TeV-scale physics probes at low energy in the LHC era

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2.5 years after the discovery of the 125 GeV resonance at the LHC:

Message from ATLAS and CMS – according to their recent publications:

- The 125 GeV resonance is **a** Higgs boson

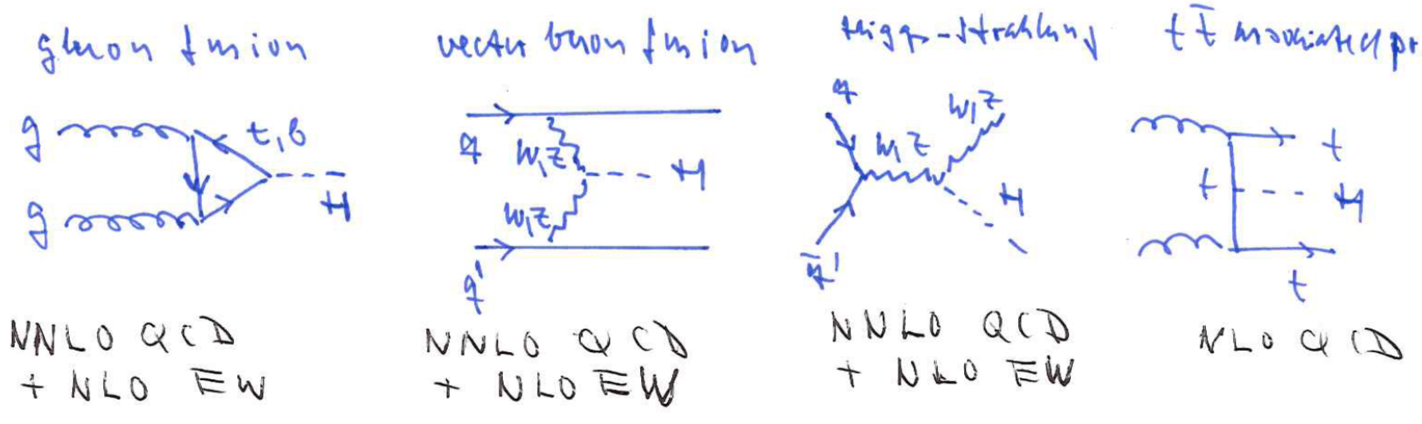
- Data compatible with identifying it with **the** Higgs boson of the Standard Model (SM)

Furthermore: plethora of results from ATLAS, CMS, LHCb:

- data on standard reactions in (very good) agreement with SM predictions
  $V = W, Z$ boson production, VV' production,
  $t\bar{t}$ & single top production, B meson decays, ...

- No sign of BSM resonances or BSM reactions

Production of $H(125\mathrm{GeV})$ in pp collisions @ LHC (7 & 8 TeV), according to SM:



ATLAS: $m_H = 125.36 \pm 0.41$ GeV, CMS: $m_H = 125.02 \pm 0.31$ GeV

very narrow resonance: $\Gamma_H^{SM} = 4$ MeV, Upper bounds on Γ_H by ATLAS & CMS

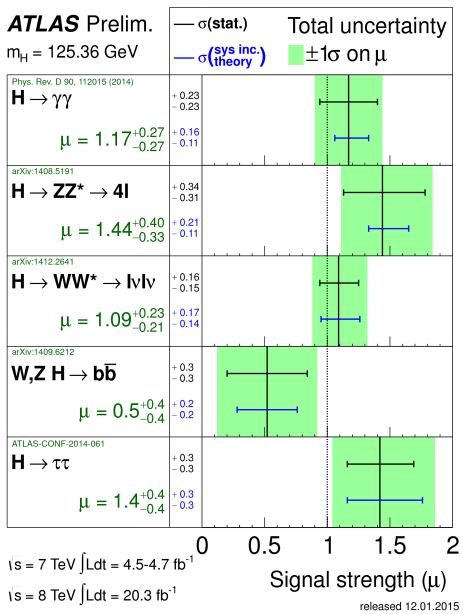
Fact that $m_H = 125$ GeV is "lucky circumstance"

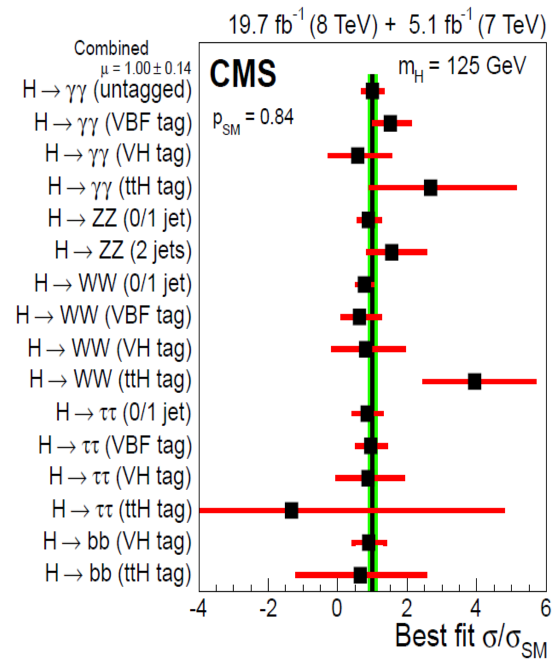
$\Rightarrow$ a number of decay modes of H observable, in particular

$$H \to b\bar{b}, \quad H \to WW^* \to 4f, \quad H \to ZZ^* \to 4f, \quad H \to \tau^-\tau^+, \quad H \to \gamma\gamma$$

Signal strenghts:

$$\mu = \frac{\sigma(pp(ij) \to H)B(H \to \text{final state})}{\sigma_{\text{SM}}(pp(ij) \to H)B_{\text{SM}}(H \to \text{final state})}$$





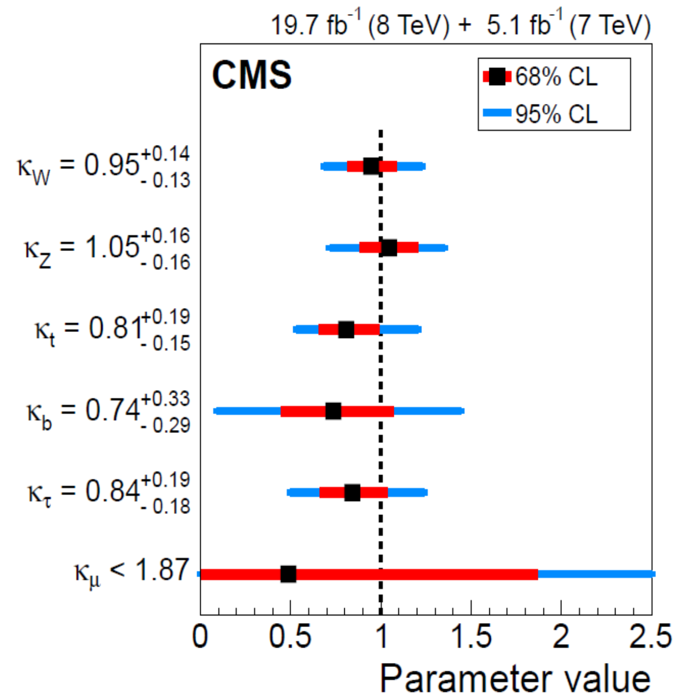
Couplings of $H(125\mathrm{GeV})$, assuming pure 0^{++}, compared with SM Higgs couplings

HVV coupling: $\kappa_V \dfrac{2m_V^2}{v}$

$V = W, Z. \quad v = 246$ GeV

Hff coupling: $\kappa_f \dfrac{m_f}{v}$

SM prediction: $\kappa_V = \kappa_f = 1$



CMS & ATLAS results agree with SM predictions.

