LEPTON FLAVOUR VIOLATION
(LECTURES 1 & 2)

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Future flavours: prospects for beauty, charm, and tau physics, ICTS, May 2 2022

OUTLINE

- lecture 1: lepton flavor in the SM
- lecture 2: LFV observables in muons
- lecture 3: LFV in taus; Higgs and flavor
- lecture 4: LFV searches and light new physics

OUTLINE LECTURES 1 & 2

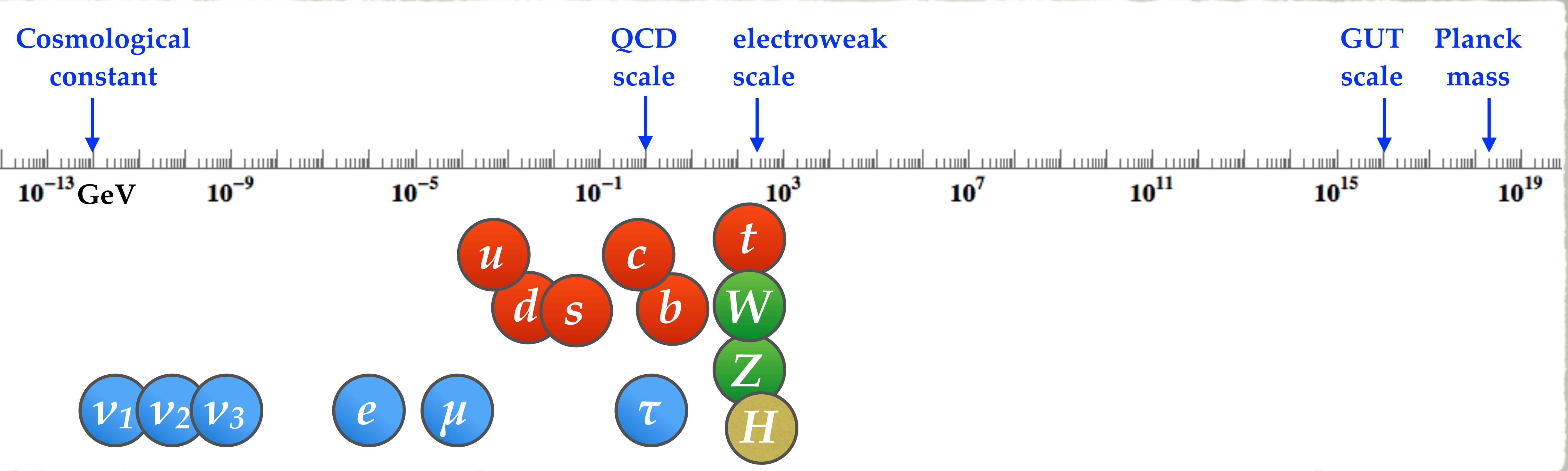
- in lectures 1 & 2:
  - leptonic vs. quark flavor structure in the standard model
  - observables sensitive to lepton flavor violation in muons

USEFUL REFERENCES

- some general introductions to flavor physics
  - Yuval Grossman's lectures in this school
  - Nir, 0708.1872, 1605.00433
  - Grossman, Tanedo, 1711.03624
  - JZ, 1903.05062
  - ...
- on lepton flavor violation
  - Calibbi, Sirognelli, 1709.00294
  - Ardu, Pezzullo, 2204.08220

QUARKS VS. LEPTONS

- when comparing quark and lepton sector of the Standard Model we observe:
- leptons of the same generation are lighter than quarks
  - smaller number of kinematically allowed decay modes for τ, μ than for t,b,c
  - *e.g.*, $B^- \to \tau^- \bar{\nu}_\tau$ allowed, while $\tau^- \to B^- \nu_\tau$ is not
- quarks carry color ⇒ bound inside hadrons
  - lepton decays are simpler to predict
- "up" leptons' (=ν's) mass ≪ "down" leptons' (=ℓ') mass
  - absolute neutrino masses not yet known
  - in many processes neutrino masses can be neglected



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QUARKS

- in the SM the flavor structure resides in the Yukawa interactions

$$\mathcal{L}_{\text{Yukawa}} \supset -Y_d^{ij}\bar{Q}_L^i H d_R^j - Y_u^{ij}\bar{Q}_L^i H^c u_R^j + \text{h.c.}$$

- $Y_{u,d}$ are 3×3 complex matrices
  - each can be diagonalized by a bi-unitary transform.
  - but not both at the same time (i.e. both can be made diagonal only after EWSB when we split Q_L into upper and lower components)
- keeping $SU(2)_L$ symmetry explicit perform quark field redefinitions

$$Q'_L = V_Q Q_L \qquad u'_R = V_u u_R \qquad d'_R = V_d d_R$$

  - so that the Yukawa matrices transform to

$$Y'_u = V_Q^\dagger Y_u V_u \qquad Y'_d = V_Q^\dagger Y_d V_d$$

- can choose a basis such that (down quark mass basis)

$$Y_d = \text{diag}(y_d, y_s, y_b), \qquad Y_u = V^\dagger \, \text{diag}(y_u, y_c, y_t)$$

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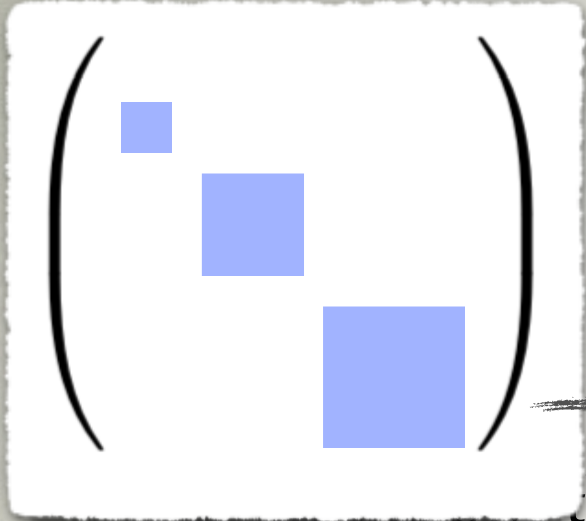
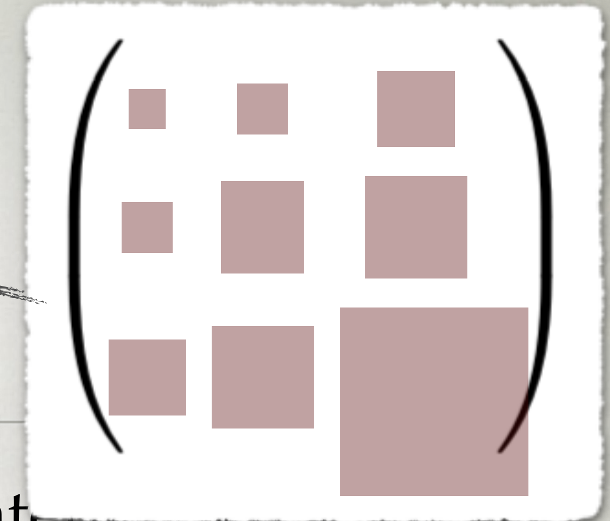
CKM matrix



QUARKS



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QUARKS

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$$Y_d = \text{diag}(y_d, y_s, y_b), \qquad Y_u = V^\dagger \, \text{diag}(y_u, y_c, y_t)$$

- can move flavor changing interactions to kinetic term by field redefinition

$$Q_L \to \begin{pmatrix} V^\dagger u_L \\ d_L \end{pmatrix}, \qquad \mathcal{M}_q = Y_q \frac{(v+h)}{\sqrt{2}}. \qquad H = \begin{pmatrix} 0 \\ (v+h)/\sqrt{2} \end{pmatrix}$$

  - in the so-called mass basis

$$\mathcal{L}_{\text{SM}} \supset (\bar{q}_i \not{D}_{\text{NC}} q_i) + \frac{g}{\sqrt{2}} \bar{u}_L^i \not{W}^+ V_{\text{CKM}}^{ij} d_L^j + m_{u_i} \bar{u}_L^i u_R^i (1 + \frac{h}{v}) + m_{d_i} \bar{d}_L^i d_R^i (1 + \frac{h}{v}) + \text{h.c.},$$

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- all flavor violation in charged currents (couplings to $W^{\pm}$)
- neutral currents are flavor conserving
  - no flavor viol. in Z couplings
  - couplings to Higgs are flavor diagonal

CKM MATRIX

- hierarchical structure + unitarity
  - encoded in Wolfenstein parametrization

$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\lambda \equiv |V_{us}| \simeq 0.22$$

- CKM matrix depends on 3 real params, 1 phase
  - 3 mixing angles, 1 phase
  - in Wolfenstein param. trade for
    - 3 real params: λ, A, ρ,
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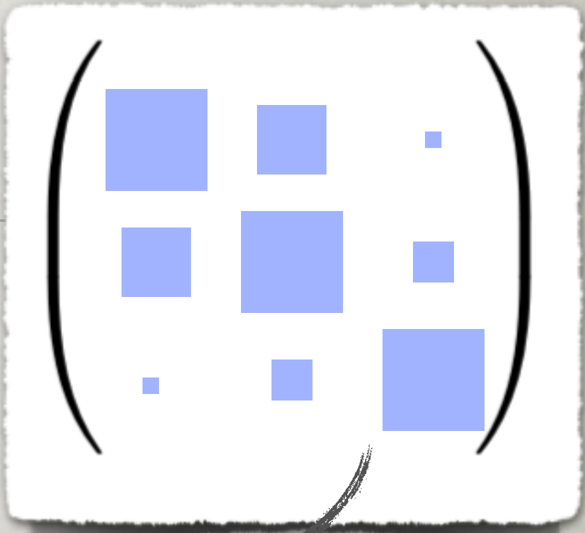

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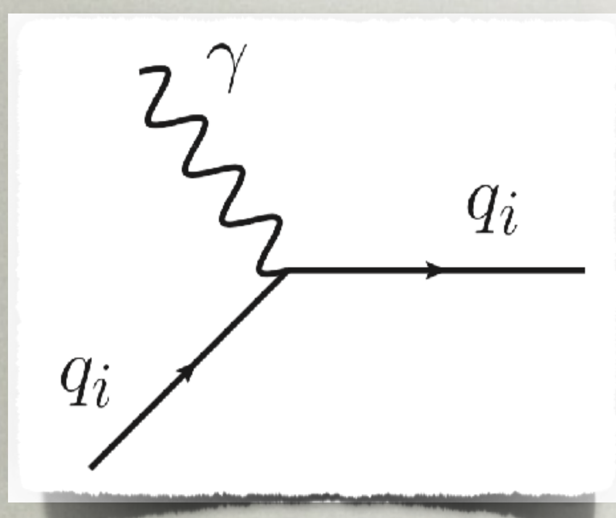
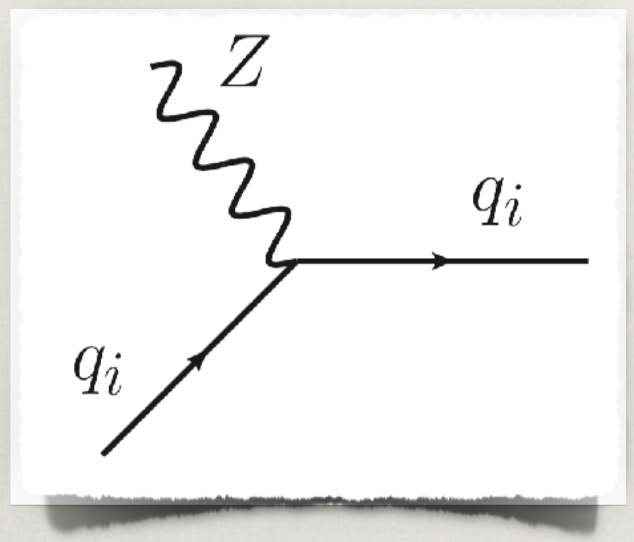
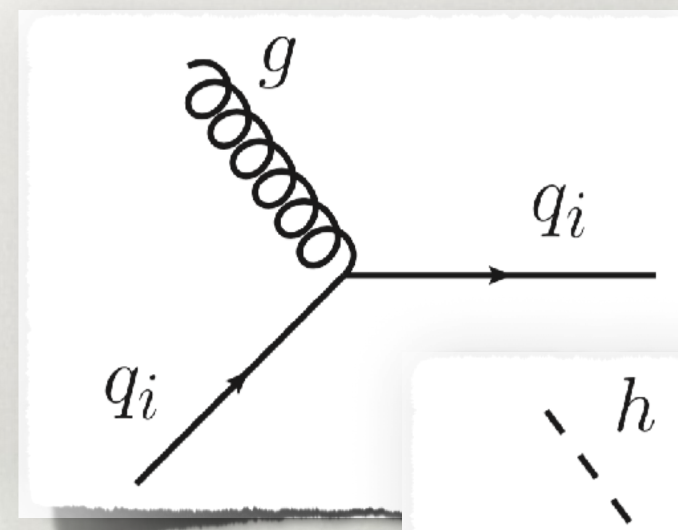
FLAVOR IN THE SM QUARK SECTOR

- neutral currents are flavor conserving (at tree level)
  - photon, gluon, *Z:* have *flavor (generation) universal* interactions







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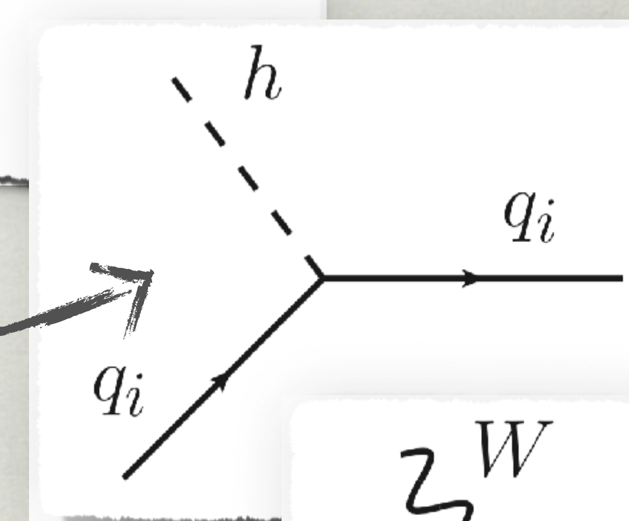
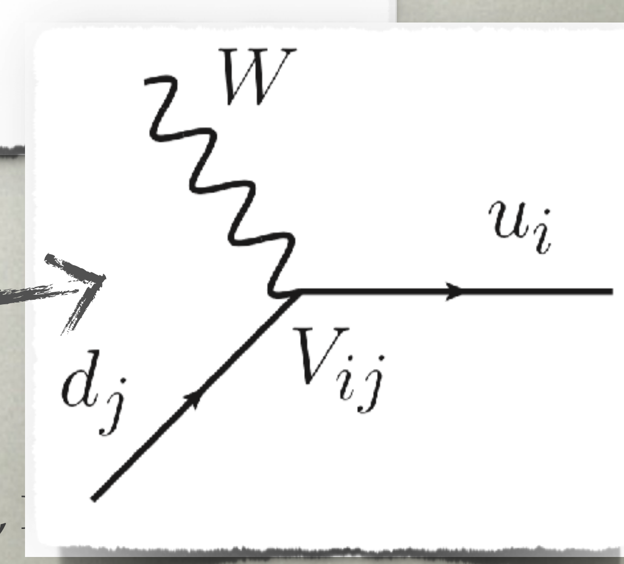
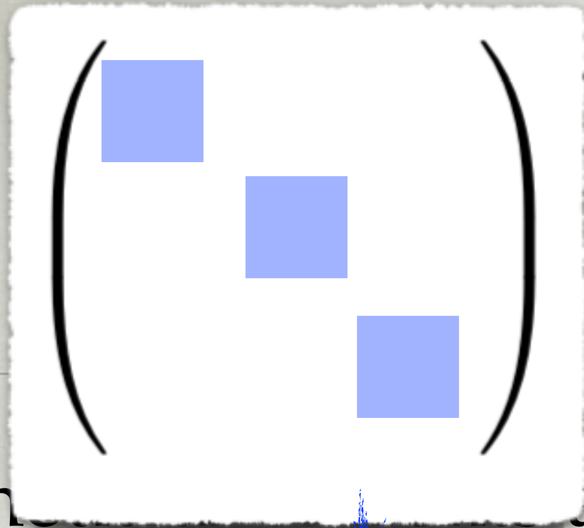


- charged currents are *flavor changing*
  - *W* couplings are flavor changing





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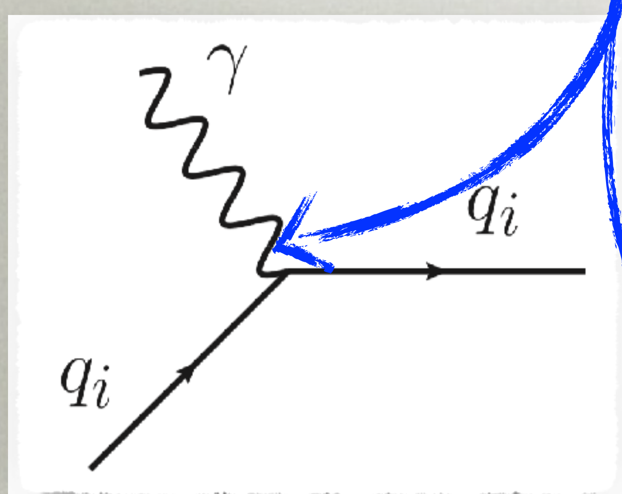

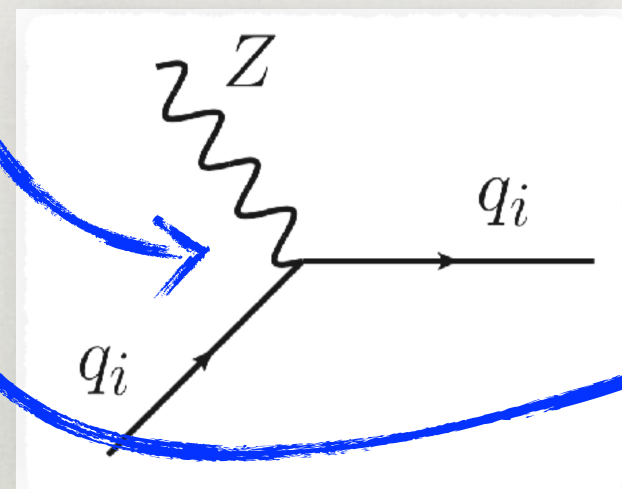

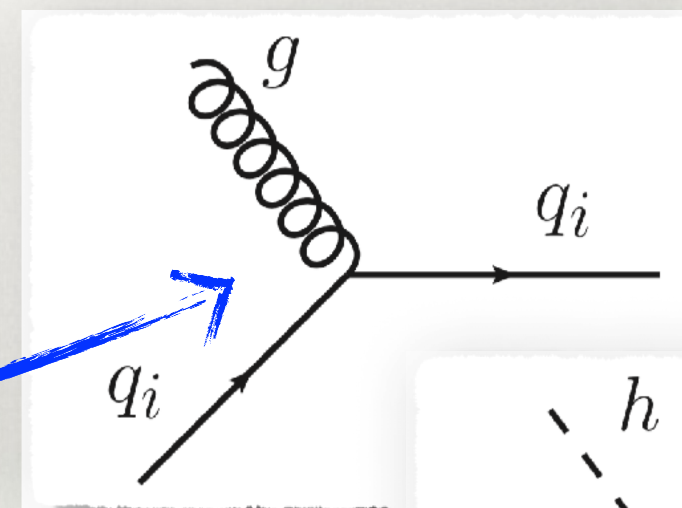

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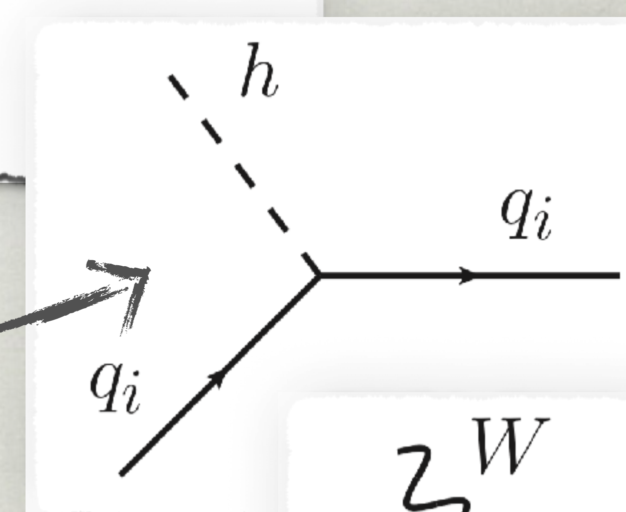

