In Search of the New Standard Model

Vincenzo Cirigliano
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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**
High- and Low-Energy Frontiers

- Two complementary strategies to probe BSM physics:
  
  **High Energy Frontier**  
  (direct access to new d.o.f)
  
  **Low Energy Frontier**  
  (indirect access to new d.o.f through virtual effects)

\[
E \quad M_{BSM} \\
E_{\text{exp}} \ll M_{BSM}
\]
High- and Low-Energy Frontiers

- Two *complementary* strategies to probe BSM physics:

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

- EWSSB 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)
- ...

- ...
High- and Low-Energy Frontiers

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  - **High Energy Frontier**
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    - EWSP mechanism
    - Directly probe scale and interactions of new heavy particles
    - ...
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    - (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
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
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  - ...

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

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{BSM}$$
High- and Low-Energy Frontiers

- Two complementary strategies to probe BSM physics:
  - High Energy Frontier (direct access to new d.o.f)
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- Both frontiers needed to reconstruct the structure, symmetries, and parameters of $L_{BSM}$ ⇒ address the outstanding open questions

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

Z→\(\mu\mu\) 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 $\sim 125-126$ 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

- $H \rightarrow γγ$
  
  - $h \rightarrow γγ$

- $H \rightarrow ZZ^* \rightarrow 4$ leptons
  
  - $h \rightarrow ℓ^+ ℓ^- ℓ'^+ ℓ'^-$

---

**CMS**

- CMS Preliminary
- 4.1σ statistical significance

**ATLAS**

- 4.5σ statistical significance

---

**CMS**

- Selected diphoton sample
- Data 2011 and 2012
- Sig + Bkg inclusive fit ($m_h = 126.5$ GeV)
- 4th order polynomial

- $\int L dt = 4.8 fb^{-1}$
- $\int L dt = 5.9 fb^{-1}$

**ATLAS**

- $H \rightarrow ZZ^* \rightarrow 4l$

- 3.4σ significance
Compatibility with SM Higgs

- Higgs signals vs SM predictions for all modes:

\[ 0.8 \pm 0.22 \]
\[ 1.2 \pm 0.3 \]
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!

![Graph showing the mass of Higgs bosons in different models: SM (valid up to $M_p$), MSSM, and Composite Higgs.](image)
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

CMS EXOTICA
95% CL Exclusion Limits

Resonances

Compositeness

4th Generation

Contact Interaction

Long Lived

LeptoQuarks

Black Holes

4th Generation

St. Rafi

37
Caveats + Lesson

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

• $W' \rightarrow e\nu, \mu\nu$

• Di-jets resonances ($W'$, $Z'$, $G'$, ...)

![Images of data plots and graphs discussing ATLAS and CMS experiments related to W' searches.](image-url)
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!

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

- Obvious opportunity for precision low-energy probes

See e.g. B. Dobrescu, ICHEP 2012
SUSY searches

- Limits depend on assumptions on the s-particle spectrum
SUSY searches

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- 1st, 2nd generation squarks + gluinos: strongest bounds (M > TeV)
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- Stop: search strategy depends on the mass, still gaps
SUSY searches

- Limits depend on assumptions on the s-particle spectrum
- 1st, 2nd generation squarks + gluinos: strongest bounds ($M > \text{TeV}$)
- Stop: search strategy depends on the mass, still gaps
- Sleptons and charginos: considerably weaker bounds
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)
- “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
How do BSM particles / interactions affect low energy dynamics?
Low Energy Frontier

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

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

\[ \Lambda \leftrightarrow M_{BSM} \quad C_i \ [g_{BSM}, M_a/M_b] \]

- 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

Q1: Neutrinos: nature, mass, impact on cosmic evolution.
- $0\nu\beta\beta$
- $\nu$ oscillation
- $\nu$ mass measurements
- Sterile $\nu$'s
- LFV

Q2: Baryon asymmetry of the universe (B, CP, non eq.)
- $T$-violation in $n$, nuclei
- EDMs

Q3: New interactions / particles present at the dawn of the universe
- muon LFV
- muon $g-2$
- CC: universality, non V-A
- NC: PV scattering, APV
- neutrino NSI
Interconnections

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Leptogenesis (LNV, CPV)

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Electroweak Baryogenesis

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LHC

neutrino NSI
Interconnections

All contribute to the “reconstruction” of $\mathcal{L}_{BSM}$
• Caveat: one is really probing, $\Lambda/C^{(5)}$, $\Lambda/[C^{(6)}_i]^{1/2}$, ....

