The Physics of Electroweak-scale right-handed neutrinos

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- Extra charged leptons: $M > 100\,GeV$.
- Bound on a 4th generation down quark: $M_{b'} > 200 - 250\,GeV$. (A number of assumptions are made in obtaining this bound)
- No firm bound on quarks that decay differently from a sequential quark. For “very long lived” quarks that can leave a charged track, the lower bound is approximately $200\,GeV$.

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- The magnitude of the magnetic moment for the electron or muon: $\mu = (1+a)\frac{q}{2m}$; $a = \frac{g-2}{2}$ is the *anomalous magnetic moment*. $g = 2$ in Dirac theory without radiative corrections.

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- Last but not least: The addition of mirror generations to the S parameter can be offset by a negative contribution from the triplet scalar sector. In addition, Majorana fermions can have negative contributions to S.

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- Non-singlet Majorana neutrinos with electroweak scale masses $\Rightarrow$ lepton-number violating processes at electroweak scale energies.
- For singlet ν_R's, the issue is much more complex, involving delicate cancellations in the Dirac mass matrix to keep the light neutrinos light.
- Doubly charged Higgs $\Rightarrow$ lepton-number violating processes at electroweak scale energies.

Implications at the LHC

- In particular, we should be able to produce ν_R's and observe their decays at colliders (LHC, etc...) as well as a doubly charged Higgs that decays into two like-sign mirror charged leptons which subsequently decay into SM leptons.

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- $\Rightarrow$ Characteristic signatures: like-sign dilepton events $\Rightarrow$ A high-energy equivalent of neutrinoless double beta decay. (see also Keung and Senjanovic (83) for L-R model.)
- That could be the smoking gun for Majorana neutrinos!

Implications at the LHC

Some details: mirror leptons

- Interactions of mirror fermions with W: $\mathcal{L}_M^{CC} = -(\frac{g}{2\sqrt{2}}) \sum_i \bar{\psi}_i^M \gamma^\mu (1+\gamma_5)[T^+ W_\mu^+ + T^- W_\mu^-] \psi_i^M$.

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- Interactions of mirror fermions with Z: $\mathcal{L}_M^{NC} = -(\frac{g}{4\cos\theta_W}) Z_\mu \{\sum_i \bar{\nu}_i^M \gamma^\mu (1+\gamma_5) \nu_i^M + \sum_i \bar{e}_i^M \gamma^\mu [(-1+4\sin^2\theta_W) - \gamma_5] e_i^M\}$.

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$$i g_M l_R^{M,T} \sigma_2 (\tau_2 \tilde{\chi}) l_R^M = g_M \big(-e_R^{M,T} \sigma_2 \frac{1}{\sqrt{2}} \chi^+ \nu_R^M + \nu_R^{M,T} \sigma_2 \nu_R^M \chi^0 - e_R^{M,T} \sigma_2 e_R^M \chi^{++} - \nu_R^{M,T} \sigma_2 e_R^M \frac{1}{\sqrt{2}} \chi^+\big)$$

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- Interactions of mirror fermions with ϕ_S:
$$\mathcal{L}_S = g_{Sl}\, l_L^\dagger\, \phi_S\, l_R^M + g'_{Sl}\, e_R^\dagger\, \phi_S\, e_L^M + H.c.$$

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- Production of ν_R's. Elementary processes:
  - $50\%\ q + \bar{q} \to Z \to \nu_R + \bar{\nu}_R$; 50% $q + \bar{q} \to Z \to \nu_R + \nu_R$
  - $50\%\ u + \bar{d} \to W^+ \to \nu_R + l_R^{M,+}$; 50% $u + \bar{d} \to W^+ \to \bar{\nu}_R + l_R^{M,+}$
  - $50\%\ \bar{u} + d \to W^- \to \bar{\nu}_R + l_R^{M,-}$; 50% $\bar{u} + d \to W^- \to \nu_R + l_R^{M,-}$

Implications at the LHC

- Elementary process $\longrightarrow$ production cross section: parton model. q and $\bar{q}$ carry a fraction x_a and x_b of the momentum of the parent hadrons a and b. Need the "parton distribution functions": $f_{i,\bar{i}}^{(a)}(x_a, M^2)$ and $f_{i,\bar{i}}^{(b)}(x_b, M^2)$, where M^2 is the invariant mass squared of the outgoing particles.

