Fundamental Symmetries and Neutrino Workshop, Chicago, August 10 2012

In Search of the New Standard Model

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Los Alamos NATIONAL LABORATORY EST. 1943

Outline

- Why a "New Standard Model"?
- The High Energy landscape
- The Low Energy landscape

↓

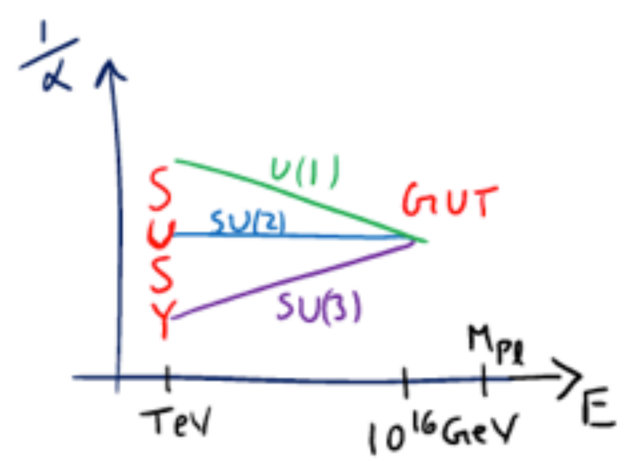
"Compelling and unique science to be done
in the next 5 years and beyond"

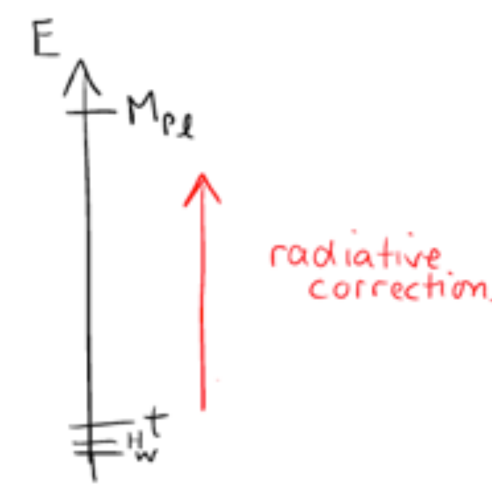
Why a "New Standard Model"?

- The SM is remarkably successful, but has no answer to a number of questions about our universe ⇒ new degrees of freedom

Empirical questions

Theoretical questions

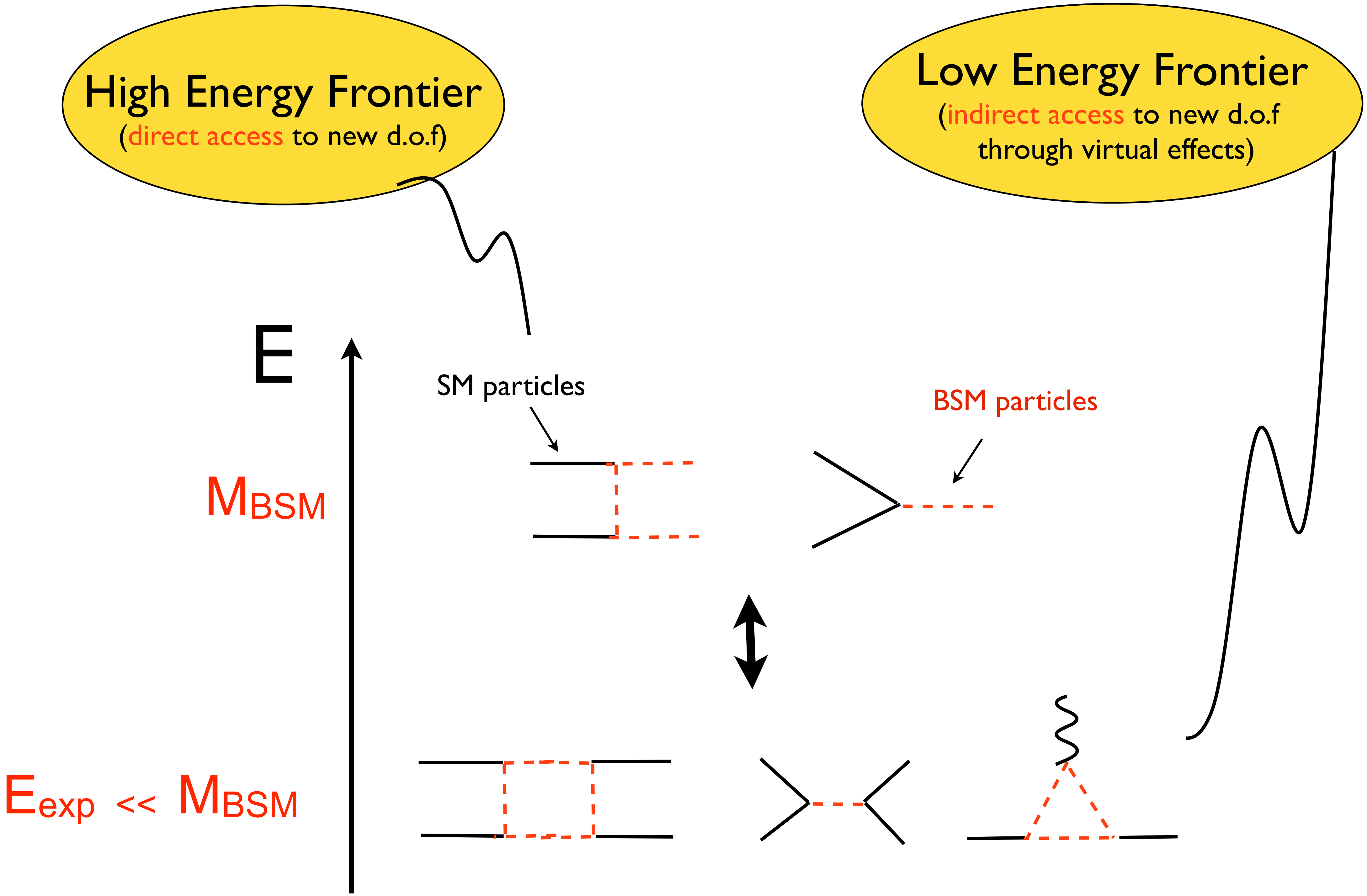




R. Sundrum
ICHEP 12

High- and Low-Energy Frontiers

- Two *complementary* strategies to probe BSM physics:



High- and Low-Energy Frontiers

- Two *complementary* strategies to probe BSM physics:

High Energy Frontier
(direct access to new d.o.f)

- EWSB mechanism
- Directly probe scale and interactions of new heavy particles
- ...

Low Energy Frontier
(indirect access to new d.o.f through virtual effects)

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

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Nuclear Physics plays a major role at the Low Energy Frontier:
"The New Standard Model" initiative in the 2007 LRP

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- Both frontiers needed to reconstruct the structure, symmetries, and parameters of $\mathcal{L}_{BSM}$ $\Rightarrow$ address the outstanding open questions

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{BSM}$$

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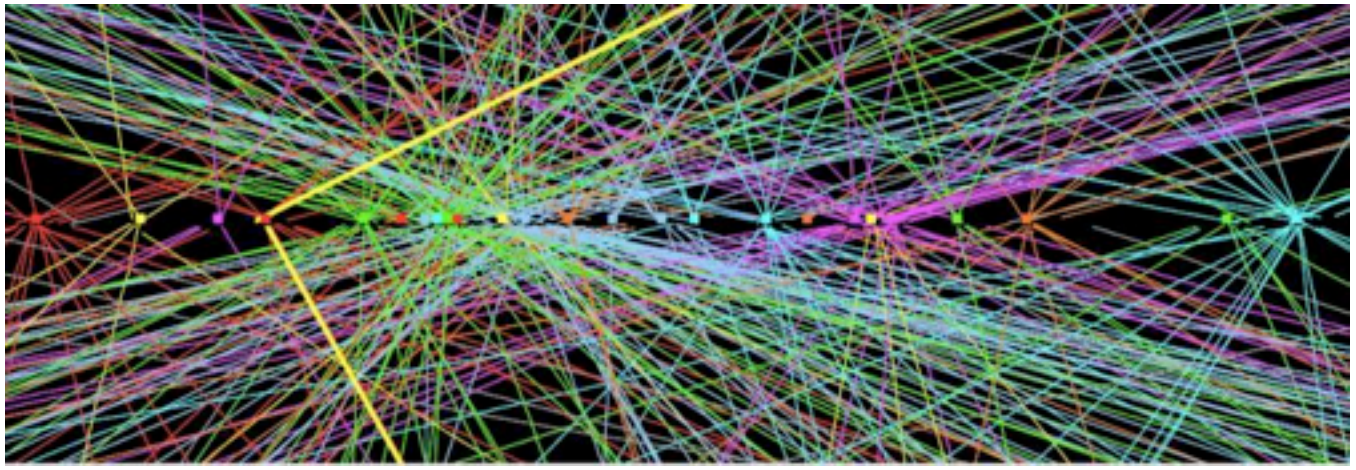
- The two frontiers are not entirely decoupled: important in setting the goals for precision tests (more on this later)

The High Energy landscape



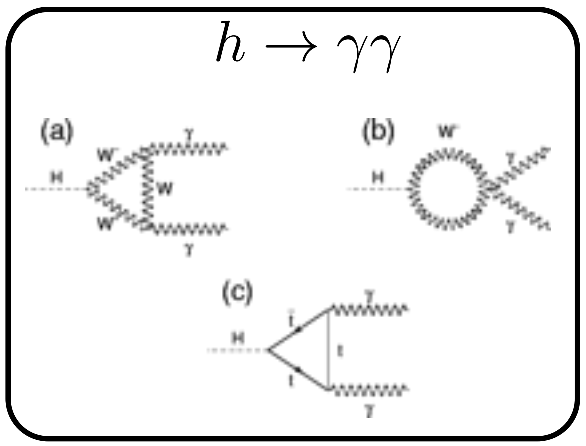
Z→ μμ event from 2012 data with 25 reconstructed vertices

What the LHC has seen

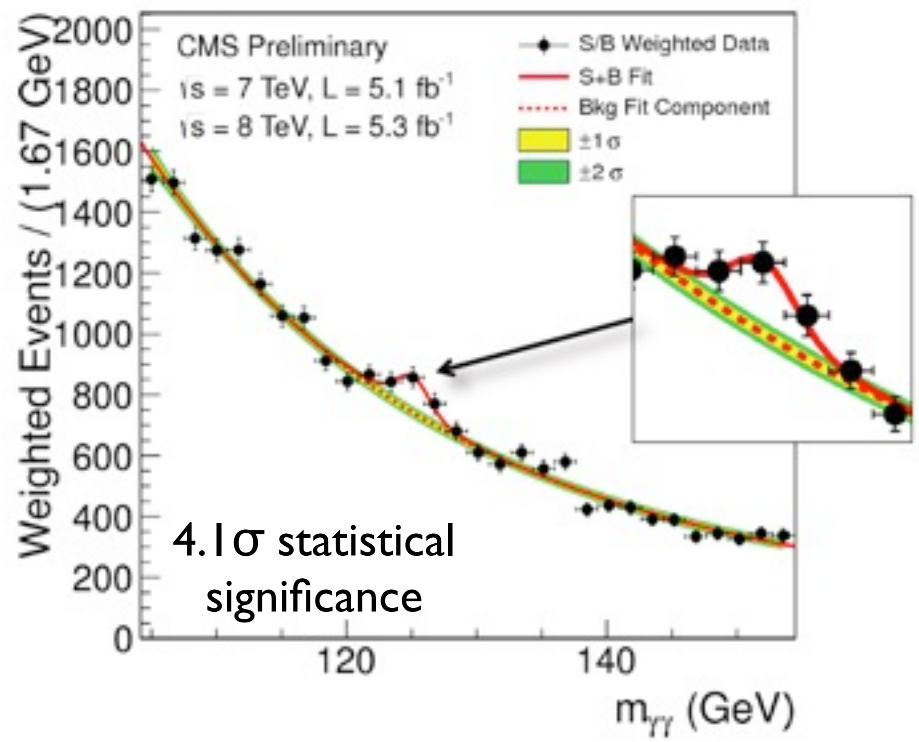
- New bosonic particle discovered ($\geq 5.0\sigma$) by CMS and ATLAS with the same mass ~125-126 GeV.
- It looks a lot like the SM Higgs (Higgs-like state in BSM scenarios)
- More data needed to understand its nature

(Some) Higgs signals

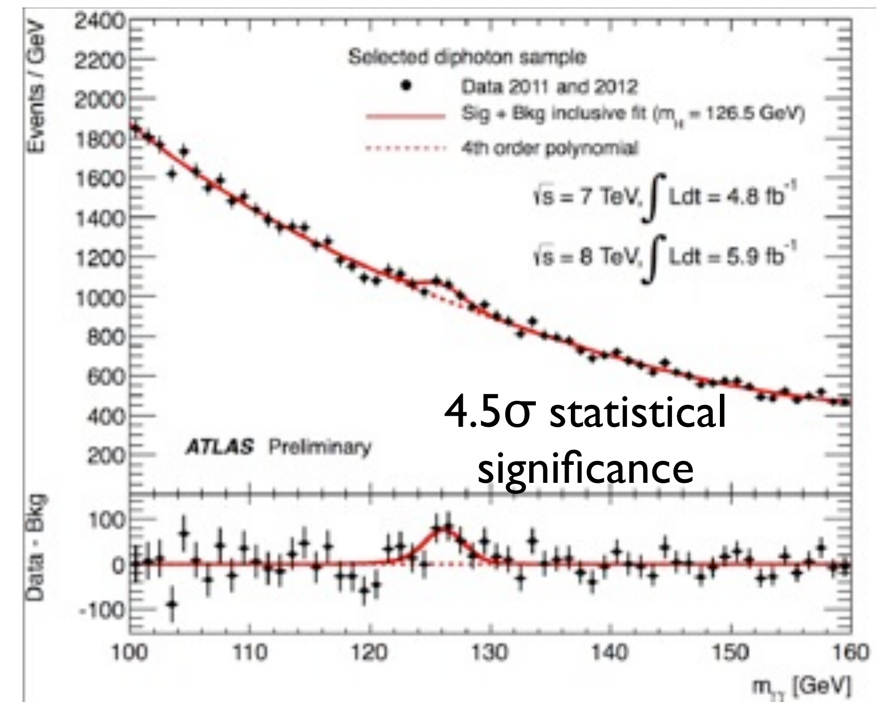
- H →γγ



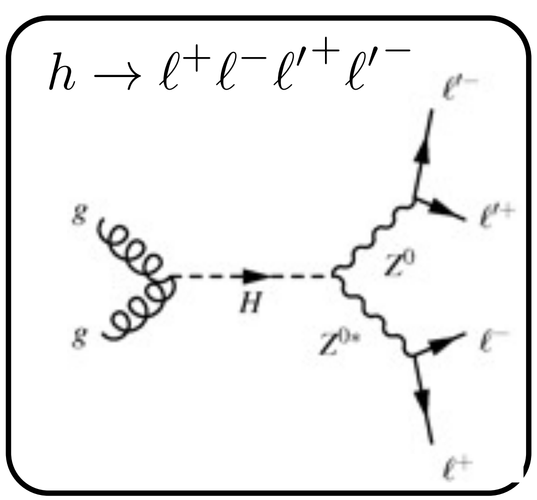
CMS

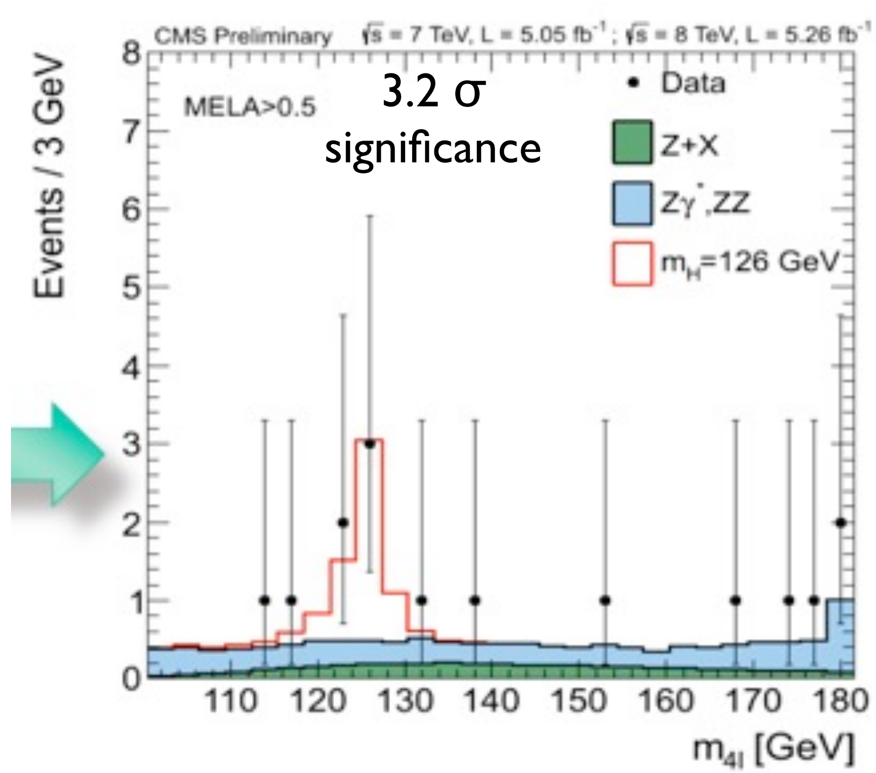


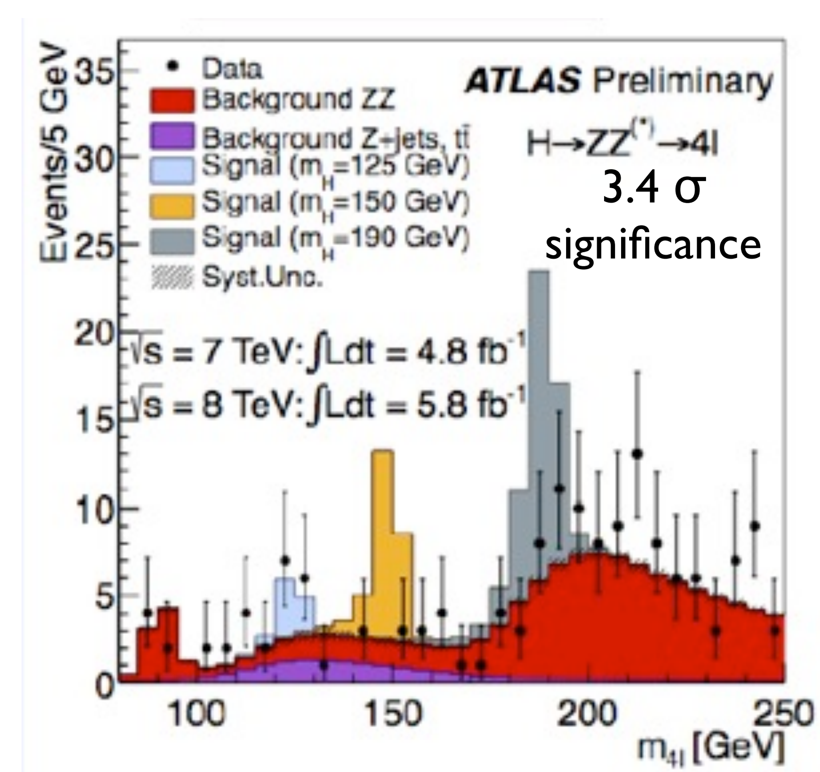
ATLAS



- H → ZZ* → 4 leptons

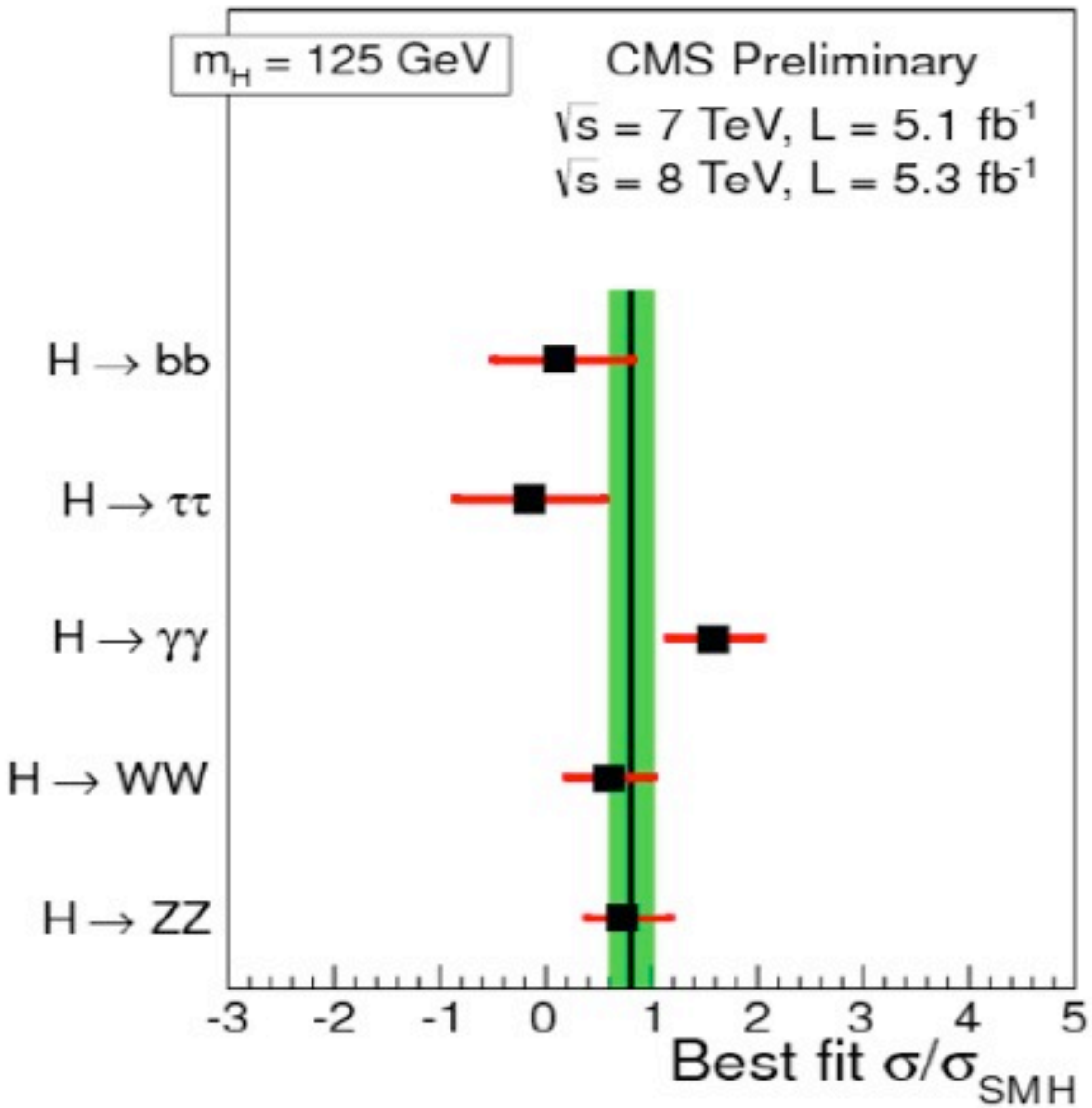


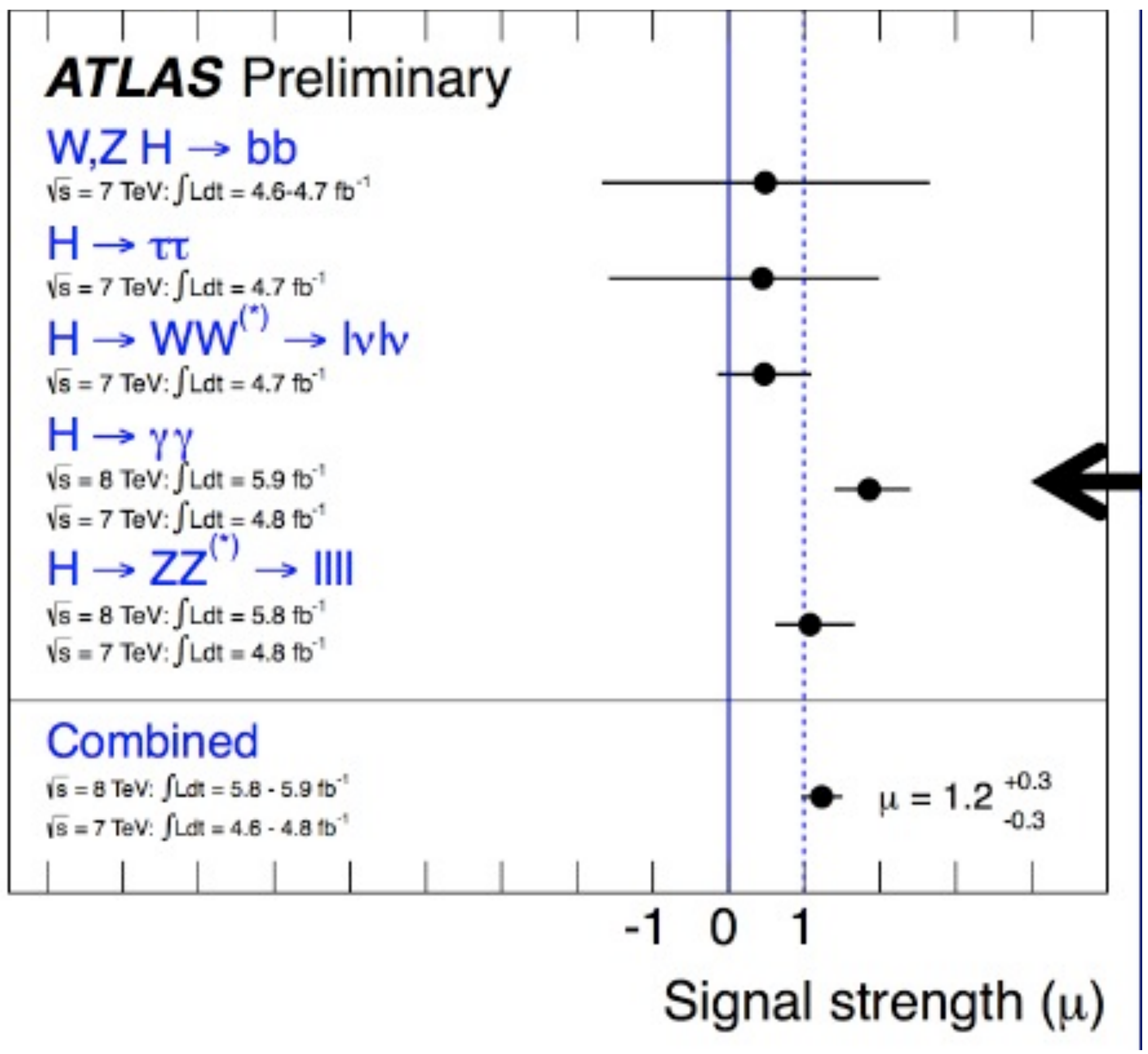




Compatibility with SM Higgs

- Higgs signals vs SM predictions for all modes:



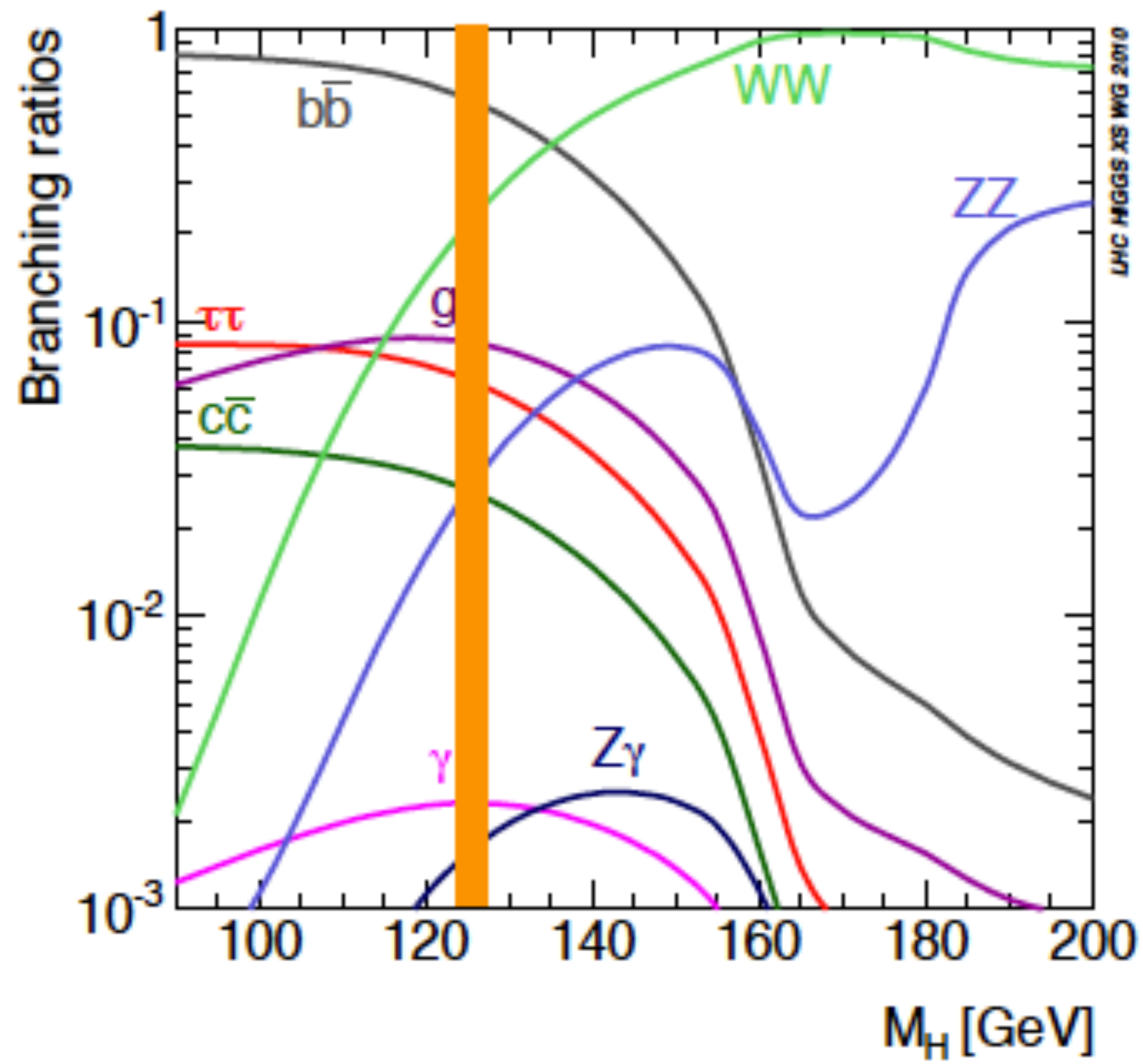


0.8 ±0.22

1.2 ±0.3

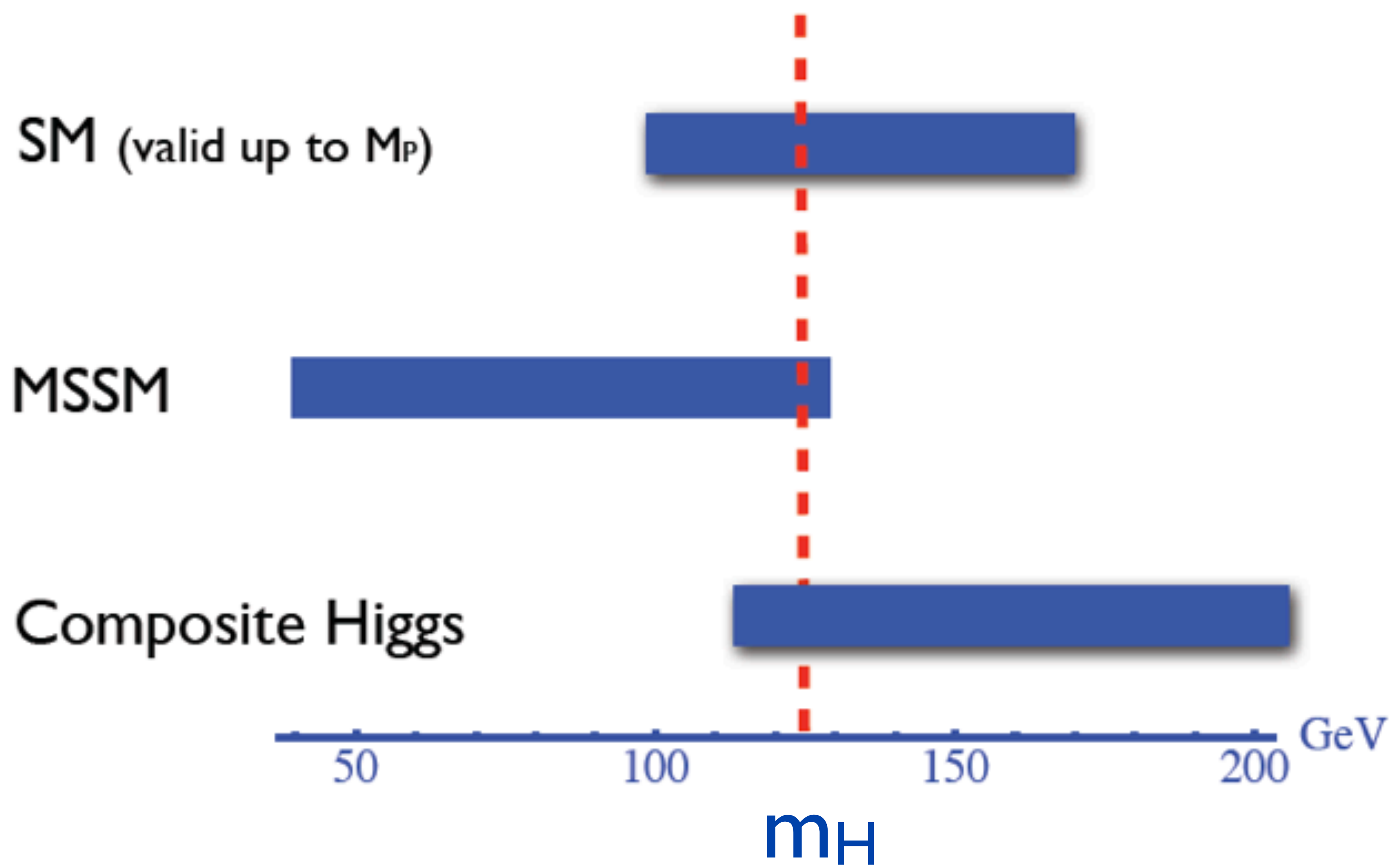
Non-standard Higgs mass?

- "Nature has been kind to experimentalists: most decay modes visible" (Fabiola Gianotti)



Non-standard Higgs mass?

