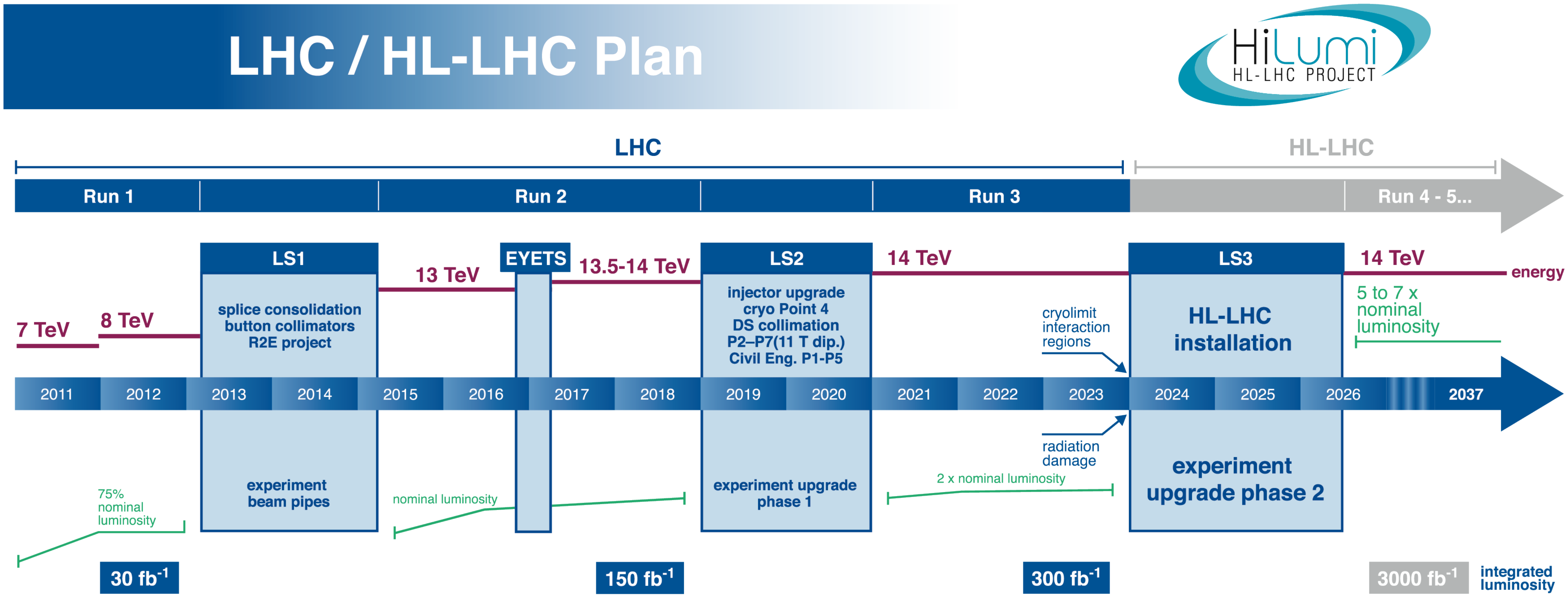
Over the Top

Top 2019 - Beijing - 26 Sep 2019

Riccardo Torre
CERN & INFN Genova

LHC physics program



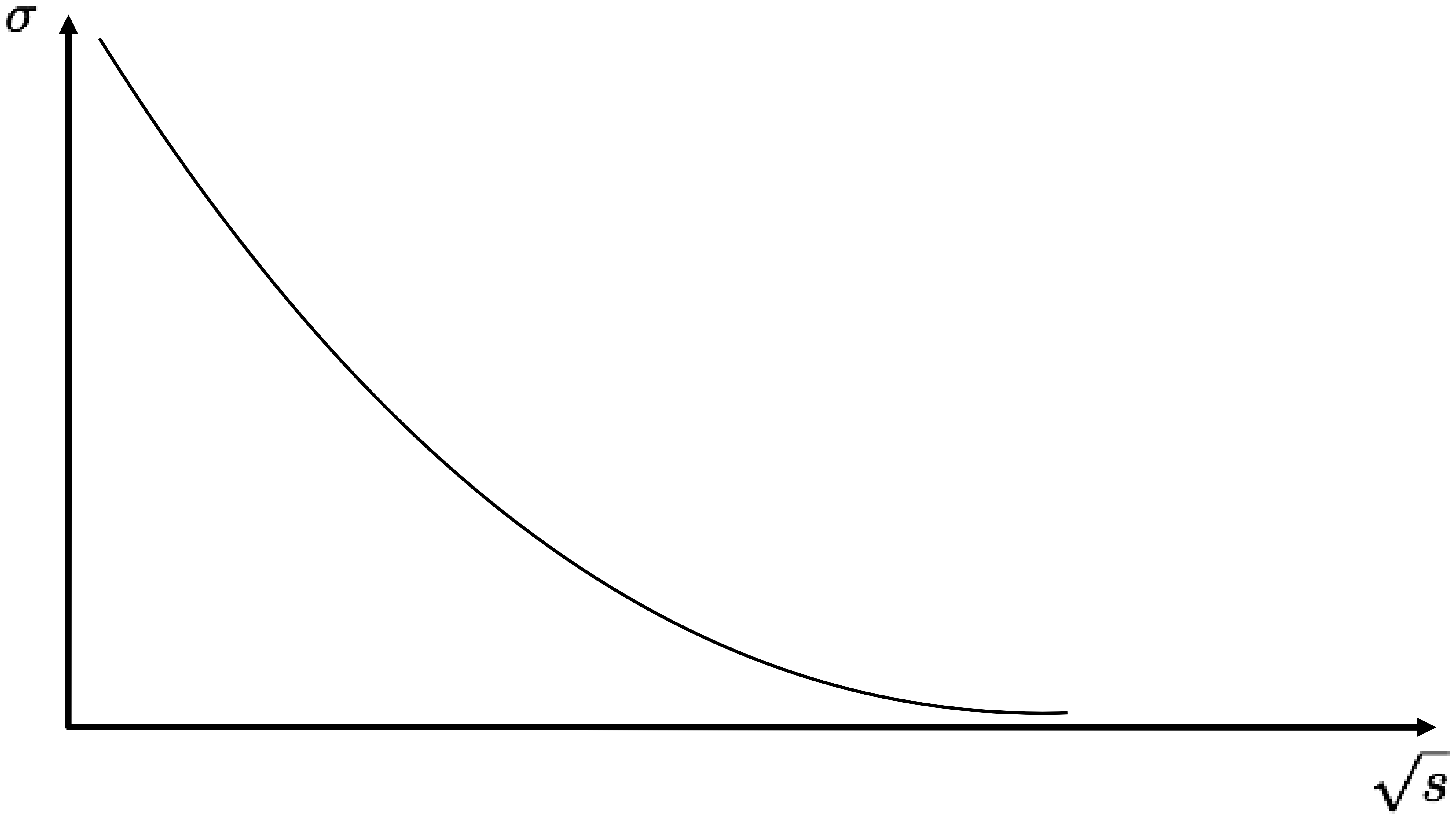
Main goal: Find signs of New Physics

direct searches

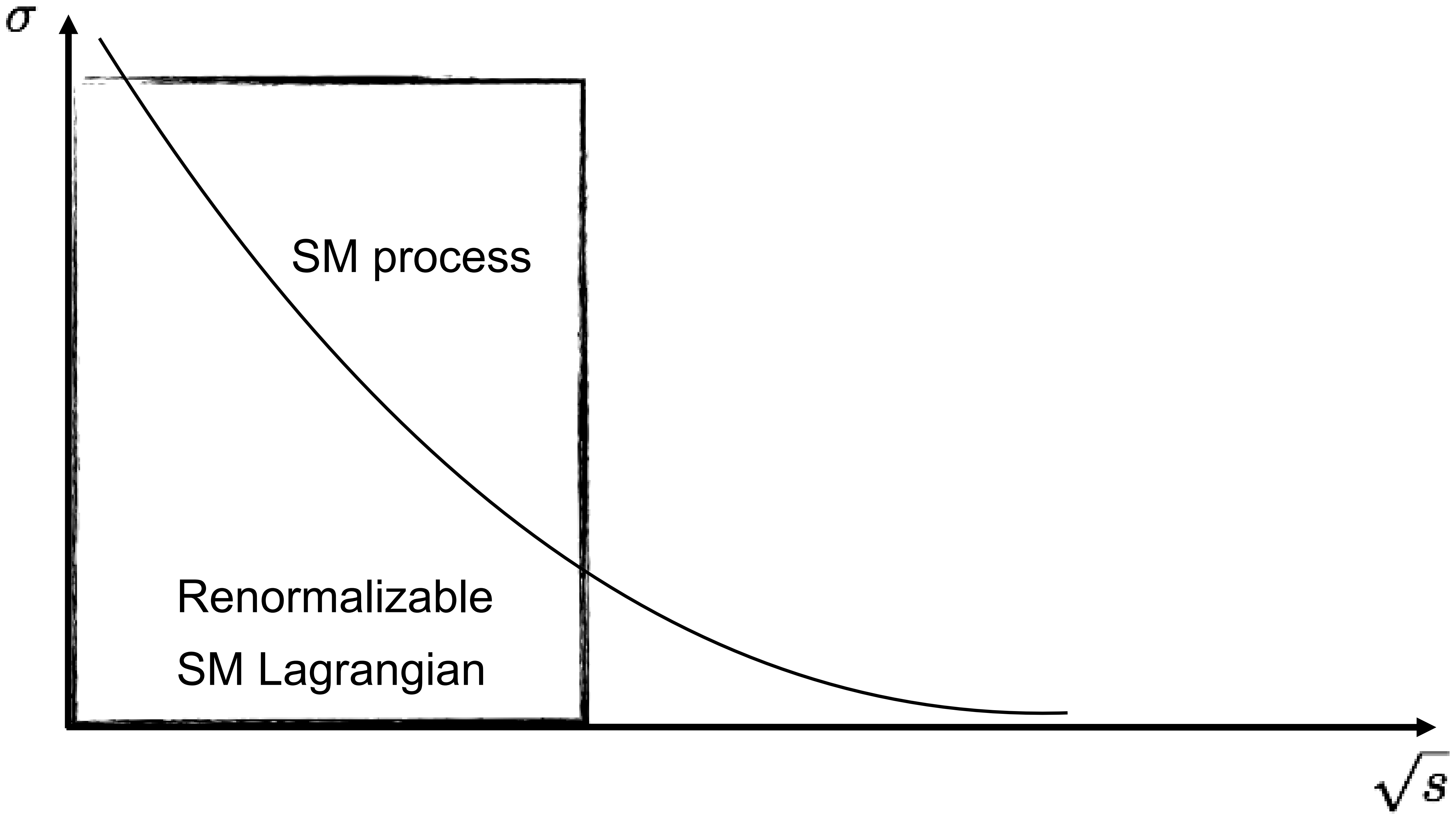
- directly: probing on-shell new physics
- indirectly: probing the effect of new physics on SM observables

