SLAC Summer Institute 2016
August 24-25 2016

Intensity Frontier-Collider Complementarity (I)

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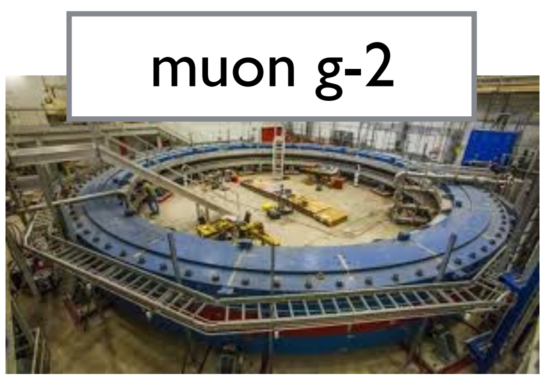
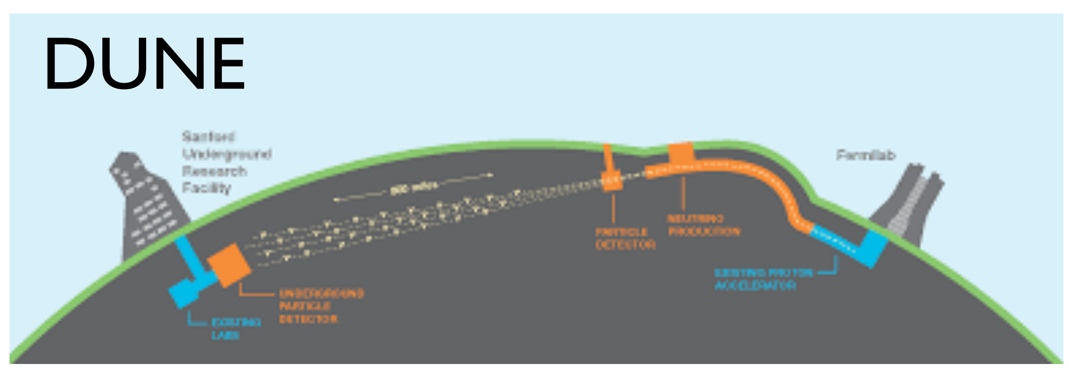
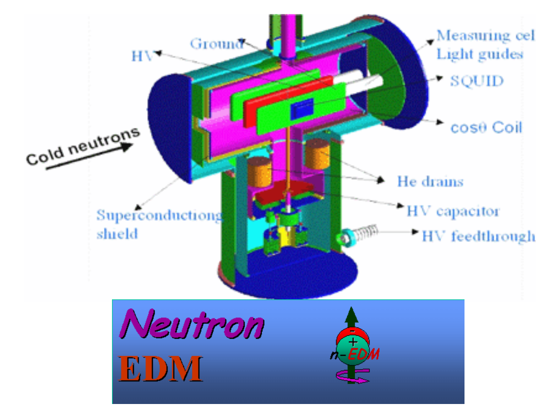
Goal of these lectures

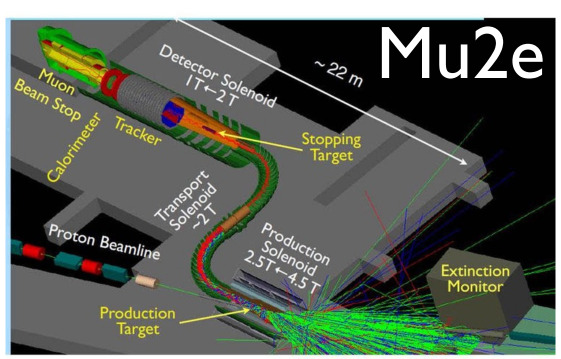
Provide an introduction to exciting physics at the Intensity Frontier

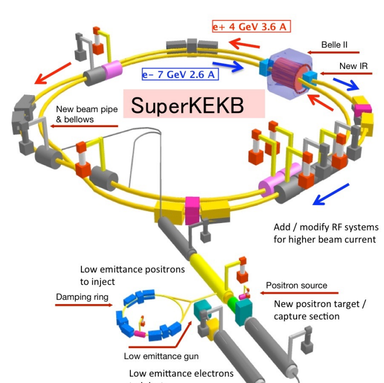
- Searches for new phenomena through precision measurements or the study of rare processes
- Requires use of powerful particle accelerators and ultra-sensitive detectors

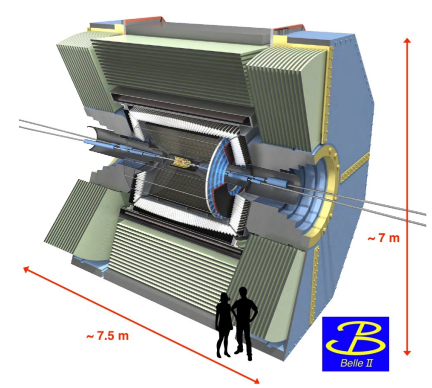


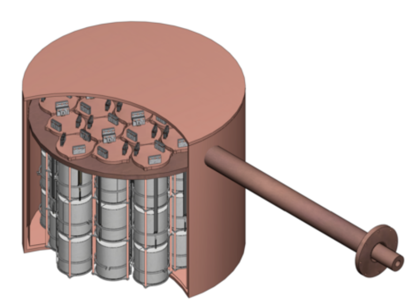












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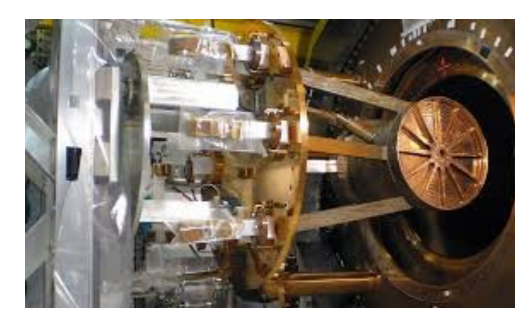

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Plan of the lectures

- Introduction: energy-intensity complementarity in broad brush
- Mini-Review of flavor and CP in the Standard Model: Intensity Frontier's traditional bread and butter
- Probing new physics at the Intensity Frontier: landscape in the LHC era
- "Zoom in" on selected Intensity Frontier probes
    - Quark Flavor Violation (highlights from K physics)
    - Lepton Flavor Violation (rare muon processes)
    - Lepton Number Violation
    - Electric Dipole Moments and CP violation

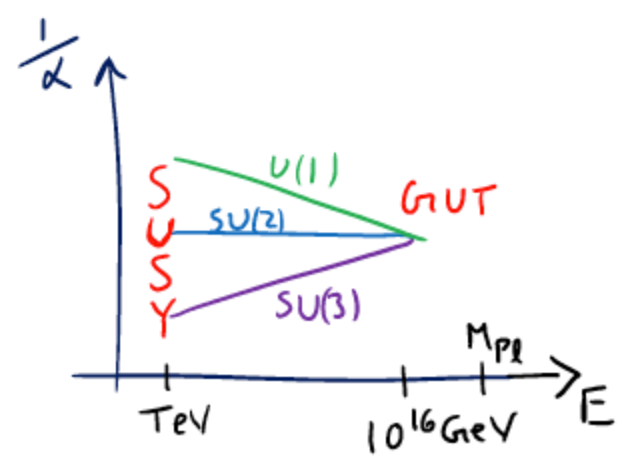
Energy - Intensity complementarity

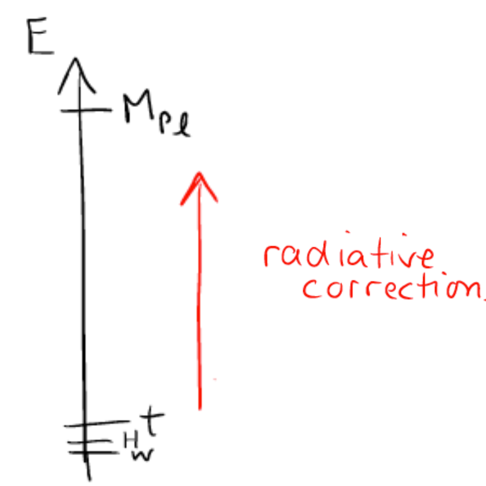
The quest for “new physics”

- The SM is remarkably successful, but can’t be the whole story

Empirical arguments

Theoretical arguments





R. Sundrum
ICHEP 12

The quest for "new physics"

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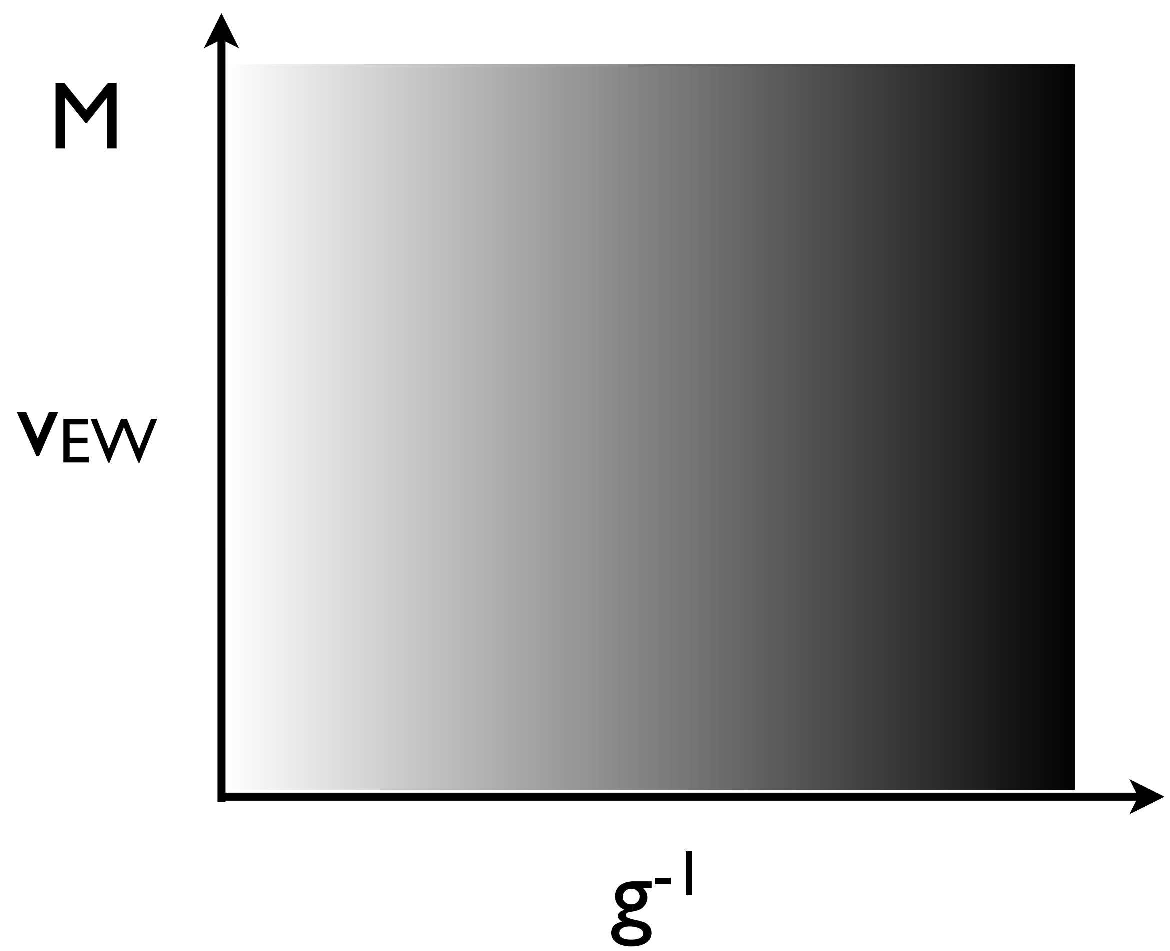
  $\Rightarrow$ new degrees of freedom (Heavy? Light & weakly coupled? Both?)



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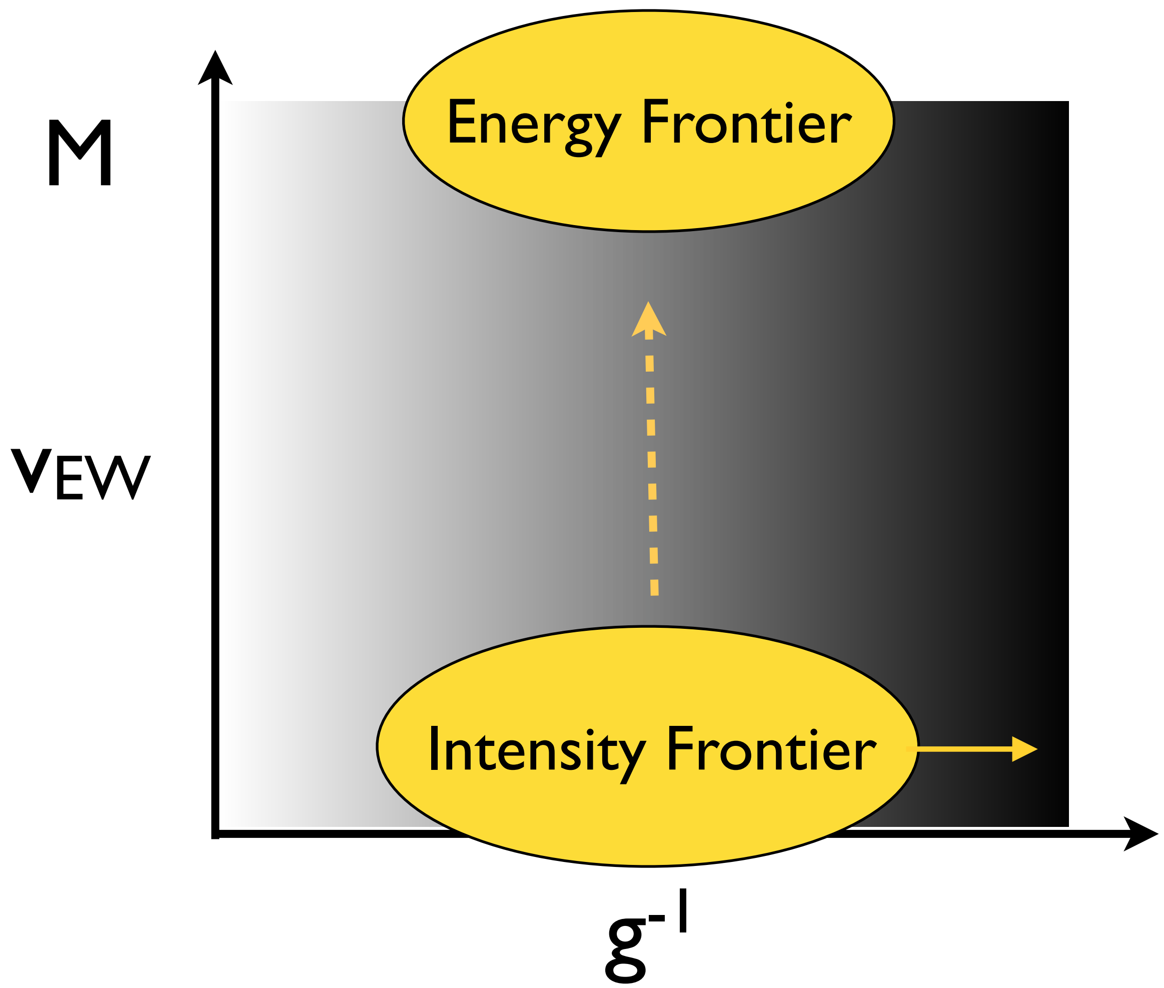
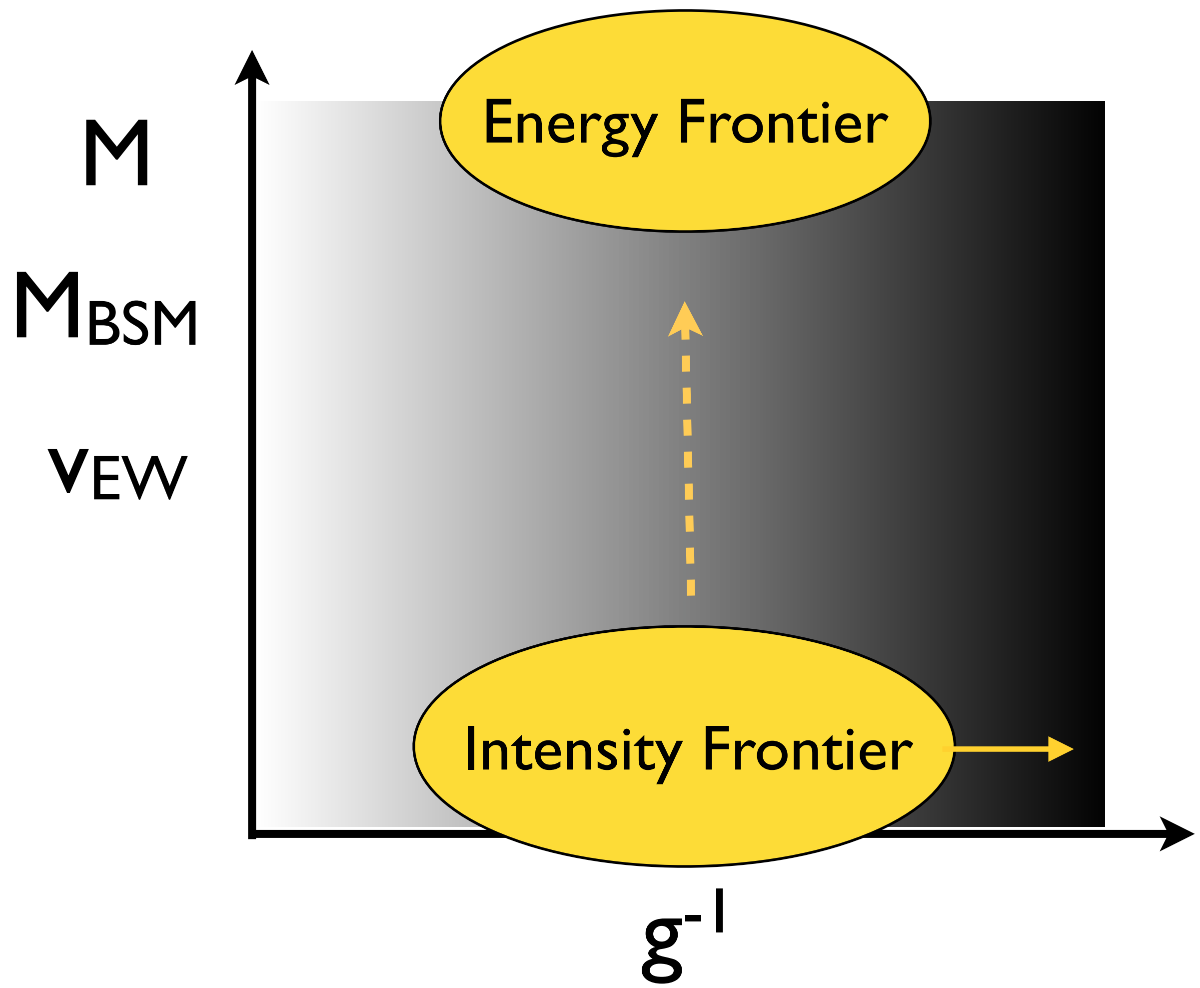


- Two approaches to probing BSM dynamics, operating in different regions of the (M,g) plane

The quest for "new physics"

