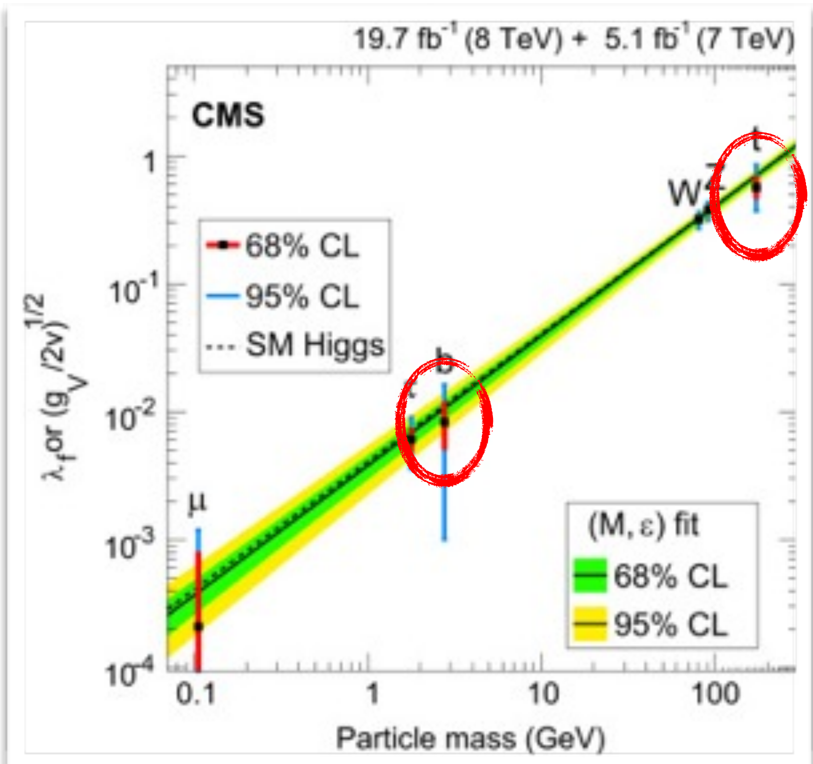
# Bounding top-quark non standard strong interactions

Daniele Barducci

w/ M. Fabbrichesi and A. Tonero

arXiv:1704.05478

# Top Quark as a BSM probe

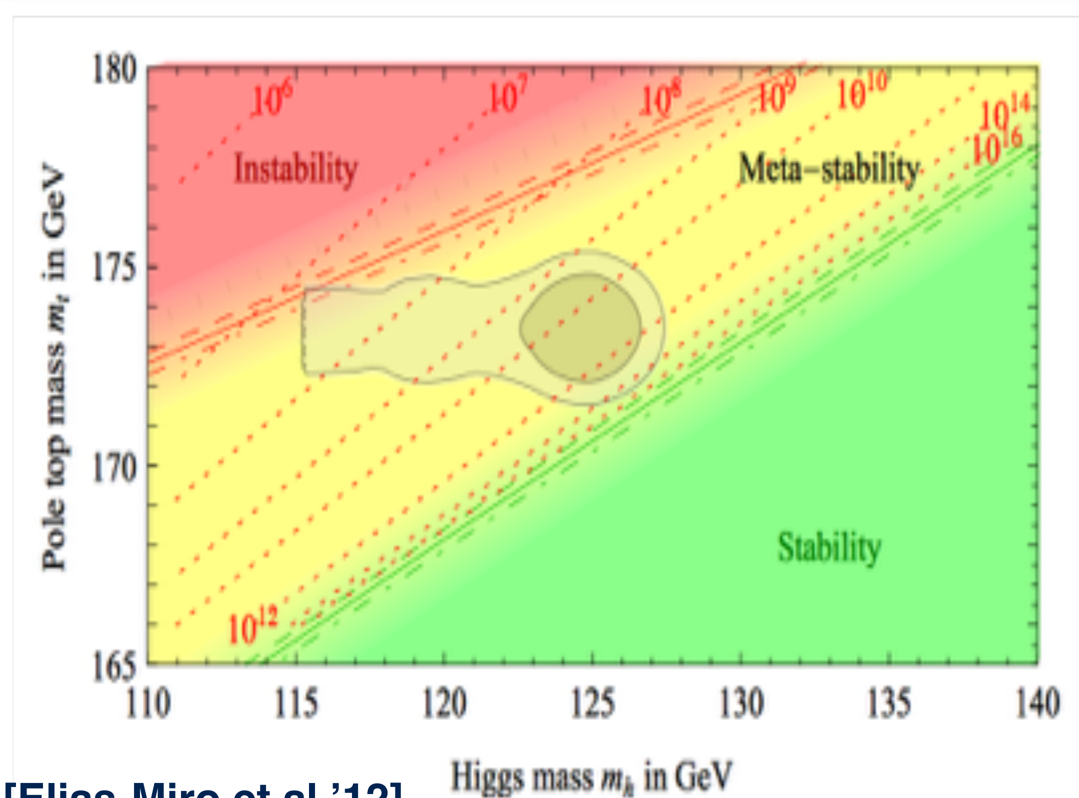



In the SM the top-quark yukawa coupling is of order one

$$y_t \sim 1 \qquad\qquad m_t \sim v$$

$$m_t/m_b \sim 4 \times m_c/m_s, 100 \times m_u/m_d$$

Following naturalness paradigm it's expected to play a special role in NP searches




[Elias-Miro et al '12]

Also intimately connected with the nature and stability of the EW vacuum

Motivates an intense program for NP searches related to top physics

# Searches for New Physics

New Physics searches can be broadly divided into two categories

# Searches for New Physics

# Direct searches for New Physics

$$M_X < \sqrt{s}$$

- New states can be resonantly produced
- We search for them through their decay into SM states

A pletora of resonances connected with the top quark

Heavy scalar

Top-Philic DM

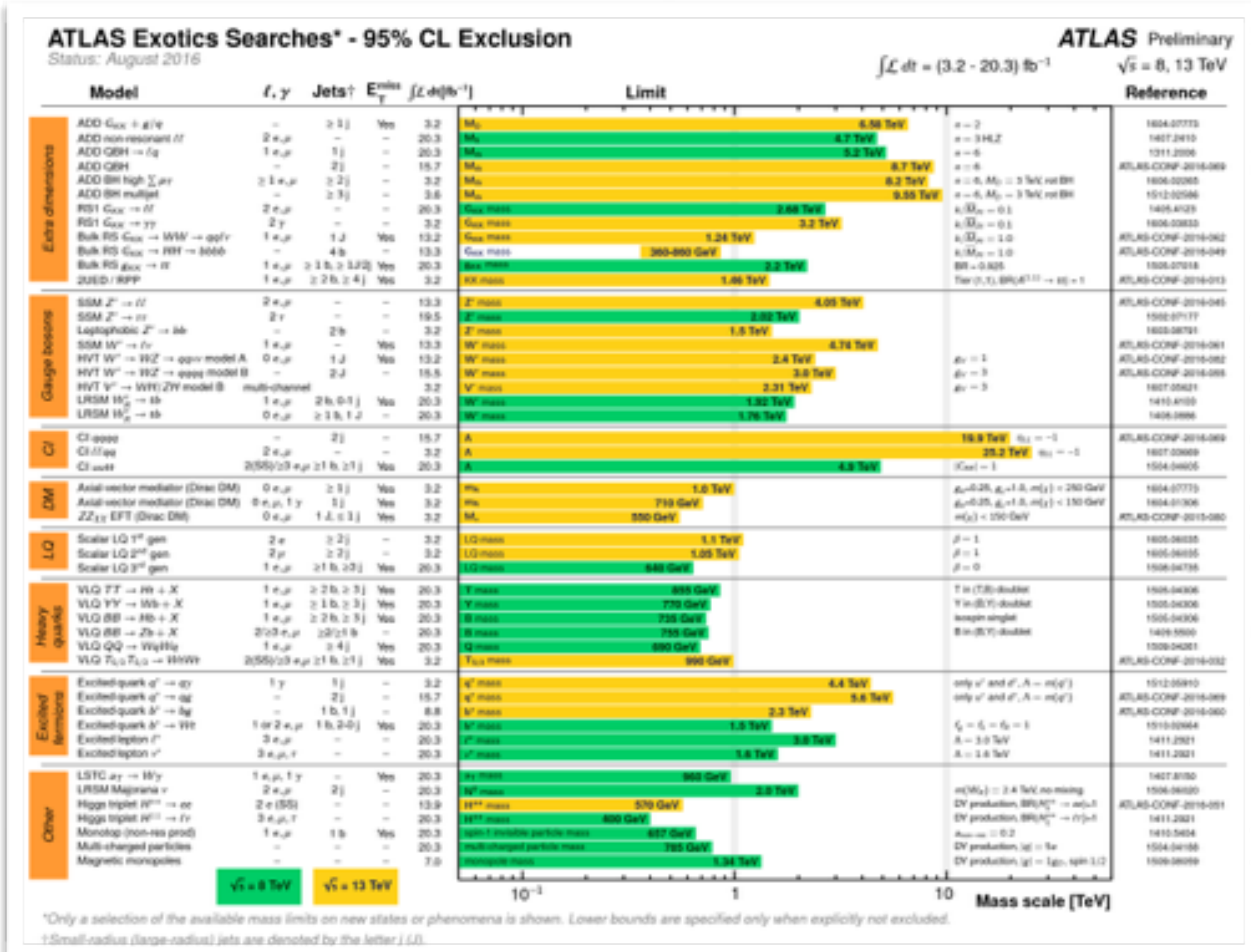
Heavy Z'

