Lepton flavour change in nuclei
ECT* Workshop
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Higgs-mediated lepton flavor violation

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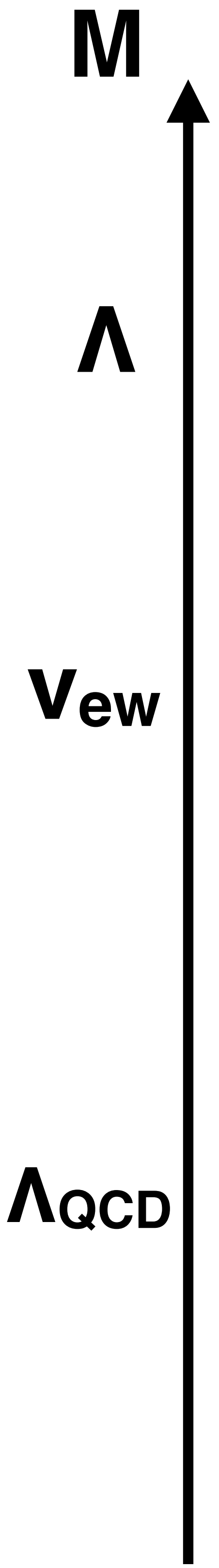
Outline

- Introduction: LFV and new physics
- Use Higgs-mediated LFV to illustrate:
  - Interplay of UV and nuclear physics in μ-to-e conversion
  - Model-diagnosing power of multiple probes

Vast literature — apologies in advance for incomplete referencing

Connecting scales with EFT: LFV



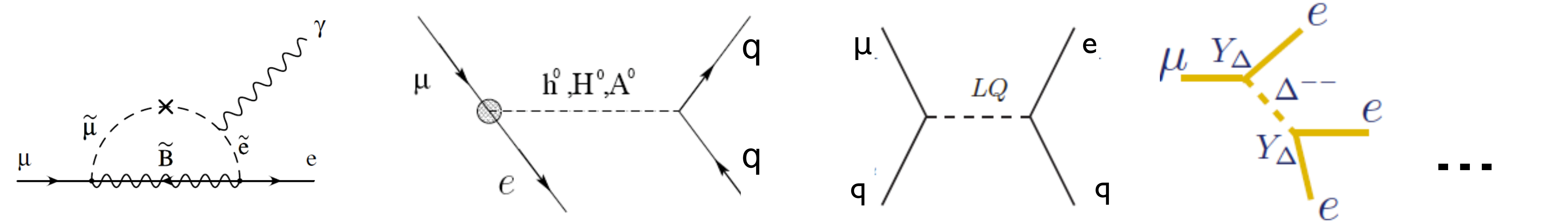
Motivated by neutrino mass, expect (hope?) that
at some scale between Planck and weak scale,
there exist new LFV and possibly LNV violating particles and interactions.

At low energy, they leave behind local operators

Connecting scales with EFT: LFV

M

Λ



Dipole: SUSY-GUT and SUSY see-saw scenarios, …

Scalar: RPV SUSY and RPC SUSY for large tan(β) and low m_A, leptoquarks, …

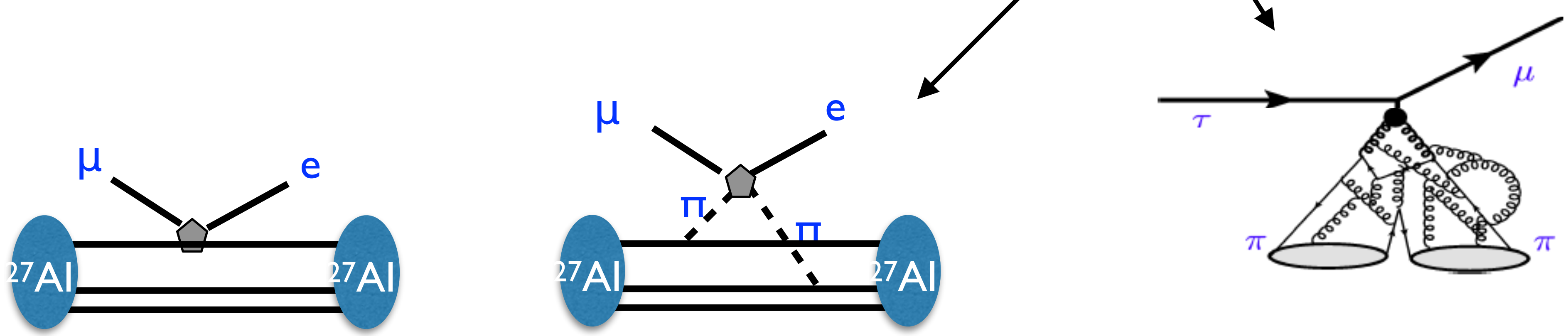
Vector Type III seesaw, LRSM, leptoquarks, …

4-lepton: Type II seesaw, RPV SUSY, LRSM, …

v_{ew}

$$\mathcal{L}_{d=6} \supset \frac{v C_D^{\alpha\beta}}{\Lambda^2}\bar{\ell}^\alpha \sigma_{\mu\nu}\ell^\beta F^{\mu\nu} + \sum_\Gamma \frac{C_\Gamma^{\alpha\beta}}{\Lambda^2}\bar{\ell}^\alpha\Gamma\ell^\beta\,\bar{q}\Gamma q + \sum_{\tilde{\Gamma}}\frac{C_{\tilde{\Gamma}}^{\alpha\beta}}{\Lambda^2}\bar{\ell}^\alpha\tilde{\Gamma}\ell^\beta\,\bar{\ell}\tilde{\Gamma}\ell$$

Λ_{QCD}



CLFV phenomenology

$$\mathcal{L}_{\rm LFV} \supset \frac{v C_D^{\alpha\beta}}{\Lambda^2} \bar{\ell}^\alpha \sigma_{\mu\nu} \ell^\beta + \sum_{\tilde{\Gamma}} \frac{C_{\tilde{\Gamma}}^{\alpha\beta}}{\Lambda^2} \bar{\ell}^\alpha \tilde{\Gamma} \ell^\beta \bar{\ell} \tilde{\Gamma} \ell + \sum_{\Gamma} \frac{C_{\Gamma}^{\alpha\beta}}{\Lambda^2} \bar{\ell}^\alpha \Gamma \ell^\beta \bar{q} \Gamma q + \frac{1}{F_{\alpha\beta}^{\Gamma}} \partial_\mu a \, \bar{\ell}^\alpha \Gamma^\mu \ell^\beta$$

Each model generates a specific pattern of operators
→ multiple CLFV measurements needed to extract the underlying physics

- New physics mass scale through any process

$$BR_{\alpha\to\beta} \sim (v_{ew}/\Lambda)^4 * |(C_n)^{\alpha\beta}|^2$$

μ-e sector:	$\Lambda/\sqrt{C} \sim 10^{4\text{-}5}$ TeV	(Muon decays)
τ-μ(e) sector:	$\Lambda/\sqrt{C} \sim 10^{2}$ TeV	(Tau decays)

CLFV phenomenology

$$\mathcal{L}_{\rm LFV} \supset \frac{v C_D^{\alpha\beta}}{\Lambda^2} \bar{\ell}^\alpha \sigma_{\mu\nu} \ell^\beta + \sum_{\tilde{\Gamma}} \frac{C_{\tilde{\Gamma}}^{\alpha\beta}}{\Lambda^2} \bar{\ell}^\alpha \tilde{\Gamma} \ell^\beta \bar{\ell} \tilde{\Gamma} \ell + \sum_{\Gamma} \frac{C_{\Gamma}^{\alpha\beta}}{\Lambda^2} \bar{\ell}^\alpha \Gamma \ell^\beta \bar{q} \Gamma q + \frac{1}{F_{\alpha\beta}^{\Gamma}} \partial_\mu a \, \bar{\ell}^\alpha \Gamma^\mu \ell^\beta$$

Each model generates a specific pattern of operators
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- New physics mass scale through any process

- Relative strength of operators ($[C_D]^{e\mu}$ vs $[C_S]^{e\mu}$…) through μ →3e vs μ →eγ vs μ →e conversion (and similarly for $\tau \to \mu$,e) ⇒ Mediators, mechanism

- Flavor structure of couplings ($[C_D]^{e\mu}$ vs $[C_D]^{\tau\mu}$…) through μ → e vs τ → μ vs τ → e ⇒ Sources of flavor breaking

CLFV phenomenology

$$\mathcal{L}_{\rm LFV} \supset \frac{v C_D^{\alpha\beta}}{\Lambda^2} \bar{\ell}^\alpha \sigma_{\mu\nu} \ell^\beta + \sum_{\tilde{\Gamma}} \frac{C_{\tilde{\Gamma}}^{\alpha\beta}}{\Lambda^2} \bar{\ell}^\alpha \tilde{\Gamma} \ell^\beta \bar{\ell} \tilde{\Gamma} \ell + \sum_{\Gamma} \frac{C_{\Gamma}^{\alpha\beta}}{\Lambda^2} \bar{\ell}^\alpha \Gamma \ell^\beta \bar{q} \Gamma q + \frac{1}{F_{\alpha\beta}^{\Gamma}} \partial_\mu a \, \bar{\ell}^\alpha \Gamma^\mu \ell^\beta$$

Each model generates a specific pattern of operators
→ multiple CLFV measurements needed to extract the underlying physics

- New physics mass scale through any process

- Relative strength of operators ($[C_D]^{e\mu}$ vs $[C_S]^{e\mu}$…) through $\mu \to 3e$ vs $\mu \to e\gamma$ vs $\mu \to e$ conversion (and similarly for $\tau \to \mu, e$) ⇒ Mediators, mechanism

- Flavor structure of couplings ($[C_D]^{e\mu}$ vs $[C_D]^{\tau\mu}$…) through $\mu \to e$ vs $\tau \to \mu$ vs $\tau \to e$ ⇒ Sources of flavor breaking

An example: Higgs-mediated LFV

- Simplest framework: LFV Yukawa couplings of the Higgs

$$\Delta\mathcal{L}_Y = -\frac{\lambda_{ij}}{\Lambda^2}\,(\bar{L}_L^i e_R^j H)\; H^\dagger H \quad \rightarrow \quad -Y_{ij}\; \bar{e}_L^i e_R^j\, h$$

Goudelis-Lebedev-Park '11
Davidson-Grenier '10
...
Harnik-Kopp-Zupan '12
Blankenburg-Ellis-Isidori 12
McKeen-Pospelov-Ritz '12
...

