Cabibbo 60: The Cabibbo Angle 60 Years Later
Accademia Nazionale dei Lincei
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The first row of the CKM matrix: puzzles and perspectives

Vincenzo Cirigliano
University of Washington

INSTITUTE for NUCLEAR THEORY

Cabibbo universality

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UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)

. . .

We want, however, to keep a weaker form of universality, by requiring the following:

(3) J_μ has "unit length," i.e., $a^2+b^2=1$.

We then rewrite J_μ as[4]

$$J_\mu = \cos\theta(j_\mu^{(0)} + g_\mu^{(0)}) + \sin\theta(j_\mu^{(1)} + g_\mu^{(1)}), \qquad (2)$$

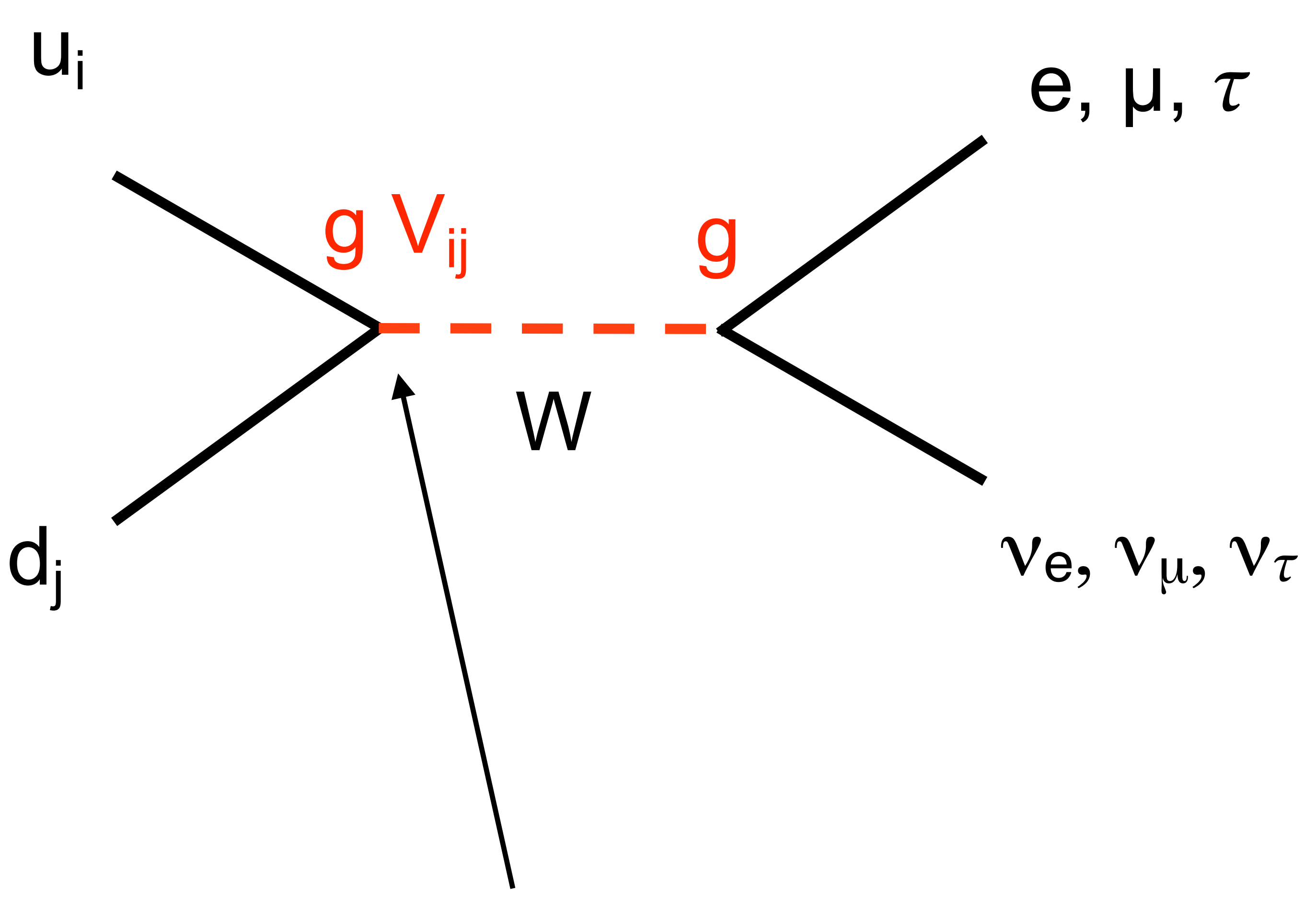
where $\tan\theta = b/a$.

. . .

Visionary, prescient

Cabibbo universality in the SM and beyond

- In the Standard Model: Cabibbo universality ⇐ unitarity of the quark mixing matrix (CKM)



$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Cabibbo-Kobayashi-Maskawa

~0..95 ~0.05 $\sim 1.5 \times 10^{-5}$

$$|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} = 1$$

$\delta V_{ud}/V_{ud} \sim 0.03\%$ $\delta V_{us}/V_{us} \sim 0.2\%$ $\delta V_{ub}/V_{ub} \sim 5\%$

V_{ud} and V_{us} are the most accurately known elements of the CKM matrix ⇒

1[st] row provides the most stringent test of universality & sensitivity to new physics

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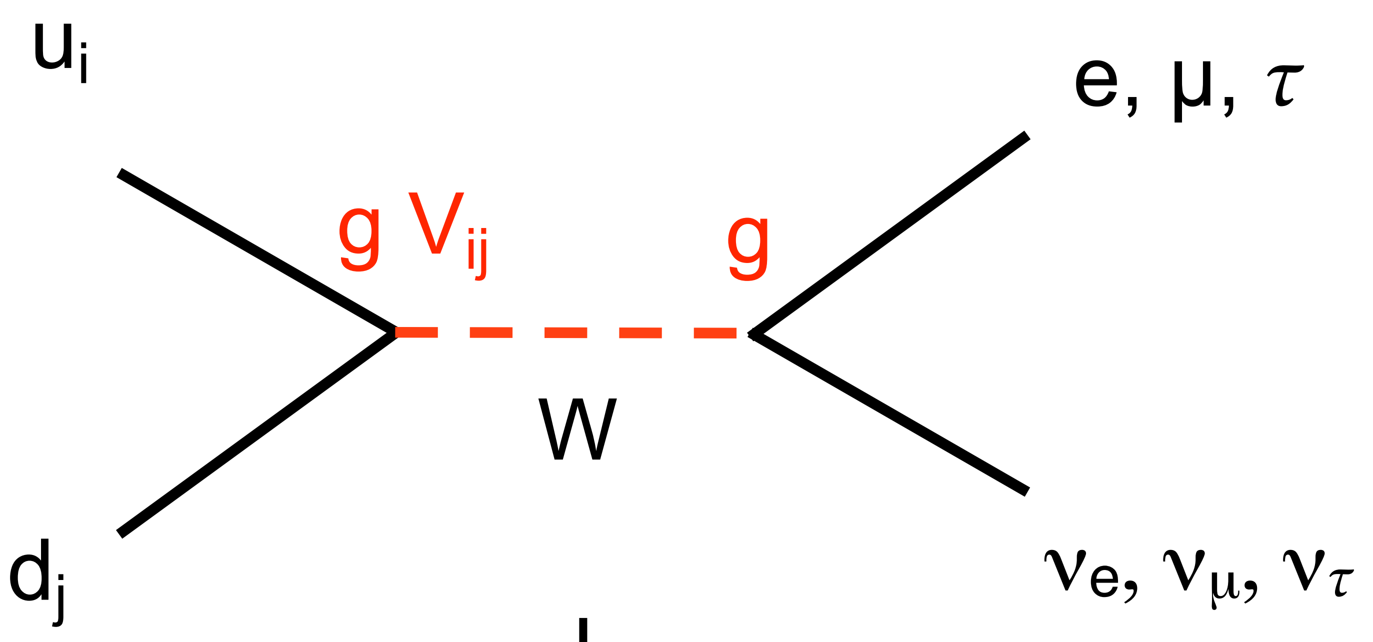

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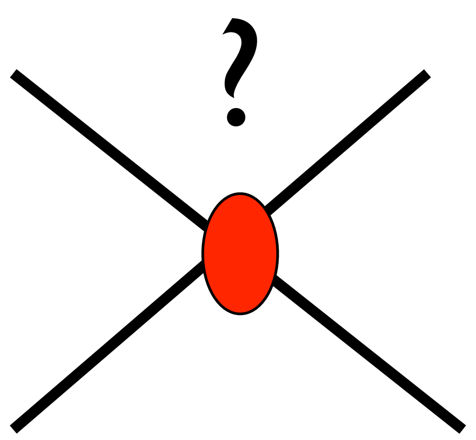

at low energy

$G_F^{(\mu)}\, V_{ij} \sim 1/v^2\, V_{ij}$

$1/\Lambda^2$

New physics can spoil universality: $|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|}^2 = 1 + O\left(\frac{v^2}{\Lambda^2}\right)$

Current precision $\Rightarrow$ probe effective scale $\Lambda \sim 10$ TeV

Compelling, timely, challenging!

Outline

- Overview: paths to V_{ud} & V_{us} and current puzzles
- A closer look: status and prospects for selected channels
- Cabibbo universality and physics beyond the Standard Model

V_{ud} & V_{us}:
status and puzzles

Paths to V_{ud} and V_{us}

	Hadron decays			Lepton decays
V_{ud}	$\pi^{\pm} \to \pi^{0} e \nu$ Nucl. $0^{+} \to 0^{+}$	$n \to p e \nu$ Nucl. mirror decays	$\pi \to \mu\nu$	$\tau \to h_{NS}\nu$
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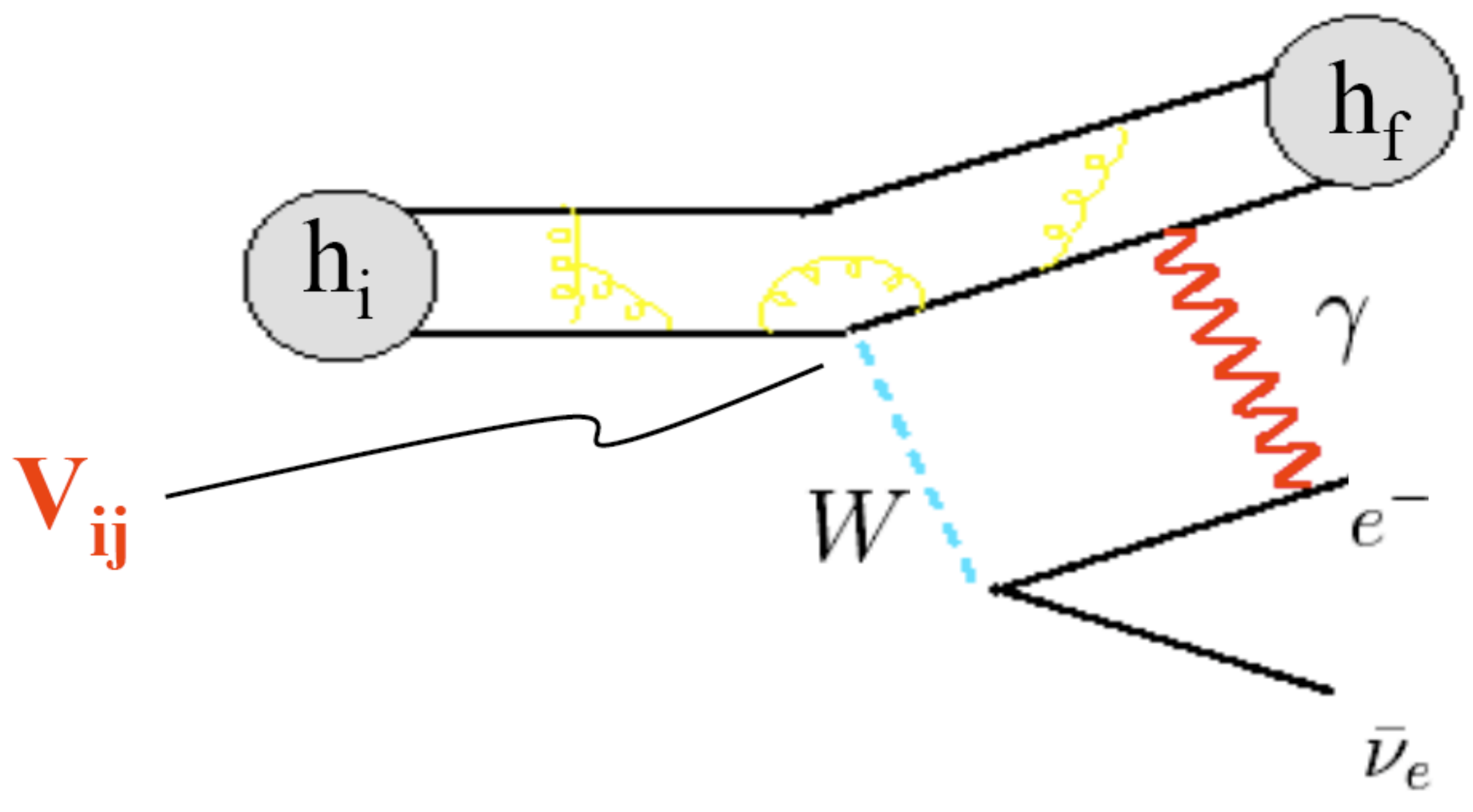
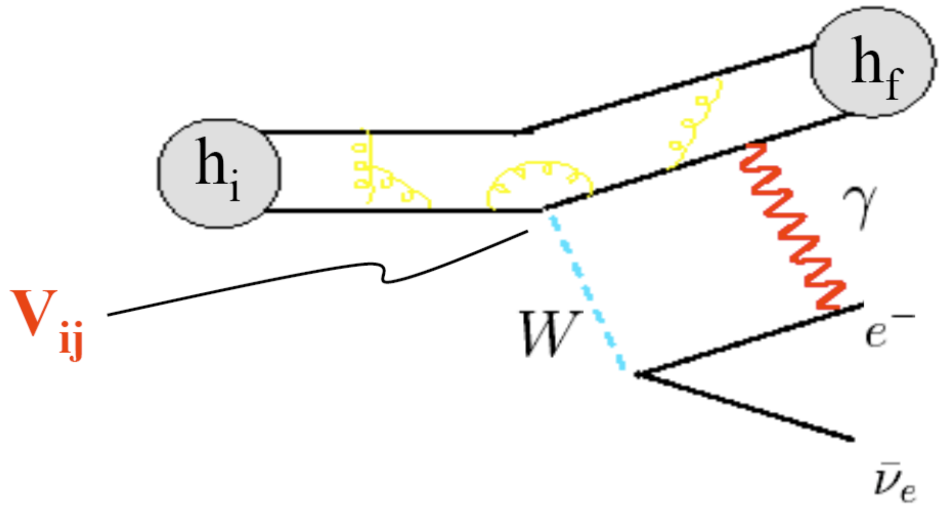


The challenge of CKM precision tests

Extract $V_{us}=\sin\theta_C = \lambda$ and $V_{ud}=\cos\theta_C \simeq 1 - \lambda^2/2$

with *sub-percent precision* from *decays involving hadrons*

(currently $\delta\lambda/\lambda \sim$ 0.2-0.5%)



$$\Gamma = G_F^2 \times |V_{ij}|^2 \times |M_{\text{had}}|^2 \times (1+\Delta_R) \times F_{\text{kin}}$$

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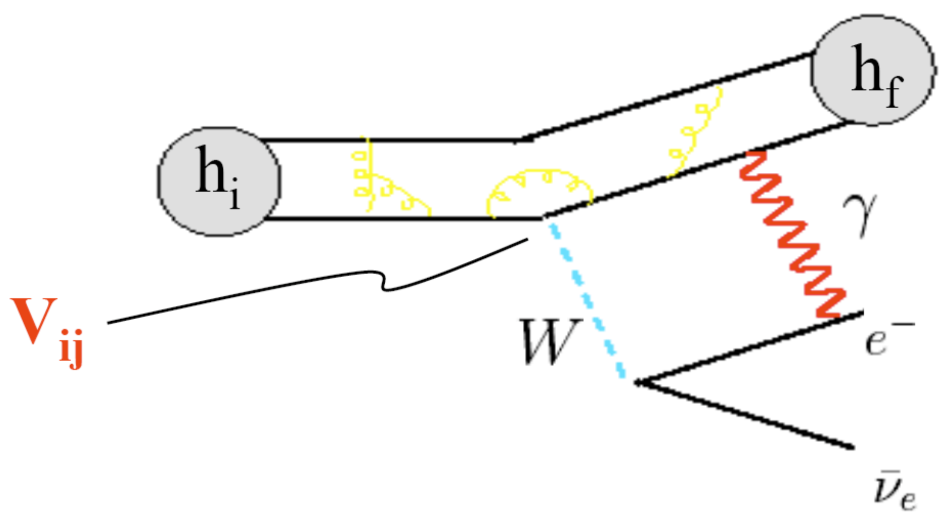

$$\Gamma = G_F^2 \times |V_{ij}|^2 \times |M_{\rm had}|^2 \times (1+\Delta_R) \times F_{\rm kin}$$

Lifetimes, BRs

Muon decay

Experimental input

Q-values, form factors, … → phase space

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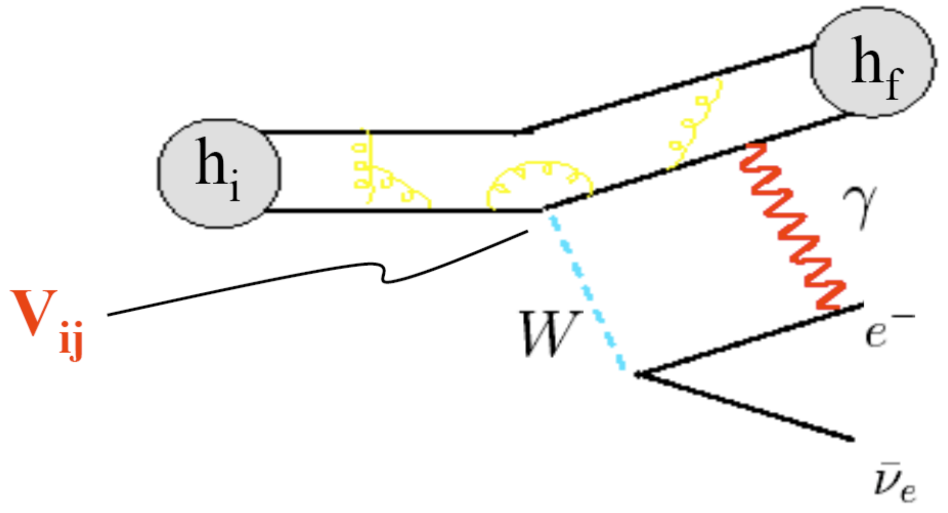

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Theory input

Hadronic / nuclear matrix elements of the weak V-A current,
including small corrections such as those induced by
electromagnetic radiative corrections [(α/π)~ $2.\times 10^{-3}$]

Experiment

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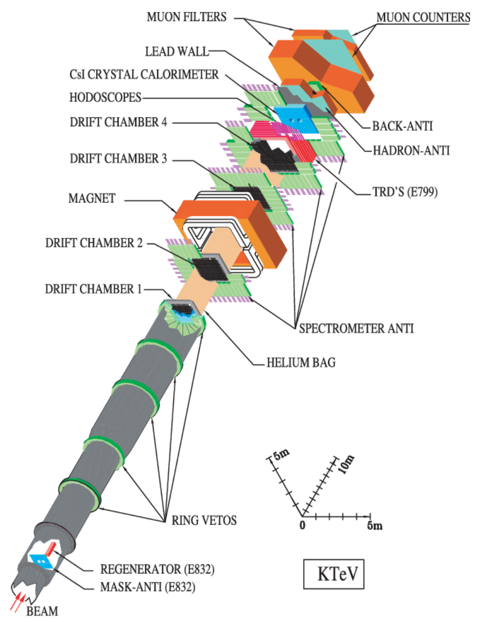
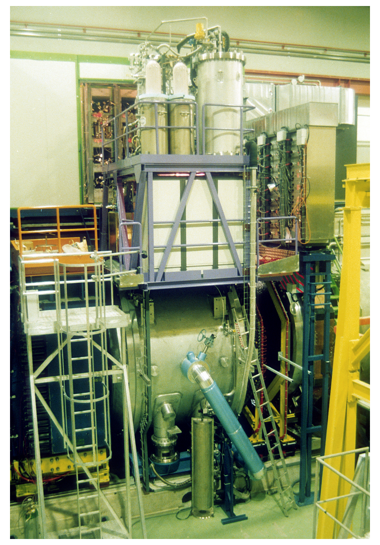
Experimental input with sub-% precision from broad array of facilities and techniques

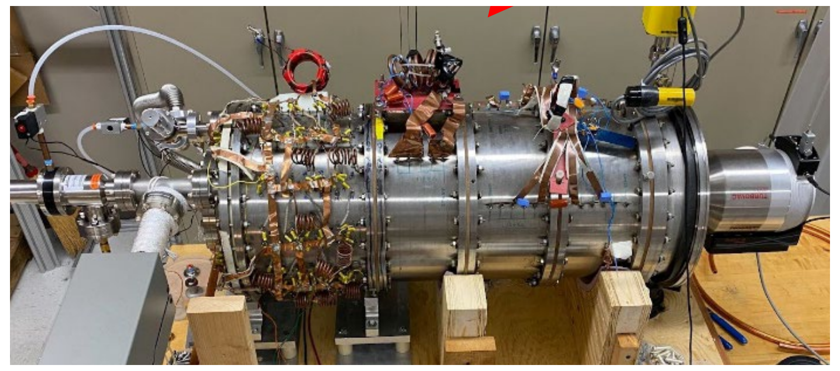
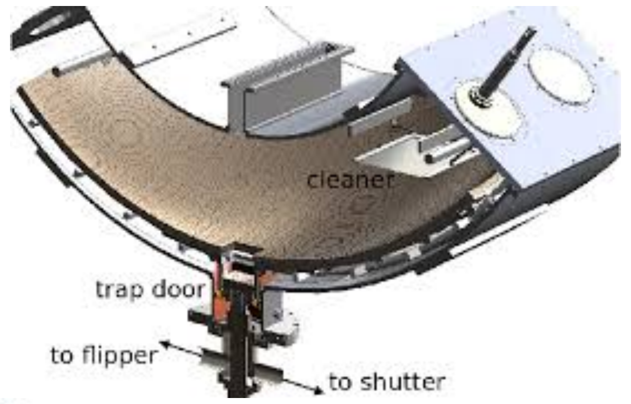
K, π, Hyperons:
Meson factories & fixed target experiments (KLOE, KTeV, NA48 ,…), with future experiment possible at CERN and PSI

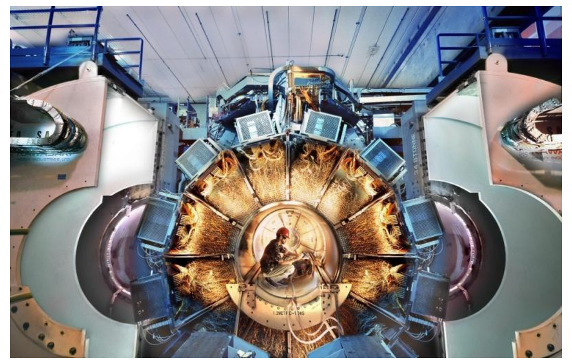


Nuclear beta decay experiments

Cold and Ultra Cold Neutron sources

τ decays:
LEP (ALEPH, OPAL), Babar, Belle, Belle-II, future tau-charm factory


Hadronic matrix elements

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Hadronic matrix elements: 'Vector - Axial' quark current

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Hadronic matrix elements: 'Vector - Axial' quark current

V

Berhends-Sirlin
Ademollo-Gatto

Traditionally "Golden modes":
<f $|V_\mu|$ i> known in SU(2) [SU(3)] limit
&
corrections are 2nd order in
SU(2) [SU(3)] breaking.
Computed in lattice QCD for K $\to\pi$

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V, A

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Need experimental input on
<f |A|i> / <f |V |i>

For neutron and hyperons,
Lattice QCD catching up but
not as precise as experiment

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V, A

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$\langle f | A | i \rangle$ / $\langle f | V | i \rangle$

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A

$\langle 0 | A_\mu | M \rangle$
(decay constants)
from Lattice QCD
[~0.2%]

Hadronic matrix elements

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V | V, A | A | V, A

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Use combination of
data and theory
(pQCD + lattice QCD)

