National Nuclear Physics Summer School 2026
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Low energy probes of physics beyond the Standard Model (3)

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Office of Science

UNIVERSITY of WASHINGTON

Flow of the lectures

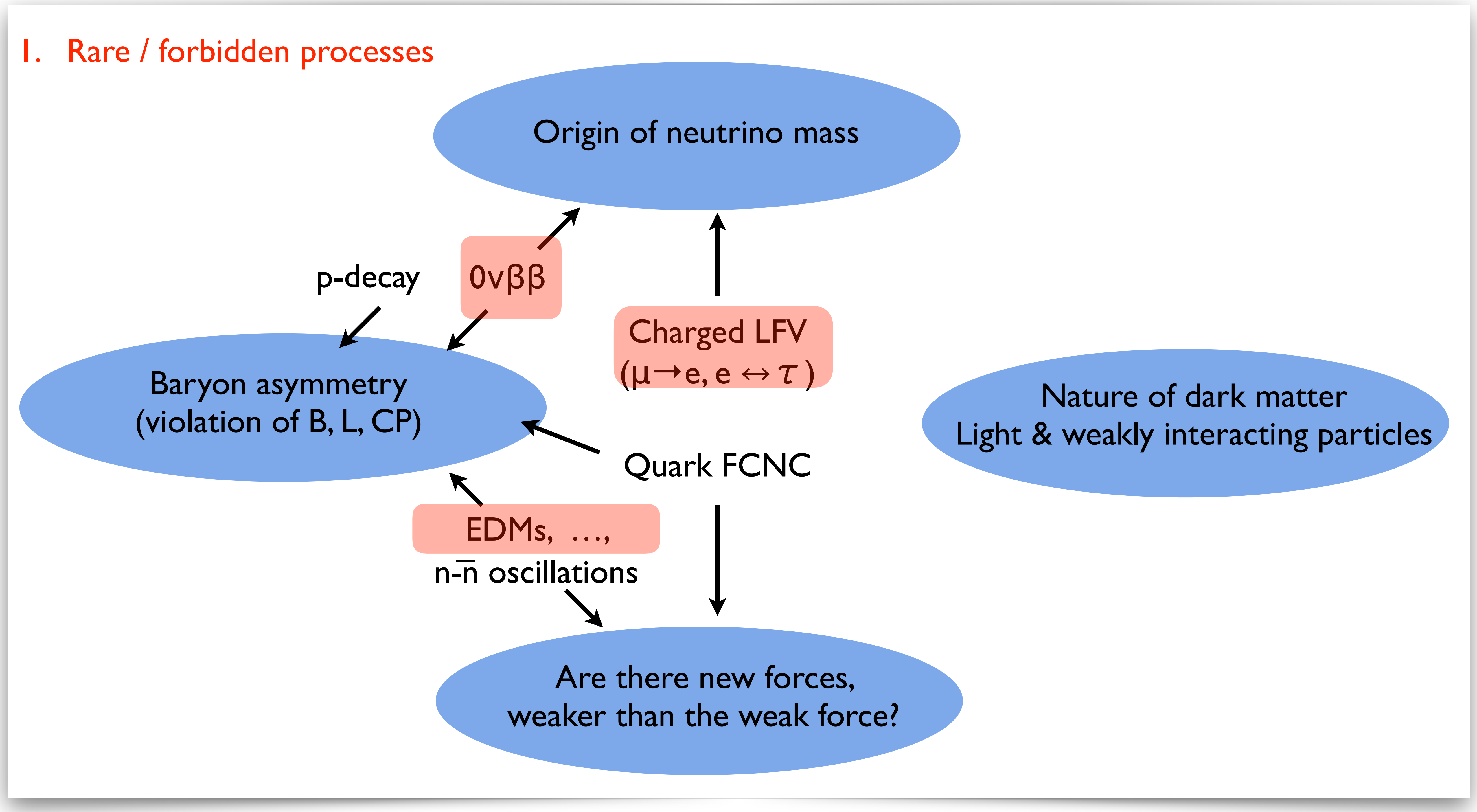
- The quest for new physics at the low-energy frontier: overview of *questions* and *probes*
- How does the precision / intensity frontier work?
  - Basics & example from history: the making of the Standard Model
  - ~~The Standard Model and its symmetries~~
  - BSM effective field theory (EFT) framework
- "Zoom in" on selected low-energy probes: illustrate methods and impact
  - Search for symmetry violation
    - Neutrino mass and symmetries: Lepton Number ~~and Lepton Flavor~~ Violation
    - CP-violation and permanent Electric Dipole Moments
  - Precision tests
    - Weak charged current (β decays), ~~neutral current (parity-violating e-scattering), muon g-2~~

Lecture 1

Lecture 2

Lecture 3

Rare / forbidden processes



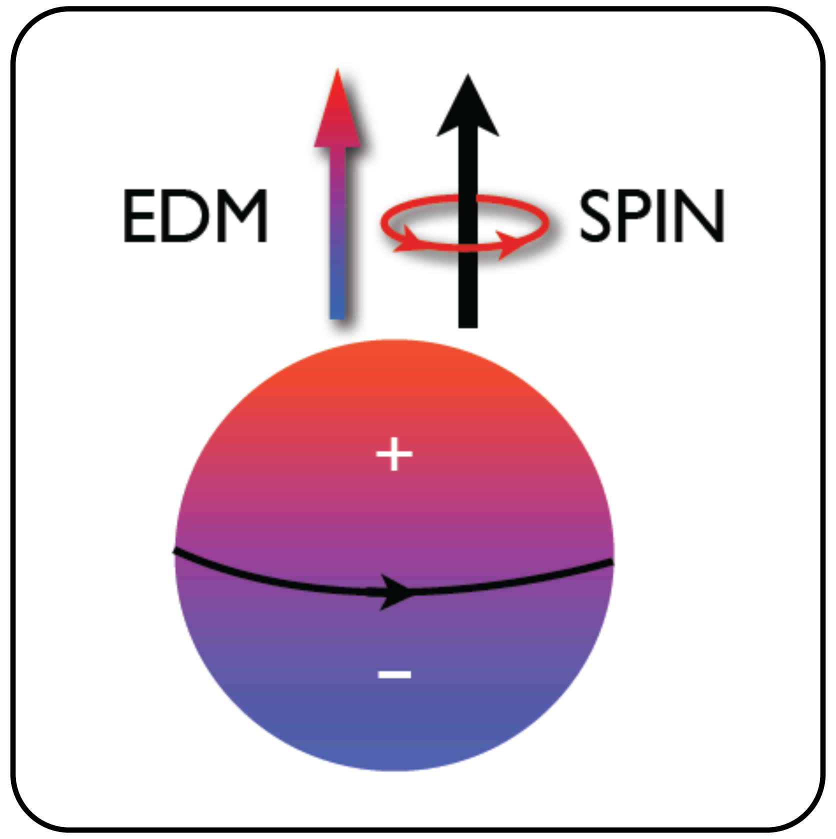
Discuss some theoretical aspects of EDMs

EDMs and symmetry breaking

- EDMs of *non-degenerate* systems violate P and T: $H = \vec{d} \cdot \vec{E}$

Classical picture →

Quantum level:
Wigner-Eckart theorem



$$\vec{d} = \sum_i q_i \, \vec{r}_i$$

$$\vec{\mathbf{d}} = d \, \vec{\mathbf{J}}$$

- CPT symmetry (holds for Lorentz-invariant quantum field theories) ⇒ nonzero EDMs signal also CP violation in the underlying theory

See Dave Kawall's lectures for experimental landscape and a lot more!

CP violation in the SM

$$\mathcal{L}_4^{CPV} = -\bar{\theta}\frac{g_s^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu} - \left(\frac{g_2}{2\sqrt{2}}W_\mu^+\ \bar{u}_i\gamma^\mu(1-\gamma_5)V_{ij}d_j + \text{h.c.}\right)$$

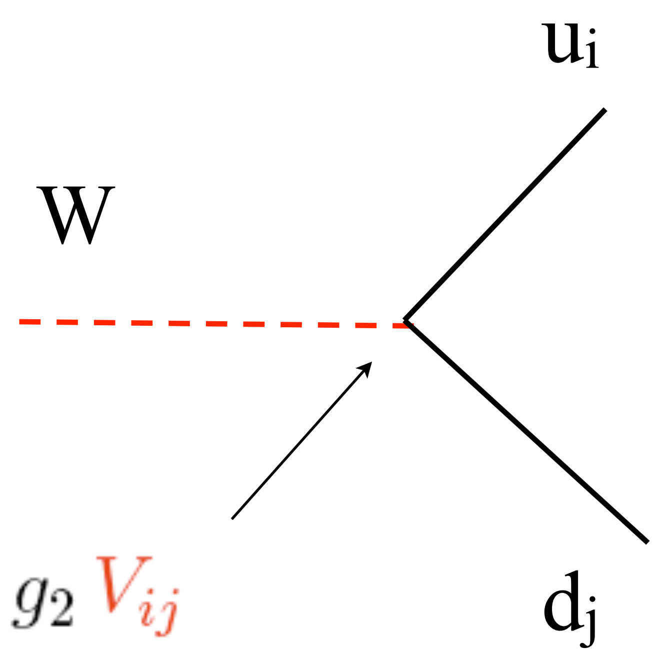
$\bar{\theta} = \theta - \text{ArgDet}(\mathcal{M}_q)$

'QCD theta term'

~ $B_c \cdot E_c$

$V_{\text{CKM}} = V_{u_L}V_{d_L}^\dagger$

Physically observable mismatch in the transformation of u_L and d_L needed to diagonalize quark masses



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

Cabibbo-Kobayashi-Maksawa (CKM) matrix

- CKM matrix is unitary:
    - 9 real parameters, but redefinition of quark phases reduces physical parameters to 4: 3 mixing angles and 1 phase

$$V_{ij} \rightarrow V_{ij}\, e^{i((\phi_d)_j - (\phi_u)_i)}$$

5 independent parameters (phase differences)

- Irreducible phase implies CP violation:

$$g_2 V_{ij}\, W^+_\mu\, \bar{u}^i_L \gamma^\mu d^j_L \;+\; g_2 V^*_{ij}\, W^-_\mu\, \bar{d}^j_L \gamma^\mu u^i_L$$

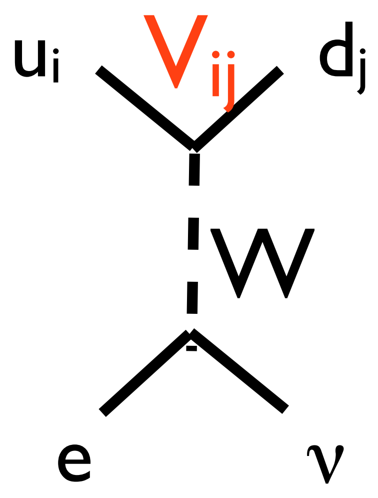
$\downarrow$ CP transformation

$$g_2 V_{ij}\, W^-_\mu\, \bar{d}^j_L \gamma^\mu u^i_L \;+\; g_2 V^*_{ij}\, W^+_\mu\, \bar{u}^i_L \gamma^\mu d^j_L$$

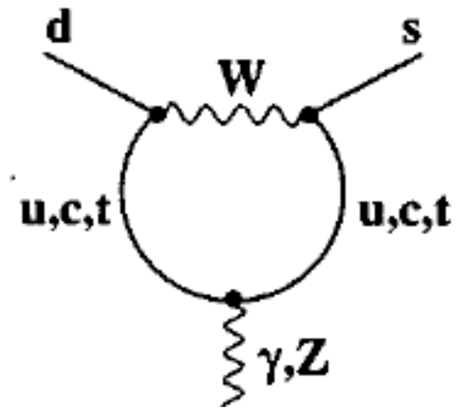
- Wolfenstein (1983) parameterization

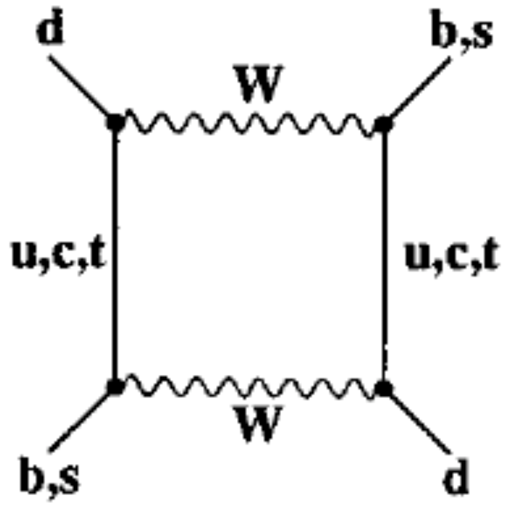
Make explicit the hierarchical structure revealed by experiment:
expand in $\lambda \approx V_{us} \approx 0.225$, with $\rho, \eta, A \sim O(1)$

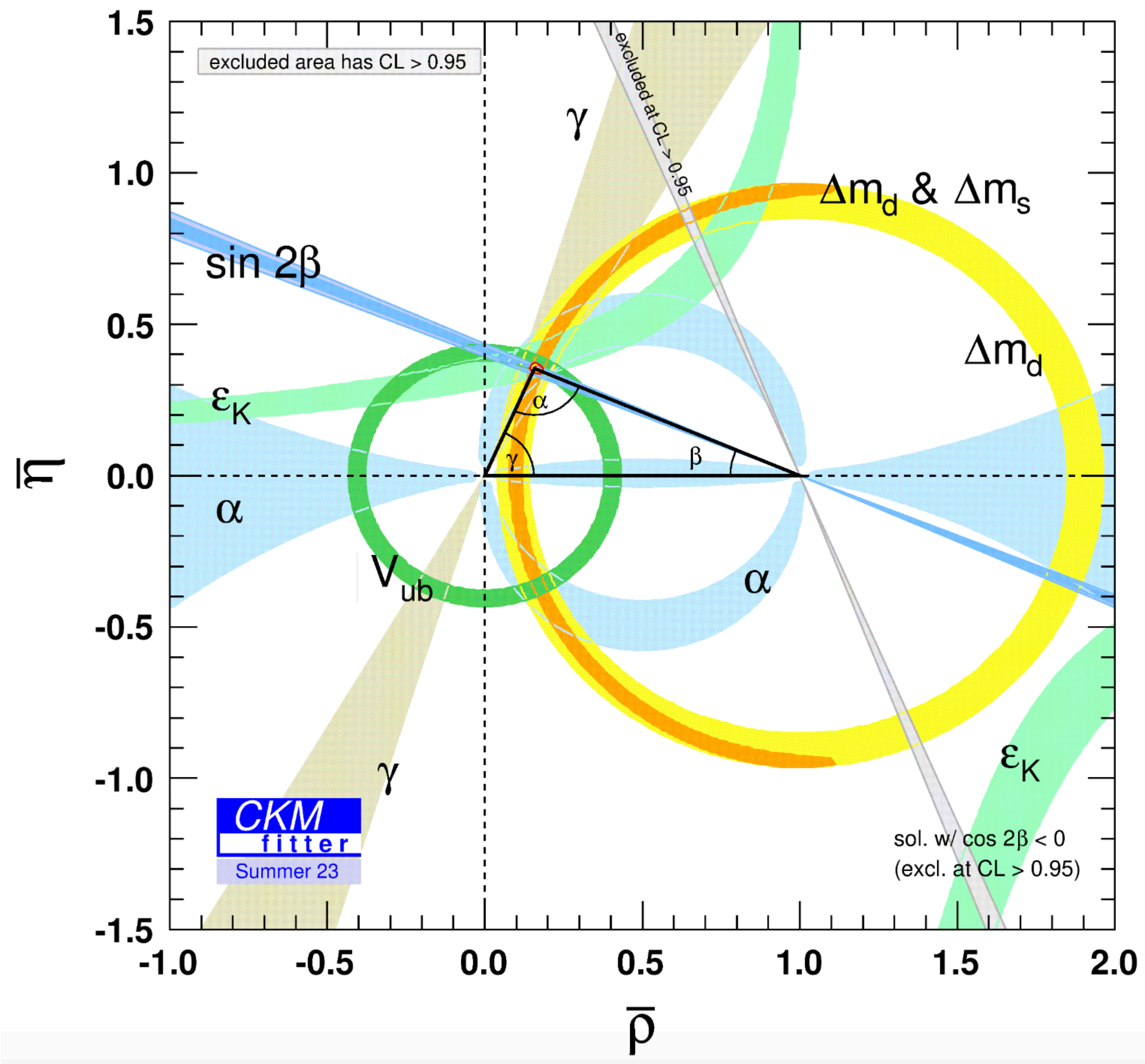
$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



- Status of the CKM matrix: quark flavor physics (including CPV) is well described by 3 mixing angles and a phase!







$$\bar{\rho} = \rho\left(1 - \frac{\lambda^2}{2}\right)$$

$$\bar{\eta} = \eta\left(1 - \frac{\lambda^2}{2}\right)$$

EDMs in the Standard Model?

$$\mathcal{L}_4^{CPV} = -\bar{\theta}\frac{g_s^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu} - \left(\frac{g_2}{2\sqrt{2}}W_\mu^+\ \bar{u}_i\gamma^\mu(1-\gamma_5)V_{ij}d_j + \text{h.c.}\right)$$

Axial transformation of quark field

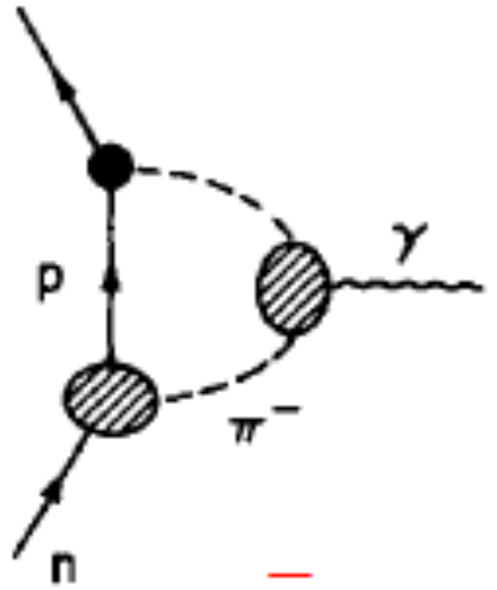
$\sim \mathbf{B_c} \cdot \mathbf{E_c}$

Baluni 1979
Crewther, Di Vecchia, Veneziano, Witten 1979

$$-m_*\,\bar{\theta}\,\bar{q}\,i\gamma_5 q$$

$\sim \boldsymbol{\sigma} \cdot (\mathbf{p_f} - \mathbf{p_i})$

$$m_* = \frac{1}{\sum_i (1/m_i)} \simeq \frac{m_u m_d}{m_u + m_d}$$



$\bar{\theta}$

$d_n < 3\ 10^{-26}$ e cm

$$d_n \sim \frac{m_*}{\Lambda_{\text{had}}^2}\, e\,\bar{\theta} \sim 10^{-17}\,\bar{\theta}\,e\text{cm}$$

$\rightarrow$ $|\bar{\theta}| < 10^{-9}$

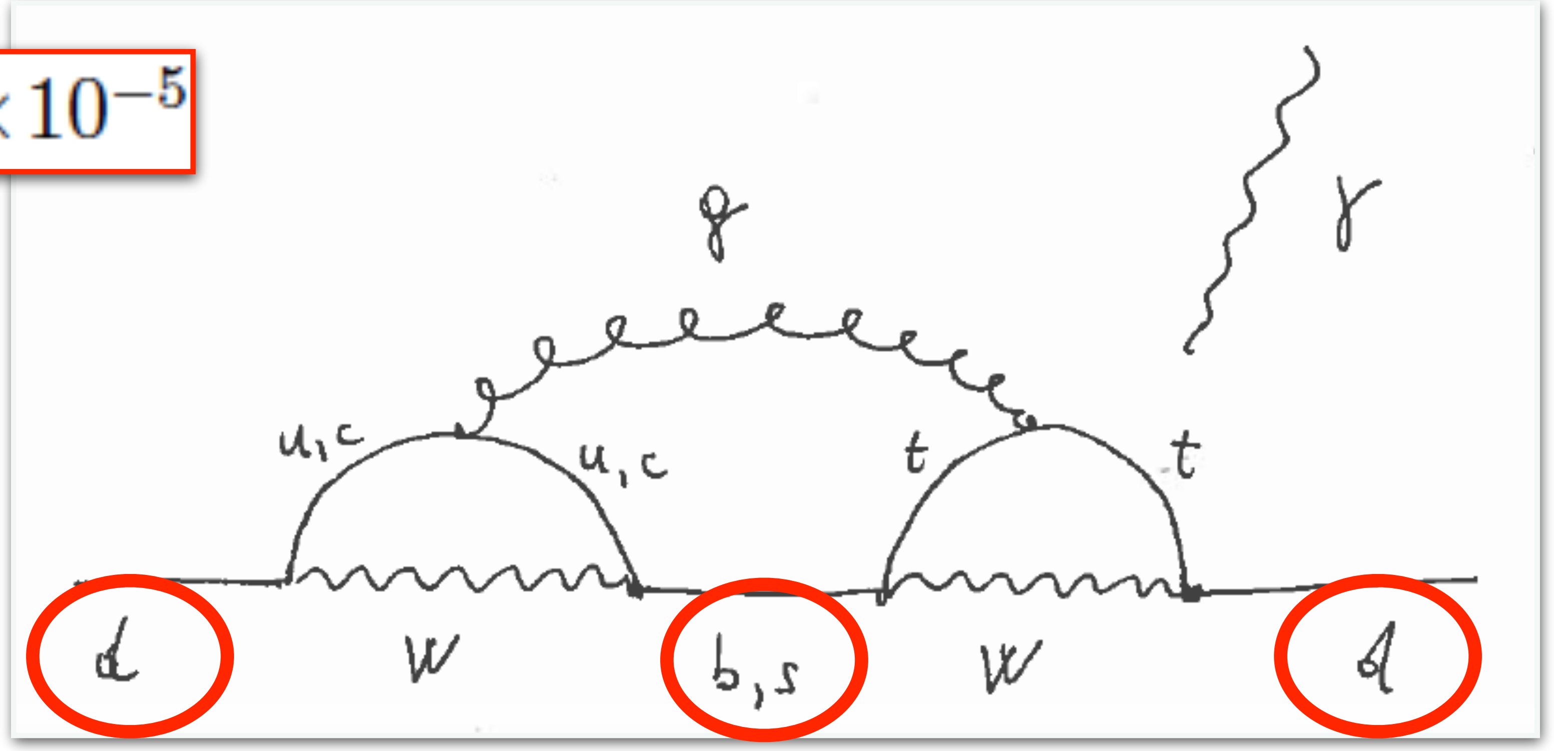
EDMs in the Standard Model?

$$\mathcal{L}_4^{CPV} = -\bar{\theta}\frac{g_s^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu} - \left(\frac{g_2}{2\sqrt{2}}W_\mu^+\ \bar{u}_i\gamma^\mu(1-\gamma_5)V_{ij}d_j + \text{h.c.}\right)$$

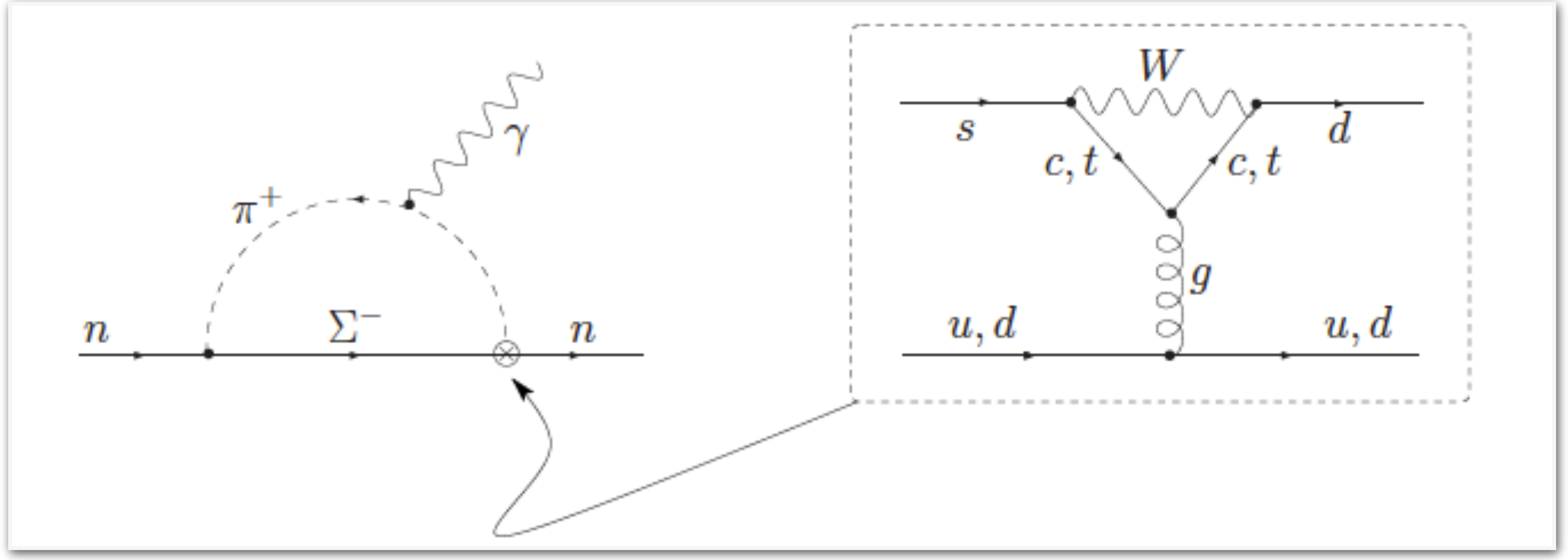
$$J_{CP} = \text{Im}(V_{tb}V_{td}^*V_{cd}V_{cb}^*) \simeq 3\times10^{-5}$$

$d_q \sim 10^{-34}$ e cm

$d_e \sim 10^{-38}$ e cm



Highly suppressed quark and lepton EDMs



Dominant contribution to nEDM

$d_n \sim 10^{-31}$ e cm

...

Pospelov-Ritz hep-ph/0504231

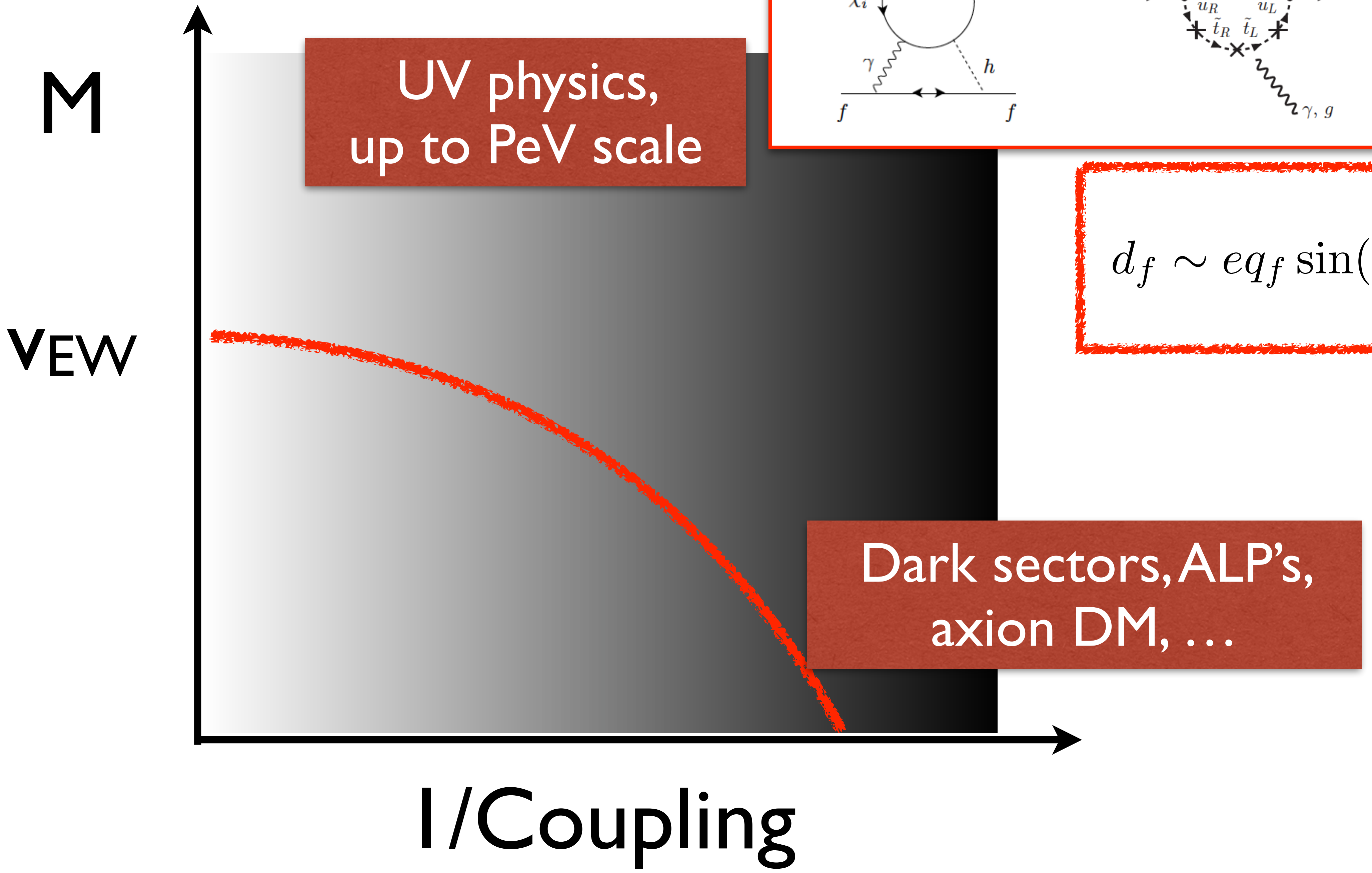
C.Y. Seng 1411.1476

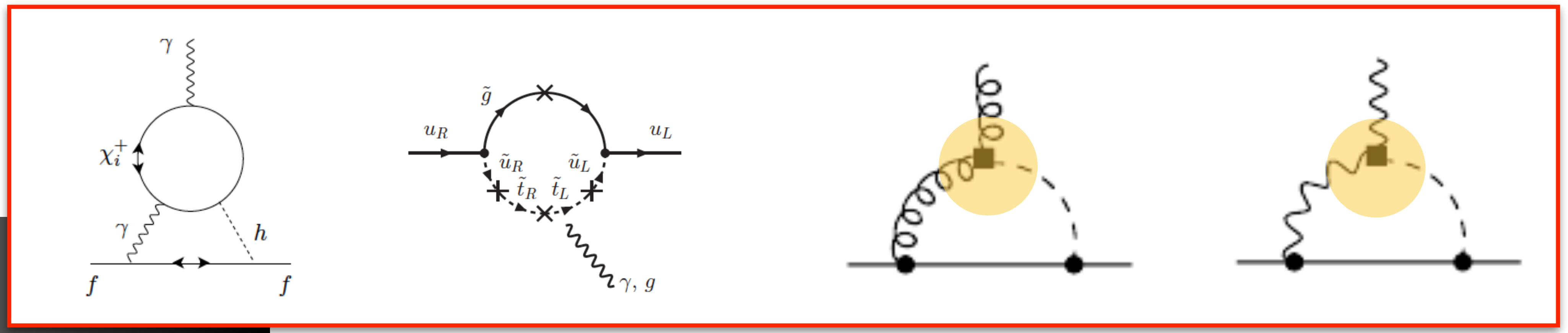
EDMs as probes of new physics

White paper 2203.08103 and refs therein

Chupp, Fierlinger, Ramsey-Musolf, Singh, 1710.02504

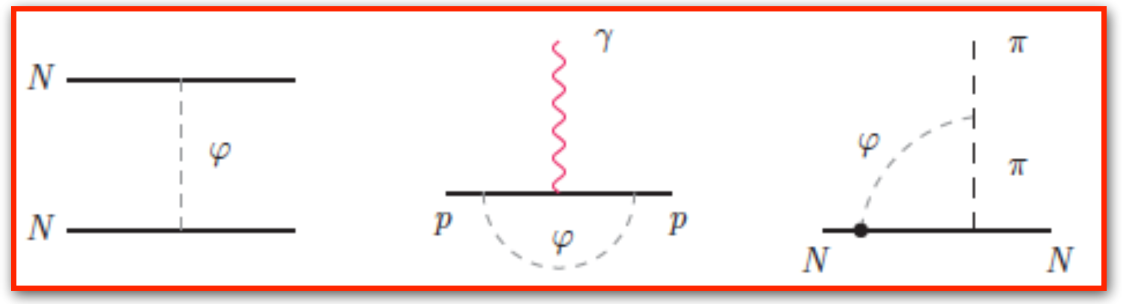
- Highly suppressed in Standard Model (CKM phase)
- A non-zero EDM would imply new physics or a tiny QCD θ-term (multiple measurements can disentangle the two)
- Sensitive to broad spectrum of new physics (Higgs sector, SUSY, ALPs…) & baryogengesis mechanisms





$$d_f \sim e q_f \sin(\delta_{\rm CPV}) \left(\frac{g^2}{16\pi^2}\right)^{\ell} \xi_{\rm FV} \frac{m_f}{M_{\rm NP}^2}$$

$$M_{\rm NP} \gtrsim \sqrt{\frac{10^{-29}\, e\,{\rm cm}}{d_e^{\rm max}}} \times \begin{cases} 50\,{\rm TeV}, & \ell = 1 \\ 2\,{\rm TeV}, & \ell = 2 \end{cases}$$



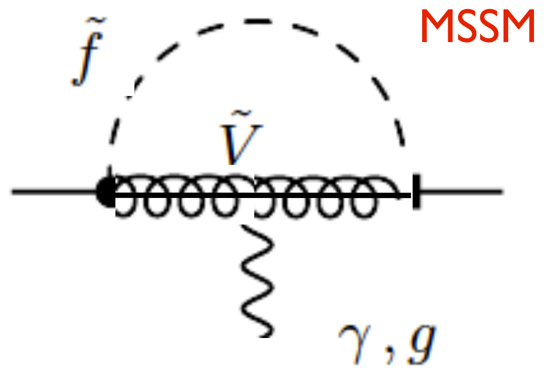
Dzuba, Flambaum, Samsonov, Stadnik, 1805.01234
Abel et al., 1708.06367
LeDall, Pospelov, Ritz 1505.01865
Mantry, Pitschmann, Ramsey-Musolf 1401.7339
…

Connecting scales

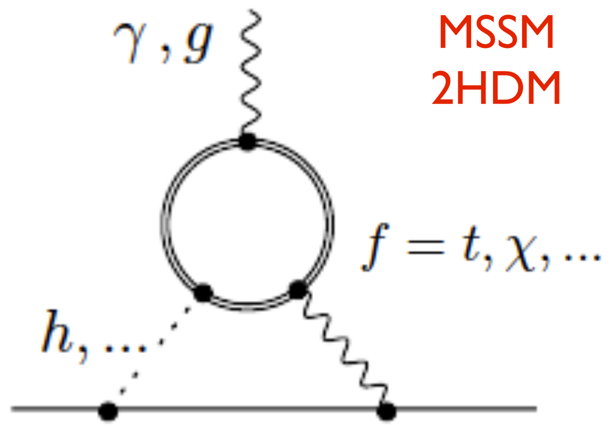
White paper 2203.08103 and refs therein

M

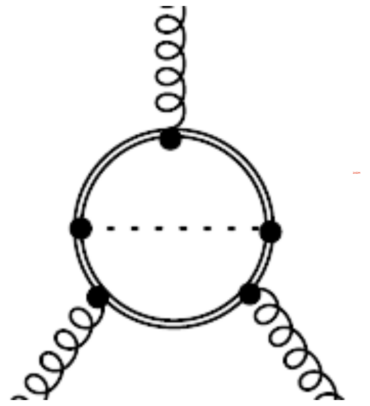
Λ



MSSM



MSSM
2HDM



2HDM

...

v_{ew}

$$\mathcal{L}_6^{CPV} = -\frac{i}{2}\sum_{f=e,u,d,s} d_f\, \bar{f}\sigma\cdot F\gamma_5 f - \frac{i}{2}\sum_{q=u,d,s} \tilde{d}_q\, g_s\, \bar{q}\sigma\cdot G\gamma_5 q + d_W \frac{g_s}{6} G\tilde{G}G + \sum_i C_i^{(4f)} O_i^{(4f)}$$

J·E   J·Ec

Λ_χ

Electric and chromo-electric dipoles of fermions

$$d_f, \tilde{d}_q \sim \frac{v_{ew}}{\Lambda^2}$$

Gluon chromo-EDM

$$d_W \sim \frac{1}{\Lambda^2}$$

Semileptonic and 4-quark

m_π

Connecting scales

White paper 2203.08103 and refs therein

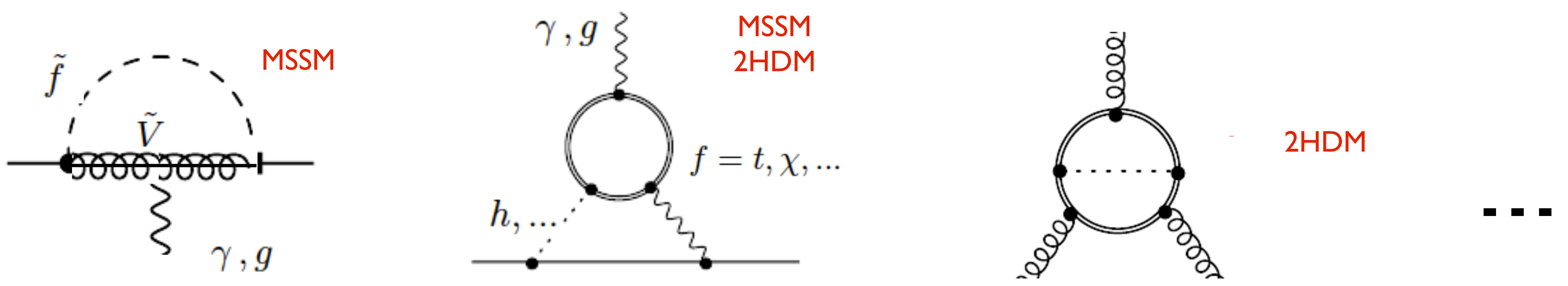
M

Λ

v_{ew}

Λ_χ

m_π



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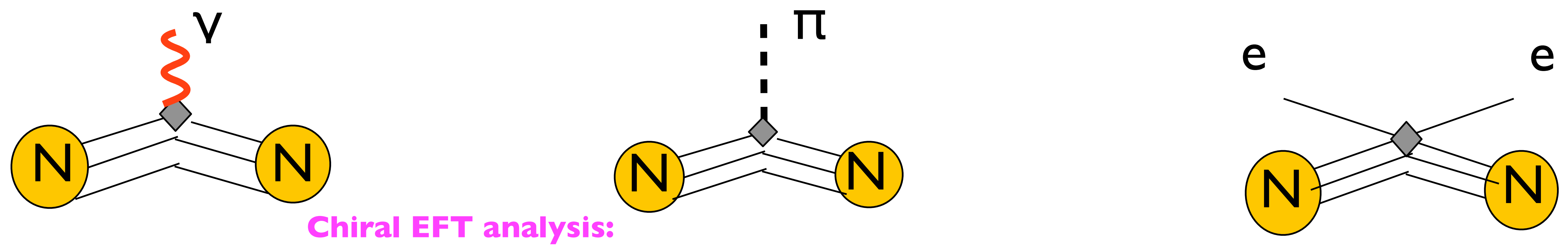
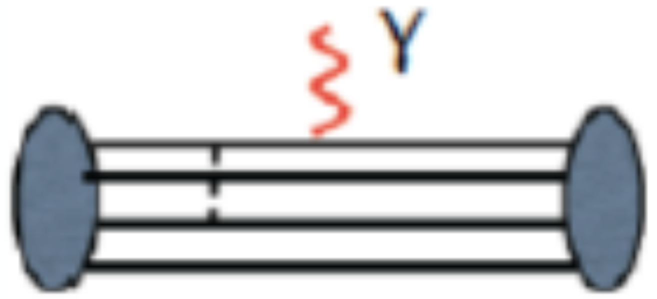
Electron and Nucleon EDMs

CP-odd πN couplings

Short-range 4N and 2N2e coupling



Chiral EFT analysis:
de Vries, Mereghetti, Timmermans, van Kolck, 1212.0990, ...



