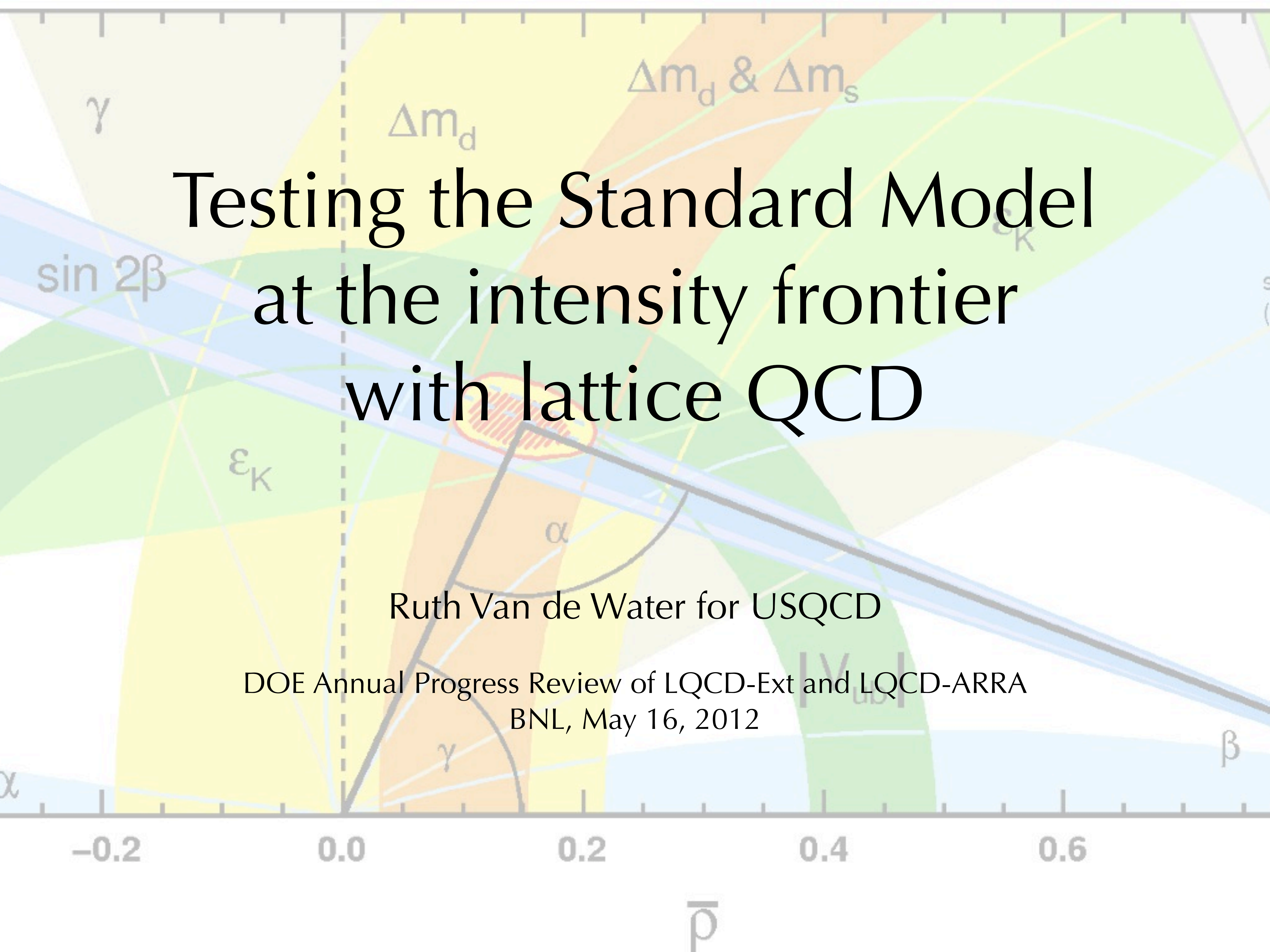
Testing the Standard Model at the intensity frontier with lattice QCD

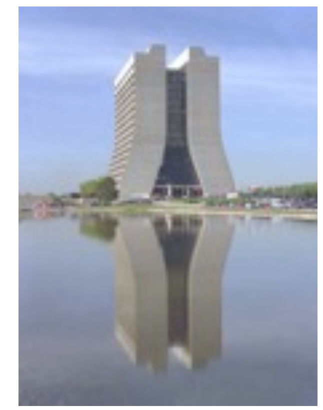
Ruth Van de Water for USQCD

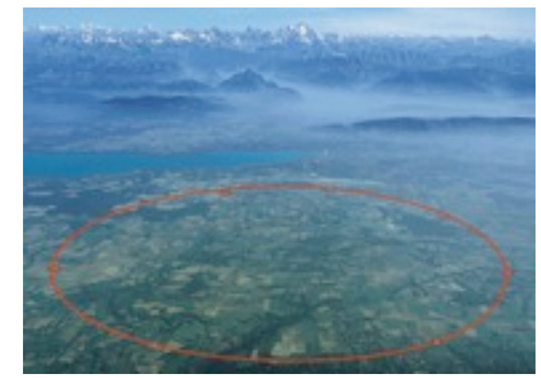
DOE Annual Progress Review of LQCD-Ext and LQCD-ARRA
BNL, May 16, 2012



Beyond-the-Standard-Model search strategies

- The experimental high-energy physics community is presently searching for new physics with two complimentary approaches



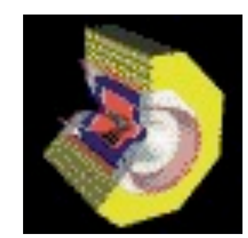


(1) Production of new particles at colliders

- *E.g.*, ATLAS and CMS may be closing in on the search for the Higgs boson…

(2) Precise measurements of Standard Model parameters

- *E.g.*, heavy flavor factories have been pouring out data to pin down CKM matrix elements & the CP-violating phase
- Upcoming high-intensity experiments will improve existing measurements and observe some rare decay processes for the first time
- Compare measurements to Standard Model predictions and look for inconsistencies



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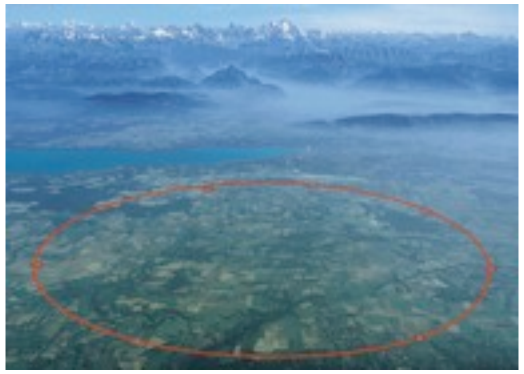

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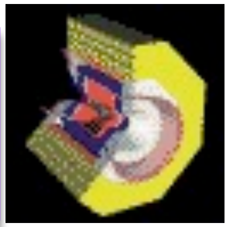
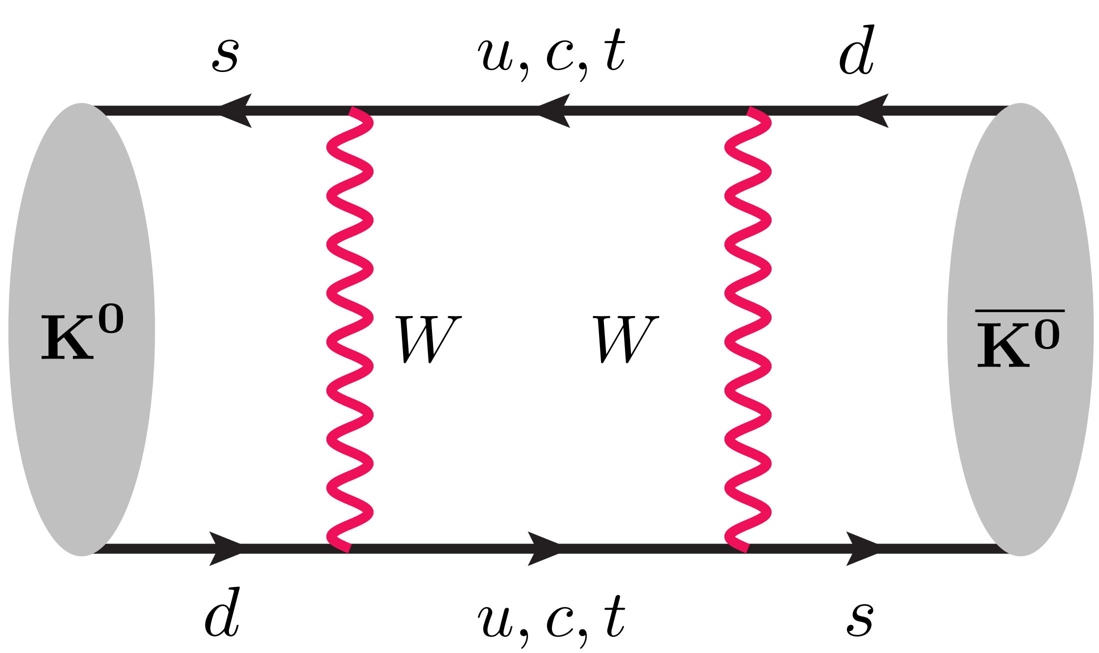
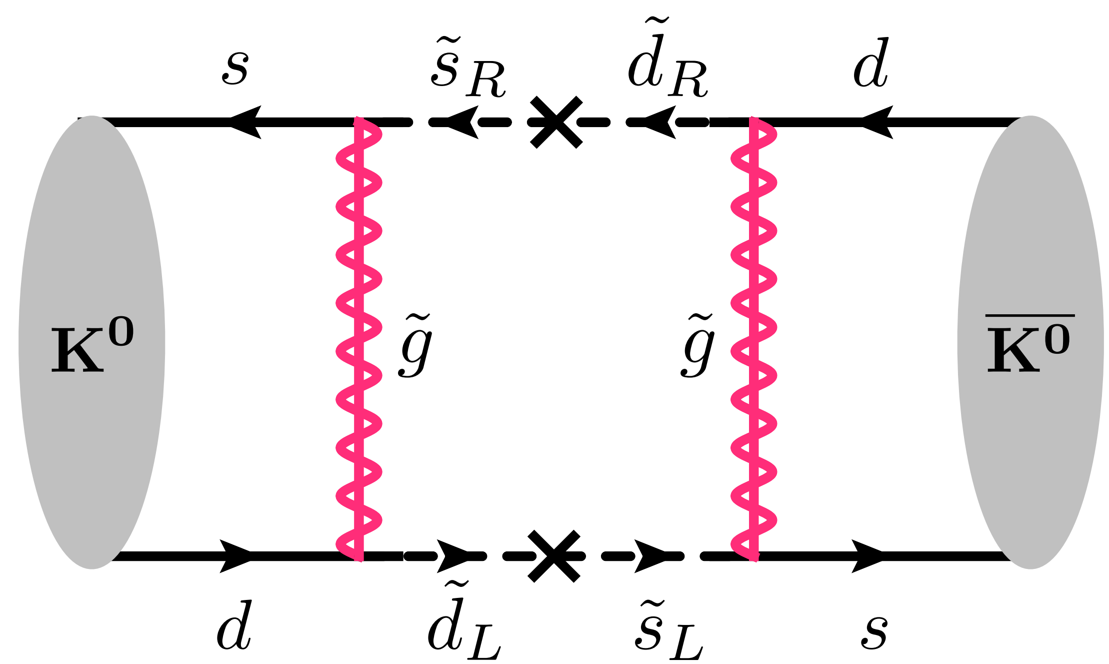
Lattice QCD calculations are needed to interpret many of their results . . .



Why study flavor physics?

- Most Standard Model extensions contain new CP-violating phases and new quark-flavor changing interactions, so we expect new physics effects in the flavor sector
- New particles will typically appear in loop-level processes such as neutral kaon mixing:

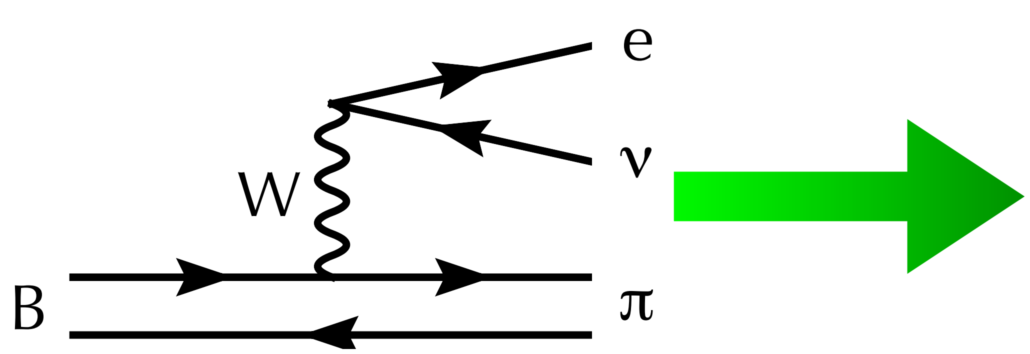


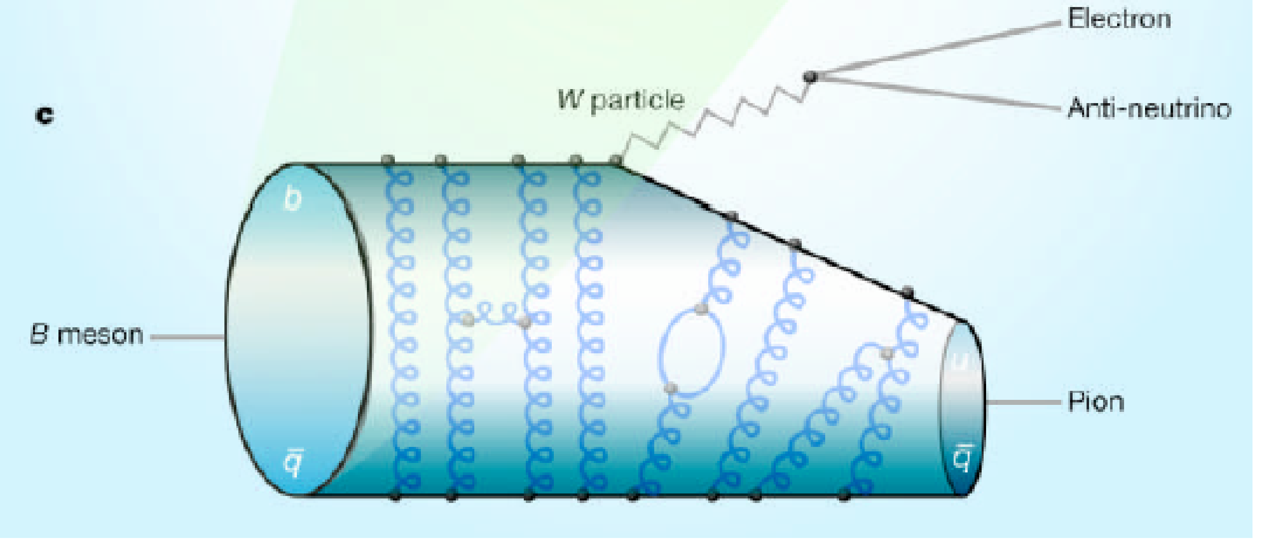


- Sensitive to physics at higher energy scales than those probed in high-p_T collider experiments, in some cases $\mathcal{O}$(1,000 - 10,000 TeV)
  [Isidori, Nir, Perez, Ann.Rev.Nucl.Part.Sci. 60 (2010) 355]

