Lattice status and prospects

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Flavor Physics and CP violation, FPCP 2017
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Decades of lattice progress

Lattice QCD calculations have gone from being essentially crude models to being high-precision tools in the last thirty years.

Exascale

Petascale

Terascale

Gigascale

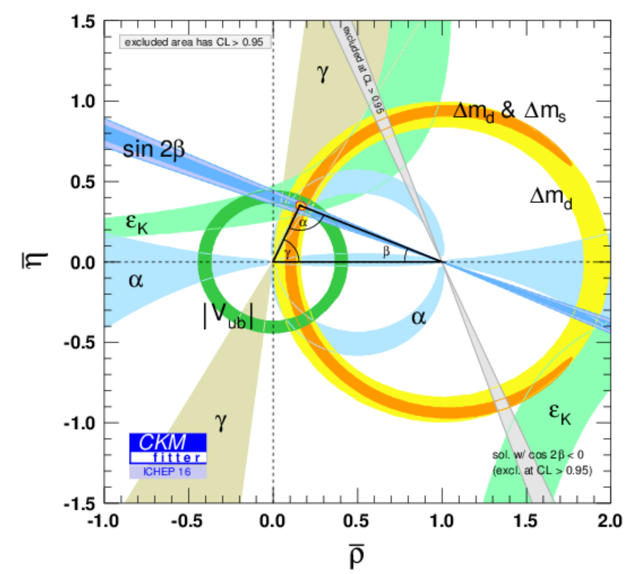
1995 — Important effects omitted (quark loops). No realistic uncertainty budgets. Lattice calculations ~ crude models.

2005 — Inclusion of light quark loops. Realistic uncertainty budgets possible.

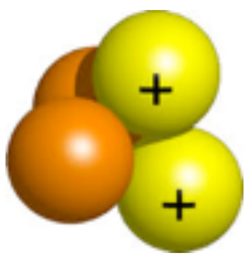
TABLE II: Error budget (in per cent) for $R_{d/s}$, ϕ_s, ϕ_d.

source	$R_{d/s}$	ϕ_s	ϕ_d
statistics	0.5	1.4	1.5
input parameters a and m_c	0.6	2.8	2.9
higher-order $\rho_{A_4^{cq}}$	0	1.3	1.3
heavy-quark discretization	0.5	4.2	4.2
light-quark discretization and χPT fits	5.0	3.9	6.3
static χPT	1.4	0.5	1.5
finite volume	1.4	0.5	1.5
total systematic	5.4	6.5	8.5

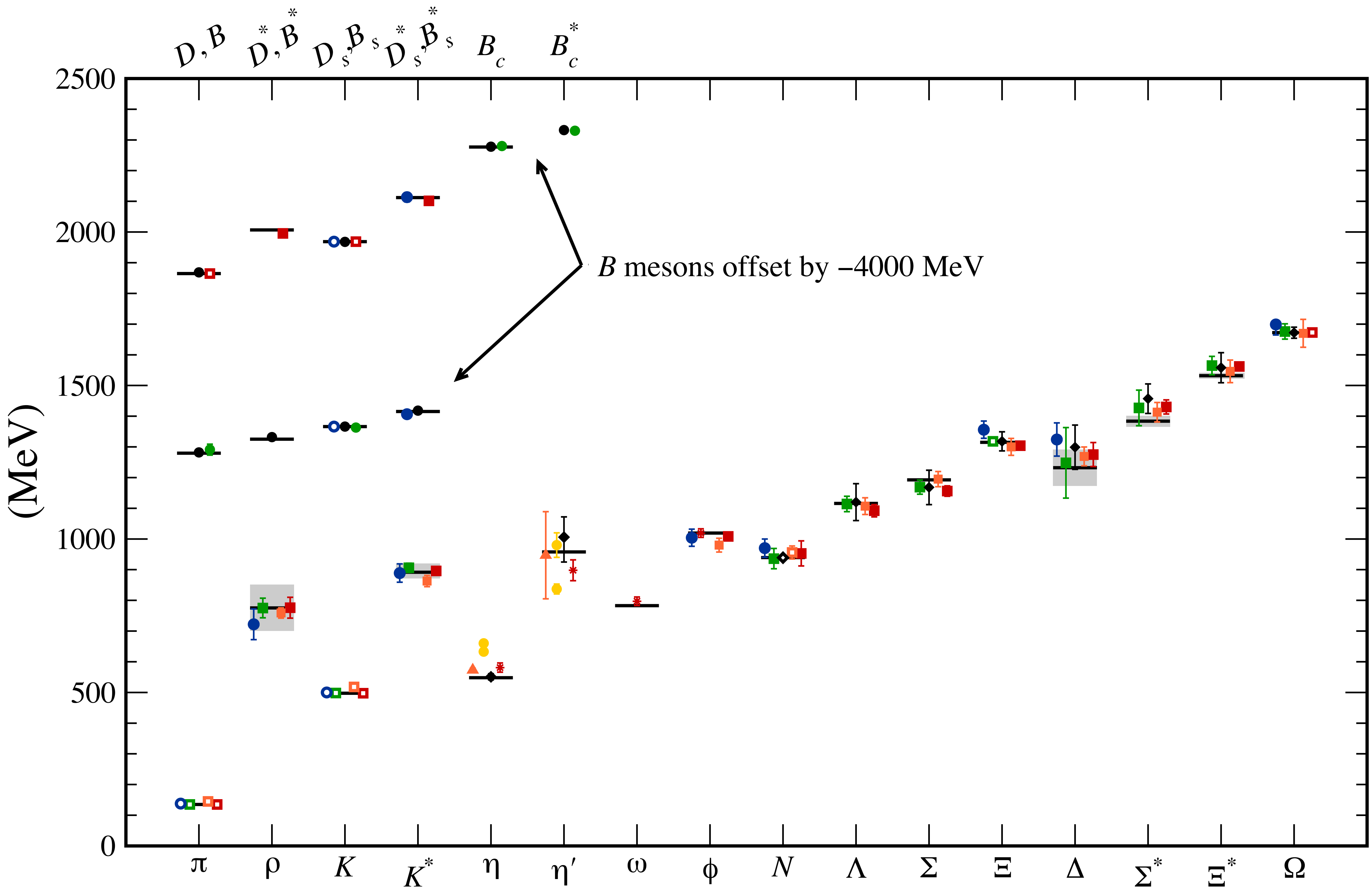
2015 — Correct light quark masses achieved on medium-size lattices. Few % uncertainties on simple quantities.



2025 — Correct light quark masses large lattices. Properties of light nuclei from first principles. < 1% uncertainties on simple quantities.



Light hadron spectrum is in very good shape.



Kronfeld

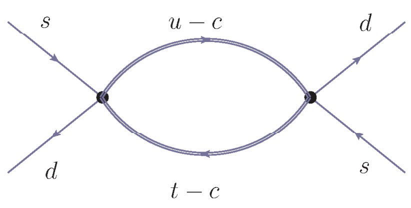
For the last fifteen years, lattice calculations have been able to calculate the properties of sufficiently simple quantities with good understanding of the calculational uncertainties.

Lattice QCD is everywhere

- Lattice QCD achieved its first phenomenologically important success in flavor physics.
- In the future: lattice calculations, major and minor, are needed *throughout* the entire future HEP experimental program.
  - g-2.
  - LHCb, Belle-2: continued improvement of CKM results.
  - mu2e, LBNE, Nova: nucleon matrix elements.
  - Underground LBNE: proton decay matrix elements.
  - LHC, Higgs decays: lattice provides the most accurate α_s and m_c now, and m_b in the future.

Decades of progress in methods.

- In the flavor factory era, important contributions to CKM physics were made with relatively simple quantities:
  - Decay constants, semileptonic decays, meson mixing.
    - N-point functions N<=3, 1 hadron at a time, mesons not baryons.
- Current frontiers in methods:
  - N-point functions, N>3.
    - ΔI=1/2 rule, ε'/ε (see Sachrajda talk)
    - g-2 light by light



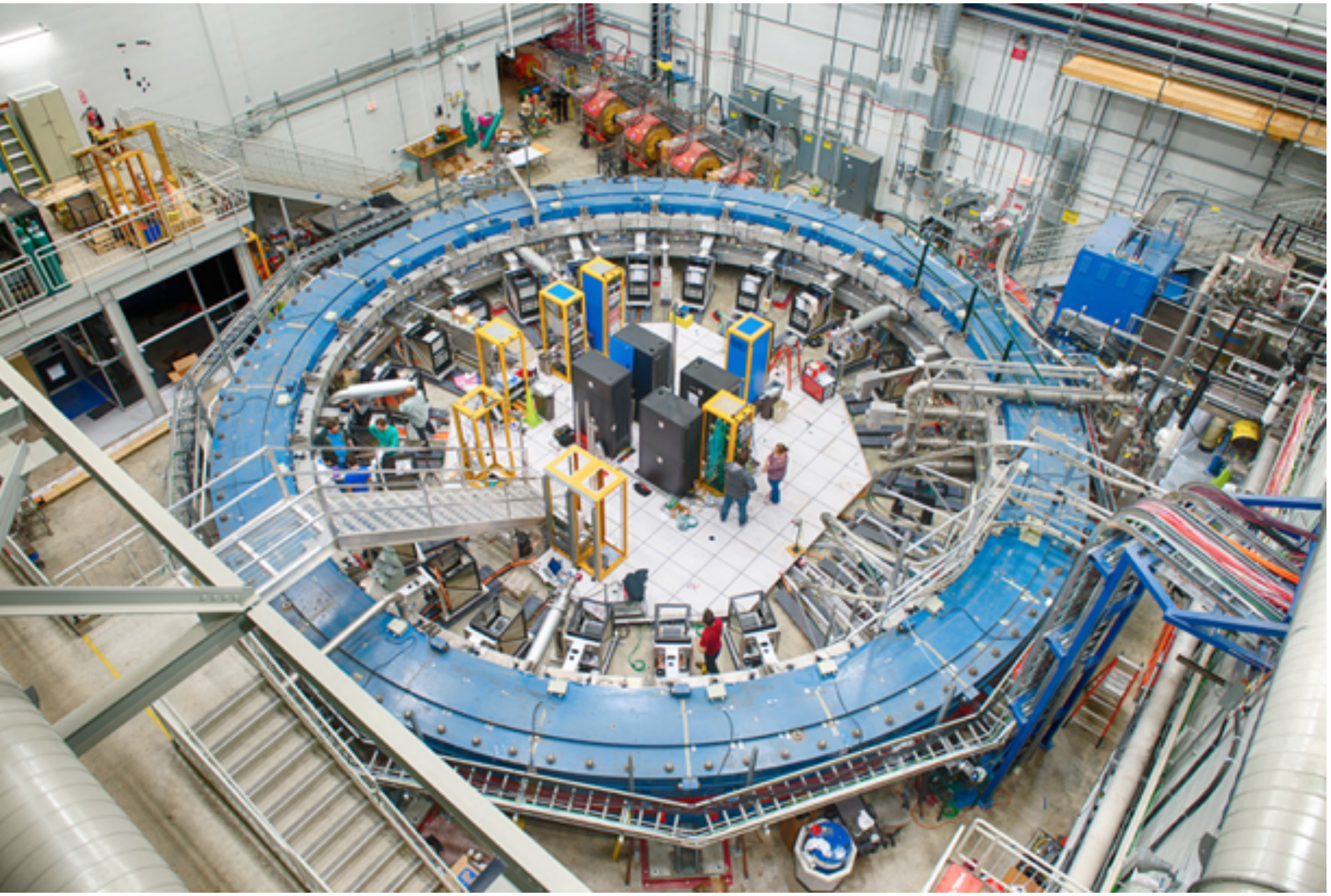
  - Multi-hadron final states
    - (Lellouch and Luescher)
    - ΔI=1/2 rule, ε'/ε, ρ decay, …

Plan of talk

- Overview of lattice QCD
- g-2
- Quark flavor physics
  - See also talks by Laiho ($B \to D^* l\nu$) and Sachrajda (ε'/ε).
- A few comments on other topics.

g-2

See also Taku Izubuchi, FPCP 2016
Hartmut Wittig, Lattice 2016
(More encyclopedic than here.)
Talks at First Workshop of the Muon g-2 Theory Initiative, 3-6 June,2017



March, 2017.
First muons circulated in the ring last Wednesday, May 31, 2017.
Engineering run now, then shutdown until November.
Data taking is planned to begin in November.
Result with 2x BNL statistics at the end of 2018,
Result with 21x BNL statistics, end of 2019.