- Achieved in the SM-EFT through a single dim-6 operator that decouples lepton mass matrix from O(h) couplings

- Good starting point if new physics is heavy, arises in many UV models

LFV Higgs couplings

$$\mathcal{L} = -Y_{e\mu}\bar{e}P_R\mu h - Y_{\mu e}\bar{\mu}P_R e h + \text{h.c.}$$

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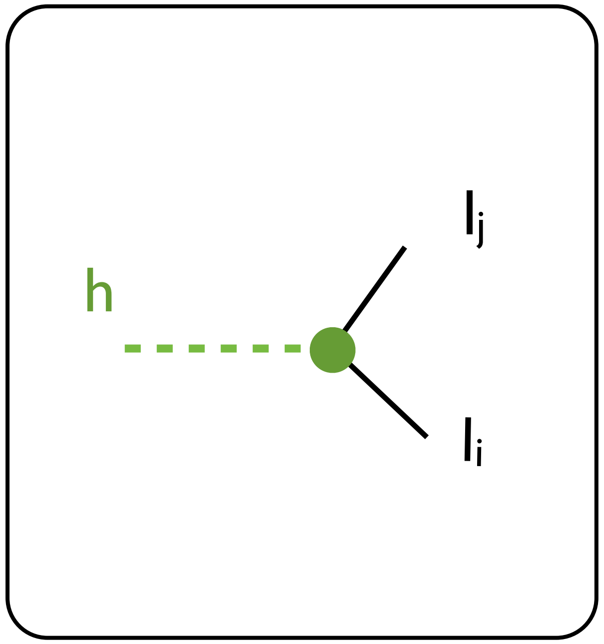
High Energy:
LFV Higgs decays



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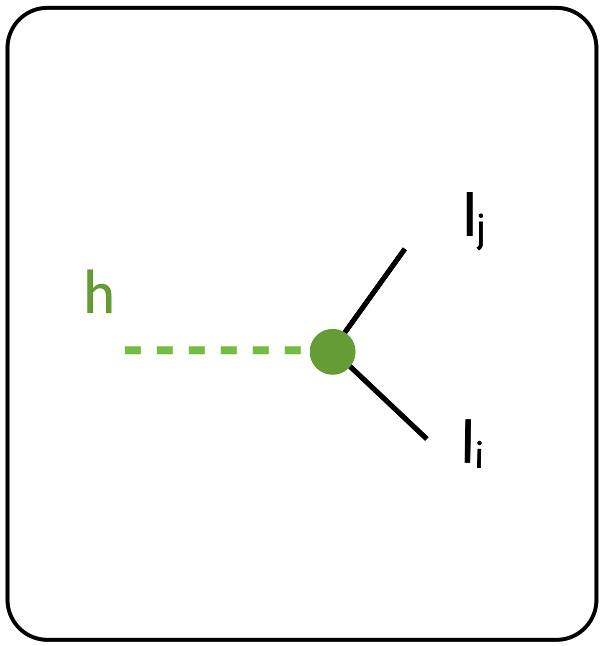
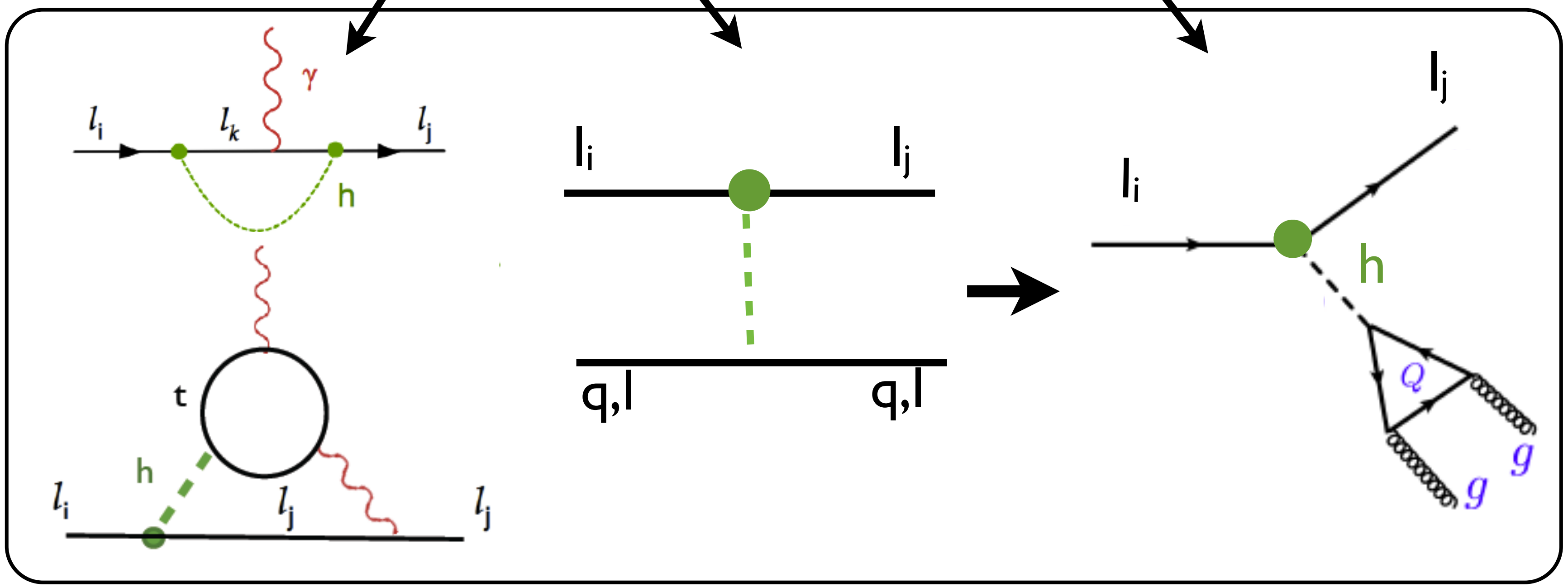
High Energy:
LFV Higgs decays

Low Energy footprints:
Dipole (D), Scalar 4-fermion (S), Gluon (G) operators





μ→eγ, μ→e , μ→3e

τ→μγ, τ→μππ, τ→3μ

μ→e , μ→3e

τ→μππ, τ→3μ

μ→e

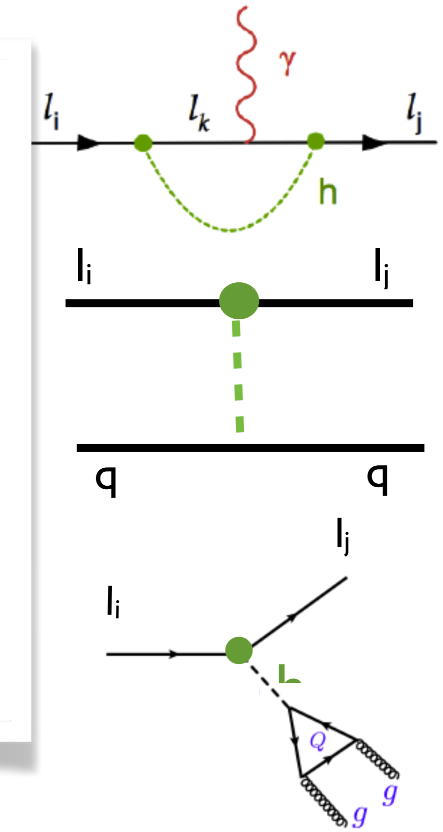
τ→μππ

Dependence on light fermion Yukawa couplings $Y_{u,d,s,\mu}$

Effective Lagrangian at low E

VC, Kaori Fuyuto, Michael Ramsey-Musolf, Evan Rule 2203.09547

$$\mathcal{L}_{\rm eff} = -\frac{1}{\Lambda^2}\sum_{\alpha=L,R}\Big[C_{D\alpha}\; m_\mu\; \bar{e}\sigma^{\lambda\nu}P_\alpha\mu\, F_{\lambda\nu} + \sum_{q=u,d,s,} C_{S\alpha}^{(q)}\; G_F m_\mu m_q\; \bar{q}q\,\bar{e}P_\alpha\mu + C_{G\alpha}\; G_F m_\mu \alpha_s\; G^a_{\lambda\nu}G^{a\,\lambda\nu}\bar{e}P_\alpha\mu + \text{h.c}\Big]$$



