Leptonic and semi-leptonic decays of heavy mesons from lattice QCD.

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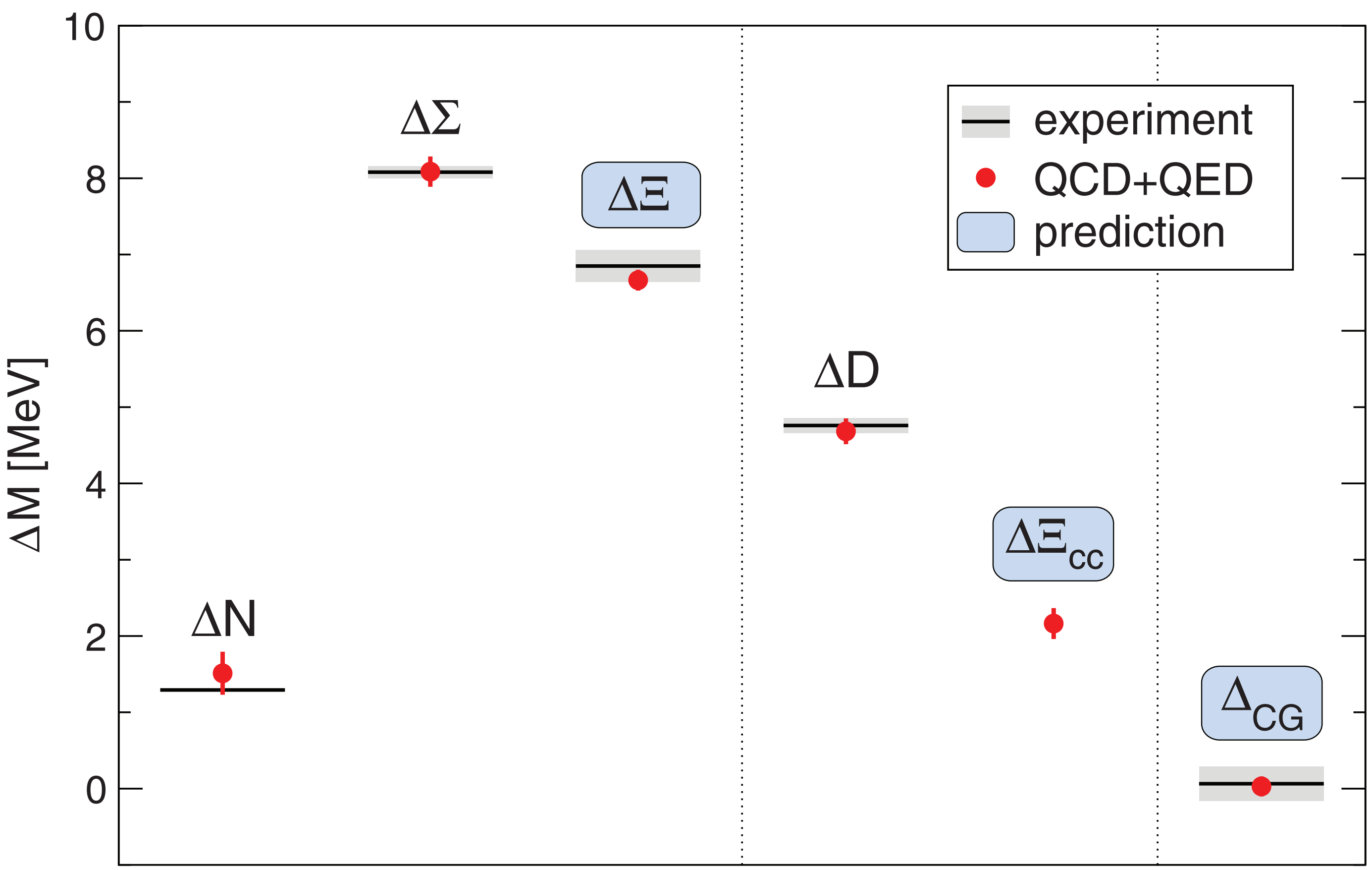
Baltimore
April 8-10, 2015

Lattice QCD

The ability of lattice QCD to calculate interesting things in quark and hadron physics has been growing by leaps and bounds for the last 15 years.



For example, last weeks Science: proton-neutron mass difference.

Must be positive for matter to be stable. Measured tiny, 0.14% of masses!

Origin traced to delicate cancelation of electromagnetic and bare quark mass effects.

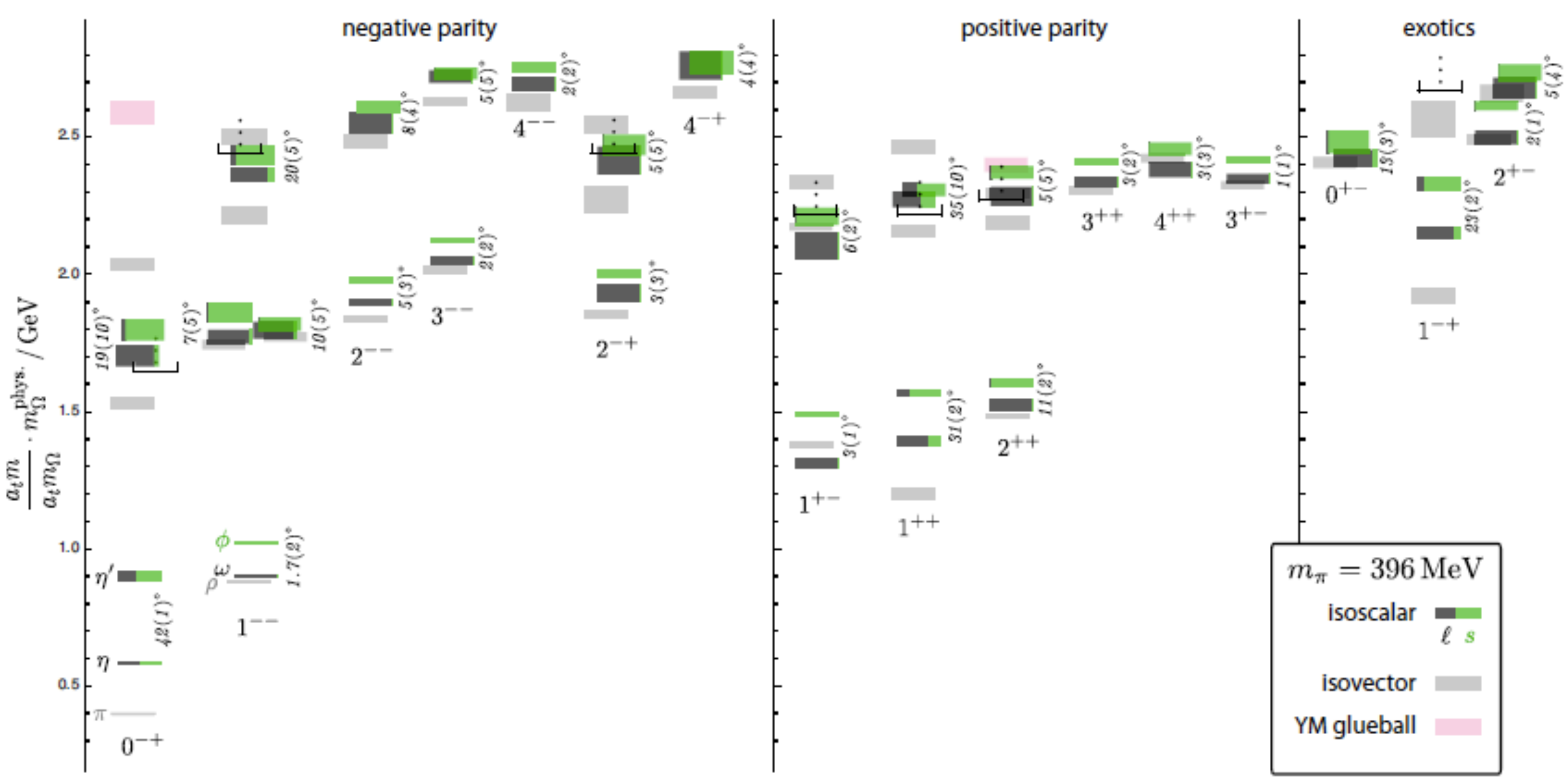
Borsanyi et al., BMW Collaboration, Science, 27 March 2015, **347** p1453.

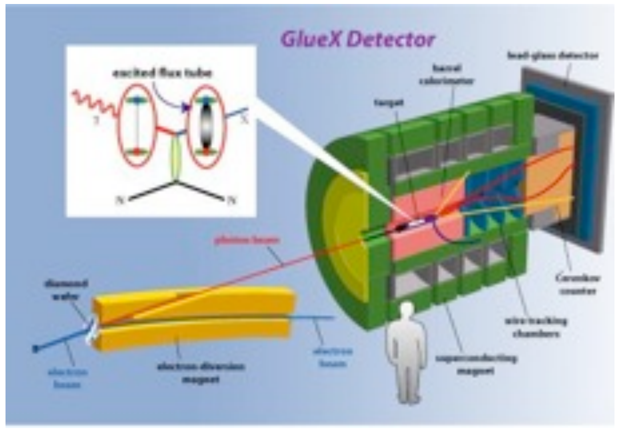
This workshop: lattice QCD for hadron and quark physics per se

rather than as a tool to study other science.

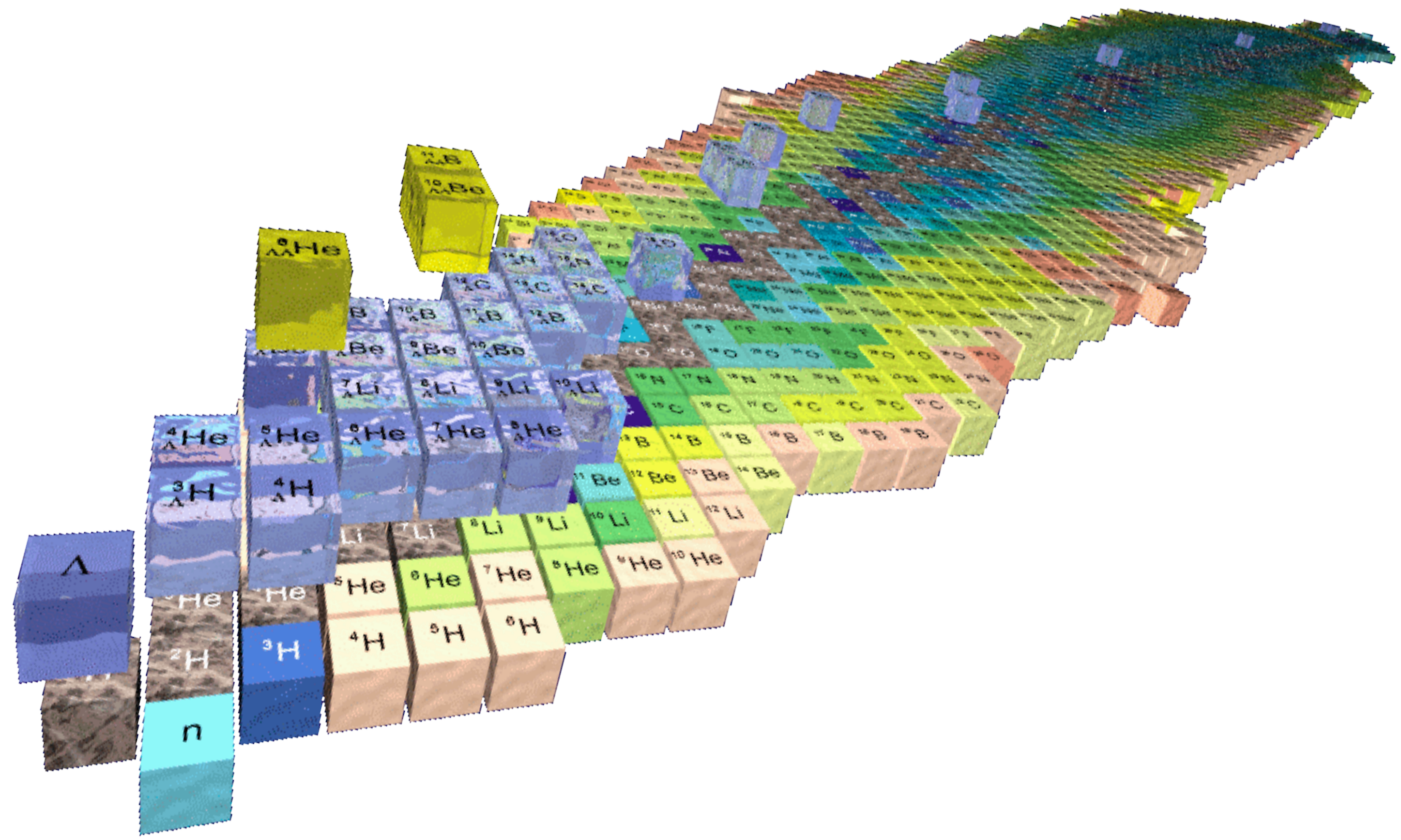
Many lattice-QCD talks on structure and spectrum of hadrons:
Liu, Qiu, Engelhardt, Izubuchi, Koutsou, Bali, Orginos, Morningstar, Mohler, Falica, Syritsyn

