National Nuclear Physics Summer School
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Fundamental Symmetries - 2

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Flow of the lectures

- Review symmetry and symmetry breaking
- Introduce the Standard Model and its symmetries

1.5 lectures

- Beyond the SM: an effective theory perspective and overview
- Discuss a number of "worked examples"
  - Precision measurements: charged current (beta decays); neutral current (PVES); muon g-2, ..
  - Symmetry tests: CP (T) violation and EDMs; Lepton Flavor and Lepton Number violation

1.5 lectures

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Today

- Beyond the SM: an effective theory perspective and overview
- Discuss a number of "worked examples"
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1.5 lectures

The Standard Model and its symmetries (Part 2)

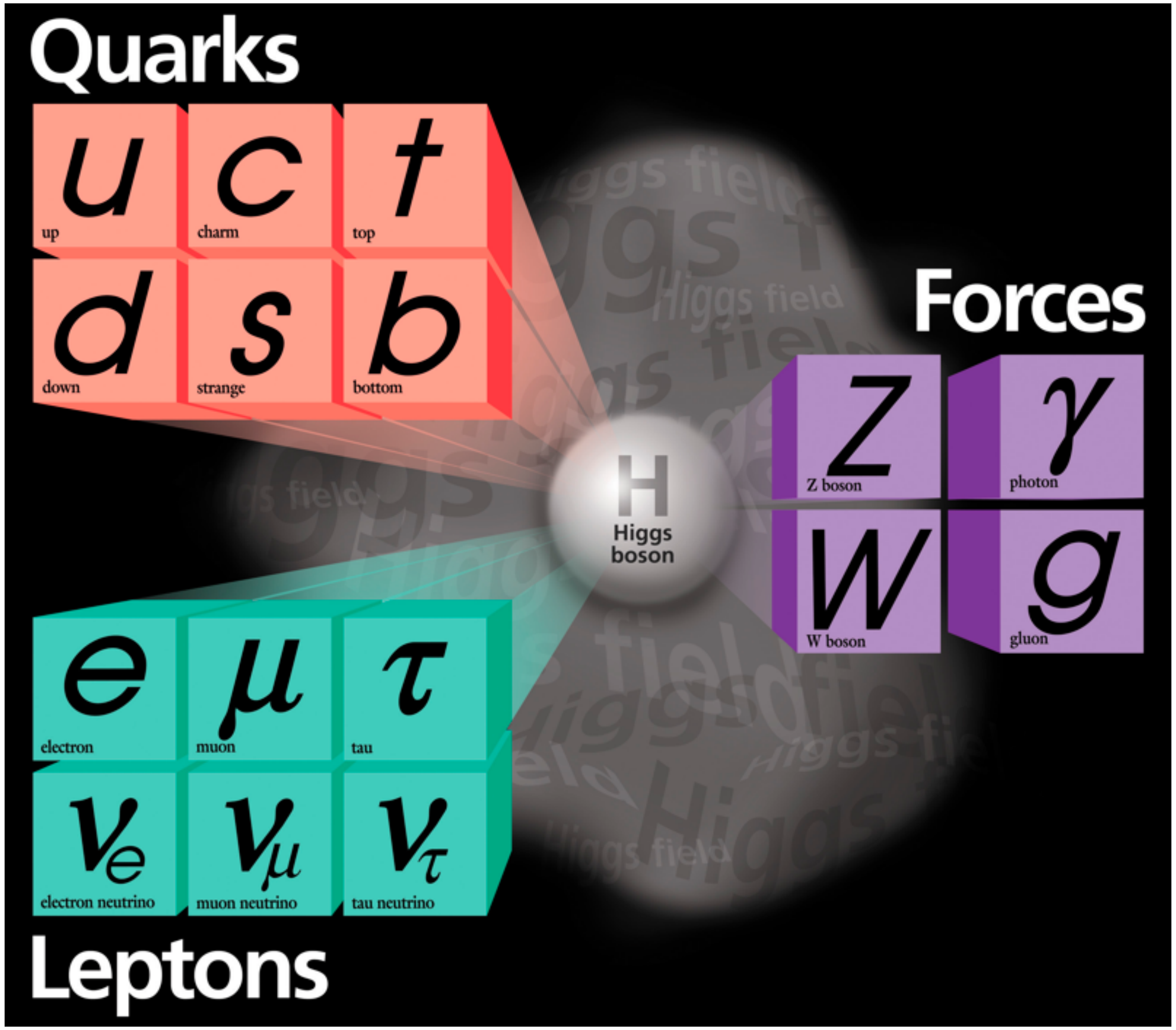
Towards a realistic model

- Identified gauge group as SU(3)xSU(2)xU(1)

- But pure gauge Lagrangian unrealistic:
    - massless fermions and gauge bosons
    - no SU(2)xU(1)- invariant mass term can be written

- Solution: add a new scalar EW doublet, the Higgs

The Standard Model



The Standard Model

- Gauge group:

$$SU(3)_c \times SU(2)_W \times U(1)_Y$$

$$\psi'(x) = e^{ig_s \alpha_A(x) \frac{\lambda_A}{2}} \psi(x)$$

$$\psi'(x) = e^{ig' \gamma(x) Y} \psi(x)$$

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

Fundamental representation (color triplets and weak doublets)

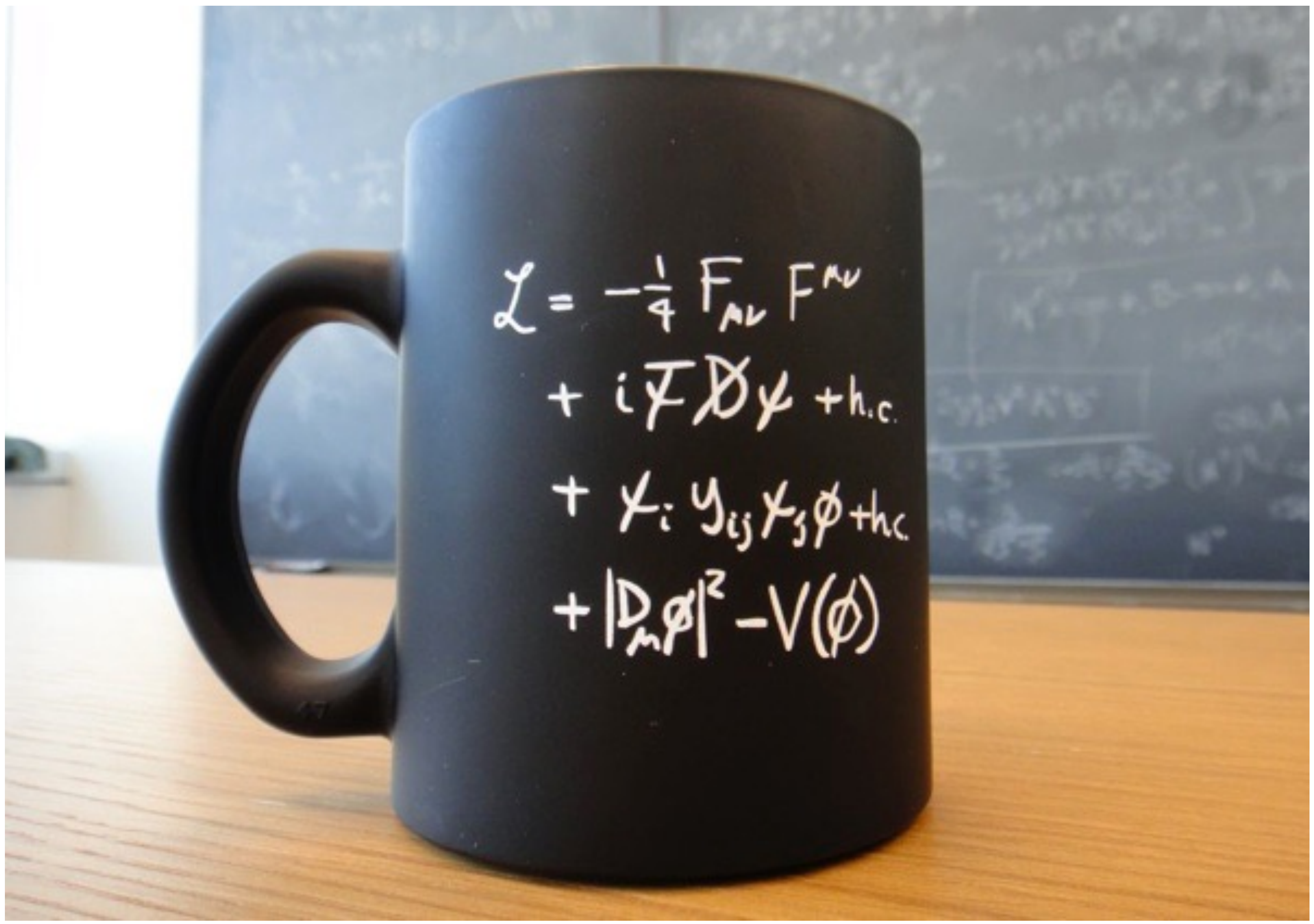
- Building blocks: fermions and Higgs

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

$$\tilde{\varphi} = \epsilon\, \varphi^* = \begin{pmatrix} \varphi^{0*} \\ -\varphi^- \end{pmatrix} \qquad (1,2,-1/2) \qquad \tilde{\varphi} \to V_{SU(2)}\, \tilde{\varphi}$$

$\epsilon = i\sigma_2$

- SM Lagrangian:



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

$$\mathcal{L}_{\text{Gauge}} = -\frac{1}{4} G^A_{\mu\nu} G^{A\mu\nu} - \frac{1}{4} W^I_{\mu\nu} W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$
$$+ i\bar{\ell} \not{D} \ell + i\bar{e} \not{D} e + i\bar{q} \not{D} q + i\bar{u} \not{D} u + i\bar{d} \not{D} d$$

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

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

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

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

EWSB →

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

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

$$v = 174\,\text{GeV}$$

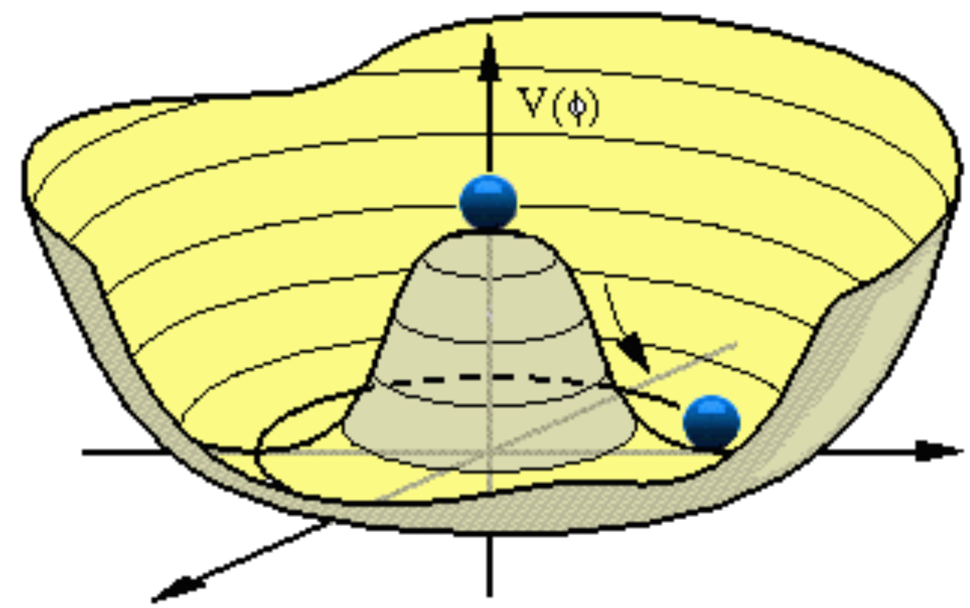
$$D_\mu = I\,\partial_\mu \;-\; ig_s\frac{\lambda^A}{2}G^A_\mu \;-\; ig\frac{\sigma^a}{2}W^a_\mu \;-\; ig'YB_\mu$$

$SU(2)_W \times U(1)_Y \to U(1)_{EM}$

- Expand around the minimum of the potential

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

$$\phi(x) = e^{i\pi_i(x)\sigma_i/v} \begin{pmatrix} 0 \\ v + \frac{h(x)}{\sqrt{2}} \end{pmatrix}$$



- Generalization of the abelian Higgs model discussed in detail earlier on

- $Q = T_3 + Y$ annihilates the vacuum → unbroken $U(1)_{EM}$. Photon remains massless, other gauge bosons ($W^\pm$, Z) acquire mass

SU(2)W x U(1)Y → U(1)EM

- Expand around the minimum of the potential

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

$$\phi(x) = e^{i\pi_i(x)\sigma_i/v}\begin{pmatrix} 0 \\ v + \frac{h(x)}{\sqrt{2}} \end{pmatrix}$$

↓

$$[m_W^2 W_\mu^+ W_\mu^- + \frac{1}{2}m_Z^2 Z_\mu Z_\mu](1 + \frac{1}{\sqrt{2}v}h)^2$$

Neutral scalar h couples to W± Z proportionally to their mass squared

Weak mixing angle

$$\theta = \arctan\frac{g'}{g}$$

$$e = g\sin\theta$$

$$W_\mu^\pm = 1/\sqrt{2}(W_\mu^1 \pm W_\mu^2)$$

$$Z_\mu = \cos\theta W_\mu^3 - \sin\theta B_\mu$$

$$A_\mu = \sin\theta W_\mu^3 + \cos\theta B_\mu$$

$$m_W = gv/\sqrt{2}$$

$$m_Z = \frac{\sqrt{g^2 + g'^2}}{2}v$$

$$m_W = m_Z\cos\theta$$

SU(2)$_W$ x U(1)$_Y$ → U(1)$_{EM}$

- Expand around the minimum of the potential

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

$$\phi(x) = e^{i\pi_i(x)\sigma_i/v} \begin{pmatrix} 0 \\ v + \frac{h(x)}{\sqrt{2}} \end{pmatrix}$$

$$[m_W^2 W_\mu^+ W_\mu^- + \frac{1}{2} m_Z^2 Z_\mu Z_\mu](1 + \frac{1}{\sqrt{2}v} h)^2$$

$$\frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2} m_h^2 h^2 - \sqrt{\frac{\lambda}{2}} m_h h^3 - \frac{\lambda}{4} h^4$$

$$m_h = 2\sqrt{\lambda} v$$

Higgs mass controlled by v
and Higgs self-coupling

$$G_F^{-1} = 2\sqrt{2} v^2$$

Fermion-Higgs sector: $\mathcal{L}_{\text{Yukawa}}$

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

- 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

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

$$f = f_L + f_R$$

Fermion-gauge sector: $\mathcal{L}_{int} = g\, A_\mu^a\, J^{\mu,a}$

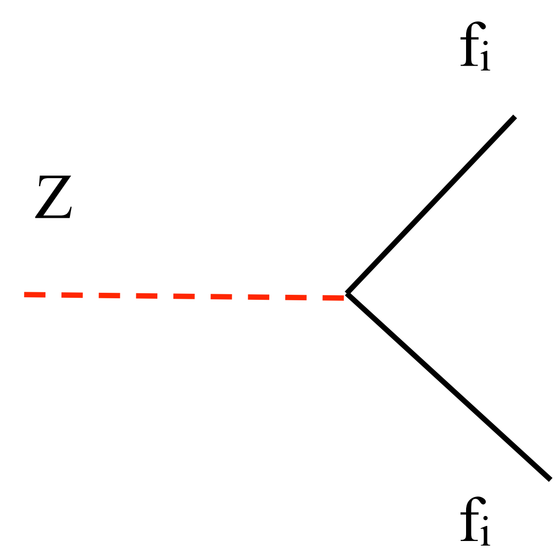
- Neutral current

$$\mathcal{L}_{\rm int} = -\frac{g}{2\cos\theta}\, Z^\mu\, \bar{\psi}_f \left(g_V^{(f)} \gamma_\mu - g_A^{(f)} \gamma_\mu \gamma_5 \right) \psi_f$$

$$\theta = \arctan\frac{g'}{g}$$

$$e = g\sin\theta,$$

$$g_V^{(f)} = T_3^{(f)} - 2\sin^2\theta\, Q^{(f)} \qquad g_A^{(f)} = T_3^{(f)}$$



- Flavor diagonal
- Both V and A: expect P-violation

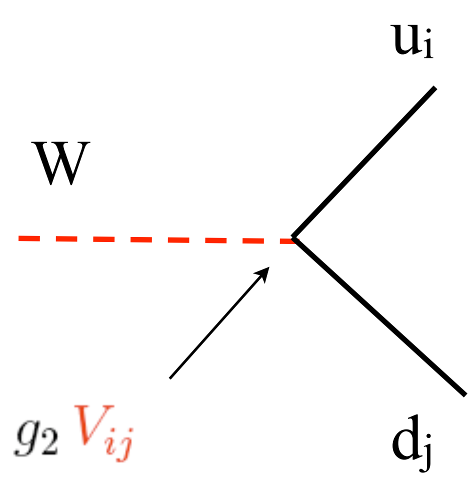
Fermion-gauge sector: $\mathcal{L}_{int} = g\, A_\mu^a\, J^{\mu,a}$

- Charged current

$$\frac{g}{\sqrt{2}} W^+ \; \bar{u}_L \gamma_\mu d_L \;\; \rightarrow \;\; \frac{g}{\sqrt{2}} W^+ \; \bar{u}'_L \, V_{\rm CKM} \, \gamma_\mu \, d'_L$$

$$V_{\rm CKM} = V_{u_L} V^\dagger_{d_L}$$

Physically observable mismatch in the transformation of u_L and d_L needed to diagonalize quark masses



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

Cabibbo-Kobayashi-Maksawa matrix

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

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

5 independent parameters (phase differences)

- Irreducible phase implies CP violation:

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

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

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

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

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

Symmetries of the Standard Model

- Now pause and take stock of what is the fate of symmetries in the SM (besides Poincare', which is built in)

  - Gauge symmetry is hidden (spontaneously broken)

  - Global (flavor) symmetries: all explicitly broken** except for U(1) associated with B, L, and L_α (individual lepton families)
  - Impact of anomalies: only B-L is conserved (but no worries at T=0)

  - P, C maximally violated by Weak interactions

  - CP (and T): violated by CKM (and QCD theta term)

** Approximate SU(2) and SU(3) vector and axial symmetries of QCD play key role in strong interactions

Symmetries of the Standard Model

- Most symmetries are broken

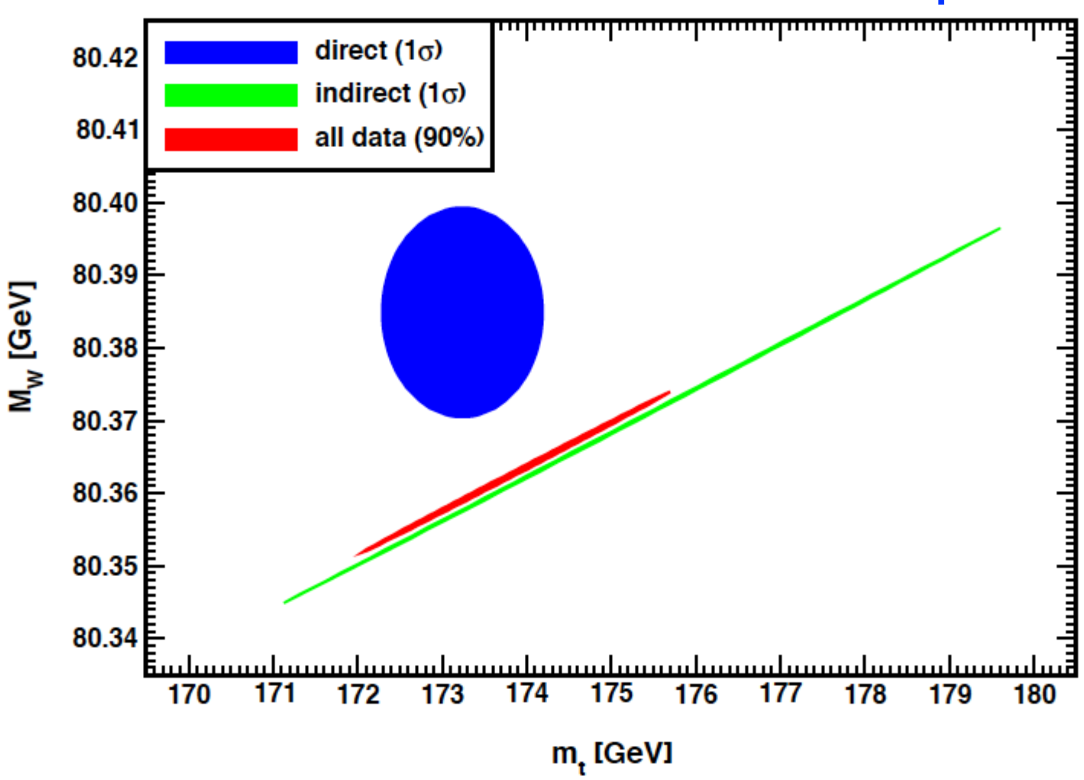
- However, SM displays approximate discrete (C, P, T) and global symmetries (B, L) observed in nature

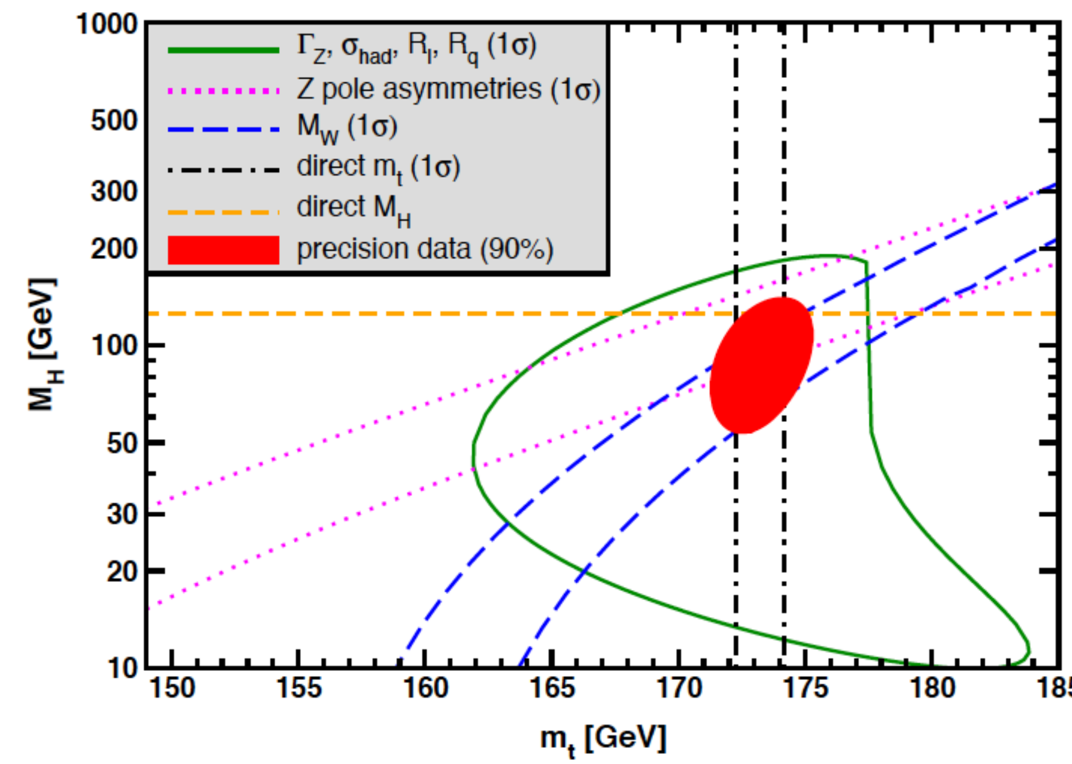
- Not an input in the model, rather an outcome that depends on the assigned gauge quantum numbers (+ renormalizability)

Status of the Standard Model

- Standard Model tested at the quantum (loop) level in both electroweak and flavor sector
- Precision EW tests are at the 0.1% level. Examples of global fits:

Note the vertical scale in this plot



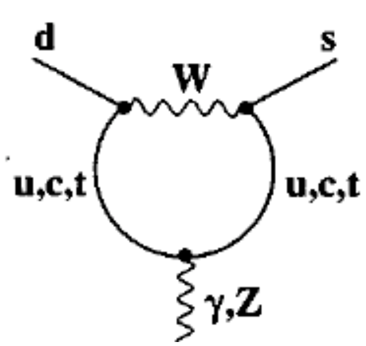


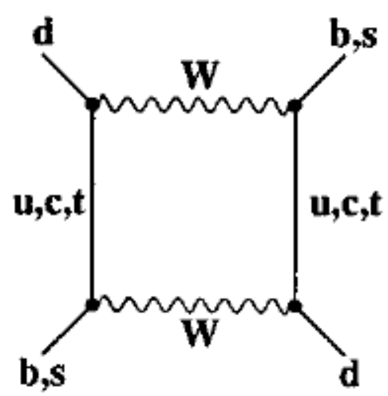
- A few "tensions" and "anomalies": g-2, … (will discuss it later on)

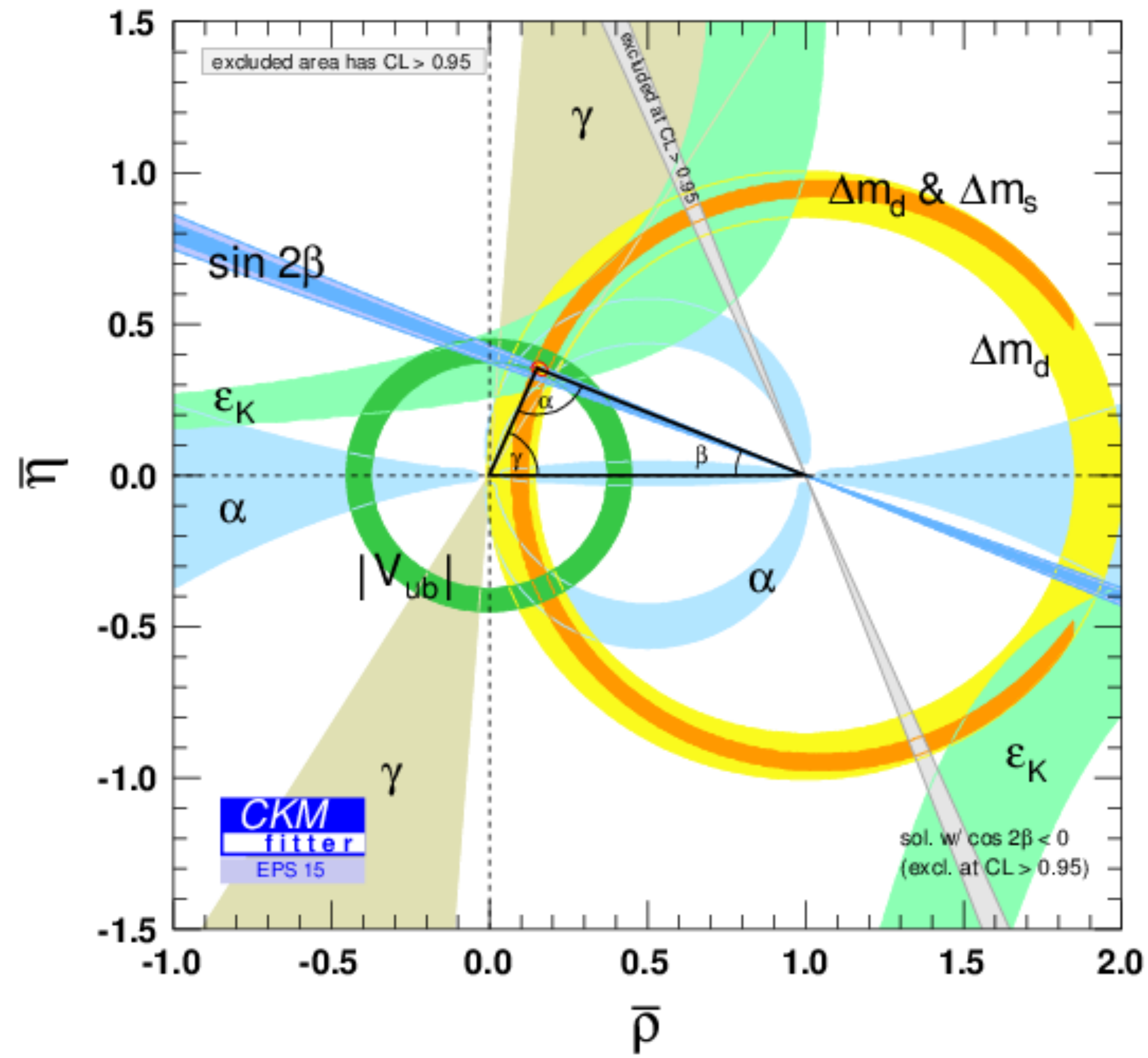
Status of the Standard Model

- Flavor physics and CP violation: K, B, D meson physics well described by CKM matrix, in terms of 3 mixing angles and a phase!

