Zuoz Summer School 2024:
“From low to high: Particle Physics at the Frontier”

Low Energy Physics (I)

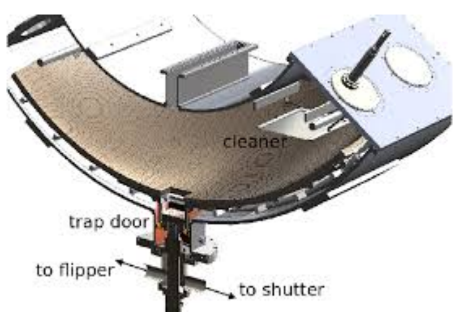
Vincenzo Cirigliano
University of Washington

INSTITUTE for NUCLEAR THEORY

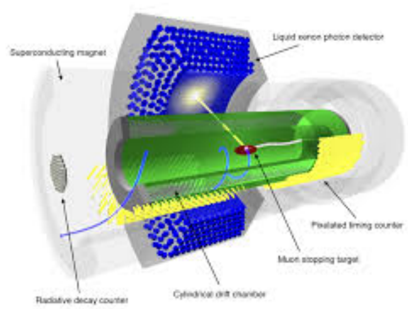
Goal of these lectures

Provide an introduction and theoretical perspective to the so-called Precision / Intensity Frontier of particle and nuclear physics:

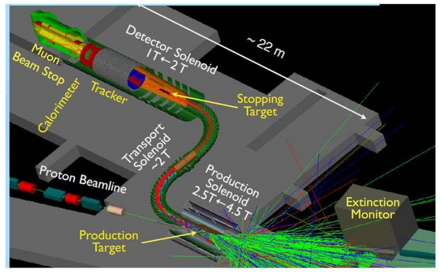
Searches for new phenomena beyond the Standard Model through precision tests or the study of rare processes *at low energy***



UCNτ

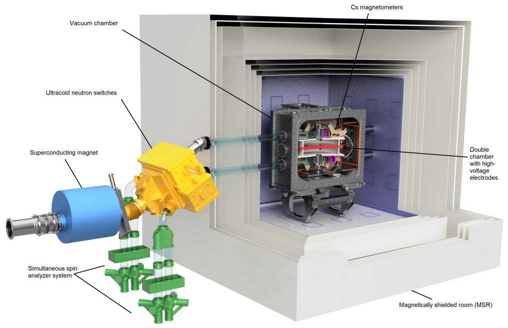


MEG-II



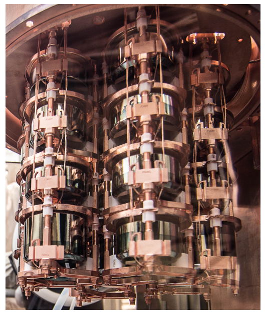
Mu2e

muon g-2

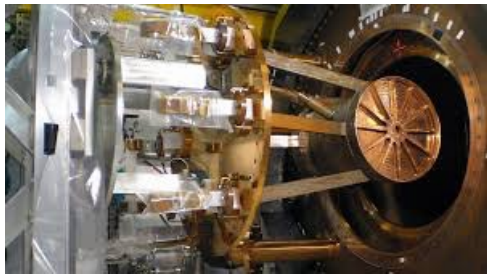


n2EDM

GERDA



Majorana



EXO 200

. . .

** The separation is arbitrary — here I will focus mostly on probes at E < b-quark mass

Flow of the lectures

- The quest for new physics at the low-energy frontier
- How does the precision / intensity frontier work? (Theory perspective)
  - An example from history: the Standard Model itself!
  - Effective field theory (EFT) framework
  - Standard Model EFT landscape in the LHC era and beyond

Lecture 1

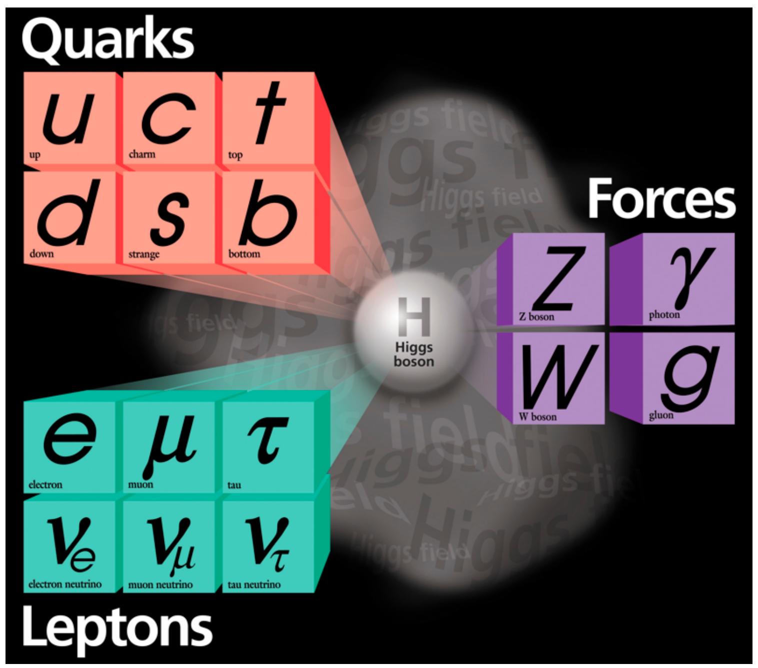
- "Zoom in" on selected low-energy probes: illustrate methods and impact
  - Precision measurements:
    - Weak charged current processes (beta decays)
  - Symmetry tests:
    - Lepton Number and Lepton Flavor Violation

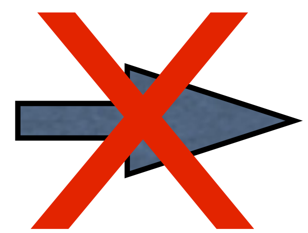
Lecture 2

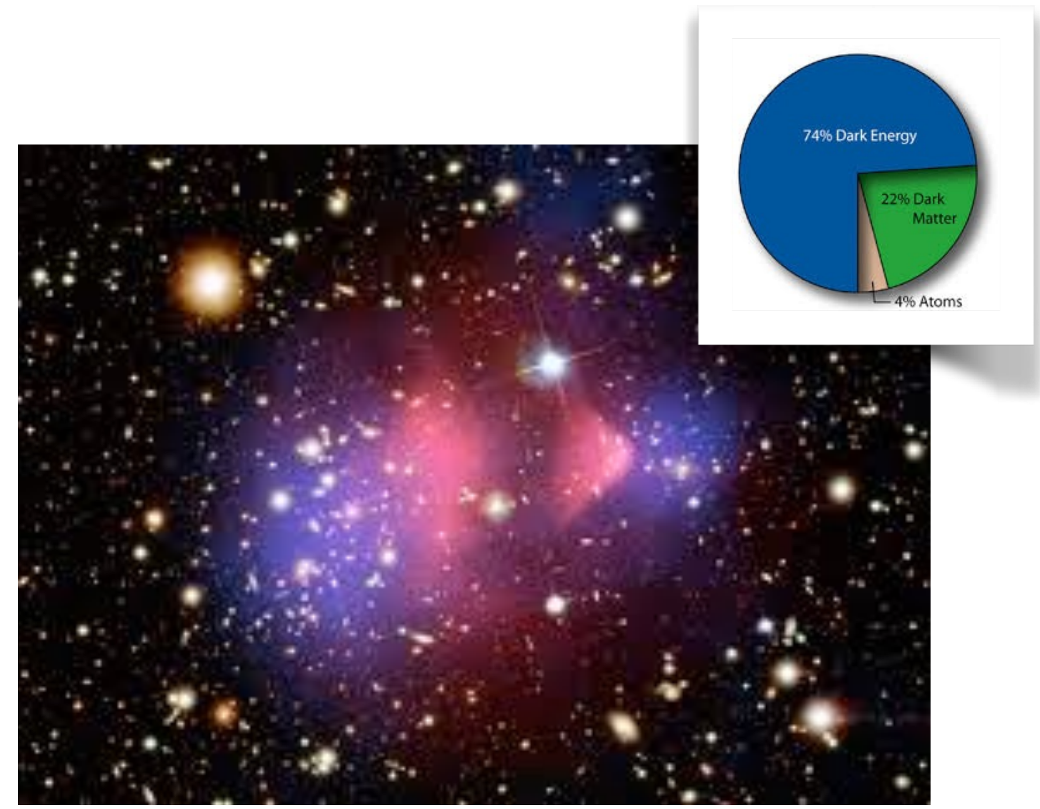
The quest for new physics at the low energy frontier

New physics: why?

- The Standard Model is remarkably successful, but it's probably incomplete







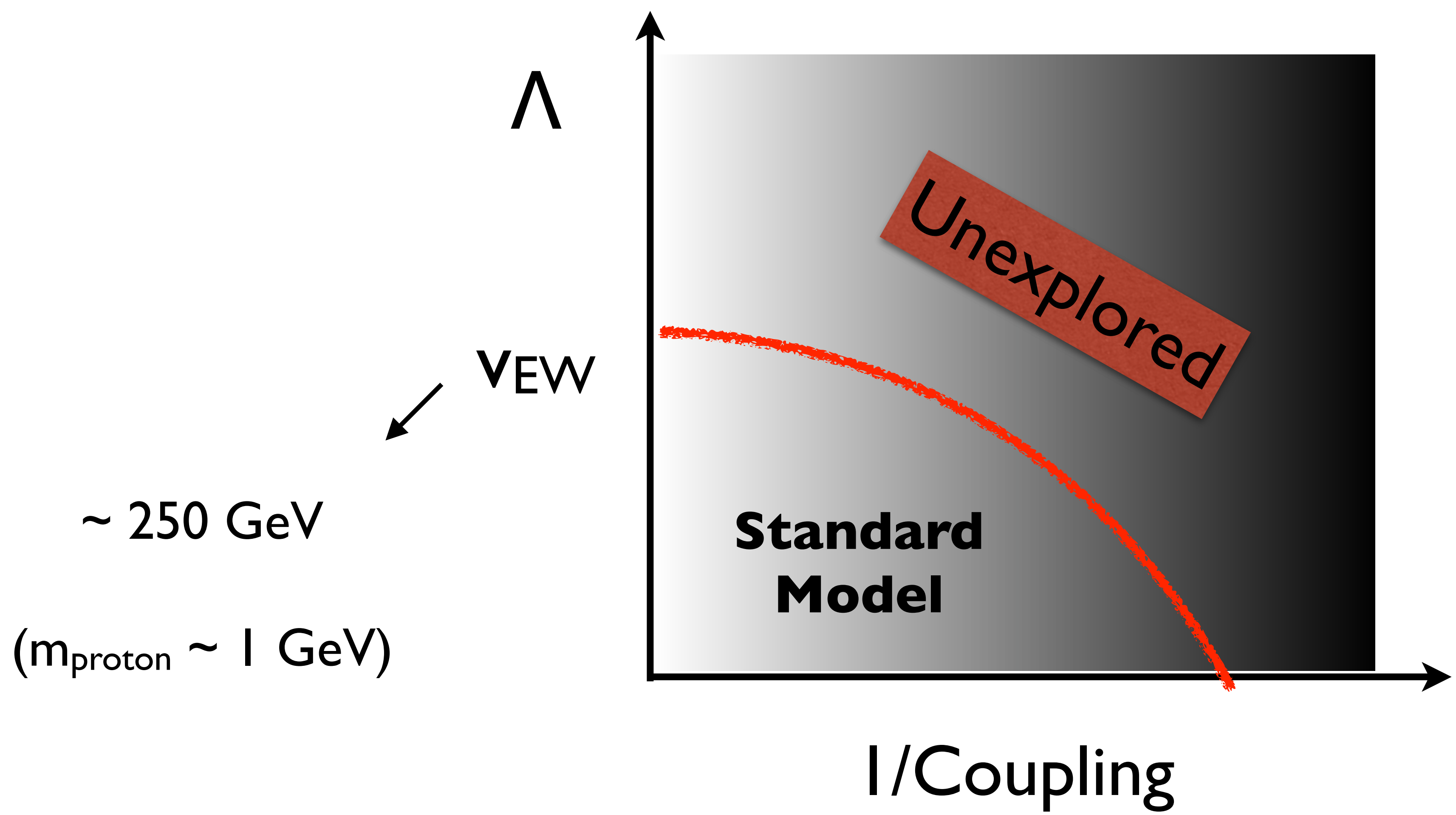
No Baryonic Matter, no Dark Matter, no Dark Energy, no Neutrino Mass

What stabilizes G_{Fermi}/G_{Newton} against radiative corrections?
Do forces unify at high E? What is the origin of families? What about gravity? …

Addressing these puzzles likely requires new physics

New physics: where?

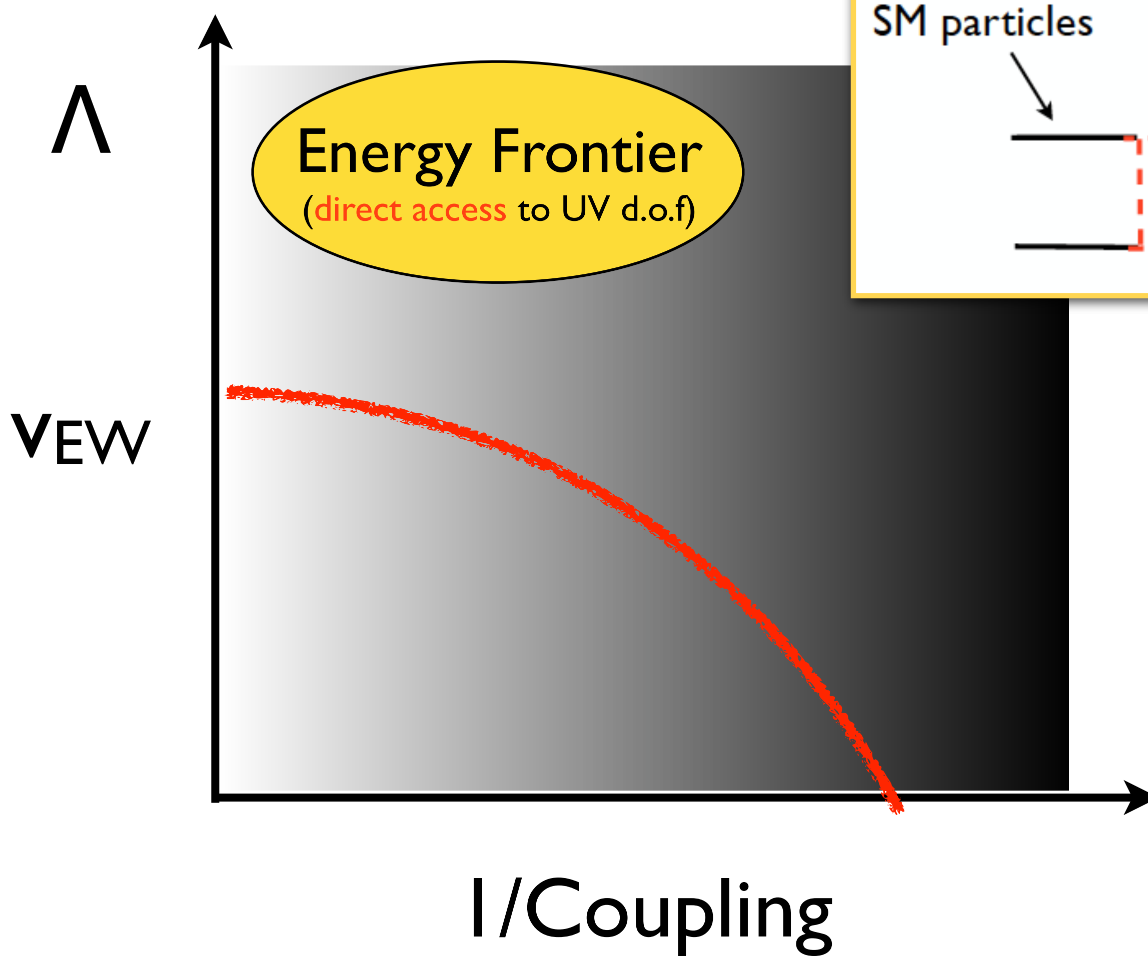
- Where is the new physics? Is it Heavy? Is it Light & weakly coupled?

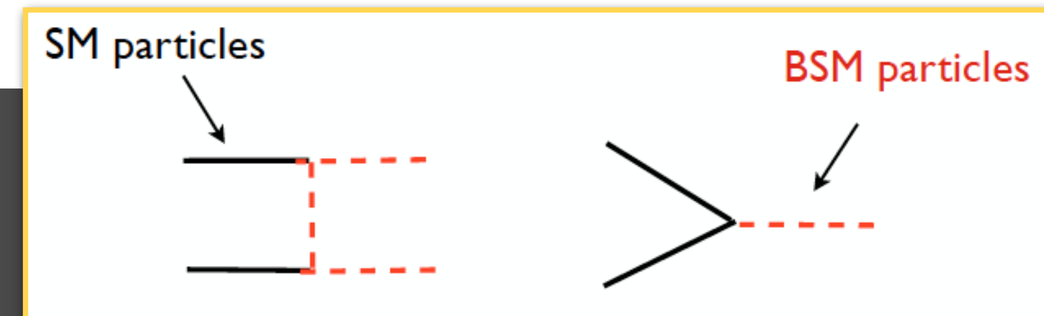


New physics: how?

- Two complementary paths to search for new physics

$$E = mc^2$$

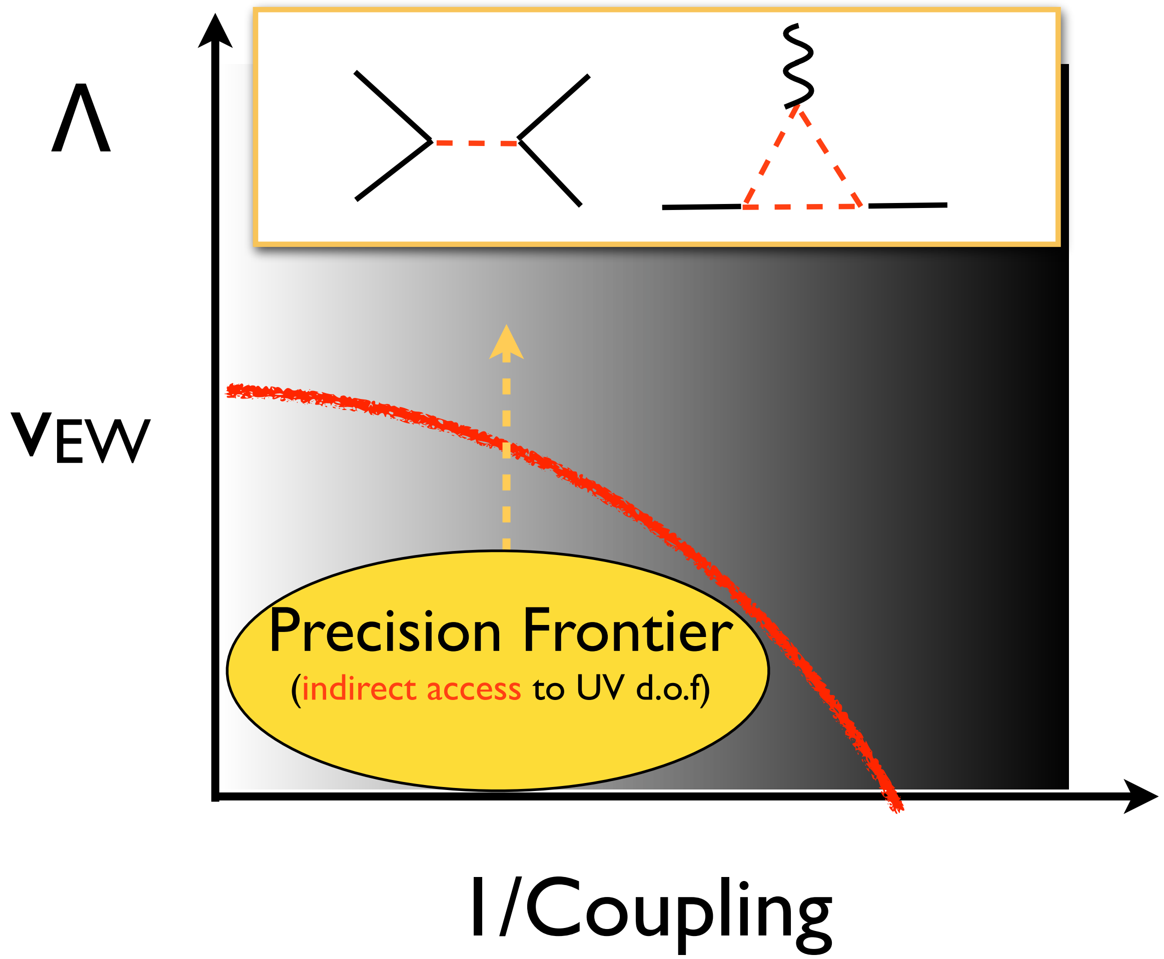




New physics: how?

