Kick-off Meeting.
Piano Triennale della Ricerca e Terza Missione (2021-2023),
Dipartimento di Fisica e Geologia.

Modelli Compositi e Teorie di Campo Efficaci a LHC e ai collider del futuro.

Vincoli di unitarietà e complementarità con le ricerche in esperimenti di bassa energia.

S. AJMAL, C. CARRIVALE, O. PANELLA, M. PRESILLA - 11 JAN. '21

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Ambito di ricerca del PTSR già attivato: 4

Fisica delle Interazioni Fondamentali

Tematiche:

- Definizione e sviluppo di modelli che prevedano l'esistenza di fermioni compositi, studio della loro dinamica nell'ambito del Modello Standard e dei possibili segnali da osservare nei futuri esperimenti di LHC e HL-LHC e/o futuri collider.
- Complementarità con esperimenti di bassa energia ($0\nu\beta\beta$)

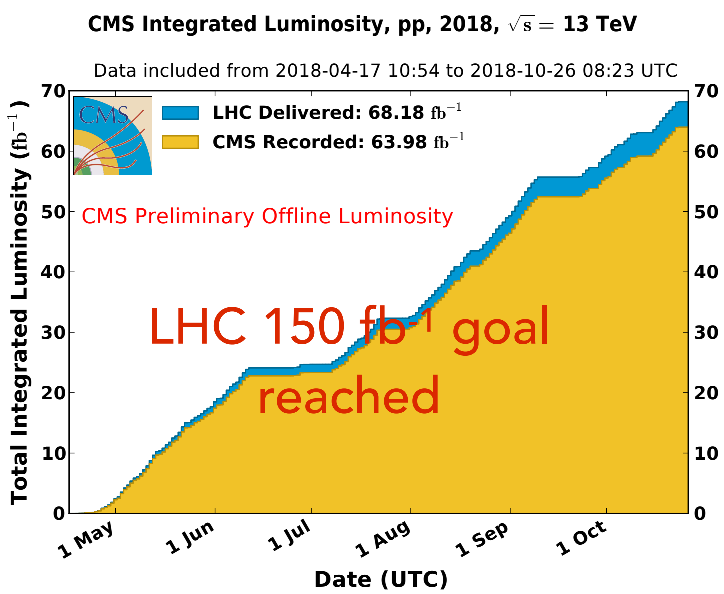
Gruppo di Ricerca

- Sehar Ajmal (Dottorato, XXXVI ciclo)
- Costanza Carrivale (Laureanda)
- Matteo Presilla (Assegnista INFN)
- Orlando Panella (Ric. INFN)

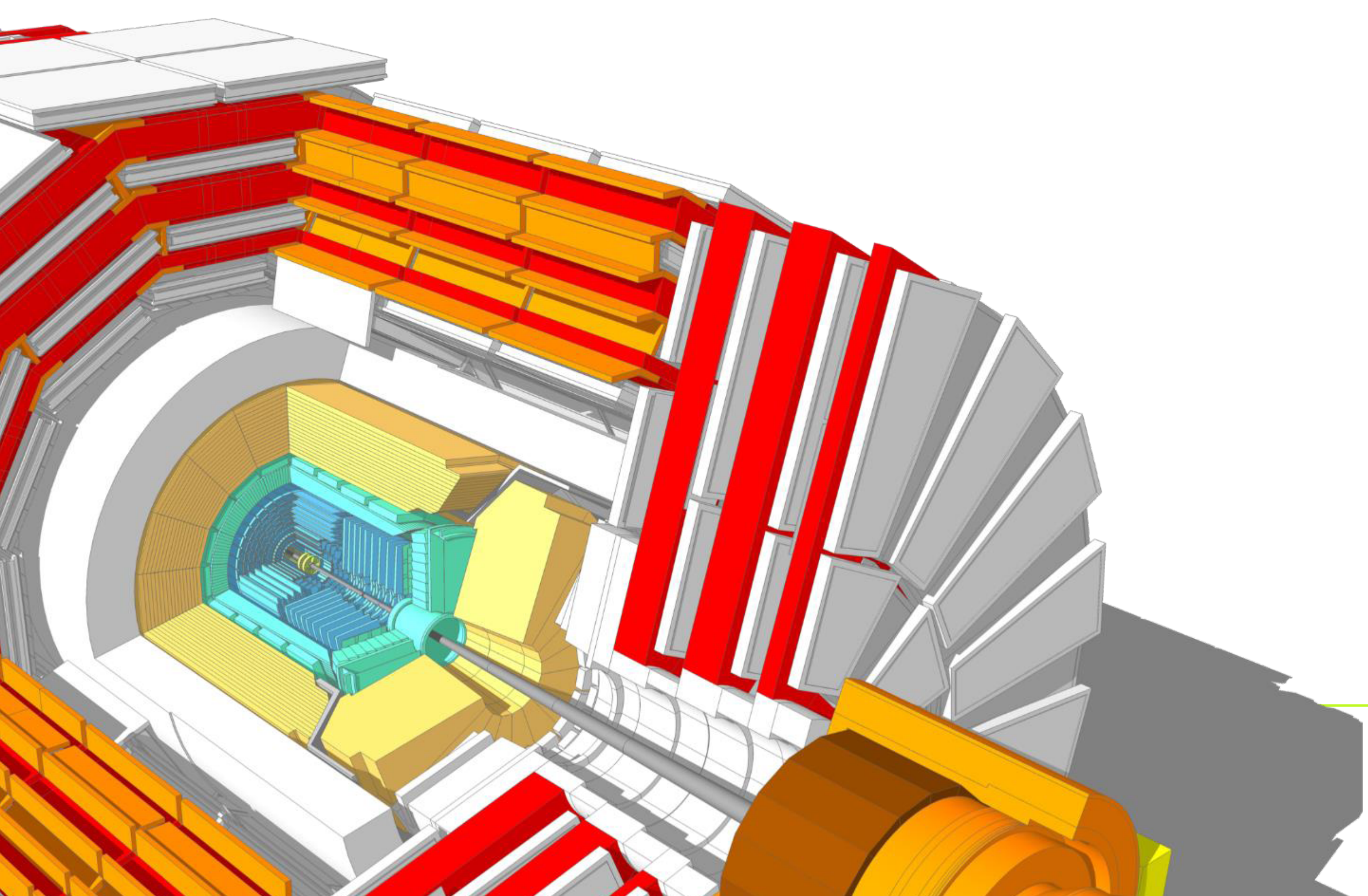
Outline

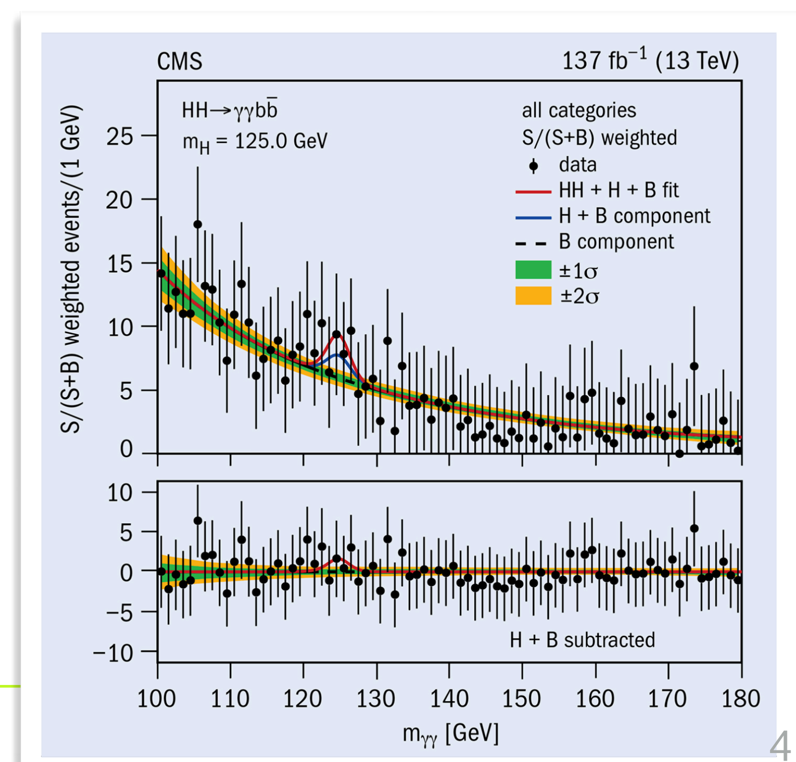
- Motivation
- Composite models, effective interactions, new resonances
- Experimental searches for exotic particles with CMS at the LHC and future colliders
- Complementarity between low energy experiments ($0\nu\beta\beta$ decay) and collider searches
- Impact of Unitarity in sensitivity to EFT operators in Vector Boson Scattering at LHC.
- Summary

Where are we?



- Almost 10 years from Higgs boson discovery
- Quality and amount of measurements beyond expectations:
  it started with Higgs detection, we target di-Higgs production
- Excellent performance of **LHC** and **CMS detector** at the end of the **LHC Run 2 data taking**





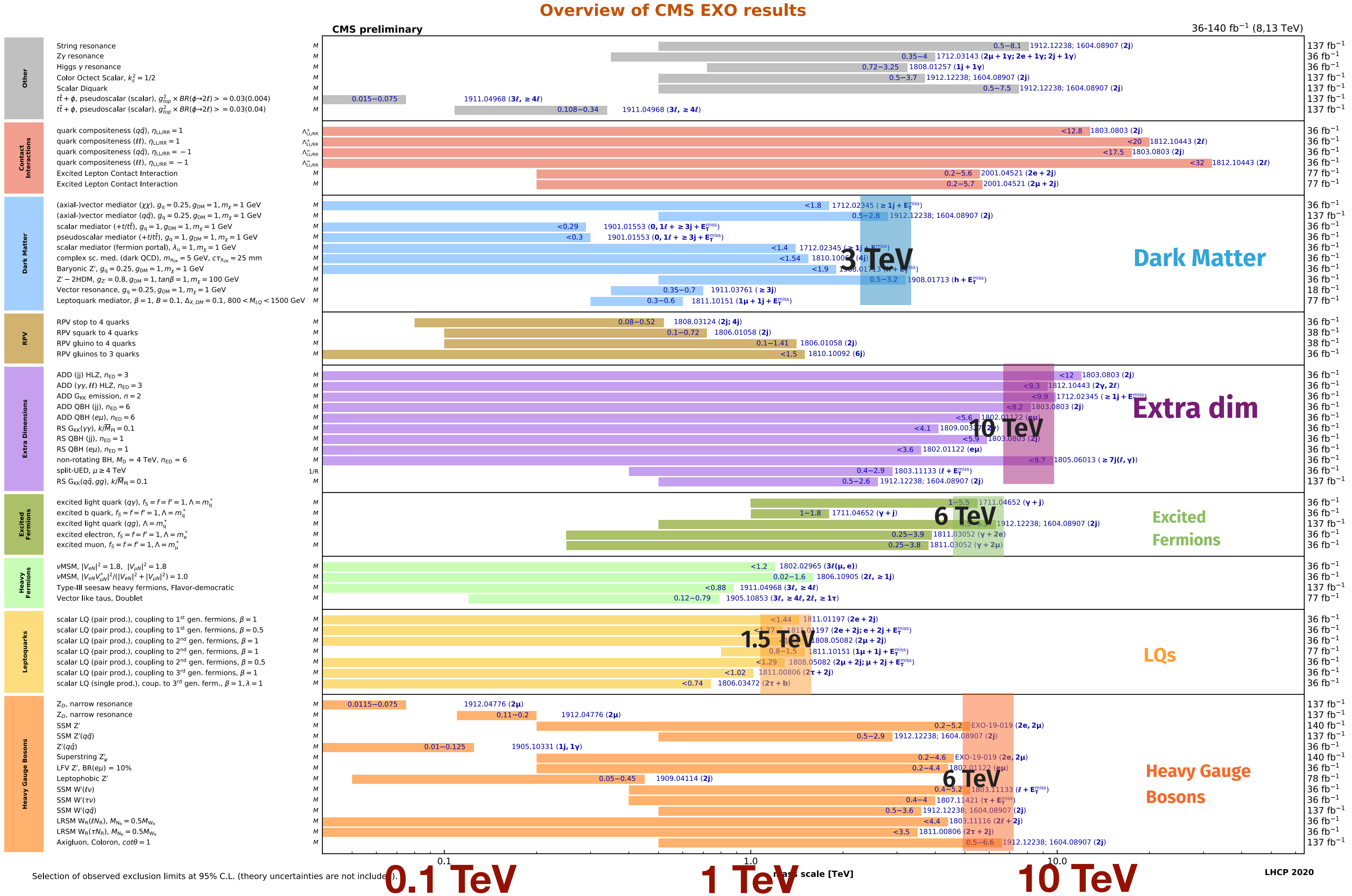
Targeting di-Higgs measurements ArXiv.2011.12373.

Where are we?

Recent CMS exclusion bounds on BSMs

No **clear** sign of TeV scale New Physics has been observed in direct searches at LHC data…

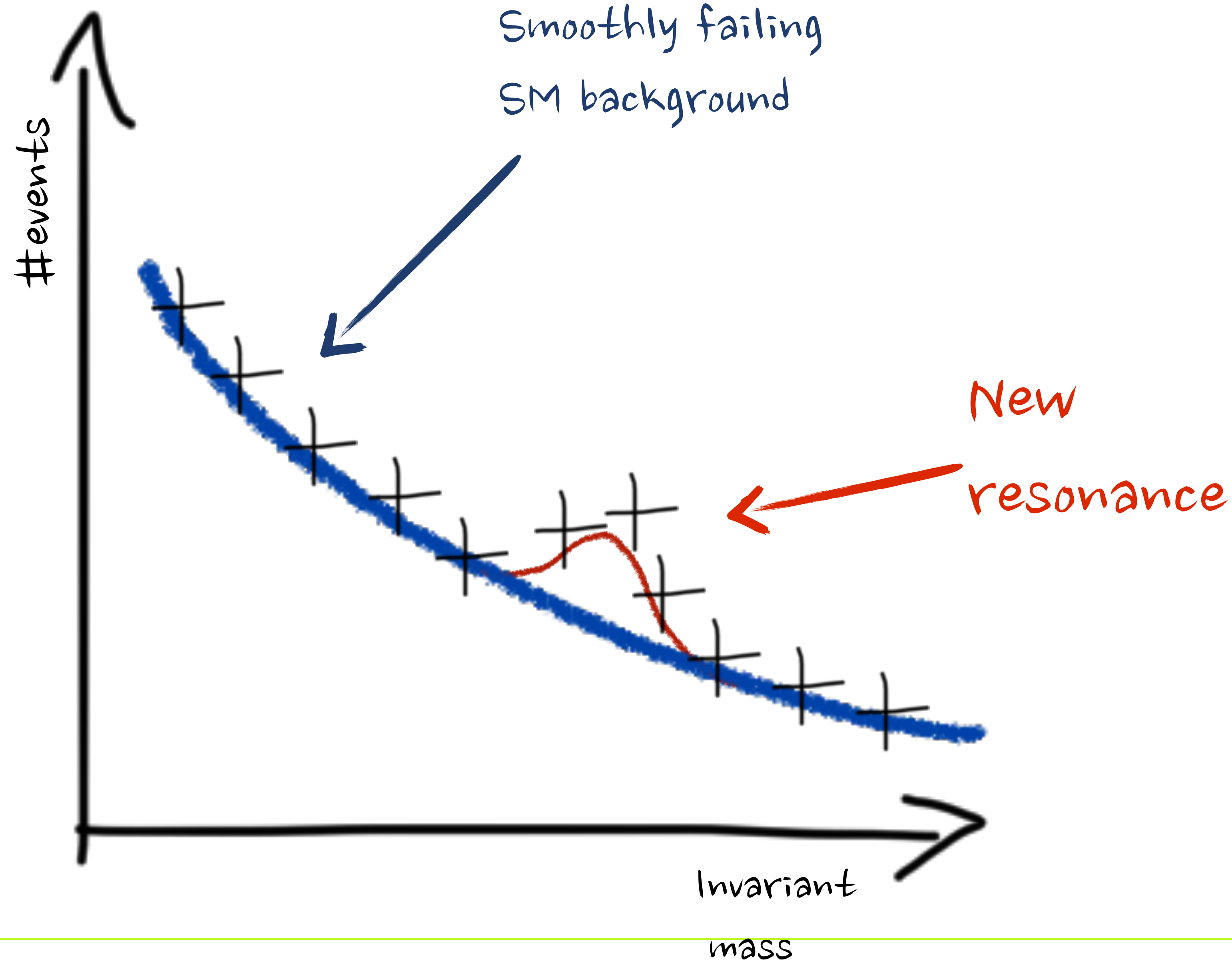
Approaching saturation of the energy frontier for the next 30 years.