- "Nature has been kind to experimentalists: most decay modes visible" (Fabiola Gianotti)
- And to theorists: can still write many papers!

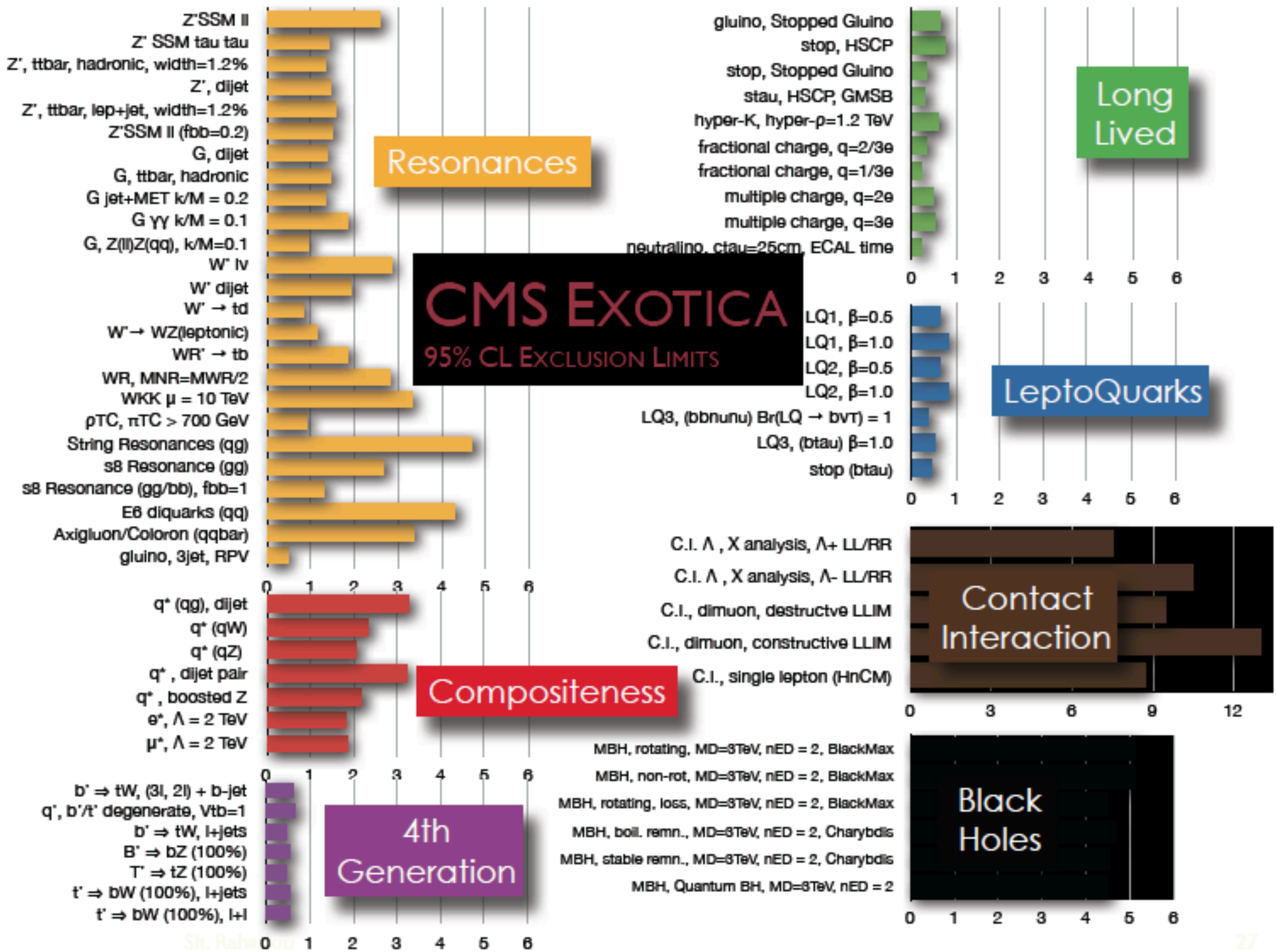


A. Pomarol, ICHEP 2012

What the LHC has not seen

- The LHC has observed no signal of physics beyond the SM (yet)
  - Generic searches (non-SUSY)
  - Dedicated SUSY searches

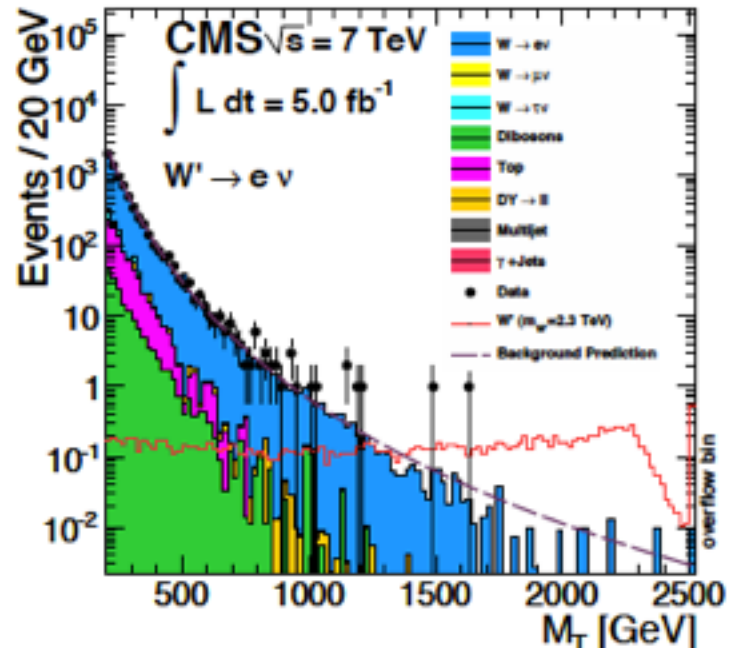
Non-SUSY: summary

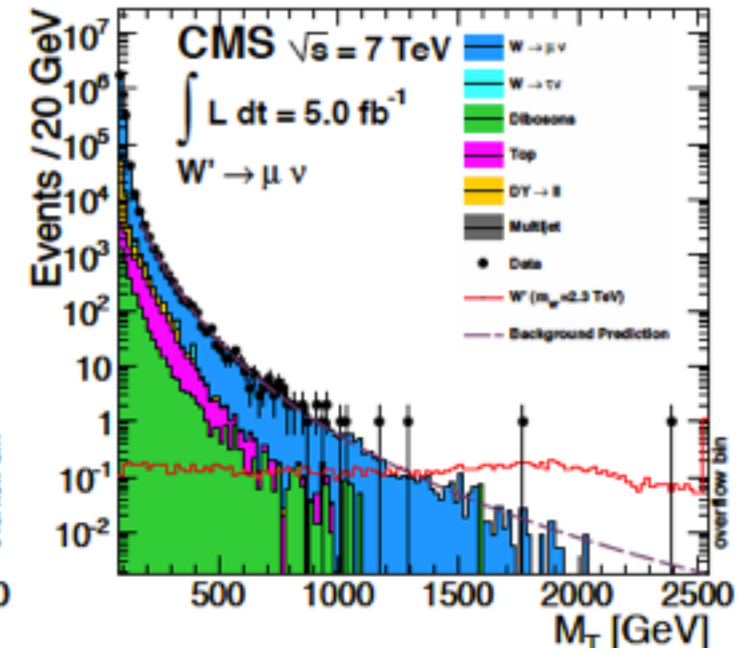


Caveats + Lesson

- ATLAS and CMS searches start at $M_{W'}$ > 500 GeV, M_{dijet} > 1 TeV
  (to cope with SM & QCD backgrounds)

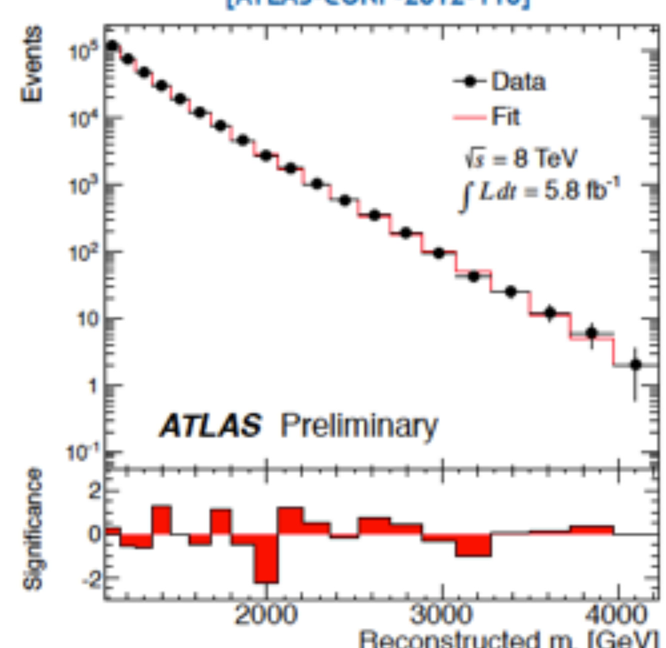
  - W ' → eν, μν



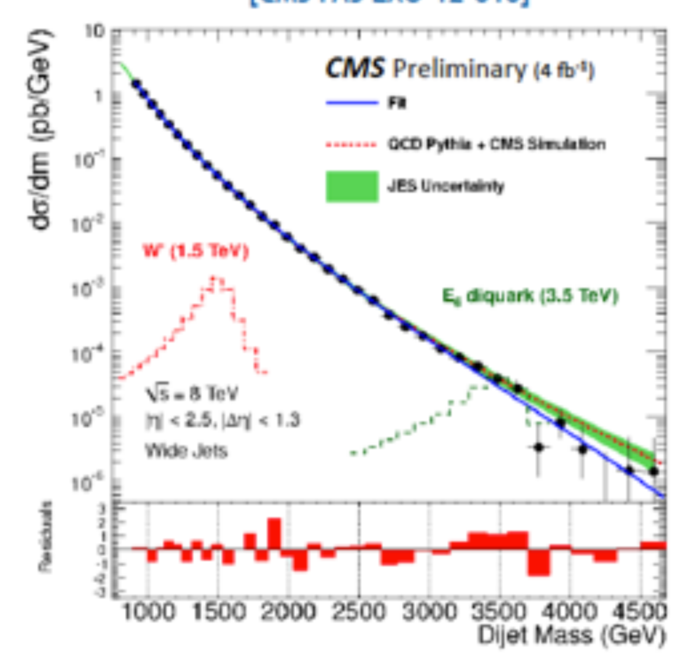


  - Di-jets resonances (W’, Z’, G’, ...)

[ATLAS-CONF-2012-110]



[CMS PAS EXO-12-016]



Caveats + Lesson

- ATLAS and CMS searches start at $M_{W'} > 500$ GeV, $M_{dijet} > 1$ TeV (to cope with SM & QCD backgrounds)

- Some consequences:

    - $g_{W'} = 0.1 g_W$ viable for $M_{W'} < 500$ GeV!
    - lepto-phobic Z' with M < 1 TeV still viable!

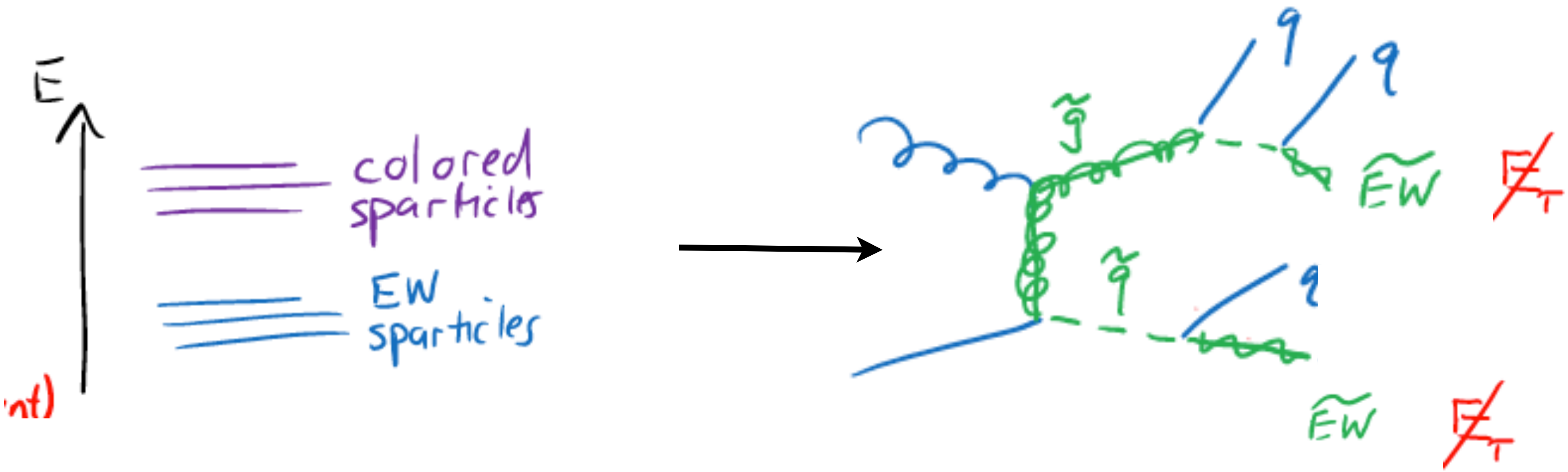
See e. g.
B. Dobrescu,
ICHEP 2012

- Lesson: particles with mass near the EW scale (few 100 GeV) pose severe challenges at the LHC

- Obvious opportunity for precision low-energy probes

SUSY searches

- Limits depend on assumptions on the s-particle spectrum



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SUSY searches

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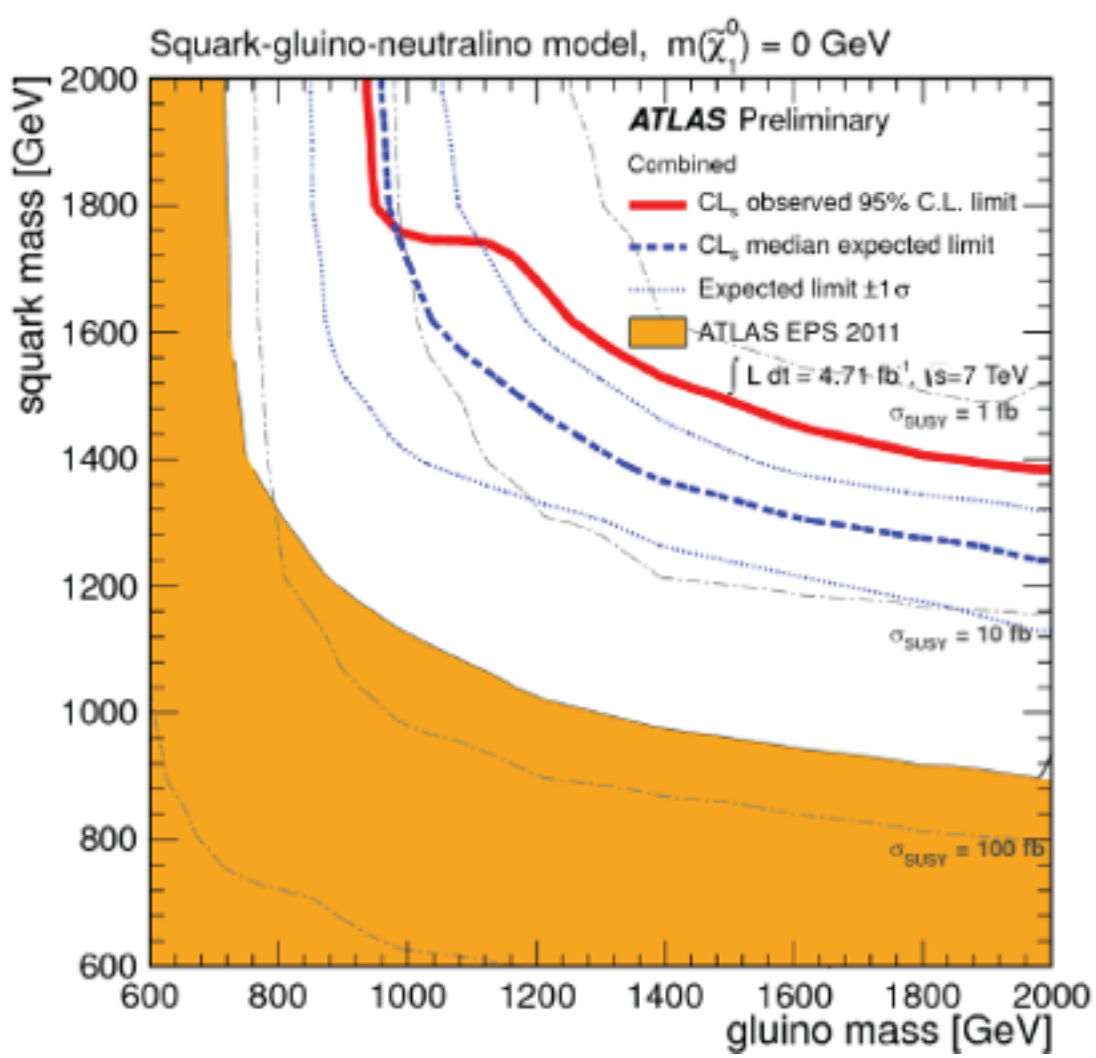

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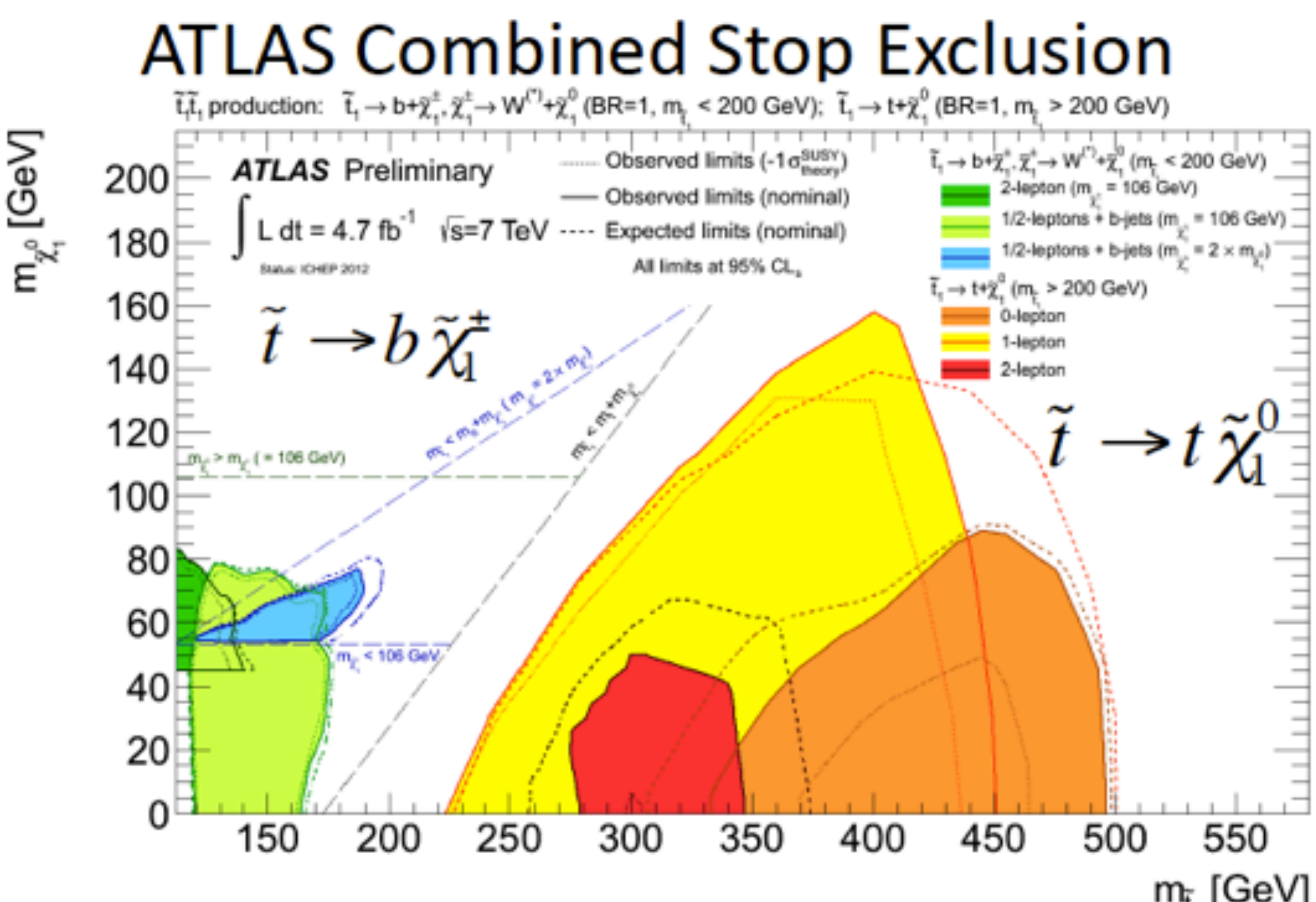
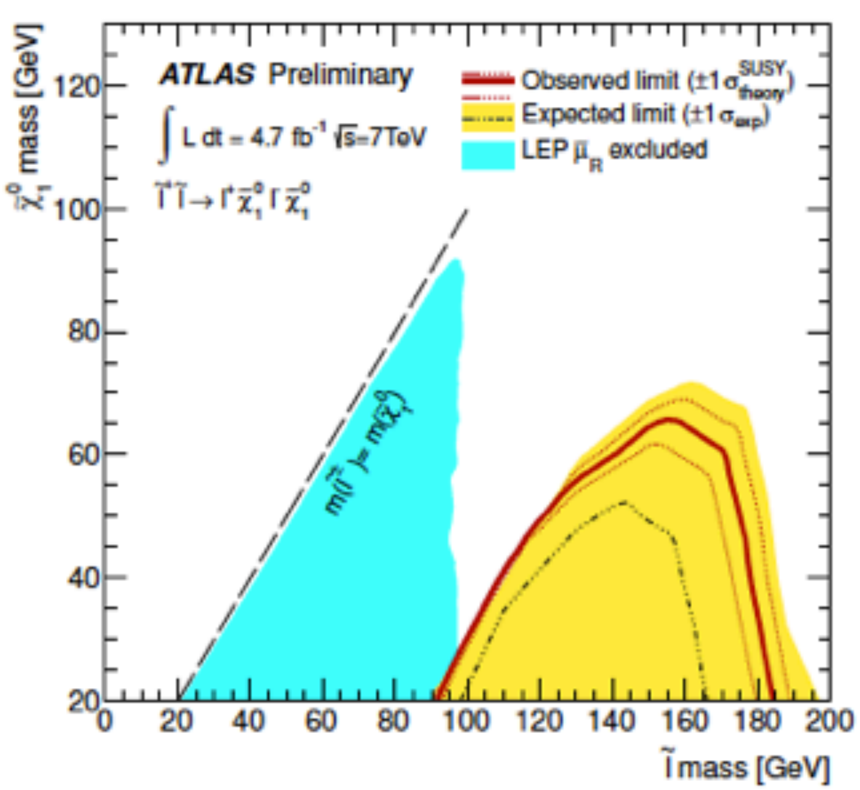
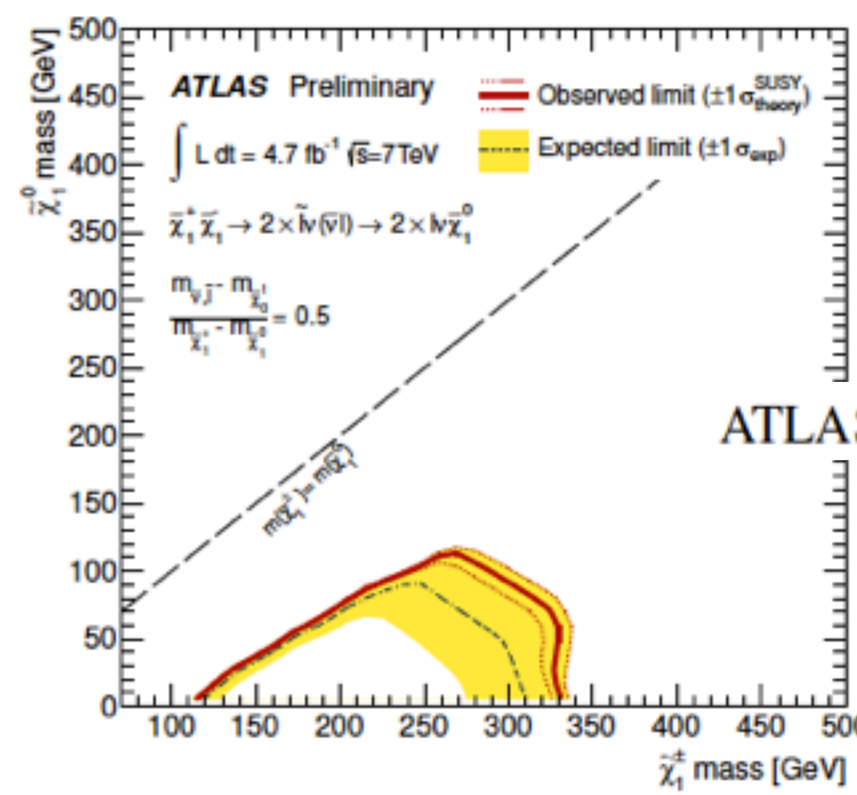


SUSY searches

- Limits depend on assumptions on the s-particle spectrum
- 1st, 2nd generation squarks + gluinos: strongest bounds (M > TeV)
- Stop: search strategy depends on the mass, still gaps
- Sleptons and charginos: considerably weaker bounds





ATLAS-CONF-2012-076

SUSY comments

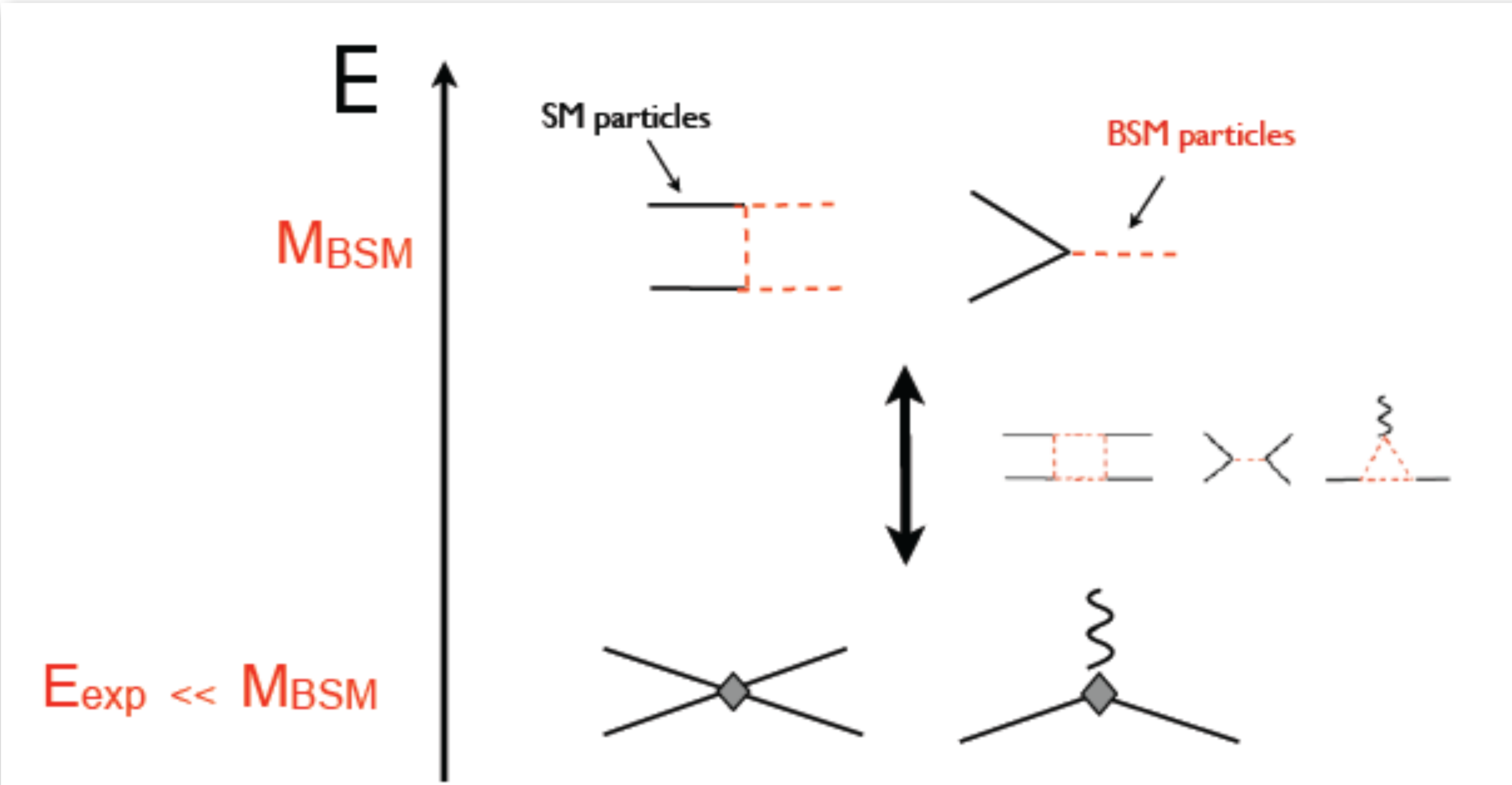
- Searches optimized for fairly large (s)mass splittings
- Small s-particle splittings still inaccessible: p_T in final state objects is reduced (need low p_T cut, still problematic)

A. Parker
ICHEP 12

- "Natural" SUSY scenarios under pressure (direct searches + Higgs mass), but:
  - Compressed SUSY spectrum still viable
  - Less standard but plausible SUSY scenarios still viable (RPV, ...)
  - In summary, weak scale SUSY is not dead!

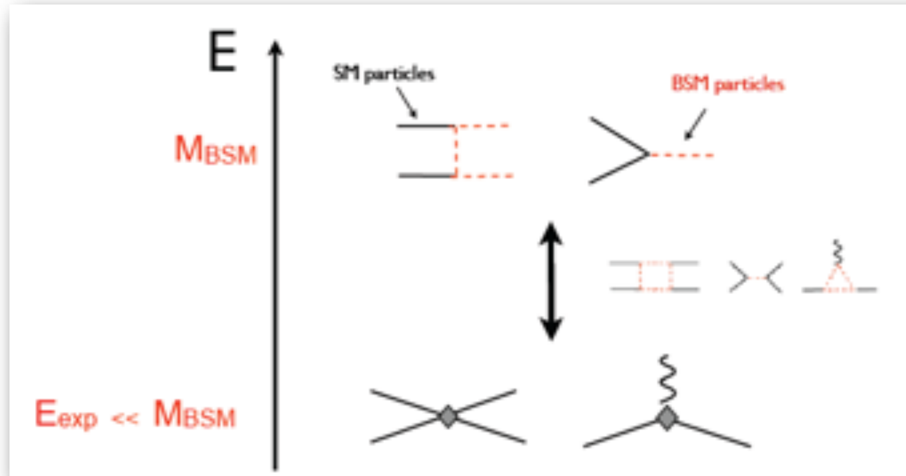
The Low Energy landscape

Low Energy Frontier



How do BSM particles / interactions affect low energy dynamics?