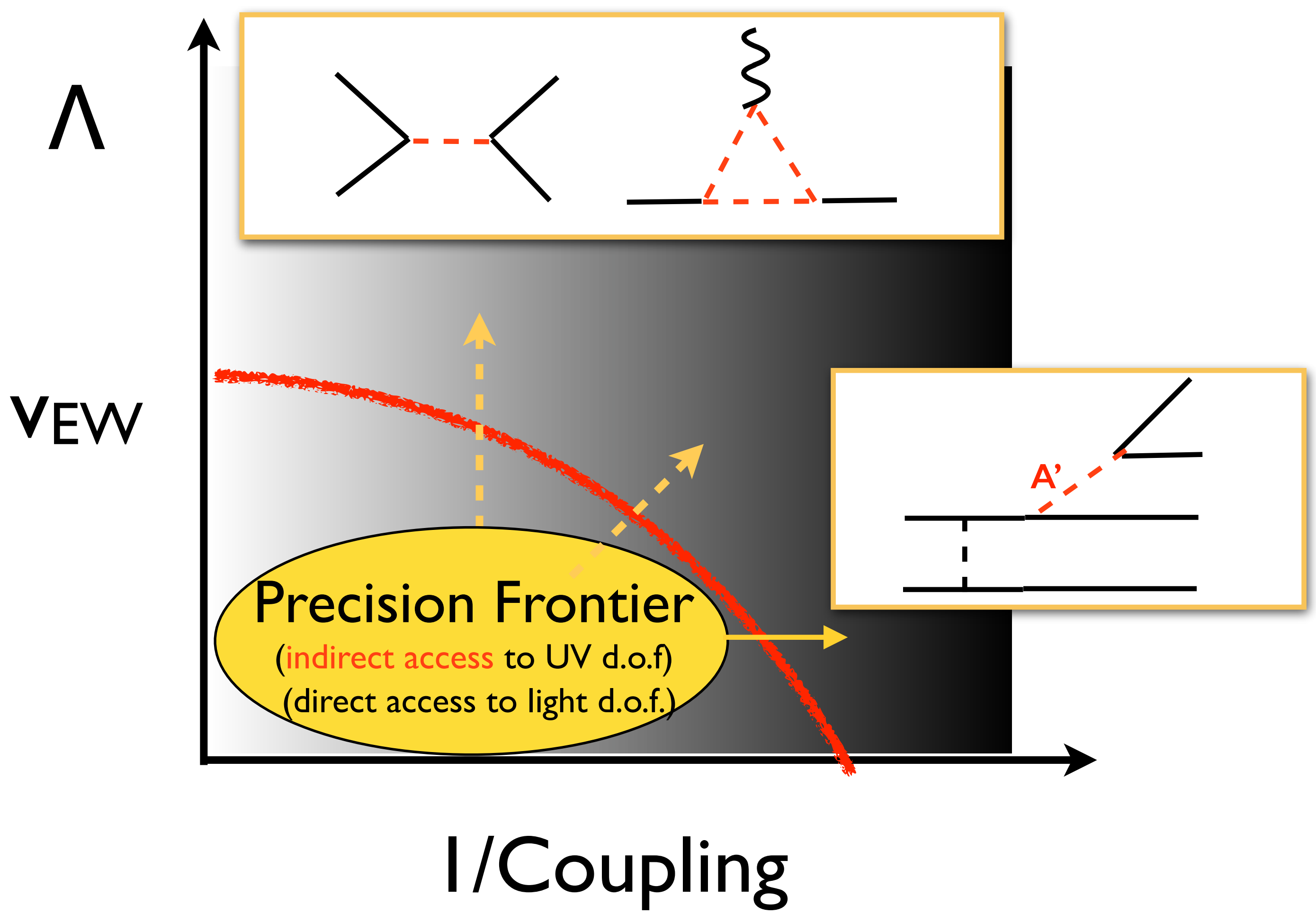
- Two complementary paths to search for new physics

$$\Delta E \, \Delta t \sim h$$



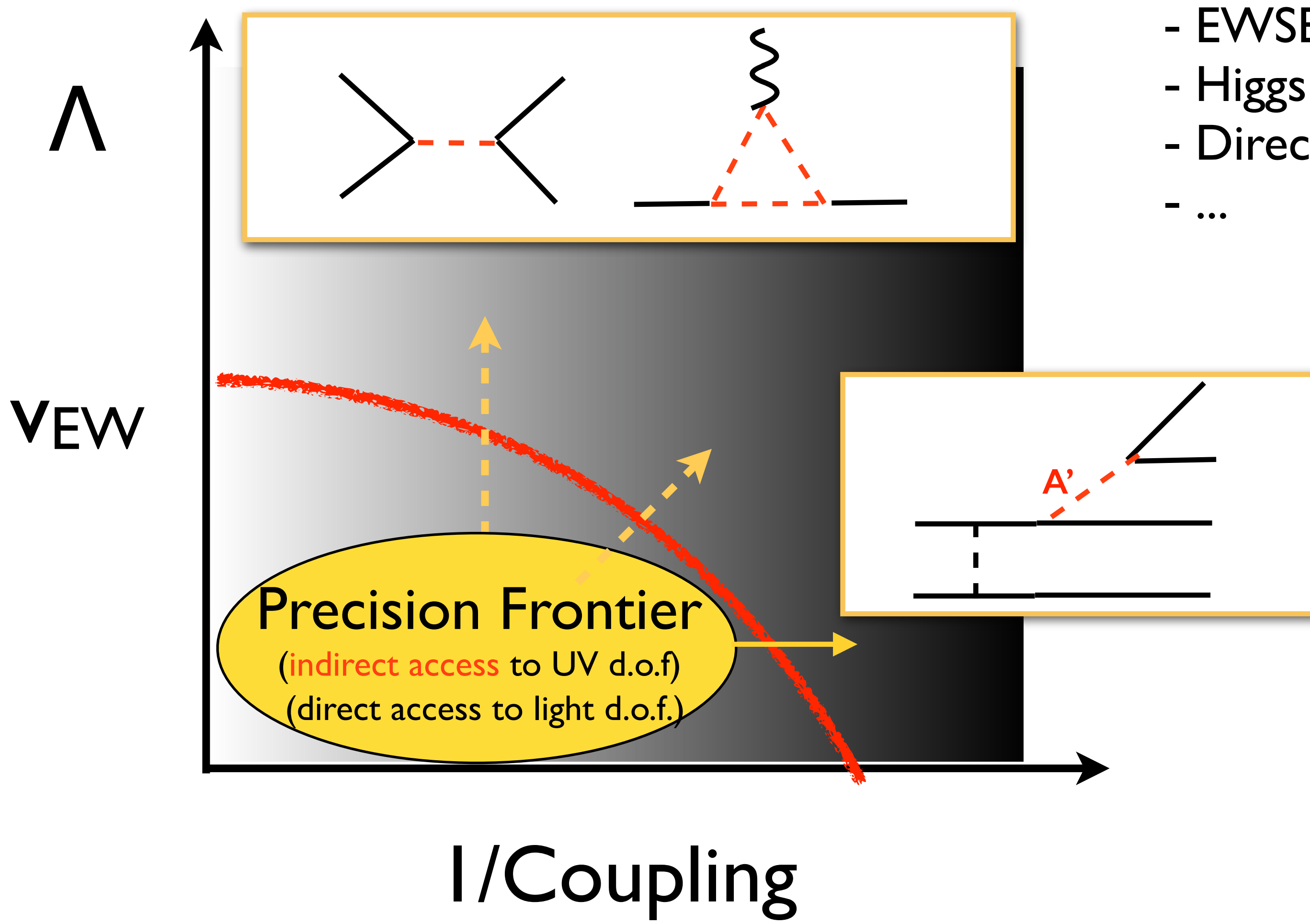
New physics: how?

- Two complementary paths to search for new physics



New physics: how?

- Two complementary paths to search for new physics



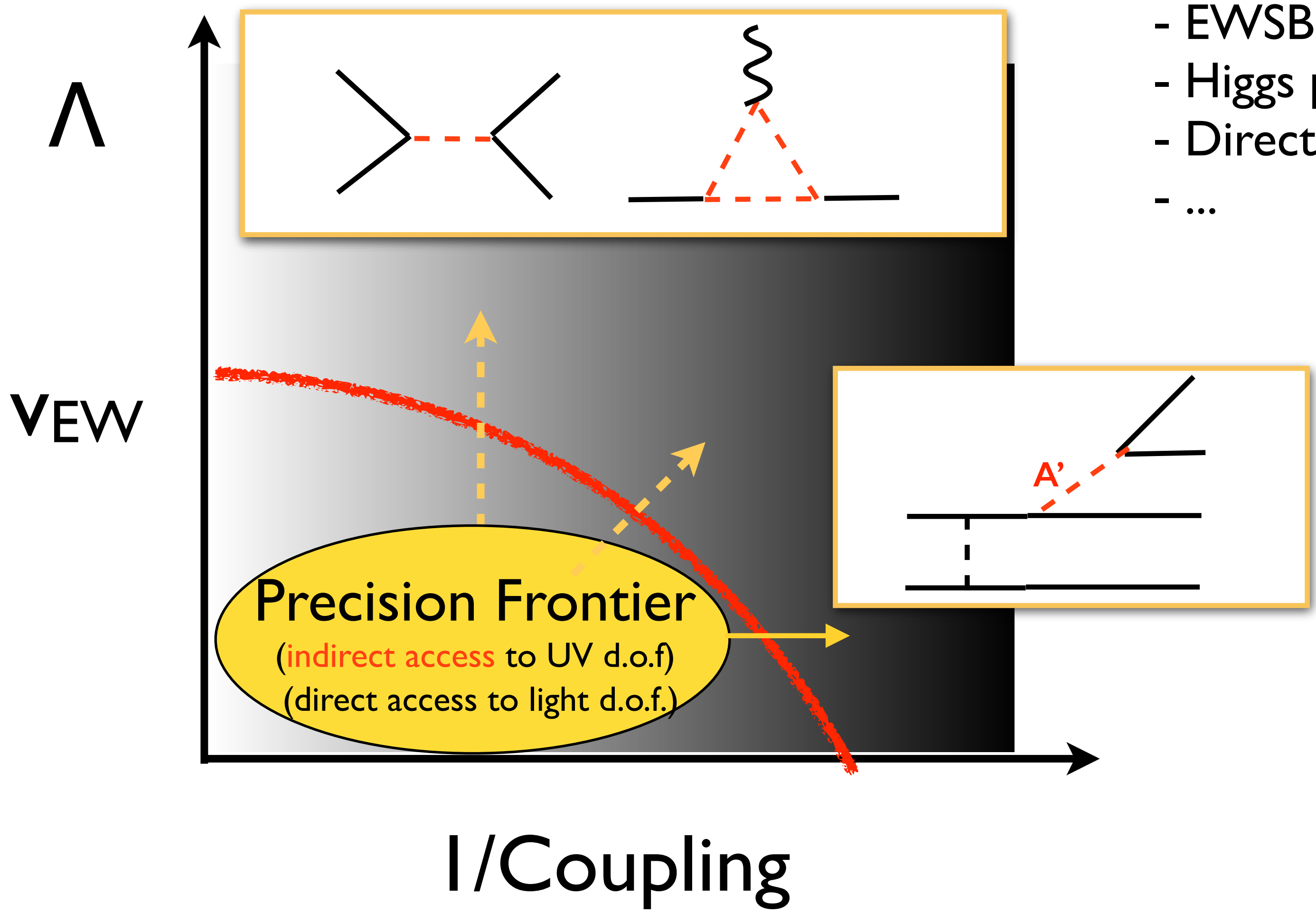
Energy frontier
- EWSB mechanism
- Higgs properties
- Direct access to heavy particles
- ...

Precision Frontier
- B and L violation
- CP violation
- Flavor violation
- Ultra-heavy mediators
- Neutrino properties
- Dark sectors
- ...

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

New physics: how?

- Two complementary paths to search for new physics



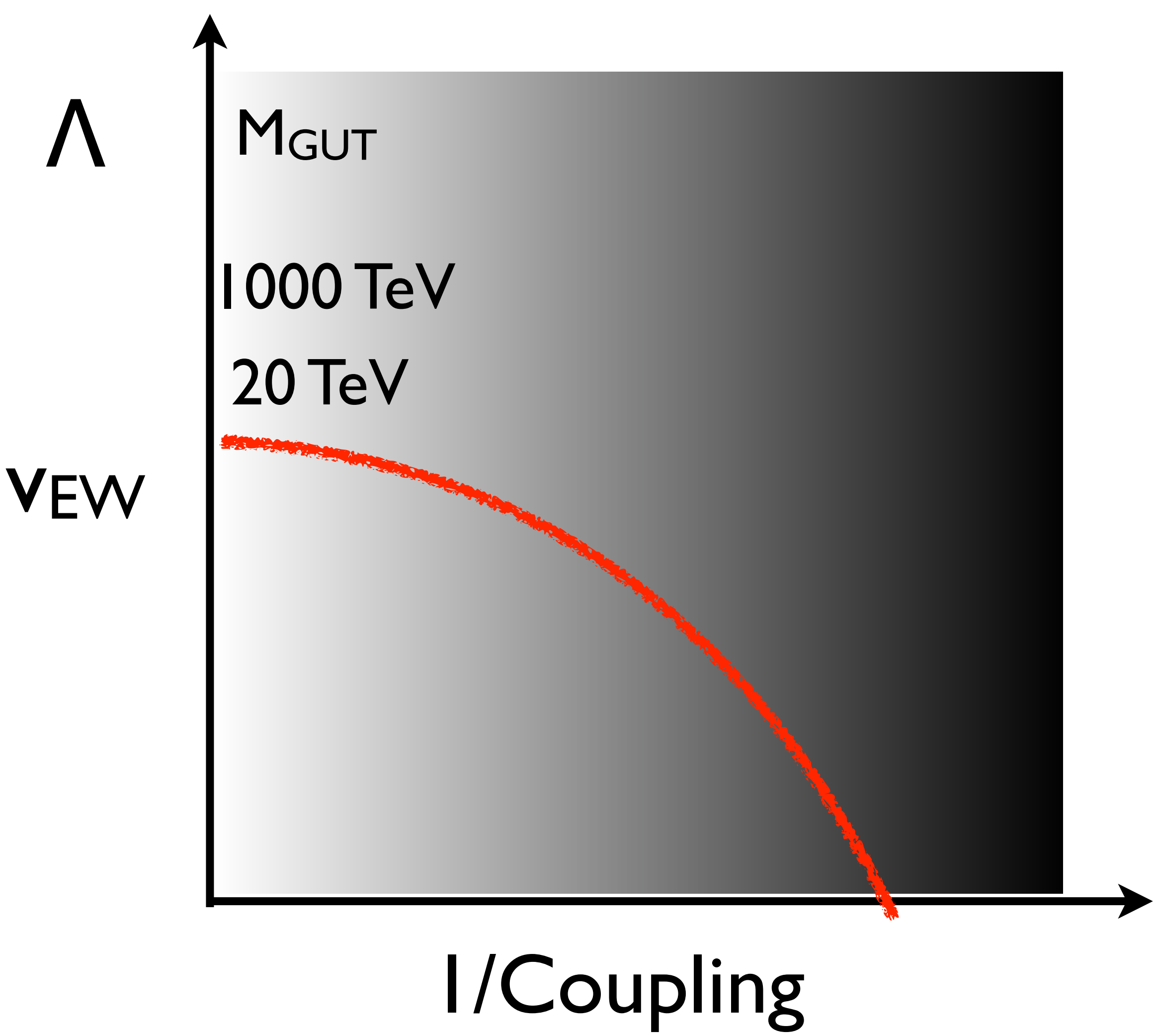
Energy frontier
- EWSB mechanism
- Higgs properties
- Direct access to heavy particles
- ...

Precision Frontier
- B and L violation
- CP violation
- Flavor violation
- Ultra-heavy mediators
- Neutrino properties
- Dark sectors
- ...

