

PERTURBATIVE UNITARITY BOUNDS FOR EFFECTIVE COMPOSITE MODELS

MATTEO PRESILLA

In collaboration with R.Leonardi, O. Panella and S. Biondini (PLB 795, 2019)

"COMPOSE-IT: unitarity for composite models and beyond the HL-LHC era"

Università degli Studi di Perugia, 27 Jan 2020

INTRODUCTION AND MOTIVATION

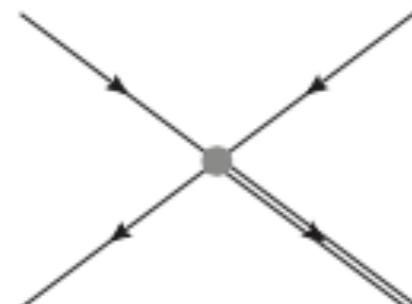
INTERACTIONS OF THE MODEL

- Compositeness of leptons and quarks is one possible scenario beyond the Standard Model
→ mass hierarchy of fermions, proliferation of the SM leptons and quark
- **Excited leptons and quarks**, e. g. e^* , N^* , q^* , with interactions among lowest-lying and excited states (same constituents) with **effective operators**

(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), ...)

1. CONTACT INTERACTIONS (CI):

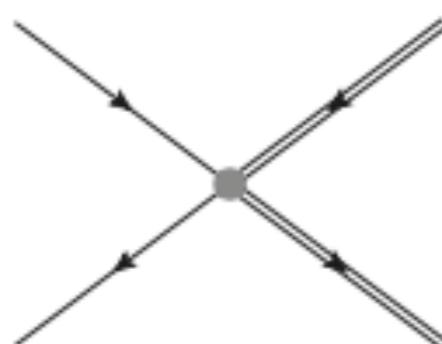
Dim-6 four-fermion operators stemming the underlying strong structure



$$\mathcal{L}_{CI}^{(6)} = \frac{g_\star^2}{\Lambda^2} \frac{1}{2} j^\mu j_\mu,$$

$$j_\mu = \eta_L \bar{\psi}_L \gamma_\mu \psi_L + \eta'_L \bar{\psi}_L^\star \gamma_\mu \psi_L^\star + \eta''_L \bar{\psi}_L^\star \gamma_\mu \psi_L + h.c.$$

$$+(L \rightarrow R)$$



common assumptions: $g_\star^2 = 4\pi$, $\eta_L \equiv 1$, $\eta_R \equiv 0$

INTRODUCTION AND MOTIVATION

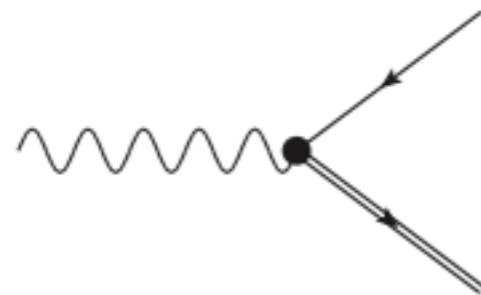
INTERACTIONS OF THE MODEL

2. GAUGE INTERACTIONS (GI):

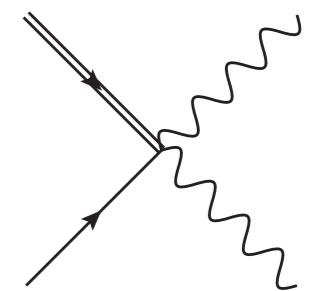
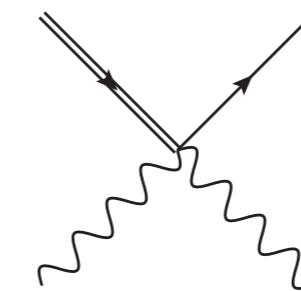
Dim-5 magnetic-type operators for interactions via SM bosons

$$\begin{aligned}\mathcal{L}_{GI}^{(5)} &= \frac{1}{2\Lambda} \bar{L}_R^\star \sigma^{\mu\nu} \left(gf \frac{\tau^a}{2} W_{\mu\nu}^a + g' f' \frac{Y}{2} B_{\mu\nu} \right) L_L + h.c., \quad L_R^{\star T} = (N_{R,\ell}, \ell_R^\star) \\ &= \frac{1}{2\Lambda} \bar{L}_R^\star \sigma^{\mu\nu} \left(g f \tau^a \partial_\mu W_\nu^a + ig^2 f W_\mu^a W_\nu^b \left[\frac{\tau^a}{2}, \frac{\tau^b}{2} \right] + g' f' \frac{Y}{2} B_{\mu\nu} \right) L_L + h.c.\end{aligned}$$

ABELIAN TERMS



NON-ABELIAN TERM



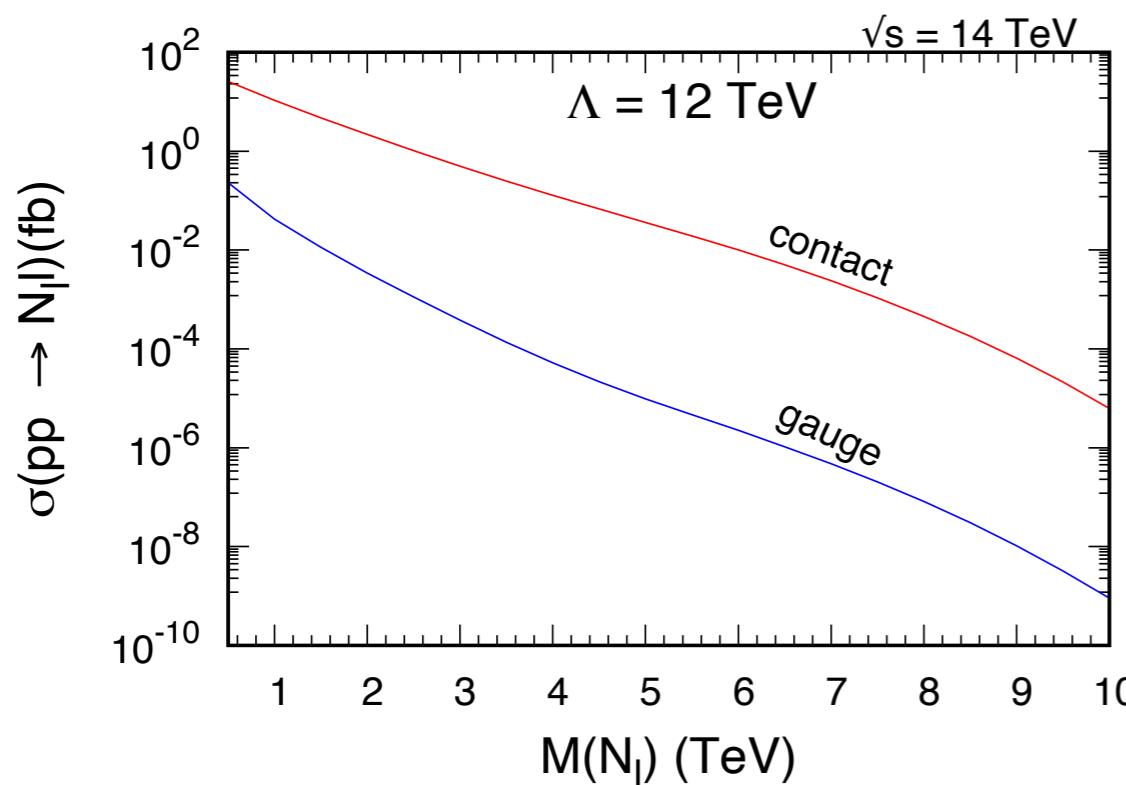
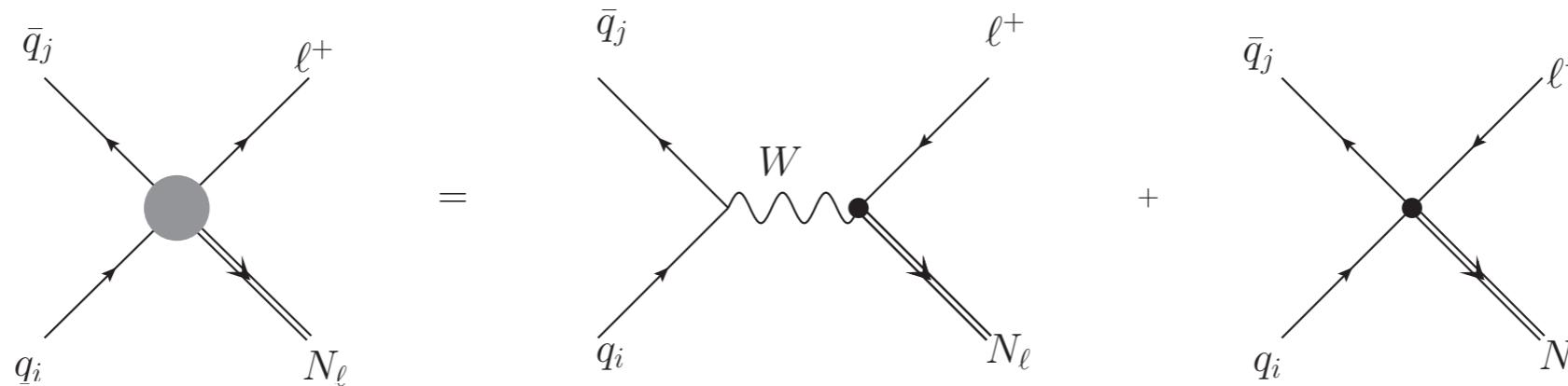
Common assumptions:

- $f = f' = 1$
- $f = -f' = 1 \implies$ coupling to photons

INTRODUCTION AND MOTIVATION

INTERACTIONS OF THE MODEL

The production cross section is given by the coherent sum of the **contact** and the **gauge** contributions



$$\mathcal{L}_{G1}^{(5)} = \frac{gf}{\sqrt{2}\Lambda} \bar{N} \sigma^{\mu\nu} \left(\partial_\mu W_\nu^+ \right) P_L \ell + \text{h.c.}, \quad f \equiv 1, \quad \frac{gf}{\sqrt{2}} \approx 1$$