Lattice QCD and precision flavor physics

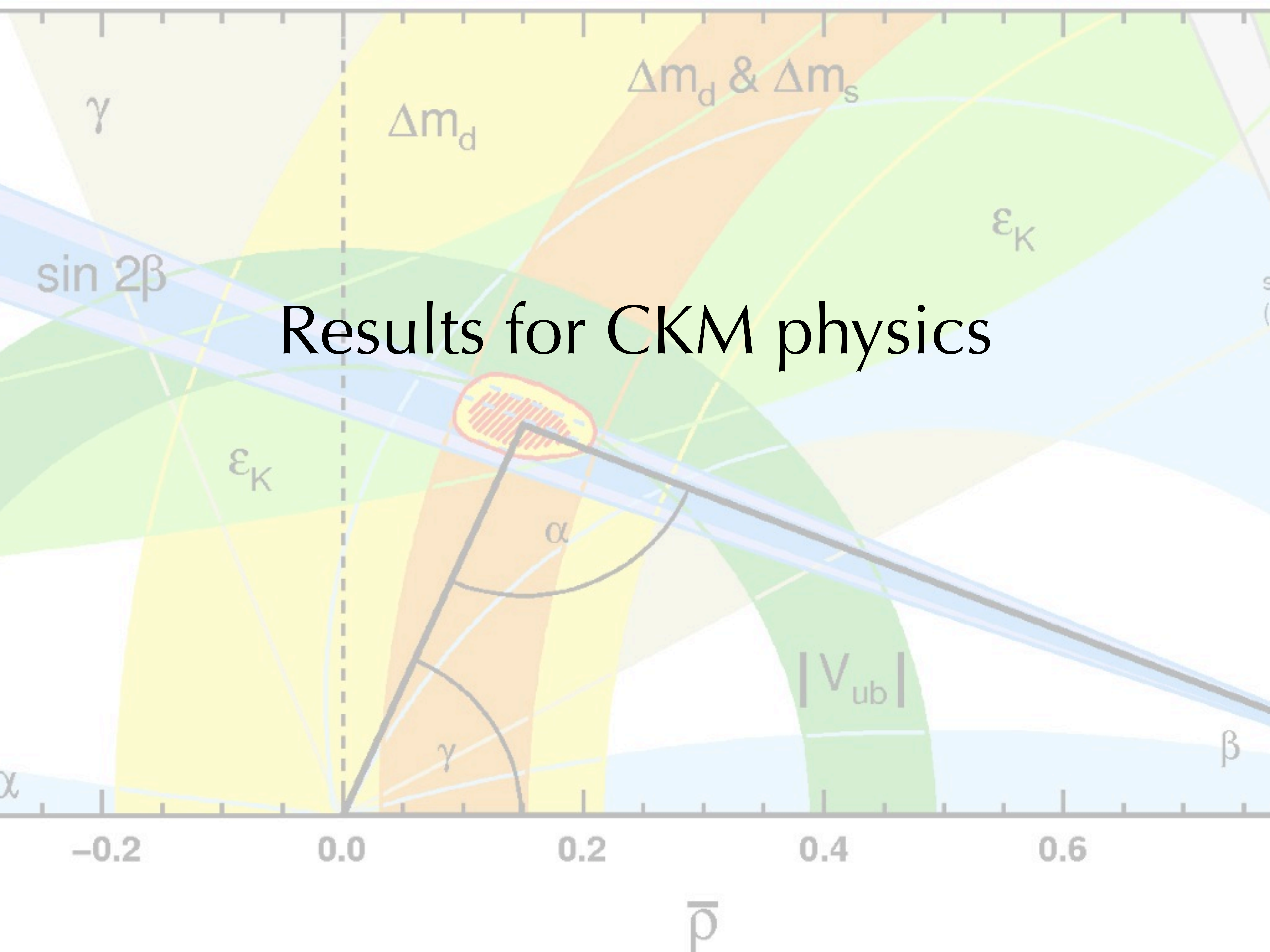
- To accurately describe weak interactions involving quarks, must include effects of confining quarks into hadrons:





- Absorb nonperturbative QCD effects into quantities such as decay constants, form factors, and bag-parameters which we must compute in lattice QCD
- These quantities are needed to interpret many experimental flavor physics results:
  - Schematically, EXPT. = CKM × LATTICE × KNOWN PERTURBATIVE FACTORS
- Precise lattice-QCD calculations of hadronic matrix elements are critical to maximize scientific output of experimental quark-flavor intensity physics program

Results for CKM physics



Lattice-QCD constraints on the CKM matrix

- CKM 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 → $\pi\nu\nu$ decays

- "Gold-plated" lattice processes allow the determination of almost all CKM matrix elements

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

*Neutral kaon mixing also gold-plated and can be used to obtain the CKM phase (ρ, η)

- USQCD has a well-established and successful program to calculate weak matrix elements needed to obtain the elements and phase of the CKM matrix (see recent Lattice 2011 plenary talks by Davies, Mawhinney, & Wittig)

Highlight: D→πℓν & D→Kℓν form factors

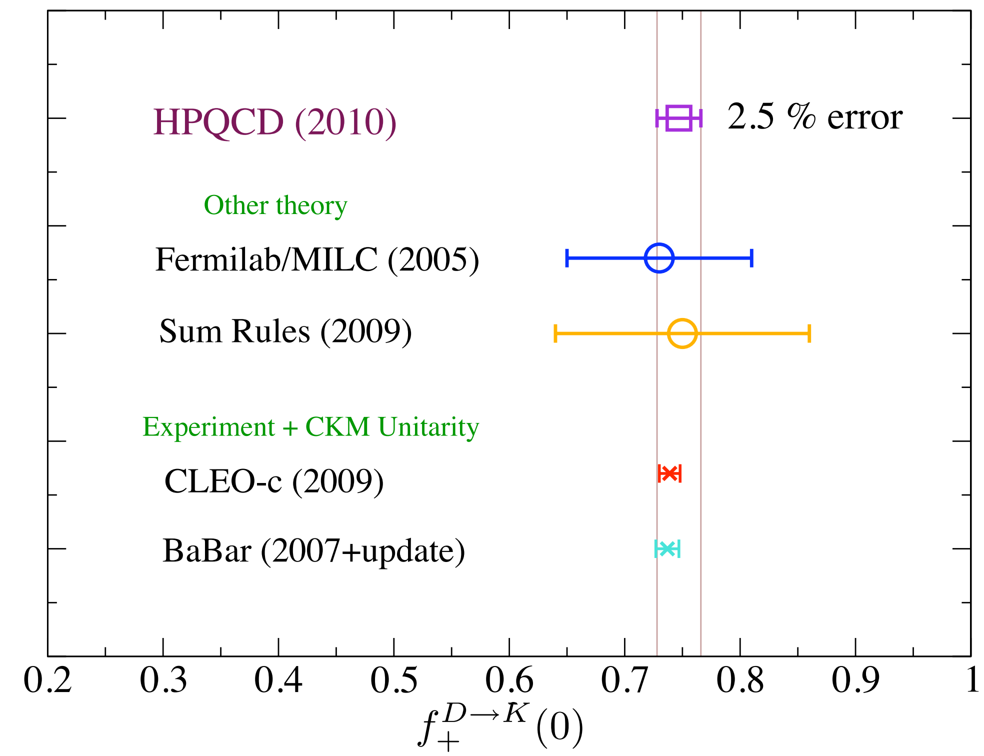
- D→πℓν and D→Kℓν form factors be combined with experimentally- measured branching fractions to obtain $|V_{cd}|$ and $|V_{cs}|$ in the Standard Model

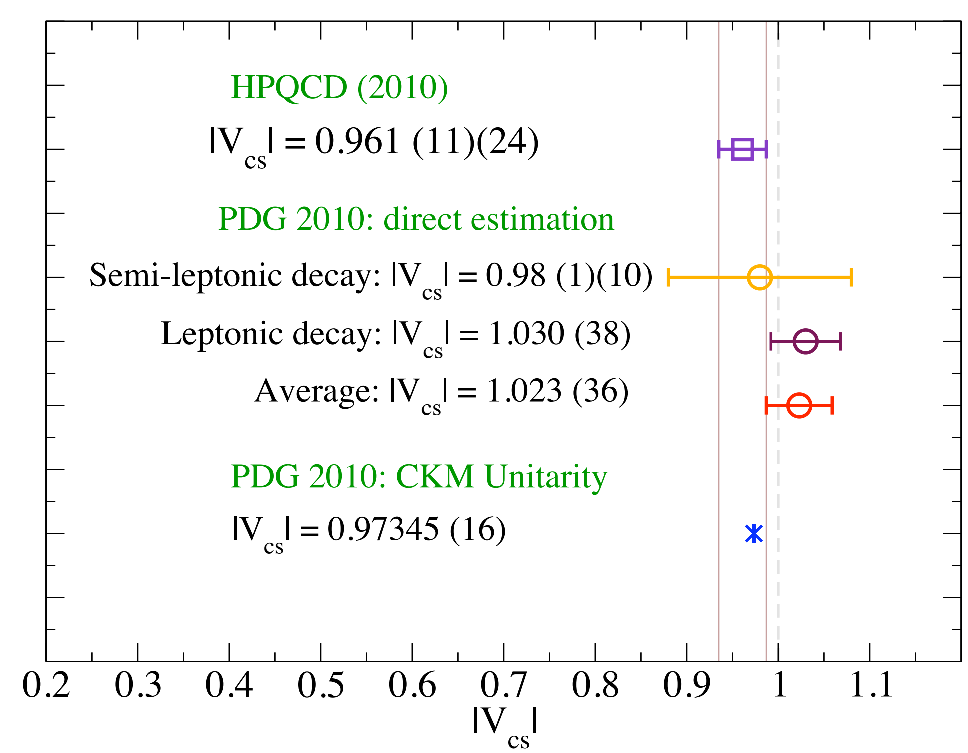
$$\frac{d\Gamma(D \to K(\pi)\ell\nu)}{dq^2} = \frac{G_F^2}{24\pi^3} |\vec{p}_{K(\pi)}|^3 |\mathbf{V_{cs(d)}}|^2 |\mathbf{f_+^{D\to K(\pi)}}(\mathbf{q^2})|^2$$

- HPQCD Collaboration recently developed new method for obtaining the D→πℓν and D→Kℓν form factors at zero momentum transfer (q^2=0) [Na et al., PRD 82 (2010) 114506, PRD 84 (2011) 114505] and reduced the lattice-QCD errors significantly

- **Results enable ~5% test of unitarity of 2nd row of the CKM matrix:**

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 0.976(50)$$





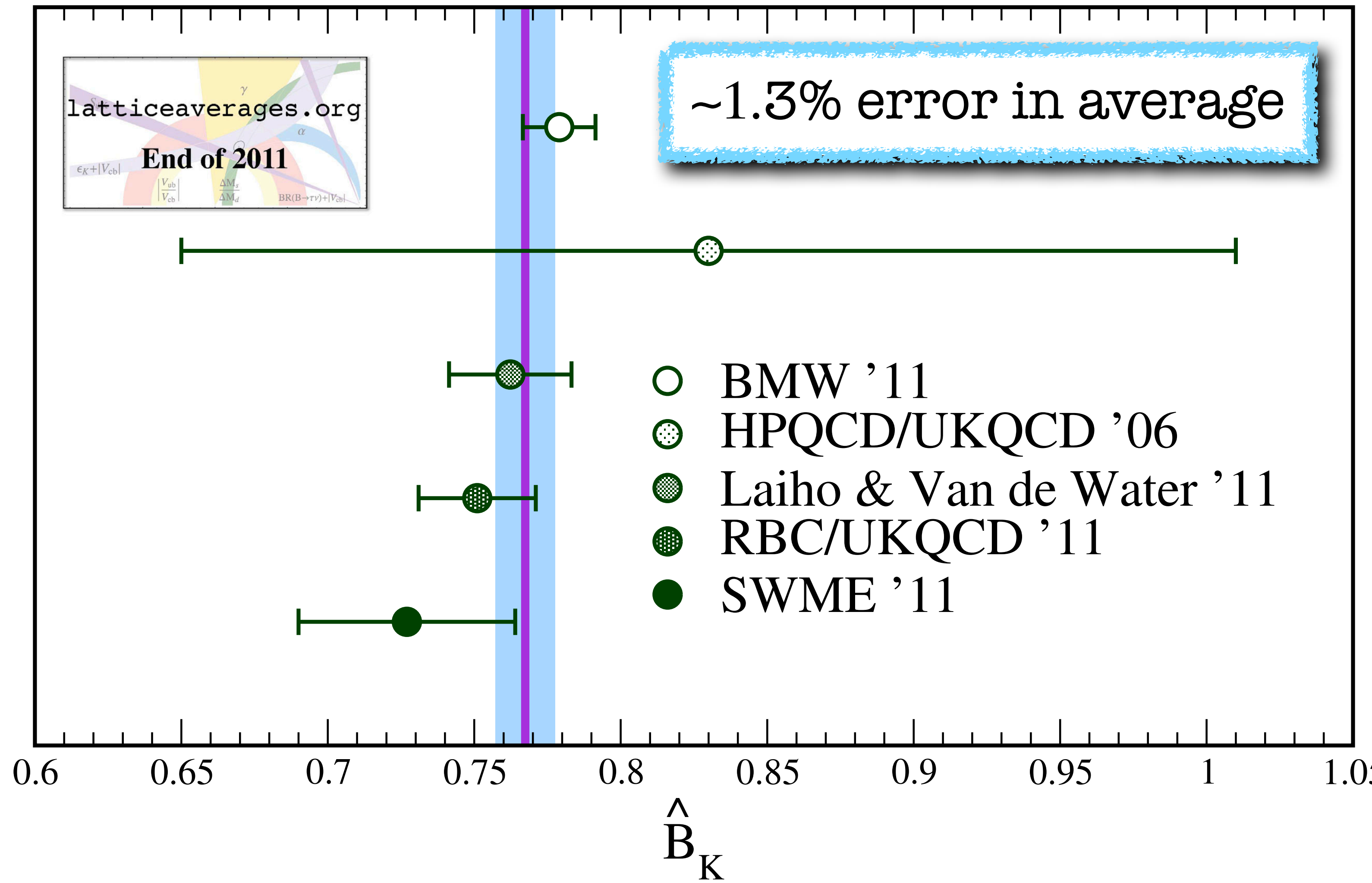
Highlight: neutral kaon mixing parameter B_K

- The amount of direct CP-violation in the neutral kaon system (ϵ_K) has been experimentally measured to sub-percent accuracy and constrains the apex of the CKM unitarity triangle

- Until recently, the constraint from ϵ_K was limited by the large error in the hadronic matrix element B_K (~10-20% in 2006)

- B_K a long-standing goal of USQCD, and significant effort has been devoted to its improvement

- Now several independent lattice-QCD calculations in good agreement



- B_K only the 4th largest uncertainty in the Standard-Model prediction for ϵ_K:
  - Below perturbative-QCD errors from short-distance coefficients [Brod & Gorbahn]
  - Largest uncertainty in the ϵ_K band is now from the ~10% parametric error in $A^4 \propto |V_{cb}|^4$

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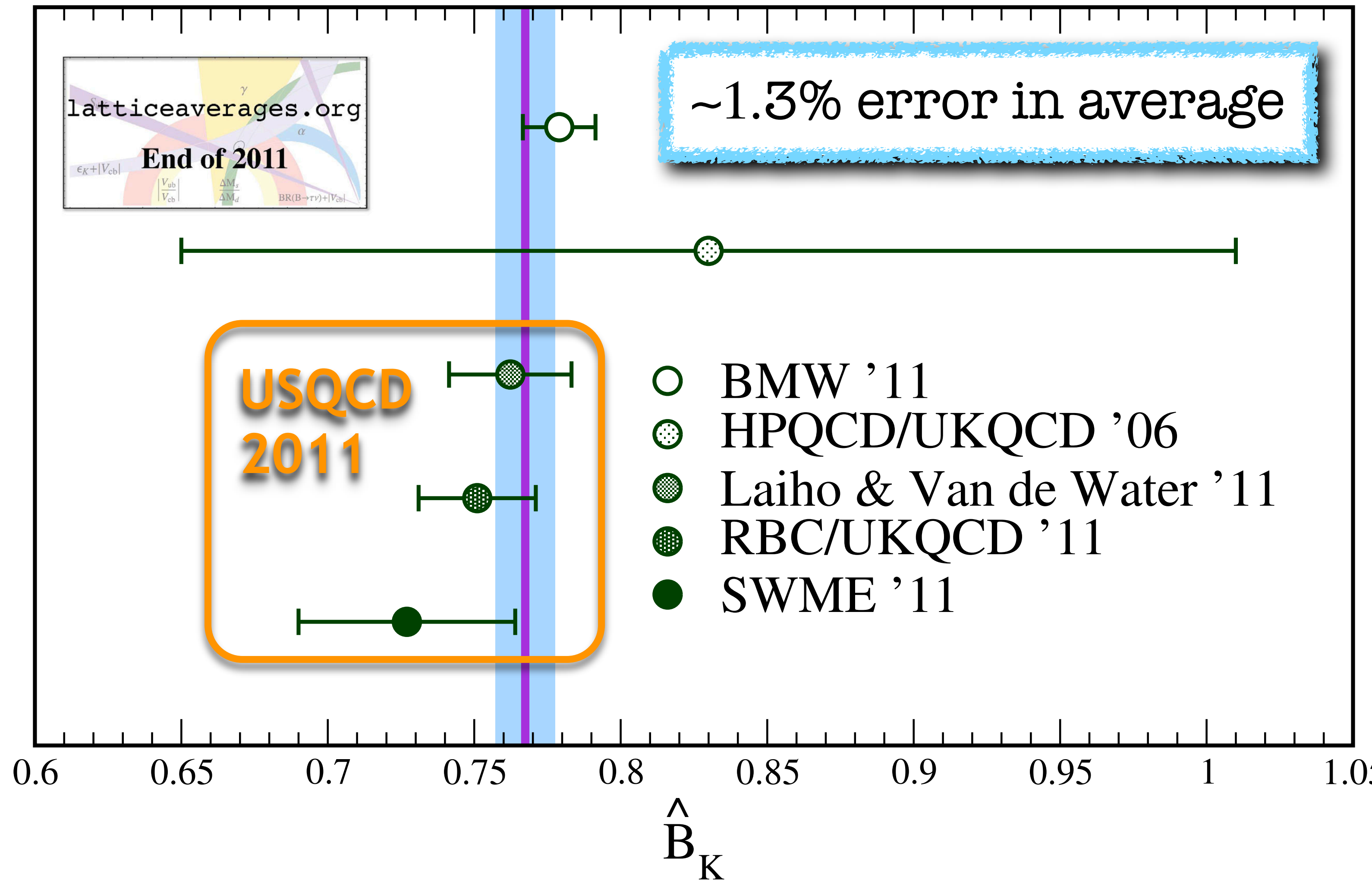

