



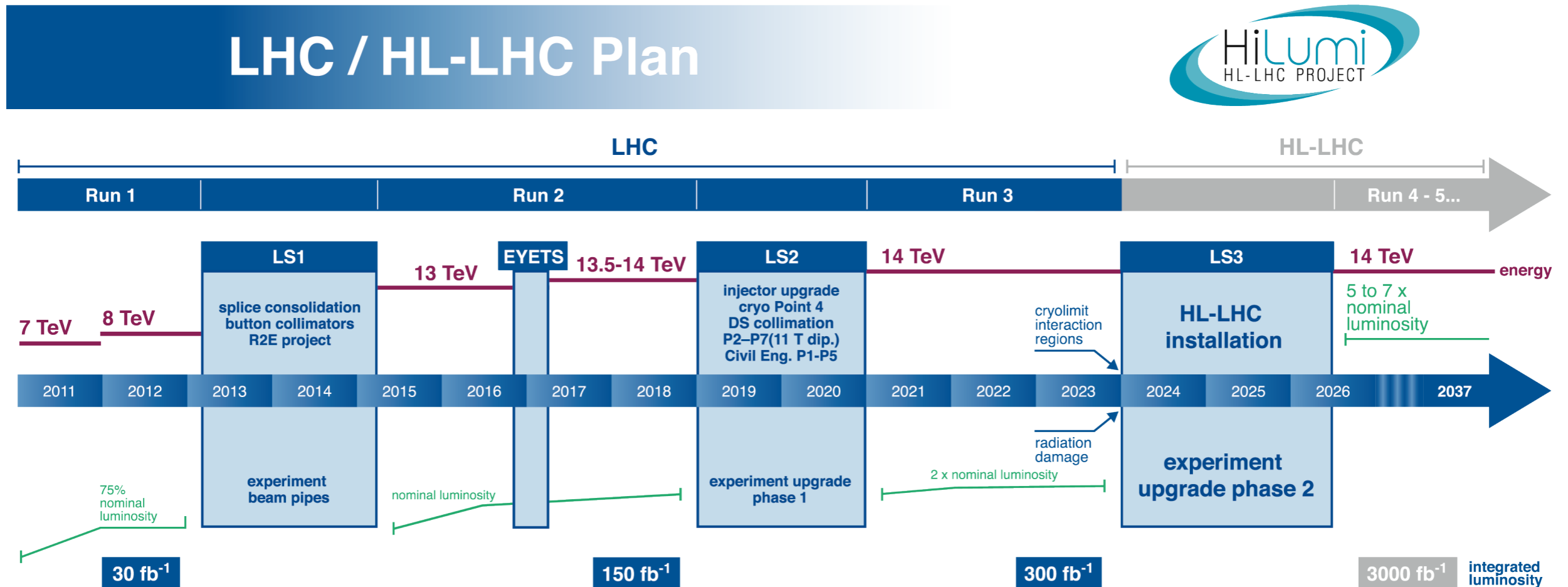
# Over the Top

Top 2019 - Beijing - 26 Sep 2019

**Riccardo Torre**  
CERN & INFN Genova



# LHC physics program



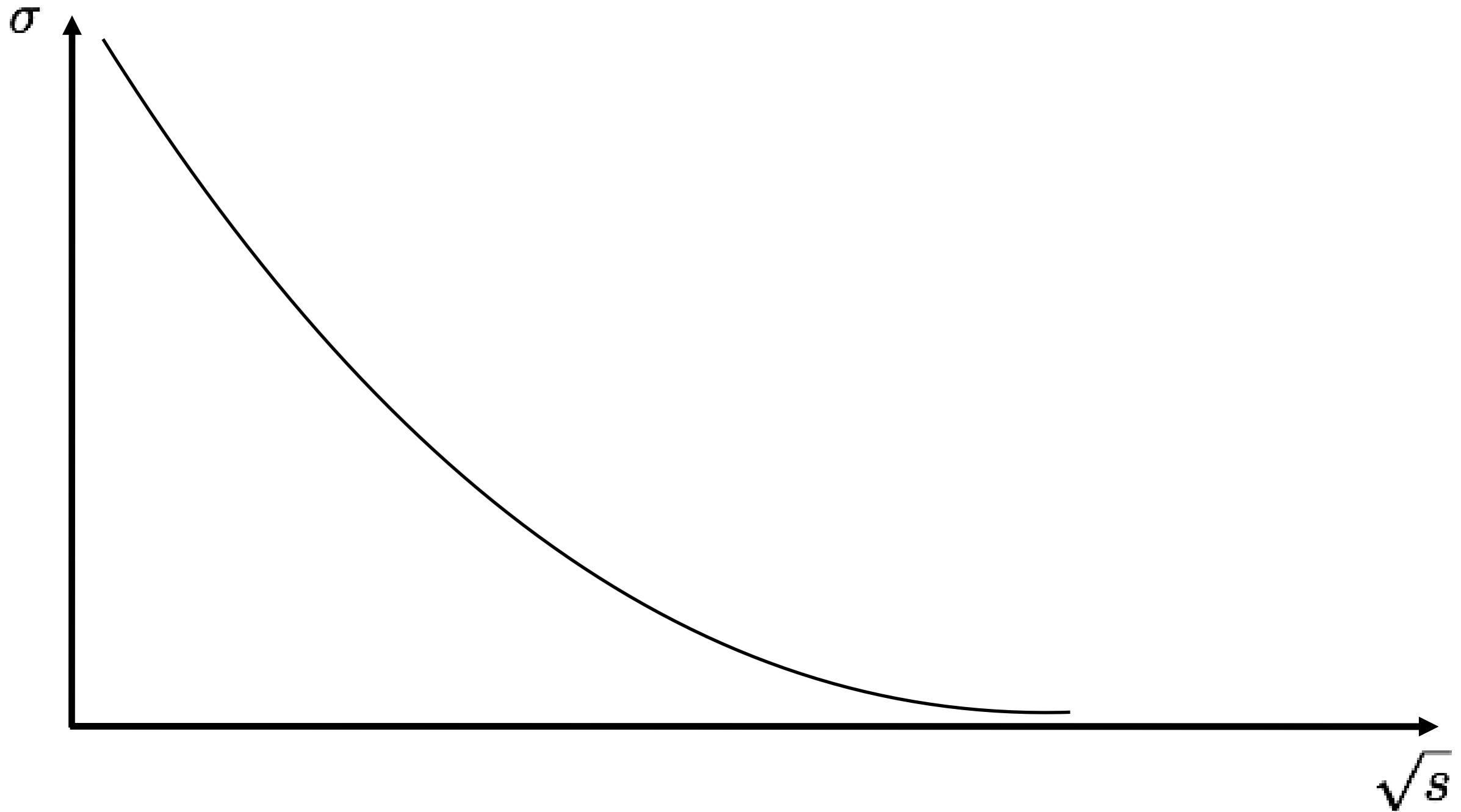
Main goal: Find signs of New Physics