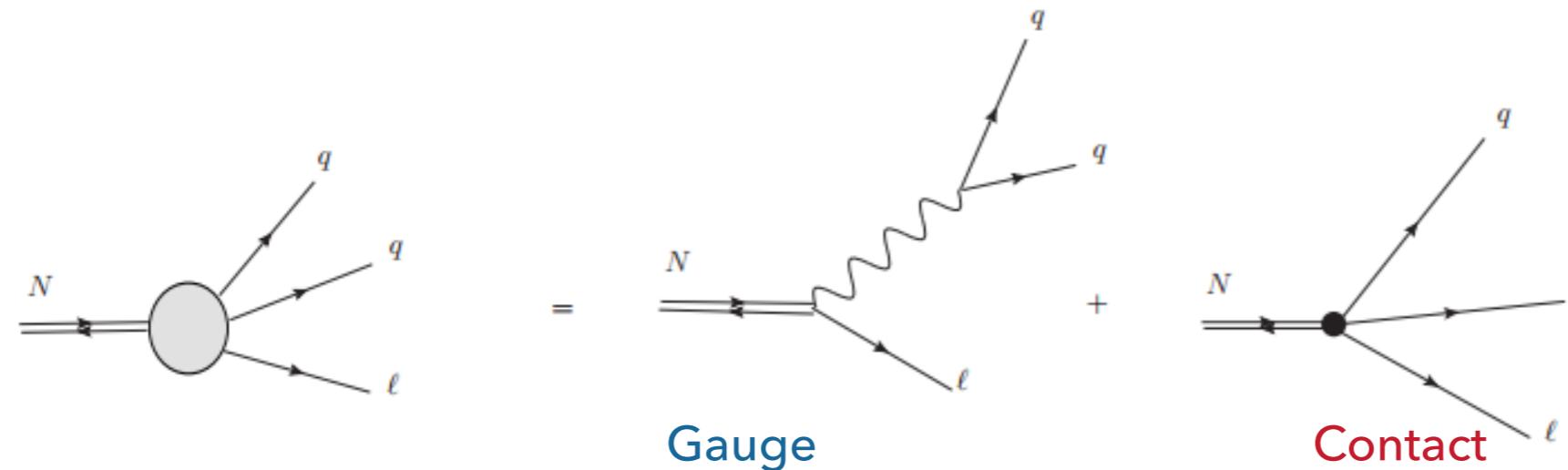
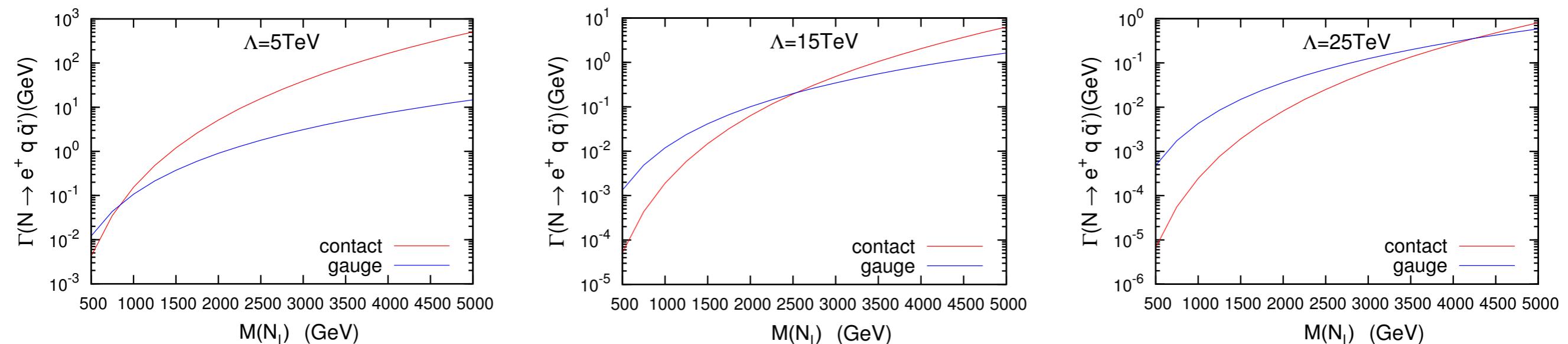
$$\mathcal{L}_{Cl}^{(6)} = \frac{g_*^2 \eta}{\Lambda^2} \bar{q}' \gamma^\mu P_L q \bar{N} \gamma_\mu P_L \ell + \text{h.c.}, \quad \eta \equiv 1, \quad g_*^2 = 4\pi$$

- Production cross sections depend both on Λ and $M(N_l)$
- **Contact interaction is dominant**
(tested up to HE-LHC collider energy)

INTRODUCTION AND MOTIVATION

INTERACTIONS OF THE MODEL

In the decay process there is an interplay of **contact** and **gauge** depending on Λ and M
 → **different decay topologies**



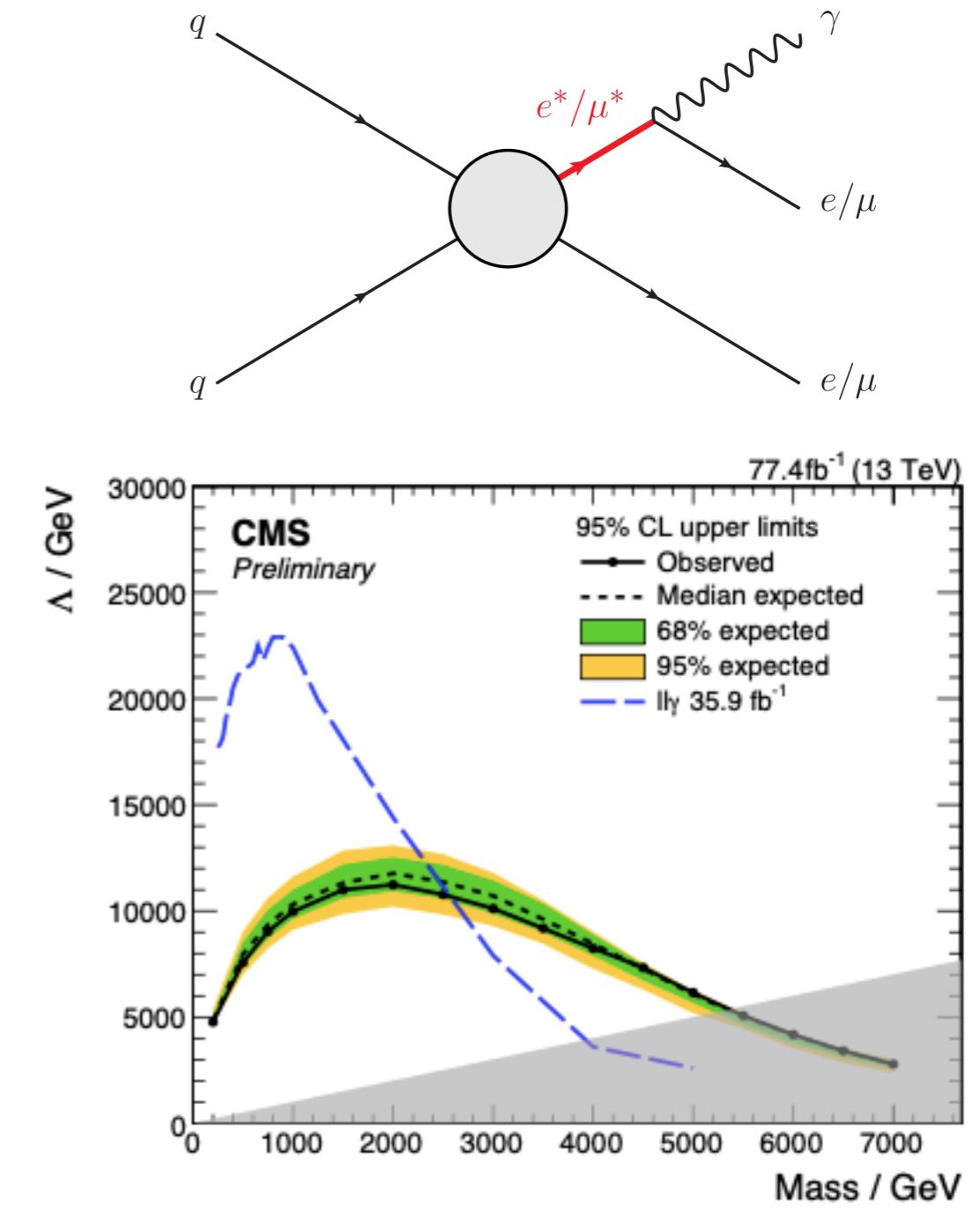
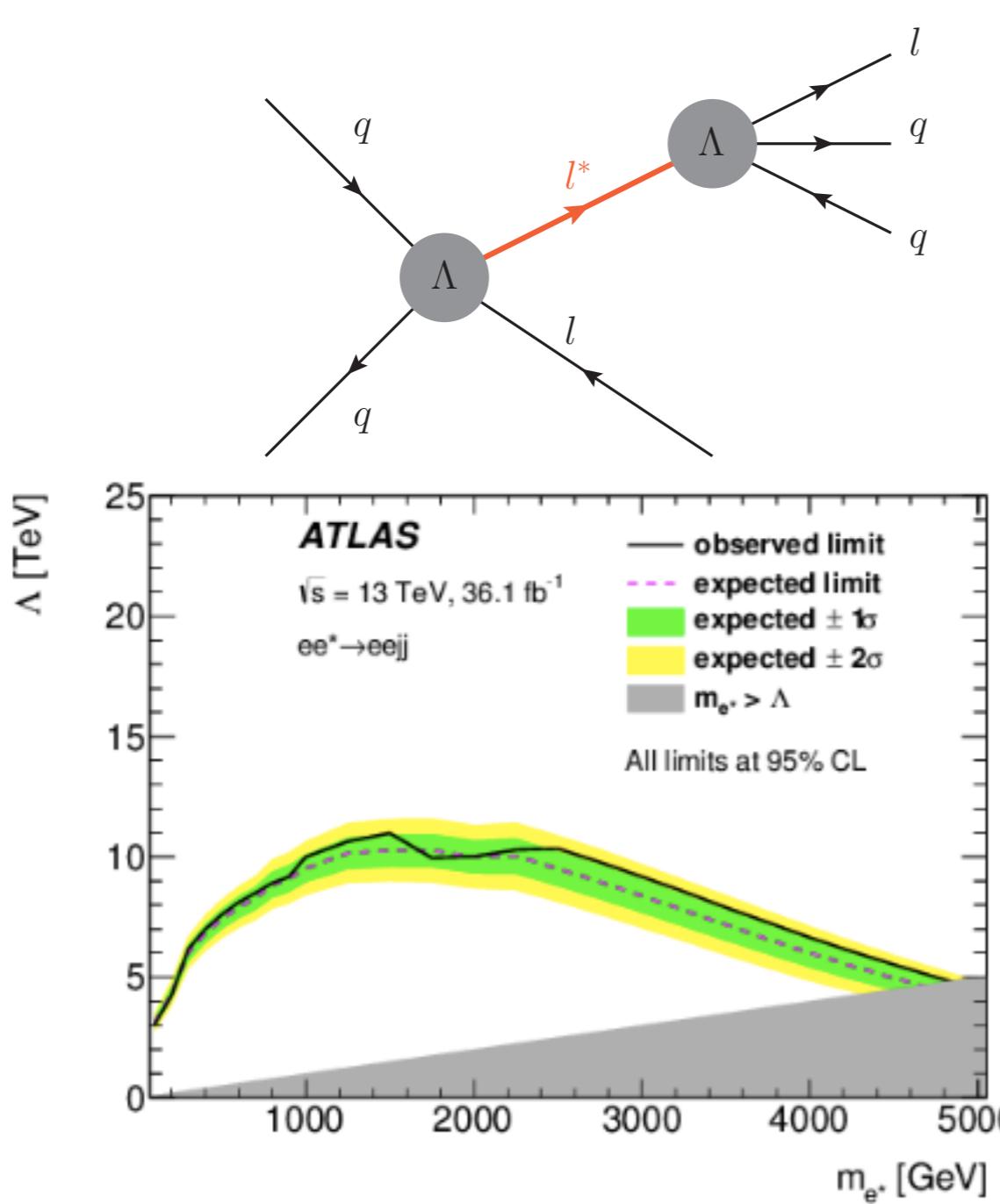
The quarks tend to overlap
 → one **fat jet** in the final state