- Matching conditions for minimal Higgs-mediated LFV: scalar and gluon →
- For C_D, see refs. in previous slide

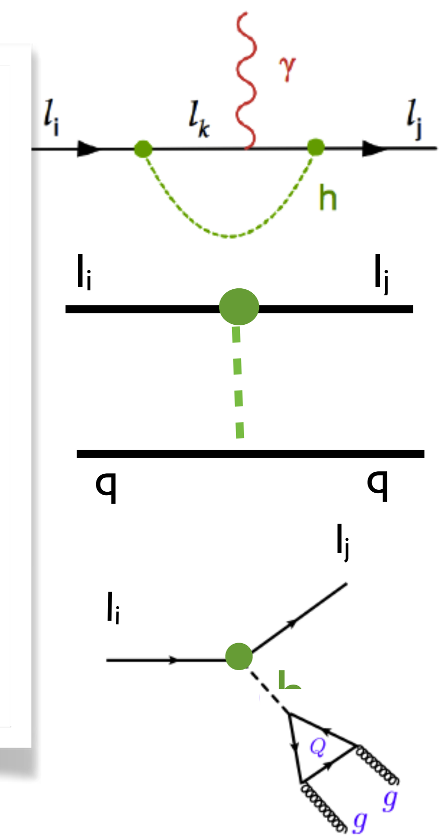
$$\frac{1}{\Lambda^2}G_F m_\mu v C_{SR}^{(q)} = -\frac{1}{m_h^2}Y_{e\mu},$$
$$\frac{1}{\Lambda^2}G_F m_\mu v C_{SL}^{(q)} = -\frac{1}{m_h^2}Y_{\mu e},$$

$$C_{G\alpha} = -1/(12\pi)\sum_{Q=c,b,t} C_{S\alpha}^{(Q)}$$

Effective Lagrangian at low E

VC, Kaori Fuyuto, Michael Ramsey-Musolf, Evan Rule 2203.09547

$$\mathcal{L}_{\rm eff} = -\frac{1}{\Lambda^2}\sum_{\alpha=L,R}\Big[C_{D\alpha}\; m_\mu\; \bar{e}\sigma^{\lambda\nu}P_\alpha\mu\, F_{\lambda\nu}$$
$$+\sum_{q=u,d,s,} C^{(q)}_{S\alpha}\; G_F m_\mu m_q\, \bar{q}q\,\bar{e}P_\alpha\mu$$
$$+\; C_{G\alpha}\; G_F m_\mu \alpha_s\, G^a_{\lambda\nu}G^{a\,\lambda\nu}\bar{e}P_\alpha\mu + \text{h.c}\Big]$$



- Matching conditions for minimal Higgs-mediated LFV: scalar and gluon →

$$\frac{1}{\Lambda^2}G_F m_\mu v C^{(q)}_{SR} = -\frac{1}{m_h^2}Y_{e\mu},$$
$$\frac{1}{\Lambda^2}G_F m_\mu v C^{(q)}_{SL} = -\frac{1}{m_h^2}Y_{\mu e},$$
$$C_{G\alpha} = -1/(12\pi)\sum_{Q=c,b,t} C^{(Q)}_{S\alpha}$$

- For C_D, see refs. in previous slide

Matching to ChPT / ChEFT (I)

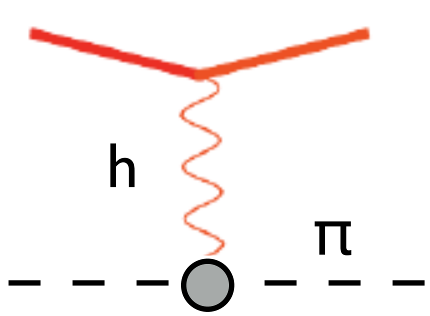
- Chiral power counting for the scalar density (expand in p/Λ_χ) with $\Lambda_\chi \sim$ GeV

$$p \sim p_N,\ m_\pi,\ q_{ext}\ (\sim m_\mu)$$

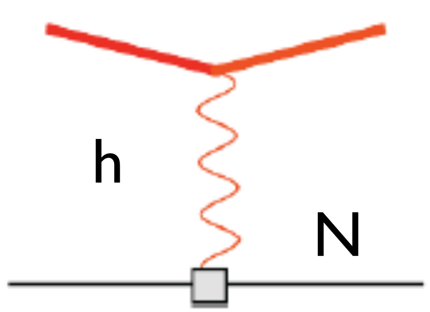
- Leading couplings controlled by

$$\frac{f_\pi^2}{4}\mathrm{Tr}\,[U^\dagger \chi + U\chi^\dagger] + c_1 \mathrm{Tr}(\chi_+)\bar{N}N$$

$$\chi = 2Bm_q\left(1+\frac{h}{\sqrt{2}v}\right) \qquad \chi_\pm = u^\dagger \chi u^\dagger \pm u\chi^\dagger u$$



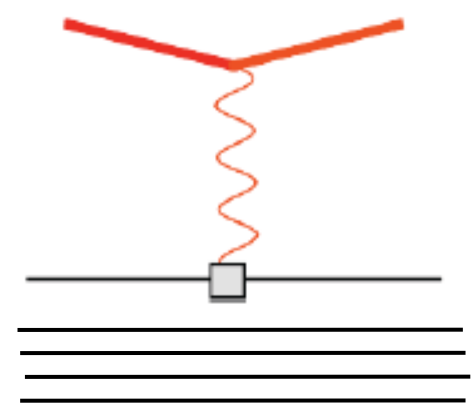
$\sim (m_\pi)^2$



$\sim c_1\,(m_\pi)^2$ $\qquad c_1 \sim 1/\Lambda_\chi$

Matching to ChPT / ChEFT (I)

- Chiral power counting for the scalar density (expand in p/Λ_χ) with $\Lambda_\chi \sim$ GeV



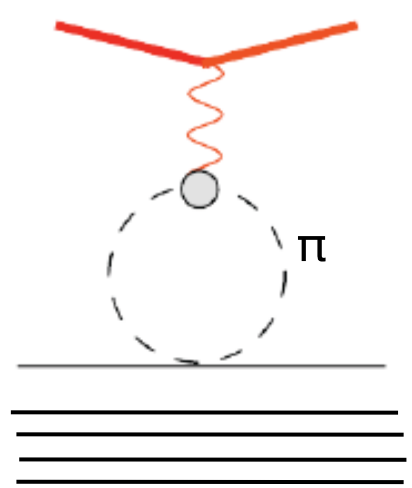
- Leading order

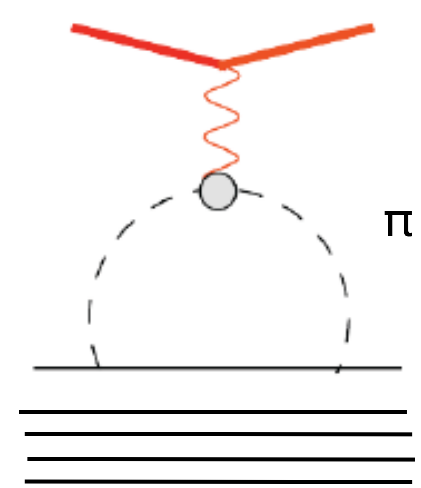
  $\sim (m_\pi)^2/\Lambda_\chi$

Nucleon "Sigma term"

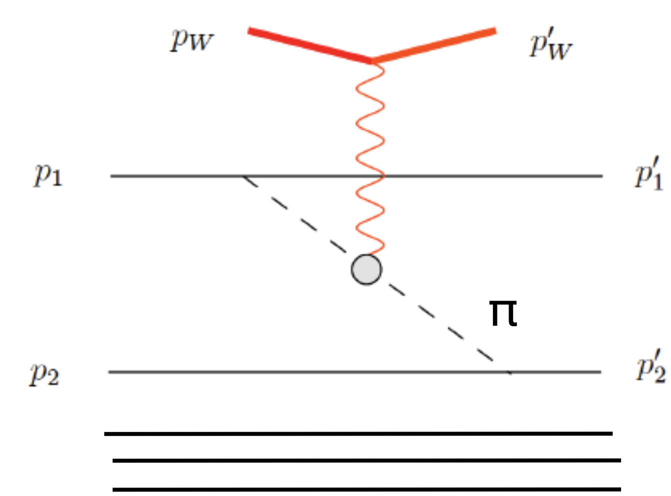
- NLO

  $\sim (m_\pi)^2/\Lambda_\chi \times (p/\Lambda_\chi)$





Scalar form factor of the nucleon



Two-nucleon operator (see Bira van Kolck's talk)

Matching to ChPT / ChEFT (2)

- One-nucleon scalar operators

Crivellin-Hoferichter-Procura 1404.7134
Korber-Nogga-deVries 1704.01150

u, d

$$\langle N(\mathbf{k}')|\, C^{(u)}_{S\alpha} m_u \bar{u}u + C^{(d)}_{S\alpha} m_d \bar{d}d \,|N(\mathbf{k})\rangle \to \bar{N}'\, J^{(1)}_{ud,\alpha}(\mathbf{q})\, N$$

$$J^{(1)}_{ud,\alpha}(\mathbf{q}) = \left[\sigma_{\pi N} - \frac{3 m_\pi^3 g_A^2}{64\pi f_\pi^2}\, F(\mathbf{q}^2/m_\pi^2)\right] C^{(0)}_{S\alpha} - \frac{\delta m_N}{4} \tau_3\, C^{(1)}_{S\alpha}$$

s

$$\langle N(\mathbf{k}')|\, C^{(s)}_{S\alpha} m_s \bar{s}s \,|N(\mathbf{k})\rangle \to \bar{N}'\, J^{(1)}_{s,\alpha}(\mathbf{q})\, N \qquad J^{(1)}_{s,\alpha}(\mathbf{q}) = \left(\sigma_s - \dot{\sigma}_s \mathbf{q}^2\right)\, C^{(s)}_{S\alpha}$$

