Emphasize recent highlights since EPS-HEP 2013!

Lattice QCD for the precision era

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Where is the new physics?

- HEP experimental community searching for **tiny effects of new heavy particles** via broad program of precision measurements, targeting process that are

  (1) Extremely rare
  (or even forbidden)
  in the Standard Model

  (2) Predicted to high theoretical precision
  in the Standard Model

neutrinos

NOvA

DUNE
Deep Underground Neutrino Experiment

charged leptons

g–2

Mu2e

quark flavor

LHCb

Belle II

BESIII

KOTO

NA62

Higgs

ilc

Muon Accelerator Program

FCC TLEP

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We do not know where the new physics lies ➜
cast a wide net!

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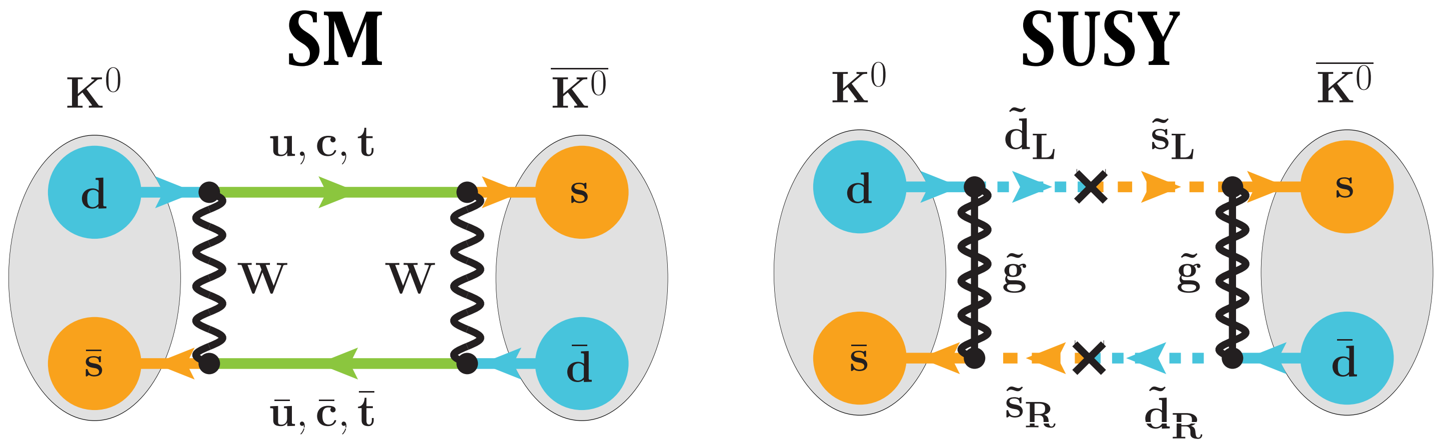
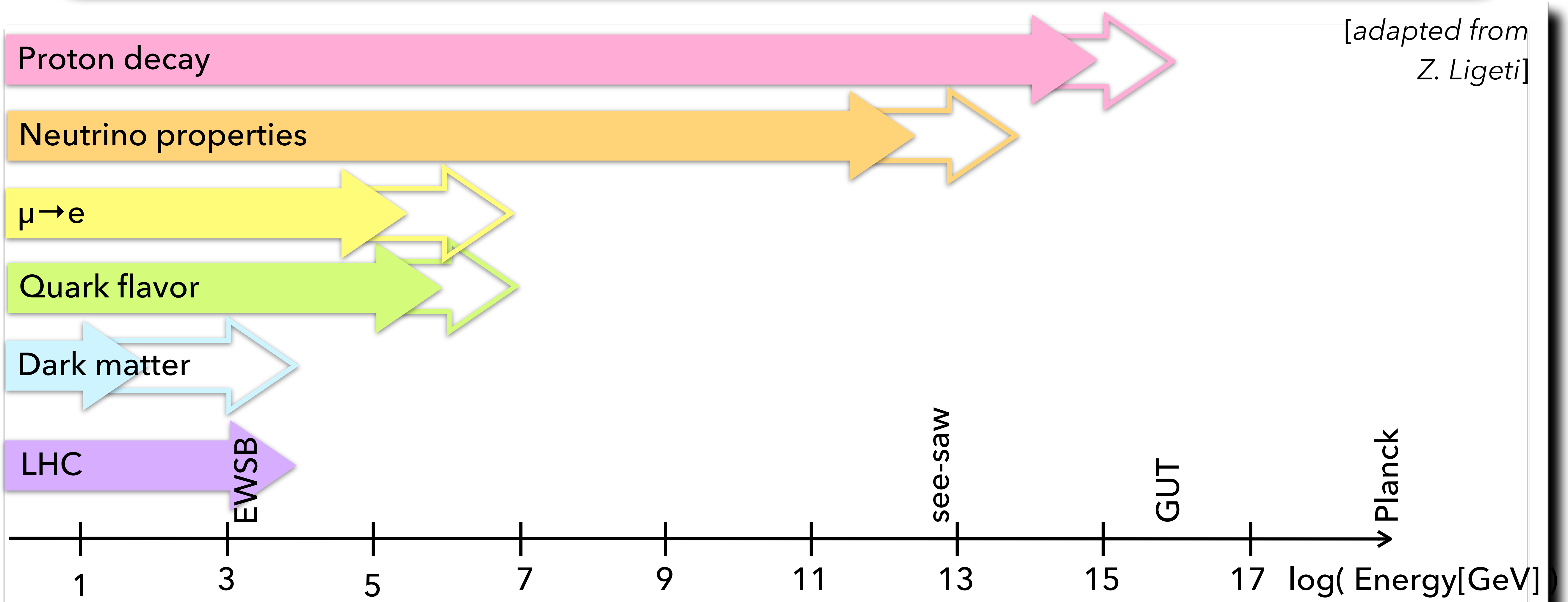
New-physics reach

Quantum-mechanical loops sensitive to new particles above the TeV scale, e.g. in neutral kaon mixing





[adapted from Z. Ligeti]

Approximate current (filled) & future (empty) experimental reach

New-physics reach

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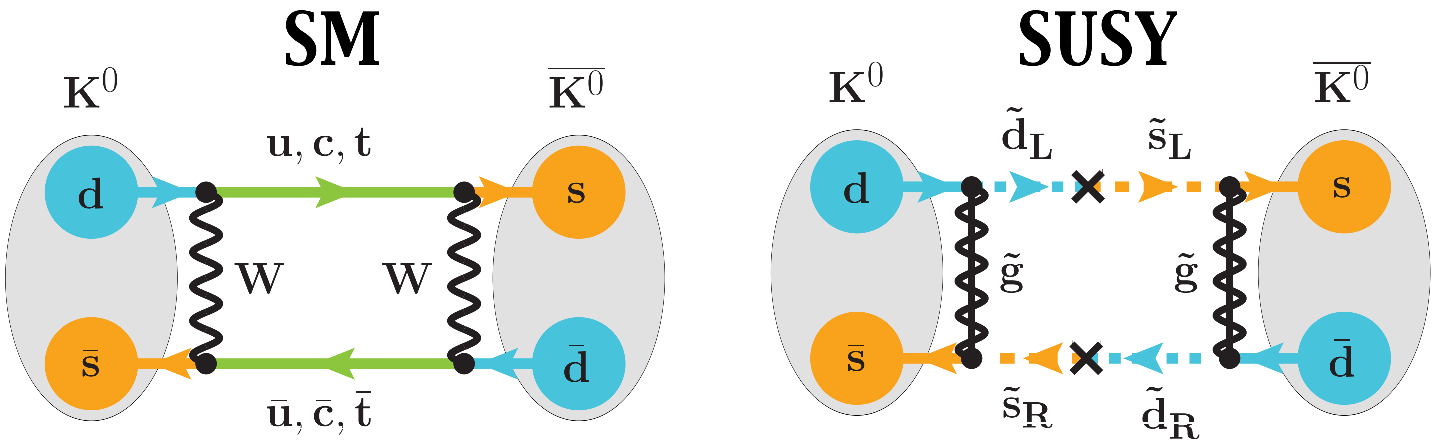

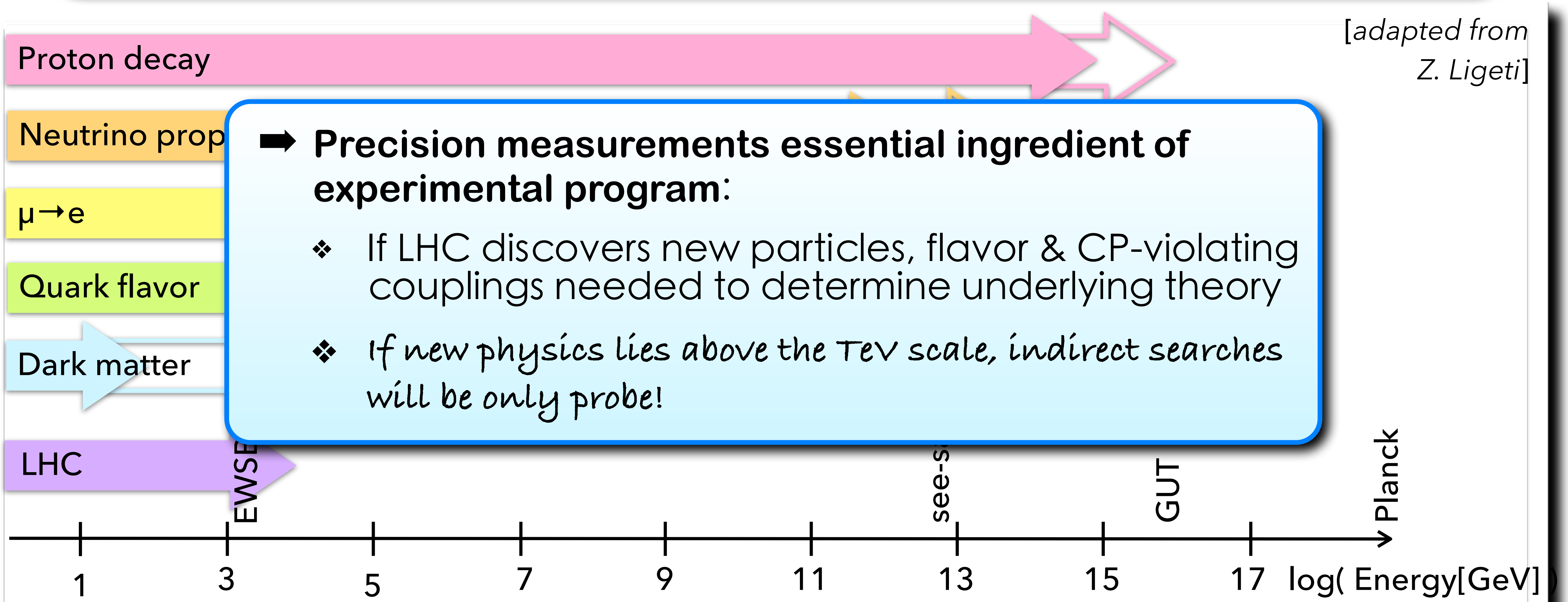

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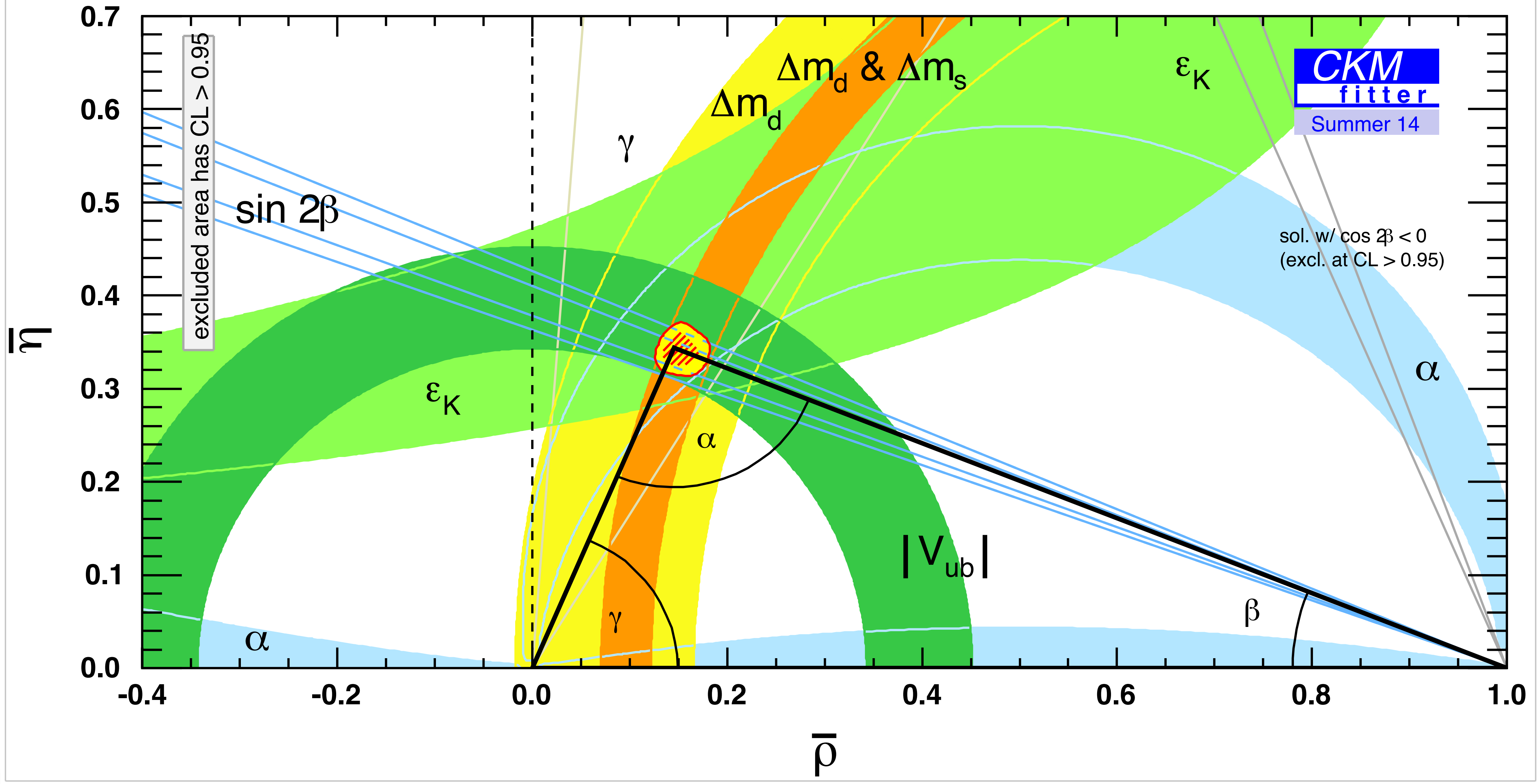
Approximate current (filled) & future (empty) experimental reach

➡ **Precision measurements essential ingredient of experimental program**:

- If LHC discovers new particles, flavor & CP-violating couplings needed to determine underlying theory
- *If new physics lies above the TeV scale, indirect searches will be only probe!*

Why lattice QCD?

global CKM unitarity-triangle fit



- Comparison between measurements and Standard-Model predictions limited in most cases by theory, often from hadronic matrix elements

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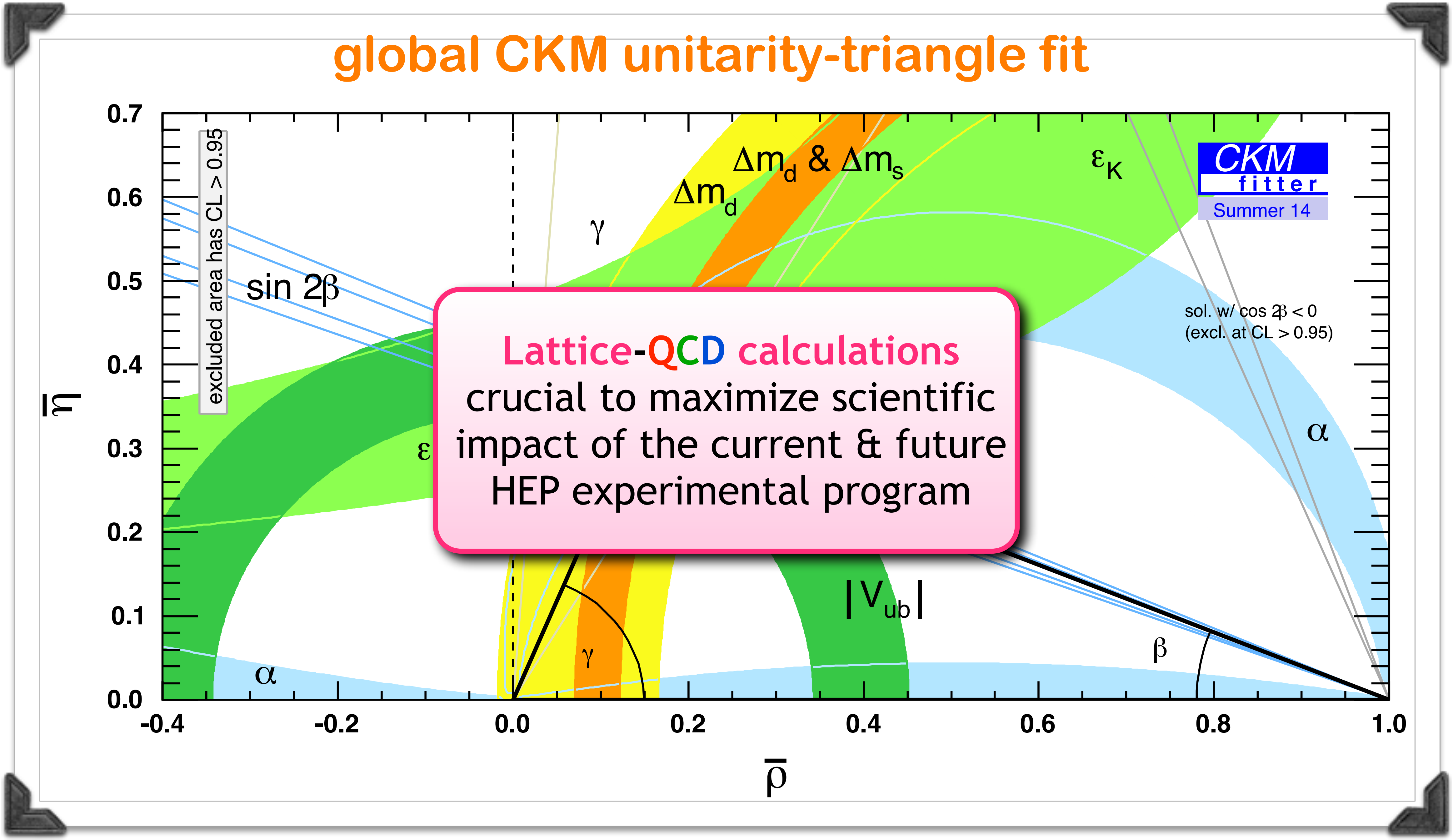
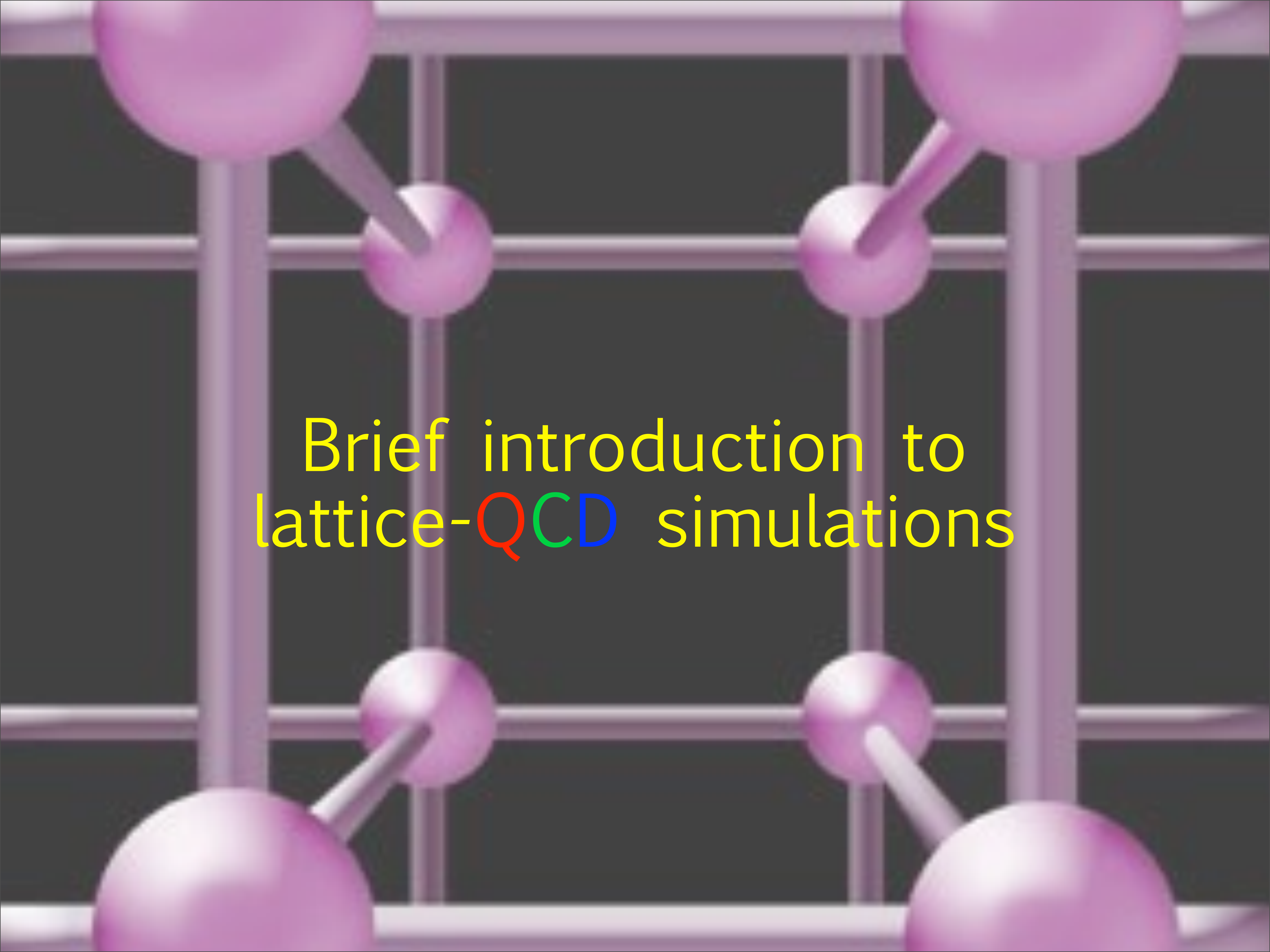

global CKM unitarity-triangle fit

Lattice-QCD calculations crucial to maximize scientific impact of the current & future HEP experimental program

- Comparison between measurements and Standard-Model predictions limited in most cases by theory, often from hadronic matrix elements



Brief introduction to lattice-QCD simulations

Quantum ChromoDynamics

$$\mathcal{L}_{\mathrm{QCD}} = \frac{1}{2g^2}\mathrm{tr}\left[F_{\mu\nu}F^{\mu\nu}\right] - \sum_{f=1}^{n_f}\bar{\psi}_f\left(\not{D}+m_f\right)\psi_f + \underbrace{\frac{i\bar{\theta}}{32\pi^2}\epsilon^{\mu\nu\rho\sigma}\mathrm{tr}\left[F_{\mu\nu}F_{\rho\sigma}\right]}_{\text{violates } CP}$$

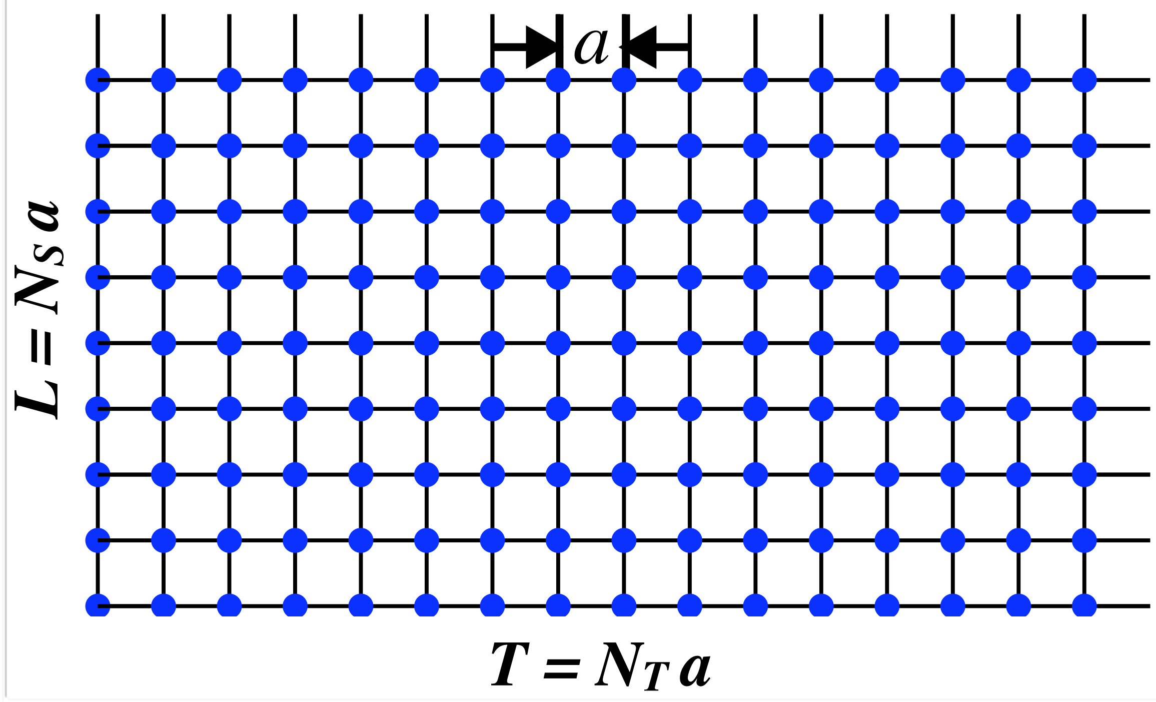
- QCD Lagrangian contains 1 + n_f + 1 parameters that can be fixed from equal number of experimental inputs

FUNDAMENTAL PARAMETER	**EXPERIMENTAL INPUT**
❖ Gauge coupling g^2	r_1, m_Ω, Υ(2S-1S), or f_π
❖ n_f quark masses m_f	m_π, m_K, $m_{J/\psi}$, m_Υ, …
❖ $\theta = 0$	neutron EDM ($\lvert\theta\rvert < 10^{-11}$)

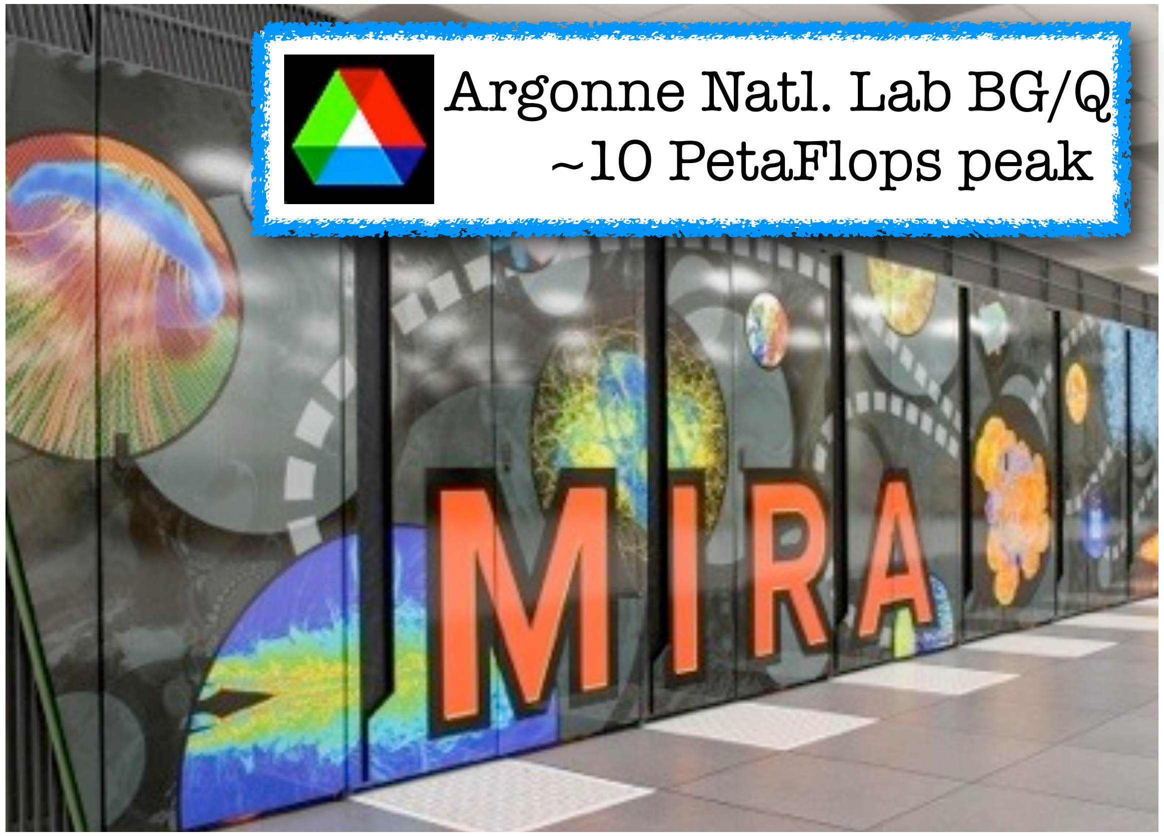
- Once the parameters are fixed, everything else is a prediction of the theory
- Calculations of hadronic parameters challenging in practice because low-energy QCD is nonperturbative

Numerical lattice QCD

- Systematic method for calculating hadronic parameters from QCD first principles
- Define QCD on (Euclidean) spacetime lattice and solve path integral numerically
  - Recover QCD when lattice spacing a→0 and box size L→∞

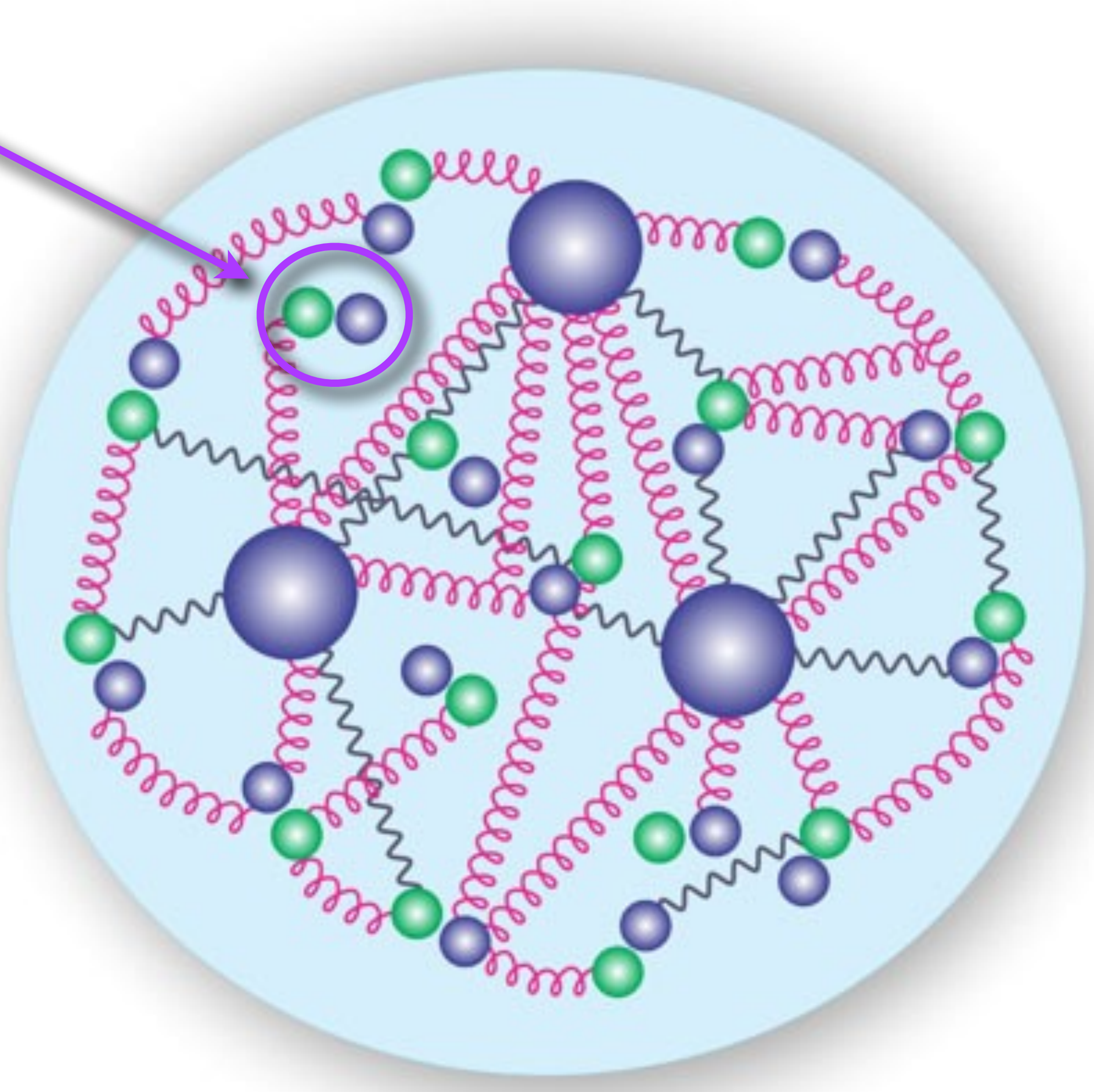


- Simulate using **Monte-Carlo methods and importance sampling**
  - Sample from all possible field configurations using a distribution given by $\exp(-S_{QCD})$
- Run codes upon **supercomputers** and dedicated clusters


Argonne Natl. Lab BG/Q
~10 PetaFlops peak

Modern lattice-QCD simulations

- Realistic simulations include dynamical u, d, s (& c) quarks in the vacuum
  - (Typically sea m_u=m_d)
- Control systematic errors using gauge-field ensembles with different parameters, *e.g.*:
  - Multiple lattice spacings to extrapolate to continuum limit (a→0)
  - Multiple up/down-quark masses to extrapolate to physical M_π =135 MeV

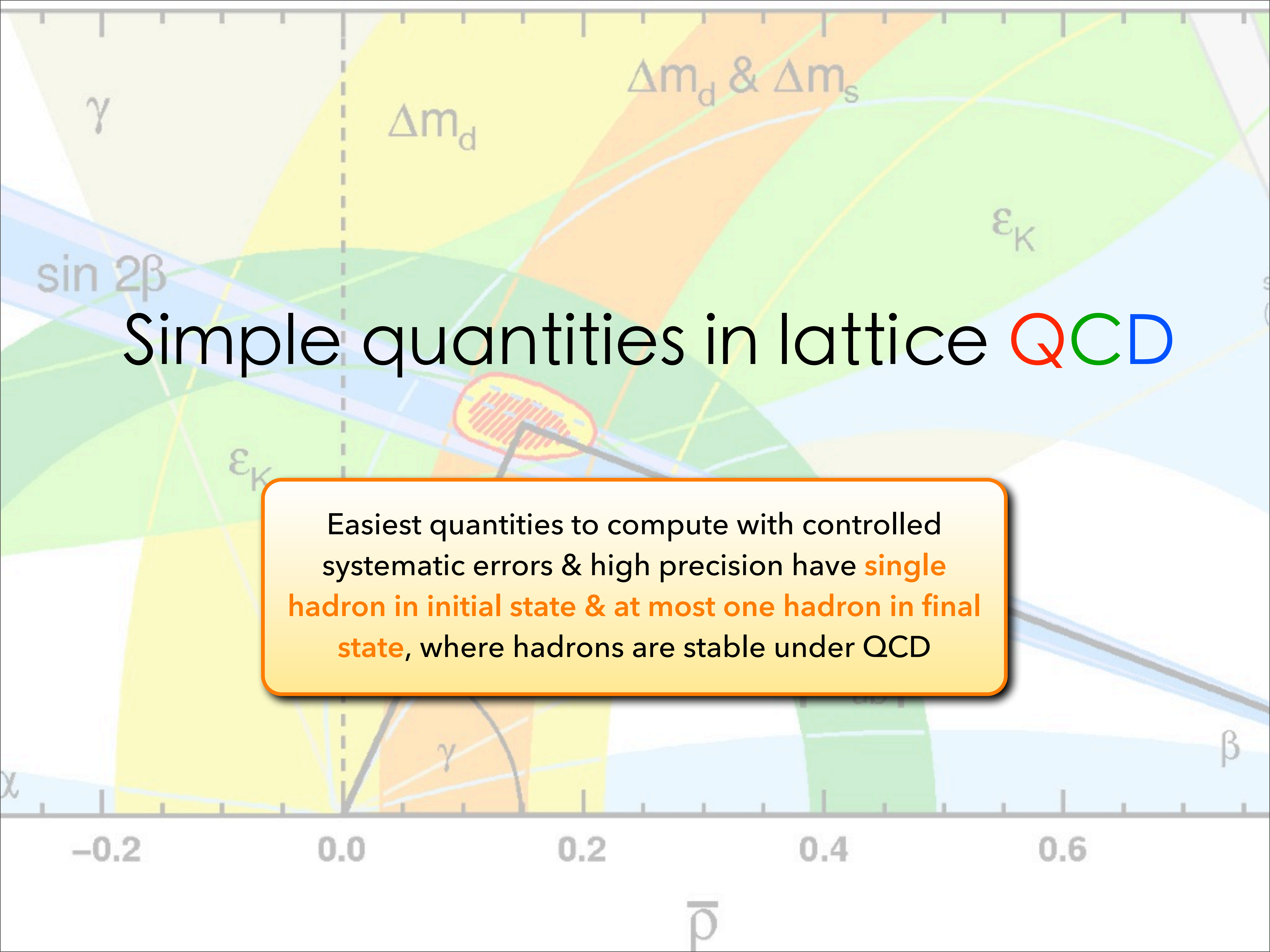


Test and validate methods by

(1) Comparison with experiment

(2) Independent calculations sensitive to different systematics

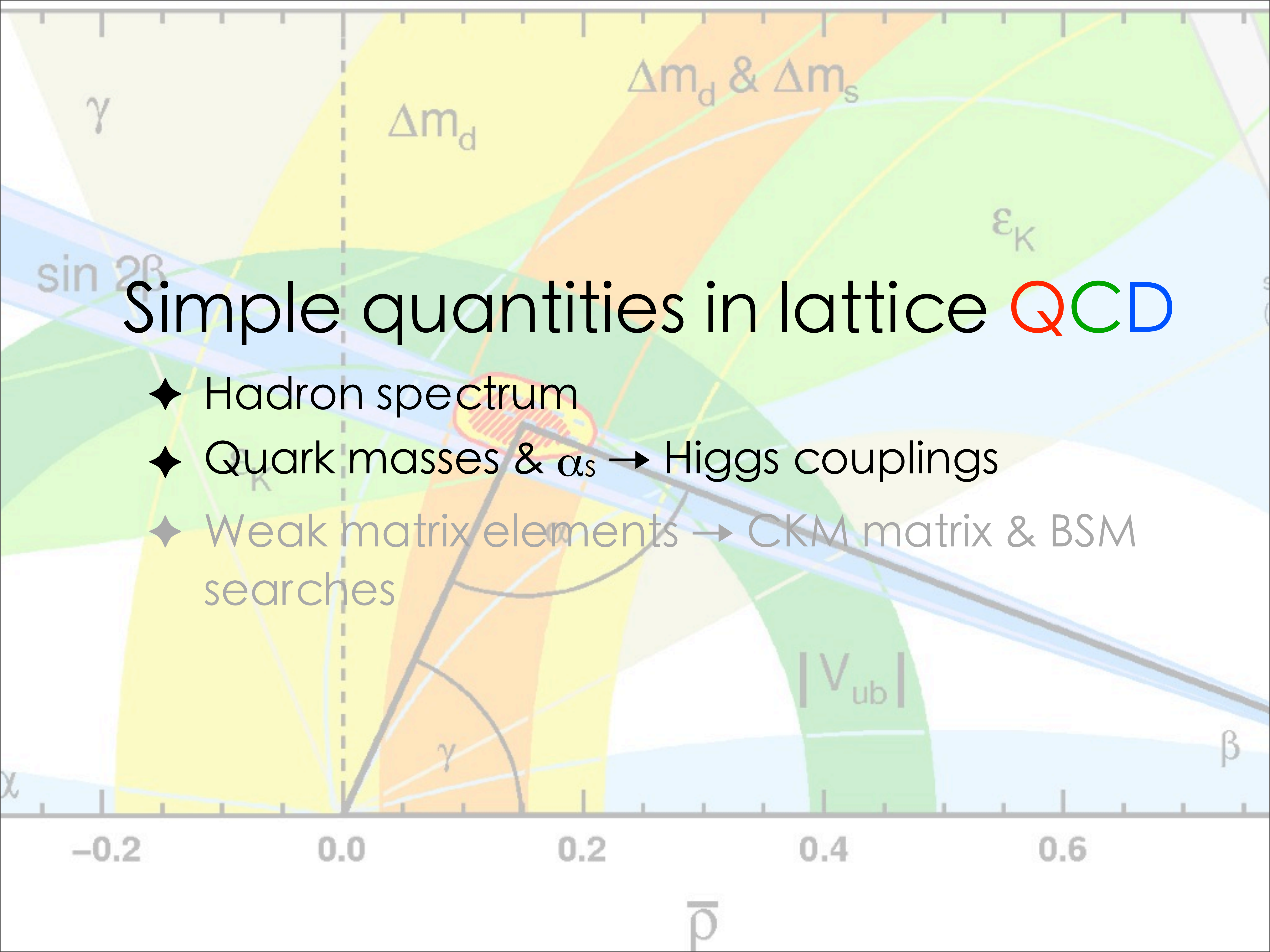
Simple quantities in lattice QCD



Easiest quantities to compute with controlled systematic errors & high precision have **single hadron in initial state & at most one hadron in final state**, where hadrons are stable under QCD

Simple quantities in lattice QCD

- Hadron spectrum
- Quark masses & α_s → Higgs couplings
- Weak matrix elements → CKM matrix & BSM searches



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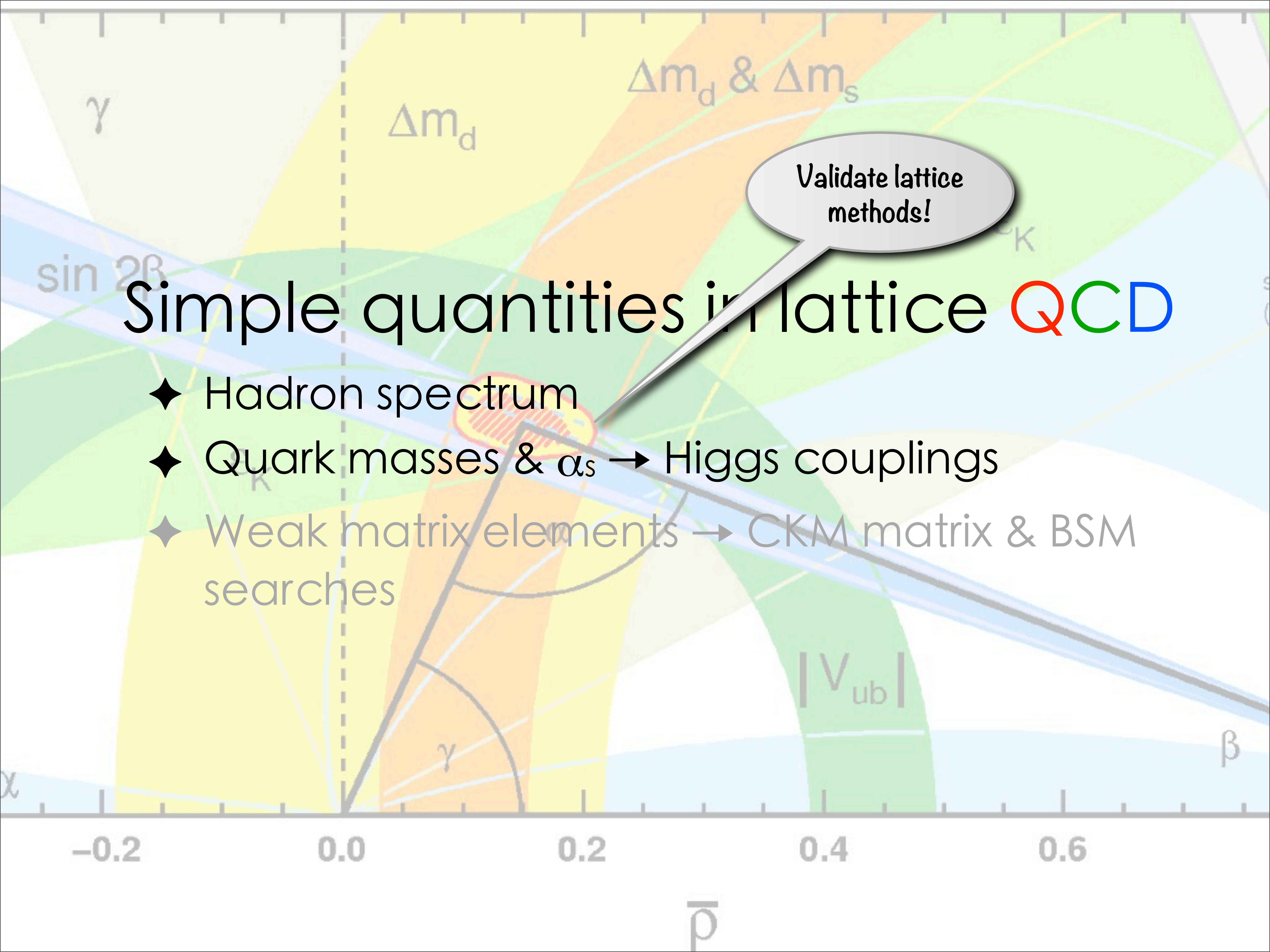


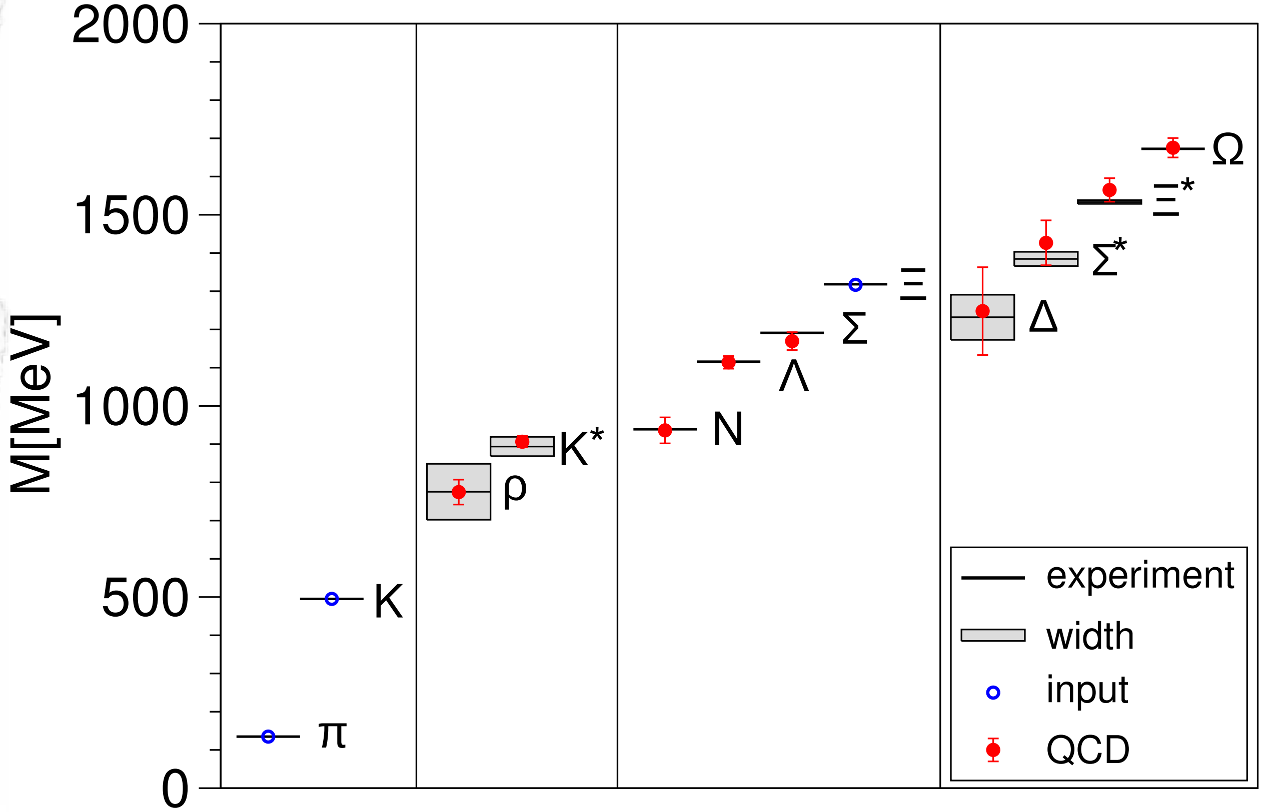
Validate lattice methods!