No preferred topology
 → two/three jets reconstructed

INTRODUCTION AND MOTIVATION

COMPOSITE MODELS IN EXPERIMENTAL SEARCHES

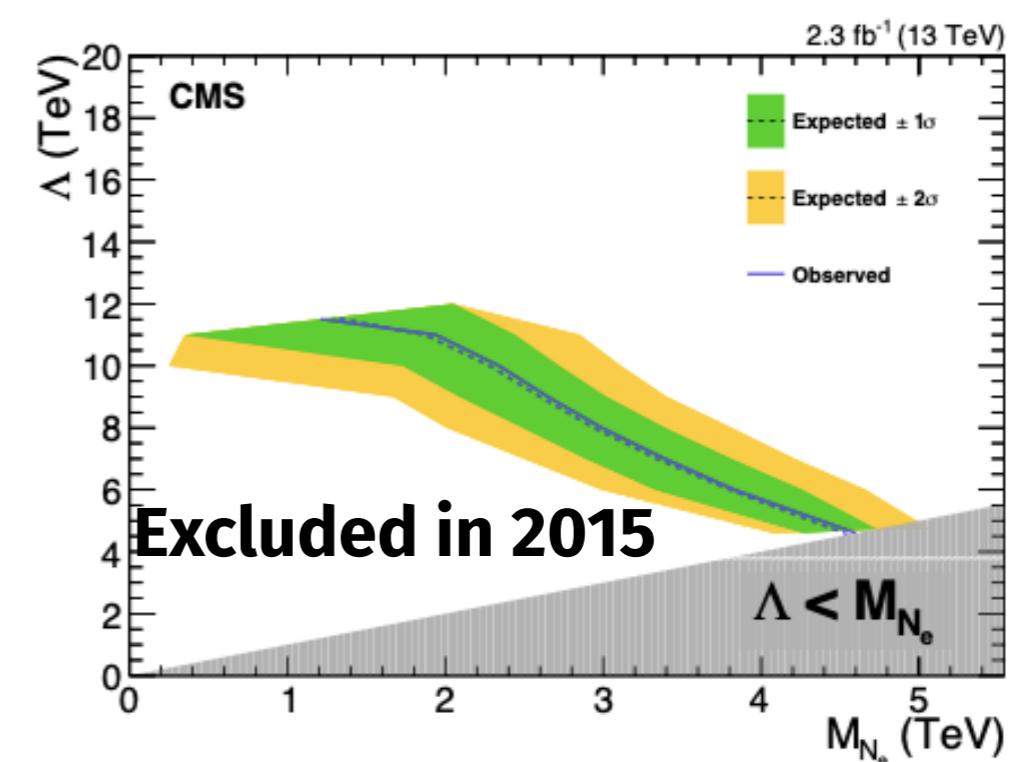
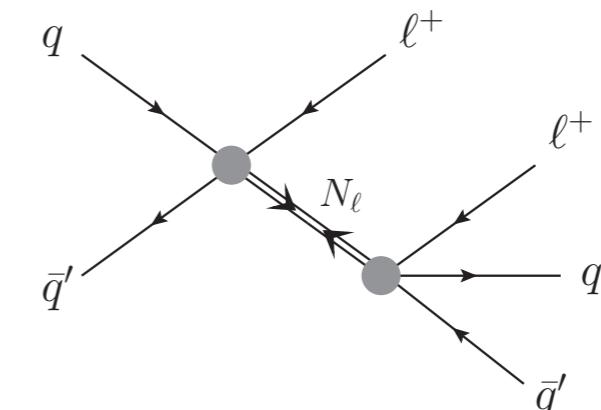
Charged leptons searches from ATLAS and CMS collaborations (Run 2) in the production channel $q\bar{q}' \rightarrow \ell^*\ell$
(arXiv.1906.03204, JHEP 1904 (2019), CMS-EXO-18-013/EXO-18-004)



INTRODUCTION AND MOTIVATION

COMPOSITE MODELS IN EXPERIMENTAL SEARCHES

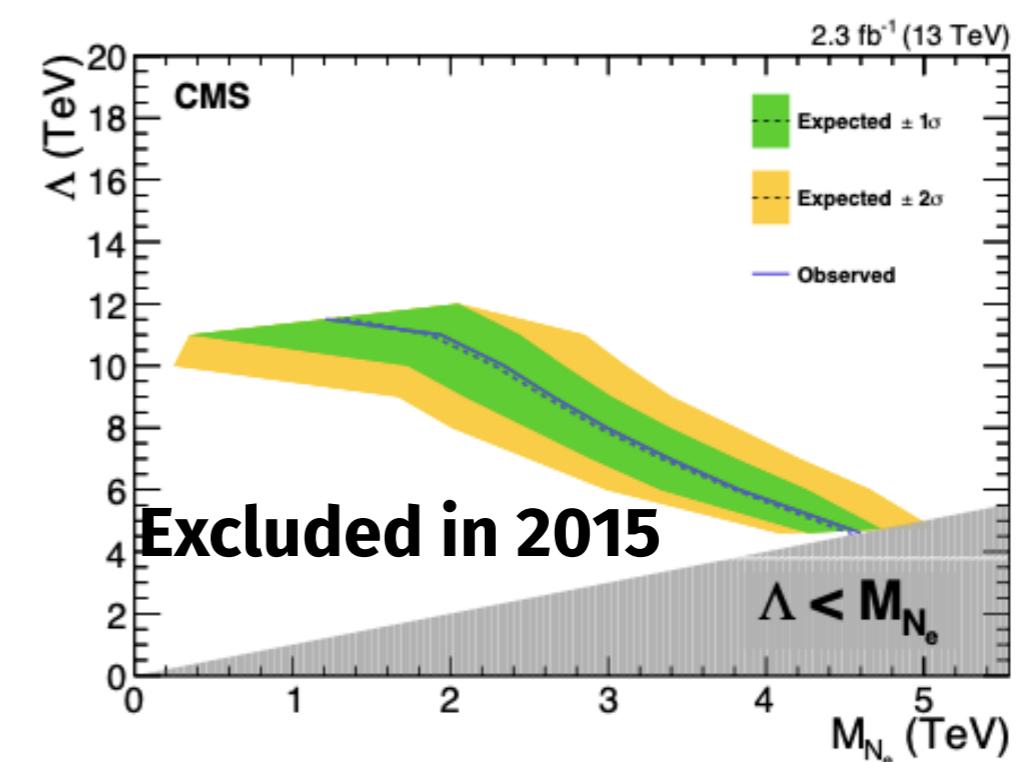
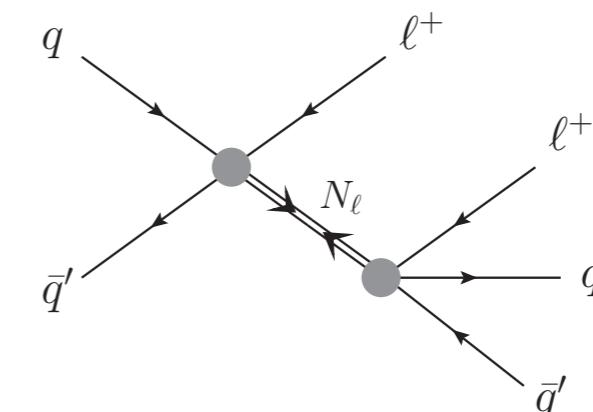
- The **neutral heavy leptons** in the model can be Majorana particles
- Possible source of **baryogenesis via leptogenesis**
 $\Gamma(N^* \rightarrow \ell + X) \neq \Gamma(N^* \rightarrow \bar{\ell} + X)$
 (arXiv. 1707.00844 - see S. Biondini's talk)
- **Single production channel** $q\bar{q}' \rightarrow N_\ell \ell$ search from the CMS Collaboration with 2015 data
 (arXiv.1706.08578, PLB 775 (2017)): no evidence for new physics found
- In the analysis: f , f' and η parameters fixed to one
 $\rightarrow (M, \Lambda)$ is the relevant space explored



INTRODUCTION AND MOTIVATION

COMPOSITE MODELS IN EXPERIMENTAL SEARCHES

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The limits on largest mass are quoted from **Exp-limits|95%CL with $M_* = \Lambda$** :

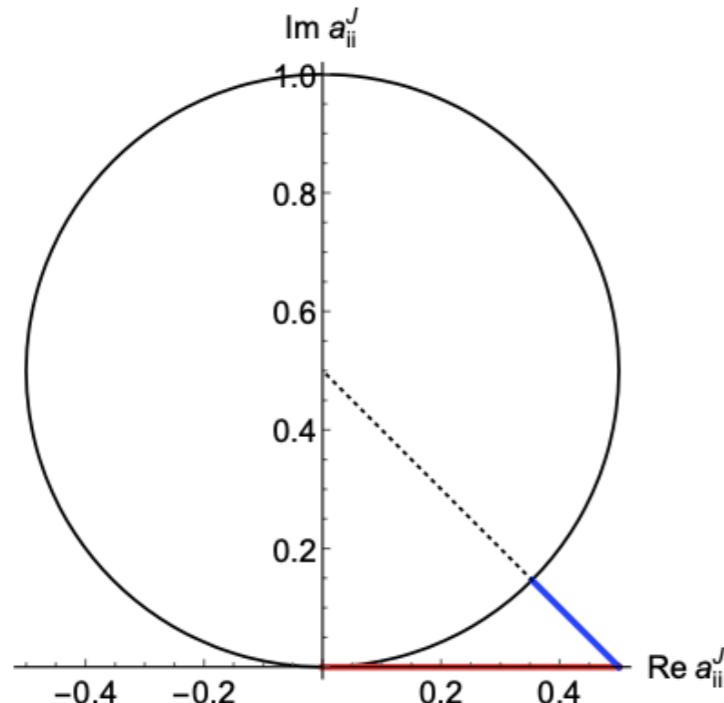
- for 2015 data analysis exclusion up to $\Lambda = M(N_e) \sim M(N_\mu) \sim 4.6$ TeV
- Is $M > \Lambda$ really justifiable being agnostic on the UV-complete theory?
- **Study of the EFT validity region of the model parameters (s, M, Λ)**

TODAY'S TALK

- **Motivation of the study**
- **Derivation of the bound for excited fermions:**
 - Sketch of the theoretical procedure
 - Implementation of the bound
- **Effects of the bound on experimental analysis**

DERIVATION OF THE BOUND

BASIC PHILOSOPHY



40% correction needed for restoring unitarity
arXiv. 1604.05746

Unitarity is just a fancy way of saying probabilities add up to 1!