precision physics

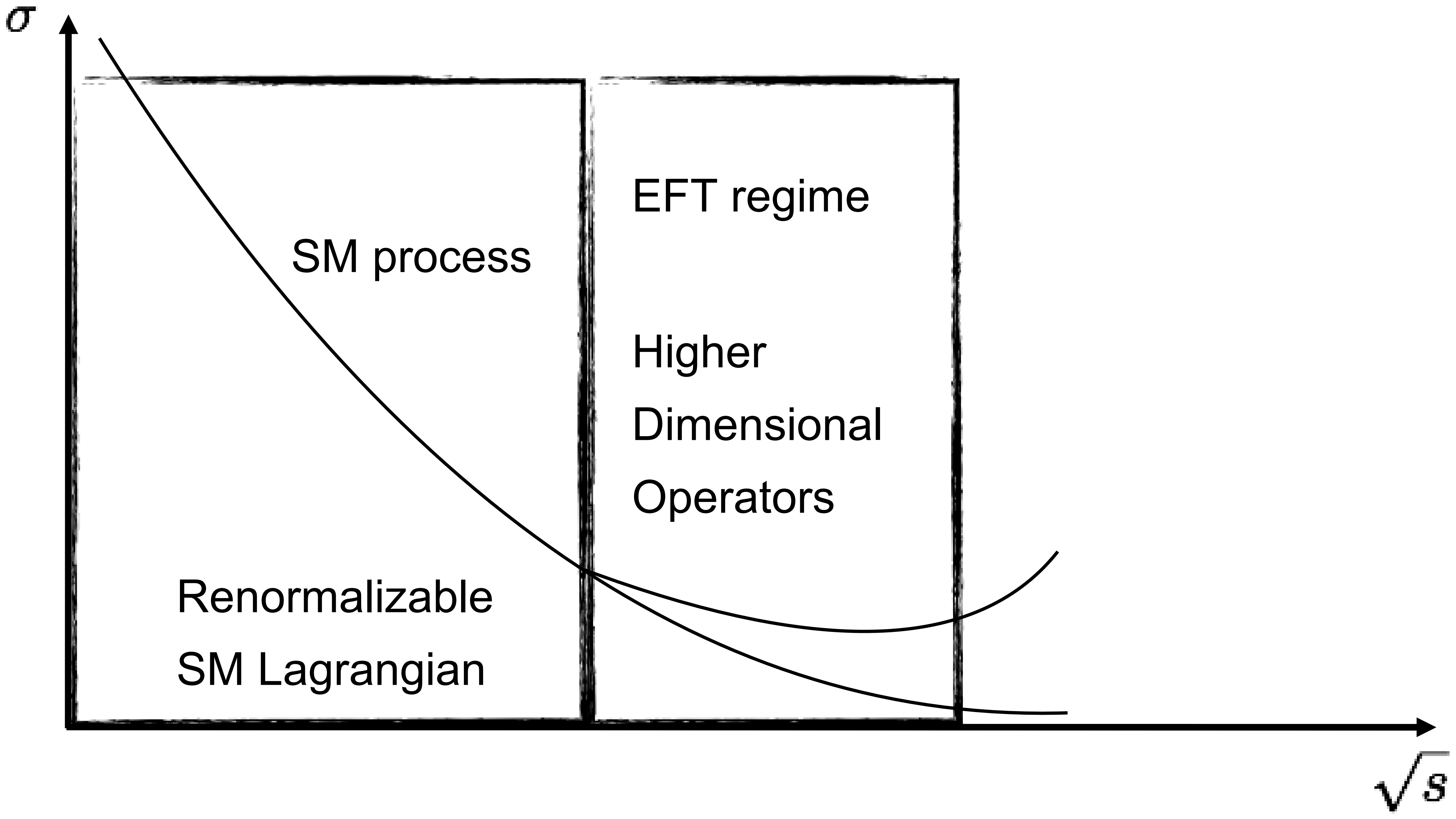
New physics: a pictorial representation



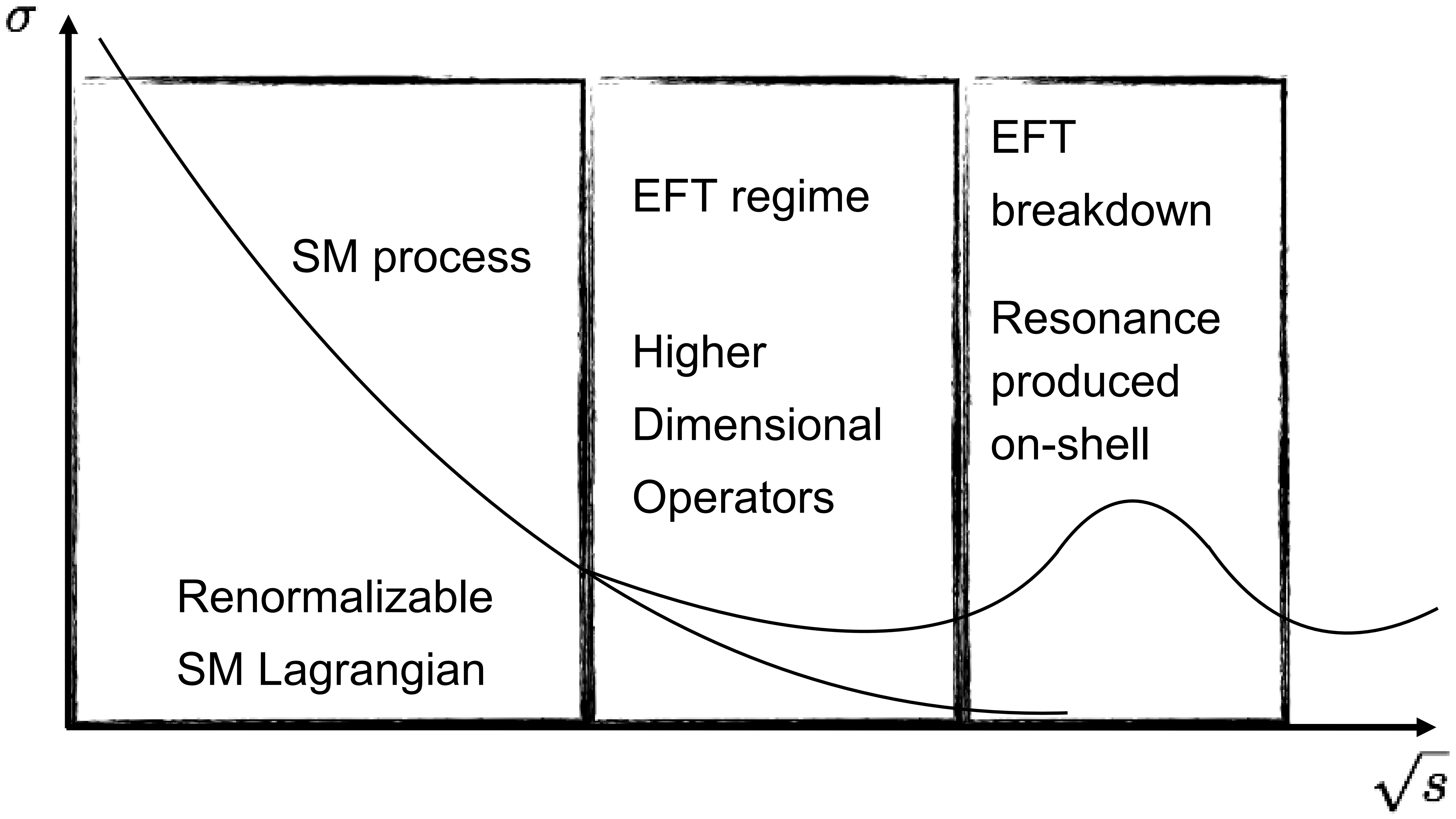
New physics: a pictorial representation



New physics: a pictorial representation



New physics: a pictorial representation



SM process

Renormalizable
SM Lagrangian

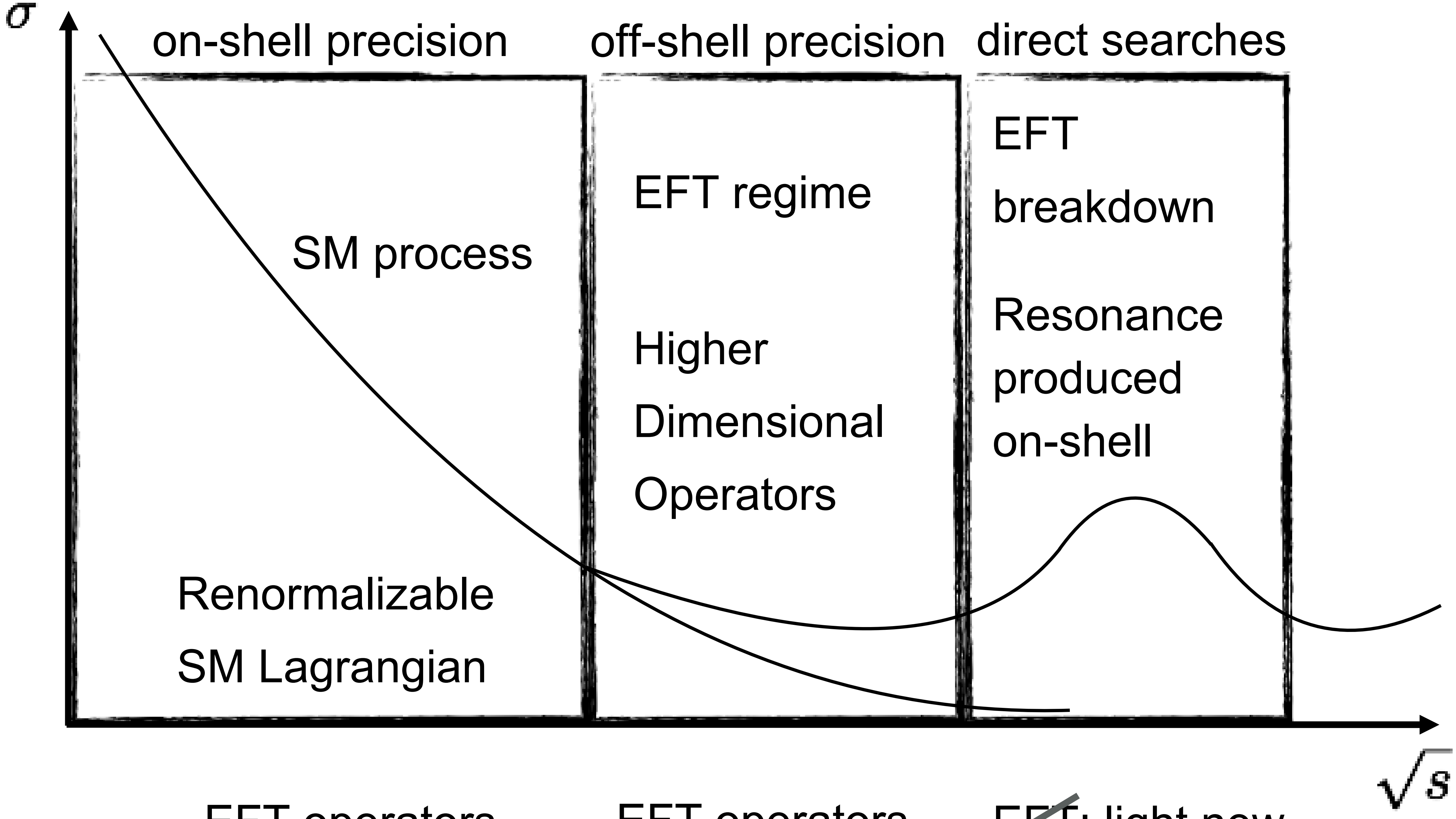
EFT regime

Higher
Dimensional
Operators

EFT
breakdown

Resonance
produced
on-shell

New physics: a pictorial representation



on-shell precision

SM process

Renormalizable
SM Lagrangian

off-shell precision

EFT regime

Higher
Dimensional
Operators

direct searches

EFT
breakdown

Resonance
produced
on-shell

Examples:

EFT operators
with Higgses

EFT operators
with derivatives

~~EFT~~: light new
physics

Naturalness in the SM

Viewing the SM as a low energy effective theory

$$\delta m_h^2 = \frac{3y_t^2}{4\pi^2}\Lambda_t^2 - \frac{9g^2}{32\pi^2}\Lambda_g^2 - \frac{3g'^2}{32\pi^2}\Lambda_{g'}^2 - \frac{3\lambda_h}{8\pi^2}\Lambda_h^2 + \ldots$$

we assume the scales Λ to be physical (e.g. masses of heavy particles)