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

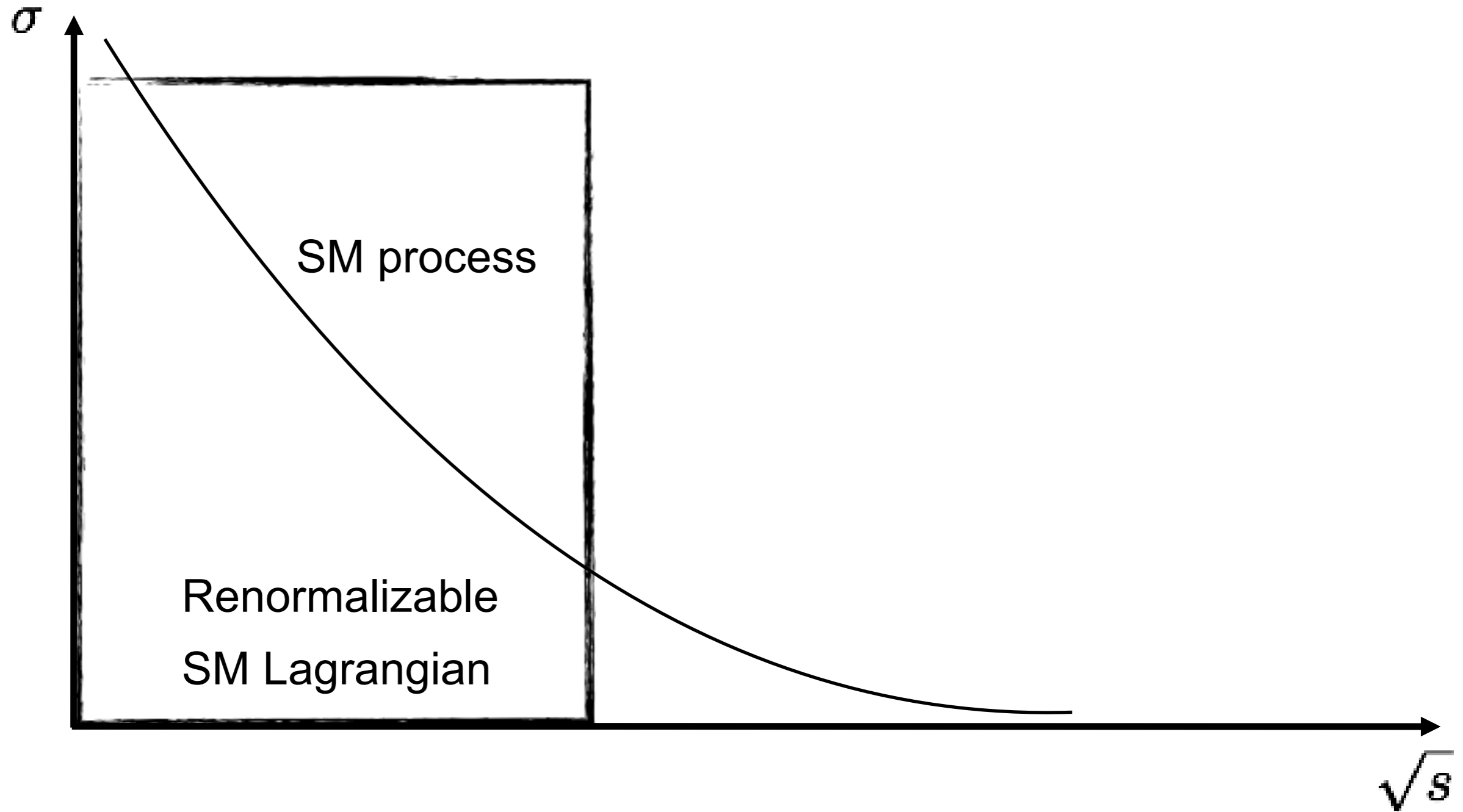
direct searches

precision physics

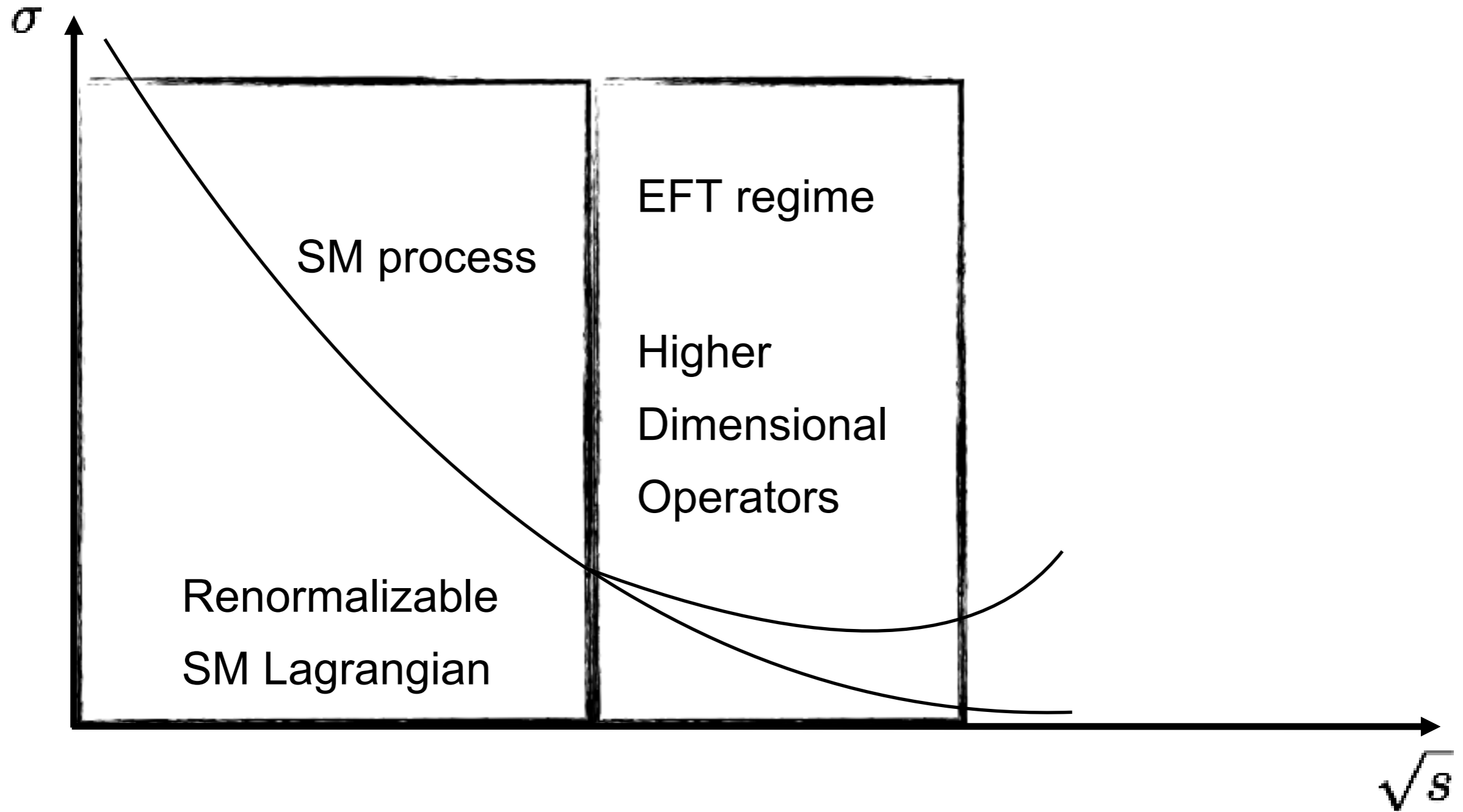
# New physics: a pictorial representation



