Lattice QCD

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Aim of this talk

- Provide a survey of results about QCD that aid the interpretation of experiments or observations in
  - particle physics,
  - nuclear physics (mostly with connections to the other two),
  - astrophysics.
- These results have all been obtained using numerical lattice gauge theory.
- Can only scratch the surface with topics that are really neat, or where I'm an (supposed to be) expert.

Big Questions ↔ Specific Questions

- Where are the sources of CP violation beyond CKM?
  - How does a b quark decay when inside a B meson?
- Do Higgs boson decays deviate from the Standard Model?
  - What are the SM parameters needed to predict Higgs BRs?
- How do refine neutrino mixing parameters?
  - How well do we know neutrino-nucleus cross sections?
- What limits can be set from dark-matter detectors?
  - How well do we know WIMP-nucleus cross sections?

LATTICE GAUGE THEORY FOR BEGINNERS

The QCD Lagrangian

- SU(3) gauge symmetry and $1 + n_f + 1$ parameters:

$$\begin{aligned}\mathcal{L}_{\text{QCD}} &= \frac{1}{g_0^2}\,\text{tr}[F_{\mu\nu}F^{\mu\nu}] \\ &\quad - \sum_f \bar{\psi}_f(\not{D} + m_f)\psi_f \\ &\quad + \frac{i\theta}{32\pi^2}\varepsilon^{\mu\nu\rho\sigma}\,\text{tr}[F_{\mu\nu}F_{\rho\sigma}]\end{aligned}$$

- Observable CP violation $\propto \theta = \vartheta - \arg\det y_f$ (if all Yukawas nonvanishing):
  - neutron electric-dipole moment sets limit $\theta \lesssim 10^{-11}$;
  - bafflingly implausible cancellation called the strong CP problem.

The QCD Lagrangian

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$$\mathcal{L}_{\rm QCD} = \frac{1}{g_0^2}\,{\rm tr}[F_{\mu\nu}F^{\mu\nu}] \qquad m_\Omega,\ \Upsilon(2S\text{-}1S),\ \text{or}\ r_1,\ w_0,\ldots.$$

$$- \sum_f \bar\psi_f(\not D + m_f)\psi_f \qquad m_\pi,\ m_K,\ m_{J/\psi},\ m_\Upsilon,\ \ldots.$$

$$+ \frac{i\theta}{32\pi^2}\varepsilon^{\mu\nu\rho\sigma}\,{\rm tr}[F_{\mu\nu}F_{\rho\sigma}] \qquad \theta = 0.$$

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  - neutron electric-dipole moment sets limit $\theta \lesssim 10^{-11}$;
  - bafflingly implausible cancellation called the strong CP problem.

Lattice Gauge Theory

K. Wilson, *PRD* **10** (1974) 2445

- Invented to understand asymptotic freedom without the need for gauge-fixing and ghosts [Wilson, hep-lat/0412043].

- Gauge symmetry on a spacetime lattice:

  - mathematically rigorous definition of QCD functional integrals;

$$\langle \bullet \rangle = \frac{1}{Z} \int \mathcal{D}U \mathcal{D}\psi \mathcal{D}\bar{\psi} \exp\left(-S\right) [\bullet]$$

  - enables theoretical tools of statistical mechanics in quantum field theory and provides a basis for constructive field theory.

- Discrete space (a la Heisenberg & Pauli) and discrete time (a la Feynman).

Numerical Lattice QCD

- Nowadays “lattice QCD” usually implies a numerical technique, in which the functional integral is integrated numerically on a computer.

- Big computers:

- Some compromises:

  - finite human lifetime ⇒ Wick rotate to Euclidean time: $x^4 = ix^0$;

  - finite memory ⇒ finite space volume & finite time extent;

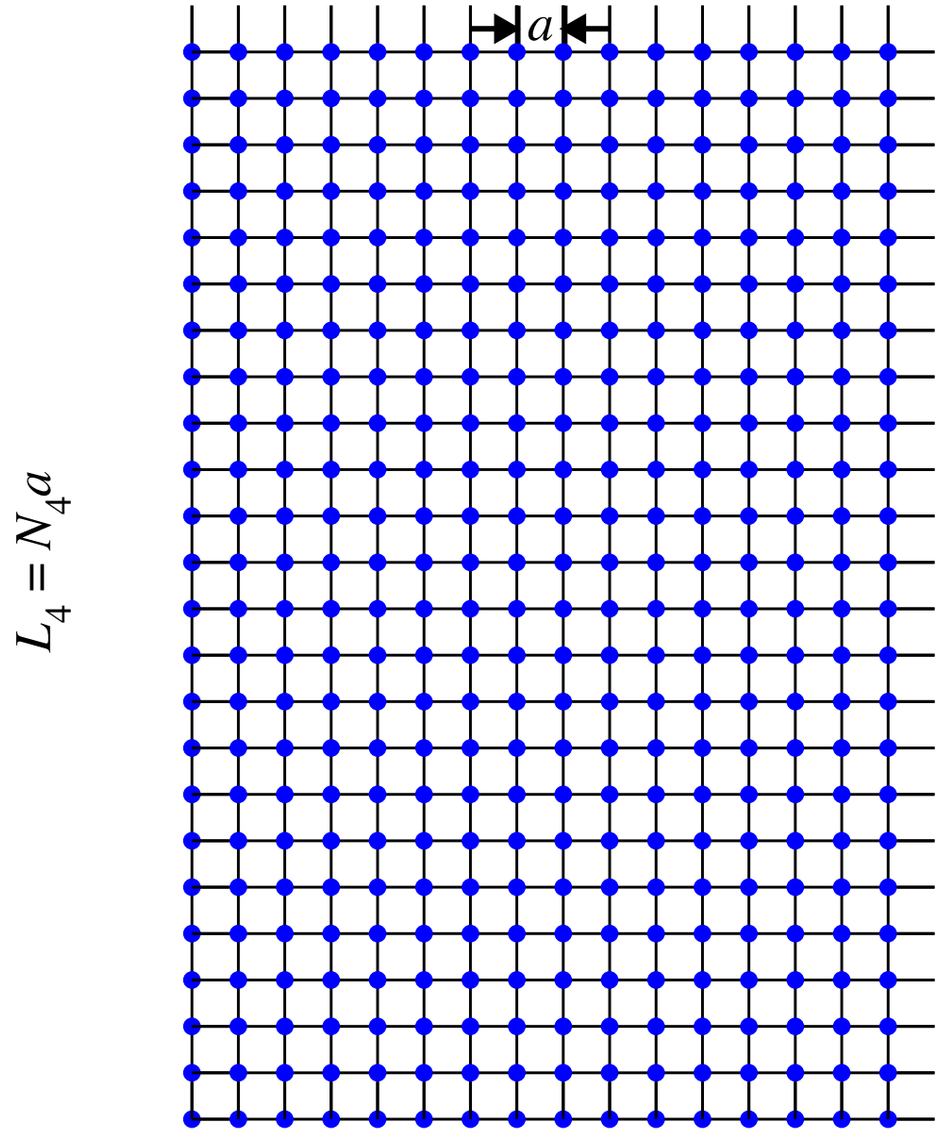
  - finite CPU power ⇒ light quarks until recently heavier than up and down.

Lattice Gauge Theory

$$\langle \bullet \rangle = \frac{1}{Z} \int \mathcal{D}U \mathcal{D}\psi \mathcal{D}\bar{\psi} \exp\left(-S\right) [\bullet]$$

$$= \frac{1}{Z} \int \mathcal{D}U \ \mathrm{Det}(\not{D} + m) \exp\left(-S_{\mathrm{gauge}}\right) [\bullet']$$

- Infinite continuum: uncountably many d.o.f. (⇒ UV divergences);
- Infinite lattice: countably many; used to define QFT;
- Finite lattice: finite dimension ~ 10^8, so compute integrals numerically.



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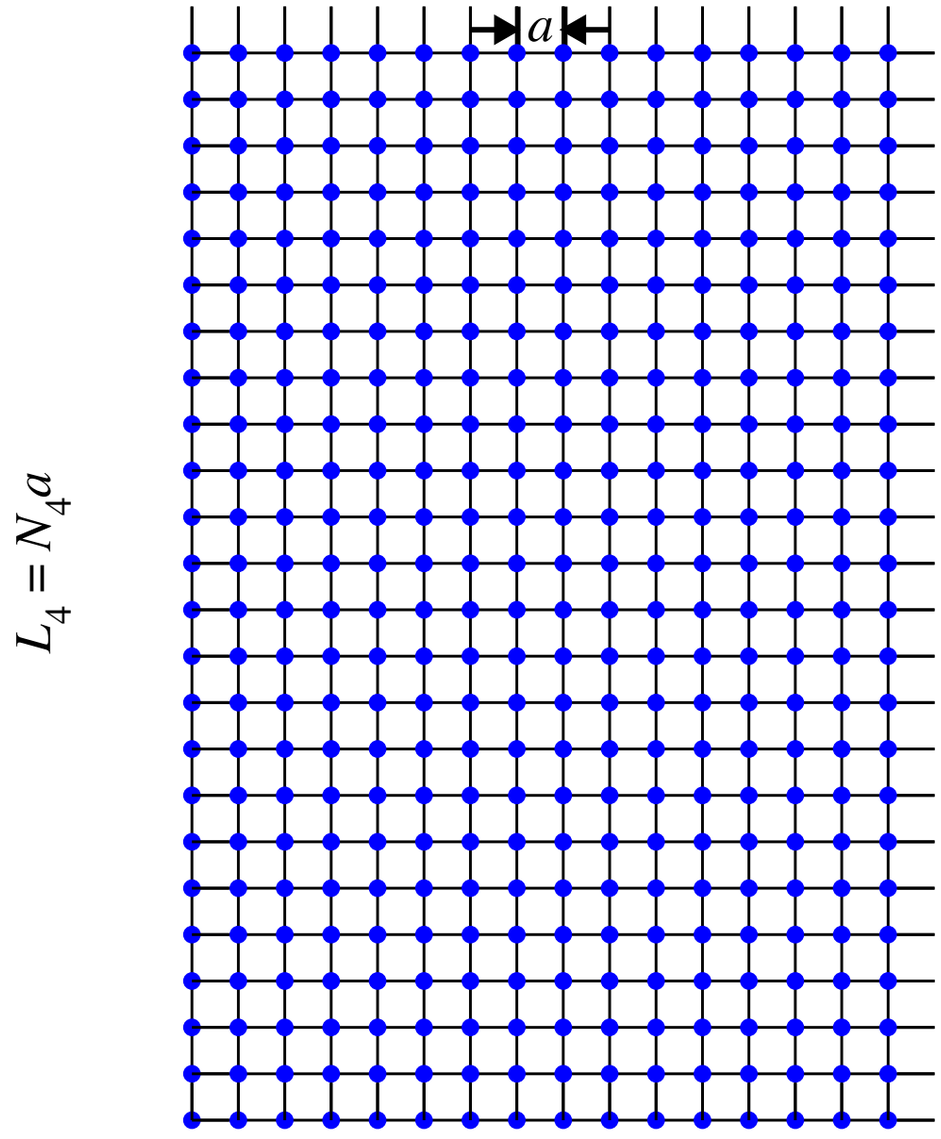

Lattice Gauge Theory

$$\langle \bullet \rangle = \frac{1}{Z} \int \underbrace{\mathcal{D}U}_{\text{MC}} \underbrace{\mathcal{D}\psi \mathcal{D}\bar{\psi}}_{\text{hand}} \exp\left(-S\right) [\bullet]$$

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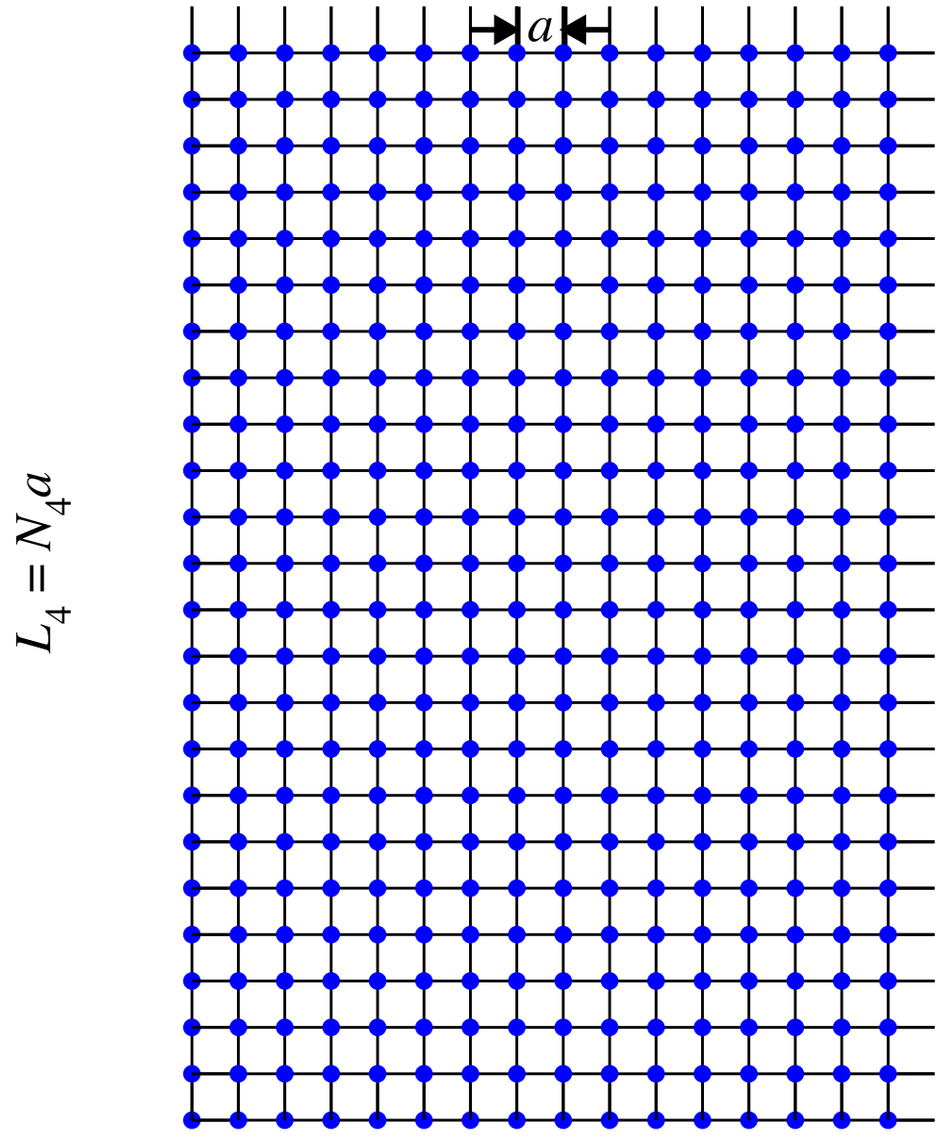


- Computationally most demanding part of lattice QCD is $\mathrm{Det}(\not{D} + m)$, which corresponds to the sea quarks.