Crucial interplay with JLab 12-GeV upgrade.
Lattice QCD is predicting the exotic spectrum from first principles before and during the GlueX experiment .





Nuclear physics



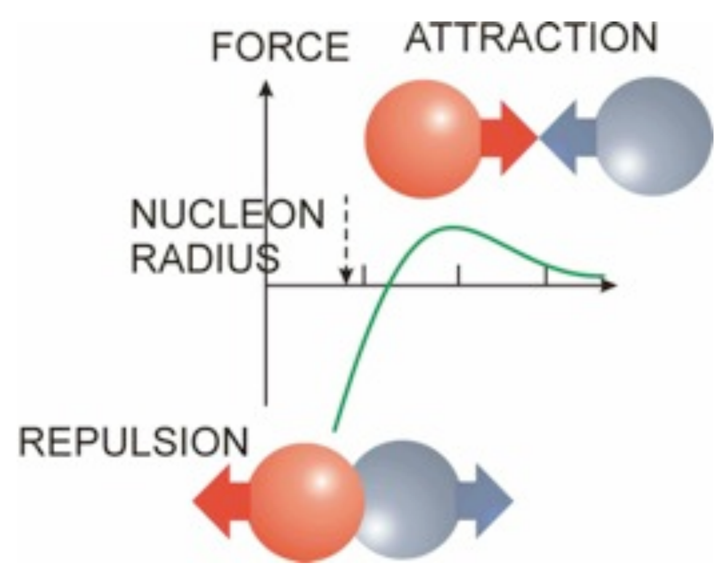
Talks on interactions of hadrons, foundation of nuclear physics:

Savage, Wilson

Solve QCD

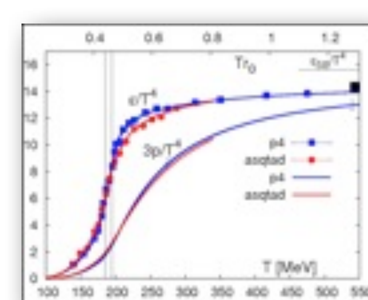
Refine chiral nuclear forces

Interactions of the Nucleon and Hyperons



and on the high-temperature transition between hadrons and quarks.

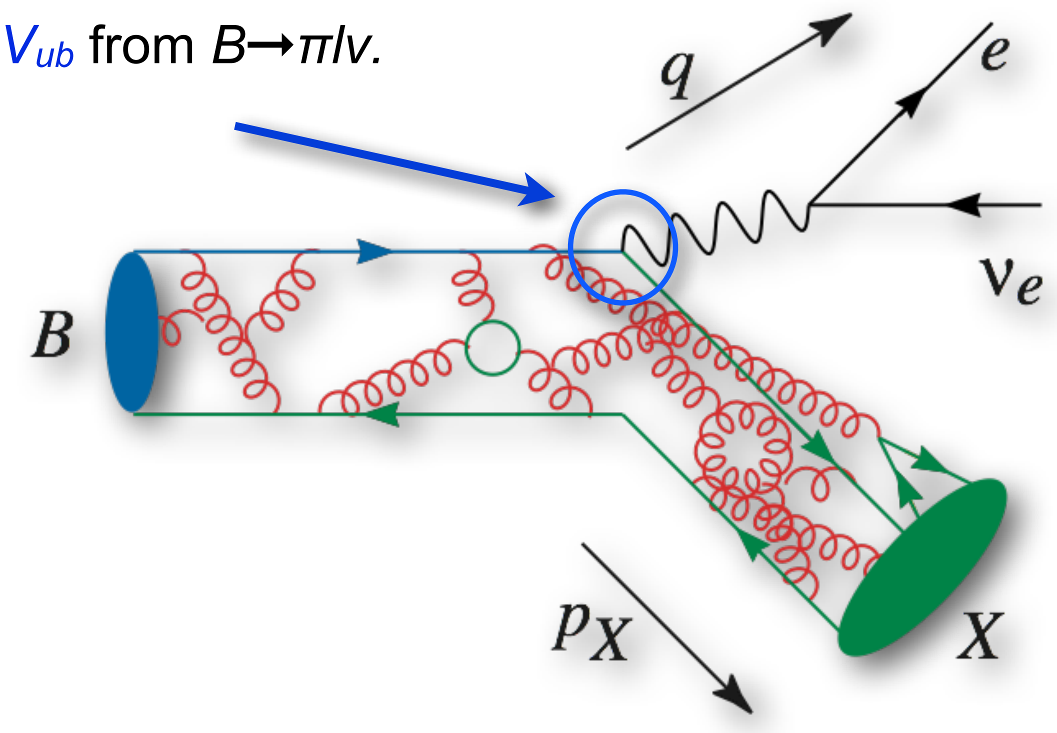
Rothkopf, Mukherjee



In particle physics, LGT is essential as a *tool*

This talk, Mawhinney, Hoebling

Determine V_{ub} from $B \to \pi l v$.



= {π, K, ...}

$B \to \pi l v$
semileptonic
decay

If we want to extract the CKM parameter V_{ub} from the experimental result for $B \to \pi l v$ decay, we have to first use lattice QCD to determine the form factor for B→πlv decay.

$$\frac{d\Gamma(B \to \pi \ell \nu)}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^3} |\boldsymbol{p}_\pi|^3 |f_+(q^2)|^2$$

The standard model

Numerous bells and whistles and 20 or 30 free parameters.

SU(3)×SU(2)×U(1),   H

$$\alpha_{\rm s},\ \alpha_{\rm w},\ \alpha_{\rm em}$$

$$m_u,\ m_d,\ m_c,\ m_s,\ m_t,\ m_b$$

$$m_e,\ m_\mu,\ m_\tau,\ m_{\nu_1},\ m_{\nu_2},\ m_{\nu_3}$$

$$M_W,\ M_H$$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \qquad \begin{pmatrix} V_{e\nu_1} & V_{e\nu_2} & V_{e\nu_3} \\ V_{\mu\nu_1} & V_{\mu\nu_2} & V_{\mu\nu_3} \\ V_{\tau\nu_1} & V_{\tau\nu_2} & V_{\tau\nu_3} \end{pmatrix}$$

Three forces
Masses
Mixings

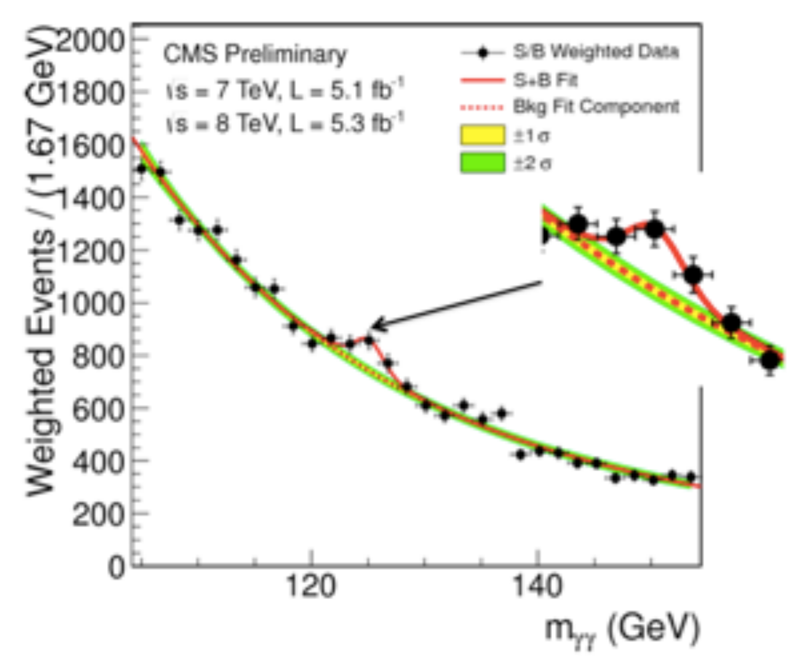
Where do these parameters come from?
Can we predict them with a more fundamental theory?

The Standard Model is *maddeningly* successful. It accounts for every particle physics experiment performed so far, sometimes to great precision (one part in a billion for the electron anomalous magnetic moment).

Why maddeningly? It contains obvious gaps and puzzles!

- Why is there more than one generation of quark?
- What is the relation between the three forces?
- What about gravity?
- What is dark matter?
- ...

Latest (2012) news: standard model predicts Higgs properties perfectly (so far).



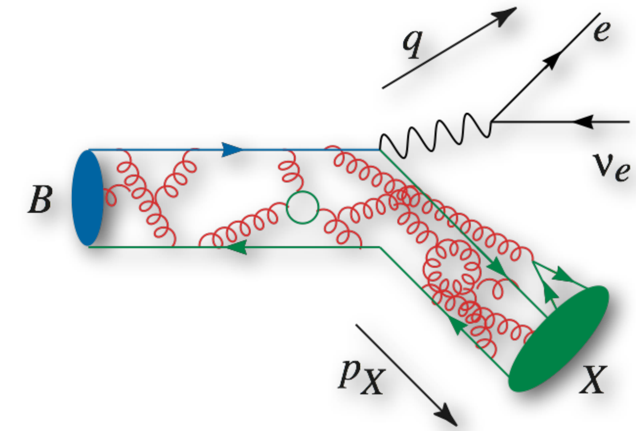
Issues in the meson decay calculations discussed in this talk.

- Do all lattice QCD methods agree with each other?
  - Yes, so far.
- Do lattice QCD calculations give the same results as other approaches to QCD?
  - Perhaps no? Exclusive and inclusive results sometimes disagree.
- Are there deviations from the standard model?
  - Yes, but can we find them?
  - Standard model predicts that the rows and columns of the CKM quark mixing matrix are orthonormal. Are they?

or, does the Wolfenstein parameterization work?