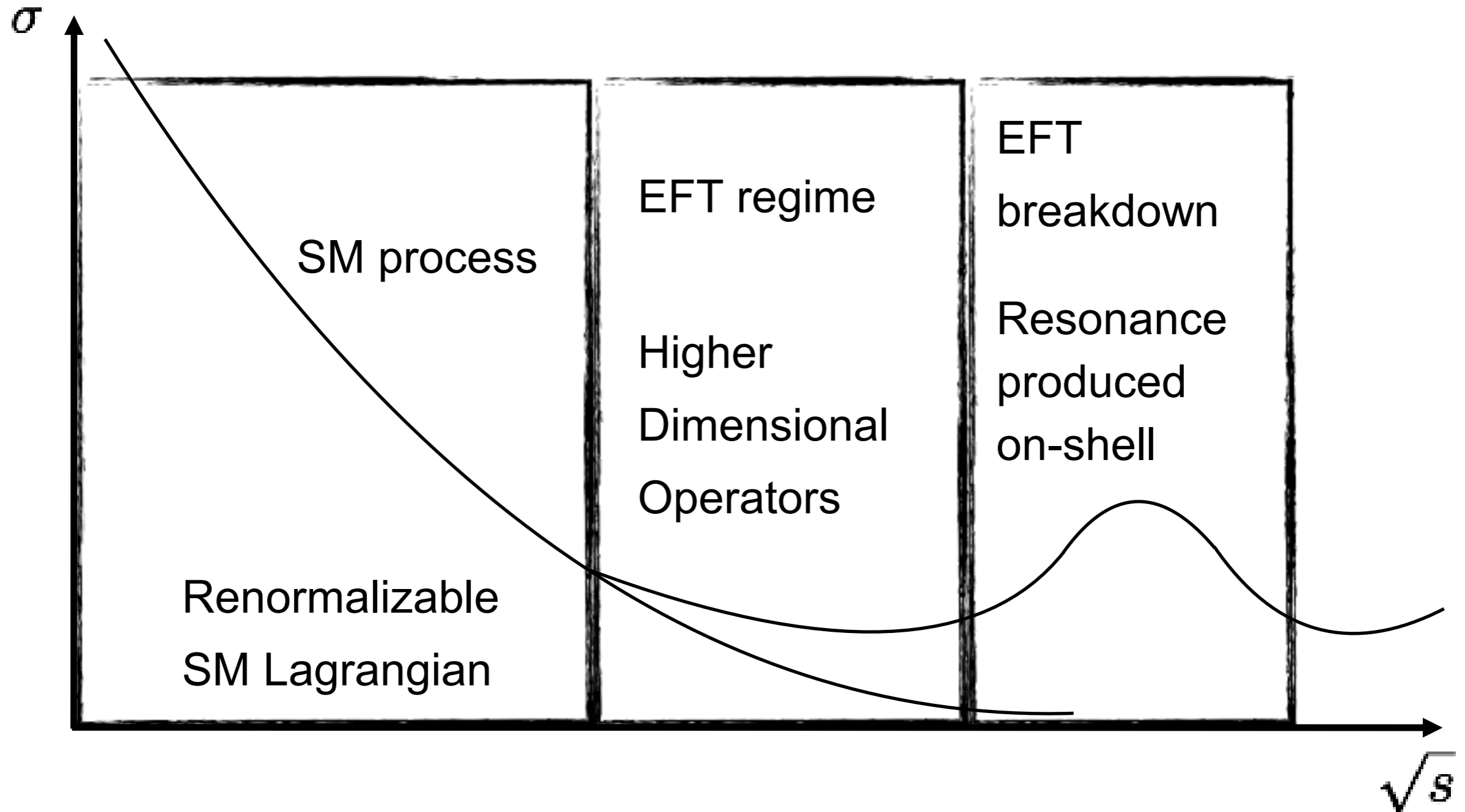
# New physics: a pictorial representation