Present exp. uncertainties still allow for interpretation: $H(125\mathrm{GeV}) \in$ {extended Higgs spectrum}

Examples: SM extensions with Higgs doublets and singlets: $|\kappa_V| < 1$

type-II 2HDM, MSSM: κ_u different from $\kappa_d = \kappa_\ell$

Spin & parity of $H(125\mathrm{GeV})$:
$J^P = 0^+$ from angular correlations in $H \to ZZ^* \to 4\ell$
However, does not exclude the possibility that H is a CP-mixture

$$|H(125\mathrm{GeV})\rangle = \cos\varphi|0^{++}\rangle + \sin\varphi|0^{-+}\rangle \quad (?)$$

because $|0^{-+}\rangle \not\to W^+W^-, ZZ$ at lowest order. (Couplings must be fermion-loop induced – small)
Can be explored with CP-odd angular correlations in $H \to \tau\tau \to$ charged prongs
(**Berge, W.B. (2008, ...)**)
LHC sensitivity: $|\sin\varphi| \gtrsim 0.1$
EDM of electron $\Rightarrow$ severe indirect upper limit on CP-odd admixture

No sign of new physics at LHC so far

- exp. analysis of standard reactions agree with SM predictions @ (N)NLO QCD + EW corrections
- decays, i.p. B decays in accord with SM
- searches for new heavy resonances unsuccessful

search for bumps in dijet production, Drell-Yan production, ...
e.g. Z' with $m_{Z'} < 2.9$ TeV excluded,
in dijet prod. resonances X up to $m_X < 5$ TeV excluded

With m_H =125 GeV and top mass m_t=173 GeV
SM of particle physics is consistent quantum field theory up to very high energy scales

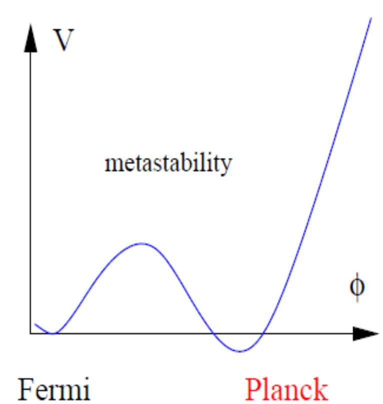
Renormalization group analysis with inputs
Higgs self-coupling: $\lambda(m_H) = m_H^2/(2v^2)$, top Yukawa coupling: $y_t(m_t) = \sqrt{2}m_t/v$, ...

- weakly coupled theory, even for energies exceeding the Planck scale

- Issue of vacuum stability: values of input parameters $\lambda, y_t, \ldots$
determine energy scale where effective potential $V_{\rm eff}(\phi)$ has degenerate 2. minimum:

$$V_{\rm eff}(\phi_1) = V_{\rm eff}(\phi_{\rm SM} = 246 {\rm GeV}), \quad V'_{\rm eff}(\phi_1) = V'_{\rm eff}(\phi_{\rm SM}) = 0 \quad \Rightarrow \quad \lambda(\mu^*) = 0, \quad \beta_\lambda^{\rm SM}(\mu^*) = 0$$

Happens at energy scale $\mu^* \sim 10^9 - 10^{13}$ GeV, (**DeGrassi et al. (2012)**)
Value of μ^* depends i.p. on precise value of m_t^R, R= (short distance) renormalization scheme.
Our ground state at $\phi_{\rm SM} \equiv v = 246 {\rm GeV}$ seems to be metastable,
but lifetime (tunneling time) $> T_{universe}$



Yet, SM not quite the ultimate theory of particle physics $\lesssim M_{\rm Planck}$:

- neutrinos oscillate $\rightarrow$ 'textbook SM' extended by massive ν_i. Dirac or Majorana?

- SM does not provide a dark matter candidate

- SM cannot explain matter-antimatter asymmetry of universe

In addition, a number of conceptual/theory drawbacks:
hierarchy problem: SM has no symmetry that protects m_H from huge radiative corrections
flavor problem: disparate quark/lepton mass spectrum, pattern of flavor mixing
CP problem of QCD, ...

Where should one search for new physics?
Trouble: Exp./observational evidence in favour of new physics does not tell us,
not even order of magnitude of associated energy scale Λ_X.

Thus, searches both at high-energy and intensity low-energy frontier necessary

Minimalistic approach: SM with 3 massive neutrinos

For illustration, 1 flavor: add right-handed **singlet** ν_R to SM

Φ = Higgs doublet field, $\tilde{\Phi} = i\sigma_2\Phi^*$, $L = (\nu_L, \ell_L)$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - [\bar{L}Y_\nu\tilde{\Phi}\nu_R + \frac{1}{2}\overline{\nu_R^c}M_R\nu_R + \text{h.c.}]$$

EW symmetry breaking $\to$ Dirac mass term (as for all other fermions) $m_D = Y_\nu v/\sqrt{2}$, and Majorana mass term M_R (cannot be generated by Higgs doublet field).

Diagonalize 2×2 neutrino mass matrix, mass eigenstates ν and N are Majorana f. with masses

$$m_\nu \simeq \frac{m_D^2}{M_R} \ll m_D \text{ if } M_R \gg m_D \quad \text{seesaw mechanism}, \qquad m_N \simeq M_R$$

Generalization to 3 flavors: $\Rightarrow$ 3 light and 3 heavy Majorana mass eigenstates ν_i and N_i.

Charged current interactions

$$\mathcal{L}_{c.c.} = -\frac{g_W}{\sqrt{2}}W_\mu^-\bar{\ell}_\alpha\gamma^\mu\left[U_{\alpha i}P_L\nu_i + \Theta_{\alpha i}P_L N_i\right] + \text{h.c.}$$

where 3×3 matrices $U \simeq (\mathrm{I}+\epsilon)V_{PMNS}$ **active-sterile mixing matrix** $\Theta \simeq m_D(M_R)^{-1}$.