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \Rightarrow \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}.$$

$B \to \pi l \nu$



Issues:

Do exclusive determinations (lattice) of V_{ub} agree with inclusive?
Are first and third rows of CKM matrix orthogonal (unitarity triangle)?

$$\langle \pi(p_\pi)|\mathcal{V}^\mu|B(p_B)\rangle = \left(p_B^\mu + p_\pi^\mu - \frac{M_B^2 - M_\pi^2}{q^2} q^\mu\right) f_+(q^2) + \frac{M_B^2 - M_\pi^2}{q^2} q^\mu\, f_0(q^2),$$

$$\langle \pi(p_\pi)|\mathcal{T}^{\mu\nu}|B(p_B)\rangle = \frac{2}{M_B + M_\pi} (p_B^\mu p_\pi^\nu - p_B^\nu p_\pi^\mu)\, f_T(q^2),$$

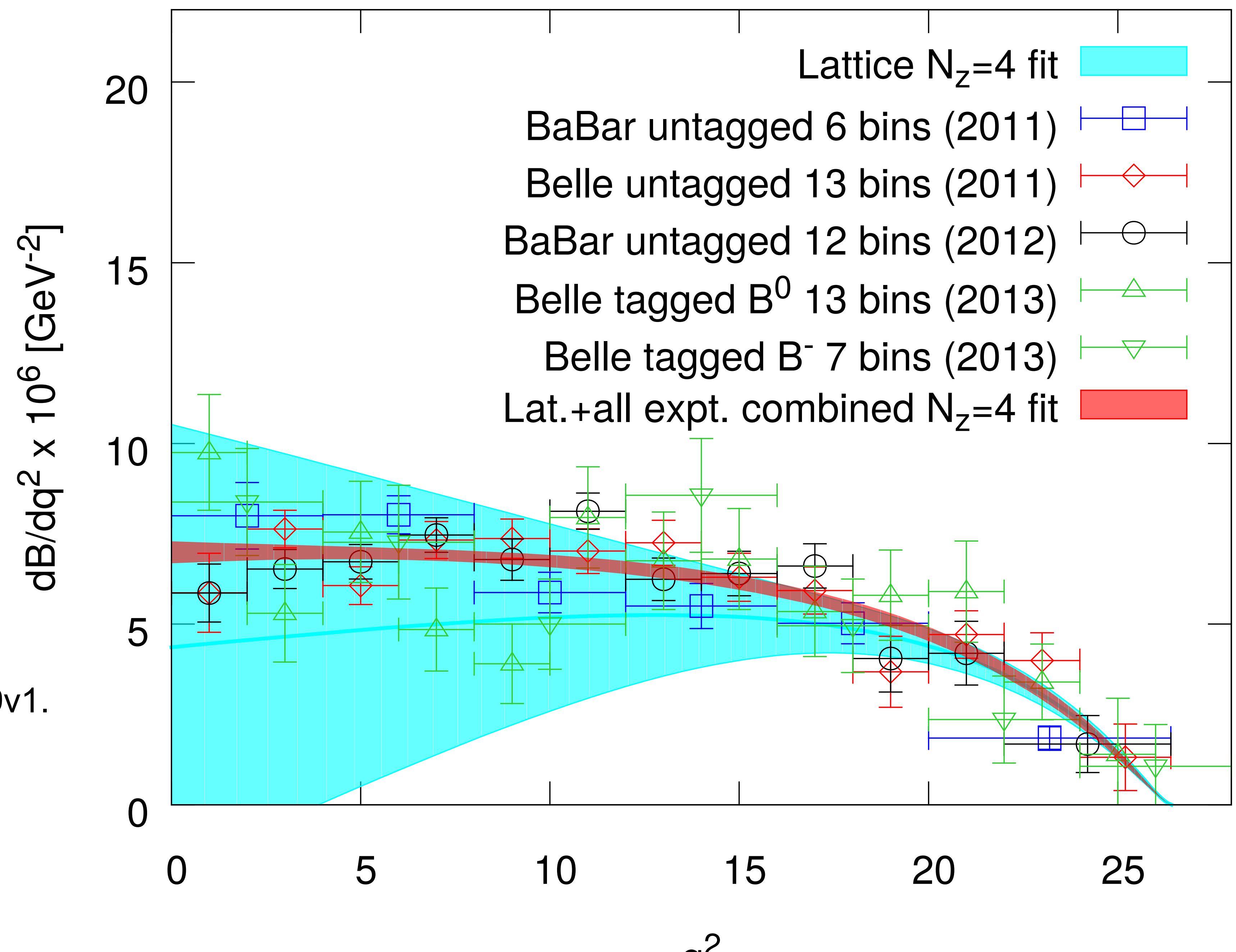
$$\mathcal{V}^\mu = \bar{q}\gamma^\mu b, \text{ and } \mathcal{T}^{\mu\nu} = i\bar{q}\sigma^{\mu\nu} b$$

Form factors giving CKM matrix elements from cross sections.

Amplitudes calculated on lattice.

$B \to \pi l \nu$

$$\frac{d\Gamma(B \to \pi \ell \nu)}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^3} |\boldsymbol{p}_\pi|^3 |f_+(q^2)|^2$$

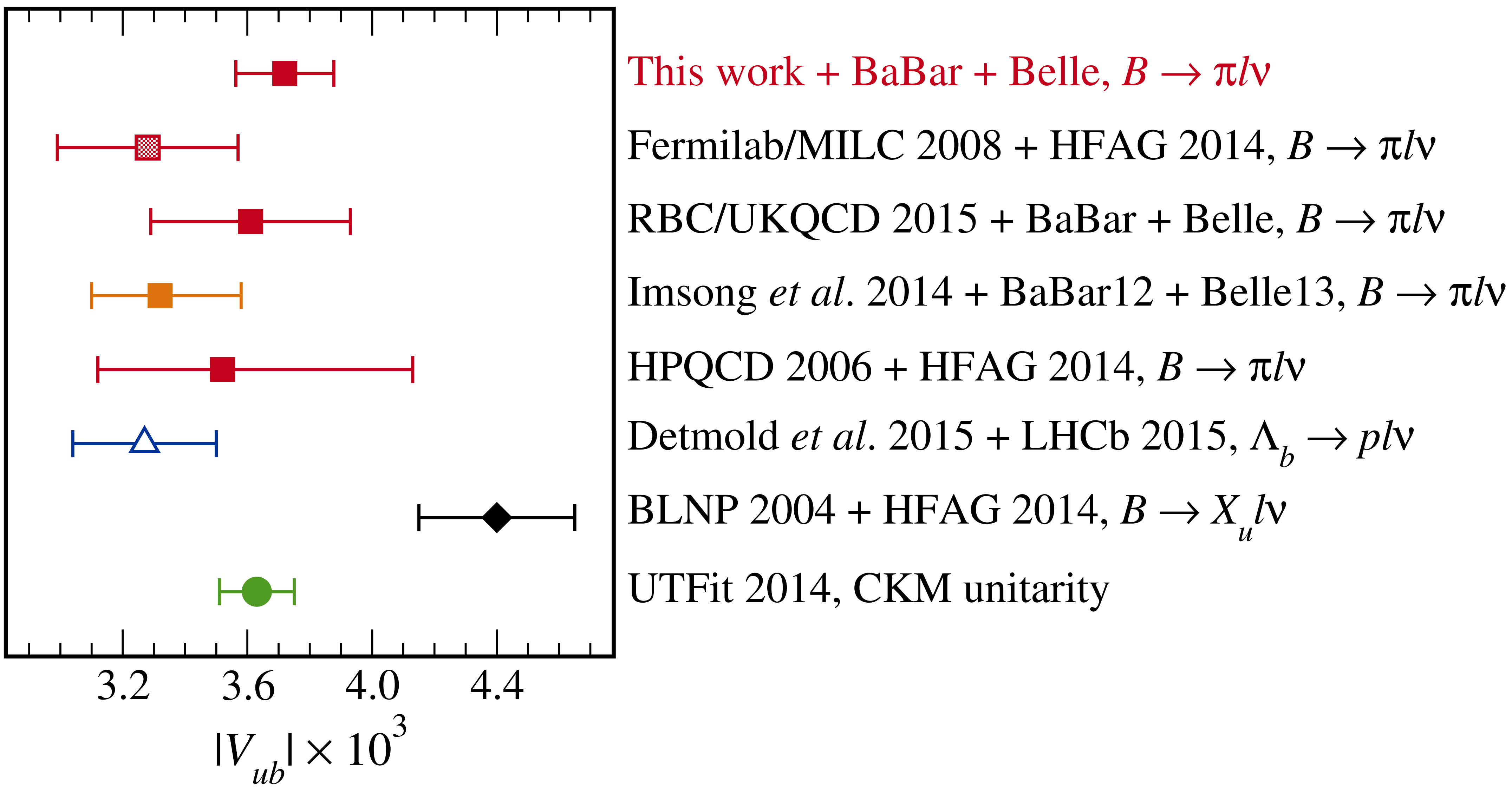


J. Bailey et al., arXiv:1503.07839v1.
Fermilab/MILC Collaborations.

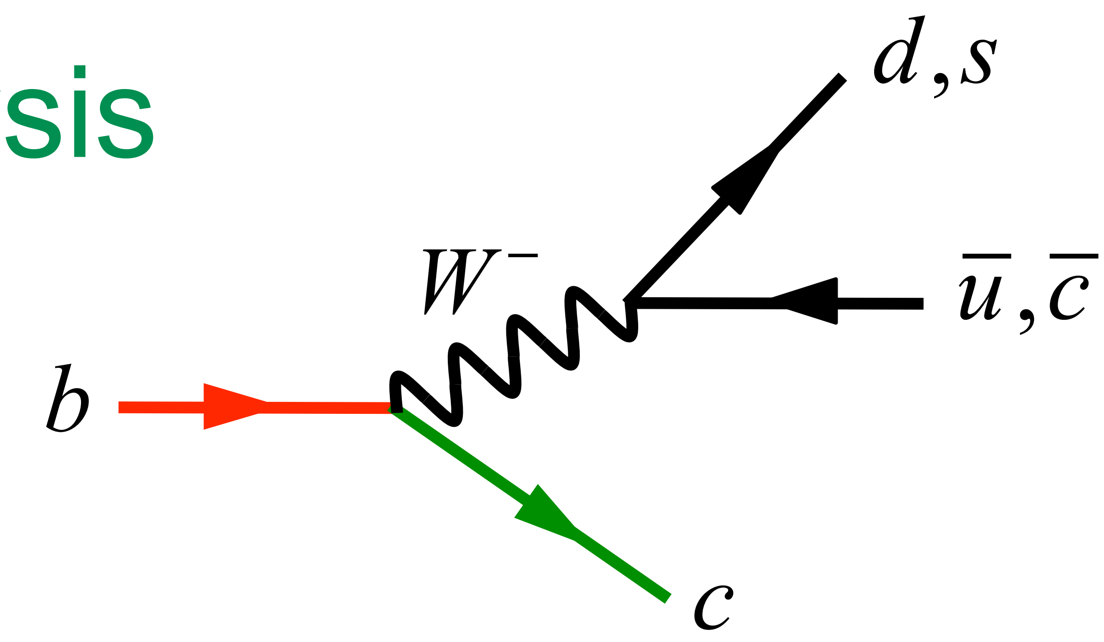
Result: $|V_{ub}| = (3.72 \pm 0.16) \times 10^{-3}$. Includes all lattice and exp. uncertainties.