Connecting scales

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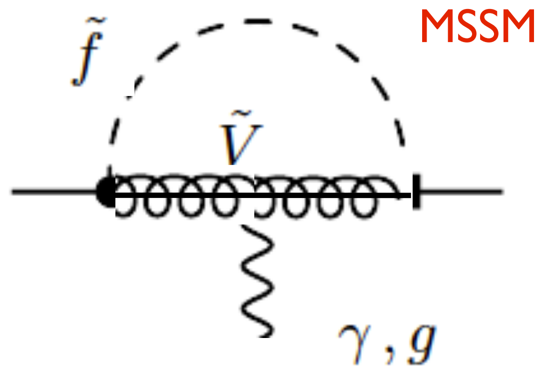
M

Λ

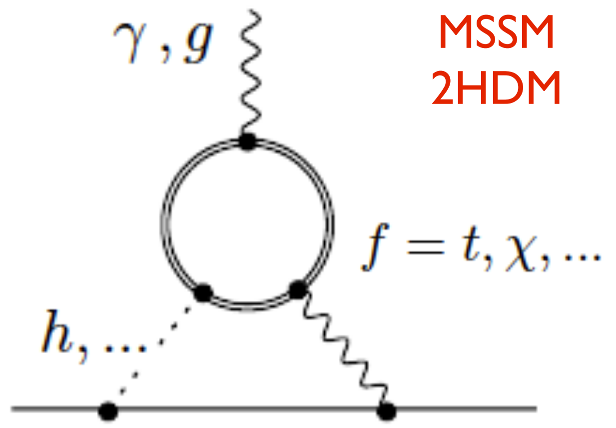
v_{ew}

Λ_χ

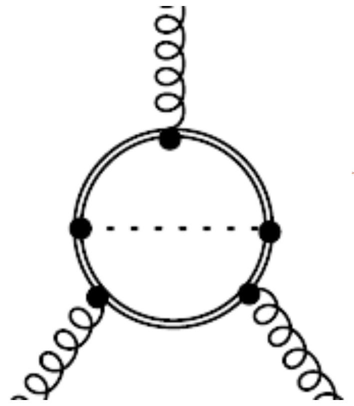
m_π



MSSM



MSSM
2HDM



2HDM

...

$$\mathcal{L}_6^{CPV} = -\frac{i}{2}\sum_{f=e,u,d,s} d_f\, \bar{f}\sigma\cdot F\gamma_5 f - \frac{i}{2}\sum_{q=u,d,s} \tilde{d}_q\, g_s\, \bar{q}\sigma\cdot G\gamma_5 q + d_W \frac{g_s}{6} G\tilde{G}G + \sum_i C_i^{(4f)} O_i^{(4f)}$$

Lattice QCD   QCD sum rules

μ=2GeV

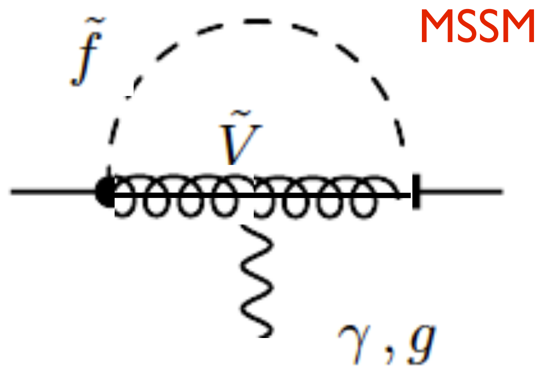
$$\begin{aligned} d_n = & -(1.5 \pm 0.7)\cdot 10^{-3}\ \bar{\theta}\, e\, \mathrm{fm} \\ & -(0.20 \pm 0.01) d_u + (0.78 \pm 0.03) d_d + (0.0027 \pm 0.016) d_s \\ & -(0.55 \pm 0.28) e\tilde{d}_u - (1.1 \pm 0.55) e\tilde{d}_d + (50 \pm 40)\ \mathrm{MeV}\, e\, \tilde{d}_G \end{aligned}$$

Connecting scales

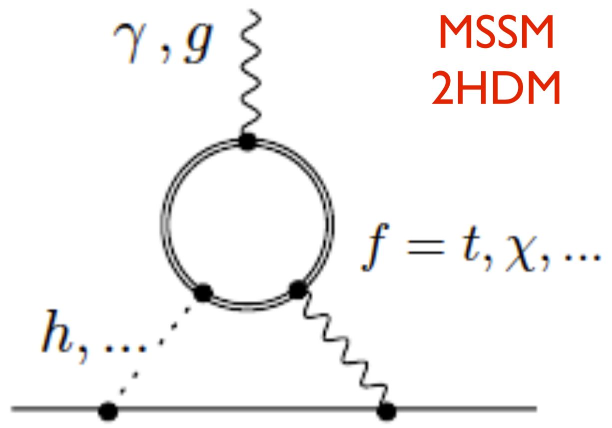
White paper 2203.08103 and refs therein

M

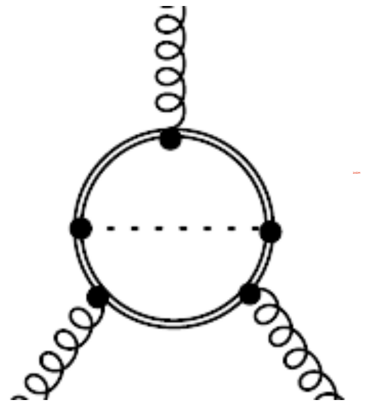
Λ



MSSM



MSSM
2HDM



2HDM

...

v_{ew}

$$\mathcal{L}_6^{CPV} = -\frac{i}{2}\sum_{f=e,u,d,s} d_f\, \bar{f}\sigma\cdot F\gamma_5 f - \frac{i}{2}\sum_{q=u,d,s} \tilde{d}_q\, g_s\, \bar{q}\sigma\cdot G\gamma_5 q + d_W \frac{g_s}{6} G\tilde{G}G + \sum_i C_i^{(4f)} O_i^{(4f)}$$

Lattice QCD QCD sum rules

Λ_χ

$$\mathcal{L} = \bar{g}_0\, \bar{N}\vec{\pi}\cdot\vec{\tau}N + \bar{g}_1\, \bar{N}\pi_3 N$$

$$\bar{g}_0 = (5 \pm 10)(\tilde{d}_u + \tilde{d}_d)\,\mathrm{fm}^{-1}\ , \qquad \bar{g}_1 = (20^{+40}_{-10})(\tilde{d}_u - \tilde{d}_d)\,\mathrm{fm}^{-1}$$

Pospelov-Ritz hep-ph/0504231 and refs therein

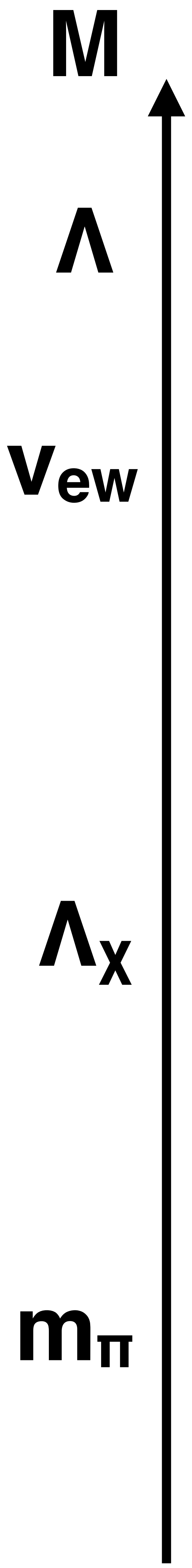
m_π

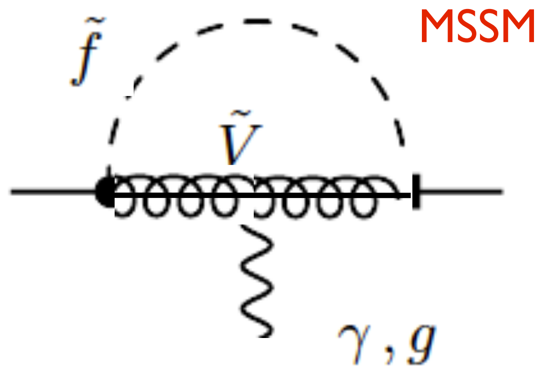
UNCERTAINTY SCOREBOARD:
Proton: same as neutron
Nuclei: worse

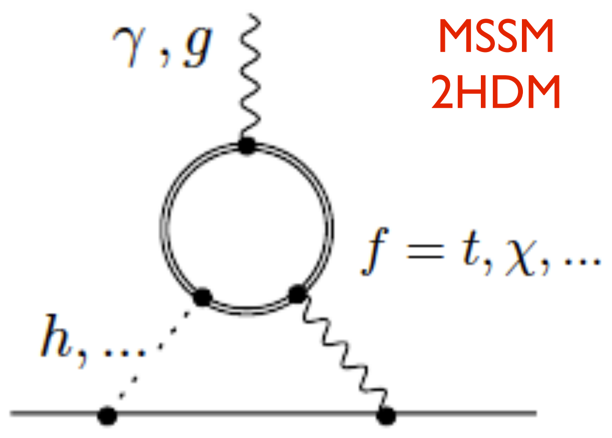
Opportunity for lattice QCD

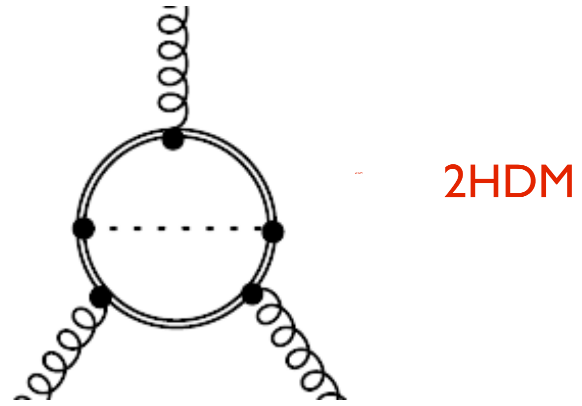
Connecting scales

White paper 2203.08103 and refs therein









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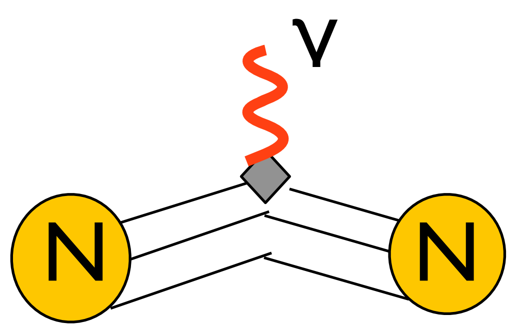
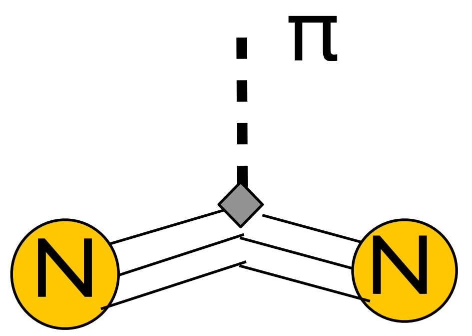
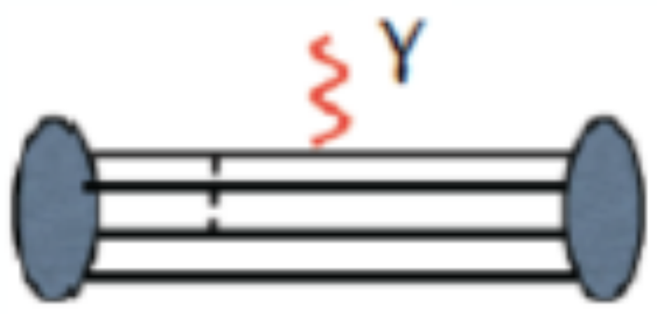
$$\mathcal{L}_6^{CPV} = -\frac{i}{2} \sum_{f=e,u,d,s} d_f \, \bar{f}\sigma\cdot F\gamma_5 f - \frac{i}{2} \sum_{q=u,d,s} \tilde{d}_q \, g_s \, \bar{q}\sigma\cdot G\gamma_5 q + d_W \frac{g_s}{6} G\tilde{G}G + \sum_i C_i^{(4f)} O_i^{(4f)}$$

Electron and Nucleon EDMs

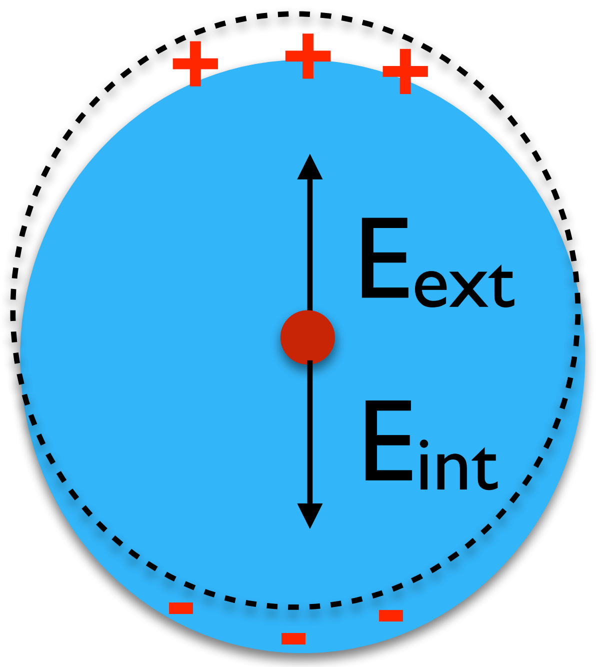


CP-odd πN couplings





At the atomic / molecular scale: work around Schiff screening
(finite size of nuclei and relativistic electron effects)
Diamagnetic atoms: O(100%) uncertainties
Paramagnetic atoms / molecules: O(10%) uncertainties



Summary: the "EDM matrix"

Hadronic scale effective couplings

(B)SM sources of CP violation

$i \in \{n, p, \ldots, ThO, \ldots, {}^{199}Hg\}$

$$d_i = \sum_j \alpha_{ij} \, \tilde{c}_j \, [\{c\}]$$

α_{ij}
Nuclear and atomic / molecular matrix elements

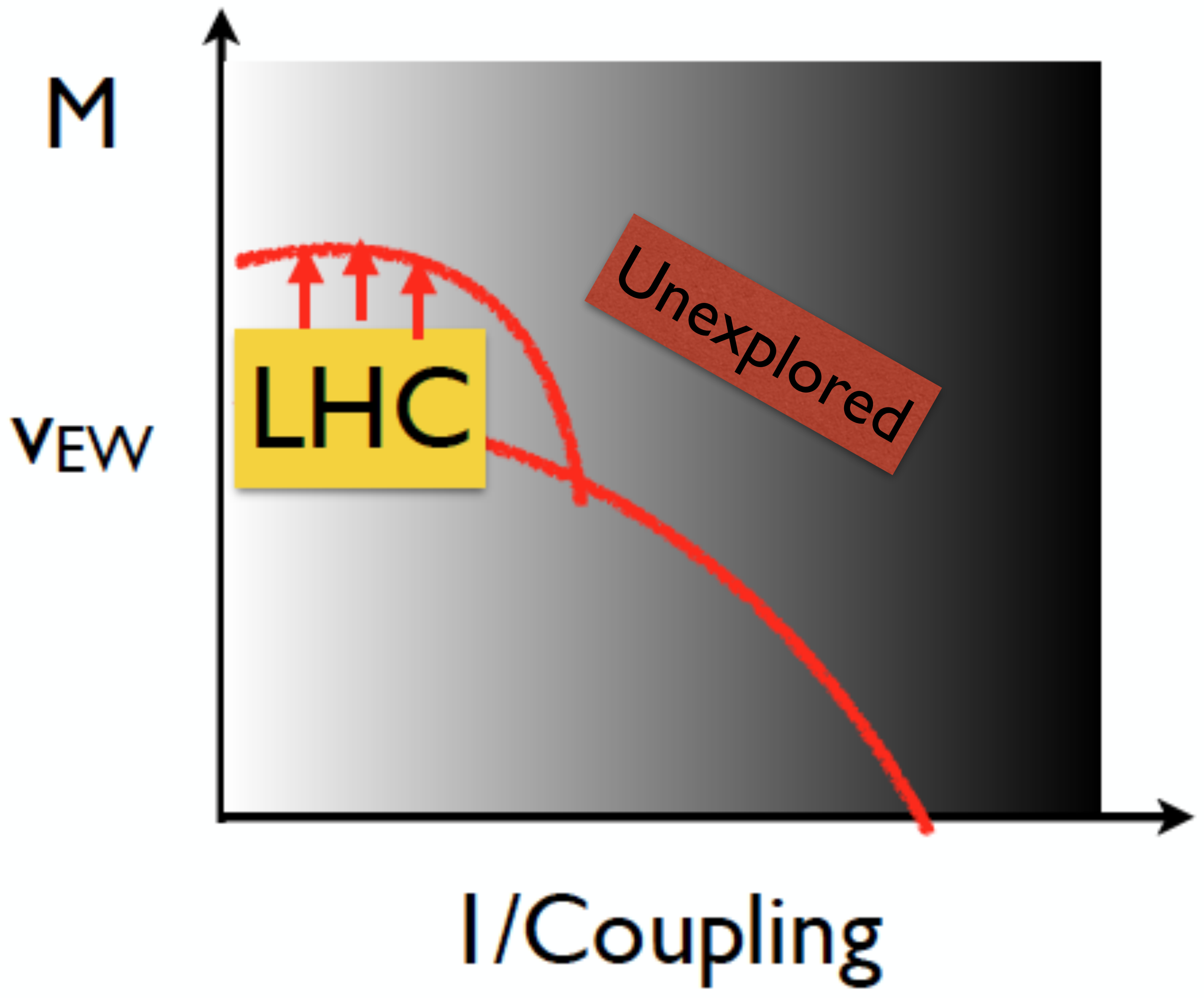
$$\tilde{c}_j = \sum_k \beta_{jk} \, c_k$$

β_{jk}
Hadronic matrix elements

- To constrain & disentangle new CPV sources need multiple probes
- Many of the coefficients α_{ij} and β_{jk} are currently poorly known:
  - *Need both* α's and β's to connect EDMs to new physics [c_k's]
  - Large uncertainties dilute constraining power: major challenge for theorists

EDMs in the LHC era

- LHC output so far:
  - Higgs boson @ 125 GeV
  - Everything else is quite heavier (or very light)

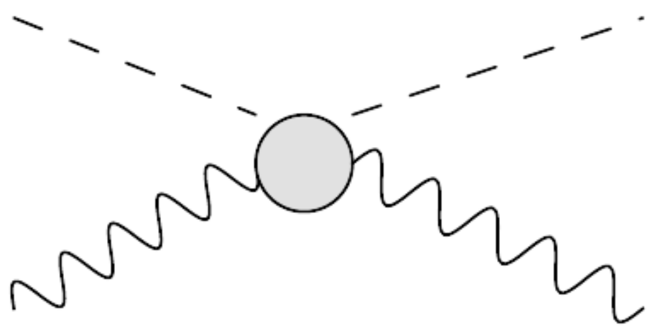


- *EDMs more relevant than ever:*
  - Strongest constraints of non-standard CPV Higgs couplings
  - One of few observables probing PeV scale supersymmetry
  - Strong constraints on baryogenesis models

EDMs and CPV Higgs couplings

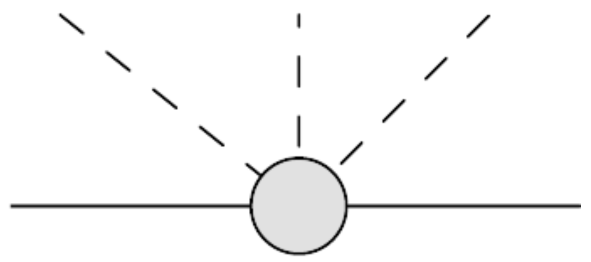
- Leading ($1/\Lambda^2$) CP-violating BSM interactions involving the Higgs:

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

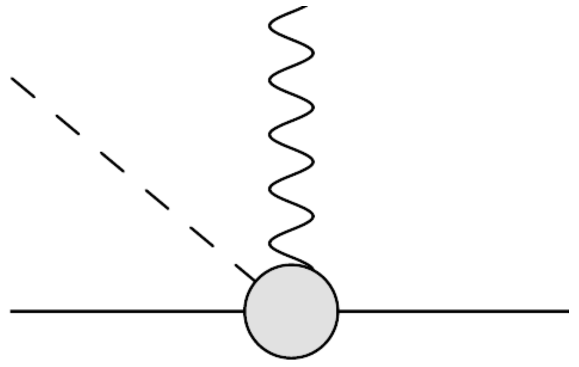


H-H-V-$\tilde{V}$

$F_{\mu\nu} \tilde{F}^{\mu\nu} \sim$ **E · B**



H-q_L-q_R: pseudo-scalar Yukawa coupling ~ **σ · (p$_f$ -p$_i$)**



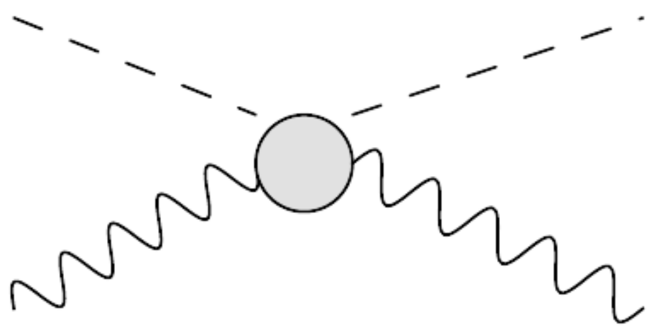
H-q_L-q_R-V: dipole ~ **σ · E**

V = g, W^a, B

EDMs and CPV Higgs couplings

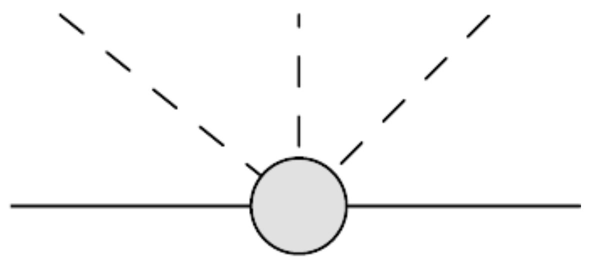
- Leading ($1/\Lambda^2$) CP-violating BSM interactions involving the Higgs:

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

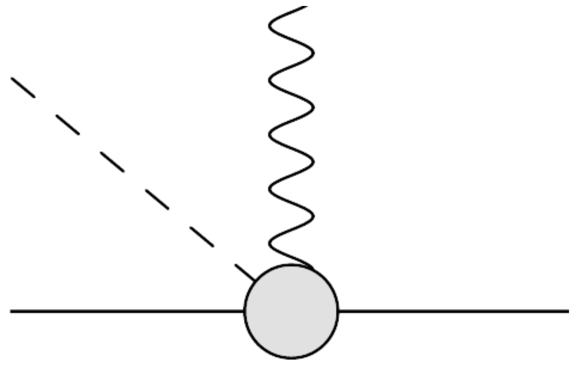


H-H-V-$\tilde{V}$

$F_{\mu\nu} \tilde{F}^{\mu\nu} \sim$ **E · B**



H-q_L-q_R: pseudo-scalar Yukawa coupling ~ **σ · (p$_f$ -p$_i$)**



H-q_L-q_R-V: dipole ~ **σ · E**

V = g, W^a, B

McKeen-Pospelov-Ritz 1208.4597

...

VC, Crivellin,, Dekens, de Vries, Hoferichter, Mereghetti, 1903.03625, Phys. Rev. Lett. 123, 051801 (2019)

...

Brod Haisch Zupan 1310.1385

Chien-VC-Dekens-de Vries-Mereghetti, 1510.00725

Brod-Stamou, 1812.12303

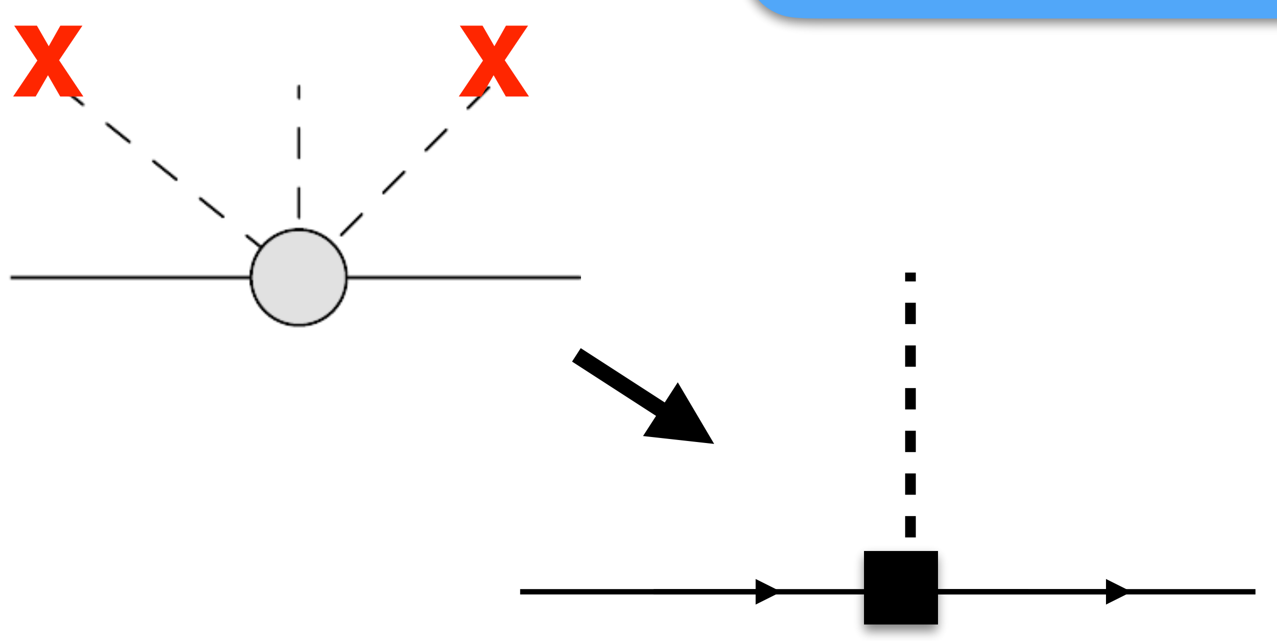
...

VC-Dekens-de Vries-Mereghetti, 1603.03049

Fuyuto & Ramsey-Musolf 1706.08548

...

Yukawa couplings to quarks



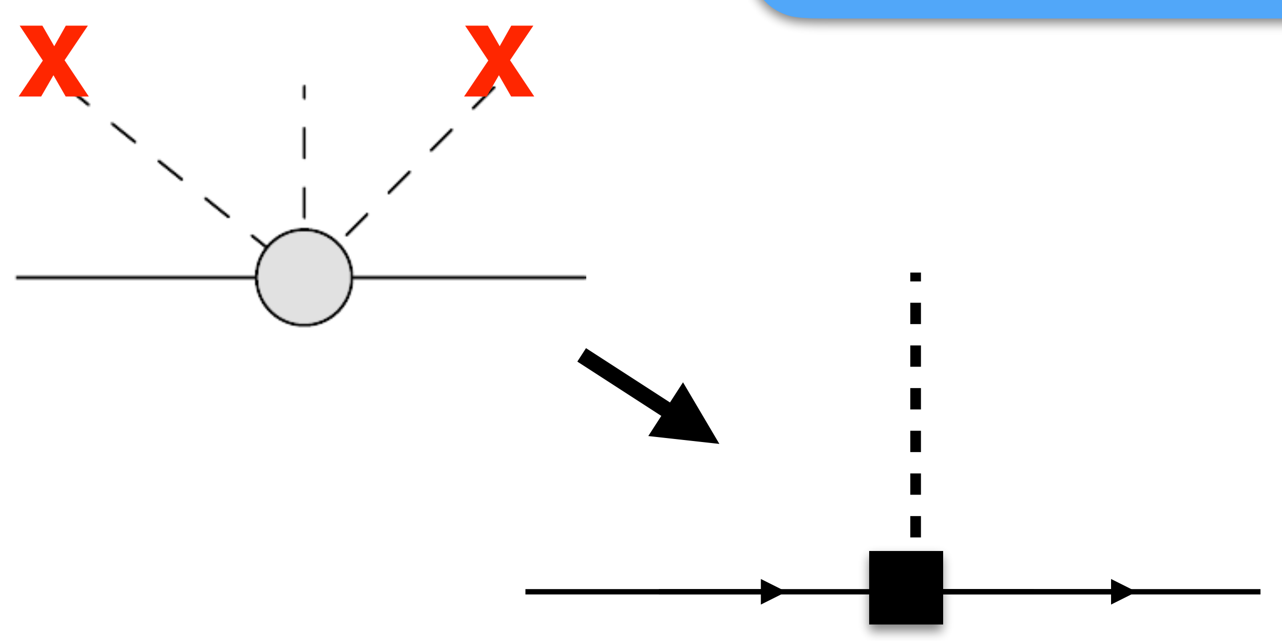
$$\mathcal{L}_6^{CPV} \supset \sum_q v^2 \, \mathrm{Im}\, Y_q' \, \bar{q} i \gamma_5 q \; h$$

Pseudo-scalar coupling
σ · (**p**$_f$ -**p**$_i$) is zero in the Standard Model

Y.-T. Chien, VC, W. Dekens, J. de Vries, E. Mereghetti, JHEP 1602 (2016) 011 [1510.00725]

Brod Haisch Zupan 1310.1385

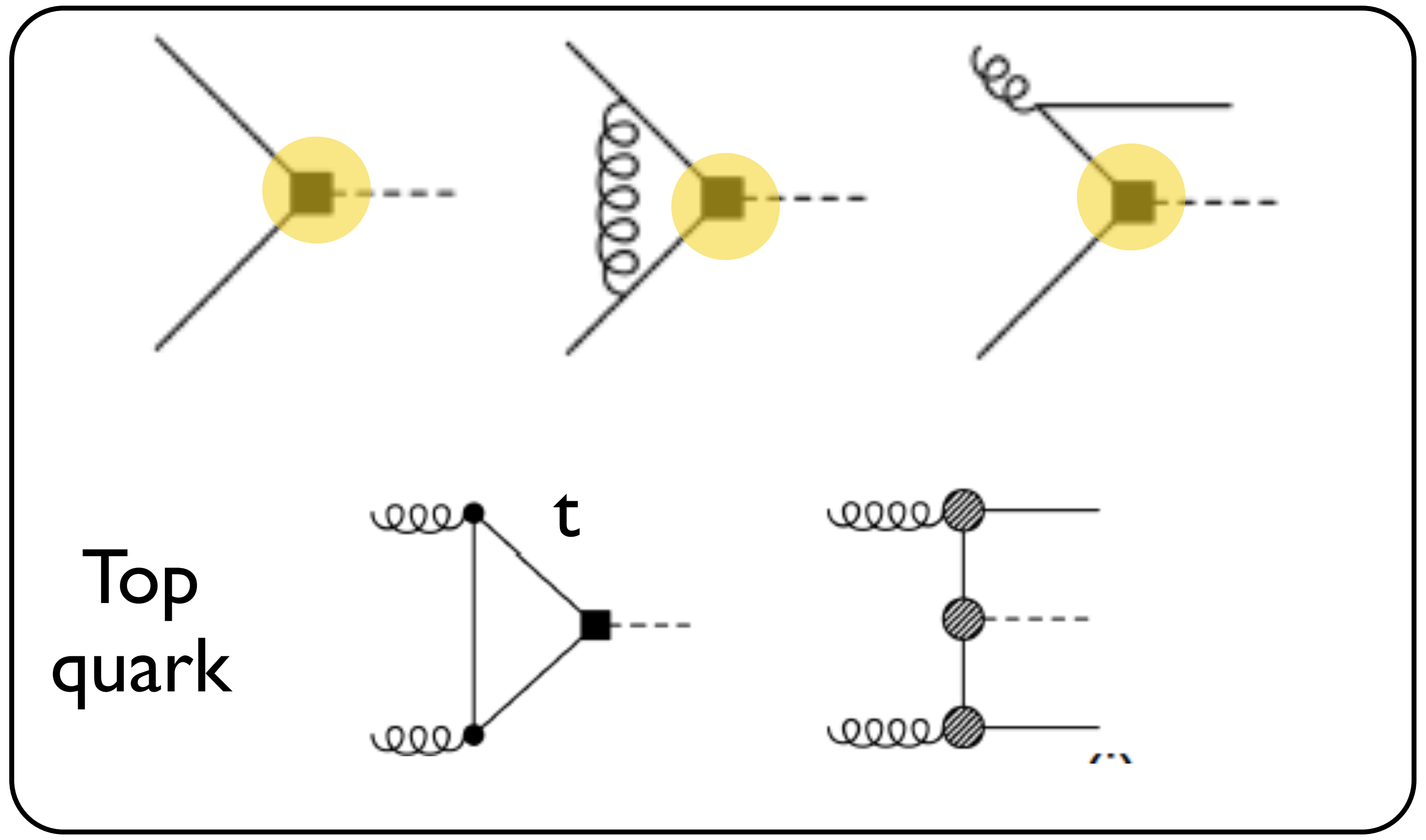
Yukawa couplings to quarks



$$\mathcal{L}_6^{CPV} \supset \sum_q v^2\, \mathrm{Im}\, Y_q'\, \bar{q} i \gamma_5 q\, h$$

Pseudo-scalar coupling
$\boldsymbol{\sigma} \cdot (\mathbf{p}_f - \mathbf{p}_i)$ is zero in
the Standard Model

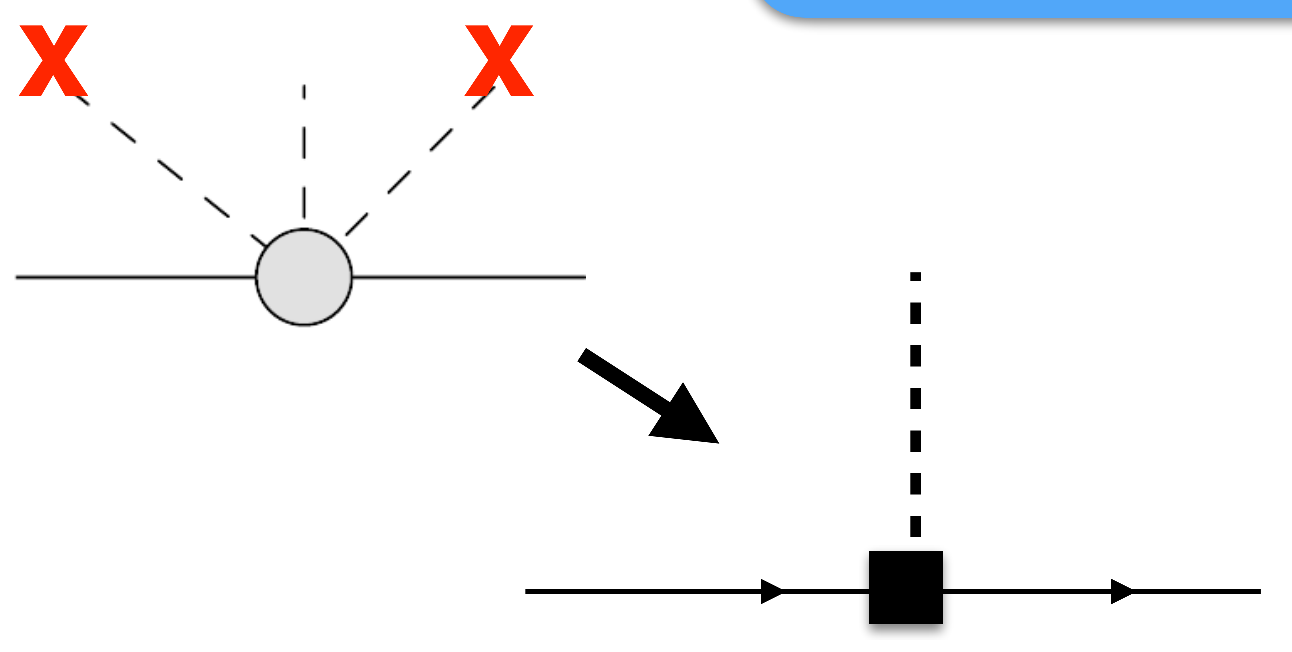
LHC: Higgs production & decay



Y.-T. Chien, VC, W. Dekens, J. de Vries, E. Mereghetti, JHEP 1602 (2016) 011 [1510.00725]

Brod Haisch Zupan 1310.1385

Yukawa couplings to quarks



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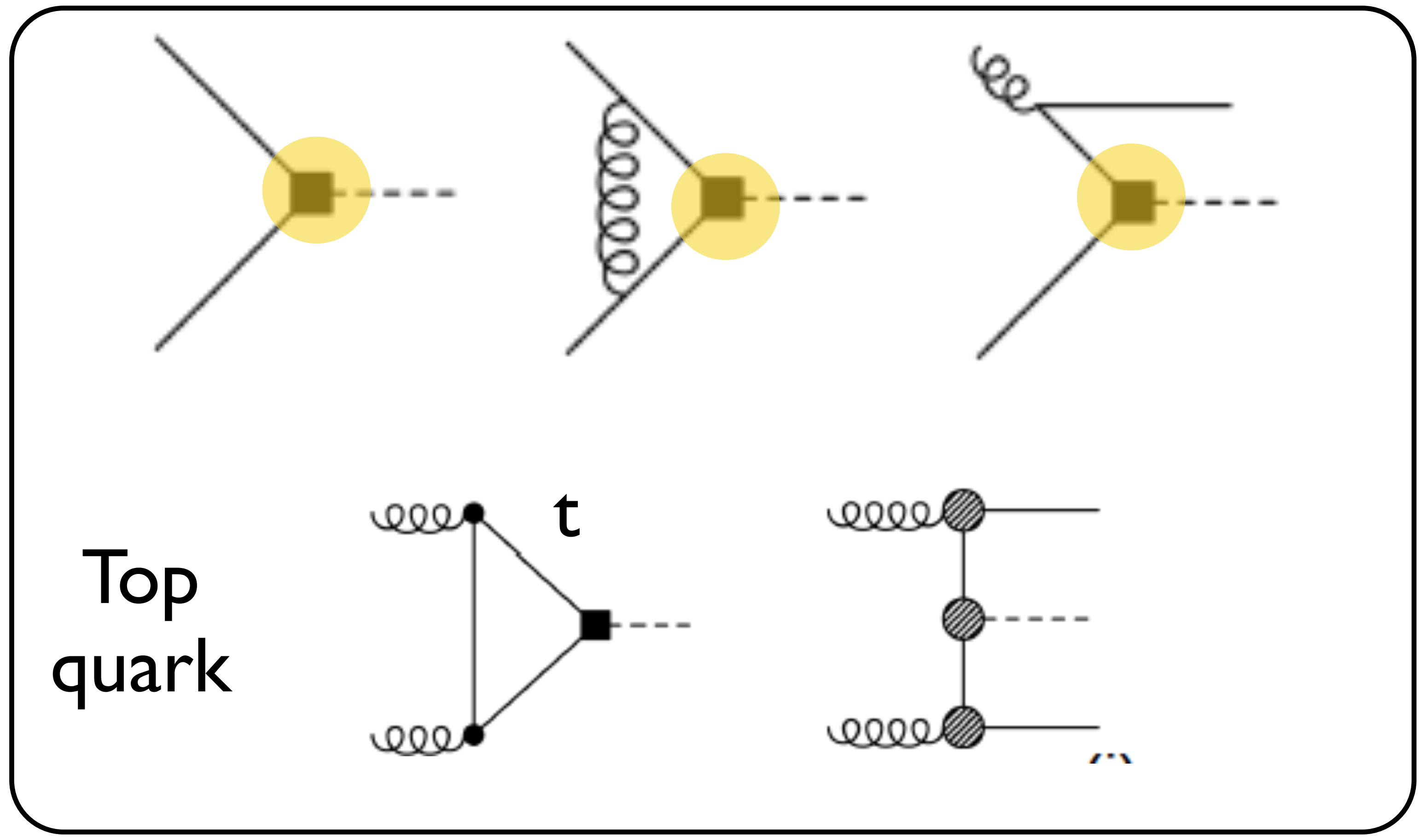
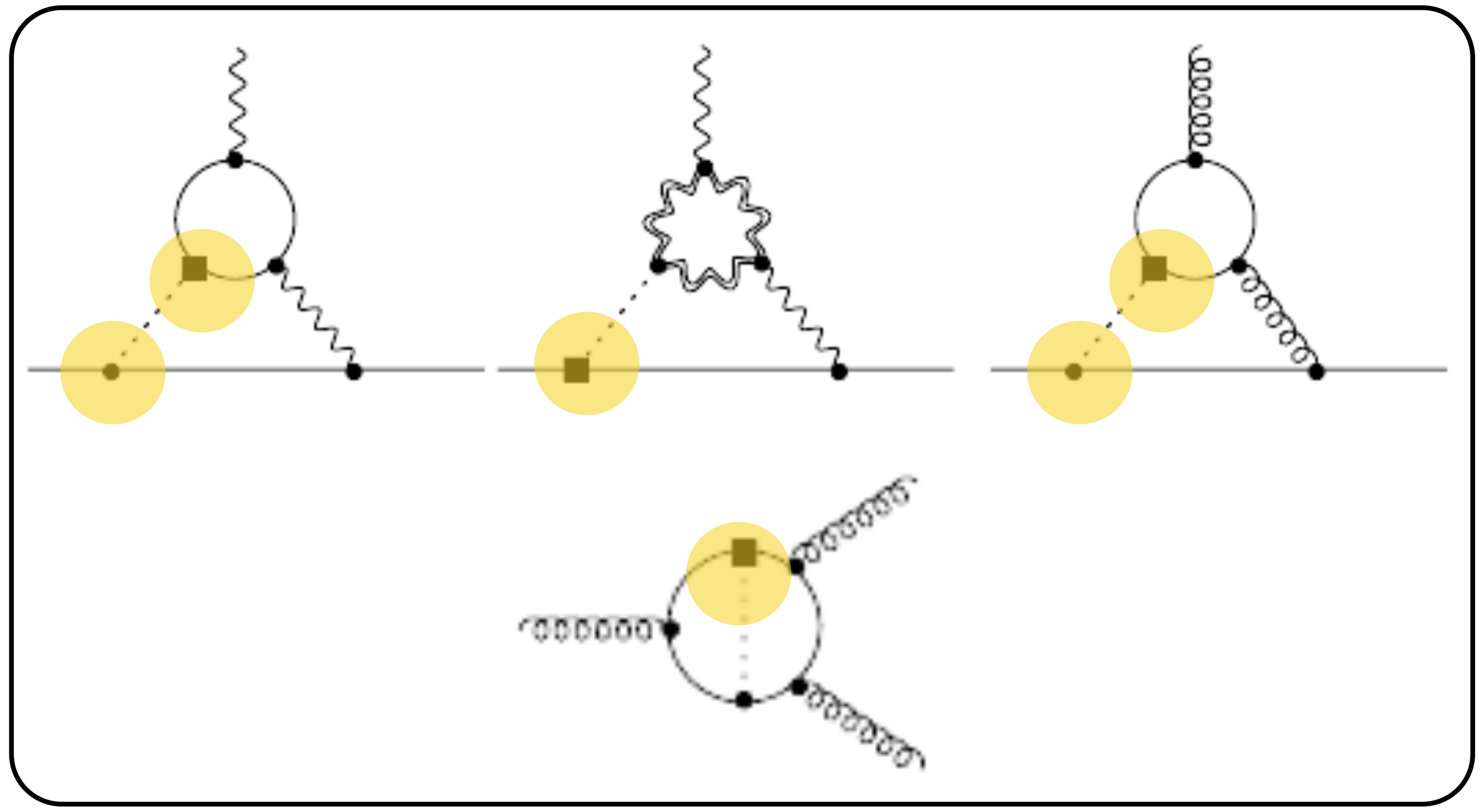
LHC: Higgs production & decay



