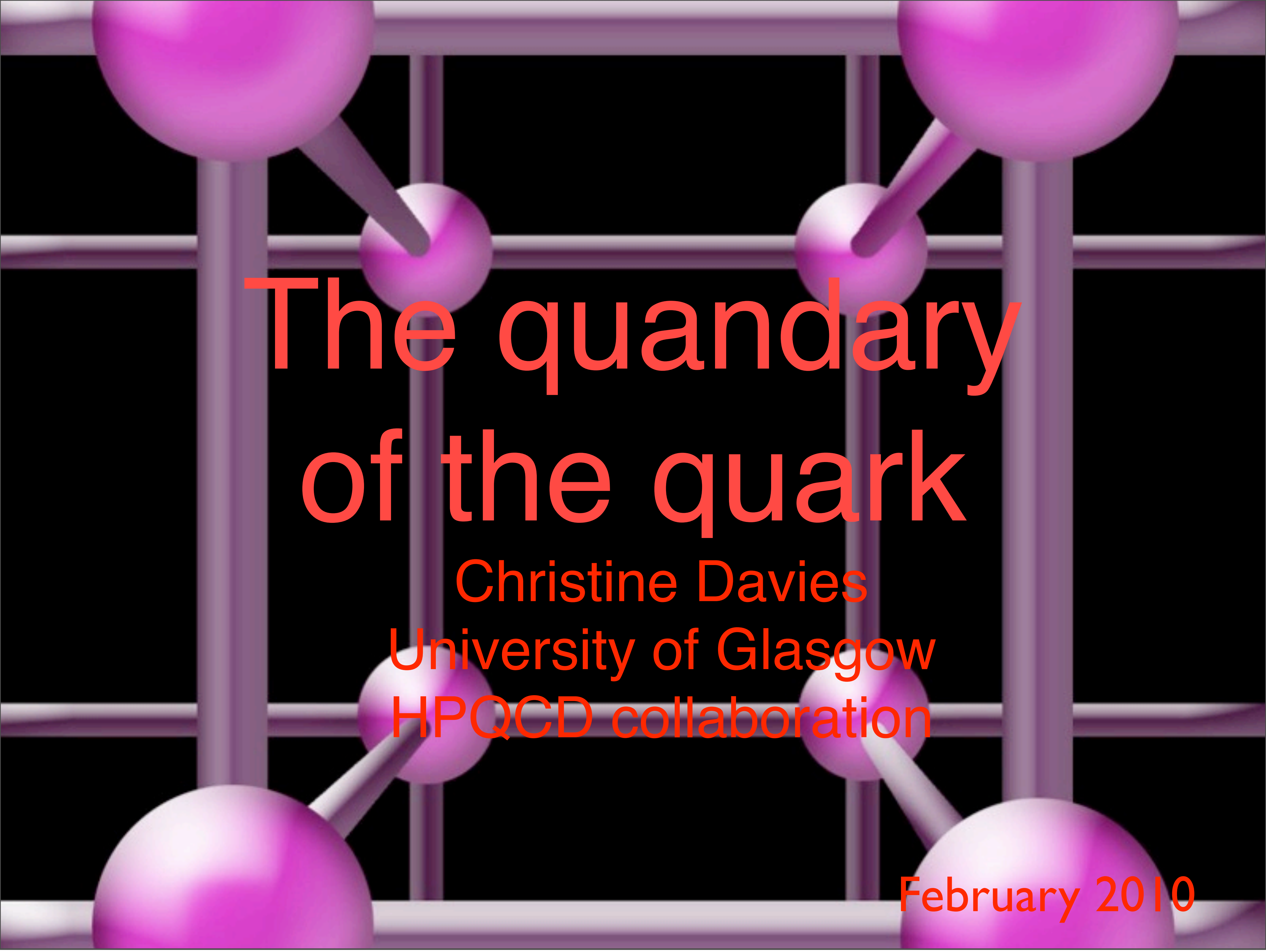
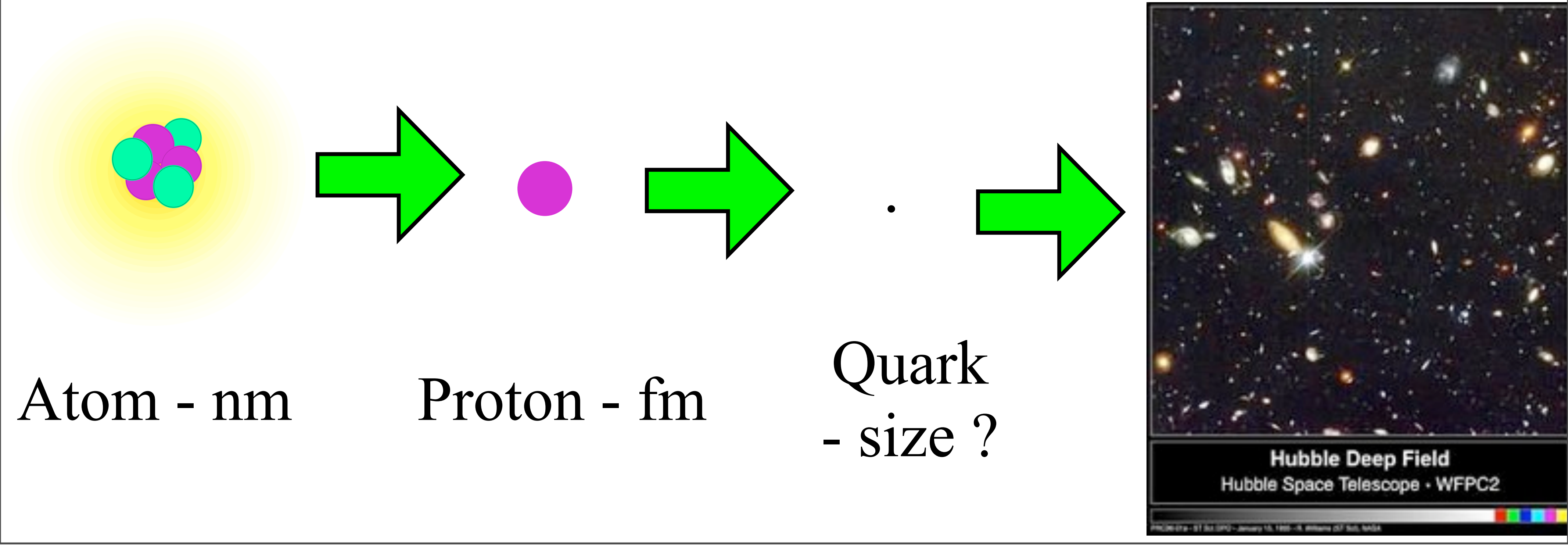


The quandary of the quark

Christine Davies
University of Glasgow
HPQCD collaboration

February 2010

Elementary particle physics: uncover the fundamental particles and interactions at the smallest distance scales

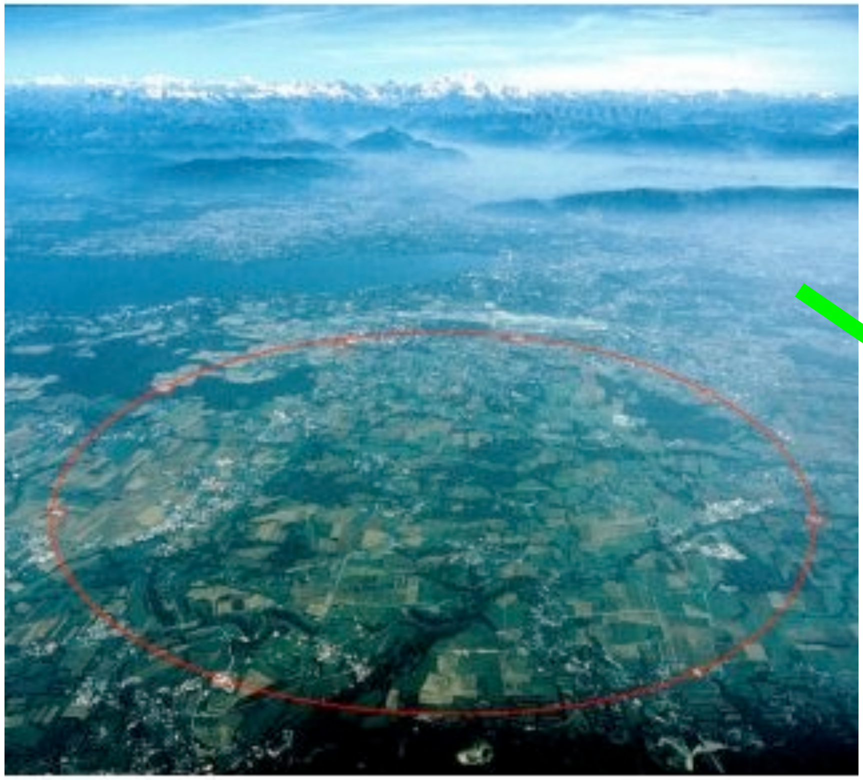


Atom - nm

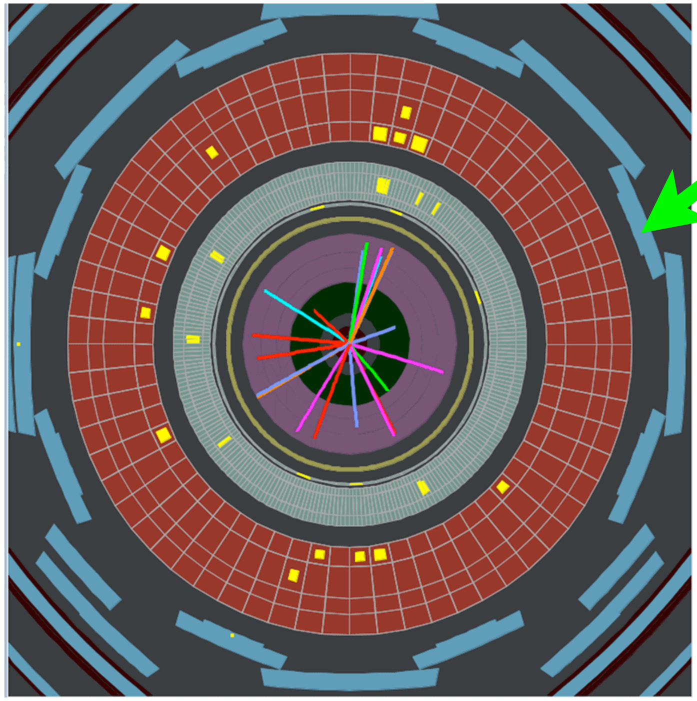
Proton - fm

Quark
- size ?