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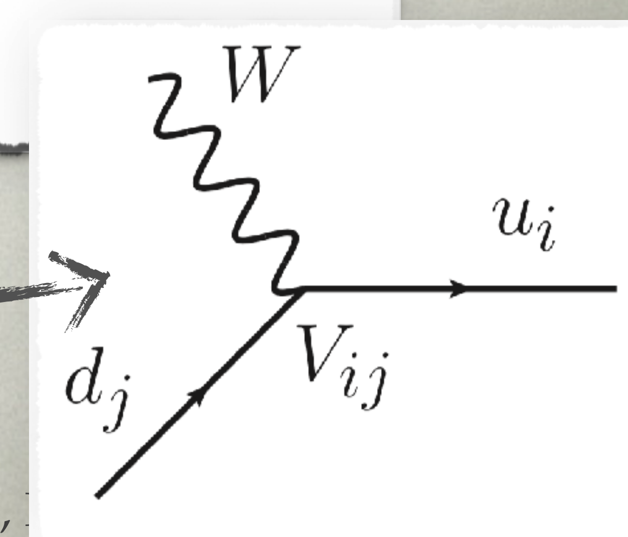

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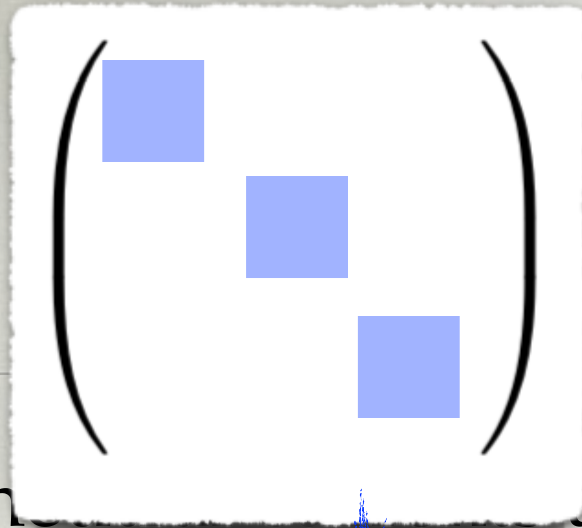

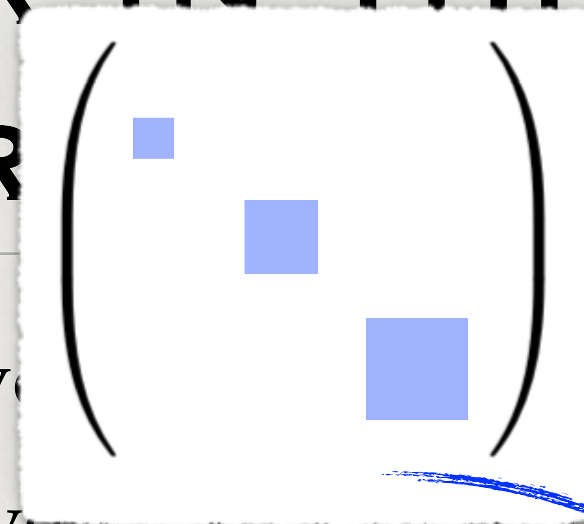

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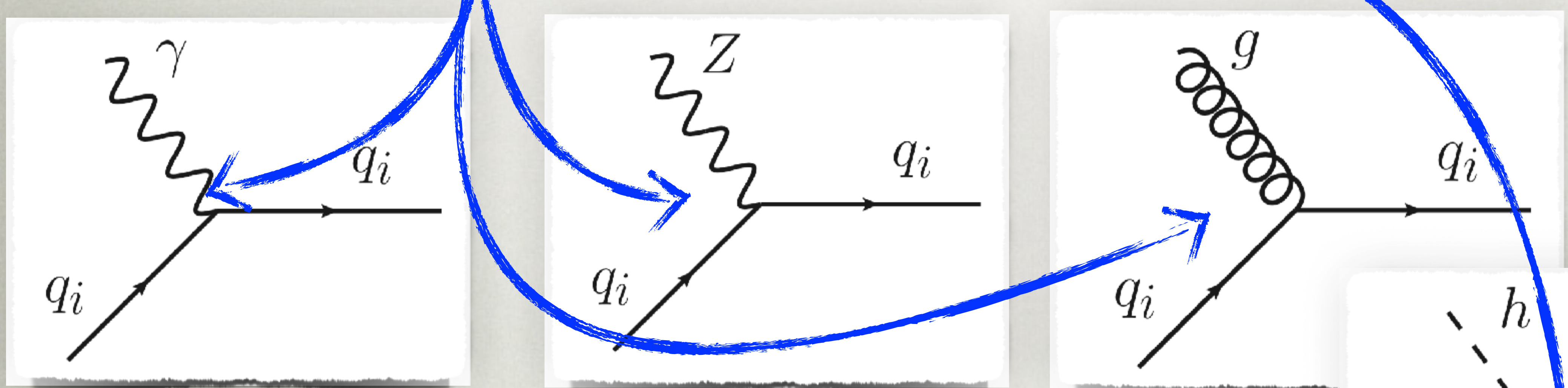

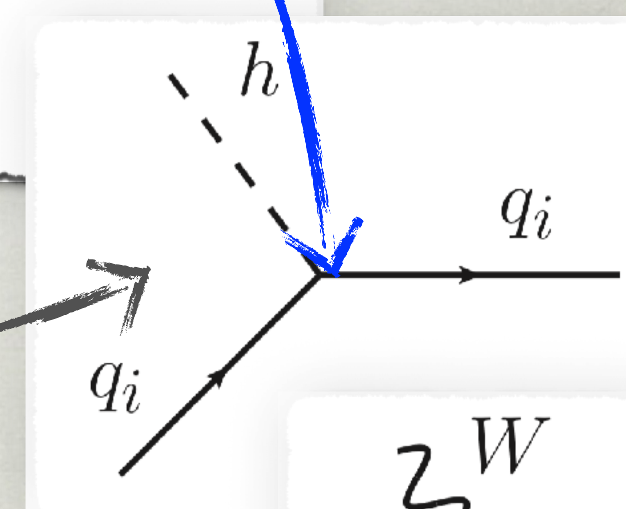

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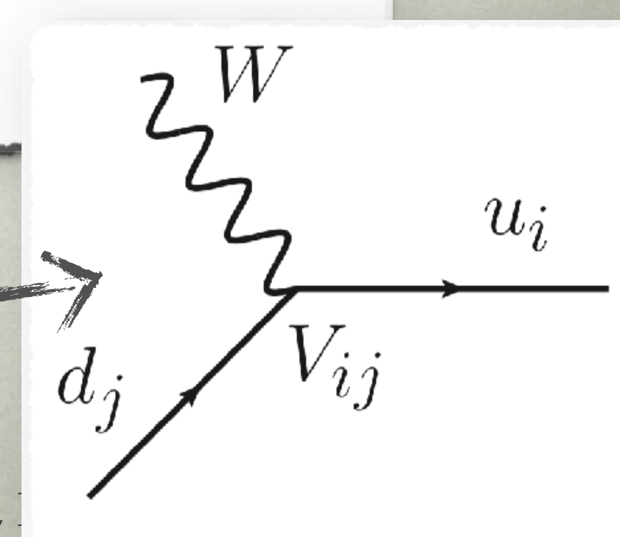

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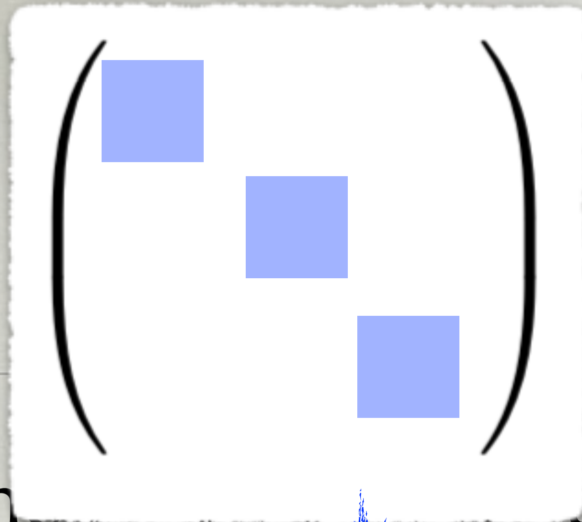

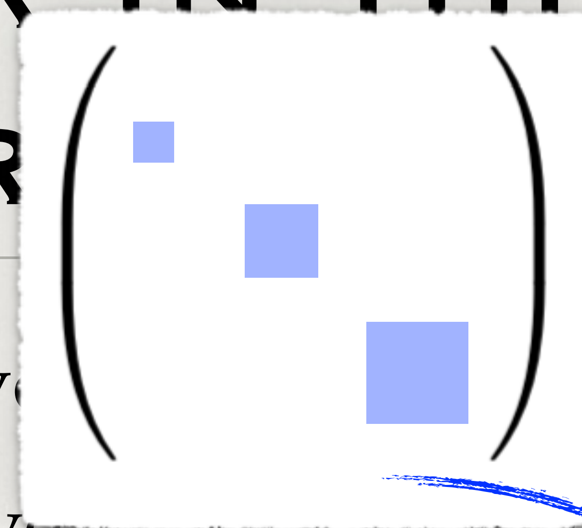

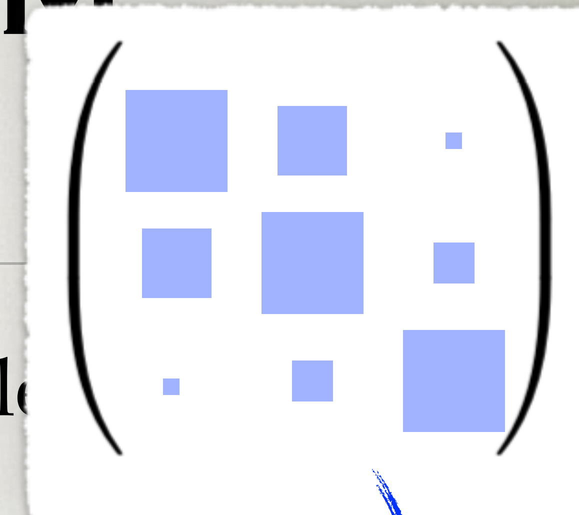

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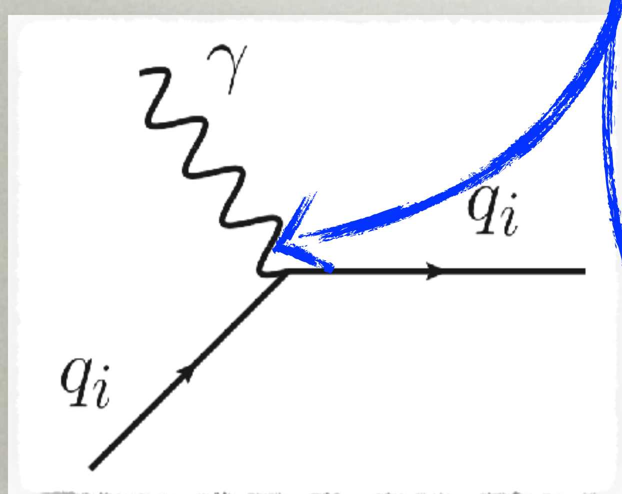

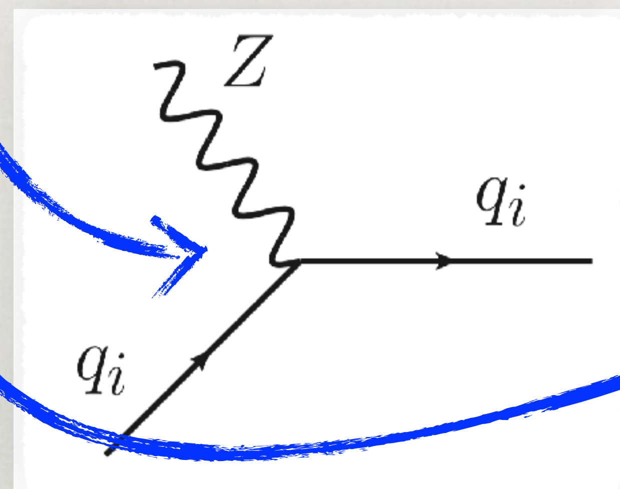

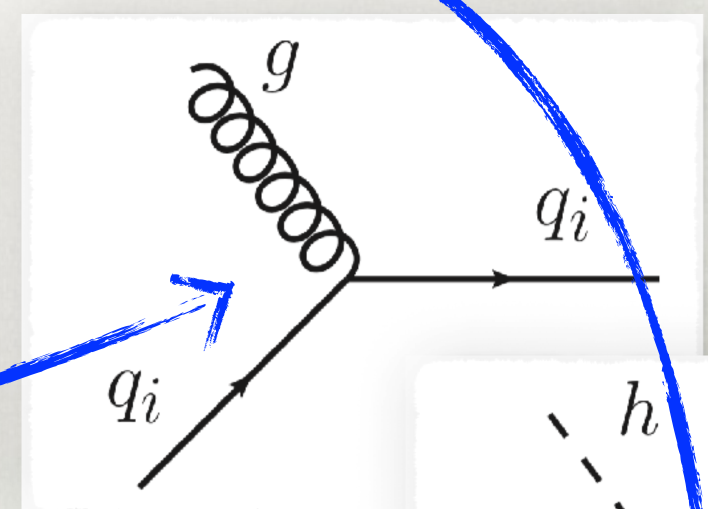

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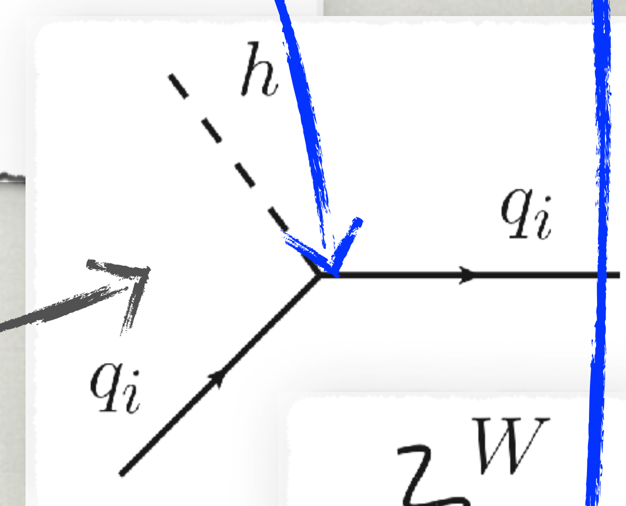

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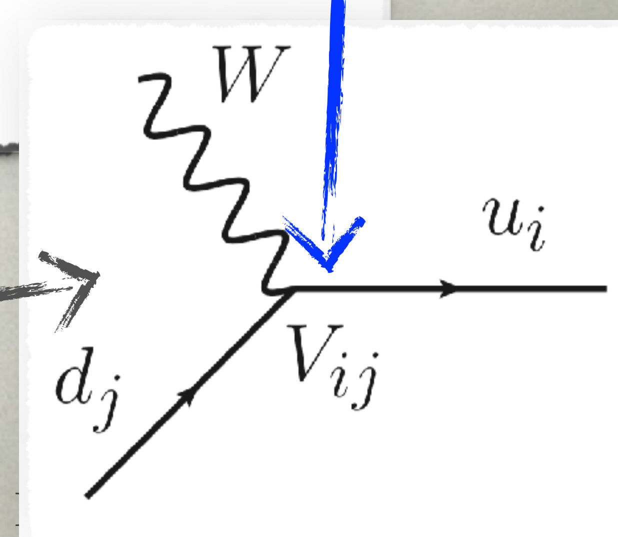


LEPTONS

- first assume that neutrino masses are zero
- extremelly good approximation in
  - collider experiments, meson decays, charged lepton decays,...
  - in each of these: $E \gg m_\nu$

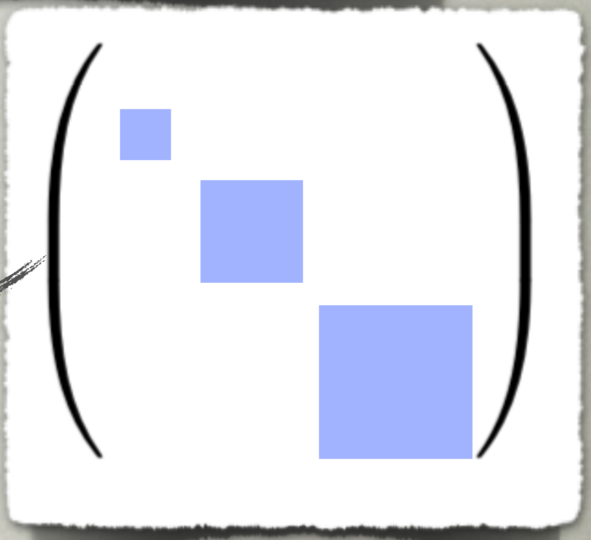
LEPTONS

- in the limits of vanishing ν masses
  - a single lepton Yukawa
  - through field redefinitions can be made diagonal, real, positive

$$\mathcal{L}_{\text{Yukawa}} \supset -Y_\ell^{ij} \bar{L}_L^i H \ell_R^j + \text{h.c.}$$

$$L_L \to V_L L_L, \quad \ell_R \to V_\ell \ell_R,$$

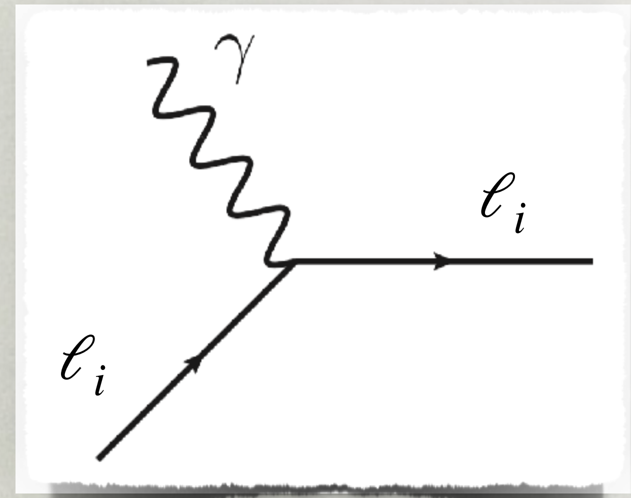
$$Y_\ell \to V_L^\dagger Y_\ell V_\ell = \text{diag}(y_e, y_\mu, y_\tau).$$