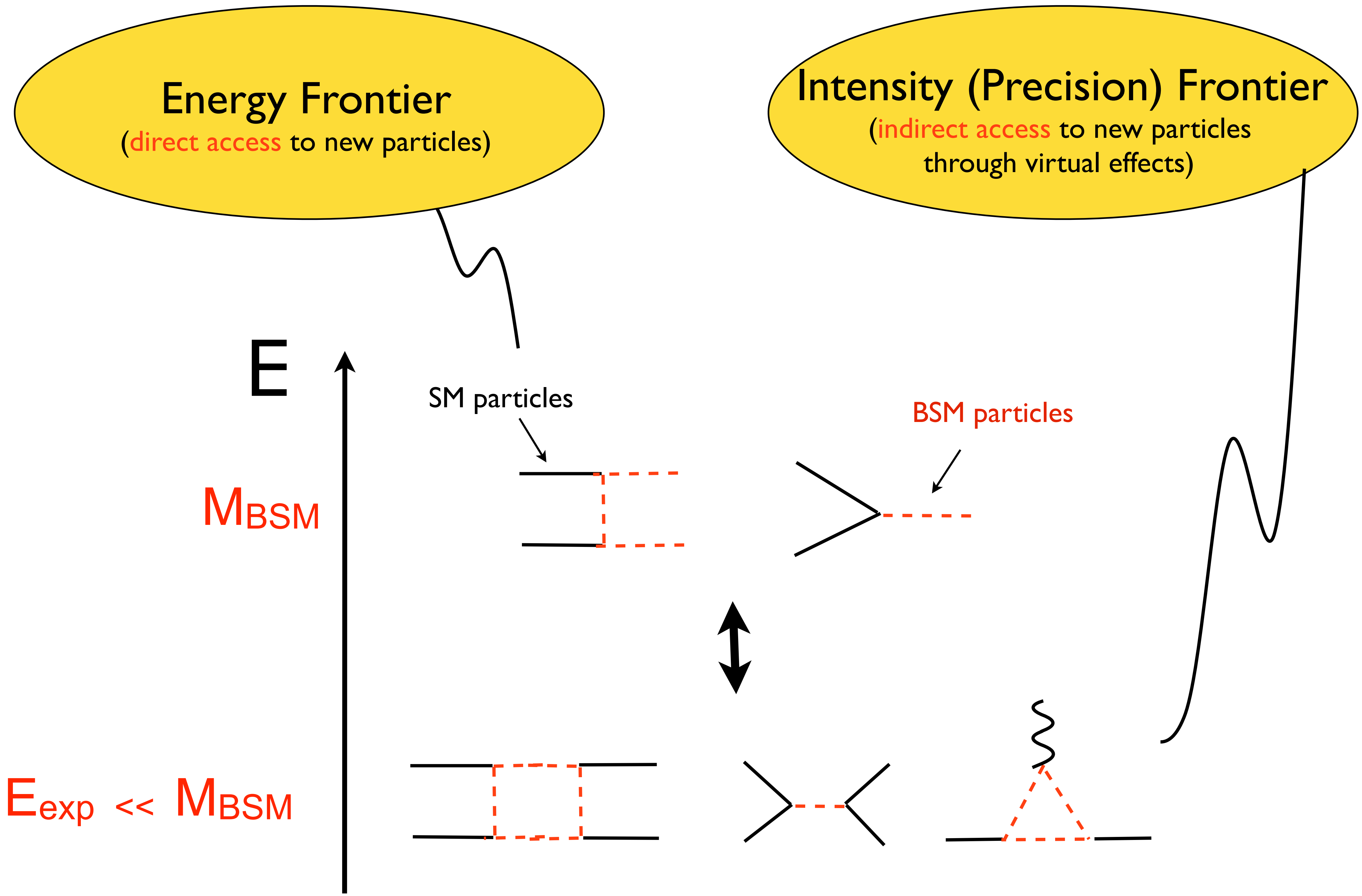
- The SM is remarkably successful, but can't be the whole story
  $\Rightarrow$ new degrees of freedom (Heavy? Light & weakly coupled? Both?)

In these lectures I will discuss Intensity Frontier probes of "heavy" new physics



- Two approaches to probing BSM dynamics, operating in different regions of the (M,g) plane

How does the Intensity Frontier work?



Complementarity

Energy Frontier
(direct access to new particles)

Intensity (Precision) Frontier
(indirect access to new particles through virtual effects)

- EWSB mechanism
- Mass and couplings of new heavy particles
- ...

- Flavor symmetries (quarks, leptons)
- CP violation (w/o flavor)
- L and B violation
- Super heavy particles (via precision tests)
- ...

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Both frontiers needed to reconstruct BSM dynamics:
structure, symmetries, and parameters of $\mathcal{L}_{BSM}$

$$\mathcal{L}_{BSM} = \mathcal{L}_{SM} + \delta\mathcal{L}_{BSM}$$

Complementarity

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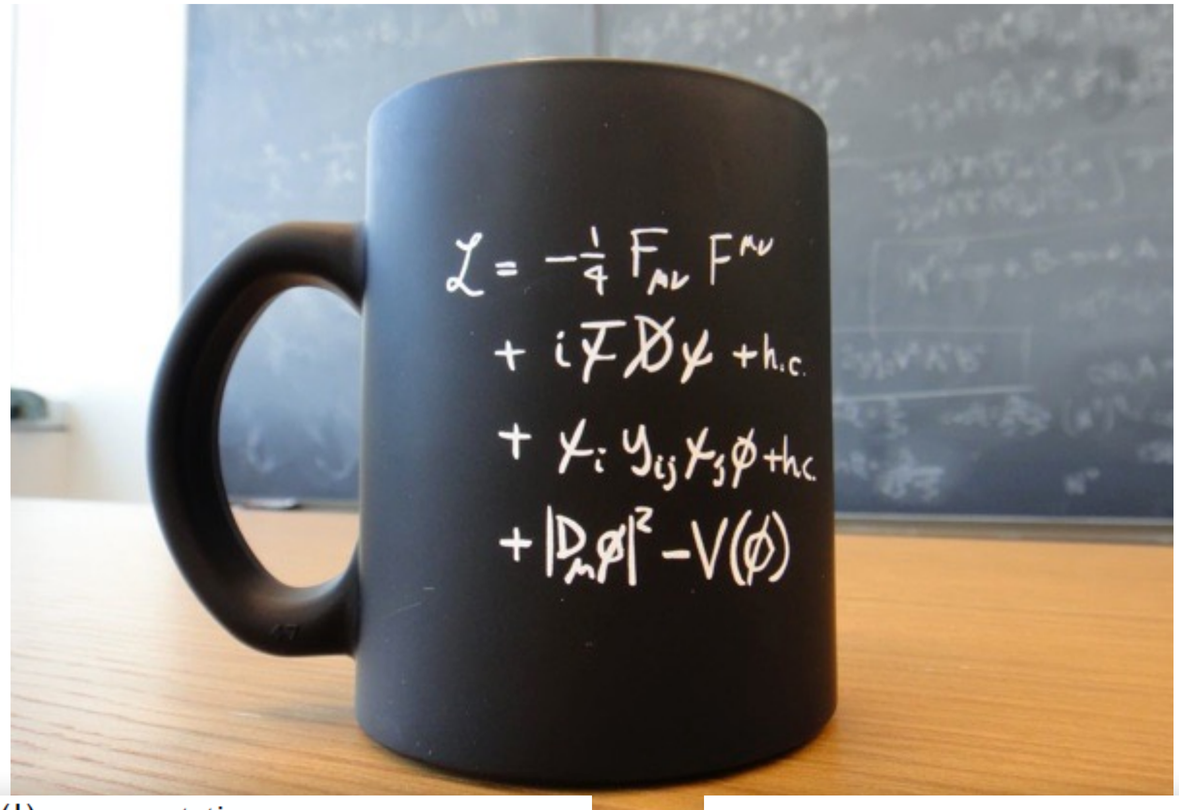
Flavor and CP in the Standard Model

The Standard Model

$$\psi = \begin{pmatrix} q \\ \ell \\ u \\ d \\ e \end{pmatrix}$$



	$SU(3)_c \times SU(2)_W \times U(1)_Y$ representation: ($\dim[SU(3)_c]$, $\dim[SU(2)_W]$, Y)	$SU(2)_W$ transformation
$l = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	(1,2,-1/2)	$l \to V_{SU(2)}\, l$
$e = e_R$	(1,1,-1)	
$q^i = \begin{pmatrix} u^i_L \\ d^i_L \end{pmatrix}$	(3,2,1/6)	$q \to V_{SU(2)}\, q$
$u^i = u^i_R$	(3,1,2/3)	
$d^i = d^i_R$	(3,1,-1/3)	
$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$	(1,2,1/2)	$\varphi \to V_{SU(2)}\, \varphi$

		$SU(3)_c \times SU(2)_W \times U(1)_Y$ representation
gluons:	G^A_μ, $A = 1 \cdots 8$, $G^A_{\mu\nu} = \partial_\mu G^A_\nu - \partial_\nu G^A_\mu + g_s f_{ABC} G^B_\mu G^C_\nu$.	(8,1,0)
W bosons:	W^I_μ, $I = 1 \cdots 3$, $W^I_{\mu\nu} = \partial_\mu W^I_\nu - \partial_\nu W^I_\mu + g \varepsilon_{IJK} W^J_\mu W^K_\nu$	(1,3,0)
B boson:	B_μ, $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$.	(1,1,0)

Gauge transformation:

$$W^I_{\mu\nu}\frac{\sigma^I}{2} \longrightarrow V(x)\left[W^I_{\mu\nu}\frac{\sigma^I}{2}\right]V^\dagger(x)$$

$$V(x) = e^{ig\beta_a(x)\frac{\sigma_a}{2}}$$

The Standard Model

$$\mathcal{L}_{SM} = \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

$$D_\mu = I\,\partial_\mu - ig_s\frac{\lambda^A}{2}G^A_\mu - ig\frac{\sigma^a}{2}W^a_\mu - ig'YB_\mu$$

$$\mathcal{L}_{\text{Gauge}} = -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

$$+ \sum_{i=1,2,3}\left(i\bar{\ell}_i \not{D}\ell_i + i\bar{e}_i\not{D}e_i + i\bar{q}_i\not{D}q_i + i\bar{u}_i\not{D}u_i + i\bar{d}_i\not{D}d_i\right)$$

- $U(3)^5$ symmetry: no notion of "flavor" (three identical copies)

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$$\mathcal{L}_{\text{Higgs}} = (D_\mu\varphi)^\dagger(D^\mu\varphi) - \lambda(\varphi^\dagger\varphi - v^2)^2 \xrightarrow{\text{EWSB}}$$

$$\langle\varphi\rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\langle\tilde{\varphi}\rangle = \begin{pmatrix} v \\ 0 \end{pmatrix}$$

$$\tilde{\varphi} = \epsilon\,\varphi^*$$

- U(3)[5] symmetry: no notion of "flavor" (three identical copies)

The Standard Model

$$\mathcal{L}_{SM} = \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

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$$+ \sum_{i=1,2,3} \left(i\bar{\ell}_i \not{D} \ell_i + i\bar{e}_i \not{D} e_i + i\bar{q}_i \not{D} q_i + i\bar{u}_i \not{D} u_i + i\bar{d}_i \not{D} d_i \right)$$

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \varphi)^\dagger (D^\mu \varphi) - \lambda(\varphi^\dagger \varphi - v^2)^2 \xrightarrow{\text{EWSB}}$$

$$\mathcal{L}_{\text{Yukawa}} = \bar{\ell}\, Y_e\, e\varphi + \bar{q}\, Y_d\, d\varphi + \bar{q}\, Y_u\, u\tilde{\varphi} + \text{h.c.}$$

$$\langle \varphi \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\langle \tilde{\varphi} \rangle = \begin{pmatrix} v \\ 0 \end{pmatrix}$$

$$\tilde{\varphi} = \epsilon\, \varphi^*$$

- U(3)^5 symmetry broken by Yukawa couplings $Y_{e,u,d}$: flavor physics!

Flavor physics in the SM

- In unitary gauge

$$\mathcal{L}_{\text{Yukawa}} = \bar{e}_L Y_e e_R \left(v + \frac{h}{\sqrt{2}}\right) + \bar{d}_L Y_d d_R \left(v + \frac{h}{\sqrt{2}}\right) + \bar{u}_L Y_u u_R \left(v + \frac{h}{\sqrt{2}}\right) + \text{h.c.}$$

$$\varphi = \begin{pmatrix} 0 \\ v + \frac{h}{\sqrt{2}} \end{pmatrix}$$

- Fermion mass matrices diagonalized by bi-unitary transformation

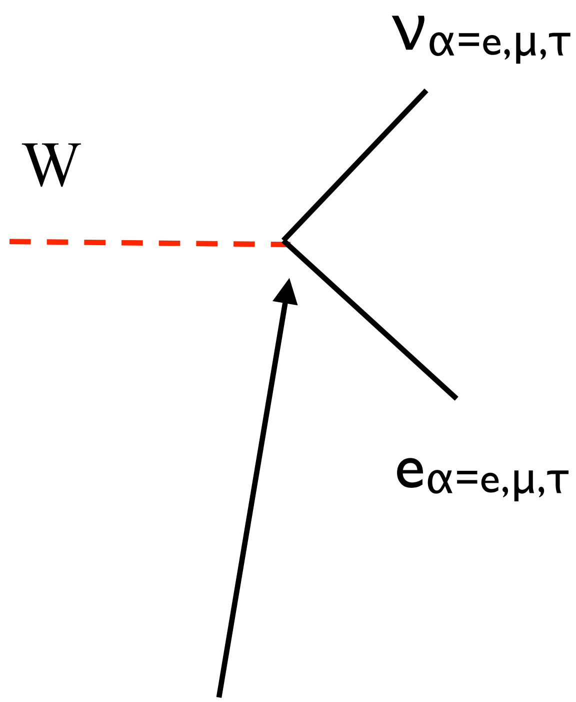
$$Y_f = V_{f_L}^\dagger \, Y_f^{\text{diag}} \, V_{f_R} \qquad f = e, d, u \qquad \longrightarrow \qquad m_{f,i} = v \left(Y_f^{\text{diag}}\right)_{ii}$$

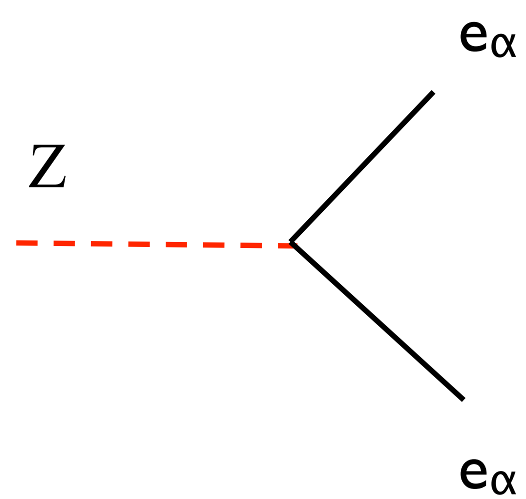
- Higgs coupling to fermions is flavor-diagonal and proportional to mass

$$\boxed{\mathcal{L}_{\text{Yukawa}} = \sum_{f=e,d,u} m_f \, \bar{f} f \left(1 + \frac{h}{\sqrt{2} v}\right)} \qquad f = f_L + f_R$$

- Gauge couplings to fermions:

1. Leptons: flavor diagonal ⇒ individual lepton flavor $L_{e,\mu\tau}$ conserved

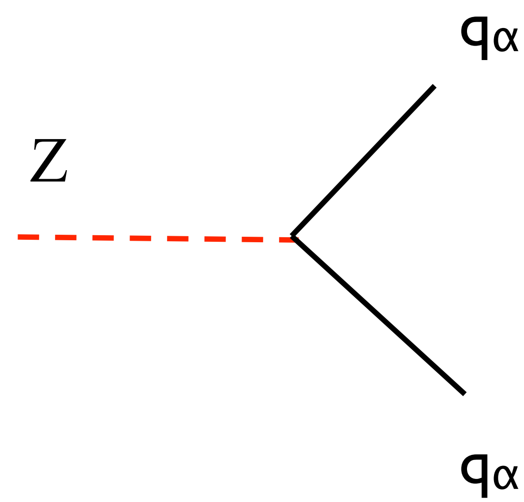




Unitary transformation of e_L needed to diagonalize charged lepton mass matrix can be reabsorbed by a redefinition of ν_L (this will change for massive neutrinos)

- Gauge couplings to fermions:

1. Leptons: flavor diagonal ⇒ individual lepton flavor $L_{e,\mu\tau}$ conserved
2. Quark: No tree-level Flavor Changing Neutral Currents (FCNC)



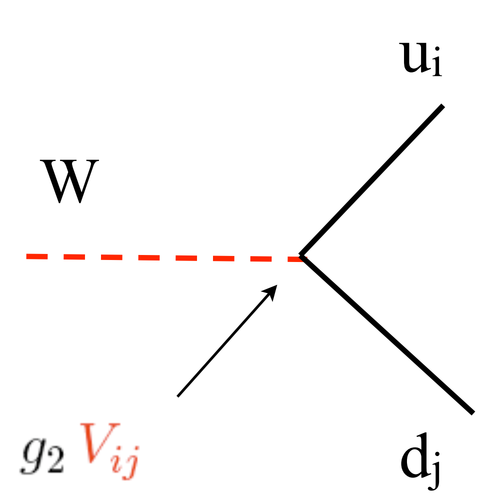
- Gauge couplings to fermions:

1. Leptons: flavor diagonal ⇒ individual lepton flavor $L_{e,\mu\tau}$ conserved
2. Quark: No tree-level Flavor Changing Neutral Currents (FCNC)
3. Quark charged current (CC): family mixing

$$\boxed{\frac{g}{\sqrt{2}}\, W_\mu^+\, \bar{u}_L\, \gamma^\mu\, d_L \;\longrightarrow\; \frac{g}{\sqrt{2}}\, W_\mu^+\, \bar{u}_L\, V_{\rm CKM}\, \gamma^\mu\, d_L}$$

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

Cabibbo-Kobayashi-Maskawa matrix:
Physically observable mismatch in the transformation of u_L and d_L needed to diagonalize quark masses



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

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

$$\boxed{V_{ij} \;\to\; V_{ij}\; e^{i((\phi_d)_j - (\phi_u)_i)}}$$

5 independent parameters (phase differences)

- Irreducible phase implies CP violation:

$$g_2 V_{ij}\, W_\mu^+\, \bar{u}_L^i \gamma^\mu d_L^j \;+\; g_2 V_{ij}^*\, W_\mu^-\, \bar{d}_L^j \gamma^\mu u_L^i$$

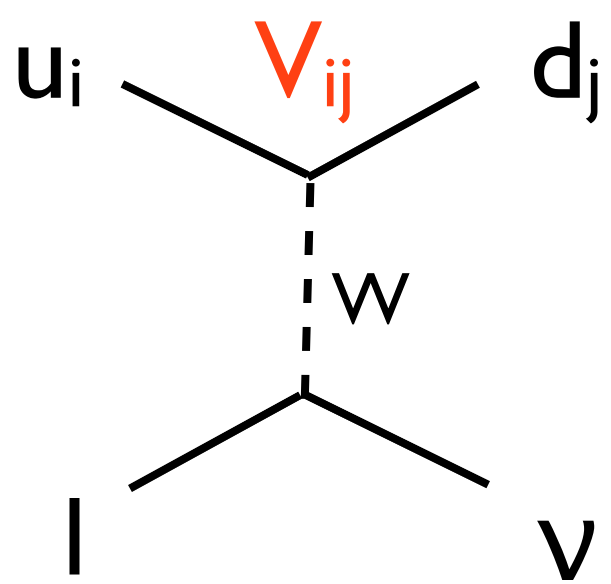
$$\Big\downarrow \quad \text{CP transformation}$$

$$g_2 V_{ij}\, W_\mu^-\, \bar{d}_L^j \gamma^\mu u_L^i \;+\; g_2 V_{ij}^*\, W_\mu^+\, \bar{u}_L^i \gamma^\mu d_L^j$$