- ✦ Hadron spectrum
- ✦ Quark masses & α_s → Higgs couplings
- ✦ Weak matrix elements → CKM matrix & BSM searches

Hadron spectrum

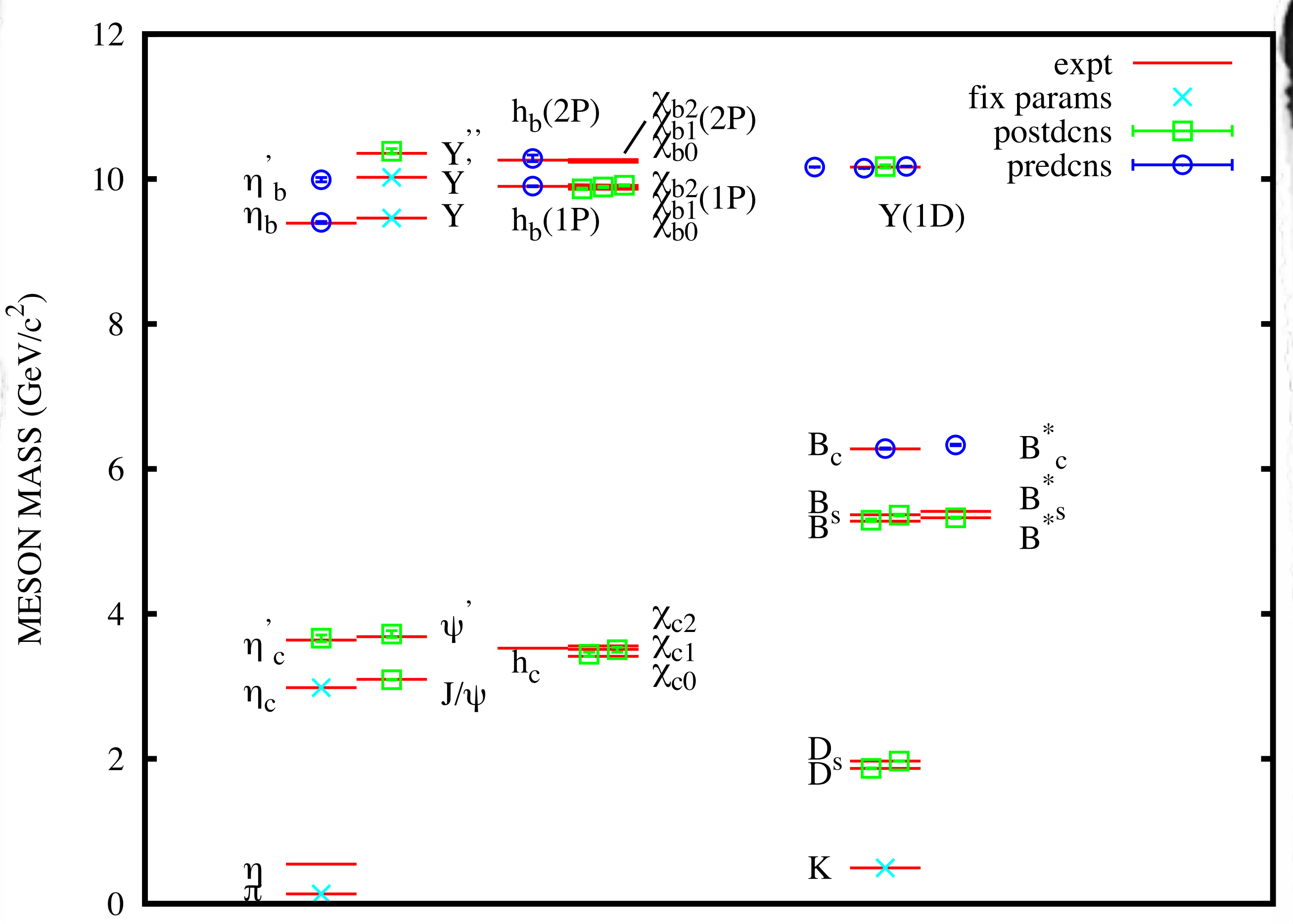
Light hadrons

[BMW, Science 322 (2008) 1224-1227]



Heavy hadrons

[HPQCD,1203.3862 (C.Davies Lattice 2011)]



- ✦ Light hadron masses much larger than constituent quark masses, so primarily due to energy stored in gluon field and to quarks′ kinetic energy

  ➡ Tests nonperturbative QCD dynamics

- ✦ Tests lattice methods for charm & bottom quarks, which often rely on effective field theories

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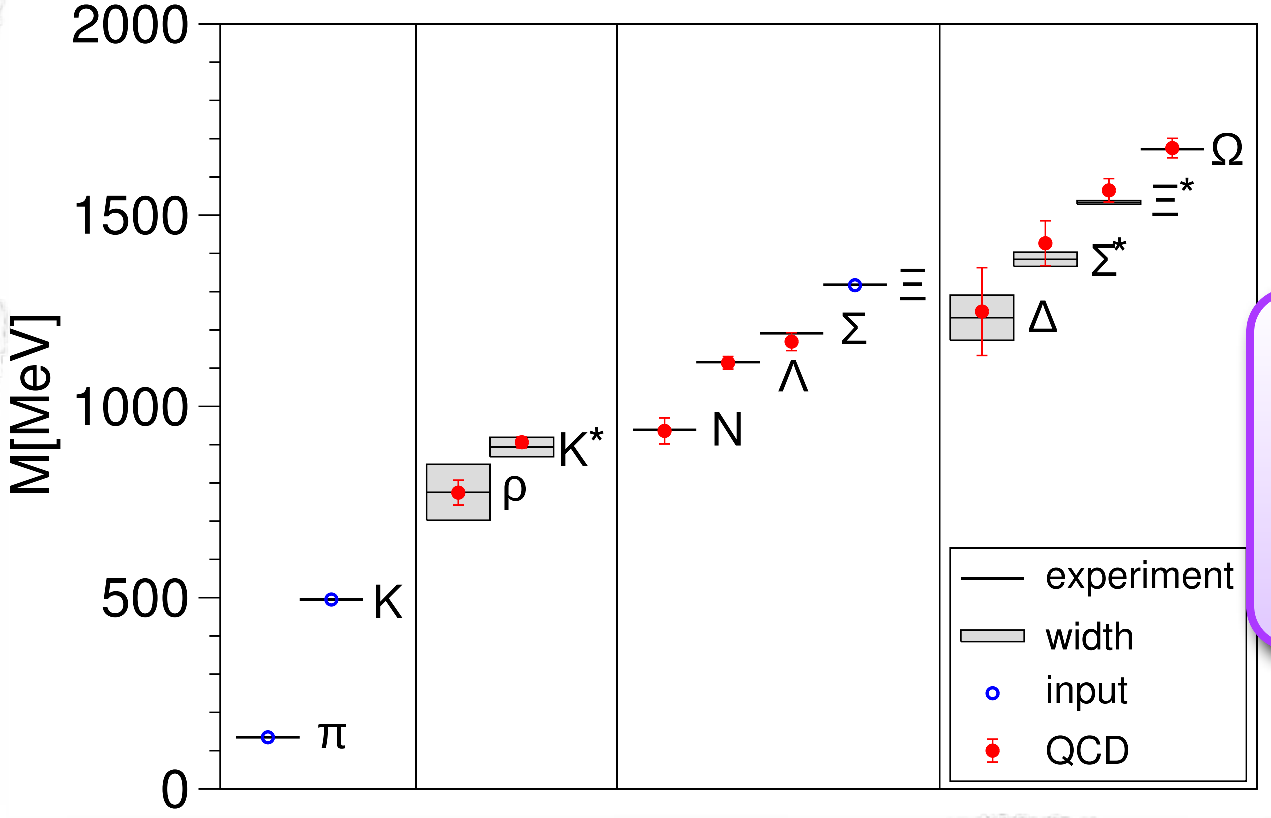

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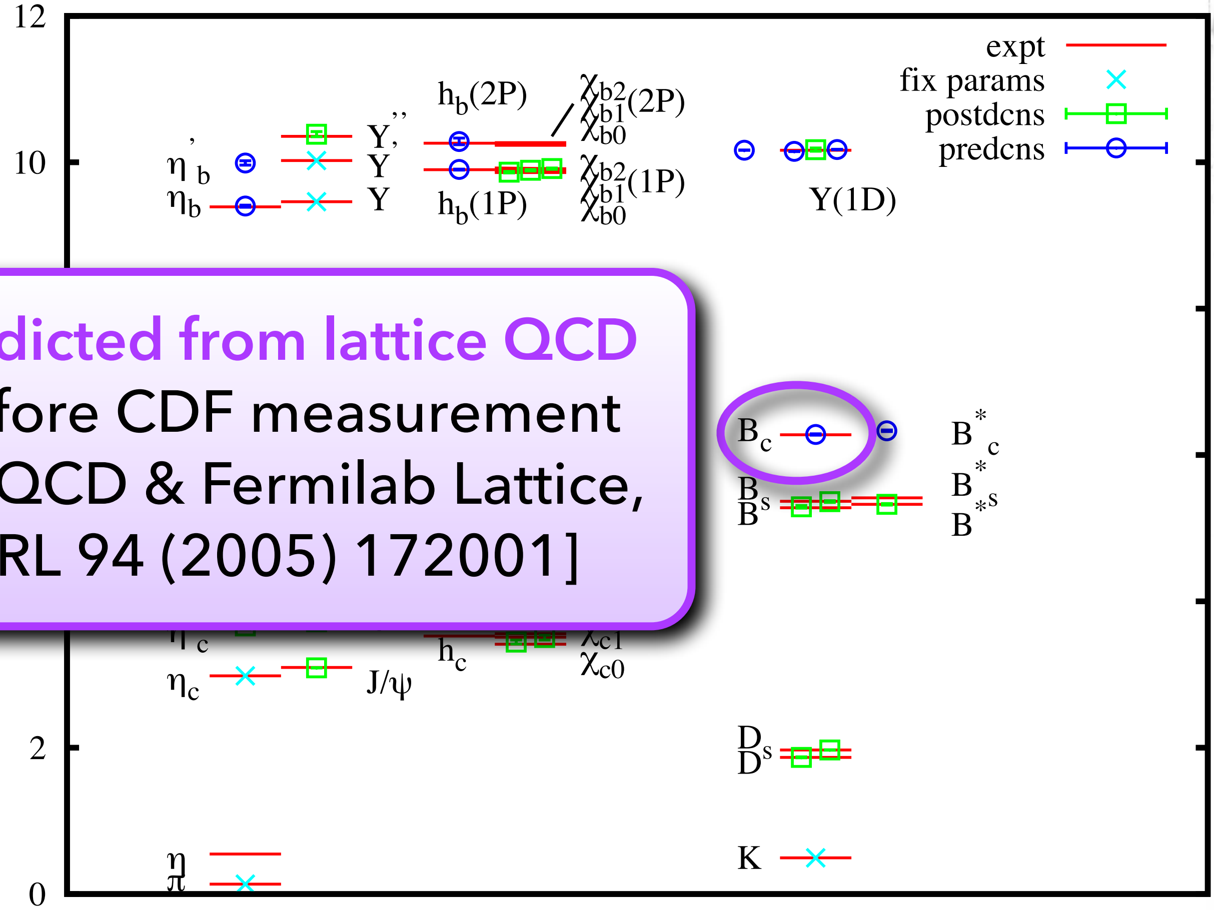


Predicted from lattice QCD
before CDF measurement
[HPQCD & Fermilab Lattice,
PRL 94 (2005) 172001]

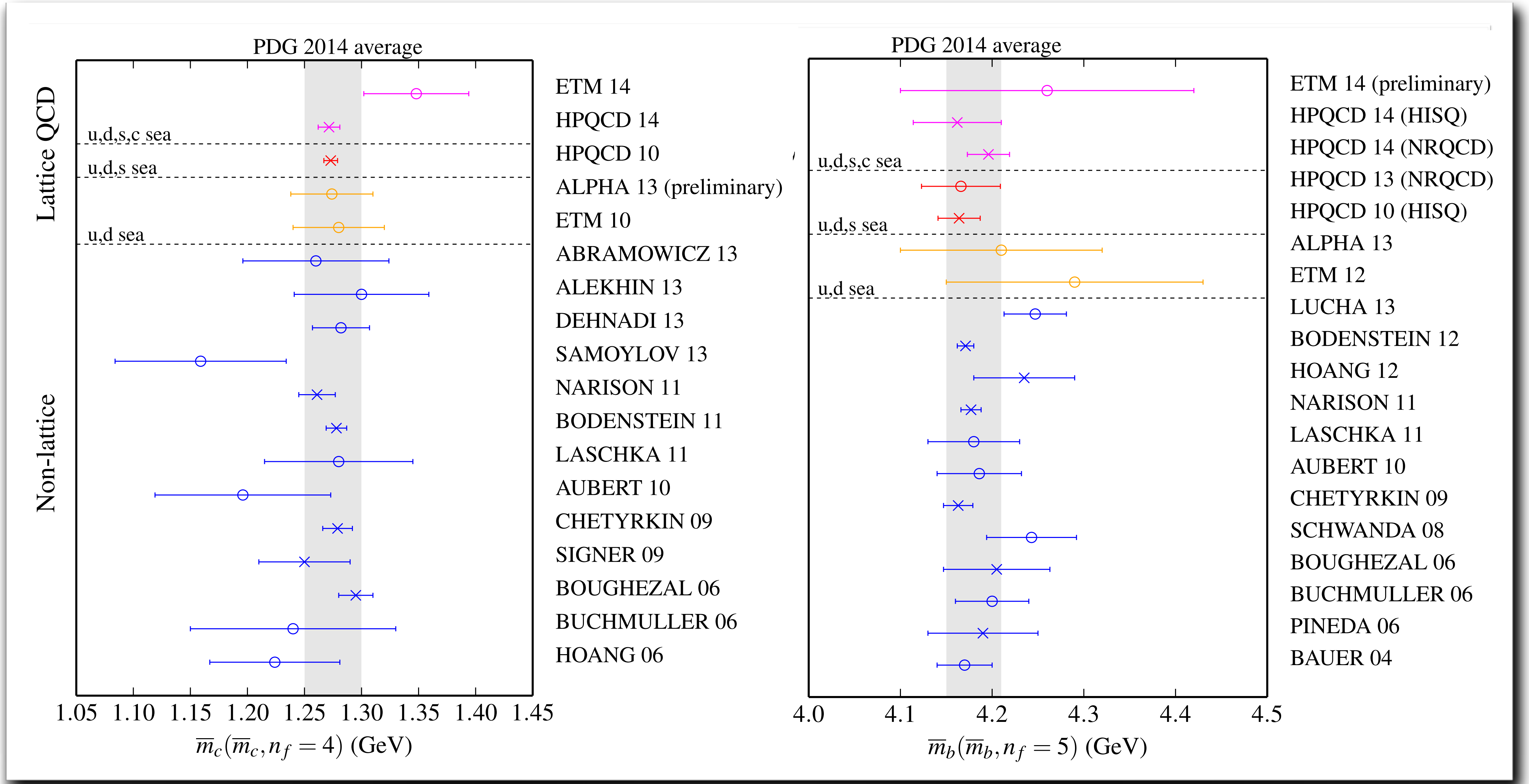
- Light hadron masses much larger than constituent quark masses, so primarily due to energy stored in gluon field and to quarks' kinetic energy

➡ **Tests nonperturbative QCD dynamics**

- Tests lattice methods for charm & bottom quarks, which often rely on effective field theories

Heavy-quark masses

- Most precise m_c and m_b obtained by fitting moments of correlation functions of the quarks' electromagnetic current to $O(\alpha_S^3)$ perturbative expressions
- Moments can be obtained from experimental e^+e^- annihilation data, and also **computed numerically with lattice-QCD simulations with negligible statistical uncertainties**



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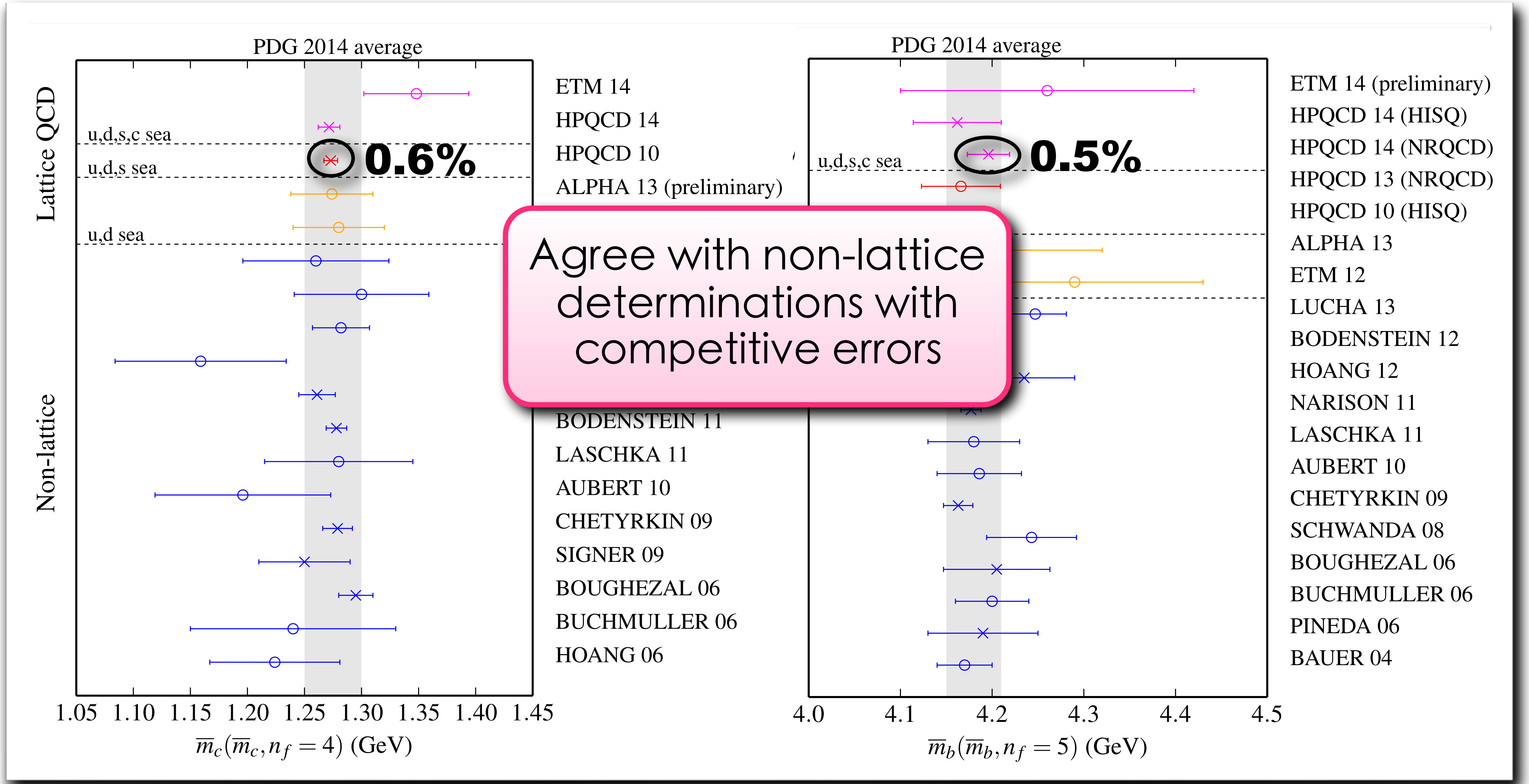
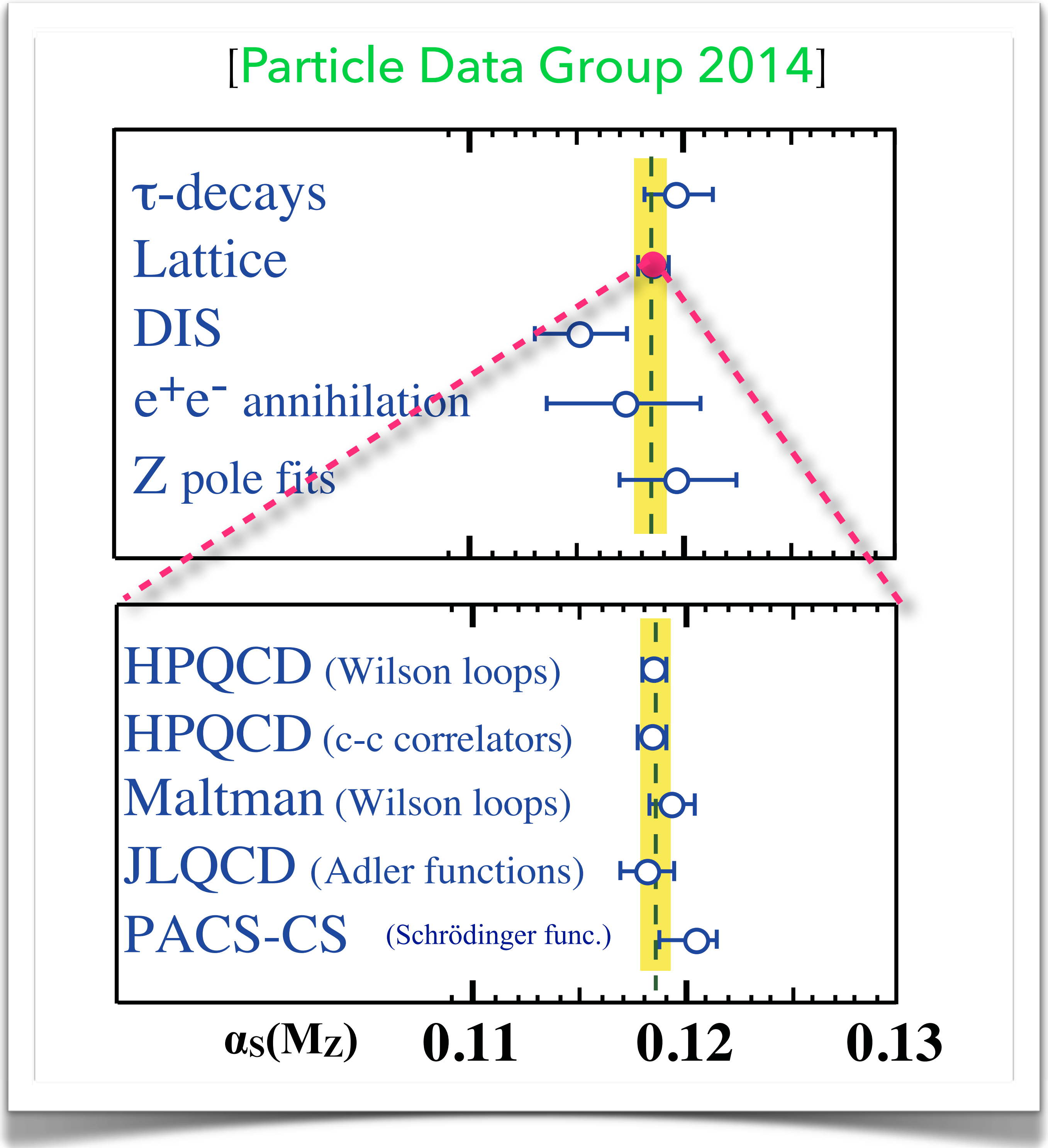


Agree with non-lattice determinations with competitive errors

Strong coupling constant

- **Several independent lattice methods available**
  - Most precise result from fitting NNNLO QCD β-function to short-distance lattice quantities built from Wilson loops (fits of heavy-quark correlators yield similar precision)
  - Approaches consistent, and **each is more precise than experiment**


[Particle Data Group 2014]

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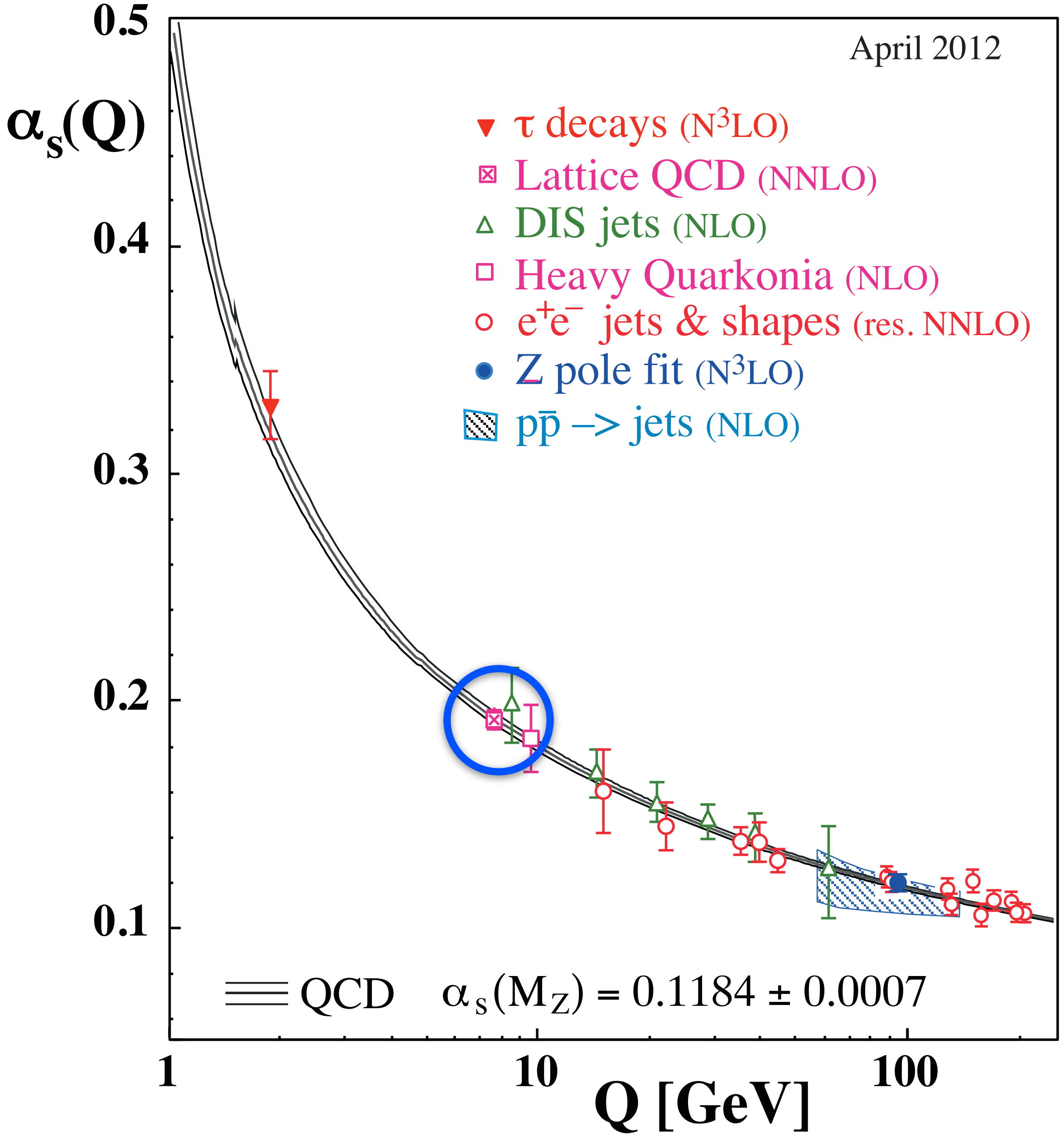
Agreement with experiment nontrivial test that

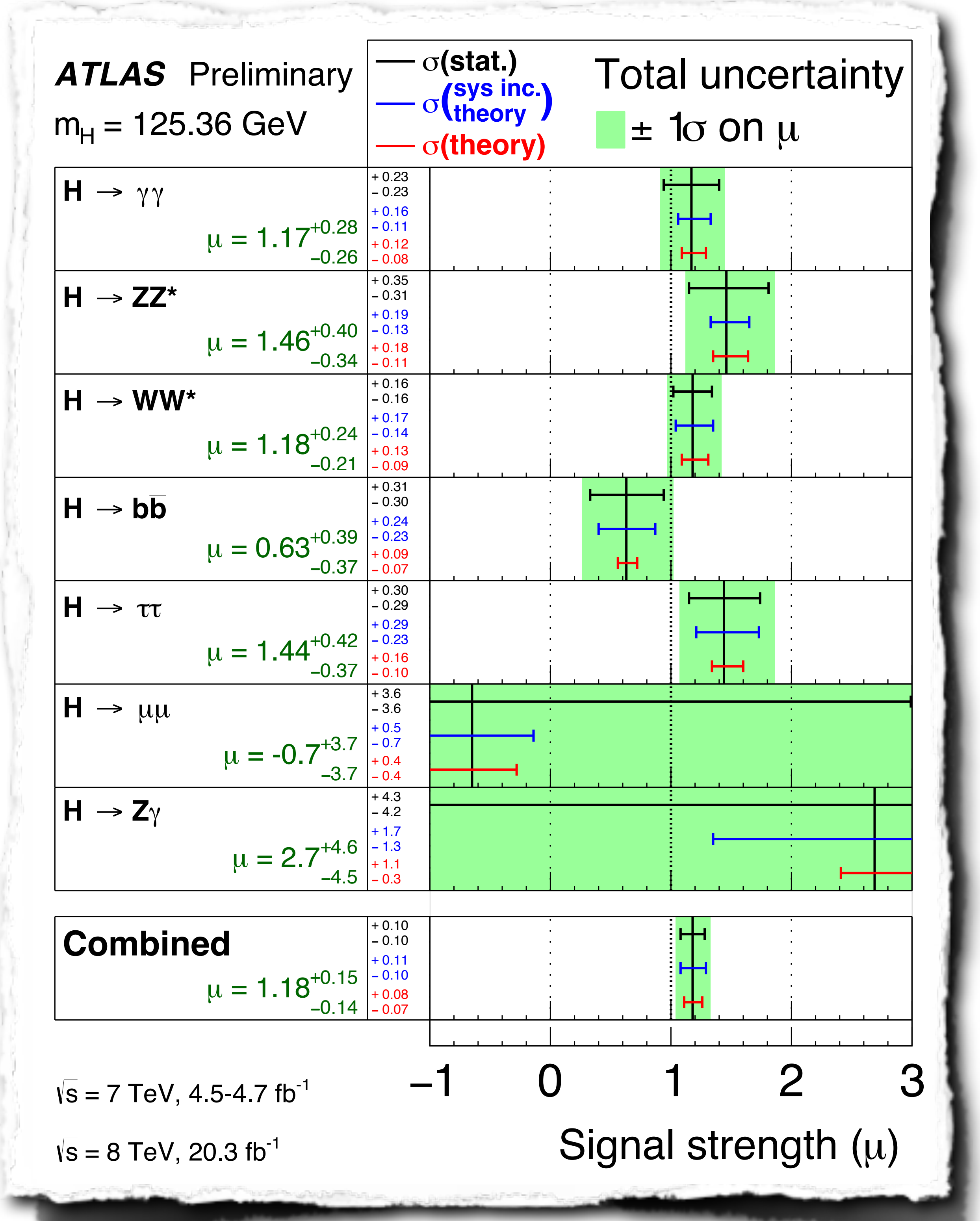
QCD of partons = QCD of hadrons

[Particle Data Group 2014]



Implications for Higgs couplings

- ✦ Observation of new physics effects at next-generation colliders requires theory errors at the sub-percent level
- ✦ Standard-Model Higgs predictions currently limited by parametric errors from b,c-quark masses and α_s [LHC Higgs X-Section WG, EPJ C71 (2011) 1753]
- ✦ Lepage, Mackenzie, & Peskin [1404.0319] showed with toy Monte Carlo that **existing lattice methods + anticipated computing resources in next decade will enable straightforward reduction in errors on m_c, m_b, & α_s to needed precision**



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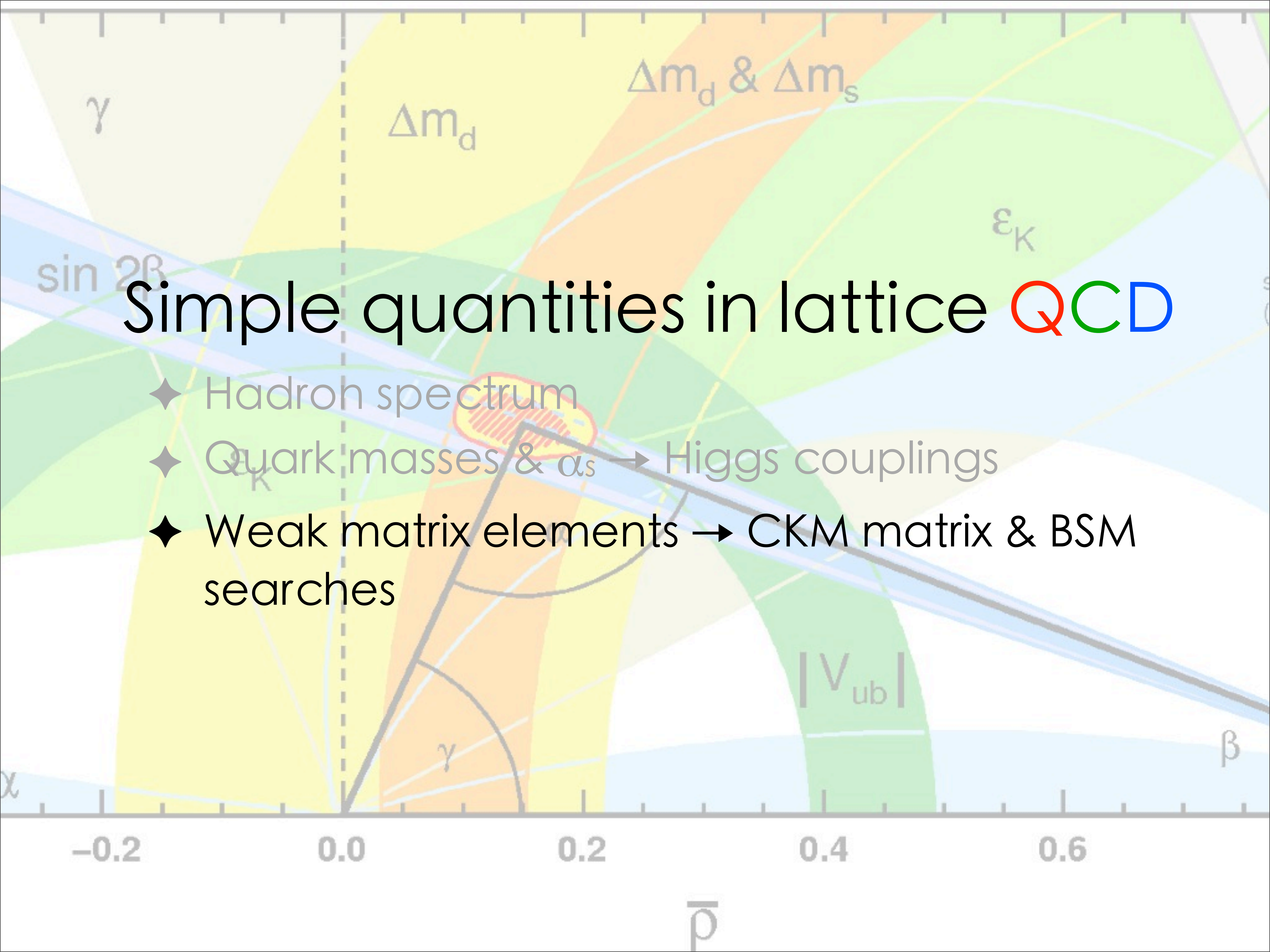

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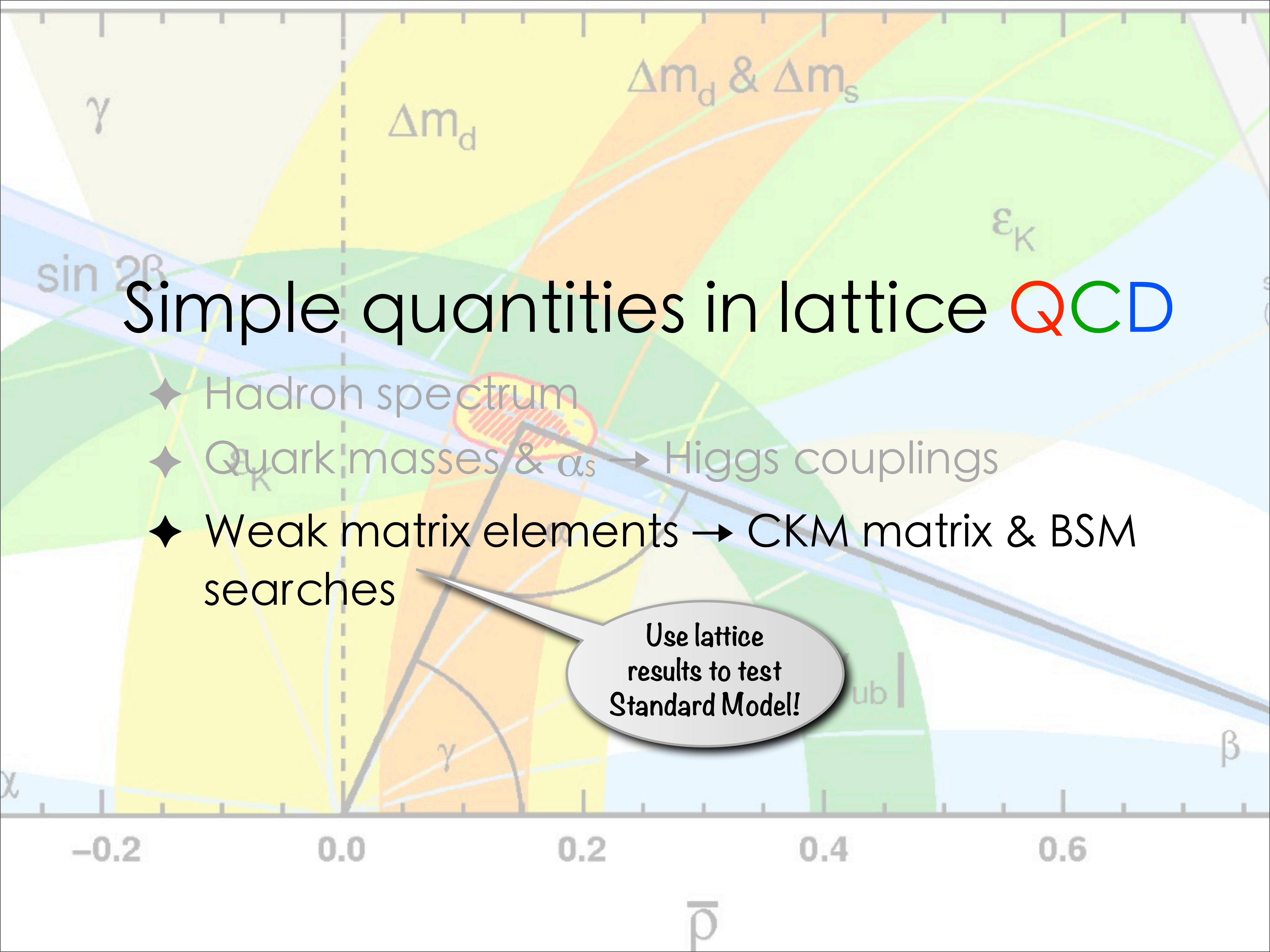
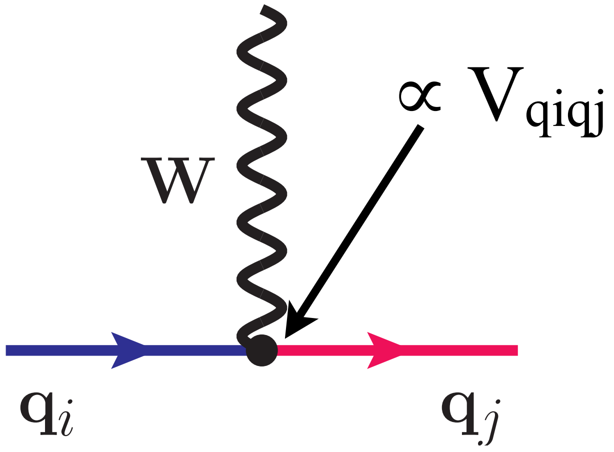
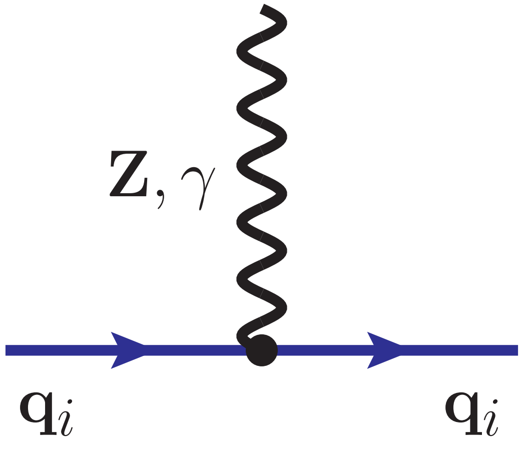
Use lattice results to test Standard Model!



