The Future of Lattice (QCD) calculations

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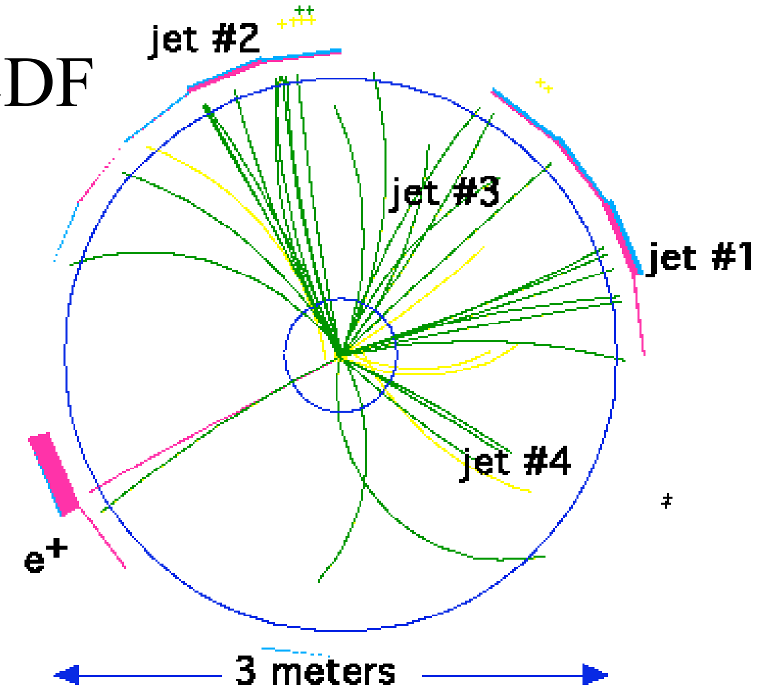
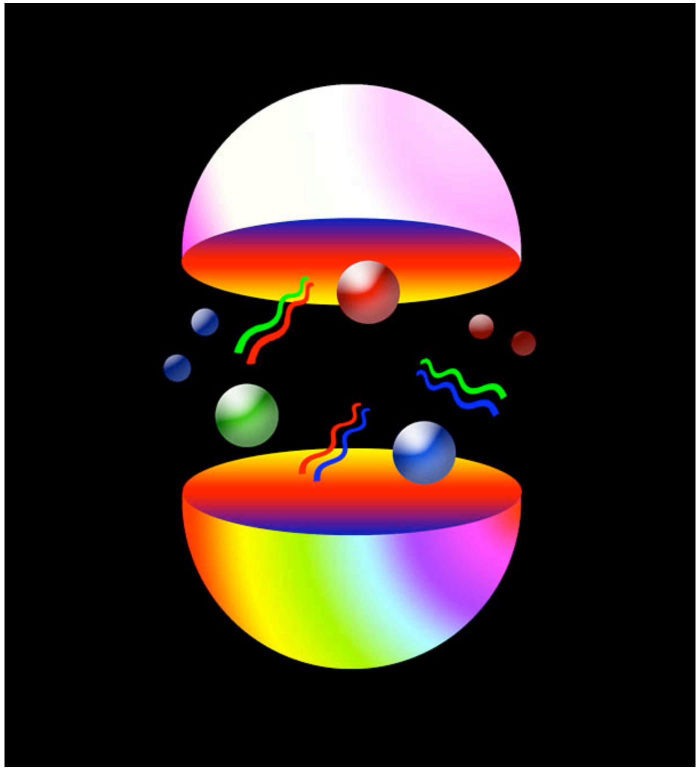
Higgs-Maxwell meeting, February 2009

QCD is a key part of the Standard Model but quark confinement complicates things.