The Precision Frontier cuts across AMO, HEP & NP

BSM probes @ low-energy frontier

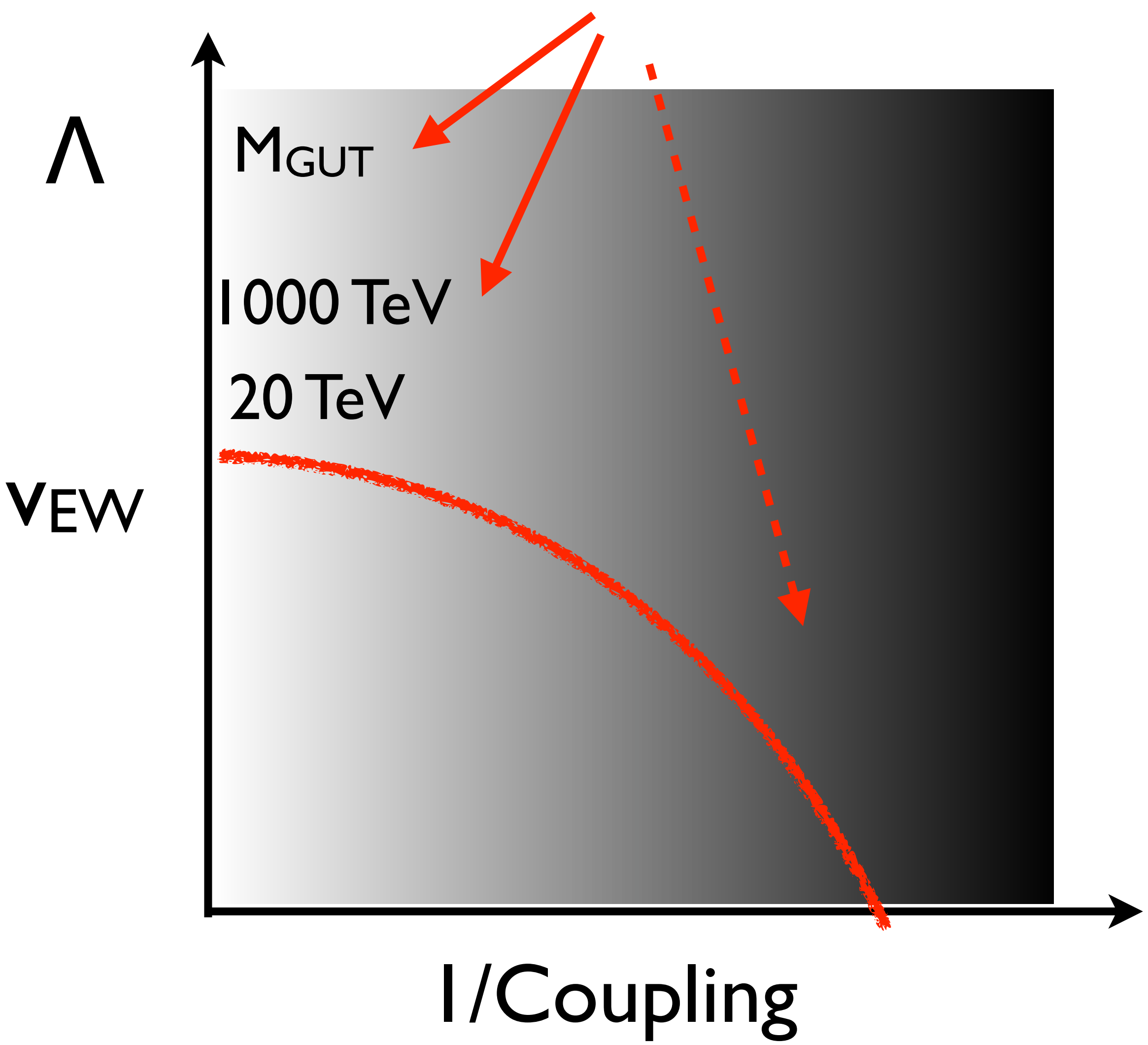
- Three classes, pushing the boundary in qualitatively different ways and at different mass scales



BSM probes @ low-energy frontier

- Three classes, pushing the boundary in qualitatively different ways and at different mass scales

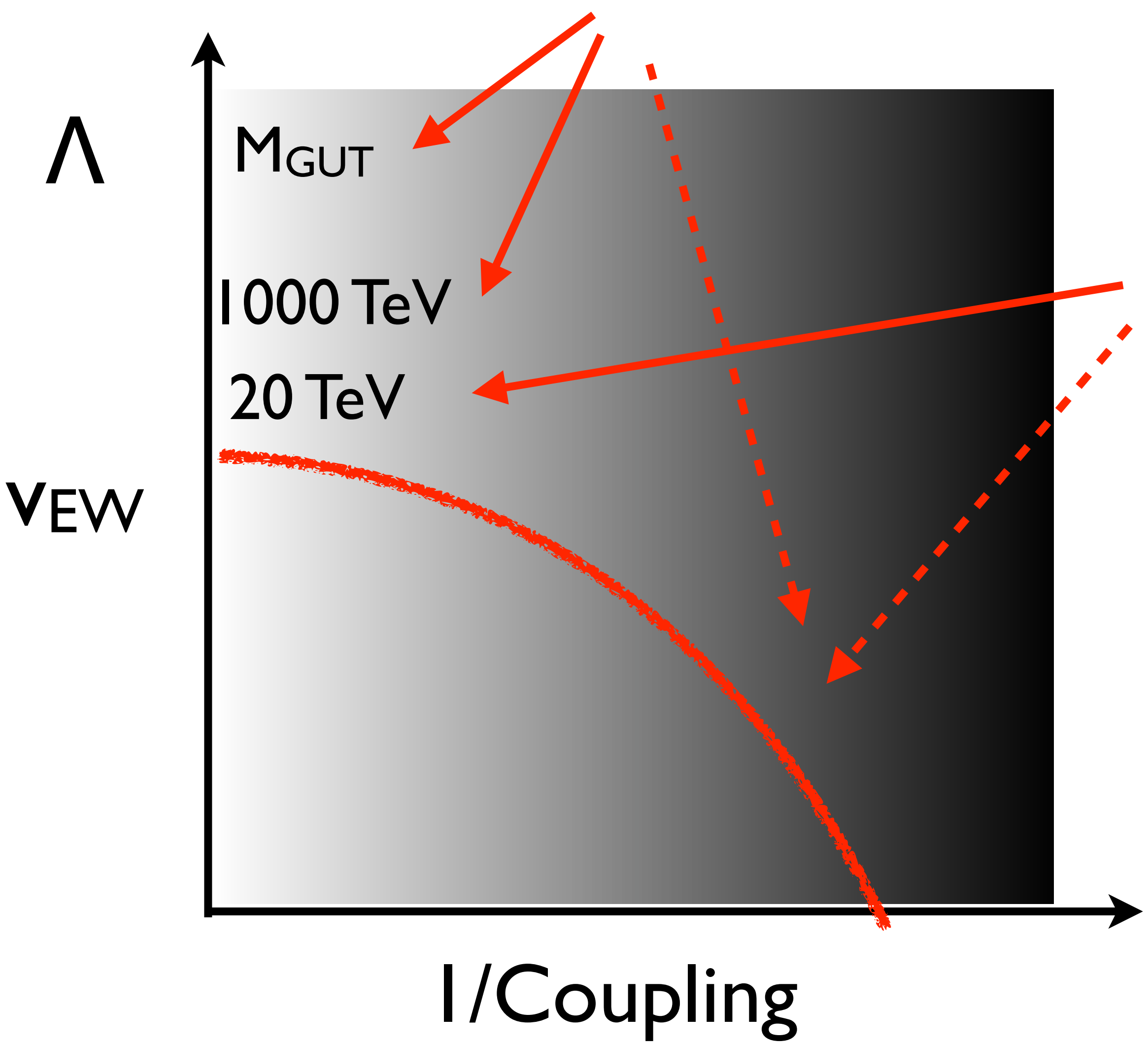
1. Searches for rare or SM-forbidden processes that probe approximate or exact symmetries of the SM (L, B, CP, L_α): $0\nu\beta\beta$ decay, p decay EDMs, LFV ($\mu\to e$,, …)



BSM probes @ low-energy frontier

- Three classes, pushing the boundary in qualitatively different ways and at different mass scales

1. Searches for rare or SM-forbidden processes that probe approximate or exact symmetries of the SM (L, B, CP, L_α): $0\nu\beta\beta$ decay, p decay EDMs, LFV ($\mu \to e$,, …)

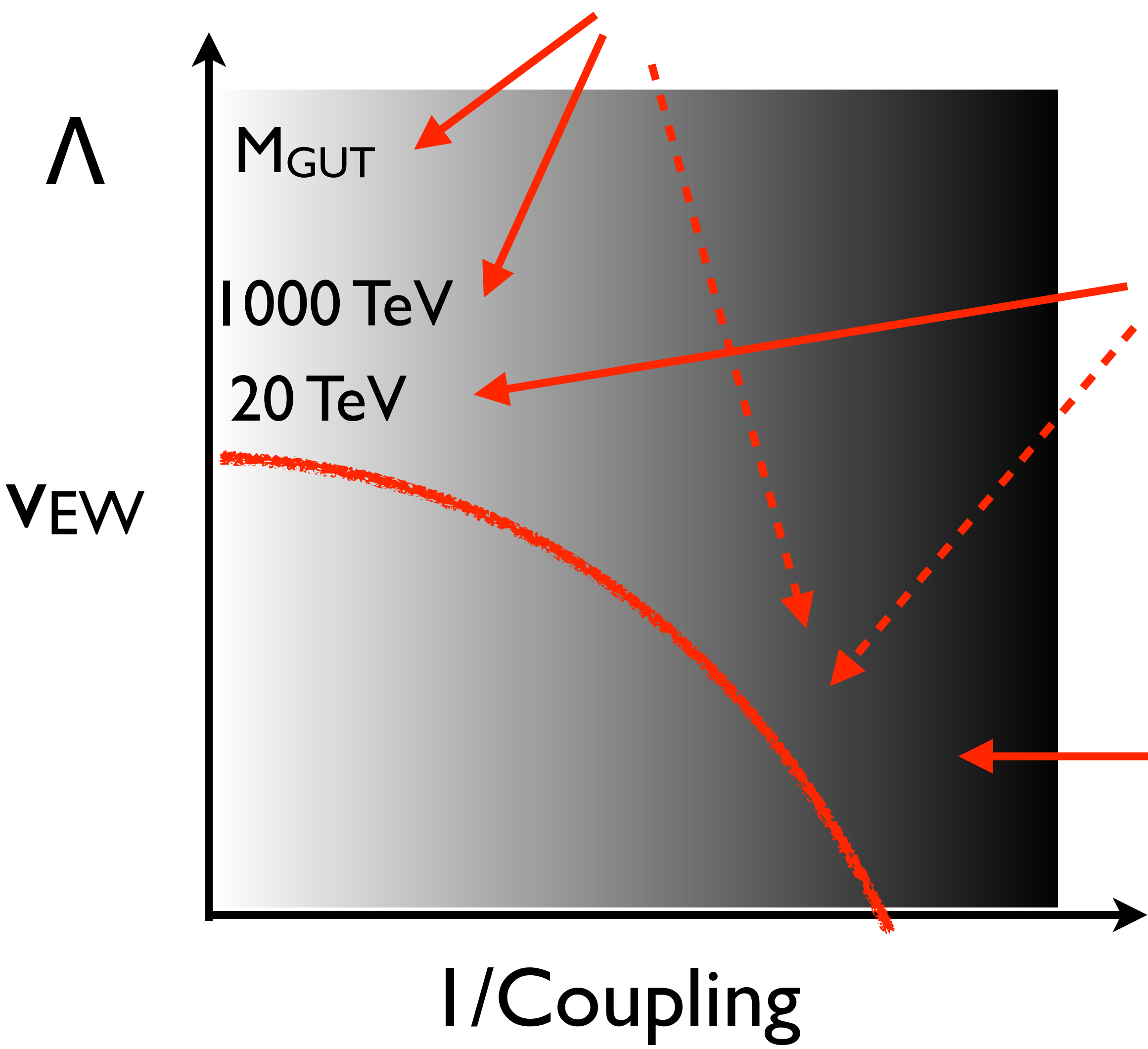


2. Precision measurements of SM-allowed processes: β-decays (mesons, neutron, nuclei), muon g-2, PV electron scattering, …

BSM probes @ low-energy frontier

- Three classes, pushing the boundary in qualitatively different ways and at different mass scales

1. Searches for rare or SM-forbidden processes that probe approximate or exact symmetries of the SM (L, B, CP, L_α): $0\nu\beta\beta$ decay, p decay EDMs, LFV ($\mu \to e$,, …)



2. Precision measurements of SM-allowed processes: β-decays (mesons, neutron, nuclei), muon g-2, PV electron scattering, …

3. Searches / characterization of light and weakly coupled particles: active ν's, sterile ν's, dark sector particles and "fifth force" mediators, axions, …

Impact of low-energy probes

- Discovery potential
  - Explore physics that is otherwise difficult / impossible to access: high mass scale; symmetry breaking; ultralight particles
  - A single deviation from SM expectation → new physics!

Impact of low-energy probes

- Discovery potential
  - Explore physics that is otherwise difficult / impossible to access: high mass scale; symmetry breaking; ultralight particles
  - A single deviation from SM expectation → new physics!

- Diagnosing power (when combining multiple probes)
  - Multiple EDM searches → underlying sources of CP violation
  - $0\nu\beta\beta$ decay, absolute ν mass measurements, ν oscillations, LFV ($\mu \to e$, $\tau \to e, \mu, \ldots$) → origin of neutrino mass
  - …

Impact of low-energy probes

- Discovery potential
  - Explore physics that is otherwise difficult / impossible to access: high mass scale; symmetry breaking; ultralight particles
  - A single deviation from SM expectation → new physics!

- Diagnosing power (when combining multiple probes)
  - Multiple EDM searches → underlying sources of CP violation
  - $0\nu\beta\beta$ decay, absolute ν mass measurements, ν oscillations, LFV ($\mu \to e$, $\tau \to e, \mu, \ldots$) → origin of neutrino mass
  - …

- Shed light on some of the big open questions about fundamental interactions

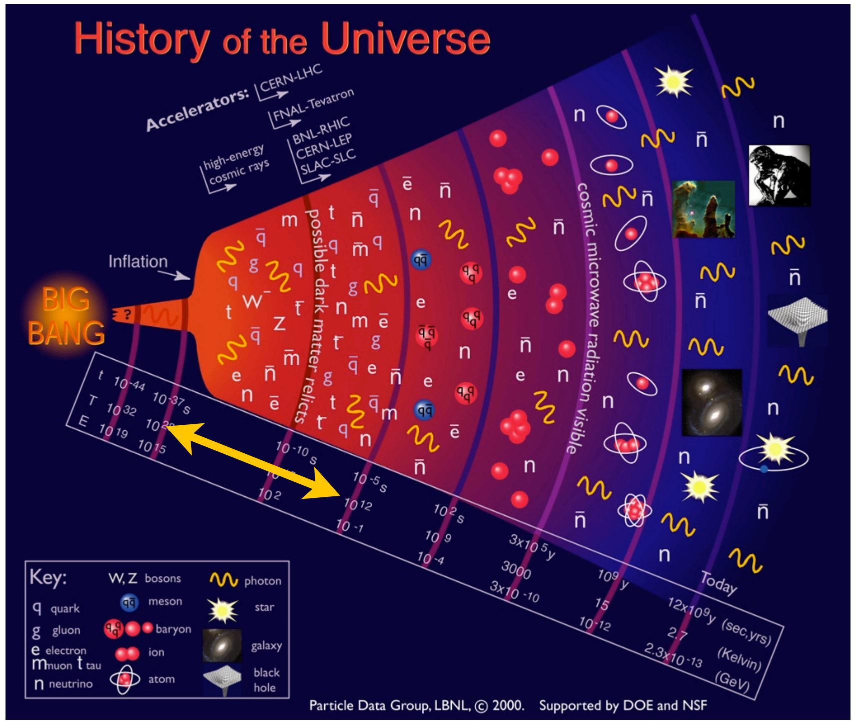
Connection to big questions

Baryon asymmetry
(violation of B, L, CP)

Baryogenesis requires (Sakharov)

- B (L) violation
- C and CP violation
- Departure from equilibrium

Baryogenesis does not work in the Standard Model



Connection to big questions

Origin of neutrino mass

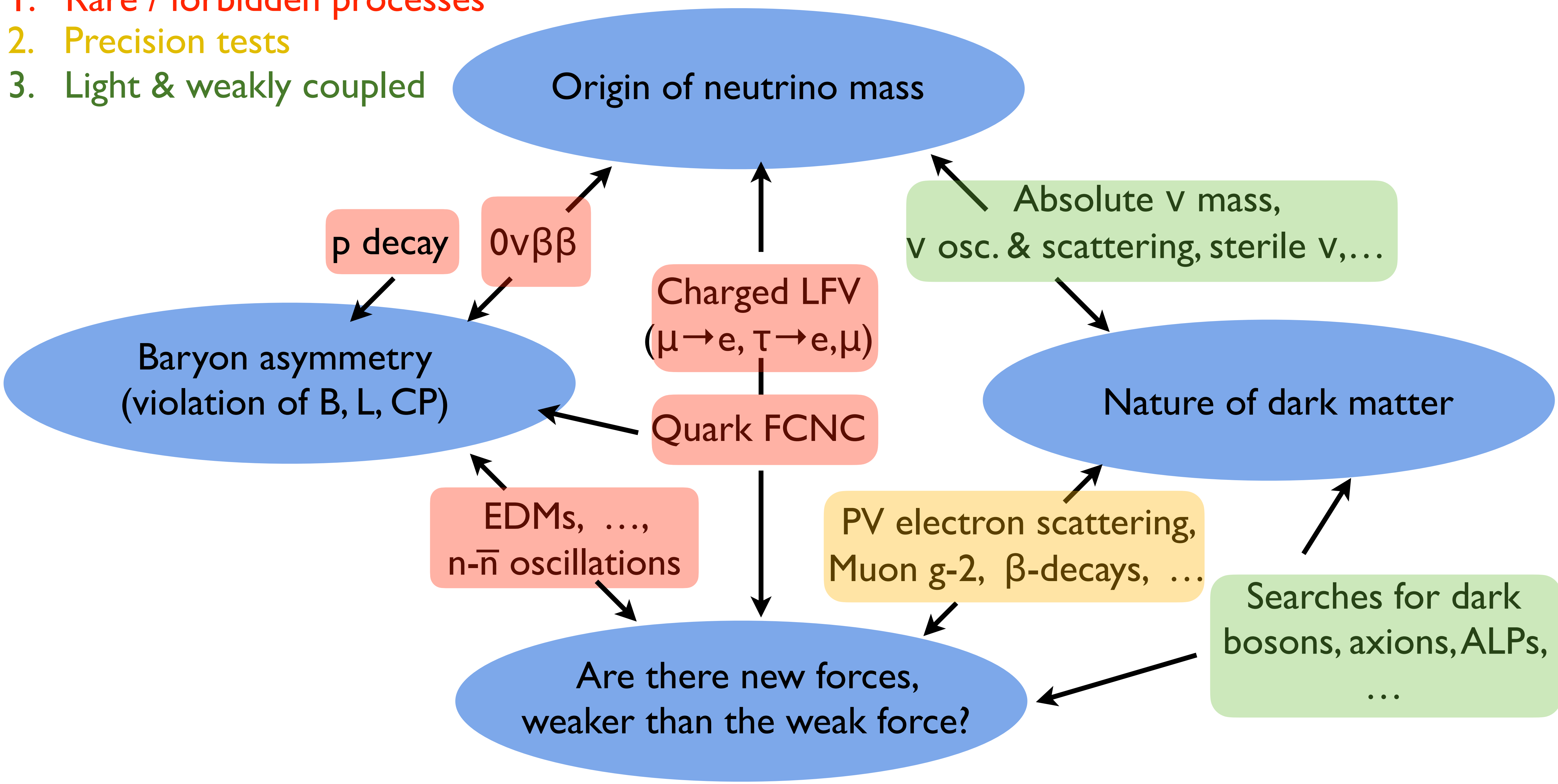
Baryon asymmetry
(violation of B, L, CP)

Nature of dark matter

Are there new forces,
weaker than the weak force?