• So beware of couplings*, loop factors, approximate symmetries, etc
Physics reach -- at a glance

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

Rare / Forbidden processes: B, L, LF, CP violation searches have largest reach -- special status of "flagship" searches

LHC

Proton decay
Neutrinos (LNV)
LFV (muons)
Quark FCNC
EDMs*
(g-2)*
CC (P)*
CC (V)
CC (S,T)*
NC (Moller)
NC (eq)

Current
Future

$\Lambda_{\text{MAX}}$ (GeV)

Log$_{10}$ $[\Lambda_{\text{MAX}}$(GeV)]

EWSB
GUT
Planck

0 2 4 6 8 10 12 14 16 18

Current
Physics reach -- at a glance

- Caveat: one is really probing, $\Lambda/C^{(5)}$, $\Lambda/[C_i^{(6)}]^{1/2}$, etc.

- So beware of couplings*, loop factors, approximate symmetries, etc.
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

$$\mathcal{L}_{\nu} \supset -\frac{1}{2} M_{\nu}^{ij} \bar{\nu}_{R}^{i} \nu_{R}^{j} + Y_{\nu}^{ij} \bar{\nu}_{R}^{i} (H^{T} i \sigma_{2} L_{L}^{j}) + \frac{1}{\Lambda} g_{\nu}^{ij} \left( \bar{L}_{L}^{i} i \sigma_{2} H \right) (H^{T} i \sigma_{2} L_{L}^{j})$$

Light sterile states? Dirac mass term Majorana mass term:

$$m_{\nu}^{ij} = \nu Y_{\nu}^{ij} \quad m_{\nu}^{ij} = \frac{\nu^{2}}{\Lambda} g_{\nu}^{ij}$$

- Many key aspects of $\nu$ dynamics remain unknown, and should be explored by experiments in the next decade
Neutrinos

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

\[ \mathcal{L}_\nu \supset -\frac{1}{2} M^{ij}_\nu \bar{\nu}_R^i \nu_R^j + Y^{ij}_\nu \bar{\nu}_R^i (H^T i\sigma_2 L^j_L) + \frac{1}{\Lambda} \frac{g^{ij}}{2} (L^i_L i\sigma_2 H) (H^T i\sigma_2 L^j_L) \]

- Light sterile states?
- Dirac mass term
- Majorana mass term:

\[ m^{ij}_\nu = v Y^{ij}_\nu \]
\[ m^{ij}_\nu = \frac{v^2}{\Lambda} g^{ij} \]

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

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

\[
\mathcal{L}_\nu \supset \frac{1}{2} M^{ij}_\nu \bar{\nu}^c_R \nu^j_R + Y^{ij}_\nu \bar{\nu}^c_R (H^T i \sigma_2 L^j_L) + \frac{1}{\Lambda} g^{ij} \left( \bar{L}^c_L i \sigma_2 H \right) (H^T i \sigma_2 L^j_L)
\]

- Light sterile states?
- Dirac mass term
- Majorana mass term:

\[
\begin{align*}
L_L &= \begin{pmatrix} \nu_l \\ e_L \end{pmatrix} \\
H &= \begin{pmatrix} h^+ \\ v + h^0 \end{pmatrix}
\end{align*}
\]

\[
\begin{align*}
m^{ij}_\nu &= \nu Y^{ij}_\nu \\
m^{ij}_\nu &= \frac{\nu^2}{\Lambda} g^{ij}
\end{align*}
\]

• 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?