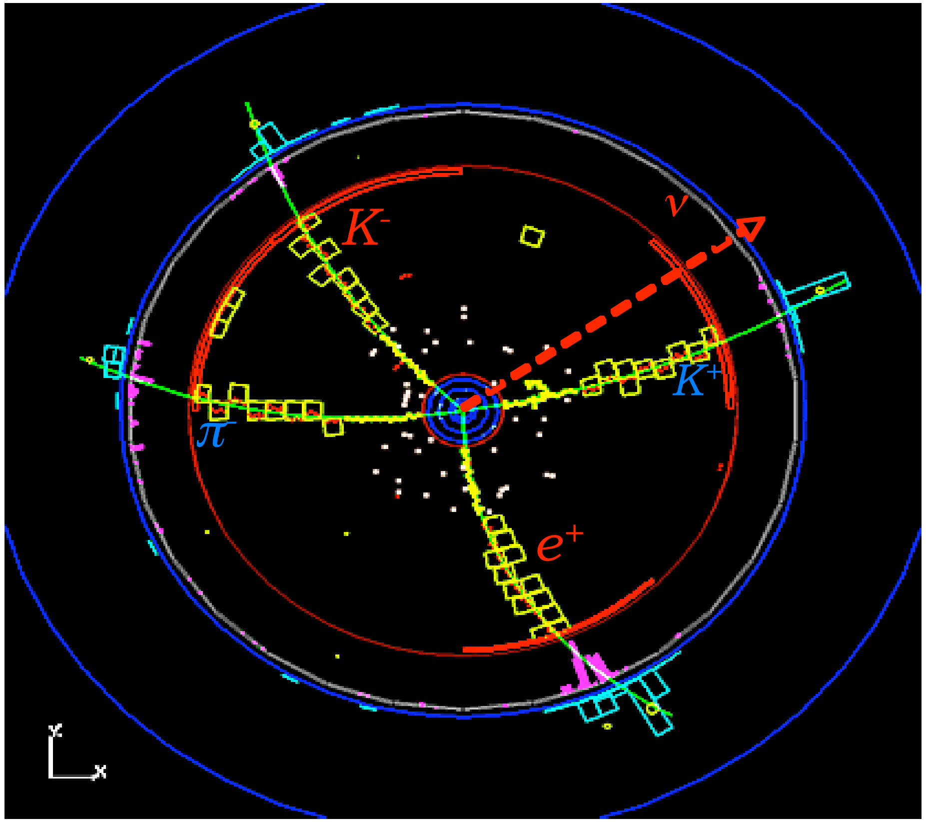
CDF



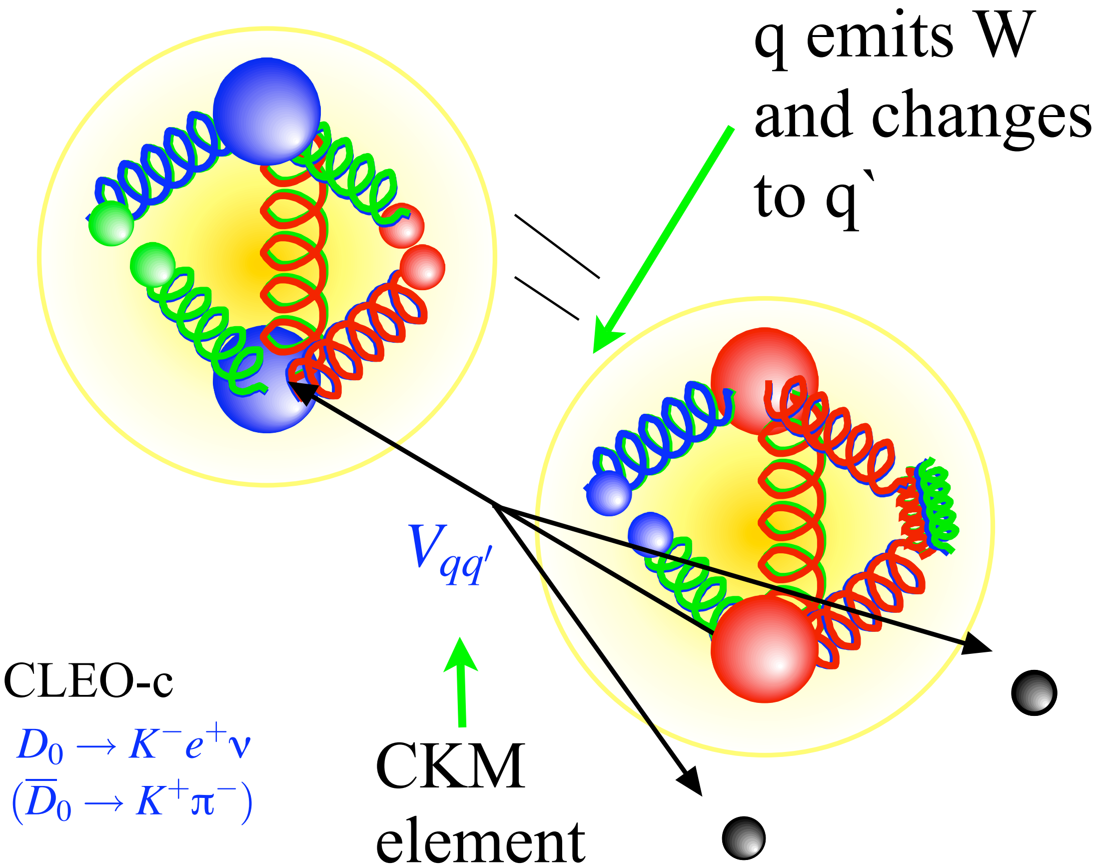
QCD only tested to 5-10% level at high energies from comparison of e.g. jet phenomena to pert.th.



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



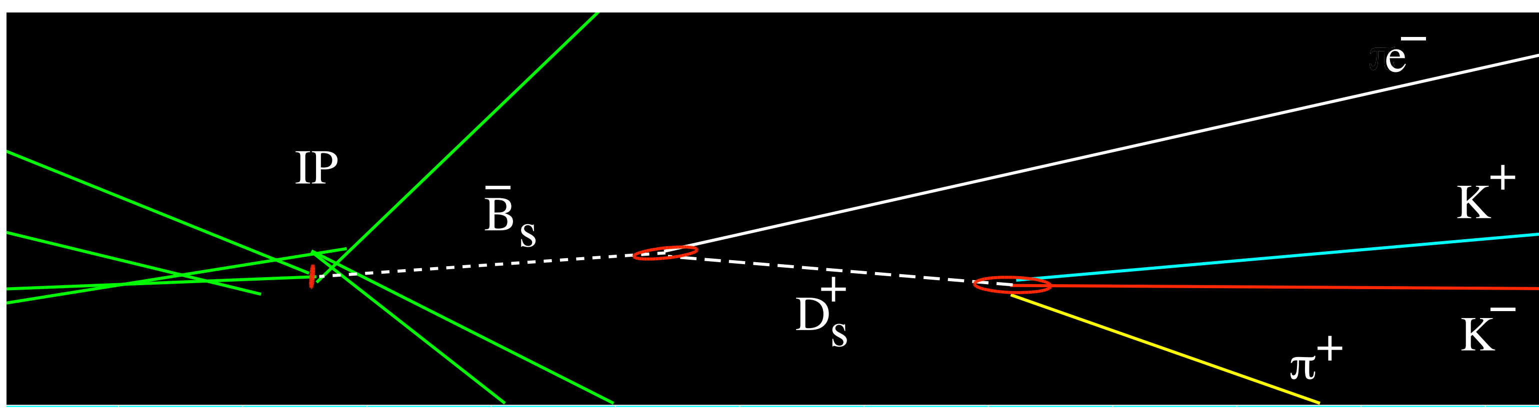
CLEO-c
$D_0 \rightarrow K^- e^+ \nu$
$(\overline{D}_0 \rightarrow K^+ \pi^-)$

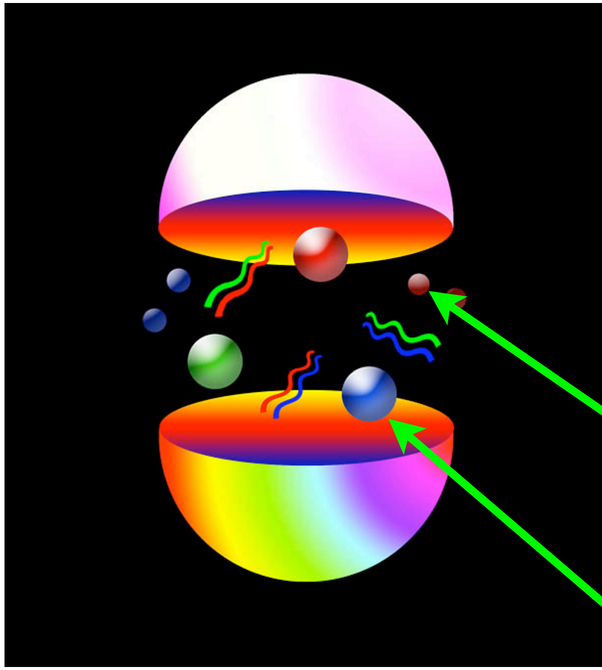


Rates for simple weak or em quark processes inside hadrons also calculable.

ALEPH $\overline{B}_s \rightarrow D_s e^- \nu$
$(D_S \rightarrow K^+ K^- \pi^+)$

Compare to exptl rate gives $V_{qq'}$ accurately





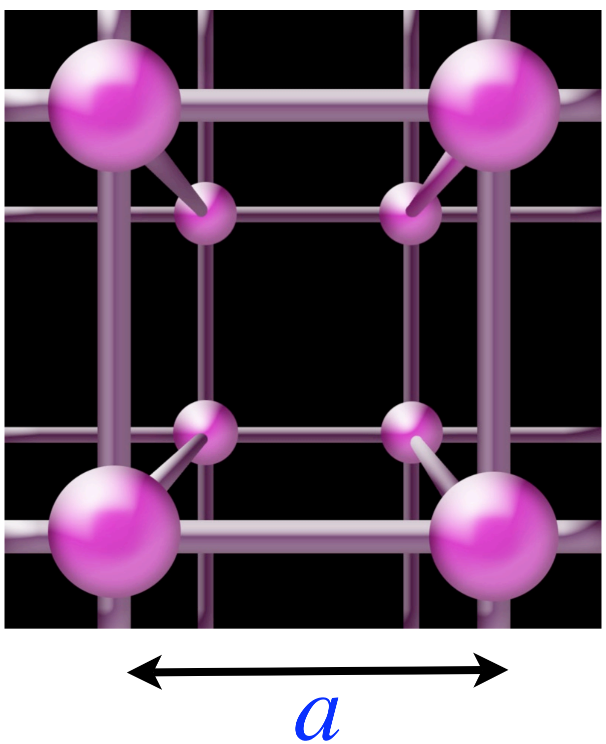
Lattice QCD = fully nonperturbative QCD calculation