Likewise: couplings of the ν_i and N_i to the Z and SM Higgs boson

masses m_i of light ν_i: eigenvalues of $-m_D^T(M_R)^{-1}m_D$

masses M_i of heavy N_i: $\simeq$ eigenvalues of M_R

- This minimal SM extension is simplest type-I seesaw model

  1 additional mass scale M_R (actually 3 M_i)

  M_R and hence masses M_i of heavy N_i can be anywhere between 10^{10} and a few GeV
  Yukawa couplings, i.e. m_D must scale accordingly such that mass diff. and mixings of light ν_i satisfy ν-oscillation data, etc.

$$\Rightarrow \quad |\sum_k \Theta^T_{\alpha k} M_k \Theta_{k\alpha'}| \simeq |(\mathcal{M}_\nu)_{\alpha\alpha'}| \lesssim 1 \text{ eV} \qquad (*)$$ Merle,Rodejohann (2006)

- mass terms of heavy neutrinos, $M_i \overline{N}_i N_i^c$, violate lepton number L
- L-violation can explain baryon asymmetry of universe, $n_B/N_\gamma \simeq 6 \times 10^{-10}$

  Baryogenesis via Leptogenesis:

i) out-of-equilibrium L-viol. decays/scatterings of N_i
$+$ CP phase(s) in mixing matrix generate $\Delta_L = N(\ell^+) - N(\ell^-) \neq 0$.
ii) Sphaleron reactions **above** EW phase transion, which violate B, L number, but conserve $B-L$ convert $\Delta_L \neq 0$ into baryon asymmetry $\Delta_B \neq 0$.

- Leptogenesis scenario works for $M_i \sim 10^{10}$ GeV, but also for $M_i \sim$ a few GeV,

  however, for $M_i \lesssim \mathcal{O}(\text{TeV})$, at least 2 of the 3 N_i must be approx. mass-degenerate

What about lepton-flavor violation (LFV) in $\mu \to e\gamma$, $\mu \to 3e$,...?

Constraint $(*)$ fulfilled

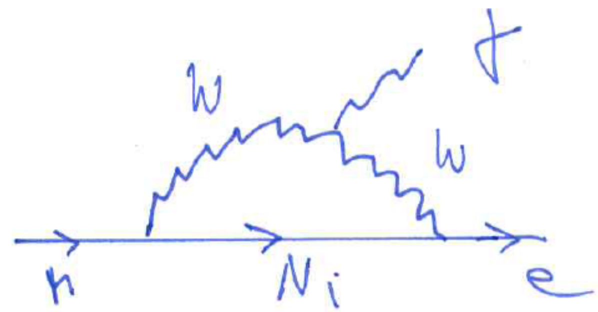
a) if $|\Theta_{\alpha k}| \ll 1 \quad \forall \alpha, k$. Then, LFV effects in $\ell \to \ell'$ significantly below present bounds
b) or by large cancellations in sum. Suggests quasi-degenerate N_i.
In this case, observable LVF effects conceivable

Case of quasi-degenerate N_i also supported by variants of type-I seesaw with approximate L number conservation, where additional scale $\mu_R \ll M_R$ is introduced, in order to separate L-number violation from LFV Mohapatra, Valle, ...

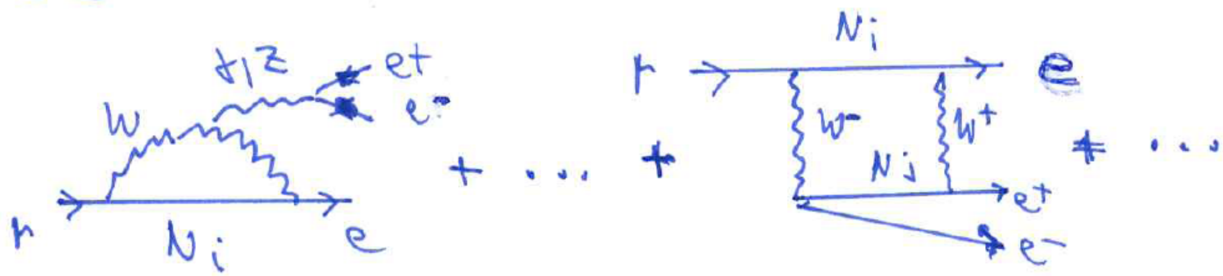
In this case, $(*)$ no longer holds – now: $\mathcal{M}_\nu \simeq \mathbf{m_D^T {M_R^T}^{-1} \mu_R m_D M_R^{-1}}$

LFV processes $\ell \to \ell'$ in type-I seesaw minimal SM ext. (SM particles + N_i)