• 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

• Sensitivity up to $W_R$ mass $\sim 6\,\text{TeV}$ with $L = 300\,\text{fb}^{-1}$
Charged Lepton Flavor Violation

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

- Experimental limits probe

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

- $B_{\mu\rightarrow e\gamma} < 1.2 \times 10^{-11}$, $B_{\mu\rightarrow 3e} < 1.0 \times 10^{-12}$
- $B_{\mu\rightarrow e\gamma}^{T_{\mu-e}} < 4.3 \times 10^{-12}$, $B_{\mu\rightarrow e\gamma}^{Au} < 8 \times 10^{-13}$, $B_{\mu\rightarrow e\gamma}^{Pb} < 4.6 \times 10^{-11}$

\[
\rightarrow \quad 10^{-13/14} \quad \text{(MEG at PSI, now running)}
\]
\[
\rightarrow \quad 10^{-14/16} \quad \text{(PSI or MuSIC?)}
\]
\[
\rightarrow \quad 10^{-16/17} \rightarrow -18 \quad \text{(Mu2e, COMET, PRISM)}
\]

- New physics at TeV scale (and reasonable mixing pattern) $\Rightarrow$ 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 \( \tan(\beta) \) and low \( m_A \)

• Vector?
  Enhanced in triplet models, Left-Right symmetric models

• Z-penguin?
• Discriminating after discovering: LFV mechanism

• $\mu \rightarrow e\gamma$ vs $\mu \rightarrow e$ 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

![Graph showing the deviation from the pattern, indicating the presence of scalar and/or vector contributions.](image)
- **Discriminating after discovering:** LFV mechanism

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

\[ \propto \tan^2 \beta / m_{SL}^2 \quad \propto \tan^3 \beta / m_A^2 \]
CP violation and EDMs

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

  ![Diagram](image)

  \[ \mathcal{H} \sim d J \cdot E \]

  neutron, atoms, nuclei

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

<table>
<thead>
<tr>
<th>Particle</th>
<th>EDM limit</th>
<th>SM (CKM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>$1.5 \times 10^{-27}$</td>
<td>$10^{-38}$</td>
</tr>
<tr>
<td>( \mu )</td>
<td>$1.1 \times 10^{-19}$</td>
<td>$10^{-35}$</td>
</tr>
<tr>
<td>( \tau )</td>
<td>$3.1 \times 10^{-16}$</td>
<td>$10^{-34}$</td>
</tr>
<tr>
<td>p</td>
<td>$6.5 \times 10^{-23}$</td>
<td>$10^{-31}$</td>
</tr>
<tr>
<td>n</td>
<td>$2.9 \times 10^{-26}$</td>
<td>$10^{-31}$</td>
</tr>
<tr>
<td>(^{199}\text{Hg})</td>
<td>$3.1 \times 10^{-29}$</td>
<td>$10^{-33}$</td>
</tr>
</tbody>
</table>

\[
\left( \frac{m_i}{\Lambda^2} \right) \sin(\phi_{CP})
\]

- Current limits: \( \Lambda \sim 100 \text{ TeV} \), for \( \phi_{CP} \sim \mathcal{O}(1) \)
- Already strong constraints on TeV-scale BSM
• Probe QCD $\theta$-term + set of BSM-induced operators

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

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

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

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

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

- 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

+ 4-fermion ops
• **Discriminating after discovering:** nucleons and light nuclei EDMs using Chiral EFT (just one example!)

<table>
<thead>
<tr>
<th>Source</th>
<th>( \theta )</th>
<th>qCEDM</th>
<th>qEDM</th>
<th>TV ( \chi I )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_p/d_n )</td>
<td>( \mathcal{O}(1) )</td>
<td>( \mathcal{O}(1) )</td>
<td>( \mathcal{O}(1) )</td>
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</tr>
<tr>
<td>( d_d )</td>
<td>( d_n + d_p )</td>
<td>( d_n + d_p - 0.2 ) ( \frac{g_1}{F_\pi} )</td>
<td>( d_n + d_p )</td>
<td>( d_n + d_p )</td>
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<td>( d_{3\text{He}} + d_{3\text{H}} )</td>
<td>( d_n + d_p )</td>
<td>( d_n + d_p - 0.6 ) ( \frac{g_1}{F_\pi} )</td>
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</tr>
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- nucleon EDM alone cannot disentangle various sources
- only for isobreaking sources \( d_d \gg d_n + d_p \)
- for isobreaking sources, both \( d_{3\text{He}} + d_{3\text{H}} \) and \( d_{3\text{He}} - d_{3\text{H}} \) differ from one-body
- for theta, only \( d_{3\text{He}} - d_{3\text{H}} \) differ from one body
- for gCEDM, qEDM, no deviation from one-body

