Unitarity bounds for effective composite models

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Workshop on Connecting Insights in Fundamental Physics:
Standard Model and Beyond

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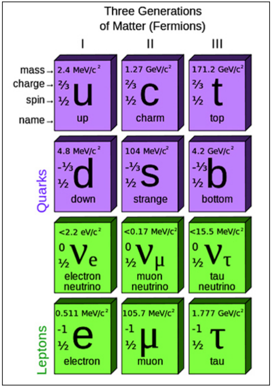
in collaboration with R. Leonardi, O. Panella and M. Presilla (PLB 795, 2019)

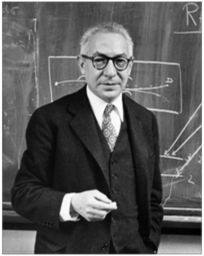
Outline

Are quarks and leptons elementary?

- proliferation of "fundamental" particles
- wide range of masses, heavier copies are unstable and decay into (e, u, d)

"Who ordered that (muon)?" *Isidor Rabi*





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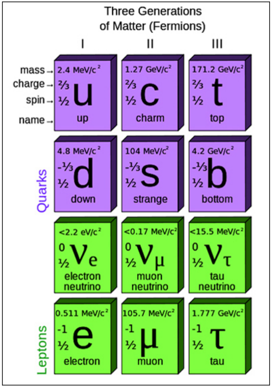


- quark and leptons substructure
  $\Rightarrow$ excited leptons and quarks, e. g. e^*, u^*, d^*

- Original phenomenological refs

  H. Terezawa (PRD 22, 1980); E. Eichten, K. D. Lane, M. E. Peskin (PRL 50, 1983);

  H. Harari (Phys. Rep., 1984); N. Cabibbo, L. Maiani, Y. Srivastava (PLB 139, 1984);

  U. Baur, M. Spira and P. M. Zerwas (PRD 42, 1990), ...

- Collider:
  small spatial dimensions and large-mass states

  LEP $\rightarrow$ HERA $\rightarrow$ Tevatron $\rightarrow$ LHC

Effective interactions and composite fermions

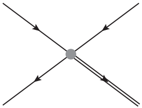
- quark and leptons substructure ⇒ excited leptons and quarks, e. g. e^*, u^*, d^*
- interactions among lowest-lying and excited states (same constituents) with effective operators

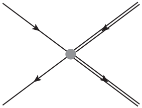
Contact interactions J. Kühn and P. M. Zerwas (1984); U. Baur, M. Spira and P. M. Zerwas (1990)

- underlying strong dynamics (*preon* interactions) at small energies

$$\mathcal{L}_{\text{CI}} = \frac{g_*^2}{2\Lambda^2} j^\mu j_\mu \,, \quad g_*^2 = 4\pi$$

$$j^\mu = \eta_L \bar{f}_L \gamma^\mu f_L + \eta_L' \bar{f}_L^* \gamma^\mu f_L + \eta_L'' \bar{f}_L^* \gamma^\mu f_L^* + h.c. + (L \to R)$$





Effective interactions and composite fermions

- quark and leptons substructure ⇒ excited leptons and quarks, e. g. e^*, u^*, d^*
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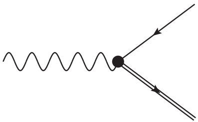
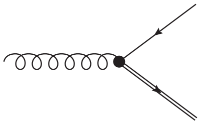
Gauge interactions N. Cabibbo, L. Maiani, Y. Srivastava (1984); U. Baur, M. Spira and P. M. Zerwas (1990)

- interaction mediated by SM gauge bosons, W^a_μ, B_μ, A^a_μ
- magnetic-coupling to preserve electromagnetic current

$$\mathcal{L}_{\rm GI} = \frac{1}{2\Lambda}\bar{f}^*_R\,\sigma^{\mu\nu}\left[g_s f_s \frac{\lambda^a}{2} G^a_{\mu\nu} + g\,f\,\frac{\boldsymbol{\tau}}{2}\mathbf{W}_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu}\right] f_L + h.c.$$





Effective interactions and composite fermions

- quark and leptons substructure $\Rightarrow$ excited leptons and quarks, e. g. e^*, u^*, d^*
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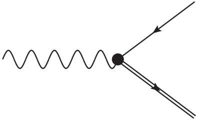
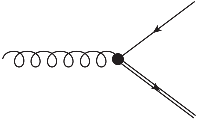
Gauge interactions N. Cabibbo, L. Maiani, Y. Srivastava (1984); U. Baur, M. Spira and P. M. Zerwas (1990)