Standard model uncertainty budget

Table 1: Summary of the Standard-Model contributions to the muon anomaly. Two values are quoted because of the two recent evaluations of the lowest-order hadronic vacuum polarization.

	VALUE ($\times 10^{-11}$) UNITS
QED ($\gamma + \ell$)	$116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_\alpha$
HVP(lo) [20]	$6\,923 \pm 42$
HVP(lo) [21]	$6\,949 \pm 43$
HVP(ho) [21]	-98.4 ± 0.7
HLbL	105 ± 26
EW	154 ± 1
Total SM [20]	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}$ ($\pm 49_{\text{tot}}$)
Total SM [21]	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}$ ($\pm 50_{\text{tot}}$)

0.6%, from e+e- exp.

25%, from hadronic models

Experimental uncertainty: 63×10^{-11} now,
goal: 17×10^{-11}.

Blum et al., arXiv:1311.2198v1 [hep-ph]

This has created an increased interest in lattice calculations among experimentalists.

Lattice gauge theorists

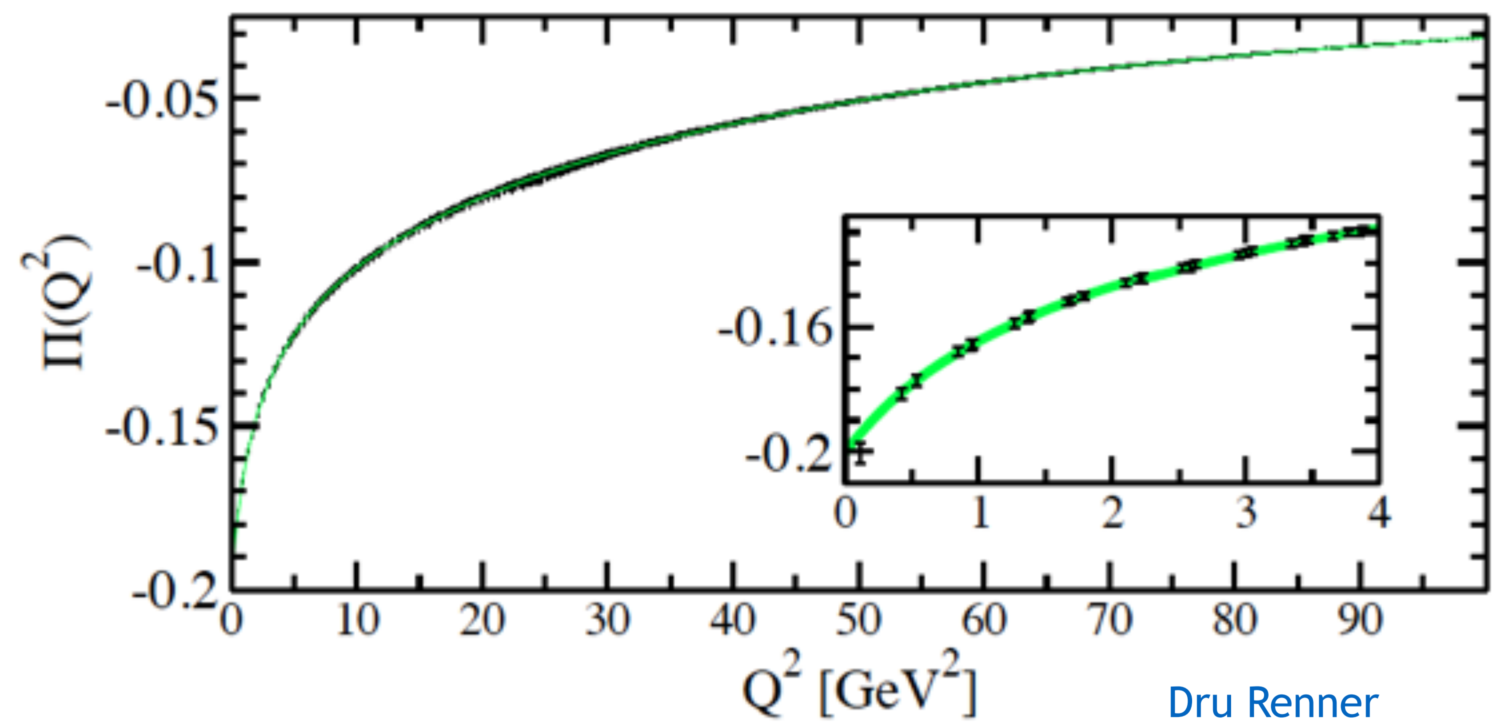
Experimenters

Vacuum polarization: general setup

- Calculate a_μ^{HVP} directly in from the Euclidean space vacuum polarization function:

$$a_\mu^{\mathrm{HVP(LO)}} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dQ^2 f(Q^2)\left[\Pi(Q^2) - \Pi(0)\right]$$

$$i\Pi_{\mu\nu}(q^2) =$$



Dru Renner

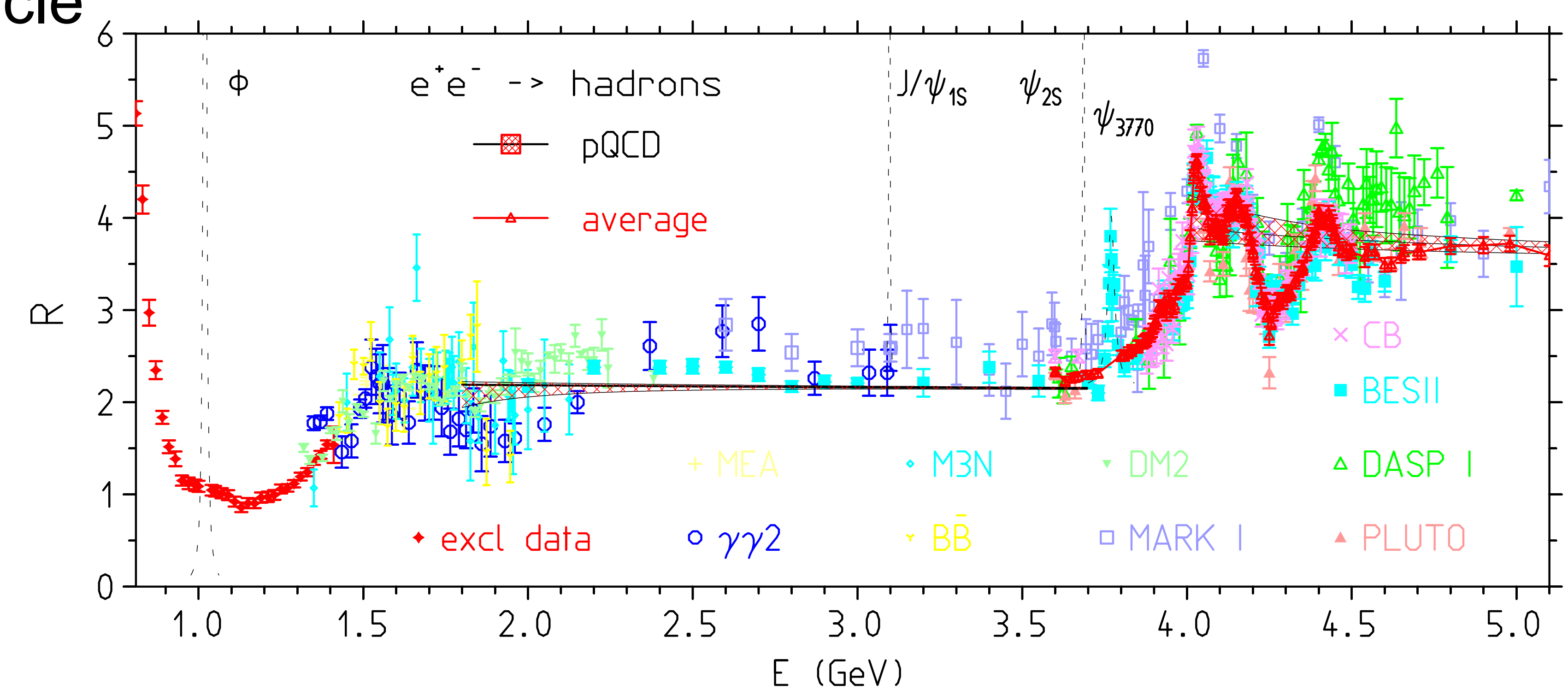
HVP from $e^+e^-\to$hadrons

- Standard-Model value for a_μ^{HVP} obtained from experimental measurement of $\sigma_{total}(e^+e^-\to\text{hadrons})$ via optical theorem:

$$a_\mu^{\mathrm{HVP}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_{\pi^0}^2}^{\infty} \mathrm{d}s \frac{R(s)K(s)}{s^2} \qquad R \equiv \frac{\sigma_{\mathrm{total}}(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

  - (Away from quark thresholds., use four-loop pQCD.)

- Includes >20 multi-particle channels with up to six



[Jegerlehner and Nyffeler, Phys.Rept. 477 (2009) 1-110]

Notable lattice work on vacuum polarization

- Blum, Phys. Rev. Lett. 91 (2003) 052001. Blum's formula.
- Aubin & Blum, Phys. Rev. D75 (2007) 114502.
- Feng et al., Phys. Rev. Lett. 107 (2011) 081802 .
- Hotzel et al., Lattice 2013.
- Boyle et al., Phys. Rev. D85 (2012) 074504.
- Della Morte et al., JHEP 1203 (2012) 055. Twisted BC.
- Aubin et al., Phys. Rev. D86 (2012) 054509. Pade approximants.
- RBC/UKQCD, PRL116, 232002 (2016). First disconnected diagrams.
- HPQCD, 1601.03071; PR D89, 114501 (2014). Moments method.