Standard-Model flavor structure



Quarks change flavor via W-boson exchange



No tree-level flavor-changing neutral currents

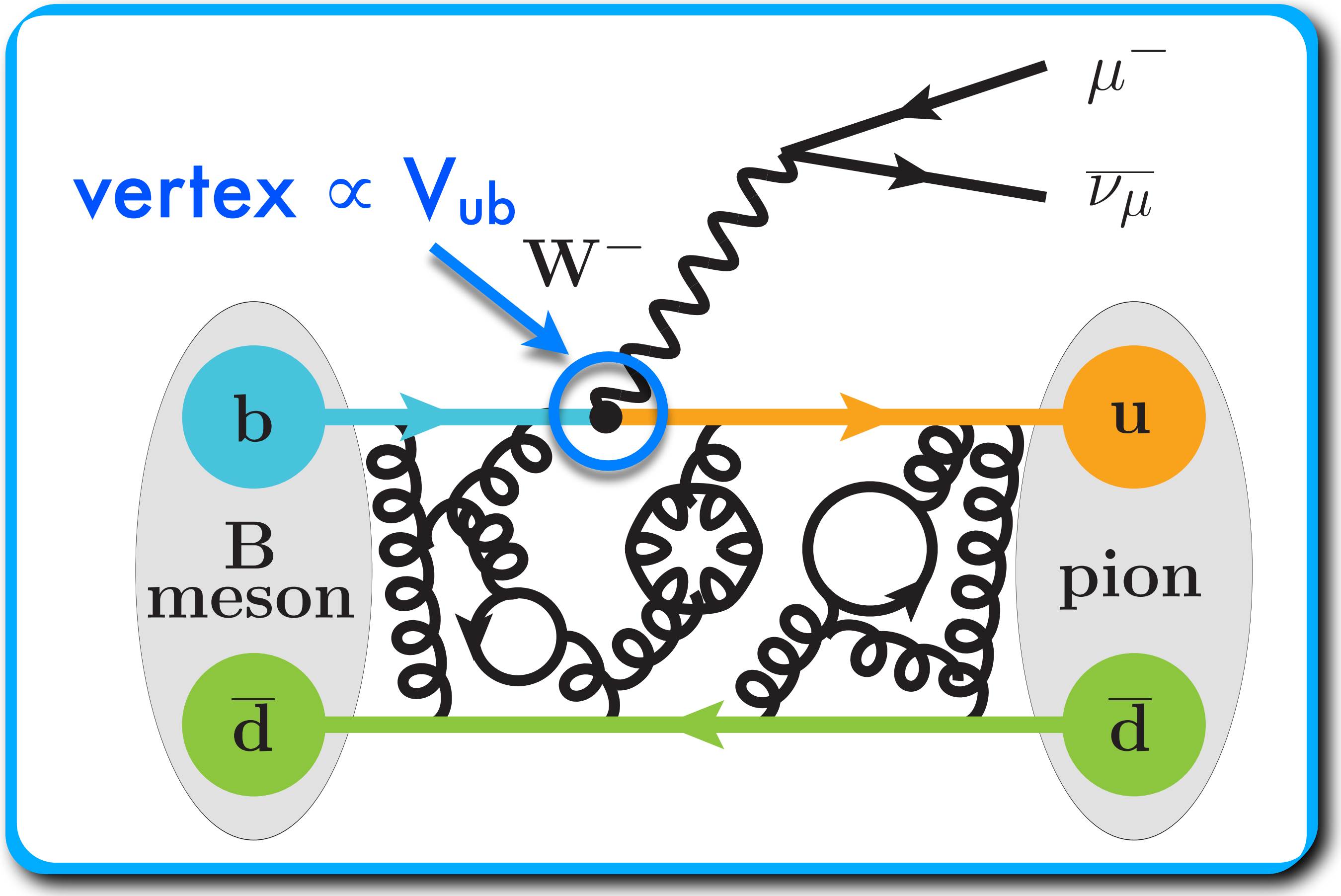
- ✦ Mixing between quark flavors under charged weak interactions parameterized by **Cabibbo-Kobayashi-Maskawa (CKM) matrix:**

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{array}{cccc} d & s & b & \\ 0.9742 & 0.2257 & 3.59 \times 10^{-3} & u \\ 0.2256 & 0.9733 & 41.5 \times 10^{-3} & c \\ 8.74 \times 10^{-3} & 40.7 \times 10^{-3} & 0.9991 & t \end{array}$$

- ✦ CKM elements & phase are parametric inputs to Standard Model predictions for many flavor-changing processes such as neutral kaon mixing and rare kaon decays

“Measuring” the CKM matrix

- Measure flavor-changing processes involving hadrons
  - Absorb nonperturbative QCD dynamics into hadronic parameters
- **Infer CKM elements within Standard Model** by comparing experimental measurements of flavor-changing interactions with theory predictions


vertex ∝ V_{ub}

$\Delta m_{(d,s)}$,

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

Compute nonperturbative QCD parameters (decay constants, form factors, B-parameters,...) numerically with **LATTICE QCD**

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

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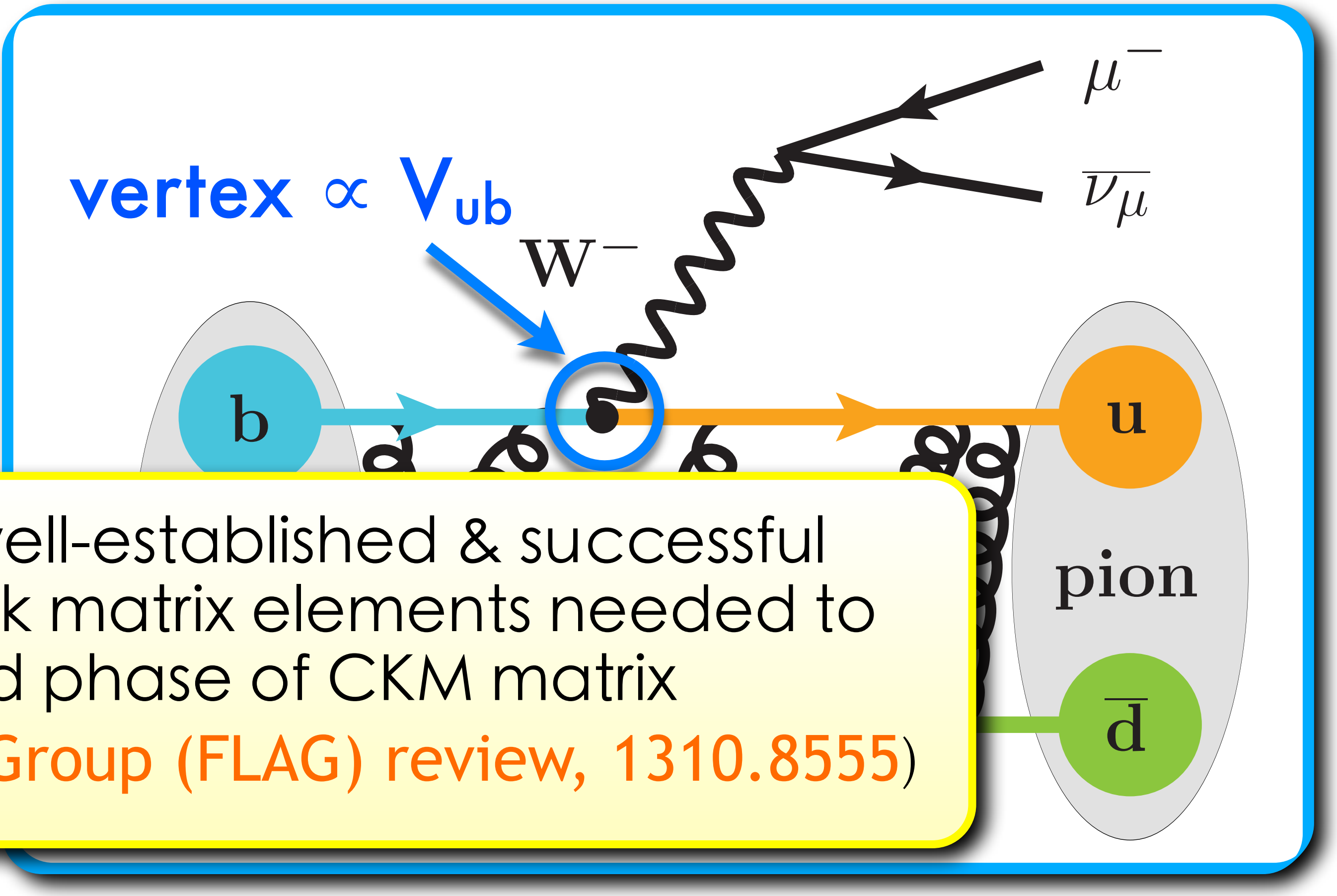

Lattice community has well-established & successful program to calculate weak matrix elements needed to obtain elements and phase of CKM matrix
(see Flavor Lattice Averaging Group (FLAG) review, 1310.8555)

$$\Delta m_{(d,s)}\,,$$

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

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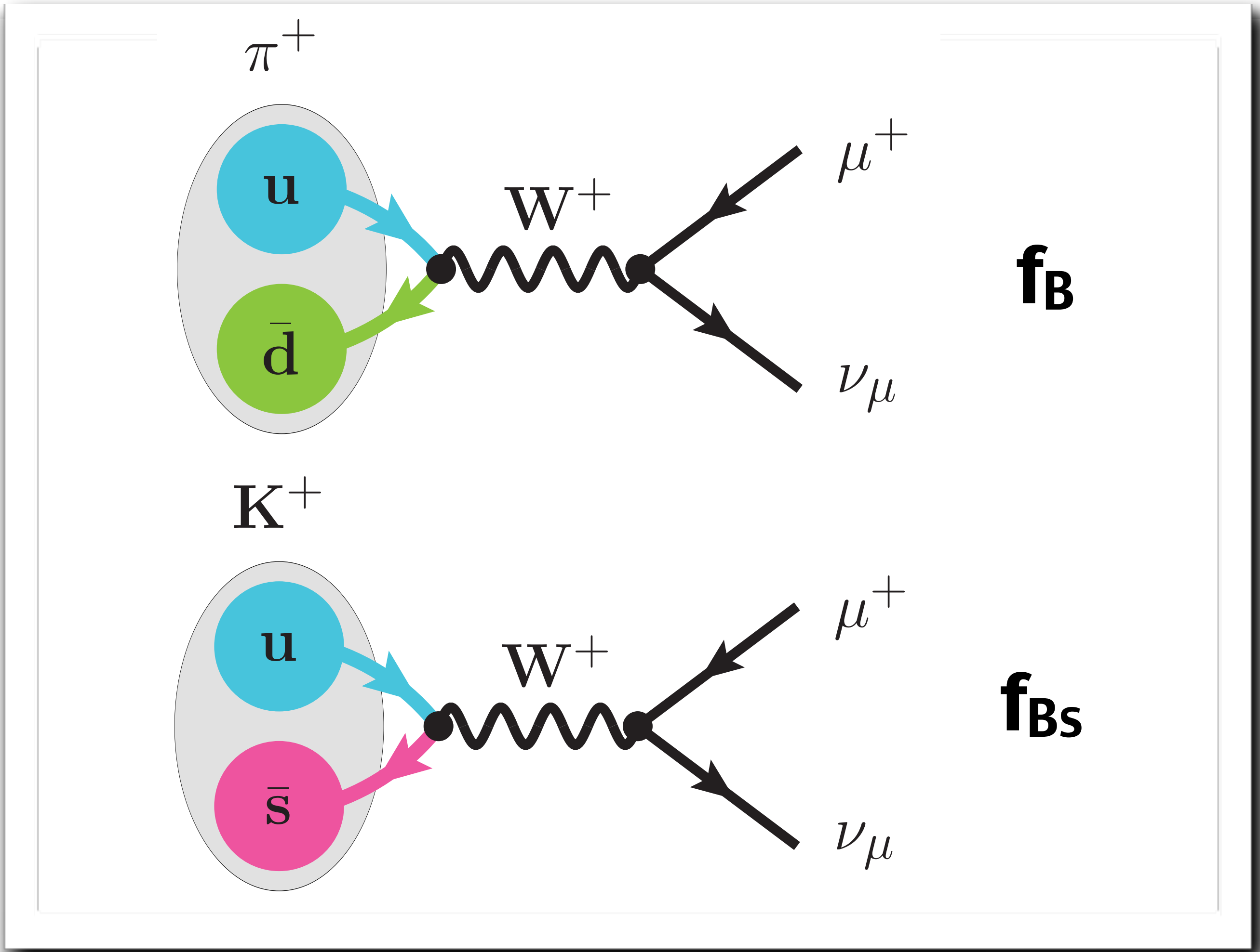
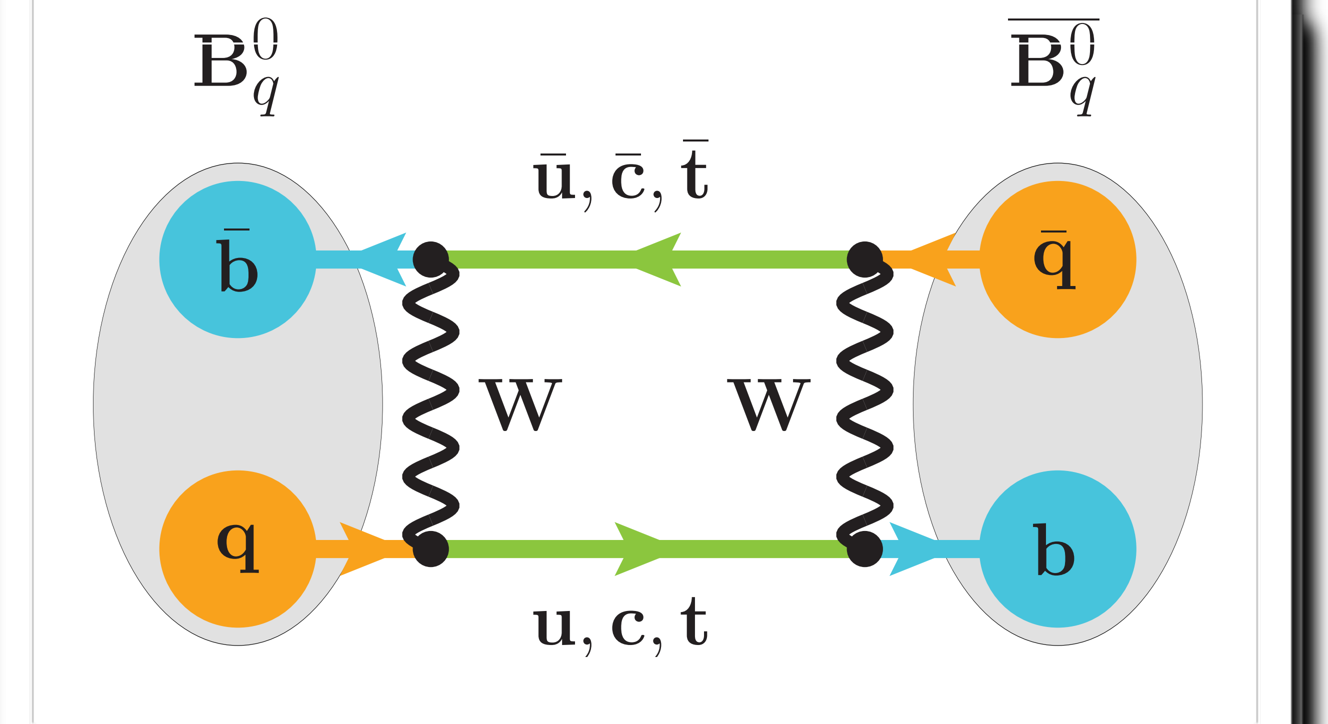
B-meson overview

See Pena Lattice '15 & Bouchard Lattice '14 heavy-flavor reviews

- Control discretization errors associated with large b-quark mass using effective theory
- Few calculations use highly improved b-quark action + very fine lattice spacings
- Some physical light-quark mass results



$\xi \equiv f_B (B_{Bd})^{1/2} / f_{Bs} (B_{Bs})^{1/2}$



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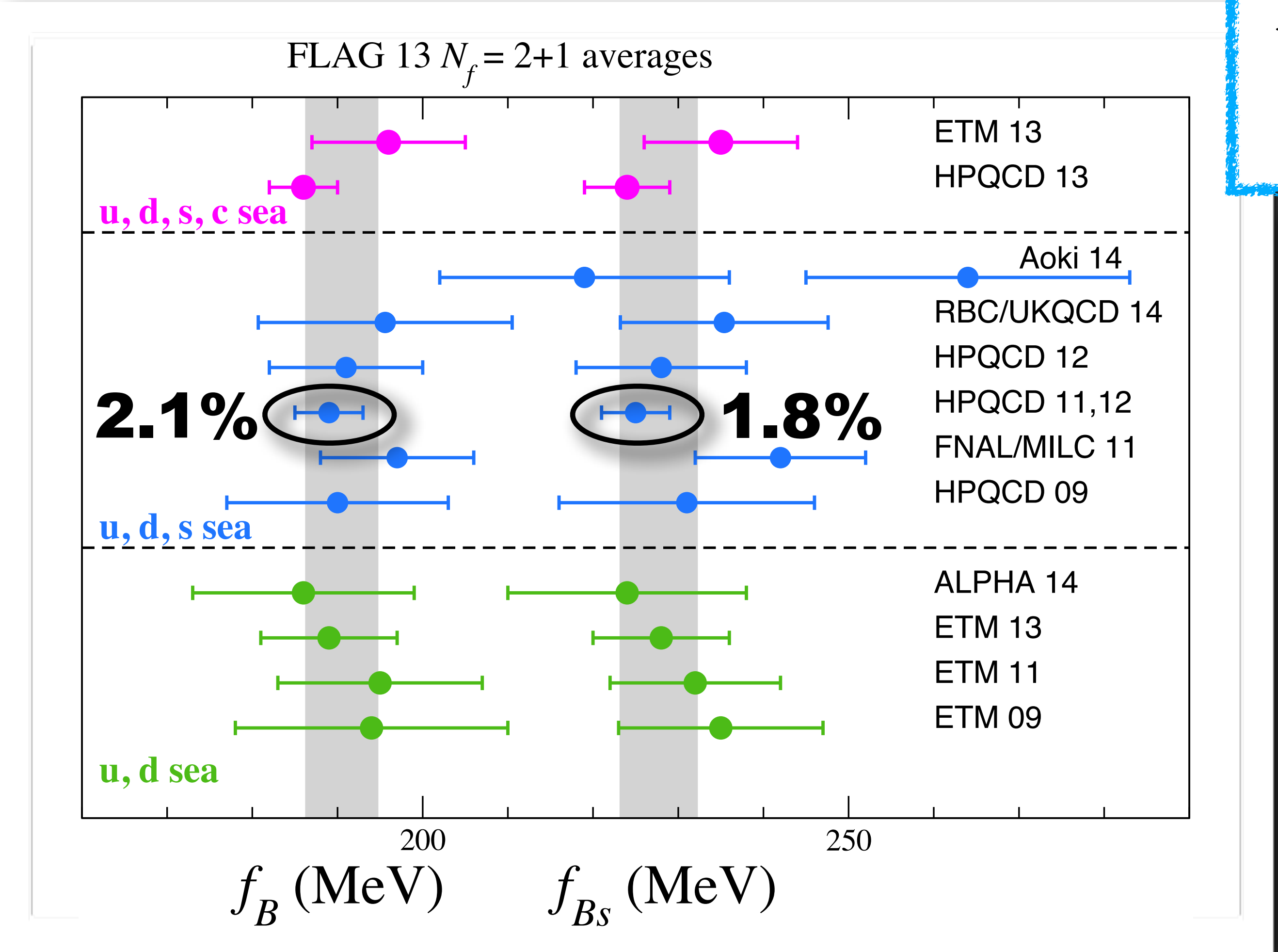
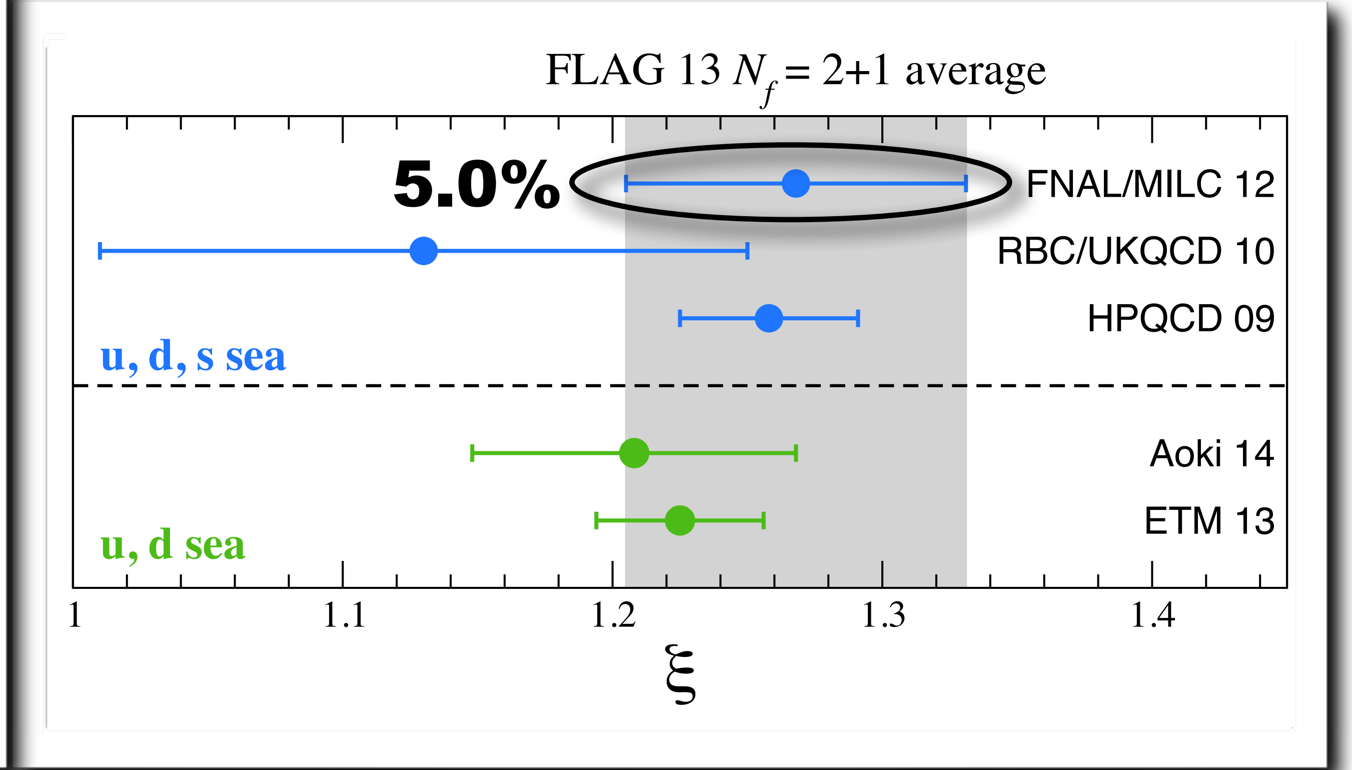
New results:

- First 3-flavor f_{B^*}, $f_{B_s}^*$, and $f_{B_c^*}$ [HPQCD, arXiv:1503.05762]
- First 3-flavor $B_s \to K l \nu$ form factors [HPQCD, PRD90 (2014) 5, 054506; RBC/UKQCD, PRDD91 (2015) 7, 074510]
- Update of FNAL/MILC $B \to D^* l \nu$ zero-recoil form factor [PRD89 (2014) 11, 114504]





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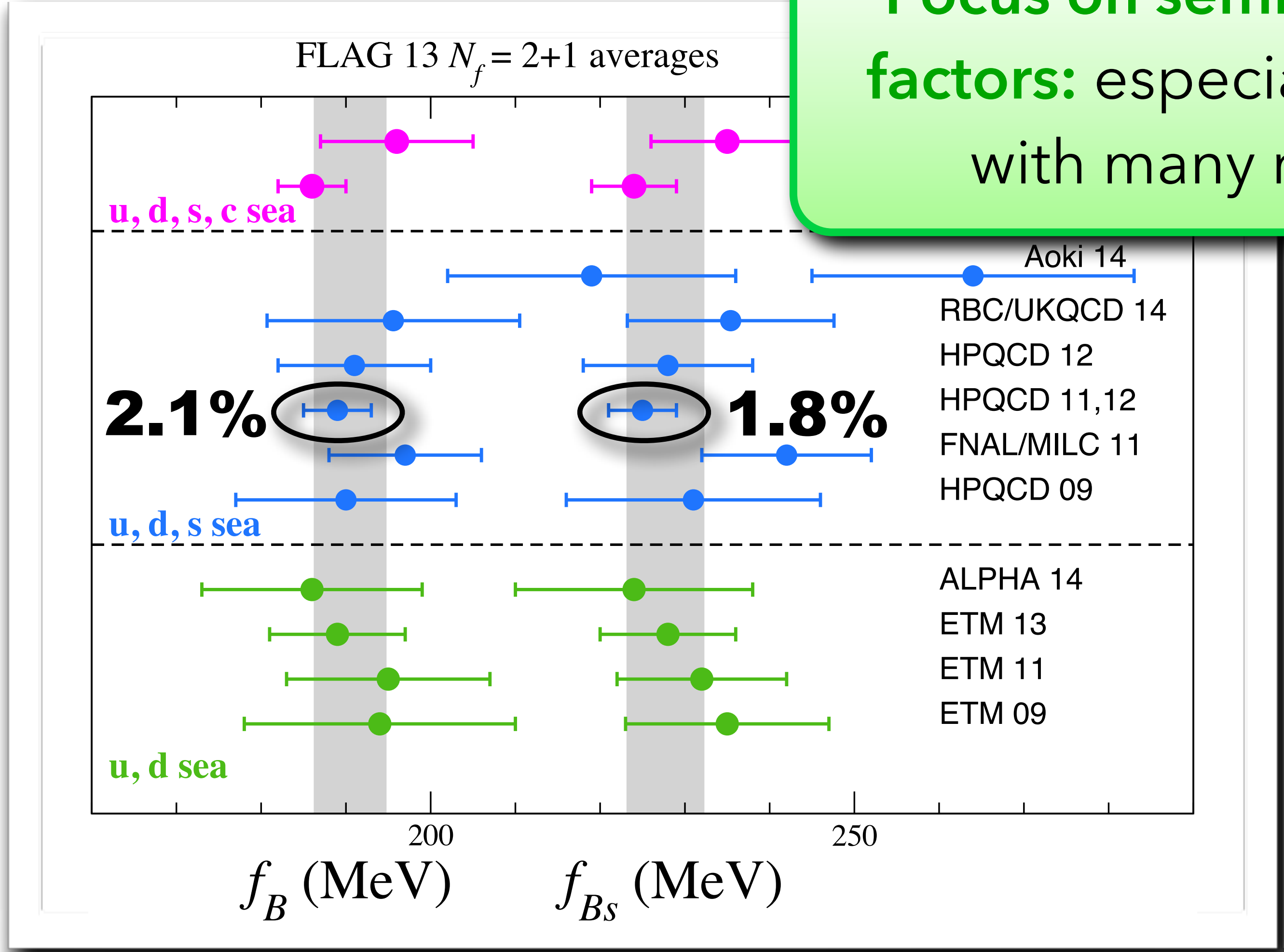
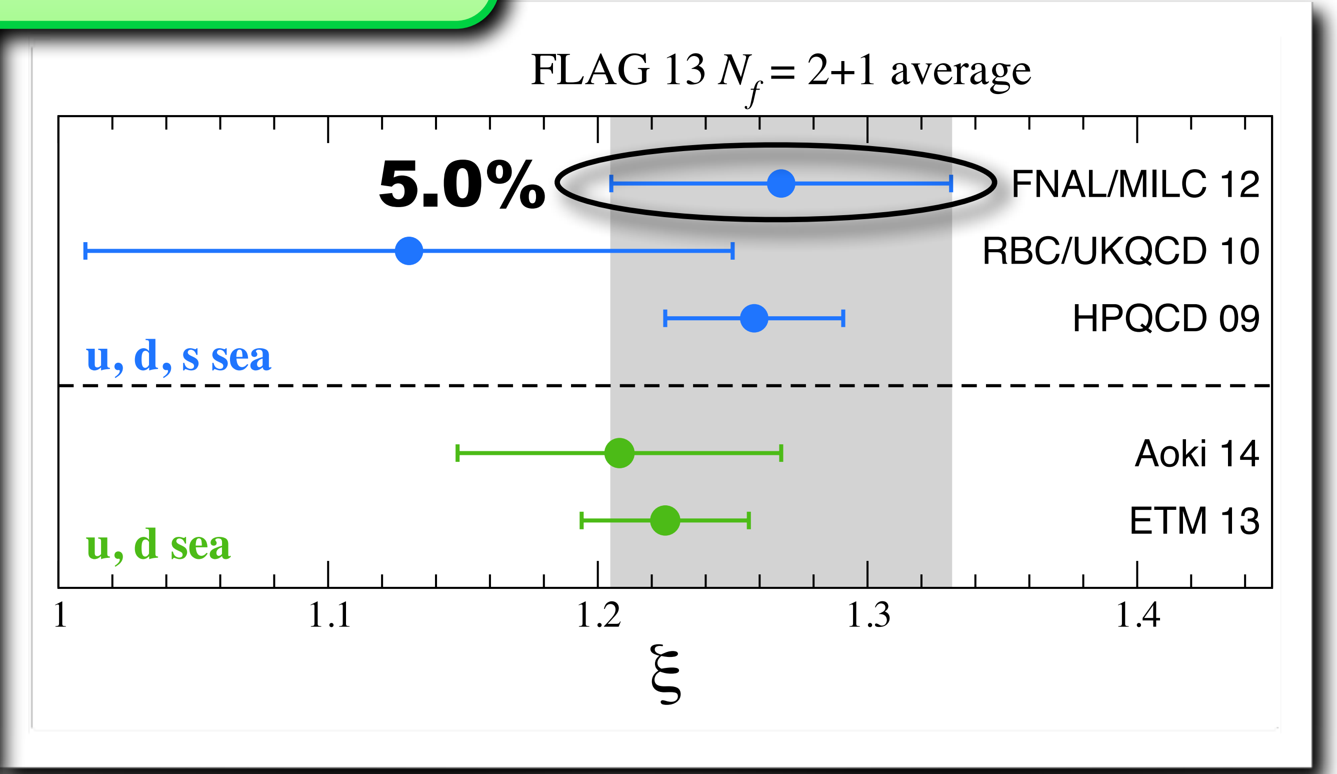
- L/MILC B→D*lν zero-recoil D89 (2014) 11, 114504]

Focus on semileptonic form factors: especially active area with many new results

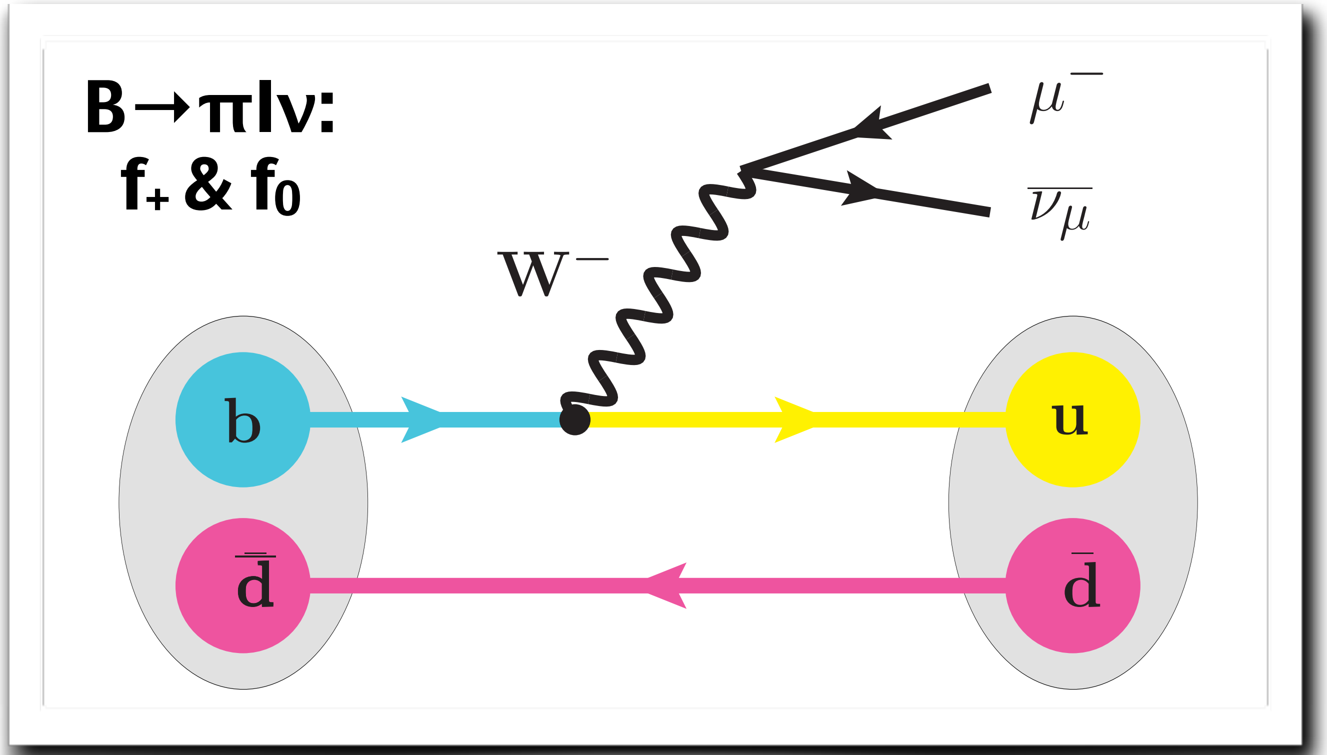




New! B→π form factors

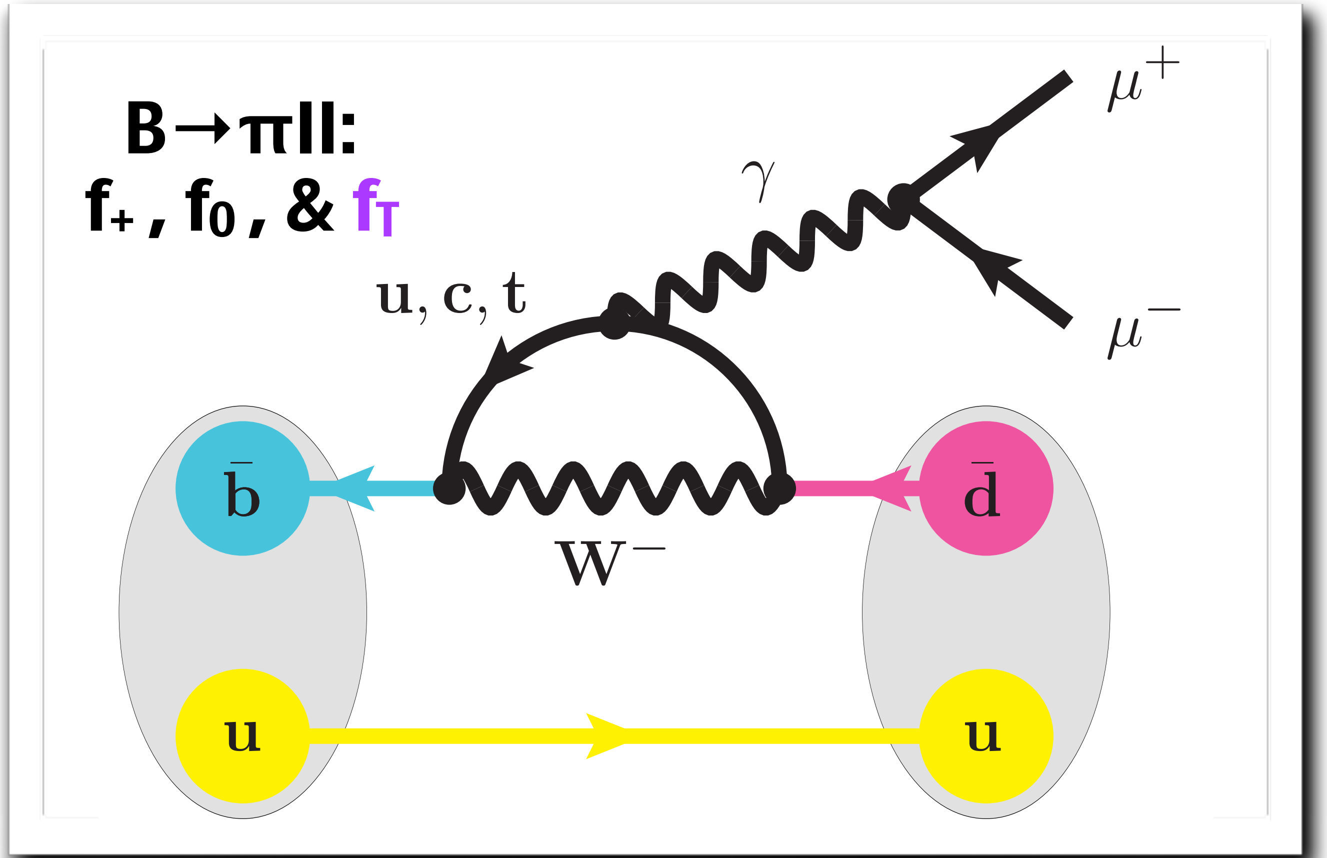
Vector (f_+) and scalar (f_0) form factors

- Two new three-flavor calculations using different light & b-quarks actions [RBC/UKQCD, RDD91 (2015) 7, 074510; FNAL/MILC arXiv:1503.07839]
- Vector form factor gives dominant contribution to B→πlν decay rate



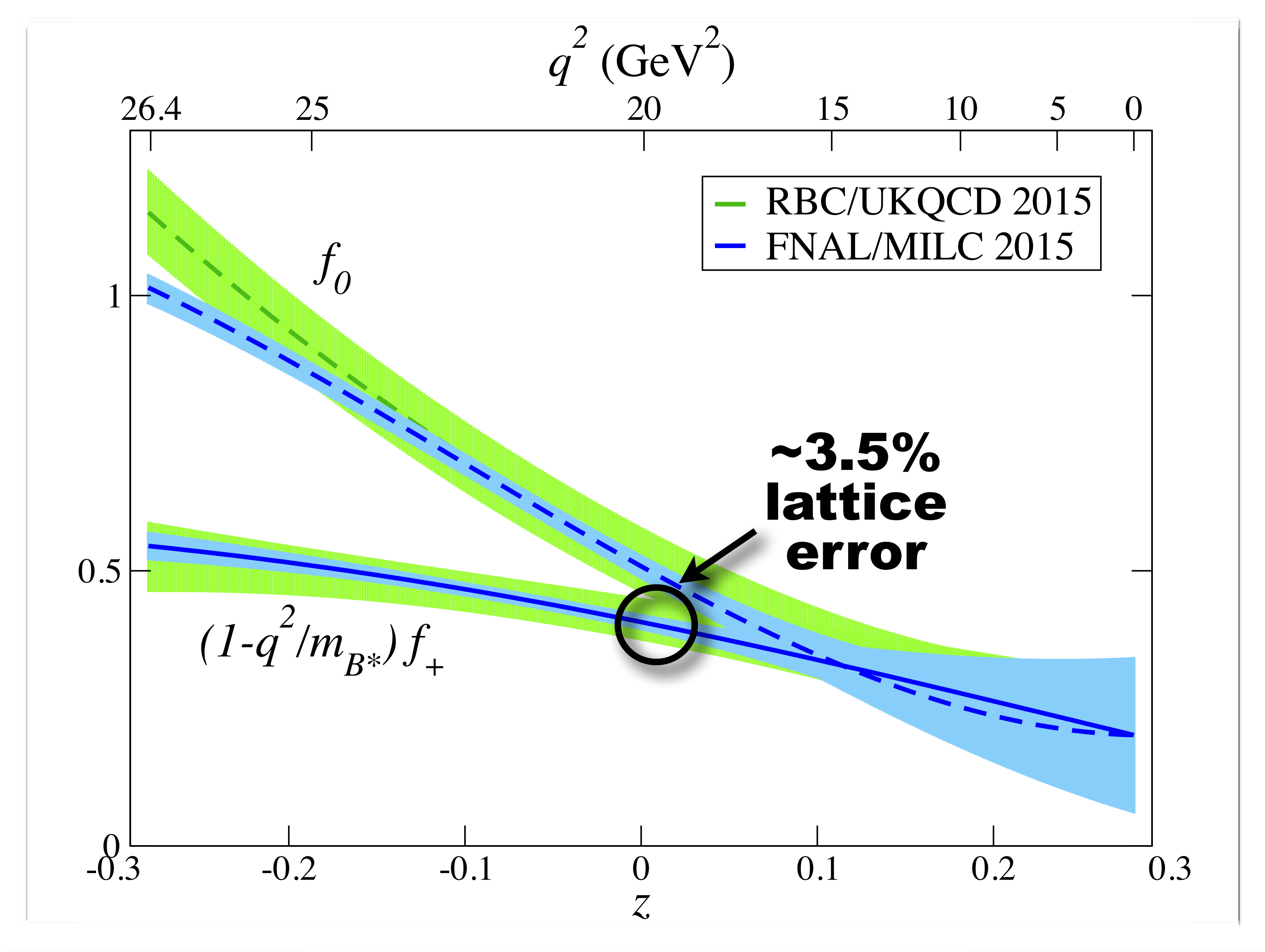
Tensor form factor (f_T)

- First three-flavor lattice calculation [FNAL/MILC, arXiv:1503.07839]
- Enables predictions of observables for all B→π semileptonic decay processes in Standard Model & all BSM theories



New! B→πℓν form factors

- **RBC/UKQCD:** first results for f_+ and f_0 [PRDD91 (2015) 7, 074510]
- **FNAL/MILC:** significant update of 2008 f_+ with increased statistics and finer lattice spacings; also first f_0 [arXiv:1503.07839]
- Independent calculations ➜ cross-check



~3.5% lattice error

New! B→$\pi\ell\nu$ form factors

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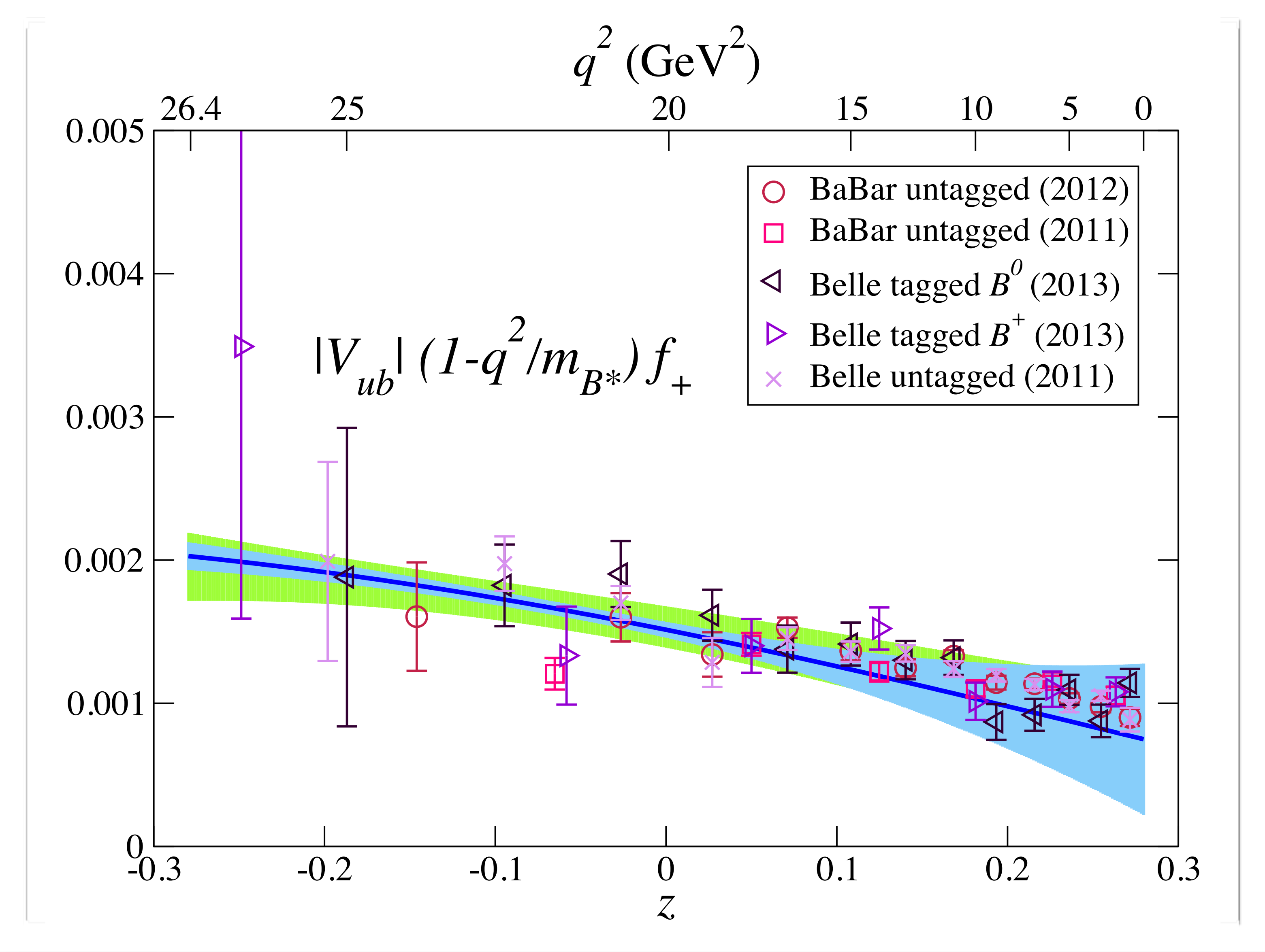
- Independent calculations ➜ cross-check
- $f_+(q^2)$ shape consistent with measured B→$\pi l \nu$ differential decay rate (dB/dq^2)
- **Obtain $|V_{ub}|$ from joint lattice + experiment fit to model-independent z-expansion**