Particle physics experiment

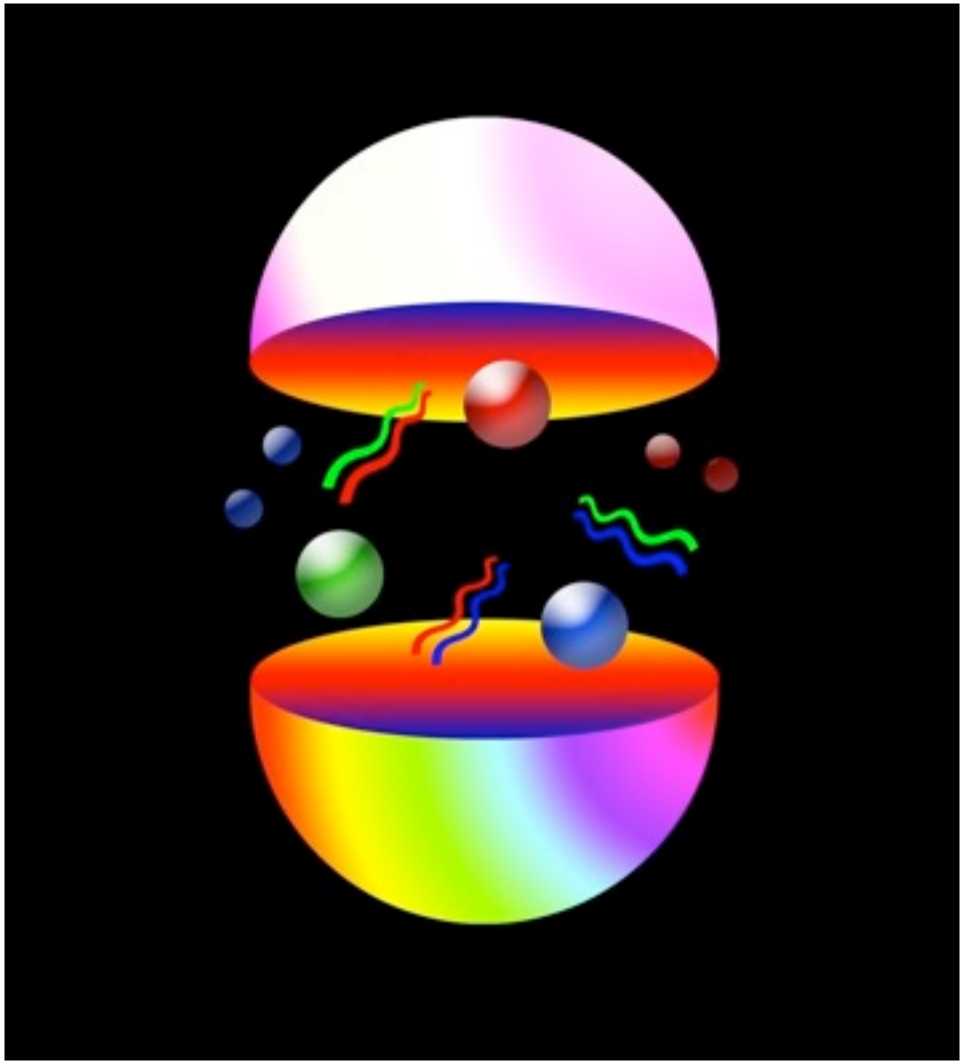


Large
Hadron
Collider
2010



Smashing protons together at high energy does not give subunits directly - just more particles!

Protons and other hadrons are made of quarks, interacting by the strong force (which also keeps the nucleus together).



Quarks never seen as free particles - to study them need accurate expt *and* theoretical calculations for hadrons.

QCD is theory of strong force - hard to calculate because strongly-coupled and nonlinear - needs numerical simulation. This is lattice QCD.

Standard Model of particle physics has:

6 quarks - $\begin{pmatrix} d \\ u \end{pmatrix} \begin{pmatrix} s \\ c \end{pmatrix} \begin{pmatrix} b \\ t \end{pmatrix} \longrightarrow$ a ‘zoo’ of hadrons

6 leptons - $\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$

3 forces (ignore gravity) : strong, weak, electromagnetic

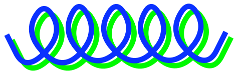
Over 20 parameters, whose origin is some deeper theory with New Physics.

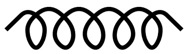
QCD is theory of strong force - mirrors QED

Quarks ↔ electrons

color charge RGB ↔ electric charge

gluons ↔ photons

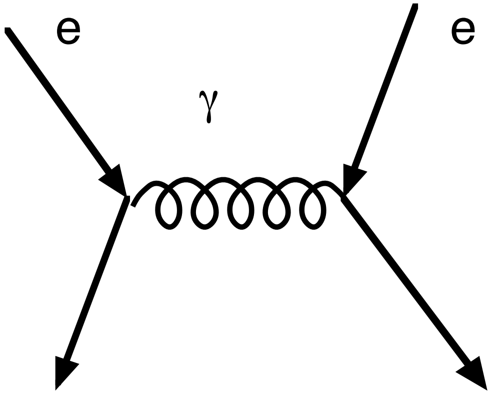




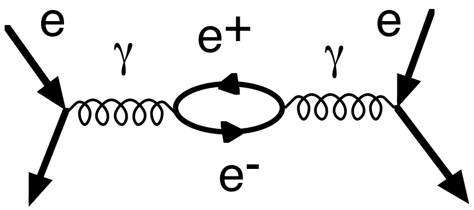
BUT QED and QCD behaviour very different:

QED - uncharged photons travel freely - easy to get free electrons - electromagnetic fields felt on macroscopic scales

Microscopically, QED very well understood as power series expansion in QED coupling



strength of interaction = e^2
= α = 0.007



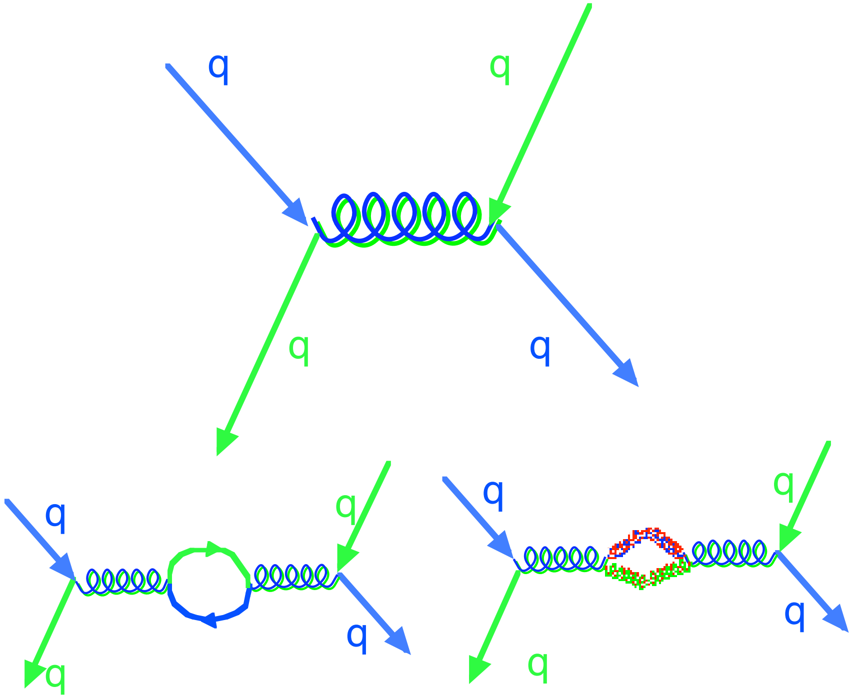
strong force is stronger than em force but not seen macroscopically

1974: strength of QCD interaction (the ‘color charge’, g) depends on the distance at which you measure it.