What do we do?

A Cartoon guide to search for new physics

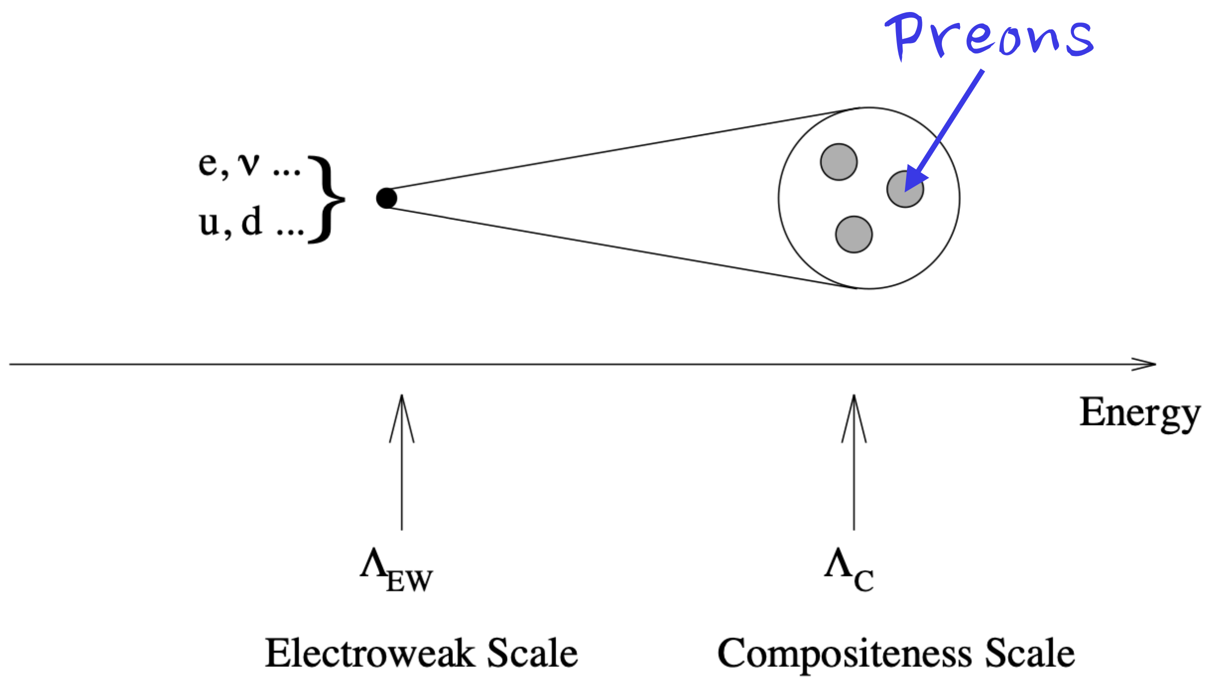
1. Direct searches:



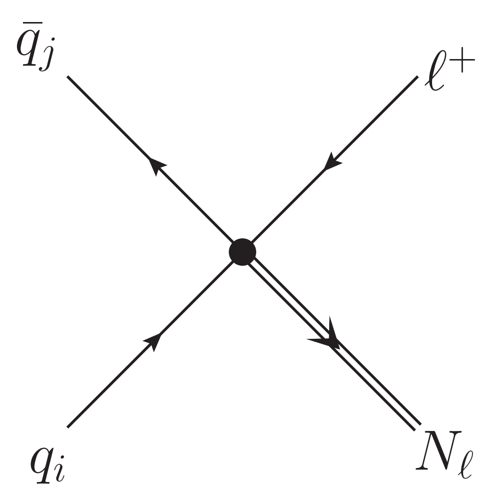
Composite Models

- Compositeness of leptons and quarks is one possible scenario beyond the Standard Model
- **Excited leptons and quarks**, e. g. e*, N*, q*, with interactions among lowest-lying and excited states (same constituents -preons-) with **effective operators, with masses smaller than the scale in which they should show up** $M^* \leq \Lambda$

H. Terezawa (PRD 22, 1980); E. Eichten, K. D. Lane, M. E. Peskin (PRL 50, 1983); H. Harari (Phys. Rep., 1984);

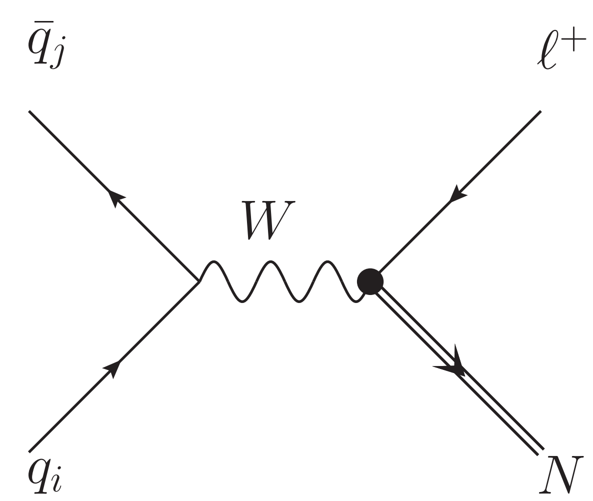


Dim-6 contact interactions:



$$\mathscr{L}_C^{(6)} = \frac{4\pi}{\Lambda^2}\frac{1}{2} j^\mu j_\mu,$$

Dimension-5 gauge interactions:



$$\mathscr{L}_G^{(5)} = \frac{1}{2\Lambda}\bar{L}_R^{\star}\sigma^{\mu\nu}\left(gf\frac{\tau^a}{2}W^a_{\mu\nu} + g'f'\frac{Y}{2}B_{\mu\nu}\right)L_L + h.c.$$

Parameters of the model: Λ, M^* (with $M^* \leq \Lambda$)

(with the other factors usually set to unity f, f', …)

Composite Models

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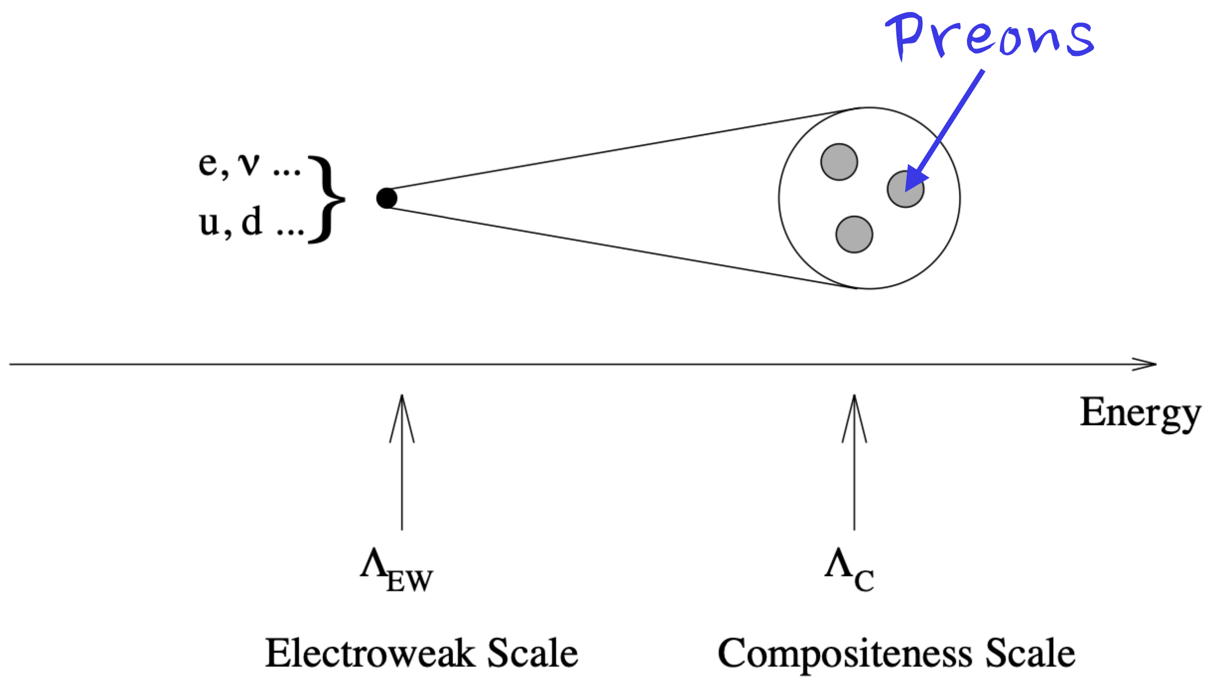
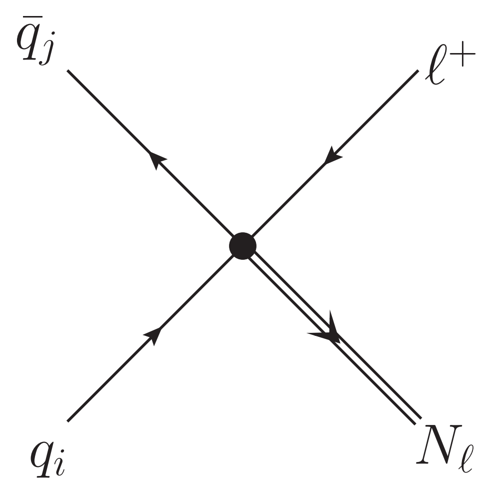


Dim-6 contact interactions:



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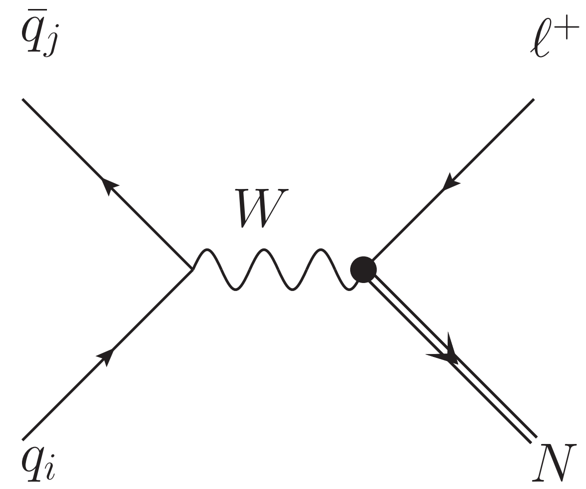

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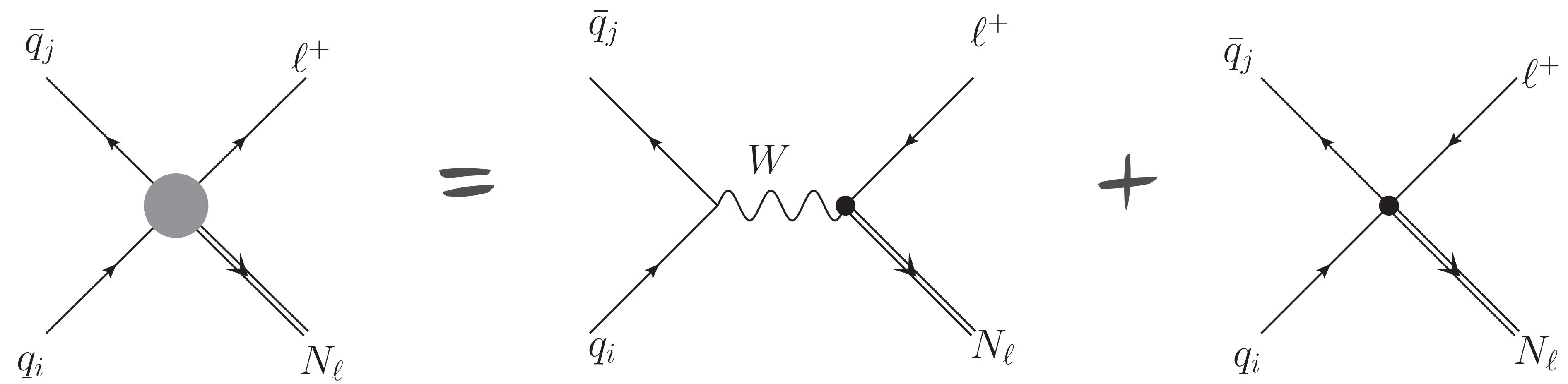
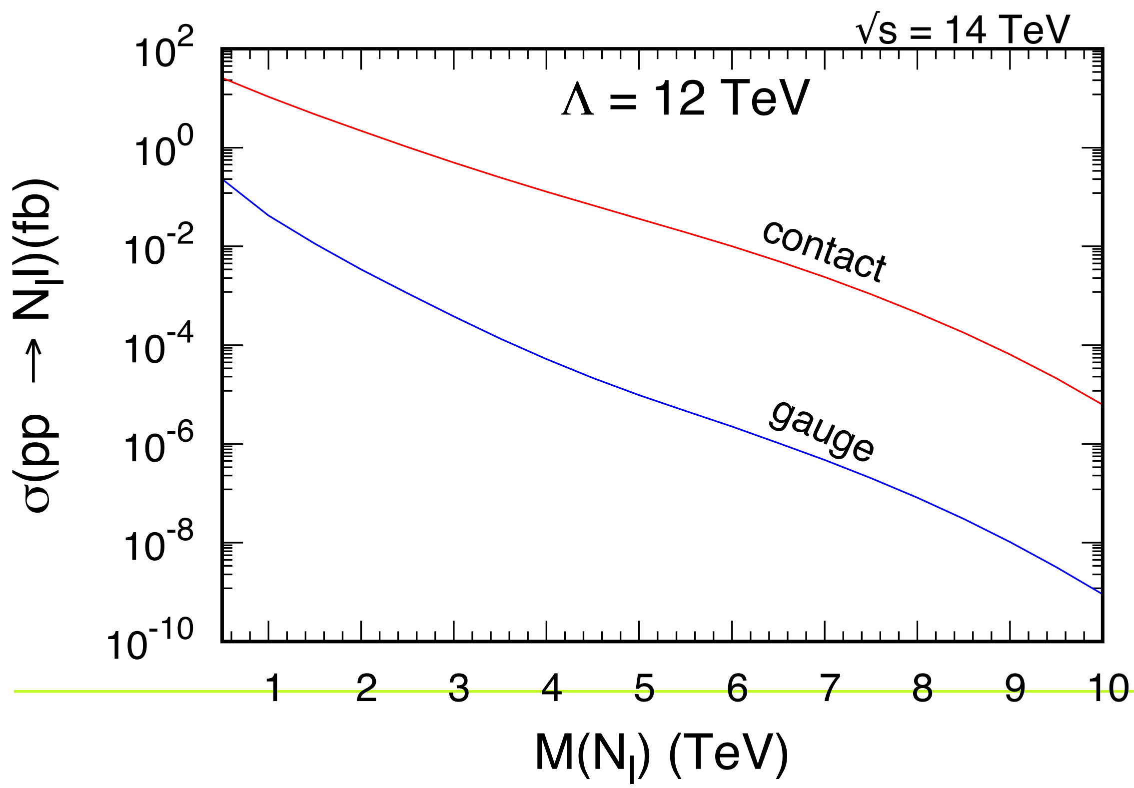
Composite models in collider searches (I)