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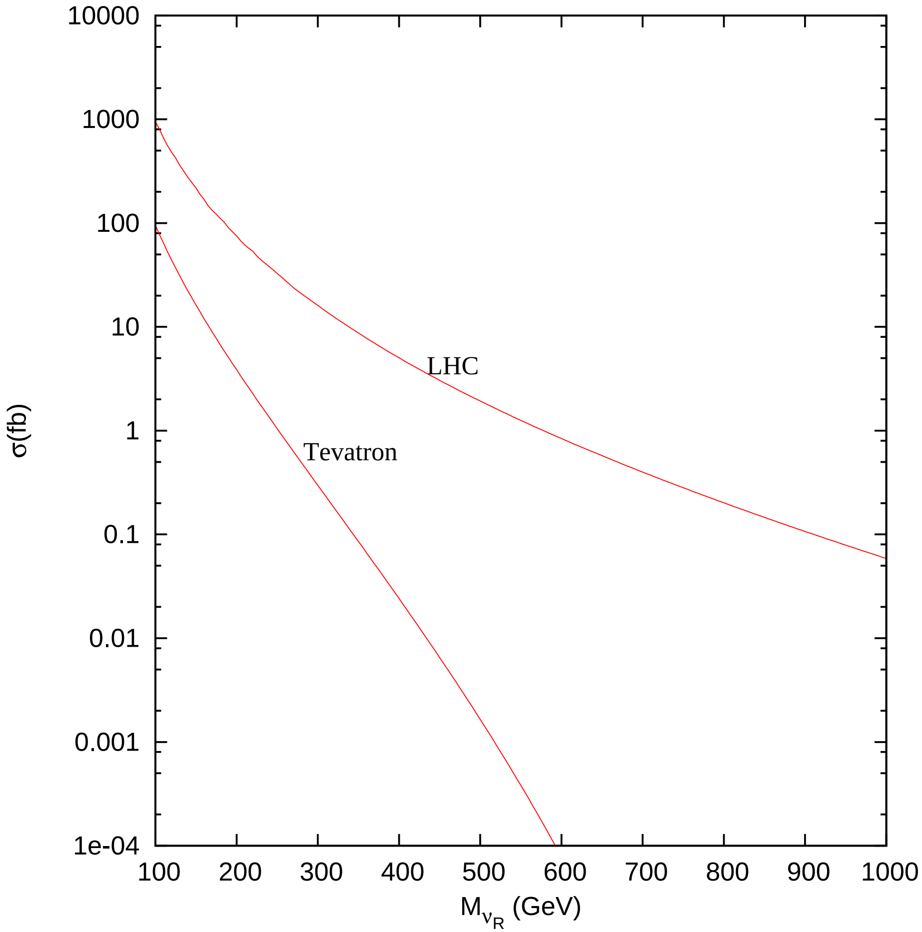
- At the Tevatron, we have $p + \bar{p}$ collisions with a center of mass energy: $\sqrt{s} = 1.8\, TeV$.
- At the LHC, we have $p + p$ collisions with a center of mass energy: $\sqrt{s} = 14\, TeV$.