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



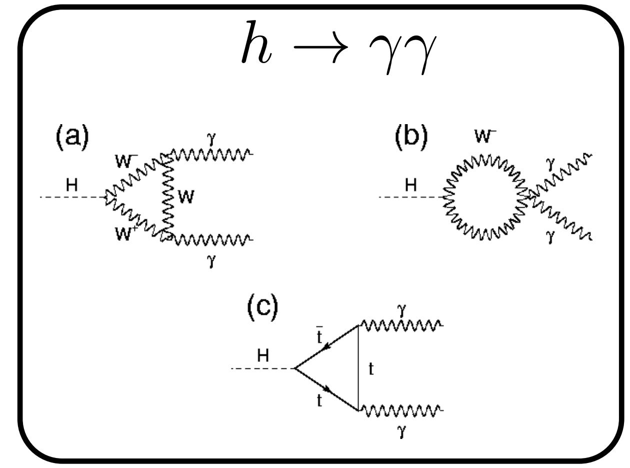


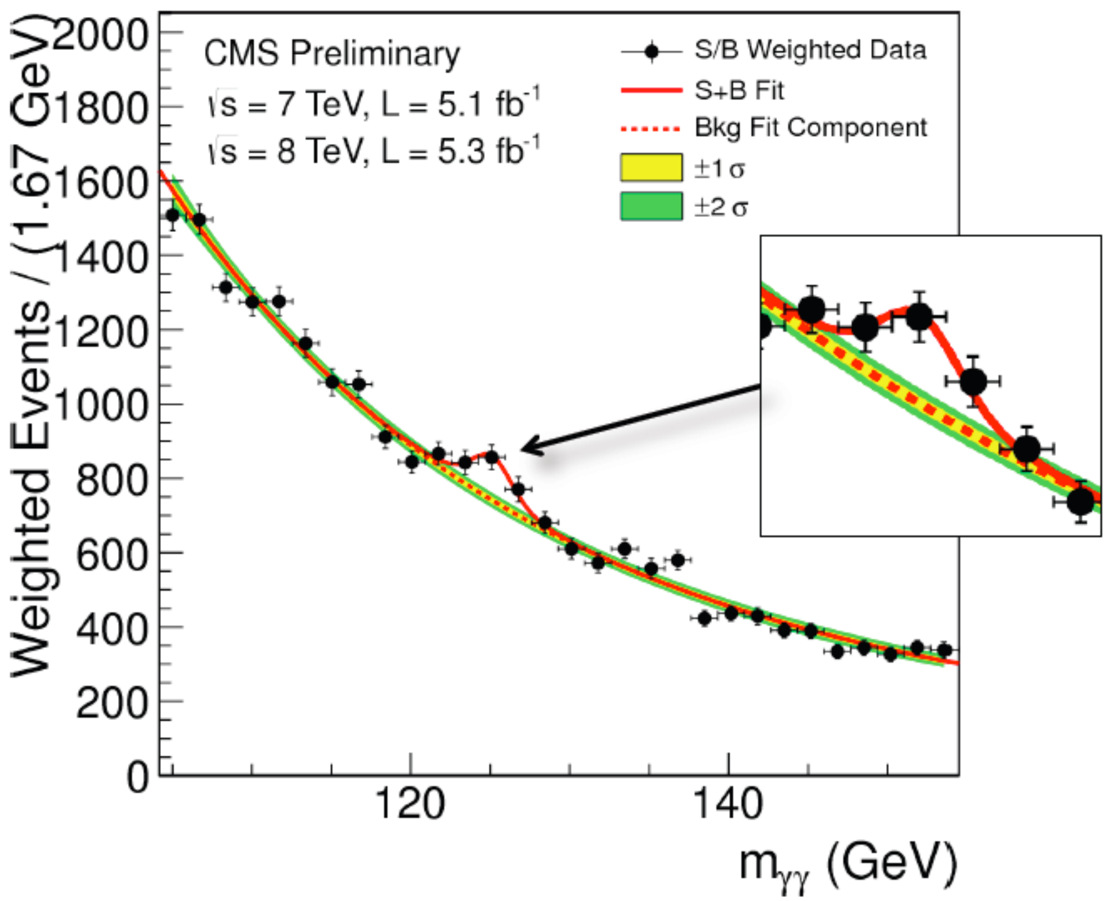


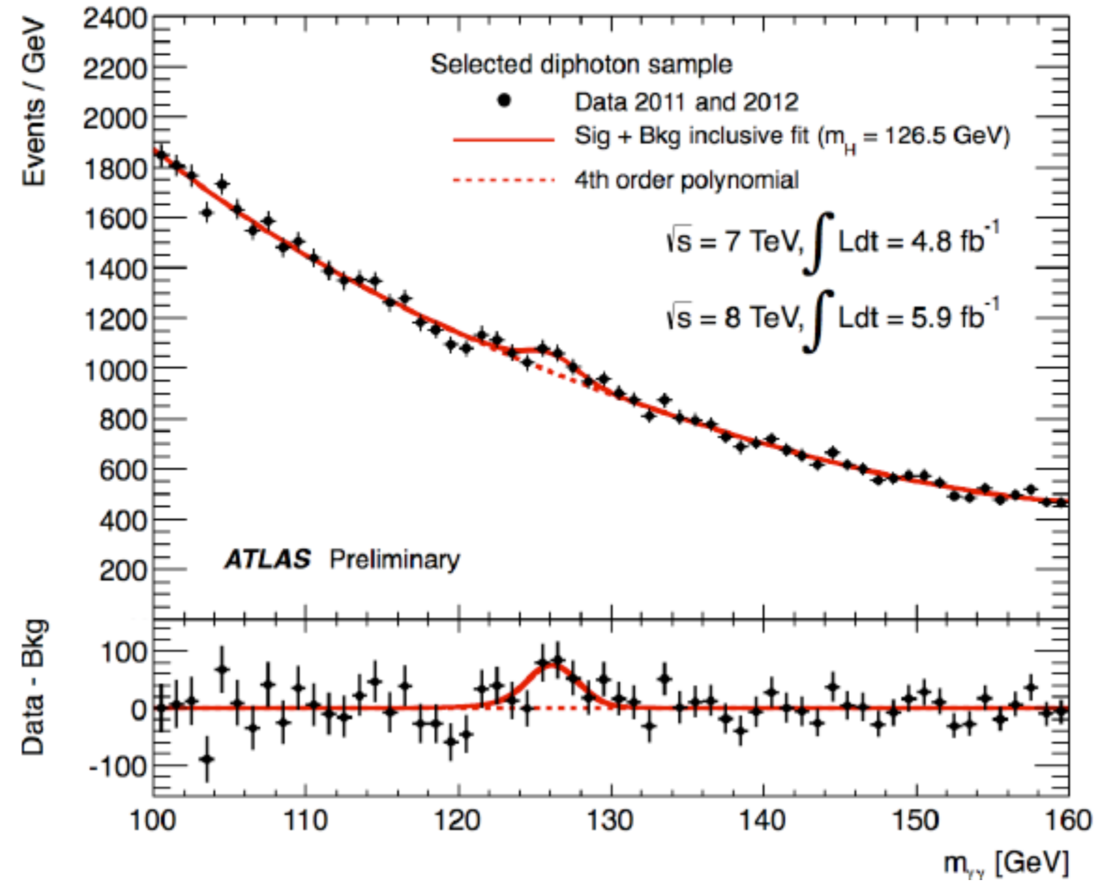
- Some recent "anomalies" in B decays

Status of the Standard Model

- Higgs boson: discovered in $H \rightarrow \gamma\gamma$ mode

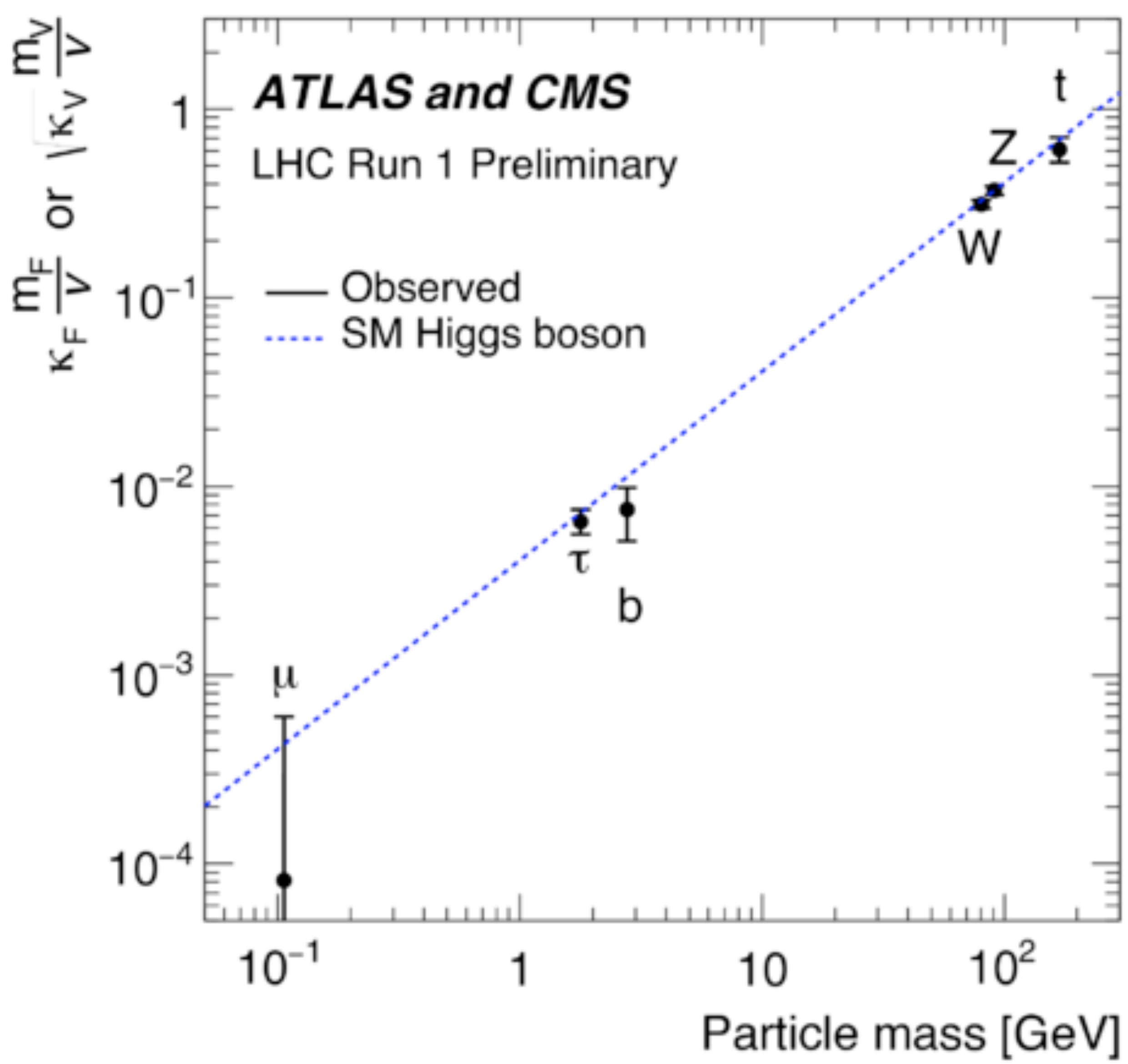






Status of the Standard Model

- Higgs boson: discovered in H →γγ mode
- So far Higgs properties are compatible with the Standard Model



- Couplings to W, Z, γ,g and t, b, τ known at 20-30% level
- But couplings to light flavors much less constrained
- Still room for deviations: is this the SM Higgs? Key question at LHC Run 2 & important target for low energy experiments

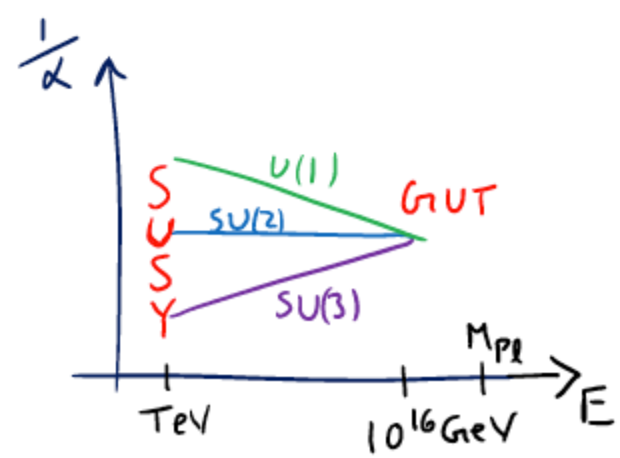
Beyond the Standard Model

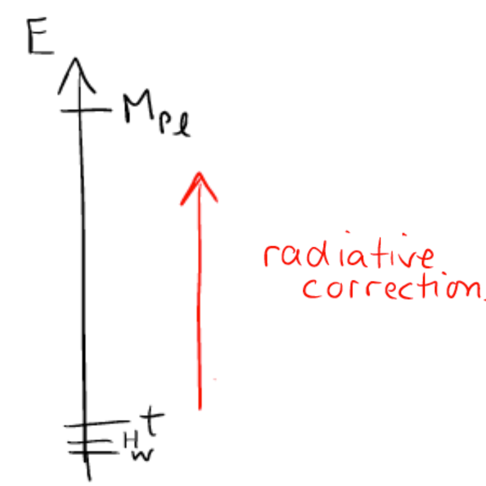
The quest for “new physics”

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

Empirical arguments

Theoretical arguments

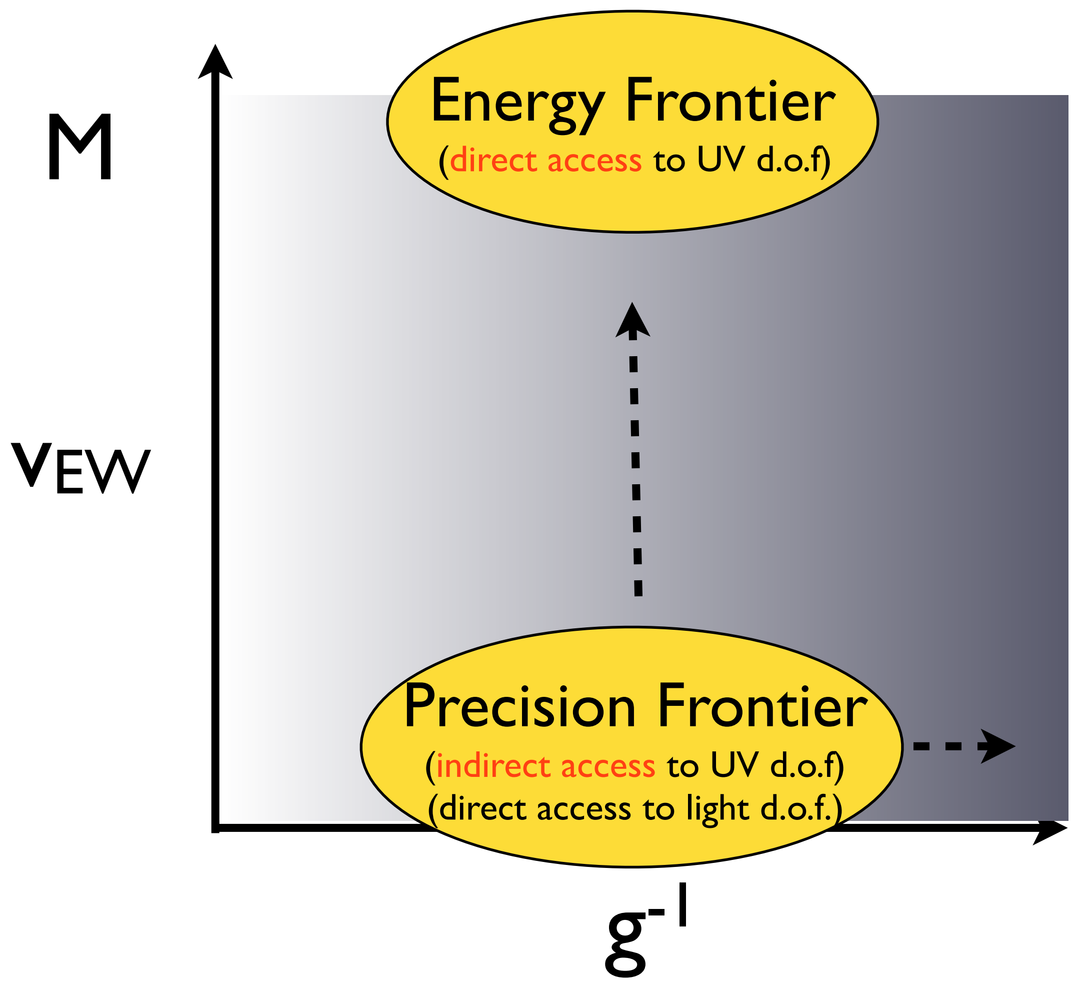




R. Sundrum
ICHEP 12

The quest for “new physics”

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



- EWSB mechanism
- Excite new heavy particles
- ...

- L and B violation
- CP violation (w/o flavor)
- Flavor symmetries (quarks, leptons)
- Precision tests (super-heavy mediators)
- ...

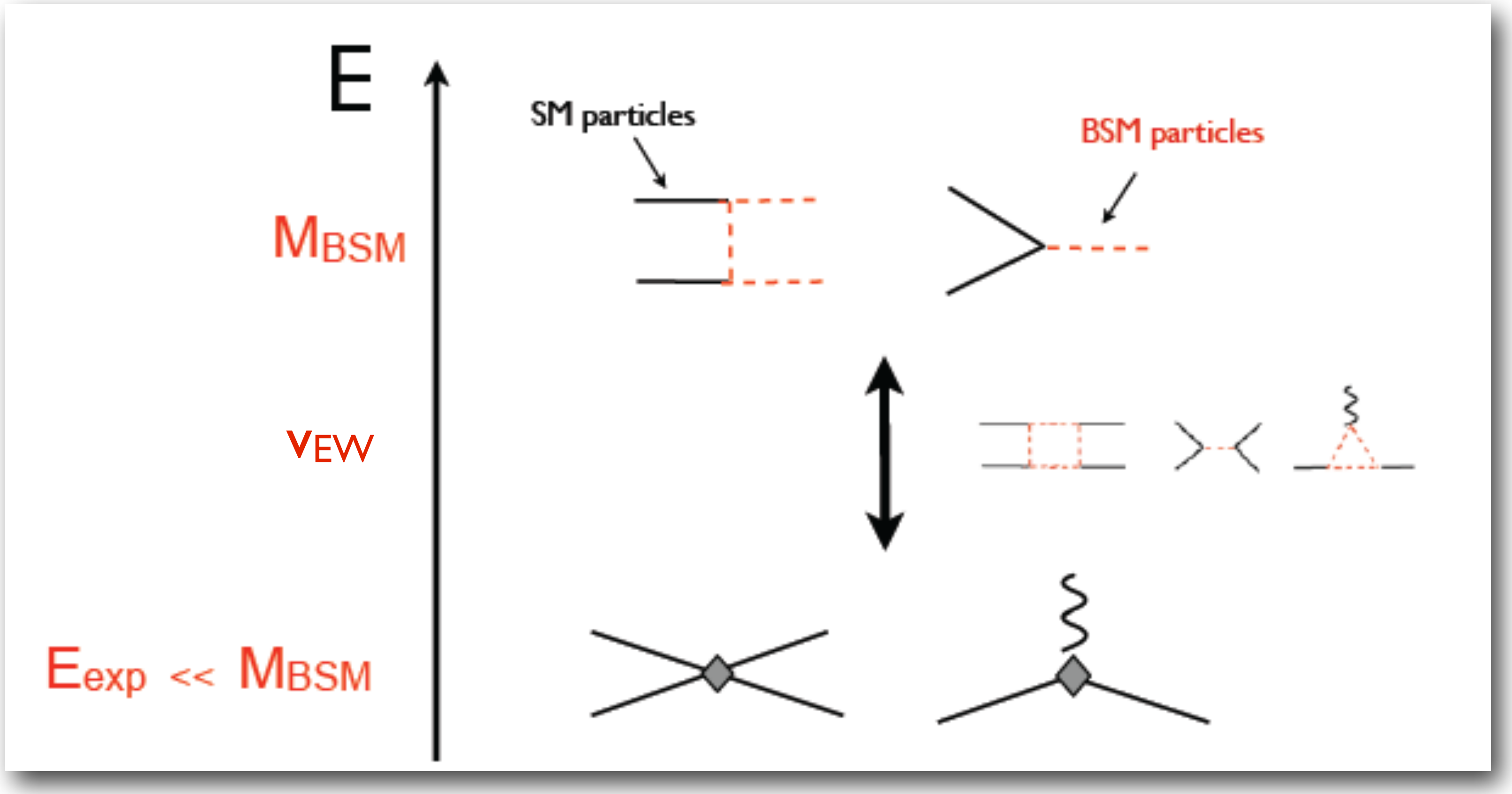
- Two approaches, both needed to reconstruct BSM dynamics (structure, symmetries, and parameters of L_{BSM})

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 sector
- Combinations of the above
- …

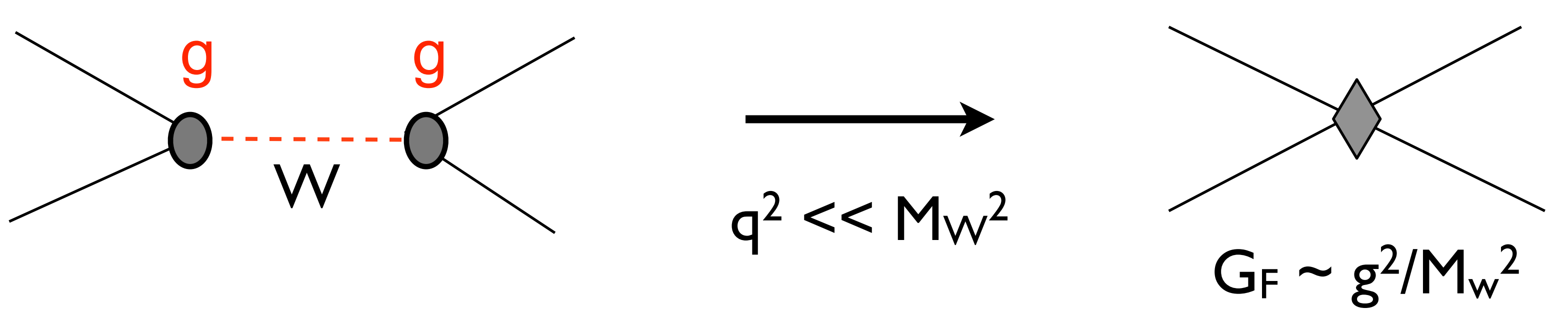
In the following, I will assume that new physics originates above the electroweak scale and discuss its low-energy footprints in the framework of effective field theory

The low-energy footprints of L_{BSM}

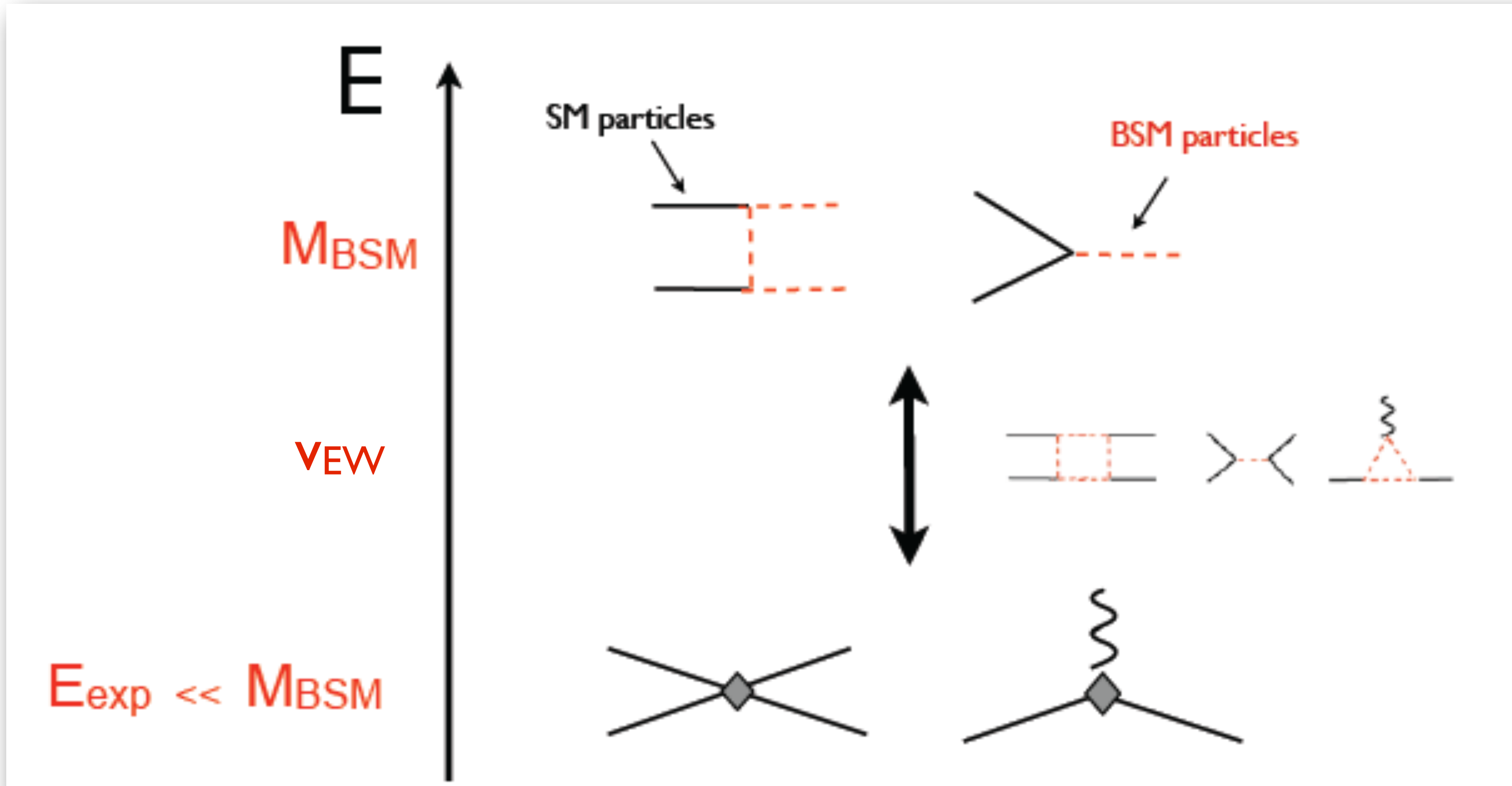


- At energy scales $E << M_{BSM}$, new physics shows up as local operators

Familiar example:



The low-energy footprints of L_{BSM}



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

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

$\Lambda \leftrightarrow M_{\rm BSM}$

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

- Each model generates its own pattern of operators: experiments at $E \ll M_{BSM}$ can *discover* and *tell apart* new physics scenarios

Role of low-E 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 (β-decays, muon g-2, Q_W, ...)

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

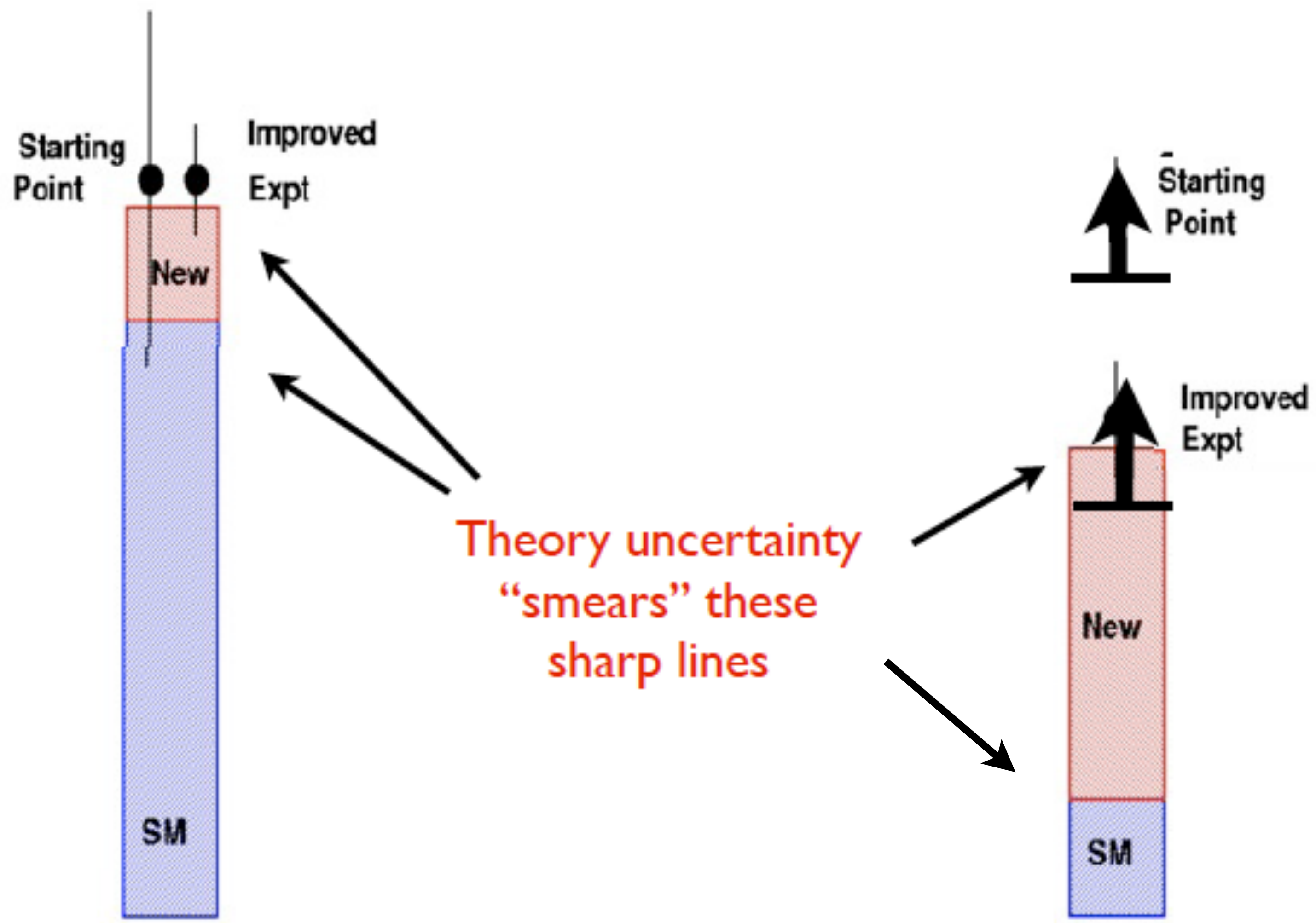


Figure copyright: David Mack

Role of low-E experiments

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

- 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)

A guided tour of L_{eff}

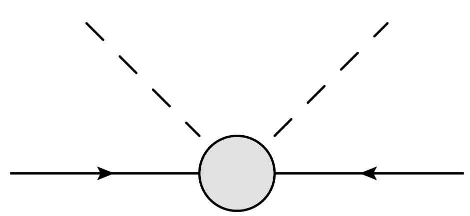
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

- Dim 5: only one operator

Weinberg 1979

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

$$C = i\gamma_2\gamma_0$$



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

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

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

A guided tour of L_{eff}

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

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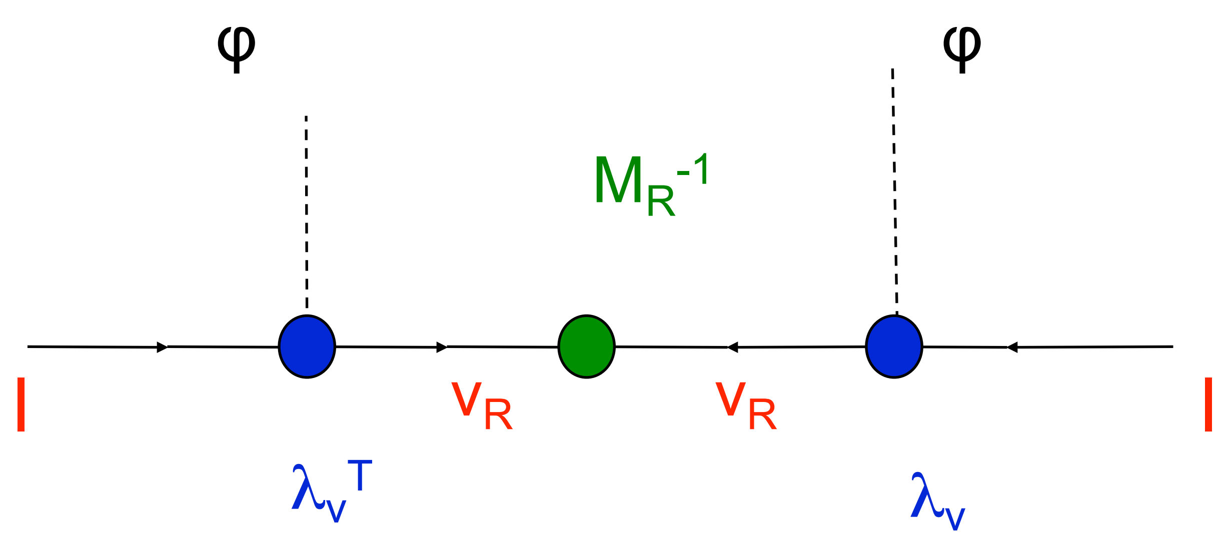
$$\frac{1}{\Lambda}\hat{O}_{\text{dim}=5} \xrightarrow{\langle\varphi\rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}} \frac{v^2}{\Lambda}\nu_L^T C \nu_L$$

