Physics Beyond the SM
Under The Higgs Lamppost

1. The Quest for the SM & Beyond
2. A Strongly-coupled EW Sector
3. A Weakly-coupled Extension
4. Flavors of Matter Fields & EFT

The Fermions: Gauge interactions [§]

$$\mathcal{L}_f = \sum_{m=1}^{F} \left(\bar{q}^0_{mL} i \not{D} q^0_{mL} + \bar{l}^0_{mL} i \not{D} l^0_{mL} + \bar{u}^0_{mR} i \not{D} u^0_{mR} \right.$$
$$\left. + \bar{d}^0_{mR} i \not{D} d^0_{mR} + \bar{e}^0_{mR} i \not{D} e^0_{mR} + \bar{\nu}^0_{mR} i \not{D} \nu^0_{mR} \right)$$

$$D_\mu q^0_{mL} = \left(\partial_\mu + \frac{ig}{2} \vec{\tau} \cdot \vec{W}_\mu + \frac{ig'}{6} B_\mu \right) q^0_{mL}$$
$$D_\mu l^0_{mL} = \left(\partial_\mu + \frac{ig}{2} \vec{\tau} \cdot \vec{W}_\mu - \frac{ig'}{2} B_\mu \right) l^0_{mL}$$

$$D_\mu u^0_{mR} = \left(\partial_\mu + \frac{2ig'}{3} B_\mu \right) u^0_{mR}$$
$$D_\mu d^0_{mR} = \left(\partial_\mu - \frac{ig'}{3} B_\mu \right) d^0_{mR}$$
$$D_\mu e^0_{mR} = \left(\partial_\mu - ig' B_\mu \right) e^0_{mR}$$
$$D_\mu \nu^0_{mR} = \partial_\mu \nu^0_{mR},$$

Gauge invariant, massless.

This leads to a large accidental global symmetry.

for 3 generations of quarks:

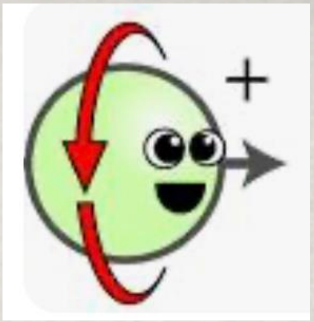
$$U(3)_{QL} \otimes U(3)_{uR} \otimes U(3)_{dR}$$
$$\rightarrow SU(3)_{QL} \otimes SU(3)_{uR} \otimes SU(3)_{dR} \otimes U(1)_B \otimes U(1)_Y$$

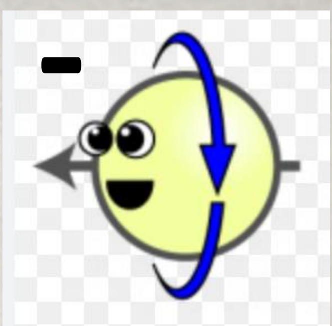
and similarly for leptons.

[§] P. Langacker: TASI Lectures 2007.

The Fermions: Masses §

However, a fermion mass must flip chirality:





$$-m_e\bar{e}e = -m_e\bar{e}\Big(\frac{1}{2}(1-\gamma_5) + \frac{1}{2}(1+\gamma_5)\Big)e = -m_e(\bar{e}_R e_L + \bar{e}_L e_R)$$

→ not SM gauge invariant L(doublet) ≠ R(singlet) !

Need something like a doublet constructing a gauge singlet:

$$y_f(\bar{f}_1, f_2)_L \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}_L f_R$$

that's the Higgs-like doublet!

(We could have guessed the Higgs!)

The gauge invariant Yukawa interactions:

(S. Weinberg, "A Model of Leptons", 1967)

Need a doublet with a flip Y: $\tilde{\phi} = i\sigma_2\phi^*$

$$\mathcal{L}_{Yuk} = -\sum_{m,n=1}^{F} \Big[\Gamma^u_{mn}\bar{q}^{\,0}_{mL}\tilde{\phi}u^0_{nR} + \Gamma^d_{mn}\bar{q}^{\,0}_{mL}\phi d^0_{nR}$$

$$+ \Gamma^e_{mn}\bar{l}^{\,0}_{mn}\phi e^0_{nR} + \Gamma^\nu_{mn}\bar{l}^{\,0}_{mL}\tilde{\phi}\nu^0_{nR}\Big] + h.c.,$$

After the EWSB,

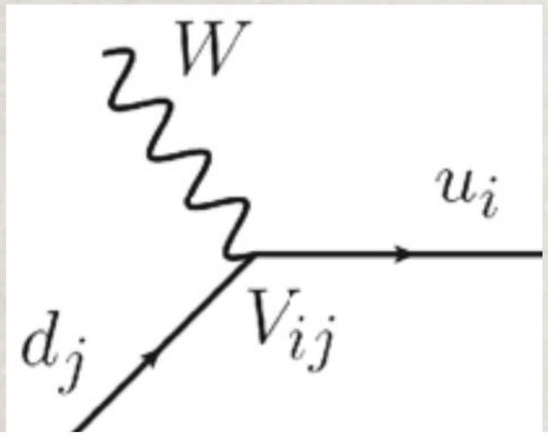
$$-\mathcal{L}_{Yuk} \to \sum_{m,n=1}^{F} \bar{u}^0_{mL}\Gamma^u_{mn}\left(\frac{\nu+H}{\sqrt{2}}\right)u^0_{mR} + (d,e,\nu)\text{ terms}$$

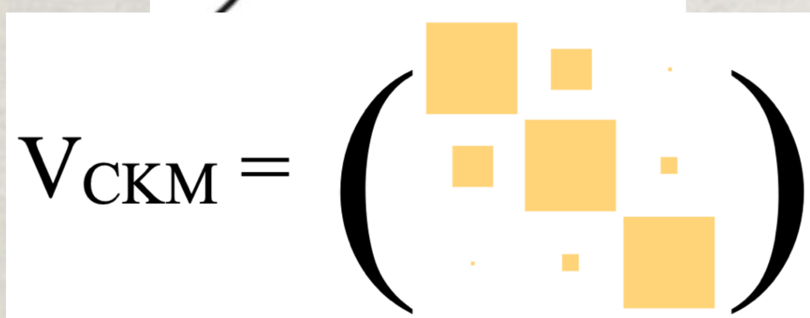
$$= \bar{u}^0_L\,(M^u + h^u H)\,u^0_R + (d,e,\nu)\text{ terms } + h.c.,$$

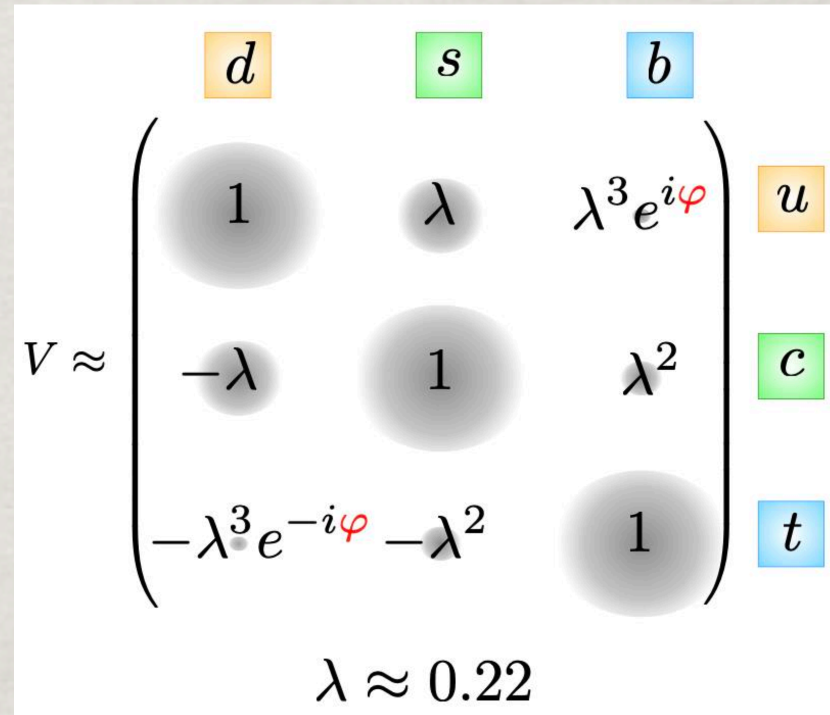
$$-\mathcal{L}_{Yuk} = \sum_i m_i\bar{\psi}_i\psi_i\left(1+\frac{g}{2M_W}H\right) = \sum_i m_i\bar{\psi}_i\psi_i\left(1+\frac{H}{\nu}\right)$$

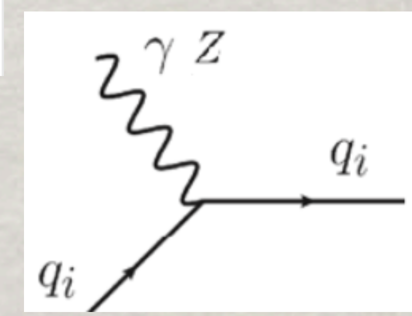
Quark mixings between gauge & mass states:

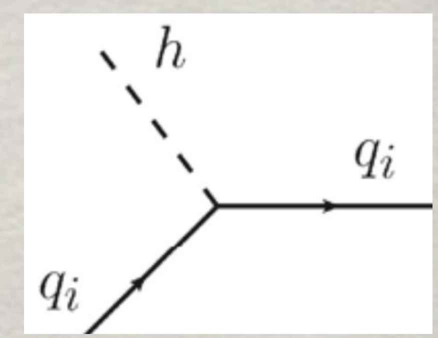
$$-\frac{g}{\sqrt{2}}(\overline{u_L}, \overline{c_L}, \overline{t_L})\gamma^\mu W_\mu^+ V_{CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + h.c.$$







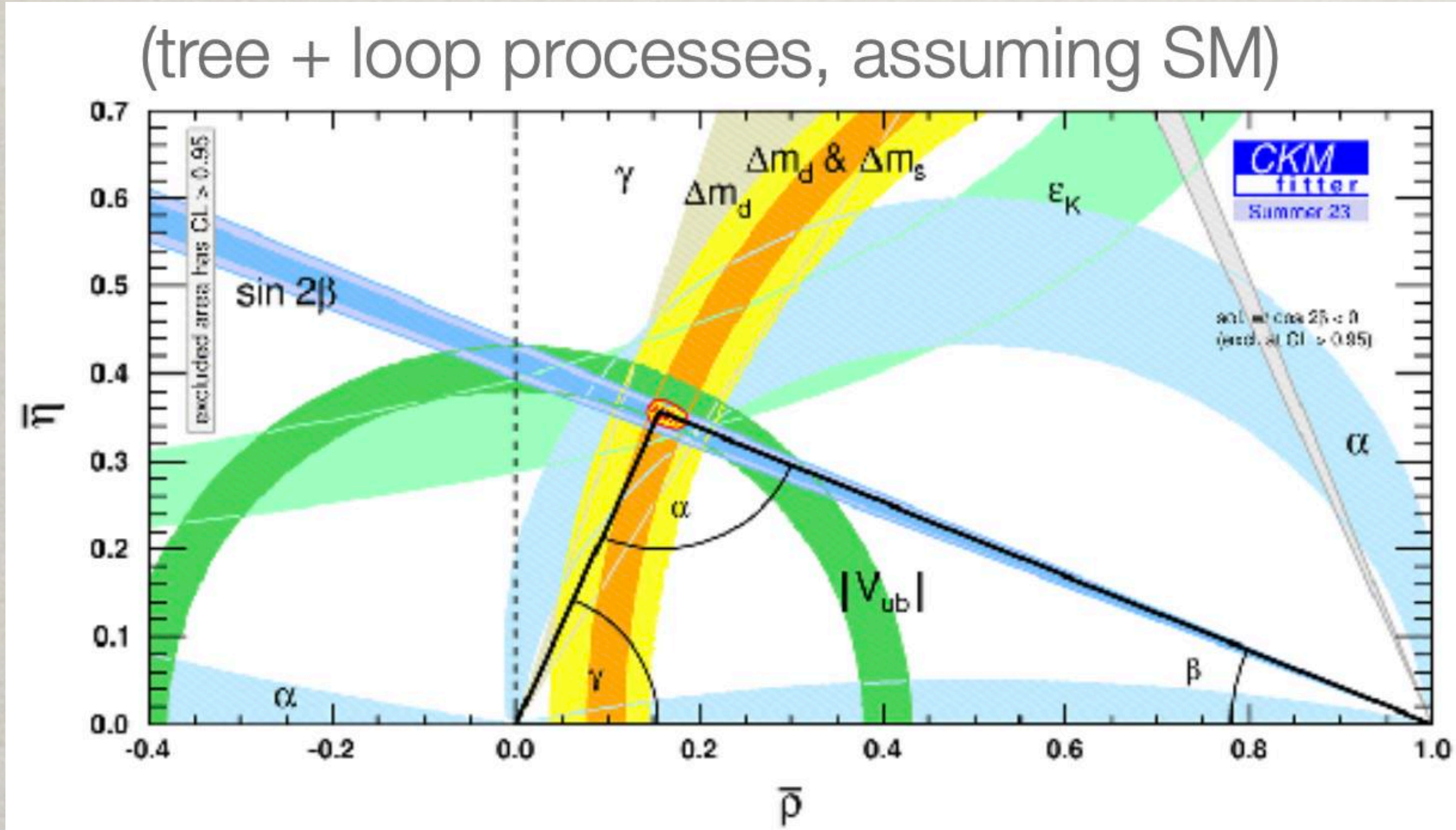


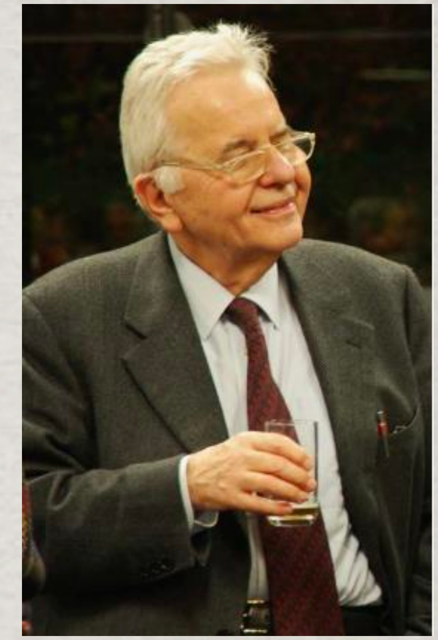


- Generation mixing, but no tree-level FCNC:
  → follow the Higgs?!
- Mixing highly hierarchical
  → family symmetry?
- Insufficient CP violation for baryon asymmetry

High successful description: CKM

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$





This leads to the **"Minimal Flavor Violation" (MFV)** hypothesis:
Flavor violation interactions follows the same pattern
as that in the SM $U(3)_{QL} \otimes U(3)_{uR} \otimes U(3)_{dR}$

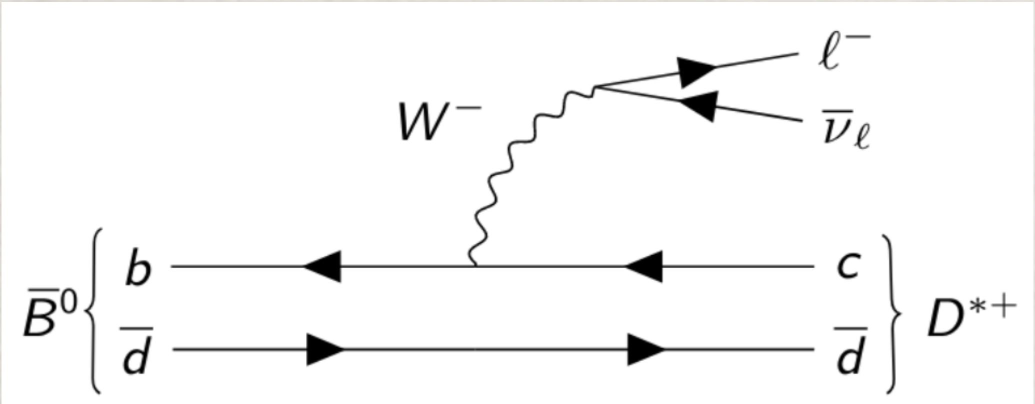
$$-\mathcal{L}_{\rm Yukawa}^{\rm SM} = Y_d^{ij}\bar{Q}_L^i \phi D_R^j + Y_u^{ij}\bar{Q}_L^i \tilde{\phi} U_R^j + {\rm h.c.}$$