\[
\mathcal{L}_{f_f=2} = -\frac{g_0}{F_\pi} \bar{N} \pi \cdot \tau N - \frac{g_1}{F_\pi} \pi_3 \bar{N} N
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<td>( d_n + d_p - 0.2 \frac{\bar{g}<em>1}{F</em>\pi} )</td>
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<td>( d_n + d_p )</td>
<td>( d_n + d_p - 0.6 \frac{\bar{g}<em>1}{F</em>\pi} )</td>
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- 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)

  - B (baryon number) violation
  - C and CP violation
  - Departure from thermal equilibrium

  • \( \Gamma(i \rightarrow f) \neq \Gamma(i \rightarrow f) \)

- Quantitative statements possible in various BSM extension
Muon $g-2$

- Serious hint of new physics

\[
a_\mu = (g_\mu - 2)/2
\]

\[
a_\mu(\text{Expt}) = 116592089(54)(33) \times 10^{-11}
\]

\[
a_\mu(\text{SM}) = 116591802(42)(26)(02) \times 10^{-11}
\]

\[\Rightarrow \Delta a_\mu = 287(80) \times 10^{-11} \quad 3.6\sigma \text{ discrepancy}\]

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

- Probe BSM mag. dipole operators

\[
\mathcal{L} \quad \xrightarrow{\text{EWSB}} \quad \frac{y_\mu}{\Lambda^2} \; \bar{\mu} \sigma^{\alpha \beta} \mu \; F_{\alpha \beta}
\]

- $3.6\sigma$ discrepancy $\Rightarrow \frac{\Lambda}{\sqrt{y_\mu}} \sim 140\,\text{TeV} \quad (\Lambda \sim 3.5\,\text{TeV})$.

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 $H \rightarrow \gamma\gamma$ (blamed on stau loops) and g-2 (stau $\sim$ smuon)

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

Giudice-Paradisi-Strumia 2012
Charged Current processes

- In the SM, W exchange $\Rightarrow$ only V-A structure, universality relations

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

Lepton universality

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

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

Cabibbo universality

Peculiar “V-A” pattern in spectra and decay correlations
Charged Current processes

- In the SM, $W$ exchange $\Rightarrow$ only $V$-$A$ structure, universality relations

\[ G_F \sim \frac{g^2 V_{ij}}{M_W^2} \sim \frac{1}{v^2} \]

- BSM: sensitive to tree-level and loop corrections from large class of models $\rightarrow$ “broad band” probe of new physics
CC processes probe ten BSM effective couplings: \( \varepsilon_i, \tilde{\varepsilon}_i \sim \left(\frac{v}{\Lambda}\right)^2 \)

\[
\mathcal{L}_{CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} (1 + \delta_{RC} + \varepsilon_L + \varepsilon_R) \\
\times \left[ \bar{\ell} \gamma_\mu (1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma_\mu \left(1 - (1 - 2 \varepsilon_R) \gamma_5\right) d \right. \\
\left. + \varepsilon_S \bar{\ell} (1 - \gamma_5) \nu_\ell \cdot \bar{u} d \right. \\
\left. - \varepsilon_P \bar{\ell} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma_5 d \right. \\
\left. + \varepsilon_T \bar{\ell} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right] + \text{h.c.}
\]
- CC processes probe ten BSM effective couplings: \( \varepsilon_i, \tilde{\varepsilon}_i \sim (v/\Lambda)^2 \)

\[
\mathcal{L}_{CC} = - \frac{G^{(0)}_F V_{ud}}{\sqrt{2}} (1 + \delta_{RC} + \varepsilon_L + \varepsilon_R)
\]