Hadronic vacuum polarization: Blum's formula

T. Blum, Phys. Rev. Lett. 91, 052001 (2003), hep-lat/0212018.

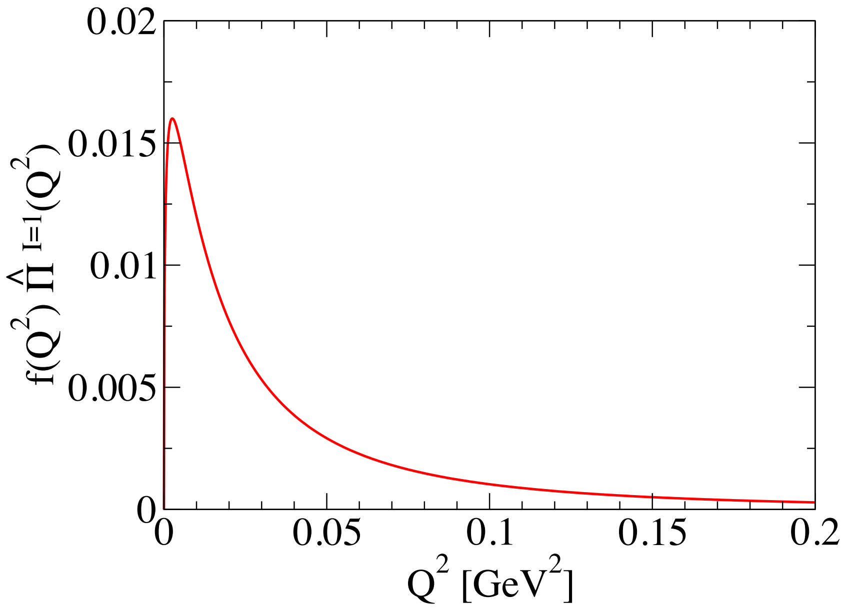
$$a_{\mu,\mathrm{HVP}}^{(\mathrm{f})} = \frac{\alpha}{\pi} \int_0^\infty dq^2 f(q^2)(4\pi\alpha Q_\mathrm{f}^2)\hat{\Pi}_\mathrm{f}(q^2) \qquad \hat{\Pi}(q^2) \equiv \Pi(q^2) - \Pi(0)$$

The four-dimensional integral yielding the hadronic vacuum polarization depends dynamically only on q^2.
The angular dependence of the kinematics factors may be integrated out with four-dimensional angular coordinates.
Result: *f* is given by:

$$f(q^2) \equiv \frac{m_\mu^2 q^2 A^3 (1 - q^2 A)}{1 + m_\mu^2 q^2 A^2}$$

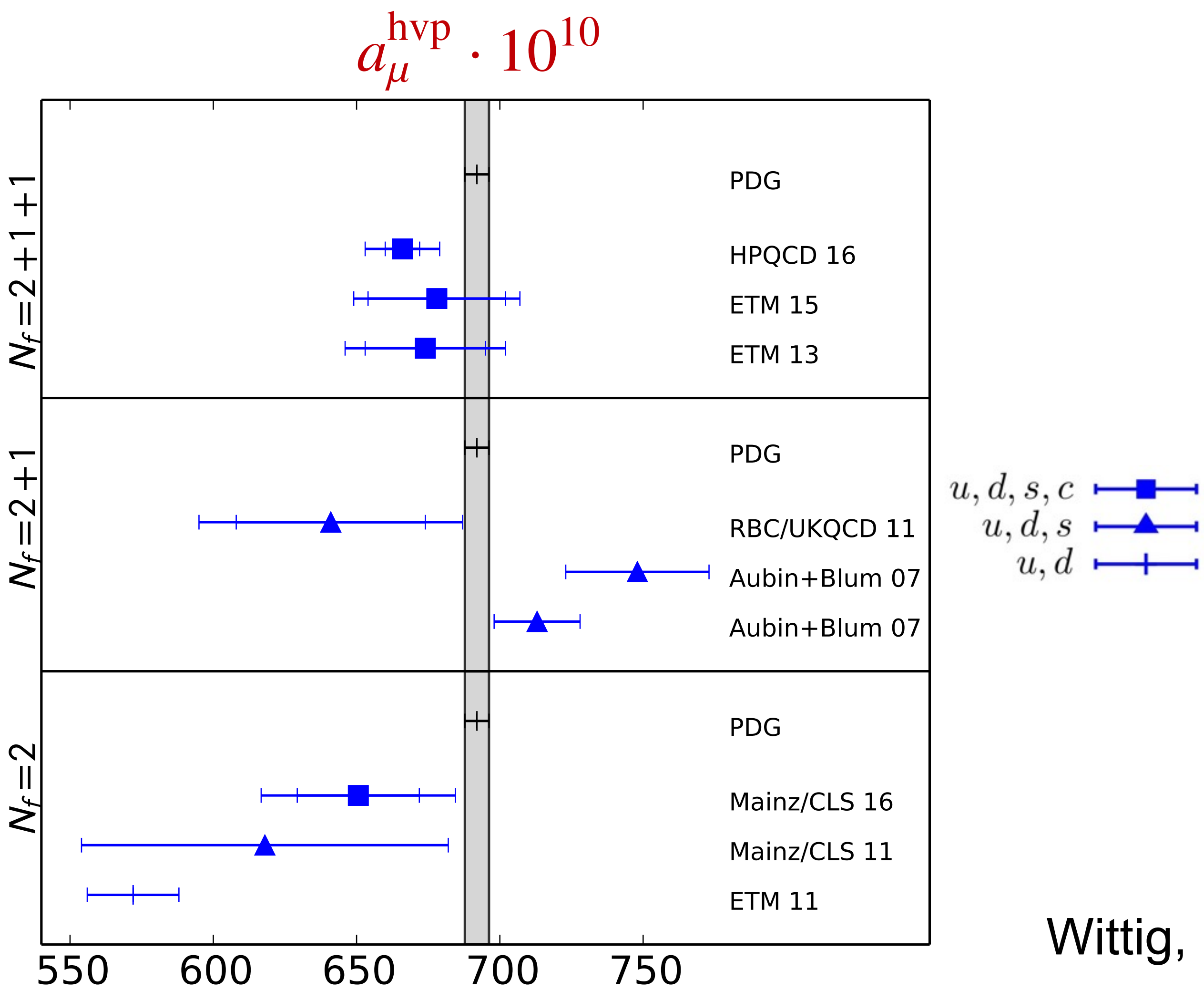
$$A \equiv \frac{\sqrt{q^4 + 4m_\mu^2 q^2} - q^2}{2m_\mu^2 q^2}$$

Combined support of dynamical and kinematical factors maxes around m_μ^2, as expected.



Golterman, Maltman, and Peris, PhysRevD. 90.074508, arXiv:1405.2389.

a_μ^{HVP}, summer 2016



Wittig, Lattice 2016

- The most precise lattice calculations claim uncertainties of ~2%.
- e+e- experiment is x3 more precise.
- To match expected g-2 experiment uncertainties, we'd like precision of 0.2 %.
- What are the prospects?

* Individual flavour contributions:

light (u,d)	≈ 90%
strange (s)	≈ 8%
charm (c)	≈ 2%

VP uncertainty future

Uncertainty dominated by isospin breaking, EM.
These effects have not been included at all yet.
Including them should reduce these dramatically.
Now in progress.

Connected diagrams

HPQCD/Fermilab/MILC.
Ruth Van de Water at Lattice 2017 and Muon g-2 Theory Initiative. 3-6 June,2017.

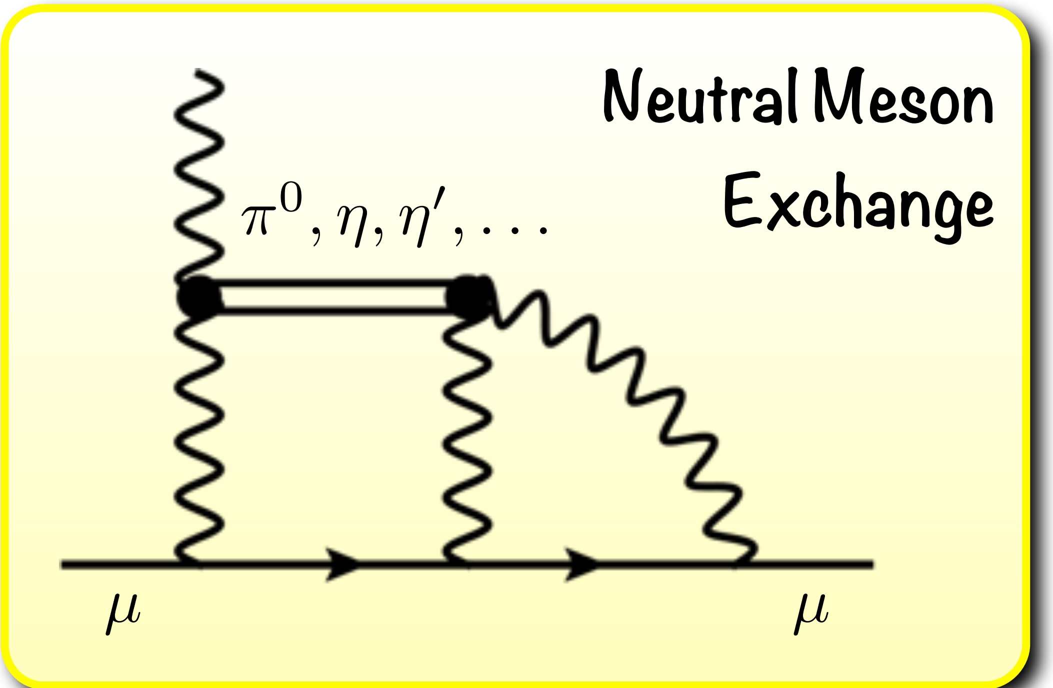
	$a_\mu^{ud,\mathrm{HVP}}$ (%) 2017 *preliminary*	$a_\mu^{ud,\mathrm{HVP}}$ (%) 1601.03071
QED corrections	1.0	1.0
Isospin-breaking corrections	1.0	1.0
Statistics + 2pt fit	0.5	0.4
Finite-volume & discretization corrections	0.4	0.7
Continuum ($a \to 0$) extrapolation	0.3	0.2
Noise reduction (t^*)	0.3	0.5
Chiral (m_l) extrapolation/interpolation	0.2	0.4
Current renormalization (Z_V)	0.2	0.2
Sea (m_s) adjustment	0.0	0.2
Padé approximants	0.0	0.4
Lattice-spacing (a^{-1}) uncertainty	0.0	< 0.05
Total	1.6	1.8