- CKM matrix and m_q govern the pattern of flavor and CPV in the SM

Pattern of flavor and CP violation

- Tree-level flavor changing charged-current processes (semi-leptonic decays can be studied to extract all $|V_{ij}|$, except for V_{td} and V_{ts})



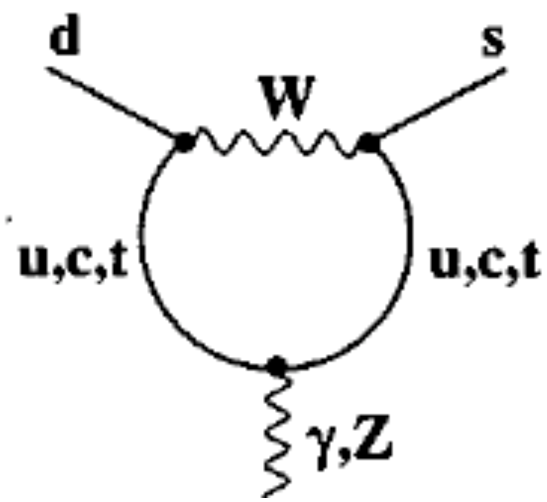
$\longleftrightarrow$

Data indicates hierarchical structure of mixing matrix

- By connecting flavor-changing charged-current vertices can obtain flavor-changing neutral currents (FCNC) at loop level

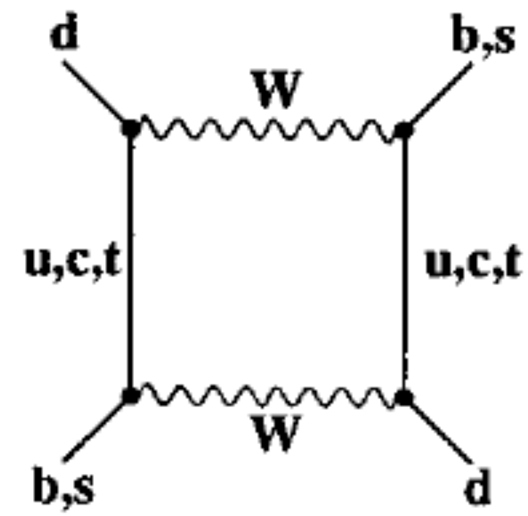
- <u>Loop-level FCNC processes: penguins and boxes</u>

ΔF=1



Sensitive to $|V_{td,ts}|$ and phases of V_{ij}

ΔF=2



Rare K and B decays

$$K \to \pi\nu\bar{\nu},\ K \to \pi\ell^+\ell^-, \ldots$$

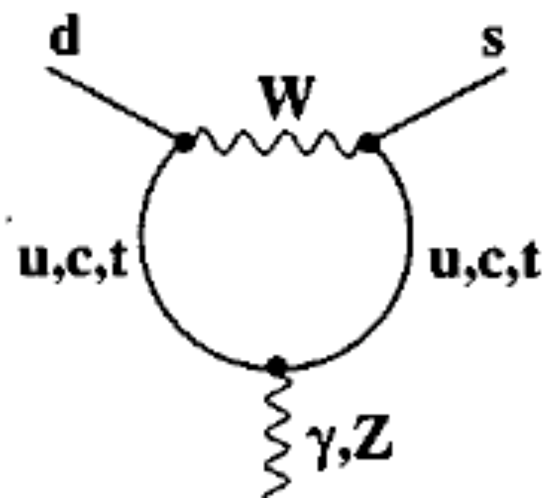
$$B \to X_s\gamma,\ B \to X_s\ell^+\ell^-, \ldots$$

Neutral meson mixing
(Δm, CPV in mixing)

$$K^0 - \bar{K}^0 \quad B^0_{d,s} - \bar{B}^0_{d,s}$$

- Loop-level FCNC processes: penguins and boxes

ΔF=1

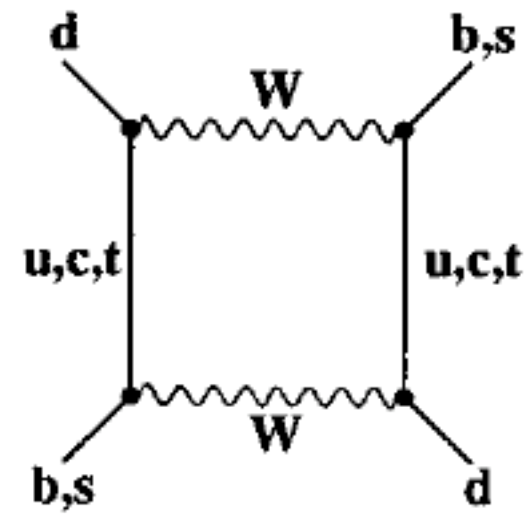


$$\lambda_i = \begin{cases} V_{is}^* V_{id} & K\text{–decays}, \quad K^0 - \bar{K}^0 \\ V_{ib}^* V_{id} & B\text{–decays}, \quad B_d^0 - \bar{B}_d^0 \\ V_{ib}^* V_{is} & B\text{–decays}, \quad B_s^0 - \bar{B}_s^0 \end{cases}$$

$$x_i = \frac{m_i^2}{M_W^2}, \qquad i = u, c, t.$$

$$\sum_{i=u,c,t} \lambda_i \, F(x_i)$$

ΔF=2



$$\sum_{i,j=u,c,t} \lambda_i \lambda_j \, \tilde{F}(x_i, x_j)$$

- Important property of FCNC: GIM mechanism

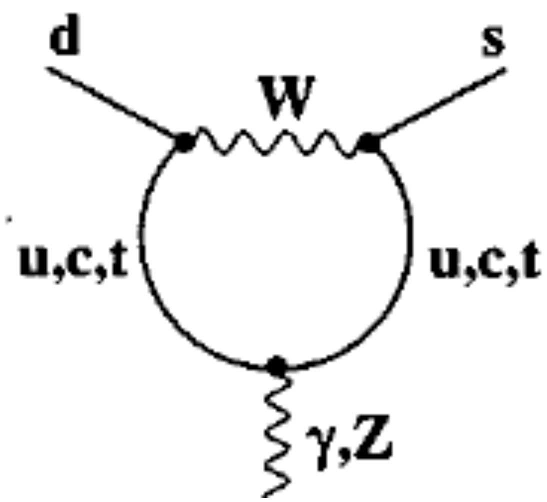
- CKM unitarity $\lambda_u + \lambda_c + \lambda_t = 0,$
- u-quark degeneracy $x_u = x_c = x_t$

→ no loop-FCNC

FCNC controlled by CKM factors and non-degeneracy of quarks

- <u>Loop-level FCNC processes: penguins and boxes</u>

ΔF=1



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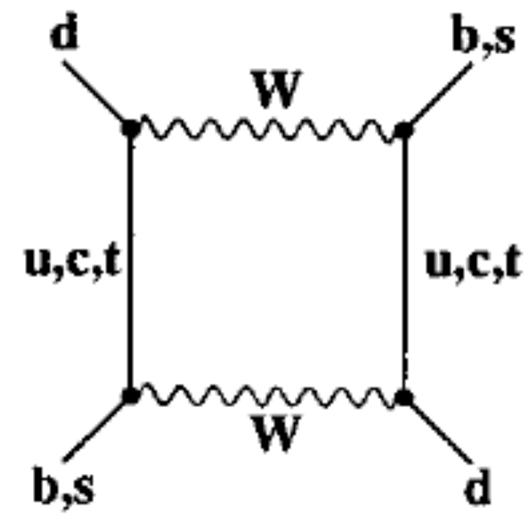
ΔF=2



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Loop-induced + GIM-suppression:
non-trivial test of the SM and sensitivity to new physics

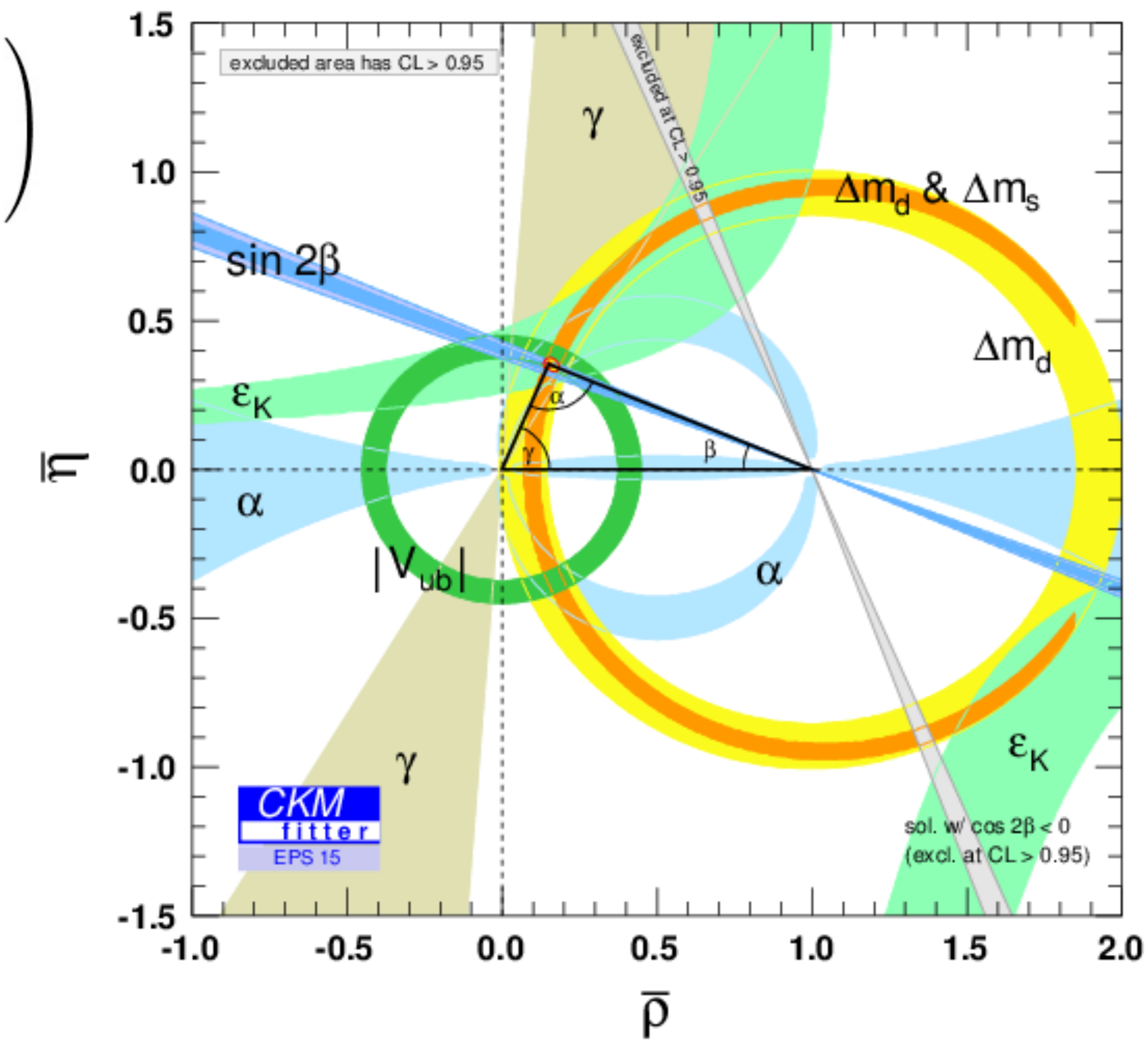
- Status of the CKM matrix: quark flavor physics (including CPV effects) is well described by 3 mixing angles and a phase!

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

Make explicit the hierarchical structure revealed by experiment: expand in $\lambda \approx V_{us} \approx 0.225$, with $\rho, \eta, A \sim O(1)$ (Wolfenstein 1983)

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

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



Discussed in greater detail by J. Zupan and H. Jawahery

Symmetries of the Standard Model

- The fate of global symmetries in the SM
  - Flavor symmetry:
    - $U(3)^5$ explicitly broken only by Yukawa couplings: specific pattern of FCNC — falsifiable!
    - U(1) associated with B, L, and $L_{\alpha=e,\mu,\tau}$ survive
    - Anomaly: only B-L is conserved

  - P, C maximally violated by weak interactions

  - CP (and T) violated by CKM (and QCD theta term*): specific pattern of CPV in flavor transitions and EDMs

$$* \qquad \mathcal{L}_\theta^{CPV} = \theta \, \frac{g_s^2}{64\pi^2} \, \epsilon^{\mu\nu\alpha\beta} G'^a_{\mu\nu} G'^a_{\alpha\beta}$$

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Approximate symmetries and symmetries broken in a very specific way offer great opportunity to probe non-standard physics at the Intensity Frontier

Flavor physics in the "νSM"

- Neutrino mass requires new degrees of freedom
- Simple / natural option: three R-handed neutrinos ν_{Ri} (gauge singlets)

$$\mathcal{L}_{\nu SM} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \left(\frac{1}{2}\nu_R^T C M_R \nu_R + \bar{\ell} Y_\nu \nu_R \tilde{\varphi} + \text{h.c.}\right)$$

Both allowed by gauge symmetry

Mass term breaks $U(1)_L$

$$\ell \to e^{i\alpha}\ell \qquad e \to e^{i\alpha}e \qquad \nu_R \to e^{i\alpha}\nu_R$$

Flavor physics in the "νSM"

- Neutrino mass requires new degrees of freedom
- Simple / natural option: three R-handed neutrinos ν_{Ri} (gauge singlets)

$$\mathcal{L}_{\nu SM} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \left(\cancel{\frac{1}{2}\nu_R^T C M_R \nu_R} + \bar{\ell}\, Y_\nu\, \nu_R\, \tilde{\varphi} + \text{h.c.} \right)$$

- Dirac neutrinos: $M_R = 0$. Complete analogy to quark sector (B → L), except for tiny ($O(10^{-10})$) Yukawa couplings

$$Y_e = V_{e_L}^\dagger Y_e^{\text{diag}} V_{eR}$$

$$Y_\nu = V_{\nu_L}^\dagger Y_\nu^{\text{diag}} V_{\nu R}$$

$$\Rightarrow \quad \boxed{\frac{g}{\sqrt{2}} W_\mu^- \; \bar{e}_L^\alpha \gamma^\mu U^{\alpha i} \, \nu_L^i}$$

$$U = V_{e_L} V_{\nu_L}^\dagger$$

Unitary mixing in CC vertex: 3 angles, 1 phase

- Majorana neutrinos: $M_R \neq 0$. L not conserved

$$\mathcal{L}_{\nu SM} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \left(\frac{1}{2} \nu_R^T C M_R \nu_R + \bar{\ell}\, Y_\nu\, \nu_R\, \tilde{\varphi} + \text{h.c.} \right)$$

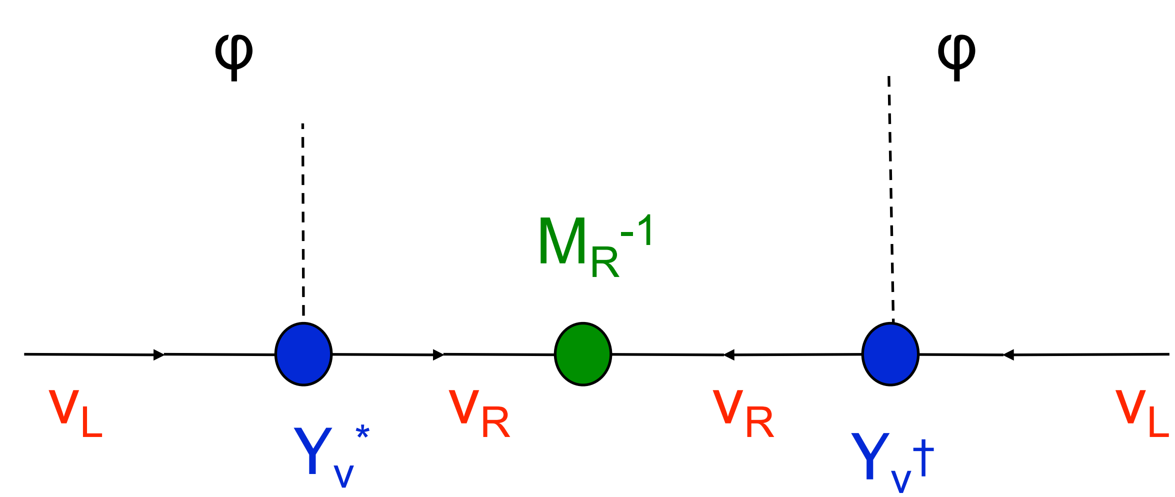
- In general 6x6 mass matrix for $\begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$: six Majorana ($\nu = \nu^c$) eigenstates

- If $M_R \gg vY_\nu$: 3 light ($\nu_L \to \nu_i$) and 3 heavy ($\nu_R \to N_i$) eigenstates

$$\mathcal{L}_{\nu SM} \supset -\frac{1}{2} \nu_L^T\, C\, m_\nu\, \nu_L$$

We could have written this term without reference to ν_R and in SU(2) gauge-invariant form (more later)

$$m_\nu = v^2\, Y_\nu^*\, M_R^{-1}\, Y_\nu^\dagger$$



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- Mixing of 3 light Majorana neutrinos: $\mathcal{L}_{\nu SM} \supset -\frac{1}{2}\nu_L^T C\, m_\nu\, \nu_L$

$$m_\nu = V_{\nu_L}^T m_\nu^{\text{diag}} V_{\nu_L}$$

$$Y_e = V_{e_L}^\dagger Y_e^{\text{diag}} V_{e_R}$$

$$\Rightarrow \boxed{\frac{g}{\sqrt{2}} W_\mu^- \, \bar{e}_L^\alpha \gamma^\mu U^{\alpha i} \nu_L^i}$$

$$U = V_{e_L} V_{\nu_L}^\dagger$$

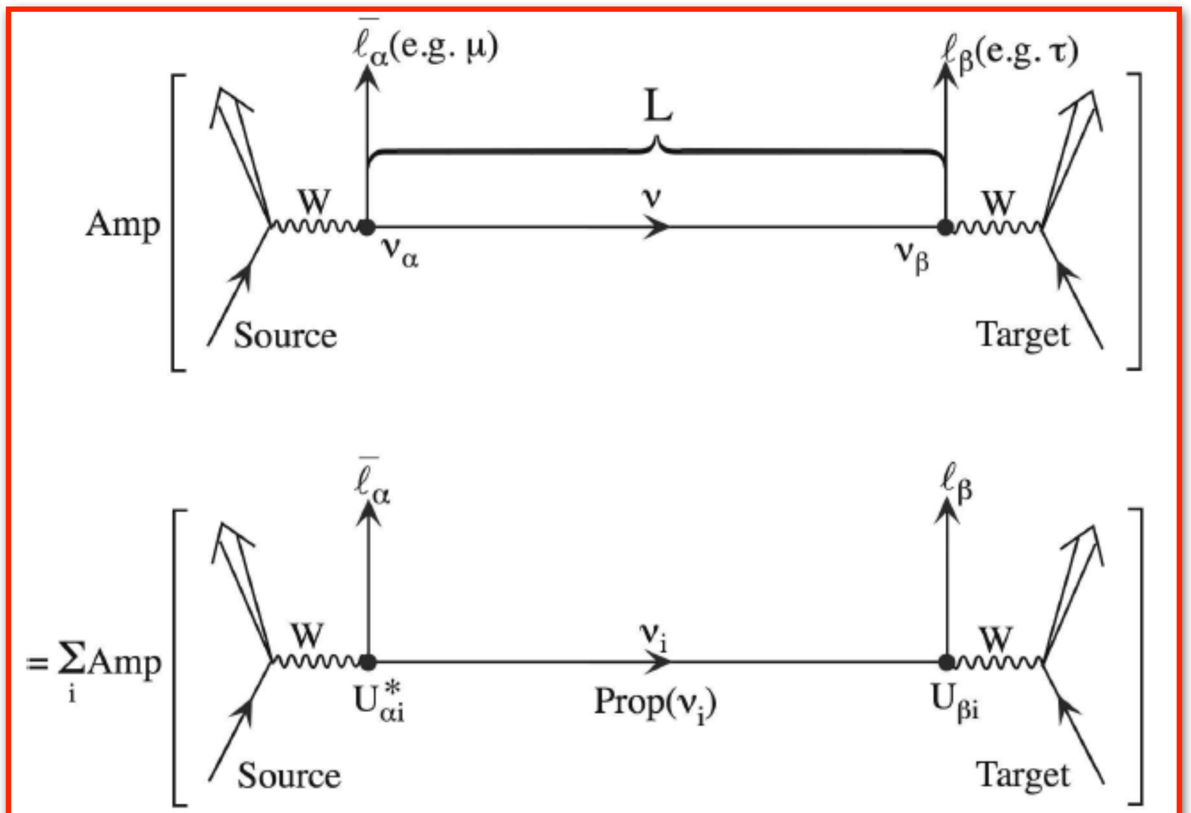
Unitary mixing in CC vertex: 3 angles, 1+2 phases

$$U = U_{\text{Dirac}} \times \begin{pmatrix} 1 & & \\ & e^{i\alpha_1} & \\ & & e^{i\alpha_2} \end{pmatrix}$$