David Gross

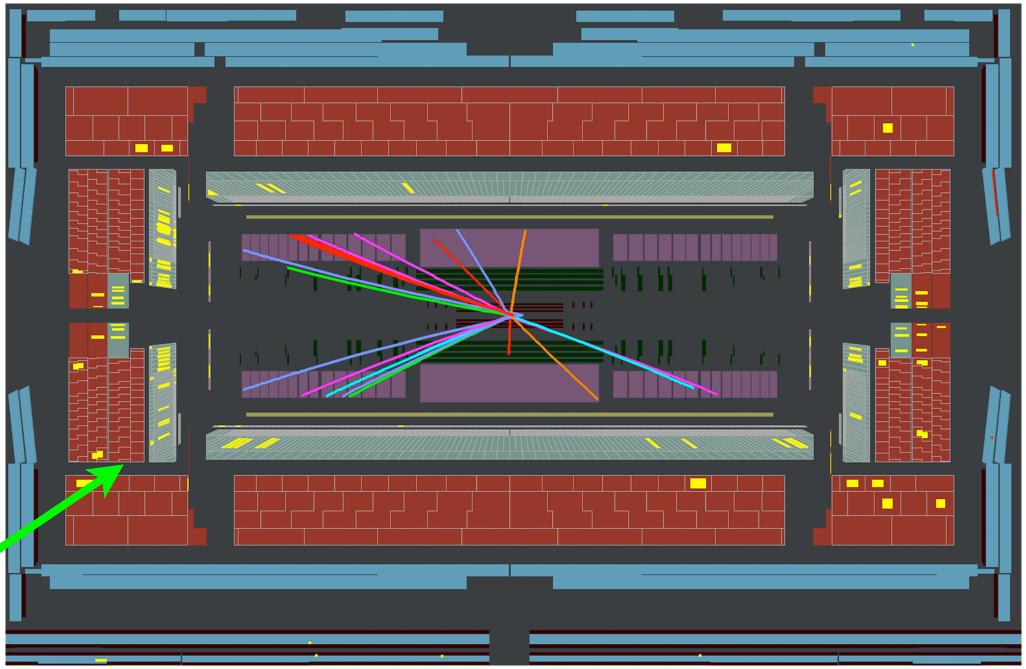
David Politzer

Frank Wilczek



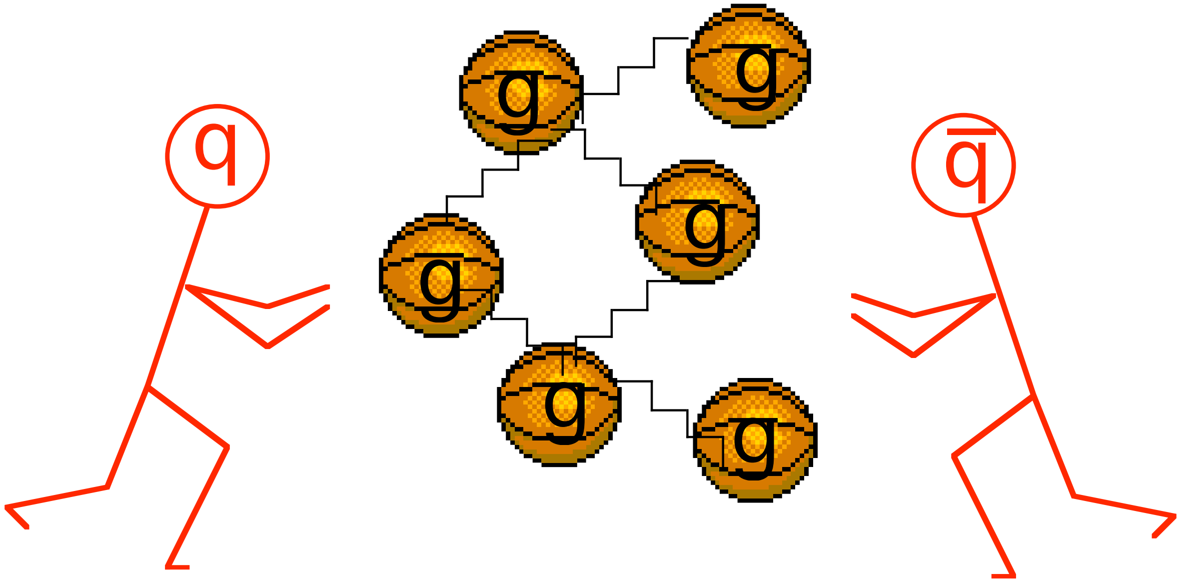
At very short distances g is small = asymptotic freedom. At v. high energies strong force is ‘simple’.

interaction strength = g^2 = $\alpha_s(r)$

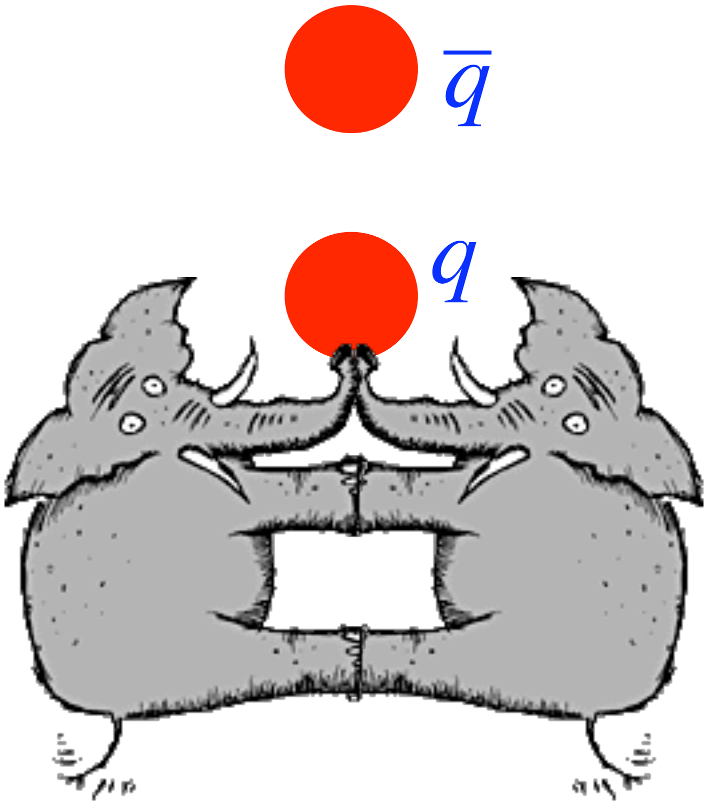


ATLAS@LHC

At large distance g becomes large and force between quark and antiquark does not fall with distance.

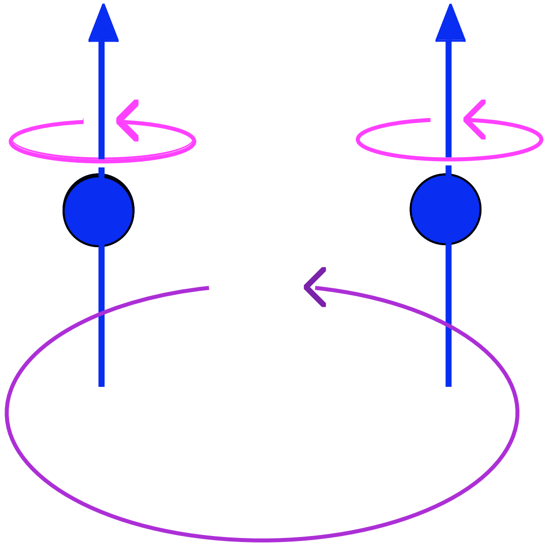


Force of attraction = weight of several elephants!



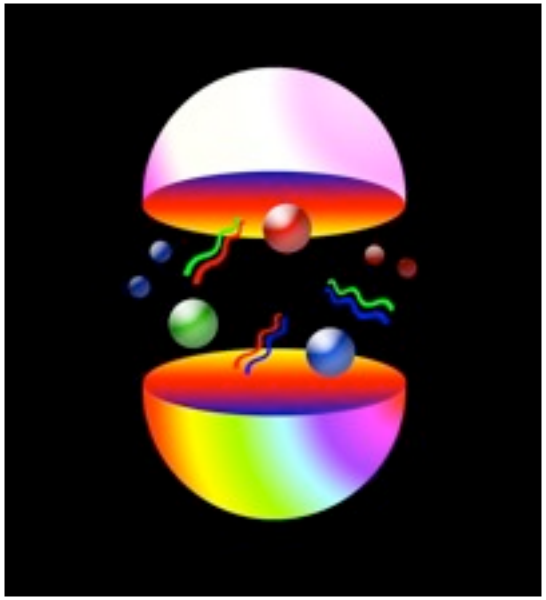
Effect is to confine quarks to bound states (hadrons) in which overall color charge = 0