From $S^\dagger S = 1$ follows the optical theorem.

What is the information in the unitarity condition applied to a certain process?

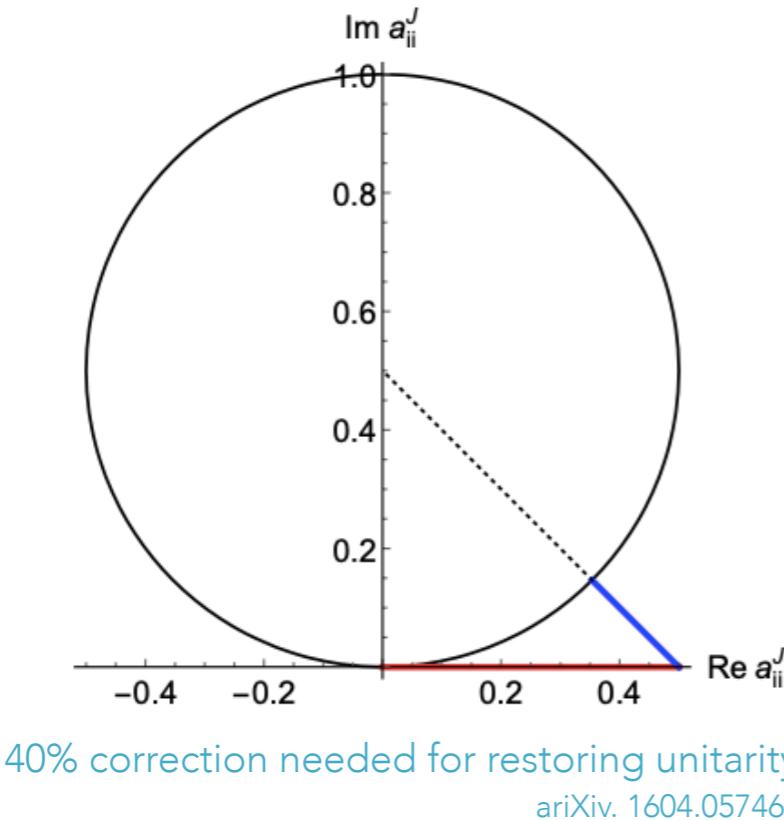
Considering the elastic scattering regime:

$$\text{Im } a_{ii}^J \geq |a_{ii}^J|^2 \implies (\text{Re } a_{ii}^J)^2 + (\text{Im } a_{ii}^J - 1/2)^2 \leq 1/4$$

Loop corrections must be important around the **unitarity violation**
(Schwartz- "QFT and the SM")

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AN OLD LESSON

Fermi theory: Dim-6 operators violate unitarity around 350 GeV.

Restored: W boson at 80 GeV.

Light pion effective theory: Pion scattering violates unitarity around 1.2 GeV.

Restored: Axial and vector resonances at 800 MeV.

Electroweak Theory: WW scattering requires new physics around 1 TeV.

Restored: SM Higgs boson at 125.5 GeV.

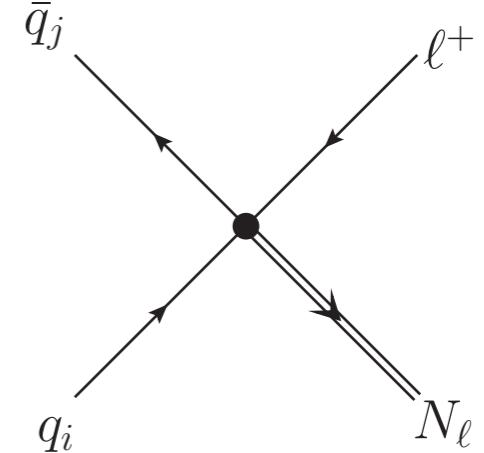


DERIVATION OF THE BOUND

SKETCH OF THE THEORETICAL PROCEDURE

The unitary bound is imposed on the subprocess $q\bar{q}' \rightarrow N_\ell \ell$ considering only the dominant CI contribution:

$$\mathcal{L}_{\text{CI}}^{(6)} = \frac{g_*^2 \eta}{\Lambda^2} \bar{q}' \gamma^\mu P_L q \bar{N}_\ell \gamma_\mu P_L \ell + \text{h.c.}, \quad \eta \equiv 1, \quad g_*^2 = 4\pi$$



Using the [partial wave decomposition](#) of the scattering amplitude:

$$\mathcal{M}_{i \rightarrow f}(\theta) = 8\pi \sum_j (2j+1) T_{i \rightarrow f}^j d_{\lambda_f \lambda_i}^{j j}(\theta)$$

The [optical theorem](#) for $2 \rightarrow 2$ inelastic scattering processes reads:

$$\sum_{f \neq i} \beta_i \beta_f |T_{i \rightarrow f}^j|^2 \leq 1, \quad \beta = \frac{\sqrt{[\hat{s} - (m_1 - m_2)^2] [\hat{s} - (m_1 + m_2)^2]}}{\hat{s}}$$

DERIVATION OF THE BOUND

SKETCH OF THE THEORETICAL PROCEDURE

- $T_{i \rightarrow f}(\theta)$ is expressed in terms of definite helicity states $\lambda_{i,f} = \pm 1/2 \Rightarrow$ possible combinations: $(+,+), (-,-), (+,-), (-,+)$
- Total angular momentum $j = 1$ gives non-zero amplitudes:

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

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

- The unitarity condition becomes then:

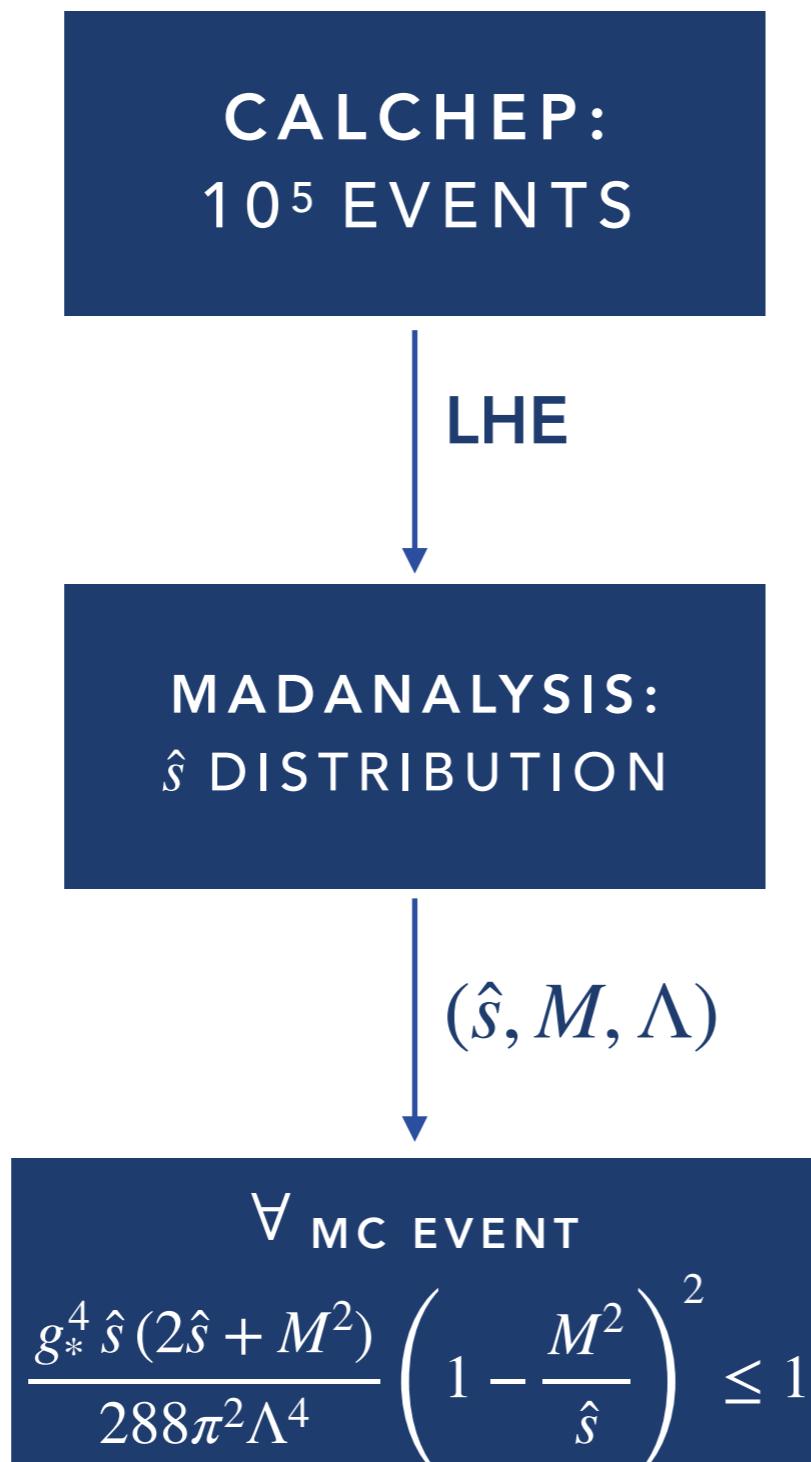
$$\sum_{f \neq i} \beta_i \beta_f \left| T_{i \rightarrow f}^j \right|^2 \leq 1 \quad \Rightarrow \quad \frac{g_*^4 \hat{s} (2\hat{s} + M^2)}{288\pi^2 \Lambda^4} \left(1 - \frac{M^2}{\hat{s}}\right)^2 \leq 1$$