Radiative corrections

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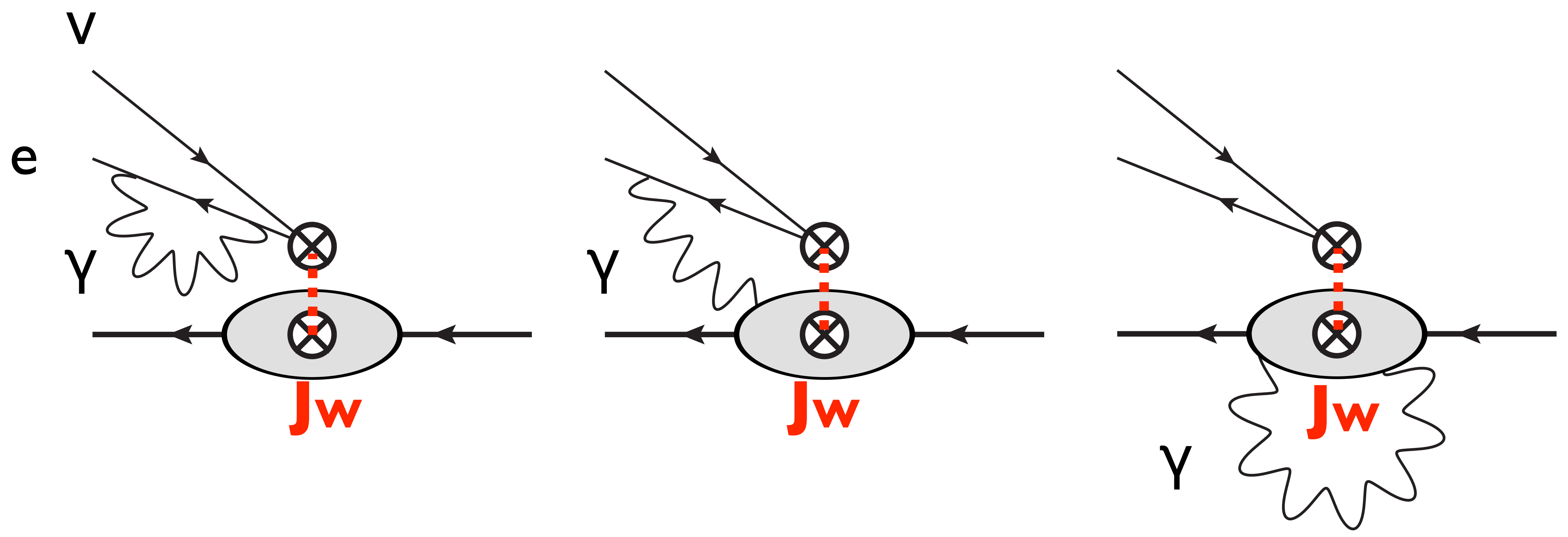
Electroweak radiative corrections

Mesons and neutron:
well developed Effective Field Theory (EFT) framework, with non-perturbative input from lattice QCD and / or dispersive methods — systematically improvable

For leptonic meson decays:
full lattice QCD+QED available



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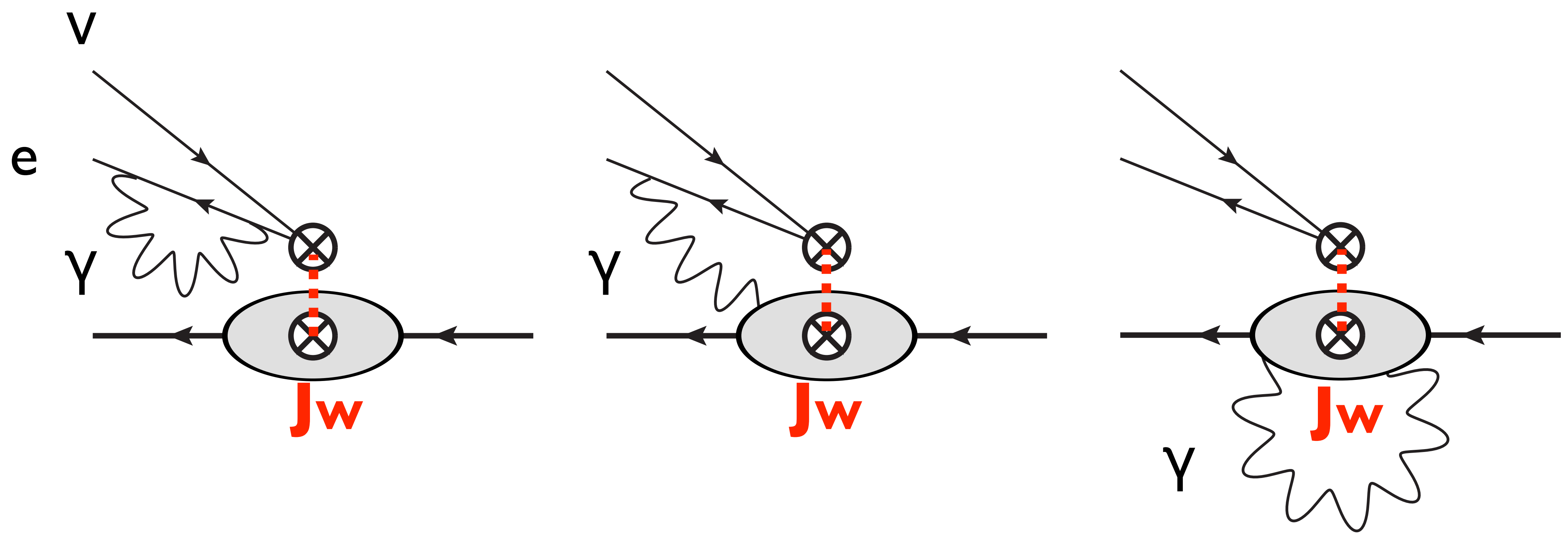
Recent activity to assess nuclear structure uncertainties:
Dispersive approach recently developed.
Work in progress towards multi-nucleon EFT to $O(G_F \alpha)$



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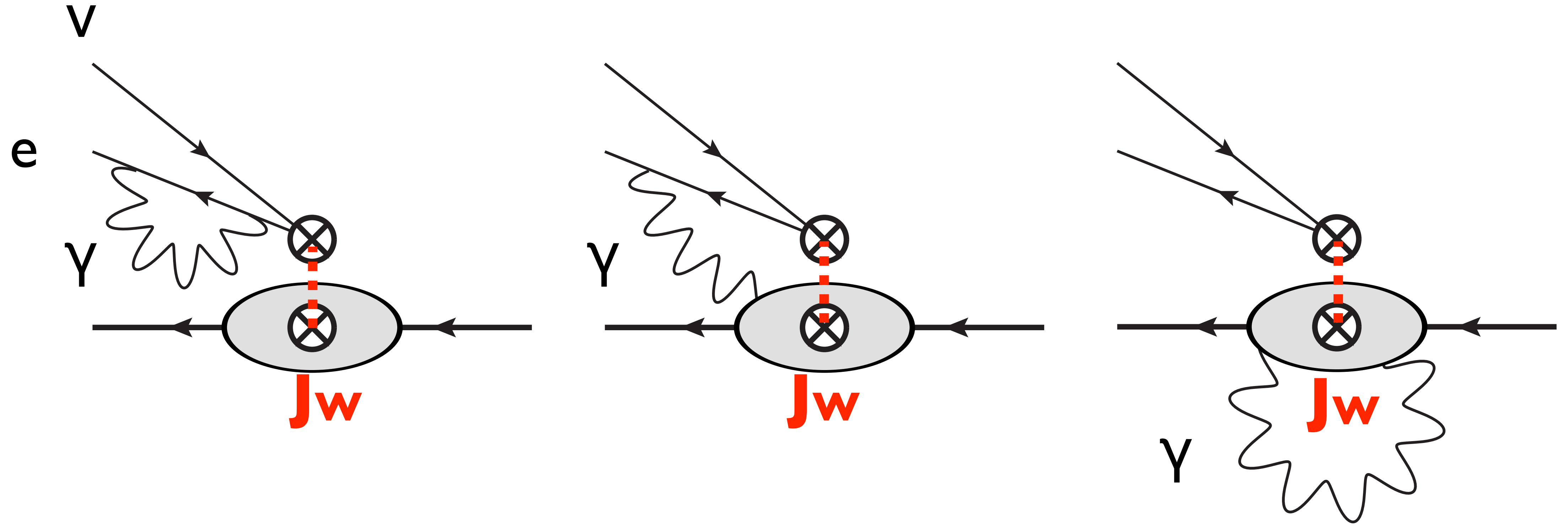
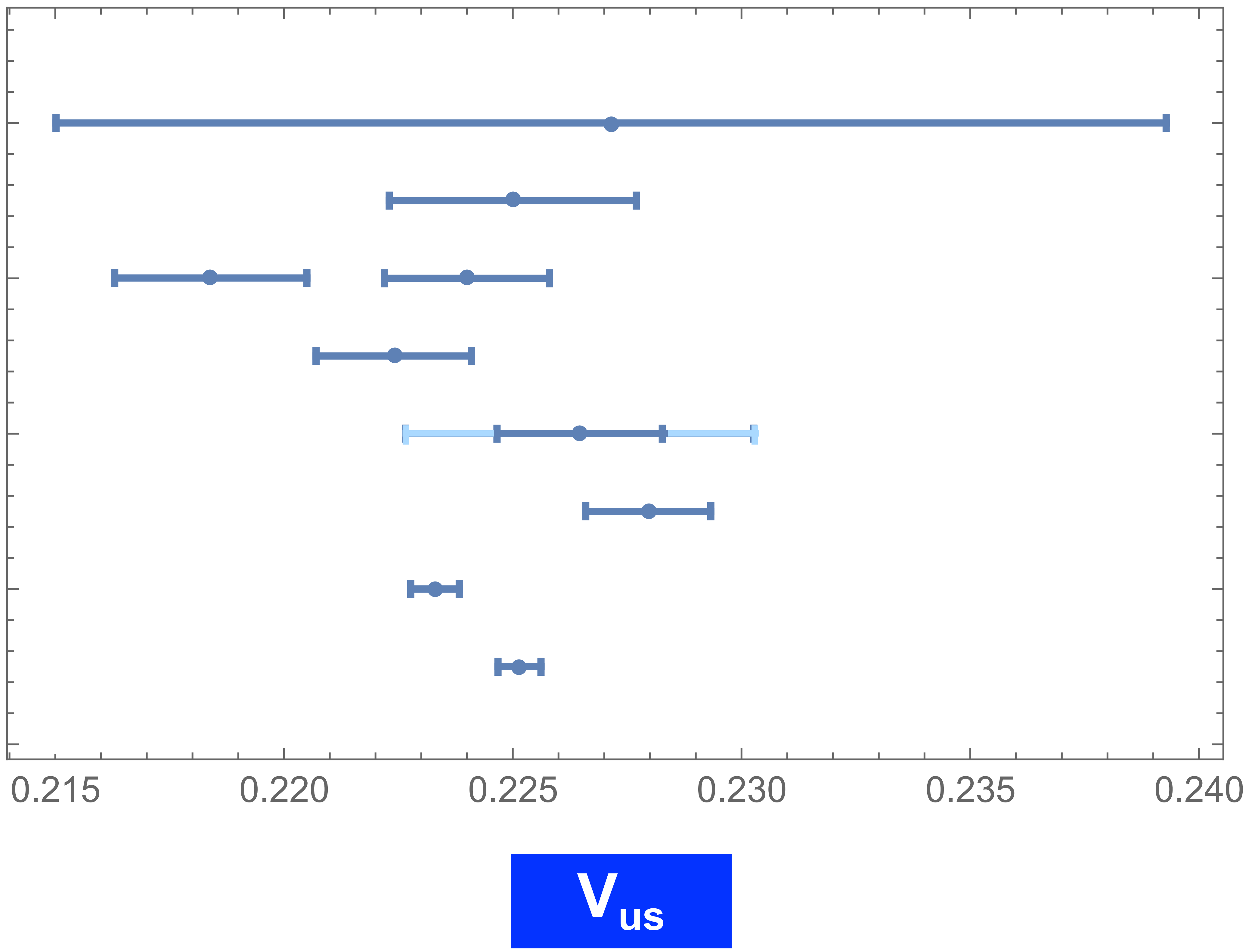


For exclusive channels, difficult to estimate the hadronic structure-dependent effects.
Lattice QCD+QED?

The Cabibbo angle — global view

Convert V_{ud} to V_{us} via unitarity

[References given in following slides]



	Fractional uncertainty	Largest uncertainty
$\pi^{\pm} \to \pi^0 e \nu$	5.3%	EXP
Hyperons	1.2% +?	EXP + TH
τ inclusive	0.8% + ?	EXP + TH
τ exclusive	0.8%	EXP + TH
$n \to p e \nu$	0.8% (1.7%) PDG	EXP
$0^+ \to 0^+$	0.6%	TH
$K \to \pi l \nu$	0.24%	EXP + TH
$K \to \mu\nu$ / $\pi \to \mu\nu$	0.21%	TH

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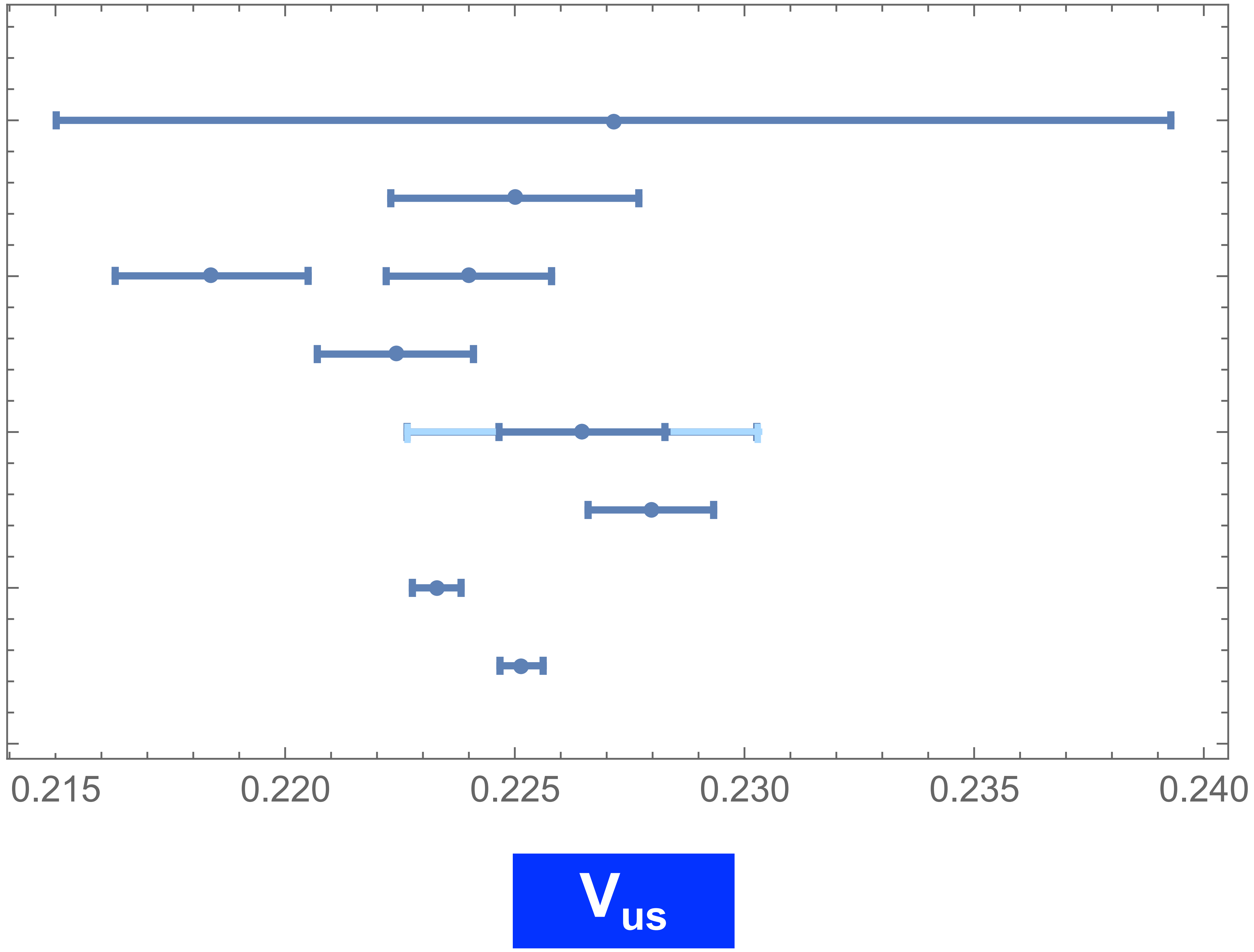

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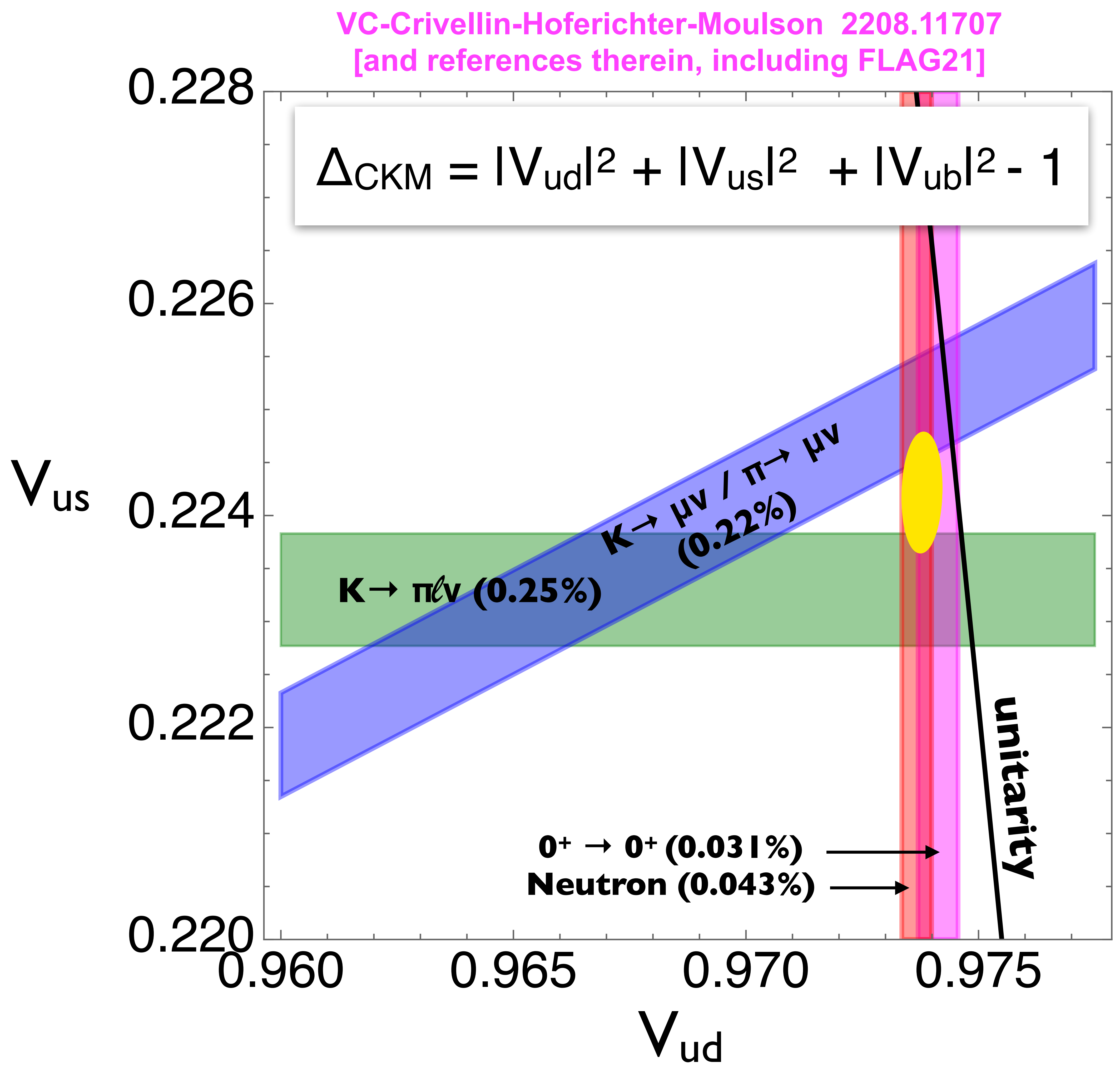
Tension among the most precise determinations

Tensions in the V_{ud}-V_{us} plane



- Bands don't intersect in the same region on the unitarity circle
- ~3σ effect in global fit ($\Delta_{CKM} = -1.48(53) \times 10^{-3}$)

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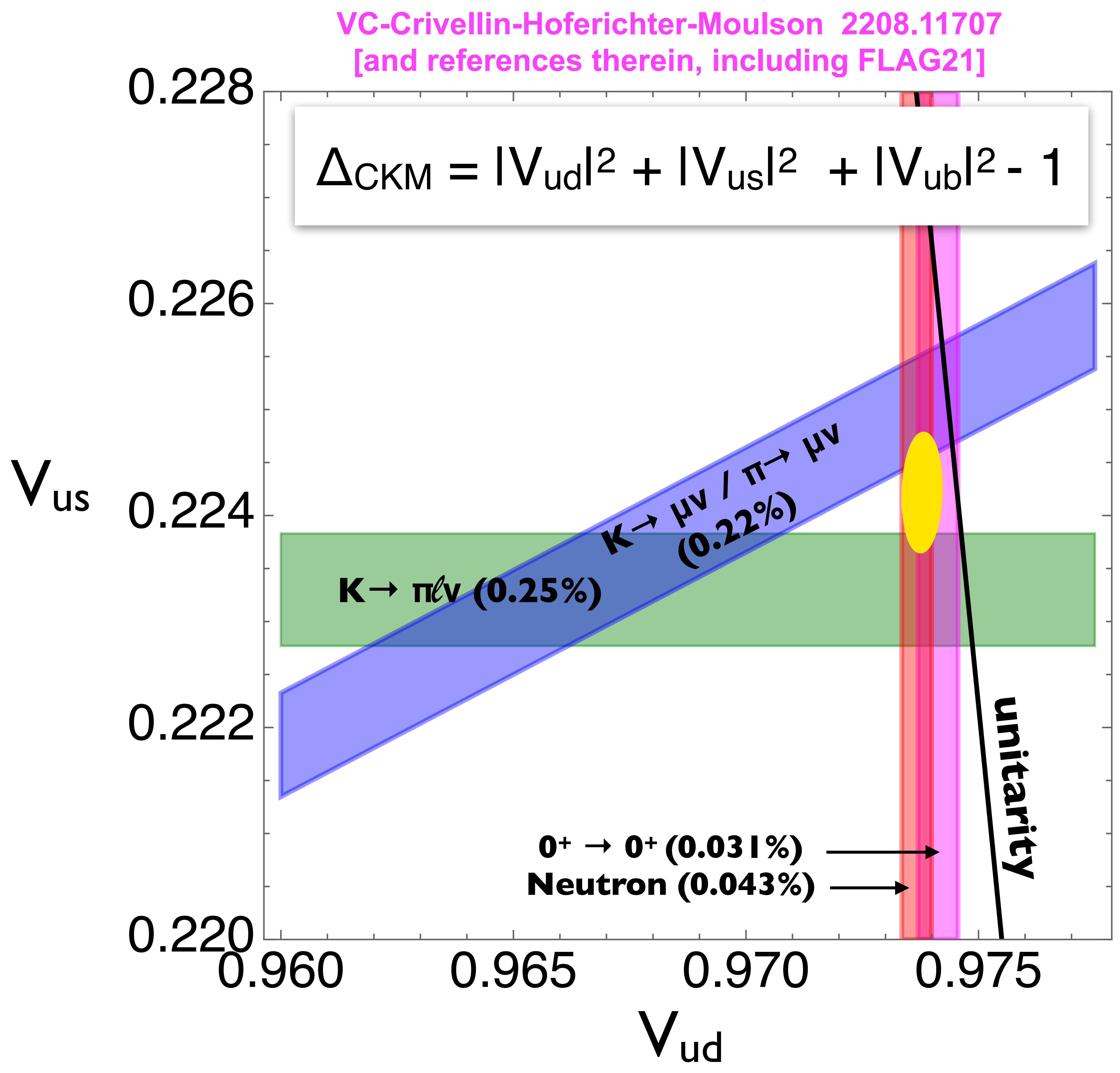

