Non-Perturbative Processes in Standard Model & New Physics:

From Standard Calculations to Machine Learning

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Physics of tiny things

$$\frac{1\ \text{g}}{} \left| \frac{1\ \text{mol}}{107.87\ \text{g}} \right| \frac{6.02 \times 10^{23}\ \text{atoms}}{\text{mol}} \approx 10^{21}\ \text{atoms}$$

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If we gave everyone their own Library of Congress:

$$\frac{1.7 \times 10^{8}\ \text{`books'}}{\text{people}} \left| \frac{8 \times 10^{9}\ \text{people}}{} \right. \approx 10^{18}\ \text{`books'}$$

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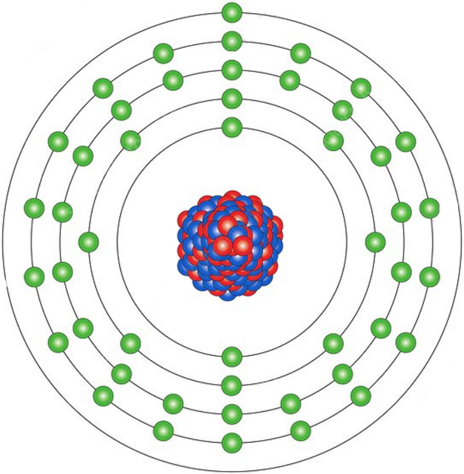
Need 1000 Earths to equate to the atoms in a silver earring!

Sub-atomic particles



47 electrons
47 protons
61 neutrons

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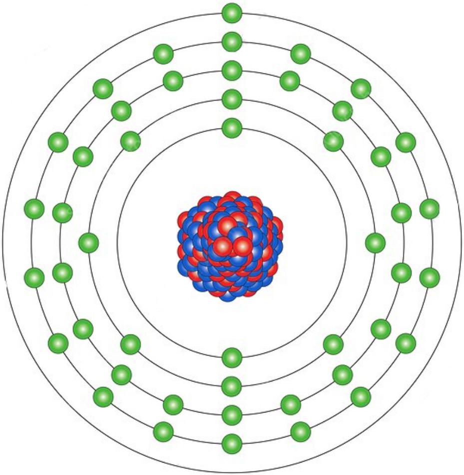

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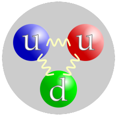
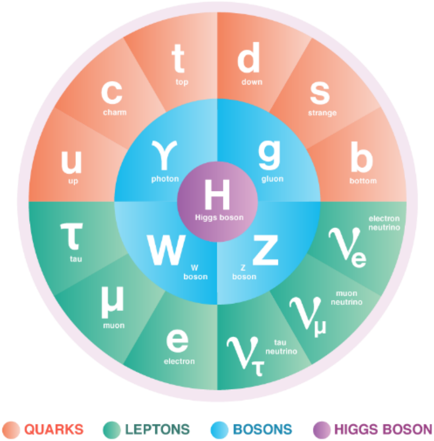
Protons and neutrons are composites of quarks:



(wikipedia.org)

Elementary particles

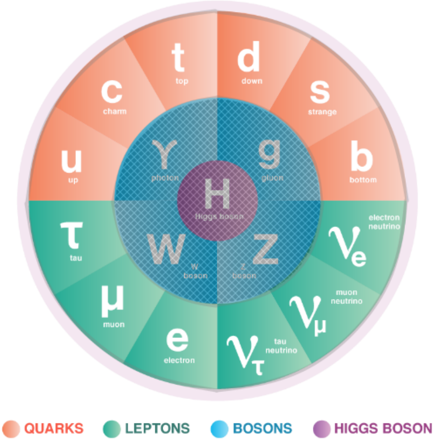


(energy.gov)

Two groups:

- Outer ring: fermions
- Inner circle : bosons

Fermions



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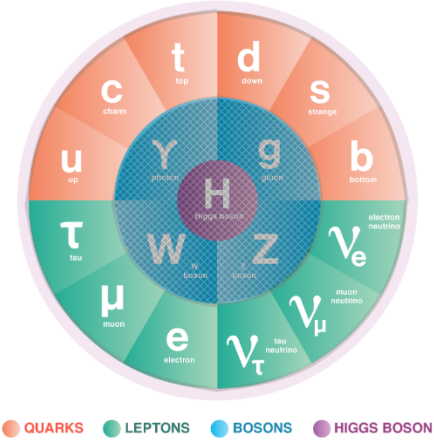
- Half-integer spin
- Pauli's exclusion principle

Fermions



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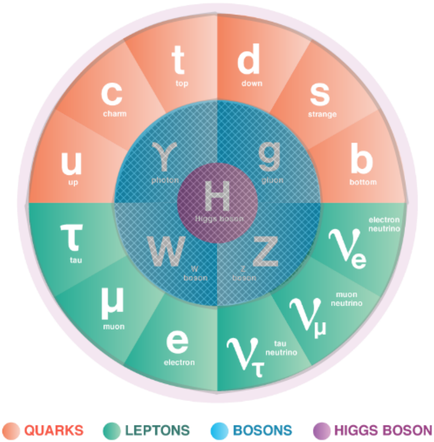

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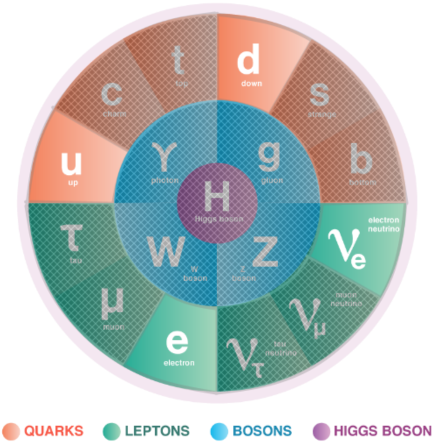

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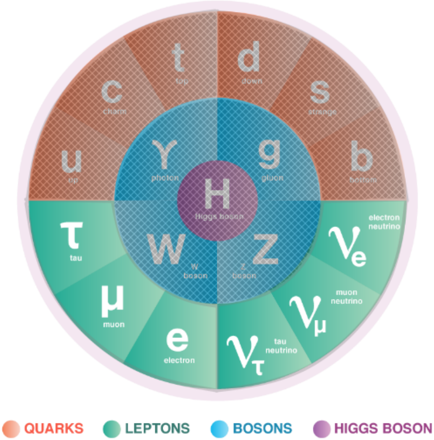
Leptons