- Affects overall normalization of “semi-leptonic” \( G_F \)

- Strong constraints from Cabibbo universality tests, precision extraction of \( V_{ud} \) \( (0^+ \to 0^+ \), neutron decay) \n
\[
\Delta_{CKM} = (1 \pm 6) \times 10^{-4}
\]

\[
\varepsilon_L + \varepsilon_R < 1 \times 10^{-3} \quad \text{@ 90% CL}
\]

\[
\Lambda > 11 \text{ TeV}
\]
CC processes probe ten BSM effective couplings: $\epsilon_i, \tilde{\epsilon}_i \sim (v/\Lambda)^2$

\[
\mathcal{L}_{CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} (1 + \delta_{RC} + \epsilon_L + \epsilon_R) \\
\times \left[ \bar{\ell} \gamma_\mu (1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma^\mu \left(1 - (1 - 2 \epsilon_R) \gamma_5 \right) \right] d
\]

- Affects relative normalization of axial and vector currents
- Neutron and nuclear decays sensitive to $(1-2\epsilon_R)^* g_A$ through lifetime and angular correlations
- Disentangling $\epsilon_R$ requires precision lattice calculations of $g_A$: we are not there (yet)
- Strong constraints from $\pi \to e\nu$ (depend on the structure of $(\varepsilon_P)^{ab}$ in lepton flavor space)

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

- Other constraints:
  - $\varepsilon_L - \varepsilon_R < 2.5 \times 10^{-3}$
  - $\Lambda_{L-R} > 3.5$ TeV
  - $\varepsilon_P < 1.2 \times 10^{-6}$
  - $\Lambda_P > 160$ TeV

@ 90% CL

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

\[
\mathcal{L}_{CC} = -\frac{G_F^{(0)}}{\sqrt{2}} \left[ \bar{\ell} \gamma_\mu (1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma_5 d 
\right.
\]

\[
+ \varepsilon_S \bar{\ell} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma_5 d
\]

\[
- \varepsilon_P \bar{\ell} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma_5 d
\]

\[
+ \varepsilon_T \bar{\ell} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \left] + \text{h.c.} \right.
\]

- Neutron and nuclear decay correlation coefficients and spectra
- $\pi \to e + \nu + \gamma$ Dalitz plot (tensor coupling)

see plots
• **Current**: $0^+ \rightarrow 0^+$ (b) and $\pi \rightarrow e \nu \gamma$ (green band)

• **Future**: neutron $b, b\nu$ @ $10^{-3}$ level ($N\bar{ab}; UCNB,b, abBA, ...$), $^6$He (b)

\[ \varepsilon_S = 2 \left( \frac{v}{\Lambda_S} \right)^2 \]
\[ \varepsilon_T = \left( \frac{v}{\Lambda_T} \right)^2 \]
\[ v = (2 \sqrt{2} G_F)^{-1/2} \]

\[ b_{0+} = (2.2 \pm 4.3) \times 10^{-3} \]

\[ |b_\nu| < 10^{-3} \]
\[ |b| < 10^{-3} \]

\[ \Lambda_S = 3.2 \text{ TeV} \]
\[ \Lambda_S = 5 \text{ TeV} \]

\[ \Lambda_T = 5 \text{ TeV} \]

Quark models:

\[ 0.25 < g_S < 1 \]
\[ 0.6 < g_T < 2.3 \]

(90% C.L.)

