PIONEER Collaboration Meeting
University of Washington, Oct 16-18 2023

Rare pion decays: theory perspective

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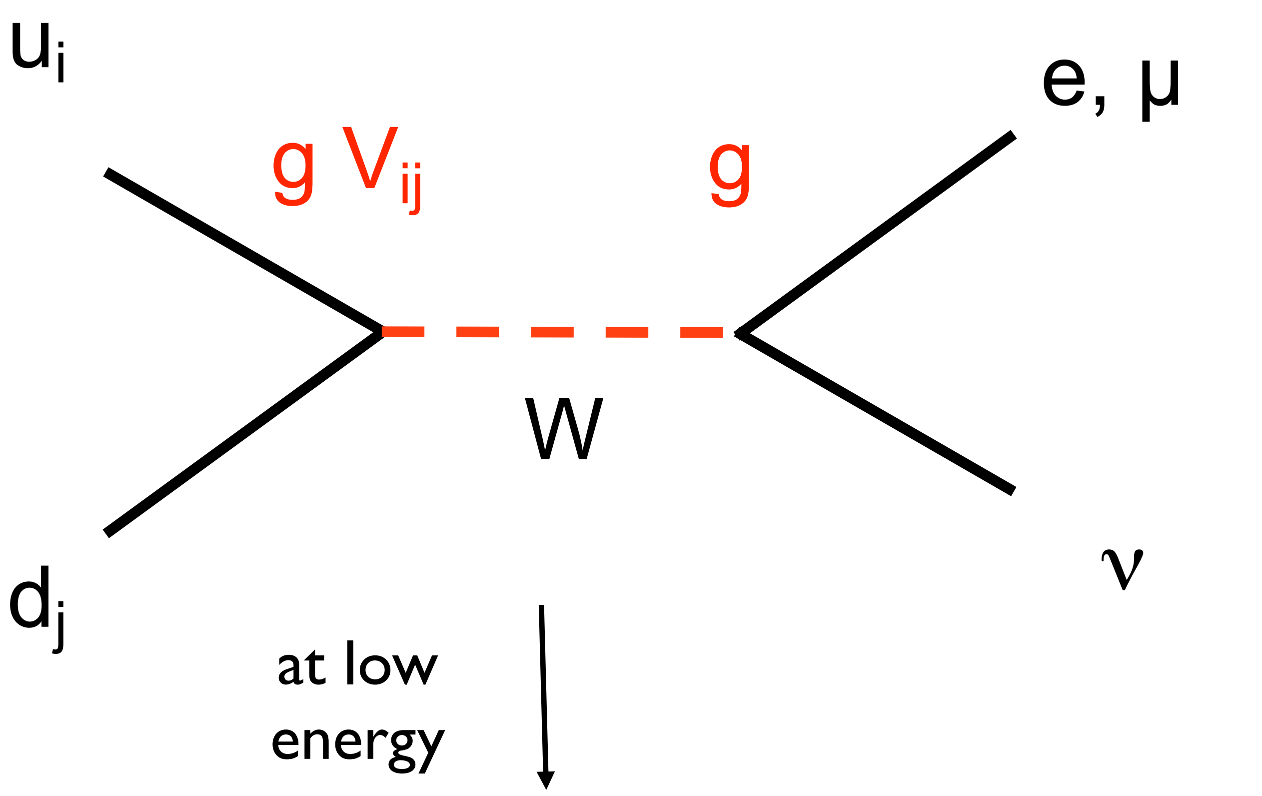
Rare pion decays: weak universality and beyond

- CC processes the SM are mediated by W exchange between L-handed fermions ⇒ universality relations



$G_F^{(\beta)} \sim g^2 V_{ij}/M_W^2 \sim G_F^{(\mu)} V_{ij}$

Lepton flavor universality

$$[G_F^{(\beta)}]_e / [G_F^{(\beta)}]_\mu = 1$$

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

Cabibbo universality
(Quark-Lepton universality)

- Rare pion decays offer a theoretically 'clean' way to test the SM universality relations
  - Precise exp. + theory may reveal BSM effects from heavy new physics
  - Direct sensitivity to light new particles (sterile neutrinos, axion-like, Majoron…)

$\pi \to e\nu$

$\pi^\pm \to \pi^0 e^\pm \nu$

Outline

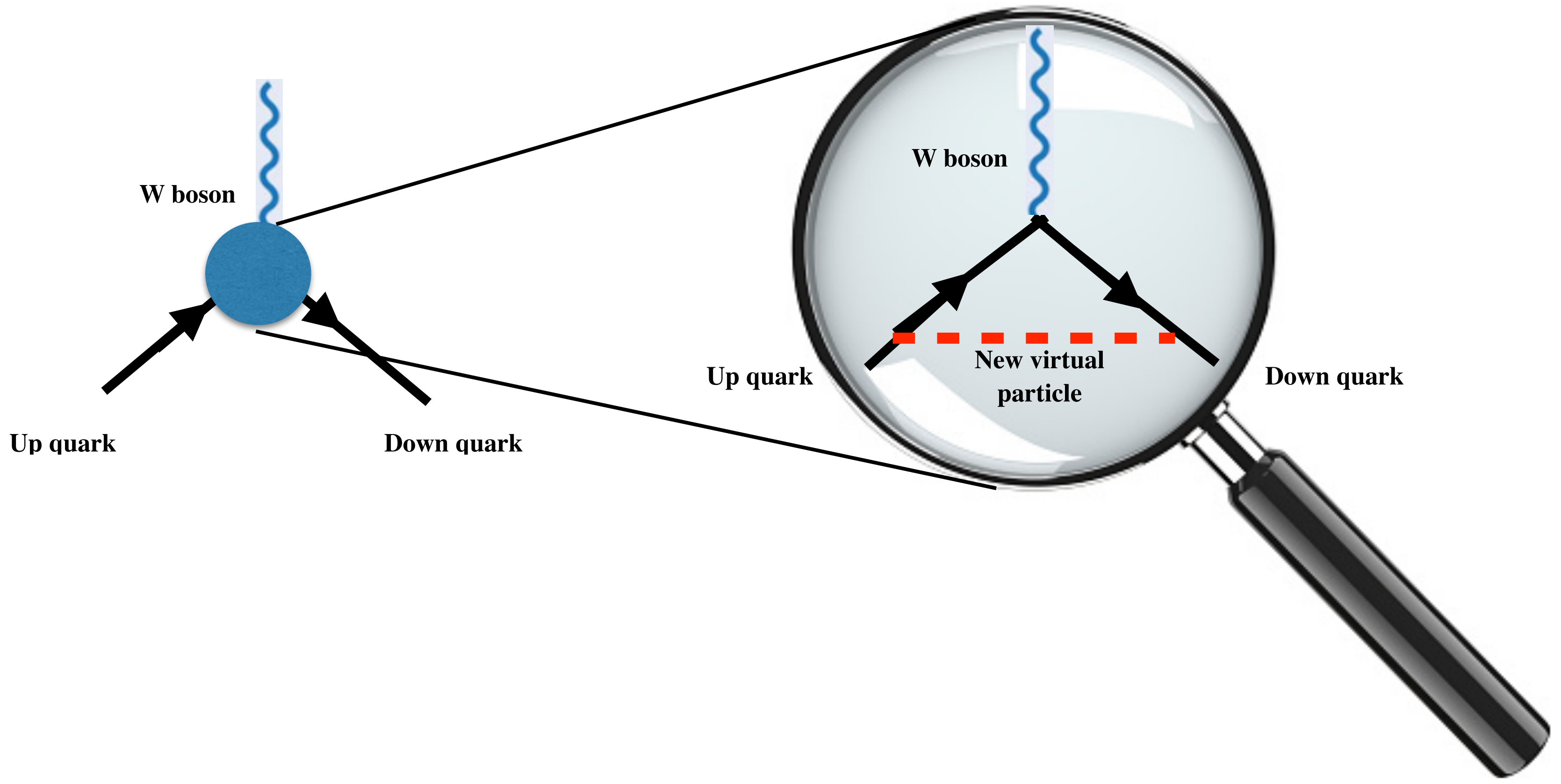
- Resource: theory talks at the 2022 Rare Pion Decay Workshop

Physics insights on RPD program	*Bill Marciano*	*Cervantes and Velasquez Room, UC Santa Cruz*	09:30 - 10:00
LFU tests across energy scales	*Toni Pich*	*Cervantes and Velasquez Room, UC Santa Cruz*	10:00 - 10:30
Coffee		*Cervantes and Velasquez Room, UC Santa Cruz*	10:30 - 10:50
Meson decays as probes of light new physics	*Asaf Dror et al.*	*Cervantes and Velasquez Room, UC Santa Cruz*	10:50 - 11:20
Tests for sterile neutrino effects	*Robert Shrock*	*Cervantes and Velasquez Room, UC Santa Cruz*	11:20 - 11:50
Status and prospects of the first-row CKM unitarity test	*MARTIN HOFERICHTER et al.*	*Cervantes and Velasquez Room, UC Santa Cruz*	09:00 - 09:30
The case for New Physics at PIONEER	*Andreas Crivellin et al.*	*Cervantes and Velasquez Room, UC Santa Cruz*	09:30 - 10:00

https://indico.cern.ch/event/1175216/timetable/#20221006.detailed

Outline

- The Standard Model baseline: theoretical status of
  - $R_{e/\mu}^{(\pi)} = \Gamma(\pi \to e\nu(\gamma)) \,/\, \Gamma(\pi \to \mu\nu(\gamma))$
  - $\Gamma(\pi^{\pm} \to \pi^0 e^{\pm} \nu(\gamma))$

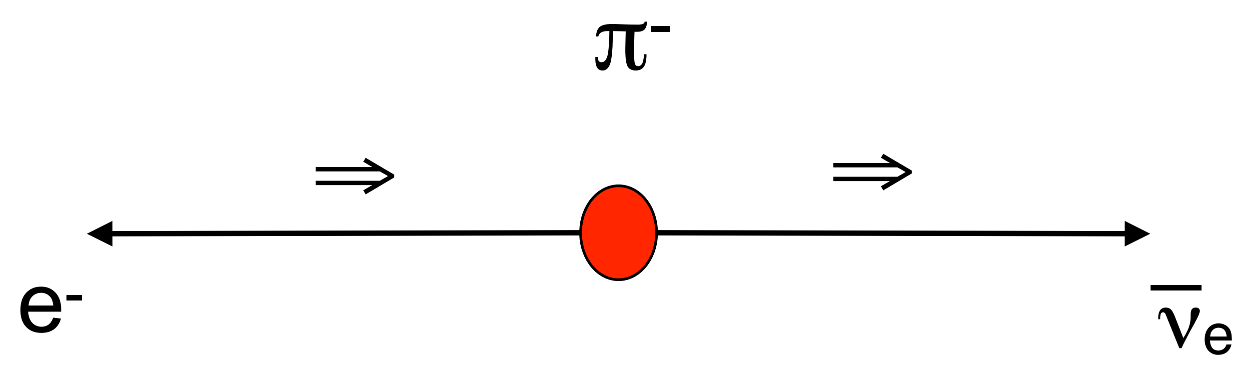


- Rare π decays as a probe of new physics:
  - Sensitivity to light and weakly coupled particles (brief)
  - Impact on lepton flavor universality tests
  - Impact on Cabibbo universality test ('active' anomaly)

The Standard Model baseline

$R_{e/\mu}(\pi) = \Gamma(\pi \to e\nu(\gamma)) \,/\, \Gamma(\pi \to \mu\nu(\gamma))$ in the SM

- Helicity suppressed the SM (V-A structure), zero if $m_e \to 0$



- Despite involving a hadron, this ratio can be predicted with high precision. Why?

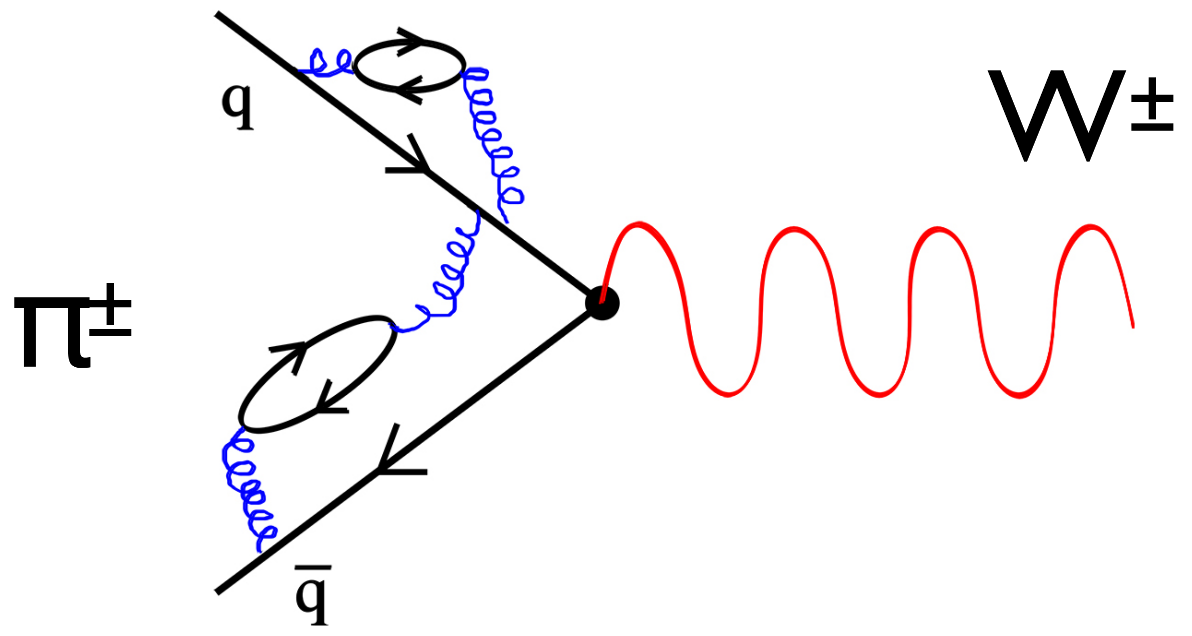


Image Copyright: Bergische Universität Wuppertal, Theoretische Physik, Fachbereich C

Theoretical analysis of $R_{e/\mu}^{(\pi)}$

P = (π,K)

$$R_{e/\mu}^{(P)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_P^2 - m_e^2}{m_P^2 - m_\mu^2}\right)^2$$

- F_π drops in the e/μ ratio → hadronic structure dependence appears only through EM corrections
- Organize calculation in EFT (ChPT): $Q \sim m_{\pi,K,\mu}/\Lambda_\chi$ $\quad \Lambda_\chi \sim 4\pi F_\pi \sim 1.2$ GeV

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- F_π drops in the e/μ ratio → hadronic structure dependence appears only through EM corrections
- Organize calculation in EFT (ChPT): $Q \sim m_{\pi,K,\mu}/\Lambda_\chi$ $\quad \Lambda_\chi \sim 4\pi F_\pi \sim 1.2\ \text{GeV}$
- NLO correction ↔ point-like mesons (Kinoshita 59)

No contact (LEC): contribution cancels in the ratio!

$$\Delta^\pi_{e^2 Q^0} \sim -3\alpha/\pi \log m_\mu/m_e \sim -3.929\%$$

Use RGE to resum large IR logs (Marciano and Sirlin 1993) $\quad \Delta^{(\pi)}_{e^4 Q^0} = 0.055(3)\%$

Theoretical analysis of $R_{e/\mu}^{(\pi)}$

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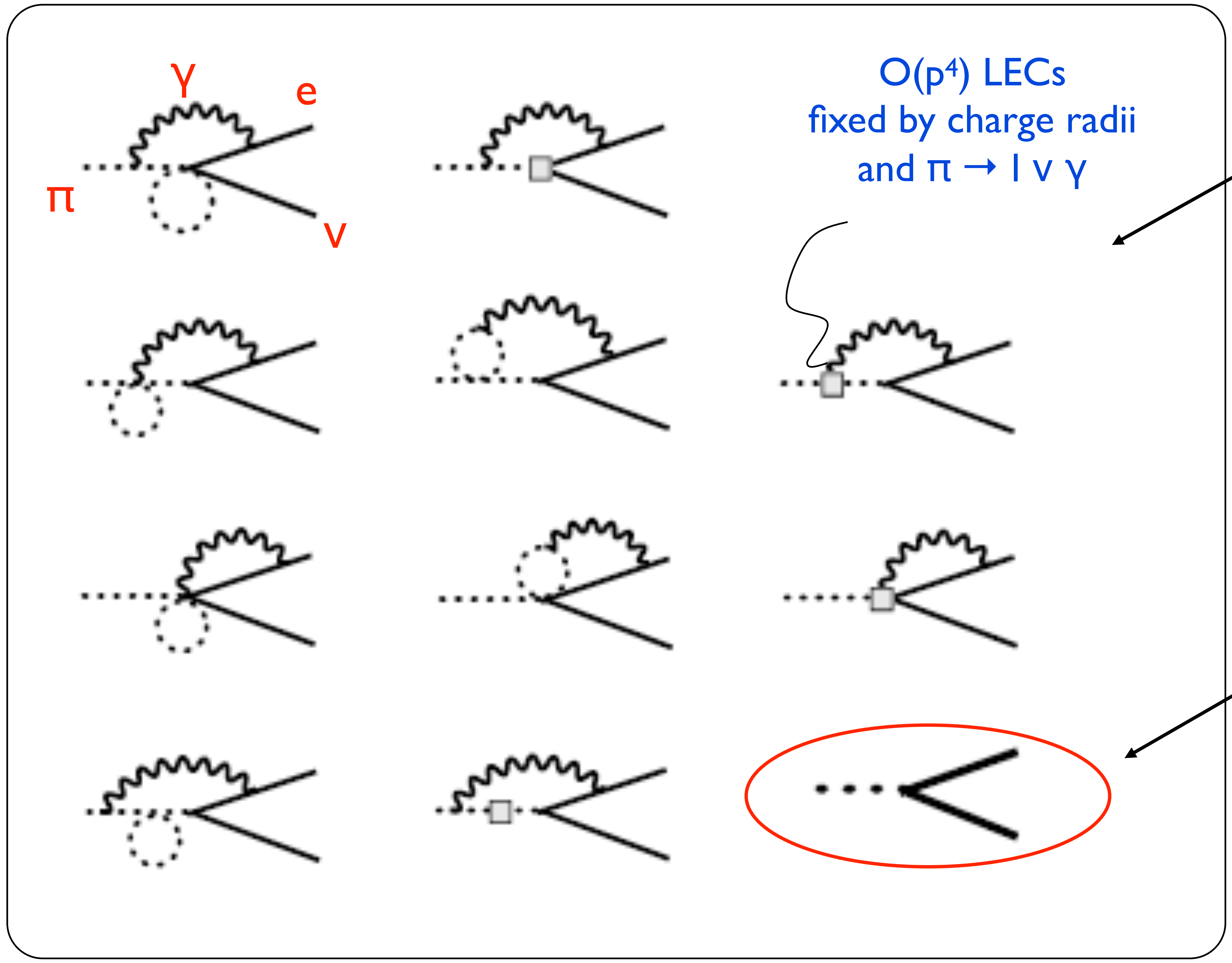
- Structure dependence appears at NNLO in ChPT!

$$\Delta^\pi_{e^2 Q^2} = 0.053(11)\%$$

$$\Delta^\pi_{e^2 Q^4} = 0.073(3)\%$$



1) One- and two-loop diagrams ⇒ model-independent single and double logs

2) $O(e^2p^4)$ Low Energy Constant (LEC:, estimated within large-N_C inspired resonance model (satisfying QCD s.d. constraints). Small contribution to final result, largest uncertainty

3) Str. Dep. Real photon emission, not helicity suppressed

Theoretical analysis of $R_{e/\mu}^{(\pi)}$

P = (π,K)

$$R_{e/\mu}^{(P)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_P^2 - m_e^2}{m_P^2 - m_\mu^2}\right)^2 \times \left[1 + \Delta^P_{e^2 Q^0} + \Delta^P_{e^2 Q^2} + \Delta^P_{e^2 Q^4} + \cdots + \Delta^P_{e^4 Q^0} + \cdots\right]$$

Theory

$$R_{e/\mu}^{(\pi)} = 1.23524(015) \times 10^{-4}$$

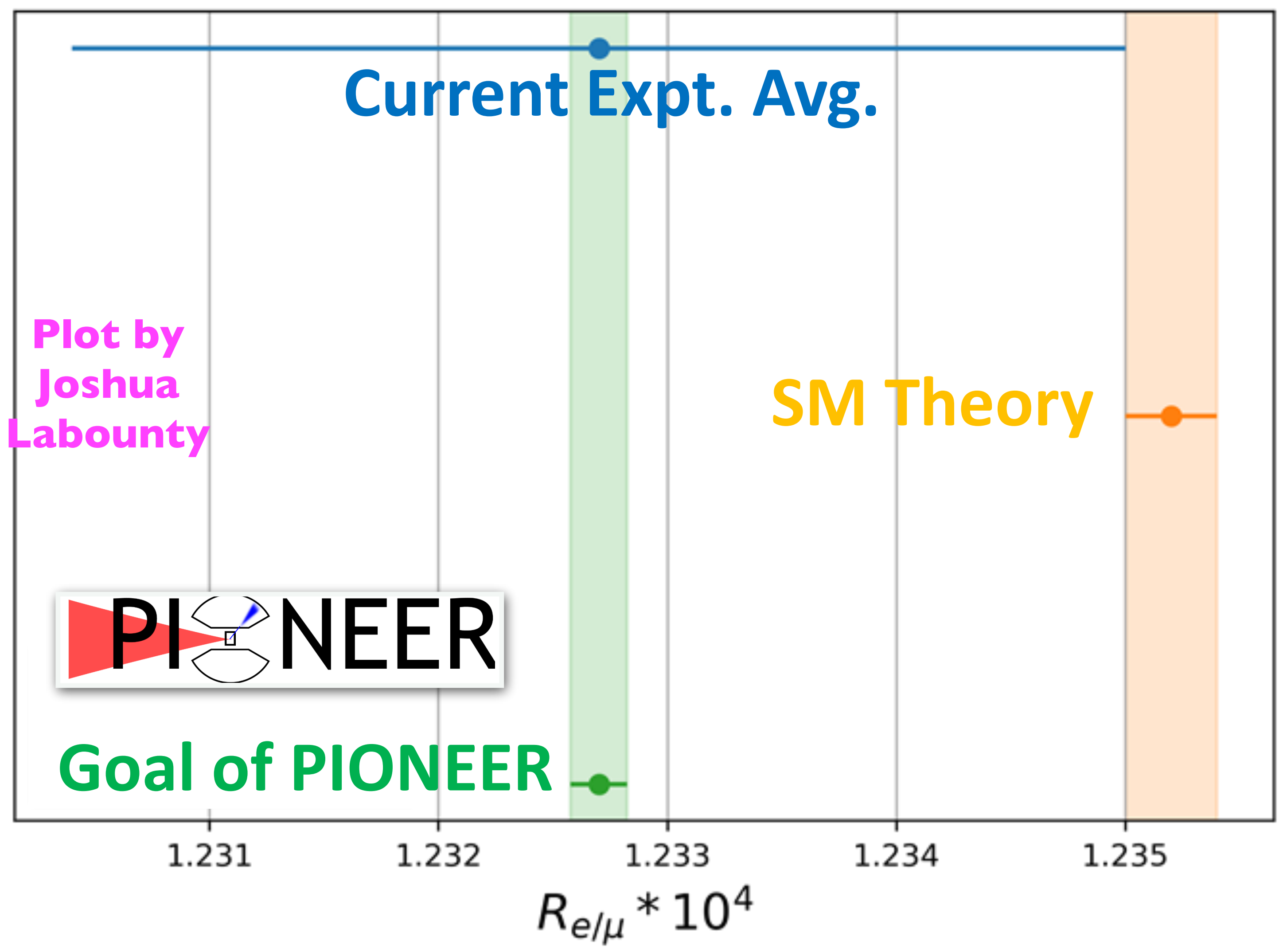
Marciano-Sirlin, 1993, PRL →
VC-Rosell 0707.3439, PRL