RECIPE

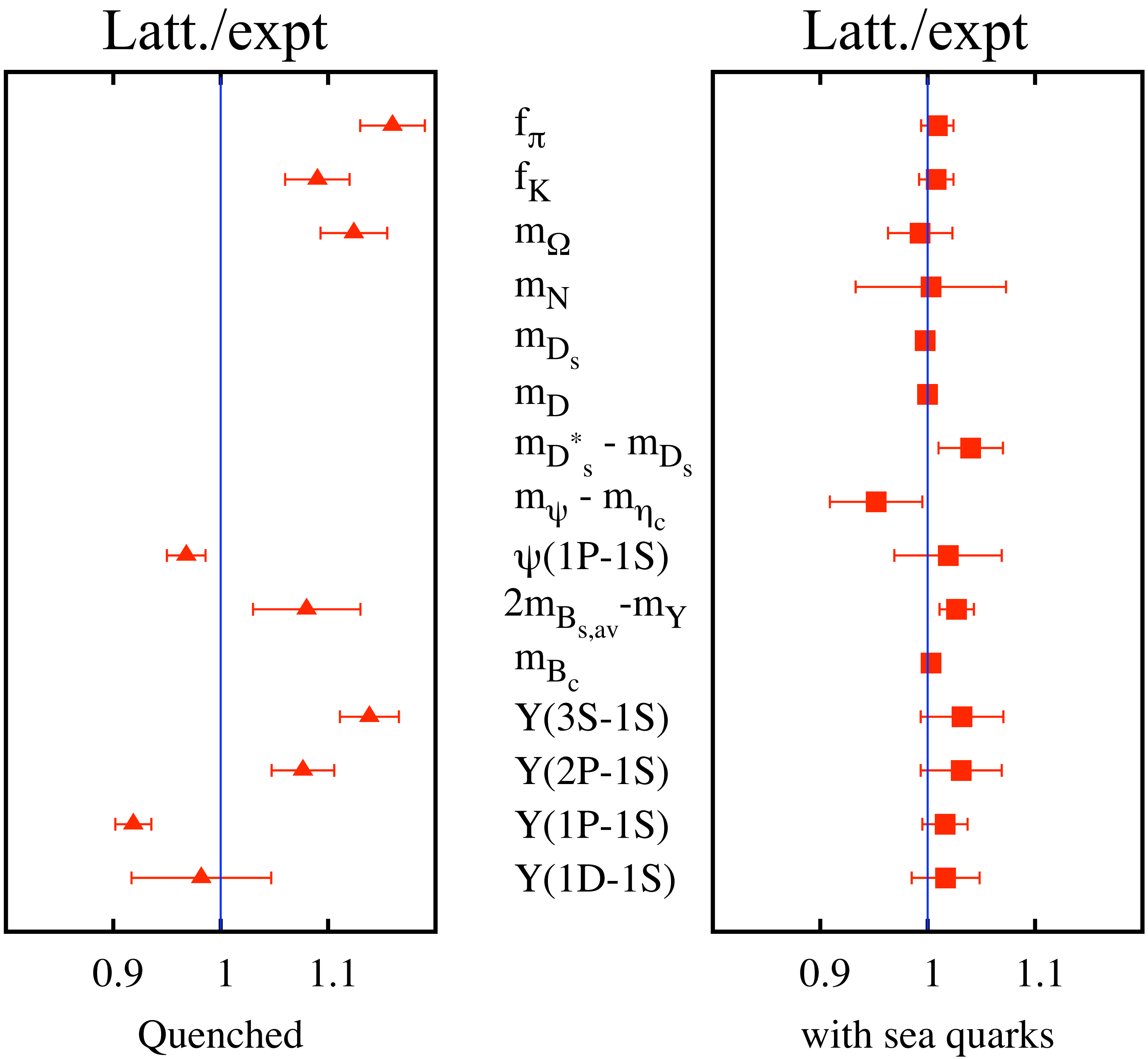
- Generate sets of gluon fields for Monte Carlo integrn of Path Integral (inc effect of sea quarks)
- Calculate averaged "hadron correlators" from valence q props.

$$< 0|M^{\dagger}(0)M(t)|0 >$$

- Fit for masses and simple matrix elements
- Fix m_q and determine a to get physical results



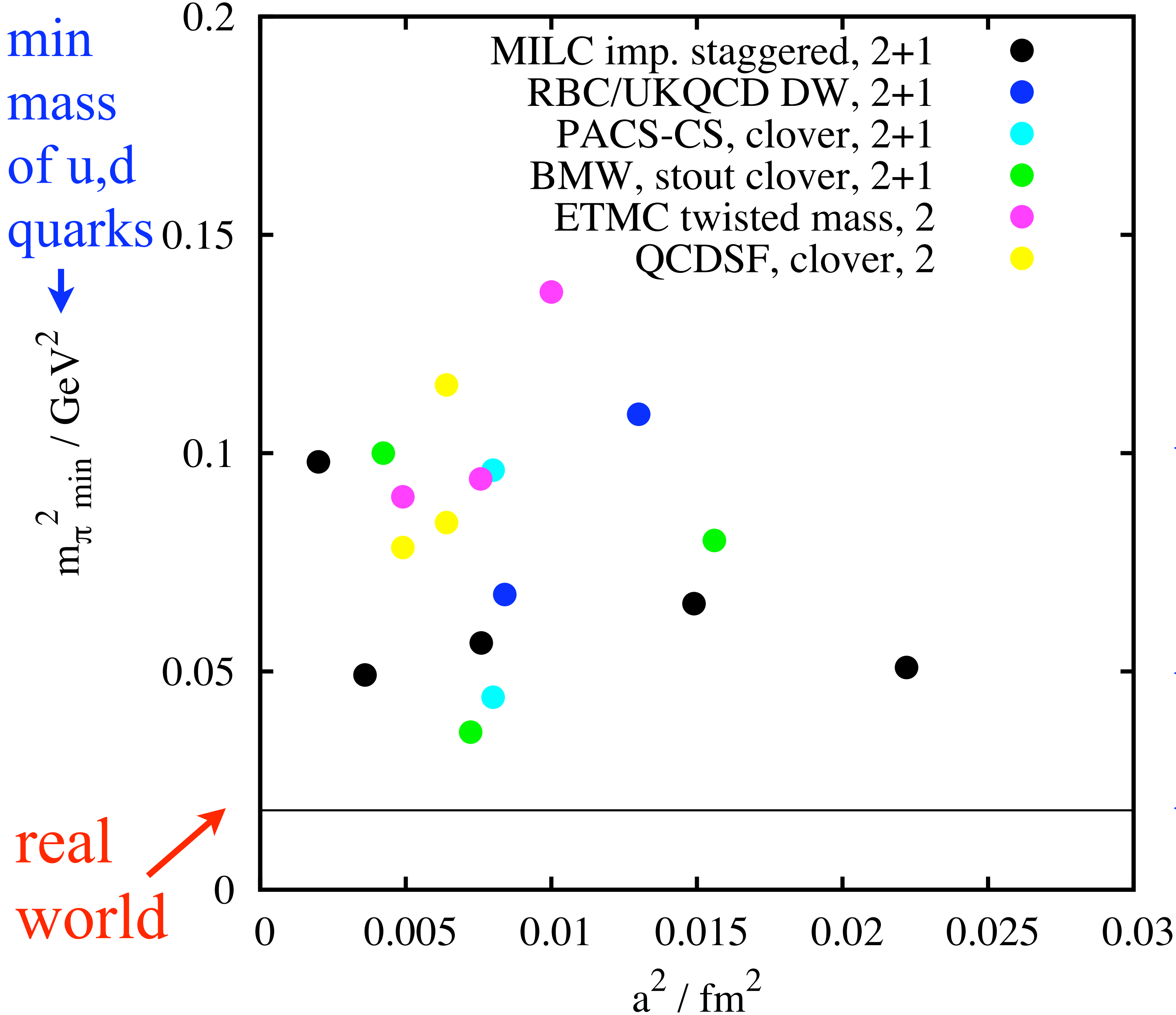
Including u, d and s sea quarks is critical for accurate results, but numerically expensive - particularly light $m_{u,d}$.



HPQCD/ MILC 2008 “ratio plot”.

Multiple values of a, and of $m_{u,d}$. Extrapolate to physical point.