$B \rightarrow \pi l \nu$

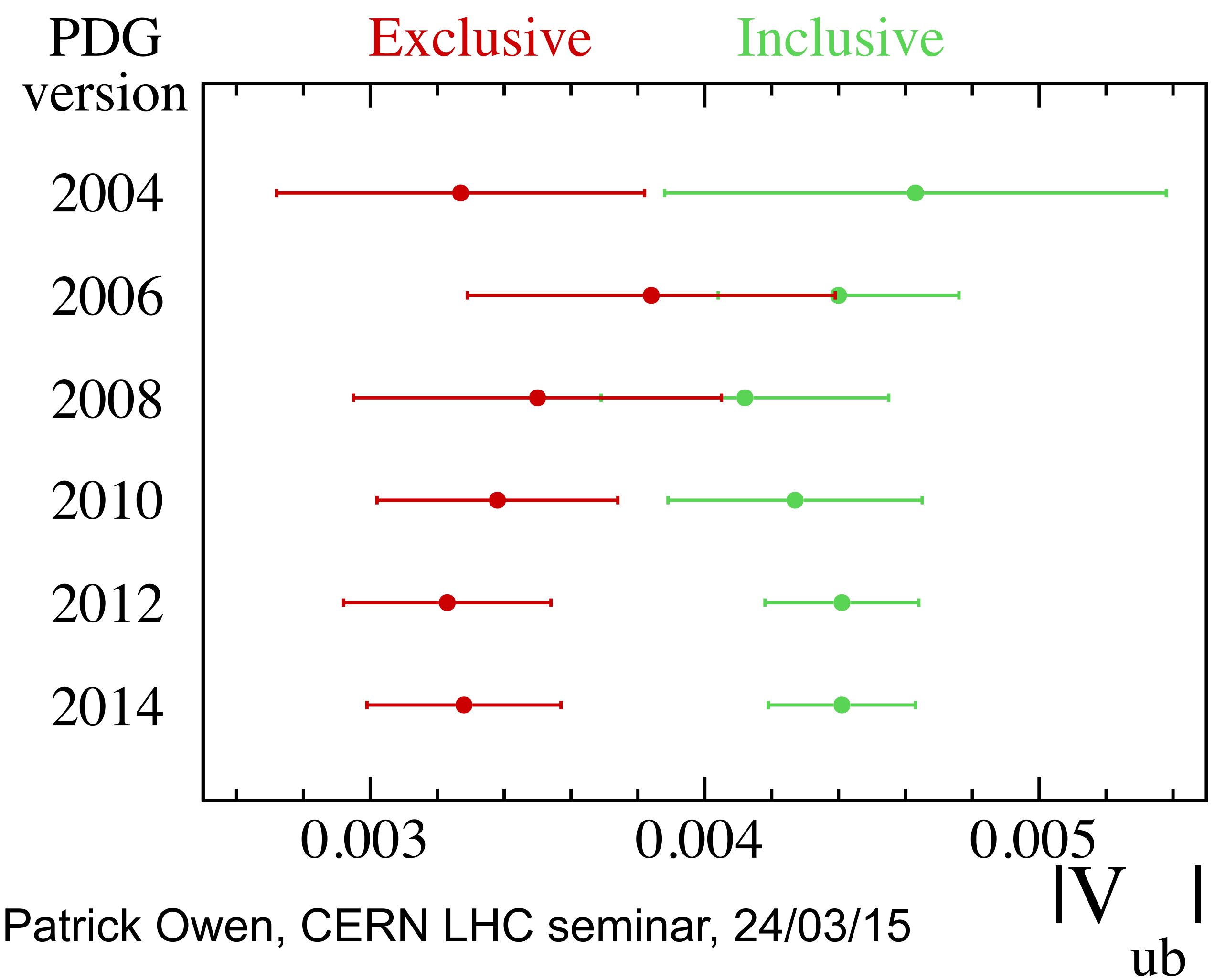
Comparison with other work.



B decays: inclusive analysis



The lifetime of the B meson is approximately equal to the lifetime of the b quark in perturbation theory. Hadronic corrections can be included via a power series of operators parameterized in powers of $(1/M_B)^n$.



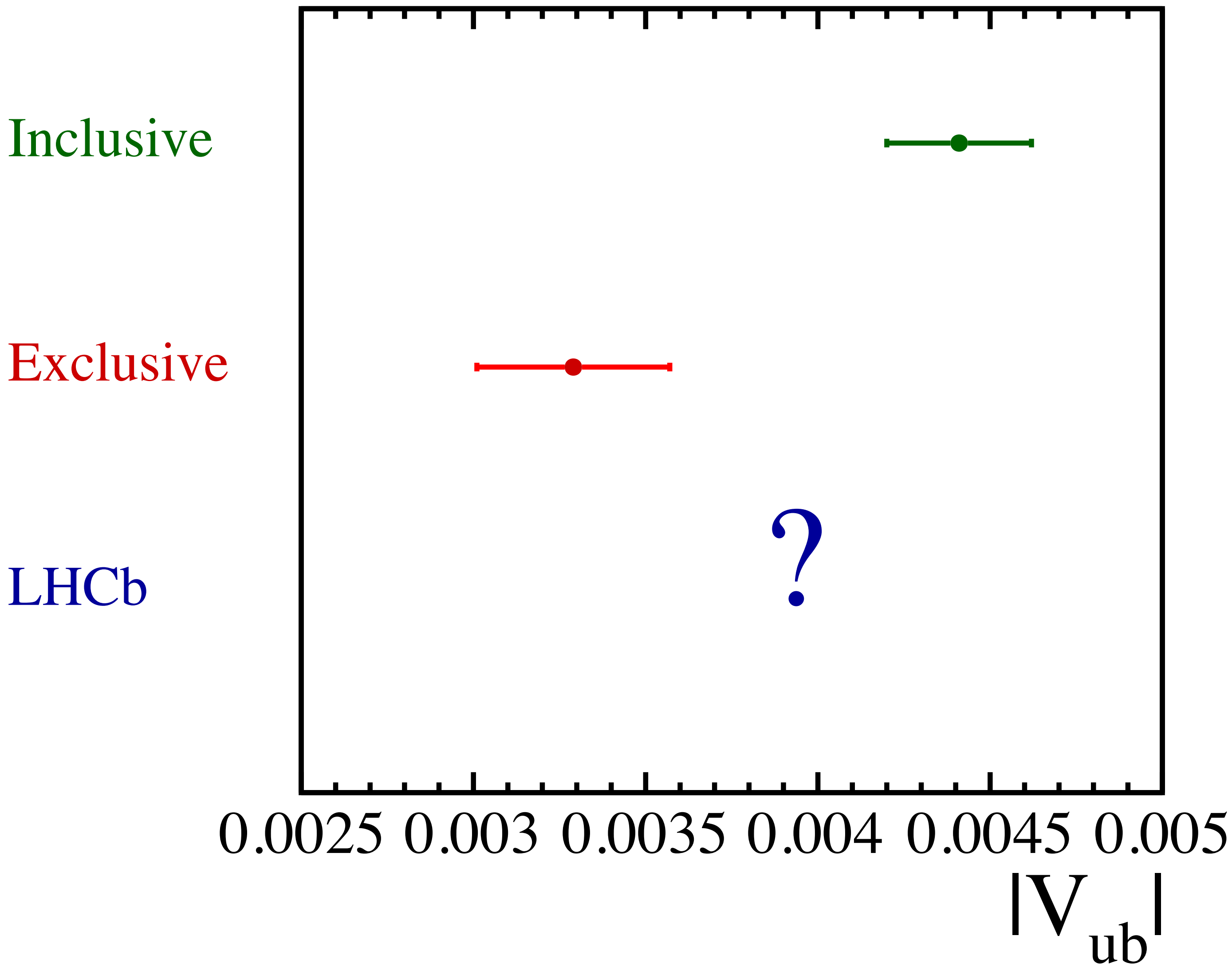
Patrick Owen, CERN LHC seminar, 24/03/15

Long time tension between inclusive and exclusive determinations of V_{ub}, as high as 3 σ.

This work reduces tension to 2.4 σ.