$\mu \to e + \gamma$



$\mu \to 3e$

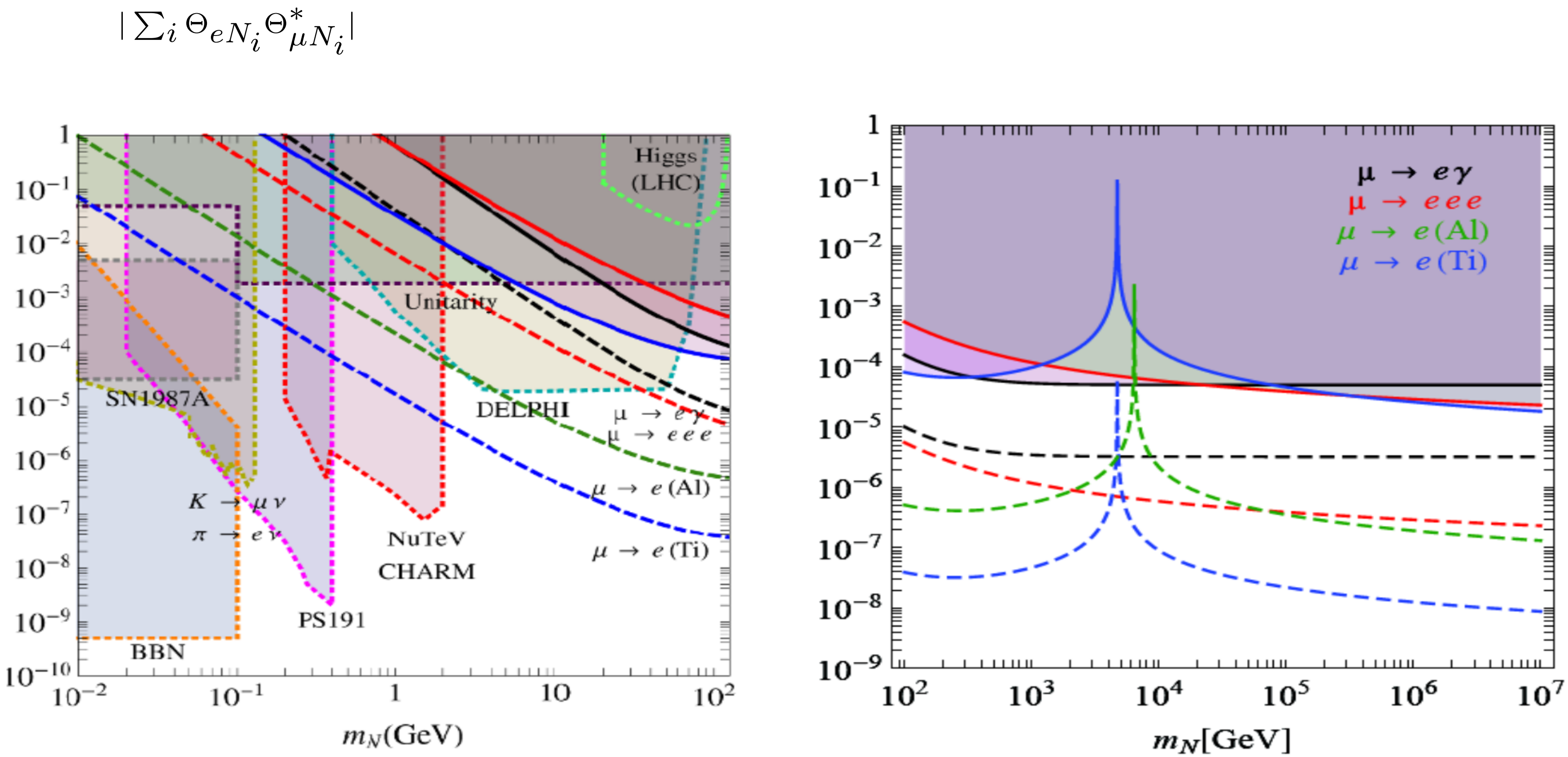


likewise : $\mu + q \to e + q$, $q = u, d, \ldots$

A number of investigatons with nearly degenerate N_i:
Dinh et al. (2012), Alonso et al. (2013), Abada et al. (2013), ...

Alonso et al. (2013) LFV with quasi-degenerate N_i, i,e., one mass scale m_N

Bounds (solid) and future sensitivity (dashed) of LFV exp. to heavy-light mixing as function of m_N
dotted = regions excluded by other exp. ...



LFV Bounds used:
$B(\mu \to e\gamma) < 2.4 \times 10^{-12}$ (previous MEG); $B(\mu \to 3e) < 10^{-12}$ (SINDRUM); $R(\mu \to e\ (\mathrm{Ti})) < 4.3 \times 10^{-12}$ (SINDRUM II)
Prospected sensitivities used here: $B(\mu \to e\gamma) \lesssim 10^{-14}$; $B(\mu \to 3e) \lesssim 10^{-16}$; $R(\mu \to e\ (\mathrm{Al})) \lesssim 10^{-16}$; $R(\mu \to e\ (\mathrm{Ti})) \lesssim 10^{-18}$

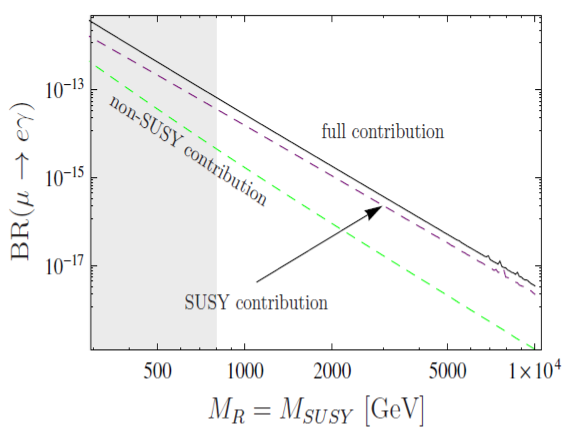
Planned LFV experiments may detect or constrain quasi-degenerate sterile neutrino scenarios
in mass range of a few GeV – a few $\times 10^3$ TeV

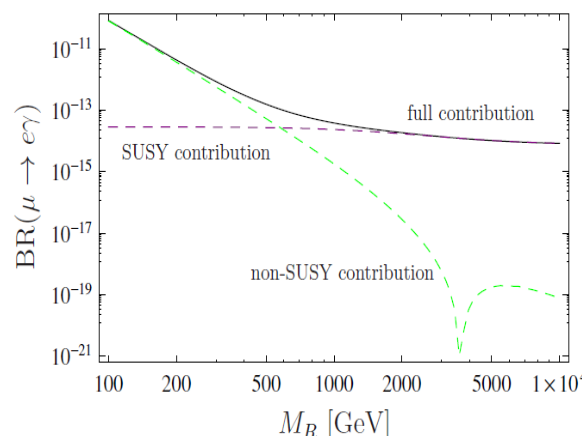
(Abada et al. (2014))

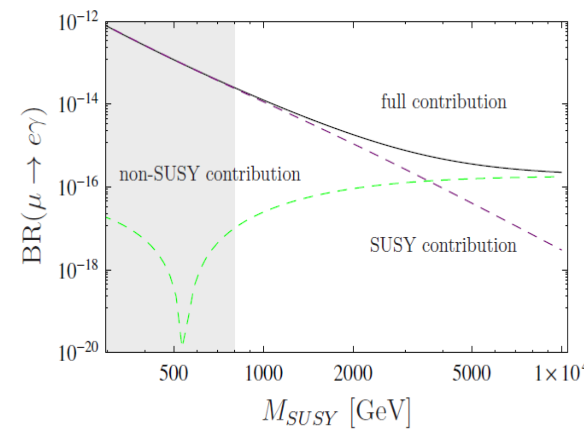
A supersymmetric variant of a model with separate LFV and L-number violation scales:
MSSM with gauge singlets: 3 (s)neutrino(s) ν_{iR}, $\tilde{\nu}_{iR}$, and 3 singlet (s)fermions S_i, $\tilde{S}_i$:
Mass scales: M_R = seesaw scale, and $M_{\rm SUSY}$ = SUSY-breaking scale
(non-SUSY version of the model is a 2HDM)

3 cases considered: (MSSM parameters: $M_0 = M_{1/2} = -A_0 \equiv M_{\rm SUSY}$, put to 1 TeV in case 2)

$M_R \simeq M_{\rm SUSY}$ $\qquad$ $M_R \ll M_{\rm SUSY}$ $\qquad$ $M_{\rm SUSY} \ll M_R$







(Shaded areas excluded by LHC searches). Analogous results for $\mu \to 3e$ and $\mu \to e$ conversion.