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



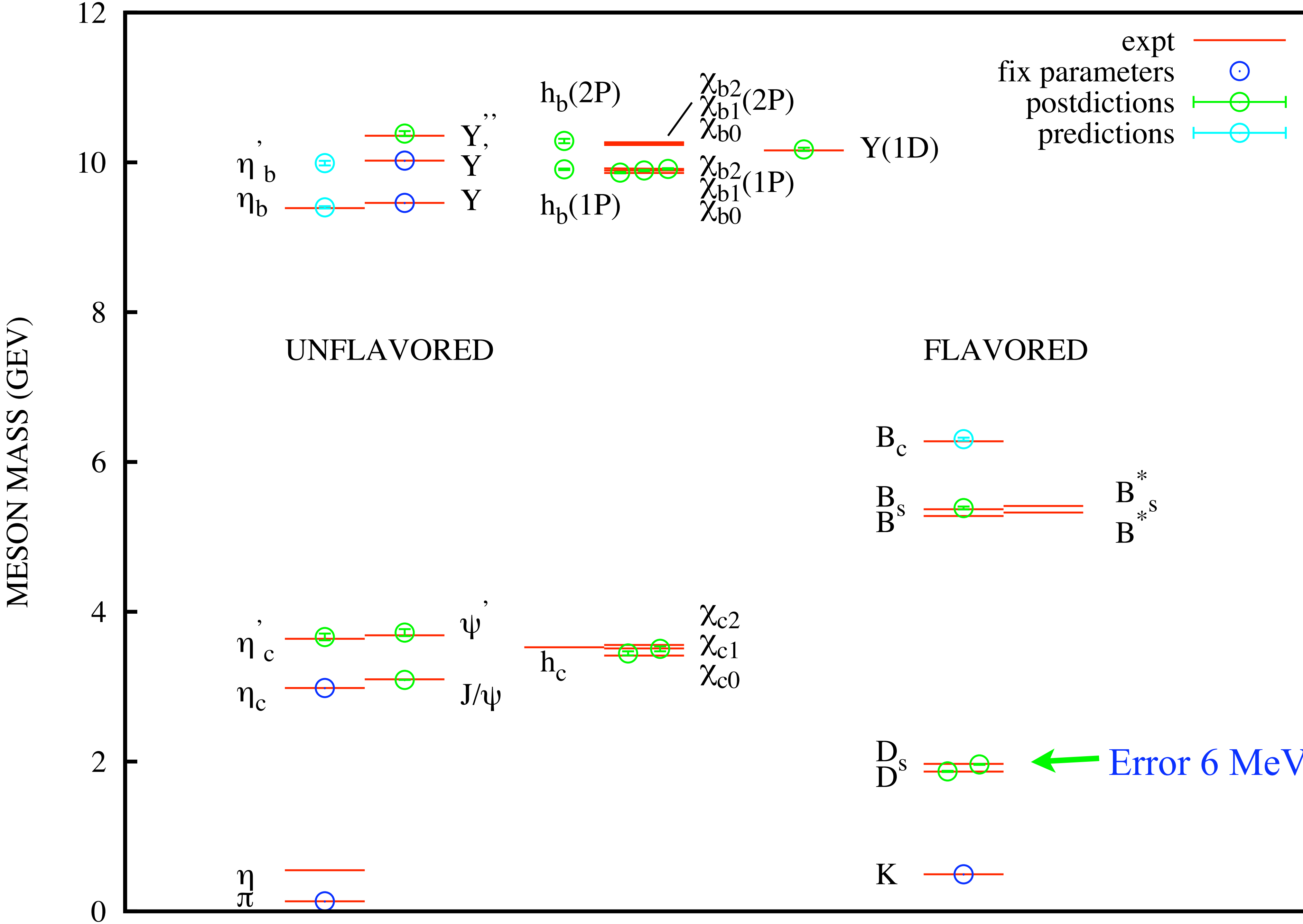
Volume of lattice also an issue - need $\sim (>2.5\mathrm{fm})^4$

$\leftarrow$ $m_{u,d} \approx m_s/5$

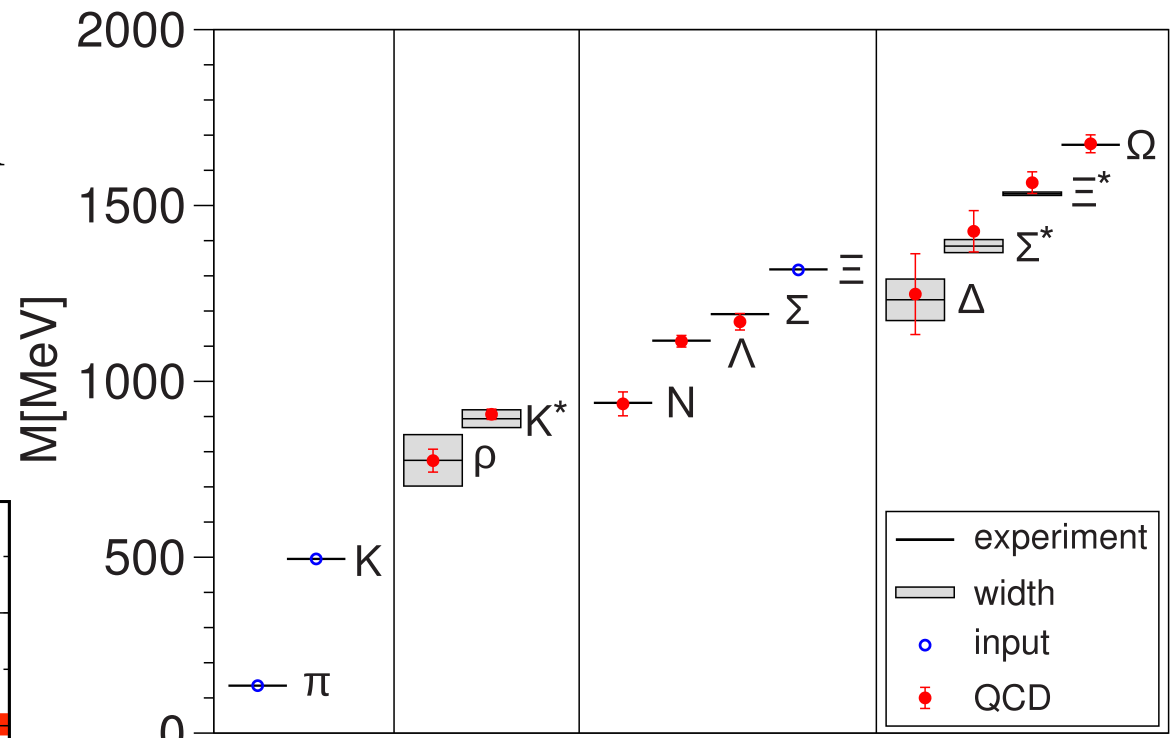
$\leftarrow$ $m_{u,d} \approx m_s/10$

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

The gold-plated meson spectrum - HPQCD 2008.