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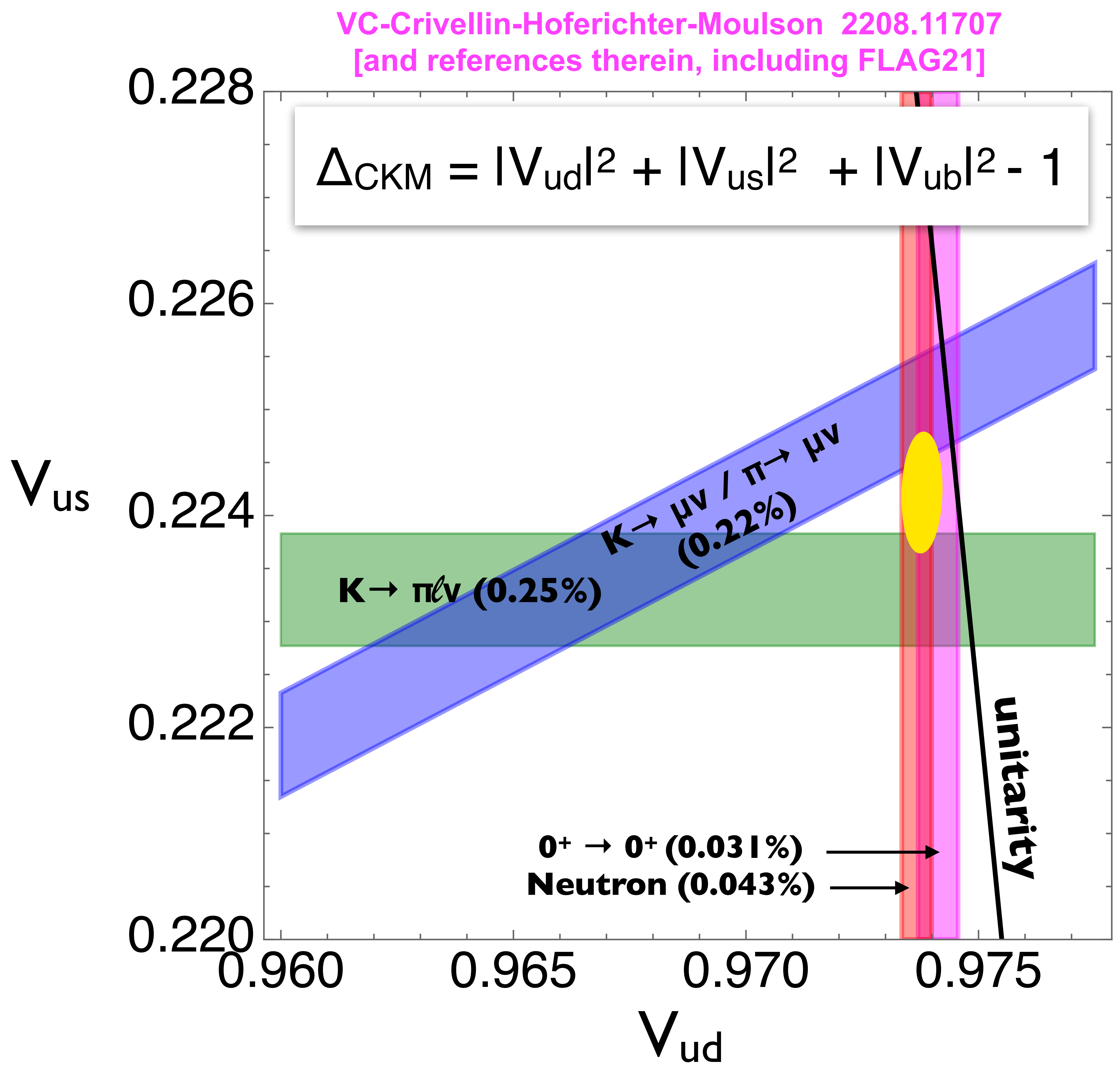
- ~3σ effect in global fit ($\Delta_{CKM} = -1.48(53) \times 10^{-3}$)

For the enthusiasts

- Until ~2018, bands *did* intersect in the same region on the unitarity circle (< 2σ)
- *Main* changes since then:
  - V_{us} from Kl3 decreased (<V> increased with smaller uncertainty, 2+1+1 lattice QCD)
  - V_{ud} decreased (radiative corrections in nuclear & neutron increased with smaller uncertainty, dispersive)

Tensions in the V_{ud}-V_{us} plane

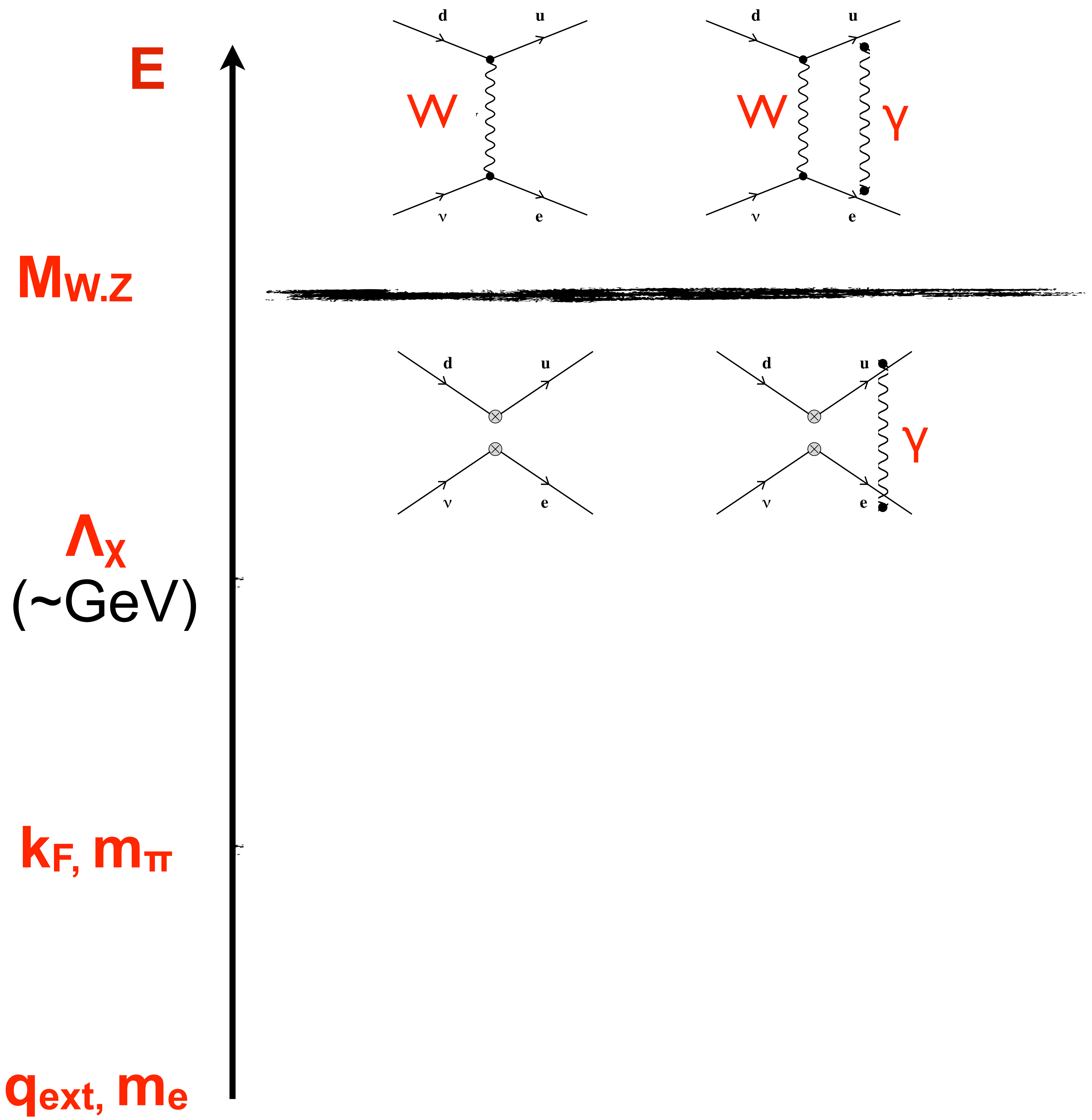


Next

- Closer look at theory and selected channels
- Possible BSM implications

A closer look

Theoretical framework



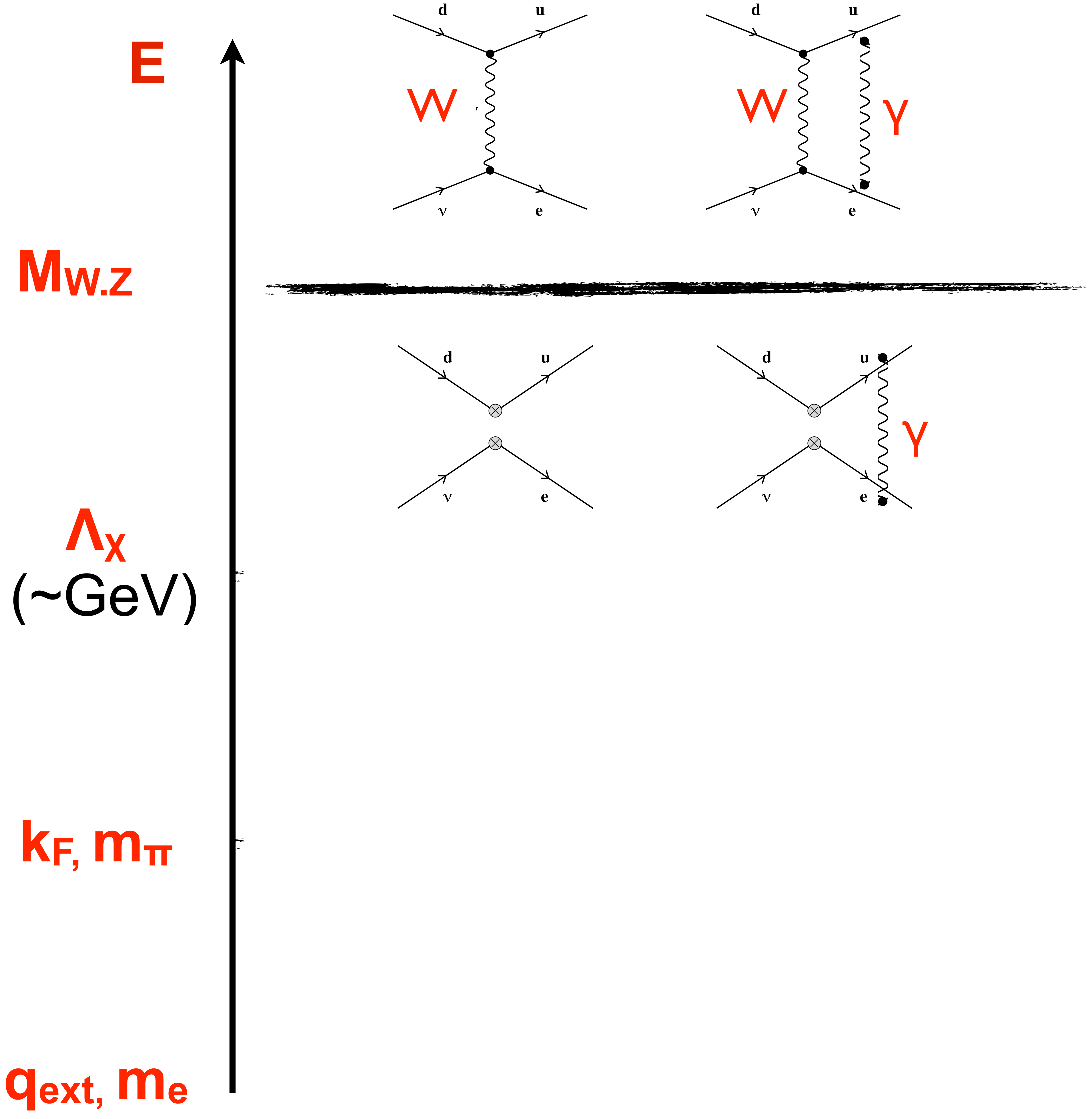
Standard Model

↓ *Perturbative matching*

$C_\beta(\mu)$ known to LL~ $(\alpha \ln(M_W))^n$ and NLL ~ $\alpha\,(\alpha_s \ln(M_W))^n$, $\alpha\,(\alpha \ln(M_W))^n$

$$\mathcal{L}_{\rm Fermi} = -\frac{G_F}{\sqrt{2}} V_{ud}\; C_\beta(\mu)\; \bar{\ell}\gamma_\alpha(1-\gamma_5)\nu_\ell\, \bar{u}\gamma^\alpha(1-\gamma_5)d + \ldots$$

Theoretical framework



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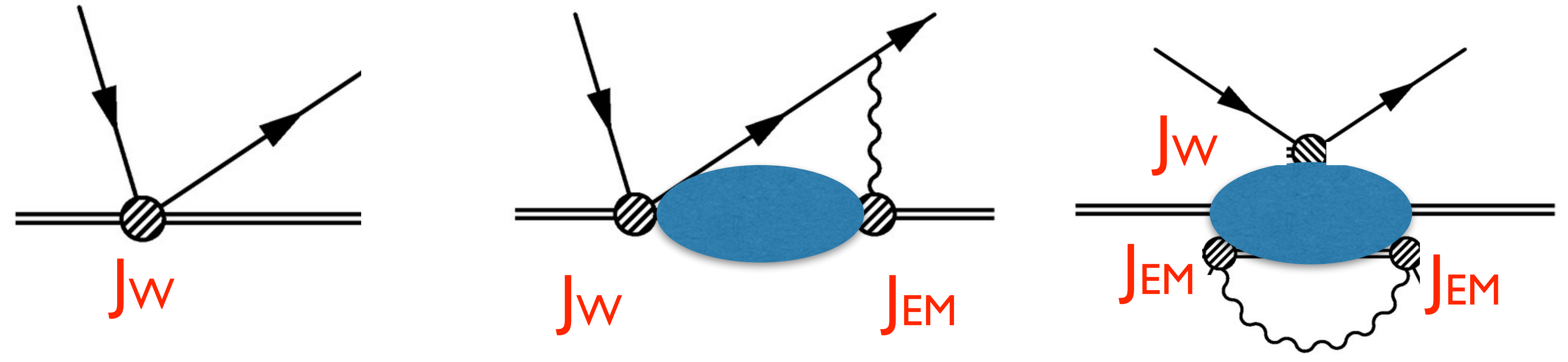
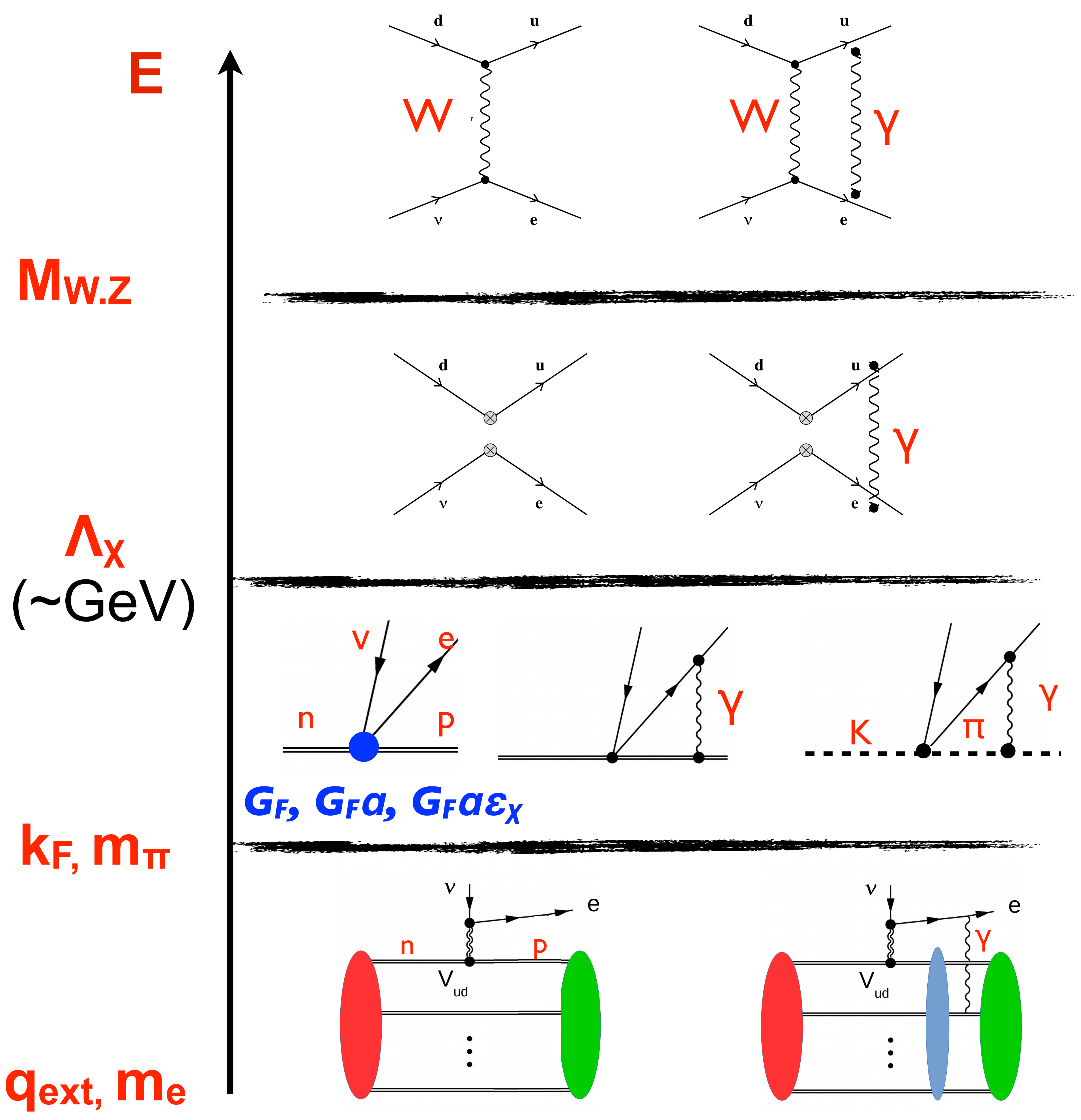
↓ *Matrix elements to O(α)*

$\langle f|$ $|i\rangle$



Direct calculation using non-perturbative methods.
Match to hadronic effective field theory.

Theoretical framework



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↓ *Non-perturbative matching: Lattice QCD, …*

Chiral Perturbation Theory $\epsilon_\chi = \{k_F, m_{\pi,K}\}/\Lambda_\chi$

LL running (NLL for nucleon)

↓ *Integrate out pions* $\epsilon_{\not\pi} = q_{\rm ext}/m_\pi$

Chiral & pion-less EFT $\epsilon_{\rm recoil} = q_{\rm ext}/\Lambda_\chi$

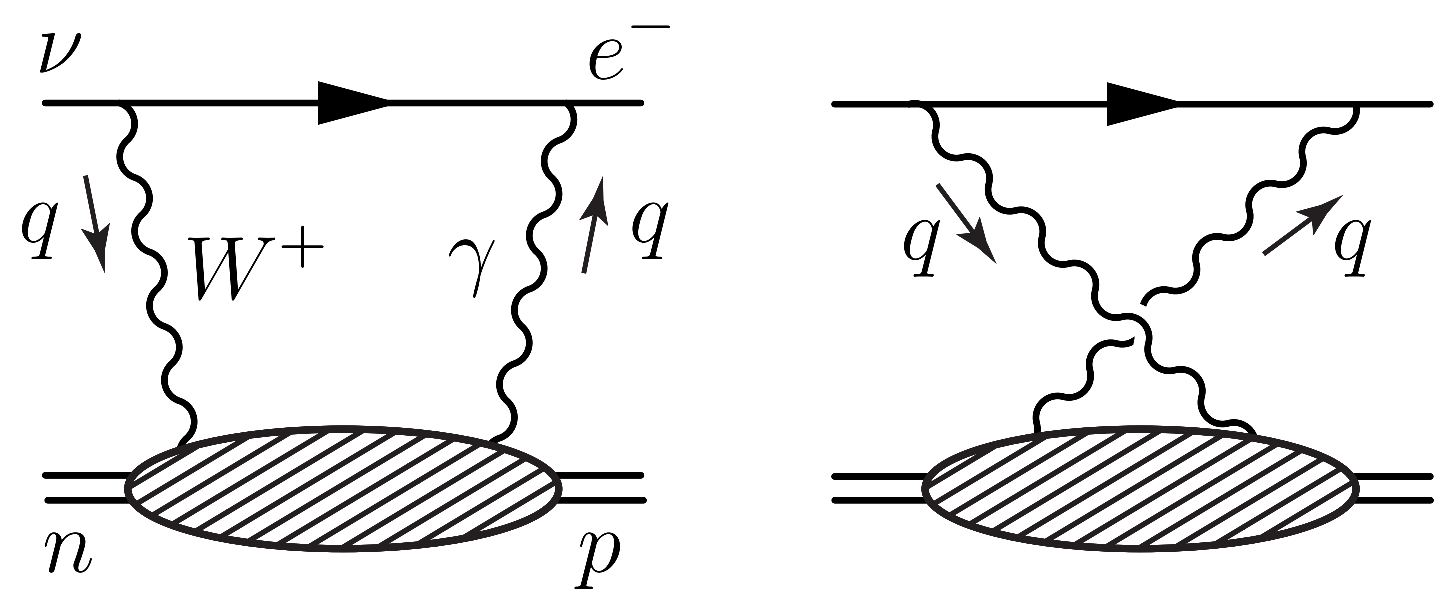
Developments in radiative corrections

- Lattice QCD approach [see talk by V. Lubicz]
- Hybrid current algebra + dispersive + Lattice QCD
- EFT for neutron ($\rightarrow$ stepping stone to EFT for nuclei)

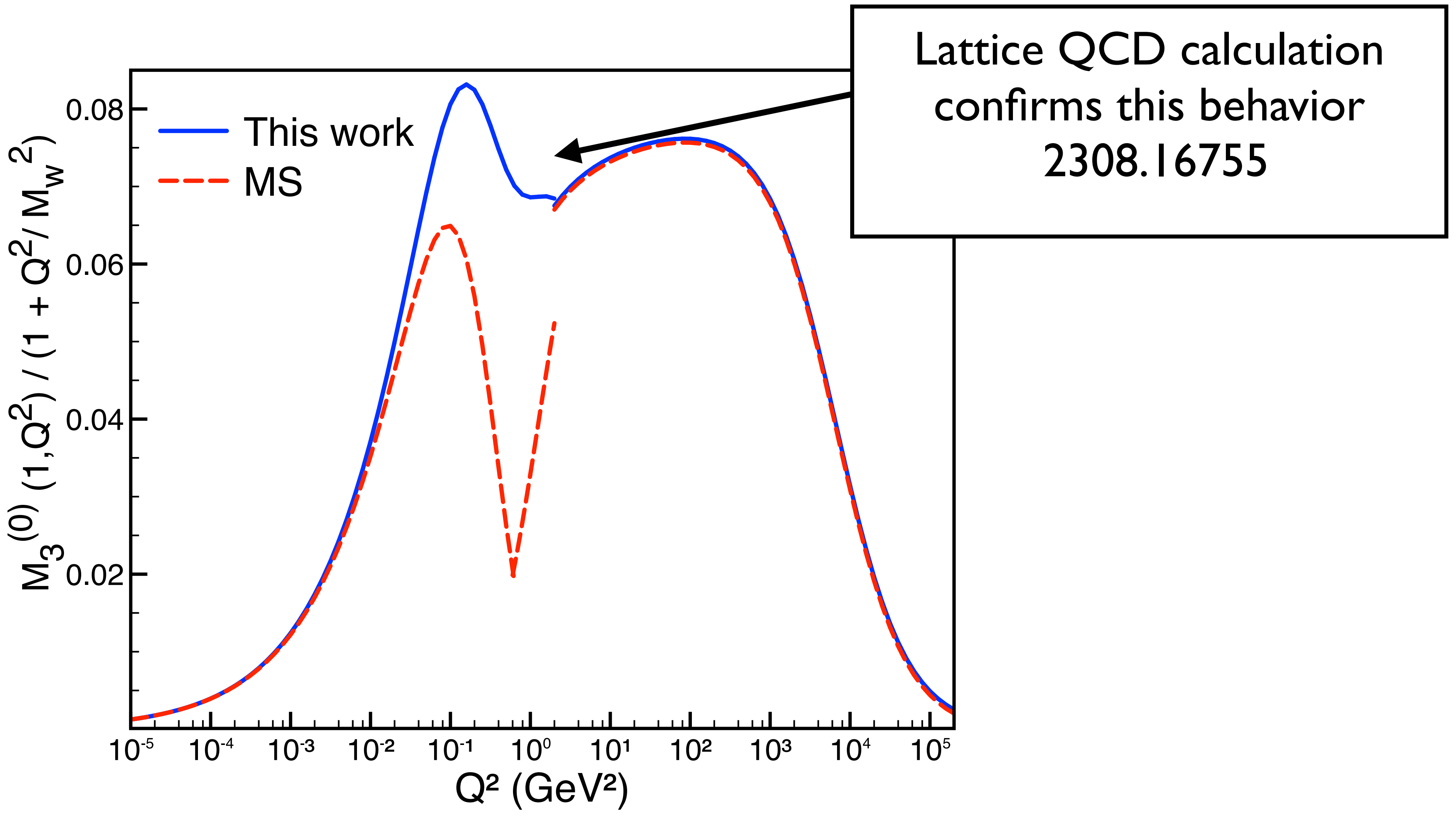
Developments in radiative corrections (1)

Seng et al. 1807.10197, Czarnecki et al, 1907.06737, Shiells et al. 2012.01580
Hayen 2010.07262 , Gorchtein-Seng 2106.09185

- Long history, starting in the 1950's. Modern approaches build upon Sirlin current algebra formulation from the '60 & '70s
- Recent new development: dispersive approach to the non-perturbative input (γ-W box) for neutron, pion, and kaon semileptonic decays & connection to LQCD
- Example: EM correction to n→p vector coupling