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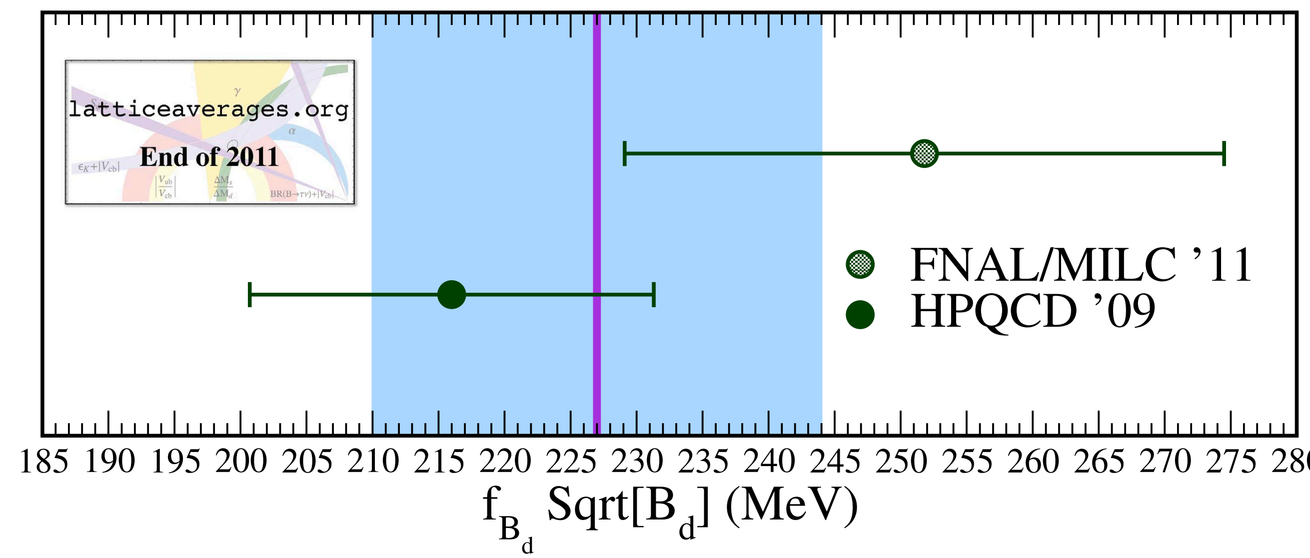
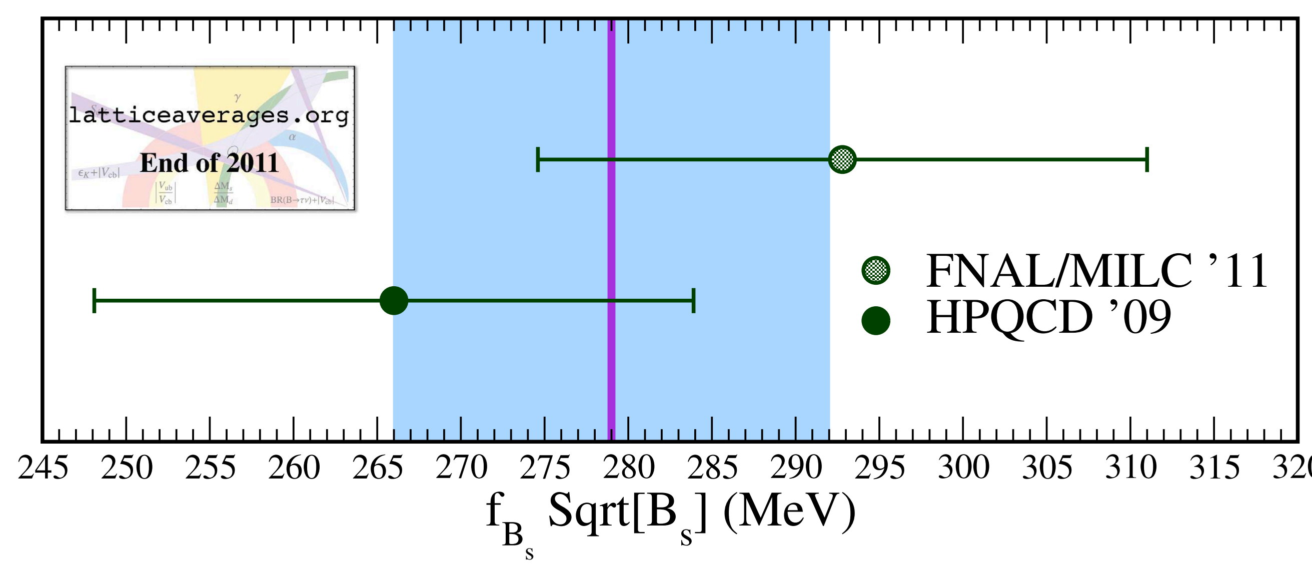
New result: $B^0_{(d,s)}$-mixing matrix elements

- The ratio of B_d to B_s oscillation frequencies (Δm_q) is measured to better than 1% constrains the apex of the CKM unitarity triangle

- Fermilab/MILC [Bouchard, Freeland, *et al.*,1112.5642] recently presented preliminary results for B-mixing matrix elements at Lattice 2011

~5-7% error in averages



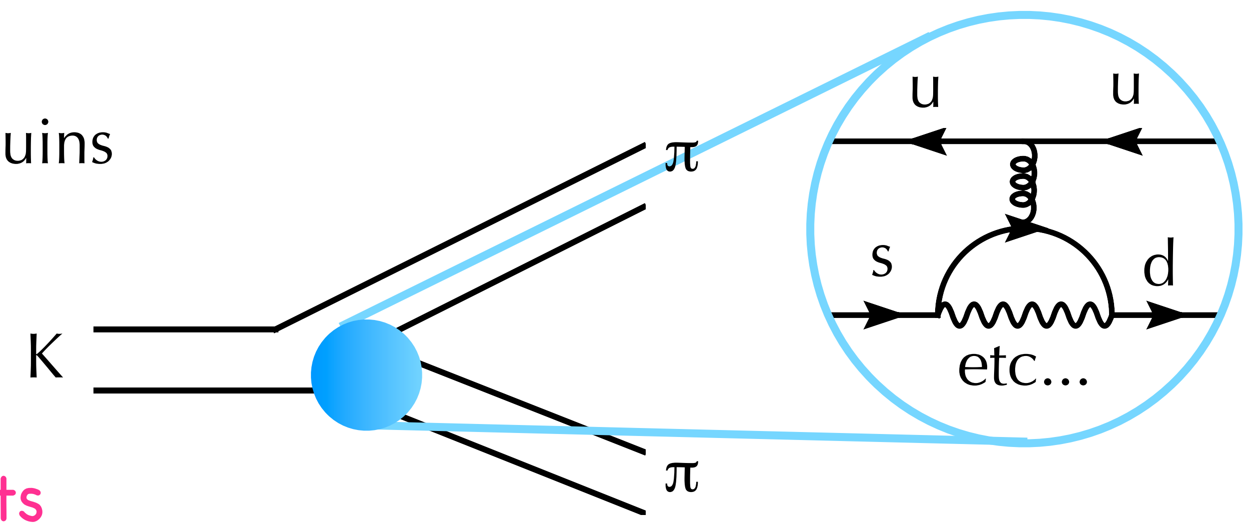


- Obtain first n_f=2+1 results for matrix elements for full basis of ΔB=2 operators that appear in beyond-the Standard Model theories (needed for model-builders)

- Dominant error currently in UT constraint from uncertainty in lattice-QCD calculations of the hadronic matrix element, but several independent USQCD calculations are underway and we expect further improvement in in the near future

Breakthrough: $K \to \pi\pi$ decay

- ϵ'_K/ϵ_K places a constraint on the CKM unitarity triangle (a horizontal band) that must intersect the solution established from ϵ_K + B-physics
  - Sensitive to new physics because it receives contributions from EW penguins
  - Measured experimentally to <10% precision, but utility for testing SM handicapped by large uncertainty in corresponding weak matrix elements



- In the past two years, RBC-UKQCD collaboration made significant progress in resolving theoretical issues associated with computing $K \to \pi\pi$ amplitudes via the "direct" Lellouch-Lüscher approach [Blum et al., PRD 84 (2011) 114503, PRL 108, 141601 (2012)]
  - ⇒ **Should soon enable first *ab initio* QCD calculation of $\Delta I=1/2$ rule and calculation of $\varepsilon'_K/\varepsilon_K$ with ~20-30% precision**
- With these projected improvements, combining the pattern of results ϵ'_K/ϵ_K with other quantities (such as $K \to \pi\nu\bar{\nu}$ decays) can help distinguish between new-physics scenarios [Buras *et al.*, Nucl.Phys. B566 (2000)]

Project goals: *how are we doing?*

- In our LQCD-ext proposal written in 2007-2008 we included the following table showing the "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*)	2011 lattice error (*actual*)
f_K/f_π	V_{us}	0.3%	0.9%	0.5%	0.6%
$f_{K\pi}(0)$	V_{us}	0.4%	0.5%	0.3%	0.5%
$D \to \pi\ell\nu$	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%
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  - ➡ For the most part we are meeting our uncertainty goals

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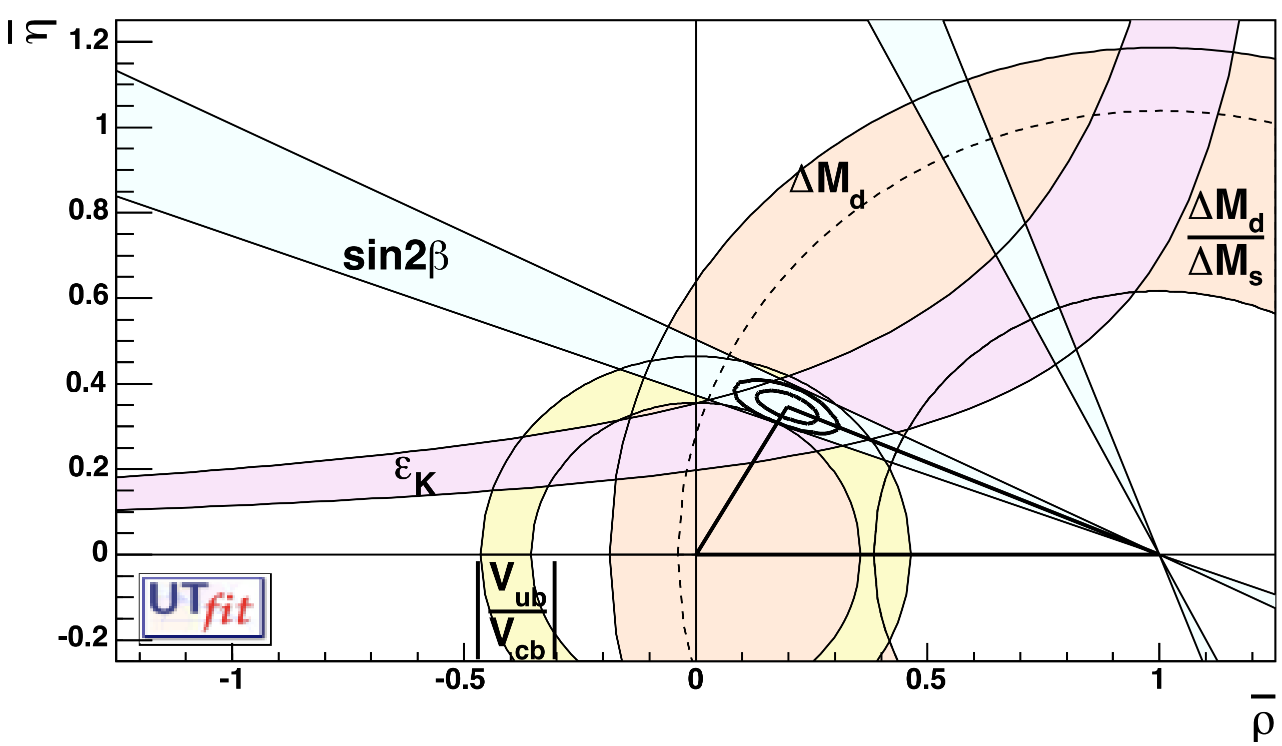
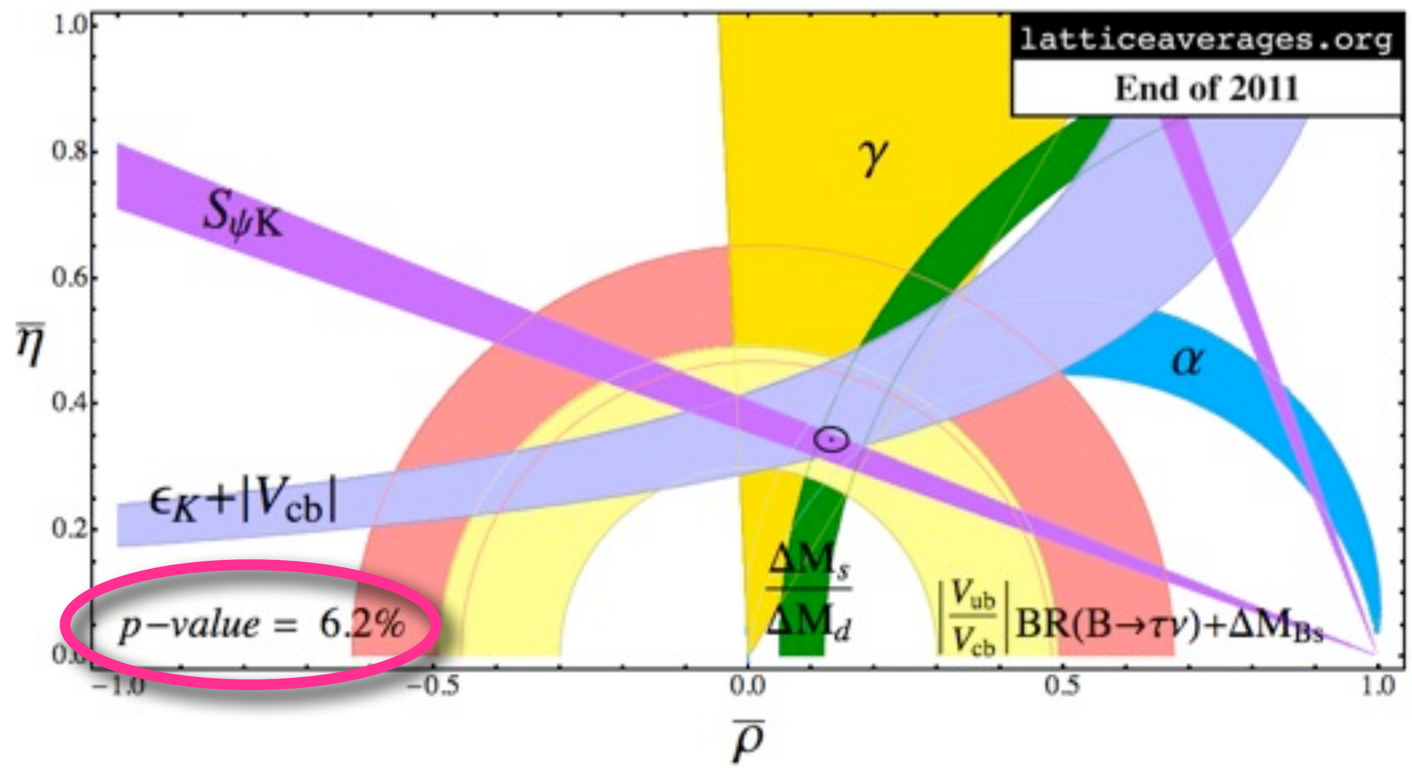
Tension in the CKM unitarity triangle?