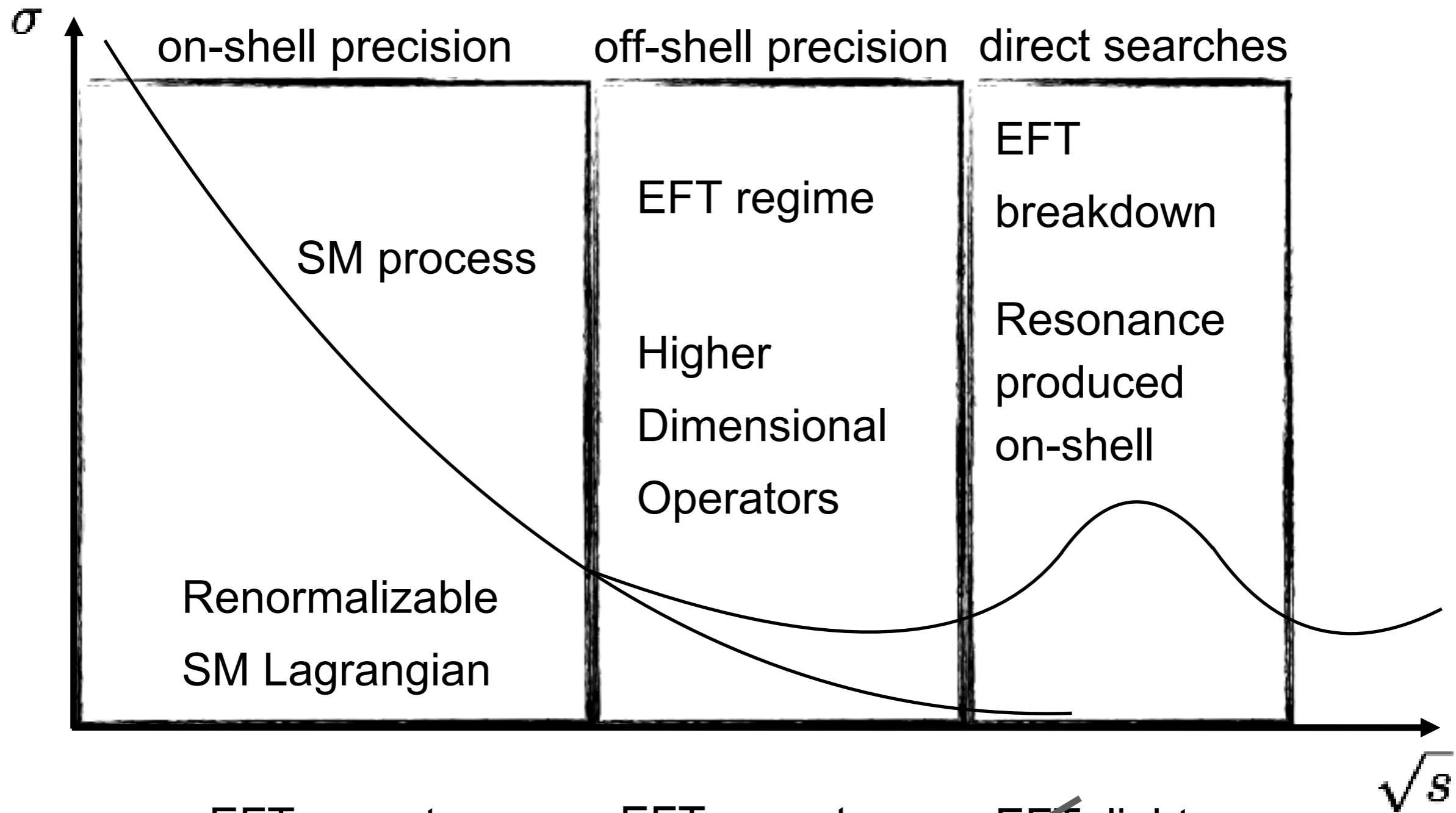
# New physics: a pictorial representation



# New physics: a pictorial representation



# New physics: a pictorial representation



Examples: EFT operators with Higgses

EFT operators with derivatives

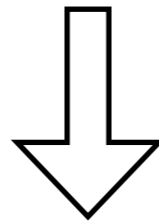
~~EFT~~: light new physics

# Naturalness in the SM

Viewing the SM as a low energy effective theory

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

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



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

numerically

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

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

ATLAS SUSY Searches\* - 95% CL Lower Limits  
July 2019

ATLAS Preliminary  
 $\sqrt{s} = 13 \text{ TeV}$

Model	Signature	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference
Inclusive Searches	$0\ e, \mu$ mono-jet	$E_{T}^{\text{miss}}$	$\tilde{g}$ [3 $\sigma$ , 8 $\sigma$ Degens]	$m(\tilde{g}) < 100 \text{ GeV}$
	$0\ e, \mu$ mono-jet	$E_{T}^{\text{miss}}$	$\tilde{g}$ [1 $\sigma$ , 8 $\sigma$ Degens]	$m(\tilde{g}) = m(\tilde{t}_1) = 5 \text{ GeV}$
	$0\ e, \mu$ mono-jet	$E_{T}^{\text{miss}}$	Forbidden	$m(\tilde{g}) < 200 \text{ GeV}$
	$0\ e, \mu$ mono-jet	$E_{T}^{\text{miss}}$	Forbidden	$m(\tilde{g}) = 900 \text{ GeV}$
3 $\nu$ gen. squarks direct production	$0\ e, \mu$ mono-jet	$E_{T}^{\text{miss}}$	Forbidden	$m(\tilde{g}) < 800 \text{ GeV}$
	$0\ e, \mu$ mono-jet	$E_{T}^{\text{miss}}$	Forbidden	$m(\tilde{g}) = m(\tilde{t}_1) = 50 \text{ GeV}$
	$0\ e, \mu$ mono-jet	$E_{T}^{\text{miss}}$	Forbidden	$m(\tilde{g}) < 400 \text{ GeV}$
	$0\ e, \mu$ mono-jet	$E_{T}^{\text{miss}}$	Forbidden	$m(\tilde{g}) = m(\tilde{t}_1) = 200 \text{ GeV}$
EW direct	$0\ e, \mu$ mono-jet	$E_{T}^{\text{miss}}$	Forbidden	$m(\tilde{g}) < 200 \text{ GeV}$
	$0\ e, \mu$ mono-jet	$E_{T}^{\text{miss}}$	Forbidden	$m(\tilde{g}) = m(\tilde{t}_1) = 300 \text{ GeV}$
	$0\ e, \mu$ mono-jet	$E_{T}^{\text{miss}}$	Forbidden	$m(\tilde{g}) < 200 \text{ GeV}$
	$0\ e, \mu$ mono-jet	$E_{T}^{\text{miss}}$	Forbidden	$m(\tilde{g}) = m(\tilde{t}_1) = 300 \text{ GeV}$
Long-lived particles	Direct $\tilde{t}_1 \tilde{t}_1^*$ prod., long-lived $\tilde{t}_1^*$	Disapp. trk	$\tilde{t}_1^*$	$m(\tilde{t}_1^*) < 100 \text{ GeV}$
	Stable $\tilde{g}$ R-hadron	Multiple	$\tilde{g}$	$m(\tilde{g}) < 100 \text{ GeV}$
	Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow q\tilde{q}^*$	Multiple	$\tilde{g}$	$m(\tilde{g}) < 100 \text{ GeV}$
	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow q\ell\tau\mu\tau$	$q\ell, \tau\mu, \tau$	$\tilde{\nu}_\tau$	$m(\tilde{\nu}_\tau) < 100 \text{ GeV}$