Experiment

$$R_{e/\mu}^{(\pi)} = 1.23270(230) \times 10^{-4}$$

PIENU Coll. , PRL 2015
PDG 2020

Theory result provides robust baseline for new physics searches.
Might be further improved in the next decade through lattice QCD+QED



Pion beta decay

- Decay rate

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

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- Phase space $\quad I_\pi = 7.3766(43) \times 10^{-8} \quad \sim \left(\frac{m_{\pi^+} - m_{\pi^0}}{m_{\pi^+}}\right)^5$

M. Hoferichter, 2022

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M. Hoferichter, 2022

- Vector form factor at t=0, controlled by isospin and its breaking

$$\langle \pi^0(p_0)|\bar{d}\gamma_\mu u|\pi^+(p_+)\rangle = \sqrt{2}\, f_+(t) \ (p_+ + p_0)_\mu \qquad t = (p_+ - p_0)^2$$

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

Behrends-Sirlin 1962 **VC-Neufeld-Pichl hep-ph/0209226, EPJC**

Pion beta decay

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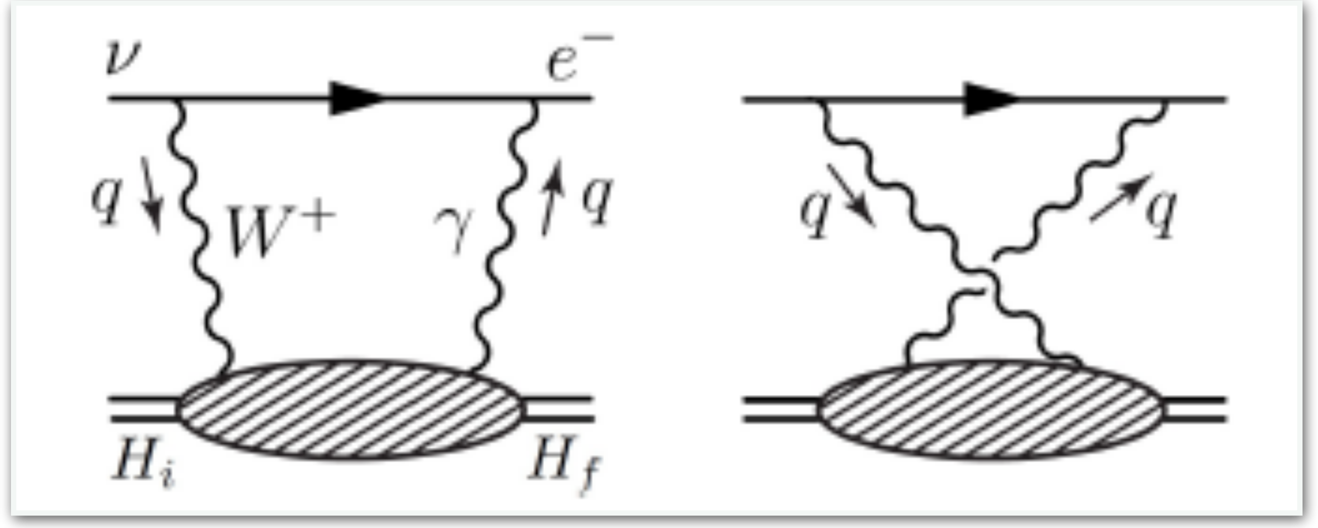
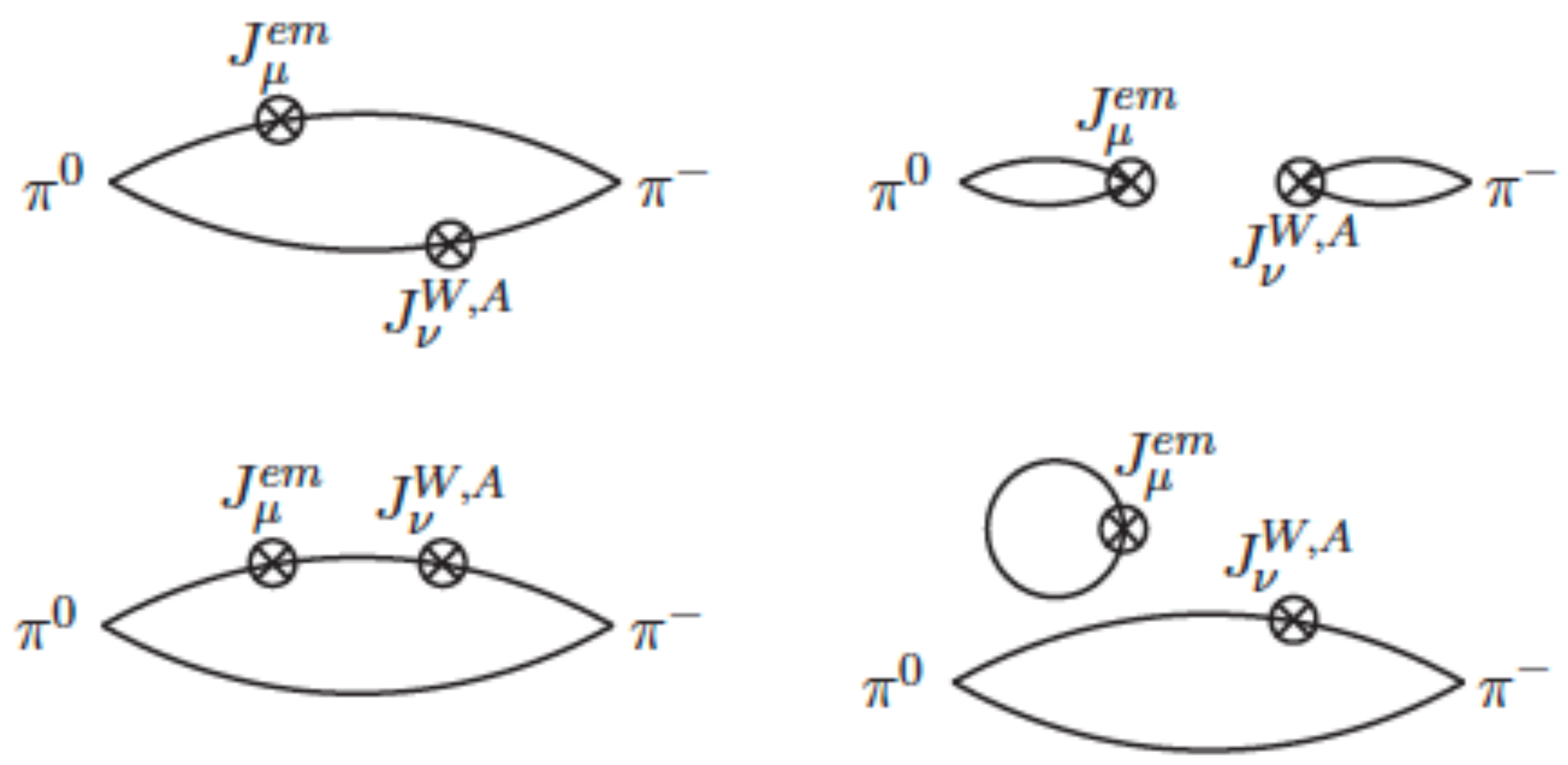
- Radiative corrections: Current algebra → ChPT to $O(e^2p^2)$ → Lattice QCD

$\mathrm{RC}_\pi = 0.0342(10)$ (ChPT) ⟶ $\mathrm{RC}_\pi = 0.0332(1)_{\gamma W}(3)_{HO}$ (LQCD)

Sirlin 1978
VC-Neufeld-Pichl 2002, EPJC
Desxotes-Genon Moussallam 2005, EPJC
Passera et al., 2011

Feng, Gorchtein, Jin, Ma, Seng , 2003.09798, PRL





Pion beta decay

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

- Current extraction of V_{ud}

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

- 0.3% uncertainty dominated by BR = $1.036(6)\times 10^{-8}$

PIBETA Coll. , hep-ex/031230, PRL

- Next largest uncertainty from phase space!

M. Hoferichter 2022

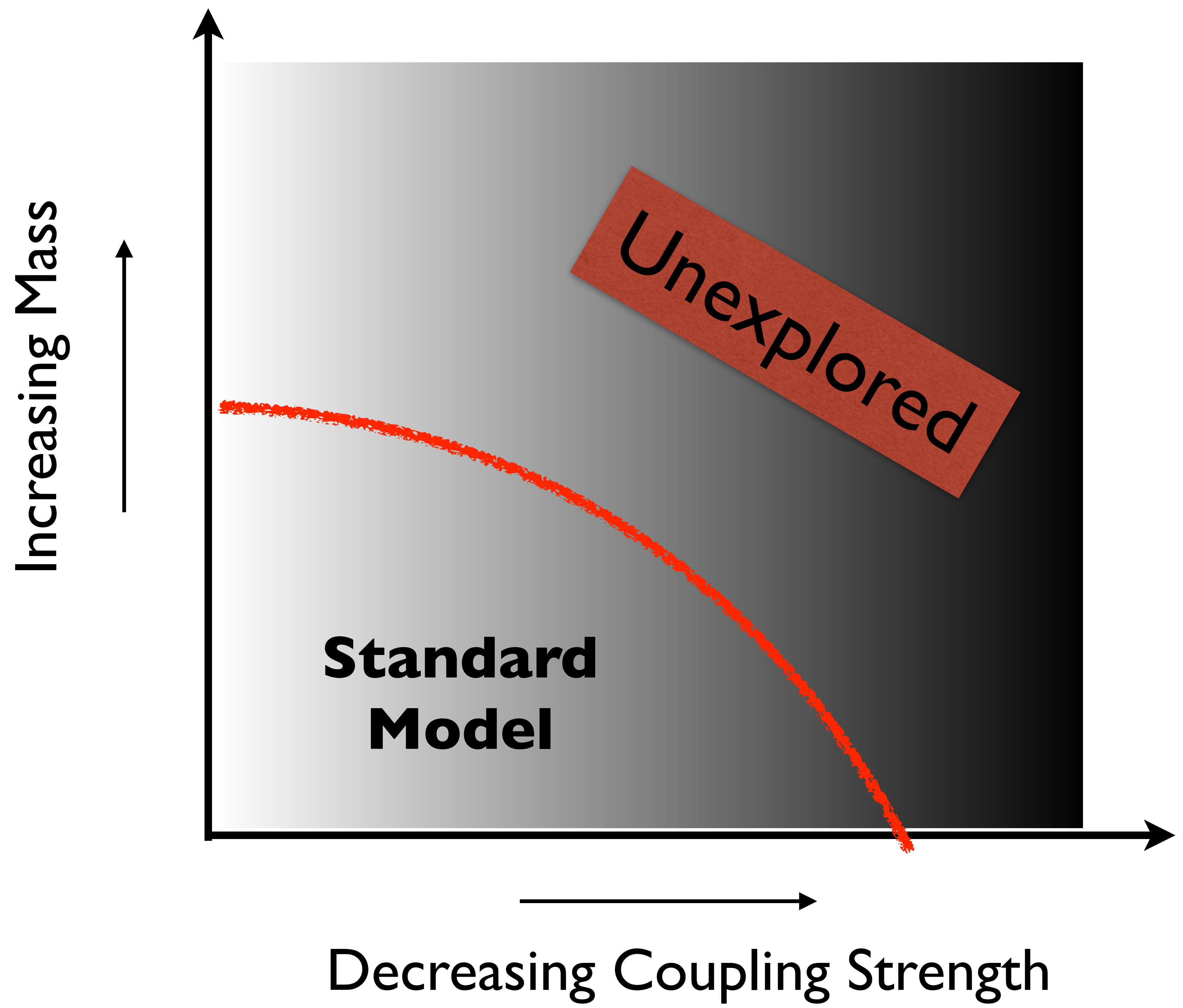
- For reference, the current best determination is

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

Rare pion decays as a probe of new physics

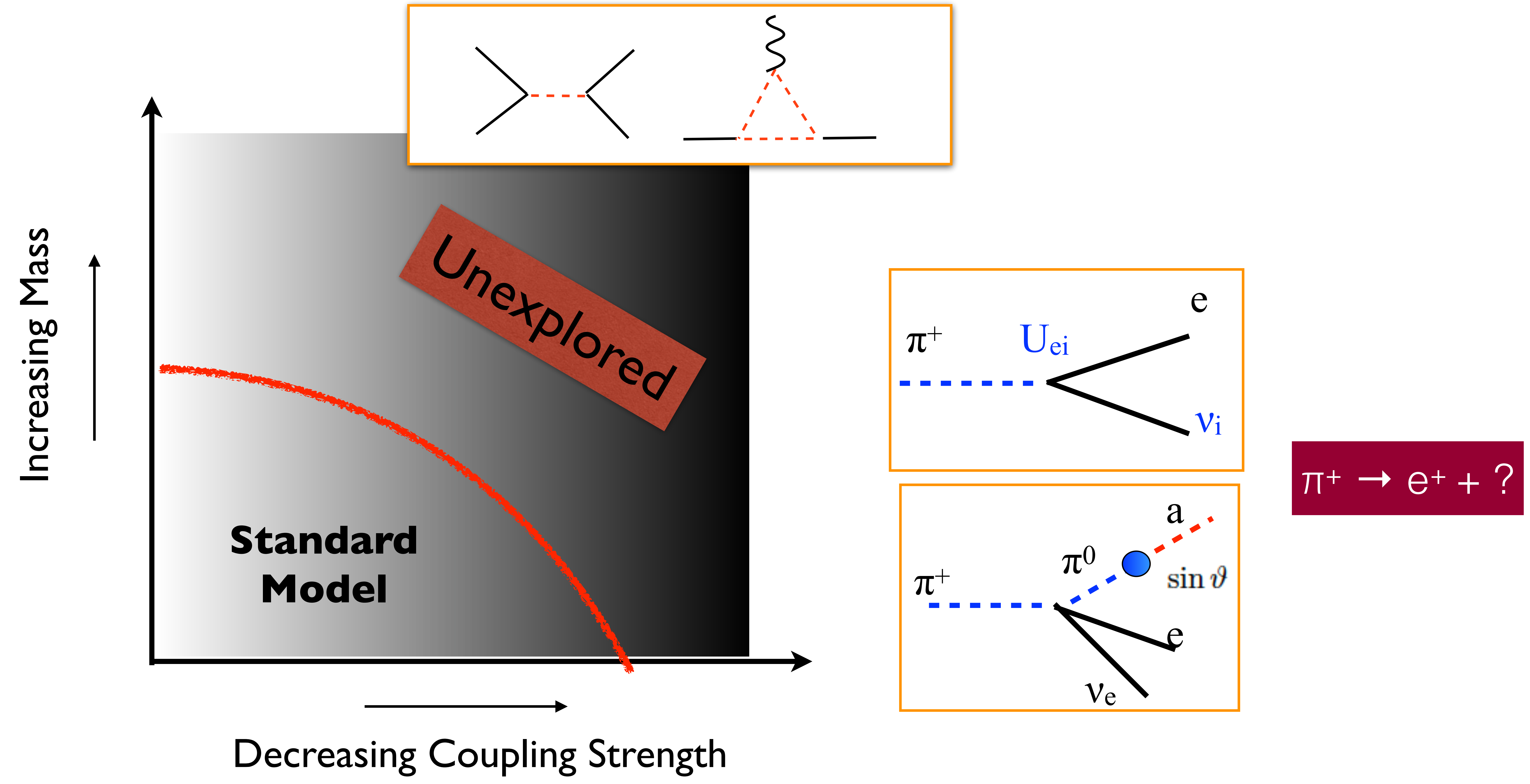
BSM sensitivity

- What kind of new physics are rare pion decays probing?
- Light and weakly coupled? Heavy?



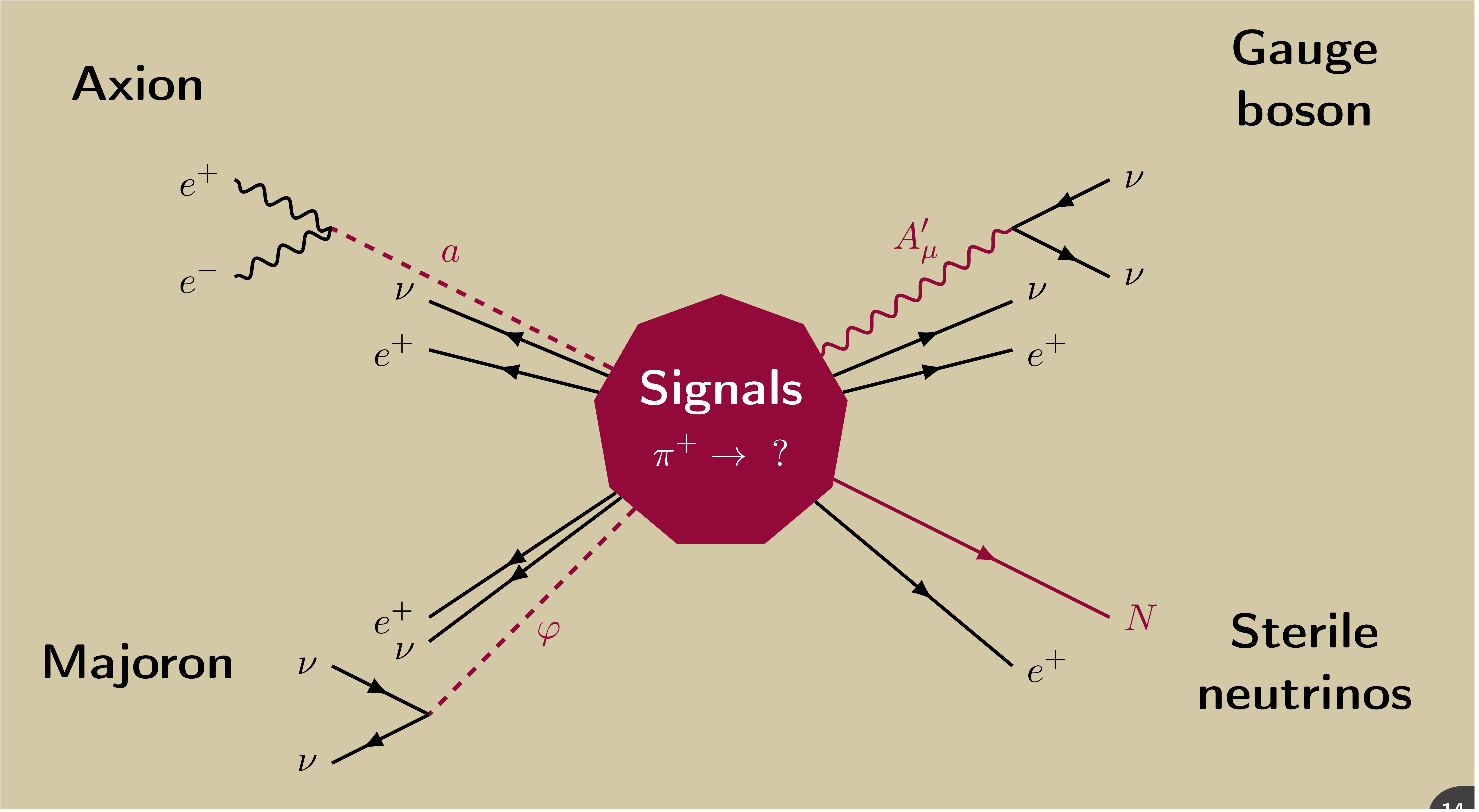
BSM sensitivity

- What kind of new physics are rare pion decays probing?
- Light and weakly coupled? Heavy? **Both!**



Sensitivity to light new physics

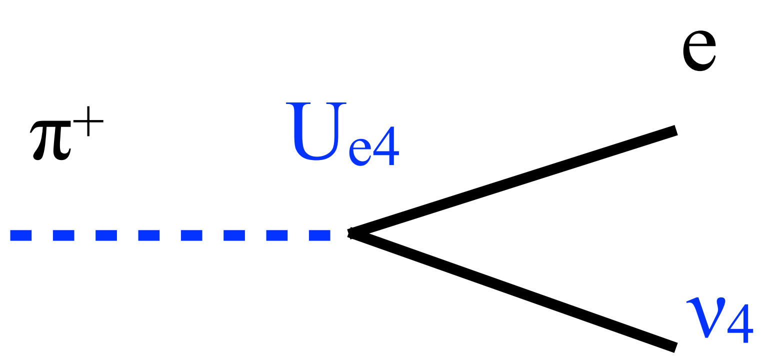
- There is sensitivity to a variety of new particles / interactions