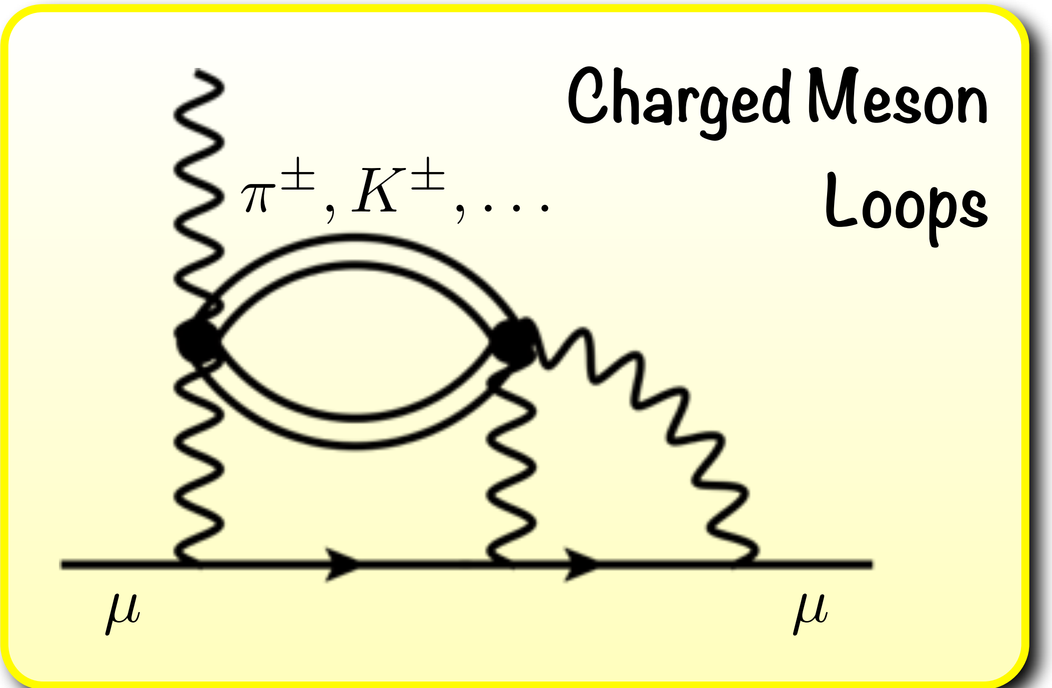
PRD 93, no. 7, 074509
from a half dozen effects, must be ground down by numerical brute force — no magic bullet.

Disconnected diagrams also needed.
Uncertainty currently estimated at 1.2%.
More study is underway.

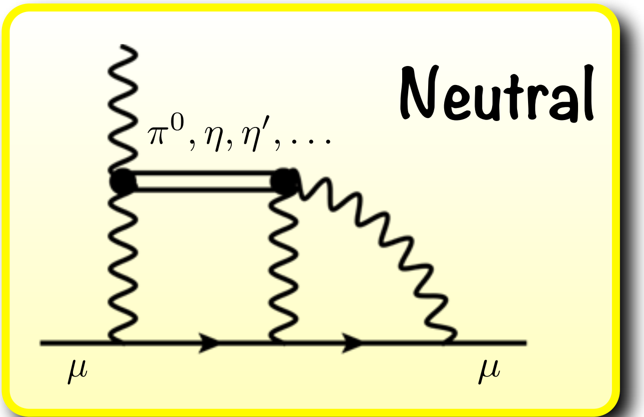
HLbL: estimation from hadronic models

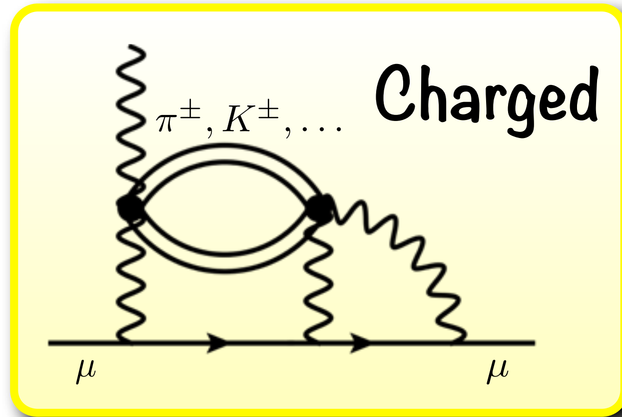
- Hadronic light-by-light contribution cannot be expressed in terms of experimental quantities and must be obtained from theory [cf. Jegerlehner and Nyffeler, Phys.Rept. 477 (2009) 1-110 and Refs. therein]
  - All recent calculations compatible with constraints from large-N_c and chiral limits
  - All normalize dominant π^0-exchange contribution to measured $\pi^0 \to \gamma\gamma$ decay width
  - Differ for form factor shape due to different QCD-model assumptions such as vector-meson dominance, chiral perturbation theory, and the large N_c limit





Hadronic light by light scattering: The "Glasgow consensus"





Estimated from hadronic models.

Prades, de Rafael, Vainshtein, 0901.0306, :0909.0953v1.

- Quoted error for a_μ^{HLbL} is based on model estimates, but does not cover spread of values.
  - π^0-exchange contribution estimated to be ~10 times larger than others.
  - Largest contribution to uncertainty ($\pm 1.9\times 10^{-10}$) attributed to charged pion and kaon loop contributions.

$$a^{\mathrm{HLbL}} = (10.5 \pm 2.6) \times 10^{-10}$$

Need $1.7\mathrm{x}10^{-10}$ to match planned experimental precision.

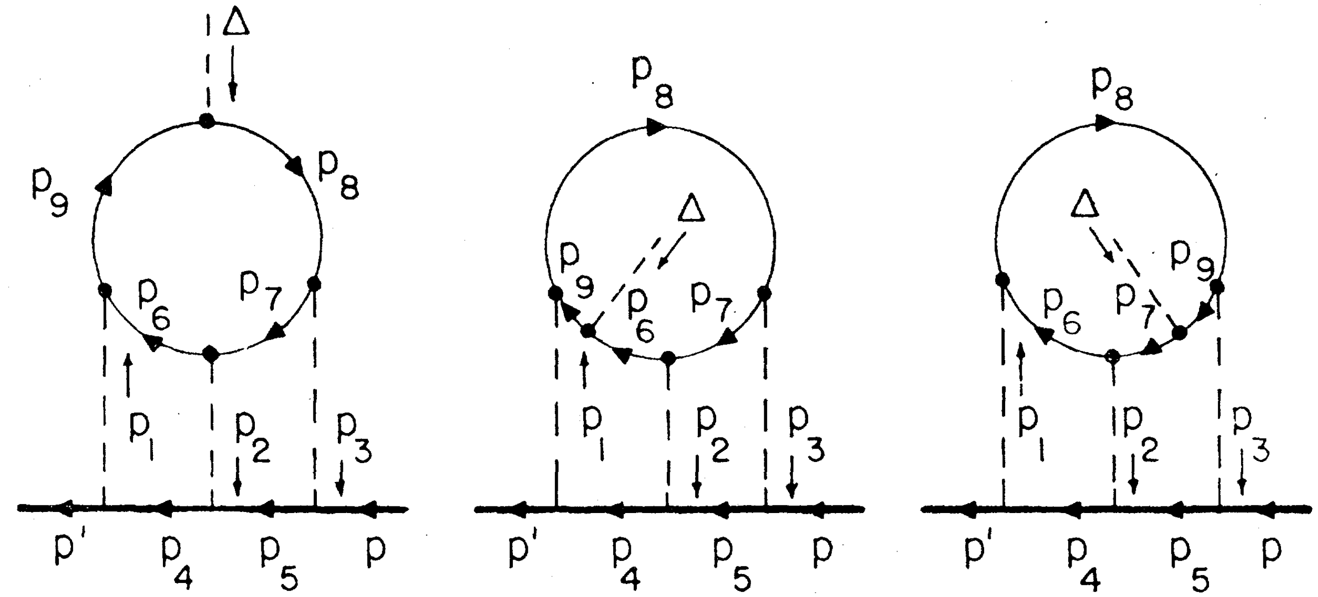
➡ Error could easily be underestimated (and comparable to that from HVP!),
and is not systematically improvable.

Notable lattice work on light-by-light scattering

- Hayakawa et al., PoS LAT2005 (2006) 353; Blum et al., PoS LATTICE2012 (2012) 022; ... Propose dynamical photons method.
- Cohen et al., PoS LATTICE2008 (2008) 159.
- Feng et al., Phys.Rev.Lett. 109 (2012) 182001.
- Rakow, Lattice 2008.
- Blum et al., PRD93, 014503 (2016); L. Jin, Lattice 2016.
- J. Green et al. (Mainz) Phys. Rev. Lek 115, 222003 (2015).

Hadronic LbL by brute force?

FIG. 1. Feynman diagrams containing subdiagrams of photon-photon scattering type. The heavy, thin, and dotted lines represent the muon, electron, and photon, respectively. There are three more diagrams obtained by reversing the direction of the electron loop.



Aldins, Brodsky, Durfner, & Kinoshita

$$M=\frac{e^2}{(2\pi)^8}\int d^4p_1d^4p_3\,p_1{}^{-2}p_2{}^{-2}p_3{}^{-2}$$
$$\times\epsilon^\mu\Pi_{\kappa\rho\sigma\mu}(-p_1,p_2,p_3,-\Delta)\bar{u}(p')\gamma^\kappa(\not{p}_4-m_\mu)^{-1}$$
$$\times\gamma^\rho(\not{p}_5-m_\mu)^{-1}\gamma^\sigma u(p)\,,\quad(2.2)$$

Five exterior photon momenta to integrate. At each point, ~64 terms (e.g., photon gamma matrices).

To do LbL with ordinary methods naively takes orders of magnitude more CPU time than simpler calculations.

and $\Pi_{\kappa\rho\sigma\mu}$ is the polarization tensor of fourth rank representing the photon-photon scattering

$$\Pi_{\kappa\rho\sigma\mu}(-p_1,p_2,p_3,-\Delta)$$
$$=\frac{-ie^4}{(2\pi)^4}\int d^4p_6\,\mathrm{Tr}[\gamma_\kappa(\not{p}_6-m_e)^{-1}\gamma_\rho(\not{p}_7-m_e)^{-1}$$
$$\times\gamma_\sigma(\not{p}_8-m_e)^{-1}\gamma_\mu(\not{p}_9-m_e)^{-1}$$
$$+(\text{five other terms})-(\text{regularization terms})].\ (2.3)$$

Replace with LQCD calculation.

Dynamical photon method

Hayakawa et al., PoS LAT2005 (2006) 353

- Method introduced by Blum and collaborators in which one computes the full hadronic amplitude, including the muon and photons, nonperturbatively.
- Treat photon field in parallel with gluon field and include in gauge link, so the simulation and analysis follows a conventional lattice-QCD calculation.
- In practice, must insert a single valence photon connecting the muon line to the quark loop “by hand” into the correlation function, then perform correlated nonperturbative subtraction to remove the dominant O(α^2) contamination.
- Three RBC papers in the last two years have developed this method into a practical tool:
    - arXiv:1510.07100, Phys.Rev. D93 (2016) no.1, 014503.
    - arXiv:1610.04603, Phys.Rev.Lett. 118 (2017) no.2, 022005.
    - arXiv:1705.01067.