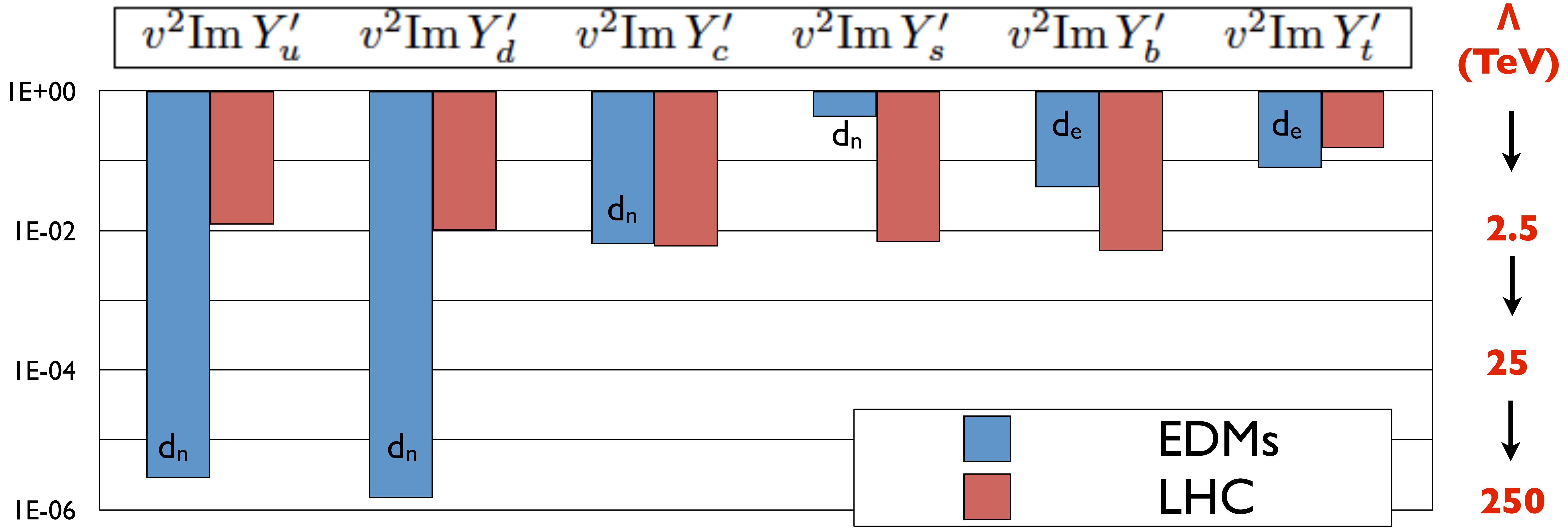
Low Energy: induce electron, neutron, mercury EDM



Y.-T. Chien, VC, W. Dekens, J. de Vries, E. Mereghetti, JHEP 1602 (2016) 011 [1510.00725]

Brod Haisch Zupan 1310.1385

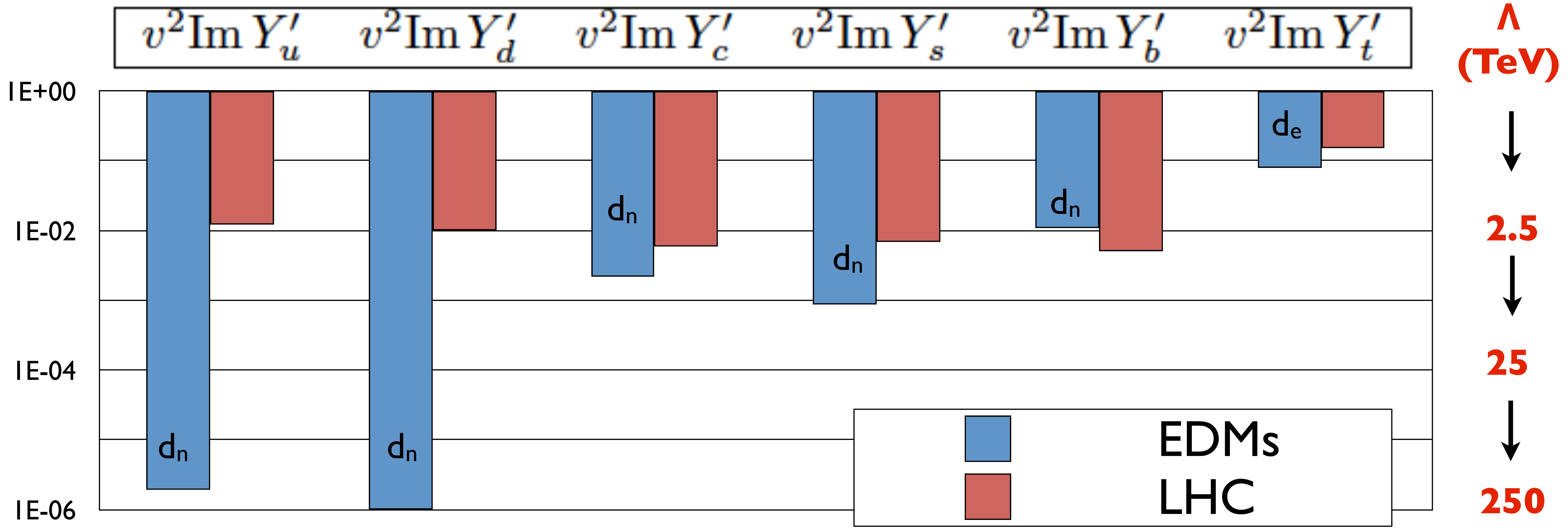
Yukawa couplings to quarks



- EDMs are teaching us something about the Higgs!
- Future: factor of 2 at LHC; EDM constraints scale linearly
- Uncertainty in matrix elements strongly dilutes EDM constraints

Y.-T. Chien, VC, W. Dekens, J. de Vries, E. Mereghetti, JHEP 1602 (2016) 011 [1510.00725]

Yukawa couplings to quarks



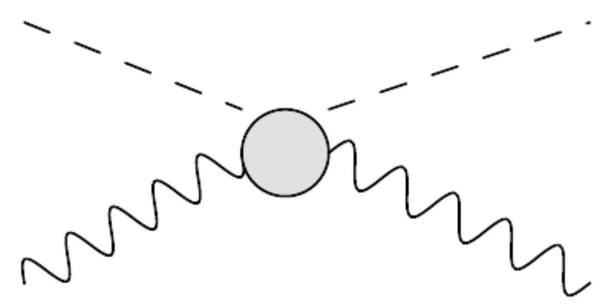
- Much stronger impact of nEDM with reduced uncertainties, for example:

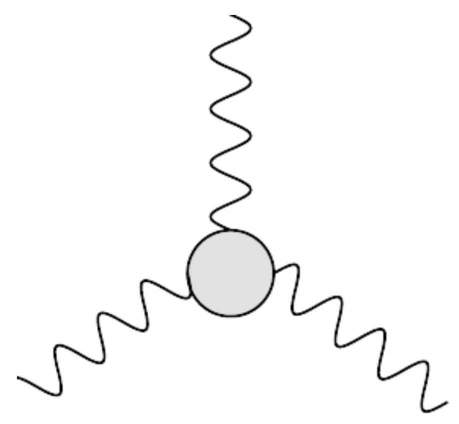
$d_{n,p}[\tilde{d}_{u,d}]$ 25% $d_{n,p}[d_W]$ 50% Target for Lattice QCD

- Experiment at 5 x 10^{-27} e cm and improved matrix elements would make nEDM the strongest probe

Higgs-gauge CPV couplings

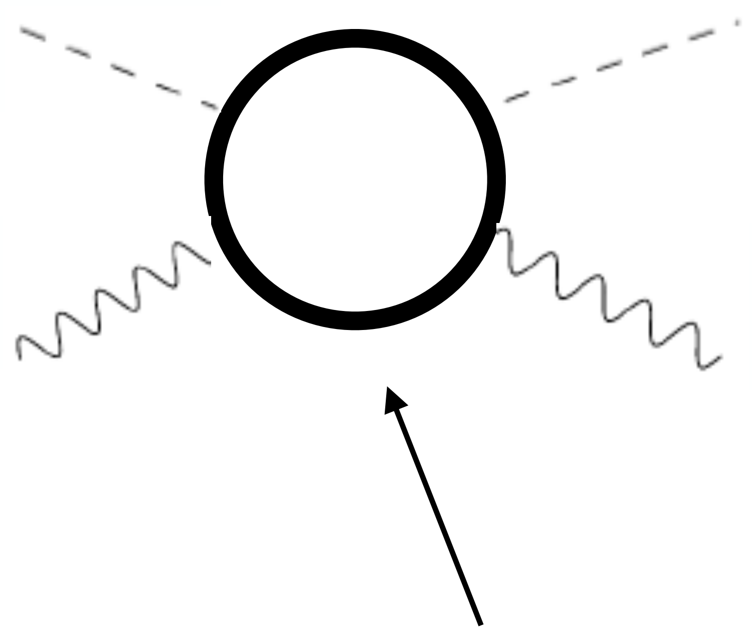
- Dominant sources of CPV (together with VVV) in so-called *universal theories*





Peskin-Takeuchi, PRL 65, 964 (1990)
Barbieri-Pomarol-Rattazzi-Strumia hep-ph/0405040
Wells-Zhang, 1510.08462

Example



New Heavy quark

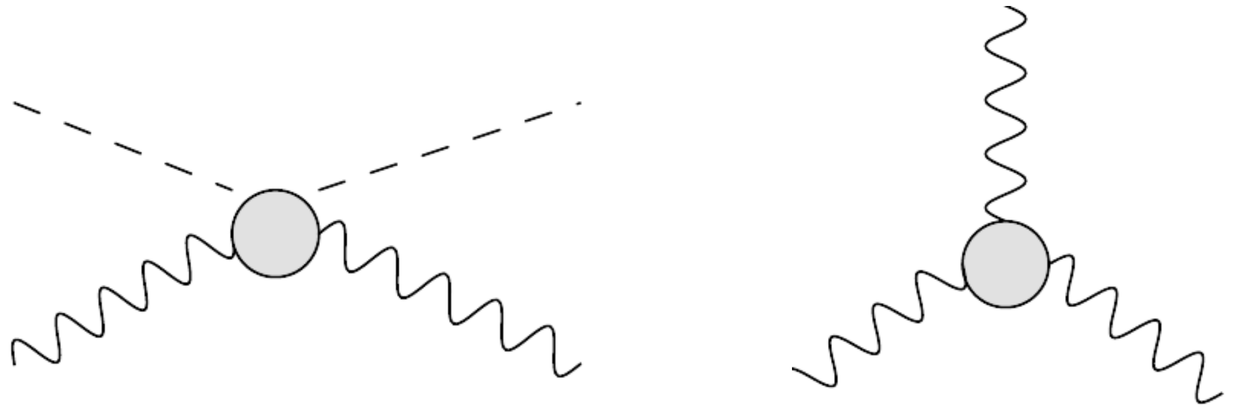
"Universal theories"

- New physics couples only to SM bosons (and to fermions through gauge currents)
- Consistent framework to analyze EW precision tests (oblique corrections, etc)
- Evade flavor constraints, scale can be low

Higgs-gauge CPV couplings

- Dominant sources of CPV (together with VVV) in so-called *universal theories*

Peskin-Takeuchi, PRL 65, 964 (1990)
Barbieri-Pomarol-Rattazzi-Strumia hep-ph/0405040
Wells-Zhang, 1510.08462



H-H-V-$\tilde{V}$ ↑

$v^2\, C_{\varphi\tilde{B}}$

$v^2\, C_{\varphi\tilde{W}}$

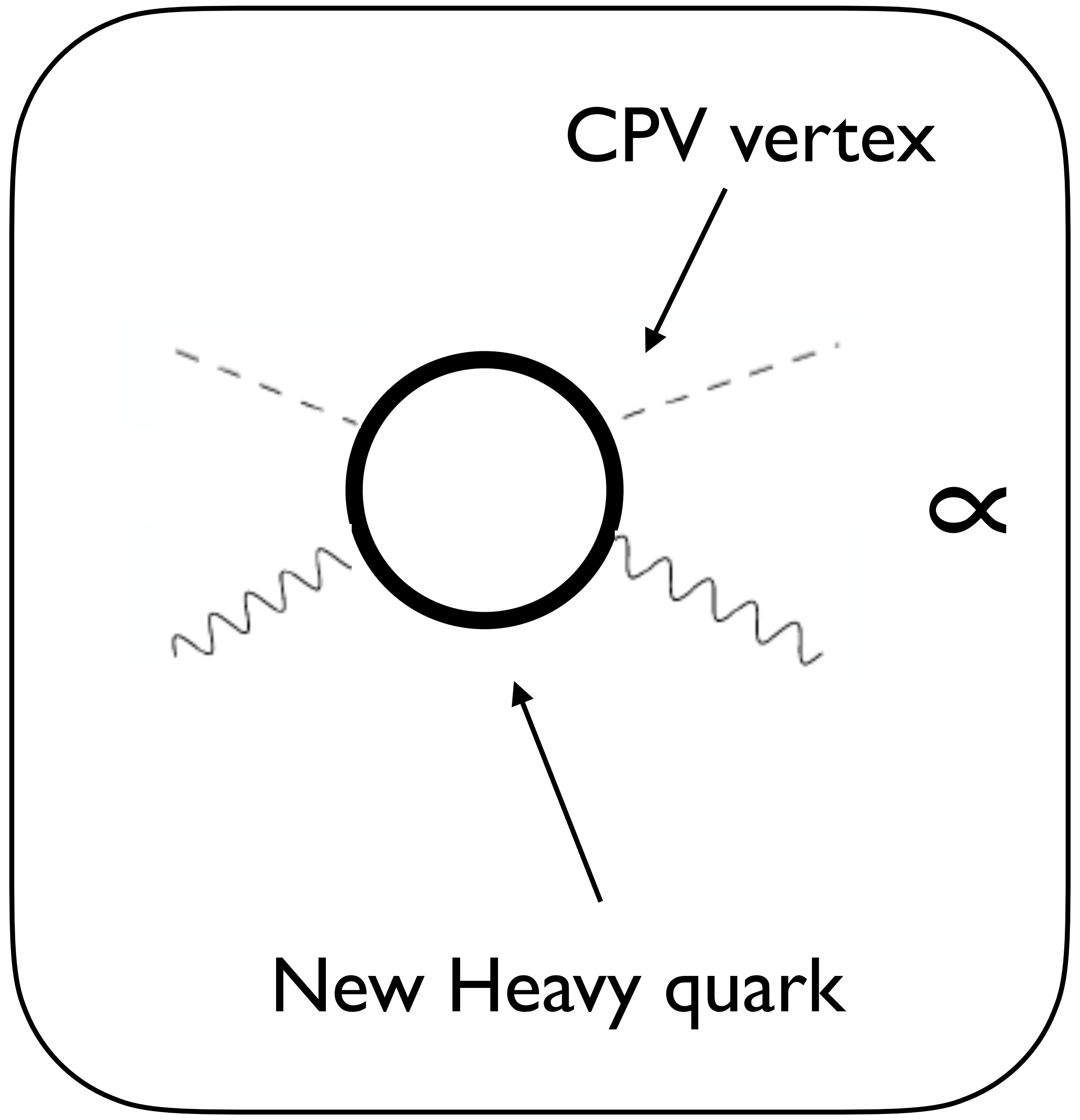
$v^2\, C_{\varphi\tilde{W}B}$

$v^2\, C_{\varphi\tilde{G}}$

V-V-$\tilde{V}$ ↑

$v^2\, C_{\tilde{W}}$

$v^2\, C_{\tilde{G}}$



$\propto F_{\mu\nu}\tilde{F}^{\mu\nu} \sim \mathbf{E}\cdot\mathbf{B}$

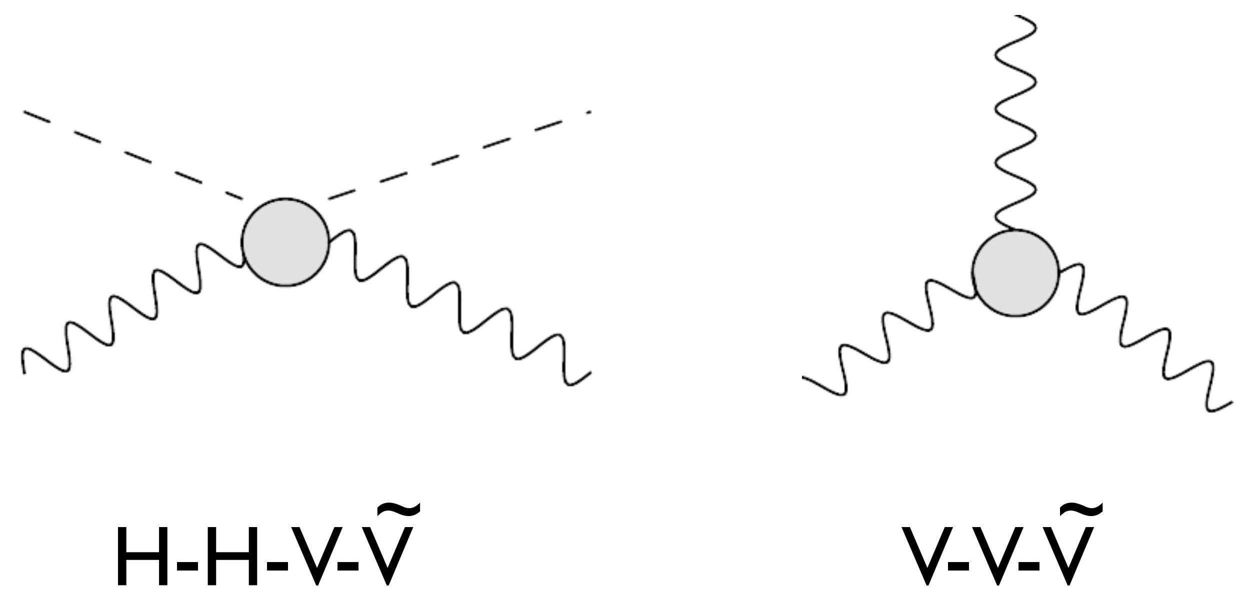
Ferreira-Fuks-Sanz-Sengupta
Eur. Phys. J. C (2017) 77:675

Six CPV couplings at $O(1/\Lambda^2)$

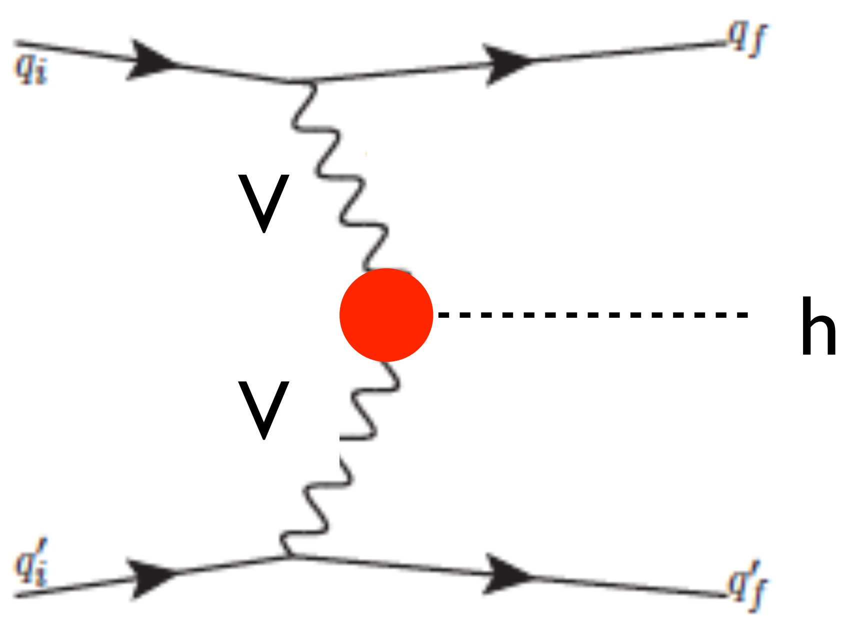
Higgs-gauge CPV couplings

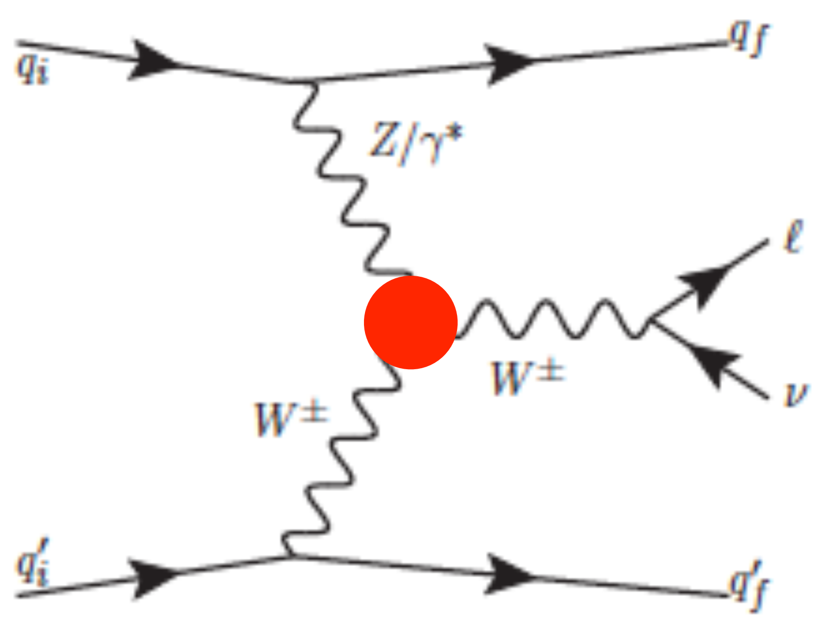
- Dominant sources of CPV (together with VVV) in so-called *universal theories*

Peskin-Takeuchi, PRL 65, 964 (1990)
Barbieri-Pomarol-Rattazzi-Strumia hep-ph/0405040
Wells-Zhang, 1510.08462



- Induce CPV angular distributions in pp → h +2 jets, pp → V +2 jets, …

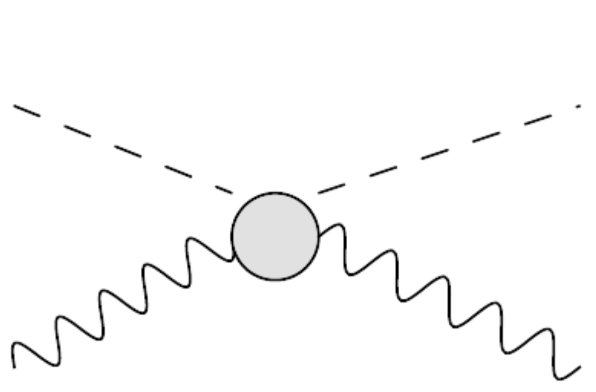




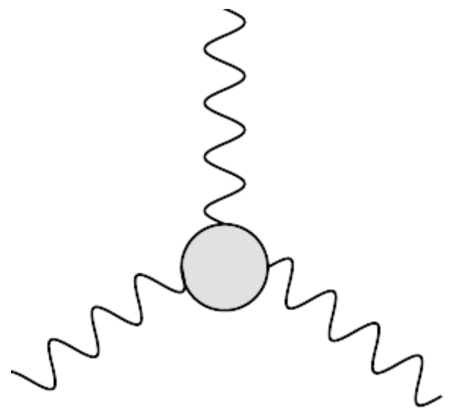
Angular distribution of the two jets ($\Delta\Phi_{jj}$) contains information about CP structure of the VVh vertex.
Triple products of momenta appear, e.g. $\mathbf{p} \cdot (\mathbf{q} \times \mathbf{k})$

Higgs-gauge CPV couplings

- Dominant sources of CPV (together with VVV) in so-called *universal theories*



H-H-V-$\tilde{V}$

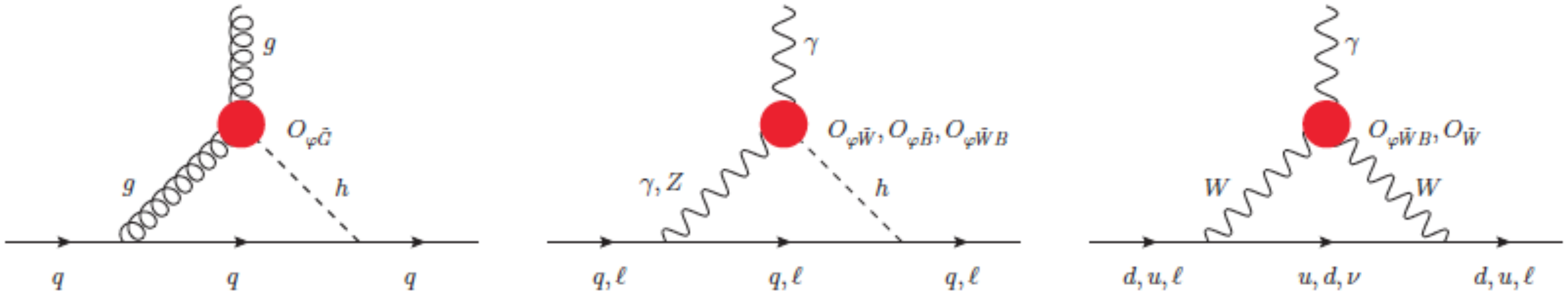


V-V-$\tilde{V}$

Peskin-Takeuchi, PRL 65, 964 (1990)
Barbieri-Pomarol-Rattazzi-Strumia hep-ph/0405040
Wells-Zhang, 1510.08462

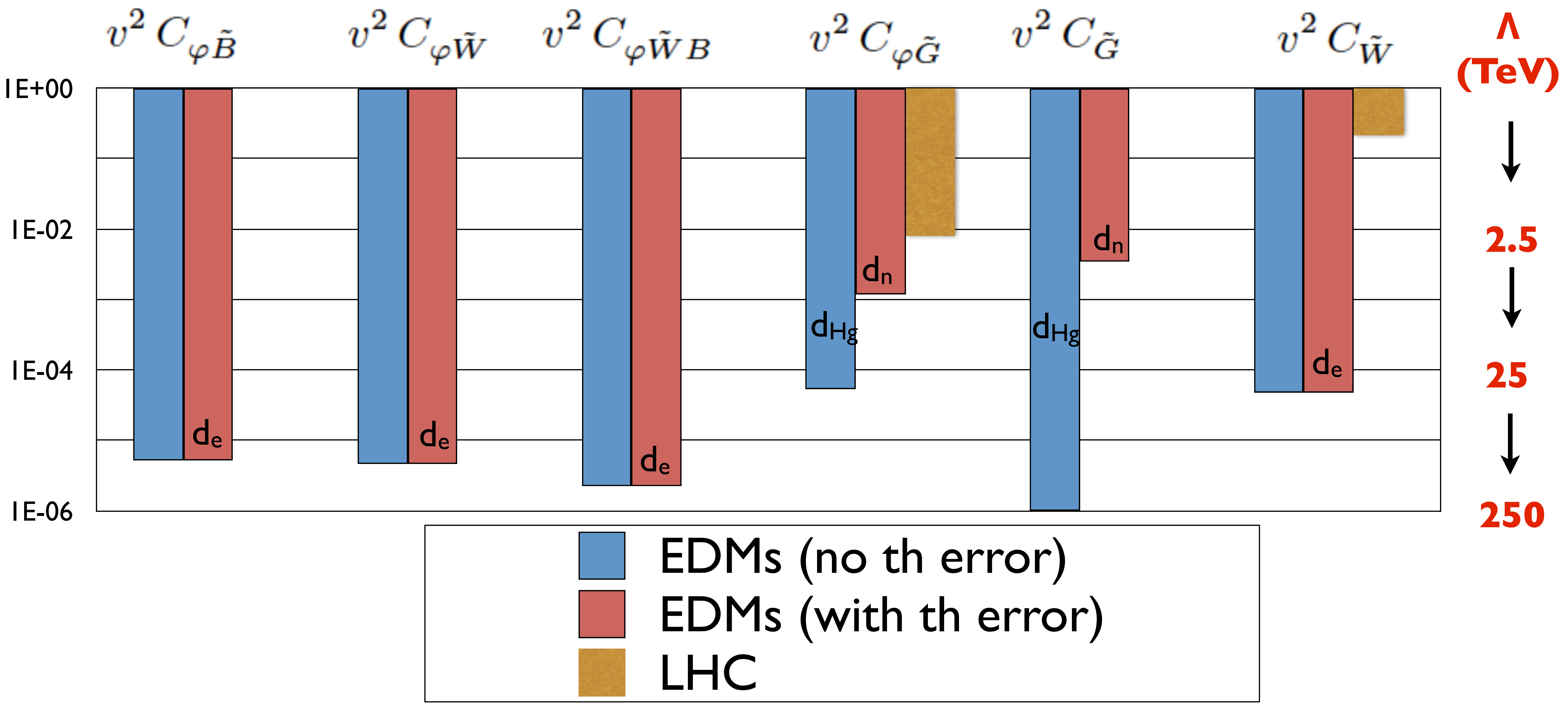
- Induce CPV angular distributions in pp → h +2 jets, pp → V +2 jets, …

- Induce light fermions (chromo)-EDMs at the 1-loop level



Higgs-gauge CPV couplings

- *Current* constraints, "turning on" one coupling at a time: EDMs vs LHC



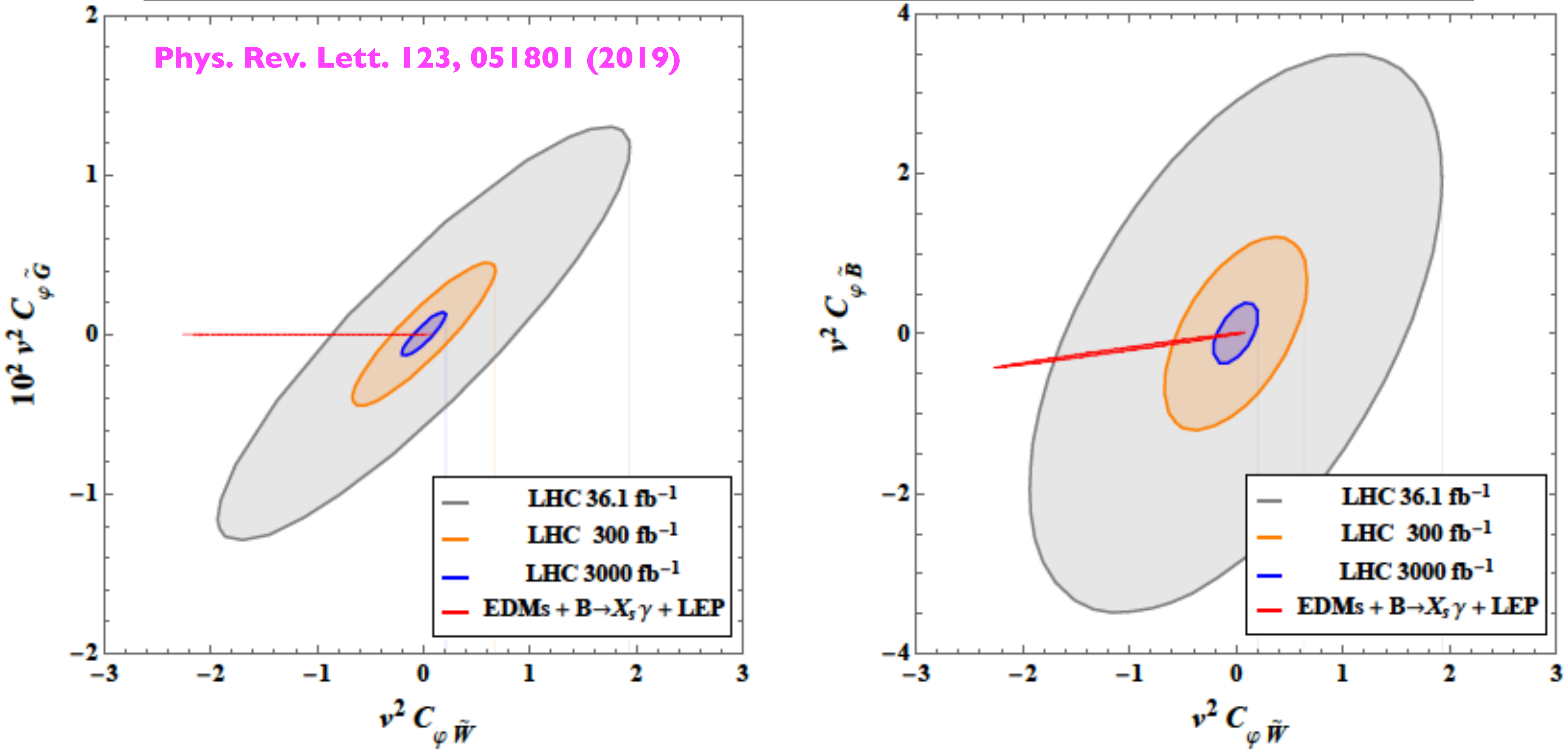
VC, A. Crivellin, W. Dekens, J. de Vries, M. Hoferichter, E. Mereghetti, 1903.03625, Phys. Rev. Lett. 123, 051801 (2019)

LHC limits from : ATLAS, 1703.04362 & Bernlochner et al., 1808.06577

Higgs-gauge CPV couplings

- *Prospective* constraints, turing on all couplings: low-energy vs LHC

$|d_{n,p,d,Ra}| < 10^{-27}$ e cm + improved theory errors



95% CL

LHC projections from Bernlochner et al., 1808.06577

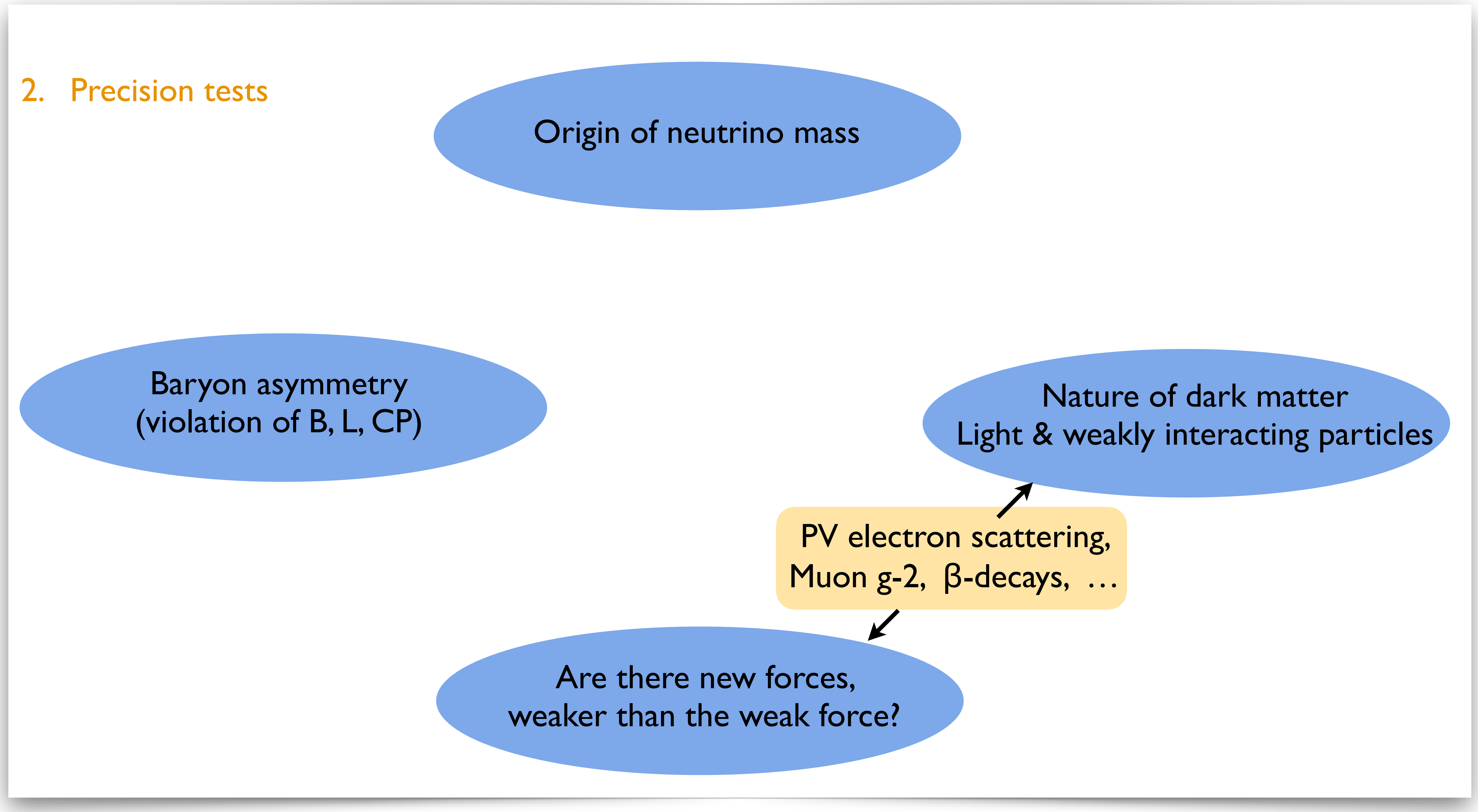
Low-energy measurements have far stronger constraining power → highly correlated allowed regions. Distinctive pattern that could be probed at the high-luminosity LHC

Outlook on EDMs and CP violation

- Interpretation of null (for now) or positive EDM searches requires bridging scales: from BSM to hadronic, nuclear, atomic, molecular
  - Reducing theory uncertainties is essential
  - Lattice QCD can have big impact on hadronic matrix elements
  - Nuclear and atomic / molecular calculations

- EDMs are a powerful probe of new sources of CP violation
  - Stringent constraints on CPV couplings of the Higgs, much stronger than collider reach
  - More generally, if new physics exists only at very high scale, EDMs may be among a handful of observables able to probe it
  - Ongoing experimental searches in multiple systems, expect high sensitivity with radioactive molecules down the road

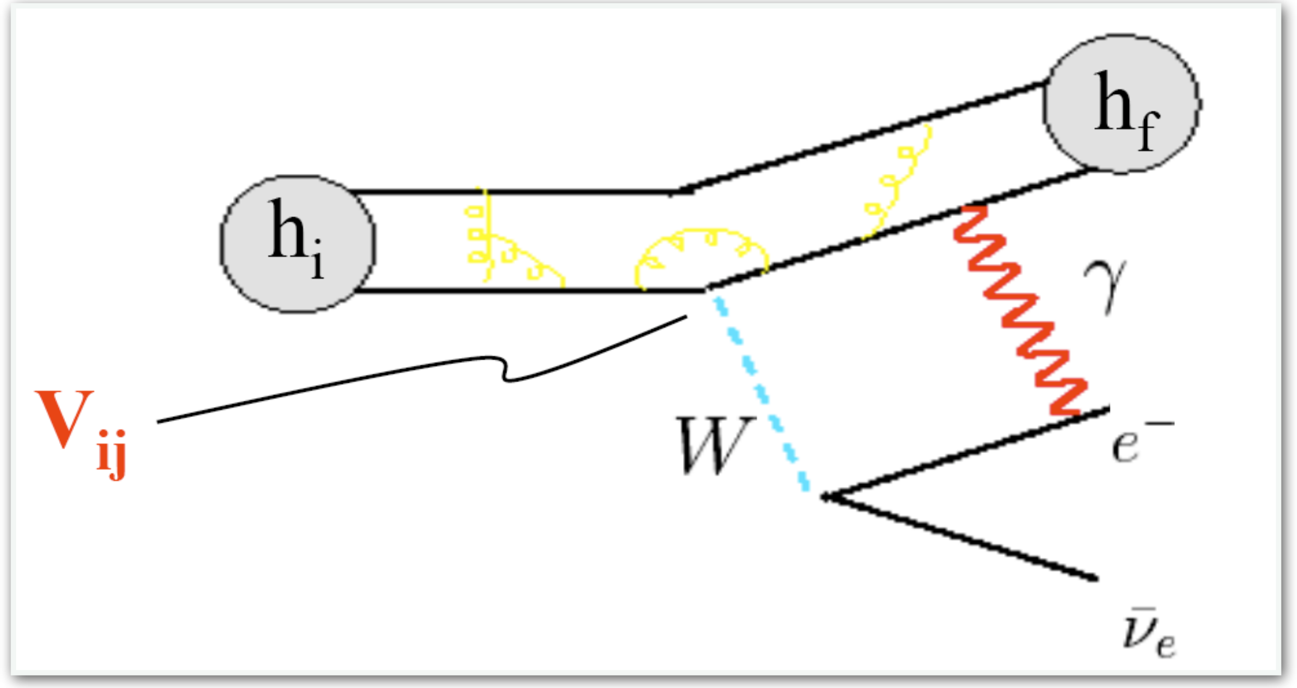
Precision tests



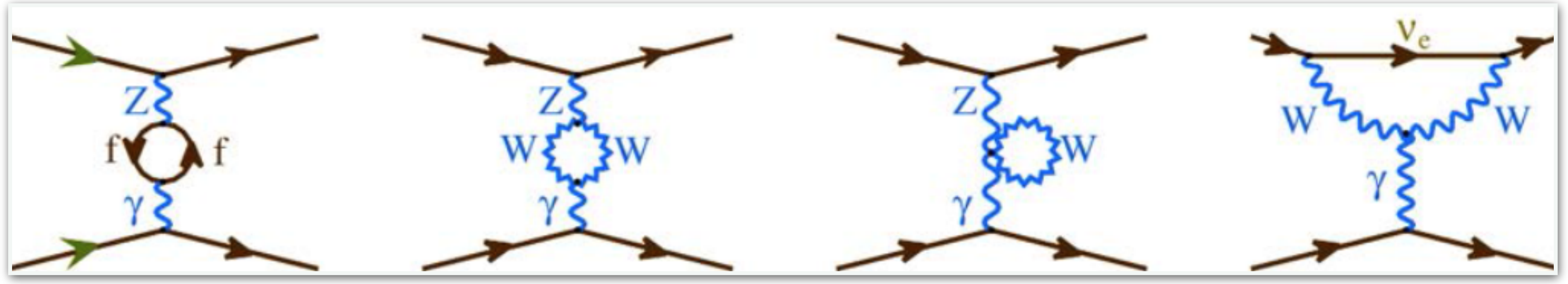
Will focus mostly on β decays

Precision tests

- Beta decays and parity-violating electron scattering (PVES) have played a central role in establishing the Standard Model
- Today, with precision approaching the 0.1% level or better (together with the muon g-2 at the <ppm level!) they probe quantum effects in the Standard Model at unprecedented levels
- Broad sensitivity to new physics