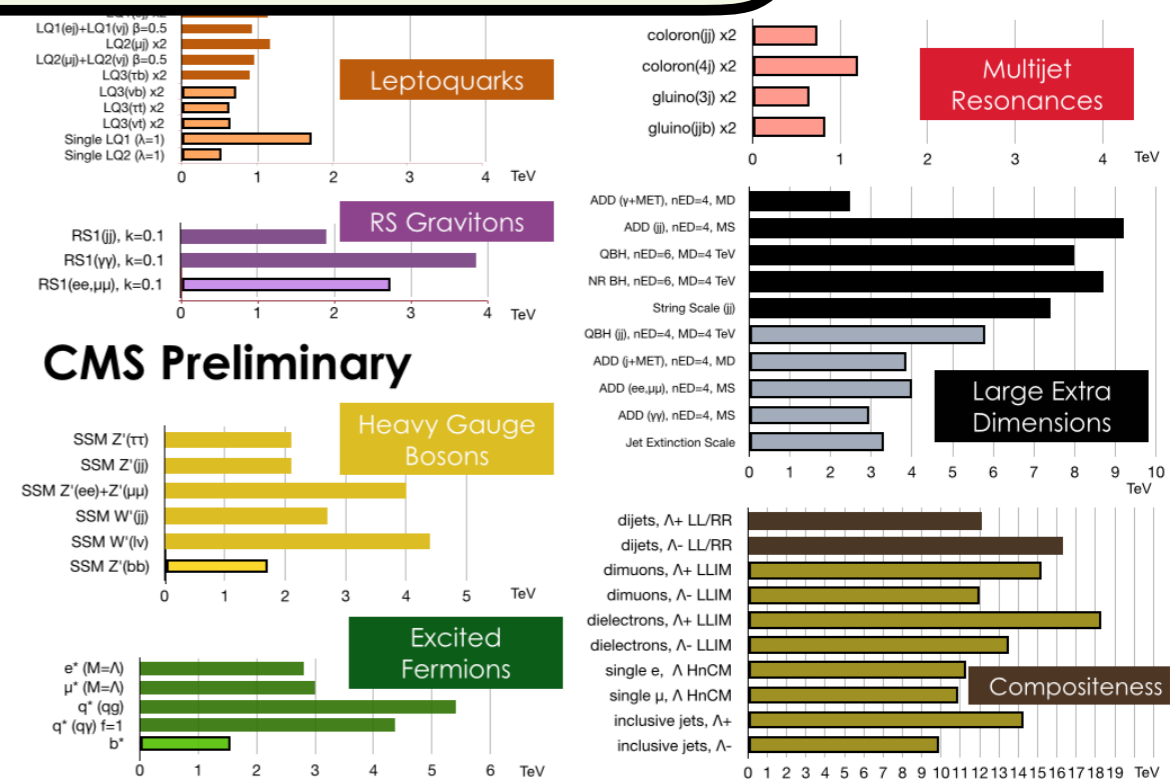
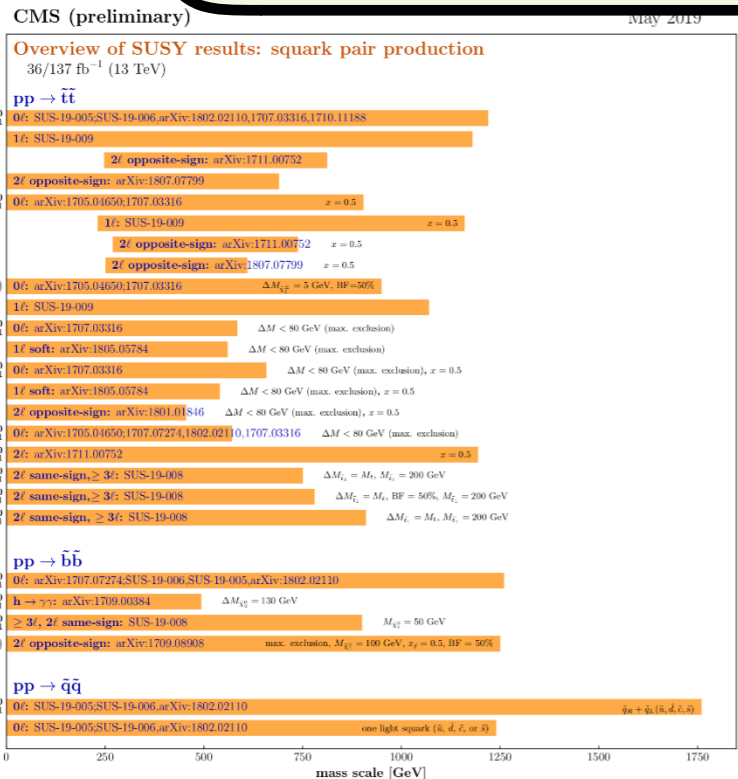
\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

ATLAS Exotics Searches\* - 95% CL Upper Exclusion Limits  
Status: May 2019

ATLAS Preliminary  
 $\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$   
 $\sqrt{s} = 8, 13 \text{ TeV}$

Model	$\ell, \gamma$	Jets	$E_{T}^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu$	$1-4\ j$	Yes	$M_{\text{Pl}}$	$n=2$
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	$-$	$-$	$M_{\text{Pl}}$	$n=3$ HLZ NLO
	ADD QBH	$2\ j$	$-$	$-$	$M_{\text{Pl}}$	$n=6$
	ADD BH high $\Sigma p_T$	$\geq 1\ e, \mu$	$\geq 2\ j$	$-$	$M_{\text{Pl}}$	$n=6, M_{\text{Pl}} = 3 \text{ TeV}$ , rot BH
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2\ e, \mu$	$-$	$-$	$Z'$ mass	$n=2$
	SSM $Z' \rightarrow \tau\tau$	$2\ \tau$	$-$	$-$	$Z'$ mass	$n=2$
	Leptophobic $Z' \rightarrow bb$	$2\ b$	$-$	$-$	$Z'$ mass	$n=2$
	SSM $W' \rightarrow \ell\nu$	$1\ e, \mu$	$\geq 1\ b, \geq 1\ Q/2$	Yes	$W'$ mass	$f/m = 1\%$
CI	CI $q\bar{q}q$	$-$	$2\ j$	$-$	$A$	$n=2$
	CI $\ell\ell q$	$2\ e, \mu$	$-$	$-$	$A$	$n=2$
	CI $\ell\ell q$	$2\ e, \mu$	$\geq 1\ b, \geq 1\ j$	Yes	$A$	$n=2$
	CI $\ell\ell q$	$2\ e, \mu$	$-$	$-$	$A$	$n=2$
DM	Axial-vector mediator (Dirac DM)	$0\ e, \mu$	$1-4\ j$	Yes	$m_{\text{DM}}$	$\tilde{g}_s = 0.25, \tilde{g}_b = 1.0, m(\tilde{g}) = 1 \text{ GeV}$
	Colored scalar mediator (Dirac DM)	$0\ e, \mu$	$1-4\ j$	Yes	$M_{\text{DM}}$	$\tilde{g}_s = 1.0, m(\tilde{g}) = 1 \text{ GeV}$
	$V_{\ell\ell}$ EFT (Dirac DM)	$0\ e, \mu$	$1, 2, 3, 4\ j$	Yes	$M_{\text{DM}}$	$m(\tilde{g}) < 150 \text{ GeV}$
	Scalar reson. $\phi \rightarrow \tau\tau$ (Dirac DM)	$0\ e, \mu$	$1, b, 0-1\ j$	Yes	$M_{\text{DM}}$	$\gamma = 0.4, \lambda = 0.2, m(\tilde{g}) = 10 \text{ GeV}$
LO	Scalar LQ 1 $^{st}$ gen	$1, 2\ e, \mu$	$\geq 2\ j$	Yes	$LQ$ mass	$\beta = 1$
	Scalar LQ 2 $^{nd}$ gen	$1, 2\ e, \mu$	$\geq 2\ j$	Yes	$LQ$ mass	$\beta = 1$
	Scalar LQ 3 $^{rd}$ gen	$2\ \tau$	$2\ b$	$-$	$LQ$ mass	$\beta(LQ_2 \rightarrow b\tau) = 1$
	Scalar LQ 3 $^{rd}$ gen	$0-1\ e, \mu$	$2\ b$	Yes	$LQ$ mass	$\beta(LQ_2 \rightarrow \tau\tau) = 0$
Heavy quarks	VLQ $TT \rightarrow H_t/Z_t/W_t + X$	$0\ e, \mu$	$1-4\ j$	Yes	$T$ mass	SM(2) doublet
	VLQ $BB \rightarrow W_t/Z_t + X$	$0\ e, \mu$	$1-4\ j$	Yes	$T$ mass	SM(2) doublet
	VLQ $T_{313} T_{313} \rightarrow W_t + X$	$2(SS) \geq 3\ e, \mu \geq 1\ b, \geq 1\ j$	Yes	$36.1$	$T_{313}$ mass	$\beta(T_{313} \rightarrow W_t) = 1, c(T_{313} W_t) = 1$
	VLQ $Y \rightarrow W_b + X$	$1\ e, \mu$	$\geq 1\ b, \geq 1\ j$	Yes	$36.1$	$\beta(Y \rightarrow W_b) = 1, c(Y W_b) = 1$
Excited fermions	Excited quark $q^* \rightarrow qg$	$-$	$2\ j$	$-$	$q^*$ mass	only $u^*$ and $d^*$ , $A = m(q^*)$
	Excited quark $q^* \rightarrow q\gamma$	$1\ \gamma$	$1\ j$	$-$	$q^*$ mass	only $u^*$ and $d^*$ , $A = m(q^*)$
	Excited quark $b^* \rightarrow b\gamma$	$-$	$1\ b, 1\ j$	$-$	$b^*$ mass	$A = 3.0 \text{ TeV}$
	Excited quark $b^* \rightarrow b\gamma$	$-$	$1\ b, 1\ j$	$-$	$b^*$ mass	$A = 1.0 \text{ TeV}$