Mixed dynamical and analytic photons…

Blum et al., PRD93, 014503 (2016);
Phys.Rev.Lett. 118 (2017) no.2, 022005.

- **New method combines dynamical QCD gauge-field configurations with exact analytic formulae for photon propagators.**
  - Exploits stochastic methods for position-space sums to control computational cost.
  - Obtain **$\lesssim$10% statistical errors at the physical pion mass** in ballpark of Glasgow consensus value $a_\mu^{\mathrm{HLbL,GC}} \times 10^{10} = 10.5(2.6)$.

$$a_\mu^{\mathrm{HLbL}} \times 10^{10} = \begin{cases} 11.60(0.96)_{\mathrm{stat.}} & \text{connected} \\ -6.25(0.80)_{\mathrm{stat.}} & \text{disconnected} \end{cases}$$

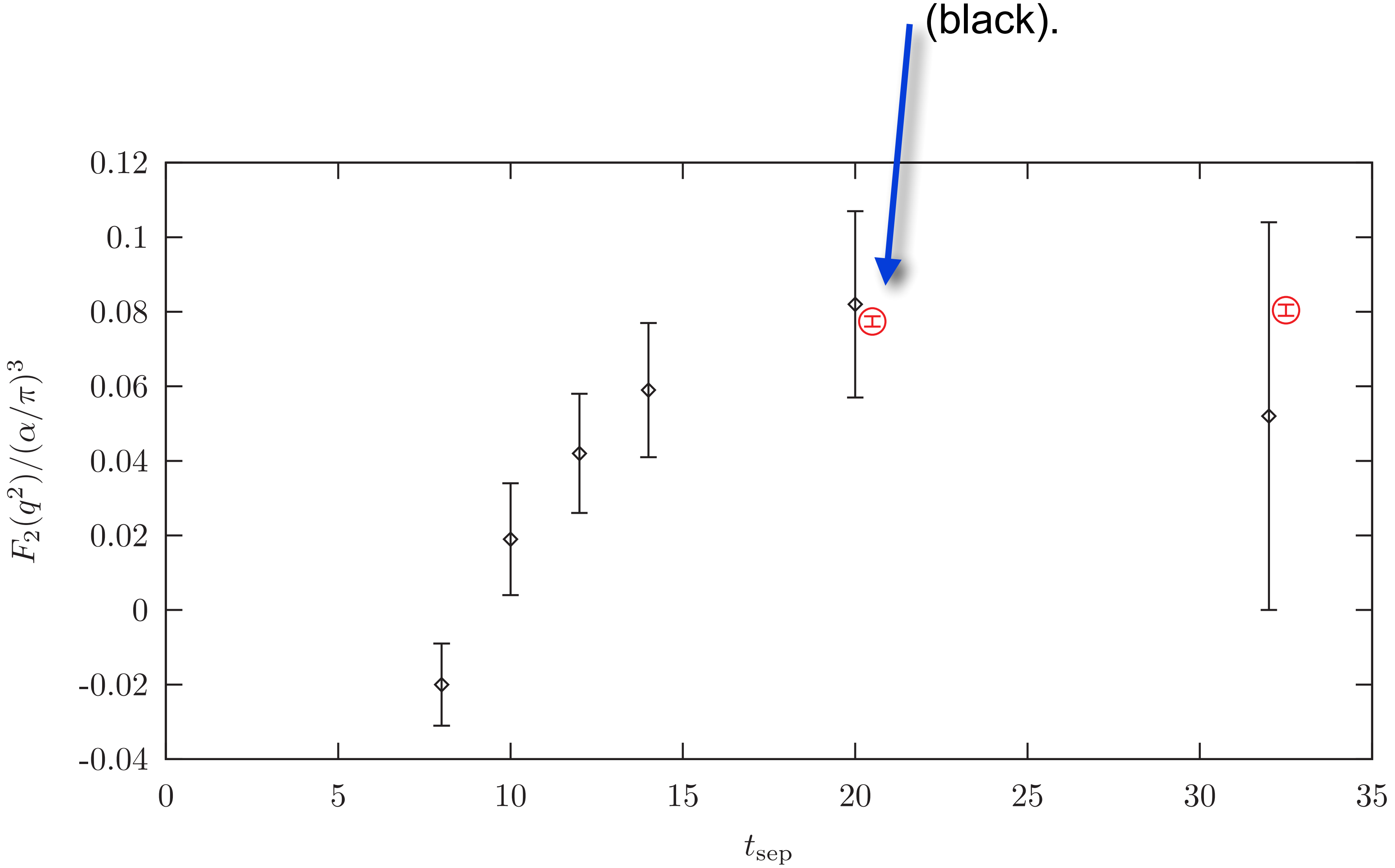
Statistical errors at least are in the ballpark required.

L. Jin, Lattice 2016; preliminary update of Blum *et al*.

- Full study of systematic errors including lattice-spacing and finite-volume effects was still needed — dynamical photons have power-law volume corrections instead of exponential in the pion mass (the usual case). **Initial results encouraging!**

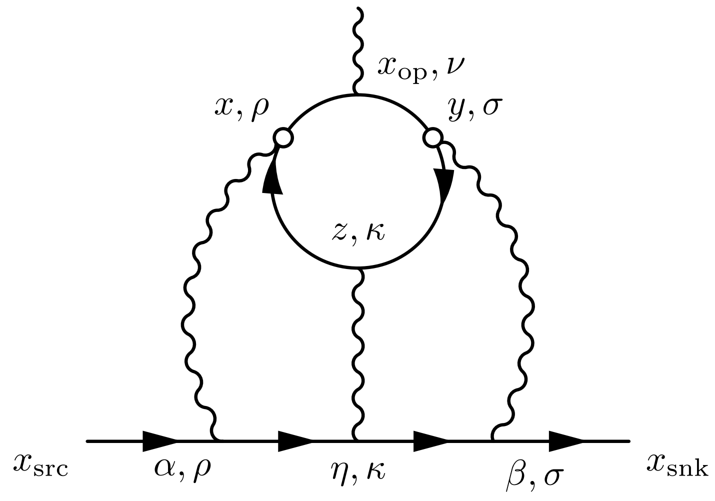
… yield a great improvement in statistics

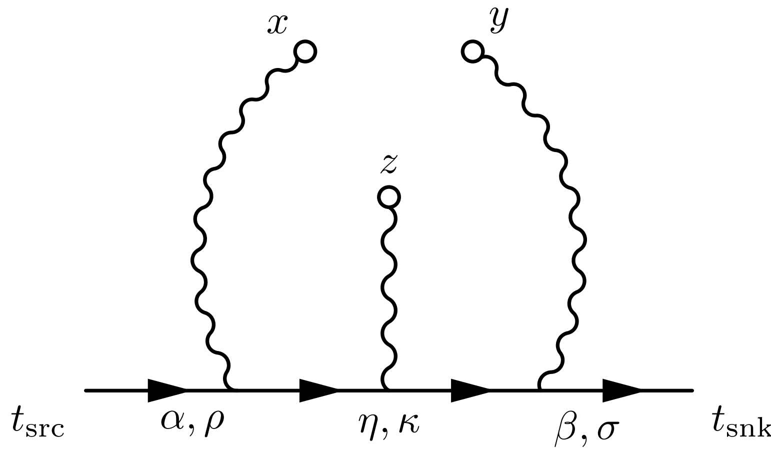
Statistical precision of new method (red) is an order of magnitude better than the previous method (black).



Dynamical photon method: finite volume errors

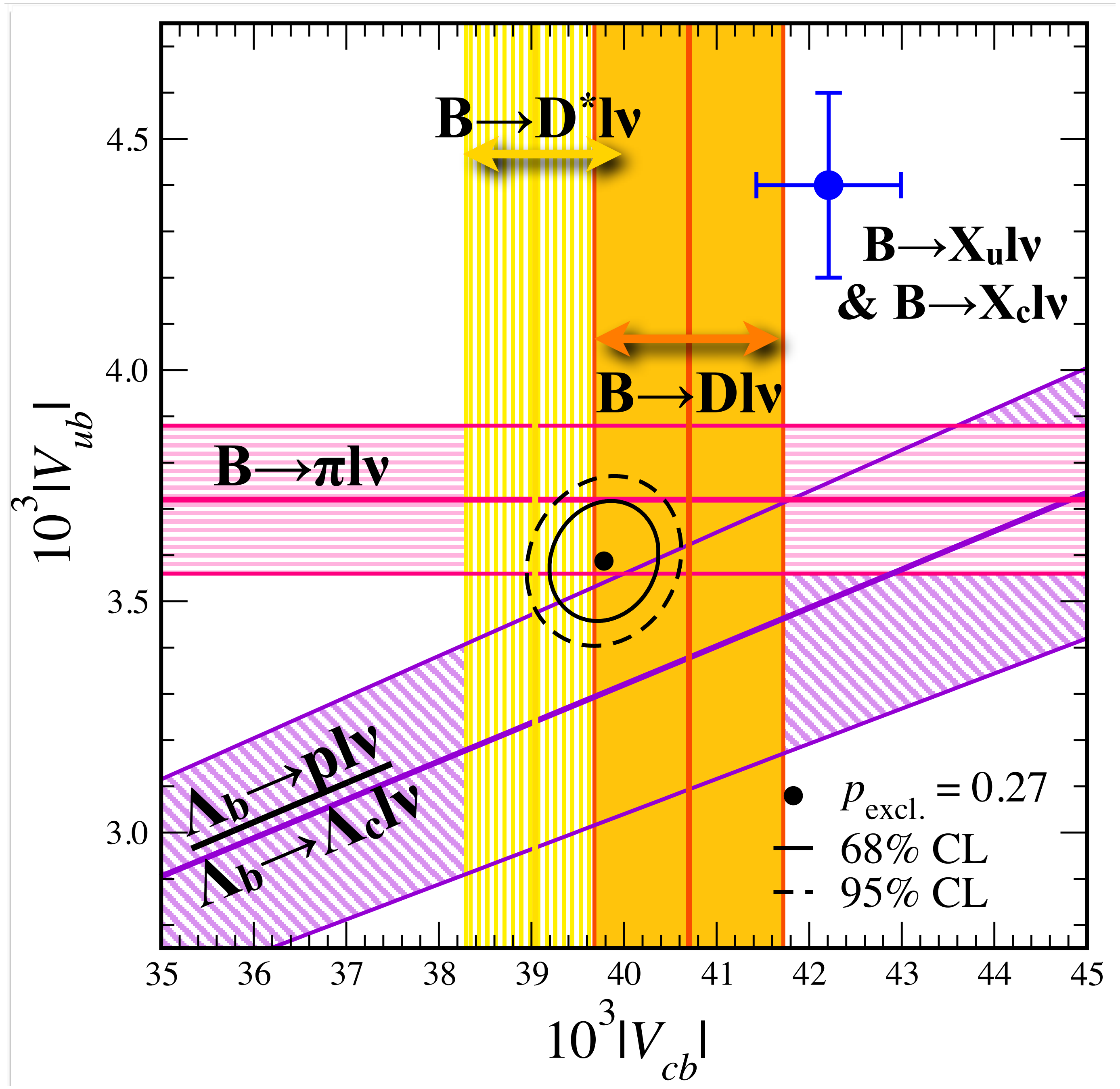
- Last year's results had no full uncertainty budget - only statistical errors.
  - They noted that finite volume errors could be large since they fall as a power of the lattice size rather than exponentially.
- This year, in arXiv:1705.01067, they improved their method by formulating the photons in infinite volume before folding into the lattice calculation.
- Their conclusion: light by light is now feasible.





