HUGS 2018
Jefferson Lab, Newport News, VA
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Fundamental Symmetries - 4

Vincenzo Cirigliano
Los Alamos National Laboratory

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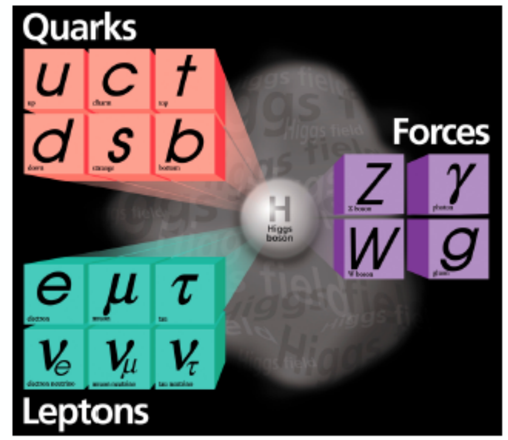
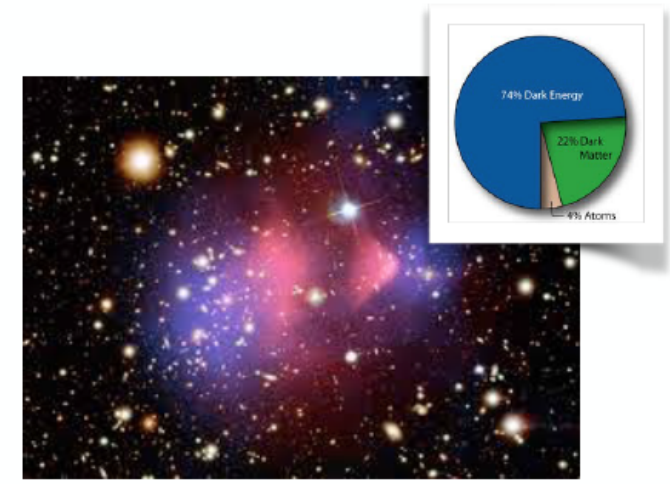
Plan of the lectures

- Review symmetry and symmetry breaking
- Introduce the Standard Model and its symmetries
- Beyond the SM:
  - hints from current discrepancies?
  - effective theory perspective
- Discuss a number of "worked examples"
  - Precision measurements: charged current (beta decays); neutral current (Parity Violating Electron Scattering).
  - Symmetry tests: CP (T) violation and EDMs; Lepton Number violation and neutrino-less double beta decay.

Beyond the SM

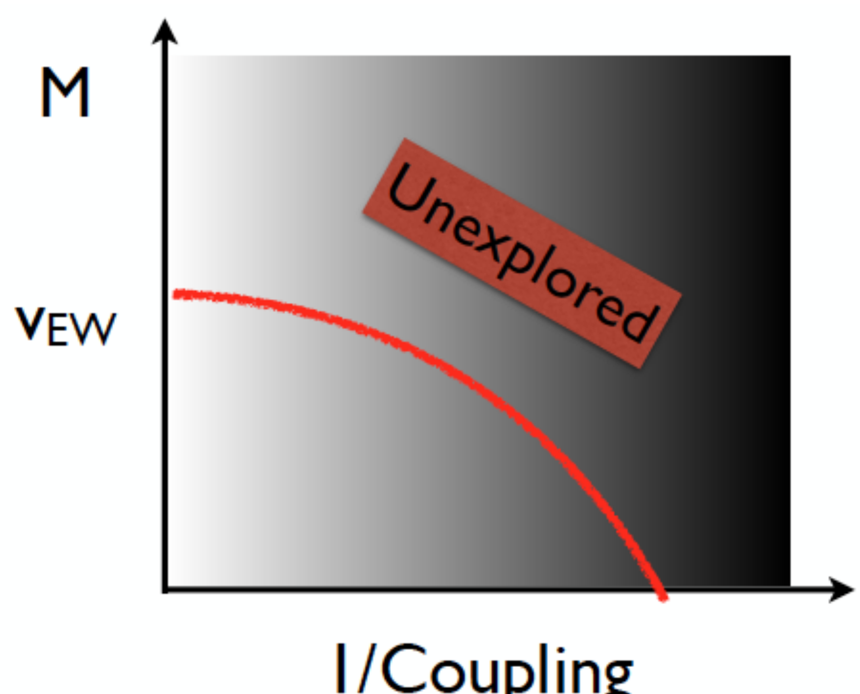
- Big open questions and experimental anomalies point to the need for new physics.





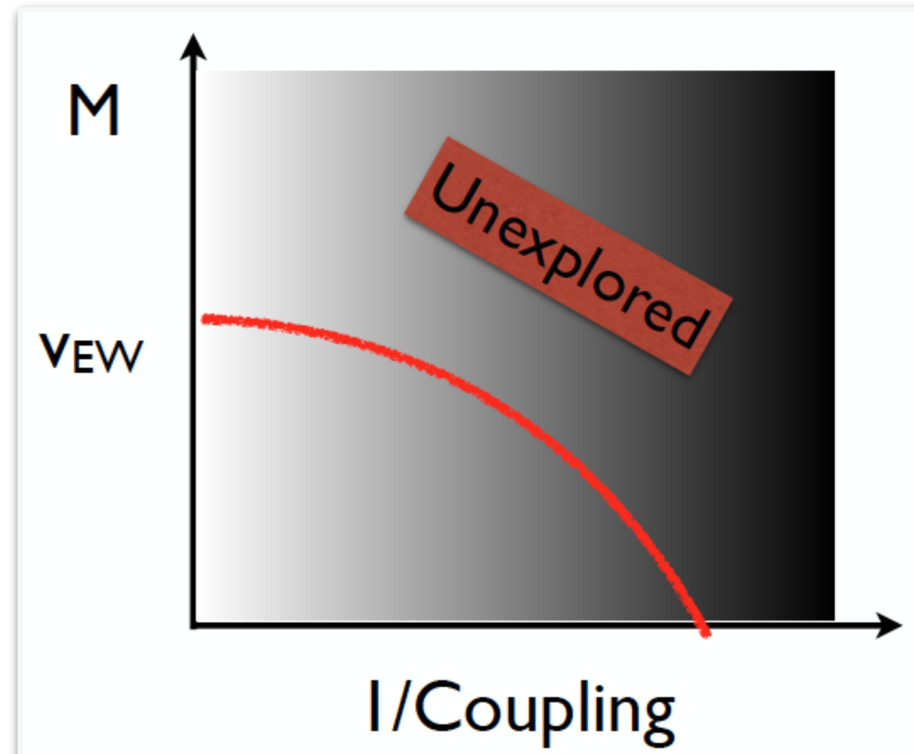
No Matter, no Dark Matter, no Dark Energy

- Search broadly at the energy and intensity / precision frontier



Models of new physics

- Extended gauge group: ($SU(2)_L \times SU(2)_R \times U(1)$, …), Grand Unified group ($SU(5)$, $SO(10)$, …)
- Extended particle content (2HDM, …)
- New symmetry: Supersymmetry
- Composite models (QCD-like EWSB)
- Dark sectors
- Combinations of the above
- …



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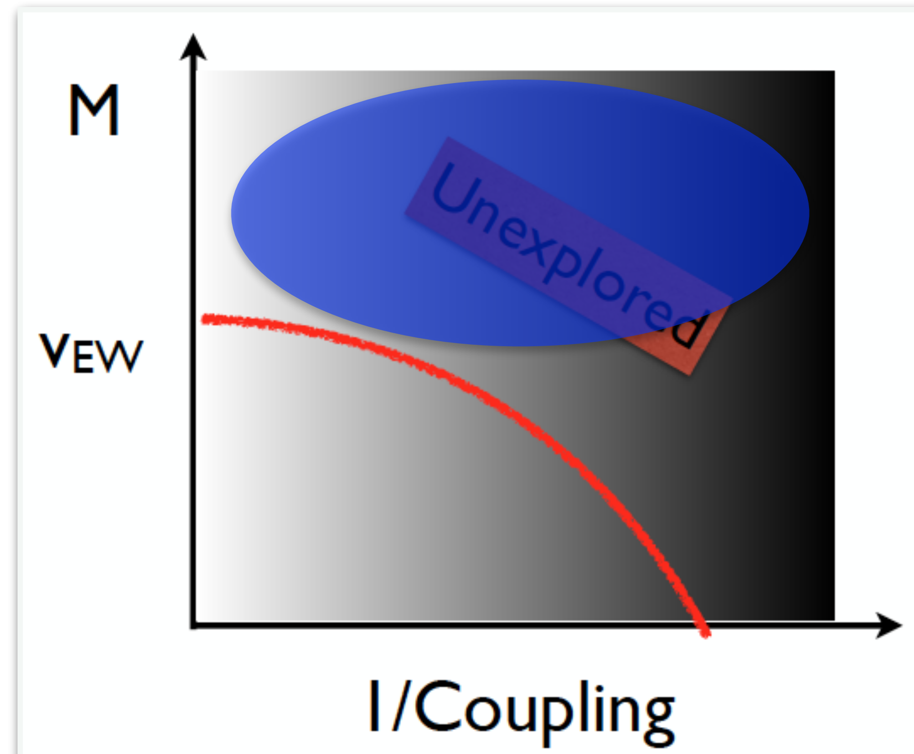
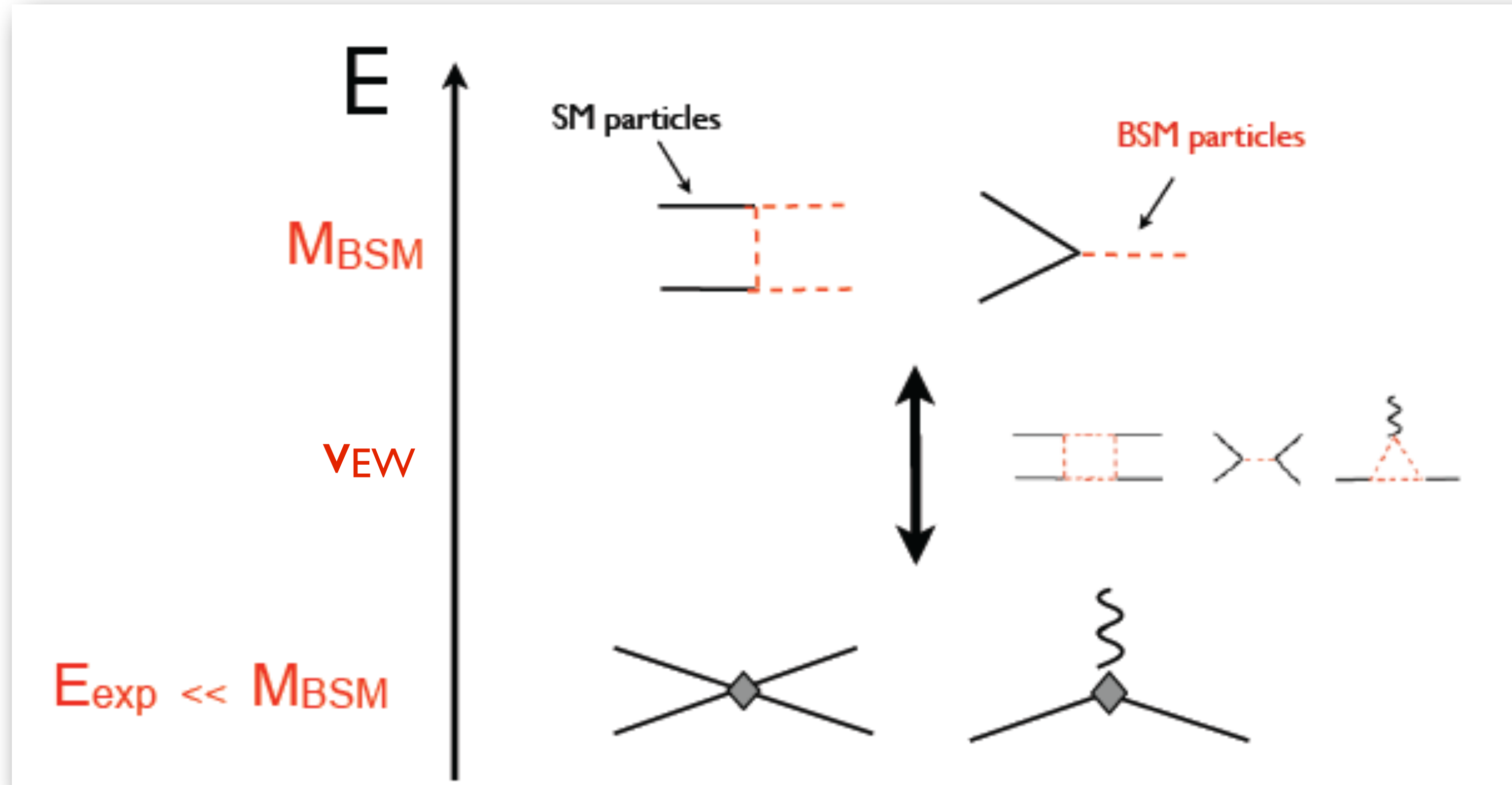


In the following, I will assume that new physics originates above the electroweak scale and discuss its low-energy footprints in the framework of effective field theory

The low-energy footprints of $\mathcal{L}_{BSM}$

- At energy $E_{exp} << M_{BSM}$, new particles can be "integrated out"
- Generate new local operators with coefficients ~ $g^k/(M_{BSM})^n$



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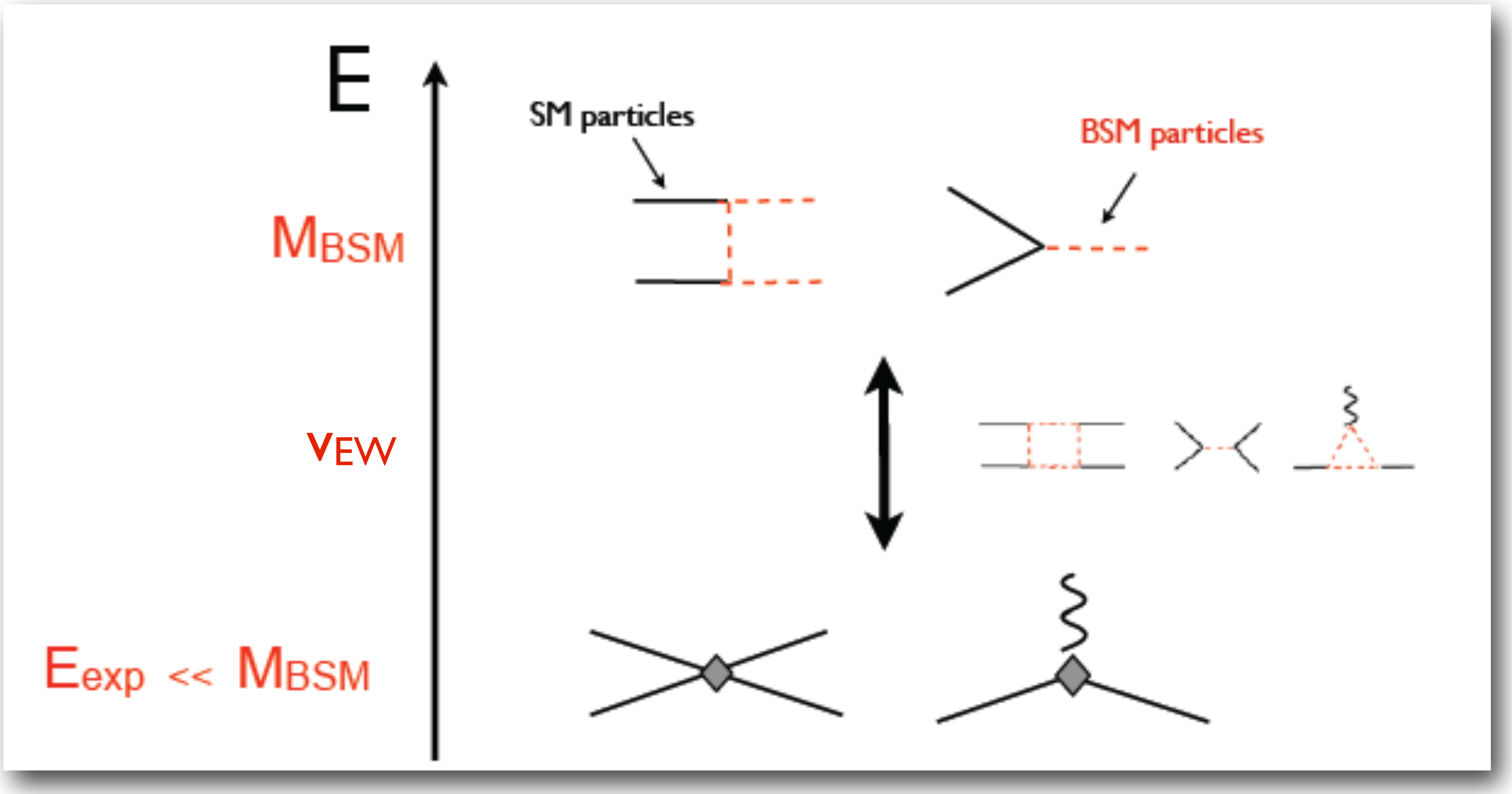
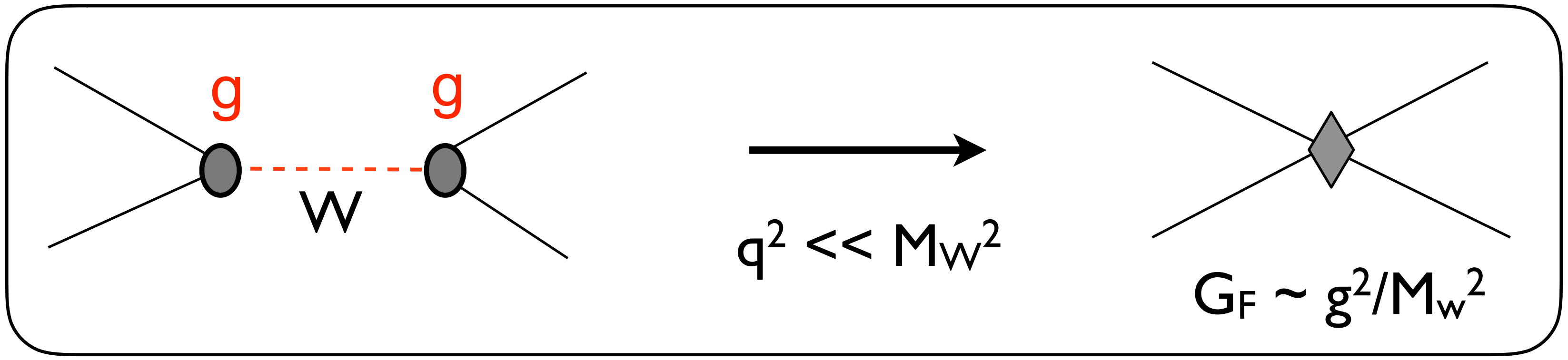


