The Lattice QCD Project

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HEPAP
Sept. 5-6, 2013

Lattice field theory for high-energy physics

- Lattice gauge theory plays a critical role in the HEP search for new physics at the Energy and Intensity Frontiers.
- In the past decade, as error budgets became fully quantitative, lattice QCD played a critical role in the success of the quark-flavor factories.
- In the coming decade, high-precision lattice gauge theory calculations are needed *throughout* the HEP experimental program, e.g.:
  - g-2, Mu2e, LBNE, Nova, CDMS, Belle-2, LHCb, CMS, Atlas, ILC.
- The USQCD planned scientific program is aligned with the HEP experimental program discussed at Snowmass.
  - We hope you will agree that facilities for numerical lattice QCD are an essential theoretical adjunct to the experimental HEP physics program.

USQCD and the US lattice community

- USQCD comprises almost all US lattice gauge theorists (~150 people).
- USQCD purchases and deploys hardware and develops software infrastructure for lattice calculations in the US.
  - The hardware bought by the LQCD project is operated as a facility (like Fermilab during the fixed-target program.
  - The smaller physics collaborations which make up USQCD compete for time on these resources for their physics.
  - Resources are allocated by the USQCD Scientific Program Committee among physics projects to meet Collaboration goals outlined in Collaboration white papers (and Snowmass documents and the Project X Physics Book).

USQCD computing activities

The Ds cluster at Fermilab

- Hardware
  - USQCD requires similar numbers of cycles on jobs of all sizes: 16-core, 100-core, 1,000-core, 10,000-core, and 100,000-core.
  - DoE Leadership Computing facilities at Argonne and Oak Ridge supply our requirements for jobs > 10,000-core.
  - We have an even larger need for cycles for jobs < 10,000-core. These are supplied predominantly by the LQCD Project, whose CD0 is under consideration.
    - Also apply at NERSC, XSEDE, Blue Waters, ...
  - DOE has supported USQCD through joint HEP/NP projects LQCD (FY06-FY09) and LQCD-ext (FY10-FY14).
  - These provide funds for dedicated capacity hardware at Fermilab, Jefferson Lab, and Brookhaven, and for support personnel.
- Software
  - USQCD has received grants for software development from the DOE's SciDAC Program since 2003. The most recent are SciDAC-3 grants from HEP and NP for about $1 M each for creating lattice QCD software infrastructure: community libraries, community codes, optimization and porting to new architectures, implementation of up-to-the-minute algorithm advances...

Anatomy of a typical lattice calculation

ALCF Blue Gene

TB file sizes

Fermilab Ds

Generate gauge configurations on a leadership facility or supercomputer center.
Many tens of millions of BG/Q core-hours in a single job.

Transfer to labs for analysis on clusters.
Comparable CPU requirements.

A single highly optimized program,
very long single tasks,
moderate I/O and data storage.
Needs high capability computing.

Large, heterogeneous analysis code base,
10,000s of small, highly parallel tasks,
heavy I/O and data storage.
Needs high capacity computing.

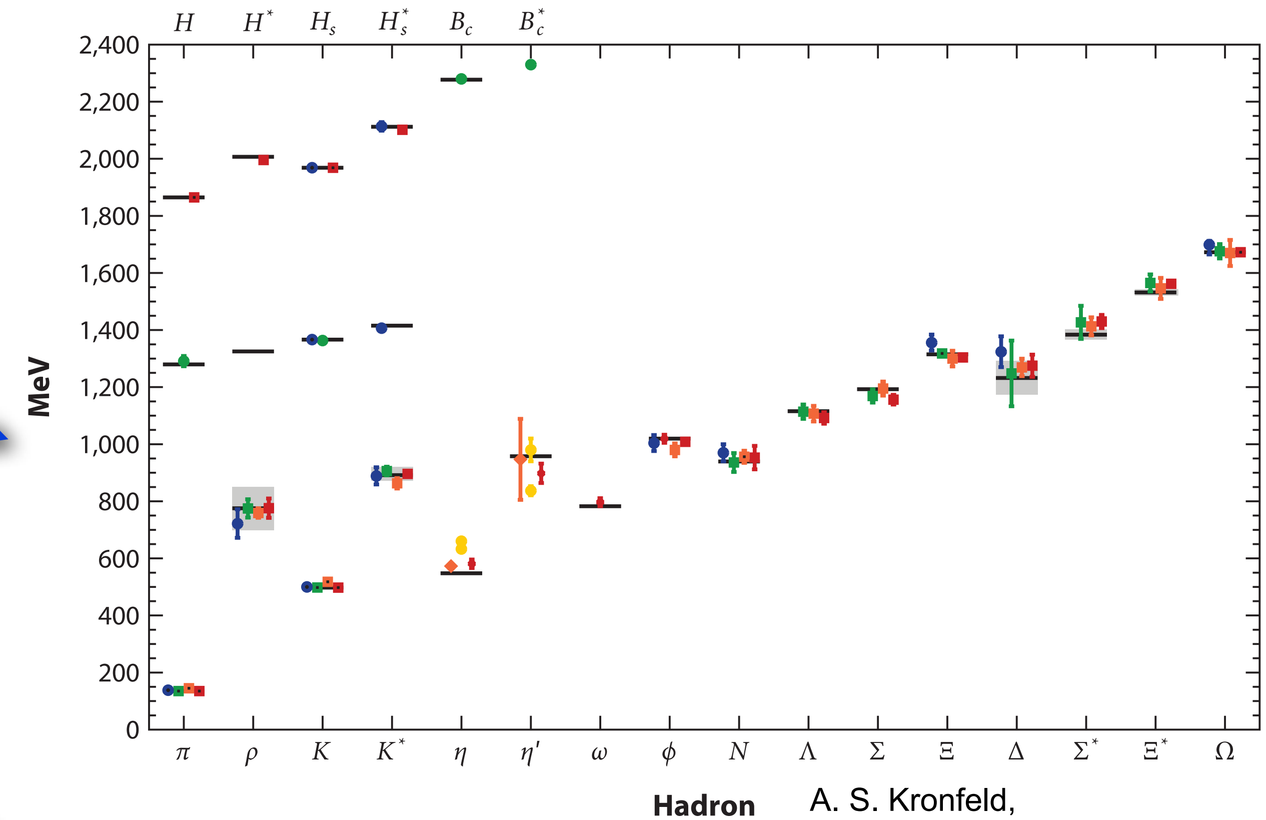
Two comparably sized tasks with quite different hardware requirements.

USQCD and the broader HEP community

- USQCD participated actively in the Snowmass process.
  - Steve Gottlieb was a convener of the Computing Frontier section, and Ruth Van de Water and Tom Blum were conveners of the Lattice Field Theory subgroup.
  - We gave talks in both the Energy Frontier and Intensity Frontier sessions and contributed to writing several of the documents.
- Members of USQCD wrote a chapter on lattice field theory for the Project X Physics Book.
- USQCD regularly organizes "Lattice Meets Experiment" workshops on such topics as:
  - Extreme QCD (2012); Beyond the Standard Model (2011 & 2012); Fluctuations, Correlations, and RHIC low energy runs (2011); Excited Hadronic States and the Deconfinement Transition (2011); Quark flavor physics (2010); ....
- Members of USQCD regularly speak at experimental collaboration meetings such as g-2, Belle, BES, ORKA, HFAG-Vxb, ...

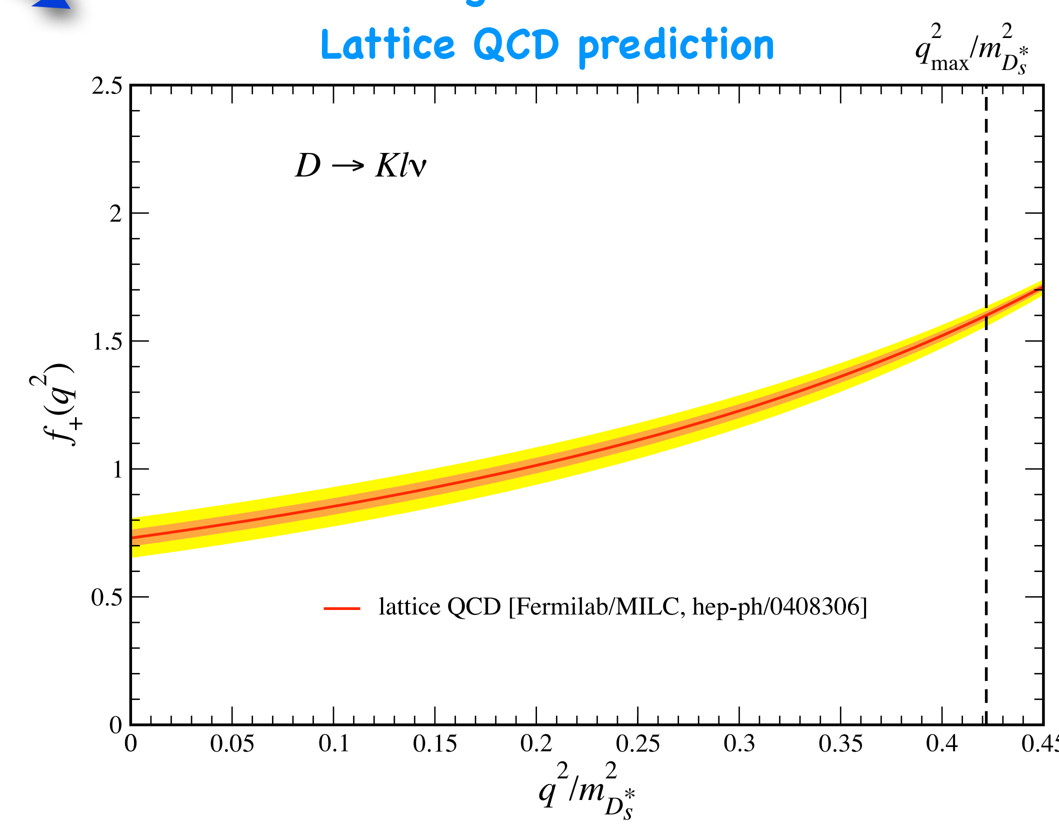
Validation of lattice calculations

- Comparison with experiment,
  e.g. hadron spectrum to 1%.
- Prediction of quantities not known in advance, e.g. shape of the $D \rightarrow K$ semileptonic form factor.
- Important calculations are checked by multiple groups using different methods, different discretizations, etc.
- Many internal checks: recovery of rotational invariance, recovery of Lorentz invariance, test of software using gauge invariance.



A. S. Kronfeld,
Ann.Rev.Nucl.Part.Sci. 62 (2012) 265-284.

August 2004:
Lattice QCD prediction



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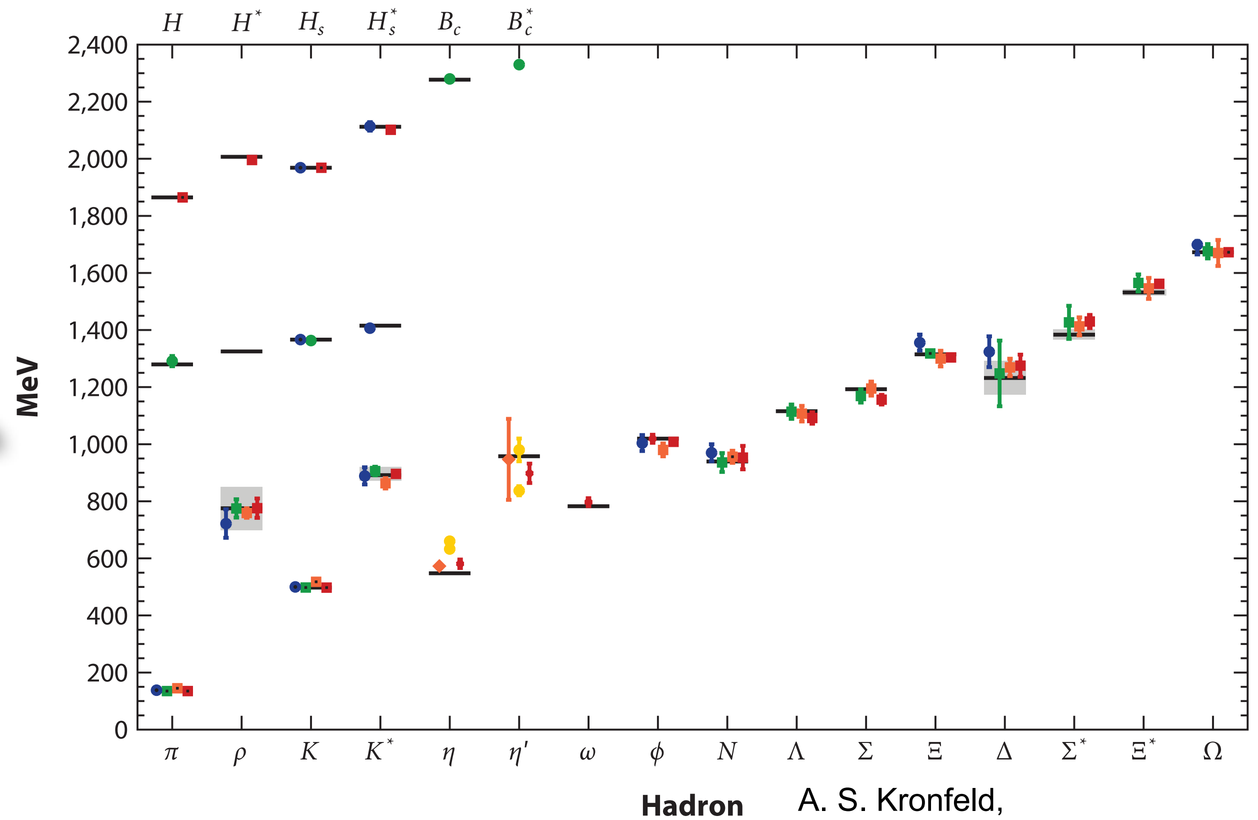
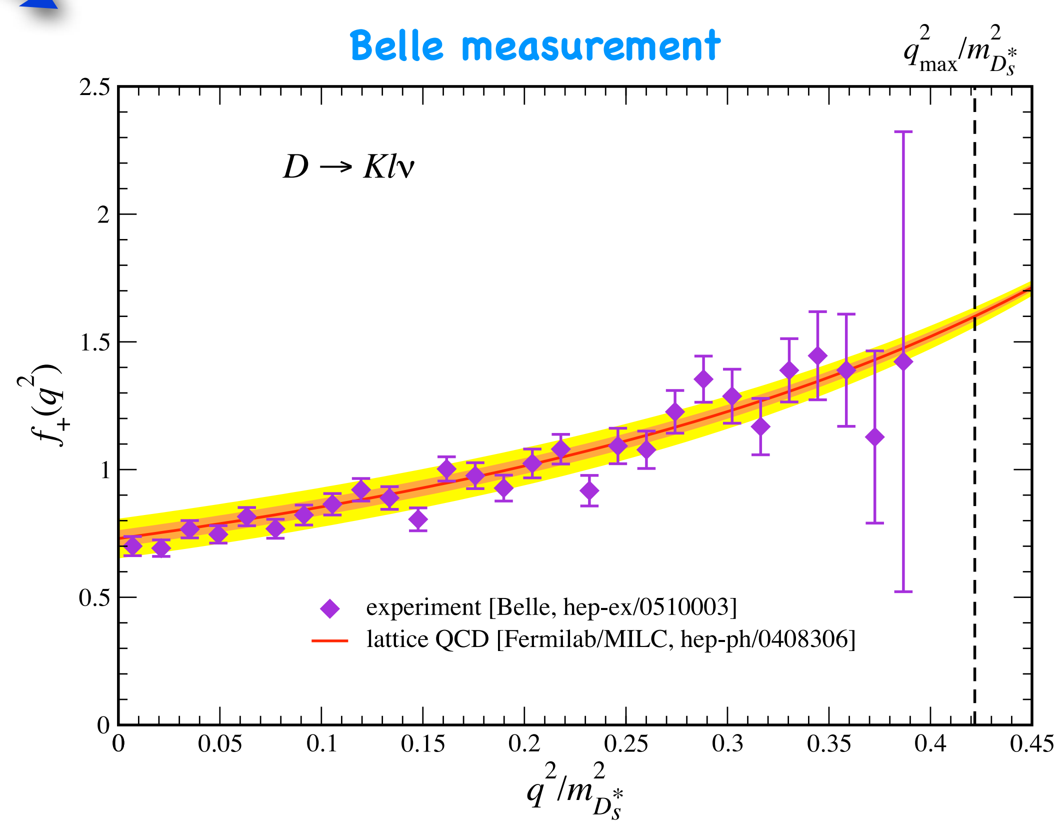


A. S. Kronfeld, Ann.Rev.Nucl.Part.Sci. 62 (2012) 265-284.

October 2005:
Belle measurement



Precision measurements of Higgs properties

- Bottom-quark mass and α_s contribute the largest uncertainties to the dominant Higgs decay channel and Higgs total width

Table 1-5. *Uncertainties on $M_H = 126$ GeV Standard Model widths arising from the parametric uncertainties on α_s, m_b, and m_c and from theory uncertainties.*

Channel	$\Delta\alpha_s$	Δm_b	Δm_c	Theory Uncertainty	Total Uncertainty
$H \to \gamma\gamma$	0%	0%	0%	±1%	±1%
$H \to b\bar{b}$	±2.3%	$^{+3.3\%}_{-3.2\%}$	0%	±2%	±6%
$H \to \tau^+\tau^-$	0%	0%	0%	±2%	±2%
$H \to WW^*$	0%	0%	0%	±0.5%	±0.5%
$H \to ZZ^*$	0%	0%	0%	±0.5%	±0.5%

Snowmass Higgs WG Report, p 5.

"Improvement in alphas and quark masses will come from lattice gauge theory. These are necessary inputs to precision Higgs theory and other precision programs."

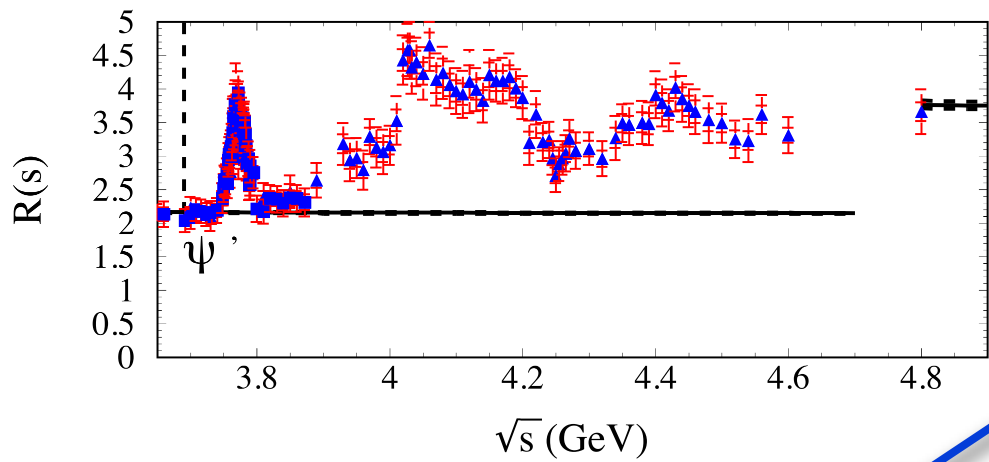
Brock/Peskin Snowmass Energy Frontier summary talk, p118.

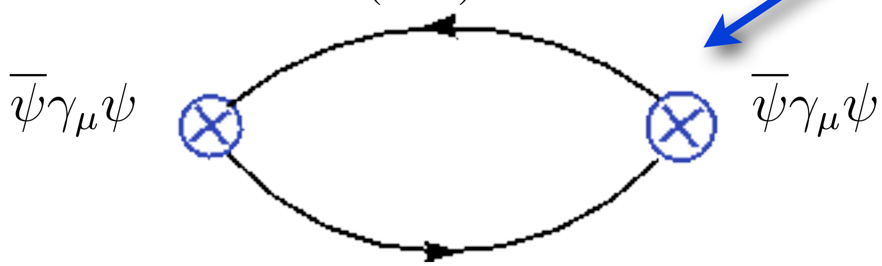
	Higgs X-section Working Group [34]	PDG[1]	Non-lattice	Lattice (2013)	Lattice (2018)	Prospects from ILC/TLEP/LHeC
$\delta\alpha_s$	0.002	0.0007	0.0012 [1]	0.0006 [24]	0.0004	0.0001–0.0006 [8, 27, 28]
δm_c (GeV)	0.03	0.025	0.013 [31]	0.006 [24]	0.004	-
δm_b (GeV)	0.06	0.03	0.016 [31]	0.023 [24]	0.011	-

Snowmass QCD WG Report, p 10.