From Jeff Dror's talk at Rare Pion Decay workshop

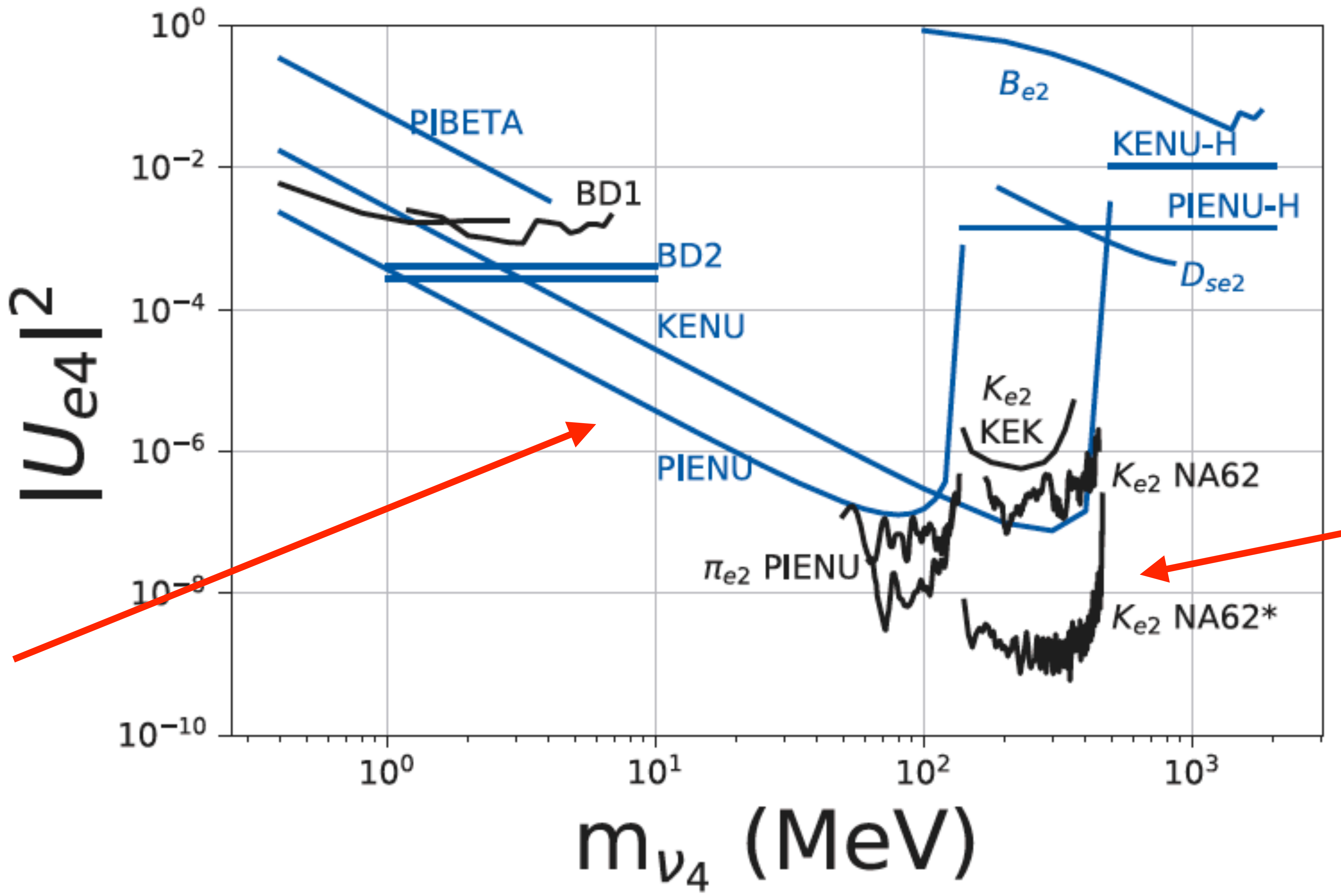
Sterile neutrinos

- Sensitivity to sterile neutrino mass & mixing
- $\pi \rightarrow e\nu_4$ provides strongest bounds on $|U_{e4}|^2$ for $m_{\nu 4} \sim 1\text{-}140$ MeV
- PIONEER improvement: order of magnitude



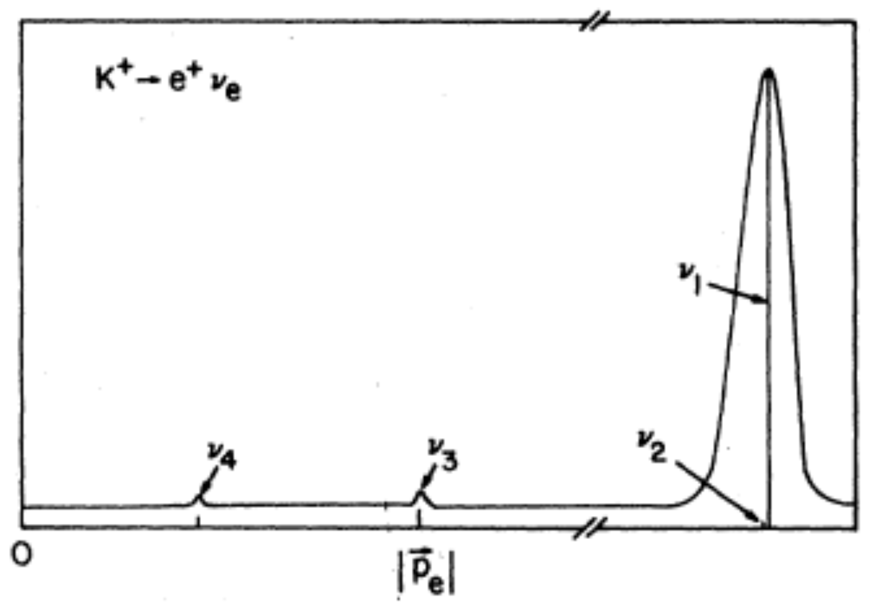
$$\nu_\ell = \sum_{i=1}^{3+n_s} U_{\ell i}\, \nu_i$$

Bryman and Shrock, 1904.06787, 1909.11198, PRD



$R_{e/\mu}(\pi)$ assuming bounds on $U_{\mu 4}$ from peak searches

Peak searches



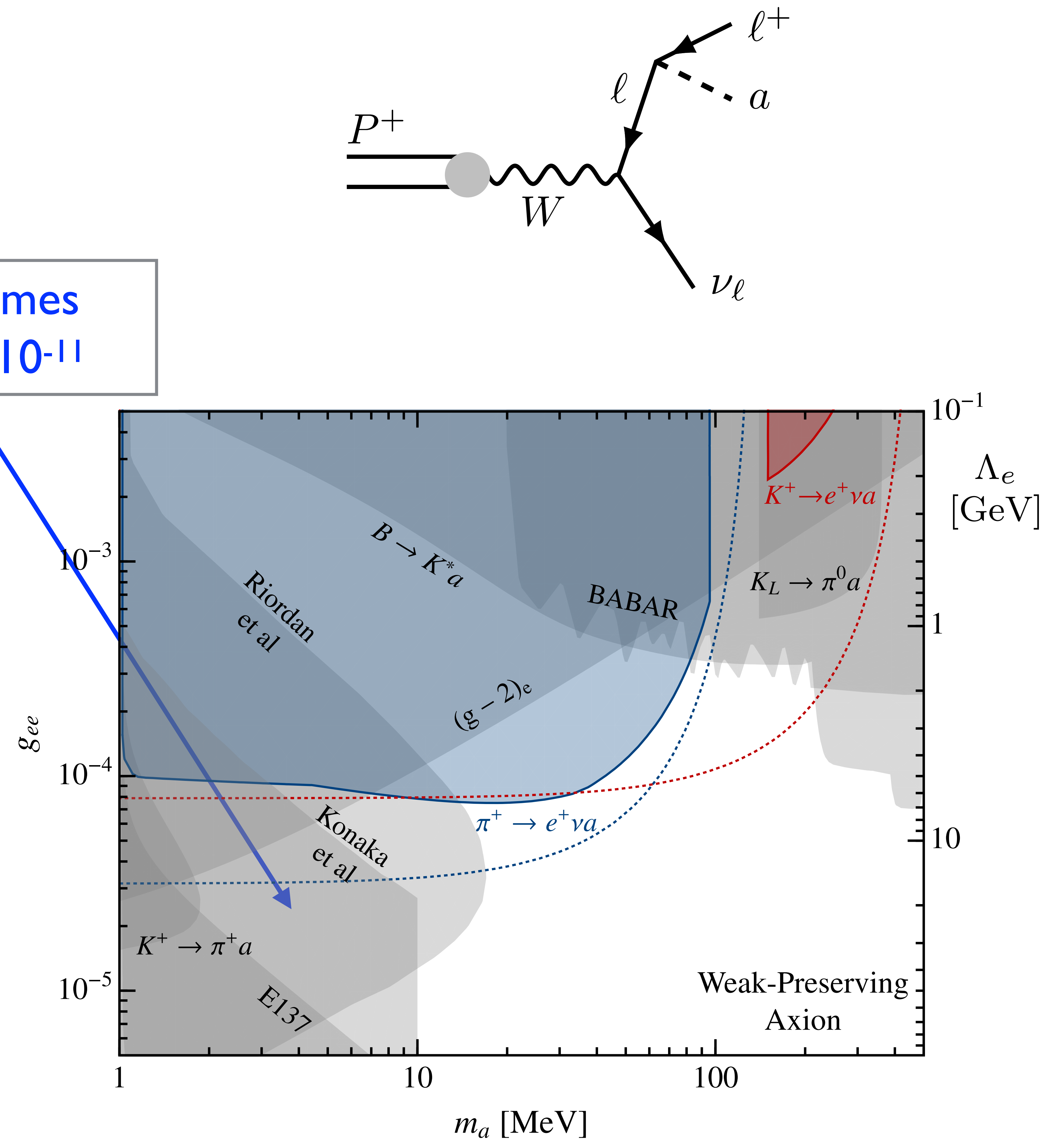
Shrock 1980-81

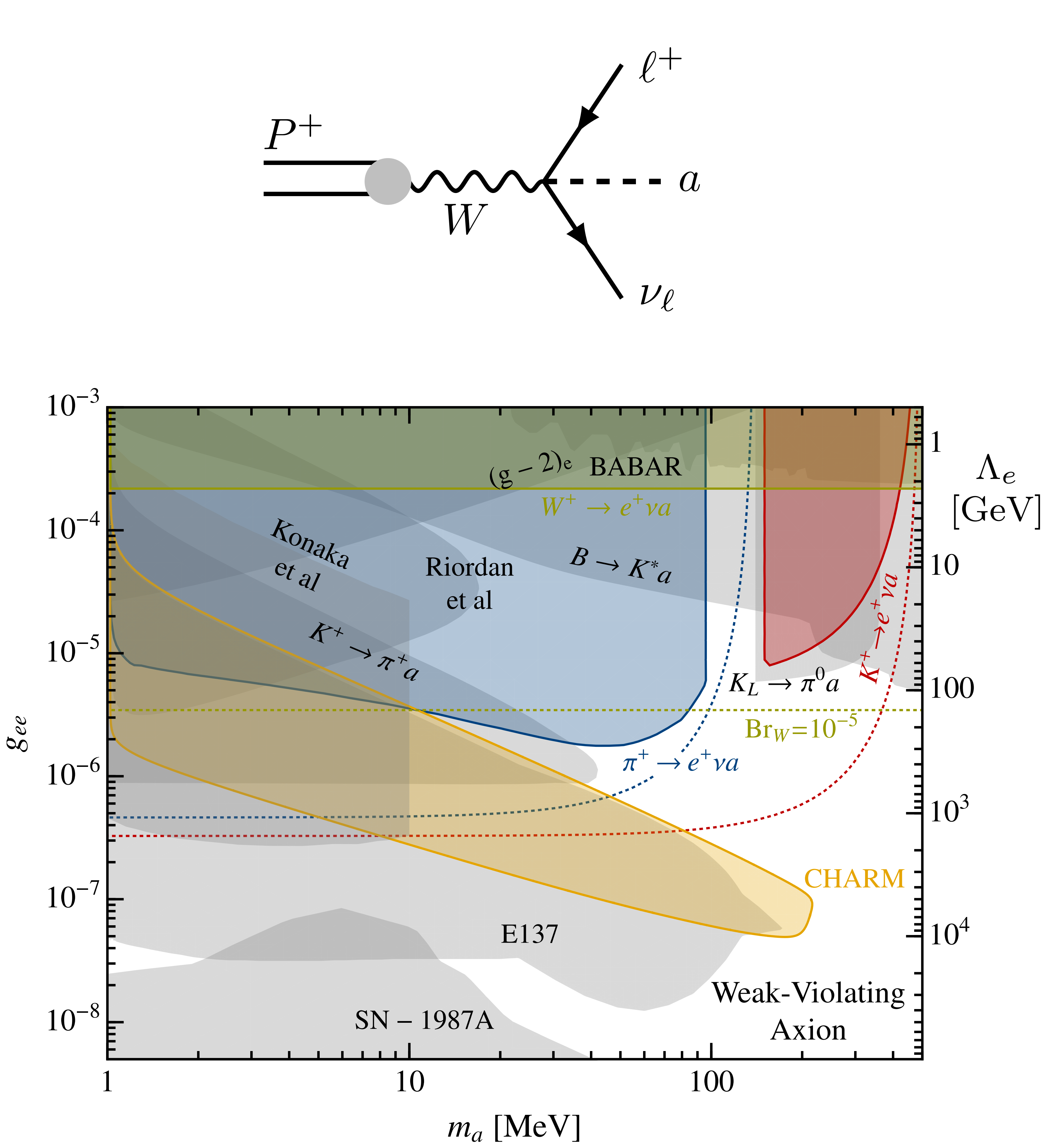
Axion-like particles

Altmanshofer-Dror-Gori 2209.00665, PRL

- Recent study of general lepto-philic axion

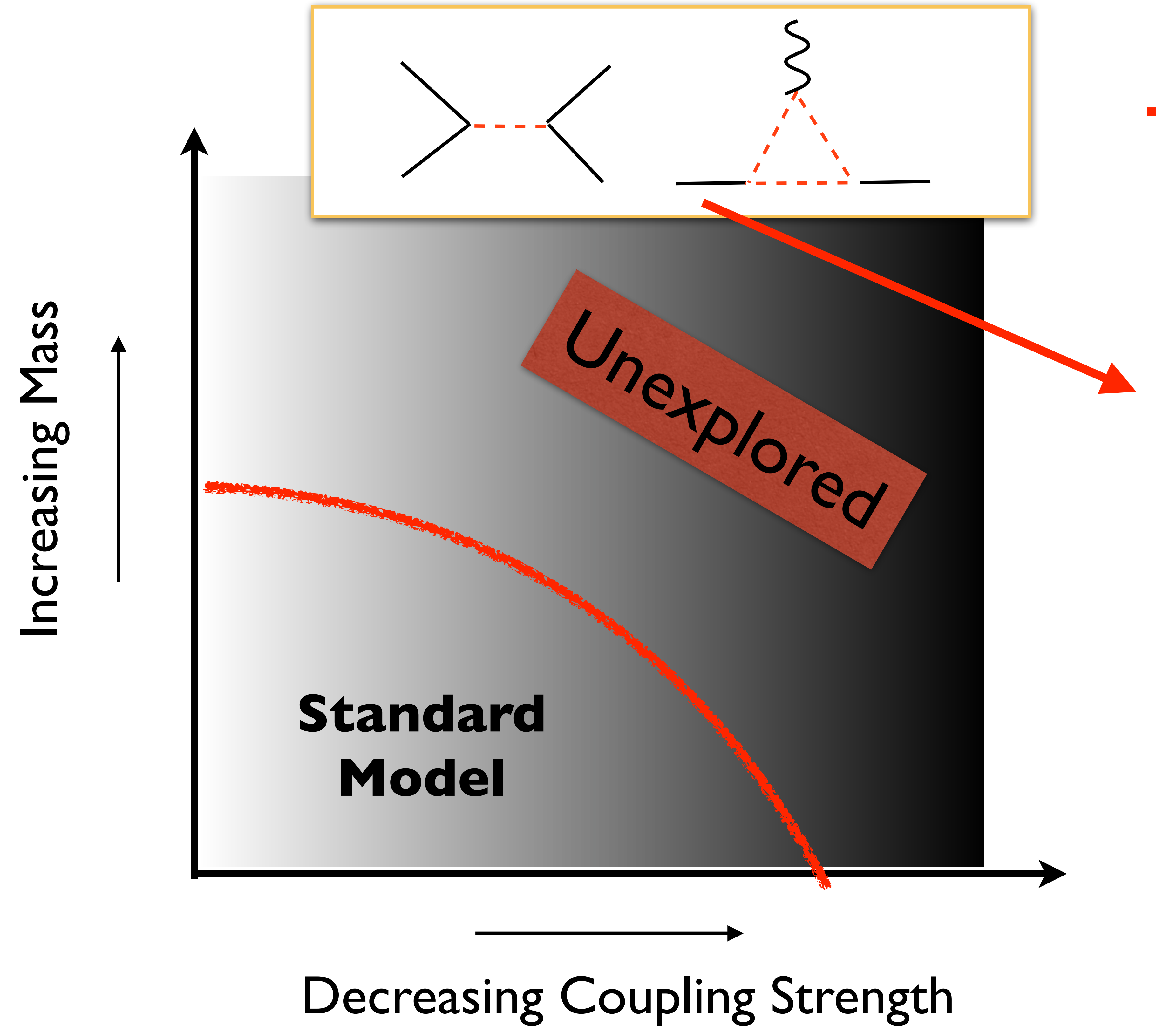
Projection assumes BR (π → aeν)~10[-11]

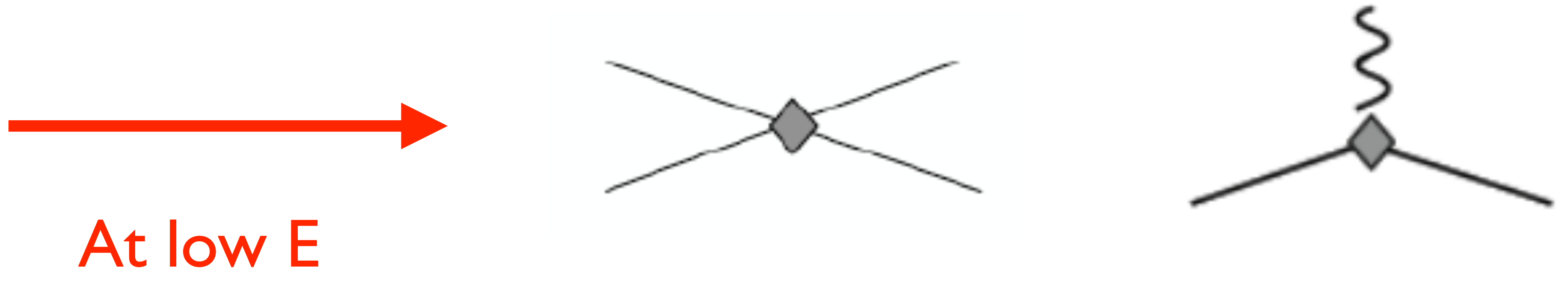




Sensitivity to heavy new physics

- Many scenarios affect CC weak processes: W', charged Higgs, Vector-like leptons and quarks, leptoquarks, …
- Their effect captured by 'low-energy' effective theory at E << M_{new}





$$\mathcal{L}_{\rm eff} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

[$\Lambda \leftrightarrow M_{Heavy}$] $C_i\ [g_{\rm BSM},\ M_a/M_b]$

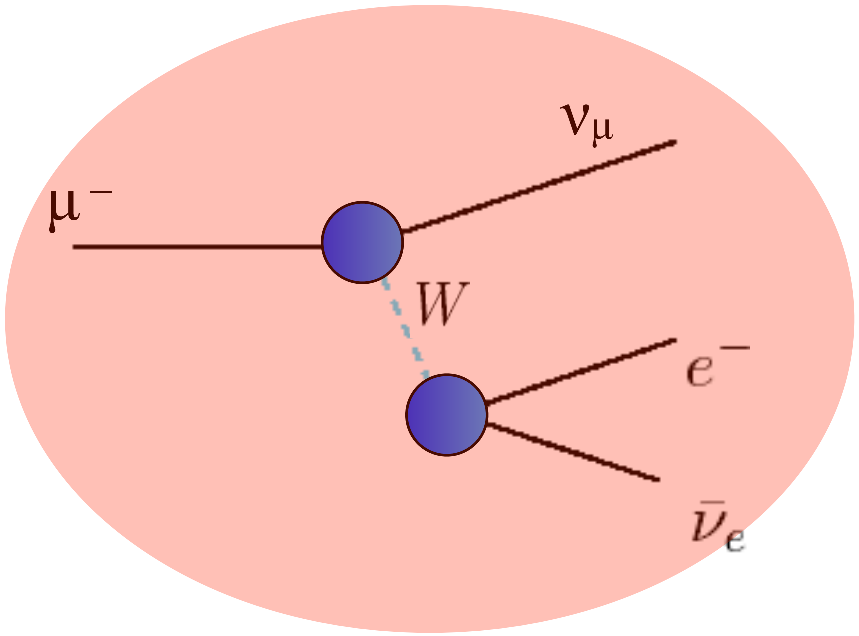
GeV-scale effective Lagrangian

VC, Gonzalez-Alonso, Jenkins 0908.1754, NPB

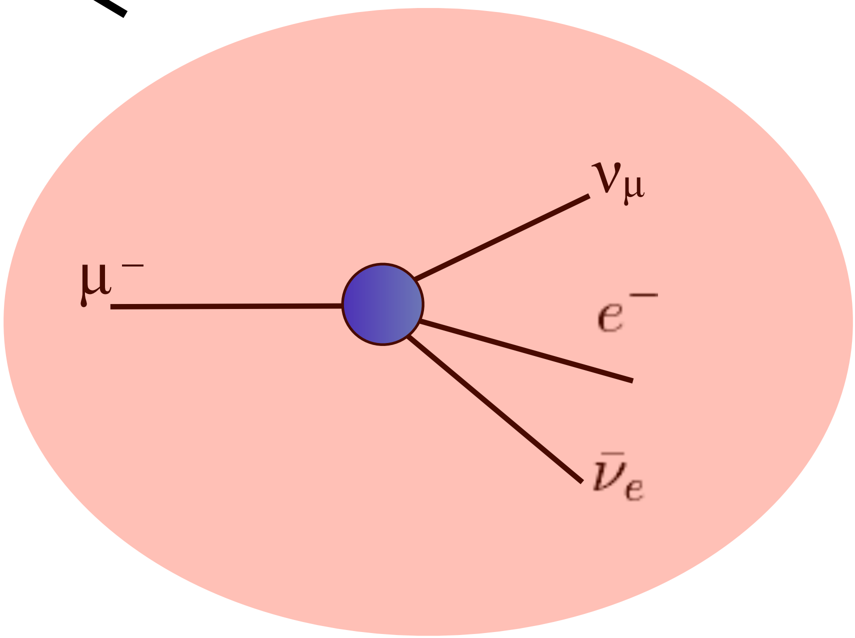
VC, Graesser, Gonzalez-Alonso 1210.4553, JHEP

Leptonic interactions

$$\mathcal{L}_{CC}^{(\mu)} = -\frac{G_F^{(0)}}{\sqrt{2}} \left(1 + \epsilon_L^{(\mu)}\right) \bar{e}\gamma^\rho(1-\gamma_5)\nu_e \cdot \bar{\nu}_\mu \gamma_\rho (1-\gamma_5)\mu \; + \; \ldots$$