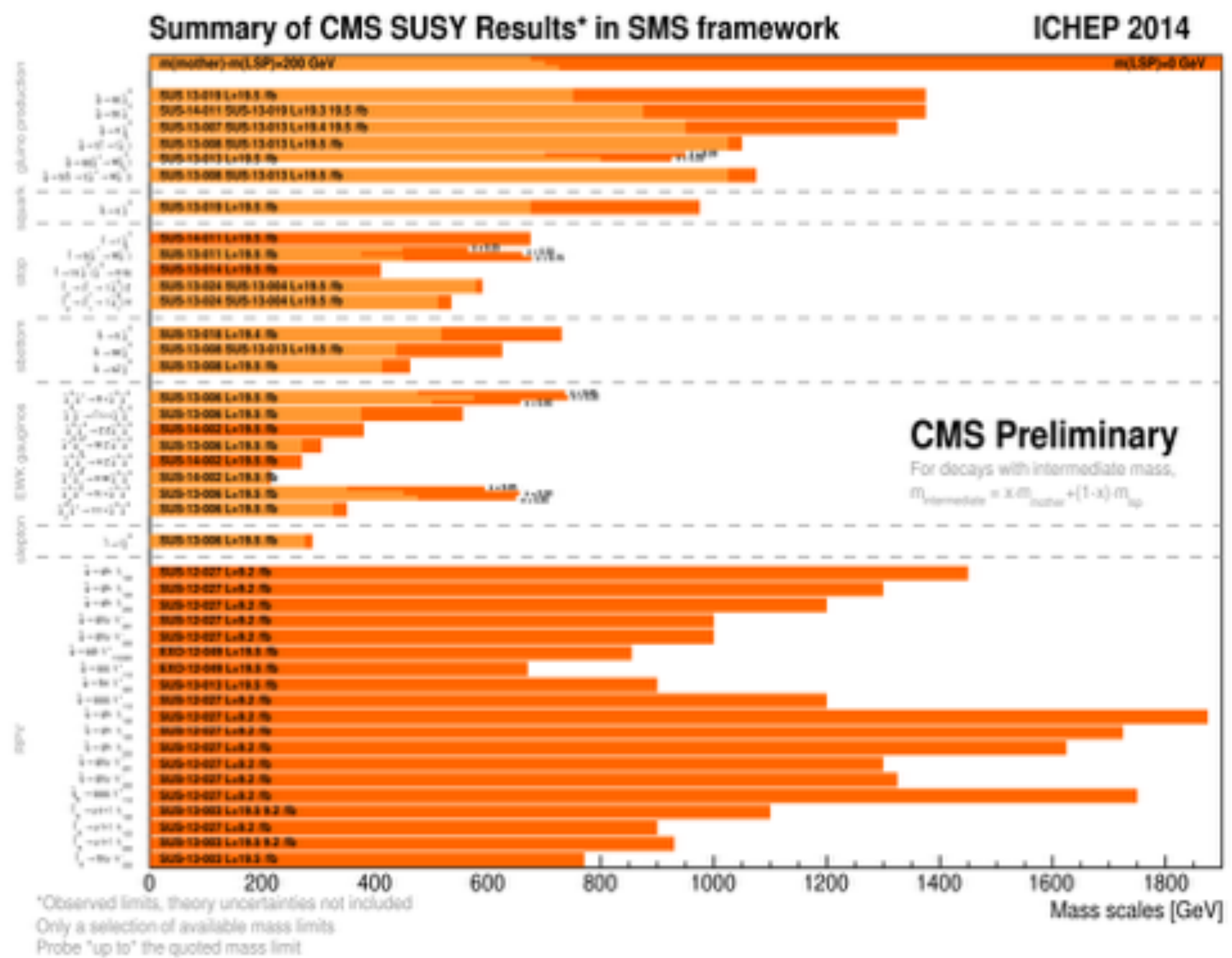
SUSY stops

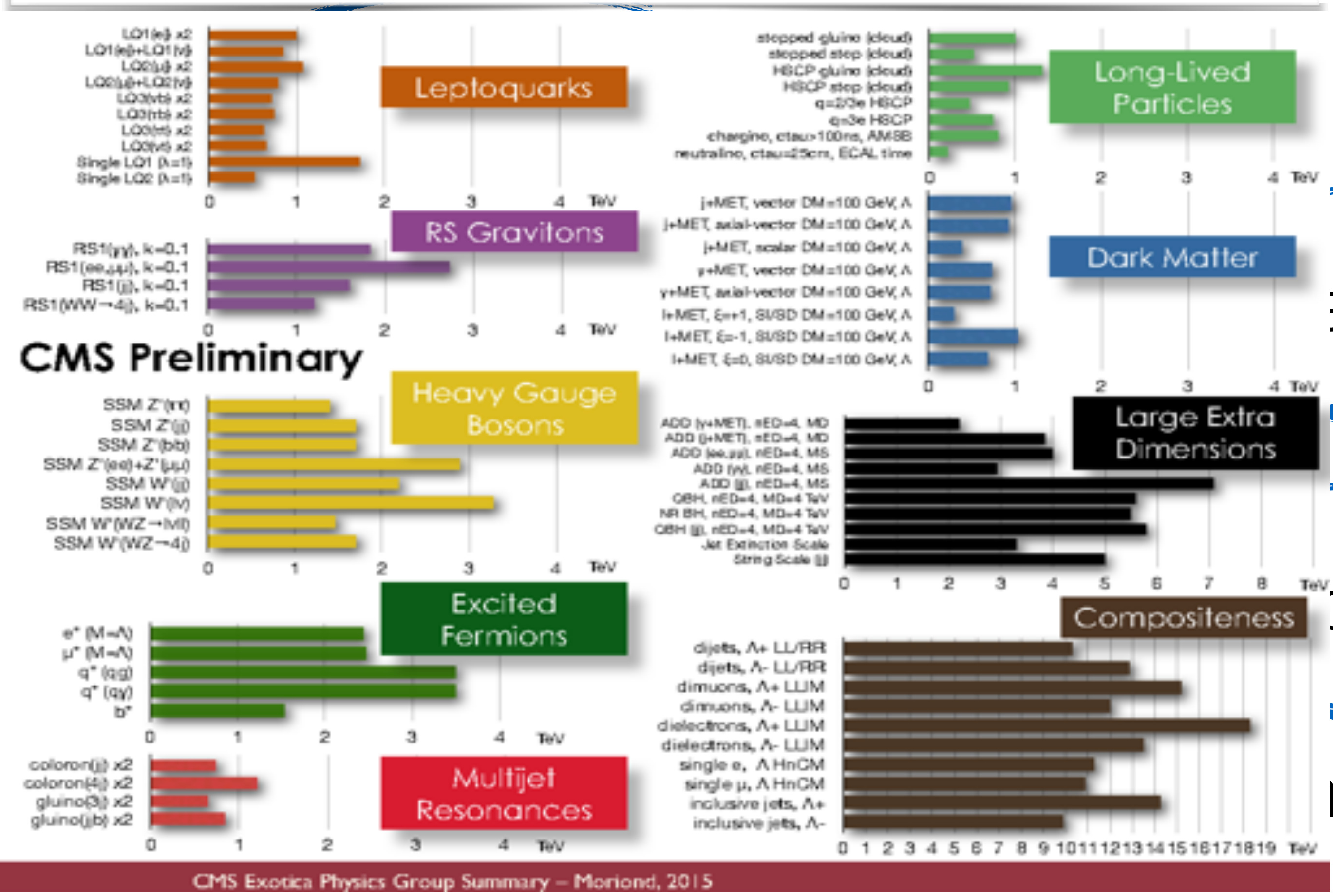
...

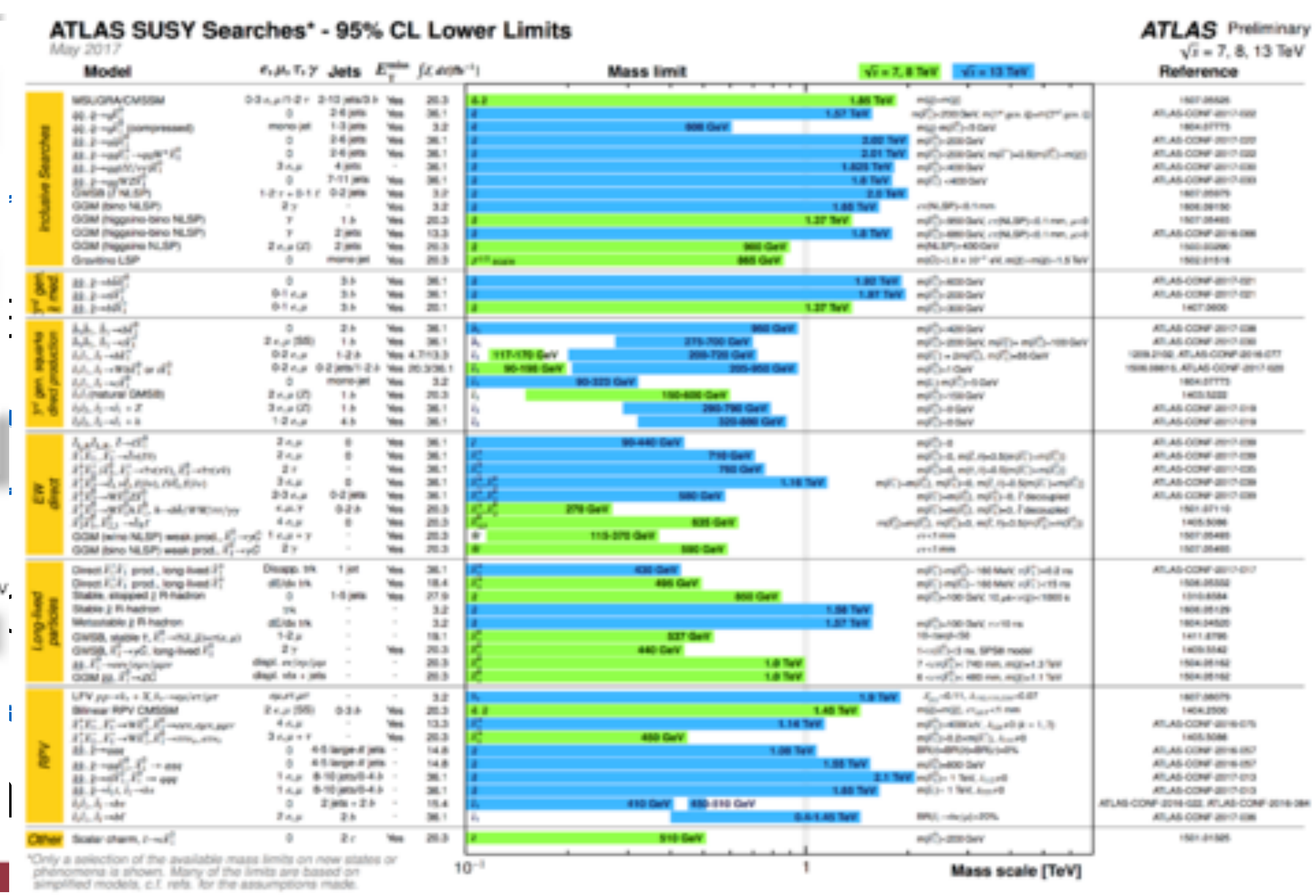
CHM top partners

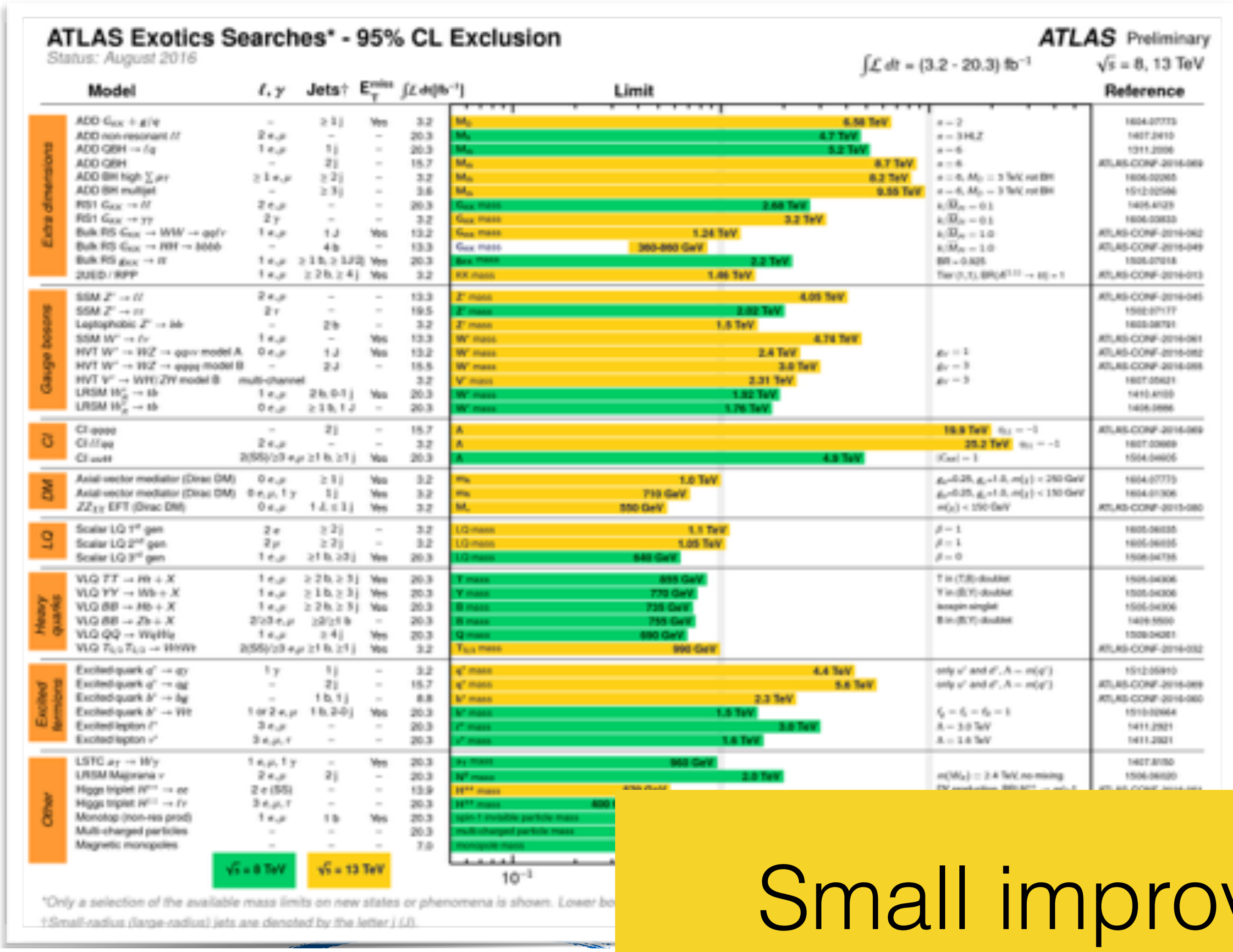
Intense experimental activity aimed at the search for these states

