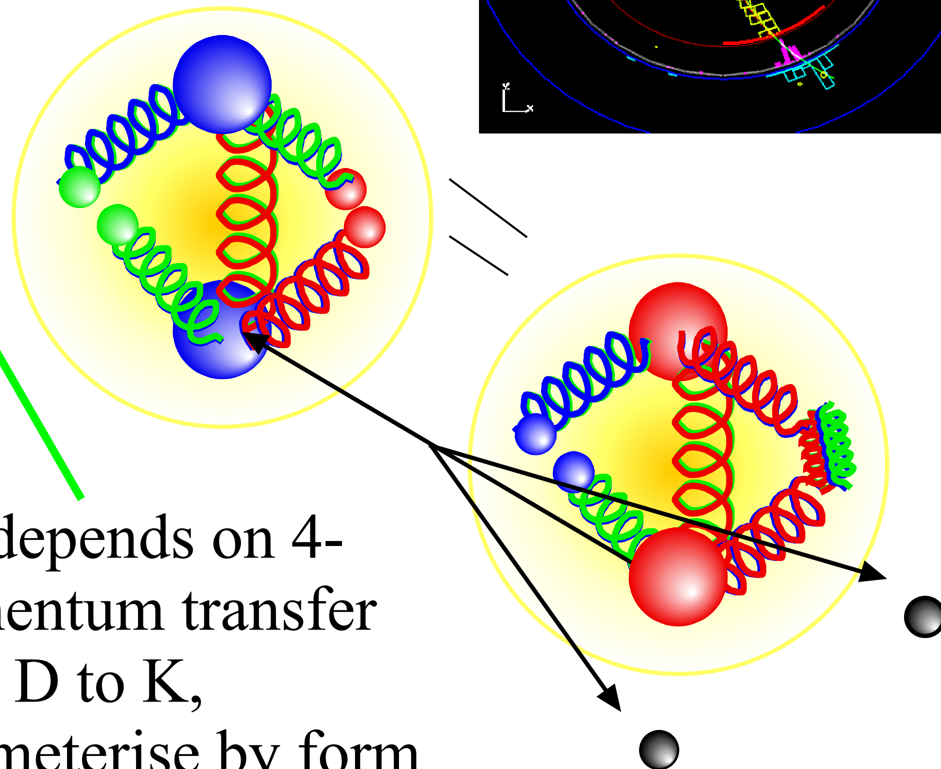


CLEO-c

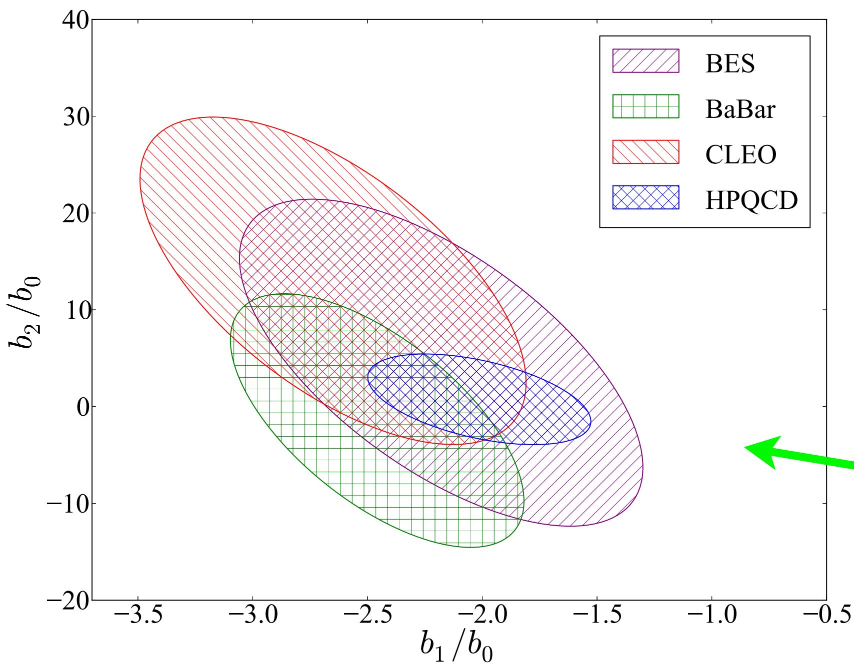
$D_0 \to K^- e^+ \nu$

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



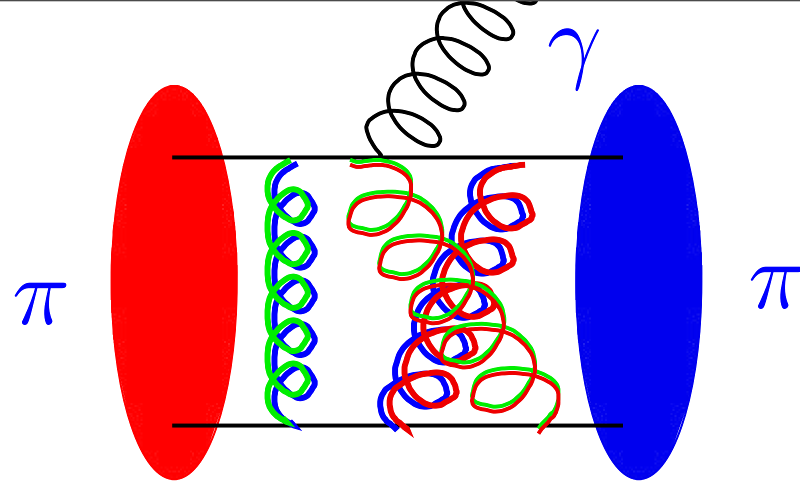


rate depends on 4-momentum transfer from D to K, parameterise by form factor.