Low Energy Frontier



- At low energy, BSM physics is described by local operators**

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

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

- Key point: each UV model generates its unique pattern of operators / couplings $\rightarrow$ different pattern of signatures in LE experiments

Low Energy Frontier

Therefore, LE measurements provide the opportunity to both discover BSM effects & discriminate among BSM scenarios:

- If sensitive enough, a single LE measurement can discover new physics (symmetry violation, deviation from SM in precision tests)
- But it is only the combination of more experiments (+ the LHC) that can help us discriminate among new SM candidates, and ultimately address some of the open questions about our universe

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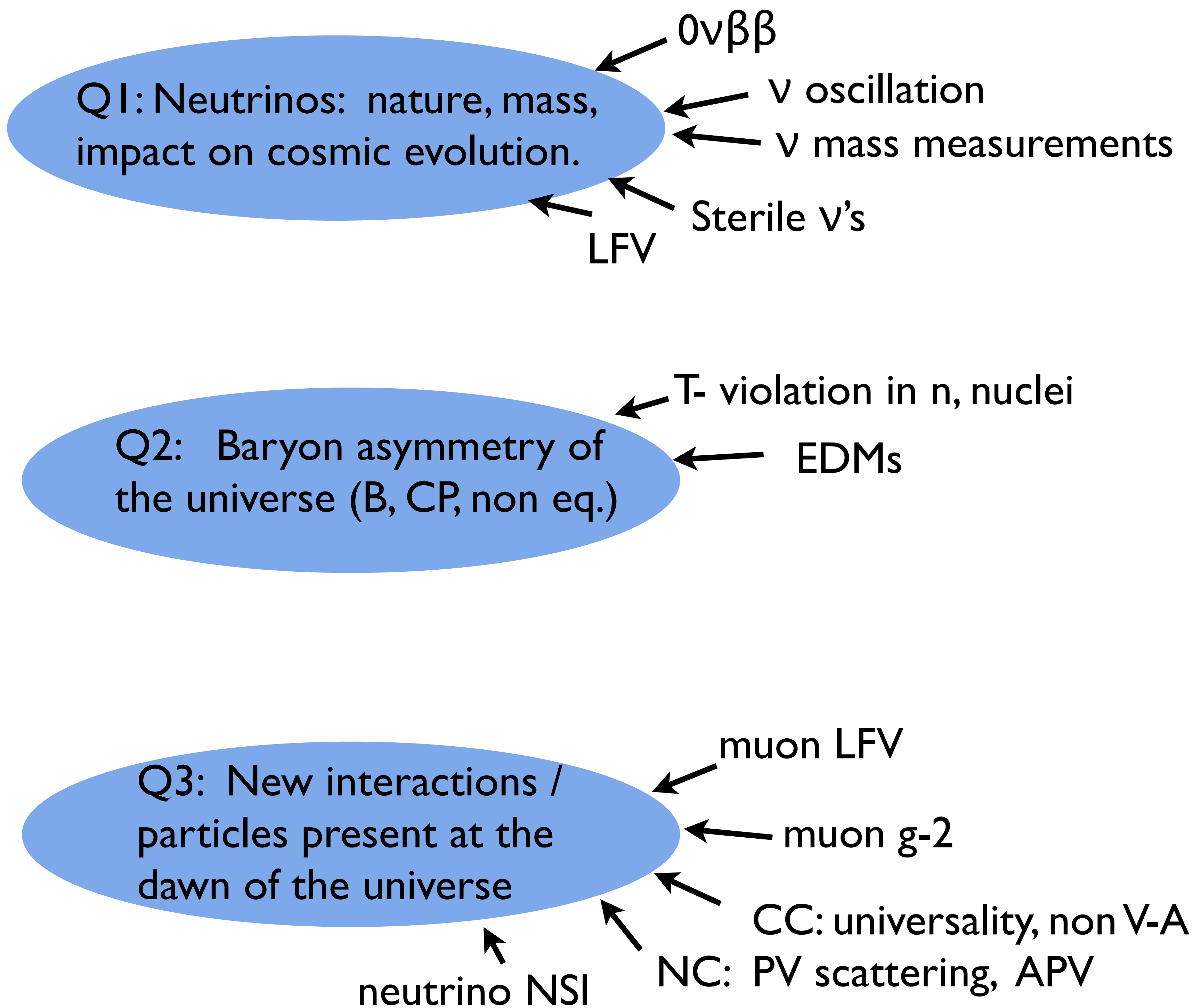
Underlines the importance of broad set of LE searches: unifying link among what might otherwise look like a bunch of scattered efforts

Interconnections



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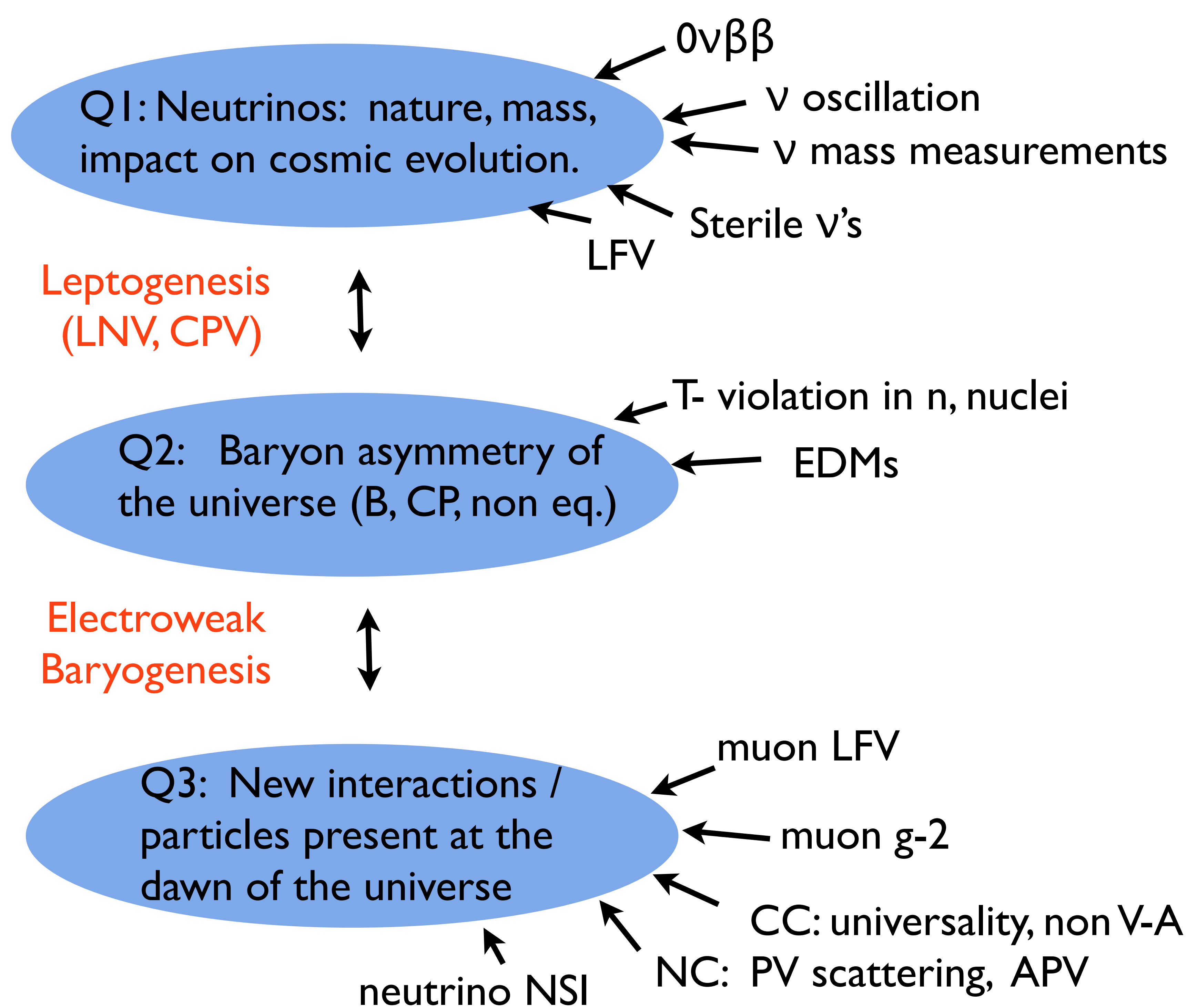

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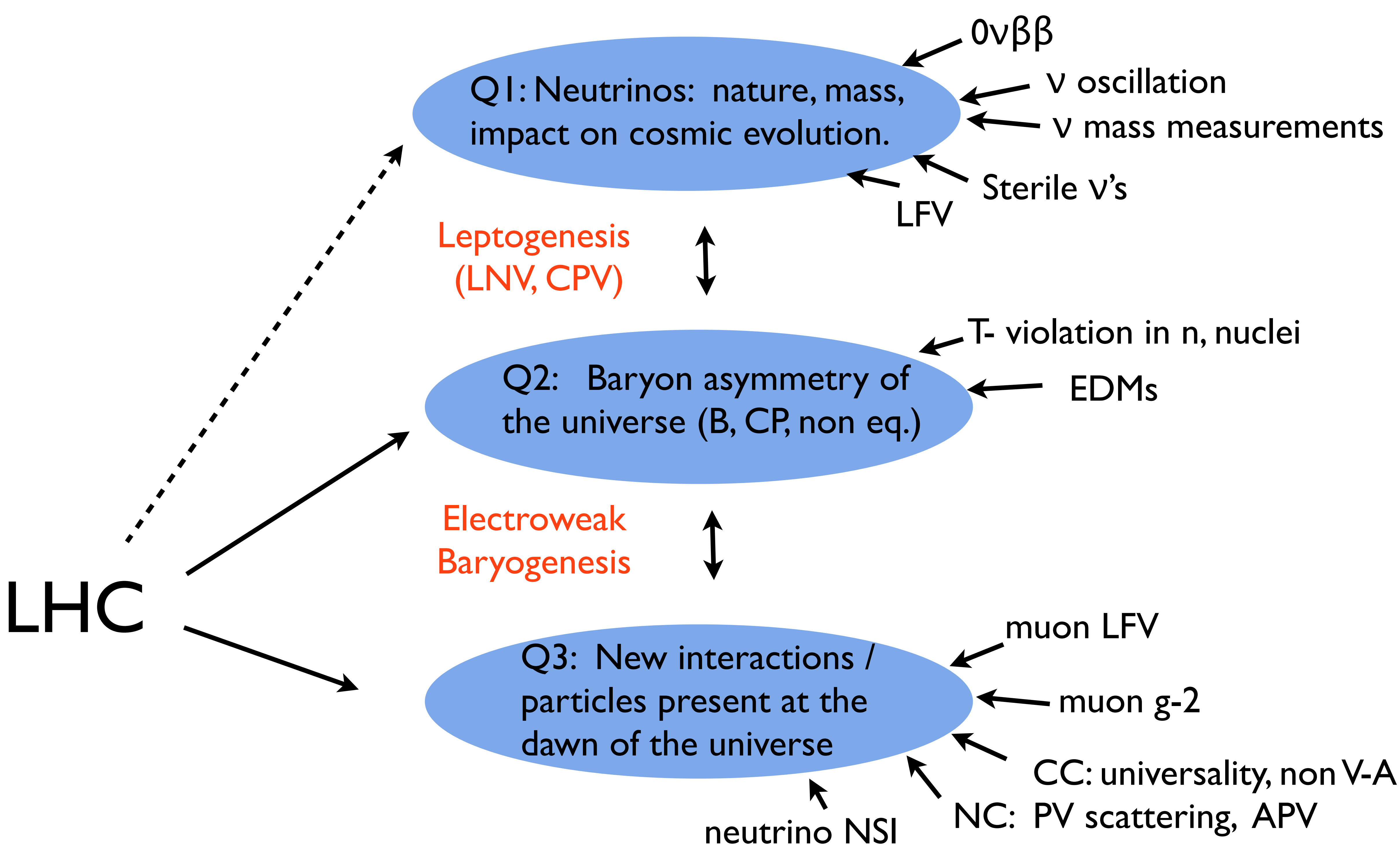

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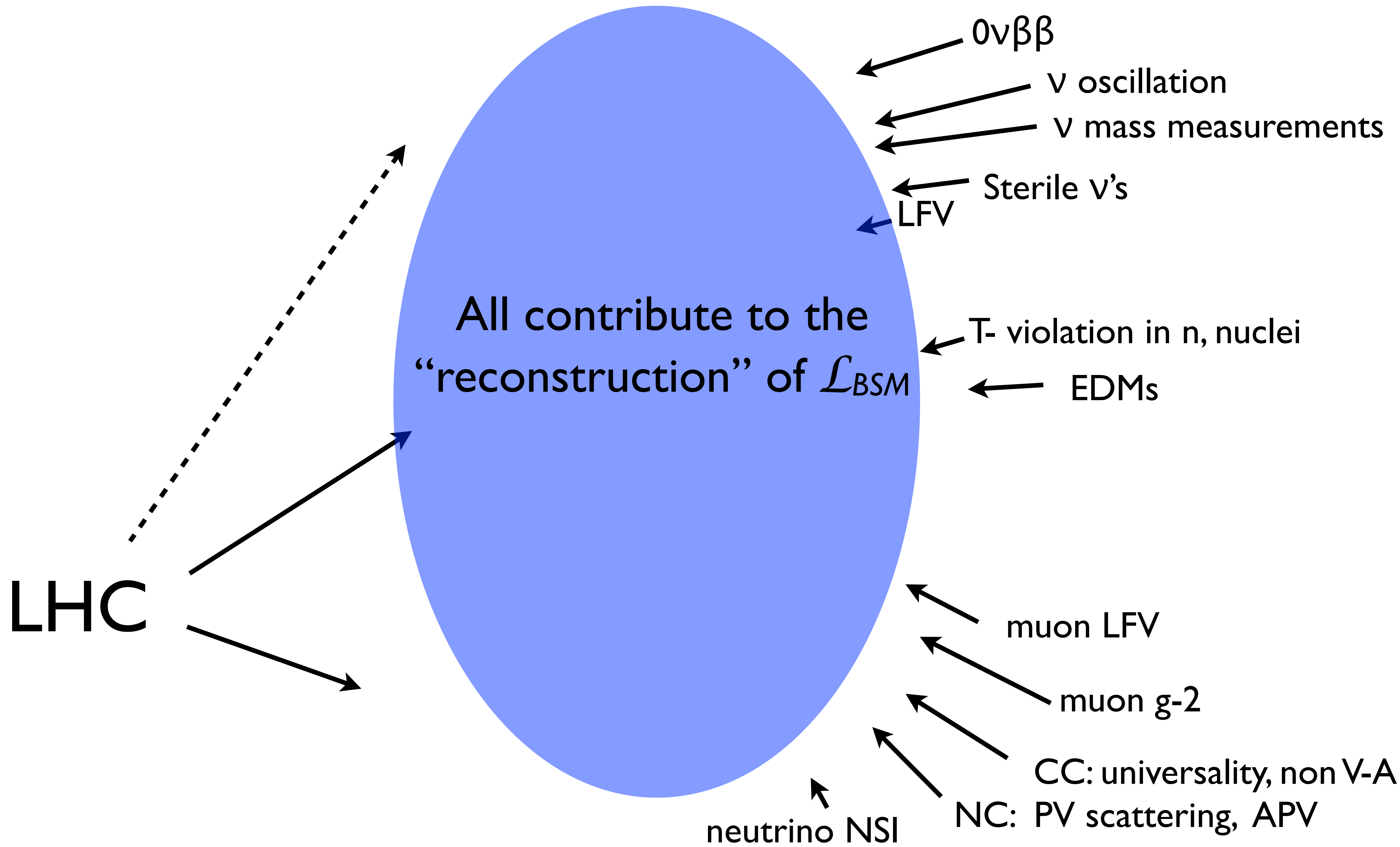
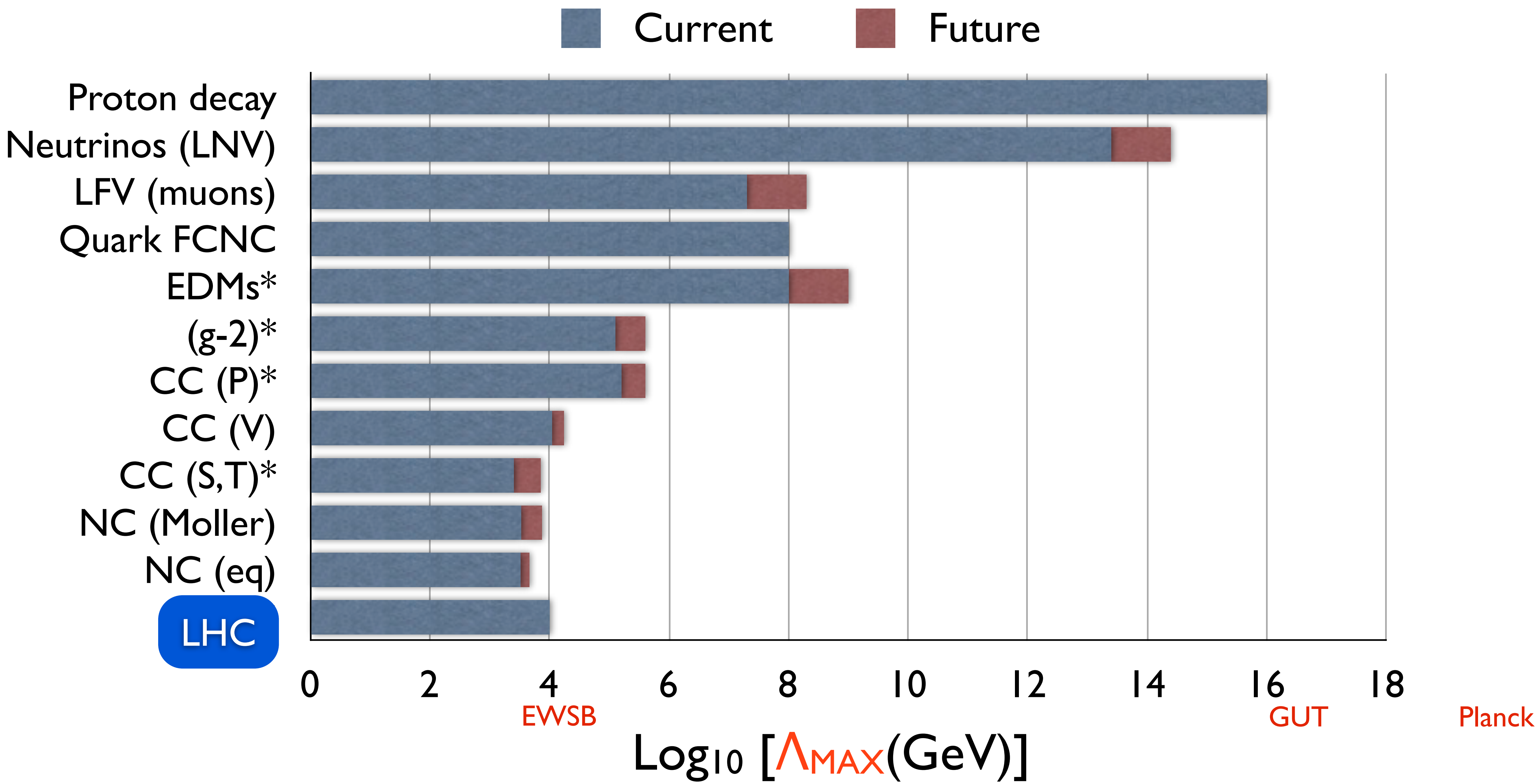


Physics reach -- at a glance



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

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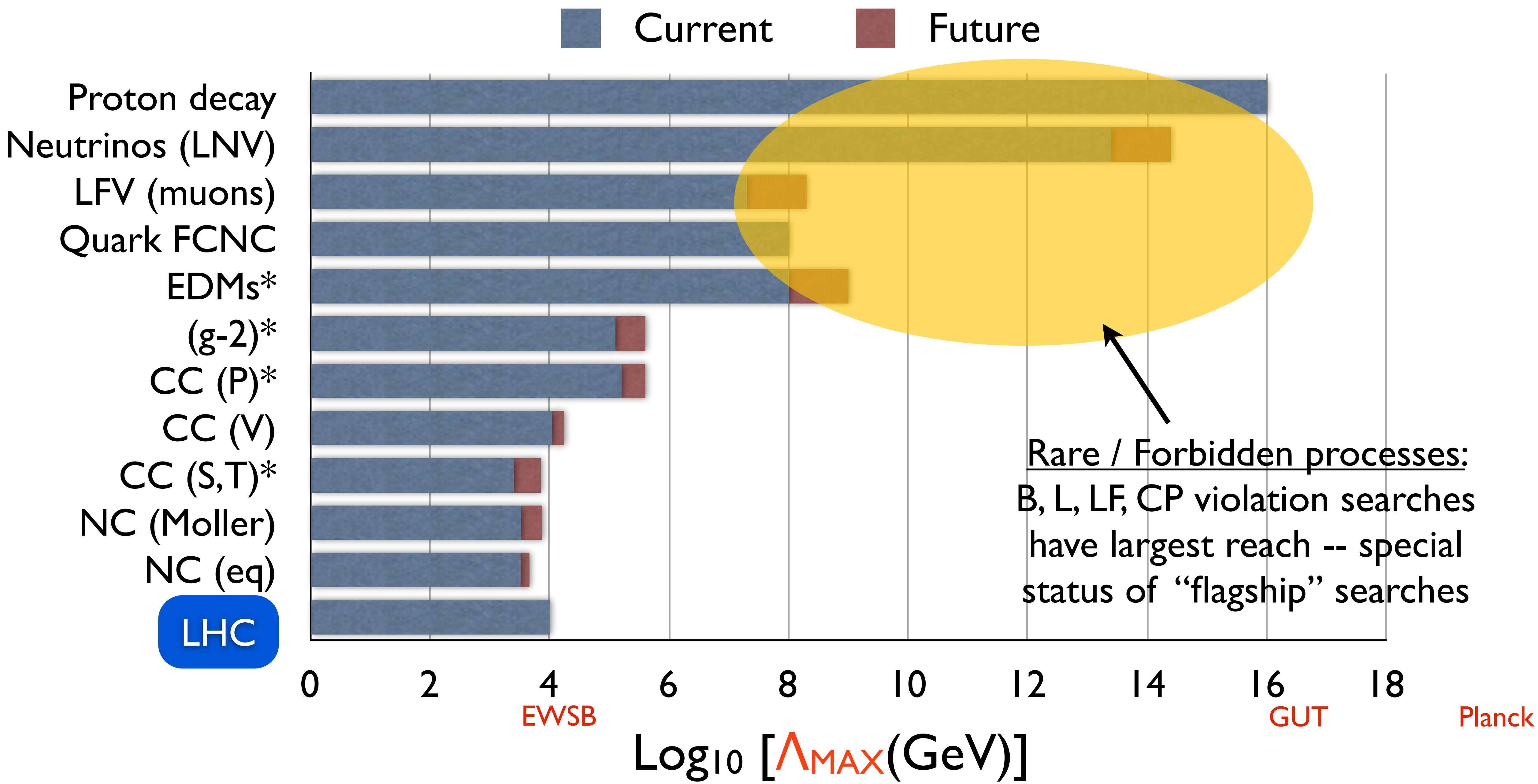

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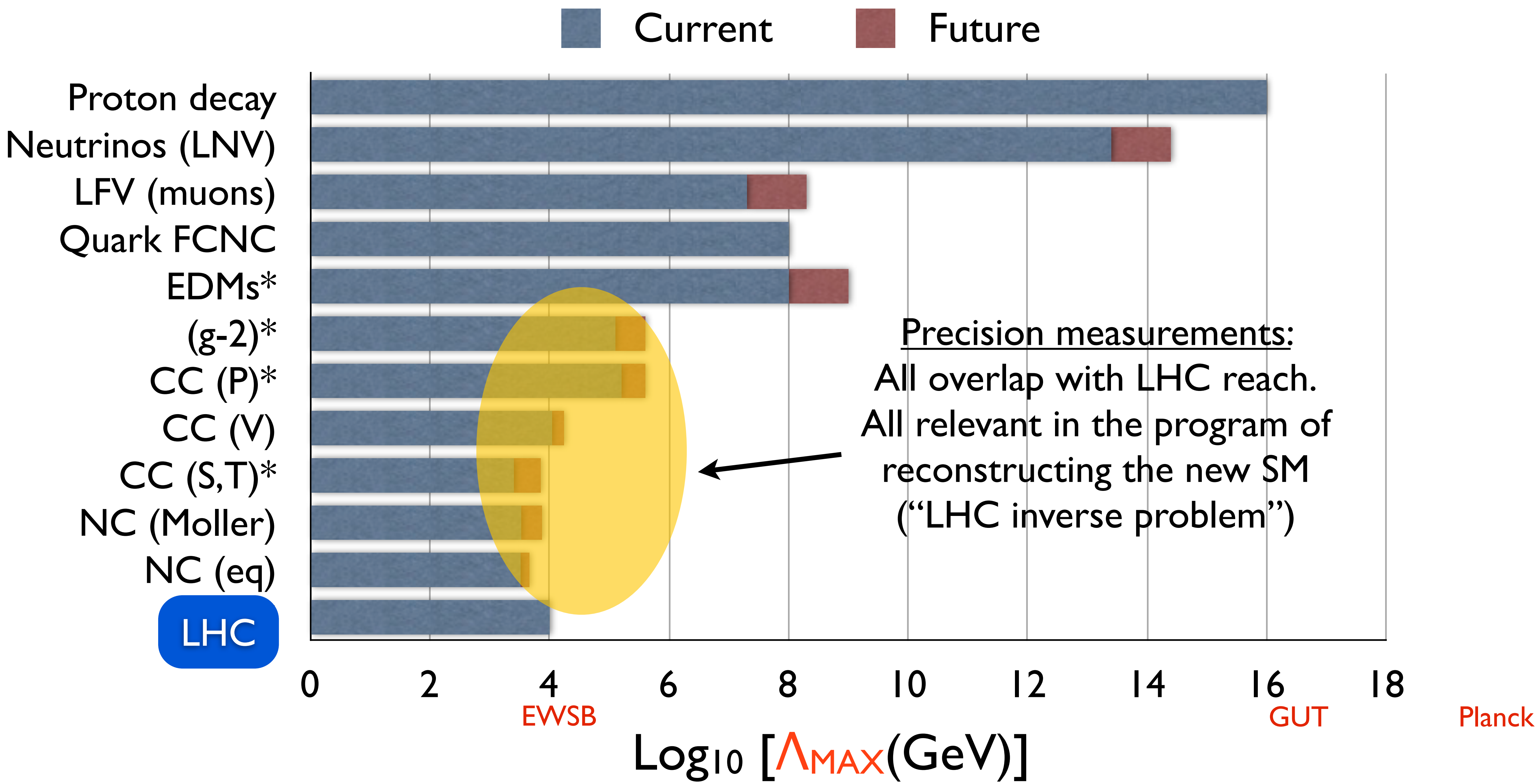

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High-level comments

- Motivation for pursuing these searches is as strong as it was in 2007 (LRP writeup)
- With new physics signals possibly arising from the LHC, low-energy probes at the current / planned level of sensitivity will be essential in understanding the BSM symmetries and discriminate dynamics (LHC inverse problem)
- One could argue that the motivation for LE frontier searches will be even stronger if there are no clear BSM signals at the LHC ("the nightmare scenario"): in that case will need to pursue
    - a broad set of searches (we don't know what to expect and where)
    - with mass reach above ~10 TeV

Next, a panoramic tour

- Organize discussion by dimension of the operator(s) probed:

  - dim 3, 4, 5, (9): neutrinos

  - dim 6: LFV, CPV

    g-2, Charged Currents, Neutral Currents, ..

- In each case, highlight

  - Discovery potential / physics reach Λ
  - Discriminating power / interplay with the LHC

Neutrinos

- Probe rich sector of $\mathcal{L}_{BSM}$, largely inaccessible at the LHC

$$\mathcal{L}_\nu \supset -\frac{1}{2} M_\nu^{ij}\, \bar{\nu}_R^{ci} \nu_R^j + Y_\nu^{ij}\, \bar{\nu}_R^i (H^T i\sigma_2 L_L^j) + \frac{1}{\Lambda}\frac{g^{ij}}{2} (\bar{L}_L^{ci} i\sigma_2 H)(H^T i\sigma_2 L_L^j)$$

$$L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad H = \begin{pmatrix} h^+ \\ v + h^0 \end{pmatrix}$$

Light sterile states?

Dirac mass term

$$m_\nu^{ij} = v\, Y_\nu^{ij}$$

Majorana mass term:

$$m_\nu^{ij} = \frac{v^2}{\Lambda}\, g^{ij}$$

- Many key aspects of ν dynamics remain unknown, and should be explored by experiments in the next decade

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- Symmetries / particle content:
  - Is lepton number (L) broken? (Dirac vs Majorana) (0νββ)
  - Are there light sterile ν's? (reactor anomaly, Gallium anomaly, LSND, MiniBoone)

Neutrinos

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$$\mathcal{L}_\nu \supset -\frac{1}{2} M_\nu^{ij}\, \bar{\nu}_R^{ci} \nu_R^j + Y_\nu^{ij}\, \bar{\nu}_R^i (H^T i\sigma_2 L_L^j) + \frac{1}{\Lambda}\frac{g^{ij}}{2} (\bar{L}_L^{ci} i\sigma_2 H)(H^T i\sigma_2 L_L^j)$$

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Majorana mass term:

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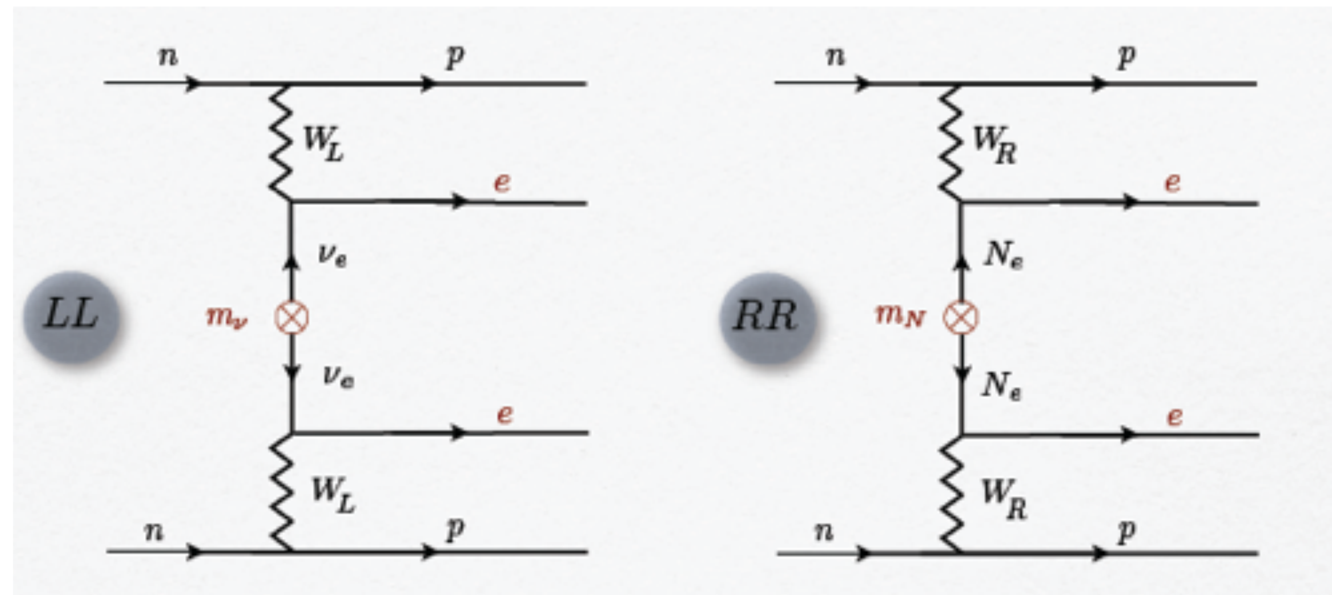
- Determine parameters of mass matrix (regardless its origin):
  - Mass scale (beta decay, $0\nu\beta\beta$*, cosmology*)
  - Mass hierarchy (oscillation experiments)
  - Mixing angles (✔), Dirac CPV phase

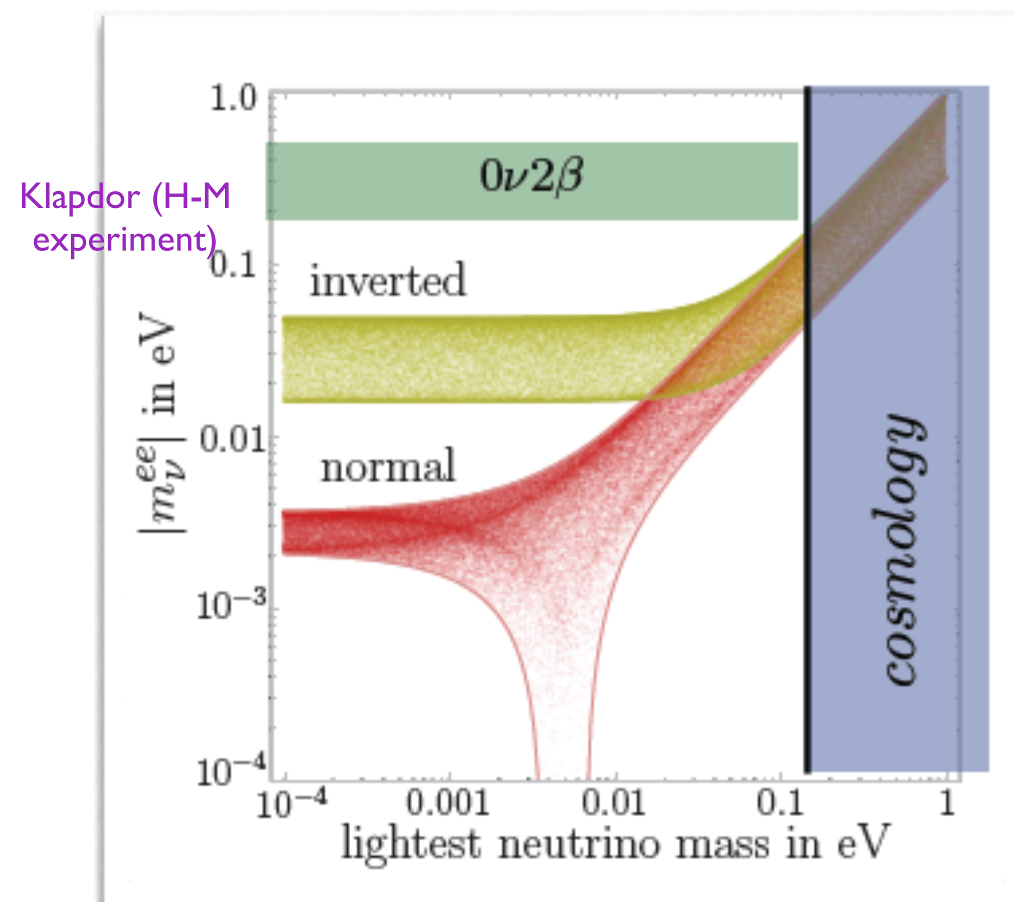
- Discriminating after discovering: LNV mechanism

- If 0νββ observed, is it due to the light ν exchange or other ~TeV scale source of LNV?



$$LL \propto \frac{G_F^2 m_\nu^{ee}}{p^2} \qquad RR \propto \frac{1}{M_{W_R}^4}\frac{1}{m_N}$$

~ TeV

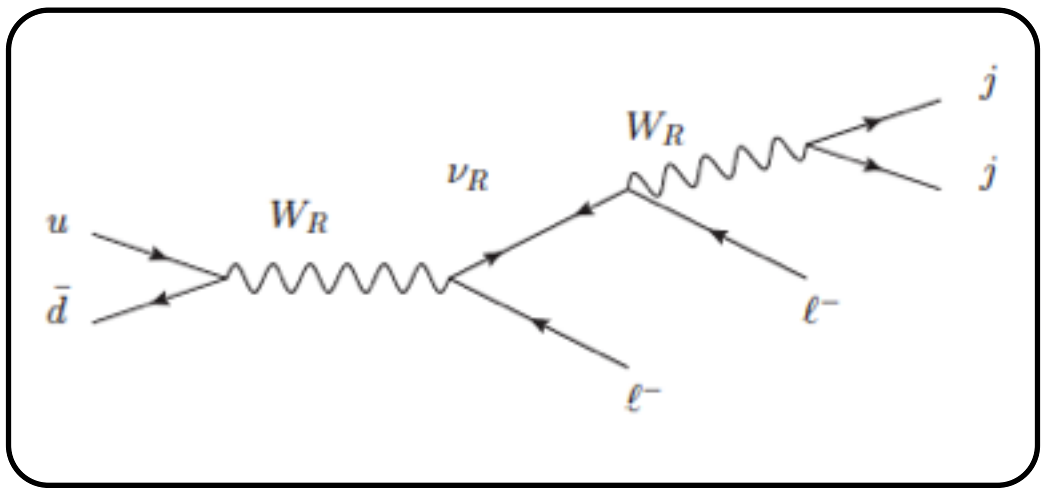


- Particularly relevant if 0νββ observed in the "degenerate" region (conflict with cosmology?)