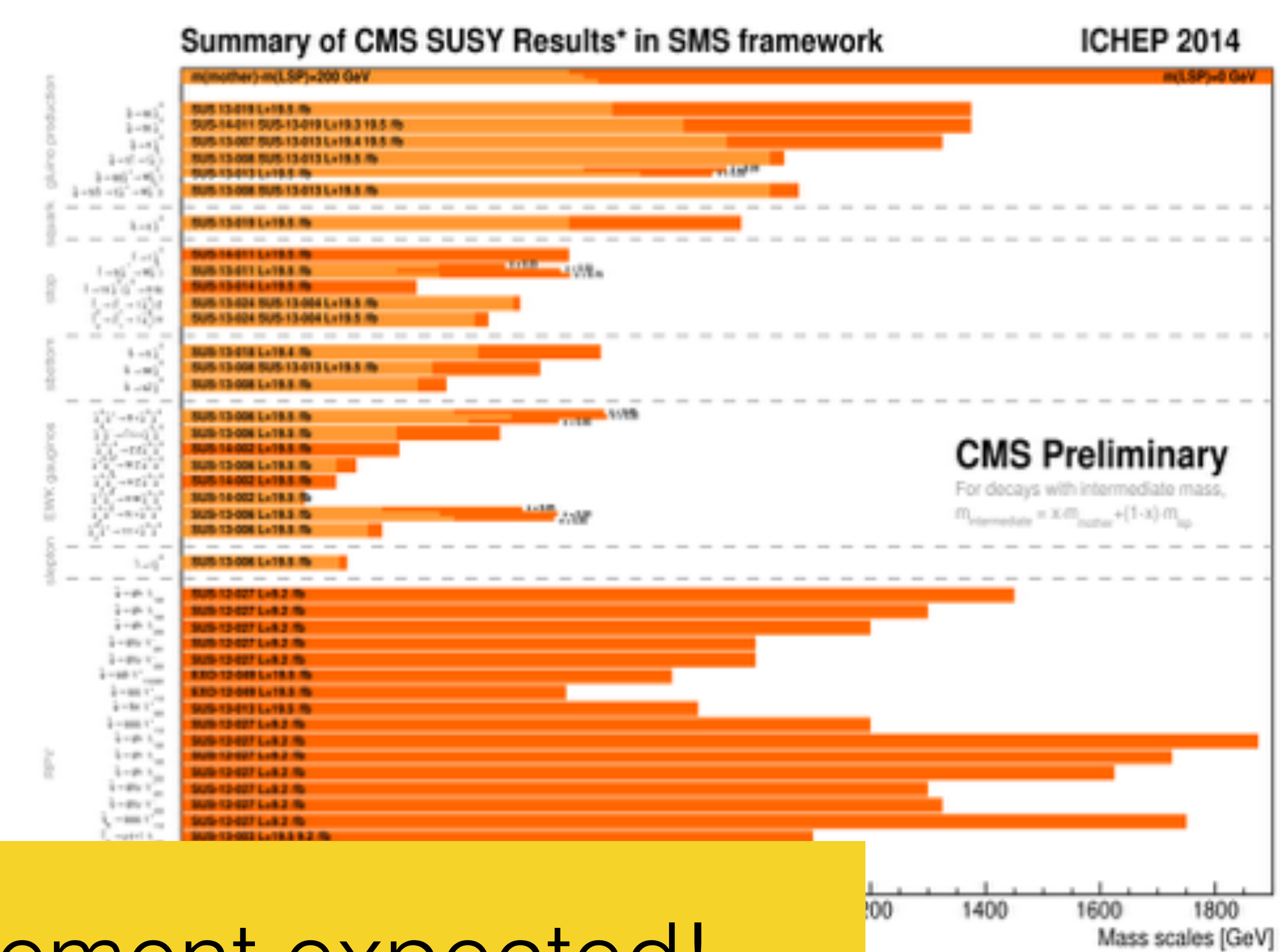

ATLAS Exotics Searches* - 95% CL Exclusion
Status: August 2016
ATLAS Preliminary
$\int \mathcal{L}\,dt = (3.2 - 20.3)$ fb$^{-1}$
$\sqrt{s}$ = 8, 13 TeV
Model
Limit
Reference
Extra dimensions
Gauge bosons
CI
DM
LQ
Heavy quarks
Excited fermions
Other
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.


Summary of CMS SUSY Results* in SMS framework
ICHEP 2014
CMS Preliminary
For decays with intermediate mass,
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit
Mass scales [GeV]

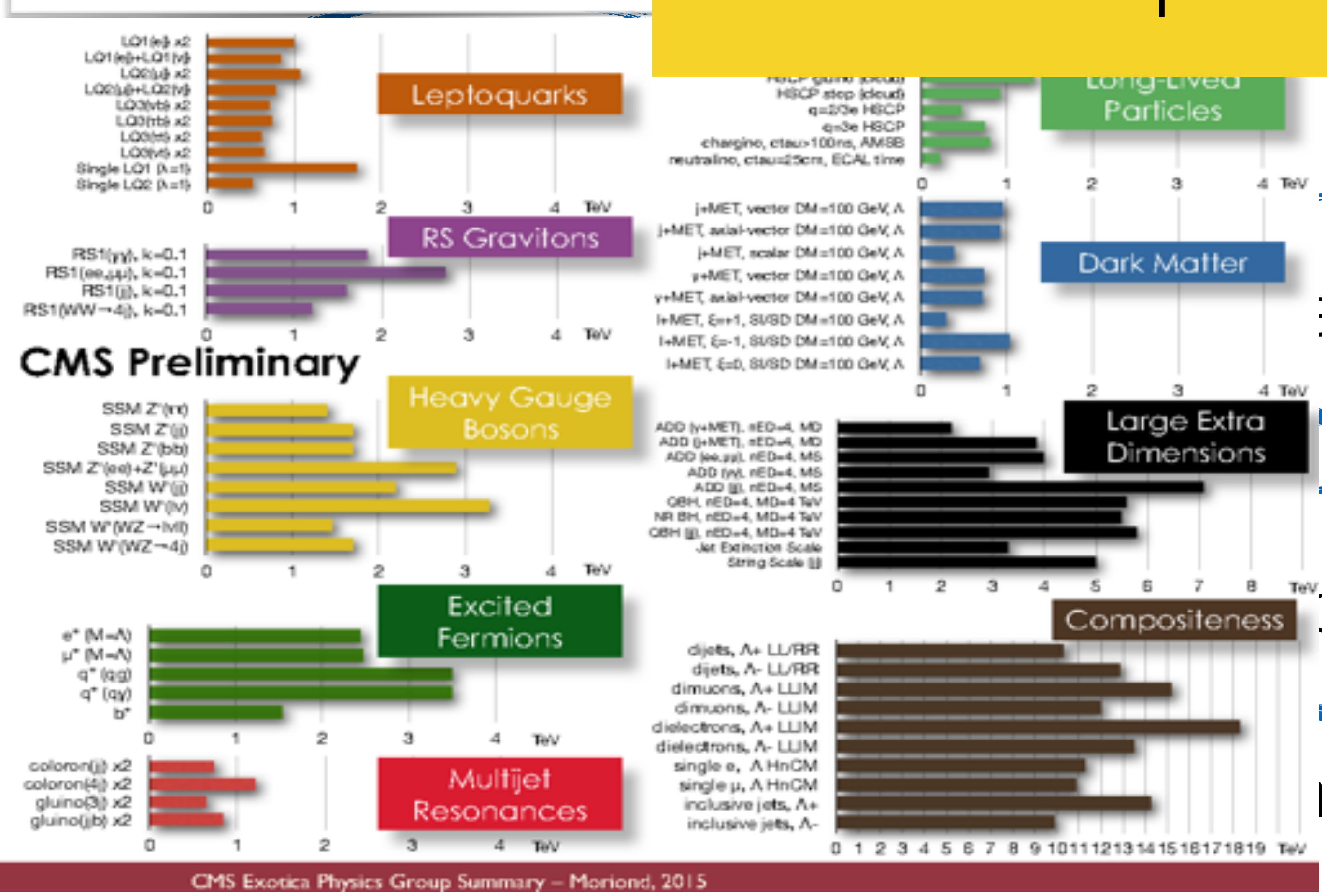

Leptoquarks
Long-Lived Particles
RS Gravitons
Dark Matter
CMS Preliminary
Heavy Gauge Bosons
Large Extra Dimensions
Excited Fermions
Compositeness
Multijet Resonances
CMS Exotica Physics Group Summary – Moriond, 2015