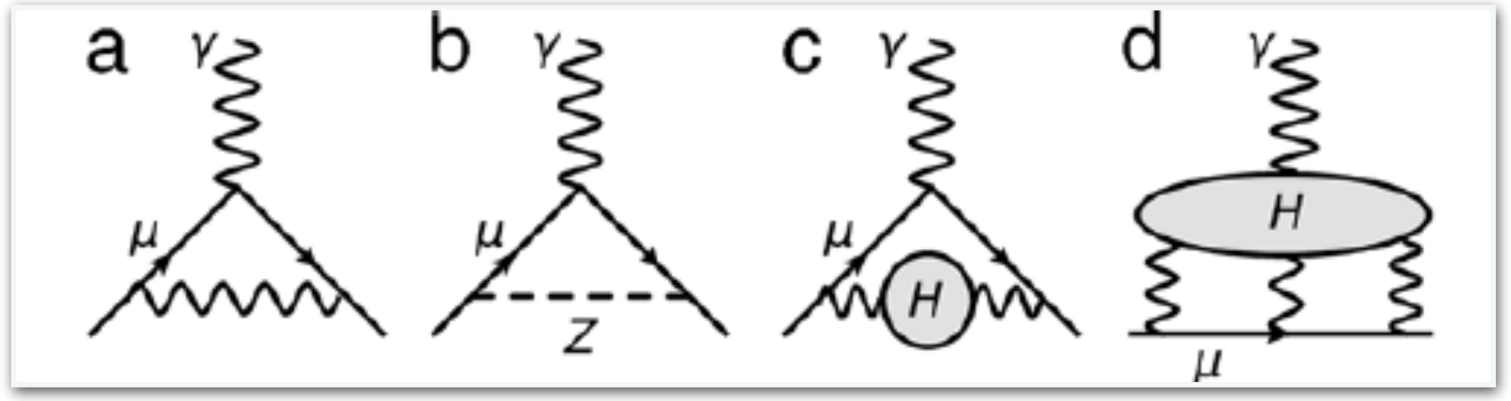


β decay



Radiative corrections to electron scattering

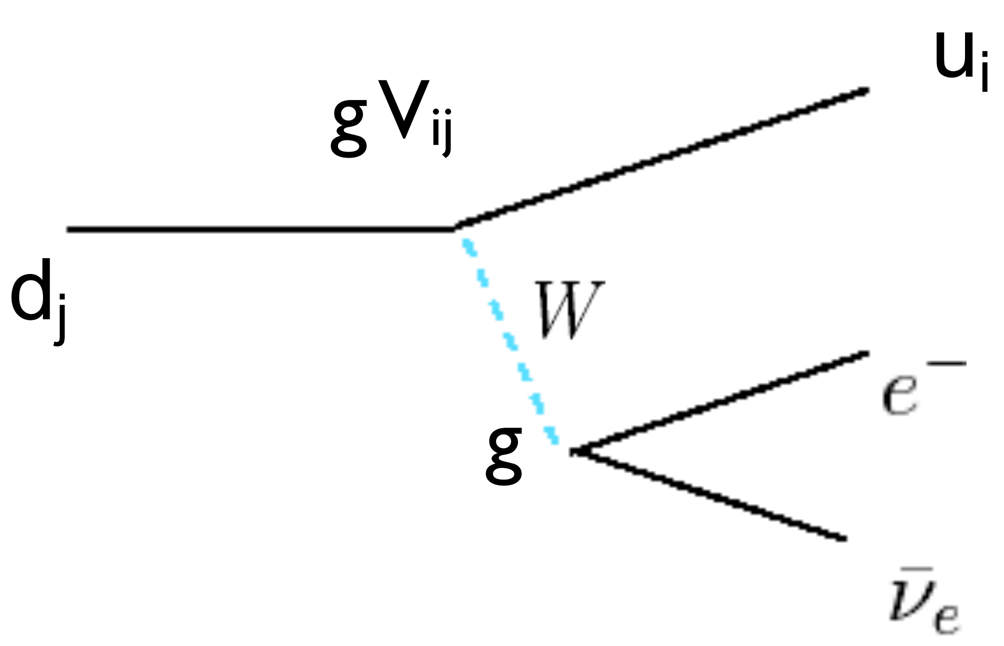
See lectures by D. Kawall



Representative diagrams for muon g-2

β decays in the SM and beyond

- In the SM, mediated by W exchange ⇒ only "V-A"; Cabibbo universality; lepton universality



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

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

Cabibbo-Kobayashi-Maskawa

Cabibbo Universality

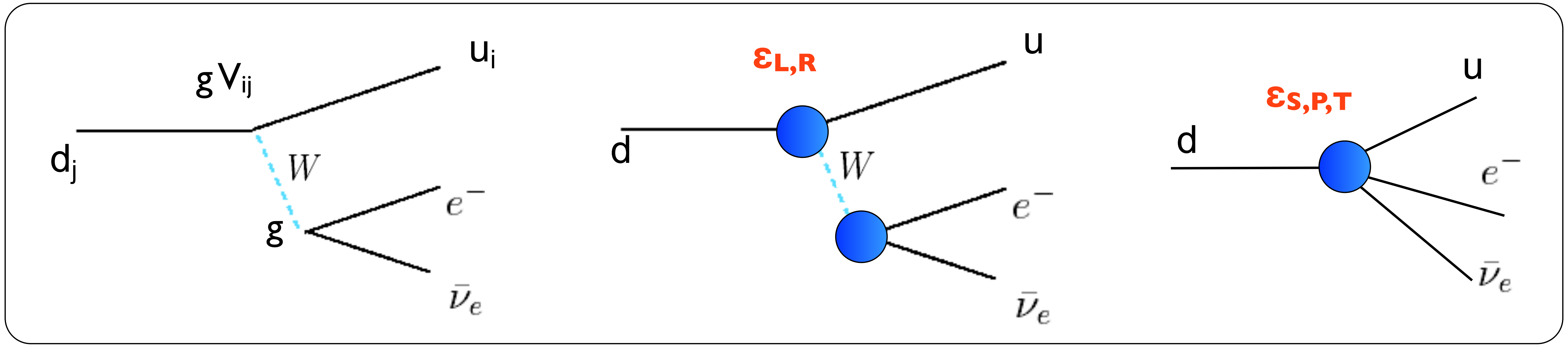
$$|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} = 1$$

$$[G_F]_e/[G_F]_\mu = 1$$

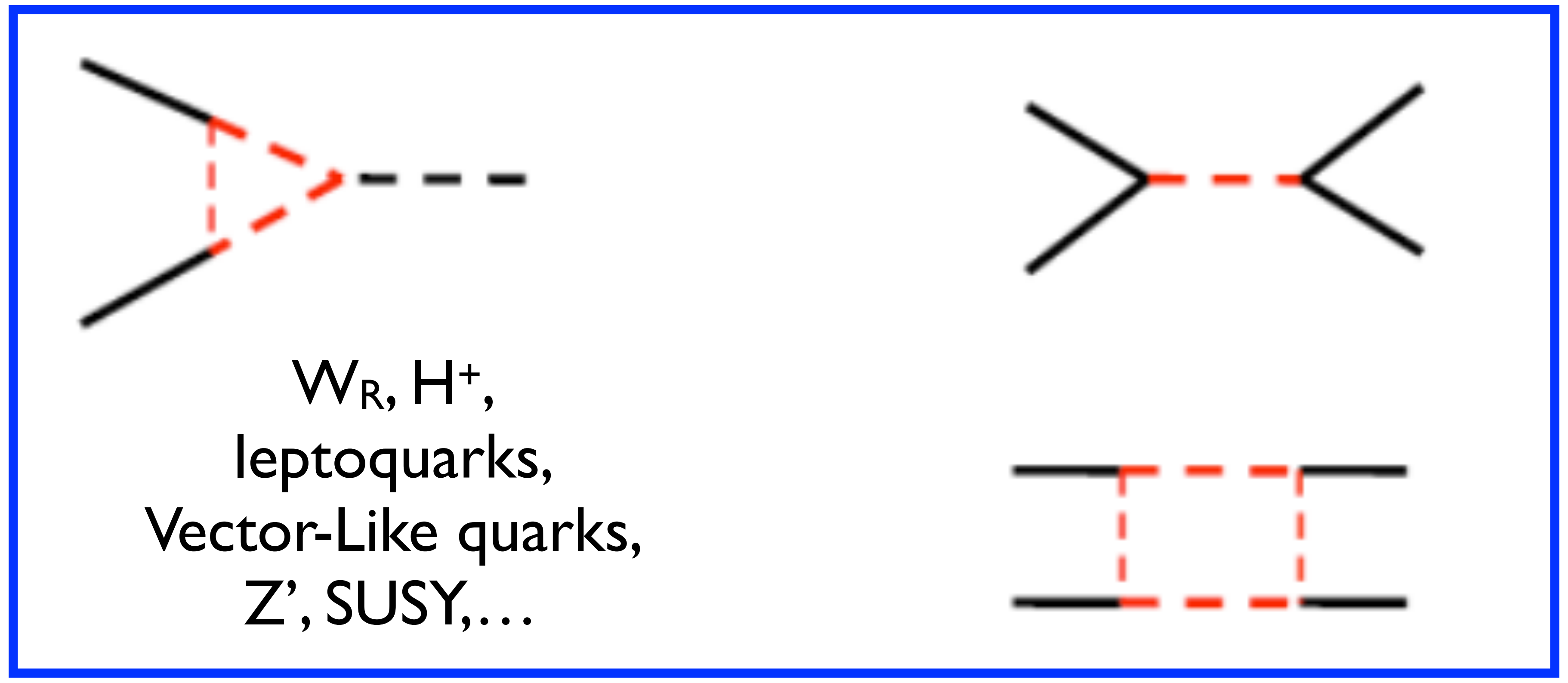
Lepton Flavor Universality (LFU)

β decays in the SM and beyond

- In the SM, mediated by W exchange ⇒ only "V-A"; Cabibbo universality; lepton universality

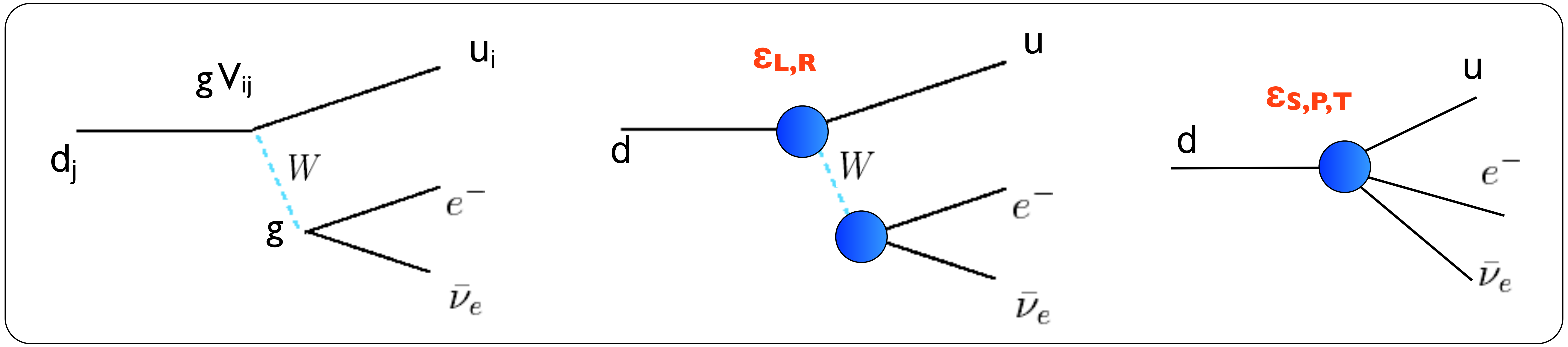


$G_F^{(\beta)} \sim G_F^{(\mu)} V_{ij} \sim 1/v^2 V_{ij}$ $\quad 1/\Lambda^2 \quad 1/\Lambda^2$



β decays in the SM and beyond

- In the SM, mediated by W exchange ⇒ only "V-A"; Cabibbo universality; lepton universality



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

$E \ll \Lambda$ ↓ $\epsilon_\Gamma \sim \tilde{\epsilon}_\Gamma \sim (v/\Lambda)^2$

$$\mathcal{L}_{\rm SM} - \frac{G_F V_{ud}}{\sqrt{2}} \sum_\Gamma \left[\epsilon_\Gamma \; \bar{\ell}\Gamma\nu_L \cdot \bar{u}\Gamma d \;+\; \tilde{\epsilon}_\Gamma \; \bar{\ell}\Gamma\nu_R \cdot \bar{u}\Gamma d \right]$$

Ten effective couplings $\Gamma = L, R, S, P, T$

- Precision of 0.1-0.01% probes Λ > 10 TeV. Several precision tests are possible....

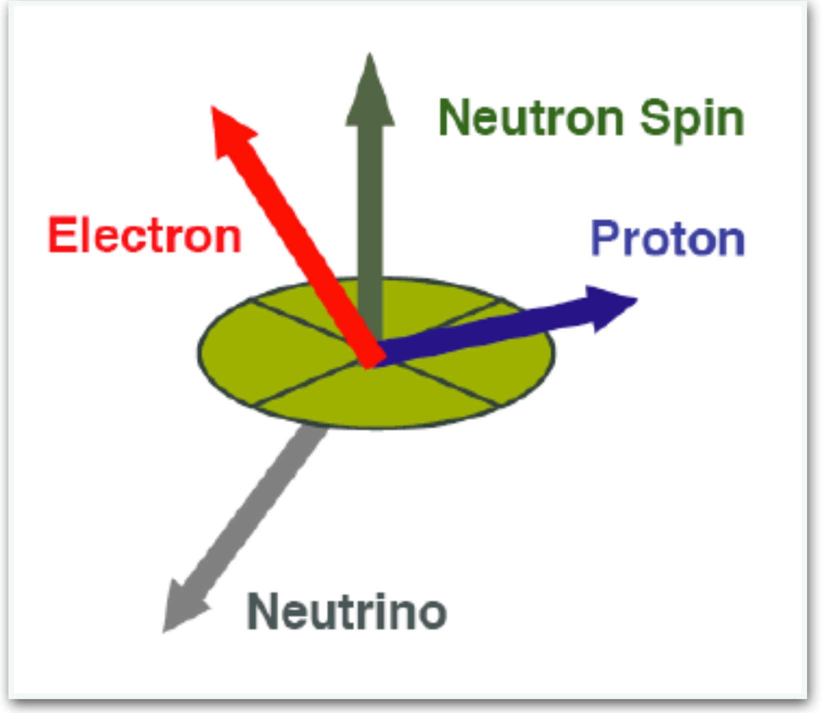
Searches for 'non V-A' currents

Measure differential decay distributions (mostly sensitive to $\varepsilon_{S,T}$)

$$d\Gamma \propto F(E_e) \left\{ 1 + b\,\frac{m_e}{E_e} + a\,\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \langle \vec{J} \rangle \cdot \left[A\,\frac{\vec{p}_e}{E_e} + B\,\frac{\vec{p}_\nu}{E_\nu} + \cdots \right] \right\}$$

Lee-Yang, 1956 **Jackson-Treiman-Wyld 1957**

b ($g_S\varepsilon_S$, $g_T\varepsilon_T$):
distortion of beta spectrum

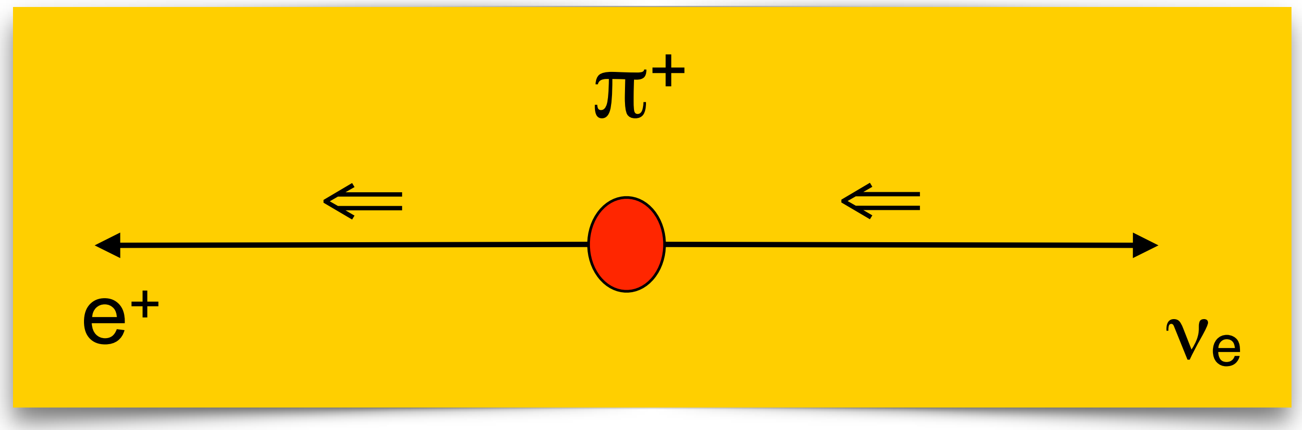


a(g_A), A(g_A) , B(g_A, $g_\alpha\varepsilon_\alpha$), ...
isolated via suitable experimental asymmetries

Bounds on $\varepsilon_{S,T}$ at the 0.1% level, Λ~5-10 TeV

Lepton universality test with pions

- $R_{e/\mu} = \Gamma\,(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$ helicity suppressed the SM (V-A), zero if $m_e \to 0$



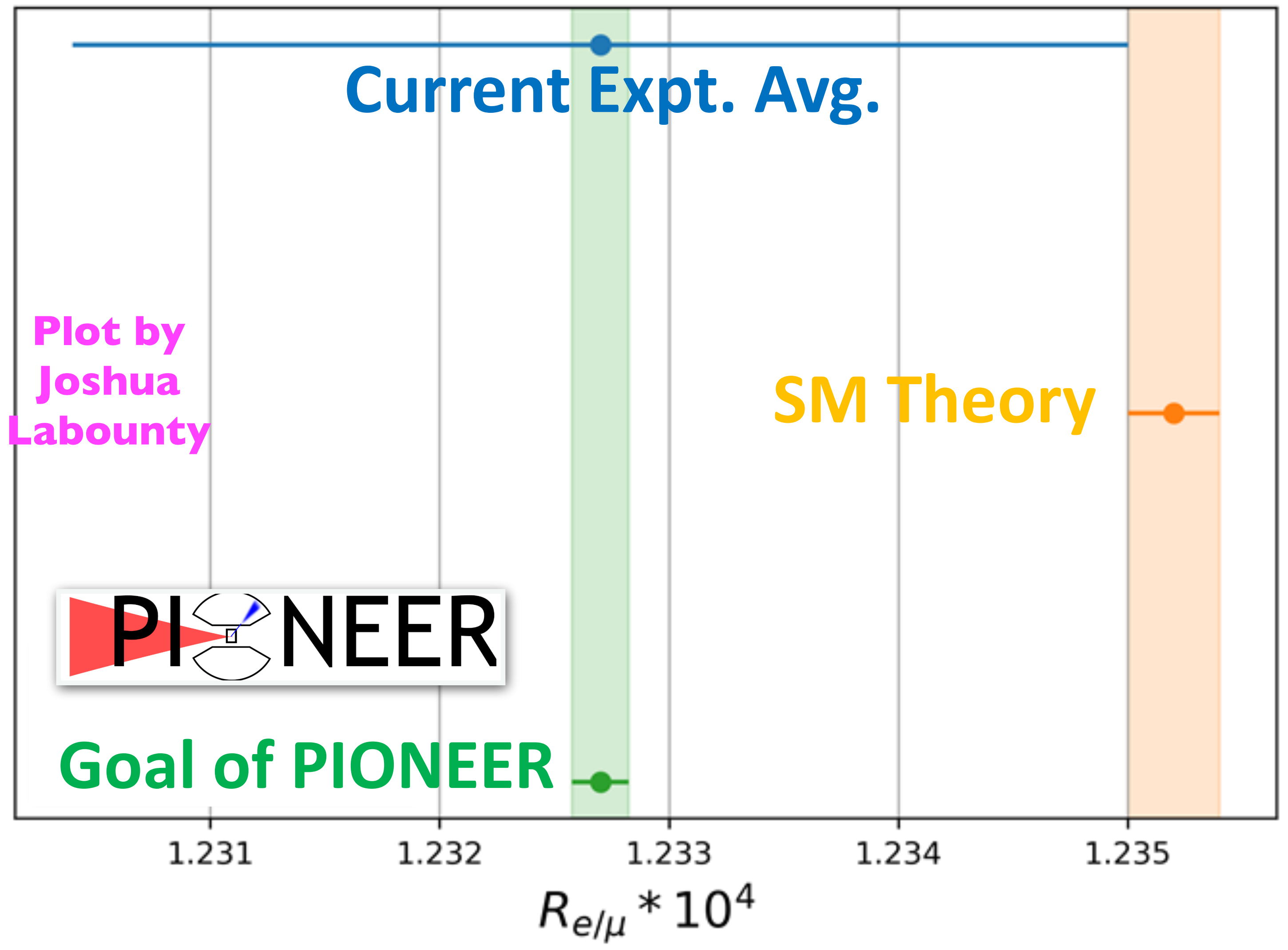
- $\sigma_{exp} \sim 15\sigma_{th} \Rightarrow$ pristine LFU test possible

VC-Rosell 0707.3439

$$R_{e/\mu}(\mathrm{SM}) = 1.23524(015) \times 10^{-4}$$
$$R_{e/\mu}(\mathrm{Exp}) = 1.23270(230) \times 10^{-4}$$

PIENU Coll.

- PIONEER @ PSI will match theoretical uncertainty. Order of magnitude gap — room for surprises! Will probe scales $\Lambda_A \sim 30$ TeV or $\Lambda_P \sim 1000$ TeV (helicity!)

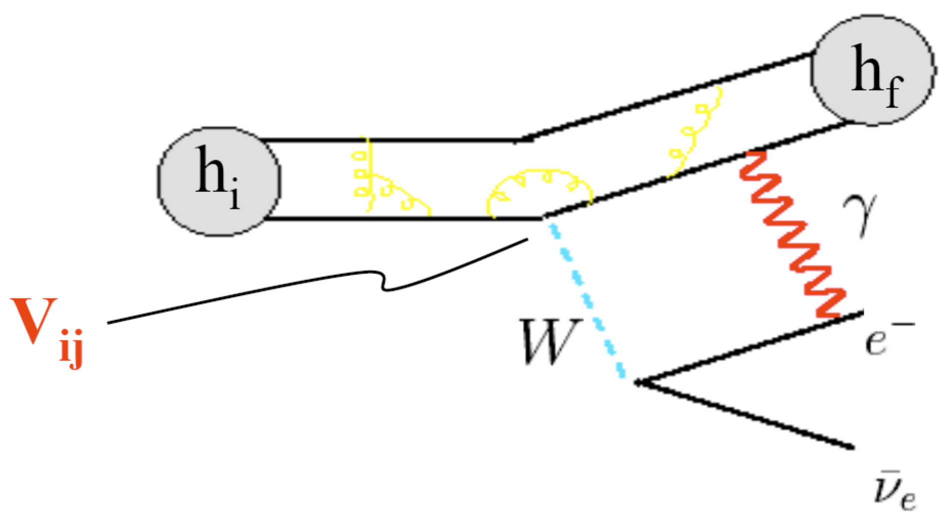


Cabibbo universality test

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 $\delta\lambda/\lambda$ ~ 0.2-0.5%)



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

Cabibbo universality test

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

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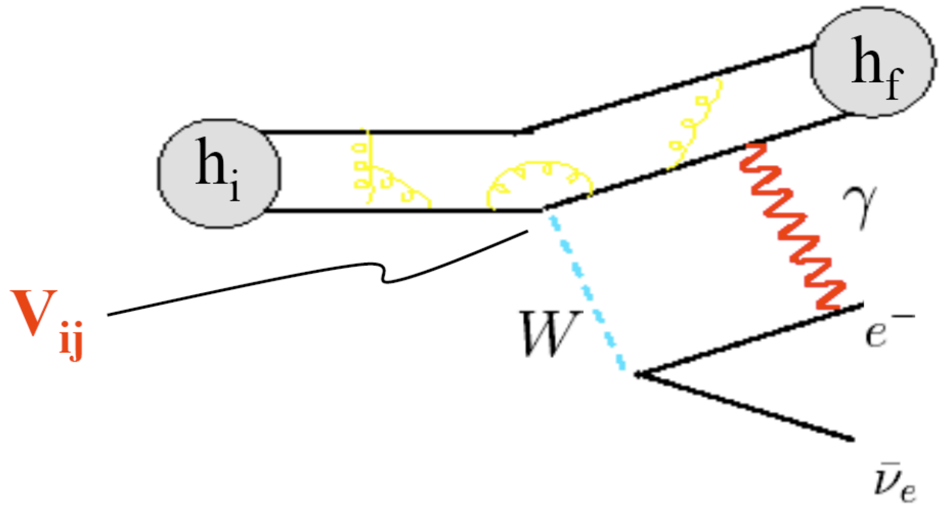


$$\Gamma = G_F^2 \times |V_{ij}|^2 \times |M_{\rm had}|^2 \times (1+\Delta_R) \times F_{\rm kin}$$

Lifetimes, BRs

Muon decay

Experimental input

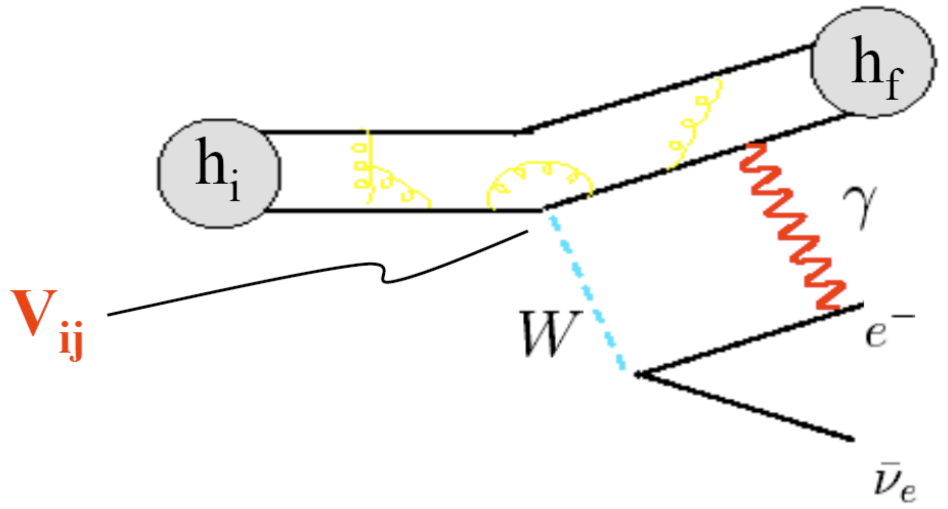
Q-values, form factors, … → phase space

Cabibbo universality test

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 $\delta\lambda/\lambda \sim 0.2\text{-}0.5\%$)



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

Theory input

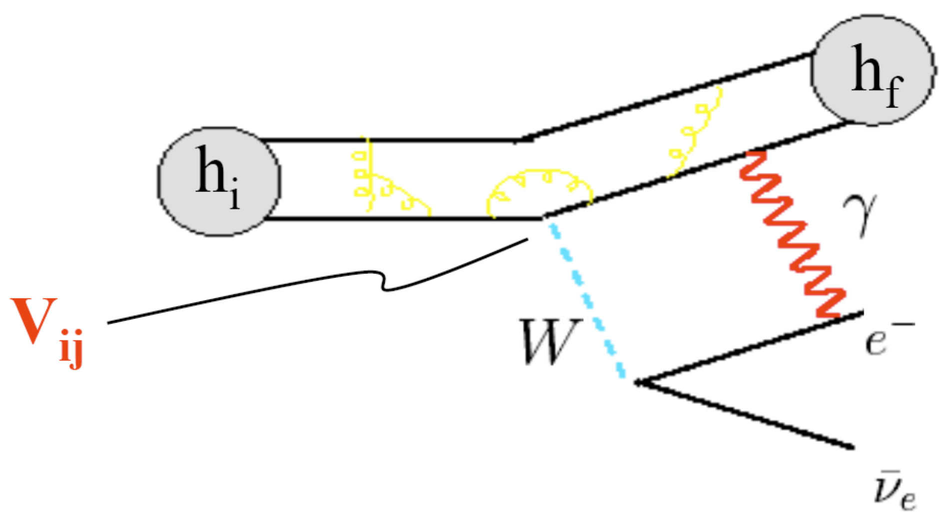
Hadronic / nuclear matrix elements of the weak V-A current, including small corrections such as those induced by electromagnetic radiative corrections $[(\alpha/\pi) \sim 2.\times 10^{-3}]$

Cabibbo universality test

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 $\delta\lambda/\lambda \sim 0.2\text{-}0.5\%$)



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

Channel-dependent effective
CKM element
(Contaminated by the BSM ε's)

Unitarity test

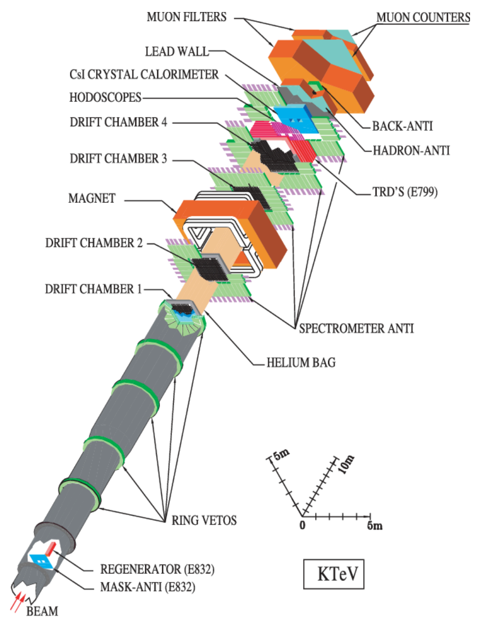
$$\Delta_{\rm CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = \mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$$

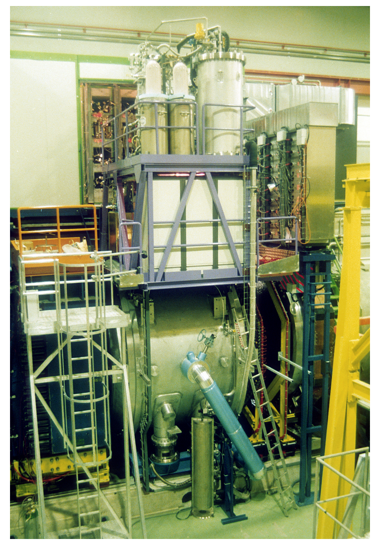
Paths to V_{ud} and V_{us}

	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	$\pi \to \mu \nu$	$\tau \to h_{NS} \nu$
V_{us}	$K \to \pi \, l \, \nu$	$\Lambda \to p e \nu, \ldots$	$K \to \mu \nu$	$\tau \to h_{S} \nu$

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

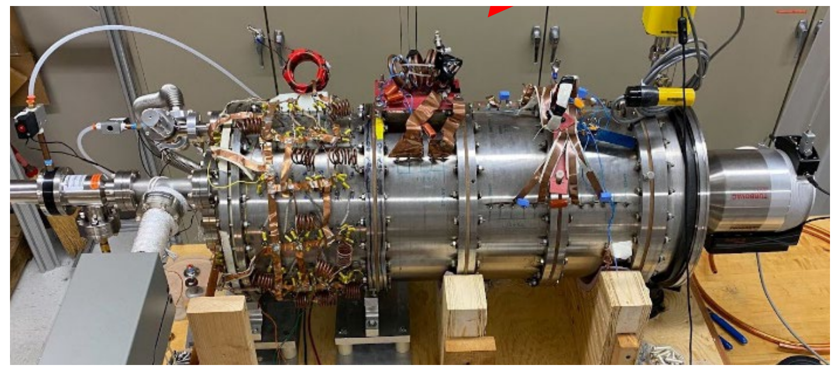
K, π, Hyperons:
Meson factories & fixed target experiments (KLOE, KTeV, NA48 ,…), with future experiment possible at CERN and PSI

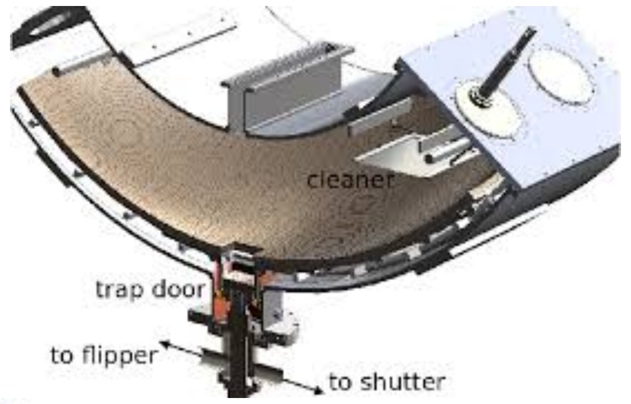




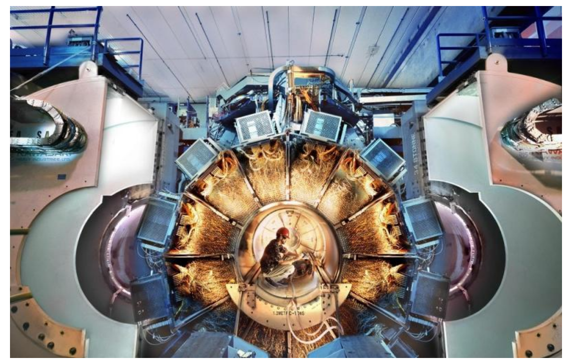
Nuclear beta decay experiments

Cold and Ultra Cold Neutron sources





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



Hadronic matrix elements

	Hadron decays			Lepton decays
V_{ud}	$\pi^{\pm} \to \pi^0 e\nu$ Nucl. $0^+ \to 0^+$	$n \to pe\nu$ Nucl. mirror decays	$\pi \to \mu\nu$	$\tau \to h_{NS}\nu$
V_{us}	$K \to \pi l \nu$	$\Lambda \to pe\nu, \ldots$	$K \to \mu\nu$	$\tau \to h_S\nu$

Hadronic matrix elements: 'Vector - Axial' quark current

V — V, A — A — V, A

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 $K \to \pi$

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

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

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

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

Radiative corrections

	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	$\pi \to \mu\nu$	$\tau \to h_{NS}\nu$
V_{us}	$K \to \pi \, l \, \nu$	$\Lambda \to p e \nu, \ldots$	$K \to \mu\nu$	$\tau \to h_{S}\nu$

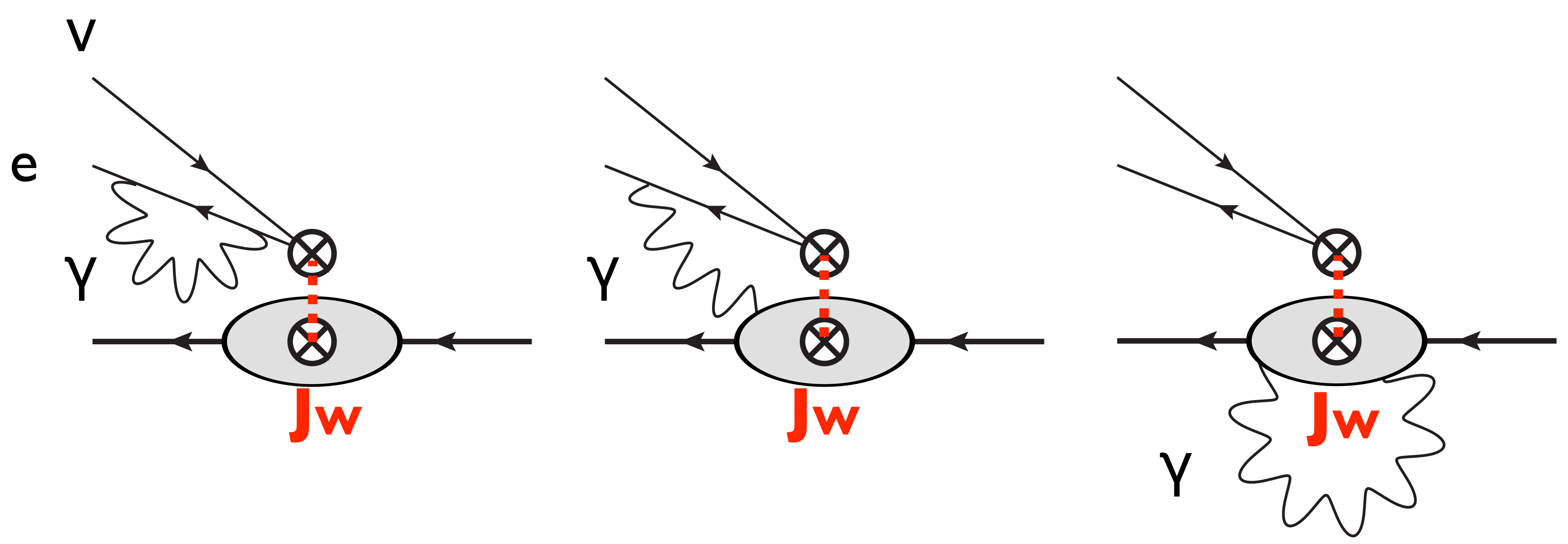
Electroweak radiative corrections

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 K and π decays:
full lattice QCD+QED available

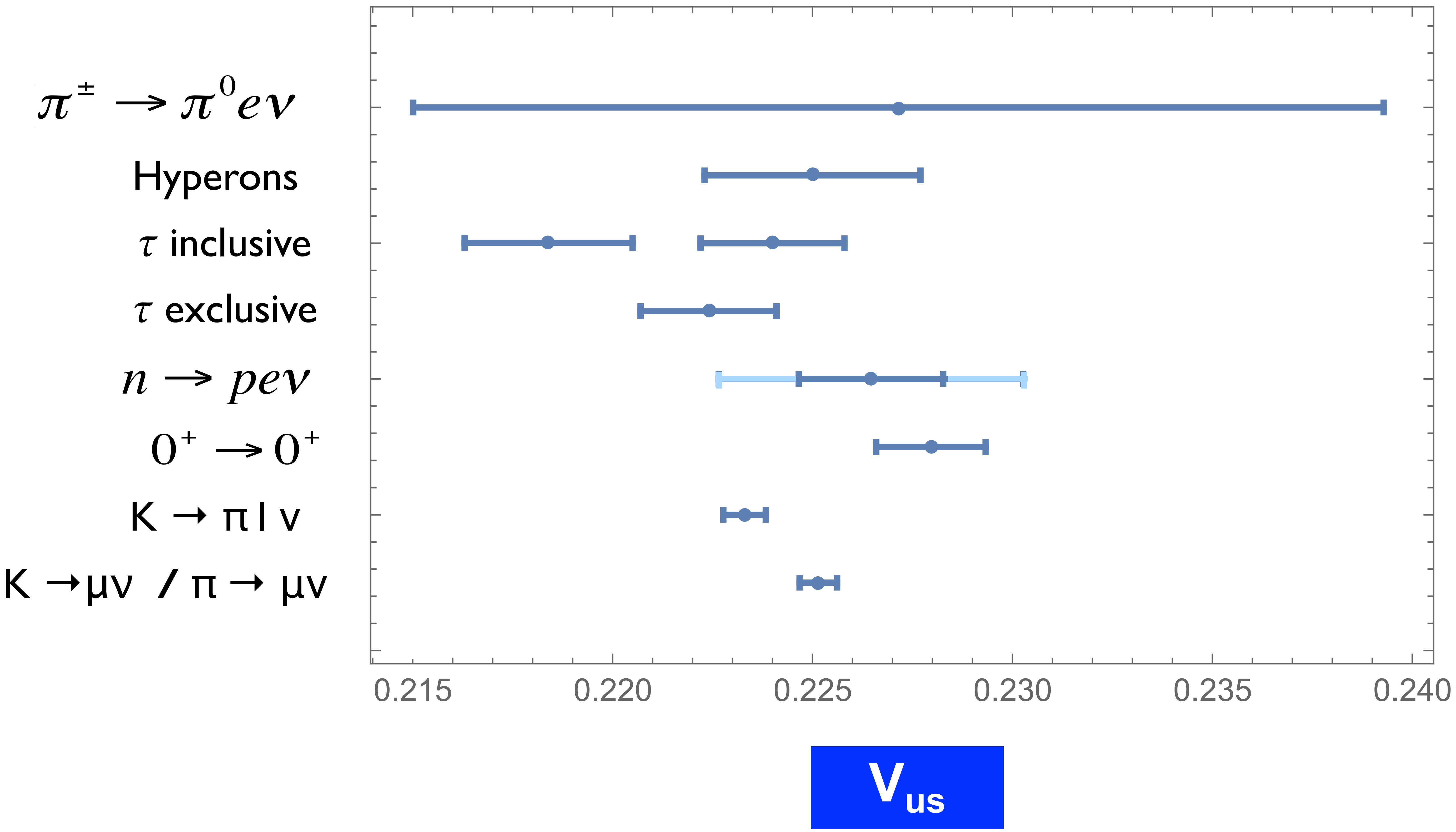
Recent activity to assess nuclear structure uncertainties:
Dispersive & EFT approaches to $O(G_F\alpha)$ recently developed.