✦ Improved lattice matrix element QCD calculations have shrunk substantially the allowed region of parameter space in the ρ−η plane and revealed a ~3σ tension in the CKM unitarity triangle [CKMfitter; Laiho, Lunghi, RV; Lunghi & Soni; UTFit]

2004



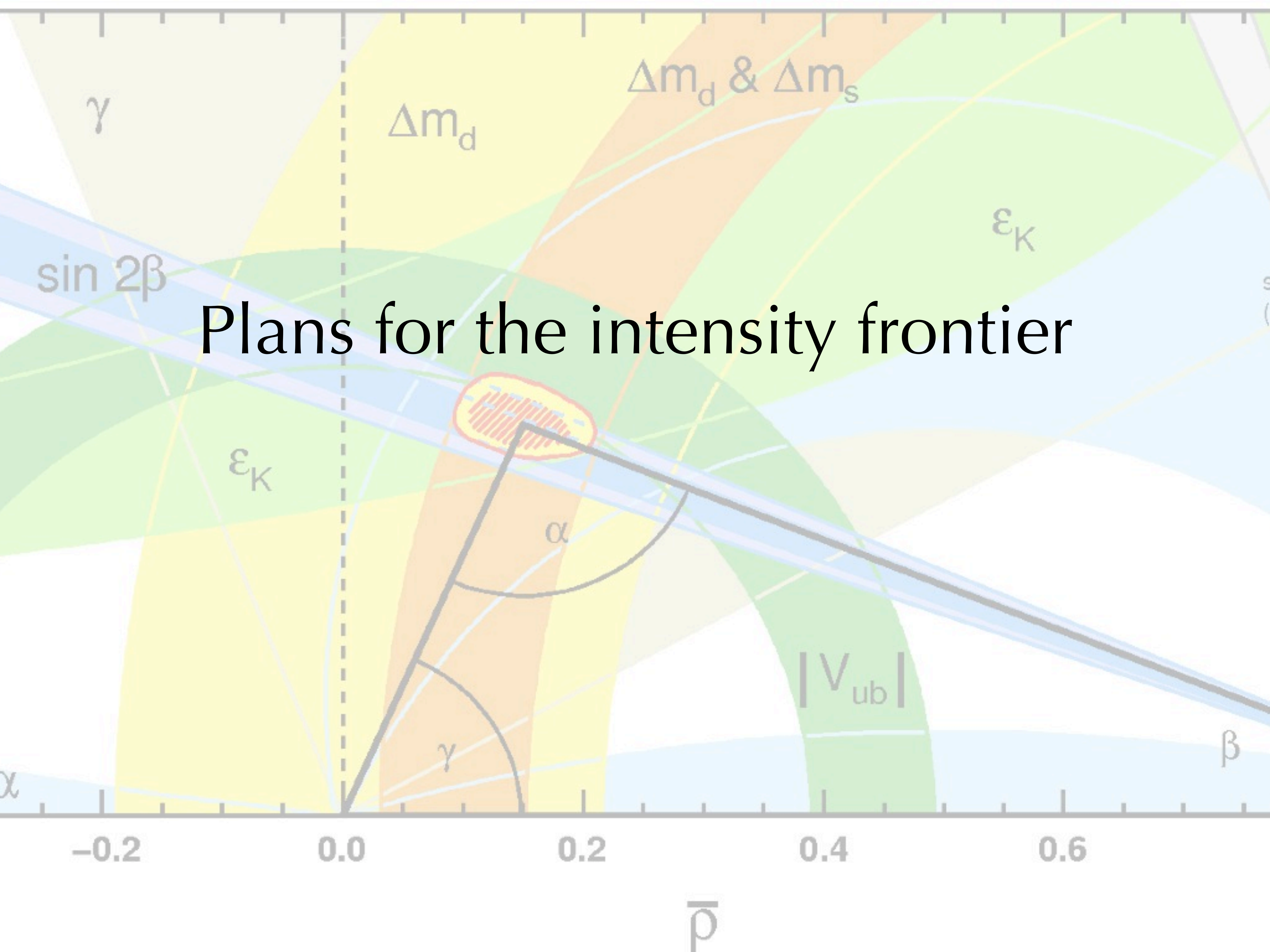
NOW



❖ Tension remains significant even omitting more problematic inputs $|V_{ub}|$ and $|V_{cb}|$

❖ Observations not consistent with simplest benchmark supersymmetry scenarios such as mSUGRA or CMSSM, but could be a supersymmetric GUT [Nierste, Moriond EW 2011]

Plans for the intensity frontier



(Select) Upcoming experiments

NOW

ATLAS/CMS
CDF/D0
Δm_s, $B_s \to \mu^+\mu^-$, ...

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

2012

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

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

2014

new muon g-2

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, ...

2017

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

ORKA
$K^+ \to \pi^+ \nu\bar{\nu}$

2020+

Project X
$K^0 \to \pi^0 \nu\bar{\nu}$,
$K^+ \to \pi^+ \nu\bar{\nu}$

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rare $b \to s\gamma$ & $b \to sll$ decays,
$(g-2)_\tau$, ...

NOW — **2012** — **2020+**

Lattice-QCD calculations needed to maximize the scientific impact of the experimental high-energy physics program

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

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

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$K^0 \to \pi^0 \nu\bar{\nu}$,
$K^+ \to \pi^+ \nu\bar{\nu}$

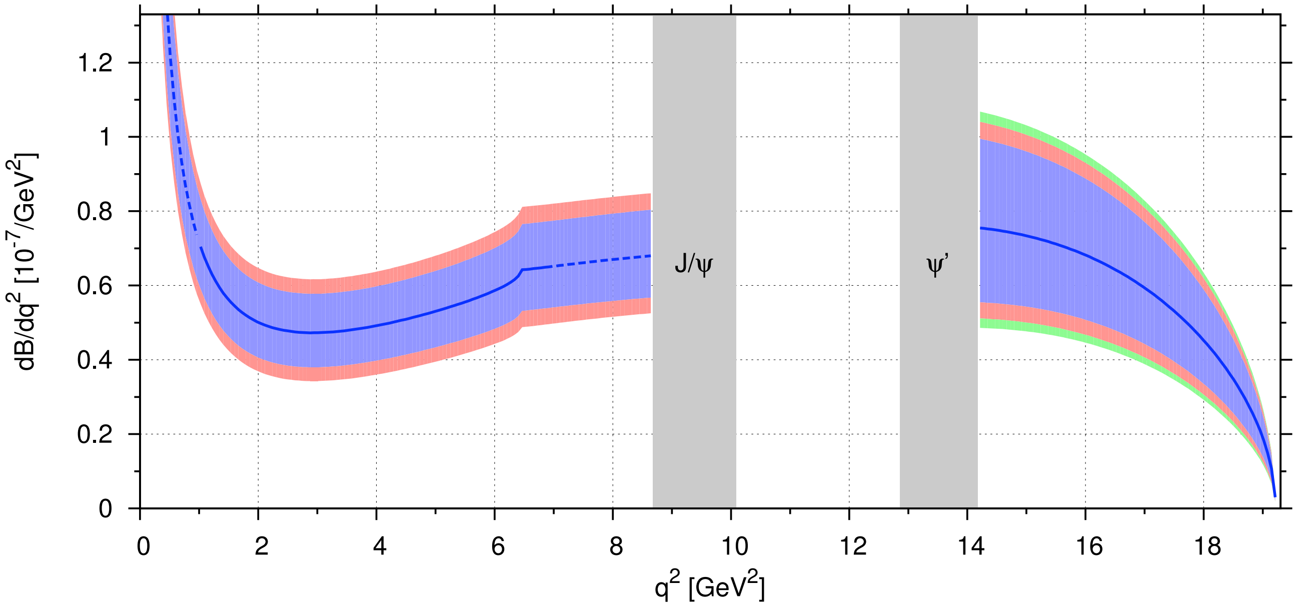
Rare decays

- Suppressed in Standard Model for several reasons:
  - **(1)** Loop suppressed, *e.g.* flavor-changing neutral currents
  - **(2)** Helicity suppressed
  - **(3)** Suppressed by CKM and color factors

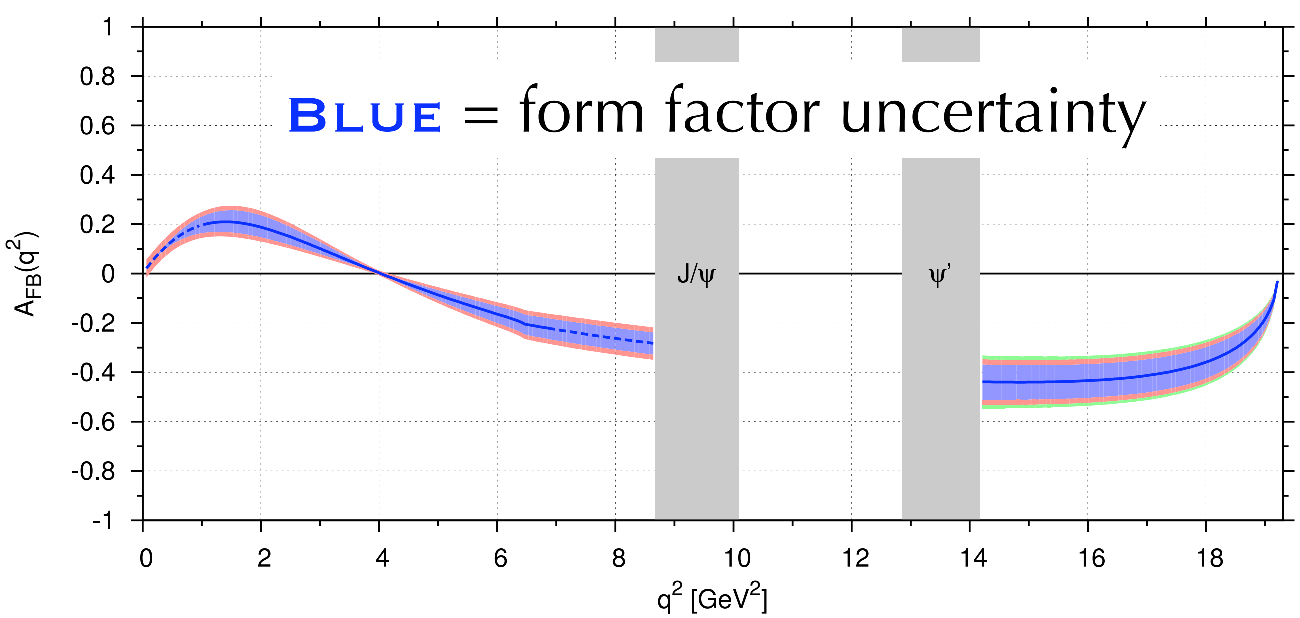
- Challenging to observe experimentally, but good new-physics search channels because BSM contributions may be easier to observe over Standard-Model background
- USQCD now expanding our program to address rare decays and other needs of upcoming heavy-flavor intensity frontier experiments

Example: $B \to K \ell^+ \ell^-$ decay

Differential branching fraction



Forward-backward asymmetry



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

- Hadronic uncertainties (shown in BLUE) dominant error for many observables in both low and high q^2 regions
- Typical form factor uncertainty from light-cone sum rules is ~15% with little room for improvement [Khodjamirian, arXiv:1101.2328]
- 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 few-percent errors in high q^2 region in next few years

Example: $K \to \pi\nu\bar{\nu}$ decays

- $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ Often called **"GOLDEN" MODES** because SM branching ratios known to a precision unmatched by any other quark FCNC processes

    - Hadronic form factor can be obtained precisely using experimental $K \to \pi\ell\nu$ data combined with chiral perturbation theory [Mescia & Smith, arXiv: 0705.2025]

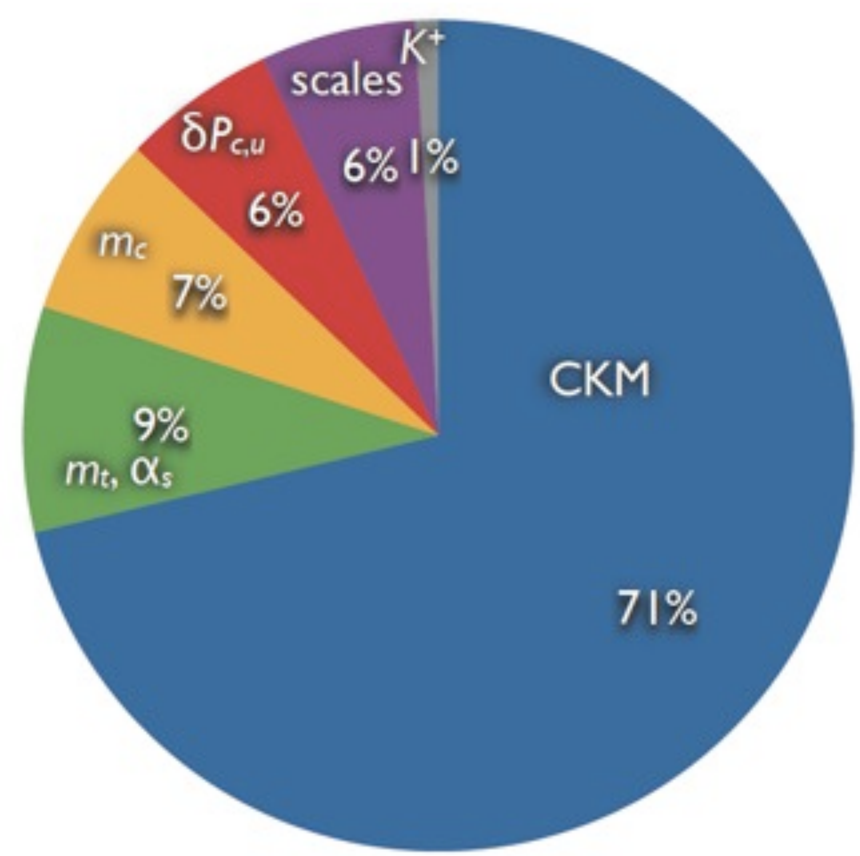
    ➡ Limited by ~10% parametric uncertainty in $A^4 \propto |V_{cb}|^4$

- Within this decade, NA62 @ CERN SPS will measure $\mathcal{O}(100)$ K^+ events (assuming the SM), and KOTO @ J-PARC will collect first K^0_L events

- By 2014, expect to halve error on $|V_{cb}|$ from lattice-QCD calculations of $B \to D^{(*)}\ell\nu$, reducing error in the SM branching fractions to ~6%

➡ Theory error in Standard-Model predictions will be commensurate with expected experimental error

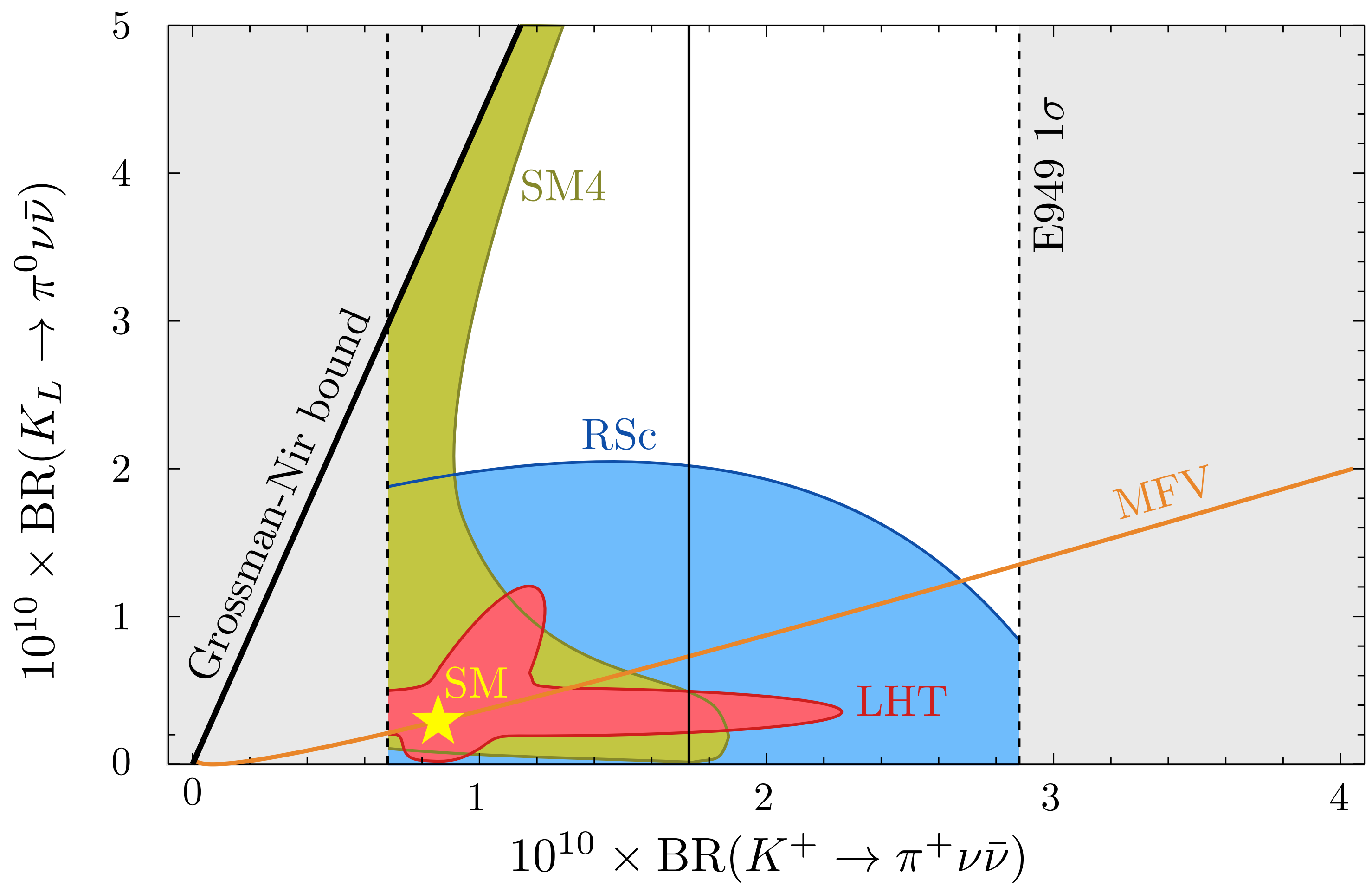
BR($K^+ \to \pi^+\nu\bar{\nu}$)



[Brod & Gorbahn Phys.Rev. D83 (2011) 034030]

Room for new physics

- Sensitive to Little Higgs models, warped extra dimensions, and 4th generation [Buras, Acta Phys.Polon.B41:2487-2561,2010]



[D. Straub, arXiv:1012.3893 (CKM 2010)]

- **Spectacular deviations from the Standard Model are possible in many new physics scenarios**
- Correlations between the two channels can help distinguish between models

Muon g-2

- Currently measured to 0.54 ppm and >3σ discrepancy with Standard Model

a_μ^{exp} = 116 592 089(54)(33) x 10^{-11} [E821]