$$\Downarrow$$

e.g. $$\Lambda_t^2 \sim \frac{4\pi^2}{3y_t^2} \times \frac{m_h^2}{\epsilon_t}$$

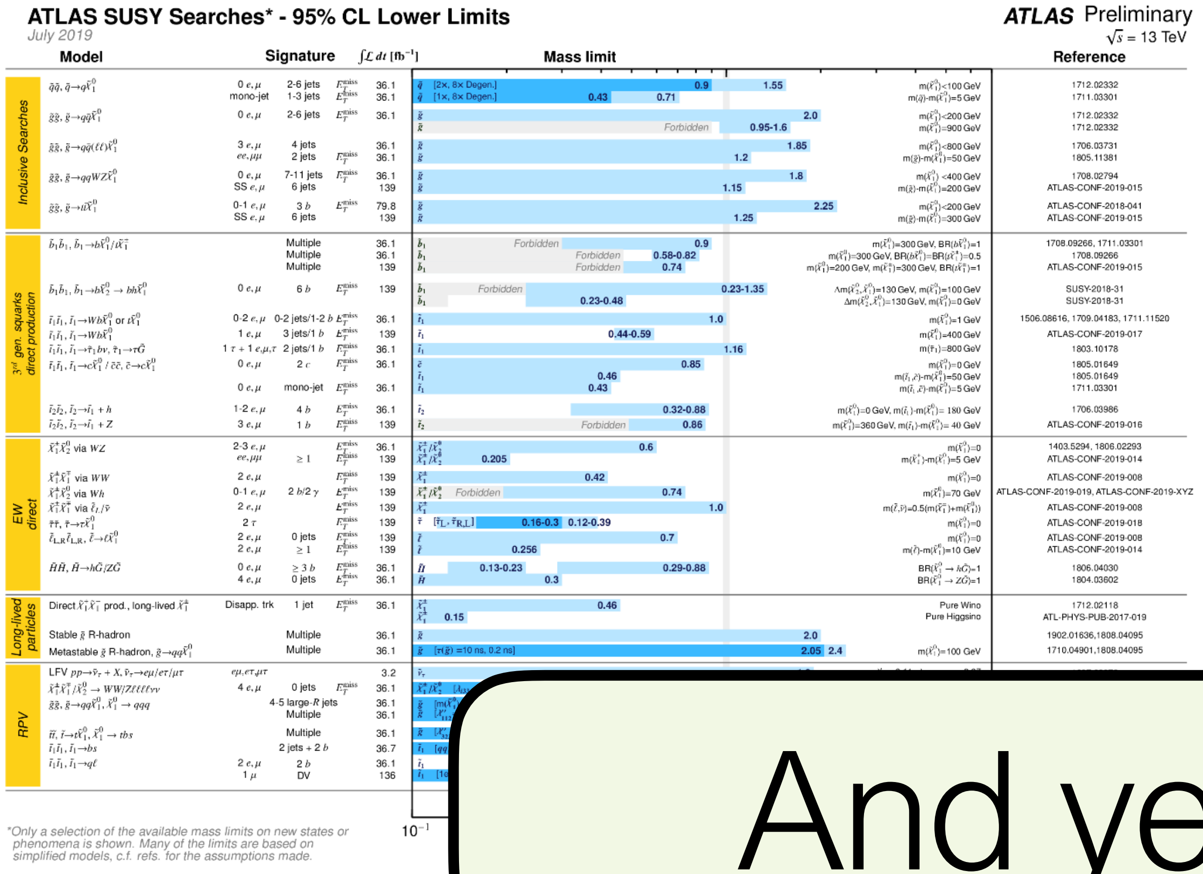
numerically

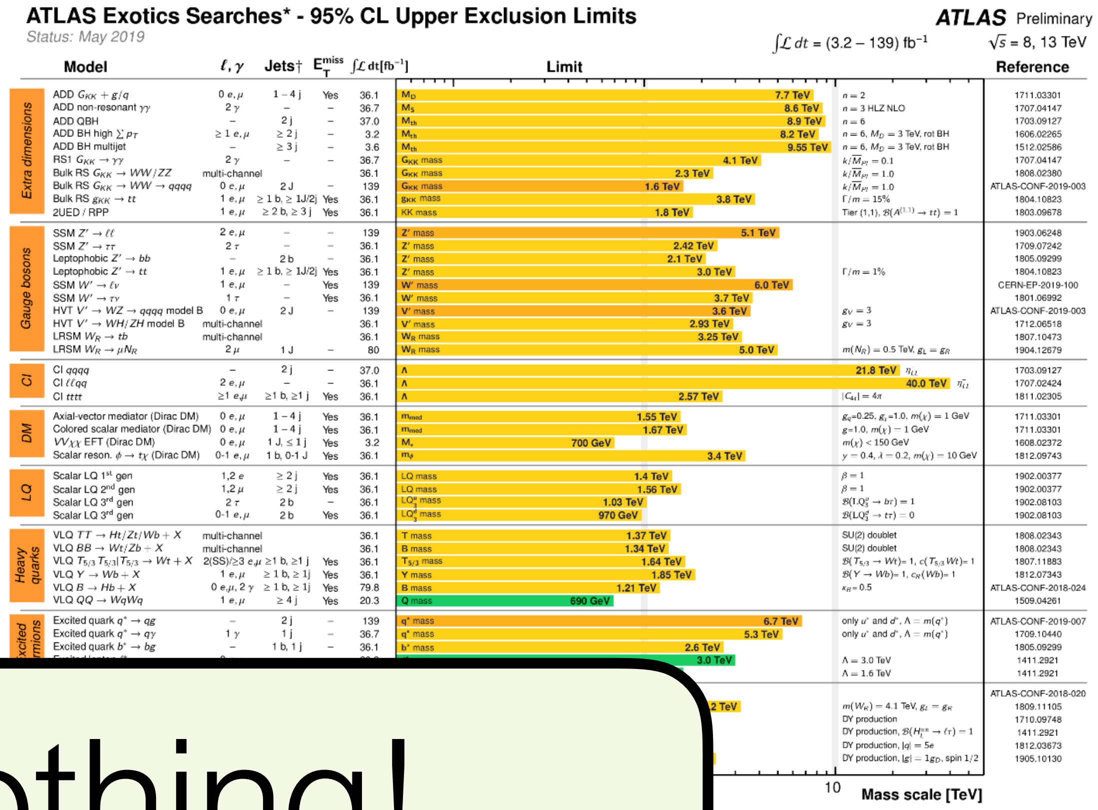
$$\Lambda_t \sim \frac{0.45}{\sqrt{\epsilon_t}}\ \text{TeV} \qquad \Lambda_g \sim \frac{1.1}{\sqrt{\epsilon_g}}\ \text{TeV} \qquad \Lambda_{g'} \sim \frac{3.7}{\sqrt{\epsilon_{g'}}}\ \text{TeV} \qquad \Lambda_h \sim \frac{1.3}{\sqrt{\epsilon_h}}\ \text{TeV}$$

States “related” to the top quark are expected to be rather light

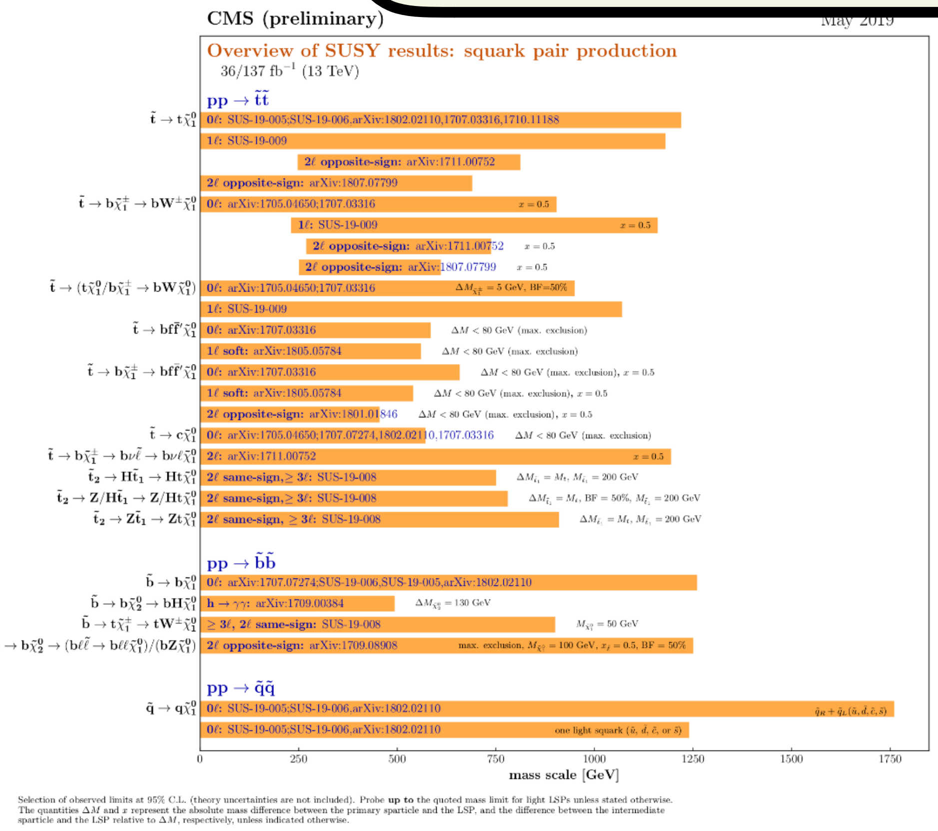
If they are colored this already implies some tuning (main player LHC!)

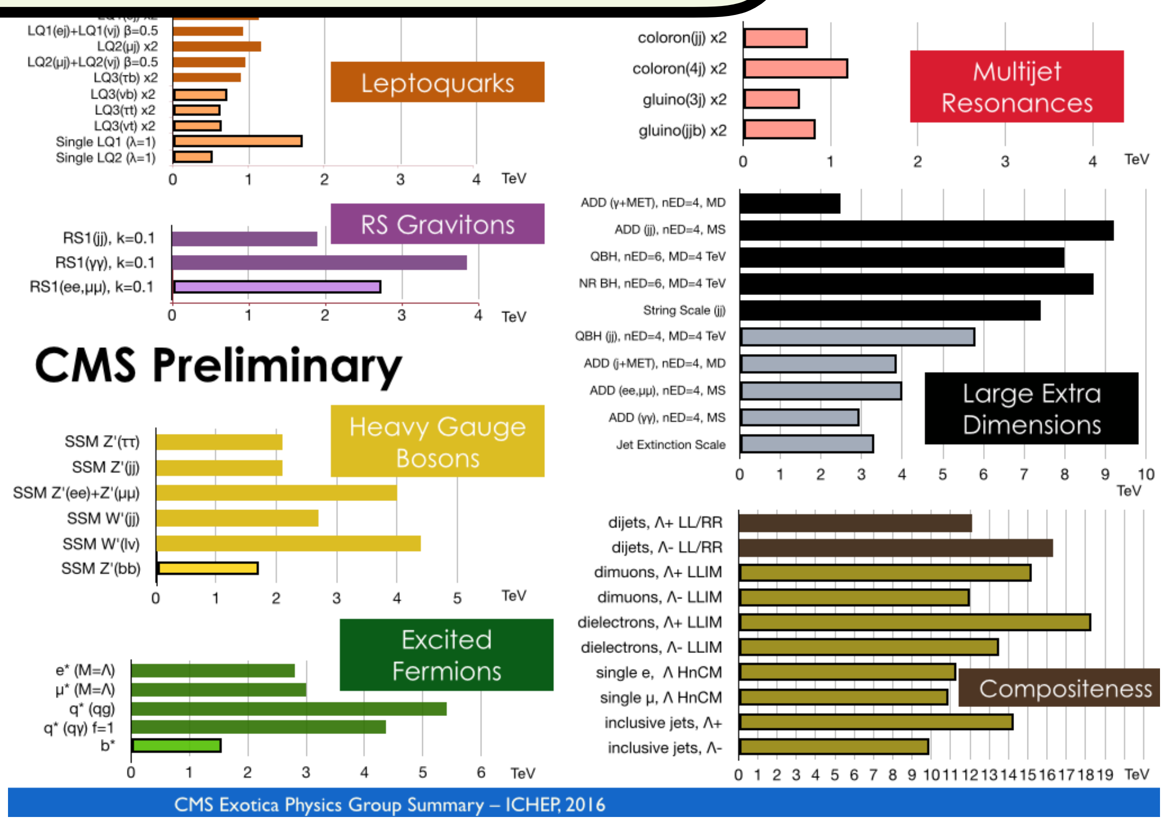
Direct searches





And yet nothing!