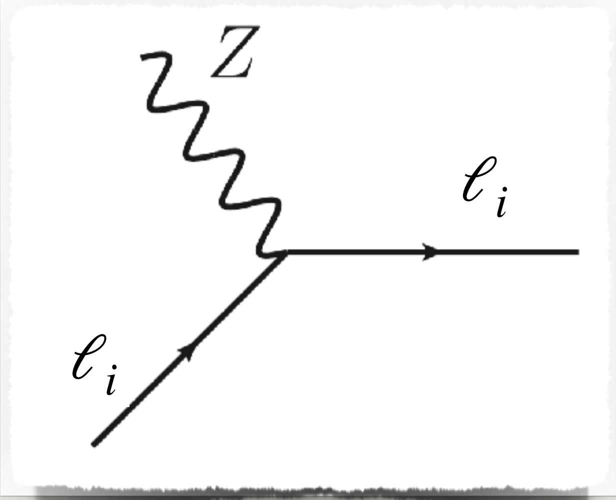


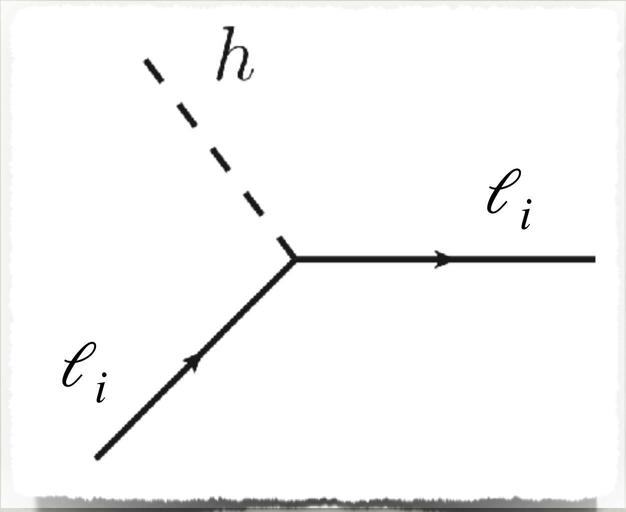
- since Y_ℓ diagonal: no FV unless $m_\nu \neq 0$
- since Y_ℓ real: no CPV unless $m_\nu \neq 0$

LEPTONS

- ⇒ in SM with massless ν no leptonic FCNCs
  - photon, *Z: flavor (generation) universal* interactions







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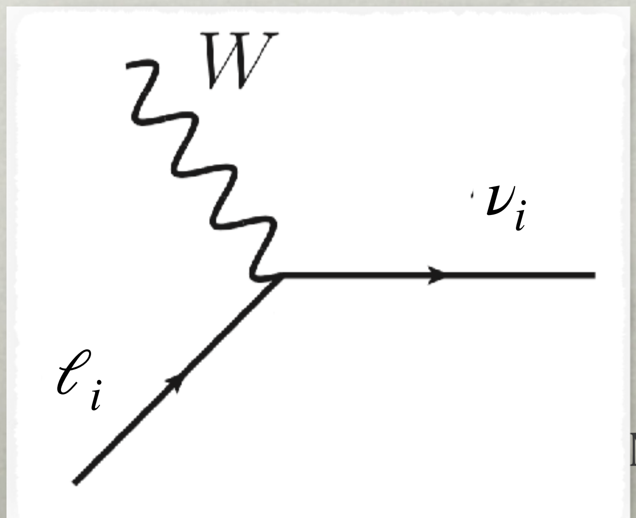

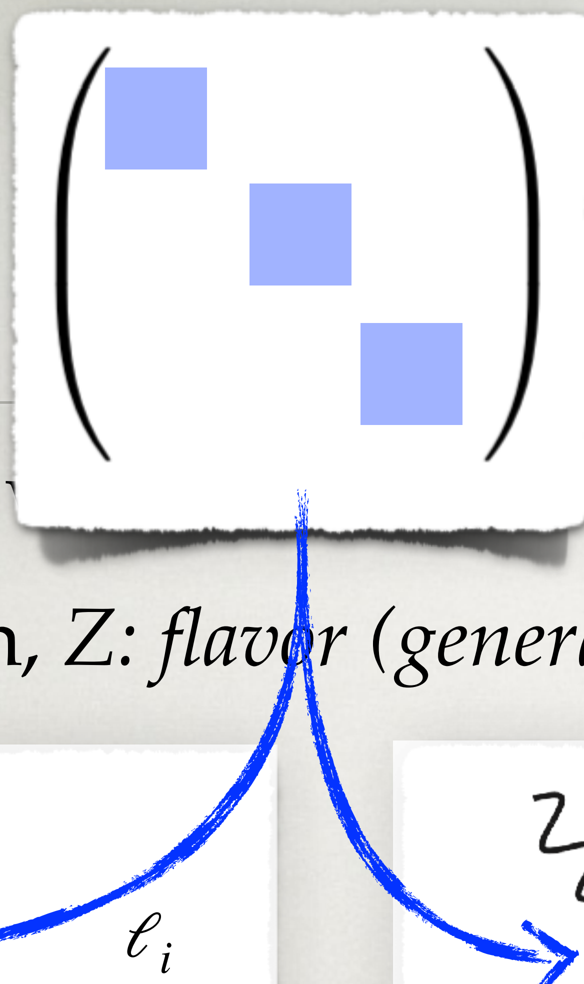

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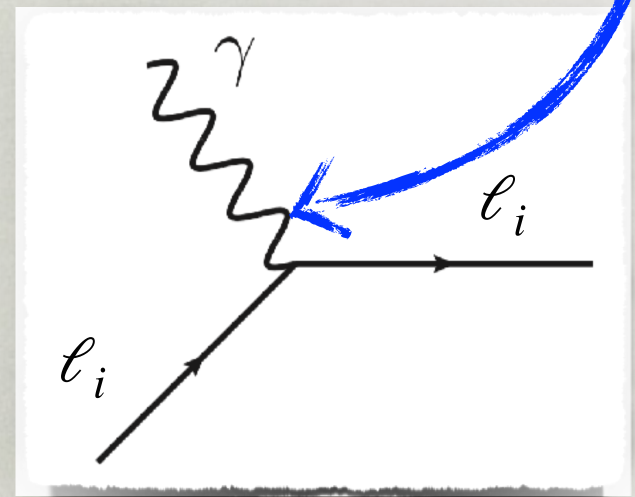

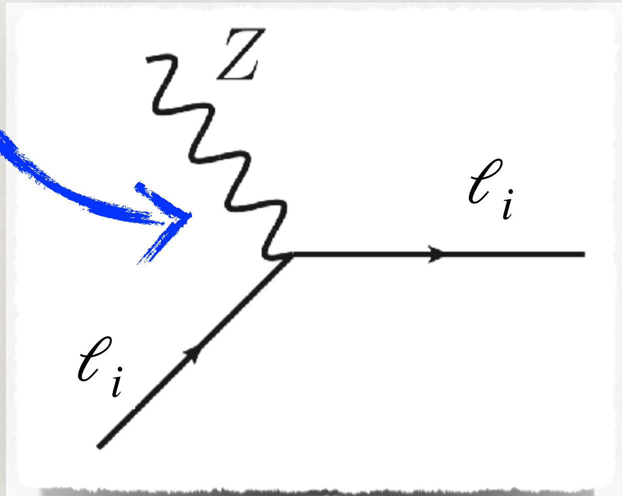

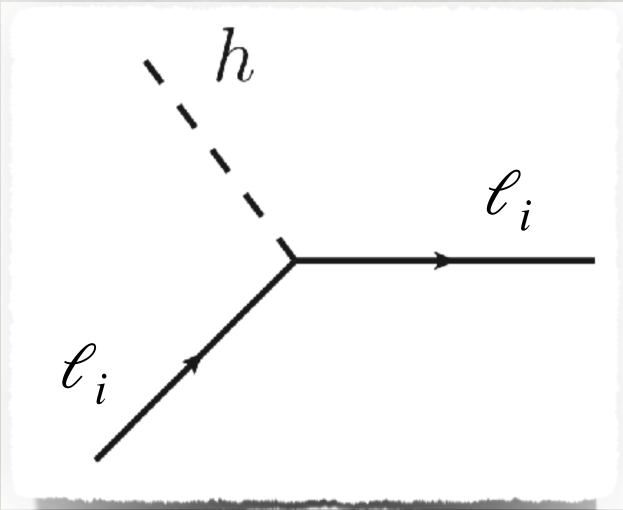

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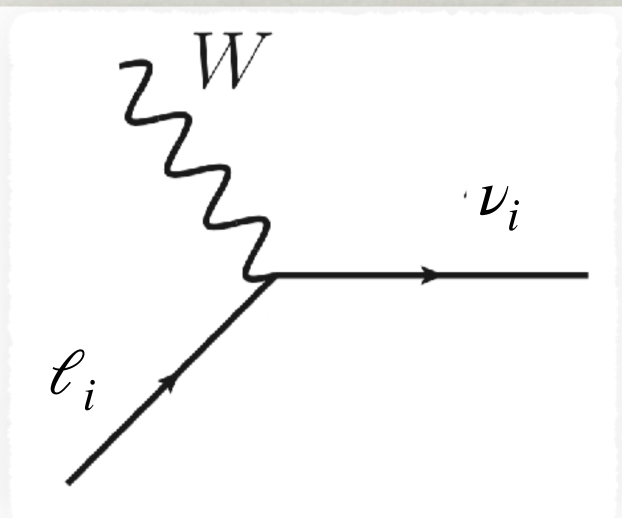

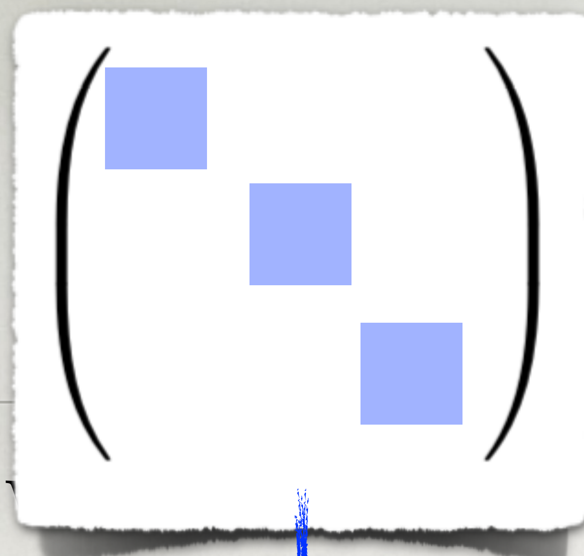

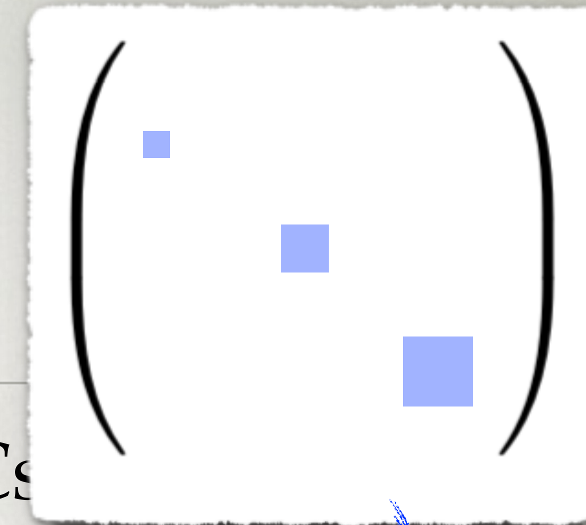

PTONS

- $\Rightarrow$ in SM v no leptonic FCNCs
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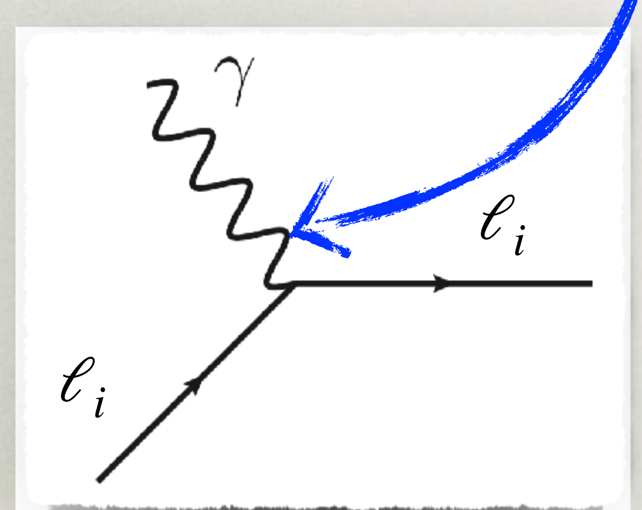

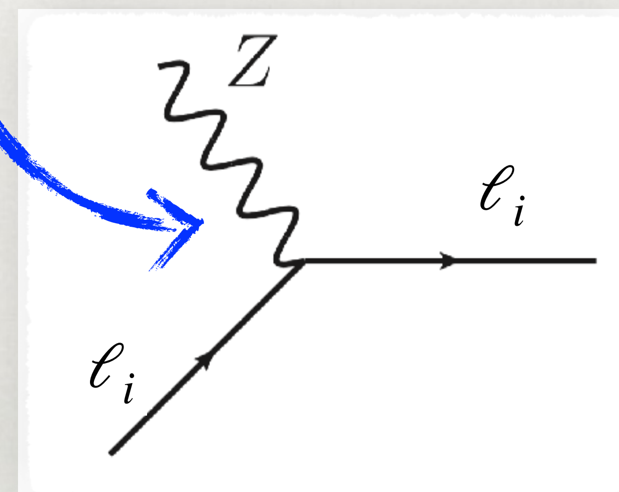

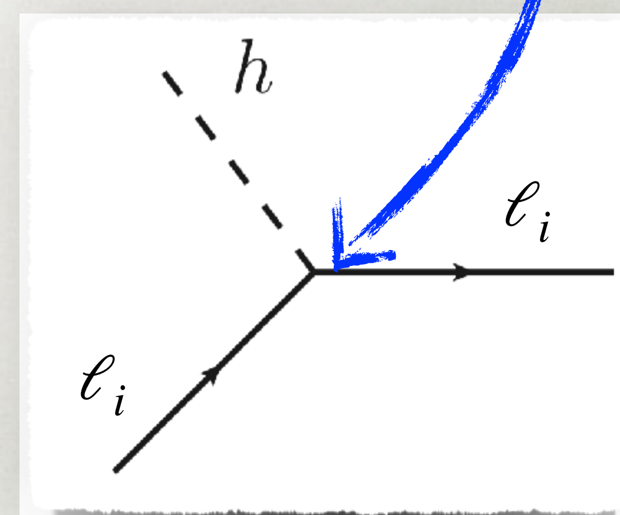

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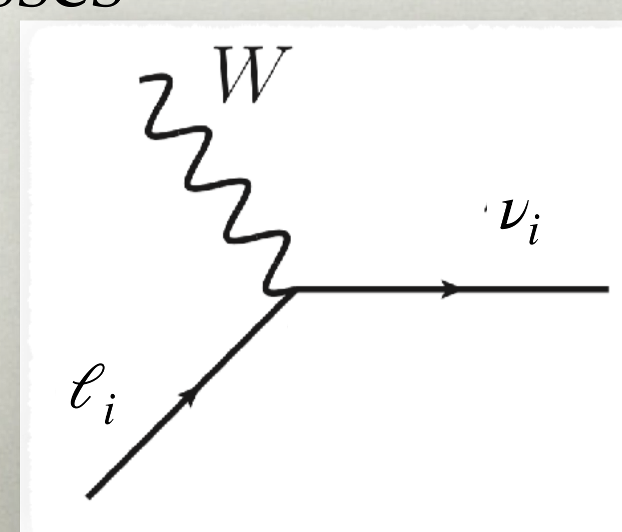
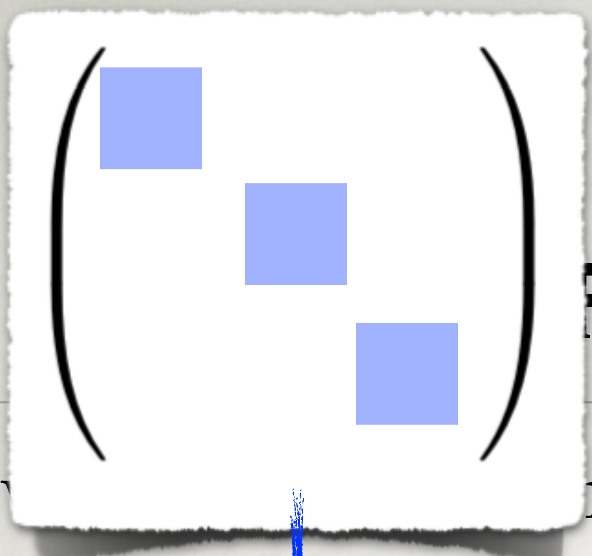
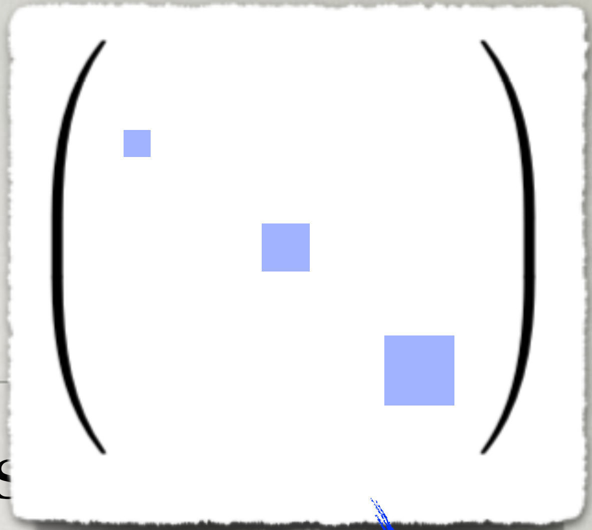
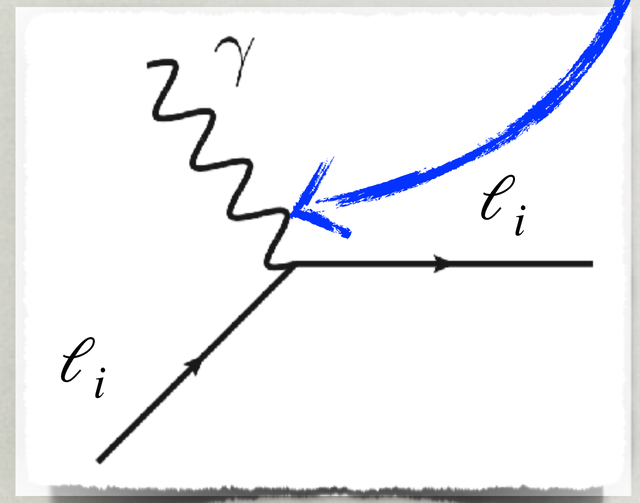