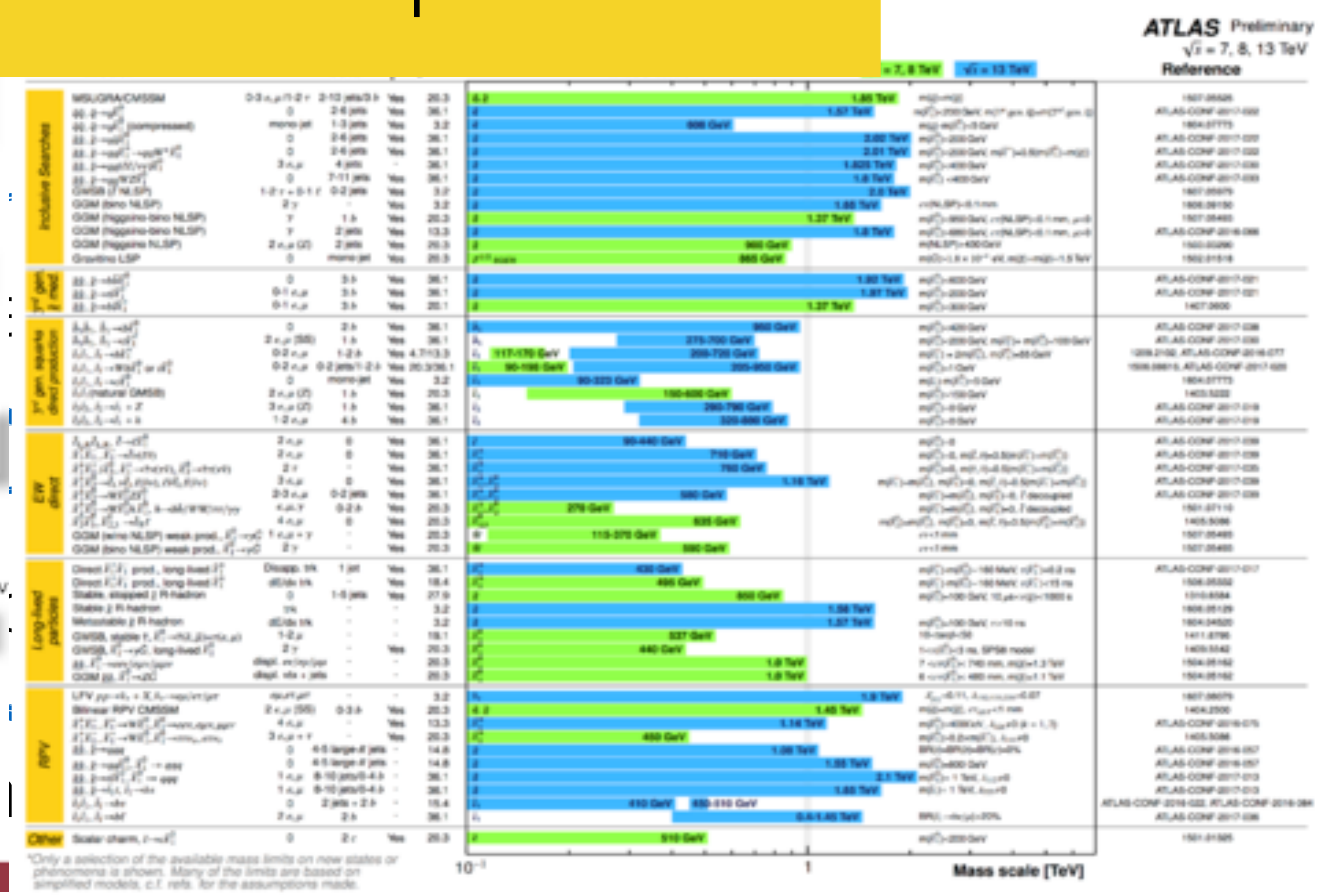

ATLAS SUSY Searches* - 95% CL Lower Limits
May 2017
ATLAS Preliminary
Model
Mass limit
Reference
Inclusive Searches
EW direct
Long-lived particles
RPV
Other
Mass scale [TeV]




Small improvement expected!



# Indirect search for New Physics

Experimental results point to a situation where $M_X \gg \sqrt{s}$

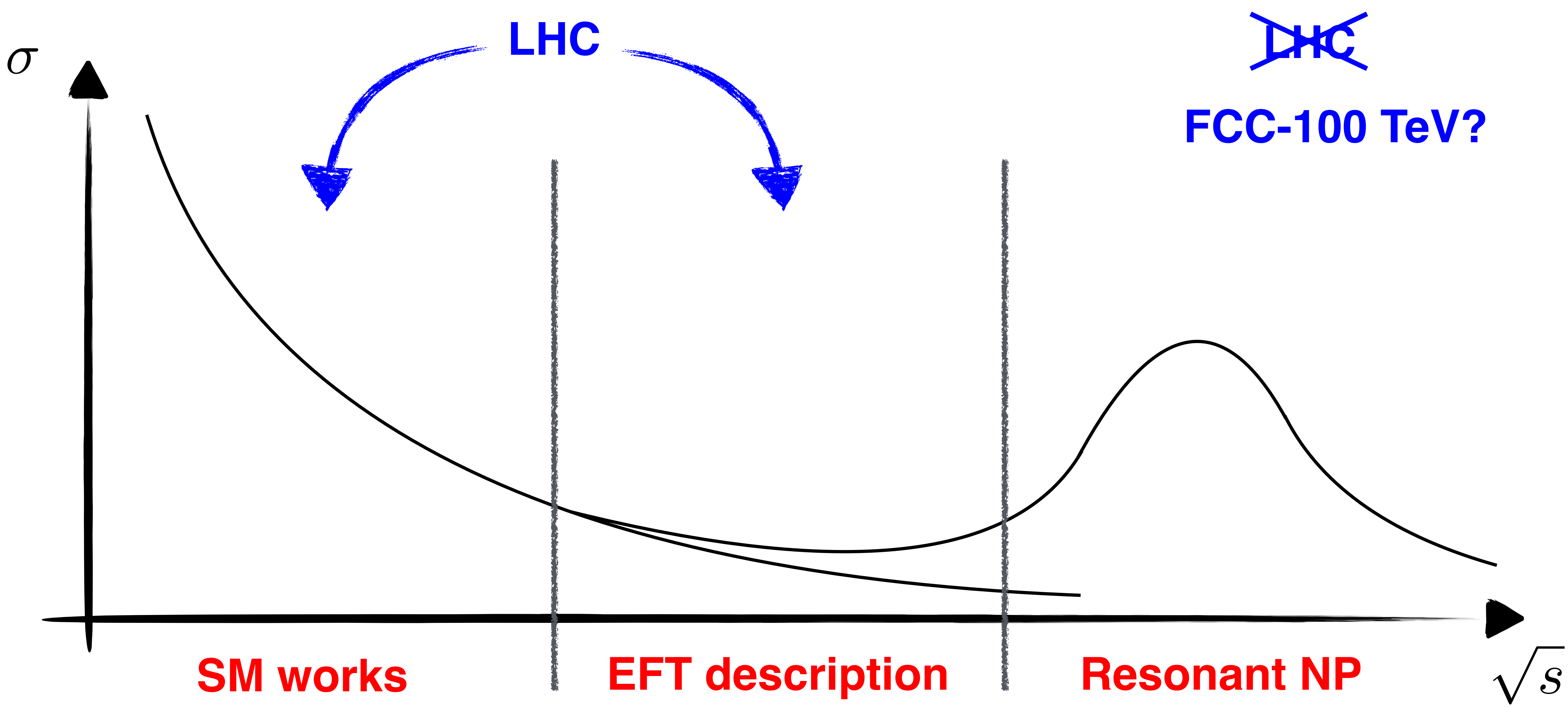
New states too heavy to be resonantly produced


$$\frac{1}{p^2 - M_X^2}$$ Heavy states can be integrated out $$\frac{1}{M_X^2}$$

Search NP indirectly through precision measurements of SM observables

Powerful and model independent tool to guide experimental efforts

# Standard Model EFT



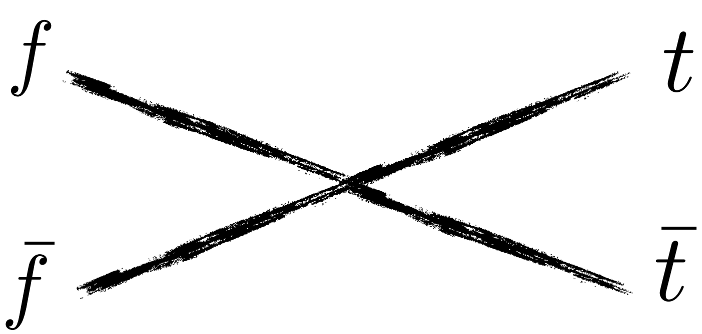

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\mathcal{O}^6 + \frac{1}{\Lambda^4}\mathcal{O}^8 + \ldots$$

# SM EFT - The top sector

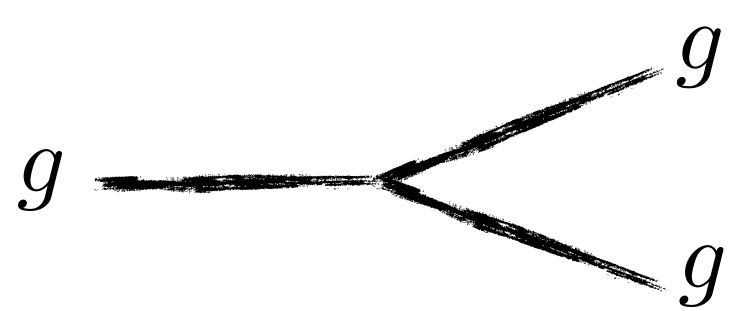
A complete - non redundant - basis of dimensions six operators identified

[Warsaw basis - Grzadkowski et al. ’10]

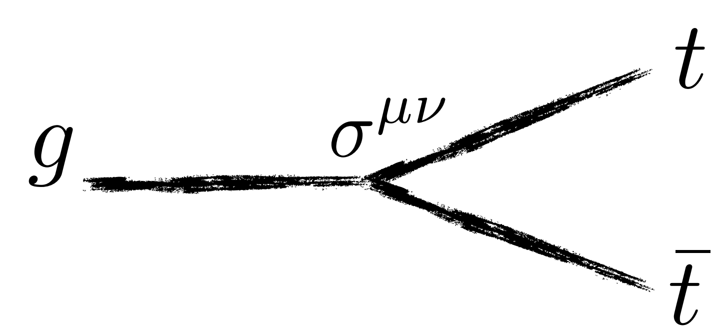
Operators affecting top quark pair production




Four fermions




Triple gluon




Dipole

<u>Assumptions: flavor independence</u>

All 4F operators enters with the same coefficient

$$\sum_f \bar{f}\gamma^\mu f \sim D_\nu G^{\nu\mu}$$

# SM EFT - The top sector

Only two operators affecting the top quark - gluon interaction

$$\mathcal{O}_1 = \frac{C_1}{\Lambda^2}\bar{t}\gamma^\mu T^a t D^\nu G^a_{\mu\nu}$$

$$\mathcal{O}_2 = \frac{C_2}{\Lambda^2}\bar{t}\sigma^{\mu\nu}T^a t D^\nu G^a_{\mu\nu}\tilde{\Phi} \xrightarrow[\text{VEV}]{} \frac{C_2}{\Lambda^2}v\,\bar{t}\sigma^{\mu\nu}T^a t D^\nu G^a_{\mu\nu}$$

They can be seen as the leading terms of the Dirac and Pauli form factors

| | |
|---|---|
| $e\,\gamma_\mu F_1(q^2) + ie\,\frac{\sigma_{\mu\nu}}{2M}q^\nu F_2(q^2)$ | Abelian - QED |
| $\frac{C_1}{\Lambda^2}\gamma^\mu f_1\left(\frac{D^2}{\Lambda^2}\right)D^\nu G_{\mu\nu} + \frac{C_2}{\Lambda}\sigma^{\mu\nu}f_2\left(\frac{D^2}{\Lambda^2}\right)G_{\mu\nu}$ | Non abelian - QCD |

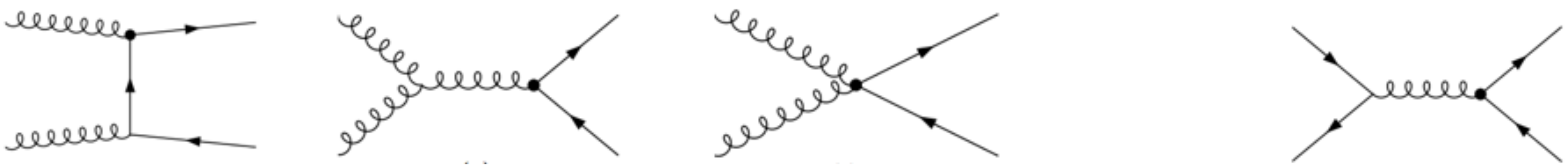
Interpretation in terms of top quark intrinsic structure

Non abelian nature however gives rise to interaction with multiple bosons

# Constraints from measurements of total tt cross section

Most precise 13 TeV LHC result

$$\sigma(pp \to t\bar{t}) = 835 \pm 3\ (\text{stat}) \pm 23\ (\text{syst}) \pm 23\ (\text{lum})\ \text{pb} \qquad \sim 3.9\%$$



$$\mathcal{O}_1 = \frac{C_1}{\Lambda^2} \bar{t}\gamma^\mu T^a t D^\nu G^a_{\mu\nu}$$