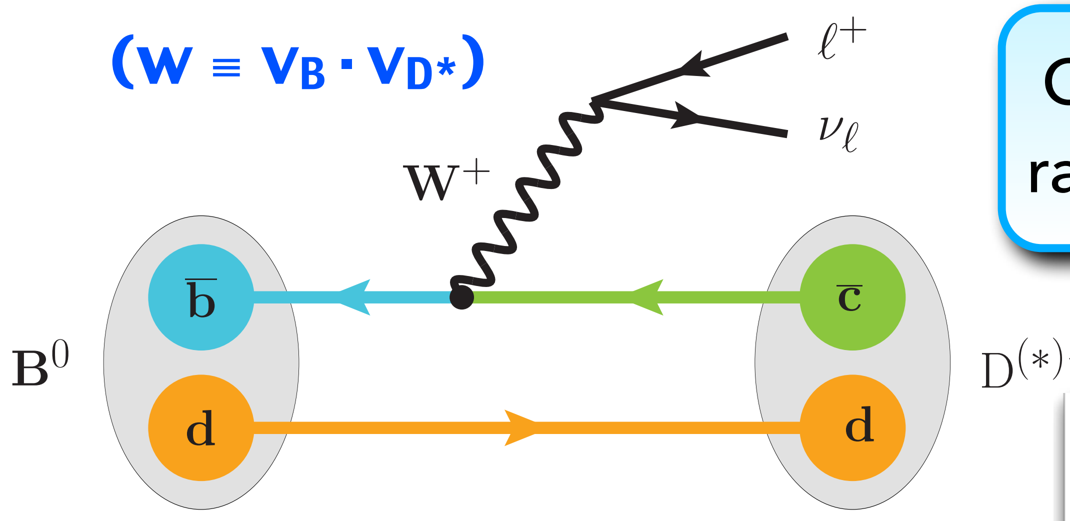


Use of all experimental & theoretical information minimizes error on $|V_{ub}|$

New! B→D$\ell\nu$ form factors @ nonzero recoil

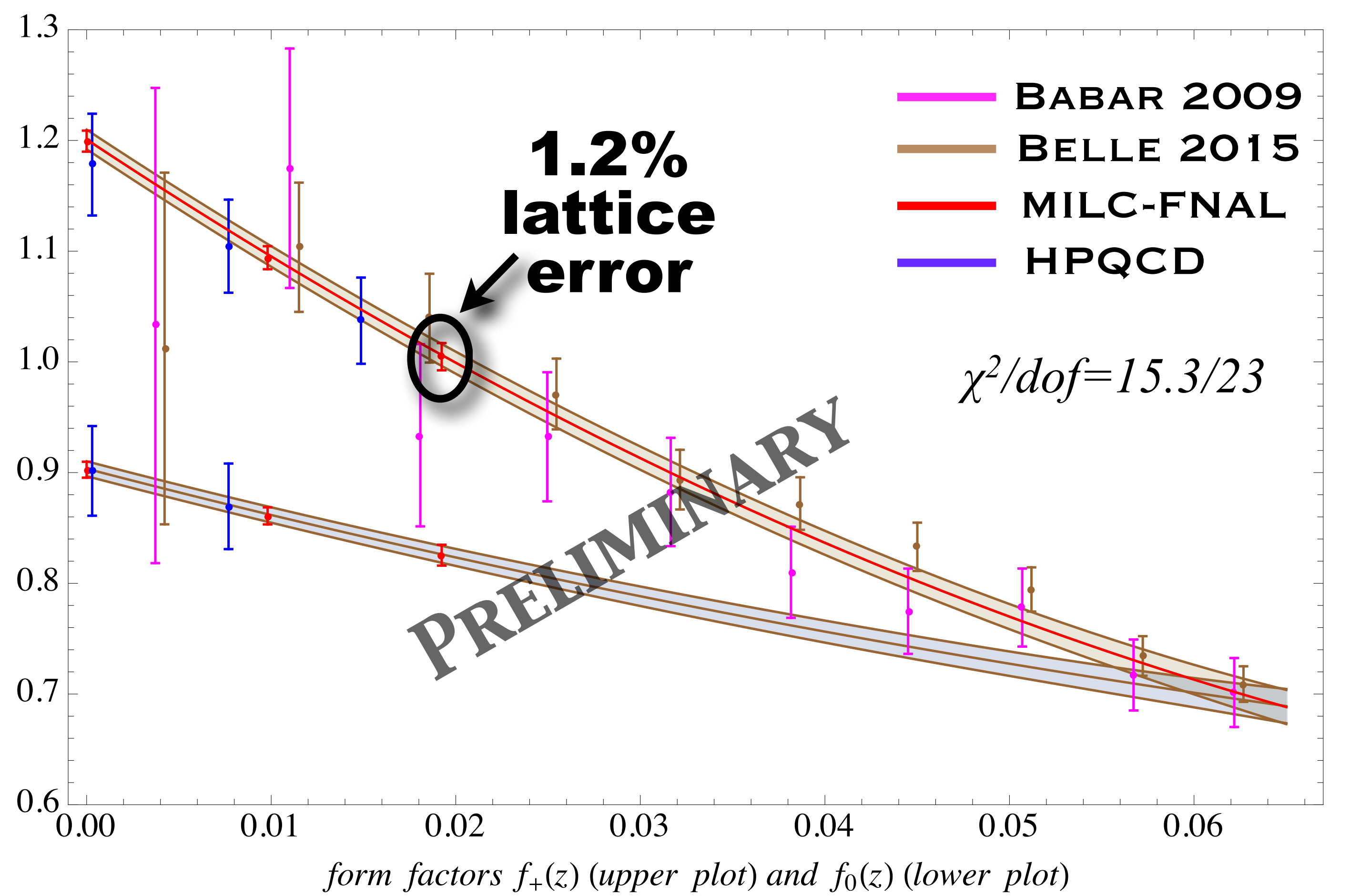
[Bailey *et al.* [FNAL/MILC], arXiv:1503.07237; Na *et al.* [HPQCD], arXiv:1505.03925]

($w \equiv v_B \cdot v_{D^*}$)



Combination with experimental rate enables **$|V_{cb}|$ determination**

- Traditionally obtain $|V_{cb}|$ from comparison of theory & experiment at zero recoil (w=1)
- **First three-flavor form factors at w>1**
    - Confirmation from two independent calculations
    - Shape consistent with experiment
- **Joint lattice + experiment fit using w>1 data reduces error on $|V_{cb}|$**



[fit from Gambino @ EPS;
Glattauer talk on Belle measurement]

New! $\Lambda_b \to p \ell \nu$ and $\Lambda_b \to \Lambda_c \ell \nu$ form factors

[Detmold, Lehner, & Meinel, arXiv:1503.01421]

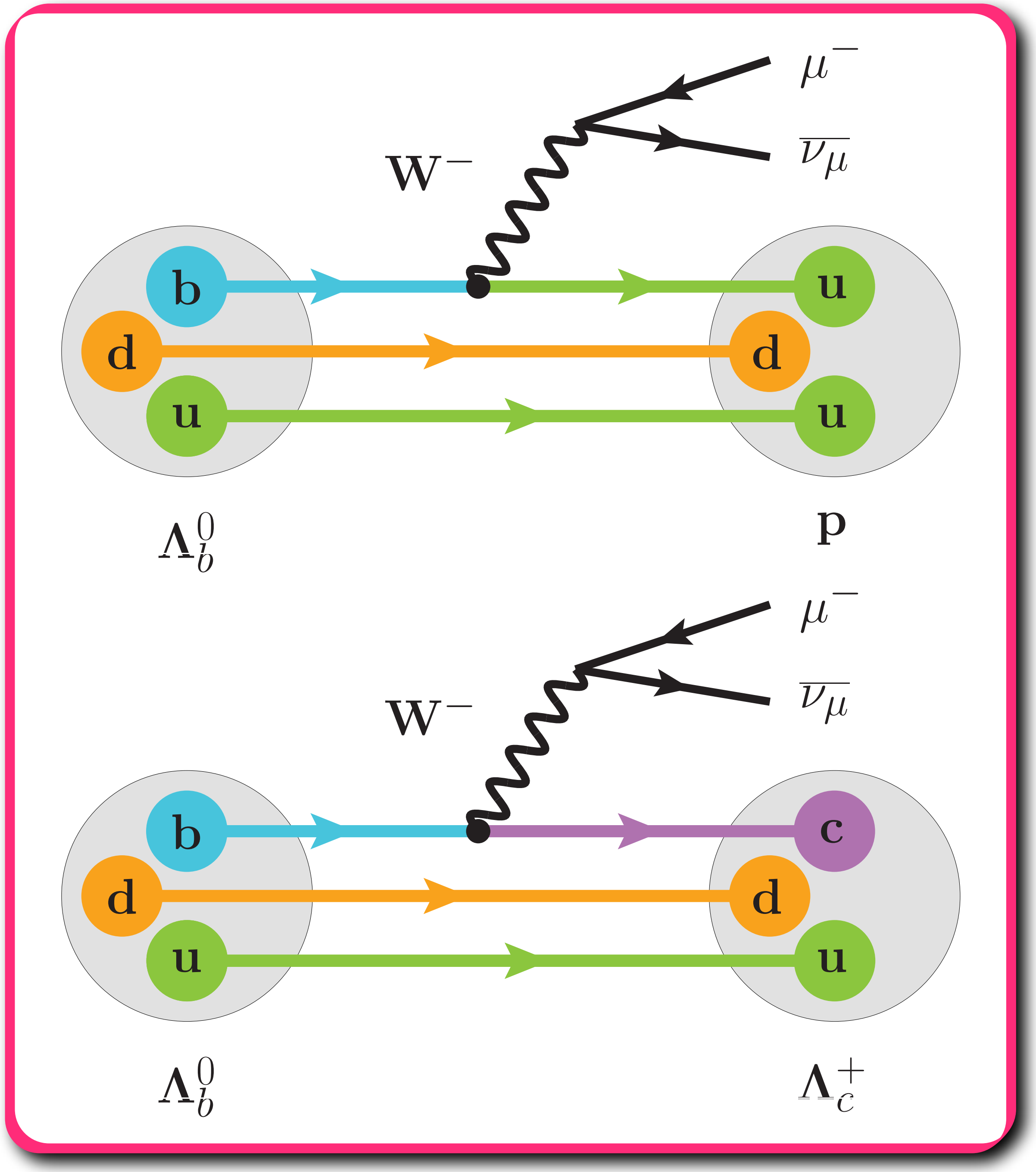
Combination with ratio of experimental rates **enables determination of $|V_{ub}|/|V_{cb}|$**

→ first from baryon decay!

- First three-flavor $\Lambda_b \to p$ form factors with relativistic b-quark at physical mass; first three-flavor $\Lambda_b \to \Lambda_c$ form factors
- Combine chiral-continuum extrapolation with q^2 fit via modified z-expansion

➡ **5.3% LQCD error on $|V_{ub}|/|V_{cb}|$:**

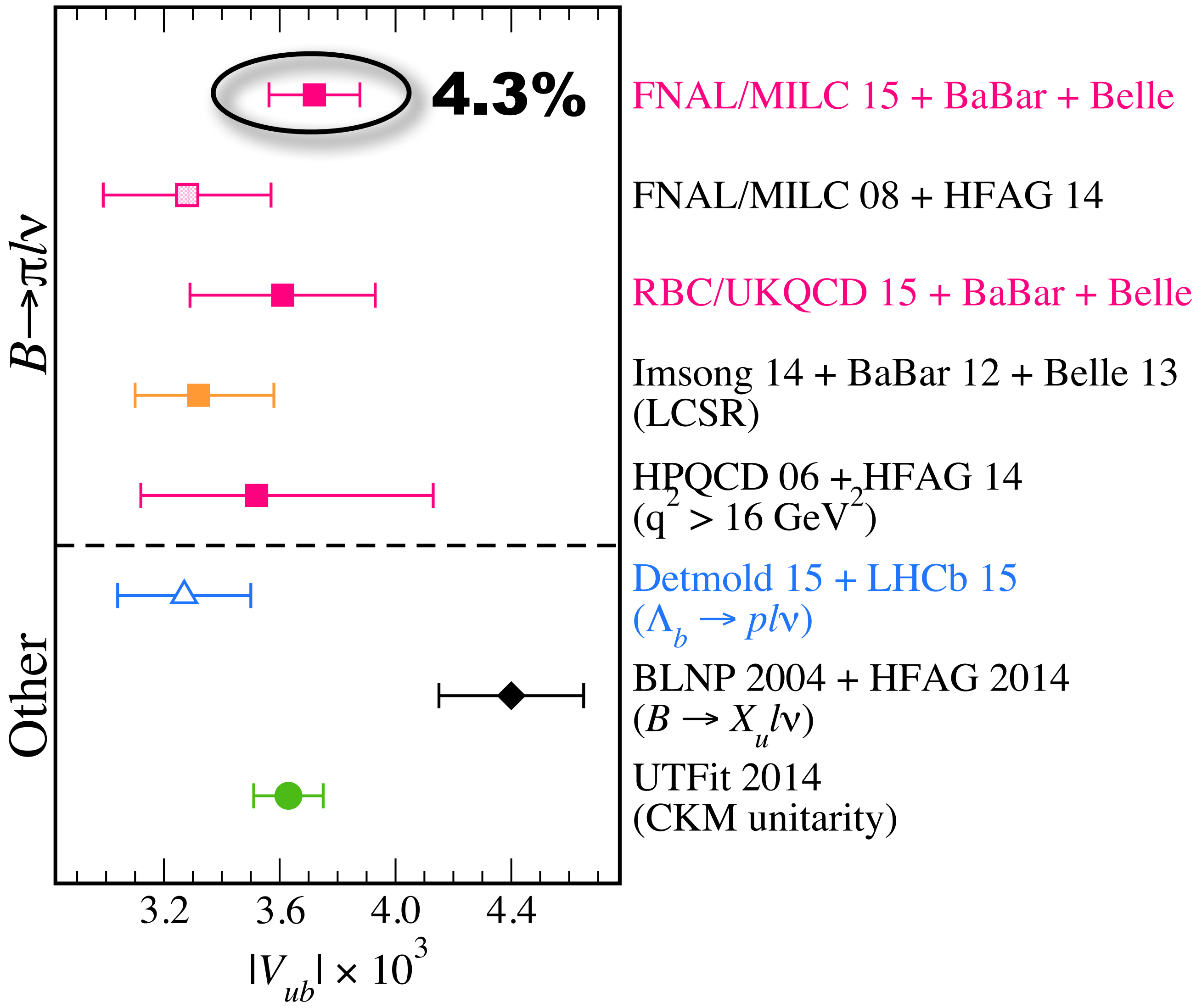
$$\frac{|V_{cb}|^2}{|V_{ub}|^2}\,\frac{\int_{15\,\mathrm{GeV}^2}^{q^2_{\mathrm{max}}} \frac{d\Gamma(\Lambda_b \to p\,\mu^- \bar{\nu}_\mu)}{dq^2}\,dq^2}{\int_{7\,\mathrm{GeV}^2}^{q^2_{\mathrm{max}}} \frac{d\Gamma(\Lambda_b \to \Lambda_c\,\mu^- \bar{\nu}_\mu)}{dq^2}\,dq^2} = 1.470 \pm 0.115 \pm 0.104$$



[See Artuso EPS-HEP talk on corresponding LHCb measurement]

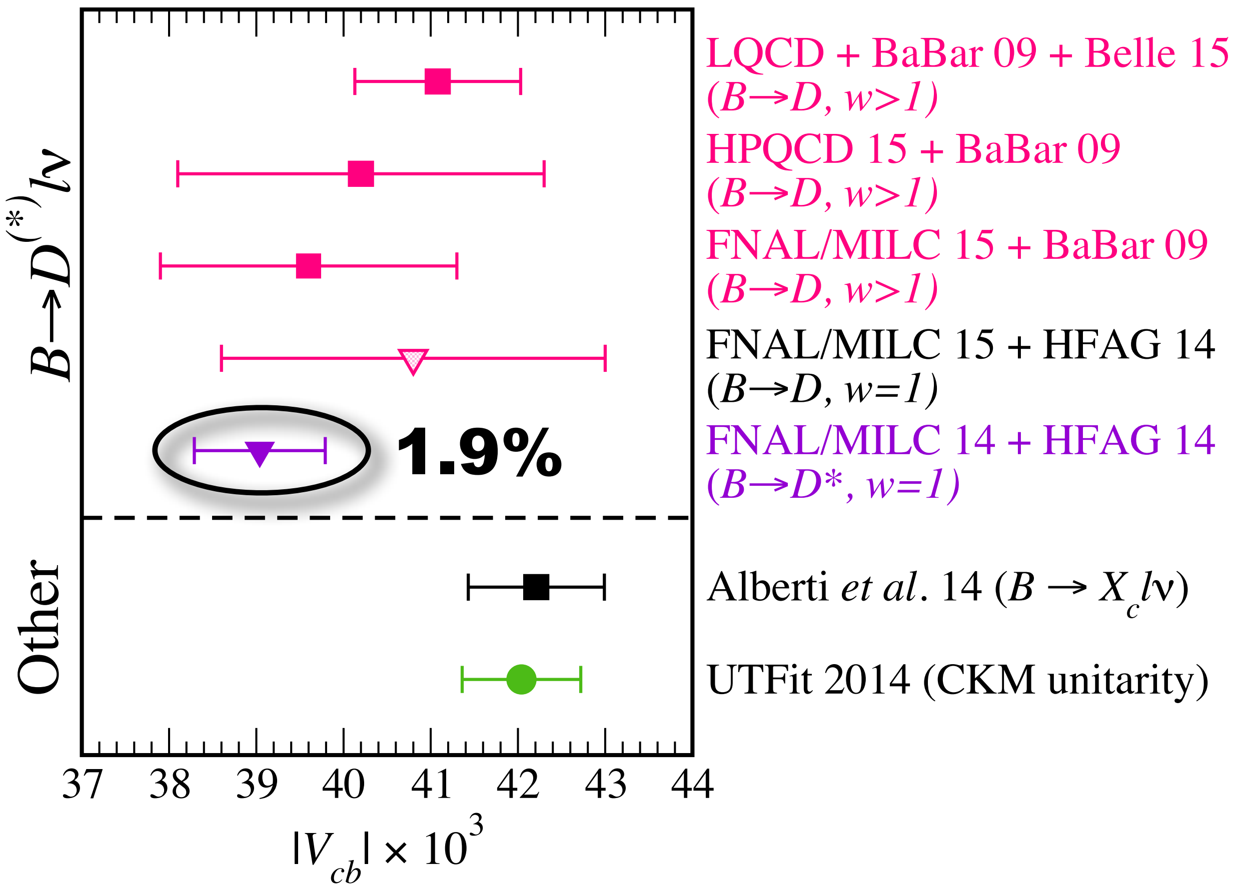
Implications for $|V_{ub}|$ & $|V_{cb}|$

$|V_{ub}|$



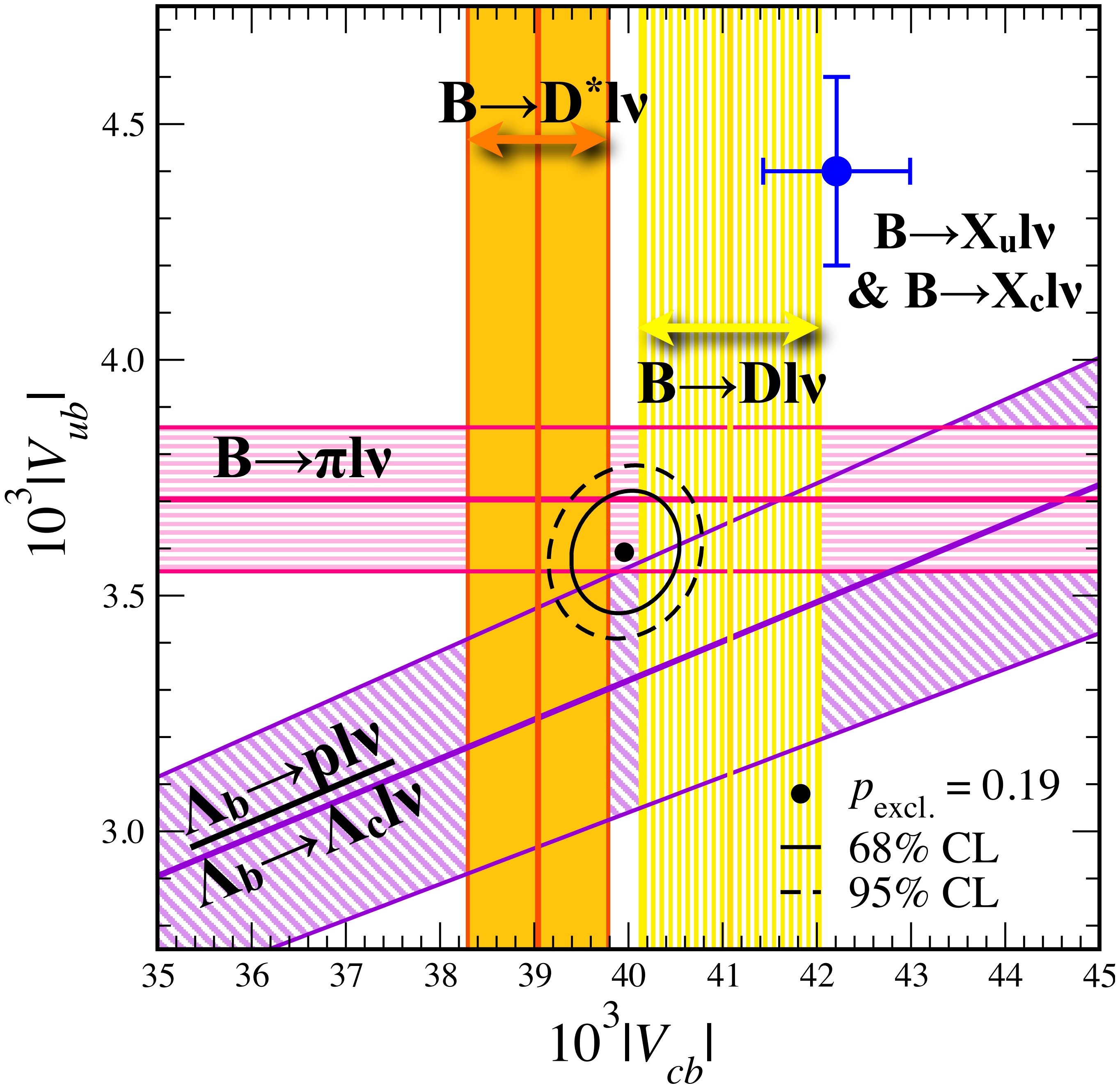
- Error on $|V_{ub}|$ from $B\to\pi l\nu$ cut by a bit more than half

$|V_{cb}|$



- QCD error in $|V_{cb}|$ from $B\to D^* l\nu$ now commensurate with experimental error
- New Belle nonzero-recoil $B\to D$ measurement raises $|V_{cb}|$

Implications for the "| V_{xb} | puzzle"

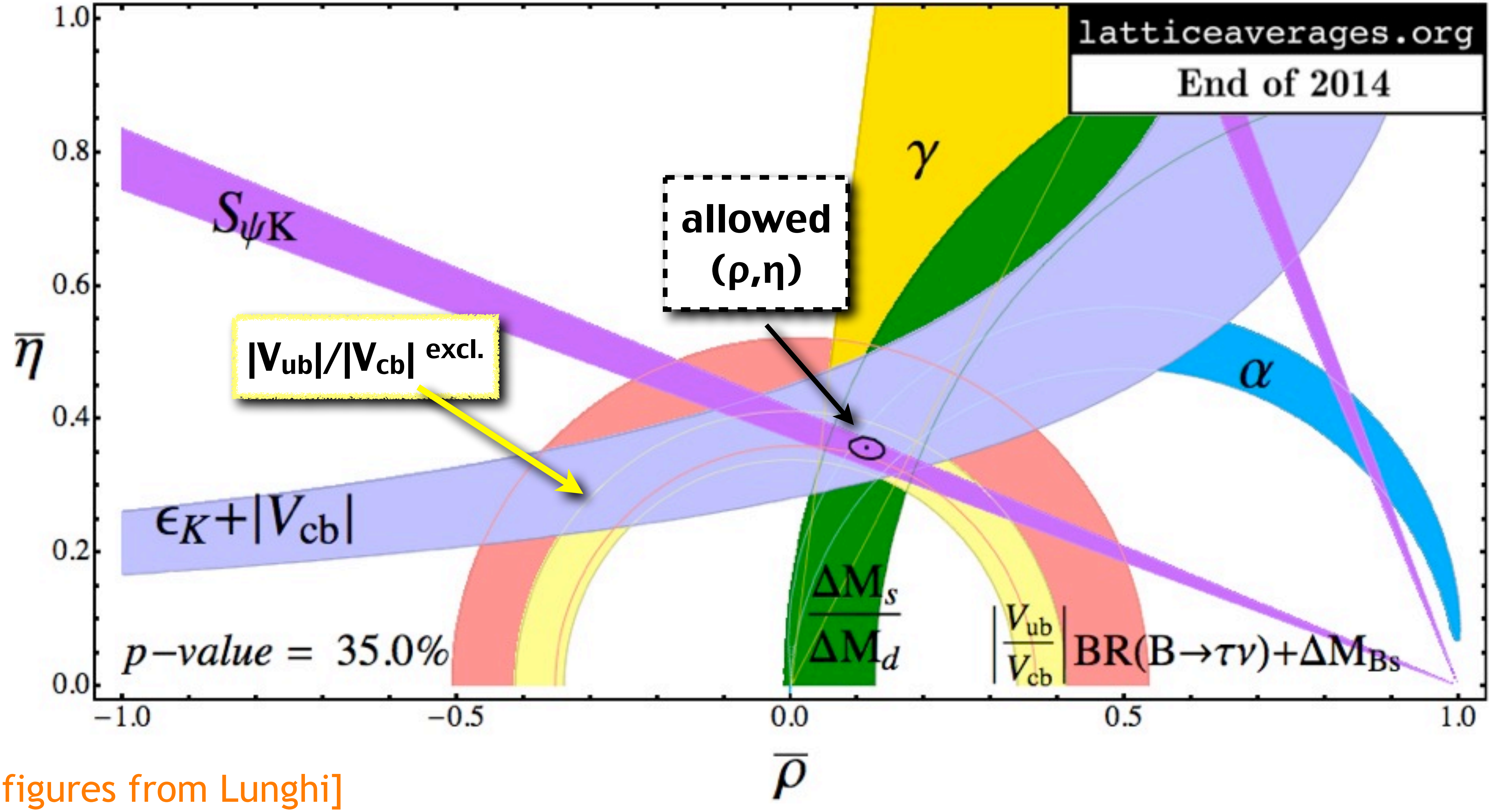


[fit from Kronfeld]

Increased lattice-QCD precision + new measurements sharpening picture of inclusive-exclusive tensions

- LQCD will continue to address "V_{xb}" puzzle through:
  - New b→u decays (e.g. $B_s \to K l \nu$)
  - Independent $\Lambda_b \to p$ & $\Lambda_b \to \Lambda_c$ form factors
  - $B \to D^* l \nu$ form factors at w>1
- $|V_{cb}|$ from $B \to D^* l \nu$ extrapolates measurement to zero recoil using CLN parameterization ➔ **time for model-independent analysis!**

Impact on global CKM UT fit

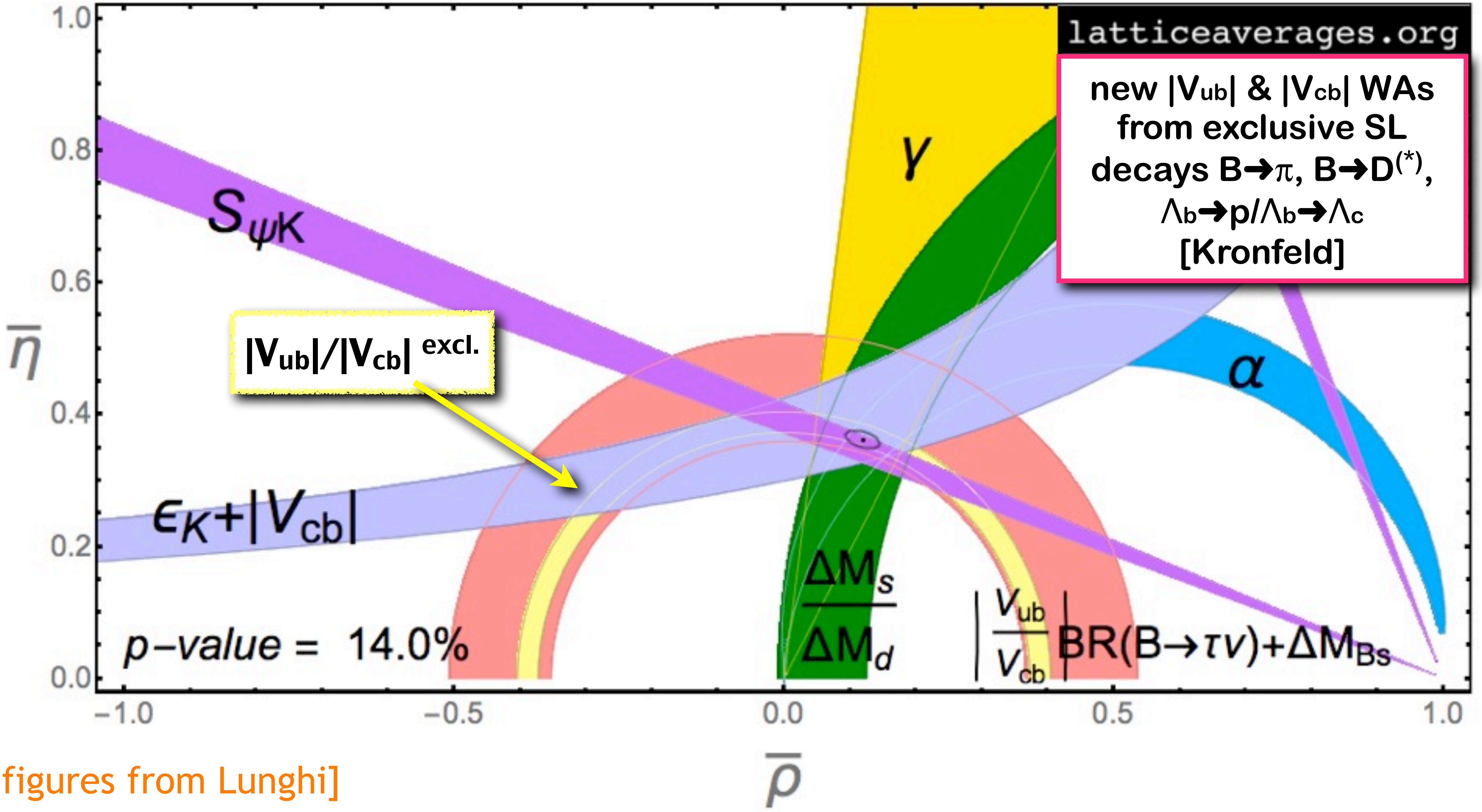


allowed (ρ,η)

$|V_{ub}|/|V_{cb}|$ excl.

[figures from Lunghi]

Impact on global CKM UT fit

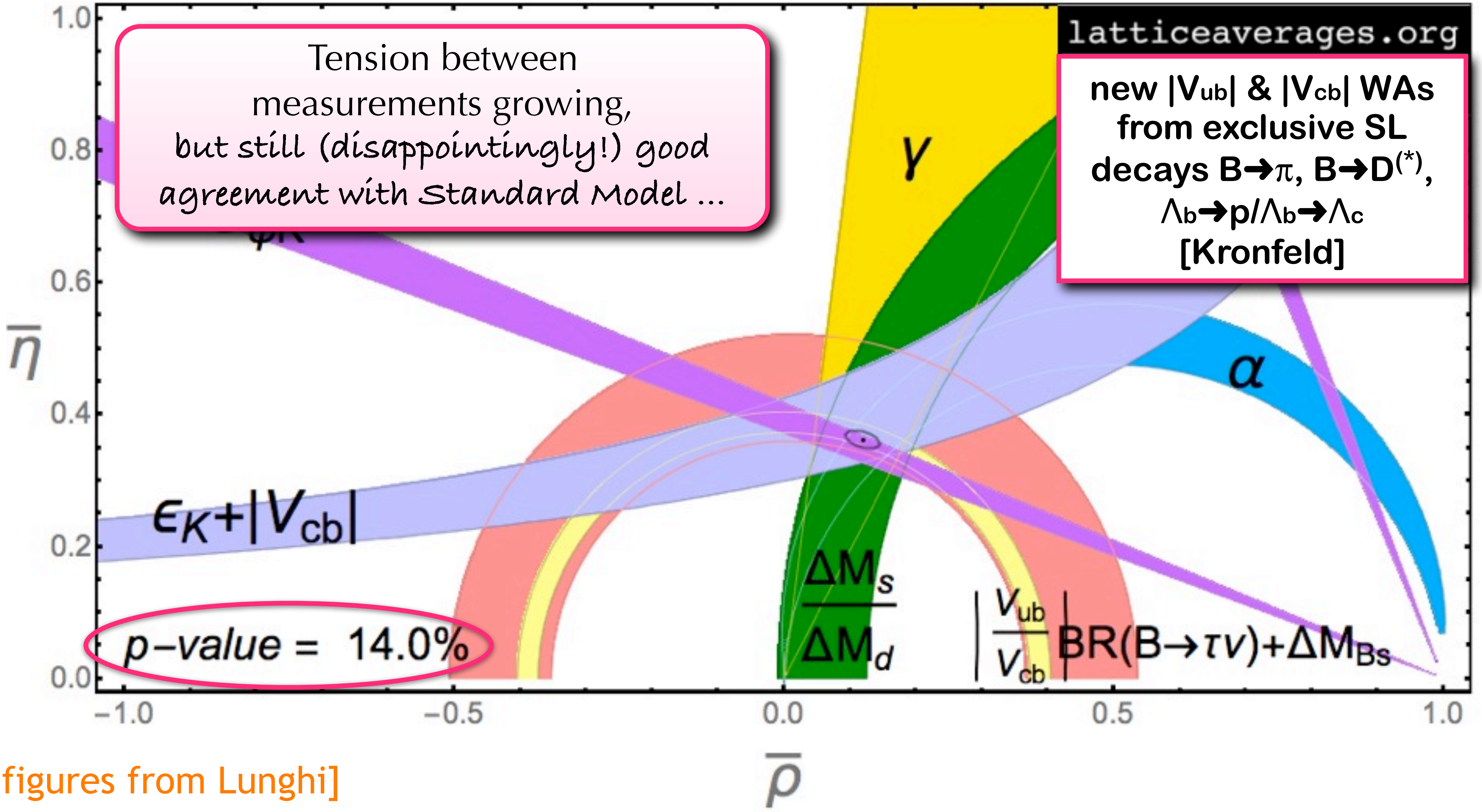


new $|V_{ub}|$ & $|V_{cb}|$ WAs from exclusive SL decays B→π, B→D$^{(*)}$, Λ_b→p/Λ_b→Λ_c [Kronfeld]

$|V_{ub}|/|V_{cb}|$ excl.

[figures from Lunghi]

Impact on global CKM UT fit

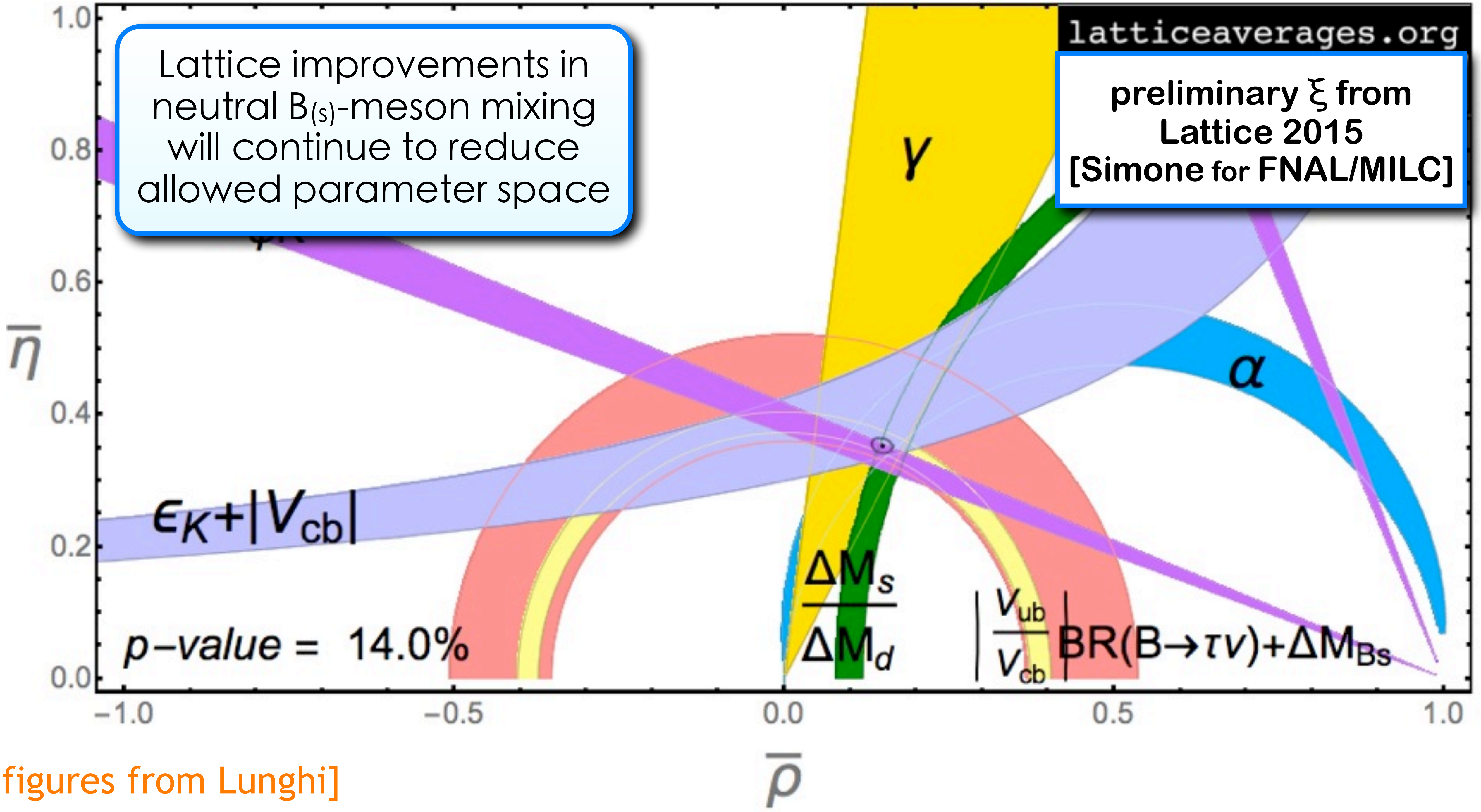


Tension between measurements growing, but still (disappointingly!) good agreement with Standard Model ...

new $|V_{ub}|$ & $|V_{cb}|$ WAs from exclusive SL decays B→π, B→$D^{(*)}$, Λ_b→p/Λ_b→Λ_c [Kronfeld]

[figures from Lunghi]

… UT fit at the end of the year?



Lattice improvements in neutral $B_{(s)}$-meson mixing will continue to reduce allowed parameter space

preliminary ξ from Lattice 2015 [Simone for FNAL/MILC]

[figures from Lunghi]

Beyond simple quantities: Muon g-2

Unable to cover numerous other exciting advances in lattice-QCD calculations of

- $K \to \pi\pi$ decays,
- long-distance matrix elements,
- nucleon structure,
- QCD resonances, ... and more!

Beyond simple quantities:

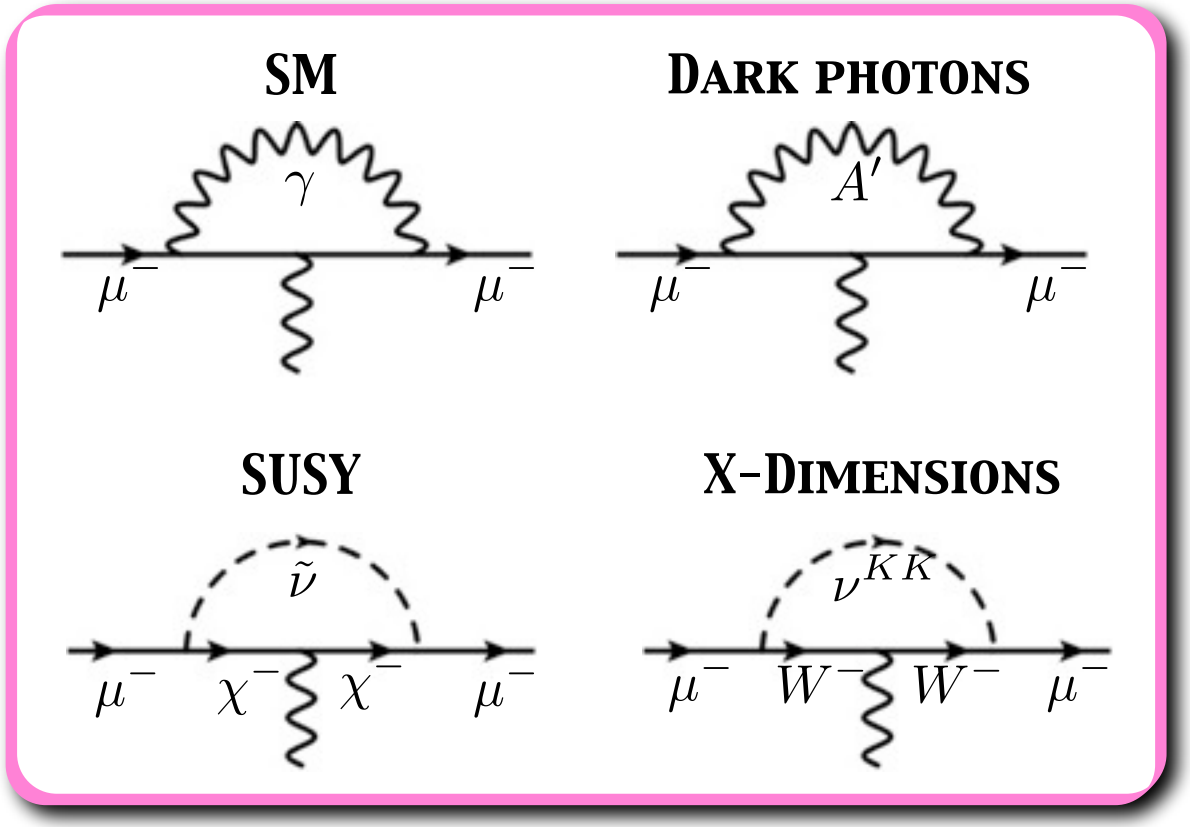
Unable to cover numerous other exciting advances in lattice-QCD calculations of

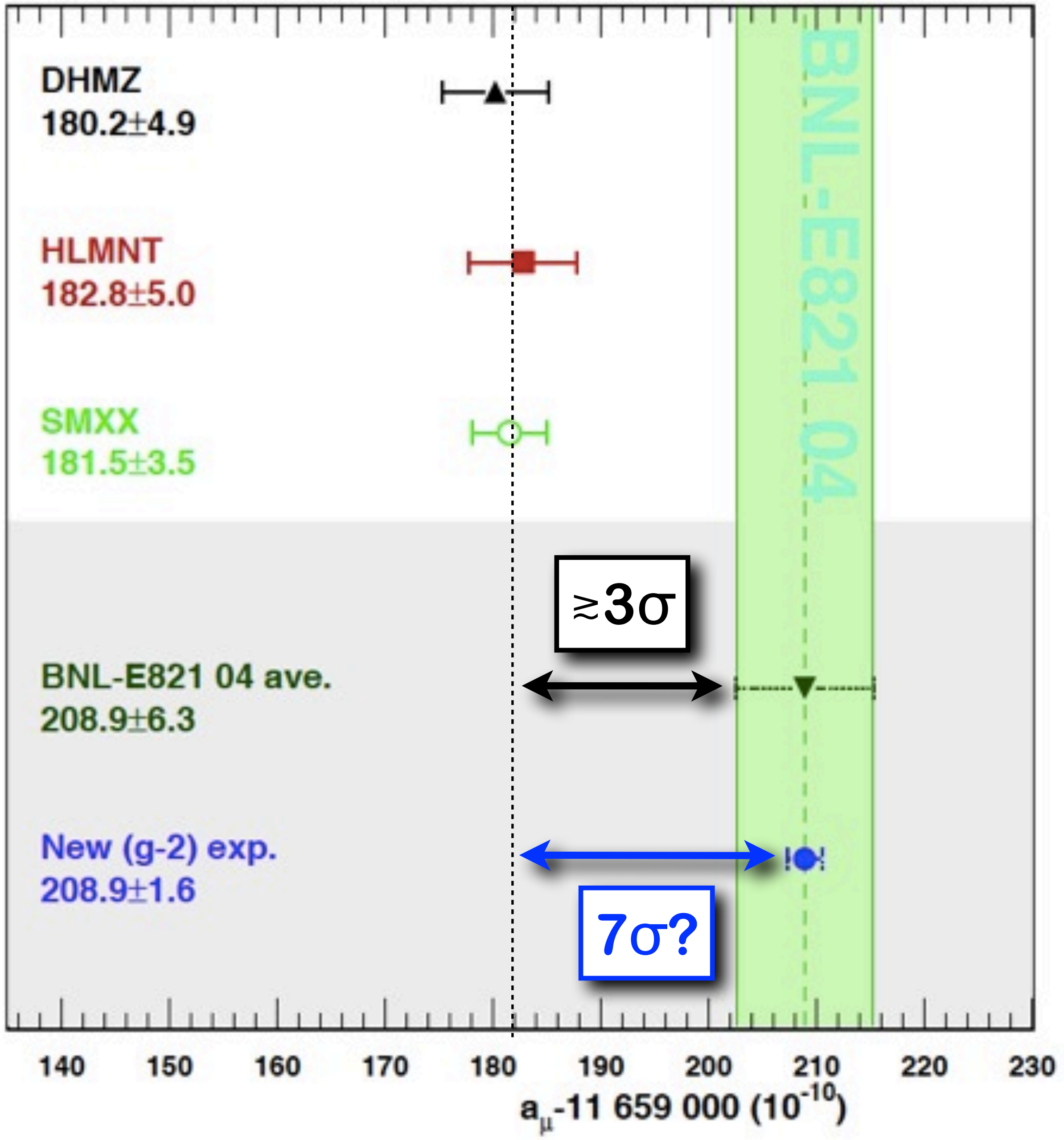
- *$K\to\pi\pi$ decays,*
- *long-distance matrix elements,*
- *nucleon structure,*
- *QCD resonances,*

First $\mathrm{Re}(\varepsilon'/\varepsilon)$ in Standard Model with controlled errors!
[RBC/UKQCD,1505.07863; Soni talk @ EPS-HEP]

Experimental status of g-2

- Muon anomalous magnetic moment (g-2) among best-measured quantities (0.54 ppm!)
  ➜ **provides some of most precise constraints on extensions of Standard Model**





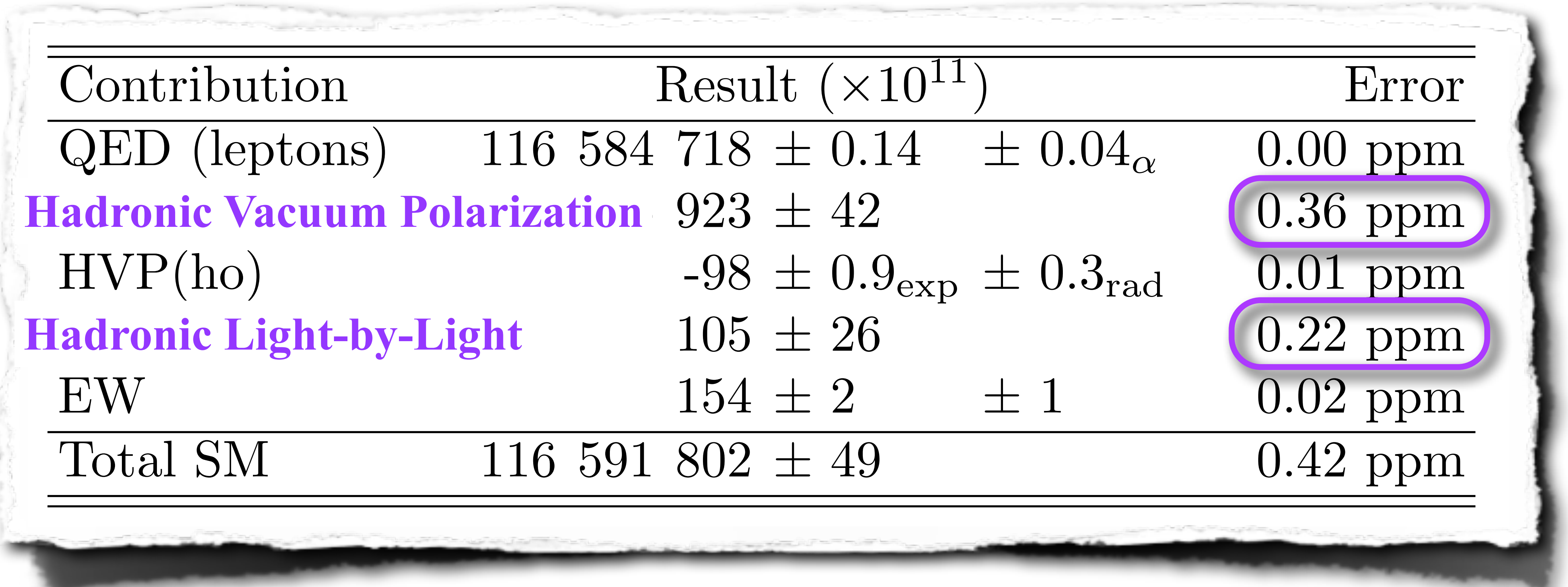
[Blum *et al.*, arXiv:1311.2198]