Both contact and gauge contribute to the total production cross section of the excited leptons

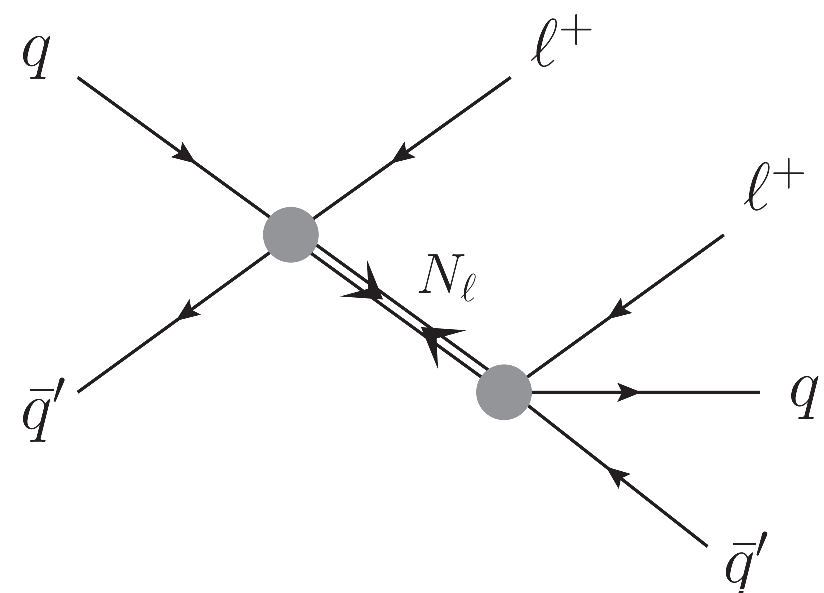


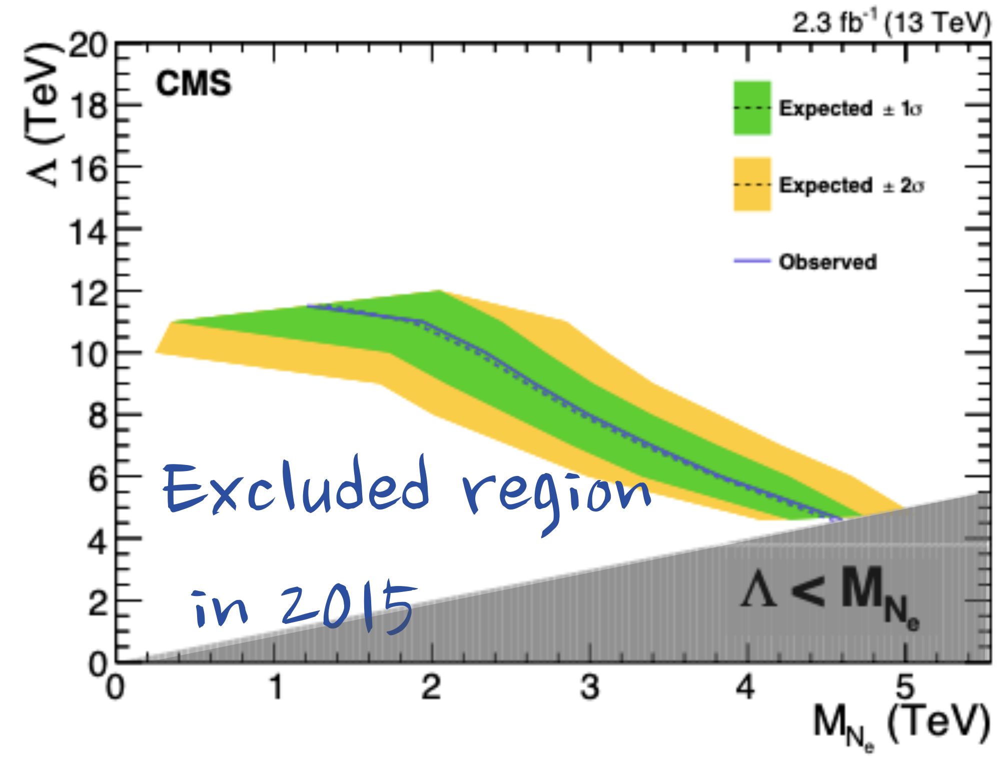


- Production cross sections depend both on **Λ** and **M(N_l)**
- **Contact interaction is dominant** (tested up to $\sqrt{s}$ = 100 TeV)

Composite models in collider searches (II)

Theoretical model widely used by LHC Collaborations.
Majorana Neutrinos (N) (arXiv.1706.08578, PLB 775 (2017))





"Brazilian plot" for HCN (arXiv.1510.07988).

Possible source of **baryogenesis via leptogenesis**

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

(arXiv. 1707.00844)

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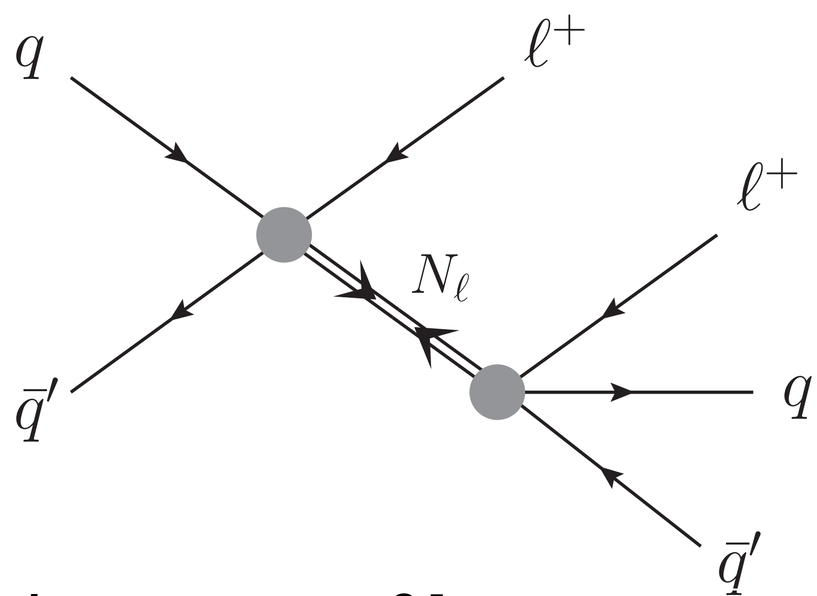

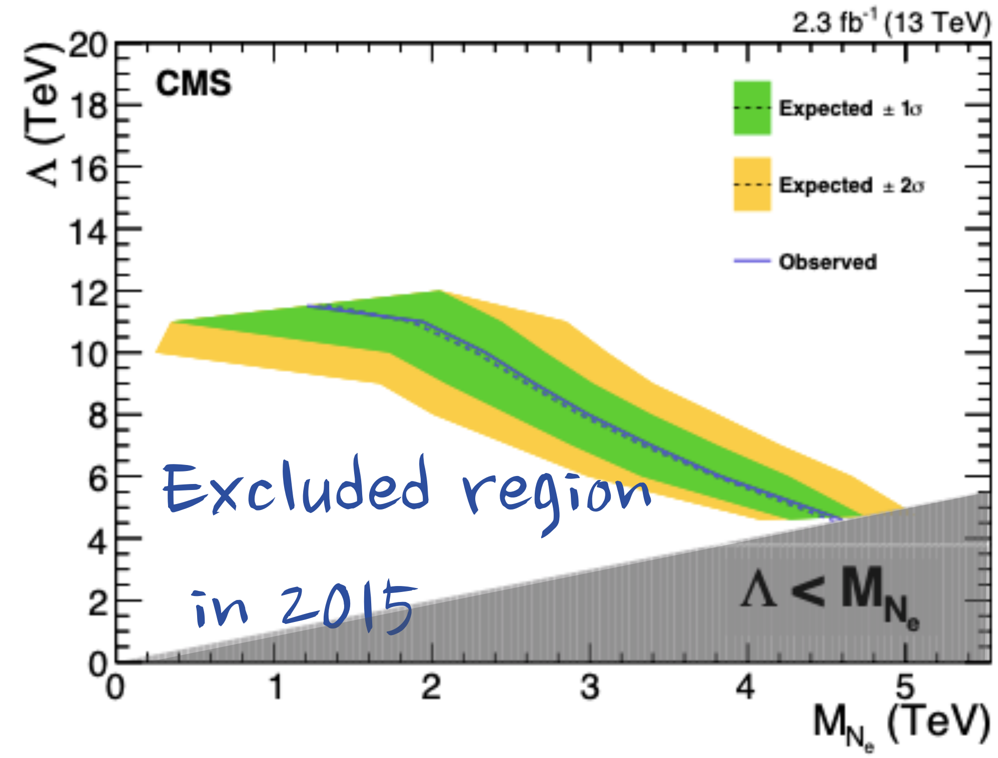

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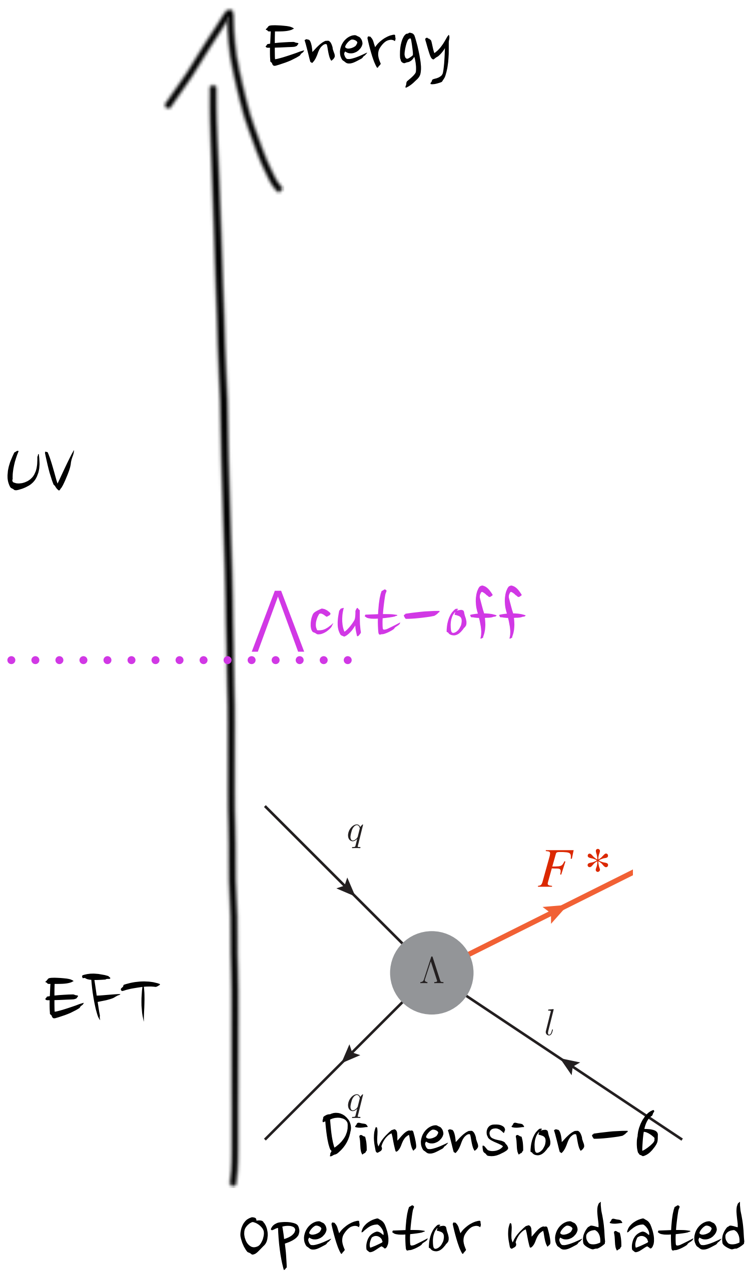
The limits on largest mass are quoted from **Exp-limits|95%CL with:** $\mathbf{M^* = \Lambda}$

- for 2015 CMS data analysis exclusion up to $\mathbf{\Lambda = M(N_e) \simeq M(N_\mu) \simeq 4.6\,TeV}$
- How do we know that the limit is in a **valid region for the EFT?**

Perturbative unitarity bound for effective composite fermions (I)

"Perturbative unitarity bounds for effective composite models", Biondini, Leonardi, Panella, Presilla (ArXiv.1903.12285, PLB)