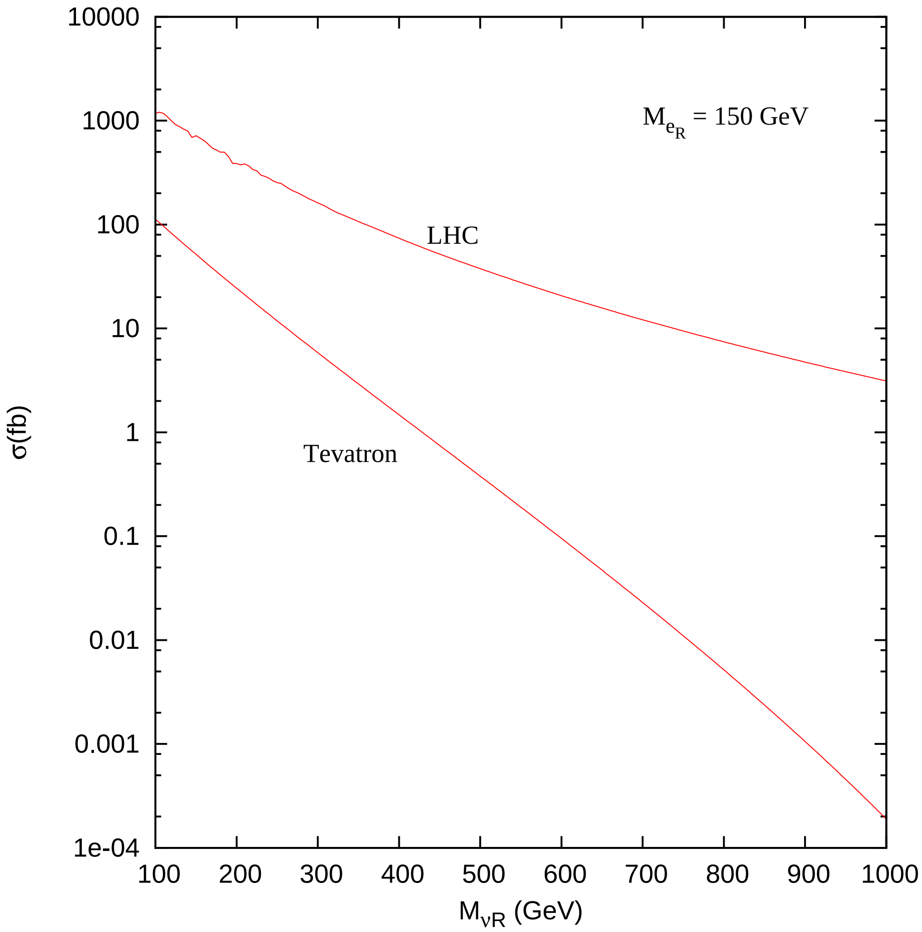
Implications at the LHC

ν_R pair production



Implications at the LHC

$e_R^M \, \nu_R$ pair production



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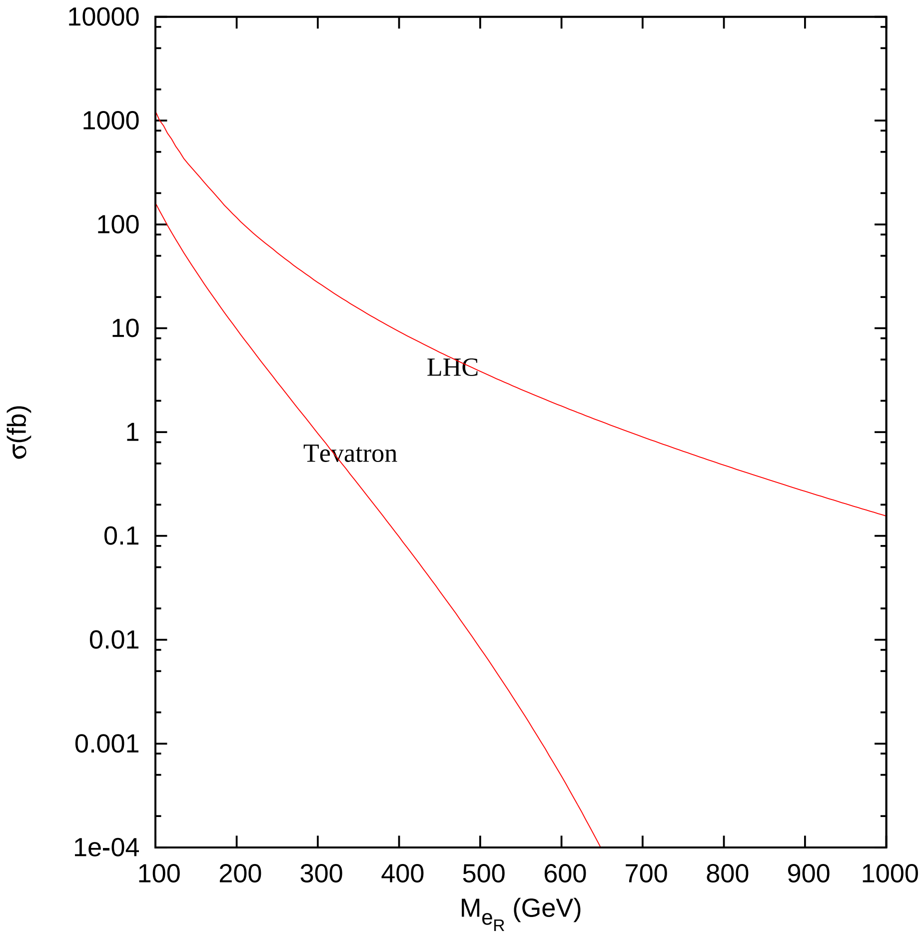

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- How many ν_R pairs at the LHC? Recall:
  $1\, barn = 10^{-24}\, cm^2$, $1\, pbarn(pb) = 10^{-36}\, cm^2$,
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- Number of ν_R pairs: $N = L\, \sigma$ where L is the luminosity (number of particles per unit area per unit time in the beam).
- With maximum luminosity at the LHC $L = 10^{34} cm^{-2} s^{-1}$: $N \sim 30,000/year$!