Gorchtein, Feng, Jin, Seng, …
2003.09798, 2003.11264, 2102.12048, 2308.16755



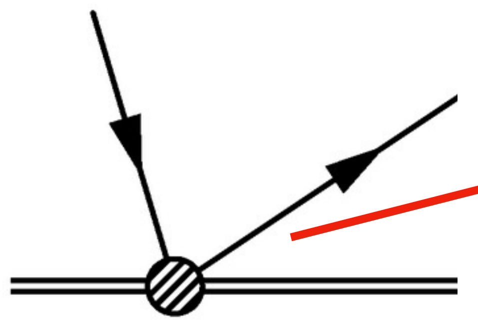
Larger correction, smaller error
It also affects nuclear decays

Ref.	Δ_R^V
Marciano, Sirlin 2006	0.02361(38)
Seng, Gorchtein, Patel, Ramsey-Musolf 2018	0.02467(22)
Czarnecki, Marciano, Sirlin 2019	0.02426(32)
Seng, Feng, Gorchtein, Jin 2020	0.02477(24)
Hayen 2020	0.02474(31)
Shiells, Blunden, Melnitchouk 2021	0.02472(18)
Combined	0.02467(27)

Developments in radiative corrections (2)

VC, W. Dekens, E. Mereghetti, O. Tomalak, 2306. 03138

- ‘End-to-end’ EFT for neutron decay, motivated by widely separated scales (M_W, Λ_χ, m_π, $m_e \sim E_e^{max}$)
  - NLL resummation of large logarithms above and below $\mu \sim \Lambda_\chi$
  - Non-perturbative input isolated as an IR-finite ‘matching’ contribution at $\mu \sim \Lambda_\chi$



$$g_V(\mu_e) = U(\mu_e, \Lambda_\chi) \left[1 + \overline{\Box}^V_{\text{Had}}(\mu_0) + \frac{\alpha(\Lambda_\chi)}{\pi} \kappa(\mu_0)\right] U(\Lambda_\chi, \mu_W)\ C_\beta(\mu_W)$$

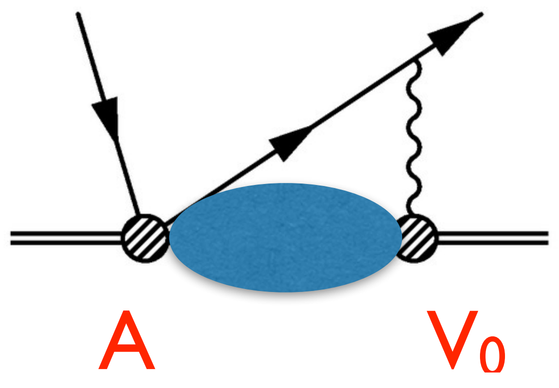
NLL RGE in ChPT and pion-less EFT

Non-perturbative ‘triangle’ diagram: the usual ‘box’ minus the DIS contributions for $Q^2 > (\mu_0)^2$, which in the EFT approach belongs to the Wilson coefficient

NLL RGE in Fermi Theory

Wilson Coefficient at $\mu_W \sim m_W$

$\overline{\Box}^V_{\text{Had}}$ ~



+0.026% shift in total radiative correction to neutron decay compared to previous literature

Developments in radiative corrections (2)

VC, W. Dekens, E. Mereghetti, O. Tomalak, 2306. 03138

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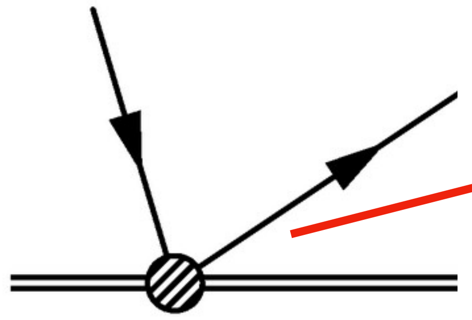

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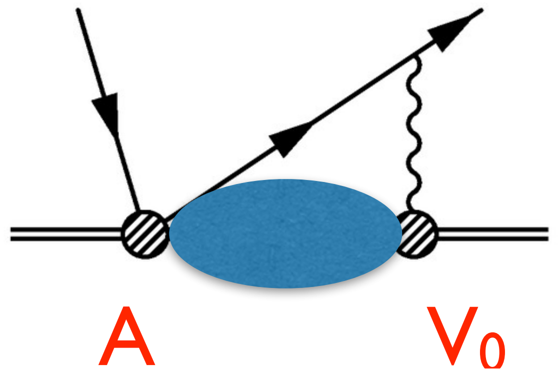
$\overline{\Box}^V_{\rm Had}$ ~ 

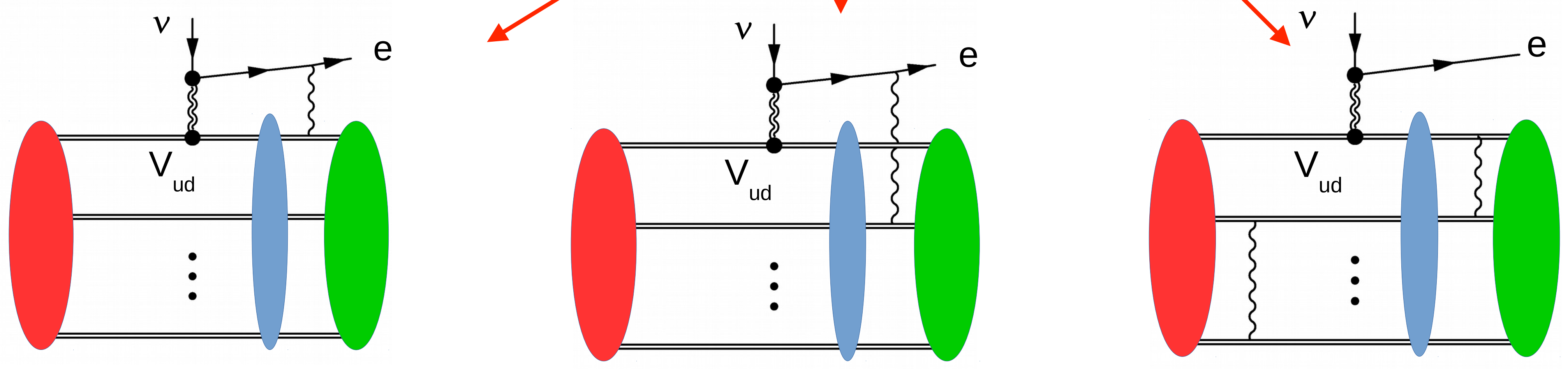
+0.026% shift in total radiative correction to neutron decay compared to previous literature

- EFT for multi-nucleon systems to $O(G_F\alpha)$ & $O(G_F\alpha\epsilon_\chi)$ is under development

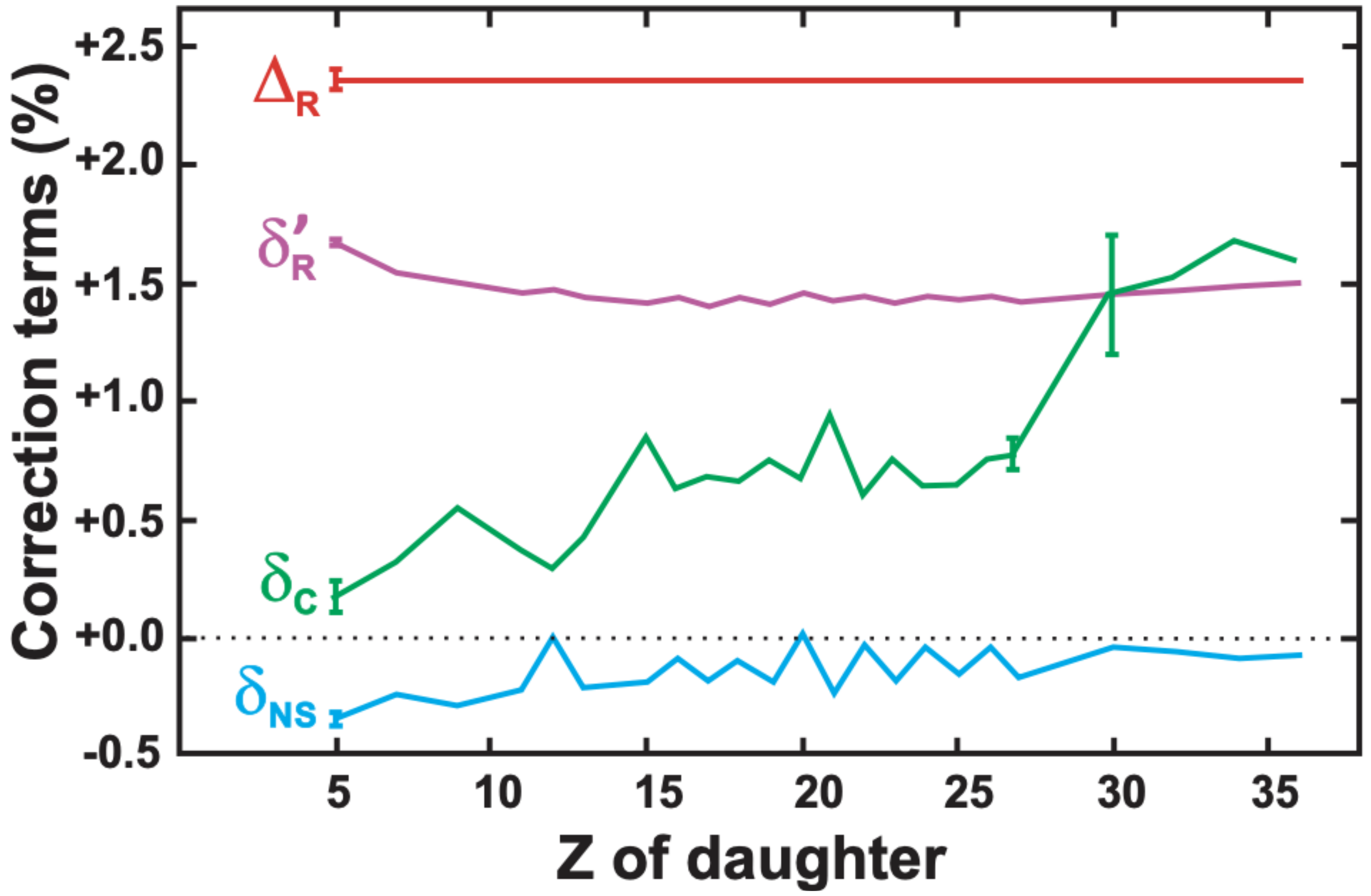
V_{ud} from nuclear $0^+ \to 0^+$ beta decays

$$|V_{ud}|^2 = \frac{2984.432(3)\ s}{ft\left(1 + \delta'_R + \delta_{NS} - \delta_C + \Delta_R^V\right)}$$

Point-like nucleus
'outer corrections'
(Z, $(E_e)^{max}$)



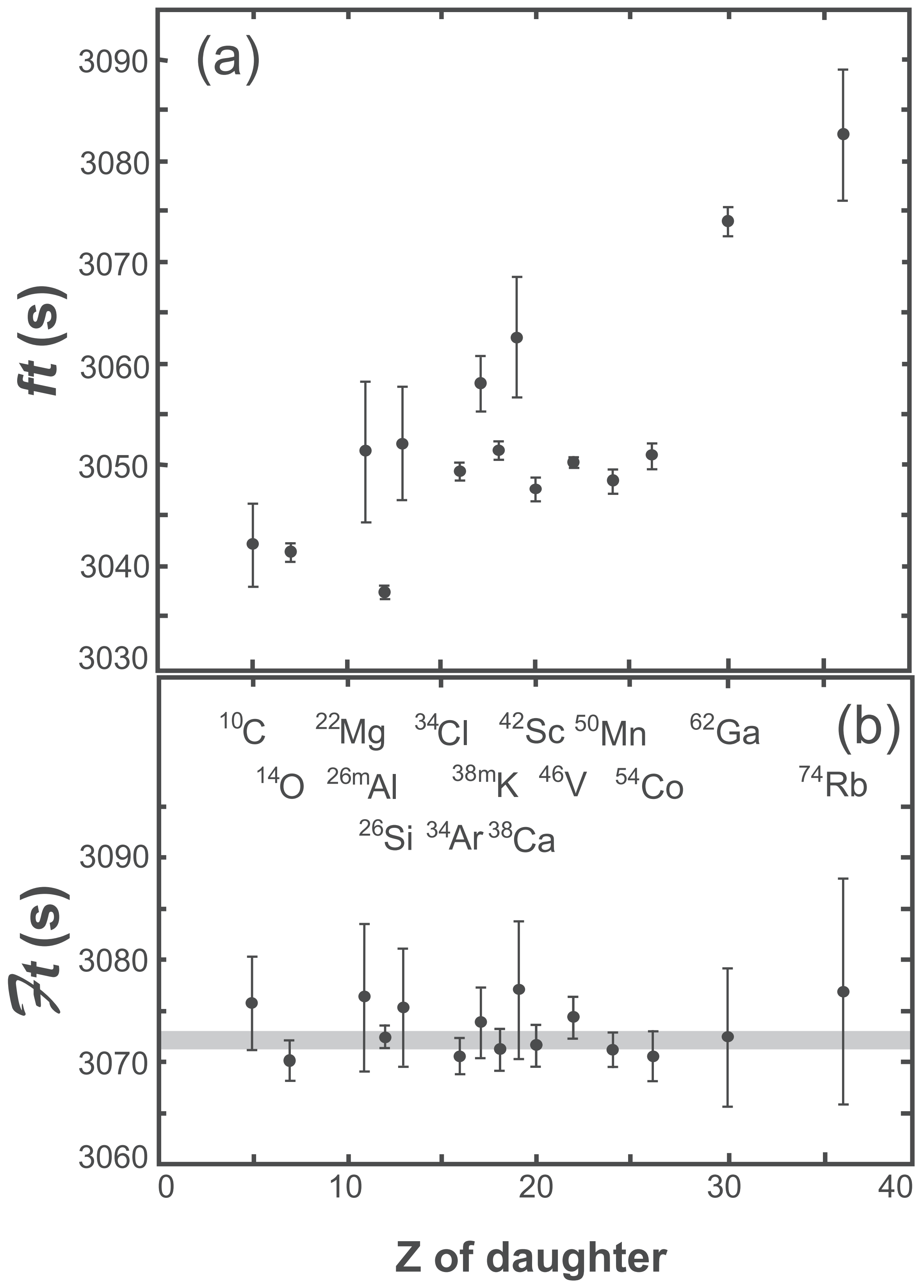
Single nucleon
`γ-W box'



Hardy-Towner, PRC 2020

V_{ud} from nuclear $0^+ \to 0^+$ beta decays

Hardy-Towner, PRC 2020



$$|V_{ud}|^2 = \frac{2984.432(3)\ s}{ft\left(1+\delta'_R+\delta_{NS}-\delta_C+\Delta^V_R\right)}$$

$\mathcal{F}t$

$$V_{ud}^{0^+\to 0^+} = 0.97367(11)_{\rm exp}(13)_{\Delta^V_R}(27)_{\rm NS}[32]_{\rm total}$$

Lots of activity

- New analysis of nuclear weak form factors and phase space f
- New approaches towards structure dependent corrections $\delta_{C,NS}$
- Controlled uncertainties will be achieved for a range of A=10, 14, …

Gorchtein, Seng 2311.00044
and references therein

V_{ud} from neutron decay

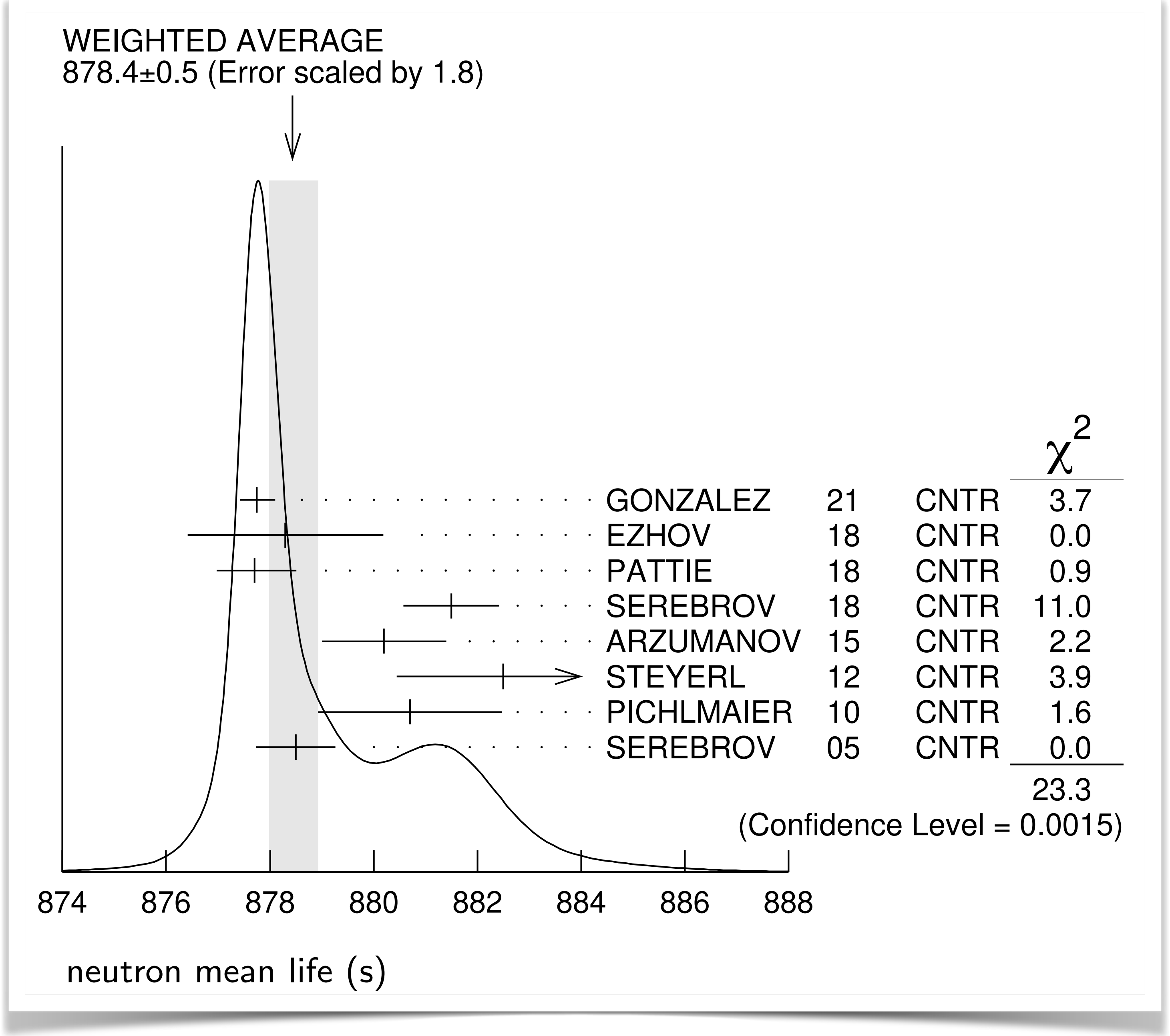
$\lambda = g_A/g_V$

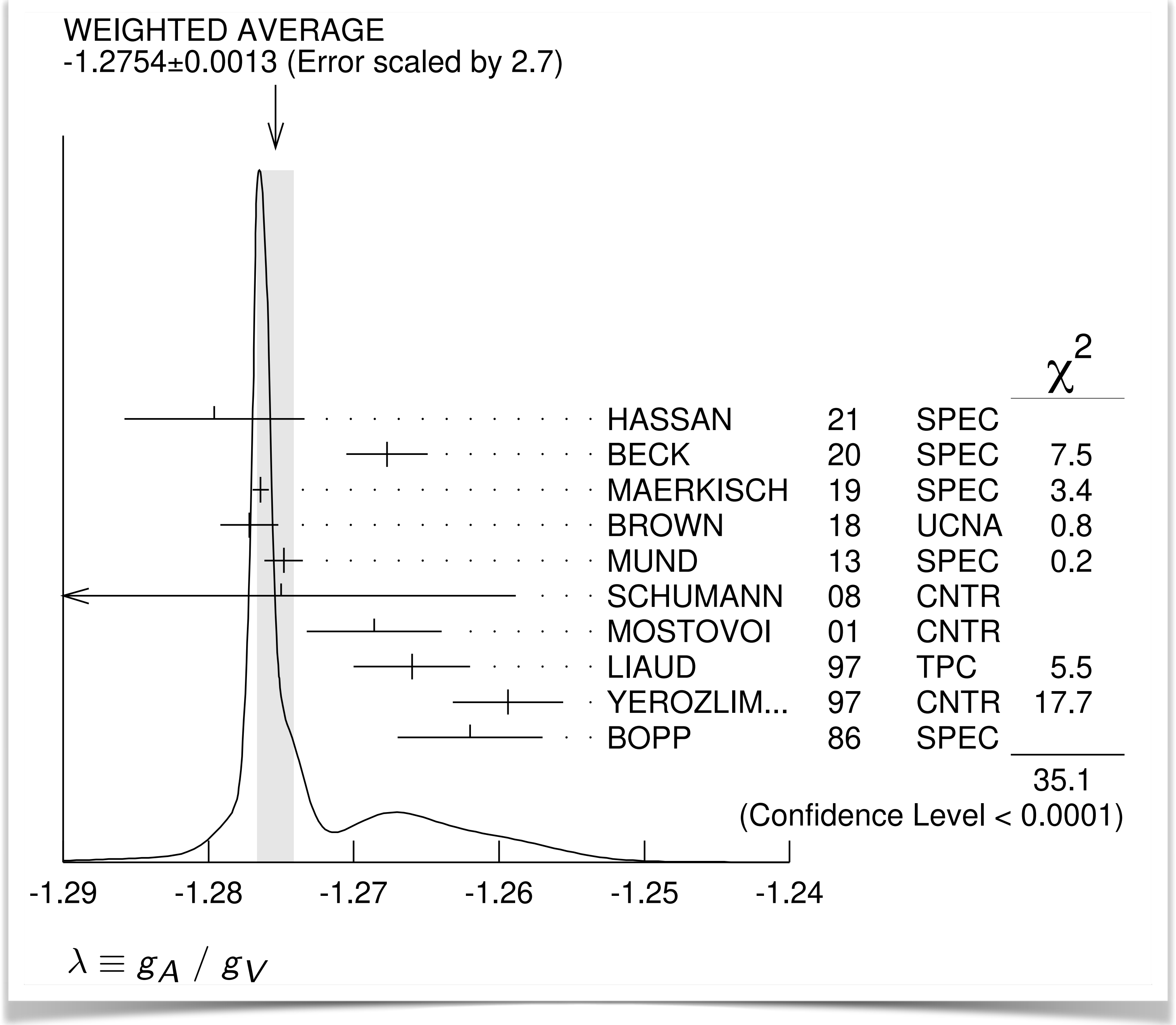
$$\Gamma_n = \frac{G_F^2 |V_{ud}|^2 m_e^5}{2\pi^3} (1 + 3\lambda^2) \cdot f_0 \cdot (1 + \Delta_f) \cdot (1 + \Delta_R),$$

$$\Delta_R = 4.044(27)\%$$
$$\Delta_f = 3.573(5)\%$$

VC, W. Dekens, E. Mereghetti, O. Tomalak, 2306. 03138

- Radiative corrections: NLL setup + LECs in terms of 'γ-W box' (dispersive & Lattice QCD)
- Experimental input: PDG averages include large scale factor, particularly for g_A/g_V





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- Experimental input: PDG averages include large scale factor, particularly for g_A /g_V

Single most precise measurements of lifetime and λ imply very competitive V_{ud}!