- First watershed of this century was to include the light sea exactly.

- Nowadays need only to discuss (in fora like this) results with

  - $n_f = 2{+}1$: strange sea + 2 as light as possible for up and down;

  - $n_f = 2{+}1{+}1$: add charmed sea to $2{+}1$.

- In recent (and, hence, coming) years, "as light as possible for up and down" means "as light as up and down in Nature".

- Second watershed of this century.

Correlators Yield Masses & Matrix Elements

- Two-point functions for masses $\pi(t) = \bar{\psi}_u \gamma_5 S \psi_d$:

$$\langle \pi(t)\pi^\dagger(0)\rangle = \sum_n |\langle 0|\hat{\pi}|\pi_n\rangle|^2 \exp(-m_{\pi_n} t)$$

- Two-point functions for decay constants:

$$\langle J(t)\pi^\dagger(0)\rangle = \sum_n \langle 0|\hat{J}|\pi_n\rangle \langle \pi_n|\hat{\pi}^\dagger|0\rangle \exp(-m_{\pi_n} t)$$

- Three-point functions for form factors, mixing:

$$\langle \pi(t)J(u)B^\dagger(0)\rangle = \sum_{mn} \langle 0|\hat{\pi}|\pi_m\rangle \langle \pi_n|\hat{J}|B_m\rangle \langle B_m|\hat{B}^\dagger|0\rangle \times \exp[-m_{\pi_n}(t-u) - m_{B_m} u]$$

- LHS needs supercomputers; RHS needs students, postdocs, junior faculty.

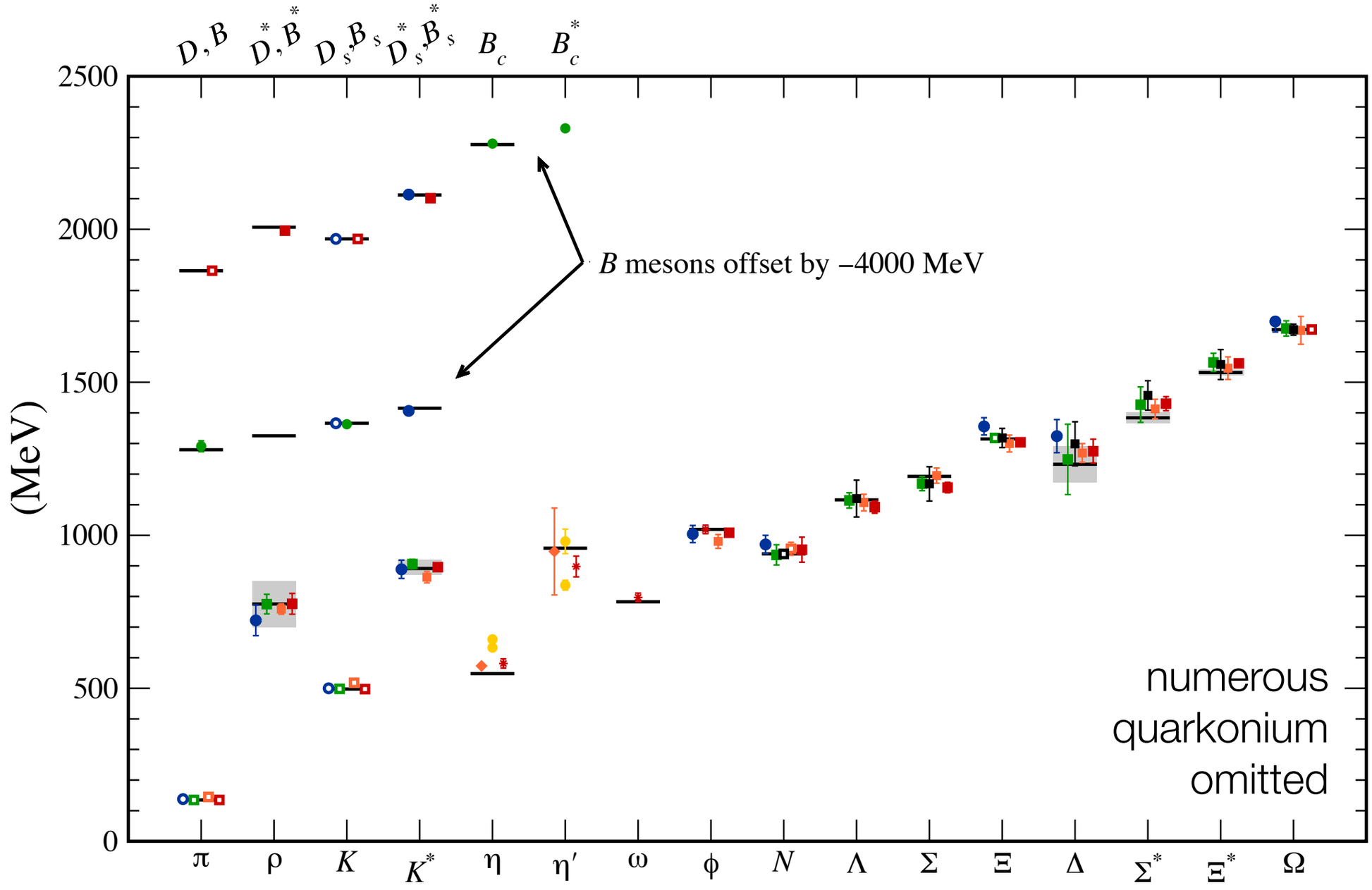
Masses in QCD: Hadrons and Quarks

Why Compute Hadron Masses?

- Show that the QCD Lagrangian generates hadron masses.
- Understand more deeply the only known mechanism for generating masses.
- Inherently quantum mechanical:
  - classical chromodynamics with massless quarks is scale invariant;
  - scale Λ_{QCD} in running coupling arises from loops, *i.e.*, quantum effects.
- Hadron masses are then $M_h = \Lambda_{\mathrm{QCD}} \mathscr{Y}_h, \quad h =$ any hadron but pion;
  $M_\pi^2 = m_q \Lambda_{\mathrm{QCD}} \mathscr{Y}_\pi$, as a pseudo-Goldstone boson.

QCD Hadron Spectrum

$\pi \ldots \Omega$: BMW, MILC, PACS-CS, QCDSF; ETM (2+1+1);
η-η': RBC, UKQCD, Hadron Spectrum (ω);
D, B: Fermilab, HPQCD, Mohler&Woloshyn



Chiral Symmetry

Y. Nambu, *PRL* **4** (1960) 380

- The hadron spectrum has a striking feature:
  - $m_\pi = 135$ MeV but $m_\varrho = 770$ MeV, $m_\mathrm{p} = 938$ MeV, *etc*.
- Nambu applied lessons from superconductivity, noting (4 years before quarks) that the pion's small mass could obtain from a *spontaneously* broken *axial* symmetry (moderated with a small amount of explicit breaking).
- QCD explained the origin: if up and down quark masses are neglected, the Lagrangian has an $SU_L(2)\times SU_R(2)$ chiral symmetry, which provides candidate axial symmetry.
- (BTW, pions break $SU_L(2)\times U_Y(1)$: without terascale EWSB, $W^\pm$ and Z would eat the pions and have masses around 100 MeV; in nature, ~0.1% mixing.)

- In the 20th century, we were already confident that QCD was a good theory of the strong interactions, based on, *e.g.*, its explanation of the SLAC deep-inelastic scattering experiments.

- Because QCD was (considered) right, and since Nambu's picture was (considered) right, it was believed that QCD must drive spontaneous chiral symmetry breaking.

- Goldstone formula: $m_\pi^2 \langle \bar{\psi}\psi \rangle = 0$, if $\langle \bar{\psi}\psi \rangle \neq 0$, then $m_\pi = 0$.

- Explicit calculation from QCD Lagrangian (using lattice gauge theory):

$$\langle \bar{\psi}\psi \rangle^{\overline{\rm MS}}(2\ {\rm GeV}) = \left[234 \pm 4_{\rm stat} \pm 17_{\rm syst}\ {\rm MeV}\right]^3$$

[from H. Fukaya et al. [JLQCD], *PRD* **83** (2011) 074501].

Light Quark Masses

- The nonzero pion (kaon) mass is very sensitive to the light (strange) masses.

- Chiral perturbation theory predicts ratios of masses, but not the overall scale.

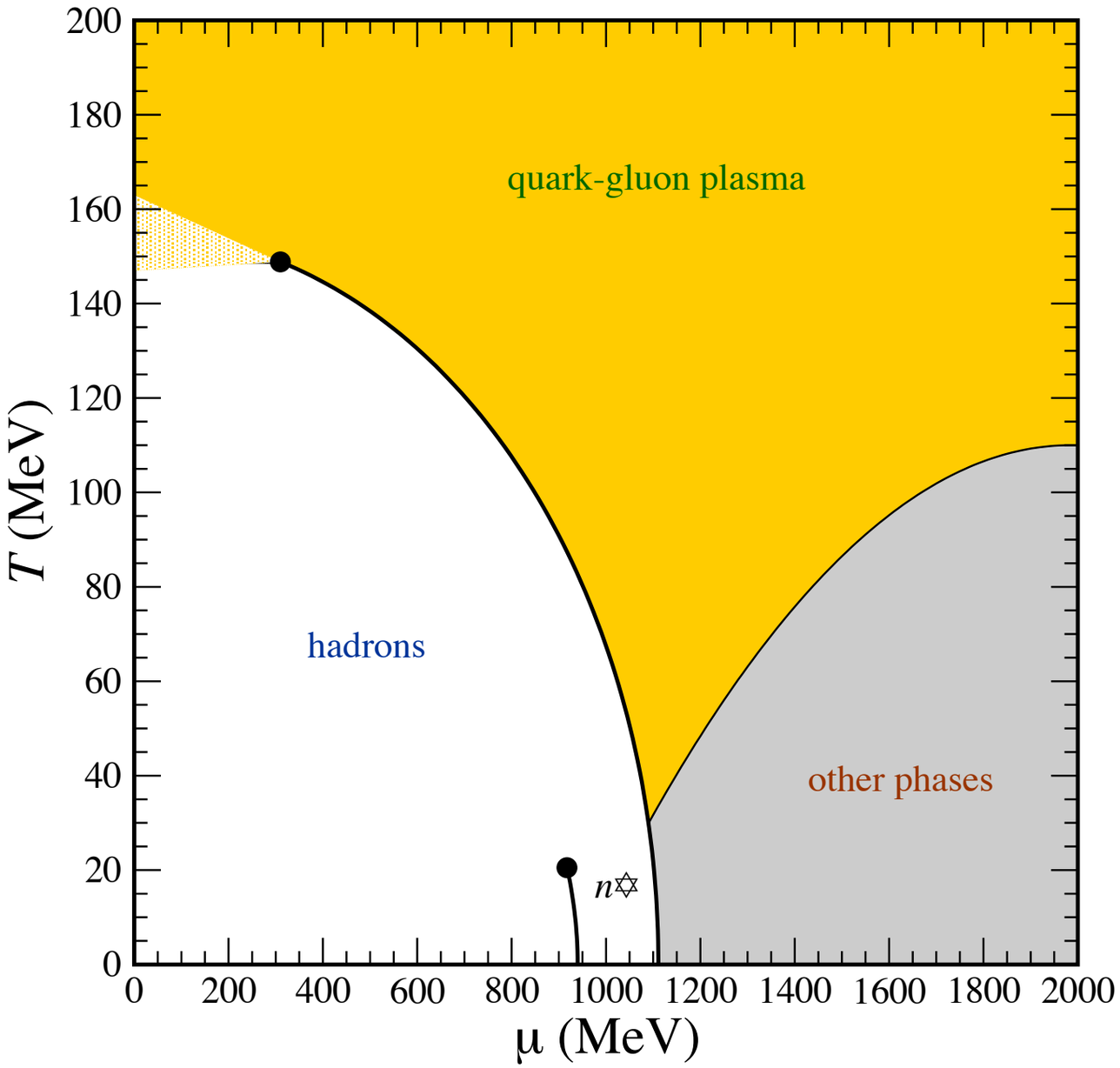
Lattice QCD	MILC	RBC	BMW	HPQCD
$\overline{m}_u(2\ \mathrm{MeV})$	1.9 ± 0.2	2.24 ± 0.35	2.15 ± 0.11	2.01 ± 0.14
$\overline{m}_d(2\ \mathrm{MeV})$	4.6 ± 0.3	4.65 ± 0.35	4.79 ± 0.14	4.79 ± 0.16
$\overline{m}_s(2\ \mathrm{MeV})$	88 ± 5	97.6 ± 6.2	95.5 ± 1.9	92.4 ± 1.5

- These are small—up & down masses are ~4 & ~9 times electron mass.