Neutrino phenomenology

- $\mathcal{L}_{\nu SM}$ largely inaccessible at the LHC: domain of the Intensity Frontier (accelerator, reactor) and Cosmic Frontier (solar, atmospheric, astro)
- Oscillation experiments sensitive to mass splittings and mixing angles

Image credit: B. Kayser



$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix},$$

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \times \frac{1}{2}\left(1 - \cos\frac{\Delta m^2 L}{2E}\right)$$

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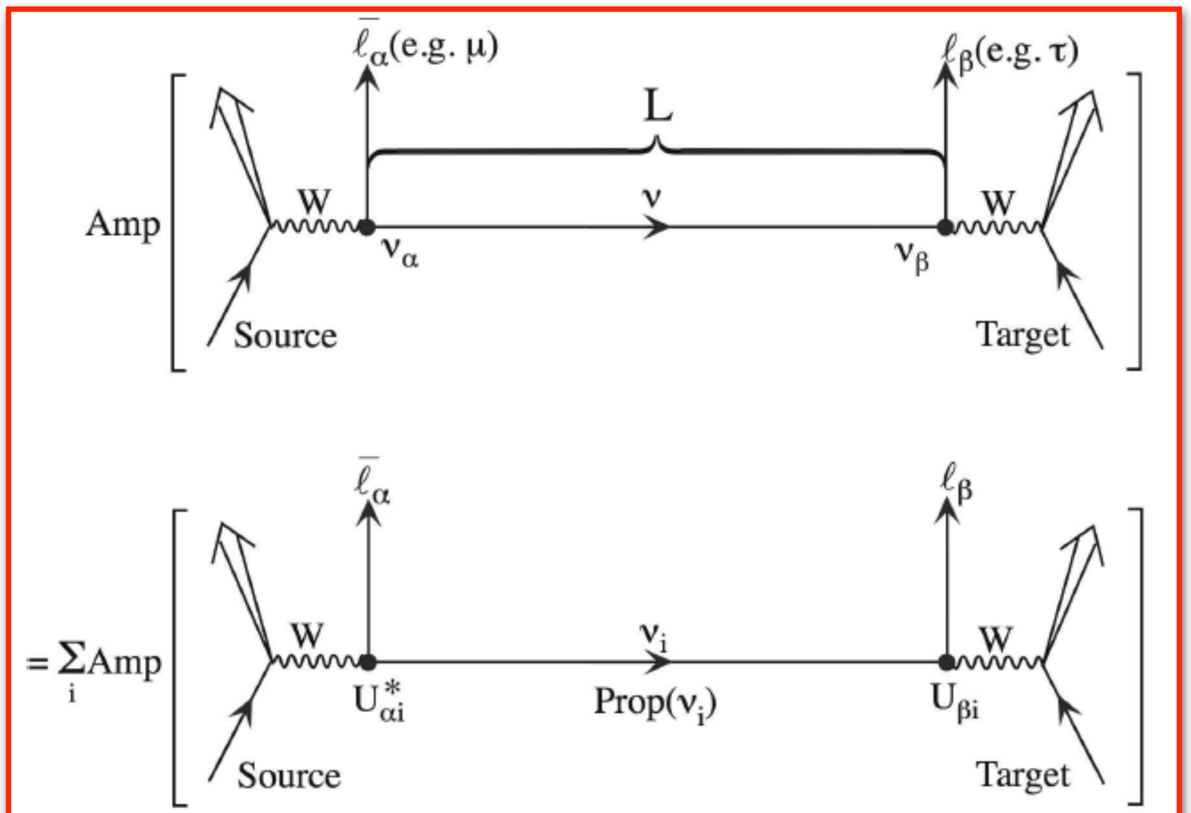
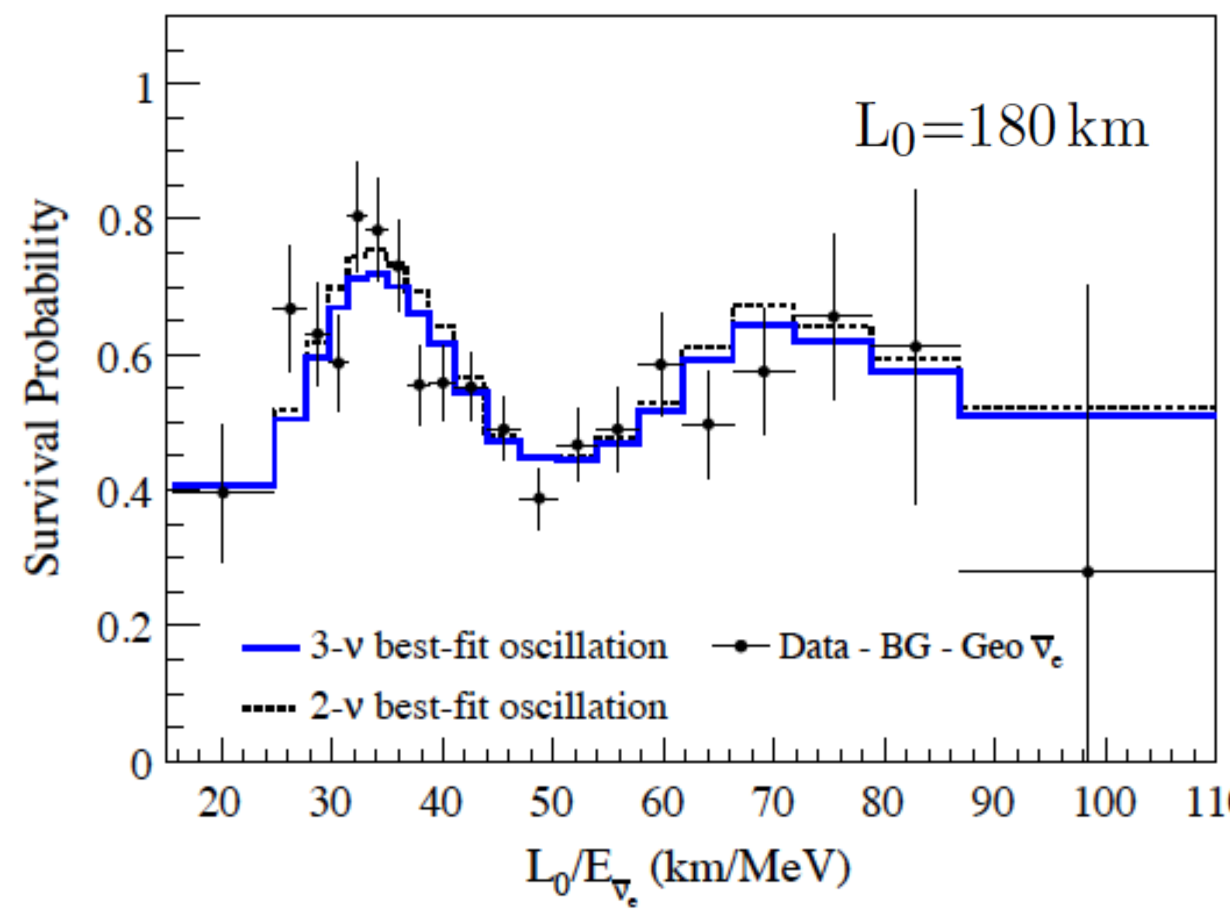


KAMLAND 2011



Reactor electron anti-neturino survival probability

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix},$$

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World data consistent with 3 light states

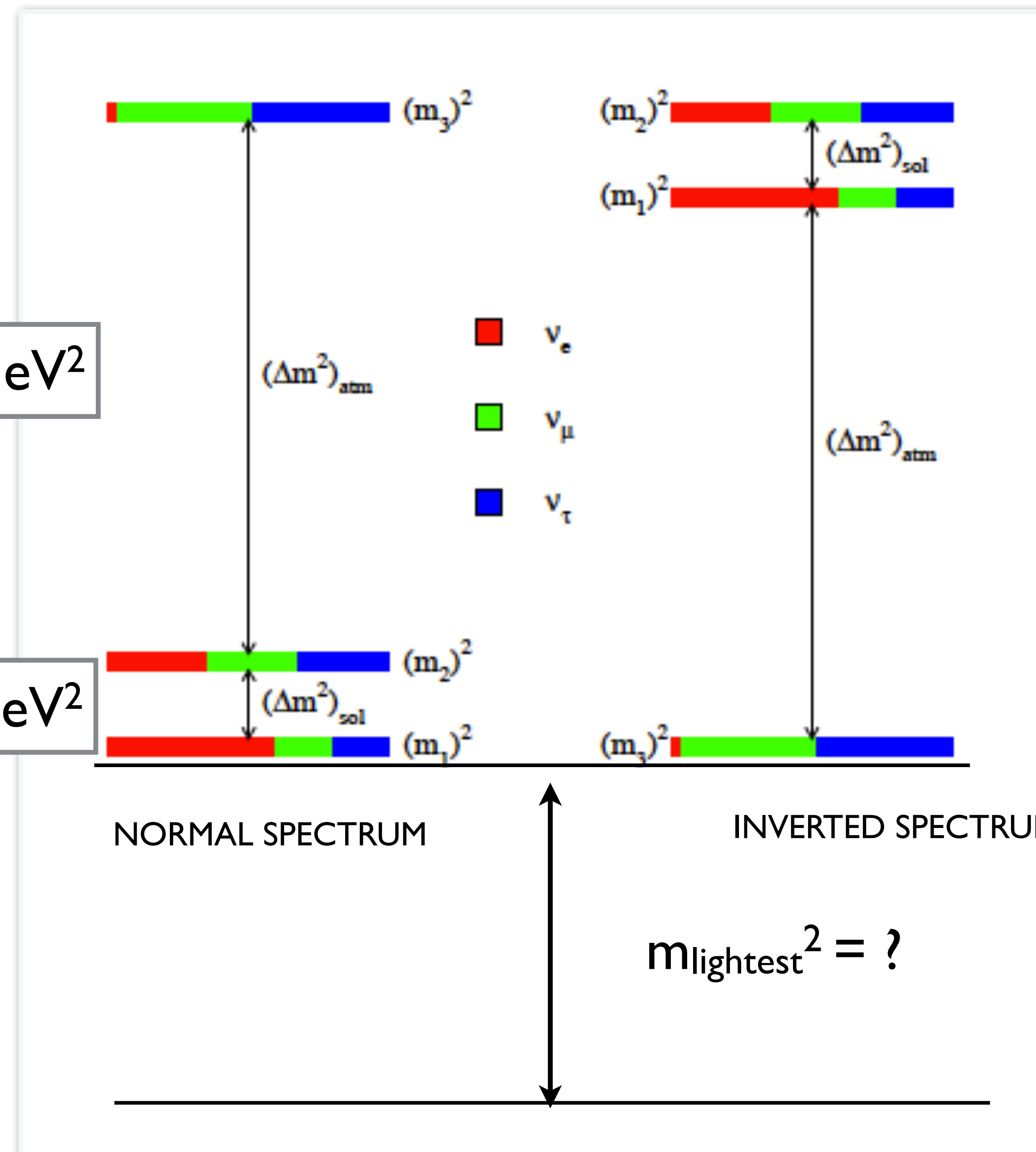
$$U \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

A. de Gouvea

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

~2.4 10^{-3} eV^2

~7.5 10^{-5} eV^2



Open questions

- Many key aspects of ν dynamics remain unknown, and will be explored by experiments in the next decade

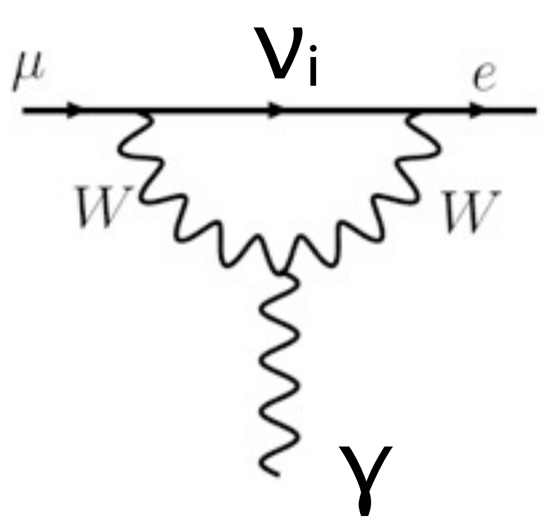
- Symmetries / particle content:
  - Is lepton number (L) broken? (Dirac vs Majorana) ($0\nu\beta\beta$)
  - Are there light sterile ν's? (short-baseline anomalies, cosmo)

- Determine parameters of mass matrix (regardless its origin):
  - Absolute mass scale (beta decay, $0\nu\beta\beta$*, cosmology*)
  - Mass ordering
  - Mixing angles (✔), CPV phase

(oscillation experiments)

Symmetry breaking in the νSM

- CC vertex & mass terms: individual flavors not conserved (ν osc.)
- Loop-level charged lepton FCNC: GIM at work → tiny effects!



Current limit on BR ~ 10^{-13}

$$\boxed{Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M_W^2}\right|^2 < 10^{-54}}$$

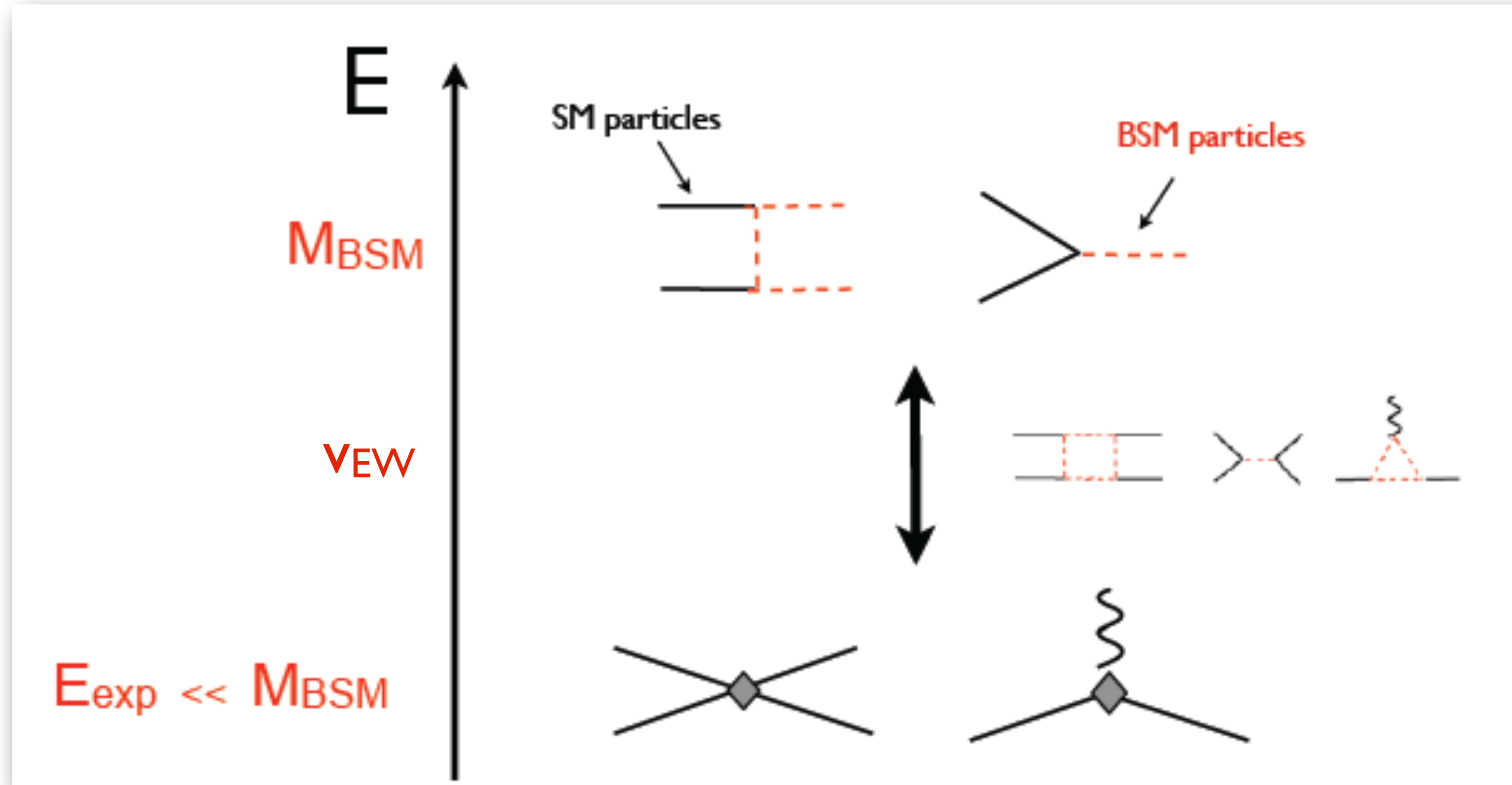
Petcov '77, Marciano-Sanda '77 ....