Maerkish et al, 1812.04666 Gonzalez et al, 2106.10375

$$V_{ud}^{\rm n,PDG} = 0.97430(2)_{\Delta_f}(13)_{\Delta_R}(82)_{\lambda}(28)_{\tau_n}[88]_{\rm total}$$

$$V_{ud}^{\rm n,best} = 0.97402(2)_{\Delta_f}(13)_{\Delta_R}(35)_{\lambda}(20)_{\tau_n}[42]_{\rm total}$$

Need improvements in lifetime and g_A /g_V .
Within reach in next 5 years

V_{us} from $K \to \pi l \nu$ decays

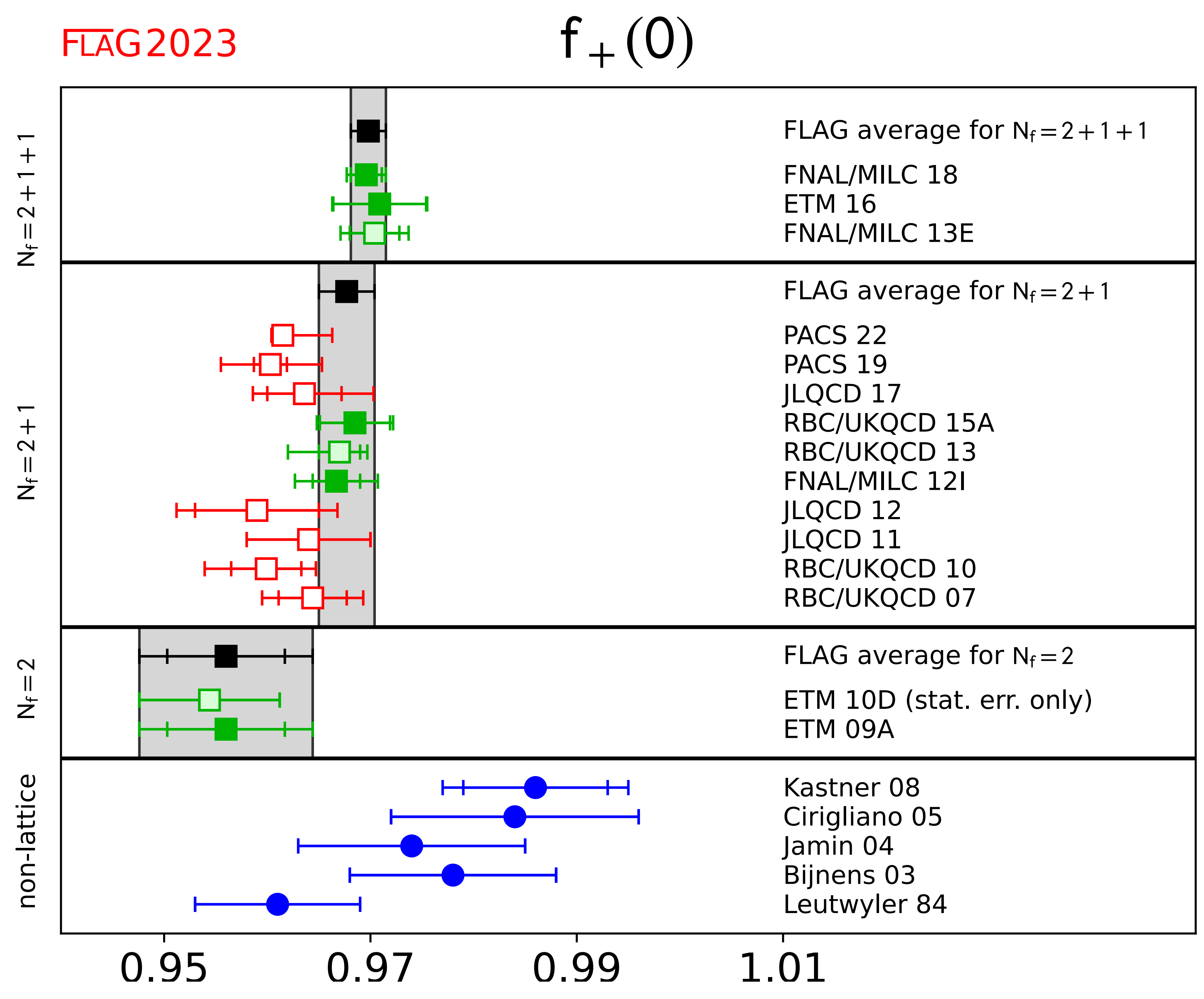
$$\Gamma_{K\to\pi\ell\nu(\gamma)} = \frac{C_K^2 G_F^2 S_{EW} |V_{us}|^2 M_K^5}{192\pi^3} |f_+^{K\pi}(0)|^2 I_{K\ell} \left(1 + 2\Delta_{K\ell}^{EM} + 2\Delta_K^{IB}\right)$$

- Lattice calculations of <π|V|K> @ 0.2%: $f_+^{K\pi}(0) = 0.9698(17)$

- New radiative corrections based on current algebra + lattice QCD. Consistent with ChPT, with much smaller uncertainties

	Cirigliano et al. '08	Seng et al. '21
$\Delta^{EM}(K^0_{e3})$ [%]	0.50 ± 0.11	**0.580 ± 0.016**
$\Delta^{EM}(K^+_{e3})$ [%]	0.05 ± 0.12	**0.105 ± 0.023**
$\Delta^{EM}(K^+_{\mu3})$ [%]	0.70 ± 0.11	**0.770 ± 0.019**
$\Delta^{EM}(K^0_{\mu3})$ [%]	0.01 ± 0.12	**0.025 ± 0.027**

NEW: Seng et al, 1910.13209, 2103.00975. 2103.4843. 2107.14708. 2203.05217. Ma et al. 2102.12048
OLD: VC, Giannotti, Neufeld 0807.4607



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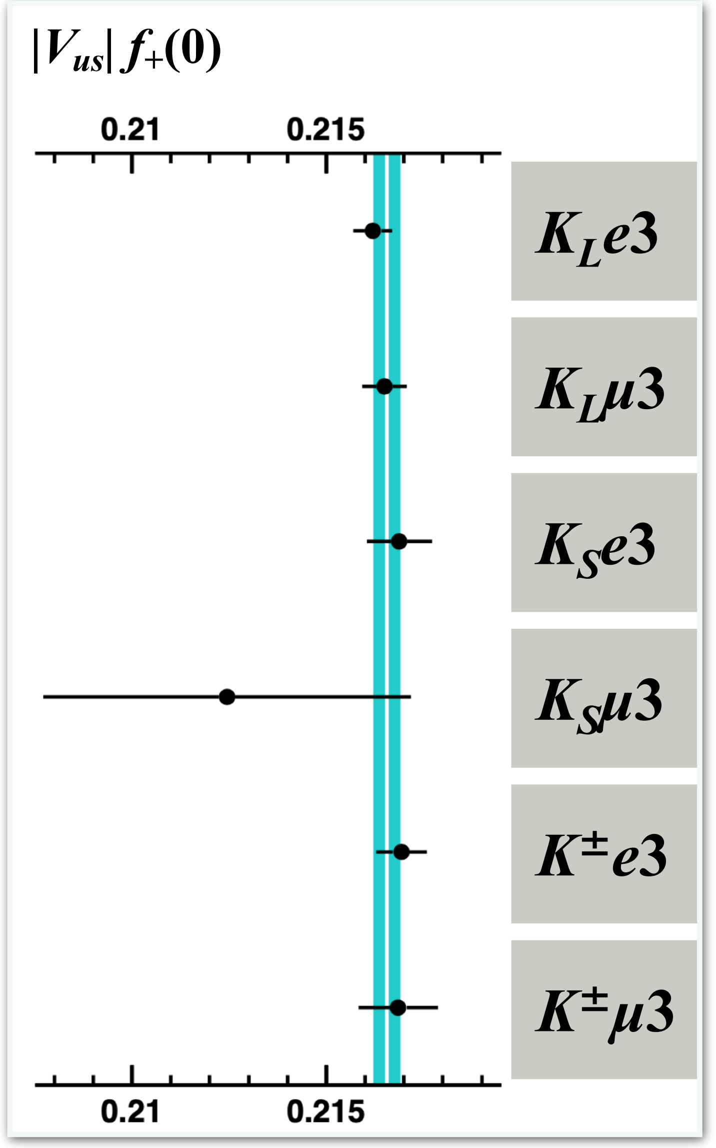
- New radiative corrections based on current algebra + lattice QCD. Consistent with ChPT, with much smaller uncertainties
- Experimental input has received only small updates since 2010

Flavianet WG, 1005.2323 Moulson 1704.04104



$$V_{us}^{K\ell 3} = 0.22330(35)_{\rm exp}(39)_{f_+}(8)_{\rm RC+IB}[53]_{\rm total}$$

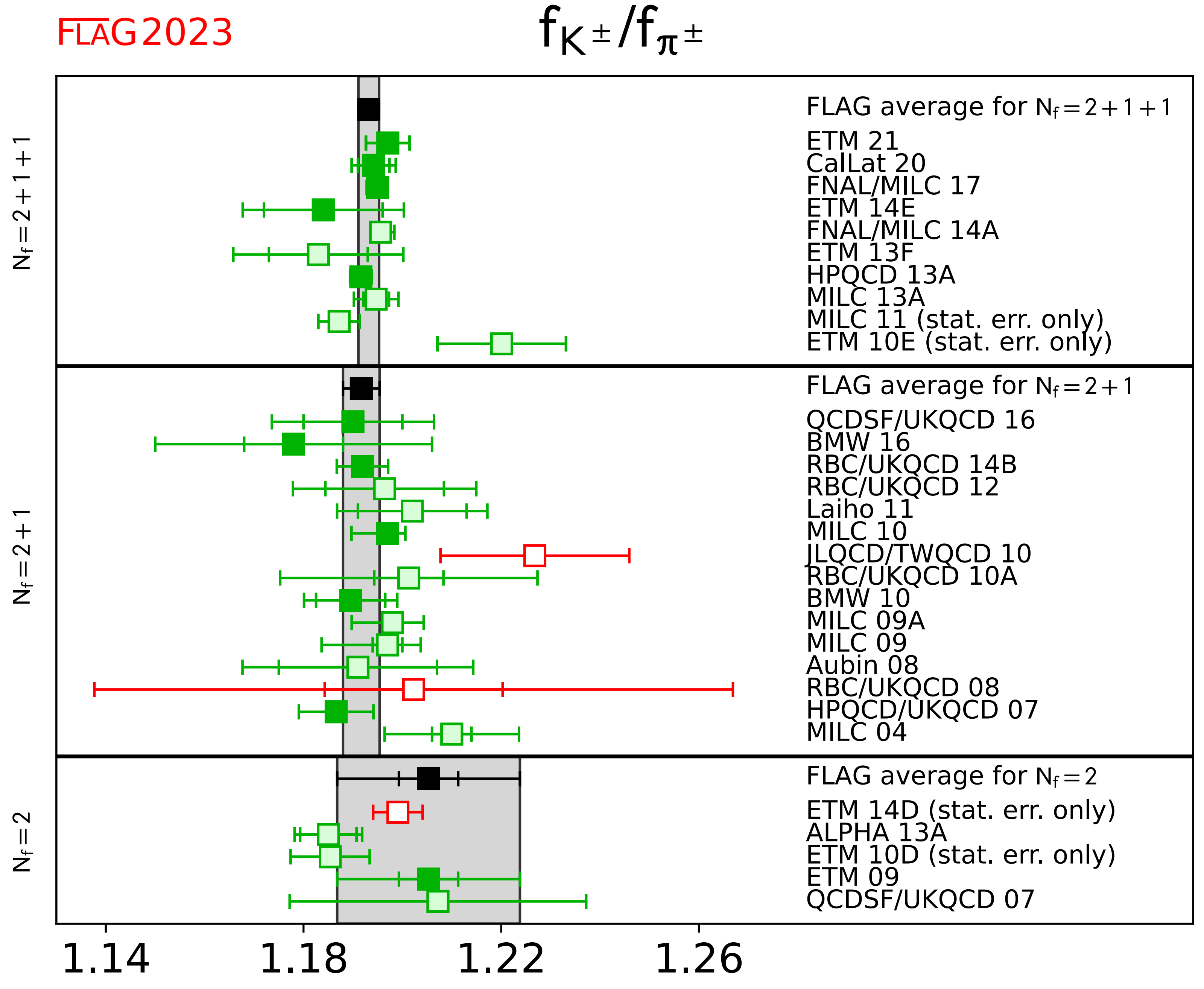
Potential issue: definition of 'isosymmetric QCD' in lattice ($f_+(0)$) vs calculations of $\Delta^{EM, IB}$

V_{us} from $K \to \mu\nu$ decays

$$\frac{|V_{us}|}{|V_{ud}|}\frac{f_K}{f_\pi} = \left(\frac{\Gamma_{K\to\mu\nu(\gamma)}}{\Gamma_{\pi\to\mu\nu(\gamma)}}\frac{m_{\pi^\pm}}{m_{K^\pm}}\right)^{1/2}\frac{1-m_\mu^2/m_{\pi^\pm}^2}{1-m_\mu^2/m_{K^\pm}^2}\left(1-\frac{\Delta^{K\pi}_{\rm RC+IB}}{2}\right)$$

- Lattice QCD calculations of F_K/F_π are at the 0.2% level
- First calculation of radiative and isospin-breaking corrections in LQCD.**
  Compatible with ChPT, factor of ~2 more precise

ChPT: VC-Neufeld, 1102.0563	** LQCD1: Di Carlo et al., 1904.08731	LQCD2: Boyle et al., 2211.12865
$\Delta^{K\pi}_{\rm RC+IB} = -1.12(21)\%$	$\Delta^{K\pi}_{\rm RC+IB} = -1.26(14)\%$	$\Delta^{K\pi}_{\rm RC+IB} = -0.86(40)\%$



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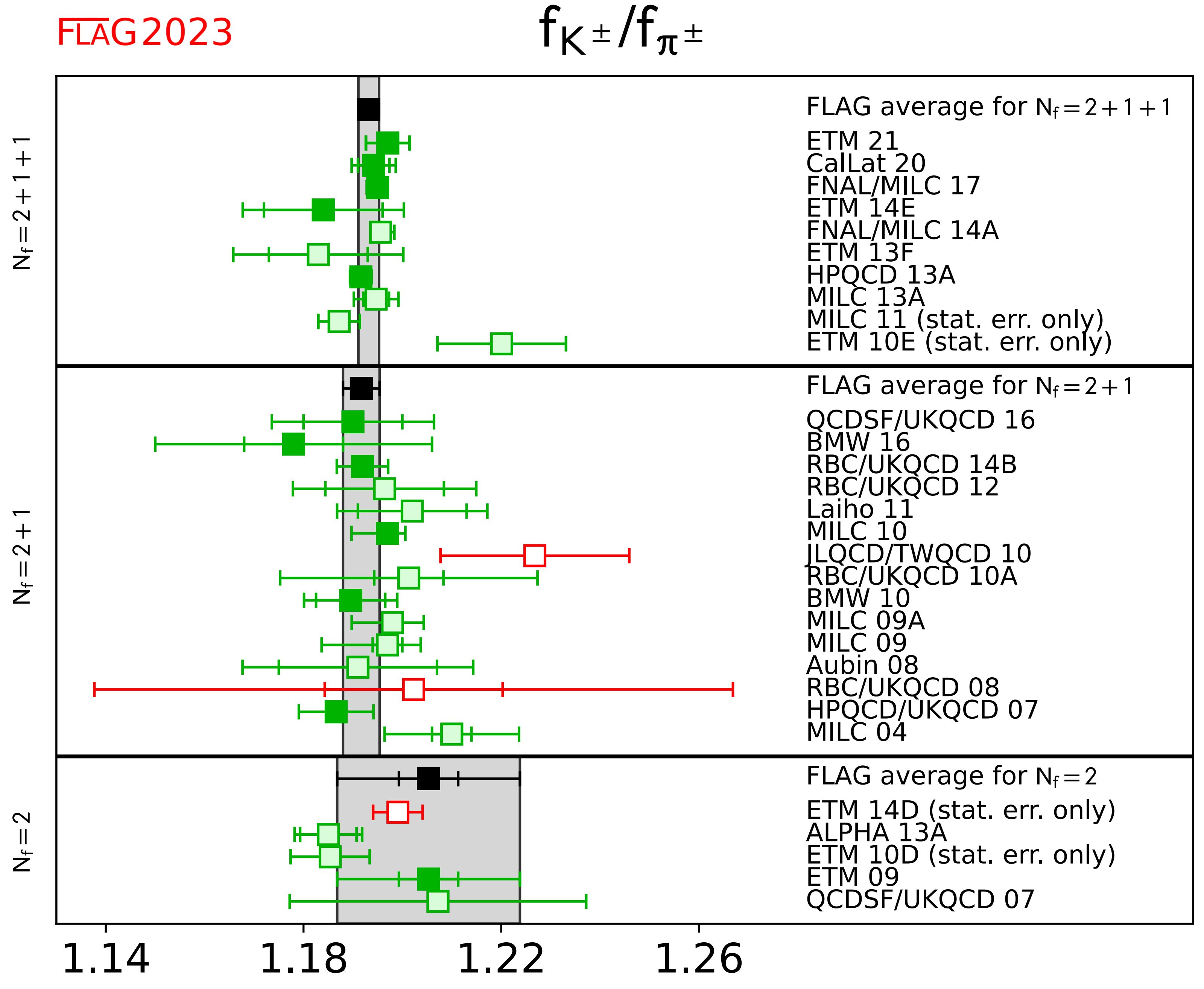

Potential issue (1):

Kmu2 BR dominated by one measurement (KLOE)

Km3/Kmu2 BR measurement at 0.2% would have significant impact

$$\left.\frac{V_{us}}{V_{ud}}\right|_{K_{\ell 2}/\pi_{\ell 2}} = 0.23108(23)_{\rm exp}(42)_{F_K/F_\pi}(16)_{\rm RC+IB}[51]_{\rm total}$$

Potential issue (2):

Isospin scheme dependence

V_{us} from hyperon decays

$$\Gamma = \frac{G_F^2}{60\pi^3}(M_B - M_b)^5(1-3\delta)|V_{us}|^2|f_1^{B\to b}(0)|^2(1+\Delta_{\rm RC})\left[1+3\left|\frac{g_1^{B\to b}(0)}{f_1^{B\to b}(0)}\right|^2+\cdots\right]$$

$$\delta = \frac{M_B - M_b}{M_B + M_b}$$

- Use SU(3) limit for vector form factor $f_1(0)$
- Extract g_1/f_1 from data

Cabibbo-Swallow-Winston. hep-ph/0307298

Decay Process	Rate (μsec^{-1})	g_1/f_1	V_{us}
$\Lambda \to pe^-\overline{\nu}$	3.161(58)	0.718(15)	0.2224 ± 0.0034
$\Sigma^- \to ne^-\overline{\nu}$	6.88(24)	−0.340(17)	0.2282 ± 0.0049
$\Xi^- \to \Lambda e^-\overline{\nu}$	3.44(19)	0.25(5)	0.2367 ± 0.0099
$\Xi^0 \to \Sigma^+ e^-\overline{\nu}$	0.876(71)	1.32(+.22/ − .18)	0.209 ± 0.027
Combined	—	—	0.2250 ± 0.0027

V_{us} @ %-level in best channels.
No theoretical uncertainty included

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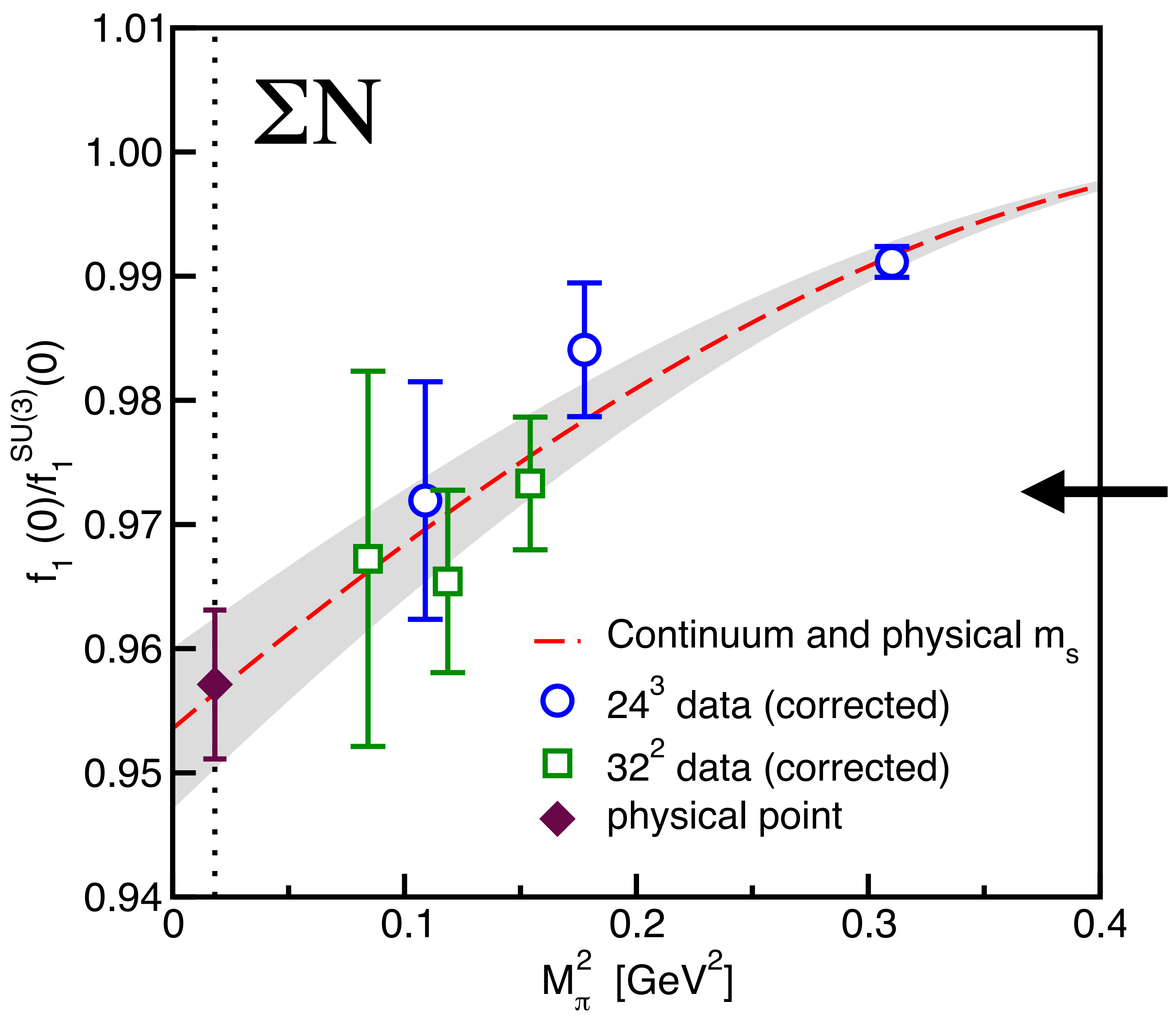
- S~~U~~(3) in $f_1(0)$: quark model, $1/N_c$, ChPT → LQCD
- Negative shift of few percent with uncertainty ~1%

2+1, DWF, 2 lattice spacings



Guadagnoli et al., heo-ph/0606181.

....

Sasaki 1708.04008

....

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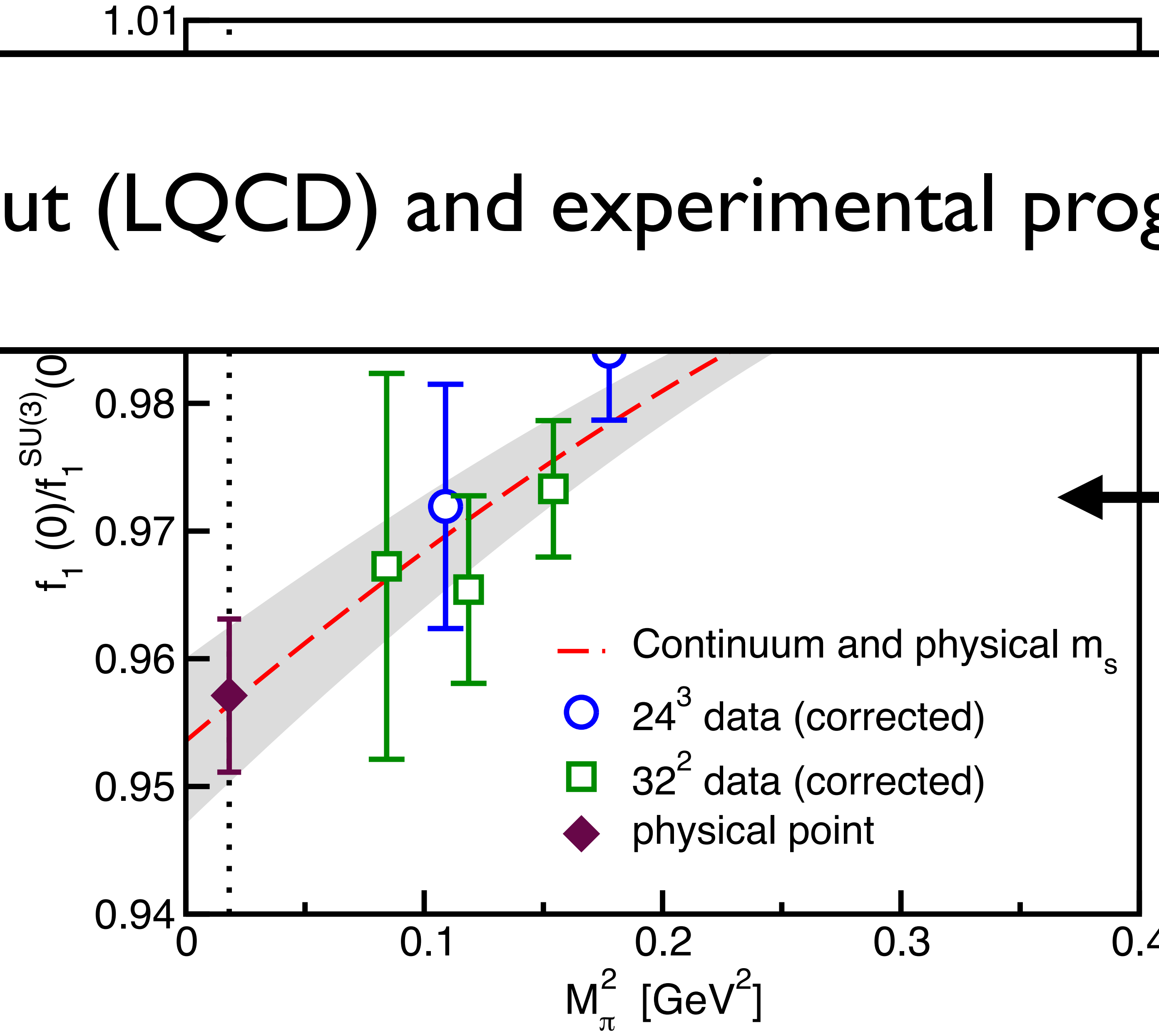

Sasaki 1708.04008

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Competitive extraction of V_{us} will require improved theory input (LQCD) and experimental progress (LHCb?)