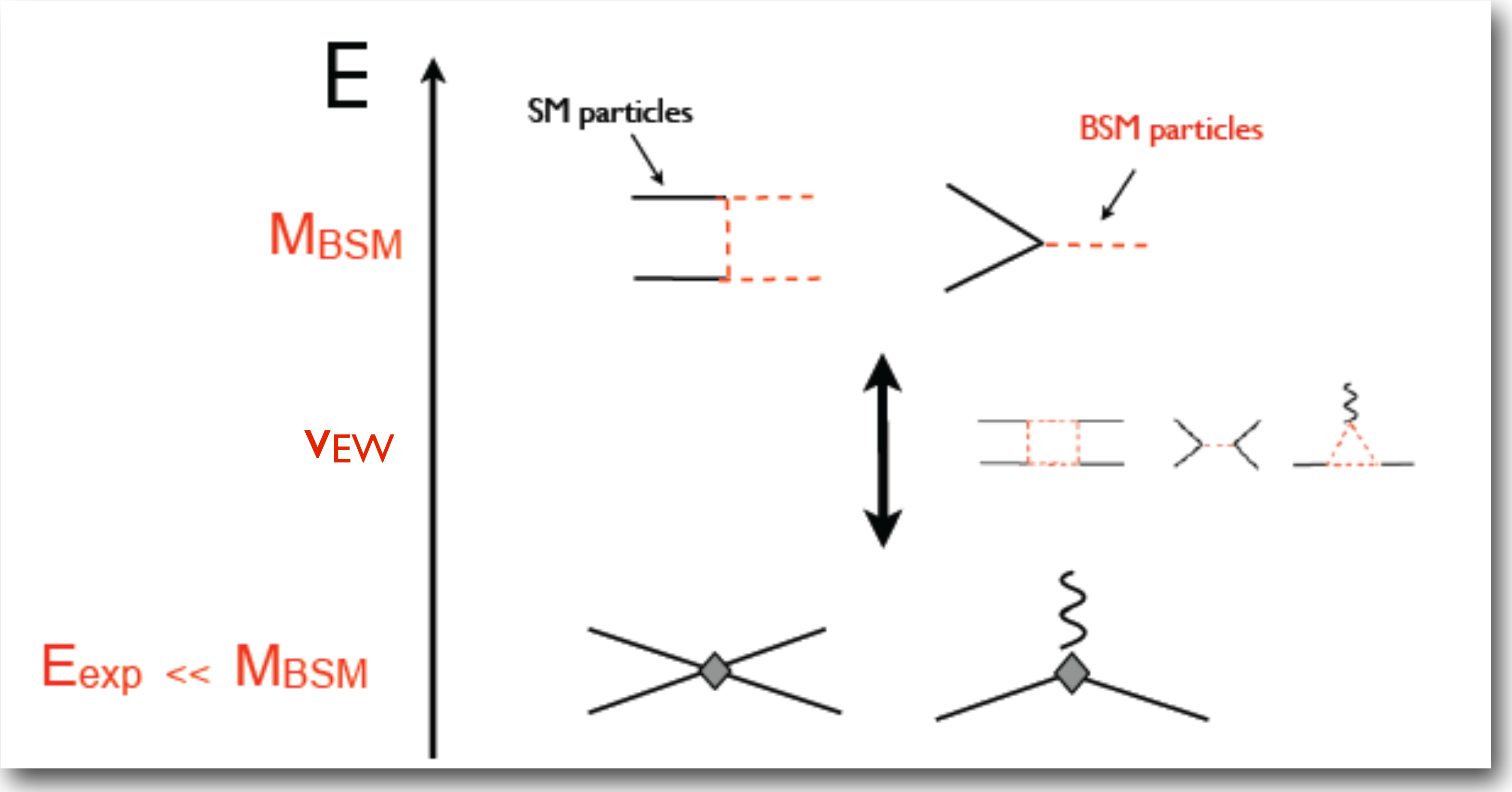
Familiar example:



Effective Field Theory emerges as a natural framework to analyze low-E implications of classes of BSM scenarios *and* inform model building

EFT framework for BSM physics

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



- EFT expansion in E/M_{BSM}, M_W/M_{BSM} [$O_i^{(d)}$ built out of SM fields]

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

$C_i \; [g_{\rm BSM}, \; M_a/M_b]$ $[\Lambda \leftrightarrow M_{BSM}]$

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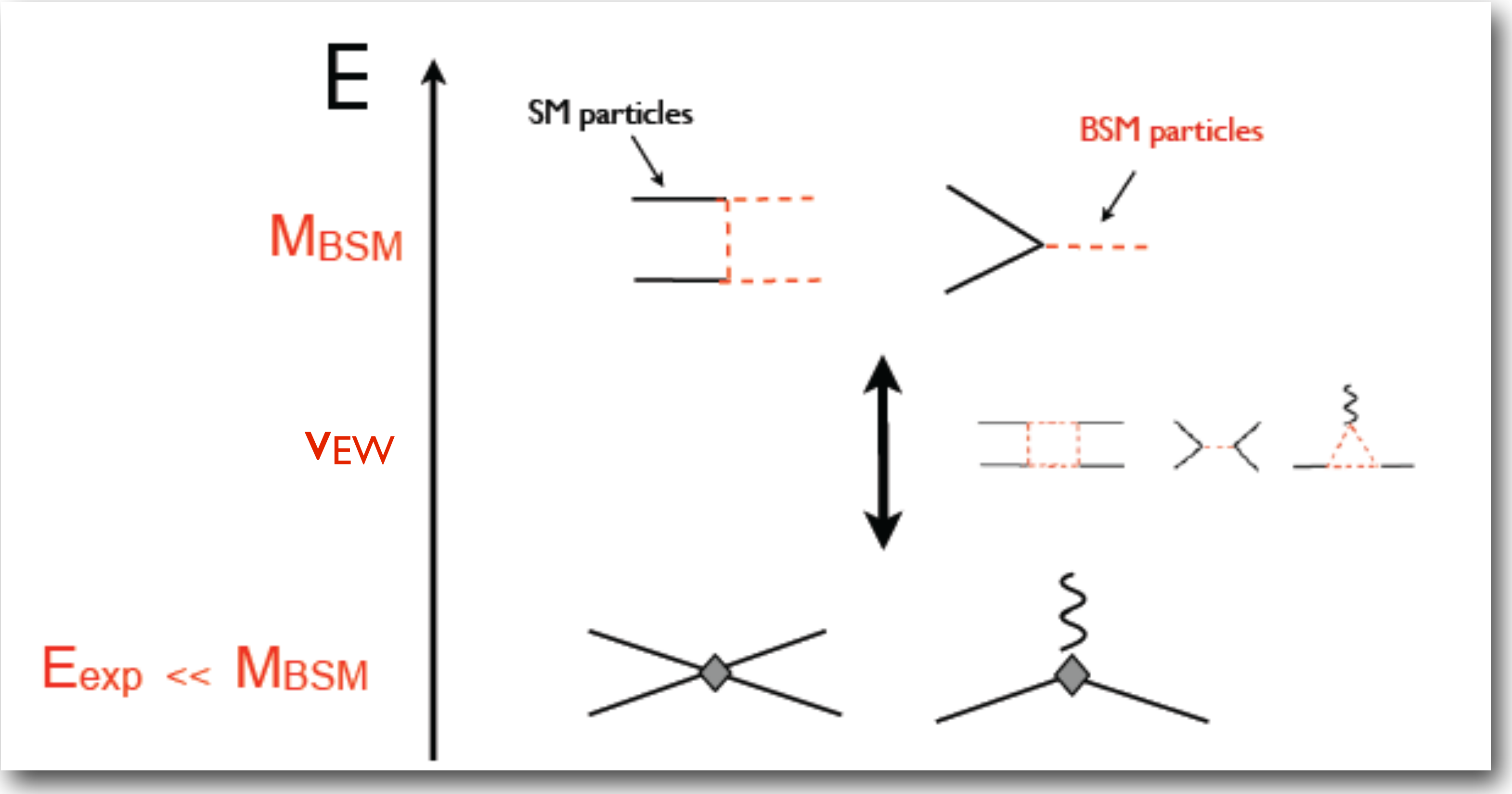
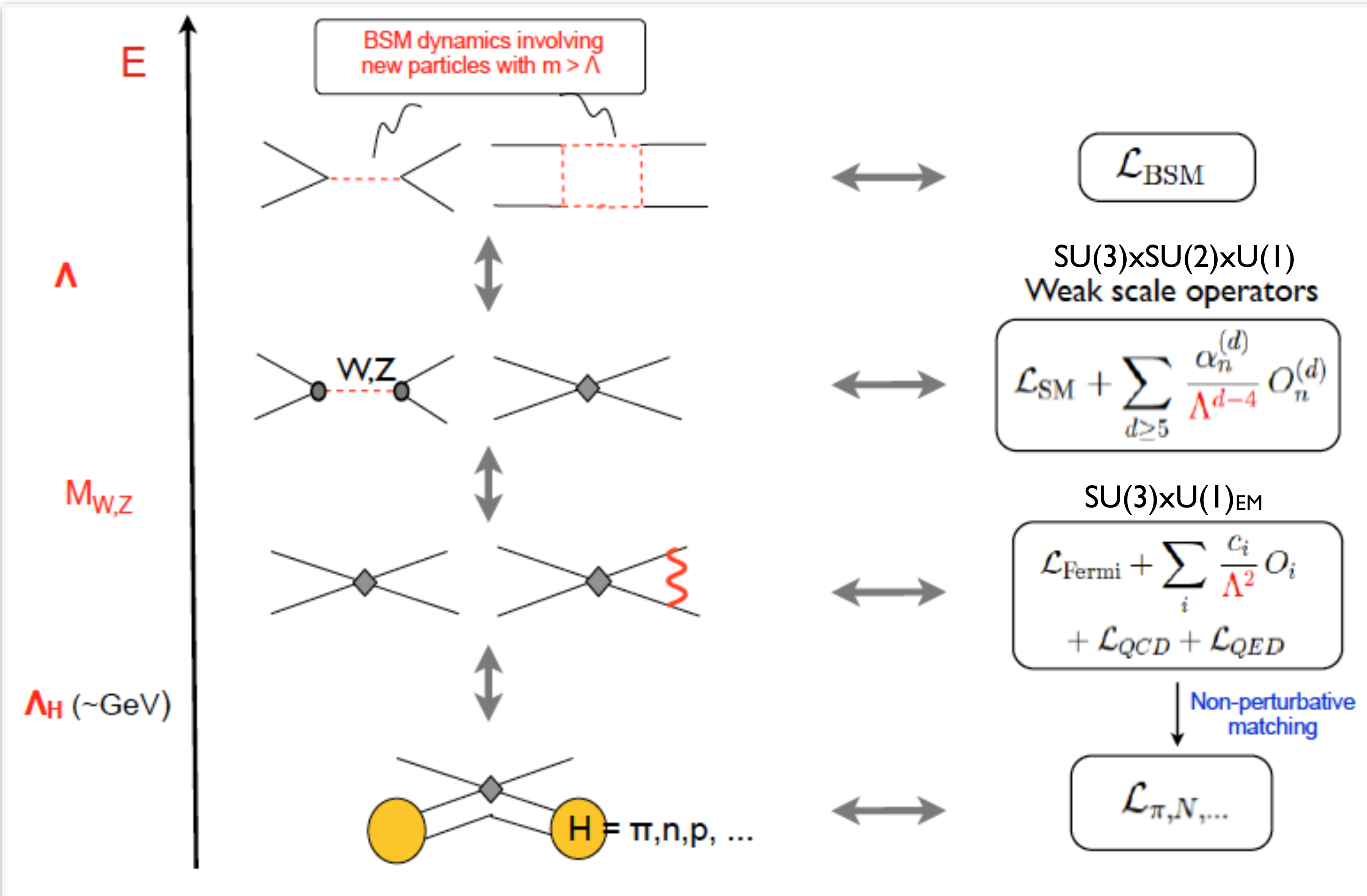


- EFT expansion in E/M_{BSM}, M_W/M_{BSM} [$O_i^{(d)}$ built out of SM fields]

- Classwork: work out canonical mass dimension of fields
  - Spinor: $[\Psi]=3/2$,
  - Scalar and vector: $[\varphi] = [V_\mu] = 1$

Connecting scales

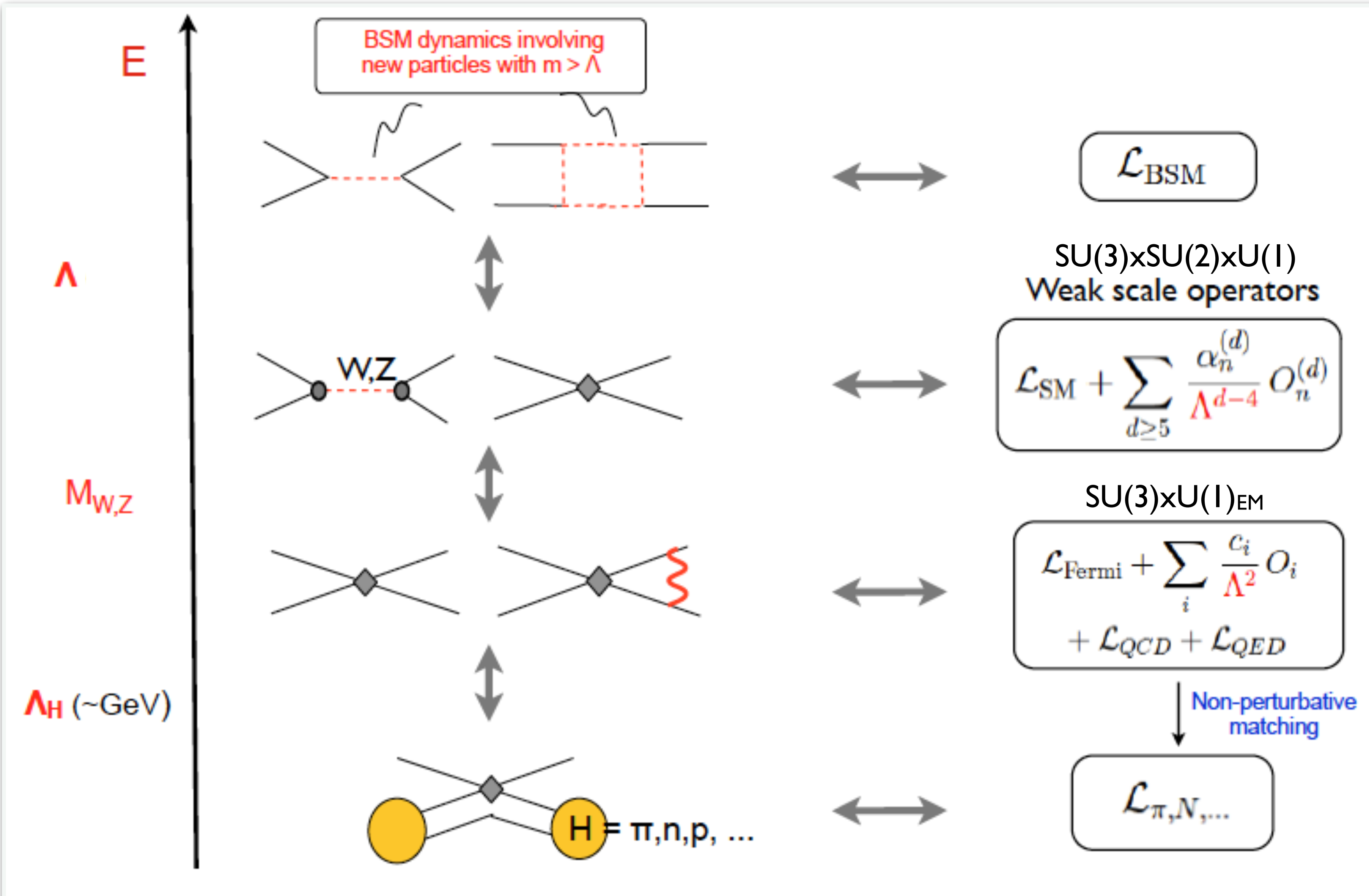
- To interpret (positive or null) searches in terms of new physics at $\Lambda > v_{ew}$ need several steps



Chiral EFT
Lattice QCD

Connecting scales

- To interpret (positive or null) searches in terms of new physics at $\Lambda > v_{ew}$ need several steps



LHC phenomenology

Chiral EFT
Lattice QCD

- If $\Lambda >$ few TeV, can use EW-scale L_{eff} for LHC: connection of low-E and collider phenomenology