Vertex corrections



4-fermion contact interaction

GeV-scale effective Lagrangian

VC, Gonzalez-Alonso, Jenkins 0908.1754, NPB

VC, Graesser, Gonzalez-Alonso 1210.4553, JHEP

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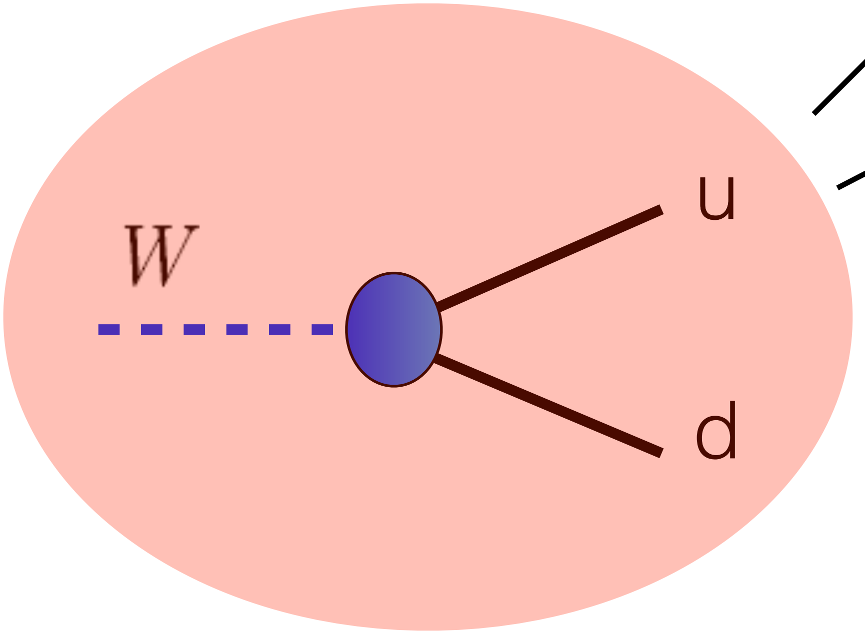
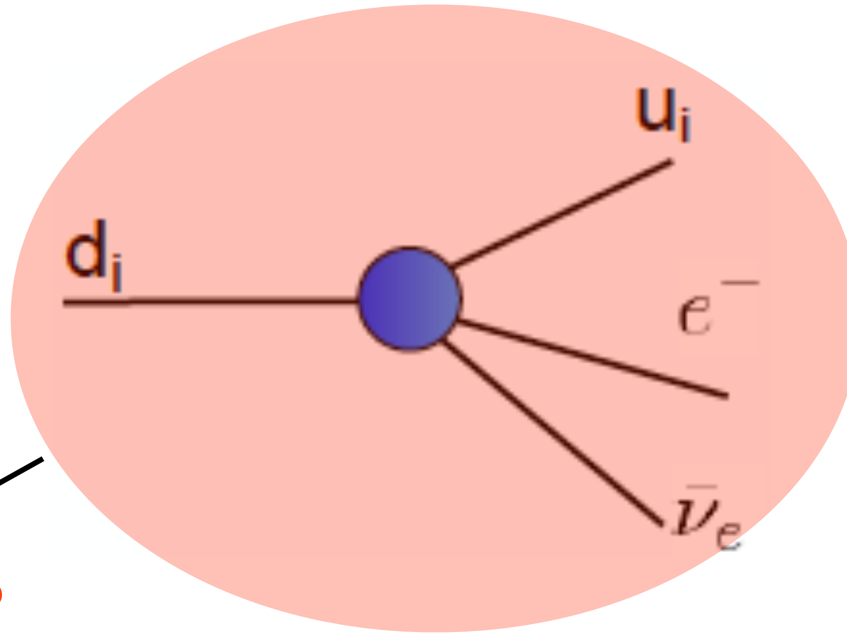
Semi-leptonic interactions

$$\begin{aligned} \mathcal{L}_{\rm CC} \ = \ & -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \times \Big[\left(\delta^{ab} + \epsilon_L^{ab}\right) \ \bar{e}_a \gamma_\mu (1-\gamma_5)\nu_b \cdot \bar{u}\gamma^\mu (1-\gamma_5) d \\ & + \ \epsilon_R^{ab} \ \bar{e}_a \gamma_\mu (1-\gamma_5)\nu_b \cdot \bar{u}\gamma^\mu (1+\gamma_5) d \\ & + \ \epsilon_S^{ab} \ \bar{e}_a (1-\gamma_5)\nu_b \cdot \bar{u} d \\ & - \ \epsilon_P^{ab} \ \bar{e}_a (1-\gamma_5)\nu_b \cdot \bar{u}\gamma_5 d \\ & + \ \epsilon_T^{ab} \ \bar{e}_a \sigma_{\mu\nu} (1-\gamma_5)\nu_b \cdot \bar{u}\sigma^{\mu\nu} (1-\gamma_5) d \Big] + \text{h.c.} \end{aligned}$$



ε_L

ε_R



ε_L

ε_S

ε_P

ε_T

$\varepsilon_i \sim (v/\Lambda)^2$

GeV-scale effective Lagrangian

VC, Gonzalez-Alonso, Jenkins 0908.1754, NPB

VC, Graesser, Gonzalez-Alonso 1210.4553, JHEP

Leptonic interactions

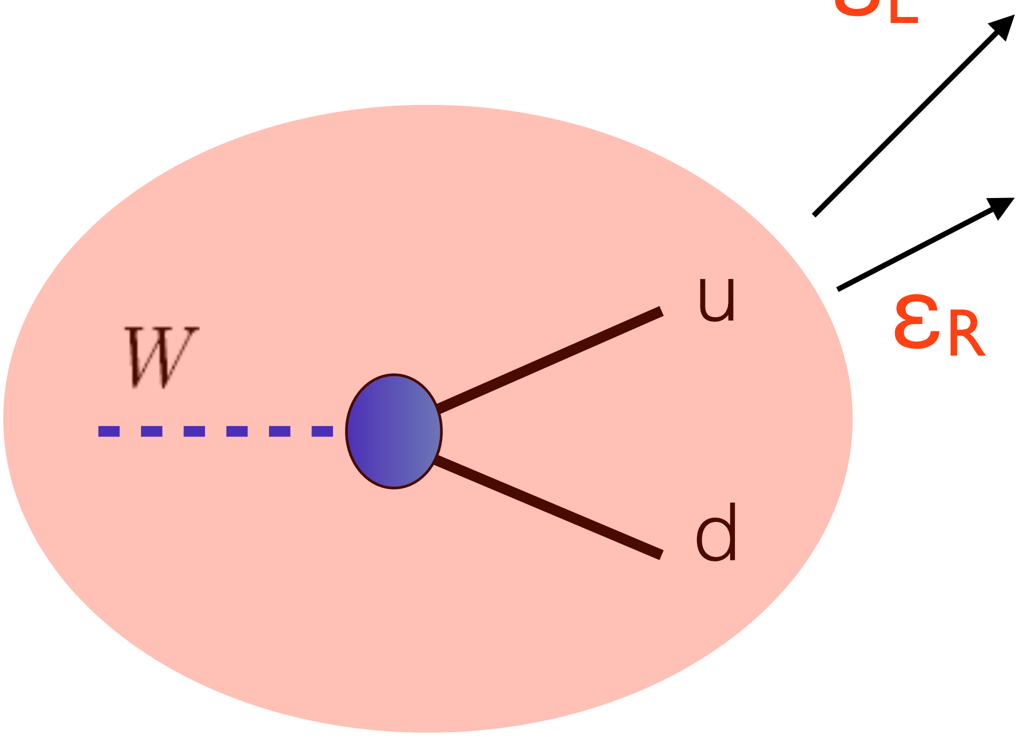
$$\mathcal{L}_{CC}^{(\mu)} = -\frac{G_F^{(0)}}{\sqrt{2}} \left(1 + \epsilon_L^{(\mu)}\right) \bar{e}\gamma^\rho(1-\gamma_5)\nu_e \cdot \bar{\nu}_\mu \gamma_\rho (1-\gamma_5)\mu \ + \ \ldots$$

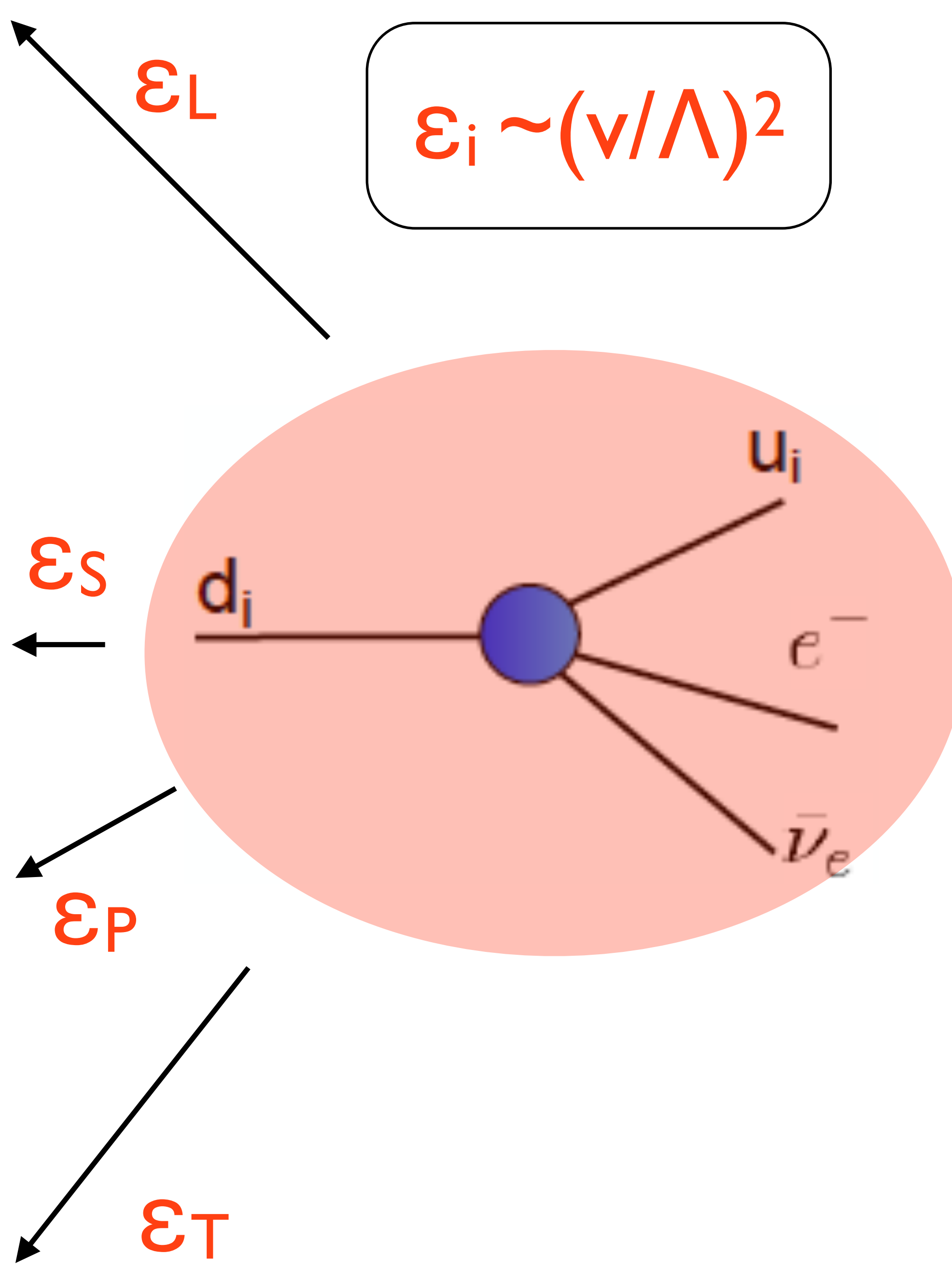
$$\frac{G_F^{(\mu)} V_{ud}}{\sqrt{2}} \left(1 - \epsilon_L^{(\mu)}\right)$$

Semi-leptonic interactions

$$\begin{aligned}\mathcal{L}_{\rm CC} = & -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \times \Big[\left(\delta^{ab} + \epsilon_L^{ab}\right) \bar{e}_a \gamma_\mu (1-\gamma_5)\nu_b \cdot \bar{u}\gamma^\mu (1-\gamma_5) d \\ & + \epsilon_R^{ab} \ \bar{e}_a \gamma_\mu (1-\gamma_5)\nu_b \cdot \bar{u}\gamma^\mu(1+\gamma_5) d \\ & + \epsilon_S^{ab} \ \bar{e}_a (1-\gamma_5)\nu_b \cdot \bar{u} d \\ & - \epsilon_P^{ab} \ \bar{e}_a (1-\gamma_5)\nu_b \cdot \bar{u}\gamma_5 d \\ & + \epsilon_T^{ab} \ \bar{e}_a \sigma_{\mu\nu} (1-\gamma_5)\nu_b \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5) d \Big] + \text{h.c.}\end{aligned}$$

$\varepsilon_i \sim (v/\Lambda)^2$





Probing LFU with $R_{e/\mu}^{(\pi)}$

$$\frac{R_{e/\mu}^{(\pi)}}{\left[R_{e/\mu}^{(\pi)}\right]^{\rm SM}} = \frac{\left|1 + \epsilon_L^{ee} - \epsilon_R - \frac{B_0}{m_e}\epsilon_P^{ee}\right|^2}{\left|1 + \epsilon_L^{\mu\mu} - \epsilon_R - \frac{B_0}{m_\mu}\epsilon_P^{\mu\mu}\right|^2} + \cdots$$

Non-interfering terms with 'wrong' neutrino flavor

- BSM axial-current contribution

$$-1.9 \times 10^{-3} < \epsilon_A^{ee} - \epsilon_A^{\mu\mu} < -0.1 \times 10^{-3}$$

$$\epsilon_A \equiv \epsilon_L - \epsilon_R$$

$\Lambda_A \sim 5.5$ TeV

Probing LFU with $R_{e/\mu}^{(\pi)}$

$$\frac{R_{e/\mu}^{(\pi)}}{\left[R_{e/\mu}^{(\pi)}\right]^{\rm SM}} = \frac{\left|1+\epsilon_L^{ee}-\epsilon_R-\frac{B_0}{m_e}\epsilon_P^{ee}\right|^2}{\left|1+\epsilon_L^{\mu\mu}-\epsilon_R-\frac{B_0}{m_\mu}\epsilon_P^{\mu\mu}\right|^2}+\cdots$$

Non-interfering terms with 'wrong' neutrino flavor

- BSM pseudoscalar contribution
  - Not helicity suppressed! $B_0(\mu) \equiv \frac{M_\pi^2}{m_u(\mu)+m_d(\mu)}$ → $B_0/m_e = 3.6 \times 10^3$ @ μ = 2 GeV
  - LFU violation ↔ $[\epsilon_P]^{\alpha\alpha} \neq \kappa\, m_\alpha$ $\quad \epsilon_P^{ee} < 5.4 \times 10^{-7}$ $\quad \Lambda_P \sim 330$ TeV

Probing LFU with $R_{e/\mu}(\pi)$

$$\frac{R^{(\pi)}_{e/\mu}}{\left[R^{(\pi)}_{e/\mu}\right]^{\rm SM}} = \frac{\left|1+\epsilon_L^{ee}-\epsilon_R-\frac{B_0}{m_e}\epsilon_P^{ee}\right|^2}{\left|1+\epsilon_L^{\mu\mu}-\epsilon_R-\frac{B_0}{m_\mu}\epsilon_P^{\mu\mu}\right|^2}+\cdots$$

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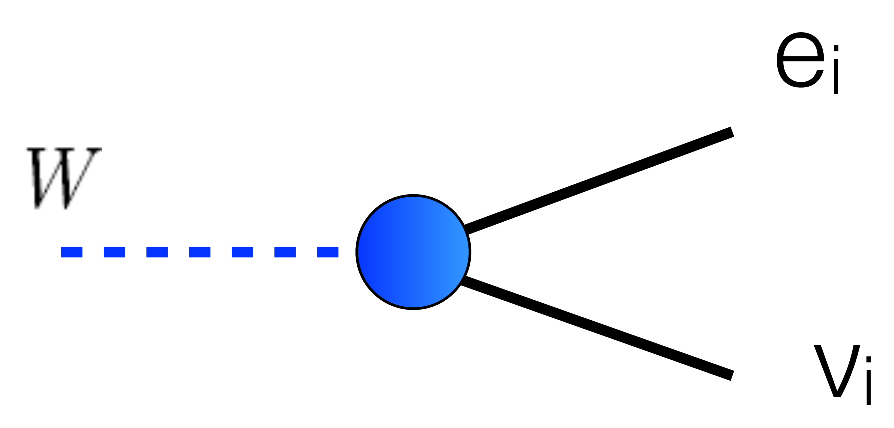
  - LFU violation ↔ $[\varepsilon_P]^{\alpha\alpha} \neq \kappa\, m_\alpha$ $\quad \epsilon_P^{ee} < 5.4 \times 10^{-7}$ $\quad \Lambda_P \sim 330$ TeV
  - Marginalizing w.r.t. ε_P^{ex} $\quad \epsilon_P^{ee} < 5.5 \times 10^{-4}$ $\quad \Lambda_P \sim 10$ TeV

$R_{e/\mu}(\pi)$ vs other probes of LFU

- Comparison possible within a given class of models
- Instructive example: LFU violation in vertex corrections, probed by decays of W, τ, K, π

A. Pich, 2012.07099
Bryman, VC, Crivellin, Inguglia, 2111.05338, ARNPS

$$\mathcal{L} \supset -i\frac{g_2}{\sqrt{2}}\bar{\ell}_i\gamma^\mu P_L \nu_j W_\mu^- \left(\delta_{ij} + \epsilon_{ij}\right) + \text{h.c.}$$



$$g_\ell \equiv g_2\left(1 + \epsilon_{\ell\ell}\right)$$

$|g_\mu / g_e|$

$B_{\tau\to\mu}/B_{\tau\to e}$	1.0017 ± 0.0016
$B_{\pi\to\mu}/B_{\pi\to e}$	1.0010 ± 0.0009
$B_{K\to\mu}/B_{K\to e}$	0.9978 ± 0.0018
$B_{K\to\pi\mu}/B_{K\to\pi e}$	1.0009 ± 0.0018
$B_{W\to\mu}/B_{W\to e}$	1.001 ± 0.003

$|g_\tau / g_\mu|$

$B_{\tau\to e}\ \tau_\mu/\tau_\tau$	1.0011 ± 0.0014
$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	0.9964 ± 0.0038
$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	0.986 ± 0.008
$B_{W\to\tau}/B_{W\to\mu}$	1.001 ± 0.010

$|g_\tau / g_e|$

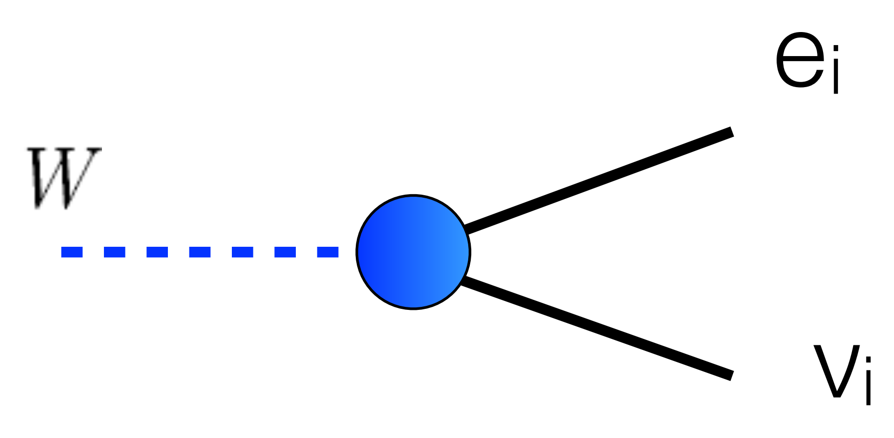
$B_{\tau\to\mu}\ \tau_\mu/\tau_\tau$	1.0028 ± 0.0015
$B_{W\to\tau}/B_{W\to e}$	1.008 ± 0.012

$R_{e/\mu}^{(\pi)}$ vs other probes of LFU

- Comparison possible within a given class of models
- Instructive example: LFU violation in vertex corrections, probed by decays of W, τ, K, π

A. Pich, 2012.07099
Bryman, VC, Crivellin, Inguglia, 2111.05338, ARNPS

$$\mathcal{L} \supset -i\frac{g_2}{\sqrt{2}}\bar{\ell}_i\gamma^\mu P_L \nu_j W^-_\mu\left(\delta_{ij}+\epsilon_{ij}\right) + \text{h.c.}$$



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$R_{e/\mu}^{(\pi)}$ gives strongest constraint on ee − μμ combination