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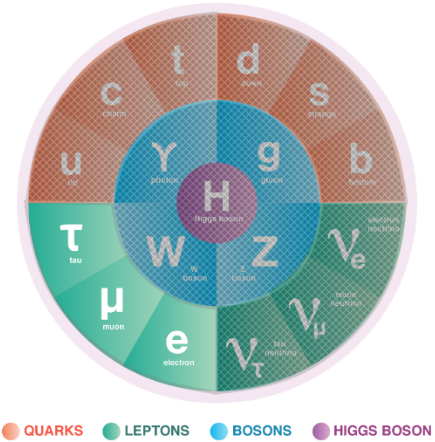
- Either charged or neutral

Charged leptons



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Have electric charge

- Particles have a (-1) elementary charge
- Anti-particles have a (+1) elementary charge

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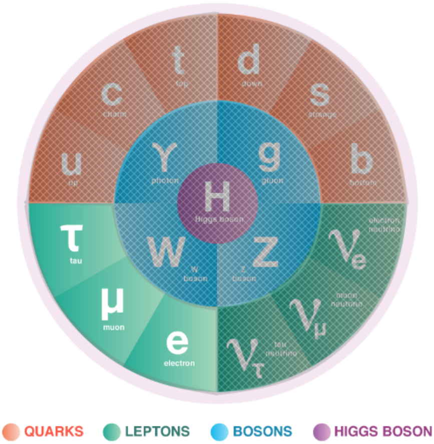

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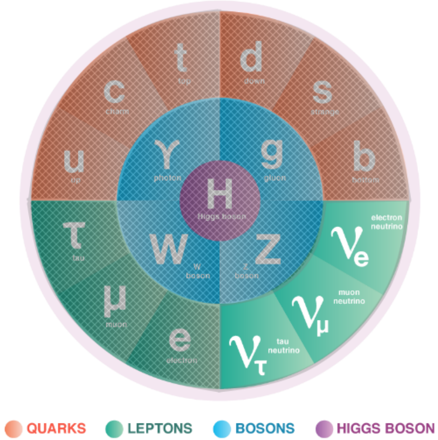
Elementary charge:

$$e = \sqrt{4\pi\alpha} \qquad \alpha \approx \frac{1}{137}$$

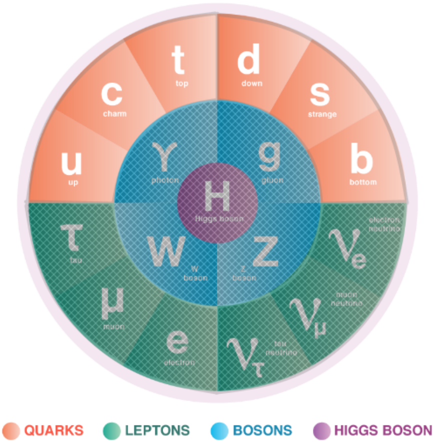
Neutral leptons



(energy.gov)

- Neutrinos have zero electric charge
- Flavor matches the charged leptons

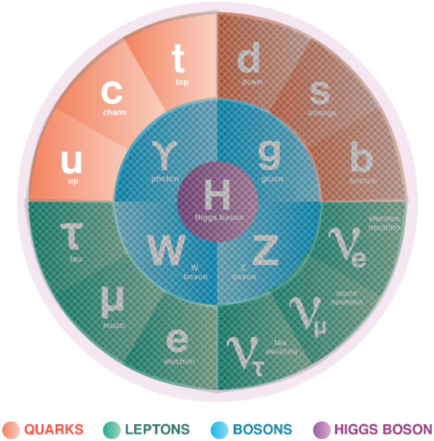
Quarks



(energy.gov)

- Carry color charge in addition to flavor and electric charge
- Either up-type or down-type

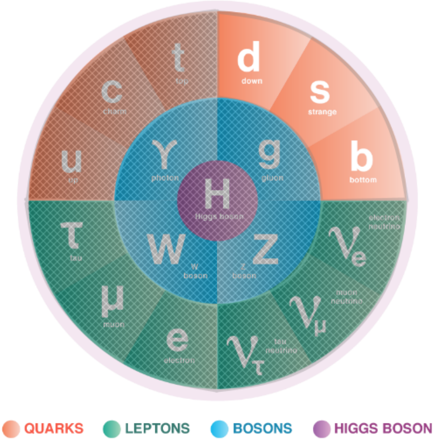
Up-type quarks



(energy.gov)

- Electric charge of $+\frac{2}{3}e$
- 1st generation: up
- 2nd and 3rd gens:
  charm and top
  heavier cousins of up

Down-type quarks

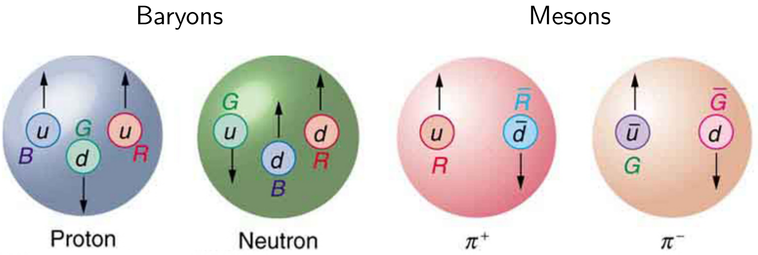


(energy.gov)

- Electric charge of $-\frac{1}{3}e$
- 1st generation: down
- 2nd and 3rd gens:
  strange and bottom
  heavier cousins of down

Composite particles

Color confinement: no free quarks are observed!