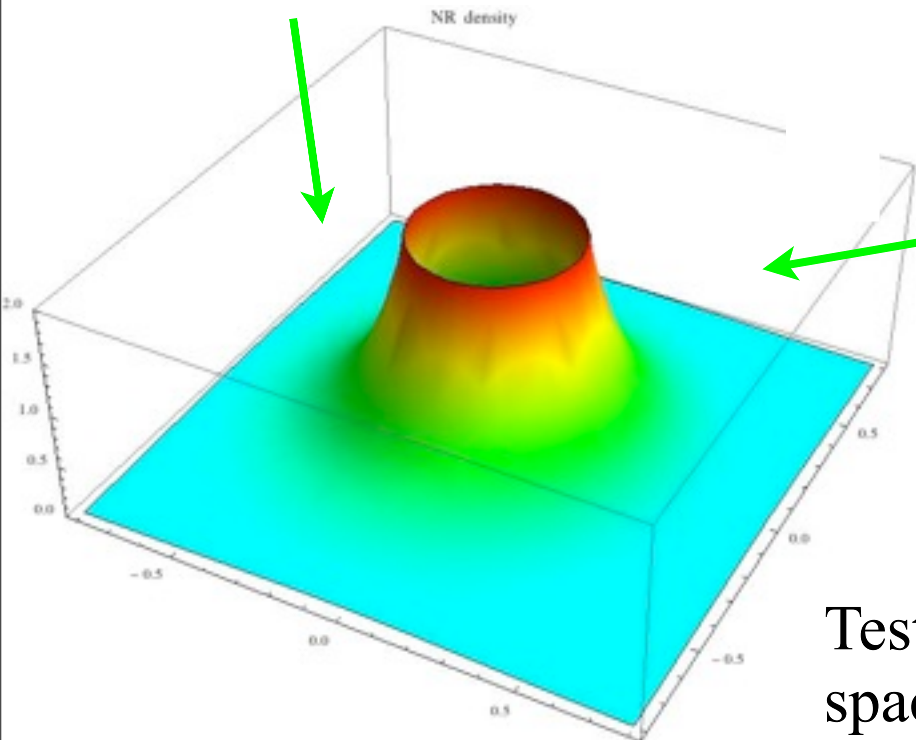


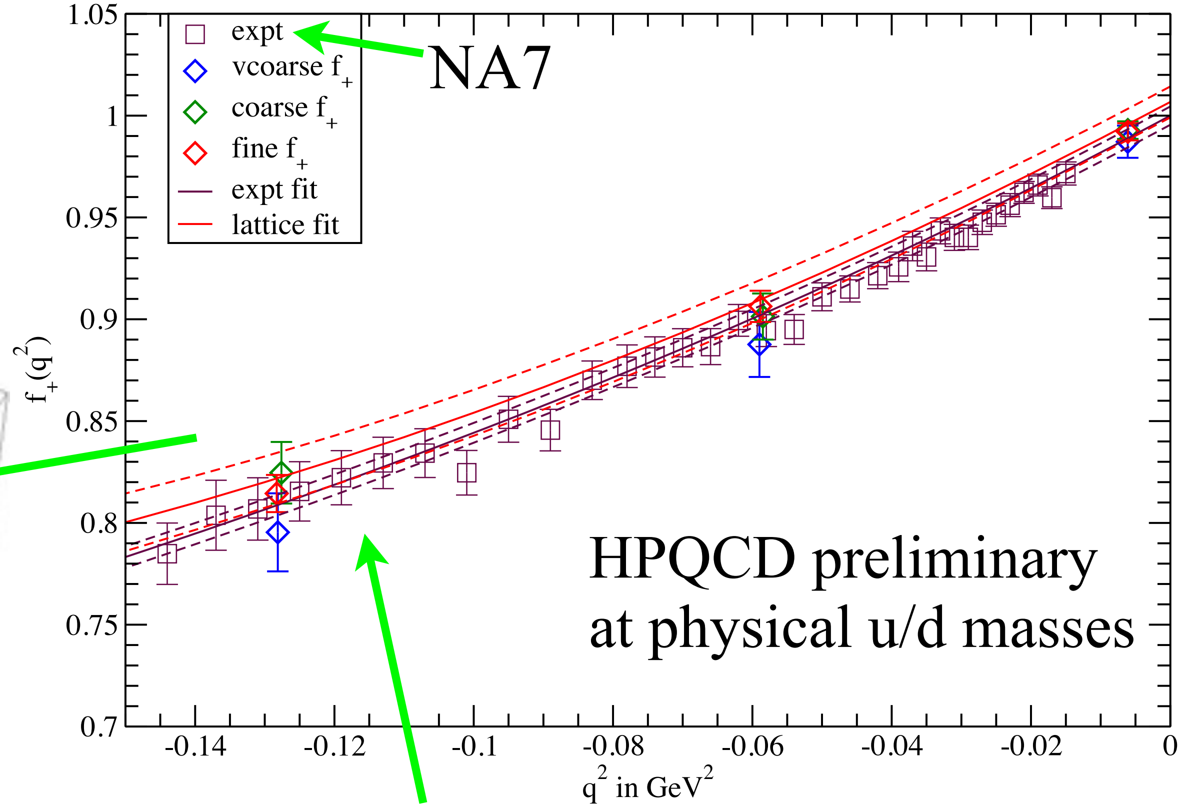
Shape of f_+ -comparing lattice QCD and experiment

The size of the π meson



Bounce an electron (photon) off a π to determine the π electric charge distribution/ internal structure





Test lattice QCD vs direct experiment at low spacelike q^2 - JLAB planning high spacelike q^2 (~5 GeV^2) indirect determination so lattice QCD calculations there are needed also.

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...