Guided tour of $\mathcal{L}_{eff}$

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

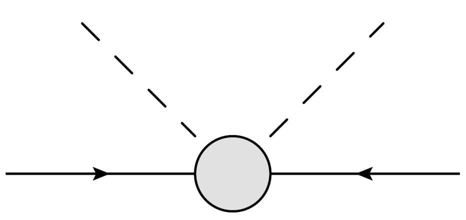
- Dim 5: only one operator

Weinberg 1979

$$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \quad \ell = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

$$\hat{O}_{\rm dim=5} = \ell^T C \epsilon \varphi \; \varphi^T \epsilon \ell$$

$$C = i\gamma_2\gamma_0$$
$$\epsilon = i\sigma_2$$



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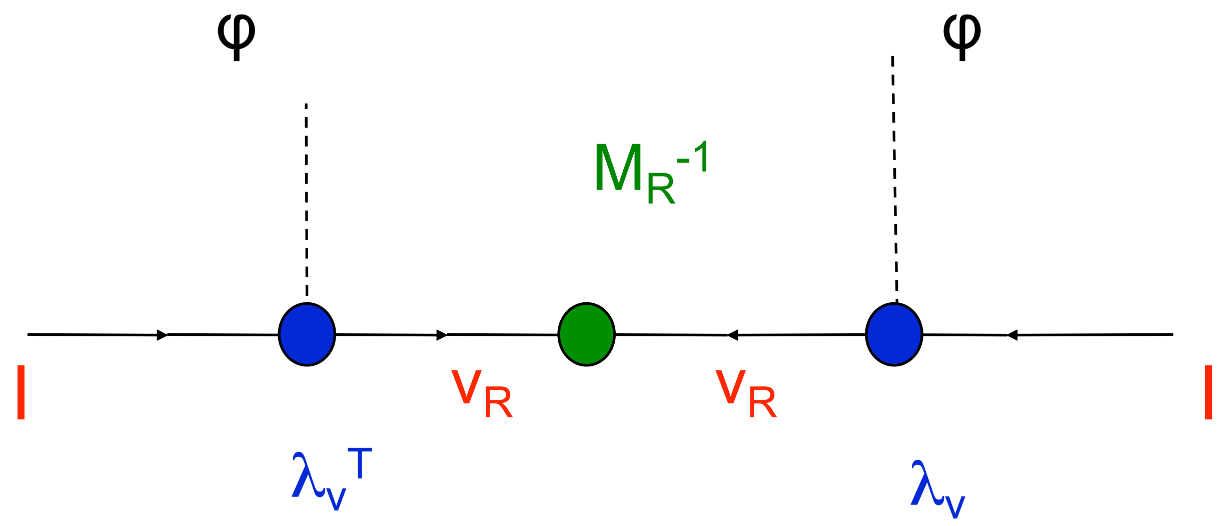
- Violates total lepton number $\ell \to e^{i\alpha}\ell \qquad e \to e^{i\alpha} e$
- Generates Majorana mass for L-handed neutrinos (after EWSB)

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

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

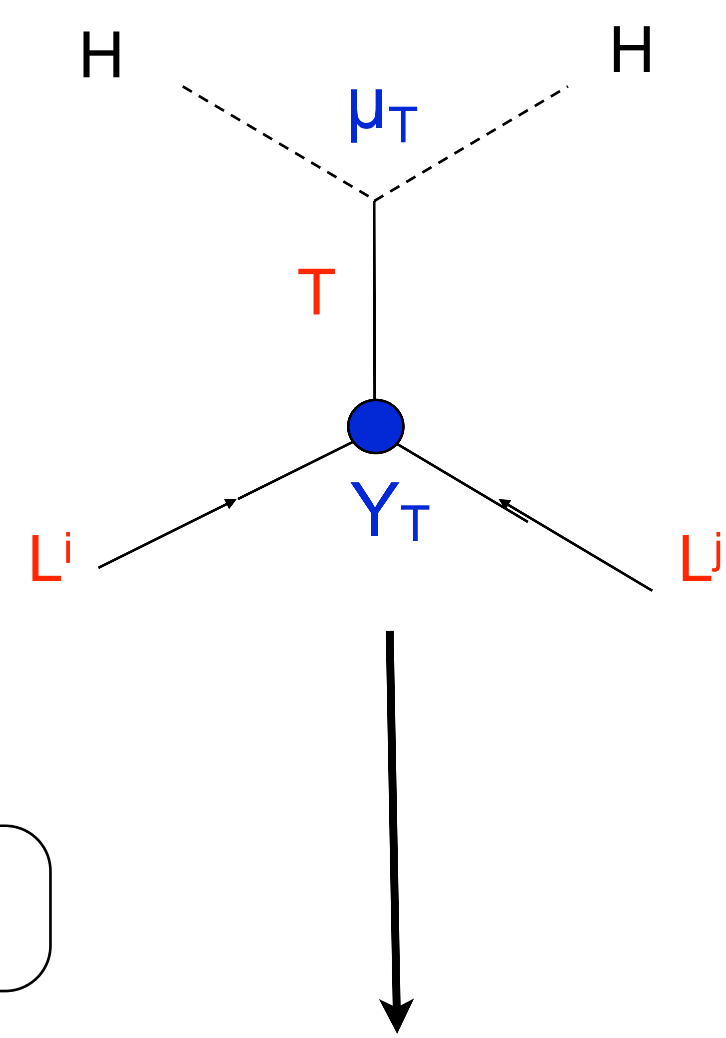
- Explicit realization of dimension-5 operator in models with heavy R-handed Majorana neutrinos



$g \sim \lambda_\nu^T M_R^{-1} \lambda_\nu$

$$\mathcal{L}_5 = g_{\alpha\beta}\, \ell_\alpha^T C \epsilon \varphi\, \varphi^T \epsilon \ell_\beta$$

- Or with triplet Higgs field:



$g \sim \mu_T M_T^{-2} Y_T$

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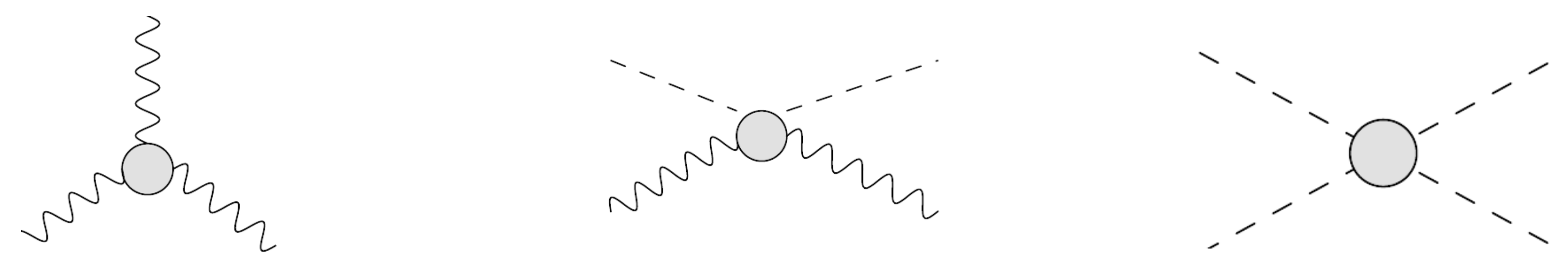
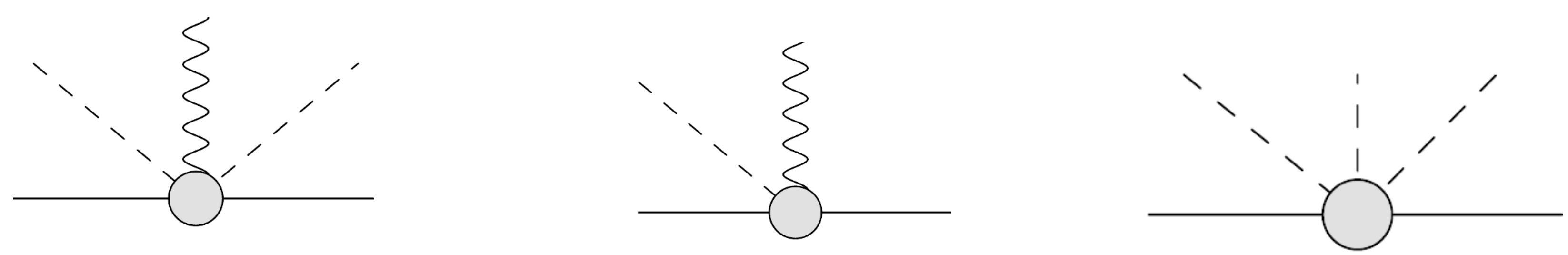
- Dim 6: affect *many* processes (59 structures not including flavor)

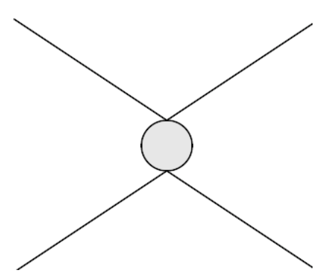
No fermions



Two fermions



Four fermions



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

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

- EFT used beyond tree-level: one-loop anomalous dimensions known

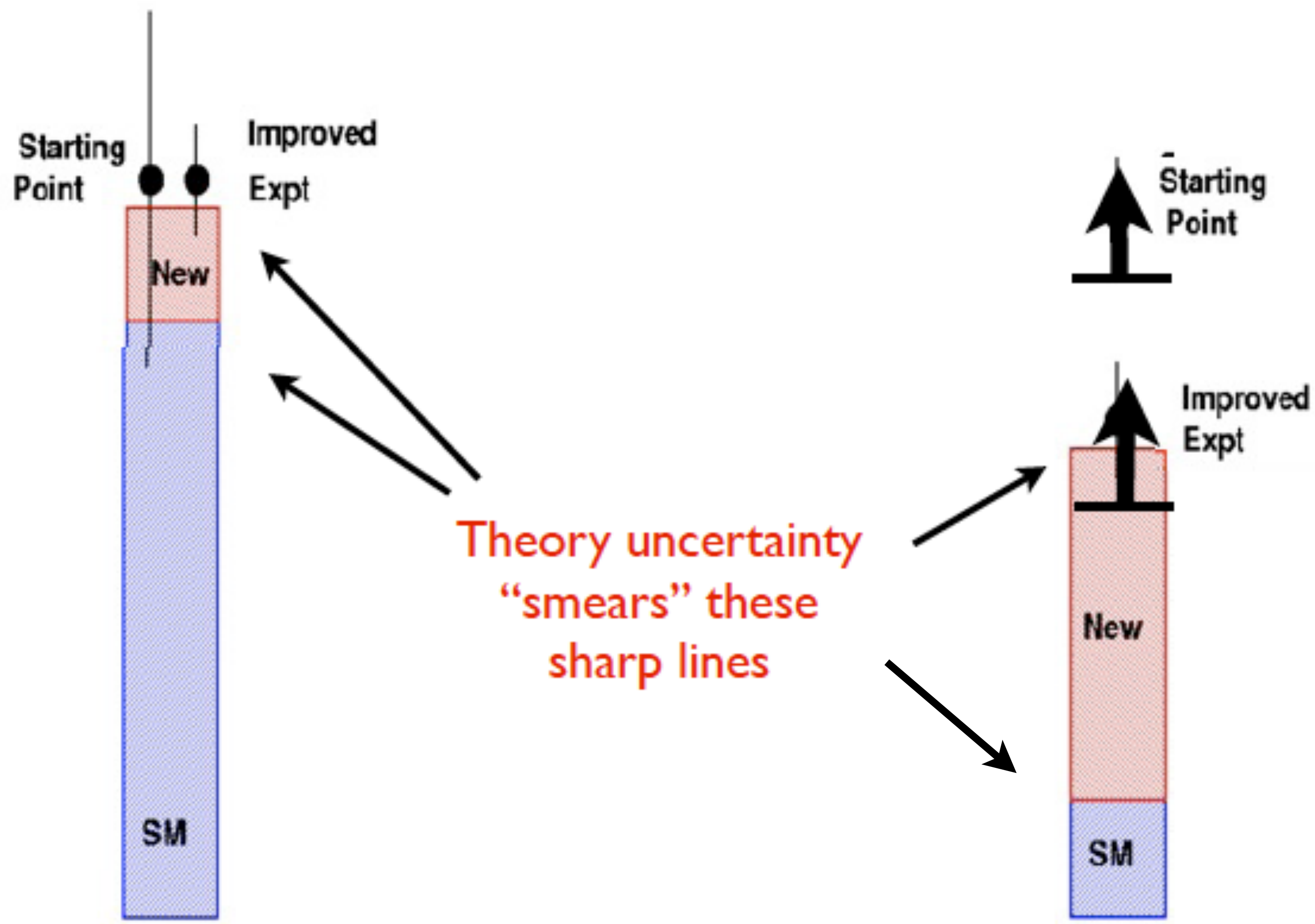
Alonso, Jenkins, Manohar, Trott 2013

Two classes of probes

- 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 (β-decays, muon g-2, Q_W, ...)

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



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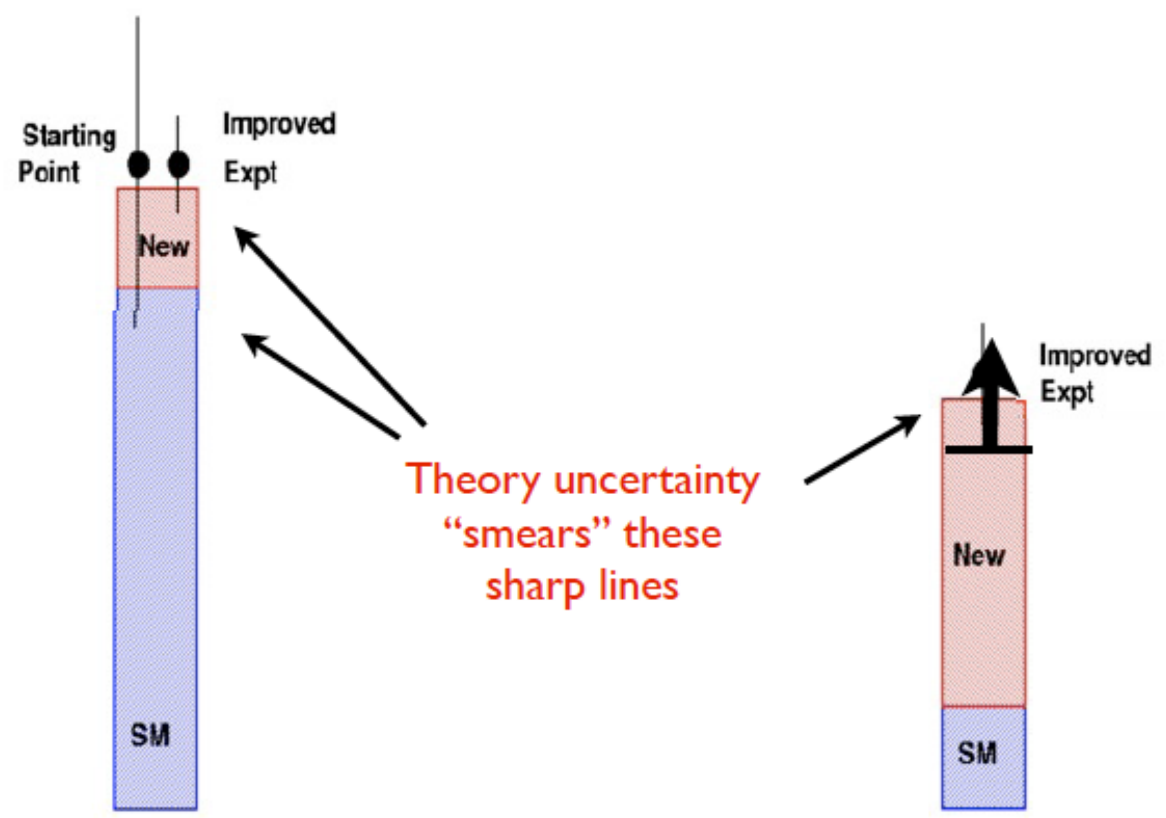
- Comment #2: each UV model generates its own pattern of operators / couplings → different signatures in LE experiments

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

Physics reach at a glance

This equation at work

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



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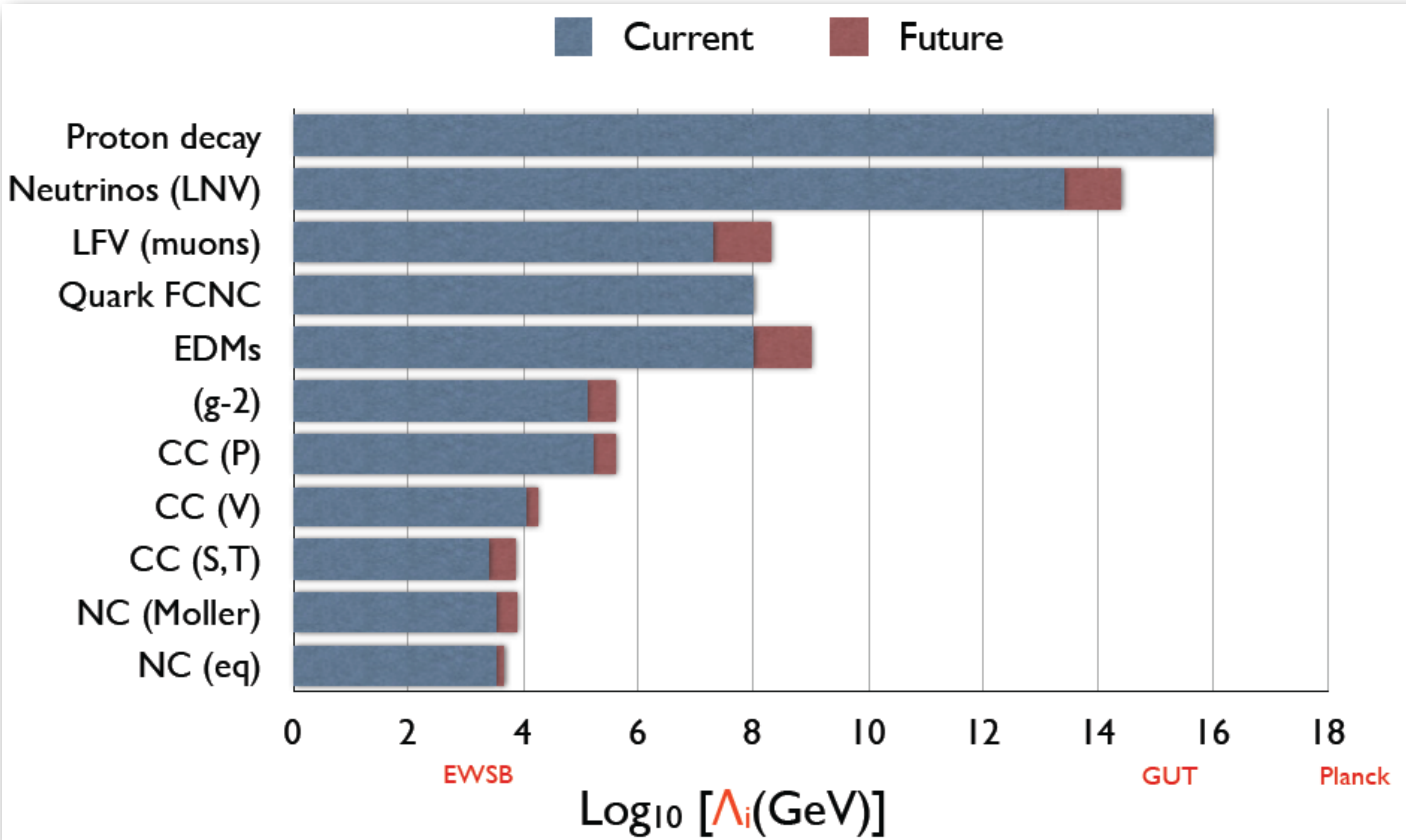