Does not affect $gg \to t\bar{t}$ production

$$\sigma(gg \to t\bar{t})/\sigma(q\bar{q} \to t\bar{t})$$

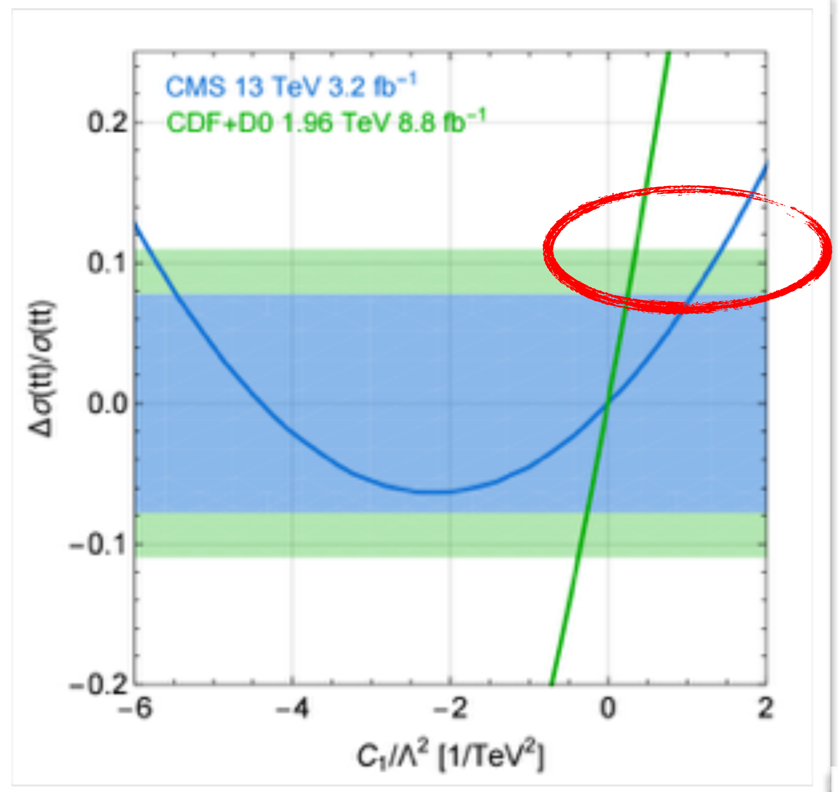
- LHC ~ 6
- Tevatron ~ 0.1

Tevatron results can still be important to bound $\mathcal{O}_1$

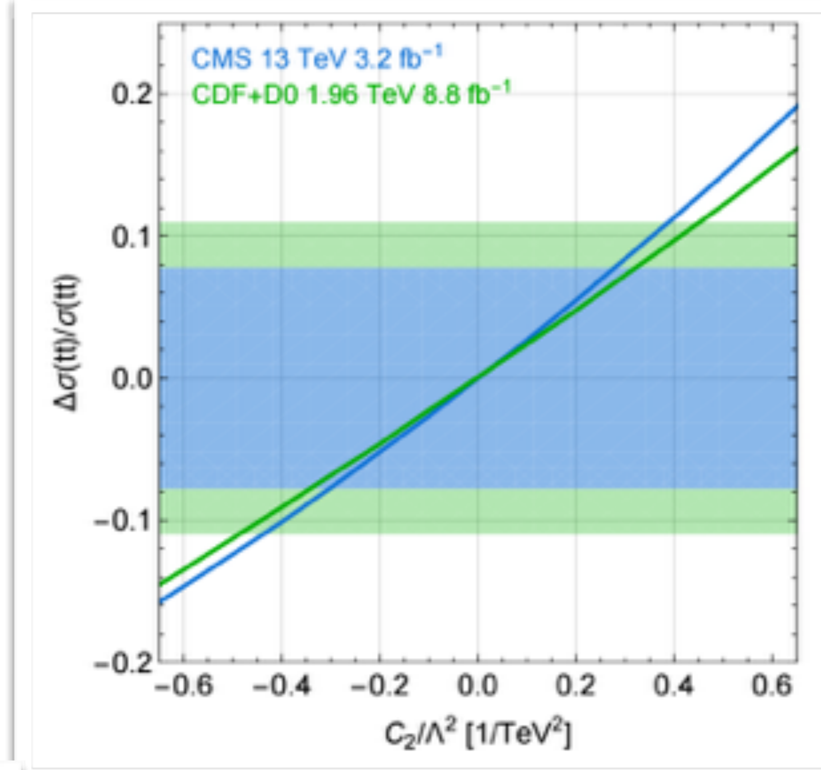
CDF and D0 final combination

$$\sigma(p\bar{p} \to t\bar{t}) = 7.65 \pm 0.42\ \text{pb} \qquad \sim 5.5\%$$

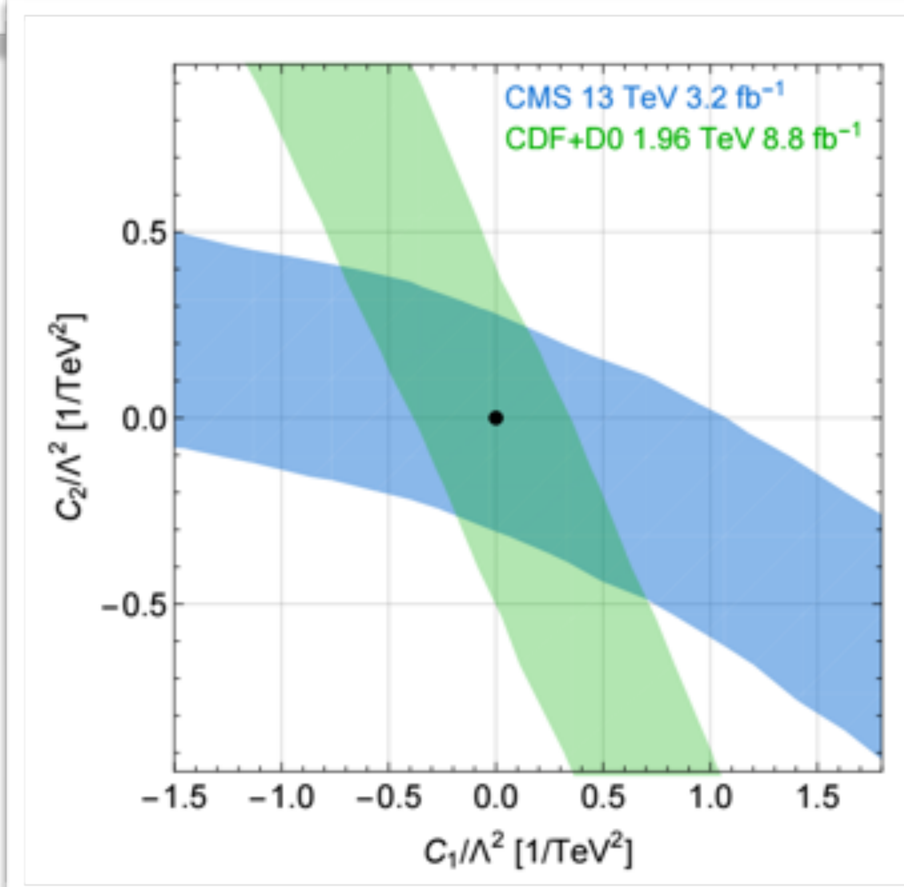
# Constraints from measurements of total tt cross section




Poor LHC sensitivity on $\mathcal{O}_1$




LHC and Tevatron measurements are complementary



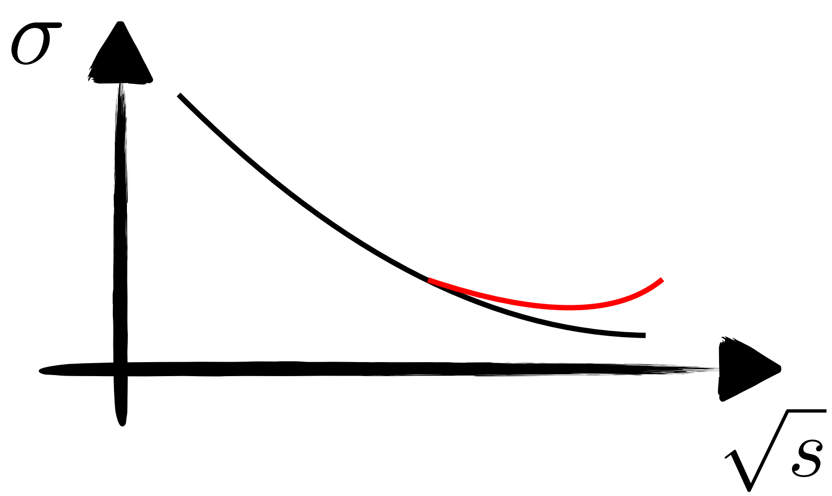
# Constraints from differential measurements