- An ILC/TLEP/muon collider goal: Higgs branching fractions to ~ 1%;
  - requires m_b to ~0.25% not to affect the analysis.
  - Lattice QCD will do this.
  - Lattice QCD has already determined m_b, m_c, and α_s more precisely than is currently being assumed in discussions of Higgs decay channels.

Quark masses and α_s from lattice QCD.





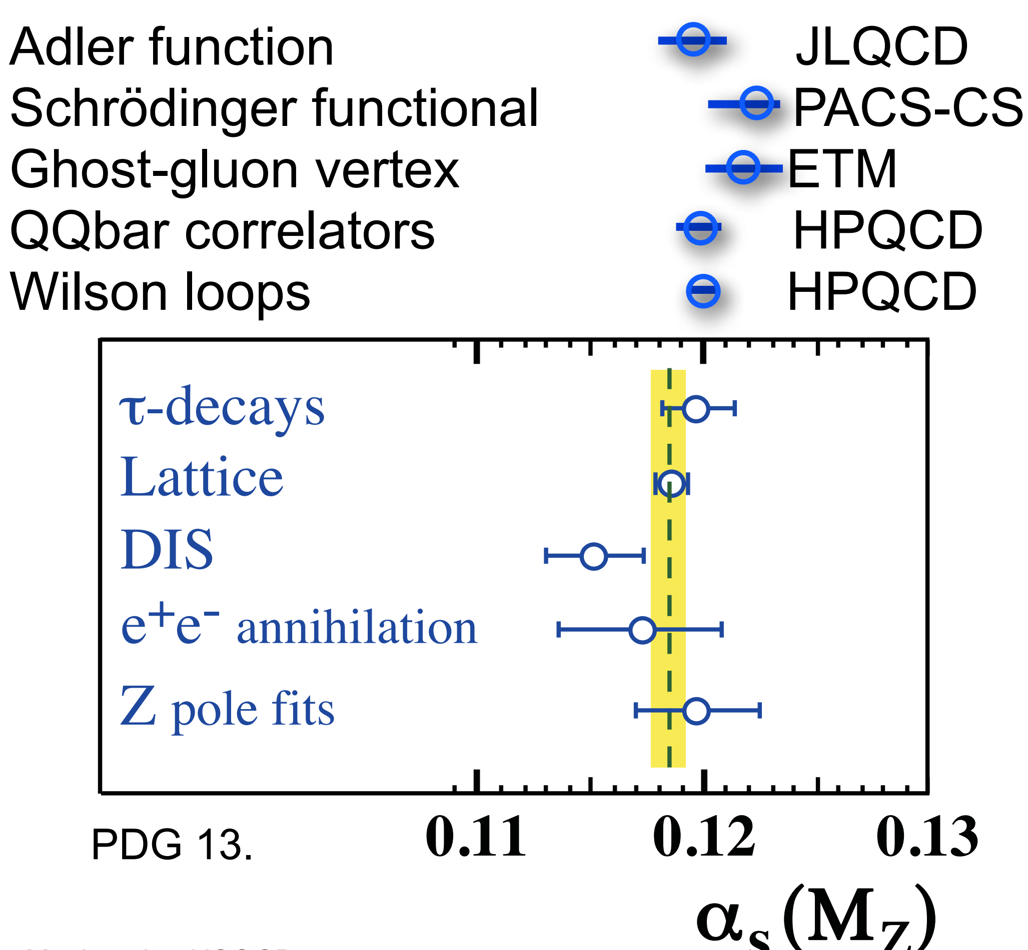
Moments of the heavy quark production cross section in e^+e^- annihilation can be related to the derivatives of the vacuum polarization to obtain the heavy quark masses.
These can easily be obtained from lattice QCD. instead of e^+e^-.

Can be calculated in perturbation theory.
Known to $O(\alpha_s^3)$ (Chetyrkin et. al.)

$$m_b(m_b, n_f = 5) = 4.164(23)\ \text{GeV}$$

$$m_c(m_c, n_f = 4) = 1.273(6)\ \text{GeV}$$

HPQCD, McNeile et al.



PDG 13.

World α_s results are very robust:
remove the two most precise lattice results and the remaining lattice results give the same answer with slightly increased errors;
remove all lattice results and the remaining results give the same answer with a little more increased errors.

PDG 13 world average:

$$\alpha_s(M_Z^2) = 0.1184 \pm 0.0007$$

$$\alpha_s(M_Z^2) = 0.1183 \pm 0.0012 \quad (\text{w/o lattice results})$$

Lattice-QCD constraints on the CKM matrix

- Cabibbo-Kobayashi-Maskawa matrix elements and phase are **fundamental parameters of the Standard Model that enter as parametric inputs to Standard Model predictions for many flavor-changing processes** such as neutral kaon mixing and $K \to \pi\nu\nu$ decays.

- Simple matrix elements involving single particles enable determinations of all CKM matrix elements except $|V_{tb}|$.

*Neutral kaon mixing can also be used to obtain the phase (ρ, η).

$$\begin{pmatrix} \mathbf{V_{ud}} & \mathbf{V_{us}} & \mathbf{V_{ub}} \\ \pi \to \ell\nu & K \to \ell\nu & B \to \ell\nu \\ & K \to \pi\ell\nu & B \to \pi\ell\nu \\ \mathbf{V_{cd}} & \mathbf{V_{cs}} & \mathbf{V_{cb}} \\ D \to \ell\nu & D_s \to \ell\nu & B \to D\ell\nu \\ D \to \pi\ell\nu & D \to K\ell\nu & B \to D^*\ell\nu \\ \mathbf{V_{td}} & \mathbf{V_{ts}} & \mathbf{V_{tb}} \\ \langle B_d|\bar{B}_d\rangle & \langle B_s|\bar{B}_s\rangle & \end{pmatrix}$$

(Experiment) = (known) x (CKM factors) × (Hadronic Matrix Element)

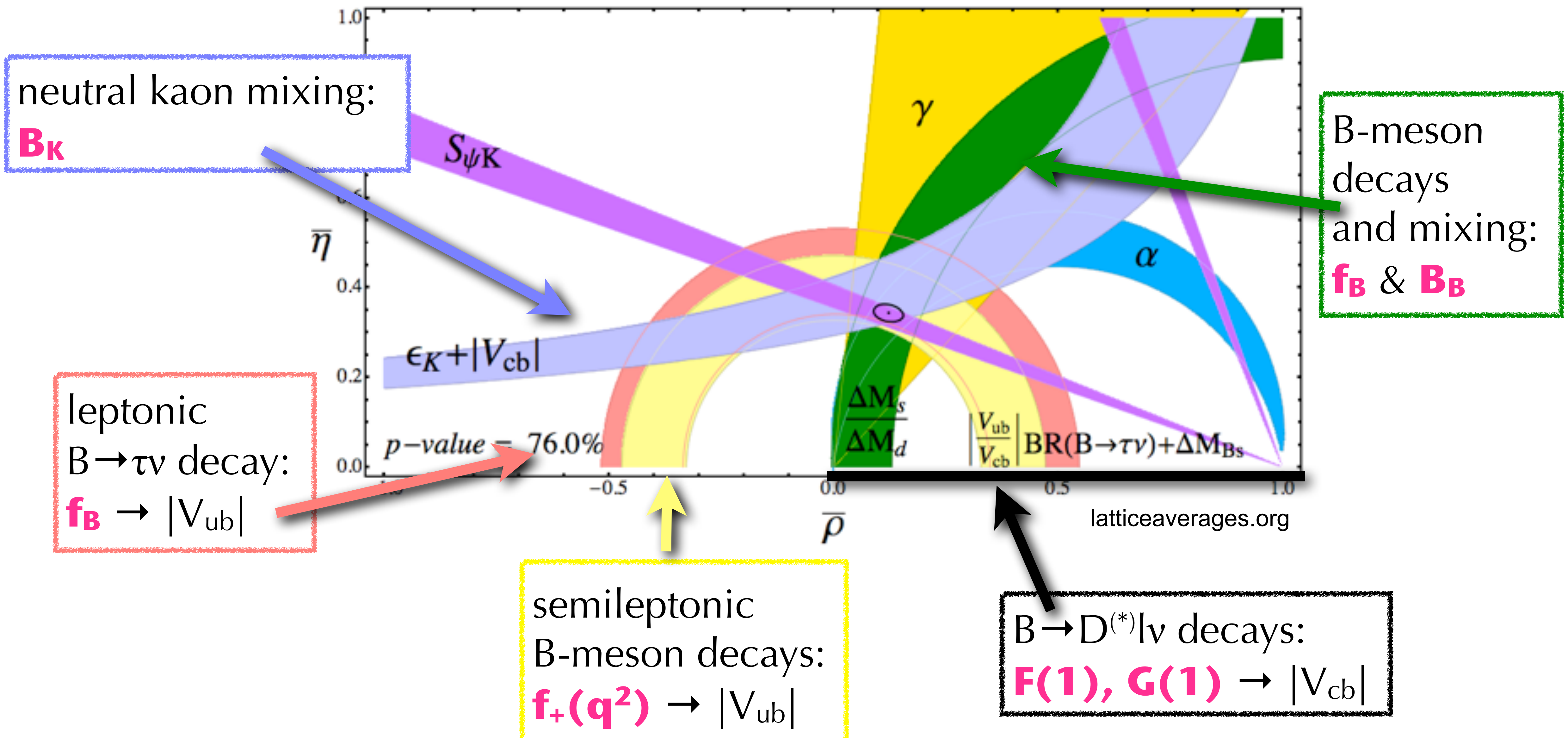
$$\epsilon_K\,,\,\Delta m_{(d,s)}\,,$$
$$\frac{d\Gamma(B \to \pi\ell\nu)}{dq^2}\,,\,\frac{d\Gamma(B \to D^{(*)}\ell\nu)}{dw}\,,\ldots$$

Absorb nonperturbative QCD effects into quantities such as decay constants, form factors, and bag-parameters that must be computed numerically with LATTICE QCD

Lattice QCD inputs to the unitarity triangle

- Standard approach to search for new physics in the flavor sector is by overconstraining the angles and sides of the CKM unitarity triangle.

- Many constraints require lattice-QCD calculations of hadronic weak matrix elements.



- USQCD calculations lead the world on all quantities shown except B_K, for which we are competitive.

Project goals: how are we doing?

- LQCD-ext proposal written in 2007-2008 showed a table of “present status and future prospects for lattice calculations which directly determine elements of the CKM matrix”.

Quantity	CKM element	present expt. error	present lattice error	2009 lattice error (*prediction*)	2013 lattice error (*actual*)
f_K/f_π	V_{us}	0.3%	0.9%	0.5%	0.4%
$f_{K\pi}(0)$	V_{us}	0.4%	0.5%	0.3%	0.4%
$D \to \pi\ell\nu$	V_{cd}	3%	11%	6%	4.4%
$D \to K\ell\nu$	V_{cs}	1%	11%	5%	2.5%
$B \to D^*\ell\nu$	V_{cb}	1.8%	2.4%	1.6%	1.8%
$B \to \pi\ell\nu$	V_{ub}	3.2%	14%	10%	8.7%

- Last column is new and shows the current errors in these same quantities.

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$f_{K\pi}(0)$					0.4%
$D \to \pi\ell\nu$					4.4%
$D \to K\ell\nu$	V_{cs}	1%	11%	5%	2.5%
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We are meeting our goals and are leading the world for all of the quantities shown

- Last column is new and shows the current errors in these same quantities.

The US flavor effort

- USQCD is leading the world in precision calculations of hadronic matrix elements needed to obtain CKM parameters and test the Standard-Model CKM framework.

- The US quark flavor effort is focusing more on the needs of experiment and phenomenology than those of other parts of the world.

  - E.g., many interesting field theory calculations are being done with $N_f = 2$, or static b quarks, ..., not directly applicable to phenomenology. (USQCD's are with N_f=3 or 4, and physical b quark masses.)

- For many quantities, especially in B physics, US calculations are not simply the best calculations, they are the only calculations.

  - $B \to D^{(*)} l\nu$ for V_{cb},

  - $B \to \pi l\nu$ for V_{ub},

  - B mixing, B_s mixing.

The LQCD-ext II Proposal

- USQCD has proposed an extension of our current hardware project hardware project for the period 2015 - 2019.
- In order to meet our scientific goals during this period, a mixture of access to the DOE's Leadership Class and acquisition of dedicated hardware is needed.
- The plan calls for sustaining around five sustained petaflop/s on each class of computer by its final year:

Fiscal Year	Dedicated Hardware (TF-Years)	Leadership Class Machines (TF-Years)
2015	325	430
2016	520	680
2017	800	1,080
2018	1,275	1,715
2019	1,900	2,720
Total	4,820	6,625

LQCD-ext II Budget

- The proposed budget for LQCD-ext II is \$23.50 M over five years.
  Coming from both HEP and NP.
  The same as for LQCD-ext plus its ARRA-funded supplement.

Fiscal Year	Hardware Budget	Operations Budget	Total Budget
2015	2.63	1.95	4.58
2016	2.63	2.02	4.65
2017	2.63	2.07	4.70
2018	2.63	2.13	4.76
2019	2.63	2.18	4.81
Totals	13.15	10.36	23.50

TABLE IX: Proposed budget for LQCD III in millions of dollars.

- LQCD-ext II will allow the accomplishment of the scientific goals outlined in the LQCD-ext II proposal, the Snowmass Computing Frontier report, and the USQCD white papers.

- The following are some examples.

Muon *g*-2

- Measured muon *g-2* disagrees with Standard-Model prediction by >3σ, and new Fermilab Muon g-2 Experiment will reduce the experimental error to approximately 0.14 ppm.
  - Dominant uncertainty in Standard-Model prediction for muon *g*-2 from hadronic light-by-light and vacuum polarization contributions.
  - Current estimate for uncertainty in light-by-light comes from the spread of models.

"Finding a new approach [for the light-by-light contributions], such as lattice QCD, in which uncertainties are systematically improvable, is crucial for making greatest use of the next round of experiments." Snowmass Charged Leptons WG Report, p 31.

Contribution	Result ($\times 10^{11}$)		Error
QED (leptons)	116 584 718 $\pm$ 0.14	$\pm$ 0.04_{α}	0.00 ppm
HVP(lo) [1]	6 923 $\pm$ 42		0.36 ppm
HVP(ho)	-98 $\pm$ 0.9_{exp}	$\pm$ 0.3_{rad}	0.01 ppm
HLbL [2]	105 $\pm$ 26		0.22 ppm
EW	154 $\pm$ 2	$\pm$ 1	0.02 ppm
Total SM	116 591 802 $\pm$ 49		0.42 ppm

Reducing hadronic light by light contribution to uncertainty requires new lattice methods. Promising early results have been obtained.

See Van de Water plenary Precision Frontier colloquium at Snowmass.

μ to e conversion (and dark matter)

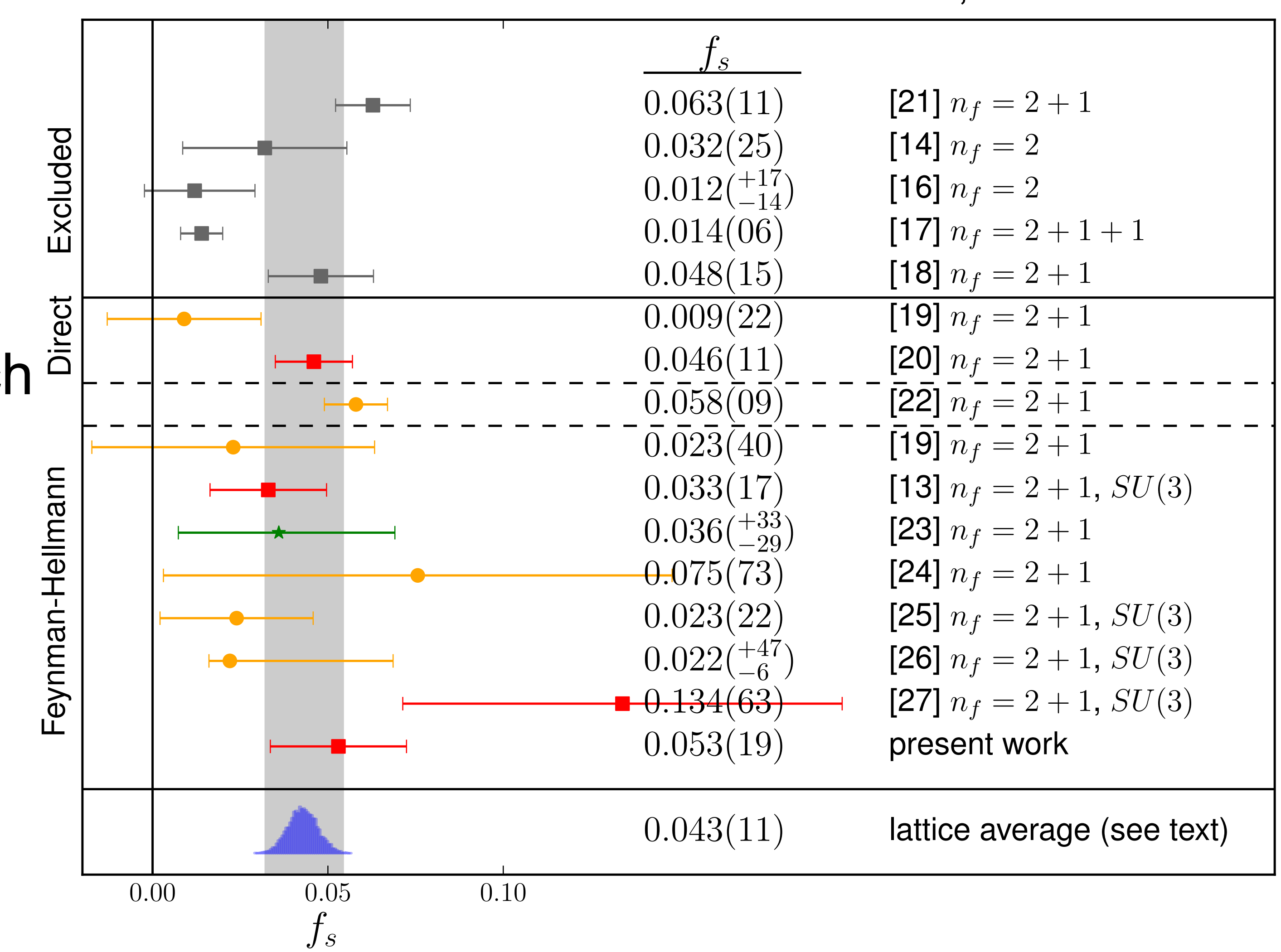
- Observation of charged-lepton flavor violation at Mu2e would be unambiguous evidence of new physics.
  - Combining measured rates of $\mu \to e\gamma$ and $\mu \to e$ conversion on different target nuclei can distinguish between theories, but predictions for $\mu \to e$ conversion rate depend upon light- and strange-quark contents of nucleon from lattice QCD.

- Same hadronic matrix elements also needed to interpret dark-matter detection experiments in which the DM particle scatters off a nucleus.

- Calculations improved significantly in recent years, and already rule out much larger values of $f_s = m_s \langle N|ss|N\rangle / M_N$ favored by early non-lattice estimates.

- Even greater precision is needed for Mu2e and dark-matter searches.
  - Realistic goal for next five years is to pin down values with ~10-20% errors.