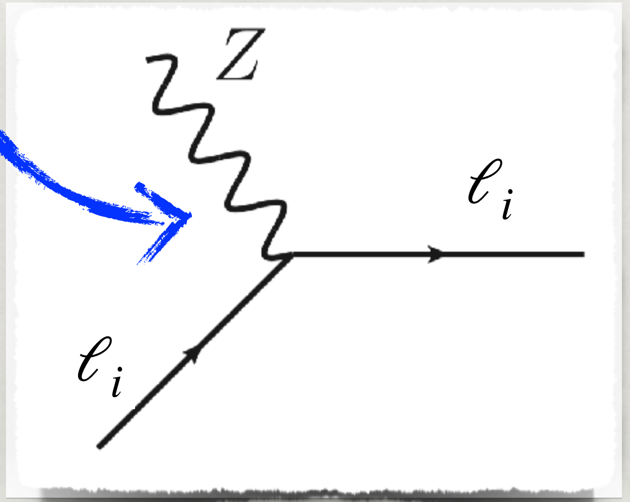


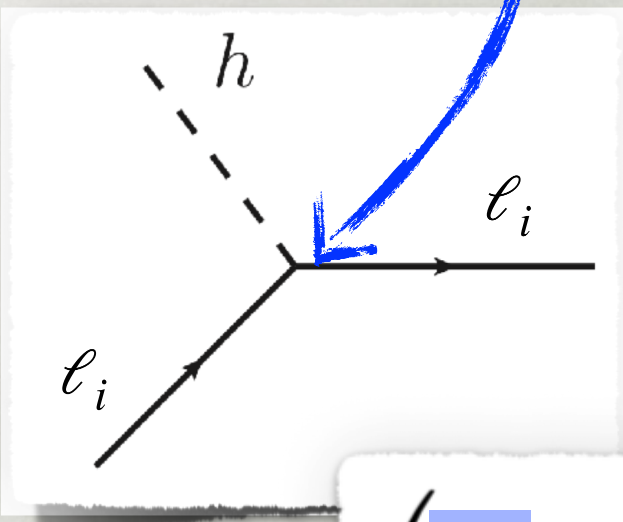


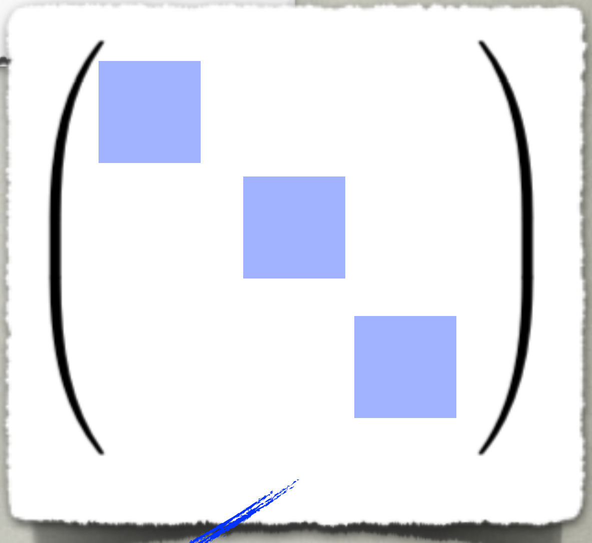
PTONS

- $\Rightarrow$ in SM v no leptonic FCNCs
  - photon, *Z: flavor (generation) universal* interactions

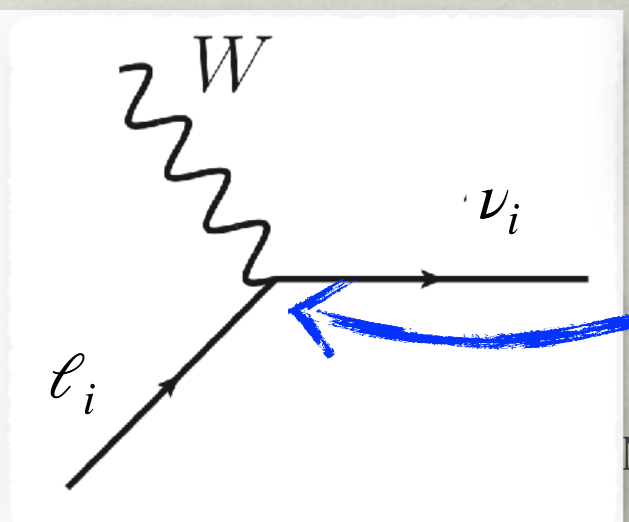








  - Higgs has *flavor diagonal* interactions
    - proportional to lepton masses
- charged currents (*W* couplings) are *flavor universal*



LEPTONS

- this means that for $m_\nu = 0$ in the SM
  - $Br(\mu^+ \to e^+ e^- e^+) = 0$
  - $Br(\mu^+ \to e^+ \gamma) = 0$
  - $Br(\tau^+ \to \mu^+ \mu^- \mu^+) = 0$
  - $Br(\tau^+ \to \mu^+ \rho^0) = 0$
  - ...

LEPTONS

- agrees well with stringent experimental bounds in PDG
  - $Br(\mu^+ \to e^+ e^- e^+) < 1.0 \times 10^{-12}$
  - $Br(\mu^+ \to e^+ \gamma) < 4.2 \times 10^{-13}$
  - $Br(\tau^+ \to \mu^+ \mu^- \mu^+) < 2.1 \times 10^{-8}$
  - $Br(\tau^+ \to \mu^+ \rho^0) < 1.2 \times 10^{-8}$
  - ...

NEUTRINO MASSES

- however, neutrinos are not completely massless
  - at some level leptonic FCNCs will arise in the SM
- how much does $m_\nu \neq 0$ matter?
- in experiments we are interested in: not too much
  - corrections suppressed by $(m_\nu/E)^n \ll 1$
  - for instance for muon decays: $E \sim m_\mu \Rightarrow m_\nu/m_\mu < 10^{-9}$

NEUTRINO MASSES

- with $QUDL$ field content m_ν forbidden in the SM
- two ways of introducing ν masses
  - *Dirac neutrinos:* add RH neutrino fields ν_R, singlets under SM + conserv. L

$$\mathcal{L}_{\text{Yukawa}} \supset -Y_\nu^{ij} \bar{L}_L^i H^c \nu_R^j + \text{h.c.}$$

3×3 complex

  - *Majorana neutrinos*: m_ν from dimension 5 Weinberg operator, is $\Delta L = 2$

$$\mathcal{L}_{\text{dim. 5}} \supset -\frac{1}{2} \frac{Y_\nu'^{ij}}{\Lambda} \left(\bar{L}_L^{ci} H^c\right)\left(H^{c*} L_L^j\right) + \text{h.c.}$$

3×3 symm., complex

- counting of physical parameters slightly differs in the two cases
  - in both cases weak (flavor) eigenstates are linear superpositions of mass eigenstates

$$\nu_{aL} = \sum_{i=1}^{3} U_{ai} \nu_{iL}, \quad a = e, \mu, \tau$$

PMNS matrix

PMNS matrix

- canonical form of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

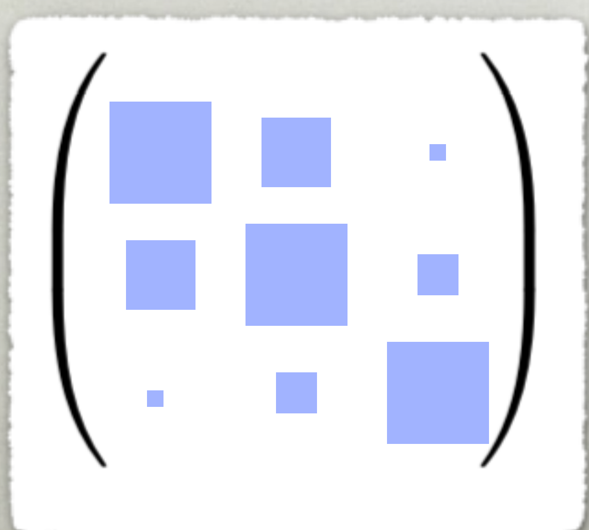
$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times P$$

- P matrix takes the form:
  - $P = 1$ for Dirac neutrinos
  - $P = \mathrm{diag}\,(1, e^{i\alpha_{21}}, e^{i\alpha_{31}})$ for Majorana ν's

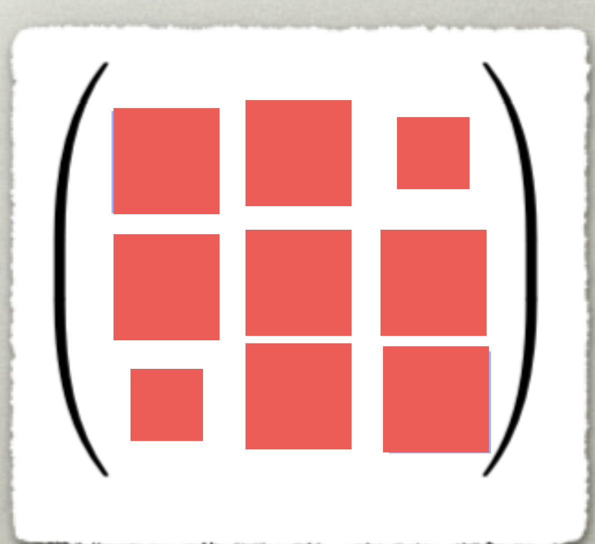
PMNS matrix

- assuming "normal ordering": $m_3 > m_2 > m_1$
  $m_2^2 - m_1^2 \sim (10^{-3}\,\mathrm{eV})^2$
  $m_3^2 - m_1^2 \sim (0.05\,\mathrm{eV})^2$
  $\sin\theta_{12} \sim \sin\theta_{23} \sim 0.5, \sin\theta_{13} \sim 0.15$
  $\delta, \alpha_{12}, \alpha_{13} = ?$

CKM matrix



PMNS matrix



$\mu \to e\gamma$ in the SM

- we already know that $\mu \to e\gamma$ vanishes for massless neutrinos
  - GIM mechanism very effective in LFV transitions
  - amplitude proportional to $A(\mu \to e\gamma) \propto m_\nu^2$

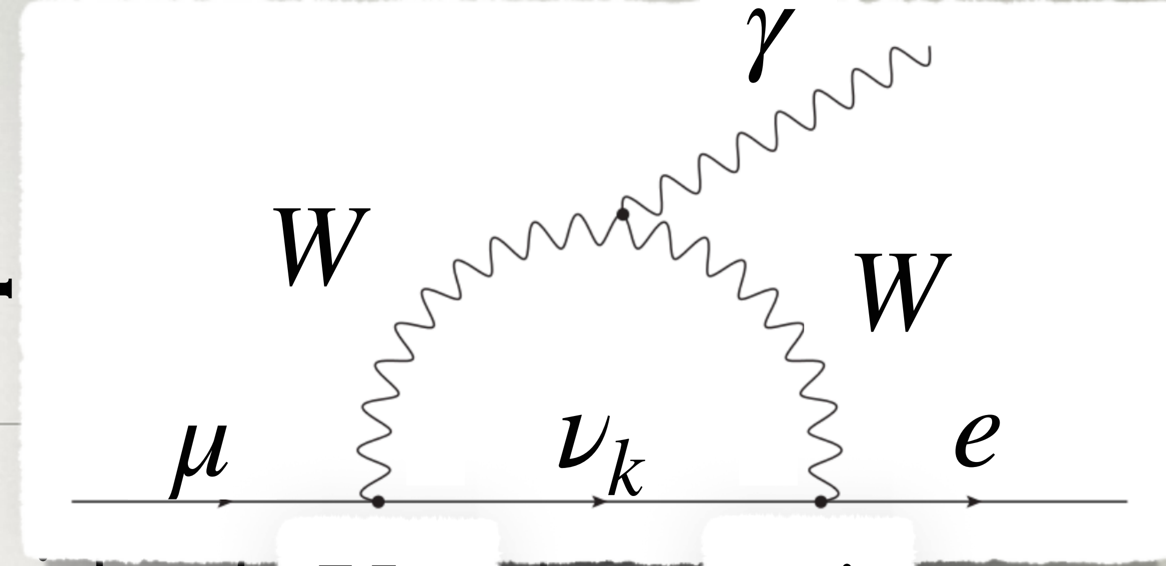
Very small !!!

$$\mathrm{BR}(\mu \to e\gamma) \simeq \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\bar{\nu})} = \frac{3\alpha}{32\pi}\left|\sum_{k=1,3} \frac{U_{\mu k}U^*_{ek}m^2_{\nu_k}}{M_W^2}\right|^2 .$$

$$\mathrm{BR}(\mu \to e\gamma) = 10^{-55} \div 10^{-54}$$

  - similar suppressions for $\mu \to 3e, \tau \to 3\mu, \mu \to e, \ldots$
- for charged LFV transitions SM is well below experimental reach
  - if found, a clear signal of new physics

$\mu \to e\gamma$ IN T



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NEW PHYSICS: SEE SAW EXAMPLE

- a simple example of new physics probed by $\mu \to e\gamma$
- a see-saw model for neutrino masses
  - allow for Majorana mass term for ν_R

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \left(Y_\nu \bar{\nu}_R \widetilde{\Phi}^\dagger L_L + \frac{1}{2} M_R \bar{\nu}_R \nu_R^c + \text{h.c.} \right).$$

Dirac mass term ⇒ mixing of ν_L and ν_R

- mass spectrum consists of Majorana neutrinos
  - 3 heavy states, mostly ν_R with masses $\sim M_R$
  - 3 light neutrinos, mostly ν_L, mass matrix

$$m_\nu = -\frac{v^2}{2} Y_\nu^T M_R^{-1} Y_\nu$$

SEE SAW AND $\mu \to e\gamma$

- due to ν_L and ν_R mixing
  - PMNS matr. does not diagonalize the full $\nu_{L,R}$ mass matrix
  - the mixing matrix $\mathcal{U}$ entering the $W - \ell - \nu$ vertex is not unitary

$$\mathcal{U} = \left(1 - \frac{v^2}{2} Y_\nu^\dagger M_R^{-2} Y_\nu\right) U\,.$$

note: in m_ν we have Y_ν^T not $Y_\nu^\dagger$

- modified prediction for $\mu \to e\gamma$

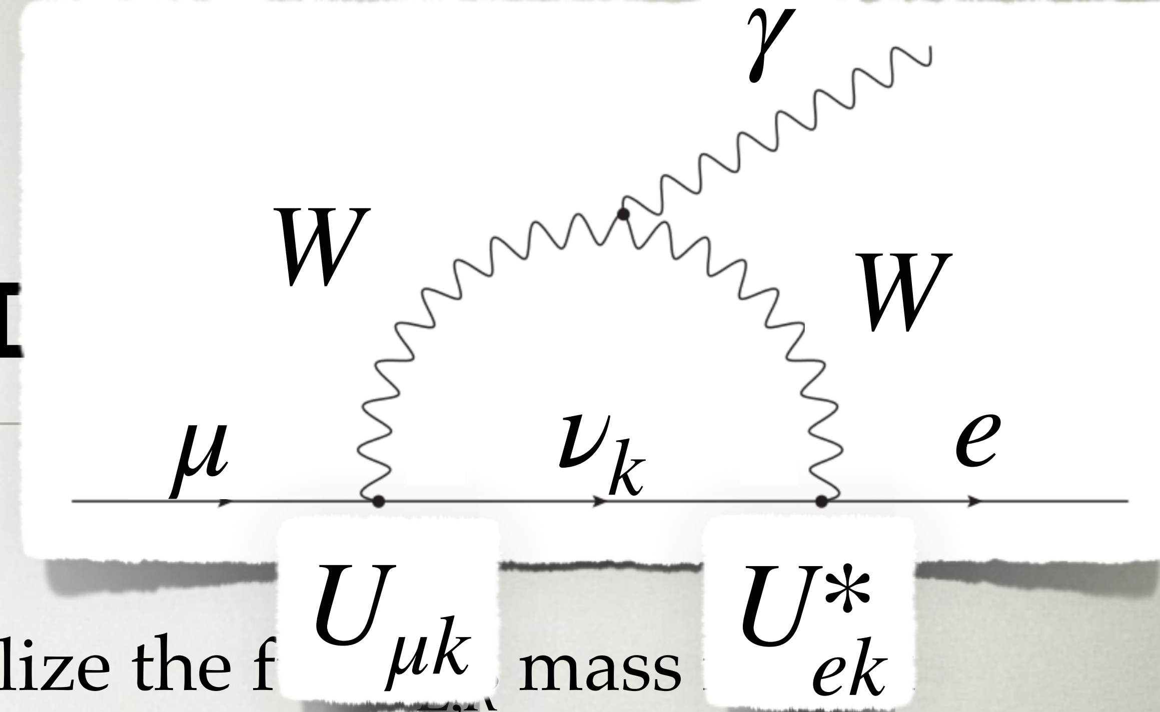
$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \frac{\left|\sum_k \mathcal{U}_{\mu k} \mathcal{U}^*_{ek} F(x_k)\right|^2}{(\mathcal{U}\mathcal{U}^\dagger)_{\mu\mu} (\mathcal{U}\mathcal{U}^\dagger)_{ee}},$$

$$F(x_k) = \tfrac{10}{3} - x_k + \mathcal{O}\left(x_k^2\right).$$

$$x_k = m_{\nu_k}^2 / M_W^2$$

  - GIM mechanism no longer fully operational
  - $Br(\mu \to e\gamma)$ not suppressed by light ν masses, can be larger