Adler et al, '75
Herczeg '01

Adler et al, '75
Herczeg '01
• **Current:** $0^+ \rightarrow 0^+$ (b) and $\pi \rightarrow e \nu \gamma$ (green band)

• **Future:** neutron b, $b \nu @ 10^{-3}$ level (Nab; UCNB,b, abBA, ...), $^6$He (b)

\[ \varepsilon_S \equiv 2 \left( \frac{v}{\Lambda_S} \right)^2 \]
\[ \varepsilon_T \equiv \left( \frac{v}{\Lambda_T} \right)^2 \]
\[ v \equiv (2 \sqrt{2} \, G_F)^{-1/2} \]

\[ \Lambda_S = 3.2 \text{ TeV} \]
\[ \Lambda_S = 5 \text{ TeV} \]

\[ \varepsilon_S = 0.8 \pm 0.6 \] (4)

\[ \varepsilon_T = 1.05(35) \]

Will reach $\delta g_S/g_S \sim 20\%$
- **CC processes** probe ten BSM effective couplings: \( \epsilon_i, \tilde{\epsilon}_i \sim (v/\Lambda)^2 \)

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

- “No interference” between SM amplitude and \( \tilde{\epsilon}_i \) couplings \((m_\nu/E_\nu)\)
- Spectra and angular correlations probe \( \tilde{\epsilon}_i \) to *quadratic order*
- Generally weaker bounds (5-10% level)

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

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

\[
+ \epsilon_i \quad \rightarrow \quad \tilde{\epsilon}_i \quad (1 - \gamma_5) \nu_\ell \quad \rightarrow \quad (1 + \gamma_5) \nu_\ell
\]
- Distinctive correlation between Cabibbo universality and lepton universality: information on sfermion spectrum
- MSSM effects (post-LHC) are at the few $\times 10^{-4}$ level
The “LHC pressure” can be addressed on a model by model basis.

However, in the “nightmare scenario” ($M_{BSM} \gg TeV$) general model-independent analysis can be performed.

The BSM couplings $\varepsilon_\alpha$ contribute to the process $p \ p \rightarrow \ e \ \nu \ + \ X$.
The “LHC pressure” can be addressed on a model by model basis.

However, in the “nightmare scenario” ($M_{BSM} \gg TeV$) general model-independent analysis can be performed.

The BSM couplings $\varepsilon_\alpha$ contribute to the process $p p \rightarrow e \nu + X$.

### Table

<table>
<thead>
<tr>
<th></th>
<th>$\varepsilon_{L+R}$</th>
<th>$\varepsilon_S$</th>
<th>$\varepsilon_T$</th>
<th>$\tilde{\varepsilon}_S$</th>
<th>$\tilde{\varepsilon}_T$</th>
<th>$\tilde{\varepsilon}_{L,R}$</th>
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<tbody>
<tr>
<td><strong>$\beta$</strong></td>
<td>$5 \times 10^{-4}$</td>
<td>$8.0 \times 10^{-3}$</td>
<td>$1.3 \times 10^{-3}$</td>
<td>$7.5 \times 10^{-2}$</td>
<td>$2.5 \times 10^{-2}$</td>
<td>$7.5 \times 10^{-2}$</td>
</tr>
<tr>
<td>LHC</td>
<td>--</td>
<td>$1.7 \times 10^{-2}$</td>
<td>$3.4 \times 10^{-3}$</td>
<td>$1.7 \times 10^{-2}$</td>
<td>$3.4 \times 10^{-3}$</td>
<td>$6.3 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

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 $\varepsilon_S$ and $\varepsilon_T$ probing effective scales $\Lambda_{S,T} \sim 7 \text{ TeV}$

• $b$ and $B$ at $10^{-4}$ level would give unmatched sensitivity
Neutral Current processes

- Precise LE measurements of $\theta_W$ + complementary (≡ probe different operators) constraints on BSM structures
• Operators probed & NP sensitivity:

**SM**

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

**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)
• Operators probed & NP sensitivity:

\[ \mathcal{L}_{PV}^{eq} = \frac{G_{\mu}}{\sqrt{2}} \sum_q \left[ C_1 q \bar{e} \gamma^{\mu} \gamma_5 e \bar{q} \gamma_{\mu} q + C_2 q \bar{e} \gamma^{\mu} e \bar{q} \gamma_{\mu} \gamma_5 q \right] \]

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)

Sensitivities to new physics:

• \( \Lambda_{new} = \sqrt{2 G_F \Delta Q_w} = 246.22 \text{ GeV}/\sqrt{\Delta Q_w} \)

• \( \Lambda_{new} = 3.4 \text{ TeV} \) (\( Q_w^o \) from E158)

• \( \Lambda_{new} = 4.6 \text{ TeV} \) (\( Q_w^p \) from Qweak)

• \( \Lambda_{new} = 2.5 \text{ TeV} \) (C1 from SoLID)

• \( \Lambda_{new} = 7.5 \text{ TeV} \) (\( Q_w^o \) from MOLLER)

• \( \Lambda_{new} = 6.3 \text{ TeV} \) (\( Q_w^p \) from P2@Mainz)

• \( \Lambda_{new} = 3.7 \text{ TeV} \) (\( g_R^2 \) from NuTeV)

• \( \Lambda_{new} = 5.2 \text{ TeV} \) (\( Q_w^n \) 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 $Q_{W^e}$
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
Opportunities

- Dark Matter:
  - Direct detection is Nuclear Physics (both Exp and Th)
  - “Dark sector” searches at JLAB
- 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
What if new interactions are not “contact” at LHC energy? How are the $\varepsilon$ bounds affected?

Explore classes of models generating $\varepsilon_S, \varepsilon_T$ at tree-level. Low-energy vs LHC amplitude:

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

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

Study dependence of the $\varepsilon$ bounds on the mediator mass $M$
Scalar resonance in s-channel

Upper bound on \( \epsilon_S \) based on \( m_T > 1 \text{ TeV} \)

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

\( \beta \) decays

contact, LHC

resonance, LHC

decoupling regime

Improvable with lower \( (m_T)^{cut} \)

But larger SM bkg

\( \sigma \) suppression due to \( m < (m_T)^{cut} \)
Tests of Nature’s Fundamental Symmetries

- Angular correlations in β-decay and search for scalar currents
  - Mass scale for new particle comparable with LHC
  - $^6\text{He}$ and $^{18}\text{Ne}$ at $10^{12}/s$

- Electric Dipole Moments
  - $^{225}\text{Ac}$, $^{223}\text{Rn}$, $^{229}\text{Pa}$ (30,000 more sensitive than $^{199}\text{Hg}$; > $10^9/s$)

- 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

---

Hendrik Schatz, NNPSS 2012 Slide 10
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

**Gallium Anomaly**

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

Radioactive Sources ($^{51}$Cr, $^{37}$Ar) in callibration of Ga Solar Exp;

$\nu_e + ^{71}$Ga $\rightarrow ^{71}$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 $\nu_e$ disappearance

**LSND, MiniBoone**

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

T.Schwetz, talk $\nu$2012

Concha Gonzalez-Garcia, ICHEP 2012
Light Sterile Neutrinos

- These explanations require $3 + N_s$ mass eigenstates $\rightarrow N_s$ sterile neutrinos
  \[ \nu_e \rightarrow \nu_e \text{ disappearance at SBL} \]
- Problem is to fit together $\nu_\mu \rightarrow \nu_e$ 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

\[ 3+1 \]

\[ 3+2 \]

T. Schwetz, talk $\nu$2012  Giunti, Laveder, 1107.1452

Concha Gonzalez-Garcia, ICHEP 2012
Neutrino Mass Scale

**Single $\beta$ decay** : Dirac or Majorana $\nu$ mass modify spectrum endpoint

\[ m_{\nu_e}^2 = \sum m_j^2 |U_{e j}|^2 = c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2 \]

**$\nu$-less Double-$\beta$ decay**:

$\iff$ Majorana $\nu's$ sensitive to Majorana phases

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

\[ m_{ee} = |\sum U_{e j}^2 m_j| \]

\[ = |c_{13}^2 c_{12}^2 m_1 e^{i\eta_1} + c_{13}^2 s_{12}^2 m_2 e^{i\eta_2} + s_{13}^2 m_3 e^{-i\delta_{CP}}| \]

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

\[ \sum m_i \]

Concha Gonzalez-Garcia, ICHEP 2012
\[ \sqrt{s} = 8 \text{ TeV}: \text{25-30\% higher } \sigma \text{ than } \sqrt{s} = 7 \text{ TeV at low } m_H \]

- 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 $t$-$\bar{t}$ bar FB asymmetry (top emitted preferentially in direction of incoming quark)

\[ A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \]

- 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?