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



The Cabibbo angle — global view

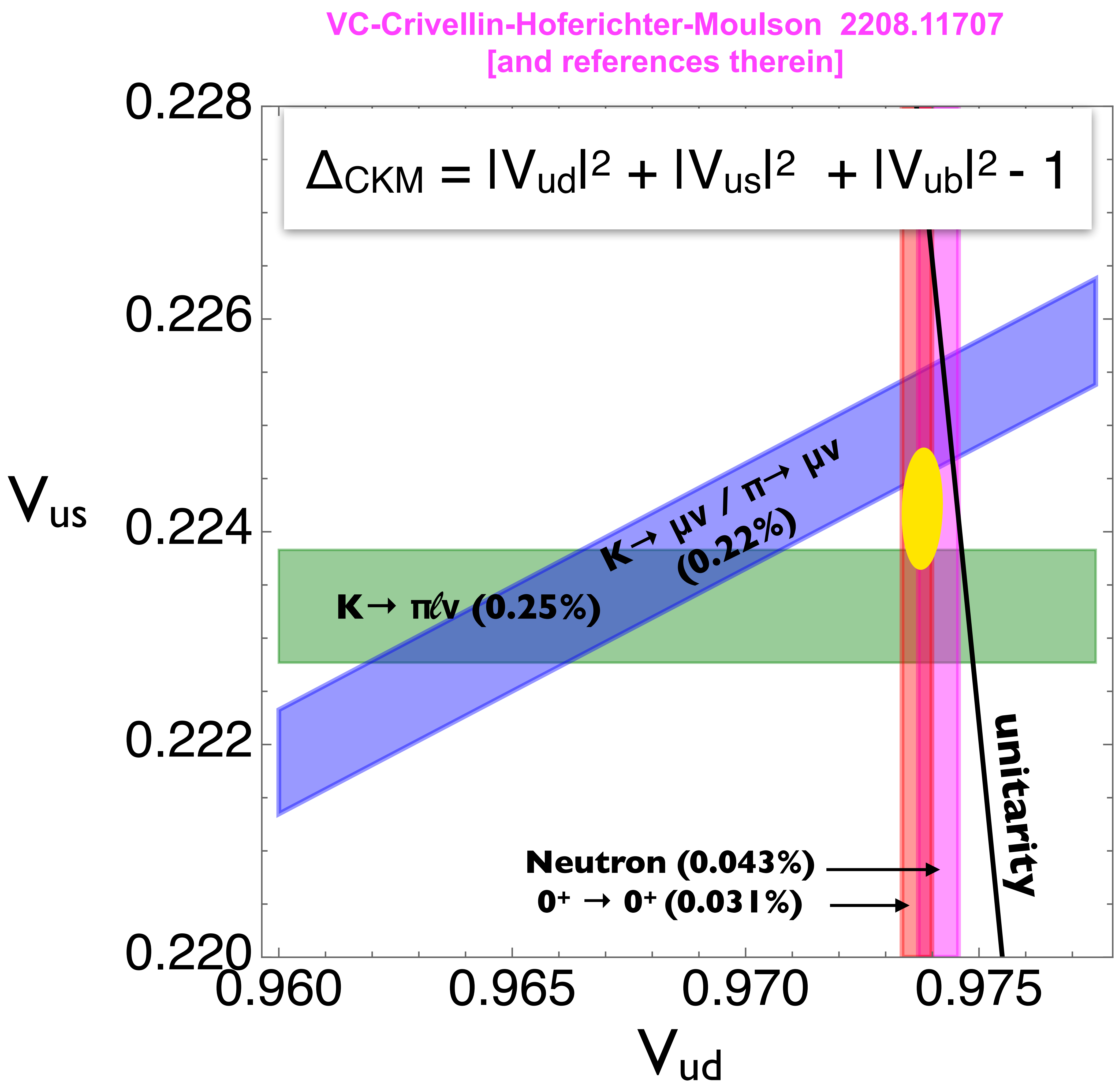
Convert V_{ud} to V_{us} via unitarity



	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
$n \to pe\nu$	0.8% (1.7%) (PDG)	EXP
$0^+ \to 0^+$	0.6% + ?	TH
K → π l ν	0.24%	EXP + TH
K →μν / π → μν	0.21%	TH

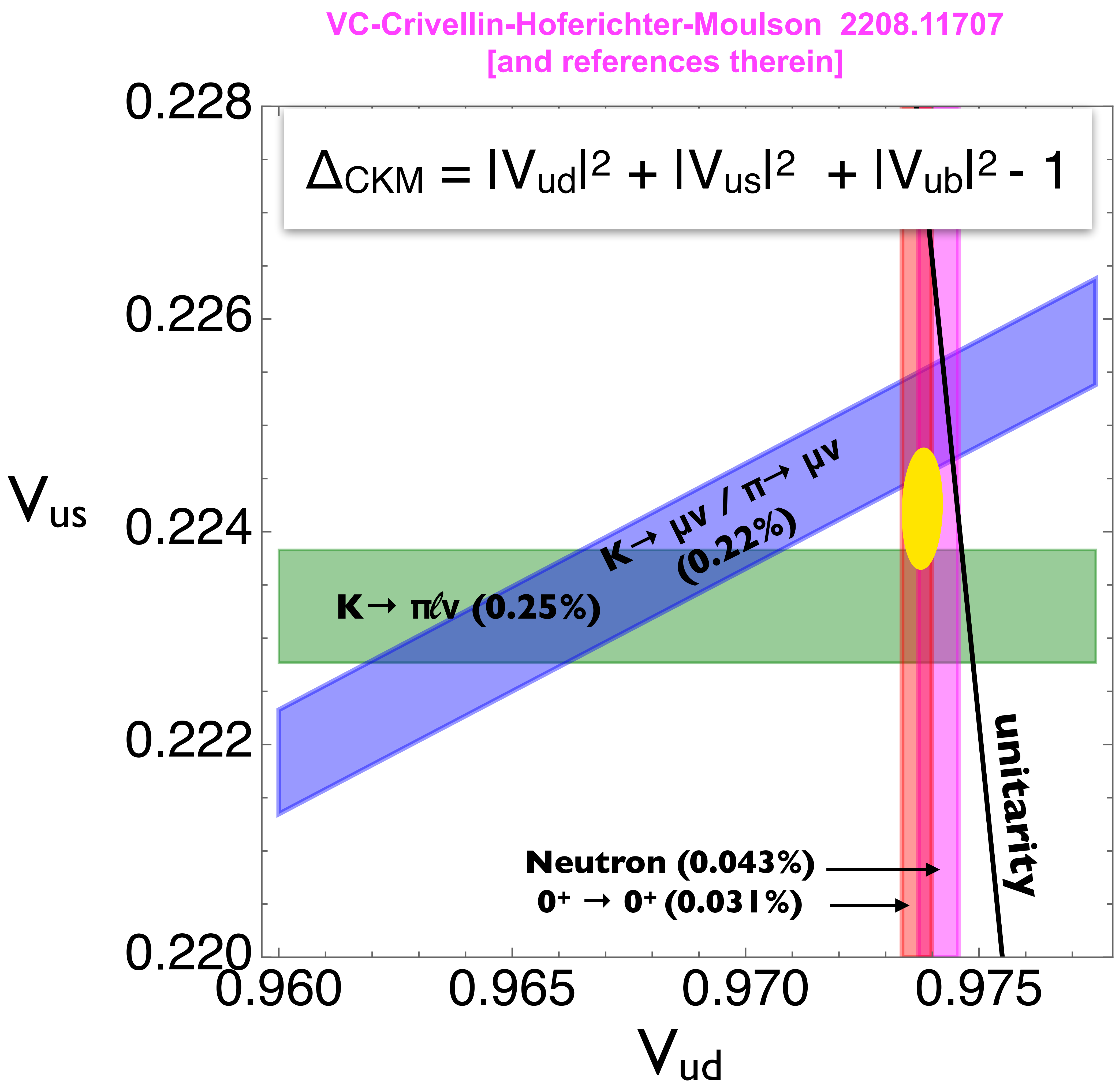
Tension among the most precise determinations

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



- Bands don't intersect in the same region on the unitarity circle
- ~3σ problem even in meson sector (Kl2 vs Kl3)
- ~3σ effect in global fit ($\Delta_{CKM} = -1.48(53) \times 10^{-3}$)

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

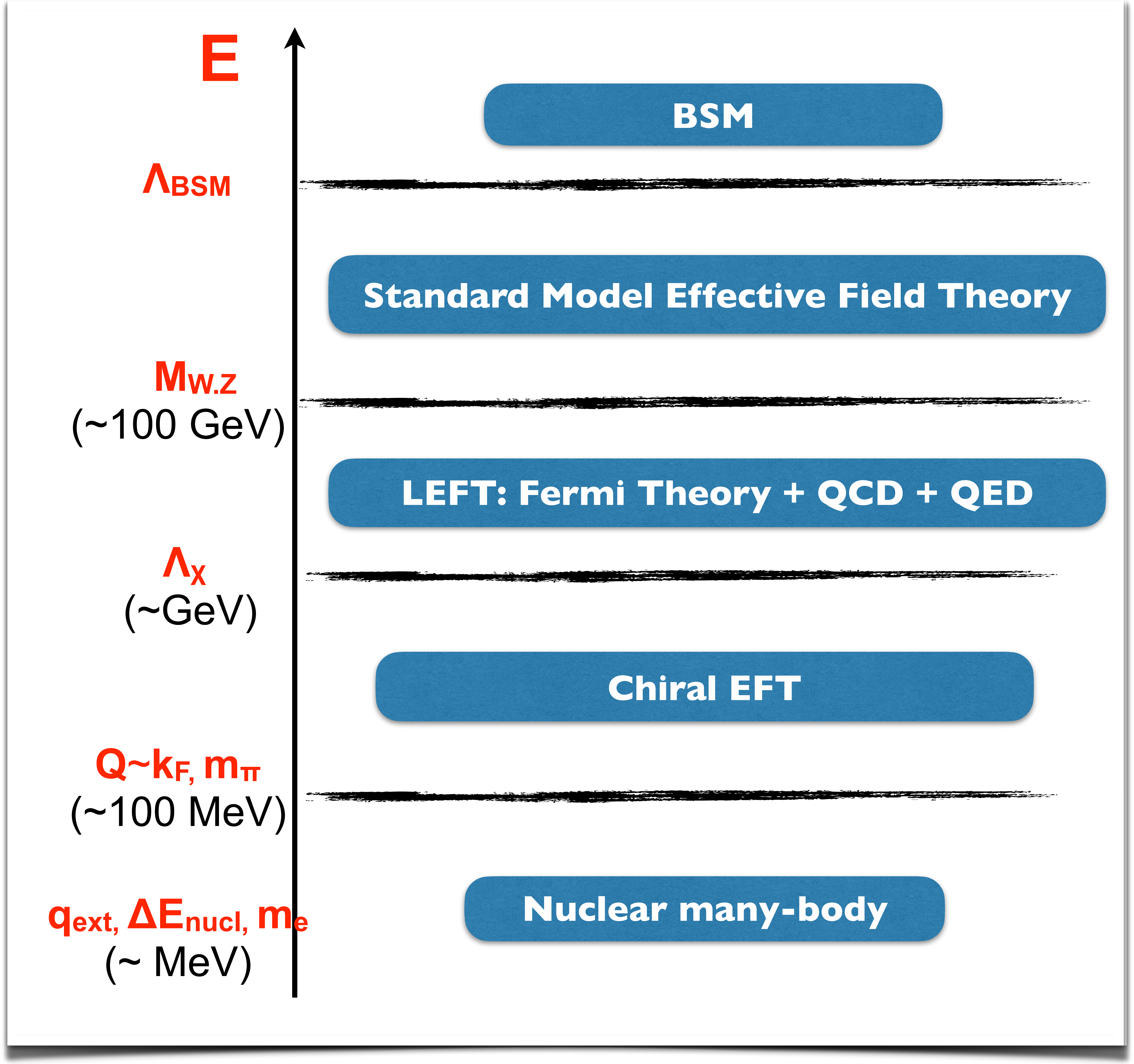


Cabibbo angle anomaly?

- Needed / expected experimental scrutiny:
  - neutron decay (will match nominal nuclear uncertainty)
  - pion beta decay (6x to 10x at PIONEER phases II, III)
  - new $K_{\mu 3}/K_{\mu 2}$ BR measurement at NA62
- Theoretical scrutiny:
  - Standard Model predictions with few $\times 10^{-4}$ precision!
  - Study possible BSM explanations that survive the constraints from other precision tests and the LHC

EFTs for β decays: from BSM to nuclei

Widely separated scales: $\Lambda_{BSM} \gg M_W \gg \Lambda_\chi \gg Q \sim k_F \sim m_\pi \gg m_e \sim q_{ext}$ ⇒ tower of EFTs



Single hadron (n or π)

VC, J. de Vries, L. Hayen, E. Mereghetti, A. Walker-Loud 2202.10439
VC, W. Dekens, E. Mereghetti, O. Tomalak, 2306. 03138
Cao, Hill. Plestid, Vander Griend 2501.17916, 2508.05741
M. Gorbahn, F. Moretti, S. Jaeger 2510.27648
VC, M. Hoferichter, N. Valori, 2602. 11253

Multi nucleons

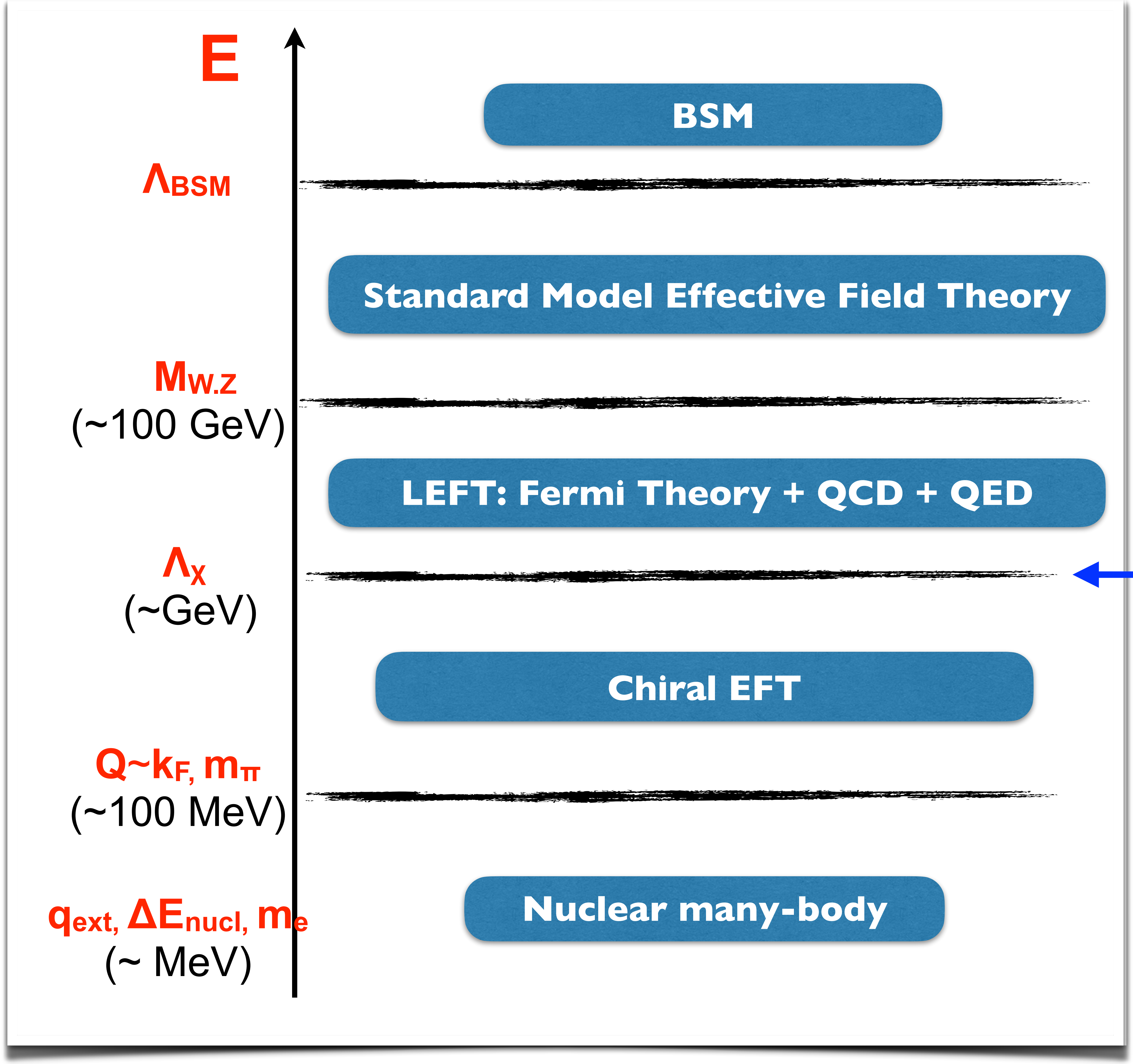
VC, W. Dekens,, J.de Vries, S. Gandolfi, M. Hoferichter, E, Mereghetti,
2405.18469 & 2405.18464

Point-like nucleus

K. Borah, R. Hill, R. Plestid, 2309.07343, 2309.15929, 2402.13307
Cao, Hill, Plestid, Vander Griend 2511.05446

EFTs for β decays: from BSM to nuclei

Widely separated scales: $\Lambda_{BSM} \gg M_W \gg \Lambda_\chi \gg Q \sim k_F \sim m_\pi \gg m_e \sim q_{ext}$ ⇒ tower of EFTs



The EFT expands amplitudes in ε's and sums large logarithms ~ $\alpha^{n+m} (\ln(\varepsilon))^n$

Non-perturbative input from Lattice QCD and dispersive methods

$\varepsilon_{SMEFT} = (m_W/\Lambda_{BSM})^2$

$\varepsilon_W = (\Lambda_\chi/m_W)^2$

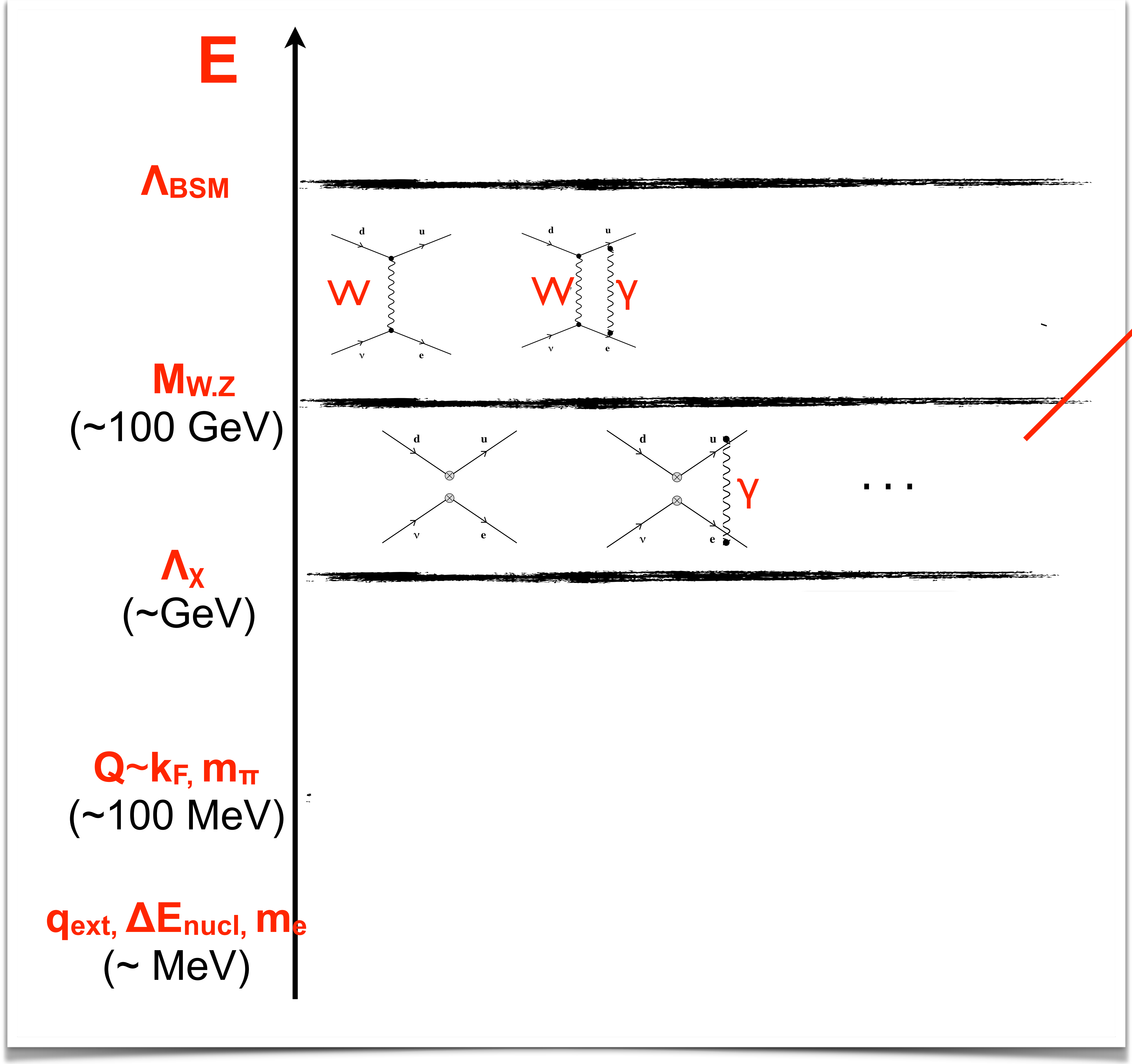
$\varepsilon_\chi = Q/\Lambda_\chi$

$\epsilon_{\not\pi} = q_{\rm ext}/m_\pi$

$\epsilon_{\rm recoil} = q_{\rm ext}/\Lambda_\chi$

Improving the SM prediction

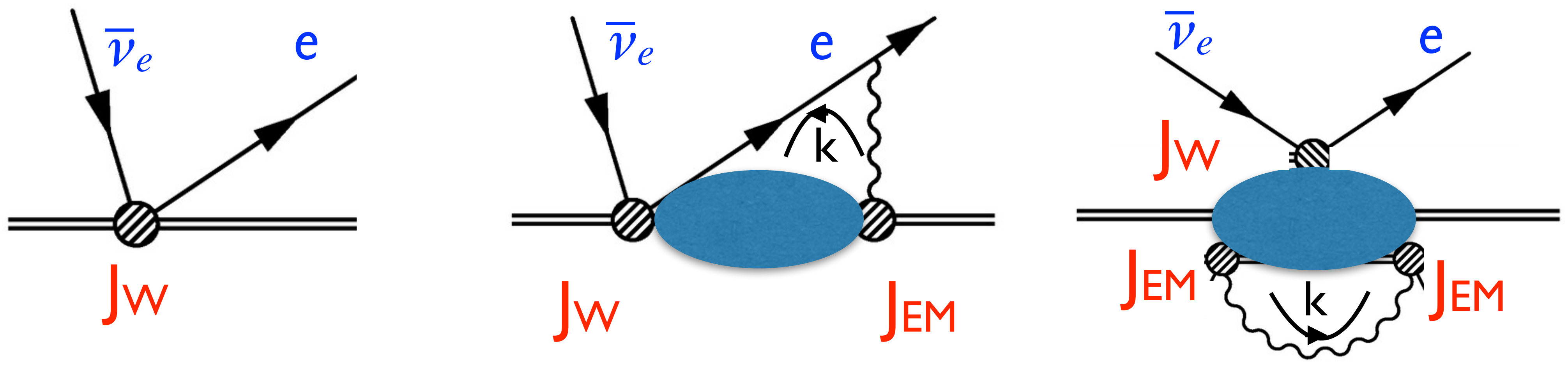
Widely separated scales: Λ_{BSM} >> M_W >> Λ_χ >> Q ~ k_F ~ m_π >> m_e ~ q_{ext} ⇒ tower of EFTs



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

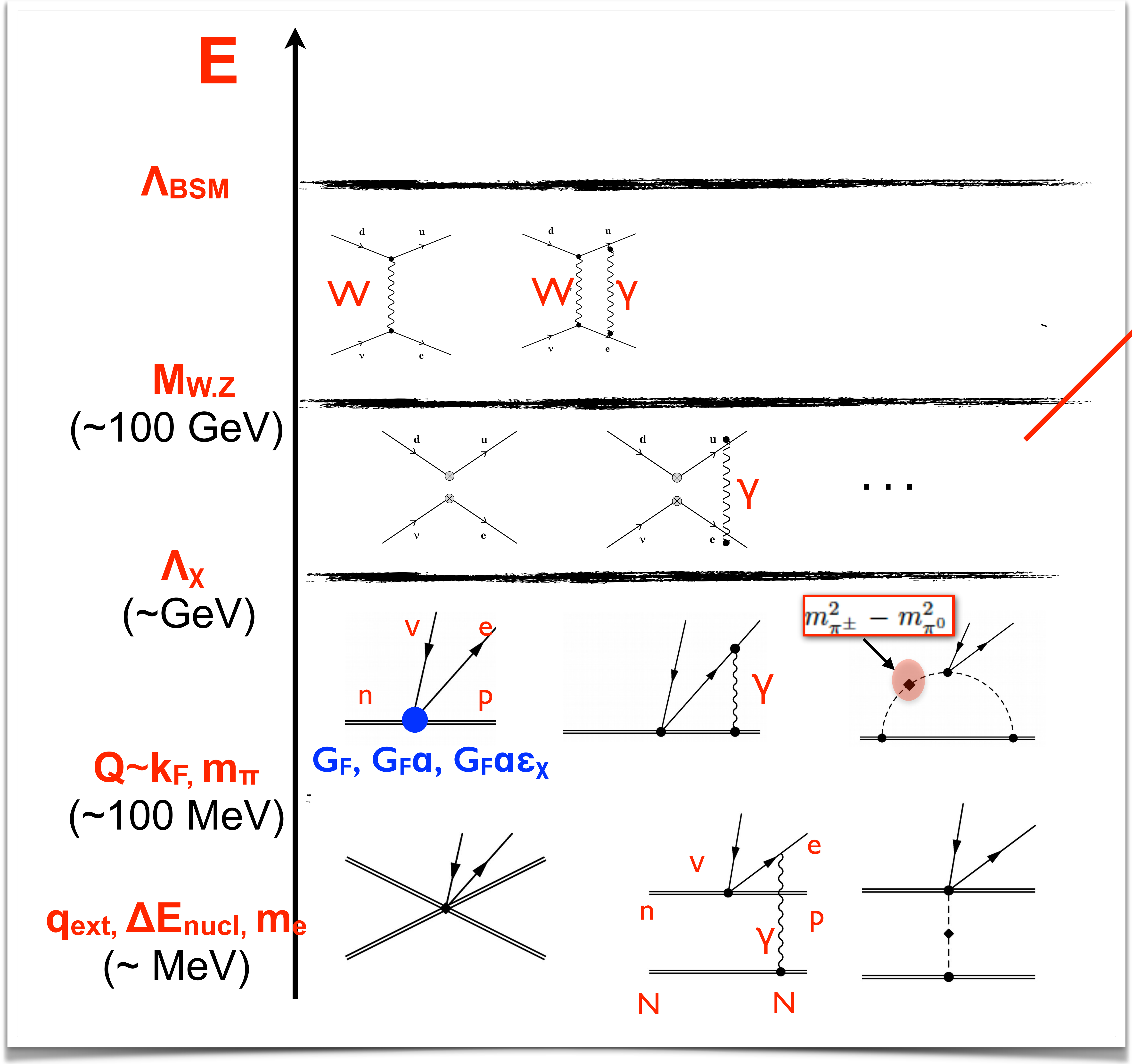
Matrix elements to O(α)

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



Improving the SM prediction

Widely separated scales: Λ_{BSM} >> M_W >> Λ_χ >> $Q \sim k_F \sim m_\pi$ >> $m_e \sim q_{ext}$ $\Rightarrow$ tower of EFTs



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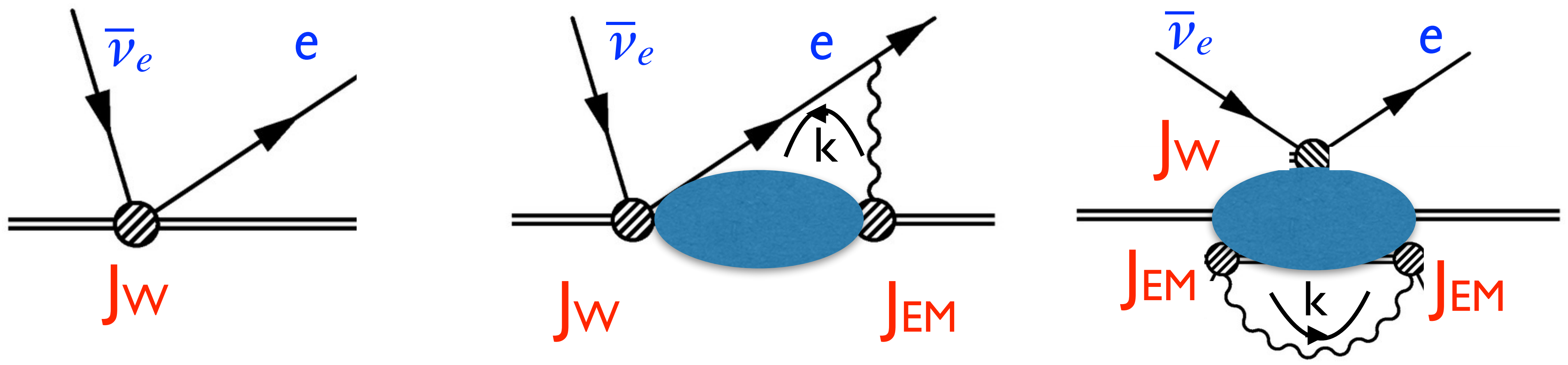
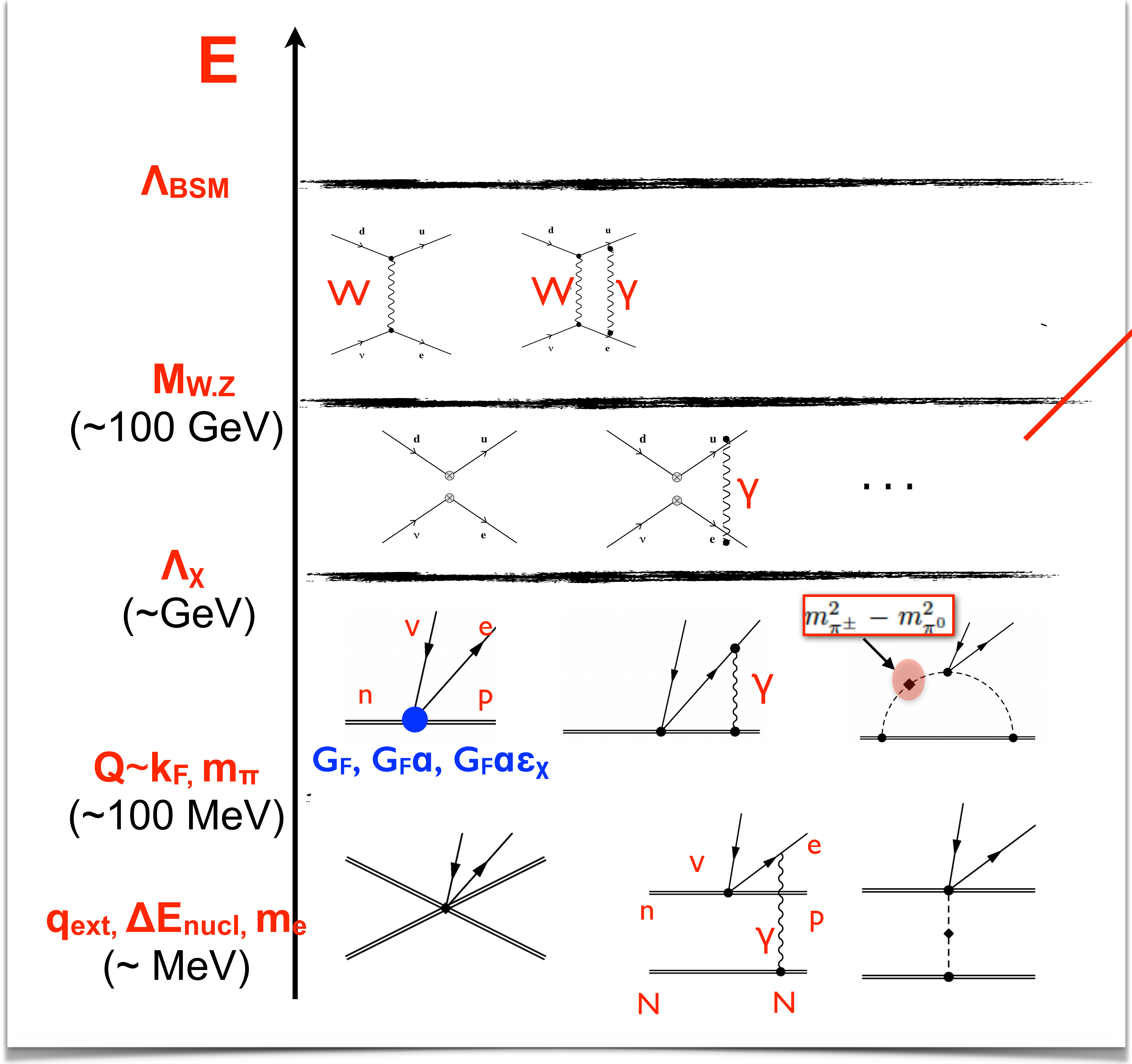


Contributions from photons of all virtualities — EFT captures them all

Hard: $(k^0, |\mathbf{k}|) > \Lambda_\chi \sim m_N \sim$ GeV
Soft: $(k^0, |\mathbf{k}|) \sim Q \sim k_F \sim m_\pi$
Potential: $(k^0, |\mathbf{k}|) \sim (Q^2/m_N,\ Q)$
Ultrasoft $(k^0, |\mathbf{k}|) \sim Q^2/m_N << k_F$

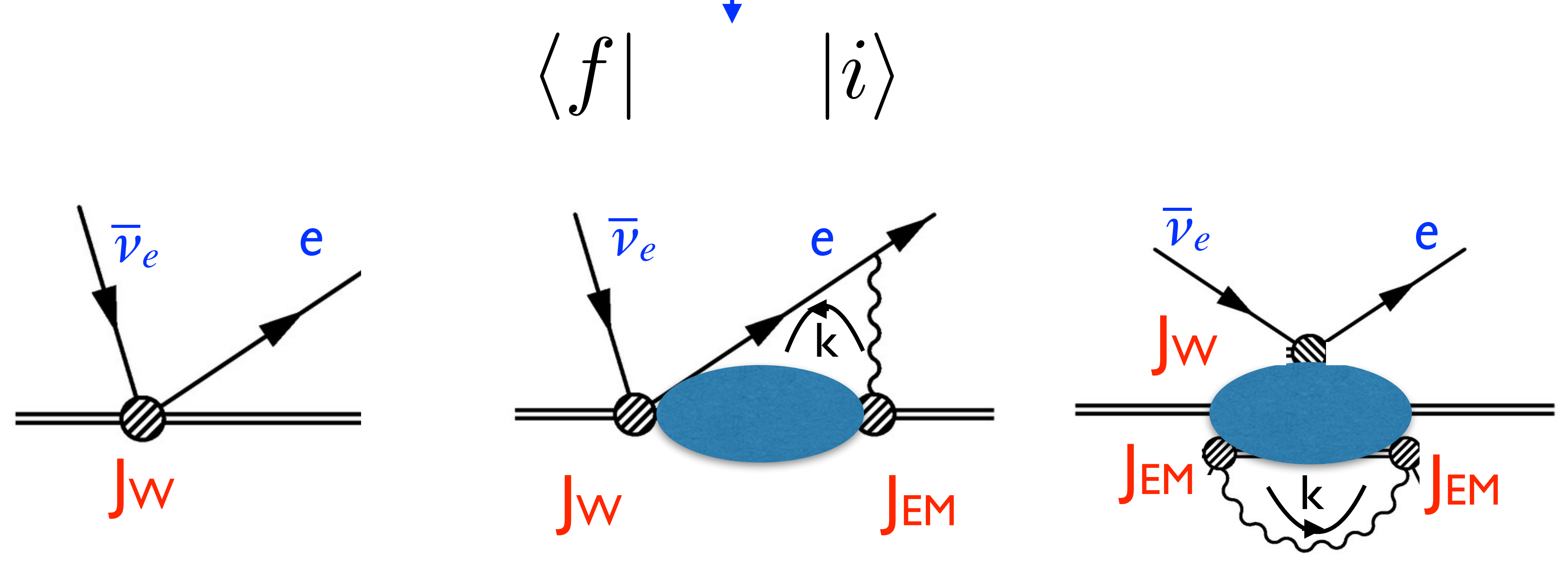
Improving the SM prediction

Widely separated scales: Λ_{BSM} >> M_W >> Λ_χ >> Q ~ k_F ~ m_π >> m_e ~ q_{ext} ⇒ tower of EFTs

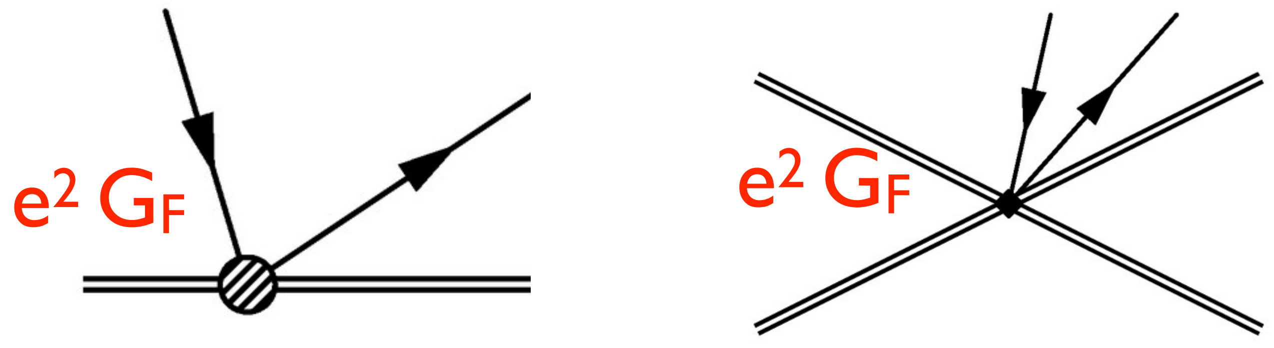


$$\mathcal{L}_{\rm Fermi} = -\frac{G_F}{\sqrt{2}} V_{ud}\ C_\beta(\mu)\ \bar{\ell}\gamma_\alpha(1-\gamma_5)\nu_\ell\,\bar{u}\gamma^\alpha(1-\gamma_5)d + \ldots$$

Matrix elements to O(α)

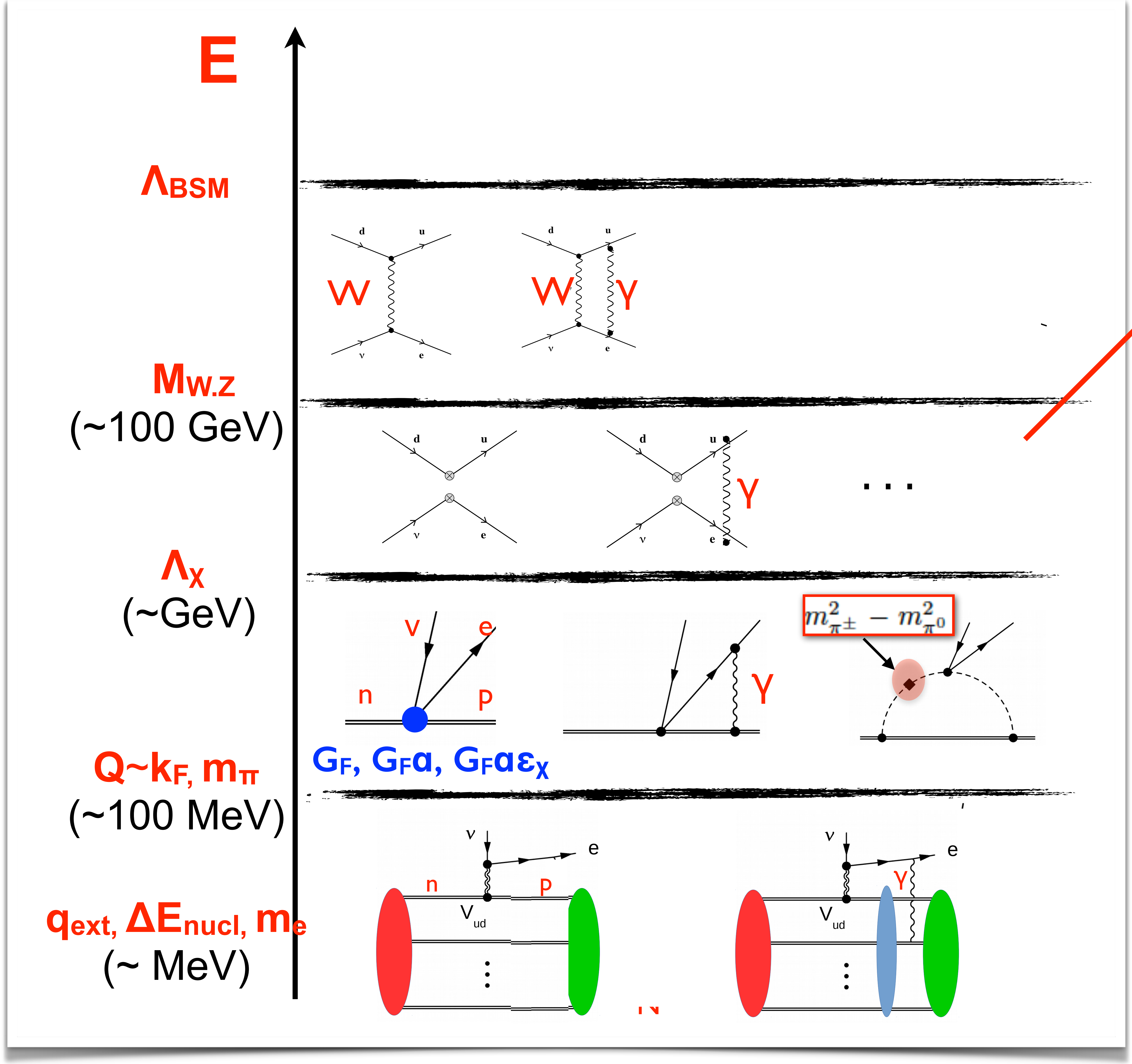


In particular, hard photons [(k^0, |**k**|) >~ Λ_χ ~ m_N ~ GeV] leave behind local interactions at low energy



Improving the SM prediction

Widely separated scales: Λ_{BSM} >> M_W >> Λ_χ >> Q ~ k_F ~ m_π >> m_e ~ q_{ext} ⇒ tower of EFTs



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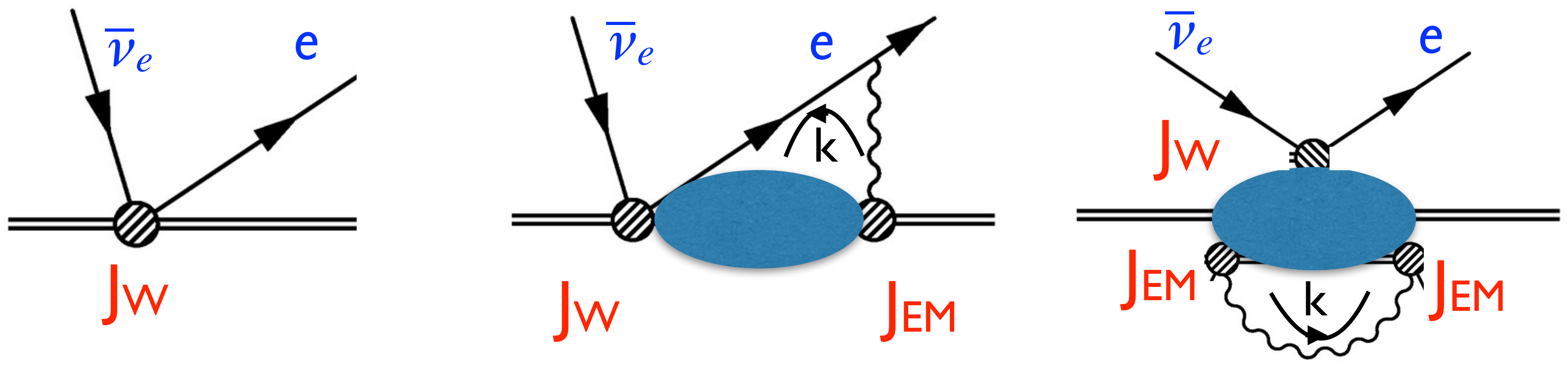