SEE SAW AND



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  - PMNS matr. does not diagonalize the f … mass …
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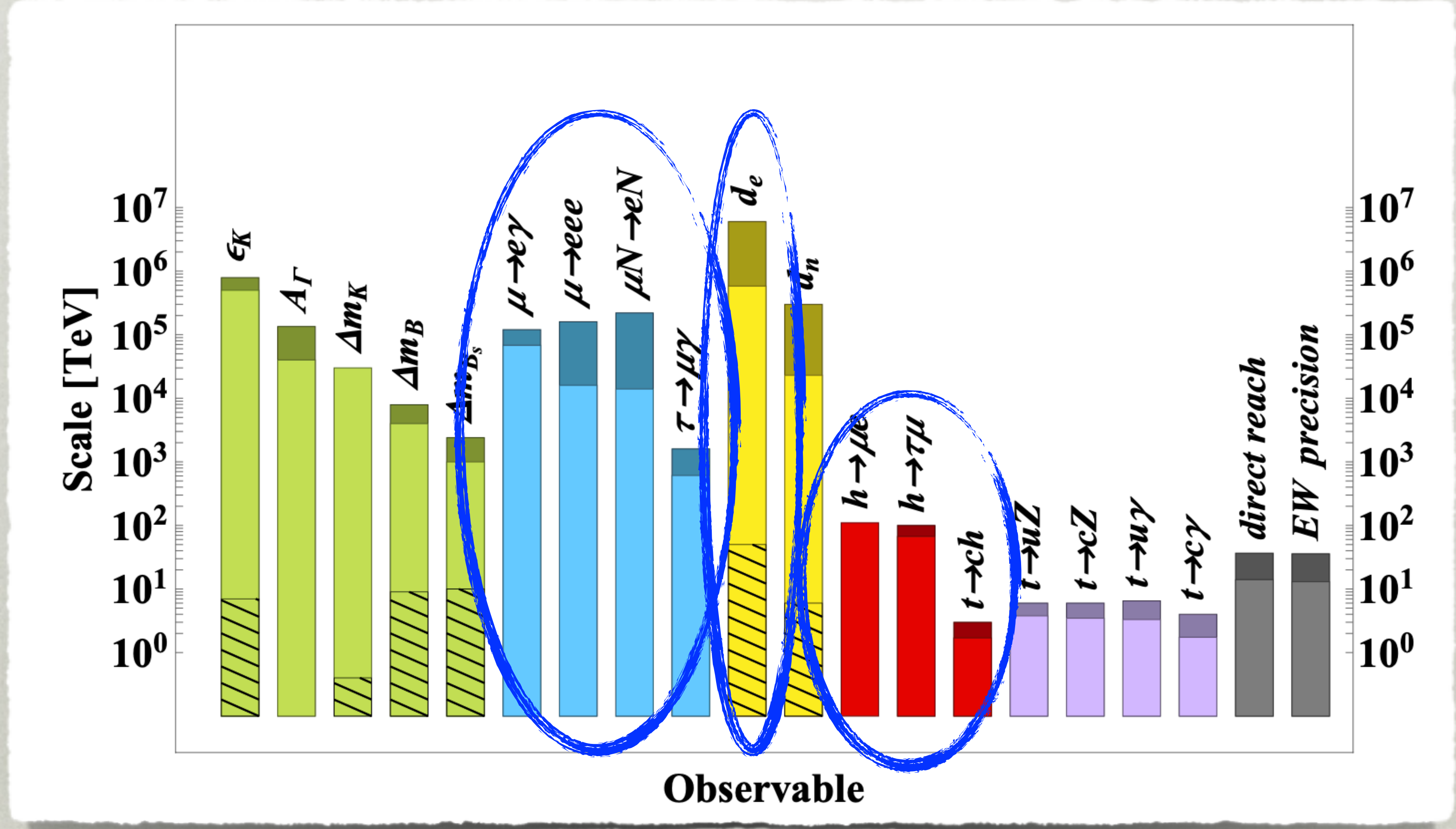
$$x_k = m^2_{\nu_k} / M^2_W$$

  - GIM mechanism no longer fully operational
  - $Br(\mu \to e\gamma)$ not suppressed by light ν masses, can be larger

SEARCHING FOR NEW PHYSICS

- LFV observables probe very high scales



- the rest of these lectures: focusing on the above observables

OBSERVABLES

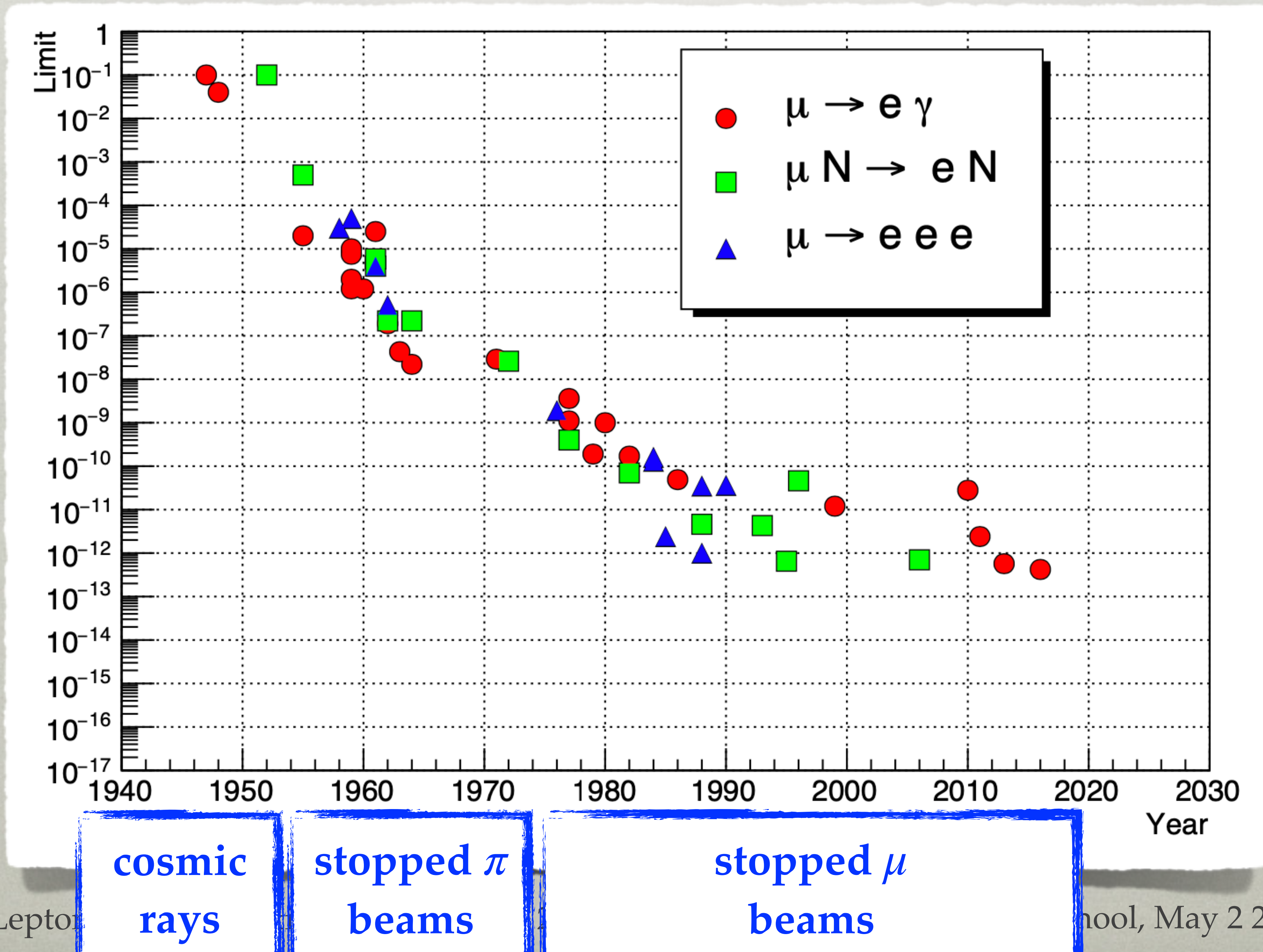
- CLFV transitions
  - $\mu \to e\gamma, \tau \to \mu\gamma, \mu \to 3e, \mu \to e$ conv., ...
- CPV probes
  - electric dipole moment (EDM) of the electron
- Higgs decays
  - $h \to \tau\tau, h \to \mu\mu, h \to \tau\mu, \ldots$

MUONS

- today: LFV muon decays
- tomorrow: all the other probes

EXPERIMENTAL PROGRESS

- steady experimental progress since 1940s



VERY RARE PROCESSES

- planned experiments aim for $Br(\mu \to \dots) \sim 10^{-15} - 10^{-18}$
- very rare: if one were to use cosmic rays passing through your hand*
  - $\Rightarrow$ would take more than the age of the Universe to collect a sample large enough for one event

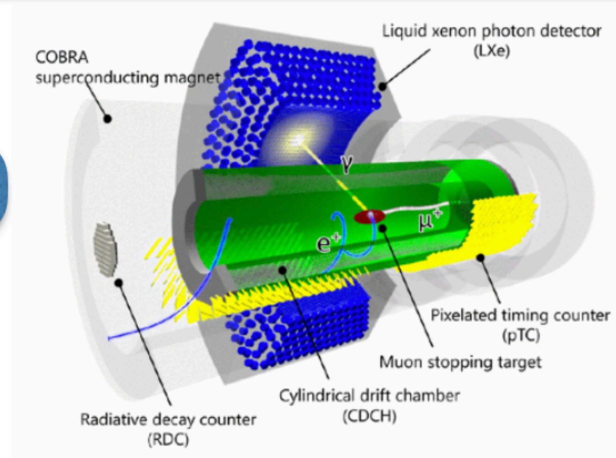
* the flux of cosmic ray muons at sea level is $\sim$ 1 muon/cm^2/min

talk by Toshiyuki Iwamoto @ FPCP2020

cLFV experiments in the world

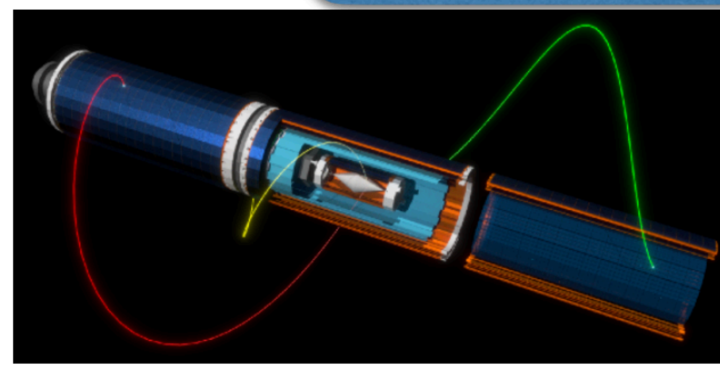
MEG II

$\mu^+ \to e^+\gamma$



Mu3e

$\mu^+ \to e^+e^+e^-$



Coincidence measurement:
DC beam needed to minimize backgrounds from accidental coincidences

BKG $\propto$ (Rate)^2

PSI

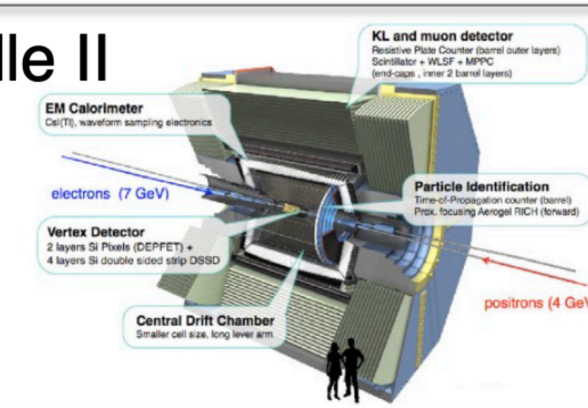
CERN

LHCb/ATLAS/CMS

$\tau \to 3\mu$, $\tau \to \mu\gamma$

KEK

Belle II

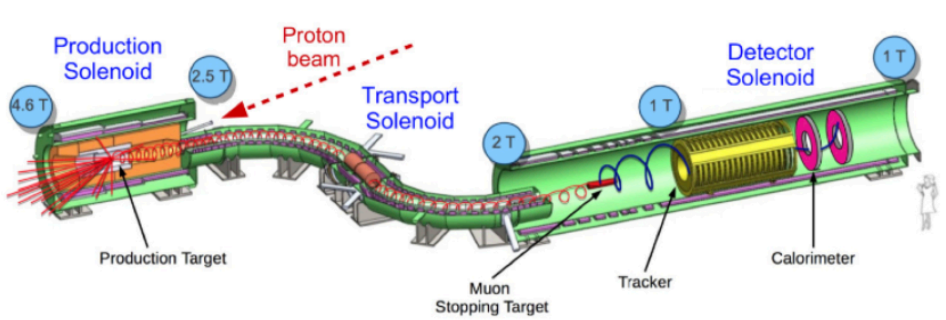


Fermilab

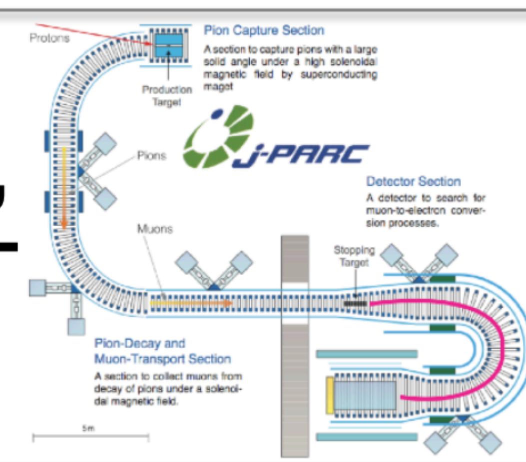
$\mu^- N \to e^- N$

J-PARC

Mu2e



DeeMe, COMET

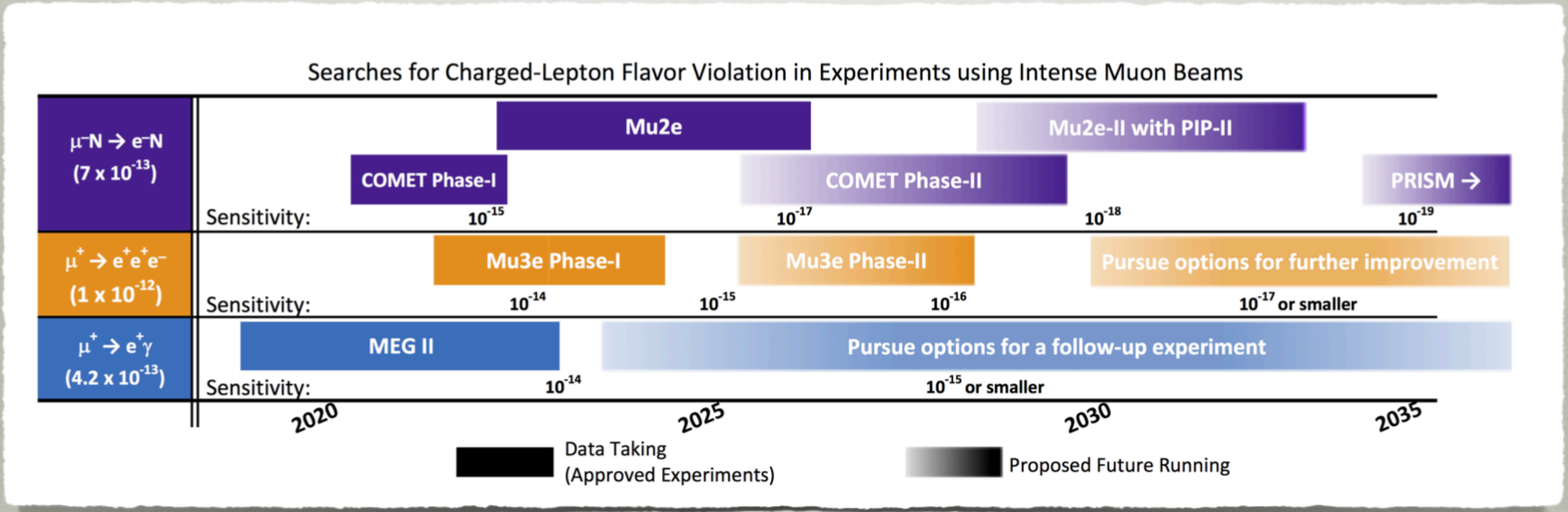


Single e^- measurement:
pulsed beam needed
Many pion-induced backgrounds after proton pulse
wait it out with 26 ns lifetime

TIMELINE

- pre-Covid timeline from 2019

Physics Briefing Book, 1910.11775



$$\mu \to e\gamma$$

$\mu \to e\gamma$ EXPERIMENTAL RESULTS

- present best bound
  - MEG (2016):
    $Br(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$

MEG coll., hep-ex/1605.05081

- future experiment (just started physics data taking)
  - MEG-II (~2025):
    $Br(\mu^+ \to e^+\gamma) < 6 \times 10^{-14}$

present status in Meucci, 2201.08200

HEAVY NEW PHYSICS

- if there is heavy NP, can be integrated out
  - results in SM Effective Field Theory (SMEFT)
  - renormalizable SM supplemented by higher dimensional operators

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + \dots$$

- $\mu \to e\gamma$ results in a dimension 6 operator

$$\mathcal{L} \supset -\frac{\sqrt{2} e\, v}{(4\pi\Lambda_{ij})^2}\, \bar{\ell}^i_{\text{L}} \sigma^{\mu\nu} \ell^j_{\text{R}} F_{\mu\nu} + \text{h.c.}\ ,$$

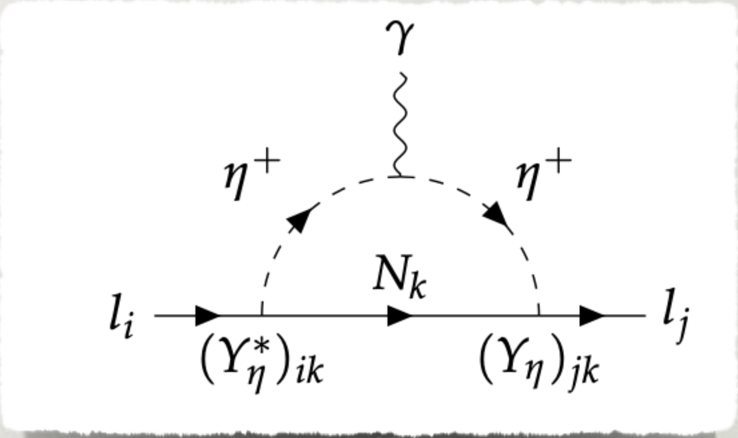
  - exp. bounds imply that it is highly suppressed

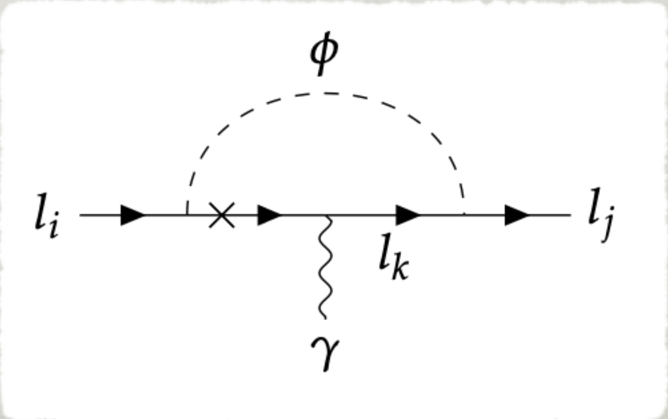
$$\mu \to e\gamma \Rightarrow \Lambda_{21} \gtrsim 3500\,\text{TeV}$$

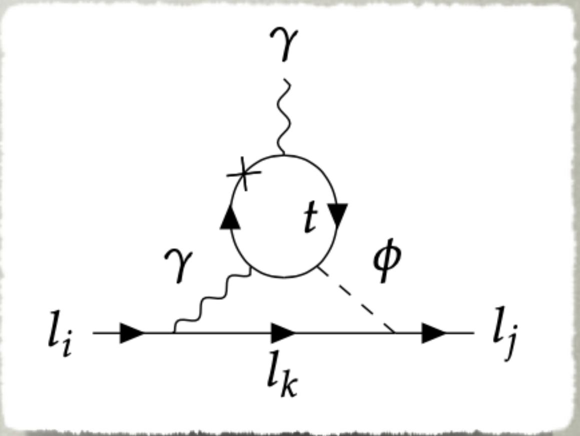
Greljo, Stangl, Thomsen, 2103.13991

NEW PHYSICS EXAMPLES FOR $\mu \to e\gamma$

- any new states with FV couplings to SM leptons will contribute to $\mu \to e\gamma$
- a selection of examples
  - neutrino mass models
    - see-saw
    - loop generated neutrino masses
  - 2 Higgs Doublet Model
  - low energy supersymmetry
  - extra dimensional models