Connection to big questions

1. Rare / forbidden processes
2. Precision tests
3. Light & weakly coupled



Theoretical challenges

- Multi-scale problem: need to connect possibly high-energy interactions written at the quark-gluon level to hadrons / nuclei

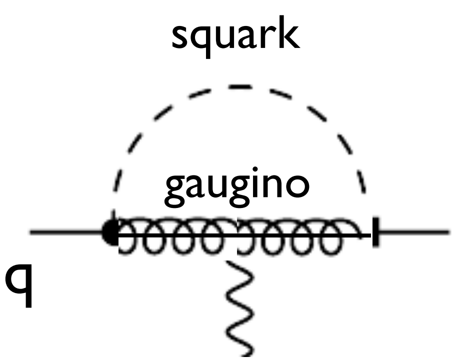
- Even when studying leptonic properties, handling hadron physics is essential (muon g-2, mu-to-e conversion, …)

- Tools: effective field theory, Lattice QCD, dispersion relations, nuclear many body methods, …

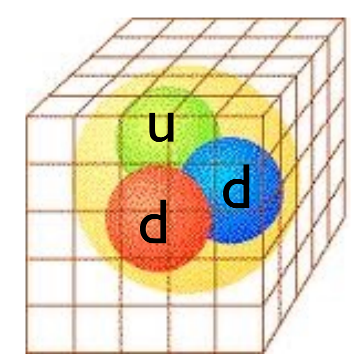
BSM scale

Hadronic scale

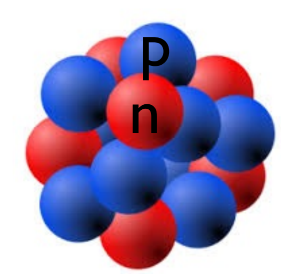
Nuclear scale



Quarks, gluons



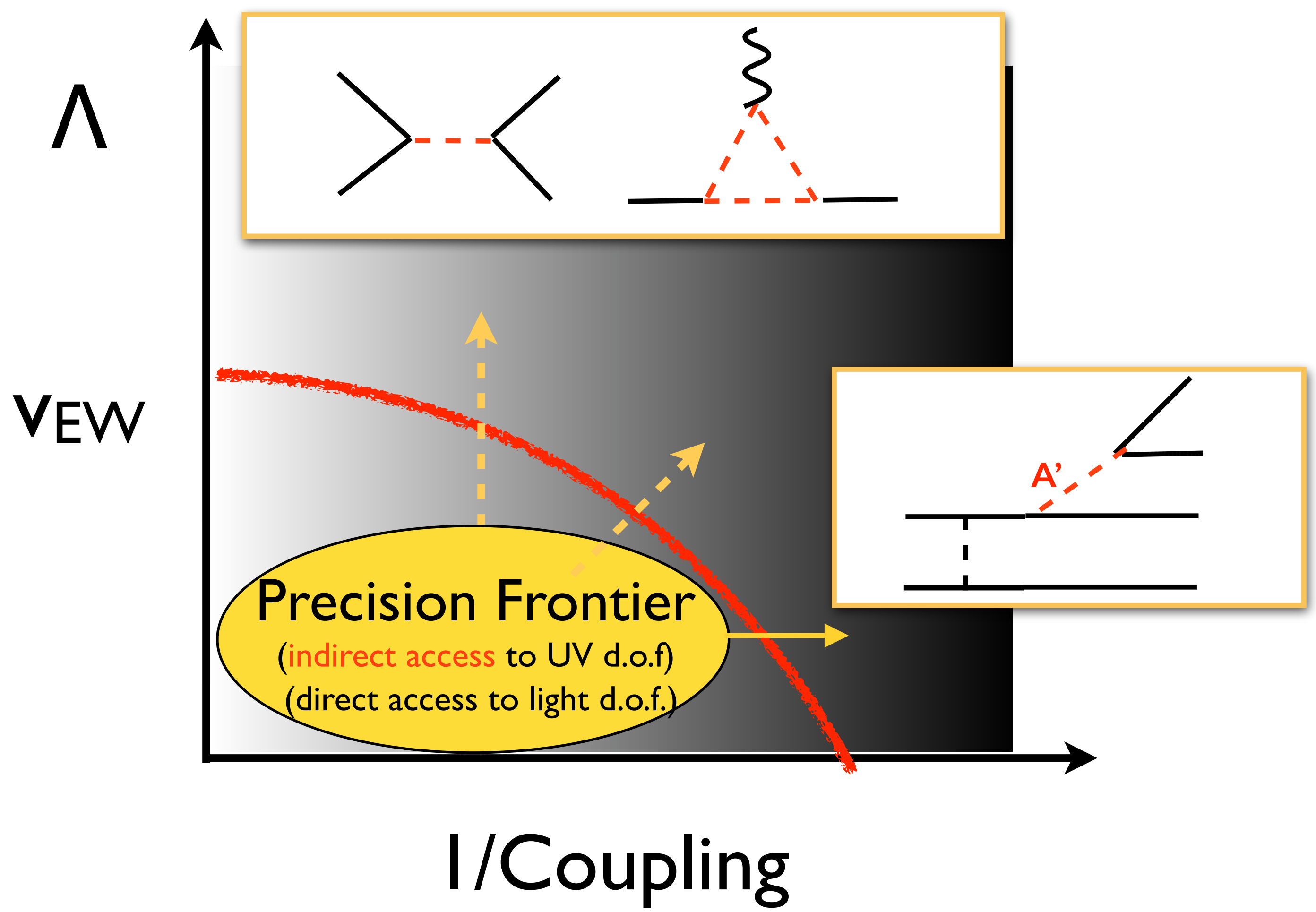
Mesons, Baryons



Nuclei

How does the precision frontier work? (Theory perspective)

Theory framework(s)

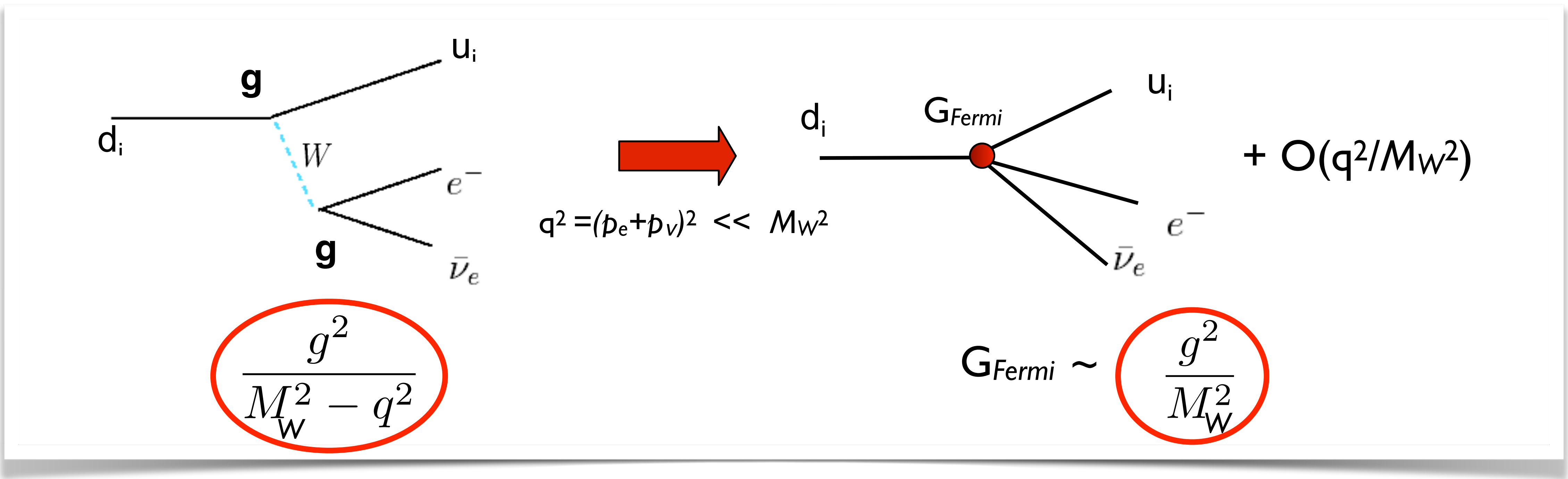


To motivate and analyze precision frontier searches, two fairly general EFT-based theory framework(s) have emerged, encompassing many underlying models

- High scale (UV) new physics: Standard Model EFT and its siblings
- Light & weakly coupled new physics: dark sectors and 'portals'

UV new physics: Standard Model EFT

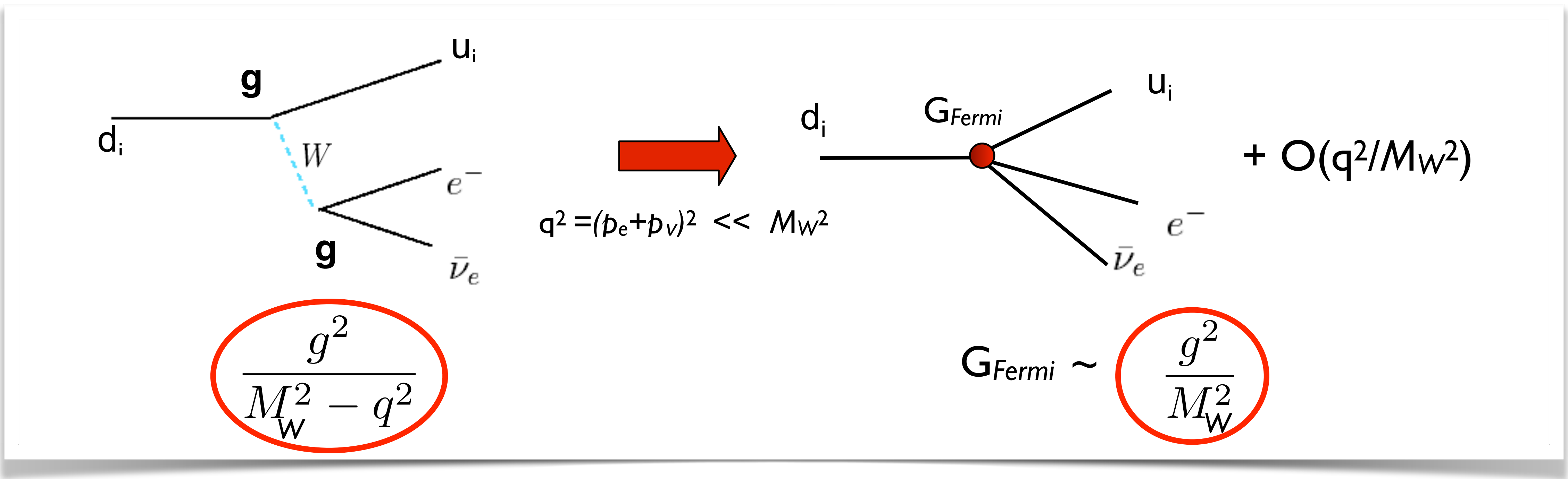
How do heavy particles affect physics at E << M?



Exchange of heavy particles generates a series of local interactions of increasing mass dimension (multiplied by inverse power of the new physics mass scale) consistent with the underlying symmetries (Lorentz, gauge, ...)

UV new physics: Standard Model EFT

How do heavy particles affect physics at E << M?



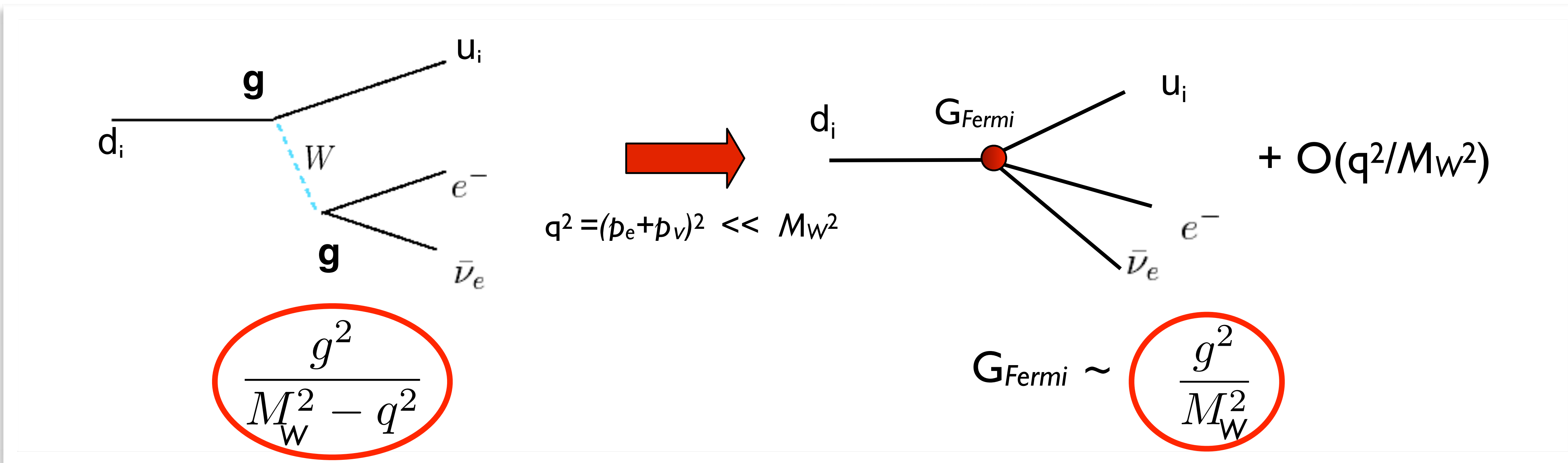
Exchange of heavy particles generates a series of local interactions of increasing mass dimension (multiplied by inverse power of the new physics mass scale) consistent with the underlying symmetries (Lorentz, gauge, ...)

Homework

- Work out mass dimension of fields:
  - Spin 1/2: $[\Psi]=3/2$
  - Spin 0 and 1: $[\Phi] = [V_\mu] = 1$

UV new physics: Standard Model EFT

How do heavy particles affect physics at E << M?



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

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

Exchange of heavy particles generates a series of local interactions of increasing mass dimension (multiplied by inverse power of the new physics mass scale) consistent with the underlying symmetries (Lorentz, gauge, …)

Appelquist-Carazzone 1975

Weinberg 1979, Wilczek-Zee1979, Buchmuller-Wyler 1986, ...

B. Grzadkowski, M. Iskrzyński , M. Misiak, J. Rosiek, 2010

Alonso, Jenkins, Manohar, Rodrigo, Trott 2013

Light & weakly coupled new physics: portals

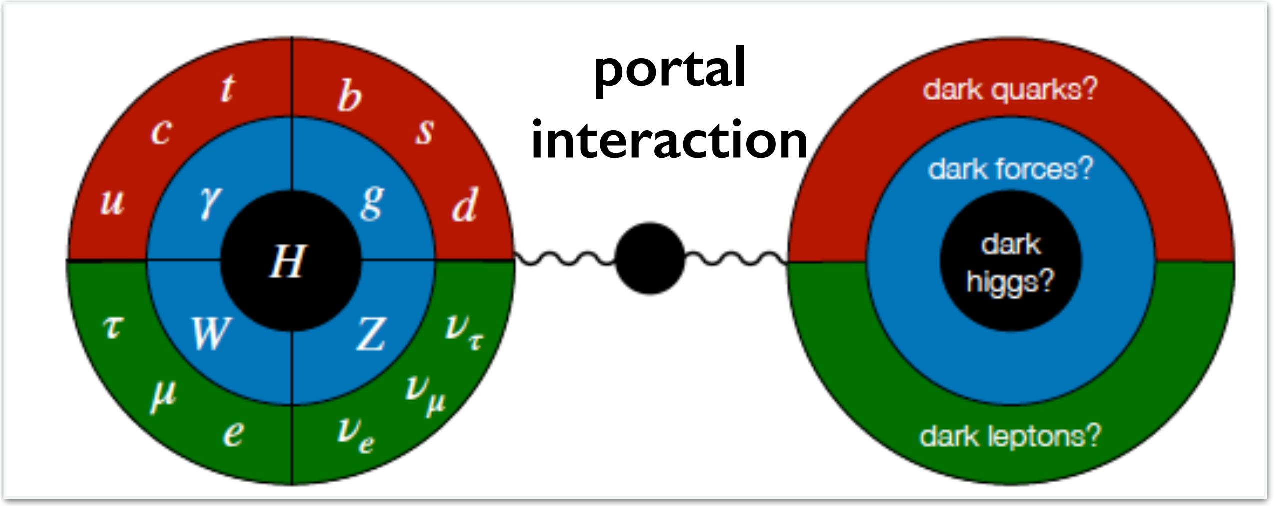
"Portals": dominant interactions through which the SM and dark sector couple
(↔ lowest dimensional SM singlet operators)

$$\mathcal{L} \sim \quad O_{\rm portals} + O\left(\frac{1}{\Lambda}\right)$$

$$O_{\rm Vector} = -\frac{\epsilon}{2}\, B^{\mu\nu} F'_{\mu\nu}$$

$$O_{\rm Neutrino} = -Y_N^{ij}\ \bar{L}_i H N_j$$

$$O_{\rm Higgs} = -H^\dagger H \left(A\, S + \lambda\, S^2\right)$$



Credit: Stefania Gori

Leading axion interactions appear at O(1/Λ):

$$aF\tilde{F}/f_a\ ,\ aG\tilde{G}/f_a\ ,\ \bar{\psi}\gamma^\mu\gamma_5\psi\,\partial_\mu a/f_a$$

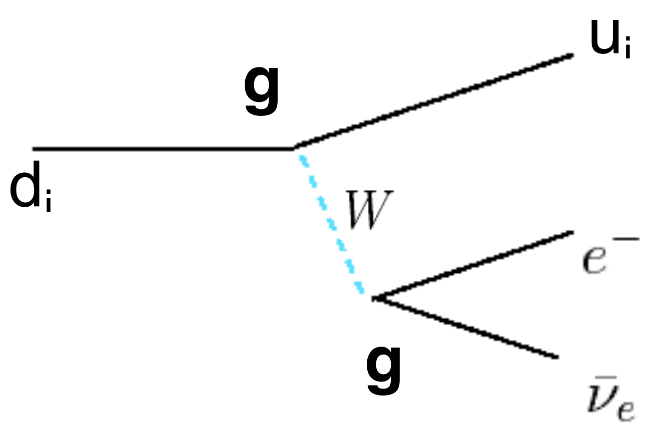
Back to UV new physics

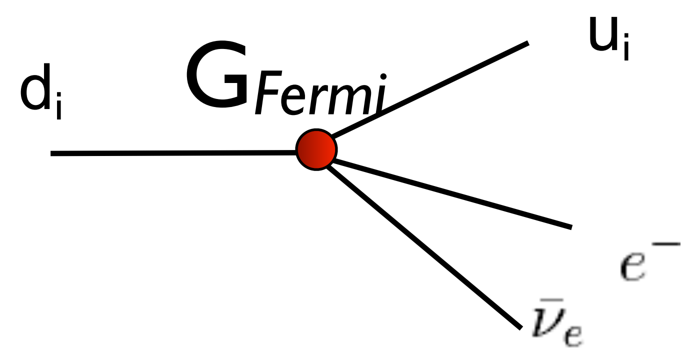
- Key point: particles of mass M affect physics at E << M by inducing
  - a shift in coupling constants of known interactions
  - new local interactions suppressed by powers of E/M

Back to UV new physics

- Key point: particles of mass M affect physics at E << M by inducing
  - a shift in coupling constants of known interactions
  - new local interactions suppressed by powers of E/M

"Top-down": heavy particle exchange generates new local interaction





$+ \, O(q^2/M_W^2)$

$$\frac{g^2}{M_W^2 - q^2}$$

$q^2 = (p_e + p_\nu)^2 \ll M_W^2$

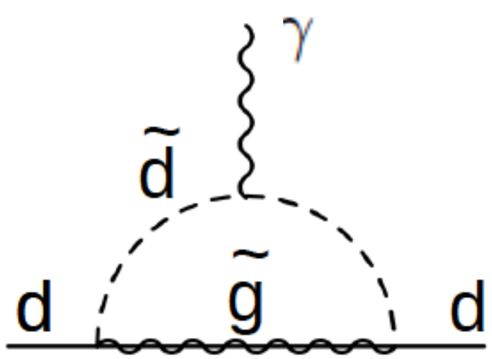
$$G_{Fermi} \sim \frac{g^2}{M_W^2}$$

Tree level example

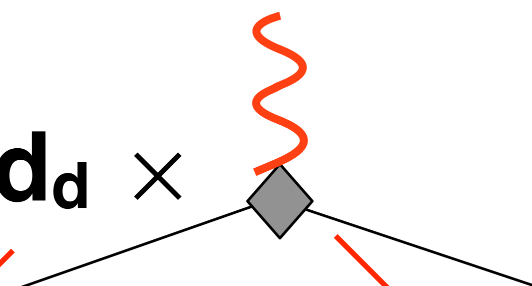
Back to UV new physics

- Key point: particles of mass M affect physics at E << M by inducing
  - a shift in coupling constants of known interactions
  - new local interactions suppressed by powers of E/M