In terms of the scale:

$$\Lambda \geq \left(\frac{\hat{s}}{3}\right)^{\frac{1}{2}} \left(1 + \frac{M^2}{2\hat{s}}\right)^{1/4} \left(1 - \frac{M^2}{\hat{s}}\right)^{1/2}$$

IMPLEMENTATION OF THE BOUND (I)

Remove all events that could not have arisen in a UV-complete theory (“**EVENT CLIPPING**”)



- $\hat{s} = x_1 x_2 s$, \sqrt{s} = machine c.m.
- 10^5 MC events with CalcHEP@LO
- MadAnalyses retrieves \hat{s} from LHEs
- For each event: (\hat{s}, M, Λ) and apply the analytical relation of the bound
- Plot a level curve with the percentage of MC events satisfying the bound

IMPLEMENTATION OF THE BOUND (II)

SEMI-ANALYTIC VALIDATION

In proton-proton collisions:

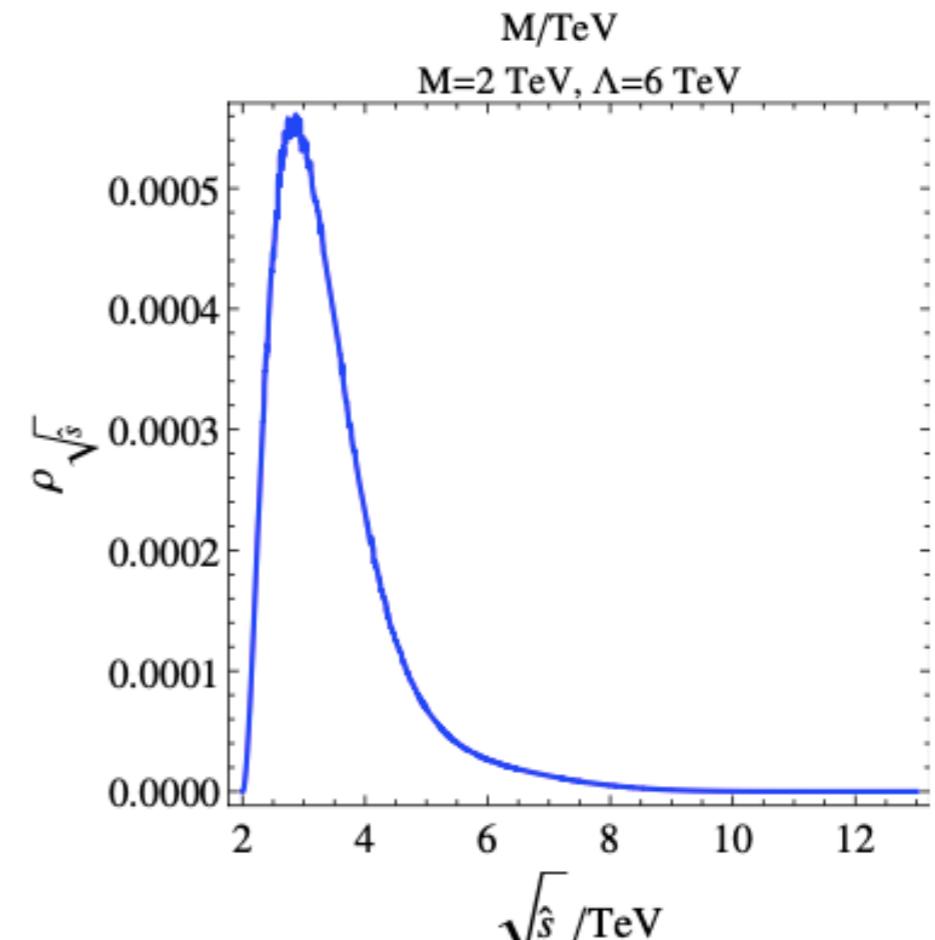
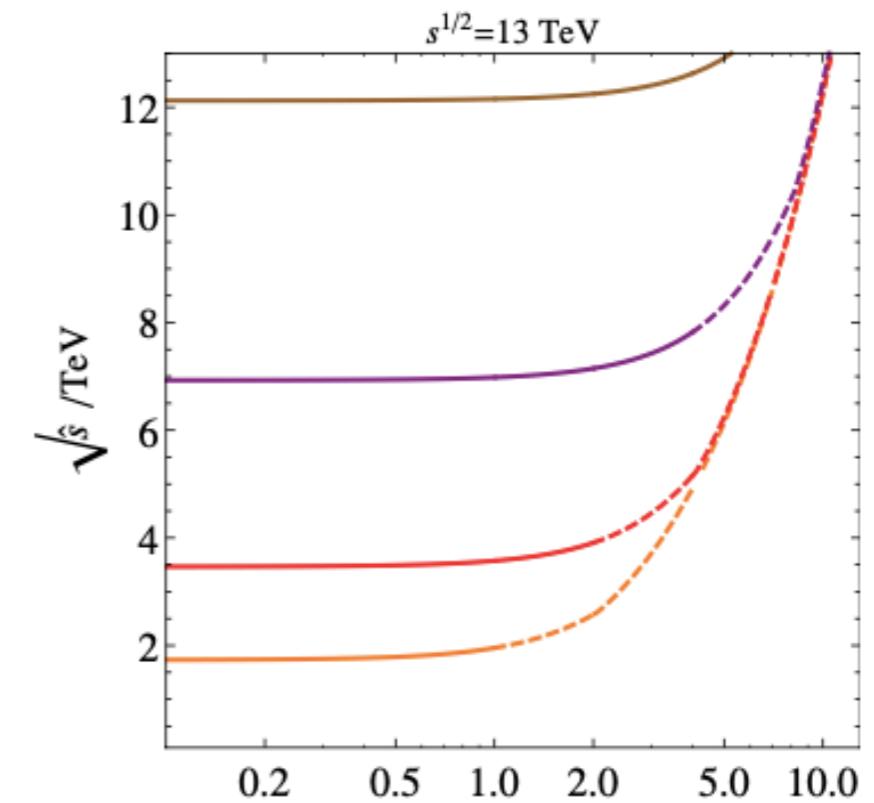
$$\sigma = \frac{1}{s} \sum_{ij} \int_{M^2}^s d\hat{s} \int_{\hat{s}/s}^1 f_i(x, Q^2) f_j\left(\frac{\hat{s}}{sx}, Q^2\right) \hat{\sigma}(M, \Lambda, \hat{s})$$

Integrating (with LHAPDF NNPDF3.0 libraries) we compute the distribution:

$$\rho \equiv \frac{1}{\sigma} \frac{d\sigma}{ds}, \text{ with normalization } \int_M^s \rho d\hat{s} = 1.$$

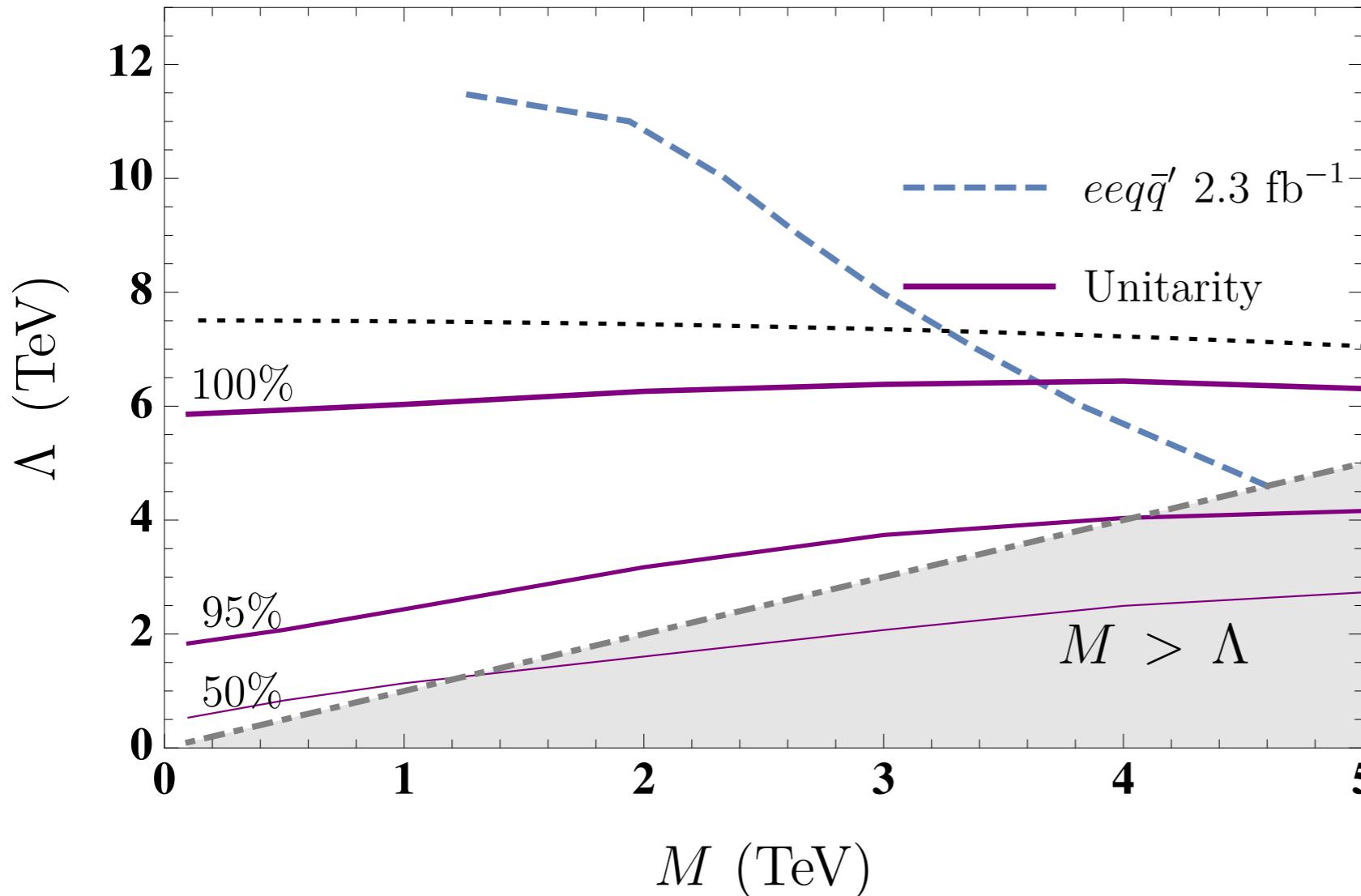
The unitarity condition can be used to restrict the extreme of integration $\hat{s}_{max}(M, \Lambda, s) \leq s$:

$$\text{Fraction of events} = \int_M^{\hat{s}_{max}} \rho_s d\hat{s}$$



RESULTS FOR RUN2

HEAVY NEUTRINO SEARCH @LHC RUN2

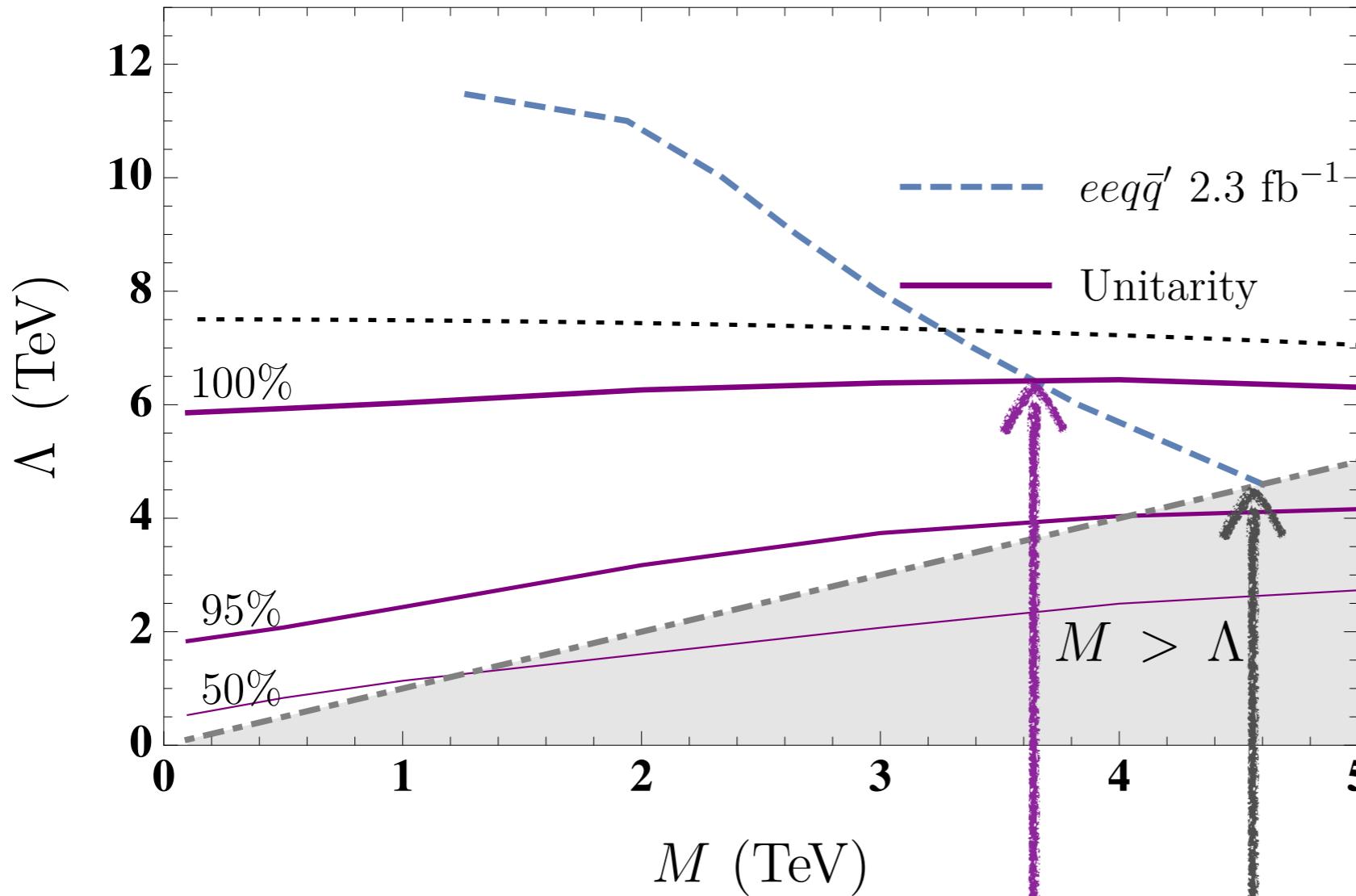


- ***blue dashed:** CMS Observed limit
- ***black dotted:** saturation of the bound
- ***purple level curves:** 100%, 95%, 50 % of MC events satisfying unitarity condition

Which unitarity curve is the reference for interpreting experimental results?

RESULTS FOR RUN2

HEAVY NEUTRINO SEARCH @LHC RUN2



HIGHEST MASS REACH
ASSUMING
ALL UNITARY EVENTS:
 $\Lambda = 4.6 \text{ TeV}, M = 3.6 \text{ TeV}$

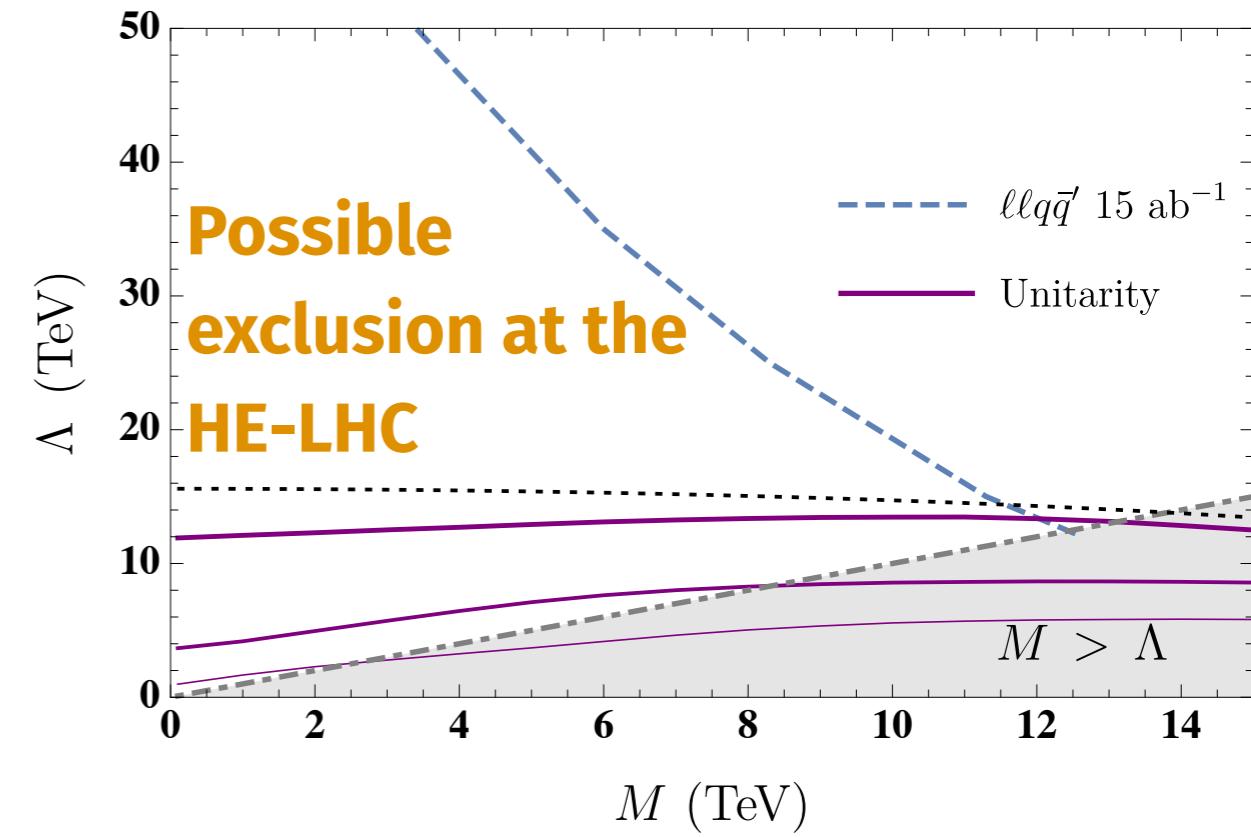
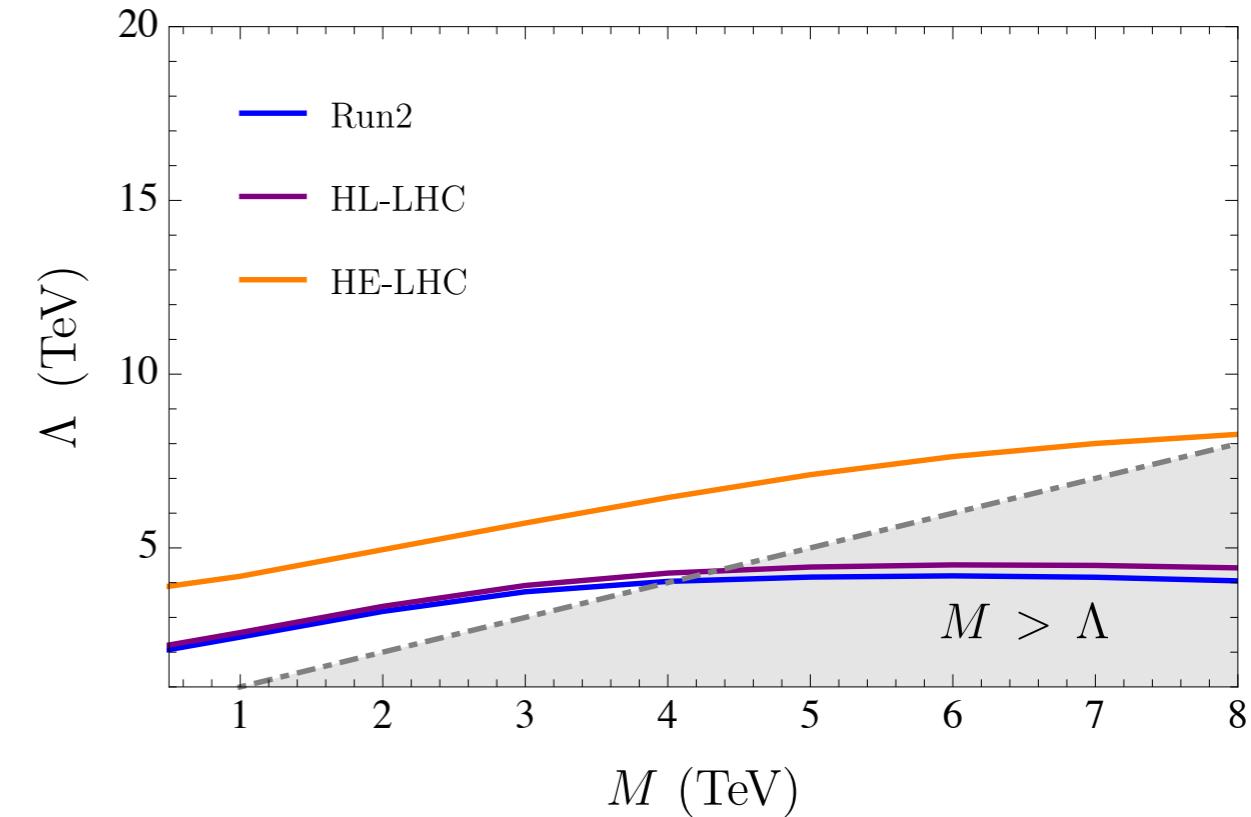
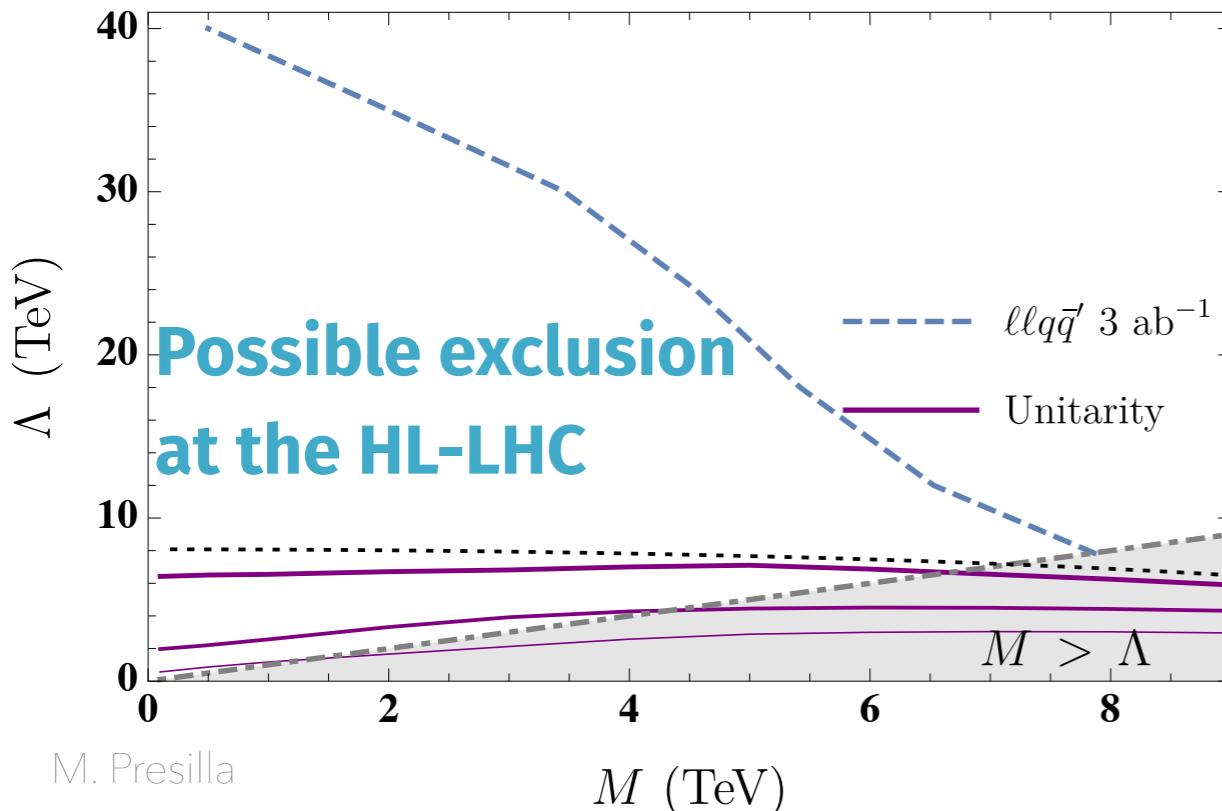
HOW CMS QUOTES
RESULTS:
 $\Lambda = M = 4.6 \text{ TeV}$