Thermodynamics and the Quark Masses

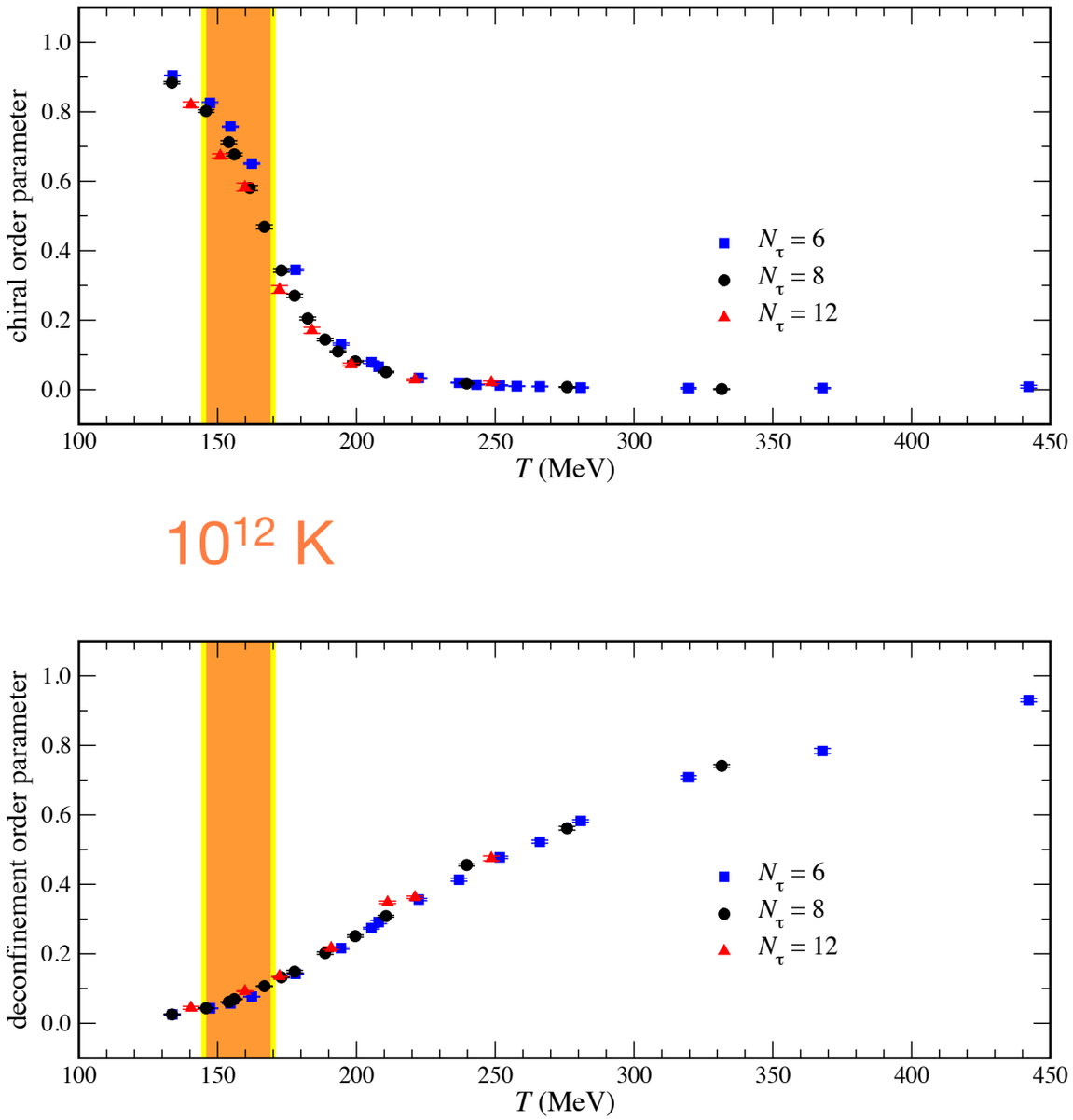
QCD Phase Diagram

- 20th century conventional wisdom: first order PT at $\mu = 0$.
- Why? Chiral symmetry says so.
- Consequence: bubbles of hadrons formed as the universe cooled.



QCD Phase Transition ($\mu = 0$)

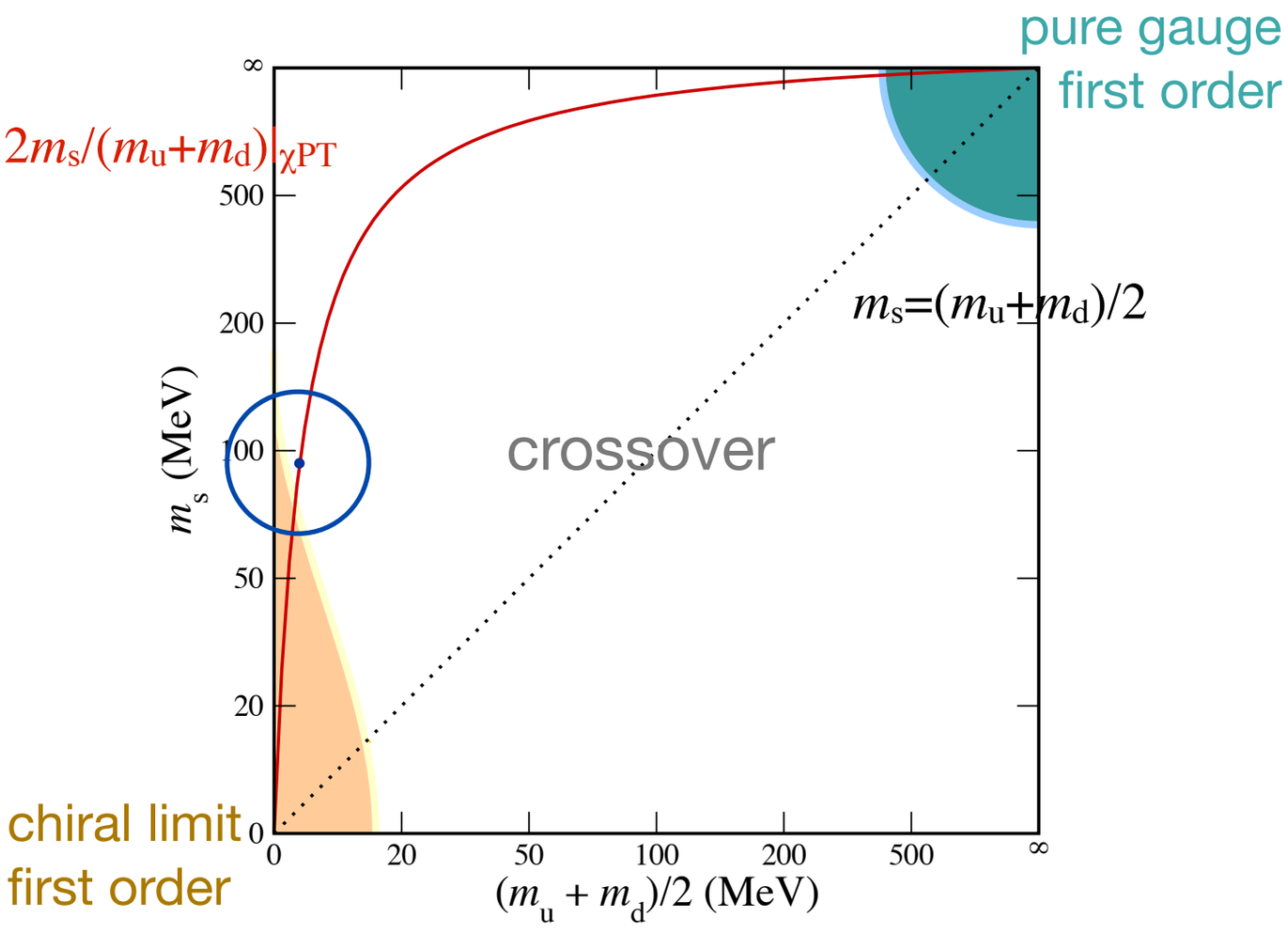
Y. Aoki *et al*. *Nature* **443** (2006) 675; A. Bazavov *et al.*, *PRD* **85** (2012) 054503



10^{12} K

- Temperature $T = 1/N_\tau a$.
- Smooth crossover to phase, in which the canonical average becomes:
  - chirally symmetric;
  - deconfined.
- Same transition temperature: also for other observables, *e.g.,* susceptibilities peak.

Quark Masses are Key



after de Forcrand & Philipsen
arXiv:0808.1096

- Explicit χSB softens the transition.
- Quark masses are small, but ...
- ... if even smaller, the $\mu = 0$ transition would be second order, or even first order.
- Implications for the early universe.

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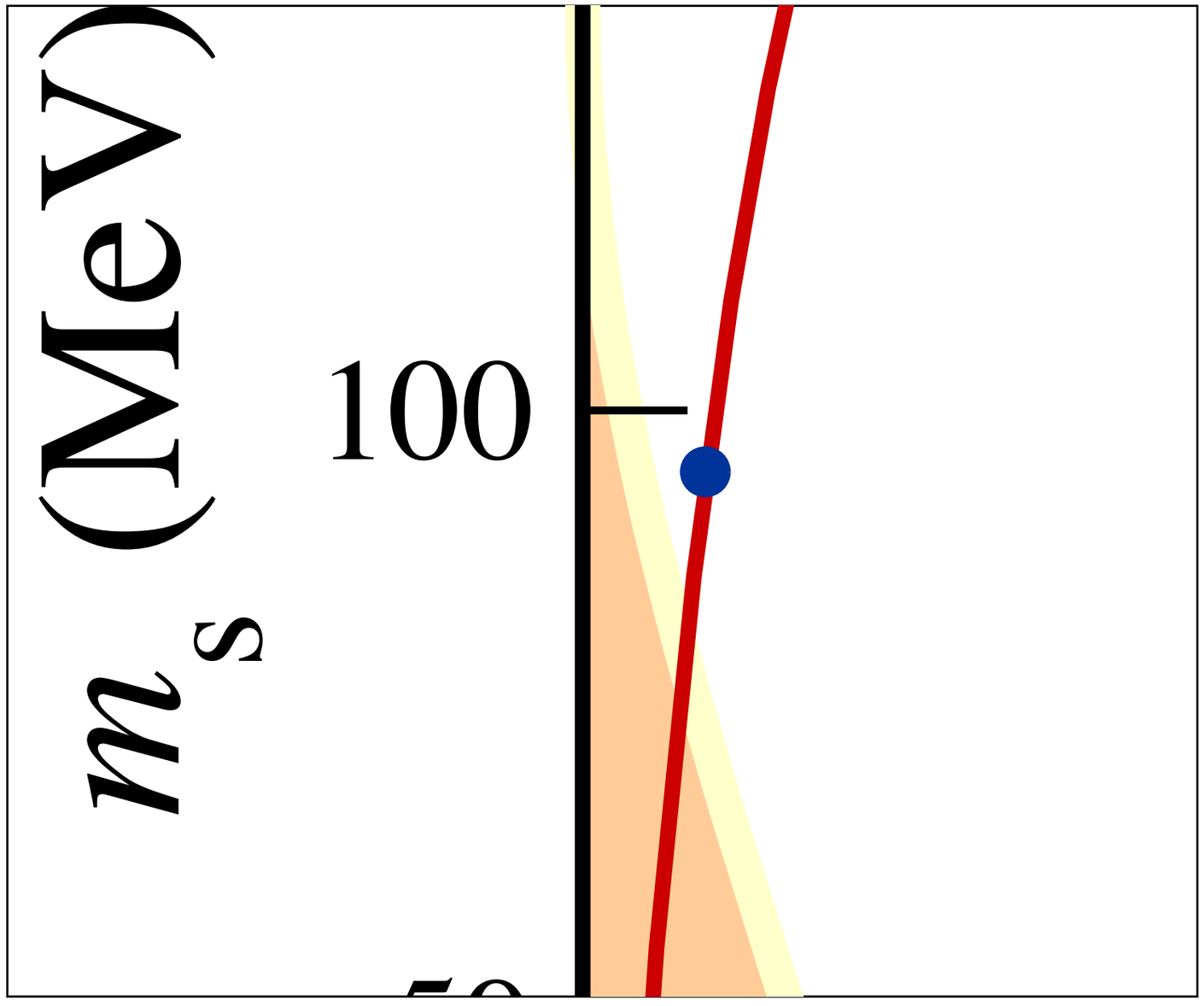

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α_s and Heavy Quark Masses:
Derived from Hadronic Properties

Strong Coupling α_s

- In lattice gauge theory, the bare coupling—$g_0^2(1/a)$— is an input. Aim is to relate this to $\alpha_s(m_Z) = g_s^2(m_Z)/4\pi$.