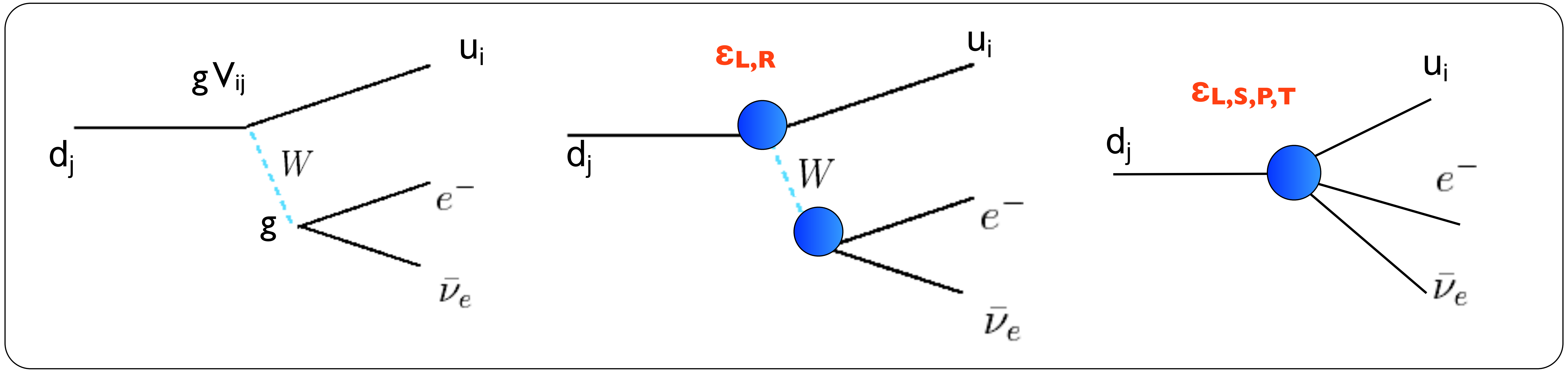
Summary of expected / desired developments

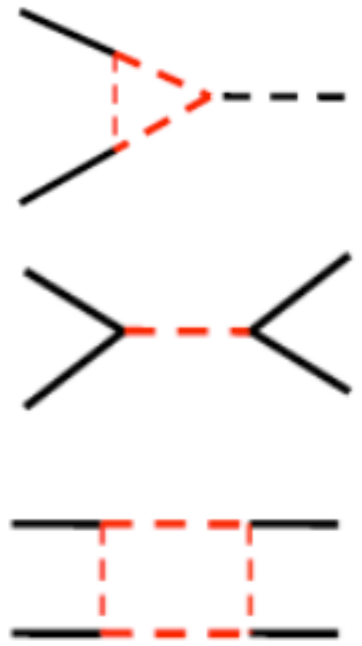
- Experiment:
  - Neutron decay: aim for $\delta\tau_n \sim 0.1s$ and $\delta g_A/g_A \sim 0.01\%$ to get $\delta V_{ud} \sim 1.5\ 10^{-4}$. [PERC, UCN$\tau$+]
  - Pion beta decay BR: 3x to 10x at PIONEER phases II, III [10+ years]
  - New $K_{\mu3}/K_{\mu2}$ BR measurement @0.2% at NA62 / HIKE would shed light on Kl3 vs Kl2 tension
  - τ decays: Belle-II will reduce experimental uncertainties by > 2x

- Theory:
  - Radiative corrections in lattice QCD+QED or hybrid: $K \to \pi l \nu$, $\pi^+ \to \pi^0 e^+ \nu$, $n \to p e \nu$, $\tau \to K \nu$, hyperons
  - Nuclear decays: EFT fto $O(G_F \alpha)$ coupled to first-principles nuclear calculations for δ_{NS}, δ_C

Cabibbo universality
and
physics beyond the Standard Model

Semileptonic processes beyond the SM





W_R, H^+, leptoquarks, Vector-Like quarks, Z', SUSY,…

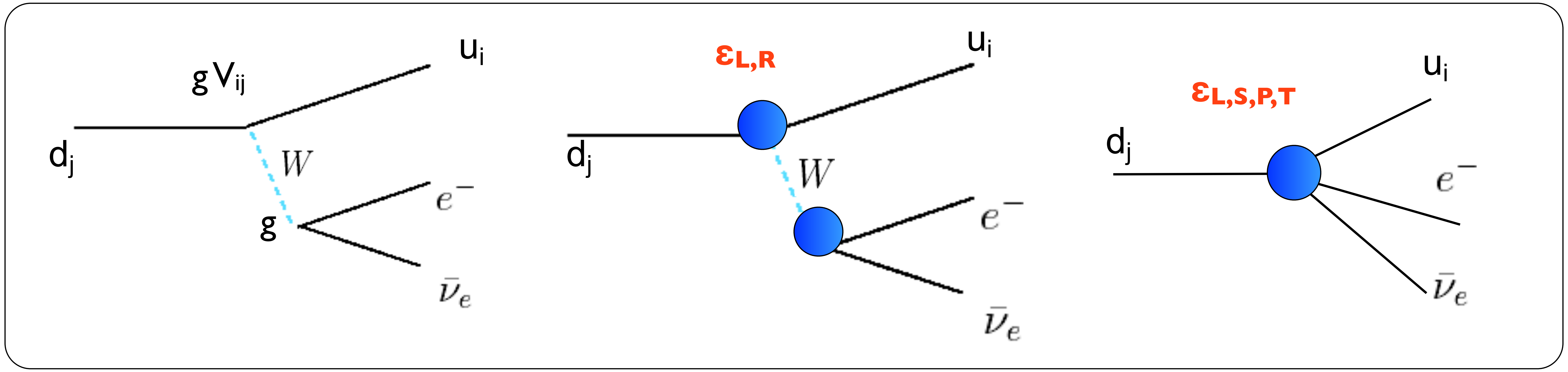
E << Λ ↓ $\varepsilon_\Gamma \sim \tilde{\varepsilon}_\Gamma \sim (v/\Lambda)^2$

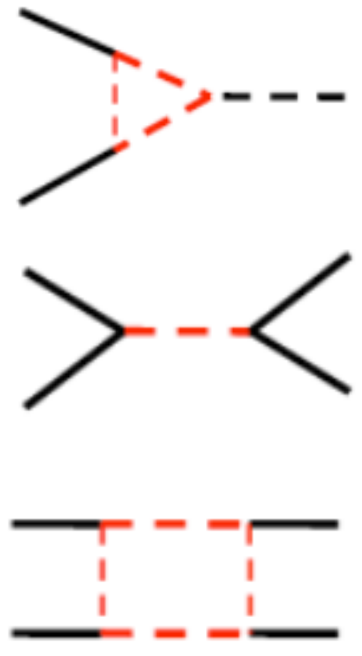
$$\mathcal{L}_{\rm SM} - \frac{G_F V_{ud_j}}{\sqrt{2}} \sum_\Gamma \left[\epsilon_\Gamma^{(j)}\, \bar\ell \Gamma \nu_L \cdot \bar u \Gamma d_j \; + \; \tilde\epsilon_\Gamma^{(j)}\, \bar\ell \Gamma \nu_R \cdot \bar u \Gamma d \right]$$

$$\Gamma = L, R, S, P, T$$

BSM effects parameterized by 10(ud) +10(us) effective couplings at E ~ GeV
They map into vertex corrections and 4-Fermion interactions above the EW scale

Semileptonic processes beyond the SM





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$$\Gamma = L, R, S, P, T$$

$\Delta_{\rm CKM}$ tension confirmed: points to specific new physics

$\Delta_{\rm CKM}$ tension removed: strong constraints, complementary to traditional 'precision electroweak observables'

Corrections to V_{ud} and V_{us}

$$|\bar{V}_{ud}|_i^2 = |V_{ud}|^2 \left(1 + \sum_\alpha C_{i\alpha}\epsilon_\alpha\right)$$

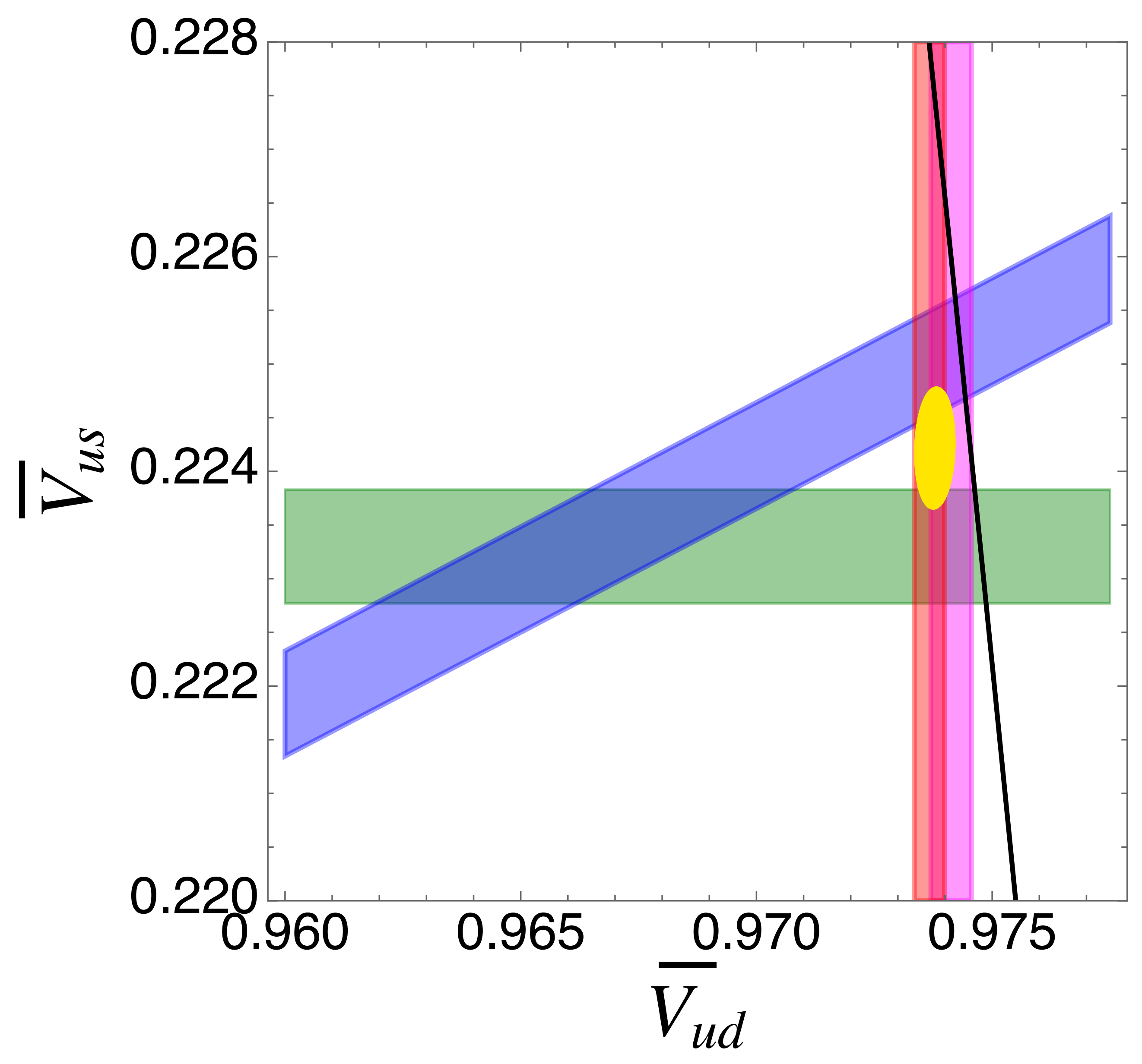
$$|\bar{V}_{us}|_j^2 = |V_{us}|^2 \left(1 + \sum_\alpha C_{j\alpha}\epsilon_\alpha\right)$$

Channel-dependent CKM elements extracted in the 'SM-like analysis'

Elements of the unitary CKM matrix

Known coefficients

BSM effective coupligs



Find set of ε's so that V_{ud} and V_{us} bands meet on the unitarity circle

Corrections to V_{ud} and V_{us}

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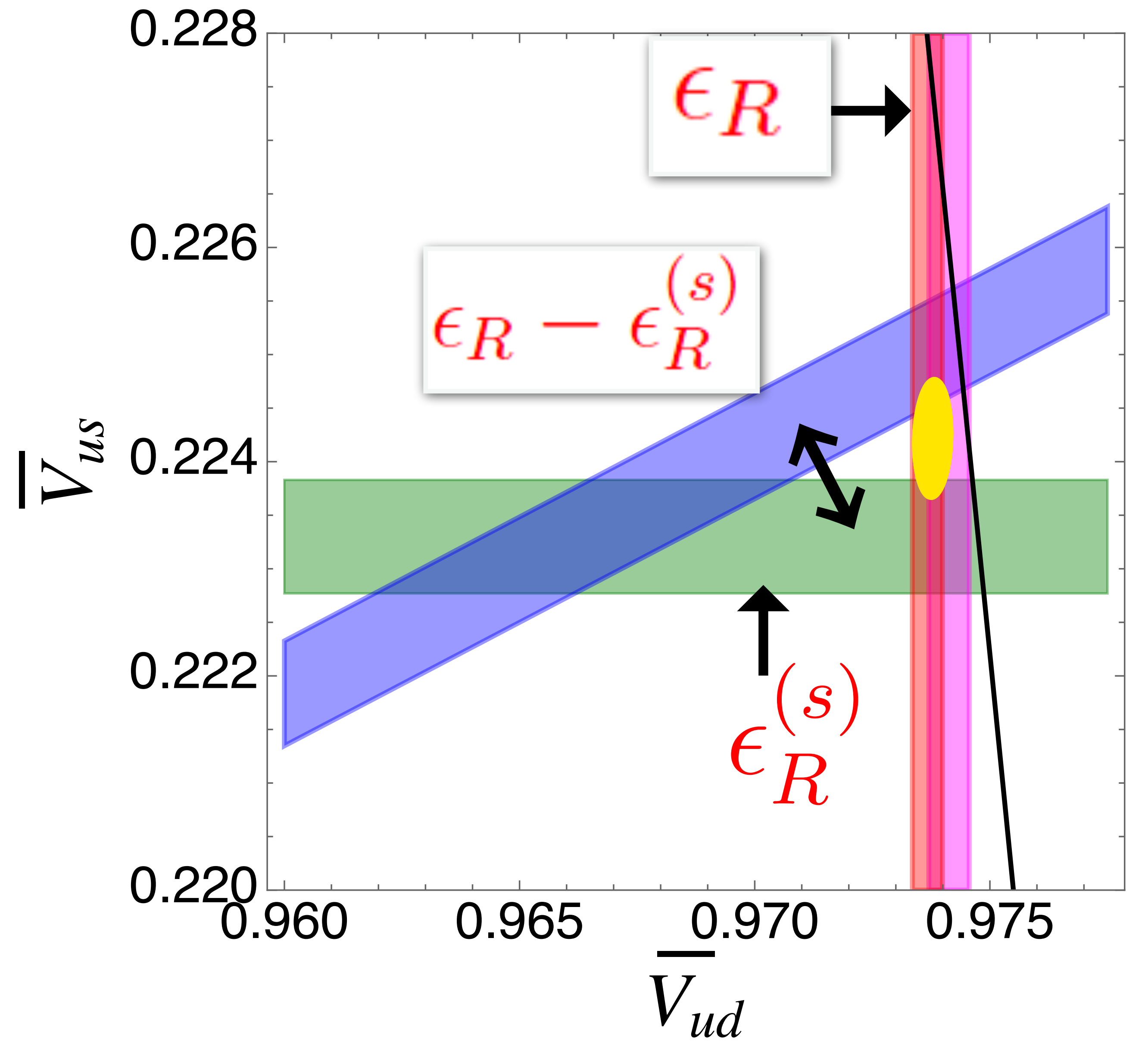


Find set of ε's so that V_{ud} and V_{us} bands meet on the unitarity circle

Simplest 'solution': right-handed (V+A) quark currents

CKM elements from vector (axial) channels are shifted by $1+\varepsilon_R$ $(1-\varepsilon_R)$.

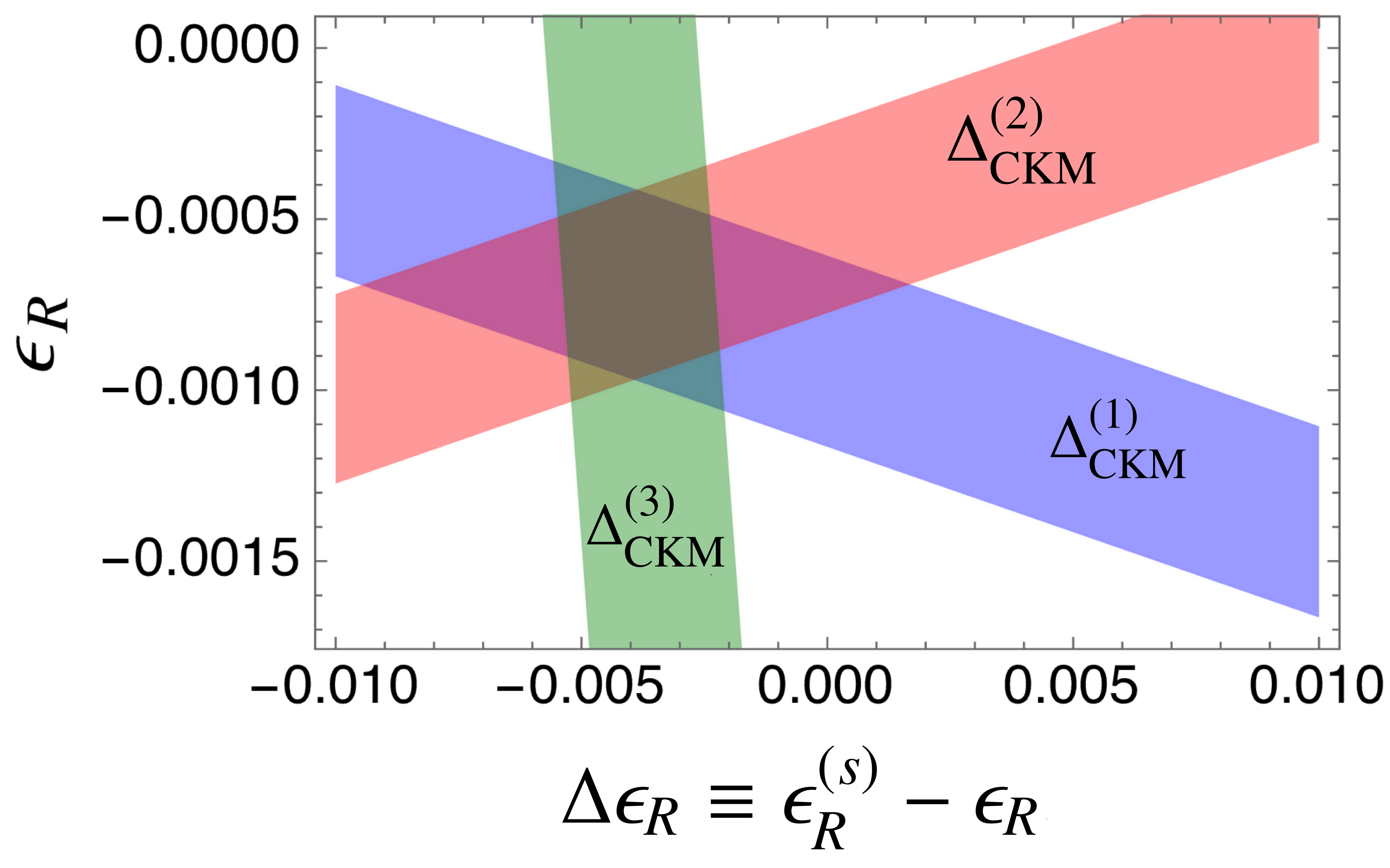
V_{us}/V_{ud} , V_{ud} and V_{us} shift in correlated way, can resolve all tensions!

Alioli et al 1703.04751
Grossman-Passemar-Schacht 1911.07821
VC-Crivellin-Hoferichter-Moulson 2208.11707
VC, W. Dekens, J. De Vries, E. Mereghetti, T. Tong, 2311.00021

For other BSM explanations, see A. Crivellin 2207.02507 and references therein

Unveiling R-handed quark currents?

VC-Crivellin-Hoferichter-Moulson 2208.11707



$$\begin{aligned}
\Delta^{(1)}_{CKM} &= |V^{\beta}_{ud}|^2 + |V^{K_{\ell 3}}_{us}|^2 - 1 \\
&= -1.76(56) \times 10^{-3} \\
\Delta^{(2)}_{CKM} &= |V^{\beta}_{ud}|^2 + |V^{K_{\ell 2}/\pi_{\ell 2},\beta}_{us}|^2 - 1 \\
&= -0.98(58) \times 10^{-3} \\
\Delta^{(3)}_{CKM} &= |V^{K_{\ell 2}/\pi_{\ell 2},K_{\ell 3}}_{ud}|^2 + |V^{K_{\ell 3}}_{us}|^2 - 1 \\
&= -1.64(63) \times 10^{-2}
\end{aligned}$$

↓

$$\epsilon_R = -0.69(27) \times 10^{-3}$$

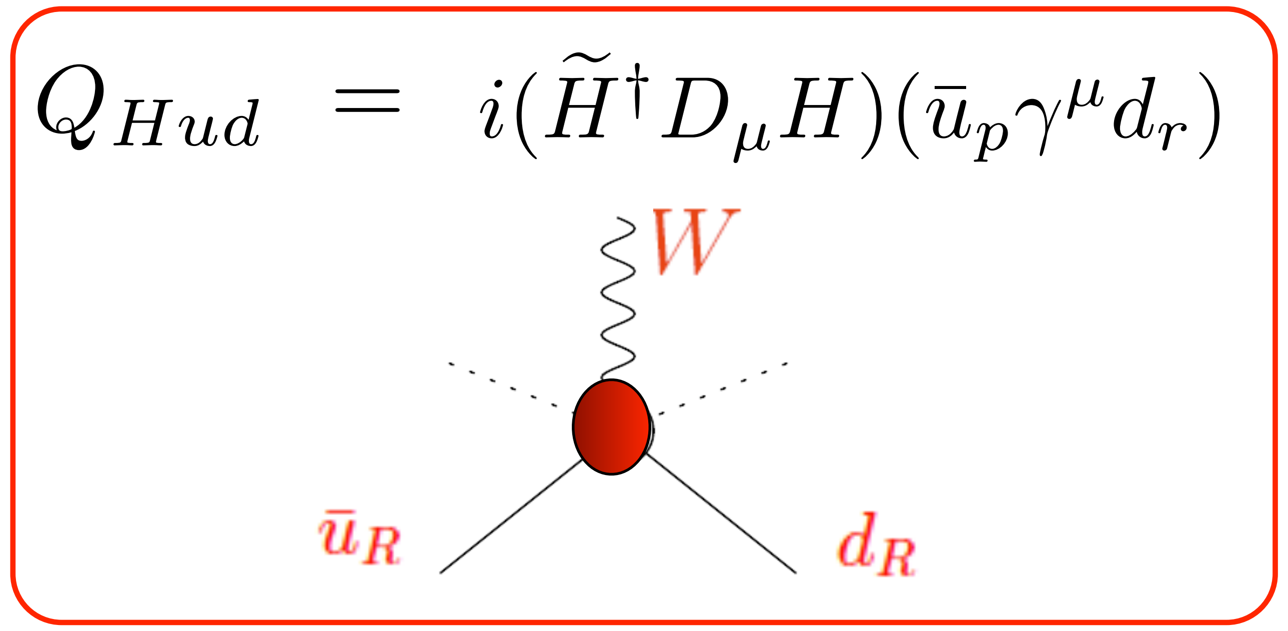
$$\Delta\epsilon_R = -3.9(1.6) \times 10^{-3}$$

$\Lambda_R \sim$ 5-10 TeV

- Preferred ranges are not in conflict with other constraints from β decays, nor from $K \to (\pi\pi)_{I=2}$
- Does the R-handed current explanation survive after taking into account high energy data?