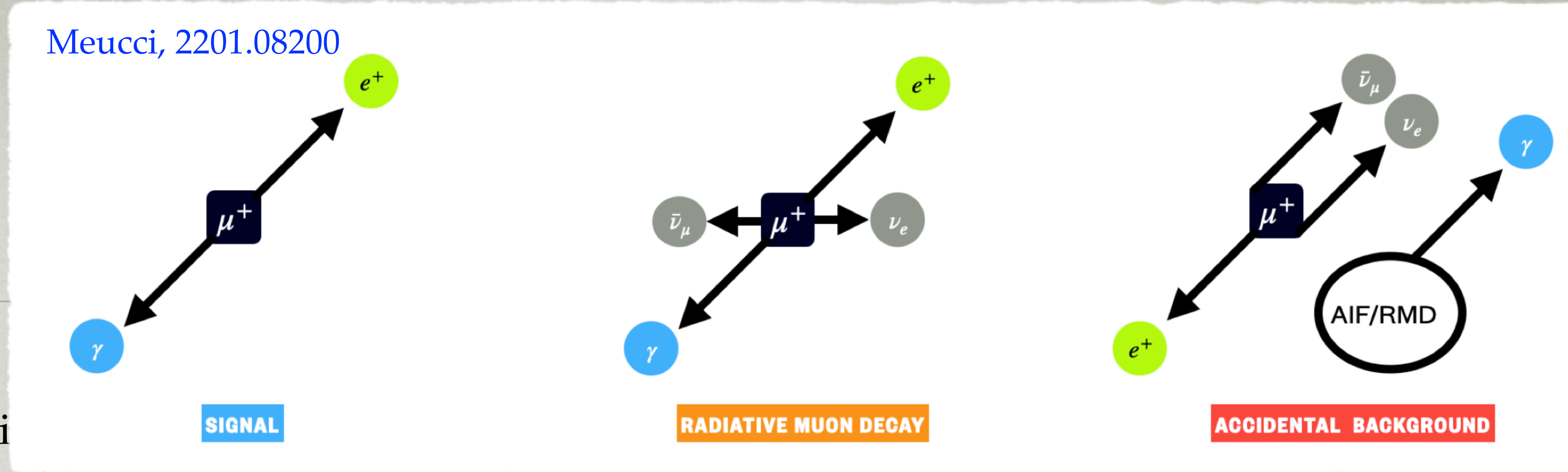






$\mu \to e\gamma$ EXPERIMENTS

- in muon rest frame e and γ are monochromatic
  - $E_e = E_\gamma \simeq m_\mu/2 \simeq 52.8\,\mathrm{MeV}$
- convenient to perform experiments with stopped muons
  - use μ^+ so that it does not get bound to nucleus, i.e., avoid the spread of line from decay in orbit
  - the measured process is thus $\mu^+ \to e^+\gamma$
- muons are stopped in the thinnest possible targets
  - so that the e^+ do not loose energy when escaping
  - search for monochromatic e^+ line at the kinematical edge of SM $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ decay (the "Michele edge")
  - require coincidence with a photon of the same energy
  - energy resolution very important to reduce SM background
    - irreducible background is the SM decay $\mu^+ \to e^+\nu_e\bar{\nu}_\mu\gamma$



- i
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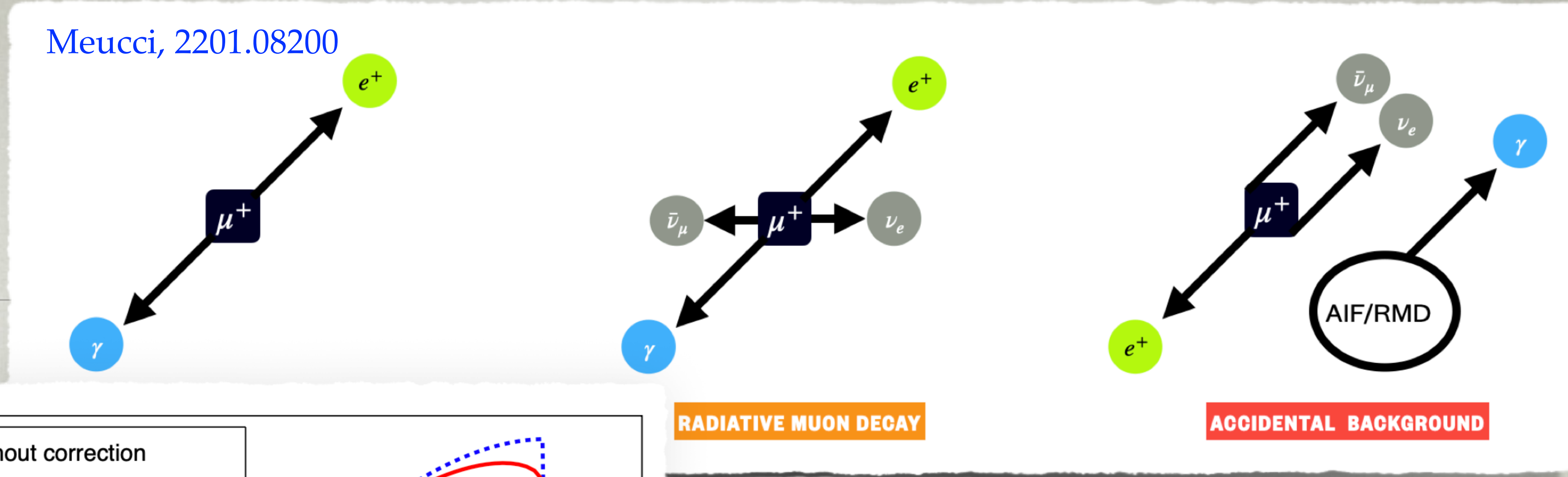

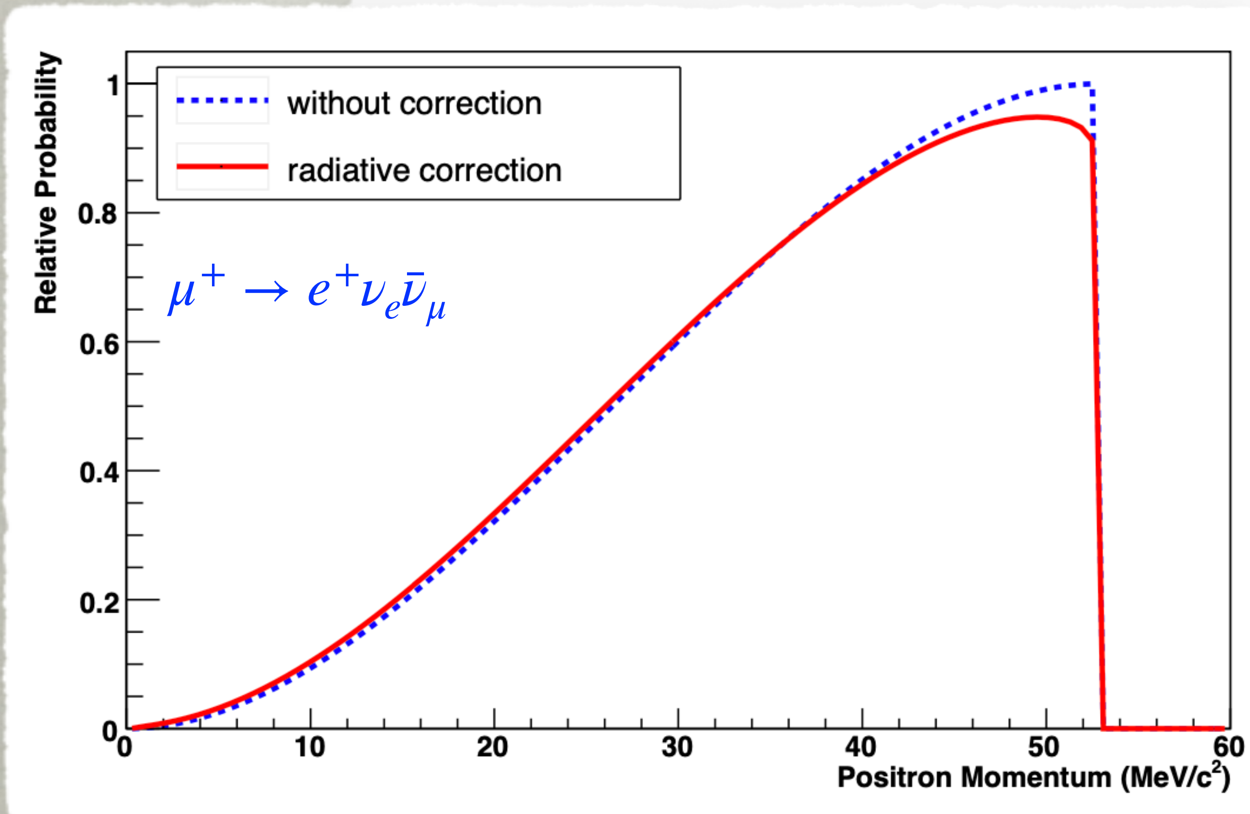

with stopped muons

und to nucleus, i.e., avoid the spread of

$\to e^+\gamma$

possible targets

gy when escaping

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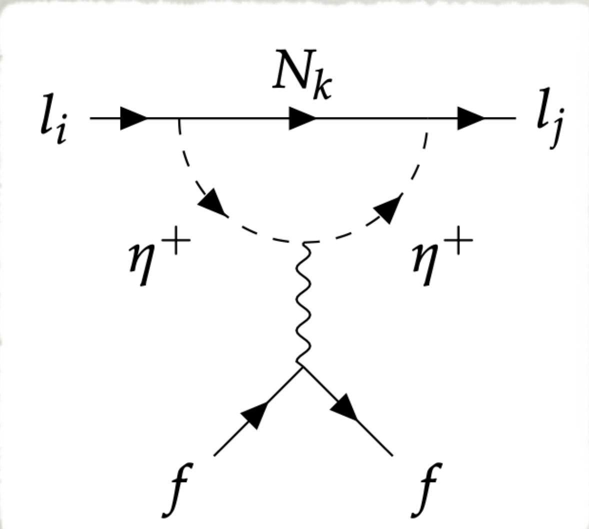
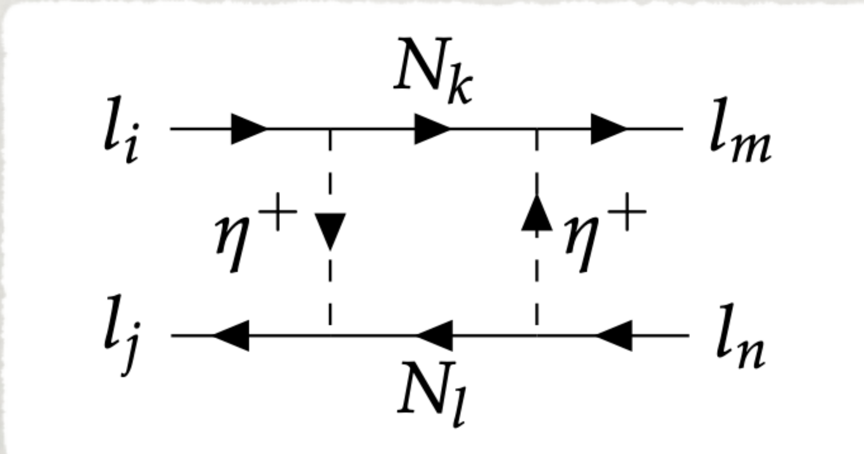
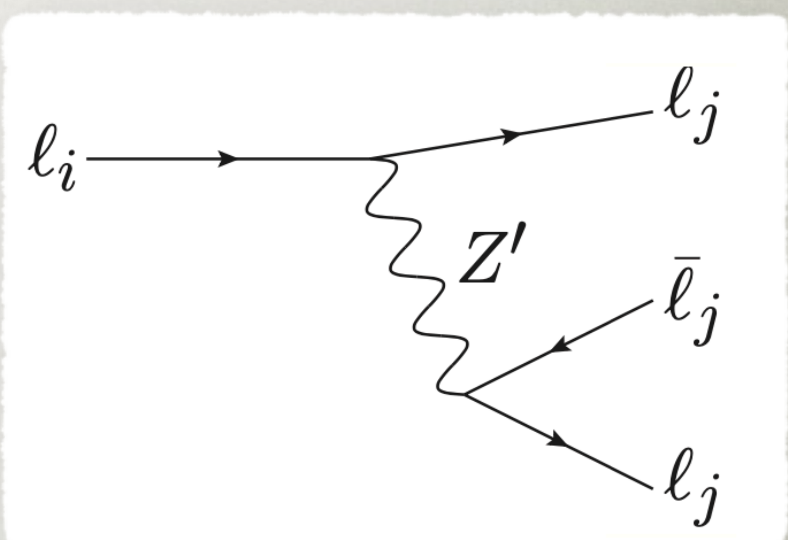
$$\mu \to 3e$$

$\mu \to 3e$

- $\mu^+ \to e^+ e^- e^+$: tree level or one loop NP contribs. possible





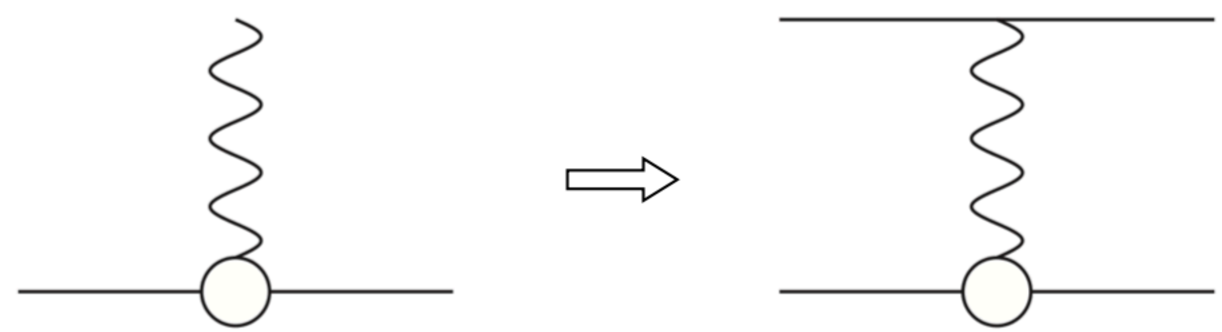


- if NP heavy, can be integrated out
  - then the $\mu \to 3e$ transition described by an EFT with
    - dipole operators $\bar{\ell}^i_{\rm L} \sigma^{\mu\nu} \ell^j_{\rm R} F_{\mu\nu}$
    - four fermion operators

$$(\bar{L}_L \gamma_\mu L_L)(\bar{L}_L \gamma^\mu L_L)$$
$$(\bar{e}_R \gamma_\mu e_R)(\bar{e}_R \gamma^\mu e_R)$$
$$(\bar{L}_L \gamma_\mu L_L)(\bar{e}_R \gamma^\mu e_R)$$

DIPOLE LIMIT

- if NP such that the dipole contribution dominates
- then $\mu \to 3e$ and $\mu \to e\gamma$ rates are related

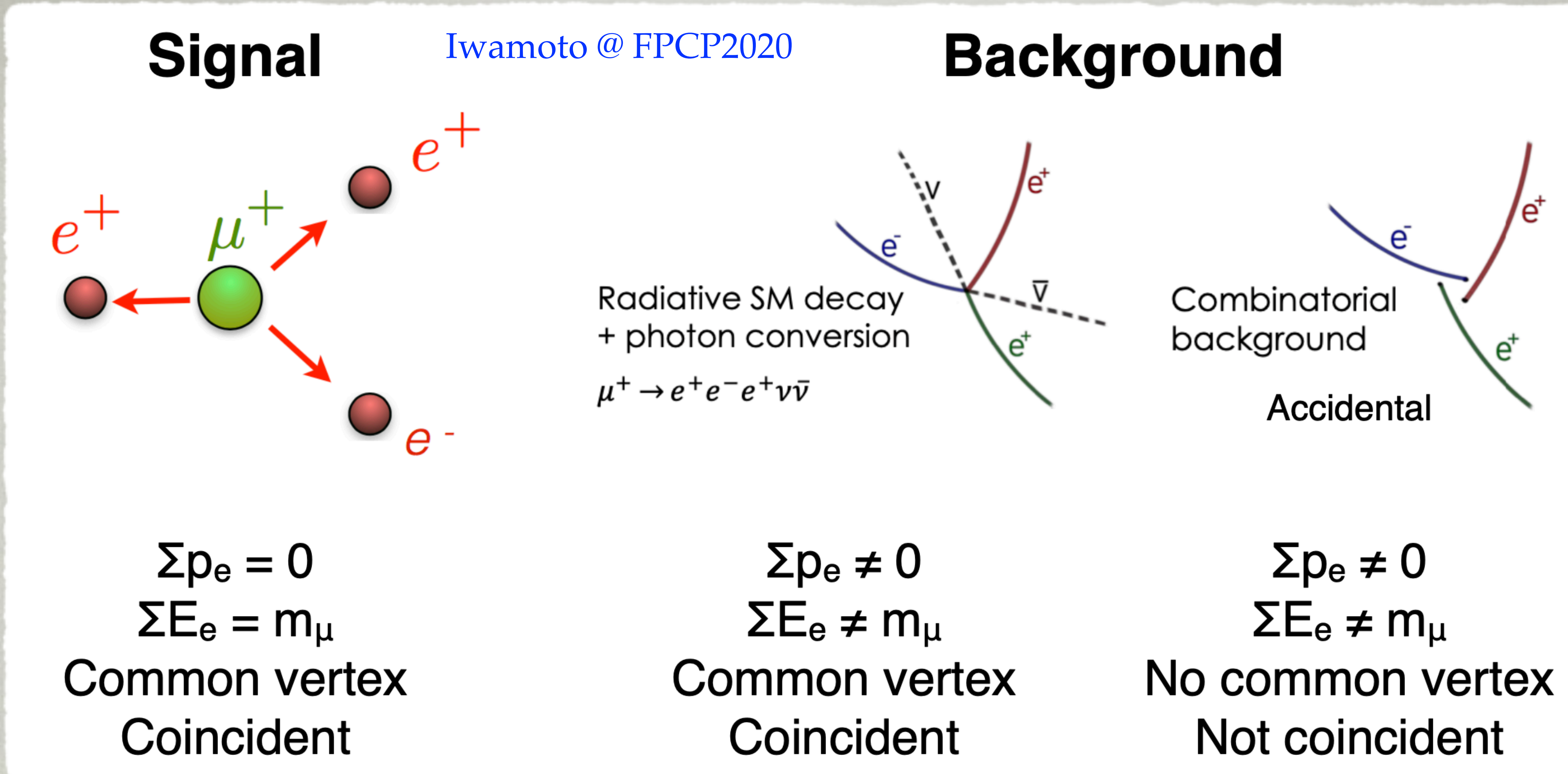


$$\mathrm{BR}(\mu \to eee) \simeq \frac{\alpha}{3\pi}\left(\log\frac{m_\mu^2}{m_e^2} - 3\right) \times \mathrm{BR}(\mu \to e\gamma)$$

- in general all operators are present
  - the above operators mix under the RG

EXPERIMENTS

- also use stopped μ^+ so the lab frame is the muon rest frame
- $\mu^+ \to e^+e^-e^+$ is a 3-body decay, so no mono-energetic particle
  - maximal energy for each e is $E_{\max} \simeq m_\mu/2$
- the signature is
  - $2e^+$ and $1e^-$ coming from common vertex (and nothing else)
  - their energy adds up to m_μ
- the main "irreducible" SM background $\mu^+ \to e^+e^-e^+\bar{\nu}_\mu\nu_e$ decay
  - two neutrinos appear as missing energy $E_{\rm inv}$
  - need very precise energy measurement to make sure $E_{e^+} + E_{e^-} + E_{e^+} = m_\mu$