- $q, \ell \in I_W = 0, \frac{1}{2}$ and $W^\pm, Z^0, \gamma \in I_W = 0, 1 \Rightarrow$ excited fermions $\in I_W \leq \frac{3}{2}$
- exotic charges for excited fermions, $Q = I_3^W + Y/2$

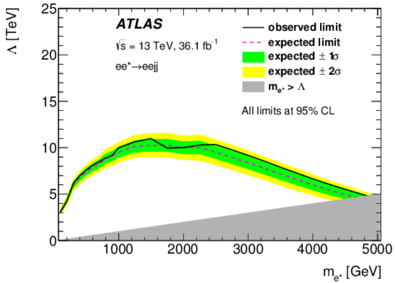
$$Q_{\ell^*} = -2 \, , Q_{q^*} = -4/3, +5/3$$

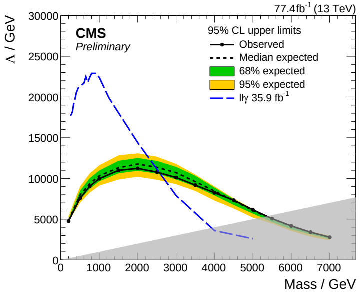




Status of current searches (excited electrons)

- single production $q\bar{q}' \to ee^*$ from ATLAS and CMS collaborations (Run 2)
  1906.03204, JHEP 1904 (2019), EXO-18-013 PAS
- exclusion regions in the (M, Λ) plane
  $\to$ area below the experimental lines is excluded

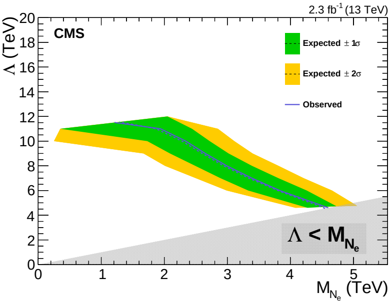




- Many other searches: CMS collaboration [PRL 105 (2010), PRL 105 (2016), ...] ATLAS collaboration [PRL 105 (2010), PRD 85 (2012), PLB 754 (2016), ...], see Li Yuan talk for q^*

Status of current searches (excited neutrinos)

- single production $q\bar{q}' \to \ell N^*$ from CMS Coll. (PLB 775, 2017)



N^* can be a Majorana particle

- possible source of baryogenesis via leptogenesis S. B. and O. Panella (2017)

$$\Gamma(N^* \to \ell + X) \neq \Gamma(N^* \to \bar{\ell} + X)$$

(ONLY) Current validation on the model parameters (M, Λ)

- the excluded region is $M > \Lambda$
- the limits on largest mass are quoted from exp-limits $|_{95\%\text{CL}}$ with $M^* = \Lambda$
- Can we consider other bounds?

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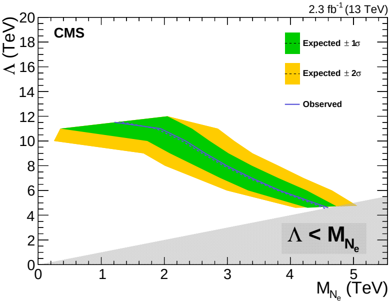

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What about perturbative unitarity on the EFT operators?

- the dimension-5 and dimension-6 operators $\approx \hat{s}/\Lambda$

$\Rightarrow$ one may want to use the EFT in its region of validity

- HOW? Imposing perturbative unitarity of the associated S-matrix $\Rightarrow$ condition on (M, Λ, s)

Tools for the unitarity bound derivation

- expansion of the scattering amplitude in partial waves

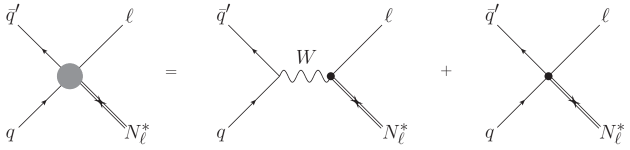
$$\mathcal{M}_{i \to f}(\theta) = 8\pi \sum_j (2j+1)\, T^j_{i \to f}\, d^j_{\lambda_f\, \lambda_i}(\theta)$$

- optical theorem on the production process brings to (for inelastic scatterings)