Implications at the LHC

Signatures

- Some ν_R are heavier than some e_R^M:
  $\nu_{Ri} \longrightarrow e_{Rj}^M + W^+$ followed by $e_{Rj}^M \longrightarrow e_{Lk} + \phi_S$.

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- $\nu_{Ri} + \nu_{Ri} \longrightarrow e_{Lk} + e_{Ll} + W^+ + W^+ + \phi_S + \phi_S$.
- Like-sign dileptons $e_{Lk} + e_{Ll}$ ($k = l$ or $k \neq l$) + 2 jets (from W) plus missing energies (from ϕ_S) $\Rightarrow$ Lepton-number violating signals!

Implications at the LHC

- Appearance of like-sign dileptons ($e^-e^-, \mu^-\mu^-, \tau^-\tau^-, e^-\mu^-, ..$) could be at a displaced vertex or near the beam pipe depending on how small or how large g_{Sl} is.

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- There is another like-sign dilepton signature with a different jet structure in our model: Production and decay of χ^{++}.

Implications at the LHC

- χ^{++} can be produced in a collider such as the LHC via a Weak Boson Fusion (WBF) process followed by its decay into $e^{M,+}\,e^{M,+}$ which subsequently transform into a pair of SM like-sign dilepton plus missing energy.

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- $W^+ + W^+ \rightarrow \chi^{++} \rightarrow e_R^{M,+} + e_R^{M,+} \rightarrow l_L^+ + l_L^+ + \phi_S + \phi_S$.

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- For χ^{++}: Only forward and backward jets from the colliding hadrons.
- For $\nu_R \nu_R$: Forward and backward jets plus 2 jets or leptons from the 2 W's.

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- For $M_{\chi^{++}} \sim 400\, GeV$ (like a 400-GeV Higgs), one expects: $\sigma \sim 1\, pb$. With maximum LHC luminosity: $N = L\sigma \approx 3 \times 10^5 / year$. One order of magnitude larger than the expected ν_R pair production with $M \sim 200\, GeV$!

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- Notice that the χ^{++} production **"measures"** the Majorana coupling $g_M \Rightarrow$ Implications on the right-handed neutrinos mass $M = g_M v_M$.

Implications at the LHC

Backgrounds

- For example: $W^\pm W^\pm W^\mp W^\mp$ with 2 like-sign W's decaying into a charged lepton plus a neutrino ("missing energy") could be a background for $\nu_{Ri} + \nu_{Ri} \rightarrow e_{Lk} + e_{Ll} + W^+ + W^+ + \phi_S + \phi_S$.

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- However, this is of O(α_W^2) in amplitude smaller than the lepton-number violating process!

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Backgrounds

- $W^+ + W^+ \to \chi^{++} \to W^+ + W^+ \to l_L^+ \nu_L l_L^+ \nu_L$ (for a generic doubly-charged scalar) could be a background for the lepton-number violating process $W^+ + W^+ \to \chi^{++} \to e_R^{M,+} + e_R^{M,+} \to l_L^+ + l_L^+ + \phi_S + \phi_S$ but it could differ in the location of the like-sign dileptons.

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- The background generally occurs close to the beam pipe while the lepton-number violating process could occur at some distance away.

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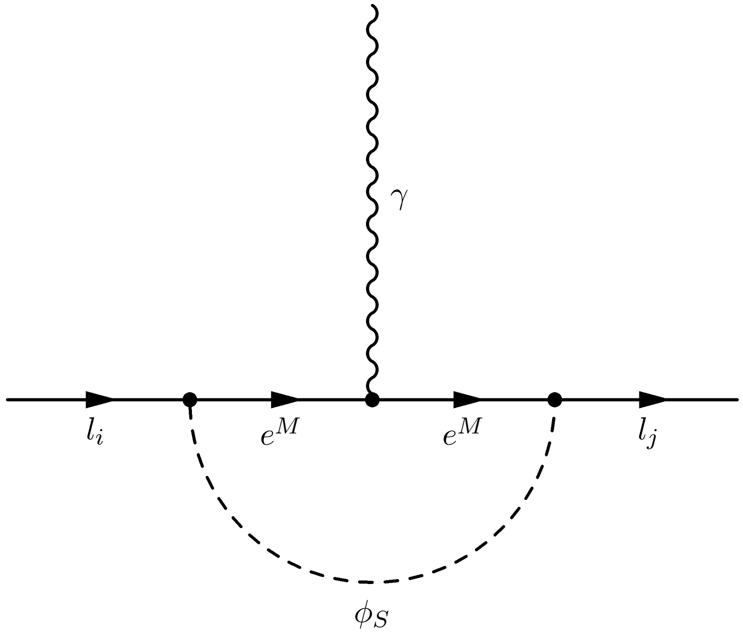
- Depending on the mass differences between ν_R and e_R^M, the decays and consequently the signals can differ from the ones shown above. Work in preparation with Dilip Ghosh and Nguyen Nhu Le.
- Deep link between the nature of the spontaneous symmetry breaking of the SM and the electroweak-scale right-handed neutrino sector! This extended Higgs sector was studied in Alfredo Aranda, J. Hernadez-Sanchez and PQH, JHEP 0811:092,2008.