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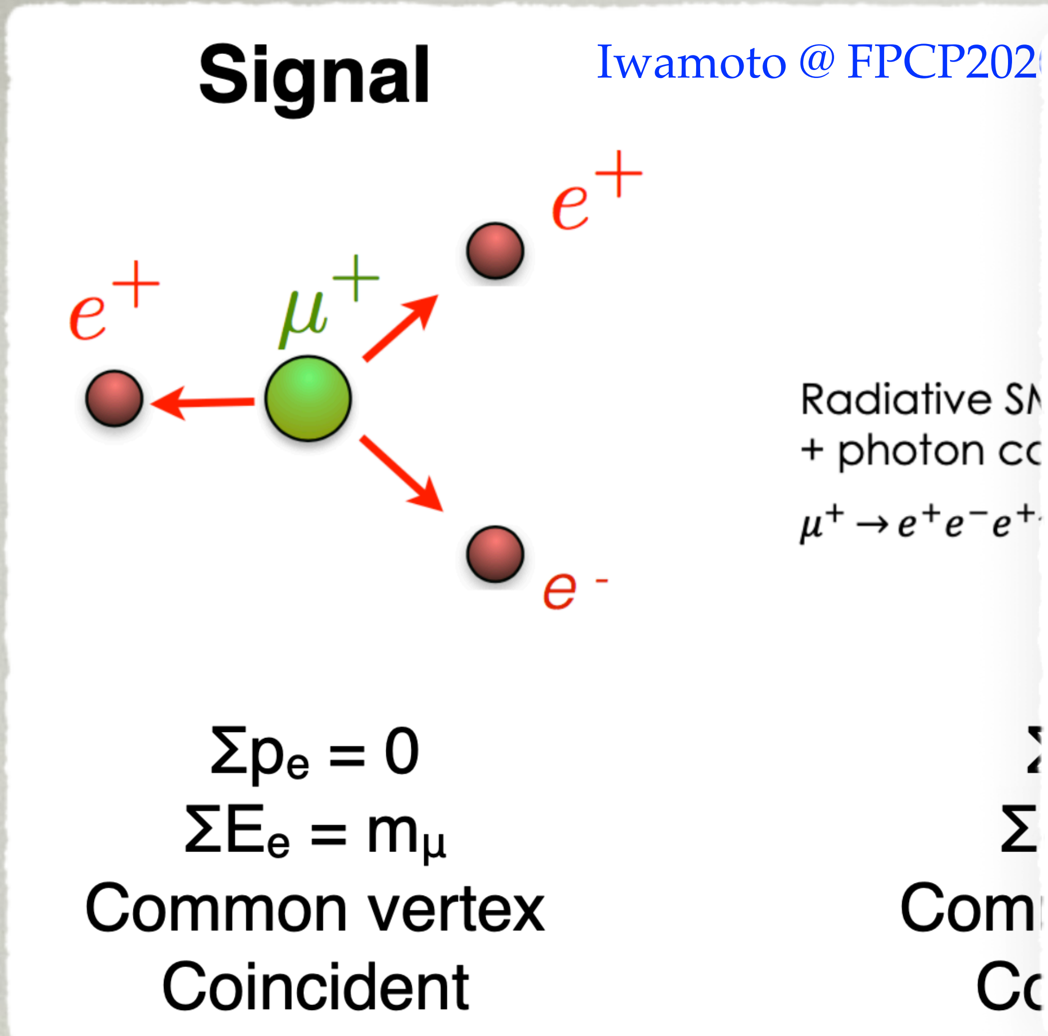

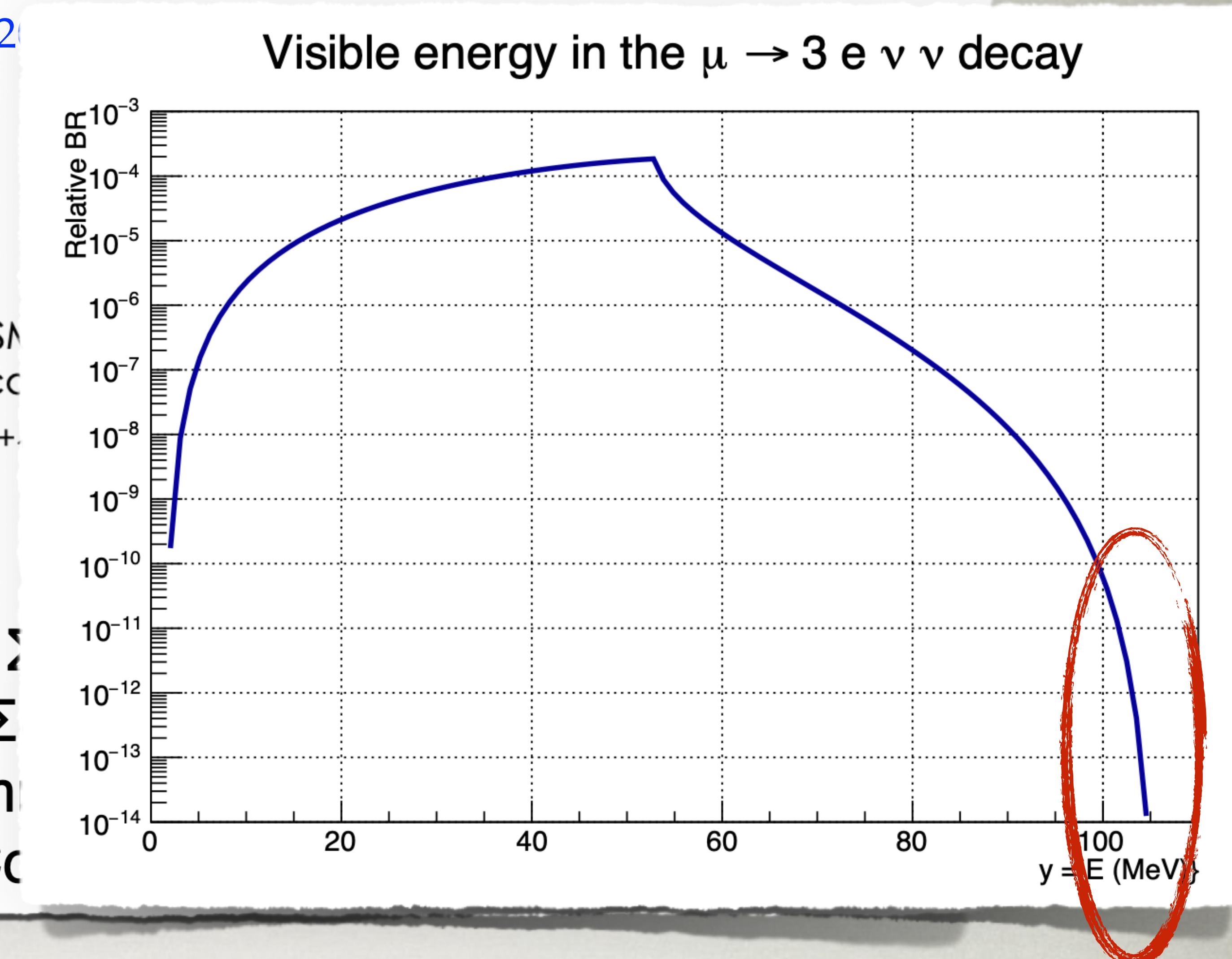

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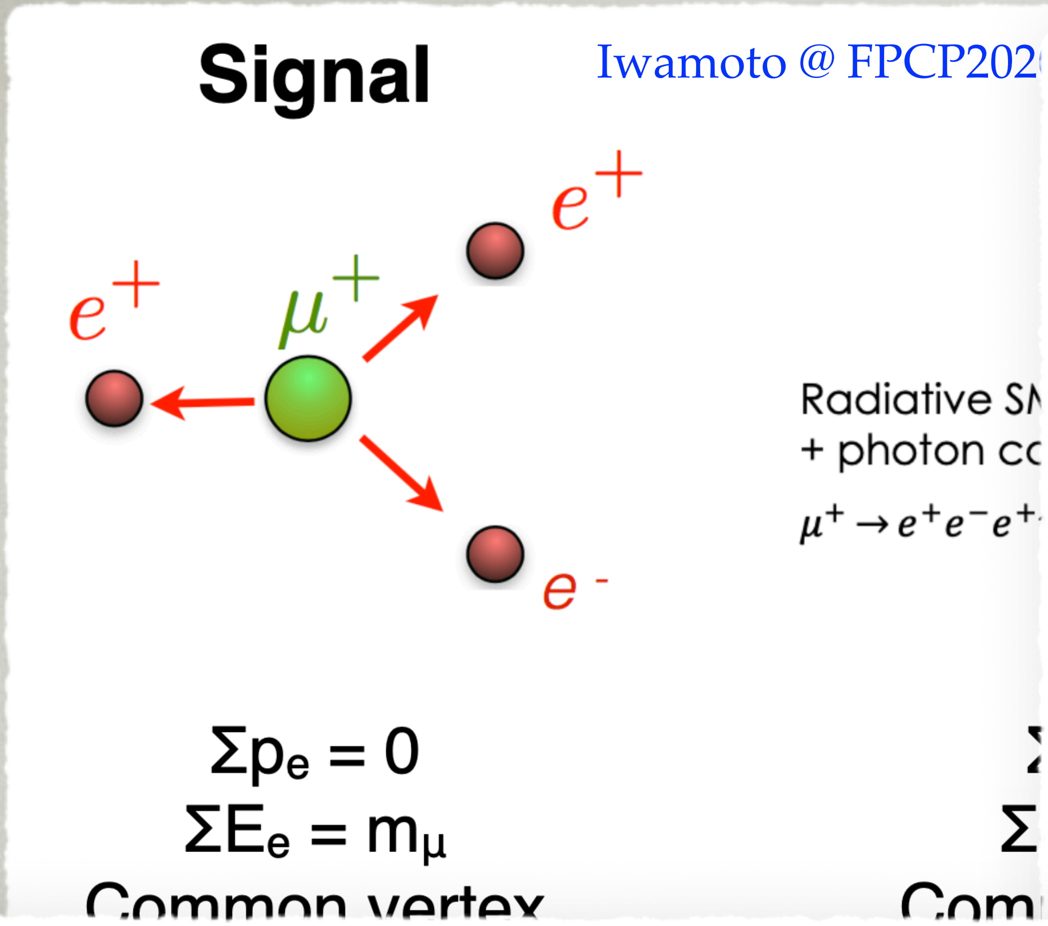
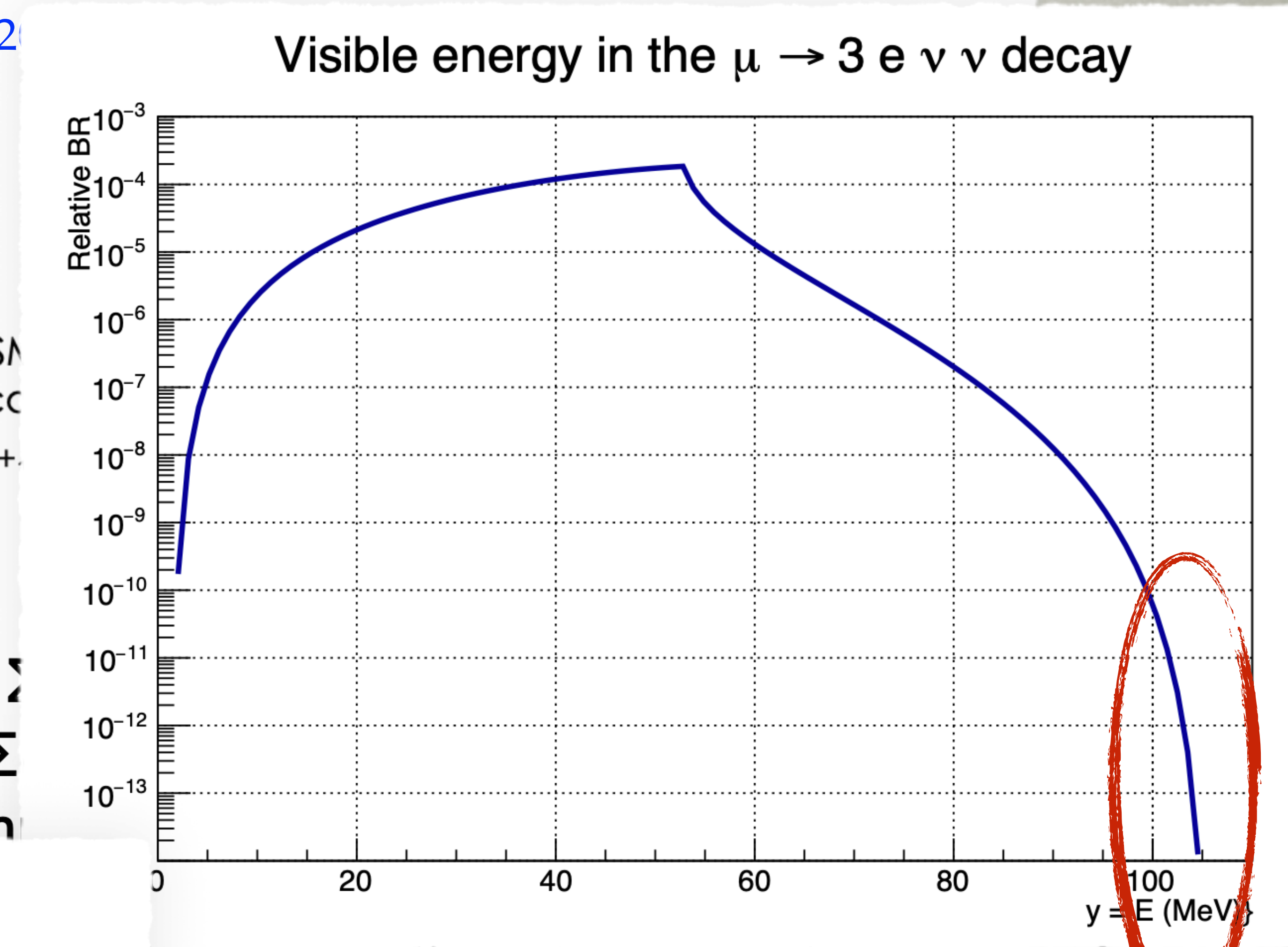
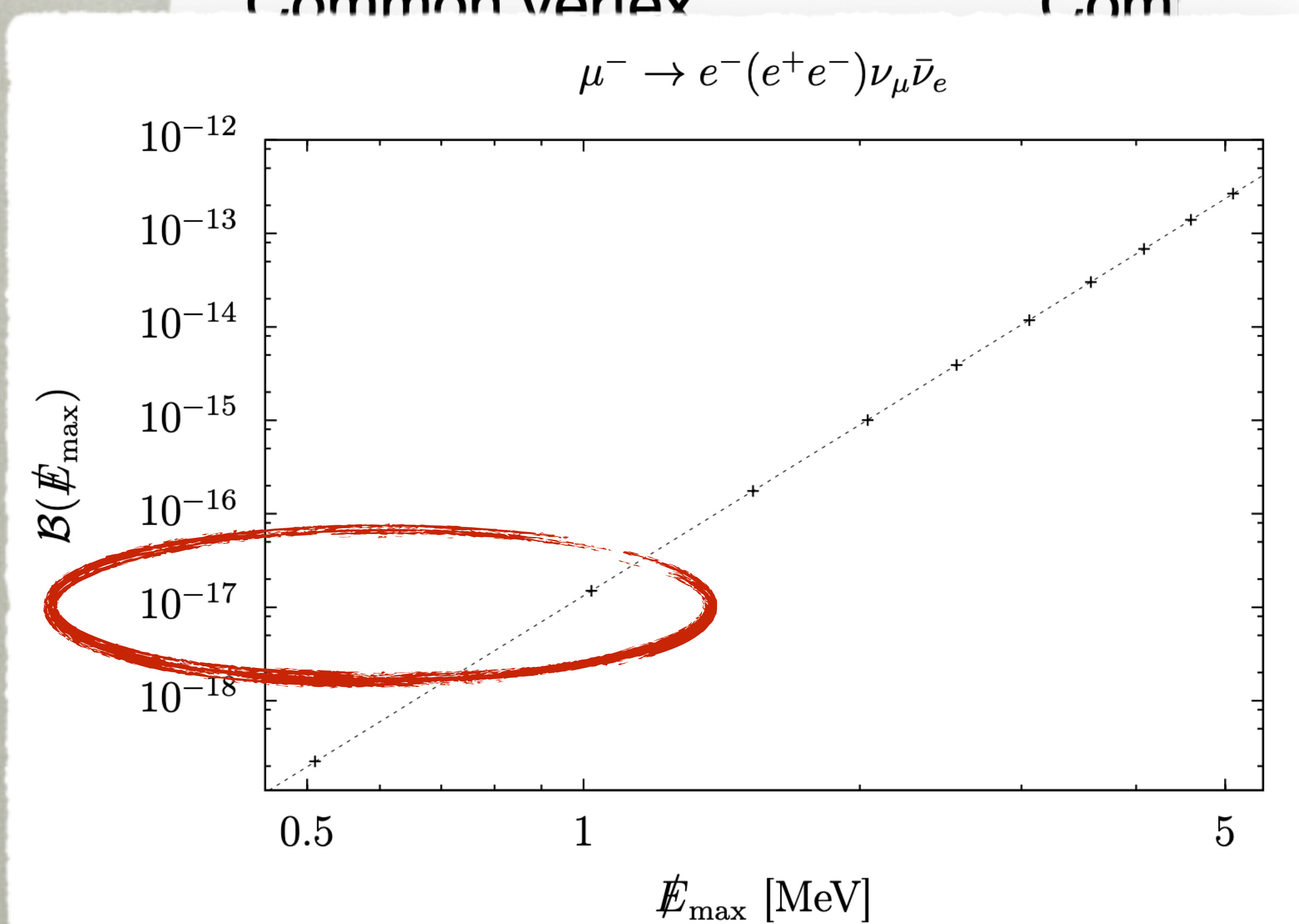
    - need very precise energy measurement to make sure $E_{e^+} + E_{e^-} + E_{e^+} = m_\mu$







nmon vertex (and nothing else)

ground $\mu^+ \to e^+e^-e^+\bar{\nu}_\mu\nu_e$ decay

sing energy $E_{\rm inv}$

asurement to make sure

- present best bound
  - SINDRUM (1988): $Br(\mu^+ \to e^+ e^- e^+) < 1.0 \times 10^{-12}$

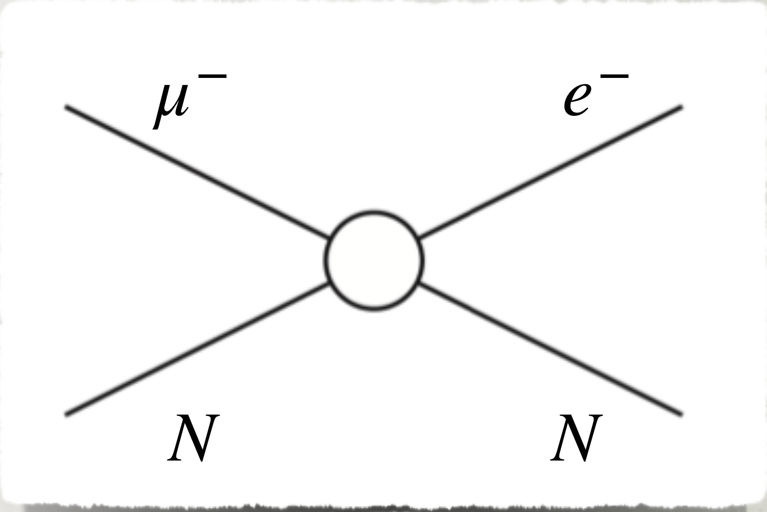
Nuclear Physics B 1988, 299

- future
  - Mu3e:
    Phase 1 (~2025): $Br(\mu \to 3e) < 2 \times 10^{-15}$
    Phase 2 (2030s): $Br(\mu \to 3e) \lesssim 10^{-16}$