And yet nothing!





The new theorists are like Sylvester Stallone

# Soft, supersoft, hypersoft

## Charged Naturalness

### Soft models

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

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

### Supersoft models

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

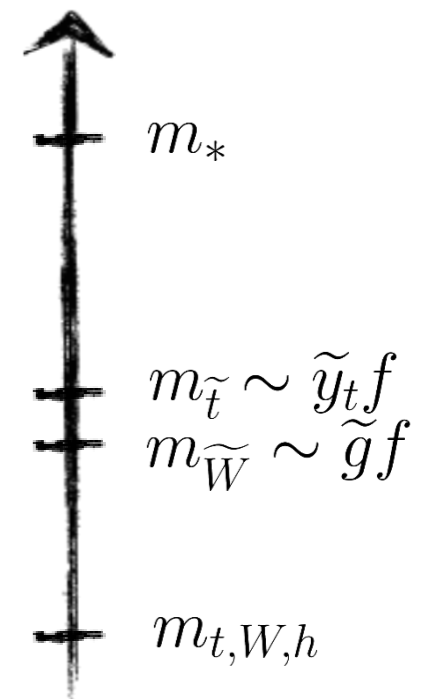
- e.g. MSSM with low scale mediation and composite models
- probed at the LHC
- moderate tuning

## Neutral Naturalness

### Hypersoft models

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

- 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

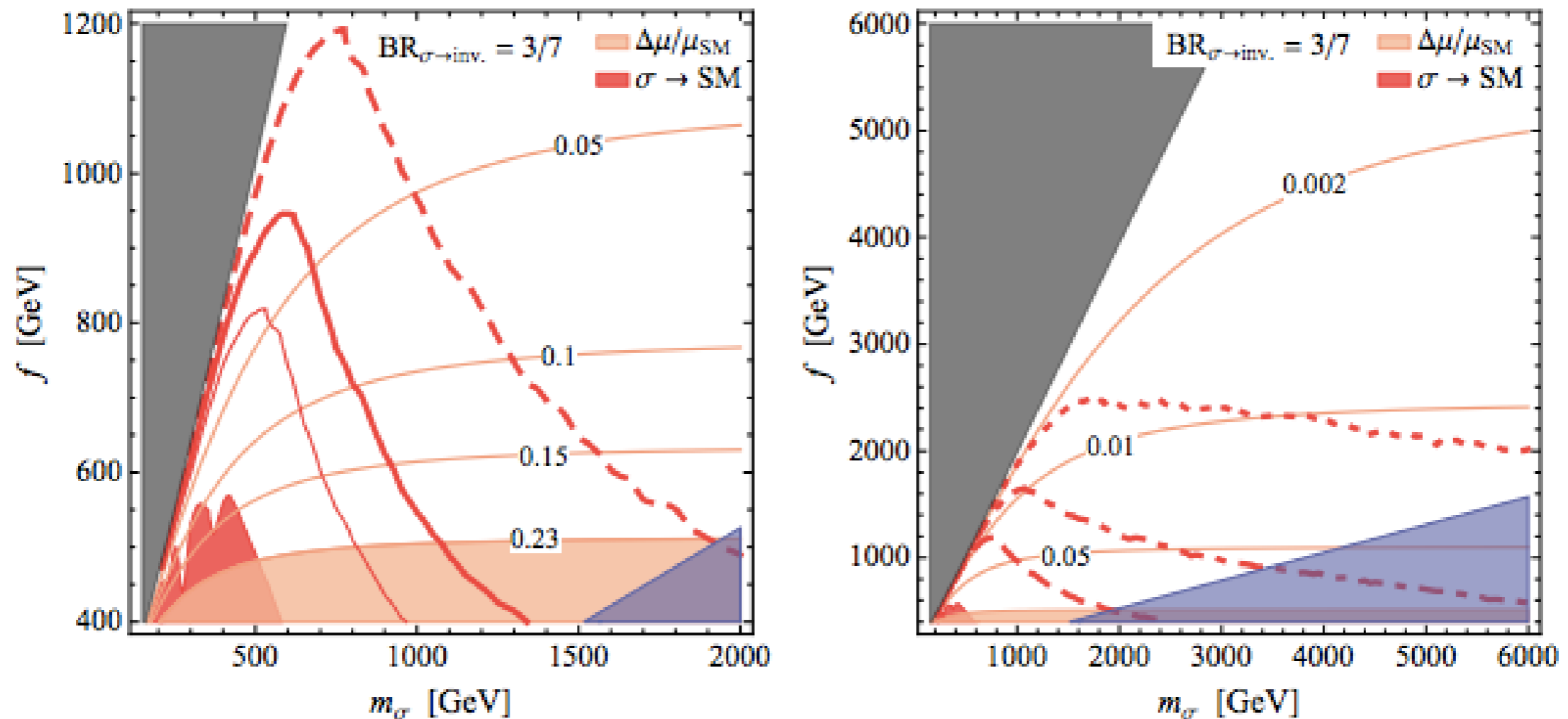
- The lightest new physics states (those tight to naturalness, i.e. to the top and the EW sector) are SM neutral or only carry SU(2) and/or U(1) charges
- Extended scalar sector (e.g. heavy singlet Higgs) and heavy  $Z'$  vector bosons
- Coupling of the new sector to the SM one is typically only mediated 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  $\lambda_*$  and the mechanism of  $Z_2$  breaking