For BSM: $Y^u \sim (3, \bar{3}, 1)\,, \qquad Y^d \sim (3, 1, \bar{3})\,.$

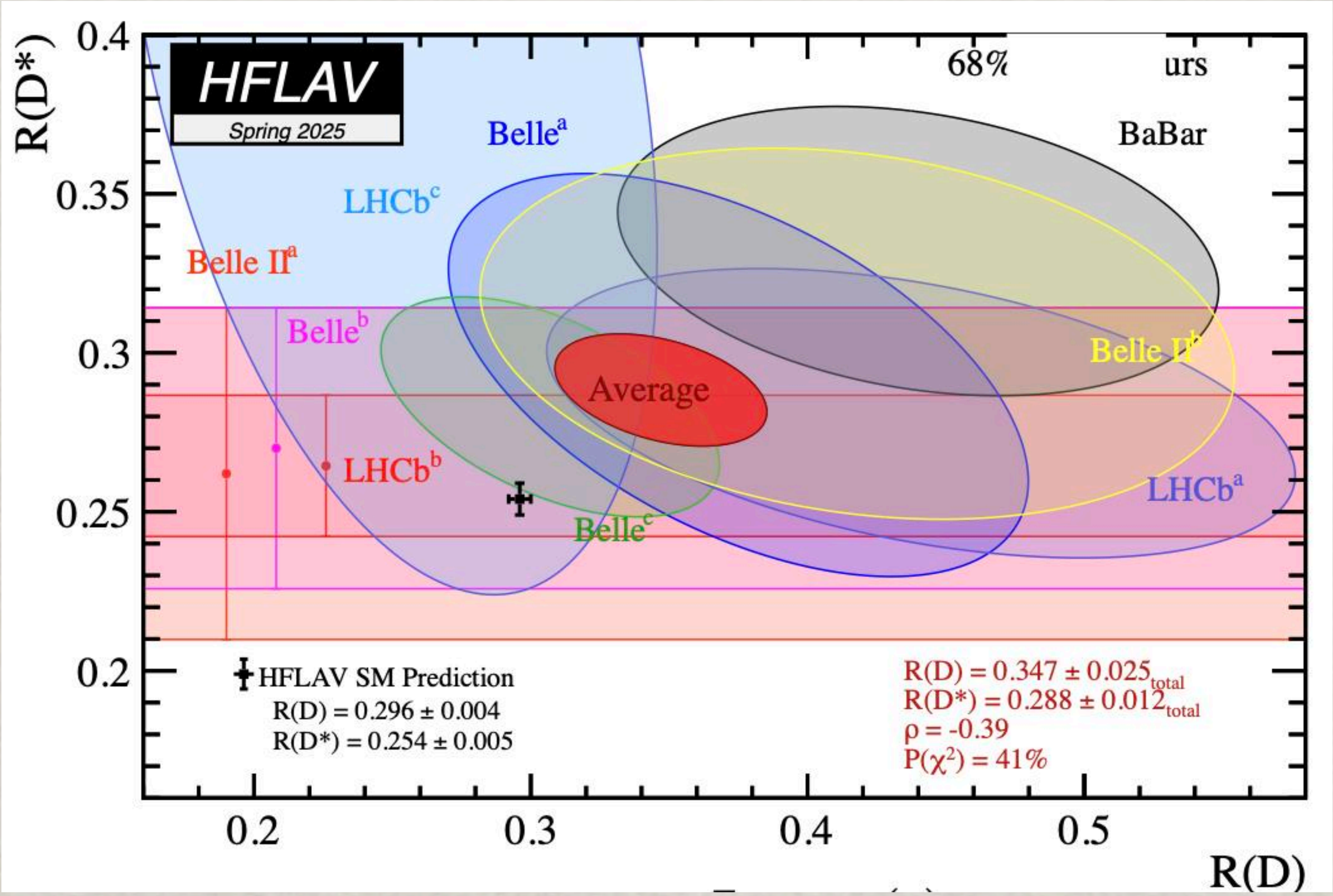
Tremendous experimental efforts:

LHCb, Belle II, tau-charm factories, kaons …

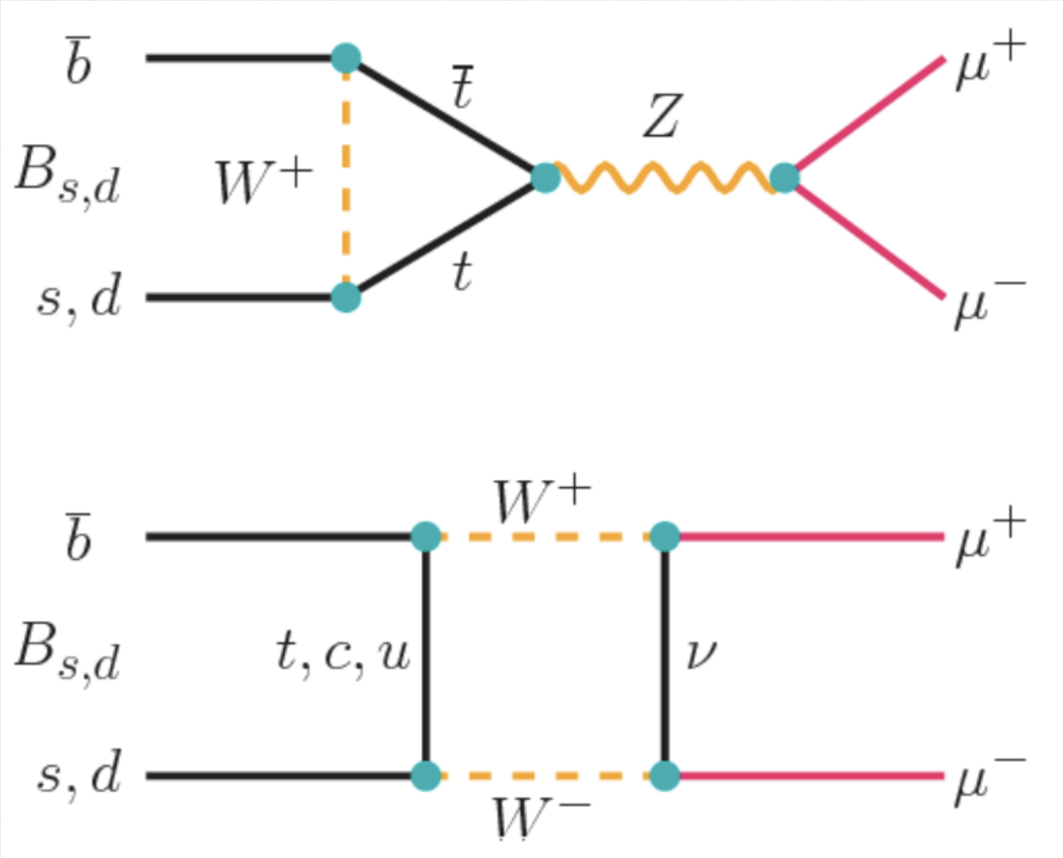
Lepton universality (anomalies?)

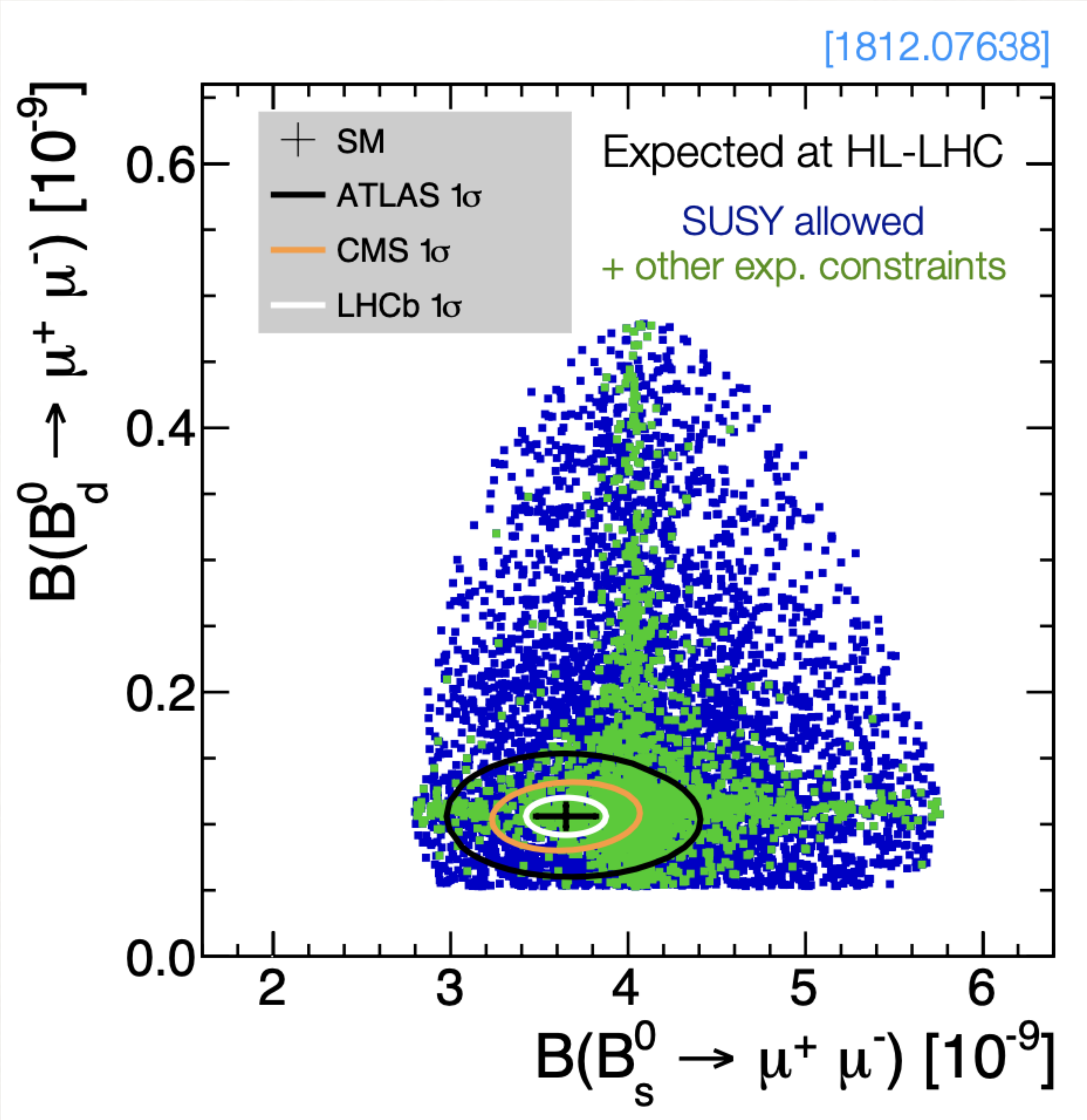


$$R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\mu^-\bar{\nu}_\mu)}$$



Rare B decays – sensitive to BSM @ high scales!