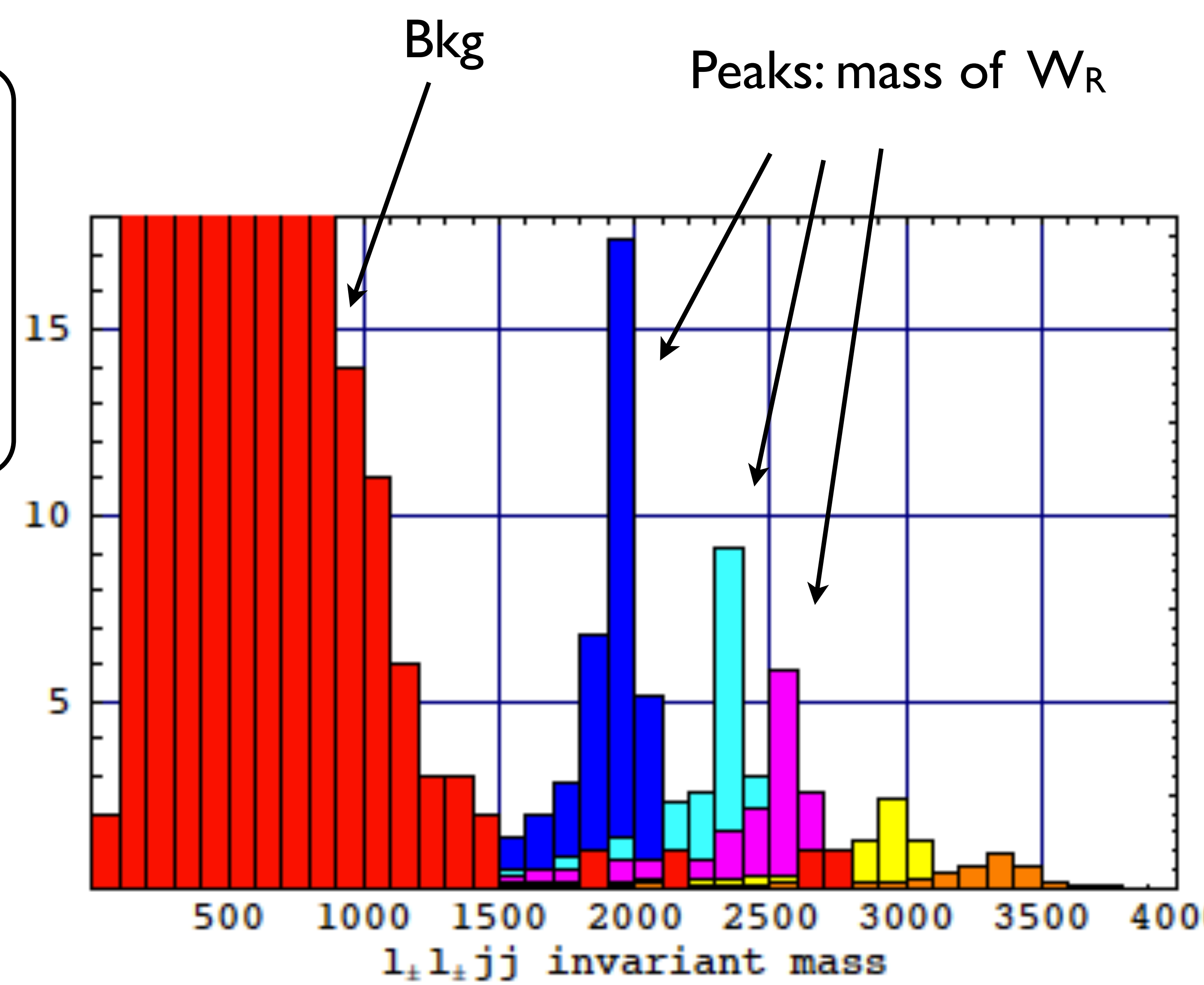
- Diagnostic tools:
  - KATRIN, Project 8, ...
  - Correlations with LFV signals
  - LHC signals: see e.g. LRSM

VC, Kurylov, Ramsey-Musolf, Vogel 2004

Maiezza, Nemevsek, Nesti, Senjianovic, 2010



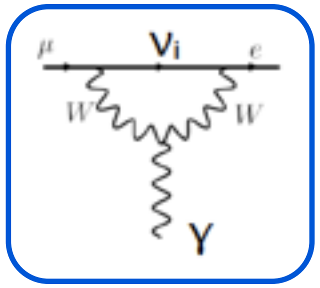
L=8 fb^{-1}, $s^{1/2}$ = 14 TeV



- Sensitivity up to W_R mass ~ 6 TeV with L = 300 fb^{-1}

Charged Lepton Flavor Violation

- In SM + massive ν, CLFV BRs negligible (10^{-54}): clean probe of BSM physics, great discovery channels



- Experimental limits probe

$$\Lambda / \sqrt{[\alpha_D]^{e\mu}} > 2 \times 10^4 \text{ TeV}$$

$B_{\mu \to e\gamma} < 1.2 \times 10^{-11}$	⟶	$10^{-13/14}$ (MEG at PSI, *now running*)
$B_{\mu \to 3e} < 1.0 \times 10^{-12}$	⟶	$10^{-14/16}$ (PSI *or* MuSIC?)
$B^{Ti}_{\mu - e} < 4.3 \times 10^{-12}$ $B^{Au}_{\mu - e} < 8 \times 10^{-13}$ $B^{Pb}_{\mu - e} < 4.6 \times 10^{-11}$	⟶	$10^{-16/17 \to -18}$ (Mu2e, COMET, PRISM)

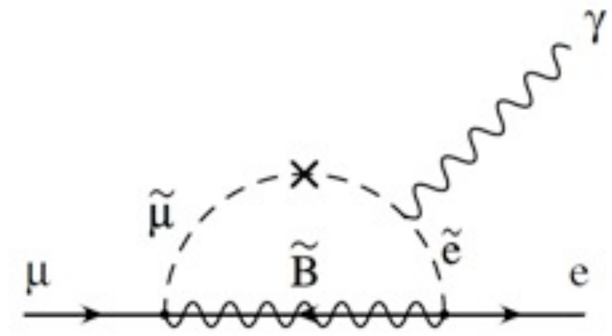
- New physics at TeV scale (and reasonable mixing pattern) ⇒

LFV signals within reach of planned searches

Discriminating after discovering: LFV mechanism

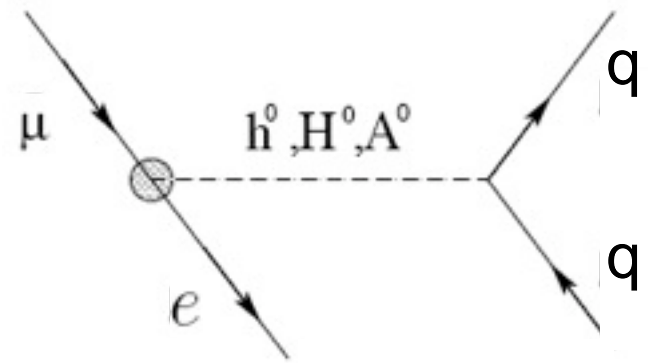
- Dipole?

Dominant in SUSY-GUT and SUSY see-saw scenarios



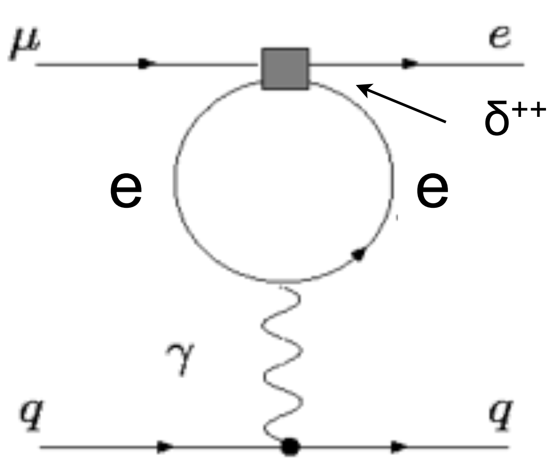
- Scalar?

Dominant in RPV SUSY and RPC SUSY for large tan(β) and low m_A



- Vector?

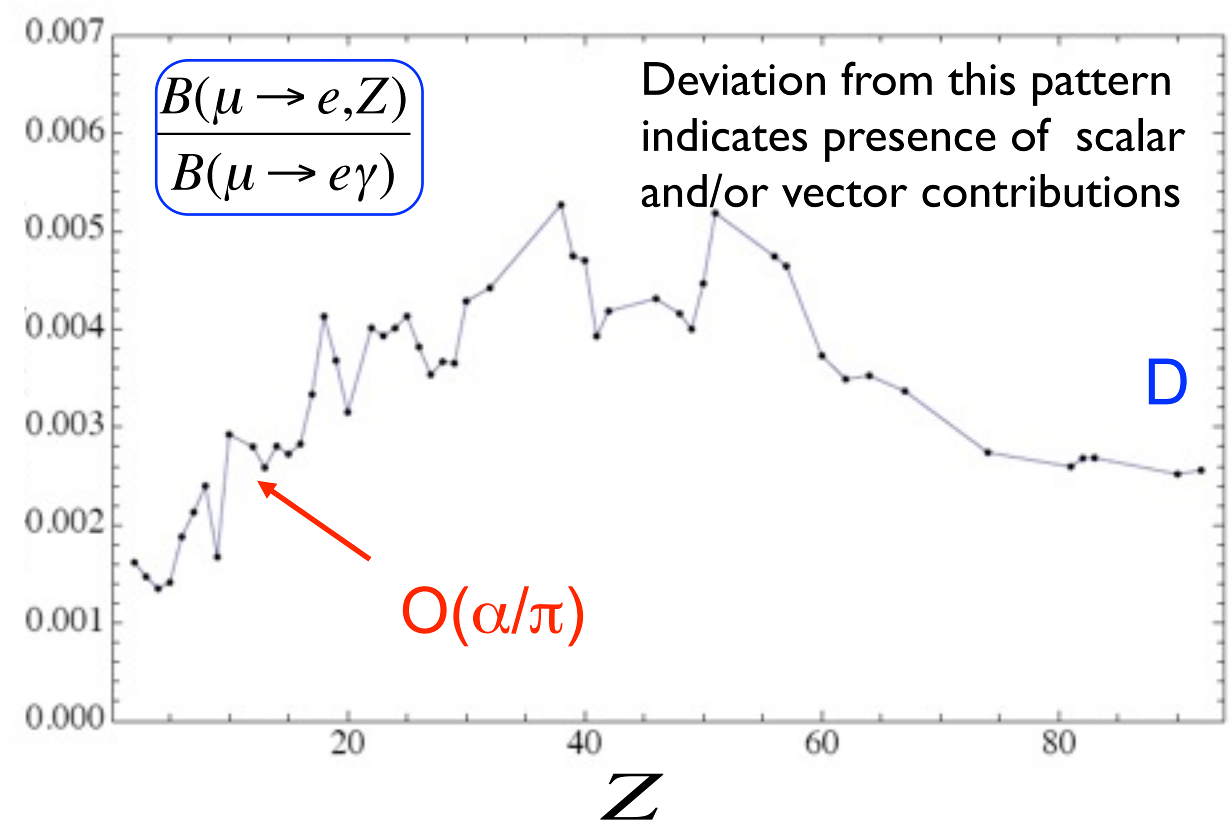
Enhanced in triplet models, Left-Right symmetric models

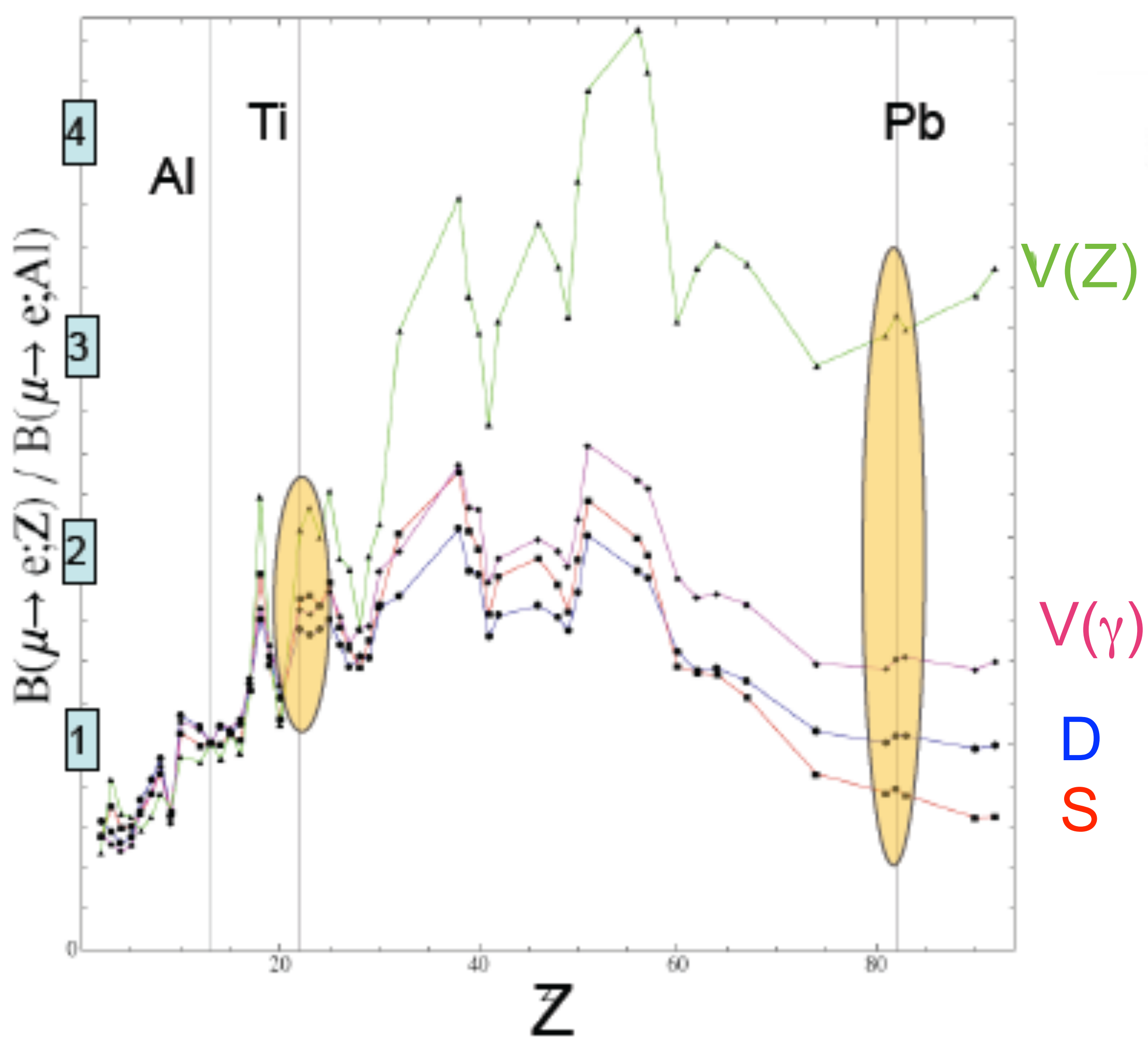


- Z-penguin?

- Discriminating after discovering: LFV mechanism

- μ →eγ vs μ →e conversion: probe non-dipole operators





- Conversion amplitude has non-trivial dependence on target, that distinguishes D,S,V underlying operators

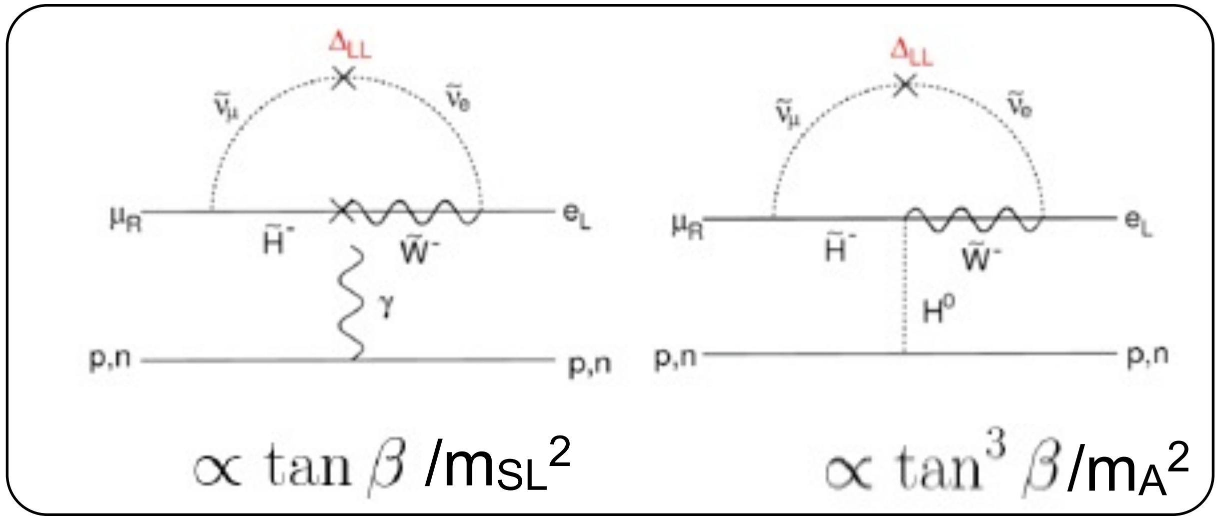
  - Discrimination: need 5% measure of Ti/Al or 20% measure of Pb/Al

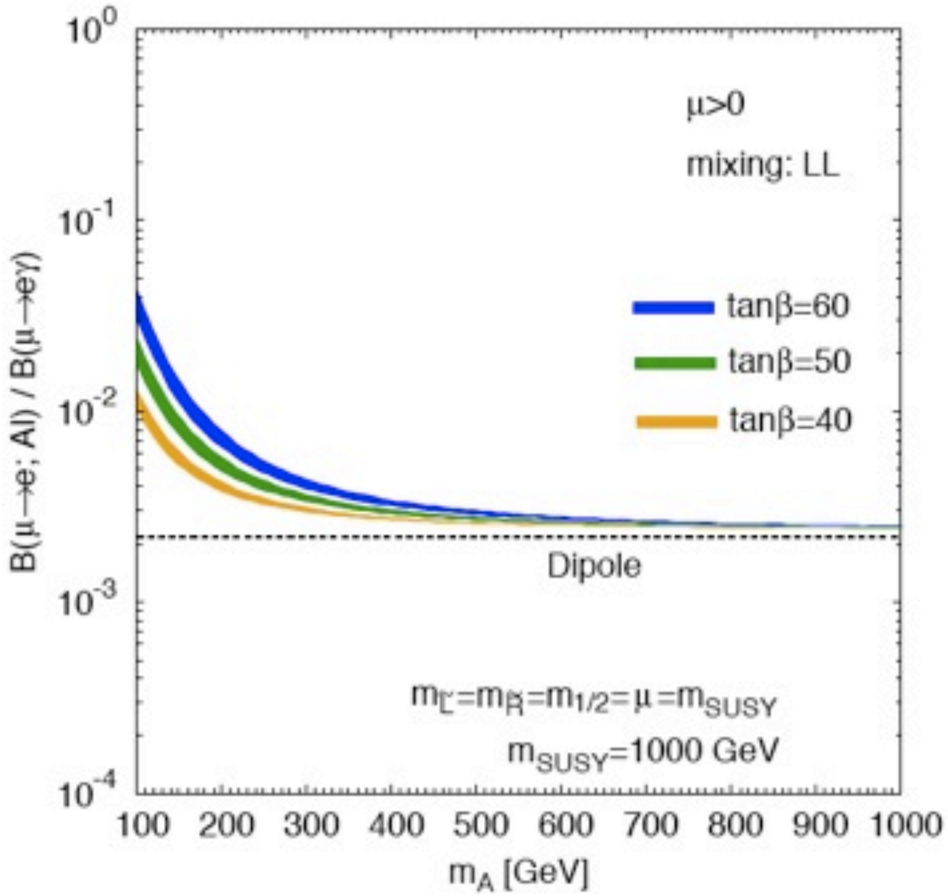
VC-Kitano-Okada-Tuzon '09

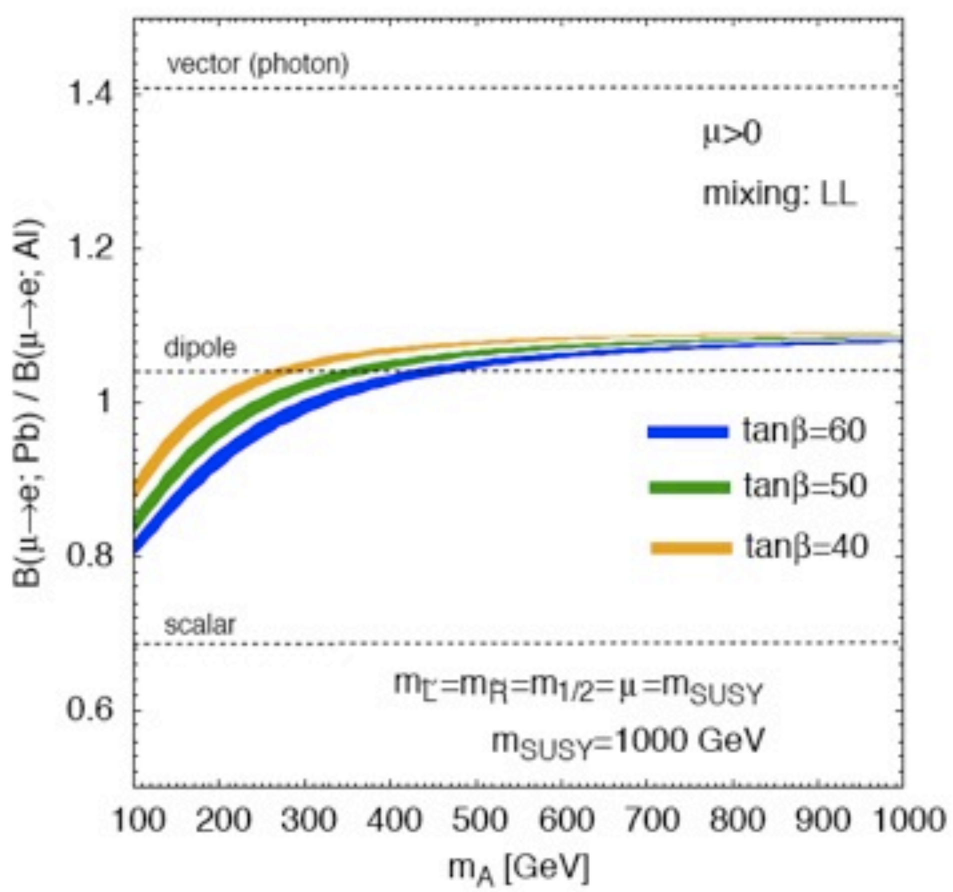
- Discriminating after discovering: LFV mechanism

- Dipole vs scalar operator (mediated by Higgs exchange) in SUSY see-saw models

Kitano-Koike-Komine-Okada 2003

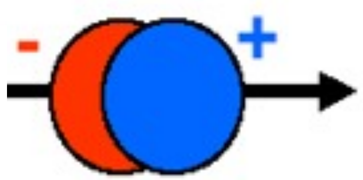






CP violation and EDMs

- EDMs of non-degenerate systems violate P and T(CP)



$$\mathcal{H} \sim d\,\vec{J}\cdot\vec{E}$$

neutron, atoms, nuclei

- Essentially no SM "background": probe flavor-diagonal BSM** sources of CP violation. All great discovery channels

EDMs in $e \cdot cm$

Particle	EDM limit	SM (CKM)
e	1.5×10^{-27}	10^{-38}
μ	1.1×10^{-19}	10^{-35}
τ	3.1×10^{-16}	10^{-34}
p	6.5×10^{-23}	10^{-31}
n	2.9×10^{-26}	10^{-31}
^{199}Hg	3.1×10^{-29}	10^{-33}

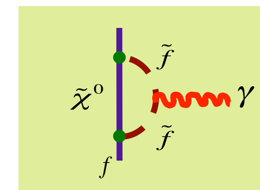
$$d_i \propto \frac{m_i}{\Lambda^2} \sin(\phi_{\rm CP})$$

- Current limits: $\Lambda \sim 100$ TeV, for $\phi_{CP} \sim O(1)$
- Already strong constraints on TeV-scale BSM

- Probe QCD θ-term + set of BSM-induced operators

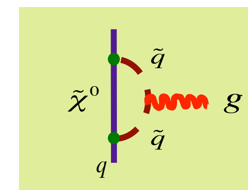
$$\mathcal{L}_4 = -\theta \frac{g_s^2}{32\pi^2} \mathrm{Tr} G_{\mu\nu} \tilde{G}_{\mu\nu}$$

$$\mathcal{L}_{6,\mathrm{qEDM}} = -\frac{1}{2}\, \bar{q}\, i\sigma^{\mu\nu}\gamma^5\, (d_0 + d_3\tau_3)\, q\, F_{\mu\nu}$$

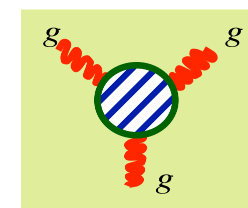


$$d_\ell, d_{0,3}, \tilde{d}_{0,3} \sim \frac{v}{\Lambda^2}$$

$$\mathcal{L}_{6,\mathrm{qCEDM}} = -\frac{1}{2}\, \bar{q}\, i\sigma^{\mu\nu}\gamma^5 \left(\tilde{d}_0 + \tilde{d}_3\tau_3\right) \lambda^a q\, G^a_{\mu\nu}$$

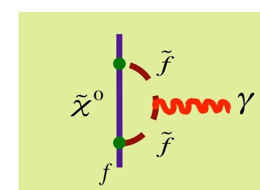


$$\mathcal{L}_{6,\mathrm{gCEDM}} = \frac{d_W}{6} f^{abc} \varepsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta} G^b_{\mu\rho} G^{c\ \rho}_{\nu}$$



$$d_W \sim \frac{1}{\Lambda^2}$$

$$\mathcal{L}_{6,\ell\mathrm{EDM}} = -\frac{d_\ell}{2}\ \bar{\ell} i\sigma^{\mu\nu}\gamma^5 \ell\, F_{\mu\nu}$$



+ 4-fermion ops

- EDMs of nucleons, light and heavy nuclei, leptons, probe different combinations of these operators.
All needed in order to *discriminate* among CPV sources.

- Theory input essential: LQCD, ChPT, many-body NP

- Discriminating after discovering: nucleons and light nuclei EDMs using Chiral EFT (just one example!)

Source	$\bar{\theta}$	qCEDM	qEDM	TV χI
d_p/d_n	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
d_d	$d_n + d_p$	$d_n + d_p - 0.2\frac{\bar{g}_1}{F_\pi}$	$d_n + d_p$	$d_n + d_p$
$d_{^3\mathrm{He}} + d_{^3\mathrm{H}}$	$d_n + d_p$	$d_n + d_p - 0.6\frac{\bar{g}_1}{F_\pi}$	$d_n + d_p$	$d_n + d_p$
$d_{^3\mathrm{He}} - d_{^3\mathrm{H}}$	$d_n - d_p - 0.3\frac{\bar{g}_0}{F_\pi}$	$d_n - d_p - 0.3\frac{\bar{g}_0}{F_\pi}$	$d_n - d_p$	$d_n - d_p$

- nucleon EDM alone cannot disentagle various sources
- only for isobreaking sources $d_d \gg d_n + d_p$

- for isobreaking sources, **both** $d_{^3\mathrm{He}} + d_{^3\mathrm{H}}$ and $d_{^3\mathrm{He}} - d_{^3\mathrm{H}}$ differ from one-body
- for theta, **only** $d_{^3\mathrm{He}} - d_{^3\mathrm{H}}$ differ from one body
- for gCEDM, qEDM, no deviation from one-body

$$\mathcal{L}_{T,f=2} = -\frac{\bar{g}_0}{F_\pi}\bar{N}\boldsymbol{\pi}\cdot\boldsymbol{\tau}N - \frac{\bar{g}_1}{F_\pi}\pi_3\bar{N}N$$

Mereghetti
van Kolck, et al

- Discriminating after discovering: nucleons and light nuclei EDMs using Chiral EFT (just one example!)

Source	$\bar{\theta}$	qCEDM	qEDM	TV χI
d_p/d_n	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
d_d	$d_n + d_p$	$d_n + d_p - 0.2\frac{\bar{g}_1}{F_\pi}$	$d_n + d_p$	$d_n + d_p$
$d_{^3\mathrm{He}} + d_{^3\mathrm{H}}$	$d_n + d_p$	$d_n + d_p - 0.6\frac{\bar{g}_1}{F_\pi}$	$d_n + d_p$	$d_n + d_p$
$d_{^3\mathrm{He}} - d_{^3\mathrm{H}}$	$d_n - d_p - 0.3\frac{\bar{g}_0}{F_\pi}$	$d_n - d_p - 0.3\frac{\bar{g}_0}{F_\pi}$	$d_n - d_p$	$d_n - d_p$

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- for theta, **only** $d_{^3\mathrm{He}} - d_{^3\mathrm{H}}$ differ from one body
- for gCEDM, qEDM, no deviation from one-body

Enhanced discriminating power with heavier nuclei + leptonic EDM

EDMs and baryogenesis

- Why do we care about discriminating the CPV mechanism?

- EDMs probe one of the necessary ingredients for baryogenesis mechanisms operative at the weak scale (T~100 GeV)

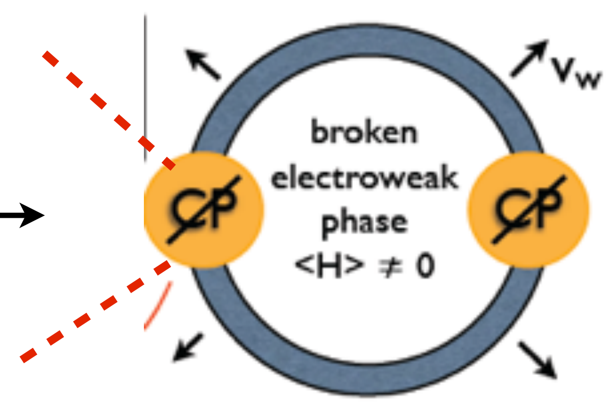
EDMs → C and CP violation

LHC (EWSB, spectrum) → Departure from thermal equilibrium

- B (baryon number) violation
- C and CP violation $\Gamma(i \to f) \neq \Gamma(\bar{i} \to \bar{f})$
- Departure from thermal equilibrium

Sakharov '67

↔



↔

- *Quantitative* statements possible in various BSM extension

Muon g-2

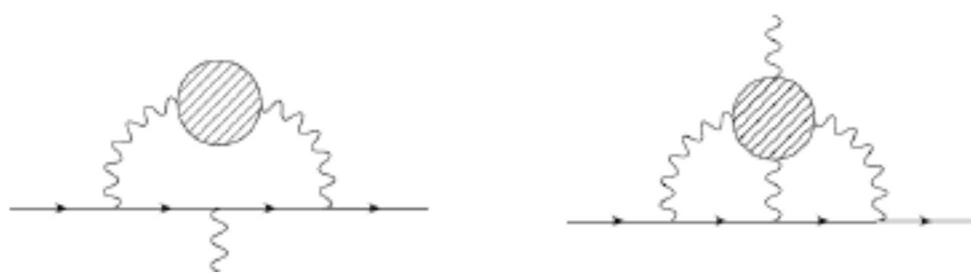
- Serious hint of new physics

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

$$a_\mu(\text{Expt}) = 116\,592\,089\,(54)(33) \times 10^{-11}$$
$$a_\mu(\text{SM}) = 116\,591\,802\,(42)(26)(02) \times 10^{-11}$$

BNL E821 (2006)

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



Dominant uncertainties: will improve with QCD + ChPT (needed!)