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

Main prediction is an extended scalar sector (radial mode)



**Figure 10.** Model with  $BR_{\sigma \rightarrow inv.} = 3/7$ . 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  $\lambda_*$  and the mechanism of  $Z_2$  breaking

**Large**  $\lambda_{\mathcal{H}} \sim g_*^2 \implies$  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



hardest to test at LHC

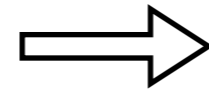
need FCC-ee/CEPC/ILC/CLIC to test Higgs couplings

and/or

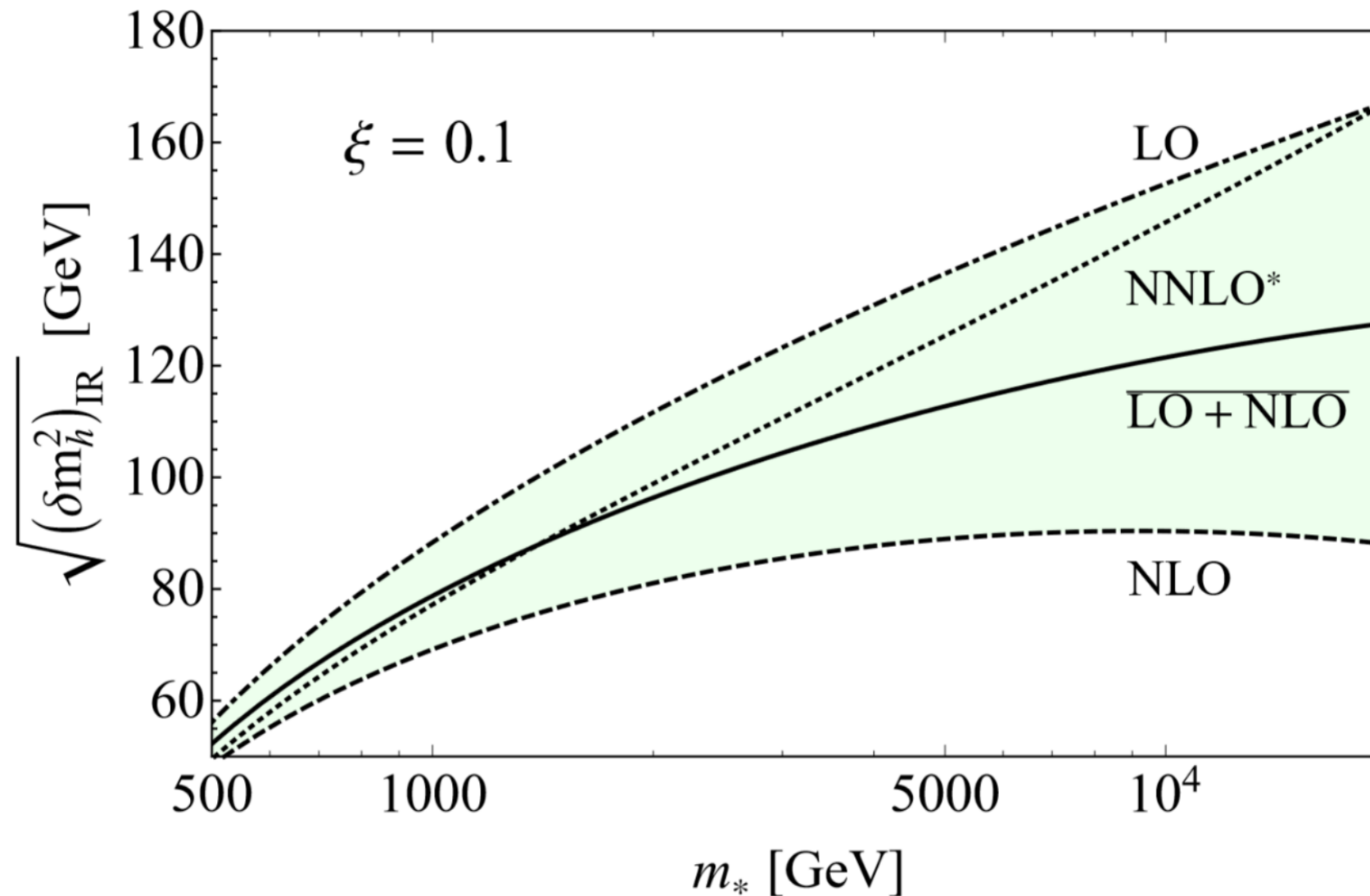
FCC-hh/SppC to access spectrum of resonances

# 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)



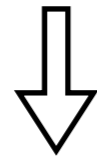
*NLL: Contino, Greco, Mahubani, Rattazzi, RT, 1702.00797*