Junnarkar & Walker-Loud, arXiv:1301.1114



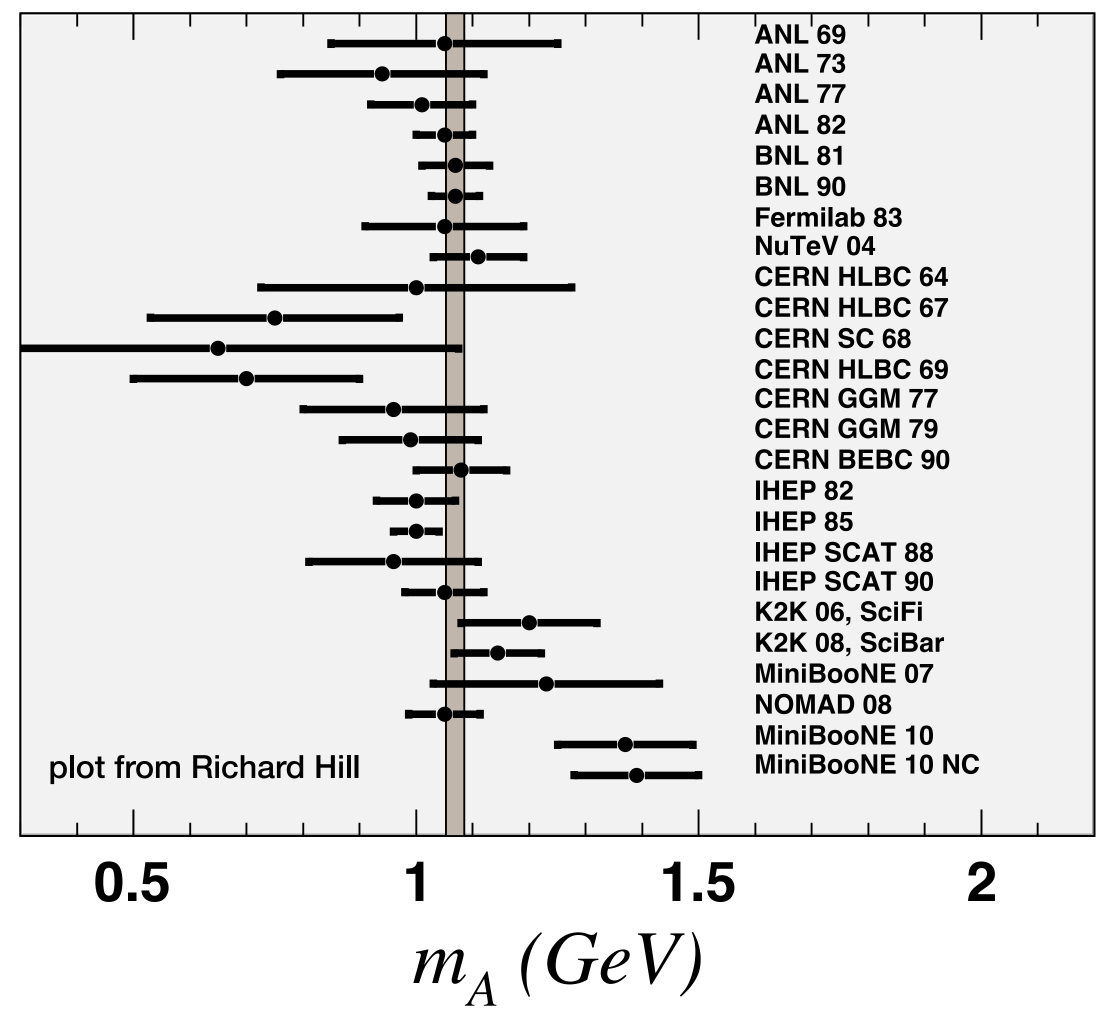
Neutrino Cross Section

- Cross section for quasielastic $\nu n \rightarrow e^- p$ and $\bar{\nu} p \rightarrow e^+ n$ scattering needed to predict signal and background rates in neutrino oscillation searches in few-GeV beams.

> *"In this [energy] region, the cross sections even off free nucleons are not very well measured (at the 10 − 40% level) and the data are in frequent conflict with theoretical predictions."*
>
> Snowmass Neutrino WG Report, p. 43

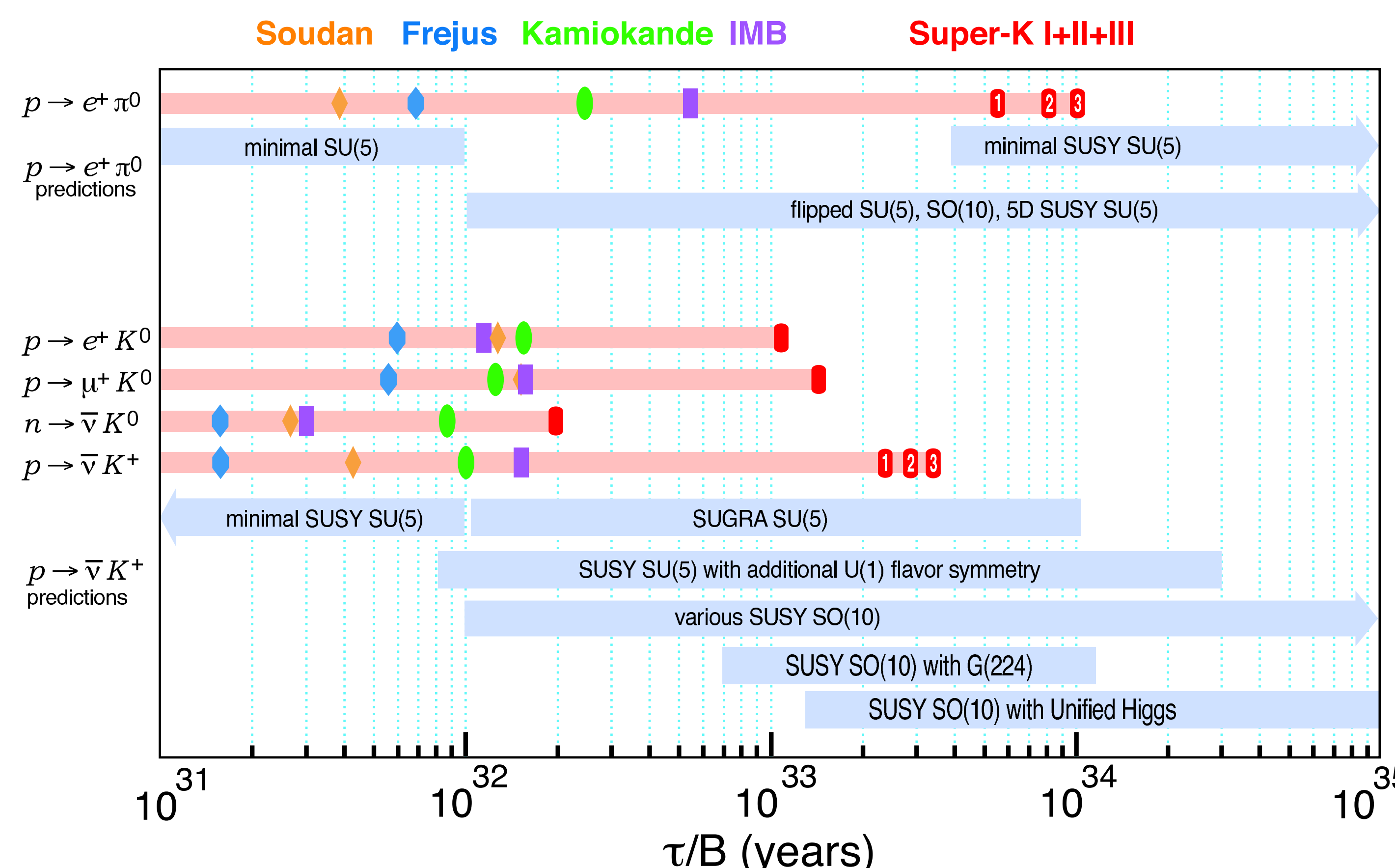
- QE scattering parameterized by vector and axial-vector hadronic form factors.
- Modern experiments have outgrown the dipole Ansatz for $F_A(q^2) = g_A(1 + q^2/m_A^2)^{-2}$: no single value of m_A fits all data.
- Lattice QCD + analyticity can reliably provide shape and normalization of $F_A(q^2)$ (c.f. $|V_{ub}|$).
- USQCD student interfacing the analyticity formalism with the GENIE MC generator being developed and used by several neutrino collaborations.

cf. Bhattacharya, Hill, Paz, arXiv:1108.0423 [hep-ph]



Proton decay

- Proton decay forbidden in the Standard Model, but a natural prediction of grand unification.
  - ➡ Observation of **proton decay would be unambiguous evidence of new physics.**
- **Proton-decay matrix elements essential to interpret limits on (or a measurement of) the proton lifetime as constraints on GUT scenarios.**
  - Lattice QCD can compute nonperturbative hadronic matrix elements $\langle \pi, K, \eta, \ldots \mid \mathcal{O}_{NP} \mid p \rangle$ of new-physics operators.

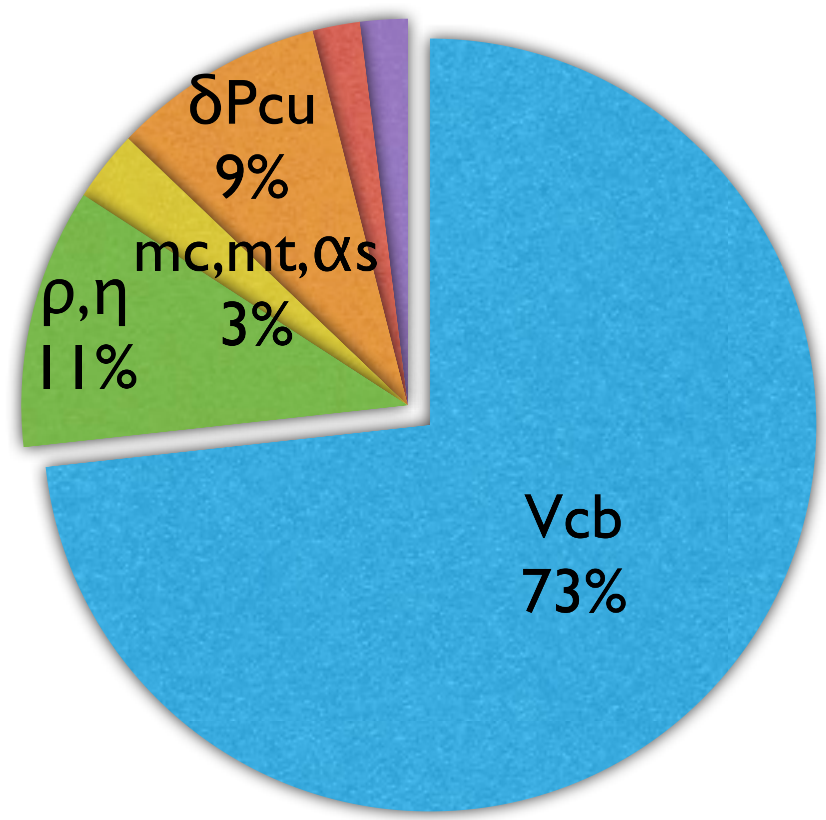


- RBC/UKQCD recently obtained **first three-flavor result for proton-decay matrix elements with a complete systematic error assessment** [Aoki,Shintani,Soni, arXiv:1304.7424].
  - Errors range from 20-40%, but use of finer lattice spacings and lighter quark masses will improve the precision of these matrix elements in the next five years.

Quark-flavor physics

- Lattice QCD will continue to be crucial for upcoming kaon and B-physics experiments, e.g.
  - Standard-Model branching ratios for rare kaon decays $K^+ \to \pi^+ \nu\nu$ and $K_L \to \pi^0 \nu\nu$ decays limited by ~10% parametric uncertainty in $A^4 \propto |V_{cb}|^4$; $|V_{cb}|$ can be obtained from exclusive $B \to D^{(*)} l\nu$ decays.
  - Standard-Model predictions for $B \to \tau\nu$ and $B_s \to \mu^+\mu^-$ rely on f_B and f_{Bs}, respectively.
  - Standard-Model branching fraction predictions for rare $b \to s$ decays (e.g. $B \to K^{(*)} l^+ l^-$) limited by hadronic form factor uncertainties.
- Now that field is more mature, expanding program to more challenging matrix elements such as $K \to \pi\pi$ decay (ΔI=1/2 rule and $\varepsilon'_K/\varepsilon_K$), long-distance amplitudes. (*e.g.* rare kaon decays, *D*-meson mixing), and multi-hadron final states (*e.g.* $D \to \pi\pi, KK, \ldots$).

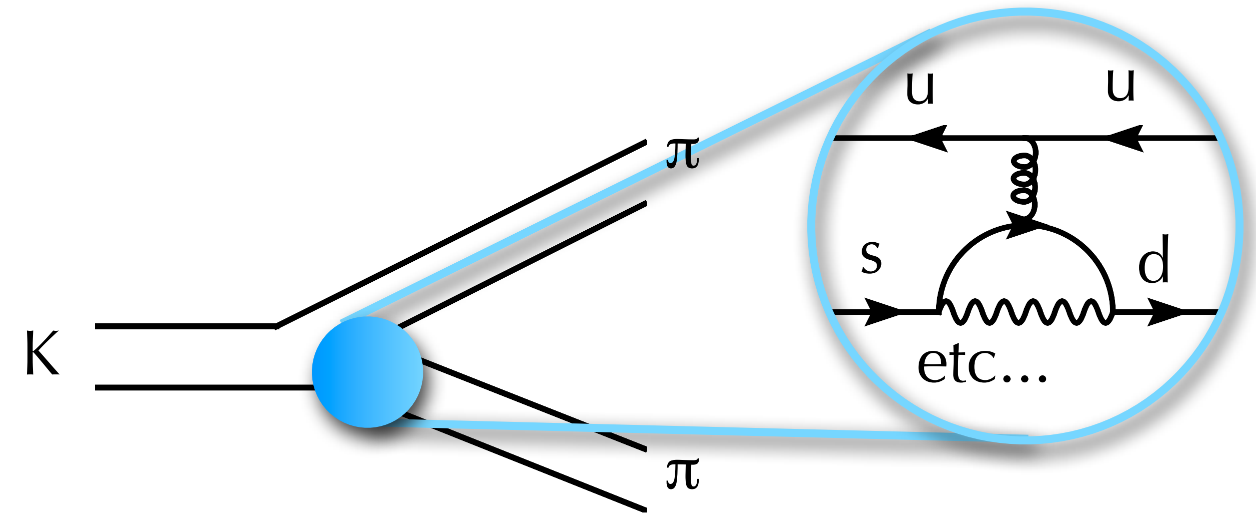
$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$



[Brod & Gorbahn PRD83 (2011) 034030]

$K \to \pi\pi$ decay and ε'/ε

- Direct CP-violation in $K \to \pi\pi$ decays (ϵ'_K/ϵ_K) sensitive to new physics because it receives contributions from EW penguins.
  - Measured experimentally to <10% precision, but **utility for testing Standard Model handicapped by large uncertainty in corresponding weak matrix elements.**



- In the past two years, the RBC-UKQCD Collaboration made significant progress in resolving theoretical issues associated with computing $K \to \pi\pi$ amplitudes.
  - Computed ΔI=3/2 matrix elements with nearly physical pion and kaon masses, and obtained Re(A_2) & Im(A_2) with ~20% errors (PRL 108 (2012) 141601).
  - Performed pilot study of ΔI=1/2 matrix elements with ~330 MeV pions (PRD **84** (2011) 114503).
- Simulations with physical pions on BG/Q at ALCF should yield first *ab initio* QCD calculation of ΔI=1/2 rule and $\varepsilon'_K/\varepsilon_K$ with ~20-30% precision in one or two years.
- With projected lattice improvements, combining the pattern of results for $\varepsilon'_K/\varepsilon_K$ with $K \to \pi\nu\nu$ decays can help distinguish between new-physics scenarios (Buras et al., NPB **566** (2000).

Non-Standard Model Higgs Physics

For "theoretical models of the Higgs field ...big ideas are proposed: supersymmetry, higher dimensions, Higgs compositeness..." Peskin Snowmass Energy Frontier Introduction, p 7.

- Many new-physics scenarios with nonperturbative dynamics can be studied quantitatively using lattice-field-theory technology.
- **Composite Higgs:** Higgs particle could be a dilaton or a pseudo-Goldstone boson.
  - New lattice methods have been developed to identify conformal or near-conformal behavior in gauge theories beyond QCD by studying the running coupling, mass anomalous dimension, and chiral-symmetry breaking pattern.
  - Current highest priority to find a viable model with a light scalar and S-parameter consistent with precision EW constraints.
  - Can then make predictions for the particle spectrum and modifications to W-W scattering that can be tested at the 14-TeV LHC run or future colliders.
- **Supersymmetry:** SUSY-breaking mechanism could be dynamical.
  - Simple candidate for SUSY-breaking sector is a supersymmetrized version of QCD.
  - Recent lattice efforts focused on studying super-Yang Mills, but long-term goal is to simulate super-QCD and compute the soft parameters of the low-energy theory.
  - Will constrain existing SUSY models and provide inputs for SUSY model building.

Spinoffs: LGT and computing in industry

- Ken Wilson, inventor of lattice gauge theory, was an early proponent of supercomputing. (In the 70s, he was programming array processors in assembly language to attack critical phenomena problems for which he won the Nobel Prize.)

- Academic purpose-built Lattice QCD computers (Caltech (Cosmic Cube), Columbia, IBM (GF11, not a commercial project), Fermilab ACPMAPS, ...) were influential in establishing the parallel computing model later adopted by industry.

- The IBM Blue Gene line was spearheaded by Al Gara, who began in supercomputing at Columbia on Norman Christ's lattice QCD computers. (The Columbia group helped design the Blue Gene/Q, such as Mira at the Argonne Leadership Computing facility.)

- NVIDIA (maker of the GPUs in Titan at the Oak Ridge Leadership computing facility) has hired two lattice gauge theorists. They help design future GPU-based supercomputers by evaluating how they would run lattice QCD algorithms.

Spinoffs: LGT and computing in experimental HEP

- In the coming decade, we will see increasing complexity in chips, with increasing hierarchies of processors and memory on each chip.
- GPUs: very complex compute modules and memory, special progamming language (CUDA) required.
  - USQCD has made its codes run very efficiently, at the cost of many person-years of effort.
  - Fermilab's lattice computing group proselytized for GPUs at the lab and found interest from the Monte Carlo builders.
- The Fermilab lattice QCD computing group is leading an effort to investigate the applicability of Intel's latest many-core chip, the Phi, with interest from many areas in HEP computing
  - Lattice QCD, off-line track reconstrution, on-line reconstruction and high-level triggers, GEANT parallelization, accelerator modeling, DES data processing, ...
  - Intel also seems to be entering the supercomputing market.

Summary 1

- The need for lattice calculations in the coming decade will be almost ubiquitous in the HEP experimental.
  - In charged lepton physics: g-2 (vacuum polarization and light by light scattering), mu2e, μeγ (nucleon scalar matrix elements).
  - In neutrino physics: LBNE, Nova, ... (nucleon axial M. E.).
  - In dark matter experiments: CDMS, ... (nucleon scalar matrix elements).
  - In underground proton decay experiments: LBNE, ... (proton decay matrix elements).
  - In quark flavor physics: Belle-2, LHCb, ... (many matrix elements with much better precision).
  - At the LHC: CMS, Atlas (strongly coupled BSM sectors).
  - At the ILC, TLEP, muon colliders: (very high precision α_s and m_b).

Summary 2

- USQCD dominated quark-flavor physics on the lattice during the era of the flavor factories.
- In the coming decade, new lattice calculations will be needed throughout the HEP experimental program.
  - We have systematically examined the future US experimental program and talked with experimenters to determine the lattice calculations that need to be done.
- The LQCD-ext II project will help us complete them.
  - Continued support of the U.S. lattice-QCD effort is essential to fully capitalize on the enormous investment in the HEP experimental program.
  - We hope that you agree.