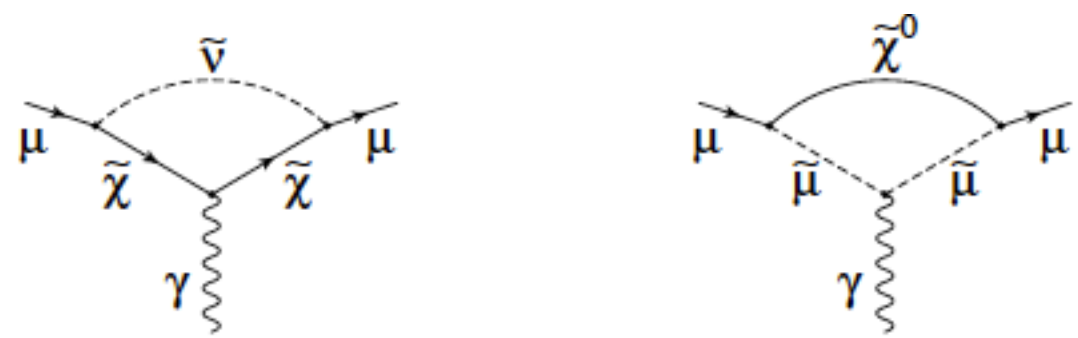
- Probe BSM mag. dipole operators $\mathcal{L} \xrightarrow{\text{EWSB}} y_\mu \frac{v}{\Lambda^2} \bar{\mu}\, \sigma^{\alpha\beta} \mu\, F_{\alpha\beta}$

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

  Strong "boundary condition" for TeV extensions of the SM

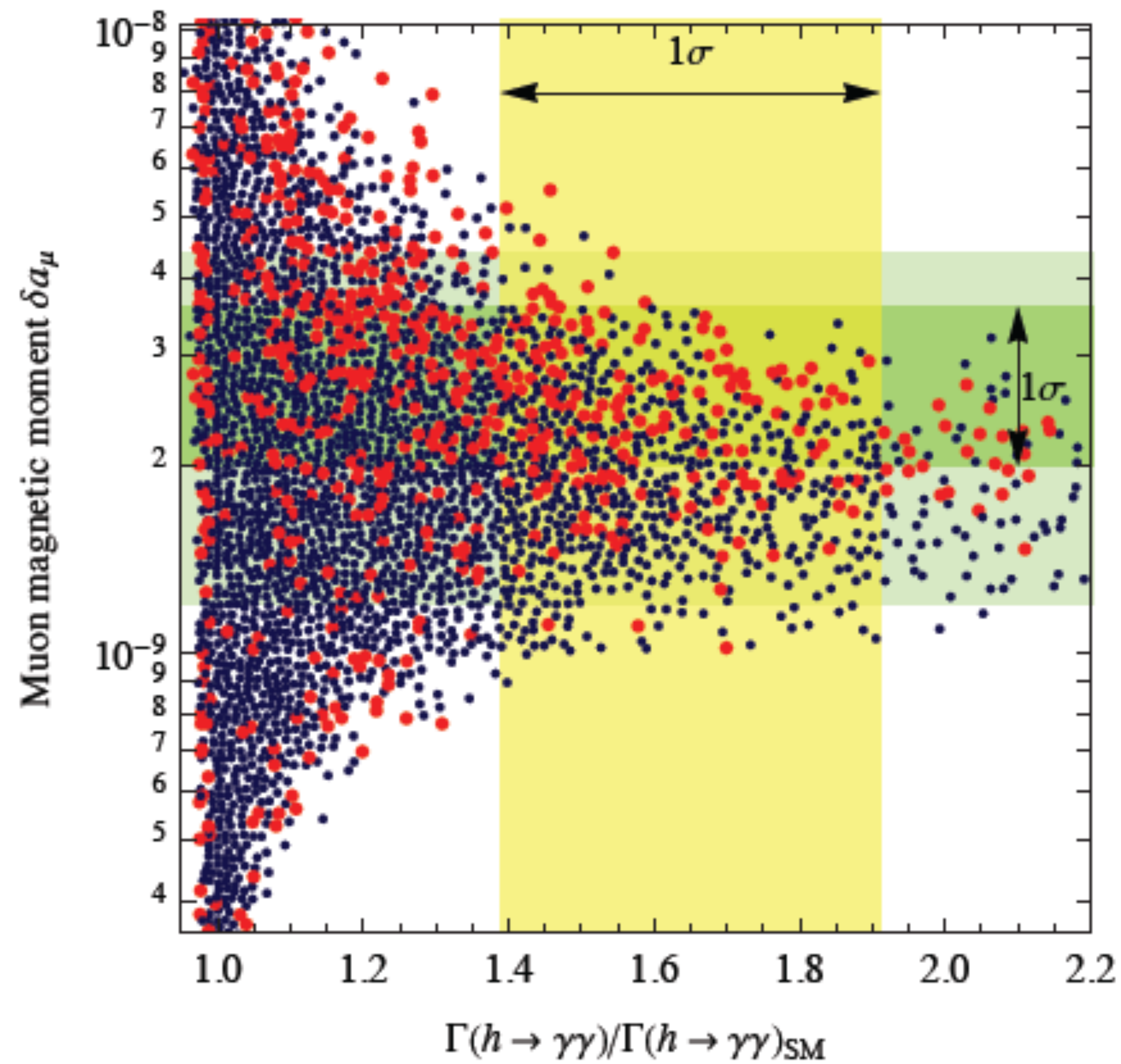
Muon g-2 and SUSY

- Leading SUSY contributions can (still) explain the discrepancy (involve sleptons, EW-inos, mildly constrained by LHC)



- Discriminating: correlation between H →γγ (blamed on stau loops) and g-2 (stau ~ smuon)

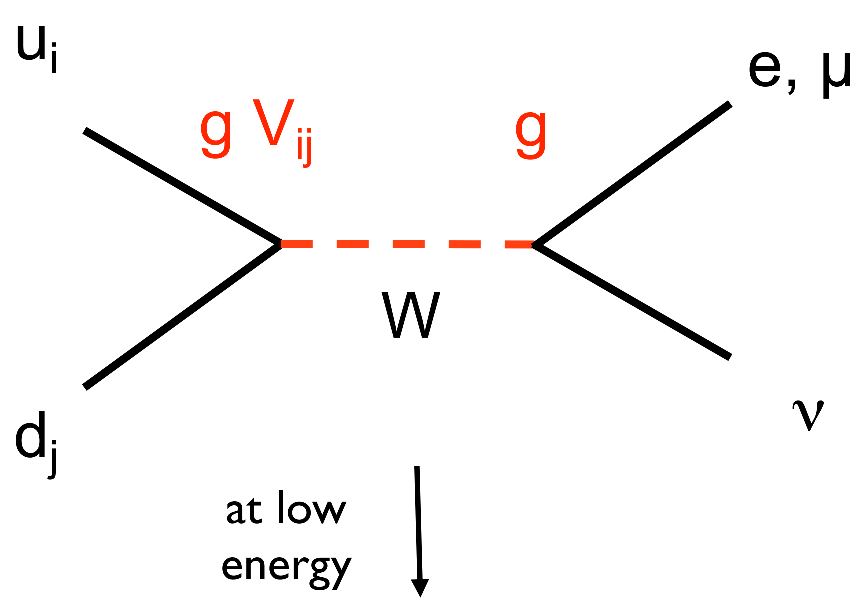
Giudice-Paradisi-Strumia 2012



- g-2 continues to be a powerful probe of SUSY (and other models) parameter space

Charged Current processes

- In the SM, W exchange ⇒ only V-A structure, universality relations



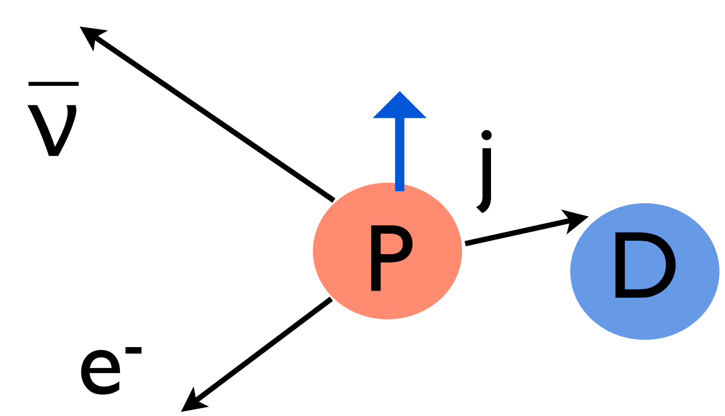
$G_F \sim g^2 V_{ij}/M_W^2 \sim 1/v^2$

Lepton universality

$$[G_F]_e/[G_F]_\mu = 1 + \Delta_{e/\mu}$$

$$|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} = 1 + \Delta_{\mathrm{CKM}}$$

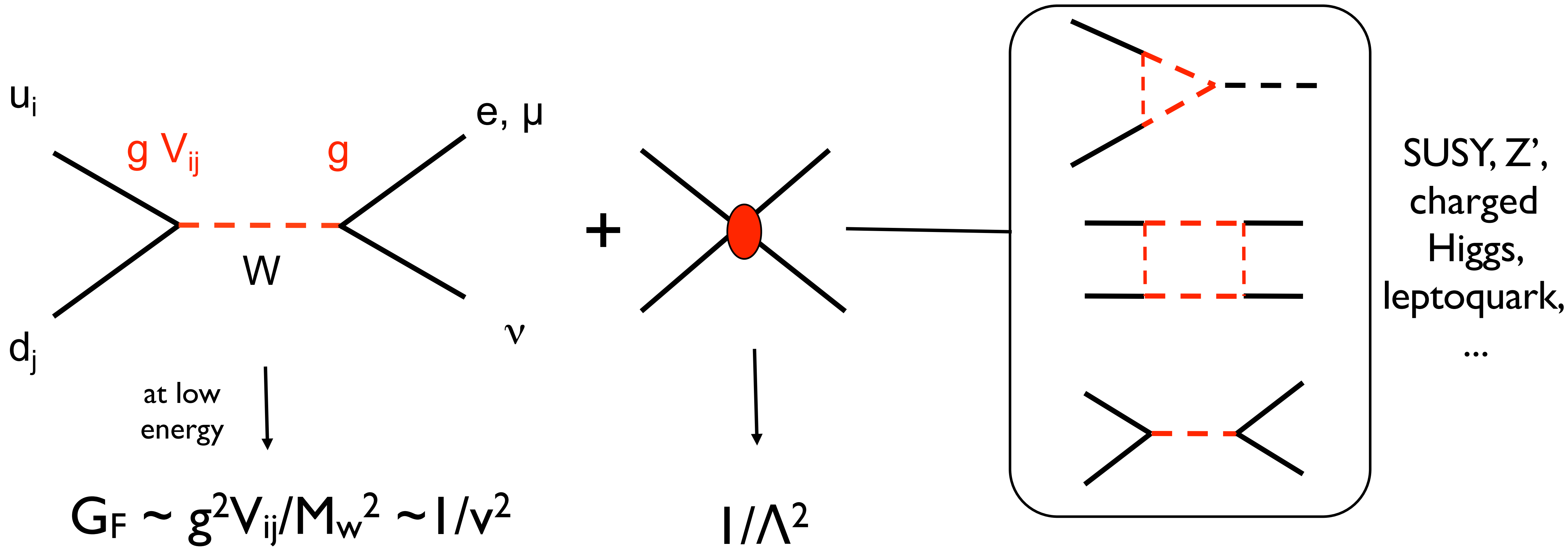
Cabibbo universality



Peculiar "V-A" pattern in spectra
and decay correlations

Charged Current processes

- In the SM, W exchange ⇒ only V-A structure, universality relations



- BSM: sensitive to tree-level and loop corrections from large class of models → “broad band” probe of new physics

- CC processes probe ten BSM effective couplings: $\varepsilon_i, \tilde{\varepsilon}_i \sim (v/\Lambda)^2$

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

- CC processes probe ten BSM effective couplings: $\varepsilon_i, \tilde{\varepsilon}_i \sim (v/\Lambda)^2$

$$\mathcal{L}_{CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} (1 + \delta_{RC} + \epsilon_L + \epsilon_R)$$

- Affects overall normalization of "semi-leptonic" G_F

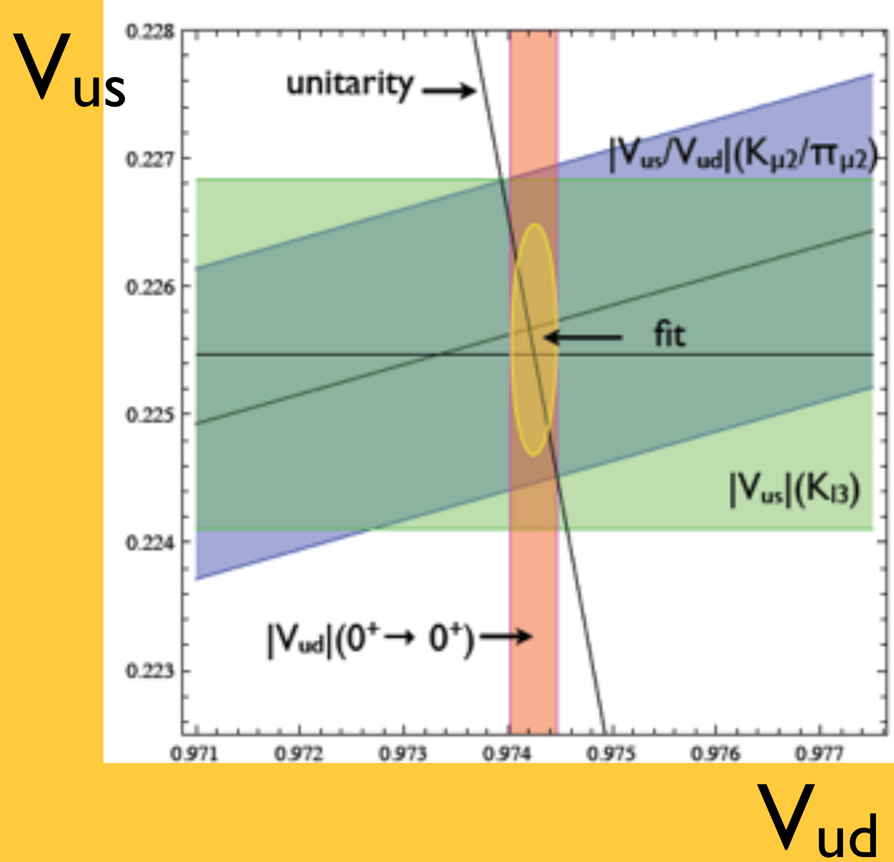
- Strong constraints from Cabibbo universality tests, precision extraction of V_{ud} ($0^+ \to 0^+$, neutron decay)

$$\Delta_{CKM} = (1 \pm 6) * 10^{-4}$$

$$\varepsilon_L + \varepsilon_R < 1 * 10^{-3}$$

$$\Lambda > 11 \text{ TeV}$$

@ 90% CL



- CC processes probe ten BSM effective couplings: $\varepsilon_i , \tilde{\varepsilon}_i \sim (v/\Lambda)^2$

$$\mathcal{L}_{\rm CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} (1 + \delta_{RC} + \epsilon_L + \epsilon_R)$$

$$\times \Big[\bar{\ell} \gamma_\mu (1-\gamma_5) \nu_\ell \cdot \bar{u} \gamma^\mu \Big(1 - (1 - 2\, \epsilon_R) \gamma_5 \Big) d$$

$$+ \epsilon_S \;\; \bar{\ell}(1$$

$$- \epsilon_P \;\; \bar{\ell}($$

$$+ \epsilon_T \;\; \bar{\ell} \sigma_{\mu\nu} (1-\gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1-\gamma_5) d \Big] + \text{h.c.}$$

- Affects relative normalization of axial and vector currents

- Neutron and nuclear decays sensitive to $(1\text{-}2\varepsilon_R)^* g_A$ through lifetime and angular correlations

- Disentangling ε_R requires precision lattice calculations of g_A: we are not there (yet)

- CC processes probe ten BSM effective couplings: $\varepsilon_i, \tilde{\varepsilon}_i \sim (v/\Lambda)^2$

$$\mathcal{L}_{CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} (1 + \delta_{RC} + \epsilon_L + \epsilon_R)$$

$$\times \Big[\bar{\ell}\gamma_\mu(\ldots$$

$$+ \epsilon_S \; \bar{\ell}(1 \ldots$$

$$- \epsilon_P \; \bar{\ell}(1 \ldots$$

$$+ \epsilon_T \; \bar{\ell}\sigma_\mu \ldots$$

- Strong constraints from $\pi \to e \nu$ (depend on the structure of $(\varepsilon_P)^{ab}$ in lepton flavor space)

$$\Delta_{e/\mu} = (-3 \pm 3) * 10^{-3}$$

$\pm 0.5 * 10^{-3}$ PEN, PIENU

$\varepsilon_L - \varepsilon_R < 2.5 * 10^{-3}$ $\quad \Lambda_{L-R} > 3.5$ TeV

$\varepsilon_P < 1.2 * 10^{-6}$ $\quad \Lambda_P > 160$ TeV

@ 90% CL

- CC processes probe ten BSM effective couplings: $\varepsilon_i, \tilde{\varepsilon}_i \sim (v/\Lambda)^2$

$$\mathcal{L}_{CC} = -\frac{G_F^{(0)} \cdots}{\sqrt{\cdots}}$$

$$\times \Big[\bar{\ell}\gamma_\mu(\cdots$$

$$+ \epsilon_S \; \bar{\ell}(1 \cdots$$

$$- \epsilon_P \; \bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d$$

$$+ \epsilon_T \; \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \Big] + \text{h.c.}$$

- Neutron and nuclear decay correlation coefficients and spectra
- π → e ν γ Dalitz plot (tensor coupling)

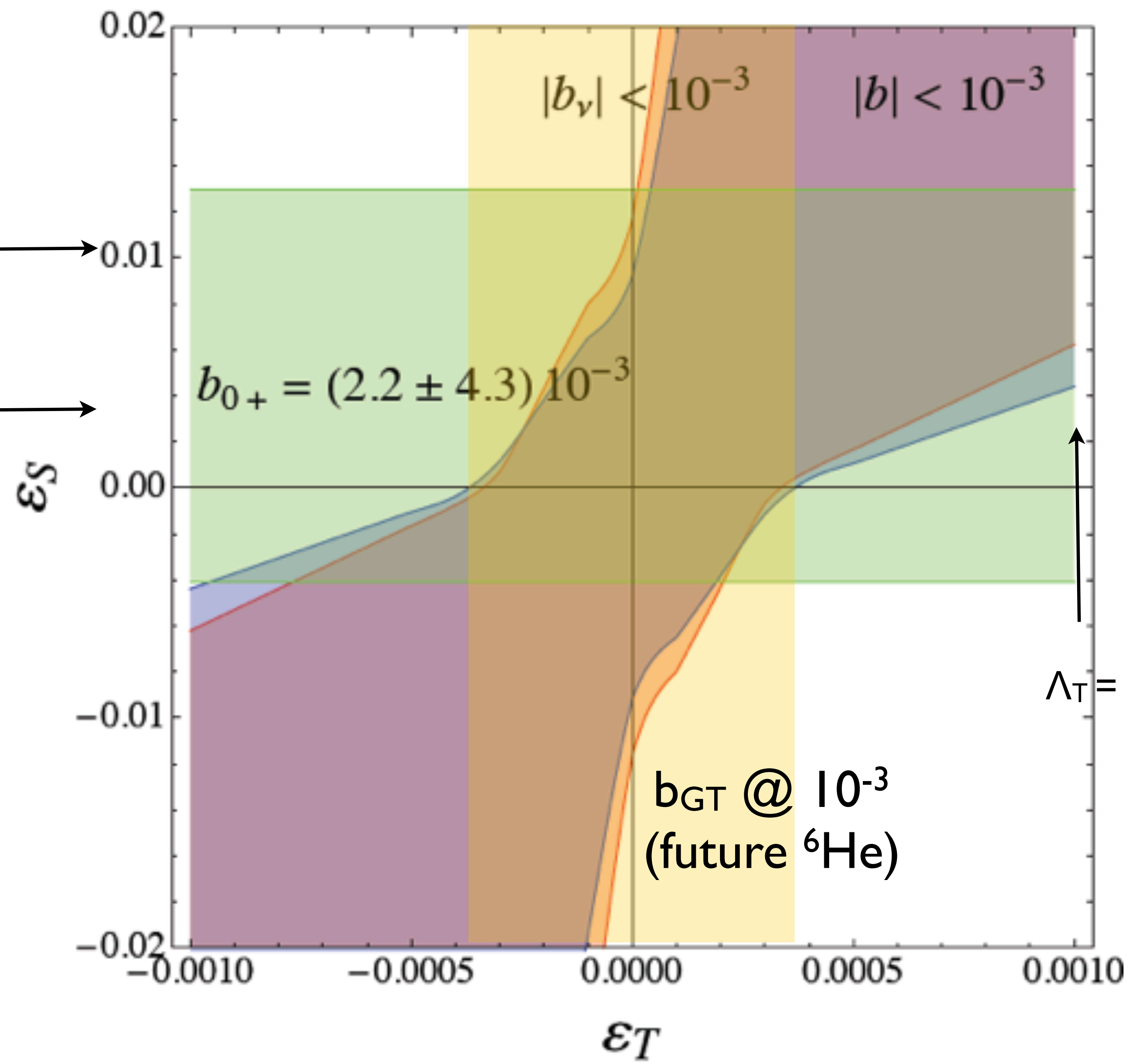
↓

see plots

- Current: $0^+ \to 0^+$ (b) and $\pi \to e\,\nu\,\gamma$ (green band)
- Future: neutron b, b_ν @ 10^{-3} level (Nab; UCNB,b, abBA, ...), ^{6}He (b)

Λ_S = 3.2 TeV →

Λ_S = 5 TeV →



(90% C.L.)

Quark models:

$0.25 < g_S < 1$

$0.6 < g_T < 2.3$

Λ_T = 5 TeV

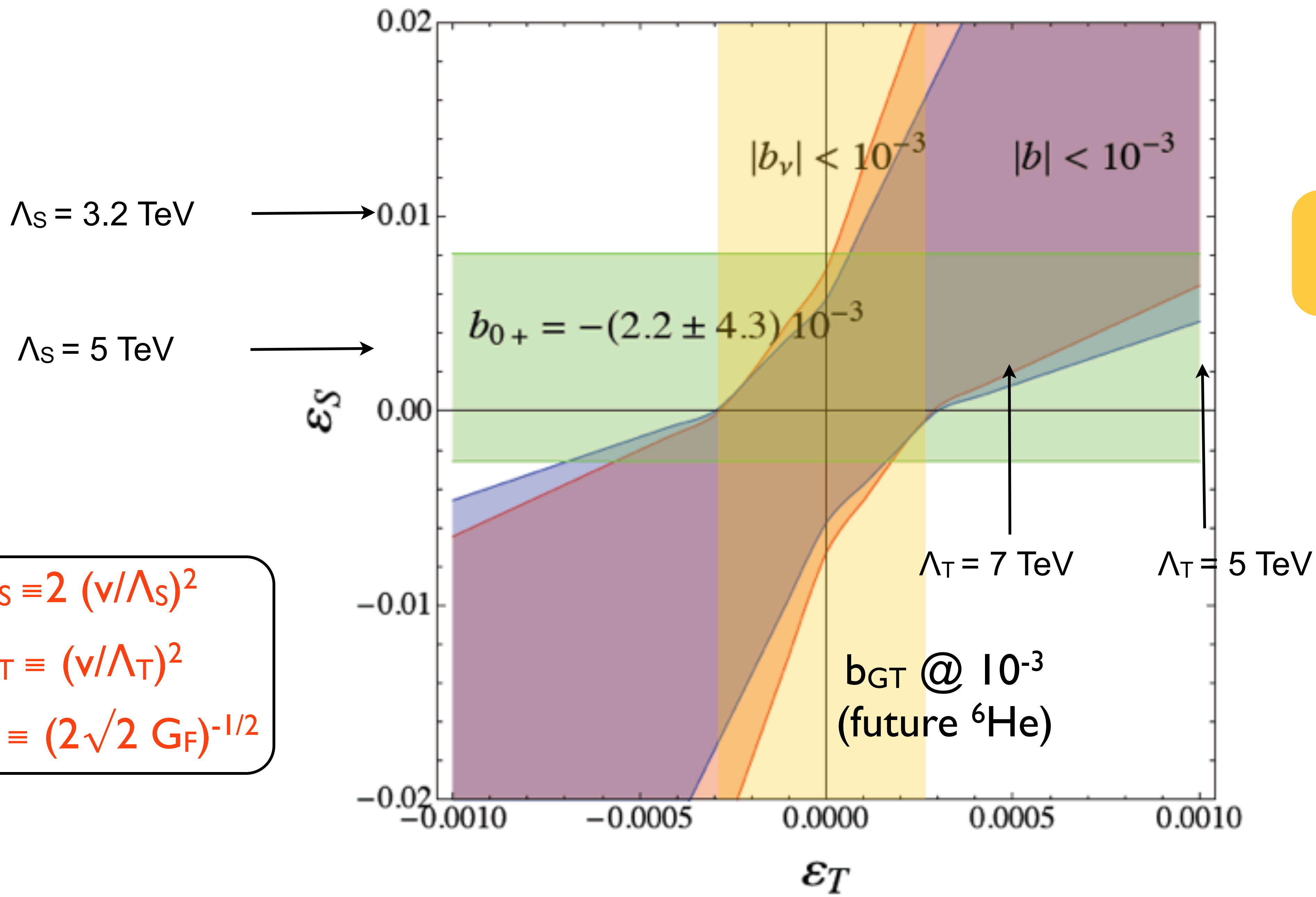
Adler et al, '75
Herczeg '01

$\varepsilon_S \equiv 2\,(v/\Lambda_S)^2$

$\varepsilon_T \equiv (v/\Lambda_T)^2$

$v \equiv (2\sqrt{2}\,G_F)^{-1/2}$

- Current: $0^+ \to 0^+$ (b) and $\pi \to e\, \nu\, \gamma$ (green band)
- Future: neutron b, b_ν @ 10^{-3} level (Nab; UCNB,b, abBA, ...), ^{6}He (b)



$\varepsilon_S \equiv 2\, (v/\Lambda_S)^2$

$\varepsilon_T \equiv (v/\Lambda_T)^2$

$v \equiv (2\sqrt{2}\, G_F)^{-1/2}$

(90% C.L.)

Lattice QCD

$g_S = 0.8\ (4)$

$g_T = 1.05(35)$

Bhattacharya, Cirigliano, Cohen, Filipuzzi, Gonzalez-Alonso, Graesser, Gupta, Lin, 2011

Will reach $\delta g_S/g_S \sim 20\%$

- CC processes probe ten BSM effective couplings: $\varepsilon_i, \tilde{\varepsilon}_i \sim (v/\Lambda)^2$

$$\mathcal{L}_{CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} (1 + \delta_{RC} + \epsilon_L + \epsilon_R)$$

- "No interference" between SM amplitude and $\tilde{\varepsilon}_i$ couplings (m_ν/E_ν)

- Spectra and angular correlations probe $\tilde{\varepsilon}_i$ to *quadratic order*

- Generally weaker bounds (5-10% level)

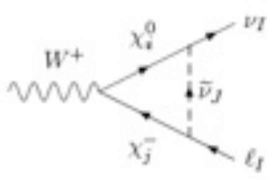
$$- \quad \epsilon_P \quad \bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d$$

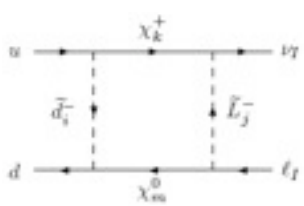
$$+ \quad \epsilon_T \quad \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \,\Big] + \text{h.c.}$$

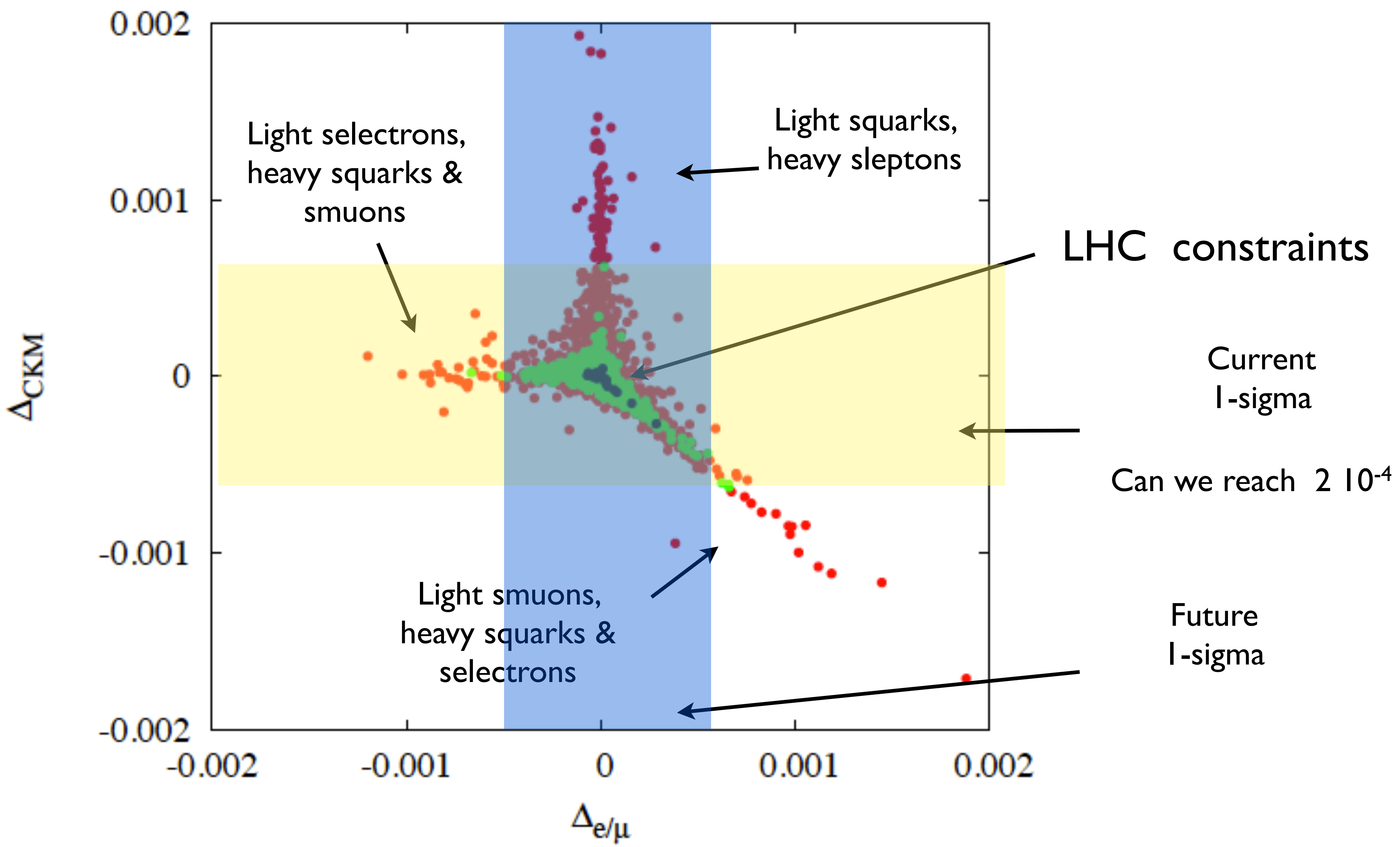
$$+ \qquad \epsilon_i \longrightarrow \tilde{\epsilon}_i \qquad (1-\gamma_5)\nu_\ell \longrightarrow (1+\gamma_5)\nu_\ell$$

Bauman, Erler, Ramsey-Musolf, arXiv:1204.0035

- Discriminating after discovering (example): CKM vs LFU in SUSY



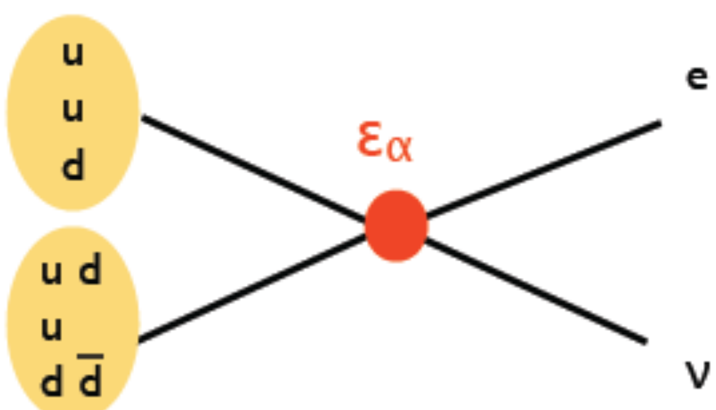


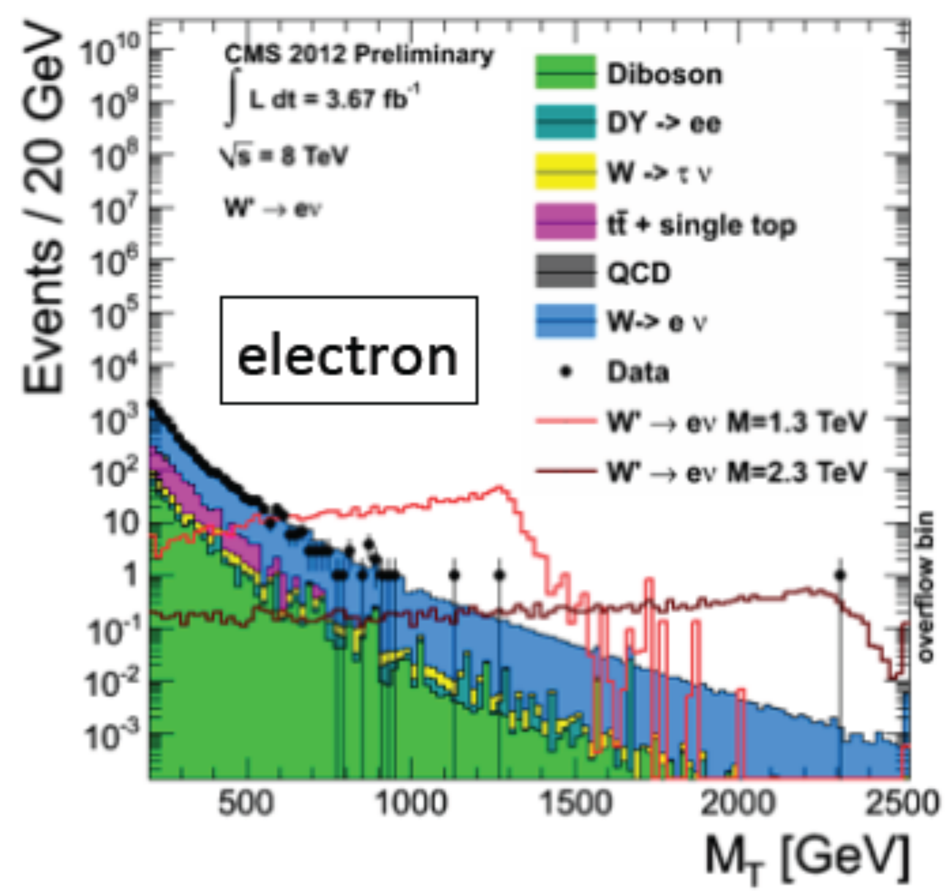


- Distinctive correlation between Cabibbo universality and lepton universality: information on sfermion spectrum
- MSSM effects (post-LHC) are at the few*10^{-4} level

β decays vs LHC

- The "LHC pressure" can be addressed on a model by model basis
- However, in the "nightmare scenario" ($M_{BSM} >>$ TeV) general model-independent analysis can be performed
- The BSM couplings ε_α contribute to the process $p\,p \rightarrow e\,\nu + X$





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- The BSM couplings ϵ_α contribute to the process $p\,p \to e\,\nu + X$

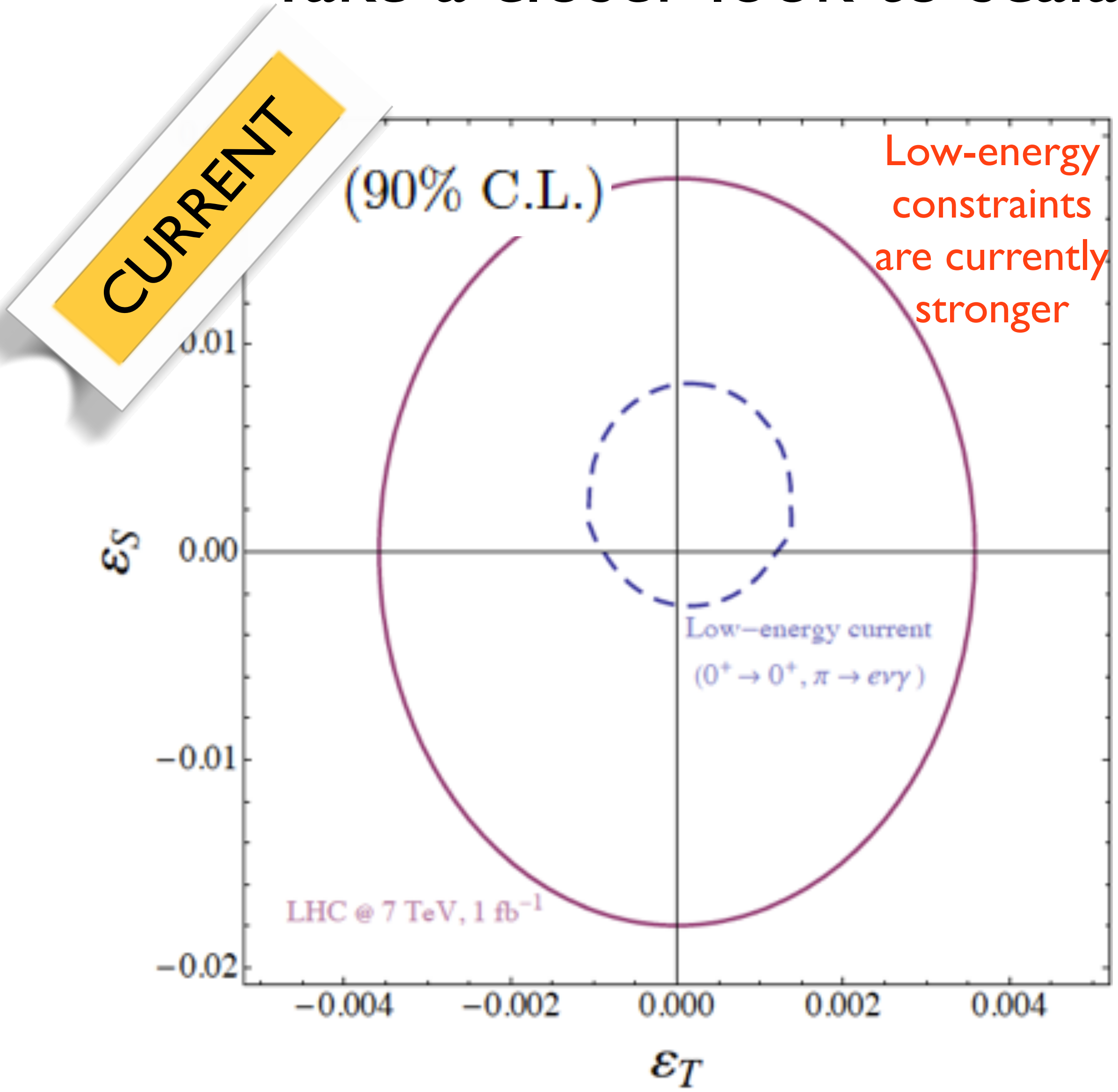
	$\epsilon_L + \epsilon_R$	ϵ_S	ϵ_T	$\tilde{\epsilon}_S$	$\tilde{\epsilon}_T$	$\tilde{\epsilon}_{L,R}$
β decays	5×10^{-4}	8.0×10^{-3}	1.3×10^{-3}	7.5×10^{-2}	2.5×10^{-2}	7.5×10^{-2}
LHC	--	1.7×10^{-2}	3.4×10^{-3}	1.7×10^{-2}	3.4×10^{-3}	6.3×10^{-3}

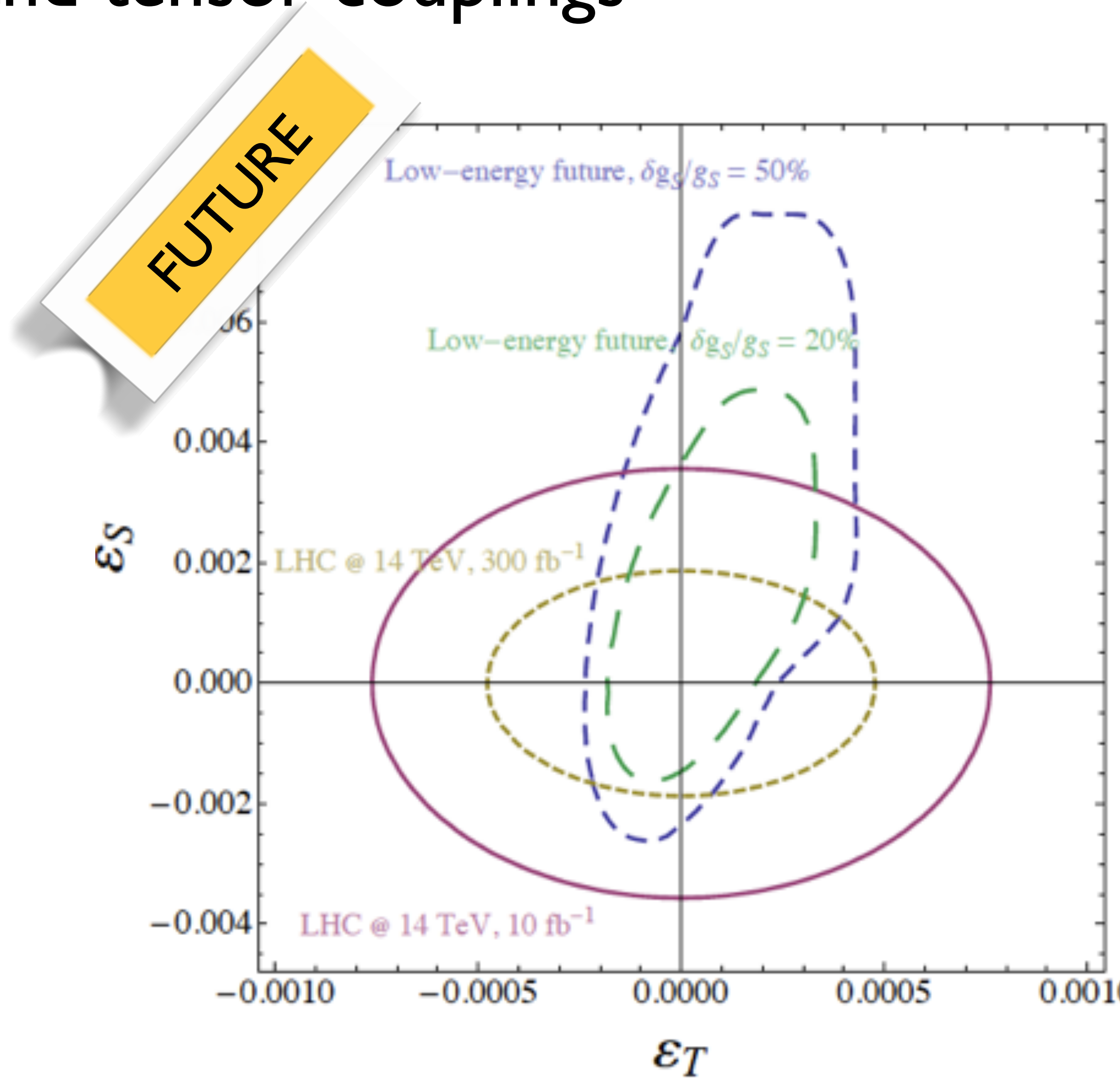
Unmatched low-energy sensitivity

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

LHC superior to low-energy!