Over The Top - USA 1987

The new theorists are like Sylvester Stallone

Soft, supersoft, hypersoft

Charged Naturalness

Soft models

$$\Lambda_{\rm NP}^2 \sim \frac{2\pi^2}{3y_t^2} \times \frac{1}{\log \Lambda_{\rm UV}/\Lambda_{\rm NP}} \times \frac{m_h^2}{\epsilon_t}$$

- e.g. MSSM with large scale mediation
- already constrained at LEP and Tevatron
- higher tuning

Supersoft models

$$\Lambda_{\rm NP}^2 \sim \frac{4\pi^2}{3y_t^2} \times \frac{m_h^2}{\epsilon_t}$$

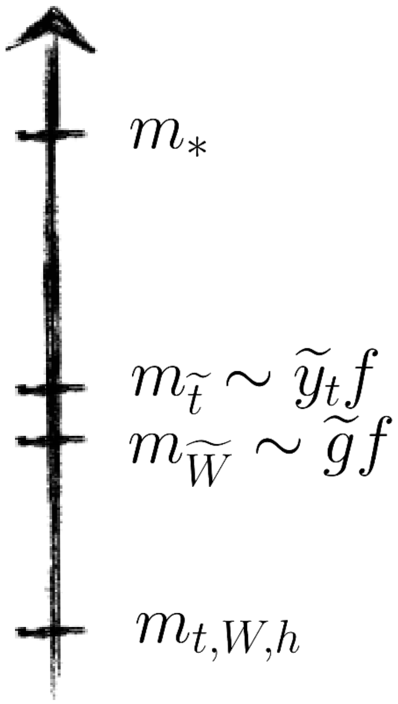
- e.g. MSSM with low scale mediation and composite models
- probed at the LHC
- moderate tuning

Neutral Naturalness

Hypersoft models

$$\Lambda_{\rm NP}^2 \sim \frac{4\pi^2}{3y_t^2} \times \frac{m_h^2}{\epsilon_t} \times \frac{g_*^2}{g_{\rm SM}^2}$$

- mass of colored objects pushed up
- evades LHC, testable at HE-LHC, FCC
- lower tuning



Neutral naturalness zoology

Several models of neutral naturalness have been proposed with the goal to change the quantum numbers of top-partners in order to relax naturalness constraints, but still get an interesting phenomenology

- Folded Supersymmetry ***Burdman, Chacko, Goh, Harnik, hep-ph/0805.4667, and many other references (InSpire)***
- Twin Higgs ***Chacko, Goh, Harnik, hep-ph/0506256, and many other references (InSpire)***
  - Supersymmetric TH ***Chang, Hall, Weiner, hep-ph/0604076***
  - Composite TH ***Barbieri, Greco, Rattazzi, Wulzer, hep-ph/1501.07803***
  - Fraternal TH ***Craig, Katz, Strassler, Sundrum, hep-ph/1501.05310***
  - Brother Higgs ***Serra, RT, hep-ph/1709.05399***
  - Exceptional TH ***Serra, Stelzl, RT, Weiler, hep-ph/1905.02203***
- Orbifold Higgs ***Craig, Knapen, Longhi, hep-ph/1410.6808***
- Hyperbolic Higgs ***Cohen, Craig, Giudice, McCullough, hep-ph/1803.03647***

All exploit new kinds of symmetries to protect the Higgs from large corrections due to colored (and in general SM charged) heavy states

Main phenomenological implications

Making exact general statements given this zoology is hard. However, most of the models share (some of) the following phenomenological features

- The lightest new physics states (those tight to naturalness, i.e. to the top and the EW sector) are SM neutral or only carry SU(2) and/or U(1) charges
- Extended scalar sector (e.g. heavy singlet Higgs) and heavy Z' vector bosons
- Coupling of the new sector to the SM one is typically only mediated by the Higgs field (which could belong to representation of larger symmetries)
- Models where the new physics coupling is large (composite models) typically show the "best" protection of the Higgs potential, but suffer from rather strong constraints from EWPT
- If new particles are completely neutral under SM and carry their own color charge, they may confine leading to missing energy and displaced signatures
- If new particles carry electric charge, they may give rise to long-lived charged particles, displaced di-lepton and di-photon pairs and missing energy signatures

Phenomenology

Phenomenology extremely rich and crucially depends on the value of λ_* and the mechanism of Z_2 breaking

Small $\lambda_{\mathcal{H}} \sim g_*^2 \Longrightarrow$ weakly coupled dynamics (e.g. SUSY TH)

Main prediction is an extended scalar sector (radial mode)

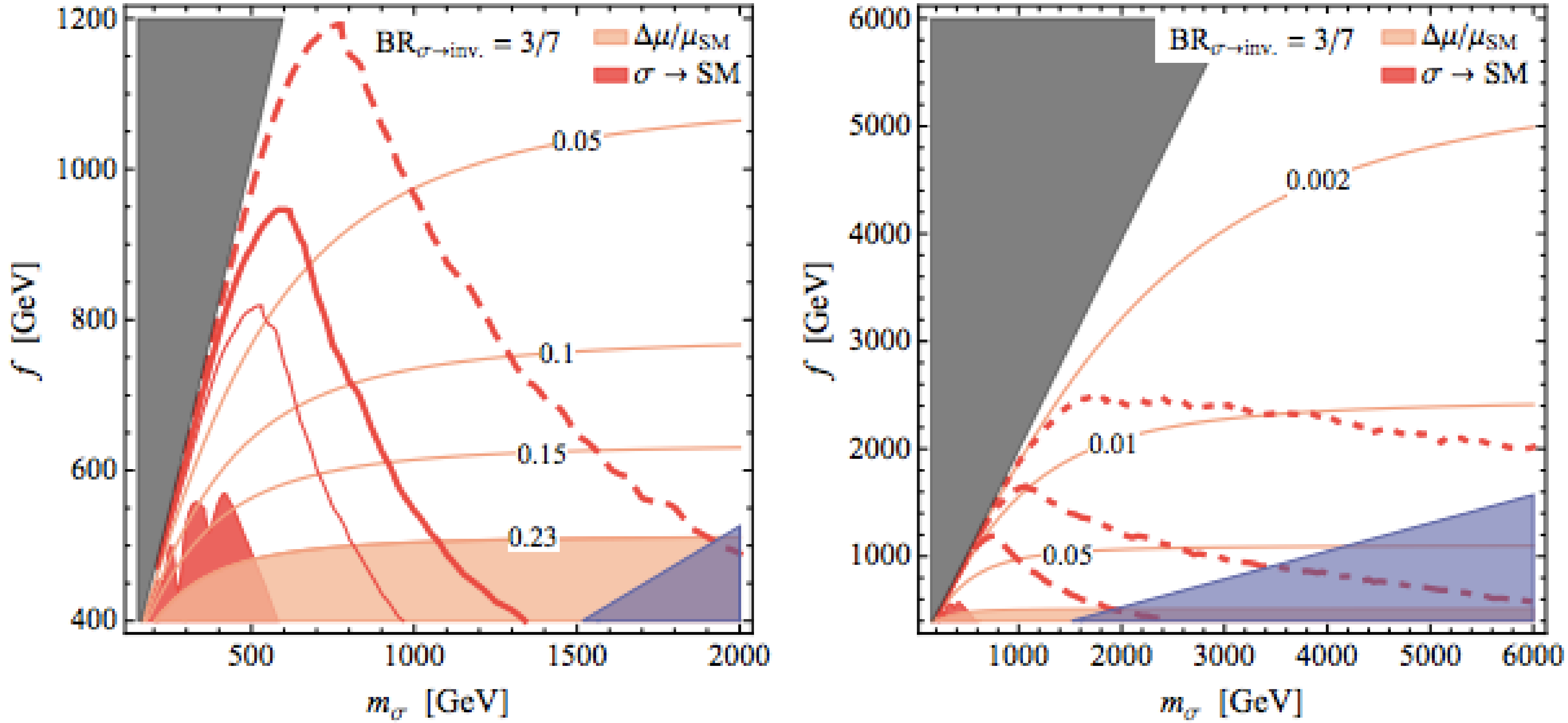


Figure 10. Model with $\mathrm{BR}_{\sigma\to\mathrm{inv.}} = 3/7$. Shaded regions: excluded at 95% C.L. by Higgs couplings (pink), excluded by direct searches (red), $\Gamma_\sigma > m_\sigma$ (blue), unphysical parameters (grey). The notation for the lines is as in figure 7.