Hadronic input

$$\sigma_{\pi N} = \frac{1}{2}\langle N|\,(m_u + m_d)(\bar{u}u + \bar{d}d)\,|N\rangle$$

$$\sigma_s = \langle N|\, m_s \bar{s}s \,|N\rangle$$

$$\epsilon = \frac{m_d - m_u}{m_d + m_u}$$

$$\delta m_N = (m_n - m_p)_{\text{strong}} \ .$$

Isoscalar / isovector combinations of Wilson Coefficients

$$C^{(0)}_{S\alpha} = \frac{C^{(u)}_{S\alpha}(1-\epsilon) + C^{(d)}_{S\alpha}(1+\epsilon)}{2}$$

$$C^{(1)}_{S\alpha} = C^{(u)}_{S\alpha}\left(1 - \frac{1}{\epsilon}\right) + C^{(d)}_{S\alpha}\left(1 + \frac{1}{\epsilon}\right)$$

Matching to ChPT / ChEFT (2)

Crivellin-Hoferichter-Procura 1404.7134
Korber-Nogga-deVries 1704.01150

- One-nucleon scalar operators

u, d

$$\langle N(\mathbf{k}')|\, C_{S\alpha}^{(u)} m_u \bar{u}u + C_{S\alpha}^{(d)} m_d \bar{d}d \,|N(\mathbf{k})\rangle \to \bar{N}' \, J_{ud,\alpha}^{(1)}(\mathbf{q}) \, N$$

$$J_{ud,\alpha}^{(1)}(\mathbf{q}) = \left[\sigma_{\pi N} - \frac{3 m_\pi^3 g_A^2}{64\pi f_\pi^2} \, F(\mathbf{q}^2/m_\pi^2)\right] C_{S\alpha}^{(0)} - \frac{\delta m_N}{4} \tau_3 \, C_{S\alpha}^{(1)}$$

s

$$\langle N(\mathbf{k}')|\, C_{S\alpha}^{(s)} m_s \bar{s}s \,|N(\mathbf{k})\rangle \to \bar{N}' \, J_{s,\alpha}^{(1)}(\mathbf{q}) \, N \qquad J_{s,\alpha}^{(1)}(\mathbf{q}) = \left(\sigma_s - \dot{\sigma}_s \mathbf{q}^2\right) \, C_{S\alpha}^{(s)}$$

Hadronic input

$$\sigma_{\pi N} = \frac{1}{2} \langle N|\, (m_u + m_d)(\bar{u}u + \bar{d}d) \,|N\rangle$$
$$\sigma_s = \langle N|\, m_s \bar{s}s \,|N\rangle$$
$$\epsilon = \frac{m_d - m_u}{m_d + m_u}$$
$$\delta m_N = (m_n - m_p)_{\text{strong}} \, .$$

From lattice QCD & dispersion relations:

$$\sigma_{\pi N} = 59.1(3.5) \ \text{MeV} \quad \text{(D)}$$
$$\sigma_s = 41(9) \text{MeV} \quad \text{(L)}$$
$$\dot{\sigma}_s = 0.3(2) \ \text{GeV}^{-1} \quad \text{(D)}$$
$$\epsilon = 0.365(23) \quad \text{(L)}$$
$$\delta m_N = 2.32(17) \ \text{MeV} \quad \text{(L)}$$

Matching to ChPT / ChEFT (3)

VC-Graesser-Ovanesyan 1205.2695
Korber-Nogga-deVries 1704.01150

- Two-nucleon scalar operator

$$\langle N(\mathbf{k}_1')N(\mathbf{k}_2')|\, C_{S\alpha}^{(u)} m_u \bar{u}u + C_{S\alpha}^{(d)} m_d \bar{d}d \,|N(\mathbf{k}_1)N(\mathbf{k}_2)\rangle \to \; \bar{N}_1' \bar{N}_2' \, J_{ud,\alpha}^{(2)}(\mathbf{q}_1, \mathbf{q}_2)\, N_1 N_2$$

$$J_{ud,\alpha}^{(2)}(\mathbf{q}_1, \mathbf{q}_2) = -\frac{g_A^2 m_\pi^2}{4 f_\pi^2} \frac{\sigma_1 \cdot \mathbf{q}_1 \, \sigma_2 \cdot \mathbf{q}_2}{(\mathbf{q}_1^2 + m_\pi^2)(\mathbf{q}_2^2 + m_\pi^2)} \tau_1 \cdot \tau_2 \, C_{S\alpha}^{(0)}$$

- Crude estimate: reduce to a single-nucleon operator by averaging over the second nucleon in a Fermi-gas model

For ^{27}Al

$$f_{\text{eff}}^{SI} = 0.43^{+0.03}_{-0.22}$$

$$\sigma_{\pi N} \to \sigma_{\pi N} - \frac{3 g_A^2 m_\pi^2 k_F}{64 \pi f_\pi^2} f_{\text{eff}}^{SI}$$

~10% negative shift

- Nuclear shell model implies smaller results (~1/2), but no way to estimate the uncertainty → need first-principles nuclear calculation

Conversion rate

$$B_{\mu\to e} = \left(\frac{v}{\Lambda}\right)^4 \frac{1}{\kappa_{\rm capt}} \left(\left|\tau^{(+1)}\right|^2 + \left|\tau^{(-1)}\right|^2 \right)$$

Two electron angular momentum states

- Amplitude receives dipole and scalar / gluon contribution

$$\tau^{(-1)} = (C_{DL} + C_{DR})\, \tau_D^{(-1)} + \tau_S^{(-1)}$$

- Dipole amplitude is controlled by nuclear charge distribution, which also determines muon and electron wave functions (key input is the proton density**)

$$\tau_D^{(-1)} = \frac{1}{m_\mu^{3/2}} \int dr\; r^2 (-E(r)) \left(g_{-1}^{(e)} f_{-1}^{(\mu)} + f_{-1}^{(e)} g_{-1}^{(\mu)} \right)$$

** Modulo effect discussed by J. Dobaczewski

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$$\tau^{(-1)} = (C_{DL} + C_{DR})\, \tau_D^{(-1)} + \tau_S^{(-1)}$$

- Scalar amplitude: Wilson coeff. ✖ hadronic input ✖ overlap integrals

C_{NL}, C_{NR} : W.C. ✖ hadronic matrix elements

$$\tau_S^{(-1)} = \frac{1}{2} G_F m_\mu^2 \sum_{N=p,n} \left[(C^\rho_{NL} + C^\rho_{NR})\, \tau^{(-1)}_{\rho_N} + \left(C^f_{NL} + C^f_{NR}\right) \tau^{(-1)}_{f_N} \right]$$

ρ_N, f_N : nucleon densities and their derivatives

$$\tau^{(-1)}_{\rho_N(f_N)} = \frac{1}{m_\mu^{5/2}} \int dr\ r^2 \left(g^{(e)}_{-1} g^{(\mu)}_{-1} - f^{(e)}_{-1} f^{(\mu)}_{-1} \right) \rho_N(f_N),$$

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- Scalar amplitude: Wilson coeff. ✖ hadronic input ✖ overlap integrals

- Size of NLO corrections to amplitudes induced by light quarks:
  - Roughly −5% from momentum-dep. in the nucleon form factor
  - Roughly −10% from two-body operator

Conversion rate

$$B_{\mu\to e} = \left(\frac{v}{\Lambda}\right)^4 \frac{1}{\kappa_{\rm capt}} \left(\left|\tau^{(+1)}\right|^2 + \left|\tau^{(-1)}\right|^2 \right)$$