Extra slides

Scientific motivation

- The experimental **HIGH-ENERGY PHYSICS** community is presently searching for new physics with two complementary approaches

(1) **The Energy Frontier:** directly produce new particles at high-energy colliders

(2) **The Intensity Frontier:** observe deviations from the Standard Model in precise measurements of rare processes that probe quantum-mechanical loop effects

- Comparison between measurements and Standard-Model predictions often limited by nonperturbative matrix elements

- The experimental **NUCLEAR PHYSICS** community aims to

(1) Determine the structure, spectrum, and interactions of hadrons

(2) Understand the properties of matter under extreme conditions

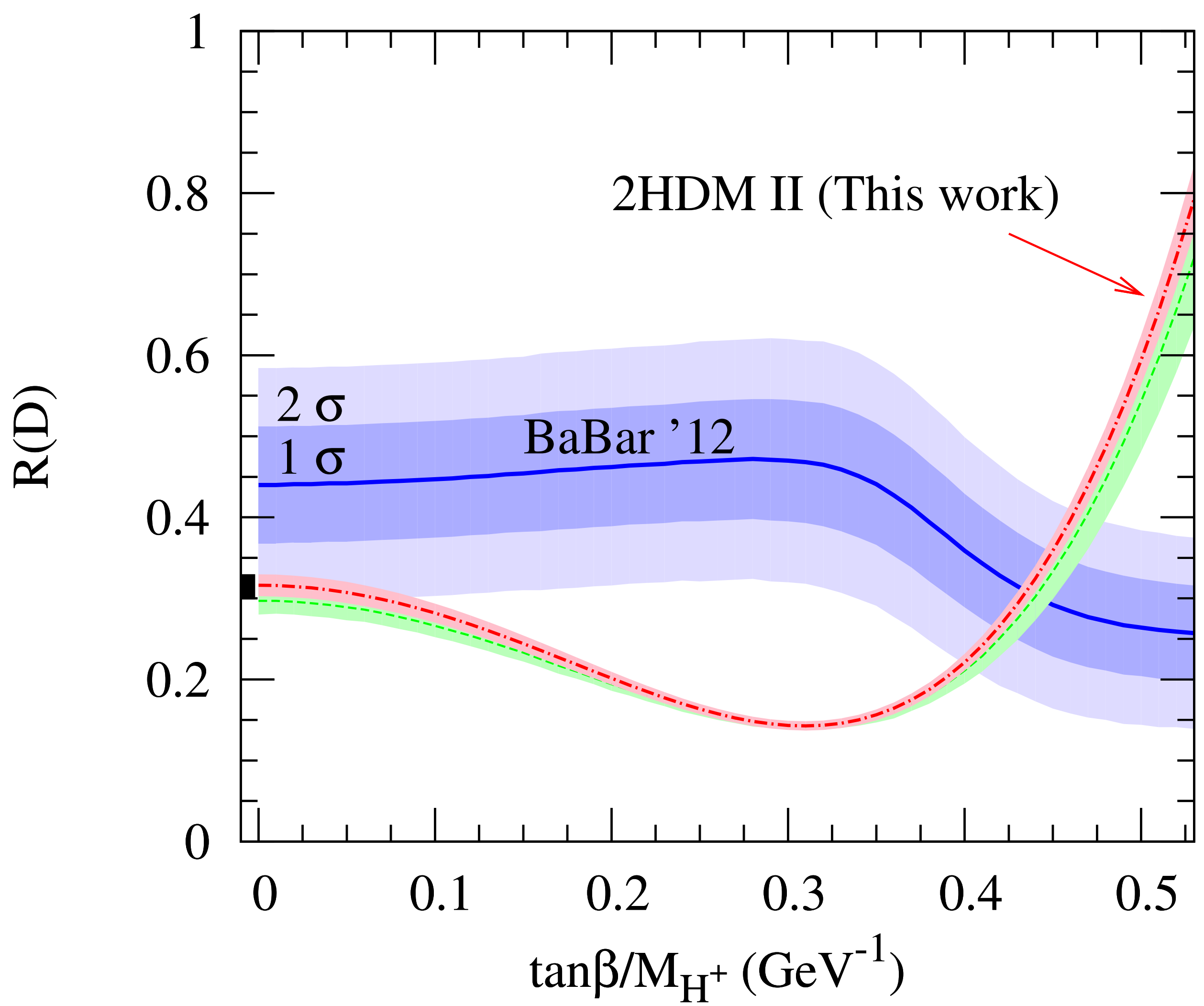
- Lattice QCD enables the determination of hadron properties from first principles

- **Lattice gauge theory is crucial to maximize the scientific output of the current and future high-energy and nuclear physics experimental programs**

2012 Highlight: R(D) from unquenched lattice QCD

- $B \to D^{(*)} \tau \nu$ decays sensitive to new-physics contributions such as from charged Higgs bosons

- Recently BaBar measured the ratios $R(D) = BR(B \to D\tau\nu)/BR(B \to Dl\nu)$, $R(D^*) = BR(B \to D^*\tau\nu)/BR(B \to D^*l\nu)$ and observed excesses in both channels that **disagree with the Standard Model by 3.4σ** [PRL 109 (2012) 101802]



- Fermilab Lattice and MILC Collaborations quickly followed with **first Standard-Model calculation of R(D) from *ab initio* lattice-QCD** [PRL 109 (2012) 071802]

- Uncertainty smaller than previous model estimate from dispersive bounds, heavy-quark symmetry, and quenched lattice QCD

- Lattice calculation of $R(D^*)$ *in progress*...

2012 Highlight:

K→πℓυ form factor in the continuum

- K→πℓυ form factor can be combined with experimentally-measured branching fraction to obtain $|V_{us}|$ in the Standard Model:

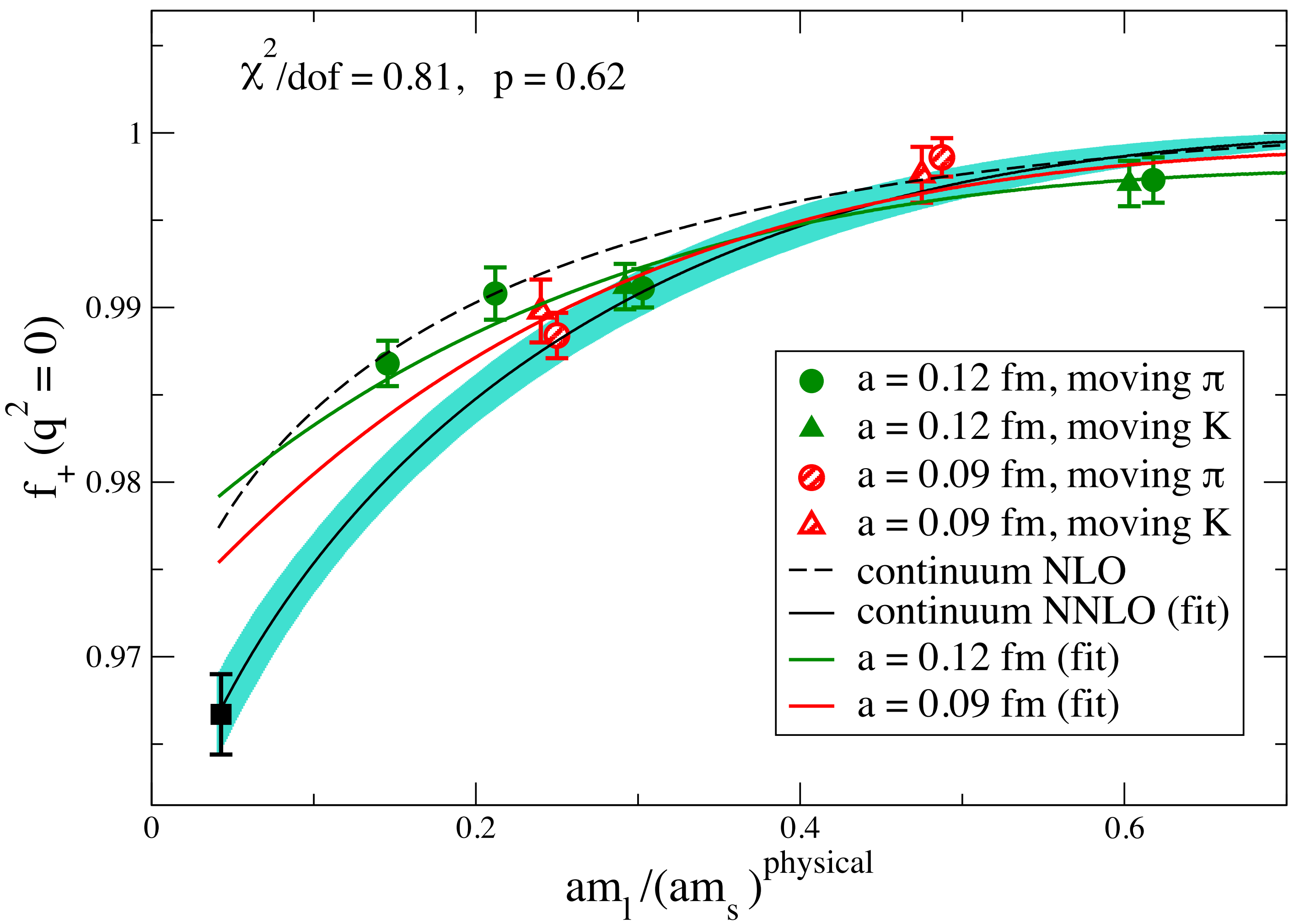
$$\Gamma(K \to \pi \ell \nu) = \frac{G_F^2 m_K^5}{192\pi^3} C_K^2 S_{\rm EW} |V_{us}|^2 |f_+^{K^0\pi^-}(0)|^2 I_{K\ell} \left(1 + \delta_{\rm EM}^{K\ell} + \delta_{SU(2)}^{K\pi}\right)^2$$

- Fermilab Lattice and MILC recently obtained the first three-flavor result for the K→πlυ form factor at zero momentum transfer with two lattice spacings and a controlled continuum extrapolation [Bazavov et al. PRD87, 073012 (2013)]

- Single most precise result for $f_+(0)$ enables 0.5% determination of $|V_{us}|$

$f_+^{K\pi}(0) = 0.9667(23)_{stat}(33)_{sys}$

$|V_{us}| = 0.2238(9)_{theo}(5)_{exp}$



2013 Highlight: f_K/f_π at the physical point

- The SU(3) flavor-breaking ratio f_K/f_π allows a determination of $|V_{ud}|/|V_{us}|$ [Marciano]

$$\frac{\Gamma(K\to l\bar{\nu}_l)}{\Gamma(\pi\to l\bar{\nu}_l)} = \left(\frac{|V_{us}|}{|V_{ud}|}\right)^2 \left(\frac{f_K}{f_\pi}\right)^2 \frac{m_K\left(1-\frac{m_l^2}{m_K^2}\right)^2}{m_\pi\left(1-\frac{m_l^2}{m_\pi^2}\right)^2}\left[1+\frac{\alpha}{\pi}(C_K-C_\pi)\right]$$

- MILC collaboration recently obtained the **first lattice-QCD determination of f_K/f_π (1) including dynamical charm** and **(2) at the physical pion mass** with highly-improved staggered (HISQ) quarks [Bazavov *et al.* PRL**110**, 172003]
  - **Eliminate error from extrapolation to physical u- and d-quark masses**

Source	f_{K^+}/f_{π^+}
Monte-Carlo statistics	0.22%
Continuum extrapolation	0.28%
Finite-volume corrections	0.14%
EM corrections	0.02%
Total	0.38%

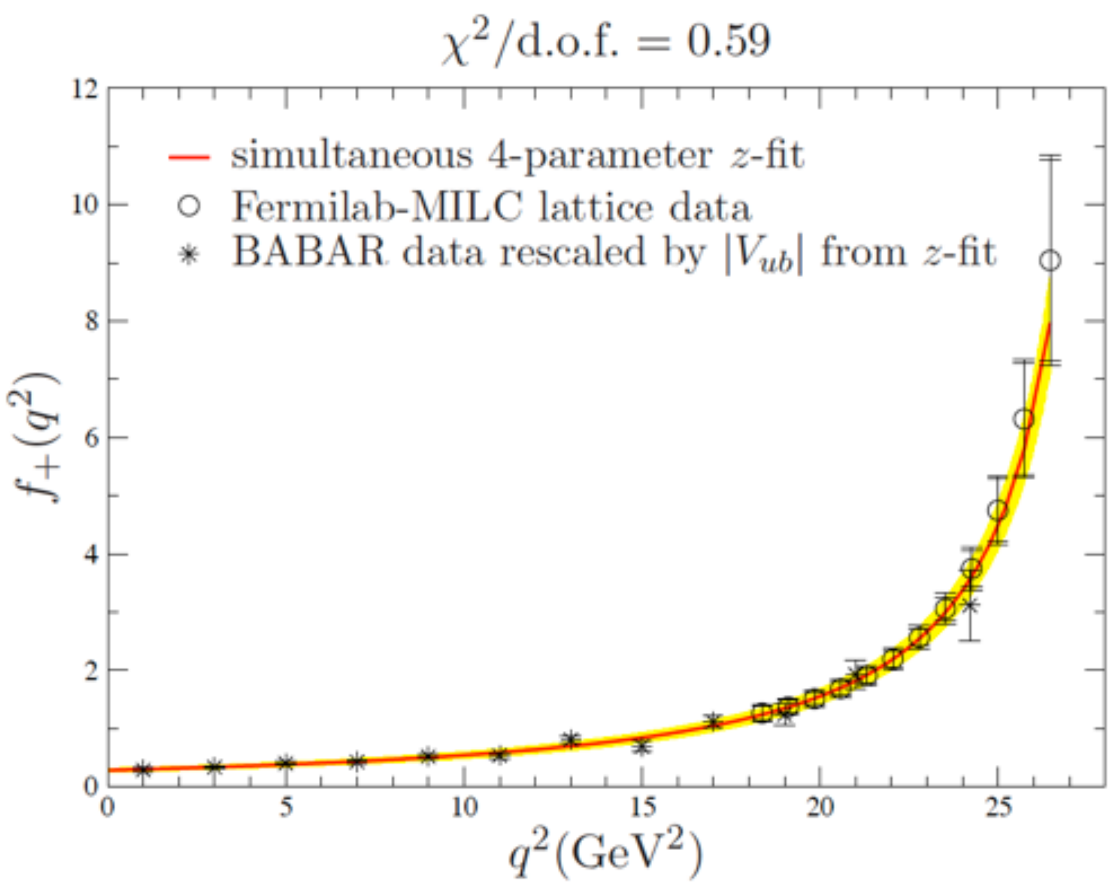
- Combined with $|V_{ud}|$ from nuclear β-decay, enables sub-percent test of unitarity of 1st row of CKM matrix

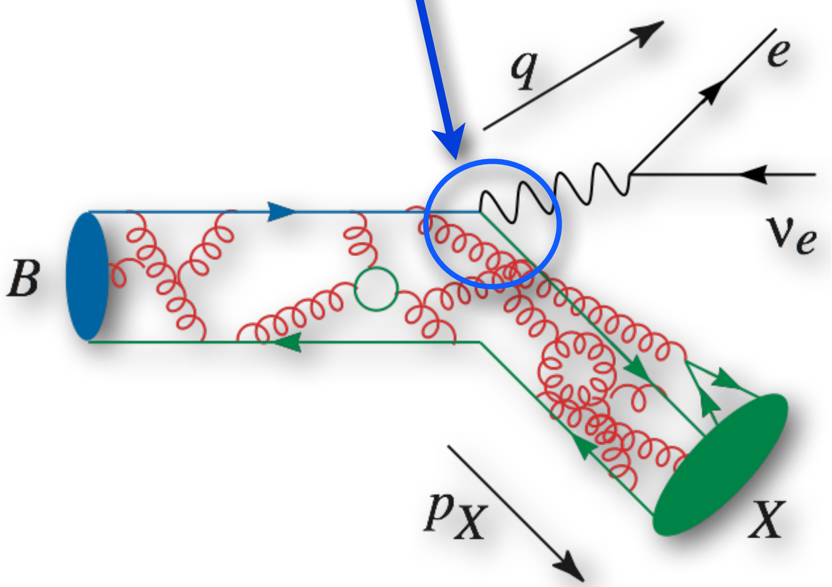
$$1-|V_{ud}|^2-|V_{us}|^2-|V_{ub}|^2 = 0.0003(6)$$

Determination of V_{ub} from $B \to \pi l \nu$

The CKM matrix element V_{ub} can be determined from the observed rate for the decay of a B meson into a pion and two leptons, $B \to \pi l \nu$, and the lattice QCD calculation of the form factor parameterizing the strong interaction effects.

$$\frac{d\Gamma(B^0 \to \pi^- \ell^+ \nu)}{dq^2} = \frac{G_F^2}{192\pi^3 m_B^3} \left[(m_B^2 + m_\pi^2 - q^2)^2 - 4m_B^2 m_\pi^2\right]^{3/2} |V_{ub}|^2 |f_+(q^2)|^2$$





Few percent determination of exclusive $|V_{ub}|$ challenging:
both lattice and experimental results are momentum dependent and highly correlated.

$B \rightarrow \pi l \nu$

Phys. Rev. **D79**:054507, 2009.

Rewrite form factors

$$f(t) = \frac{1}{P(t)\phi(t,t_0)} \sum_{k=0}^{\infty} a_k(t_0)\, z(t,t_0)^k$$

$$z(t,t_0) = \frac{\sqrt{t_+ - t} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - t} + \sqrt{t_+ - t_0}}$$

$-.3<z<.3$

Unitarity + analyticity:
$\Sigma a_k^2 \lesssim 1$.

Heavy quark theory
(Becher, R. Hill):
$\Sigma a_k^2 \sim (\Lambda_{QCD}/m_b)^3$.

PHYSICAL REVIEW D **83**, 071101(R) (2011)

Measurement of the decay $B^0 \rightarrow \pi^- \ell^+ \nu$ and determination of $|V_{ub}|$

(The Belle Collaboration)

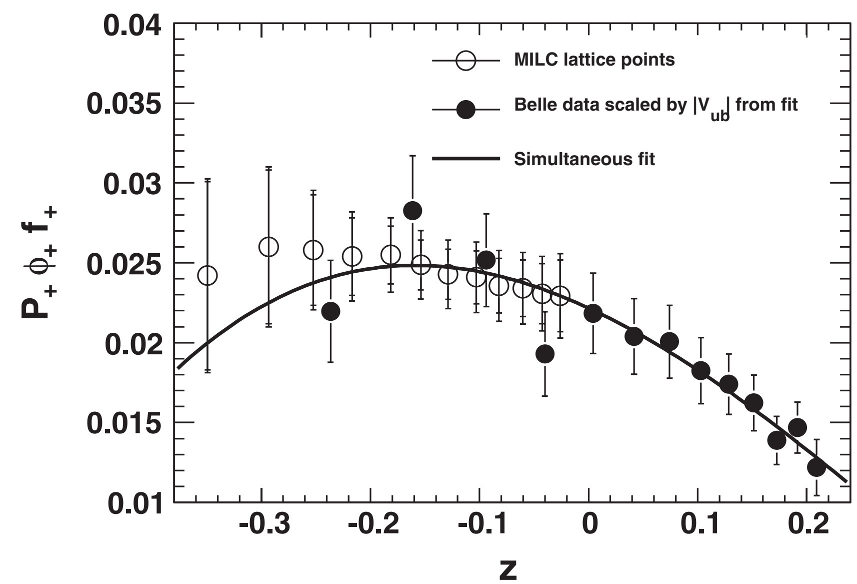


FIG. 3. $|V_{ub}|$ extraction from a simultaneous fit of experimental (closed circles) and FNAL/MILC lattice QCD results (open circles) [9]. The error for each experimental data point is the total experimental uncertainty. The smaller error bars of the lattice QCD results are statistical only while the larger ones also include systematic uncertainties.

$$|V_{ub}| = (3.43 \pm 0.33) \times 10^{-3}$$

Recent BaBar result also uses our work.

Most accurate calculation
of exclusive determination
of V_{ub} so far.