Flavor physics in theory: a serious challenge!

BSM: **much harder** to accommodate!

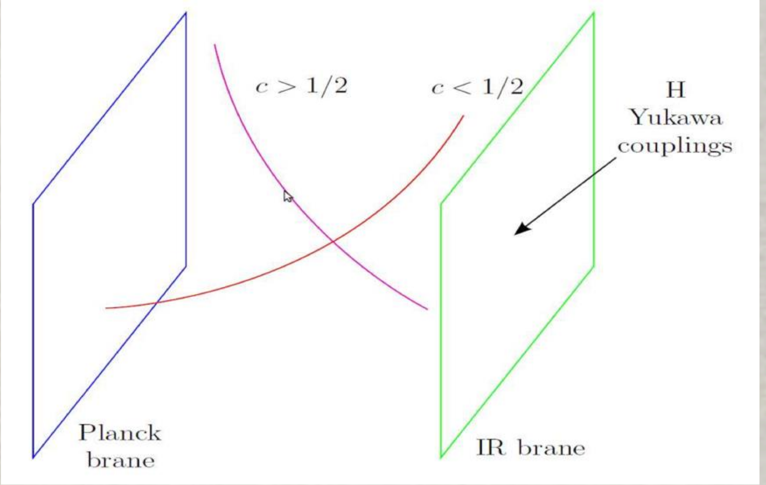
- Generate multiple mass scales
- Avoid FCNC
- Avoid Excessive CP violation

- Why the flavor mixing aligned with the SM Yukawa form?

→ Minimal Flavor Violation (MFV)

- Horizontal flavor symmetry: Froggatt-Nielson mechanism

$$(Y_u)_{ij} \sim \left(\frac{\langle\phi\rangle}{M}\right)^{[q_i]-[u_j]}, \qquad (Y_d)_{ij} \sim \left(\frac{\langle\phi\rangle}{M}\right)^{[q_i]-[d_j]}$$



- Warped extra-dimension: Couplings determined by the overlap with the EW brane.
- Radiative generation of m_f :
  light generation masses loop suppressed $\sim 1/16\pi^2 \sim 10^{-2}$.

Vibrant field in experimental explorations!

Neutrinos are massive
thus mix as well

ν's: the most elusive/least known particle in the SM:

- How many species: 3 $\boldsymbol{\nu}_L$'s + N_R?
- Absolute mass scale: $m_{\nu} \sim y_{\nu}\, v < 1$ eV?

  or a new physics scale via "see-saw": $m_\nu \sim \kappa \frac{\langle H^0 \rangle^2}{M}$
- Flavor oscillations & CP violation?
- Mixing with sterile ν's?
- Portal to dark sector?

Studying neutrino physics has been rewarding:
6+ Nobel Prizes related to ν's!

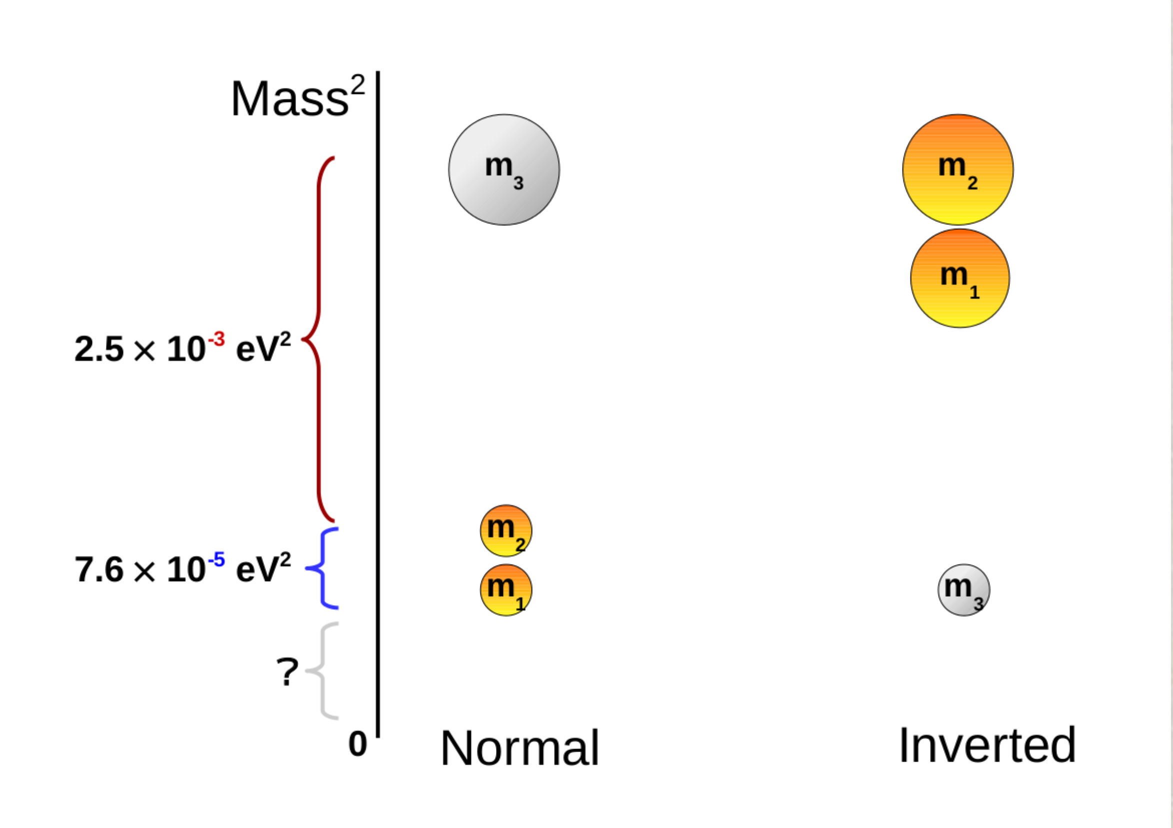
Great playground for theory & experimentation!

The neutrino mixing: PMNS

(Pontecorvo–Maki–Nakagawa–Sakata)

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \mathrm{diag}(1, e^{i\frac{\alpha_{21}}{2}}, e^{i\frac{\alpha_{31}}{2}})$$

Parameter	best-fit
Δm^2_{21} $[10^{-5}$ eV$^2]$	7.37
$\Delta m^2_{31(23)}$ $[10^{-3}$ eV$^2]$	2.56 (2.54)
$\sin^2\theta_{12}$	0.297
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589
$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215
$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216
δ/π	1.38 (1.31)



- Bi-maximal mixing, only small θ_{13}
- New sources of CP violation?
- Dirac mass (Yukawa)? or Majorana (not from h)?

SM as a low-energy effective field theory:

The leading SM gauge invariant operator is at dim-5:*

$$\frac{1}{\Lambda}(y_\nu L H)(y_\nu L H) + \text{h.c.} \quad \Rightarrow \quad \frac{y_\nu^2 v^2}{\Lambda} \overline{\nu_L}\, \nu_R^c .$$

*S. Weinberg, Phys. Rev. Lett. 1566 (1979)

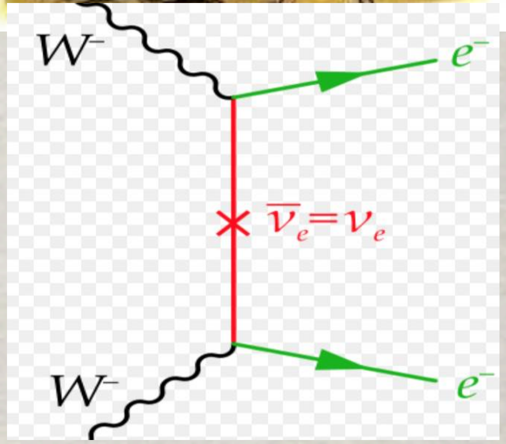
Implications:

- Theoretical: Λ → new scale / particles, implies an underlying (UV) theory!

The See-saw spirit: †

If $m_\nu \sim 1$ eV, then $\Lambda \sim y_\nu^2\,(10^{14}$ GeV$)$.

$$\Lambda \Rightarrow \begin{cases} 10^{14} \text{ GeV for } y_\nu \sim 1; \\ 100 \text{ GeV for } y_\nu \sim 10^{-6}. \end{cases}$$



- Observational:

ΔL=2 → Majorana mass (Majorana neutrinos)

→ Opens the door to BSM ν physics at low & high energies!

†Yanagita (1979); Gell-Mann, Ramond, Slansky (1979), S.L. Glashow (1980); Mohapatra, Senjanovic (1980) …

UV-complete theoretical Models:

The Weinberg operator non-renormalizable
→ Need Ultra-Violet completion at/above Λ .

Group representations based on SM $SU_L(2)$ doublets:

$$2 \otimes 2 = 1(\text{singlet}) + 3(\text{triplet})$$

→ There are three possibilities:

- Type I: Fermion singlets $\otimes (L\ H)_S$
- Type II: Scalar triplet $\otimes (L\ L)_T$
- Type III: Fermion triplets $\otimes (L\ H)_T$

E. Ma: PRL 81, 1771 (1998).
For recent reviews: Z.Z. Xing: arXiv:1406.7739;
Y. Cai, TH, T. Li & R. Ruiz: arXiv:1711.02180.