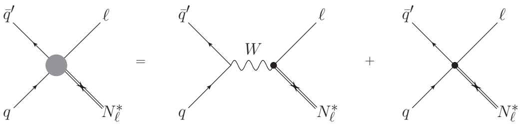
$$\sum_{f \neq i} \beta_i \beta_f \left| T^j_{i \to f} \right|^2 \leq 1\,, \quad \beta = \frac{\sqrt{[\hat{s} - (m_1 - m_2)^2]\,[\hat{s} - (m_1 + m_2)^2]}}{\hat{s}}$$

E. Endo and Y. Yamamoto, JHEP 1406 (2014); T. Corbett, O.J.P. É boli, M.C. Gonzalez-Garcia, PRD 96 (2017)

- focus on one process: $q\bar{q}' \to \ell N^*_\ell$

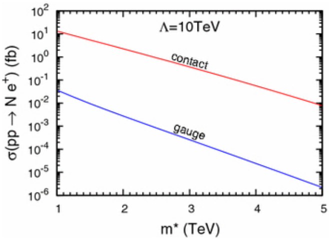


Derivation of the bound



$$\mathcal{L}_{\text{CI}} = \frac{g_*^2\,\eta}{\Lambda^2}\bar{q}'\gamma^\mu P_L q\,\bar{N}\gamma_\mu P_L \ell + h.c.\,, \quad \eta \equiv 1\,, \quad g_*^2 = 4\pi$$

$$\mathcal{L}_{\text{GI}} = \frac{g\,f}{\sqrt{2}\Lambda}\bar{N}\sigma^{\mu\nu}(\partial_\mu W_\nu^+)P_L\ell + h.c.\,, \quad f \equiv 1\,, \quad \frac{g\,f}{\sqrt{2}} \approx 1$$



- $\sigma_{CI}(q\bar{q} \to N^*\ell) \gg \sigma_{GI}(q\bar{q} \to N^*\ell)$
- assume one production process (CI o GI) at a time when computing the unitarity bound

Unitarity bound for Contact Interactions

- $\mathcal{M}_{i\to f}$ is decomposed in terms of definite helicity states
- helicity of each particle in the initial or final state is $\lambda = \pm 1/2$

$$(+,+),\ (+,-),\ (-,+),\ (-,-)$$

$$T^{j=1}_{(-,+)\to(-,+)} = -\frac{\hat{s}\, g_*^2}{12\pi\Lambda^2}\left(1-\frac{M^2}{\hat{s}}\right)^{\frac{1}{2}}$$

$$T^{j=1}_{(-,+)\to(+,+)} = \frac{\sqrt{\hat{s}}\, M\, g_*^2}{12\sqrt{2}\pi\Lambda^2}\left(1-\frac{M^2}{\hat{s}}\right)^{\frac{1}{2}}$$

- only $j=1$ contributes from initial state
- the massive N^* gives heleicity flip $\Rightarrow (+,+)$ in the final state

$$\sum_{f\neq i}\beta_i\beta_f\left|T^j_{i\to f}\right|^2 \leq 1 \quad \Rightarrow \quad \frac{g_*^4\, \hat{s}\,(2\hat{s}+M^2)}{288\pi^2\Lambda^4}\left(1-\frac{M^2}{\hat{s}}\right)^2 \leq 1$$

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$$\Lambda \geq \left(\frac{\hat{s}}{3}\right)^{\frac{1}{2}}\left(1+\frac{M^2}{2\hat{s}}\right)^{1/4}\left(1-\frac{M^2}{\hat{s}}\right)^{1/2}, \quad g_*^2 = 4\pi$$

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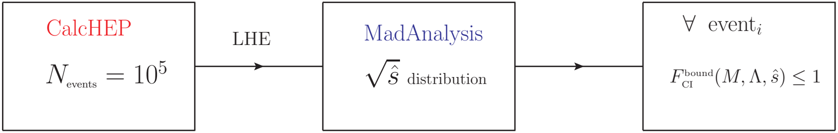
Implementation of the bound

- $\hat{s} = x_1 x_2 s$, $\sqrt{s}$ = machine c.o.m. energy
- $\sqrt{\hat{s}}$ is distributed in the interval $[M, \sqrt{s}]$ for the event signal