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

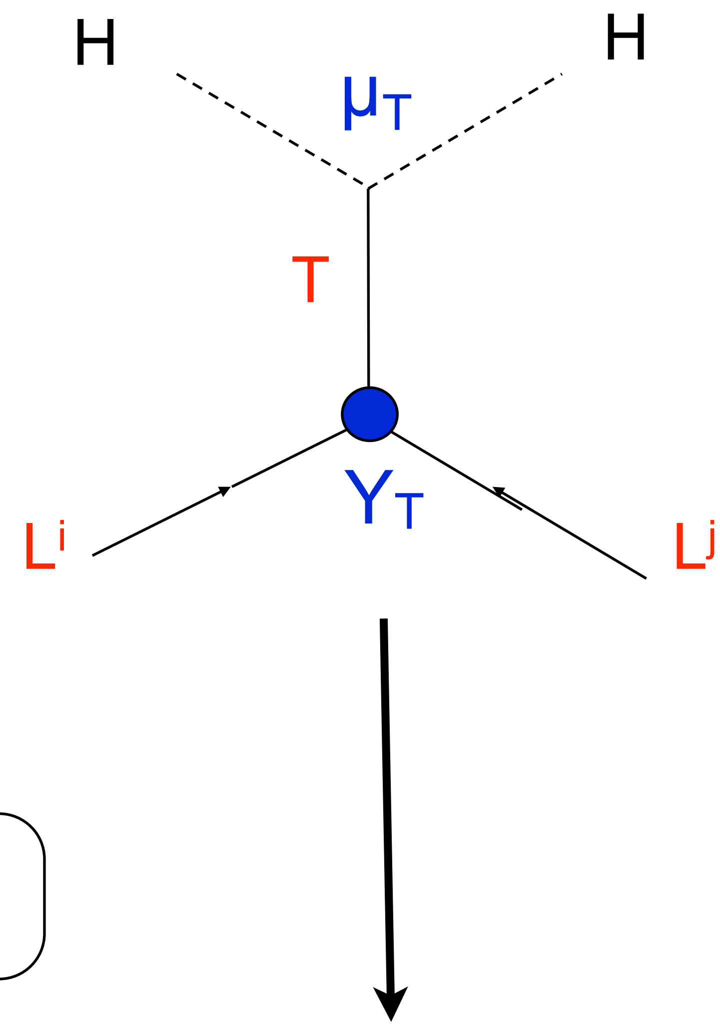
- Explicit realization of dimension-5 operator in models with heavy R-handed Majorana neutrinos



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

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

- Or with triplet Higgs field:



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

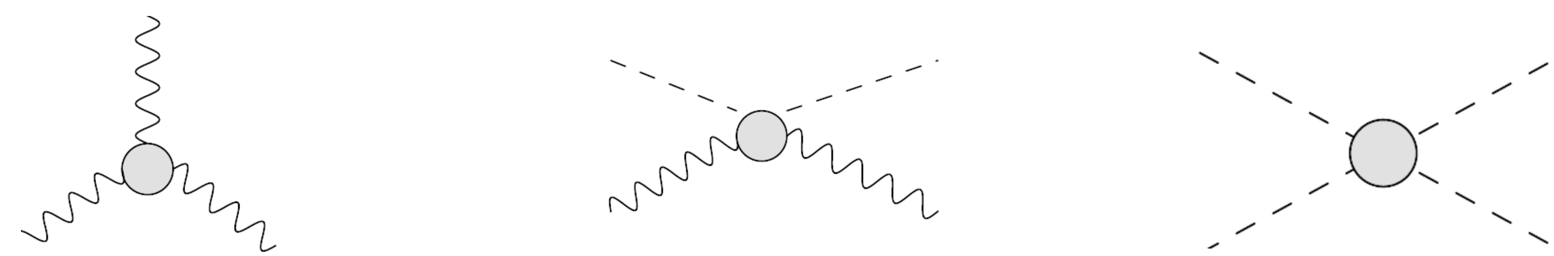
$$\mathcal{L}_5 = g_{\alpha\beta}\, \ell_\alpha^T C \epsilon \varphi\, \varphi^T \epsilon \ell_\beta$$

A guided tour of L_{eff}

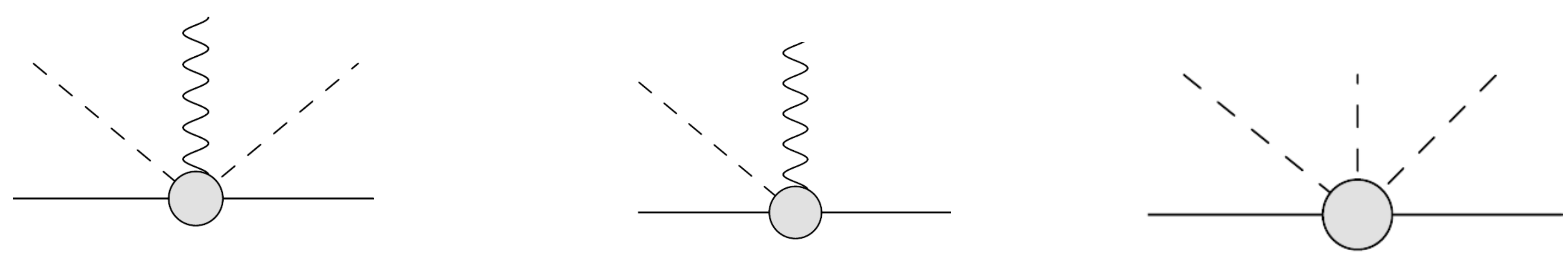
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

- Dim 6: affect *many* processes

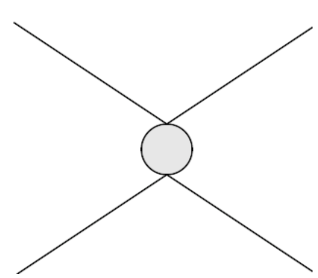
No fermions



Two fermions



Four fermions



A guided tour of L_{eff}

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

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, ...

Physics reach at a glance

This equation at work

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

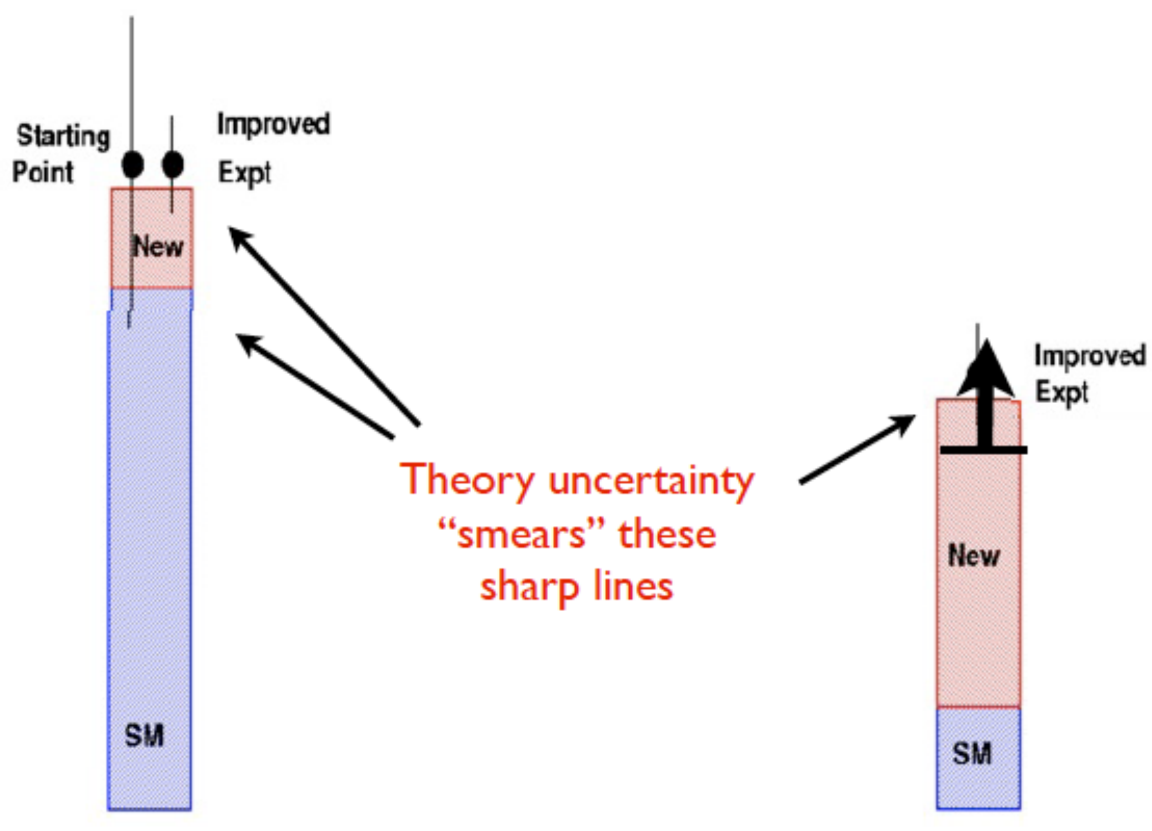
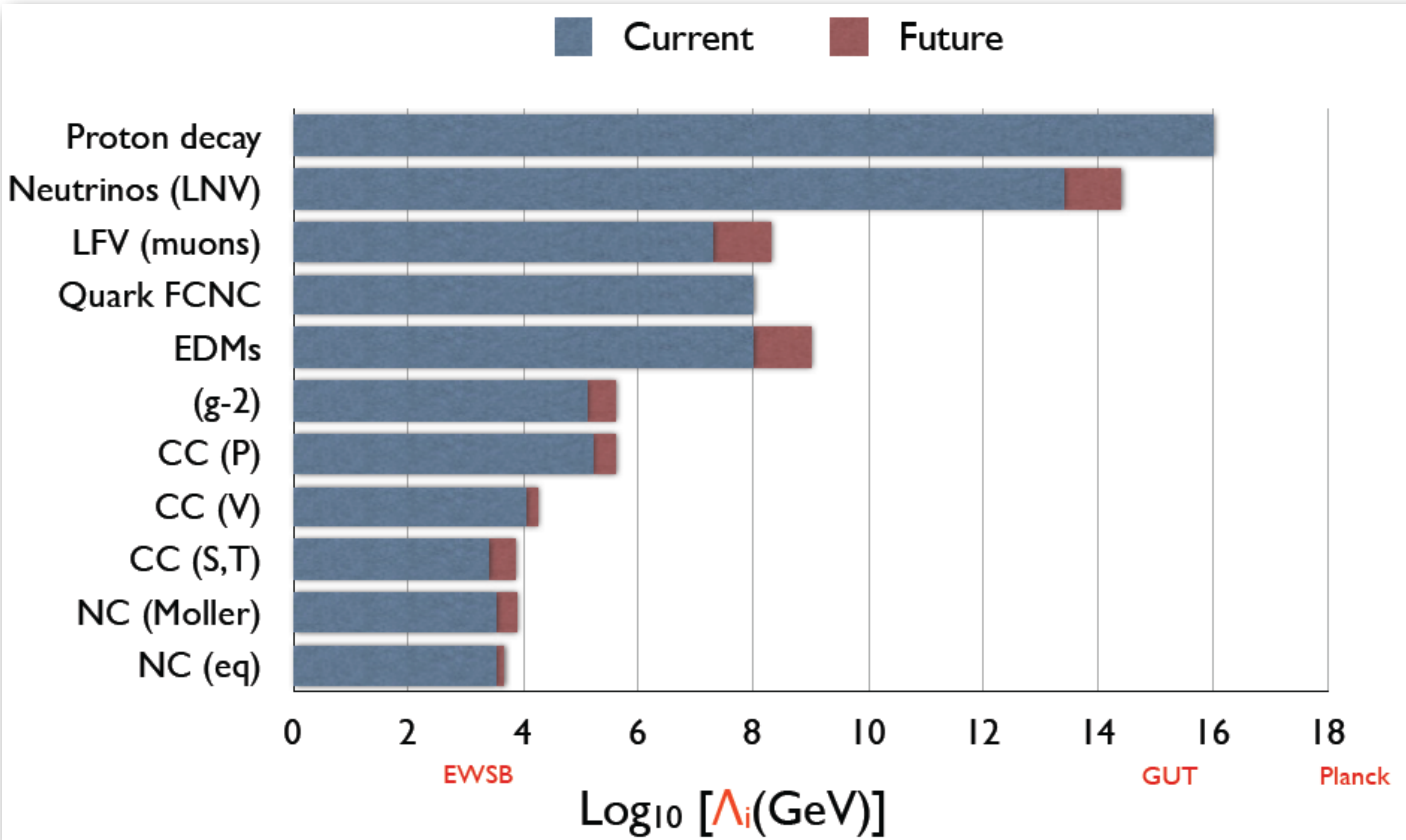


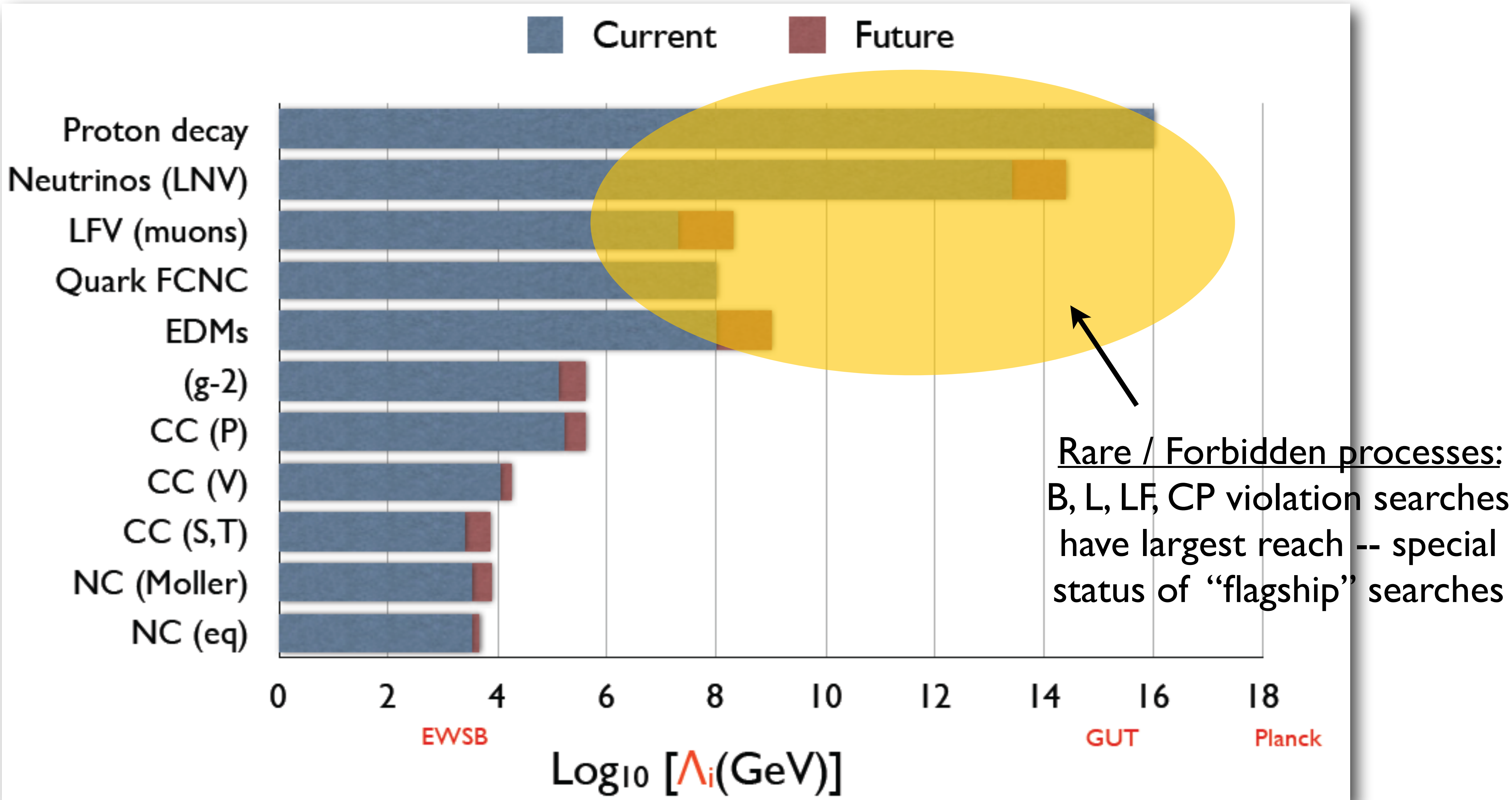
Figure copyright: David Mack

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 , etc

Physics reach at a glance



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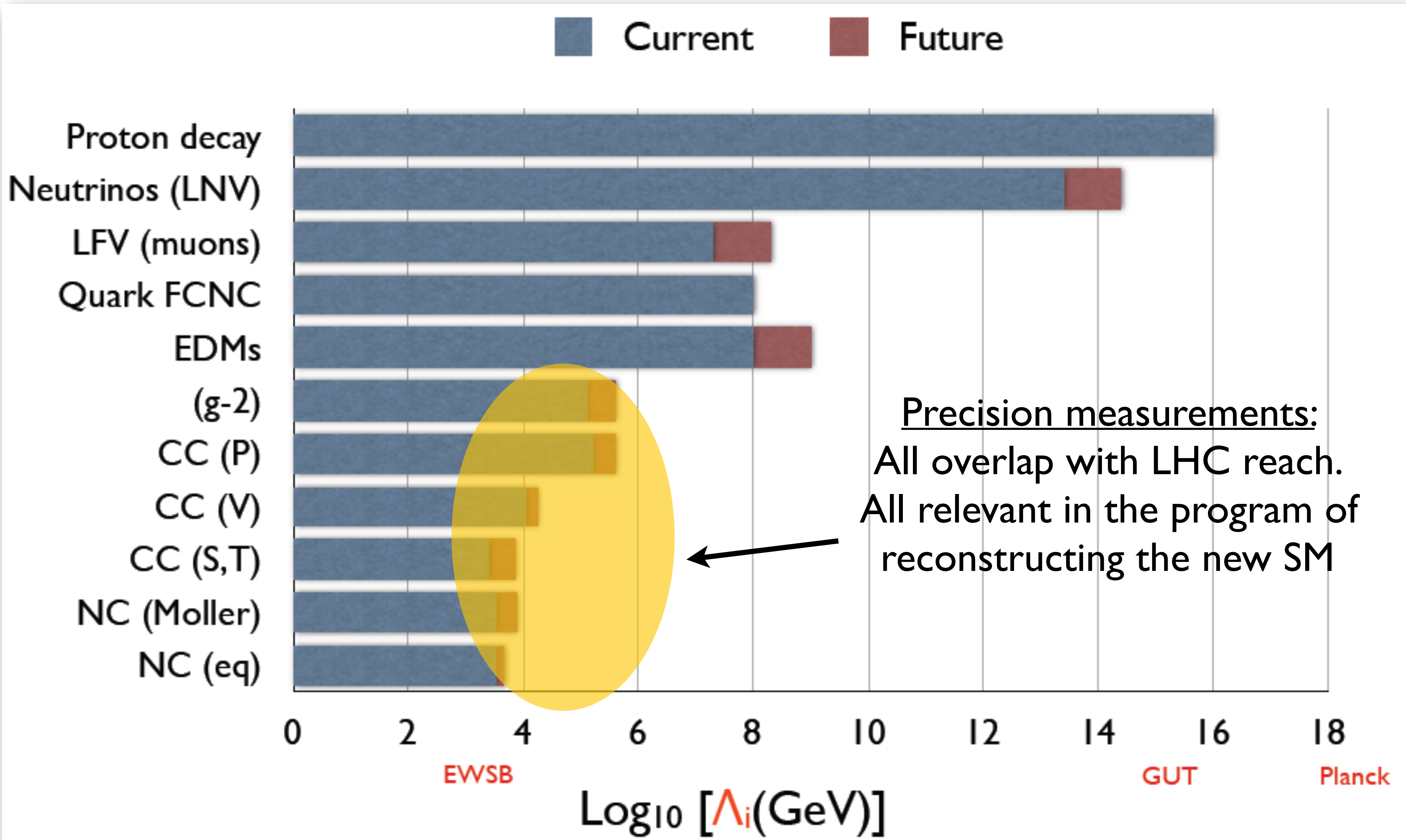
Physics reach at a glance



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

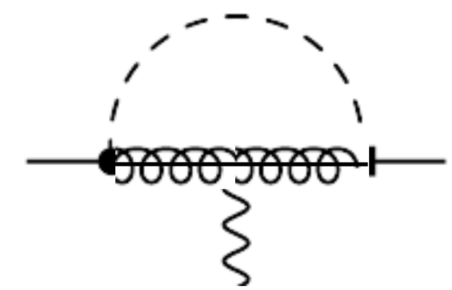
Challenges

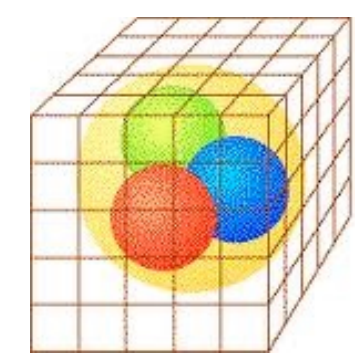
- Precision experiments
- Theory: control physics over many scales and hadronic / nuclear environment

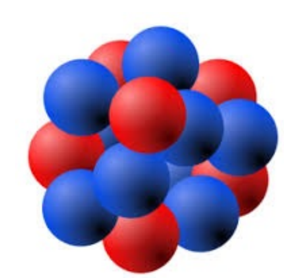
BSM scale (TeV?)

Nucleon scale
(chiral EFT, Lattice QCD)

Nuclear scale
(nuclear structure)

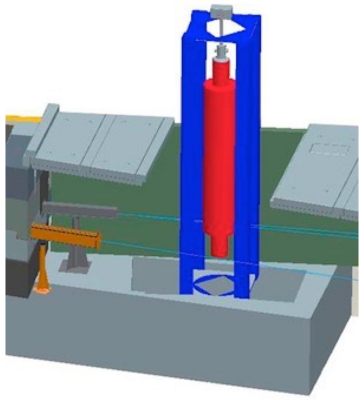






Next steps

- “Worked examples” that connect to NP experimental program
- Precision measurements: beta decays, PV electron scattering, muon g-2

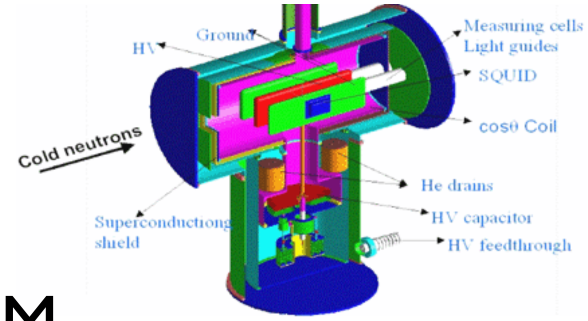


Nab

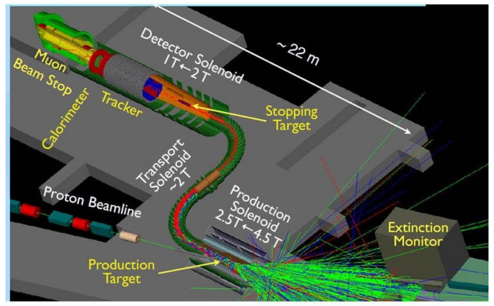
Qweak

muon g-2

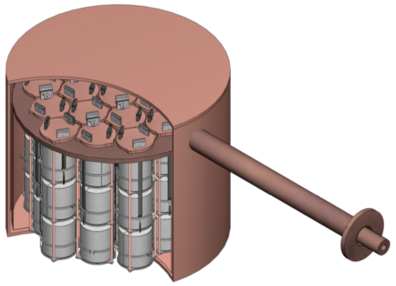
- Symmetry tests: Electric Dipole moments, LFV in muon processes, $0\nu\beta\beta$ and LNV



nEDM

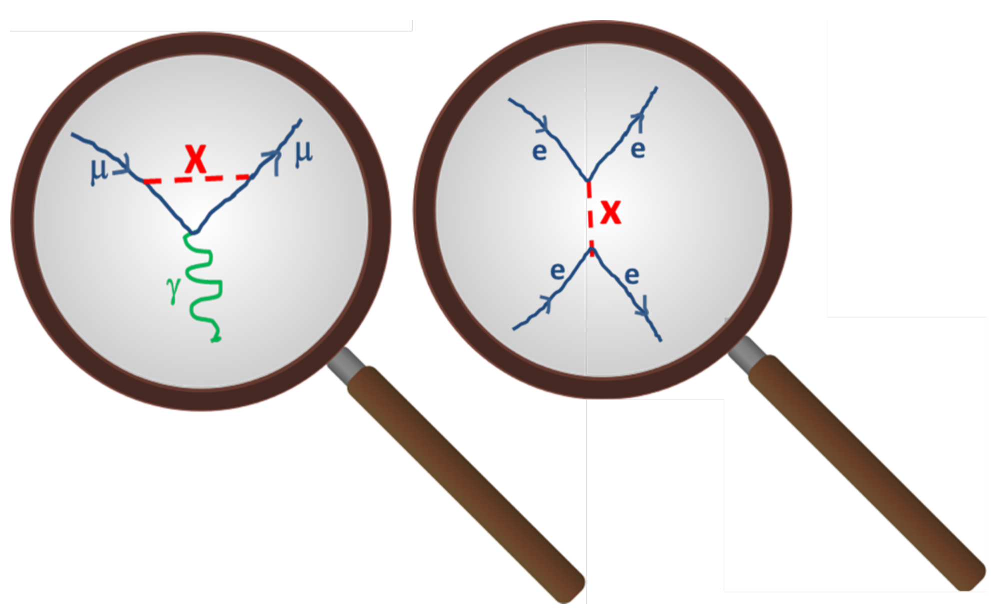


Mu2e

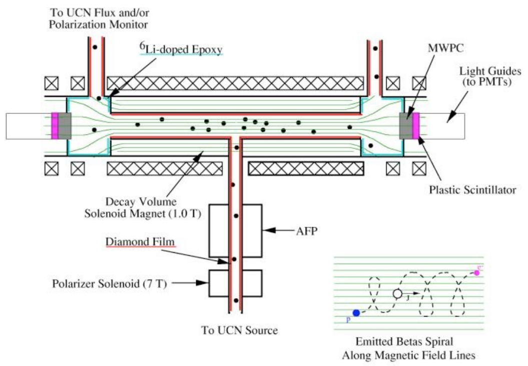


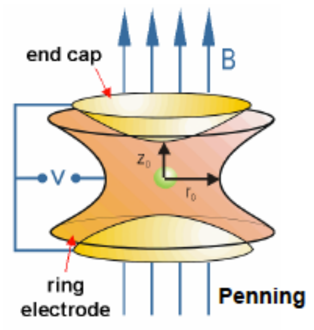
Majorana

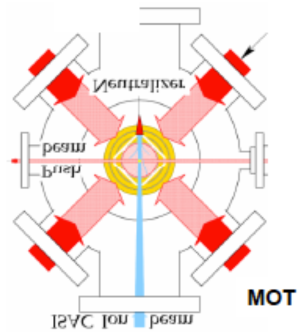
Precision measurements as probes of new physics

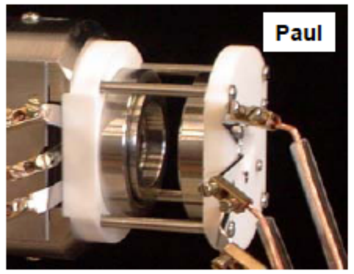


Charged Current



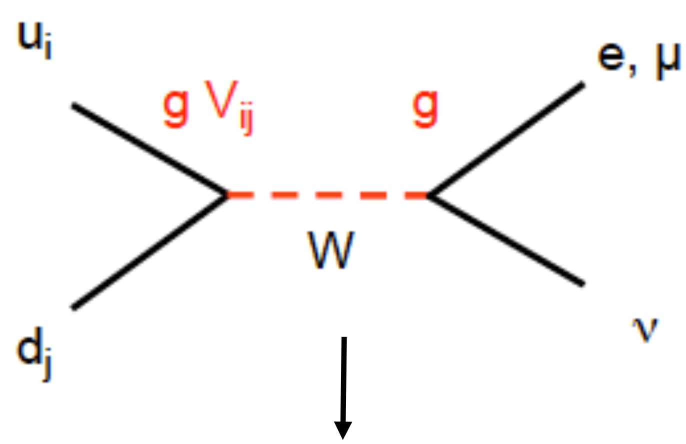






β-decays and BSM physics

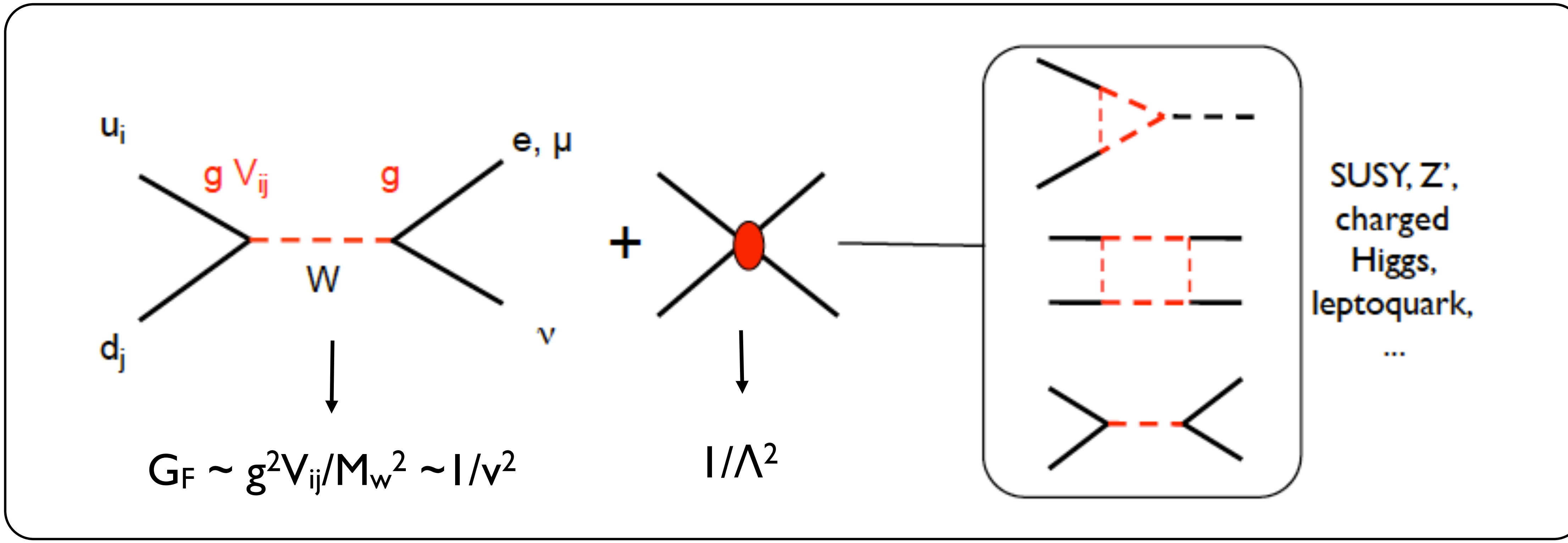
- In the SM, W exchange (V-A, universality)



$G_F \sim g^2 V_{ij}/M_W^2 \sim 1/v^2$

β-decays and BSM physics

- In the SM, W exchange (V-A, universality)



- Broad band sensitivity to BSM physics
- Name of the game: precision! To probe BSM scale Λ, need expt. & th. at the level of $(v/\Lambda)^2$: therefore 10^{-3} is a well motivated target
- Precision at or approaching 0.1%. Probe scale Λ ~ 5-10 TeV

- Effect of *any* new physics encoded in ten *quark-level* couplings

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

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

Observables have linear sensitivity to ε_i (interference with SM)

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

- Effect of *any* new physics encoded in ten *quark-level* couplings

$$
\begin{aligned}
\mathcal{L}_{CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \times \Big[& (1+\epsilon_L)\ \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
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& + \epsilon_S\ \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}d \\
& - \epsilon_P\ \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d \\
& + \epsilon_T\ \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \Big] + \text{h.c.} \\
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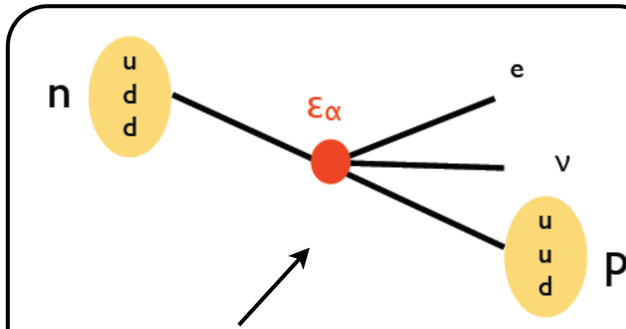
$$\epsilon_i\ ,\tilde{\epsilon}_i \sim (M_W/\Lambda)^2$$

Observables have linear sensitivity to ϵ_i (interference with SM)

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

Example: $g_{V,A,S,T,P}$



$$\langle p|\bar{u}\Gamma d|n\rangle = g_\Gamma\, \bar{\psi}_p \Gamma \psi_n$$

- To connect experiment to (B)SM couplings, need radiative corrections + hadronic & nuclear matrix elements

How do we probe the ε's?