Case $M_R \ll M_{\rm SUSY}$:
future LFV searches sensitive to $M_R \sim$ a few TeV in this non-minimal scenario

CP violation and EDMs

Hadrons:

All CPV effects observed in the lab. (K, B decays) can be explained by KM mechanism,
i.e., phase $\delta_{\rm KM}$ in mixing matrix $V_{\rm CKM}$ of charged weak quark-current interactions
KM CPV $\quad\leftrightarrow\quad$ flavor structure of SM quark sector

KM $\Rightarrow$ CPV effects in **flavor-diagonal** reactions/observables very small,
e.g. neutron EDM several orders of magnitude below present exp. sensitivities

Leptons:

SM minimally extended by 3 right-handed Dirac or Majorana neutrinos:
mixing matrix $V_{\rm PMNS}$ with 1 (3) observable CP phase(s) if ν Dirac (Majorana)
$\Rightarrow$ CPV in neutrino oscillations if Dirac phase $\neq 0$.

flavor-diagonal CPV, i.p. electron, muon EDM:
If $\nu =$ Dirac, d_e tiny. $\quad d_\ell^{\rm KM} \sim \frac{m_\ell}{m_e} \times 10^{-38}$ ecm, due to "CP pollution" from quark sector
Khriplovich, Pospelov (1991)
If $\nu =$ Majorana, $d_\ell \neq 0$ at 2 loops, but $d_e^{\rm Maj.} = \mathcal{O}(m_e m_\nu^2 G_F^2) \sim 10^{-43}$ e cm
Archambault et al. (2004)

CP violation besides KM-type?

Many SM extensions, e.g. multi-Higgs models, MSSM, NMSSM, left-right symmetric models,...
$\longrightarrow$ extended Higgs and Yukawa sector, and/or extended gauge sector
$\longrightarrow$ additional, new CPV interactions of quarks, leptons, and new particles

- CPV unrelated to KM-type mixing of quarks and leptons
- strength of CPV can be non-universal (Higgs CPV)

EDMs are highly sensitive probes of non-KM type CPV

many non-KM type CPV models outdated/severely constrained by negative searches so far.

A motivating argument from outside of the laboratory:
Attempts to explain matter-antimatter asymmetry
by baryogenesis at electroweak phase transition in early universe, $T_{\mathrm{EW}} = \mathcal{O}(100\,\mathrm{GeV})$
The EW baryogenesis scenario does not work in SM:
Primary reason:
a strong 1. order EW phase transition is required (departure from thermal equilibrium),
but in SM with $m_{Higgs} = 125$ GeV, symmetric phase $\rightarrow$ broken phase is continuous cross-over.
Even if extra spin-0 fields are invoked to get strong 1. order phase transition:
If KM is only source of CPV, scenario does not work (present consensus) – new CPV is required.

However, is no hard argument for existence of new CPV unrelated to KM-type quark/lepton mixing, as baryogenesis via leptogenesis is a viable alternative

Electric dipole moments

A) Charged leptons

electron	exp. using atom/molecule	limit on $\lvert d_e\rvert$ [e cm] (90% CL)
	Tl Regan et al. (2002)	1.6×10^{-27}
	YbF Hudson et al. (2011)	1.06×10^{-27}
	ThO Baron et al. (2014)	8.7×10^{-29}
muon	Bennett et al. (2009)	$\lvert d_\mu\rvert < 1.8 \times 10^{-19}$ (95% C.L.)
WDM of tau d_τ^Z	Heister et al. (2003)	$\lvert \mathrm{Re} d_\tau^Z\rvert < 5 \times 10^{-18}$ (95% C.L.)

As to electron EDM bounds from above paramagnetic systems:

$$\Delta E = \hbar\omega = -d_e \mathcal{E}_{\rm eff} - w_s \frac{G_F}{\sqrt{2}} C_S \qquad (*)$$

where ω measured, $\mathcal{E}_{\rm eff}$, w_S from atomic/molec. calculations,
C_S = coupling of P- & T-odd electron-nucleon interaction $\sum_N \bar{N} N \bar{e} i\gamma_5 e$
For **ThO**: $\mathcal{E}_{\rm eff} = (84 \pm 5)$ GV/cm, $w_S = (1.9 \pm 0.3)\hbar$ MHz, (1401.2284, 1308.0414)
putting $C_S = 0 \Rightarrow$ upper bound on $\lvert d_e\rvert$, putting $d_e = 0 \Rightarrow \lvert C_S\rvert < 5.9 \times 10^{-9}$

Relation (*) applies also to Tl and YbF
more conservative bounds if 2-parameter fits to measured ΔE are made

Energy scale Λ, associated with new CPV, probed by present bound on d_e?

'Agnostic' estimate, assuming $d_e \propto m_e$:

$$d_e/e \sim \kappa \left(\frac{\alpha_W}{4\pi}\right)^n \frac{m_e}{\mathbf{\Lambda^2}} \sin \varphi_{\rm CP}$$

$\alpha_W = \alpha/\sin^2\theta_W$, n = number of loops of dominant contribution
κ value of dim.less loop function
$\mathbf{\Lambda}$ = scale of new physics associated with $\sin\varphi_{\rm CP} \neq 0$.

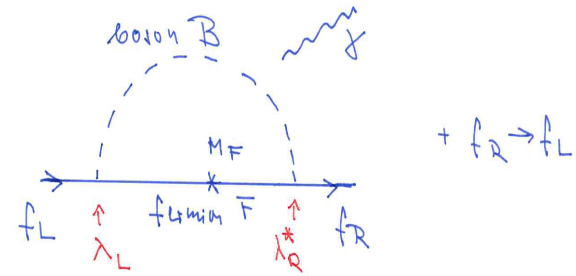
Using $|d_e| < 10^{-28}$ e cm, and putting $\sin\varphi_{\rm CP} \sim 1$ and $\kappa \sim 0.1 - 1$:

If 1-loop contrib. dominates $\Rightarrow$ $\mathbf{\Lambda} \gtrsim 4.8 - 15$ TeV

If 2-loop contrib. dominates $\Rightarrow$ $\mathbf{\Lambda} \gtrsim 0.23 - 0.73$ TeV

Generic 1-loop amplitudes which generate $d_f \neq 0$, $f = \ell, q$

- B (spin 0 or 1) must couple both to $f_L \& f_R$
- $\mathrm{Im}(\lambda^L \lambda^{R*}) \neq 0$, i.e. nonzero CPV phase



Examples:

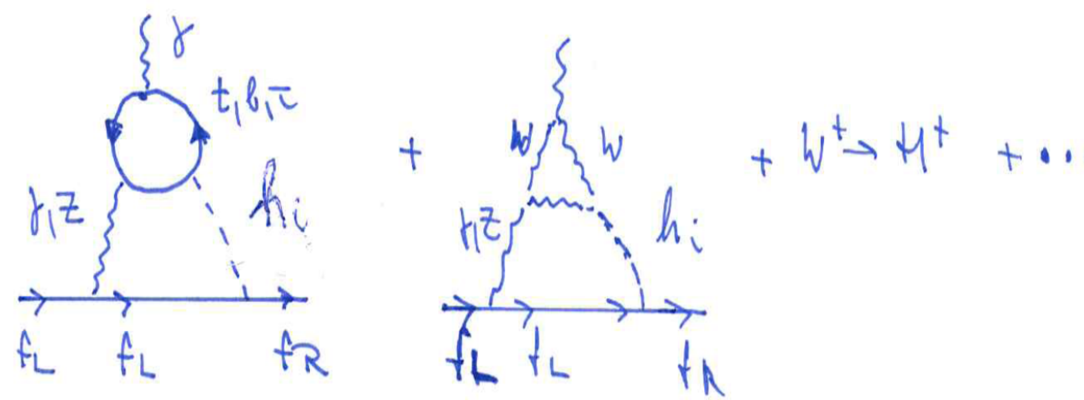
$*$ minimal SUSY (MSSM) with only 2 additional, flavor-independent CPV phases:
For f = lepton: F= neutralino/chargino, B = charged/neutral slepton
However, severe bounds from $|d_e|_{\exp}$:
if $m_{\tilde{\chi}}, m_{\tilde{\ell}} \sim$ a few 100 GeV, then CPV phase $|\sin(\varphi_A - \varphi_\mu)| \lesssim 10^{-3}$

$*$ left-right-symmetric extensions:
For f = lepton: F= massive Majorana ν, $B = W$, mixture of W_L and W_R

$*$ 2HDM extensions: CPV but flavor-conserving neutral Higgs-boson exchange:

$$F = f, B = h_i$$

In models with Higgs-sector CPV,
2-loop contributions $\gg$ 1-loop
for light $f = \ell, q$



Consider 2-Higgs doublet extensions of SM (with no tree level FCNC):

• type-II 2HDM with CPV in neutral Higgs sector

Yukawa couplings of neutral spin-0 h_i (mass basis)

$$\mathcal{L}_Y = -\sum_{f,i} \frac{m_f}{v}(\mathbf{a_{f,i}}\bar{f}f + \mathbf{b_{f,i}}\bar{f}i\gamma_5 f)h_i \qquad \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} h \\ H \\ A \end{pmatrix}$$

$$h_1 \equiv h(125\text{GeV}) \simeq \cos\varphi[h\cos\beta + H sin\beta] + A\ \mathbf{sin}\varphi, \qquad \tan\beta \equiv v_2/v_1$$

likewise h_2, h_3, i.e., h_i are CP mixtures

h_i exchange generates d_ℓ. For $\ell = e, \mu$ dominant contrib. at 2 loops ($\propto m_\ell$)

Recent analysis: `Inoue et al. 1403.4257`

Using $m_{h_1} = 125$ GeV, $m_{h_2}, m_{h_3}, m_{H^\pm} \gtrsim 400$ GeV and exp. upper bound on d_e resp. ThO:

$\Rightarrow$ $|\sin\varphi| \gtrsim 0.01$ and $\tan\beta \lesssim 20$ excluded

• `Jung, Pich (2014):` "aligned 2HDM", slightly more general than type-II 2HDM

new CPV due to neutral Higgs mixing

and new CP phases in aligned Yukawa matrices $Y_u = \zeta_u^* M_u$, $Y_{d,\ell} = \zeta_{d,\ell} M_{d,\ell}$

Bound on d_e $\rightarrow$ values of CP parameter $|\mathrm{Im}\zeta_{\mathbf{u}}\zeta_\ell^*| \gtrsim 0.05$ excluded for a range of Higgs masses

What does $|d_e| < 10^{-28}$ e cm tell us about EDM of muon?

How does d_ℓ scale with m_ℓ? There is no universal scaling law.

Flavor-conserving CPV neutral Higgs-boson exchange:

$$(d_\ell)_{1-\text{loop}} \propto m_\ell^3, \qquad (d_\ell)_{2-\text{loop}} \propto m_\ell$$

$$\text{For } \ell = e, \mu : \quad |(d_\ell)_{2-\text{loop}}| \gg |(d_\ell)_{1-\text{loop}}|$$

$$\Rightarrow \qquad \mathbf{d}_\mu \approx \frac{\mathbf{m}_\mu}{\mathbf{m_e}} \mathbf{d_e} \quad \Rightarrow \quad |\mathbf{d}_\mu| \lesssim \mathbf{10^{-26}}\, \text{e cm} \quad (*)$$

Relation $(*)$ applies also to MSSM and to a number of other BSM models

Chirality flip $\ell_L \leftrightarrow \ell_R$ can also be caused by mass term of internal fermion F, e.g., toy model: spin-zero leptoquark χ with no (or severely suppressed) generation-changing couplings (W.B. (1990))

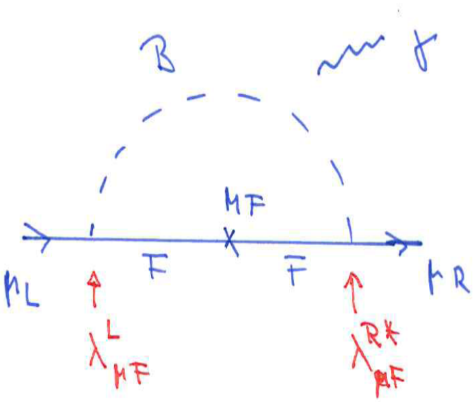
$$\mathcal{L}_I = -\sum_{i=1}^{3} [\lambda_i^{\mathbf{L}} \bar{u}_{iR} \ell_{iL} + \lambda_i^{\mathbf{R}} \bar{u}_{iL} \ell_{iR}]\chi \ + \ \text{h.c.}$$

If $\lambda_i^L \propto m_{u_i}, \lambda_i^R \propto m_{\ell_i}$, and $\text{Im}(\lambda_i^L \lambda_i^{R*}) \neq 0$, then scaling relation for 1-loop lepton EDMs:

$$d_\tau \ : \ d_\mu \ : \ d_e \simeq m_t^2 m_\tau \ : \ m_c^2 m_\mu \ : \ m_u^2 m_e$$

In this case, exp. bound on $|\text{Re} d_\tau^Z|$ provides strongest constraint on $d_\mu \to |d_\mu| < 10^{-23}$ **e cm**

$d_\mu \neq 0$ associated with CPV in lepton-flavor violation and $\mu \to e\gamma$



$+ \ \mu_R \to \mu_L$

if d_μ is generated by LFV and CPV couplings
assoc. with FV transition $\mu_{L,R} \leftrightarrow$ "3. generation fermion or boson" F or B (e.g. $\tilde{\tau}$)

then expect also couplings $e_{L,R}FB \quad \Rightarrow \quad \mu \to e\gamma$
Relate $|d_\mu|$ and $B(\mu \to e\gamma)$.
MEG bound $B(\mu \to e\gamma) < 5.7 \times 10^{-13} \quad \longrightarrow$

$$|\mathbf{d}_\mu| \lesssim \mathbf{10^{-24}} \sin\varphi_{\mathbf{CP}} \ [\mathrm{e\ cm}]$$

If d_μ is generated by LFV CPV $\quad\Rightarrow\quad$ CP-conserving LFV, i.p. $\mu \to e\gamma$.