- Caveat: horizontal axis is $\Lambda/C^{(5)}, \ \Lambda/[C_i^{(6)}]^{1/2}$, ...
- So beware of couplings, loop factors, approximate symmetries , etc

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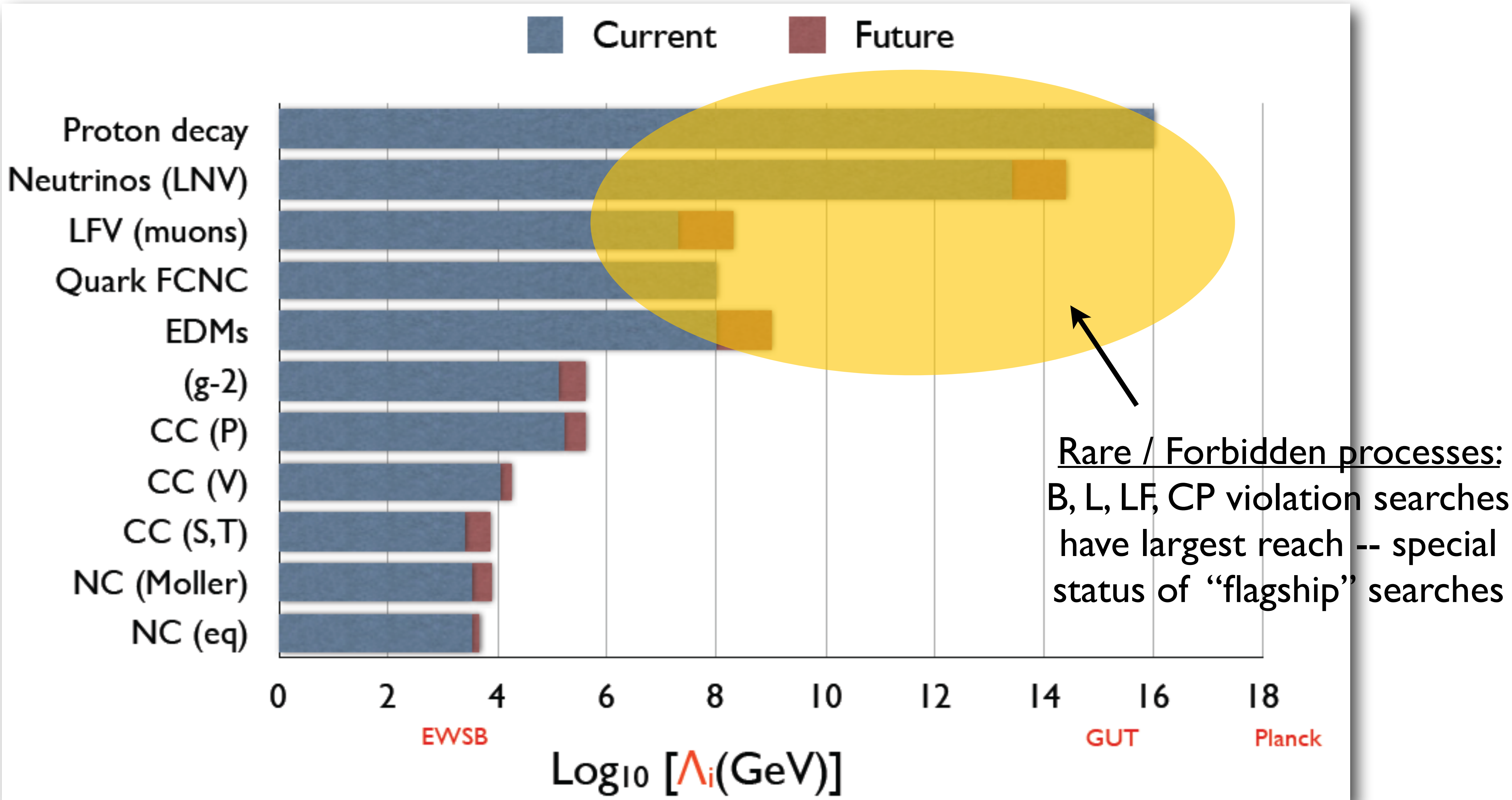

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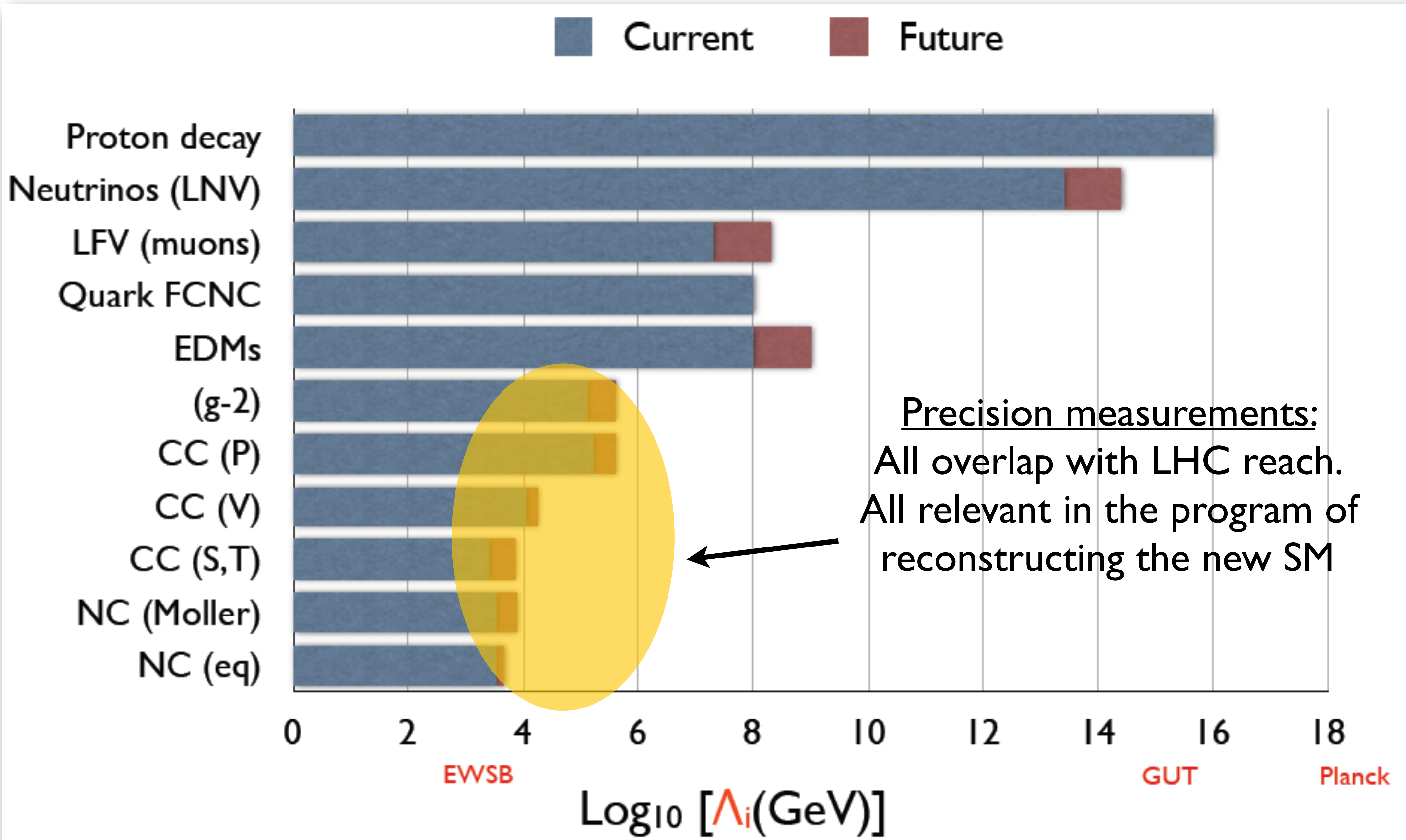

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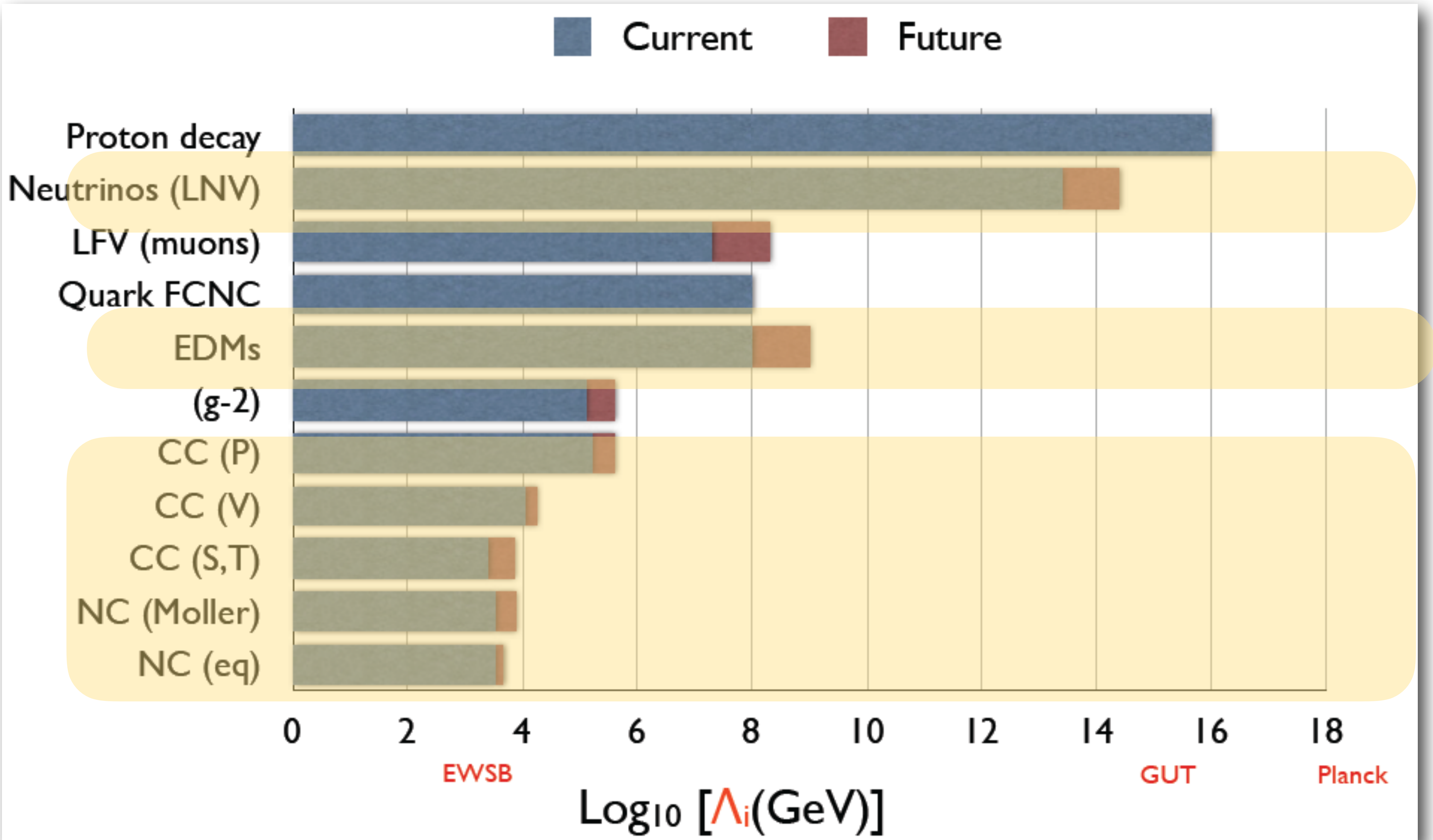
Next steps

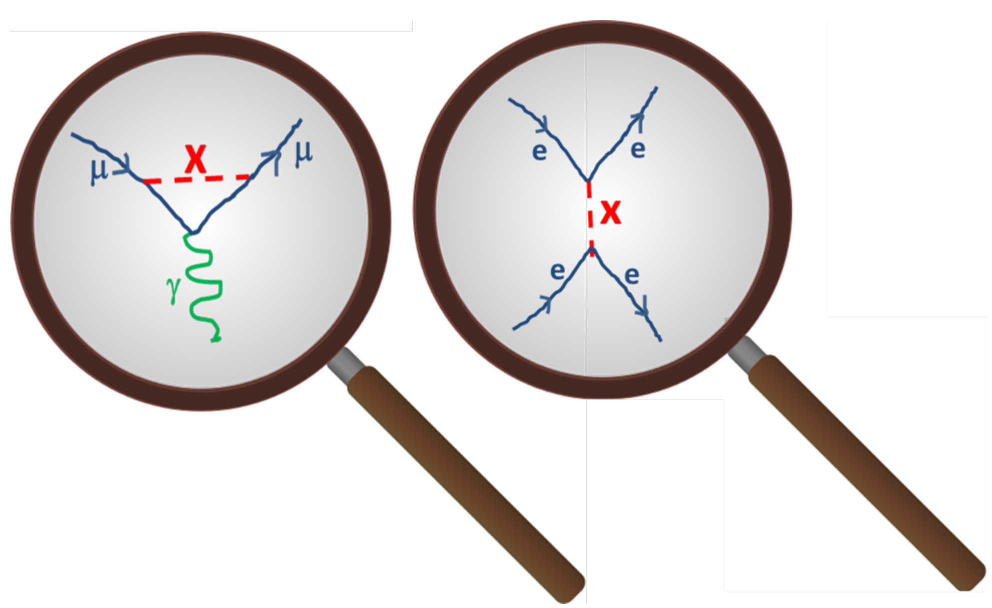


Current
Future
Proton decay
Neutrinos (LNV)
LFV (muons)
Quark FCNC
EDMs
(g-2)
CC (P)
CC (V)
CC (S,T)
NC (Moller)
NC (eq)
0
2
4
6
8
10
12
14
16
18
EWSB
GUT
Planck
Log10 [Λi(GeV)]

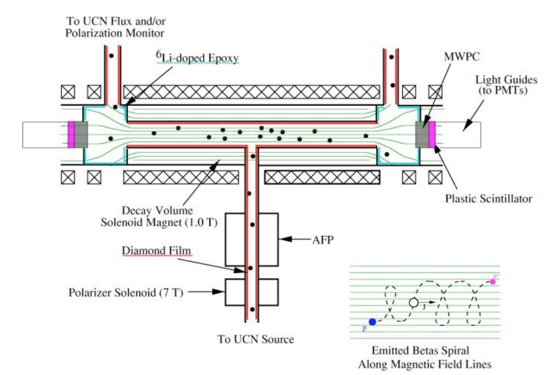
Plan of the lectures

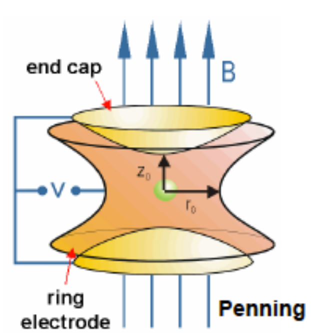
- Review symmetry and symmetry breaking
- Introduce the Standard Model and its symmetries
- Beyond the SM:
    - hints from current discrepancies?
    - effective theory perspective
- Discuss a number of "worked examples"
    - Precision measurements: charged current (beta decays); neutral current (Parity Violating Electron Scattering).
    - Symmetry tests: CP (T) violation and EDMs;
      Lepton Number violation and neutrino-less double beta decay.