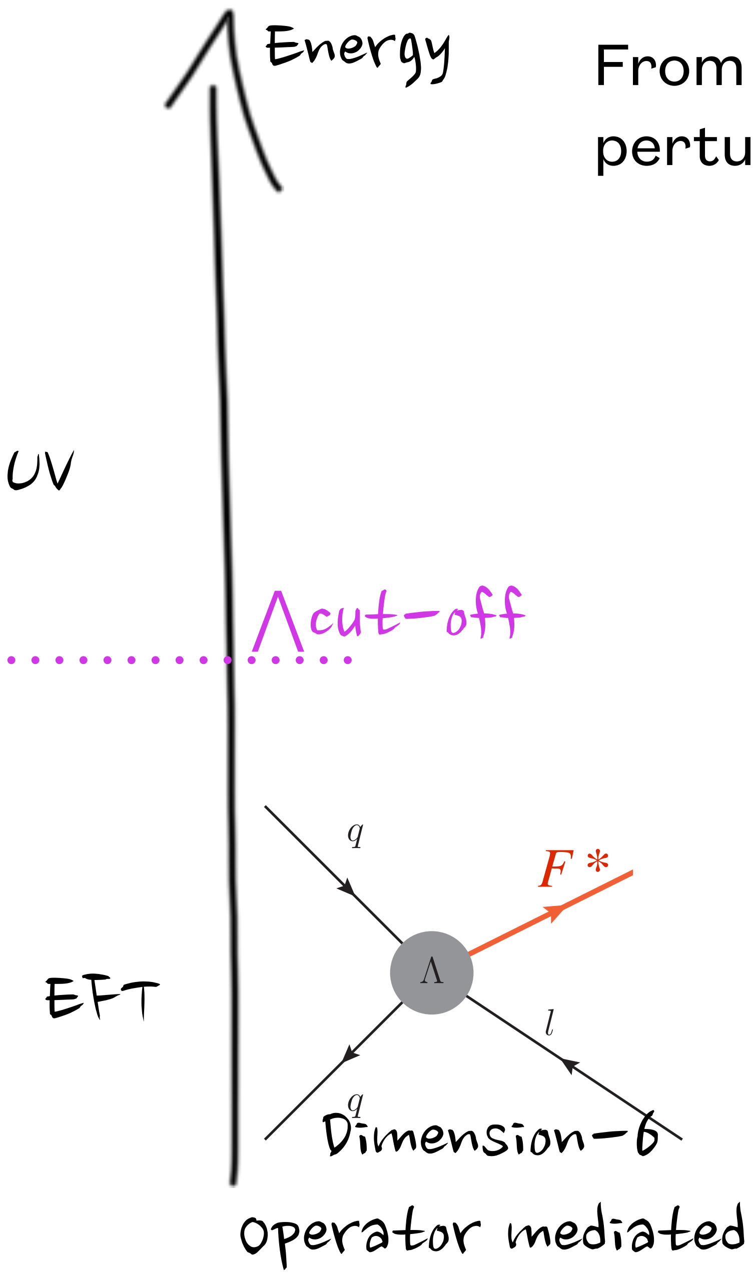


- Dominant production for excited leptons at the LHC: $q\bar{q}' \to N_\ell \ell$
- The production cross-section of the Contact Interaction **(dimension-6) Lagrangian** grows rapidly with collision energy:

$$\mathcal{O}_6 = \frac{g_*^2}{\Lambda^2}(\bar{q}\gamma^\mu P_L q')(\bar{F}^*\gamma_\mu P_L l) \quad \Rightarrow \hat{\sigma} \simeq \frac{g_*^4}{192\pi\Lambda^2}\frac{E^2}{\Lambda^2}$$

- The probability for the transition can be > 1! There must be some cut-off for the validity of this EFT.

Perturbative unitarity bound for effective composite fermions (II)*



From Optical Theorem in proton-proton collisions, we can obtain a perturbative unitarity bound for the EFT production process:

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

EFT scale

Excited Fermion mass

C.o.M. energy of parton system

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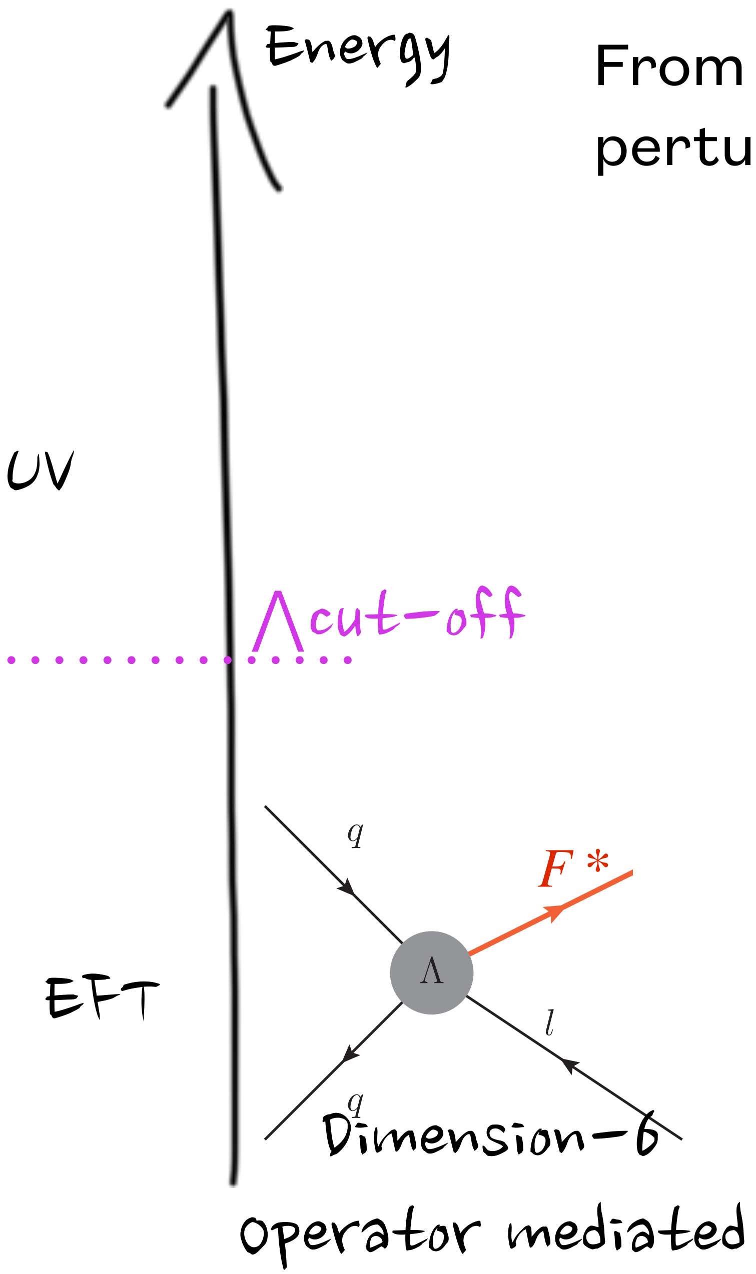

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EFT scale

C.o.M. energy of parton system

fixing $(\hat{s}, M^*)$ we know the allowed Λ values for the EFT

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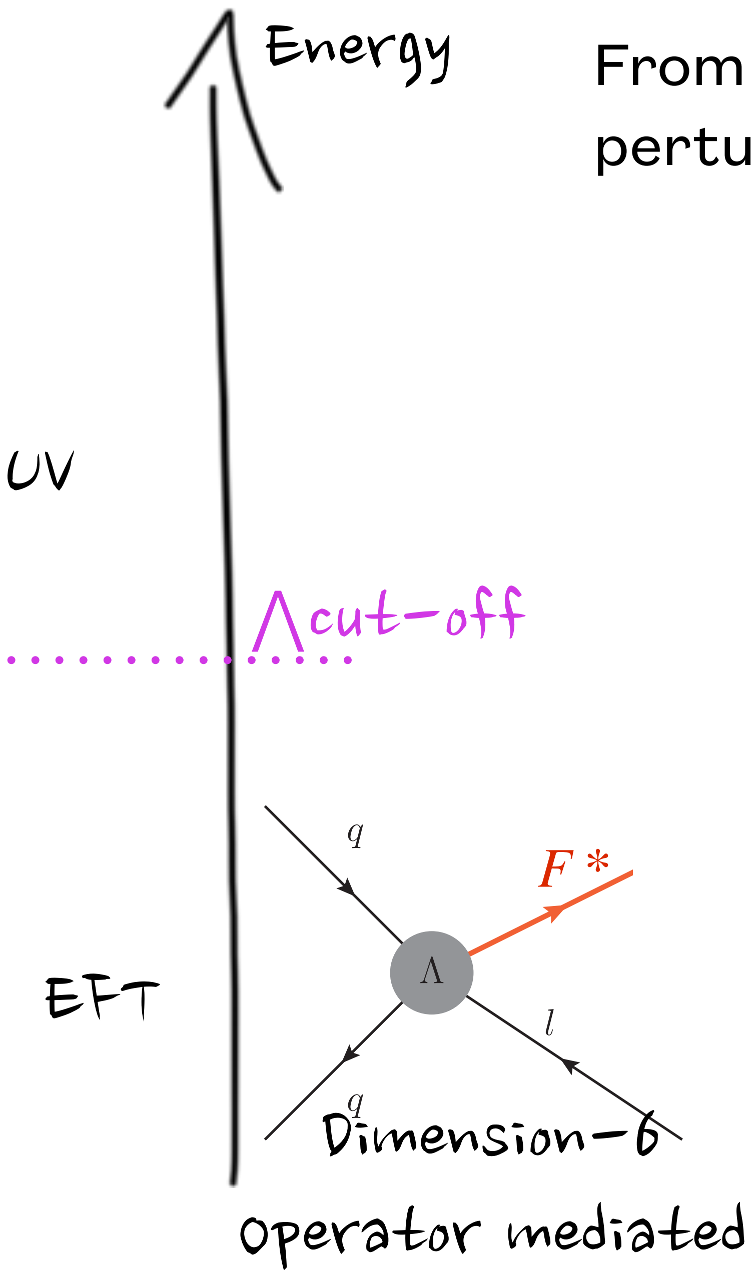
Perturbative unitarity bound for effective composite fermions (II)*



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EFT scale

C.o.M. energy of parton system

Physical Interpretation

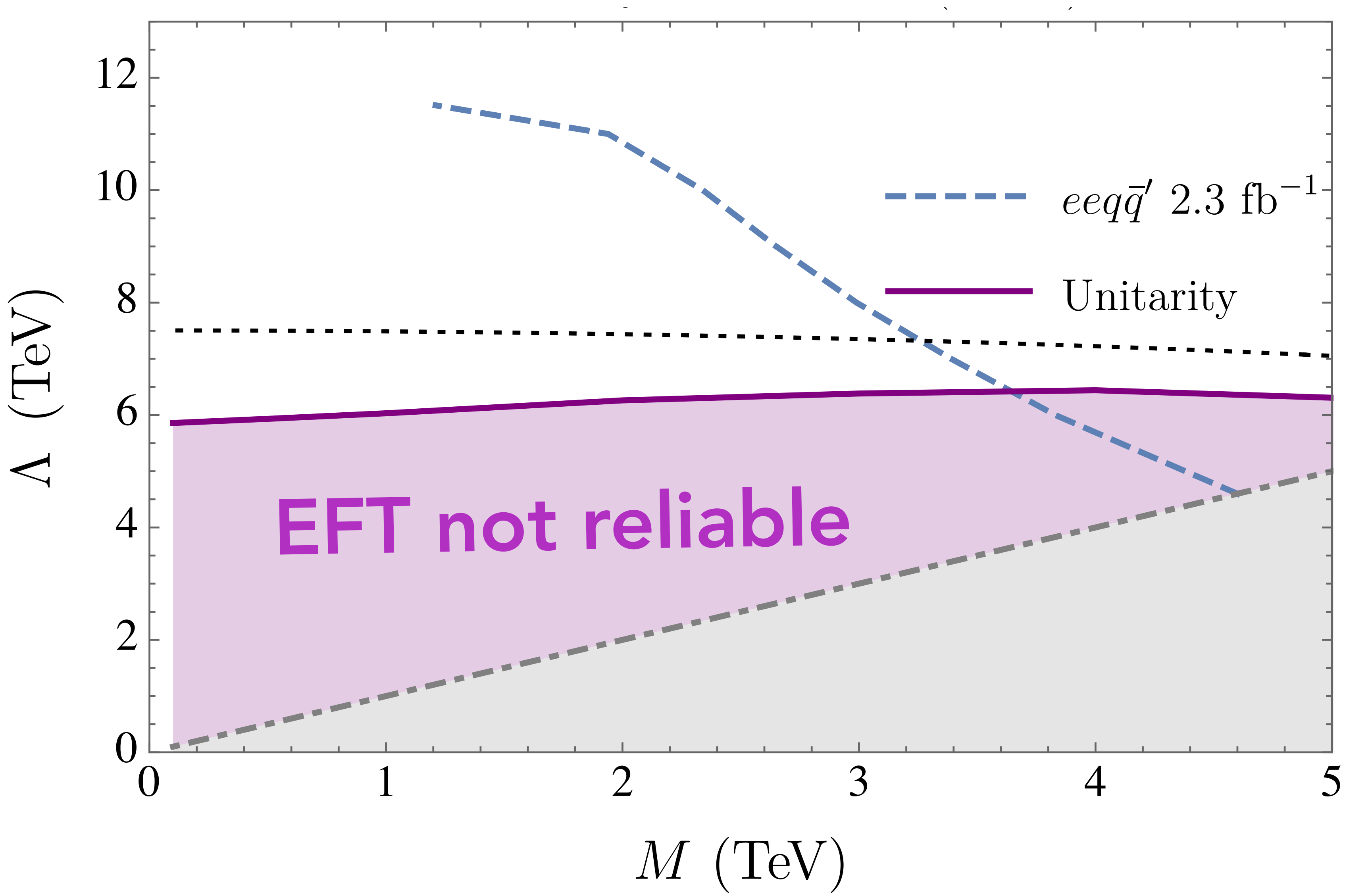
A modification to $\mathcal{O}_6$ must appear before the bound is violated:

- UV completion of a new dynamics, or
- **higher terms in the operator expansion.**

*"Perturbative unitarity bounds for effective composite models", Biondini, Leonardi, Panella, Presilla (ArXiv.1903.12285, PLB)