Radiative corrections

- The interactions:
  $\mathcal{L}_S = (l_L^{\dagger}\, g_{Sl}\, l_R^M + e_R^{\dagger}\, g_{Sl}^{'}\, e_L^M)\, \phi_S + H.c.$ can give rise to lepton flavor violating (LFV) processes such as



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- $B(\mu \to e\,\gamma) = \frac{|\sum_i(\frac{m_E}{m_i})(U^{E*}_{i\mu}\,U^E_{ei})|^2}{|\sum_i(\frac{m_E}{m_i})(U^{E*}_{i\tau}\,U^E_{\mu i})|^2} \times \frac{B(\tau \to \mu\,\gamma)}{0.174} \times (\frac{m_\tau}{m_\mu})^2$

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- $B(\mu \to e\,\gamma)_{exp} < 1.2 \times 10^{-11}$;
  $B(\tau \to \mu\,\gamma)_{exp} < 6.8 \times 10^{-8}$ (Babar);
  $B(\tau \to \mu\,\gamma)_{exp} < 4.5 \times 10^{-8}$ (Belle).

Radiative corrections

- In the model, $U^E = U_L^{l,\dagger}\, g_{Sl}\, U_R^{l^M}$ where U_L^l and $U_R^{l^M}$ are matrices that diagonalize the SM and mirror charged lepton mass matrices.

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- In that special case, $\lambda < 0.01$.

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- Interesting correlations between LFV processes and LHC signatures!

Other Implications

- From mirror fermions $\Rightarrow$ V+A contributions to V-A SM interactions were calculated with emphasis on possible Wtb anomalous couplings (With Phuoc Ha, in preparation).

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- Astrophysical implications including possibilities of warm dark matter, pulsar kicks, etc..from an extension of the model. (PQH, Nucl.Phys.B805:326-355,2008) which, in addition to active right-handed neutrinos, include sterile left and right-handed neutrinos, some of which have keV masses.

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- Much awaits to be known about the nature of what gives masses to elementary particles.
- Are the above two questions deeply linked to each other?

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- In the meantime, let's have a quick tour of the facilities....