Buttazzo, Sala, Tesi, 1505.05488 [hep-ph]

Phenomenology

Phenomenology extremely rich and crucially depends on the value of λ_* and the mechanism of Z_2 breaking

Large $\lambda_{\mathcal{H}} \sim g_*^2$ $\Longrightarrow$ strongly coupled dynamics

Composite TH

Barbieri, Greco, Rattazzi, Wulzer, 1501.07803 [hep-ph]

Low, Tesi, Wang, 1501.07890 [hep-ph]

- Z_2 broken only in EW sector (e.g. only by twin hypercharge)
- cosmology is a challenge
- only signature in Higgs coupling modifications, Higgs invisible decays and EWPT

$\Downarrow$

hardest to test at LHC

need FCC-ee/CEPC/ILC/CLIC to test Higgs couplings

and/or

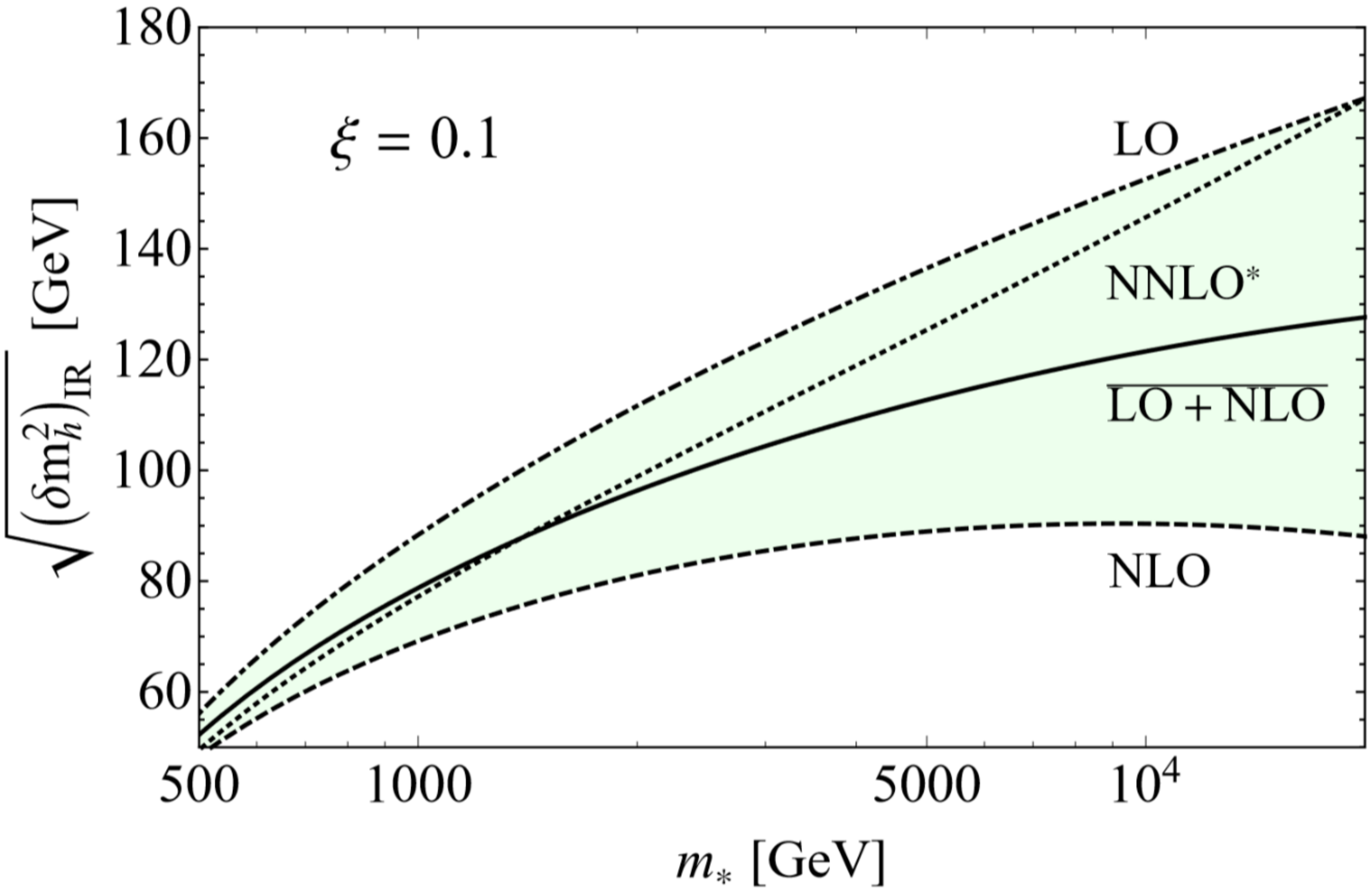
FCC-hh/SppC to access spectrum of resonances

Higgs mass

Infrared contribution to Higgs mass is dominant and almost saturates the observed value

⟹

the LL typically overshoots but resummation is expected to decrease (like in SM)