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

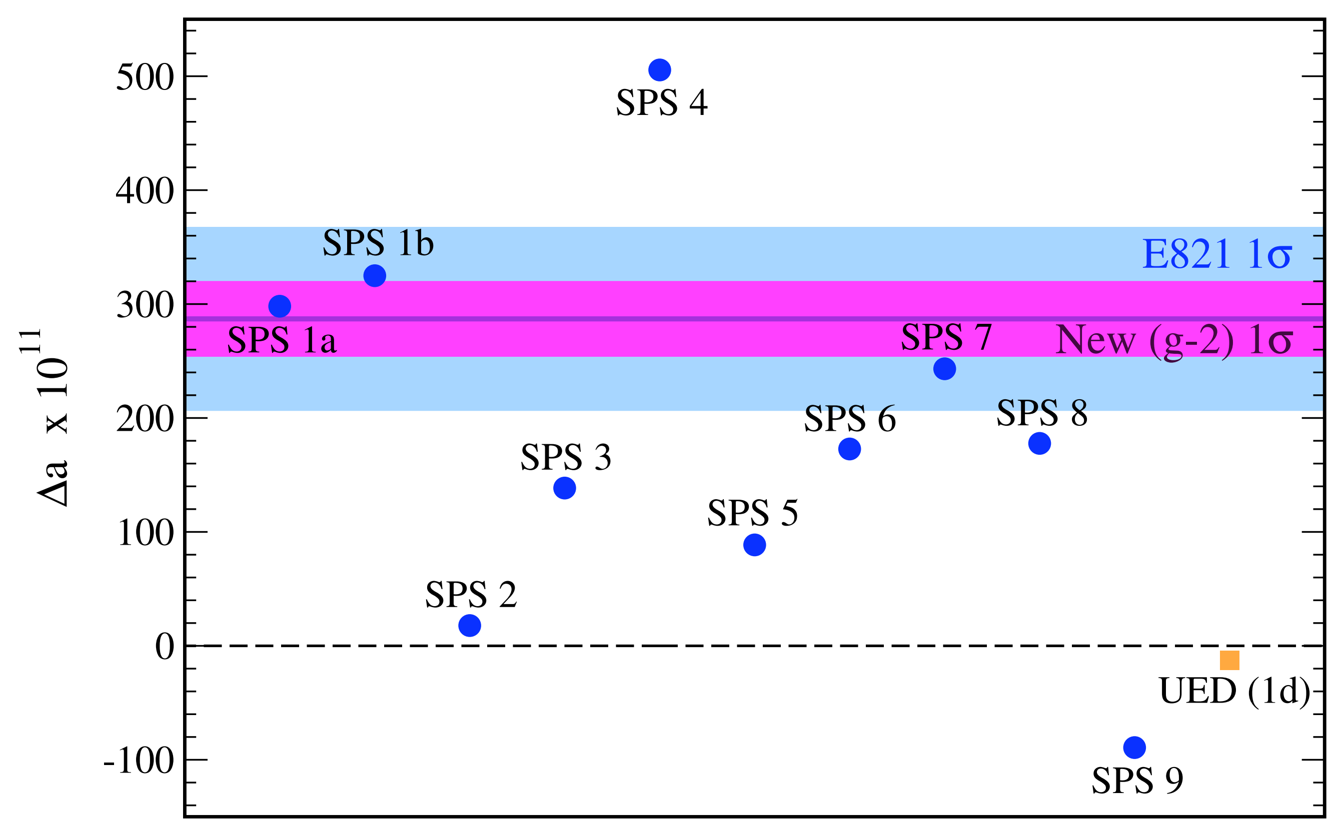
- Extremely **sensitive probe of heavy mass scales in the several hundred GeV range**

- Different new-physics scenarios predict a wide range of contributions to g-2, so precise experimental measurements and theoretical predictions can:

(1) Rule out numerous new-physics scenarios

(2) Distinguish between models with similar LHC signatures

(3) Determine the parameters of the TeV-scale theory that is realized in nature



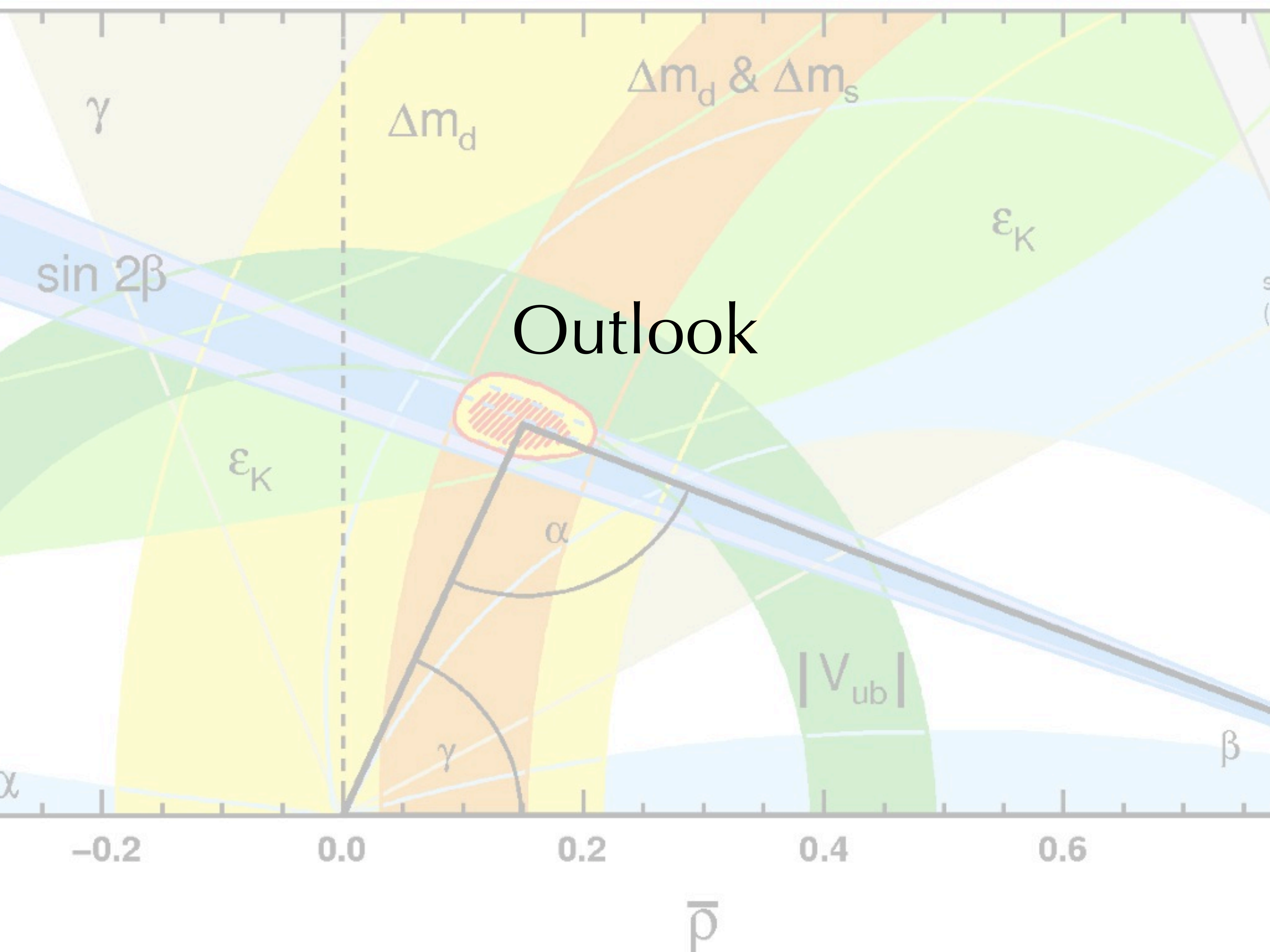
Future prospects

- **New g-2 experiment** will reduce error to 0.14 ppm: with this precision (and fixed central values), will test the Standard Model at >7σ level
  - Reduction in theoretical uncertainty on Standard-Model hadronic light-by-light contribution to 10-15% (and more reliable error estimate!) needed to match target experimental precision

- USQCD research and development efforts on lattice calculations of a_μ^{HLbL} ongoing:
  - RBC Collaboration [Hayakawa *et al.*, PoS LAT2005 (2006) 353] developed a promising method for calculating a_μ^{HLbL} using QCD + QED lattice simulations
  - Alternative approach to compute the $\pi^0 \to \gamma\gamma$ form factor with lattice QCD underway by JLAB [Cohen *et al.*, PoS LATTICE2008 (2008) 159] and JLQCD [Shintani *et al.*, PoS LAT2009 (2009) 246]

- Precision goals challenging, and will likely need further theoretical developments as well as expected increase in computing power

Outlook



Forecasts and plans

(1) Still work needed to obtain precision comparable to experiment for many quantities

- Future increases in computing power will help most sources of uncertainty, either directly or indirectly
- Improved algorithms and analysis methods being pursued, but difficult to predict

Quantity	CKM element	present expt. error	present lattice error	2014 lattice error	2020 lattice error	error from non-lattice method
f_K/f_π	V_{us}	0.2%	0.6%	0.3%	0.1%	–
$f_{K\pi}(0)$	V_{us}	0.2%	0.5%	0.2%	0.1%	1% (ChPT)
$D \to \pi\ell\nu$	V_{cd}	2.6%	10.5%	4%	1%	–
$D \to K\ell\nu$	V_{cs}	1.1%	2.5%	2%	< 1%	5% (ν scatt.)
$B \to D^*\ell\nu$	V_{cb}	1.8%	1.8%	0.8%	< 0.5%	< 2% (Incl. $b \to c$)
$B \to \pi\ell\nu$	V_{ub}	4.1%	8.7%	4%	2%	10% (Incl. $b \to u$)
$B \to \tau\nu$	V_{ub}	21%	6.4%	2%	< 1%	–
ξ	V_{ts}/V_{td}	1.0%	2.5%	1.5%	< 1%	–

Forecasts and plans

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(2) Given success with simplest quantities, expanding repertoire of calculations, e.g.:

- Rare B-decays such as $B \to K^{(*)} l^+ l^-$ and $B \to K^* \gamma$
- $K \to \pi\pi$ decays ($\Delta I = 1/2$ rule and ϵ'/ϵ)

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(3) Sub-percent precision will require including previously neglected effects such as:

- Isospin breaking in sea sector (*in progress*)
- Dynamical charm quark (*in progress*)

Flavor physics and the LHC

- Lattice flavor physics calculations will be important no matter what the LHC finds:

NOTHING → If new physics is above the TeV scale, **indirect searches in the flavor sector and elsewhere at the intensity frontier will be our only probe**

A SINGLE "HIGGS" → Precision flavor measurements (and corresponding lattice calculations of beyond-the-Standard Model hadronic matrix elements) will be needed to distinguish between new-physics models

A PARTICLE "ZOO" → Once ATLAS and CMS will measure the spectrum, **precision flavor measurements will be needed to extract the couplings and determine the underlying structure of the theory**

Summary and outlook

- Lattice QCD provides indispensable results for weak matrix elements needed to extract CKM matrix elements and test the Standard Model in the quark-flavor sector
  - Experimental observations are consistent with the Standard Model CKM framework at the ~10% level, but there are now hints in the flavor sector of a non-Standard Model source of CP violation

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- Lattice matrix … impact of LHCb, Super-B facto… …oming intensity frontier experi…

With continued support, we look forward to the coming decade's interplay between experiment, theory, and lattice QCD

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- Although we have made significant progress, still more work needed to obtain precision comparable to experiment for many quantities
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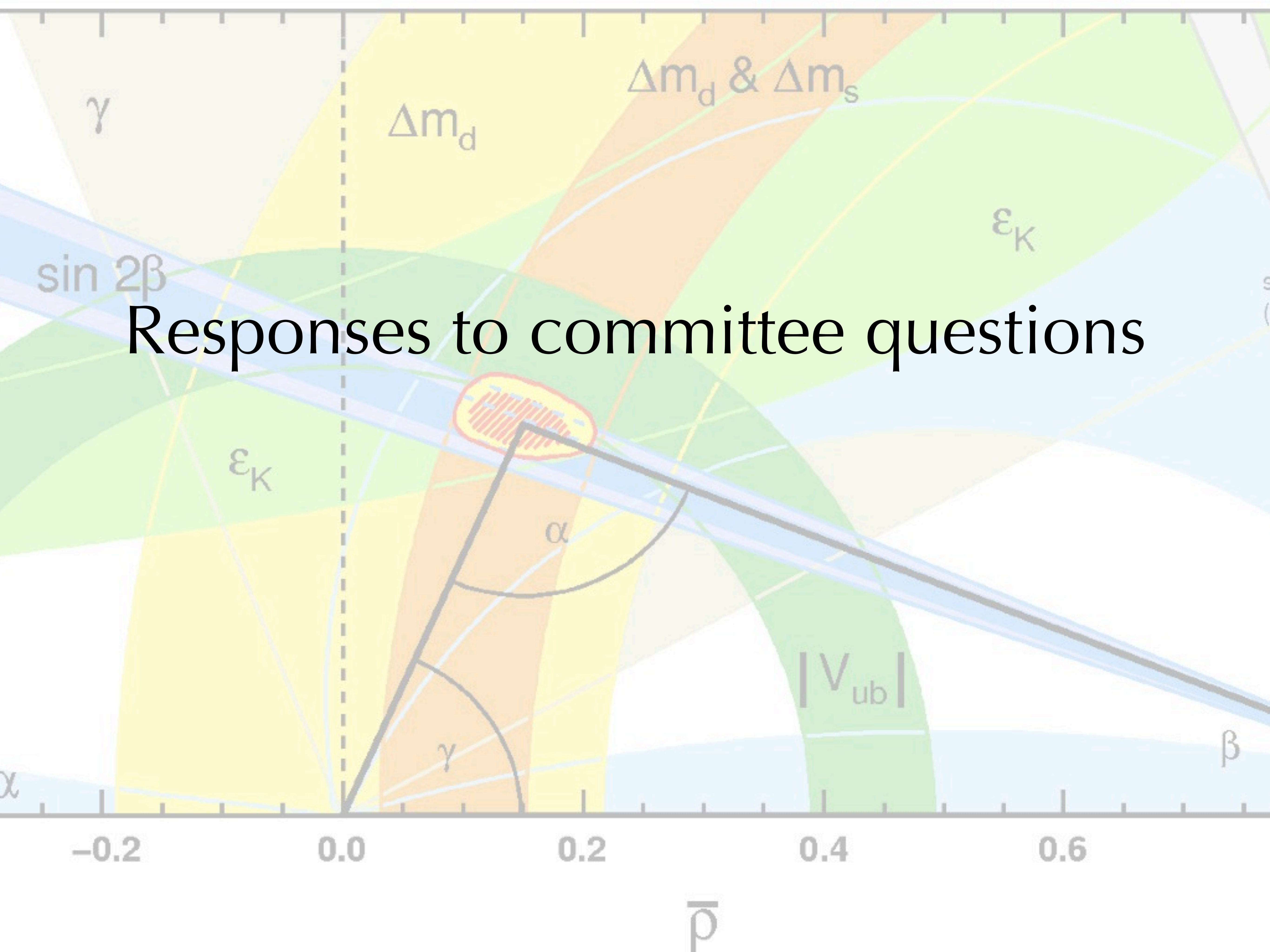
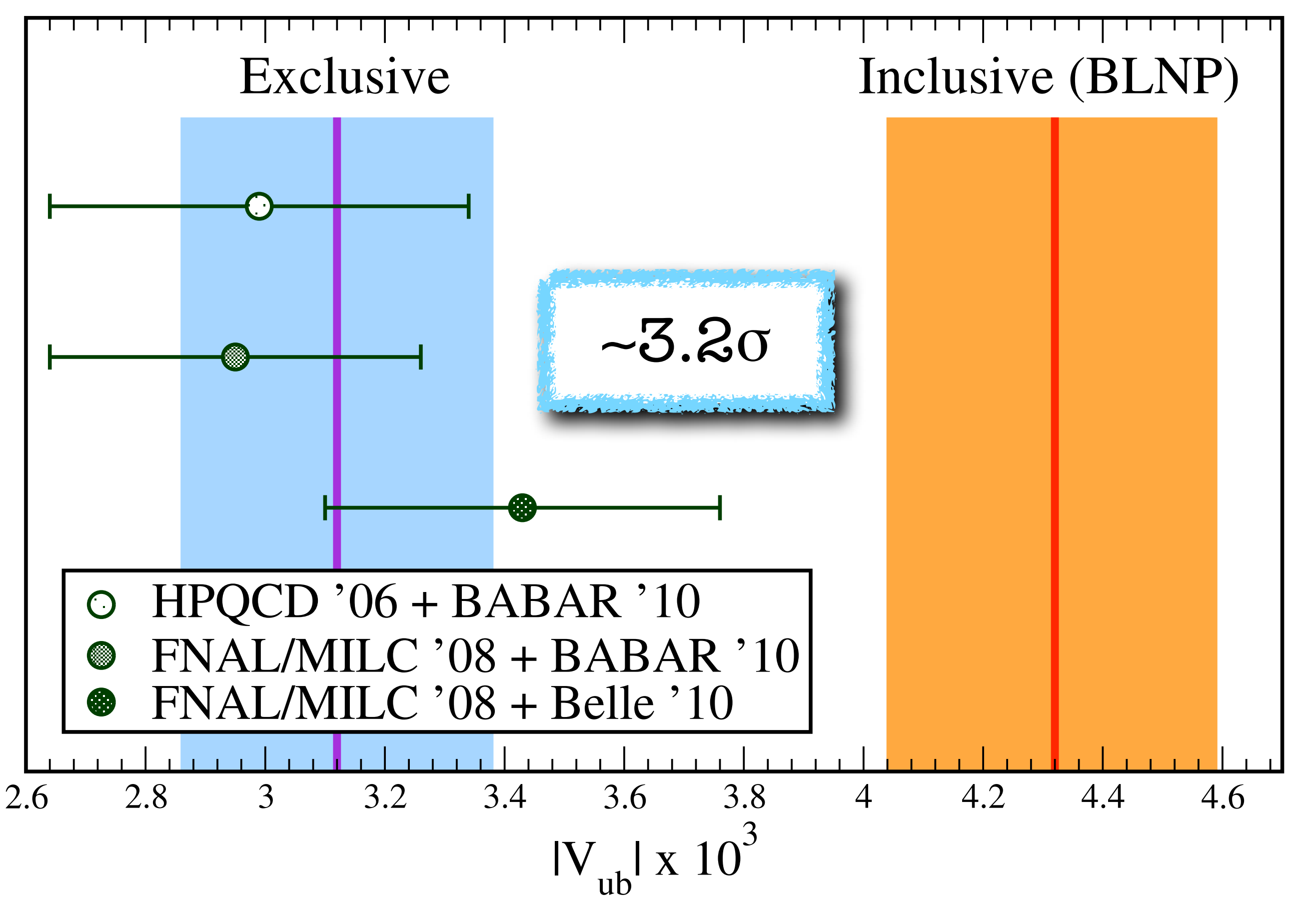
Responses to committee questions



Top three priorities for lattice HEP?