(pressbooks-dev.oer.hawaii.edu)

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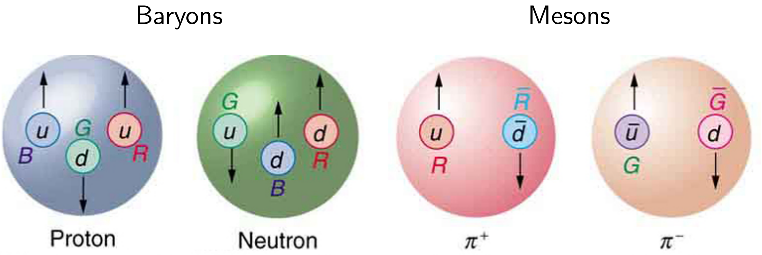

(pressbooks-dev.oer.hawaii.edu)

Two base requirements to create from quarks:

- Electric charge: whole number (in units of elementary charge, e)
- 'Color neutral'

Composite particles - electric charge

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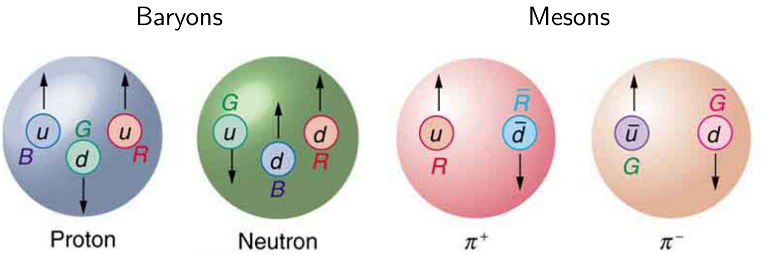

(pressbooks-dev.oer.hawaii.edu)

Proton:

$$+\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=\frac{2+2-1}{3}=+1$$

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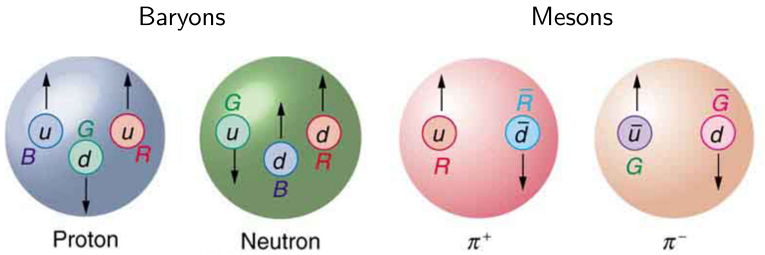

(pressbooks-dev.oer.hawaii.edu)

Neutron:

$$+\frac{2}{3} - \frac{1}{3} - \frac{1}{3} = \quad \frac{2-1-1}{3} = 0$$

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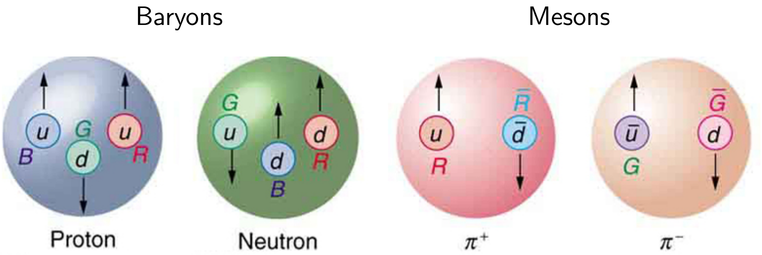

(pressbooks-dev.oer.hawaii.edu)

Positively charged pion (π^+):

$$+\frac{2}{3} + \frac{1}{3} = \frac{2+1}{3} = +1$$

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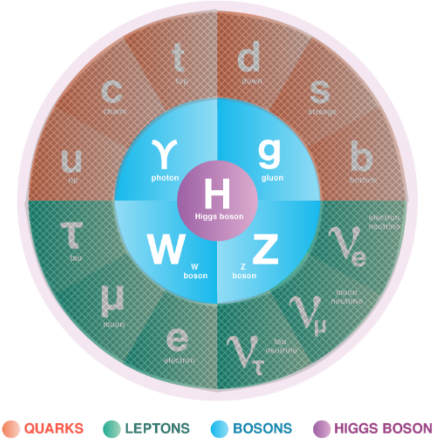
$$\text{meson} = q_1 + \bar{q}_2$$

Bosons



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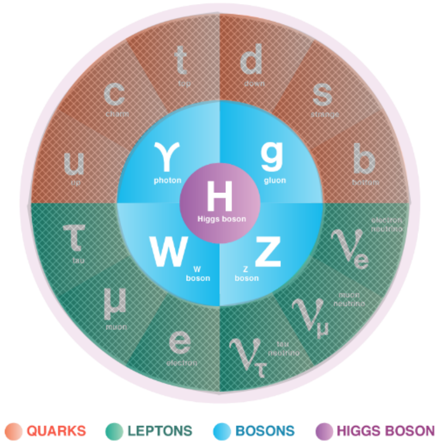
Whole-integer spin:

- Higgs has spin-0
- Others are spin-1

Bosons



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Spin-1 bosons carry fundamental forces:

- photons: electromagnetism
- $W^{\pm}$ and Z: weak-force
- gluons: strong force
- (postulated) graviton: gravity

Standard Model

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- Gauge theory that is invariant under the gauge group:
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- Abelian:
  Gauge transformations commute:
  e.g. Weak hypercharge
- Non-Abelian:
  Gauge transformations do not commute:
  e.g. Electroweak theory, Quantum Chromodynamics
- Higgs mechanism causes spontaneous symmetry breaking (needed for non-zero particle masses):
$$SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{QED}$$

Standard Model Lagrangian

- Standard Model Lagrangian often broken up into four smaller Lagrangians:

$$\mathcal{L}_{SM} = \mathcal{L}_{kinetic} + \mathcal{L}_{gauge} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}$$

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$$\mathcal{L}_{kinetic} = \bar{L}_L i \not{D} L_L + \bar{e}_R i \not{D} e_R + \bar{Q}_L i \not{D} Q_L + \bar{d}_R i \not{D} d_R + \bar{u}_R i \not{D} u_R$$

(where L_L (e_R) are the left (right) chiral lepton doublet (singlet) fields, and similar is true for the Q_L, u_R, and d_R quark fields)

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  Derives from a dimensionless action (in natural units):
  $\mathcal{S} = \int d^4 x \mathcal{L}$