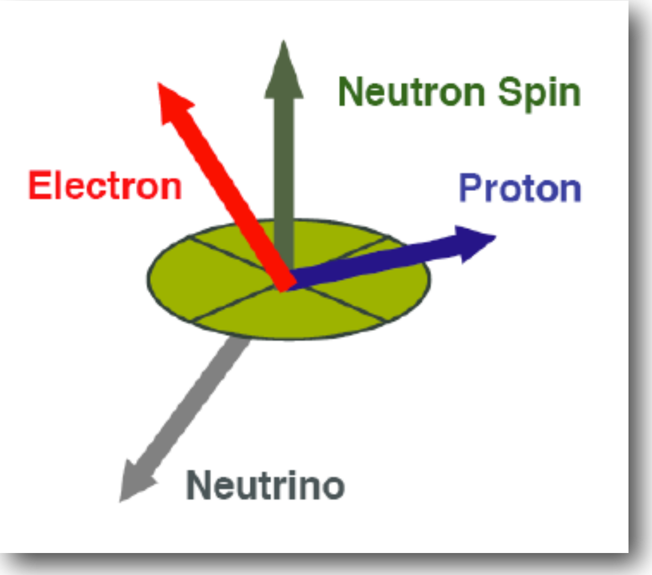
- Rich phenomenology, two classes of observables:

1. Differential decay rates (probe non V-A via "b" and correlations)

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

Lee-Yang, Jackson-Treiman-Wyld

$a(\varepsilon_\alpha)$, $A(\varepsilon_\alpha)$, $B(\varepsilon_\alpha)$, ...
isolated via suitable
experimental asymmetries



How do we probe the ε's?

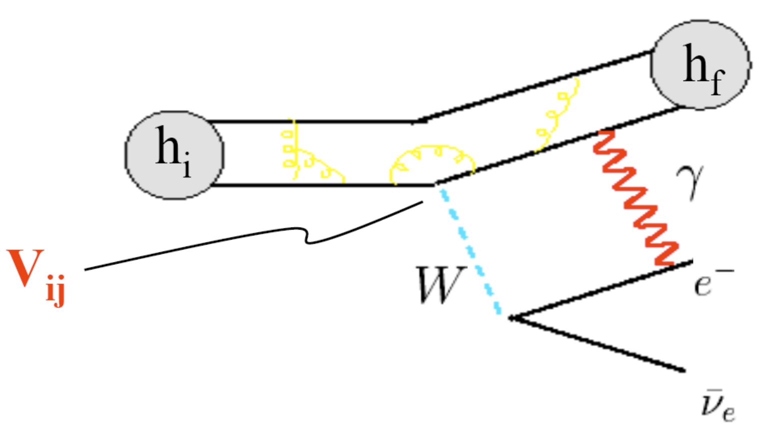
- Rich phenomenology, two classes of observables:

  1. Differential decay rates (probe non V-A via "b" and correlations)

  2. Total decay rates (probe mostly V, A via extraction of V_{ud}, V_{us})

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

Channel-dependent effective CKM element



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

Summary of low energy constraints

- 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)

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

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

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	$\sim 5 - 10\%$	

Summary of low energy constraints

- 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*

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

Non-standard coupling	Observable	Current sensitivity	Prospective sensitivity
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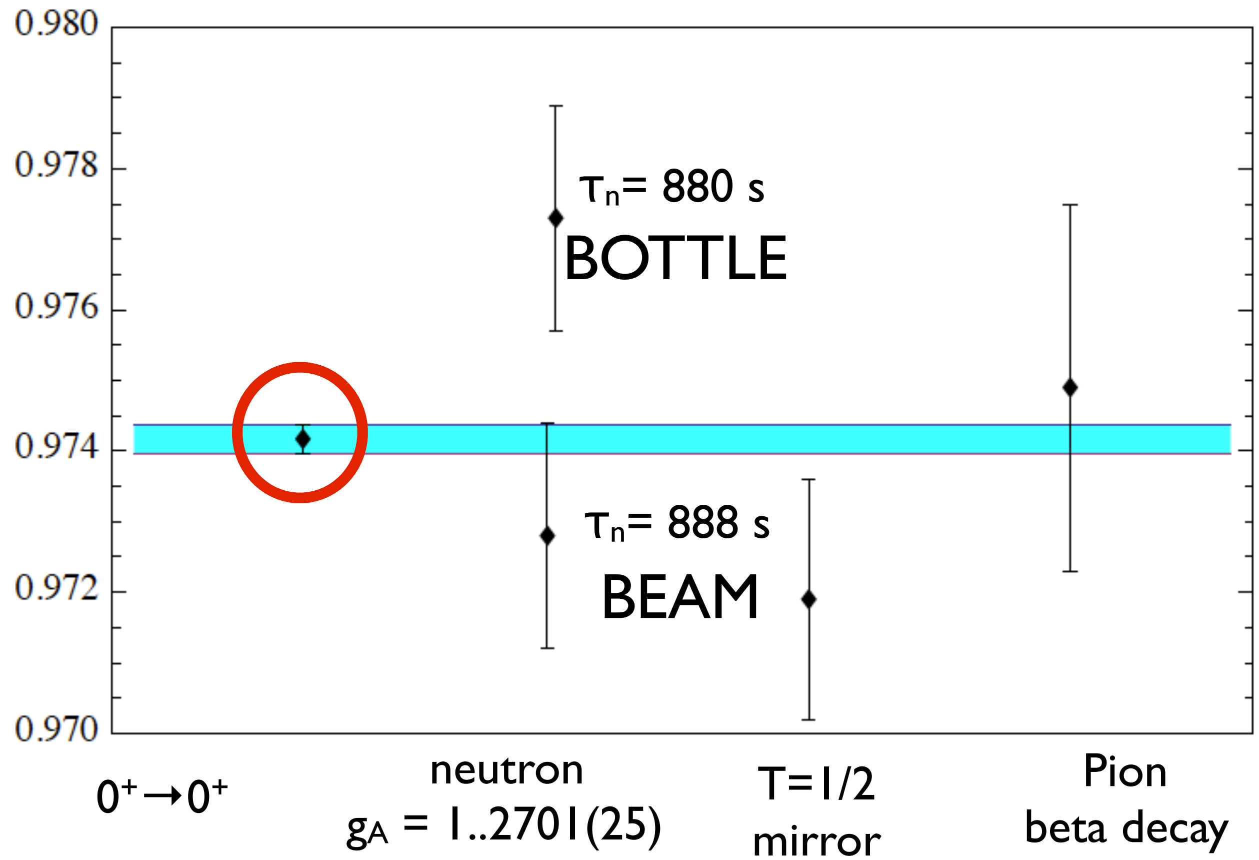
CKM unitarity: input

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

CKM unitarity: input

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

V_{ud}



$V_{ud} = 0.97417(21)$

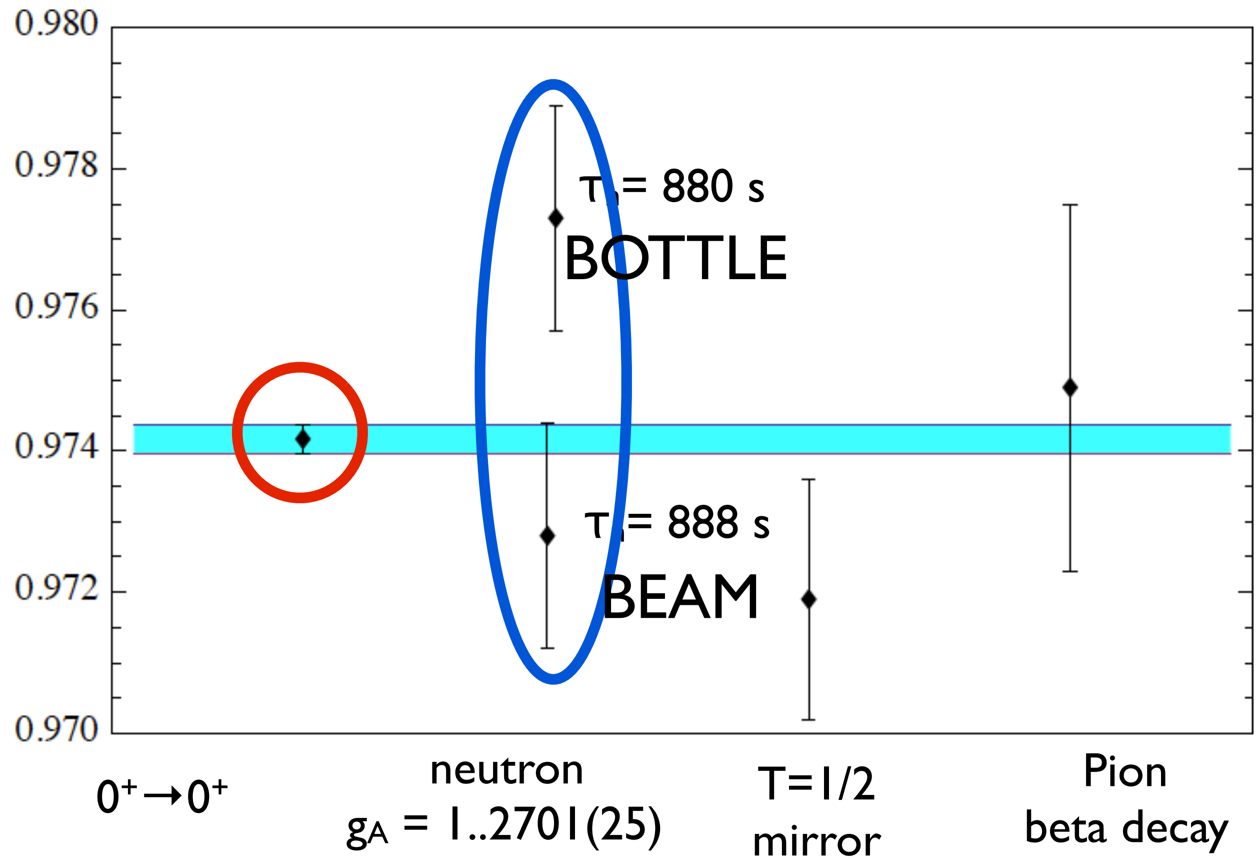
Hardy-Towner 2014

- Extraction dominated by $0^+ \to 0^+$ transitions

CKM unitarity: input

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

V_{ud}



V_{ud} = 0.97417(21)

Hardy-Towner 2014

- Extraction dominated by $0^+ \to 0^+$ transitions

- Not yet competitive:

$$V_{ud} = \left[\frac{4908.7(1.9)\ s}{\tau_n\,(1 + 3g_A^2)}\right]^{1/2}$$

Czarnecki, Marciano, Sirlin 2004

V_{ud} from $0^+ \to 0^+$ nuclear β decays

$$\frac{1}{t} = \frac{G_\mu^2 |V_{ud}|^2 m_e^5}{\pi^3 \log 2} f(Q)\ (1 + RC) \longrightarrow f\, t\ (1 + RC) = \frac{2984.48(5)\ s}{|V_{ud}|^2}$$

$$(1 + RC) = (1 - \delta_C)\ (1 + \delta_R)\ (1 + \Delta_C)$$

$\langle f | \tau_+ | i \rangle = \sqrt{2}\,(1 - \delta_C/2)$

Coulomb distortion
of wave-functions

$\delta_C \sim 0.5\%$

Towner-Hardy
Ormand-Brown

Nucleus-dependent
rad. corr.
(Z, E^{max} ,nuclear structure)

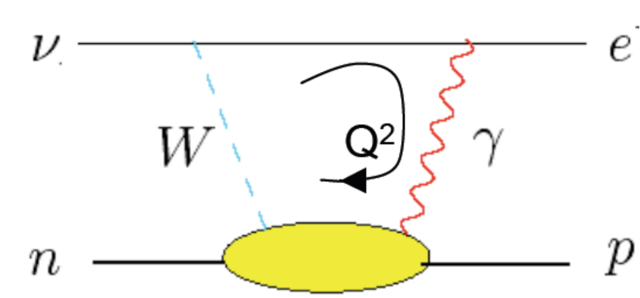
$\delta_R \sim 1.5\%$

Sirlin-Zucchini '86
Jaus-Rasche '87

Nucleus-independent
short distance rad. corr.

$\Delta_R \sim 2.4\%$

Marciano-Sirlin '06



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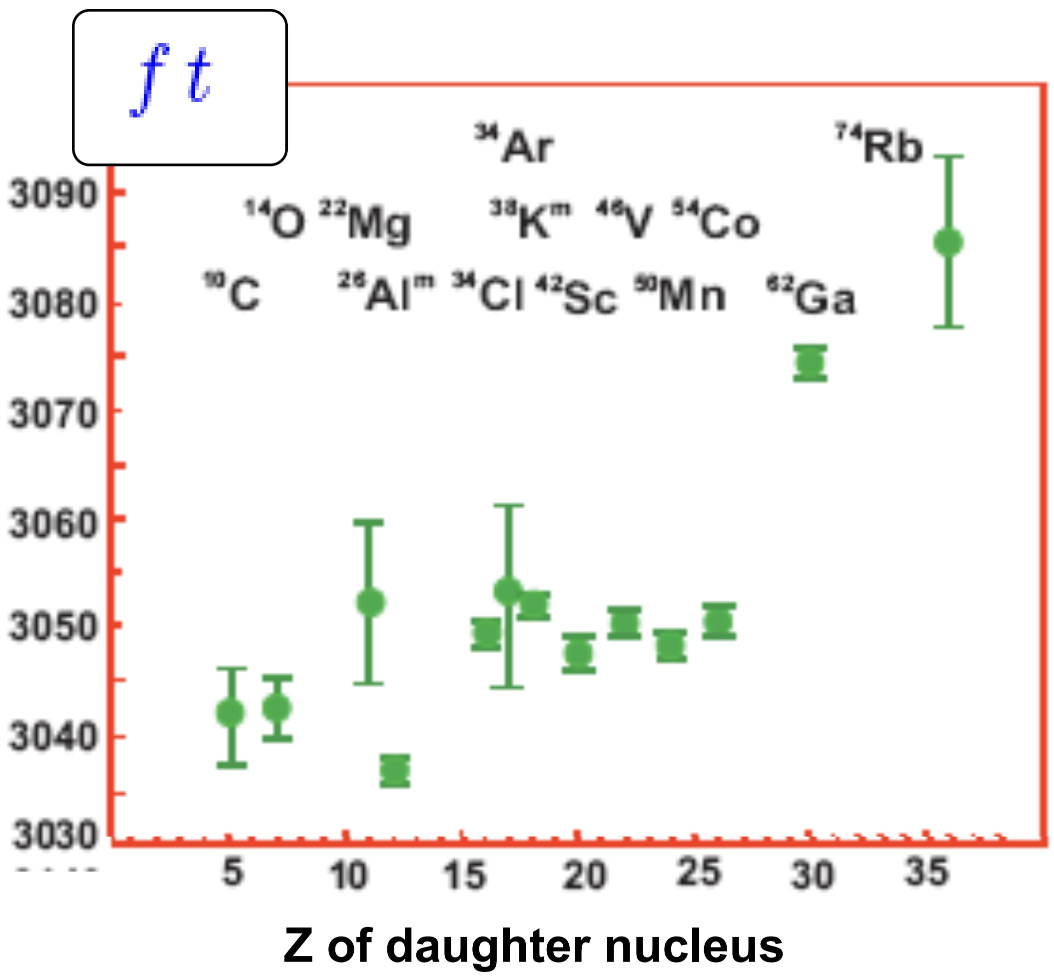
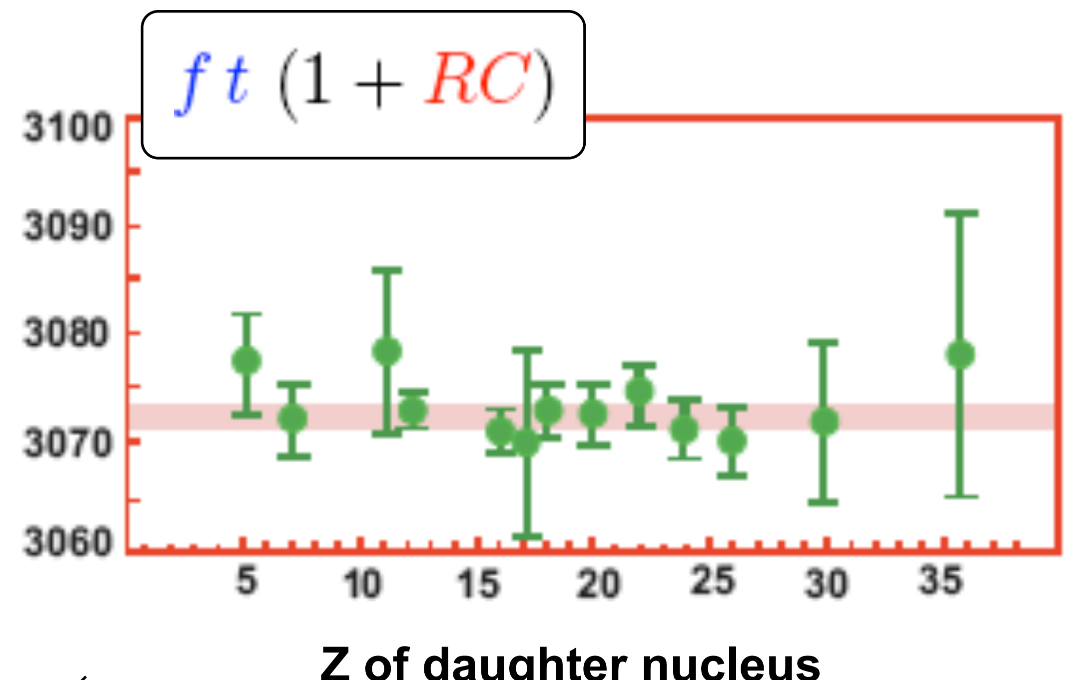
Towner-Hardy, Sirlin-Zucchini, Marciano-Sirlin



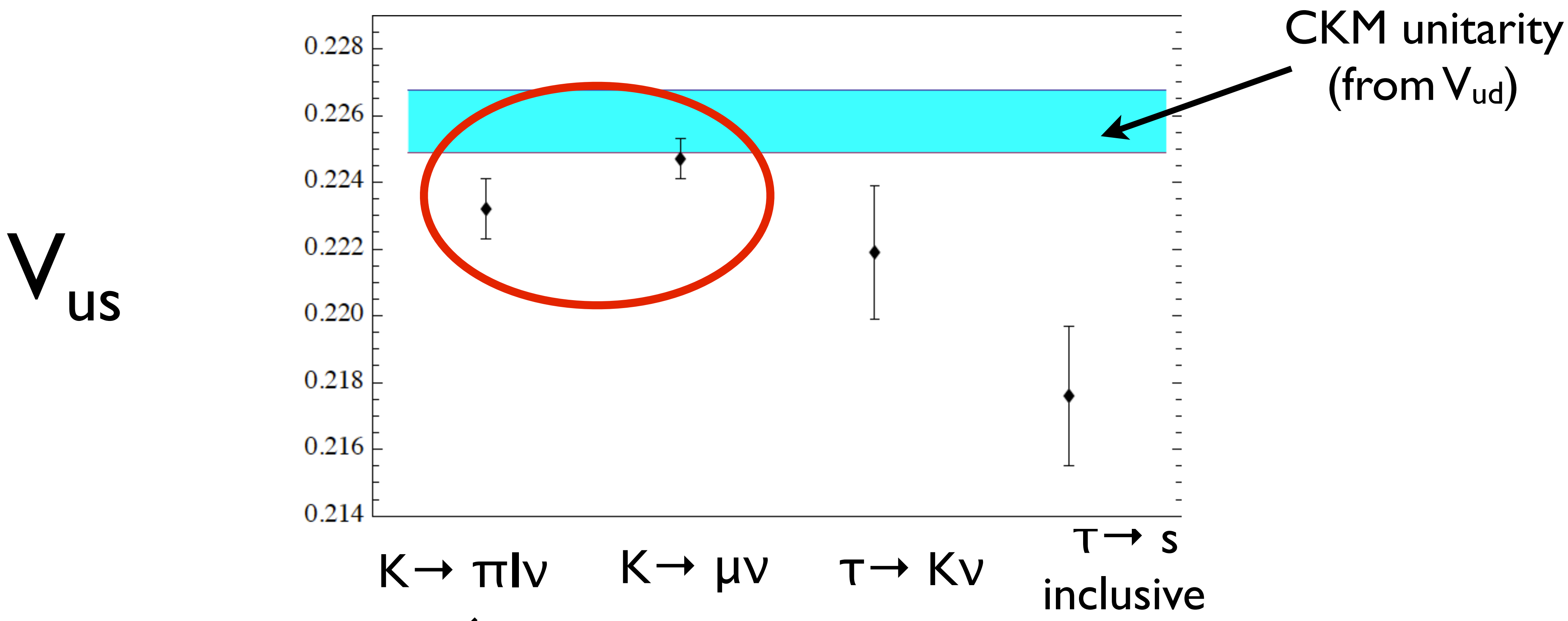


$$V_{ud} = 0.97417\,(21)$$

Townwer-Hardy 2014

CKM unitarity: input

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



$$\langle \pi | V_\mu | K \rangle \propto f_+(0)(p_K + p_\pi)_\mu + \ldots$$

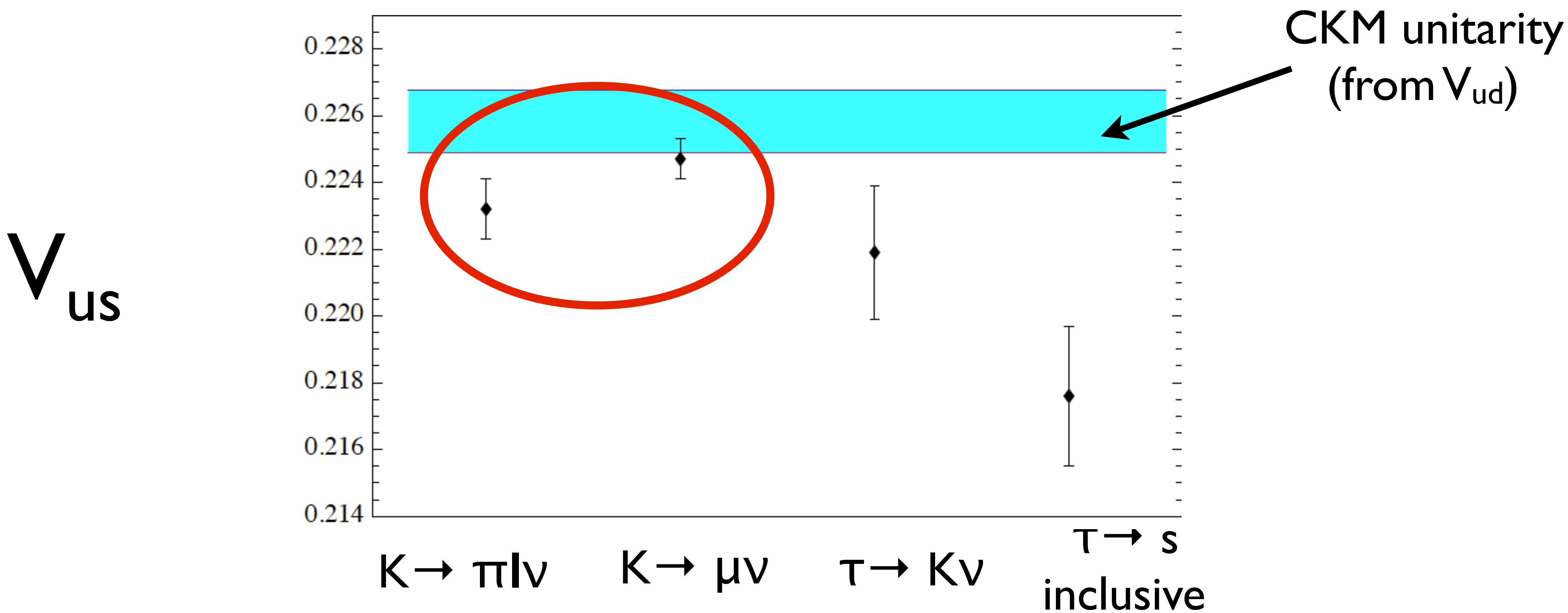
$$V_\mu = \bar{s}\gamma_\mu u$$

$$\langle 0 | A_\mu | K \rangle \propto F_K (p_K)_\mu$$

$$A_\mu = \bar{s}\gamma_\mu \gamma_5 u$$

CKM unitarity: input

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



- New LQCD calculations have led to smaller V_{us} from $K \to \pi l \nu$

$f_+^{K\to\pi}(0) = 0.959(5) \to 0.970(3)$

$F_K/F_\pi = 1.1960(25)$ [stable]

$m_\pi \to m_\pi^{phys}$, $a \to 0$, dynamical charm

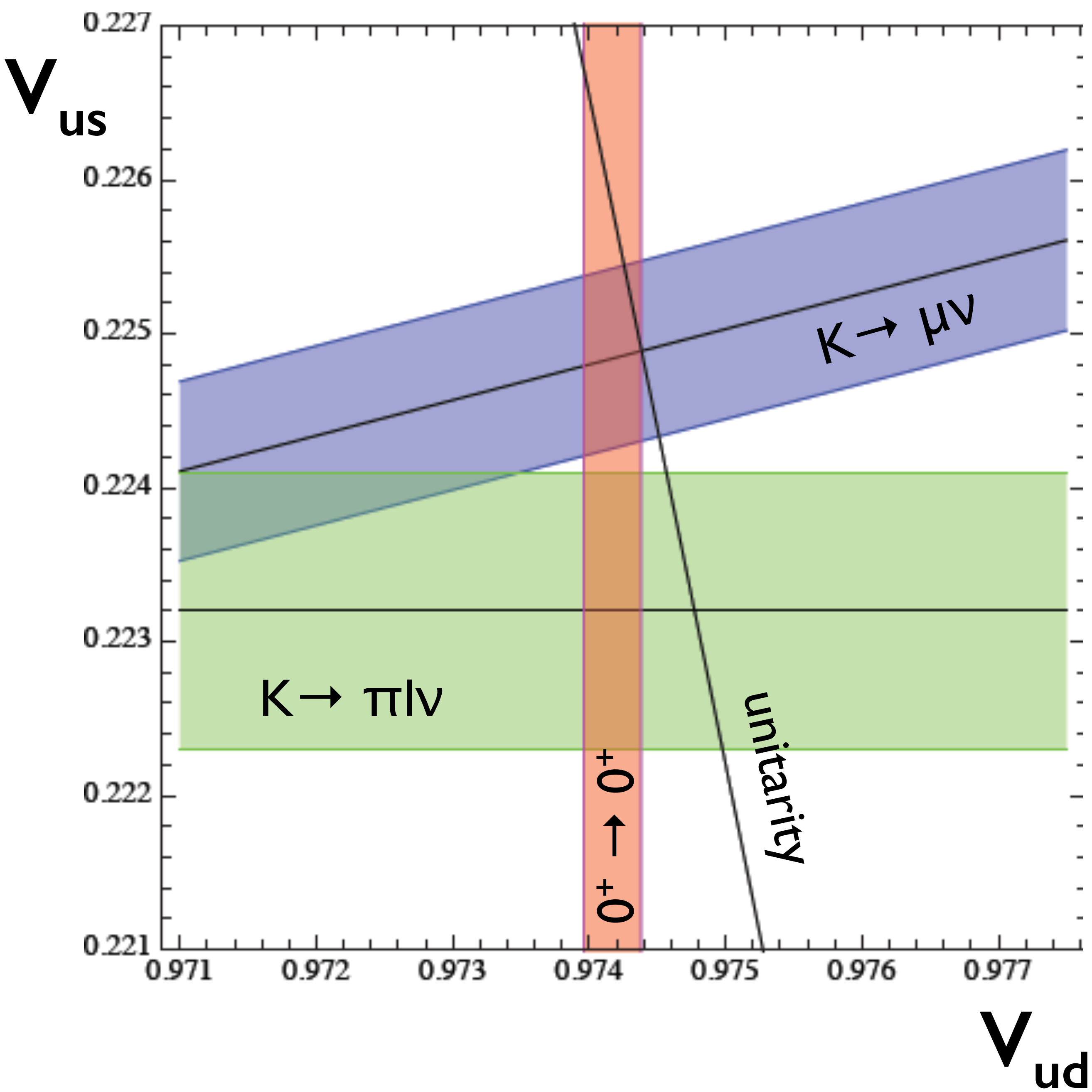
$V_{us} = 0.2254(13) \to 0.2231(9)$

$V_{us} / V_{ud} = 0.2313(7)$

FLAG 2016

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→ μν

Δ_{CKM} = - (4 ± 5) ∗ 10^{-4} 0.9σ

Δ_{CKM} = - (12 ± 6) ∗ 10^{-4} 2.1σ

V_{us} from K→ πlν

- No longer perfect agreement:
  - New physics?
  - Underestimated th. errors? [δ_C (A,Z), $f_+(0)$, F_K/F_π]

CKM unitarity: opportunities

- Given high stakes (0.05% EW test), it is highly desirable to
  - Assess robustness of δ_C: nucl. str. calculations + expt. validation
  - Pursue V_{ud} @ 0.02% through neutron decay

$$V_{ud} = \left[\frac{4908.7(1.9)\ s}{\tau_n\,(1+3g_A^2)}\right]^{1/2}$$

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

BL2, BL3 (cold beam), UCNτ, ...