NLL: Contino, Greco, Mahbubani, Rattazzi, RT, 1702.00797

Higgs potential vs EWPO

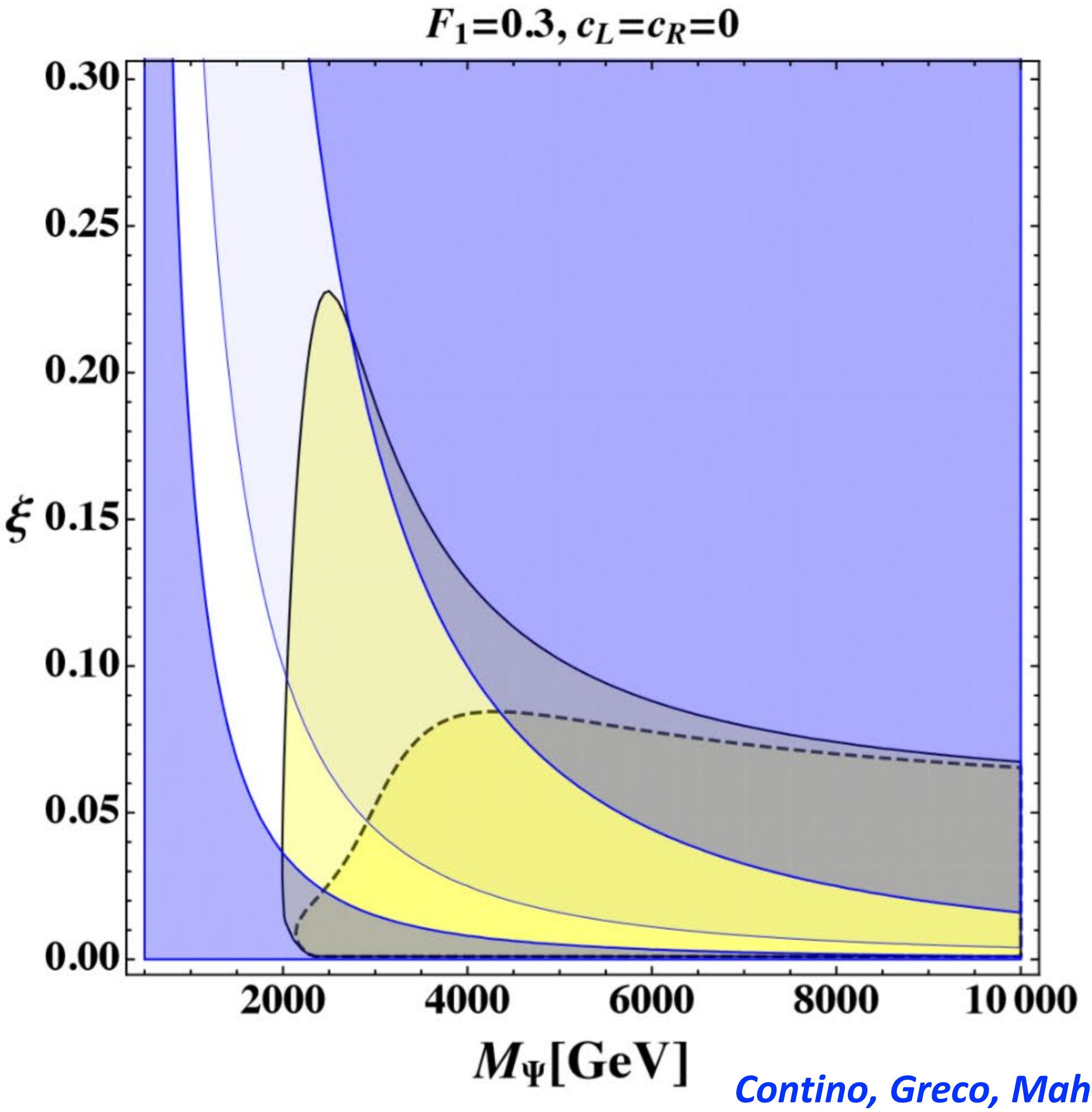
Fix UV contribution to the Higgs mass

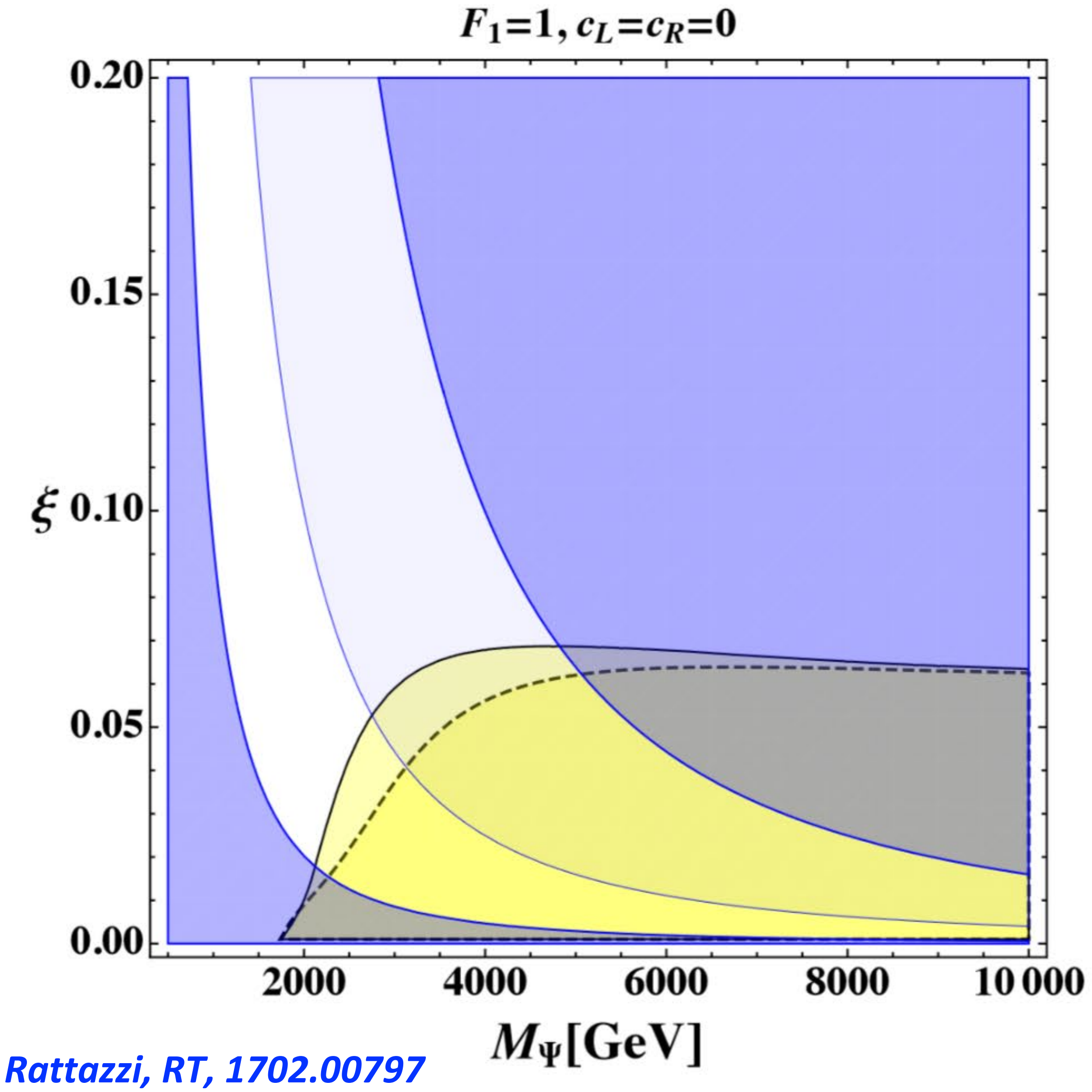
Fix all SM inputs including top and Higgs mass

$\Downarrow$

Interplay between Higgs potential and EWPO (2 site model enough to calculate)

Main effects from $\hat{S}, \hat{T}, \delta g_{Zb_Lb_L}$