- **BNL measurement** disagrees with Standard Model by ≳3σ, while

  Fermilab Muon g-2 Experiment aims to reduce error by factor of four

Theoretical status of g-2

- Uncertainty on SM prediction dominated by nonperturbative hadronic contributions



Contribution	Result ($\times 10^{11}$)		Error
QED (leptons)	116 584 718 $\pm$ 0.14	$\pm\ 0.04_{\alpha}$	0.00 ppm
Hadronic Vacuum Polarization	923 $\pm$ 42		0.36 ppm
HVP(ho)	-98 $\pm\ 0.9_{\mathrm{exp}}$	$\pm\ 0.3_{\mathrm{rad}}$	0.01 ppm
Hadronic Light-by-Light	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

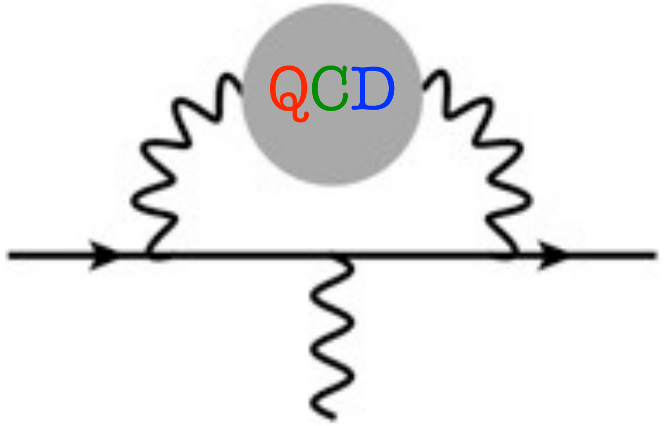
[1] Davier, Hoecker, Malaescu, Zhang, Eur.Phys.J. C71 (2011) 1515

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

Theoretical status of g-2

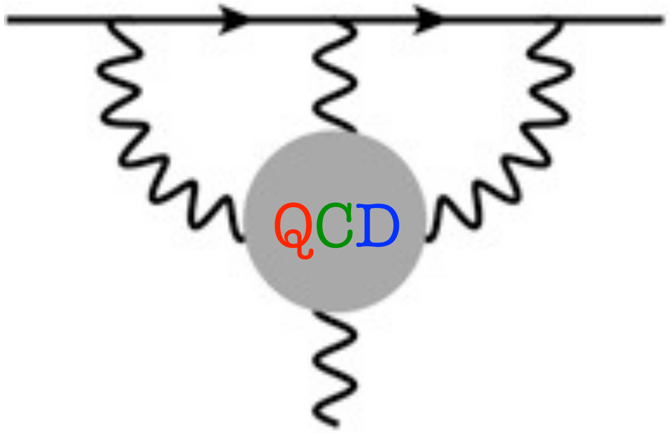
- Uncertainty on SM prediction dominated by nonperturbative hadronic contributions
- To leverage the anticipated experimental measurement, the SM theory error must be shored-up and brought to a comparable precision

Hadronic vacuum polarization (HVP)



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

Hadronic light-by-light (HLbL)



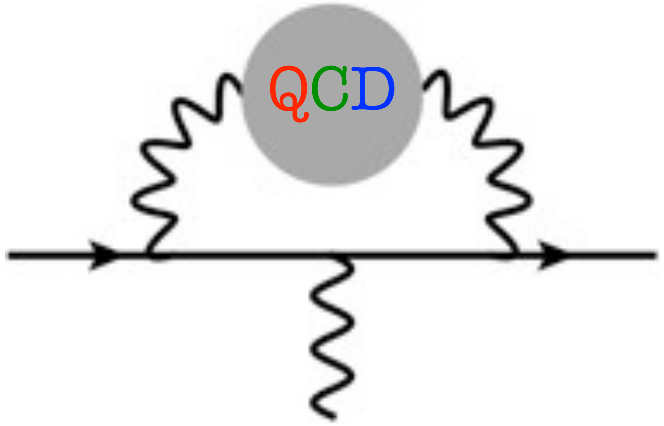
estimated from QCD models such as large N_c, χPT, vector meson dominance, etc…

(subjective and somewhat controversial)

Theoretical status of g-2

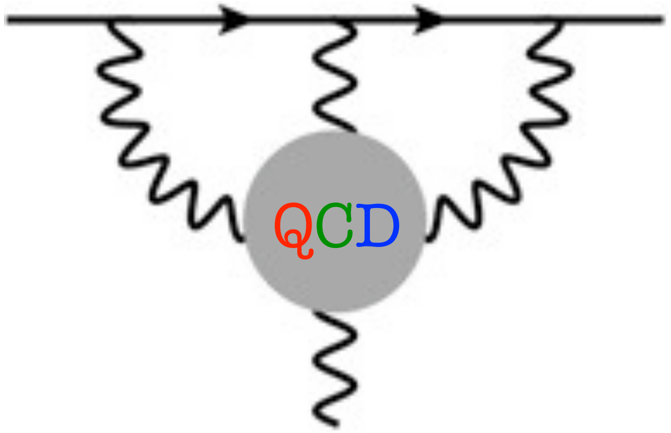
- Uncertainty on SM prediction dominated by nonperturbative hadronic contributions
- To leverage the anticipated experimental measurement, the SM theory error must be shored-up and brought to a comparable precision
- Both hadronic contributions are calculable, in principle, with lattice QCD

Hadronic vacuum polarization (HVP)



methods are in place, and first results have been reported from different collaborations and with different approaches

Hadronic light-by-light (HLbL)



very difficult, but methods being developed and tested

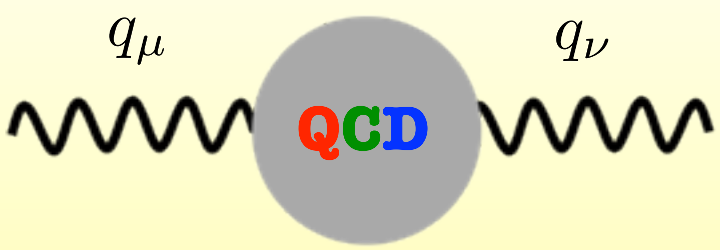
Standard lattice method for a_μ^{HVP}

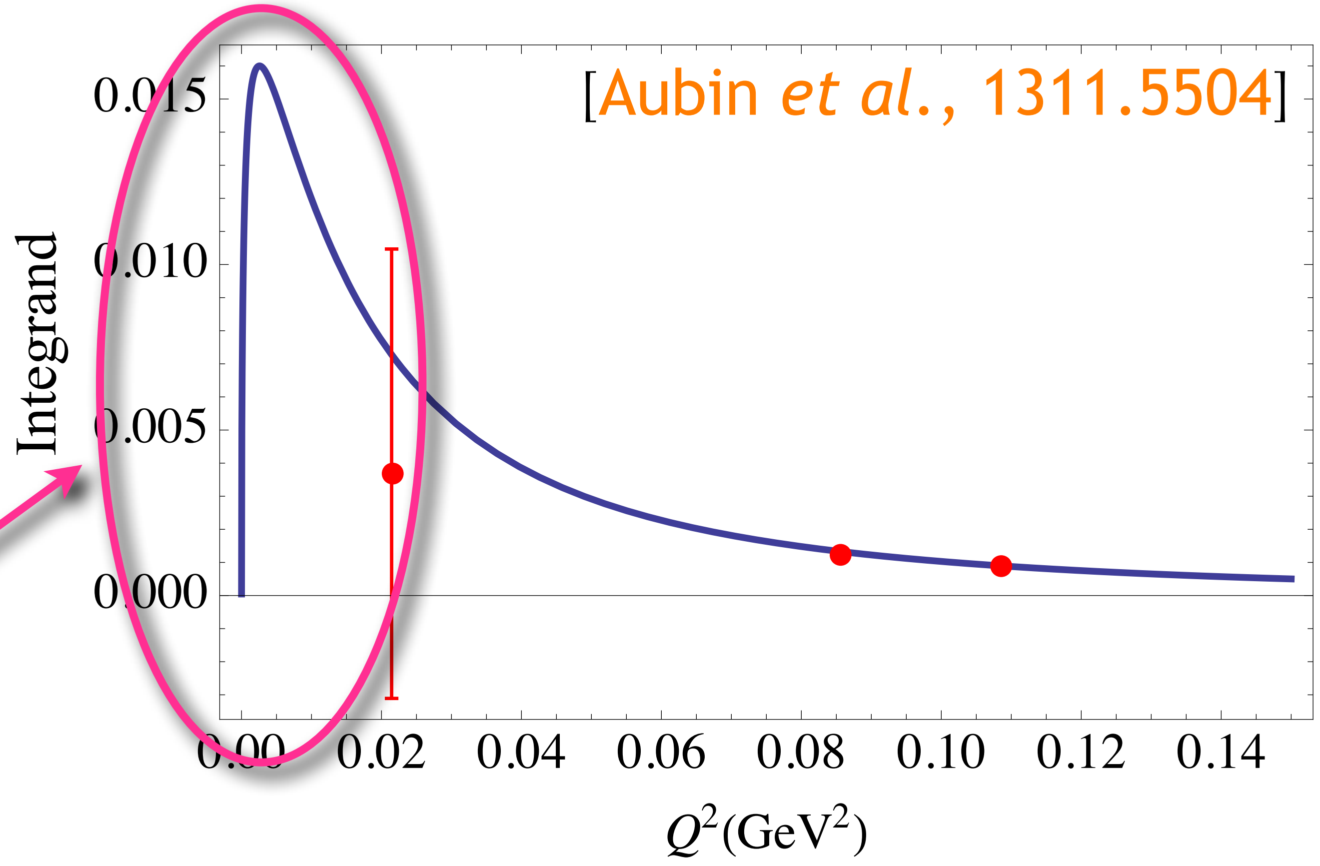
[Blum, Phys.Rev.Lett. 91 (2003) 052001]

- Calculate a_μ^{HVP} directly from Euclidean space vacuum polarization function $\Pi(Q^2)$
  - **$\Pi(Q^2)$ captures nonperturbative QCD effects ➜ compute numerically in lattice QCD** from simple two-point correlation function of electromagnetic quark current
  - 1-loop QED integral accounts for interaction between muon and external photon field
- Challenging because integrand $f(Q^2)[\Pi(Q^2)-\Pi(0)]$ peaks around $Q^2 \approx (m_\mu/2)^2$, where lattice data is sparse and noisy

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

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



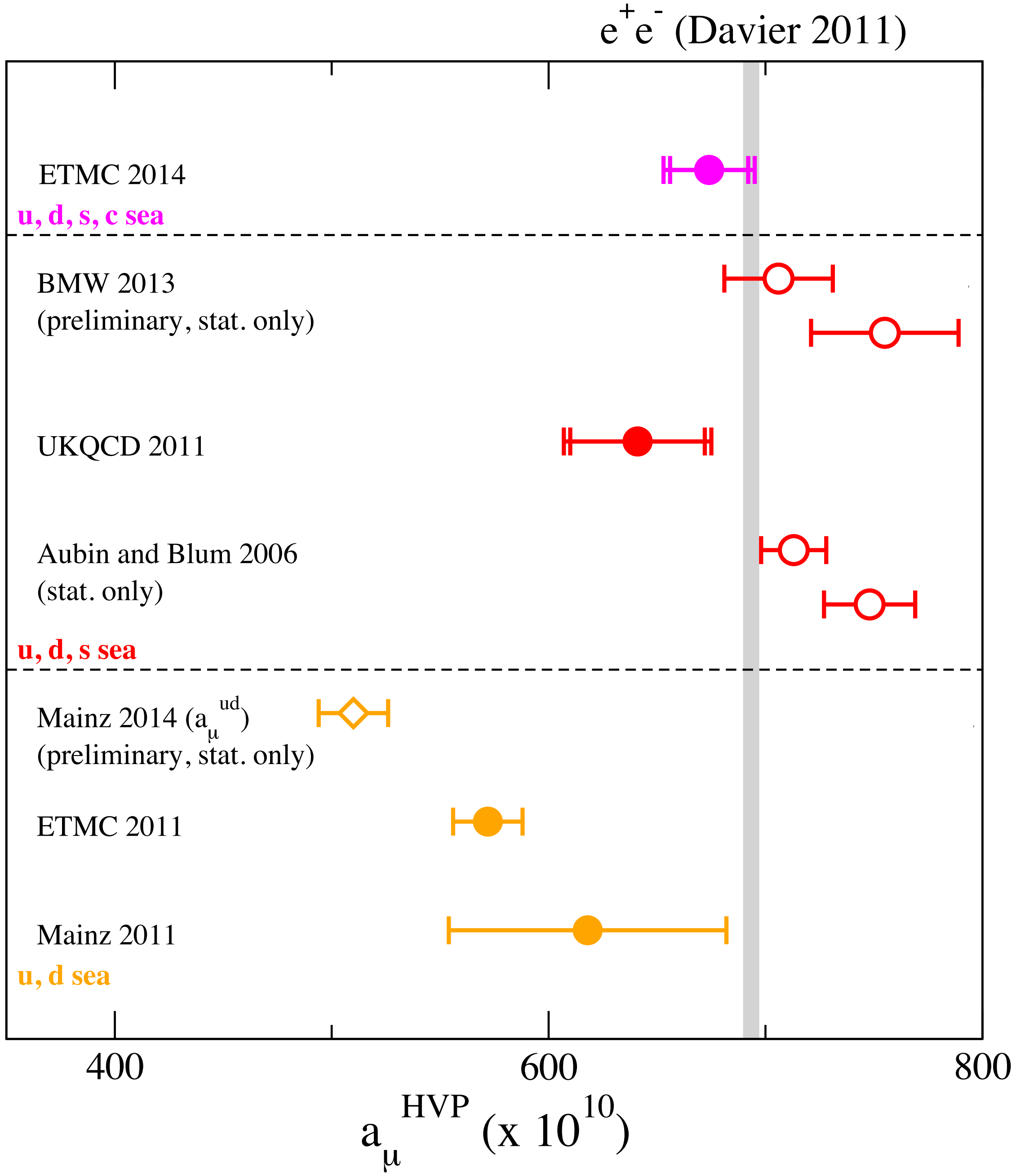


[Aubin *et al.*, 1311.5504]

Recent lattice progress on a_μ^{HVP}

- **Statistical-error-reduction techniques:** all-mode averaging [Blum *et al*, PRD 88 (2013) 094503], stochastic sources [Marinkovic *et al.*, 1502.05308]
- **Methods for controlling q^2 extrapolation:**
  - Padé approximants to remove hidden model systematics in q^2 extrapolation [Aubin et al.,PRD86 (2012) 054509]
  - Twisted boundary conditions to access smaller momentum values below $(2\pi/L)$ [Della Morte *et al.*, JHEP 1203 (2012) 055; Aubin *et al.*, PRD88 (2013) 7, 074505]
  - **Moments method to sidestep $q^2 \to 0$ extrapolation** by expressing a_μ^{HVP} in terms of derivatives of $\Pi(q^2)$ at $q^2=0$ [Chakraborty *et al.* (HPQCD), PRD89 (2014) 11, 114501]

Active research area with several independent ongoing efforts!



Recent lattice progress on a_μ^{HVP}

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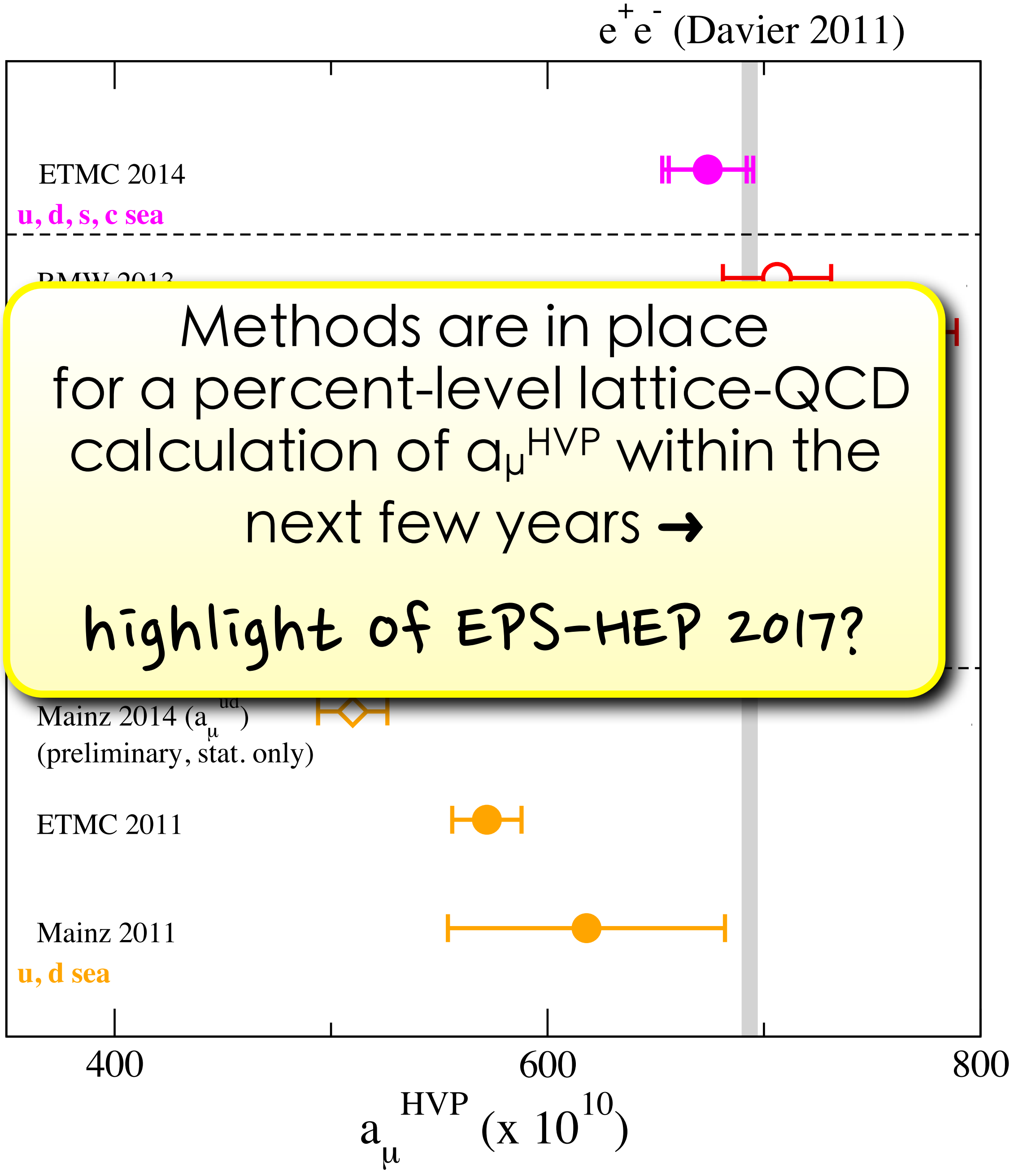
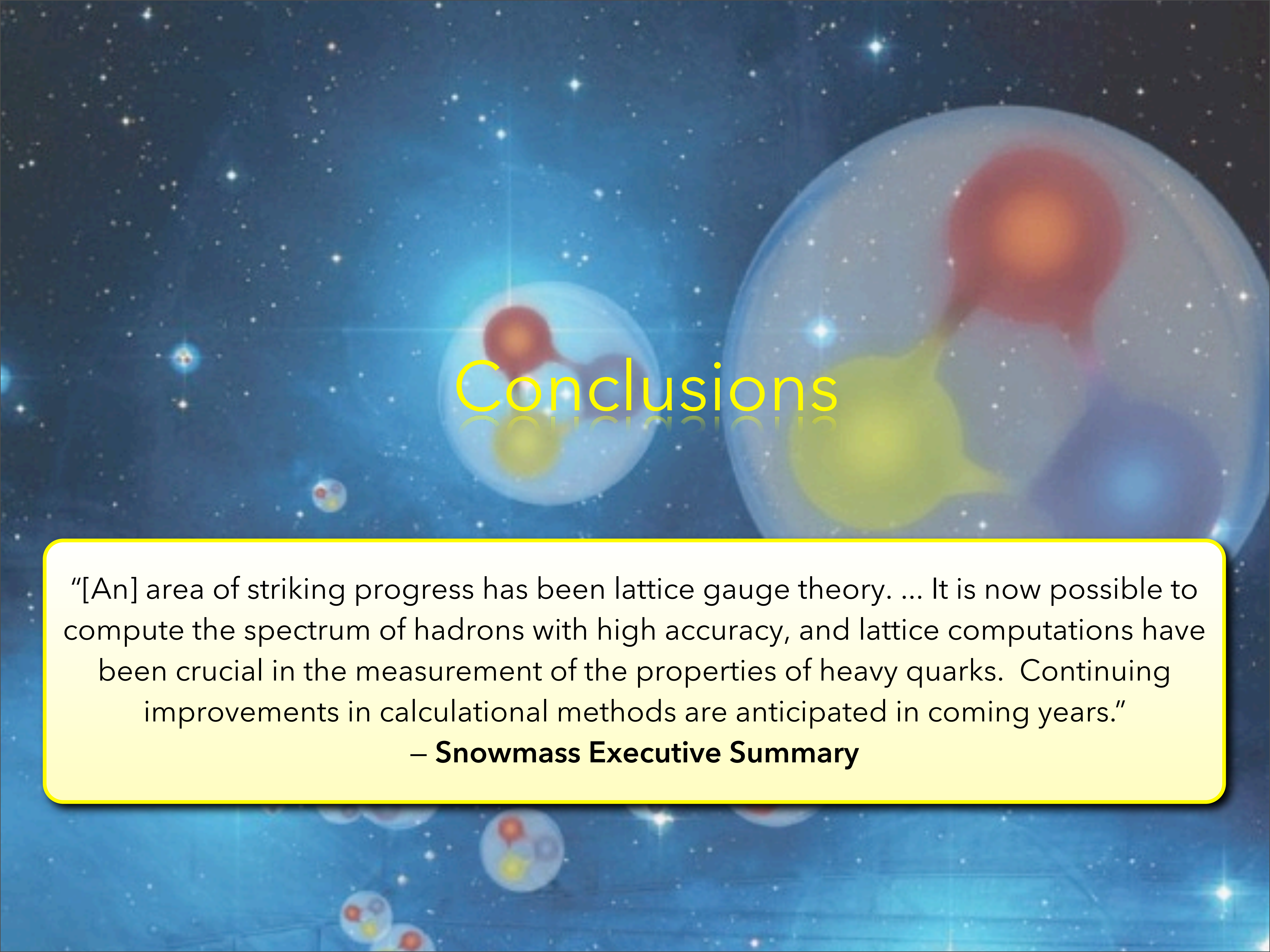


Methods are in place for a percent-level lattice-QCD calculation of a_μ^{HVP} within the next few years →

highlight of EPS-HEP 2017?



Conclusions

> “[An] area of striking progress has been lattice gauge theory. … It is now possible to compute the spectrum of hadrons with high accuracy, and lattice computations have been crucial in the measurement of the properties of heavy quarks. Continuing improvements in calculational methods are anticipated in coming years.”
>
> – **Snowmass Executive Summary**

Summary & outlook

- Lattice-QCD calculations needed throughout current & future experimental high-energy physics program
  - For precision measurements of rare kaon and B decays, muon g-2, neutrino oscillation parameters, Higgs properties, ...
  - For searches for μ→e conversion, dark matter, proton decay, nucleon EDMs, ...
- **Ambitious worldwide lattice-QCD program in place to deliver the needed theoretical support** by
  - **Increasing precision of present calculations** of parameters of the QCD Lagrangian & simplest quark flavor-changing matrix elements
  - **Providing first reliable QCD calculations of new, more challenging quantities** such as muon g-2, long-distance amplitudes, decays to QCD resonances or multi-hadron final states, ...
- Theoretical innovation in methods & algorithms drive progress in lattice QCD, but sufficient computational resources are absolutely essential!

Summary & outlook

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  - **Increasing** CD Lagrangian & simplest qu
  - **Providing first reliable QCD calculations of new, more challenging quantities** such as muon g-2, long-distance amplitudes, decays to QCD resonances or multi-hadron final states, ...

Future experiments, aided by lattice-QCD calculations, will continue to tighten the noose on the Standard Model and probe the nature of whatever new particles and forces lie beyond

- Theoretical innovation in methods & algorithms drive progress in lattice QCD, but sufficient computational resources are absolutely essential!

Further reading

See Lattice 2015 website for more hot-off-the-press results!

LATTICE 2015 KOBE

LATTICE2015

The 33rd International Symposium on Lattice Field Theory

Kobe International Conference Center, Kobe, Japan

Tuesday, July 14 - Saturday, July 18, 2015

http://www.aics.riken.jp/sympo/lattice2015

Topics

- Algorithms and Machines
- Applications Beyond QCD
- Chiral Symmetry
- Hadron Spectroscopy and Interactions
- Hadron Structure
- Nonzero Temperature and Density
- Physics Beyond the Standard Model
- Standard Model Parameters and Renormalization
- Theoretical Developments
- Vacuum Structure and Confinement
- Weak Decays and Matrix Elements

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Lattice 2014 review talks:

- ✤ "Weak interactions of pions and kaons"
- ✤ "Testing the Standard Model under the weight of heavy flavors"

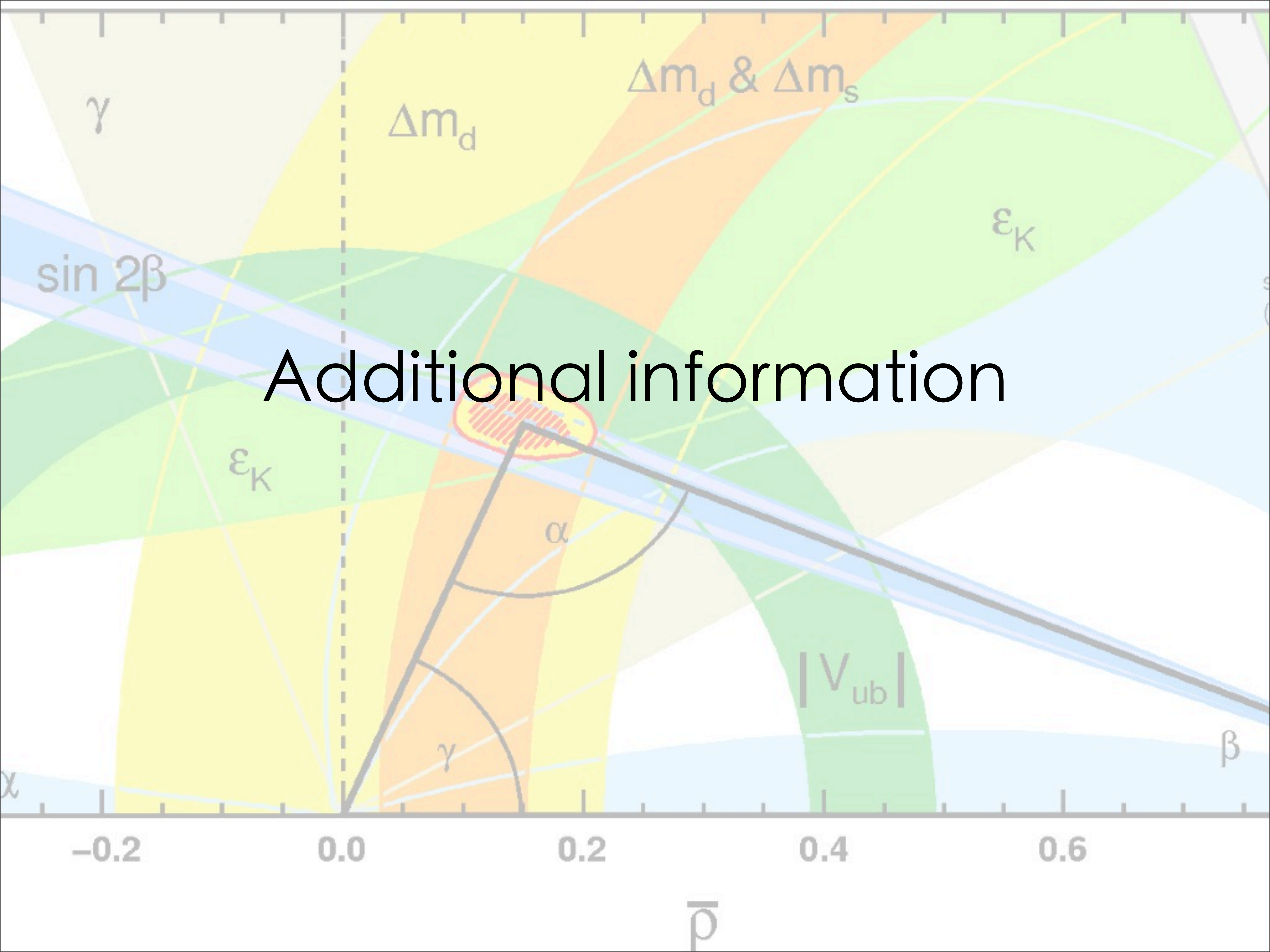
2013 FLAG report:

- ✤ "Review of lattice results concerning low-energy particle physics"

Snowmass working-group reports:

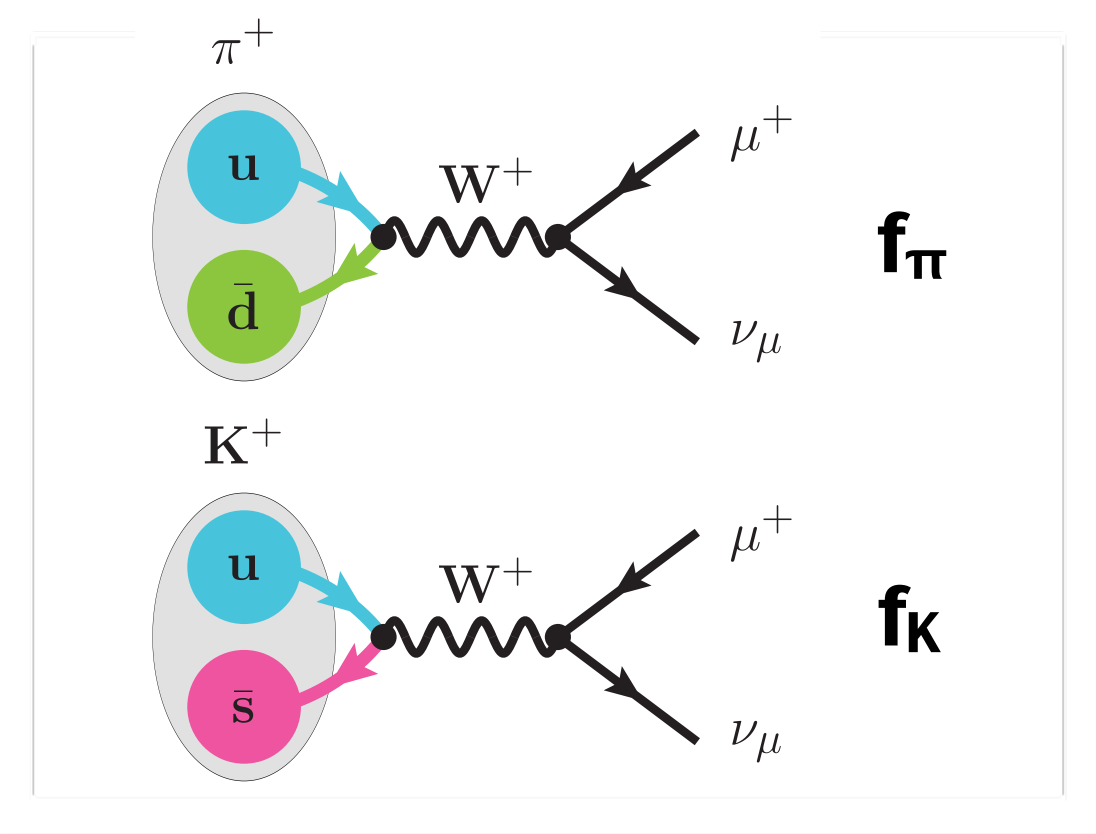
- ✤ "Charged Leptons"
- ✤ "Higgs Working Group Report …"
- ✤ "Lattice field theory … Scientific goals and computing needs"
- ✤ "Report of … QCD Working Group"
- ✤ "Report of … Quark Flavor Physics Working Group"

Additional information

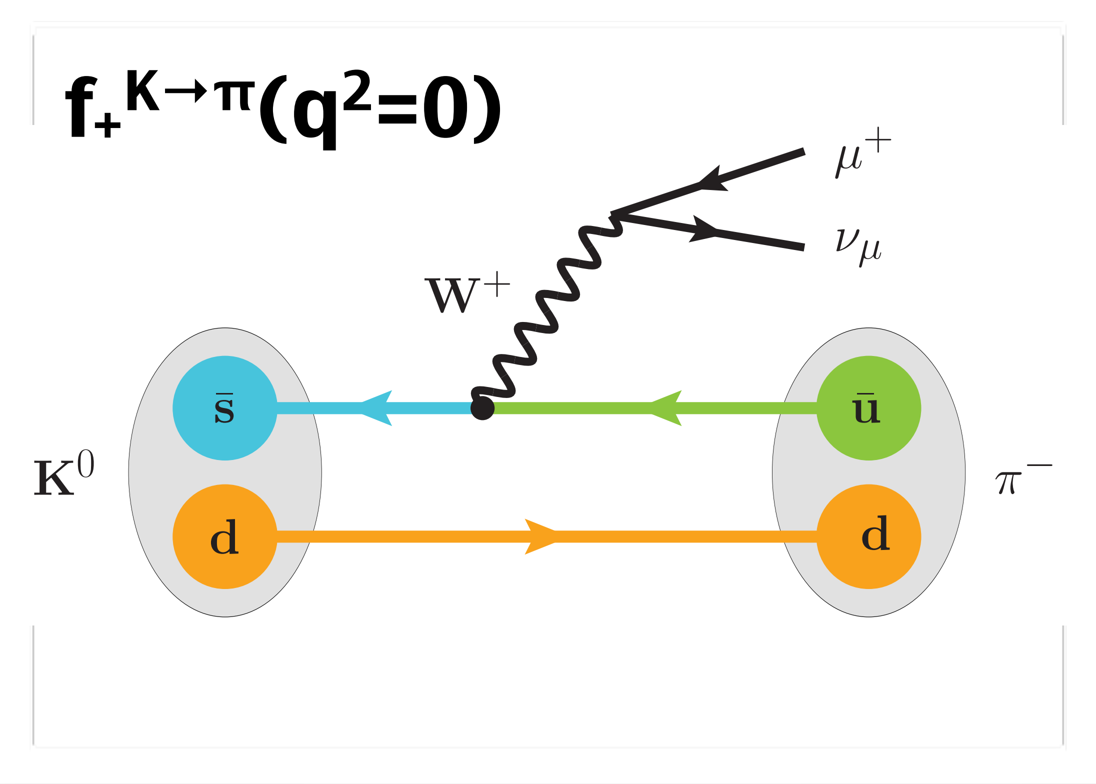


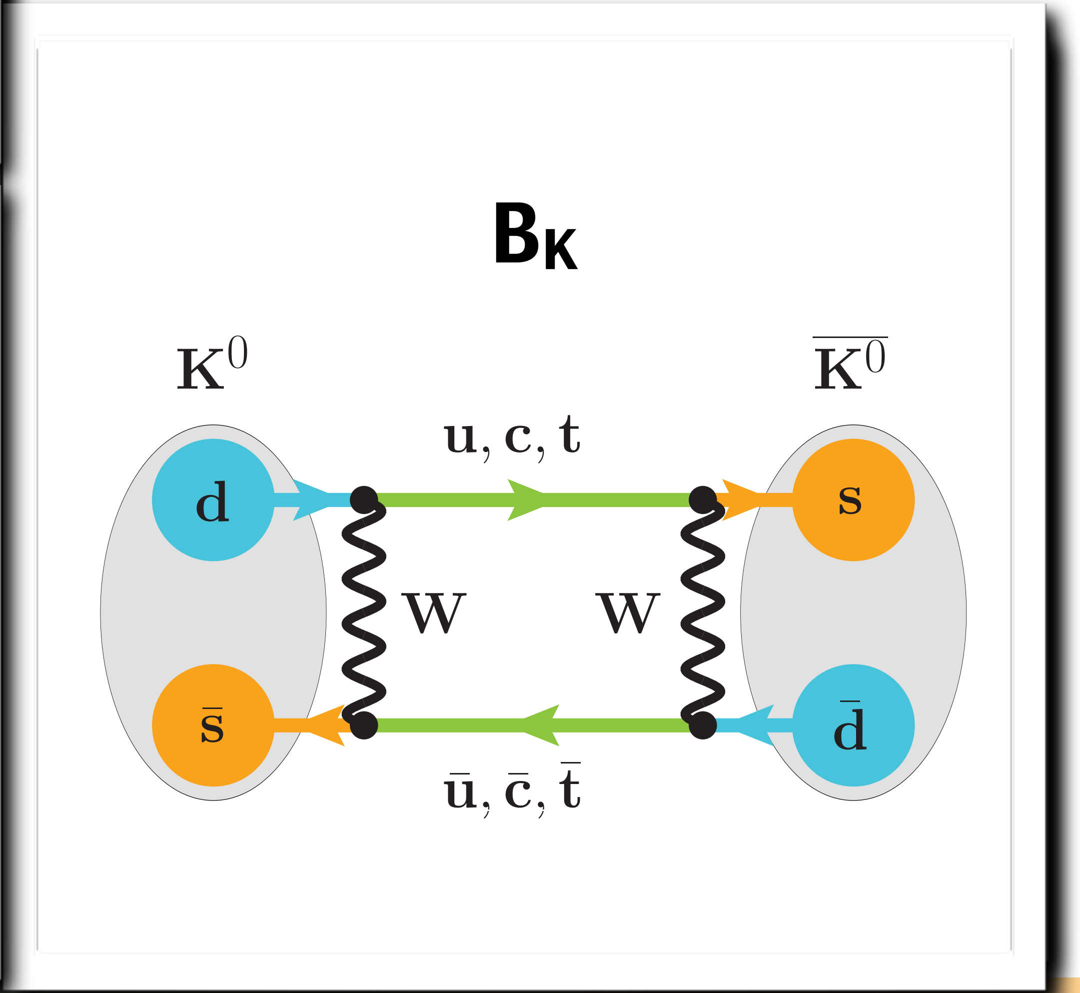
Kaon overview

See Lattice '15 light-flavor review by Jüttner
& ICHEP '14 meson-mixing review by Carrasco



- For all simple quantities
  - Physical light-quark masses
  - Nonperturbative or no renormalization
  - Confirmation from independent results
- (Sub-)percent precision ➜ **EM & isospin-breaking becoming relevant**





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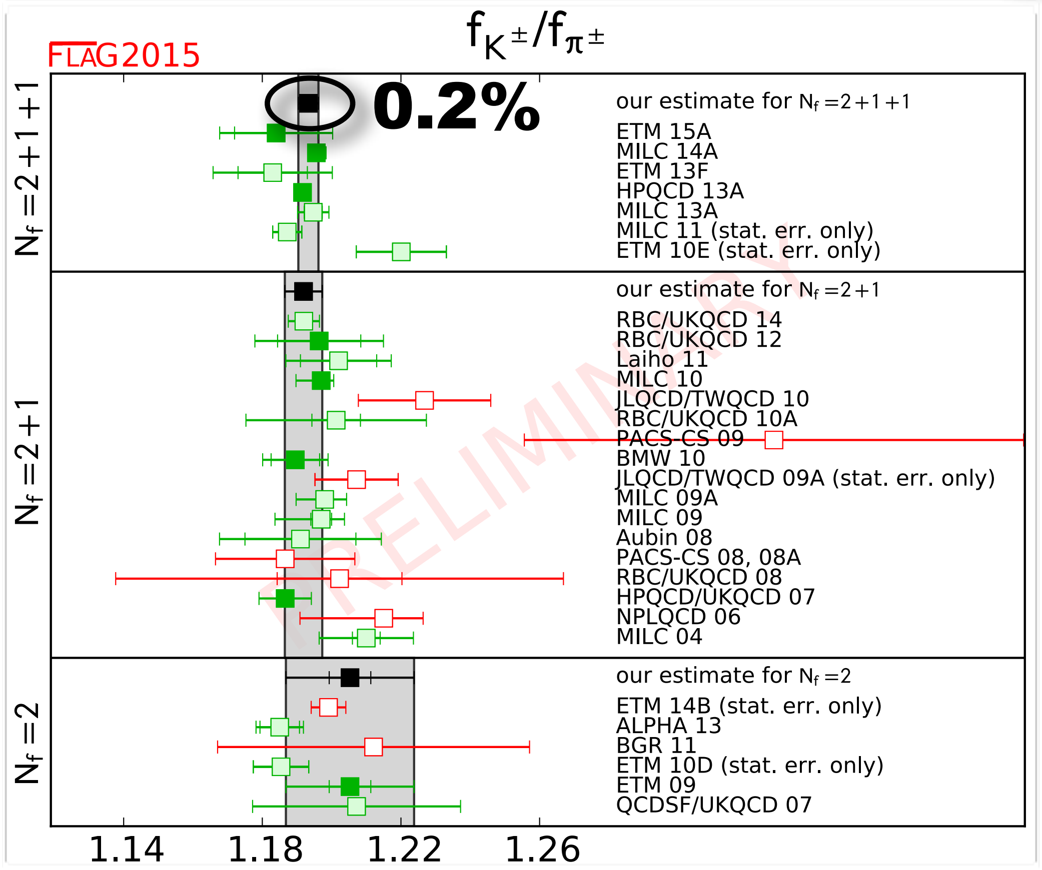