- $L_{\alpha=e,\mu,\tau}$ broken: but unobservable effects in charged lepton sector. Extremely clean probe of BνSM dynamics: no background!
- L broken by Majorana mass — specific expectations in 0νββ

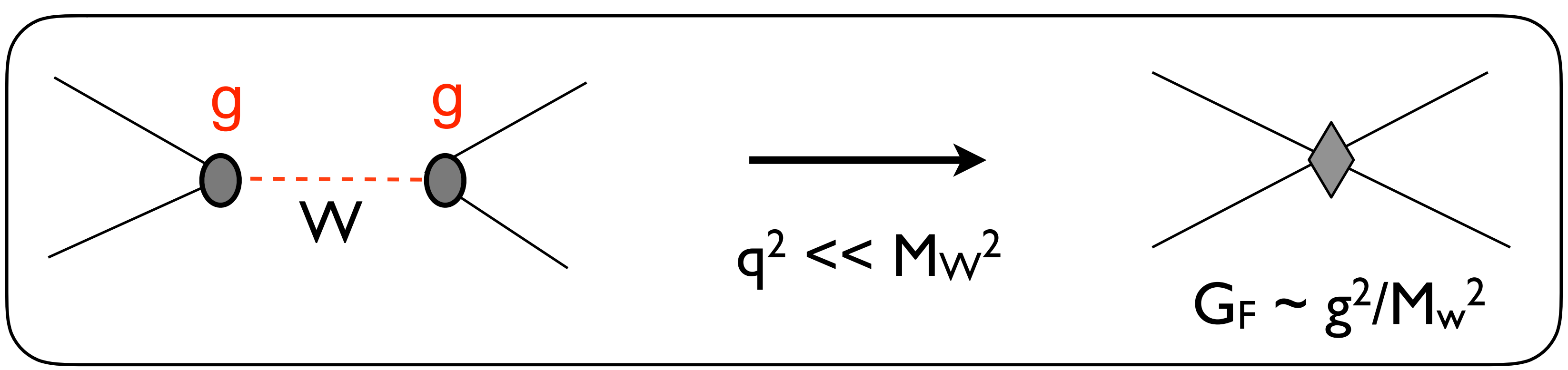
Probing new physics at the Intensity Frontier: landscape in the LHC era

Probing $\mathcal{L}_{BSM}$ at the intensity frontier

- I.F. experiments don't excite new states
- Low-energy footprints of heavy new physics → local operators



Familiar example:



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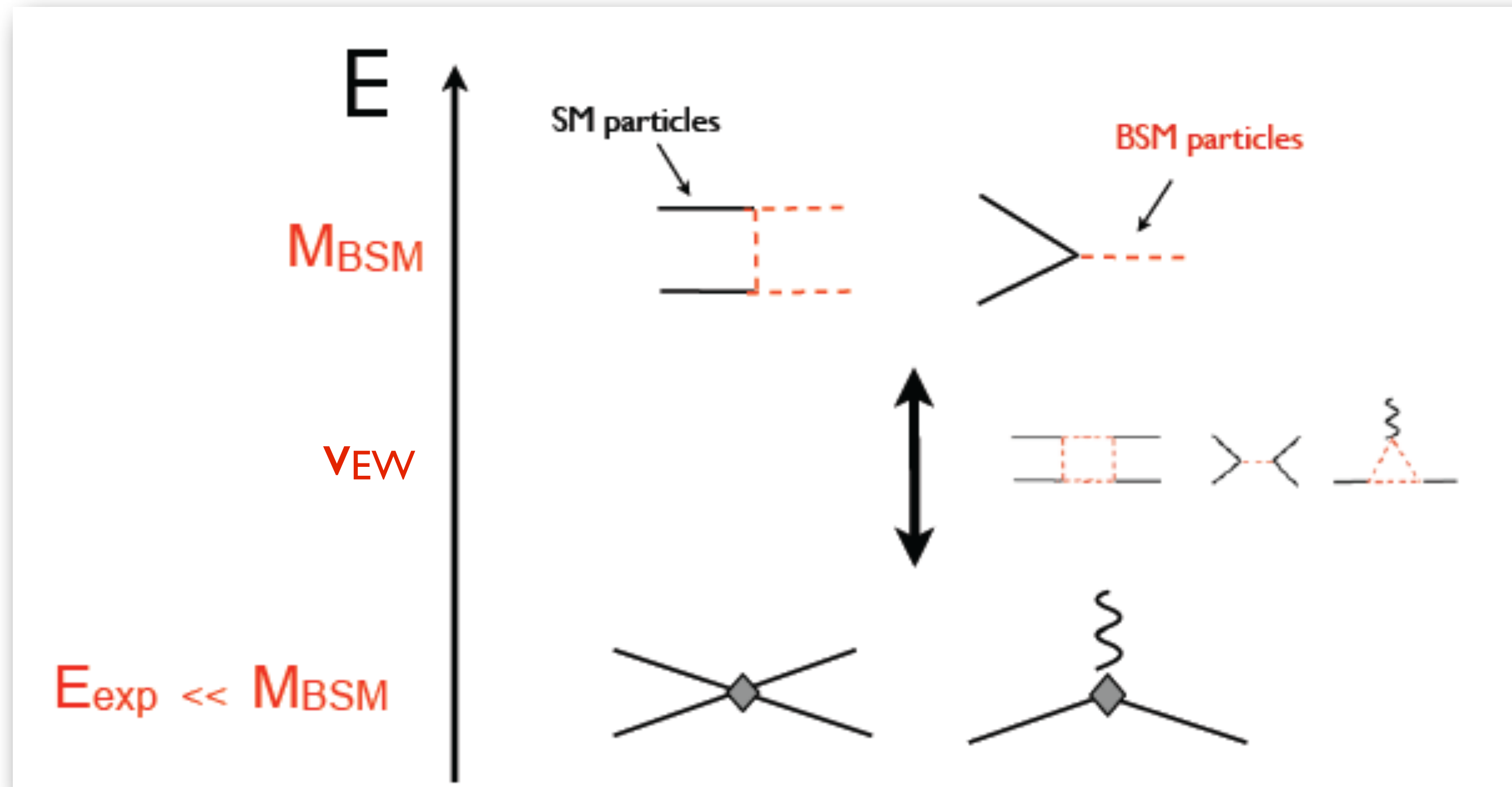

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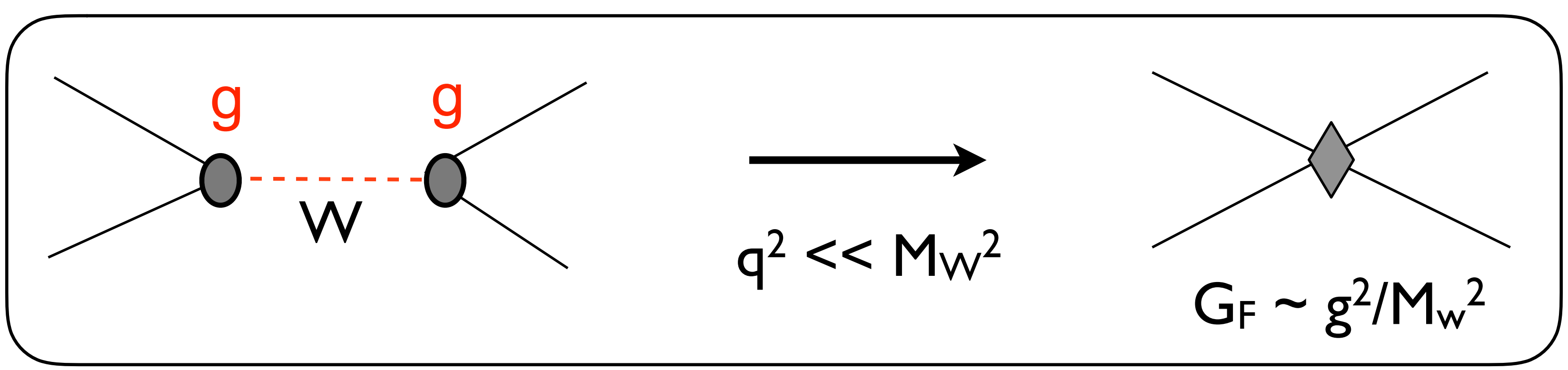
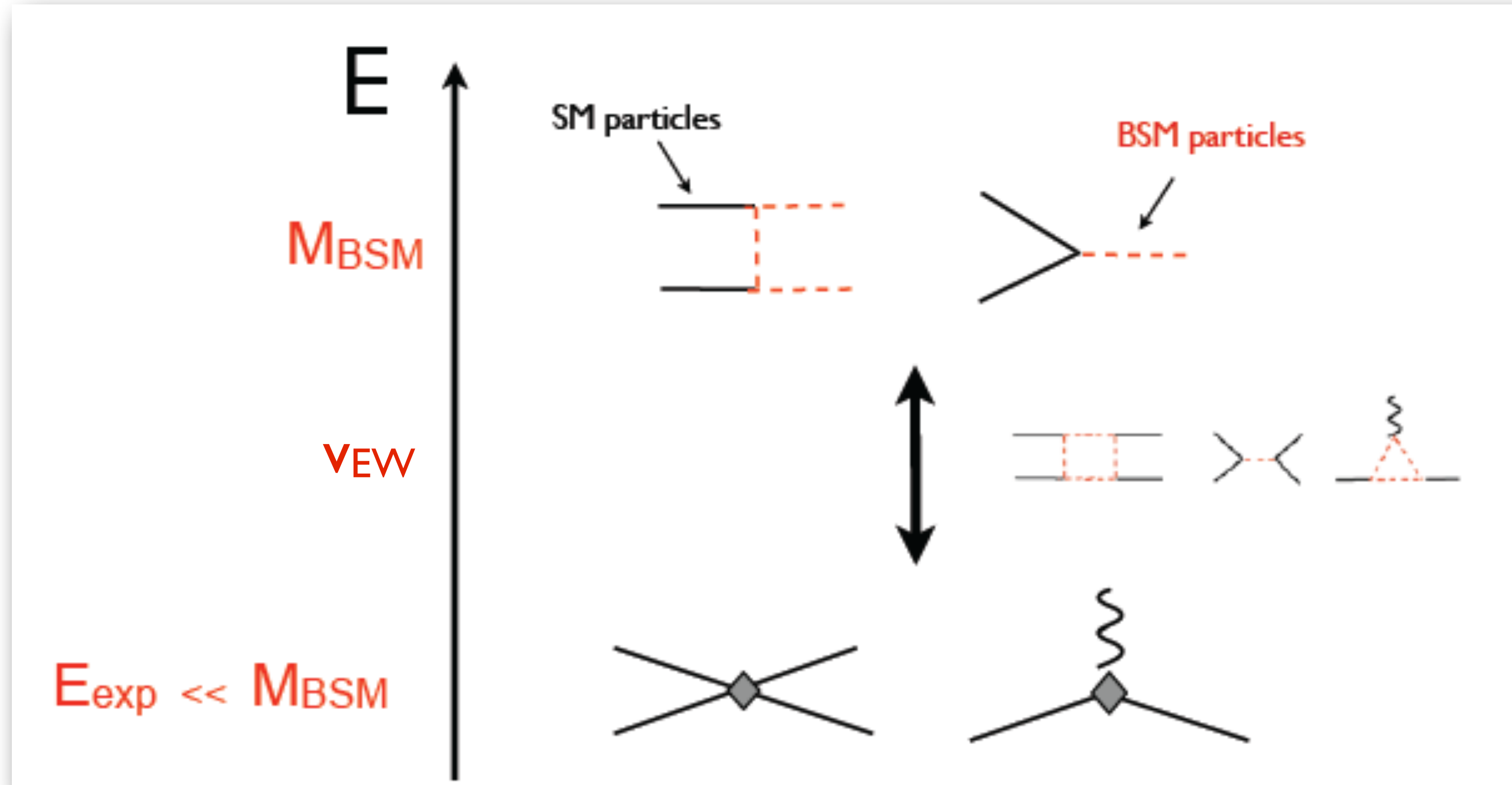


Effective Field Theory: unified framework to analyze low-energy implications of BSM scenarios *and* inform model building

EFT framework

- Assume mass gap
  $M_{BSM} > G_F^{-1/2} \sim v_{EW}$
- Degrees of freedom:
  SM fields (+ possibly ν_R)
- Symmetries: SM gauge group; but no flavor, B, L, CP



- EFT expansion in E/M_{BSM}, M_W/M_{BSM}

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

[$\Lambda \leftrightarrow M_{BSM}$]

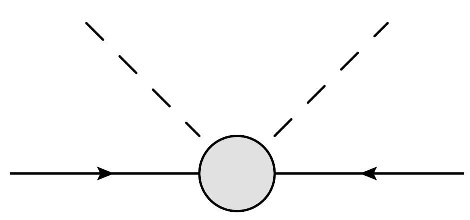
A guided tour of $\mathcal{L}_{eff}$

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

- Dim 5: only one operator

Weinberg 1979

$$\boxed{\hat{O}_{\rm dim=5} = \ell^T C \epsilon \varphi \, \varphi^T \epsilon \ell} \qquad C = i\gamma_2\gamma_0$$



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- Dim 5: only one operator

Weinberg 1979

$$\boxed{\hat{O}_{\rm dim=5} = \ell^T C \epsilon \varphi \, \varphi^T \epsilon \ell} \qquad C = i\gamma_2\gamma_0$$

- Violates total lepton number $\ell \to e^{i\alpha}\ell \qquad e \to e^{i\alpha} e$
- Generates Majorana mass for L-handed neutrinos (after EWSB)

$$\frac{1}{\Lambda}\hat{O}_{\rm dim=5} \xrightarrow{\langle\varphi\rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}} \frac{v^2}{\Lambda}\nu_L^T C \nu_L$$

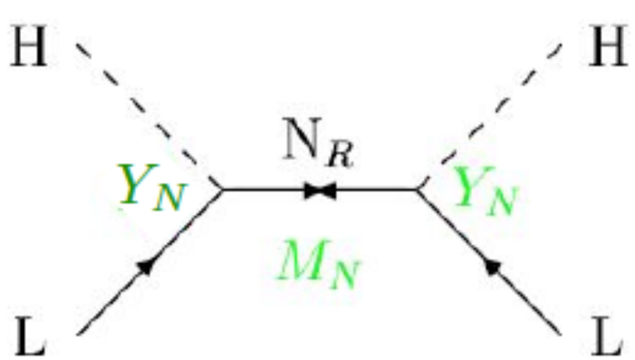
- "See-saw": $m_\nu \sim 1\,{\rm eV} \;\to\; \Lambda \sim 10^{13}\,{\rm GeV}$

- “Unpacking”dim-5 operator at tree-level: see-saw models

$$\mathcal{L}_5 = g_{\alpha\beta}\,\ell_\alpha^T C\epsilon\varphi\,\varphi^T\epsilon\ell_\beta \longrightarrow (m_\nu)_{\alpha\beta} = v^2\,g_{\alpha\beta}$$

Type I: Fermion singlet

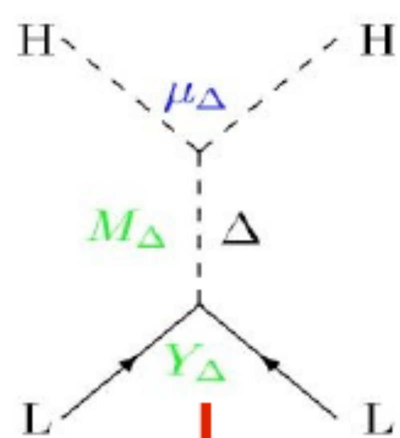
N_{R_i}



$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Type II: Scalar triplet

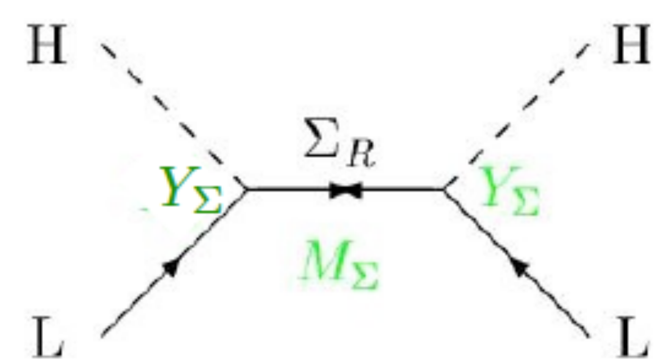
$\Delta \equiv (\Delta^{++}, \Delta^{+}, \Delta^{0})$



$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Type III: Fermion triplet

$\Sigma_i \equiv (\Sigma_i^{+}, \Sigma_i^{0}, \Sigma_i^{-})$



$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

A guided tour of $\mathcal{L}_{eff}$

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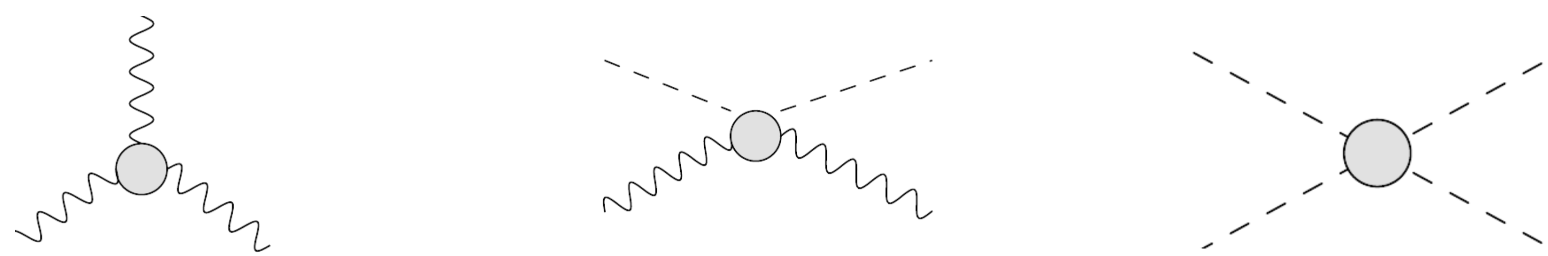
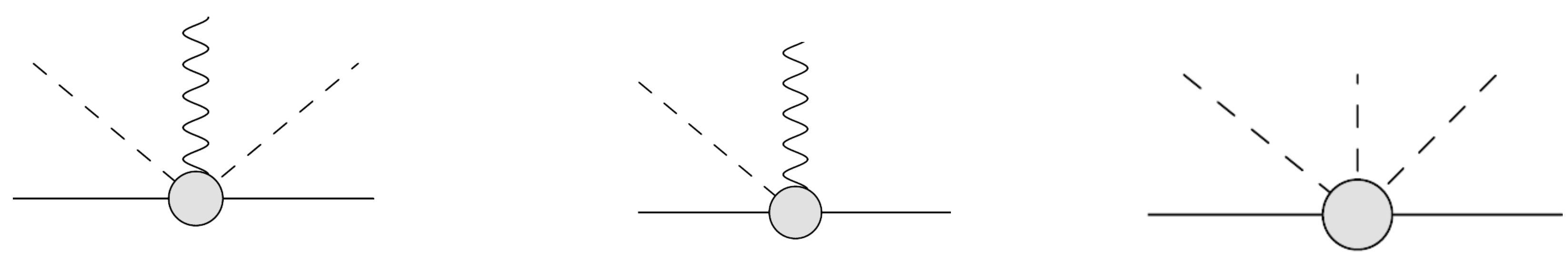
- Dim 6: affect *many* processes (59 structures not including flavor)

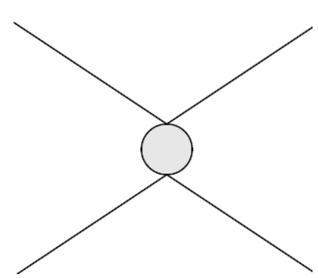
No fermions



Two fermions



Four fermions



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Weinberg 1979
Wilczek-Zee1979
Buchmuller-Wyler 1986, ...
Grzadkowski-Iskrzynksi-
Misiak-Rosiek (2010)

- Dim 6: affect *many* processes
  - B violation
  - Gauge and Higgs boson couplings
  - CPV, LFV, qFCNC, ...
  - g-2, Charged Currents, Neutral Currents, ...

Impact of IF experiments

- Comment #1: $O_i^{(d)}$ can be roughly divided in two classes

(i) Those that give corrections to SM "allowed" processes: probe them with precision measurements (muon g-2, β-decays, Q_W, ...)