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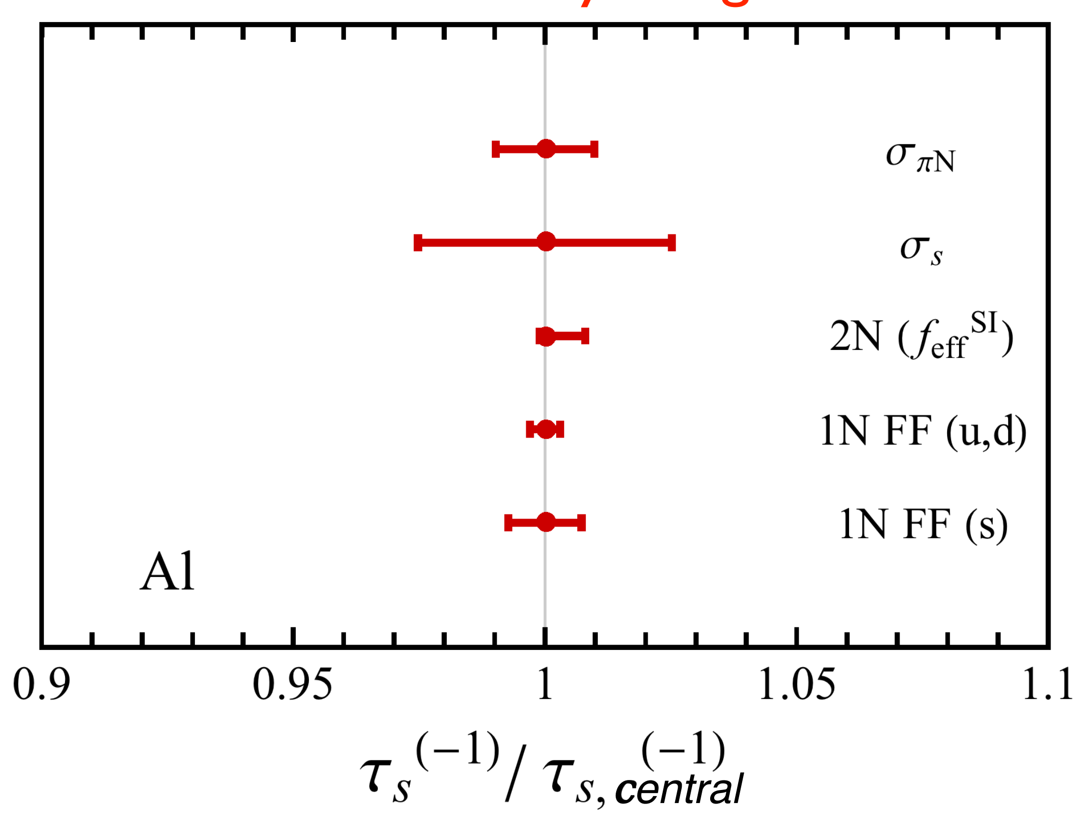
Uncertainty budget



- Largest hadronic uncertainty arises at LO (from sigma terms)
- LO uncertainty from neutron density not a big problem when info from pionic atoms is available (not for ^{44}Ti)
- The quite uncertain NLO NN term does note have huge impact for this choice of short-distance physics

Conversion rate

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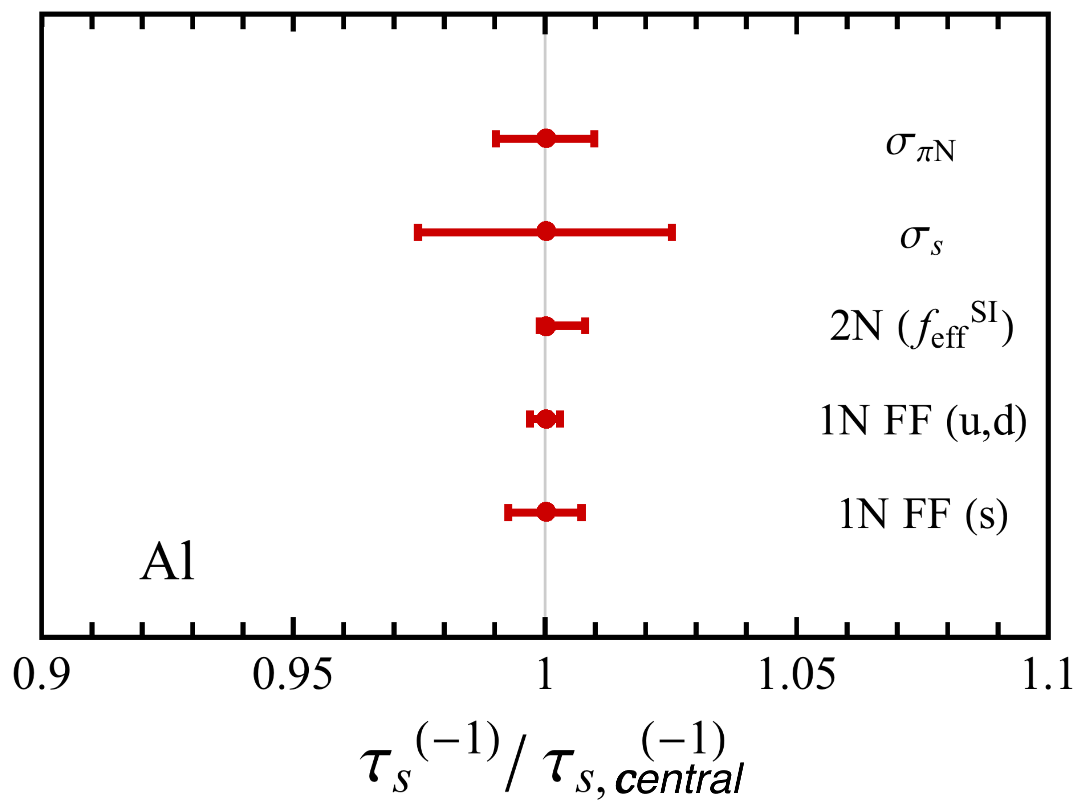
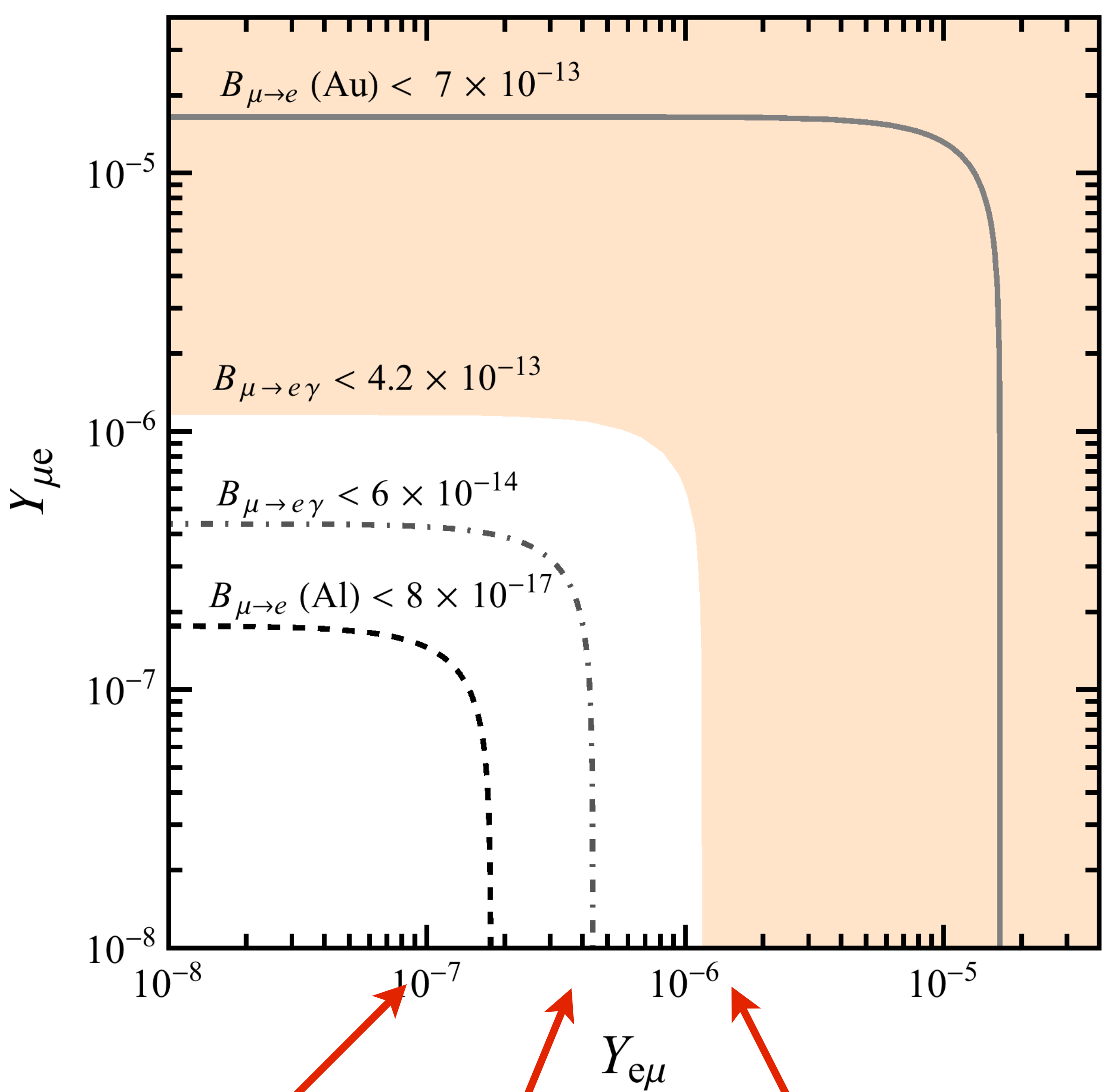


- Impact of NLO corrections on rate depends on short-distance physics.
- Largest (−20%) when light-quarks dominate
- Typically similar or larger to LO error ⇒ phenomenologically relevant

Pattern of LFV μ decays

VC, Fuyuto, Ramsey-Musolf, Rule 2203.09547



Future μ→e

Future & Current μ→eγ

- μ→eγ is currently probing $|Y_{\mu e}| \sim 10^{-6}$, which corresponds to BR(h→μe) < 10^{-9}
- Upcoming μ→e conversion experiments will probe $|Y_{\mu e}| \sim 10^{-7}$
- Correlated signals in μ→e transitions provide opportunity to test hypothesis of Higgs-mediated LFV