Cabibbo-Kobayashi-Maskawa matrix

- The Higgs field is responsible for the masses of the elementary particles

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$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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- Standard Model Effective Field Theory (SMEFT) can be used to study these SM deficiencies and search for BSM physics
  - Constructed using the SM fields
  - Higher-dimensional operators are generated at a new physics scale, Λ, which is not known

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda} \sum_i c_i^{(5)}(\mu) Q_i^{(5)} + \mathcal{O}\left(\frac{1}{\Lambda^2}\right)$$

Perturbation Theory

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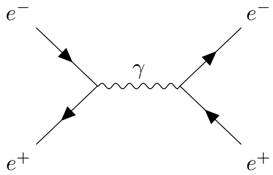
tree-level $\propto g^2$



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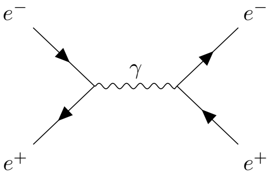
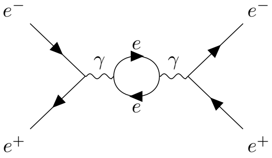


one loop $\propto g^4$



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Light Dark Matter

Only gravitational evidence of DM
- Can we see it elsewhere?

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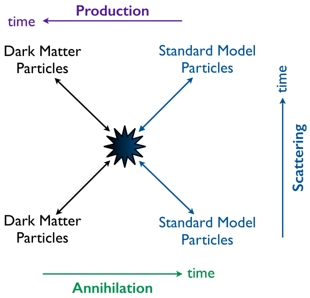
If DM couples to quarks, we can find:
-Final states with other particles
-Final states by itself
i.e. ‘Invisible widths’



(particleastro.brown.edu)

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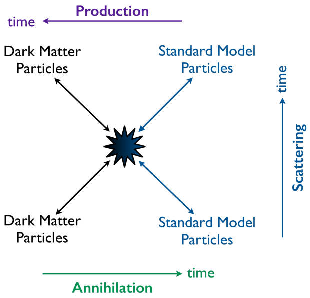
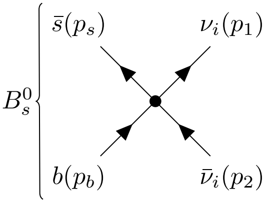


(particleastro.brown.edu)

Light DM: $M_{DM} < 2.5$ GeV
Can use heavy mesons decays to probe for it!

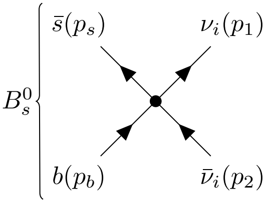
Invisible background



Main background in SM for invisible widths are neutrinos:

- Lowest order in G_F is $M \to \nu\bar{\nu}$

Invisible background



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Experimental sensitivities:

$$\mathcal{B}(B_s \to \not{E}) < 1.3 \times 10^{-4} \text{ (Belle (2012))}$$
$$\mathcal{B}(B_d \to \not{E}) < 2.4 \times 10^{-5} \text{ (BaBar (2012))}$$
$$\mathcal{B}(D^0 \to \not{E}) < 9.4 \times 10^{-5} \text{ (Belle (2017))}$$

Two body SM decay for $M \to \not{E}$

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2\theta_W} \sum_{l=e,\mu,\tau} \sum_k \lambda_k X^l(x_k) J^\mu_{Qq} \left(\overline{\nu}^l_L \gamma_\mu \nu^l_L\right)$$

Two body SM decay for $M \to \not{E}$

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Tiny branching ratios:

$$\boxed{\mathcal{B}(B_q \to \nu\overline{\nu}) = C|V_{tb}V^*_{tq}|^2 X(x_t)^2 x_\nu^2} \longrightarrow$$

$$C \equiv \frac{G_F^2 \alpha^2 f_{B_q}^2 M_{B_q}^3}{16\pi^3 \sin^4 \theta_W \Gamma_{B_q}}$$

Helicity suppression! $x_\nu^2 \equiv \left(\frac{m_\nu}{M_B}\right)^2$

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with $m_\nu \approx 0.1$ eV

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Badin, Petrov (2010)

with $m_\nu \approx 0.1$ eV

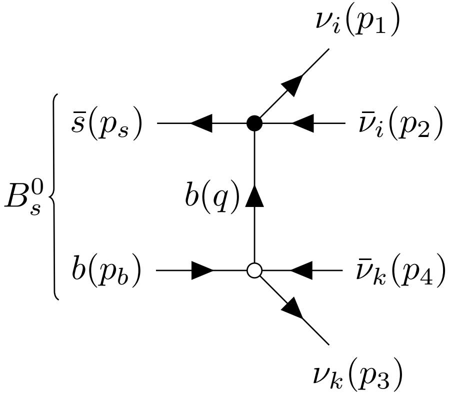
SM background is so small,
can we use it to find new physics?

However, SM invisible decay has more terms!!

$$\mathcal{B}\left(M \to \not{E}\right) = \mathcal{B}\left(M \to \nu\bar{\nu}\right) + \boxed{\mathcal{B}\left(M \to \nu\bar{\nu}\nu\bar{\nu}\right)} + \ldots$$

Bhattacharya, Grant, Petrov
Phys.Rev.D 99 (2019) 9, 093010
arXiv: 1809.04606 [hep-ph]

Two neutrino pair production



i, *k* are lepton flavors

Vertex Key:

- ●: 2 body $\mathcal{L}_{eff}$
- ○: Effective Z propagator

Some calculation details

Amplitude:

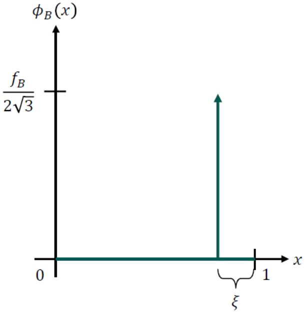
$$\mathcal{A}_s = -\frac{G_F^2 \alpha V_{ts}^* V_{tb} X(x_t)}{4\pi \sin^2\theta_w} \sum_{i,k} L^{\mu}_{\ell_i} L^{\nu}_{\ell_k} \langle 0 | \bar{s} \Gamma_{\mu\nu} b | B_s \rangle$$