Tour 1

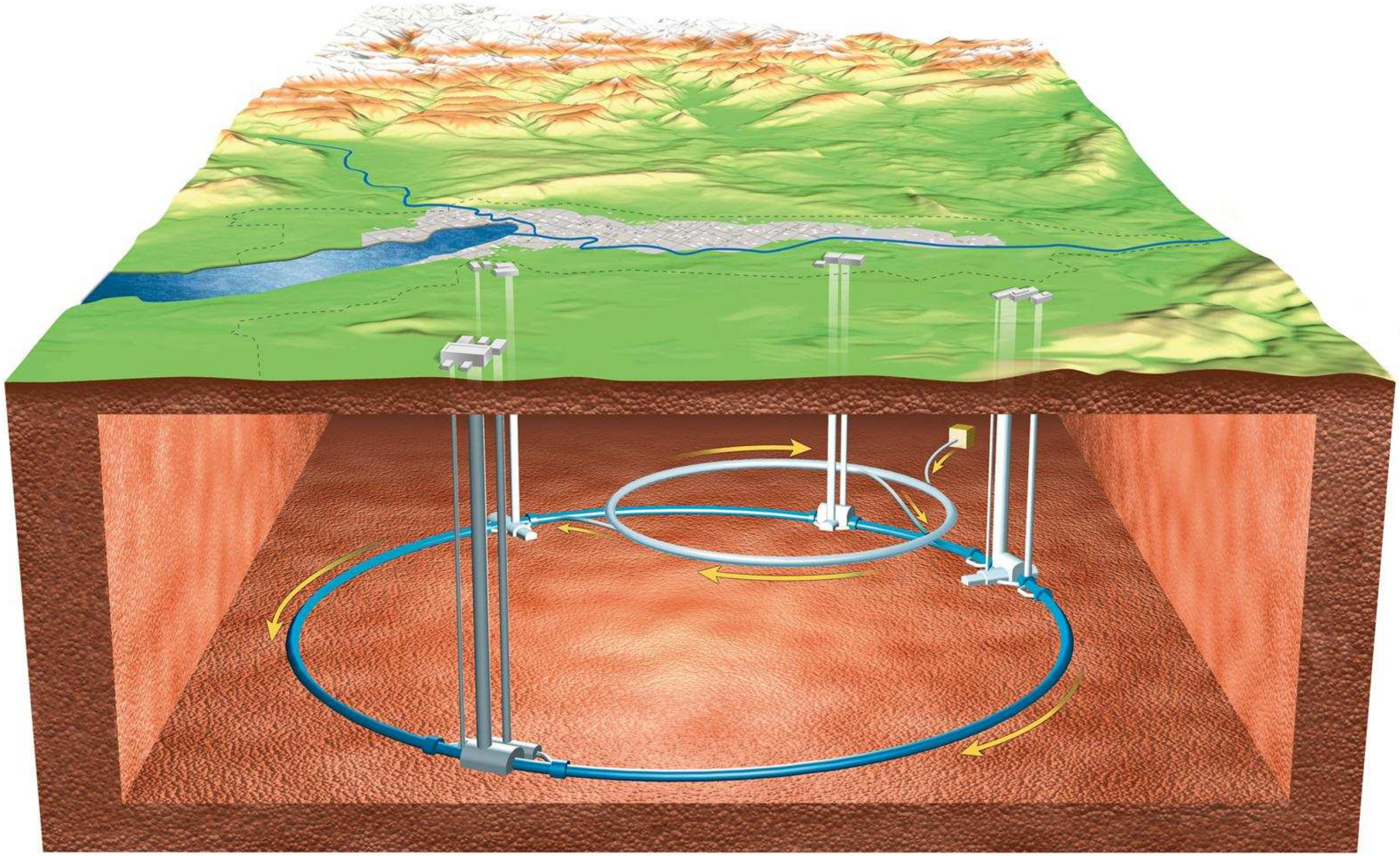
CERN

Tour 2

CERN2

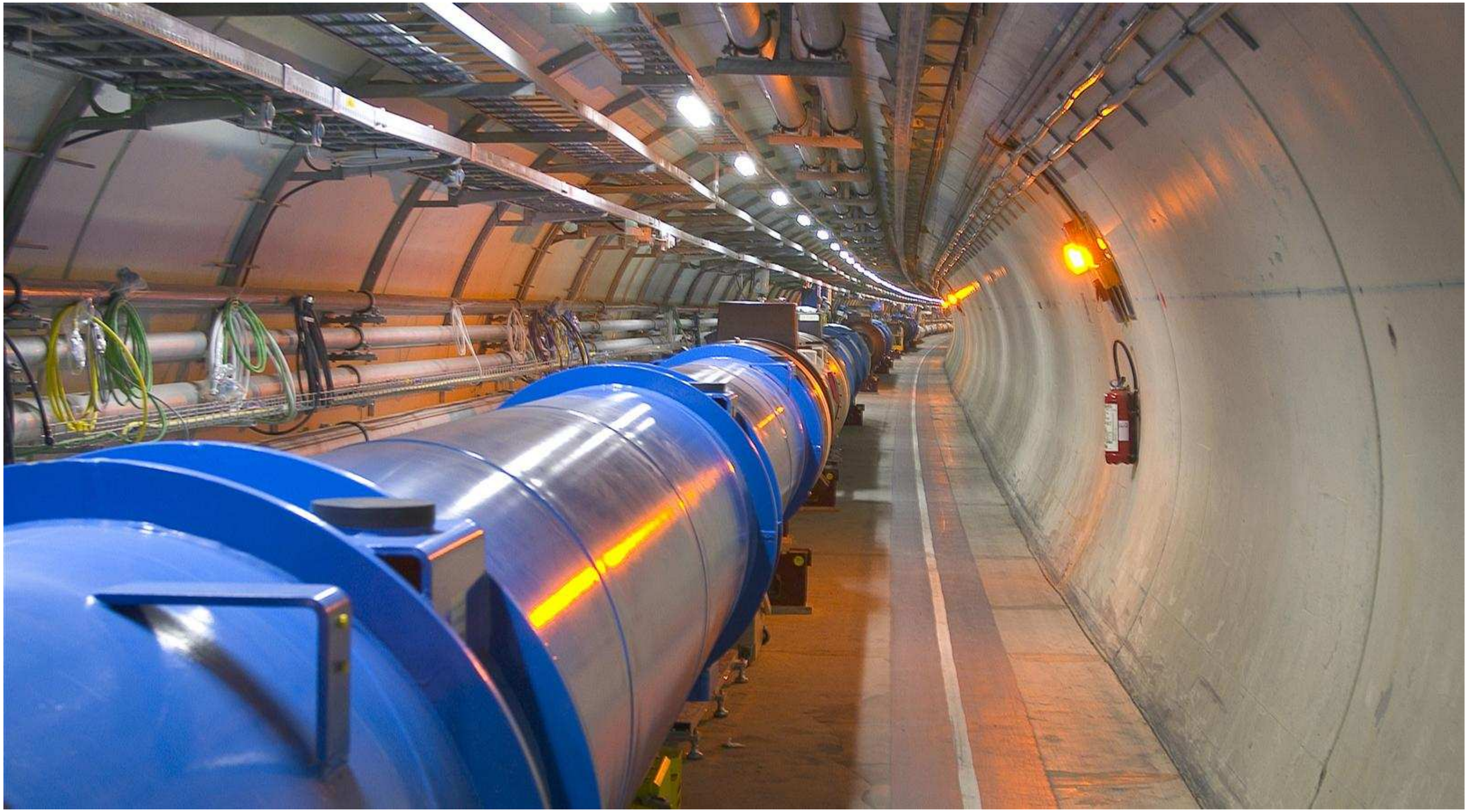