$\Lambda^0_b \to P\mu\nu$

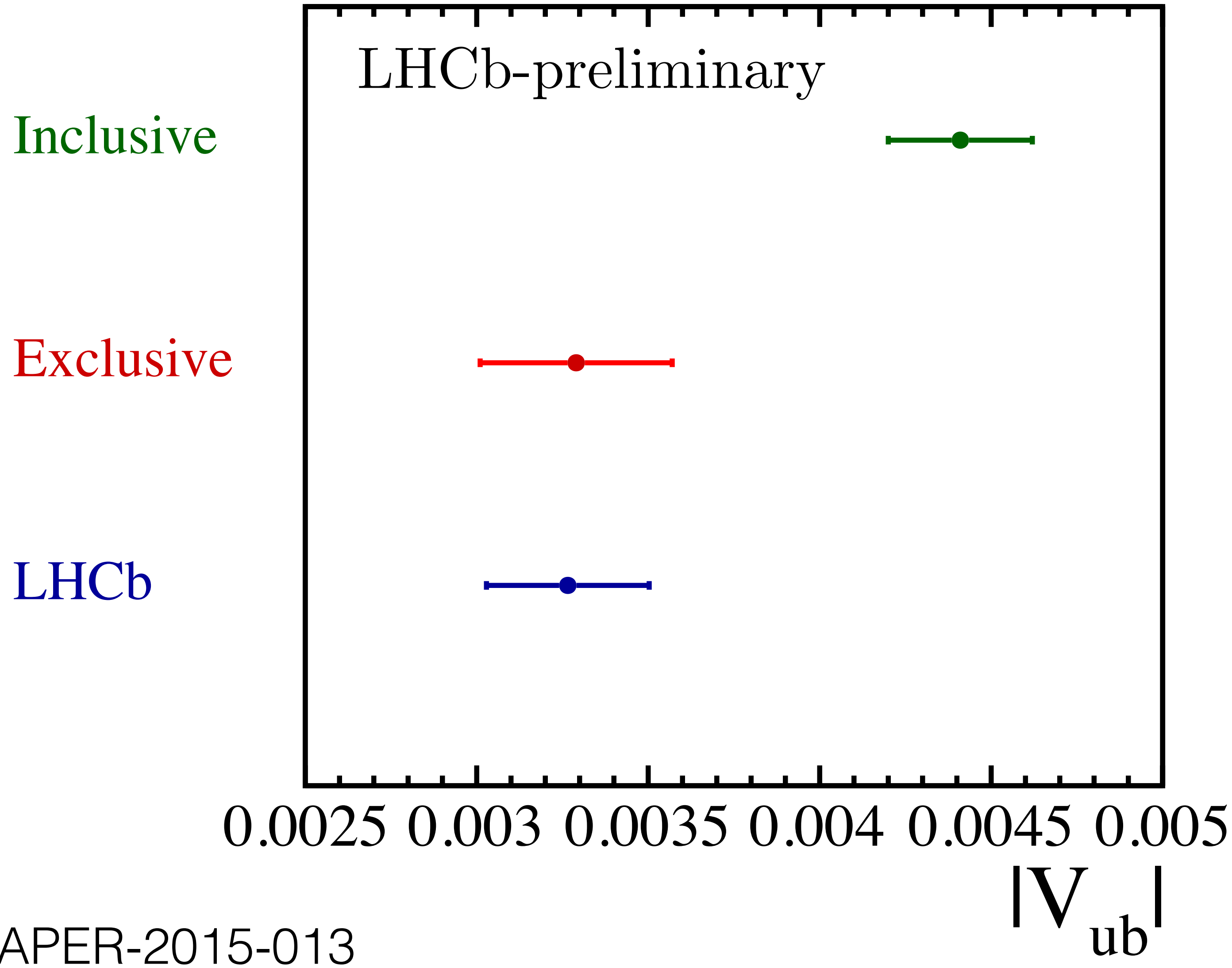
Reminder: world averages



Patrick Owen, CERN LHC seminar, 24/03/15

$\Lambda^0_b \to P\mu\nu$

LHCb $|V_{ub}|$ result

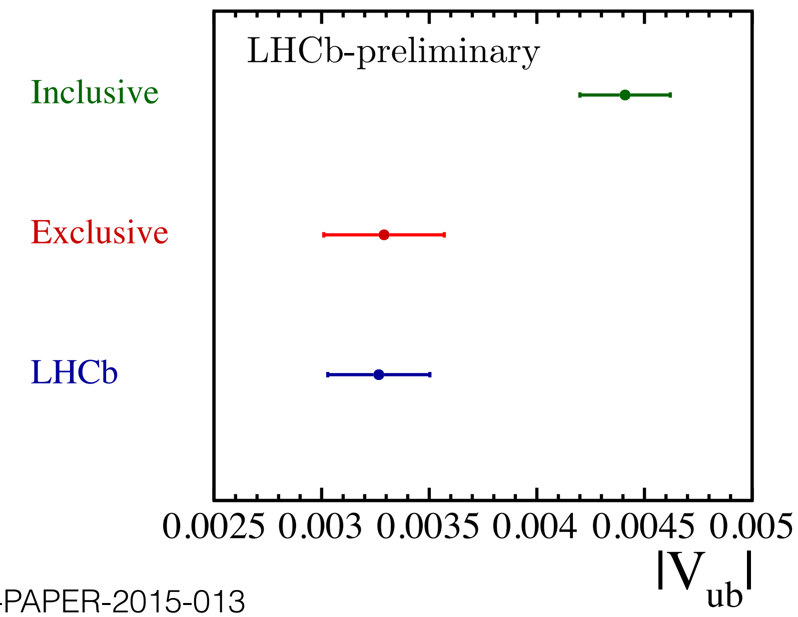


LHCb-PAPER-2015-013

Patrick Owen, CERN LHC seminar, 24/03/15

$\Lambda^0_b \rightarrow P\mu\nu$

LHCb $|V_{ub}|$ result



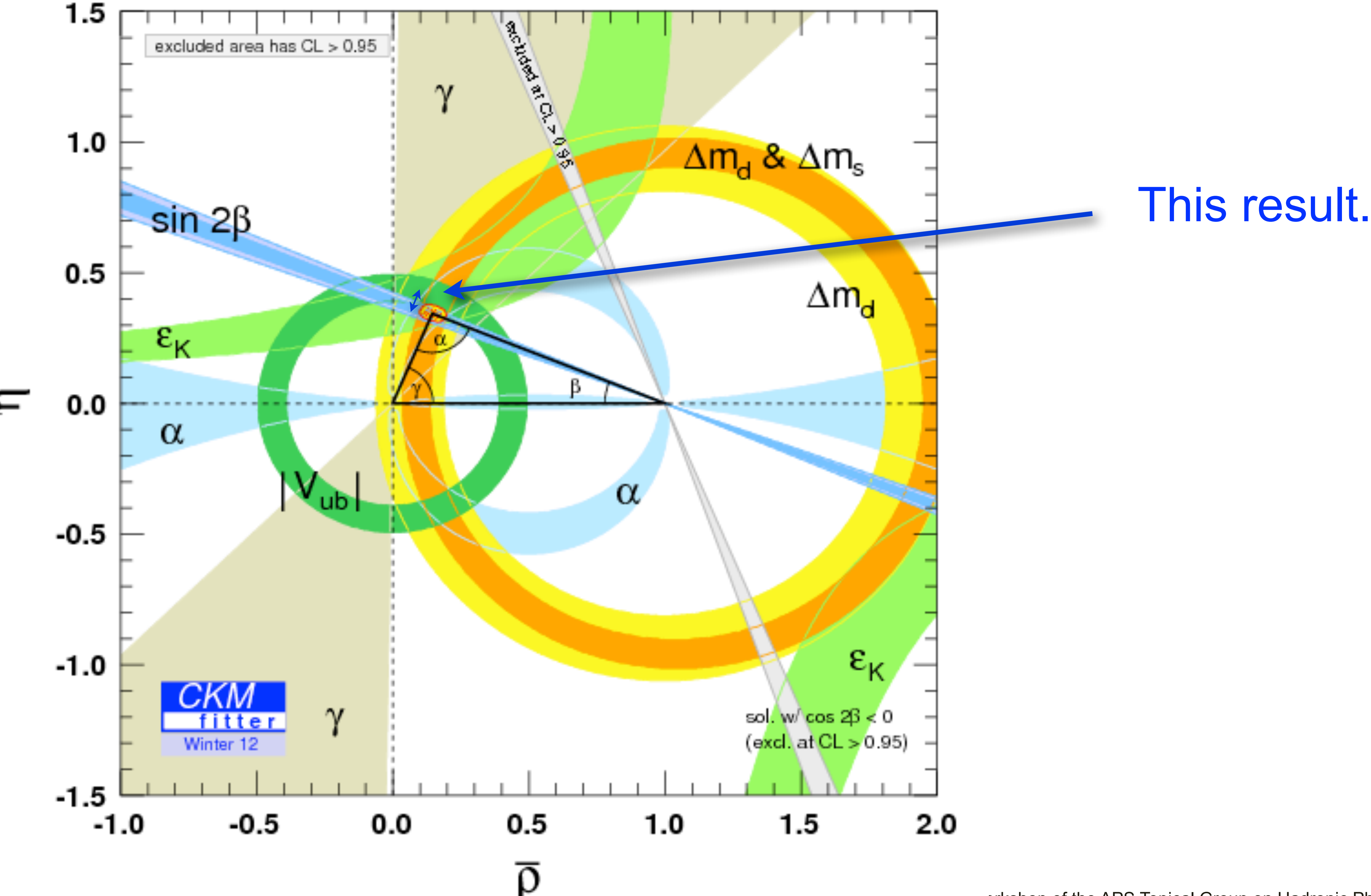
LHCb-PAPER-2015-013

- Different experiment (LHCb) from *B* results (B factories.)
- Different process.
- Different lattice gauge theory groups
  - (W. Detmold, C. Lehner, S. Meinel, arXiv:1503.01421, vs. Fermilab/MILC and HPQCD.)
- Different lattice gauge theory methods.
  - Domain-wall vs. staggered fermion discretization.

Hard to see how to get different answers from lattice calculations.
Also not easy to get BSM physics to produce such an effect.

$B\to\pi l\nu$: unitarity triangle

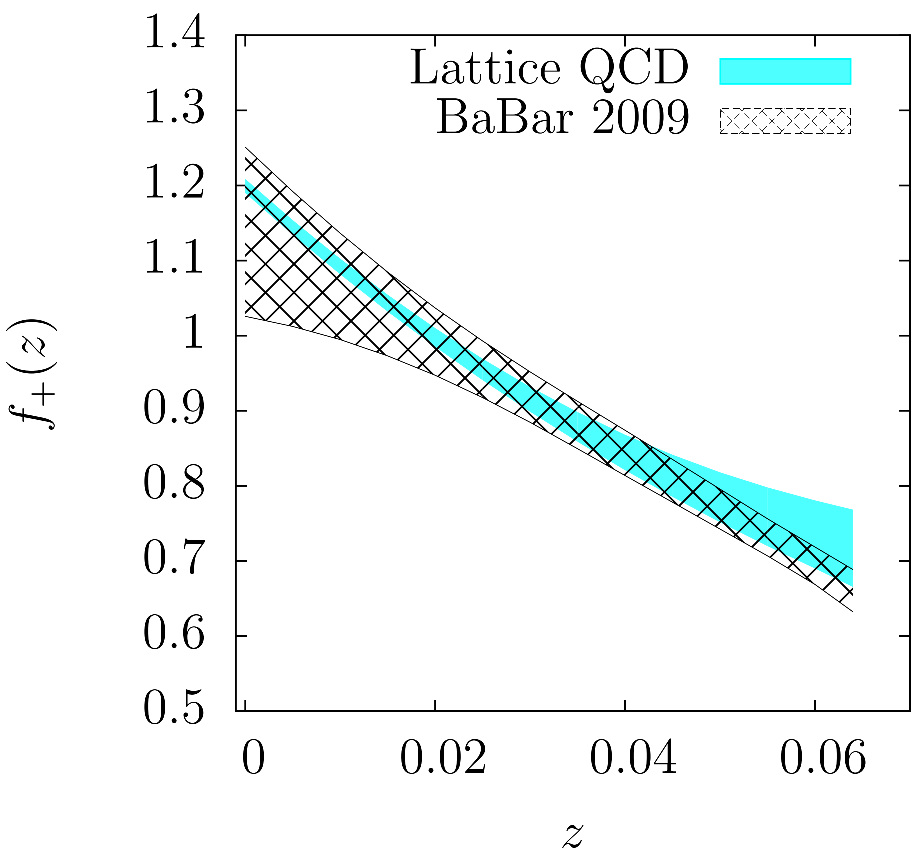
New results do not uncover tension in unitarity triangle first/ third row unitarity relations.