BR(μ→e,Al) / BR(μ→eγ) = 8.7(3) 10^{-3} **

BR(μ→e,Ti) / BR(μ→e,Al) = 1.5(1)

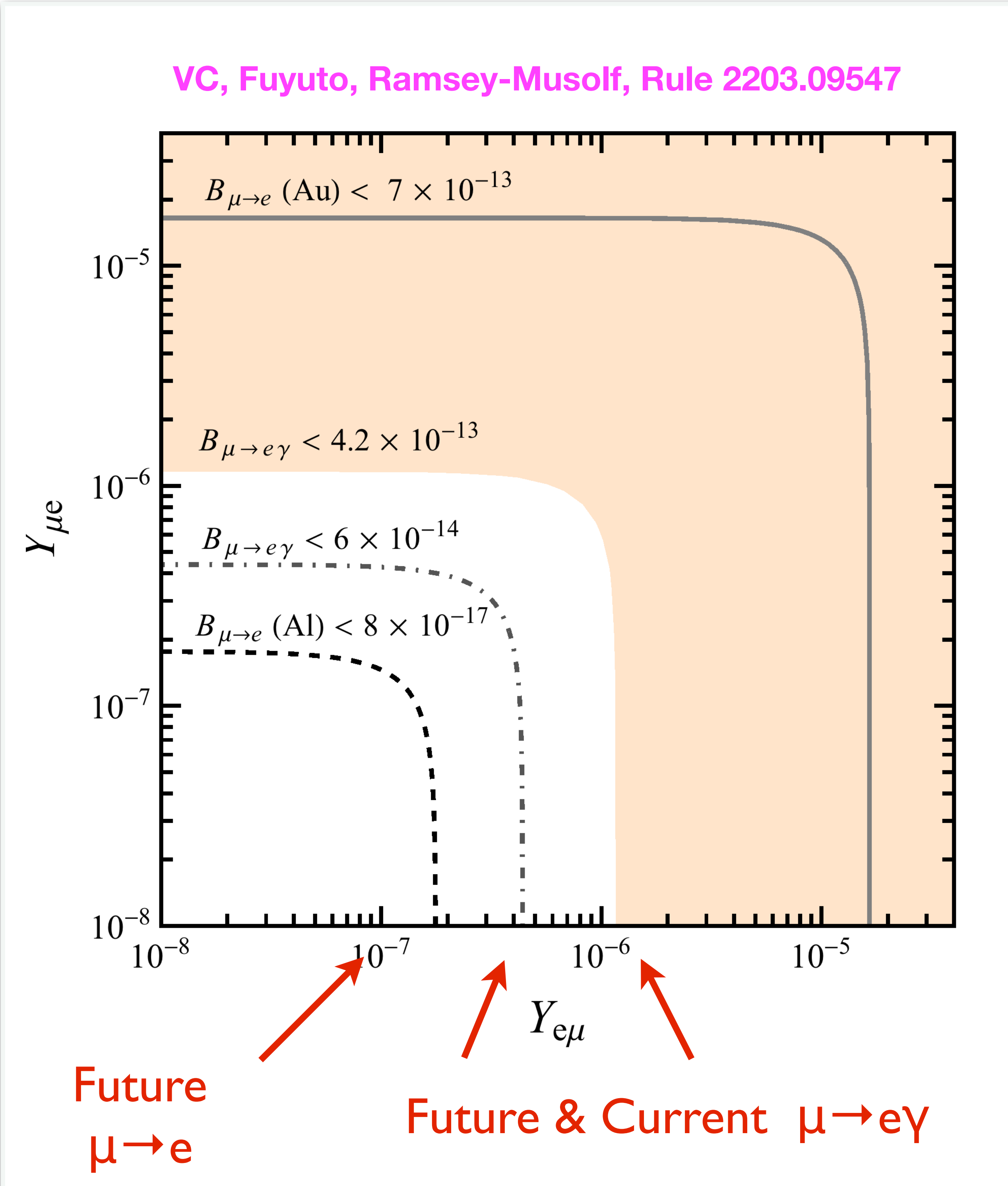
VC, Fuyuto, Ramsey-Musolf, Rule 2203.09547

(See also Crivellin et al. 1404.7134)

* Diagonal couplings set to SM value

** LO result is 9.0(3) 10^{-3}

Pattern of LFV μ decays



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BR(μ→e,Al) / BR(μ→eγ) = 8.7(3) 10^{-3} **

BR(μ→e,Ti) / BR(μ→e,Al) = 1.5(1)

VC, Fuyuto, Ramsey-Musolf, Rule 2203.09547

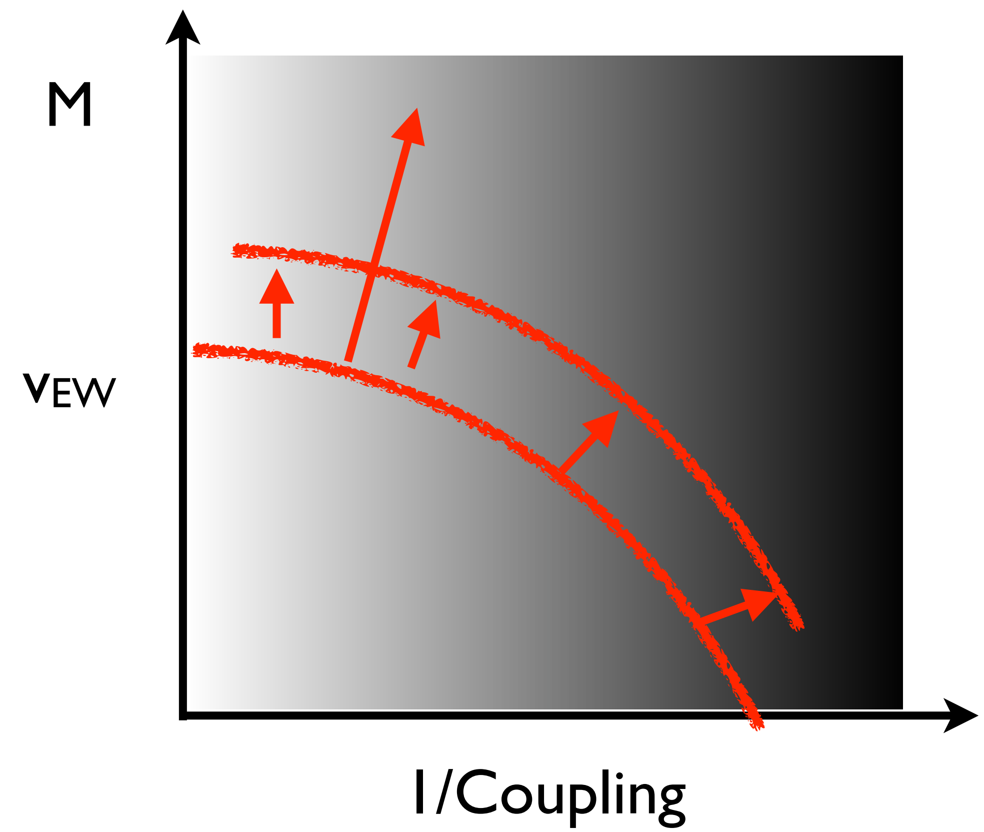
(See also Crivellin et al. 1404.7134)

- Further scrutiny of uncertainties is desirable

Conclusions & Outlook

- Charged LFV processes probe a broad spectrum of new physics
  - *Discovery* tools: clean, very high scale reach
  - *Model-diagnosing* tools: mediators, sources of flavor breaking

- Higgs-mediated LFV
  - Illustrated the interplay of UV physics with hadronic / nuclear aspects of μ-to-e conversion
  - If a discovery is made, μ-to-e processes can be used to test the hypothesis of Higgs-mediated LFV



Conclusions & Outlook

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Exciting experimental prospects

★ 4 (1-2) orders of magnitude improvement in μ (τ) decays

★ LHC & EIC will be competitive in τ-μ and τ-e transitions ($h \to \tau\mu$, $e \to \tau$)