(1) $|V_{ub}|$

- Currently a >3σ tension between determinations of $|V_{ub}|$ from exclusive $B \to \pi l \nu$ decays and inclusive $B \to X_u l \nu$ decays
- Particularly worrisome because large deviations from Standard Model not expected in tree-level processes, so likely indicates underestimated uncertainties
- Lattice-QCD calculations of $B \to \pi l \nu$ & $B_s \to K l \nu$ can be used for independent determinations of $|V_{ub}|_{excl}$, while calculations of f_B are needed to interpret measurements of $B \to \tau \nu$ as determinations of $|V_{ub}|$



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(2) $|V_{cb}|$

- Limiting uncertainty in unitarity-triangle constraint from ϵ_K and in Standard-Model predictions for $K\to\pi\nu\nu$ is $A^4 \propto |V_{cb}|^4$
- Need lattice-QCD calculations of $B\to D l\nu$ & $B\to D^* l\nu$ form factors at nonzero recoil

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(3) Muon g-2

- Result of new Fermilab g-2 experiment can only be interpreted as constraint on or discovery of new physics if the Standard-Model prediction is reliable and with sufficiently small uncertainties
- Need lattice-QCD calculation of hadronic light-by-light & hadronic vacuum polarization contributions

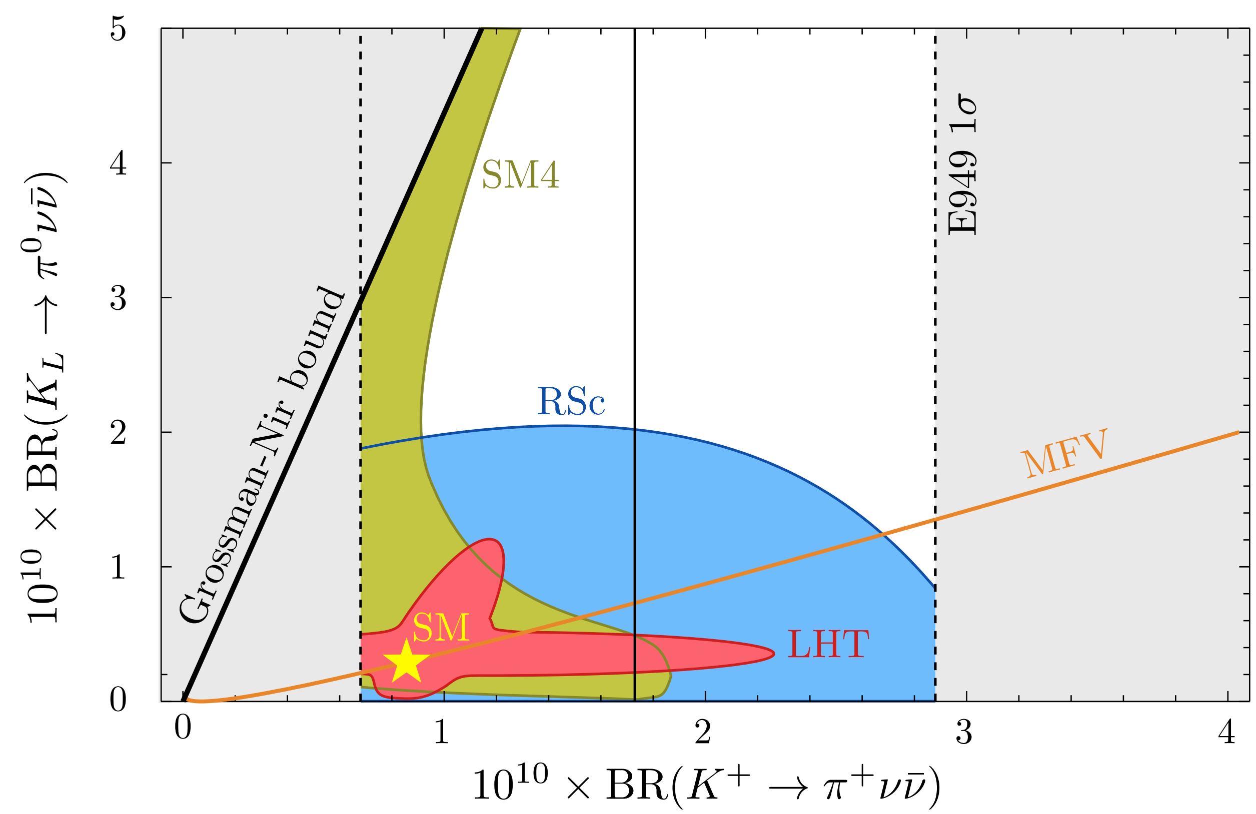
A possible "home-run" for lattice HEP?

- $K \to \pi\nu\nu$ decays can receive large new-physics contributions in both SUSY and many non-SUSY scenarios

	LHT	RSc	4G	2HDM	RHMFV
$D^0 - \bar{D}^0$ (CPV)	★★★	★★★	★★	★★	
ϵ_K	★★	★★★	★★	★★	★★
$S_{\psi\phi}$	★★★	★★★	★★★	★★★	★★★
$S_{\phi K_S}$	★	★	★★		
$A_{\rm CP}(B \to X_s\gamma)$	★		★		
$A_{7,8}(K^*\mu^+\mu^-)$	★★	★	★★		
$B_s \to \mu^+\mu^-$	★	★	★★★	★★★	★★
$K^+ \to \pi^+\nu\bar{\nu}$	★★★	★★★	★★★		★★
$K_L \to \pi^0\nu\bar{\nu}$	★★★	★★★	★★★		★★
$\mu \to e\gamma$	★★★	★★★	★★★		
$\tau \to \mu\gamma$	★★★	★★★	★★★		
$\mu + N \to e + N$	★★★	★★★	★★★		
d_n	★	★★★	★	★★★	
d_e	★	★★★	★	★★★	
$(g-2)_\mu$	★	★★	★		

Table 3. "DNA" of flavour physics effects for the most interesting observables in a selection of non-SUSY models. ★★★ signals large NP effects, ★★ moderate to small NP effects and ★ implies that the given model does not predict visible NP effects in that observable. Empty spaces reflect my present ignorance about the given entry.

[Buras, Acta Phys.Polon, B41:2487-2561,2010]



[D. Straub, arXiv:1012.3893 (CKM 2010)]

- Improved lattice-QCD calculations of $|V_{cb}|$ plus an observed experimental excess with respect to the Standard-Model prediction **could definitely establish the presence of new physics in the flavor sector at the >5σ level**

Other possible lattice-QCD "home-runs"

5σ new-physics discovery also possible and well-motivated in other quantities where the Standard-Model predictions depend critically on nonperturbative matrix elements from lattice QCD

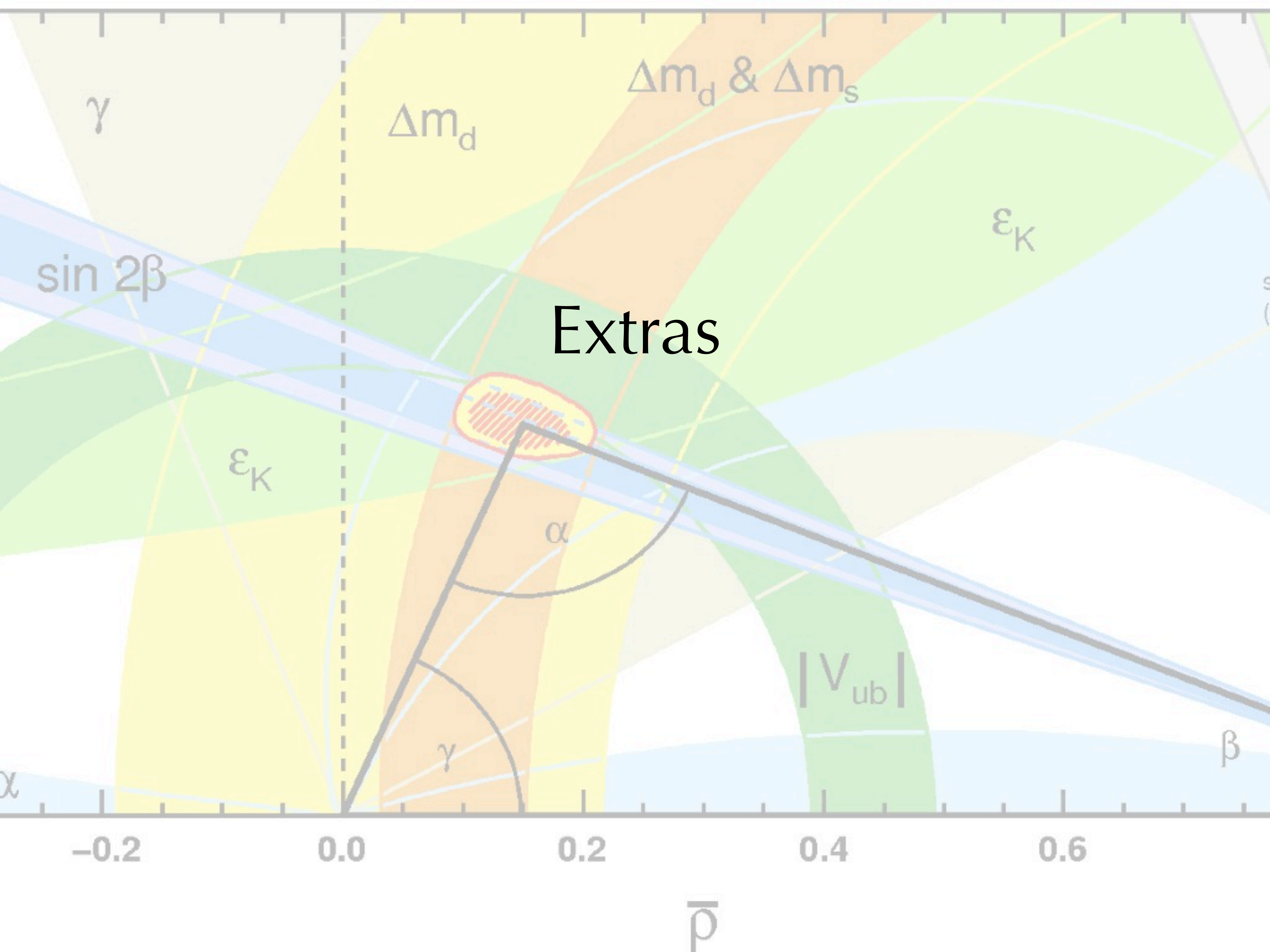
(1) $\varepsilon'_K/\varepsilon_K$

- Determining that the experimental value of $\varepsilon'_K/\varepsilon_K$ is inconsistent with the Standard Model

(2) Muon g-2

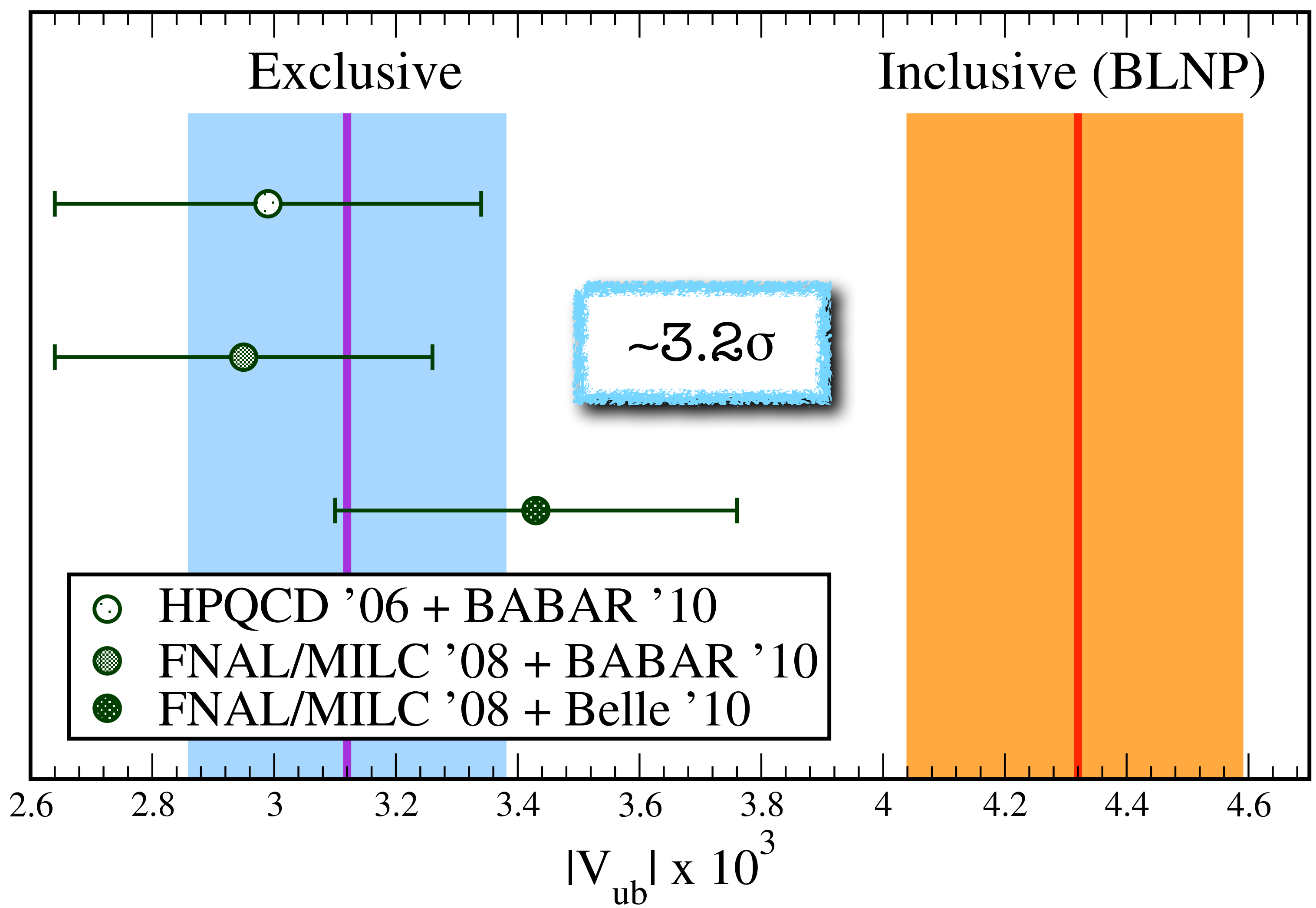
- Determining that the value of muon g-2 measured at BNL (and soon to be improved at Fermilab) is inconsistent with the Standard Model

Extras



The "$|V_{ub}|$ puzzle"

- Long-standing puzzle is the **tension between determinations of $|V_{ub}|$ from exclusive $B \to \pi l \nu$ decays and inclusive $B \to X_u l \nu$ decays**