$B \to \pi l \nu$

Phys. Rev. **D79**:054507, 2009.

Rewrite form factors

$$f(t) = \frac{1}{P(t)\phi(t,t_0)} \sum_{k=0}^{\infty} a_k(t_0)\, z(t,t_0)^k$$

Accounts for B* pole (like Becirevic-Kaidalov parameterization).

PT calculable function to make a_ks look simple.

$$z(t,t_0) = \frac{\sqrt{t_+ - t} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - t} + \sqrt{t_+ - t_0}}$$

$-.3<z<.3$

Unitarity + analyticity:
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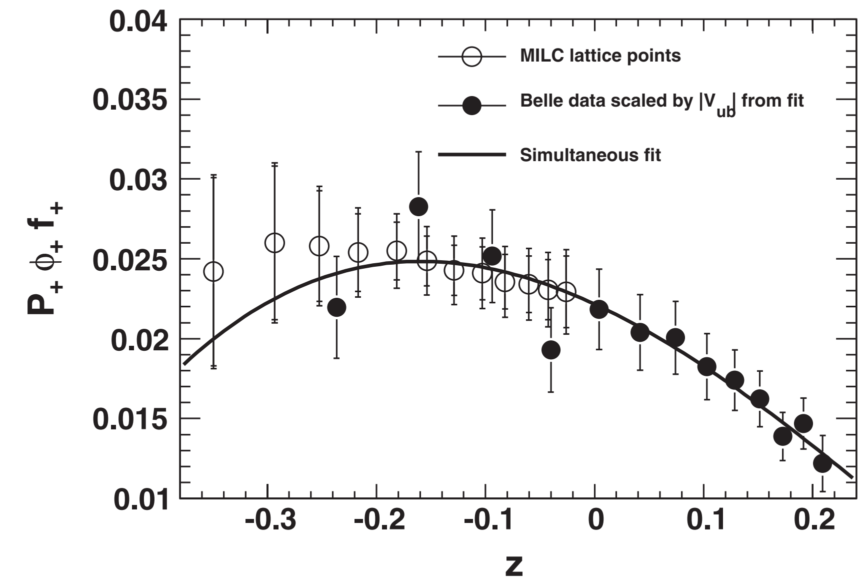

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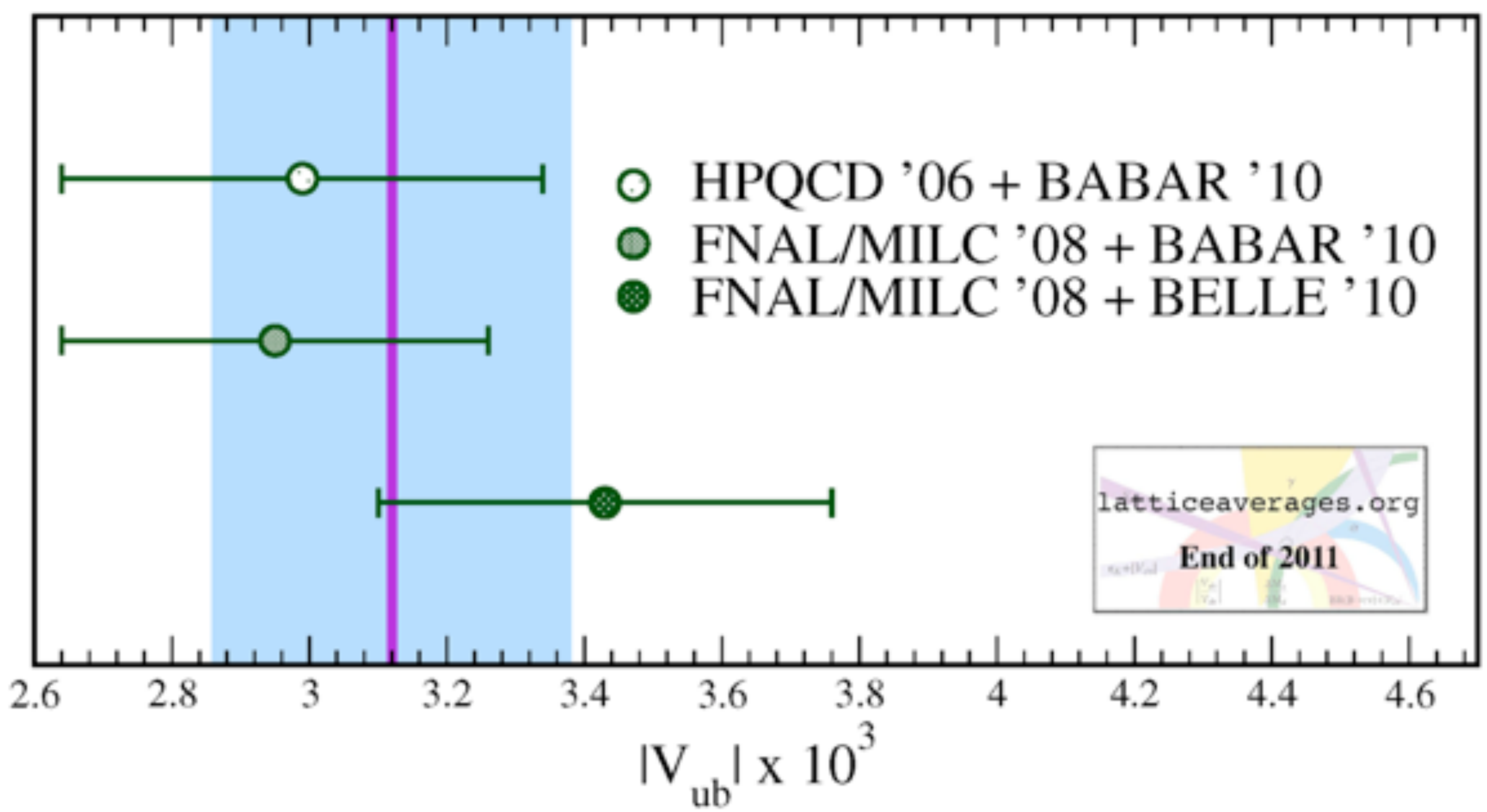
Determination of V_{ub} from $B \to \pi l \nu$



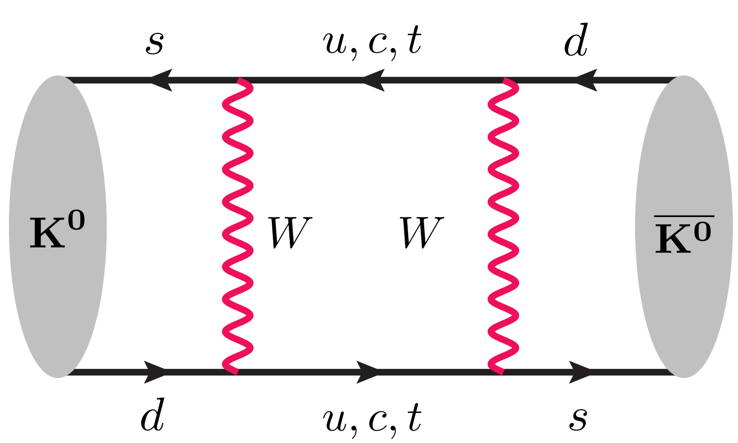
Uncertainty from combined fit ~ 8%.

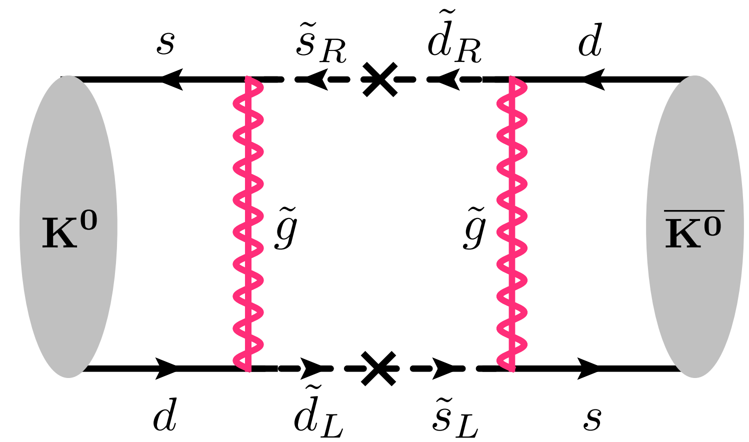
- Several groups have improved calculations underway;
- Should be able to reduce the lattice errors in $|V_{ub}|$ to the current experimental level of ~4-6%

Why search at the intensity frontier?

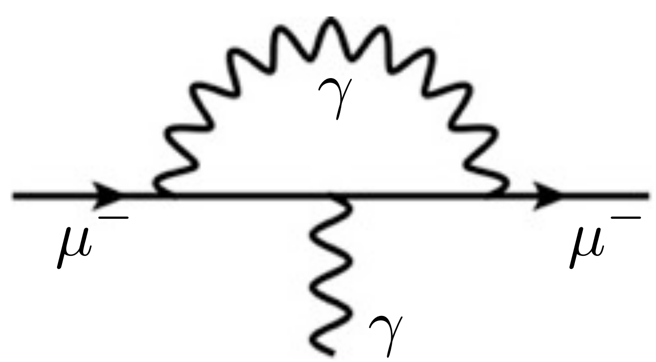
- Precision measurements probe quantum-mechanical loop effects, e.g.:

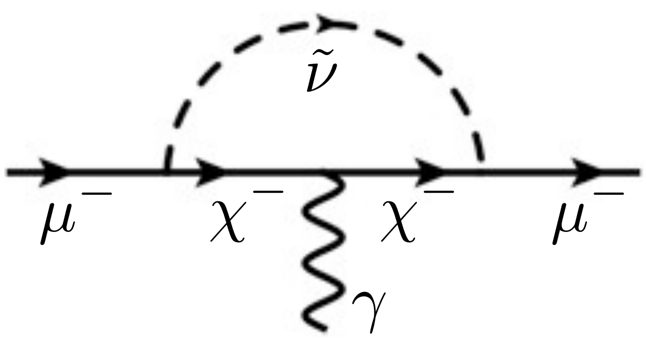
neutral kaon mixing





muon g-2





- Sensitive to physics at higher energy scales than those probed at LHC, in some cases O(1,000 - 10,000 TeV) [Isidori, Nir, Perez, Ann.Rev.Nucl.Part.Sci. 60 (2010) 355]

- If new particles are discovered at ATLAS & CMS, precise measurements will still be needed to extract the flavor & CP-violating couplings and determine the underlying structure of the theory

(Select) Upcoming experiments

NOW

ATLAS/CMS
Δm_s, $B_s \to \mu^+\mu^-$, ...

LHCb
rare $b \to s\gamma$ & $b \to sll$ decays, $B_s \to \mu^+\mu^-$, D-mixing...

2013

E14 "KOTO" @ J-PARC
$K^0 \to \pi^0 \nu\bar{\nu}$

2014

Belle II
$\sin(2\beta)$, $B \to \tau(\mu)\nu$, $B \to \pi(\rho) l\nu$, $B \to D^{(*)} l\nu$, rare $b \to s\gamma$ & $b \to sll$ decays, ...

NA62 @ CERN SPS
$K^+ \to \pi^+ \nu\bar{\nu}$

2016

new muon g-2

ORKA
$K^+ \to \pi^+ \nu\nu$

2019

Mu2e

2020+

Project X @ Fermilab
$K^0 \to \pi^0 \nu\bar{\nu}$

LBNE
neutrino mixing & mass hierarchy, proton decay, ...

Scientific goals and 5-year plan

- **USQCD aims to support the US HEP experimental intensity-physics program** by "improv[ing] the accuracy of QCD calculations to the point where they no longer limit what can be learned from high precision experiments that seek to test the Standard Model" — *USQCD HEP SciDAC-3 proposal*

- 2013 White Paper *"Lattice QCD at the Intensity Frontier"* outlines a program of calculations matched to experimental priorities

  (1) "Improve the calculation of the matrix elements needed for the CKM unitarity fit"

  (2) "Calculate ... new, more computationally demanding, matrix elements that are needed for the interpretation of planned (and in some cases old) experiments"

- Target quantities and precision goals **developed with input from experimentalists and phenomenologists** (primarily quark-flavor and muon g-2)

  - Currently in discussions with neutrino and charged-lepton communities to expand lattice-QCD portfolio relevant for LBNE, Mu2e, etc...

Computational developments

- Petascale computing resources will enable simulations with increased statistics, lighter pions, finer lattice spacings, and larger volumes, thereby helping most sources of uncertainty

- The following improvements will become widespread over the next five years

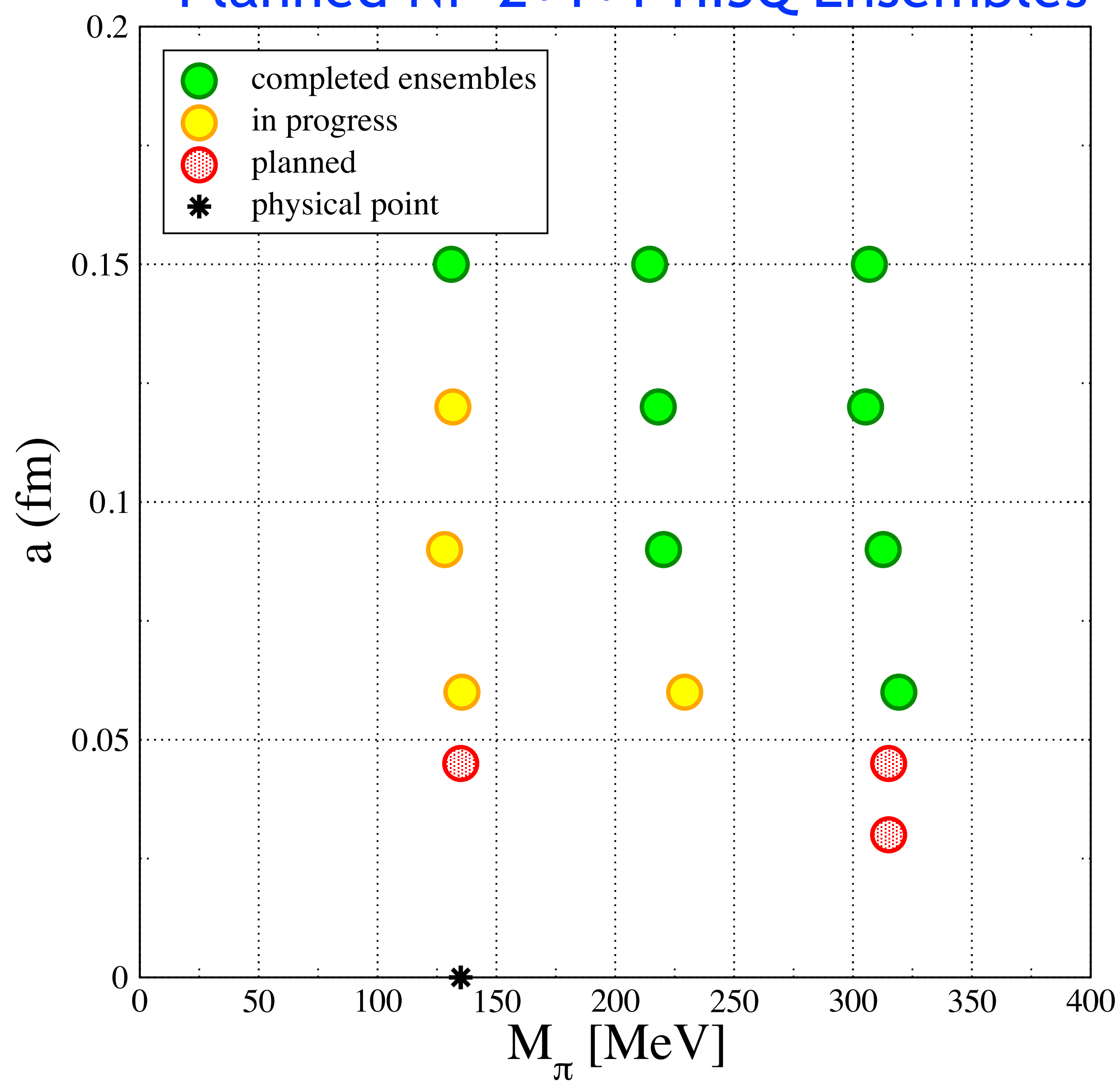
  (1) **Simulations with physical-mass pions**

  (2) Systematic inclusion of isospin-breaking and EM

  (3) Dynamical charm quarks

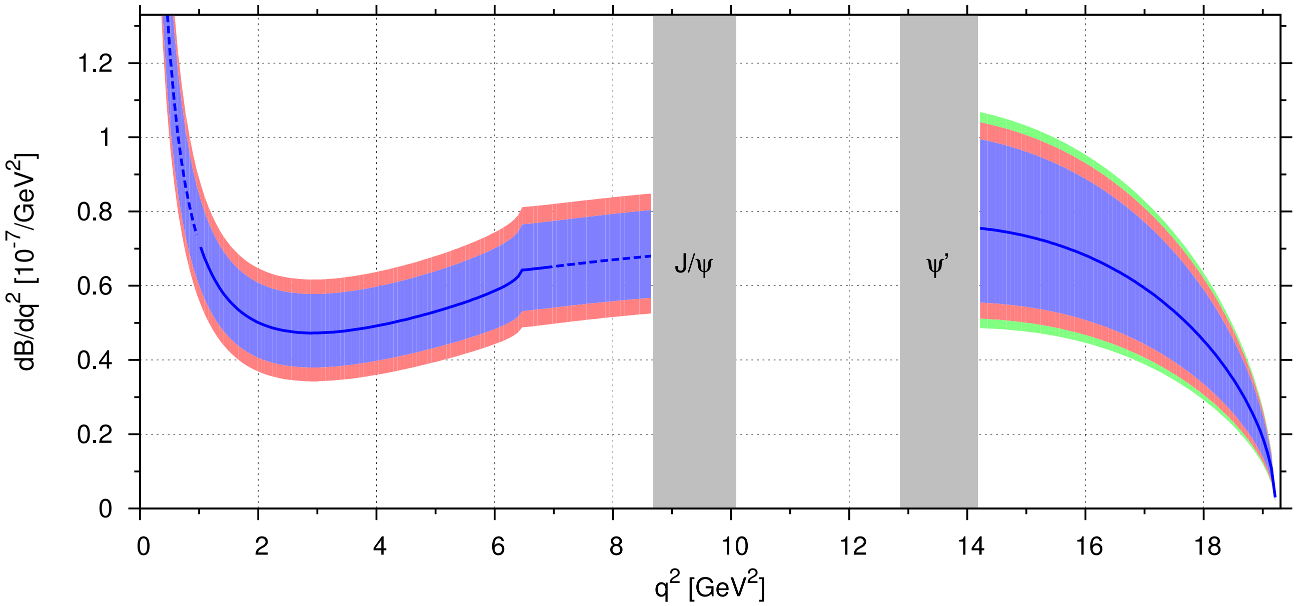
- **Improved algorithms and analysis methods also being pursued**, but difficult to predict