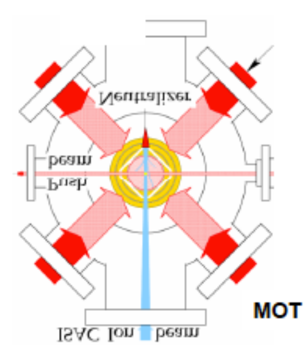
Precision measurements as probes of new physics

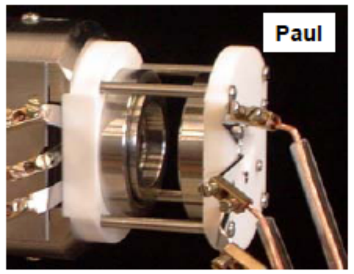


Charged Current



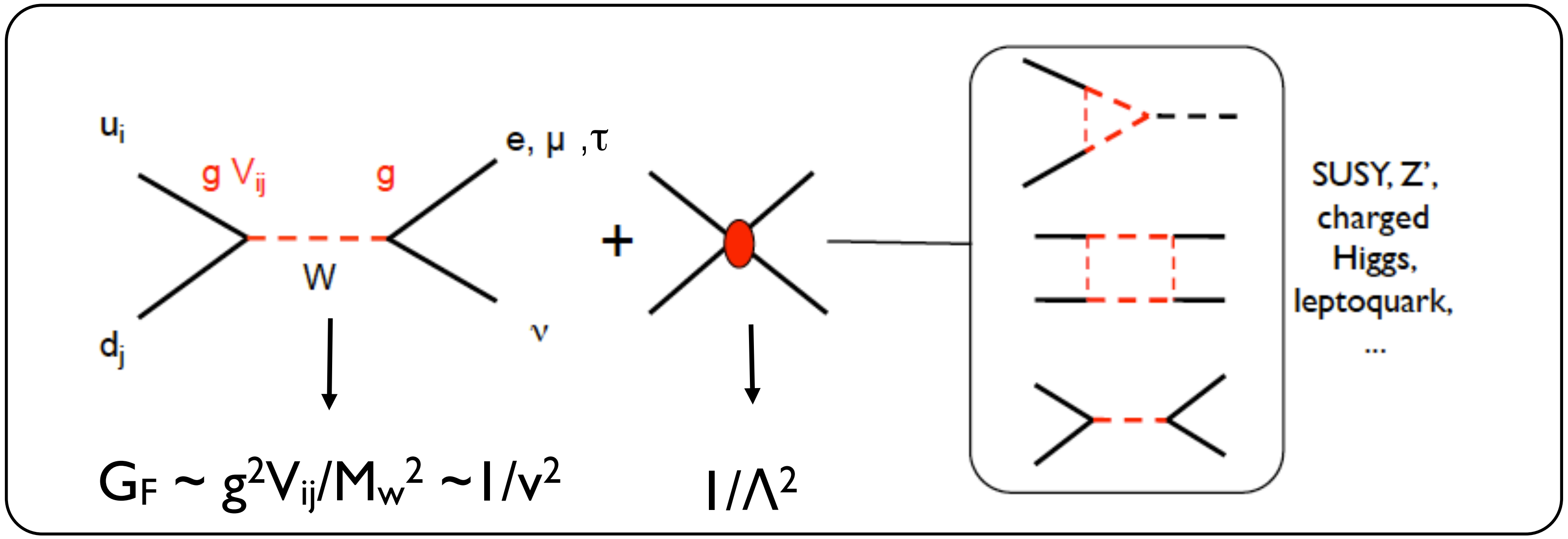






β-decays and BSM physics

- In the SM, W exchange ⇒ V-A currents, universality



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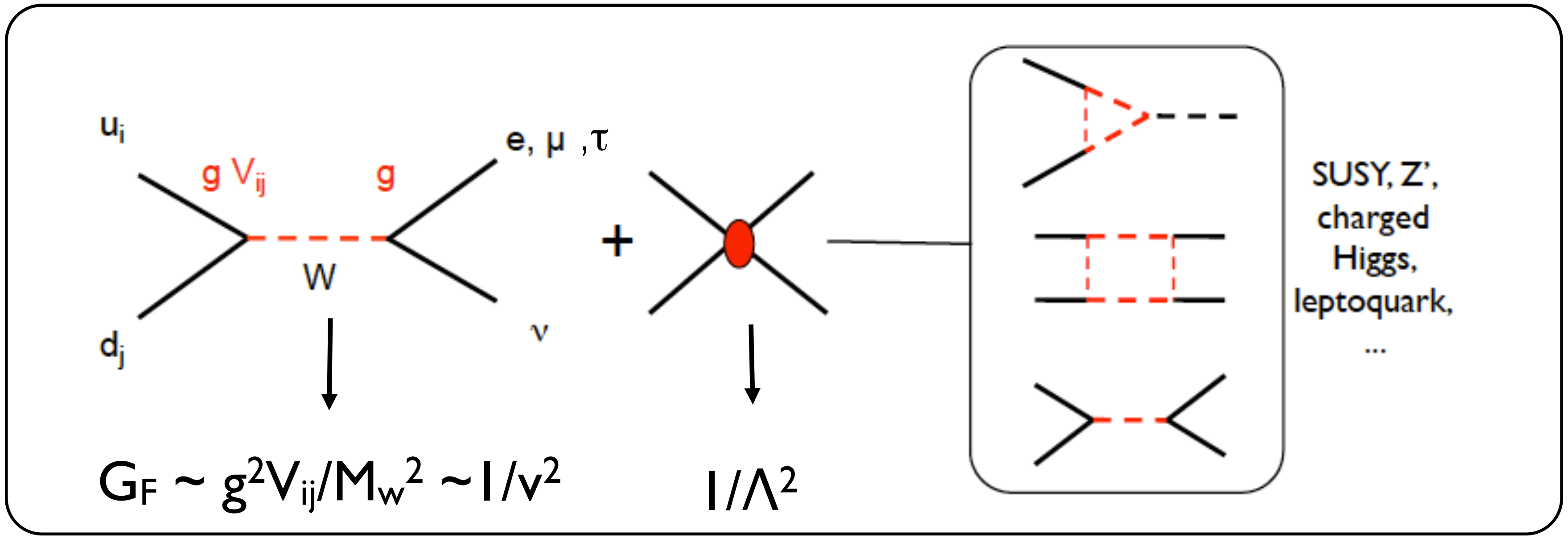

SUSY analyses:

Bauman, Erler, Ramsey-Musolf, arXiv:1204.0035,
...
Hagiwara et al1995
...
Barbieri et al 1985
...

- Sensitivity to broad variety of BSM scenarios

- Experimental and theoretical precision at or approaching 0.1% level
  Probe effective scale Λ in the 5-10 TeV range

Effective Lagrangian at E~GeV

- New physics effects are encoded in ten quark-level couplings

$$
\begin{aligned}
\mathcal{L}_{\rm CC} &= -\frac{G_F^{(0)} V_{u_i d_j}}{\sqrt{2}} \\
&\times \Big[(1 + \delta_{RC} + \epsilon_L) \;\; \bar{\ell}\gamma_\mu (1-\gamma_5)\nu_\ell \cdot \bar{u}_i \gamma^\mu (1-\gamma_5) d_j \\
&+ \epsilon_R \;\; \bar{\ell}\gamma_\mu (1-\gamma_5)\nu_\ell \cdot \bar{u}_i \gamma^\mu (1+\gamma_5) d_j \\
&+ \epsilon_S \;\; \bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u}_i d_j \\
&- \epsilon_P \;\; \bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u}_i \gamma_5 d_j \\
&+ \epsilon_T \;\; \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}_i \sigma^{\mu\nu}(1-\gamma_5) d_j \Big] + \text{h.c.}
\end{aligned}
$$

$\epsilon_i \;, \tilde{\epsilon}_i \sim (M_W/\Lambda)^2$

← Linear sensitivity to ϵ_i (interference with SM)

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$$
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\times & \Big[(1+\delta_{RC}+\epsilon_L)\ \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}_i\gamma^\mu(1-\gamma_5)d_j \\
+ & \ \epsilon_R\ \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}_i\gamma^\mu(1+\gamma_5)d_j \\
+ & \ \epsilon_S\ \bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u}_i d_j \\
- & \ \epsilon_P\ \bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u}_i\gamma_5 d_j \\
+ & \ \epsilon_T\ \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}_i\sigma^{\mu\nu}(1-\gamma_5)d_j \Big] + \text{h.c.}
\end{aligned}
$$

$$\epsilon_i\ ,\tilde{\epsilon}_i \sim (M_W/\Lambda)^2$$

← Linear sensitivity to ε_i (interference with SM)

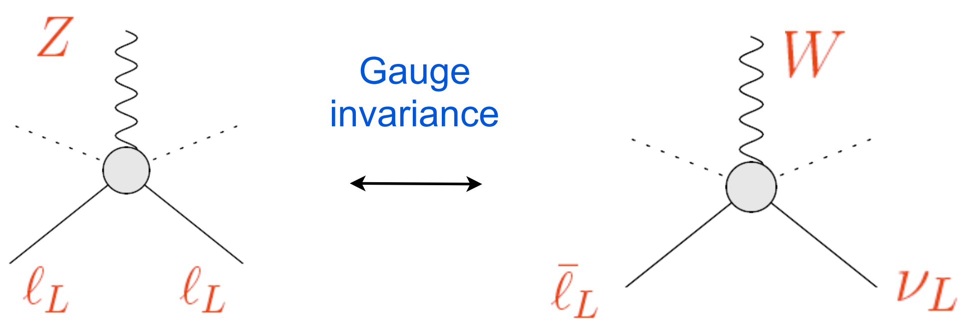
$$+ \quad \epsilon_i \longrightarrow \tilde{\epsilon}_i \qquad (1-\gamma_5)\nu_\ell \longrightarrow (1+\gamma_5)\nu_\ell$$

← Quadratic sensitivity to $\tilde{\varepsilon}_i$ (interference suppressed by m_ν/E)

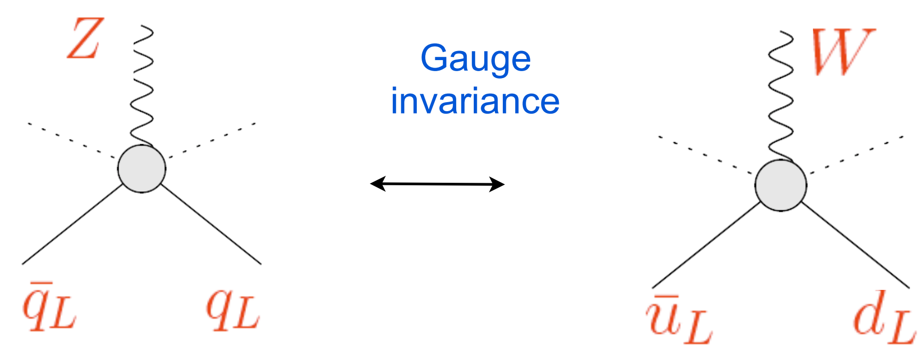
Relation to weak-scale operators

- ε_L : vertex corrections and 4-fermion contacts

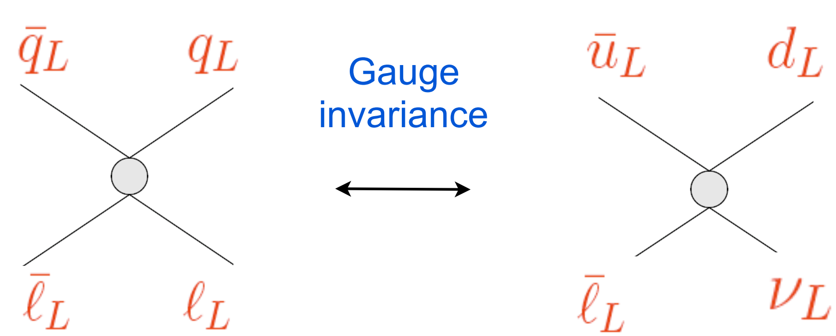
$$O_{\varphi l}^{(3)} = i(\varphi^\dagger D^\mu \sigma^a \varphi))(\bar{l}\gamma_\mu \sigma^a l)$$



$$O_{\varphi q}^{(3)} = i(\varphi^\dagger D^\mu \sigma^a \varphi)(\bar{q}\gamma_\mu \sigma^a q)$$



$$O_{lq}^{(3)} = (\bar{l}\gamma^\mu \sigma^a l)(\bar{q}\gamma_\mu \sigma^a q)$$



$$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$

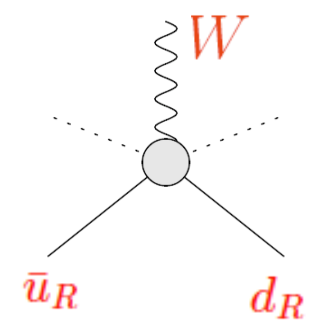
$$q^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}$$

$$l^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}$$

Relation to weak-scale operators

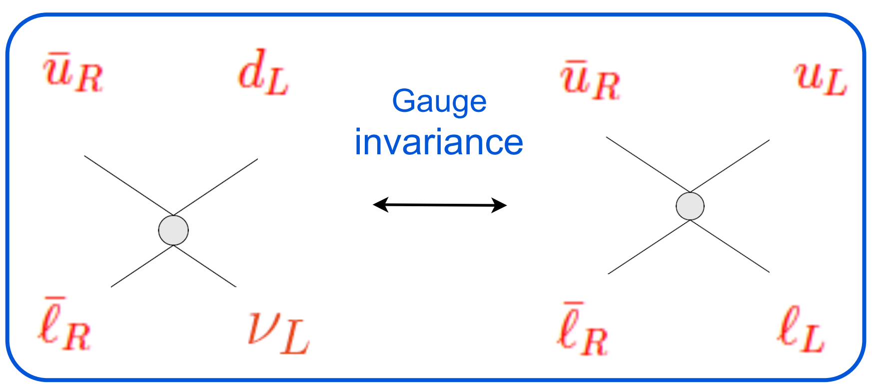
- ε_R ⇔ weak-scale R-handed quark coupling

$$O_{\varphi\varphi} \;=\; i(\varphi^T \epsilon D_\mu \varphi)(\overline{u}\gamma^\mu d)$$



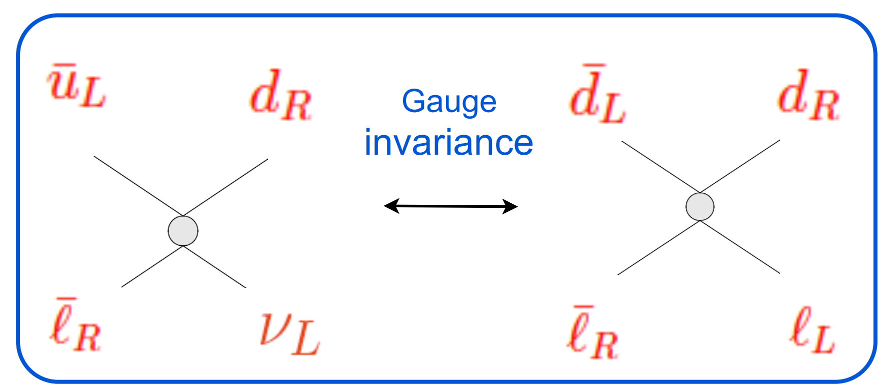
- $\varepsilon_{S,P}$ ⇔ 2 independent scalar structures

$$O_{lq} \;=\; (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.}$$



$\varepsilon_S+\varepsilon_P$

$$O_{qde} \;=\; (\bar{\ell}e)(\bar{d}q) + \text{h.c.}$$



$\varepsilon_S-\varepsilon_P$

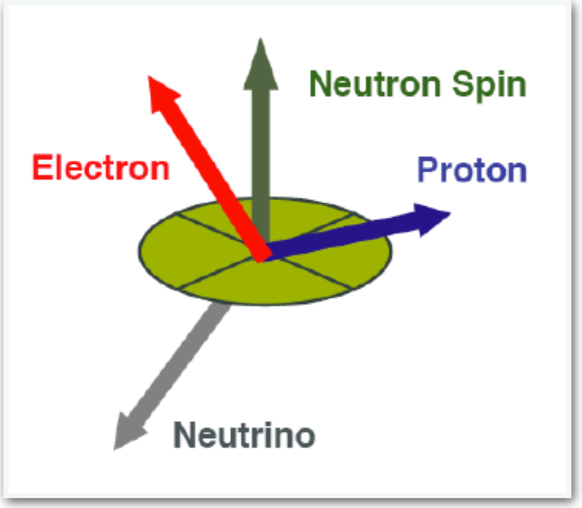
- ε_T ⇔ weak-scale tensor structure $\quad O^t_{lq} \;=\; (\bar{l}_a\sigma^{\mu\nu}e)\epsilon^{ab}(\bar{q}_b\sigma_{\mu\nu}u) + \text{h.c.}$

How do we probe the ε's?

- Differential decay distribution

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

Lee-Yang, 1956   Jackson-Treiman-Wyld 1957



$a(g_A, g_\alpha \varepsilon_\alpha)$, $A(g_A, g_\alpha \varepsilon_\alpha)$, $B(g_A, g_\alpha \varepsilon_\alpha)$,

...

isolated via suitable experimental asymmetries

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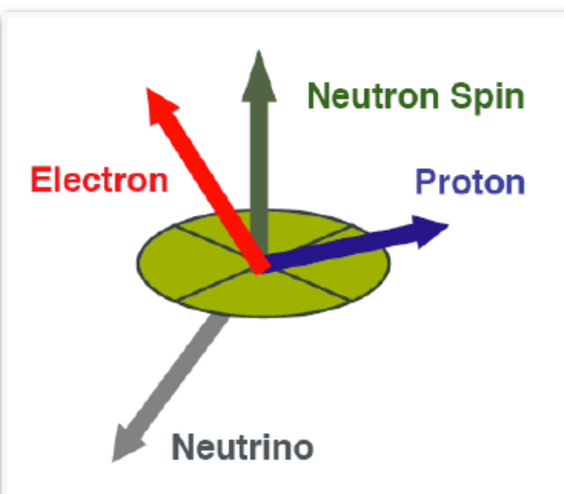
Lee-Yang, 1956 Jackson-Treiman-Wyld 1957



$a(g_A, g_\alpha \varepsilon_\alpha)$, $A(g_A, g_\alpha \varepsilon_\alpha)$, $B(g_A, g_\alpha \varepsilon_\alpha)$, …

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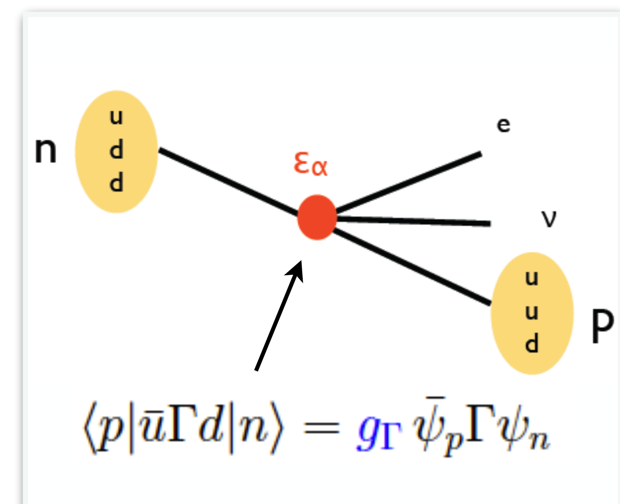
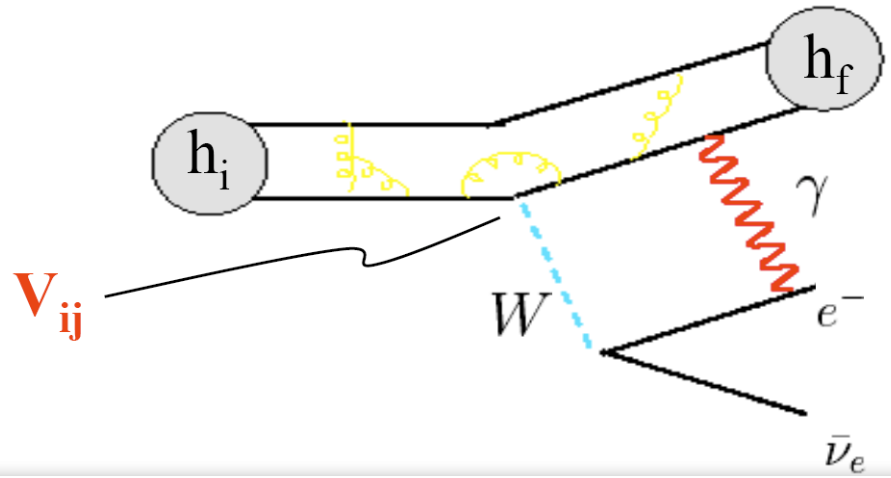


Theory input: $g_{V,A,S,T}$ (great progress in lattice QCD) + rad. corr.