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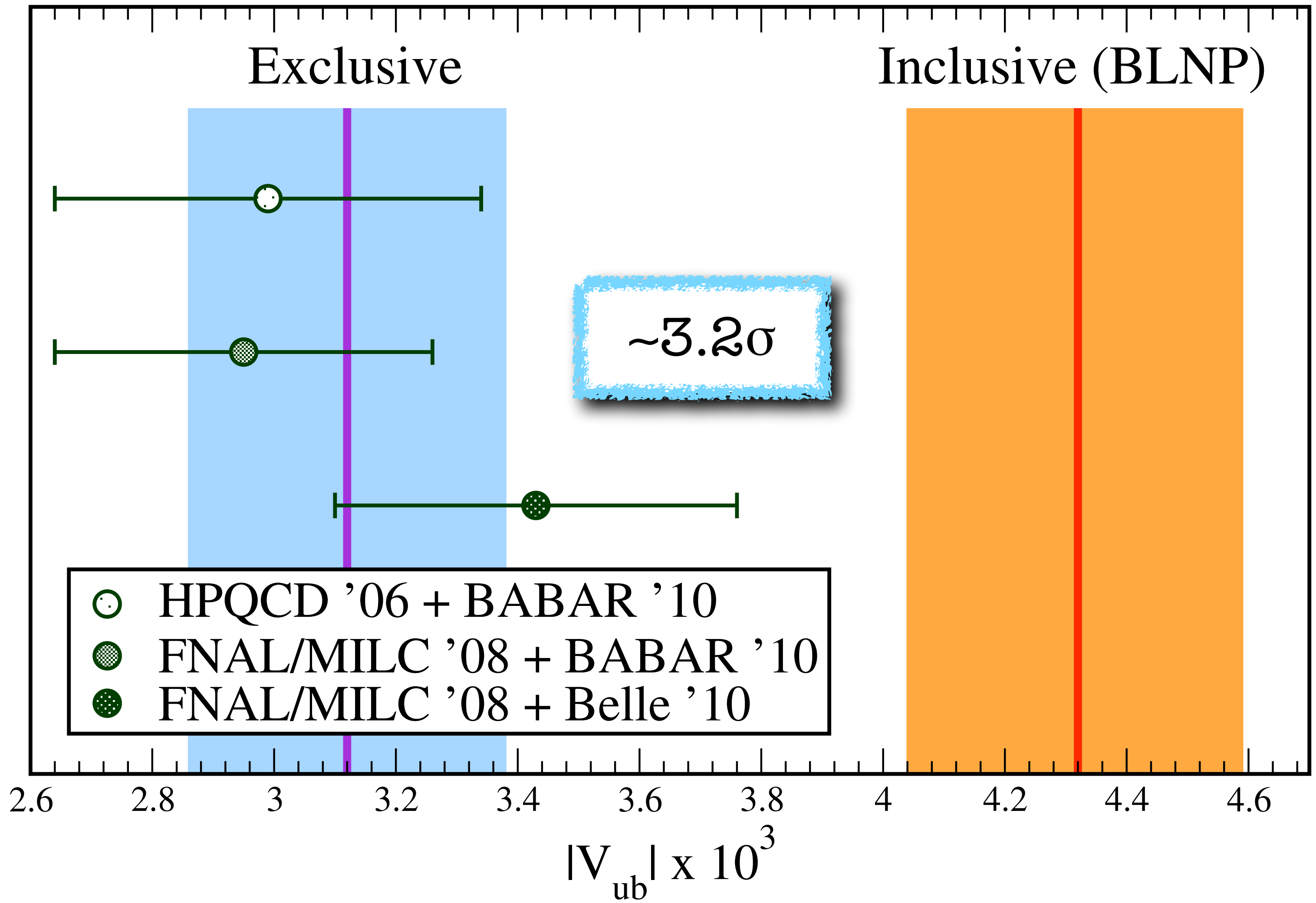

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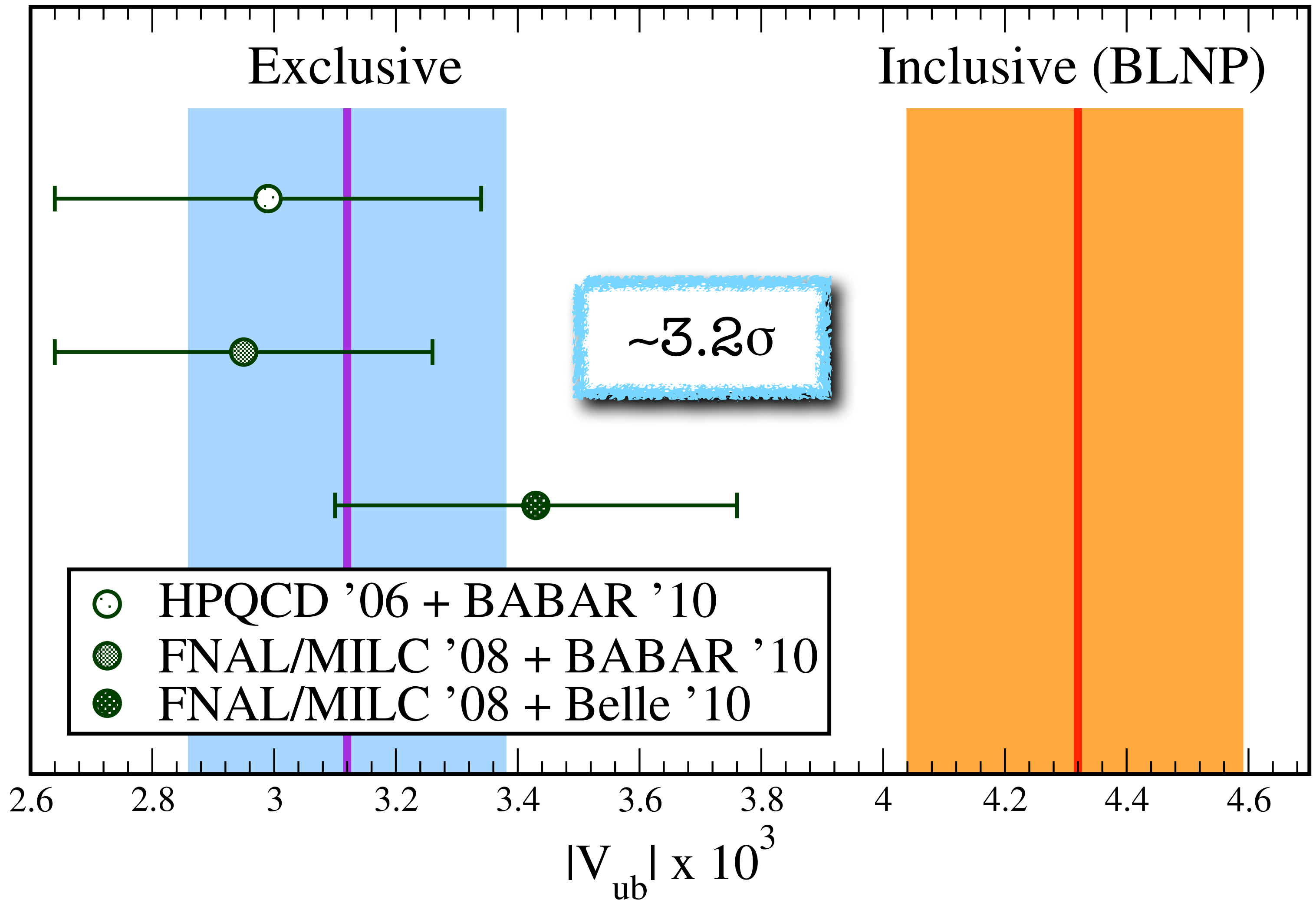

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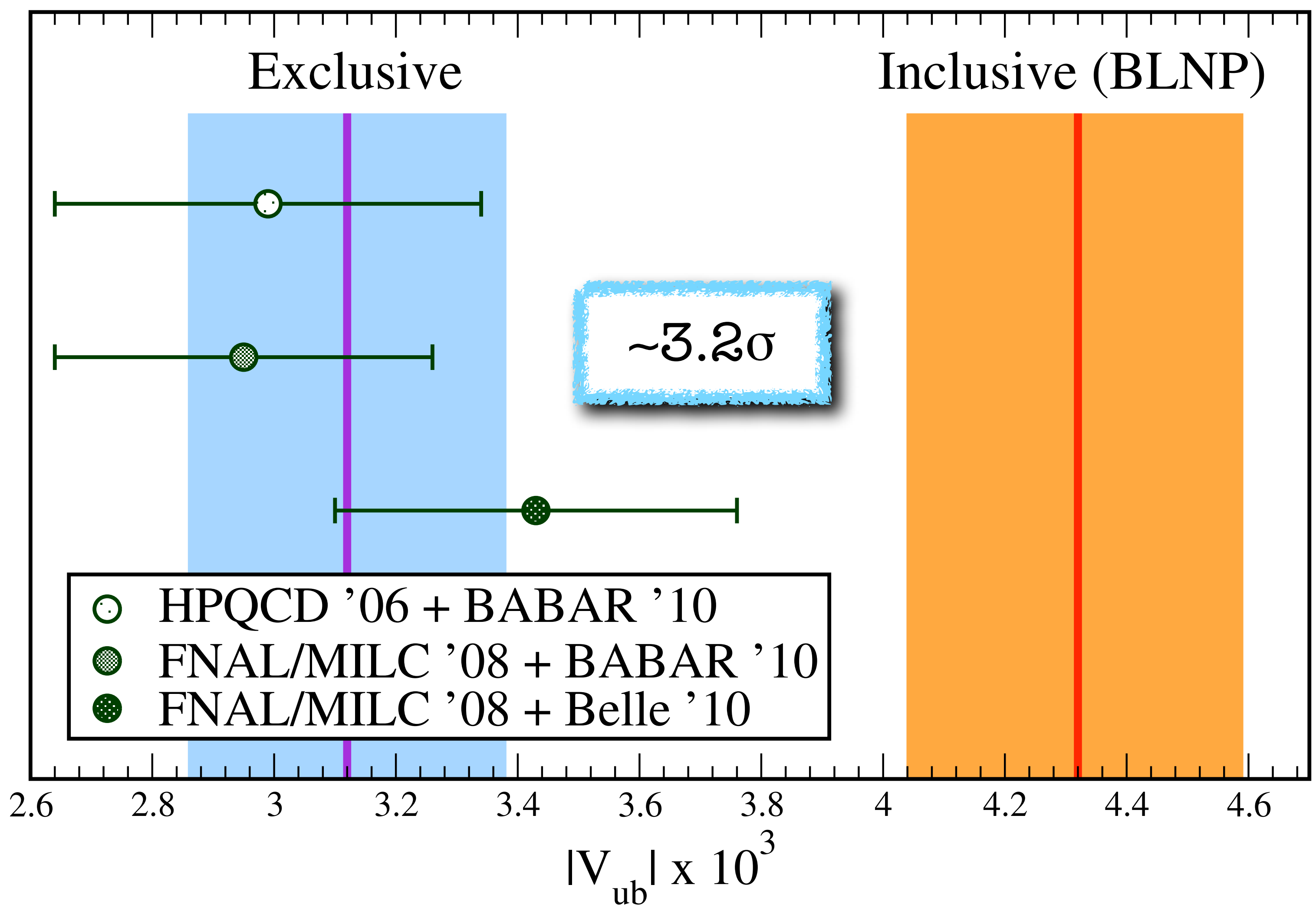

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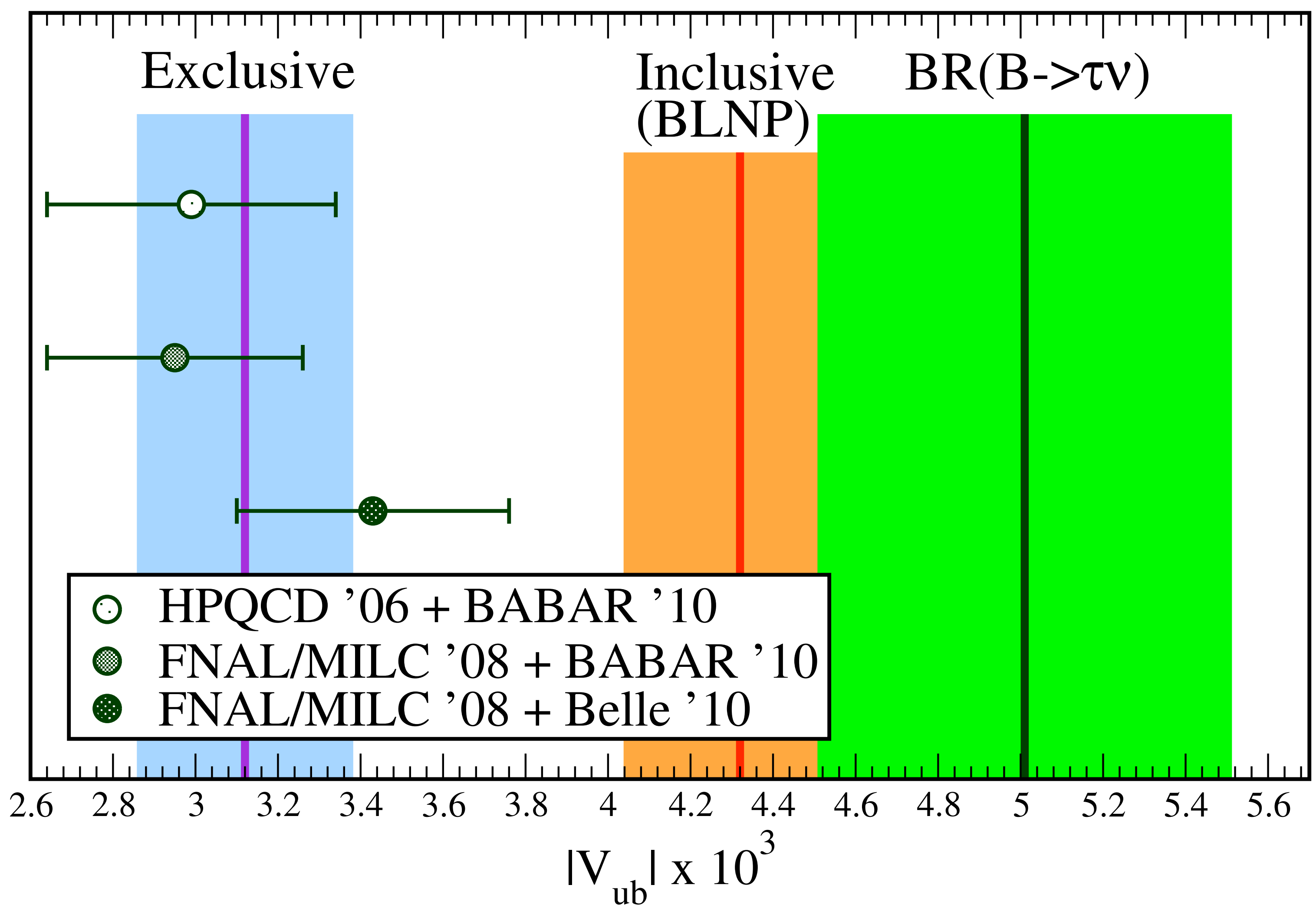
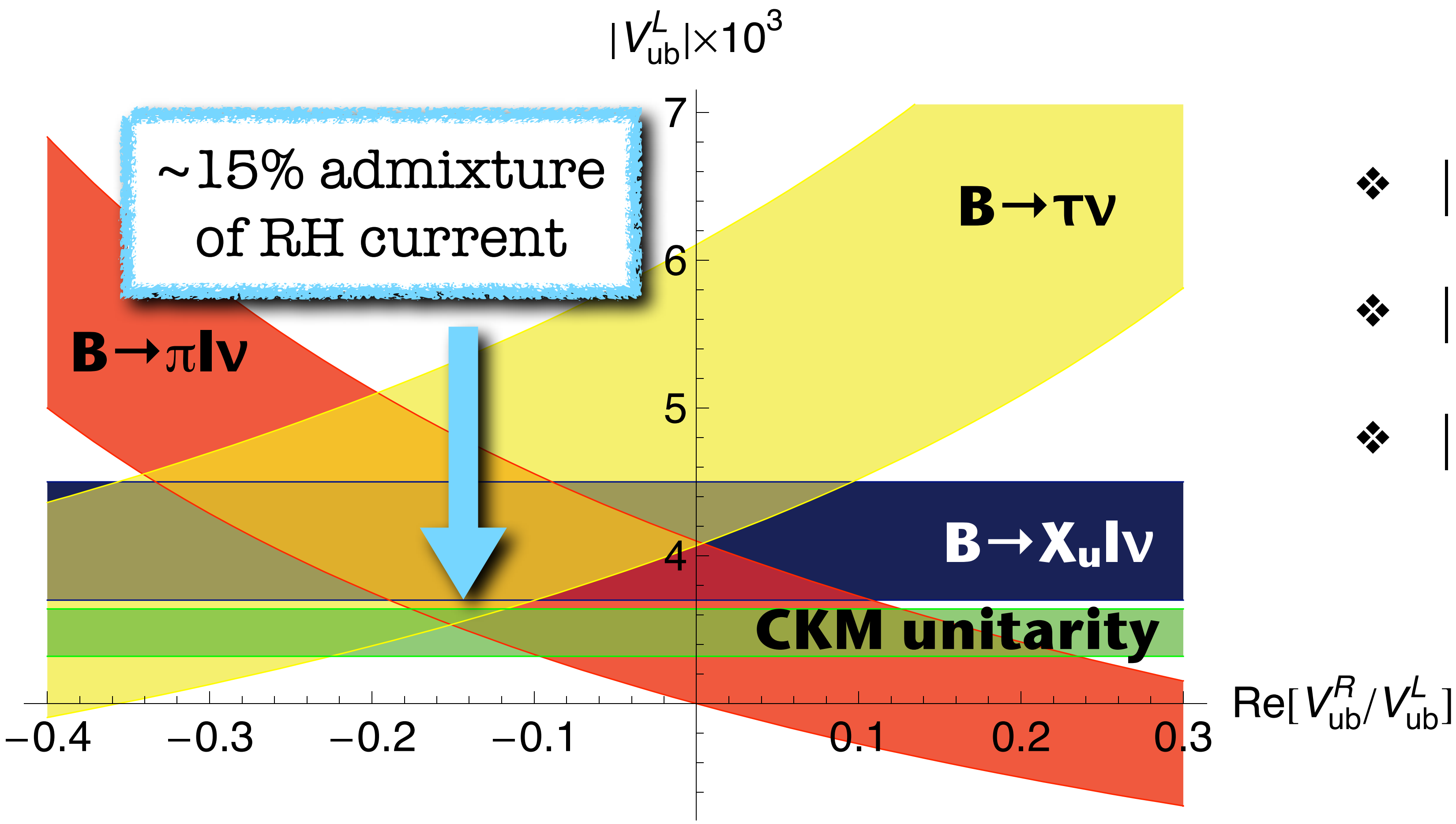


- Inclusive $|V_{ub}|$ varies depending upon theoretical framework and is highly sensitive to the input b-quark mass
- $BR(B\to\tau\nu)$ will be measured to greater precision at Belle II and super-B
- $|V_{ub}|$ can be obtained from other exclusive decay channels such as $B_s\to K\mu\nu$

Right-handed currents?