B➞{D, D*}lv

Issues:
Again, inclusive results are ~3σ above exclusive

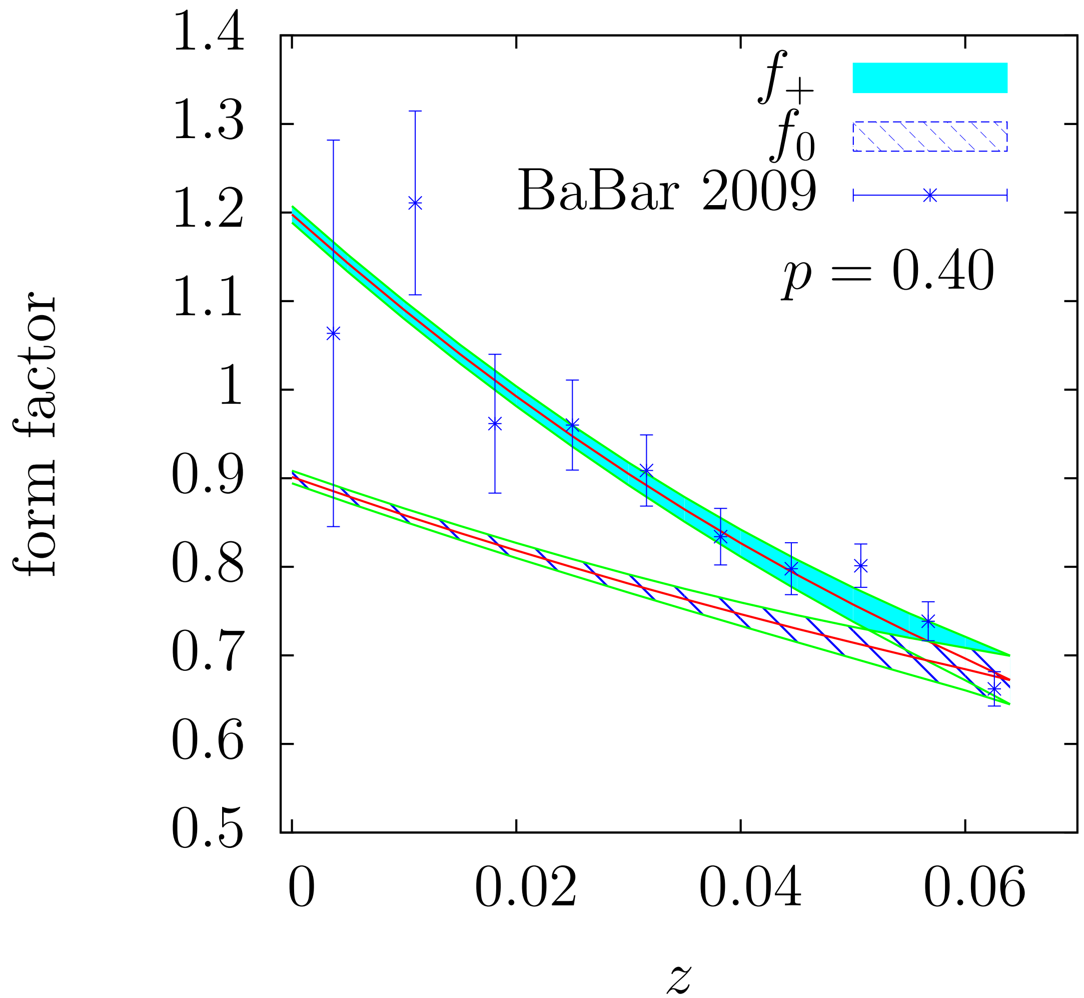
B➞Dlv



Lattice and experiment simultaneous fit.

J. Bailey et al., arXiv:1503.07237v1.
Fermilab/MILC Collaborations.

$B \rightarrow Dl\nu$



Result:

$$|V_{cb}| = (39.6 \pm 1.7_{\text{QCD+exp}} \pm 0.2_{\text{QED}}) \times 10^{-3}$$

Error budget at w=1.1

Source	$f_+(\%)$	$f_0(\%)$
Statistics+matching+χPT cont. extrap.	1.2	1.1
(Statistics)	(0.7)	(0.7)
(Matching)	(0.7)	(0.7)
(χPT/cont. extrap.)	(0.6)	(0.5)
Heavy-quark discretization	0.4	0.4
Lattice scale r_1	0.2	0.2
Total error	1.2	1.1

$B \rightarrow D^{*}l\nu$

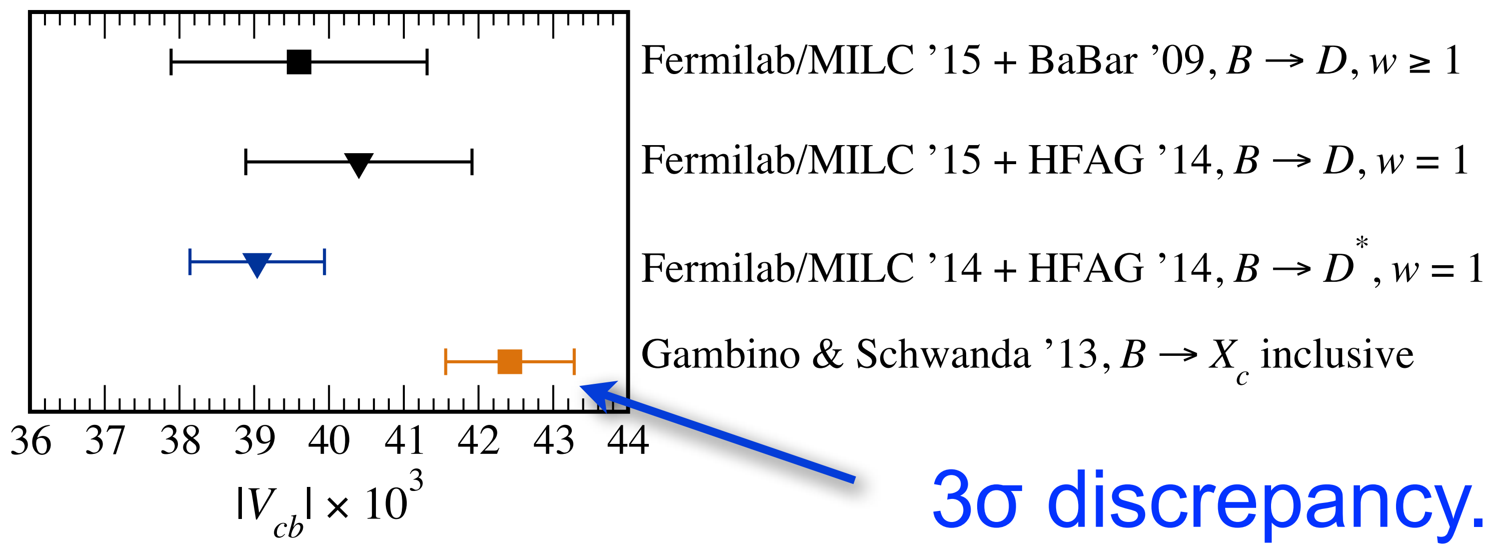


FIG. 12. Comparison of exclusive and inclusive determinations of $|V_{cb}| \times 10^3$. Triangles denote an extrapolation to zero recoil, while squares use data over a wide kinematic range. The color code is black, blue (dark gray), and orange (light gray) for $B \to D\ell\nu$, $B \to D^*\ell\nu$, and $B \to X_c\ell\nu$, respectively.

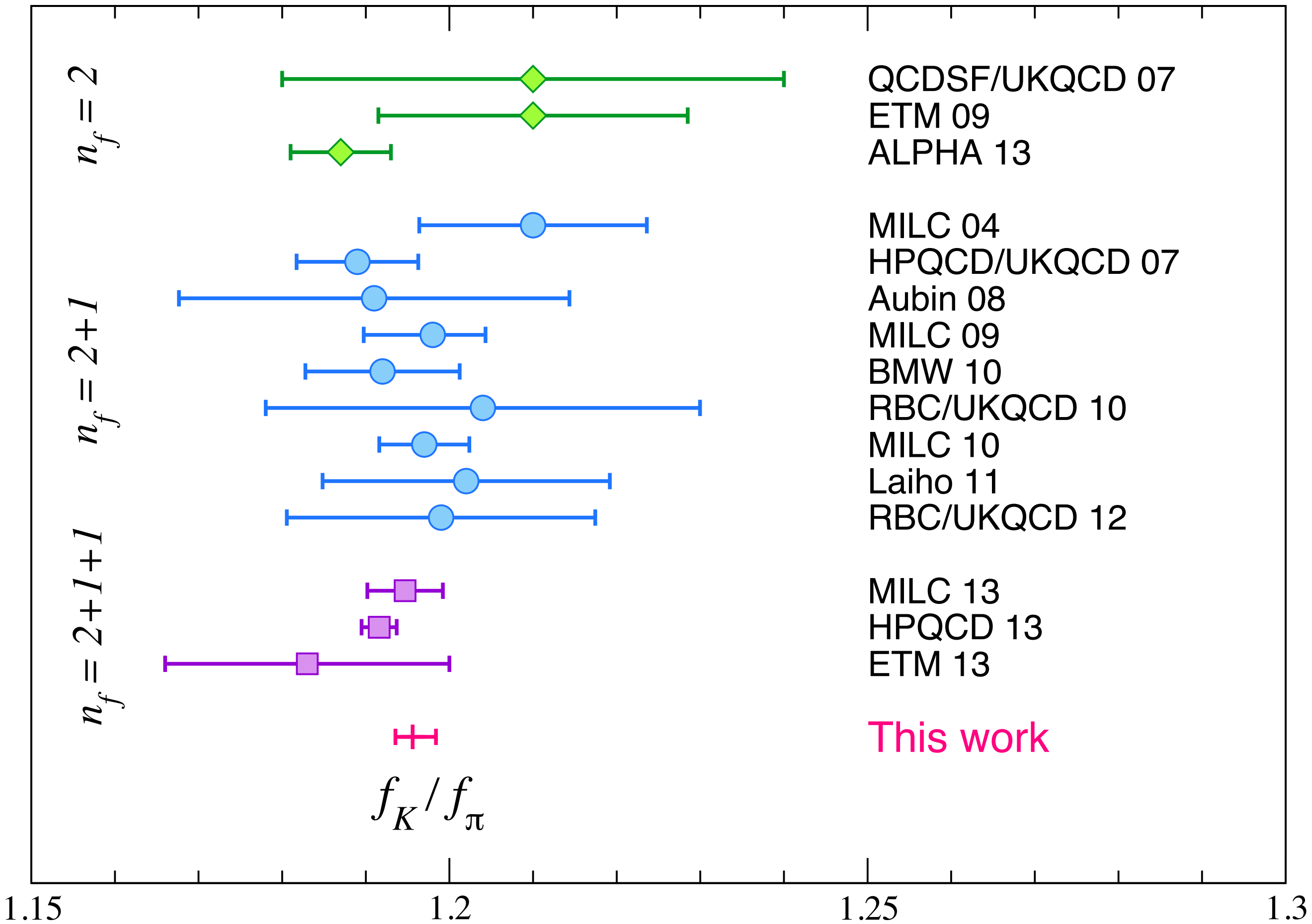
Uncertainty	$h_{A_1}(1)$
Statistics	0.4%
Scale (r_1) error	0.1%
χPT fits	0.5%
$g_{D^*D\pi}$	0.3%
Discretization errors	1.0%
Perturbation theory	0.4%
Isospin	0.1%
Total	1.4%

Good theoretical understanding of form of most uncertainties.

J. Bailey et al., arXiv:1403.0635v2.
Fermilab/MILC Collaborations.

f_π, f_K, $K\to\pi l\nu$

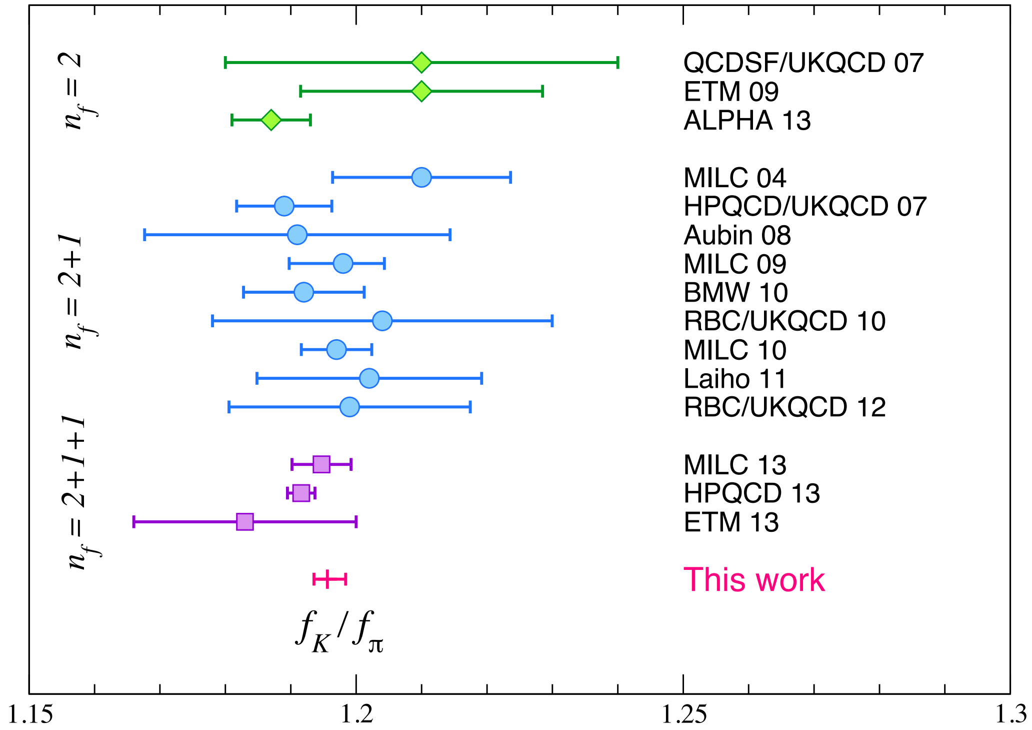
Issues:
Is the first row of the CKM matrix normalized to 1?