Contino, Greco, Mahbubani, Rattazzi, RT, 1702.00797

Phenomenology

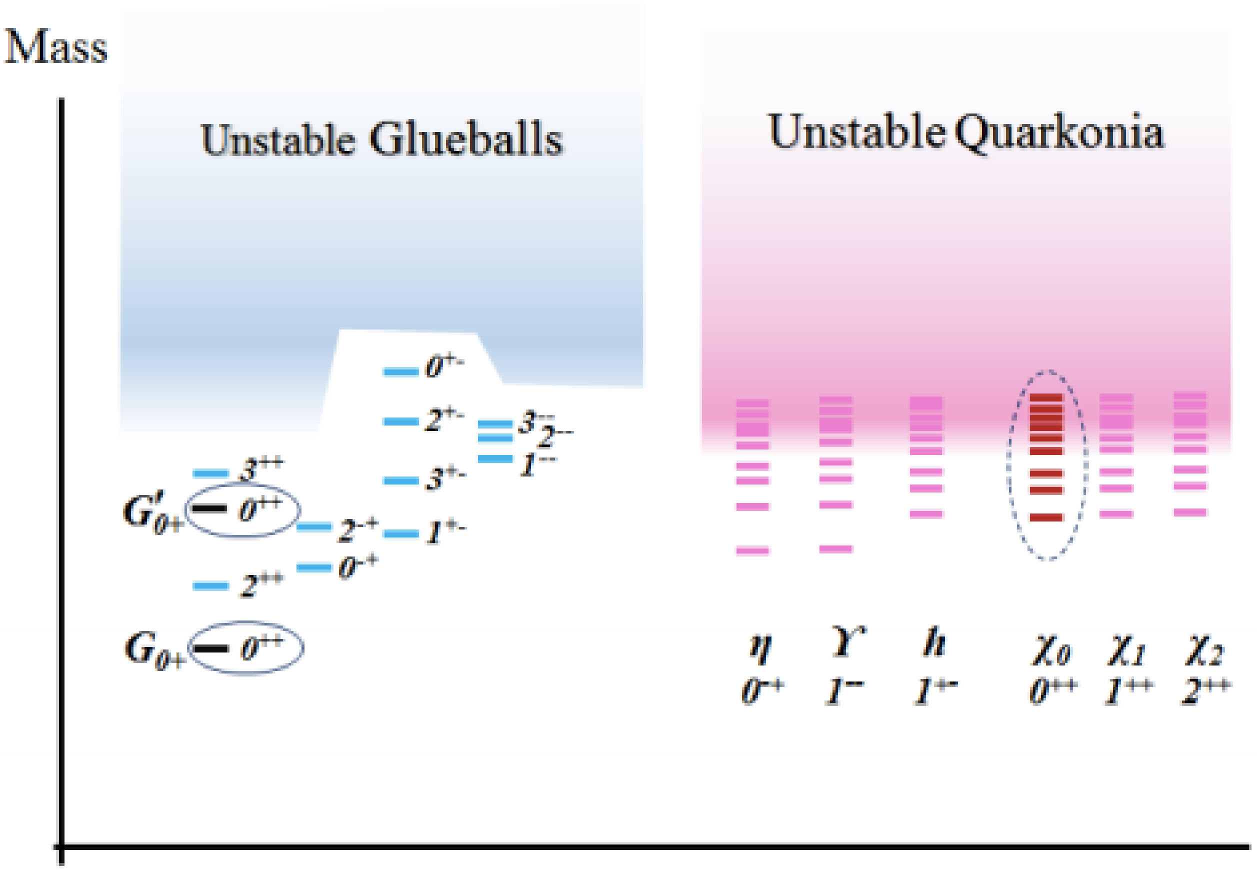
Phenomenology extremely rich and crucially depends on the value of g_* and the mechanism of Z_2 breaking

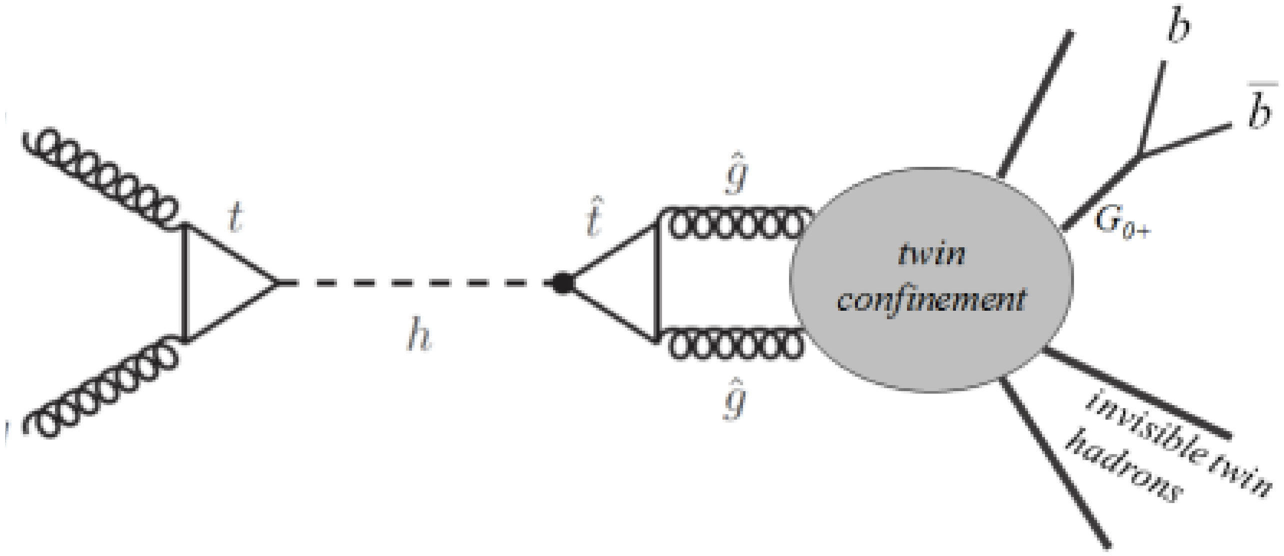
Large $\lambda_{\mathcal{H}} \sim g_*^2$ $\Longrightarrow$ strongly coupled dynamics (e.g. Composite TH)