Planned Nf=2+1+1 HISQ Ensembles

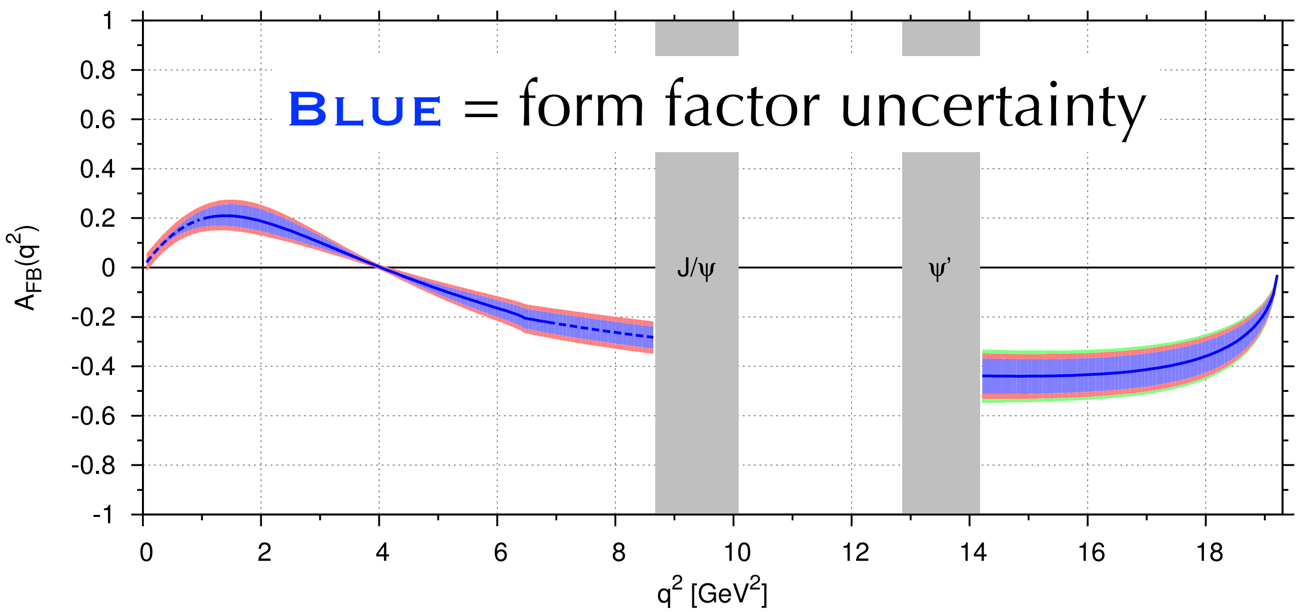


Rare B decays

Differential branching fraction



Forward-backward asymmetry



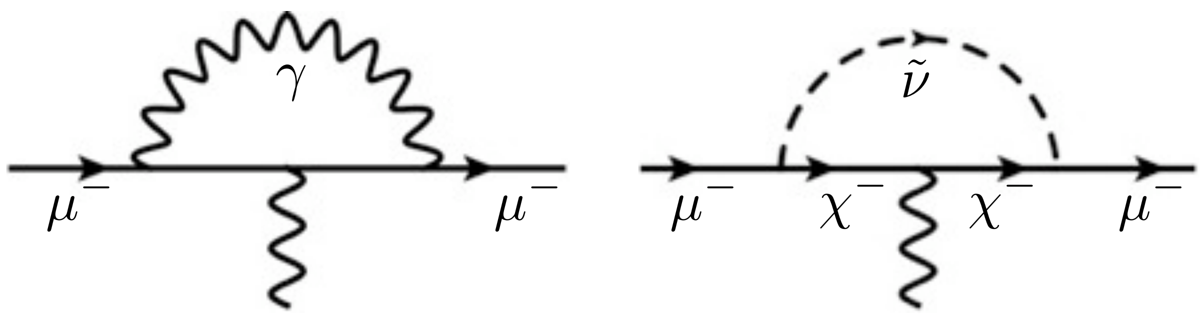
[Bobeth, Hiller, & van Dyk, JHEP 1007 (2010) 098]

- Standard Model branching fraction predictions for many $b \to s$ processes limited by hadronic form factor uncertainties
- E.g., hadronic uncertainties are dominant error for $B \to K^* l^+ l^-$ decay observables over all q^2
- Lattice QCD calculations are underway of $B \to K \ell^+ \ell^-$ [Zhou *et al.* (Fermilab/MILC), arXiv:1111.0981] and of $B \to K^* \ell^+ \ell^-$ & $B \to K^* \gamma$ [Liu *et al.*, arXiv:1101.2726]
  - Expect first lattice-QCD results for $B \to K \ell^+ \ell^-$ by the end of the year with few-percent errors in the high-q^2 region

Muon anomalous magnetic moment

- **Sensitive probe of heavy mass scales in the several hundred GeV range**
- New particles can generate significant non-Standard Model contributions in well-motivated models such as Supersymmetry or warped extra dimensions

SM SUSY



$$a_\mu^{\rm SUSY} \propto \left(\frac{m_\mu}{M_{\rm SUSY}}\right)^2 \tan(\beta)\,{\rm sign}(\mu)$$

- Muon g-2 currently measured experimentally to <u>0.54 ppm</u>

$a_\mu^{exp} = 116\ 592\ 089(54)(33) \times 10^{-11}$ [E821]

$a_\mu^{exp} - a_\mu^{SM} = 287(80) \times 10^{-11}$ [3.6σ]

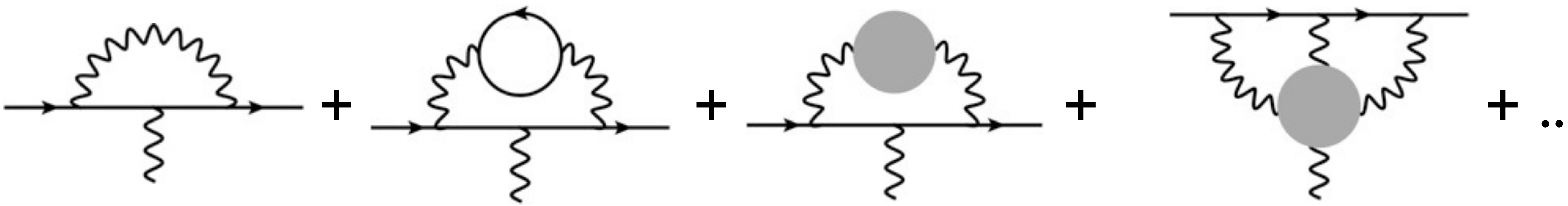
  - A >3σ discrepancy with the Standard Model, assuming you trust the SM prediction...

- **New Muon g-2 experiment** will reduce error by a factor of four to <u>0.14 ppm</u>
  - Reduction in theoretical uncertainty on SM prediction to the same level (with more reliable error estimate!) needed to conclusively establish the presence of new physics with the planned measurement

Standard-Model contributions to g-2

Hadronic vacuum polarization (HVP):

Hadronic light-by-light (HLbL):



QED (4 loops) & EW (2 loops)

from experimental result for $e^+e^- \to$ hadrons plus dispersion relation

estimated from models such as large N_c, vector meson dominance, χPT, etc...

Contribution	Result ($\times 10^{11}$)		Error
QED (leptons)	116 584 718 $\pm$ 0.14	$\pm\, 0.04_\alpha$	0.00 ppm
HVP(lo) [1]	6 923 $\pm$ 42		0.36 ppm
HVP(ho)	-98 $\pm\, 0.9_{\mathrm{exp}}$	$\pm\, 0.3_{\mathrm{rad}}$	0.01 ppm
HLbL [2]	105 $\pm$ 26		0.22 ppm
EW	154 $\pm$ 2	$\pm$ 1	0.02 ppm
Total SM	116 591 802 $\pm$ 49		0.42 ppm

[1] Davier, Hoecker, Malaescu, Zhang, Eur.Phys.J. C71 (2011) 1515
[2] Prades, de Rafael, Vainshtein, arXiv:0901.030

Recent lattice-QCD progress

- Lattice QCD can provide calculations of the hadronic contributions from QCD first principles with controlled uncertainties that are systematically improvable

- USQCD research and development efforts on both hadronic contributions are ongoing

Hadronic vacuum polarization

- Aubin et al.,[Phys.Rev. D86 (2012) 054509] introduced model-independent fitting approach based on analytic structure of $\Pi(Q^2)$ using Padé approximants to eliminate potentially hidden systematic associated with vector-meson dominance fits

- Theoretical improvements + increased computing resources should enable a lattice-QCD determination with few-percent error on the timescale of New g-2

Hadronic light-by-light

- RBC Collaboration [Hayakawa *et al.*, PoS LAT2005 (2006) 353] developed a **promising method using QCD + QED lattice simulations** that is simpler and cleaner than the correlation function of 4 currents, but calculation still in early stages

- Over the next few years, US lattice-QCD community will **increase both human and computing resources devoted to this high-priority calculation**

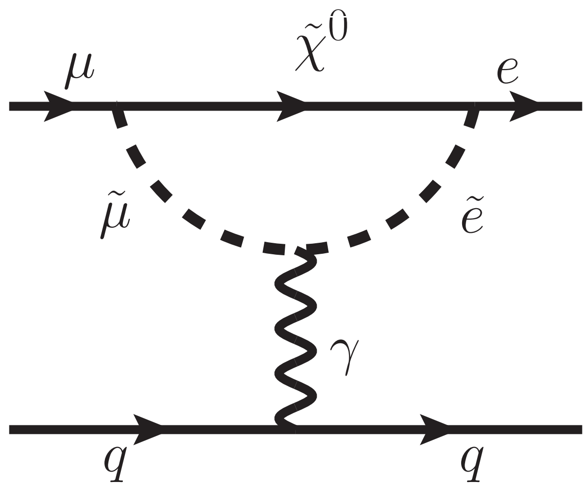
Muon-to-electron conversion

- Charged-lepton flavor violation highly suppressed in the Standard Model

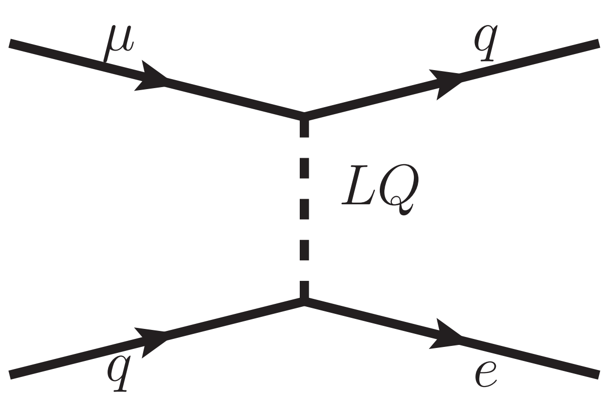
  ➡ Observation of CLFV would be unambiguous evidence of new physics

- Many new-physics models allow for CLFV and predict rates close to current limits

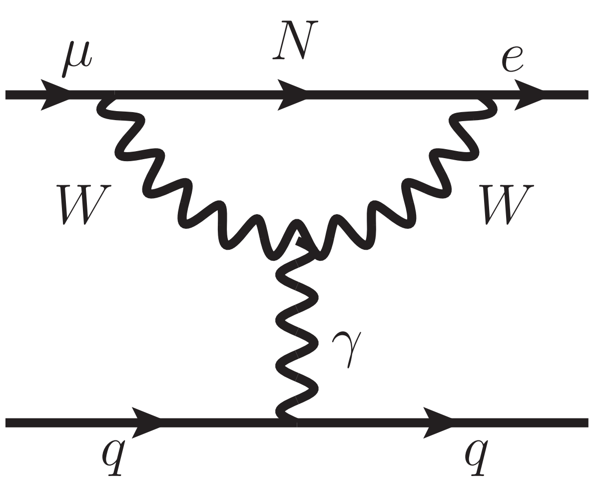
SUSY



LEPTOQUARKS



TYPE-I SEESAW



- **Mu2e Experiment @ Fermilab (with Project X)** aims to search for $\mu N \to eN$ with a sensitivity four orders of magnitude below the current best limit

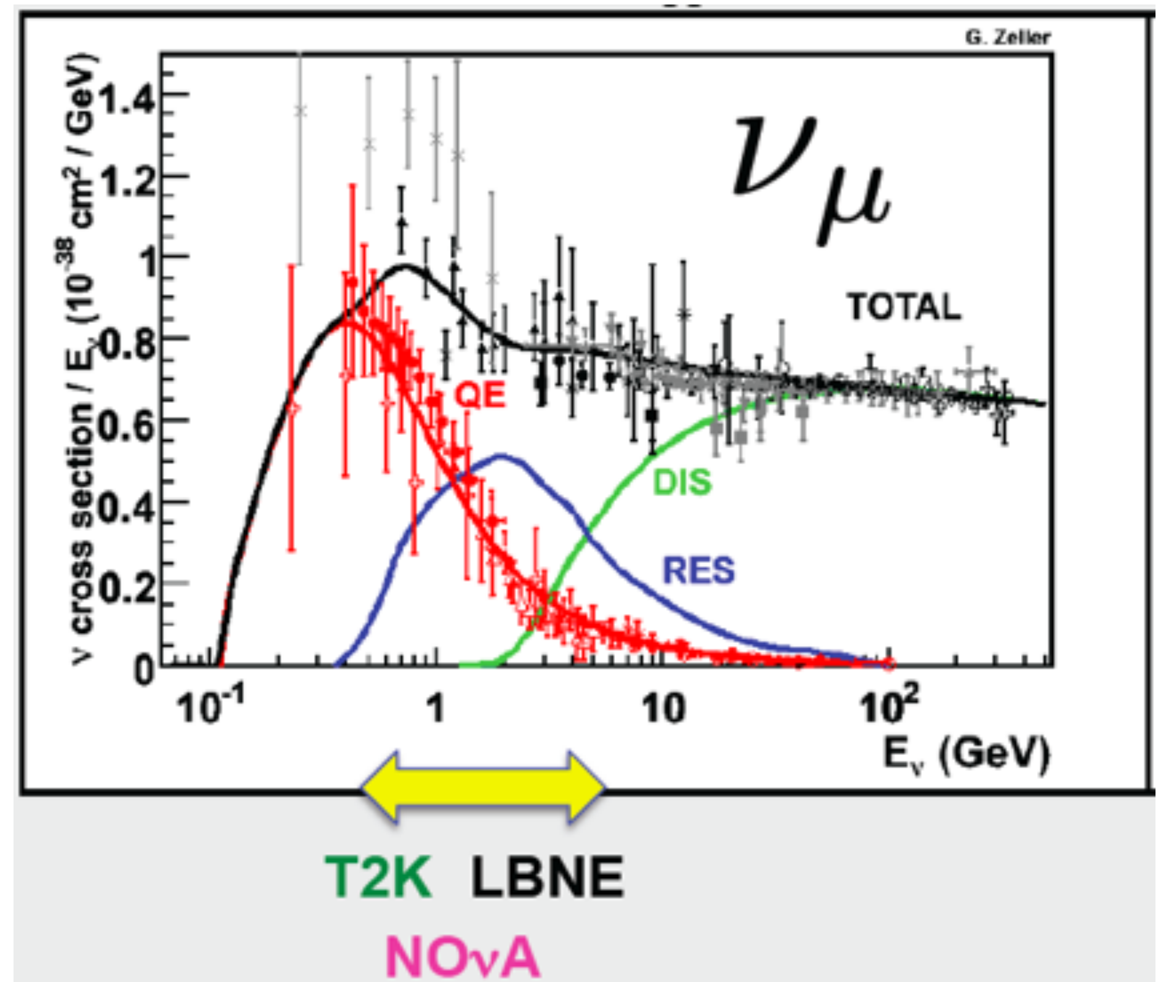
- **MEG@PSI** searching for $\mu \to e\gamma$, while **Mu3e** proposes improved search for $\mu \to eee$

- Combining measured rates of $\mu \to e\gamma$ and $\mu \to e$ conversion on different target nuclei can distinguish between models and reveal information on underlying theory

Neutrino physics

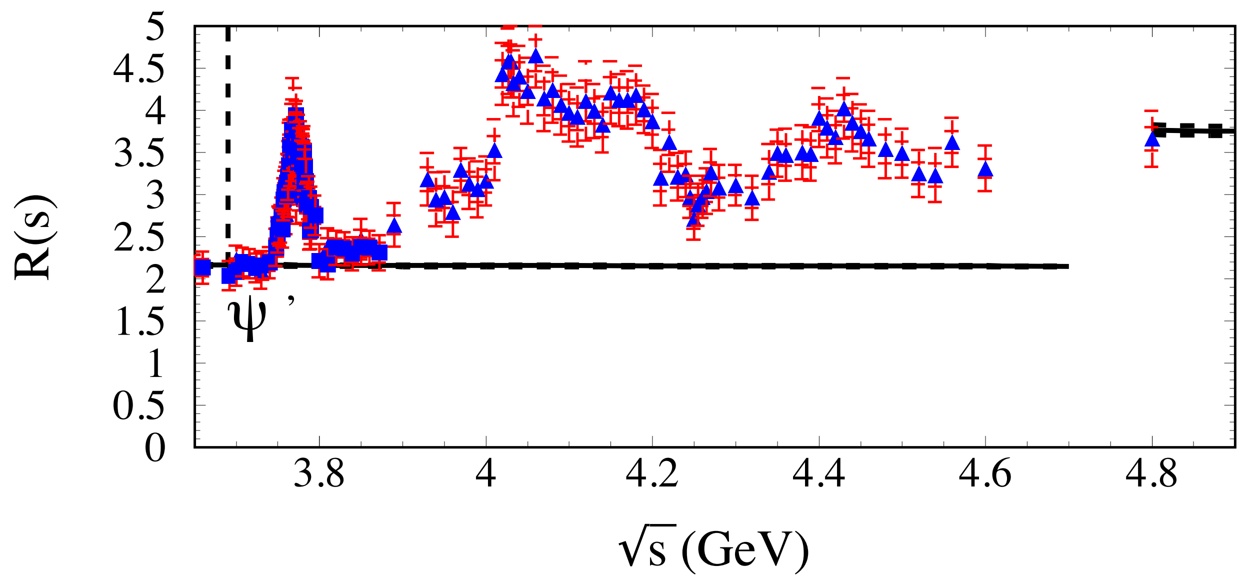
- **Understanding neutrino-nucleon scattering essential to determine the flux of incoming neutrinos and interpret experimental measurements**
  - Accelerator neutrino experiments are in the low-energy regime most complicated by the nuclear environment
  - Cross section for quasi-elastic $\nu_\mu n \to \mu p$ and $\nu_\mu p \to \mu n$ scattering is parameterized by hadronic form factors that can be computed from first principles with lattice QCD

[Formaggio & Zeller, RMP 84, 1307 - 1341, 2012]



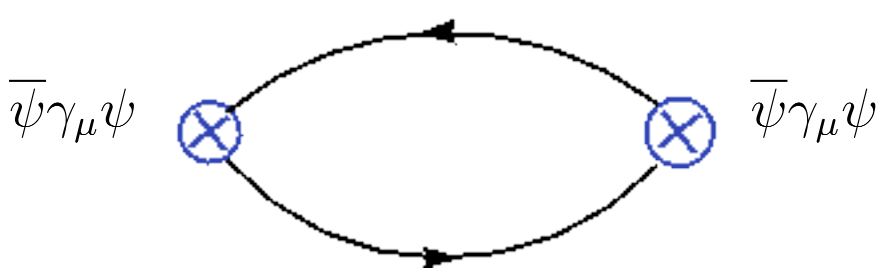
- **Observation of proton decay would be unambiguous evidence of new physics**
  - Lattice-QCD calculations of proton-decay matrix elements $\langle \pi, K, \eta, \ldots \mid O_{NP} \mid p \rangle$ essential to interpret limits on (or a measurement of) the proton lifetime as constraints on GUT models

$e+e- \longrightarrow m_c$



$$\mathcal{M}_n \equiv \int \frac{ds}{s^{n+1}} R_Q(s)$$

Moments of the heavy quark production cross section in e^+e^- annihilation can be related to the derivatives of the vacuum polarization at q^2=0.