- Two main strategies:

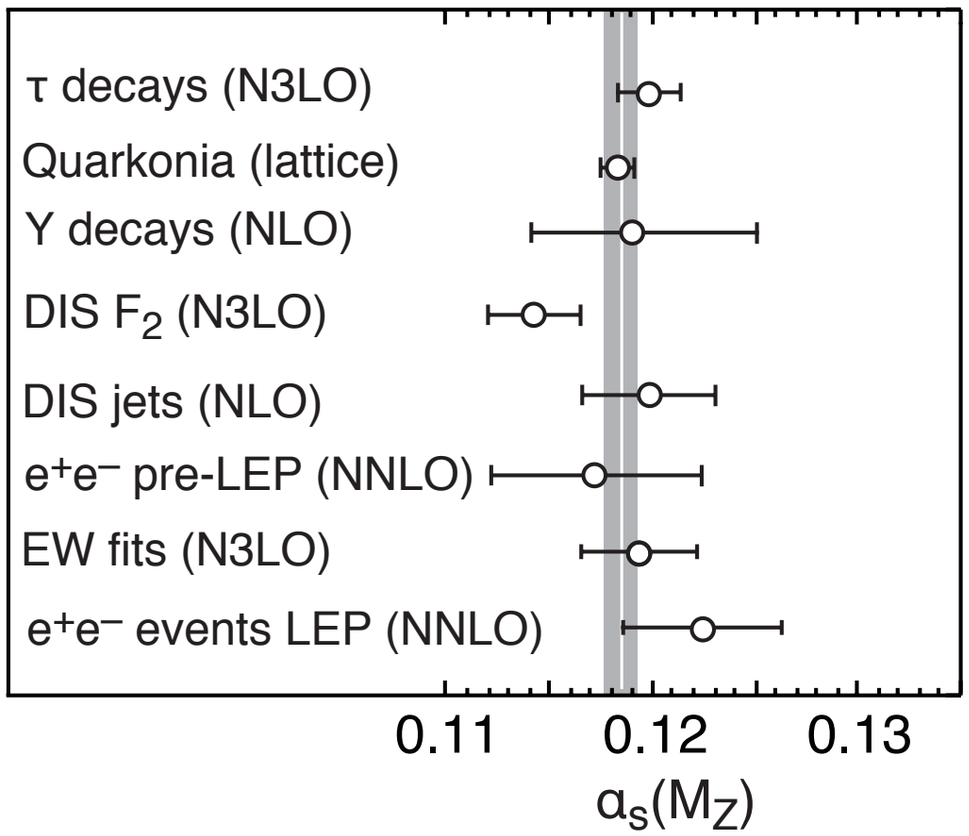
  - compute a short-distance lattice quantity (*e.g.*, small Wilson loop, Creutz ratio of small Wilson loops, ...); compare MC with (lattice) PT $\rightarrow \alpha_s(1/a)$;

  - compute short-distance "$1/Q$" continuum quantity (*e.g.*, J-J correlator, Schrödinger functional, ghost vertex); compare MC with PT $\rightarrow \alpha_s(Q)$.

Results for α_s (all $n_f = 2{+}1$):

- Schrödinger [PACS-CS, arXiv:0906.3906] | Adler [JLQCD, arXiv:1002.0371]:
  - $\alpha_s(m_Z) = 0.1205(8)(5)(+0/-17)$ | $\alpha_s(m_Z) = 0.1181(3)(+13/-4)$;
- Wilson Creutz, *etc.* [HPQCD, arXiv:0807.1687 | Maltman, arXiv:0807.2020]:
  - $\alpha_s(m_Z) = 0.1183(8)$ | $0.1192(11)$;
- Charmonium correlator [HPQCD + Karlsruhe, arXiv:0805.2999]:
  - $\alpha_s(m_Z) = 0.1174(12)$ | $0.1184(6)$ [update in arXiv:1004.4285];
- Bethke's world average (without lattice | with HPQCD WL) [arXiv:0908.1135]:
  - $\alpha_s(m_Z) = 0.1186(11)$ | $0.1184(7)$.

QCD of hadrons = QCD of partons



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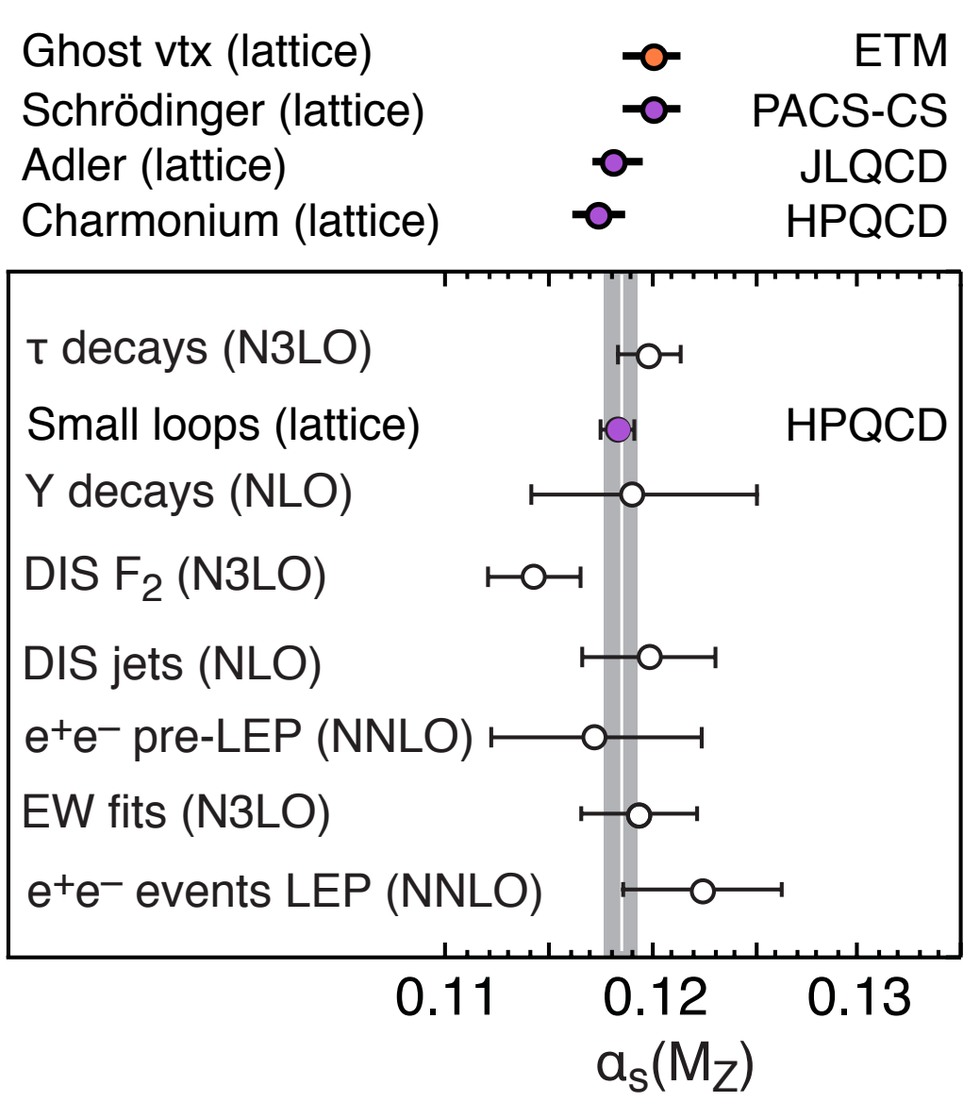
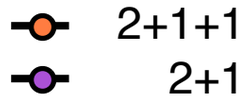




Bethke, arXiv:0908.1135

Heavy Quark Masses

- The charmonium correlator also yields impressive precision on the charm mass [Bochkarev & de Forcrand, hep-lat/9505025]; analogous to determination from e^+e^- by Chetyrkin *et al.*:

  - lattice + PT: $m_c(m_c) = 1.273(6)$ GeV [arXiv:1004.4285];

  - e^+e^- + PT: $m_c(m_c) = 1.279(13)$ GeV [arXiv:0907.2110].

- Similarly, $m_b(m_b) = 4.164(23)$ GeV [HPQCD, arXiv:1004.4285],
  cf. $m_b(m_b) = 4.163(16)$ GeV from e^+e^- + PT [arXiv:0907.2110].

- Also, $m_c/m_s = 11.85(16)$ [HPQCD, arXiv:0910.3102], which led to the right-most column in the table of light-quark masses.

QCD Parameters and Precision Higgs Physics

Lepage, Mackenzie, Peskin, arXiv:1404.0319

- Future Higgs expts will aim to measure BRs to better than a few %, where physics BSM could cause deviations. Look at relative errors in couplings.

- Main source of uncertainty in SM Higgs BRs is parametric: α_s, m_b, m_c:

$$\delta_b = 1.0\delta m_b(10) \oplus (-0.28)\delta\alpha_s(m_Z) \overset{?}{<} 0.3\%$$

$$\delta_c = 1.0\delta m_c(3) \quad \oplus (-0.80)\delta\alpha_s(m_Z) \overset{?}{<} 0.7\%$$

$$\delta_g = 1.2\delta\alpha_s(m_Z) \qquad\qquad\qquad\quad \overset{?}{<} 0.6\%$$

- Using today's best (LQCD) estimates of α_s, m_b, and m_c, LMP find parametric uncertainties at this level (within a factor of 2 for δ_b).

- So some improvement is needed, but the program is feasible.

- What are the prospects? LMP [arXiv:1404.0319] forecast

	$\delta m_b(10)$	$\delta\alpha_s(m_Z)$	$\delta m_c(3)$	δ_b	δ_c	δ_g
current errors	0.70	0.63	0.61	0.77	0.89	0.78
+ PT	0.69	0.40	0.34	0.74	0.57	0.49
+ LS	0.30	0.53	0.53	0.38	0.74	0.65
+ LS^2	0.14	0.35	0.53	0.20	0.65	0.43
+ PT + LS	0.28	0.17	0.21	0.30	0.27	0.21
+ PT + LS^2	0.12	0.14	0.20	0.13	0.24	0.17
+ PT + LS^2 + ST	0.09	0.08	0.20	0.10	0.22	0.09
ILC goal				0.30	0.70	0.60

- Here PT means to calculate 4th-order QCD, LS to add $a = 0.03$ fm, LS^2 to add $a = 0.023$ fm also, ST to add ×100 statistics.

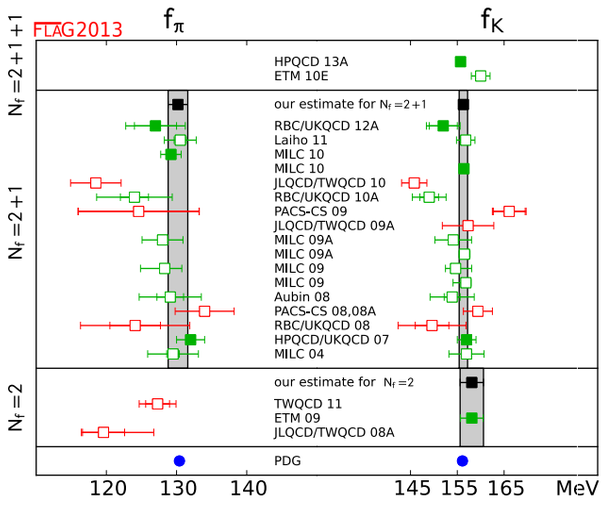
- Reductions feasible on ILC time scale (assuming support for QCD theorists).

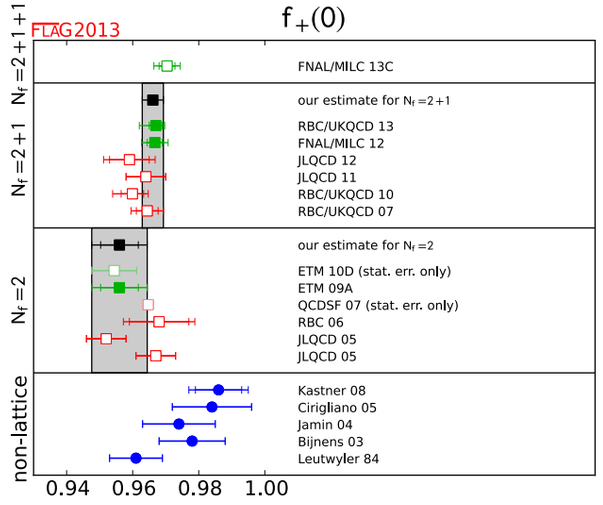
Flavor Physics

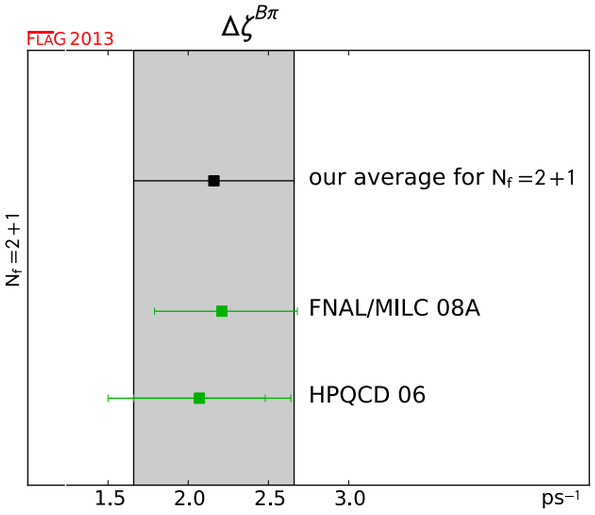
CKM and Lattice QCD

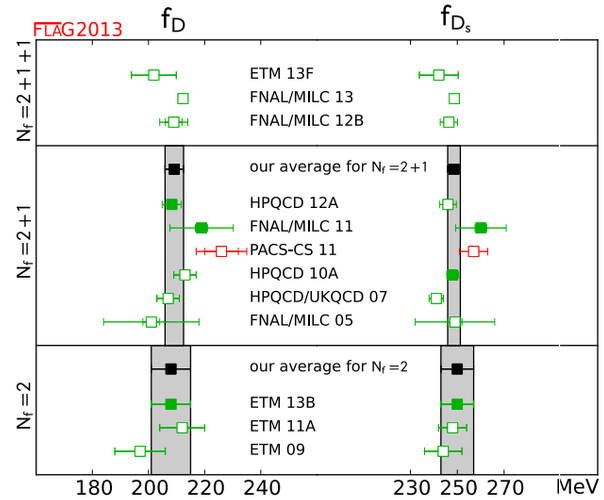
- Gold-plated quantities available to (over)determine CKM matrix.
- Further matrix elements for flavor-changing neutral currents—
  - which arise in many extensions of the Standard Model.
- Flavor Lattice Averaging Group FLAG 2013 Flavour Lattice Averaging Group:
  - self-selected group drawn from most major lattice QCD collaborations;
  - sets quality criteria and produces averages of quantities germane to CKM;
  - compare & contrast to the PDG perhaps 30 years ago.