Using that $d_\mu = -eF^A_{2,\mu\mu}(0)/2m_\mu$, $\quad \mu \to e\gamma \leftrightarrow$ dipole transition form factors, and the MEG bound, one may relate the muon EDM and $B(\mu \to e\gamma)$:

$$|d_\mu| = e\frac{\sqrt{6}G_F m_\mu}{12\pi}\sqrt{B(\mu \to e\gamma)}\; R \quad < 10^{-28} R \;[\mathrm{e\;cm}]$$

$$\text{where} \quad R \equiv \frac{|(F_2^A)_{\mu\mu}/(2m_\mu)|}{\left[\sum_{i=V,A}|(F_2^i)_{\mu e}/(m_\mu + m_e)|^2\right]^{1/2}}$$

Take, e.g., a LFV & CPV interaction involving a heavy fermion F and heavy spin-0 boson B:

$$\mathcal{L}_I = -\sum_\ell [\lambda^{\mathbf{L}}_{\boldsymbol{\ell}\mathbf{F}}\overline{F}_R \ell_L + \lambda^{\mathbf{R}}_{\boldsymbol{\ell}\mathbf{F}}\overline{F}_L \ell_R]B \;+\; \mathrm{h.c.}$$

Assume that $\lambda^{\mathbf{L}}_{\boldsymbol{\ell}\mathbf{F}} = (m_\ell/M)\mathbf{V}^{\mathbf{L}}_{\boldsymbol{\ell}\mathbf{F}}$ and $\lambda^{\mathbf{R}}_{\boldsymbol{\ell}\mathbf{F}} = (m_\ell/M)\mathbf{V}^{\mathbf{R}}_{\boldsymbol{\ell}\mathbf{F}}$

$$\Rightarrow \quad R \simeq \sqrt{2}\,\frac{m_\mu}{m_e}\frac{|V^L_{\mu F}V^{R*}_{\mu F}|}{[|V^L_{\mu F}V^{R*}_{eF}|^2 + |V^R_{\mu F}V^{L*}_{eF}|^2]^{1/2}}\sin\varphi_{\mathbf{CP}}$$

Assume further that $|V^{L,R}_{\mu F}/V^{L,R}_{eF}| \sim 10^2 \quad \Rightarrow \quad |\mathbf{d}_\mu| < \mathbf{10^{-24}}\sin\varphi_{\mathbf{CP}}\;[\mathrm{e\;cm}]$

B) **EDM of neutron** $|d_n| < 2.9 \times 10^{-26}$ ecm (Baker et al. (2006))

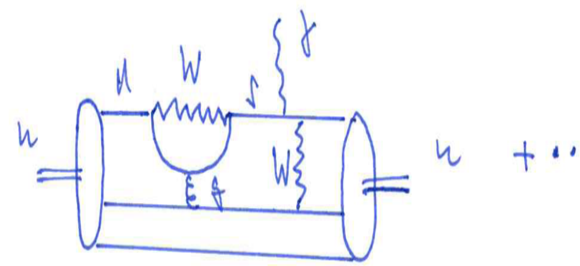
Theory: Effective low-energy light quark/gluon/photon Lagrangian $\mathcal{L}_{CP}$ at $\mu \sim 1$ GeV

$$\mathcal{L}_{CP} = \frac{\bar{\theta}}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu} - i\sum_q \frac{\mathbf{d_q}}{2}\bar{q}\sigma_{\mu\nu}\gamma_5 q F^{\mu\nu} - i\sum_q \frac{\tilde{\mathbf{d}}_\mathbf{q}}{2}\bar{q}\sigma_{\mu\nu}\gamma_5 G^{\mu\nu} q + \frac{1}{3}\mathbf{f_{3G}} G\tilde{G}G + \text{CPV 4-quark int.} + \ldots.$$

where $\mathbf{d_q}, \tilde{\mathbf{d}}_\mathbf{q}, \mathbf{f_{3G}}, \mathbf{C_{4q}}, \ldots$ depend on parameters of specific model.

Standard Model, assuming $\bar{\theta}$=0:
Quark (chromo) EDMs induced by $\delta_{\mathbf{KM}}$:
generated only at 3 loops and are chirality-suppressed, $d_d \simeq 10^{-34}$ e cm Czarnecki, Krause (1997)

More important for d_n:
T-viol. long-distance contribution
Khriplovich, Zhitnitski; Gavela et al. (1982)



Loop-less T-viol. non-local effective 6-quark interactions may also be important
Mannel, Uraltsev (2012)

$$\mathbf{d_n^{KM}} \approx 10^{-32} \text{ e cm}, \qquad \text{factor 5 - 10 uncertainty}$$

$|d_n|_{\rm exp} < 2.9 \times 10^{-26}$ ecm $\quad \Rightarrow \quad |\bar{\theta}| < 10^{-10}$

• $\bar{\theta} = 0$: $\quad \mathcal{L}_{\rm SM} \subset \mathcal{L} \longleftarrow U(1)_{\rm P.Q.}$ symmetry, spont. broken $\longrightarrow$ axion (not in sight)

• $\bar{\theta} \neq 0$ not excluded: e.g. spontaneous P-, T-violation at GUT scale $\rightarrow \bar{\theta}$ finite
but no viable model known

Other non-KM sources of CPV:

• MSSM with additional universal CP phases from superpot. & soft SUSY-breaking terms:
With bounds on phases from $|d_e|_{exp}$ and $m_{\rm squark}, m_{gluino} \sim$ a few TeV $\rightarrow |d_n| < 10^{-27}$ e cm
barring fine-tuning/non-universality scenarios

• non-SUSY 2-Higgs doublet extensions with Higgs sector CPV:
dominant contributions: d, u quark (chromo) EDMs at 2-loops analogous to d_e,
gluon 'chromo EDM' f_{3G} (2 loops)
Confronting Type-II model discussed above with $|d_e|_{exp}$ Inoue et al. (2014)
$\Rightarrow$ bounds on model parameters

$\Rightarrow |\mathbf{d_n}| \lesssim \mathbf{10^{-27}}$e cm $\quad - \quad$ modulo uncertainties in calc. neutron matrix element