A. Bazavov et al., Phys.Rev. D90 (2014) 7, 074509, arXiv:1407.3772v2, Fermilab/MILC Collaborations.

$$f_{K^+}/f_{\pi^+} \;=\; 1.1956(10)_{\rm stat}\;{}^{+23}_{-14}|_{a^2\,\rm extrap}(10)_{\rm FV}(5)_{\rm EM}$$

f_π, f_K, $K \to \pi l \nu$

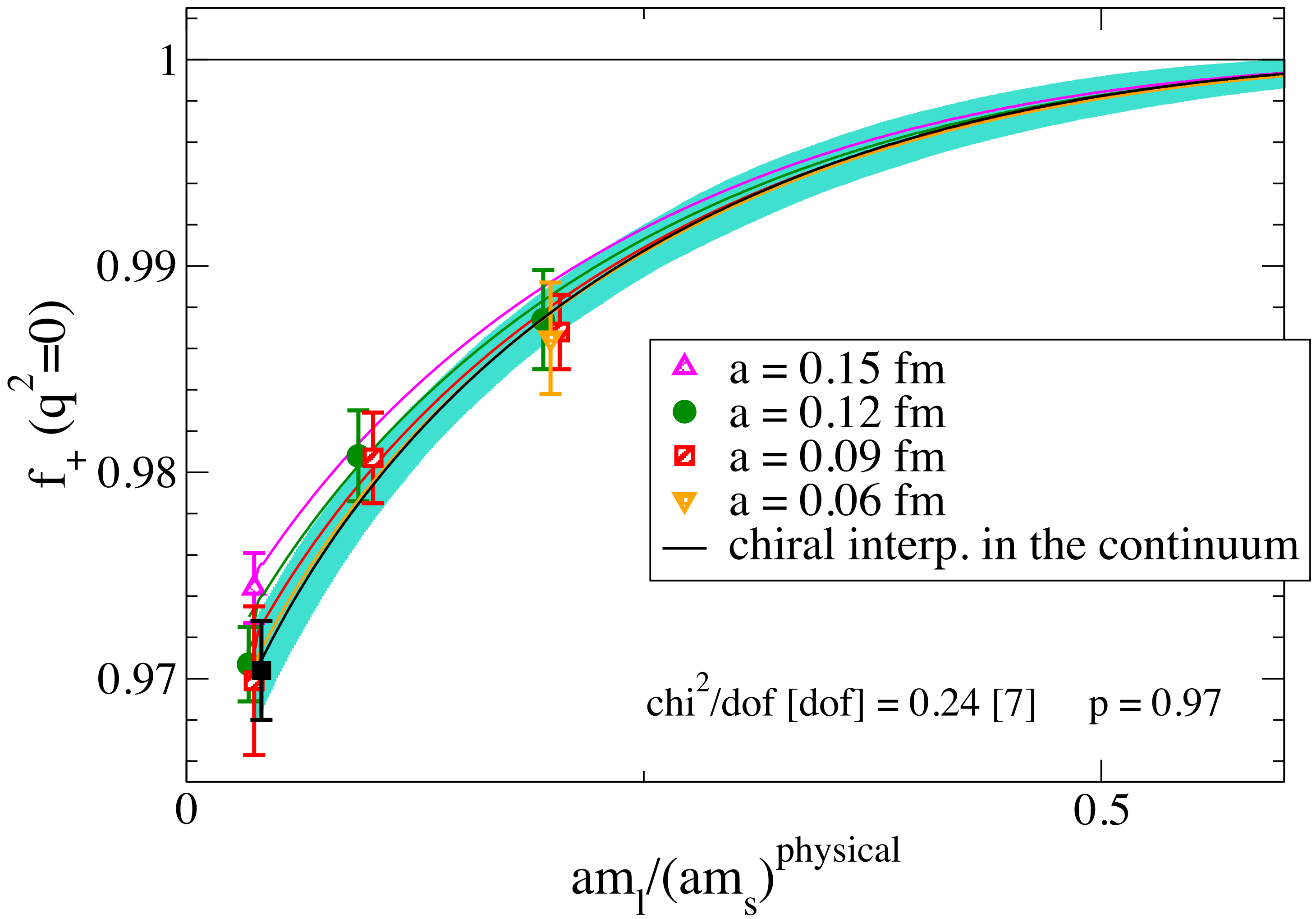


$$1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 = 0.00026(51)\,.$$

Very high precision, but

Perfect agreement with unitarity.

f_π, f_K, $K \to \pi l \nu$



A. Bazavov et al., Phys.Rev.Lett. 112 (2014) 11, 112001, arXiv:1312.1228v2. Fermilab/MILC Collaborations.

$$|V_{us}| = 0.22290(74)_{f_+(0)}(52)_{\text{expt}} = 0.22290(90)$$

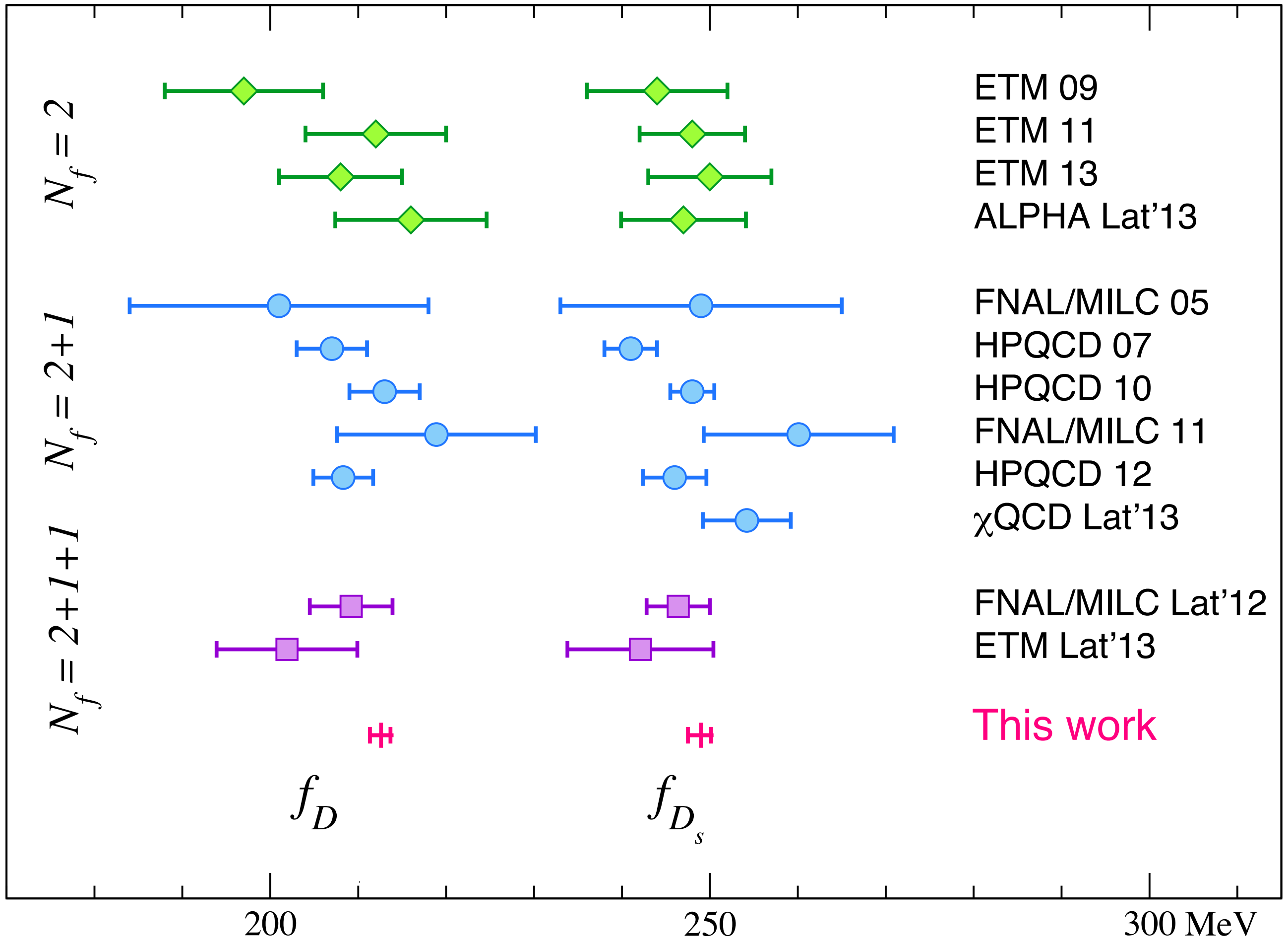
$$\Delta_u \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1$$

$$\Delta_u = -0.00115(40)_{V_{us}}(43)_{V_{ud}}$$

Very high precision;
<~2 σ tension with unitarity.

f_D, f_{Ds}

Issues:
Is the second row of the CKM matrix normalized to 1?



A. Bazavov et al., arXiv:1407.3772v2.
Fermilab/MILC Collaborations.

f_D, f_{Ds}

Issues:
Is the second row of the CKM matrix normalized to 1?

$$
\begin{aligned}
f_{D^+} &= 212.6 \pm 0.4_{\rm stat}\ {}^{+0.9}_{-0.8}|_{a^2\,{\rm extrap}} \pm 0.3_{\rm FV} \pm 0.0_{\rm EM} \pm 0.3_{f_\pi\,{\rm PDG}}\ {\rm MeV}\,, \\
f_{D_s} &= 249.0 \pm 0.3_{\rm stat}\ {}^{+1.0}_{-0.9}|_{a^2\,{\rm extrap}} \pm 0.2_{\rm FV} \pm 0.1_{\rm EM} \pm 0.4_{f_\pi\,{\rm PDG}}\ {\rm MeV}\,, \\
f_{D_s}/f_{D^+} &= 1.1712(10)_{\rm stat}\left({}^{+24}_{-31}\right)_{a^2\,{\rm extrap}}(3)_{\rm FV}(5)_{\rm EM}\,, \\
f_{D^+} - f_D &= 0.47(1)_{\rm stat}\left({}^{+11}_{-\ 4}\right)_{a^2\,{\rm extrap}}(0)_{\rm FV}(4)_{\rm EM}\ {\rm MeV}\,,
\end{aligned}
$$

$$1 - |V_{cd}|^2 - |V_{cs}|^2 - |V_{cb}|^2 = -0.07(4)$$

Tiny bit of tension with unitarity.