Type I Seesaw: Singlet N_R's – Sterile neutrinos

$$L_{aL} = \begin{pmatrix} \nu_a \\ l_a \end{pmatrix}_L, \quad a = 1,2,3; \qquad N_{bR}, \quad b = 1,2,3,\ldots n \geq 2.$$

Dirac plus Majorana mass terms: $$\begin{pmatrix} \overline{\nu_L} & \overline{N^c_L} \end{pmatrix} \begin{pmatrix} 0_{3\times 3} & D^{\nu}_{3\times n} \\ D^{\nu T}_{n\times 3} & M_{n\times n} \end{pmatrix} \begin{pmatrix} \nu^c_R \\ N_R \end{pmatrix}$$

Majorana neutrinos:

$$\nu_{aL} = \sum_{m=1}^{3} U_{am}\nu_{mL} + \sum_{m'=4}^{3+n} V_{am'} N^c_{m'L},$$

$$N^c_{aL} = \sum_{m=1}^{3} X_{am}\nu_{mL} + \sum_{m'=4}^{3+n} Y_{am'} N^c_{m'L},$$

<u>The charged currents:</u>

$$-\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} W^+_\mu \sum_{\ell=e}^{\tau} \sum_{m=1}^{3} U^*_{\ell m}\, \overline{\nu_m} \gamma^\mu P_L \ell + \text{h.c.}$$

$$+ \frac{g}{\sqrt{2}} W^+_\mu \sum_{\ell=e}^{\tau} \sum_{m'=4}^{3+n} V^*_{\ell m'}\, \overline{N^c_{m'}} \gamma^\mu P_L \ell + \text{h.c.}$$

Type I Seesaw features:

😀 Existence of N_R (possibly low mass*)

$$U^2_{\ell m} \sim V^2_{PMNS} \approx \mathcal{O}(1);\ \ V^2_{\ell m} \approx m_\nu / m_N.$$

$U_{\ell m},\ \Delta m_\nu$ are from oscillation experiments

m_N a free parameter: could be accessible!

🙁 But difficult to see N_R:

The mixing is typically small, mass wide open:

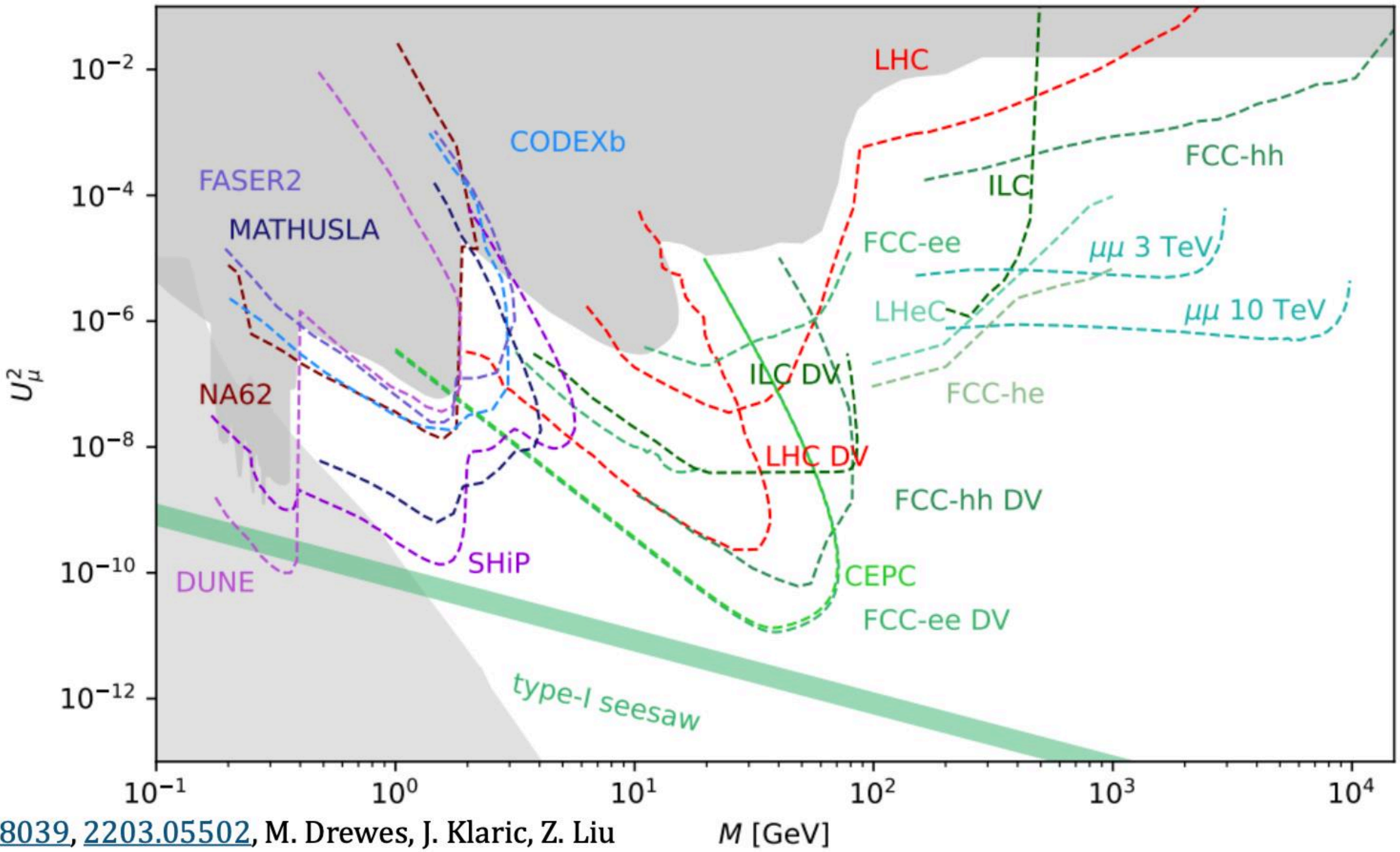
$$V^2_{\ell m} \approx (m_\nu/eV)/(m_N/GeV) \times 10^{-9}$$
$$< 6 \times 10^{-3} (low\ energy\ bound)$$

- Fine-tune or hybrid could make it sizeable.
- "Inverse seesaw"

Casas and Ibarra (2001);
A. Y. Smirnov and R. Zukanovich Funchal (2006);
A. de Gouvea, J. Jenkins and N. Vasudevan (2007);
W. Chao, Z. G. Si, Z. Z. Xing and S. Zhou (2008).

Complementarity @ high & low masses

- **For displaced HNL signatures, more experiments can join the search**
- HL-LHC timescale: FASER2, MATHUSLA, CODEXb, DUNE can probe low masses



2203.08039, 2203.05502, M. Drewes, J. Klaric, Z. Liu

J. Hogan

Type II Seesaw: No need for N_R, with Φ-triplet*

With a scalar triplet $\Phi\ (Y=2)$: $\varphi^{\pm\pm}, \varphi^{\pm}, \varphi^{0}$ (many representative models).
Add a gauge invariant/renormalizable term:

$$Y_{ij} L_i^T C (i\sigma_2) \Phi L_j + \text{h.c.}$$

That leads to the Majorana mass:

$$M_{ij} \nu_i^T C \nu_j + \text{h.c.}$$

where

$$M_{ij} = Y_{ij} \langle \Phi \rangle = Y_{ij} v' \lesssim 1 \text{ eV},$$

Very same gauge invariant/renormalizable term:

$$\mu H^T (i\sigma_2) \Phi^\dagger H + \text{h.c.}$$

predicts

$$v' = \mu \frac{v^2}{M_\varphi^2},$$

leading to the Type II Seesaw. †

*Magg, Wetterich (1980); Lazarides, Shafi (1981); Mohapatra, Senjanovic (1981). ...

†In Little Higgs model: T.Han, H.Logan, B.Mukhopadhyaya, R.Srikanth (2005).

Type II Seesaw features*

- Triplet vev → Majorana mass → neutrino mixing pattern!

$H^{\pm\pm} \to \ell_i^{\pm} \ell_i^{\pm}$ → neutrino mixing pattern!