$\delta g_A/g_A \sim 0.025\%$
($\delta a/a$, $\delta A/A \sim 0.1\%$)

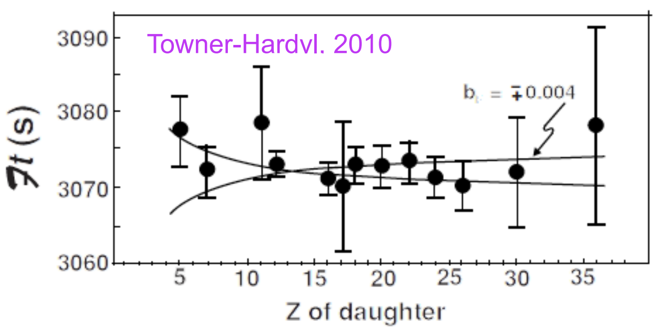
aCORN, Nab, UCNA+, ...

Scalar and tensor couplings

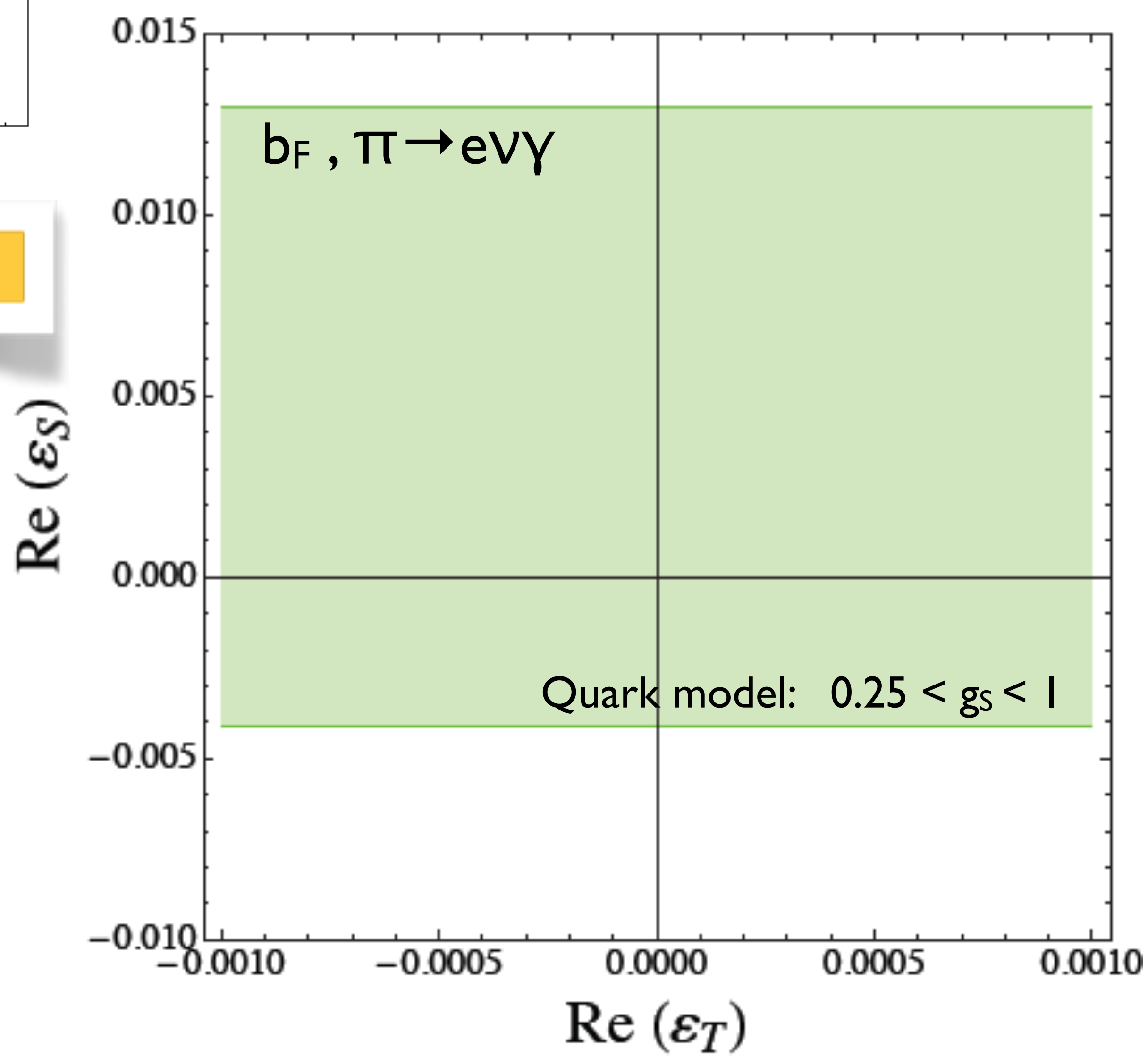
CURRENT

- Current most sensitive probes**:

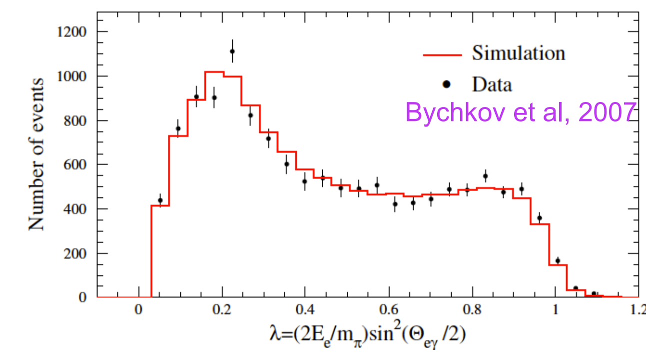
$0^+ \to 0^+$ (b_F)



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



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



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

$f_T = 0.24(4)$

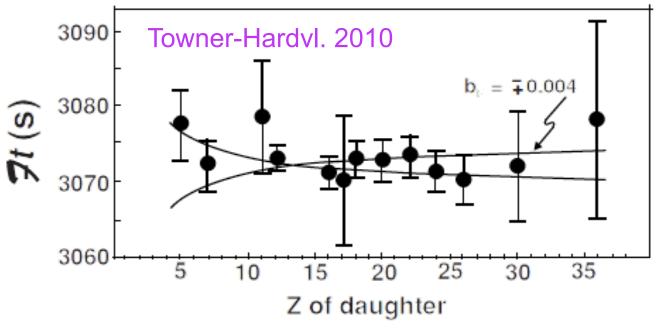
** For global analysis see Wauters et al, 1306.2608

Scalar and tensor couplings

CURRENT

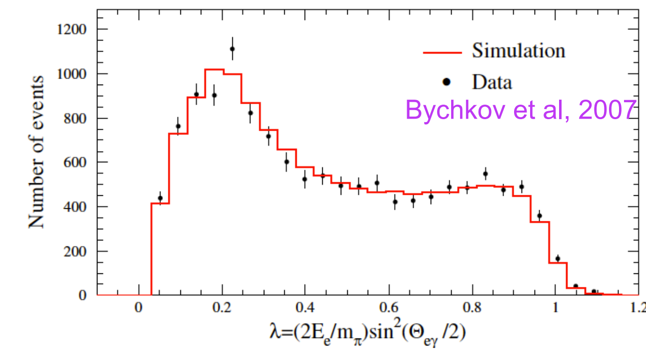
- Current most sensitive probes**:

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



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

$\pi \rightarrow e\nu\gamma$



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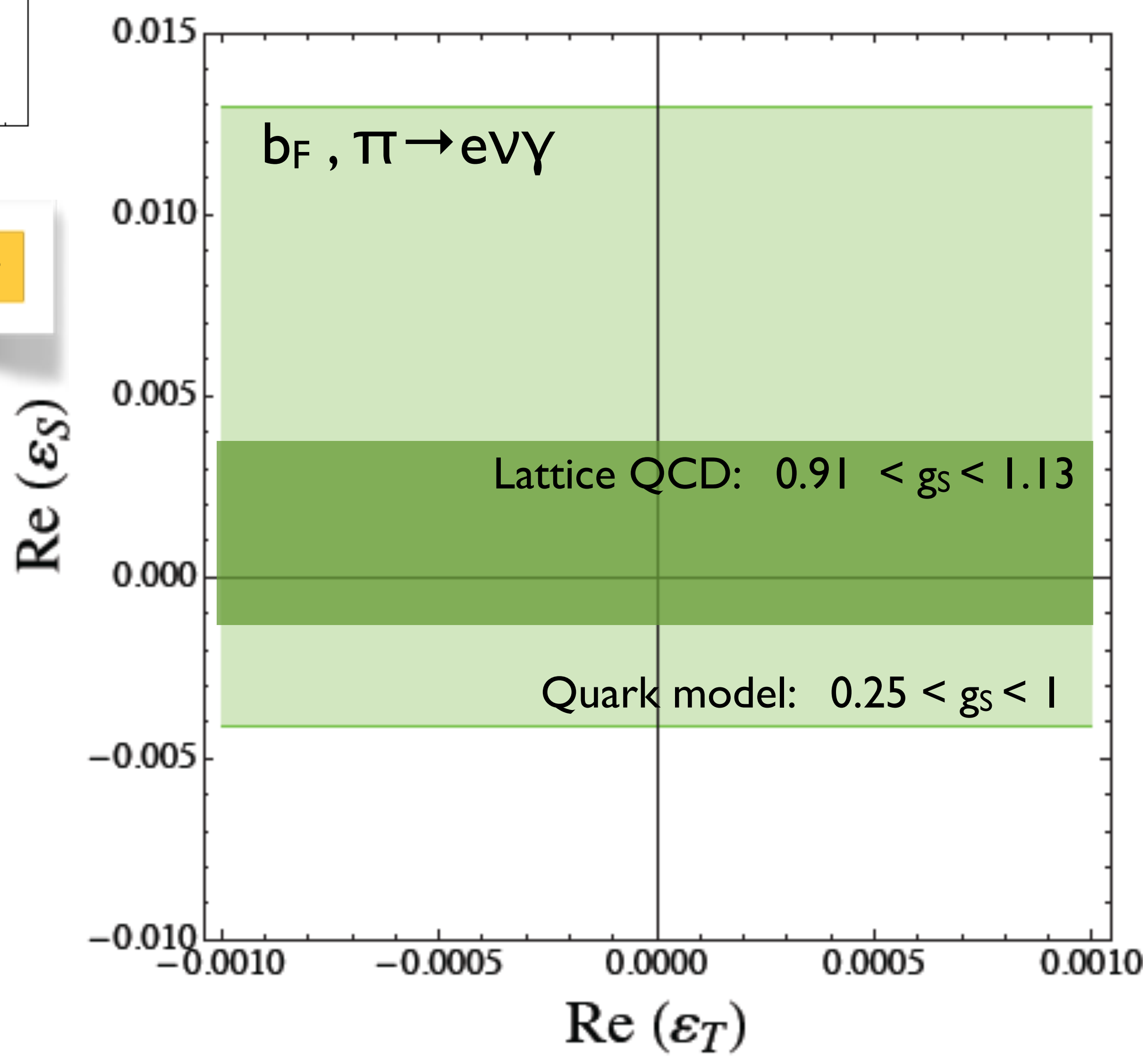


Impact of improved theoretical calculations using lattice QCD

Bhattacharya, et al 1110.6448

R. Gupta et al. 2014

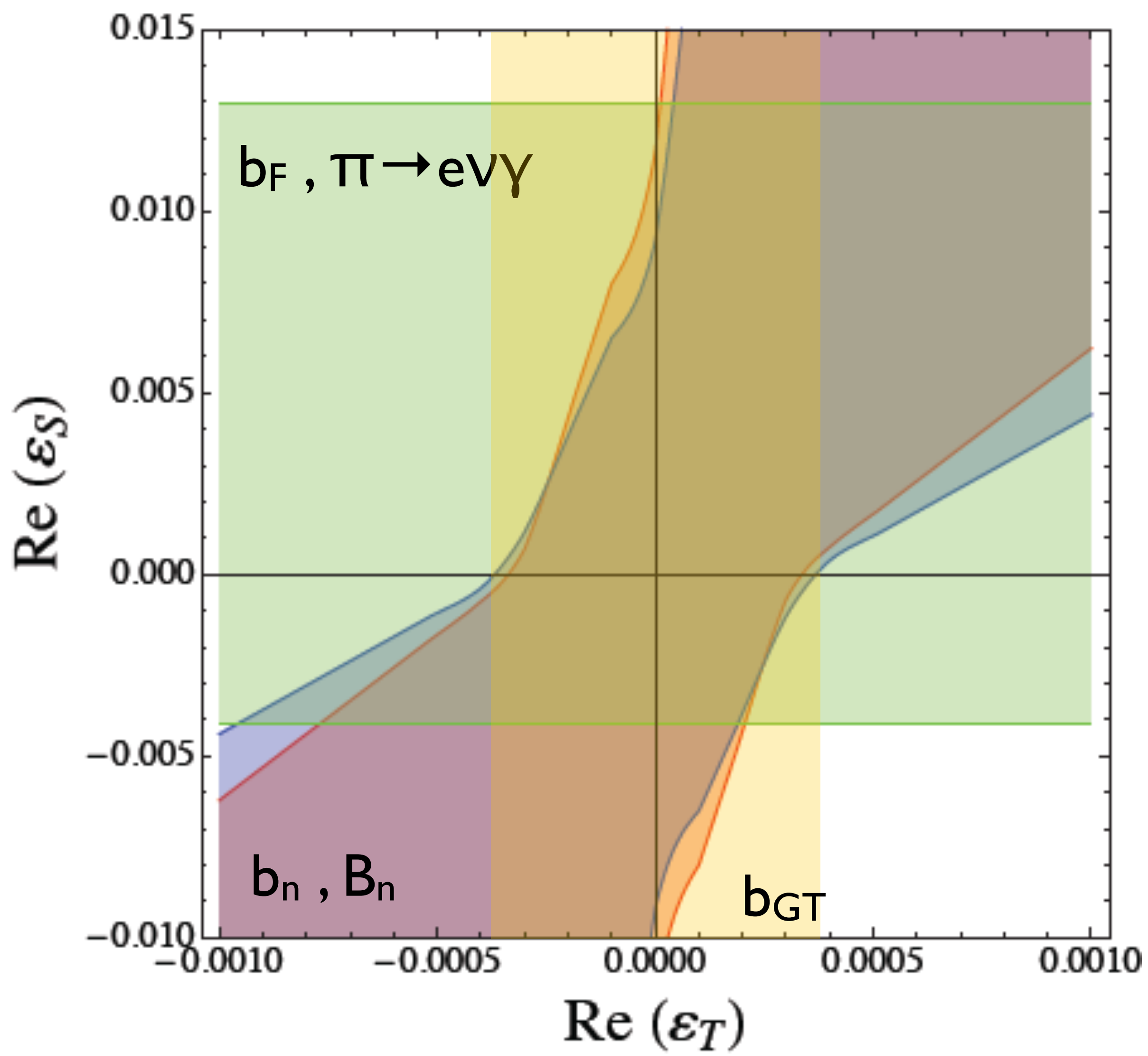
** For global analysis see Wauters et al, 1306.2608

Scalar and tensor couplings

FUTURE

- Several precision measurements on the horizon (neutron & nuclei)
- For definiteness, study impact of b_n, B_n @ 10^{-3}; b_{GT} (^{6}He, ...) @10^{-3}

Nab,
UCNB,
^{6}He,
...



Quark model:

$0.25 < g_S < 1$

$0.6 < g_T < 2.3$

Herczeg 2001

Scalar and tensor couplings

FUTURE

- Several precision measurements on the horizon (neutron & nuclei)
- For definiteness, study impact of b_n, B_n @ 10^{-3}; b_{GT} (^{6}He, ...) @10^{-3}

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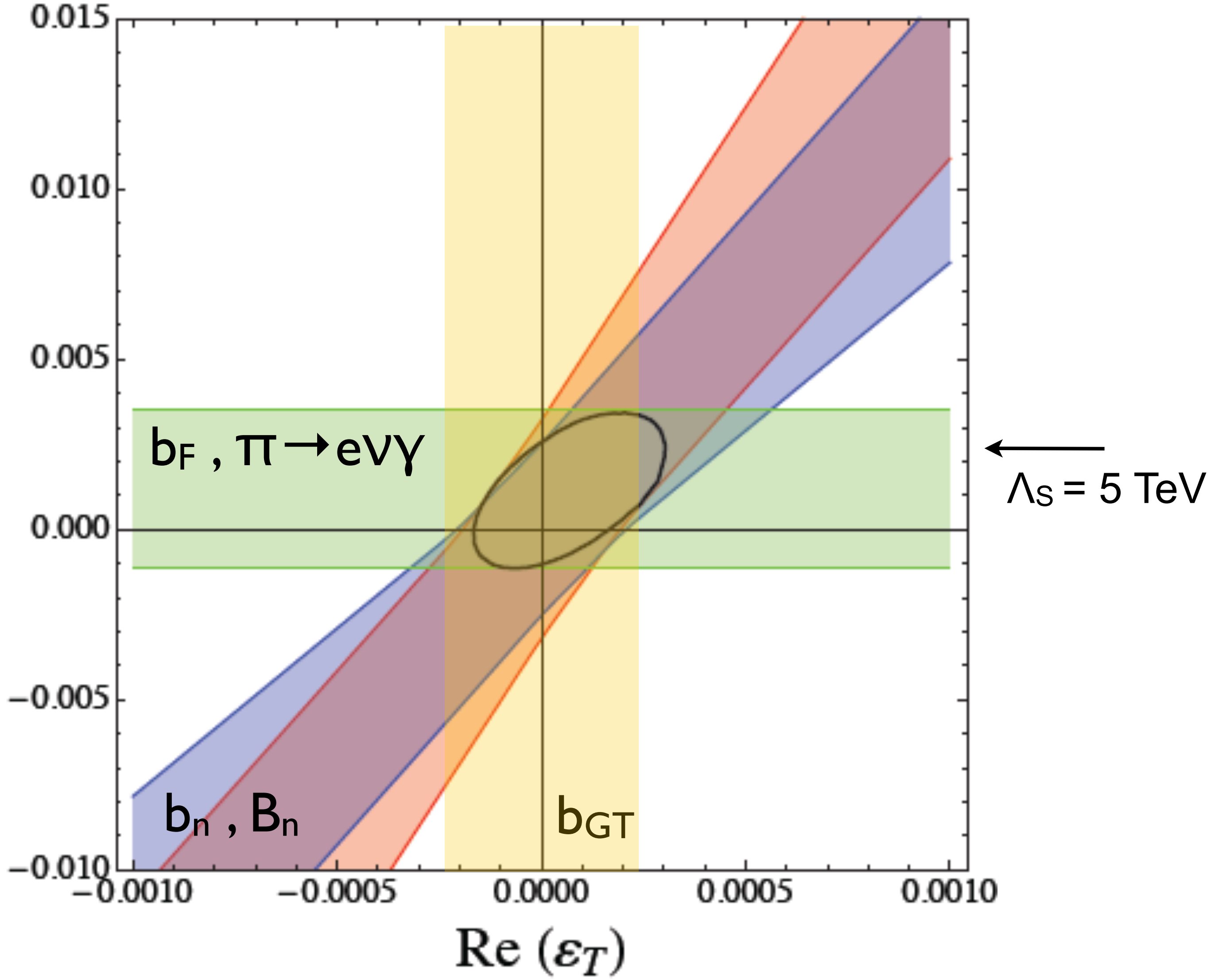


Lattice QCD 2014

$0.91 < g_S < 1.13$

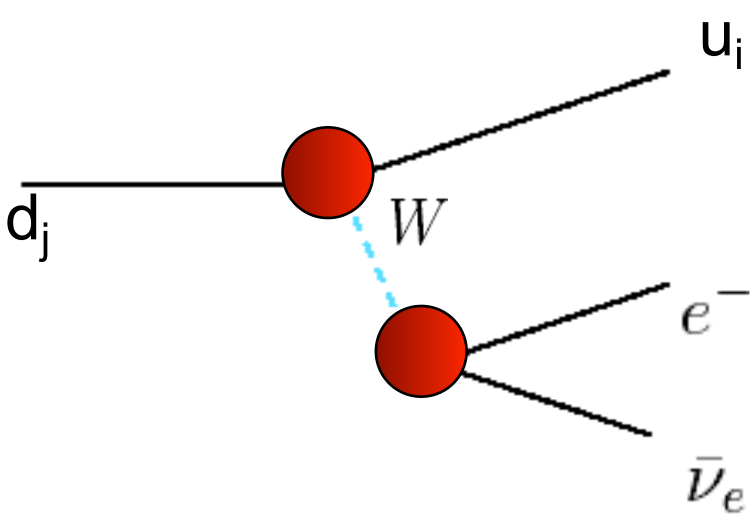
$1.0 < g_T < 1.1$

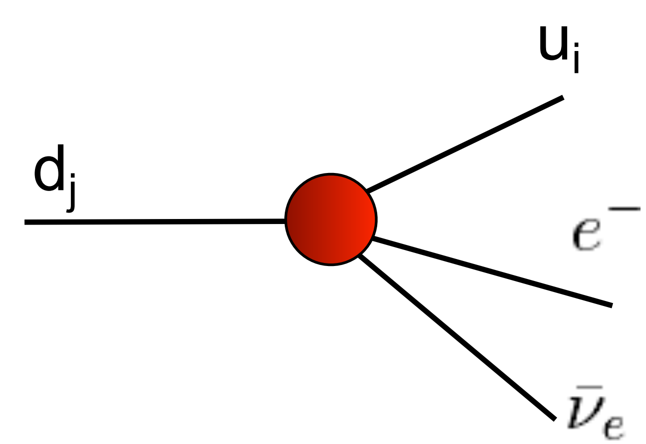
R. Gupta et al. 2014

- Can greatly improve existing limits on ε_T, probing $\Lambda_T \sim 10$ TeV

High energy constraints

- The new physics that contributes to ε_α affects other observables!
- Relative strength of constraints depends on the specific model
- Model-independent statements possible in "heavy BSM" limit:
  M_{BSM} > TeV → new physics looks point-like at the weak scale





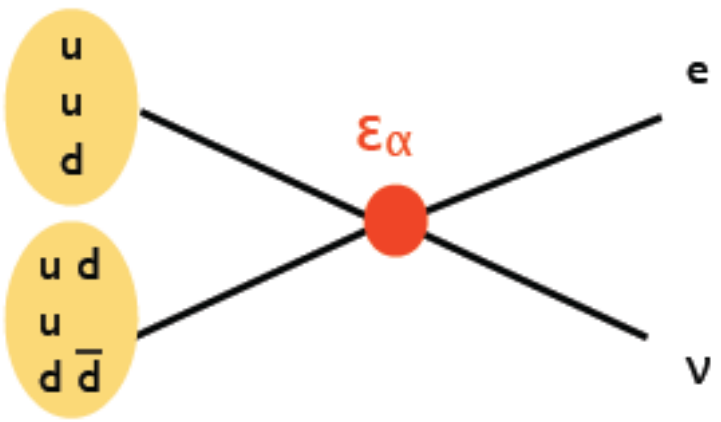
Vertex corrections strongly constrained by Z-pole observables (Δ_{CKM} is at the same level)

Four-fermion interactions "poorly" constrained: σ_{had} at LEP would allow Δ_{CKM} ~0.01 and non V-A structures at ε_i ~ 5%. What about LHC?

VC, Gonzalez-Alonso, Jenkins 0908.1754

LHC constraints

- Heavy BSM limit: all ε_α couplings contribute to the process
  $p\ p \rightarrow e\ \nu + X$



T. Bhattacharya, VC, et al, 1110.6448
VC, Gonzalez-Alonso, Graesser, 1210.4553

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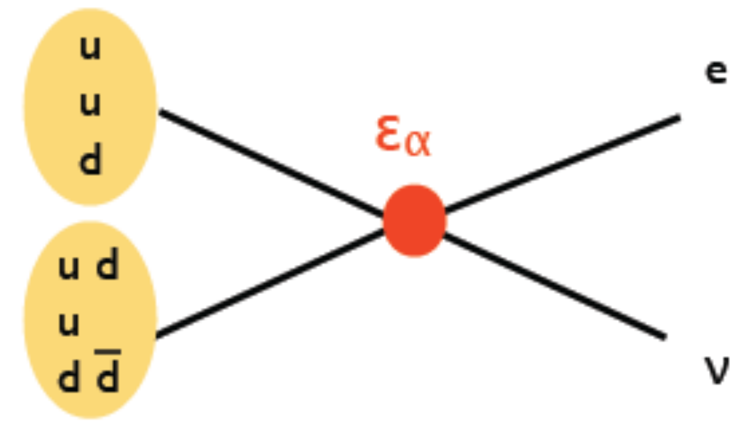
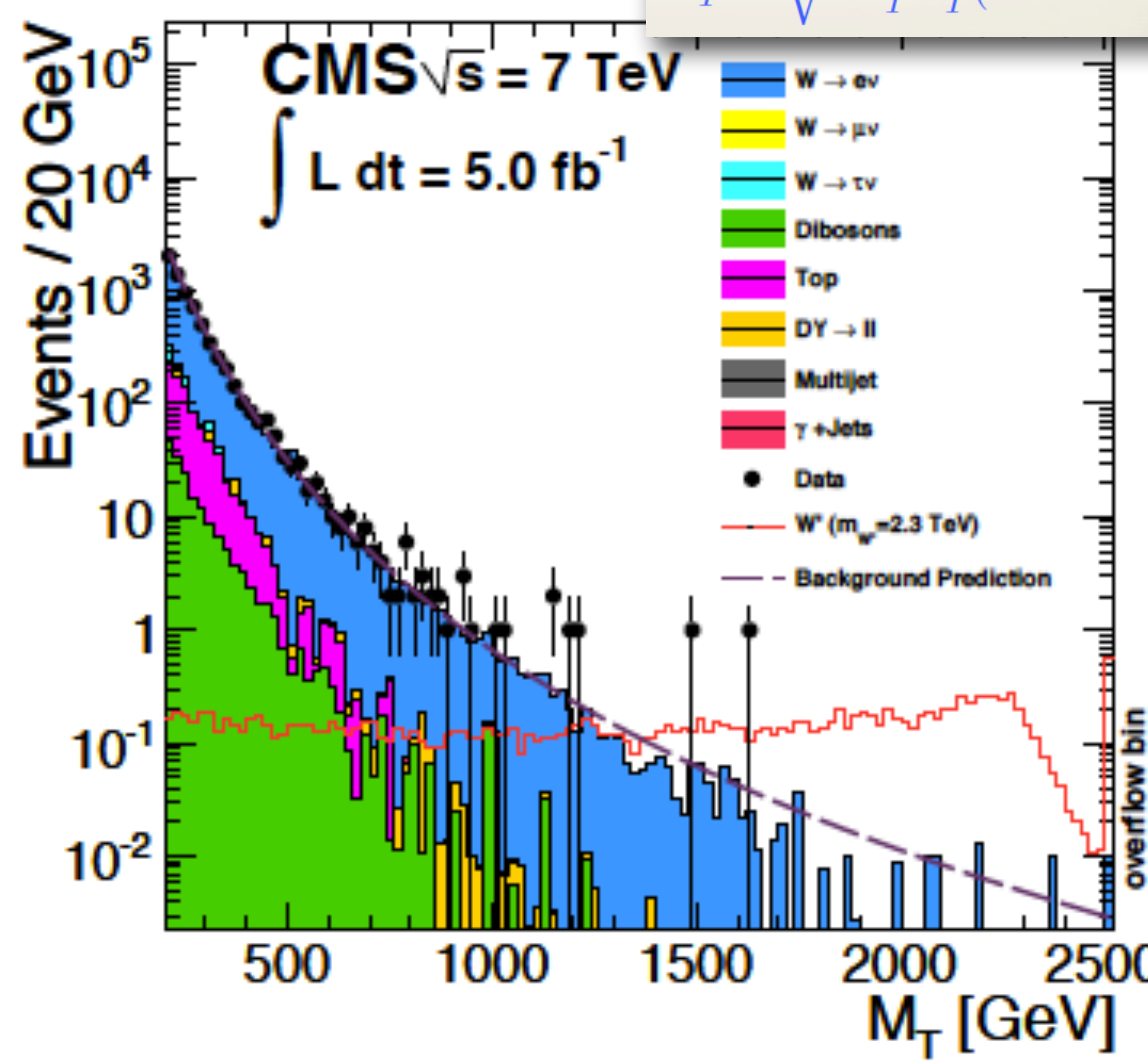


- No excess events at high m_T
  $\Rightarrow$ bounds on ε_α
- Current bounds at the level of 0.3%-1%, depending on the operator

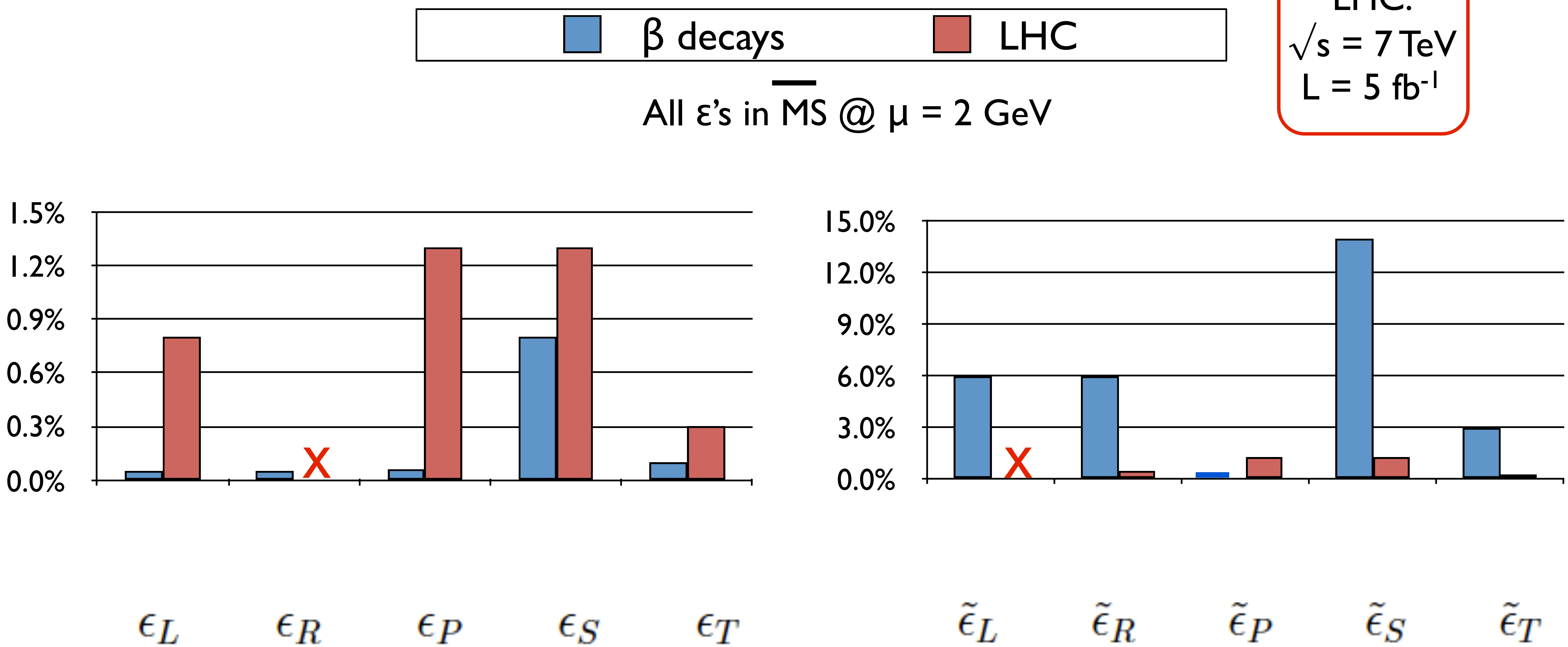
$$m_T \equiv \sqrt{2E_T^e E_T^\nu (1-\cos\Delta\phi_{e\nu})}$$