Quark flavor physics: tensions

See Van de Water, ICHEP 2016 and FPCP 2016



Fit from Kronfed.

V_{ub}

- 2× smaller error on $|V_{ub}|$ from $B \to \pi l\nu$
- Determinations from inclusive & exclusive semileptonic B decays continue to differ by >2σ …

V_{cb}

- Exclusive $|V_{cb}|$ from $B \to Dl\nu$ over full kinematic range agrees with exclusive value
- Lattice-QCD calculation of $B \to D^* l\nu$ at nonzero recoil in progress ... perhaps "puzzle" will resolve itself?

ρ-η plane

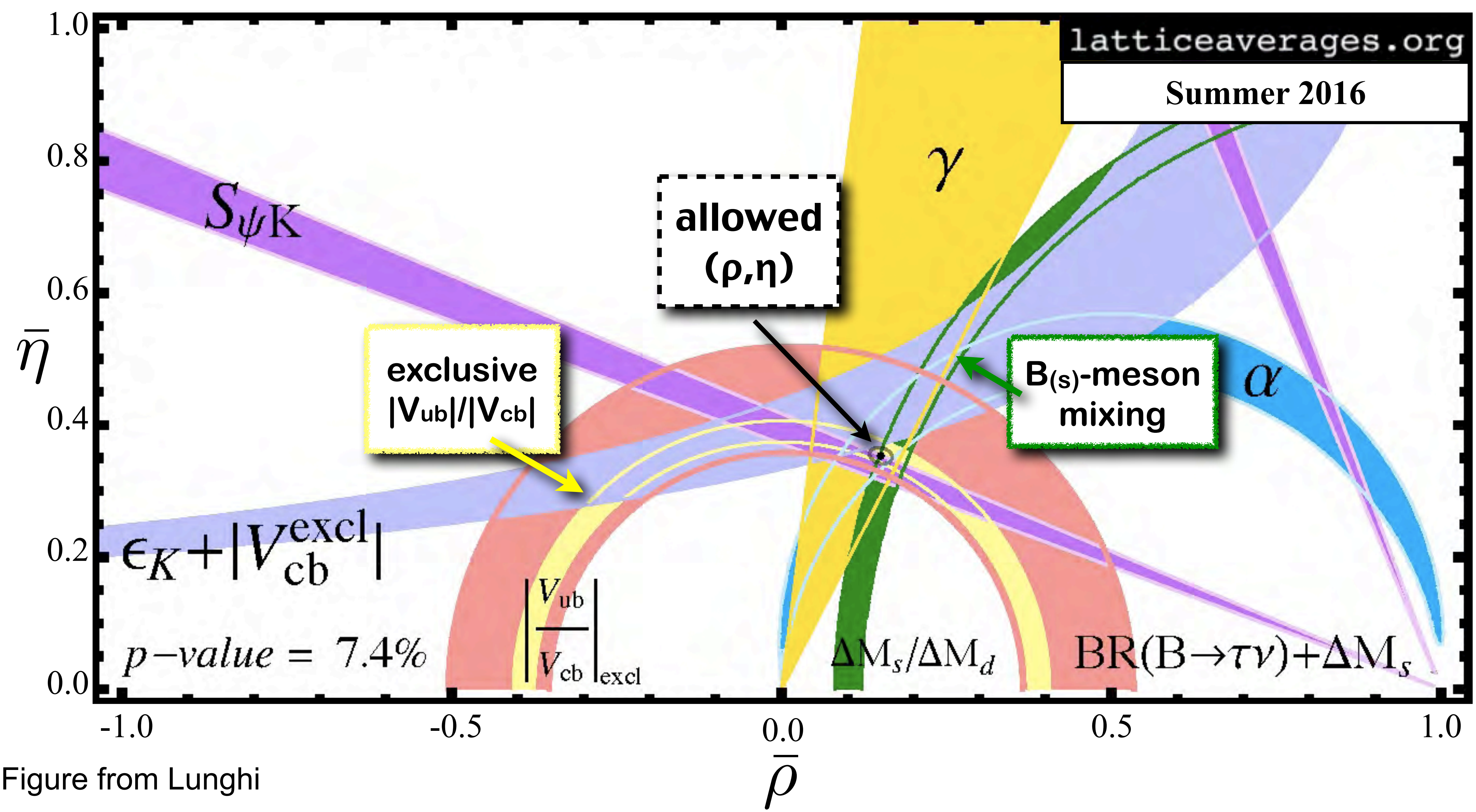


Figure from Lunghi

Quark flavor physics

Not that many papers in the last year, but a lot is happening.

> 30 flavor talks scheduled at Lattice 2017, June 18-24 Granada.

- 14:30 Semileptonic B-meson decays to light pseudoscalar mesons on the HISQ ensembles - Kronfeld
- 14:50 $B \rightarrow \pi\ell\nu$ with M\"{o}bius Domain Wall Fermions - Colquhoun
- 15:10 $B_s \to K \ell\nu$ form factors with 2+1 flavors - Gottlieb
- 15:30 Nonperturbative determination of form factors for semileptonic Bs meson decays - Witzel
- 15:50 HQET form factors for $B_s→K\ell\nu$ decays beyond leading order - Koren
- 16:40 The $B_s \rightarrow D_s$ decay with highly improved staggered quarks and NRQCD - Mclean
- 17:00 $\bar{B}\rightarrow D^\star \ell \bar{\nu}$ at non-zero recoil - Aviles-Casco
- 17:20 Calculation of $\bar{B} \rightarrow D^\ast \ell \bar{\nu}$ form factor at zero-recoil using the Oktay-Kronfeld action - Park
- 17:40 Decay constant and semileptonic form factors of Bc meson - Mathur

More talks at Lattice 2017

- 15:00 Semileptonic B_c decays from highly improved staggered quarks and NRQCD - Lytle
- 15:20 $\Lambda_b \to \Lambda(1520) \ell^+\ell^-$ form factors with moving NRQCD - Rendon
- 15:40 Charmed and bottom pseudoscalar meson decay constants and quark masses m_b and m_c from HISQ simulations - Komijani
- 16:00 Improving the theoretical prediction for the $B_s-\bar{B}_s$ width difference: matrix elements of next-to-leading order $\Delta B = 2$ operators - Wingate
- 16:20 Neutral D-meson mixing matrix elements in three-flavor lattice QCD - El-Khadra
- 17:10 D meson semileptonic form factors in Nf=3 QCD with Moebius domain-wall quarks - Kaneko
- 17:30 Charm baryon semileptonic decays with lattice QCD - Meinel
- 17:50 Scalar and vector form factors for the $D \to \pi(K) \ell\nu$ and towards $B \to \pi(K) \ell\nu$ semileptonic decays with Nf=2+1+1 Twisted femions - Salerno
- 18:10 Tensor form factor for the $D \to \pi(K)$ transitions with Twisted Mass fermions. - Riggio
- 18:30 $D \rightarrow Kl\nu$ semileptonic decay in lattice QCD with HISQ - Chakraborty
- 18:50 Charm Physics with Domain Wall Fermions - Tsang

Still more talks at Lattice 2017

- 09:00 On the Ds* and charmonia leptonic decays - Blossier
- 09:20 Leptonic decay constants for D-mesons from 3-flavour CLS ensembles - Eckert
- 09:40 Total decay and transition rates from LQCD: (I) The method and a numerical test - Robaina
- 10:00 Total decay and transition rates from LQCD: (II) Applications and extensions - Hansen
- 10:20 Inclusive B decay calculations with analytic continuation - Hashimoto
- 10:40 Electromagnetic Corrections to Decay Amplitudes - Martinelli
- 11:30 BSM Kaon Mixing at the Physical Point - Kettle
- 11:50 Non-leptonic kaon decays at large N_c - Donini
- 12:10 Including electromagnetism in K->pipi decay calculations - Christ
- 12:30 The K_L-K_S Mass Difference - Sachrajda
- 12:50 Rare kaon decays K -> pi l+ l- with 3 flavours - Lawson
- 13:10 Progress in the improved lattice calculation of direct CP-violation in the Standard Model - Kelly

Work in progress: f_B, f_{Bs}, m_q

Javad Komijani at Lattice 2017
for Fermilab/MILC

$$
\begin{aligned}
f_{D^+} &= 212.71 \pm 0.27_{\mathrm{stat}} \pm 0.26_{\mathrm{sys}} \pm 0.21_{f_{\pi^+},\mathrm{PDG}} \ \mathrm{MeV} \\
f_{D_s} &= 249.96 \pm 0.26_{\mathrm{stat}} \pm 0.23_{\mathrm{sys}} \pm 0.19_{f_{\pi^+},\mathrm{PDG}} \ \mathrm{MeV} \\
f_{B^+} &= 189.79 \pm 0.77_{\mathrm{stat}} \pm 0.34_{\mathrm{sys}} \pm 0.24_{f_{\pi^+},\mathrm{PDG}} \ \mathrm{MeV} \\
f_{B_s} &= 231.16 \pm 0.69_{\mathrm{stat}} \pm 0.28_{\mathrm{sys}} \pm 0.24_{f_{\pi^+},\mathrm{PDG}} \ \mathrm{MeV}
\end{aligned}
$$

Follows HPQCD approach with highly improved staggered quarks with m_c<m_q<m_b.

The quark masses are in MeV and the $\overline{\mathrm{MS}}$ scale is set to $\mu = 2\mathrm{GeV}$.