$H^{\pm\pm} \to W^{\pm} W^{\pm}$. Competing channel

Variations

Naturally embedded in L-R symmetric model:#

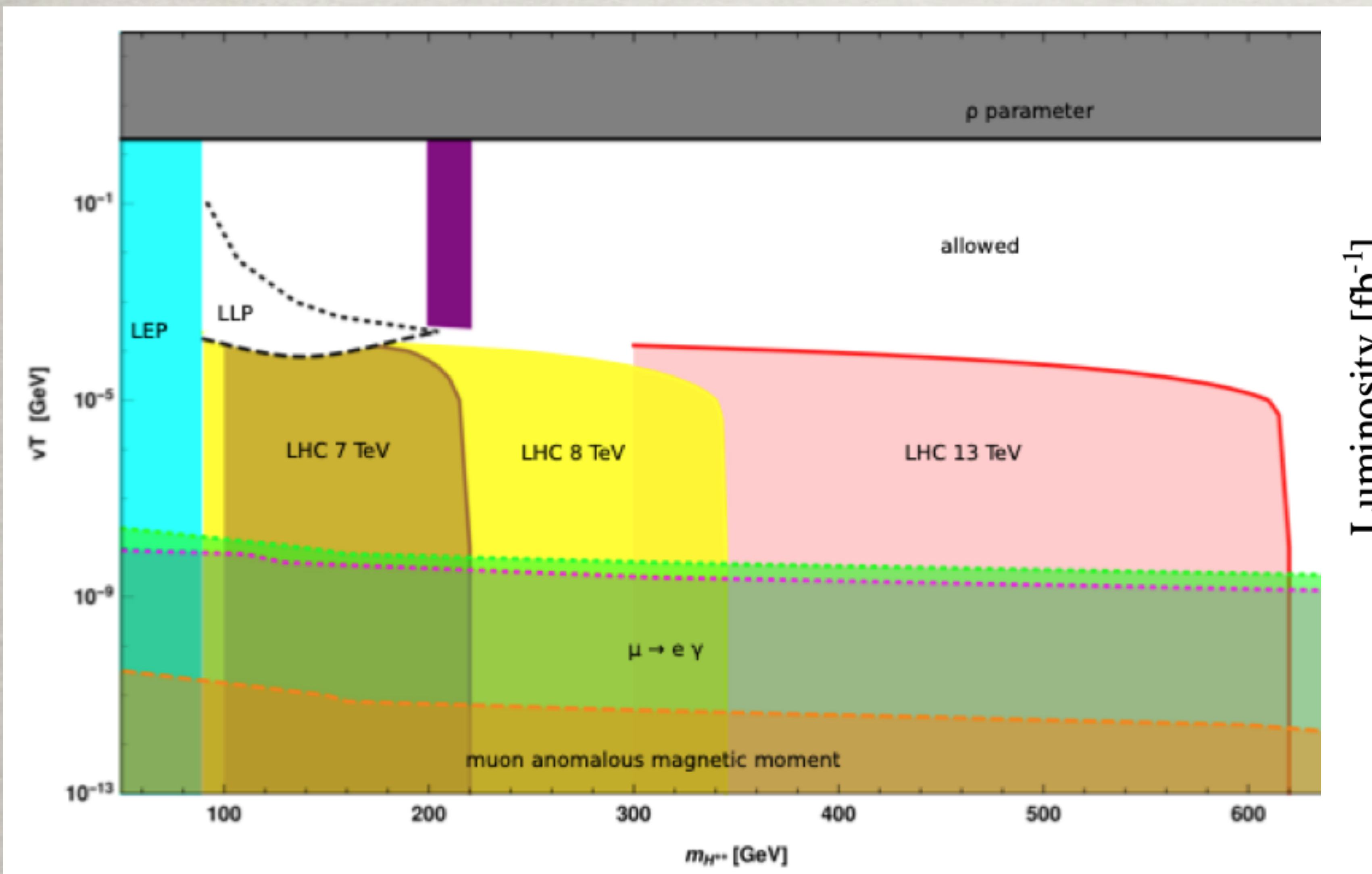
$W^{\pm}_R \to N_R e^{\pm}$

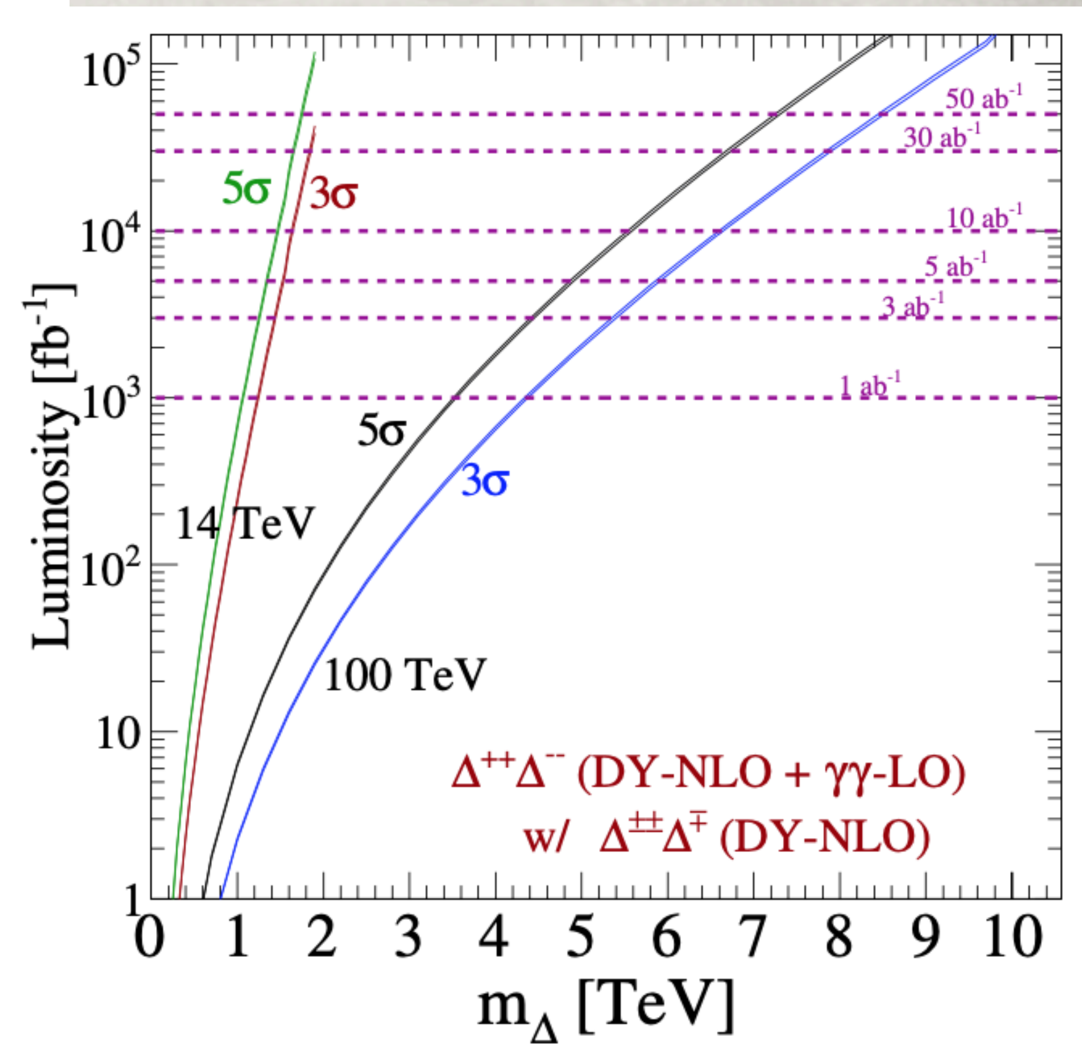
(* Large Type I signals via W_R-N_R)

† Pavel Fileviez Perez, Tao Han, Gui-Yu Huang, Tong Li, Kai Wang, arXiv:0803.3450 [hep-ph]

Mohapatra, Senjanovic (1981). ...

Type II continued: $H^{\pm\pm}$ & $H^{\pm}$





BSM Whitepaper: arXiv:2203.08039

Type III Seesaw: with a fermionic triplet*

With a lepton triplet $T\ (Y=0)$: $T^+\ T^0\ T^-$, add the terms:

$$-M_T(T^+T^- + T^0T^0/2) + y_T^i H^T i\sigma_2 T L_i + \text{h.c.}$$

These lead to the Majorana mass:

$$M_{ij} \approx y_i y_j \frac{v^2}{2M_T}.$$

Again, the seesaw spirit: $m_\nu \sim v^2/M_T$.

Features:

Demand that $M_T \lesssim 1$ TeV, $M_{ij} \lesssim 1$ eV,

Thus the Yukawa couplings:†

$$y_j \lesssim 10^{-6},$$

making the mixing $T^{\pm,0} - \ell^{\pm}$ very weak.

T^0 a Majorana neutrino;

Decay via mixing (Yukawa couplings);

$T\overline{T}$ Pair production via EW gauge interactions.

*Foot, Lew, He, Joshi (1989); G. Senjanovic et al. …

Radiative Seesaw Models*

- New fields + (Z_2) symmetry → no tree-level mass terms
- Close the loops: Quantum corrections could generate m_ν.

Suppressions (up to 3-loops) make both m_ν and M low:

$$m_\nu \sim (\frac{1}{16\pi^2})^\ell (\frac{v}{M})^k \ \mu$$

With (Majorana) mass scale **μ**

Generic features:

- New scalars: φ^0, $H^\pm$, $H^{\pm\pm}$, …

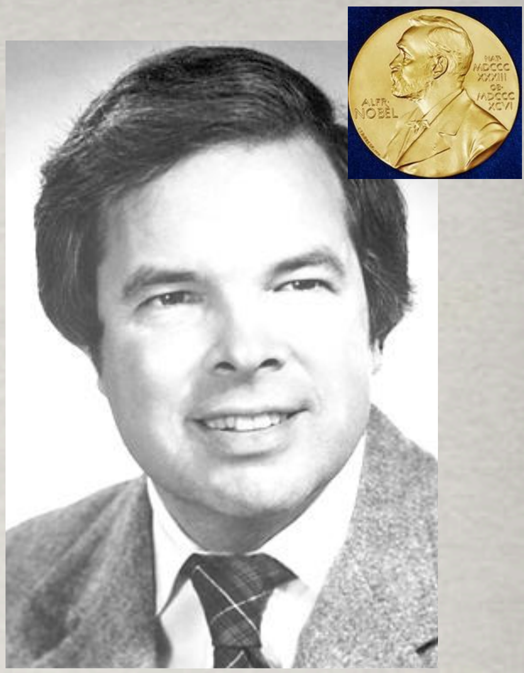
→ BSM Higgs physics, possible flavor relations

- Additional Z_2 symmetry → Dark Matter ***η***

$h^0 \to \eta\eta$ invisible!