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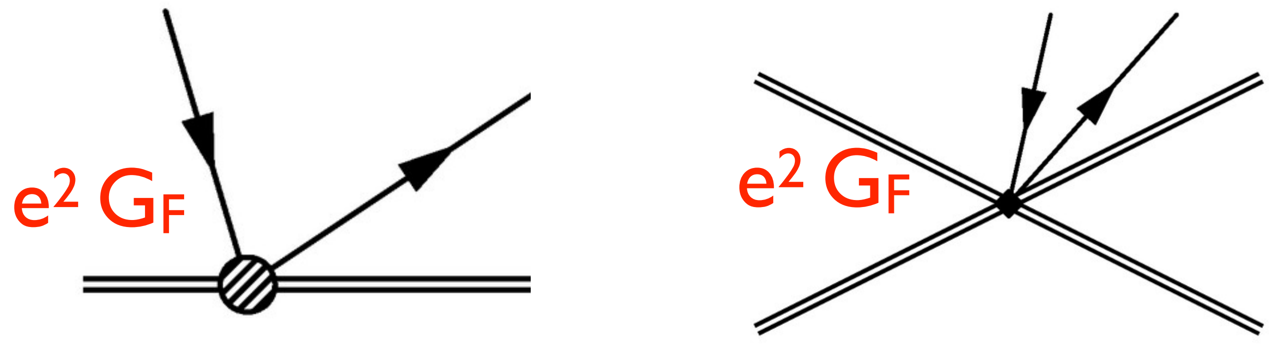
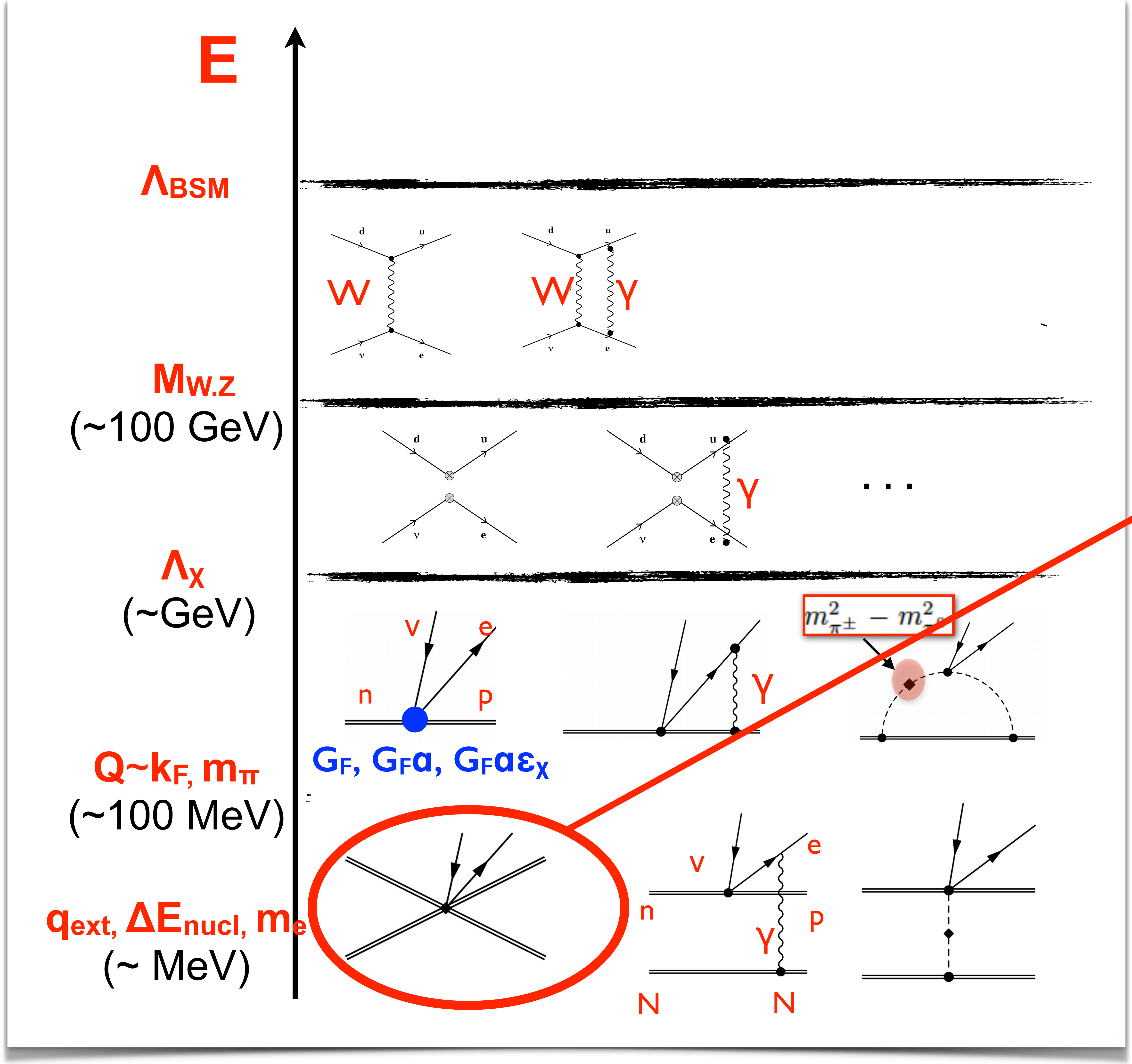


Improving the SM prediction

Widely separated scales: Λ_{BSM} >> M_W >> Λ_χ >> Q ~ k_F ~ m_π >> m_e ~ q_{ext} $\Rightarrow$ tower of EFTs



Multi nucleon

Hard photons induce NN → NNeν contacts $\Rightarrow$

$$\mathcal{L}_W^{2b} = -\sqrt{2}e^2 G_F V_{ud}\, \bar{e}_L \gamma_0 \nu_L \times$$

$$N^\dagger \tau^+ N \,\left(e^2 g_{V1}^{NN}\, N^\dagger N + e^2 g_{V2}^{NN}\, N^\dagger \tau^3 N\right)$$

Renormalization $\Rightarrow$ $g^{NN}_{V1,V2} \sim \frac{1}{F_\pi^2 \Lambda_\chi}$

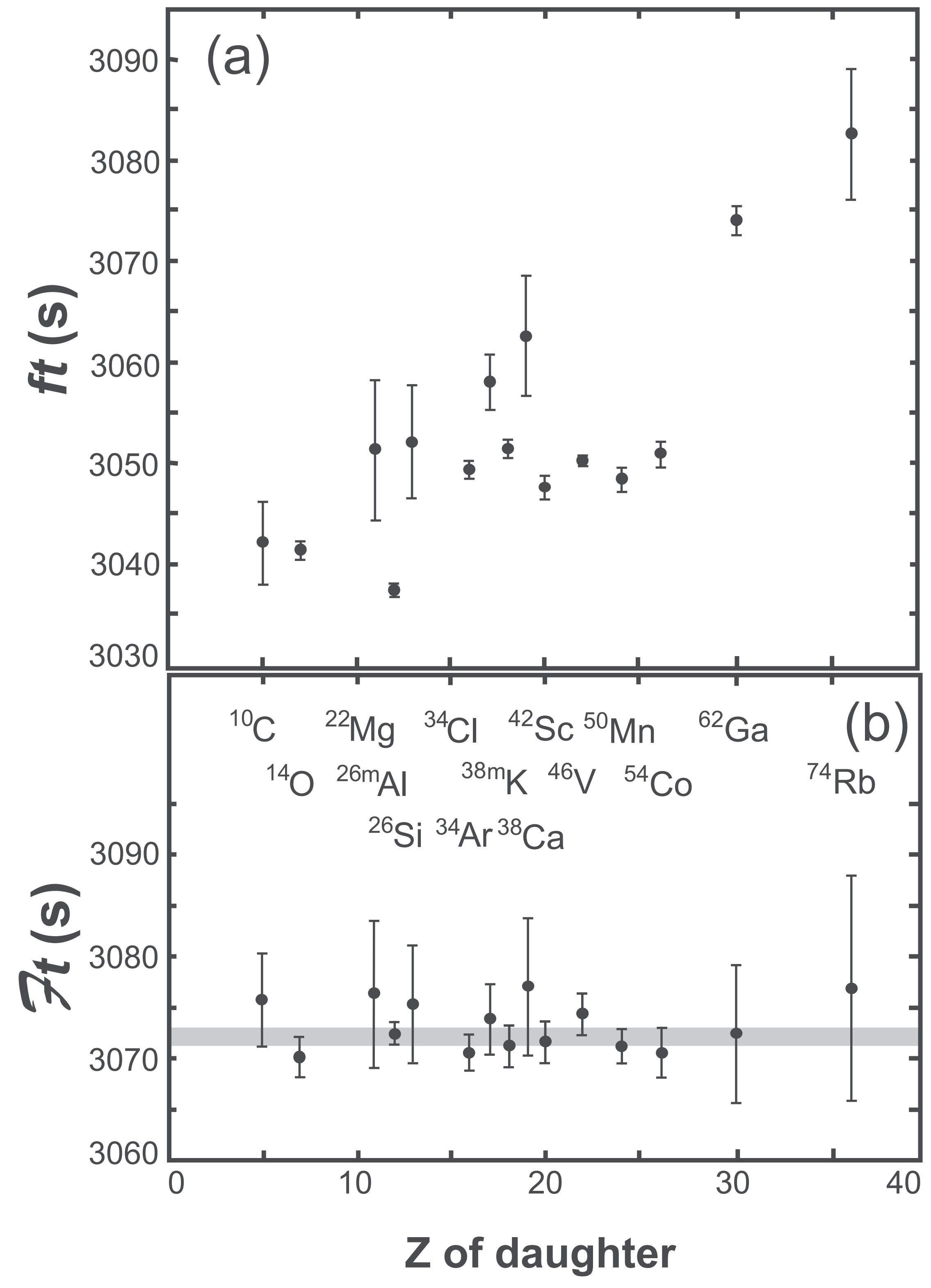
Two body potentials of O($G_F\alpha\varepsilon_\chi$) *involves two* currently unknown LECs!

Impact on V_{ud} and path forward

VC, W. Dekens,, J.de Vries, S. Gandolfi, M. Hoferichter, E, Mereghetti, 2405.18469, 2405.18464

- EFT has led to reduced uncertainties in the neutron and pion decay rate

Hardy-Towner, PRC 2020



- For nuclear decay, the EFT has identified new short-range corrections and (temporarily) increased the uncertainty

- Exploratory study in $^{14}O \to {}^{14}N$ decay (with QMC) ⇒

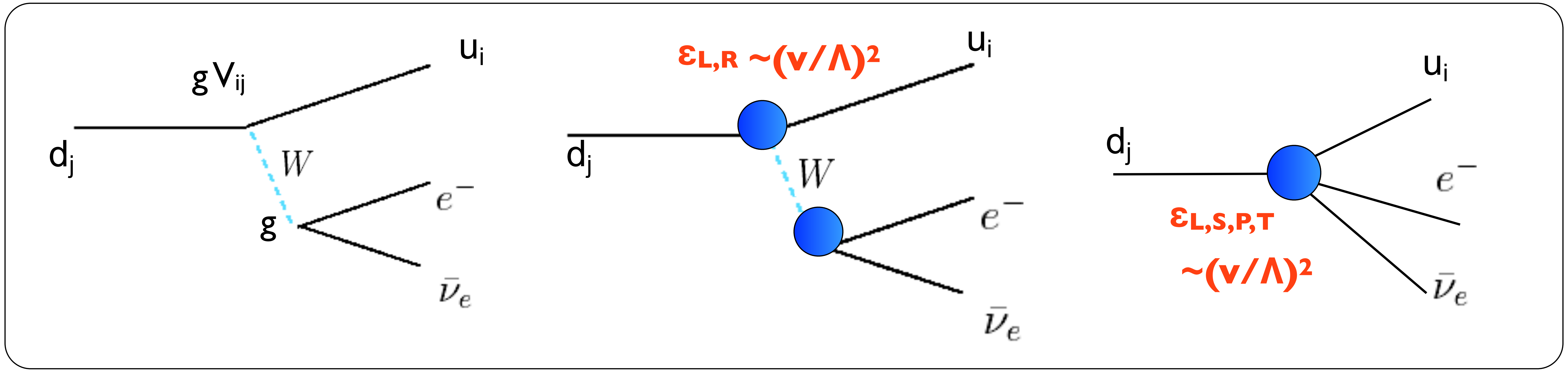
  δV_{ud} (nuclear structure) ~ $0.00031_{\text{models}} \to 0.00052_{\text{EFT+QMC}}$

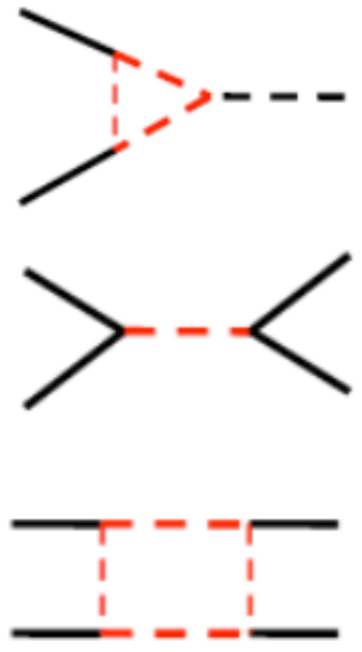
- LECs can be obtained by
  - Fitting data (along with V_{ud} and possibly BSM effective couplings) once NME calculations for several isotopes become available
  - Theory: dispersive analysis, Lattice QCD

Implications for new physics

Despite all the caveats, it is interesting to look at what we might learn if the `Cabibbo Anomaly' survives!

Implications for new physics





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

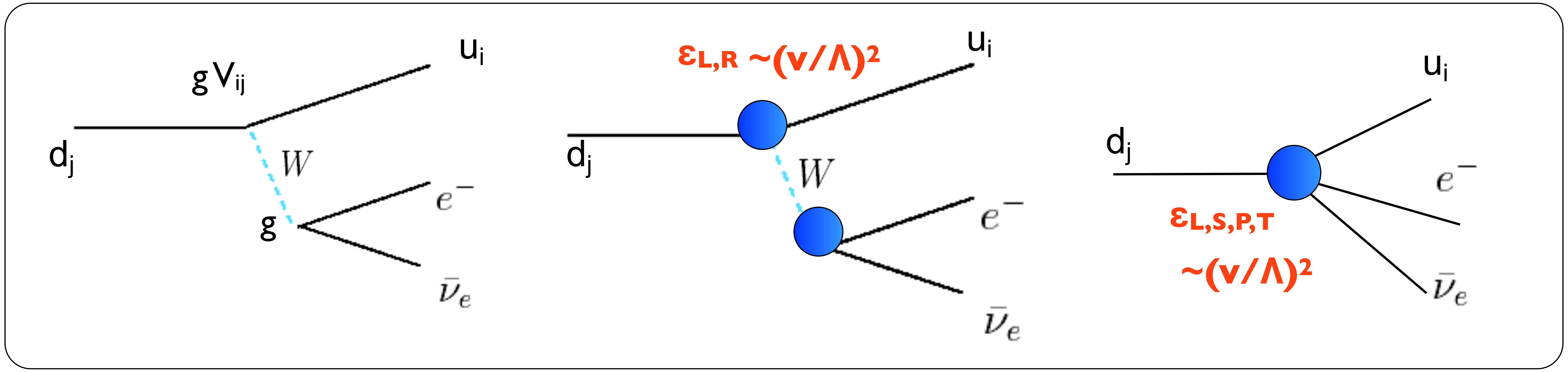
E ~ GeV ↓

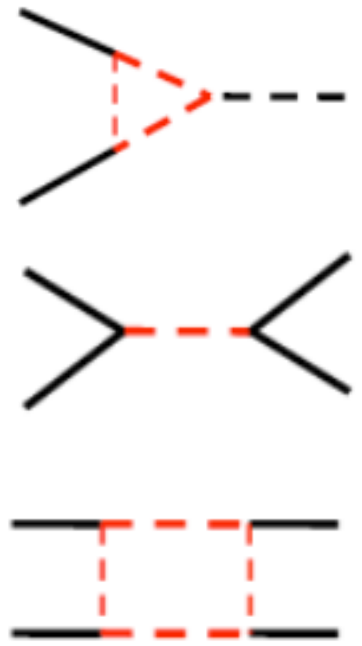
$$\mathcal{L}_{\rm SM} - \frac{G_F V_{ud_j}}{\sqrt{2}} \sum_{\Gamma} \left[\epsilon_{\Gamma}^{(j)}\ \bar{\ell}\Gamma\nu_L \cdot \bar{u}\Gamma d_j \ + \ \tilde{\epsilon}_{\Gamma}^{(j)}\ \bar{\ell}\Gamma\nu_R \cdot \bar{u}\Gamma d \right]$$

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

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

Implications for new physics





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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'

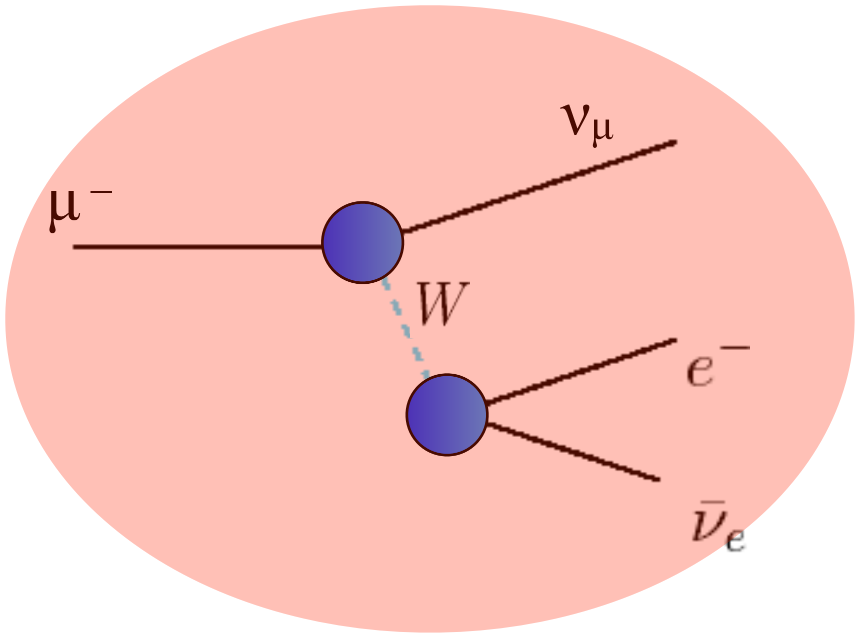
GeV-scale effective Lagrangian

VC, Gonzalez-Alonso, Jenkins 0908.1754, NPB

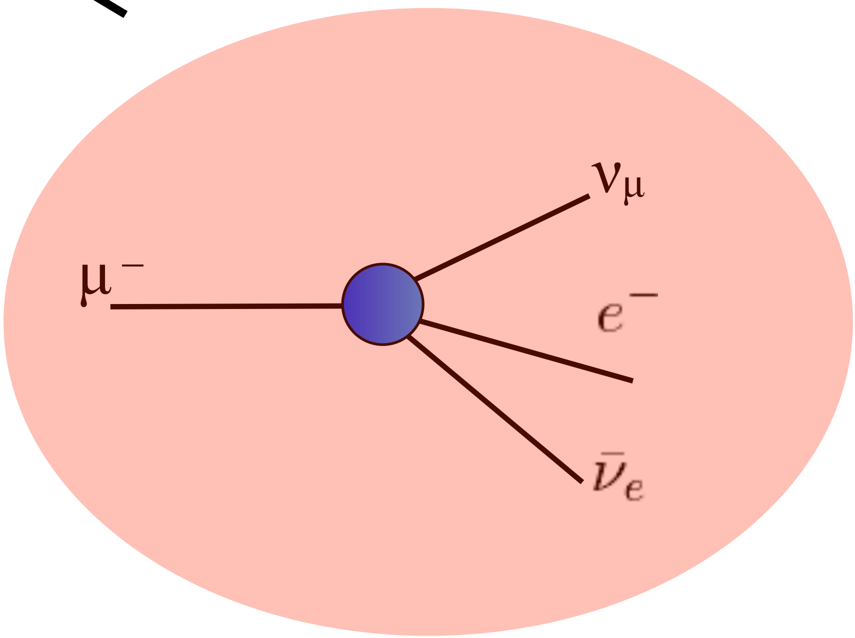
VC, Graesser, Gonzalez-Alonso 1210.4553, JHEP

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

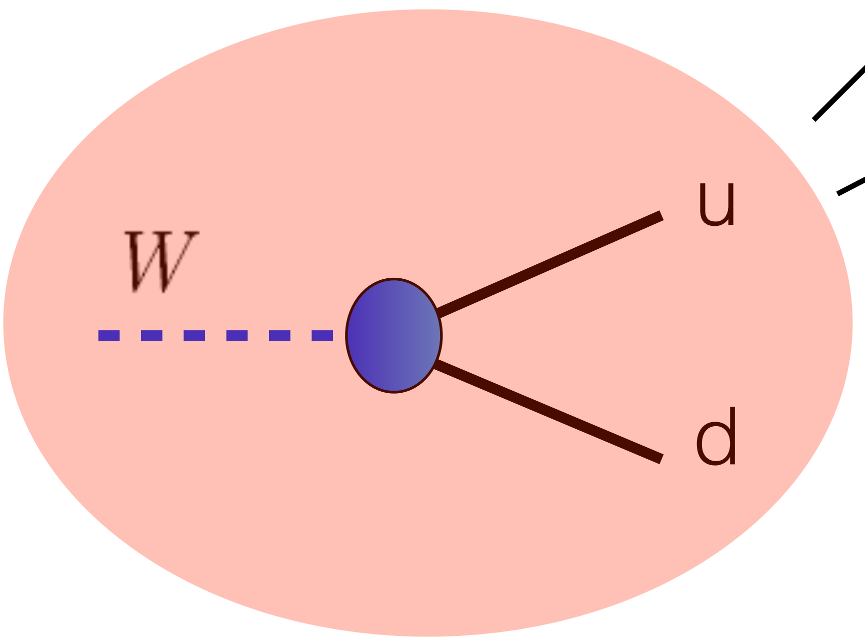
VC, Graesser, Gonzalez-Alonso 1210.4553, JHEP

Leptonic interactions

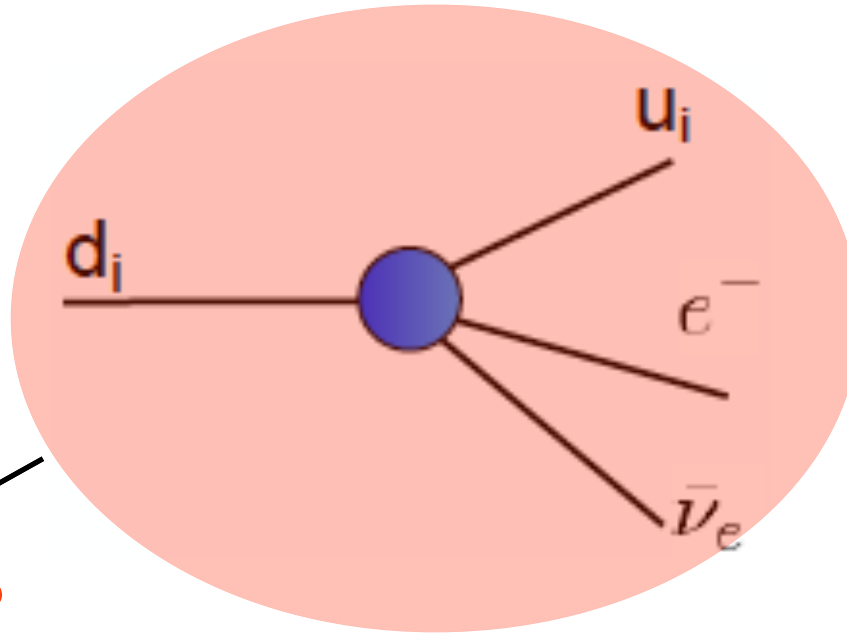
$$\mathcal{L}_{CC}^{(\mu)} = -\frac{G_F^{(0)}}{\sqrt{2}} \left(1 + \epsilon_L^{(\mu)}\right) \bar{e}\gamma^\rho(1-\gamma_5)\nu_e \cdot \bar{\nu}_\mu \gamma_\rho (1-\gamma_5)\mu \ + \ \ldots$$

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

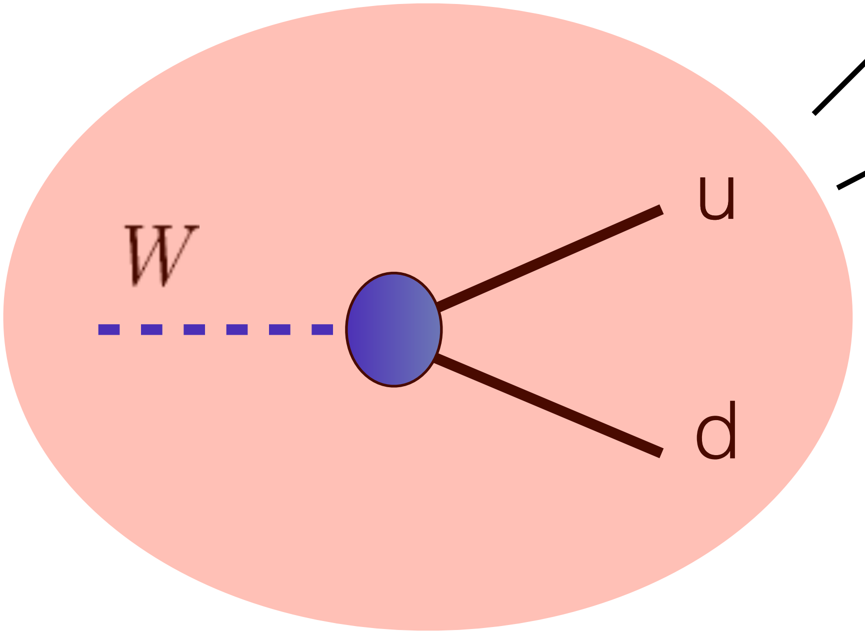
Leptonic interactions

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

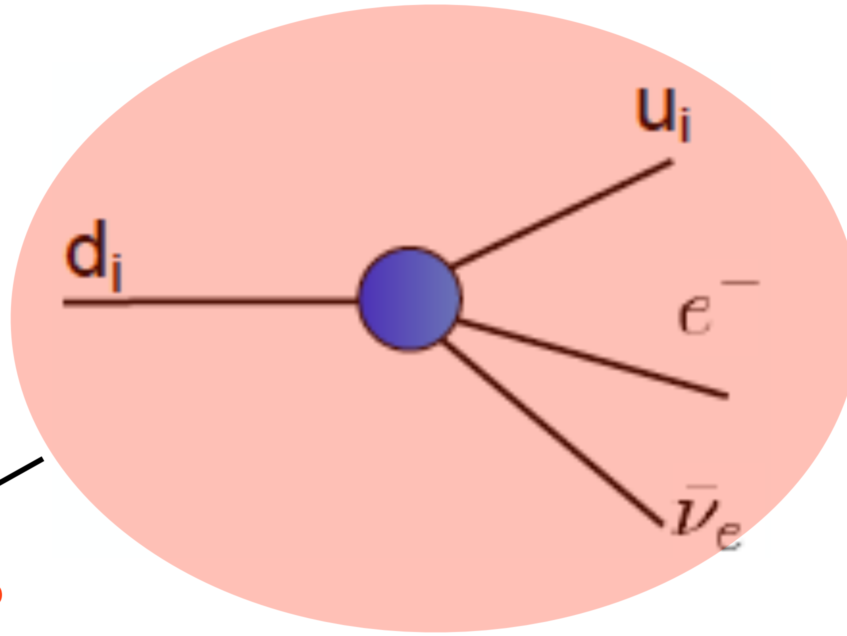
Semi-leptonic interactions

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

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



ε_L ε_R



ε_L ε_S ε_P ε_T

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

Corrections to V_{ud} and V_{us}

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

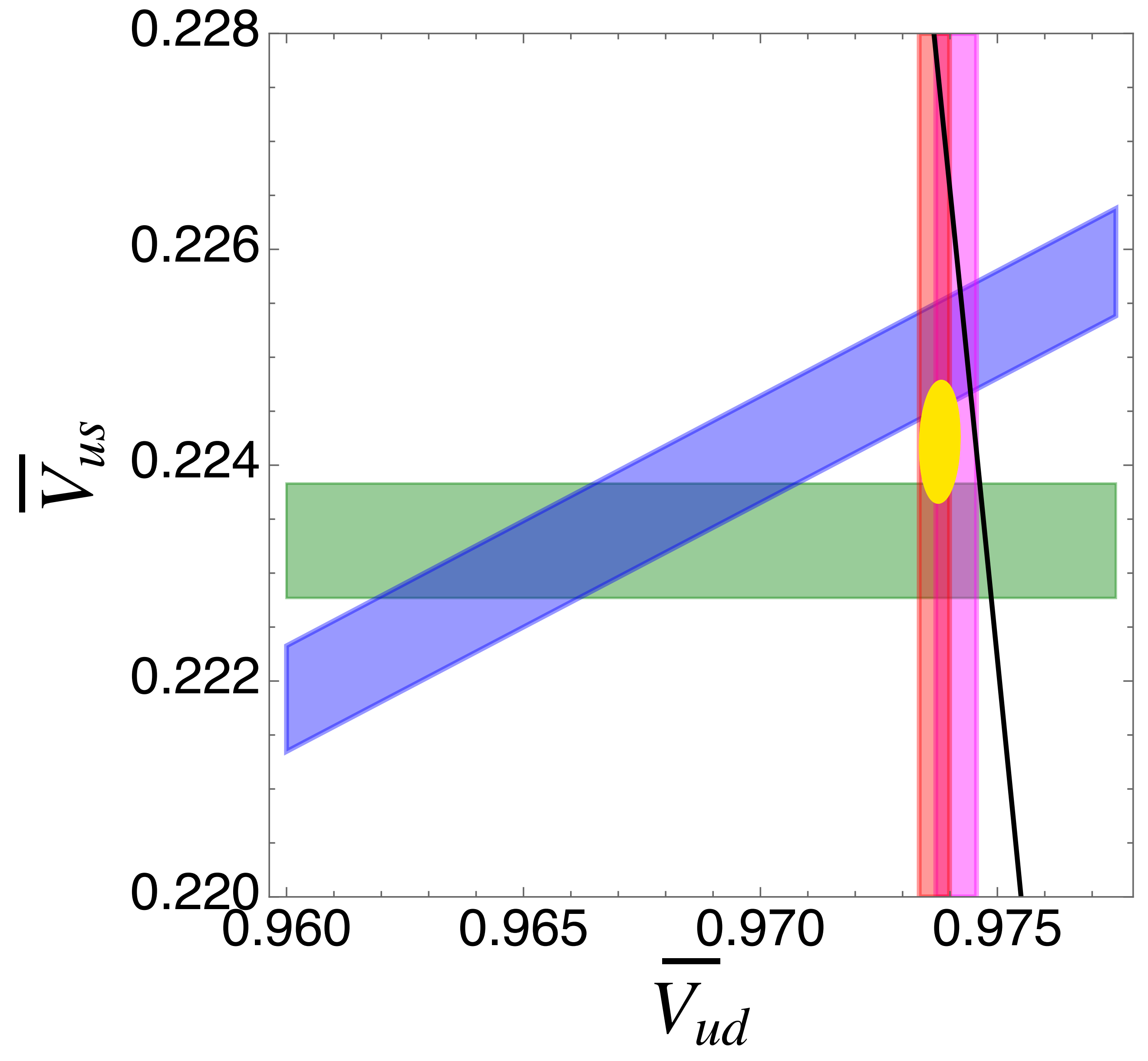
$$|\bar{V}_{us}|_j^2 = |V_{us}|^2 \left(1 + \sum_\alpha C_{j\alpha}\epsilon_\alpha\right)$$

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

Elements of the unitary CKM matrix

Known coefficients

BSM effective coupligs



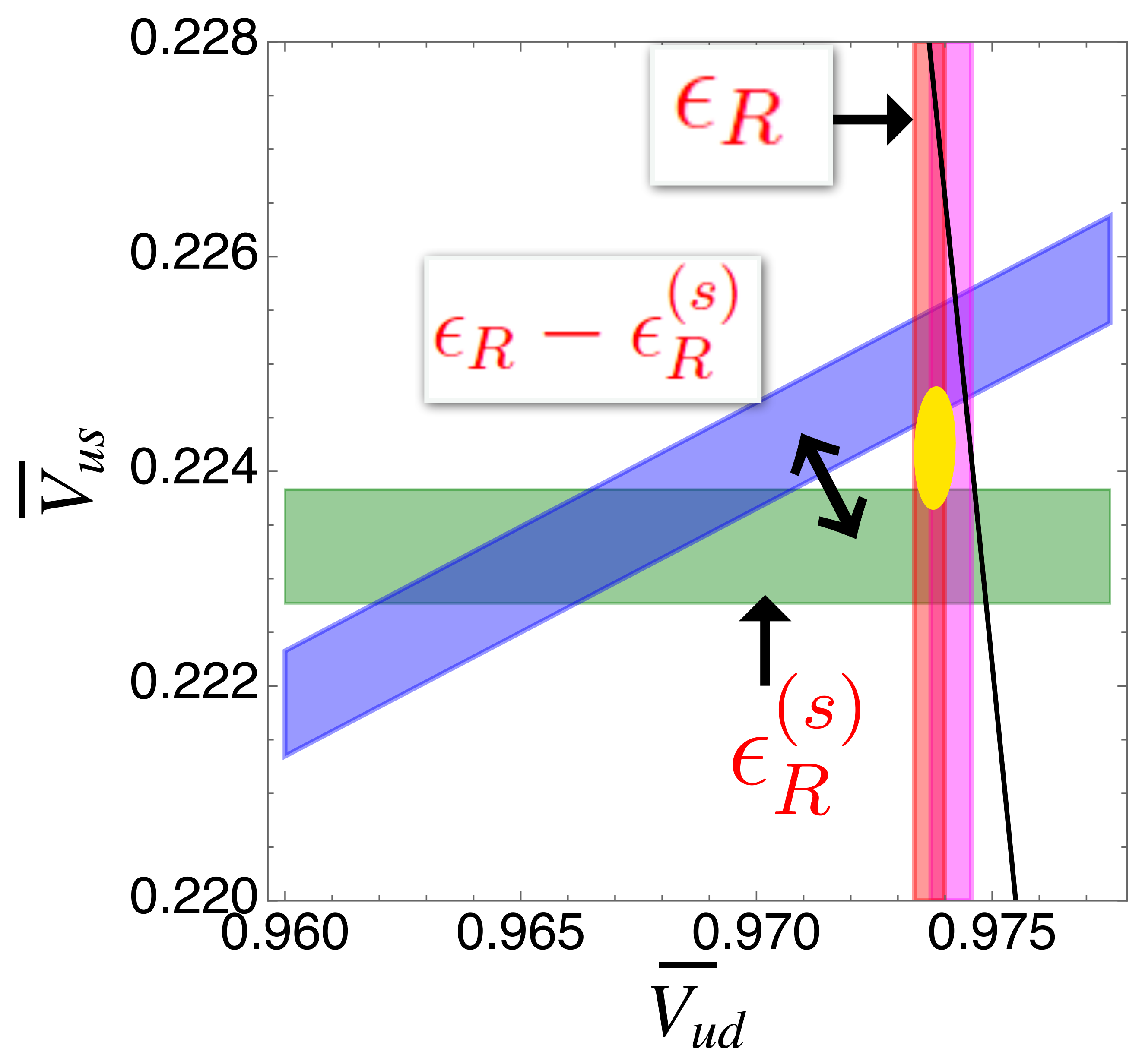
Find set of ε's so that V_{ud} and V_{us} bands meet on the unitarity circle

Corrections to V_{ud} and V_{us}

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

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

- Channel-dependent CKM elements extracted in the 'SM-like analysis'
- Elements of the unitary CKM matrix
- Known coefficients
- BSM effective couplings



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

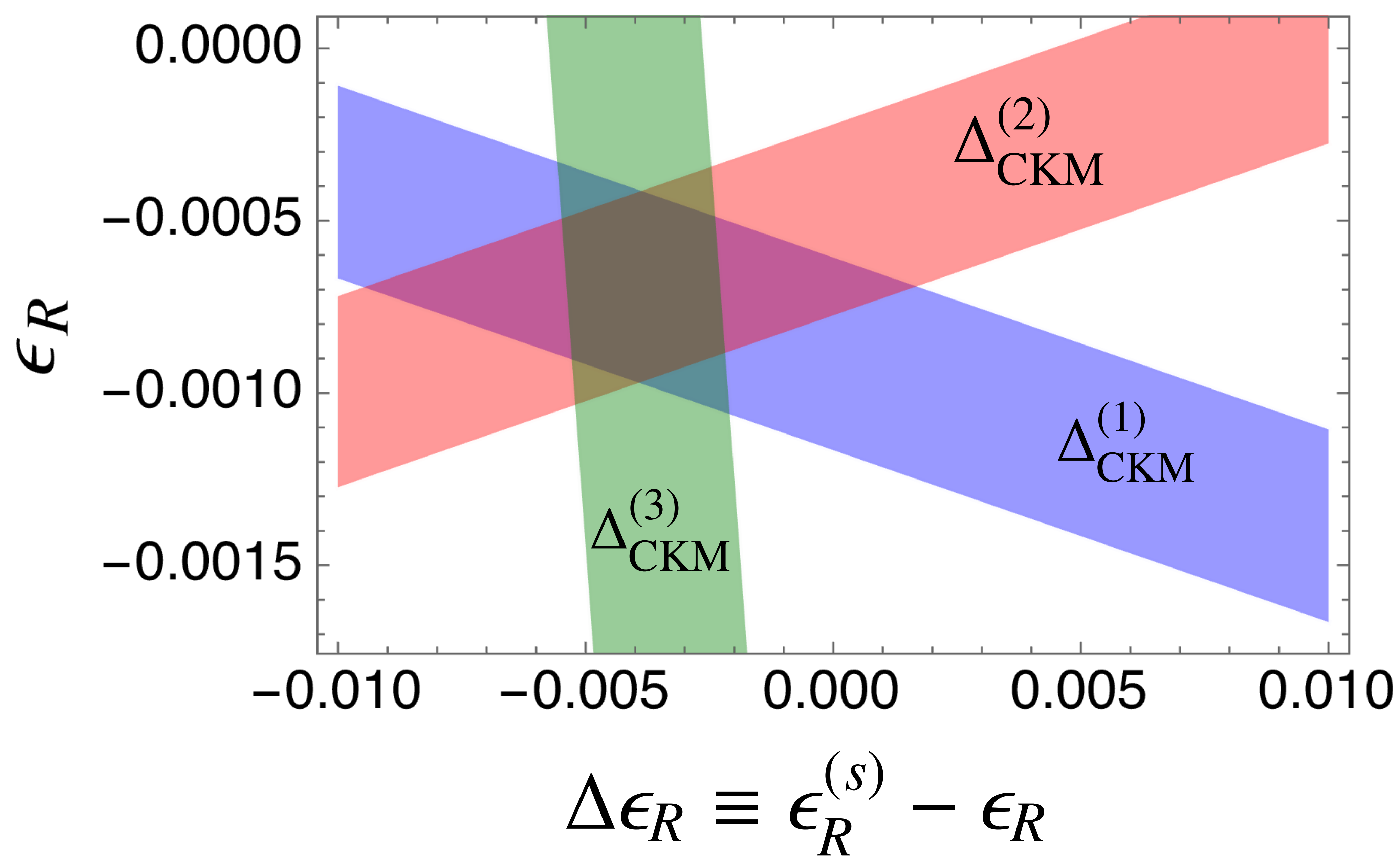
CKM elements from vector (axial) channels are shifted by $1+\varepsilon_R$ $(1-\varepsilon_R)$.

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

Unveiling R-handed quark currents?

VC-Crivellin-Hoferichter-Moulson 2208.11707



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

↓

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

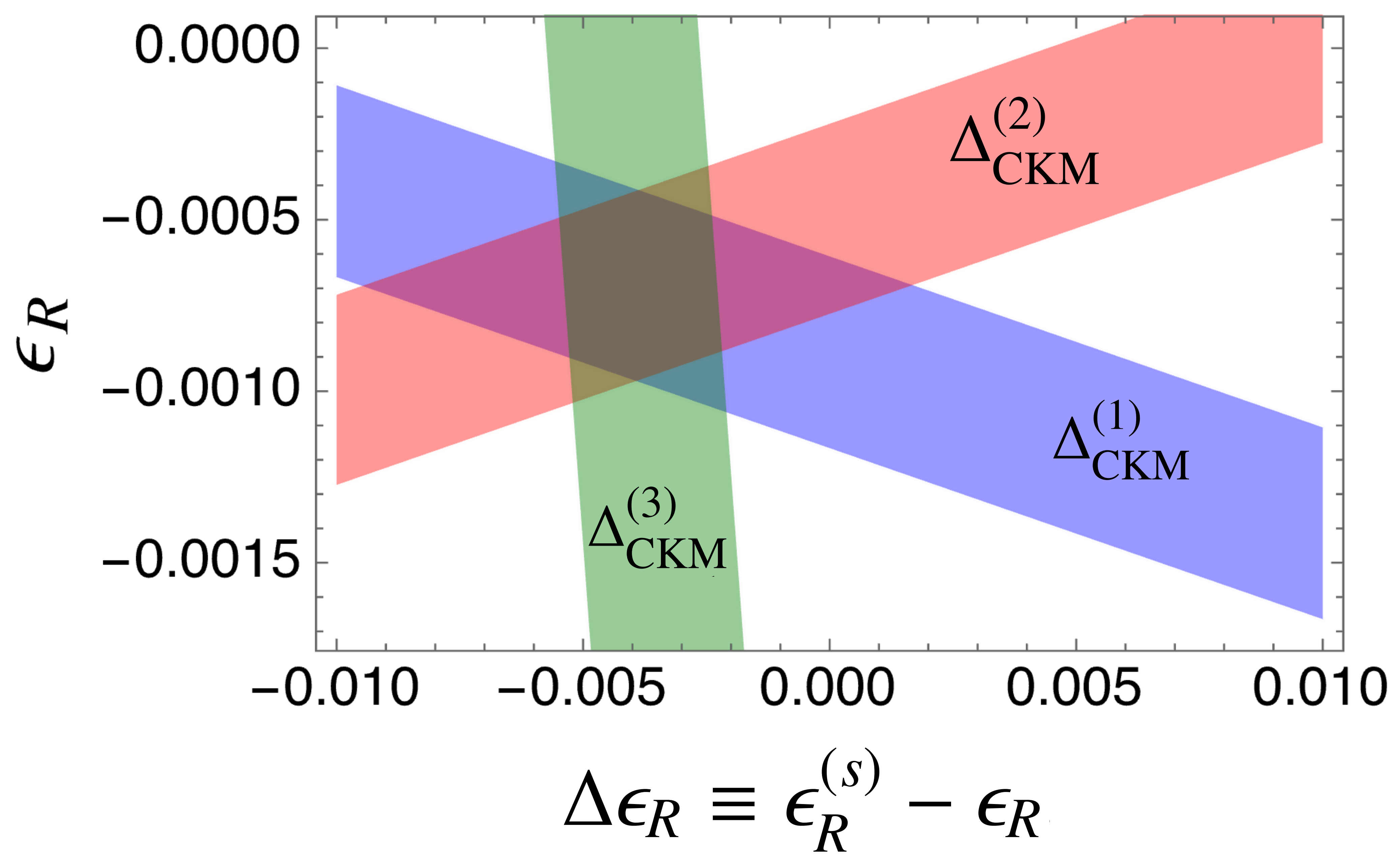
$$\Delta\epsilon_R = -3.9(1.6) \times 10^{-3}$$

Λ_R ~5-10 TeV

- Preferred ranges are not in conflict with constraints from other low-E probes
- Does the R-handed current explanation survive after taking into account high energy data?