Simple quark model:

$$\langle 0 | \, \bar{s} \Gamma^{\mu\nu} b \, | B_s \rangle = \int_0^1 dx \mathrm{Tr}\left[\Gamma^{\mu\nu} \psi_B\right]$$

$$\psi_B = \frac{I_c}{\sqrt{6}} \phi_B(x) \gamma^5 \left(\not{P}_B + M_B g_B(x) \right)$$

$$\phi_B(x) = \frac{f_B}{2\sqrt{3}} \delta(1 - x - \xi)$$



Branching fraction results

$$\mathcal{B}\left(M \to \not{E}\right) = \boxed{\mathcal{B}\left(M \to \nu\bar{\nu}\right)} + \boxed{\mathcal{B}\left(M \to \nu\bar{\nu}\nu\bar{\nu}\right)} + \ldots$$

$$\boxed{\begin{aligned} B_s &: 3.07 \times 10^{-24} \\ B_d &: 1.24 \times 10^{-25} \\ D^0 &: 1.1 \times 10^{-30} \end{aligned}}$$

Badin, Petrov (2010)

$$\boxed{\begin{aligned} B_s &: (5.48 \pm 0.89) \times 10^{-15} \\ B_d &: (1.51 \pm 0.28) \times 10^{-16} \\ D^0 &: (2.96 \pm 0.39) \times 10^{-27} \\ K_S^0 &: (5.62 \pm 0.78) \times 10^{-25} \\ K_L^0 &: (2.72 \pm 0.49) \times 10^{-22} \end{aligned}}$$

9 orders of magnitude!

Bhattacharya, Grant, Petrov
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Consequences

- We can no longer set constraints of neutrino masses using the branching fractions from invisible widths:

  $\mathcal{B}\left(M \to \nu\bar{\nu}\right) \propto m_\nu^2, \quad$ but $\mathcal{B}\left(M \to \nu\bar{\nu}\nu\bar{\nu}\right)$ is not and is dominant

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- Using invisible widths to probe for new physics is less viable
  A much larger branching ratio means 'less room' for new physics
  All depends on precision of experimental measurement,
  which are currently insufficient

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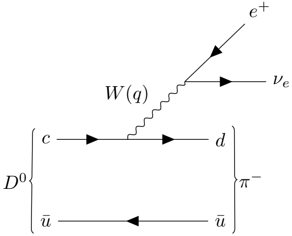
CKM matrix element $|V_{cd}|$

Weak hadronic decays can be used to measure CKM matrix elements.
- Semileptonic decays reduce the number of 'unknowns'

$$\frac{d\Gamma(D \to \pi \bar{e} \nu_e)}{dq^2} \propto |V_{cd} F_+(q^2)|^2$$



However, there are still two 'unknowns'!

Form factors

Form factors encode all hadronic dynamics that cannot be analytically calculated from first principles

- the first derivative encodes the effective volume size of the quark transition

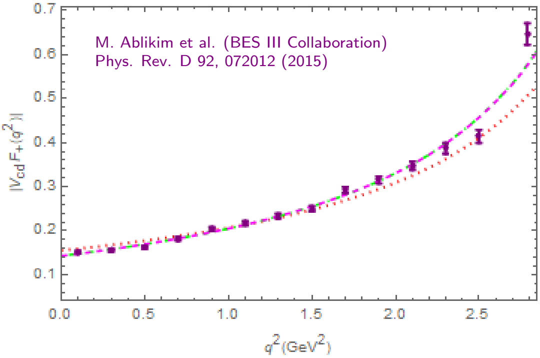
Calculations of them are one of a couple categories:

- partial momentum range calculations with lattice QCD or QCD sum rules
- full momentum range calculations with phenomenological parameterizations
- Z-expansion to improve calculations

Form factor parameterizations

Some common model choices compared to the BES III dataset are:

- Simple pole
- BK model
- BZ model



What uncertainty should be assigned to the choice of a particular shape for the fit function?

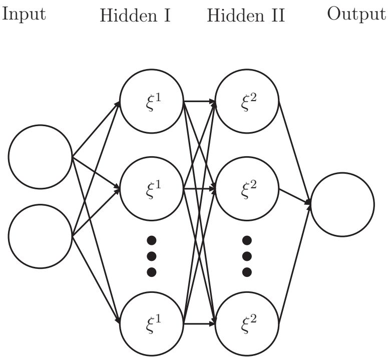
Does introducing a specific form induce a bias in the interpretation of the results?

Artificial neural networks and High Energy Physics

- Can be used as unbiased estimators of data
  - Hornic et al. (1989)
- Collaborations use similar techniques used to parameterize nuclear data, i.e. NNPDF collaboration
  - Forte et al. (2002)
- ANNs are widely used in HEP
  - Jet finding algorithms
  - Parton distribution functions
  - Reducing background noise in data

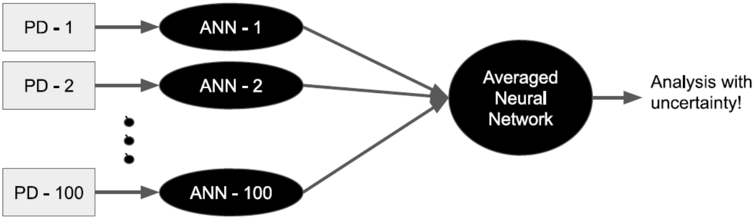
ANN implementation

- Multi-layer fully-connected feed-forward ANN with back propagation
- Supervised learning
- Two inputs: q^2 and scaled q^2
- Used the sigmoid activation function