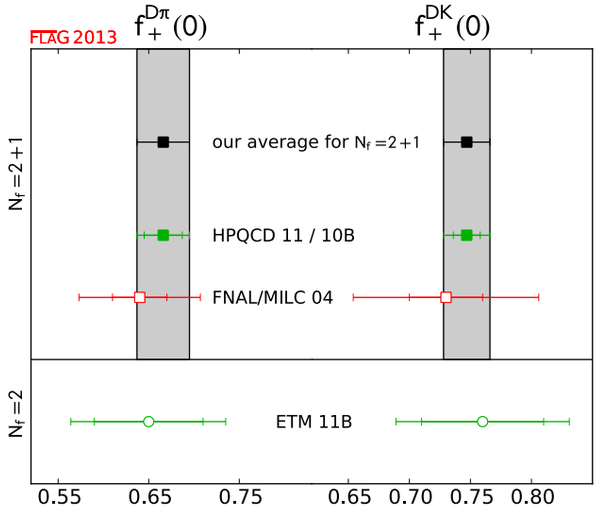
FLAG 2013
Flavour Lattice Averaging Group

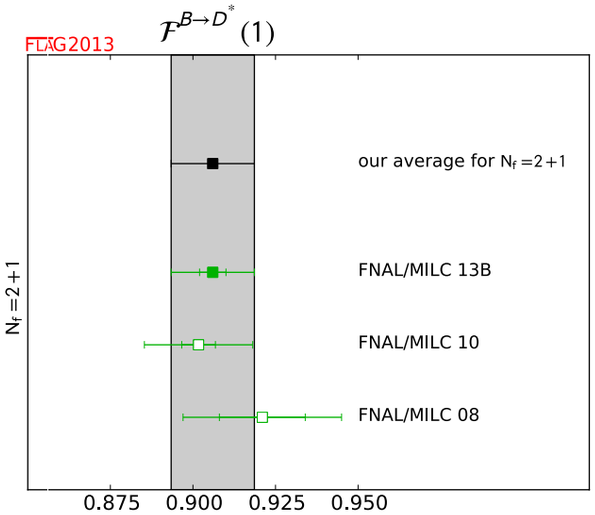


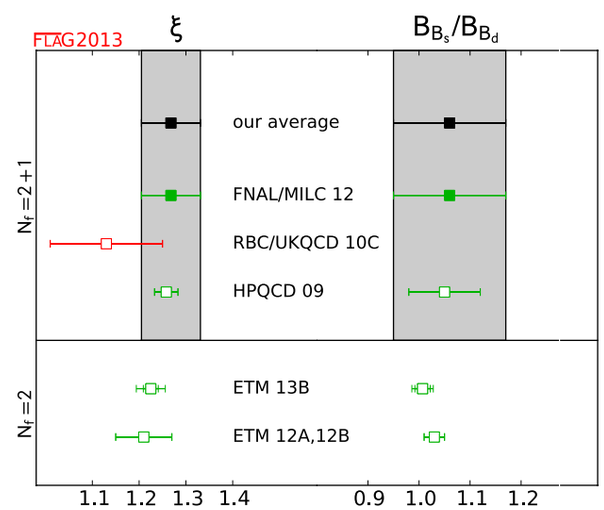


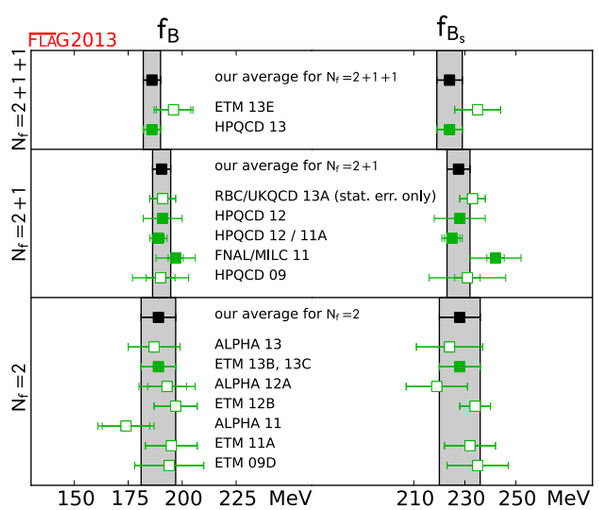


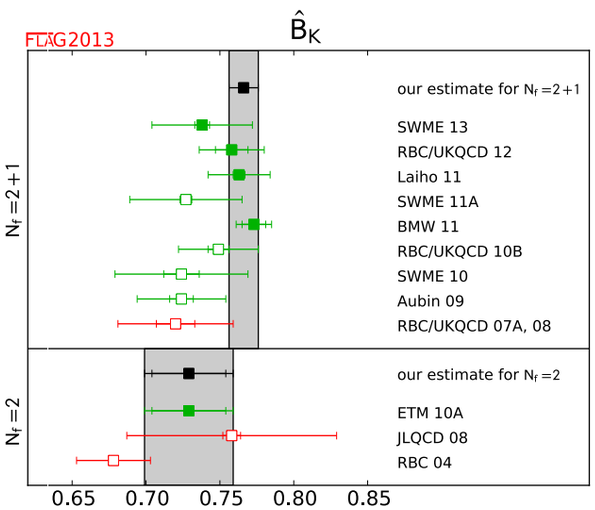












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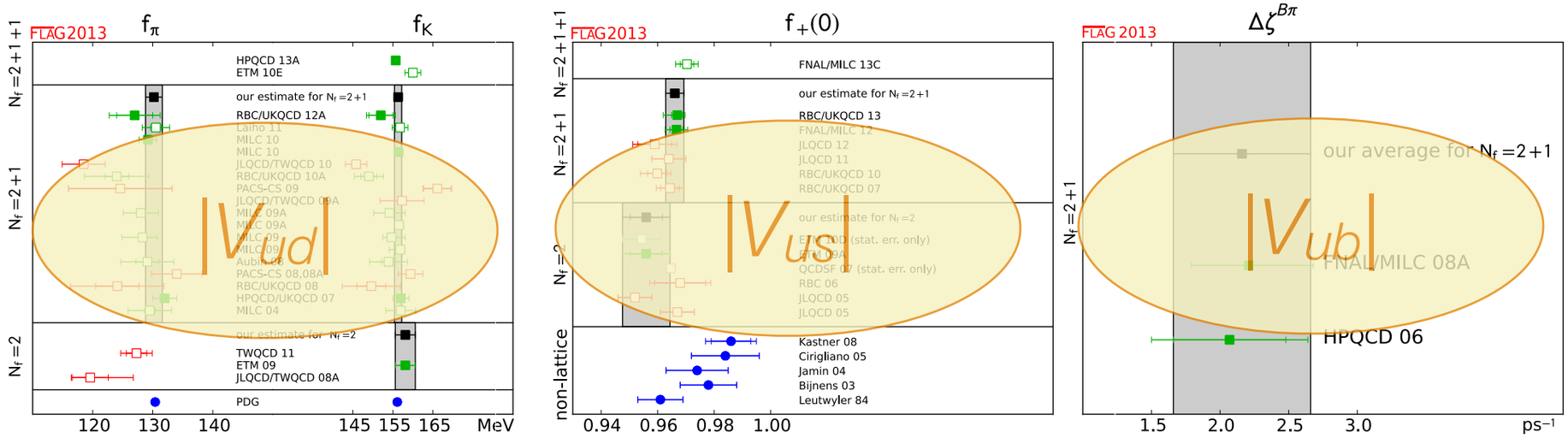
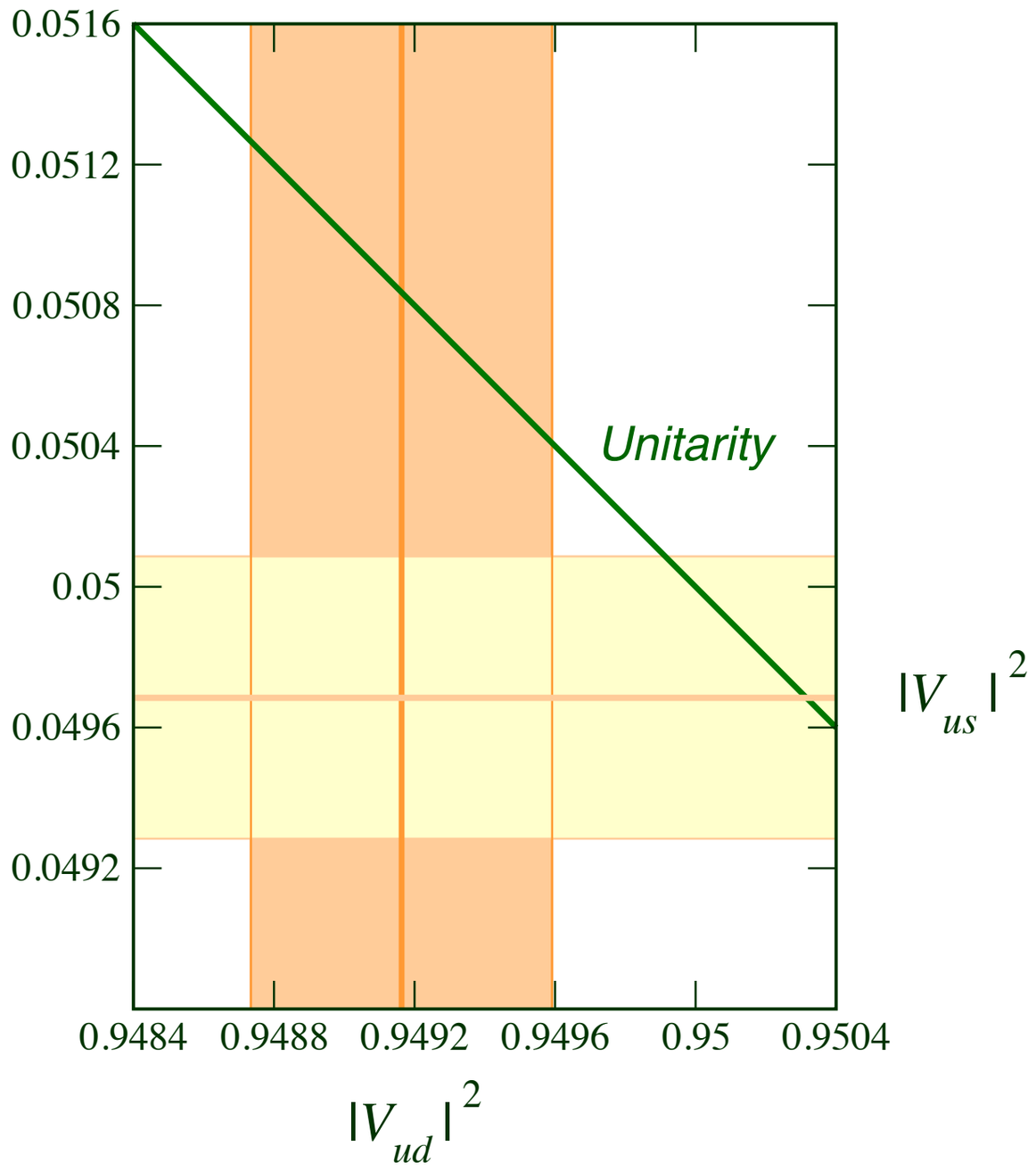
Flavour Lattice Averaging Group



Semileptonic $K \to \pi l \nu$ for $|V_{us}|$

- aka the Cabibbo angle.
- Appears throughout flavor physics.
- esp. in first-row unitarity test: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$?
- Now $|V_{us}|^2$ is as precise as $|V_{us}|^2$ (from nuclear physics).
- Similar precision from f_K/f_π [arXiv:1407.3772].