- Best fit consistent with SM at 95% CL
- Obviously more data needed
• Are there ν Non Standard Interactions (NSI), as hinted to by solar neutrino data?

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

• Largely unconstrained by LHC (for light mediator of NSI)
The (tight!) region of parameter space in which EWB is viable is determined by consistency with: (i) 1\textsuperscript{st} order phase transition, (ii) direct searches, (iii) Higgs mass constraint, (iv) one-loop EDMs.

**Example: MSSM**

Universal “B-ino” and “W-ino” phases

\[ d_{e,n} \propto \sin \phi_\mu \quad Y_B \propto \sin \phi_\mu \]

\[ \phi_1 = \phi_2 = \phi_\mu \]
Example: MSSM

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

- For a given point in the MSSM parameter space, determine CPV phase $\phi_\mu$ by enforcing successful baryogenesis: then calculate EDMs

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

Universal “B-ino” and “W-ino” phases

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

- Project on the $\mu$-$M_1$ plane
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• Project on the $\mu$-$M_1$ plane
**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.

- 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.

\[
d_{e,n} \propto \sin \phi_{\mu} \quad Y_B \propto \sin \phi_{\mu}
\]

Universal “B-ino” and “W-ino” phases

\[
\phi_1 = \phi_2 \equiv \phi_{\mu}
\]

- Project on the \(\mu\)-\(M_1\) plane.

VC, Li, Profumo, Ramsey-Musolf 2010
- Several operators (≡ mechanisms) at dim6: rich phenomenology

- Dominant in SUSY-GUT and SUSY seesaw scenarios
- Dominant in RPV SUSY and RPC SUSY for large \( \tan(\beta) \) and low \( m_A \)

\[
L_{\text{eff}} \supset \frac{[\alpha_D]^{ij}}{\Lambda^2} \phi^+ \bar{e}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{[\alpha_S]^{ij}}{\Lambda^2} \bar{e}_R e_L \bar{q}_L d_R \\
+ \frac{[\alpha_V^{(Z)}]^{ij}}{\Lambda^2} \bar{\ell}_L \gamma_{\mu} \ell_L \phi^+ D^{\mu} \phi + \frac{[\alpha_V^{(\gamma)}]^{ij} e_q}{\Lambda^2} \bar{\ell}_L \gamma_{\mu} \ell_L \bar{q}_L \gamma^{\mu} q_L + \ldots
\]

- Z-penguin
- Enhanced in triplet models, Left-Right symmetric models

... + 4-lepton operators
Universality reach

- **Cabibbo universality:**
  \[ \Delta_{\text{CKM}} = (1 \pm 6) \times 10^{-4} \]
  Error equally shared between \( V_{ud} \) and \( V_{us} \)

- **Lepton universality:**
  \[ \varepsilon_L + \varepsilon_R < 1 \times 10^{-3} \] @ 90% CL
  \[ \Lambda > 11 \text{ TeV} \]

- **Lepton universality:**
  \[ \Delta_{e/\mu} = (-3 \pm 3) \times 10^{-3} \] @ 90% CL
  \[ \epsilon_L - \epsilon_R < 2.5 \times 10^{-3} \]
  \[ \Lambda_{L-R} > 3.5 \text{ TeV} \]
  \[ \epsilon_P < 1.2 \times 10^{-6} \]
  \[ \Lambda_P > 160 \text{ TeV} \]
QCD and constraints on $\varepsilon_{S,T}$

$\delta g_s/g_s = 10\%$
$\delta g_s/g_s = 20\%$
$\delta g_s/g_s = 50\%$

$\delta g_{S,T}/g_{S,T} \sim 20\%$ from LQCD needed to fully exploit experimental advances

(90% C.L.)

Current lattice results