Quarks come in 6 different flavours: up, down, strange, charm, bottom, top

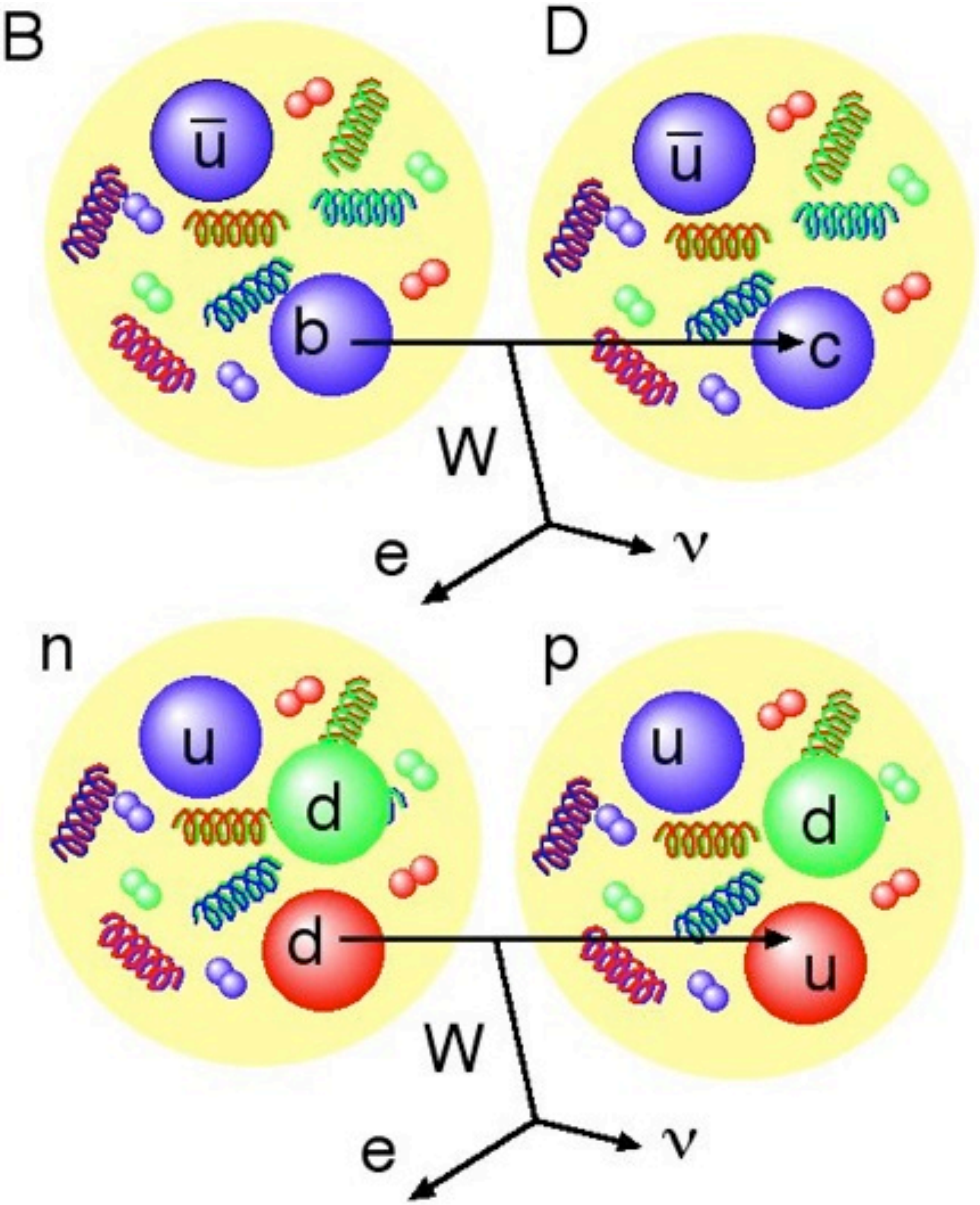


Known hadrons are:
mesons $\bar{q}q$ e.g. $\pi^+ = u\bar{d}$
baryons qqq e.g. $p^+ = uud$
but many different configurations

Over 100 particles with different masses and properties! Some (relatively) long-lived, others only fleeting.



In principle all the masses and properties are calculable from QCD if we can solve it at low energies/long distances. Also allows us to determine quark properties like m_q and $\alpha_s(r)$

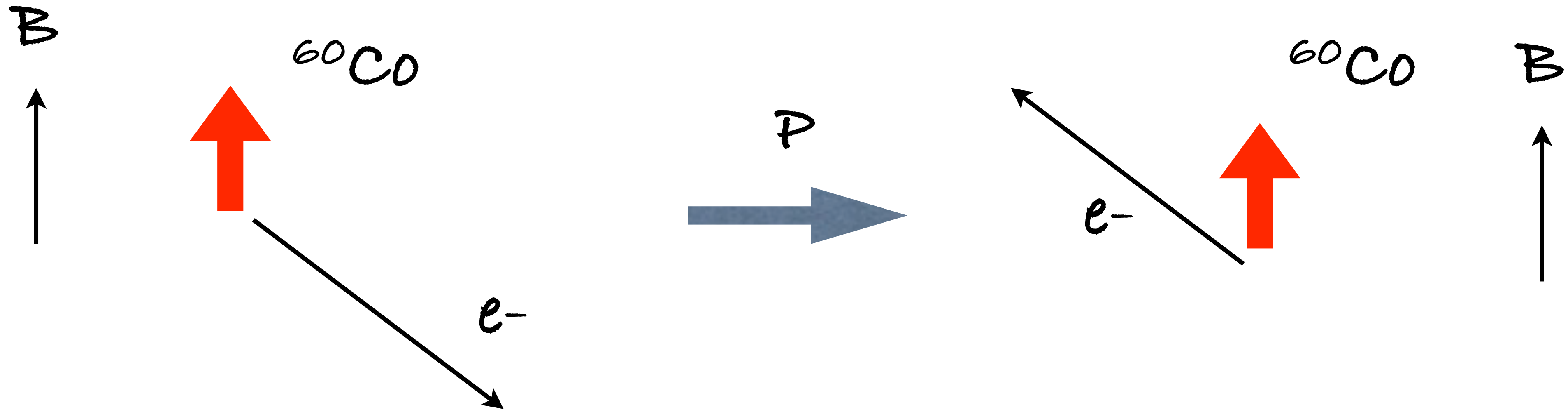


Quarks also feel the weak force and one quark type changes into another on emitting a W, e.g. nuclear beta decay

Quark decay occurs inside hadrons and so, to understand this, QCD effects have to be included fully.

Important because of symmetry breaking ..

1956 Weak decays violate parity symmetry, P: $\bar{x} \rightarrow -\bar{x}$



$$^{60}Co \rightarrow {}^{60}Ni + e^{-} + \bar{\nu}_e$$

Co atom spin lined up in B field.
See e^- from beta decay
preferentially in opposite dirn -
this violates P.

Chien-Shiung Wu

Physicists were horrified, but it seemed to be true that CP was preserved.

CP = charge conjugation
x parity

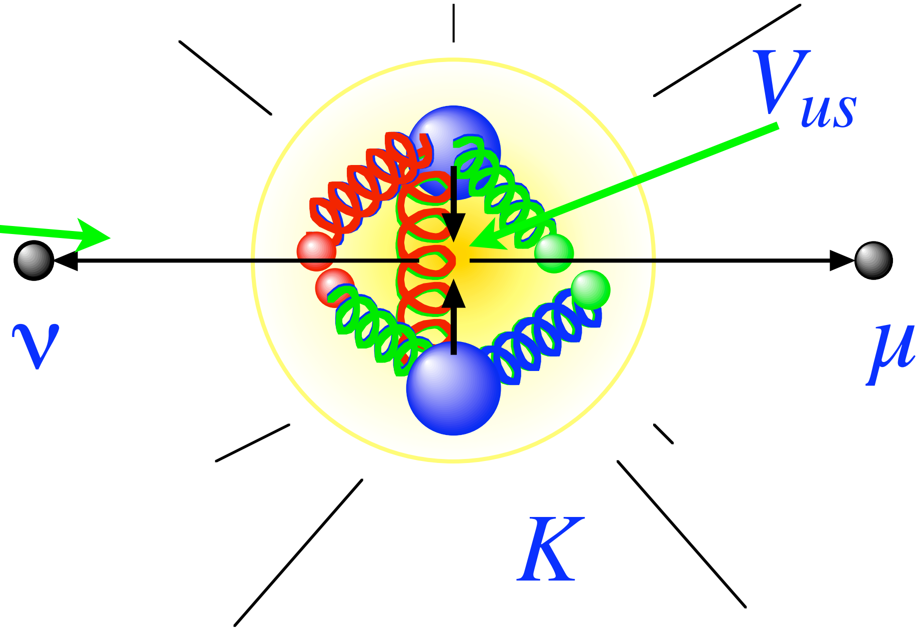
1964 CP violation was discovered ⟶ a difference between matter and antimatter

Nature does distinguish - but can the Standard Model?

Yes, if the coupling strength between different quark types and W boson can be complex

Cabibbo-Kobayashi-Maskawa (CKM) matrix contains these numbers - 3x3 unitary matrix can be complex

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

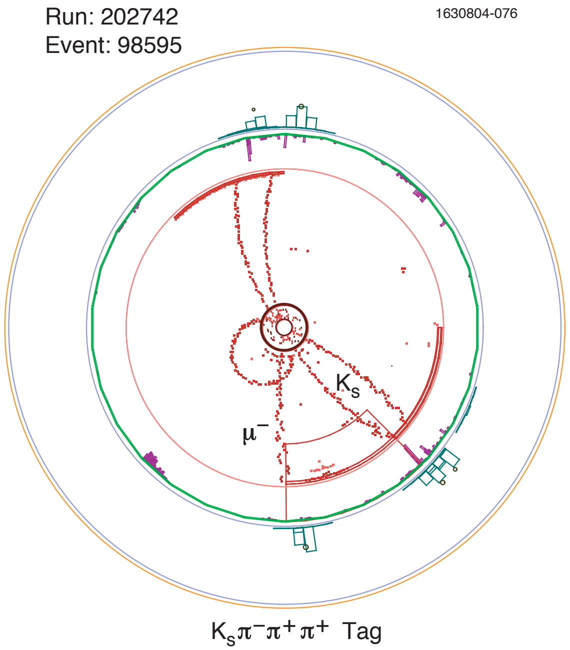


Expt = CKM x theory(QCD)

V_{ab} appears in trivial way in decay processes involving quarks a + b. Calculating QCD effects is non-trivial - need precision lattice QCD to get accurate CKM results.