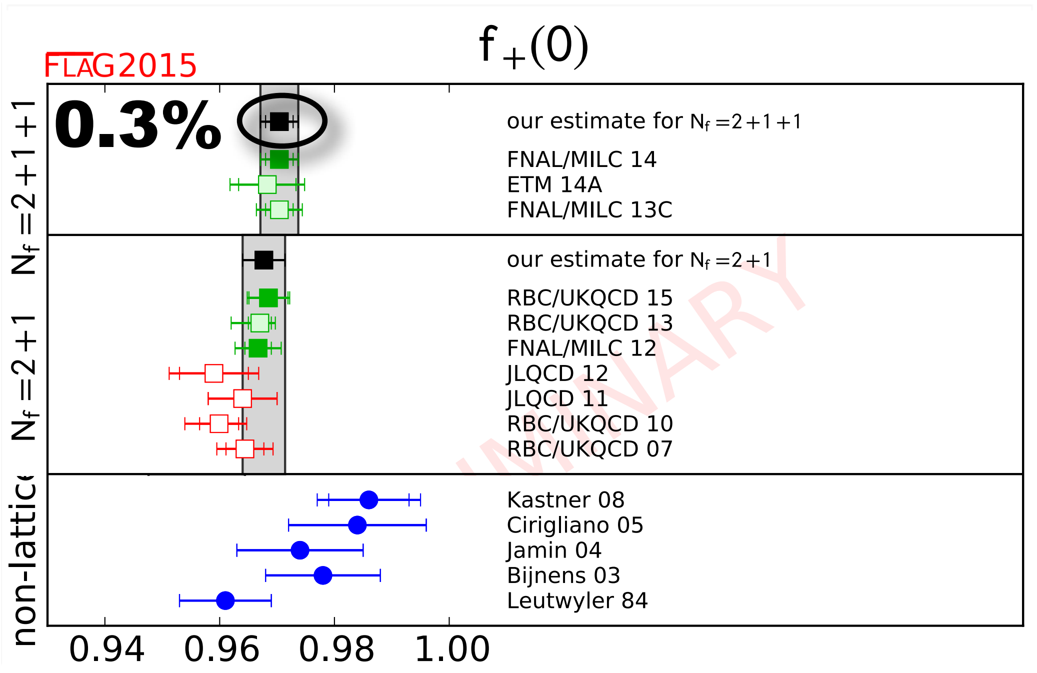

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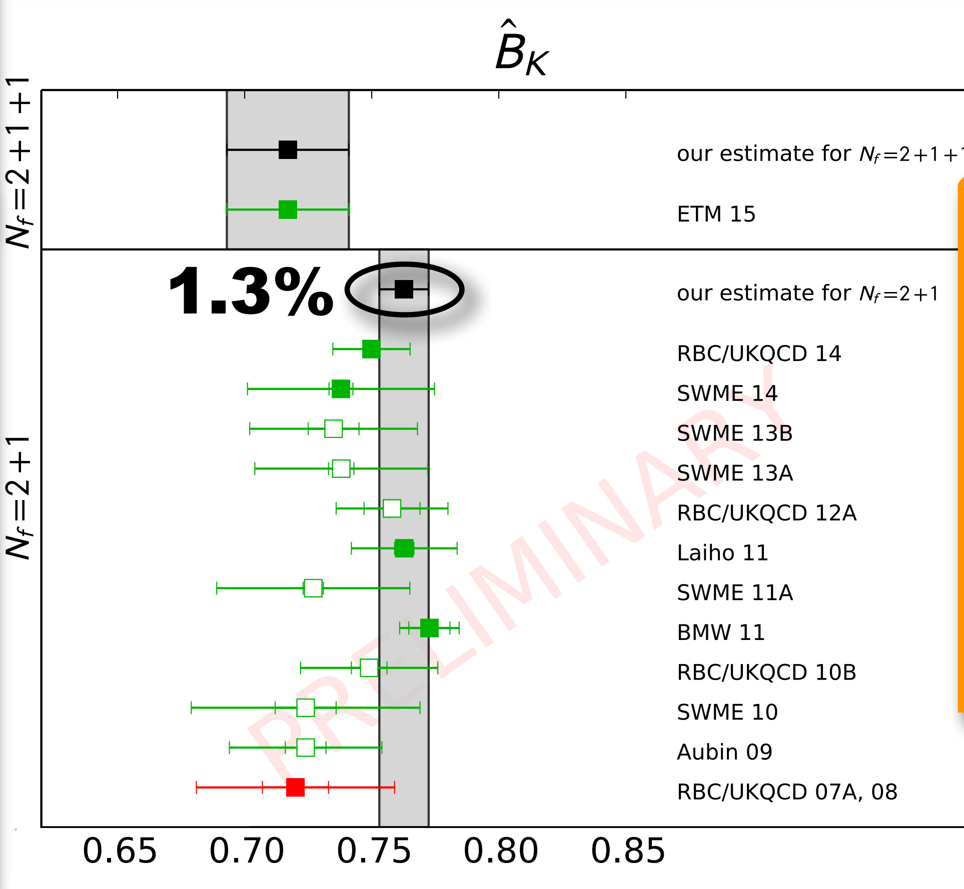
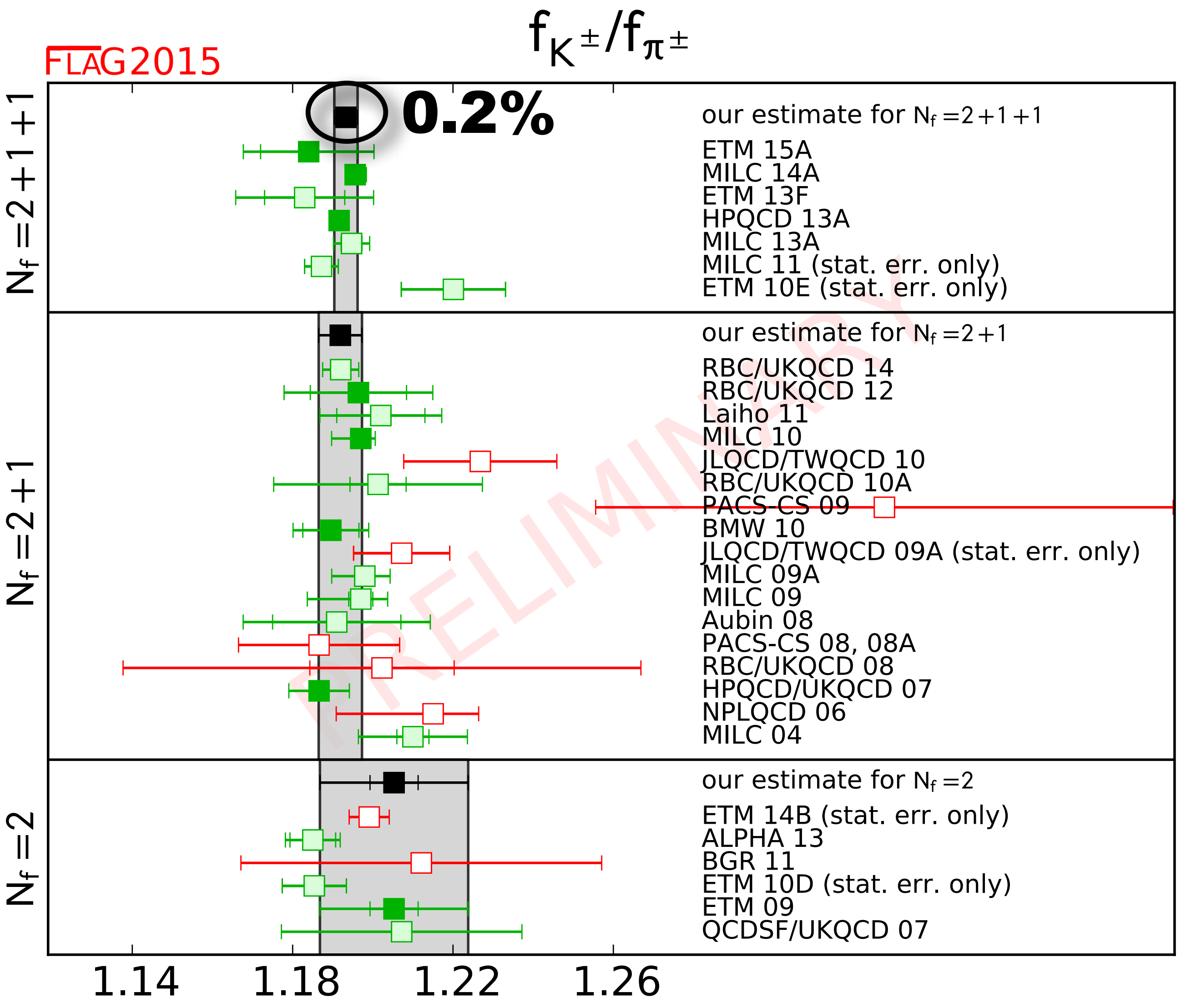
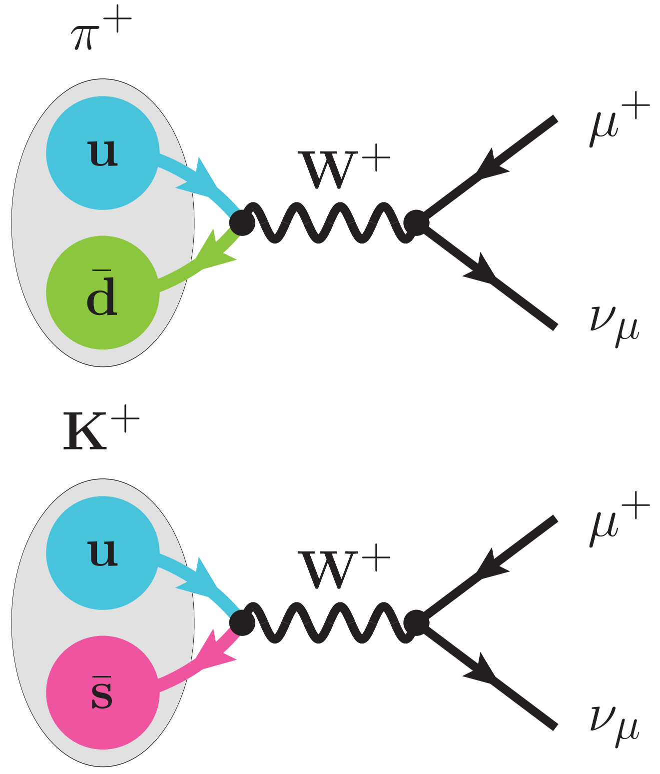


- Kaon-mixing matrix elements of all possible $\Delta S=2$ BSM operators also available

Pion & kaon decay constants

- **Decay-constant ratio f_K/f_π can be computed to sub-% precision with lattice QCD:**
  - Statistical fluctuations correlated between numerator & denominator
  - $f_K=f_\pi$ in SU(3) limit $m_s=m_{ud}$, so some systematics suppressed by $(m_s-m_{ud})/\Lambda_{QCD}$



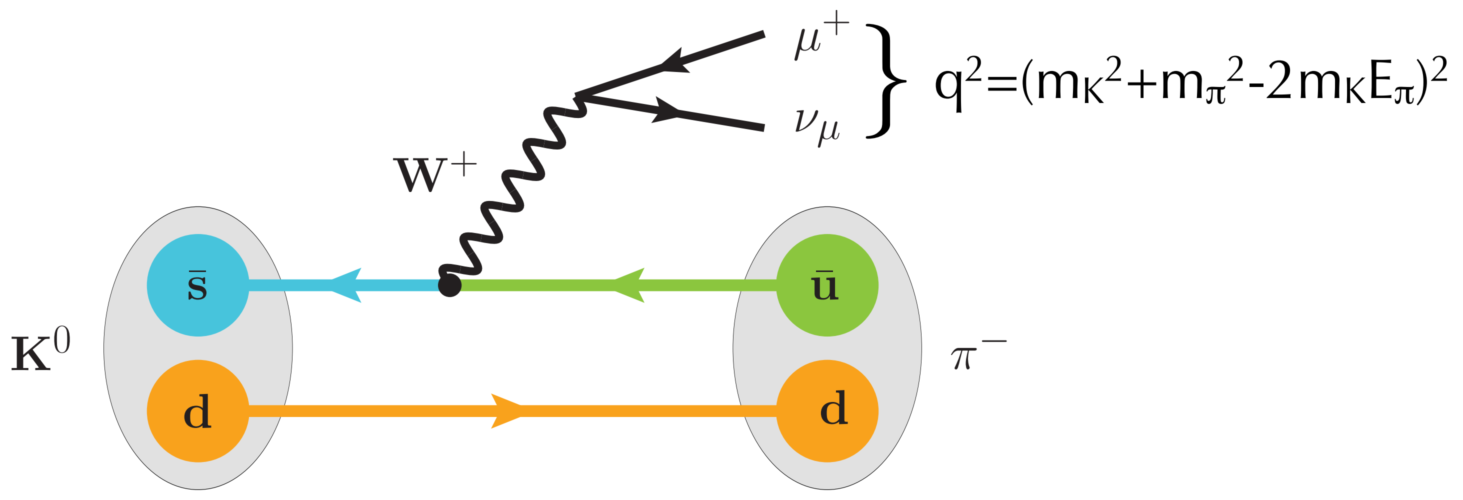


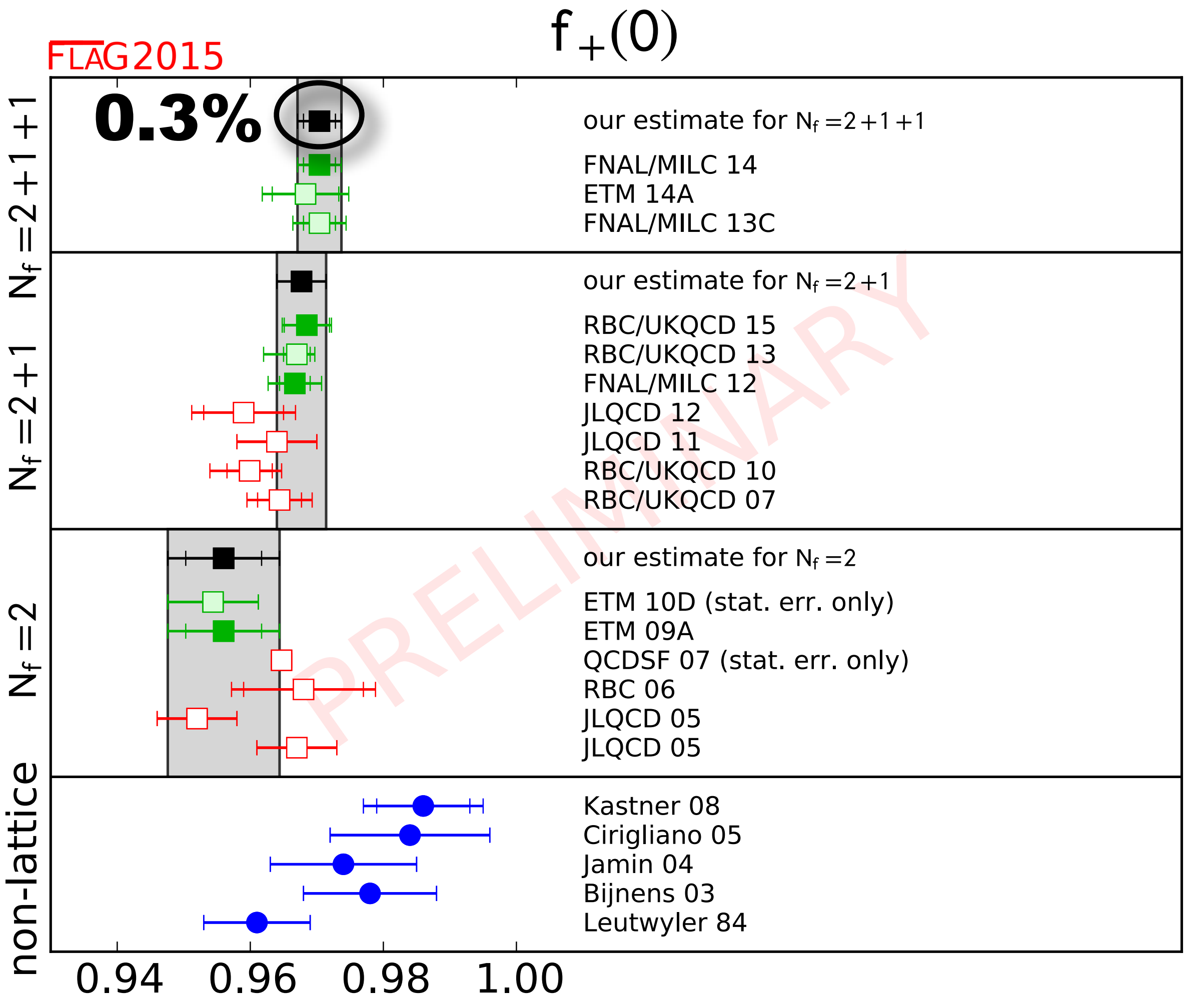
Combination with experimental decay rates enables **$|V_{ud}|/|V_{us}|$ determination** [Marciano]

$K \to \pi \ell \nu$ semileptonic form factor

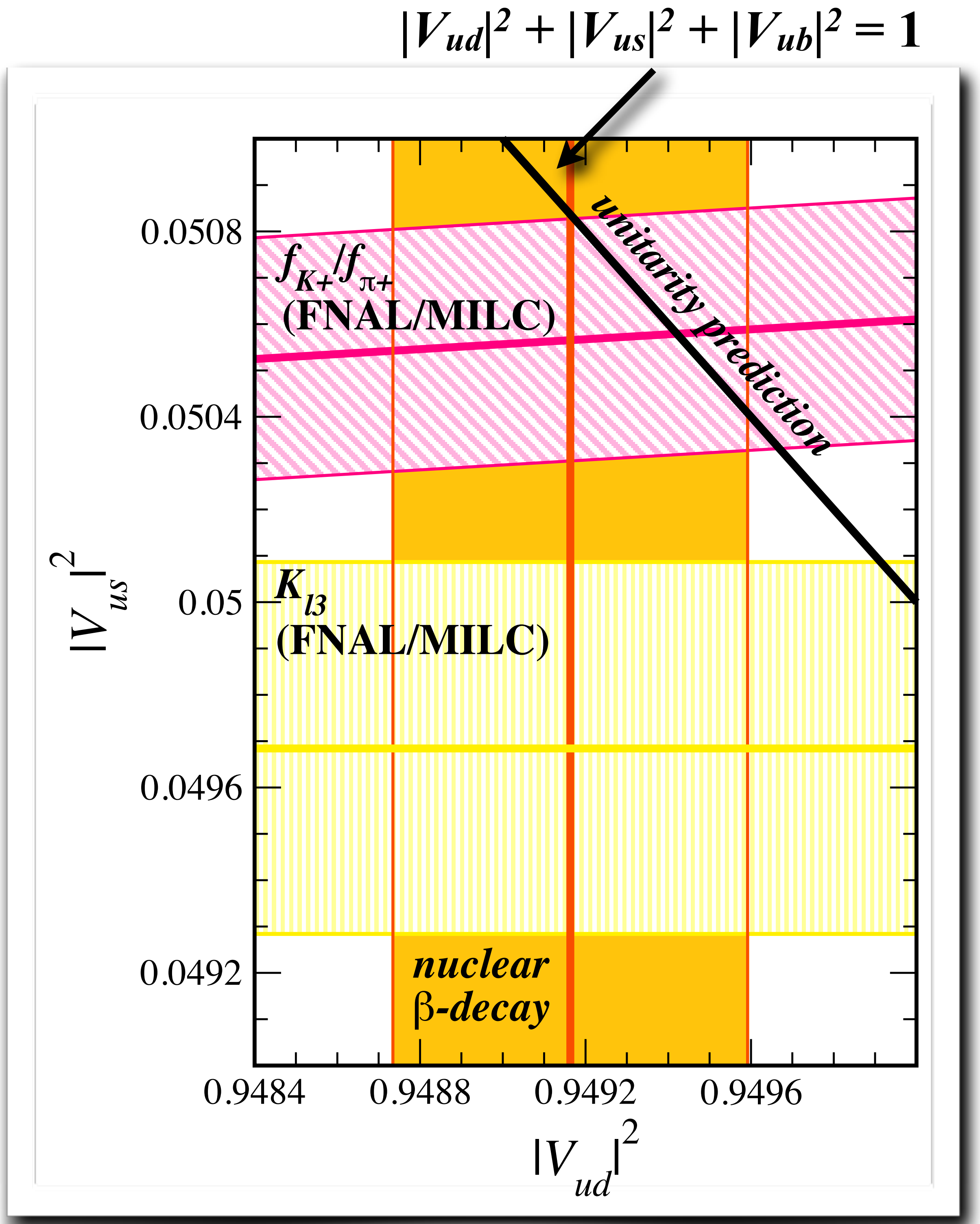
- **Zero-recoil form factor $f_+(q^2=0)$ highly constrained by $SU(3)_f$ and chiral symmetries**:
  - $f_+(0) = 1$ in SU(3) limit $m_s=m_{ud}$
  - Leading-order correction to unity is known function of $\{m_\pi, m_K, f_\pi\}$ [Leutwyler & Roos]
  - $f_2=-0.023$ numerically small because second-order in $(m_K^2-m_\pi^2)$ [Ademollo-Gatto]
- Lattice-QCD calculation does not require renormalization

Combination with experimental rate enables **$|V_{us}|$ determination**





Implications for 1st row of CKM matrix



- Using preliminary 2015 K→πlυ form factor from FLAG, latest experimental $f_+^{K\pi}(0) \times |V_{us}|$ from Moulson [1411.5252] and $|V_{ud}|$ from Hardy & Towner [1411.5987]:

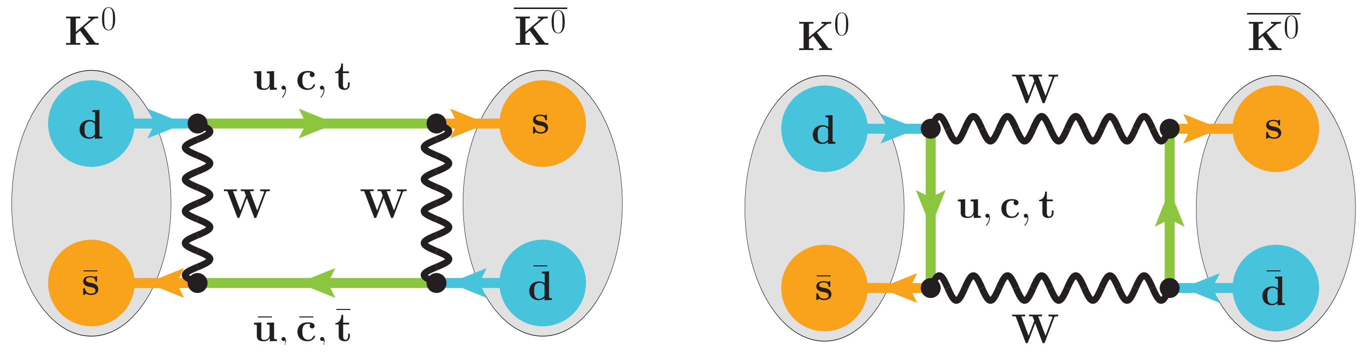
$$\boxed{\begin{array}{c}|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 \\ = -0.0021(29)_{Vus}(41)_{Vud}\end{array}}$$

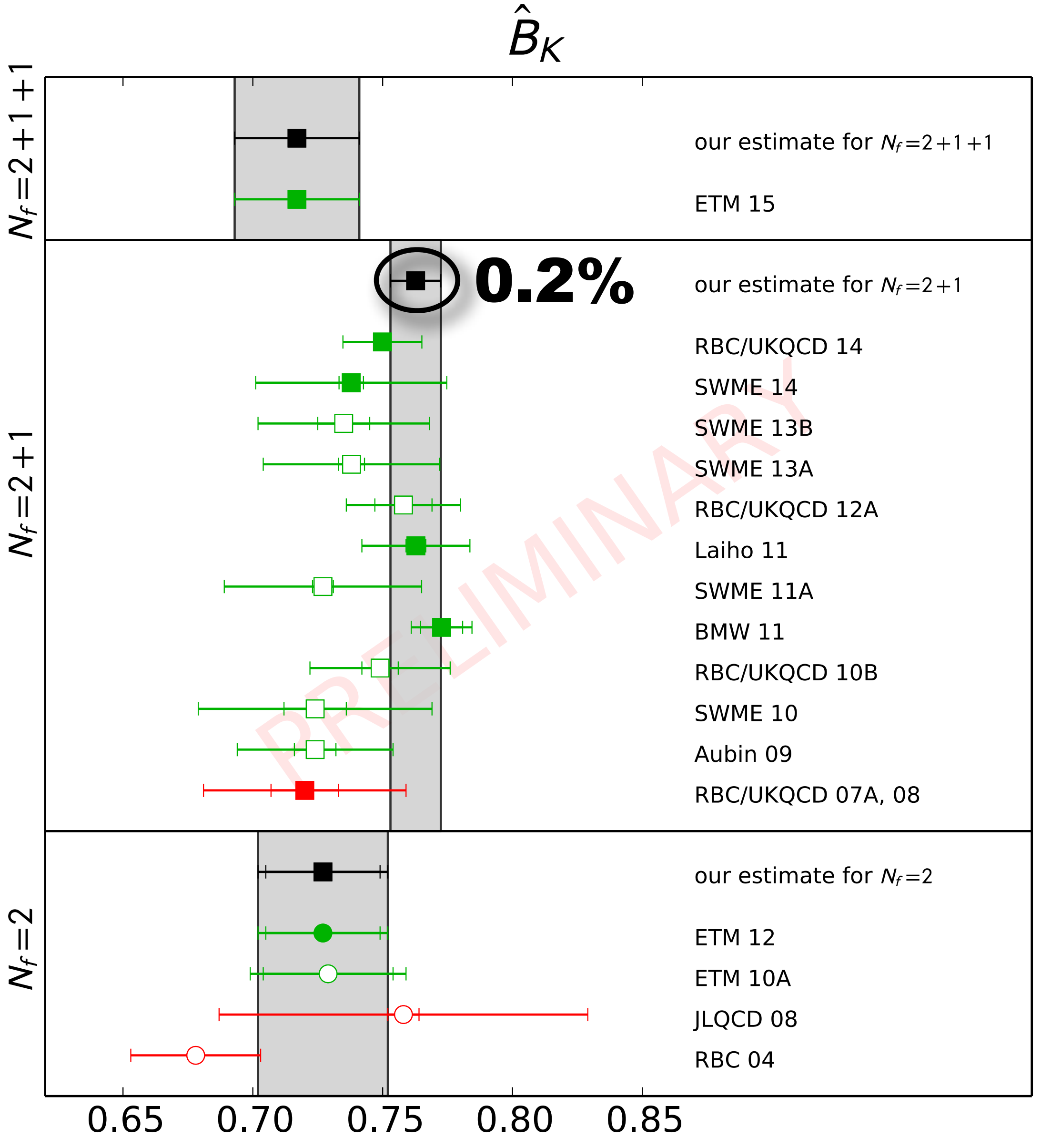
- **Error on $|V_{us}|^2$ now smaller than on $|V_{ud}|^2$**
  - ➡ Motivates revisiting error on $|V_{ud}|$ from nuclear β decays
- **2.1σ tension between K→πlυ, f_K/f_π, and unitarity prediction**

Neutral kaon mixing parameter

- ✦ Percent-level lattice-QCD calculation of B_K enabled by:
  - ❖ **Chiral fermion actions**
  - ❖ **Nonperturbative renormalization**
- ✦ Kaon mixing constrains scale of new physics with generic O(1) flavor couplings to ≳ 10,000 TeV [Isidori, Nir, Perez (2010)]
  - ❖ **Lattice-QCD results for matrix elements of all possible ΔS=2 BSM operators available** for model building

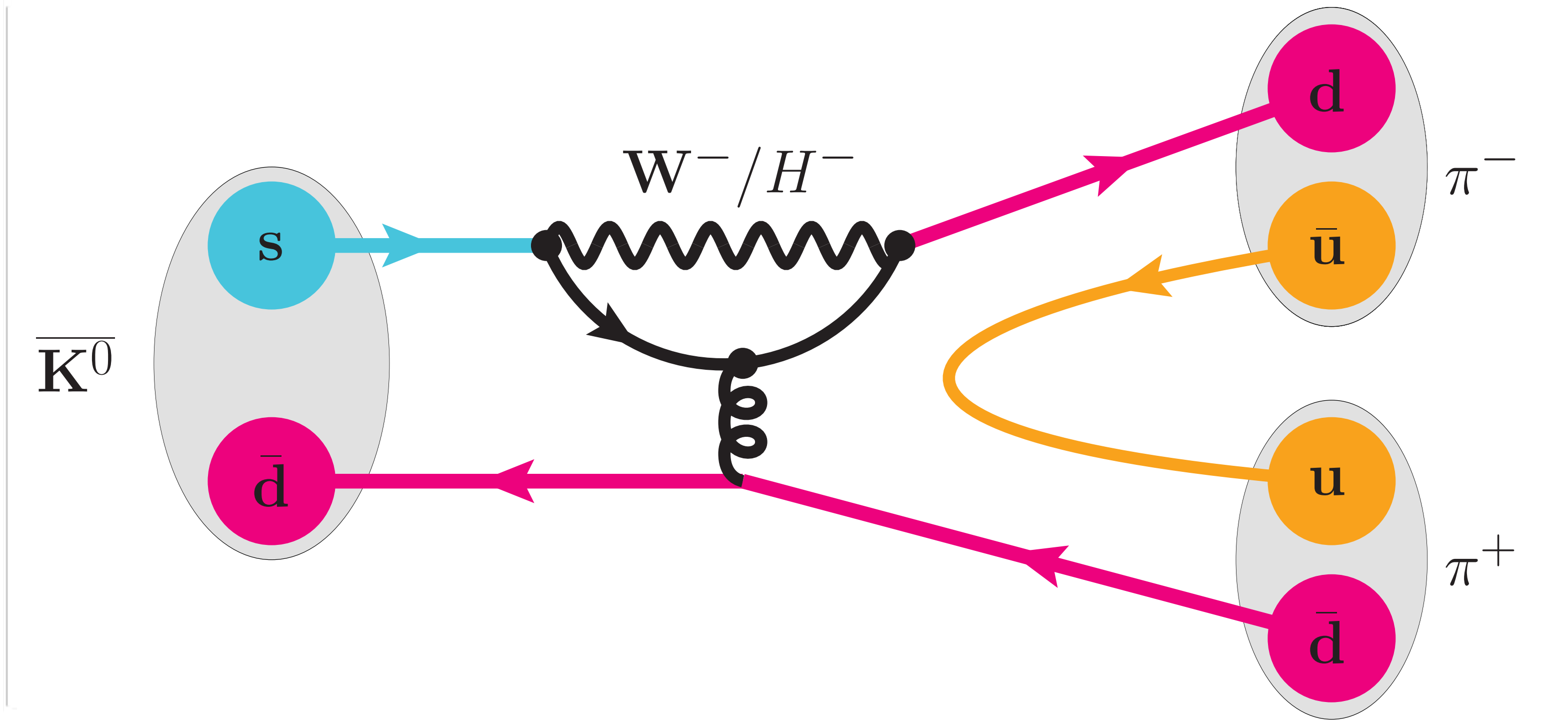
Combination with measurement of indirect CP violation in kaon system (ε_K) **constrains CKM phase**





K→ππ decays

See Kelly Lattice 2015 Review



- Sensitive to new particles, interactions, sources of CP violation
- "ΔI=1/2 rule": empirically observe enhancement $\mathrm{Re}A_0/\mathrm{Re}A_2 \simeq 22.5$

✦ Describe ΔS=1 FCNC transitions with effective Hamiltonian

$$\mathcal{H}_{\rm eff}(\Delta S=1) = \frac{G_F}{\sqrt{2}} \sum_{i=1}^{10} \Big(V_{us}^* V_{ud}\, z_i(\mu) - V_{ts}^* V_{td}\, y_i(\mu) \Big) Q_i(\mu)$$

- ❖ Short-distance effects factorized in Wilson coefficients → continuum perturbation theory
- ❖ Long-distance effects factorized in **matrix elements** $\langle\pi\pi|Q_i|K\rangle$ → **lattice QCD**

✦ New physics above EW scale modifies Wilson coefficients, but hadronic matrix elements remain the same

New! K → ππ matrix elements

- **Lattice complication:** additional Lüscher formalism needed to relate amplitudes calculated in Euclidean box to physical observables in Minkowski space [Briceño review, PoS LATTICE2014 (2015) 008]
- **First complete three-flavor K → ππ amplitudes with controlled errors using domain-wall (chiral) fermions**
- Also first Wilson-fermion results from Ishizuka et al. [arXiv:1505.05289] with heavy, zero-momentum pions

Emerging explanation of ΔI=1/2 rule:
Significant cancellation between dominant contributions to Re(A_2) which does not occur for Re(A_0)

ΔI=3/2 amplitude (A_2)

[RBC/UKQCD, PRDD91 (2015) 7, 074502]

- Physical-mass pions, continuum limit, and approximately physical kinematics
- → **~10% errors on Re(A_2), Im(A_2)**
- Dominant uncertainty from perturbative truncation error in continuum Wilson coefficients

ΔI=1/2 amplitude (A_0)

[RBC/UKQCD, arXiv:1505.07863]

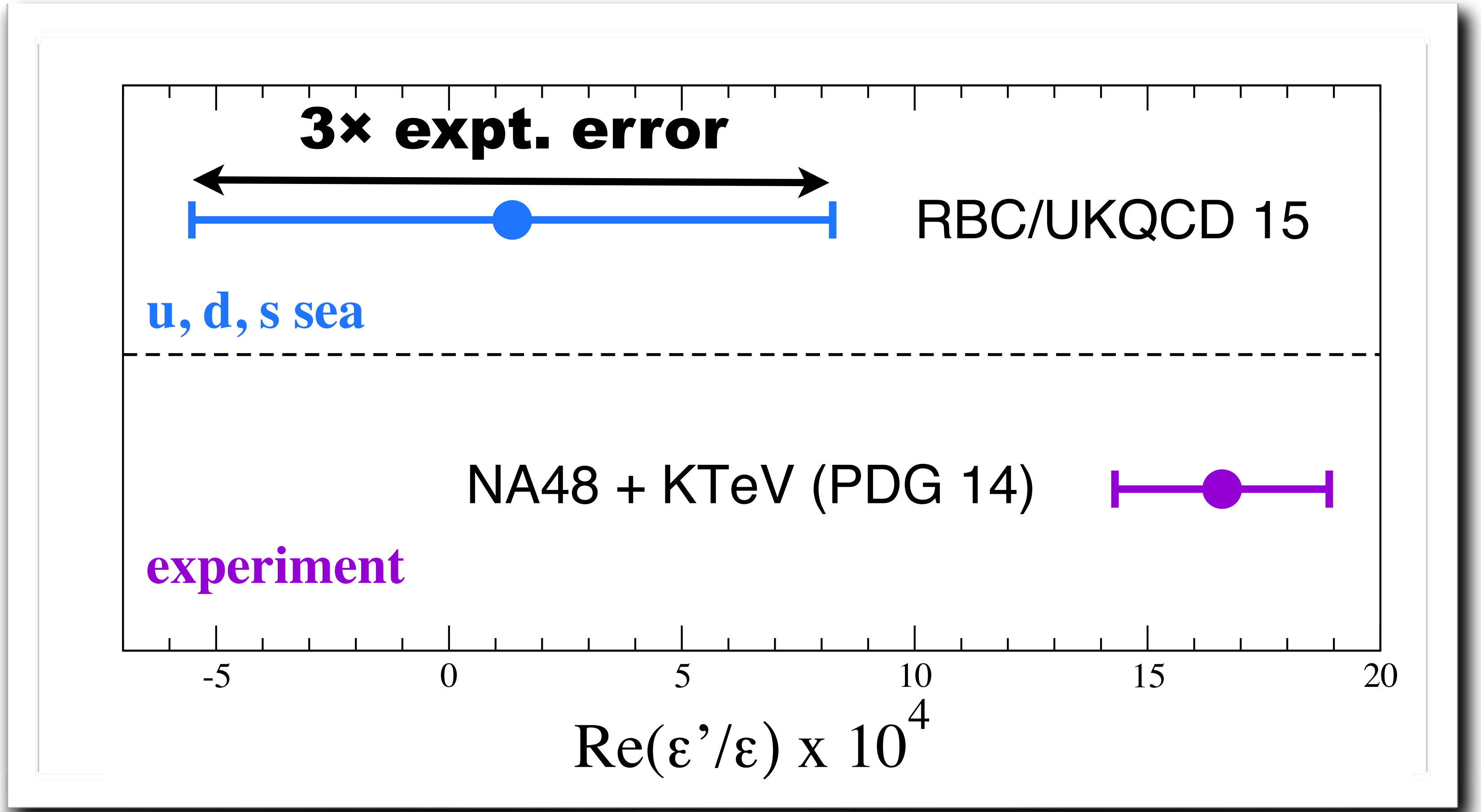
- 170 MeV pions with physical kinematics
- Small spatial volume $m_\pi L \approx 3.2$ and single lattice spacing a~0.14 fm
- → **~35% error on Re(A_0)**
- Will be reduced with higher statistics, larger volumes, continuum limit, ...

New! Re(ε'/ε) in the Standard Model

[RBC/UKQCD, arXiv:1505.07863]

- Measures direct CP violation in K → ππ decays

$$\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right) \approx \frac{1}{6}\left[\frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)} - 1\right]$$



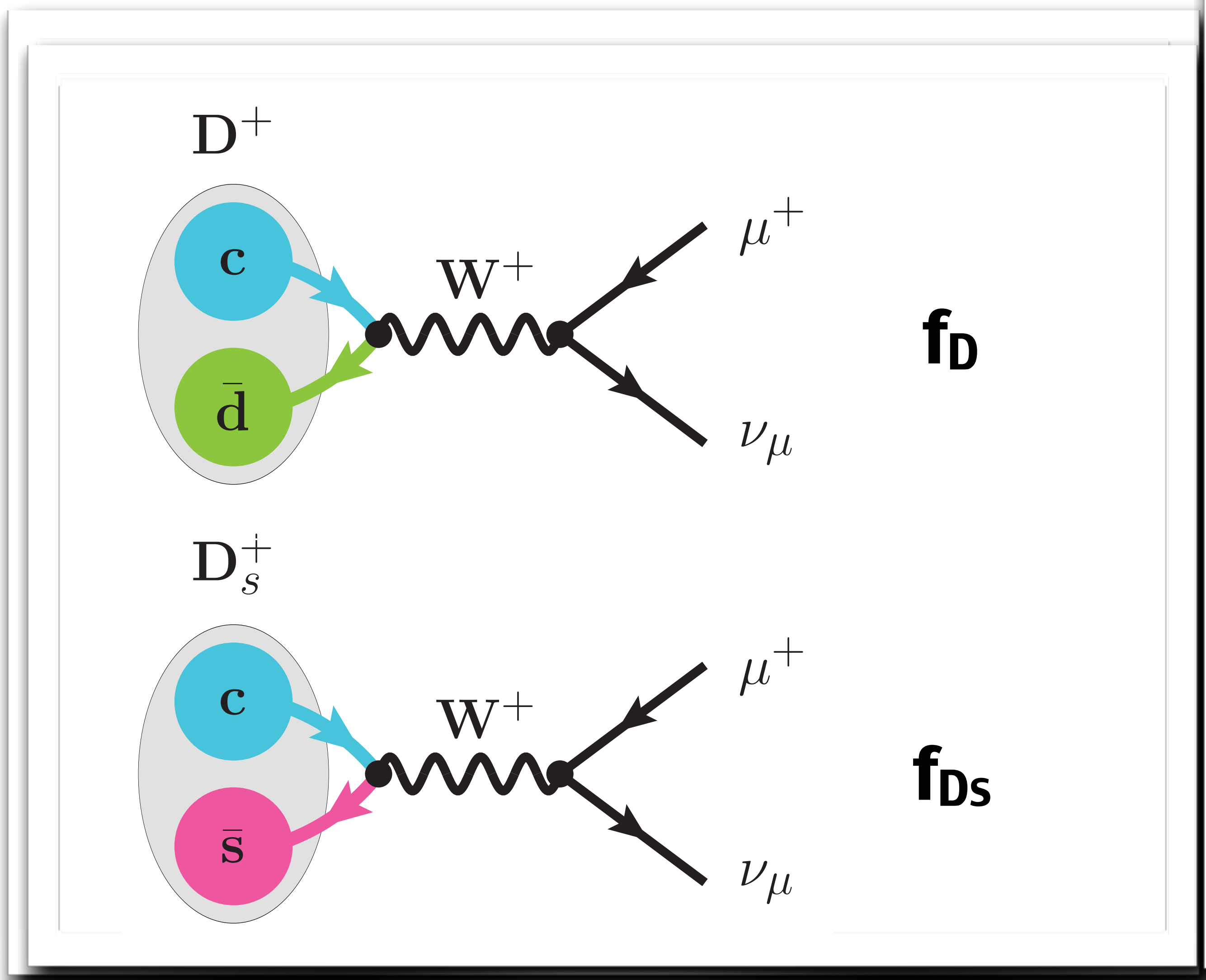
- Lattice Im(A_0,A_2) + experimental Re(A_0,A_2) **→ first Re(ε'/ε) in Standard Model with controlled errors**

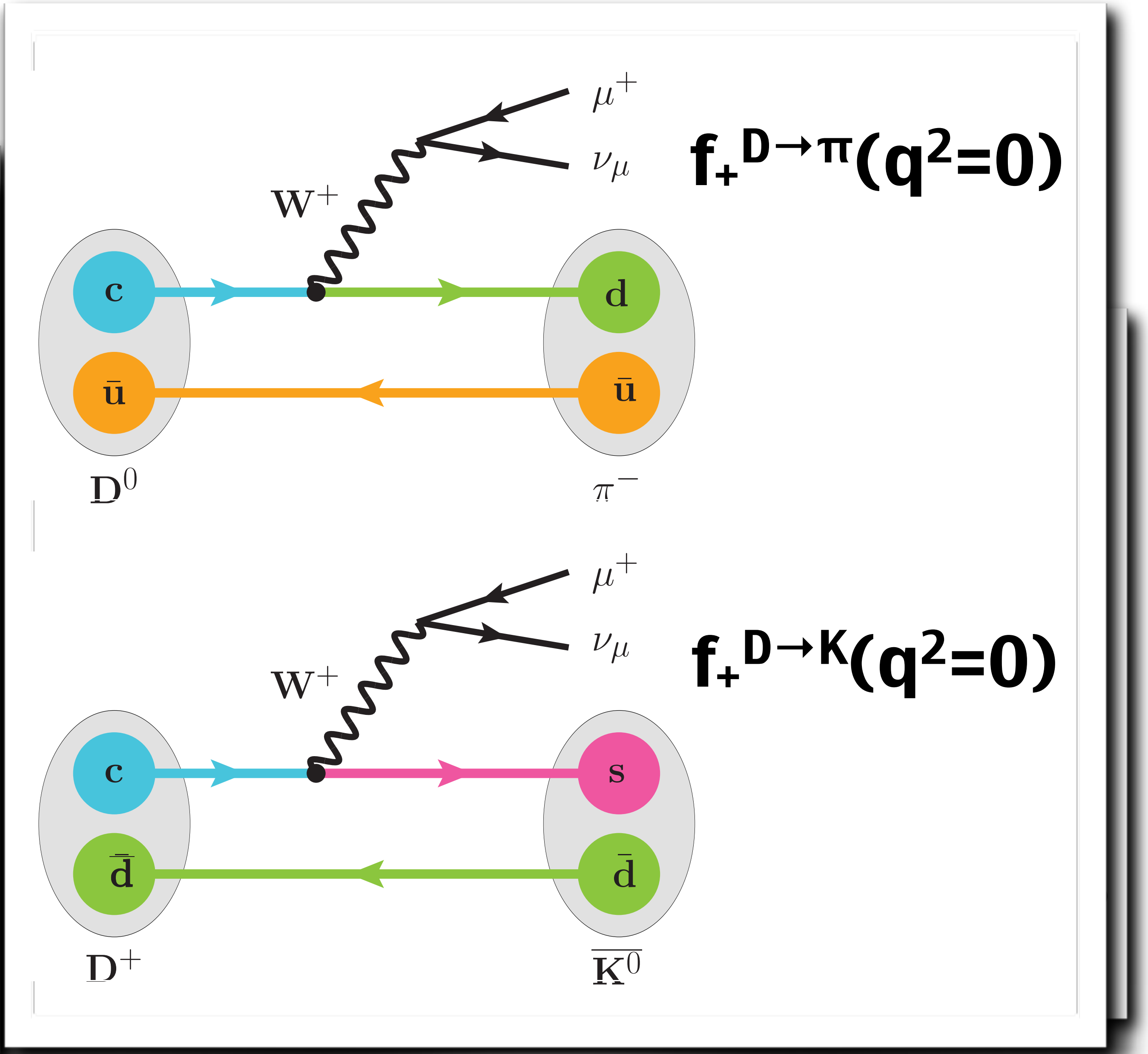
Lattice-QCD calculation of Re(ε'/ε) with ~10% uncertainty achievable in the forseeable future!