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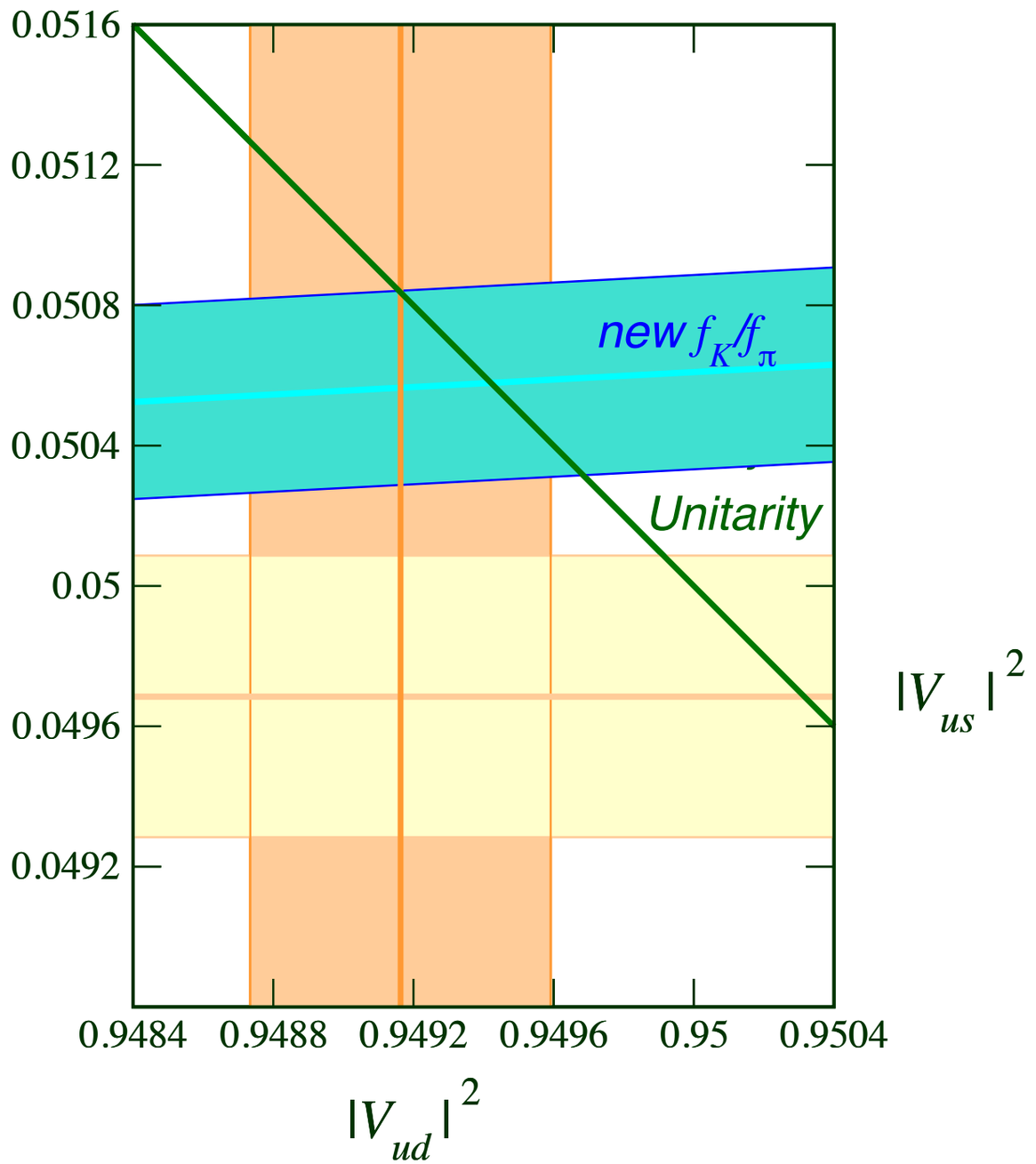
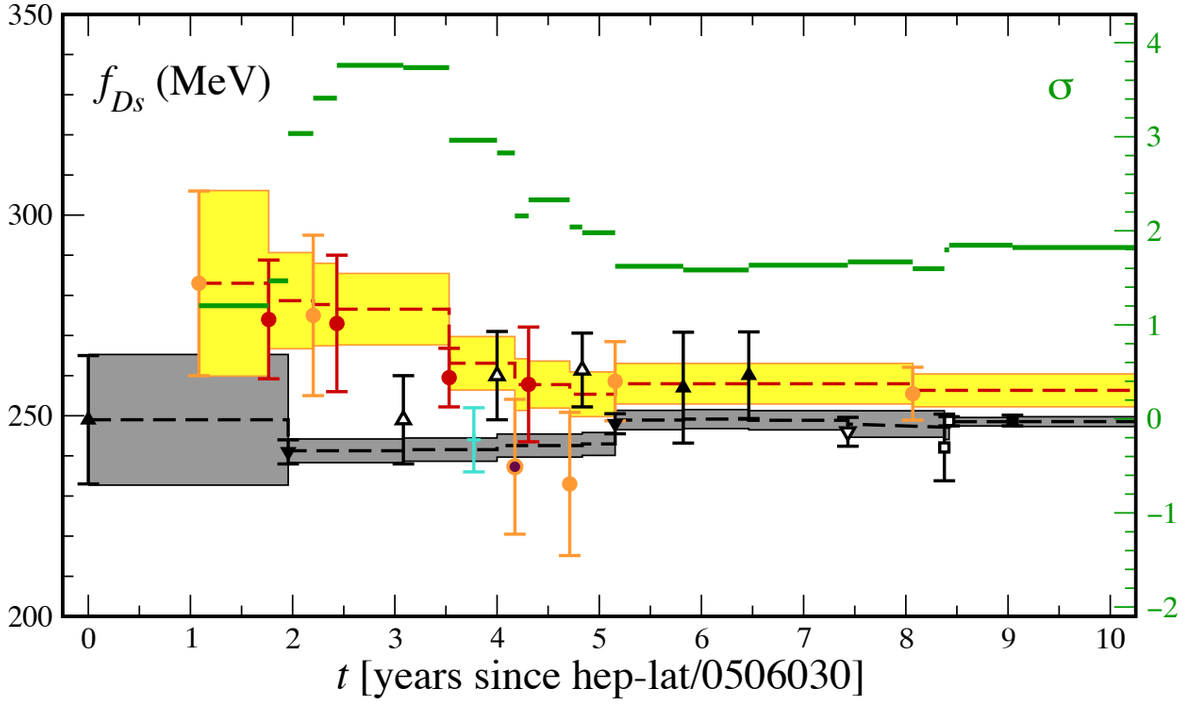
- Appears throughout flavor physics.
- esp. in first-row unitarity test: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$?
- Now $|V_{us}|^2$ is as precise as $|V_{us}|^2$ (from nuclear physics).
- Similar precision from f_K/f_π [arXiv:1407.3772].

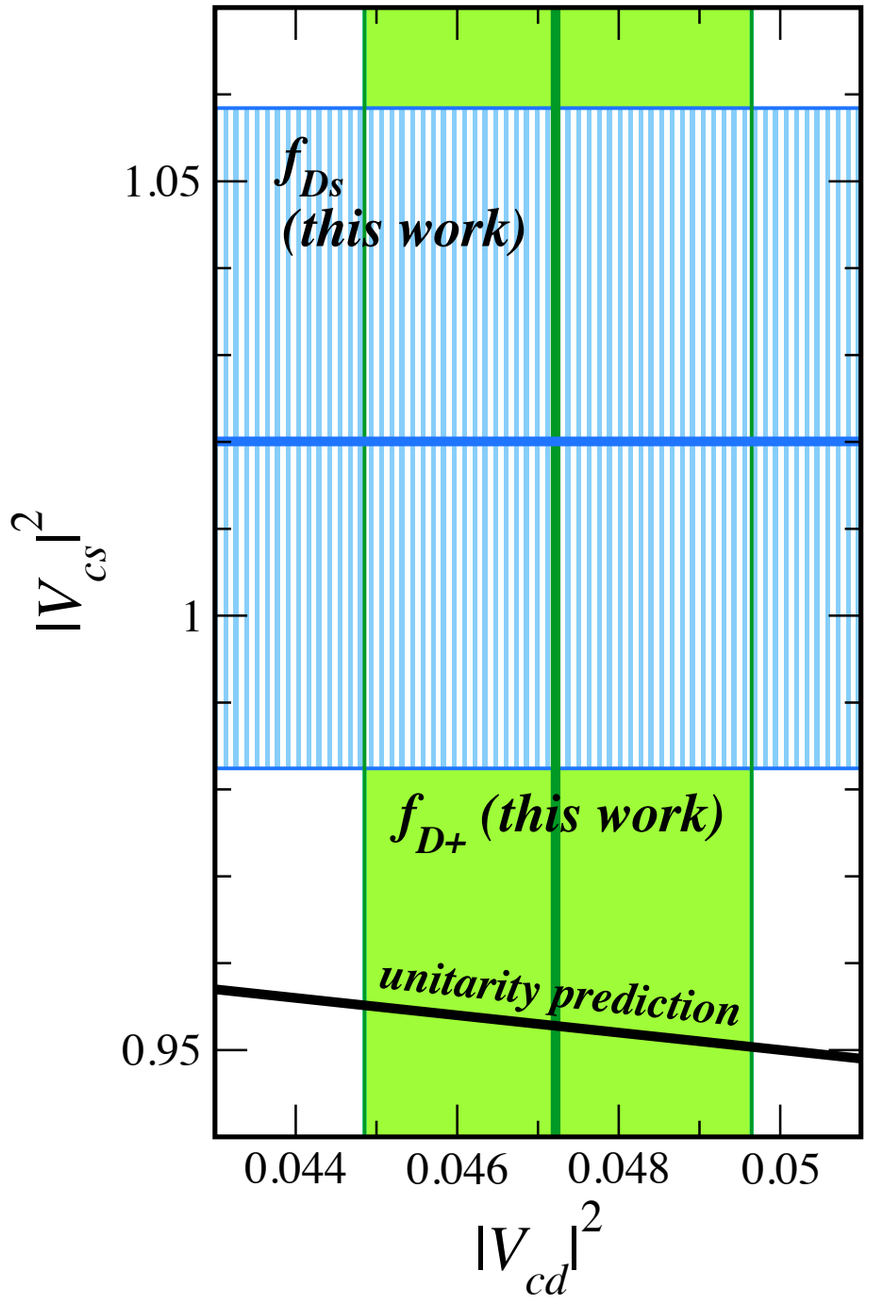


Leptonic $D \to l\nu$ and $D_s \to l\nu$ for $|V_{cd}|$ for $|V_{cs}|$

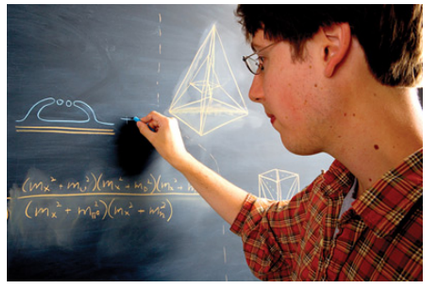
- HISQ action allows us to treat charmed quarks with the same method as strange, down, and up.

- Here the QCD uncertainty is smaller than the experimental uncertainty.





Semileptonic $B \to D^* l \nu$ for $|V_{cb}|$



- Like $|V_{us}|$, $|V_{cb}|$ appears everywhere, *e.g.*, in FCNC rare kaon decays.

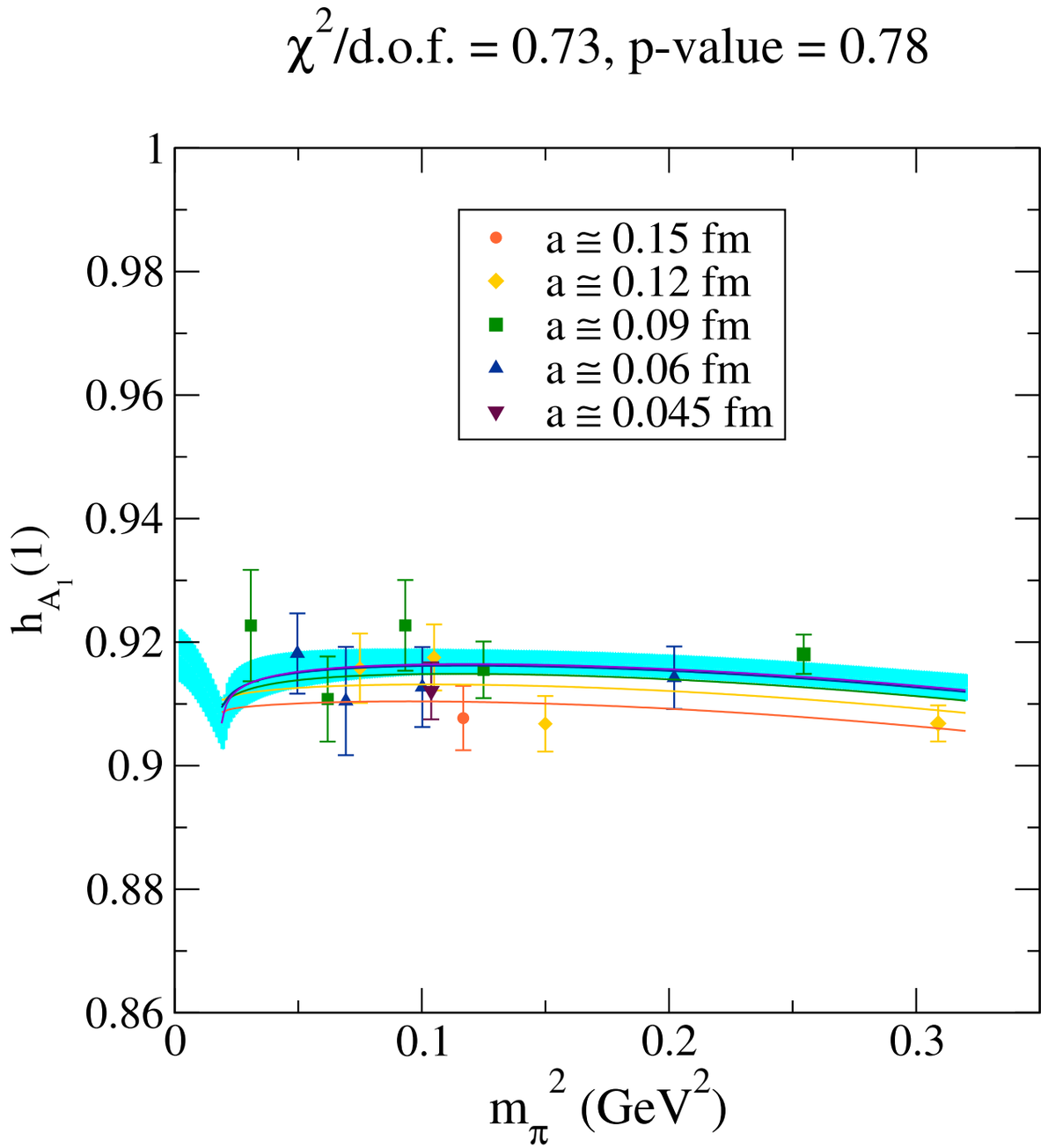
- We find

$$\mathscr{F}(1) = 0.906 \pm 0.04 \pm 0.12$$

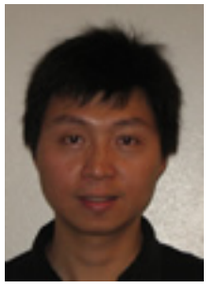
or

$$10^3 |V_{cb}| = 39.04 \pm 0.49_{\text{expt}} \pm 0.53_{\text{QCD}} \pm 0.19_{\text{QED}}$$

- QCD error as small as expt; as small as inclusive-decay method.