	Central	Alt.1	Alt.2	Alt.3	FV	EM1	EM2	EM3	α_S	f_π PDG
$m_s(\mu)$	92.32(49)	-0.039	-0.009	+0.072	+0.077	-0.005	-0.15	-0.001	$\pm$ 0.53	$\pm$ 0.36
$m_d(\mu)$	4.649(26)	+0.012	+0.008	-0.001	+0.007	+0.037	+0.001	-4.2e-05	$\pm$ 0.027	$\pm$ 0.018
$m_u(\mu)$	2.133(17)	-0.0023	-0.0015	+0.0029	+0.0049	-0.035	+0.001	-1.9e-05	$\pm$ 0.012	$\pm$ 0.0084
$\frac{m_c}{m_{p4s}}$	29.44(3)	+0.003	-0.0035	-0.023	-0.015	+0.003	+0.054	-0.026	$\pm$ 0.001	$\pm$ 0.031
$\frac{m_c}{m_s}$	11.777(12)	+0.001	-0.0014	-0.0092	-0.0059	+0.0013	+0.022	-0.01	$\pm$ 0.0002	$\pm$ 0.012
$\overline{m}_c$	1271(5)	-0.3	-0.19	-0.0056	+0.3	+0.047	+0.17	-0.8	$\pm$ 9.6	$\pm$ 0.94
$\frac{m_b}{m_{p4s}}$	134.74(22)	+0.036	+0	-0.1	-0.093	+0.01	+0.23	+0.014	$\pm$ 0.006	$\pm$ 0.22
$\frac{m_b}{m_s}$	53.90(09)	+0.014	+0	-0.042	-0.037	+0.004	+0.092	+0.0056	$\pm$ 0.002	$\pm$ 0.088
$\overline{m}_b$	4192(14)	-0.56	-0.34	+0.011	+0.5	+0.064	+0.21	+0.33	$\pm$ 7.8	$\pm$ 5.8

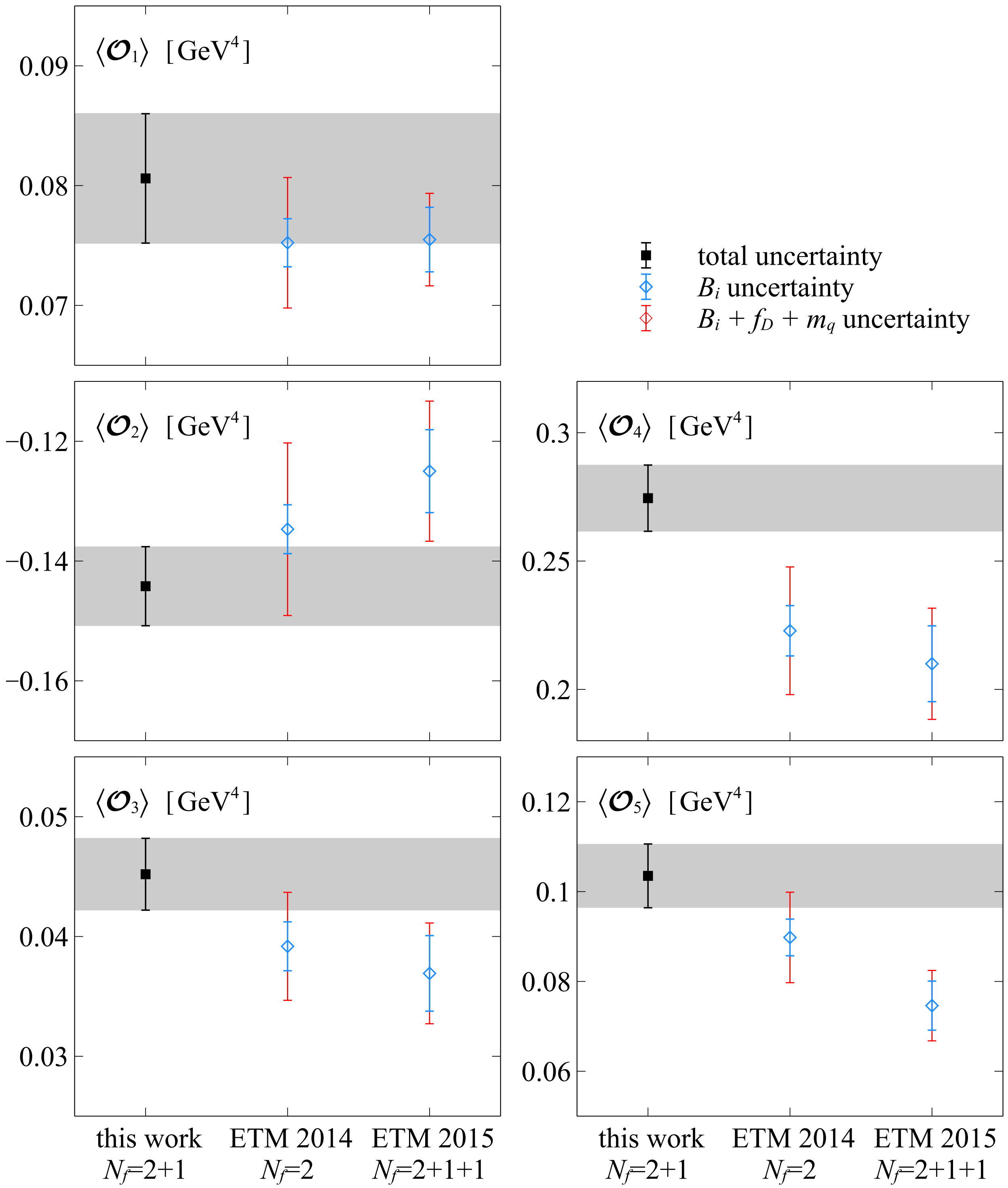
Rivals HPQCD's correlation function moments method in precision.

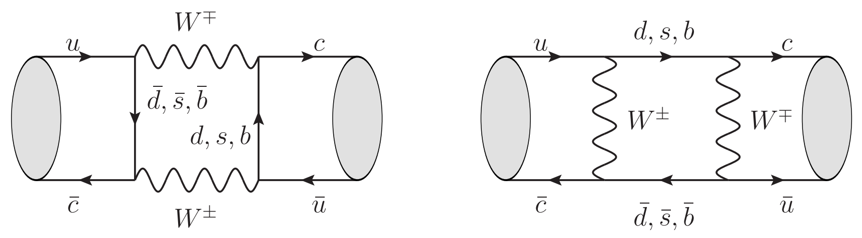
Aside: *Lattice QCD is everywhere*.

- Everyone knows that lattice has a critical role in flavor, g-2, but
- Virtually any kind of physics will need nonperturbative corrections when the precision goals get high enough.
  - Neutrino physics, high energy e+e- scattering, ..
- Example: searching for BSM physics in Higgs partial widths at a high luminosity ILC.
  - Goal is to measure partial widths to 0.5% accuracy.
  - $\Rightarrow$ Need standard model prediction to 0.5%.
  - $\Rightarrow$ Need m_b to 0.5%.

Work in progress: short-distance *D*-*D*bar mixing

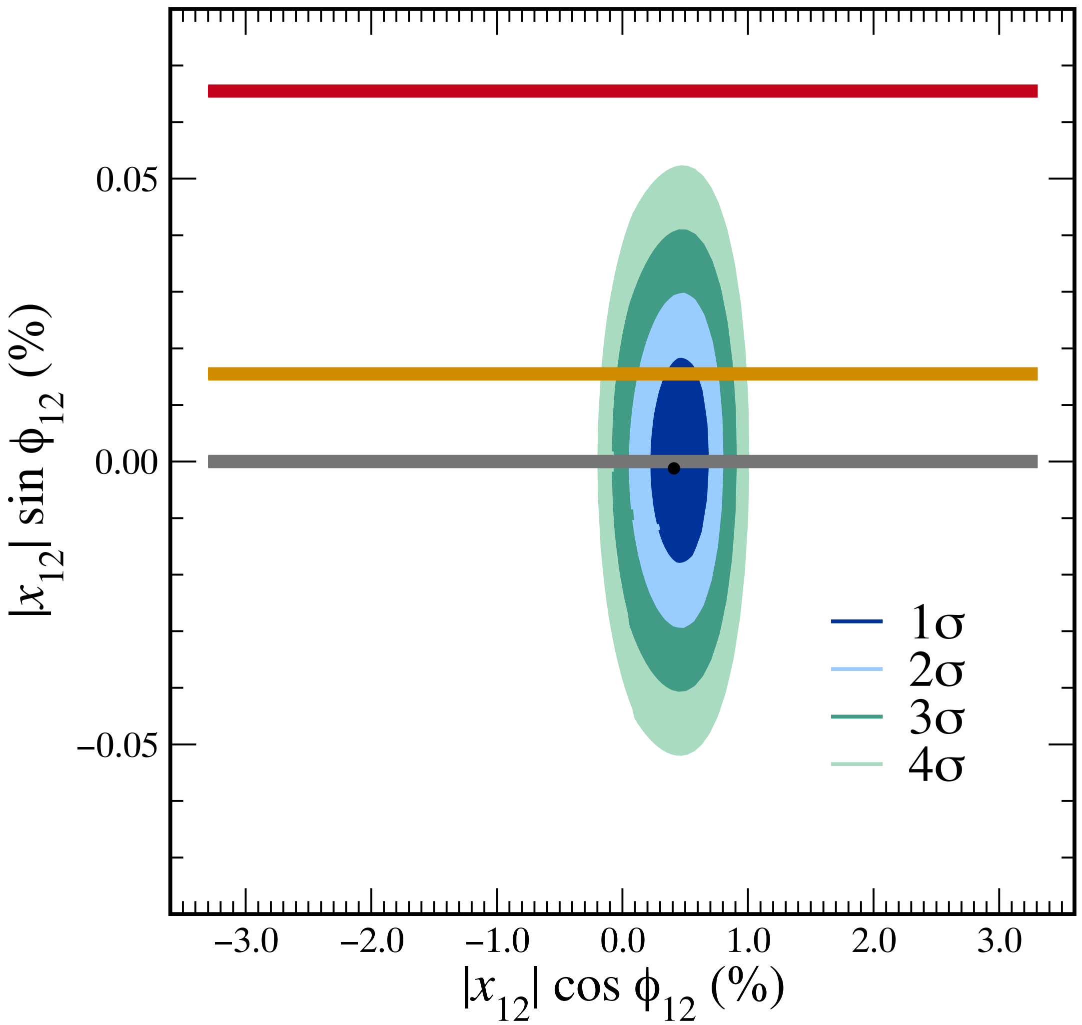
Jason Chang, Lattice 2017
for Fermilab MILC

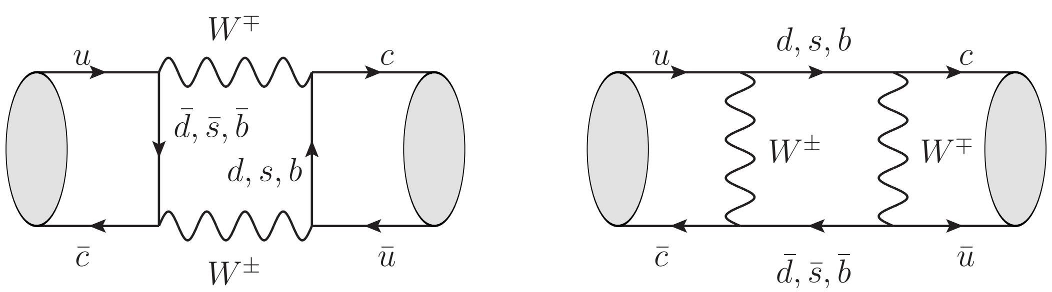




D-*D*bar mixing has long distance effects more important than *K*-*K*bar mixing.
We're looking at short-distance part only.