* Zee (1980, 1986); Babu (1988); Ma (2006), Aoki et al. (2009).

Effective Field Theory



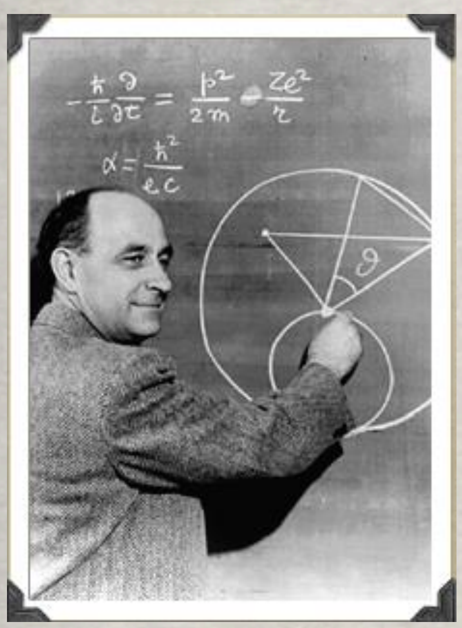
In terms of a large **physical scale** Λ, below which the theory is valid:

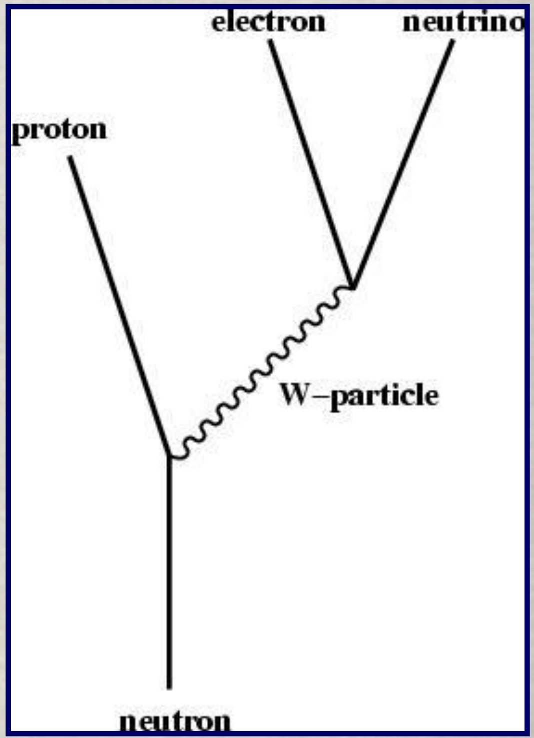
(relevant operators)

$$\mathcal{L} = \sum c_i \Lambda^n \mathcal{O}_n = \cancel{c_0 \Lambda^4 + c_2 \Lambda^2 \mathcal{O}_{\mathrm{dim}\ 2} + c_3 \Lambda \mathcal{O}_{\mathrm{dim}\ 3}}$$

$$+ \underline{c_4 \mathcal{O}_{\mathrm{dim}\ 4}} + \underline{\frac{c_6}{\Lambda^2} \mathcal{O}_{\mathrm{dim}\ 6} + \ldots}$$

(marginal operators) (irrelevant operators)





1st example: beta decay $n \rightarrow p^+ e^- \nu$

➔ Charged current interaction: $W^{\pm}$

$$-\mathcal{L}^{cc}_{eff} = \frac{G_F}{\sqrt{2}} J^{\mu}_{W} J^{\dagger}_{W\mu}, \qquad J^{(\pm)}_{\lambda} = \sum_i \bar{\psi}_i \tau_{\pm} \gamma_{\lambda} (1 - \gamma_5) \psi_i,$$

The fact $G_F = (300\ \mathrm{GeV})^{-2}$ implies that:

- A new mass scale to show up at O(100 GeV)!
- Partial-wave Unitarity requires E < 300 GeV !

Many successful example:

- Weak interactions at low energies (Fermi theory).
- Chiral perturbation theory — low energy interactions of hadrons
- Heavy quark effective theory (B and D mesons)

EFT is a consistent systematic approach for calculations.

A “poor man’s approach”:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{M^2} \mathcal{O}_i^{(6)} + \sum_j \frac{D_j}{M^4} \mathcal{O}_j^{(8)} + \cdots$$

- Don’t know the couplings C_i & D_j, but O(1)?
- Don’t know the scale M, but O(1 – 50 TeV)?
- Each order is smaller by $1/M^2$, but how many terms?

Standard Model Effective Field Theory: SMEFT

A gauge invariant EFT with SM fields, H-doublet

(Buchmüller and Wyler, Grzadkowski, Iskrzyǹski, Misiak, Rosiek)

At dim-6, there 8 types of operators:

$(H^{+}H)^{3}$, $D^{2}(H^{+}H)$, $G^{2}(H^{+}H)$, G^{3}, $F^{2}H^{3}$, $F^{2}GH^{3}$, $F^{2}DH^{2}$, F^{4}

where H the Higgs, D derivative, G gauge tensor, F fermion

76 hermitian operators which preserve *B* and *L*
2499 including flavor indices

Lepton flavor violation bounds $\Lambda > 10^{2}$ - 10^{4} TeV

K-Kbar mixing, heavy quark bounds $\Lambda >$ 1 - 6 TeV

LHC bounds on EW physics $\Lambda >$ a few TeV

Gino Isidori, David M. Straub: Minimal Flavour Violation and Beyond

Operator	Bound on Λ	Observables
$H^\dagger\left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} Q_L\right)(eF_{\mu\nu})$	6.1 TeV	$B \to X_s\gamma$, $B \to X_s \ell^+\ell^-$
$\frac{1}{2}(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L)^2$	5.9 TeV	ϵ_K, Δm_{B_d}, Δm_{B_s}
$H_D^\dagger\left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} T^a Q_L\right)(g_s G^a_{\mu\nu})$	3.4 TeV	$B \to X_s\gamma$, $B \to X_s \ell^+\ell^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right)\left(\overline{E}_R \gamma_\mu E_R\right)$	2.7 TeV	$B \to X_s \ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$i\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right) H_U^\dagger D_\mu H_U$	2.3 TeV	$B \to X_s \ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right)\left(\overline{L}_L \gamma_\mu L_L\right)$	1.7 TeV	$B \to X_s \ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right)(eD_\mu F_{\mu\nu})$	1.5 TeV	$B \to X_s \ell^+\ell^-$

Higgs Effective Field Theory: HEFT

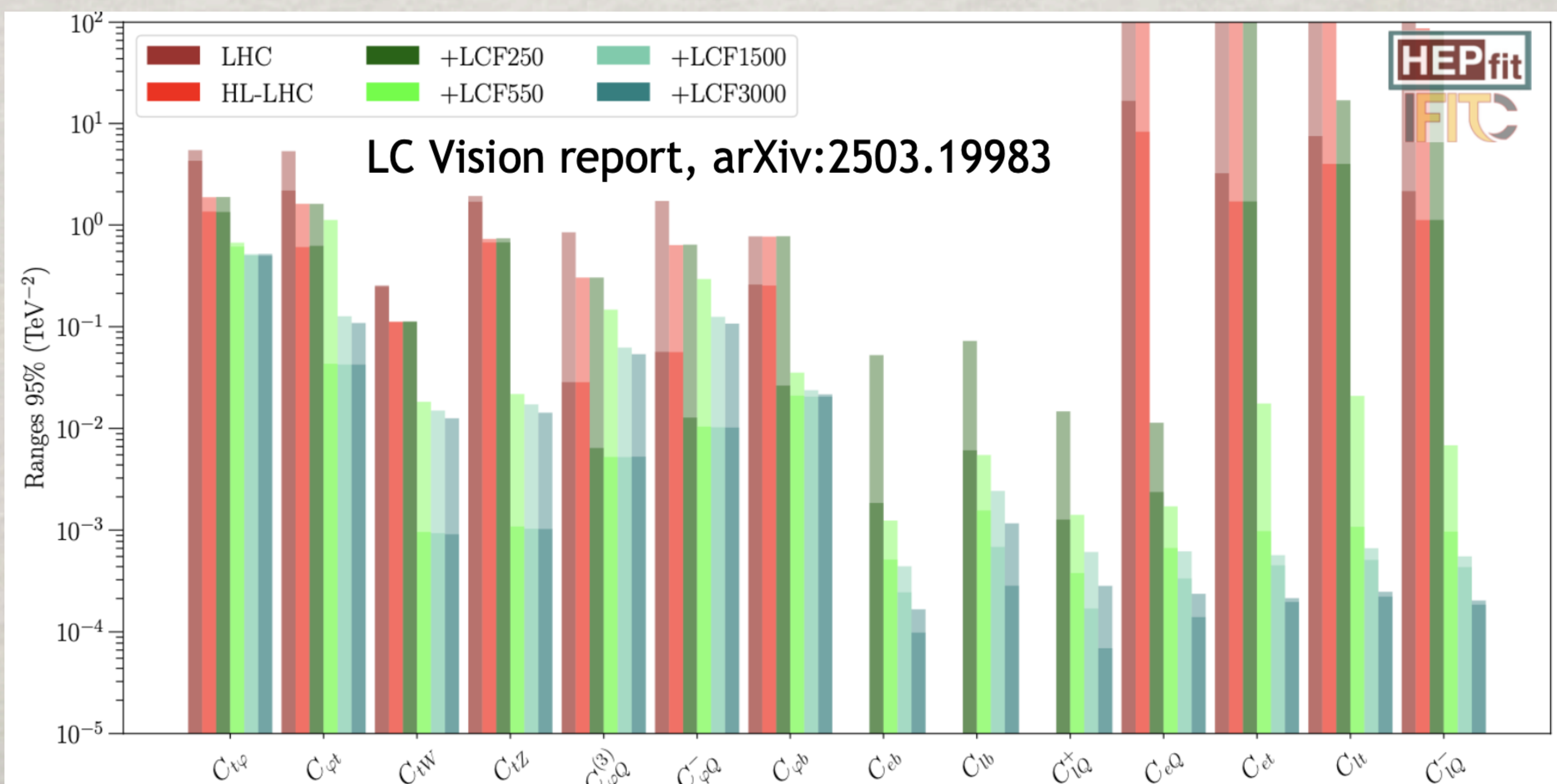
A gauge invariant EFT non-linear realization, no SM Higgs doublet