Unveiling R-handed quark currents?

VC-Crivellin-Hoferichter-Moulson 2208.11707



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

↓

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

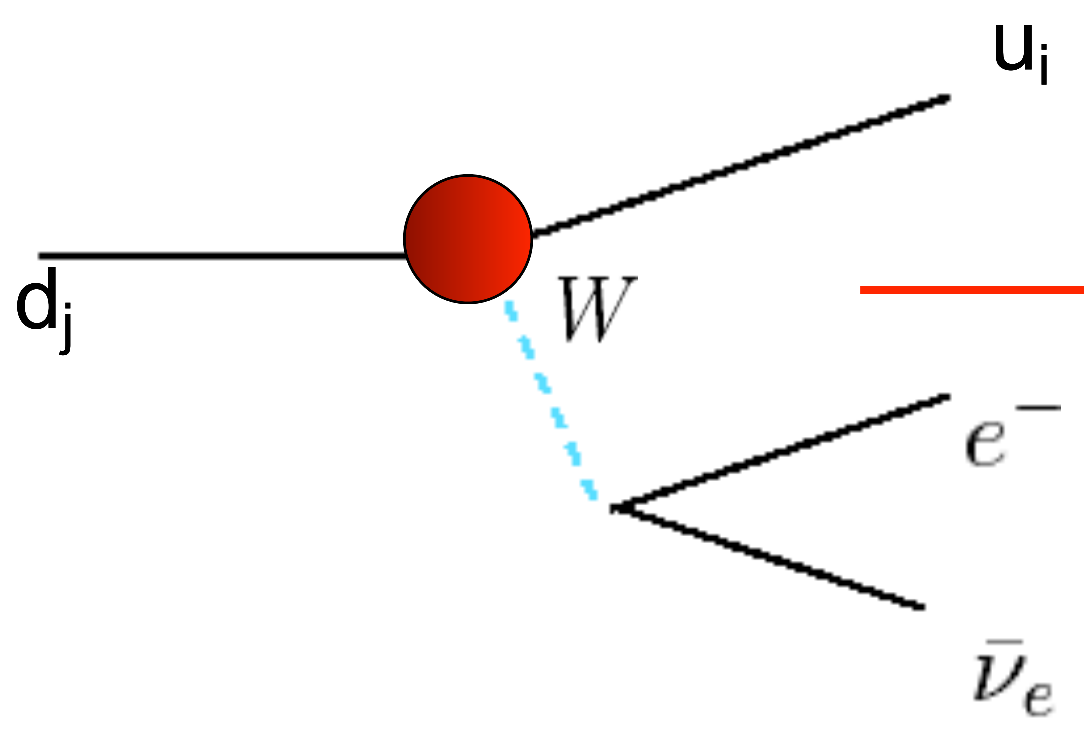
$$\Delta\epsilon_R = -3.9(1.6) \times 10^{-3}$$

Λ_R ~5-10 TeV

- Preferred ranges are not in conflict with constraints from other low-E probes
- Does the R-handed current explanation survive after taking into account high energy data? Yes!

High scale origin of ε_R

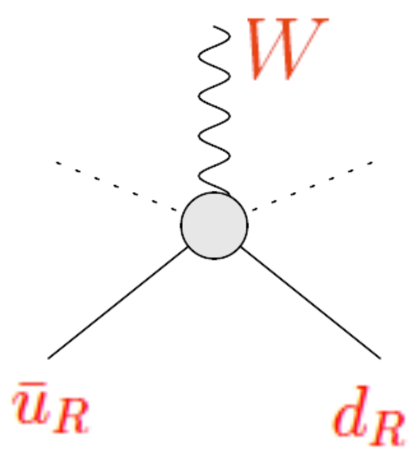
- ε_R originates from SU(2)xU(1) invariant vertex corrections



Building blocks

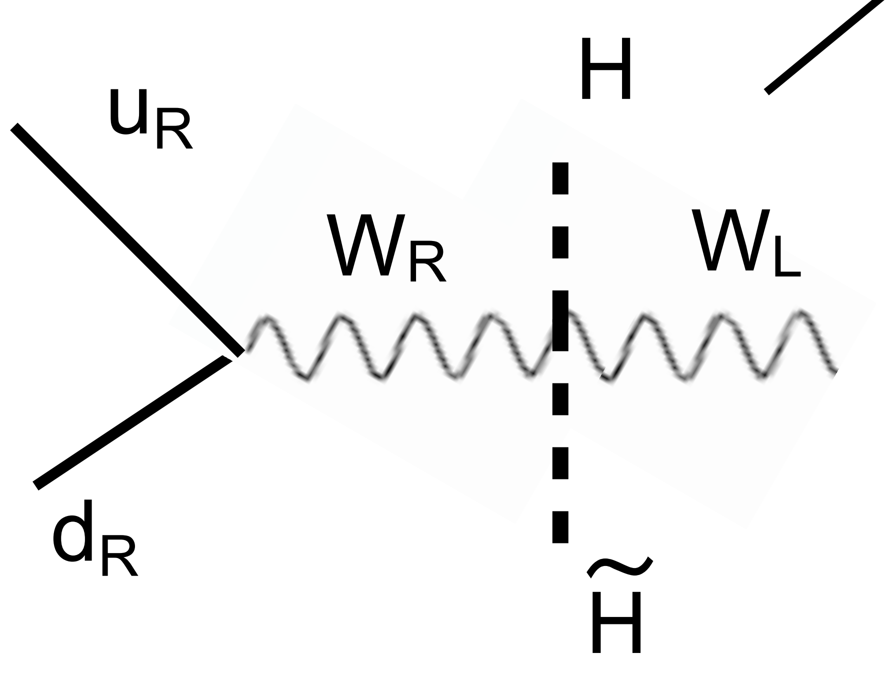
$$l^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix} \quad q^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix} \quad H = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$

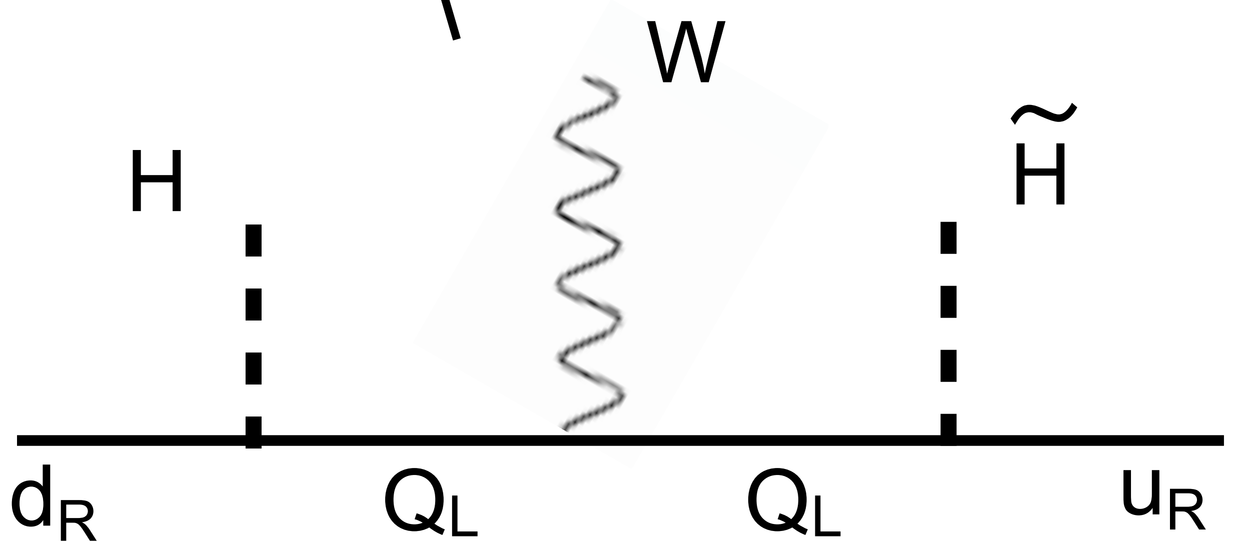
$$Q_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$$



ε_R

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



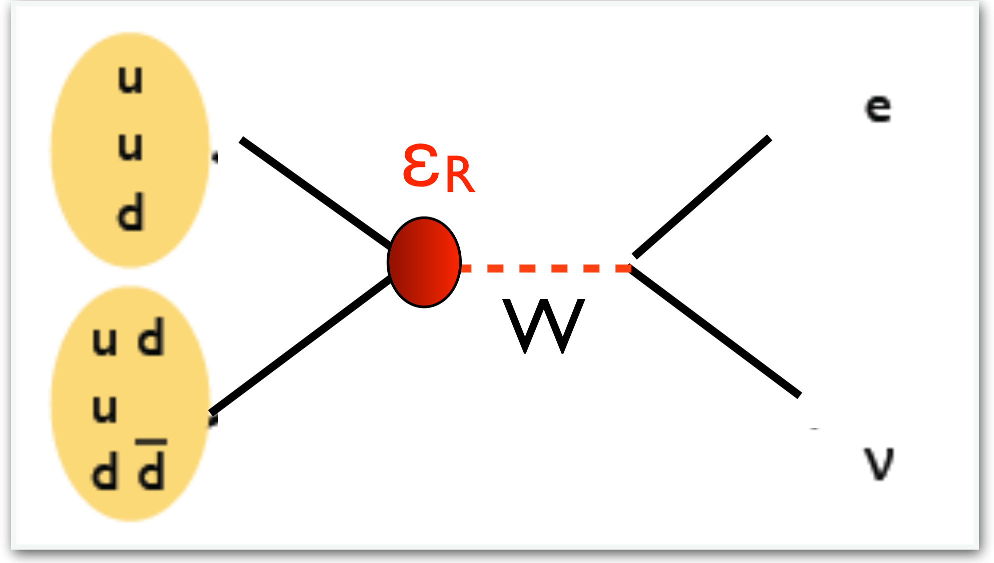


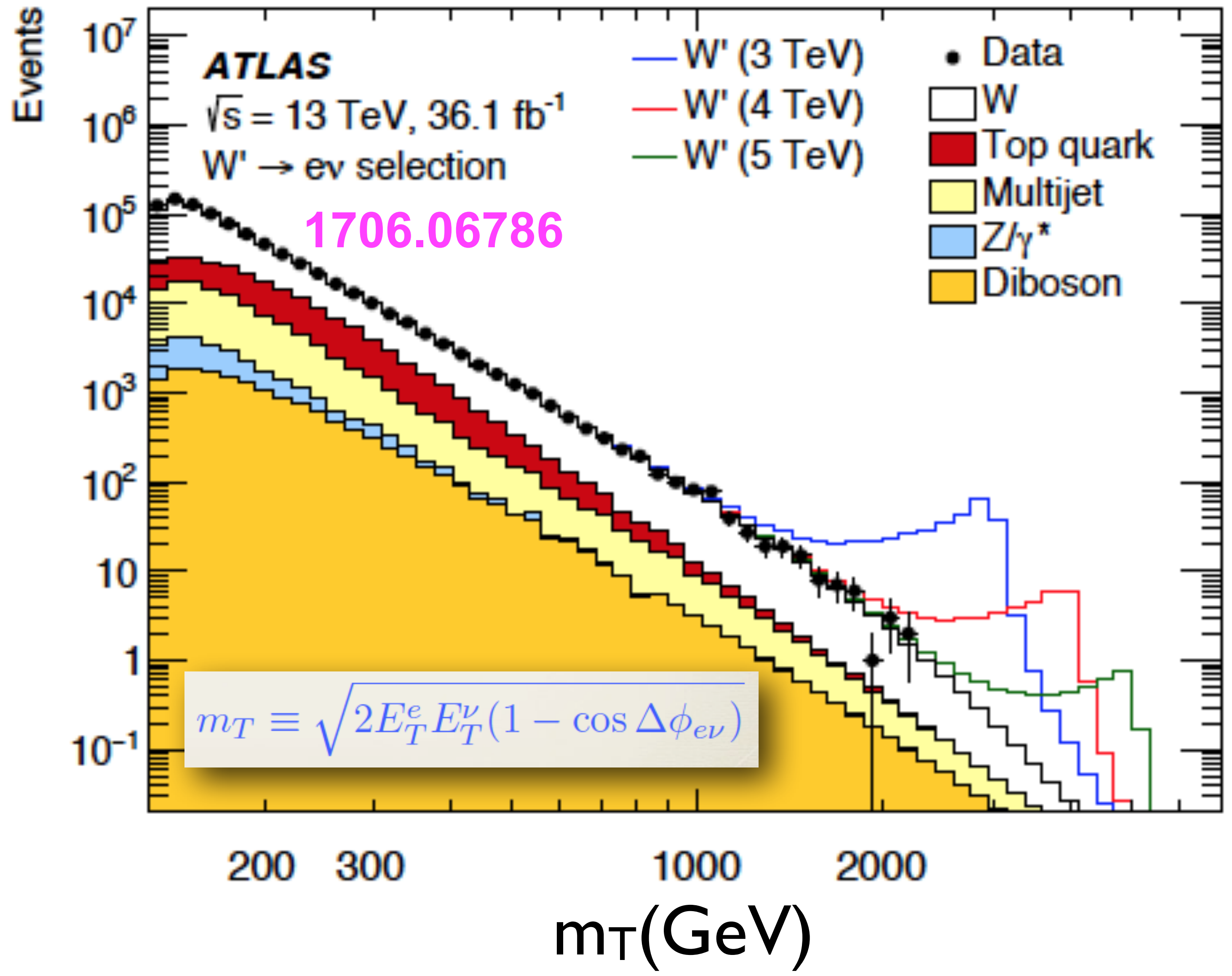
Belfatto-Berezhiani 2103.05549. …
Belfatto-Trifinopoulos 2302.14097

Collider constraints on εR are weak

Contribute tp pp → eν+X at the LHC

LHC: pp → eν + X

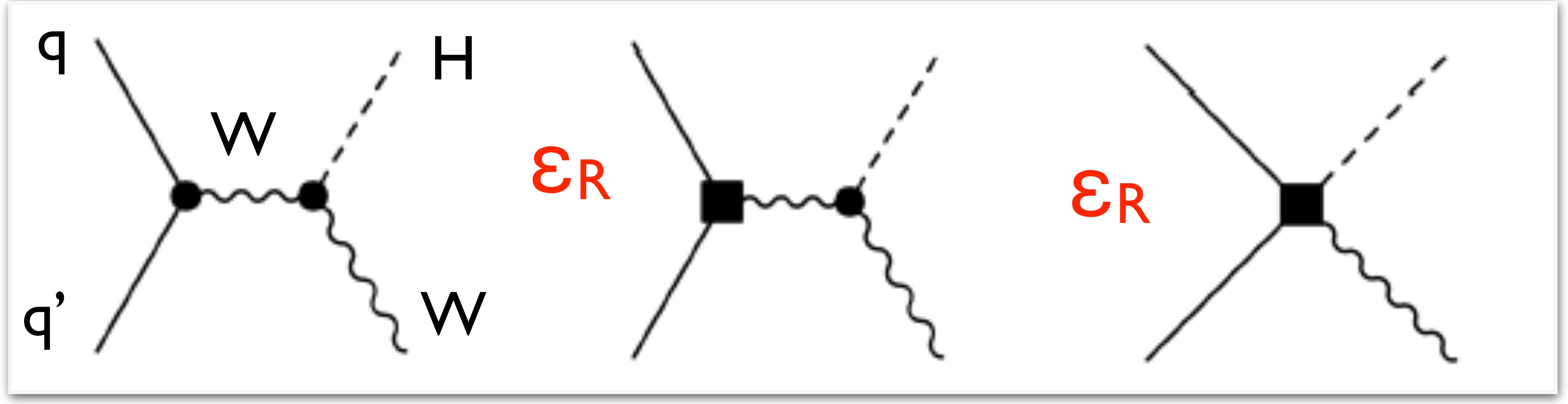




New contribution has same shape as the SM W exchange → weak sensitivity

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

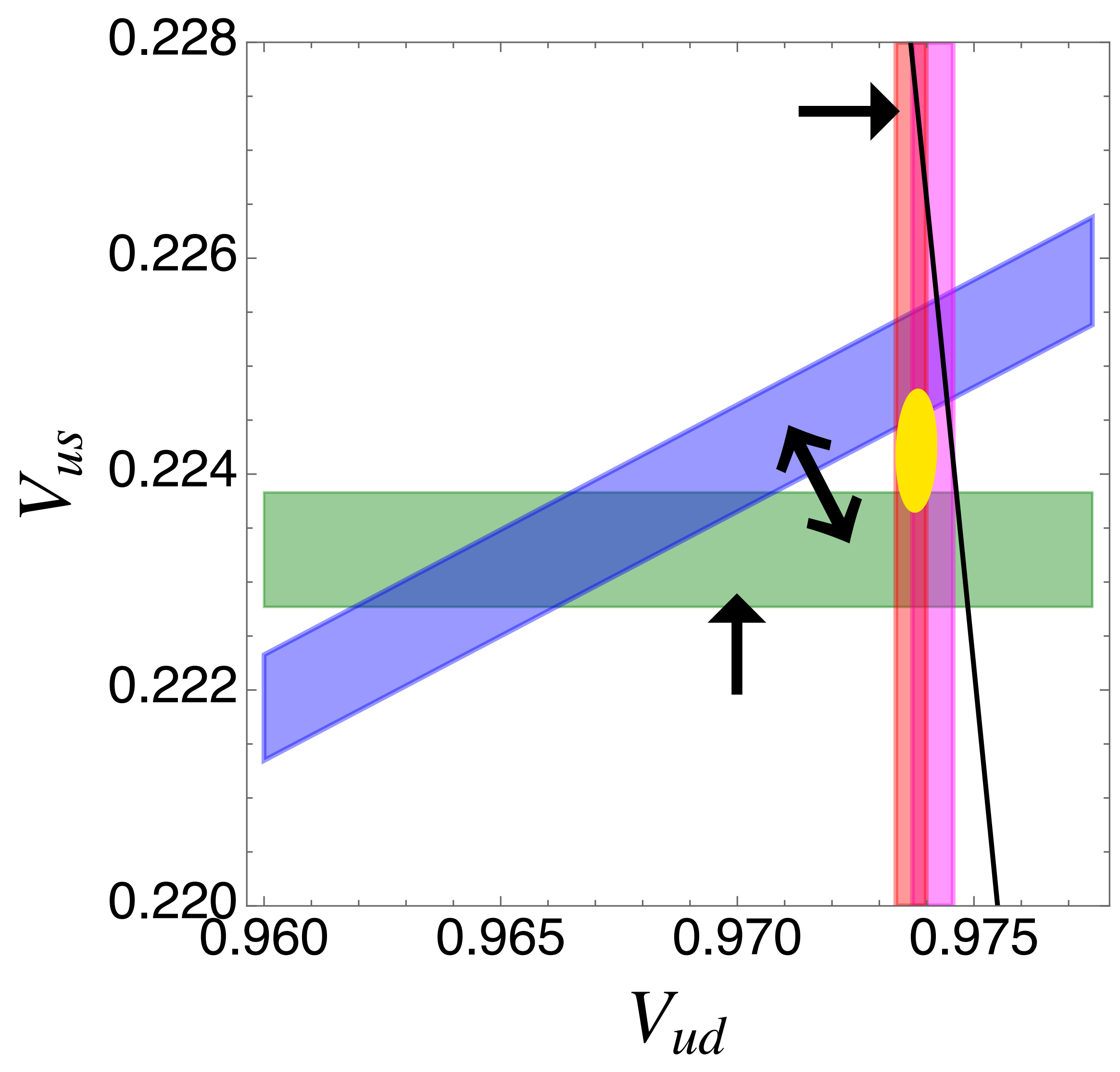
Contributes to associated Higgs + W production at the LHC

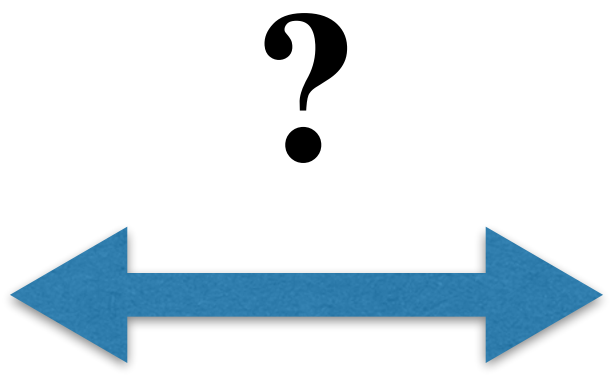


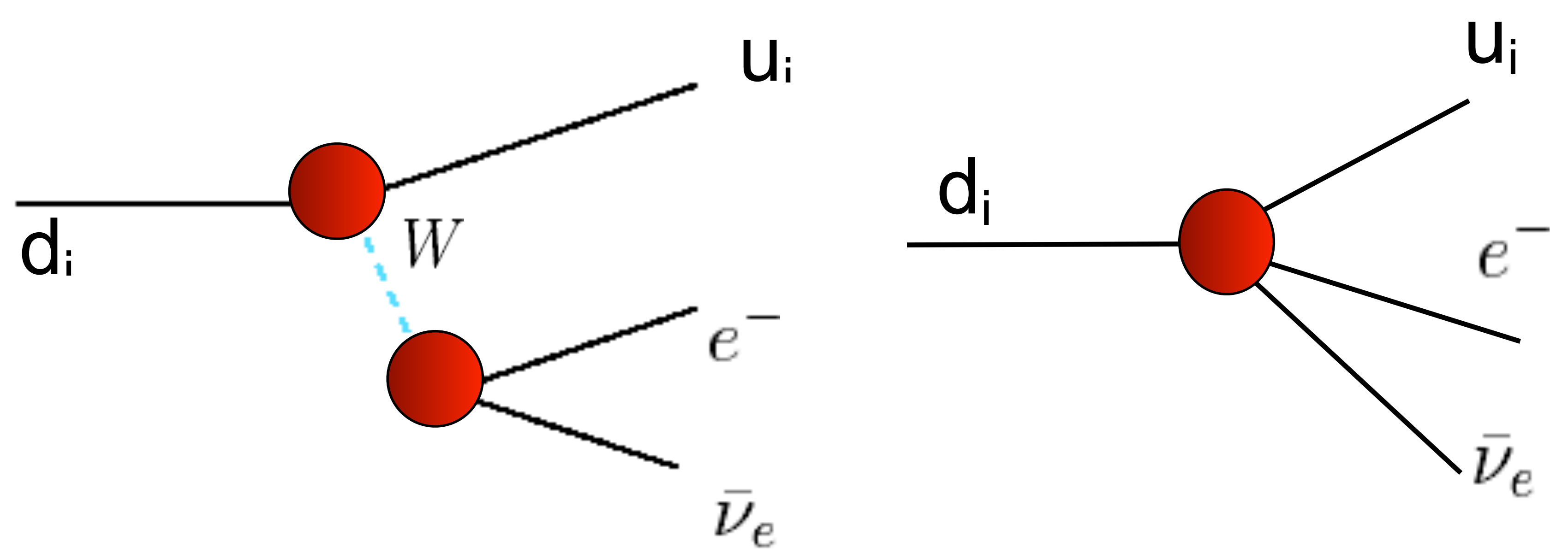
S. Alioli, VC, W. Dekens, J. de Vries, E. Mereghetti 1703.04751

Current LHC results allow for to εR ~ 5%

Broader perspective

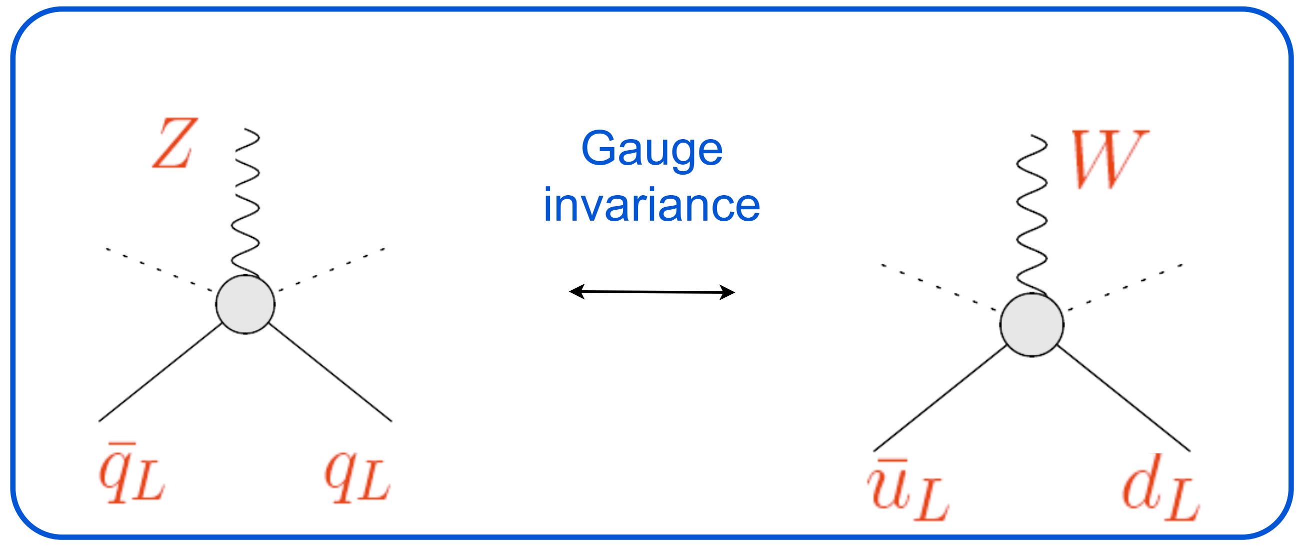




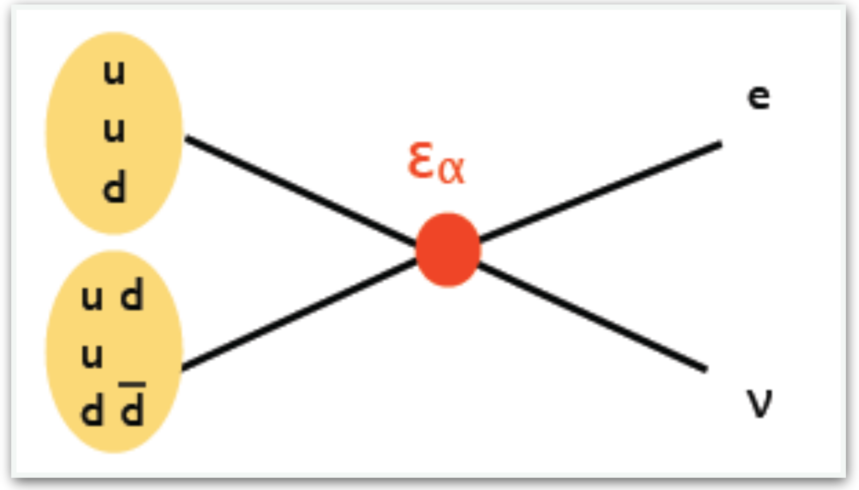


- New physics contributing to β decays also affects
  - Precision electroweak observables
  - Drell-Yan processes at colliders

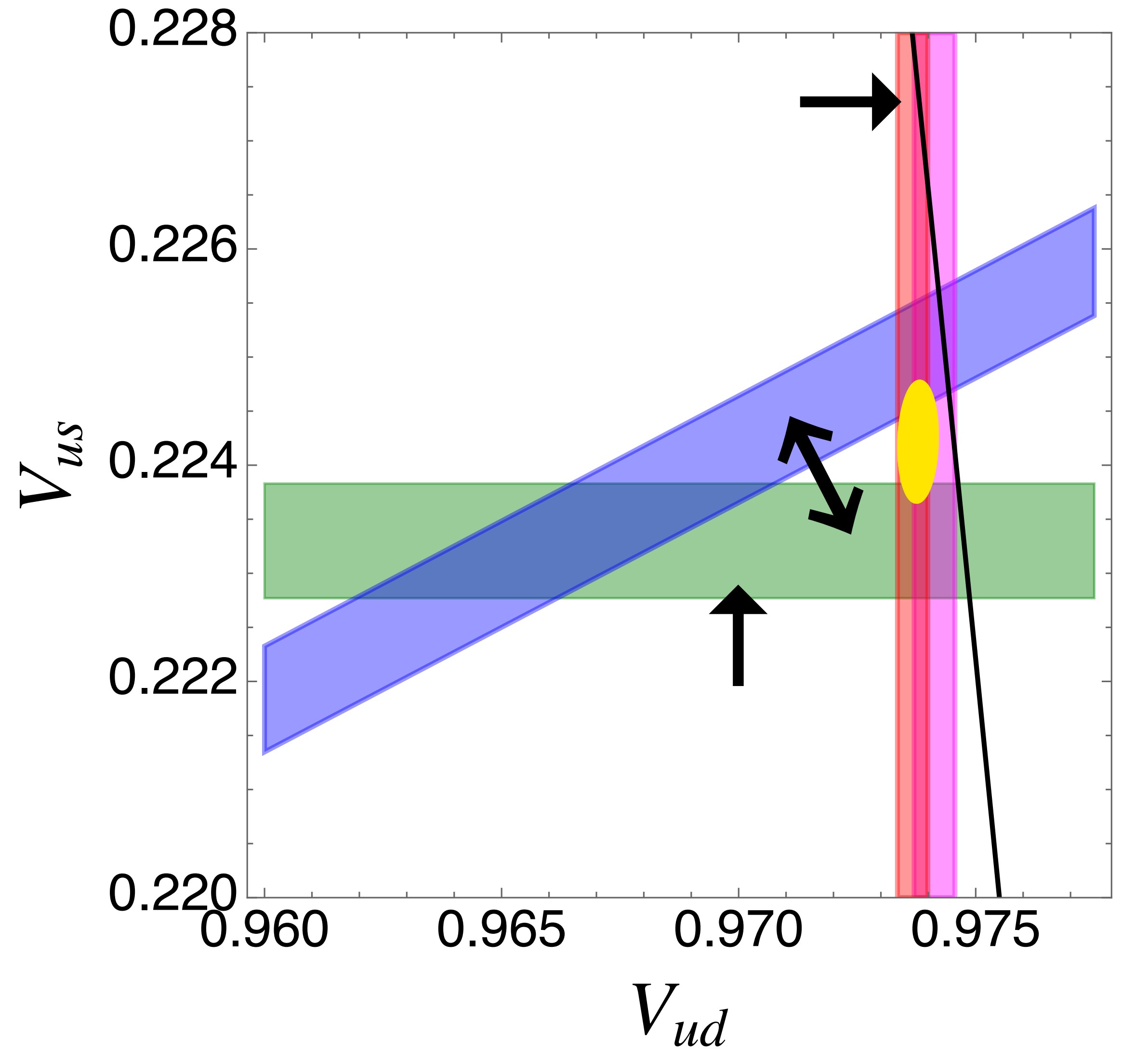
Z-pole observables

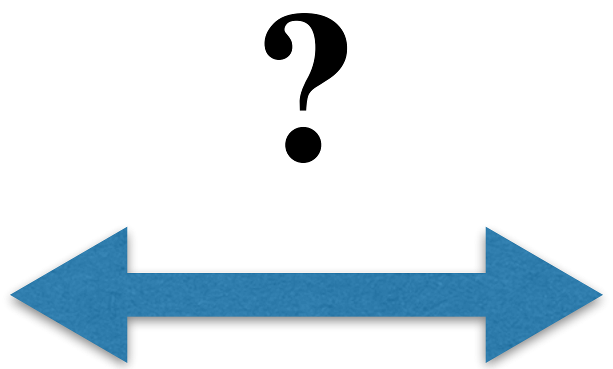


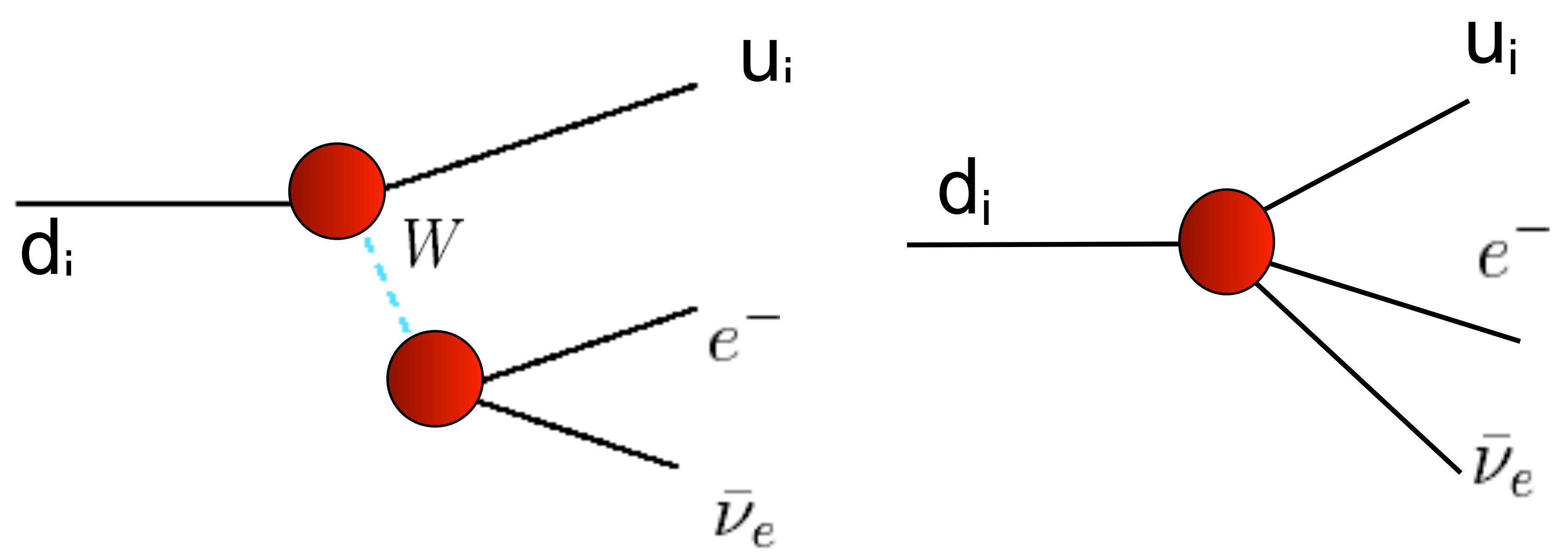
LHC: pp → eν + X



Broader perspective

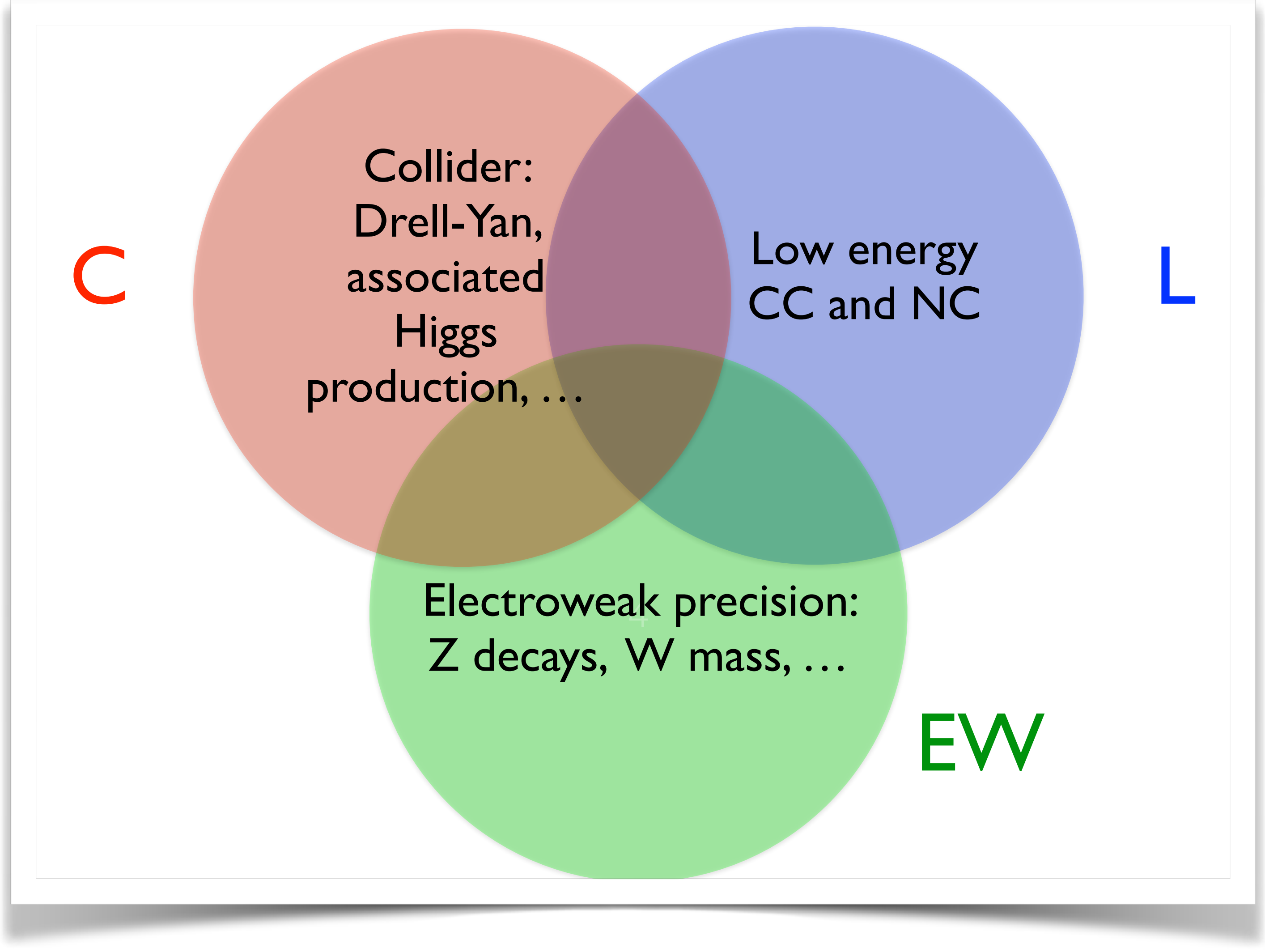






- New physics contributing to β decays also affects
  - Precision electroweak observables
  - Drell-Yan processes at colliders

- Need the 'CLEW' framework to analyze the impact of β decays on new physics (~40 operators)

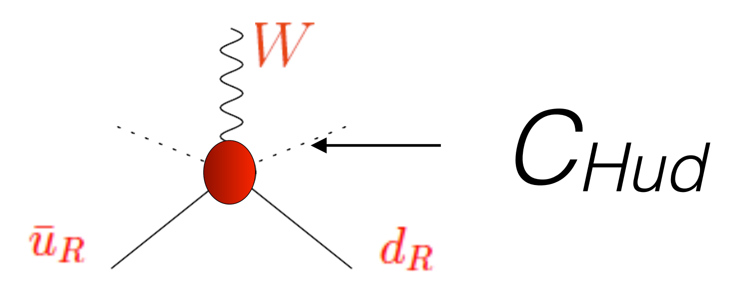


VC, W. Dekens, J. De Vries, E. Mereghetti, T. Tong, JHEP 03 (24) 33, arXiv: 2311.00021

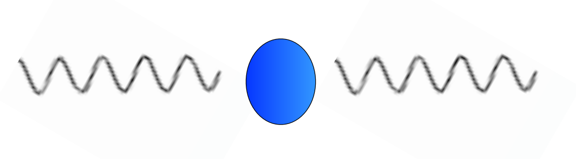
A ‘CLEWed’ analysis

- Performed CLEW fit within SMEFT. Scanned model space by ‘turning on’ 10 classes of effective couplings

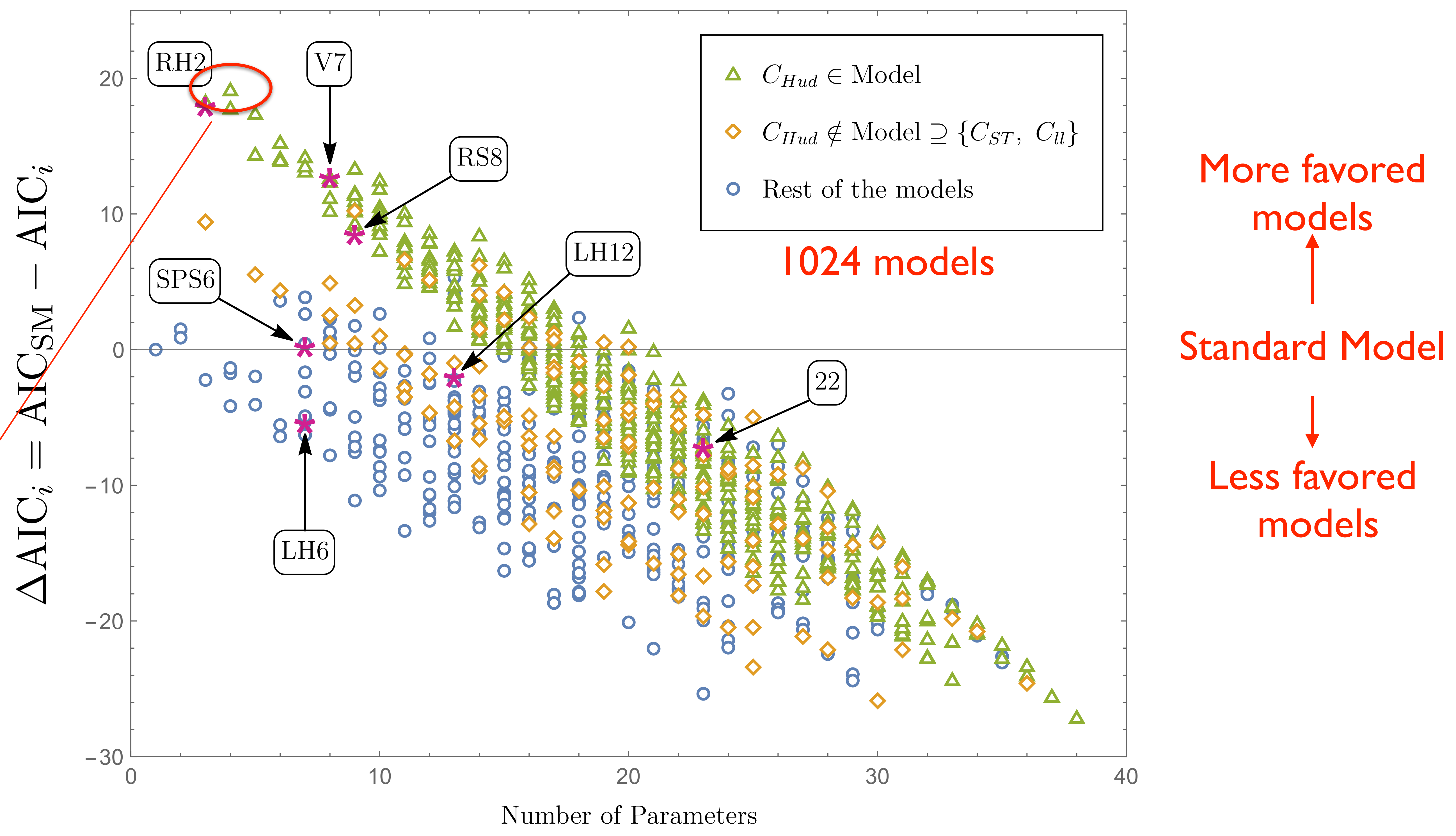
- Model selection? Akaike Information Criterion [AIC = 2k - ln(L)) favors models with Right-Handed Charged Currents of quarks (V+A)