First implementation

- $N = 10^5$ MC events with CalcHEP at Leading Order: $\sqrt{s} = 13,\ 14,\ 27$ TeV
- LHE files passed to MadAnalyses to retrieve $\sqrt{\hat{s}}$ for each event$_i$
- interface the event$_i(\sqrt{s}, M^*, \Lambda)$ with

$$\frac{g_*^4\, \hat{s}\,(2\hat{s} + M^2)}{288\pi^2\Lambda^4}\left(1 - \frac{M^2}{\hat{s}}\right)^2 \leq 1$$

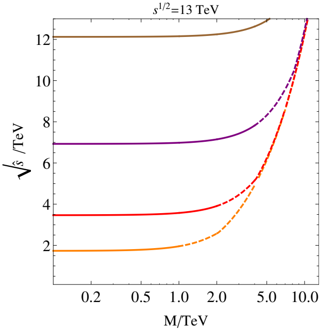


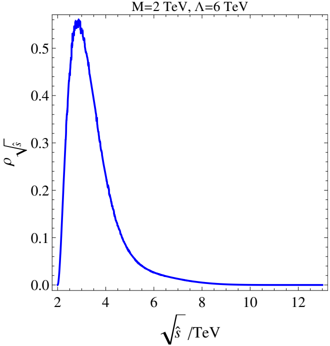
Second implementation: semi-analytic check

$$\sigma = \frac{1}{s} \sum_{ij} \int_{M^2}^{s} d\hat{s} \int_{\hat{s}/s}^{1} f_i\left(x, Q^2\right) f_j\left(\frac{\hat{s}}{s\,x}, Q^2\right) \hat{\sigma}(M, \Lambda, \hat{s})$$

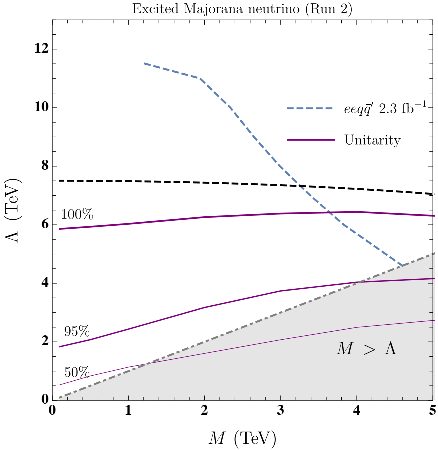
$$\rho_{\sqrt{\hat{s}}} \equiv \frac{1}{\sigma} \frac{d\sigma}{d\sqrt{\hat{s}}} \Rightarrow \text{event fraction} = \int_{M}^{\sqrt{\hat{s}_{\rm max}}} \rho_{\sqrt{\hat{s}}}\, d\sqrt{\hat{s}}$$

- the unitarity bound provides the integration boundary $\sqrt{\hat{s}_{\rm max}}(M, \Lambda, s) \leq s$

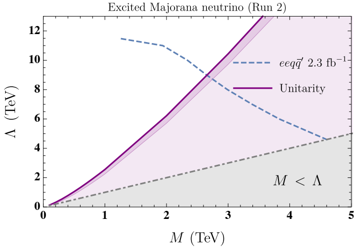




Results for N^* at LHC Run 2



- Currently in PLB and arXiv
  Erratum ready for submission



- Dashed line are observed limits on data from CMS Coll. (PLB 775, 2017),
- purple lines (100%, 95%, 50%) stable against implementation 1 and 2

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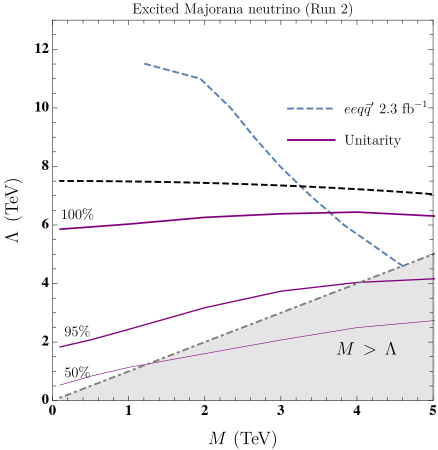

- saturation of the bound for large Λ
- rather high sensitivity to event fraction
- special thanks to Andrey Kamenshchikov and Oleg Zenin (ATLAS collaboration)

- $M \leq 4.6$ TeV with $M \leq \Lambda$
- $M \leq 3.6$ TeV with 100% unitarity
- $M \leq$??? TeV with 95% unitarity