$$U = e^{2i\phi^a T_a/v} \quad \text{with} \quad \phi^a T_a = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\phi^0}{\sqrt{2}} & \phi^+ \\ \phi^- & -\frac{\phi^0}{\sqrt{2}} \end{pmatrix},$$

$$\mathcal{L}_{Uh} = \frac{v^2}{4} \mathrm{tr}[D_\mu U^\dagger D^\mu U] F_U(H) + \frac{1}{2}\partial_\mu H \partial^\mu H - V(H)$$

125-GeV Higgs boson is a "singlet-like"!

$SU(2)_L$ relations for H are absent.



SMEFT BSM vs. HEFT BSM

$$\varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi^+ \\ v + H + i\phi^0 \end{pmatrix},$$

$$\mathcal{L}_{\mathrm{SMEFT},\mu\phi} = -\sum_{n=1}^{\infty} \frac{c_\varphi^{(2n+4)}}{\Lambda^{2n}} (\varphi^\dagger \varphi)^{n+2}$$

$$U = e^{2i\phi^a T_a/v} \quad \text{with} \quad \phi^a T_a = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\phi^0}{\sqrt{2}} & \phi^+ \\ \phi^- & -\frac{\phi^0}{\sqrt{2}} \end{pmatrix},$$

$$\mathcal{L}_{Uh} = \frac{v^2}{4} \mathrm{tr}[D_\mu U^\dagger D^\mu U] F_U(H) + \frac{1}{2} \partial_\mu H \partial^\mu H - V(H)$$

weakly coupled @ ***Λ*** (SUSY, 2HDM …)

strongly coupled @ **4π υ** (Composite, T', $\boldsymbol{\rho}_{TC}$ …)

LHC → Higgs coupling SM-like ~ few %

but (light) fermion Yukawa's wide open to explore:

$$-\sum_{n=1}^{\infty} \frac{c_{\ell\varphi}^{(2n+4)}}{\Lambda^{2n}} (\varphi^\dagger \varphi)^n (\bar{\ell}_L \varphi \mu_R + \text{h.c.})$$

$$-\frac{v}{\sqrt{2}} \left[\bar{\ell}_L Y_\ell(H) U P_- \ell_R + \text{h. c.} \right]$$

$$Y_\ell(H) = \frac{\sqrt{2} m_\mu}{v} + \sum_{k \geq 1} y_{\ell,k} \left(\frac{H}{v} \right)^k$$

E. Celada, TH et al., arXiv:2312.13082

In these lectures:

1. The Quest for the SM & Beyond

The SM is tested to the highest energy scale accessible to date, and can be valid to an exponentially high scale. Yet it is incomplete: neutrino mass; DM; baryonic asymmetry.

Higgs boson may serve as a portal to BSM physics.

2. Strongly-coupled EW Sector

Higgs is a composite state, as a Nambu-Goldstone boson, showing up with a form factor, or with T', W', Z' partners.

3. A Weakly-coupled Extension

SUSY extension: top-squark, gluino, multiple Higgs, DM…

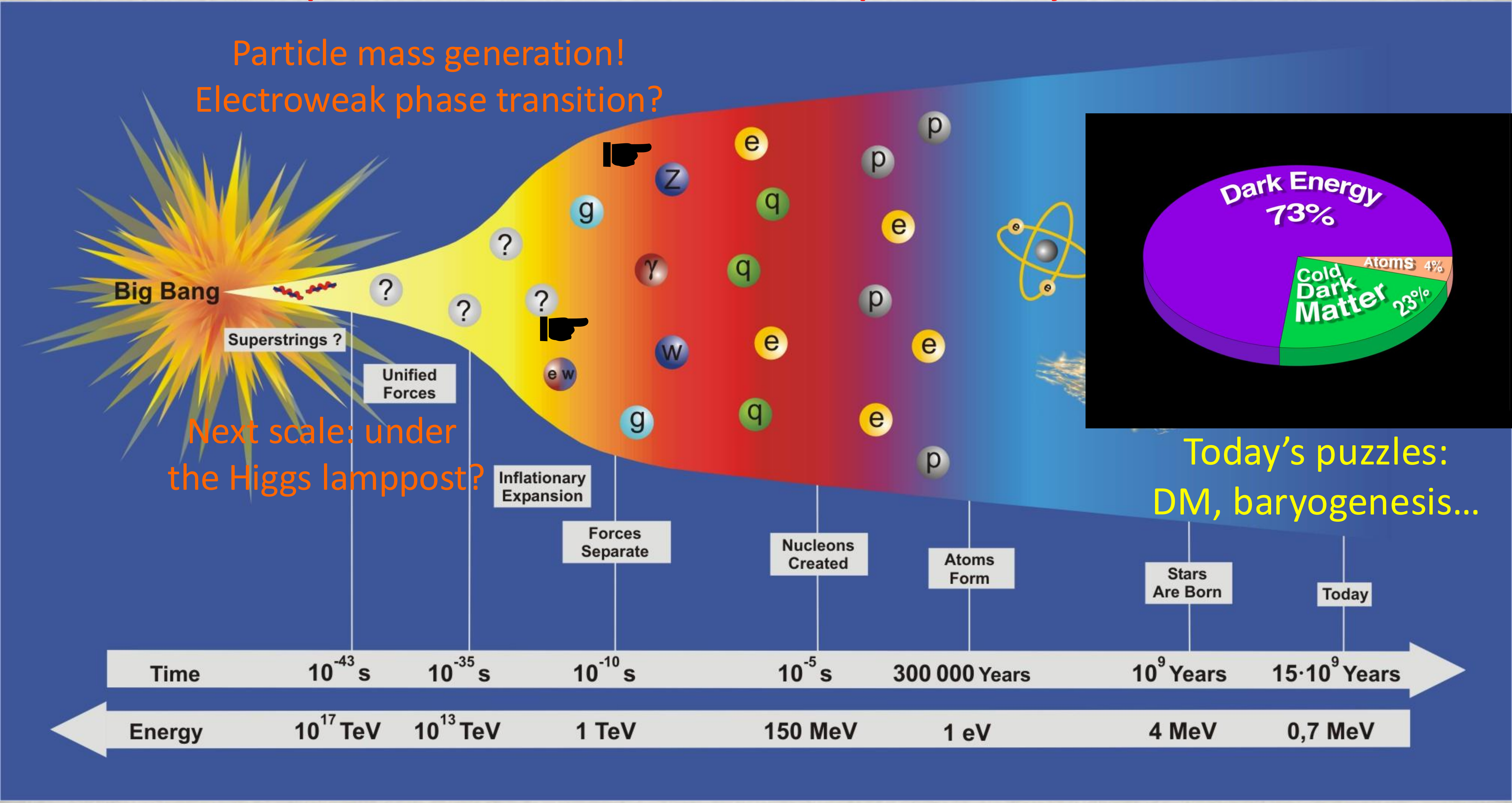
4. Flavors of Matter Fields & EFT

Precision flavor / neutrino physics keep the promise to probe higher scales.

Concluding Remarks

Uninterrupted discoveries in the past 50 years led us to …

Particle mass generation!
Electroweak phase transition?



Next scale: under
the Higgs lamppost?

Today's puzzles:
DM, baryogenesis…

Exploration of BSM Physics remains Exciting!

Danke Sehr !