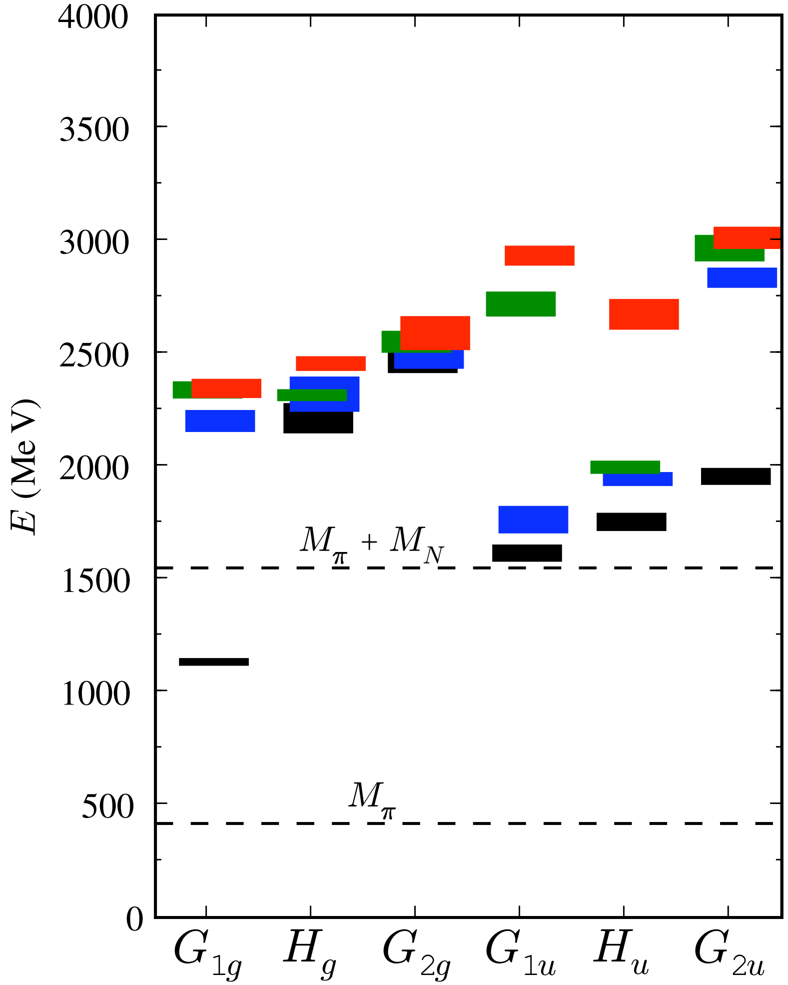


Light hadron spectrum including baryons with ‘fat clover’ quarks



BMW collaboration 2008

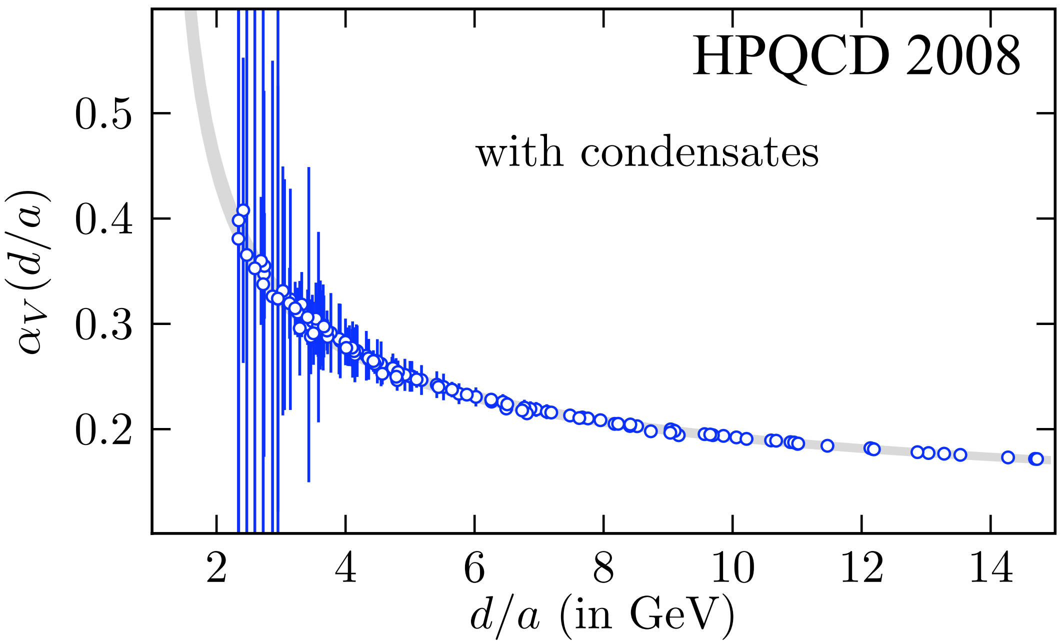
HSC collaboration - Morningstar LAT08



Preliminary excited baryon spectrum using anisotropic lattices.

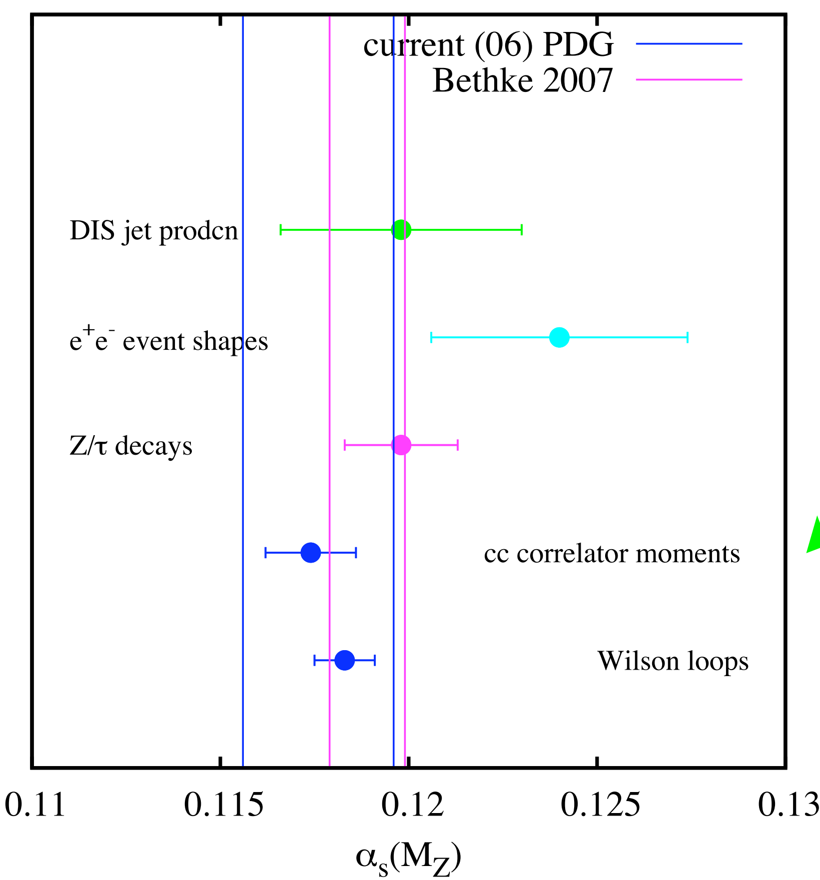
Needed by ‘hadron physicists’ @JLAB and FAIR.