★ Muon processes have unmatched sensitivity in probing μ-e transitions

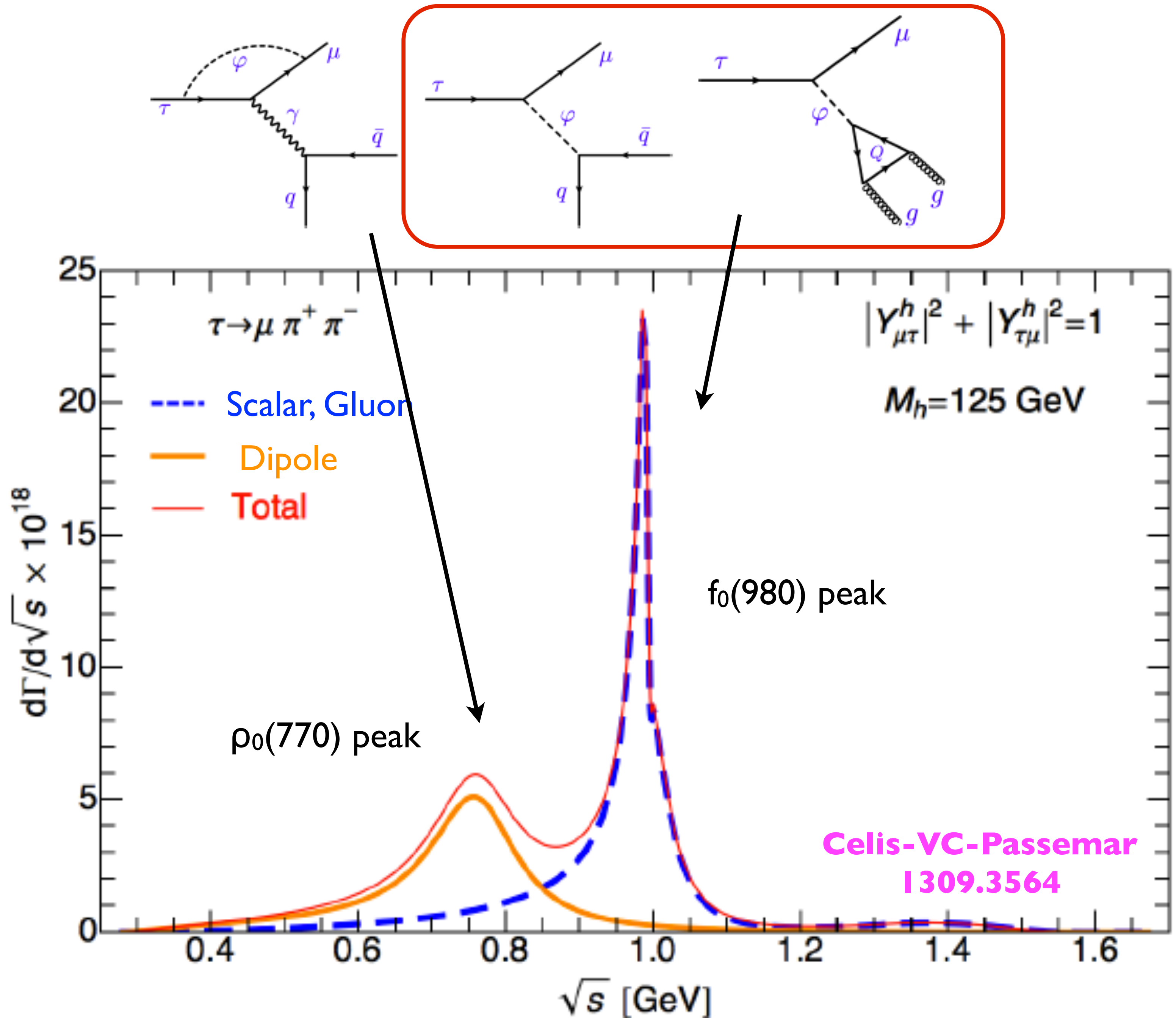
Backup

Pattern of LFV τ decays

- Radiative mode dominates, followed by ππ and 3 lepton

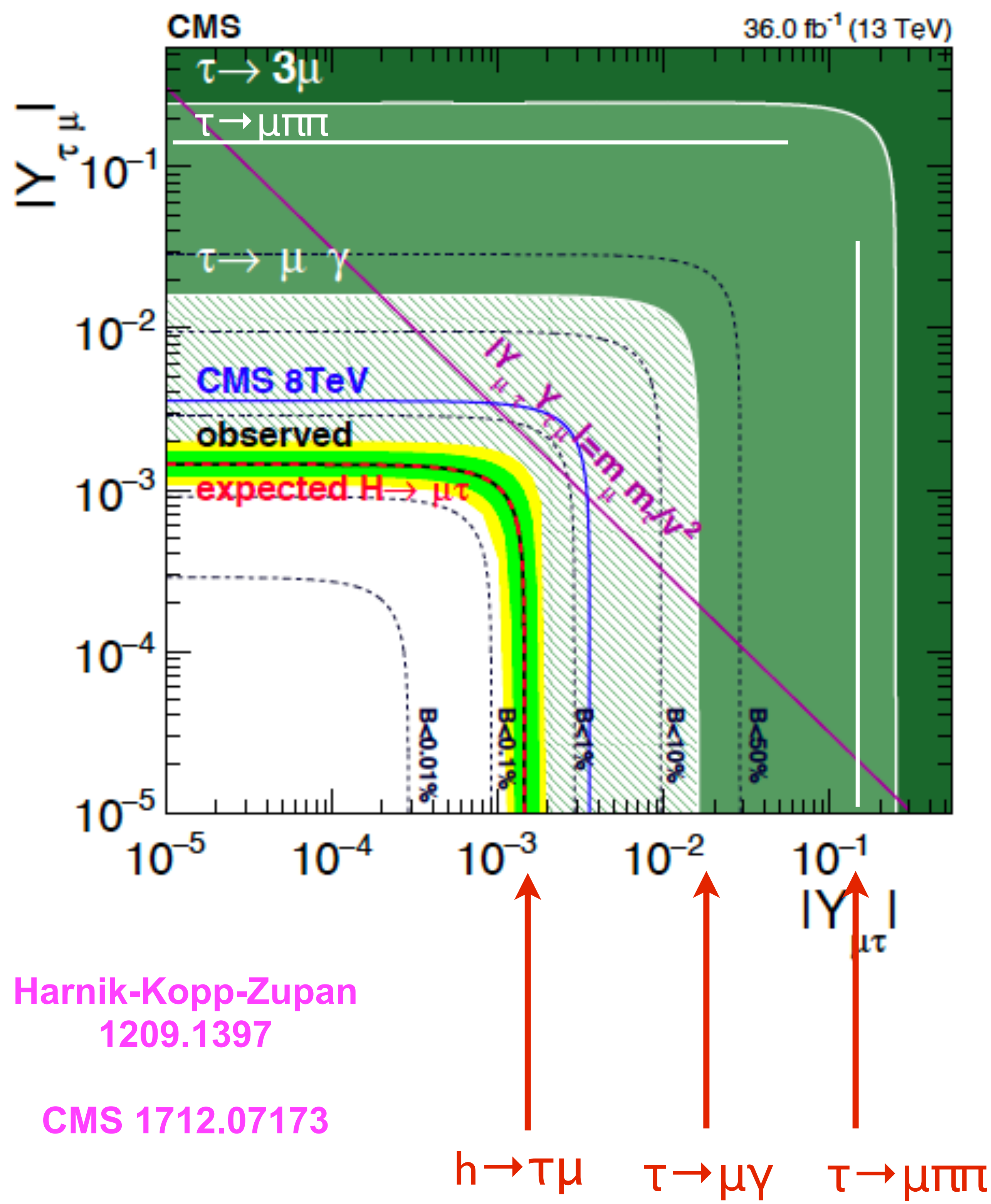
$B(\tau \to \mu\pi^+\pi^-) / B(\tau \to \mu\gamma) = 0.7(1) \times 10^{-2}$

- τ→μππ controlled by Higgs-specific combination of D, S, G → unique signature in ππ spectrum



Plot assumes SM values for $Y_{u,d,s}$, but strength of the $f_0(980)$ peak depends on light quark Yukawas