$\sigma(pp \to t\bar{t}) \sim 800 \text{ pb}$

$\mathcal{L} = 100 \text{ fb}^{-1} \to 8 \times 10^{7}$ top pairs

$\mathcal{L} = 3000 \text{ fb}^{-1} \to 24 \times 10^{8}$ top pairs

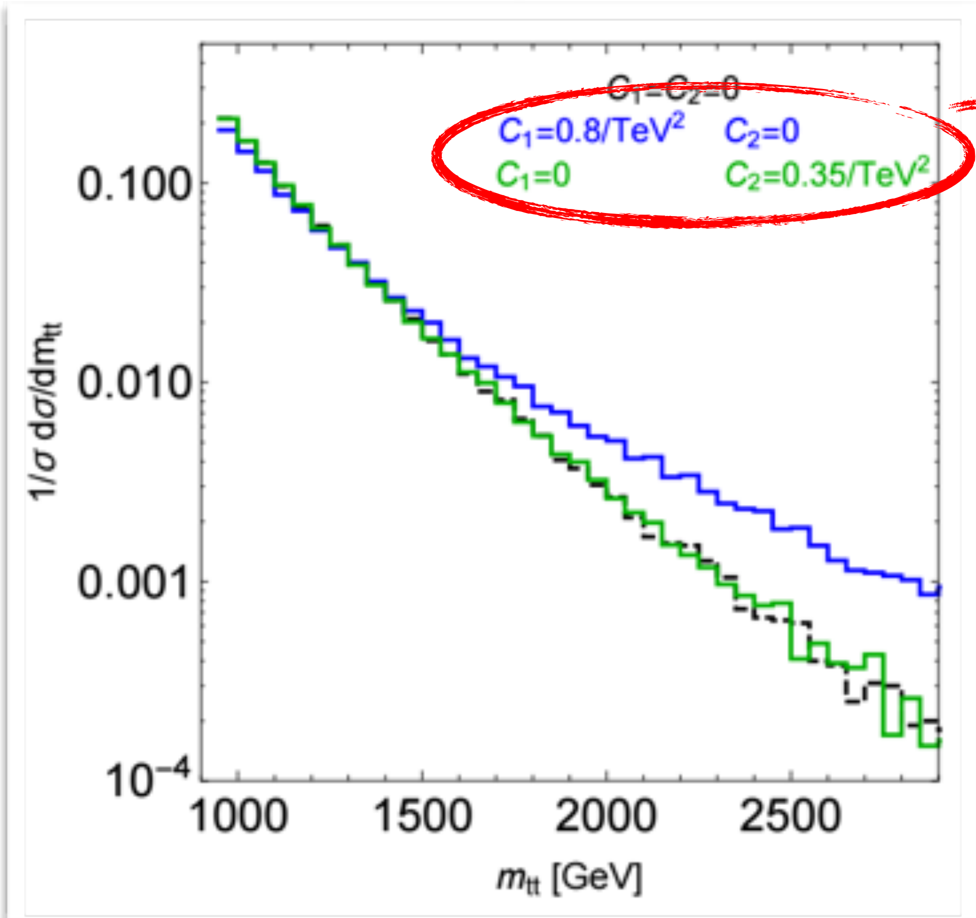
The LHC acts as a top factory



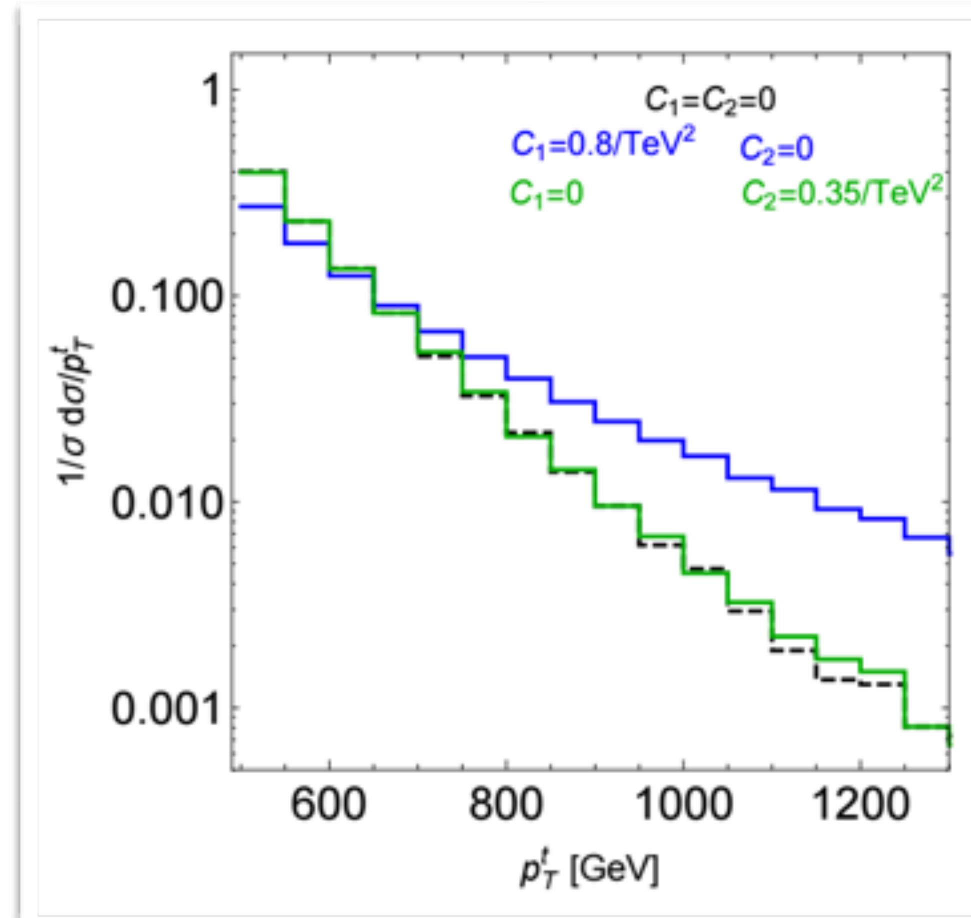

High statistic expected in the tails of the differential distributions, i.e. where we are more sensitive to higher dimensional operators

Differential measurements are a powerful probe to test the top quark EFT

# Constraints from differential measurements




**Within the bounds from total xs**




Insertion of the $\mathcal{O}_1$ operator causes a stronger enhancement at high masses

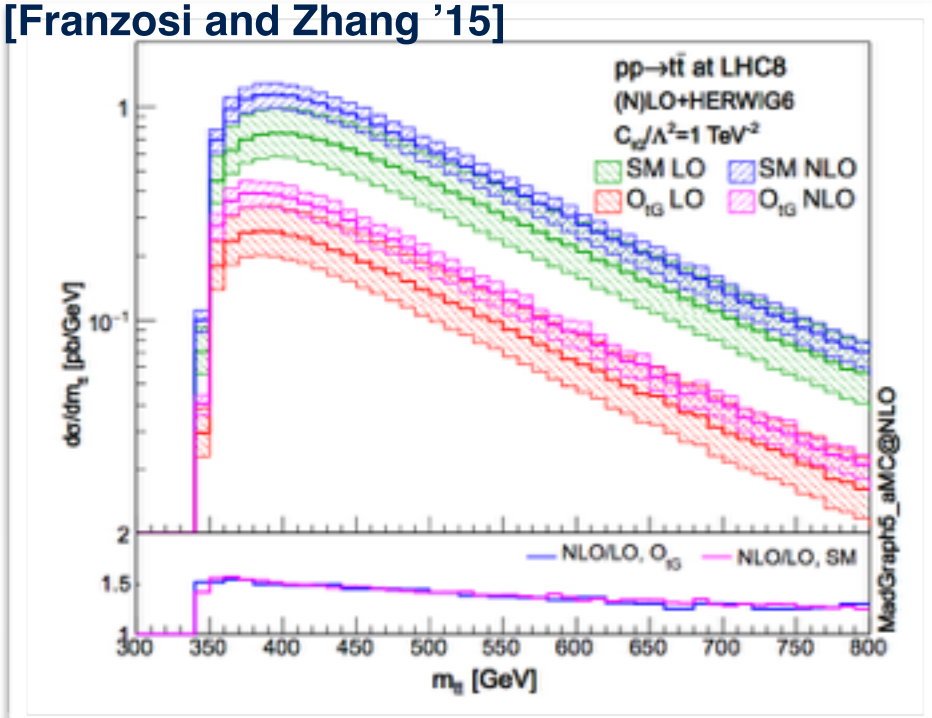
Normalized distributions less sensitive to the insertion of the operator $\mathcal{O}_2$

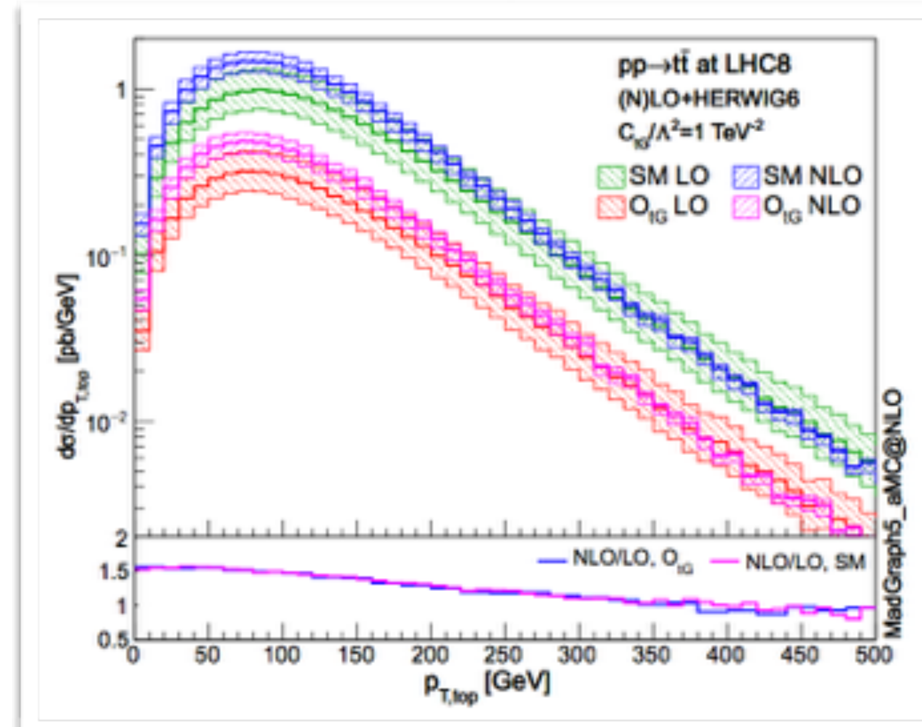
This suggests that $\mathcal{O}_1$ can be constrained independently of $\mathcal{O}_2$!

# Higher order corrections impact

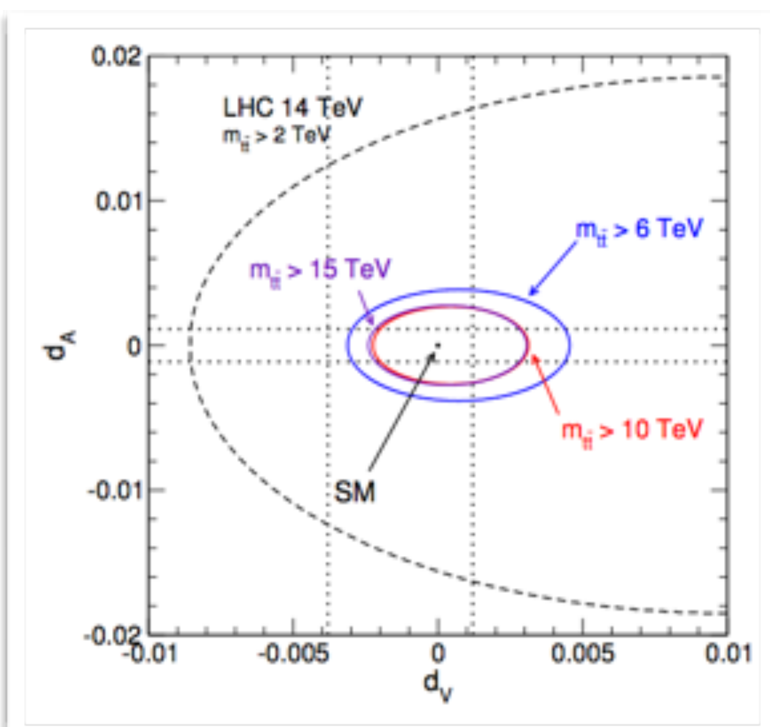
Inclusion of NLO corrections for the $\mathcal{O}_2$ operator

[Franzosi and Zhang '15]



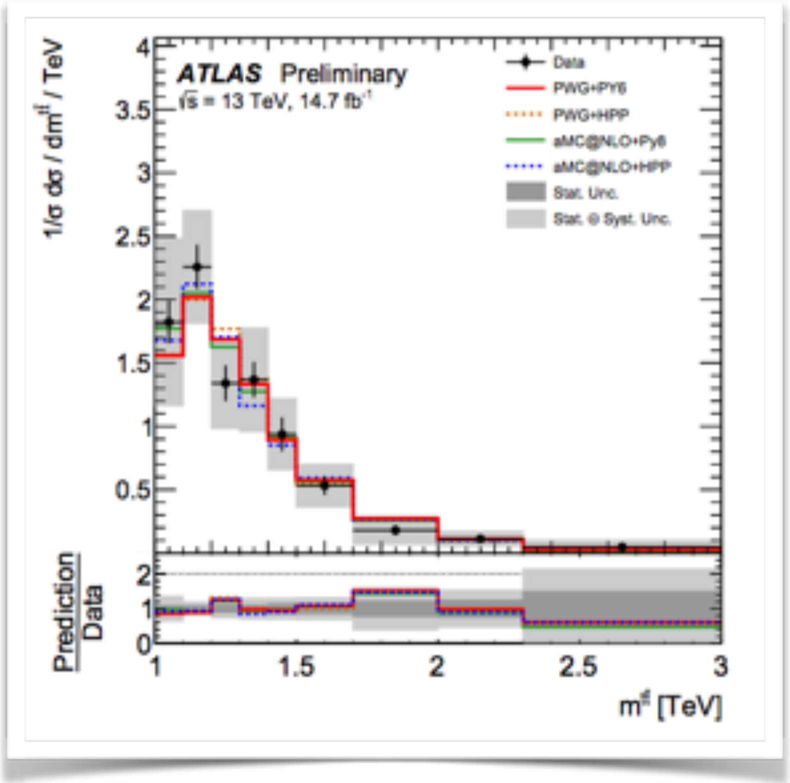

Total and diff. k-factors equal for SM and EFT - cancels out in normalized xs




Shape difference in $\mathcal{O}_2$ relevant for a future FCC -100 TeV

[Aguilar-Saavedra et al '14]