(ii) Those that violate (approximate) SM symmetries: mediate rare/forbidden processes (qFCNC, LFV, LNV, BNV, EDMs)

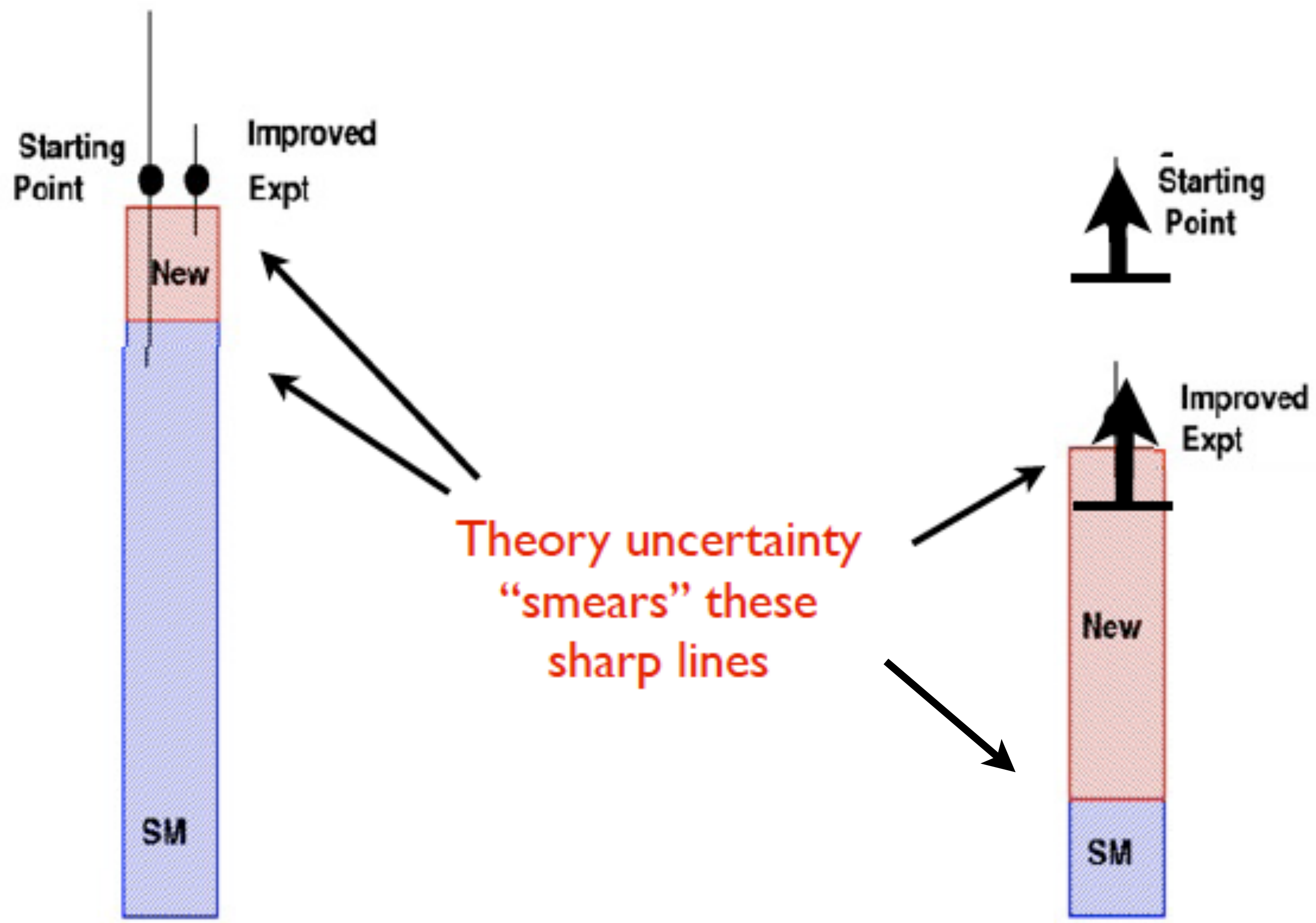

Figure copyright: David Mack

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- Comment #2: each UV model generates its own pattern of operators / couplings → different signatures in LE experiments

Therefore, LE measurements provide the opportunity to both discover BSM effects & discriminate among BSM scenarios (maximal impact in combination with the LHC)

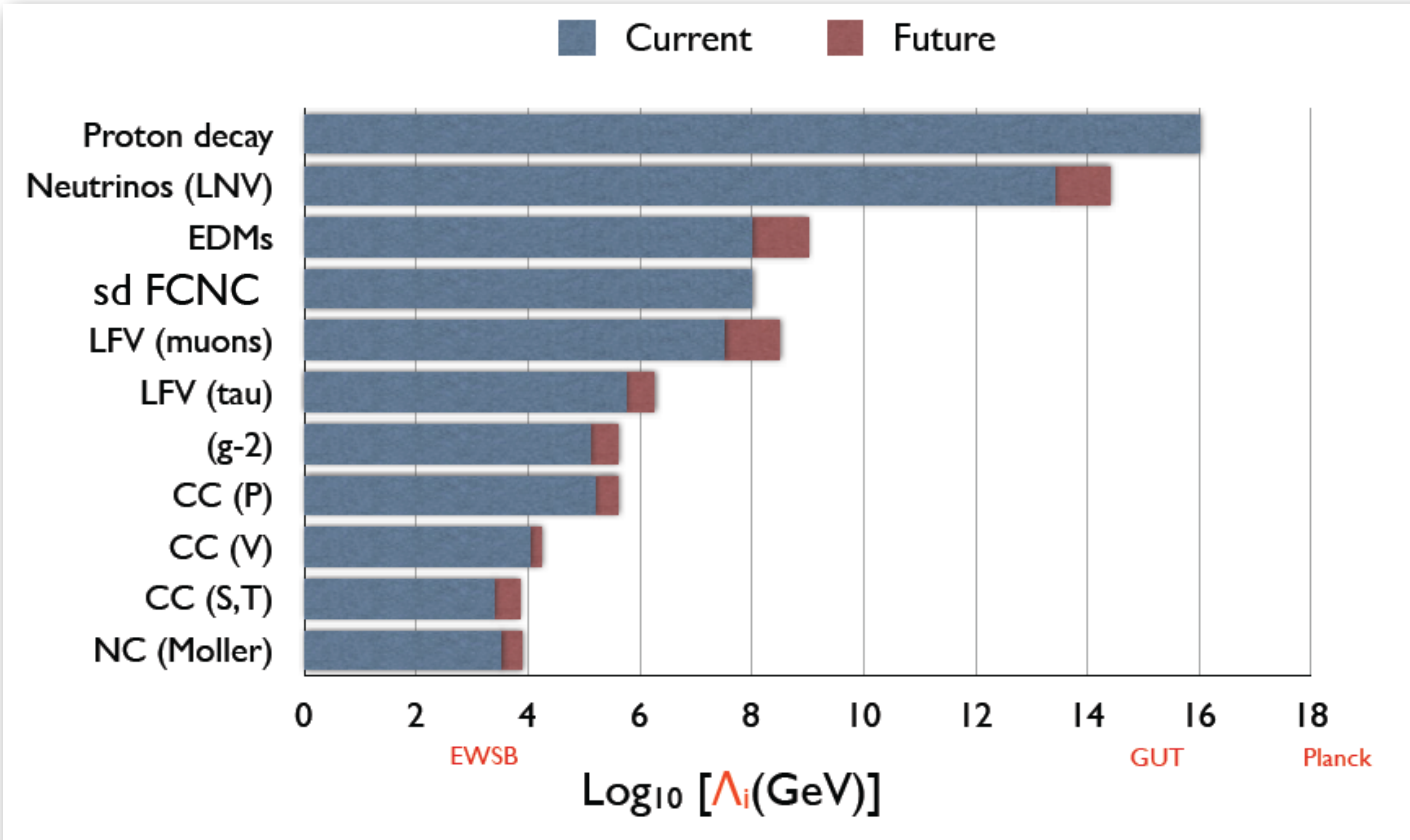
Physics reach at a glance

This equation at work

$$\boxed{\delta O_{\rm BSM}(\Lambda) \lesssim (O_{\rm exp} - O_{\rm SM})}$$

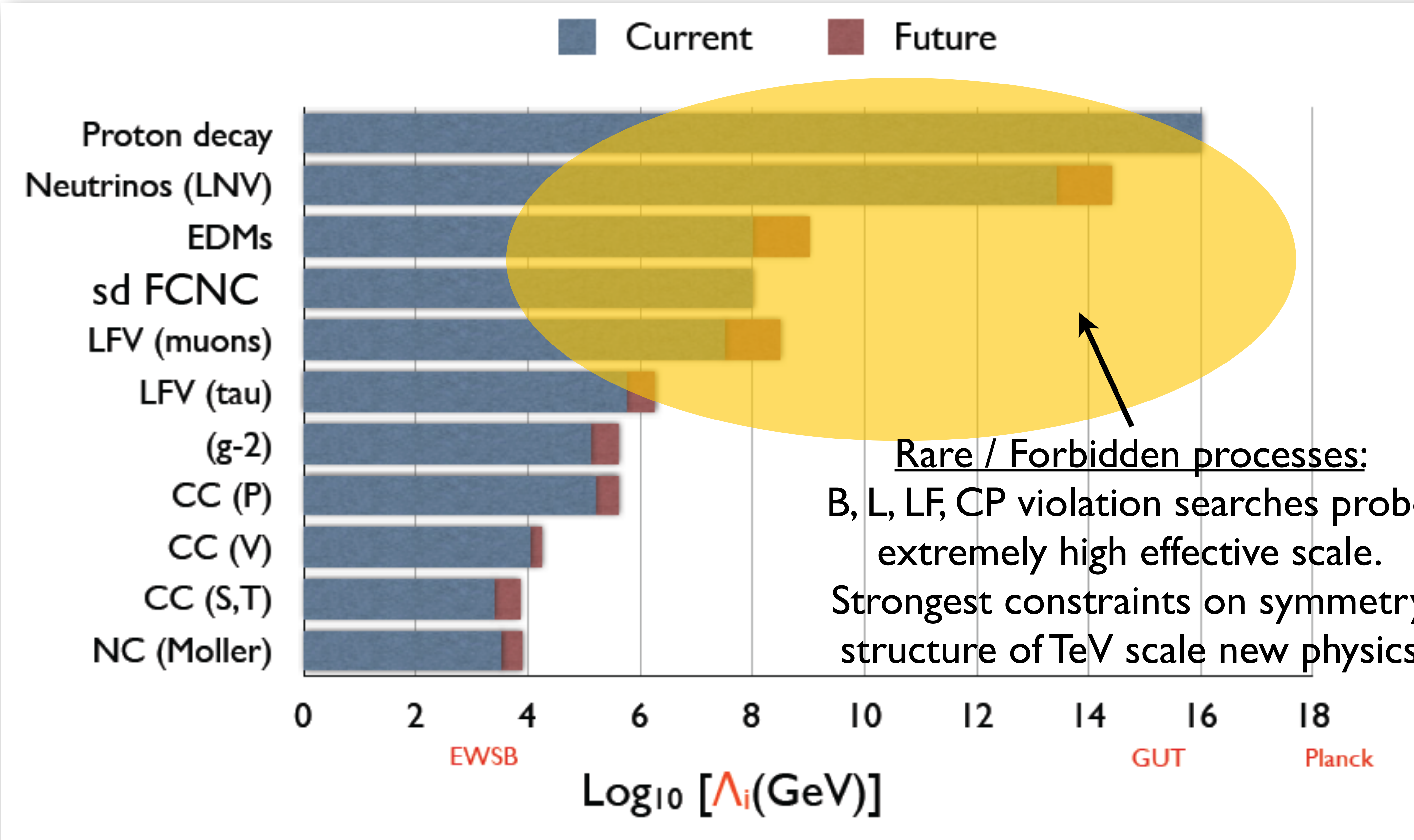
(for any observable *O*, $\delta O_{\rm BSM} \sim \Lambda^{-n}$ $n = 2, 4, ..$)

Physics reach at a glance



- Caveat: horizontal axis is $\Lambda/C^{(5)}, \ \Lambda/[C_i^{(6)}]^{1/2}$, ...
- So beware of couplings, loop factors, approximate symmetries

Physics reach at a glance



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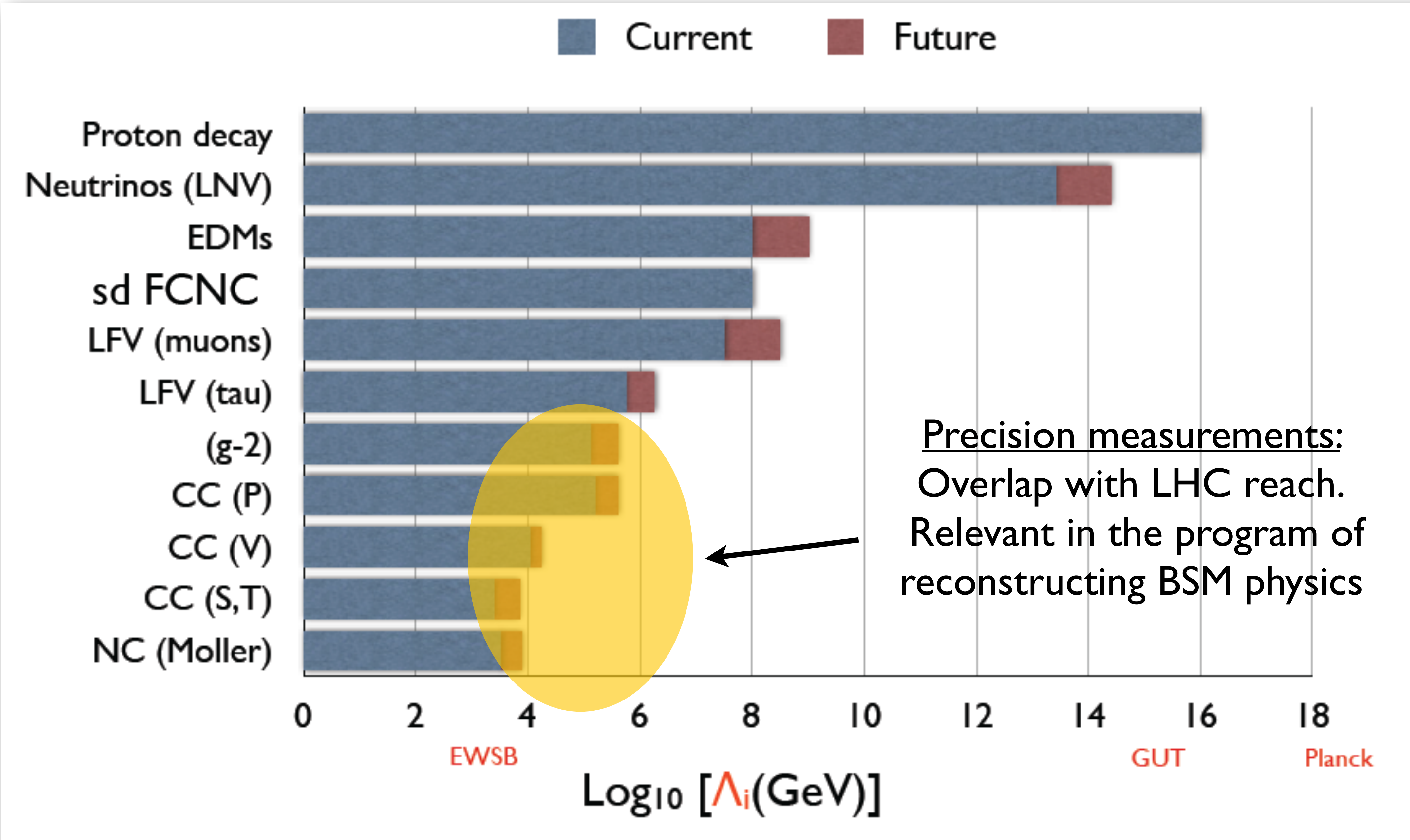

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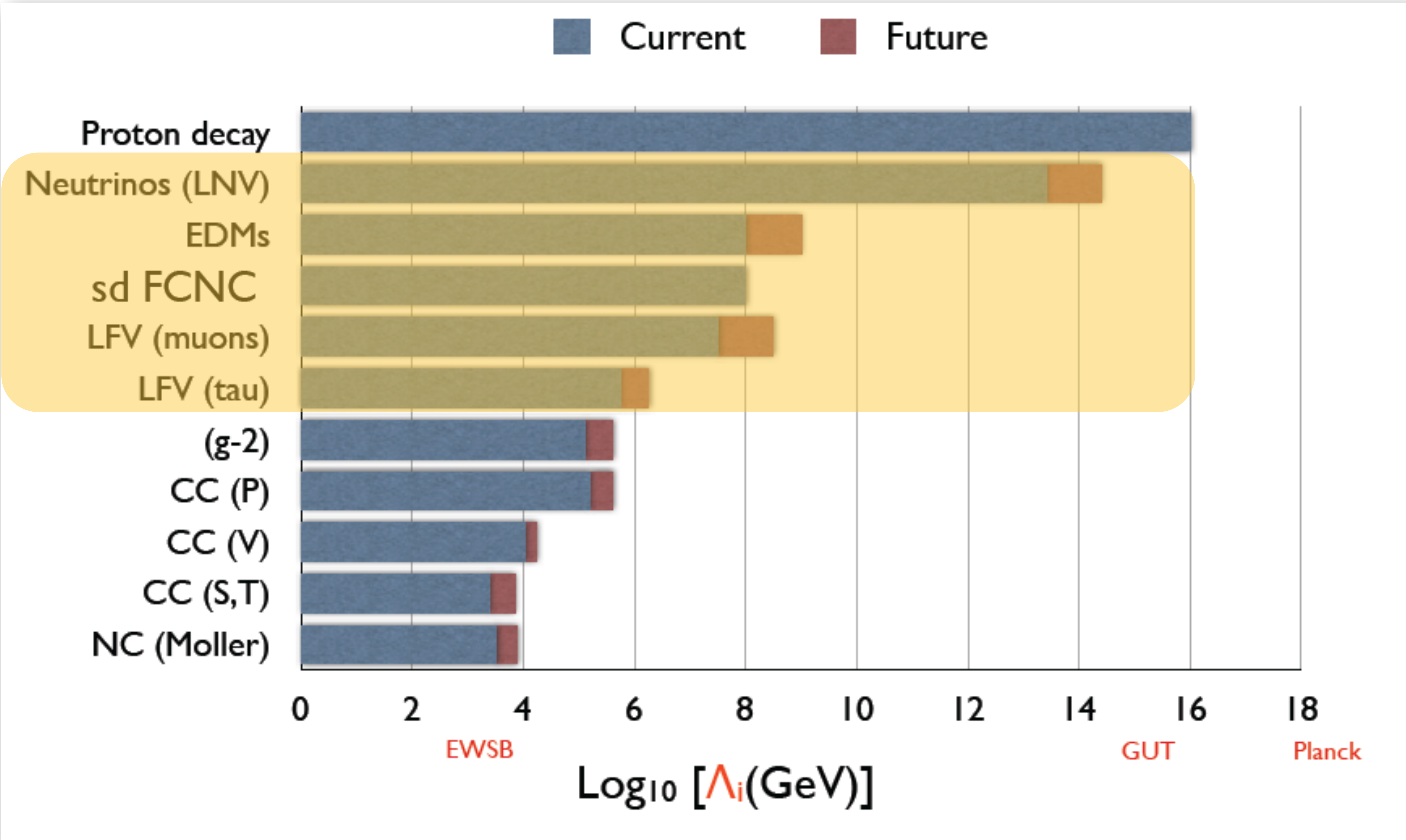
Next steps



- Zoom into specific probes, highlighting
  - Physics reach: discovery potential
  - Model diagnosing power
  - Impact on Higgs couplings

Quark FCNCs (rare K decays)