- Best fit to CLEW data: two RH CC vertex corrections and the S parameter



VC, W. Dekens, J. De Vries, E. Mereghetti, T. Tong, JHEP 03 (24) 33, arXiv: 2311.00021



CKM “anomaly” not ruled out by other data!
Unitarity test provides relevant input to unravel possible new physics.
Vector-like quark scenario is testable at the High-Luminosity LHC

Precision beta decay outlook

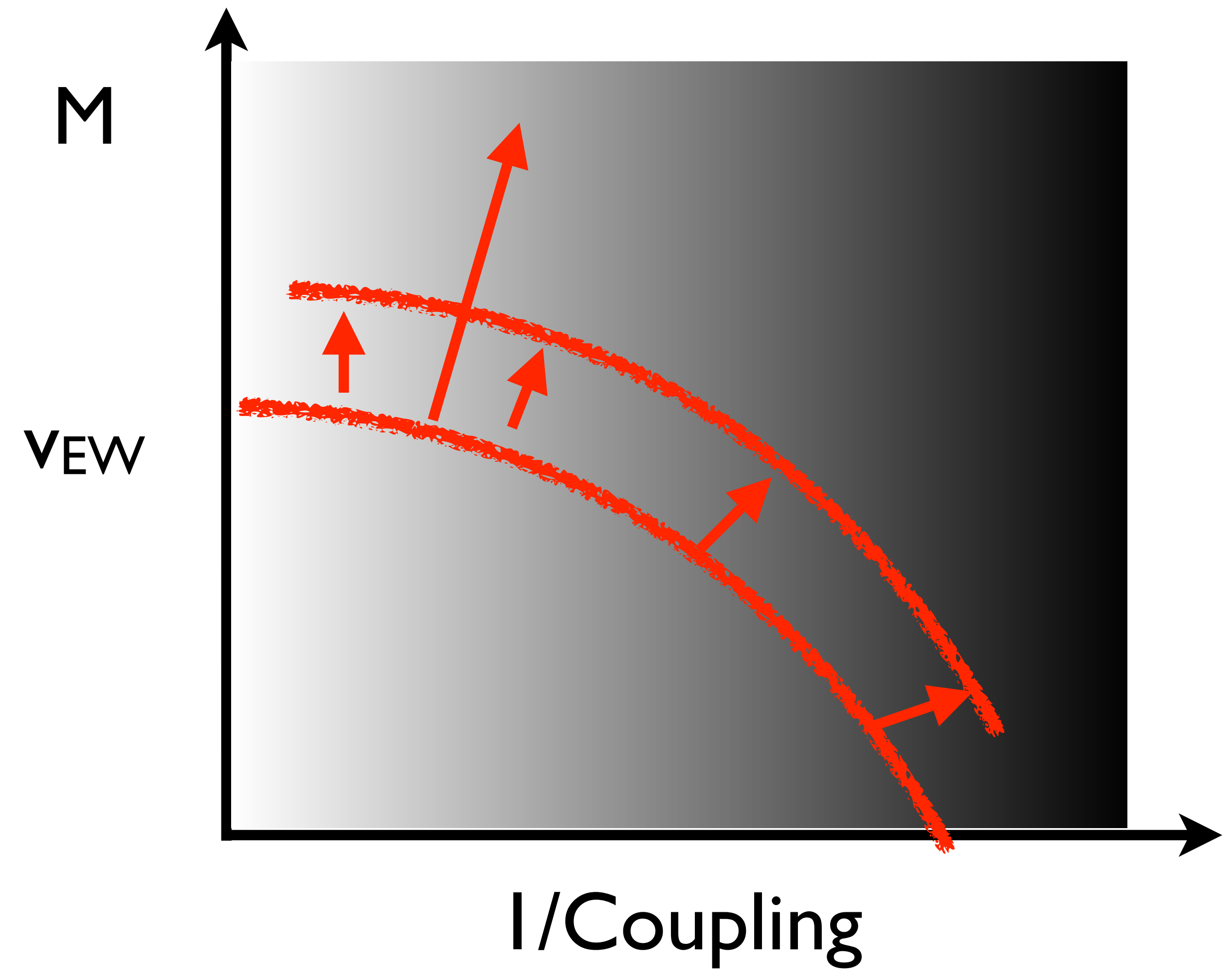
- Current tensions in Cabibbo universality test could point to new physics at $\Lambda \sim$ few TeV, with right-handed quark-W couplings a viable and testable culprit. However …

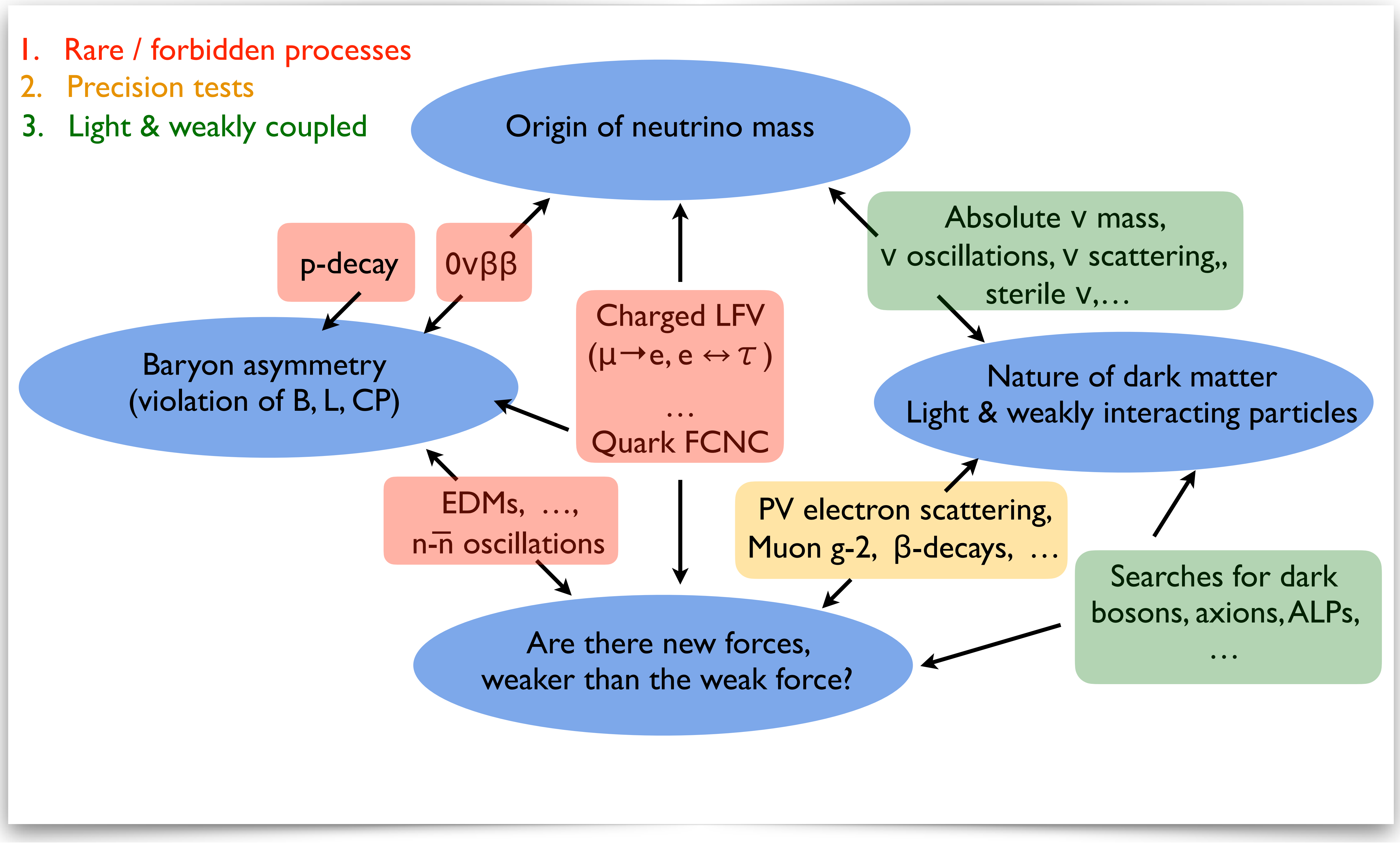
- Both experimental and theoretical scrutiny is needed! Progress expected on several fronts:
  - Experiment: neutron, K, π, τ
  - Theory: lattice QCD+QED for neutron, K, π; EFT+ 'ab-initio' methods for nuclei

Active are of experimental and theoretical investigation

Concluding comments

- Vibrant experimental program at the low-energy Precision / Intensity Frontier is exploring uncharted territory in the search for new physics, in a complementary way to other frontiers



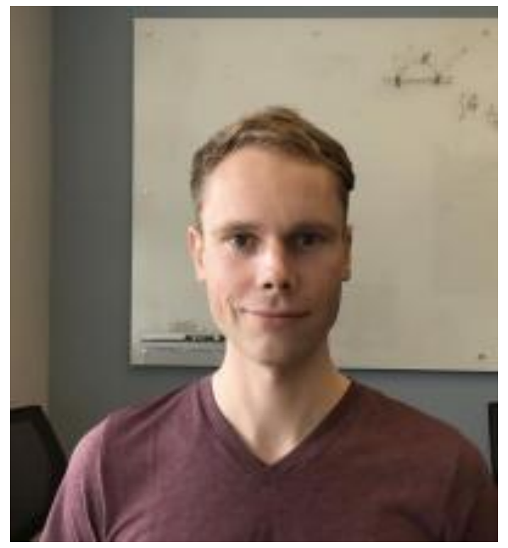


- The low-energy frontier probes BSM physics related to the 'big questions'

- Theoretical challenges addressed by a combination of EFT, lattice QCD and other non-perturbative methods

Thanks to collaborators!


Maria Dawid


Wouter Dekens


Ayala Glick-Magid

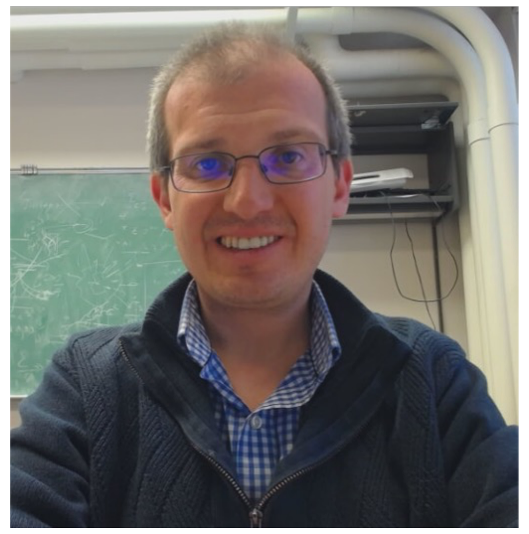

Chien-Yeah Seng


Sasha Tomalak


Jordy de Vries


Stefano Gandolfi


Martin Hoferichter


Emanuele Mereghetti

Saori Pastore


Bira van Kolck


Andre' Walker-Loud

Thank you!

T. D. Lee in a drawing by Bruno Touschek

Bruno Touschek (1921-1978)

Backup

(Incomplete) List of acronyms

- ALPs: Axion-Like Particles
- BNV: Baryon Number Violation
- CC: (weak) charged current
- CP: Charge-Parity
- CPV: CP Violation
- EDM: Electric Dipole Moment
- EFT: Effective Field Theory
- FCNC: Flavor Changing Neutral Currents
- IR: infrared
- LEFT: Low Energy EFT (below the weak scale)
- LFV: Lepton Flavor Violation
- LNV: Lepton Number Violation
- NC: (weak) neutral current
- SM: Standard Model
- SMEFT: Standard Model EFT
- UV: ultraviolet

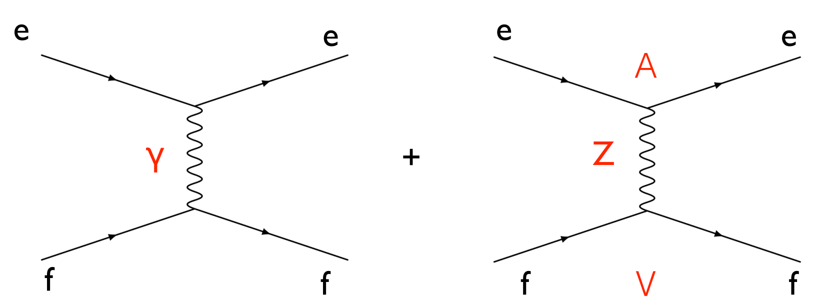
PVES on the weak mixing angle θ_W

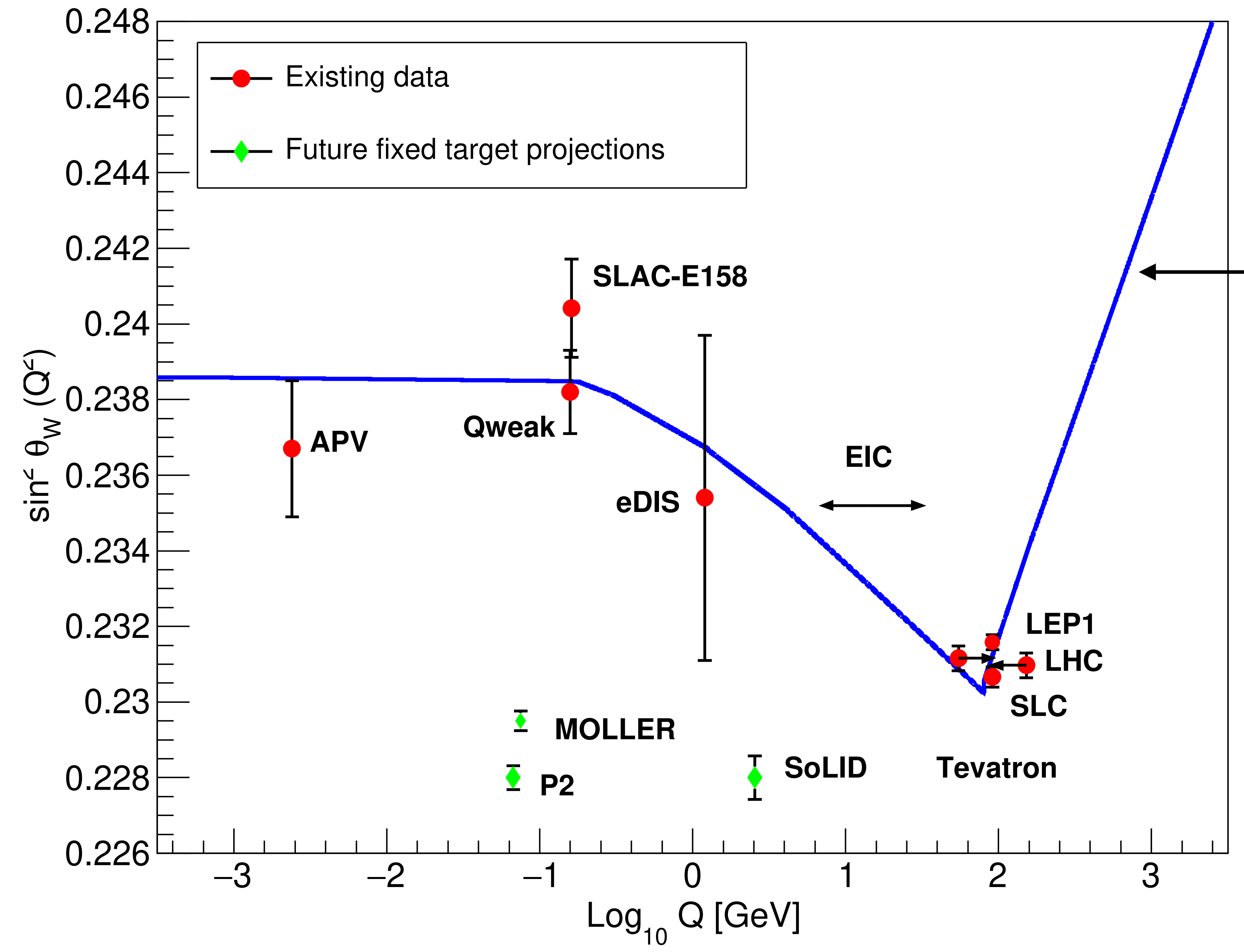
$A_{PV} = (\sigma_R - \sigma_L)/(\sigma_R + \sigma_L)$

↕

Generated by γ-Z interference

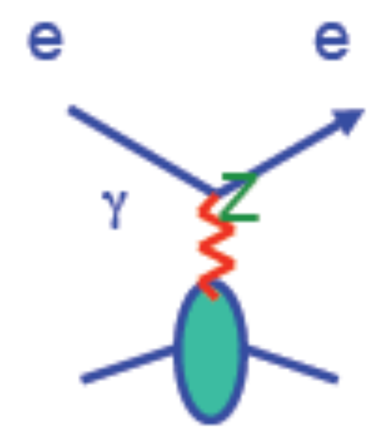
Access to
$\theta_W = \text{ArcTan}(g_1/g_2)$



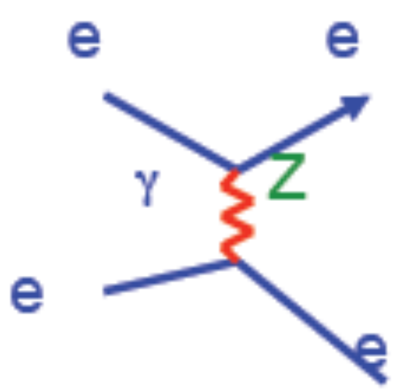


SM prediction: relating EW measurements at Q~100 GeV to low-energy

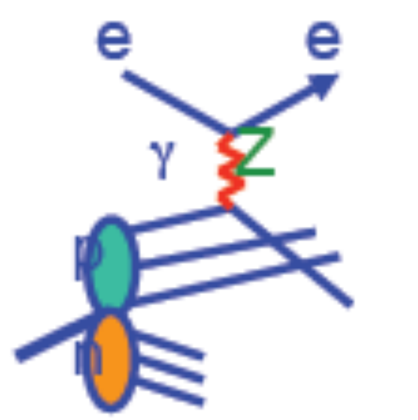
Erler & Ferro-Hernandez, 1712.09146 and references therein



ep (Q-Weak, P-2)



Purely leptonic (MOLLER):
will reach level of Z-pole measurements



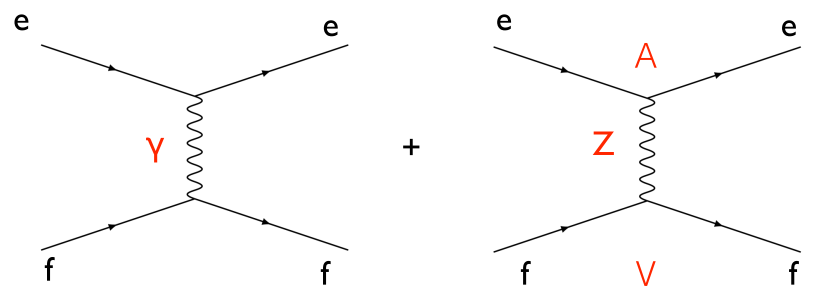
e-DIS (SoLID)

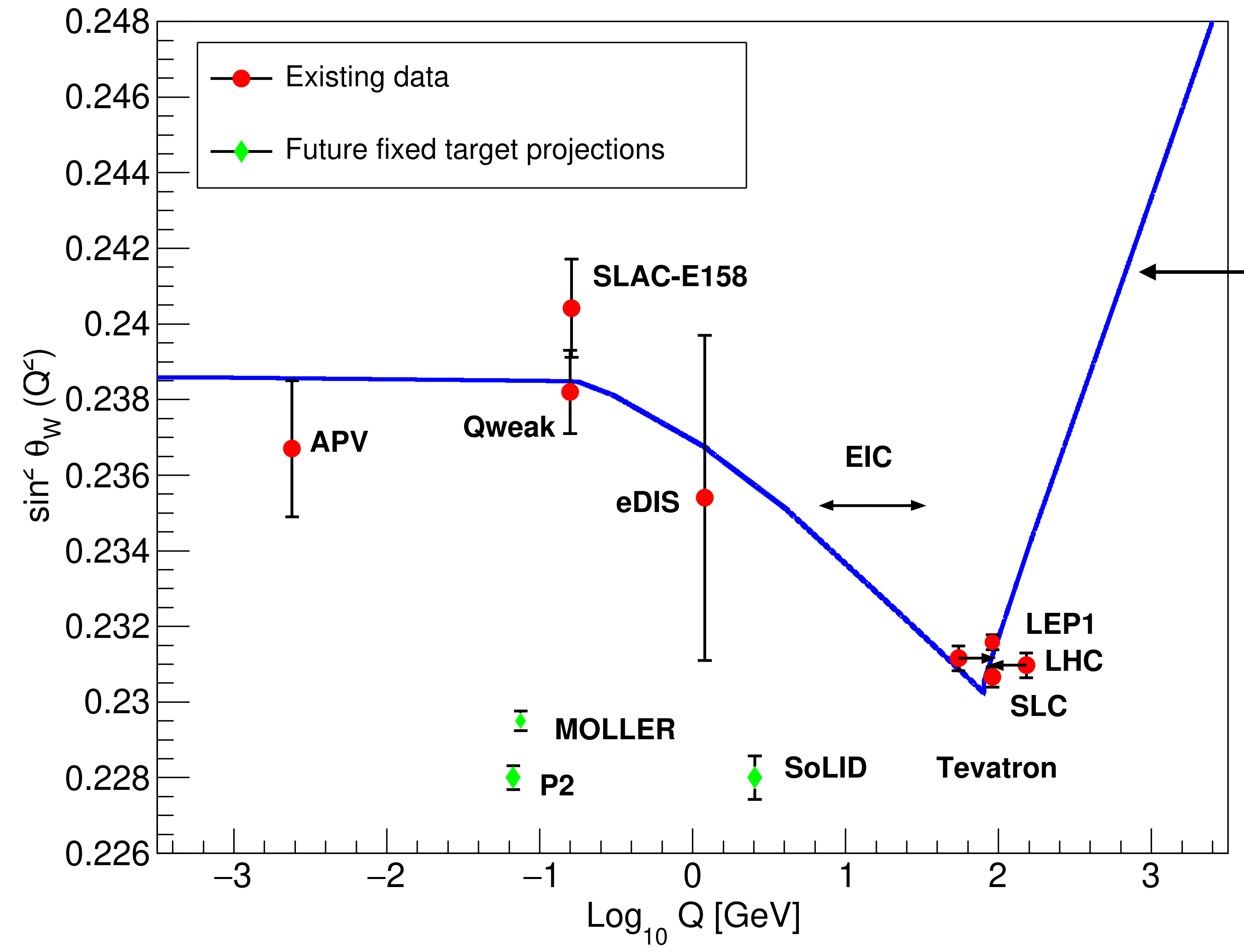
PVES on the weak mixing angle θ_W

$A_{PV}=(\sigma_R-\sigma_L)/(\sigma_R+\sigma_L)$

Generated by γ-Z interference

Access to
$\theta_W = \mathrm{ArcTan}(g_1/g_2)$

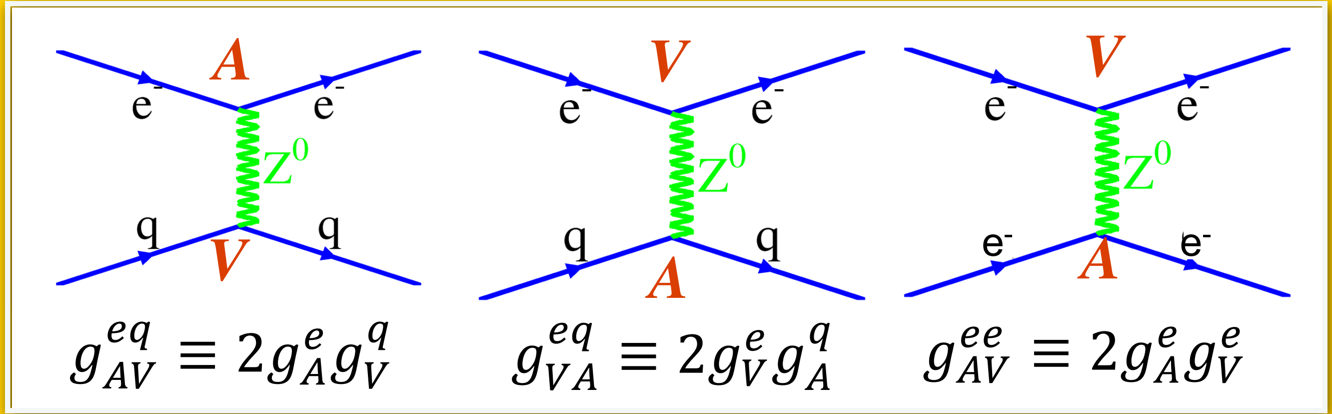




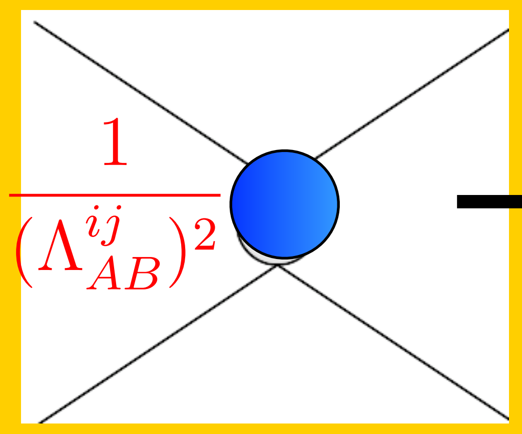
SM prediction: relating EW measurements at Q~100 GeV to low-energy

Erler & Ferro-Hernandez, 1712.09146 and references therein

Based on J. Erler et al. 1401.6199



vs

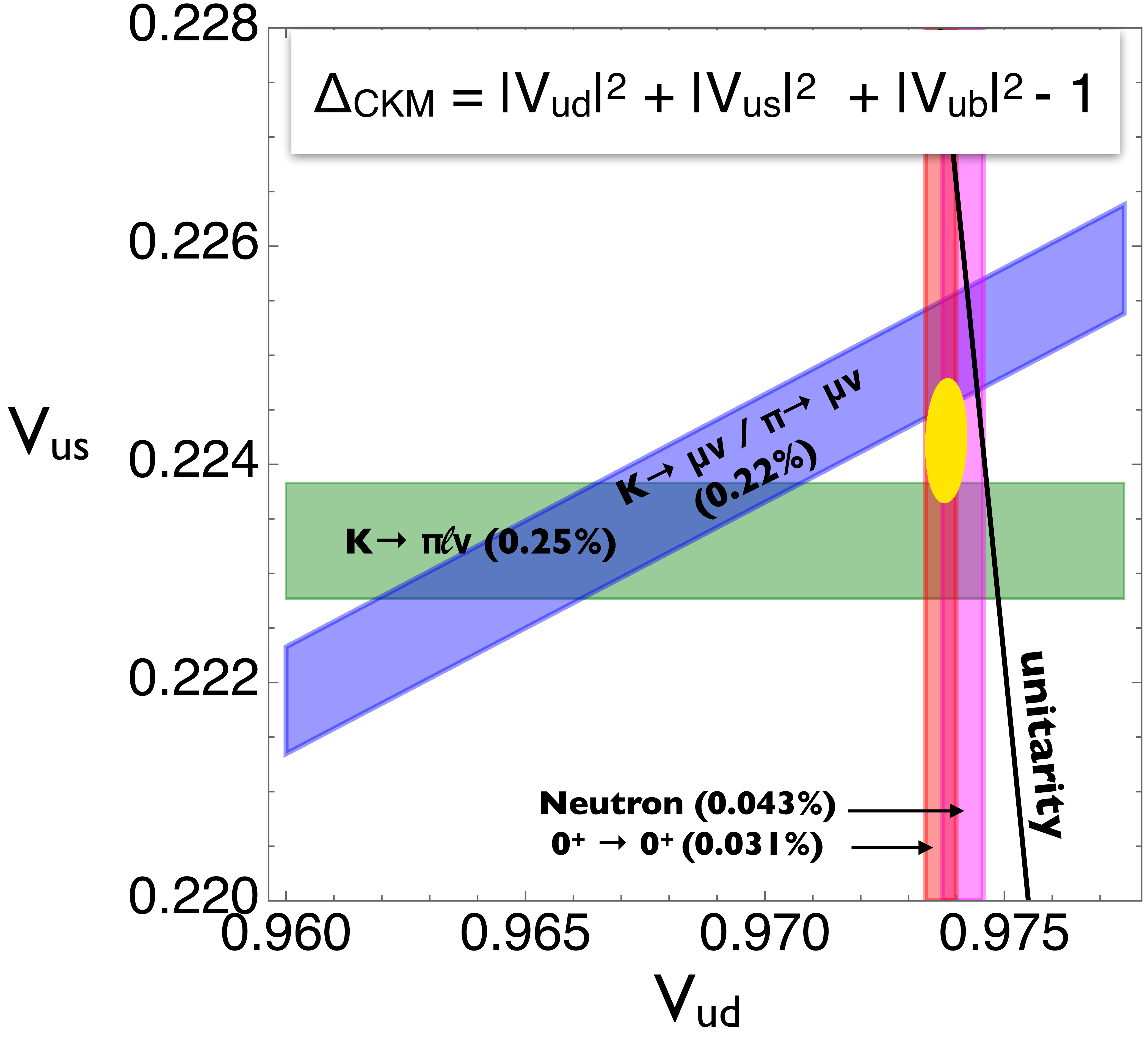


$\Lambda_{AV}^{eq} \sim 13$ TeV	(P-2)
$\Lambda_{VA}^{eq} \sim 6$ TeV	(SoLID)
$\Lambda_{AV}^{ee} \sim 11$ TeV	(MOLLER)

Complementarity with LHC + sensitivity to low-scale new physics (Z', …)

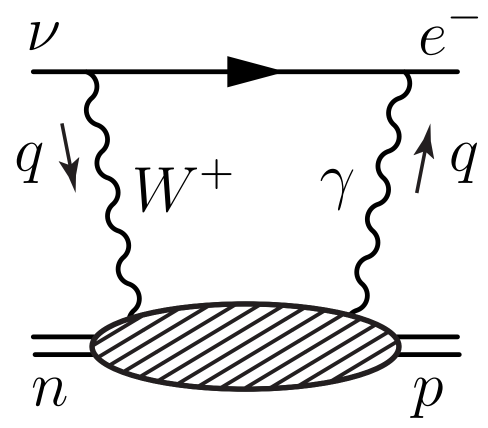
Tensions in the V_{ud}-V_{us} plane

VC-Crivellin-Hoferichter-Moulson 2208.11707
[and references therein]



Neutron input:

$$|V_{ud}|^2 \tau_n (1 + 3 g_A^2)(1 + \Delta_{RC}) = 5099.3(3)\,\mathrm{s}$$



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

Feng, Gorchtein, Jin, Seng, … 2308.16755

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

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

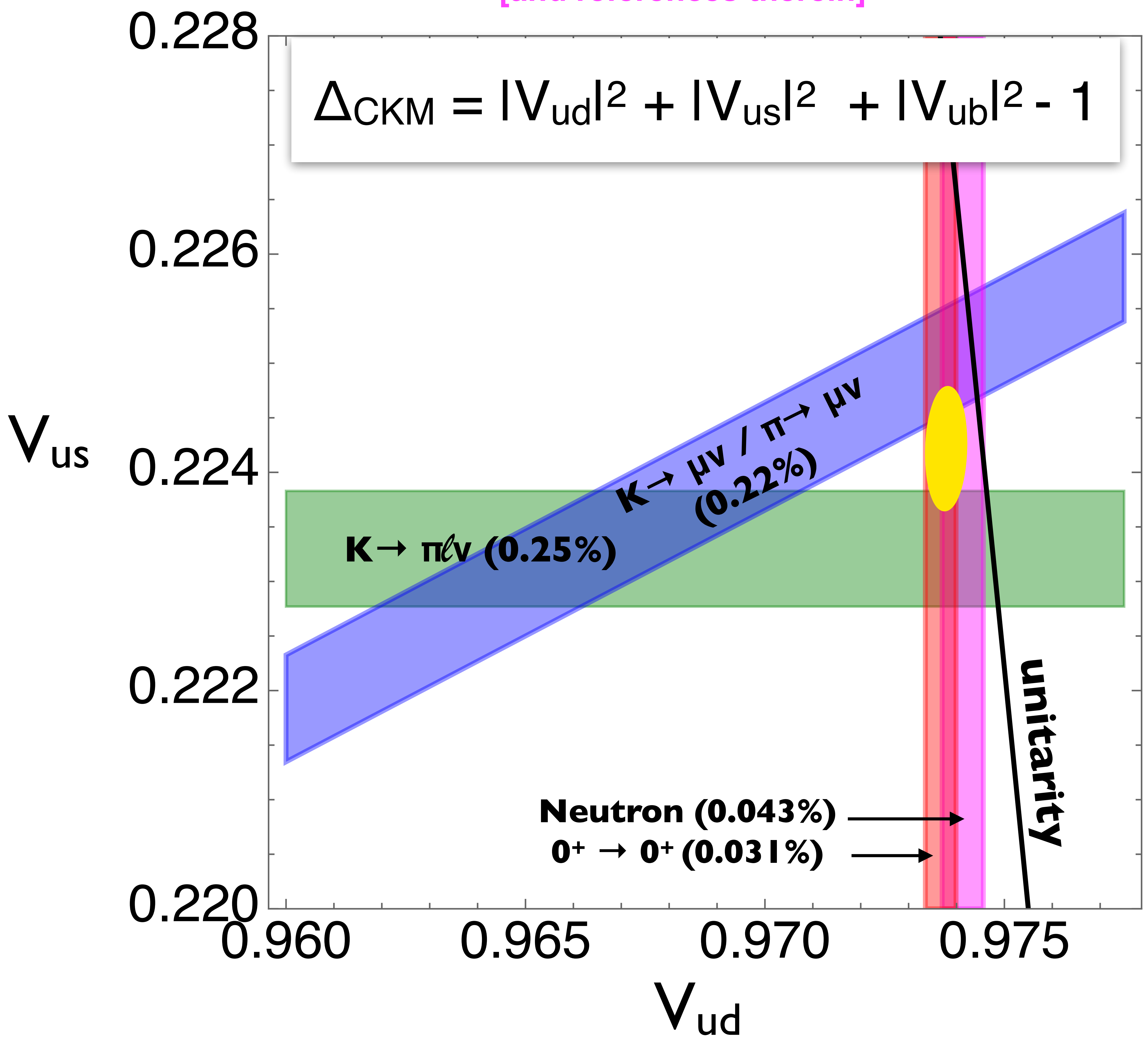
Maerkish et al, 1812.04666

Gonzalez et al, 2106.10375

$\lambda = g_A/g_V$

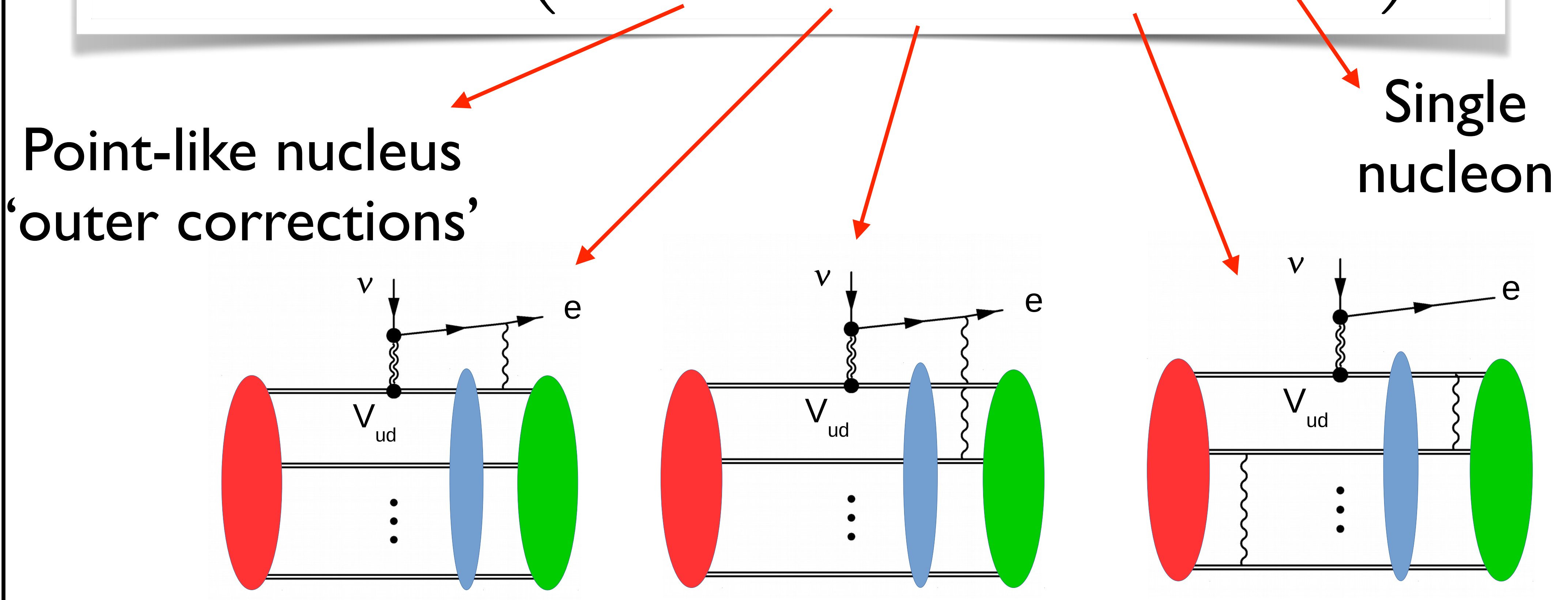
Tensions in the V_{ud}-V_{us} plane

VC-Crivellin-Hoferichter-Moulson 2208.11707
[and references therein]



$0^+ \rightarrow 0^+$ input

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



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

Hardy-Towner, PRC 2020

Gorchtein, Seng 2311.00044
review and references therein

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

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

- 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
- 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) $\Delta^{(\pi)}_{e^4 Q^0} = 0.055(3)\%$

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

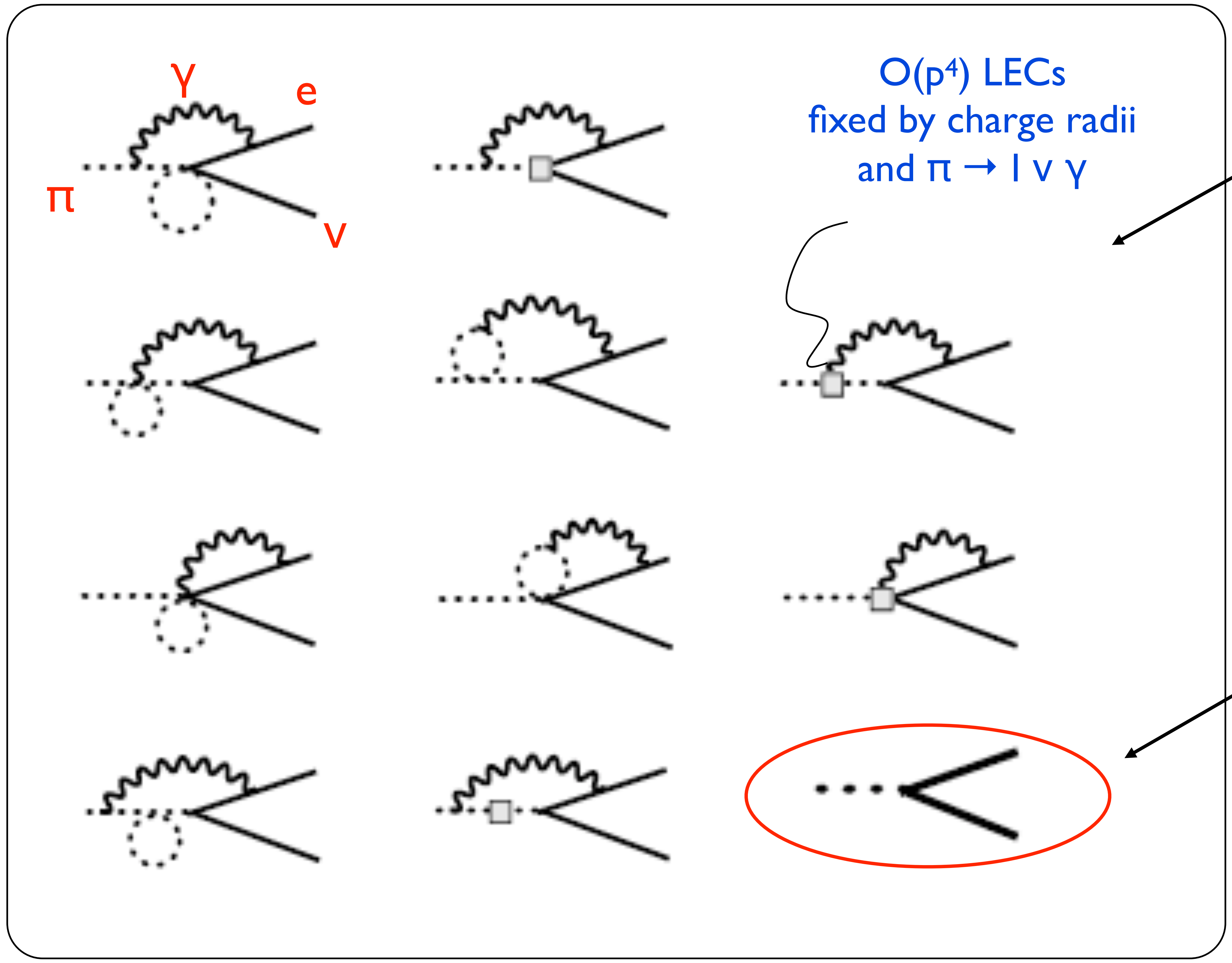
P = (π,K)

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

- 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