- Take a closer look to scalar and tensor couplings

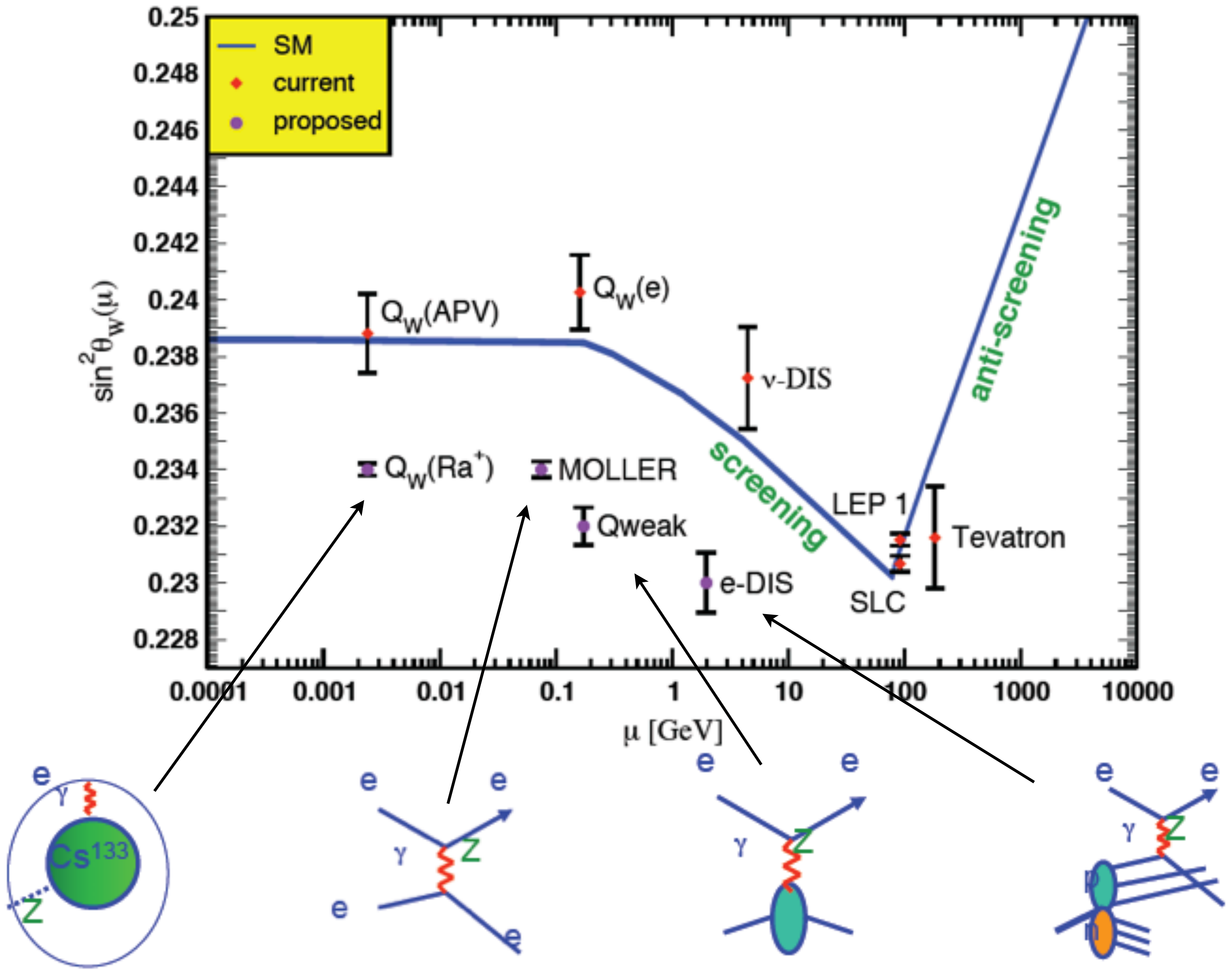




- LHC and b, B at 10^{-3} level will compete in setting strongest bounds on ε_S and ε_T probing effective scales $\Lambda_{S,T} \sim 7$ TeV
- b and B at 10^{-4} level would give unmatched sensitivity

Neutral Current processes

- Precise LE measurements of θ_W + complementary (≡probe different operators) constraints on BSM structures



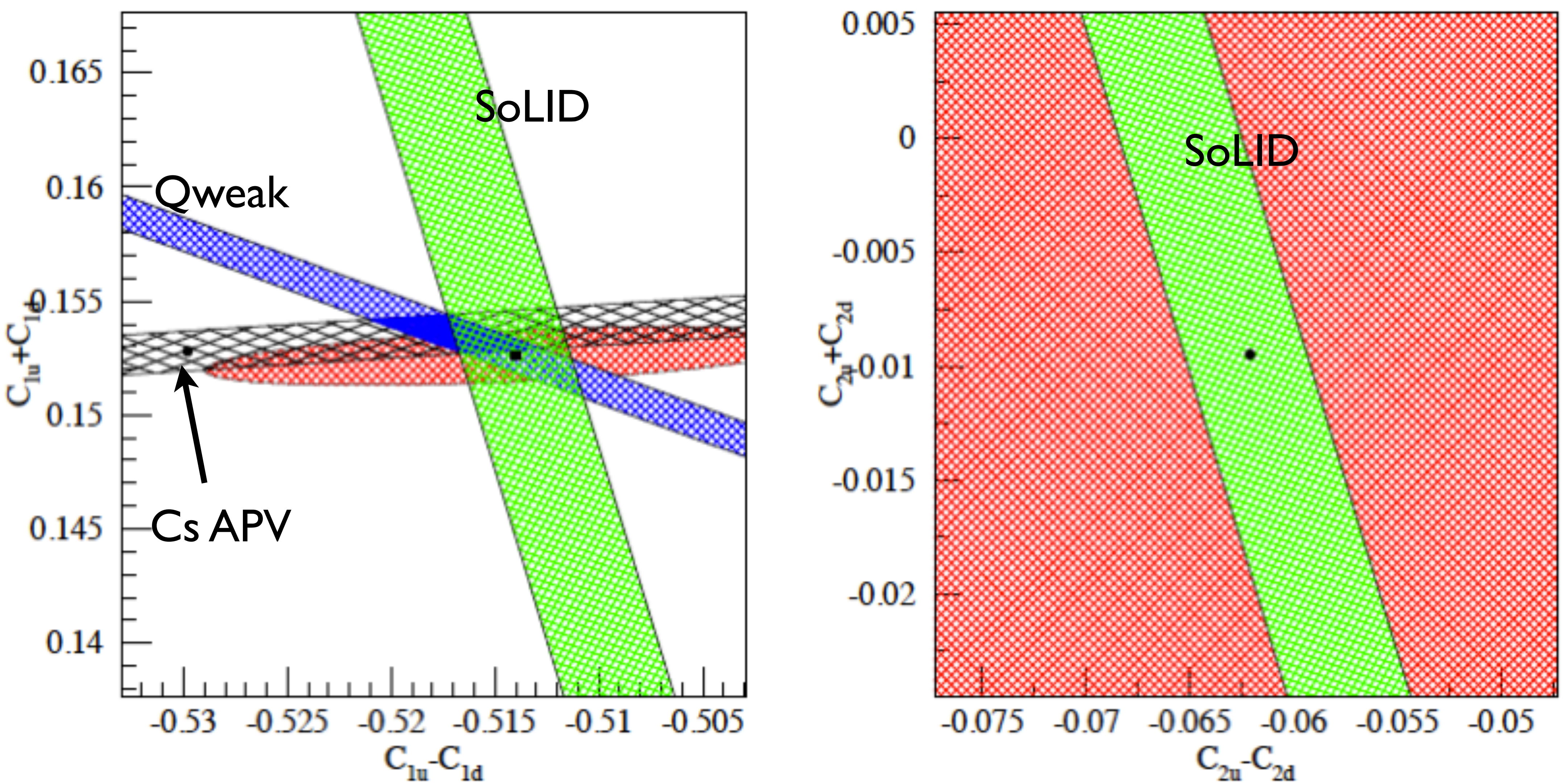
J. Erler

- Operators probed & NP sensitivity:

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

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

+ purely leptonic (Moller)



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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 (Moller)

Sensitivities to new physics

- $\Lambda_{new} \simeq [\sqrt{2}\, G_F\, \Delta Q_W]^{-1/2} = 246.22\ \mathrm{GeV}/\sqrt{\Delta Q_W}$
  - $\Lambda_{new} \simeq 3.4$ 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)
  - $\Lambda_{new} \simeq 6.3$ 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)

- Discriminating power / complementarity to LHC:

- Model independent: sensitivity to different operators. Analysis of LHC constraints in “contact” limit not available

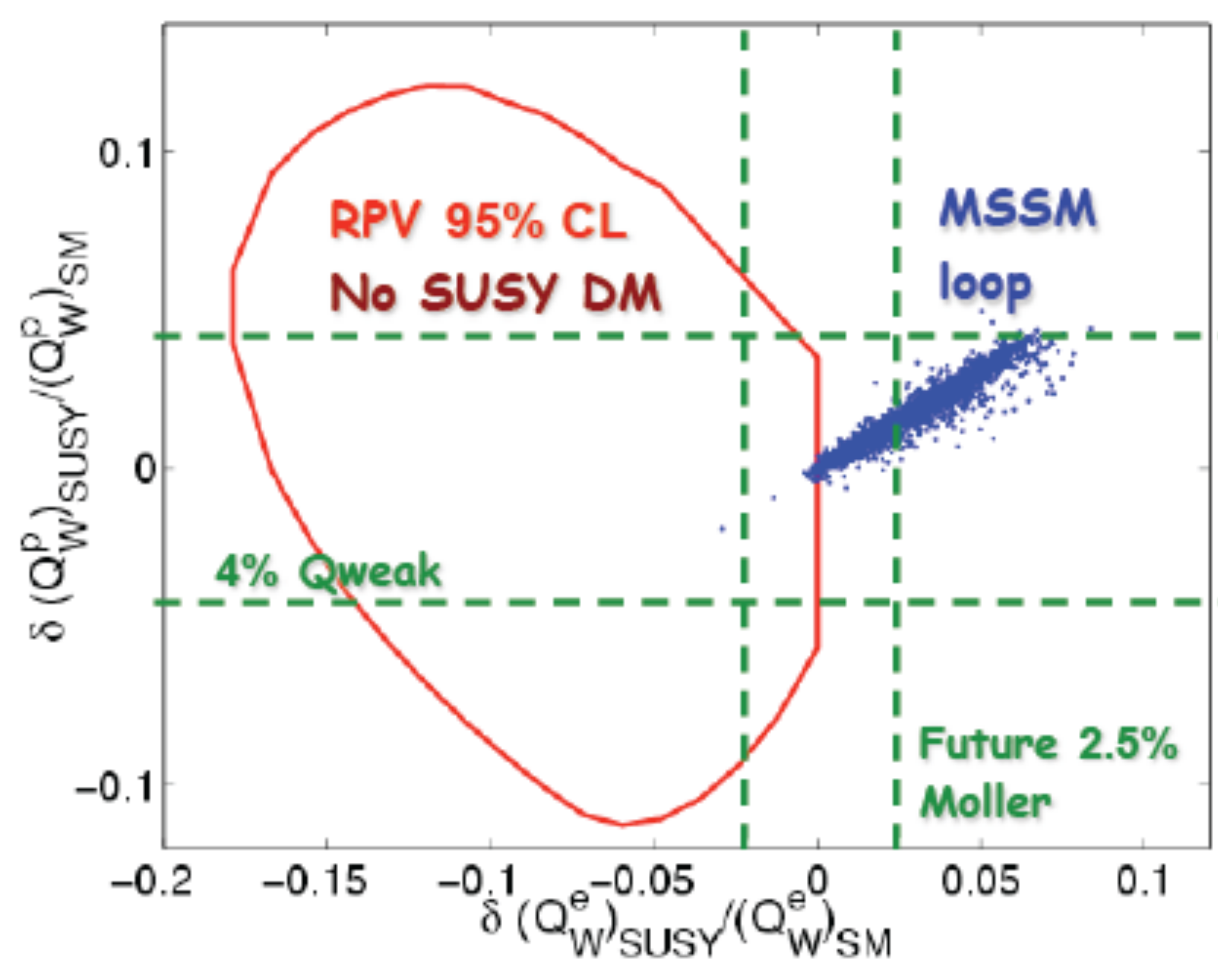
- Models (vast literature):

- Lepto-phobic Z’ (unique sensitivity if $M_{Z'} < 1$ TeV)

Buckley + Ramsey-Musolf, Ng

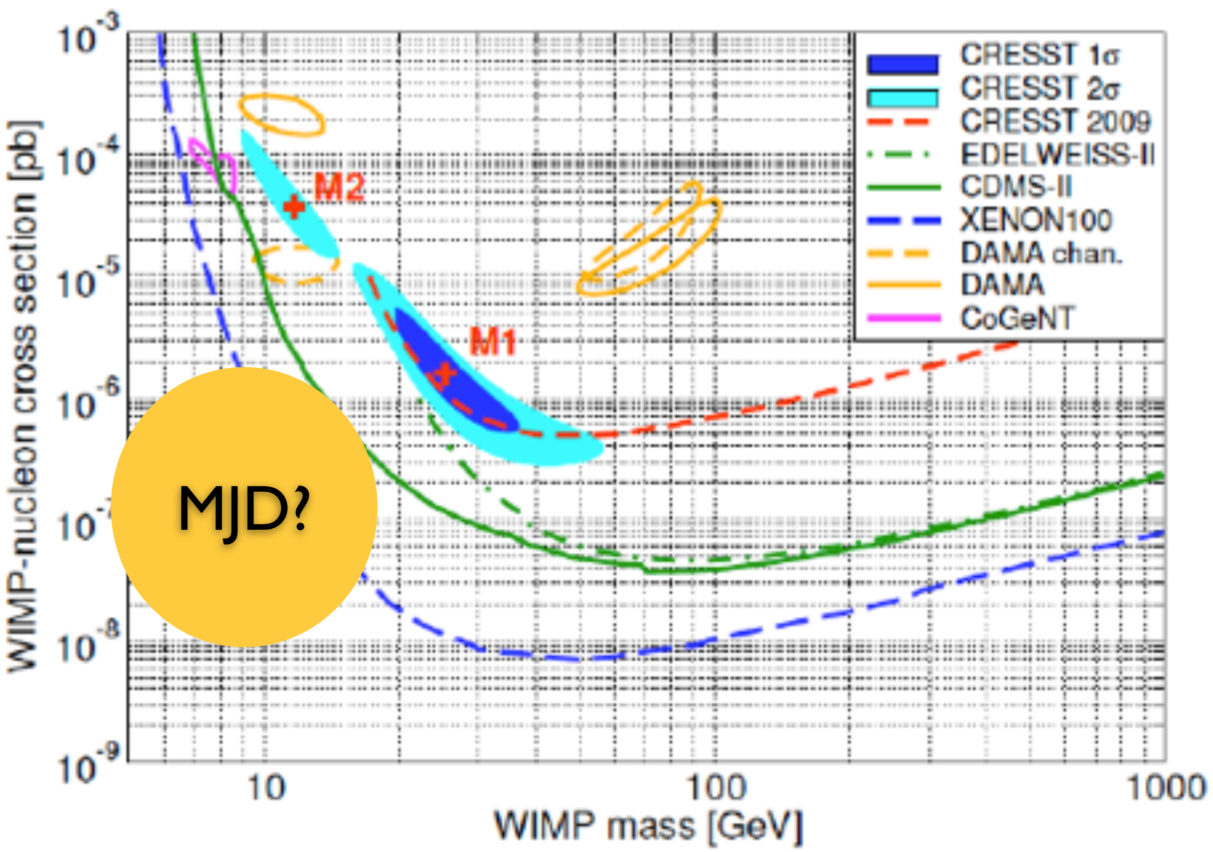
- SUSY: correlation between Q_W^p and Q_W^e

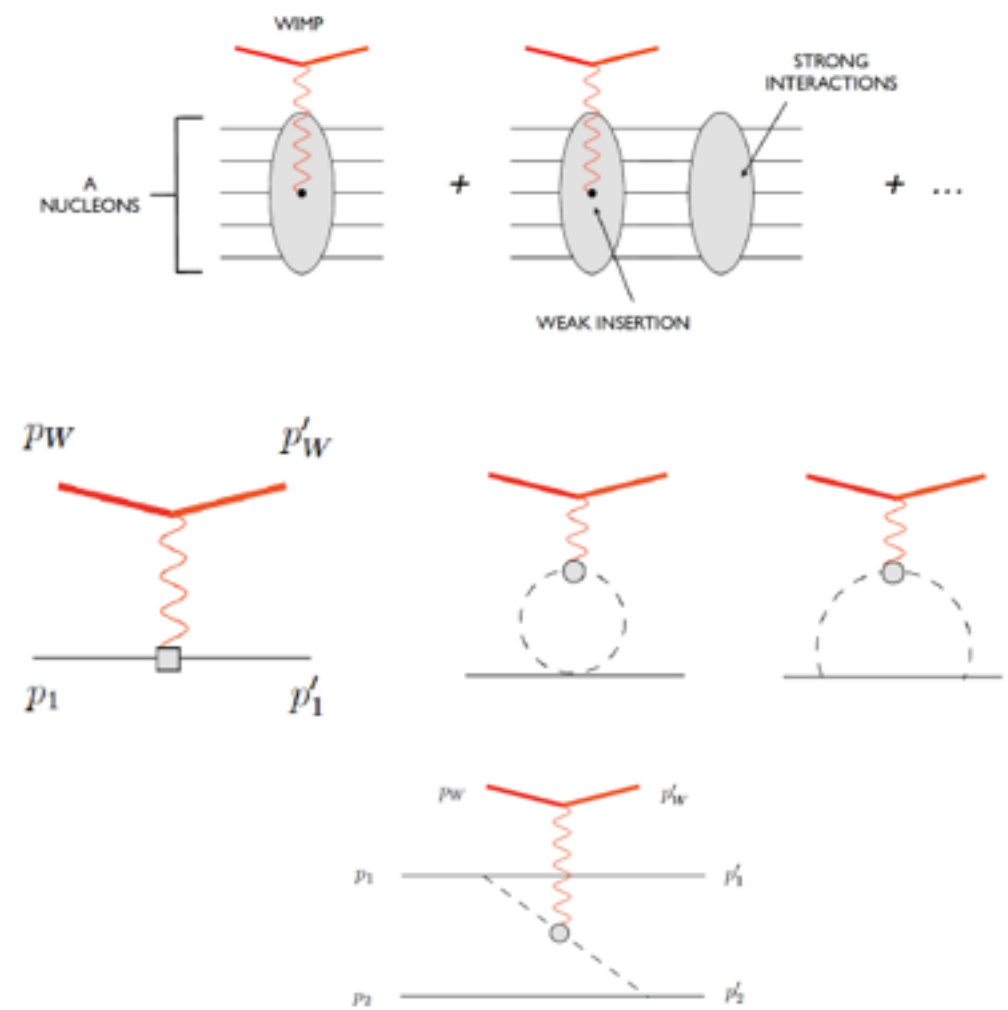
Kurylov, Ramsey-Musolf, Su (2003)



Opportunities

- Dark Matter:
  - Direct detection is Nuclear Physics (both Exp and Th)

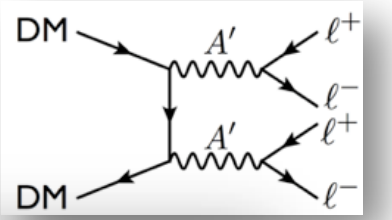




Engel, Vogel et al, '90s
VC-Graesser-Ovanesyan, Haxton et al,, Schwenk et al, 2012

Opportunities

- Dark Matter:
  - Direct detection is Nuclear Physics (both Exp and Th)
  - “Dark sector” searches at JLAB



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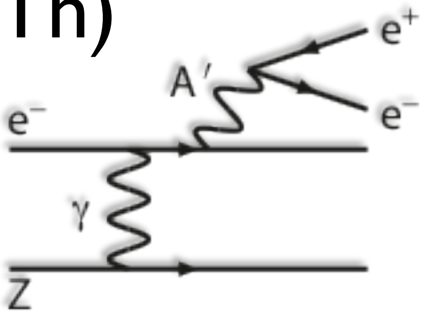

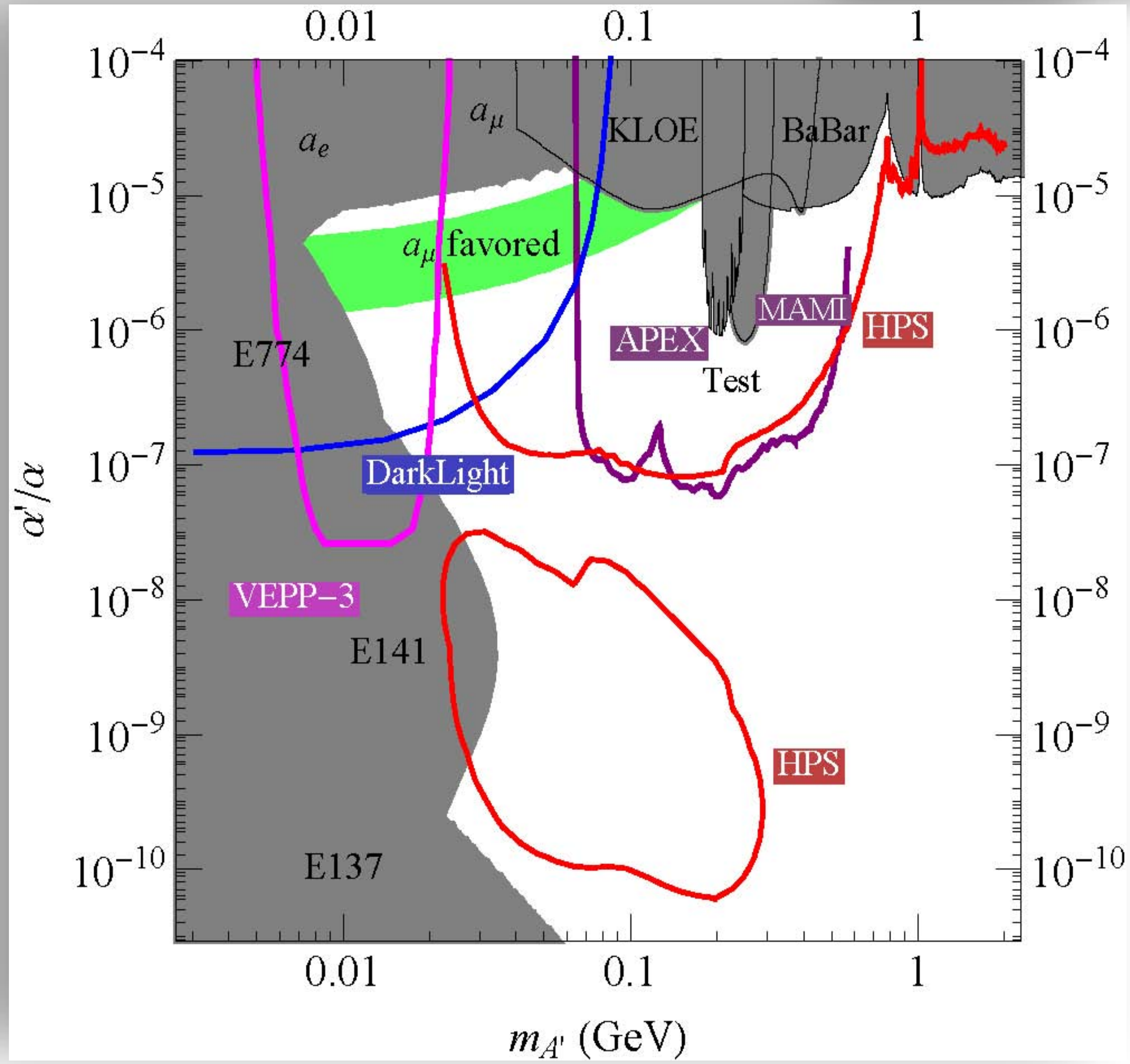

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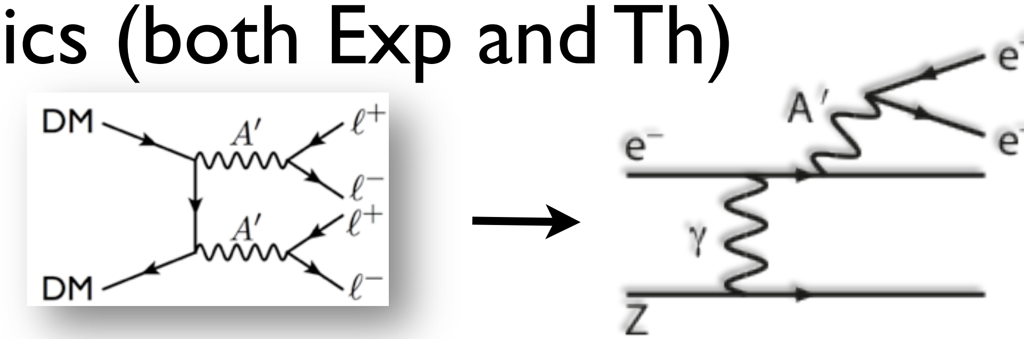


- Project X: muon program, n-nbar oscillations, n EDM, ...
- EIC
    - Electroweak measurements?
    - $e \rightarrow \tau$ LFV? [vs superB factories]
- FRIB
    - Is there a TH + EXPT roadmap?

(My) Conclusions

In order to reconstruct the New SM (and in absence of an emerging one), need to pursue broadest possible set of low-energy searches.

The US NP program has been setting up an impressive portfolio, with flagship measurements characterized by high discovery potential and a suite of high precision measurements that will enable the essential model-discriminating power.

They all play a role in telling us what the New Standard Model is (not).

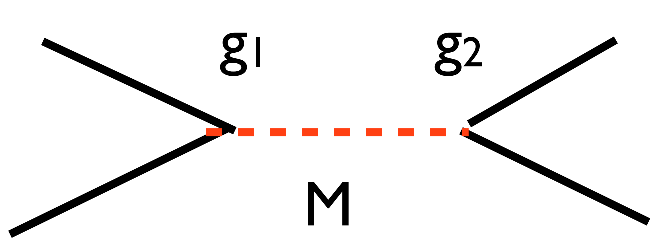
Finally, let's not forget that theory is essential to carry out this program.