RESULTS FOR HL/HE-LHC

DIFFERENT COLLIDER SCENARIOS

The bound is applied to **HL-LHC** (13 TeV, 3 ab⁻¹) and **HE-LHC** (27 TeV, 15 ab⁻¹) projection studies ("Yellow Report", [arXiv:1902.10229](https://arxiv.org/abs/1902.10229)).

As the collision energy increases the unitarity bound becomes stronger, since the c.m. energy of the process tends to be larger.



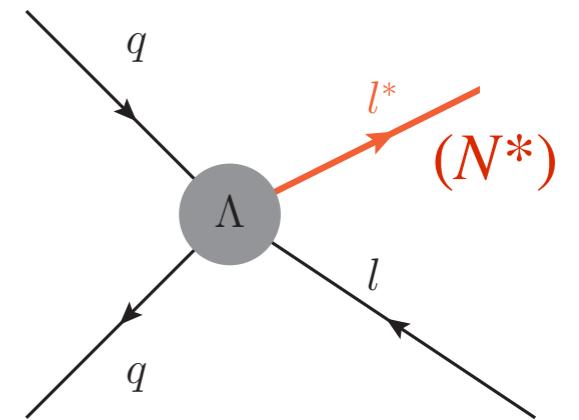
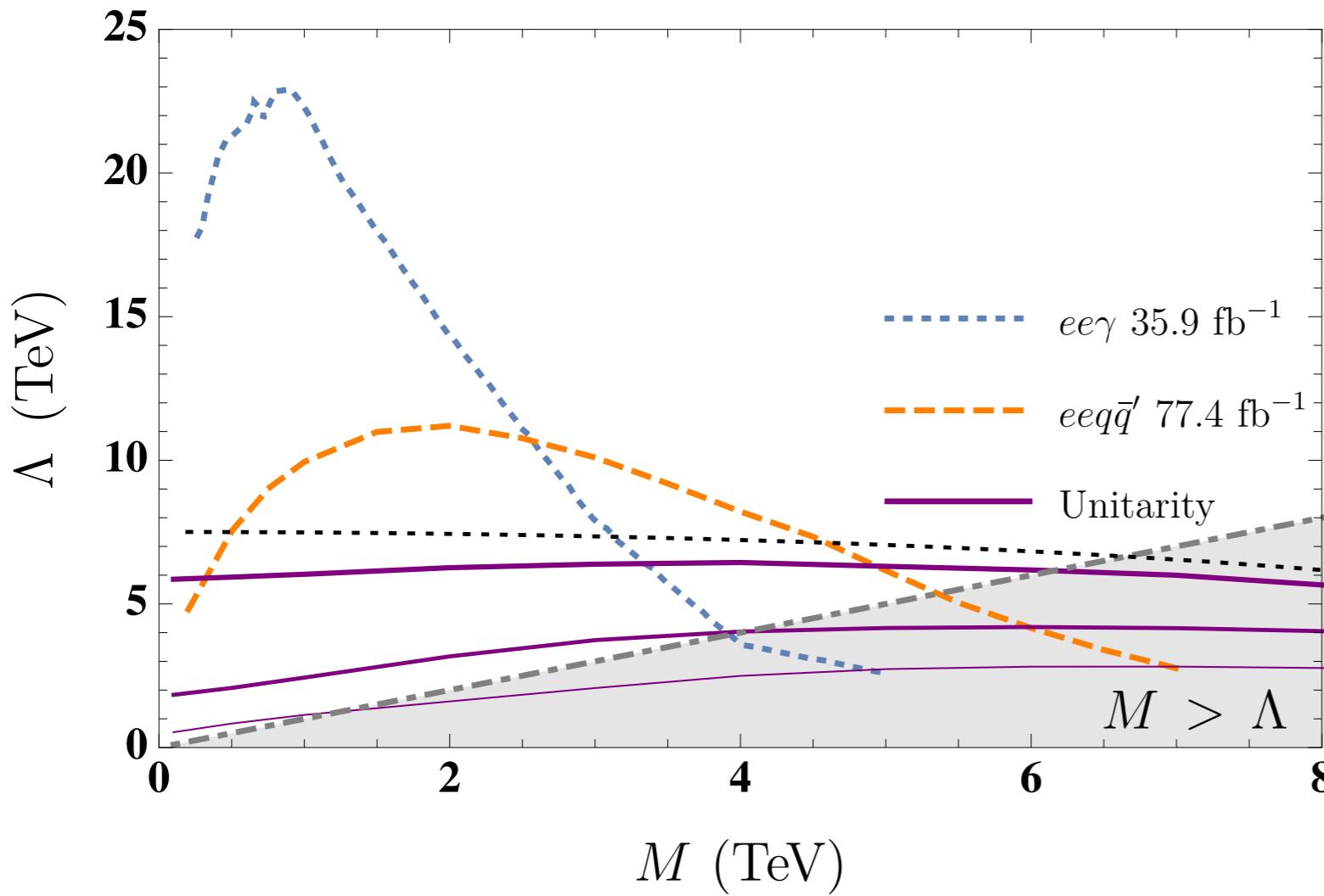
RESULTS FOR RUN2

CHARGED LEPTONS

Charged leptons (e^* , μ^* , q^*) are produced in with the **same vertex with CI**

→ the bound can be directly compared to more experimental results

Excited charged lepton (Run 2)