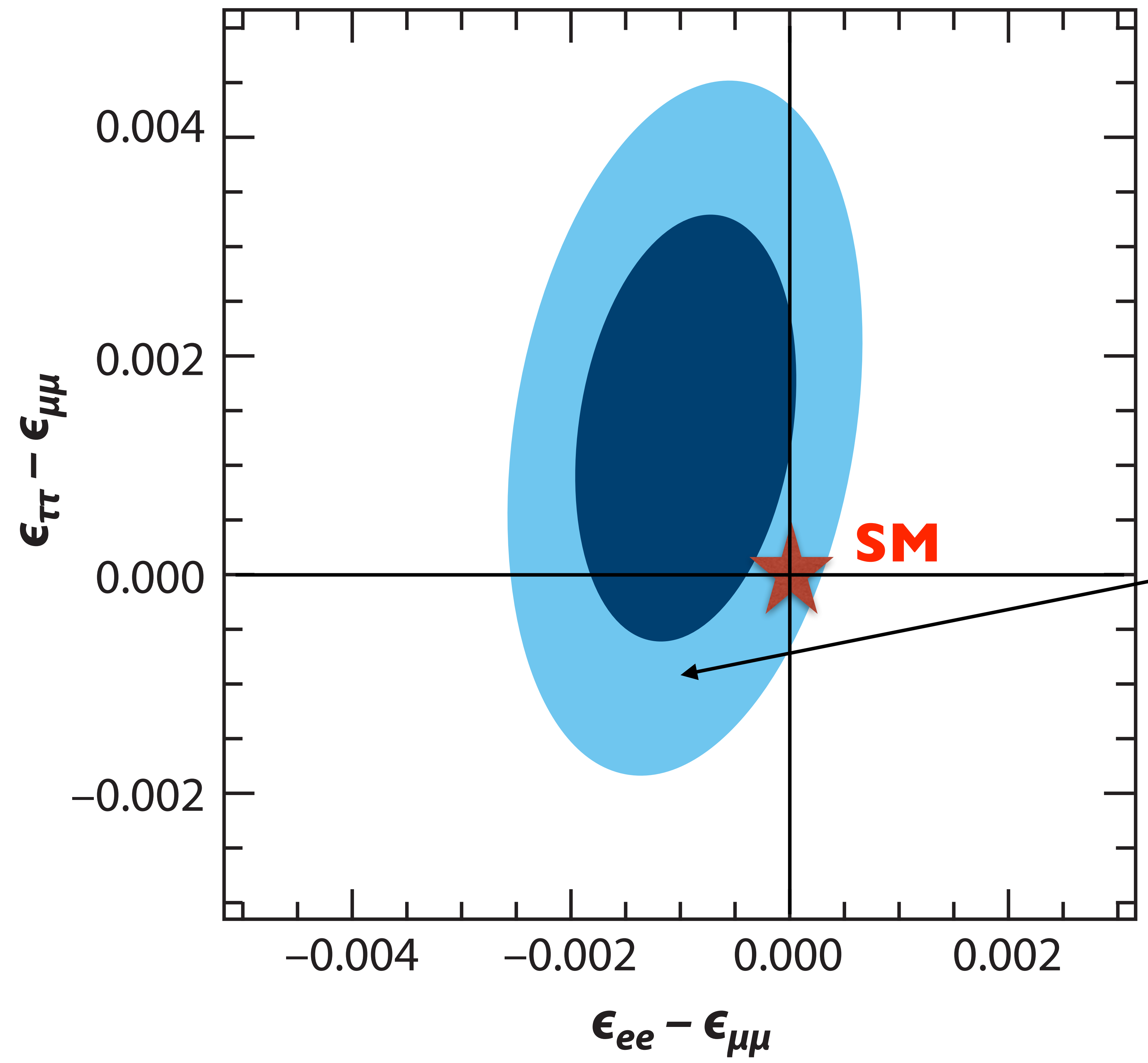
$|g_\tau/g_e|$

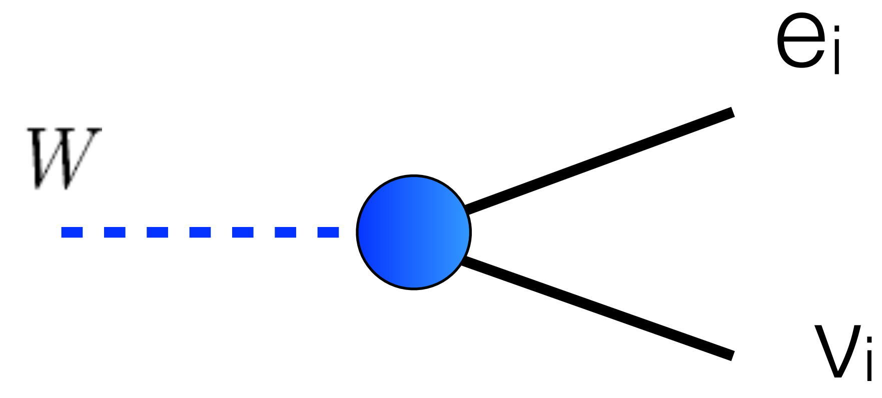
$B_{\tau\to\mu}\ \tau_\mu/\tau_\tau$	1.0028 ± 0.0015
$B_{W\to\tau}/B_{W\to e}$	1.008 ± 0.012

$R_{e/\mu}^{(\pi)}$ vs other probes of LFU

- Comparison possible within a given class of models
- Instructive example: LFU violation in vertex corrections, probed by decays of W, τ, K, π
- Global fit [except for B decays]:

Bryman, VC, Crivellin, Inguglia, 2111.05338, ARNPS





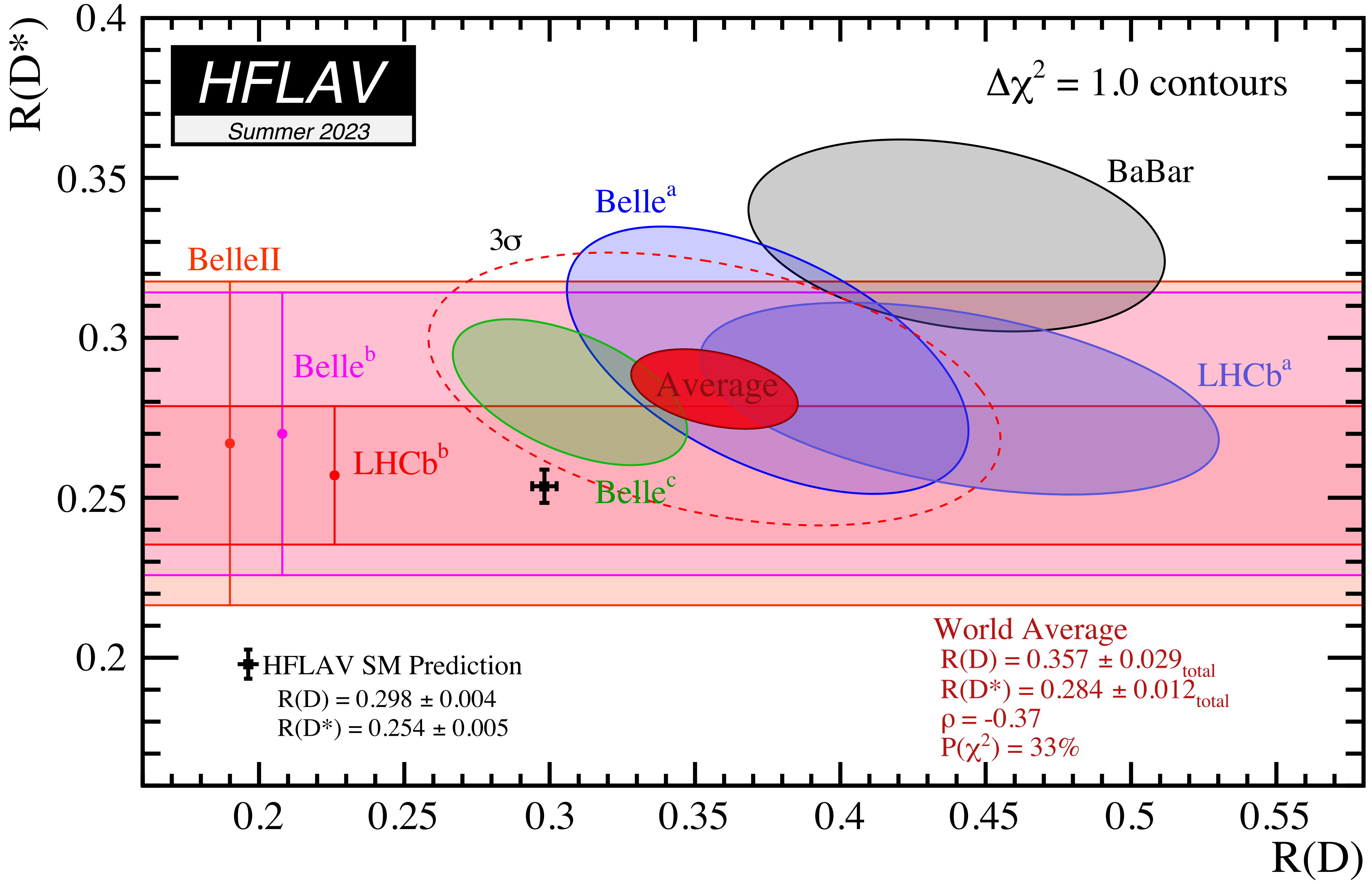
$$g_\ell \equiv g_2 \, (1 + \epsilon_{\ell\ell})$$

PIONEER will have strong impact on the horizontal scale in this plot

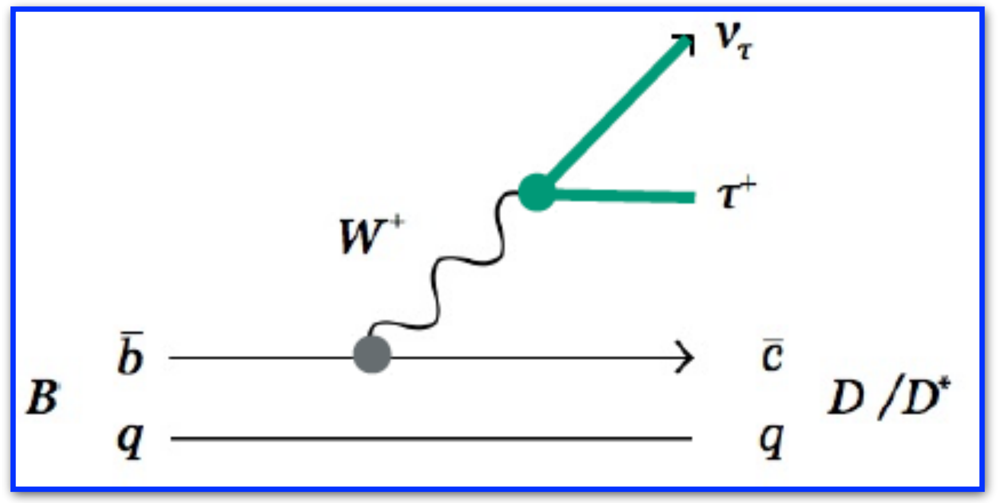
LFU hint in CC b→c decays

- 3σ deviation from LFU in CC decays involving tau vs light lepton flavors

$\ell = \{e, \mu\}$



$$R(D^{(*)}) = \frac{\mathrm{Br}\left[B \to D^{(*)}\tau\nu\right]}{\mathrm{Br}\left[B \to D^{(*)}\ell\nu\right]}$$



$$b \to c\, \ell\nu$$

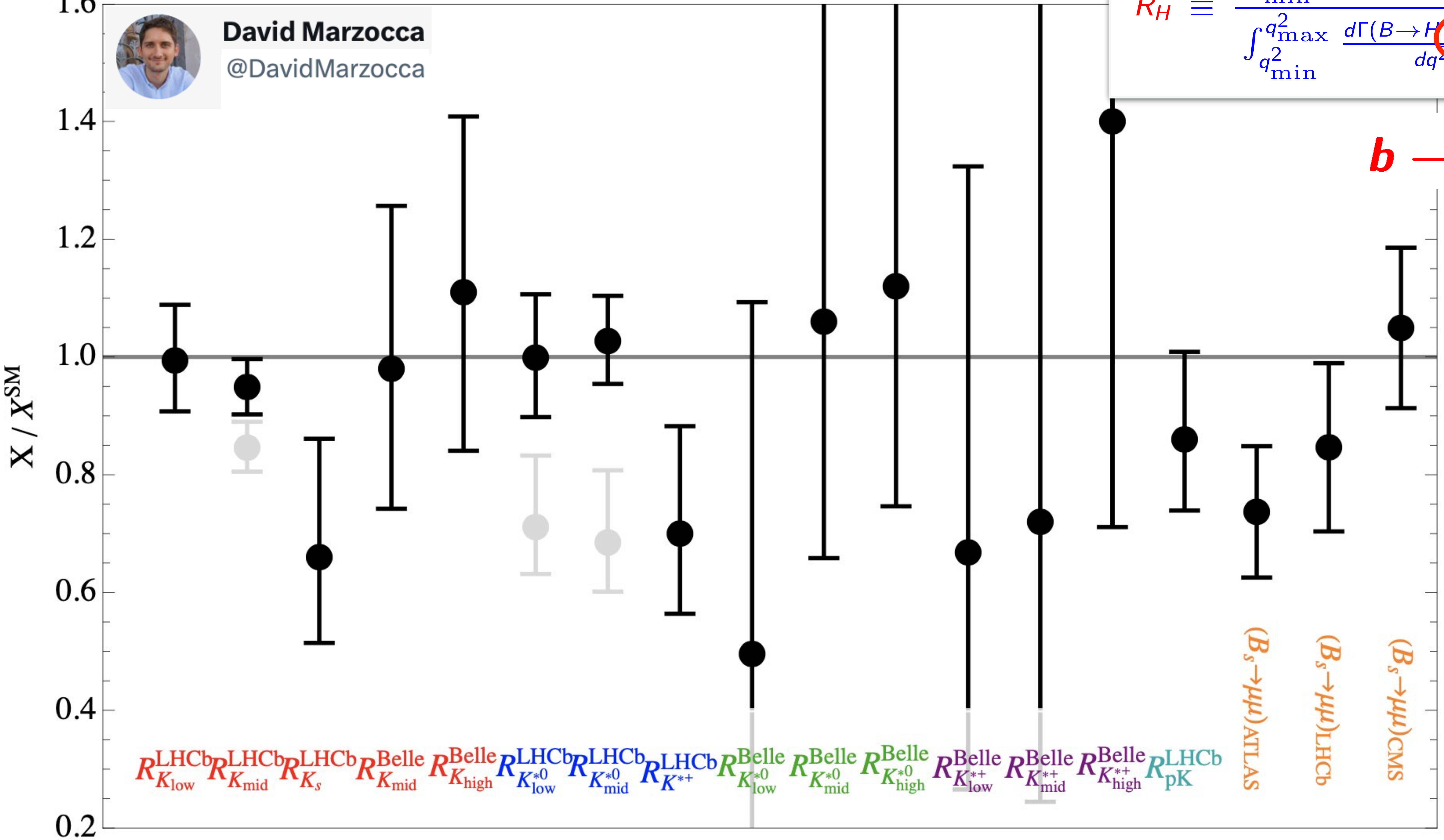
- Can be explained by a number of models, e.g. leptoquarks with specific flavor couplings

- However, for light lepton flavors:

$$\frac{\Gamma(B \to D^{(*)}\mu\nu)}{\Gamma(B \to D^{(*)}e\nu)} \rightarrow \left|\frac{g_\mu}{g_e}\right| = 0.989 \pm 0.012$$

Jung-Straub 1801.01112

The b→s LFU anomalies are ~ gone



$$R_H \equiv \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B\to H\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B\to He^+e^-)}{dq^2} dq^2} \overset{SM}{=} 1 \pm \mathcal{O}(10^{-2})$$

$b \to s\,\ell^+\ell^-$

Cabibbo universality tests

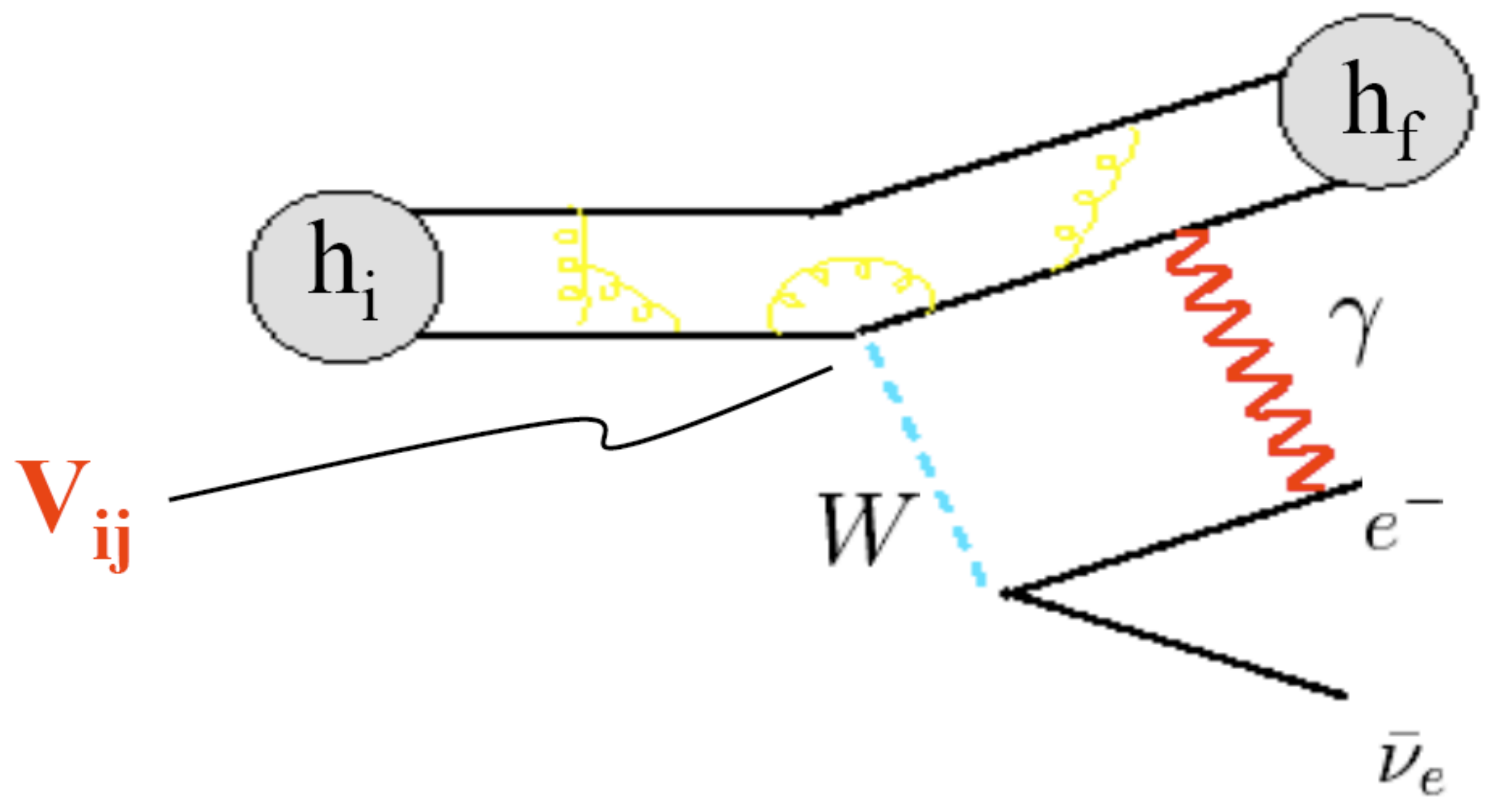
Extract $V_{ud}=\cos\theta_C$ and $V_{us}=\sin\theta_C$ from total decay rates

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

CKM element

Hadronic matrix element

Radiative corrections: $(\alpha/\pi) \sim 2.\times 10^{-3}$ and smaller effects



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CKM element

Hadronic matrix element

Radiative corrections: $(\alpha/\pi) \sim 2.\times 10^{-3}$ and smaller effects

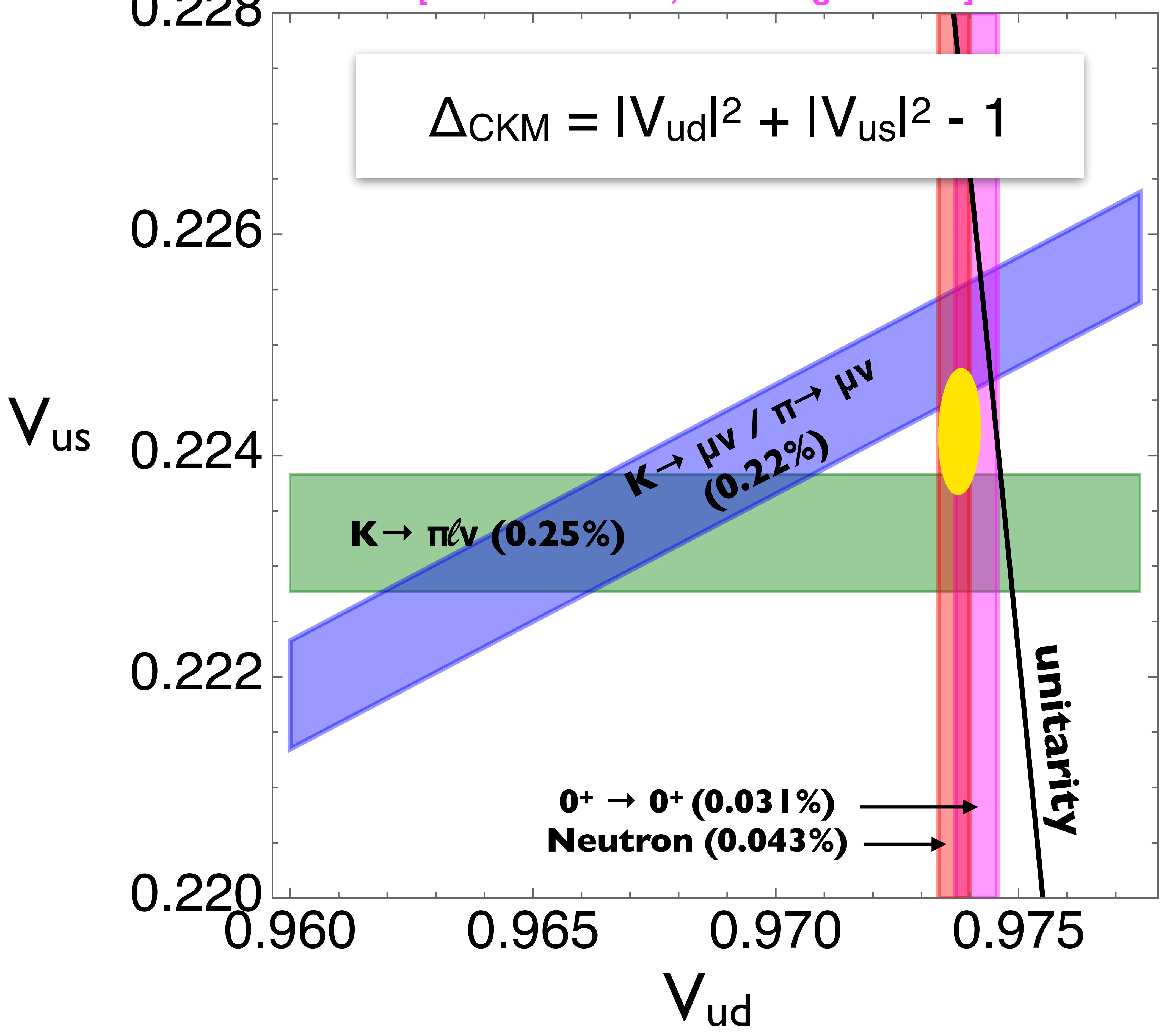
Unitarity test

$$\Delta_{\rm CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = 0$$

The Cabibbo angle anomaly

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

VC-Crivellin-Hoferichter-Moulson 2208.11707
[and refs therein, including FLAG21]