T. Bhattacharya, VC, et al, 1110.6448
VC, Gonzalez-Alonso, Graesser, 1210.4553

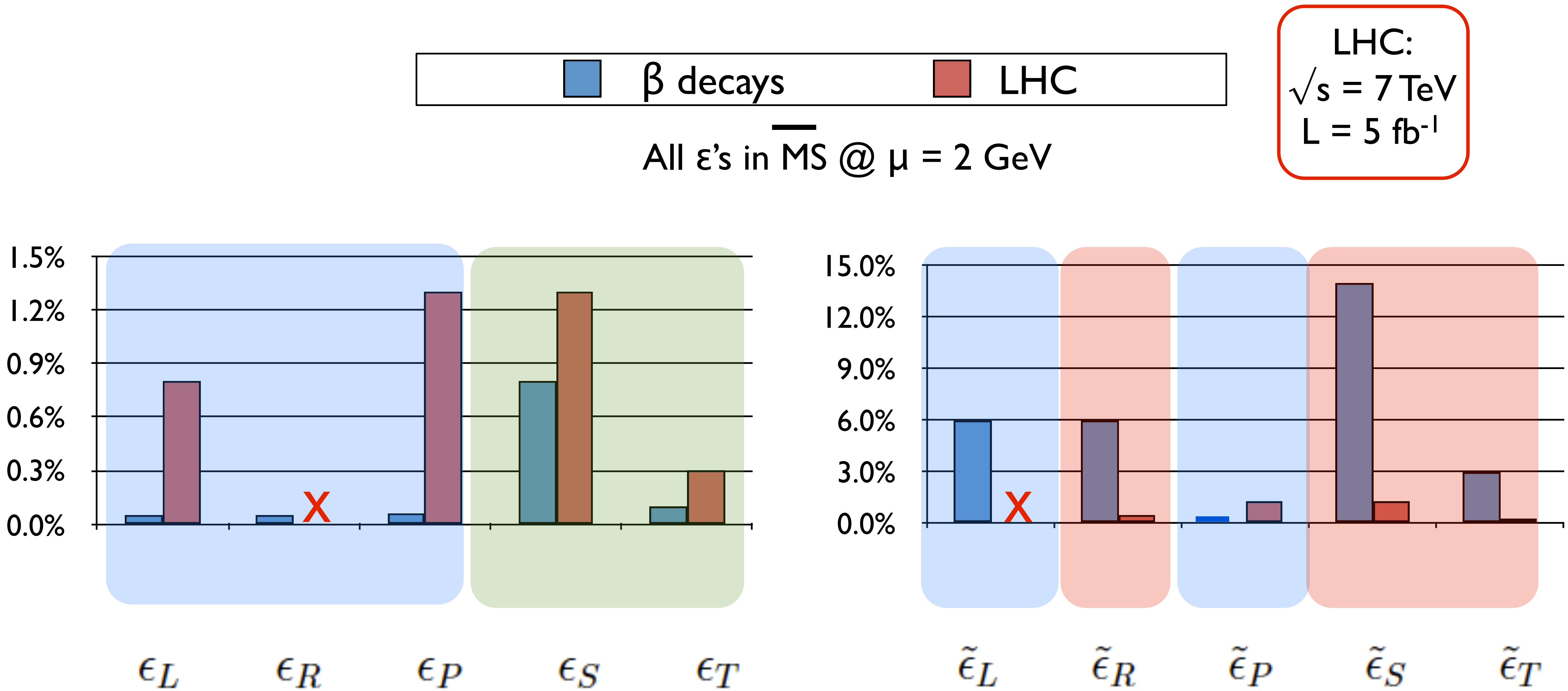
β decays vs LHC reach

LHC:
$\sqrt{s}$ = 7 TeV
L = 5 fb^{-1}



VC, Gonzalez-Alonso, Graesser, 1210.4553

β decays vs LHC reach



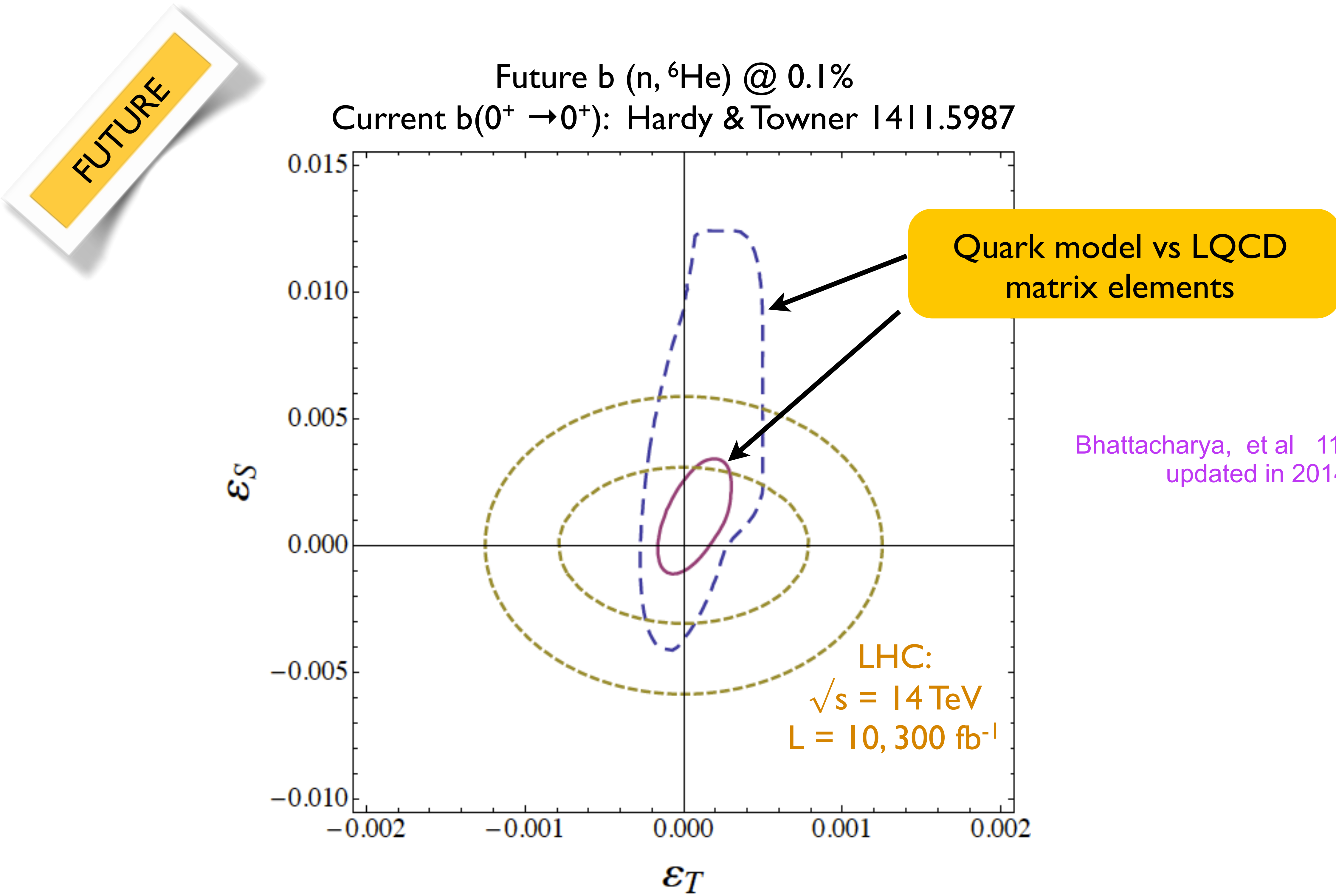
Unmatched low-energy sensitivity and future reach

LHC limits close to low-energy. Interesting interplay in the future

LHC reach already stronger than low-energy

VC, Gonzalez-Alonso, Graesser, 1210.4553

- Scalar and tensor operators: β-decays can probe deeper than the LHC!



Bhattacharya, et al 1110.6448, updated in 2014

Connection to models

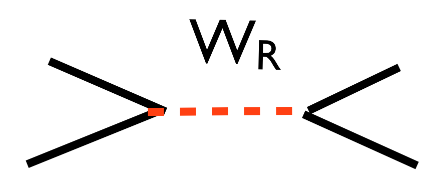
- A given model → set overall size and pattern of ϵ_α couplings
- Beta decays can play very useful diagnosing role. Qualitative picture:

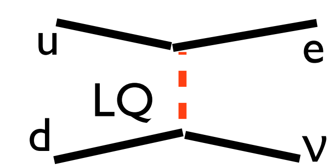
	ϵ_L	ϵ_R	ϵ_P	ϵ_S	ϵ_T
LRSM	x	✓	x	x	x
LQ	✓	x	✓	✓	✓
2HDM	x	x	✓	✓	x
MSSM	✓	✓ (small)	✓ (small)	✓ (small)	✓ (small)
YOUR FAVORITE MODEL		...		...	

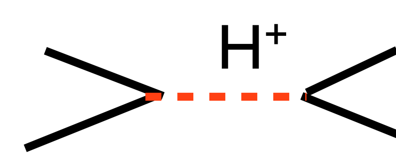
Can be made quantitative

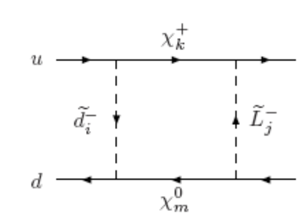
Bauman, Erler, Ramsey-Musolf, arXiv:1204.0035

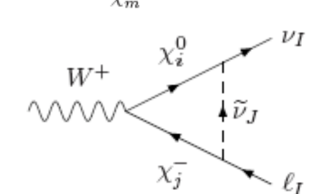
Profumo, Ramsey-Musolf, Tulin hep-ph/0608064











Neutral Current

Neutral analogue of V-A CC interaction?

- Speculation by Zel'dovic before the incorporation within the SU(2)xU(1) model of electroweak interactions

PARITY NONCONSERVATION IN THE FIRST ORDER IN THE WEAK-INTERACTION CONSTANT IN ELECTRON SCATTERING AND OTHER EFFECTS

Ya. B. ZEL'DOVICH

Submitted to JETP editor December 25, 1958
J. Exptl. Theoret. Phys. (U.S.S.R.) 36, 964-966 (March, 1959)

WE assume that besides the weak interaction that causes beta decay,

$$g(\bar{P}ON)(\bar{e}^- O\nu) + \text{Herm. conj.}, \quad (1)$$

there exists an interaction

$$g(\bar{P}OP)(\bar{e}^- Oe^-) \quad (2)$$

with $g \approx 10^{-49}$ and the operator $O = \gamma_\mu(1 + i\gamma_5)$ characteristic[1] of processes in which parity is not conserved.*

Then in the scattering of electrons by protons the interaction (2) will interfere with the Coulomb scattering, and the nonconservation of parity will appear in terms of the first order in the small quantity g. Owing to this it becomes possible to test the hypothesis used here experimentally and to determine the sign of g.

The matrix element of the Coulomb scattering is of the order of magnitude e^2/k^2, where k is the momentum transferred ($\hbar = c = 1$). Consequently, the ratio of the interference term to the Coulomb term is of the order of gk^2/e^2. Substituting $g = 10^{-5}/M^2$, where M is the mass of the nucleon, we find that for $k \sim M$ the parity nonconservation effects can be of the order of 0.1 to 0.01 percent.

In the scattering of fast ($\sim 10^9$ ev) longitudinally polarized electrons through large angles by unpolarized target nuclei it can be expected that the cross-sections for right-hand and left-hand electrons (i.e., for electrons with $\sigma \cdot p > 0$ and $\sigma \cdot p < 0$) can differ by 0.1 to 0.01 percent. Such an effect is a specific test for an interaction not conserving parity.

A magnetized iron plate can served as a source

not expect a[illegible] ing electron[illegible] electrons wi[illegible] the magnetiz[illegible]

The inter[illegible] the electron levels of different parities in the free atom.

In the hydrogen atom the probability of the metastable transition $2S_{1/2} \to 1S_{1/2}$, which appears on account of the admixture of $2P_{1/2}$ to the $2S_{1/2}$, still turns out to be even smaller that the transition probability on account of the magnetic moment of the electron, and is less than the probability of the two-quantum transition $2S \to 1S$ by a factor of more than 10^7. Finally, the interaction (2) leads to a rotation of the plane of polarization of visible light by any substance not containing molecules optically active in the ordinary sense of the words. The rotation of the plane of polarization also occurs because the weak interaction mixes atomic electronic states of different parity. A calculation of the effect gives an expression of the form

$$|n_{right} - n_{left}| \sim N_a(a^4/\lambda)g|\psi_S(0)||\psi_P(0)|/(E_P - E_S), \quad (3)$$

where n is the index of refraction for circularly polarized light; $N_a \sim a^{-3}$ is the number density of the atoms; a is the linear dimension of an atom; λ is the wavelength of the light; $|\psi_S(0)| \sim 1/a^{3/2}$; in $|\psi_P(0)|$ there are nonvanishing "small components" χ, given by $\chi \sim (\hbar/2mc)\sigma \operatorname{grad} \varphi$, where φ are the "large components": $|\psi_P(0)| \sim (\hbar/mc)a^{-5/2}$, so that

$$|n_{right} - n_{left}| \sim (g/a^3\Delta E_{SP})(\lambda/mc\hbar) \sim 10^{-20}. \quad (4)$$

Rotation of the plane of polarization by 1 radian occurs in a length of the order $\lambda/10^{-20} = 10^{15}$ cm, so that even in the first order in g the effect obviously cannot be observed.

How plausible is the assumption that the interaction (2) exists? [illegible]

1958

Discovery of neutral currents in $\nu_\mu e \to \nu_\mu e$ would be made in 1973

Krishna Kumar

PARITY NONCONSERVATION IN THE FIRST ORDER IN THE WEAK-INTERACTION CONSTANT IN ELECTRON SCATTERING AND OTHER EFFECTS

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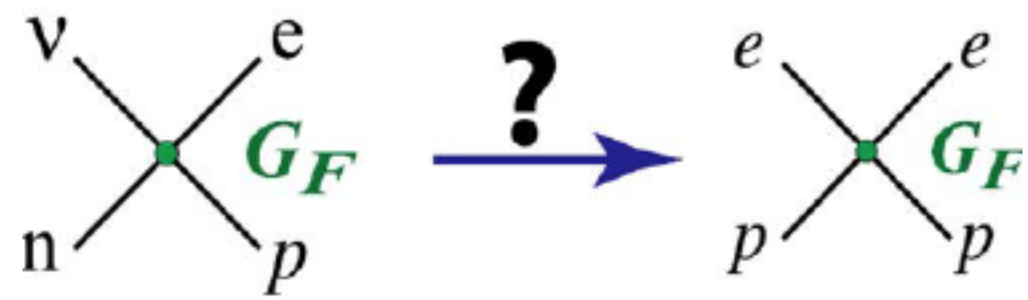


$$\sigma \;\alpha\; |A_{EM} + A_{weak}|^2$$

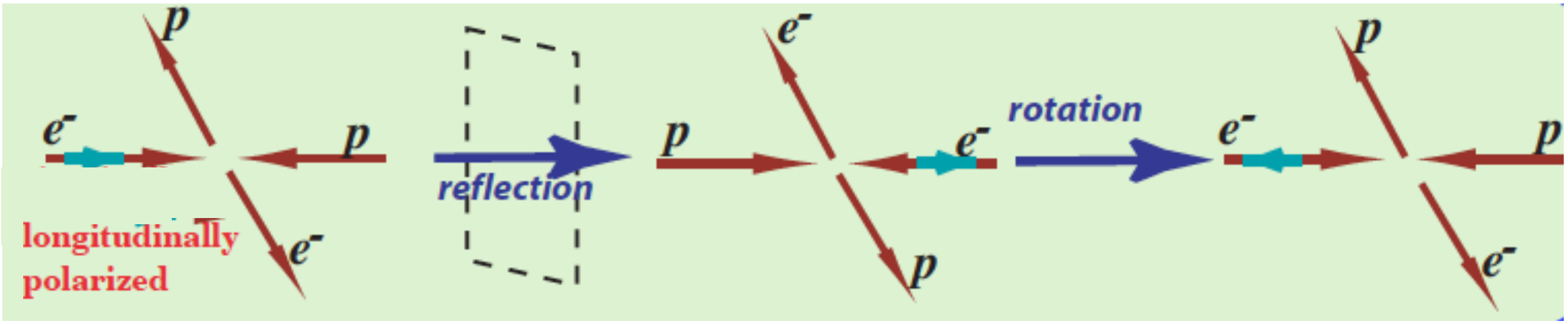
$$\sim |A_{EM}|^2 + 2A_{EM}A^*_{weak} + \ldots$$

Parity violating

$$A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

Krishna Kumar

- A_{PV} violates parity:



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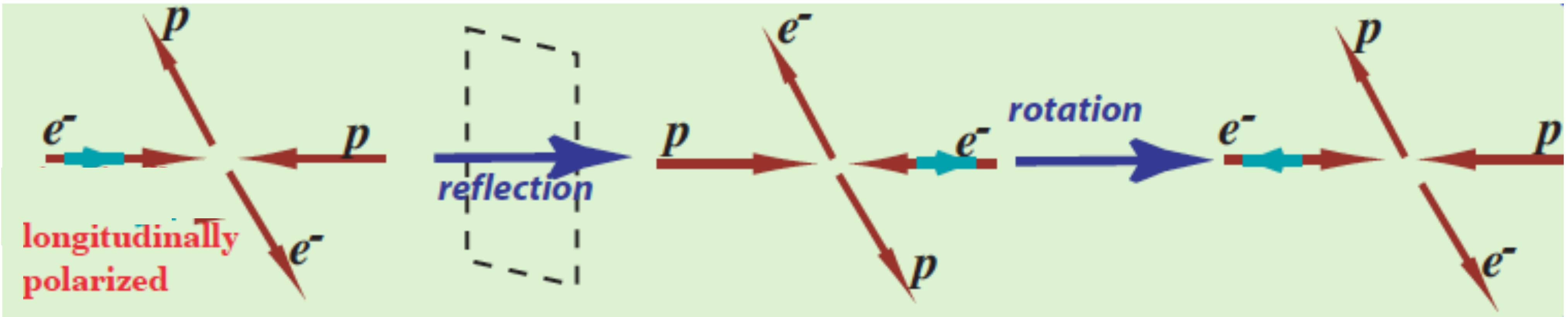
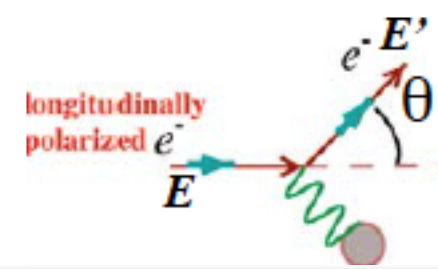


- Expected size of the effect:

The matrix element of the Coulomb scattering is of the order of magnitude e^2/k^2, where k is the momentum transferred ($\hbar = c = 1$). Consequently, the ratio of the interference term to the Coulomb term is of the order of gk^2/e^2. Substituting $g = 10^{-5}/M^2$, where M is the mass of the nucleon, we find that for $k \sim M$ the parity nonconservation effects can be of the order of 0.1 to 0.01 percent.



4-momentum transfer

$$Q^2 = 4EE'\sin^2\frac{\theta}{2}$$

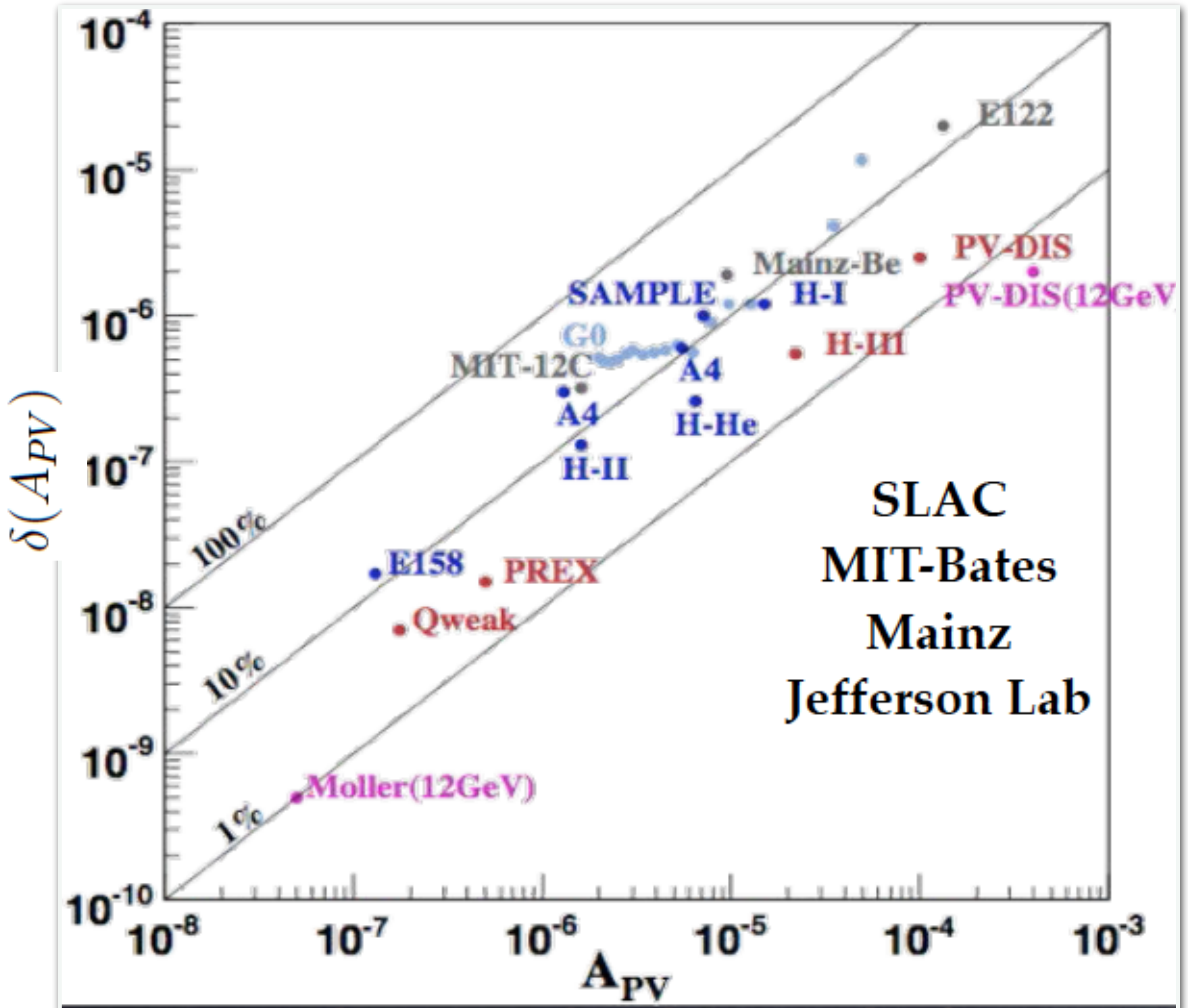
$$A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_{EM}} \sim \frac{G_F Q^2}{4\pi\alpha}$$

$$A_{PV} \sim 10^{-4} \cdot Q^2 (\mathrm{GeV}^2)$$

Tiny asymmetries!

Krishna Kumar

- Through 4 decades of technical progress, parity-violating electron scattering (PVES) has become a precision tool



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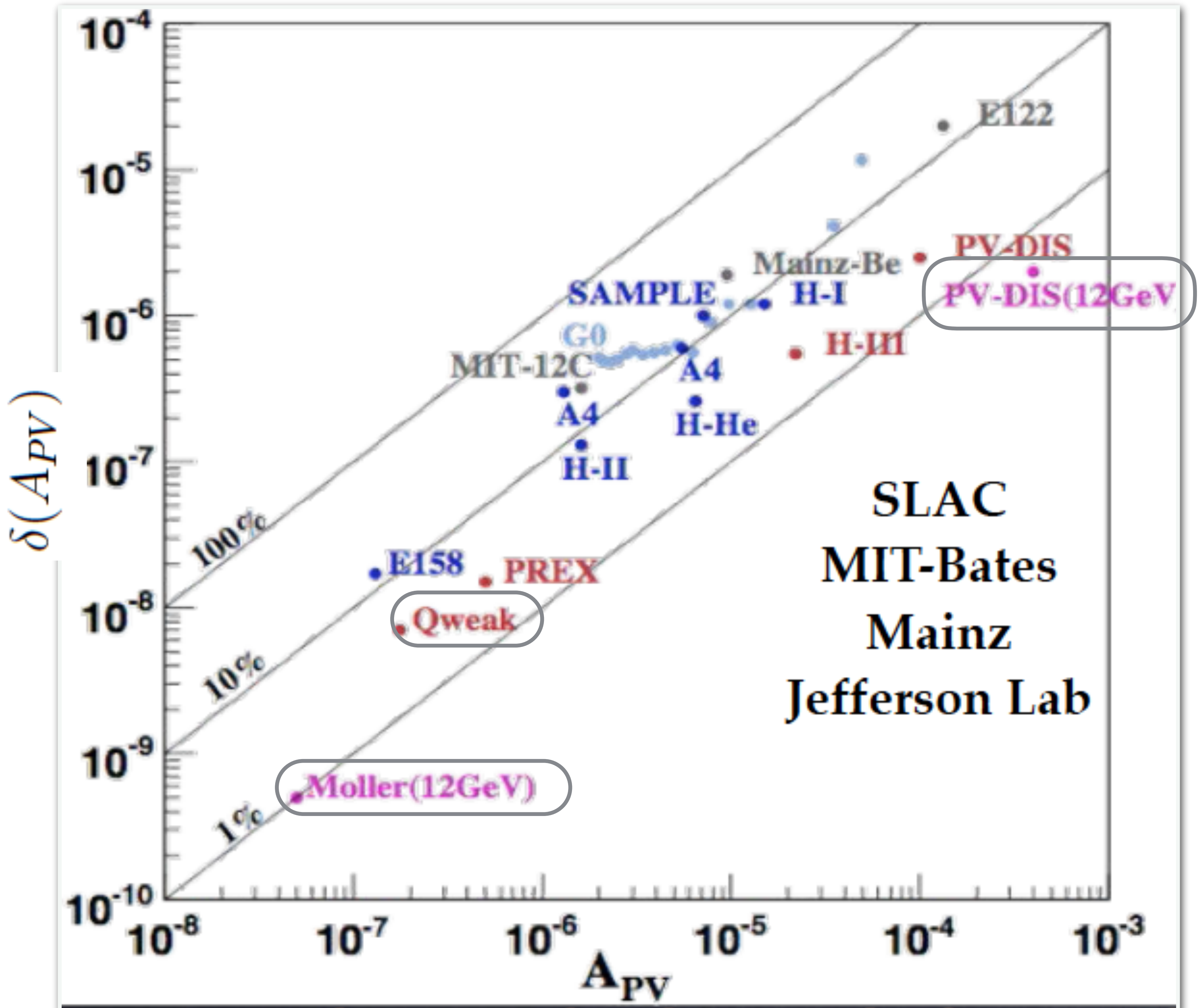

Krishna Kumar

A_{PV} in the Standard Model

- Neutral currents predicted in the Standard Model

$$\mathcal{L}_{\rm int} = -\frac{g}{2\cos\theta}\; Z^{\mu}\; \bar{\psi}_f \left(g_V^{(f)}\gamma_\mu - g_A^{(f)}\gamma_\mu\gamma_5\right)\psi_f$$

$$\theta = \arctan\frac{g'}{g}$$

$$e = g\sin\theta,$$

$$g_V^{(f)} = T_3^{(f)} - 2\sin^2\theta\, Q^{(f)} \qquad g_A^{(f)} = T_3^{(f)} \qquad Q_W^{(f)} = 2\, g_V^{(f)}$$

Weak charge of the fermion

Krishna Kumar

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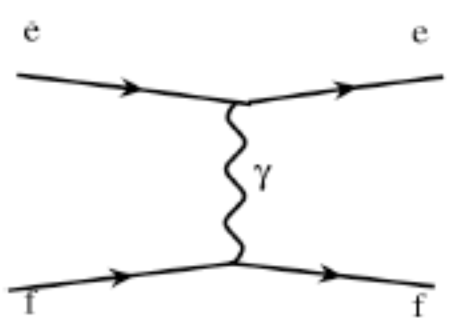

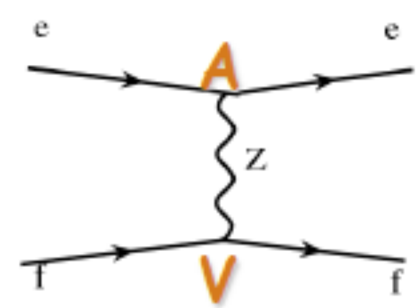

$$A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha} \left(g_A^e g_V^T + \beta\, g_V^e g_A^T \right)$$

- Through g_V, A_{PV} provides a handle on weak mixing angle

Krishna Kumar

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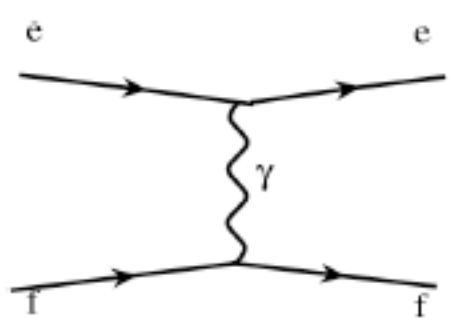
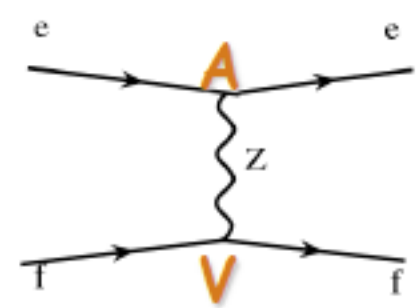




$$A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha}\left(g_A^e g_V^T + \beta\, g_V^e g_A^T\right)$$

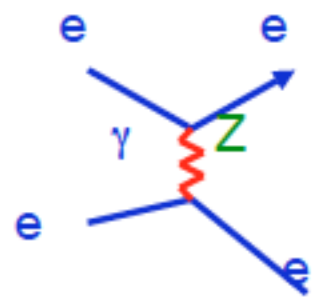
$$Q_W = 1 - 4\sin^2\theta_W$$

For electron and proton

$$\frac{\delta(Q_W)}{Q_W} \sim 10\% \Longrightarrow \frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \sim 0.5\%$$

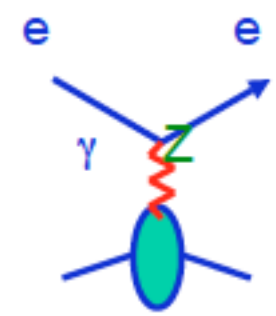
Experimental processes

Møller Scattering



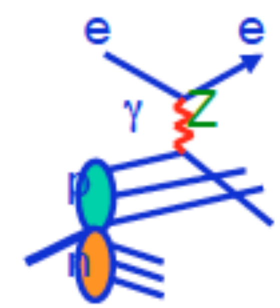
- Purely Leptonic

Q-Weak (JLab)