D-meson summary

See Pena Lattice '15 &
Bouchard Lattice '14 heavy-flavor reviews

- Small errors due to
  - Physical light-quark masses
  - Improved charm-quark actions + fine lattice spacings
  - No renormalization (PCAC)





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- Small errors due to
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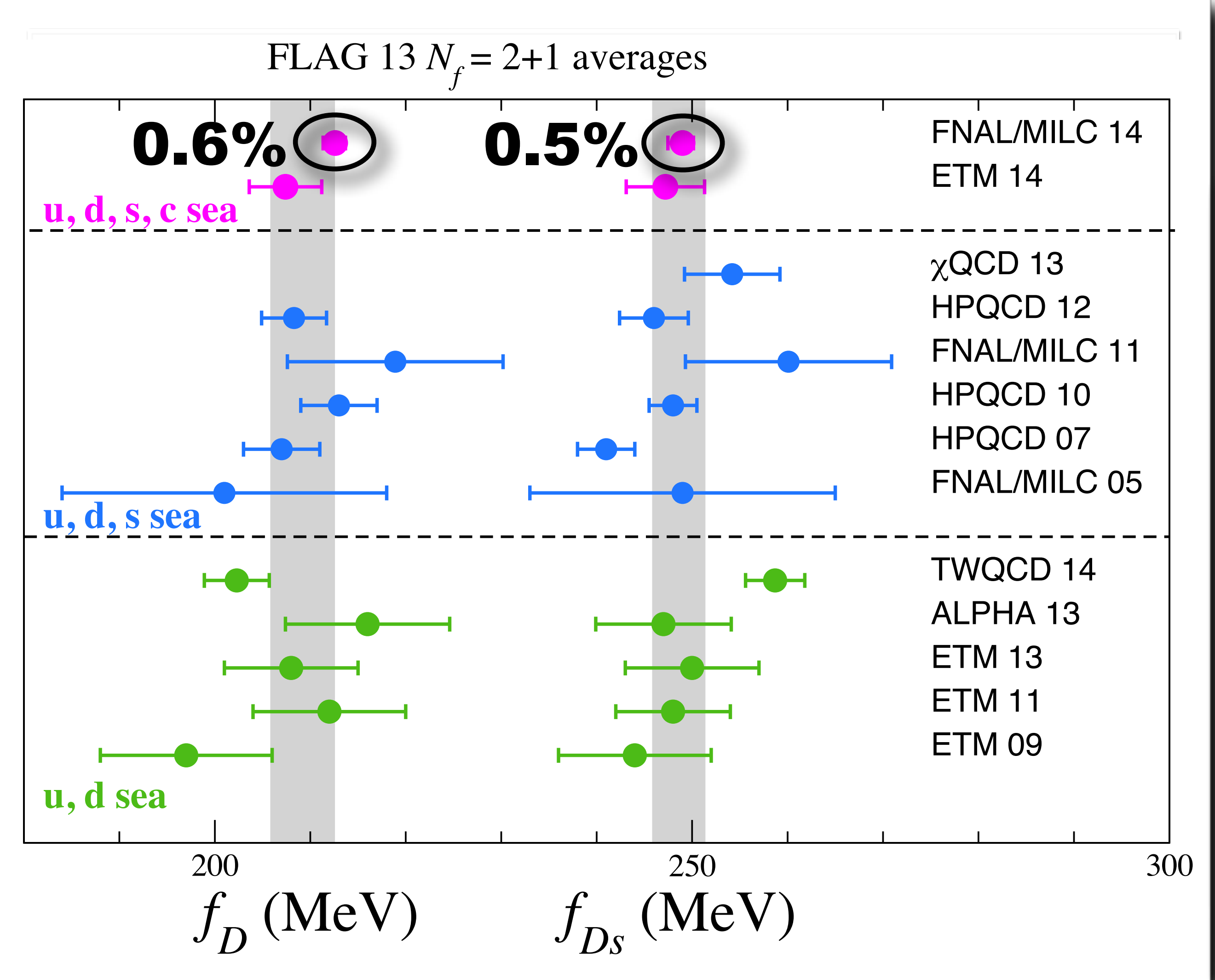
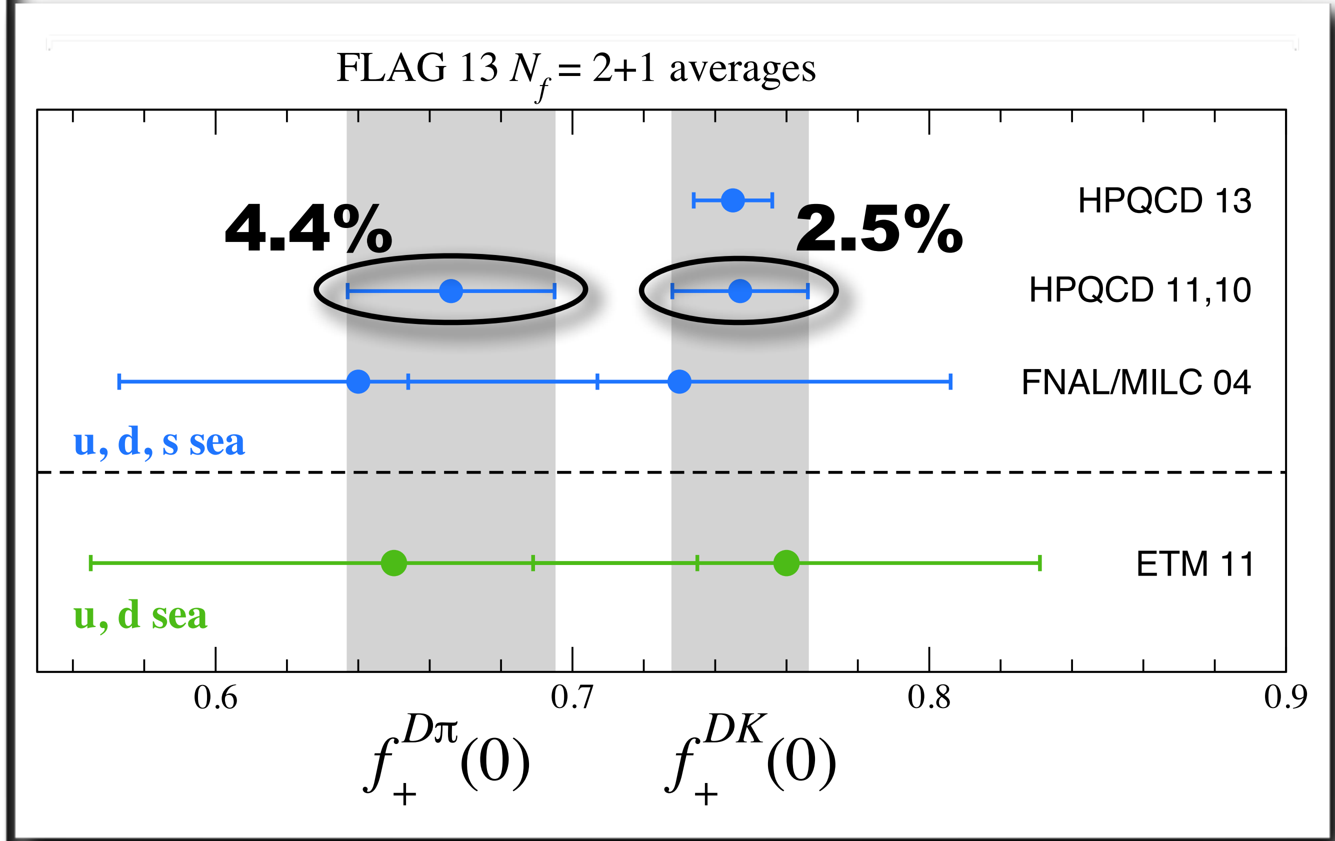
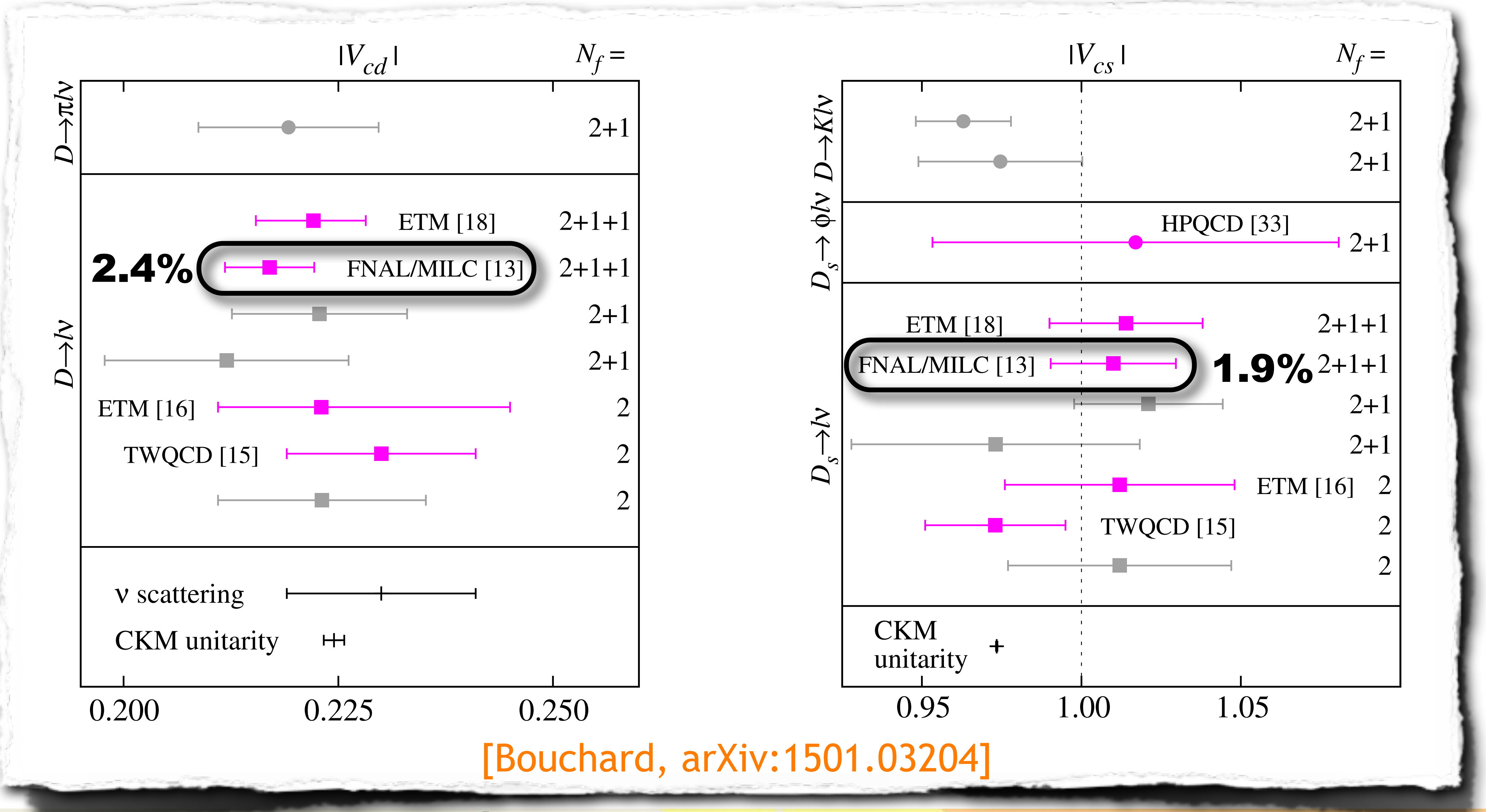
- *Recent highlights:*
- First 3-flavor $D_s \to \varphi l \nu$ form factors [HPQCD, PRD90 (2014) 7, 074506]
- First 4-flavor D-mixing matrix elements (all five $\Delta C=2$ SM & BSM operators, only short-distance contributions) [ETM, 1505.06639]





Implications for 2nd row of CKM matrix

- **$|V_{cd}|$ & $|V_{cs}|$ from leptonic $D_{(s)}$ decays limited by experimental errors**
- Slight tension between $|V_{cs}|$ from leptonic & semileptonic decay



[Bouchard, arXiv:1501.03204]

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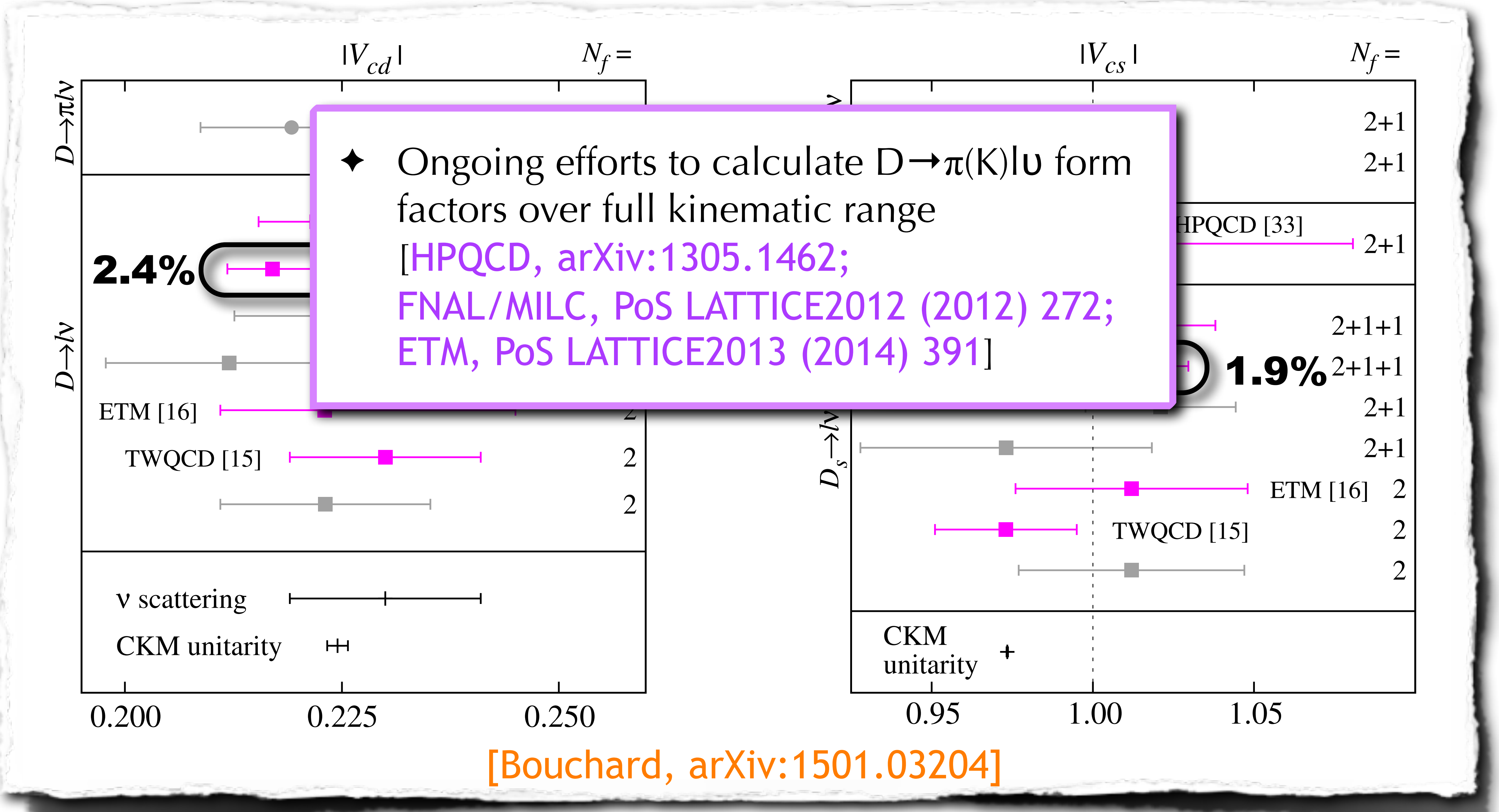


- Ongoing efforts to calculate $D\to\pi(K)l\nu$ form factors over full kinematic range [HPQCD, arXiv:1305.1462; FNAL/MILC, PoS LATTICE2012 (2012) 272; ETM, PoS LATTICE2013 (2014) 391]

[Bouchard, arXiv:1501.03204]

New! Neutral B-mixing matrix elements

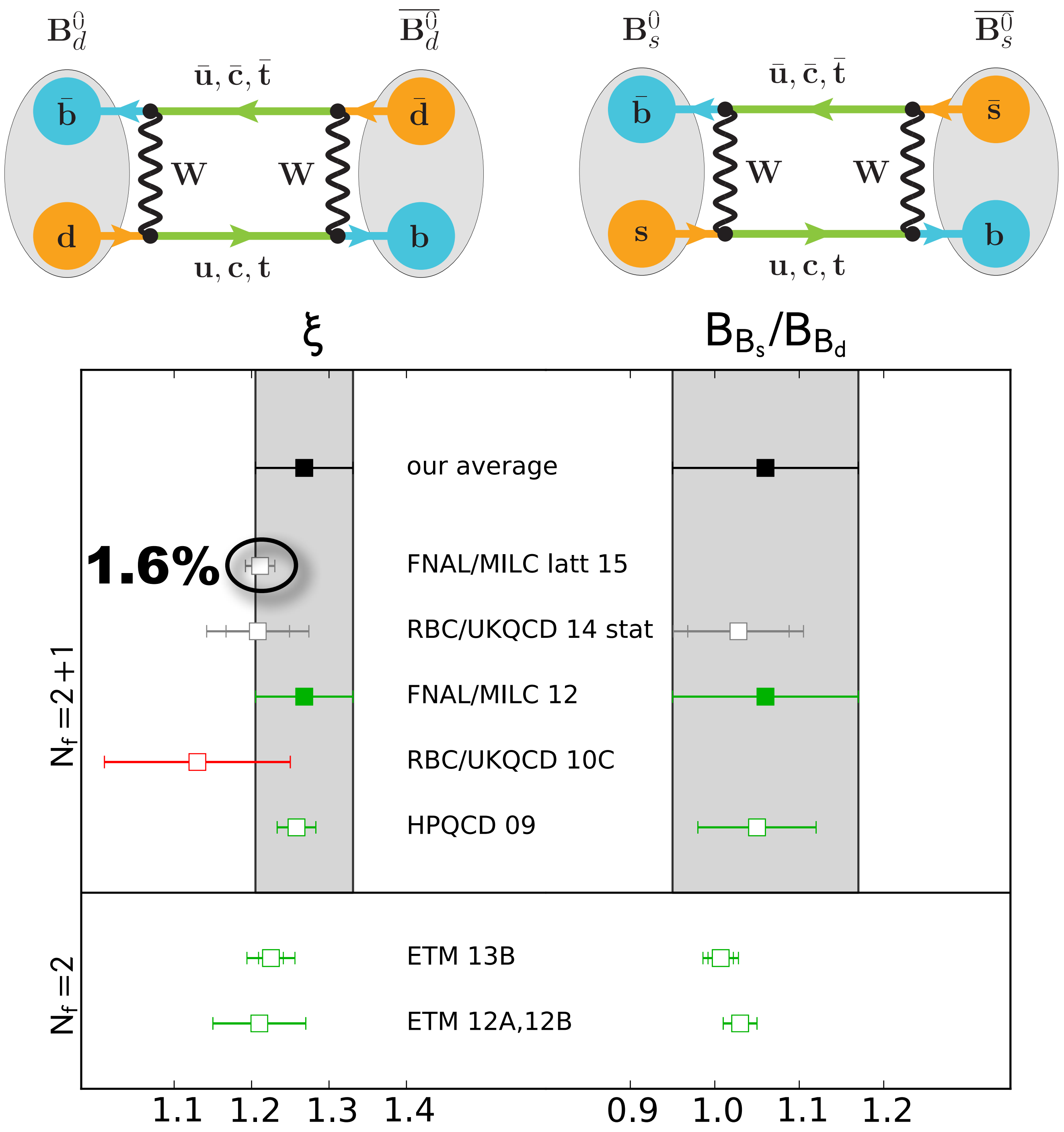
[Bouchard, Freeland, *et. al* [FNAL/MILC], *presented at Lattice 2015*]

Combination with measurement of B_d/B_s oscillation frequencies constrains apex of CKM unitarity triangle

- **Matrix-element ratio $\xi \equiv f_{B_d}\,\mathrm{Sqrt}[B_{B_d}]/f_{B_s}\,\mathrm{Sqrt}[B_{B_s}]$ can be computed precisely because:**
  - Statistical fluctuations correlated
  - B_d & B_s matrix elements equal in SU(3) limit, so some systematics suppressed by $(m_s - m_{ud})/\Lambda_{QCD}$
- Preliminary FNAL/MILC calculation with increased statistics, lighter quark masses, & finer lattice spacings

$$\xi = 1.211(19) \Rightarrow$$

$$|V_{td}|/|V_{ts}| = 0.2069(6)_{\mathrm{exp}}(32)_{\mathrm{LQCD}}$$



[figure from Pena, Lattice 2015]

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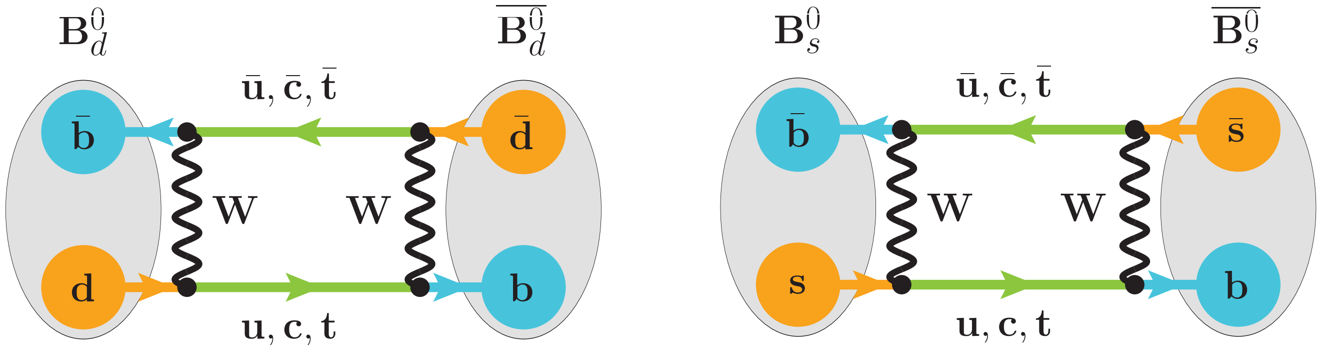
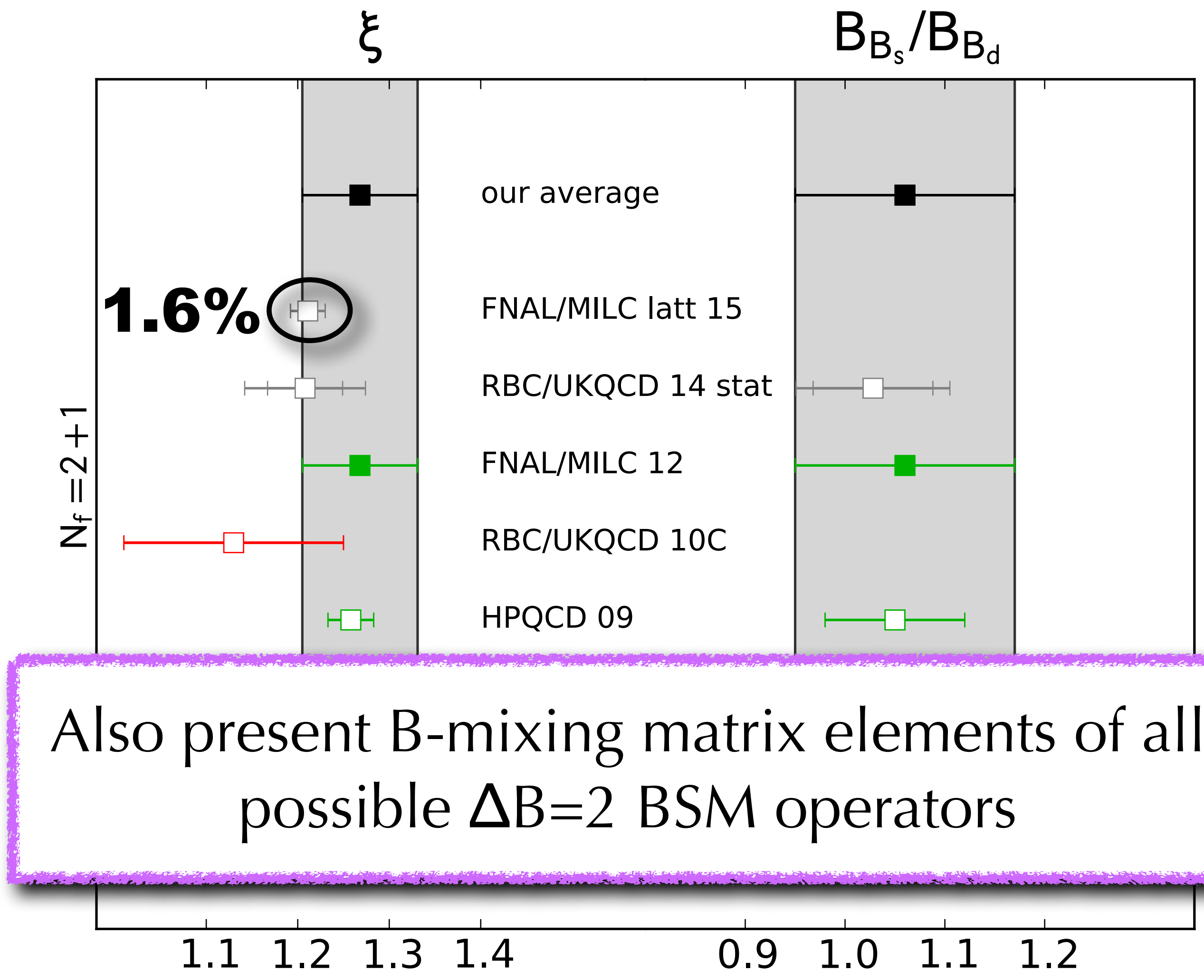




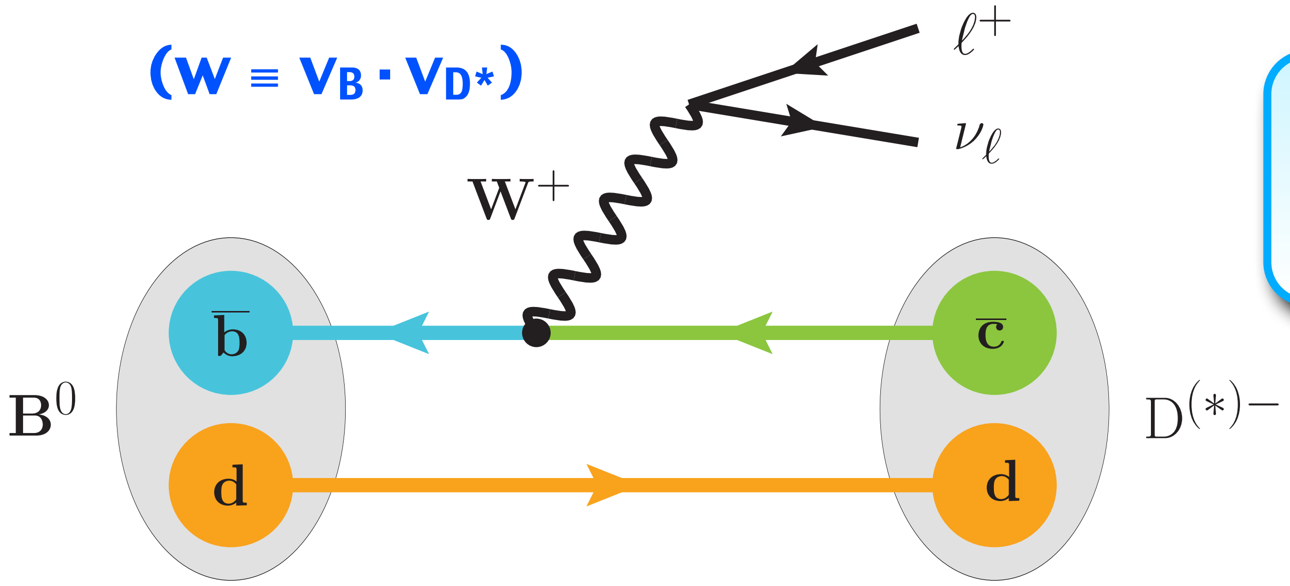
Also present B-mixing matrix elements of all possible ΔB=2 BSM operators

[figure from Pena, Lattice 2015]

New! $B \to D^* \ell \nu$ form factor @ zero recoil

[Bailey *et al.* [FNAL/MILC], PRD89 (2014) 11, 114504]

- Only need one normalization point from lattice QCD ➜ **choose zero recoil (w=1) where it can be computed most precisely**
  - $F(1) \to 1$ in the static limit ($m_b = m_c \to \infty$) [Isgur & Wise], and Luke's theorem ensures that the leading heavy-quark corrections to F(1) are of $\mathcal{O}(1/m_b^2, 1/m_c^2)$
  - Can compute form factor using double ratio of lattice three-point correlation functions in which statistical and systematic errors largely cancel
- New FNAL/MILC calculation with increased statistics, lighter quark masses, & finer lattice spacings ➜ **1.4% precision on F(1)**

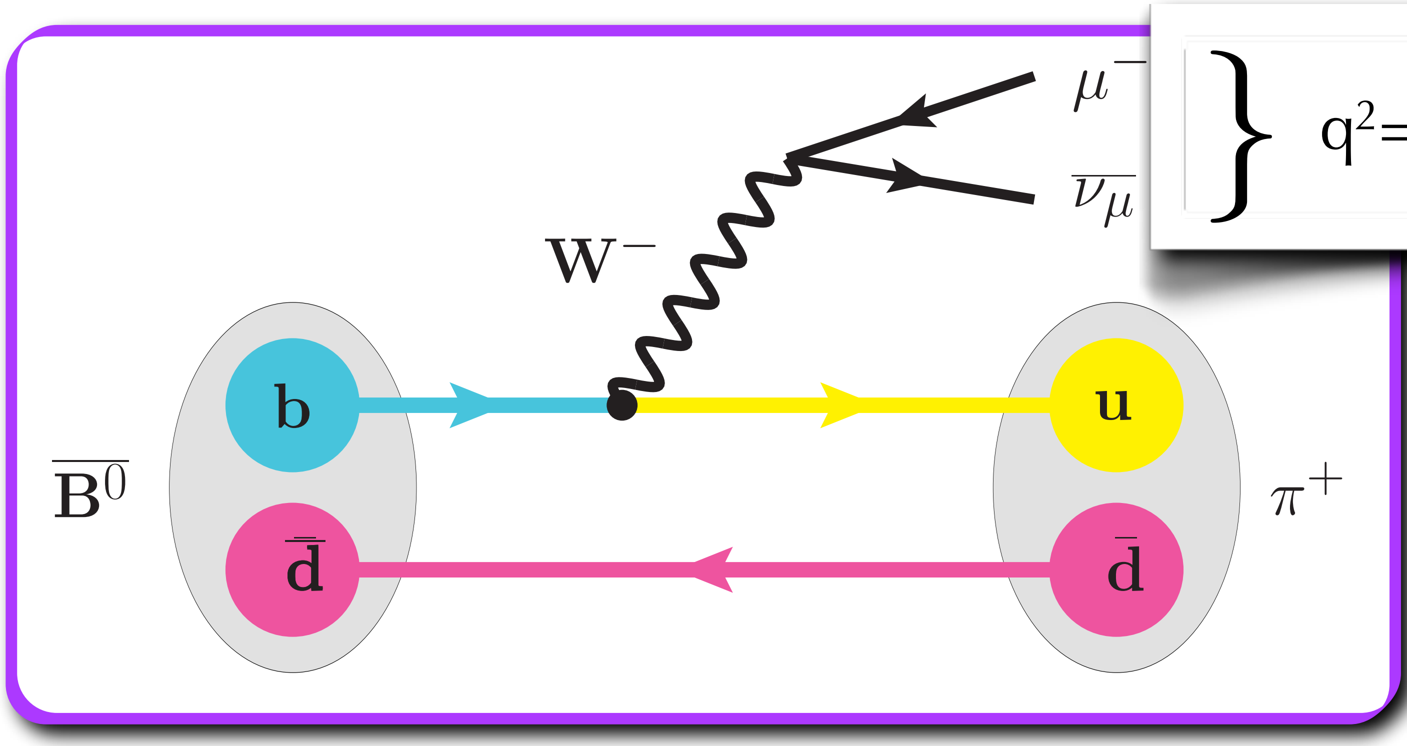


($w \equiv v_B \cdot v_{D^*}$)

Combination with experimental rate enables **$|V_{cb}|$ determination**

$F(1) = 0.906(4)_{\text{stat}}(12)_{\text{sys}}$

$|V_{ub}|$ from $B \to \pi \ell \nu$ decay



$$\Big\}\ q^2=(m_B^2+m_\pi^2-2m_BE_\pi)^2$$

- $B \to \pi \ell \nu$ semileptonic decay enables determination of $|V_{ub}|$ via:

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

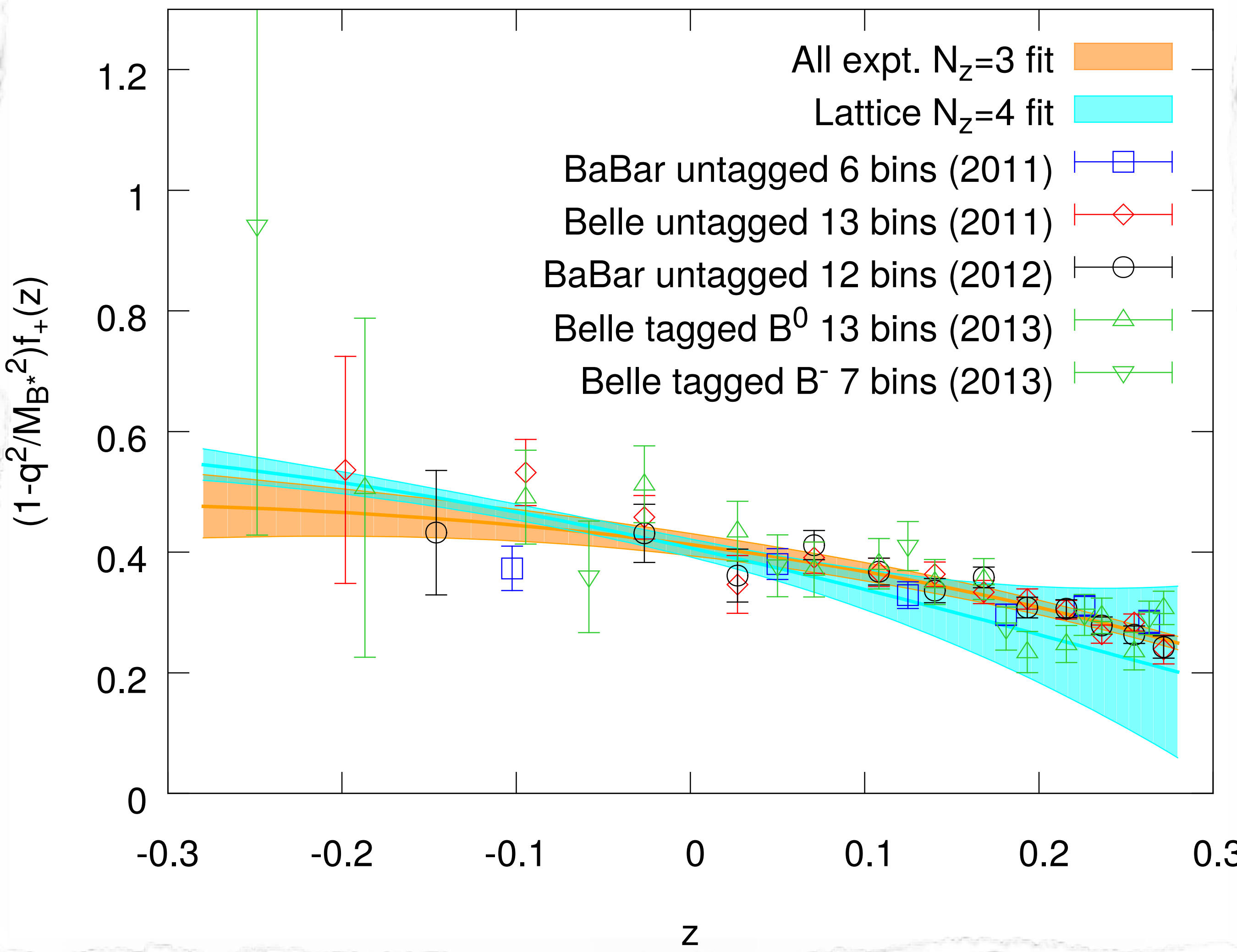
- **Few percent determination of exclusive $|V_{ub}|$ challenging because:**
  - Lattice statistical & discretization errors grow with increasing pion momentum ➜ determination of **hadronic form factor $f_+(q^2)$** best at large momentum-transfer (q^2)
  - Experimental branching fraction most precise at low q^2

Lattice + experiment fit for $|V_{ub}|$

- Fit lattice-QCD and experimental data together to model-independent parameterization ("z-expansion") based on analyticity, unitarity, and crossing symmetry [Boyd, Grinstein, Lebed, PRL74, 4603 (1995); Bourrely, Caprini, Lellouch, PRD79 (2009) 013008]
- Relative normalization ($|V_{ub}|$) free parameter determined in fit
- Combined fit to Belle, BaBar, and 2015 FNAL/MILC lattice data yields $|V_{ub}|$ with a 4.3% uncertainty:

$$|V_{ub}| = 3.72(16) \times 10^{-3}$$

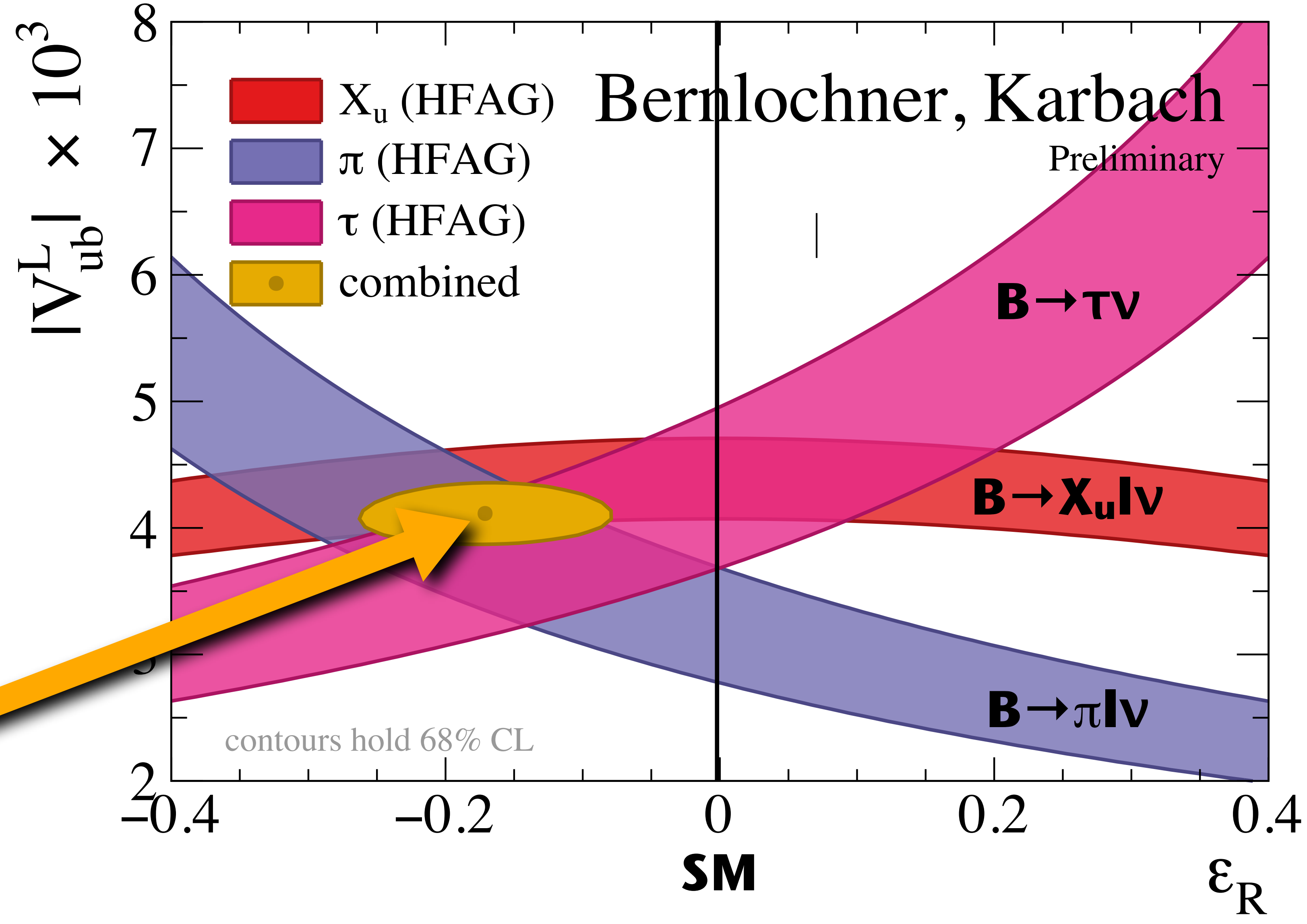
[FNAL/MILC], arXiv:1503.07839]



Use of all experimental & theoretical information minimizes error in $|V_{ub}|$

A sign of new physics?

- Can ease $|V_{ub}|$ tension by allowing small right-handed contribution to Standard-Model weak current [Crivellin, PRD81 (2010) 031301]

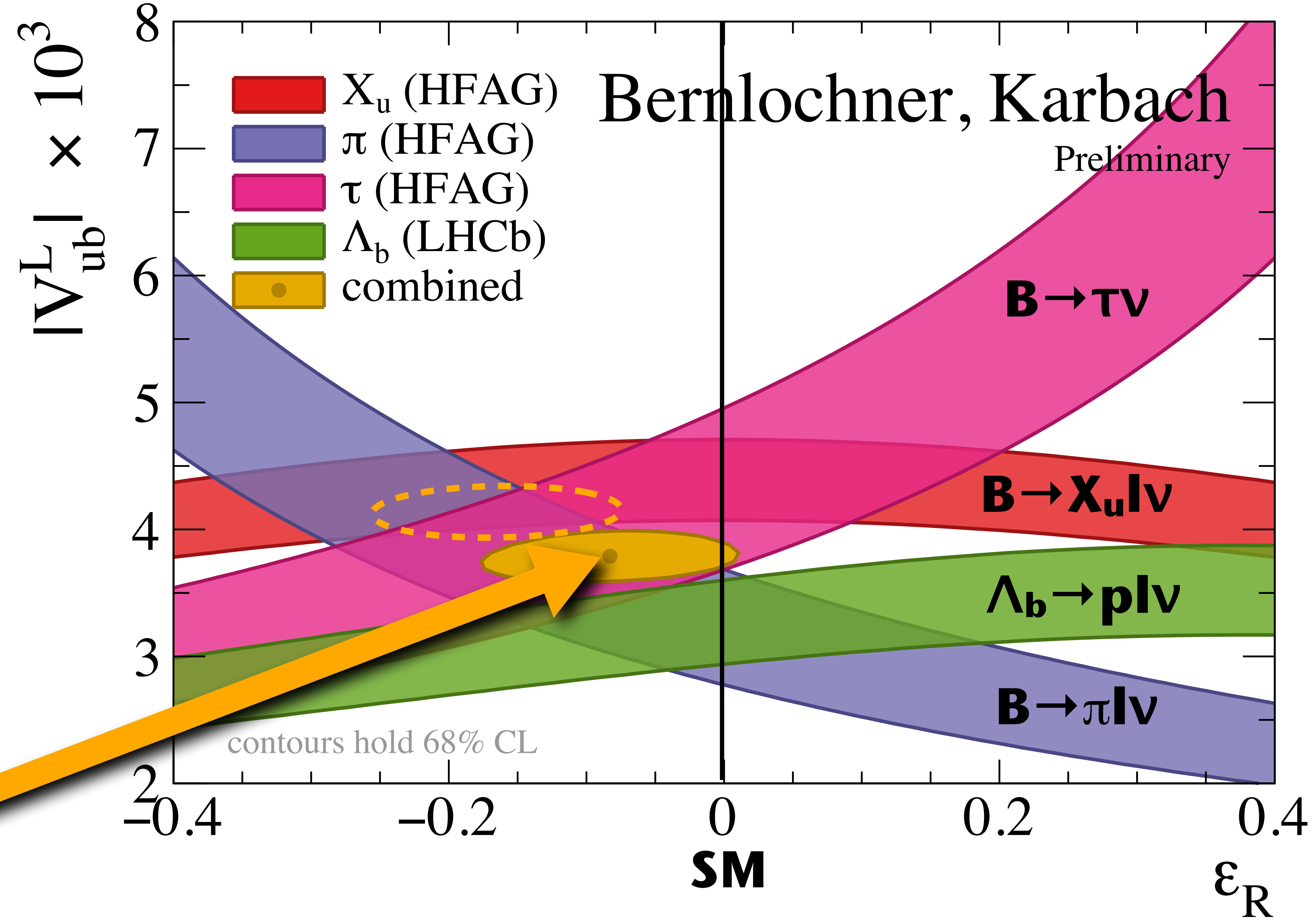


~15% admixture of RH current

[based on Bernlochner *et al.*, PRD 90, 094003 (2014)]

A sign of new physics?