τ-μ sector: h vs τ decays

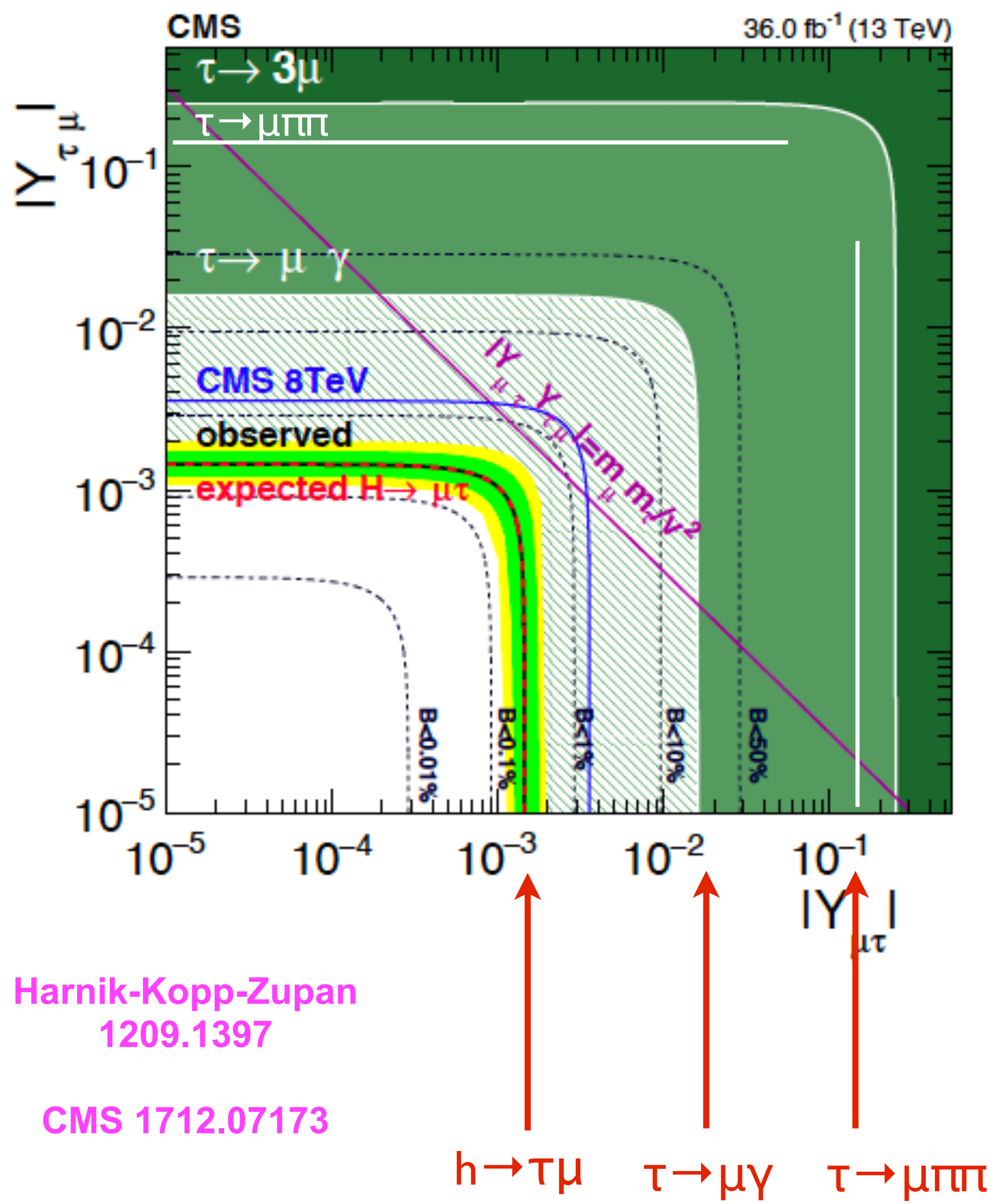


Harnik-Kopp-Zupan
1209.1397

CMS 1712.07173

- Assuming SM values for $Y_{u,d,s}$, current tau BRs ($\sim 10^{-(7\text{-}8)}$) imply $Y_{\tau\mu,\tau e} < 0.01\text{-}0.1$, which translates into BR($h \to \mu\tau$) < 0.1
- LHC (CMS) limit BR($h \to \mu\tau$) <0.25% (95%CL) is stronger: $|Y_{\tau\mu,\mu\tau}| < 0.0011$

τ-μ sector: h vs τ decays



Harnik-Kopp-Zupan 1209.1397

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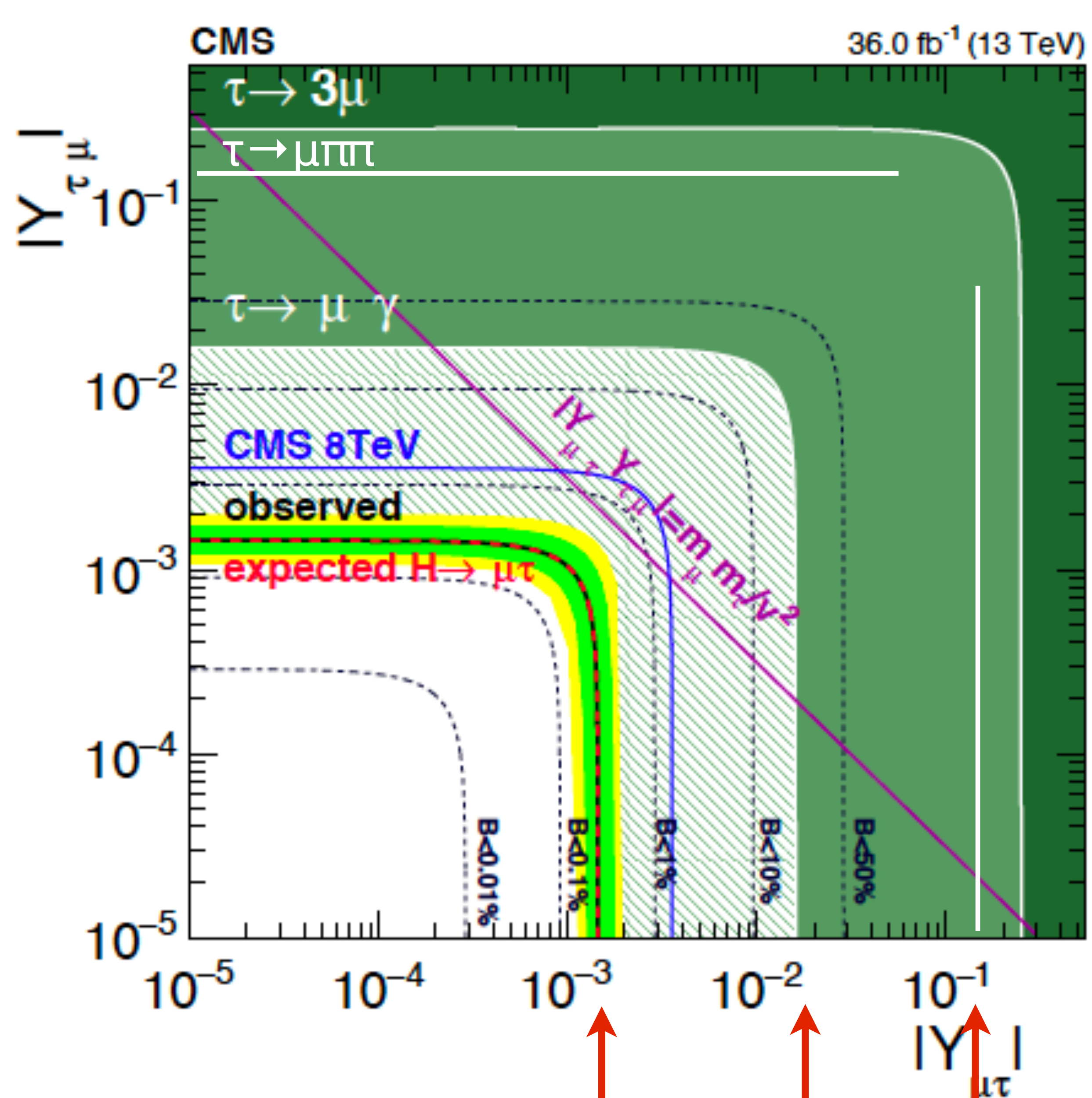
- Assuming SM values for $Y_{u,d,s}$, current tau BRs ($\sim 10^{-(7-8)}$) imply $Y_{\tau\mu,\tau e} < 0.01$-$0.1$, which translates into BR(h→μτ) < 0.1
- LHC (CMS) limit BR(h→μτ) <0.25% (95%CL) is stronger: $|Y_{\tau\mu,\mu\tau}| < 0.0011$
- If use SM values for $Y_{u,d,s}$, CMS bound implies

$$B(\tau\to\mu\gamma) < 4\times10^{-10}$$
$$B(\tau\to\mu\pi^+\pi^-) < 2.7\times10^{-12}$$
$$B(\tau\to\mu\pi^0\pi^0) < 0.8\times10^{-12}$$

Challenging target for next generation

τ-μ sector: h vs τ decays



h→τμ   τ→μγ   τ→μππ

Harnik-Kopp-Zupan 1209.1397

CMS 1712.07173

- Assuming SM values for $Y_{u,d,s}$, current tau BRs ($\sim 10^{-(7-8)}$) imply $Y_{\tau\mu,\tau e} < 0.01$-$0.1$, which translates into BR($h \to \mu\tau$) < 0.1
- LHC (CMS) limit BR($h \to \mu\tau$) <0.25% (95%CL) is stronger: $|Y_{\tau\mu,\mu\tau}| < 0.00143$
- If use $Y_{u,d,s} \sim Y_b$, CMS bound implies

$B(\tau \to \mu\gamma) < 4.0 \times 10^{-10}$

$B(\tau \to \mu\pi^+\pi^-) < 5.5 \times 10^{-9}$

$B(\tau \to \mu\pi^0\pi^0) < 2.7 \times 10^{-9}$

Within reach of next generation

Matching for gluon operator

- Similar to scalar density, one- and two-body terms

$$\langle N(\mathbf{k}')|\, C_{G\alpha}\alpha_s G^a_{\lambda\nu} G^{a\,\lambda\nu}\, |N(\mathbf{k})\rangle \to \bar{N}'\, J^{(1)}_{G,\alpha}(\mathbf{q})\, N$$

$$\langle N(\mathbf{k}'_1)N(\mathbf{k}'_2)|\, C_{G\alpha}\alpha_s G^a_{\lambda\nu} G^{a\,\lambda\nu}\, |N(\mathbf{k}_1)N(\mathbf{k}_2)\rangle \to \bar{N}'_1\bar{N}'_2\, J^{(2)}_{G,\alpha}(\mathbf{q}_1,\mathbf{q}_2)\, N_1 N_2$$

$$J^{(1)}_{G,\alpha}(\mathbf{q}) = -\frac{8\pi}{9} C_{G\alpha} \left(m_N - \left[\sigma_{\pi N} - \frac{3 m_\pi^3 g_A^2}{64\pi f_\pi^2} F(\mathbf{q}^2/m_\pi^2) \right] + \frac{\delta m_N}{2}\tau_3 - \left(\sigma_s - \dot{\sigma}_s \mathbf{q}^2\right) \right)$$

$$J^{(2)}_{G,\alpha}(\mathbf{q}_1,\mathbf{q}_2) = -\frac{8\pi}{9} C_{G\alpha}\, \frac{g_A^2 m_\pi^2}{4 f_\pi^2}\, \frac{\sigma_1\cdot\mathbf{q}_1\, \sigma_2\cdot\mathbf{q}_2}{(\mathbf{q}_1^2+m_\pi^2)(\mathbf{q}_2^2+m_\pi^2)} \tau_1\cdot\tau_2\,.$$