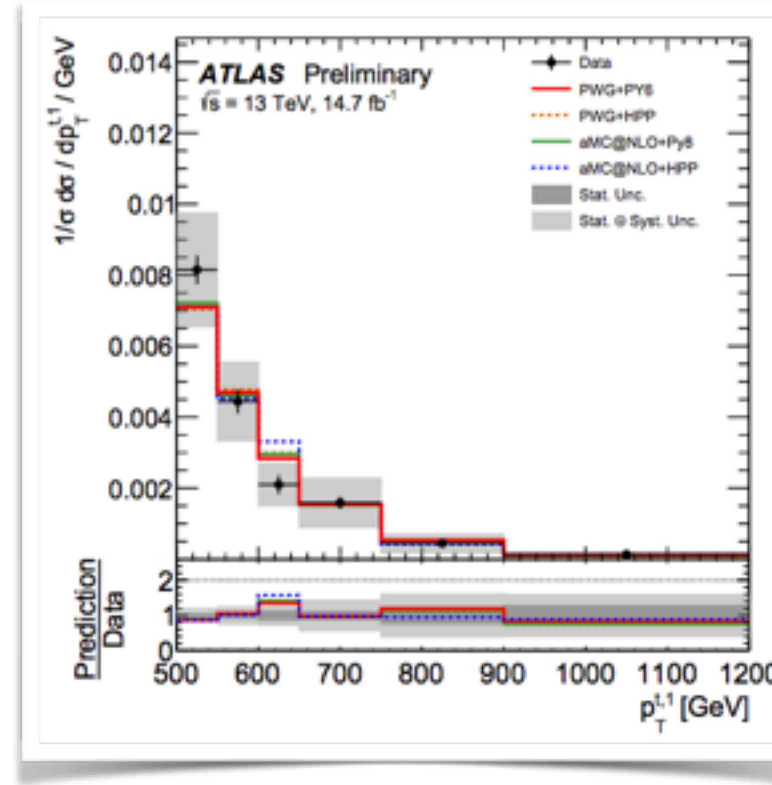
# Constraints from differential measurements

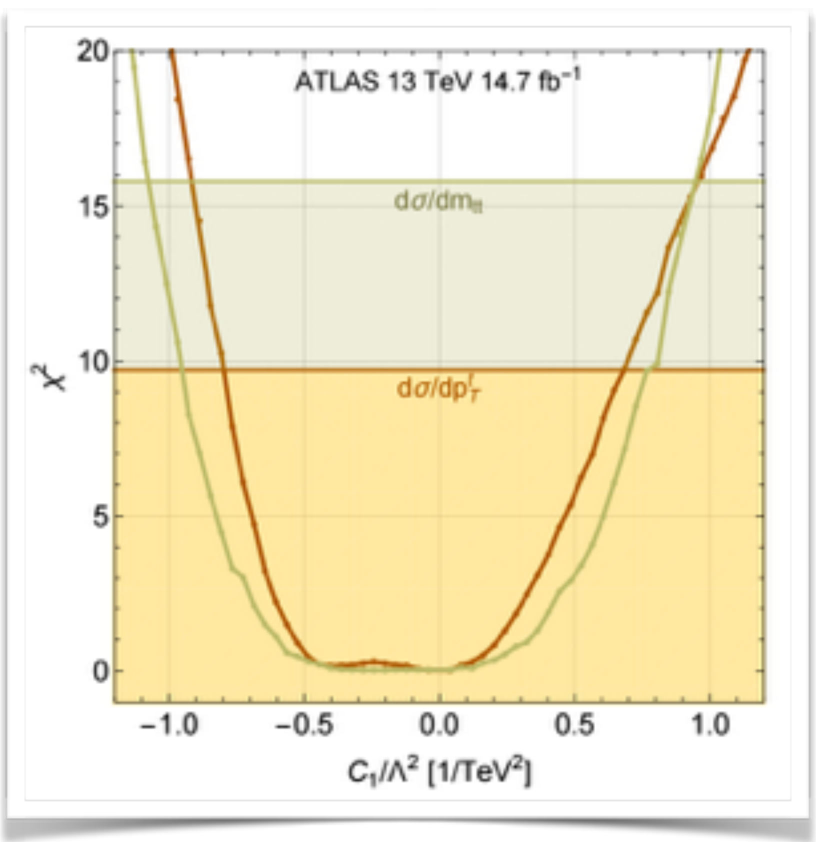



| $m_{t\bar{t}}$ [TeV] | 1.0 | 1.1 | 1.2 | 1.3 | 1.4 | 1.5 | 1.7 | 2.0 | 2.3-3.0 |
|---|---|---|---|---|---|---|---|---|---|
| Error [%] | 36 | 20 | 25 | 30 | 31 | 32 | 63 | 58 | 123 |

| $p_T^t$ [TeV] | 0.5 | 0.55 | 0.6 | 0.65 | 0.75 | 0.9-1.2 |
|---|---|---|---|---|---|---|
| Error [%] | 19 | 25 | 28 | 45 | 73 | 95 |

**[ATLAS-CONF-2016-100]**



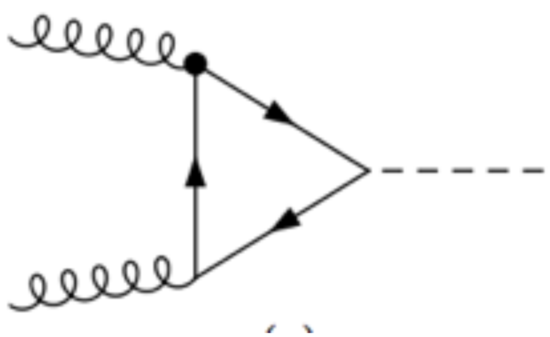



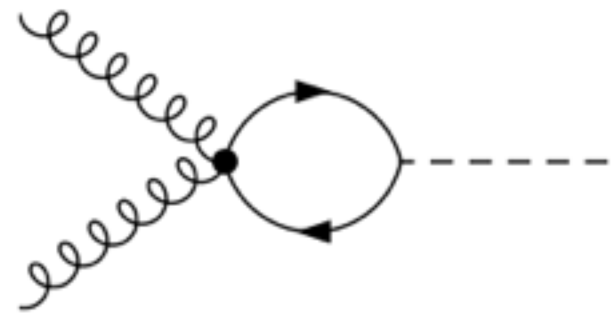

Perform a $\chi^2$ fit

$$|C_1| < 0.7/\mathrm{TeV}^2$$

comparable to the bound obtained by total cross section measurement

# Constraints from Higgs observables





$$\mathcal{O}_1 = \frac{C_1}{\Lambda^2}\bar{t}\gamma^\mu T^a t D^\nu G^a_{\mu\nu}$$

$\mathcal{O}_1$ vanishes when coupled to on-shell gluons

Higgs production cross section constrain only the $\mathcal{O}_2$ operator

$$(\mathcal{M}_{\mathcal{O}_2})^{ab}_{\lambda_1\lambda_2} = 4\times g_s\frac{y_t}{\sqrt{2}}\frac{2C_2}{\Lambda}\frac{1}{16\pi^2}(m_H^2 g_{\mu\nu} - 2q_{2\mu}q_{1\nu})\varepsilon^\mu_{\lambda_1}(q_1)\varepsilon^\nu_{\lambda_2}(q_2)\,\mathrm{Tr}\left[T^aT^b\right]\times\left\{\frac{1}{\bar{\epsilon}}+1+\log\frac{\mu^2}{m_t^2}\right.$$
$$\left.+\frac{m_t^2}{m_H^2}\log^2\left(\frac{\sqrt{m_H^4-4m_t^2m_H^2}+2m_t^2-m_H^2}{2m_t^2}\right)+\frac{\sqrt{m_H^4-4m_t^2m_H^2}}{m_H^2}\log\left(\frac{\sqrt{m_H^4-4m_t^2m_H^2}+2m_t^2-m_H^2}{2m_t^2}\right)\right\}$$

Counter-term proportional to $\mathcal{O}_{HG} = H^\dagger H G^a_{\mu\nu}G_a^{\mu\nu}$

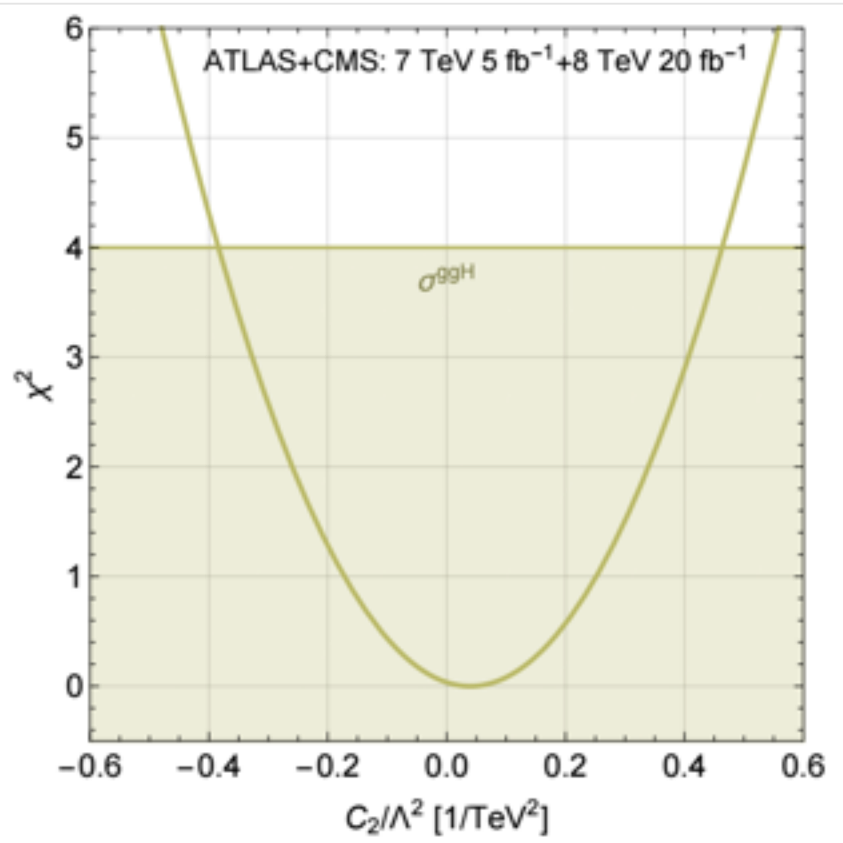
Fix $\mu = m_H$

# Constraints from Higgs observables

$$\mu_{\mathcal{O}_2} \simeq 1 + 0.755\ \text{TeV}^2 \frac{C_2}{\Lambda^2}\,.$$

| Production process | ATLAS+CMS | ATLAS | CMS |
|---|---|---|---|
| $\mu_{\text{ggF}}$ | $1.03^{+0.17}_{-0.15}$ | $1.25^{+0.24}_{-0.21}$ | $0.84^{+0.19}_{-0.16}$ |