Impact of the bound on collider searches

EXAMPLE FROM CMS RUN2 ANALYSIS



***blue dashed:**
CMS Observed limit in 2015

***black dotted:**
saturation of the bound ($\hat{s} = s$)

***purple level curves:**
100% of MC events satisfying unitarity condition
[same approach in Endo, Yamamoto - 1403.6610]

Impact of the bound on collider searches

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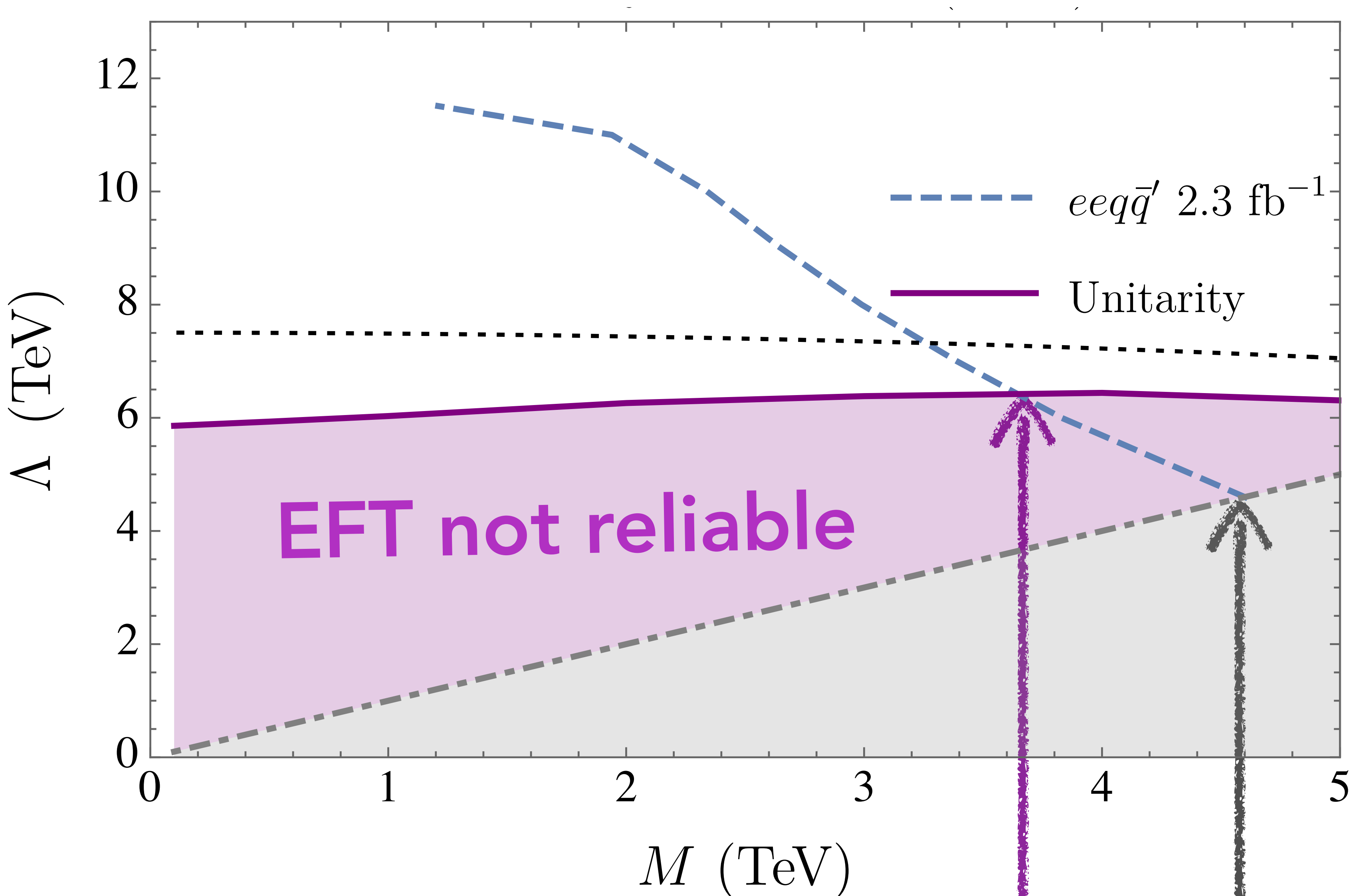

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[same approach in Endo, Yamamoto - 1403.6610]

HIGHEST MASS REACH ASSUMING ALL UNITARY EVENTS:
$\Lambda = 6\,TeV, M = 3.6\,TeV$

HOW CMS QUOTES RESULTS:
$\Lambda = M = 4.6\,TeV$

Impact of the bound on collider searches

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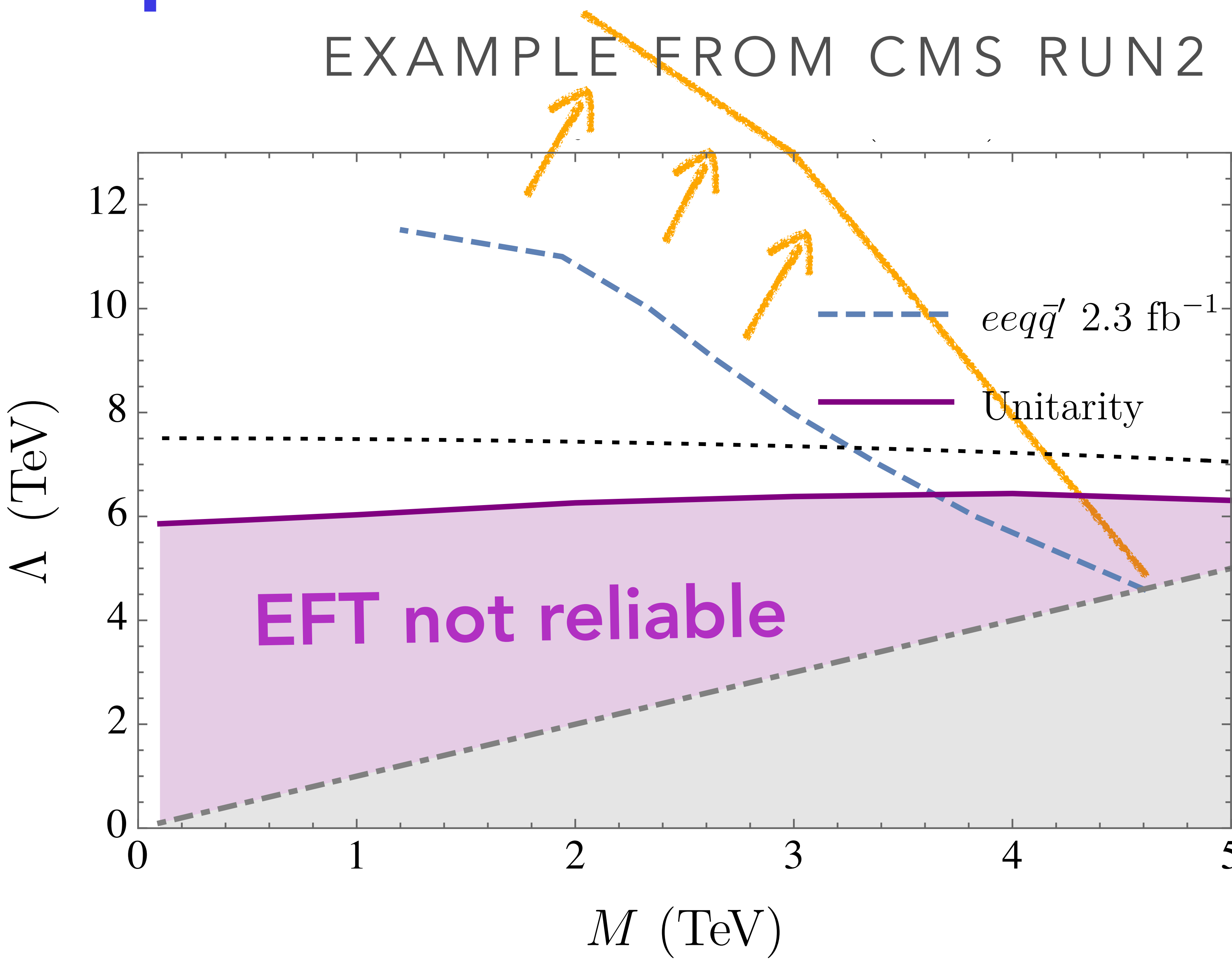

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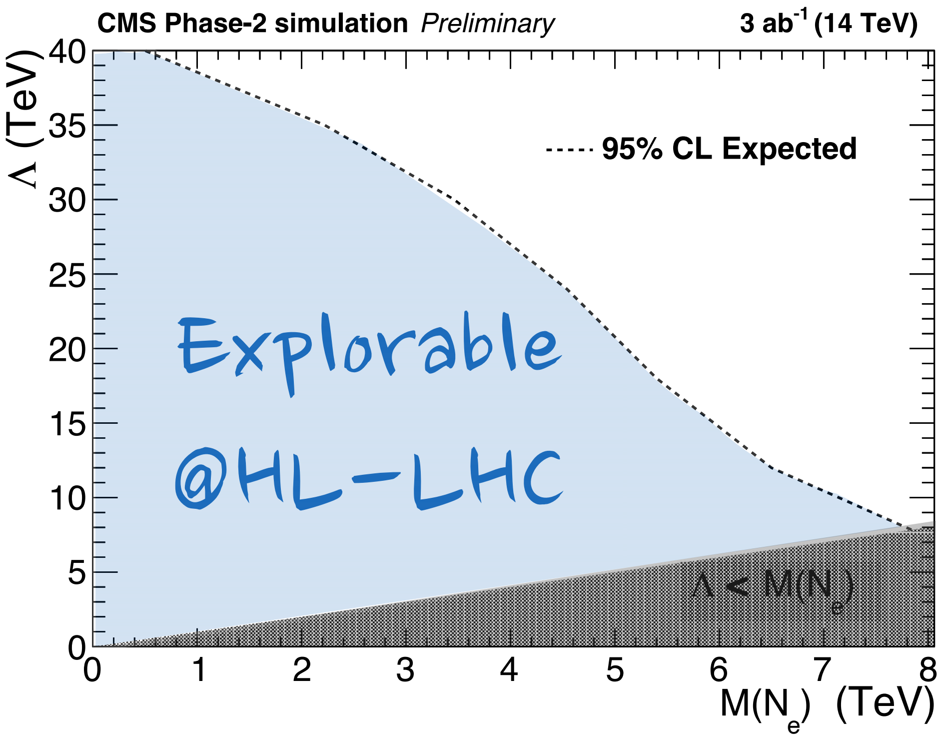
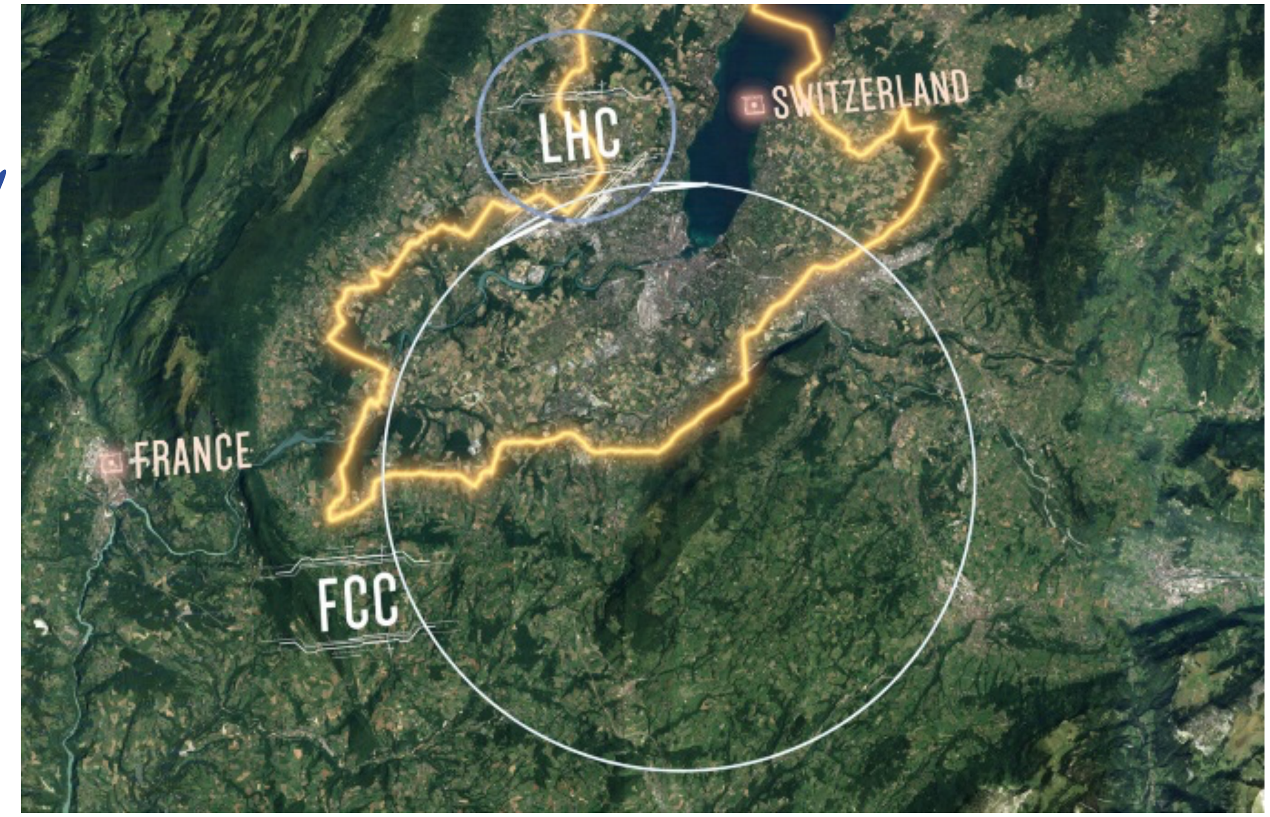
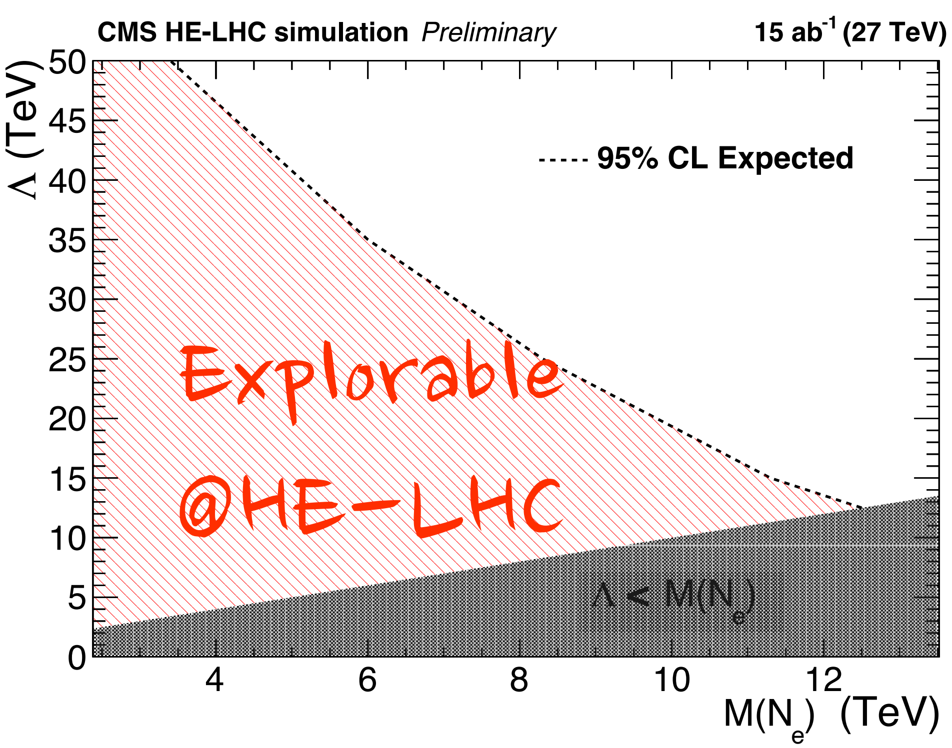
UNITARITY CAN HAVE A KEY ROLE IN THE OPTIMISATION OF THE SEARCH