"Top-down": heavy particle exchange generates new local interaction



$d_d \times$



$+ \, O(v^4/M_{SUSY}^4)$

$$\frac{\alpha_s}{4\pi}\frac{v^2}{M_{SUSY}^2} \times \phi_{CP} \times 10^{-22}\, e\,\mathrm{cm}$$

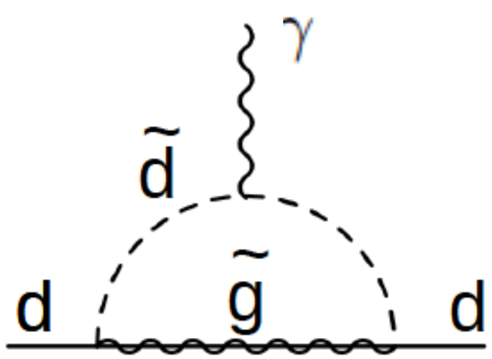
$\mathbf{S_d \cdot E}$

Loop level example

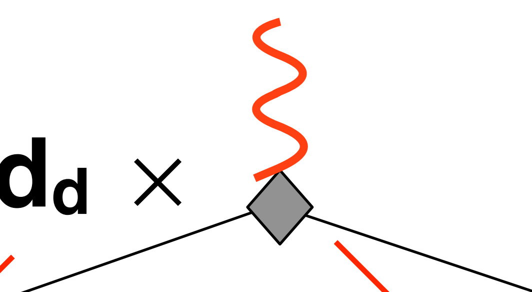
Back to UV new physics

- Key point: particles of mass M affect physics at E << M by inducing
  - a shift in coupling constants of known interactions
  - new local interactions suppressed by powers of E/M

"Top-down": heavy particle exchange generates new local interaction



$\Longleftrightarrow$ $\mathbf{d_d} \times$



$+ \, O(v^4/M_{SUSY}^4)$

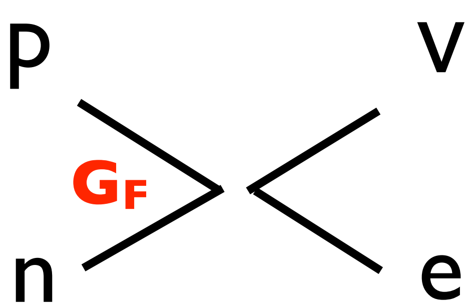
$$\frac{\alpha_s}{4\pi} \frac{v^2}{M_{SUSY}^2} \times \phi_{CP} \times 10^{-22} \, e\,\text{cm}$$

$\mathbf{S_d \cdot E}$

But one can take a "bottom-up" approach, too,
in order to infer properties of underlying new physics.
(This is the SMEFT approach)

Example from history

Fermi, 1934



Current-current, parity conserving

Fermi scale:
$\Lambda_F = G_F^{-1/2} \sim 250$ GeV

Fermi's theory of beta decays ($n \to p\, e\, \bar{\nu}_e$):

Postulate new local interaction (that respects Lorentz invariance and charge conservation) in terms of "light" degrees of freedom (n, p, e, ν_e):

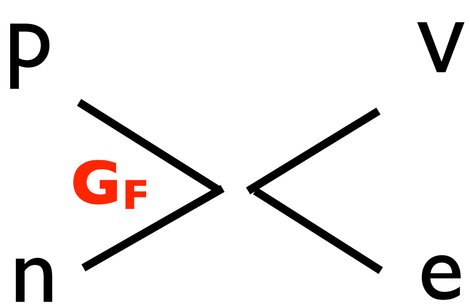
$$H \sim G_F\, \bar{p}\Gamma n\, \bar{e}\Gamma \nu_e$$

Coupling constant $G_F \equiv 1/\Lambda_F^2$ determined by fitting the "slow" beta decay rates ⇒

point to mass scale $\Lambda_F >> m_n \sim$ GeV

Example from history

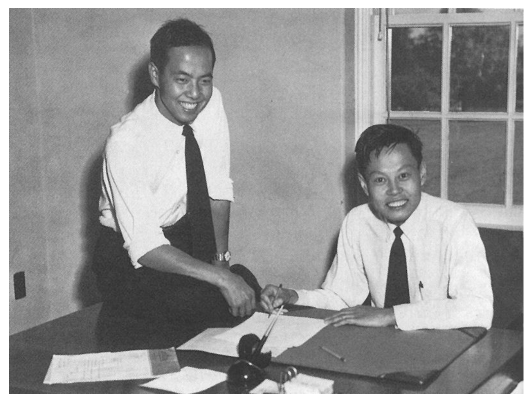
Fermi, 1934

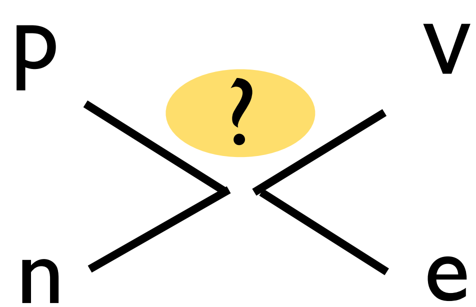


Current-current,
parity conserving

Fermi scale:
$\Lambda_F = G_F^{-1/2} \sim 250$ GeV

Lee and Yang, 1956



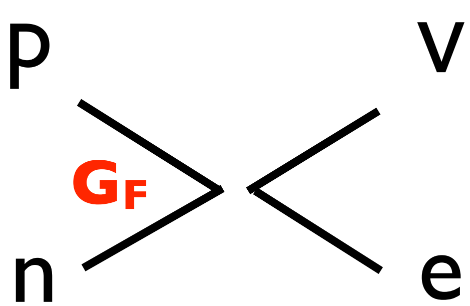


Parity conserving:
VV, AA, SS, TT ...
Parity violating: VA, SP, ...

Lee and Yang:
use most general Lorentz-invariant interaction

Example from history

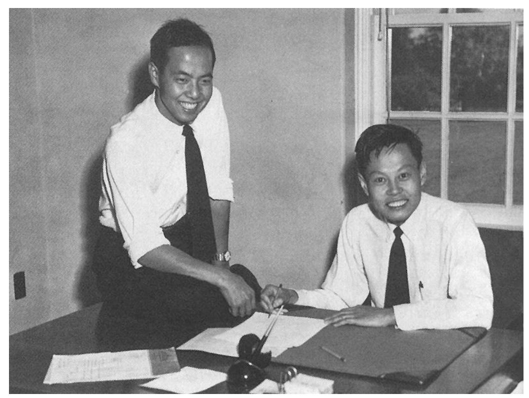
Fermi, 1934

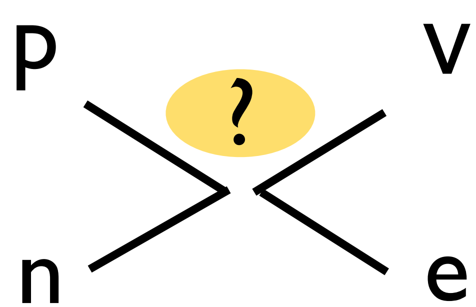


Current-current, parity conserving

Fermi scale:
$\Lambda_F = G_F^{-1/2} \sim 250$ GeV

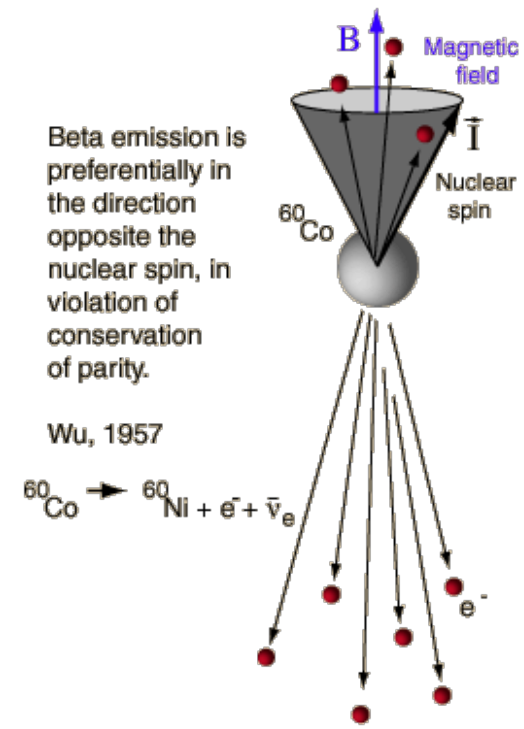
Lee and Yang, 1956





Parity conserving:
VV, AA, SS, TT ...
Parity violating: VA, SP, ...

Lee and Yang:
use most general Lorentz-invariant interaction

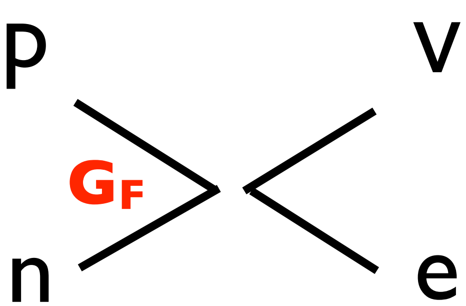


C-S Wu

Experiment: parity is violated!
(but could be VA, SP, …)

Example from history

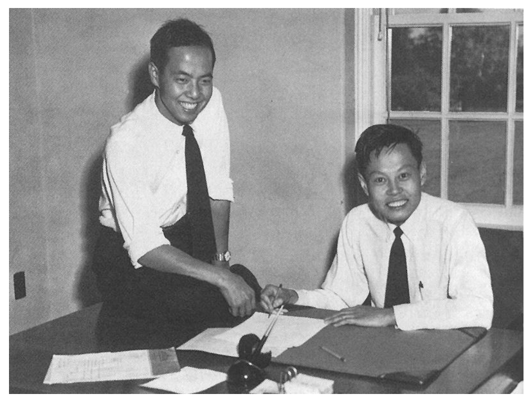
Fermi, 1934

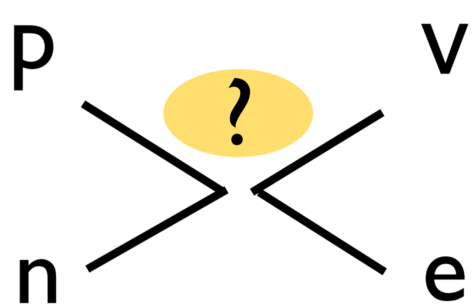


Current-current,
parity conserving

Fermi scale:
$\Lambda_F = G_F^{-1/2} \sim 250$ GeV

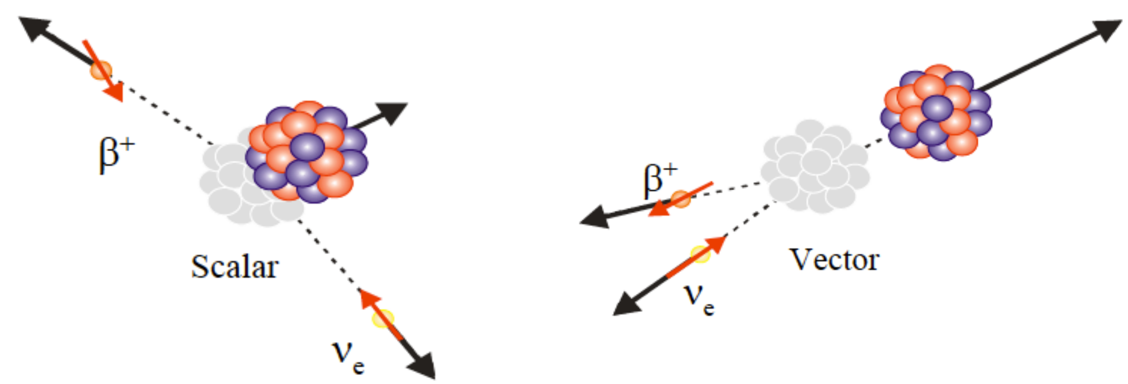
Lee and Yang, 1956





Parity conserving:
VV, AA, SS, TT ...
Parity violating: VA, SP, ...

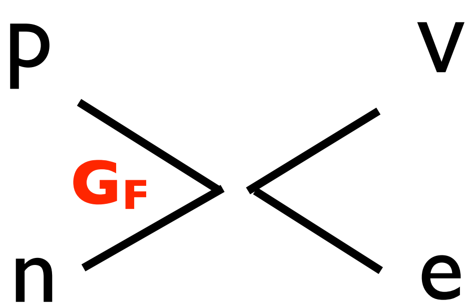
Differential decay distributions depend on structure of currents



Model diagnosing!

Example from history

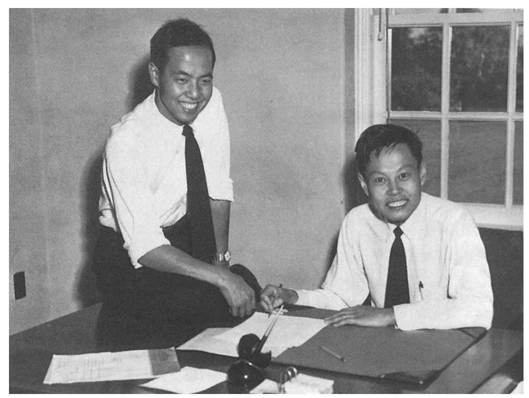
Fermi, 1934

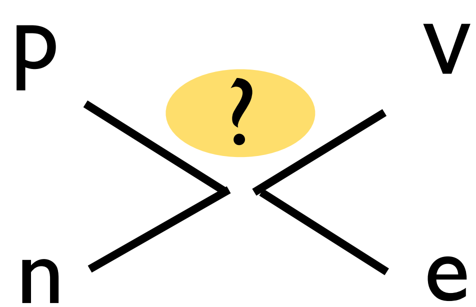


Current-current, parity conserving

Fermi scale:
$\Lambda_F = G_F^{-1/2} \sim 250$ GeV

Lee and Yang, 1956





Parity conserving:
VV, AA, SS, TT ...
Parity violating: VA, SP, ...

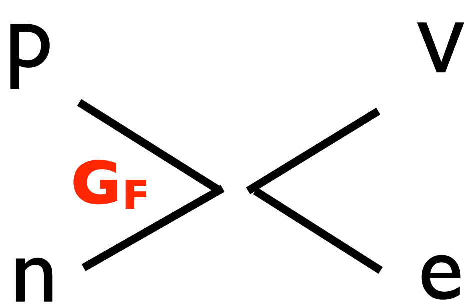
Marshak & Sudarshan,
Feynman & Gell-Mann 1958

It's (V-A)*(V-A) !!

"V-A was the key"
S. Weinberg

Example from history

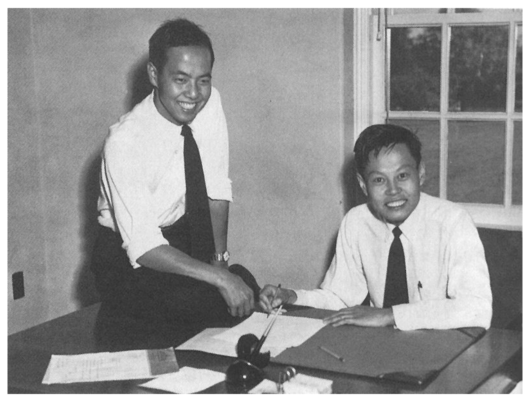
Fermi, 1934

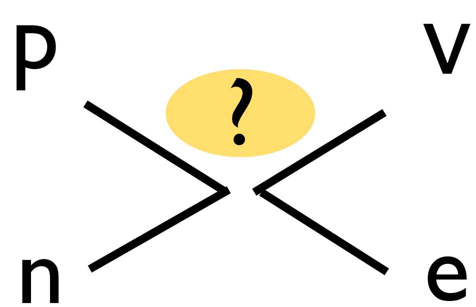


Current-current,
parity conserving

Fermi scale:
$\Lambda_F = G_F^{-1/2} \sim 250$ GeV

Lee and Yang, 1956





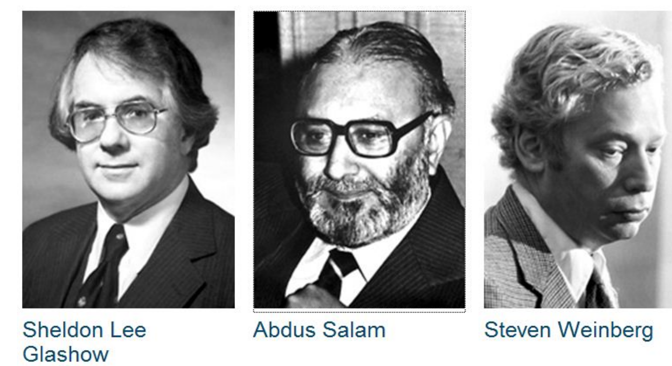
Parity conserving:
VV, AA, SS, TT ...
Parity violating: VA, SP, ...

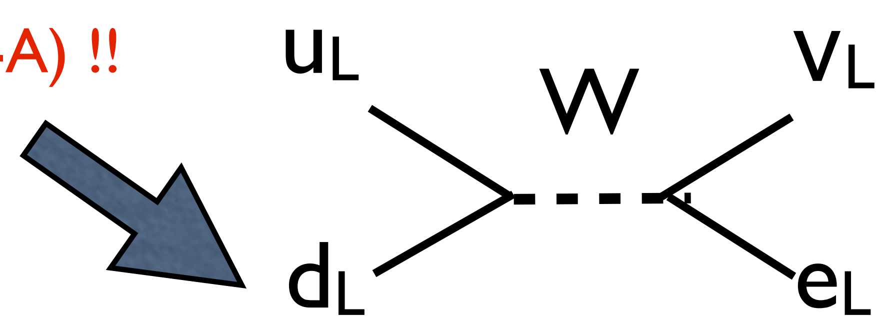
Marshak & Sudarshan,
Feynman & Gell-Mann 1958

It's (V-A)*(V-A) !!

"V-A was the key"
S. Weinberg

Glashow,
Salam,
Weinberg



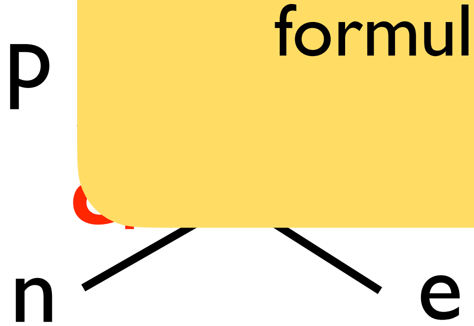


Embed in non-abelian
chiral gauge theory,
predict neutral currents

Example from history

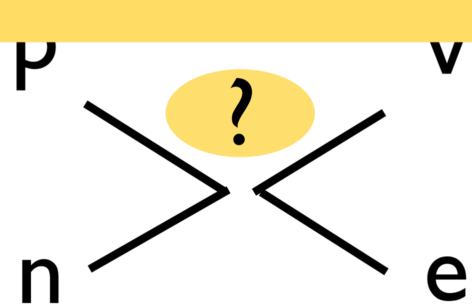
Lessons: nuclear beta decays were able to

- "Detect" physics originating at $\Lambda_F = G_F^{-1/2} \sim 250$ GeV >> E_{exp}
- Point to key features of the underlying interactions, that led to the formulation of the Standard Model

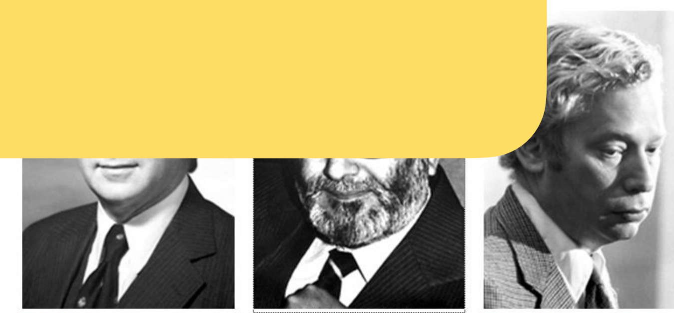


Current-current, parity conserving

Fermi scale:
$\Lambda_F = G_F^{-1/2} \sim 250$ GeV



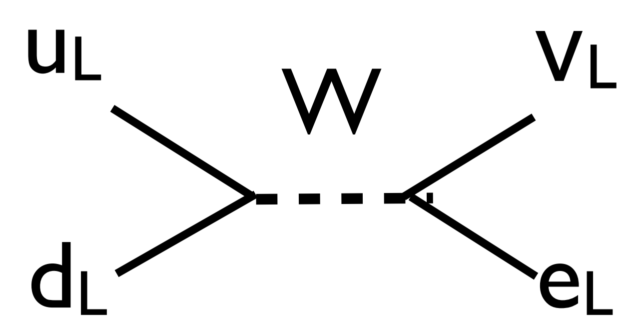
Parity conserving: VV, AA, SS, TT ...
Parity violating: VA, SP, ...