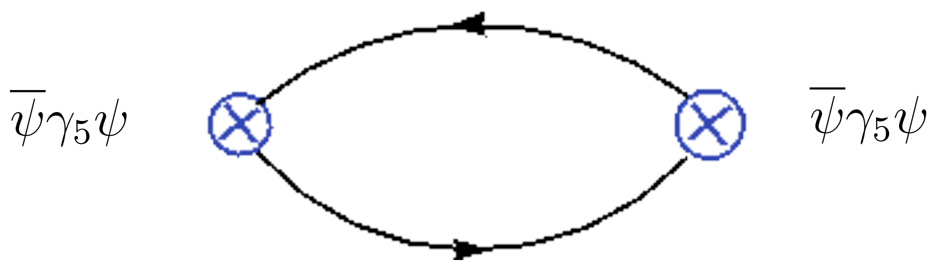


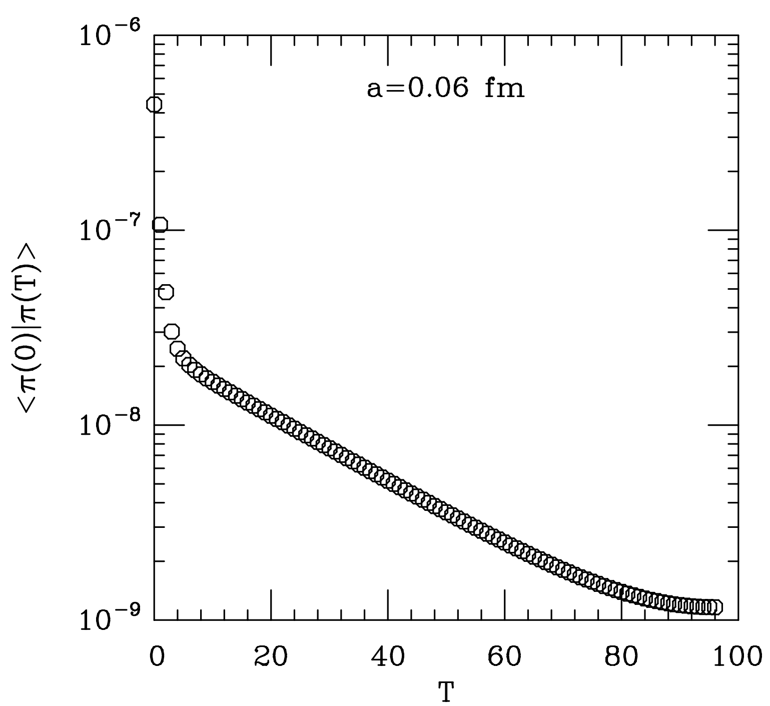
$$\mathcal{M}_n = \frac{12\pi^2}{n!}\left(\frac{d}{dq^2}\right)^n \Pi_Q(q^2)|_{q^2=0}$$

Can be calculated in perturbation theory.
Known to O(α_s^3) (Chetyrkin et. al.)

Lattice QCD

can also compute such correlation functions with high accuracy.





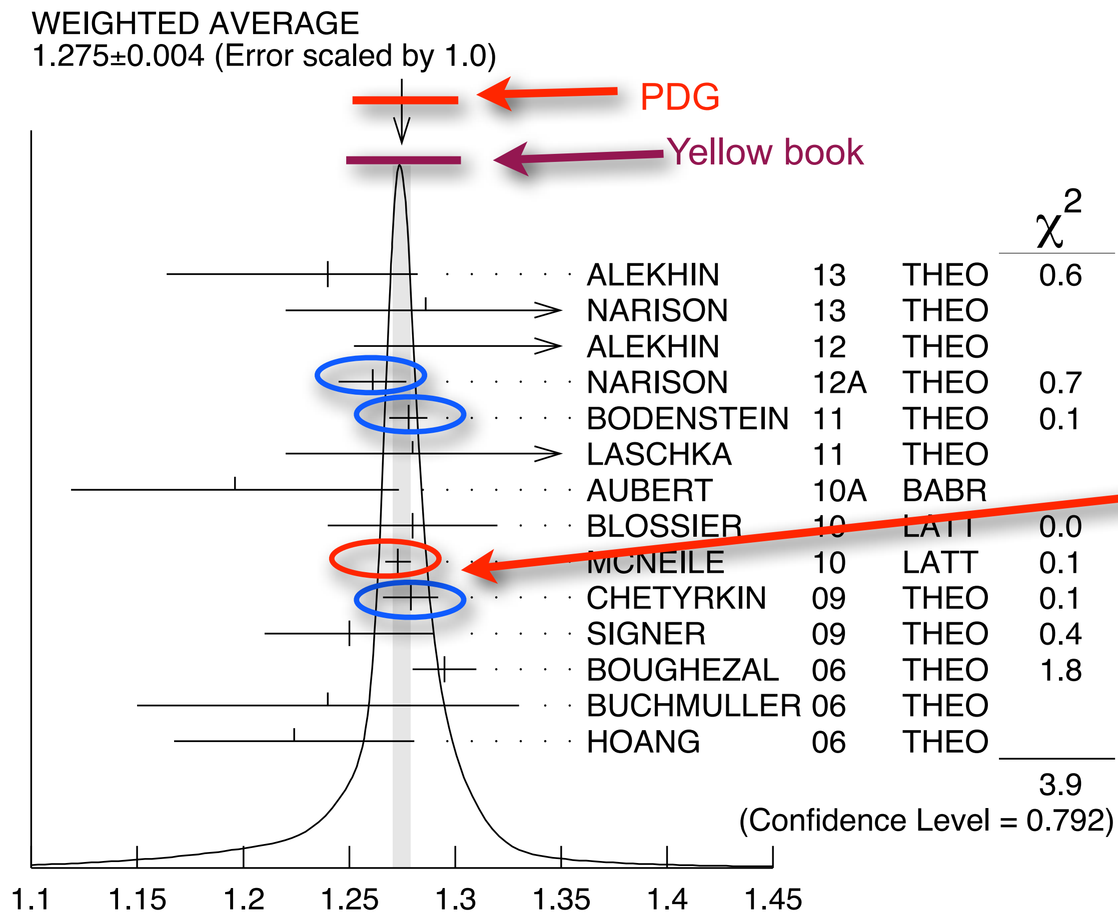
Correlation functions of all currents can be calculated in perturbation theory (and with the lattice). The most precise m_c can be obtained by choosing the one that is most precise on the lattice: the pseudoscalar correlator.

$$G(t) = a^6 \sum_{\mathbf{x}} (am_{0h})^2 \langle 0 | j_5(\mathbf{x}, t) j_5(0,0) | 0 \rangle,$$

$$G_n \equiv \sum_t (t/a)^n G(t),$$

Perturbation theory to $\alpha_s{}^3$ from the Karlsruhe group.

m_c results



PDG, Beringer et al., 2013.

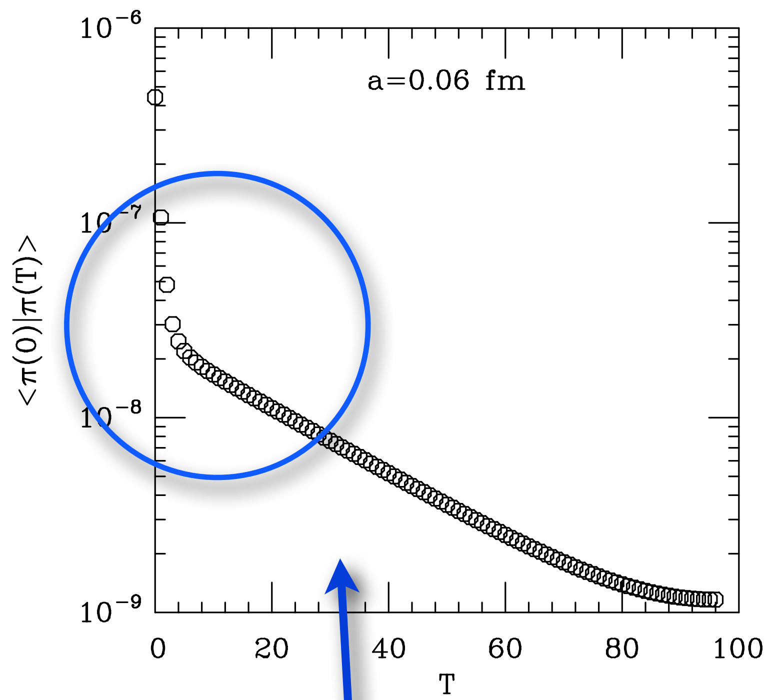
	$m_c(3)$
a^2 extrapolation	0.2%
Perturbation theory	0.5
Statistical errors	0.1
m_h extrapolation	0.1
Errors in r_1	0.2
Errors in r_1/a	0.1
Errors in m_{η_c}, m_{η_b}	0.2
α_0 prior	0.1
Gluon condensate	0.0
Total	0.6%

$$m_c(m_c, n_f = 4) = 1.273(6)\ \mathrm{GeV}$$

HPQCD, McNeile et al.

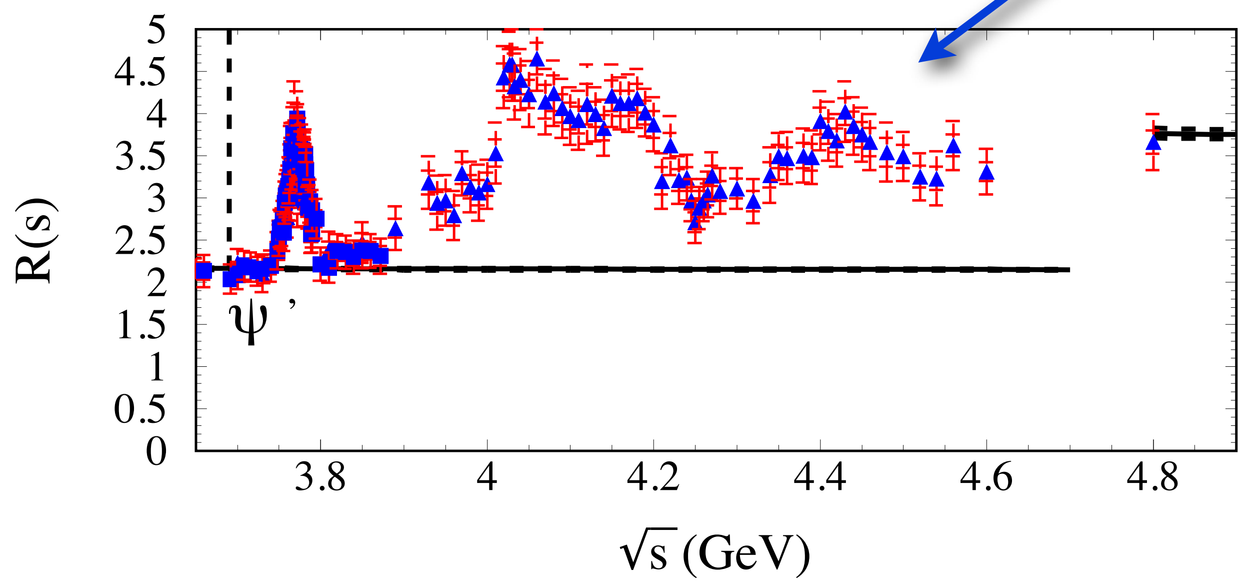
Uncertainty is dominated by the same perturbation theory used in all of the most precise results.

Why can lattice determinations of m_c from correlation functions be more precise than those from e^+e^-?

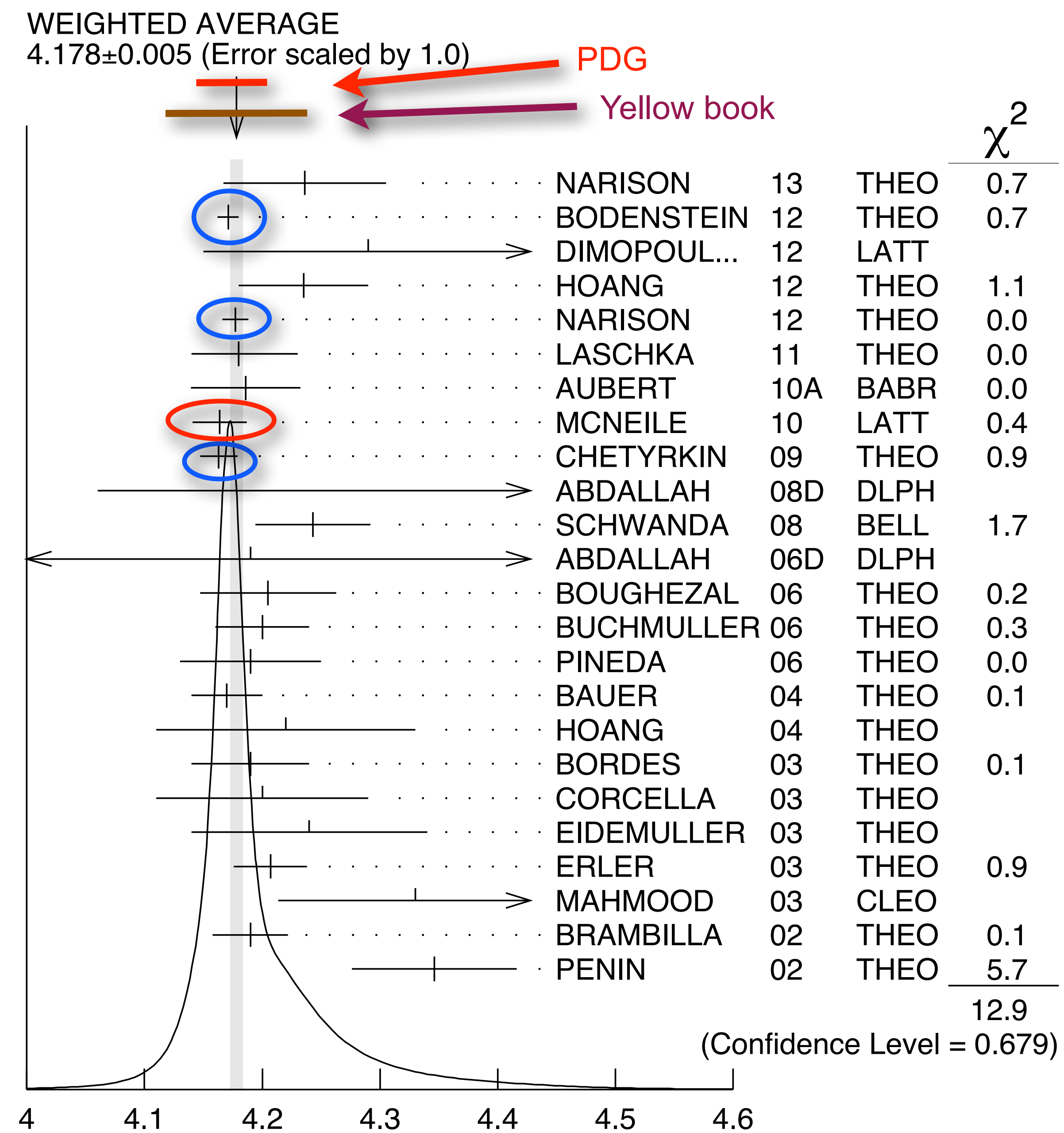


Moments of correlation functions are even easier than what I earlier told you have been considered the easiest quantities for the last ten years.
We need the correlation functions at finite *T*, and not their asymptotic form at large *T*.

Because this is cleaner data than this.



m_b



PDG, Beringer et al., 2013.

The most precise non-lattice determinations of m_c use e^+e^- annihilation data and ITEP sum rules. (Karlsruhe group, Chertyrkin et al.)

Recent lattice determination uses the same type of perturbation theory, but lattice QCD to supply the correlation functions rather than experiment.

For m_b, perturbative errors are tiny. $(\alpha(m_b)^4 << \alpha(m_c)^4.)$

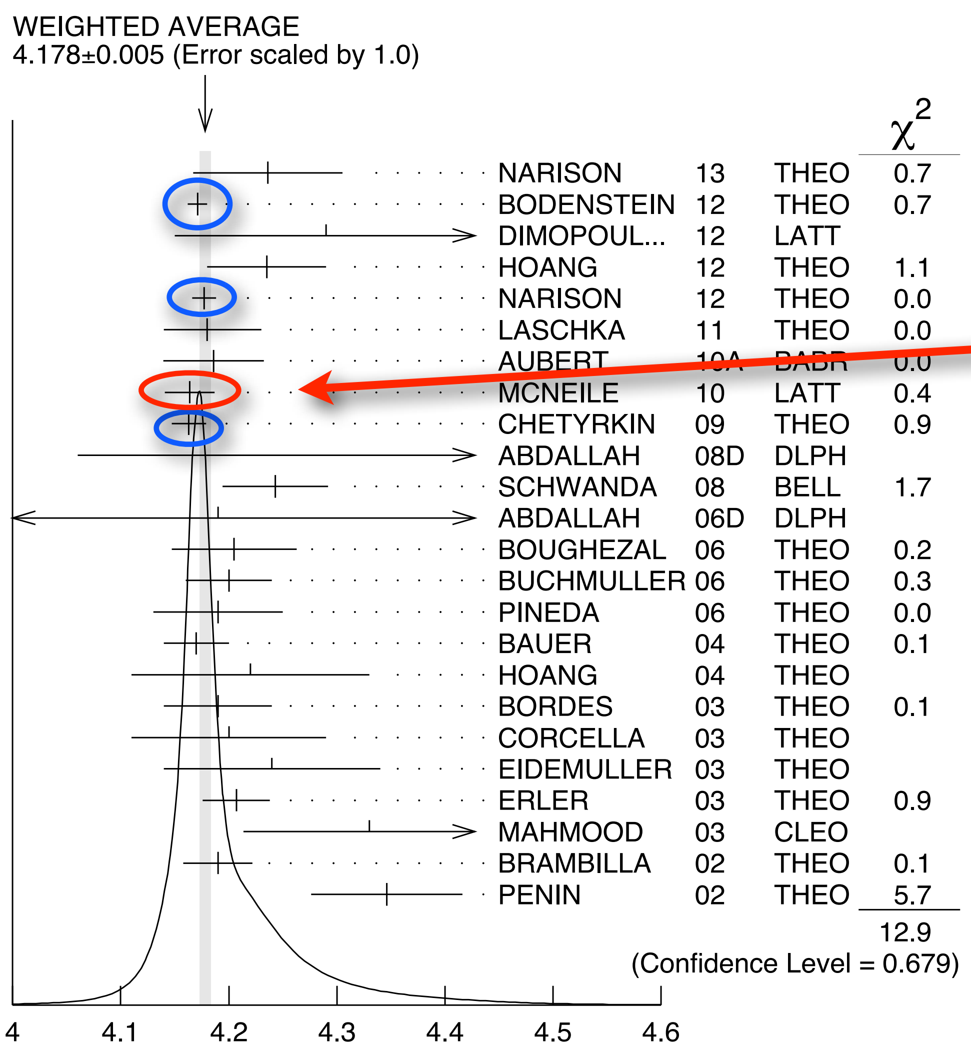
m_b results

For m_b, these lattice correlator methods are just barely working at a=0.045 fm. (They treat the b as light compared with $1/a$.)

Need a=0.03 fm to be comfortable.

Discretization errors and statistics dominate current uncertainties. Both can be attacked with brute force computing power.

Needed configurations are projected to be generated in the next few years.