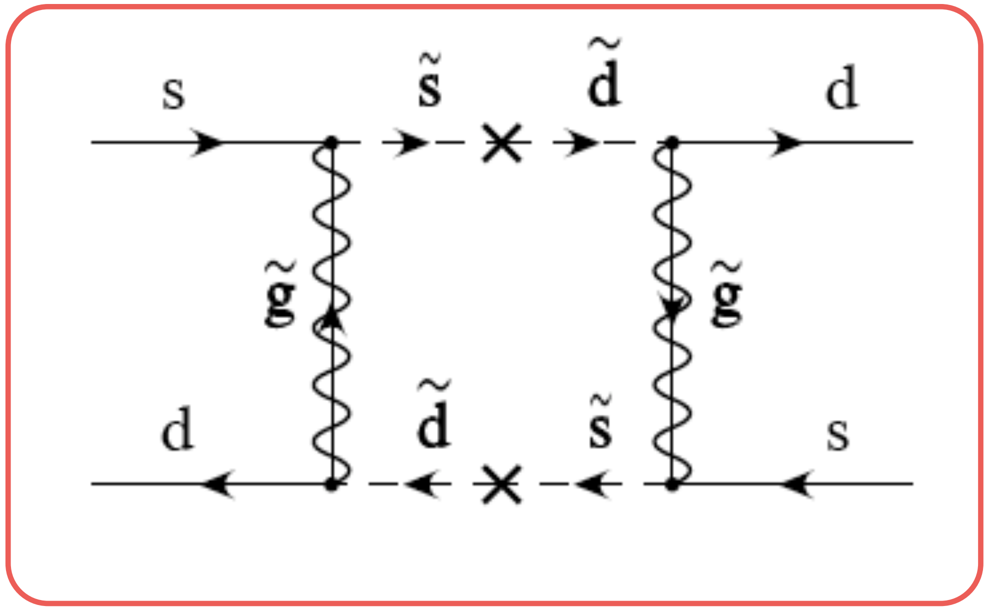
Flavor physics beyond the SM

- In the SM, $U(3)^5$ symmetry broken only by Y_U and Y_D

- BSM, new sources of $U(3)^5$ flavor-symmetry breaking are possible

- A major goal of flavor physics in the LHC era is to explore the flavor structure of BSM scenarios (that hopefully will emerge at the LHC)

- As a matter of fact, we already know that if M_{BSM} ~TeV, the flavor structure of new physics cannot be generic ("flavor problem")



- Important Example: CP violation in neutral kaon mixing

$$|K^0\rangle = |d\bar{s}\rangle$$
$$|\overline{K^0}\rangle = |\bar{d}s\rangle$$
$$\downarrow$$
$$K_L = K_{\text{heavy}}$$
$$K_S = K_{\text{light}}$$

$$\boxed{i\,\frac{d}{dt}\begin{pmatrix} K^0 \\ \overline{K^0} \end{pmatrix} = \left(M - i\,\frac{\Gamma}{2}\right)\begin{pmatrix} K^0 \\ \overline{K^0} \end{pmatrix}}$$

- $K_{L,S}$ not eigenstates of CP: non-zero asymmetries

$$\delta_L = \frac{\Gamma(K_L \to \pi^-\ell^+\nu) - \Gamma(K_L \to \pi^+\ell^-\bar{\nu})}{\Gamma(K_L \to \pi^-\ell^+\nu) + \Gamma(K_L \to \pi^+\ell^-\bar{\nu})} \;\propto\; 2\,\mathrm{Im}\langle K^0|H_{\Delta S=2}|\bar{K}^0\rangle$$

$$\boxed{(3.32 \pm 0.06) \times 10^{-3}}$$

$$\boxed{\mathcal{L}_{\text{eff}} \supset \frac{c_{\Delta S=2}}{\Lambda^2}\; \bar{s}_L\gamma^\mu d_L\; \bar{s}_L\gamma_\mu d_L \longleftrightarrow \frac{\Lambda}{\sqrt{c_{\Delta S=2}}} > 10^4\ \text{TeV}}$$

- For M_{BSM} ~ TeV, some effective new flavor symmetry must be at work

Minimal Flavor Violation

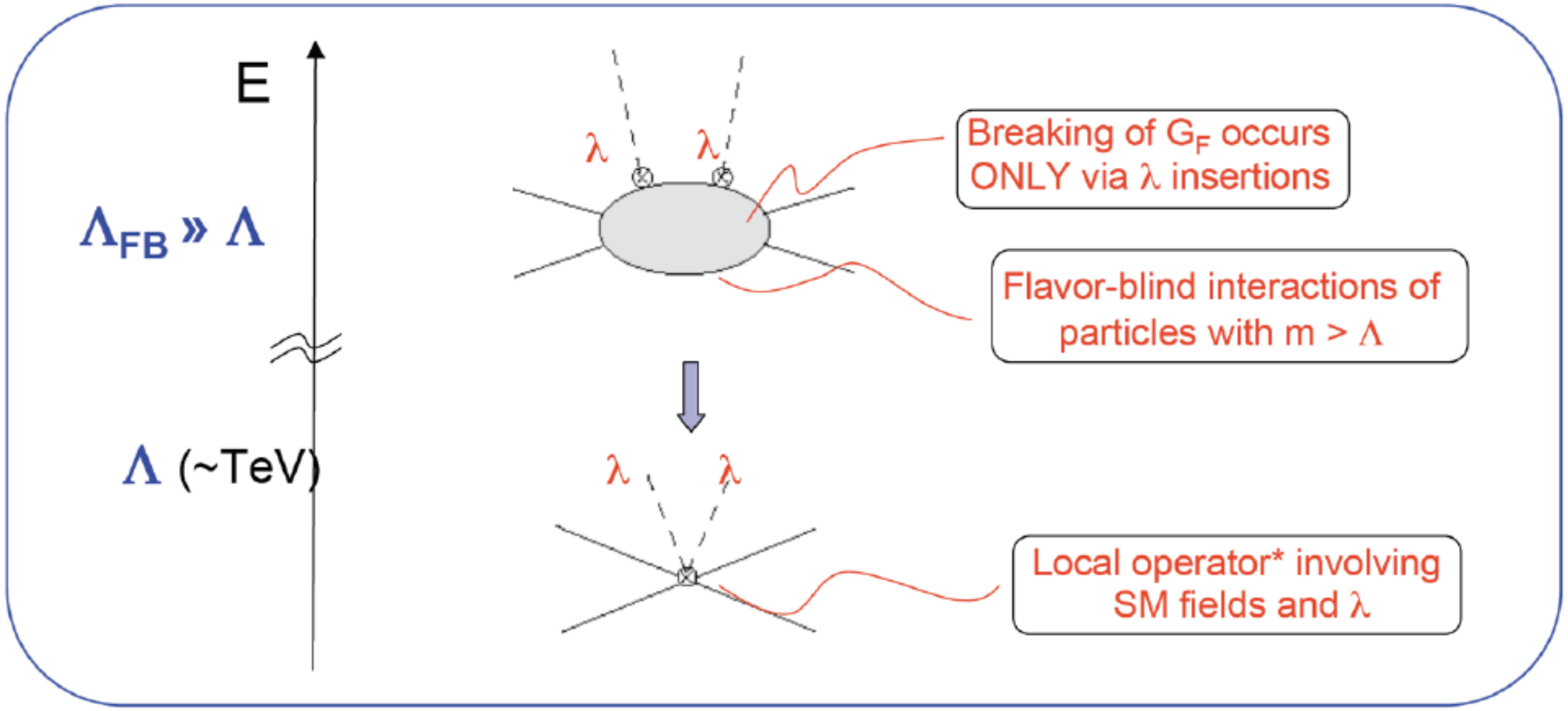
- MFV hypothesis is the most "conservative" of such symmetry principles:

Even beyond the SM, the only sources of flavor symmetry ($U(3)^5$) breaking are proportional to the Yukawa matrices

Georgi-Chivukula '86, Hall-Randall '90, Buras et al '99, D'Ambrosio et al ;'02

- Can be incorporated in explicit models (SUSY, Technicolor, ex. d)

- Can be formulated in EFT language



- Example of MFV operator mediating FCNC:

$$O_{F1} = H^\dagger\ \bar{D}_R\,\sigma^{\mu\nu}\left(\lambda_D\,\lambda_U\lambda_U^\dagger\right)Q_L\ F_{\mu\nu} \longrightarrow\ \bar{d}_R^{i'}\,\sigma^{\mu\nu}\ m_D^i\Delta_{FC}^{ij}\ d_L^{j'}\ F_{\mu\nu}$$

$$\boxed{(\Delta_{FC})_{ij} = (\lambda_U\lambda_U^\dagger)_{ij} \simeq \left(\frac{m_t}{v}\right)^2\ V_{3i}^*\,V_{3j}}$$

Normalization

Mixing pattern

1. FCNC suppression follows from Cabibbo hierarchy.
   Flavor problem essentially “solved”: $\Lambda \sim$ TeV is now allowed

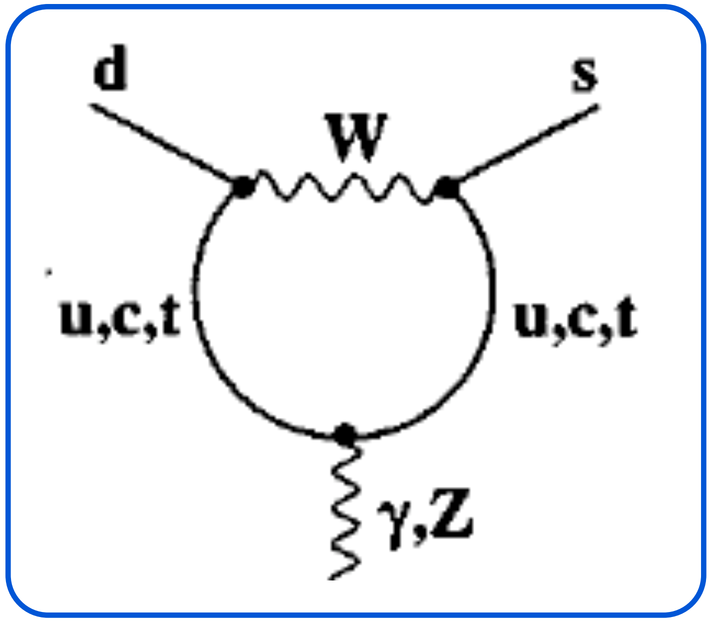
2. Predictive framework, relates $d_i \to d_j$ transitions. Can be tested

3. Useful benchmark scenario

Special role of rare K decays

- Rare K decay: deep probe of new flavor-breaking structures

$$d_i \;\rightarrow\; d_j\;(\gamma,\;\ell^+\ell^-,\;\nu\bar{\nu})$$



- No SM tree-level contribution
- Strong suppression from λ^5 CKM factor (enhanced sensitivity to BSM effect)
- Predicted with high precision ("short-distance" dominated)

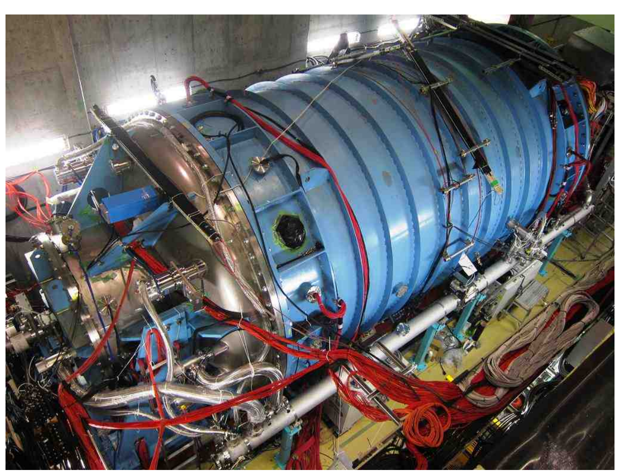
$$A(s \rightarrow d) \;\sim\; \frac{g^2}{(4\pi\, v)^2}\; y_t^2 V_{ts} V_{td}^* \;+\; \frac{\delta_{sd}}{\Lambda^2}$$

λ^5 suppression in the SM

- Theory + Experiment status and prospects

Observable	SM Theory	Current Expt.	Future Experiments
$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$	$7.81(75)(29) \times 10^{-11}$	$1.73^{+1.15}_{-1.05} \times 10^{-10}$ E787/E949	$\sim$10% at NA62 $\sim$5% at ORKA $\sim$2% at *Project X*
$\mathcal{B}(K^0_L \to \pi^0 \nu \bar{\nu})$	$2.43(39)(6) \times 10^{-11}$	$< 2.6 \times 10^{-8}$ E391a	1[st] observation at KOTO $\sim$5% at *Project X*

1311.1076 and refs therein: 1st error parametric, 2nd intrinsic



CERN NA62

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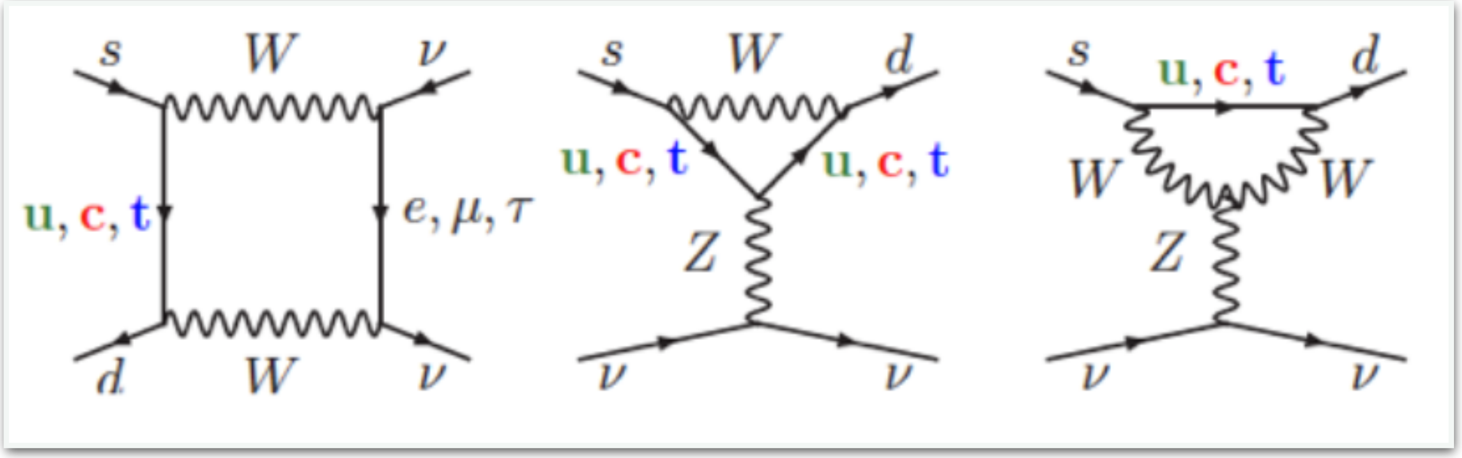
$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$	$7.81(75)(29) \times 10^{-11}$	$1.73^{+1.15}_{-1.05} \times 10^{-10}$ E787/E949	~10% at NA62 ~5% at ORKA ~2% at *Project X*
$\mathcal{B}(K_L^0 \to \pi^0 \nu\bar{\nu})$	$2.43(39)(6) \times 10^{-11}$	$< 2.6 \times 10^{-8}$ E391a	1st observation at KOTO ~5% at *Project X*

1311.1076 and refs therein: 1st error parametric, 2nd intrinsic

- "Golden modes" ($K\to \pi\nu\nu$) predicted quite precisely in the SM
  - Quadratic GIM suppresses light-quark (long-distance) contribution
  - Semi-leptonic matrix elements related by isospin to $K \to \pi\, e\, \nu$



- Theory + Experiment status and prospects

Observable	SM Theory	Current Expt.	Future Experiments
$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$	$7.81(75)(29) \times 10^{-11}$	$1.73^{+1.15}_{-1.05} \times 10^{-10}$ E787/E949	$\sim$10% at NA62 $\sim$5% at ORKA $\sim$2% at *Project X*
$\mathcal{B}(K^0_L \to \pi^0 \nu\bar{\nu})$	$2.43(39)(6) \times 10^{-11}$	$< 2.6 \times 10^{-8}$ E391a	1st observation at KOTO $\sim$5% at *Project X*

1311.1076 and refs therein: 1st error parametric, 2nd intrinsic

- "Golden modes" ($K \to \pi\nu\nu$) predicted quite precisely in the SM

- O(10%) exp. precision (SM BR) ⇒ $\Lambda \sim 300$ TeV (generic flavor structure)

  $\Lambda \sim 10$ TeV (MFV structure, λ^5 suppression)

EFT approach: Kaon matrix

Uli Haisch,
S. Jaeger

$$\mathcal{L}_{\rm eff} = \sum_i C_i Q_i$$

Operator		$K^+ \to \pi^+ \nu\bar\nu$	$K_L \to \pi^0 \nu\bar\nu$	$K_L \to \pi^0 l^+ l^-$	$K_L \to l^+ l^-$	$K^+ \to l^+ \nu$	$P_T(K^+ \to \pi^0 \mu^+ \nu)$	$\Delta_{\rm CKM}$	ϵ'/ϵ	ϵ_K
$Q_{lq}^{(1)}$	$(\bar D_L \gamma_\mu S_L)(\bar L_L \gamma^\mu L_L)$	✓	✓	✓	hs	—	—	—	—	—
$Q_{lq}^{(3)}$	$(\bar D_L \gamma_\mu \sigma^i S_L)(\bar L_L \gamma^\mu \sigma^i L_L)$	✓	✓	✓	hs	hs	✓	✓	—	—
Q_{qe}	$(\bar D_L \gamma_\mu S_L)(\bar l_R \gamma^\mu l_R)$	—	—	✓	hs	hs	✓	✓	—	—
Q_{ld}	$(\bar d_R \gamma_\mu s_R)(\bar L_L \gamma^\mu L_L)$	✓	✓	✓	hs	—	—	—	—	—
Q_{ed}	$(\bar d_R \gamma_\mu s_R)(\bar l_R \gamma^\mu l_R)$	—	—	✓	hs	—	—	—	—	—
$Q_{lq}^\dagger$	$(\bar u_R S_L)(\bar l_R L_L)$	—	—	—	—	✓	✓	✓	—	—
$(Q_{lq}^t)^\dagger$	$(\bar u_R \sigma_{\mu\nu} S_L)(\bar l_R \sigma^{\mu\nu} L_L)$	—	—	—	—	—	?	?	—	—
Q_{qde}	$(\bar d_R S_L)(\bar L_L l_R)$	—	—	✓	✓	—	—	—	—	—
$Q_{qde}^\dagger$	$(\bar D_L s_R)(\bar l_R L_L)$	—	—	✓	✓	✓	✓	✓	—	—
$Q_{\phi q}^{(1)}$	$(\bar D_L \gamma_\mu S_L)(\phi^\dagger D^\mu \phi)$	✓	✓	✓	hs	—	—	—	✓	(✓)
$Q_{\phi q}^{(3)}$	$(\bar D_L \gamma_\mu \sigma^i S_L)(\phi^\dagger D^\mu \sigma^i \phi)$	✓	✓	✓	hs	hs	✓	✓	✓	(✓)
$Q_{\phi d}$	$(\bar d_R \gamma_\mu s_R)(\phi^\dagger D^\mu \phi)$	✓	✓	✓	hs	—	—	—	✓	(✓)

- $K \to \pi\nu\nu$ sensitive to 6 operators
- 3 essentially unconstrained: can induce large deviations
- 3 "Z penguins": constraints from ε'?

EFT approach: Kaon matrix

- In this framework, can study both
  - “Discovery potential” of rare decays: given the constraints from other observables, how large of a deviation from the SM can one expect?
  - “Diagnosing power”: correlations among observables
- Focus on Z-penguins
  - Most interesting, since they contribute to ε'/ε
  - Dominant operators in many models

Correlations in K decays

Uli Haisch, S. Jaeger

- If Z-penguins dominate (MSSM, RS, ...)