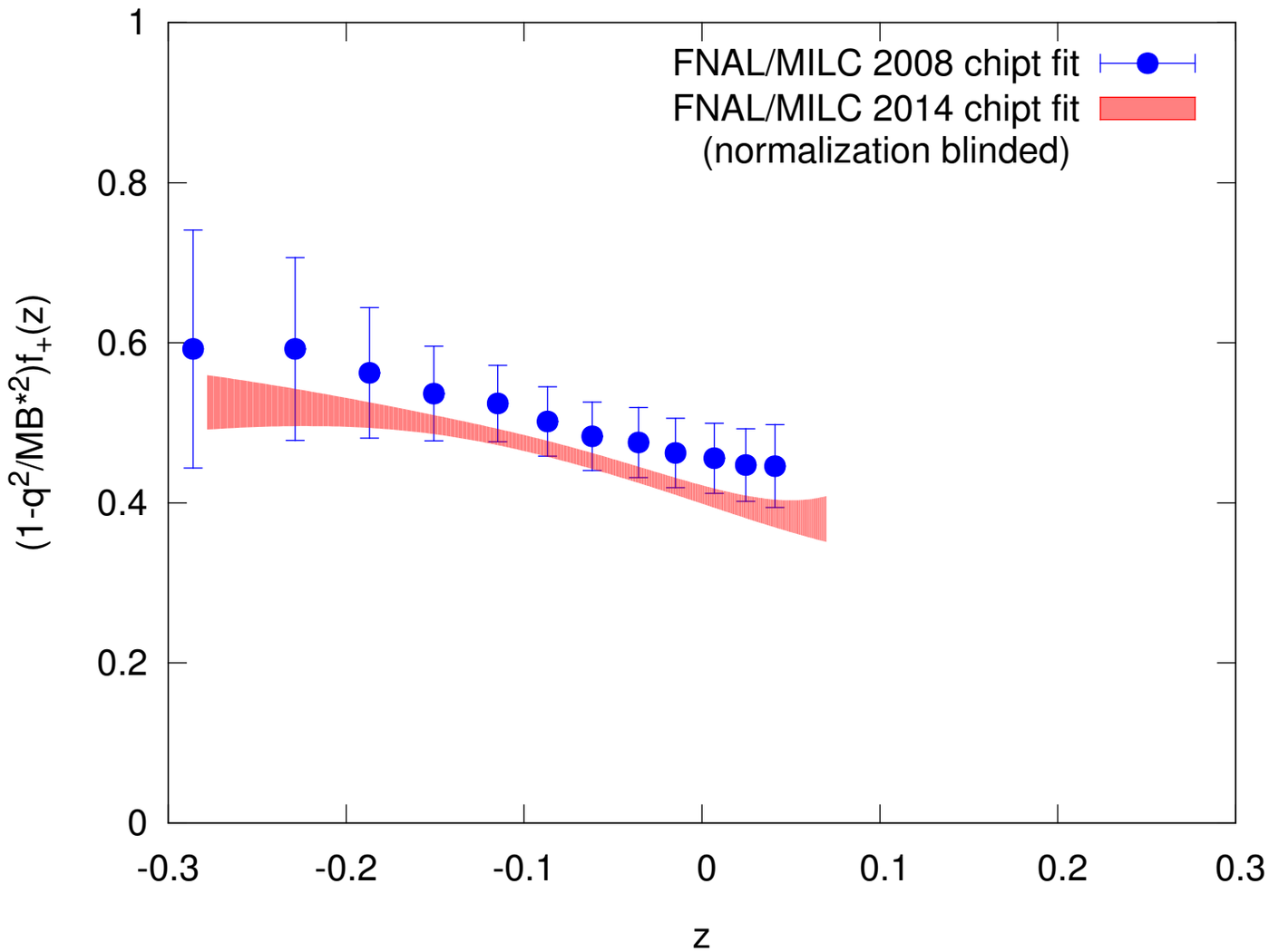


Semileptonic $B \to \pi l \nu$ for $|V_{ub}|$



- Much more precise than 2008.
- **PRELIMINARY! BLINDED!!**
- z variable extends range.
- Functional fitting method.
- Relative norm'n yields $|V_{ub}|$.
- Total error on $|V_{ub}|$: 4.1%.

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



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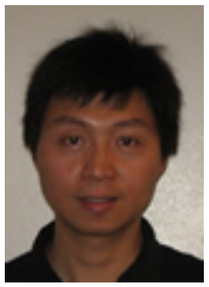

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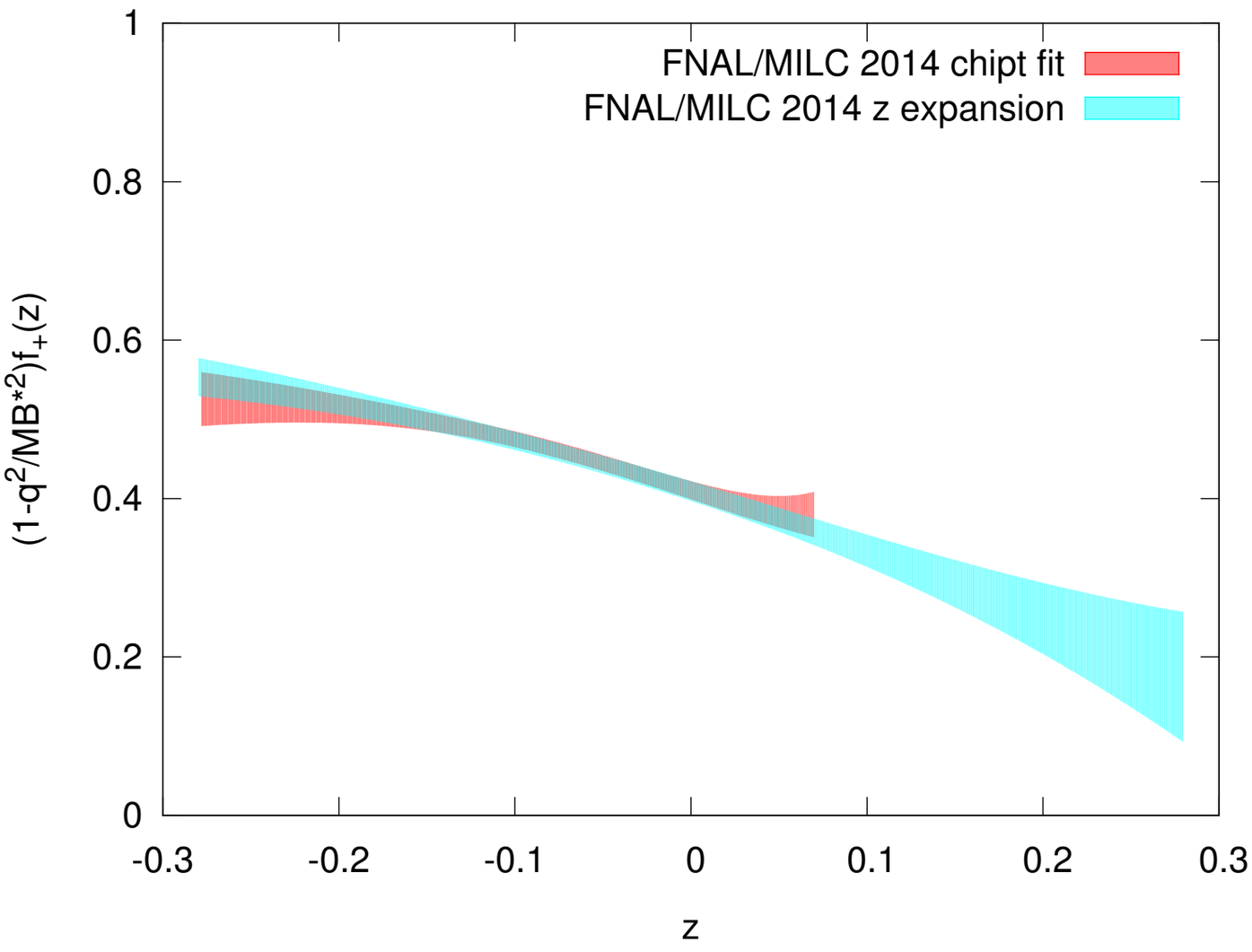

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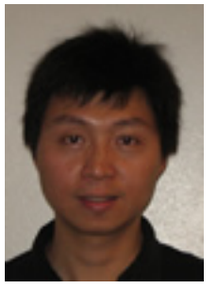

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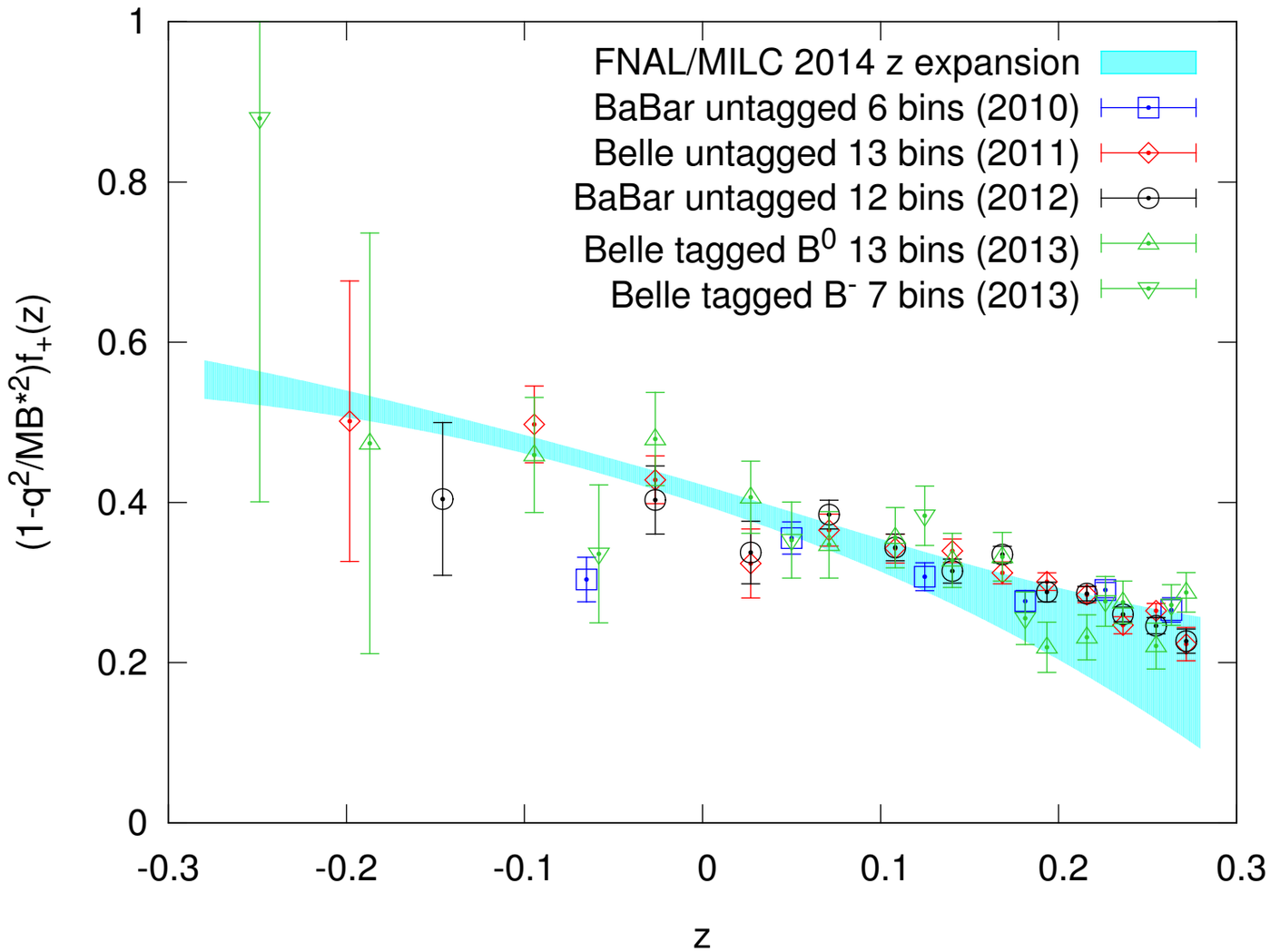

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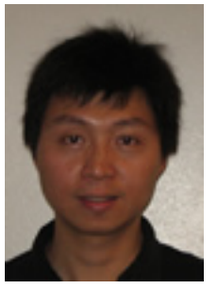