	$m_b(10)$
a^2 extrapolation	0.6%
Perturbation theory	0.1
Statistical errors	0.3
m_h extrapolation	0.1
Errors in r_1	0.1
Errors in r_1/a	0.3
Errors in m_{η_c}, m_{η_b}	0.1
α_0 prior	0.1
Gluon condensate	0.0
Total	0.7%

$$m_b(m_b, n_f = 5) = 4.164(23)\ \text{GeV}$$

m_b results

For m_b, these lattice correlator methods are just barely working at a=0.045 fm. (They treat the b as light compared with 1/a.)
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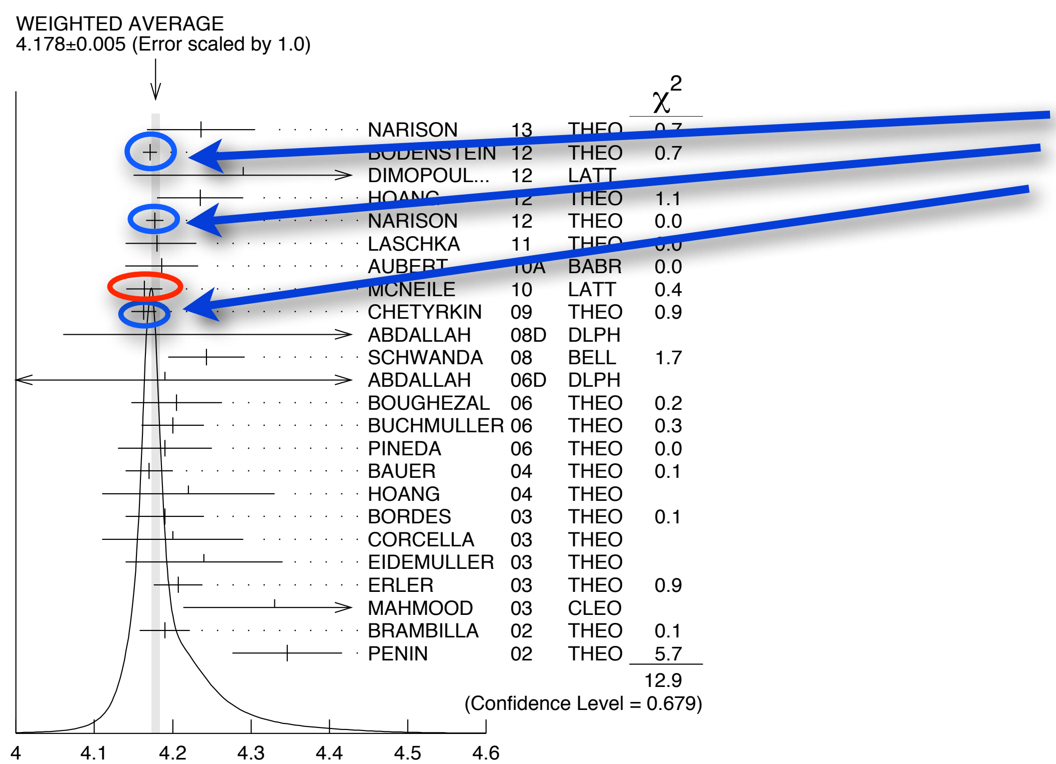
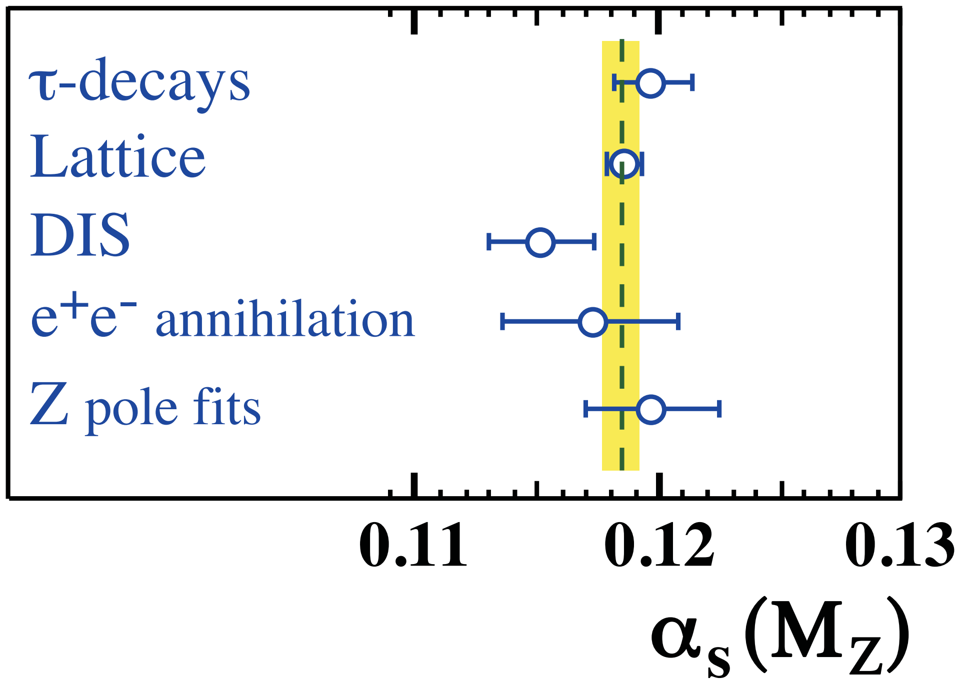


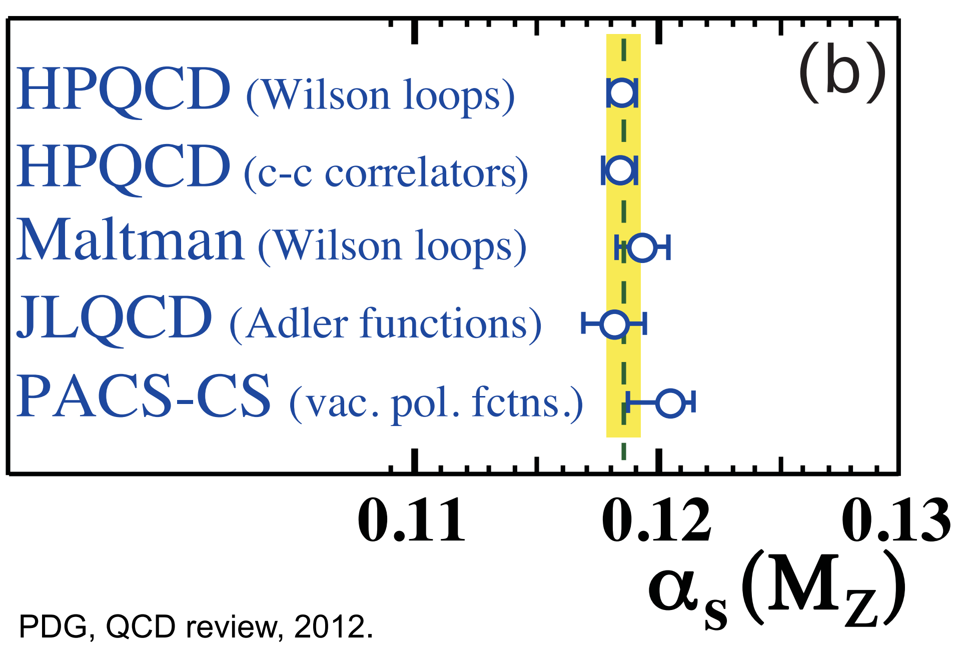
The three most precise determinations of mb using moments of e^+e^- data arrive at different estimates of the precision.

Coming lattice calculations should be able to confirm (or not) the more more precise claims.
Unlike m_c, where the lattice and e^+e^- determinations share the same perturbation theory, perturbative uncertainties are neglible and the lattice and e^+e^- determinations will have totally independent uncertainties.

α_s



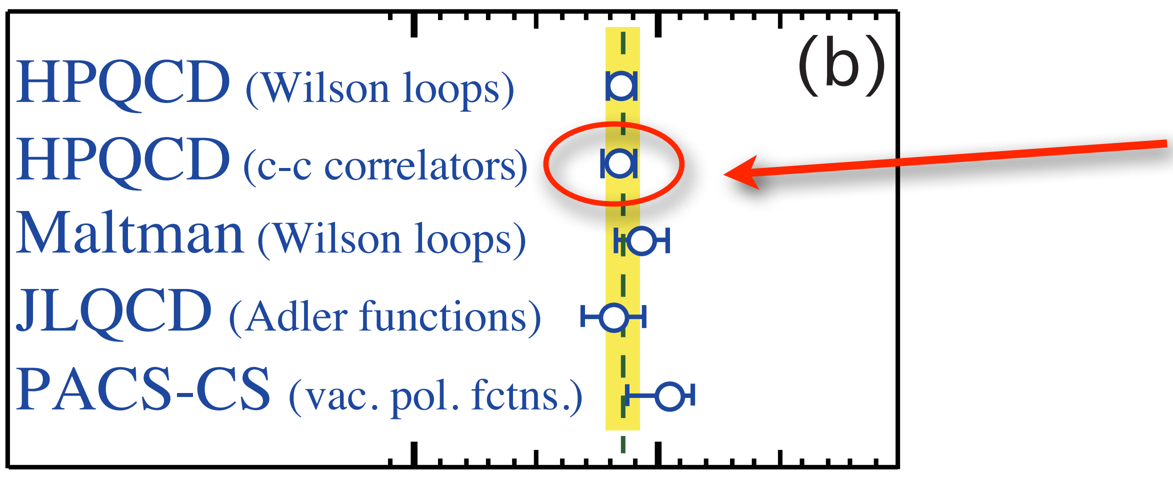
There are multiple ways of determining α_s, both with and without the lattice.



PDG, QCD review, 2012.

There are several lattice determinations equal to or more precise than all the non-lattice determinations together.

α_s results: correlator method

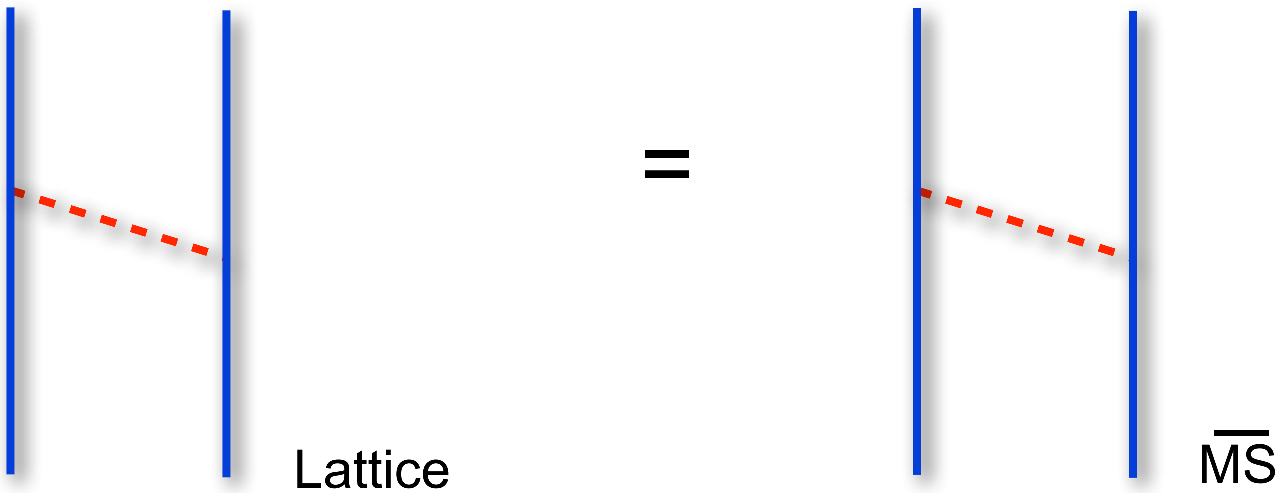


	$\alpha_{\overline{\mathrm{MS}}}(M_Z)$
a^2 extrapolation	0.2%
Perturbation theory	0.4
Statistical errors	0.2
m_h extrapolation	0.0
Errors in r_1	0.1
Errors in r_1/a	0.1
Errors in m_{η_c}, m_{η_b}	0.0
α_0 prior	0.1
Gluon condensate	0.2
Total	0.6%

Results are dominated by perturbation theory. May by hard to improve without next term in perturbation theory.

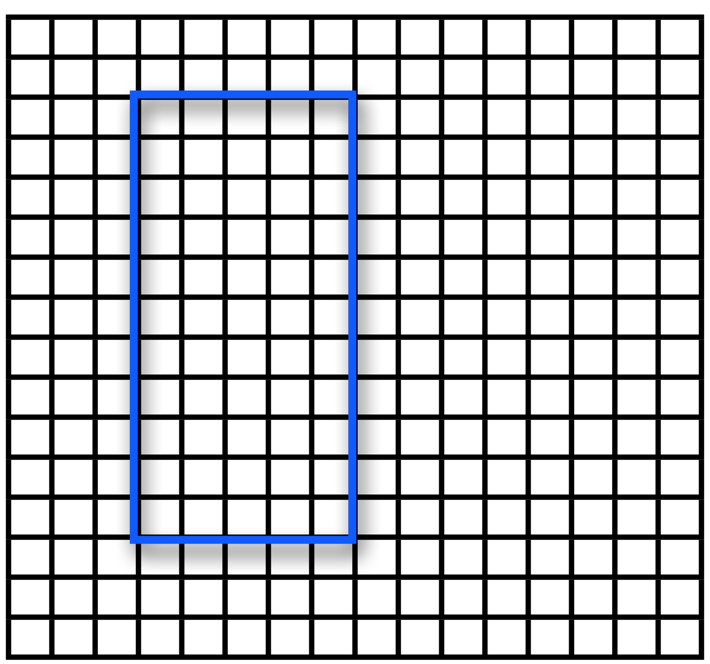
α_s results: Wilson loops

α_s can be determined with lattice calculations of many other quantities, e.g., the heavy quark potential.



to obtain α_s $\overline{MS}$.

Lattice calculates the heavy quark potential from Wilson loops.



HPQCD has determined α_s directly from Wilson loops.

Result compatible with their correlator result, similar precision:
$\alpha_s = 0.1184(6)$, but
totally different uncertainties, heavy use of lattice perturbation theory.

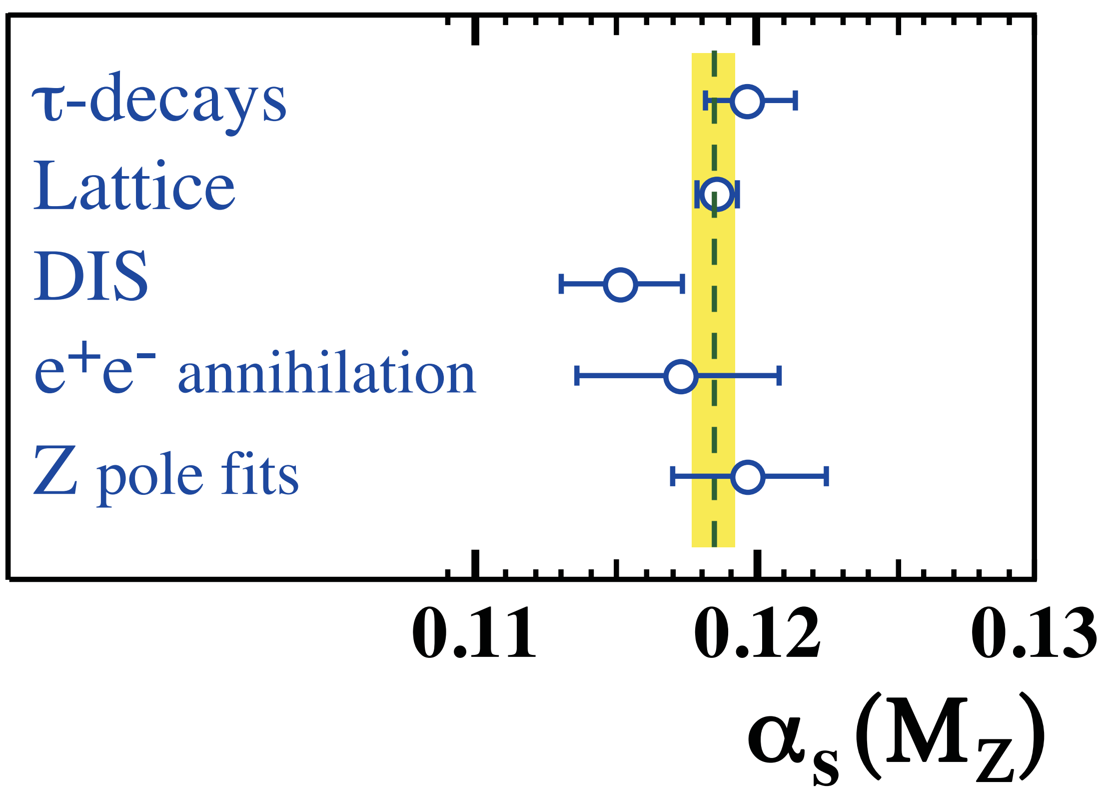
α_s, other lattice results

There are numerous good ways of determining α_s using lattice QCD.

- The Adler function, JLQCD. Phys.Rev. D82 (2010) 074505.
  - $\alpha_s = 0.1181 \pm 0.0003{+}0.0014{-}0.0012$
- The Schrödinger functional, PACS-CS. JHEP 0910:053,2009.
  - $\alpha_s = 0.1205(8)(5)(+0/-17)$
- The ghost-gluon vertex, European Twisted Mass Collaboration (ETM). Phys.Rev.Lett. 108 (2012) 262002.
  - $\alpha_s = 0.1200(14)$

PDG

2012, combined the lattice numbers in a weighted average.
It takes a combined error of the most precise of the inputs.



PDG

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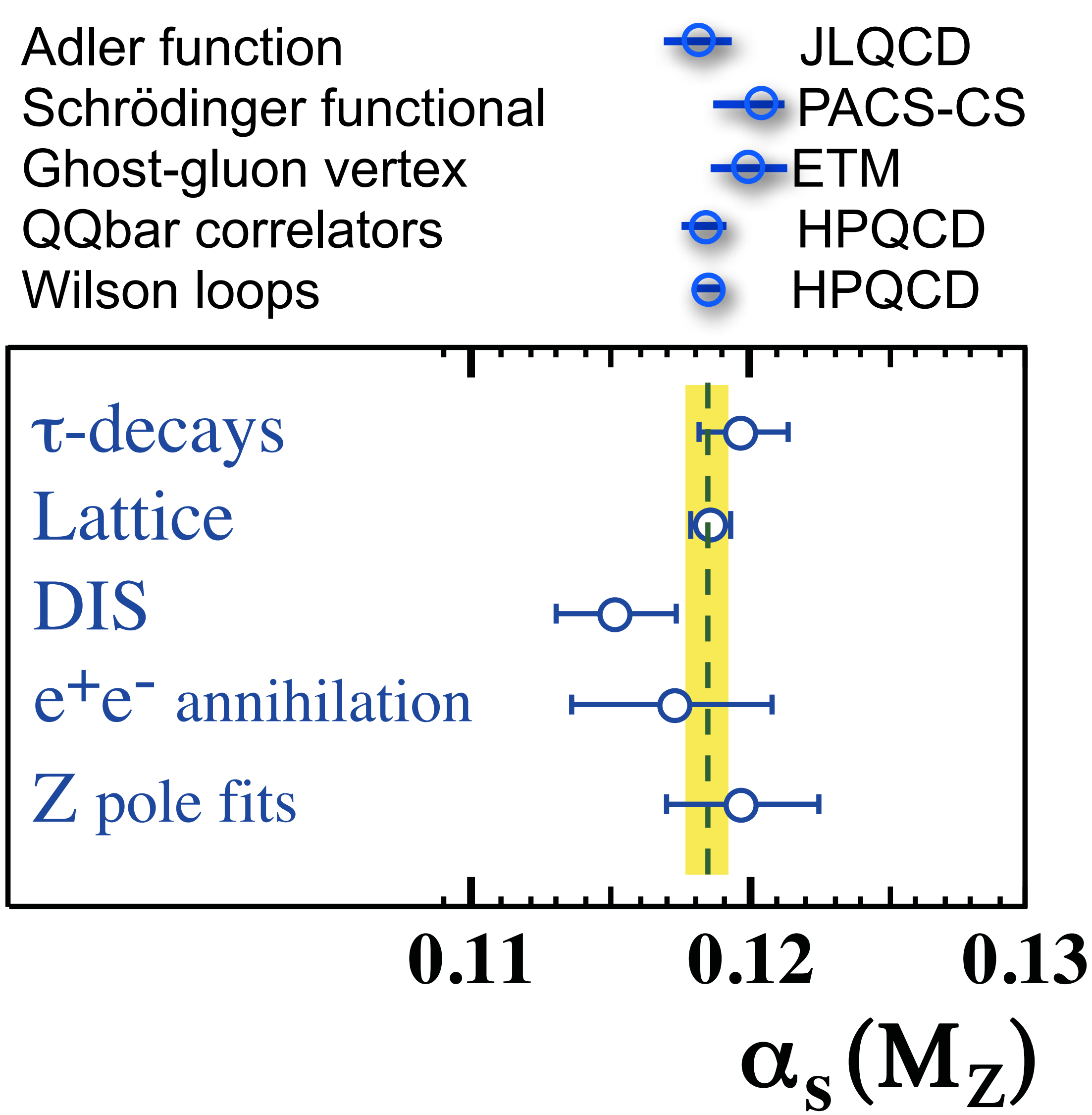

The lattice results (2013) are dominated by the two most precise results from HPQCD, but there are several other lattice results from Europe and Japan, all of which agree with each other and each which is more precise than any non-lattice result.