Sheldon Lee Glashow Abdus Salam Steven Weinberg

It's (V-A)*(V-A) !!

"V-A was the key"
S. Weinberg



Embed in non-abelian chiral gauge theory, predict neutral currents

Fast forward ~60 years: SMEFT

- Describe effects of new physics originating at $\Lambda >> \Lambda_F \sim v_{ew}$ through local operators (the low-energy footprints of heavy states)

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

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

- "Standard Model EFT" (SMEFT):
  - ★ Build operators out of SM fields
  - ★ Impose Lorentz + SM gauge symmetry, but no other symmetry (B, L, CP, flavor)
  - ★ Organize operators according to mass dimension: power counting in E/Λ, M_W/Λ. At a given order the EFT is renormalizable and predictive

Fast forward ~60 years: SMEFT

- Describe effects of new physics originating at $\Lambda >> \Lambda_F \sim v_{ew}$ through local operators (the low-energy footprints of heavy states)

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

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

- "Standa…
  - ★ Build …
  - ★ Impos… CP, flavor)
  - ★ Orga… E/Λ, M_W/Λ.
    At a g…

You are seeing here the 3 tenets of any EFT:

- Identify relevant degrees of freedom
- Identify the symmetries of the problem
- Power counting — expansion parameter

Fast forward ~60 years: SMEFT

- Describe effects of new physics originating at $\Lambda >> \Lambda_F \sim v_{ew}$ through local operators (the low-energy footprints of heavy states)

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

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

- Other EFTs differ in particle content and/or symmetry realization
  - νSMEFT: SMEFT + ν_R
  - HEFT: EFT for G.B ~ ChPT. Higgs h is a singlet. More general Higgs potential

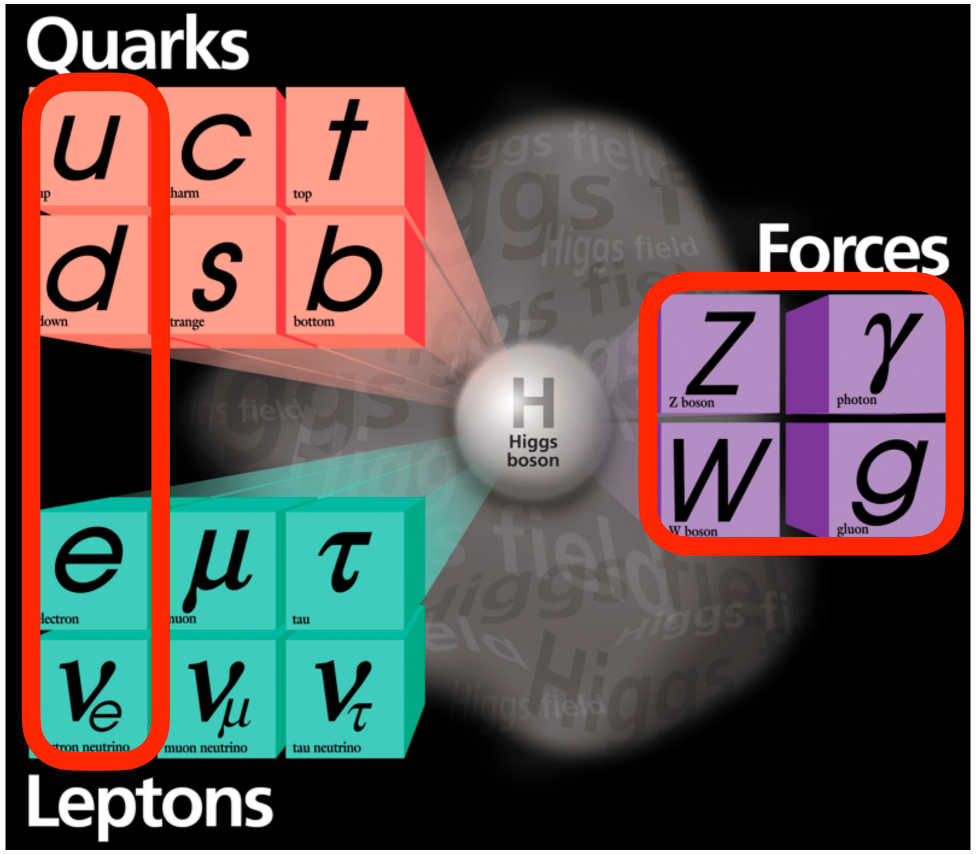
Why use EFTs for new physics

- General framework encompassing classes of models
- Efficient tool to analyze and compare experiments at different scales (from collider to table-top)
- The steps below UV scale Λ apply to *all* models: in particular, the hadronic / nuclear aspects can be treated once and for all…
- Very useful diagnosing tool in this "pre-discovery" phase
- Inform model building (success story provided by the SM itself). EFT and model approaches are not mutually exclusive!

Some details on the SM(EFT)

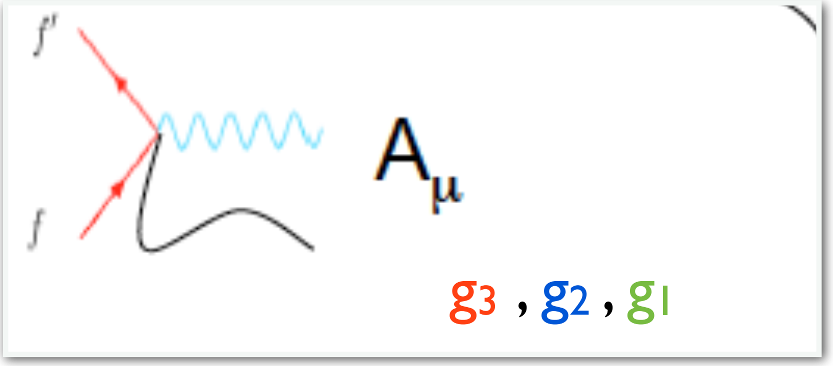
The Standard Model in pictures

Spin 1/2:
ordinary matter
+ 2 heavier
generations



Spin 1: force carriers

Interactions governed by gauge symmetry principle
$SU(3)_c$ x $SU(2)_W$ x $U(1)_Y$

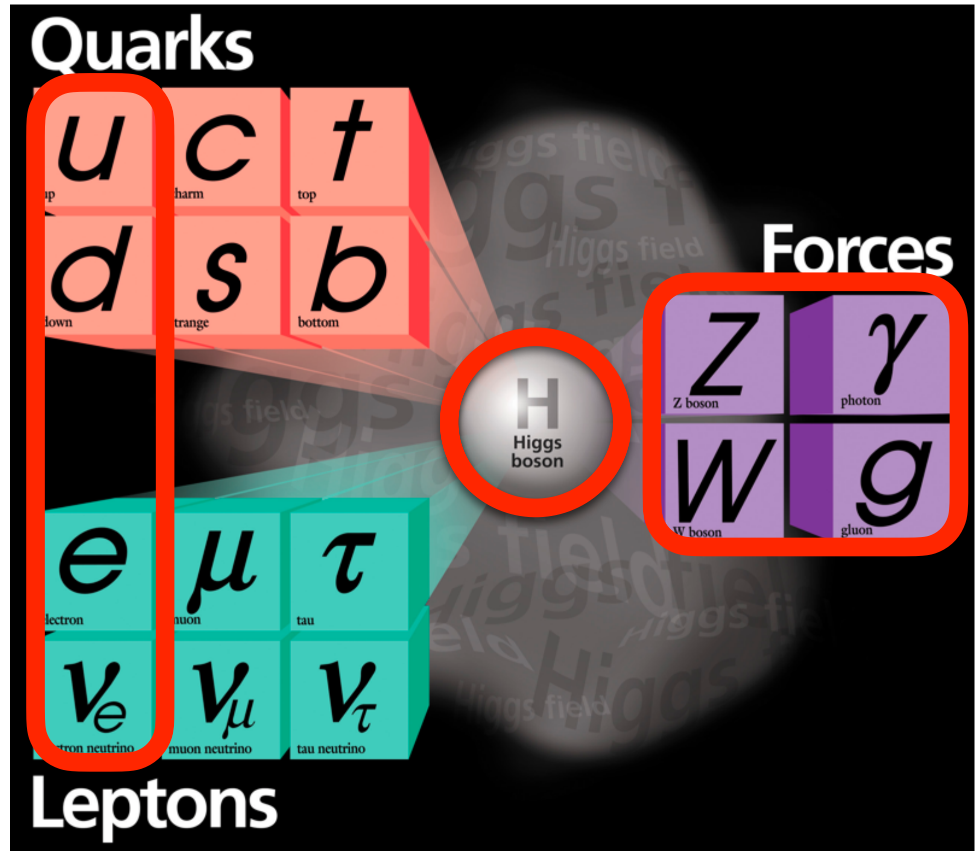


$$\mathcal{L}_I(x) \sim J_\mu(x)\, A^\mu(x)$$

The Standard Model in pictures

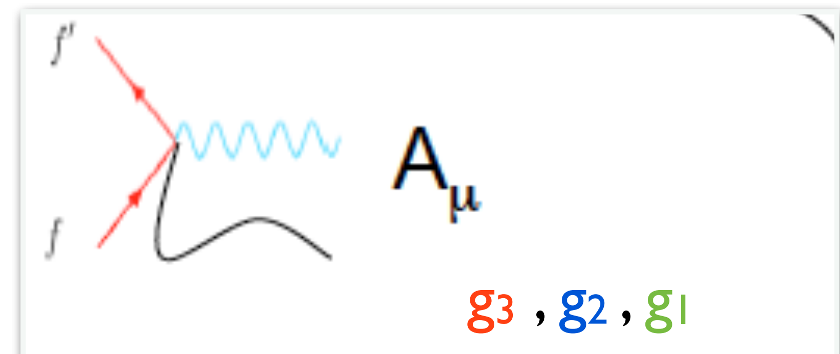
Spin 1/2:
ordinary matter
+ 2 heavier
generations

Spin 0: Higgs boson

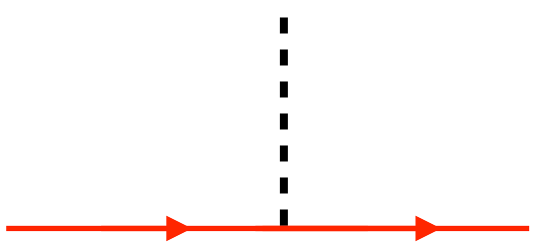


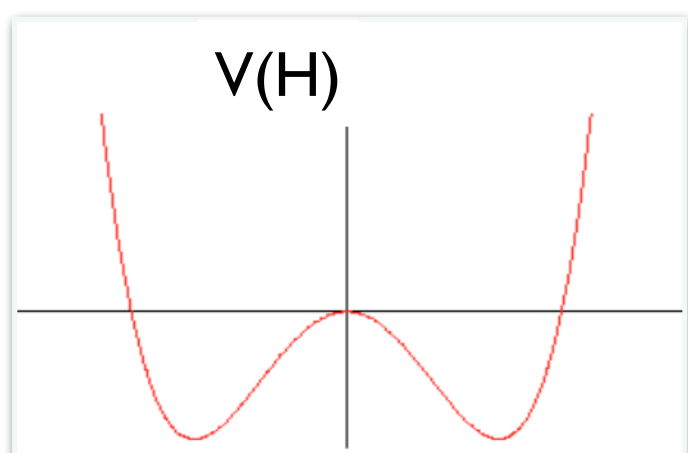
Spin 1: force carriers

Interactions governed by
gauge symmetry principle
$SU(3)_c \times SU(2)_W \times U(1)_Y$



$$\mathcal{L}_I(x) \sim J_\mu(x)\, A^\mu(x)$$

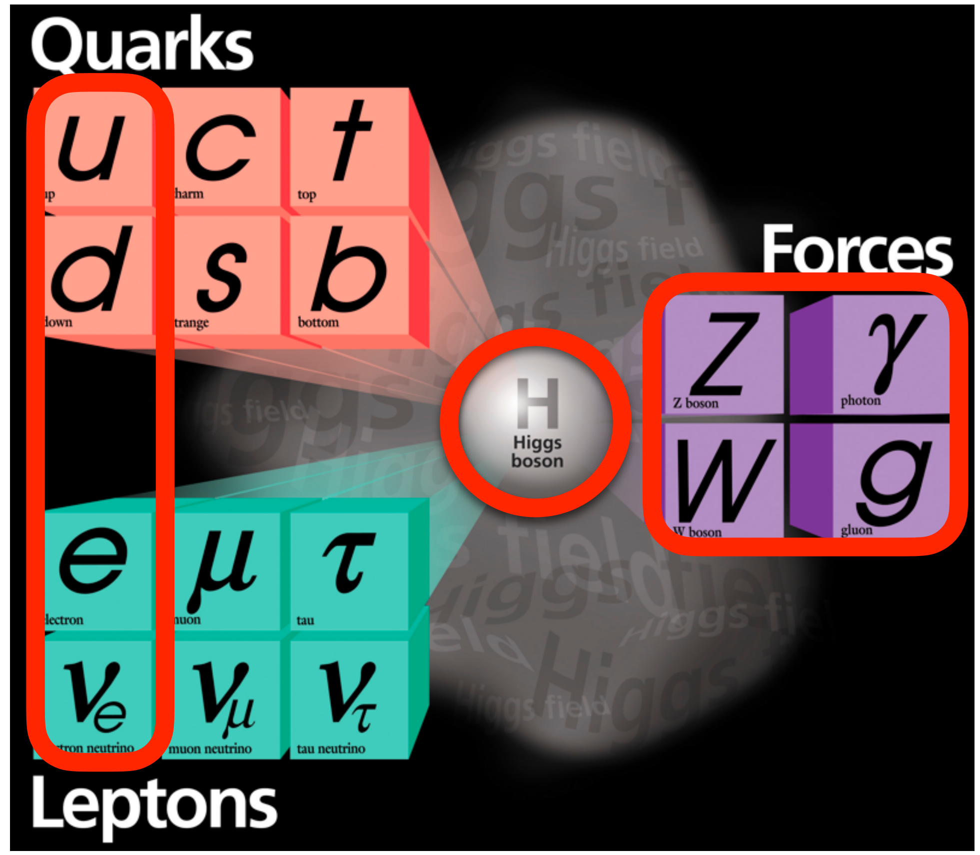




The Standard Model in pictures

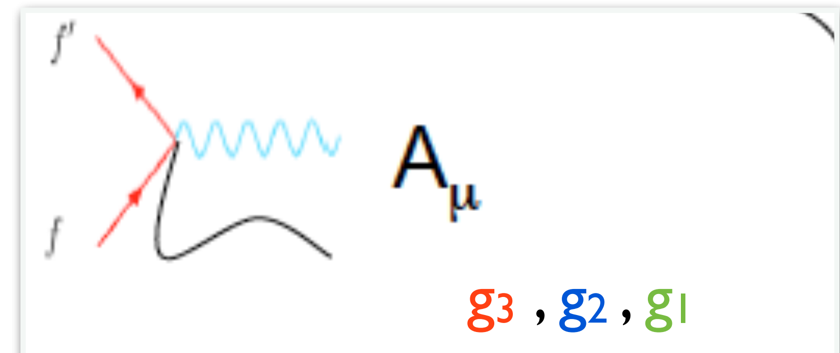
Spin 0: Higgs boson

Spin 1/2:
ordinary matter
+ 2 heavier
generations



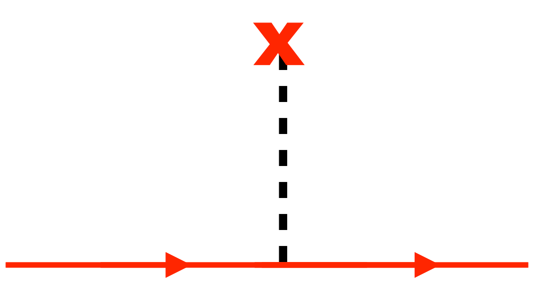
Spin 1: force carriers

Interactions governed by
gauge symmetry principle
$SU(3)_c \times SU(2)_W \times U(1)_Y$

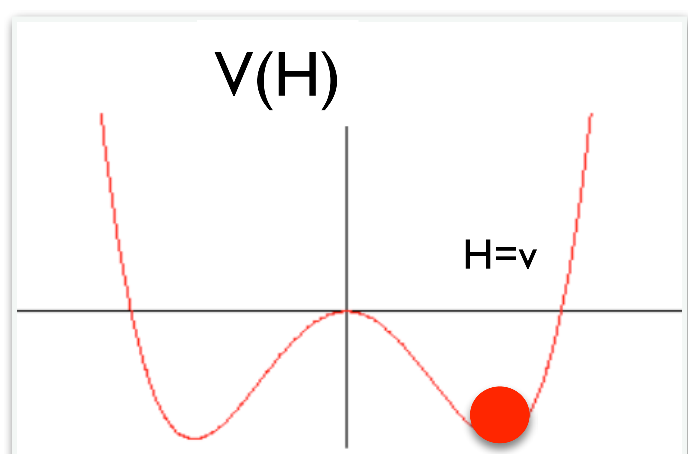


$$\mathcal{L}_I(x) \sim J_\mu(x)\, A^\mu(x)$$

Higgs mechanism



Massive quarks
and leptons



Massive EW gauge bosons
(short range weak force)

SM(EFT): building blocks

- Gauge group: G= $SU(3)_c \times SU(2)_W \times U(1)_Y$
- Building blocks: fields and their "charges" (transformation properties under G)

	$SU(3)_c \times SU(2)_W \times U(1)_Y$ 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)	$\varphi \to V_{SU(2)}\, \varphi$

$Q = T_3 + Y$

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

Gauge transformation:

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

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

SM(EFT): building blocks

- Gauge group: G= $SU(3)_c$ x $SU(2)_W$ x $U(1)_Y$
- Building blocks: fields and their "charges" (transformation properties under G)

	$SU(3)_c$ x $SU(2)_W$ x $U(1)_Y$ 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)	$\varphi \to V_{SU(2)}\, \varphi$

		$SU(3)_c$ x $SU(2)_W$ x $U(1)_Y$ 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, $I = 1 \cdots 3$, $W^I_{\mu\nu} = \partial_\mu W^I_\nu - \partial_\nu W^I_\mu + g \epsilon_{IJK} W^J_\mu W^K_\nu$	(1,3,0)
B boson:	B_μ, $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$.	(1,1,0)

Gauge transformation:
$$W^I_{\mu\nu} \frac{\sigma^I}{2} \to V(x) \left[W^I_{\mu\nu} \frac{\sigma^I}{2} \right] V^\dagger(x)$$
$$V(x) = e^{ig\beta_a(x)\frac{\sigma_a}{2}}$$

$Q = T_3 + Y$

- Recipe to build Standard Model Lagrangian: write down all operators of mass dimension ≤ 4 ** that respect gauge and Lorentz symmetry
- SMEFT: go beyond dimension 4

The SMEFT Lagrangian: dim=4

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

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

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

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

The SMEFT Lagrangian: dim=4

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

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

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

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

U(3) [3 families!] for each fermionic gauge multiplet,
e. g. $q_i \to M_{ij} q_j$, $M \in U(3)$

- This Lagrangian has a large flavor symmetry group: $U(3)^5$.
  Nothing distinguishes the three families.