Fraternal TH

Craig, Katz, Strassler, Sundrum, 1501.05310 [hep-ph]

- Z_2 broken in the color sector (e.g. by RG induced by different matter content)
- twin QCD has a larger confinement scale





Twin hadrons can provide dark matter candidates

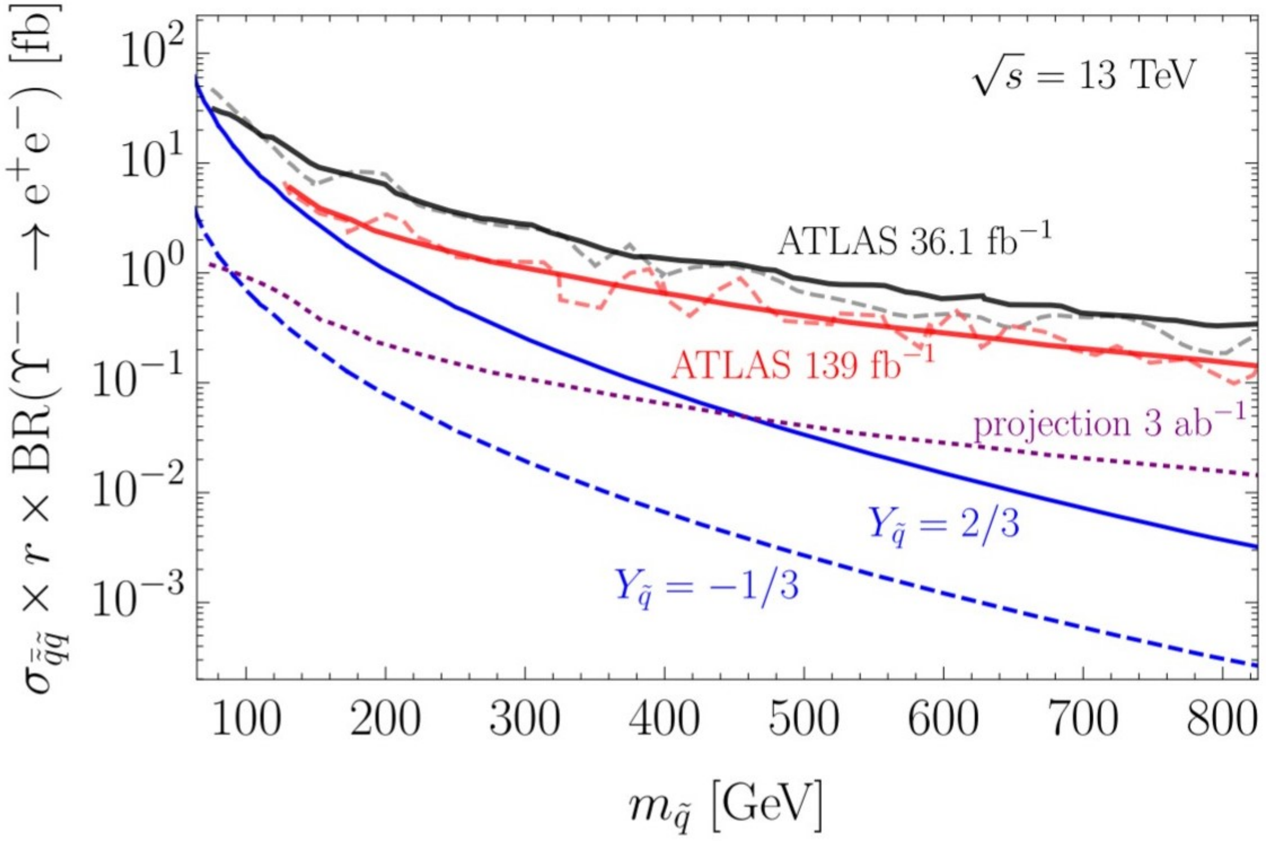
García, Lasenby, March-Russell, 1505.07109 [hep-ph], 1505.07410 [hep-ph]
Craig, Katz, 1505.07113 [hep-ph]
Farina, 1506.03520 [hep-ph]
Farina, Monteux, Shin, 1604.08211 [hep-ph]

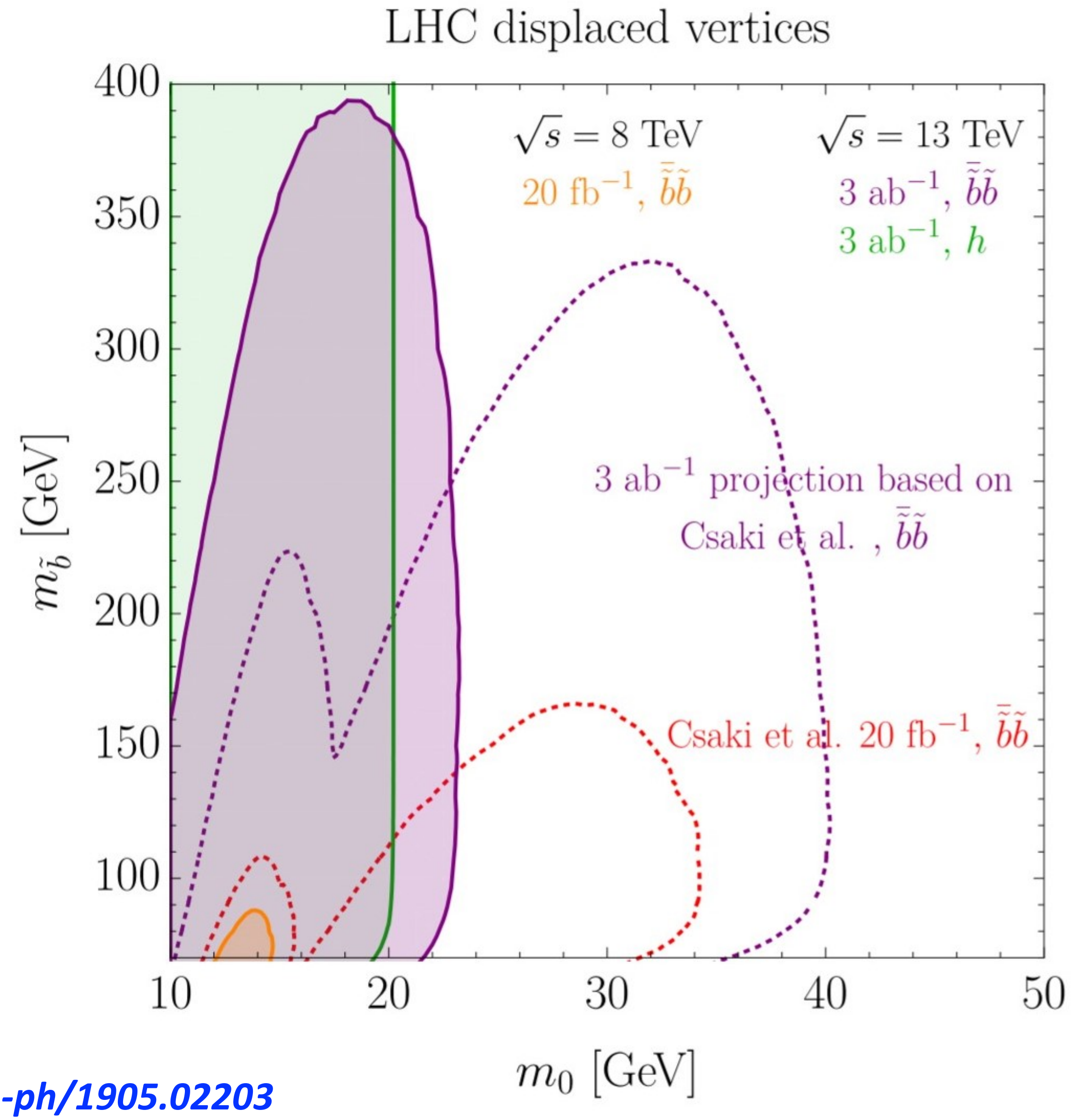
Phenomenology

Phenomenology extremely rich and crucially depends on the value of g_* and the mechanism of Z_2 breaking

Large $\lambda_{\mathcal{H}} \sim g_*^2$ $\Longrightarrow$ strongly coupled dynamics (e.g. Composite TH)

Exceptional TH





Serra, Stelzl, RT, Weiler, hep-ph/1905.02203

Conclusions

- LHC has falsified most of the best candidate BSM models addressing Naturalness
- Two approaches are possible: EFT (which becomes more and more motivated) and clever model building (that I defined Over the Top)
- In the second case Neutral Naturalness is the next theory challenge to target with experiments
- In the worst case only future colliders can really constrain these scenarios
- Many alternatives though predict interesting, spectacular, new and observable new signatures already at the LHC
- Key direct signatures are heavy scalars and displaced vertices, while indirect constraints come from EW precision measurements (also off-shell)
- HL-LHC should certainly extensively study these signatures. Despite the model building behind them is Over the Top, there is still a “picture” of new physics that deserves to be covered experimentally

THANK YOU