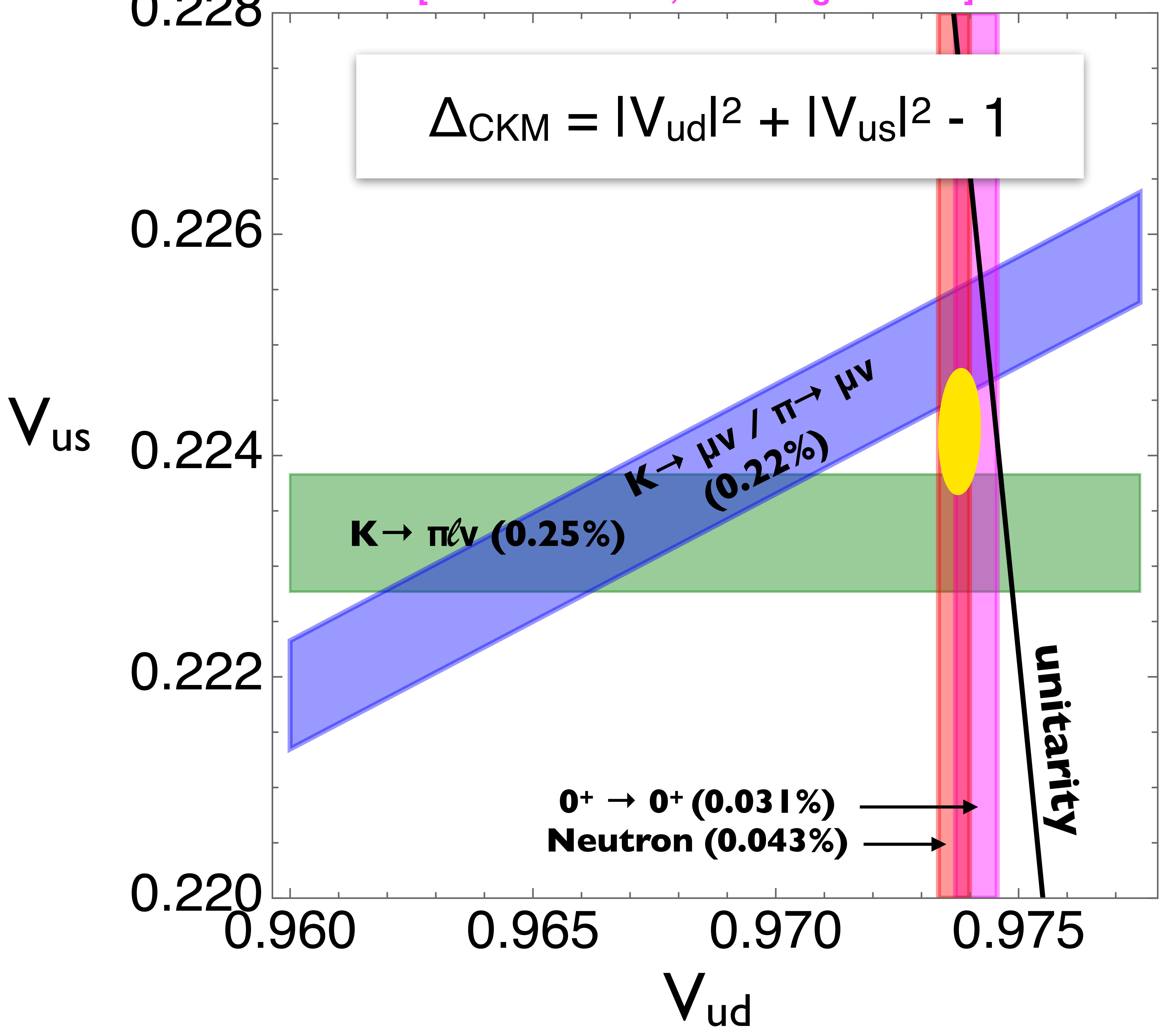


- The ‘anomalies’:
  - ~3σ effect in global fit (Δ_{CKM}= −1.48(53) ×10^{-3})
  - V_{ud} and V_{us} from different processes → different Δ_{CKM}
  - ~3σ problem in meson sector (Kl2 vs Kl3)

The Cabibbo angle anomaly

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

VC-Crivellin-Hoferichter-Moulson 2208.11707
[and refs therein, including FLAG21]



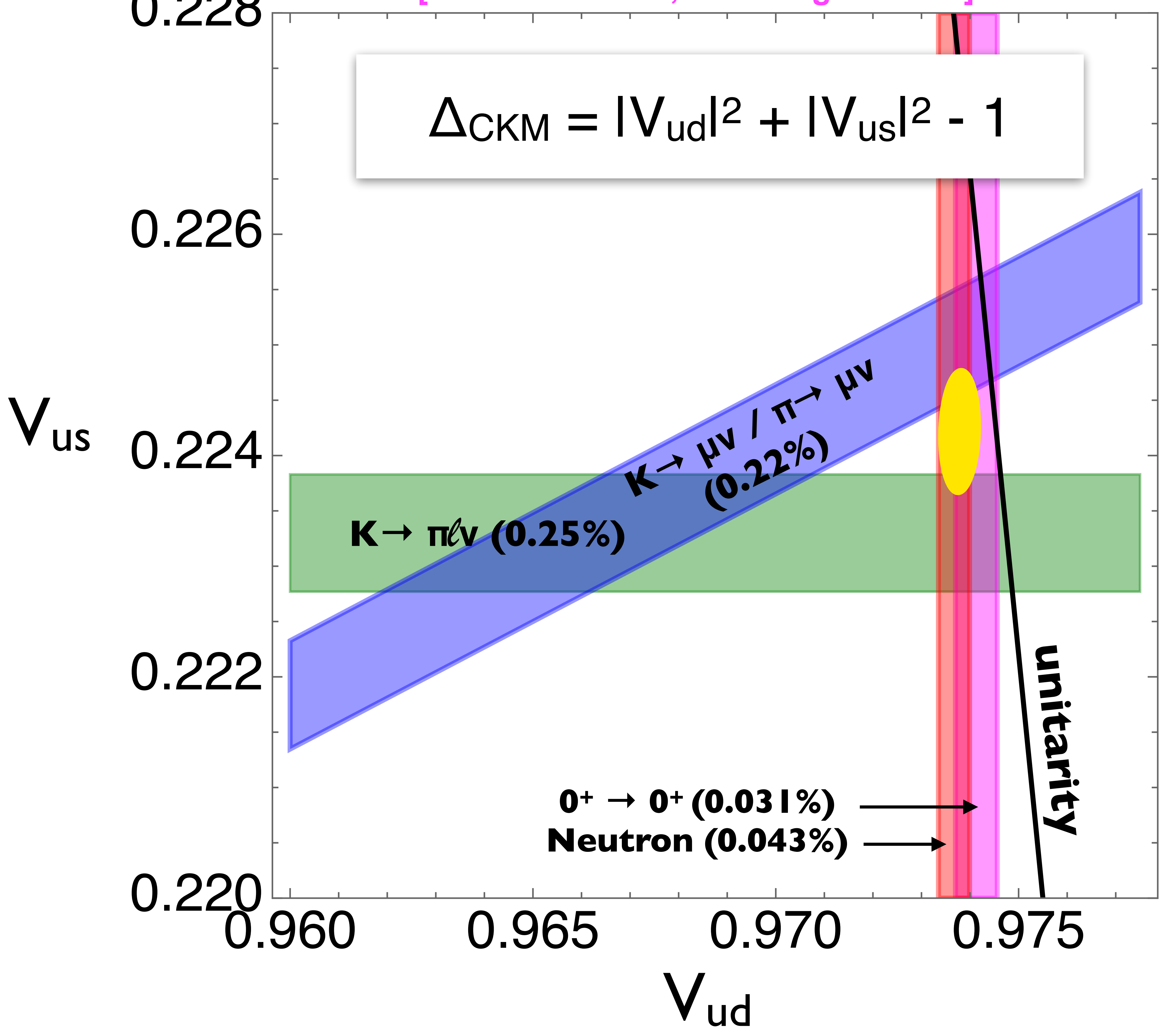
- Expected experimental improvements
  - neutron decay (will match nominal nuclear uncertainty)
  - possibly new $K_{\mu 3}/K_{\mu 2}$ BR measurement at NA62 & HIKE
  - pion beta decay (3x to 10x at PIONEER phases II, III)

- Further theoretical scrutiny of SM prediction
  - Lattice gauge theory: K→π vector f.f., rad. corr. for Kl3
  - EFT for neutron and nuclei, with goal $\delta\Delta_R \sim 2\times 10^{-4}$
  - …

The Cabibbo angle anomaly

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

VC-Crivellin-Hoferichter-Moulson 2208.11707
[and refs therein, including FLAG21]



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  - …

What about new physics explanations?

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

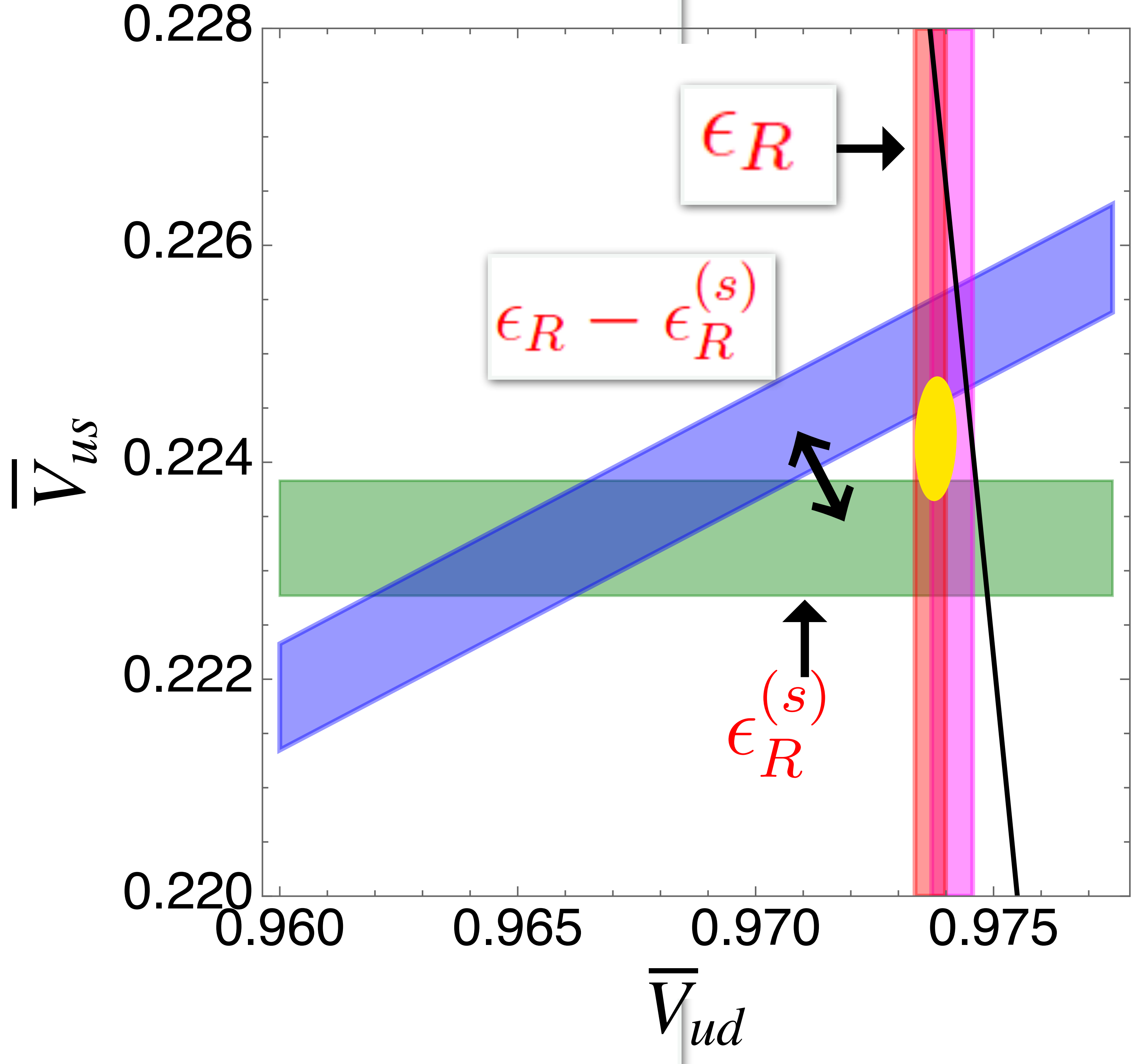
Find set of ε's so that V_{ud} and V_{us} bands meet on the unitarity circle

Right-handed quark couplings

- Right-handed currents (in the 'ud' and 'us' sectors)

Alioli et al 1703.04751, JHEP
Grossman-Passemar-Schacht 1911.07821 JHEP
VC-Crivellin-Hoferichter-Moulson 2208.11707, PLB

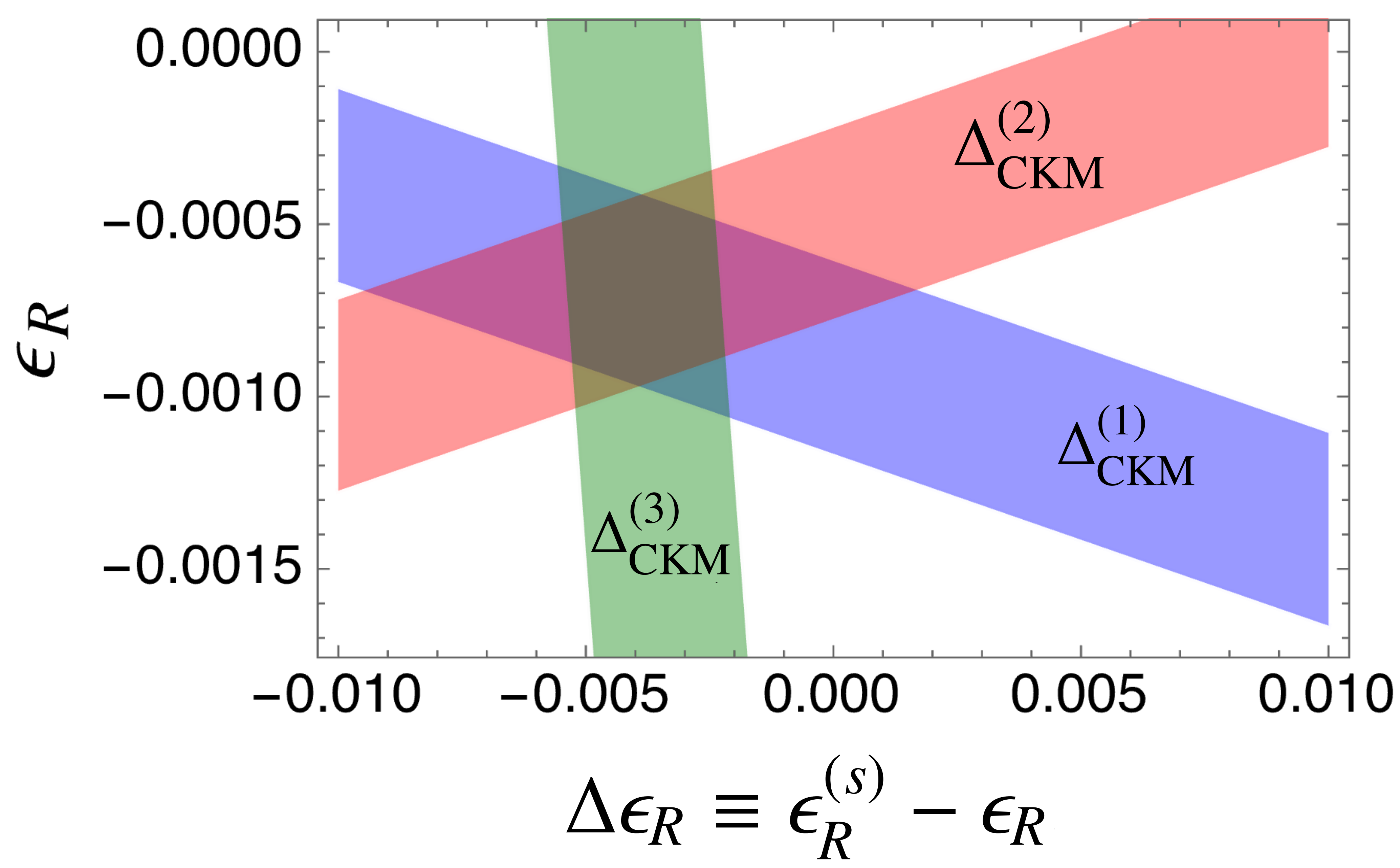
$$
\begin{aligned}
|\bar{V}_{ud}|^2_{0^+\to 0^+} &= |V_{ud}|^2\left(1+2\,\epsilon_R\right)\\
|\bar{V}_{ud}|^2_{n\to pe\bar{\nu}} &= |V_{ud}|^2\left(1+2\,\epsilon_R\right)\\
|\bar{V}_{us}|^2_{Ke3} &= |V_{us}|^2\left(1+2\,\epsilon_R^{(s)}\right)\\
|\bar{V}_{ud}|^2_{\pi e3} &= |V_{ud}|^2\left(1+2\,\epsilon_R\right)\\
|\bar{V}_{us}|^2_{K\mu 2} &= |V_{us}|^2\left(1-2\,\epsilon_R^{(s)}\right)\\
|\bar{V}_{ud}|^2_{\pi\mu 2} &= |V_{ud}|^2\left(1-2\,\epsilon_R\right)
\end{aligned}
$$



- CKM elements from vector (axial) channels are shifted by $1+\epsilon_R$ ($1-\epsilon_R$). V_{us}/V_{ud}, V_{ud} and V_{us} shift in anti-correlated way, can resolve all tensions!

Unveiling R-handed quark currents?

VC-Crivellin-Hoferichter-Moulson 2208.11707



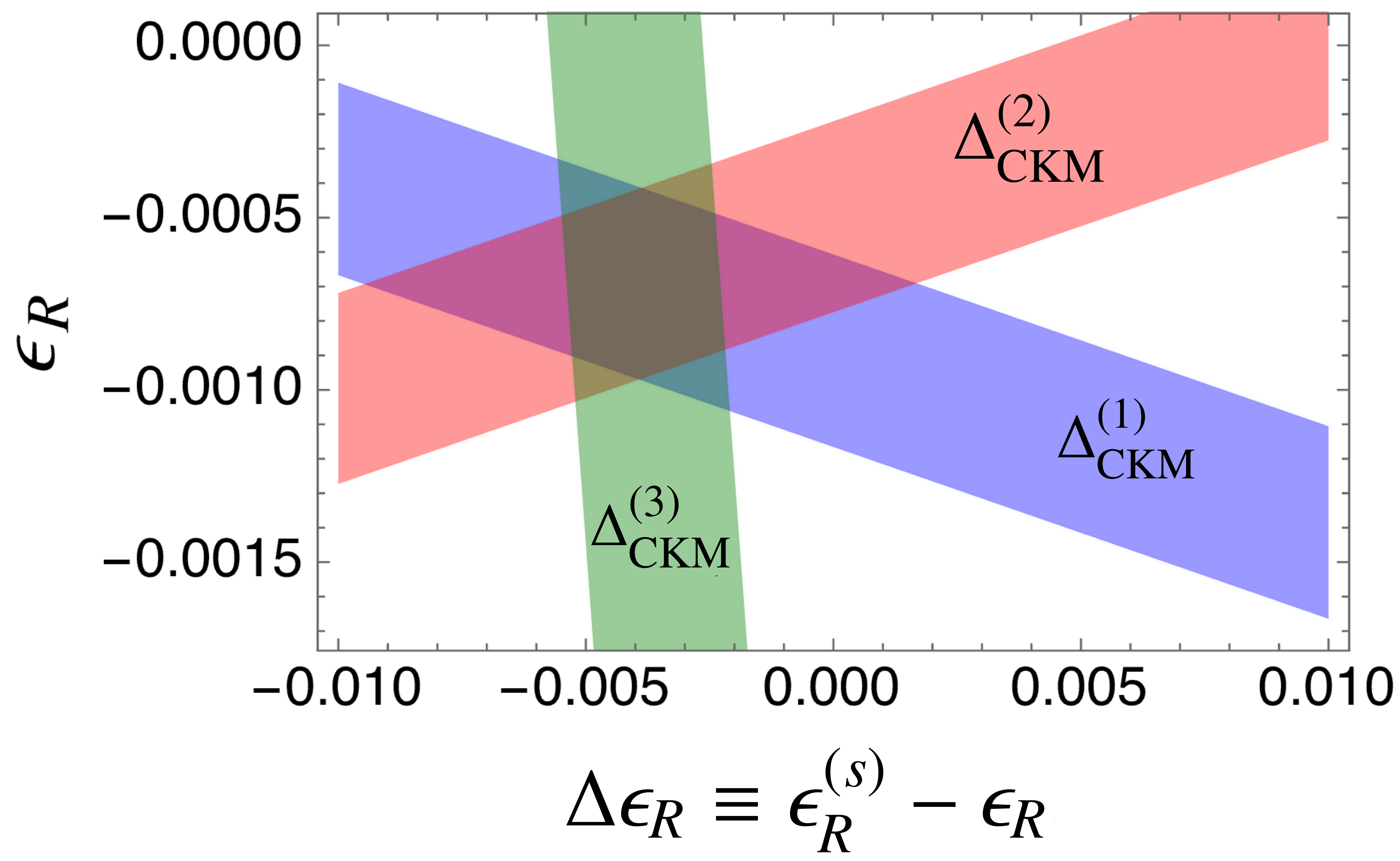
$$\Delta^{(1)}_{CKM} = |V_{ud}^{\beta}|^2 + |V_{us}^{K_{\ell 3}}|^2 - 1 = -1.76(56) \times 10^{-3}$$

$$\Delta^{(2)}_{CKM} = |V_{ud}^{\beta}|^2 + |V_{us}^{K_{\ell 2}/\pi_{\ell 2},\,\beta}|^2 - 1 = -0.98(58) \times 10^{-3}$$

$$\Delta^{(3)}_{CKM} = |V_{ud}^{K_{\ell 2}/\pi_{\ell 2},\,K_{\ell 3}}|^2 + |V_{us}^{K_{\ell 3}}|^2 - 1 = -1.64(63) \times 10^{-2}$$

Unveiling R-handed quark currents?