Bhattacharya, et al 1606.07049

How do we probe the ε's?

- Decay rate



$$\Gamma_k = (G_F^{(\mu)})^2 \times |\bar{V}_{ij}|^2 \times |M_{\rm had}|^2 \times (1 + \delta_{RC}) \times F_{\rm kin}$$

Channel-dependent effective CKM element

Hadronic / nuclear matrix elements (ε_α) and radiative corrections

LQCD, χPT, dispersion relations, ...

Snapshot of the field

- This table summarizes a large number of measurements and th. input
- Already quite impressive. Effective scales in the range Λ= 1-10 TeV ($\Lambda_{SM} \approx$ 0.2 TeV)

$$\tilde{Y}(E_e) = \frac{Y(E_e)}{1 + b\, m_e/E_e + \ldots}$$

Non-standard coupling	Observable	Current sensitivity	Prospective sensitivity
$\mathrm{Re}(\epsilon_L + \epsilon_R)$	Δ_{CKM}	$\sim 0.05\%$	$< 0.05\%$ *
$\mathrm{Im}(\epsilon_R)$	D_n	$\sim 0.05\%$	
$\epsilon_P, \quad \tilde{\epsilon}_P$	$R_\pi = \frac{\Gamma(\pi\to e\nu)}{\Gamma(\pi\to\mu\nu)}$	$\sim 0.05\%$	
$\mathrm{Re}(\epsilon_S)$	$b, \ B, \ [\tilde{a}, \ \tilde{A}, \ \tilde{G}]$	$\sim 0.5\%$	$< 0.3\%$
$\mathrm{Im}(\epsilon_S)$	R_n	$\sim 10\%$	
$\mathrm{Re}(\epsilon_T)$	$b, \ B, \ [\tilde{a}, \ \tilde{A}, \ \tilde{G}], \quad \pi \to e\nu\gamma$	$\sim 0.1\%$	$< 0.03\%$
$\mathrm{Im}(\epsilon_T)$	$R_{^8Li}$	$\sim 0.2\%$	$\sim 0.05\%$
$\tilde{\epsilon}_{\alpha\neq P}$	a, b, B, A	$\sim 5 - 10\%$	

VC, S.Gardner, B.Holstein 1303.6953
Gonzalez-Alonso & Naviliat-Cuncic 1304.1759
Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

Snapshot of the field

- This table summarizes a large number of measurements and th. input
- Already quite impressive. Effective scales in the range Λ= 1-10 TeV ($\Lambda_{SM} \approx$ 0.2 TeV)
- Focus on probes that depend on the ε's *linearly*

$$\tilde{Y}(E_e) = \frac{Y(E_e)}{1 + b\, m_e/E_e + \ldots}$$

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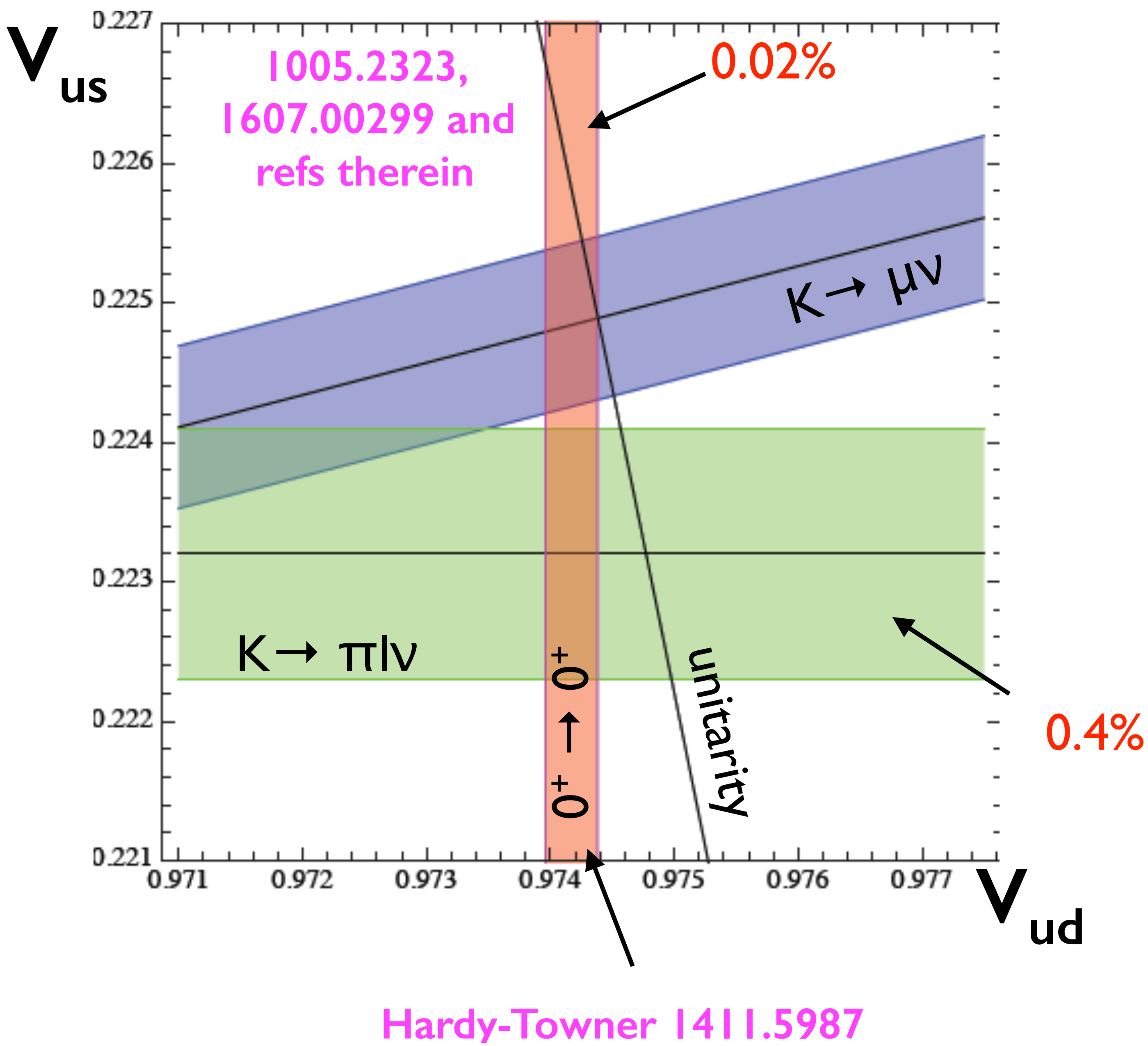
CKM unitarity test

$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + \cancel{|\bar{V}_{ub}|^2} = 1 + \Delta_{\mathrm{CKM}}(\epsilon_i)$$



V_{us} from K→ μν

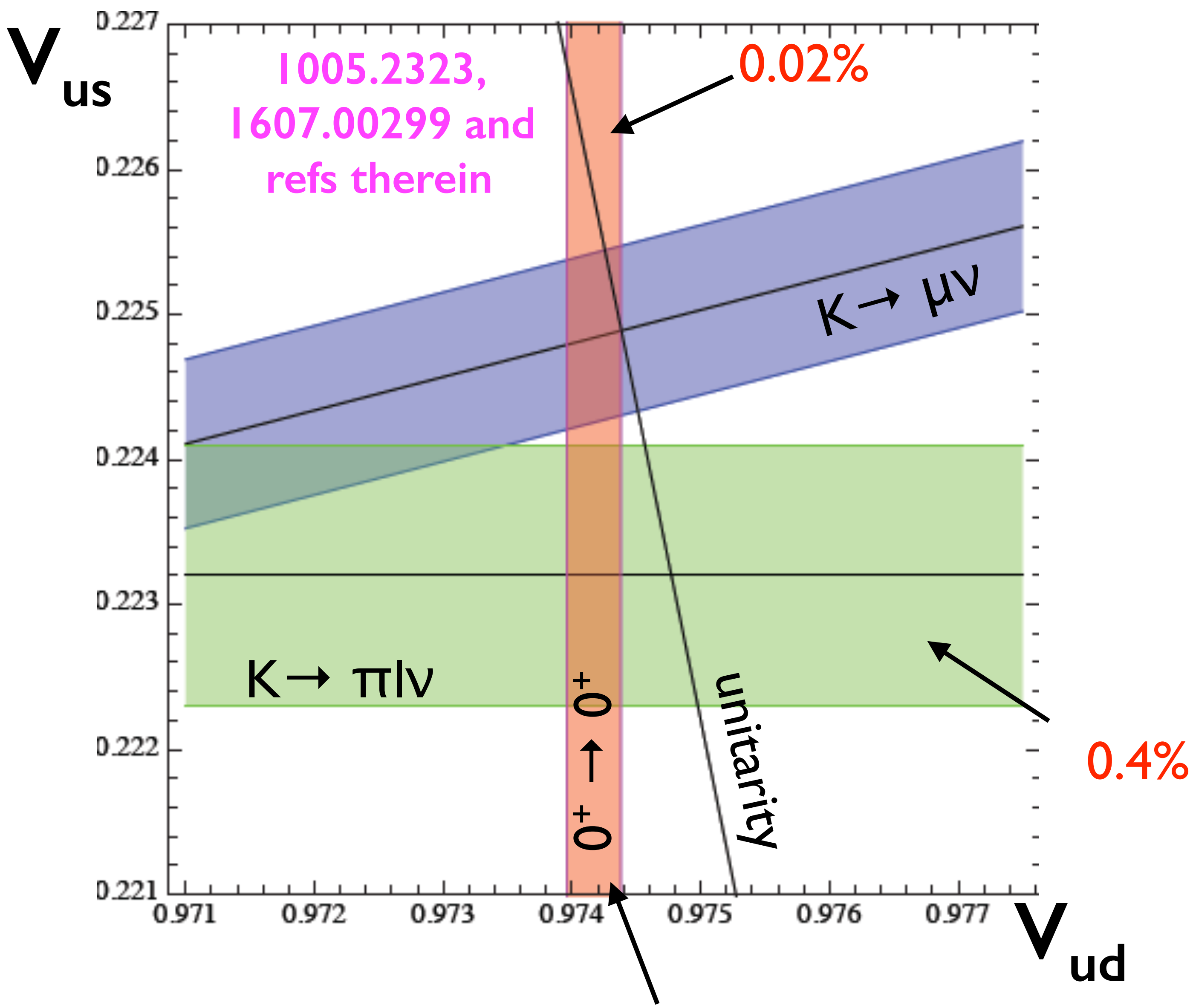
Δ_{CKM} = - (4 ± 5) ∗ 10^{-4} ~ 1σ

Δ_{CKM} = - (12 ± 6) ∗ 10^{-4} ~ 2σ

V_{us} from K→ πlν

CKM unitarity test

$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + |\bar{V}_{ub}|^2 = 1 + \Delta_{\rm CKM}(\epsilon_i)$$



V_{us} from $K \to \mu\nu$

$\Delta_{\rm CKM} = -(4 \pm 5) * 10^{-4}$ ~ 1σ

$\Delta_{\rm CKM} = -(12 \pm 6) * 10^{-4}$ ~ 2σ

V_{us} from $K \to \pi l \nu$

Hint of something?

[$\varepsilon_{R,P}^{(s)}$, $\varepsilon_L + \varepsilon_R$, SM th input]

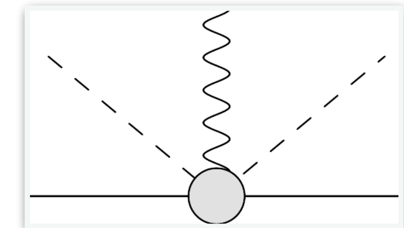
Worth a closer look: at the level of the best LEP EW precision tests, probing scale Λ~10 TeV.

Ongoing/future neutron measurements will provide competitive extraction of V_{ud}

Probing $\varepsilon_{L,R}$ couplings

- *Assume* $\varepsilon_{L,R}$ are induced by gauge vertex corrections at high scale (SM-EFT)

- Low energy probes:
  - $\Delta_{CKM} \propto \varepsilon_L + \varepsilon_R$
  - $\delta\Gamma_{(\pi \to \mu\nu)} \propto \varepsilon_L - \varepsilon_R$ [f_π from LQCD]
  - Neutron decay correlations (A, a, B) → $\lambda = g_A (1 - 2\, \varepsilon_R)$
  - QWeak, Z-pole → ε_L



$$\varphi^\dagger \tau^a D_\mu \varphi \;\; \bar{q}_L \tau^a \gamma^\mu q_L$$

$$\varphi^T \epsilon D_\mu \varphi \;\; \bar{u}_R \gamma^\mu d_R$$

Probing $\varepsilon_{L,R}$ couplings

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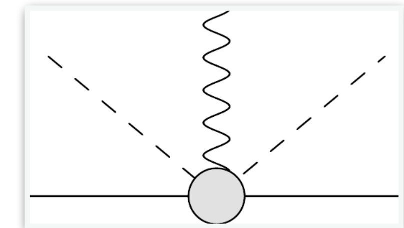

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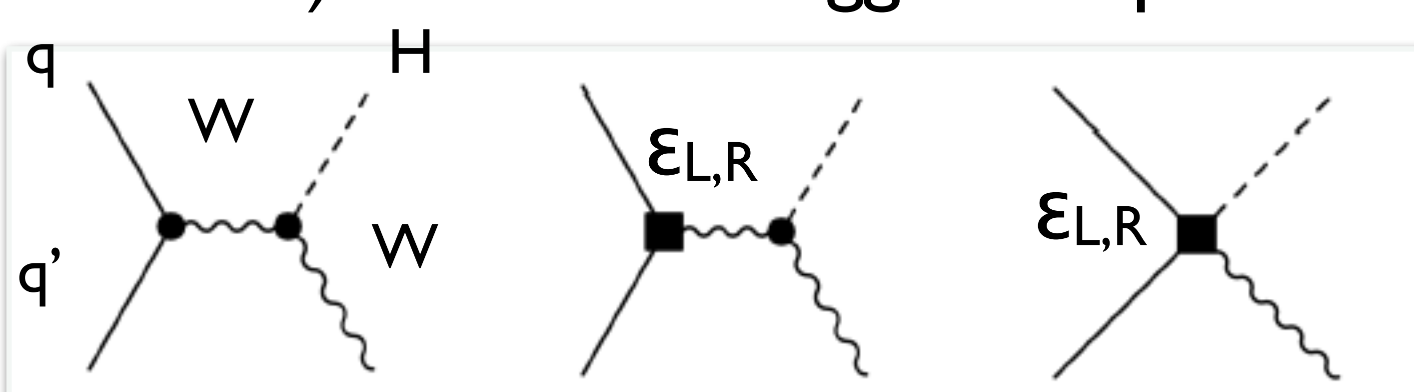
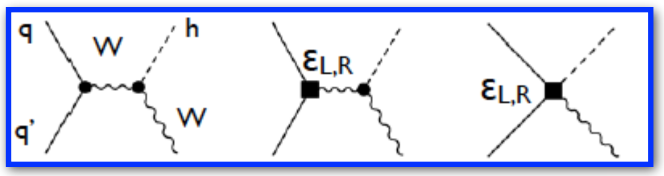
- LHC (if Λ > few TeV): associated Higgs + W production