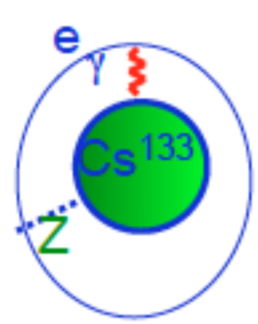


- Coherent quarks in p

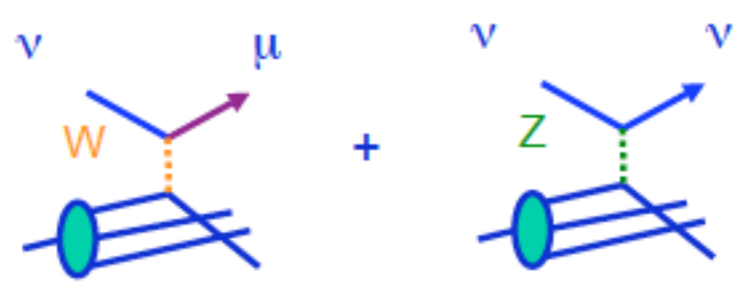
DIS-Parity



Atomic Parity Violation



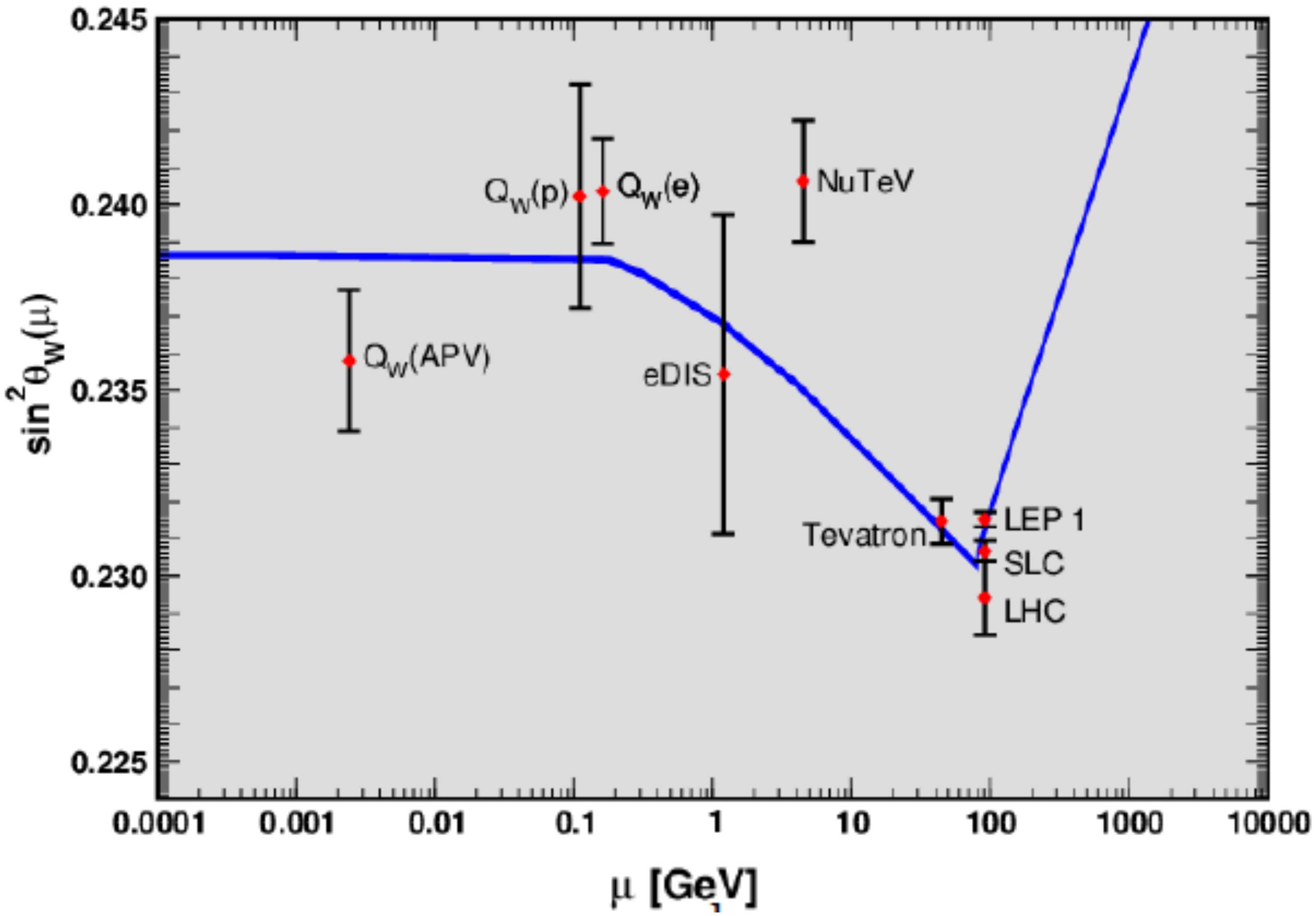
Neutrino Scattering



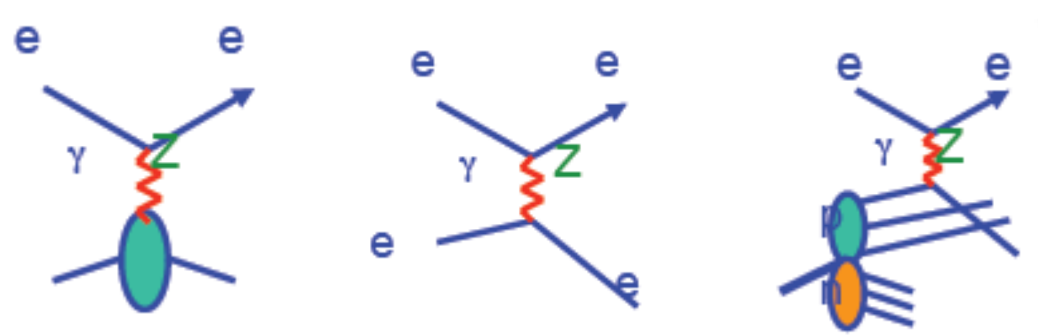
Courtesy of P. Reimer and R. Arnold

Impact of PVES

- Precise LE measurements of θ_W & constraints on BSM



J. Erler



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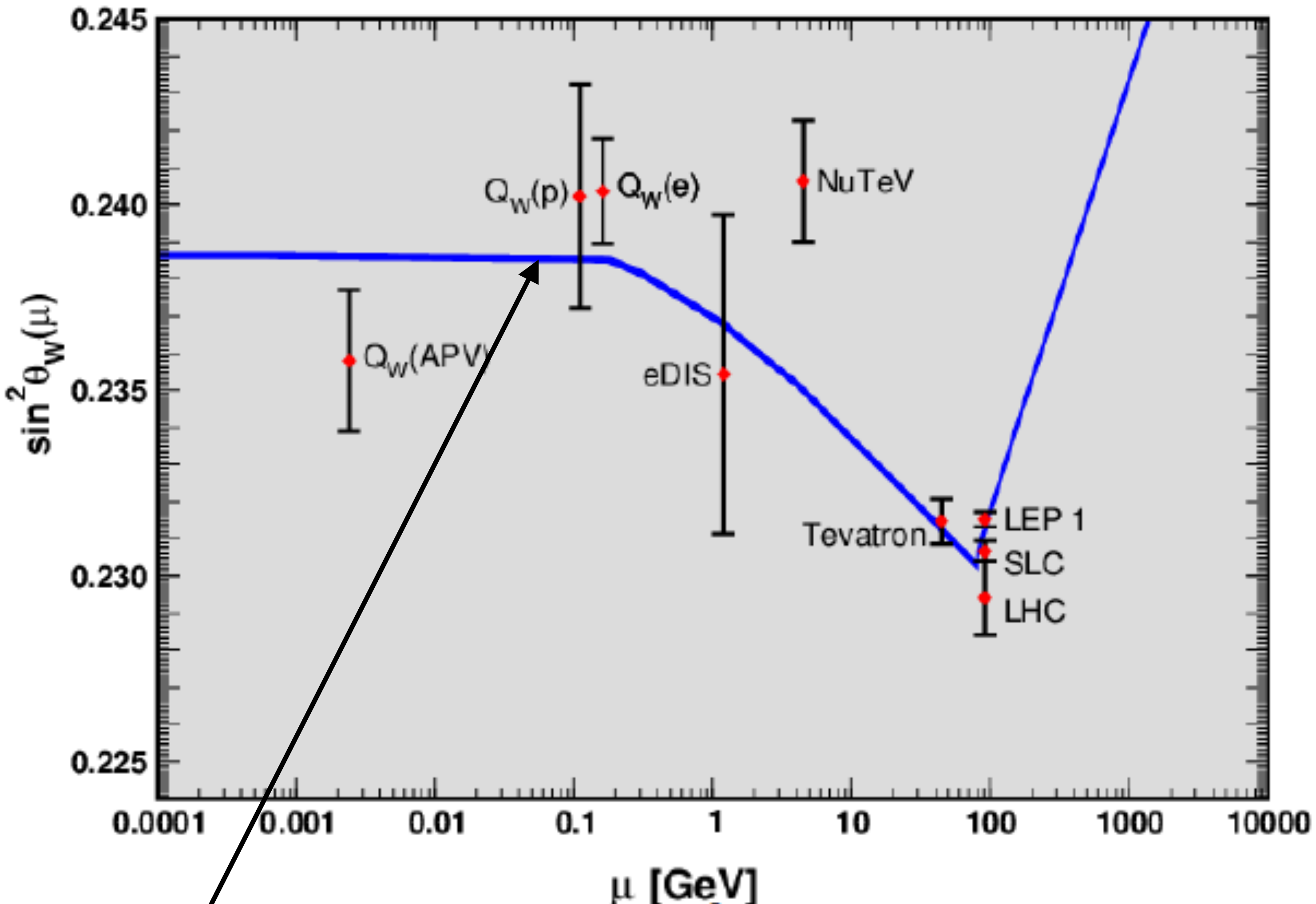
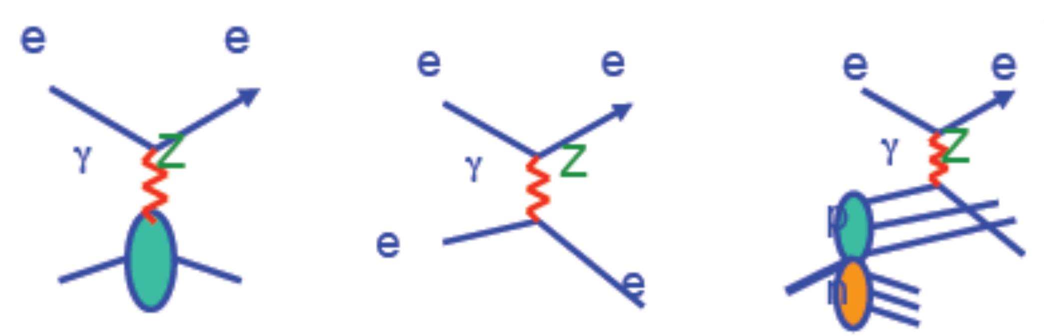
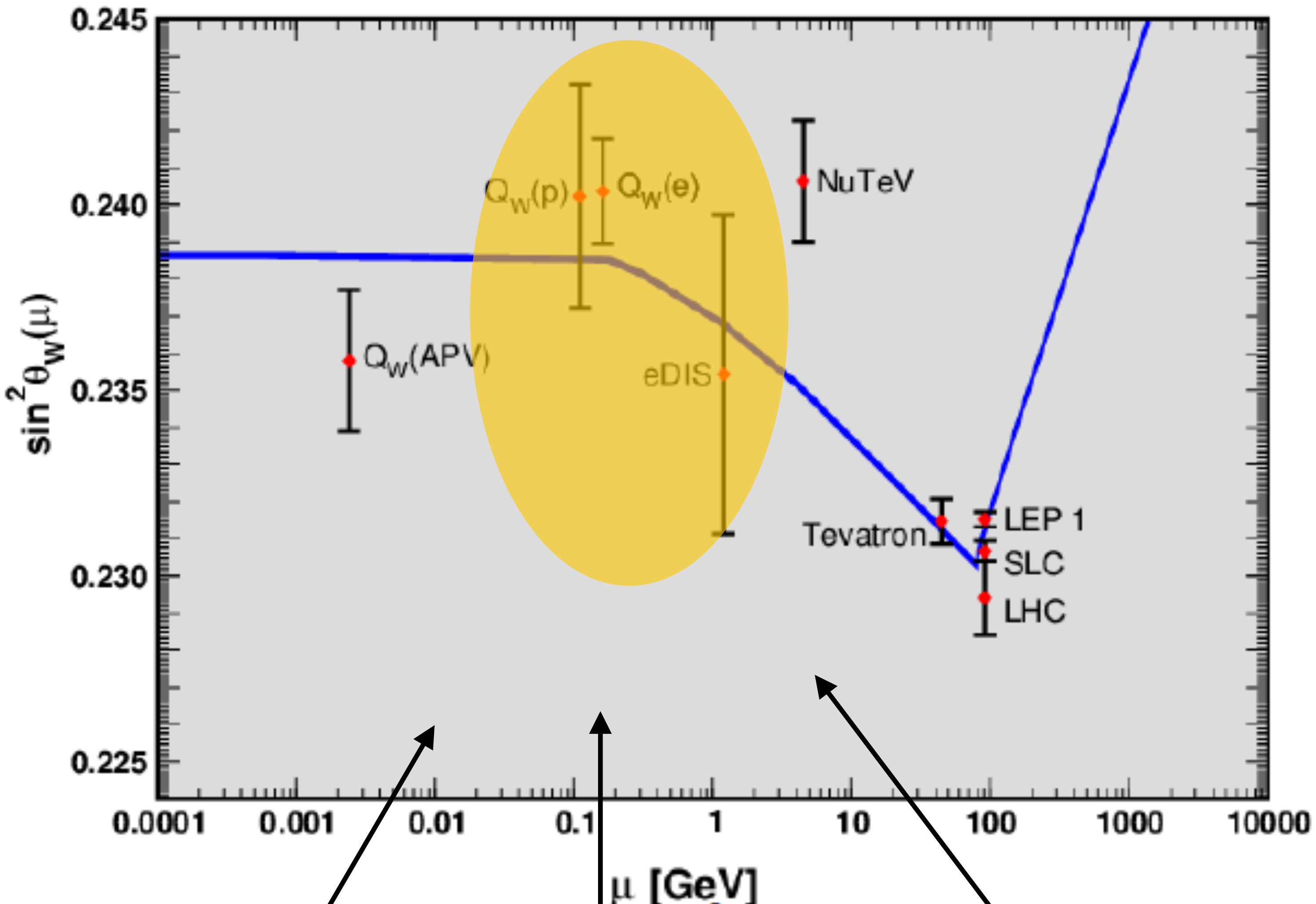




First measurement of $Q_W(p)$ by Qweak @ JLab, using only 4 % of data

Impact of PVES

- Precise LE measurements of θ_W & constraints on BSM



J. Erler

SoLID will

Qweak will improve $Q_W(p)$ by factor of 3

MOLLER@JLab will improve $Q_W(e)$ by factor of 5

SoLID@JLab will improve eDIS by factor of ~3

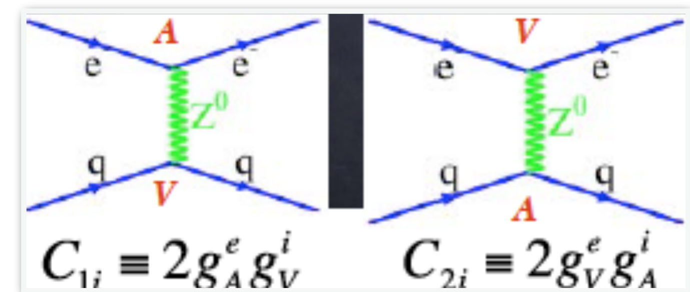
Effective Lagrangian and A_{PV}

- At low-energy PV in neutral current described by effective Lagrangian

SM

$$\mathcal{L}^{eq}_{PV} = \frac{G_\mu}{\sqrt{2}} \sum_q [C_{1q} \bar{e}\gamma^\mu\gamma_5 e \bar{q}\gamma_\mu q + C_{2q} \bar{e}\gamma^\mu e \bar{q}\gamma_\mu\gamma_5 q]$$

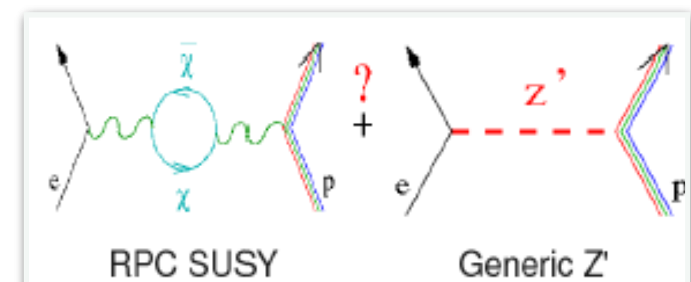
$$\begin{aligned}
C_{1u} &= -\tfrac{1}{2} + \tfrac{4}{3}\sin^2\theta_W \approx -0.19 \\
C_{1d} &= \tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W \approx 0.35 \\
C_{2u} &= -\tfrac{1}{2} + 2\sin^2\theta_W \approx -0.04 \\
C_{2d} &= \tfrac{1}{2} - 2\sin^2\theta_W \approx 0.04
\end{aligned}$$

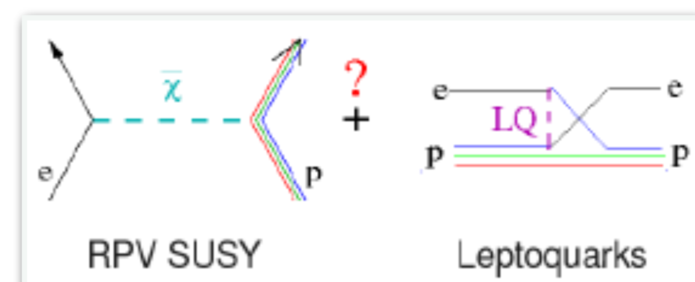


BSM

$$\mathcal{L}_{eq} = \sum_{i,j=L,R} \frac{g^2_{ij}}{\Lambda^2} \bar{e}_i\gamma_\mu e_i \bar{q}_j\gamma^\mu q_j$$

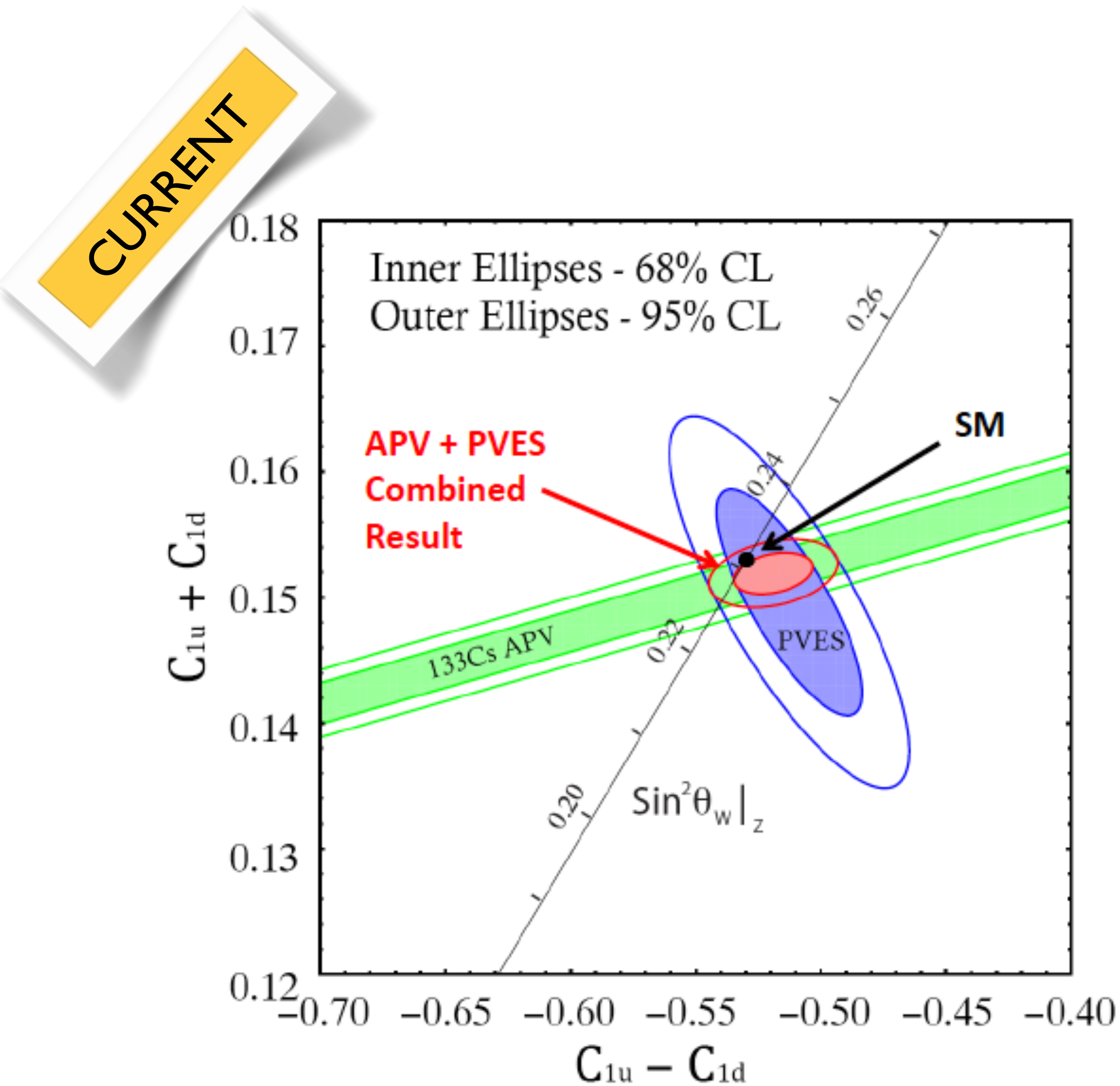
+ purely leptonic





- Operators probed & NP sensitivity:

SM $\mathcal{L}_{\rm PV}^{eq} = \frac{G_\mu}{\sqrt{2}} \sum_q [C_{1q} \bar{e}\gamma^\mu\gamma_5 e \bar{q}\gamma_\mu q + C_{2q} \bar{e}\gamma^\mu e \bar{q}\gamma_\mu\gamma_5 q]$



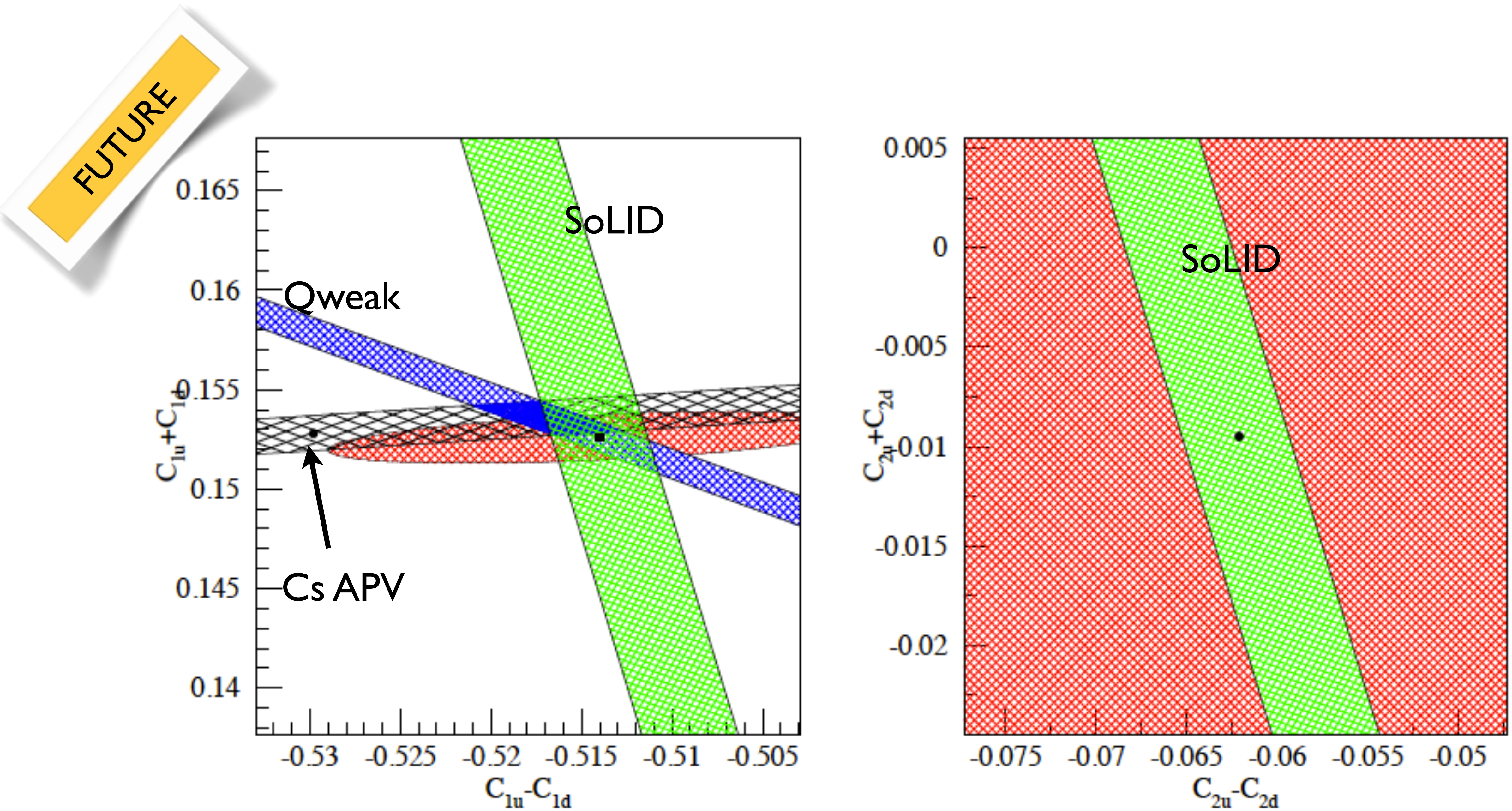
- Improved precision on quark couplings

$$C_{1u} = -0.1835 \pm 0.0054$$

$$C_{1d} = 0.3355 \pm 0.0050$$

- Operators probed & NP sensitivity:

SM $$\mathcal{L}^{eq}_{\rm PV} = \frac{G_\mu}{\sqrt{2}} \sum_q [C_{1q} \bar{e}\gamma^\mu\gamma_5 e \bar{q}\gamma_\mu q + C_{2q} \bar{e}\gamma^\mu e \bar{q}\gamma_\mu\gamma_5 q]$$



- Operators probed & NP sensitivity:

BSM $$\mathcal{L}_{eq} = \sum_{i,j=L,R} \frac{g_{ij}^2}{\Lambda^2}\, \overline{e}_i \gamma_\mu e_i\, \overline{q}_j \gamma^\mu q_j$$

+ purely leptonic (Moller)

J. Erler

Sensitivities to new physics

- $\Lambda_{new} \simeq [\sqrt{2}\, G_F\, \Delta Q_W]^{-1/2} = 246.22\ \text{GeV}/\sqrt{\Delta Q_W}$
  - $\Lambda_{new} \simeq$ 3.4 TeV (Q_W^e from E158)
  - $\Lambda_{new} \simeq$ 4.6 TeV (Q_W^p from Qweak)
  - $\Lambda_{new} \simeq$ 2.5 TeV (C_{ij} from SoLID)
  - $\Lambda_{new} \simeq$ 7.5 TeV (Q_W^e from MOLLER) ← Best contact-interaction reach for leptonic operators, at low OR high-energy
  - $\Lambda_{new} \simeq$ 6.3 TeV (Q_W^p from P2@Mainz)
  - $\Lambda_{new} \simeq$ 3.7 TeV (g_R^2 from NuTeV)
  - $\Lambda_{new} \simeq$ 5.2 TeV (Q_W^n from APV in Cs)

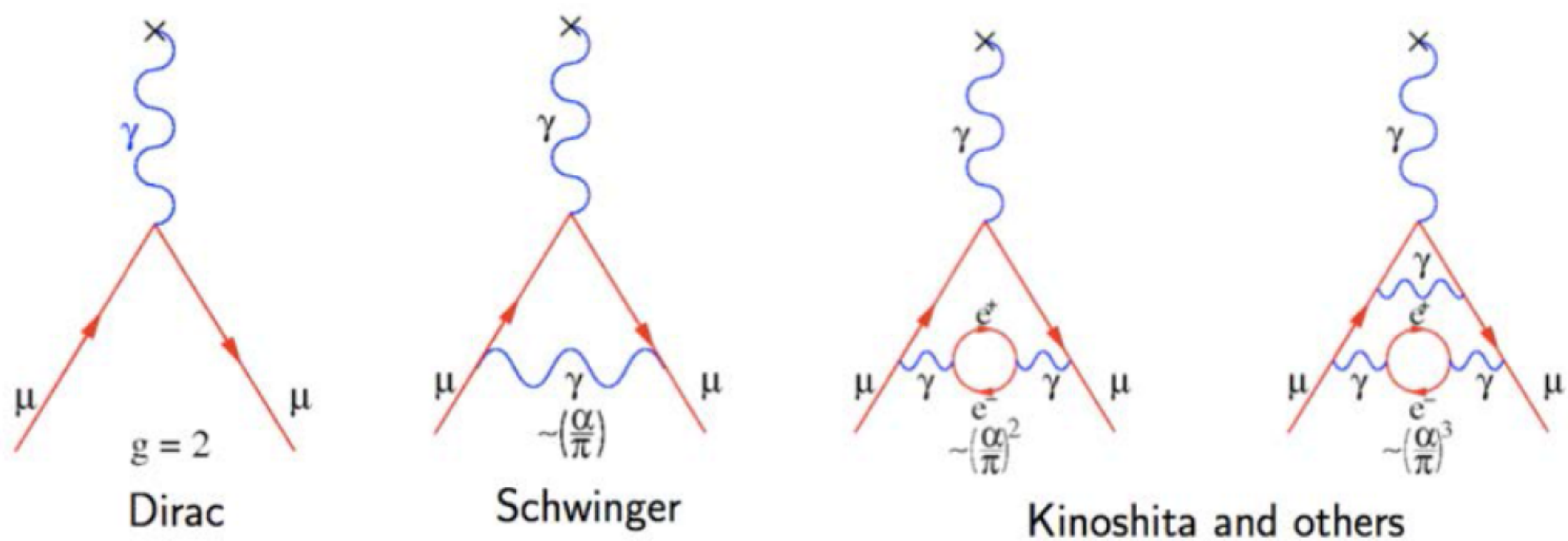
Muon "g-2"

D. Kawall

Lepton magnetic moments

$$\vec{\mu} = g\frac{e}{2mc}\vec{s}, \qquad \vec{s} = \frac{\hbar}{2}\vec{\sigma}$$

- Dirac predicts g=2 in 1928
- 1947: Measurements find $g_e \neq 2$
- Schwinger calculated $g_e = 2(1 + a_e) \qquad a_e = \frac{(g_e - 2)}{2} = \frac{\alpha}{2\pi} \approx 0.00116$



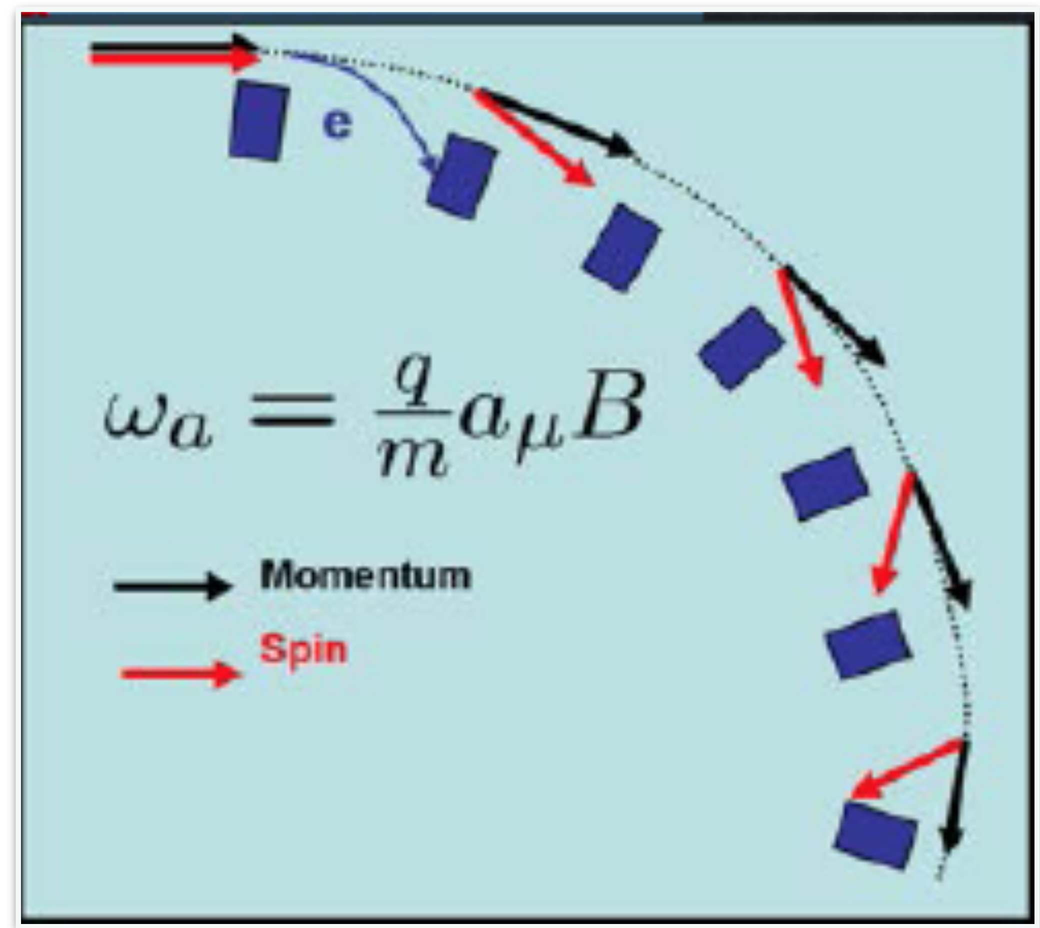
Great success of QED

D. Hertzog

- Current experimental precision: $\Delta g_e = 5.2\times10^{-13}$ and $\Delta g_\mu = 1.2\times10^{-9}$
  - g_e used to extract electromagnetic coupling
  - g_μ used to challenge the SM!