Future collider prospects



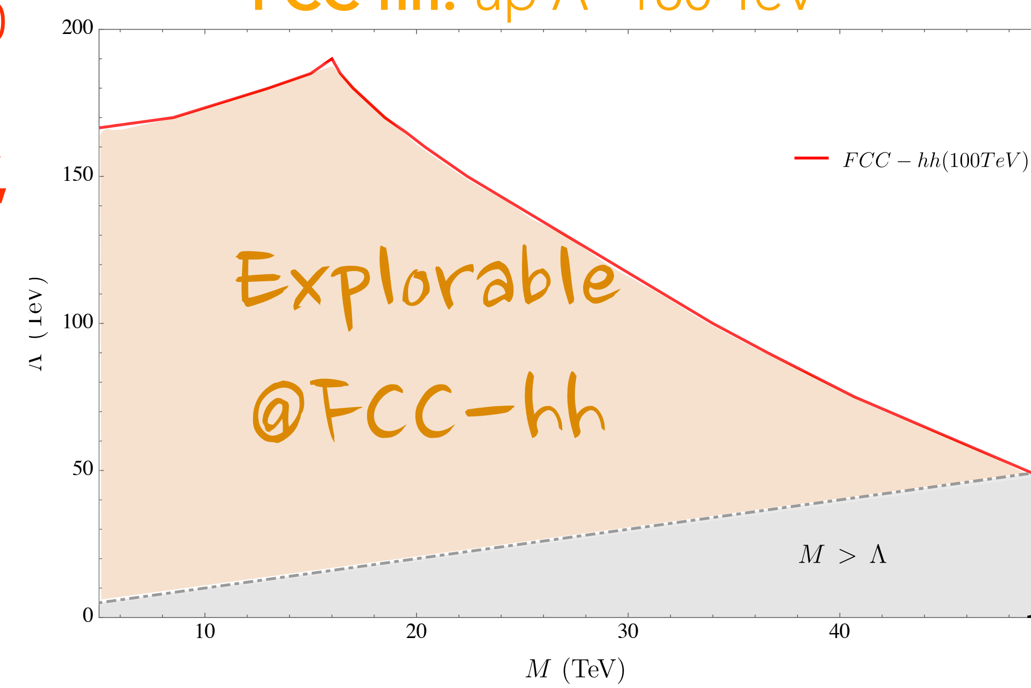
HL-LHC: with 20 times statistics **doubling Λ reach**





HE-LHC: twice energetic and 60 times more statistics **=>M(N) up to 12 TeV, Λ up to 55 TeV**

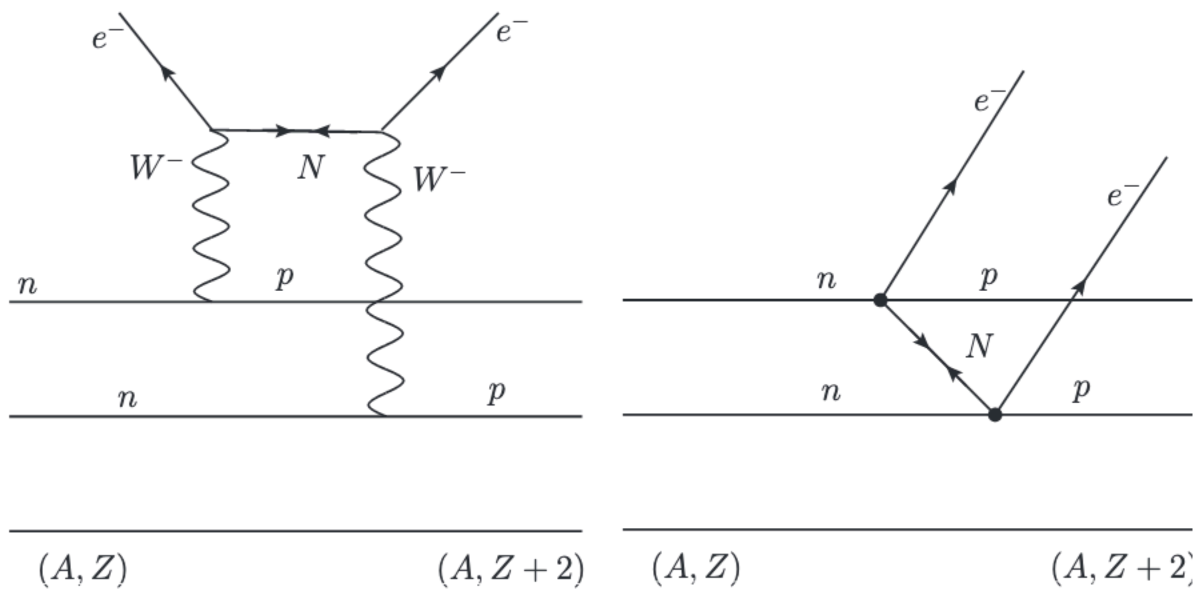
FCC-hh: up Λ~180 TeV



Published in: CERN Yellow Rep.Monogr. 7 (2019).

Neutrinoless double beta decay ($0\nu\beta\beta$) and composite neutrinos

S. Biondini, S. Dell'Oro, R. Leonardi, S. Marcocci, O. Panella, M. Presilla, F. Vissani arXiv:2111.01053



(a) Gauge interactions. negligible

(b) Contact interactions. dominant

(O. Panella et al, PRD 1997)

- Lepton Number violating decay typically associated to massive Majorana neutrinos
- ${}^{76}\text{Ge} \to {}^{76}\text{Se} + 2e^-$ (PRL2020 KamLAND-Zen Collab.) $T_{1/2}(90\%\,\text{C.L.}) > 1.8 \times 10^{26}$ yr
- ${}^{136}\text{Xe} \to {}^{136}\text{Ba} + 2e^-$ (PRL 2020 Gerda Collab.) $T_{1/2}(90\%\,\text{C.L.}) > 1.07 \times 10^{26}$ yr
- Non observation of $0\nu\beta\beta$ is converted in constraints on the BSM model

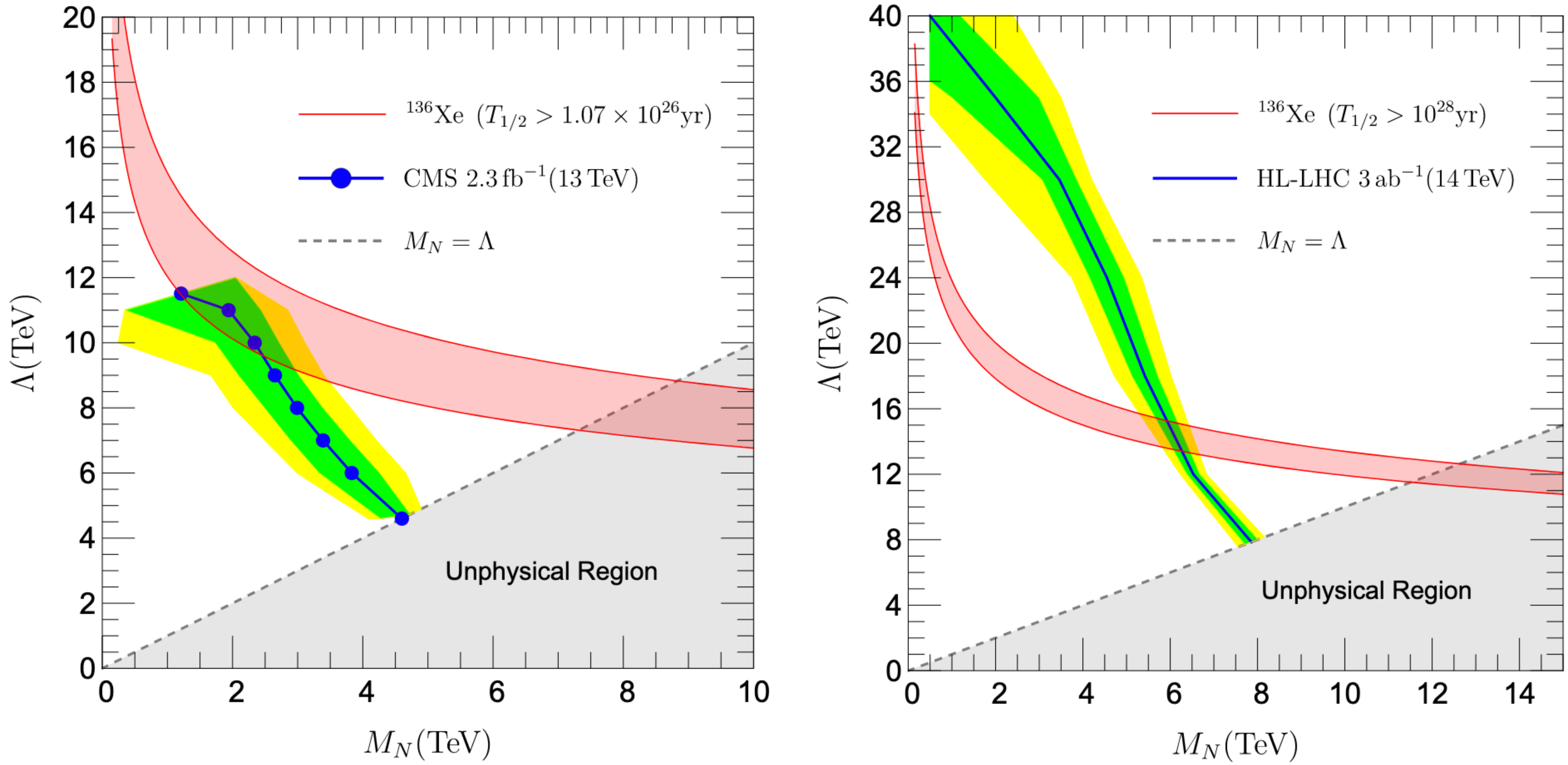
Nuclear Physics — Phase Space

$$\left[T_{1/2}\right]^{-1} = \left(\frac{g_*^2}{\Lambda^2}\right)^4 \frac{\eta_L^4\, g_A^4\, m_p^2}{64\, M_N^2} |\mathscr{M}^{0N}|^2 \frac{G_{01}}{(G_F \cos\theta_c)^4}$$

Constraints on model parameters

$$\Lambda \geq \frac{g_*}{2^{3/4}} \sqrt{\frac{\eta_L\, g_A}{G_F \cos\theta_c}} \left(\frac{m_p}{M_N}\right)^{\frac{1}{4}} \left(G_{01}\, |\mathscr{M}^{0N}|^2\, T_{1/2}^{\text{exp.}}\right)^{\frac{1}{8}}$$

Complementarity of low-energy and high-energy probes

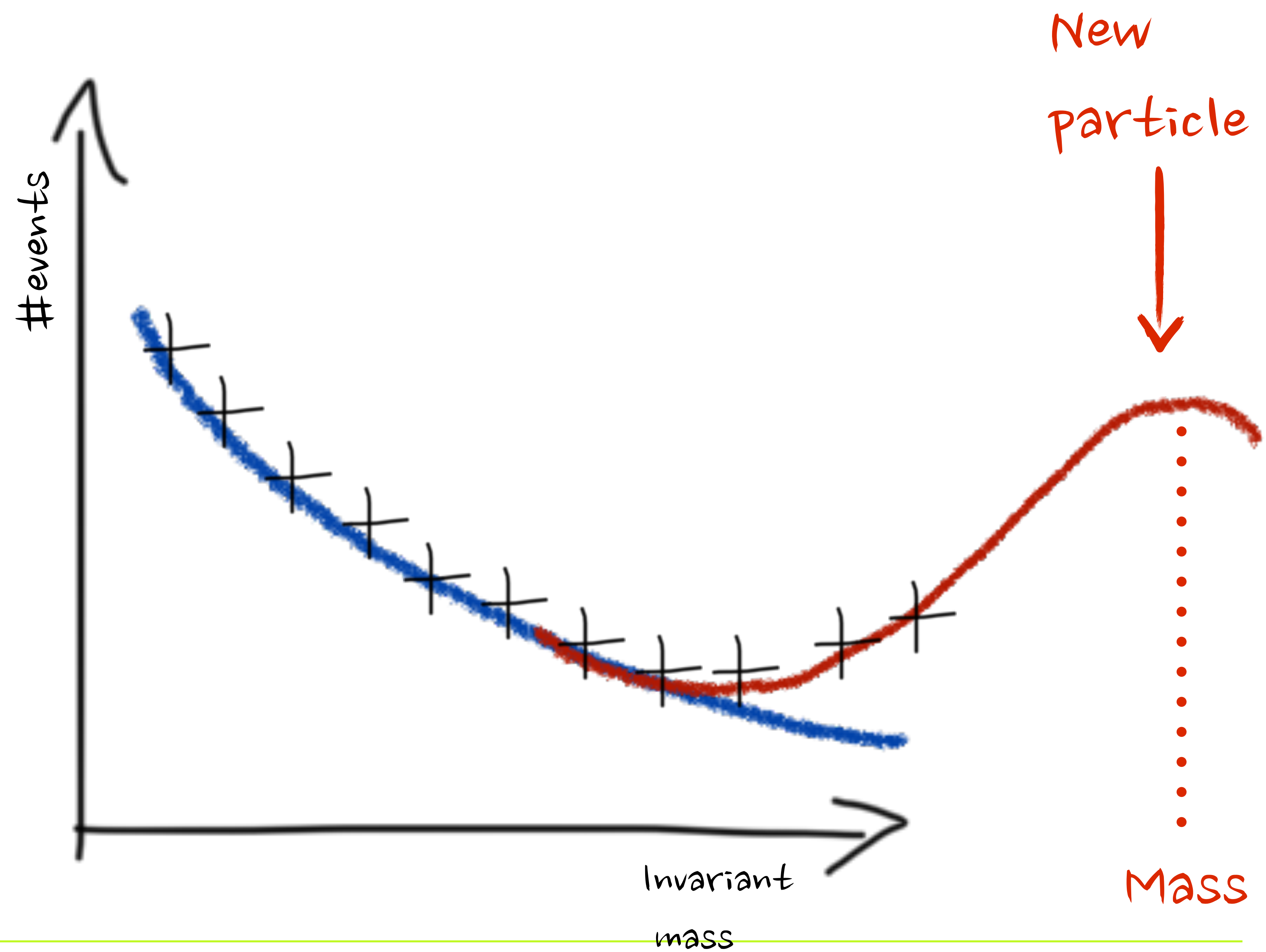


- $0\nu\beta\beta$ highly competitive with LHC (run II) and HL-LHC (large mass region)
- New results from CMS analysis of full run II data set available soon

What do we do?