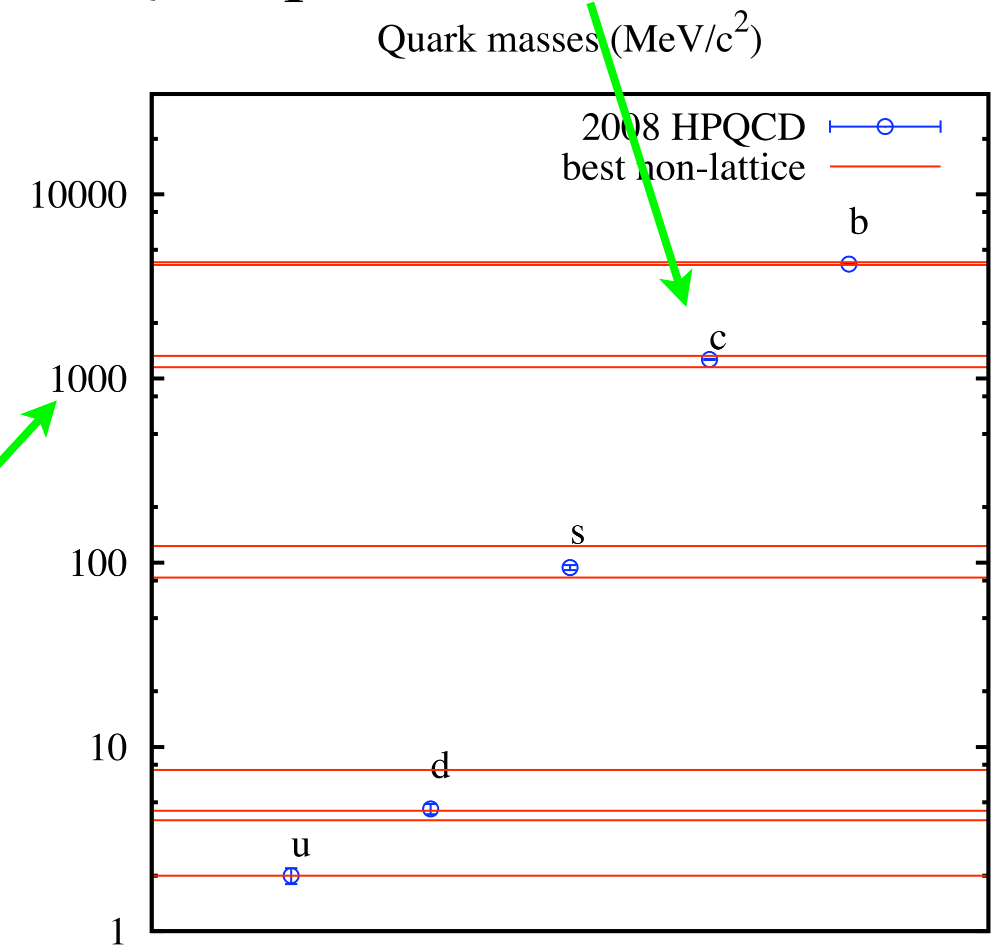
α_s and m_q



1% achieved with α_s^3 lattice QCD pert. th. and 6 values of a

1% achieved with α_s^3 cont. QCD pert. th. and 4 a

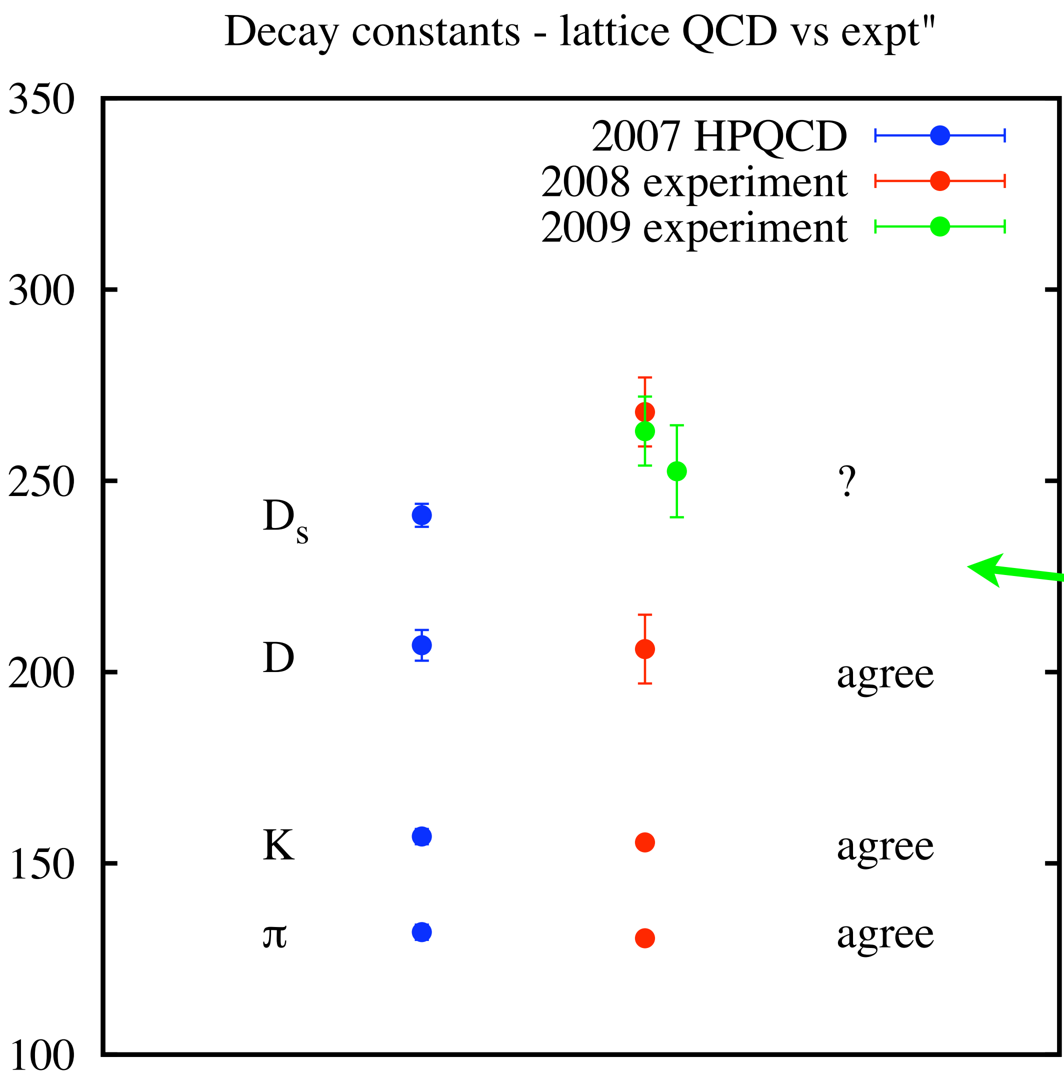


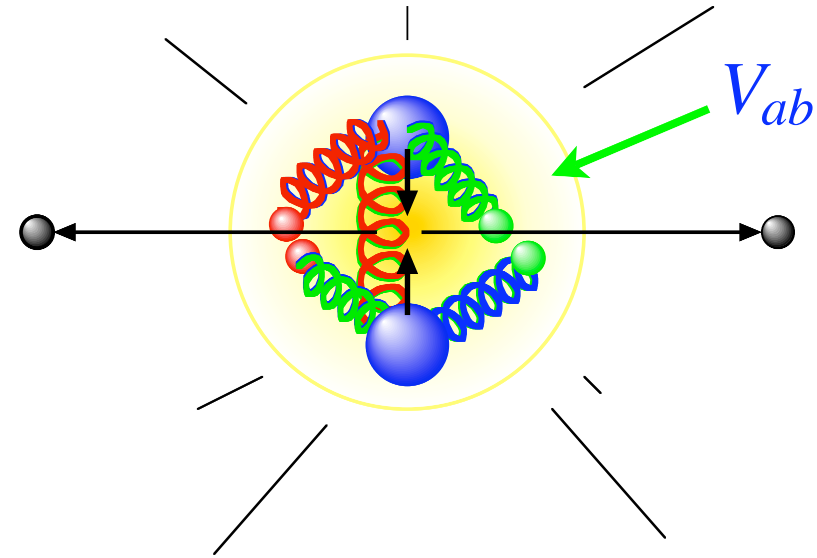


Lattice QCD and precision weak decay rates - 2 examples:

Annihilation to leptons via a W

$$Br(H \to \mu\nu) \propto V_{ab}^2 f_H^2$$





LQCD ahead of expt.
- 2% determination of f_D, f_{Ds}

For f_B, exptl error 30%, lattice 6%.

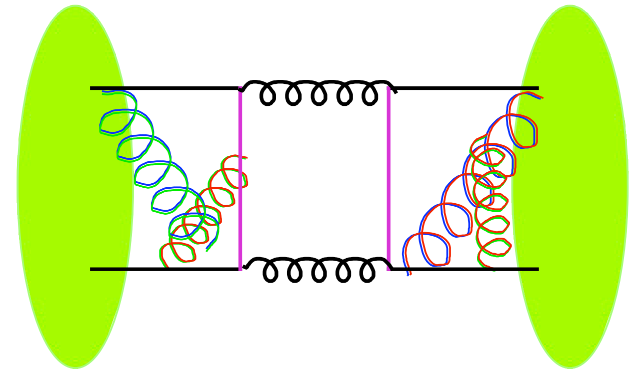
K/B/Bs mixing - LQCD is behind expt.