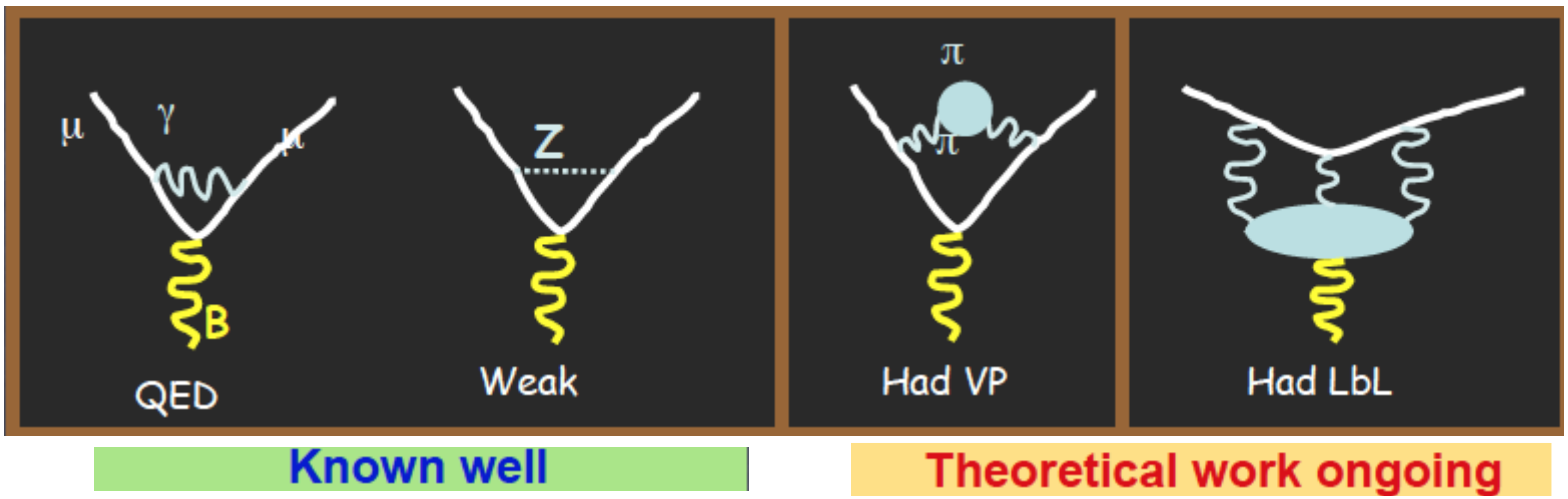
$$\omega_C = \frac{eB}{mc\gamma}$$

- How is g_μ (a_μ) measured?
  - Exploit the fact that momentum and spin do not precess in the same way in a B field
  - Relative frequency ω_a proportional to (g-2)*B



$$\omega_S = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

- Current experimental precision: $\Delta g_e = 5.2\times10^{-13}$ and $\Delta g_\mu = 1.2\times10^{-9}$
  - g_e used to extract electromagnetic coupling
  - g_μ used to challenge the SM!
- At this level of precision, g_μ (a_μ) depends on loops from all Standard Model particles that couple to the muon



Known to 5 loops!
Kinoshita et al 2012

D. Hertzog

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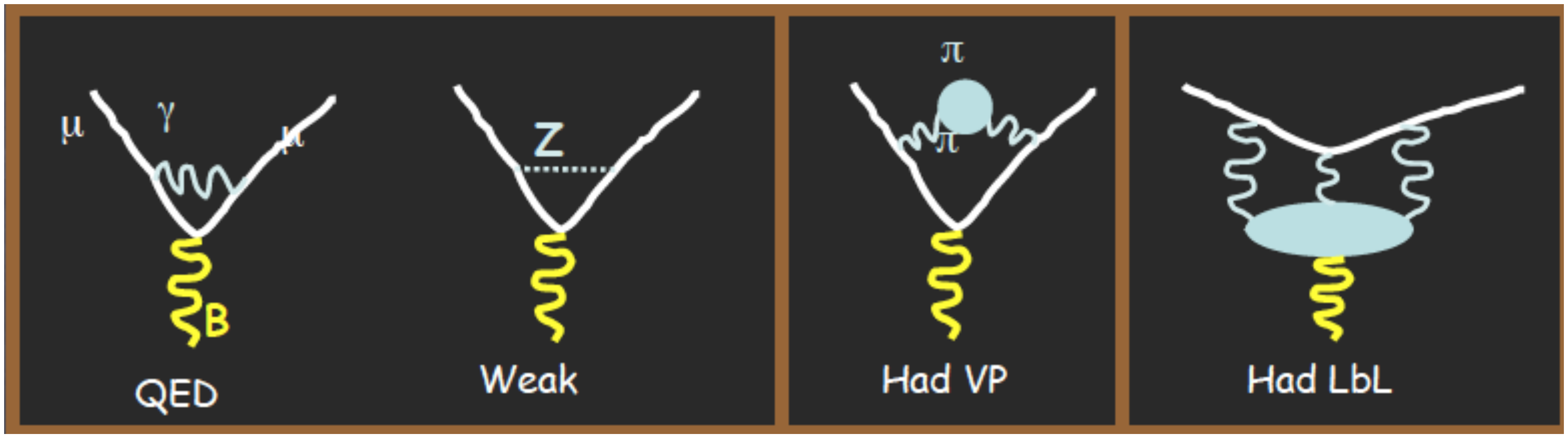
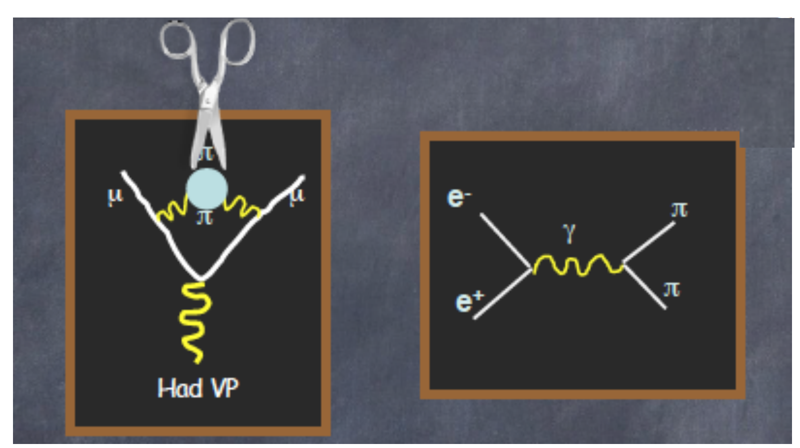


Known well

Theoretical work ongoing

Known to 5 loops!
Kinoshita et al 2012



g-2 contribution linked to cross-section $e^+e^- \rightarrow$ hadrons

D. Hertzog

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    - g_e used to extract electromagnetic coupling
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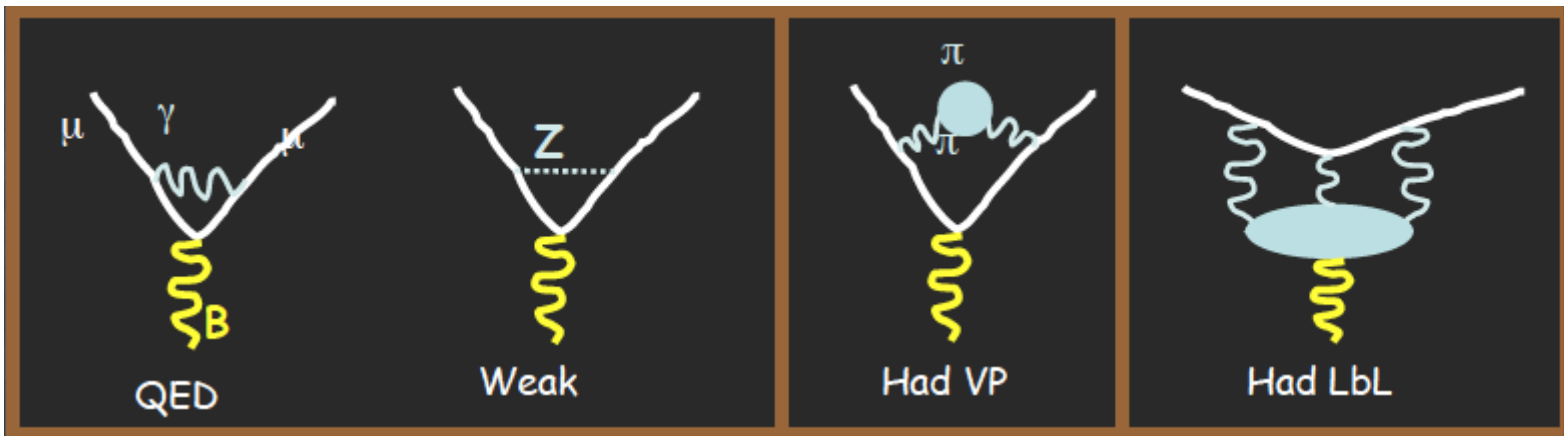


Known well | Theoretical work ongoing

- Anatomy:

	VALUE ($\times 10^{-11}$) UNITS
QED ($\gamma + \ell$)	$116\,584\,718.853 \pm 0.022 \pm 0.029_\alpha$
HVP(lo)*	$6\,923 \pm 42$
HVP(ho)	-98.4 ± 0.7
H-LBL	105 ± 26
EW	$154 \pm 1 \pm 2$
Total SM	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$

D. Hertzog

Where are we?

- Serious hint of new physics

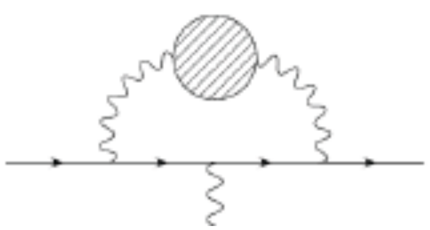
$$a_\mu = (g_\mu - 2)/2$$

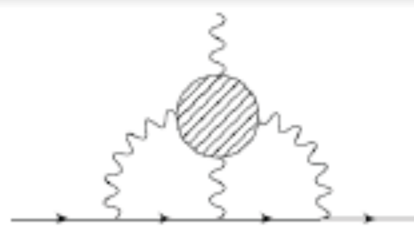
$$a_\mu(\text{Expt}) = 116\,592\,089\,(54)(33) \times 10^{-11}$$

$$a_\mu(\text{SM}) = 116\,591\,802\,(42)(26)(02) \times 10^{-11}$$

BNL E821 (2006)

$$\Rightarrow \Delta a_\mu = 287(80) \times 10^{-11}$$ 3.6σ discrepancy





Dominant uncertainties: ongoing efforts to improve these results using Lattice QCD

D. Hertzog

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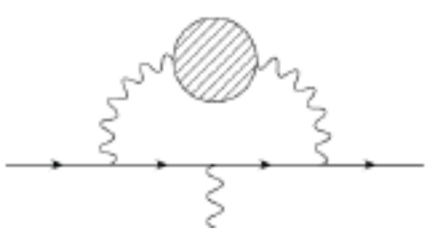
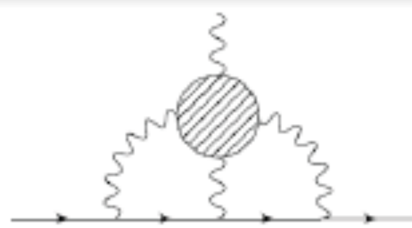
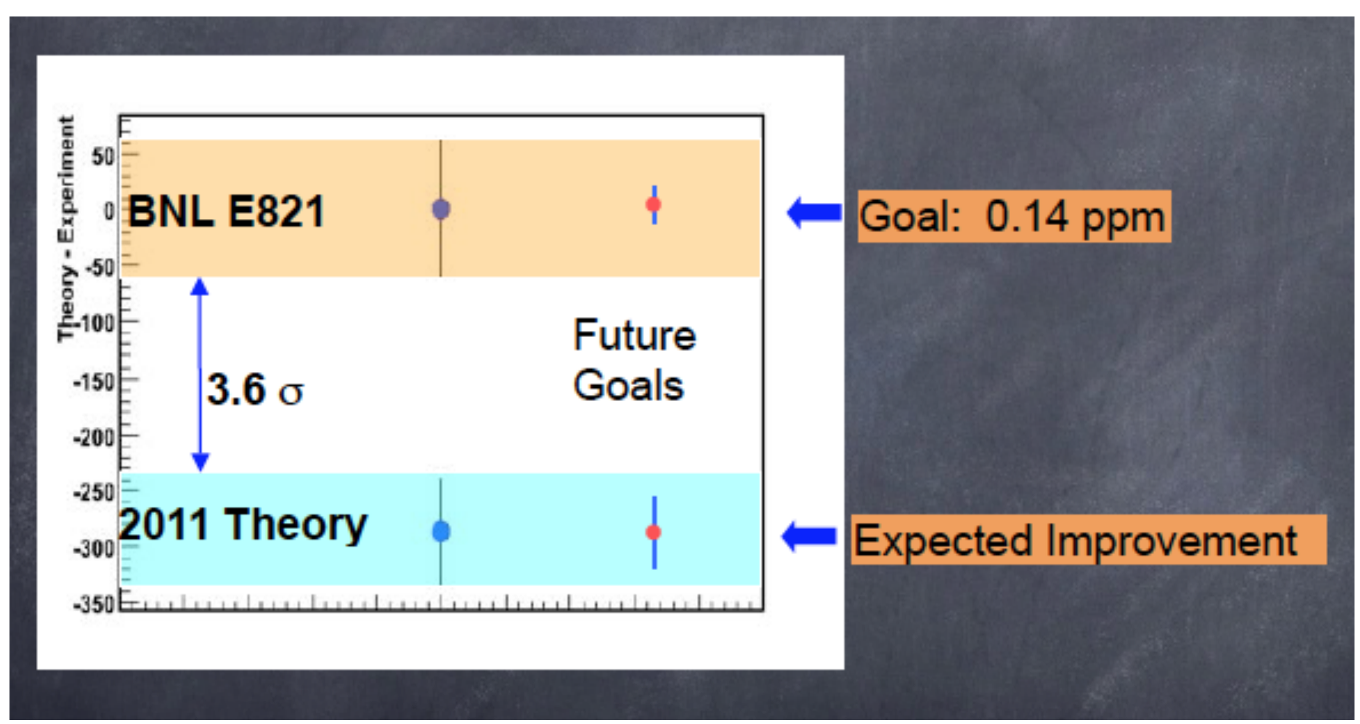




Dominant uncertainties: ongoing efforts to improve these results using Lattice QCD



New g-2 at Fermilab will improve uncertainty factor of 4

Where are we?

- Serious hint of new physics

$$a_\mu = (g_\mu - 2)/2$$

$$a_\mu(\text{Expt}) = 116\,592\,089\,(54)(33) \times 10^{-11}$$

BNL E821 (2006)

$$a_\mu(\text{SM}) = 116\,591\,802\,(42)(26)(02) \times 10^{-11}$$

$$\Longrightarrow \quad \Delta a_\mu = 287(80) \times 10^{-11}$$

3.6σ discrepancy

Dominant uncertainties: ongoing efforts to improve these results using Lattice QCD

- Probe BSM mag. dipole operators $\mathcal{L} \xrightarrow{\text{EWSB}} y_\mu \frac{v}{\Lambda^2} \bar{\mu}\, \sigma^{\alpha\beta} \mu\, F_{\alpha\beta}$

- 3.6σ discrepancy $\Rightarrow \Lambda/\sqrt{y_\mu} \sim 140$ TeV ($\Lambda \sim 3.5$ TeV).

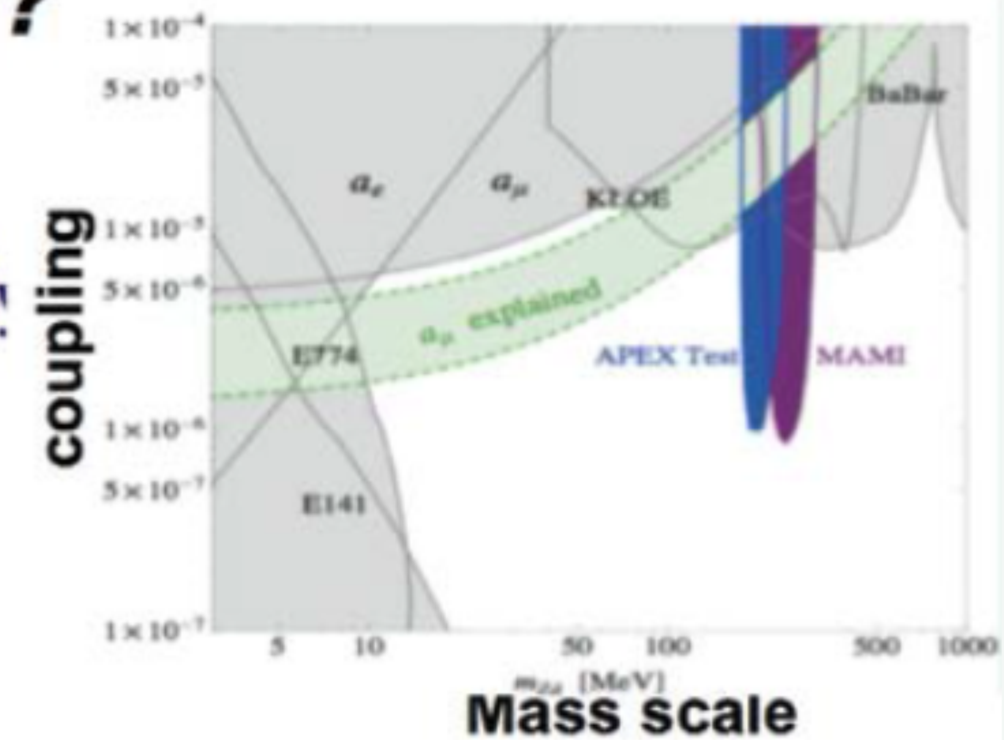
  Strong "boundary condition" for TeV extensions of the SM

D. Hertzog

Impact on models

New physics enters through *loops. What might the g-2 signal imply?*

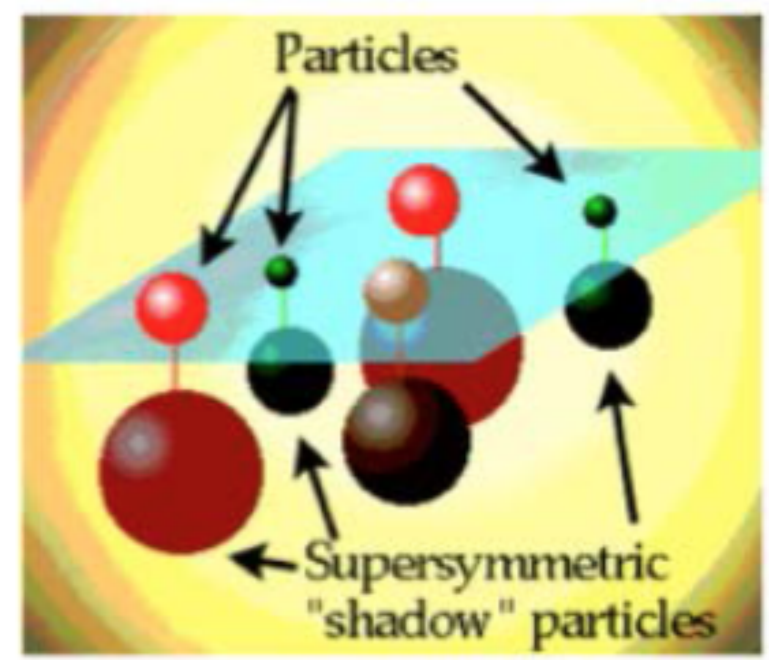
- **Dark Photons**
  - light new vector particles V kinetically mixed with the photon



- **Supersymmetry**

$$a_\mu^{SUSY} \approx 130 \times 10^{-11} \left(\frac{100\ \text{GeV}}{M_{SUSY}} \right)^2 \tan\beta\ \text{sign}(\mu)$$

Difficult to measure at the LHC



- **The Uninvented**
  - Perhaps the most important of all

Backup

BSM: dimension 5

- Construct all possible dim=5 effective operators in detail: this illustrates the method and leads to a physically interesting result

- Fermions only (and derivatives)? No: Use [Ψ]=3/2 and gauge invariance [Ψ's belong to chiral representations]
- Scalars only, vectors only? No: use [φ] = [V] =1 and gauge invariance
- Vectors + Fermions & Vectors + scalars? No
- So, we are lead to consider operators with fermions (2) and scalars (2) and no derivatives

- If scalars are φ and φ* ⇒
  - total hypercharge Y of fermions Ψ_1 and Ψ_2 is 0
  - need a multiplet and its charge-conjugate
  - but cannot make non-vanishing Lorentz scalar of dim3 ($\bar{\psi}\psi = 0$)

- We are left with building blocks φ, φ, Ψ_1, Ψ_2
  - Forming $SU(2)_W$ invariants: $\varphi^T \varepsilon \varphi = 0$ ⇒ Ψ_1, Ψ_2 must be doublets (so we are left with l or q)

Recall: $\epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$

- If scalars are φ and φ^* $\Rightarrow$
  - total hypercharge Y of fermions Ψ_1 and Ψ_2 is 0
  - need a multiplet and its charge-conjugate
  - but cannot make non-vanishing Lorentz scalar of dim3 ($\bar{\psi}\psi = 0$)

- We are left with building blocks φ, φ, Ψ_1, Ψ_2
  - Forming $SU(2)_W$ invariants: $\varphi^T\varepsilon\varphi = 0 \Rightarrow \Psi_1, \Psi_2$ must be doublets (so we are left with l or q)
  - $l^T\varepsilon\varphi$ and $\varphi^T\varepsilon l$ are $SU(2)_W$ and $U(1)_Y$ invariant
  - Connect them to make Lorentz scalar:

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

- Could one replace l with q? No: invariance under $SU(3)_c$ and $U(1)_Y$

- Conclusion: there is only one dim=5 operator (Weinberg '79)

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

  - it violates total lepton number ($l \to e^{i\alpha}\, l$, $e \to e^{i\alpha} e$)
  - it generates Majorana mass for L-handed neutrinos (after EWSB)

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

  - light neutrino mass scale ($\leq$ eV) points to high scale of lepton number breaking

$$m_\nu \sim 1\,{\rm eV} \ \to\ \Lambda \sim 10^{13}\,{\rm GeV}$$

- Building blocks details: gauge fields

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

Gauge transformation:

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

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

The case for $\delta\tau_n \sim 0.3$s

- Key ingredient for V_{ud} @ 0.02%, free of nucl. structure (→ Δ_{CKM} test)

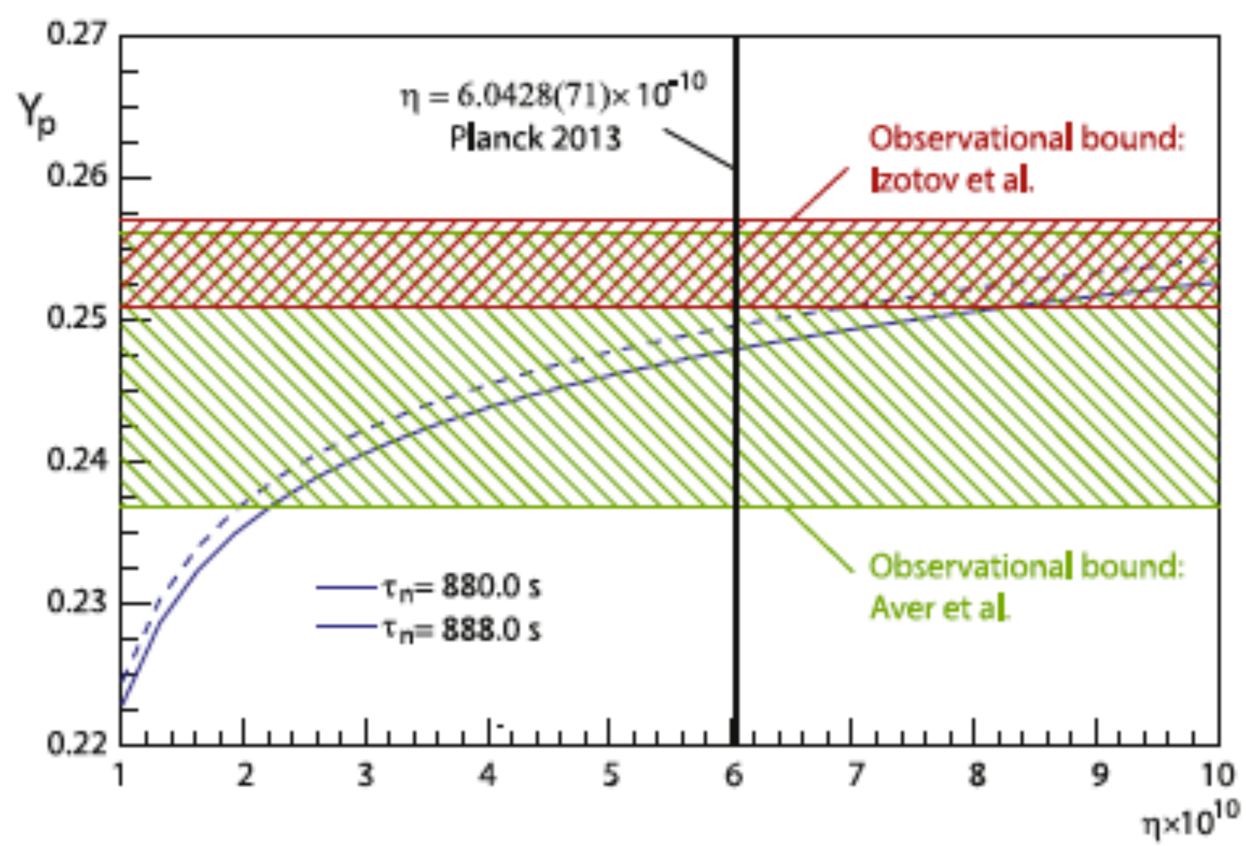
- V_{ud} (n) and V_{ud} ($0^+ \rightarrow 0^+$) sensitive to different new physics!

$$\frac{\bar{V}_{ud}|_n}{\bar{V}_{ud}|_{0^+}} = 1 + c_S\,\epsilon_S + c_T\,\epsilon_T$$

c_S, c_T ~O(1)

- Remove largest error in the prediction of primordial ^{4}He abundance

Observations may reach this level in the next decade



Definition of D and R

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 \xi \left\{ 1 + b\,\frac{m_e}{E_e} + a\,\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \left\langle \frac{\vec{J}}{J} \right\rangle \cdot \left[A\,\frac{\vec{p}_e}{E_e} + B\,\frac{\vec{p}_\nu}{E_\nu} + D\,\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right] + \cdots \right\}$$

$$\begin{aligned} &\omega(\langle \mathbf{J} \rangle, \boldsymbol{\sigma} | E_e, \Omega_e) dE_e d\Omega_e = \\ &\quad \frac{F(\pm Z, E_e)}{(2\pi)^4} p_e E_e (E_0 - E_e)^2 dE_e d\Omega_e \times \\ &\quad \xi \left\{ 1 + b\frac{m}{E_e} + \frac{\mathbf{p}_e}{E_e} \cdot \left(A\frac{\langle \mathbf{J} \rangle}{J} + G\boldsymbol{\sigma} \right) + \boldsymbol{\sigma} \cdot \left[N\frac{\langle \mathbf{J} \rangle}{J} \right. \right. \\ &\quad \left. \left. + Q\frac{\mathbf{p}_e}{E_e + m} \left(\frac{\langle \mathbf{J} \rangle}{J} \cdot \frac{\mathbf{p}_e}{E_e} \right) + R\frac{\langle \mathbf{J} \rangle}{J} \times \frac{\mathbf{p}_e}{E_e} \right] \right\} \end{aligned}$$

$$D_{\text{BSM}} = \frac{1}{1 + 3\lambda^2} \left[4\lambda\, \text{Im}(\epsilon_R) + 8 g_S g_T\, \text{Im}\left(\epsilon_S \epsilon_T^* + \tilde{\epsilon}_S \tilde{\epsilon}_T^* \right) \right]$$

$$R_n = \frac{1}{1 + 3\,\lambda^2} \left[-8 g_T\,(2\lambda + 1)\, \text{Im}(\epsilon_T) - 2 g_S\, \lambda\, \text{Im}(\epsilon_S) \right]$$

$$R_{^8\text{Li}} = -\frac{1}{3} \frac{8 g_T}{g_A}\, \text{Im}(\epsilon_T)$$