A Cartoon guide to search for new physics

2. Indirect searches:



Effective field theory approach

More generally:
we can invoke some UV theory that we are still not able to catch

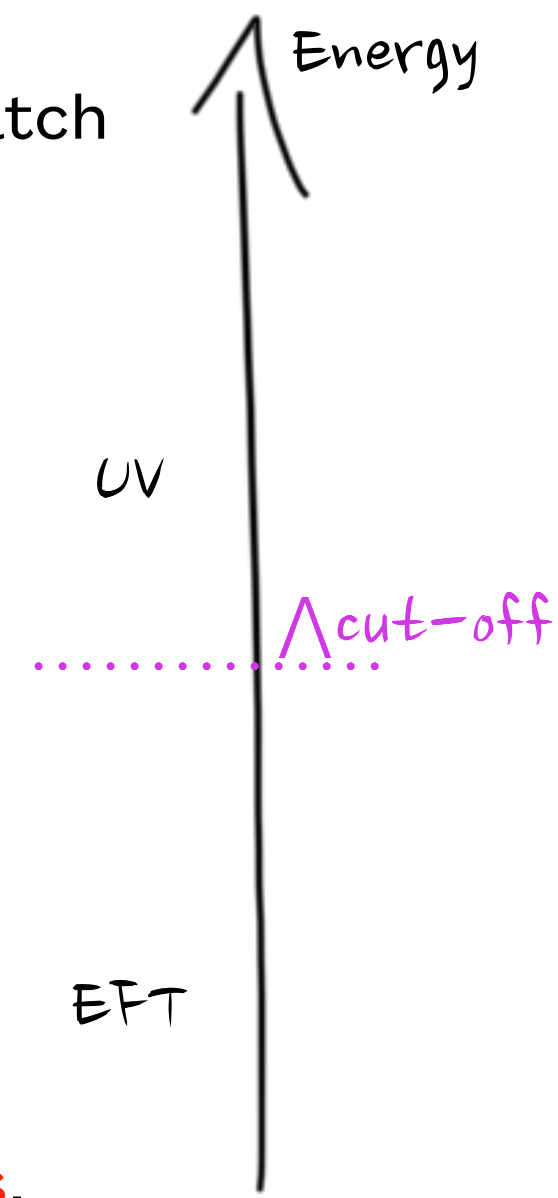
Bottom-up approach: build a Taylor expansion

$$\mathscr{L}_{BSM} \xrightarrow[(E \ll M)]{} \mathscr{L}_{\text{eft}} \simeq \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \cdots$$

$$\sum_i c_i \frac{\mathcal{O}_i}{\Lambda^2}$$

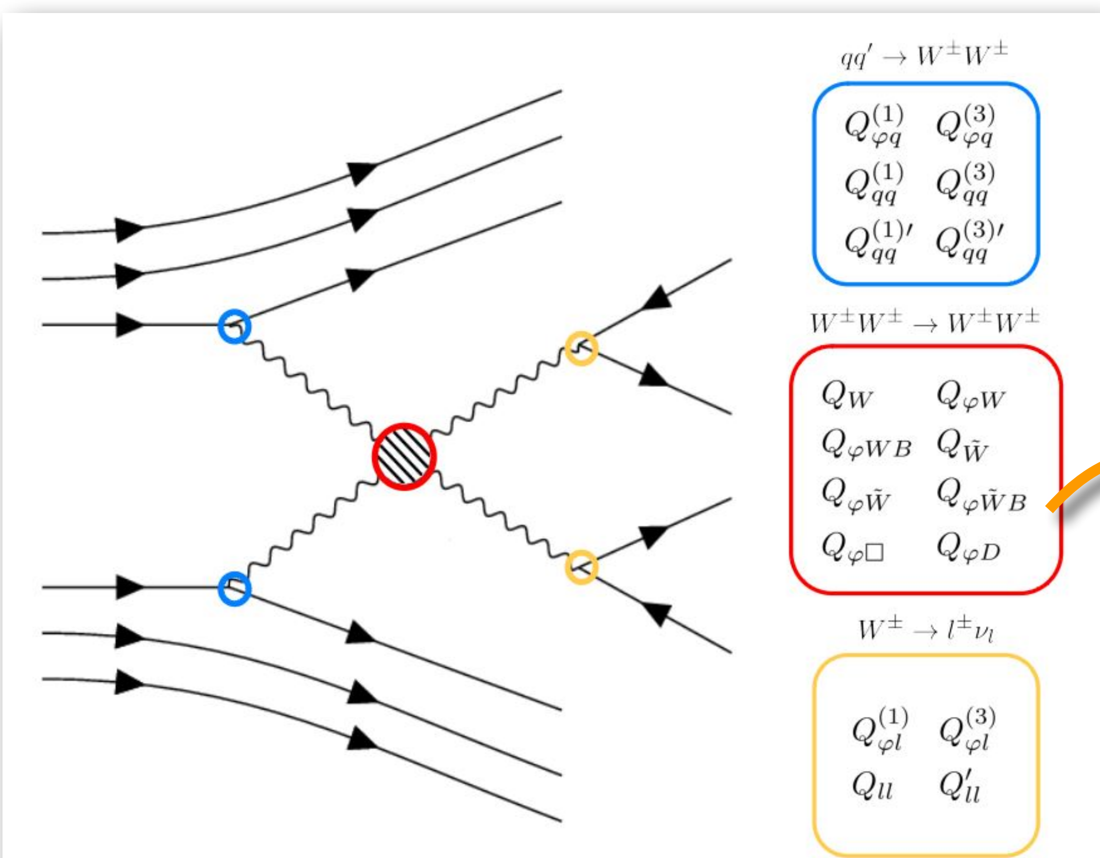
New BSM couplings
(Wilson coefficients)

BSM scale



In practice it's an expansion in fields and their derivatives.

Vector Boson Scattering processes and unitarity interpretation (I)



Same-sign W VBS:

$$qq' \to W^\pm W^\pm jj \to l\nu_l l'\nu_{l'} jj$$

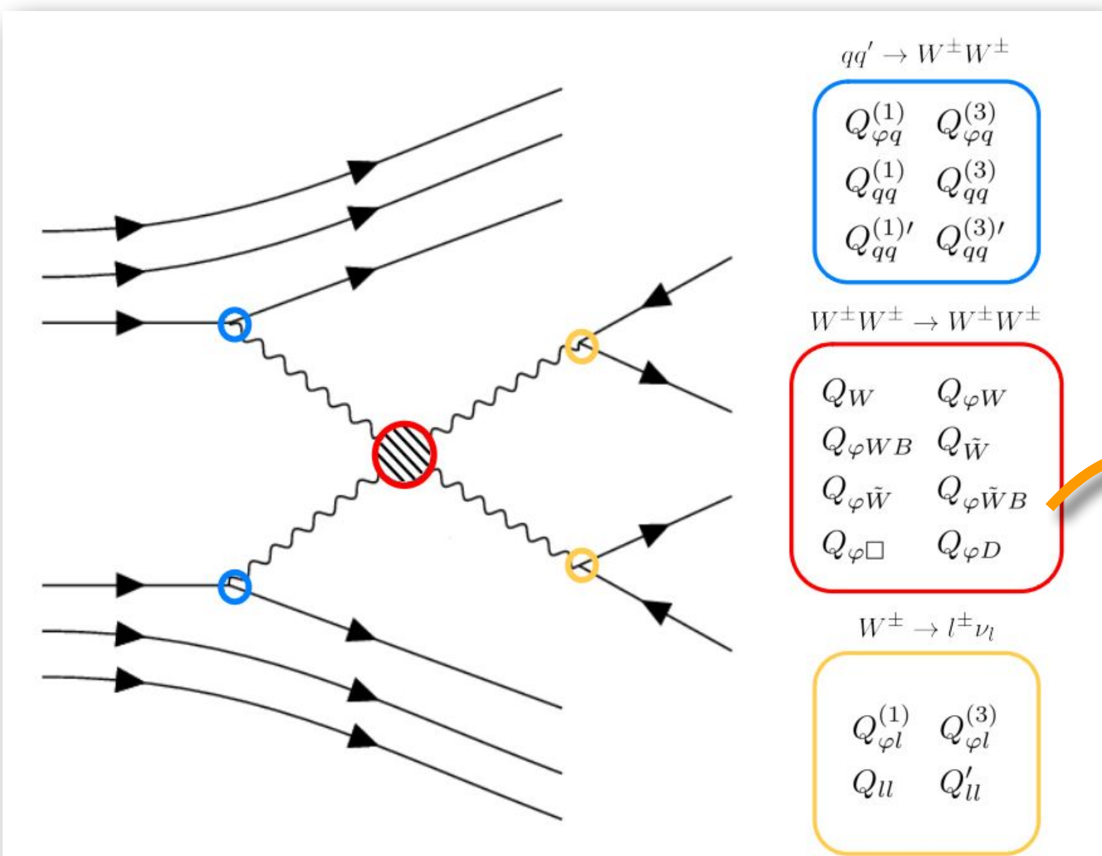
In the EFT framework, the introduction of dim6 operators leads to amplitude divergences in WW→WW process

$$\mathcal{M}(c_W) = 12\bar{g}\frac{c_W}{\Lambda^2}\hat{s} \to \infty \quad \text{for} \quad \hat{s} \to \infty$$

Vector Boson Scattering processes and unitarity interpretation (I)

Importance of VBS processes in search of New Physics at LHC:

- Purely-EW decay channel of Ws presents both **triple gauge couplings** and **quartic gauge couplings**
- VBS processes lead to **unitarity violation** in SM → restored with the introduction of Higgs-mediated channels → Strictly related to **EWBS sector**



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Vector Boson Scattering processes and unitarity interpretation (II)

* MC simulation

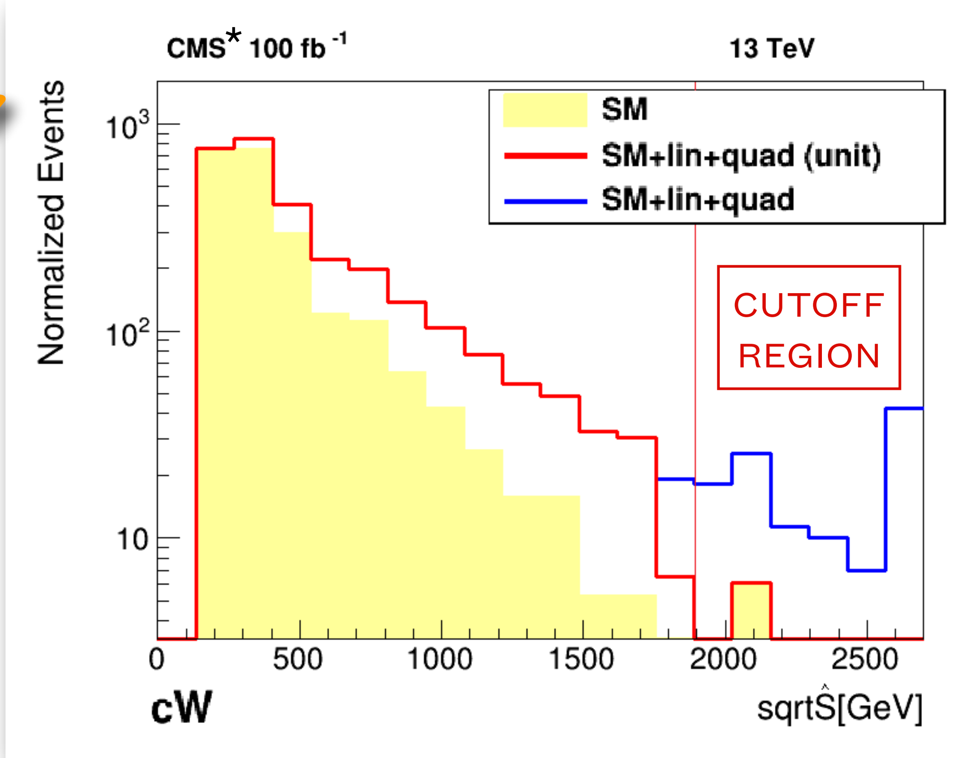
The inclusion of unitarity constraints in analysis validates EFT approach for search of New Physics

Implementation:

Cut off the BSM events above the unitarity bound

Op.	$\sqrt{\hat{s}_u}$ *
Q_W	≤ 1.8 TeV
$Q_{\varphi WB}$	-
$Q_{\varphi\Box}$	≤ 5.0 TeV
$Q_{\varphi D}$	≤ 7.1 TeV
$Q_{\tilde{W}}$	≤ 1.8 TeV
$Q_{\varphi\tilde{W}}$	≤ 7.1 TeV
$Q_{\varphi\tilde{W}B}$	-

* $|c_i| = 1$, $\Lambda = 1$ TeV



Aim of the work:

Quantify the impact of the introduction of the bound on the width of confidence intervals of dim6 Wilson coefficients

Vector Boson Scattering processes and unitarity interpretation (II)

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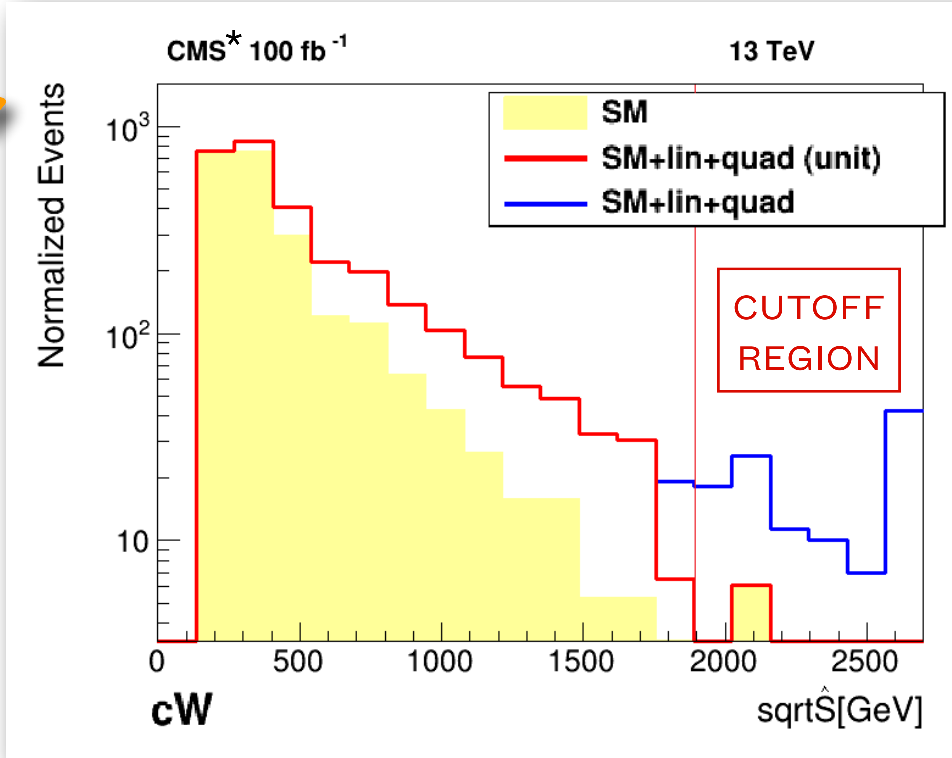
$Q_{\varphi\tilde{W}B}$	-