Tour 3

CERN3



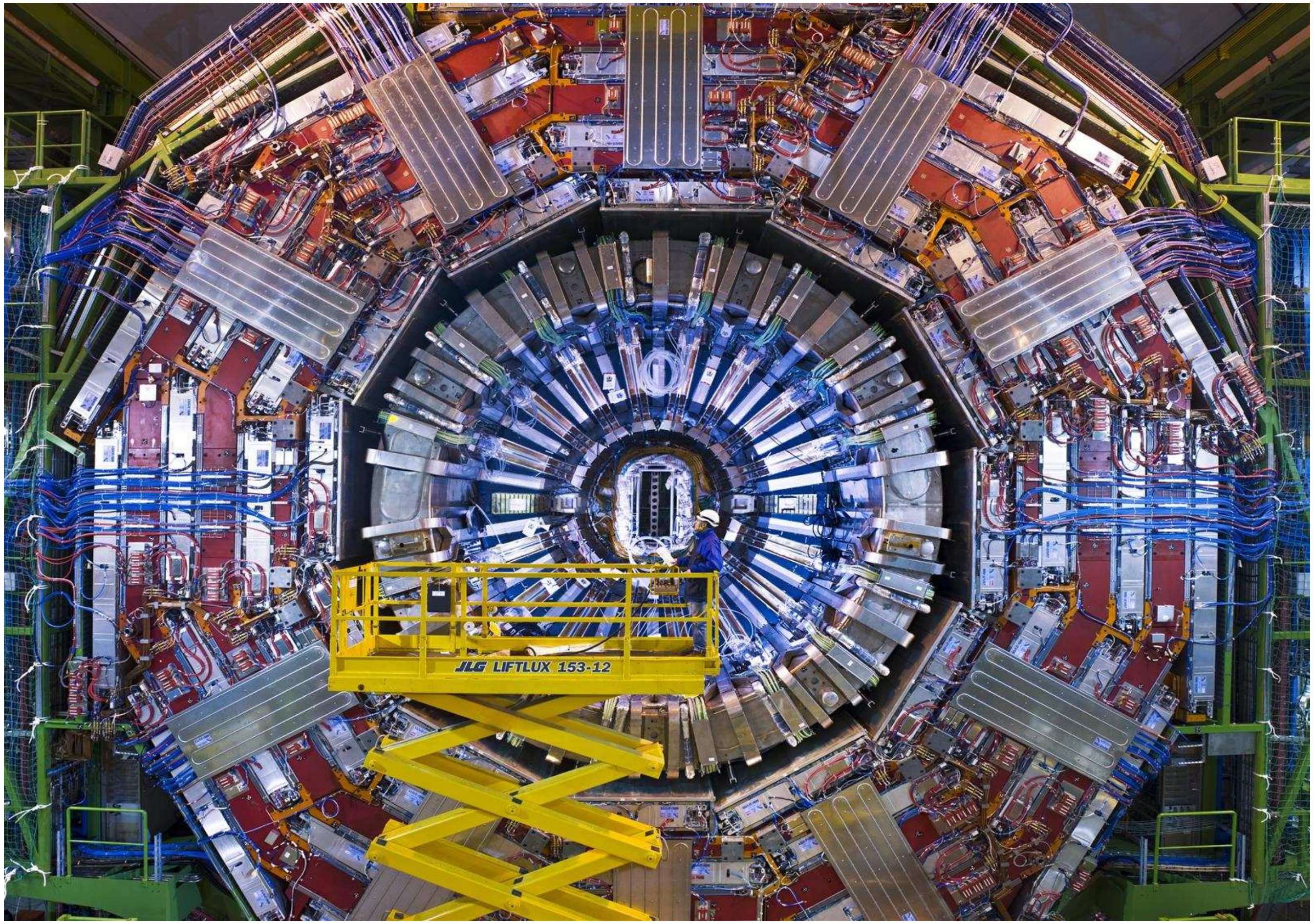
The machine

LHC