Extra Slides

VC, Graesser, Passemar, in progress

β decays vs LHC (2)

- What if new interactions are not "contact" at LHC energy? How are the ε bounds affected?
- Explore classes of models generating $\varepsilon_{S,T}$ at tree-level. Low-energy vs LHC amplitude:



$$A_\beta \sim g_1 g_2 / M^2 \equiv \varepsilon$$

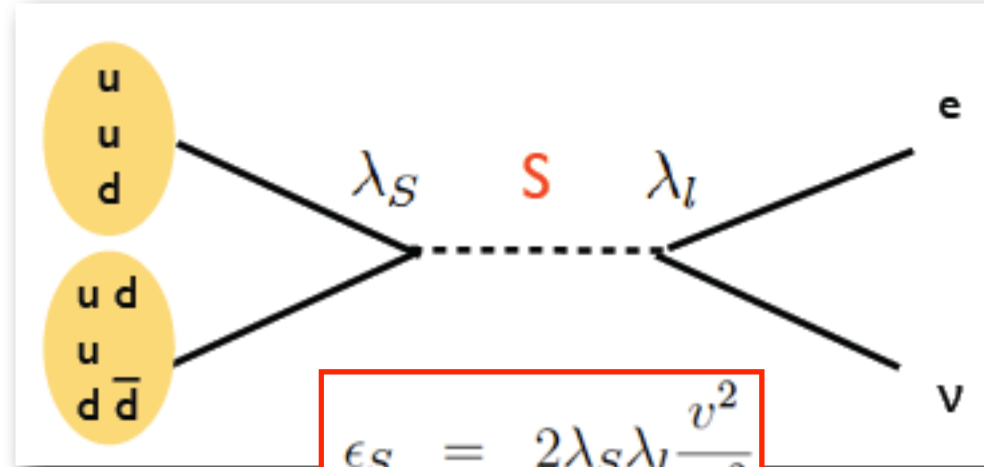
$$A_{LHC} \sim \varepsilon \, F[\sqrt{s}/M, \sqrt{s}/\Gamma(\varepsilon)]$$

- Study dependence of the ε bounds on the mediator mass M

VC, Graesser, Passemar, in progress

s-channel mediator

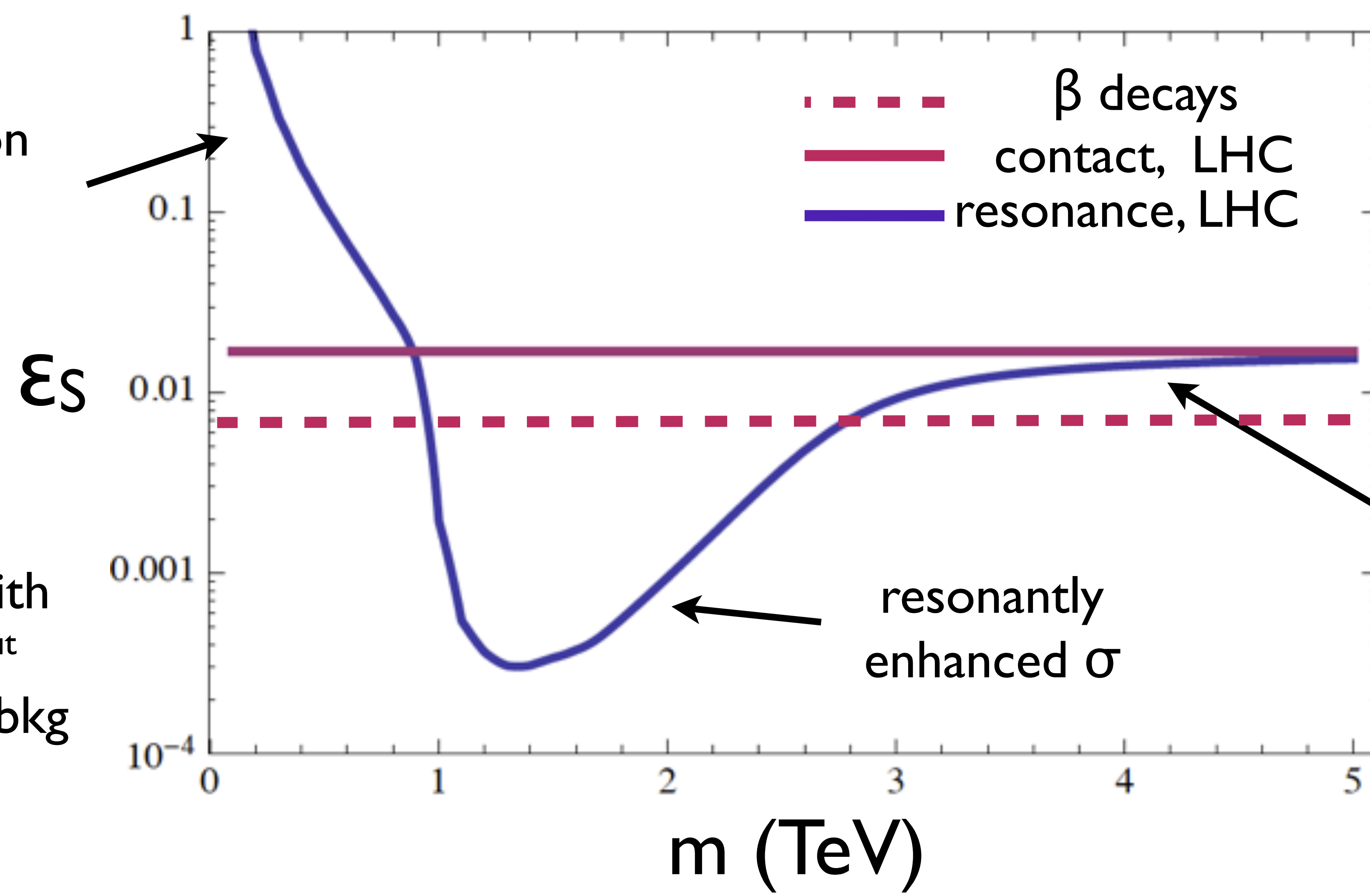
- Scalar resonance in s-channel
- Upper bound on ε_S based on m_T > 1 TeV



$$\epsilon_S = 2\lambda_S\lambda_l\frac{v^2}{m^2}$$

σ suppression due to $m < (m_T)^{cut}$

Improvable with lower $(m_T)^{cut}$
But larger SM bkg

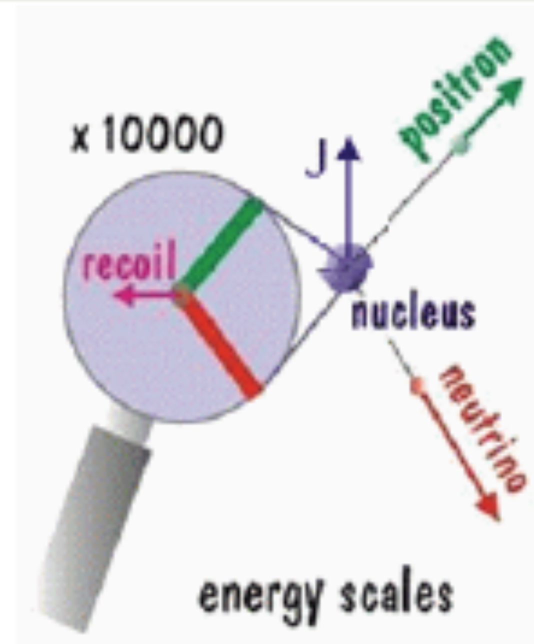


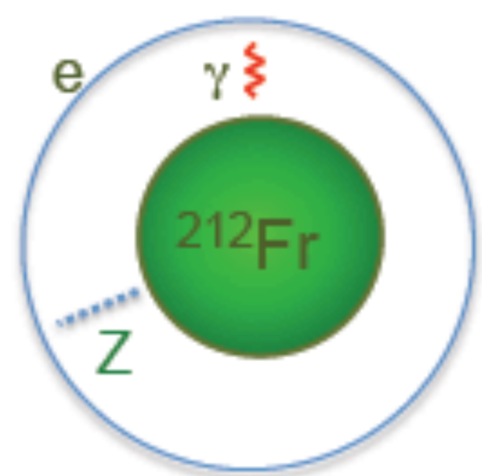
resonantly enhanced σ

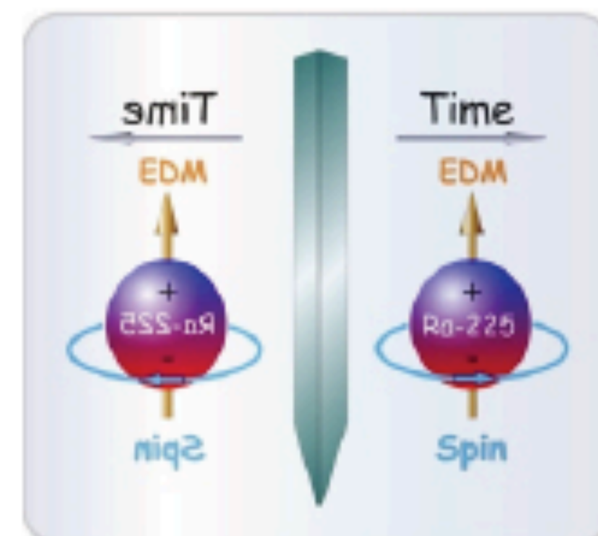
decoupling regime

Tests of Nature's Fundamental Symmetries

- Angular correlations in β-decay and search for scalar currents
  - Mass scale for new particle comparable with LHC
  - ^{6}He and ^{18}Ne at 10^{12}/s
- Electric Dipole Moments
  - ^{225}Ac, ^{223}Rn, ^{229}Pa (30,000 more sensitive than ^{199}Hg; > 10^{9}/s)
- Parity Non-Conservation in atoms
  - weak charge in the nucleus (francium isotopes; 10^{9}/s)
- Unitarity of CKM matrix
  - V_{ud} by super allowed Fermi decay
  - Probe the validity of nuclear corrections







$$\begin{vmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{vmatrix}$$

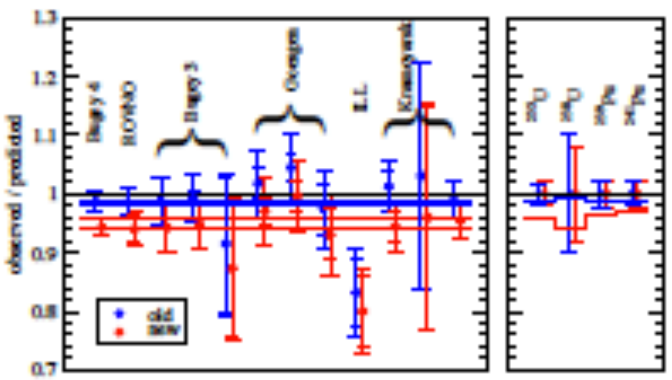
Light Sterile Neutrinos

- Several Observations which can be Interpreted as Oscillations with $\Delta m^2 \sim \text{eV}^2$

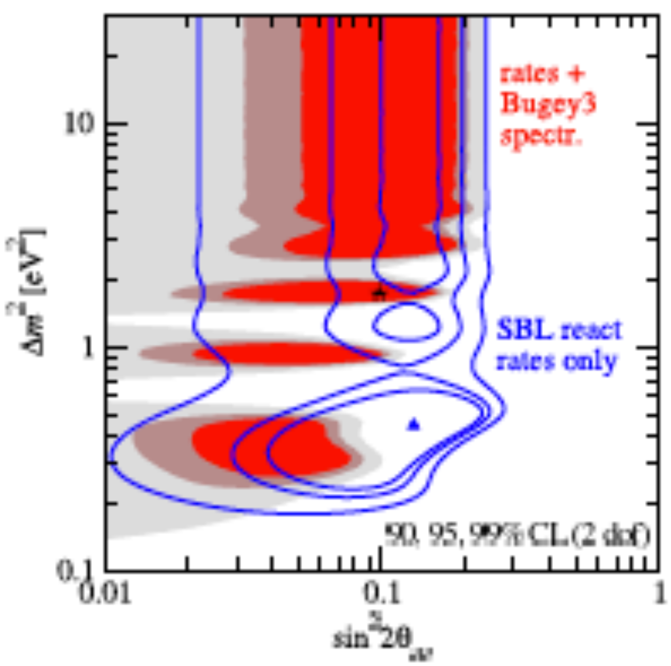
Reactor Anomaly

New reactor flux calculation

$\Rightarrow$ Deficit in data at $L \lesssim 100$ m



Explained as ν_e disappearance



T.Schwetz, talk ν2012

Gallium Anomaly

Acero, Giunti, Laveder, 0711.4222
Giunti, Laveder,1006.3244

Radioactive Sources (^{51}Cr, ^{37}Ar)

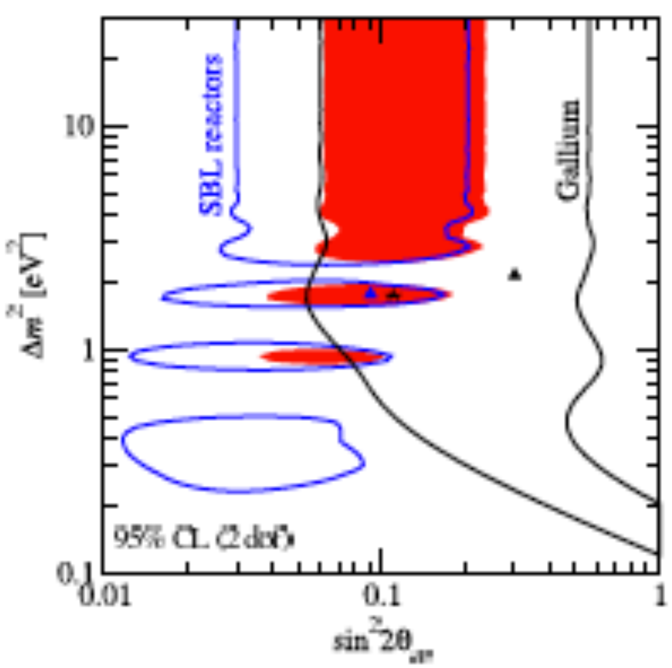
in callibration of Ga Solar Exp;

$\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$

Give a rate lower than expected

$$R = \frac{N_{\text{obs}}}{N^{\text{th}}_{\text{Bahc}}} = 0.86 \pm 0.05 \; (2.8\sigma)$$

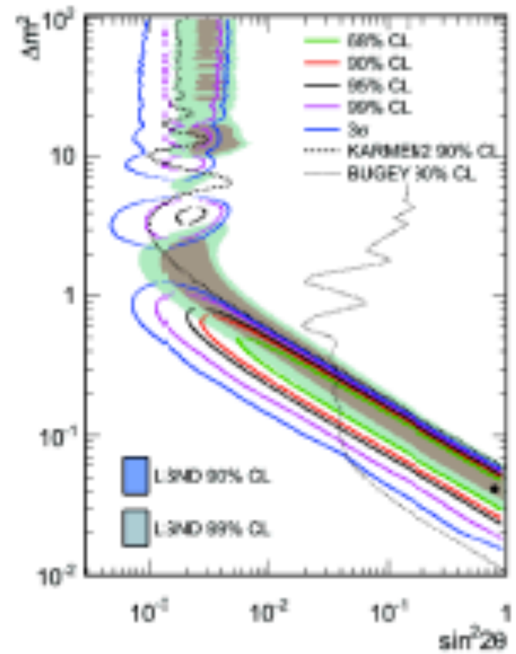
Explained as ν_e disappearance



T.Schwetz, talk ν2012

LSND, MiniBoone

$\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



Concha Gonzalez-Garcia, ICHEP 2012

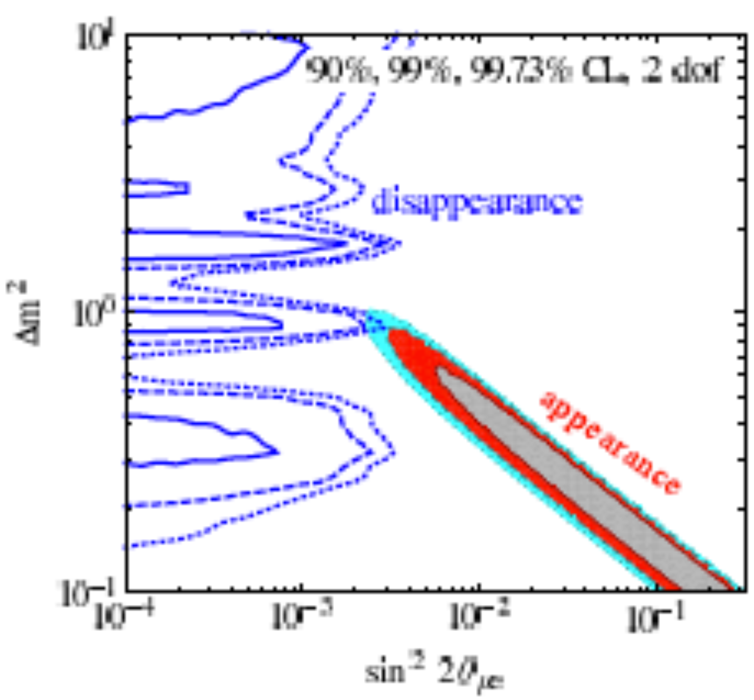
Light Sterile Neutrinos

- These explanations require $3{+}N_s$ mass eigenstates $\rightarrow$ N_s sterile neutrinos

- Problem is to fit together
  - $\nu_e \rightarrow \nu_e$ disappearance at SBL
  - $\nu_\mu \rightarrow \nu_e$ appearance at SBL
  - $\nu_\mu \rightarrow \nu_\mu$ no-disappearance at SBL (CDHS,ATM,MINOS)

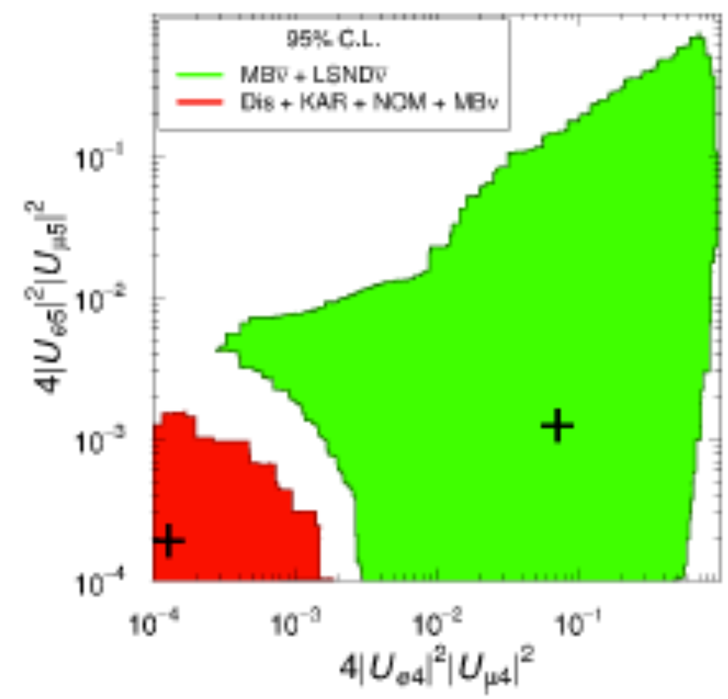
- Generically: $P(\nu_e \rightarrow \nu_\mu) \sim |U^*_{ei} U_{\mu i}|$ [i =heavier state(s)]
  - But $|U_{ei}|$ constrained by $P(\nu_e \rightarrow \nu_e)$ disappearance data
  - And $|U_{\mu i}|$ constrained by $P(\nu_\mu \rightarrow \nu_\mu)$ disappearance data
  - $\Rightarrow$ Severe tension

3+1



T.Schwetz, talk ν2012

3+2

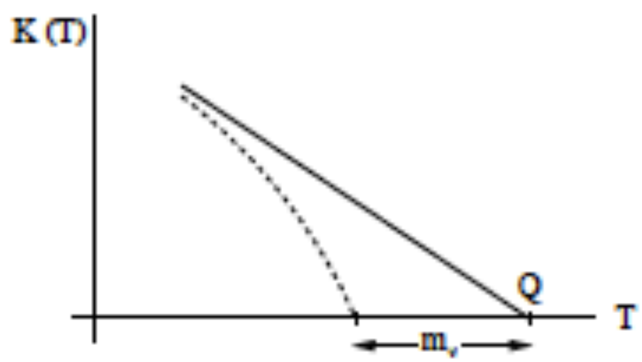


Giunti, Laveder, 1107.1452

Concha Gonzalez-Garcia, ICHEP 2012

Neutrino Mass Scale

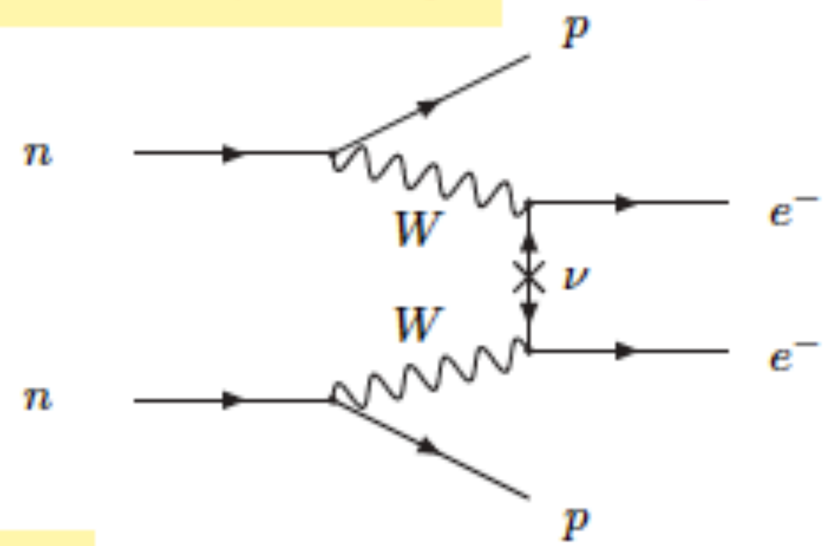
Single β decay : Dirac or Majorana ν mass modify spectrum endpoint



$$m^2_{\nu_e} = \sum m_j^2 |U_{ej}|^2 = c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2$$

ν-less Double-β decay: $\Leftrightarrow$ Majorana $\nu' s$ sensitive to Majorana phases

If m_ν only source of ΔL $\quad (T^{0\nu}_{1/2})^{-1} \propto (m_{ee})^2$



$$m_{ee} = |\sum U_{ej}^2 m_j|$$

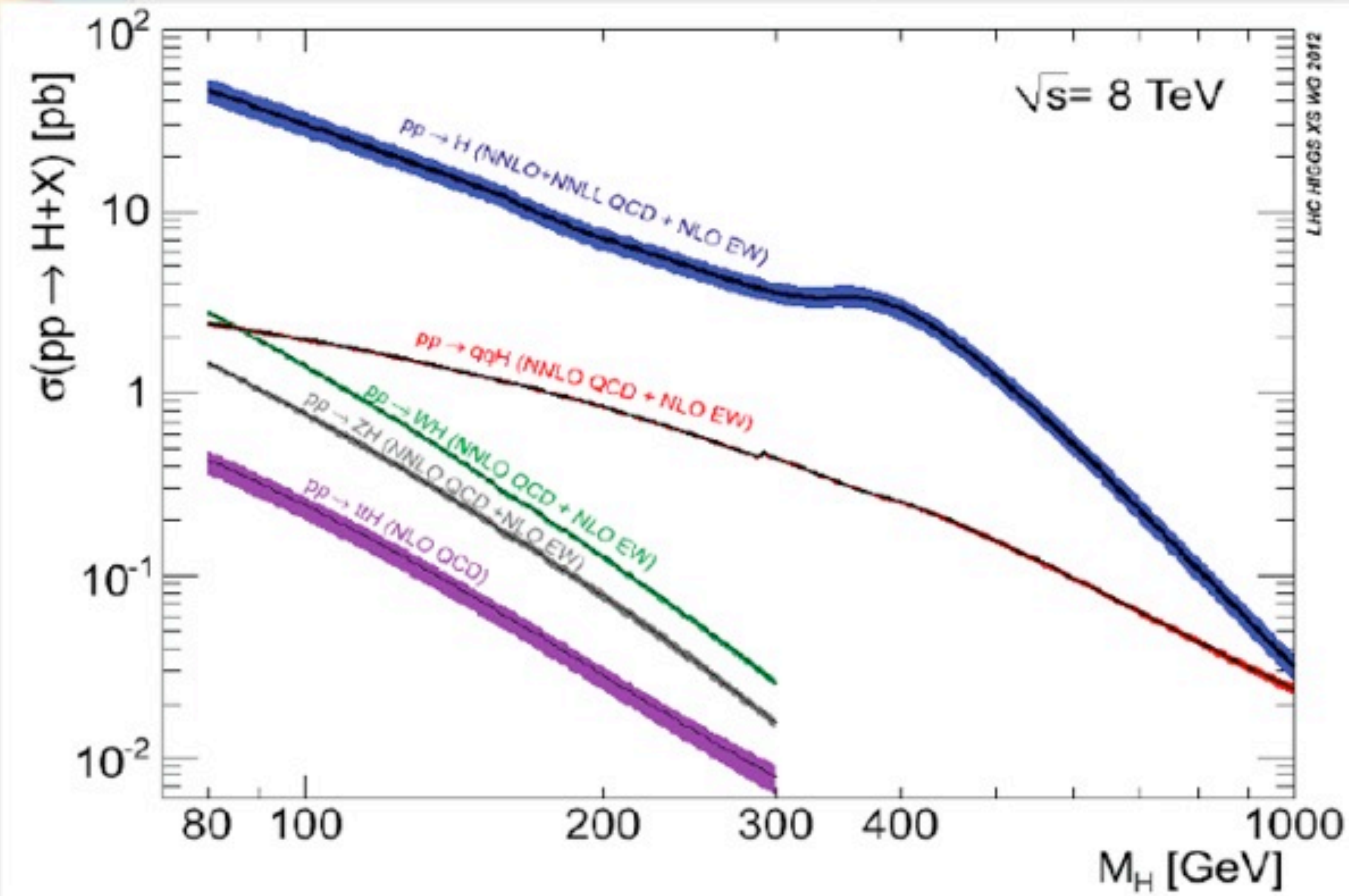
$$= \left| c_{13}^2 c_{12}^2 m_1 \, e^{i\eta_1} + c_{13}^2 s_{12}^2 m_2 \, e^{i\eta_2} + s_{13}^2 m_3 \, e^{-i\delta_{CP}} \right|$$

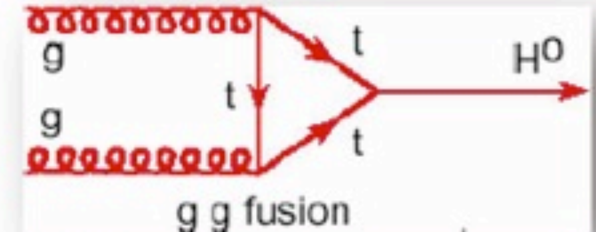
COSMO Neutrino mass (Dirac or Majorana)
modify the growth of structures

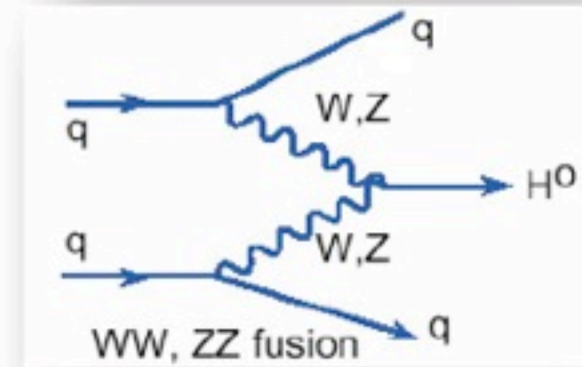
$$\sum m_i$$

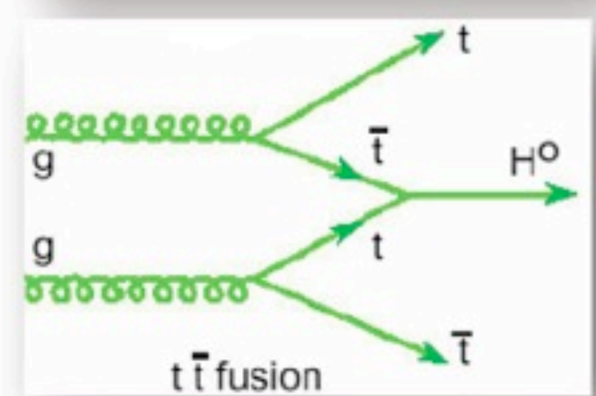
Concha Gonzalez-Garcia, ICHEP 2012

Higgs boson production



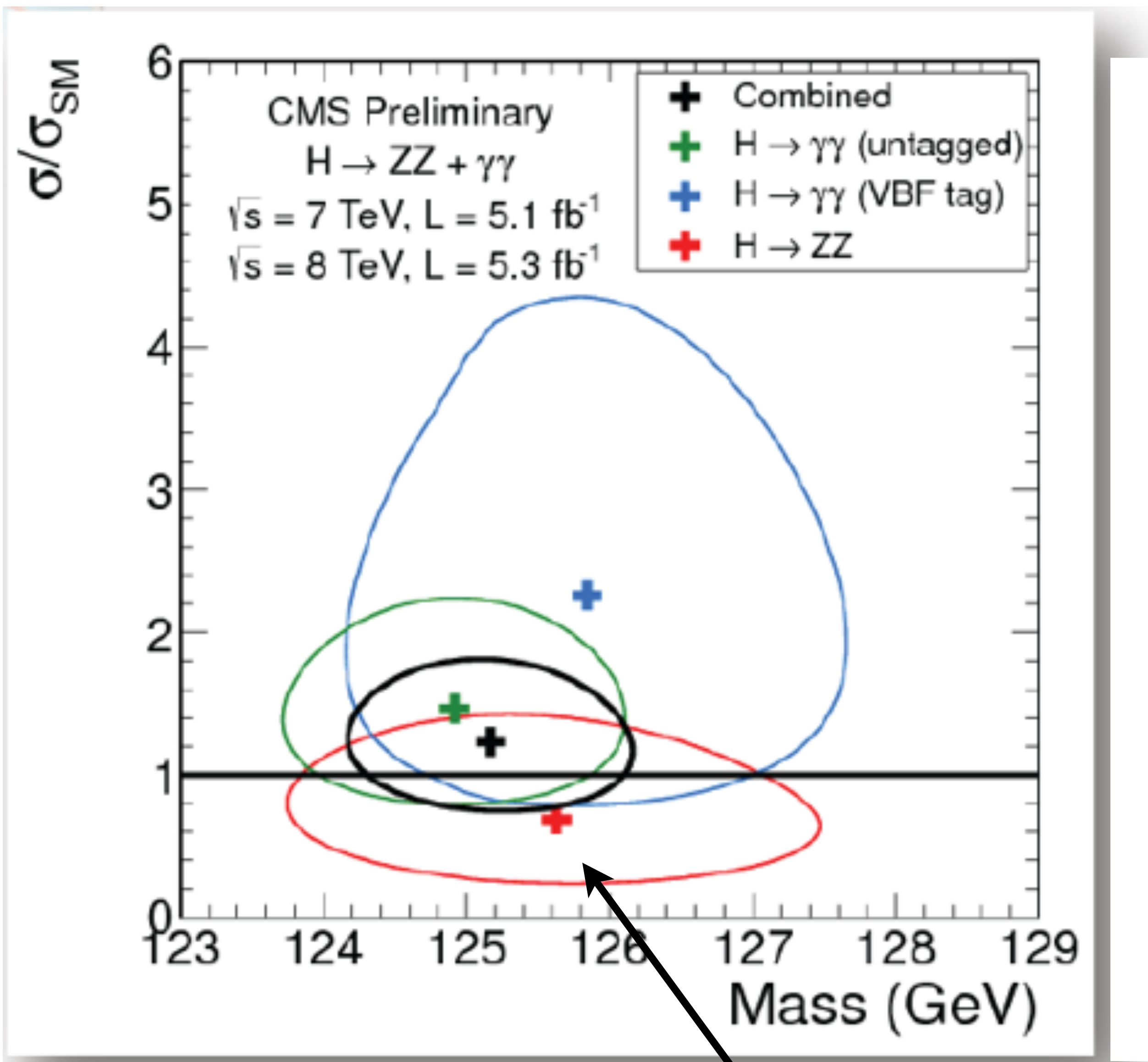


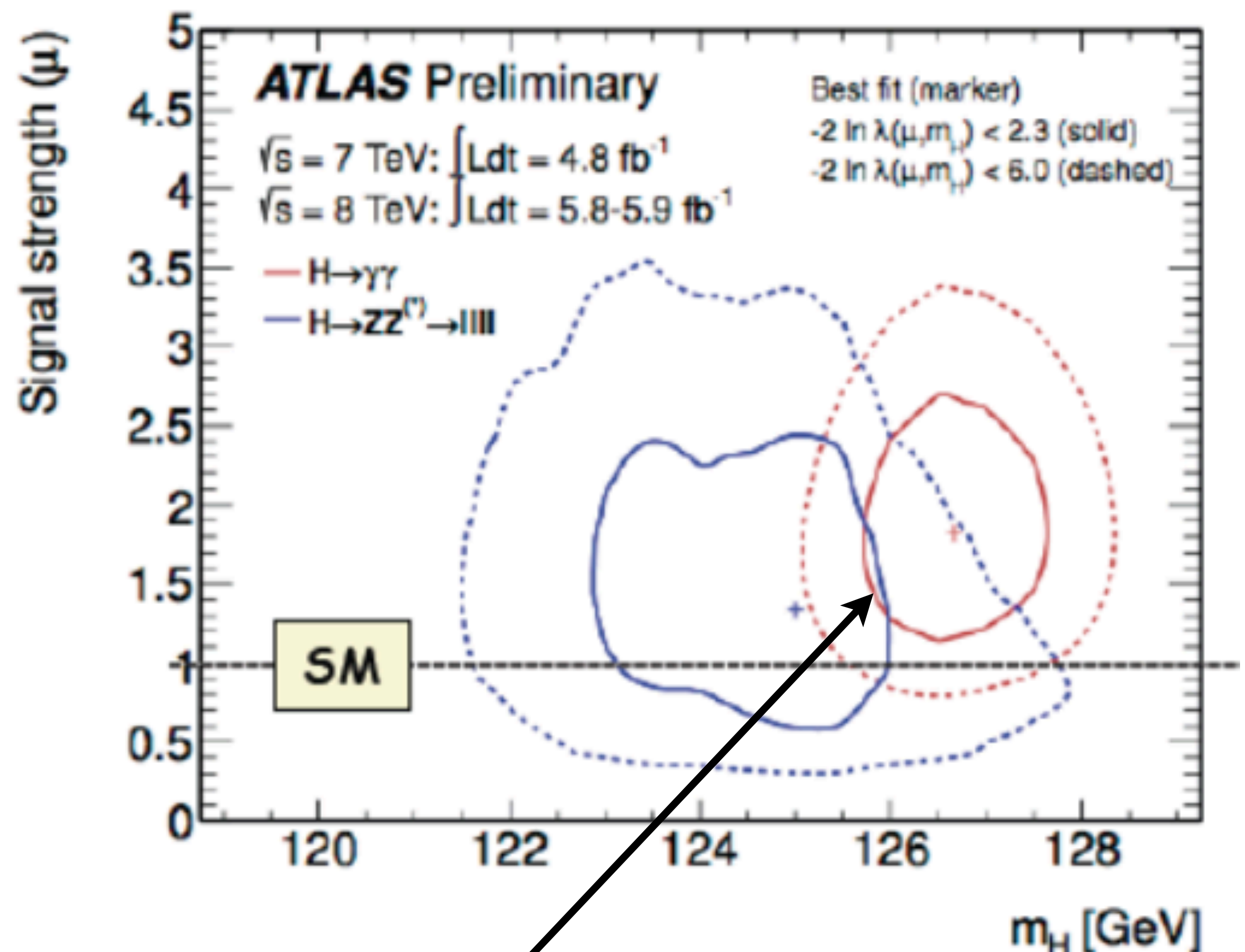




- $\sqrt{s}$=8 TeV: 25-30% higher σ than $\sqrt{s}$=7 TeV at low m_H
- All production modes to be exploited
  - gg VBF VH ttH
  - Latter 3 have smaller cross sections but better S/B in many cases

Characterization of the excess



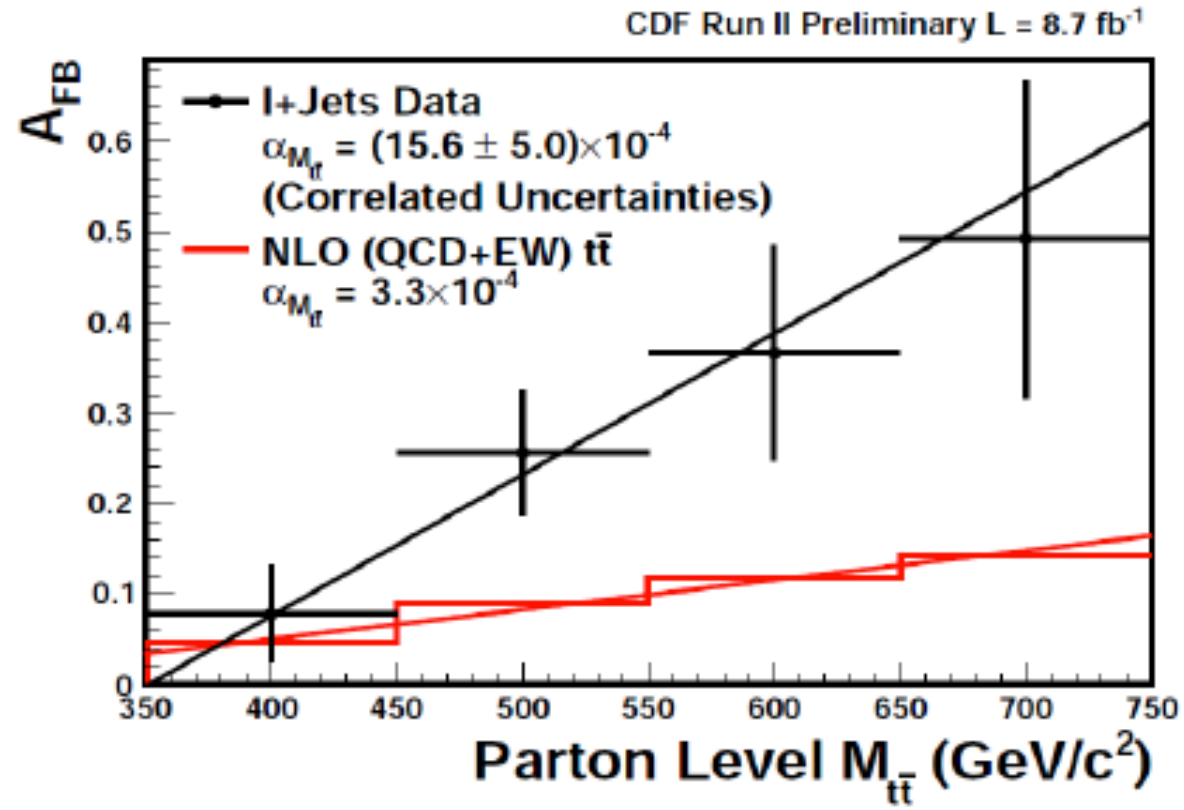


$m_H \sim 125$ GeV

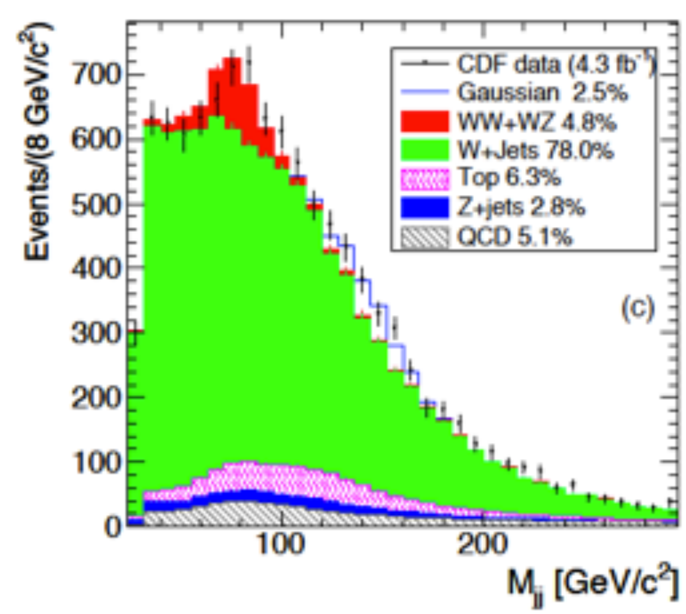
What the Tevatron has seen

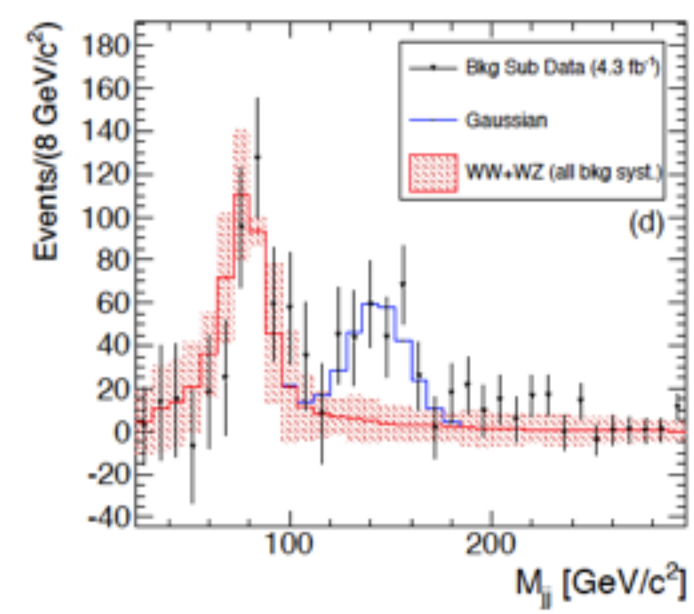
- Discrepancy with SM prediction in t-tbar FB asymmetry (top emitted preferentially in direction of incoming quark)

$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$



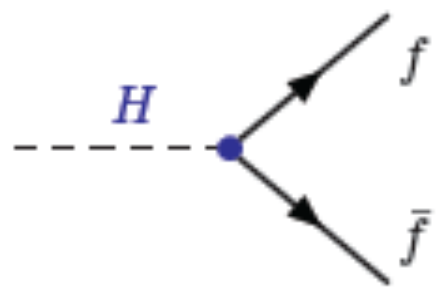
- Excess in the invariant mass distribution of jet pairs produced in association with W ($p\,\bar{p} \rightarrow j\,j + W$)

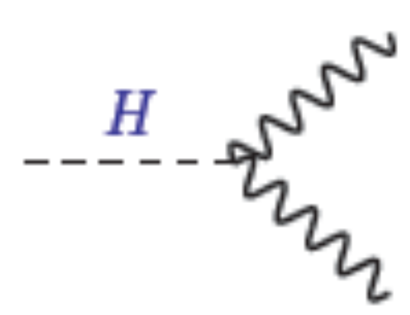




Non-standard Higgs couplings?