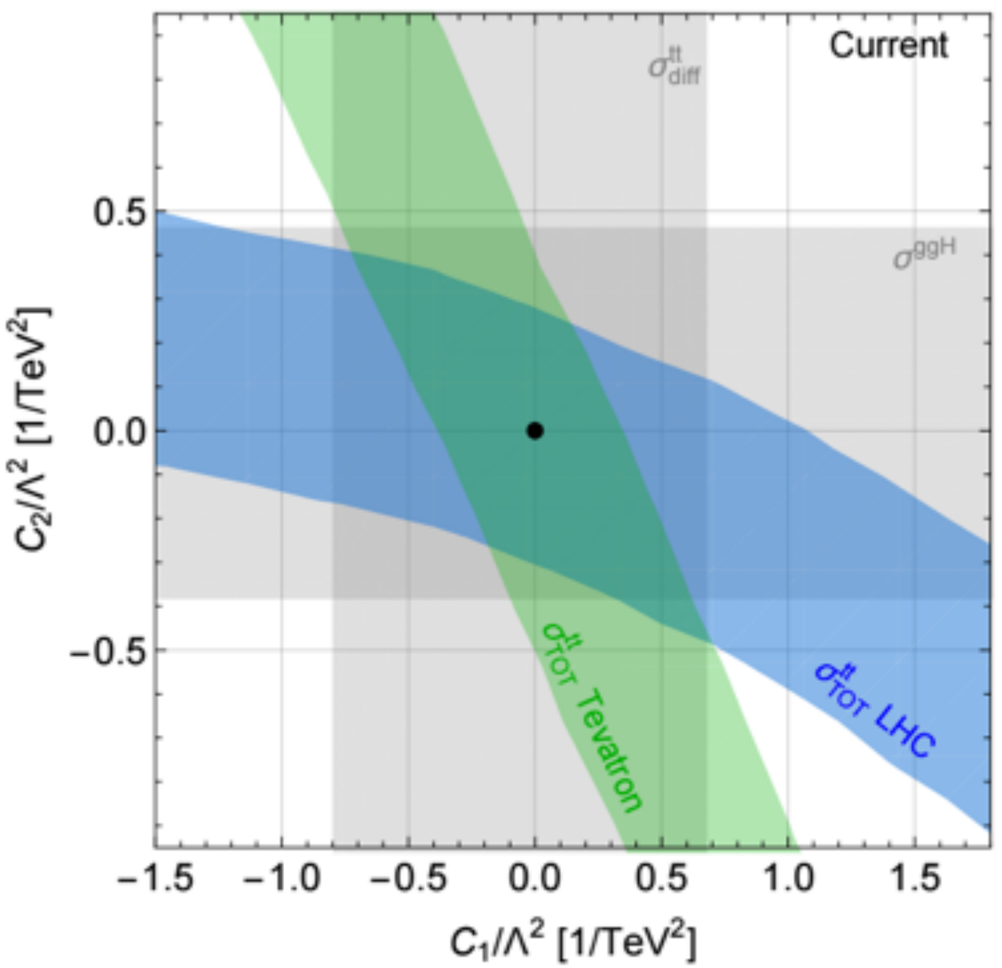
**ATLAS & CMS Run-1 combination**




$$|C_2| < 0.4/\text{TeV}^2$$

comparable to the bound obtained by total cross section measurement

# Prospects for the LHC




Current measurements can already be used to set competitive and independent limits on $\mathcal{O}_1$ and $\mathcal{O}_2$

Total $t\bar{t}$ cross section measurements dominated by systematics ~4%

Unlikely to improve

Differential $t\bar{t}$ measurements and Higgs couplings determination are expected to become more precise with accumulation of more statistics

# Prospects for the LHC

## Differential measurements

Assume a luminosity dependent rescaling of the systematic uncertainties with a 15% floor

$$\left.\frac{\Delta\sigma}{\sigma}\right|_{\mathcal{L}} = \text{Max}\left[0.15, \left.\frac{\Delta\sigma}{\sigma}\right|_{\mathcal{L}_0} \times \sqrt{\frac{\mathcal{L}}{\mathcal{L}_0}}\right]$$

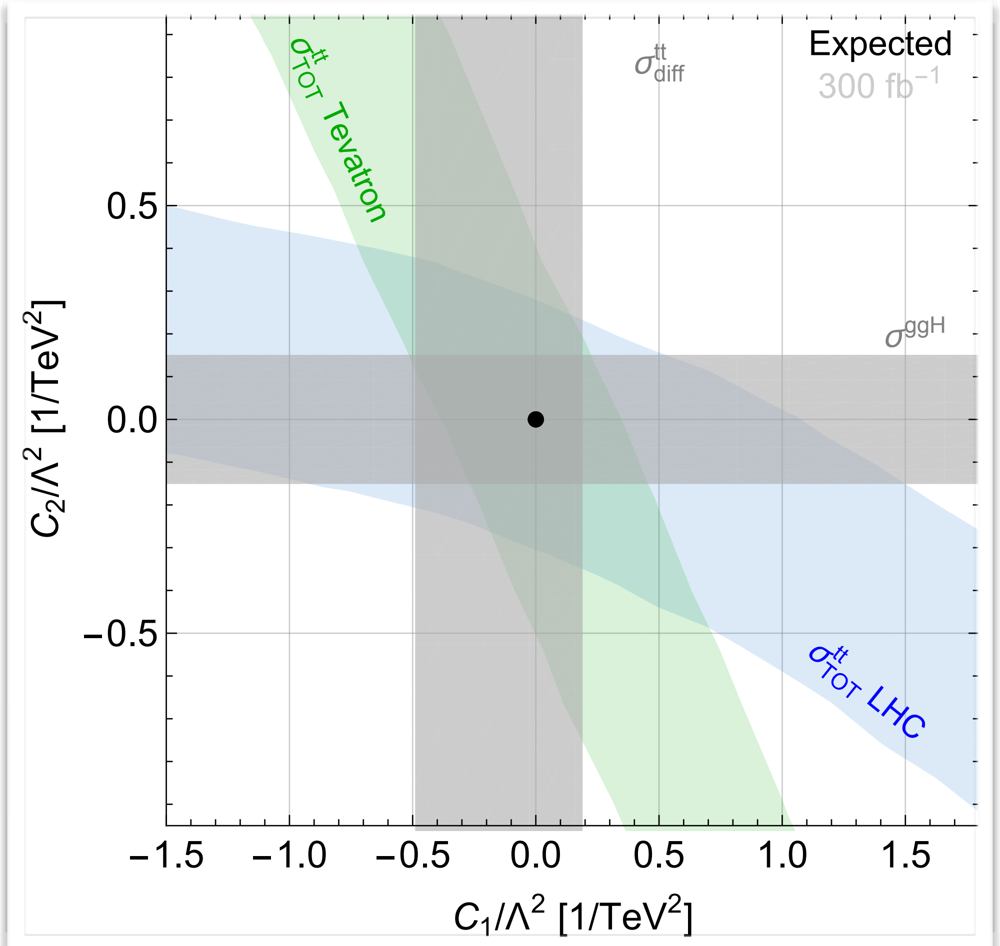
## Higgs signal strength

**[CMS-NOTE-2012-006]**

| Coupling | Uncertainty (%) | | | |
|---|---|---|---|---|
| | 300 fb$^{-1}$ | | 3000 fb$^{-1}$ | |
| | Scenario 1 | Scenario 2 | Scenario 1 | Scenario 2 |
| $\kappa_\gamma$ | 6.5 | 5.1 | 5.4 | 1.5 |
| $\kappa_V$ | 5.7 | 2.7 | 4.5 | 1.0 |
| $\kappa_g$ | 11 | 5.7 | 7.5 | 2.7 |
| $\kappa_b$ | 15 | 6.9 | 11 | 2.7 |
| $\kappa_t$ | 14 | 8.7 | 8.0 | 3.9 |
| $\kappa_\tau$ | 8.5 | 5.1 | 5.4 | 2.0 |

Assume CMS projections on Higgs coupling measurements

# SM EFT - the top sector



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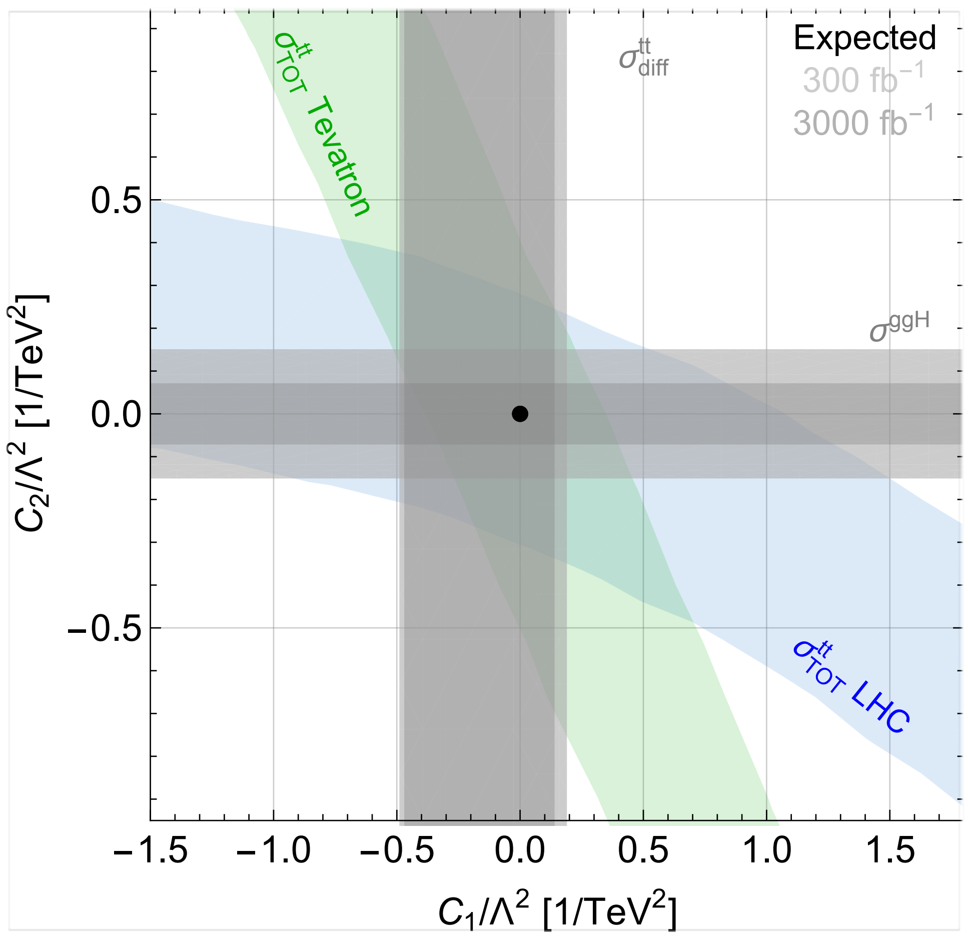


| LHC 300 fb$^{-1}$ | LHC 3000 fb$^{-1}$ |
|---|---|
| $-0.49 < C_1/\Lambda^2 < 0.19$ | $-0.47 < C_1/\Lambda^2 < 0.19$ |
| $-0.15 < C_2/\Lambda^2 < 0.15$ | $-0.07 < C_2/\Lambda^2 < 0.07$ |

Higgs coupling with 300/fb will provide the most stringent limits of $\mathcal{O}_2$

At the end of the LHC program most stringent limits on $\mathcal{O}_1$ and $\mathcal{O}_2$ can be set

Bound on NP scale

$$C_1 = C_2 = 4\pi \quad \rightarrow \quad \Lambda \sim 5 \text{ TeV}$$

Within EFT validity

# Conclusions

- Searches for NP are testing the TeV scale also in the top sector
- No signs on heavy resonances in LHC data - NP too heavy?

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- EFT framework provide a model independent approach for NP searches
- It's important to test the impact of many observables in the top quark coupling determination. Relevant also for global fit approaches
- Normalized distributions for top quark production together with Higgs production measurements provide independent observables to bound non standard top-gluon interactions
- These observables are expected to be more sensitive than total cross section measurements which is already dominated by systematics

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Thank you!