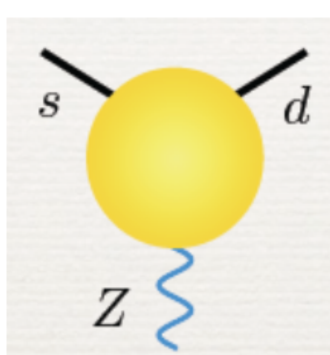
$$(V_{ts}^* V_{td}\, C_{\rm SM} + C_{\rm NP})\, \bar d_L \gamma_\mu s_L Z^\mu + \widetilde C_{\rm NP}\, \bar d_R \gamma_\mu s_R Z^\mu$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar\nu) \propto (\mathrm{Im} X)^2 ,$$

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar\nu(\gamma)) \propto |X|^2 ,$$

$$X = X_{\rm SM} + \frac{1}{\lambda^5} \left(C_{\rm NP} + \widetilde C_{\rm NP}\right) ,$$

$$\frac{\varepsilon_K'}{\varepsilon_K} \propto -\mathrm{Im}\Big[\lambda_t\,(-1.4 + 13.8 R_6 - 6.6 R_8) + (1.5 + 0.1 R_6 - 13.3 R_8)\left(C_{\rm NP} - \widetilde C_{\rm NP}\right)\Big]$$



Impact on CP-violation in K→ ππ decays

$$\eta_{+-} \equiv \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \simeq \epsilon + \epsilon'$$

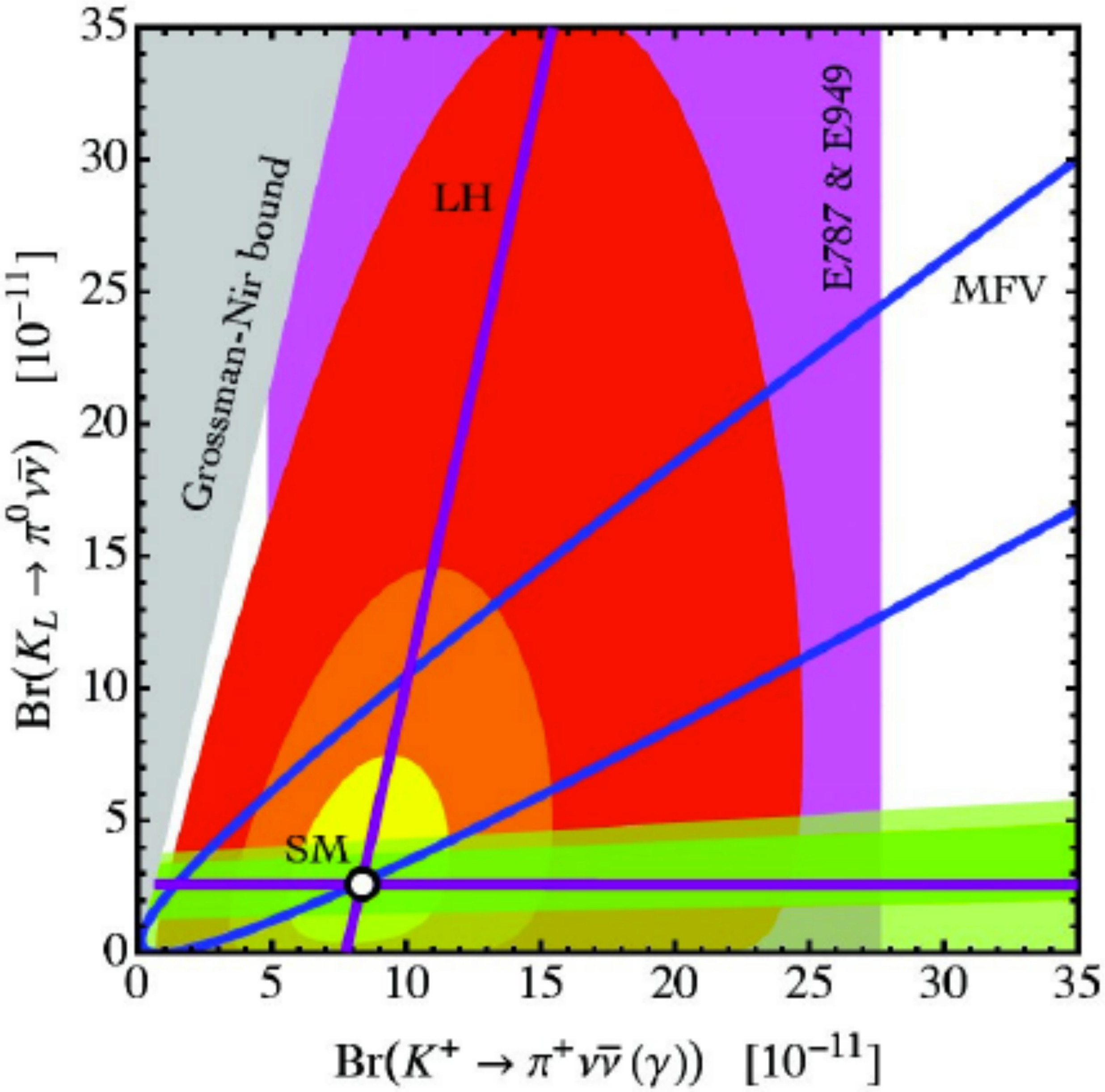
$$\eta_{00} \equiv \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} \simeq \epsilon - 2\epsilon'$$

$$\frac{|\eta_{00}|^2}{|\eta_{+-}|^2} = 1 - 6\,\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right)$$

Correlations in K decays

Uli Haisch,
S. Jaeger

- If Z-penguins dominate (MSSM, RS, ...)



$$(V_{ts}^* V_{td}\, C_{\rm SM} + C_{\rm NP})\, \bar{d}_L \gamma_\mu s_L Z^\mu + \widetilde{C}_{\rm NP}\, \bar{d}_R \gamma_\mu s_R Z^\mu$$

- $|C_{\rm NP}| \leq 0.5\, |\lambda_t C_{\rm SM}|$
- $|C_{\rm NP}| \leq |\lambda_t C_{\rm SM}|$
- $|C_{\rm NP}| \leq 2\, |\lambda_t C_{\rm SM}|$

$$C_{\rm NP} = |C_{\rm NP}|\, e^{i\phi_C}$$

- $C_{\rm NP} \propto \lambda_t C_{\rm SM}$

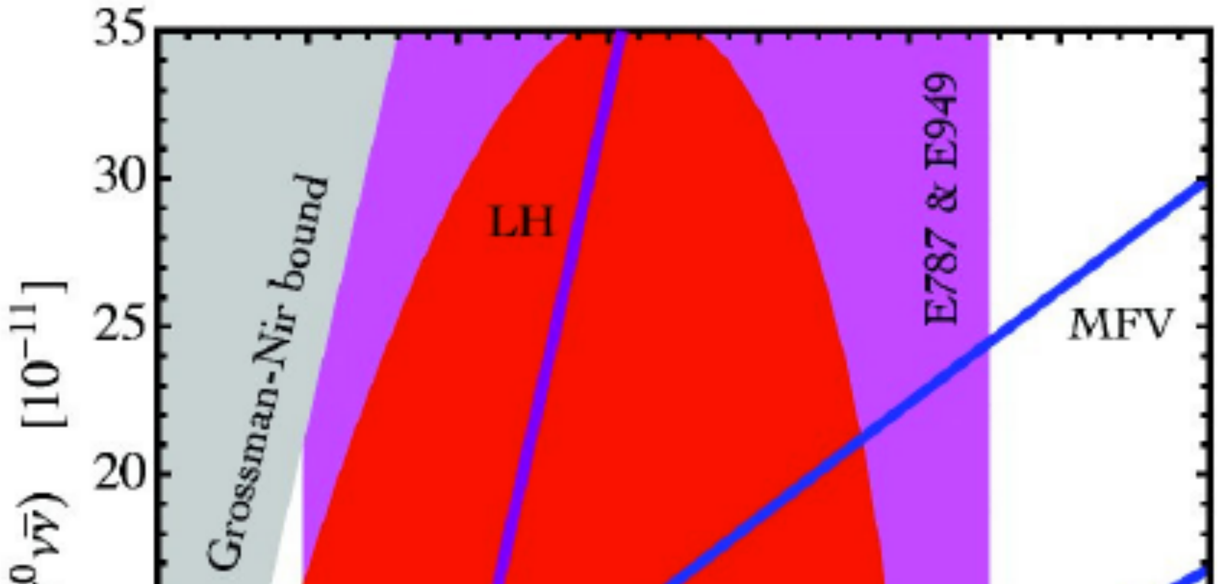
- $\epsilon'/\epsilon \in [0.5, 2]\, (\epsilon'/\epsilon)_{\rm SM}$
- $\epsilon'/\epsilon \in [0.2, 5]\, (\epsilon'/\epsilon)_{\rm SM}$

- 50% deviations from SM BR still possible in $K_L \to \pi^0 \nu\nu$. Should influence ultimate experimental sensitivity (5% of SM BR)

Correlations in K decays

Uli Haisch, S. Jaeger

- If Z-penguins dominate (MSSM, RS, ...)



$$(V_{ts}^* V_{td}\, C_{\rm SM} + C_{\rm NP})\, \bar d_L \gamma_\mu s_L Z^\mu + \widetilde C_{\rm NP}\, \bar d_R \gamma_\mu s_R Z^\mu$$

- $|C_{\rm NP}| \leq 0.5\,|\lambda_t C_{\rm SM}|$
- $|C_{\rm NP}| \leq |\lambda_t C_{\rm SM}|$
- $|C_{\rm NP}| \leq 2\,|\lambda_t C_{\rm SM}|$

- K→ πνν modes provide a win-win opportunity
  - Sizable (non λ^5 suppressed) BSM effect is possible
  - Even if BSM is small (MFV, Z-penguin, …), can still detect it due to “clean” SM prediction

- 50% deviations from SM BR still possible in $K_L \to \pi^0\nu\nu$. Should influence ultimate experimental sensitivity (5% of SM BR)

Backup

Anomalous symmetry breaking

- Action is invariant, but path-integral measure is not!

$$\boxed{\int [d\psi][d\bar{\psi}]\ e^{iS[\psi,\bar{\psi}]}}$$

$$\psi \to \psi' \qquad \bar{\psi} \to \bar{\psi}'$$

$$S[\psi, \bar{\psi}] = S[\psi', \bar{\psi}']$$

$$\int [d\psi][d\bar{\psi}] = \int [d\psi'][d\bar{\psi}']\,\mathcal{J} \qquad \mathcal{J} \neq 1$$

Anomalous symmetry breaking

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$$\int [d\psi][d\bar{\psi}]\; e^{iS[\psi,\bar{\psi}]}$$

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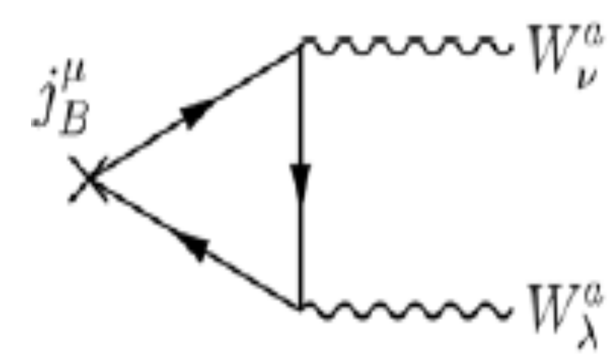
$$\int [d\psi][d\bar{\psi}] = \int [d\psi'][d\bar{\psi}']\,\mathcal{J} \qquad \mathcal{J} \neq 1$$

- Important examples: trace (scale invariance) and chiral anomalies

- Baryon (B) and Lepton (L) number are anomalous in the SM

$$\partial_\mu J^\mu_B = \partial_\mu J^\mu_L = i\frac{N_F}{32\pi^2}\left(-g_2^2 F^{a\mu\nu}\widetilde{F}^a_{\mu\nu} + g_1^2 f^{\mu\nu}\widetilde{f}_{\mu\nu}\right)$$



- Only B-L is conserved; B+L is violated; negligible at zero temperature

Basics of meson-antimeson mixing

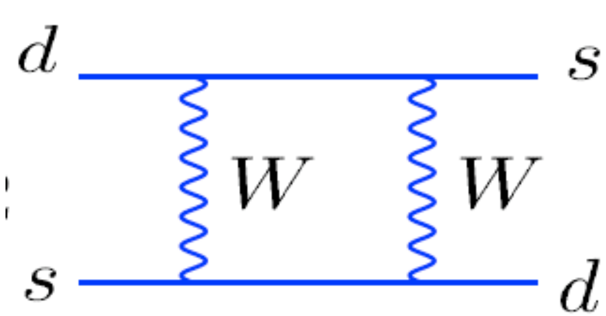
- Mixed states $a|P^0\rangle + b|\bar{P}^0\rangle$ evolve according to:

$$\boxed{\frac{d}{dt}\begin{pmatrix} a \\ b \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} a \\ b \end{pmatrix}}$$

CPT: $\begin{array}{l} M_{11} = M_{22} \\ \Gamma_{11} = \Gamma_{22} \end{array}$ Hermiticity $\begin{array}{l} M_{21} = M_{12}^* \\ \Gamma_{21} = \Gamma_{12}^* \end{array}$ CP: $\begin{array}{l} M_{12} = M_{12}^* \\ \Gamma_{12} = \Gamma_{12}^* \end{array}$

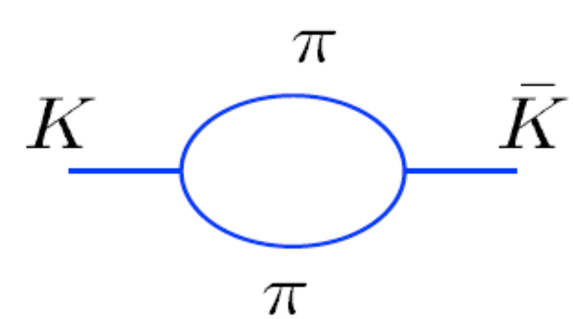
$$\Gamma_{12} = \sum \pi\delta(m_P - E_n)\,\langle P^0|H_{\Delta F=1}|n\rangle\langle n|H_{\Delta F=1}|\bar{P}^0\rangle$$

$$M_{12} = \langle P^0|H_{\Delta F=2}|\bar{P}^0\rangle \;+\; \mathcal{P}\sum_n \frac{\langle P^0|H_{\Delta F=1}|n\rangle\langle n|H_{\Delta F=1}|\bar{P}^0\rangle}{m_P - E_n}$$



Short distance (dominant in $B_{d,s}$, prop. to $|V_{td}|$ and $|V_{ts}|$)

Long distance (important in K, D)



- Mass eigenstates

$$|P_{1,2}\rangle \;=\; p\,|P^0\rangle \;\pm\; q|\bar{P}^0\rangle \qquad\qquad |p|^2 + |q|^2 = 1$$

$$\boxed{\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}}$$

- Mass and lifetime differences

$$\Delta M = M_2 - M_1 = -2\,\mathrm{Re}\left[\frac{q}{p}\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\right]$$

$$\Delta\Gamma = \Gamma_1 - \Gamma_2 = -4\,\mathrm{Im}\left[\frac{q}{p}\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\right]$$

- Time evolution of state produced as P^0 or $\bar{P}^0$

$$\boxed{\begin{aligned} |P^0(t)\rangle &= g_+(t)|P^0\rangle + \frac{q}{p}g_-(t)|\bar{P}^0\rangle \\ |\bar{P}^0(t)\rangle &= \frac{p}{q}g_-(t)|P^0\rangle + g_+(t)|\bar{P}^0\rangle \end{aligned}}$$

$$g_\pm(t) = \frac{1}{2}e^{-iM_1 t}\, e^{-\frac{1}{2}\Gamma_1 t}\left[1 \pm e^{-i\Delta M\, t} e^{\frac{1}{2}\Delta\Gamma t}\right]$$

- Can measure ΔM and ΔΓ (infer CKM couplings)
- CP violation in mixing (|q/p| ≠ 1): mass eigenstates are not CP eigenstates
- In K system, usually define "impurity" parameter $\bar{\epsilon}$

$$|K_{S/L}\rangle = N_{\bar{\epsilon}}\left(|K^0_\pm\rangle + \bar{\epsilon}|K^0_\mp\rangle\right)$$

$$\boxed{\frac{p}{q} = \frac{1+\bar{\epsilon}}{1-\bar{\epsilon}}}$$

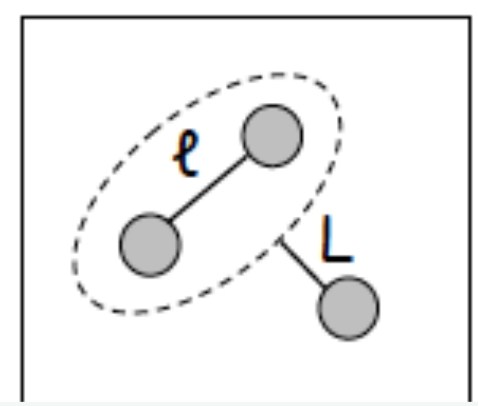
CP properties of 2 and 3 pion states

CP-ology

- $J^P(K) = 0^-$
- $J^P(\pi) = 0^-$ $C(\pi^0) = +1$ [$\pi^0 \to \gamma\gamma$ and $C(\gamma) = -1$]

- $\pi\pi$:
  $P(\pi\pi) = P(\pi)^2 (-1)^\ell = (-1)^\ell$ [$\pi^0\pi^0$: even ℓ]
  $C(\pi^0\pi^0) = +1$, $C(\pi^+\pi^-) = P(\pi^+\pi^-) = (-1)^\ell$
  Exchange = CP $\Rightarrow$ $CP(\pi\pi) = +1$
- $K \to \pi\pi$:
  $J(\pi\pi) = \ell(\pi\pi) = 0 \Rightarrow P(\pi\pi) = +1, C(\pi\pi) = +1$

- $\pi\pi\pi$:
  $|\ell-L| \leq J(\pi\pi\pi) \leq |\ell+L|$
  $P(\pi\pi\pi) = P(\pi)^3 (-1)^\ell (-1)^L = (-1)^{\ell+L+1}$ [$\pi^0\pi^0\pi^0$: even ℓ, $P=(-1)^{L+1}$]
  $C(\pi^0\pi^0\pi^0) = +1$, $C(\pi^+\pi^-\pi^0) = (-1)^\ell$
- $K \to \pi\pi\pi$:
  $J(\pi\pi\pi) = 0 \Rightarrow \ell = L \Rightarrow P(\pi\pi\pi) = -1$
  $CP(\pi^0\pi^0\pi^0) = -1$ $CP(\pi^+\pi^-\pi^0) = (-1)^{\ell+1}$
  $\ell>0$ is kinematically suppressed



M. Sozzi

Minimal Flavor Violation

- Recall: $U(3)^5$ invariance of $\mathcal{L}_{\rm gauge}$ broken only by Yukawas:

$$\bar{Q}_L^i\, \lambda_D^{ij}\, d_R^j\, H \qquad \bar{Q}_L^i\, \lambda_U^{ij}\, u_R^j\, H_c$$

$$\lambda_D \to \boxed{\frac{m_D^{\rm diag}}{v}} \qquad \lambda_U \to \boxed{V_{\rm CKM}^\dagger\, \frac{m_U^{\rm diag}}{v}}$$

1 - Observe that Yukawa interactions are formally invariant if

$$\lambda_D \to V_L\, \lambda_D\, V_D^\dagger \qquad\qquad \lambda_U \to V_L\, \lambda_U\, V_U^\dagger$$

2 - Construct higher dim. local operators (BSM physics) that are formally invariant under $G_f = U(3)^5$

Neutrino phenomenology

- $\mathcal{L}_{\nu SM}$ largely inaccessible at the LHC: domain of the Intensity Frontier (accelerator, reactor) and Cosmic Frontier (solar, atmospheric, astro)
- Oscillation experiments sensitive to mass splittings and mixing angles

World data consistent with 3 light states, but other light ν not excluded

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

Parameter	best-fit ($\pm 1\sigma$)
Δm^2_{21} [10^{-5} eV ^{2}]	$7.54^{+0.26}_{-0.22}$
$\|\Delta m^2\|$ [10^{-3} eV ^{2}]	2.43 ± 0.06 (2.38 ± 0.06)
$\sin^2\theta_{12}$	0.308 ± 0.017
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	$0.455^{+0.039}_{-0.031}$,
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	$0.0234^{+0.0020}_{-0.0019}$
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	$0.0240^{+0.0019}_{-0.0022}$
δ/π (2σ range quoted)	$1.39^{+0.38}_{-0.27}$ ($1.31^{+0.29}_{-0.33}$)

PDG 2014