2009.11690

$\mu \to e$ CONVERSION

$\mu^- N \to e^- N$ CONVERSION



- $\mu^- N \to e^- N$ conversion:
  - μ^- converts to e^- in the field of nucleus, without emission of ν's
- the μ^- is first stopped in target, and quickly forms muonic atom
  - the $\mu^- N \to e^- N$ conversion has two body kinematics
  - results in monochromatic e^- with energy

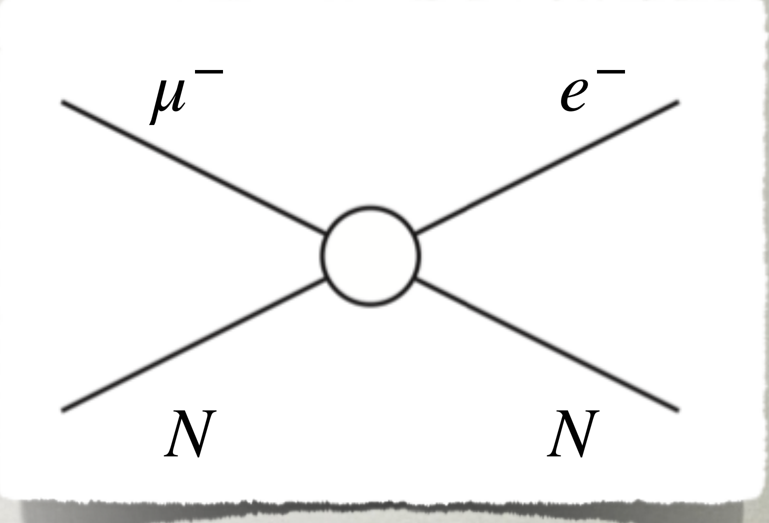
$$E_e = m_\mu - E_b - \frac{m_\mu^2}{2m_N}$$

muonic binding energy $E_b \sim Z^2\alpha^2 m_\mu/2$

kin. eng. of the nucleon

  - e.g. in Al (used in Mu2e), $E_e = 104.96\,\mathrm{MeV}$

$\mu^- N \to e^- N$ conversion



- if NP effects described by EFT, the relevant higher dim. ops. are
  - dipole operators $\bar{\ell}^i_{\mathrm{L}} \sigma^{\mu\nu} \ell^j_{\mathrm{R}} F_{\mu\nu}$
  - four fermion operators with quarks

$$(\bar{L}_L\gamma_\mu L_L)(\bar{Q}_L\gamma^\mu Q_L)$$
$$(\bar{L}_L\gamma_\mu \tau_I L_L)(\bar{Q}_L\gamma^\mu \tau_I Q_L)$$
$$(\bar{e}_R\gamma^\mu e_R)(\bar{Q}_L\gamma_\mu Q_L)$$
$$(\bar{L}_L\gamma_\mu L_L)(\bar{d}_R\gamma^\mu d_R)$$
$$(\bar{e}_R\gamma_\mu e_R)(\bar{d}_R\gamma^\mu d_R)$$

$$(\bar{L}_L\gamma_\mu L_L)(\bar{u}_R\gamma^\mu u_R)$$
$$(\bar{e}_R\gamma_\mu e_R)(\bar{u}_R\gamma^\mu u_R)$$
$$(\bar{L}^a_L e_R)(\bar{d}_R Q^a_L)$$
$$(\bar{L}^a_L e_R)\epsilon_{ab}(\bar{Q}^b_L u_R)$$
$$(\bar{L}^a_i \sigma_{\mu\nu} e_R)\epsilon_{ab}(\bar{Q}^b_L \sigma^{\mu\nu} u_R)$$

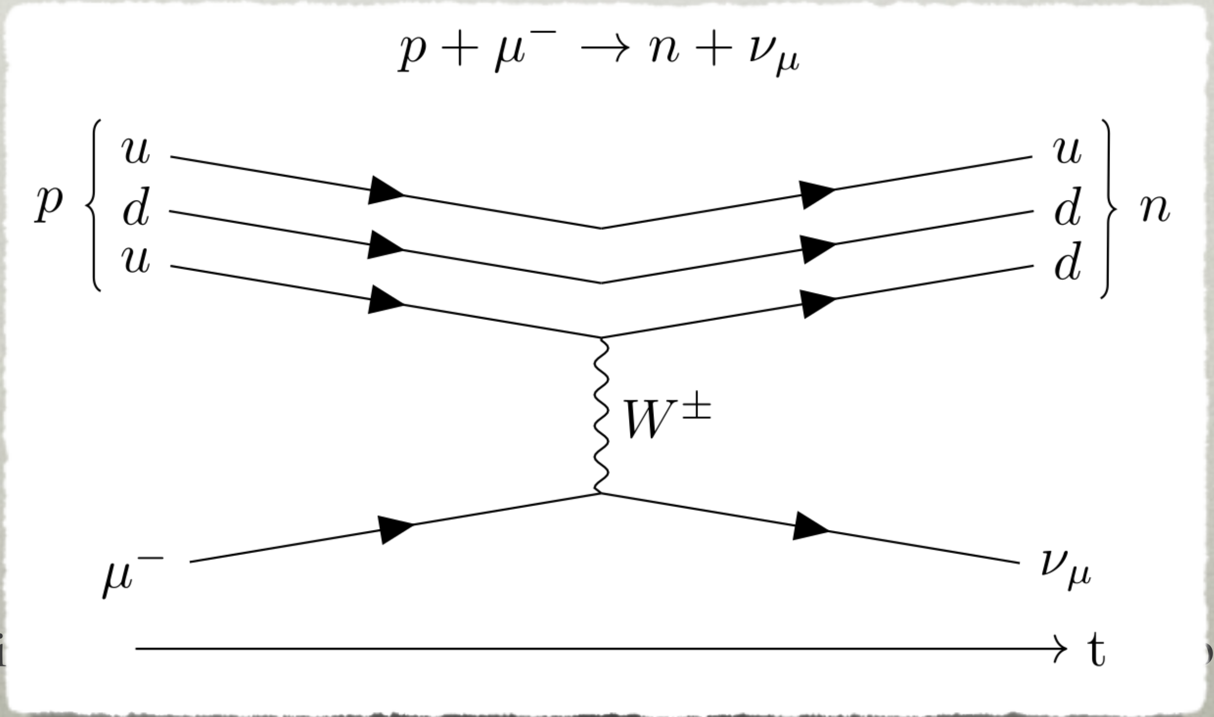
- general treatment rather complicated
  - requires predictions for nuclear matrix elements
  - no first principle calculations for elements used as targets, approximate nucl-th treatments

$\mu^- N \to e^- N$ CONVERSION

- results are quoted in terms of normalized conversion rate

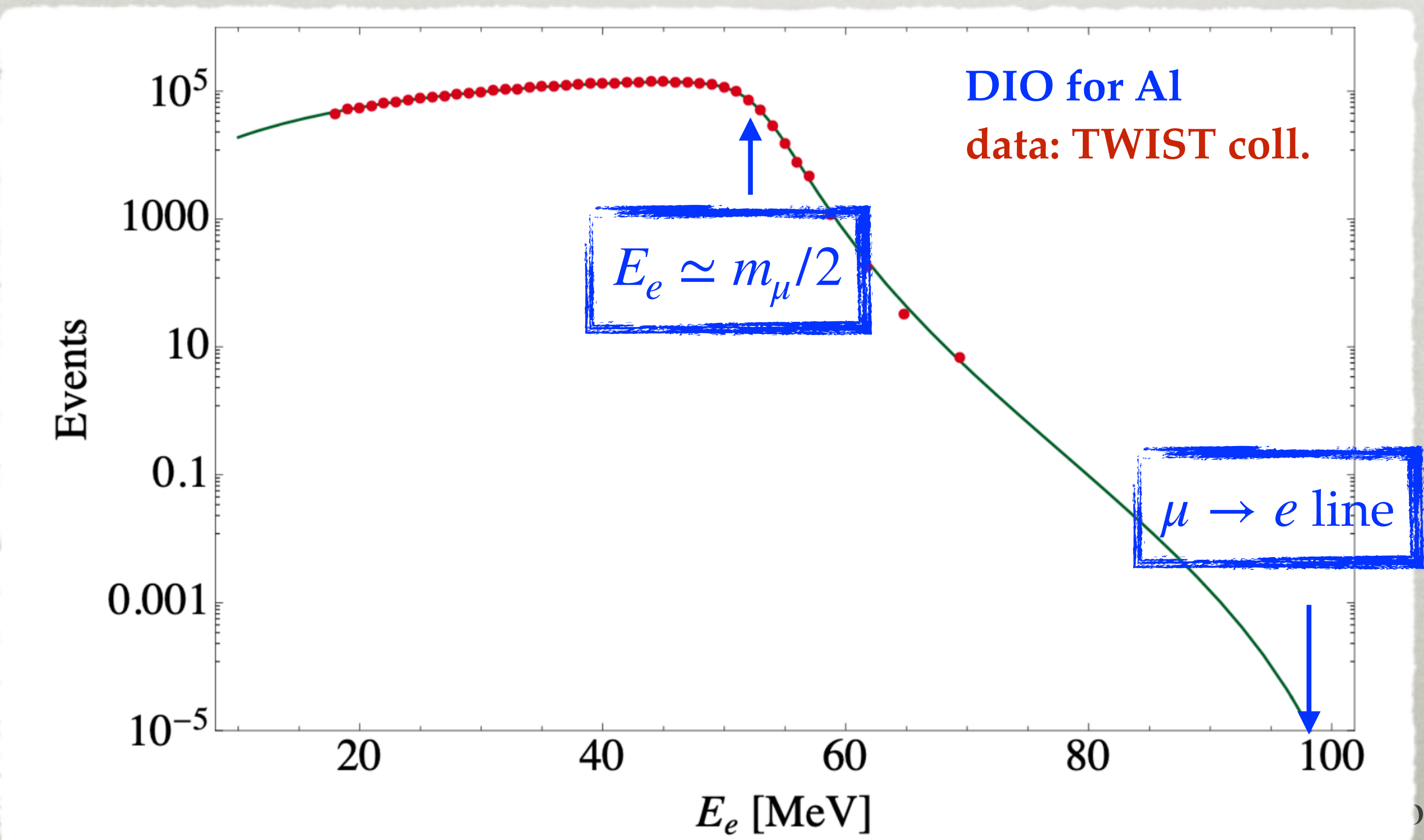
$$R_{\mu e} \;=\; \mathrm{CR}(\mu N \to eN) \;\equiv\; \frac{\Gamma(\mu - e \text{ conversion})}{\Gamma(\text{nuclear capture})}$$

  - normalization to nuclear capture rate reduces theoretical uncertainties



$\mu^- N \to e^- N$ conversion

- experimentally $\mu \to e$ conversion offers many advantages over, e.g., $\mu \to e\gamma$
  - the only intrinsic bckgd is $\mu^- \to e^- \nu_\mu \bar{\nu}_e$ decay in orbit
  - in $\mu^- N \to e^- N$ the e^- is at the kinematical edge of DIO



$\mu^- N \to e^- N$ CONVERSION

Physics Letters B 1993, 317, 631
Eur. Phys. J. C 2006, 47

- present bound
  - SINDRUM-II (1993, 2006): $R_{\mu e} < 6.1(7.1) \times 10^{-13}$ on Ti (Au)
- future (on C)
  - DeeMee: $R_{\mu e} \lesssim 1(0.2) \times 10^{-13}$ on C (SiC)
- future (on Al)
  - COMET Phase 1: $R_{\mu e} \lesssim 10^{-15}$
  - Mu2e & COMET Phase-II: $R_{\mu e} \lesssim 10^{-17}$
  - Mu2e-II: $R_{\mu e} \lesssim 10^{-18}$

COMPLEMENTARY PROBES

- complete list of dim 6 CLFV operators

4-leptons operators		**Dipole operators**	
$Q_{\ell\ell}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{L}_L\gamma^\mu L_L)$	Q_{eW}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\tau_I\Phi W^I_{\mu\nu}$
Q_{ee}	$(\bar{e}_R\gamma_\mu e_R)(\bar{e}_R\gamma^\mu e_R)$	Q_{eB}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\Phi B_{\mu\nu}$
$Q_{\ell e}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{e}_R\gamma^\mu e_R)$		
2-lepton 2-quark operators			
$Q^{(1)}_{\ell q}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{Q}_L\gamma^\mu Q_L)$	$Q_{\ell u}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{u}_R\gamma^\mu u_R)$
$Q^{(3)}_{\ell q}$	$(\bar{L}_L\gamma_\mu\tau_I L_L)(\bar{Q}_L\gamma^\mu\tau_I Q_L)$	Q_{eu}	$(\bar{e}_R\gamma_\mu e_R)(\bar{u}_R\gamma^\mu u_R)$
Q_{eq}	$(\bar{e}_R\gamma^\mu e_R)(\bar{Q}_L\gamma_\mu Q_L)$	$Q_{\ell edq}$	$(\bar{L}^a_L e_R)(\bar{d}_R Q^a_L)$
$Q_{\ell d}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{d}_R\gamma^\mu d_R)$	$Q^{(1)}_{\ell equ}$	$(\bar{L}^a_L e_R)\epsilon_{ab}(\bar{Q}^b_L u_R)$
Q_{ed}	$(\bar{e}_R\gamma_\mu e_R)(\bar{d}_R\gamma^\mu d_R)$	$Q^{(3)}_{\ell equ}$	$(\bar{L}^a_i\sigma_{\mu\nu}e_R)\epsilon_{ab}(\bar{Q}^b_L\sigma^{\mu\nu}u_R)$
Lepton-Higgs operators			
$Q^{(1)}_{\Phi\ell}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{L}_L\gamma^\mu L_L)$	$Q^{(3)}_{\Phi\ell}$	$(\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar{L}_L\tau_I\gamma^\mu L_L)$
$Q_{\Phi e}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}_R\gamma^\mu e_R)$	$Q_{e\Phi 3}$	$(\bar{L}_L e_R\Phi)(\Phi^\dagger\Phi)$

probed by
$\mu \to e\gamma$
$\mu \to 3e$
$\mu \to e$

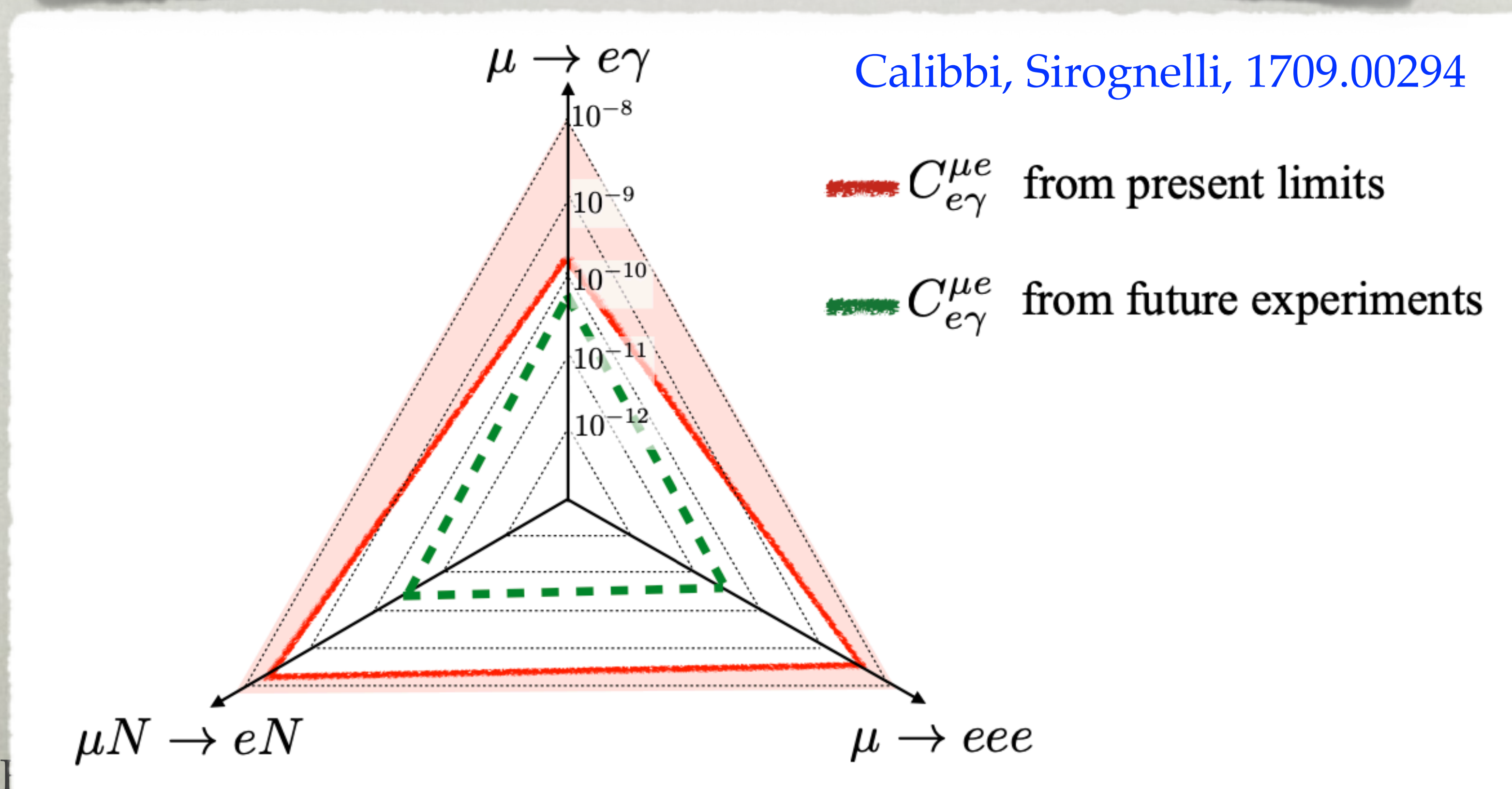
J. Zup

DIPOLE OPERATOR DOMINANCE

- simplified scenario - assume the dipole operator dominates
- interesting to compare the reach of different experiments

$$\mathrm{BR}(\mu \to eee) \simeq \frac{\alpha}{3\pi}\left(\log\frac{m_\mu^2}{m_e^2} - 3\right) \times \mathrm{BR}(\mu \to e\gamma)\,,$$

$$\mathrm{CR}(\mu\ \mathrm{N} \to e\ \mathrm{N}) \simeq \alpha \times \mathrm{BR}(\mu \to e\gamma)\,.$$



UPSHOT

- several different probes in rare muon decays
  - can probe different types of new physics
  - also disentangle different contributions
- significant improvements projected

BACKUP SLIDES