VC-Crivellin-Hoferichter-Moulson 2208.11707



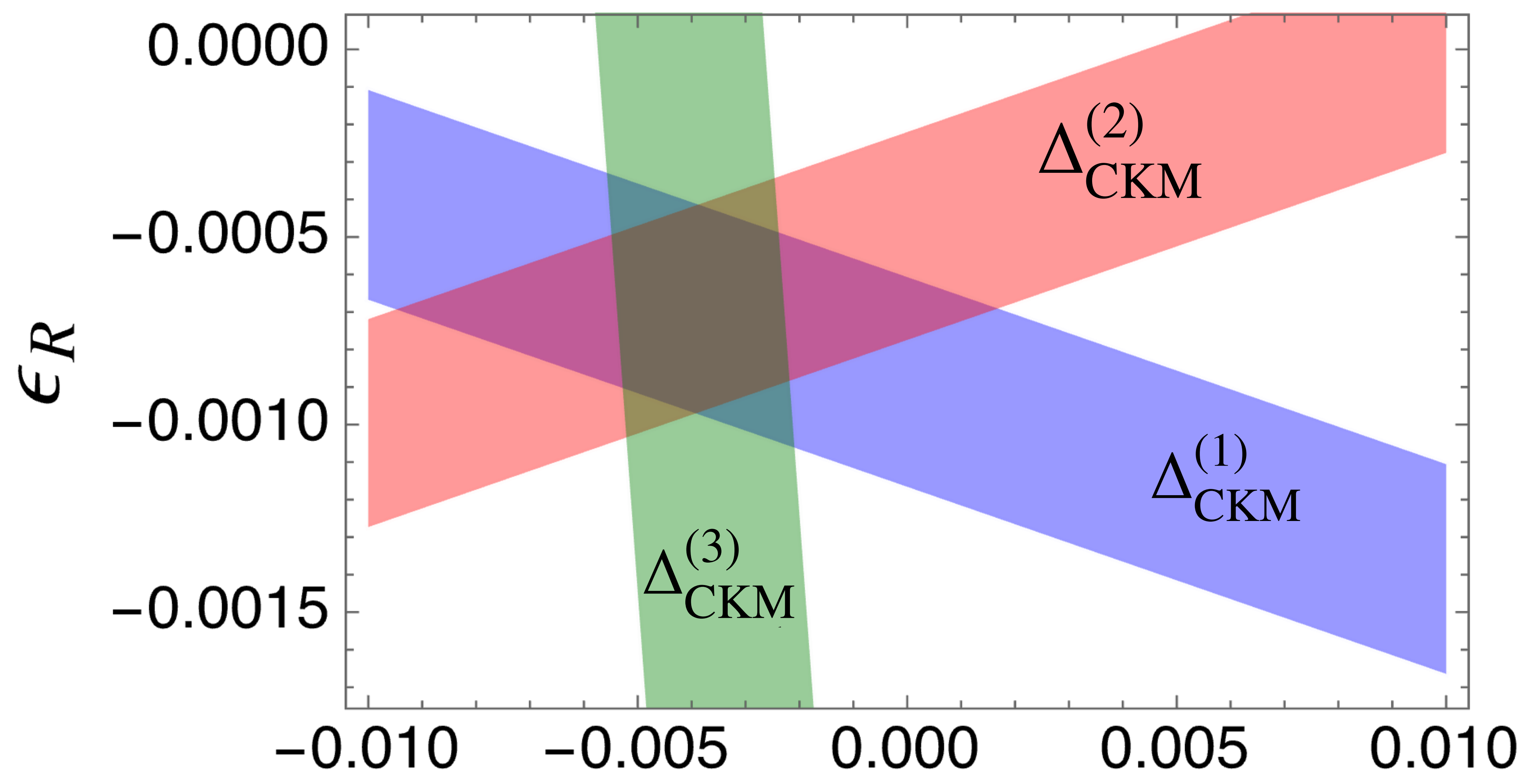
$$\Delta^{(1)}_{\rm CKM} = 2\epsilon_R + 2\Delta\epsilon_R V_{us}^2,$$
$$\Delta^{(2)}_{\rm CKM} = 2\epsilon_R - 2\Delta\epsilon_R V_{us}^2,$$
$$\Delta^{(3)}_{\rm CKM} = 2\epsilon_R + 2\Delta\epsilon_R (2 - V_{us}^2)$$

$$\epsilon_R = -0.69(27) \times 10^{-3}$$
$$\Delta\epsilon_R = -3.9(1.6) \times 10^{-3}$$

Λ_R ~ 5-10 TeV

Unveiling R-handed quark currents?

VC-Crivellin-Hoferichter-Moulson 2208.11707



$$\Delta\epsilon_R \equiv \epsilon_R^{(s)} - \epsilon_R$$

$$\Delta_{\rm CKM}^{(1)} = 2\epsilon_R + 2\Delta\epsilon_R V_{us}^2,$$
$$\Delta_{\rm CKM}^{(2)} = 2\epsilon_R - 2\Delta\epsilon_R V_{us}^2,$$
$$\Delta_{\rm CKM}^{(3)} = 2\epsilon_R + 2\Delta\epsilon_R (2 - V_{us}^2)$$

$$\epsilon_R = -0.69(27) \times 10^{-3}$$
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Λ_R ~ 5-10 TeV

- Preferred ranges are not in conflict with other constraints from β decays

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

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

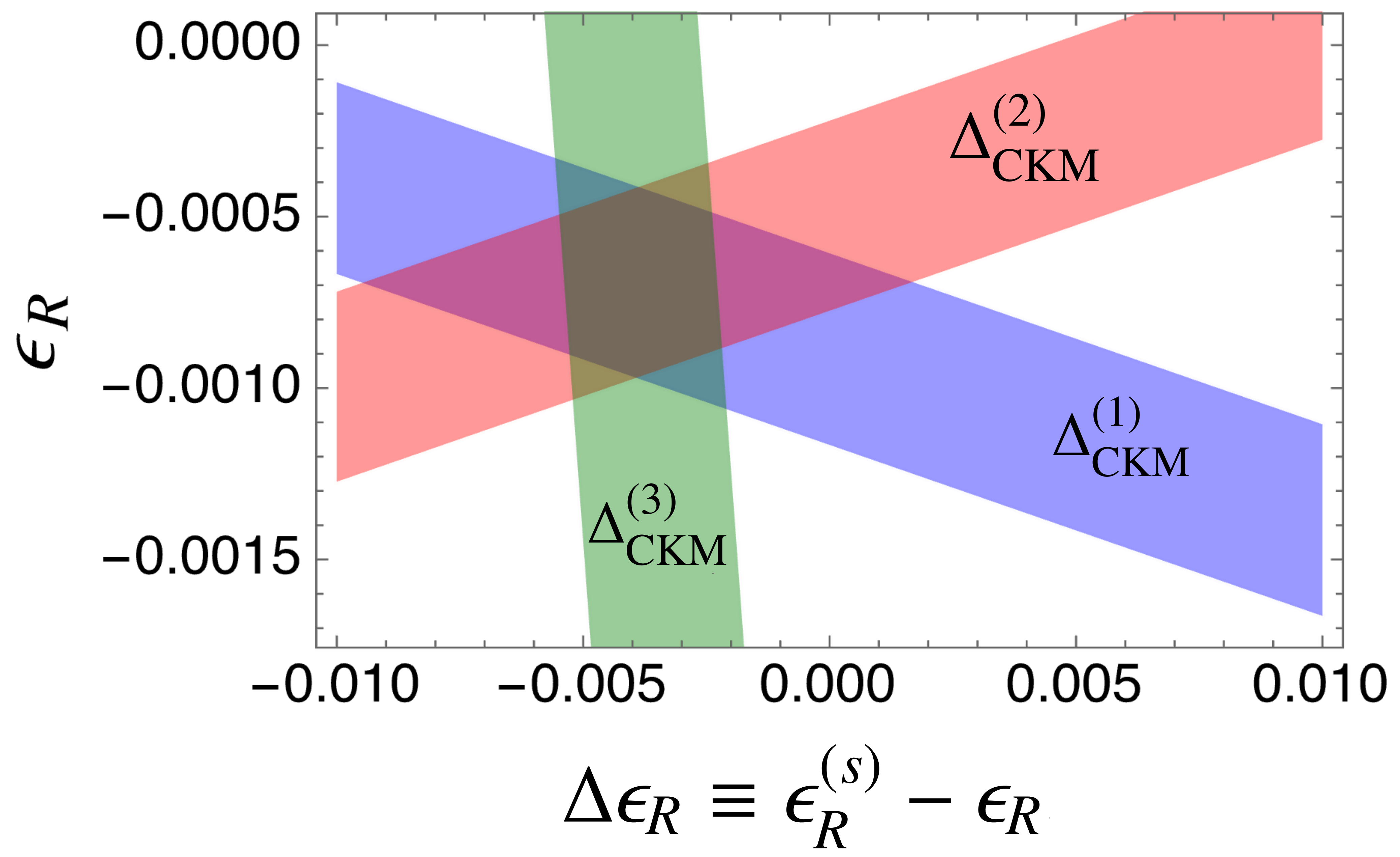
$$\lambda \equiv \frac{g_A}{g_V}$$

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

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

Unveiling R-handed quark currents?

VC-Crivellin-Hoferichter-Moulson 2208.11707



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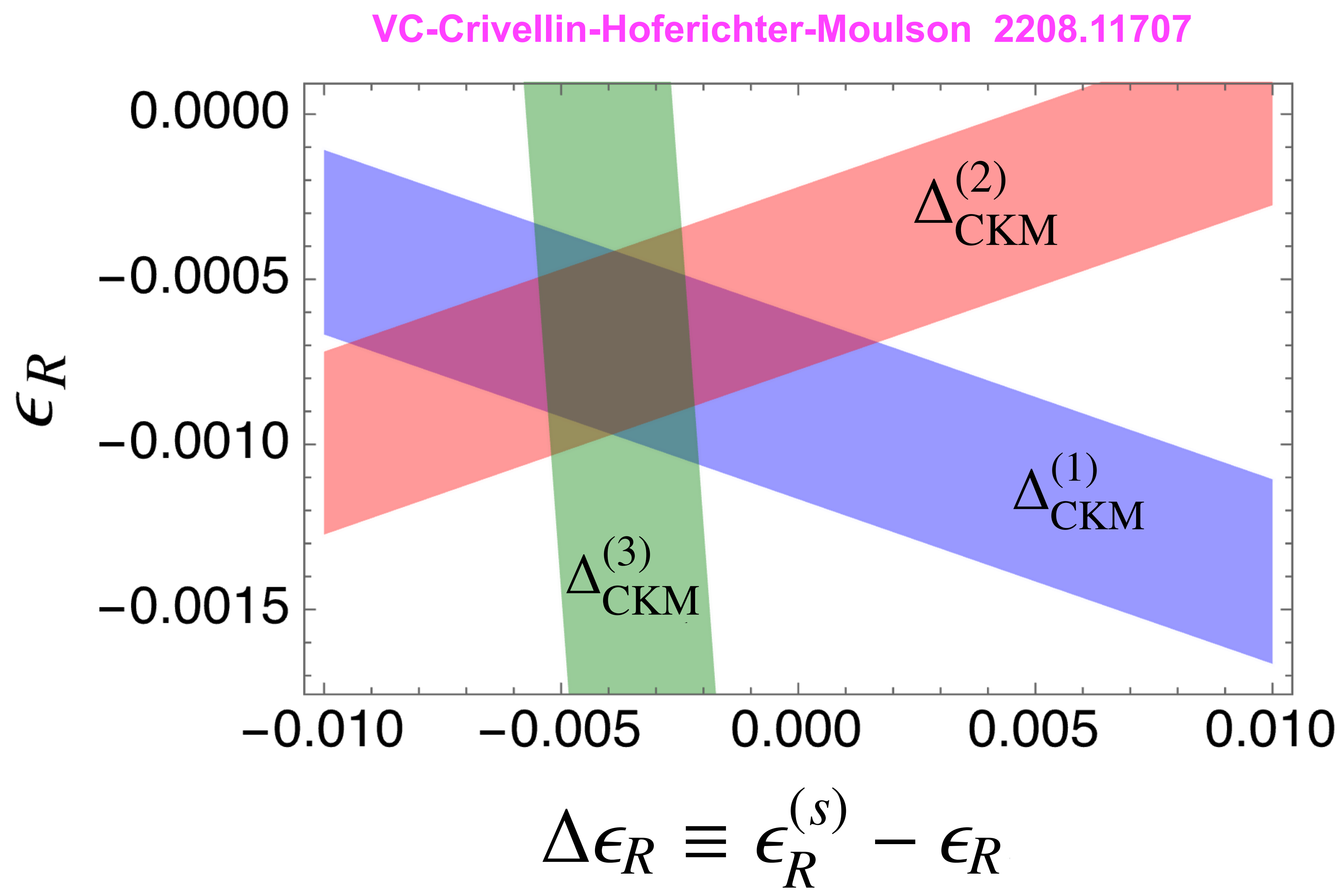
$$\epsilon_R = -0.69(27) \times 10^{-3}$$
$$\Delta\epsilon_R = -3.9(1.6) \times 10^{-3}$$

$\Lambda_R \sim$ 5-10 TeV

- Can PIONEER help falsify this scenario? This RH solution implies
  - No impact on $R_{e/\mu}^{(\pi)}$: the R-handed quark couplings are LFU up to higher order in (v/Λ)
  - V_{ud} extracted from $\Gamma(\pi^\pm \to \pi^0 e^\pm \nu(\gamma))$, neutron decay, and $0^+ \to 0^+$ should be the same

Unveiling R-handed quark currents?



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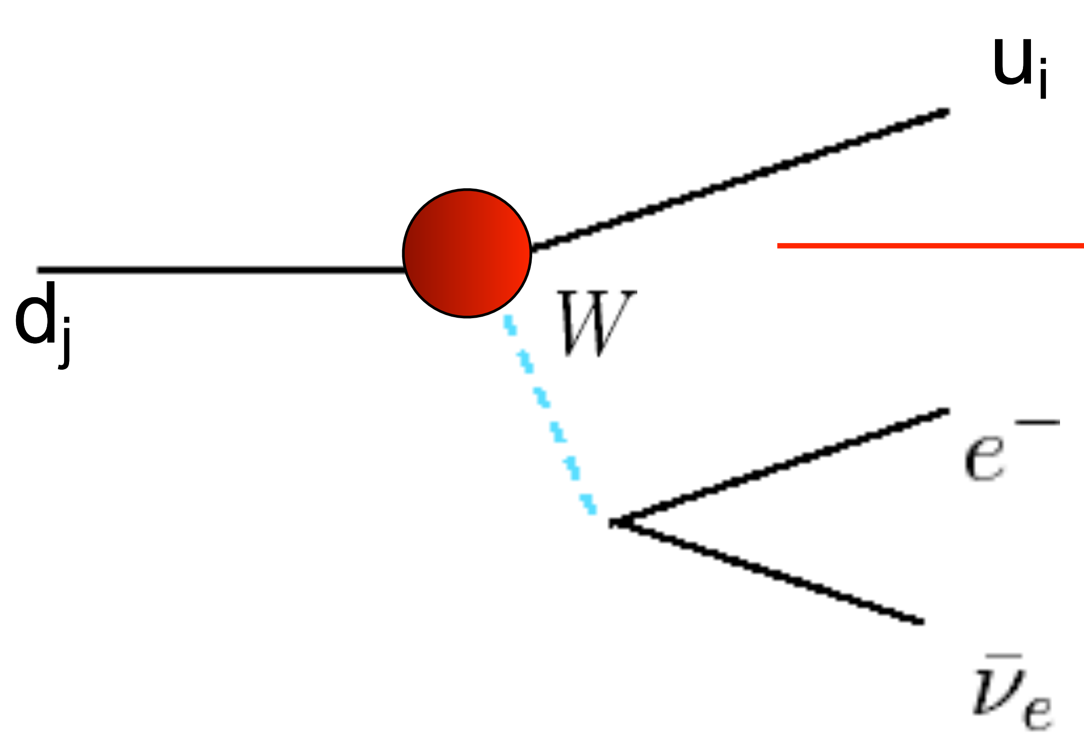
$$\epsilon_R = -0.69(27) \times 10^{-3}$$
$$\Delta\epsilon_R = -3.9(1.6) \times 10^{-3}$$

Λ_R ~ 5-10 TeV

- Does the R-handed current explanation survive after taking into account high energy data?

High scale origin of εR

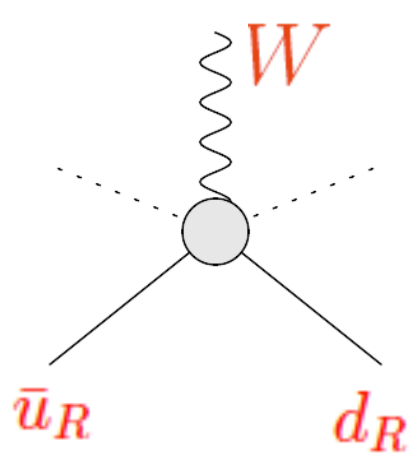
- ε_R originates from SU(2)xU(1) invariant vertex corrections



Building blocks

$$l^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix} \quad q^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix} \quad H = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$

$$Q_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$$



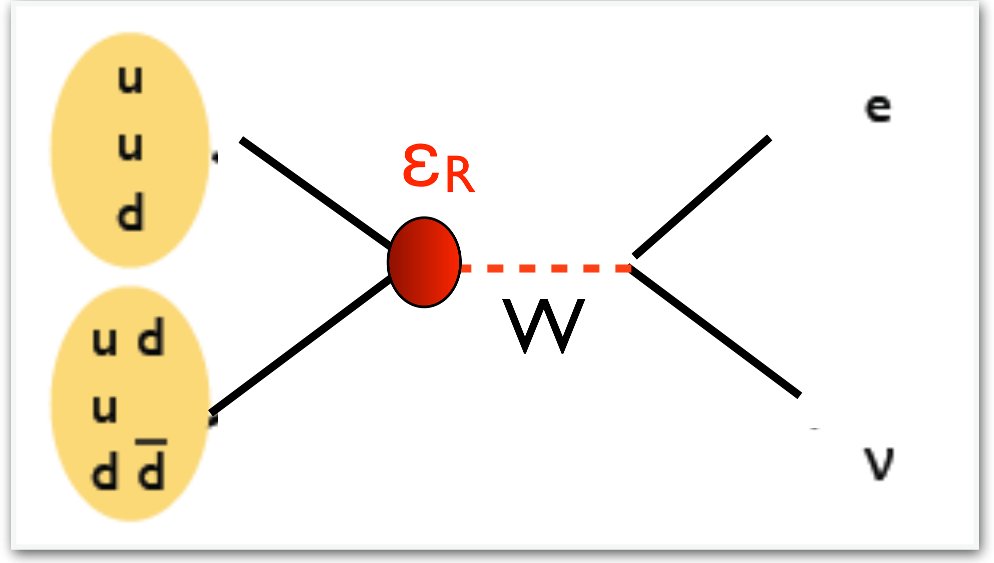
ε_R

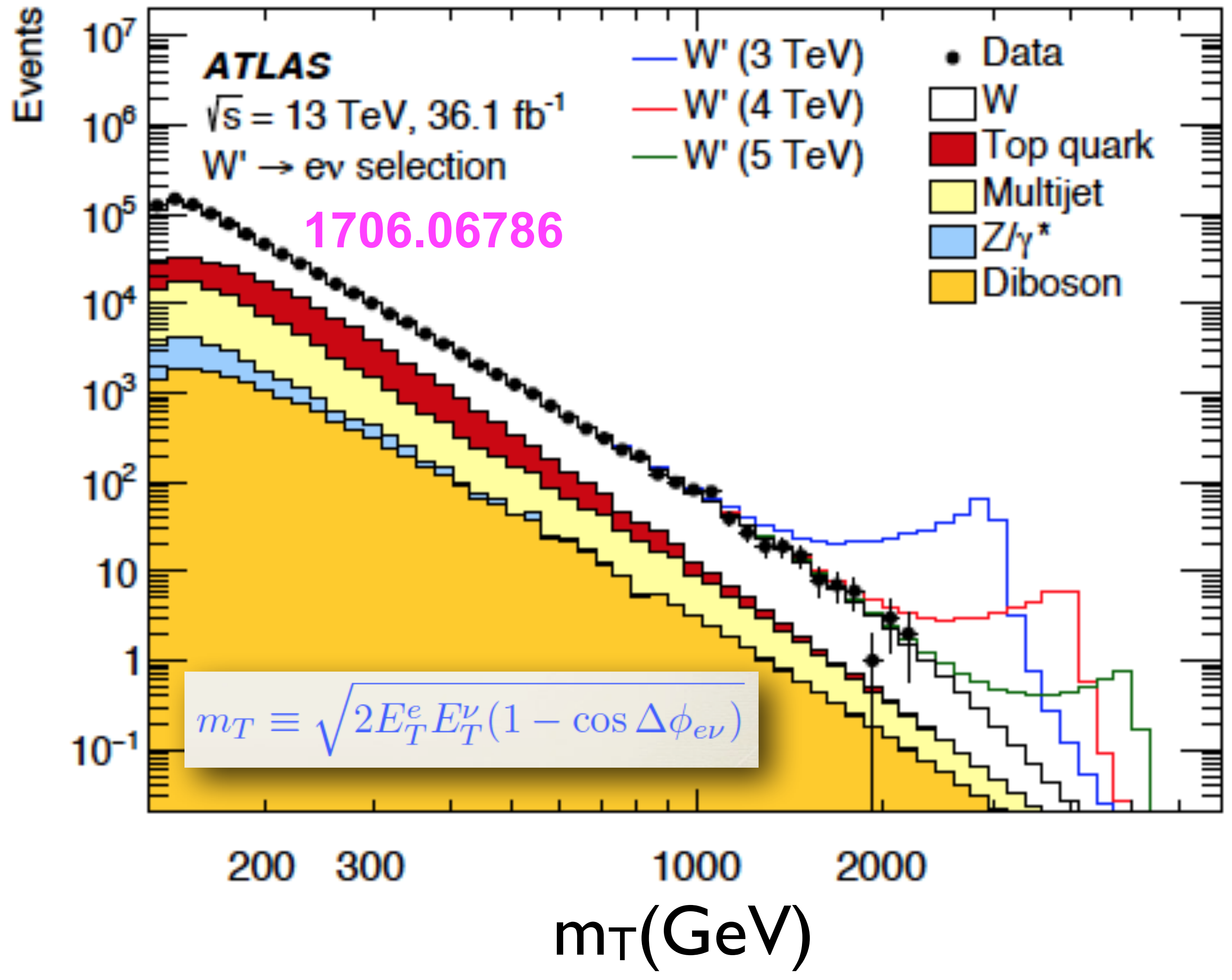
- Can be generated by W_L-W_R mixing in Left-Right symmetric models or by exchange of vector-like quarks