The SMEFT Lagrangian: dim=4

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

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

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

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

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

EWSB →

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

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

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

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

- $Y_{e,u,d}$ matrices are the only couplings that distinguish the three families

Standard Model symmetries (1)

- Gauge symmetry: color is manifest, SU(2)xU(1) is hidden (Higgs mechanism)

Standard Model symmetries (1)

- Gauge symmetry: color is manifest, SU(2)xU(1) is hidden (Higgs mechanism)

- Global internal symmetries:
  - $U(3)^5$ explicitly broken only by Yukawa couplings*
  - U(1) associated with B, and $L_{\alpha=e,\mu,\tau}$ survive (hence $L= L_e + L_\mu + L_\tau$)
  - Anomaly: only B-L is conserved

* Approximate global symmetries: Flavor $SU(n)_L \times SU(n)_R$ (n=2,3), …

Standard Model symmetries (1)

- Gauge symmetry: color is manifest, SU(2)xU(1) is hidden (Higgs mechanism)

- Global internal symmetries:
  - $U(3)^5$ explicitly broken only by Yukawa couplings*
  - U(1) associated with B, and $L_{\alpha=e,\mu,\tau}$ survive (hence $L= L_e + L_\mu + L_\tau$)
  - Anomaly: only B-L is conserved

- Discrete symmetries:
  - 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

* Approximate global symmetries: Flavor $SU(n)_L x SU(n)_R$ (n=2,3), …

Standard Model symmetries (2)

- Global symmetries such as B and $L_{\alpha=e,\mu,\tau}$ are *not an input* in the construction of the model, rather an *outcome* that depends on the field content and the fact that we included only operators up to dimension 4

- Weinberg called these "accidental symmetries"

- Accidental symmetries are typically broken by higher dimensional operators obeying Lorentz and Gauge invariance

Standard Model symmetries (2)

- Global symmetries such as B and $L_{\alpha=e,\mu,\tau}$ are *not an input* in the construction of the model, rather an *outcome* that depends on the field content and the fact that we included only operators up to dimension 4

- Weinberg called these "accidental symmetries"

- Accidental symmetries are typically broken by higher dimensional operators obeying Lorentz and Gauge invariance

Accidental symmetries and symmetries broken in a very specific way in the SM (flavor, CP) offer great opportunity to probe physics beyond the SM

Guided tour of $\mathcal{L}_{eff}$ beyond dim. 4

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

Guided tour of $\mathcal{L}_{eff}$ beyond dim. 4

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

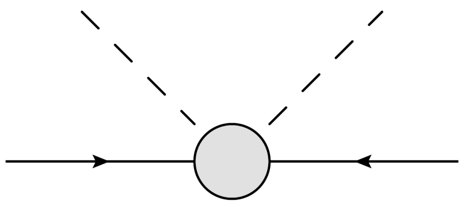
- Dim 5: only one operator

Weinberg 1979

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

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

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



Guided tour of $\mathcal{L}_{eff}$ beyond dim. 4

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

- Dim 5: only one operator

Weinberg 1979

$$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \quad \ell = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad \hat{O}_{\rm dim=5} = \ell^T C \epsilon \varphi \, \varphi^T \epsilon \ell \qquad \begin{array}{c} C = i\gamma_2\gamma_0 \\ \epsilon = i\sigma_2 \end{array}$$

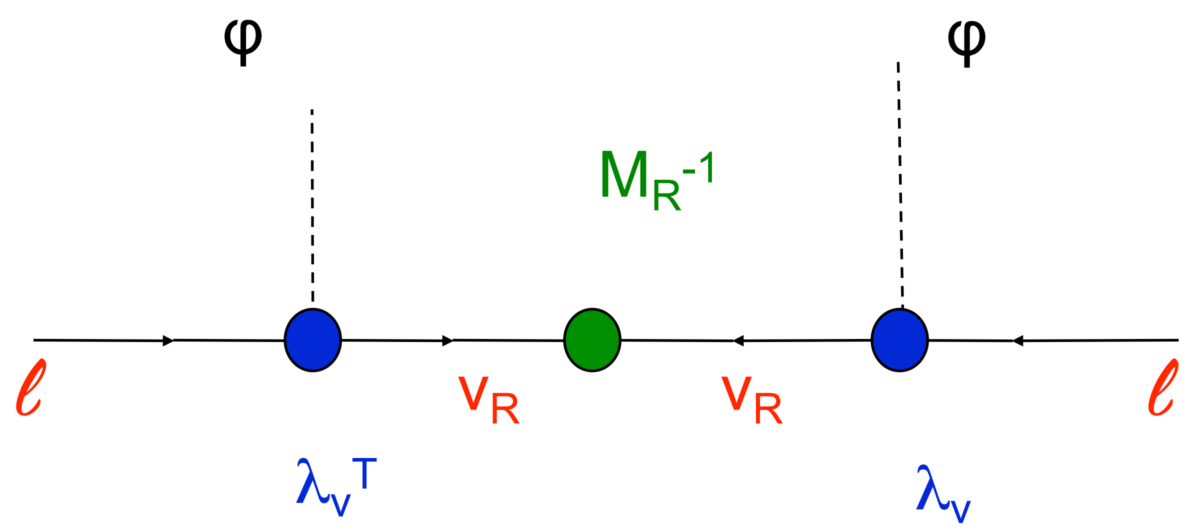
- Violates total lepton number $\quad \ell \to e^{i\alpha}\ell \qquad e \to e^{i\alpha} e$

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

- Example: explicit realization of dimension-5 operator in models with heavy R-handed Majorana neutrinos



Integrate out heavy ν_R

$$g_{\alpha\beta} \sim (\lambda_\nu^T M_R^{-1} \lambda_\nu)_{\alpha\beta}$$

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

Guided tour of $\mathcal{L}_{eff}$ beyond dim. 4

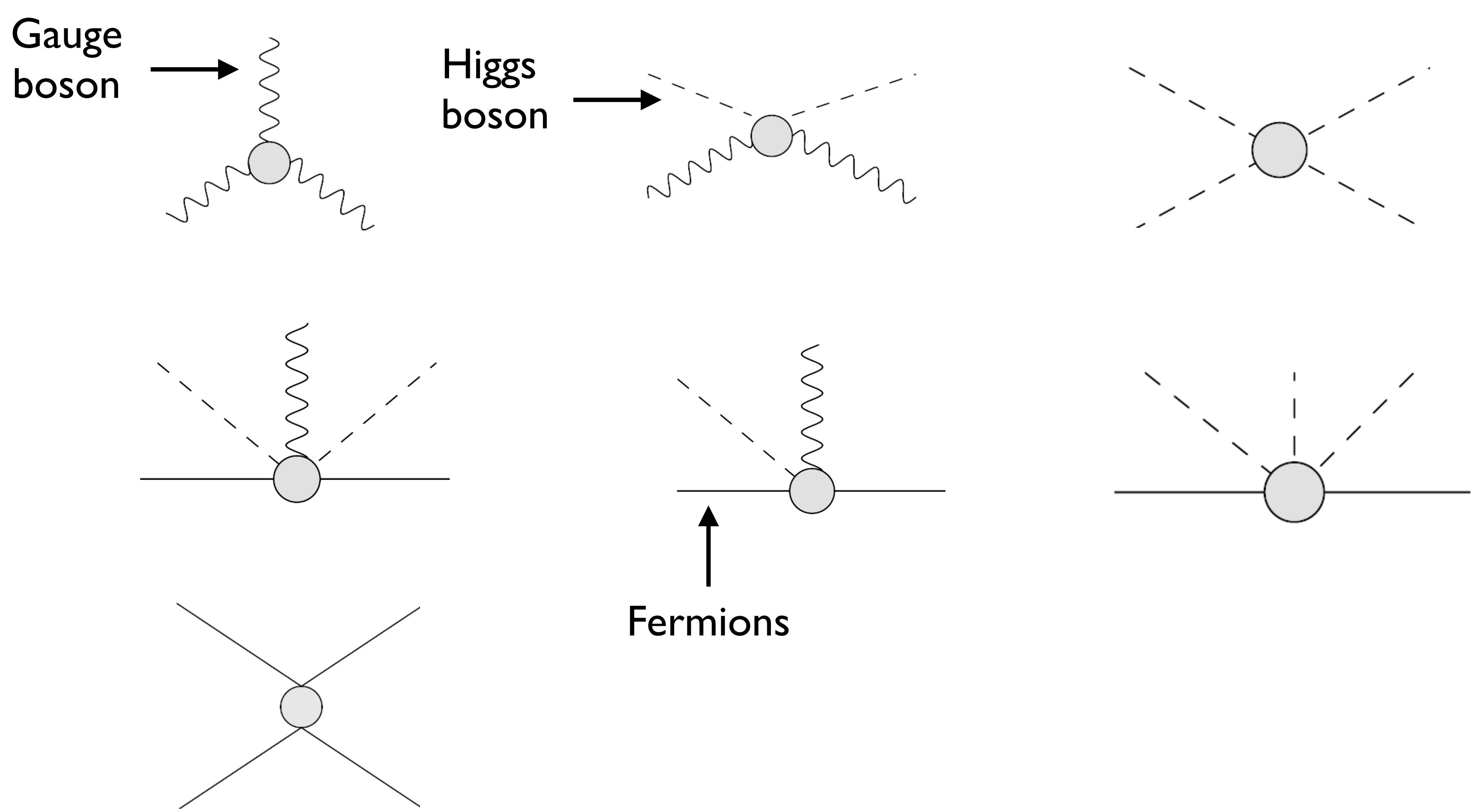
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

- Dim 6: affect *many* processes (59 structures not including flavor → 2499 if one counts flavor structures)

No fermions

Two fermions

Four fermions



Guided tour of $\mathcal{L}_{eff}$ beyond dim. 4

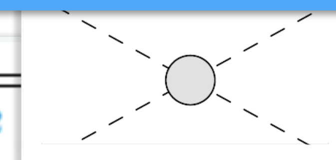
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

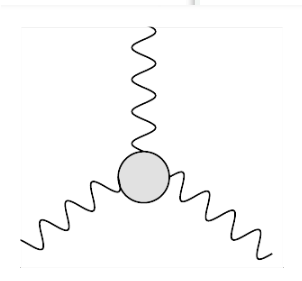
- Dim 6: affect *many* processes
  - B violation (ΔB=ΔL=1)
  - Gauge and Higgs boson couplings [LHC as a precision frontier tool!]
  - CPV, LFV, qFCNC, ...
  - Corrections to g-2, Charged Currents, Neutral Currents, …
- EFT beyond tree-level: one-loop *running of effective couplings* is known

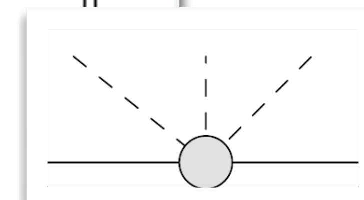
Weinberg 1979
Wilczek-Zee1979
Buchmuller-Wyler 1986, ...
Grzadkowski-Iskrzynksi-Misiak-Rosiek (2010)

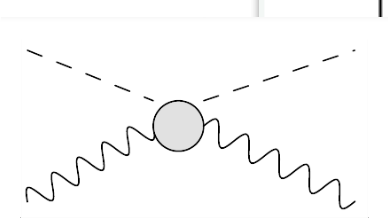
Alonso, Jenkins, Manohar, Trott 2013

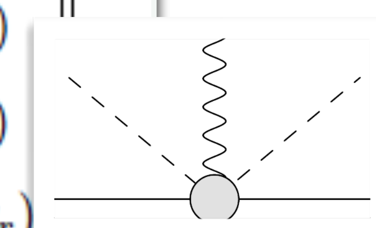
Full dim-6 operator basis (1)



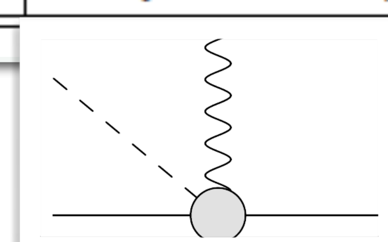








X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu} e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\,\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu} u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\,\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

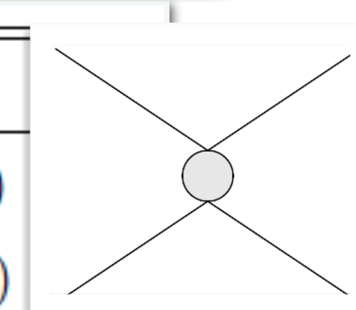


$$\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi \equiv i\varphi^\dagger\left(D_\mu - \overleftarrow{D}_\mu\right)\varphi$$

$$\varphi^\dagger i\overleftrightarrow{D}_\mu^I\,\varphi \equiv i\varphi^\dagger\left(\tau^I D_\mu - \overleftarrow{D}_\mu\tau^I\right)\varphi$$

Grzadkowski-Iskrzynksi-Misiak-Rosiek (2010) 1008.4884

Full dim-6 operator basis (2)

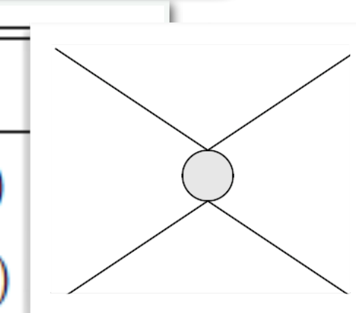


$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		*B*-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Grzadkowski-Iskrzynksi-Misiak-Rosiek (2010) 1008.4884

Full dim-6 operator basis (2)



$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

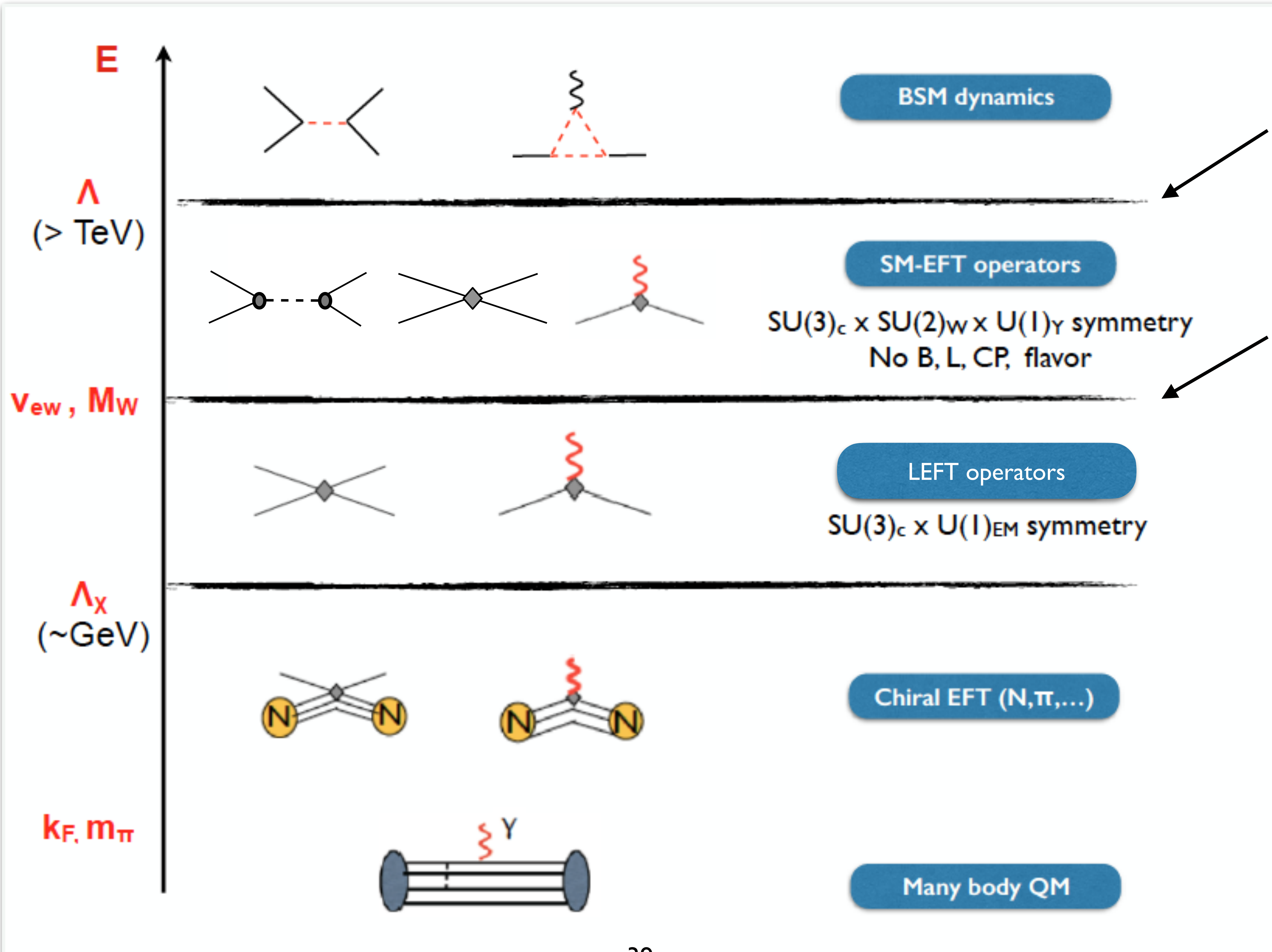
Homework

- Find which dim.6 operators may affect the process you are studying (as an experimentalist or a theorist)
- What type of UV models can generate those operators? (Useful info in de Blas et al, 1711.10391)

Grzadkowski-Iskrzynksi-Misiak-Rosiek (2010) 1008.4884

Bridging scales: a tower of EFTs

To connect UV physics to low-energy processes, use multiple EFTs

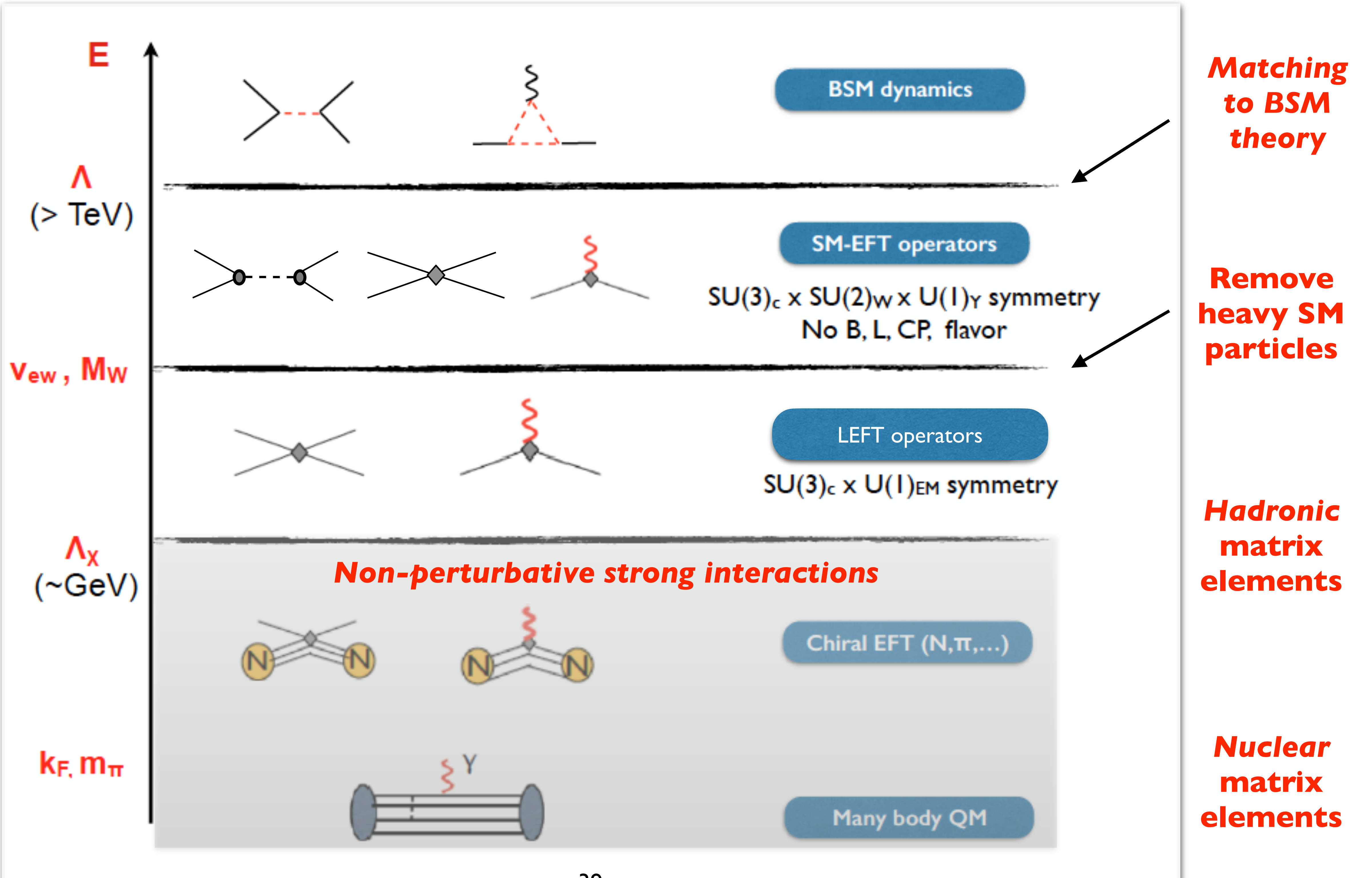


Matching to BSM theory

Remove heavy SM particles

Bridging scales: a tower of EFTs

To connect UV physics to low-energy processes, use multiple EFTs



What scales are we probing?