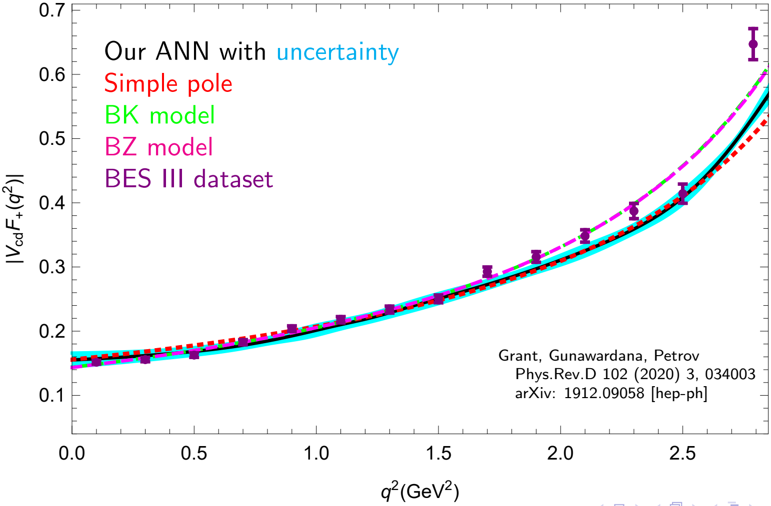


Pseudo-data generation

- Generated pseudo-data with Monte Carlo algorithm from BES III dataset
- Created 10 ANNs with unique PD set and weights (biases)
- Averaged results together and found standard deviation



ANN vs parameterizations



Comparing derivatives

Can expand the form factor (with the CKM matrix element) in the following way

$$\left|V_{cd}F_{+}\left(q^2\right)\right| = \left|V_{cd}F_{+}(0)\right|\left(1 + F_1 q^2 + F_2 q^4 + \ldots\right)$$

Form factor	$\lvert V_{cd}F_{+}(0)\rvert \times 10^{-2}$	$F_1 \times 10^{-1}$ GeV^{-2}	$F_2 \times 10^{-1}$ GeV^{-4}
ANN (this work)	14.92 ± 0.14	2.062 ± 0.261	0.869 ± 0.290
$F_{+}^{\mathrm{pole}}(q^2)$	15.57 ± 0.10	2.4830 ± 0.0001	1.2330 ± 0.0001
$F_{+}^{\mathrm{BK}}(q^2)$	14.37 ± 0.16	3.170 ± 0.072	1.669 ± 0.055
$F_{+}^{\mathrm{BZ}}(q^2)$	14.35 ± 0.25	2.961 ± 0.306	1.540 ± 0.271

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If you plan on using a phenomenological parameterization:

We suggest using the BZ model, or an even higher pole model,
and the simple pole model should probably be avoided

Using moments to bound FF

Moments of heavy-light invariant amplitude:

$$\chi_+^{(n)} = \frac{1}{\pi}\int_{t_+}^{\infty} dt \frac{\mathrm{Im}\ \Pi_+(t+i\epsilon)}{t^{n+1}}, \qquad \text{w/}\ \ \mathrm{Im}\ \Pi_+(t+i\epsilon) \geq y(t)\left|F_+(t)\right|^2$$

$$\therefore \quad |F_+(0)| \leq h^{(n)}\left(\chi_+^{(n)}, F_1, F_2\right)$$

Moment, n	$\chi_+^{(n)NP} \times 10^{-3}$	$\chi_+^{(n)PT} \times 10^{-3}$	$\chi_+^{(n)} \times 10^{-3}$
1 $\left(\text{in GeV}^{-2}\right)$	0.98 ± 0.25	6.37 ± 0.67	7.35 ± 0.89
2 $\left(\text{in GeV}^{-4}\right)$	0.35 ± 0.12	0.80 ± 0.15	1.15 ± 0.26
3 $\left(\text{in GeV}^{-6}\right)$	0.13 ± 0.05	0.14 ± 0.04	0.27 ± 0.09

Bound results

Moment, n	$\lvert F_+(0)\rvert$, upper bound	$\lvert V_{cd}\rvert$, lower bound
1	1.49 ± 1.13	0.100 ± 0.077
2	2.05 ± 1.32	0.073 ± 0.047
3	3.25 ± 1.70	0.046 ± 0.024

- These results are consistent with the value quoted by the Particle Data Group:

$$\lvert V_{cd}\rvert = 0.218 \pm 0.004$$

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Lepton flavor violation

Flavor-changing neutral currents can be experimental probes for physics beyond the Standard Model:

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Do the charged leptons also have cross-generational interactions?

Muon to electron transitions

Most interesting (charged) lepton flavor violation is $\mu \to e$ transitions:

process	current sensitivity	future sensitivity
$\mu \to e\gamma$	$< 4.2 \times 10^{-13}$ (MEG)	$\sim 10^{-14}$ (MEG II)
$\mu \to e\gamma\gamma$	$< 7.2 \times 10^{-11}$ (Crystal Box)	
$\mu \to e\bar{e}e$	$< 1.0 \times 10^{-12}$ (SINDRUM)	$\sim 10^{-16}$ (Mu3e)
$\mu A \to eA$	$< 7 \times 10^{-13}$ (SINDRUM II)	$\sim 10^{-16}$ (COMET, Mu2e) $\sim 10^{-18}$ (PRISM/PRIME)

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Davidson et. al. proposed Flavor-changing Rayleigh operators

- Interaction between a muon, an electron, and two photons
- Obviously probes the $\mu \to e\gamma\gamma$ interaction
- Also probes the $\mu A \to eA$ interaction

Rayleigh operators

$$\mathcal{L}_{RO} = \left(-\frac{1}{\Lambda^3}\right) \Big[\bar{e}\left(C_{F\tilde{F}R}P_R + C_{F\tilde{F}L}P_L\right)\mu F_{\alpha\beta}\tilde{F}^{\alpha\beta} + \bar{e}\left(C_{FFR}P_R + C_{FFL}P_L\right)\mu F^{\alpha\beta}F_{\alpha\beta}\Big]$$

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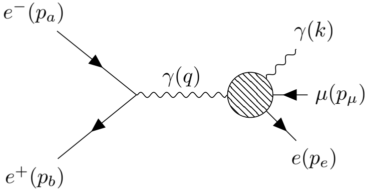
However, there are other SM currents we can use to construct this interaction!