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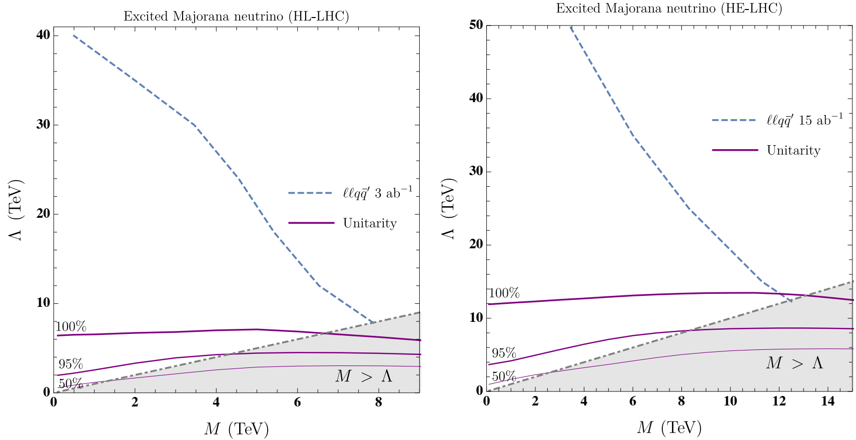
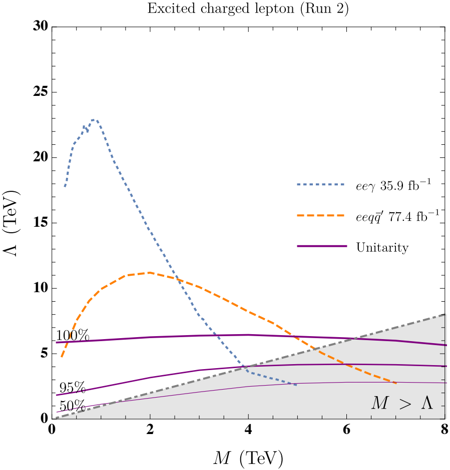
Results for N^* at HL- and HE-LHC



- Dashed lines expected limits from CMS Coll. (PLB 775, 2017)
- Visible dependence on the machine nominal energy $\sqrt{s} = 14,\ 27$ TeV

Results for e^* at LHC Run 2



- $M \lesssim 4$ TeV and $M \lesssim 5.5$ TeV

- unitarity bound 100%

  $M \lesssim 3.4$ TeV and $M \lesssim 5.0$ TeV

- unitarity bound 95%

  $M \lesssim 4$ TeV and $M \lesssim 6.0$ TeV

- unitarity bound 50%

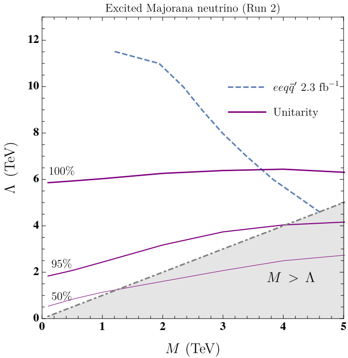
  $M \lesssim 5$ TeV and $M \lesssim 7.0$ TeV

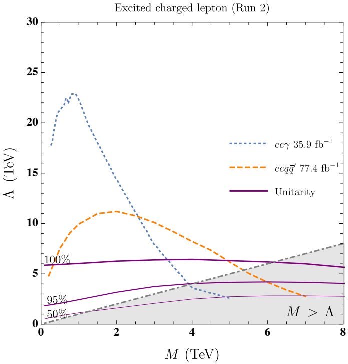
- Dashed line from CMS Coll. JHEP 1904 (2019) and CMS-PAS-EXO-18-013
- the bound is applicable because of the same vertex for the CI process

Summary and future work

- Effective composite models: unitarity bound for dimension-5 and dimension-6 (GI and CI)
- Focus on excited neutrinos (and charged leptons)
- Two implementations and agreement with experimental colleagues

$\Rightarrow$ additional way to look at the constraints on (M, Λ) parameter space





- the unitarity bound and $M > \Lambda$ can be used simultaneously

  $\rightarrow$ adopt the stronger of the two?

- agnostic on the UV completion, allow $M > \Lambda$ and keep only the unitarity bound

  $\rightarrow$ largest M according to the required events fraction (e.g. 100%, 95%, 50%)

- estimate the theoretical error on the bound, look at the $\hat{s}/\Lambda$ expansion

- apply the unitarity bounds to other searches $\Rightarrow$ excited quarks

  CMS: PLB 738 (2014); JHEP 1601 (2016); PLB 781 (2018)