‘B factory’ (b quark) expts have made huge progress ..

BELLE@KEK



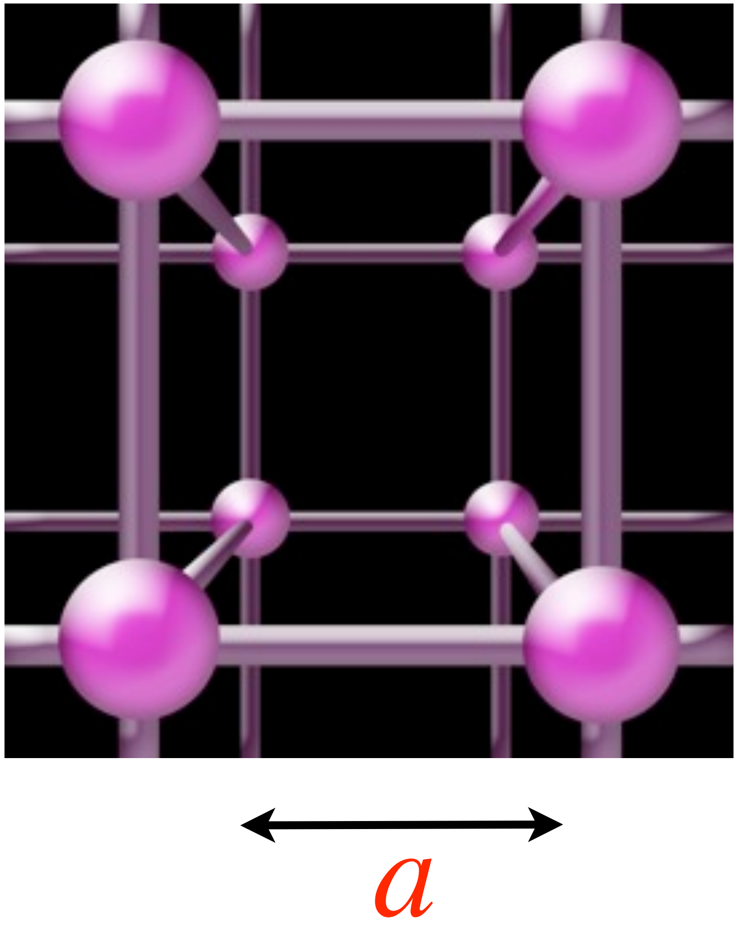
CLEOc@CESR

BaBar@SLAC

‘D factory’ (c quark) expts check precision lattice QCD results for B

FUTURE: LHCb, BES ....

Lattice QCD



- Solve QCD by numerical evaluation of path integral:

$$\int dA_\mu d\psi d\overline{\psi} e^{-S_{QCD}}$$

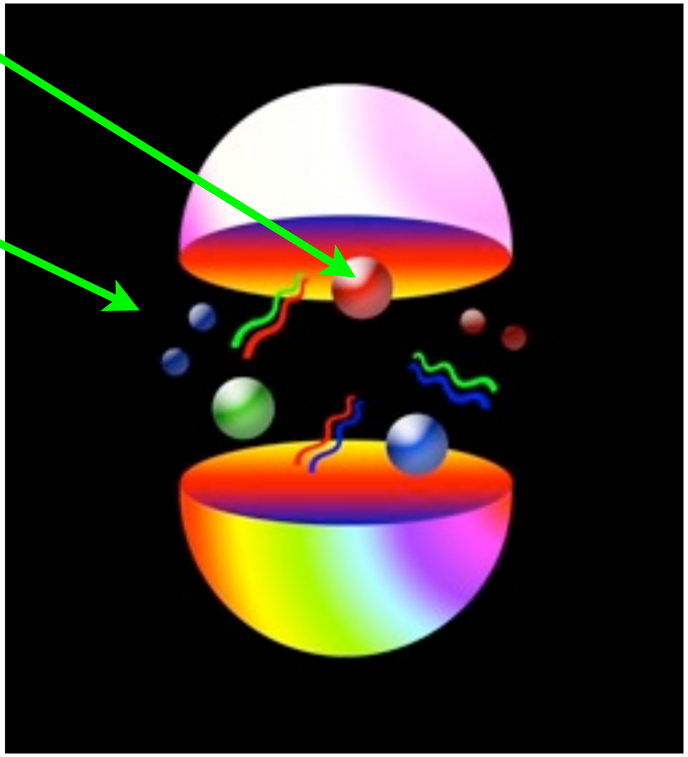
- make integral finite with a space-time lattice
- Importance sampling - make gluon configs - ‘snapshots of vacuum’ and propagate quarks through them.
- ‘Measure’ e.g. hadron correlators on the gluon configs to calc. hadron masses and weak decay rates

Handling light quarks is a big headache

$$L_{q,QCD} = \overline{\psi}(\gamma \cdot D + m)\psi \equiv \overline{\psi} M \psi$$

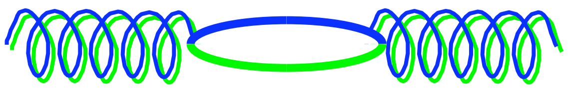
For valence quarks, need to calc. M^{-1}
For sea quarks need to inc. $det(M)$
in making gluon configs

Very costly as $m_q \rightarrow 0$

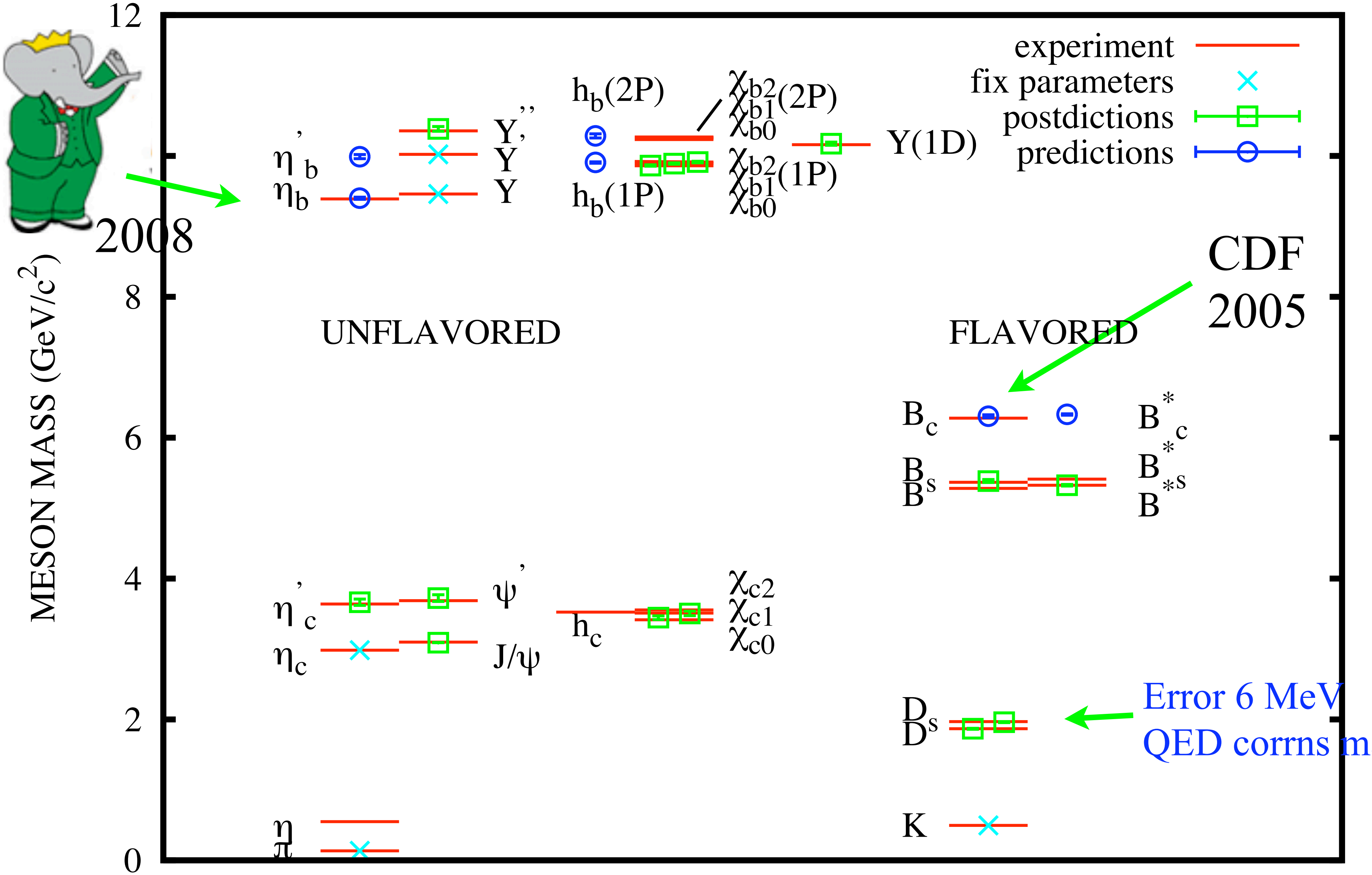


Early calcs:
Quenched Approximation - omitted sea quarks. Gives 10-20% errors.