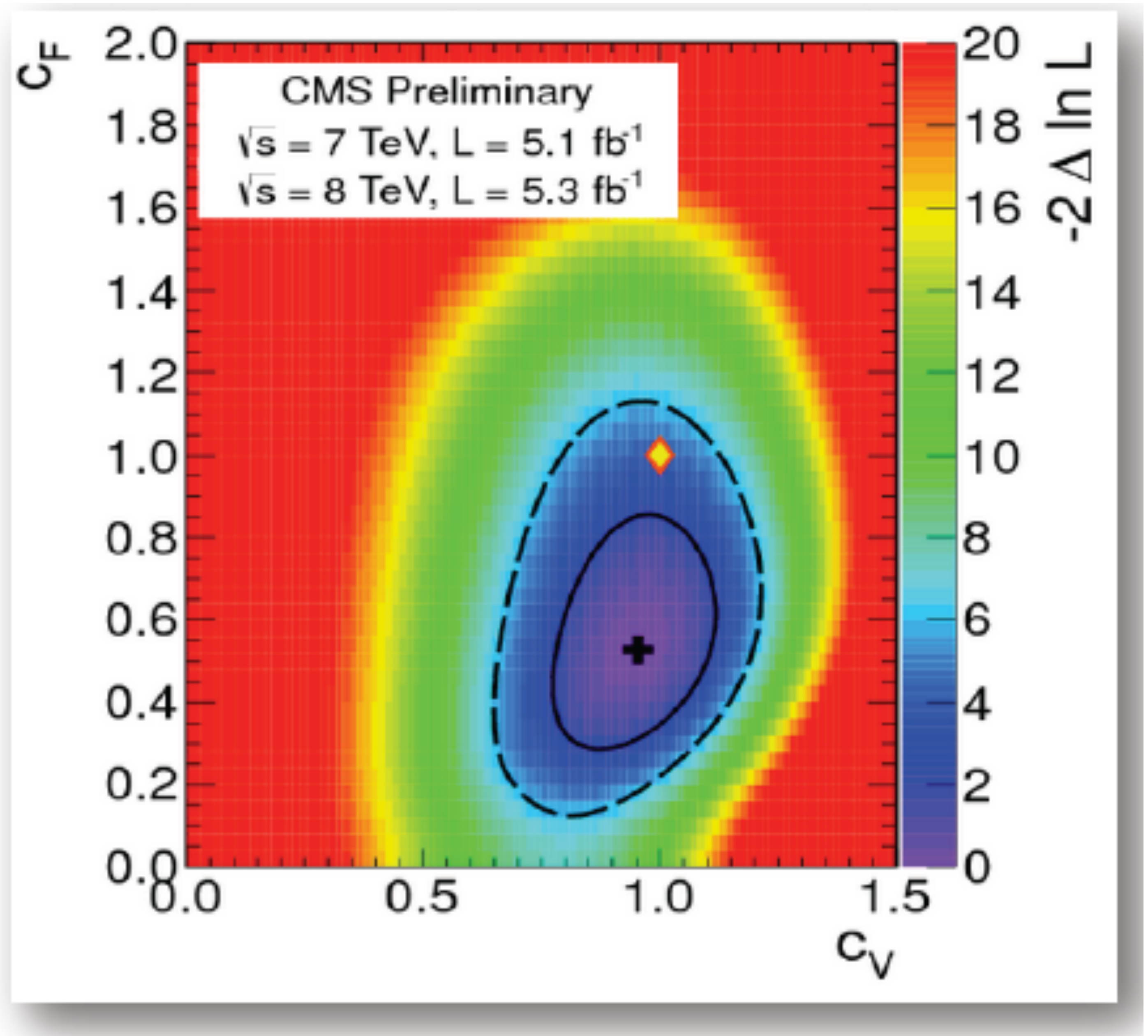
C_F





C_V

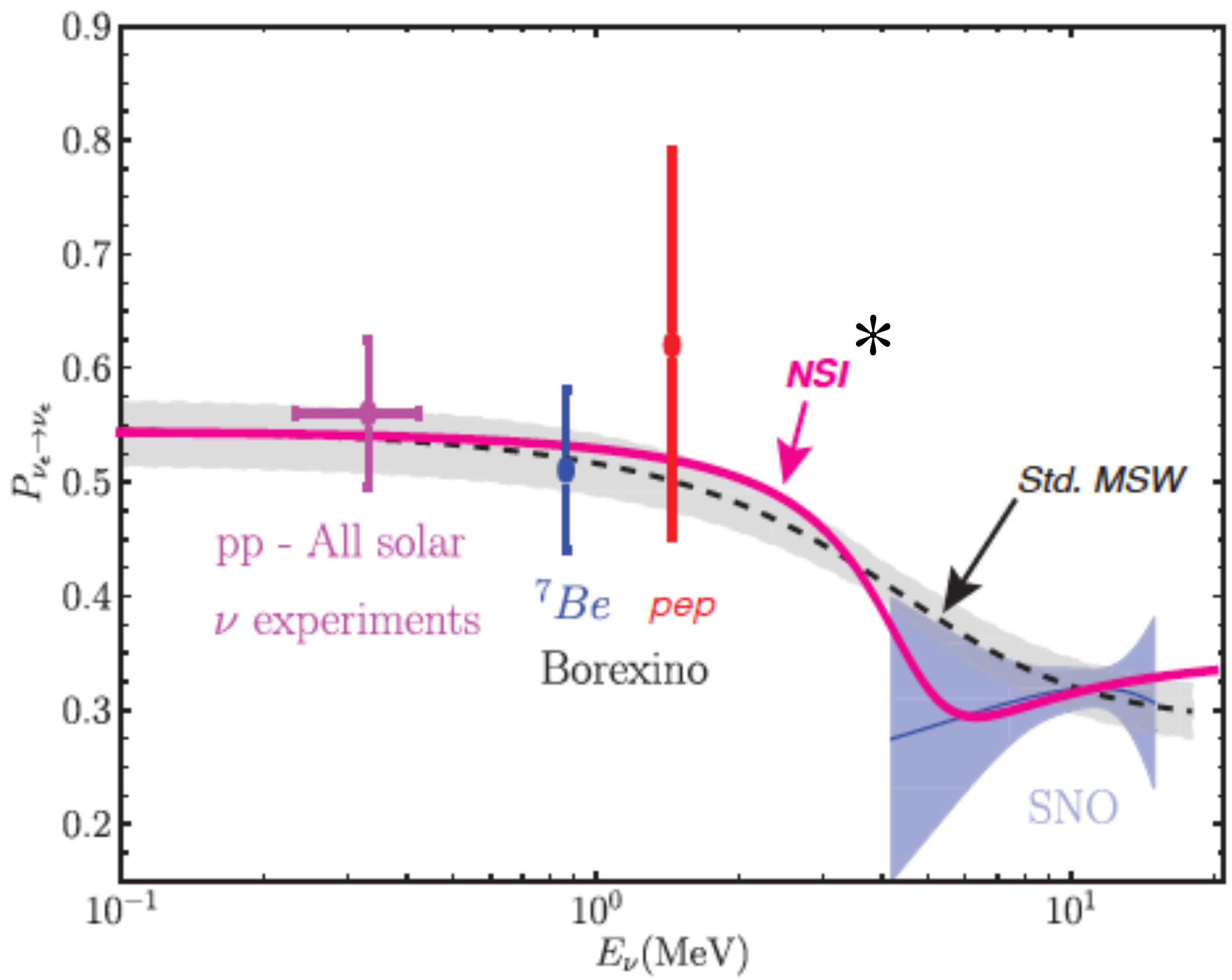
- Best fit consistent with SM at 95% CL
- Obviously more data needed



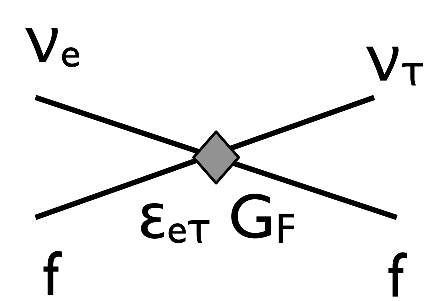
solid contour: 68% CL
dashed contour: 95% CL

- Are there ν Non Standard Interactions (NSI), as hinted to by solar neutrino data?

Friedland, Shoemaker 2012



* Uses $\varepsilon_{e\tau}$ =0.4



- Largely unconstrained by LHC (for light mediator of NSI)

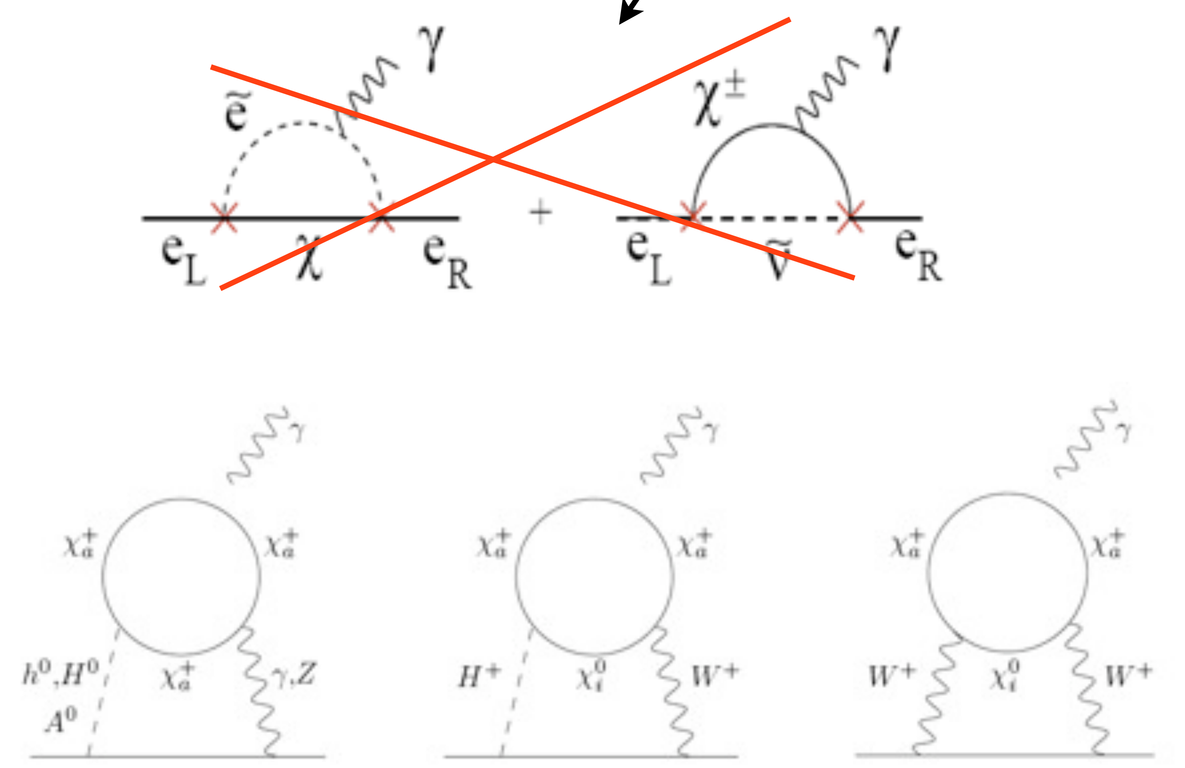
Example: MSSM

- The (tight!) region of parameter space in which EWB is viable is determined by consistency with: (i) 1[st] order phase transition, (ii) direct searches, (iii) Higgs mass constraint, (iv) one-loop EDMs

$$d_{e,n} \propto \sin \phi_\mu \qquad Y_B \propto \sin \phi_\mu$$

Universal "B-ino" and "W-ino" phases

$$\phi_1 = \phi_2 \equiv \phi_\mu$$



Chang-Chang-Keung. Giudice-Romanino, Pilaftsis, Li, Profumo, Ramsey-Musolf

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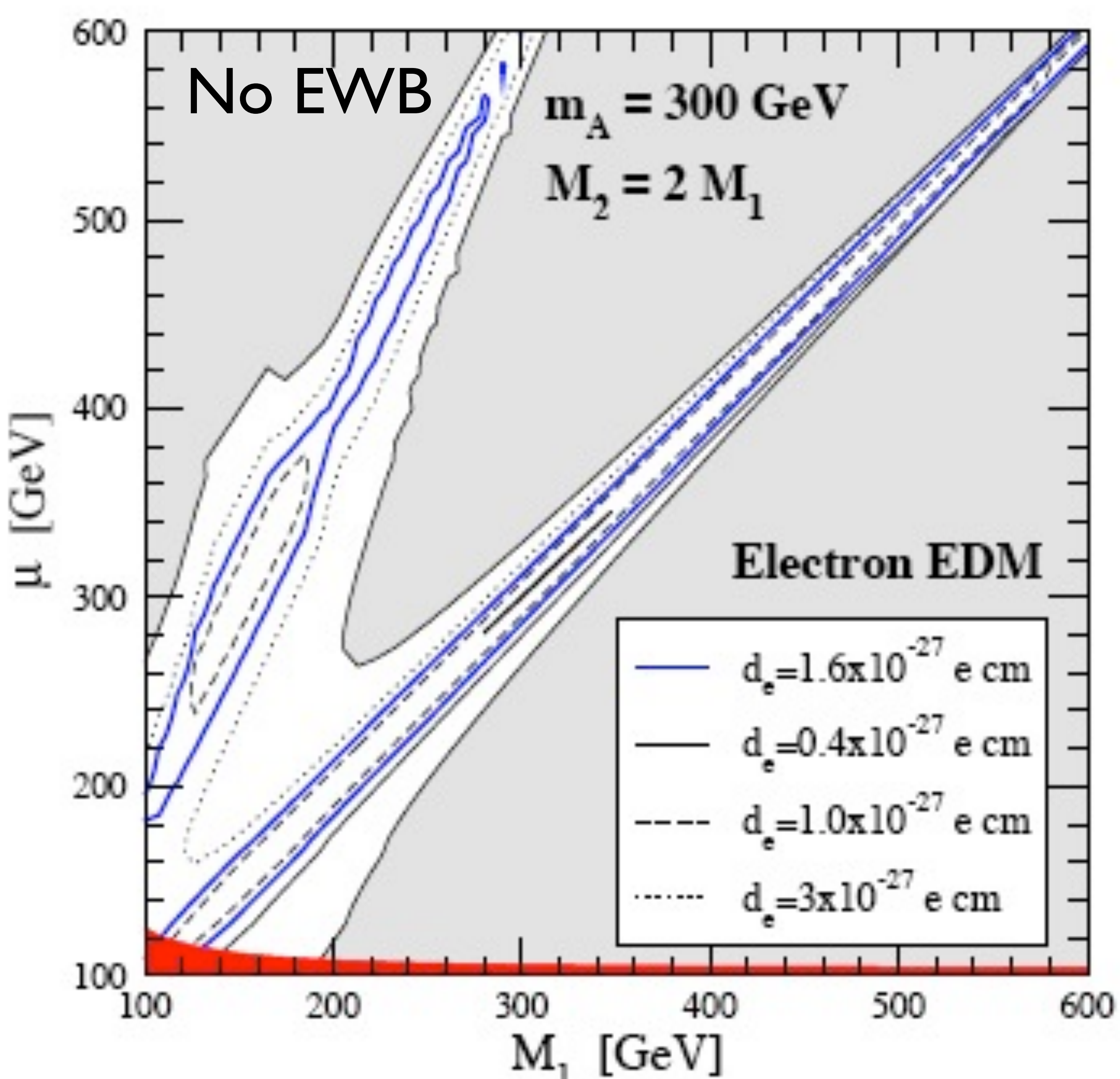
- Project on the μ-M_1 plane



VC, Li, Profumo, Ramsey-Musolf 2010

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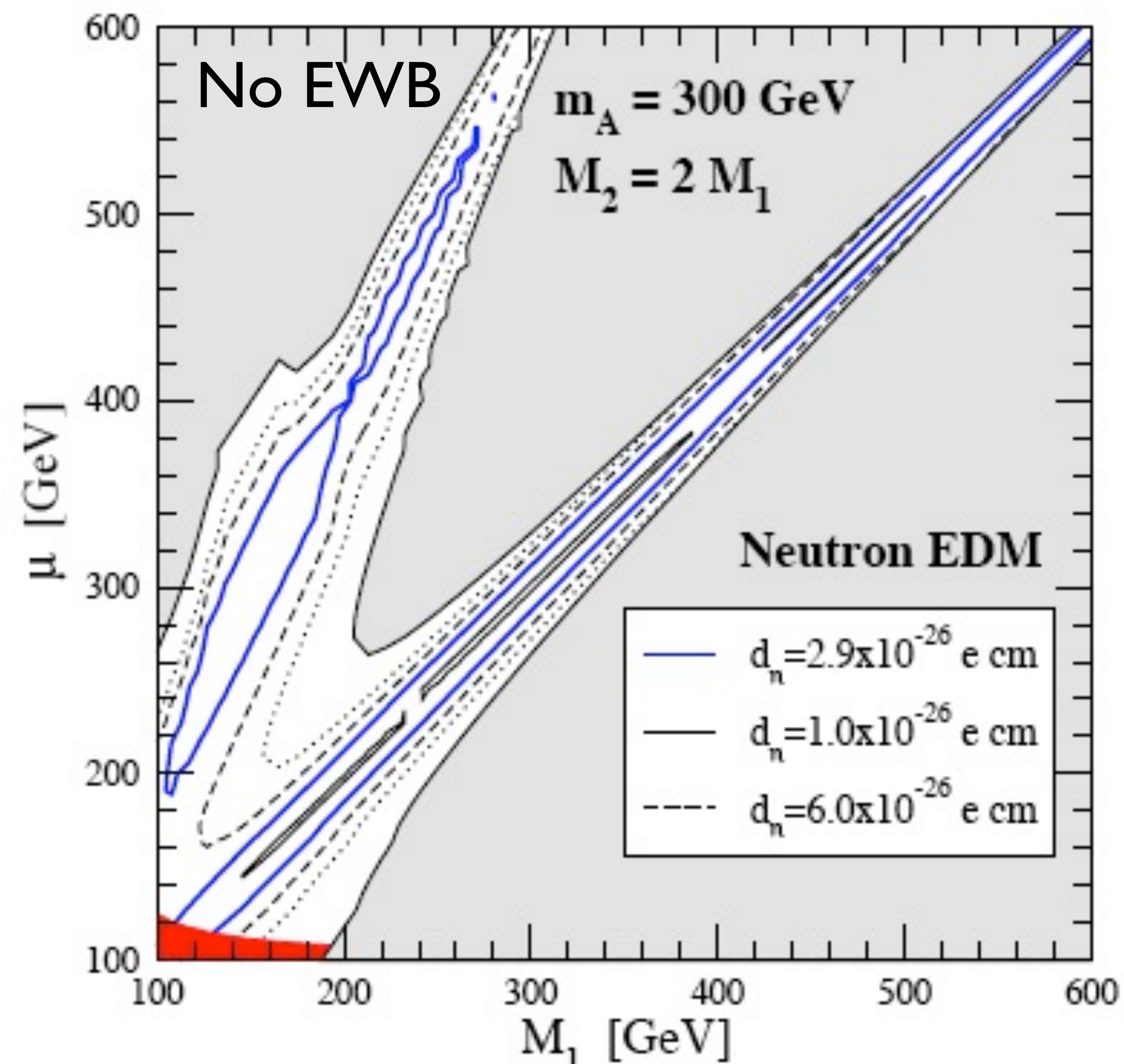


VC, Li, Profumo, Ramsey-Musolf 2010

Example: MSSM

- The (tight!) region of parameter space in which EWB is viable is determined by consistency with: (i) 1st order phase transition, (ii) direct searches, (iii) Higgs mass constraint, (iv) one-loop EDMs

- Successful SUSY baryogenesis implies "guaranteed signals" for e and n EDMs, within reach of the next generation experiments

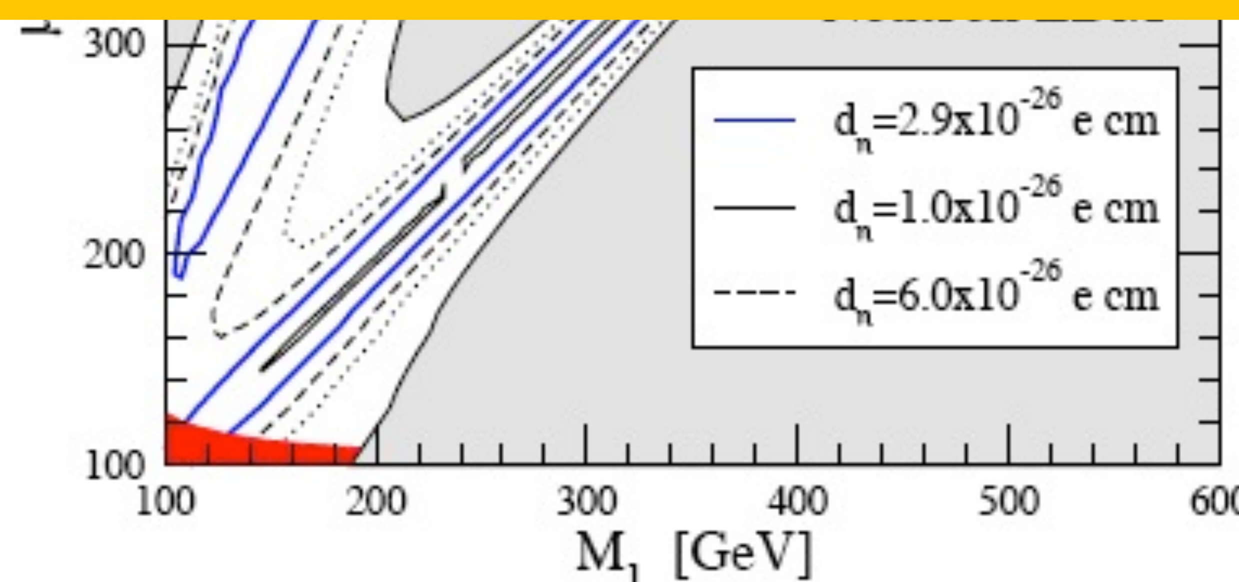
- CAVEAT: outstanding (order-of-magnitude) theoretical uncertainties in transport calculations are being addressed

$$d_{e,n} \propto \sin \phi_\mu \qquad Y_B \propto \sin \phi_\mu$$

Universal "B-ino" and "W-ino" phases

$$\phi_1 = \phi_2 \equiv \phi_\mu$$

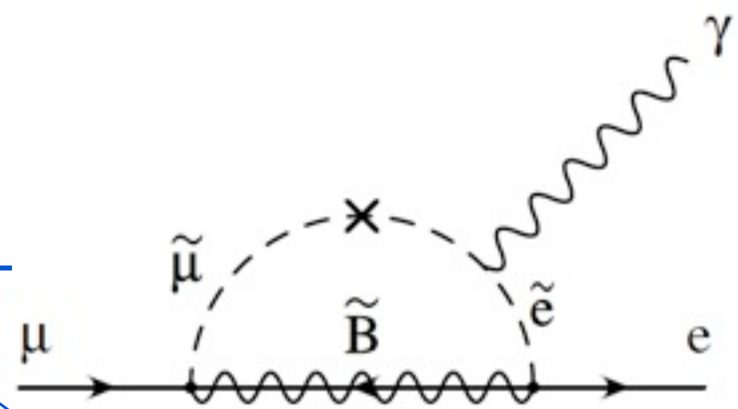
- Project on the μ-M_1 plane



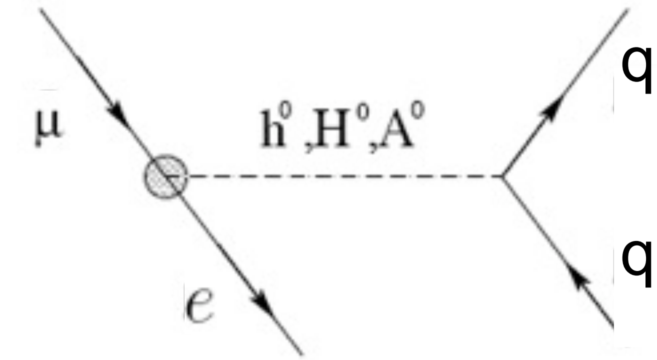
VC, Li, Profumo, Ramsey-Musolf 2010

- Several operators (≡mechanisms) at dim6: rich phenomenology

Dominant in SUSY-GUT and SUSY see-saw scenarios



Dominant in RPV SUSY and RPC SUSY for large tan(β) and low m_A

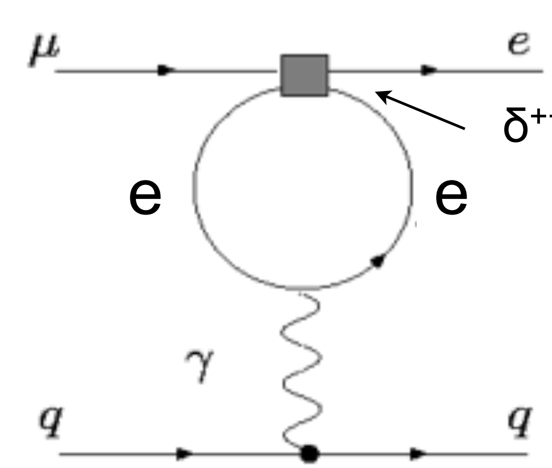


$$\mathcal{L}_{eff} \supset \frac{[\alpha_D]^{ij}}{\Lambda^2}\, \varphi^\dagger\, \bar{e}^i_R \sigma_{\mu\nu} \ell^j_L\, F^{\mu\nu} + \frac{[\alpha_S]^{ij}}{\Lambda^2}\, \bar{e}^i_R \ell^j_L\, \bar{q}_L d_R$$

$$+ \frac{[\alpha_{V(Z)}]^{ij}}{\Lambda^2}\, \bar{\ell}^i_L \gamma_\mu \ell^j_L\, \varphi^\dagger D^\mu \varphi + \frac{[\alpha_{V(\gamma)}]^{ij} e_q}{\Lambda^2}\, \bar{\ell}^i_L \gamma_\mu \ell^j_L\, \bar{q}_L \gamma^\mu q_L + \ldots$$

Z-penguin

Enhanced in triplet models, Left-Right symmetric models



... + 4-lepton operators

Universality reach

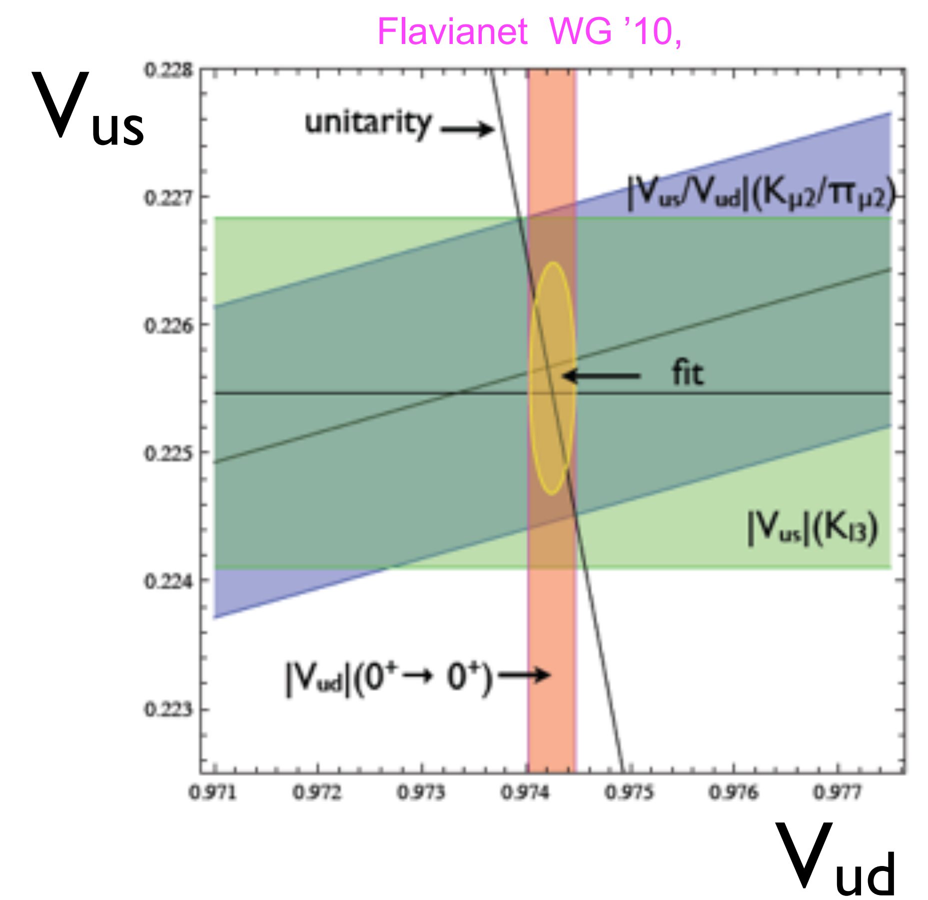
- Cabibbo universality:

$$\Delta_{CKM} = (1 \pm 6) * 10^{-4}$$

Error equally shared between V_{ud} and V_{us}

$$\varepsilon_L + \varepsilon_R < 1 * 10^{-3}$$
$$\Lambda > 11 \text{ TeV}$$

@ 90% CL



- Lepton universality:

$\pm 0.5 * 10^{-3}$

PEN, PIENU

$$\Delta_{e/\mu} = (-3 \pm 3) * 10^{-3}$$

@ 90% CL

$$\varepsilon_L - \varepsilon_R < 2.5 * 10^{-3}$$
$$\Lambda_{L-R} > 3.5 \text{ TeV}$$
$$\varepsilon_P < 1.2 * 10^{-6}$$
$$\Lambda_P > 160 \text{ TeV}$$

QCD and constraints on $\varepsilon_{S,T}$