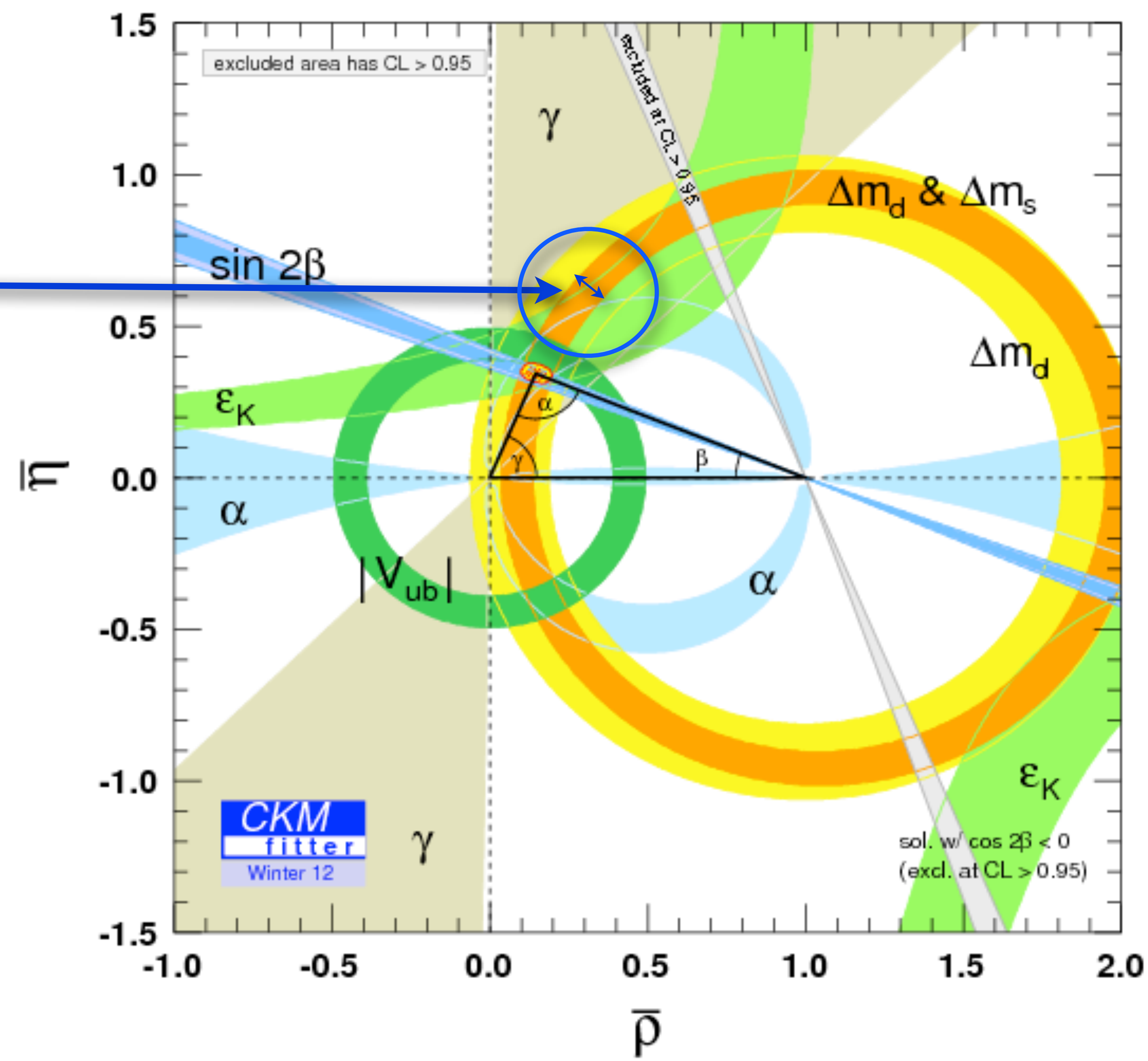
$\overline{B}B$, $\overline{B}_s B_s$ mixing

No recent results, but an important fact to mention.

Existing experimental errors on meson mixing are generically about 0.5%.

Precision of mixing bounds on the unitarity triangle are dominated by lattice theory, currently 5% (FLAG).

Existing experimental data will be much more valuable once improved theory calculations are completed.



Summary: success in the past

- Lattice QCD calculations played an essential role in the success of the flavor programs of the Tevatron and flavor factories.
  - So far, no failures of the standard model.
  - Much work yet to do, e.g., matching the precision of BBbar mixing results.
- They have a key role to play in the coming LHCb and Belle-2 programs.
- A much richer role than this awaits them in the future US particle physics experimental program.

Lattice QCD in the future of particle physics

2013, the P5 report outlined the future of US particle physics.

- Use the Higgs boson as a new tool for discovery.
- Pursue the physics associated with neutrino mass.
- Identify the new physics of dark matter.
- Understand cosmic acceleration: dark energy and inflation.
- Explore the unknown: new particles, interactions, and physical principles.

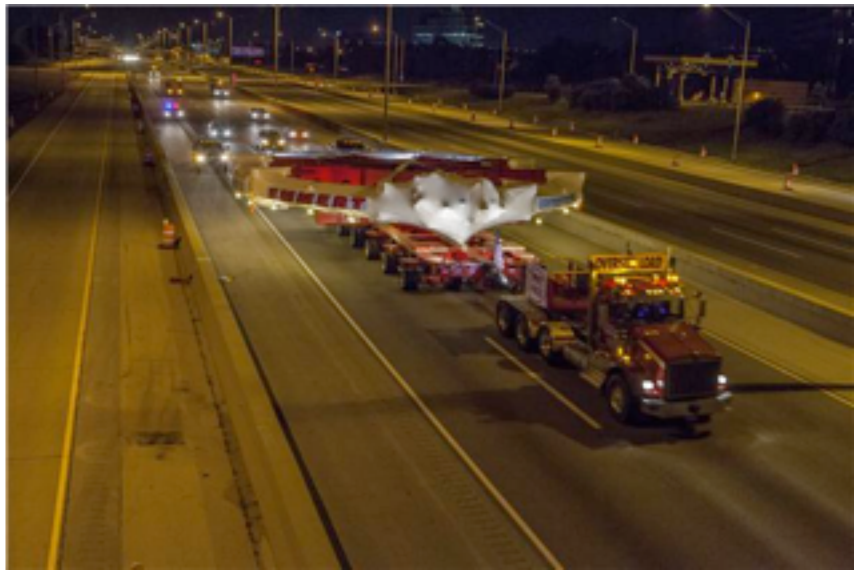
Lattice QCD calculations will be required throughout this program.

Coming US experiments

Goals of experiments are in particle physics, but the methods and groups come from both the NP and HEP communities.

Muon physics.

g-2 experiment



Searching for BSM effects in deviation from SM prediction of anomalous magnetic moment of muon.
Cannot reach potential without new lattice QCD calculations.

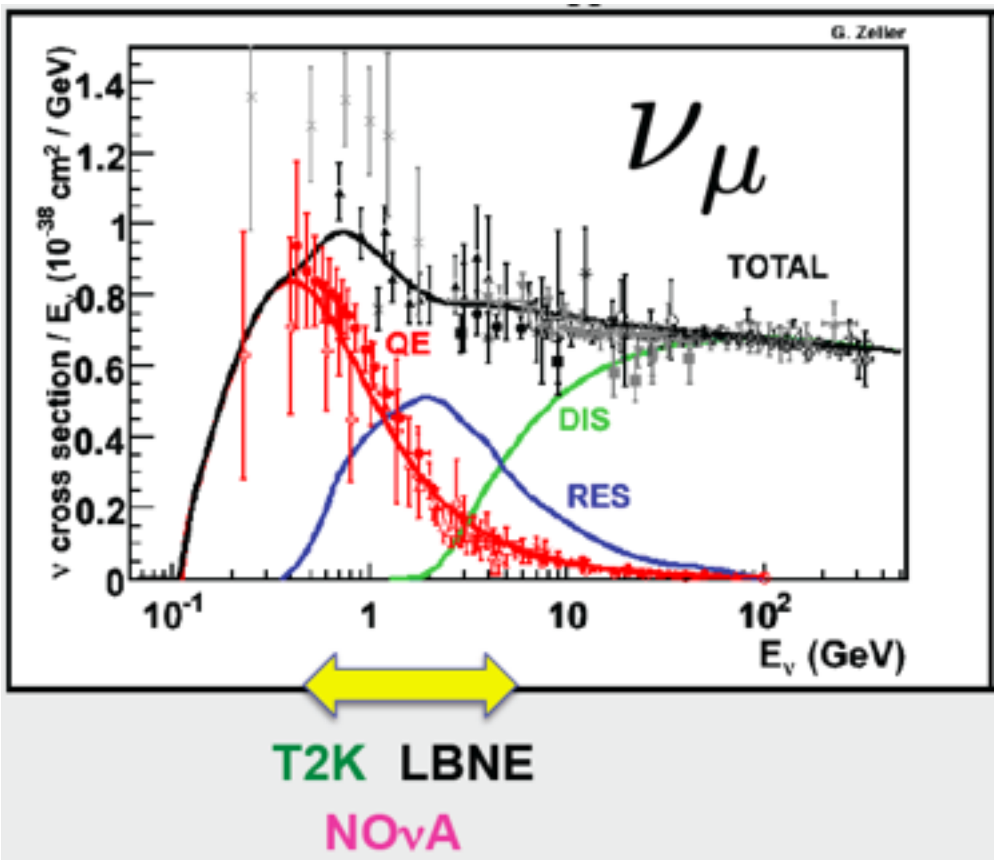
Mu2e experiment

If new physics is indicated by observation of μ→e transition lattice QCD calculations needed to interpret in terms of fundaments physics.

Coming US experiments

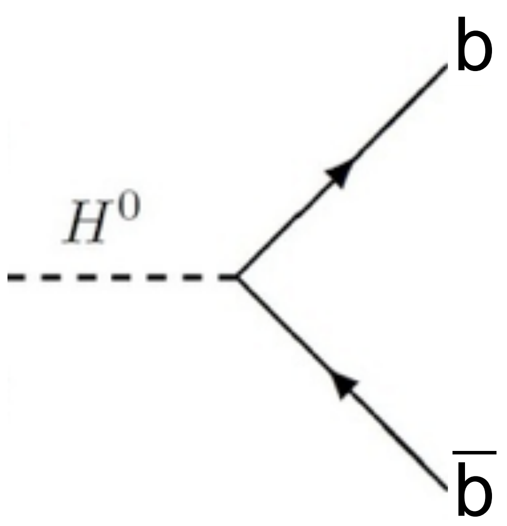
Neutrinos

The nucleon component of nucleon and nuclear contributions can now be removed by lattice calculations. Results will be integrated into the Genie Monte Carlo.



Higgs decays

Search for BSM effects in <1% determinations of Higgs decays will require SM inputs to that precision; e.g., m_b to <1%/



Conclusion: The flavor program established lattice QCD as a critical tool in the HEP program. Lattice QCD will be an essential tool throughout particle physics from now on.