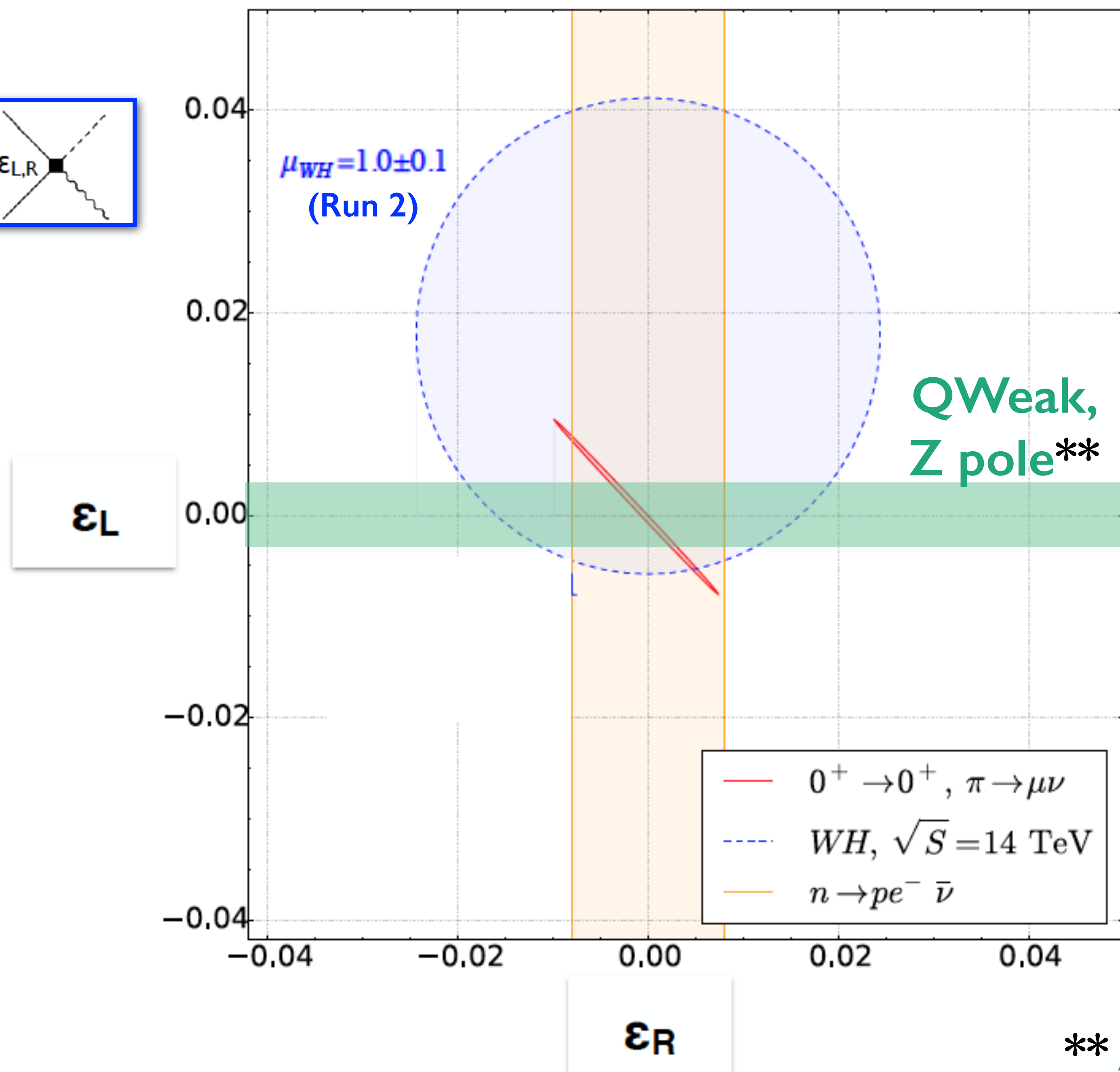


Probing $\varepsilon_{L,R}$ couplings

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

Updated plot courtesy of E. Mereghetti





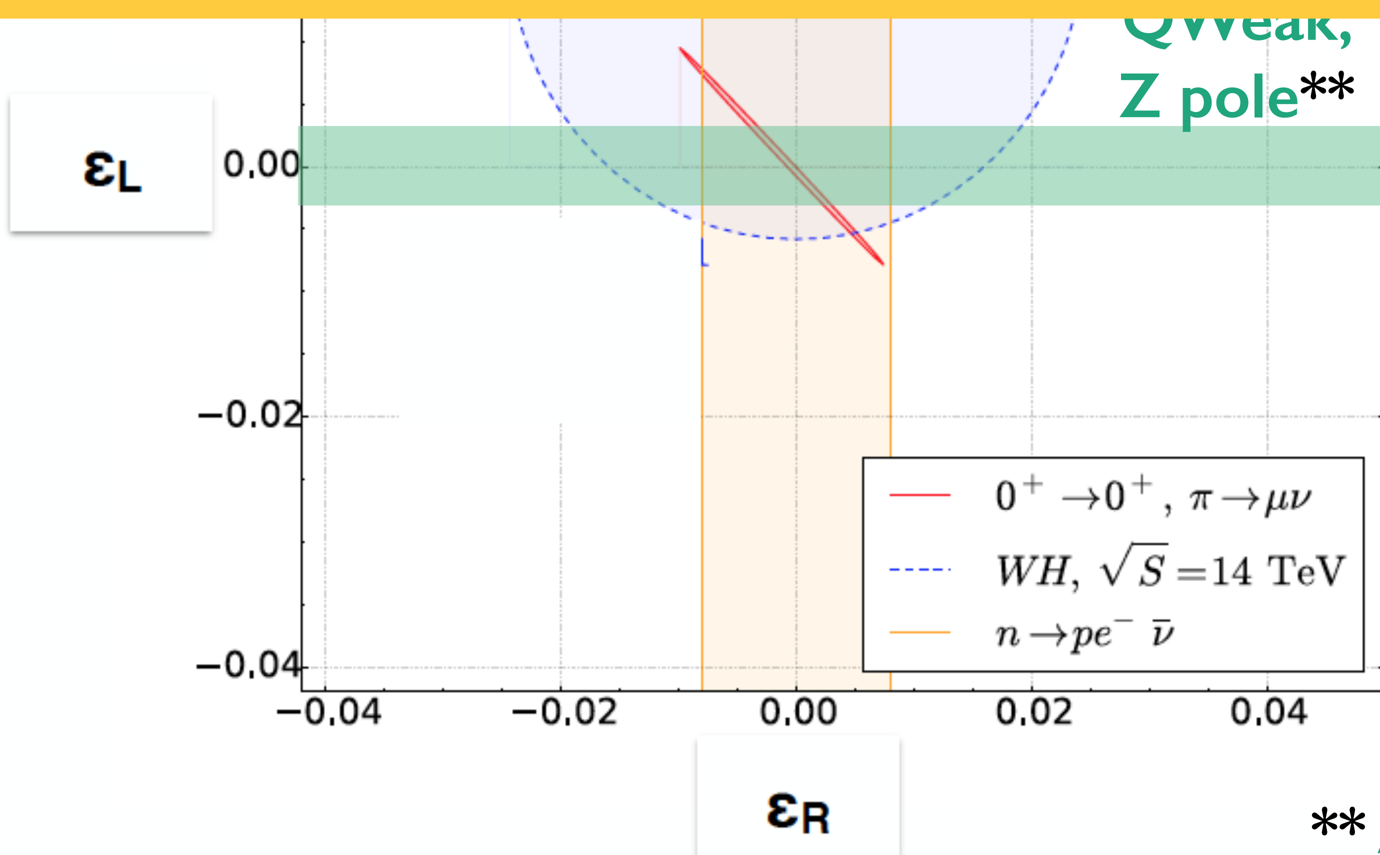
- Δ_{CKM} provides strongest constraint, followed by QWeak
- Neutron decay + LQCD: approaching competitive sensitivity to ε_R

Constraint on ε_R uses $g_A = 1.285(17)$ (CalLat 1710.06523)

** Adam Falkowski, private communication, PRELIMINARY

Probing $\varepsilon_{L,R}$ couplings

- Several lessons:
  - Low-energy can be quite competitive with collider bounds
  - Connection between CC and NC (gauge invariance!)
  - Caveat: additional BSM operators can relax these constraints. Combination of low- and high-energy constraints helps reducing "flat directions" in parameter space of couplings



competitive sensitivity to ε_R

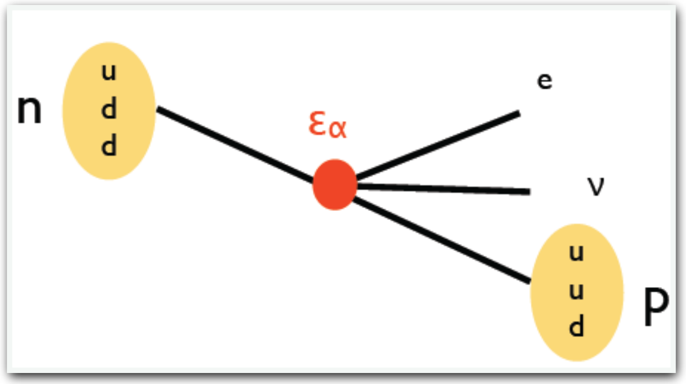
Constraint on ε_R uses g_A = 1.285(17) (CalLat 1710.06523)

** Adam Falkowski, private communication, PRELIMINARY

Probing $\varepsilon_{S,T}$ couplings

- π, neutron & nuclear decays:
  - Current: $b(0^+ \rightarrow 0^+)$ [ε_S]; $\pi \rightarrow e \nu \gamma$ [ε_T]
  - Future: b_n, B_n [$\varepsilon_{S,T}$] @ 10^{-3}; b_{GT} [ε_T](^{6}He, ...) @10^{-3}

$n \rightarrow p\, e\, \nu$



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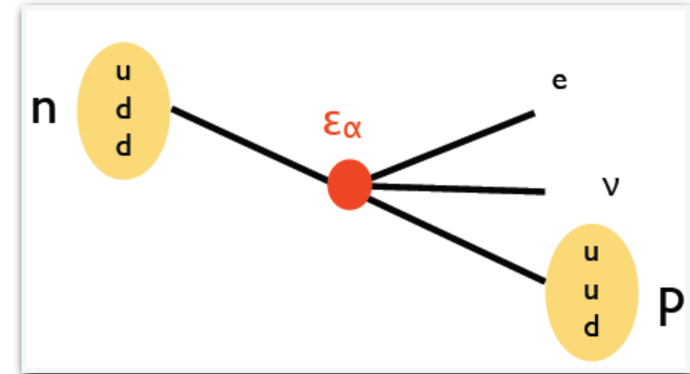
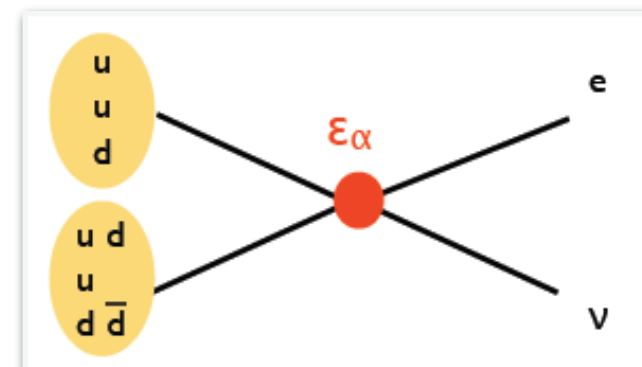
$n \to p e \nu$

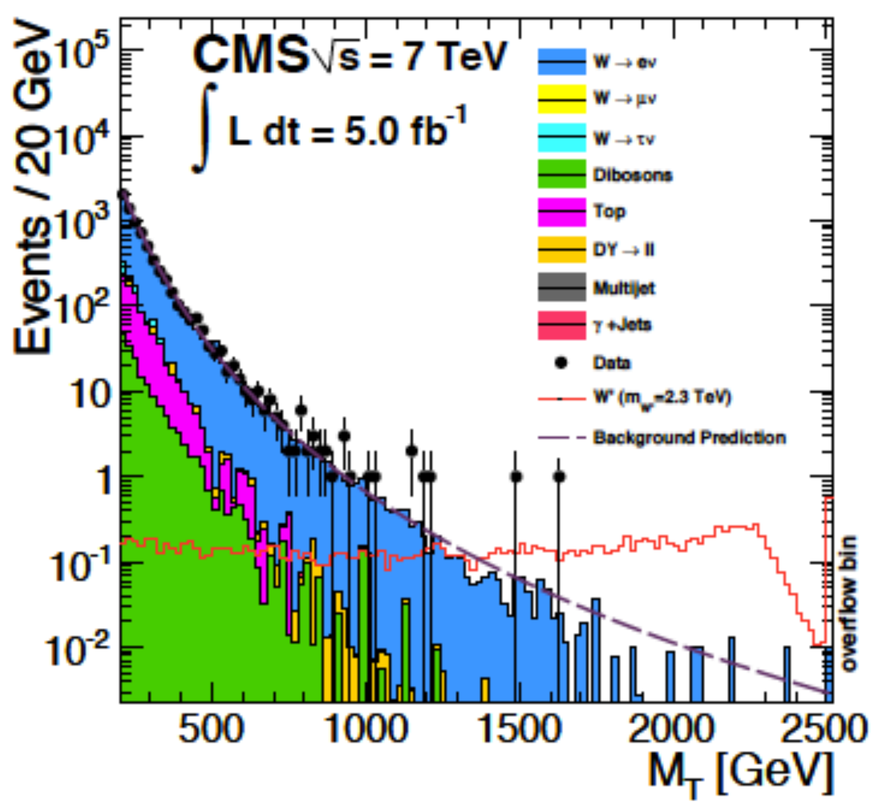


$pp \to e \nu + X$



- Collider: for heavy new mediators probe *same* $\varepsilon_{S,T}$

$$m_T \equiv \sqrt{2E_T^e E_T^\nu (1 - \cos \Delta\phi_{e\nu})}$$



$n_{obs}(m_T > m_{T,cut}) = \varepsilon_{eff} \times L \times (\sigma_W + \sigma_S \times |\varepsilon_S|^2 + \sigma_T \times |\varepsilon_T|^2)$

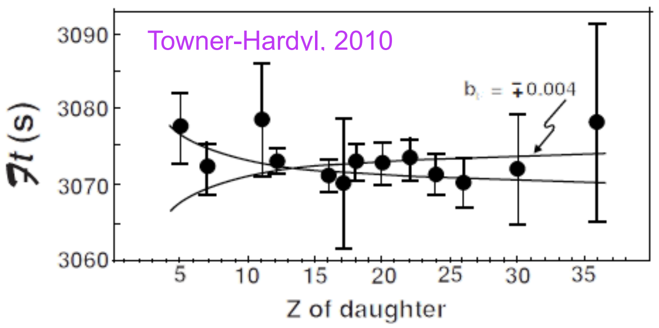
T. Bhattacharya et al, 1110.6448

VC, Gonzalez-Alonso, Graesser, 1210.4553

...

Probing $\varepsilon_{S,T}$ couplings

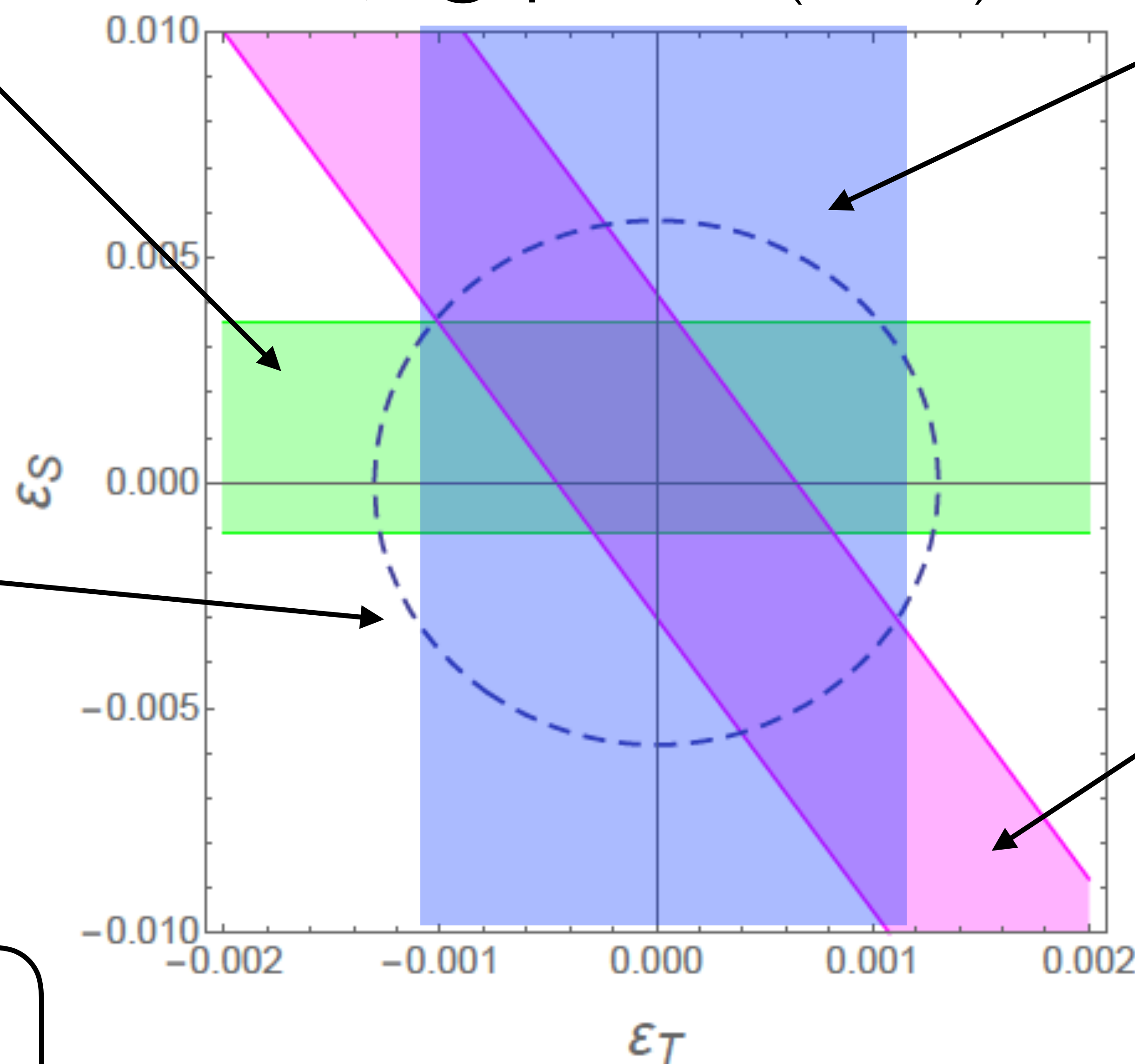
$0^+ \to 0^+$ (b_F)



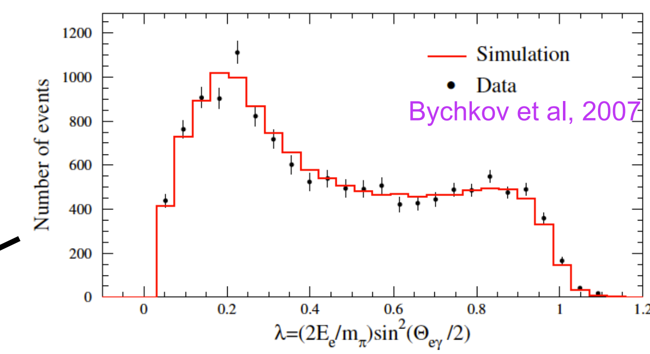
$-1.0\times10^{-3} < g_S\ \varepsilon_S < 3.2\times10^{-3}$

CURRENT

$\varepsilon_{S,T}$ @ μ= 2 GeV (MS-bar)