Rayleigh operators in electron-position collisions

- This interaction can be probed in a much simpler environment:

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



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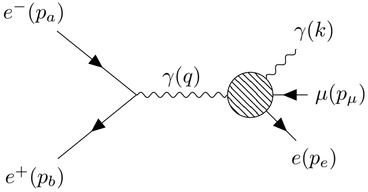

Aside from π^0 current, there are several others that can be calculated

- ρ^0 current
- Higgs current
- Fermion triangle loop amplitudes

Neutral meson currents

Possible long range contributions from meson currents:

- Pion interacting with two photons (one real and one virtual)

$$FR^{\nu\tau}_{\pi^0\gamma\gamma} = \quad ie^2 F_{\pi^0\gamma\gamma^*}(-q^2) p_{\pi,\alpha} k_\beta \varepsilon^{\nu\tau\alpha\beta}$$

(Xiao, Ma (2003))

- Rho transitions from photon (Vector meson dominance)

$$\mathcal{L}_{\rho^0,VMD} = \quad \frac{e\ f_\rho}{2}(F_{\mu\nu}\rho^{\mu\nu} + 2J^\rho_\mu A^\mu)$$

(Golowich, Pakvasa (1995), Schildknecht (1972), Sakurai (1969))

- Meson interacting with LFV current

$$\mathcal{L}_{M,LFV} = -\frac{1}{\Lambda^2}\sum_q [(C_{\pi,R}\bar{\mu}\gamma^\mu P_R e + C_{\pi,L}\bar{\mu}\gamma^\mu P_L e)(\bar{q}\gamma_\mu\gamma_5 q)$$
$$+ (C_{\rho,R}\bar{\mu}\gamma^\mu P_R e + C_{\rho,L}\bar{\mu}\gamma^\mu P_L e)(\bar{q}\gamma_\mu q)]$$

(Hazard, Petrov (2016))

Higgs current

Has similar interactions as the pion current:

- Pion interacting with two photons (one real and one virtual)

$$FR_{H^0\gamma\gamma} = \quad -\frac{ie^2 g_W}{(4\pi)^2 m_W} F_{H\gamma\gamma}((k\cdot q)g^{\nu\tau} - k^\nu q^\tau)$$

(Marciano, Zhang, and Willenbrock (2012))

- Higgs interacting with LFV current

$$\begin{aligned}\mathcal{L}_{H^0,LFV} = -\frac{1}{\Lambda^2}\Big[&\left(H^\dagger H\right)(C^*_{He}(\bar{\mu}P_L e) + C_{He}(\bar{\mu}P_R e)) \\ &+ \left(H^\dagger i\overleftrightarrow{D}_\mu H\right)\Big((C^{(1)}_{H\ell} + C^{(3)}_{H\ell})(\bar{\mu}\gamma^\mu P_L e) \\ &\qquad + C_{He}(\bar{\mu}\gamma^\mu P_R e)\Big)\Big]\end{aligned}$$

(Petrov, Blechman (2016))

Fermionic triangle loops amplitudes

- Two vertices of the triangle loop are photons, so the LFV current can only be scalar, pseudoscalar, or axial
  - The vector currents are zero due to Furry's Theorem
  - The tensor currents also cancels to zero

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$$\Delta_S = -\frac{i\alpha_e Q^2}{2\pi} I_S(k\cdot q, k^2, q^2, m_f)(k^\nu q^\tau - g^{\nu\tau}(k\cdot q))$$

$$\Delta_P = \frac{\alpha_e Q^2}{2\pi} I_P(k\cdot q, k^2, q^2, m_f)\epsilon^{\nu\tau kq}$$

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$$\Delta_A = \frac{\alpha_e Q^2}{16\pi}\Big(I_{A1}\epsilon^{\alpha\nu\tau q} + I_{A2}\epsilon^{\alpha\nu\tau k} + I_{A3}k^\alpha\epsilon^{\nu\tau kq} + I_{A4}q^\alpha\epsilon^{\nu\tau kq} + I_{A5}k^\nu\epsilon^{\alpha\tau kq} + I_{A6}q^\nu\epsilon^{\alpha\tau kq} + I_{A7}q^\tau\epsilon^{\alpha\nu kq}\Big)$$

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- Leptonic loops only have axial currents from SMEFT operators

Fermionic triangle loops amplitudes

$$\mathcal{L}_{\Delta_\ell} = -\frac{1}{\Lambda^2}\left[(\bar{\ell}\gamma_\alpha P_R \ell)(C_{ee}(\bar{\mu}\gamma^\alpha P_R e) + C_{\ell e}(\bar{\mu}\gamma^\alpha P_L e)) \right.$$
$$\left. + (\bar{\ell}\gamma_\alpha P_L \ell)(C_{\ell\ell}(\bar{\mu}\gamma^\alpha P_L e) + C_{\ell e}(\bar{\mu}\gamma^\alpha P_R e))\right]$$

Fermionic triangle loops amplitudes

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$$+ (\bar{\ell}\gamma_\alpha P_L \ell)(C_{\ell\ell}(\bar{\mu}\gamma^\alpha P_L e) + C_{\ell e}(\bar{\mu}\gamma^\alpha P_R e))\Big]$$

$$\mathcal{L}_{\Delta_u} = -\frac{1}{\Lambda^2}\Big[(\bar{u}\gamma_\alpha P_R u)(C_{eu}(\bar{\mu}\gamma^\alpha P_R e) + C_{\ell u}(\bar{\mu}\gamma^\alpha P_L e))$$
$$+ (\bar{u}\gamma_\alpha P_R u)((C^{(1)}_{\ell q} - C^{(3)}_{\ell q})(\bar{\mu}\gamma^\alpha P_L e) + C_{qe}(\bar{\mu}\gamma^\alpha P_R e))$$
$$- (\bar{u} P_R u) C^{(1)*}_{\ell equ}(\bar{\mu} P_L e) - (\bar{u} P_L u) C^{(1)}_{\ell equ}(\bar{\mu} P_R e)\Big]$$