- A (very) rough indication of discovery potential is given by reach in Λ
- Effective scale probed by an experiment can be obtained through this equation:

Contribution to observable 'O' induced by SMEFT operators →

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

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

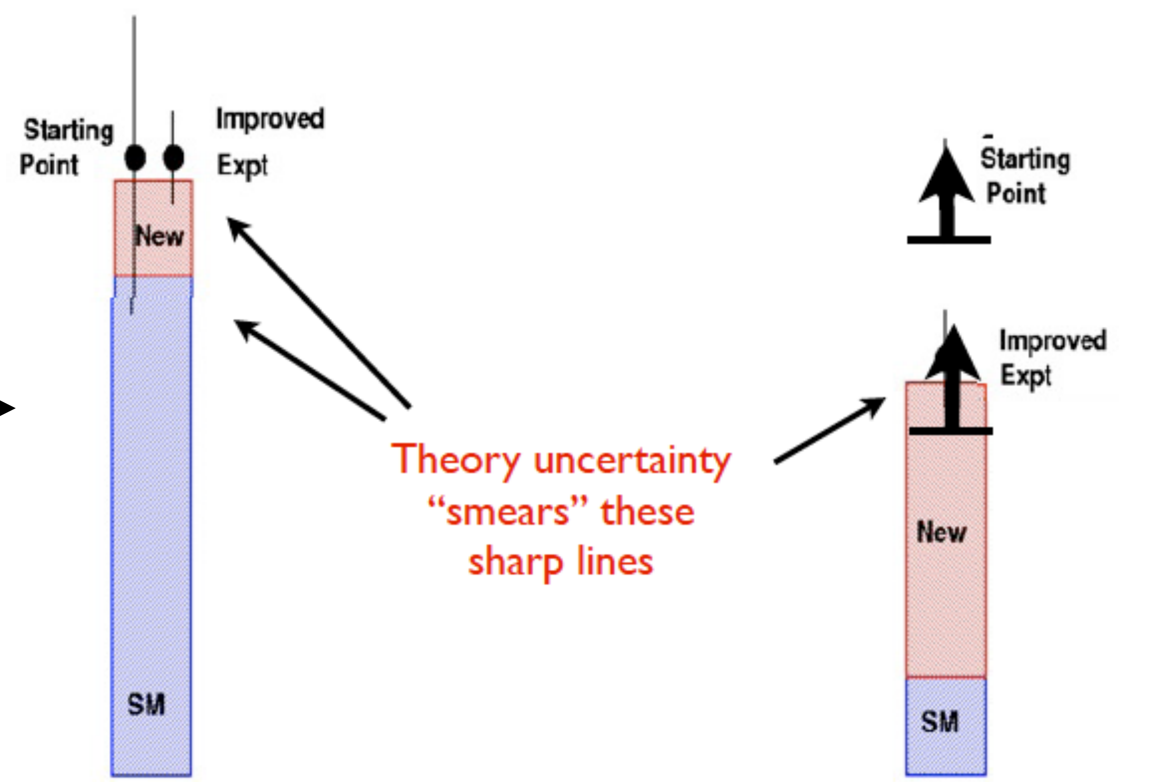
What scales are we probing?

- A (very) rough indication of discovery potential is given by reach in Λ
- Effective scale probed by an experiment can be obtained through this equation:

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

Contribution to observable 'O' induced by SMEFT operators

(for any observable O, $\delta O_{BSM} \sim (v/\Lambda)^n \quad n=2,4,..$)

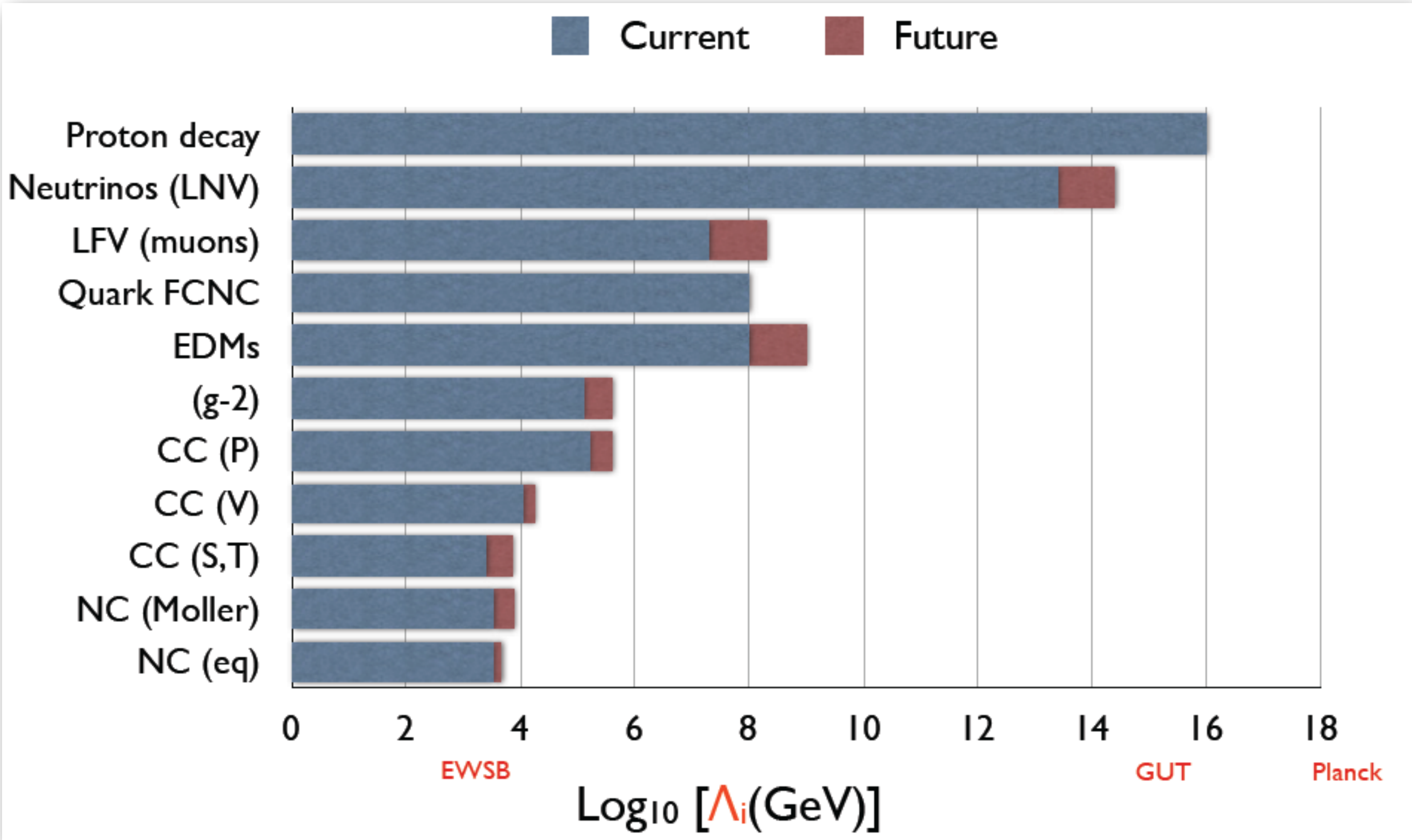


Precision tests: need high-precision theory and experiment

Rare / forbidden processes

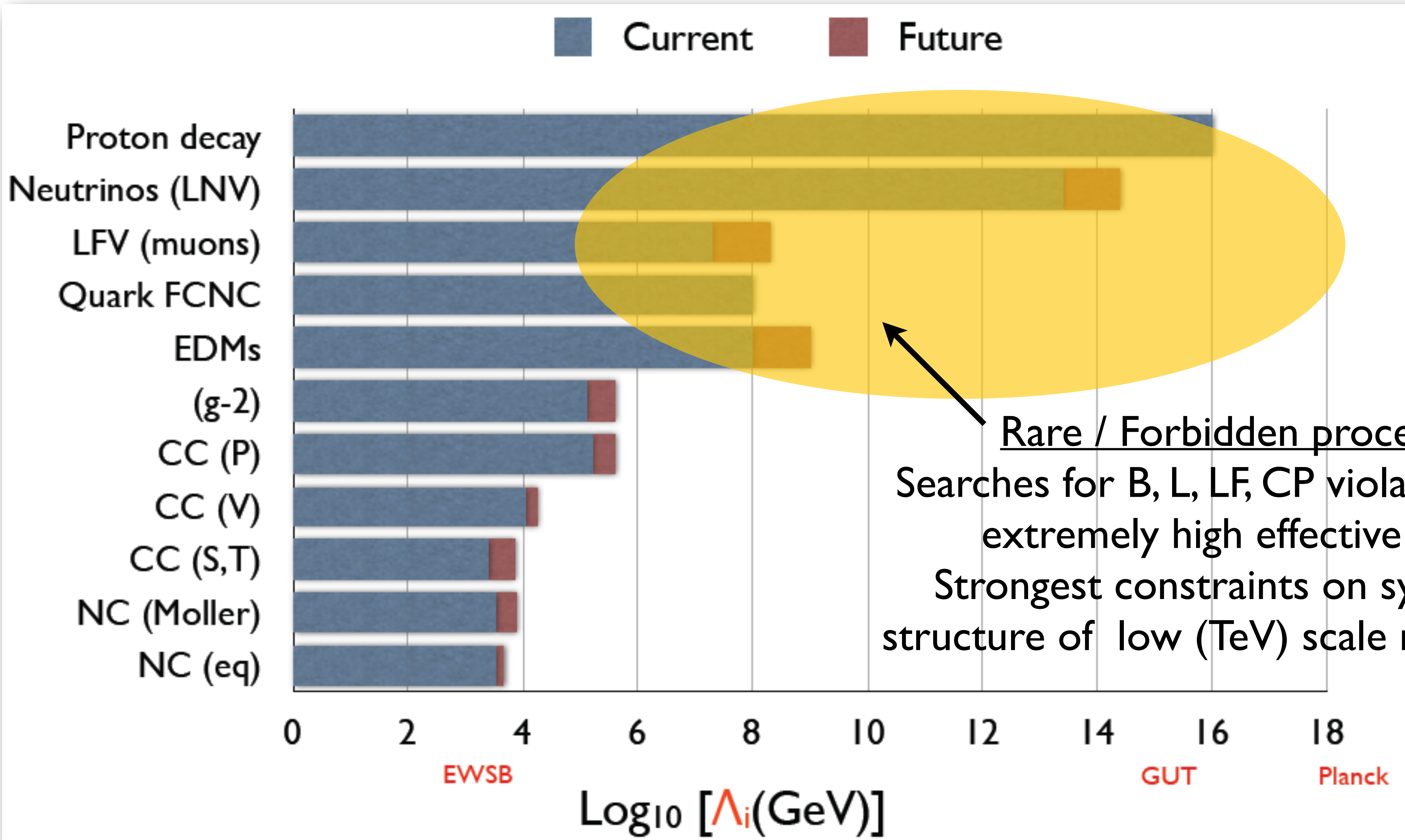
Figure copyright: David Mack

What scales are we probing?



Λ ~ *maximal* scale probed by a given measurement, obtained by assuming O(1) couplings (for all probes) and one-loop factor for g-2, EDMs, LFV, FCNC

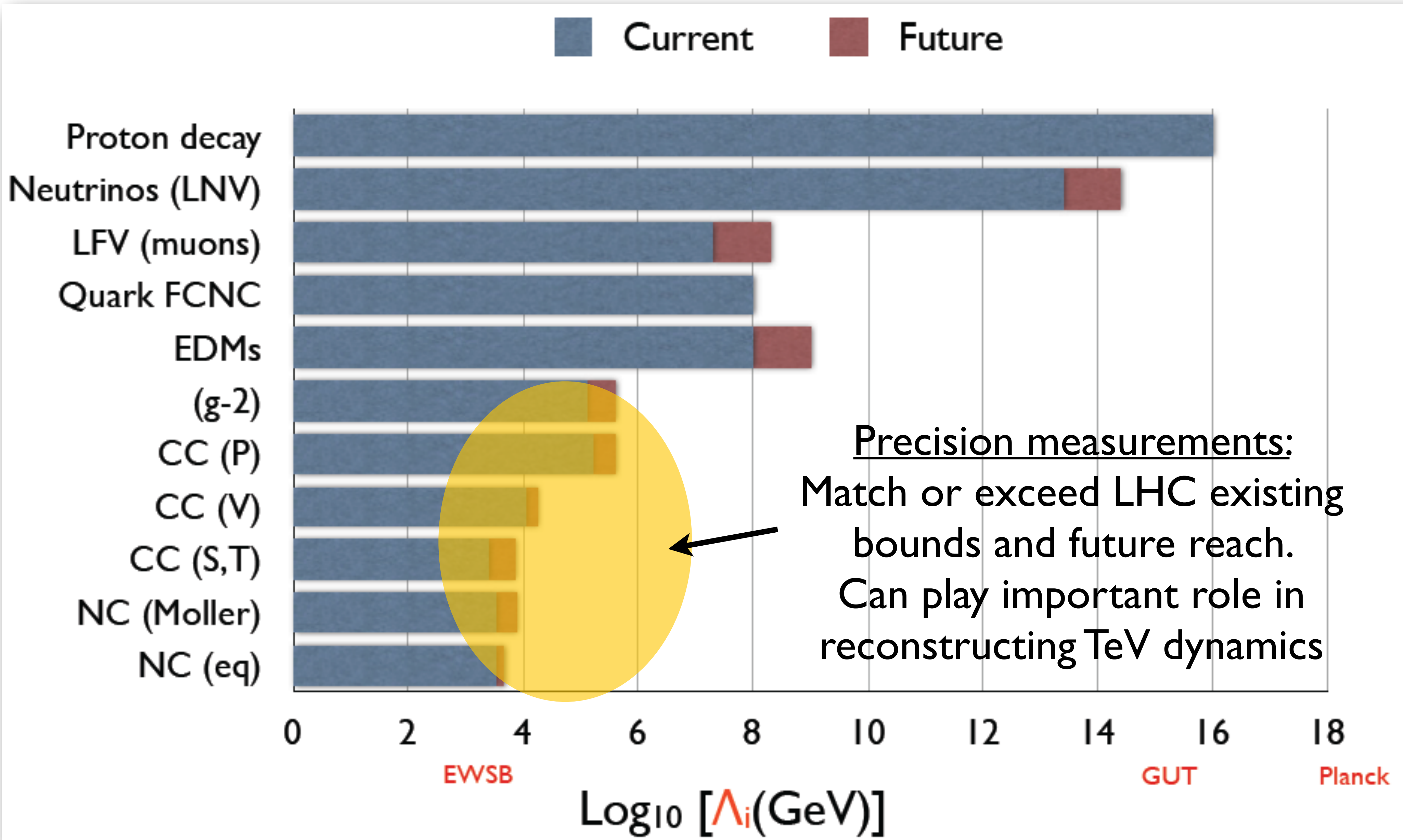
What scales are we probing?



<u>Rare / Forbidden processes:</u>
Searches for B, L, LF, CP violation probe extremely high effective scale.
Strongest constraints on symmetry structure of low (TeV) scale new physics

Λ ~ *maximal* scale probed by a given measurement, obtained by assuming O(1) couplings (for all probes) and one-loop factor for g-2, EDMs, LFV, FCNC

What scales are we probing?



Λ ~ *maximal* scale probed by a given measurement, obtained by assuming O(1) couplings (for all probes) and one-loop factor for g-2, EDMs, LFV, FCNC

Backup

(Incomplete) List of acronyms

- ALPs: Axion-Like Particles
- BNV: Baryon Number Violation
- CC: (weak) charged current
- CP: Charge-Parity
- CPV: CP Violation
- EDM: Electric Dipole Moment
- EFT: Effective Field Theory
- FCNC: Flavor Changing Neutral Currents
- IR: infrared
- LEFT: Low Energy EFT (below the weak scale)
- LFV: Lepton Flavor Violation
- LNV: Lepton Number Violation
- NC: (weak) neutral current
- SM: Standard Model
- SMEFT: Standard Model EFT
- UV: ultraviolet

Anomalous symmetry breaking

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

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

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

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

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

Anomalous symmetry breaking

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

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

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

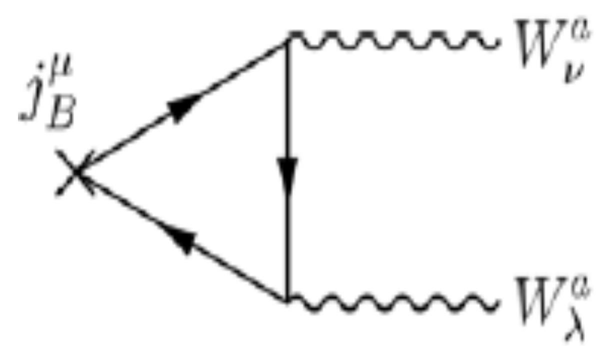
$$S[\psi,\bar{\psi}] = S[\psi',\bar{\psi}']$$

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

- 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 (large rates at high temperature)