$\pi \to e\,\nu\,\gamma$



$-2.0\times10^{-4} < f_T\ \varepsilon_T < 2.6\times10^{-4}$

$f_T = 0.24(4)$

LHC 20 fb^{-1}
@ 8 TeV

Gonzalez-Alonso 2013
Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

$V_{ud}(0^+)/V_{ud}(n)$
$\delta\tau_n$ = 0.8 s

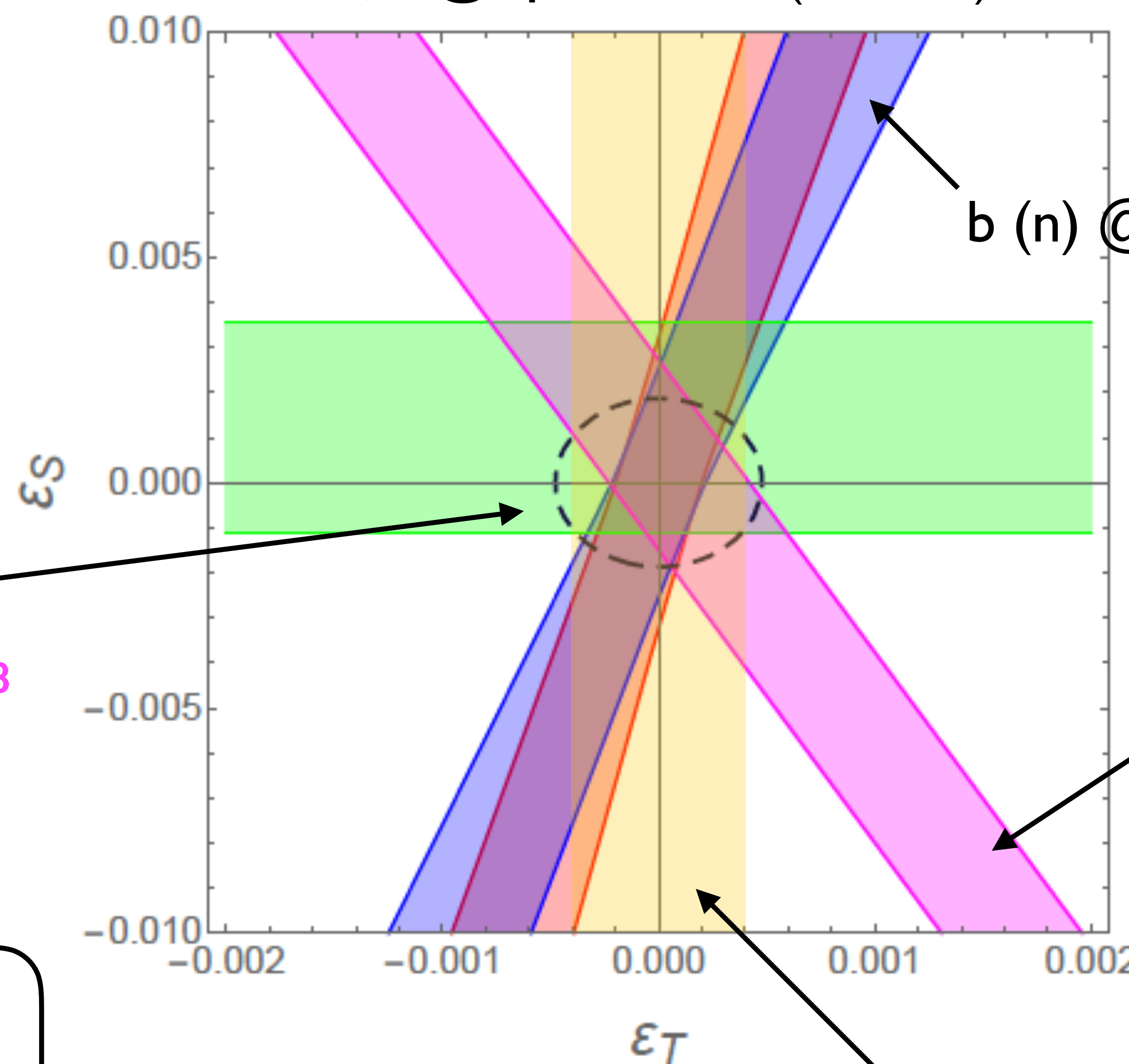
Pattie-Hickerson-Young 1309.2499

g_S = 1.01(10)
g_T = 0.99(4)
Bhattacharya et al (PNDME) 2018, to appear

Probing $\varepsilon_{S,T}$ couplings

FUTURE

$\varepsilon_{S,T}$ @ μ= 2 GeV (MS-bar)



b (n) @ 0.001

b (^{6}He) @ 0.001

LHC 300 fb^{-1}
@ 14 TeV

Bhattacharya et al 1110.6448

Alioli-Dekens-Girard-Mereghett- 1804.07407

Prospective beta decay measurements competitive with LHC ~5 years from now, probing mass scales $\Lambda_{S,T}$ ~ 5-10 TeV

V_{ud} $(0^+)/V_{ud}(n)$:
$\delta A/A$ ~ 0.1%
$\delta\tau_n$= 0.3 s

Pattie-Hickerson-Young 1309.2499

g_S =1.01(10)
g_T =0.99(4)

Bhattacharya et al (PNDME) 2018, to appear

Additional Material

Familiar example in detail

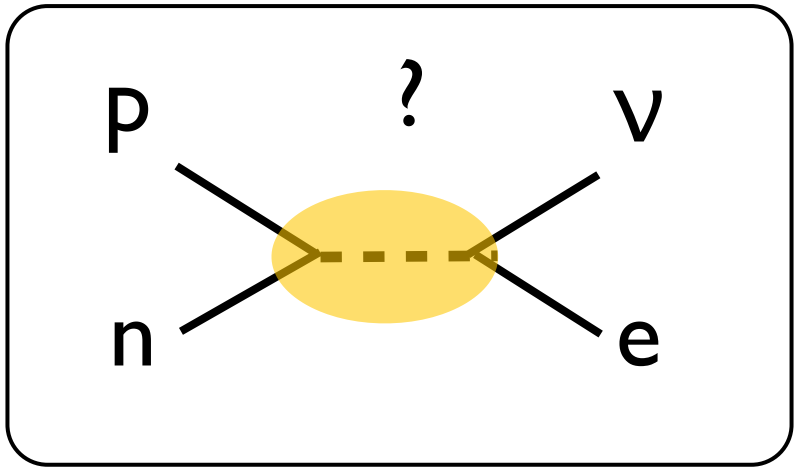
- Perform simple matching calculation: SM to Fermi-Lee-Yang theory

- Ingredients for FLY effective theory:

  ★ Degrees of freedom: n, p, e, $(\nu_e)_{L/R} = (1 \pm \gamma_5)/2\ \nu_e$

  ★ Symmetries: Lorentz, $U(1)_{EM}$ gauge invariance

  ★ Power counting in E/Λ_W: non-derivative 4-fermion interactions



Familiar example in detail

- Perform simple matching calculation: SM to Fermi-Lee-Yang theory
- Most general interaction involves product of fermion bilinears

Dimensionless coefficients

$$\mathcal{L}_{\rm eff} \supset \frac{c_{12}}{\Lambda_W^2} \; \bar{p}\,\Gamma_1\, n \;\; \bar{e}\,\Gamma_2\, \nu_e$$

Scale of weak interactions

Operators of mass dimension 6
(recall $[\Psi] = m^{3/2}$)
that conserve electric charge

Dirac structures:

$$\Gamma_i = I, \; \gamma_5, \; \gamma_\mu, \; \gamma_\mu\gamma_5, \; \sigma_{\mu\nu} = i/2[\gamma_\mu, \gamma_\nu]$$

S P V A T

Familiar example in detail

- Perform simple matching calculation: SM to Fermi-Lee-Yang theory
- Most general interaction involves product of fermion bilinears
- Impose Lorentz invariance: $\mathcal{L}_{\text{eff}} = \mathcal{L}_{V,A} + \mathcal{L}_{S,P} + \mathcal{L}_T$

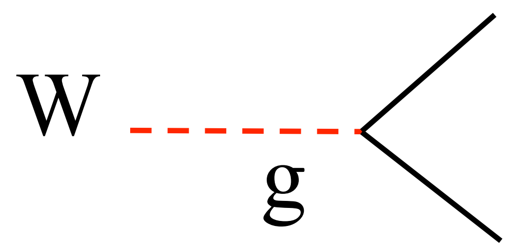
$$-\mathcal{L}_{V,A} = \bar{p}\gamma_\mu n \;\; \bar{e}\gamma^\mu (C_V + C_V' \gamma_5)\nu_e \;+\; \bar{p}\gamma_\mu\gamma_5 n \;\; \bar{e}\gamma^\mu\gamma_5 (C_A + C_A' \gamma_5)\nu_e$$

$$-\mathcal{L}_{S,P} = \bar{p}n \;\; \bar{e}(C_S + C_S' \gamma_5)\nu_e \;+\; \bar{p}\gamma_5 n \;\; \bar{e}\gamma_5 (C_P + C_P' \gamma_5)\nu_e + \text{h.c.}$$

$$-\mathcal{L}_T = \frac{1}{2}\,\bar{p}\sigma_{\mu\nu} n \;\; \bar{e}\sigma^{\mu\nu} (C_T + C_T' \gamma_5)\nu_e \;+\; \text{h.c.}$$

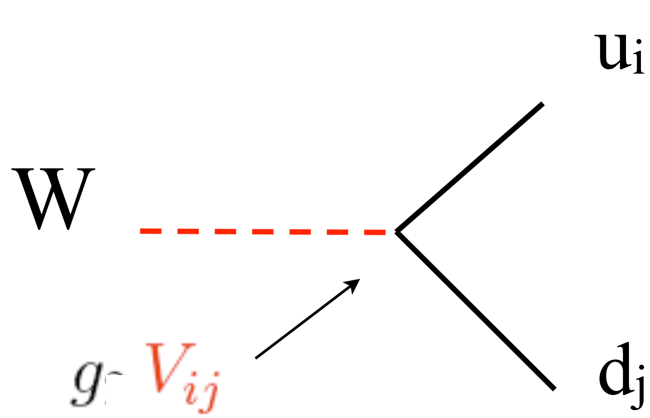
Familiar example in detail

- Perform simple matching calculation: SM to Fermi-Lee-Yang theory
- W-fermion vertices in the SM:
  - Leptons:



$$l = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

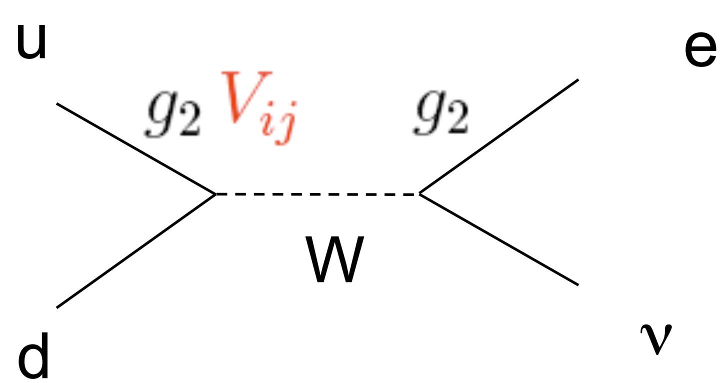
  - Quarks:



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

- Calculate d → u e ν amplitude within the SM

- Exploit hierarchy of scales: $m_{had} \ll M_{W,Z,t}$

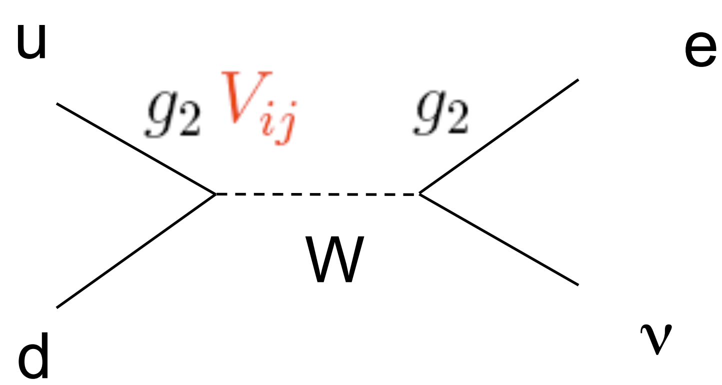


$$A = \frac{g^2}{8} V_{ud} \frac{i}{k^2 - M_W^2} \bar{u}\gamma_\mu(1-\gamma_5)d \; \bar{e}\gamma^\mu(1-\gamma_5)\nu_e$$

Expand W propagator: $k^2 \ll (M_W)^2$

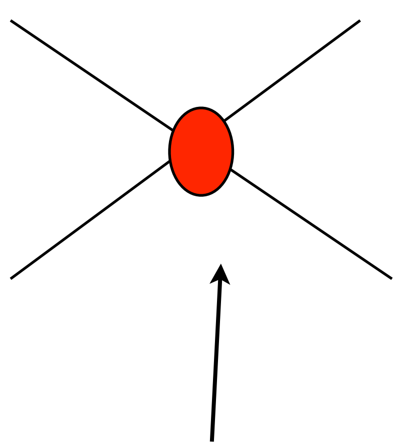
- Calculate d → u e ν amplitude within the SM

- Exploit hierarchy of scales: $m_{had} \ll M_{W,Z,t}$



$$A = \frac{g^2}{8} V_{ud} \frac{i}{k^2 - M_W^2}\, \bar{u}\gamma_\mu(1-\gamma_5)d\; \bar{e}\gamma^\mu(1-\gamma_5)\nu_e$$

- To lowest order in k^2/M_W^2, same answer is obtained in a theory with no W and a new local 4-quark operator with (V-A)x(V-A) structure



$$\mathcal{L}_{\rm eff}^{SL} = -\frac{G_F}{\sqrt{2}} V_{ud}\, \hat{O} \;+\; h.c. \qquad \frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

$$\hat{O} = \bar{u}\gamma_\mu(1-\gamma_5)d\; \bar{e}\gamma^\mu(1-\gamma_5)\nu_e$$

$$A = -i\frac{G_F}{\sqrt{2}} V_{ud}\, \langle \hat{O} \rangle \;+\; O\left(\frac{k^2}{M_W^2}\right)$$

- Next step: go from quark-level to nucleon level description

$$\langle p|\bar{u}\gamma_\mu d|n\rangle = g_V\, \bar{u}_p \gamma_\mu u_n + O(q)$$

$$q = p_n - p_p$$

$$\langle p|\bar{u}\gamma_\mu\gamma_5 d|n\rangle = g_A\, \bar{u}_p \gamma_\mu \gamma_5 u_n + O(q)$$

$$g_V = 1 \qquad g_A \simeq 1.27$$

- Final results of matching calculation:

$$C_V = C'_V = \frac{g^2}{8M_W^2} V_{ud} \equiv \frac{1}{\Lambda_W^2}$$

$$C_A = C'_A = -g_A \frac{g^2}{8M_W^2} V_{ud}$$

$$C_{S,P,T} = C'_{S,P,T} = 0$$

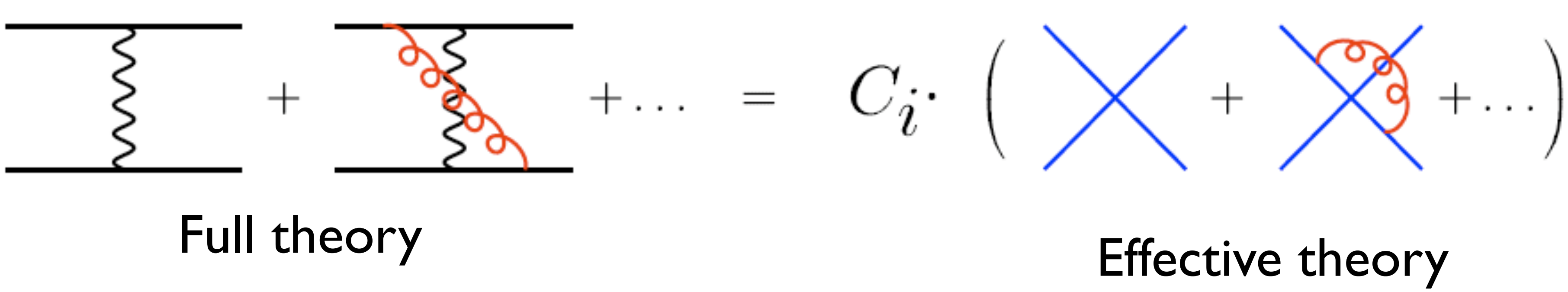
- Effective couplings know about masses and coupling constants of the underlying theory

- Effective scale Λ_W does not coincide in general with mass of new particle (factors of couplings, possibly loops....)

- This was a simple example of matching calculation in EFT:

$$A_{\text{full}} = \sum_i C_i \langle O_i \rangle \equiv A_{EFT}$$

  - ★ "Integrate out" heavy d.o.f (W,Z,t); write L_{eff} in terms of local operators built from low-energy d.o.f.
  - ★ To a given order in E/M_W, determine effective couplings (Wilson coefficients) from the matching condition $A_{\text{full}} = A_{\text{EFT}}$ with amplitudes involving "light" external states
  - ★ We did matching at tree-level, but strong and electroweak higher order corrections can be included



Impact of neutron measurements

- Independent extraction of V_{ud} @ 0.02% requires:

$$\bar{V}_{ud} = \left[\frac{4908.6(1.9)\ s}{\tau_n \ (1 + 3\bar{g}_A^2)} \right]^{1/2}$$

Marciano, Sirlin 2006

$\delta\tau_n \sim 0.35$ s
$\delta\tau_n/\tau_n \sim 0.04$ %

$\delta g_A/g_A \sim 0.15\% \rightarrow 0.03\%$
($\delta a/a$, $\delta A/A \sim 0.14\%$)

UCNτ @ LANL [$\tau_n \sim 877.7(7)(3)$s]
is almost there, will reach $\delta\tau_n \sim 0.2$ s
1707.01817

$\delta A/A$ and $\delta a/a < 0.2\%$ within
reach of Nab, PERC, UCNA+