* $|c_i| = 1,\ \Lambda = 1$ TeV



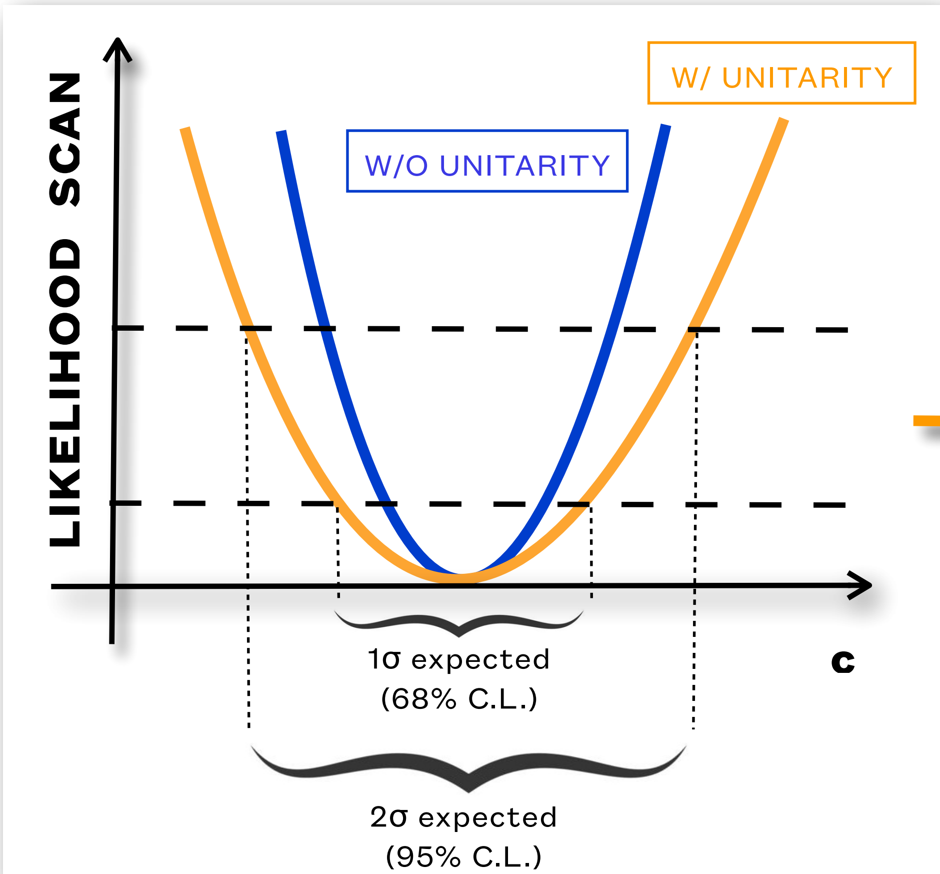
Impact of unitarity bounds on experimental search:

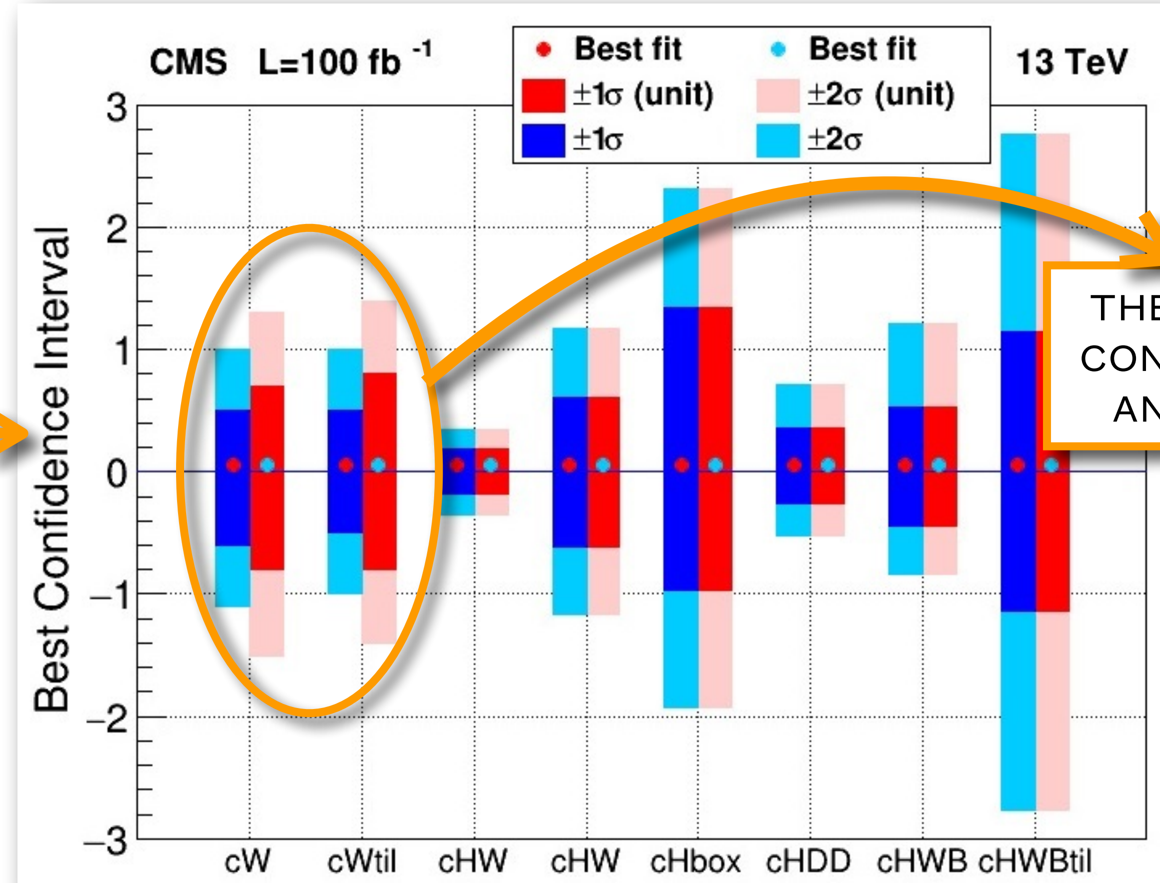
- Cutting off a percentage of BSM events makes us **less sensitive to effects of New Physics**
- Reduce the accuracy with which EFT parameters (Wilson coefficients) can be determined → estimated through the extraction of **confidence intervals**

Aim of the work:

Quantify the impact of the introduction of the bound on the width of confidence intervals of dim6 Wilson coefficients

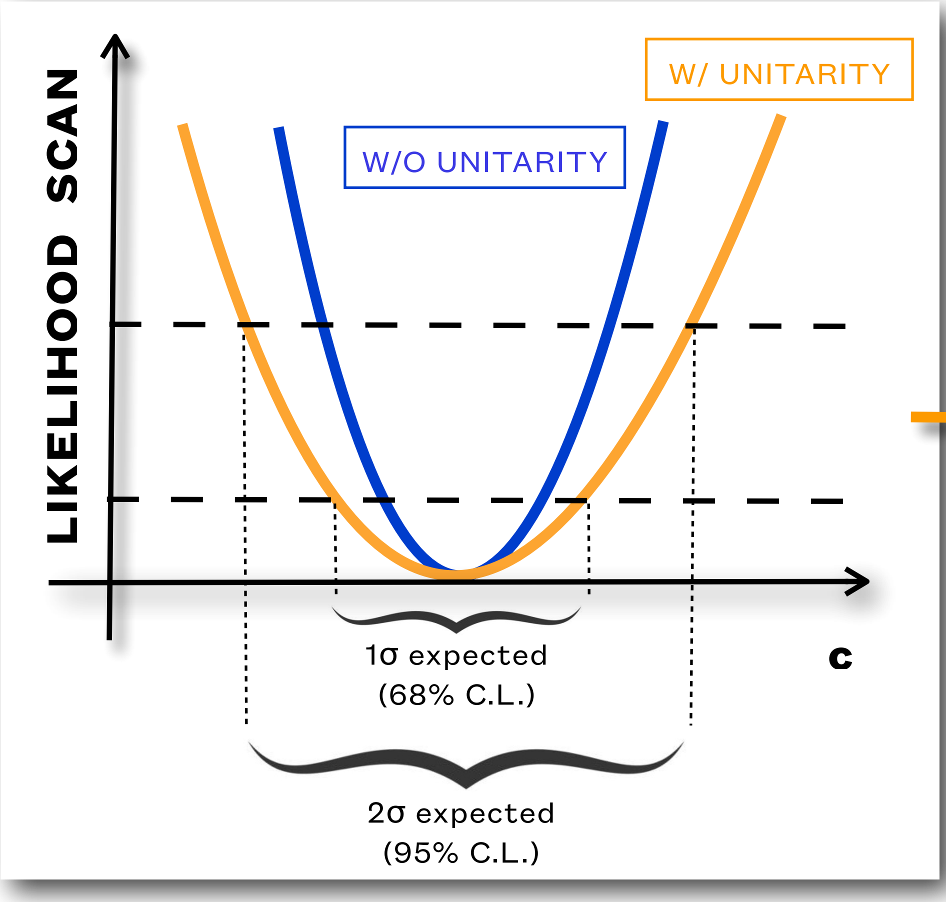
Vector Boson Scattering processes and unitarity interpretation (III)

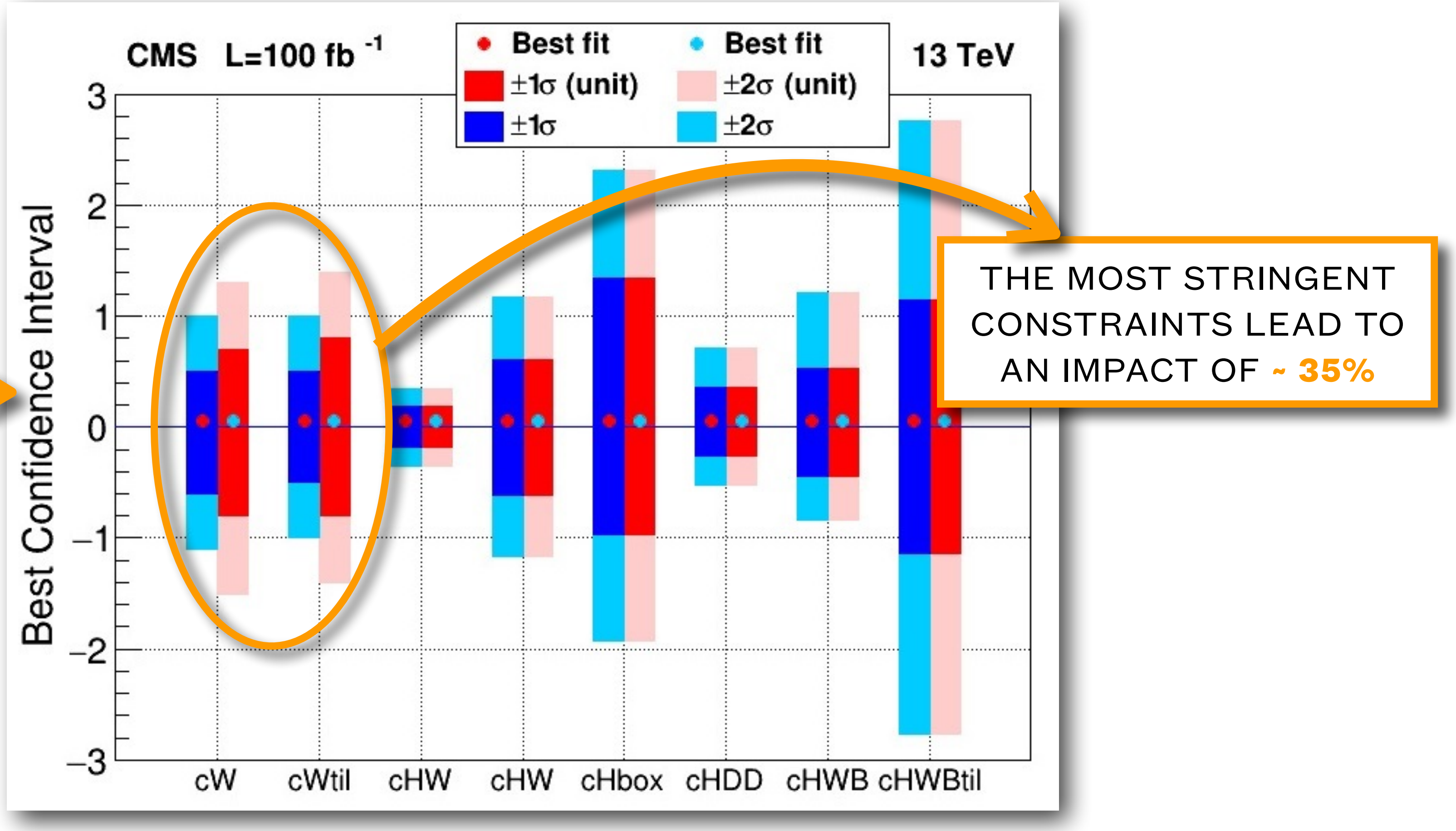




THE MOST STRINGENT CONSTRAINTS LEAD TO AN IMPACT OF ~ 35%

Vector Boson Scattering processes and unitarity interpretation (III)





Summary:

- In principle the **impact of unitarity constraints is not entirely negligible** → must be studied case by case for each operator who influences the process under examination
- A **more realistic estimate** of confidence intervals can be obtained with the inclusion of background processes and detector simulation → **future goal for VBS ssWW**

Summary

- Research activities mainly focus on phenomenology of BSM physics, in particular composite models effective interactions and study of specific signatures at LHC.
- In recent years a strong SYNERGY has been developed with the experimental CMS groups of Perugia and Padova with activities of theoretical support to analyses of LHC data.
- A first CMS analysis on Heavy Composite Majorana Neutrinos (2.3 fb^{-1} data of RunII 2015 at LHC) is published: Phys. Lett. B 775 (2017) 315-337
- A "reload" of the CMS analysis on the search for heavy composite Majorana neutrinos with the complete data set of Run II 136 fb^{-1} of luminosity is pre-approved. We have given theory support the Collaboration. Unitarity constraints have been implemented.
- Collaboration with F. Vissani (GSSI) and S. dell'Oro (Milano) on the constraint to contact interacitons in composite models from neutrino-less double beta decay ($0\nu\beta\beta$).
- Study of the impact of unitarity in VBS within the SMEFT model.
- Ongoing research project on composite models with four fermion effective interactions of the NJL type. Collaboration with Vanderblit Univerisity e IcraNet (Pescara).

Tesi di Laurea Magistrale/Dottorato su fenomenologia modelli compositi

- S. Biondini [LM-2011] "Phenomenology of excited doubly charged heavy leptons at LHC", [Physical Review D, 85, 095018, (2012)] e lavoro su "Exotic leptons at future linear colliders", [Physical Review D 92 , 015023 (2015)] →PhD @ Monaco (TUM)
- R. Leonardi [LM-2013] "Doubly charged leptons with contact interactions" PRD 90, 035001 (2014)
- R. Leonardi (gruppo IV+CMS) e L. Alunni (CMS), dottorato XXIX ciclo. (Heavy Composite Majorana Neutrinos - HCMN-). [Eur. Phys. J. C (2016) 76:593, CMS-PAS-16-026]
- R. Leonardi (gruppo IV+CMS) dottorato XXIX ciclo. "Production of exotic quarks at the LHC" -[Phys. Rev. D 96 (2017) 075034]- Collaborazione con Brown University.
- M. Presilla [LM, Febbraio 2017], with R. Leonardi e O. Panella (Like Sign dileptons with Mirror type composite neutrinos at the HL-LHC) arXiv:1811.00374 (Working group 3, Xabier Vid Cidal et al. CERN Yellow Report: CERN-LPCC-2018-05, Workshop on Physics at HL-LHC and perspectives at HE-LHC)
- C. Carrivale [LM, Febbraio 2022] with M. Presilla and L. Fanò (Study of the impact of unitarity bounds on VBS processes at LHC)
- L. Pacioselli [LM, Aprile 2022] with M. Presilla (Composite models in neutrino less double beta decay)