- Elegant solution provided by a right-handed weak current with coupling V_{ub}^R [Crivellin, Phys.Rev. D81 (2010) 031301], which enters as:

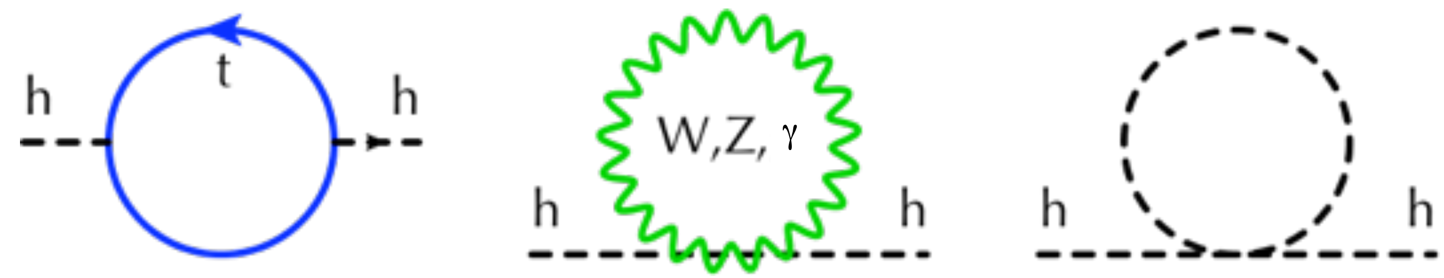


- $|V_{ub}^L+V_{ub}^R|^2$ in $B\to\pi l\nu$
- $|V_{ub}^L-V_{ub}^R|^2$ in $B\to\tau\nu$,
- $|V_{ub}^L|^2+|V_{ub}^R|^2$ in $B\to X_u l\nu$

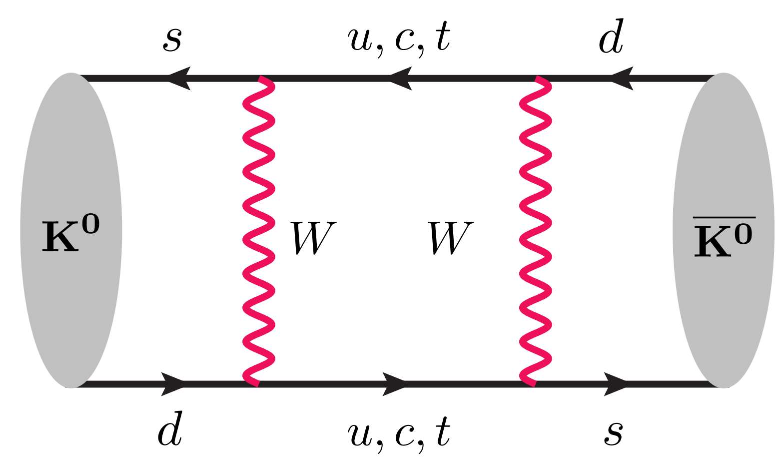
- In practice, however, cannot realize this scenario in simplest left-right asymmetric models while satisfying other flavor constraints, especially from kaon mixing [Blanke, Buras, Gemmler, Heidsieck, arXiv:1111.5014 [hep-ph]]

The "new-physics flavor puzzle"

- Naturalness and fine tuning suggest that new physics is preferred near the TeV scale



- Precision measurements in the quark-flavor sector, however, rule out the possibility of large TeV-scale new-physics contributions to flavor-changing neutral currents



➡ New TeV-scale physics realized in nature must have highly non-generic flavor structure, e.g.

- ❖ Phases aligned with the Standard Model as in Minimal Flavor Violation
- ❖ Couplings unnaturally tiny

- Both ATLAS & CMS and heavy-flavor experiments are needed to address this tension

Flavor-physics sensitivity to NP

	LHT	RSc	4G	2HDM	RHMFV
$D^0 - \bar{D}^0$ (CPV)	★★★	★★★	★★	★★	
ϵ_K	★★	★★★	★★	★★	★★
$S_{\psi\phi}$	★★★	★★★	★★★	★★★	★★★
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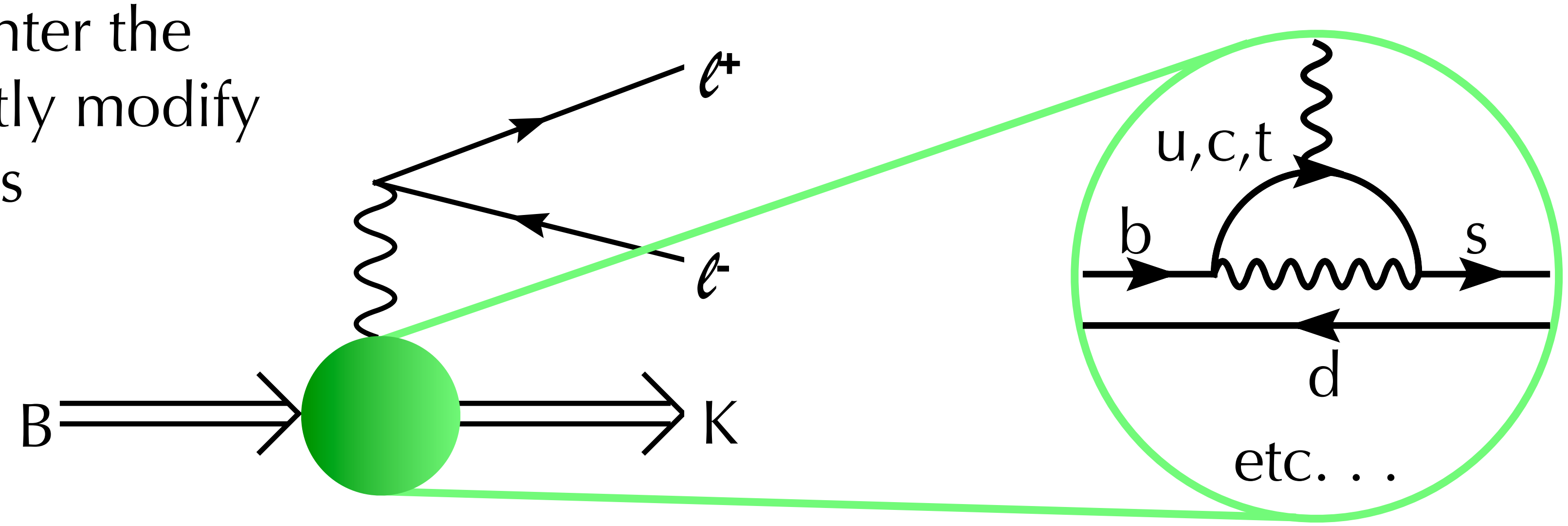
Rare b→s transitions

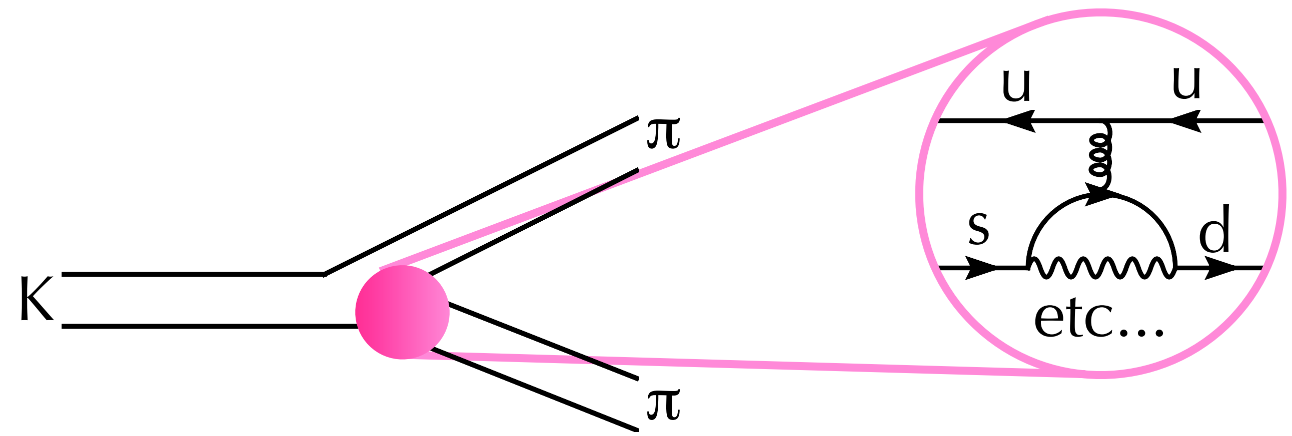
- In the next several years, **LHCb** and **super-B factories** will improve measurements of (or discover) many rare b→s transitions, *e.g.*:
  - $B_s \to \mu^+\mu^-$ (1-loop EW penguin transition and helicity suppressed)
  - $B \to K^*\gamma$ (1-loop radiative penguin transition)
  - $B \to K^{(*)} \ell^+\ell^-$ (1-loop EW penguin transition)
- New particles can enter the loops and significantly modify the decay amplitudes



- Standard Model branching fraction predictions for many b→s processes limited by hadronic form factor uncertainties

$K\to\pi\pi$ decay (ϵ'_K/ϵ_K)

- CP-violating $K\to\pi\pi$ decay sensitive to some of the same penguin diagrams (and hence new physics) as $K\to\pi\nu\bar{\nu}$



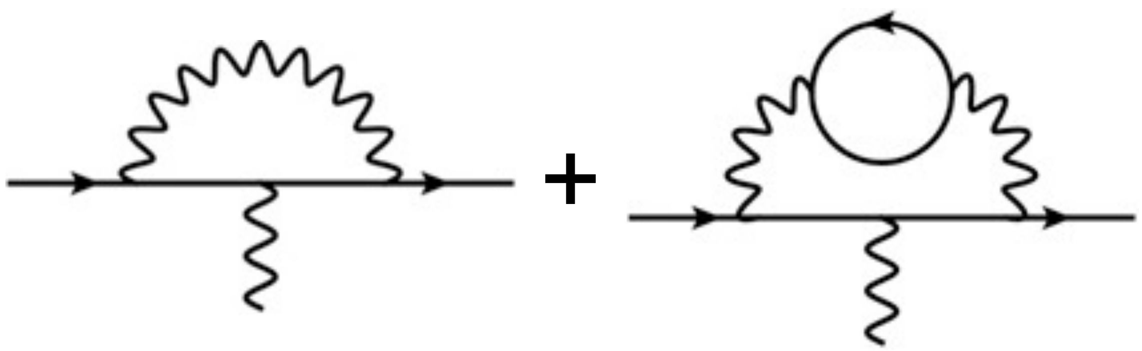
- Re(ϵ'_K/ϵ_K) Measured experimentally to better than 10% precision, but utility for constraining new physics handicapped by large uncertainty in corresponding weak matrix elements

- In the past two years, RBC-UKQCD collaboration made significant progress in resolving theoretical issues associated with computing $K\to\pi\pi$ amplitudes via the "direct" Lellouch-Lüscher approach [Blum et al., PRD 84 (2011) 114503, PRL 108, 141601 (2012)]

  - ⇒ **Should soon allow lattice-QCD calculations of $\varepsilon'_K/\varepsilon_K$ with ~20-30% precision**

- With these projected improvements, combining the pattern of results for $K\to\pi\nu\bar{\nu}$ and $\varepsilon'_K/\varepsilon_K$ can help distinguish between new-physics scenarios [Buras *et al.*, Nucl.Phys. B566 (2000)]

Muon g-2 in the Standard Model



QED (4 loops) & EW (2 loops)

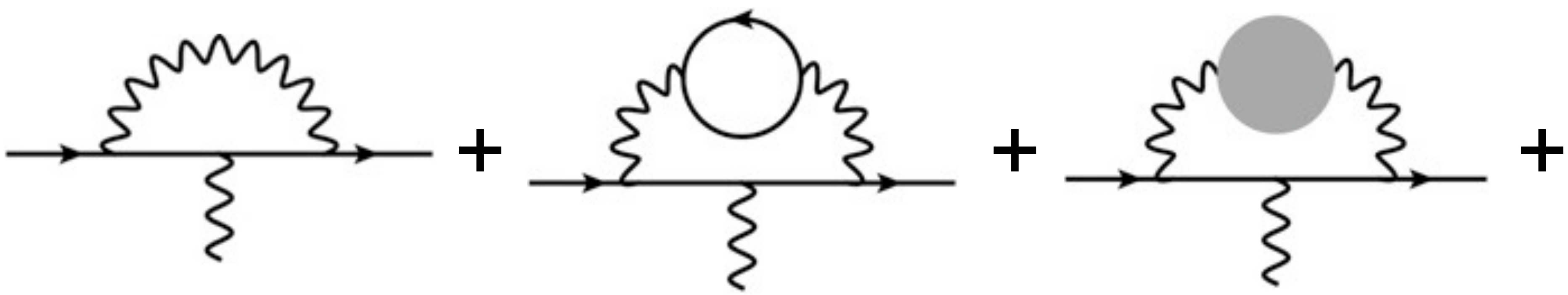
Contribution	Result ($\times 10^{11}$)		Error
QED (leptons)	116 584 718 $\pm$ 0.14	$\pm$ 0.04_{α}	0.00 ppm
HVP(lo) [1]	6 923 $\pm$ 42		0.36 ppm
HVP(ho)	-98 $\pm$ 0.9_{exp}	$\pm$ 0.3_{rad}	0.01 ppm
HLbL [2]	105 $\pm$ 26		0.22 ppm
EW	154 $\pm$ 2	$\pm$ 1	0.02 ppm
Total SM	116 591 802 $\pm$ 49		0.42 ppm

[1] Davier, Hoecker, Malaescu, Zhang, Eur.Phys.J. C71 (2011) 1515

[2] Prades, de Rafael, Vainshtein, arXiv:0901.030

Muon g-2 in the Standard Model

Hadronic vacuum polarization (HVP):



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

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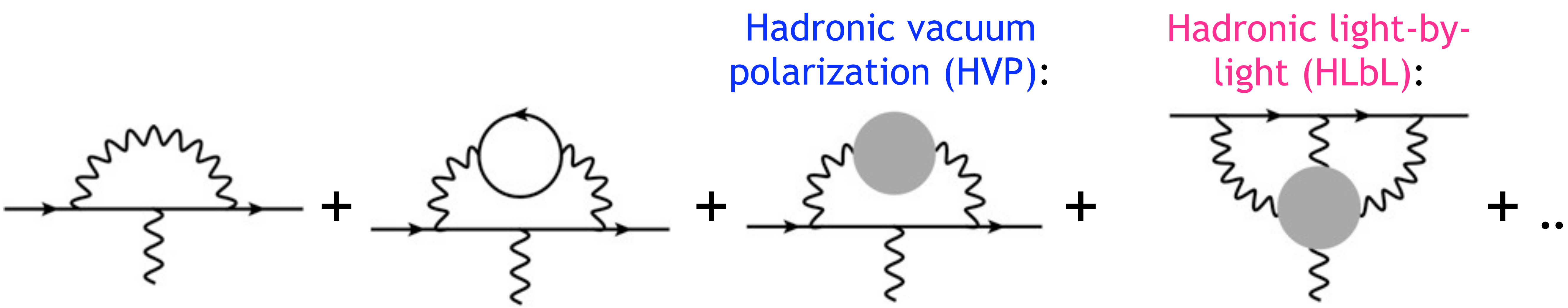

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estimated from models such as large N_c, vector meson dominance, χPT, etc...

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Prospects for new-physics searches

- Projected experimental and lattice QCD progress should allow **stringent Standard Model tests and new physics searches in many promising channels**, *e.g.*:

		Current errors		5+ years	
Quantity	lattice input	experiment	LQCD	experiment	LQCD
$\mathcal{B}(B \to \tau\nu)$	$f_B^2 \|V_{cb}\|^2$	21%	13%	3%	4%
$\mathcal{B}(B \to K\ell^+\ell^-)$	$f_{\{0,+,T\}}^{B\to K}(q^2)$	10%	~25% (LCSR)	4%	4%
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	$\|V_{cb}\|^4$	64%	10%	3%	6%
$\mathcal{B}(K_L^0 \to \pi^0\nu\bar{\nu})$	$\|V_{cb}\|^4$	—	10%	3%	6%
$\mathrm{Re}(\epsilon'_K/\epsilon_K)$	$B_6^{(1/2)}, B_8^{(3/2)}$	8%	>100%	8%	<20%
$(g-2)_\mu$	a_μ^{HLbL}	0.42 ppm	0.22 ppm (model estimate)	0.14 ppm	10% (0.09 ppm)

See USQCD Collaboration white paper at
http://www.usqcd.org/documents/HiIntensityFlavor.pdf
for further details