Fermionic triangle loops amplitudes

$$
\begin{aligned}
\mathcal{L}_{\Delta_\ell} = -\frac{1}{\Lambda^2}\Big[&(\bar{\ell}\gamma_\alpha P_R \ell)(C_{ee}(\bar{\mu}\gamma^\alpha P_R e) + C_{\ell e}(\bar{\mu}\gamma^\alpha P_L e)) \\
&+ (\bar{\ell}\gamma_\alpha P_L \ell)(C_{\ell\ell}(\bar{\mu}\gamma^\alpha P_L e) + C_{\ell e}(\bar{\mu}\gamma^\alpha P_R e))\Big] \\
\mathcal{L}_{\Delta_u} = -\frac{1}{\Lambda^2}\Big[&(\bar{u}\gamma_\alpha P_R u)(C_{eu}(\bar{\mu}\gamma^\alpha P_R e) + C_{\ell u}(\bar{\mu}\gamma^\alpha P_L e)) \\
&+ (\bar{u}\gamma_\alpha P_R u)((C_{\ell q}^{(1)} - C_{\ell q}^{(3)})(\bar{\mu}\gamma^\alpha P_L e) + C_{qe}(\bar{\mu}\gamma^\alpha P_R e)) \\
&- (\bar{u}P_R u)C_{\ell equ}^{(1)*}(\bar{\mu}P_L e) - (\bar{u}P_L u)C_{\ell equ}^{(1)}(\bar{\mu}P_R e)\Big] \\
\mathcal{L}_{\Delta_d} = -\frac{1}{\Lambda^2}\Big[&(\bar{d}\gamma_\alpha P_R d)(C_{ed}(\bar{\mu}\gamma^\alpha P_R e) + C_{\ell d}(\bar{\mu}\gamma^\alpha P_L e)) \\
&+ (\bar{d}\gamma_\alpha P_R d)((C_{\ell q}^{(1)} + C_{\ell q}^{(3)})(\bar{\mu}\gamma^\alpha P_L e) + C_{qe}(\bar{\mu}\gamma^\alpha P_R e)) \\
&+ (\bar{d}P_R d)C_{\ell edq}^{*}(\bar{\mu}P_L e) + (\bar{d}P_L d)C_{\ell edq}(\bar{\mu}P_R e)\Big]
\end{aligned}
$$

Matching

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- To match the two operator types together, need to expand SMEFT operators to leading order terms first:
  - Heavy quark (t & b) loops expanded as $m_f \to \infty$ to order $\mathcal{O}\left(\frac{1}{m_f}\right)$
    - Expanding the triangle loop functions: $\Delta_S, \Delta_P, \Delta_A$
  - Higgs current expanded as $m_H \to \infty$ to order $\mathcal{O}\left(\frac{1}{m_H^2}\right)$
    - Expanding the propagator $\propto \frac{1}{(k\cdot q)-m_H^2}$

Comparing operators

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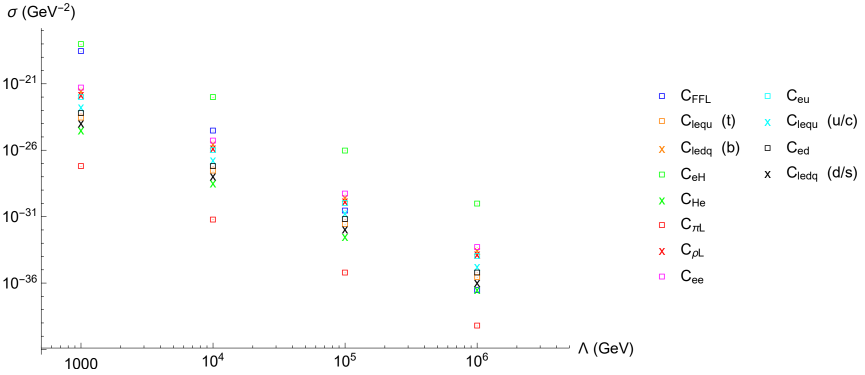
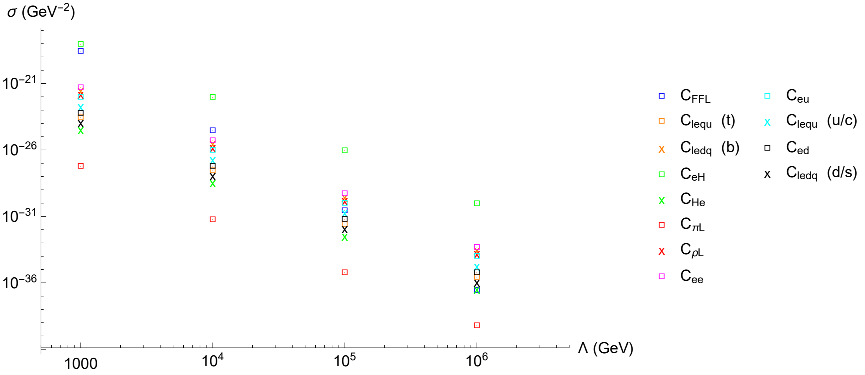
- Comparing Wilson Coefficients influence:
  Set one WC to 1, and all others to 0
- Interesting observation, all operators of the 'same type' had relatively the same influence
  i.e. All up-type quark loop axial operators had the same influence,
  but were different from the scalar/pseudoscalar operators

Results



σ (GeV⁻²)
10^{-21}
10^{-26}
10^{-31}
10^{-36}
1000
10^4
10^5
10^6
Λ (GeV)
C_{FFL}
C_{lequ} (t)
C_{ledq} (b)
C_{eH}
C_{He}
$C_{\pi L}$
$C_{\rho L}$
C_{ee}
C_{eu}
C_{lequ} (u/c)
C_{ed}
C_{ledq} (d/s)

Results



We expect the new physics scale to be at or above 1 TeV:

If CLFV is ever measured, likely dominated by the virtual Higgs current

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Conclusions

- Measured the next perturbative order for invisible widths of heavy mesons:
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- Calculated an LFV cross-section for electron-positron collisions using many different currents:
  - We expect the new physics scale to be at or above 1 TeV, the Higgs current will be the most likely to dominate
  - However, the closer the NP scale is to 1 TeV, the Rayleigh operators become equally probable

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- My adviser: Alexey Petrov
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- My research mentors: Gillian Ryan and Christopher Kelly
- My parents, John and Peggy Grant, family, friends, and girlfriend, Miki Kamiya for their continued love and support
- Matthew Lewis:

  "First, get your Ph.D. (in Physics),
  then whatever is next is up to you."

Questions?