- Can ease $|V_{ub}|$ tension by allowing small right-handed contribution to Standard-Model weak current [Crivellin, PRD81 (2010) 031301]
- RH currents disfavored by Λ_b decays (taking $|V_{cb}|$ from $B \to D^* l\nu$ + HFAG to obtain $|V_{ub}|$)

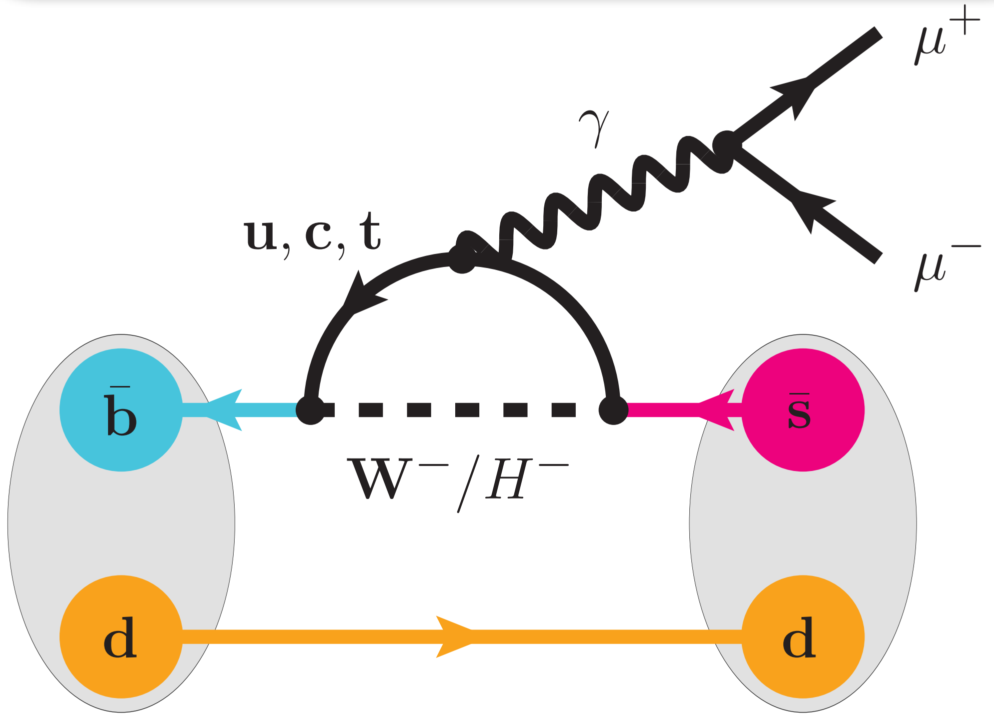


p=0.03

[based on Bernlochner *et al.*, PRD 90, 094003 (2014)]

New! $B \to K^{(*)}\ell^+\ell^-$ form factors

b→s flavor-changing neutral-current processes **sensitive to new particles & interactions**



- First three-flavor lattice form factors
- Enable predictions of observables (decay rate, forward-backward asymmetry, ...) in Standard Model & all BSM theories

$B \to Kl^+l^-$

[HPQCD, PRD88 (2013) 054509]

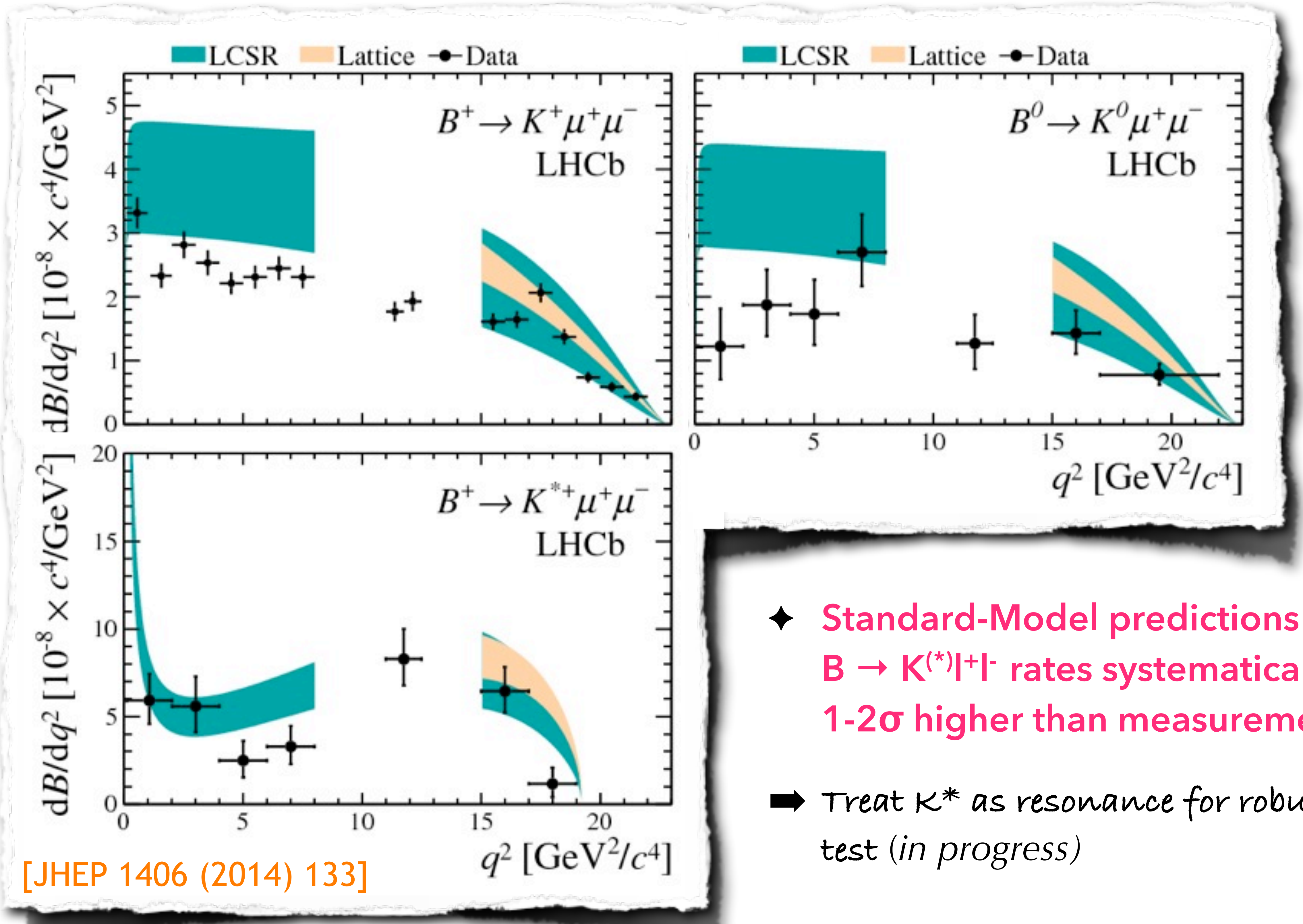
- Vector, scalar, and tensor form factors
- Use model-independent z-expansion to extend results over full q^2 range

$B_{(s)} \to K^*$ and $B_s \to \varphi$

[Horgan *et al.*, PRDD89 (2014) 9, 094501]

- Conference update [arXiv:1501.00367] includes correlations between form factors through kinematic constraints
- Use modified z-expansion to extend results over full q^2 range
- *Caveat: K* and φ treated as stable hadrons in simulations

Implications for new-physics searches

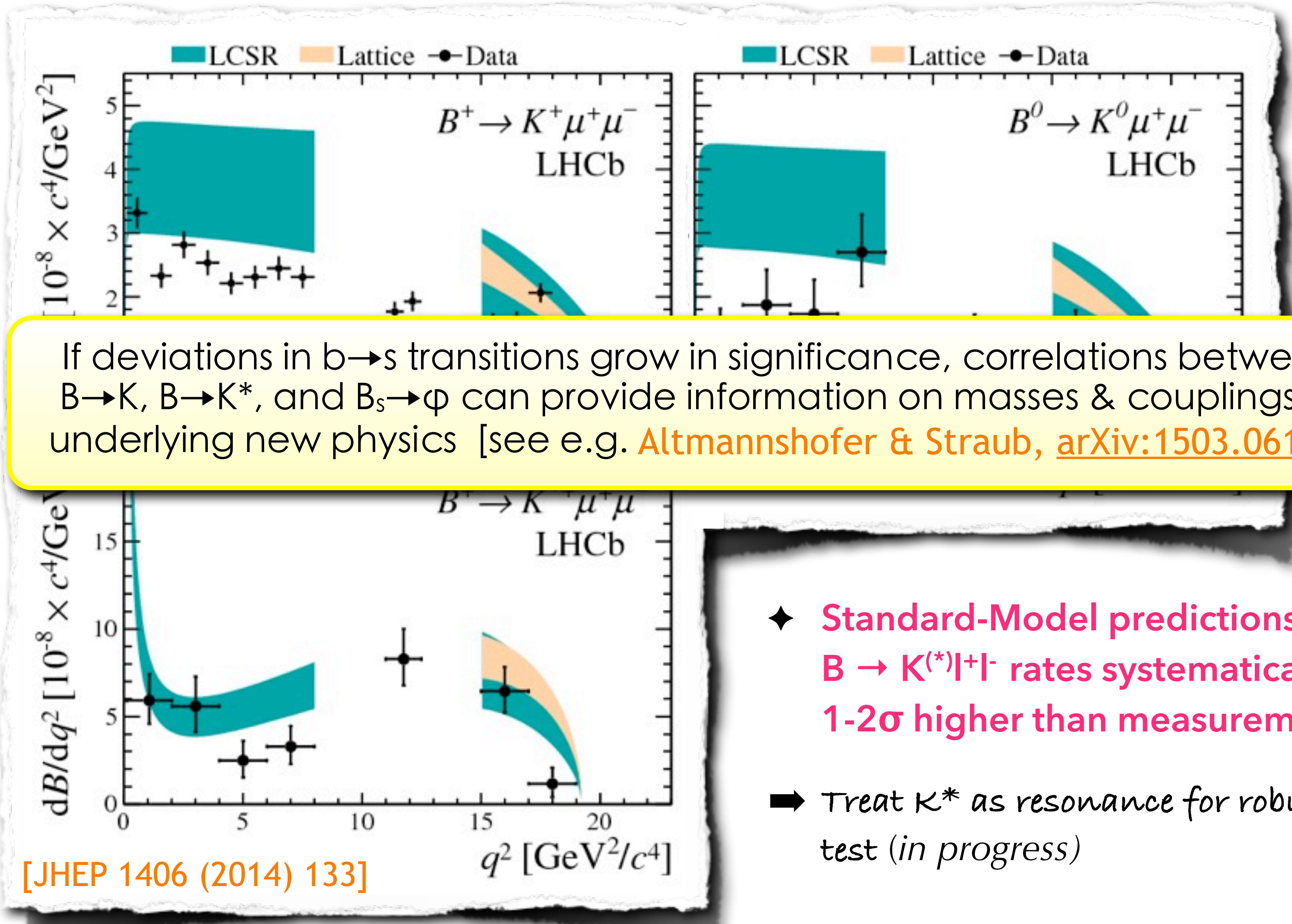


[JHEP 1406 (2014) 133]

- **Standard-Model predictions for B → $K^{(*)}l^+l^-$ rates systematically 1-2σ higher than measurements**

➡ Treat K* as resonance for robust test *(in progress)*

Implications for new-physics searches



[JHEP 1406 (2014) 133]

If deviations in b→s transitions grow in significance, correlations between B→K, B→K*, and B_s→φ can provide information on masses & couplings of underlying new physics [see e.g. Altmannshofer & Straub, arXiv:1503.06199]

- ✦ **Standard-Model predictions for B → $K^{(*)}l^+l^-$ rates systematically 1-2σ higher than measurements**

➡ Treat K* as resonance for robust test *(in progress)*

$B_s \rightarrow \mu^+\mu^-$ decay

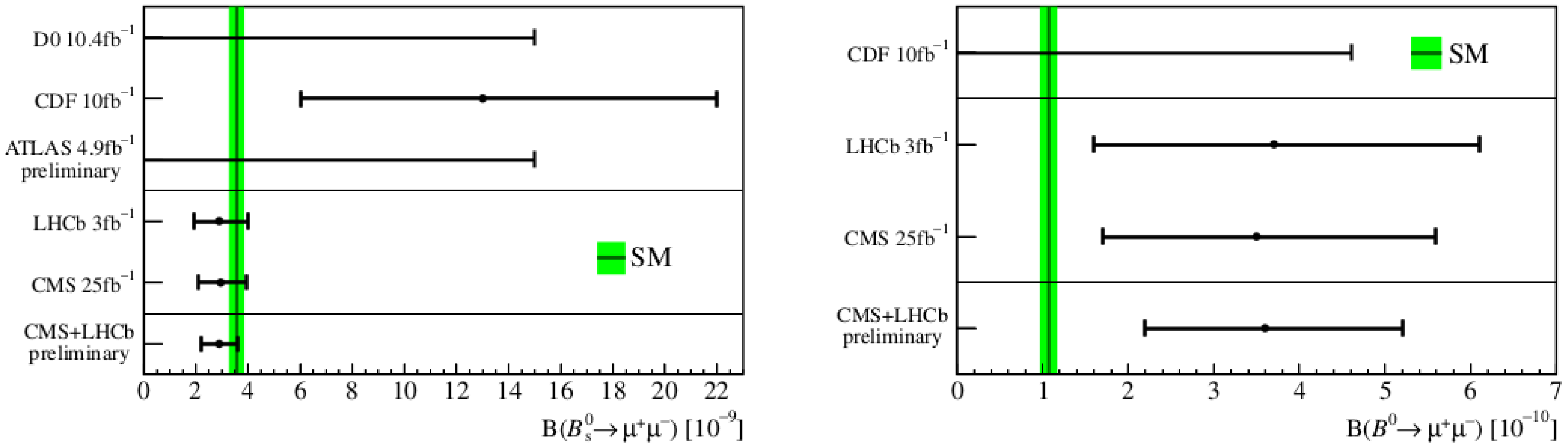
Combined LHCb + CMS Result

new @ EPS2013

Observation:

BR$(B_s \rightarrow \mu^+\mu^-)$ = $(2.9 \pm 0.7) \times 10^{-9}$

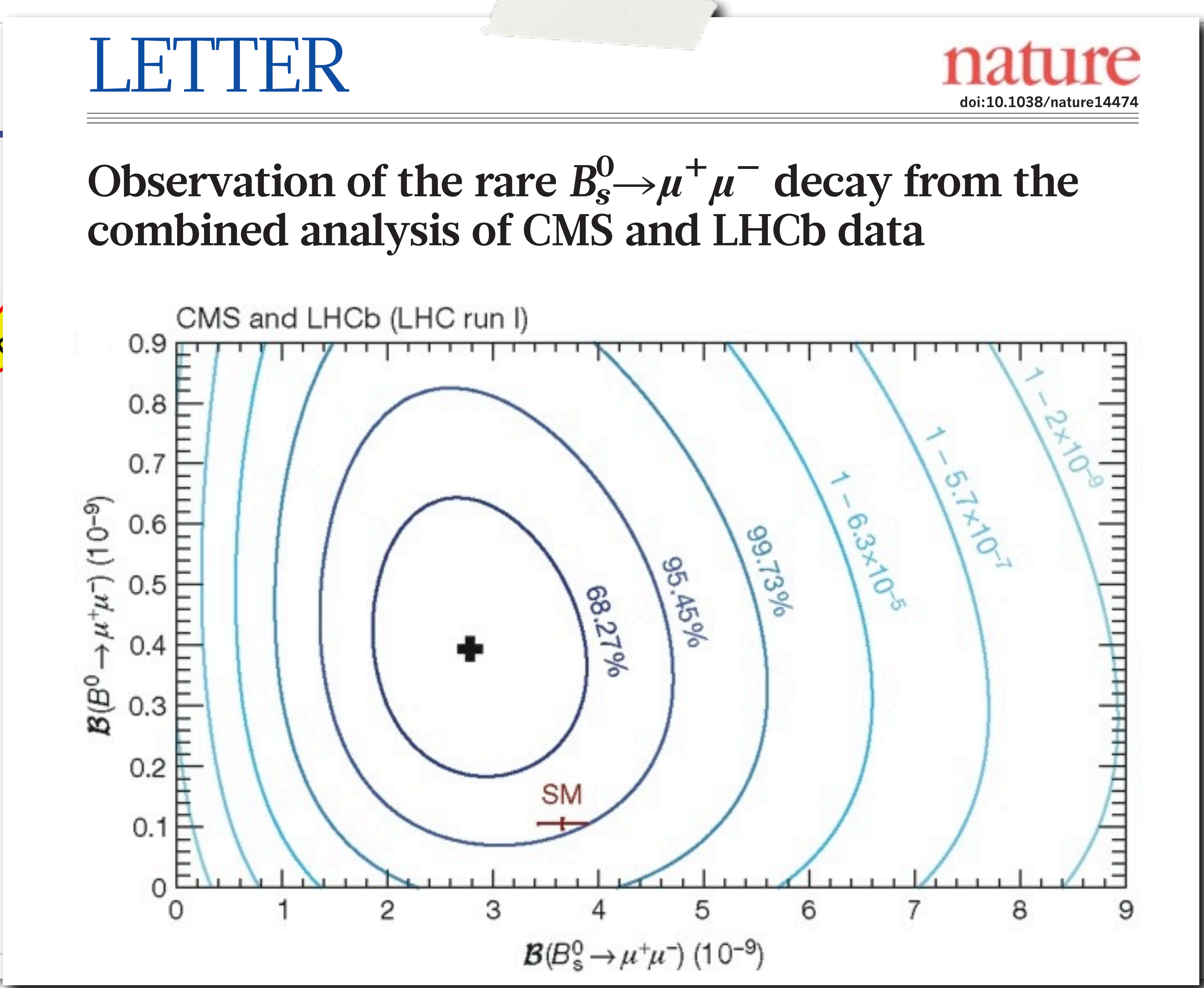
BR$(B^0 \rightarrow \mu^+\mu^-)$ = $3.6^{+1.6}_{-1.4} \times 10^{-10}$



LHCb-CONF-2013-012, CMS-PAS-BPH-13-007

[S. Hansmann-Menzemer, EPS 2013]

$B_s \to \mu^+\mu^-$ decay



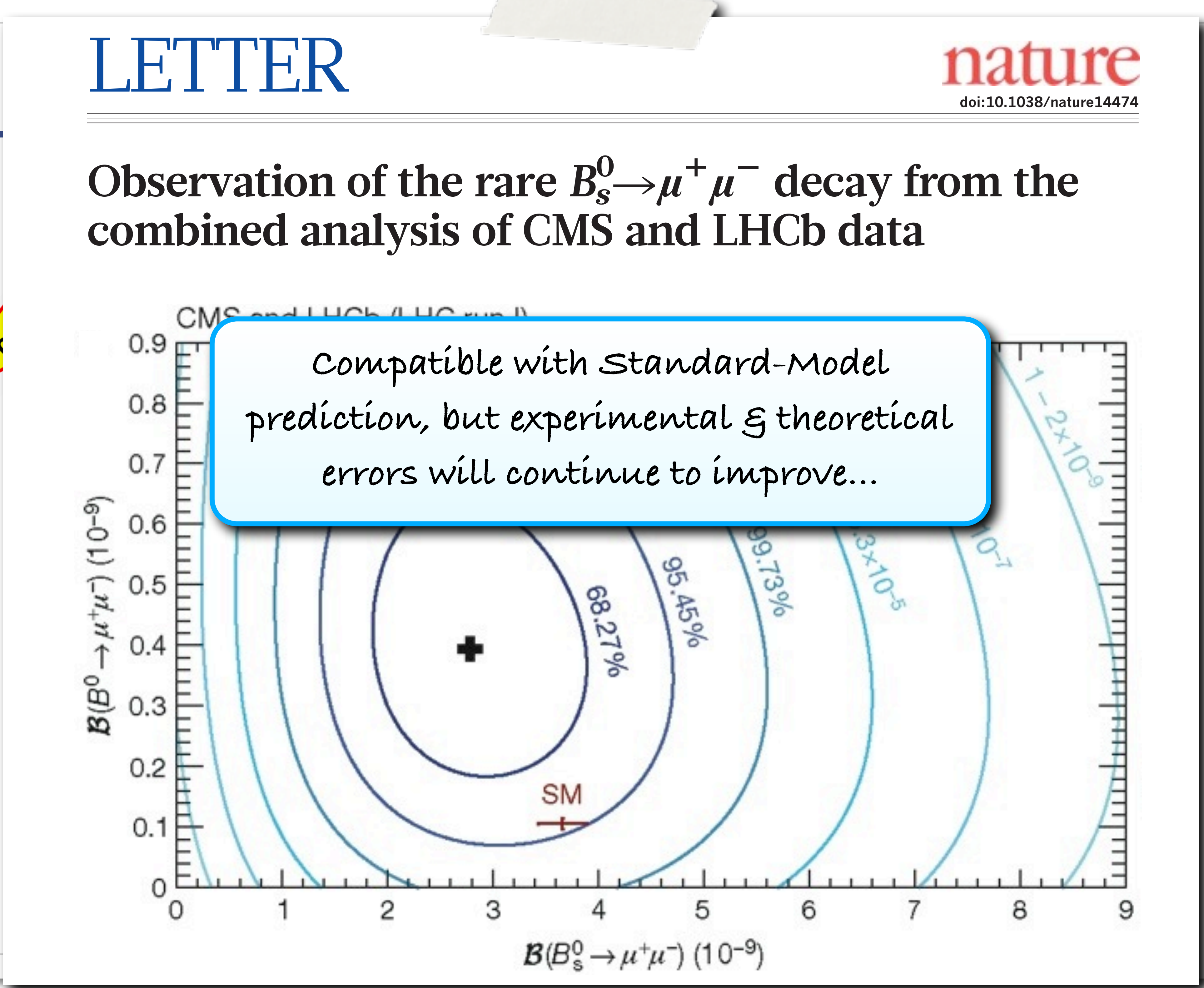
LETTER

nature

doi:10.1038/nature14474

Observation of the rare $B_s^0 \to \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data

$B_s \to \mu^+\mu^-$ decay



LETTER

nature

doi:10.1038/nature14474

Observation of the rare $B_s^0 \to \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data

Compatible with Standard-Model prediction, but experimental & theoretical errors will continue to improve...

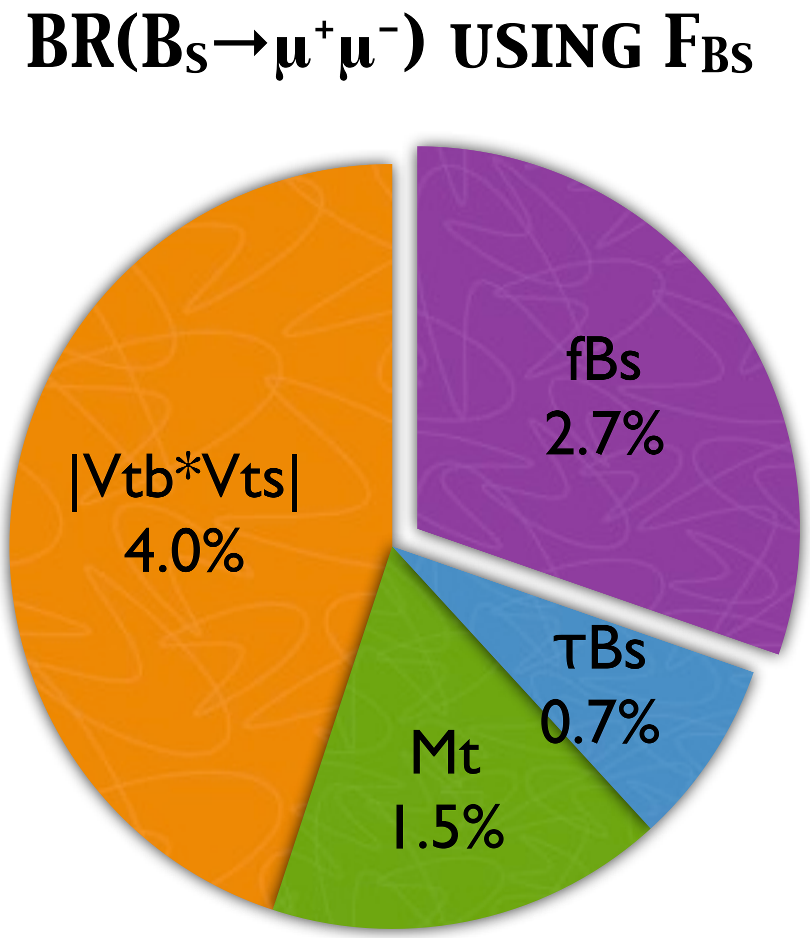
Standard-Model prediction for $B_s \to \mu^+\mu^-$

- Standard-Model rate proportional to **pseudoscalar decay constant f_{B_s}**

$$\Gamma(B_s \to \mu^+\mu^-) = \frac{G_F^2}{\pi}\, \underbrace{Y\left(\frac{\alpha}{4\pi \sin^2\Theta_W}\right)^2}_{\substack{\text{perturbative QCD} \\ \text{\& EW corrections}}} m_{B_s} \mathbf{f}_{B_s}^2 |V_{tb}^* V_{ts}|^2 m_\mu^2 \sqrt{1 - 4\frac{m_\mu^2}{m_B^2}}$$

- Current **uncertainty in Standard-Model prediction ~5% using 2011 lattice-QCD calculation of f_{B_s}** from HPQCD [McNiele *et al.*, PRD85 (2012) 031503]

- Error in f_{B_s} will continue to improve with analysis of data at even finer lattice spacings ➜ limited by error on $|V_{tb}^*V_{ts}|$ for foreseeable future

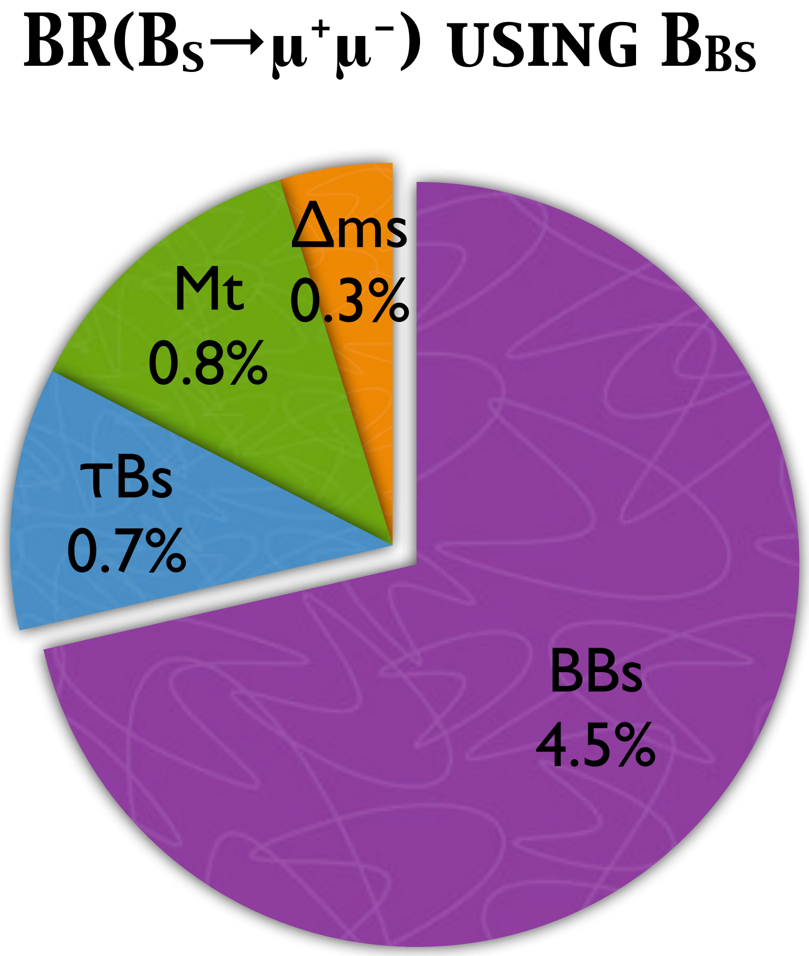


BR($B_s \to \mu^+\mu^-$) USING F_{B_s}

[Buras *et al.*, JHEP 1307 (2013) 77]

Standard-Model prediction for $B_s \to \mu^+\mu^-$

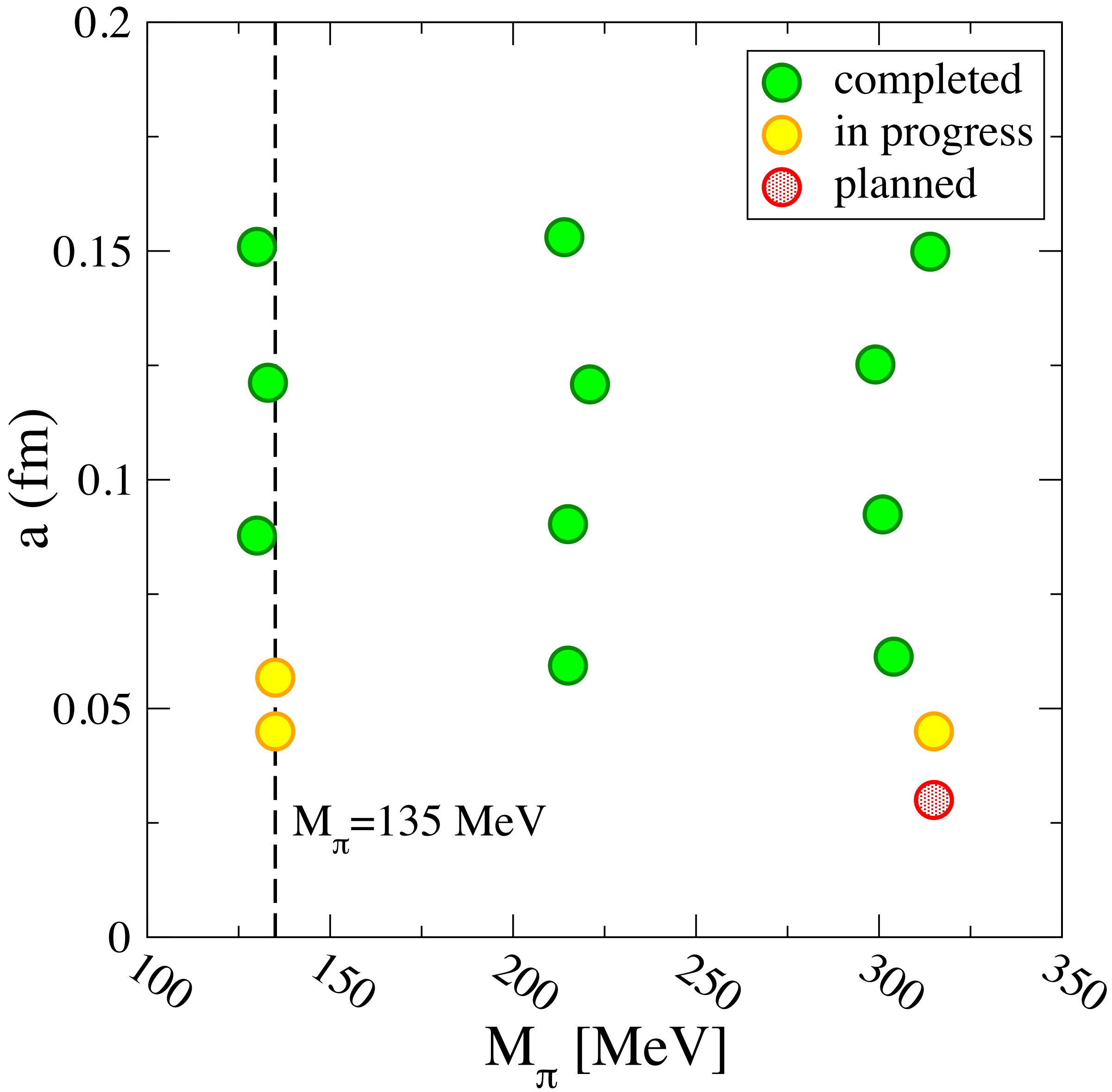
- ✦ Alternatively, can express Standard-Model rate in terms of oscillation frequency Δm_s and **hadronic matrix element B_{B_s}**
- ✦ Obtain similar precision for **uncertainty in Standard-Model prediction using 2009 lattice-QCD calculation of B_{B_s}** from HPQCD [Gamiz *et al.*, PRD80 (2009) 014503]
- ✦ Uncertainty in Standard-Model theory prediction via this approach will shrink with anticipated improvements in B_s-mixing matrix elements



[Buras *et al.*, JHEP 1307 (2013) 77]

Controlling lattice-QCD systematics

- Statistical errors dictated by number of gauge-field configurations (sample size)
- To control systematic errors, generate sets of gauge-field ensembles with different parameters, *e.g.*:



MILC Collaboration's QCD ensembles

Controlling lattice-QCD systematics

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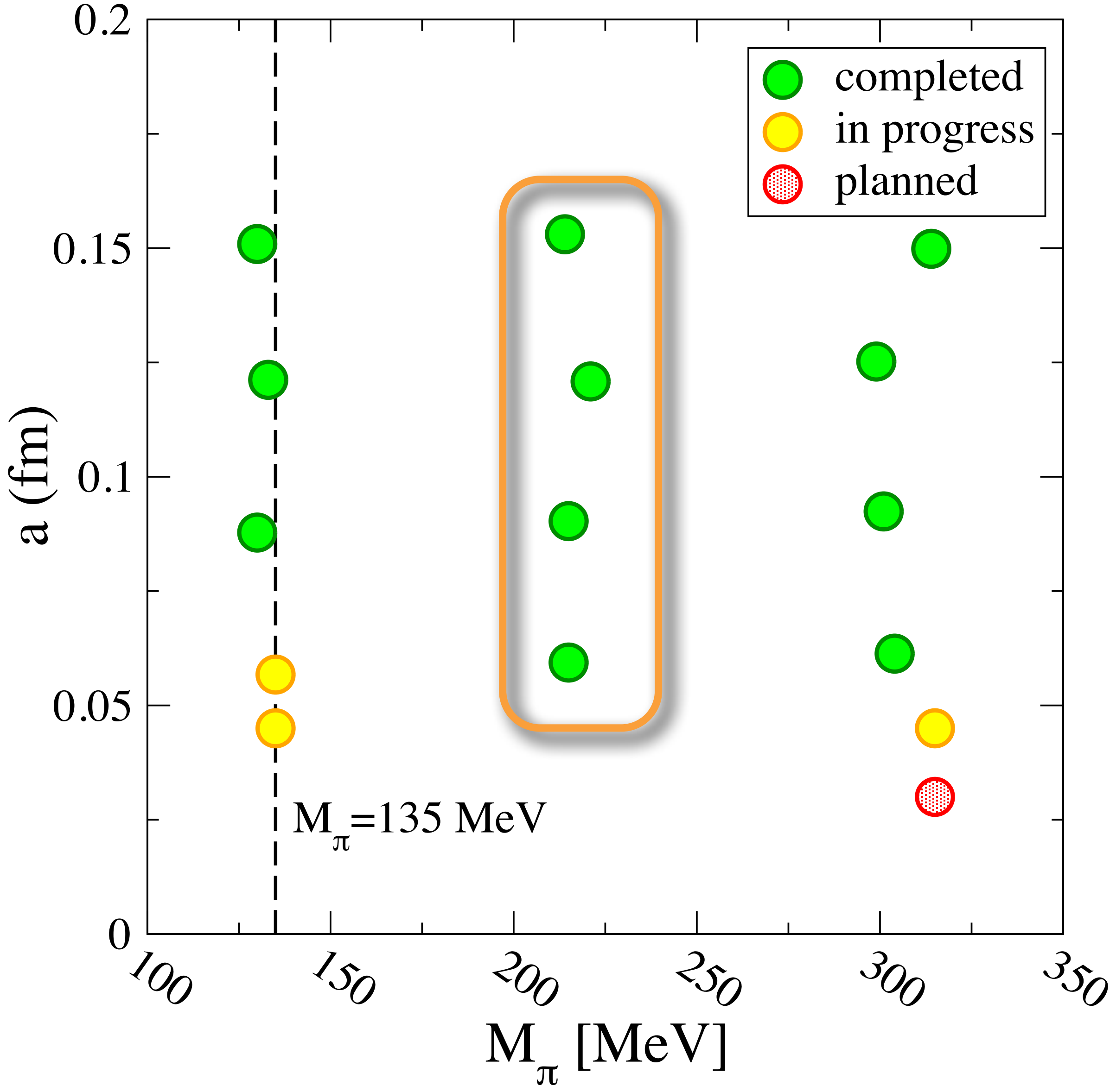
  - **Multiple lattice spacings** to extrapolate to continuum limit (a→0)

MILC Collaboration's QCD ensembles



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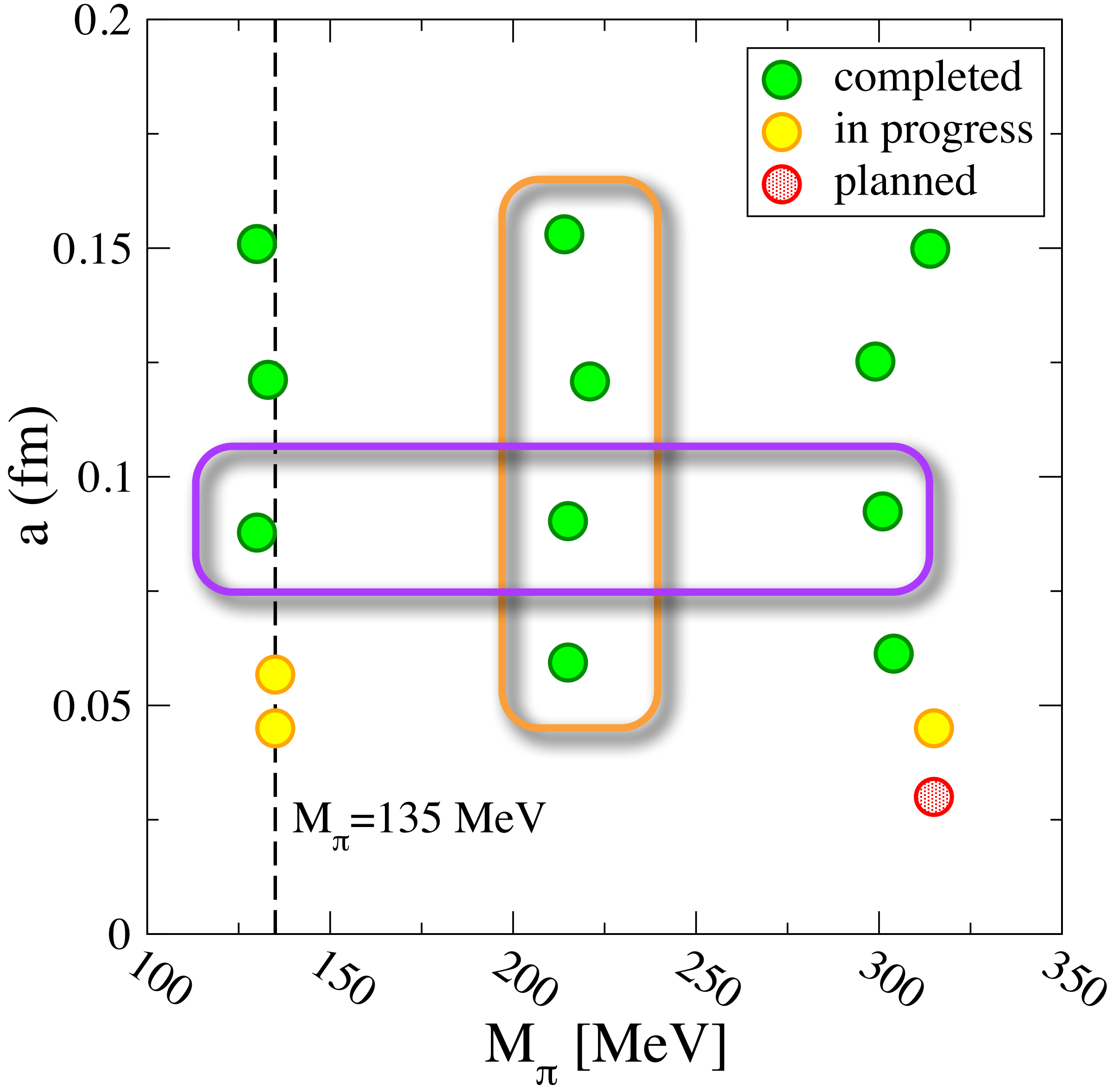

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    - Multiple spatial volumes to estimate finite-size effects

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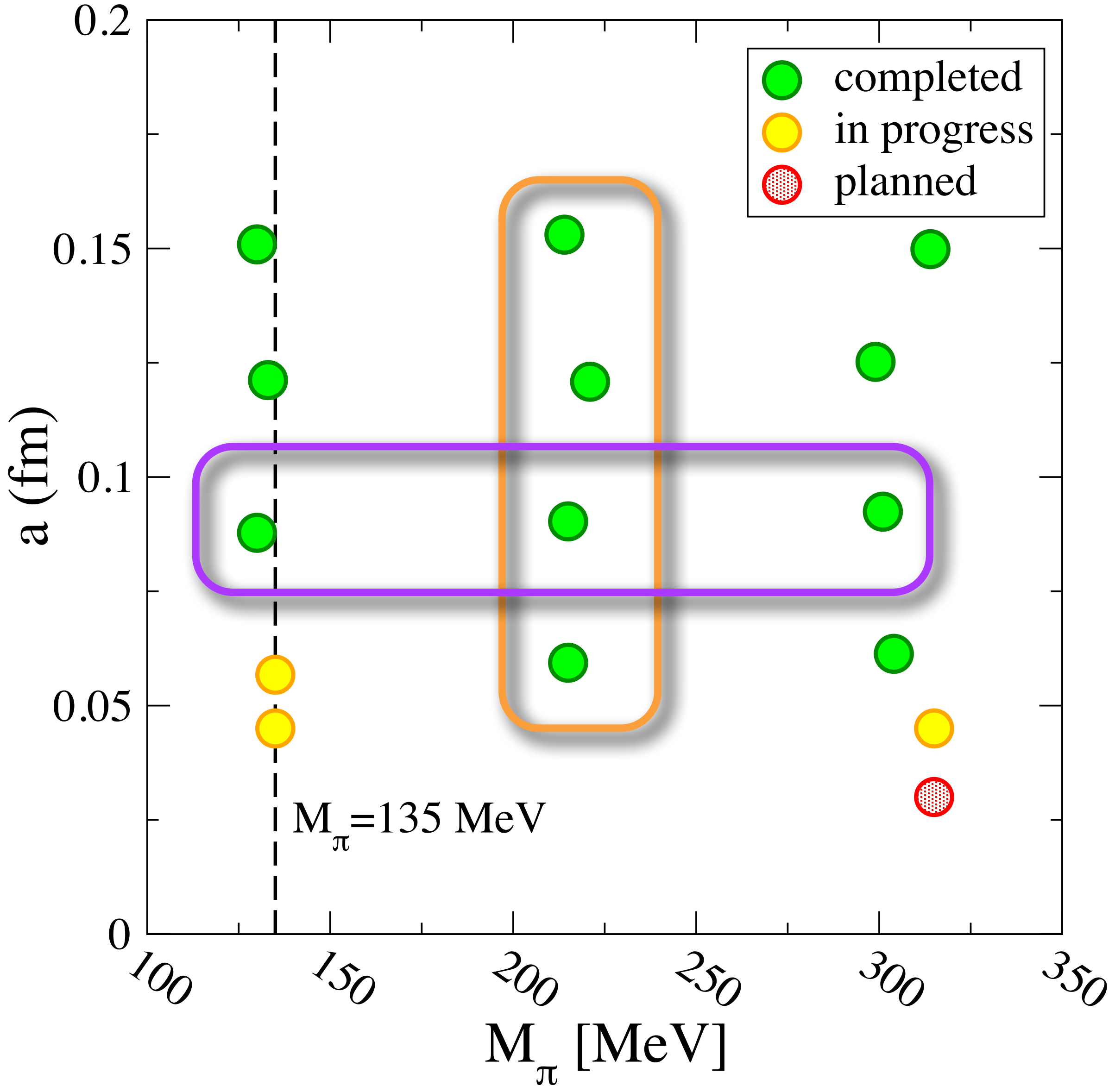

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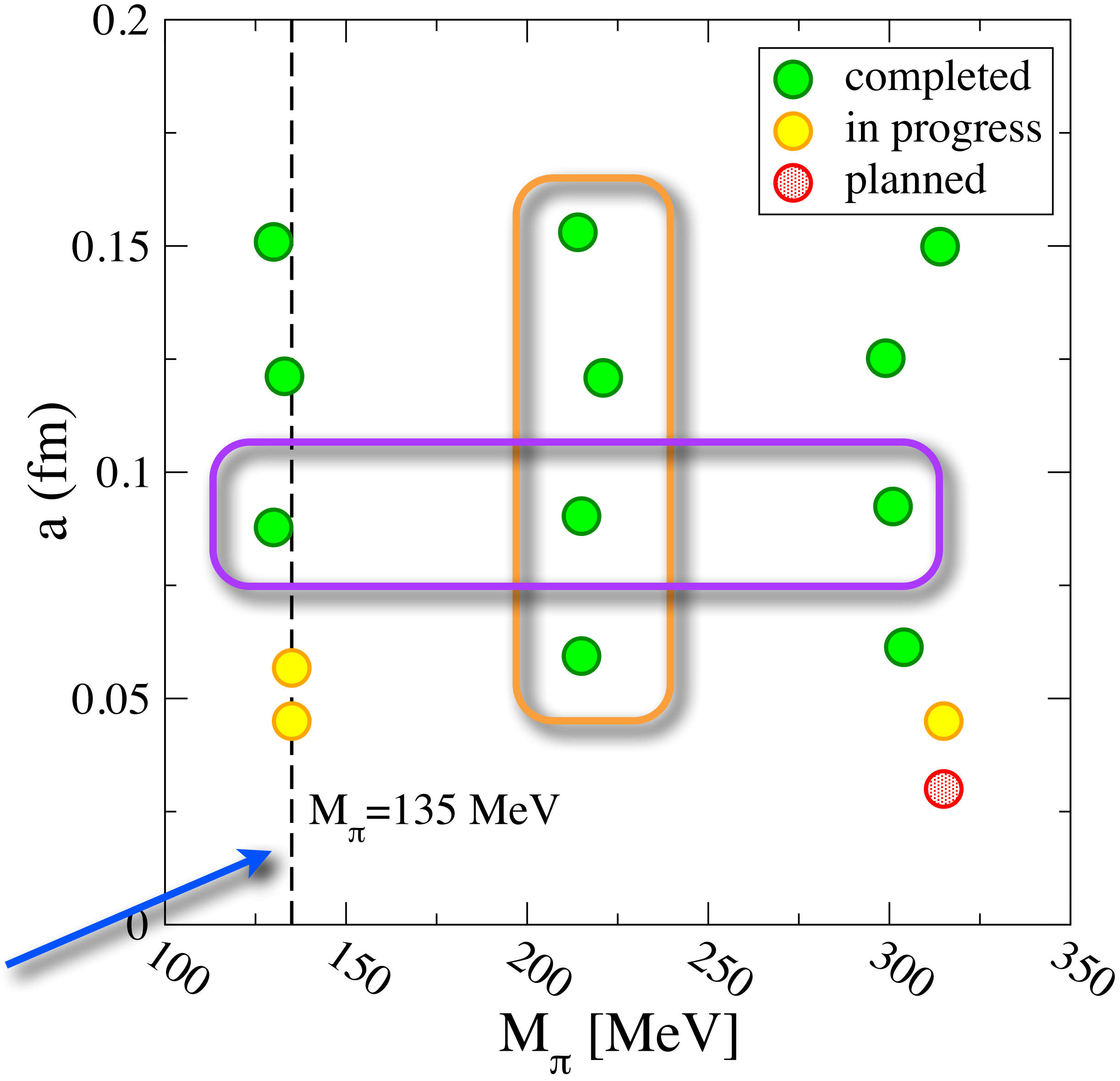
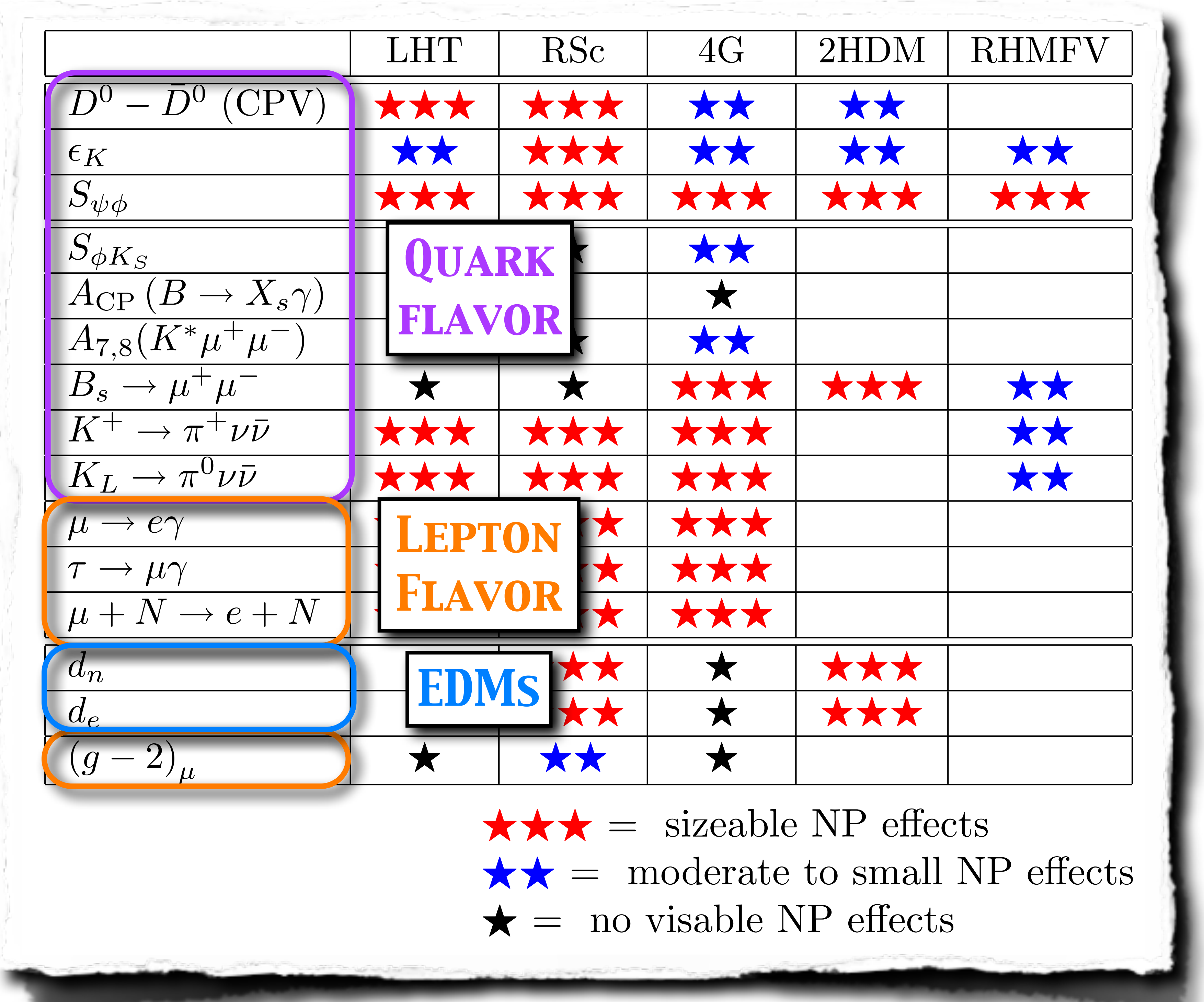


Latest generation supercomputers enabling simulations with physical u,d-quark masses, & number of results obtained at physical point is growing rapidly!

New-physics complementarity



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

★★★ = sizeable NP effects
★★ = moderate to small NP effects
★ = no visable NP effects

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

- Different processes & observables sensitive to different new-physics scenarios
  - Pattern of measurements can distinguish between models & constrain model parameters

We do not know where the new physics lies ➜ *cast a wide net!*