- Agree with ETM 2015 results.





*D-D*bar mixing has long distance effects more important than *K-K*bar mixing.
We're looking at short-distance part only.

SM contributions, both long- and short-distance, are highly Cabibbo suppressed.
BSM effects need not be, so calculation of the BSM mixing operators enable bounds on new physics assuming no Cabibbo suppression.

FIG. 17. $|x_{12}|e^{i\phi_{12}}$ plotted as a complex number. With no new physics, the Standard-Model estimate (gray bar) is compatible with the experimental best-fit contours (blue regions). The other two bars show predictions for the complex x_{12} in two specific new-physics scenarios, corresponding to the simple "$\mathcal{O}_5$-only" model described in the text. The gold bar shows the SM+NP region with model parameter $\Lambda_{\rm NP} = 40\,000$ TeV, while the red bar shows the choice $\Lambda_{\rm NP} = 18\,000$ TeV. The former value is compatible with current experimental bounds, while the latter is ruled out.

Summary

- The needs for lattice-QCD calculations are broader and deeper than ever before.
- *Lattice QCD is everywhere.*

Backup

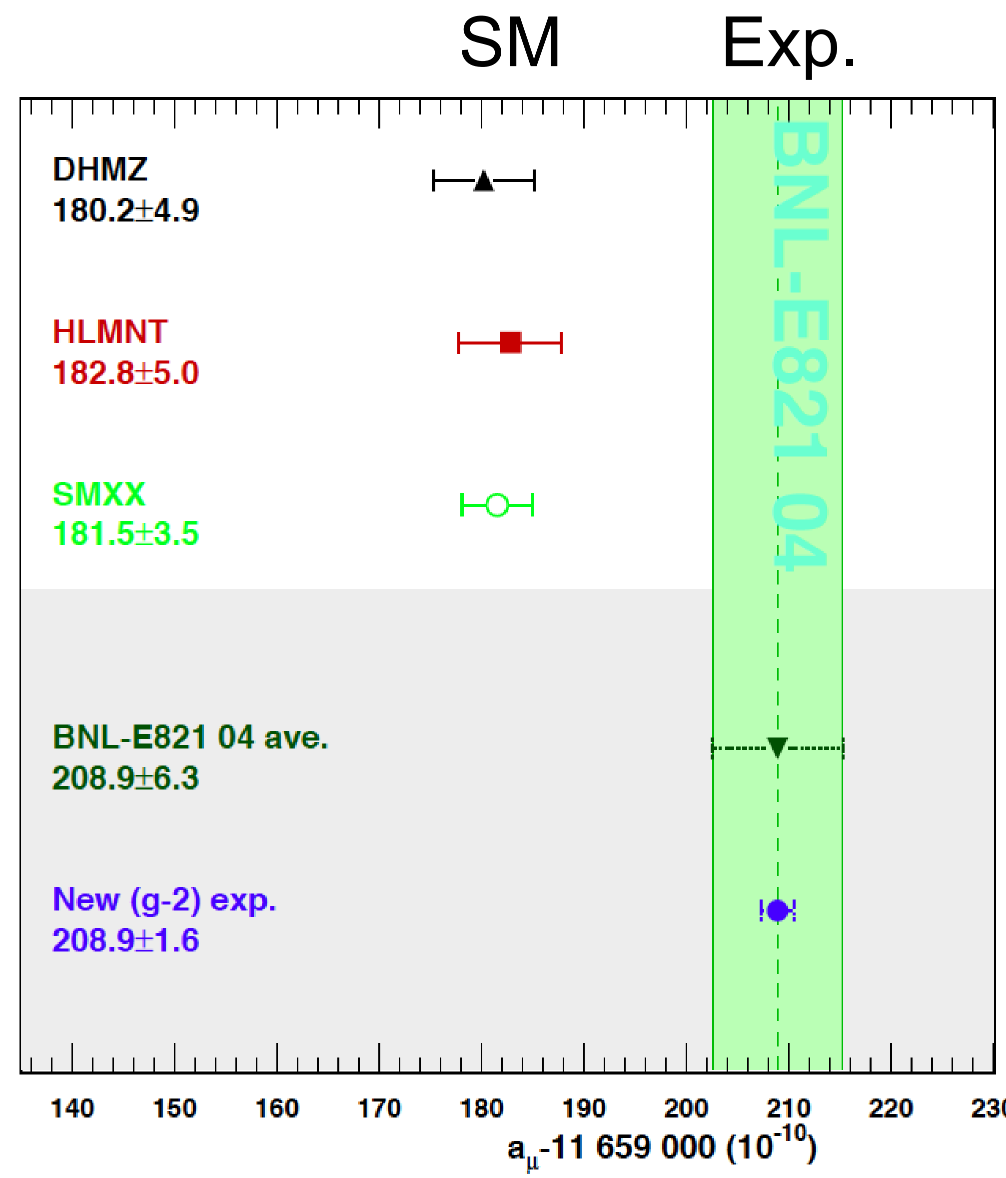
Results for f

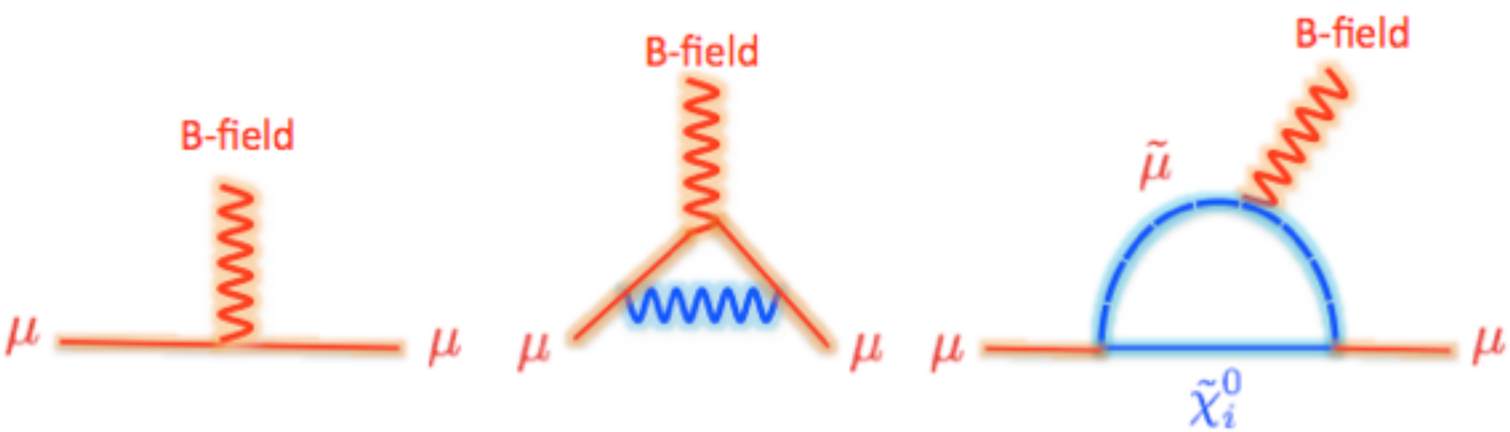
$$\begin{aligned}
f_{D^+} &= 212.71 \pm 0.27_{\rm stat} \pm 0.26_{\rm sys} \pm 0.21_{f_{\pi^+,\rm PDG}}\ \mathrm{MeV} \\
f_{D_s} &= 249.96 \pm 0.26_{\rm stat} \pm 0.23_{\rm sys} \pm 0.19_{f_{\pi^+,\rm PDG}}\ \mathrm{MeV} \\
f_{B^+} &= 189.79 \pm 0.77_{\rm stat} \pm 0.34_{\rm sys} \pm 0.24_{f_{\pi^+,\rm PDG}}\ \mathrm{MeV} \\
f_{B_s} &= 231.16 \pm 0.69_{\rm stat} \pm 0.28_{\rm sys} \pm 0.24_{f_{\pi^+,\rm PDG}}\ \mathrm{MeV} \\
f_{D_s}/f_{D^+} &= 1.1752 \pm 0.0007_{\rm stat} \pm 0.0007_{\rm sys} \pm 0.0003_{f_{\pi^+,\rm PDG}} \\
f_{B_s}/f_{B^+} &= 1.2180 \pm 0.0032_{\rm stat} \pm 0.0014_{\rm sys} \pm 0.0003_{f_{\pi^+,\rm PDG}} \\
f_{B_s}/f_{B^0} &= 1.2105 \pm 0.0028_{\rm stat} \pm 0.0010_{\rm sys} \pm 0.0003_{f_{\pi^+,\rm PDG}} \\
f_{B_s}/f_{D_s} &= 0.9248 \pm 0.0022_{\rm stat} \pm 0.0003_{\rm sys} \pm 0.0002_{f_{\pi^+,\rm PDG}}
\end{aligned}$$

BNL-E821

Standard-model theory disagrees with the results of g-2 of the muon experiment BNL E821 by several σ.

Could be experimental or theoretical error, or it could be new physics.



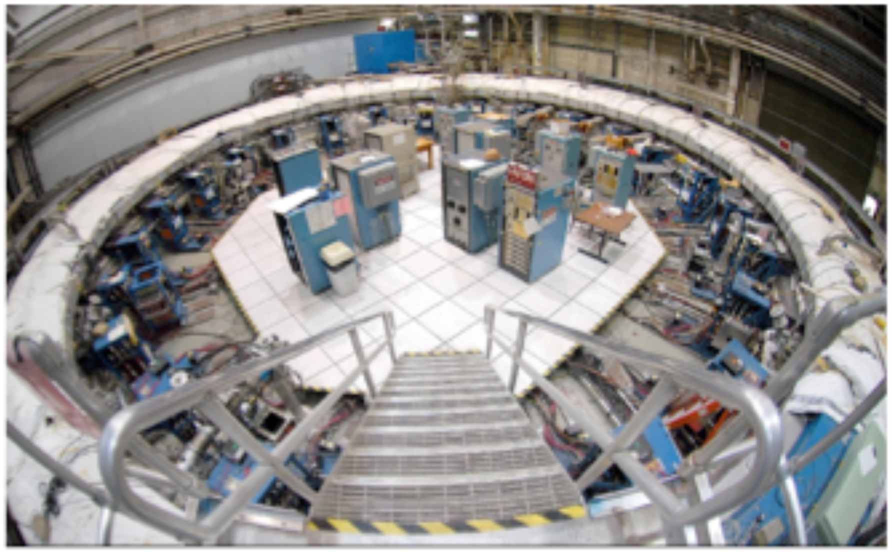


"Dirac Interaction"
g=2

QED "Schwinger Interaction"
(g-2)=α/π

BSM SUSY interaction

➜ Move to Fermilab; continue with more muons.



BNL Storage Ring during data-taking in 2001

The magnet moves up the Mississippi

The magnet arrives at Fermilab