VC, Hayen, deVries, Mereghetti, Walker-Loud, 2202.10439
VC, W. Dekens, J. De Vries, E. Mereghetti, T. Tong, 2311.00021

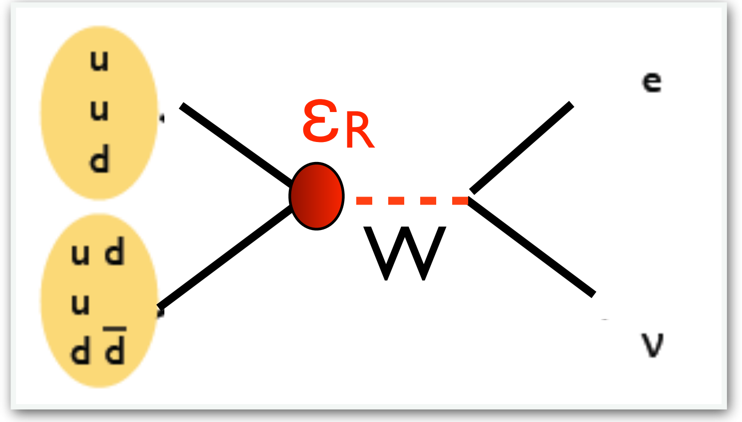
ε_R: high scale origin and constraints



- ε_R originates from SU(2)xU(1) invariant vertex corrections
- ε_R only weakly constrained by LHC processes

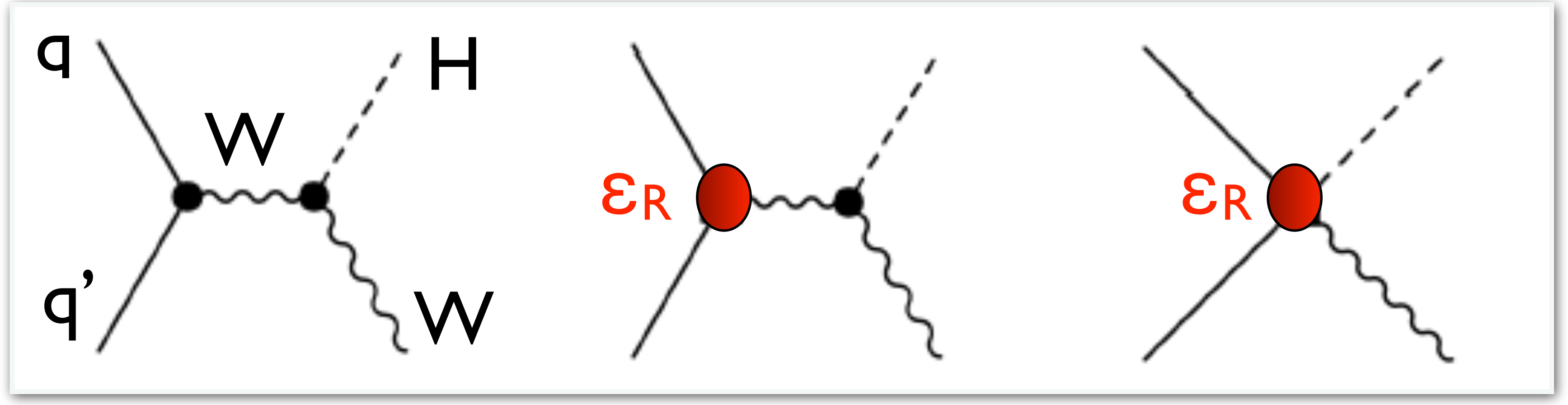
Same shape as the SM W exchange → weak sensitivity

pp → eν + X



VC, Graesser, Gonzalez-Alonso 1210.4553

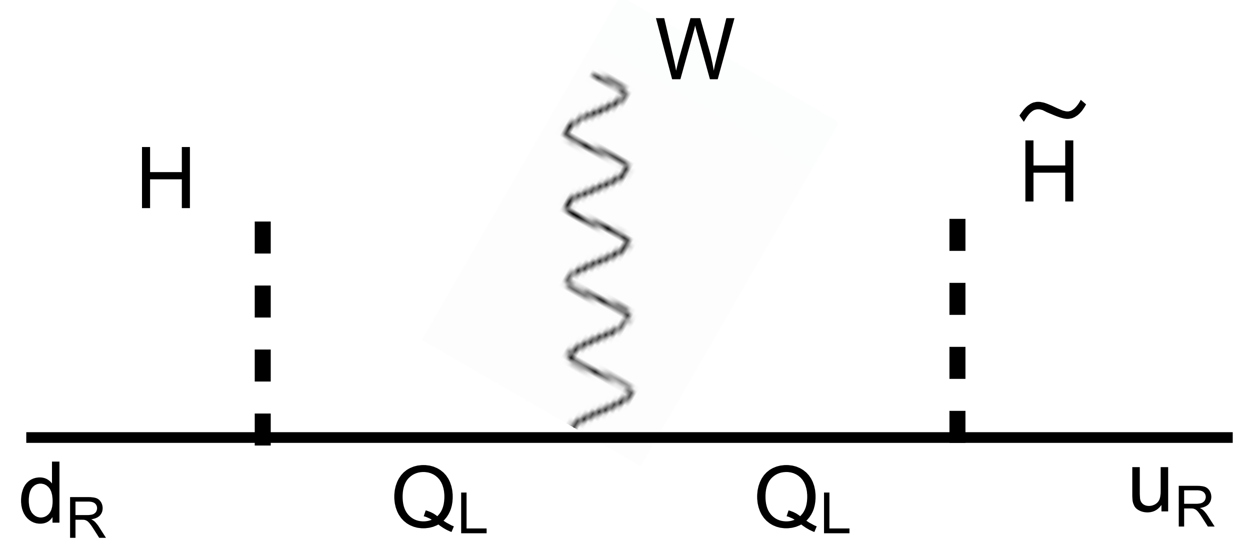
Associated Higgs +W production



S. Alioli, VC, W. Dekens, J. de Vries, E. Mereghetti 1703.04751

Current LHC results allow for to $\varepsilon_R \sim 5\%$

- ε_R can be generated at tree level by W_L-W_R mixing in LRSM or by exchange of vector-like quarks**



**Belfatto-Berezhiani 2103.05549. … **Belfatto-Trifinopoulos 2302.14097

60 years later…

The Cabibbo angle is the cornerstone of the CKM matrix and the
Cabibbo universality test is a precision tool to explore what may lie beyond the Standard Model

- Current tensions in Cabibbo universality test could point to new physics at $\Lambda \sim$ few TeV, with right-handed quark-W couplings a viable and testable culprit. However …

- Both experimental and theoretical scrutiny is needed! Progress expected on several fronts:
    - Experiment: neutron, K, π, τ
    - Theory: lattice QCD+QED for neutron, K, π; EFT+ 'ab-initio' methods for nuclei

Vibrant experimental and theoretical activities promise interesting developments

Backup

V_{ud} from pion β decay

$$\Gamma(\pi^+ \to \pi^0 e^+ \nu(\gamma)) = \frac{G_\mu^2 |V_{\rm ud}|^2 m_{\pi^+}^5 \, |f_+^\pi(0)|^2}{64\pi^3} (1 + {\rm RC}_\pi) I_\pi \,,$$

- Vector form factor

$$f_+(0) = 1 - \frac{1}{(4\pi F_\pi)^2} \frac{(M_{K^+}^2 - M_{K_0}^2)^2_{\rm QCD}}{24 M_K^2} = 1 + O\left(\frac{m_u - m_d}{\Lambda_{\rm QCD}}\right)^2$$

- Radiative corrections

$${\rm RC}_\pi = 0.0342(10) \quad ({\rm ChPT})$$

VC-Neufeld-Pichl 2002

→ Box diagram

$${\rm RC}_\pi = 0.0332(1)_{\gamma W}(3)_{HO} \quad ({\rm LQCD})$$

Feng, Gorchtein, Jin, Ma, Seng , 2003.09798

↓

$$V_{ud}^{(\pi\beta)} = 0.97386\,(281)_{BR}\,(9)_{\tau_\pi}\,(14)_{RC}\,(28)_{I_\pi}\,[283]_{\rm total}$$

Theory in great shape.
0.3% total error on V_{ud}
dominated by
BR = $1.036(6)\times 10^{-8}$
[PIBETA , hep-ex/ 0312030]

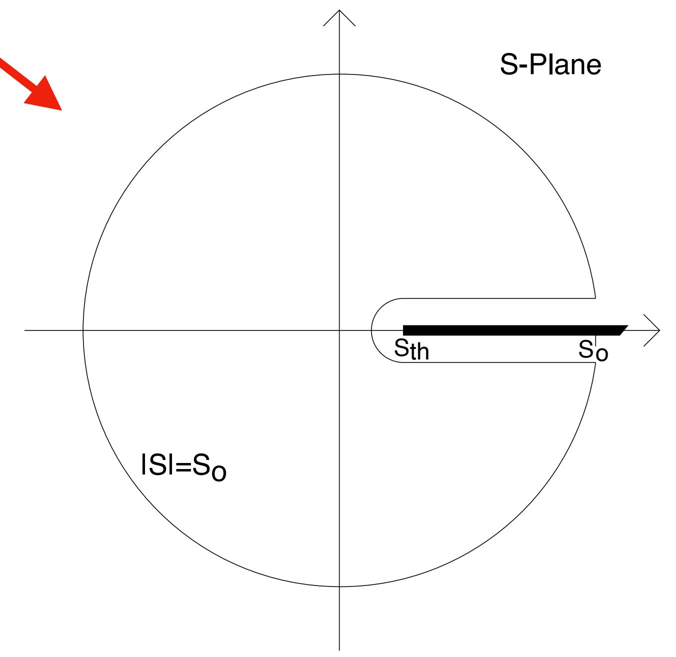
Experiment needs order-of-magnitude improvement in precision to be competitive → PIONEER @ PSI
2203.01908

V_{us} from tau decays

- Inclusive ($\tau \to X_s \nu$): need integrated spectral functions + $\Delta\Pi_{jj}(s)$ on the $|s| = s_0 \sim m_\tau^2$ circle (OPE → Lattice QCD)

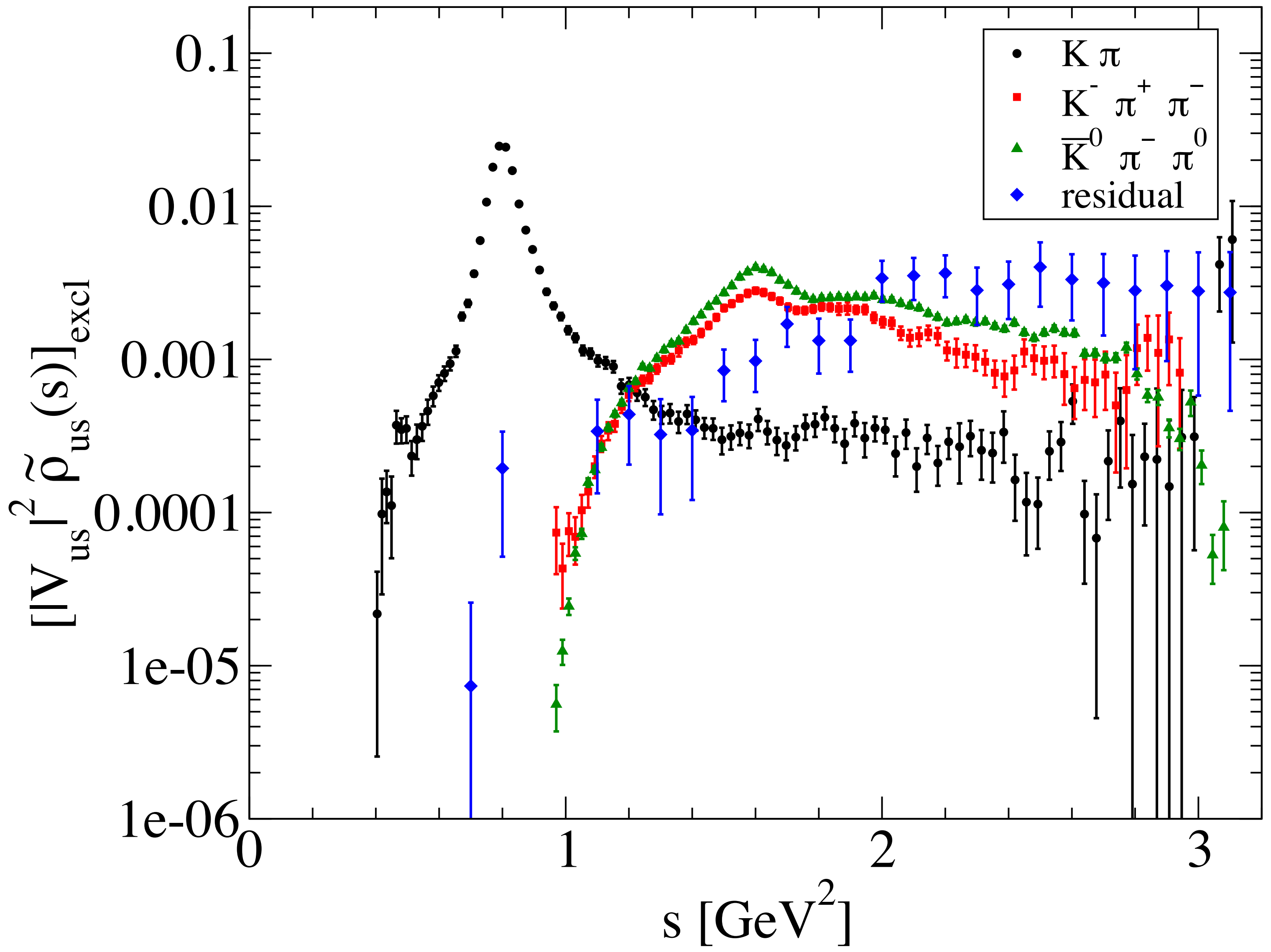
$$R_\tau = \frac{\Gamma[\tau \to \text{hadrons}\ \nu_\tau]}{\Gamma[\tau \to \bar{\nu}_e e \nu_\tau]}$$

$$\frac{R_{\tau,ud}}{|V_{ud}|^2} - \frac{R_{\tau,us}}{|V_{us}|^2} = \delta R_{\tau,th}$$



Gamiz et al. hep-ph/0212230, hep-ph/0408044, ...

$$\int_0^{s_0} \omega(s)\Delta\rho(s)ds = -\frac{1}{2\pi i}\oint_{|s|=s_0} \omega(s)\Delta\Pi(-s)ds$$



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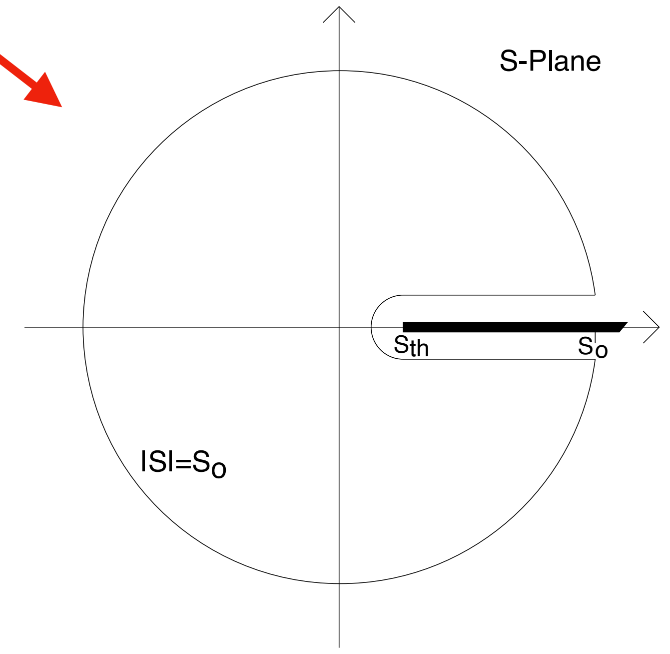
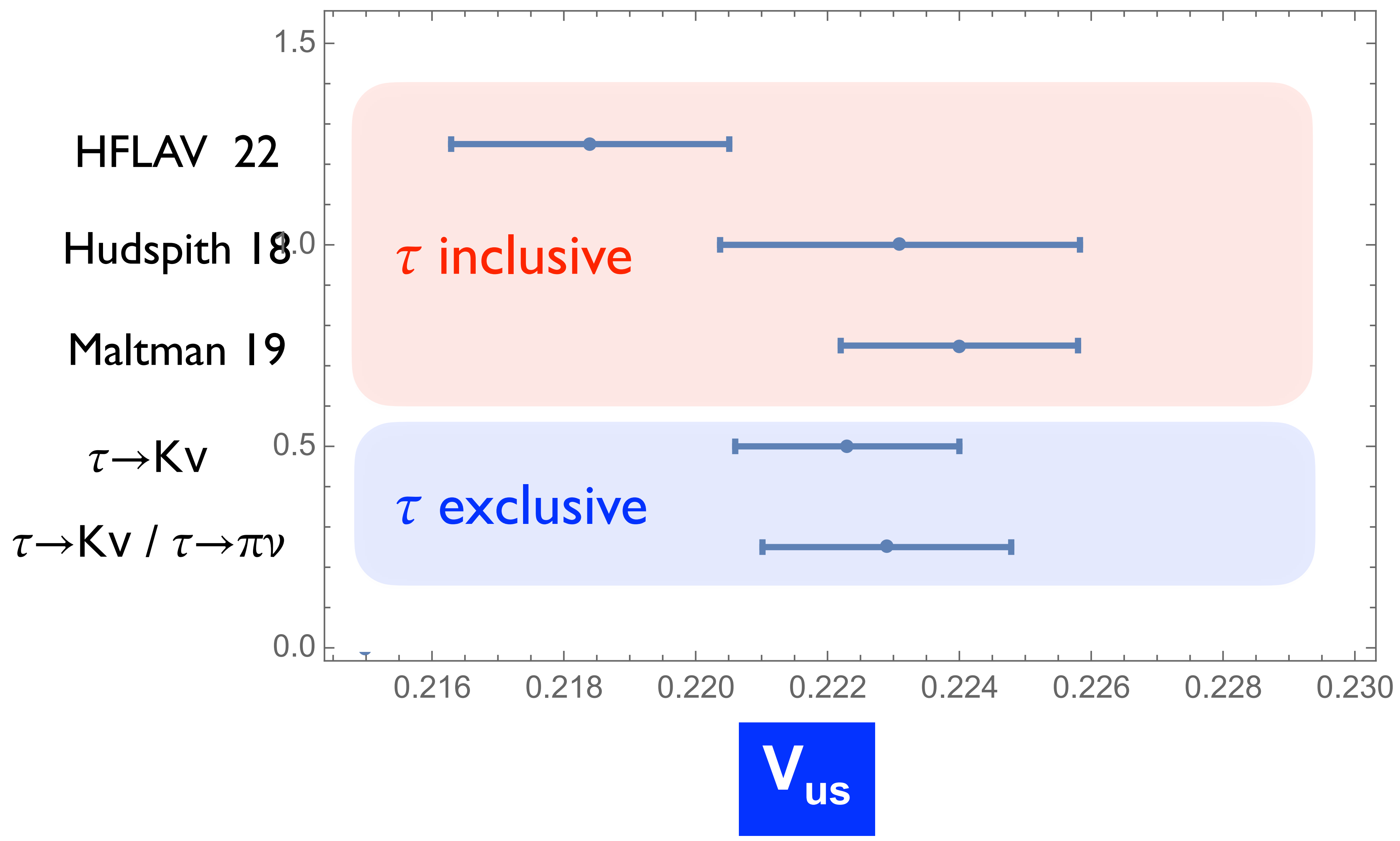


Gamiz et al. hep-ph/0212230, hep-ph/0408044, ...

- Exclusive ($\tau \to K\nu$ / $\tau \to \pi\nu$): need partial widths, decay constants (LQCD) & radiative corrections

From A. Lusiani, Talk at MITP ELECTRO 2022



A. Lusiani, HFLAG WG (1909.12524)

method	experiment [%]	theory [%]	lattice QCD [%]	rad.corr. [%]
$\tau \to X_s \nu$	0.84	0.49		
$\tau \to K / \tau \to \pi$	0.72		0.18	0.40
$\tau \to K$	0.69		0.19	0.29

Experimental prospects:

Belle-II and possibly tau-charm factory & FCC-ee

Theory prospects:

(1) Radiative corrections are a bottleneck for exclusive modes;

(2) lattice QCD will provide first-principles inclusive determination [see V. Lubicz talk]

Falsifying R-handed current hypothesis

- Compare g_A extracted from experiment and Lattice QCD

$$\lambda \equiv \frac{g_A}{g_V}$$

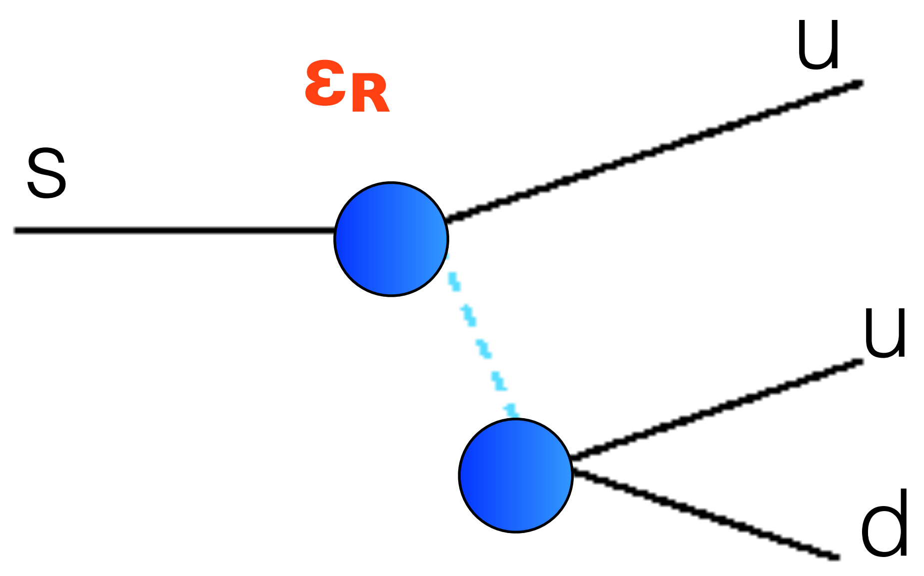
$$\delta_{RC} \simeq (2.0 \pm 0.6)\%$$

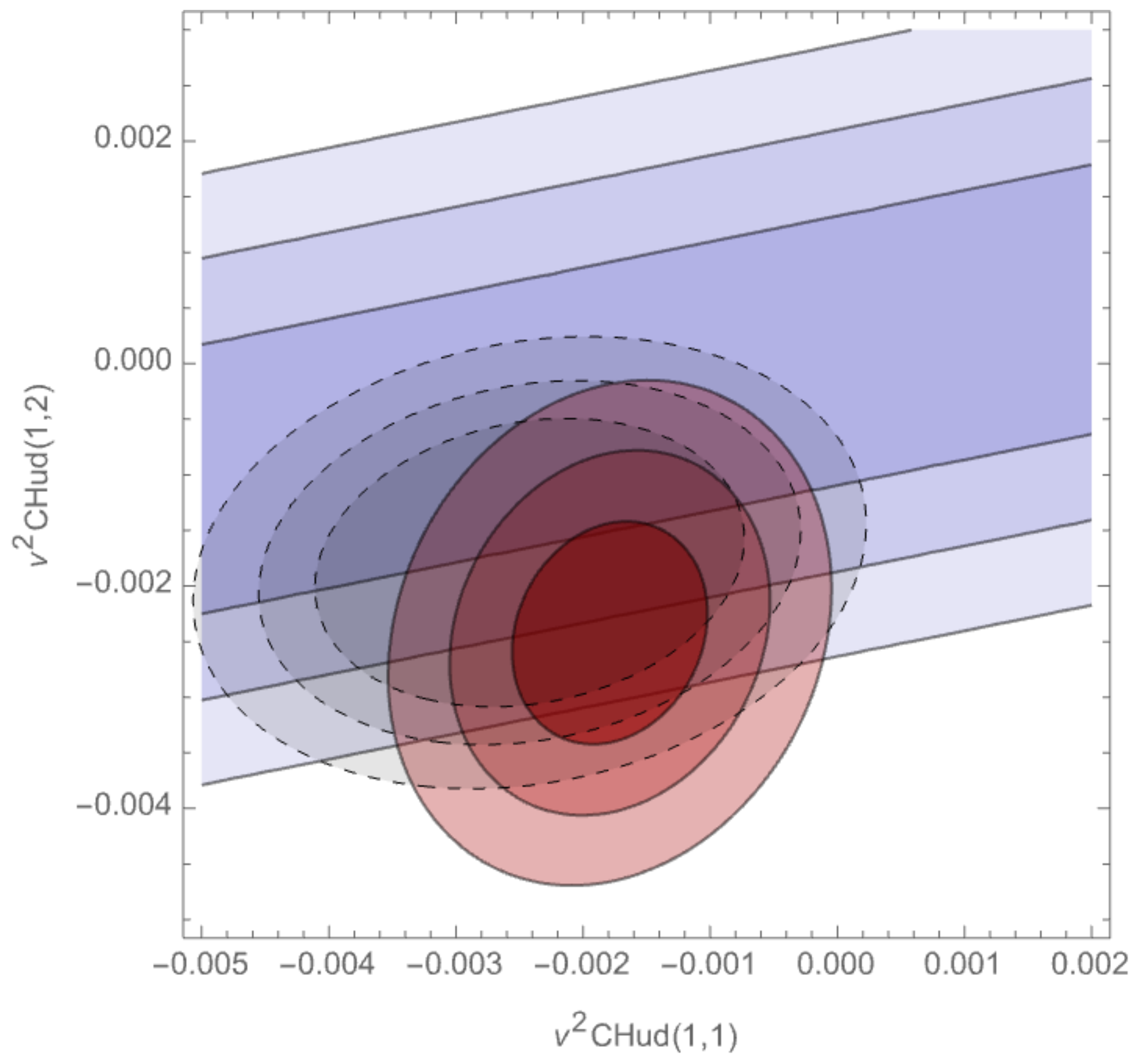
$$\boxed{\frac{\lambda^{\rm exp}}{\lambda^{\rm QCD}} = 1 + \delta_{\rm RC} - 2\epsilon_R}$$