Now:
include sea u, d and s quarks but use multiple u/d masses and extrapolate.



Results for ‘gold-plated’ meson masses from lattice QCD



2008

CDF 2005

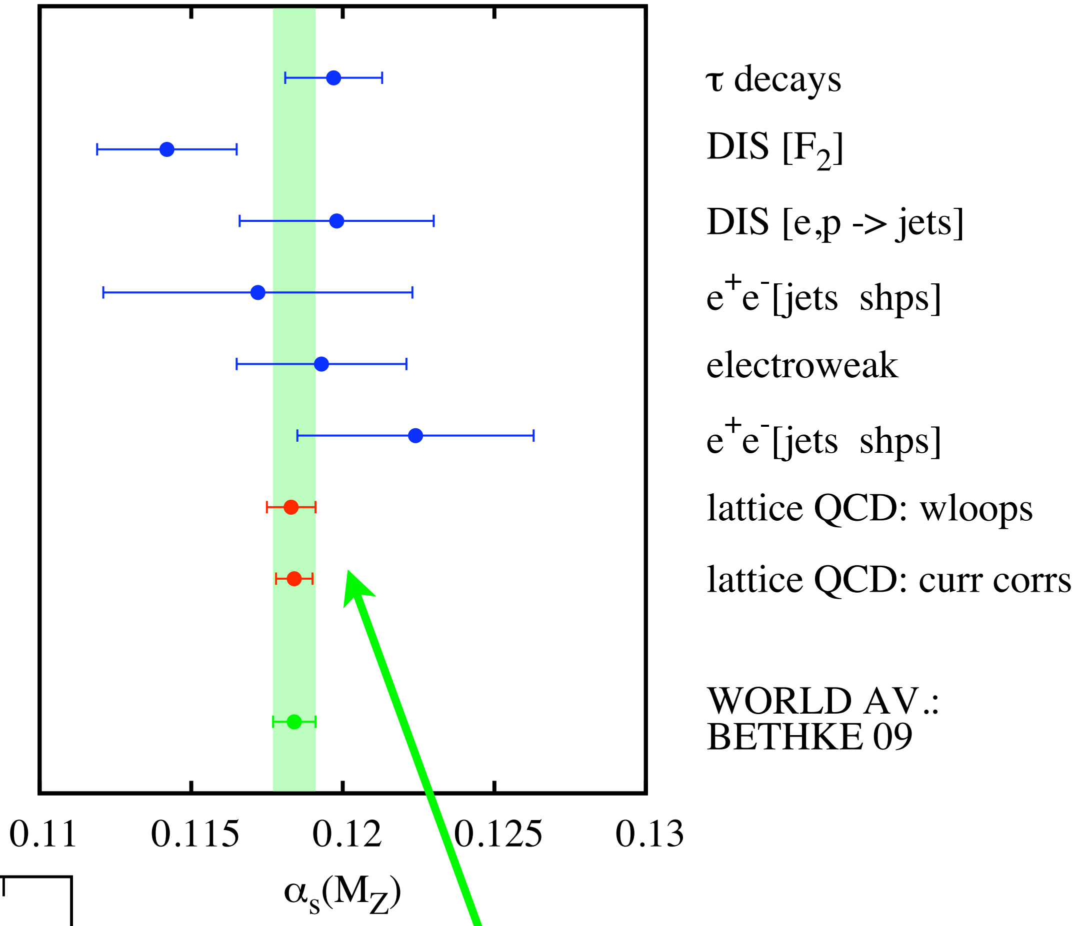
Error 6 MeV

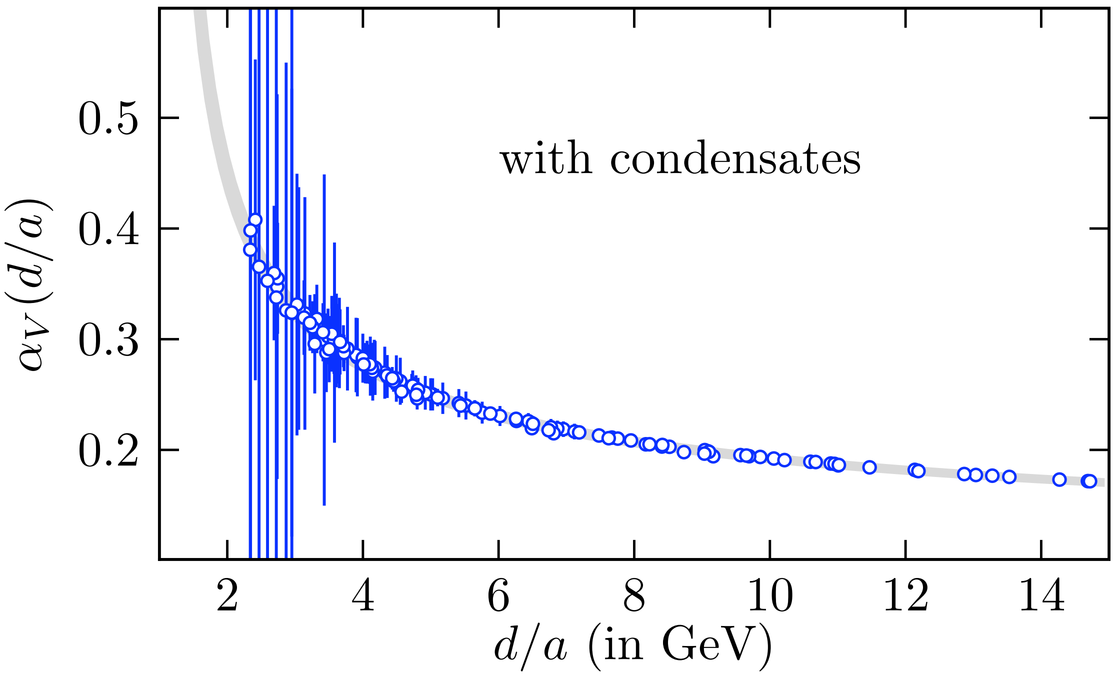
QED corrns matter!

HPQCD collaboration

Determining QCD parameters

Determining g is equivalent to determining the distance scale at which g acts i.e. the lattice spacing.





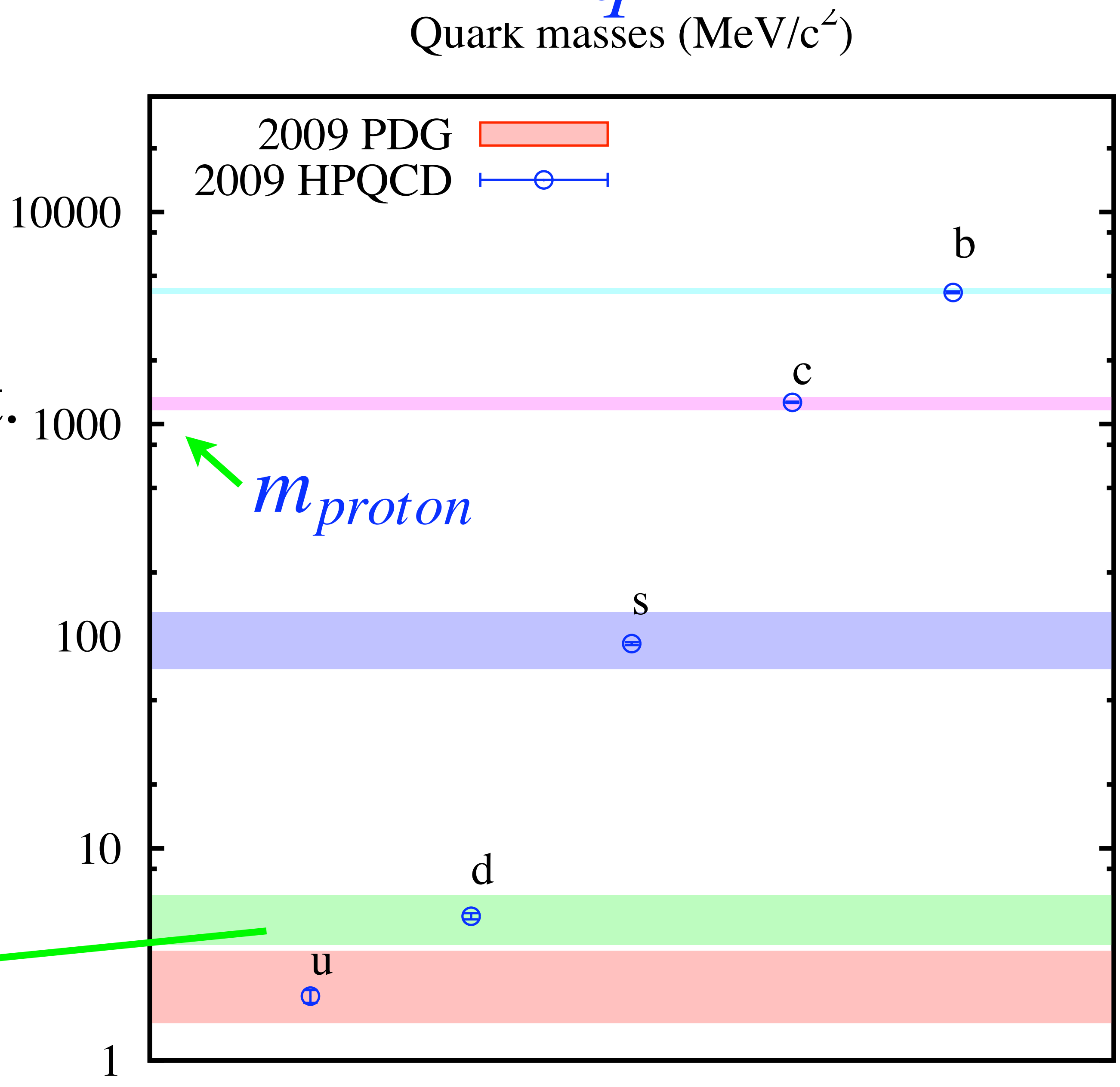
Lattice QCD is the best way to determine g - also see g ‘running’