High Energy constraints on ε_R are weak

Contribute tp pp → eν+X at the LHC

LHC: pp → eν + X

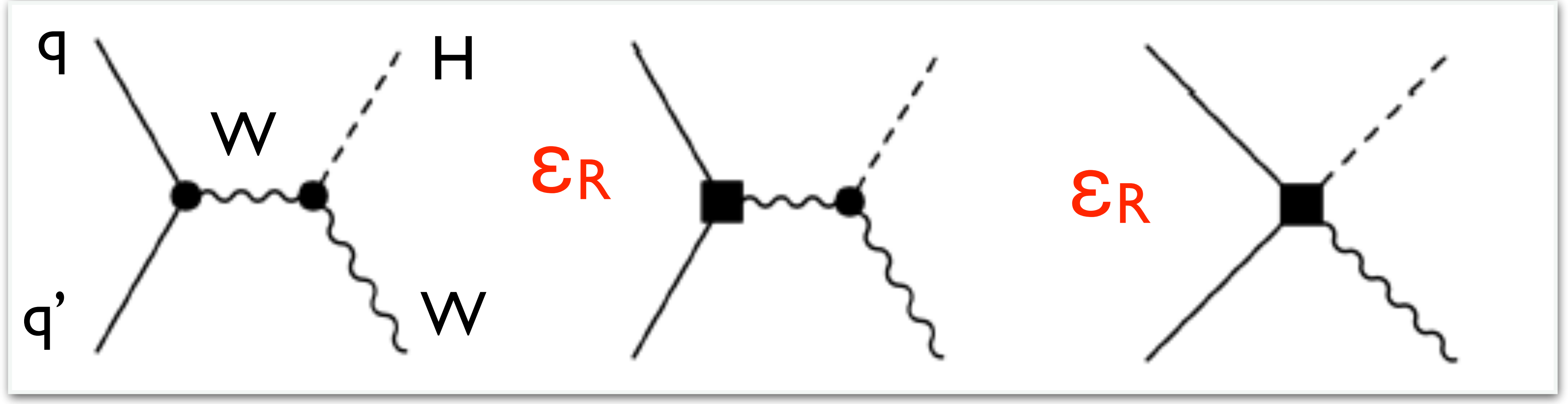




New contribution has same shape as the SM W exchange → weak sensitivity

VC, Graesser, Gonzalez-Alonso 1210.4553
Alioli-Dekens-Girard-Mereghetti 1804.07407
Gupta et al. 1806.09006
…

Contributes to associated Higgs + W production at the LHC

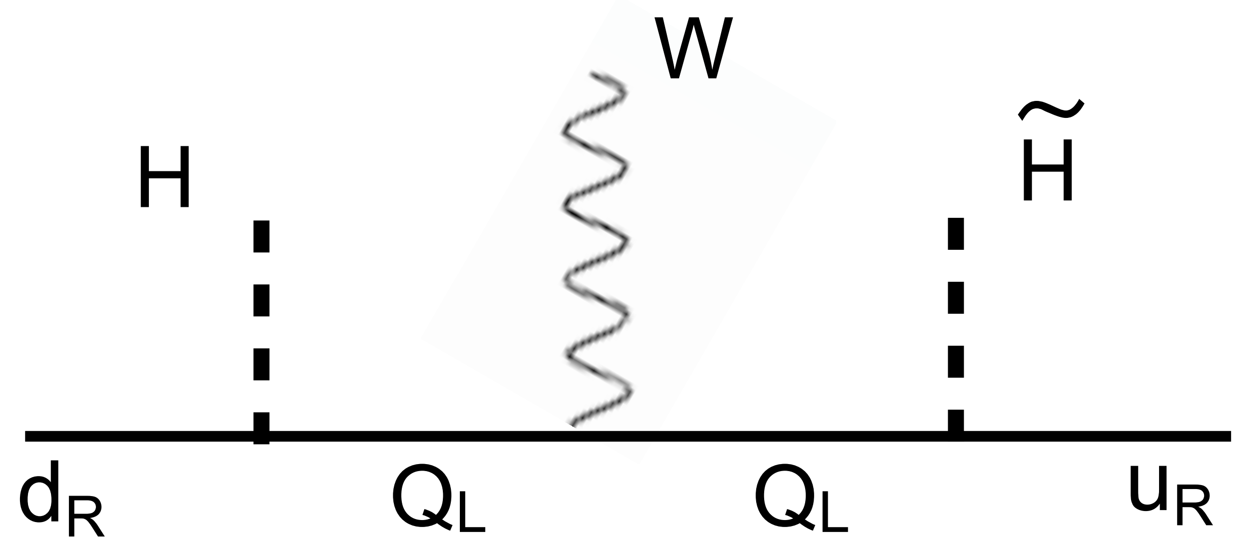


S. Alioli, VC, W. Dekens, J. de Vries, E. Mereghetti 1703.04751

Current LHC results allow for to ε_R ~ 5%

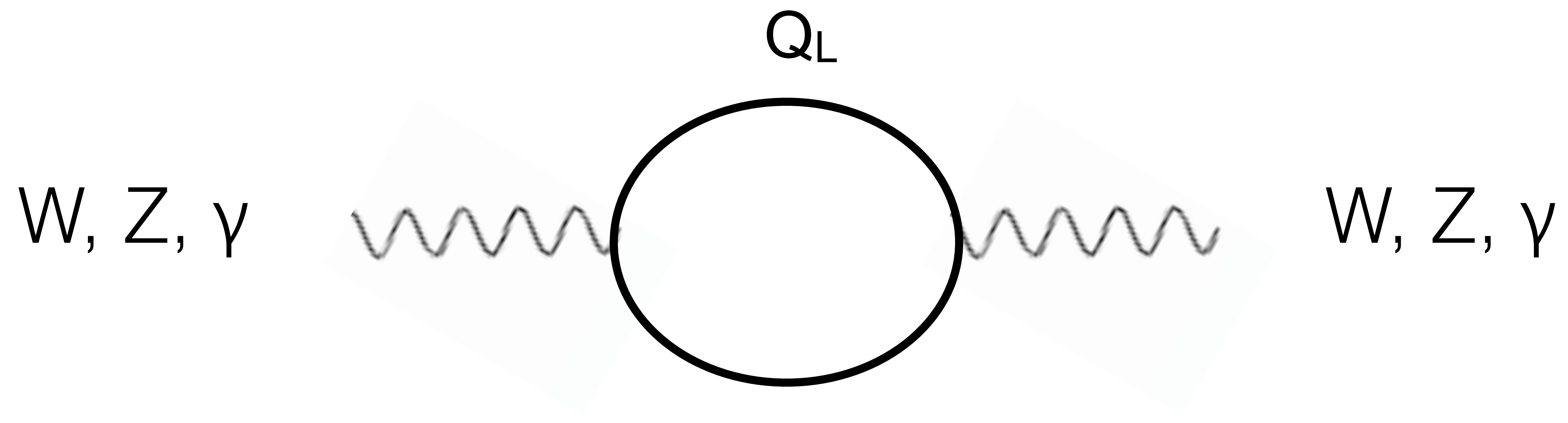
An explicit model?

- Vector-like quarks:



Belfatto-Trifinopoulos 2302.14097

- It can not only fix the Cabibbo angle anomaly, but also the W-mass anomaly (CDF result ~7σ larger than SM)



- Testable at the High Luminosity LHC and FCC

Conclusions & Outlook

- Rare pion decays enable stringent tests of the universality of weak interactions, probing new physics from very high scale as well as light and weakly coupled particles

- PIONEER will explore unconstrained parameter space in several models involving particles that are light and very weakly coupled: dedicated analyses?

- 10x improvement in $R_{e/\mu}(\pi) = \Gamma(\pi \to e\nu(\gamma)) \,/\, \Gamma(\pi \to \mu\nu(\gamma))$ will probe very high effective scales, up to $\Lambda_P \sim$ 30-1000 TeV and $\Lambda_A \sim$ 30 TeV

- 3x improvement in π_β can help diagnose BSM origin of the Cabibbo angle anomaly (CAA). A ~20x improvement will provide V_{ud} with smallest theory uncertainty

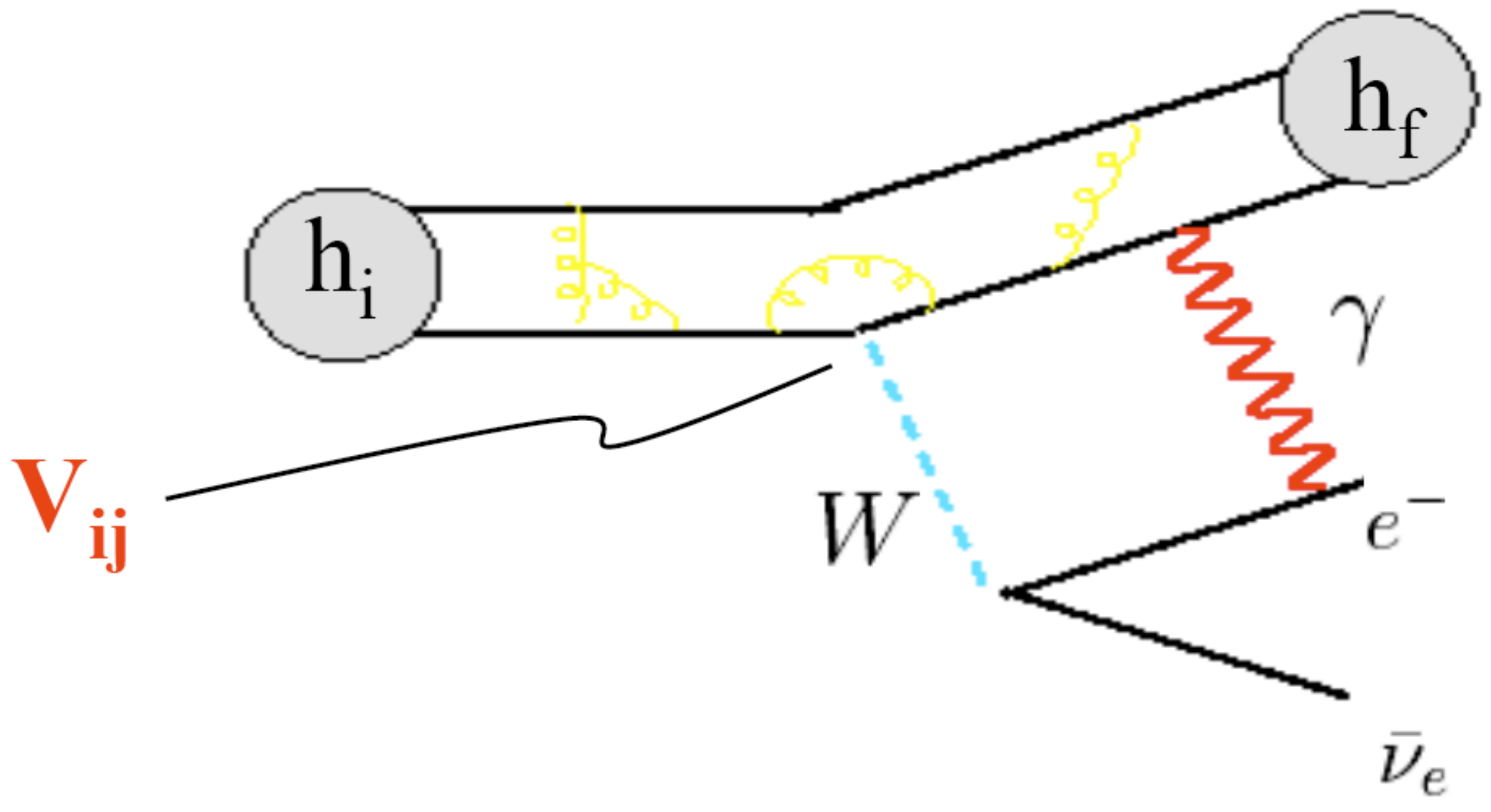
Backup

Paths to V_{ud} and V_{us}

V_{ud}	$0^+ \to 0^+$ $(\pi^\pm \to \pi^0 e \nu)$	$n \to p e \bar{\nu}$ (Mirror transitions)	$\pi \to \mu\nu$
V_{us}	$K \to \pi l \nu$	$(\Lambda \to p e \bar{\nu}, \ldots)$	$K \to \mu\nu$

(Hadronic τ decays)

Quark current mediating the decay → V | V, A | A



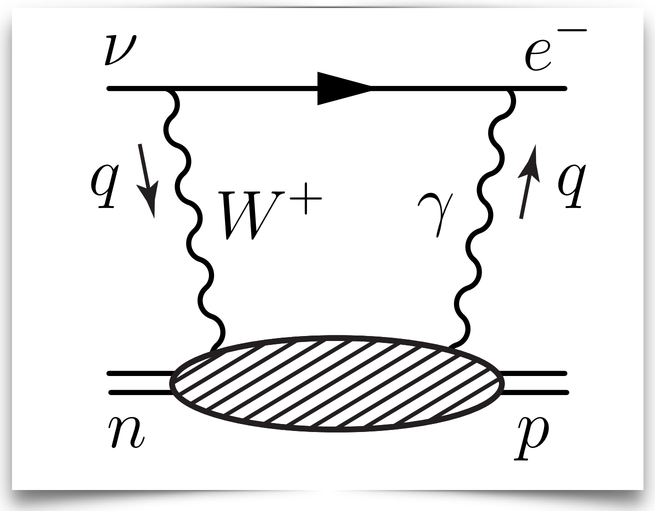
Input from *many* experiments and *many* theory papers

Paths to V_{ud} and V_{us}

V_{ud}	$0^+ \to 0^+$ $(\pi^\pm \to \pi^0 e\nu)$	$n \to p e \bar{\nu}$ (Mirror transitions)	$\pi \to \mu\nu$
V_{us}	$K \to \pi l \nu$	$(\Lambda \to p e \bar{\nu}, \ldots)$	$K \to \mu\nu$

(Hadronic τ decays)

Comment1: Modern approaches to rad. corr. build upon Sirlin current algebra formulation from the '60 & '70s
New wave of "inner" radiative corrections (n, nuclei) initiated by dispersive analysis of Seng, Gorchtein, Patel, Ramsey-Musolf 2018, all the way to very recent lattice QCD calculation by Ma et al, 2308.16755



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

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

Hardy-Towner, PRC 2020
Seng et al. 1812.03352
Gorchtein 1812.04229

See talk by Chien Yeah Seng for status of other corrections

Paths to V_{ud} and V_{us}

V_{ud}	$0^+ \to 0^+$ $(\pi^\pm \to \pi^0 e\nu)$	$n \to pe\bar{\nu}$ (Mirror transitions)	$\pi \to \mu\nu$
V_{us}	$K \to \pi l \nu$	$(\Lambda \to pe\bar{\nu},\ldots)$	$K \to \mu\nu$

(Hadronic τ decays)

Comment 2: neutron decay is beginning to provide very competitive δV_{ud}

$$V_{ud}^{\text{n, PDG}} = 0.97441(3)_f(13)_{\Delta_R}(82)_\lambda(28)_{\tau_n}[88]_{\text{total}}$$

$$V_{ud}^{\text{n, best}} = 0.97413(3)_f(13)_{\Delta_R}(35)_\lambda(20)_{\tau_n}[43]_{\text{total}}$$ ⟵ Most precise measurements

Maerkish et al, 1812.04666

$\lambda = g_A/g_V$

Gonzalez et al, 2106.10375

τ_n

Corrections to V_{ud} and V_{us}

- General case

$$|\tilde{V}_{ud}|^2_{0^+\to 0^+} = |V_{ud}|^2 \left(1 + 2\left(\epsilon_L^{ee} + \epsilon_R - \epsilon_L^{(\mu)}\right) + c_{0^+}^S(Z)\ \epsilon_S^{ee}\right)$$

$$|\tilde{V}_{ud}|^2_{n\to pe\bar{\nu}} = |V_{ud}|^2 \left(1\ +\ 2\left(\epsilon_L^{ee} + \epsilon_R - \epsilon_L^{(\mu)}\right) + c_n^S \epsilon_S^{ee} + c_n^T \epsilon_T^{ee}\right)$$

$$|\tilde{V}_{us}|^2_{Ke3} = |V_{us}|^2 \left(1 + 2\left(\epsilon_L^{ee(s)} + \epsilon_R^{(s)} - \epsilon_L^{(\mu)}\right)\right)$$

$$|\tilde{V}_{ud}|^2_{\pi e3} = |V_{ud}|^2 \left(1 + 2\left(\epsilon_L^{ee} + \epsilon_R - \epsilon_L^{(\mu)}\right)\right)$$

$$|\tilde{V}_{us}|^2_{K\mu 2} = |V_{us}|^2 \left(1 + 2\left(\epsilon_L^{\mu\mu(s)} - \epsilon_R^{(s)} - \epsilon_L^{(\mu)}\right) - 2\frac{B_0}{m_\ell}\,\epsilon_P^{\mu\mu(s)}\right)$$

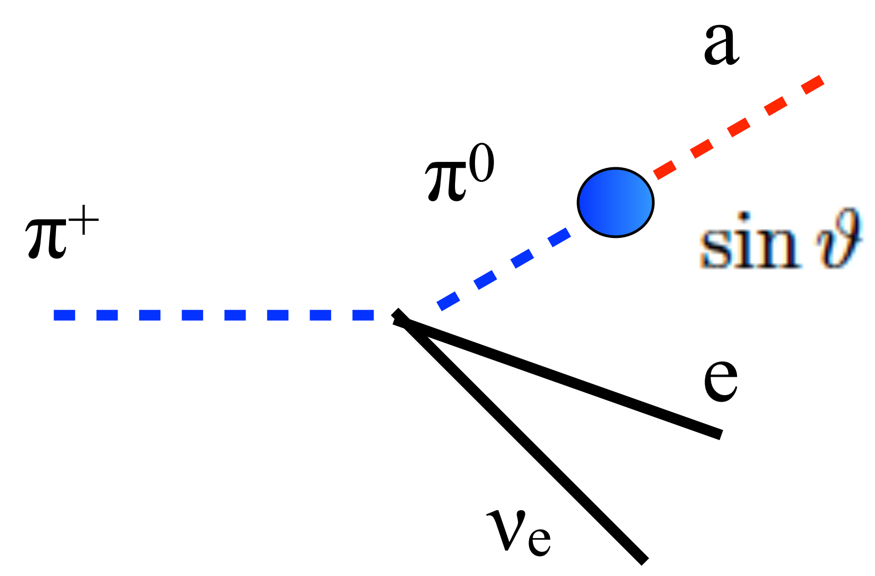
$$|\tilde{V}_{ud}|^2_{\pi\mu 2} = |V_{ud}|^2 \left(1 + 2\left(\epsilon_L^{\mu\mu} - \epsilon_R - \epsilon_L^{(\mu)}\right) - 2\frac{B_0}{m_\ell}\,\epsilon_P^{\mu\mu}\right)$$

$\varepsilon_S^{(s)}$: shifts the slope of the scalar form factor, at levels well below EXP and TH uncertainties

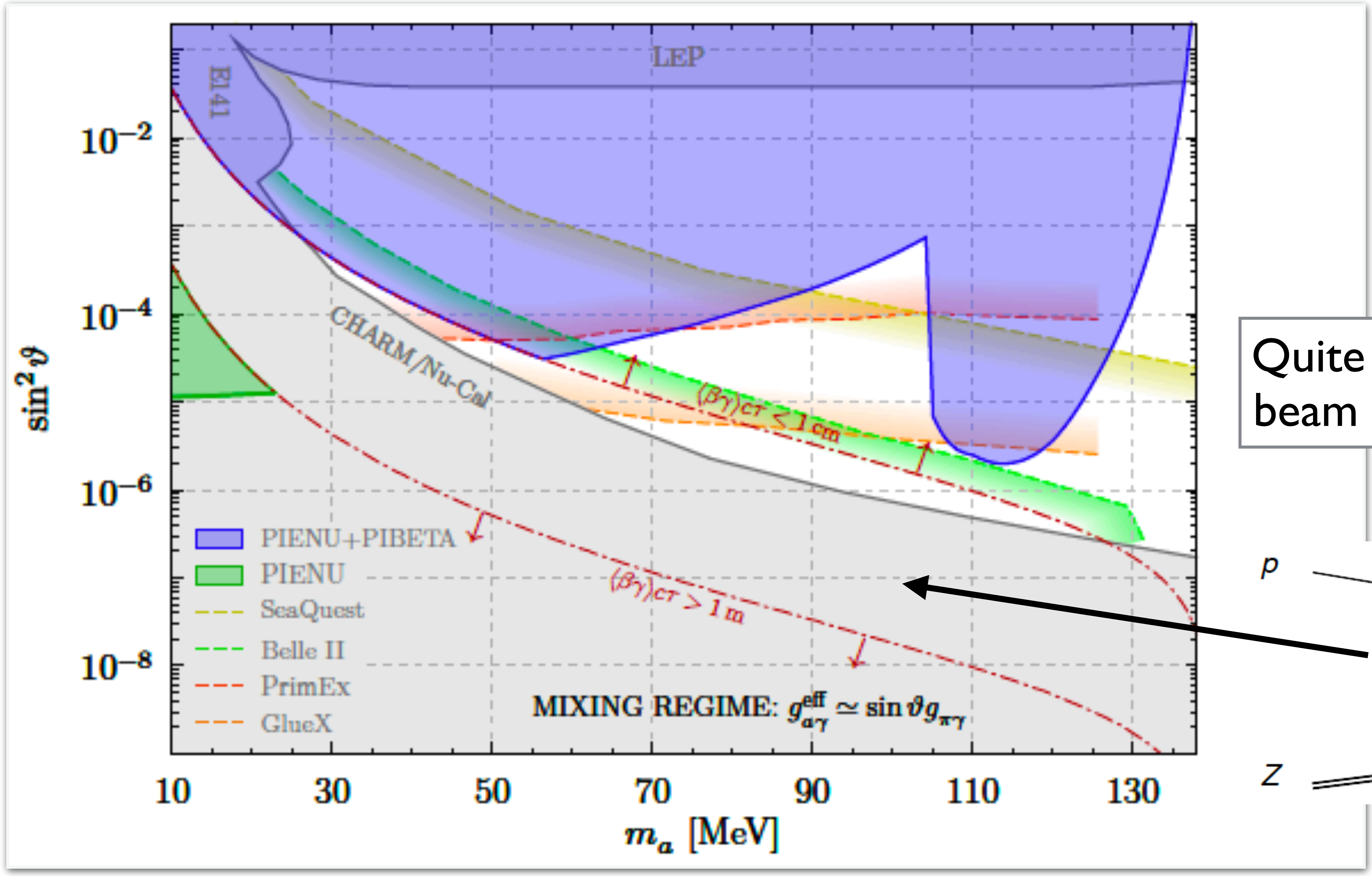
$\varepsilon_T^{(s)}$: suppressed by m_{lept}/m_K

Axion-like particles

- a-π^0 mixing induces the decay $\pi^+ \to ae\nu$
- Would affect E_{cal} distribution in PIENU and the γγ opening angle distribution in PIBETA



Altmanshofer-Gori-Robinson 1909.00005



Quite complementary to beam dump experiments