$$\epsilon_R \;=\; -0.2(1.2)\%$$

VC, Hayen, deVries, Mereghetti, Walker-Loud, 2202.10439

- $K \to (\pi\pi)_{I=2}$ decay amplitude: experiment vs Lattice QCD





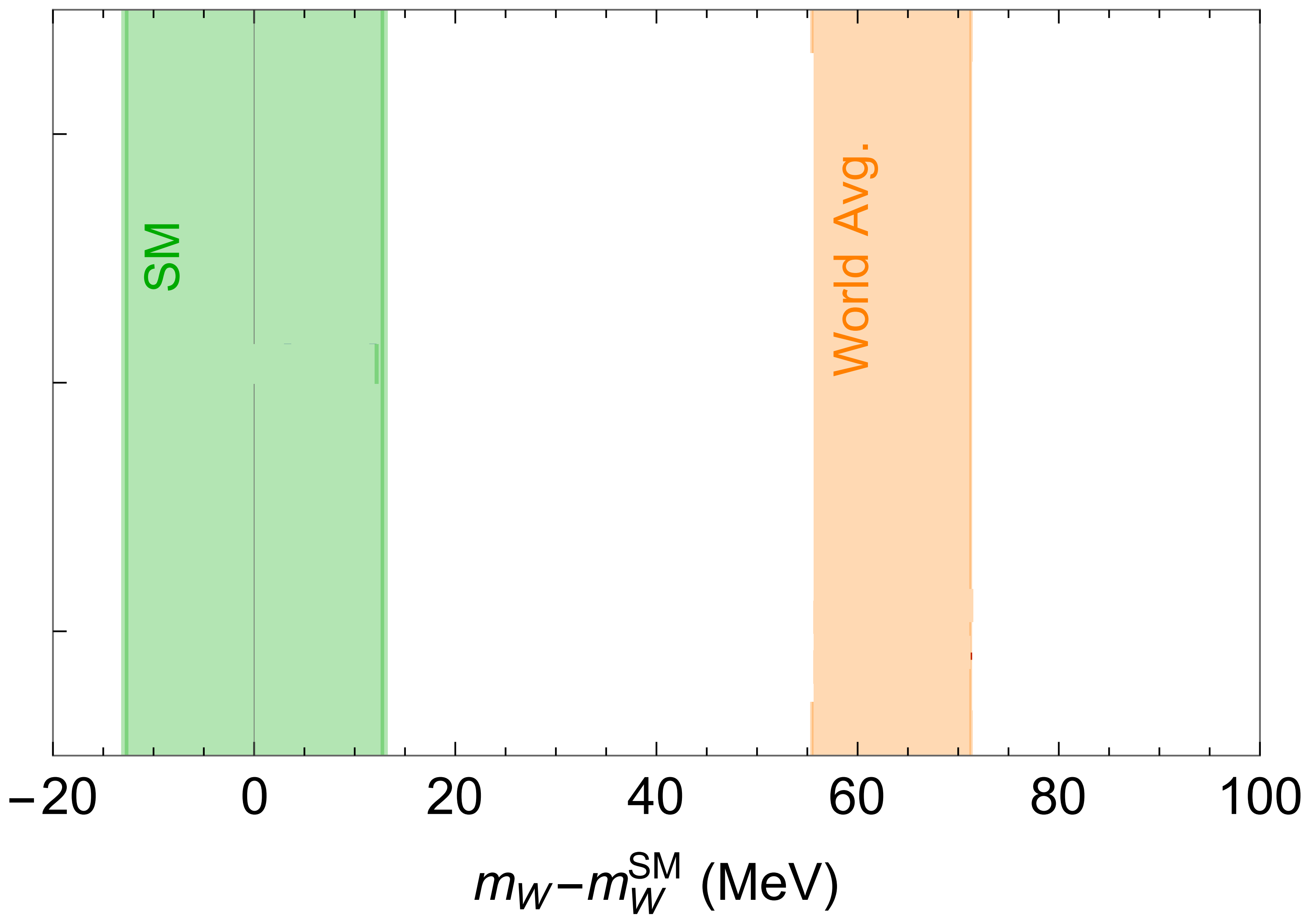
VC, W. Dekens, J. De Vries, E. Mereghetti, T. Tong, 2311.00021

Broader impact (even if tension disappears)

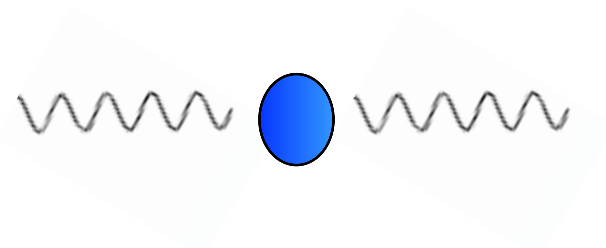
VC, Dekens, deVries, Mereghetti, Tong 2204.08440, 2311.00021

- Cabibbo universality test quantitatively and qualitatively affects global fits to precision EW observables
- Example: explanations of m_W 'anomaly' in SMEFT + U(3)[5]

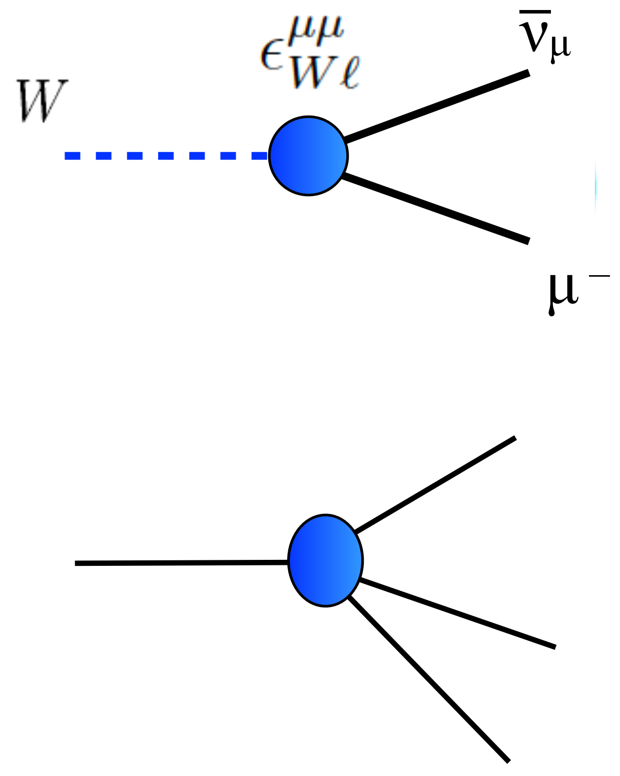
$$\frac{\delta m_W^2}{m_W^2} = v^2 \, \frac{s_w c_w}{s_w^2 - c_w^2} \left[2\, C_{HWB} + \frac{c_w}{2 s_w} \, C_{HD} + \frac{s_w}{c_w} \left(2\, C_{Hl}^{(3)} - \hat{C}_{ll} \right) \right]$$



'Oblique corrections'



Shift to G_F



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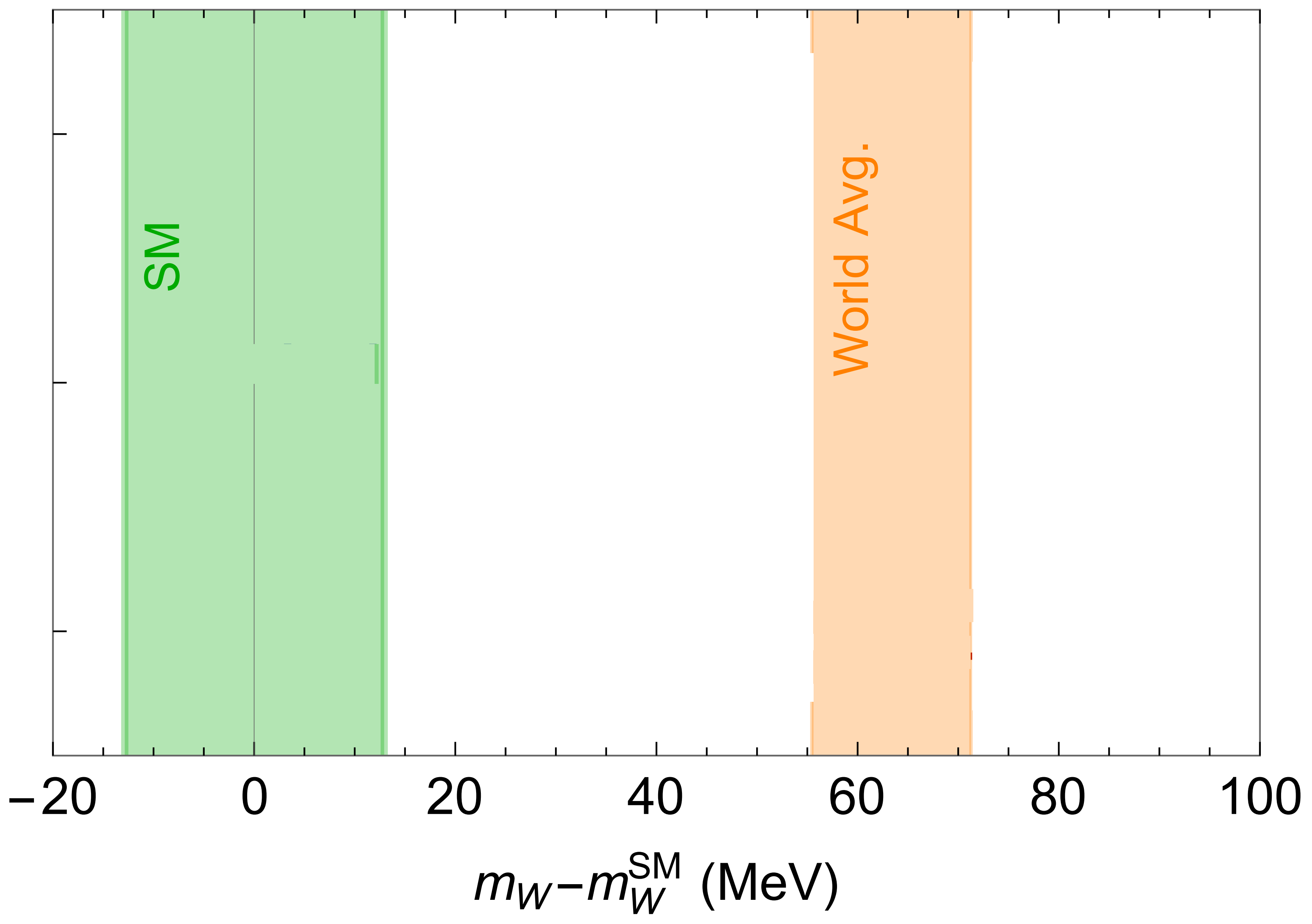
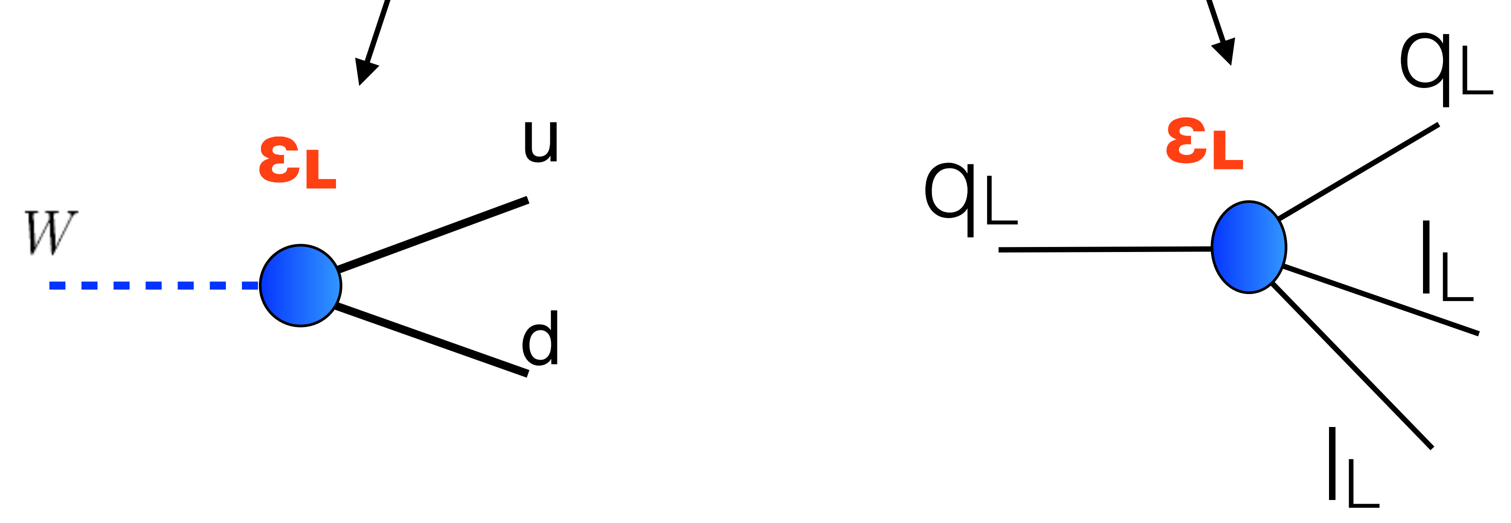


$$\Delta_{\rm CKM} = v^2 \left[C_\Delta - 2\, C_{lq}^{(3)} \right]$$

$$C_\Delta = 2 \left[C_{Hq}^{(3)} - C_{Hl}^{(3)} + \hat{C}_{ll} \right]$$



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VC, Dekens, deVries, Mereghetti, Tong 2204.08440, 2311.00021

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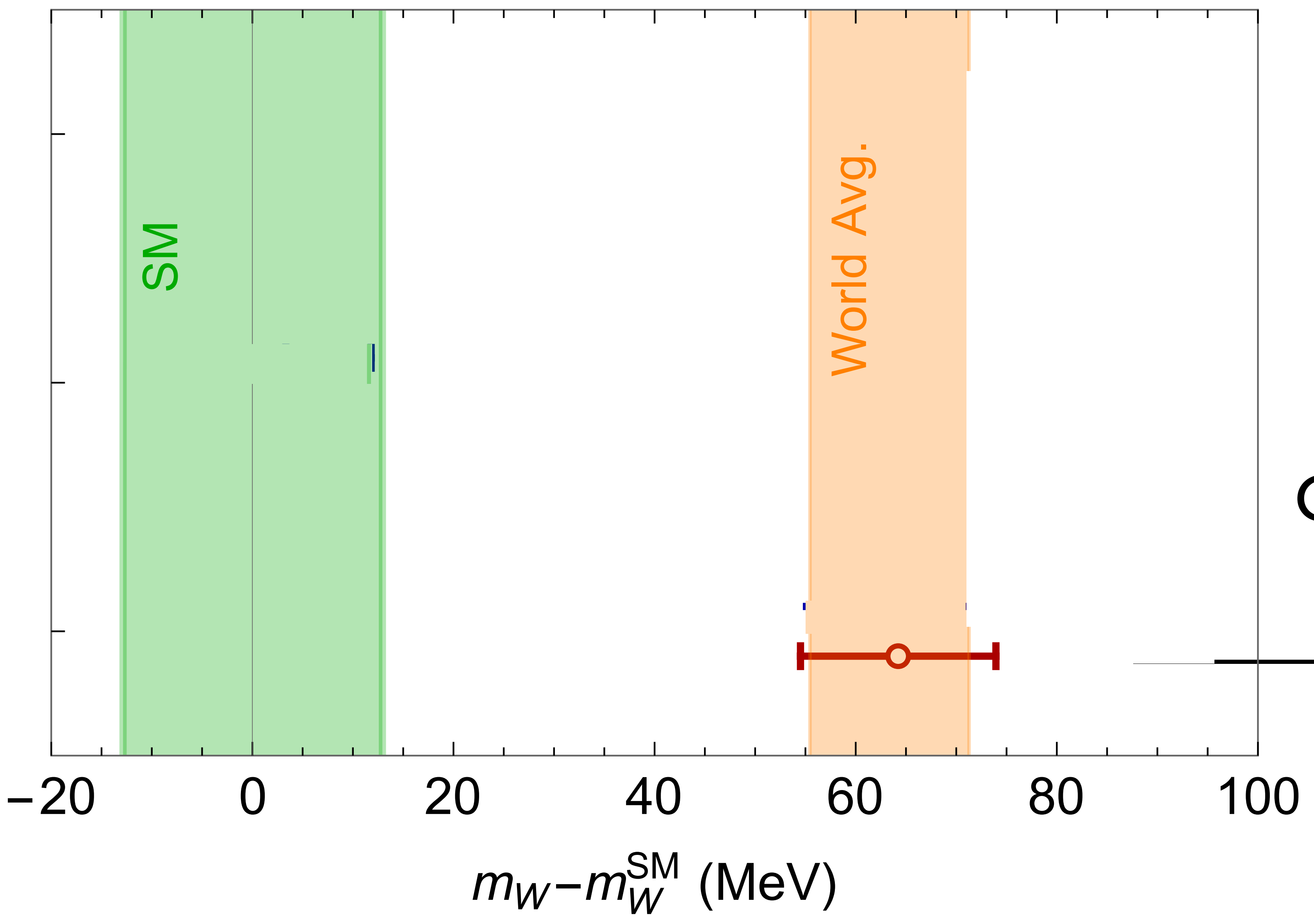

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deBlas et al 2204.04204, Bagnaschi et al 2204.05260, …

Global fit to EWPO without $\Delta_{\rm CKM}$ ⇒ too large a C_Δ

$$\Delta_{\rm CKM}^{\rm EWfit} = -(0.012 \pm 0.005)\,,$$

Broader impact (even if tension disappears)

VC, Dekens, deVries, Mereghetti, Tong 2204.08440, 2311.00021

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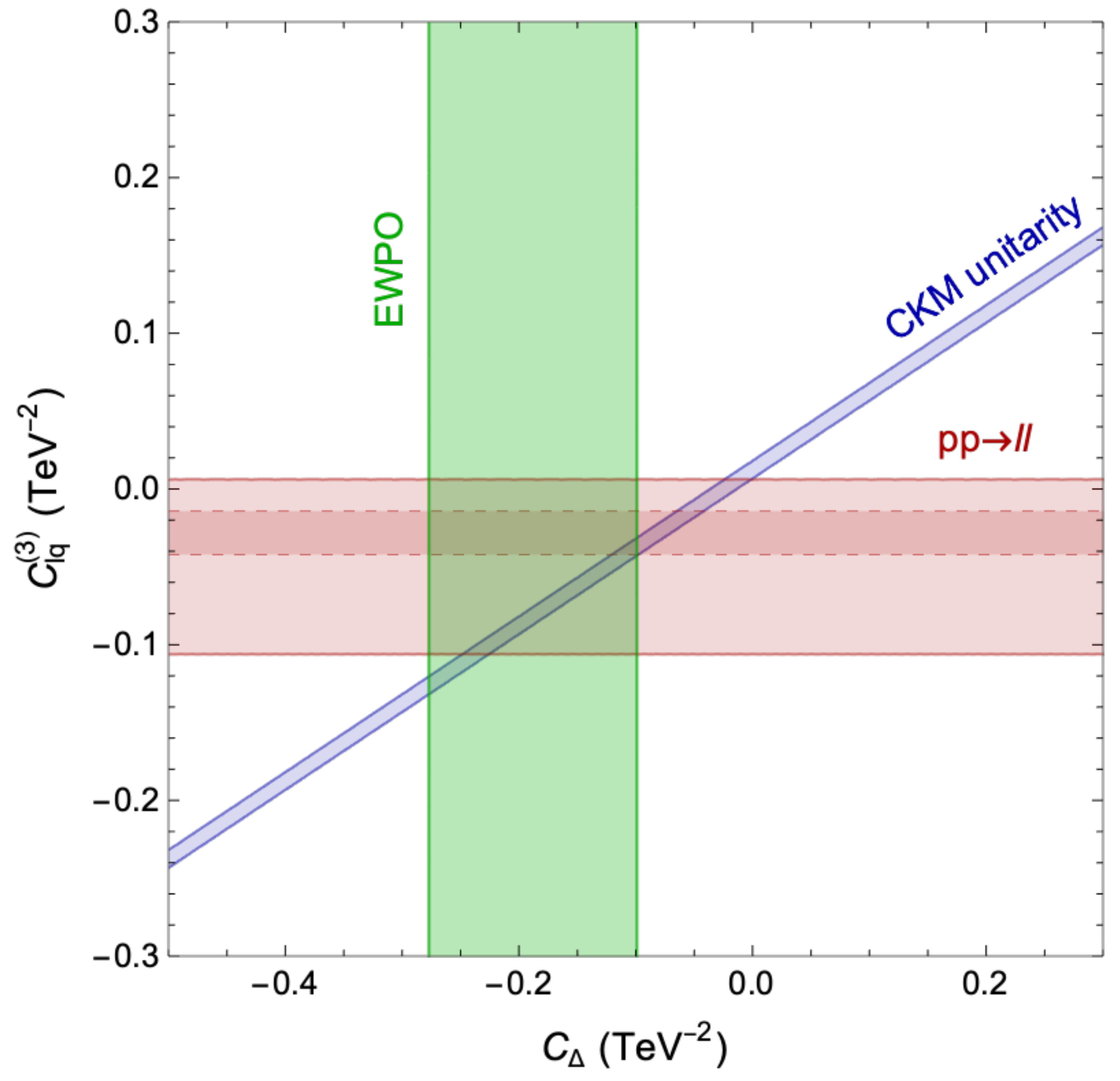

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- Include Δ_{CKM} & decouple from m_W by turning on $C_{lq}^{(3)}$: but constraints from Drell-Yan at the LHC can't be ignored!

Broader impact (even if tension disappears)

VC, Dekens, deVries, Mereghetti, Tong 2204.08440, 2311.00021

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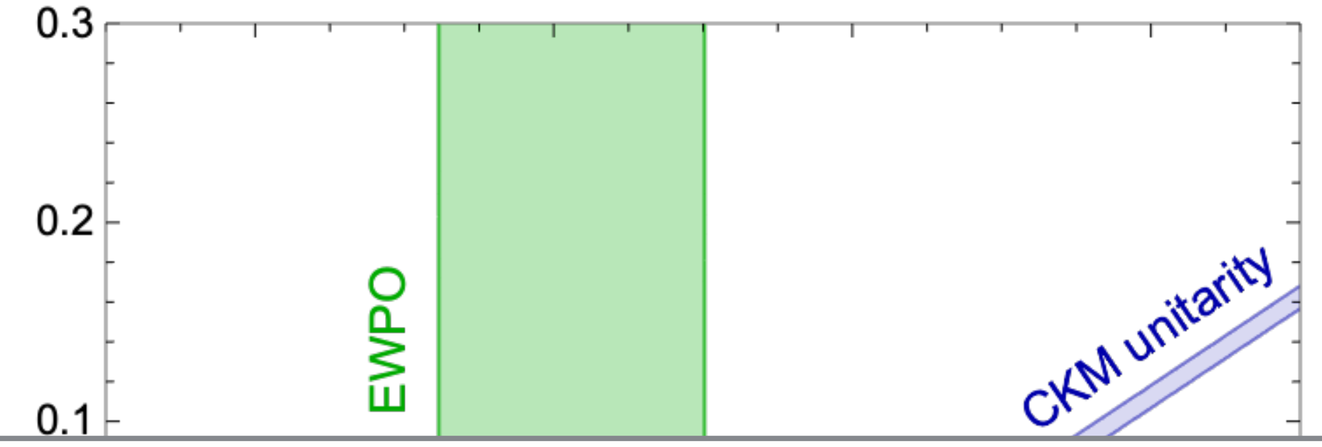

$$\Delta_{\rm CKM} = v^2 \left[C_\Delta - 2\, C_{lq}^{(3)} \right]$$

Quantitative point: best fit values for effective couplings with or without $\Delta_{\rm CKM}$ change

Qualitative point: global analyses of 'electroweak precision observables' should be extended to include low-energy (such as $\Delta_{\rm CKM}$) and collider (such as Drell-Yan) observables