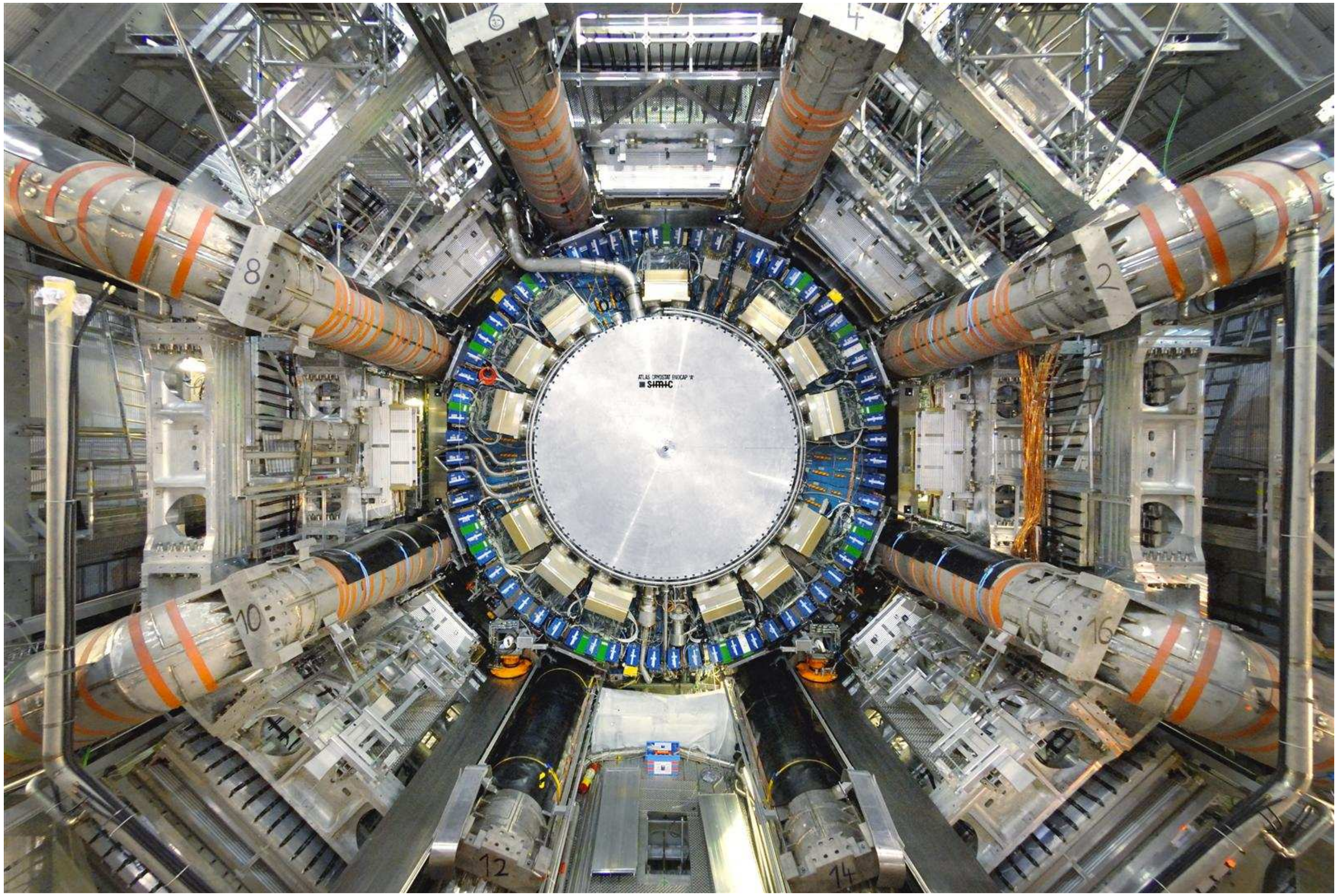
CMS detector

CMS



ATLAS detector

ATLAS



Simulation of a Higgs event

Higgs