HPQCD collaboration

Determining parameters of QCD: m_q

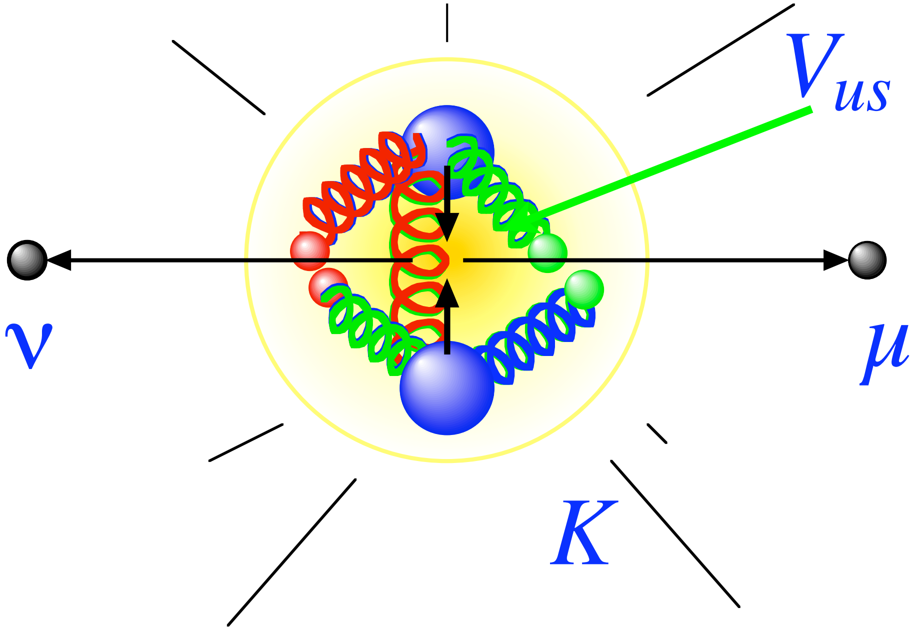
Masses are parameters in lattice QCD action - determine by getting hadrons masses right.

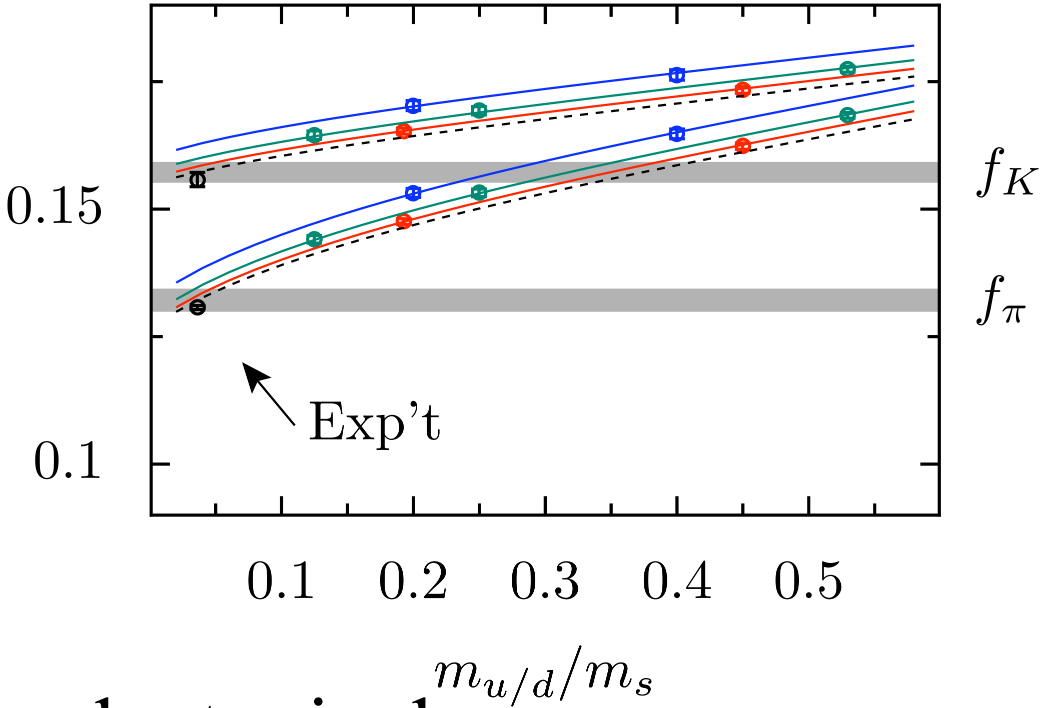
Visible Universe is made of QCD binding energy!



HPQCD collaboration

Programme to determine CKM elements - recent highlights





K decay constant parameterises leptonic decay.

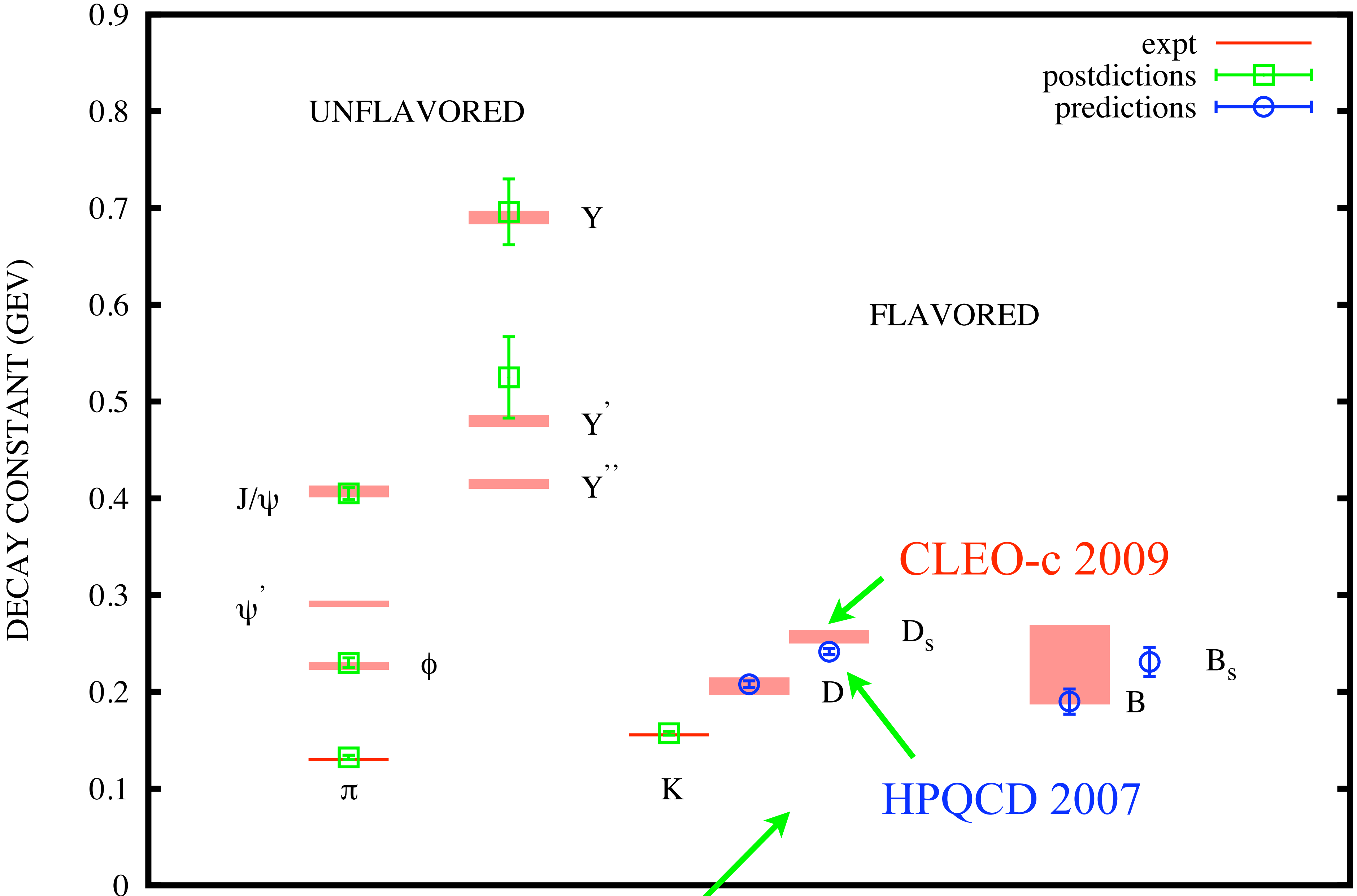
Ratio of K/π combined with expt. (KLOE)

$$V_{us} = 0.2262(14)$$ (current world's best but theory still dominates error)

$$1 - V_{ud}^2 - V_{us}^2 - V_{ub}^2 = 0.0006(8)$$ test of first row unitarity of CKM matrix

Follana et al, HPQCD, 0706.1726[hep-lat]

or, use V_{ab} from elsewhere and compare lattice QCD and expt for decay constants. Inc. also electromagnetic decays.