For B:

$$\xi = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}}$$

lattice QCD

ratio reduces error



$$\frac{|V_{td}|}{|V_{ts}|} = \xi\sqrt{\frac{\Delta M_d}{\Delta M_s}\frac{M_{B_s}}{M_{B_d}}}$$

$\xi = 1.26(3)$ HPQCD 2009

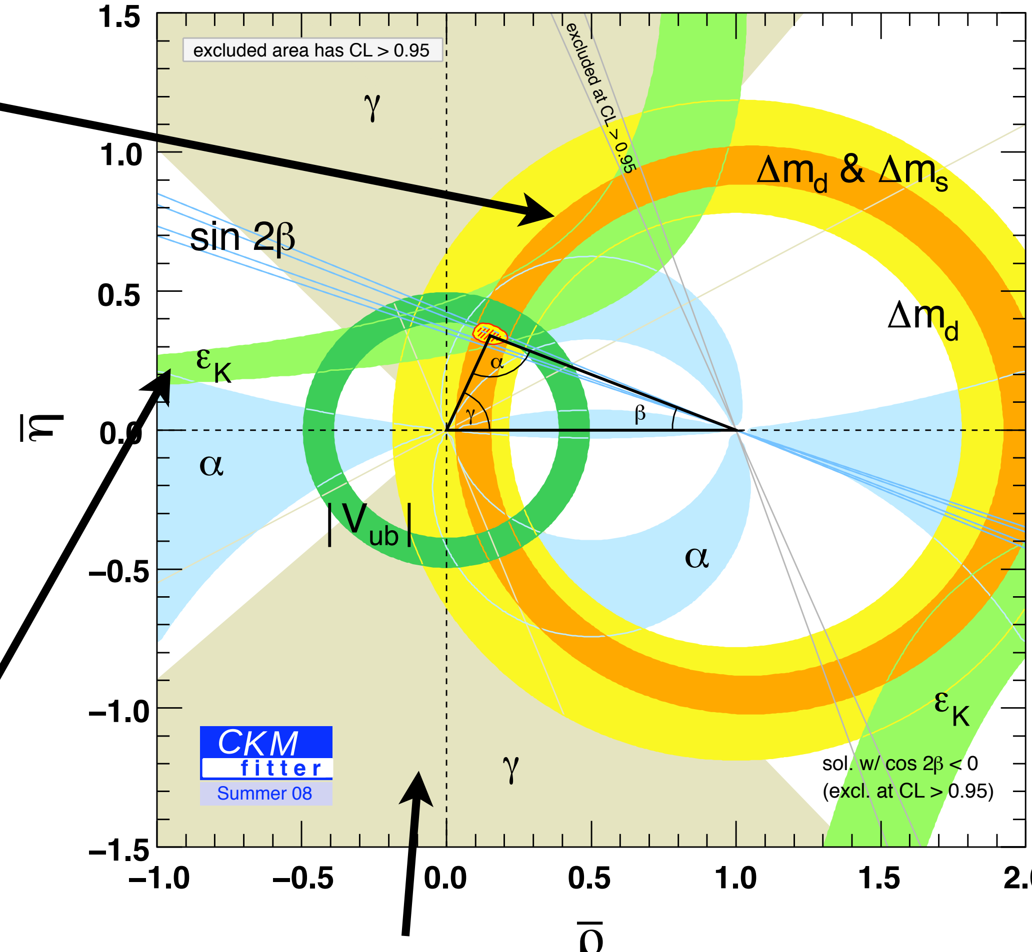
$\frac{\Delta M_d}{\Delta M_s} = 0.0285(3)$ expt

For K (no ratio possible) :

$\varepsilon_K = 2.229(10) \times 10^{-3}$ expt

$B_K^{\overline{MS}}(2\text{GeV}) = 0.524(30)$

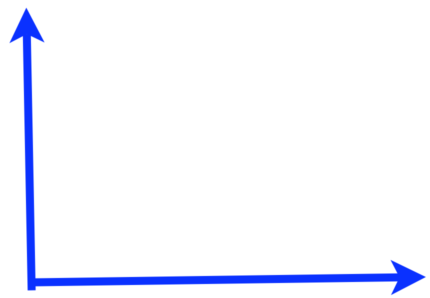
RBC/UKQCD 2008



similar pic. for SL decays ...

Future directions

Energy frontier



Precision frontier

Lattice QCD contributes here e.g.

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9999(10)$$

$\rightarrow \Lambda_{BSM} > \approx 3\text{TeV}$

	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

Complete error budgets now available for lattice calcs

$\rightarrow$ Tests of SM at sub-percent level will be possible

Sub-percent errors needs (depending on quantity):

- Better than 0.5% determn of the lattice spacing.
- Lighter $m_{u,d}$ for less chiral extrapoln uncertainty
- Bigger volumes, e.g. $(4\text{fm})^4$, to reduce syst. error
- Higher statistics for calcs with a lot of noise.
- Improved pert. and nonpert. normalisation of lattice operators (where required). New methods underway.

"2nd generation" gluon configurations now being made. Include improvements such as:

- $m_u \neq m_d$. Allows electromagnetic effects to be inc. (affect hadron masses at few MeV level). Better m_u, m_d.
- c quarks in the sea. Can check the effect of this.
- Further improved gluon action for lower disc. errors.

What can we achieve in five years?

For calcs required to extract CKM, progress required is clear

process/ latt. calc.	K mixing	$K \to \pi l \nu$ $f_+(0)$	$\frac{K \to l\nu}{\pi \to l\nu}$ (f_K/f_π)	$D, D_s \to l\nu$ $(f_{D_{(s)}})$	B, "B_s" $\to l\nu$ $(f_{B_{(s)}})$	$B \to D, \pi l \nu$ $f_+(q^2)$	B_s, B_d mixing	$\sqrt{ratio}$ (ξ)
current lattice error	7% disc.	0.5% chiral	0.6% volume	2% a	6% normln	4-10% stat. chiral normln	6% normln stat.	3% chiral stat.
current exptl error	0.5%	0.2%	0.2%	4%	30%	4%	1%	0.5%
future lattice error	2%	0.2%	0.3%	0.5%	2%	2-4%	3%	1%

+ penguins, further boxes and related calcs......

Other calculations are harder - some need development of new methods

• Masses for excited baryons/mesons, glueballs, hybrids, unstable/mixed particles very challenging, important for nuclear physics expt. (+light nuclei?)

• $K \to \pi\pi$ decays and ε'. Needs two-particle final states to be handled (which can be done in principle here) or better handling of $K \to \pi$ and $K \to 0$ cases.

• Matrix elements involving flavor singlet "disconnected diagrams" e.g. $< N|s\bar{s}|N >$, $m_{\eta'}$.
Very noisy, need high stats.