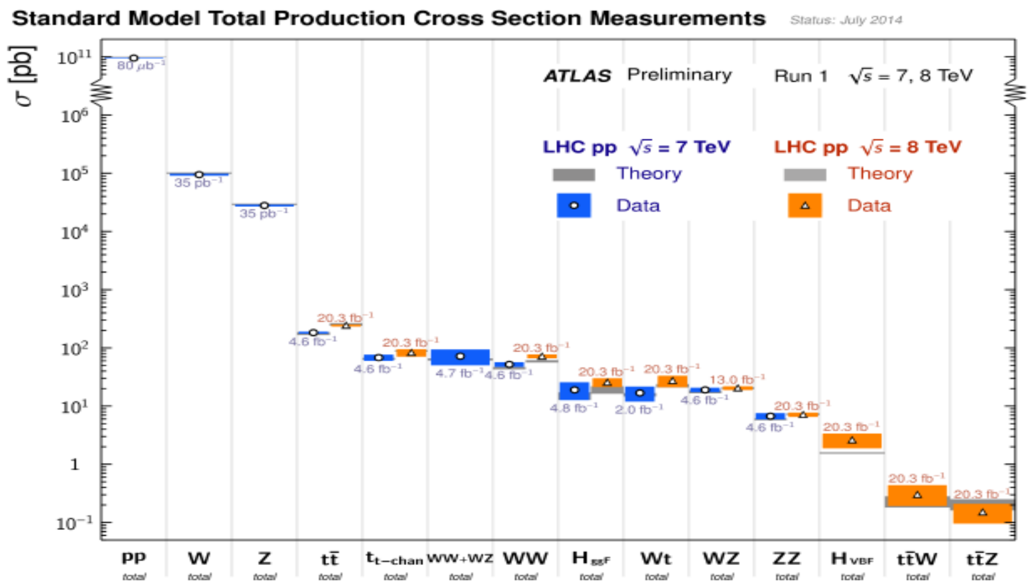
Outstanding theoretical challenge (Lattice QCD):
For given $\mathcal{L}_{CP}$, reliable computation of T-odd part of matrix element $\langle n|J_\mu^{\rm em}|n\rangle$

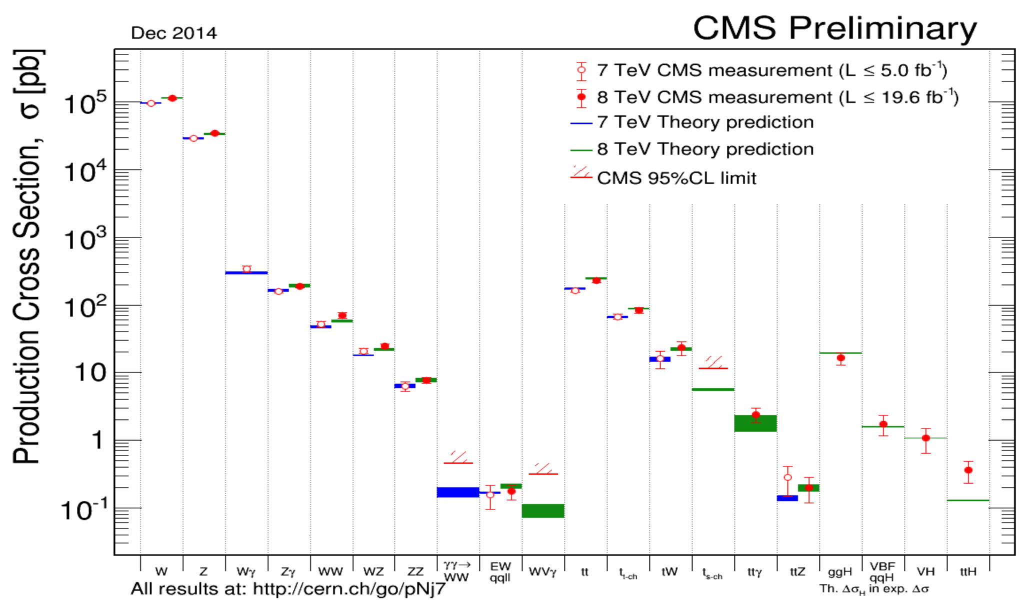
Summary

- SM of particle physics is a consistent theory, probably up to scales of M_{Planck}
- Nevertheless, ν-oscillations, dark matter,... indicate that there is "something in addition"
- However, no solid clue at which scale "something in addition" should show up
- Thus, both high-energy and low-energy searches required – obviously complementary
- Searches for LFV in μ decays & $\mu \to e$ transitions:
  Sensitivity unchallenged by high-energy collider experiments
  Among others, probe sterile neutrino scenarios in mass range of a few GeV to $\sim 10^3$ TeV
- EDMs: highly sensitive probes of non-KM CPV, i.p. flavour-diagonal CPV.
- No hard argument for a non-zero effect, e.g. for neutron EDM well above SM. expectation
- Yet, the impressive sensitivities reached/planned in n exp. and atomic/molecular exp.
  have had and will have strong impact on BSM model building,
  i.e., on our insight into TeV scale physics

Additional slides

ATLAS & CMS results on standard reactions and SM predictions





Parameterization-invariant measure of KM CPV is

$$D_{CP} = \prod_{\substack{i>j \\ u,c,t}} (m_i^2 - m_j^2) \prod_{\substack{i>j \\ d,s,b}} (m_i^2 - m_j^2) \quad J_{CP}$$

where

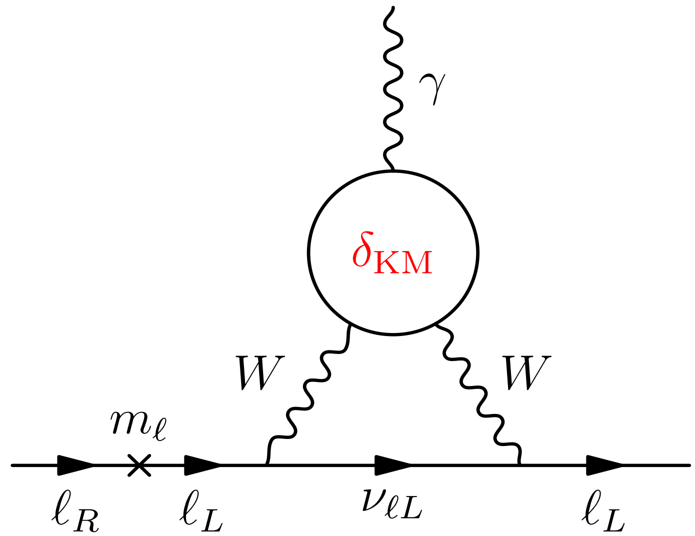
$$J_{CP} = \mathrm{Im}(\mathbf{V_{ud}} \mathbf{V_{cb}} \mathbf{V^*_{ub}} \mathbf{V^*_{cd}}) \simeq 3 \times 10^{-5}$$

i.e., KM CPV $\longleftrightarrow$ flavor structure of SM

Lepton EDMs

$d_\ell^{\rm KM} \neq 0$ due to "CP pollution" from quark sector – via CPV form factor of W boson

Khriplovich, Pospelov (1991)



If ν Majorana fermions, then $d_\ell \neq 0$ at 2-loops, but much smaller than $d_\ell^{\rm KM}$

Archambault et al. (2004)