CLEO-c 2009

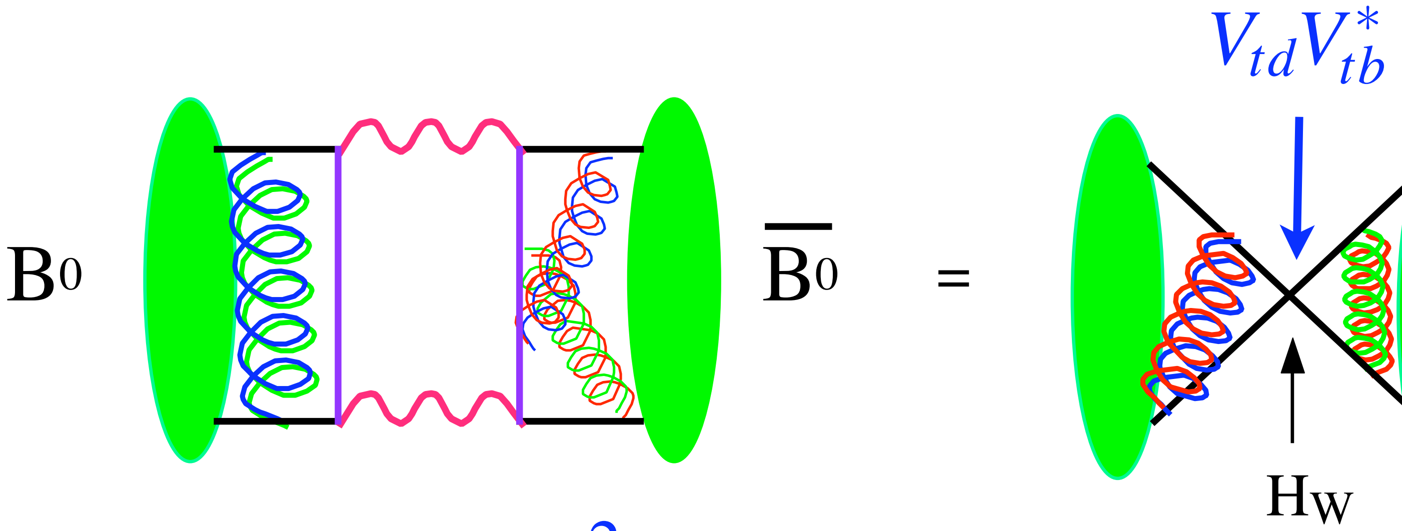
HPQCD 2007

2σ discrepancy - a hint?

HPQCD collaboration

New physics more likely in neutral B mixing

Neutral B (and K) mix - gives rise to ‘oscillations’. Mixing determined by box diagram. Calculate in lattice QCD



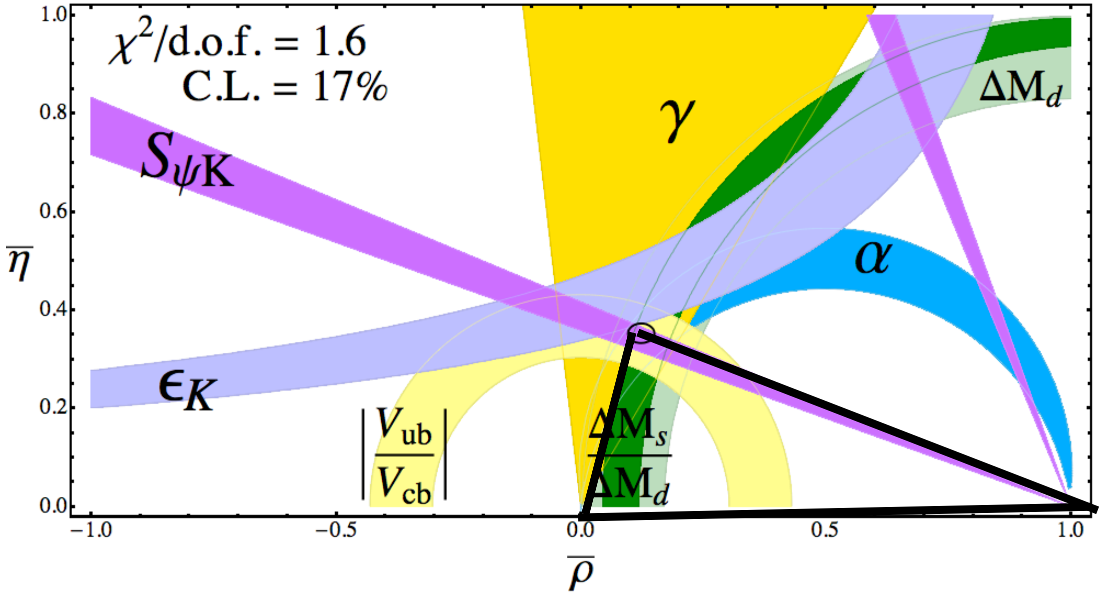
Parameterise with $f_B^2 B_B$ where f_B is decay constant.

Using ratio for B_s to B_d $\xi = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_B\sqrt{B_B}}$ $\longrightarrow$ $|\frac{V_{td}}{V_{ts}}| = \xi\sqrt{\frac{\Delta M_d M_{B_s}}{\Delta M_s M_{B_d}}}$

lattice QCD results (HPQCD): E. Dalgic et al, HPQCD, hep-lat/0610104

$f_{B_s}\sqrt{\hat{B}_{B_s}} = 0.281(21) GeV$ 5% error on ξ : work in progress

Lattice QCD calculations are key to constraining sides of CKM Unitarity triangle



current situation

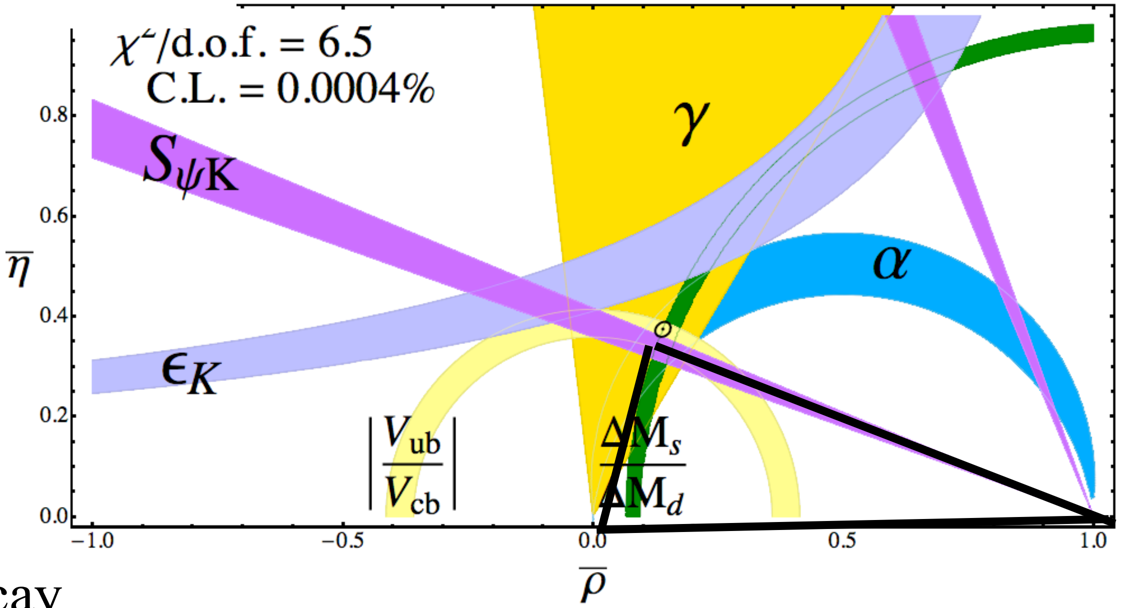
tensions developing at 2 sigma level.

Future with 1% lattice errors for

B_K, f_K

$\xi,\ f_{B_s}\sqrt{B_{B_s}}$

V_{ub}, V_{cb} from exclusive SL decay



R. van der Water, LAT09 0902.1815[hep-lat]

Conclusions

- Lattice QCD is now providing precision results for the physics of the strong force.

Gold-plated meson masses accuracy: a few MeV/c^2

Quark masses : 1-2%

color charge (α_s) : 1%

Weak decay and mixing rates for mesons: a few %

- Further work ongoing to pin down CKM elements and understand quark weak interactions.

- Other work: spectrum of excited baryons, glueballs etc, phases of QCD at high temperature, other strongly coupled theories etc etc etc