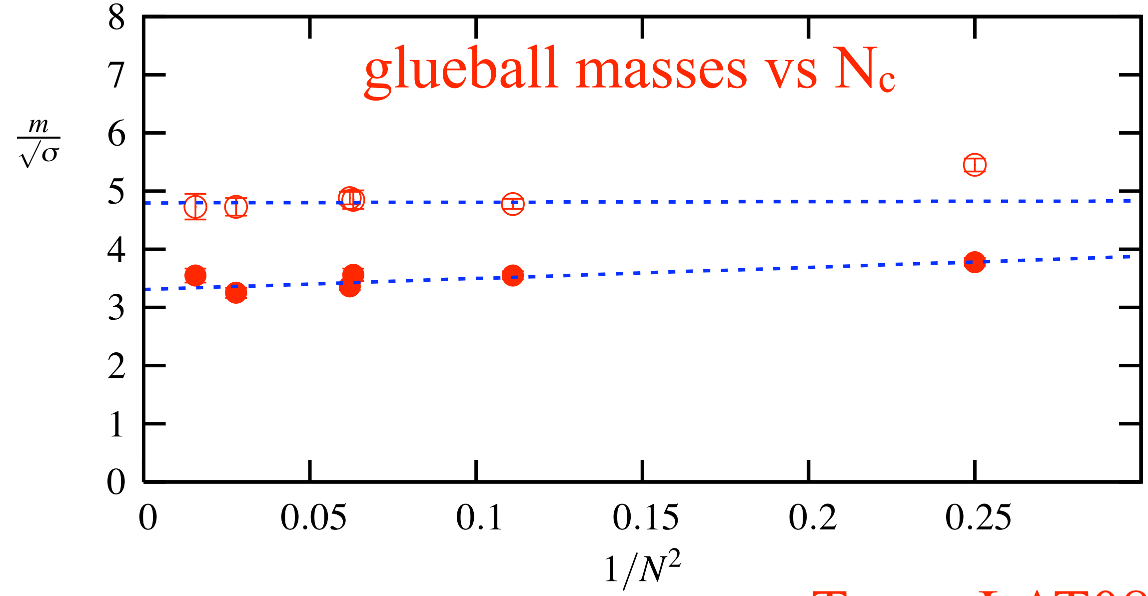
• Phase diagram of QCD at finite temp. /non-zero baryon density for heavy ion collisions - expensive and, at finite μ, lose positive probabilities.

More speculative stuff

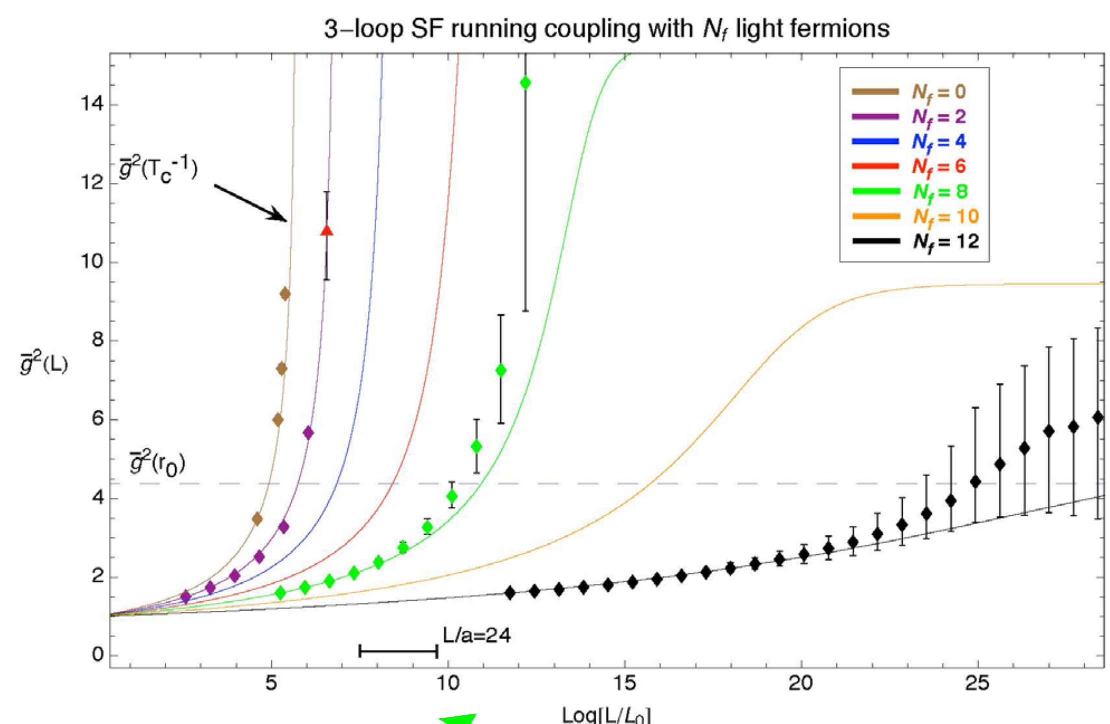
BSM discovery at LHC → non-perturbative studies of new models

Current small-scale studies are of QCD-like models with e.g. large N_c (string dualities) or N_f (walking technicolor), or simple SUSY models.

Large scale studies will be extremely challenging

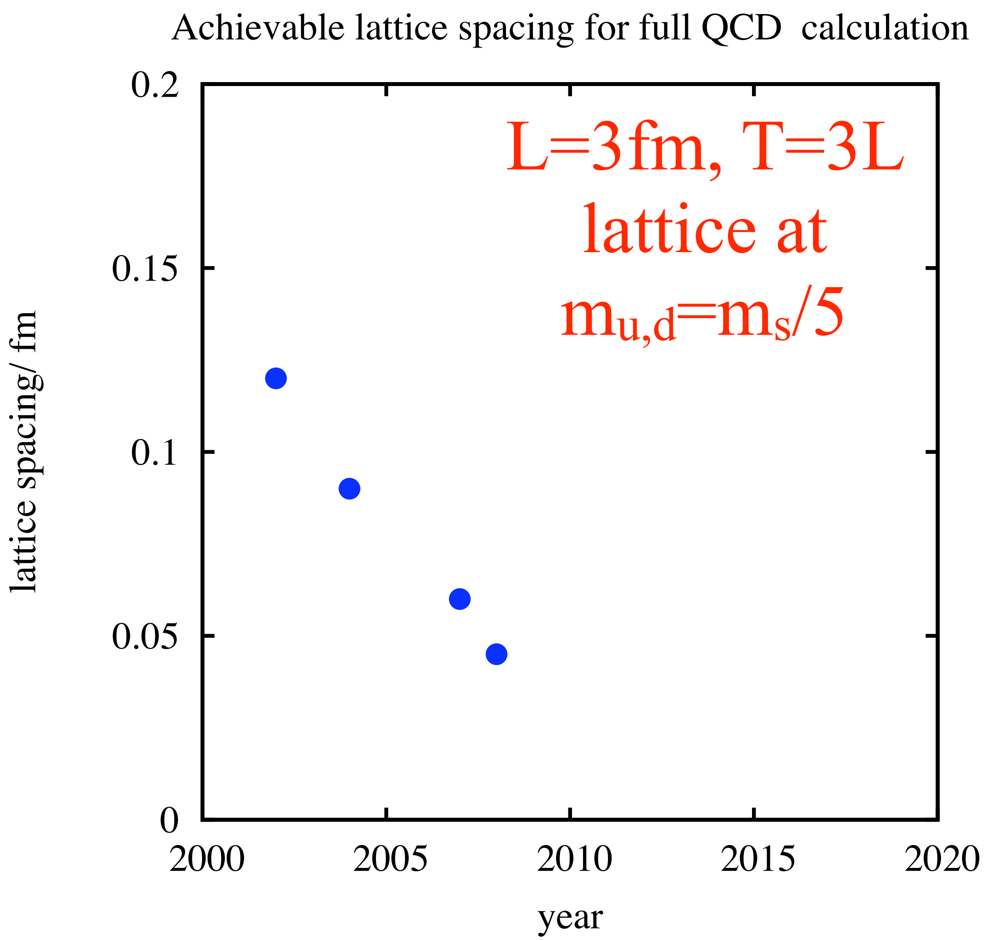


Teper, LAT08



g^2 flow with N_f →

Fleming, LAT08



BlueGene/P at Argonne - 0.5Pflops

Computers will get more powerful - next scale is exaflops - 10^{18} flops

Will this mean bigger collaborations? or, if configs and software made publicly available, can small groups still thrive?