$M \leq 4$ TeV and $M \leq 5.5$ TeV

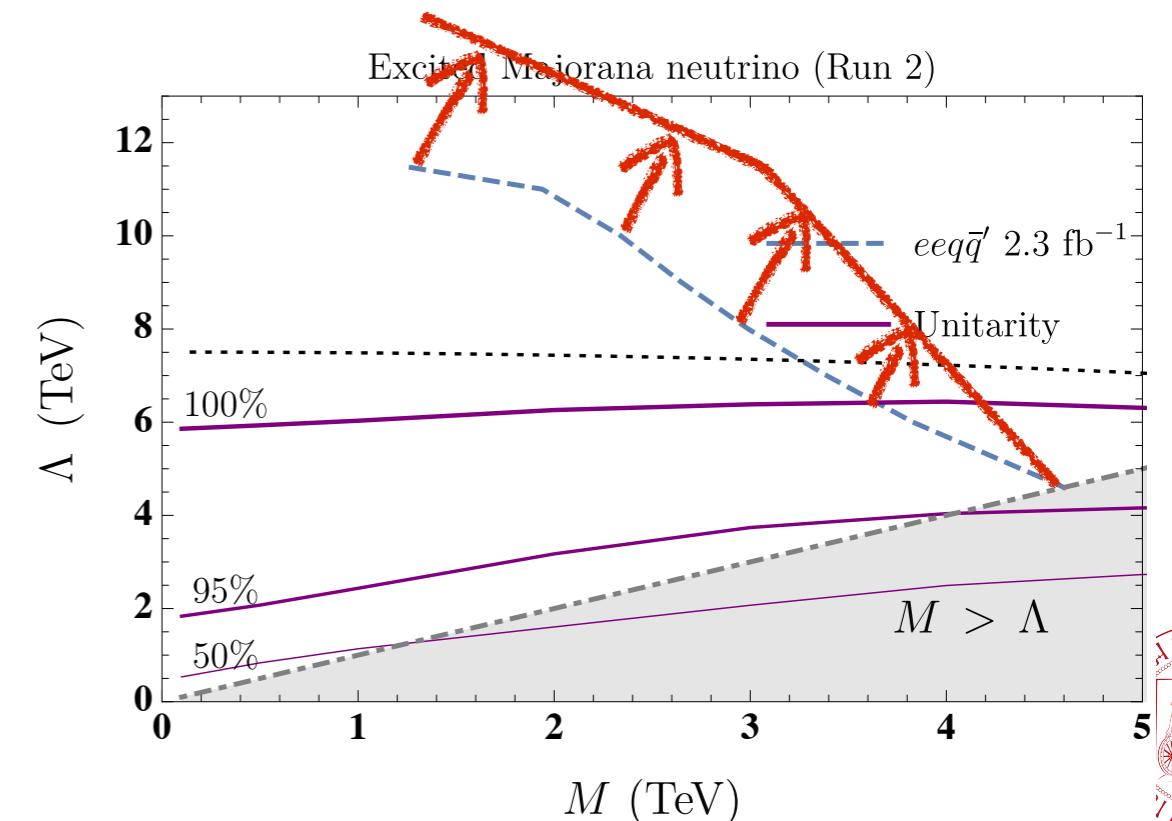
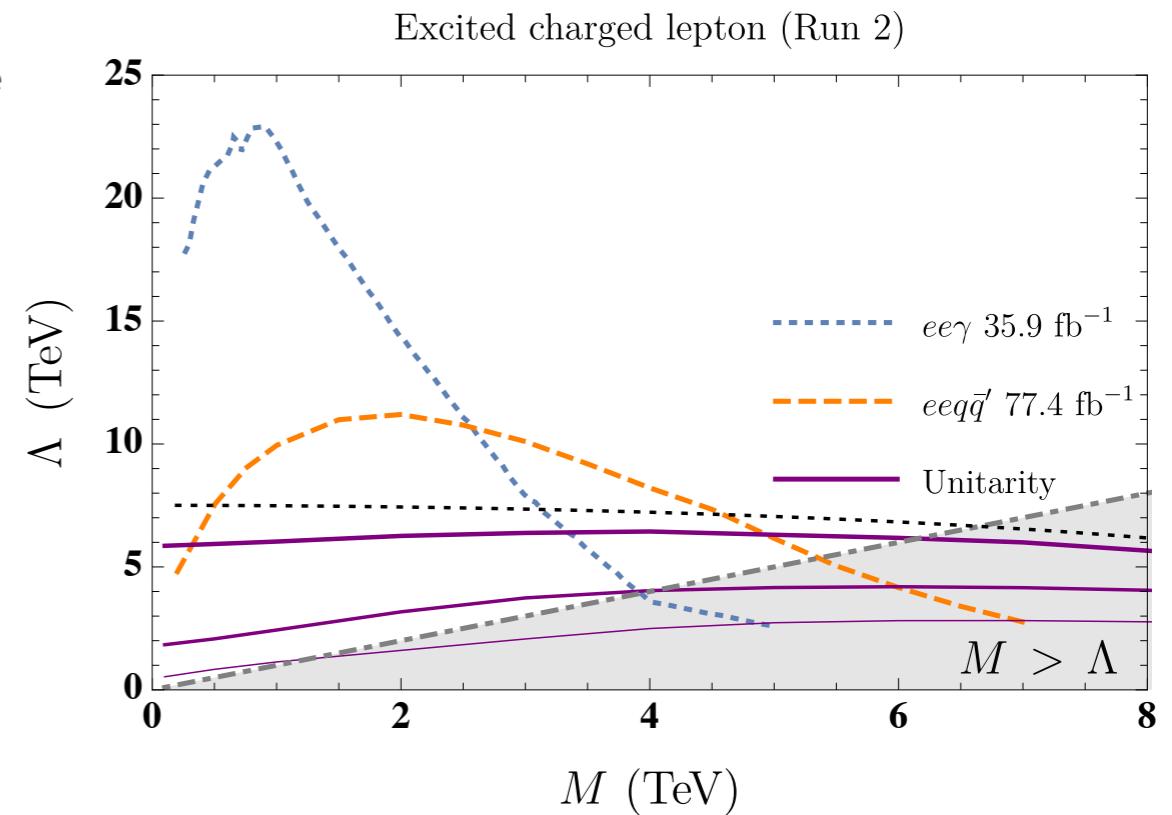
***Unitarity bound 100%:**
 $M \leq 3.4$ TeV and $M \leq 5.0$ TeV

***Unitarity bound 95%:**
 $M \leq 4$ TeV and $M \leq 6.0$ TeV

***Unitarity bound 50%:**
 $M \leq 5$ TeV and $M \leq 7.0$ TeV

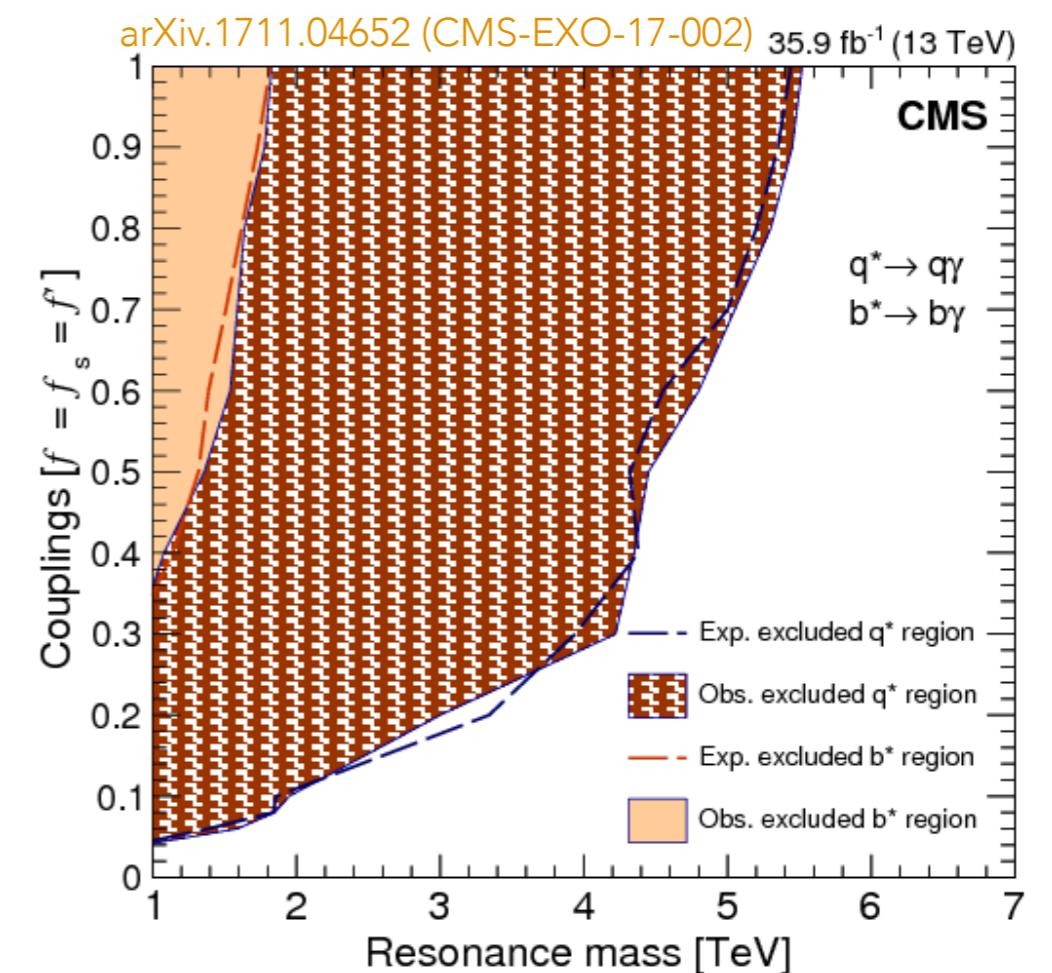
SUMMARY

- Unitarity is widely discussed in literature, but most of the time overlooked by experimental collaborations
- A fully unitary prescription is needed to interpret experimental data correctly in an EFT scenario
- Effective composite models: unitarity bound for dimension-5 and dimension-6 (GI and CI)
- Focus on excited Majorana neutrinos (+ charged leptons!)
- Two implementations and agreement with experimental colleagues
(thanks to O.Zenin and colleague from ATLAS for the independent cross-check!)
- Unitarity is an additional and more rigorous way of interpreting experimental constraints on (M, Λ) parameter space
- Guideline for new analyses strategy



OPEN QUESTIONS (I)

- **M> Λ vs. UNITARITY:** which one consider?
- Is M> Λ really justifiable being agnostic on the UV-complete theory?
(as for QCD where emergent resonances have **masses > scale**)
- Exploration of **smaller f,f', η** couplings parameter space is needed
(preferred by Leptogenesis - see S. Biondini's talk)
- Non-abelian gauge interactions and collider searches: new exotic searches portals?



OPEN QUESTIONS (II)

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- Several unitarization methods exist, bringing to different results → estimate of the [theoretical error](#) could be a solution
[\(see R. Morales' contribution -arXiv.1907.06668\)](#)
- How can we [translate theoretical prescriptions to](#) (a finite number of) MC events used in [experimental analyses?](#)

BACKUP

The bound for Gl:

$$\mathcal{L}_{\text{G1}}^{(5)} = \frac{gf}{\sqrt{2}\Lambda} \bar{N} \sigma^{\mu\nu} \left(\partial_\mu W_\nu^+ \right) P_L \ell + \text{h.c.}, \quad f \equiv 1, \quad \frac{gf}{\sqrt{2}} \approx 1$$

$$T_{(-,+)\rightarrow(-,+)}^{j=1} = -\frac{ig^2}{24\pi\Lambda} \frac{\hat{s}^{3/2}}{\hat{s} - m_W^2} \left(1 - \frac{M^2}{s} \right)^{\frac{1}{2}}$$

$$T_{(-,+)\rightarrow(+,+)}^{j=1} = \frac{ig^2}{24\sqrt{2}\pi\Lambda} \frac{\hat{s}M}{\hat{s} - m_W^2} \left(1 - \frac{M^2}{\hat{s}} \right)^{\frac{1}{2}}$$

$$\frac{g^4}{1152\pi^2\Lambda^2} \frac{\hat{s}^2 (2\hat{s} + M^2)}{(\hat{s} - m_W^2)^2} \left(1 - \frac{M^2}{\hat{s}} \right)^2 \leq 1$$