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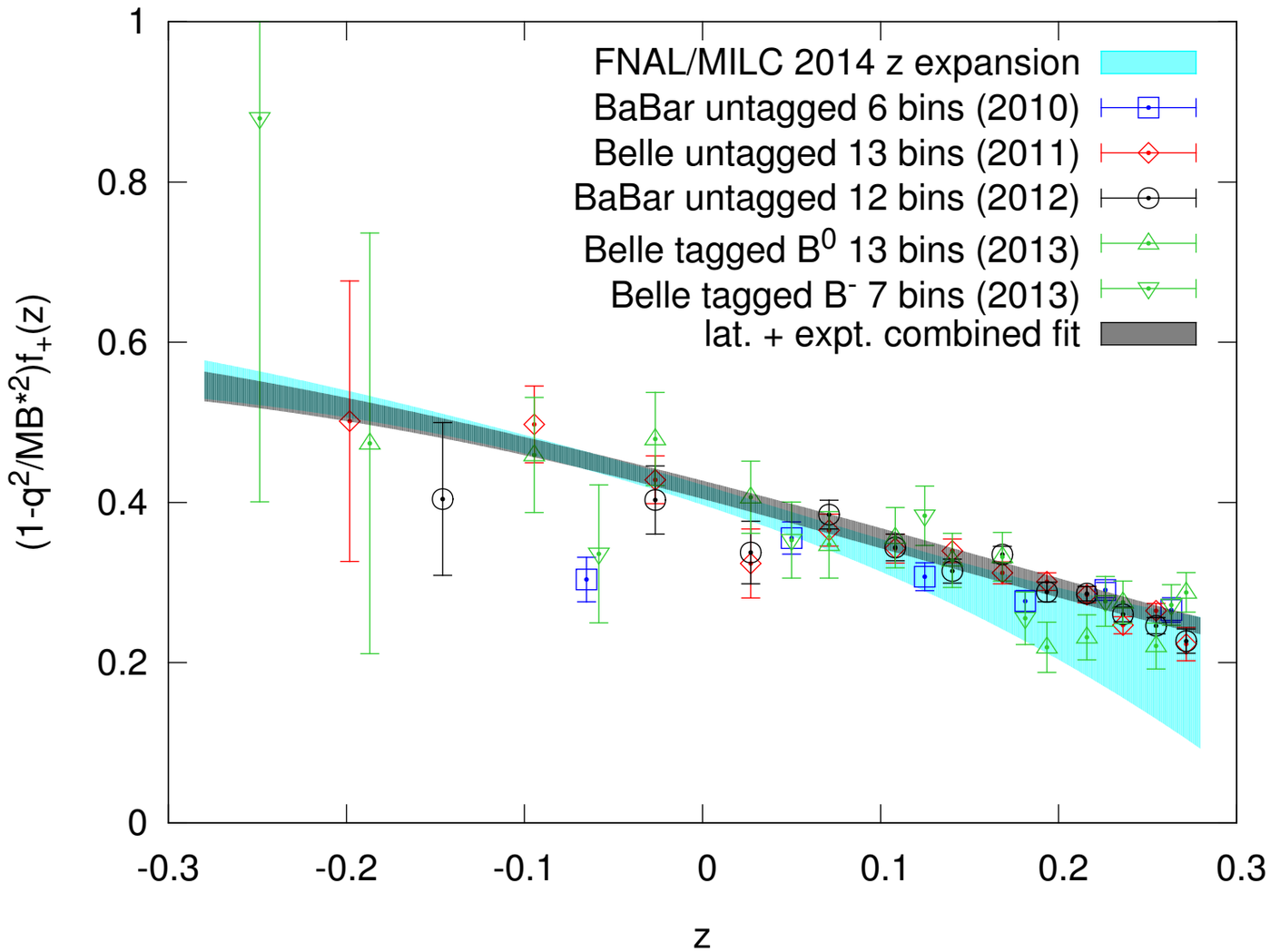

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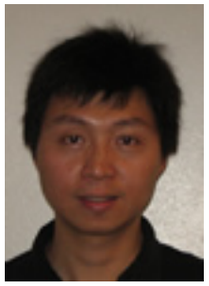

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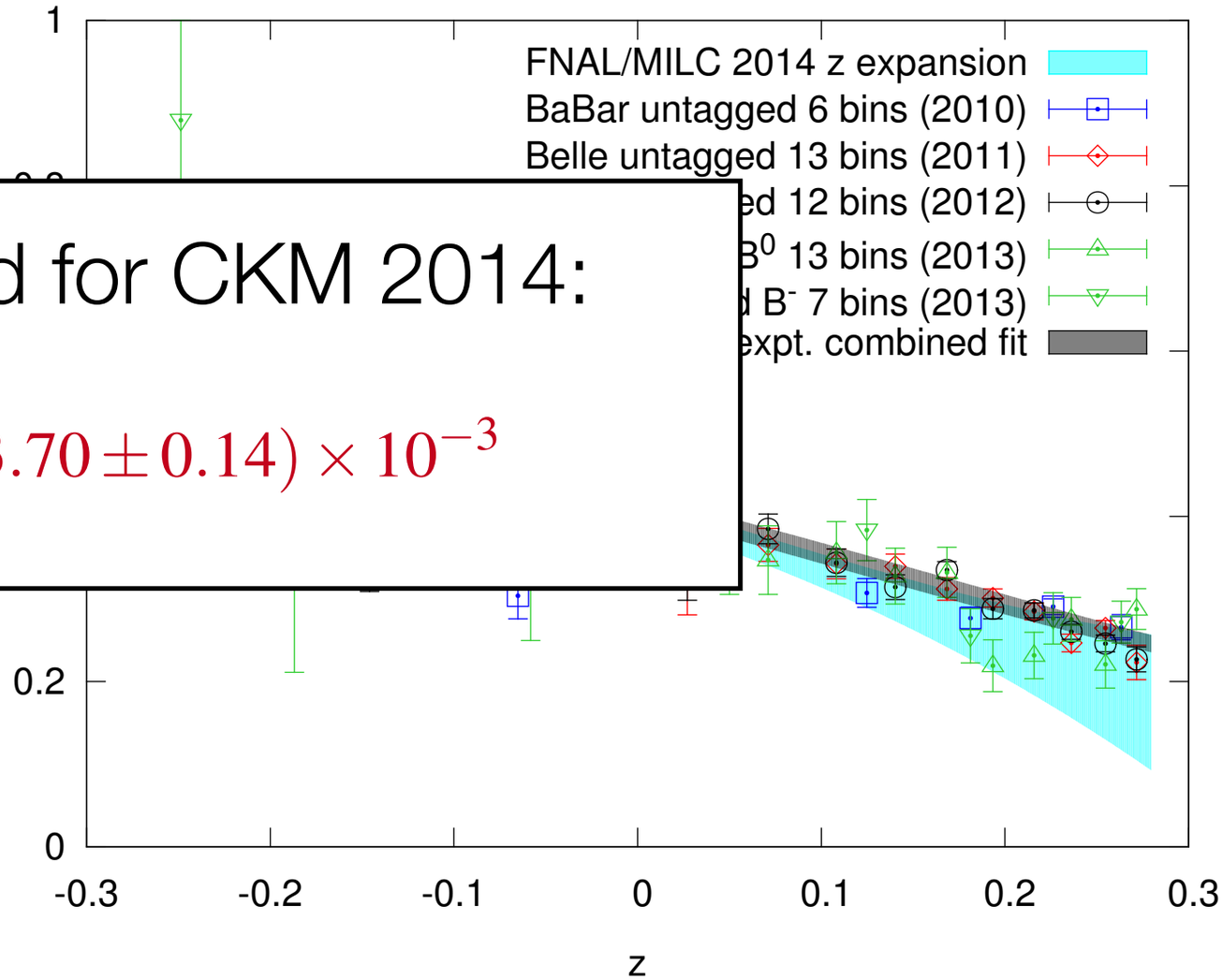
Unblinded for CKM 2014:

$$|V_{ub}| = (3.70 \pm 0.14) \times 10^{-3}$$



Lessons

- Lattice QCD plays a crucial role for neutral-meson mixing (K, B, B_s).
- Lattice QCD plays a key role in $|V_{us}|$, $|V_{cs}|$, $|V_{ub}/V_{cb}|$, $|V_{cb}|$.
- Suite of experiments, pQCD, and lQCD shows that CKM flavor violation and KM CP violation predominates.
- Still room for new physics: tension at 2–3σ level:
  - confidence level of global fit improves more, if NP in kaon mixing [LLV];
  - ε_K band uses corrections of Nierste, Ligeti, ASK [hep-ph/0201071].

Computing and Collaboration

Two Kinds of Computing

- First, we compute 600–2000 Monte Carlo snapshots of the lattice gauge field

$$\langle \bullet \rangle = \frac{1}{Z} \int \mathcal{D}U \prod_{f=1}^{n_f} \det(\not{D} + m_f) \exp\left(-S_{\text{gauge}}\right) [\bullet'] \approx \frac{1}{C} \sum_{c=0}^{C-1} \bullet'[U^{(c)}]$$

  needing a huge number of huge jobs to create the $\{U^{(c)}\}$.

- Next, compute $\bullet'$, followed by the curve-fitting in

$$\langle \pi(t) \pi^\dagger(0) \rangle = \sum_n |\langle 0|\hat{\pi}|\pi_n\rangle|^2 \exp(-m_{\pi_n} t)$$

  need an enormously huge number of large ($\bullet'$) small-to-medium (m_π) jobs.

  - Lattice theorists have pioneered the use of GPUs to make such computing cost effective; now spinning off to HEP experiment.

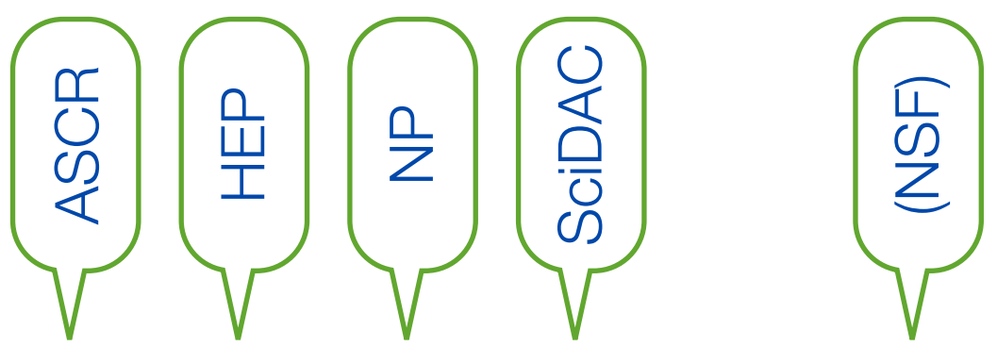
- The problem naturally splits into two parts:
  - generating $\{U^{(c)}\}$ requires capability machines, e.g., BlueGene/Q or Cray;
  - working out the $\bullet'$ and the curve fitting requires capacity machines.

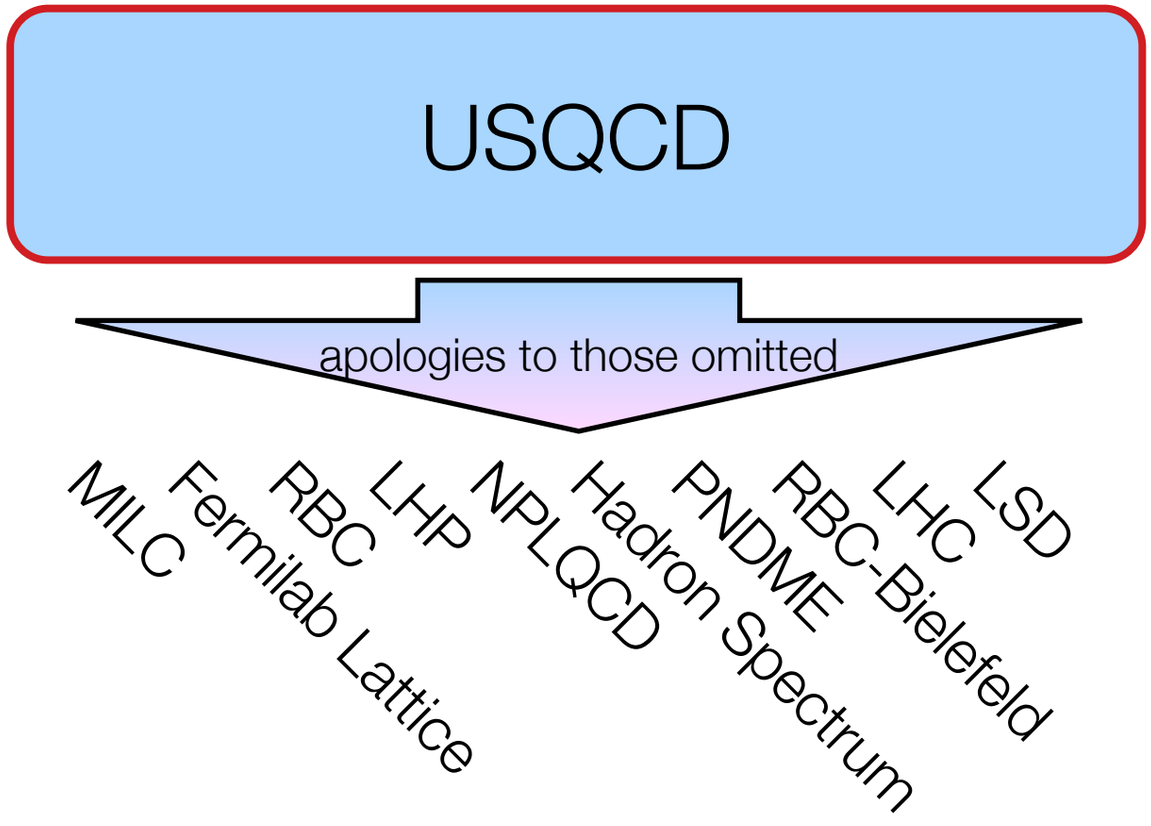
"leadership class" BlueGene/Q at ALCF

dedicated PC/GPU cluster at Fermilab

USQCD Collaboration

- The US DOE uses a successful, innovative model for providing resources.
- Computer resources flow to USQCD:
  - capability at big centers;
  - capacity at BNL, Fermilab, JLab.
- USQCD allocates the resources to underlying science collaborations.
- Big-idea discussions at a high level.
- Technical discussions at a low level.





Summary and Challenges

Summary: from "QCD *should* work this way" to "QCD *does* work this way"

- Quantitative
  - Scale anomaly:
  - Hadron masses:
  - Chiral condensate $\langle \bar{q} q \rangle$:
  - Precise α_s, m_c, m_b:
  - Flavor physics:
  - Smooth crossover:
- Qualitative
  - Mass from quantum mechanics;
  - Your mass = E_0/c^2;
  - QCD breaks chiral symmetry;
  - $\text{QCD}_{\text{hadrons}} = \text{QCD}_{\text{partons}}$
  - CKM dominates; whole story?
  - Cooling universe.

Challenges

- Particle physics, nuclear physics, astrophysics:
  - 1% precision for flavor physics—include isospin $m_u < m_d$, QED;
  - non-QCD gauge theories of electroweak symmetry breaking;
  - nucleon axial form factor, needed for neutrino physics;
  - strangeness content of the nucleon, needed for WIMP cross sections;
  - reliable moments for the nucleon's gluon distribution;
  - larger chemical potential for heavy-ion physics & neutron stars;
  - excited and multi-hadron states, mixing, and, soon enough, small nuclei.

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Thank you!