# Higgs potential vs EWPO

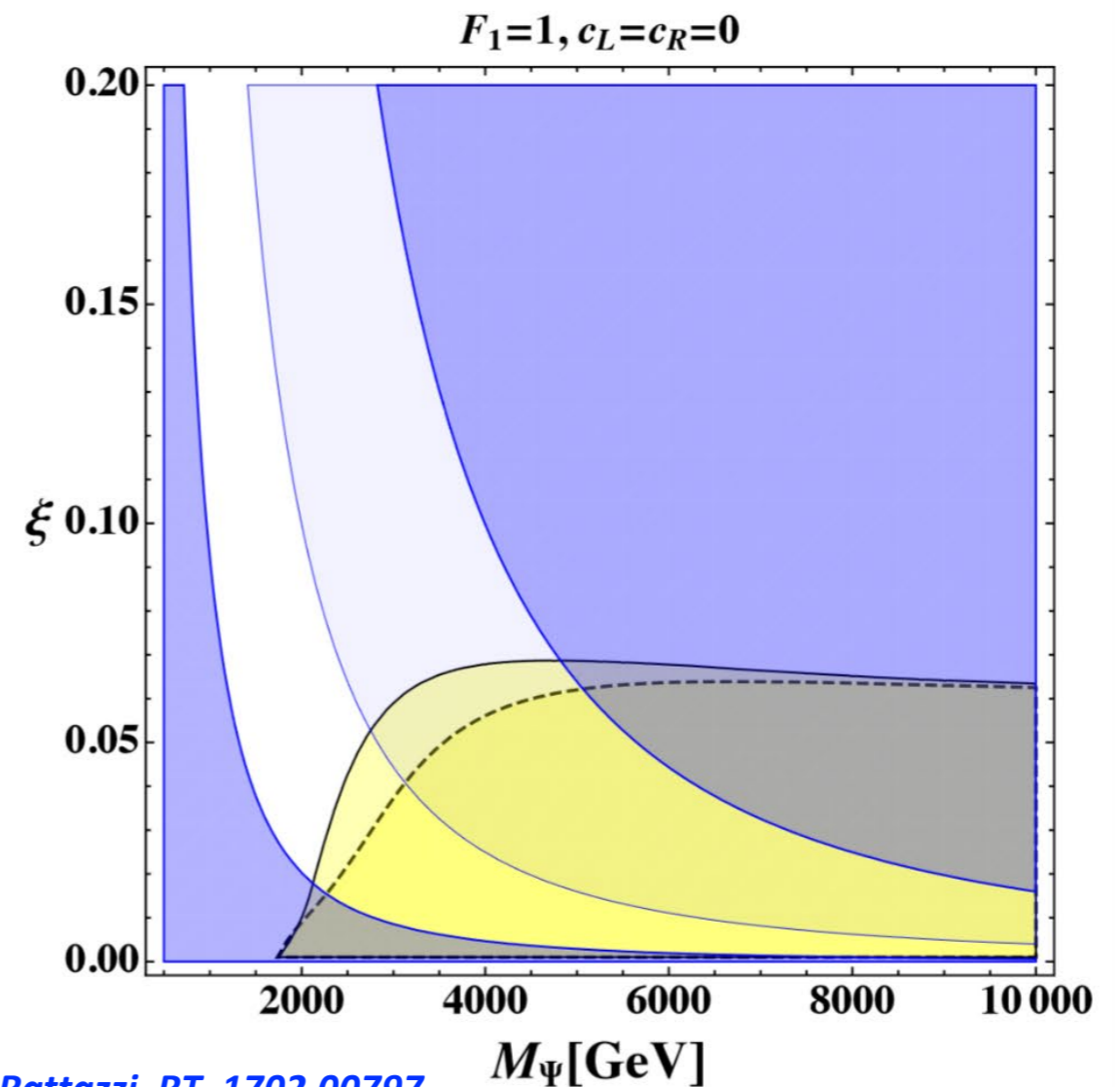
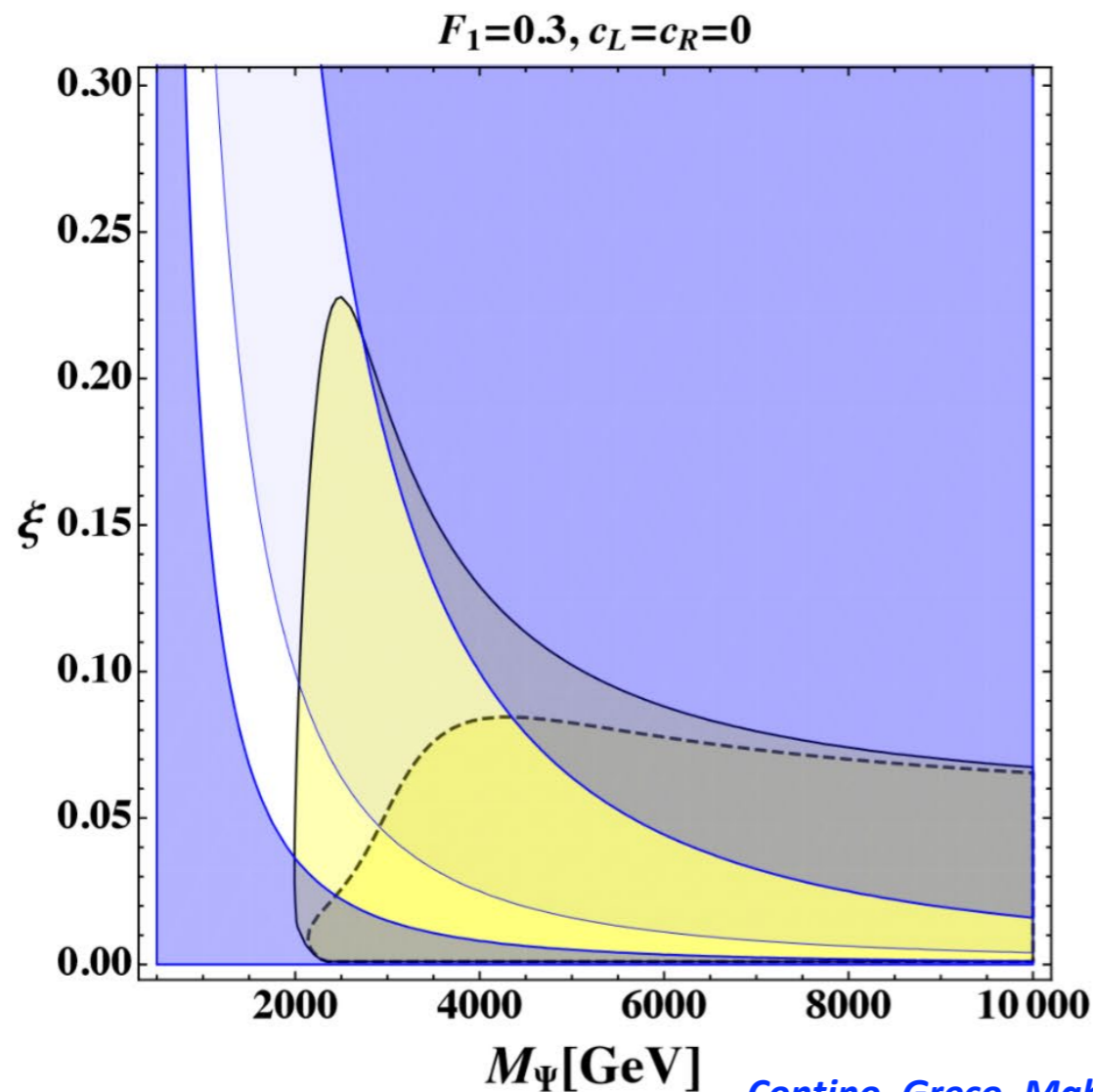
Fix UV contribution to the Higgs mass

Fix all SM inputs including top and Higgs mass



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

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



*Contino, Greco, Mahubani, Rattazzi, RT, 1702.00797*

# Phenomenology

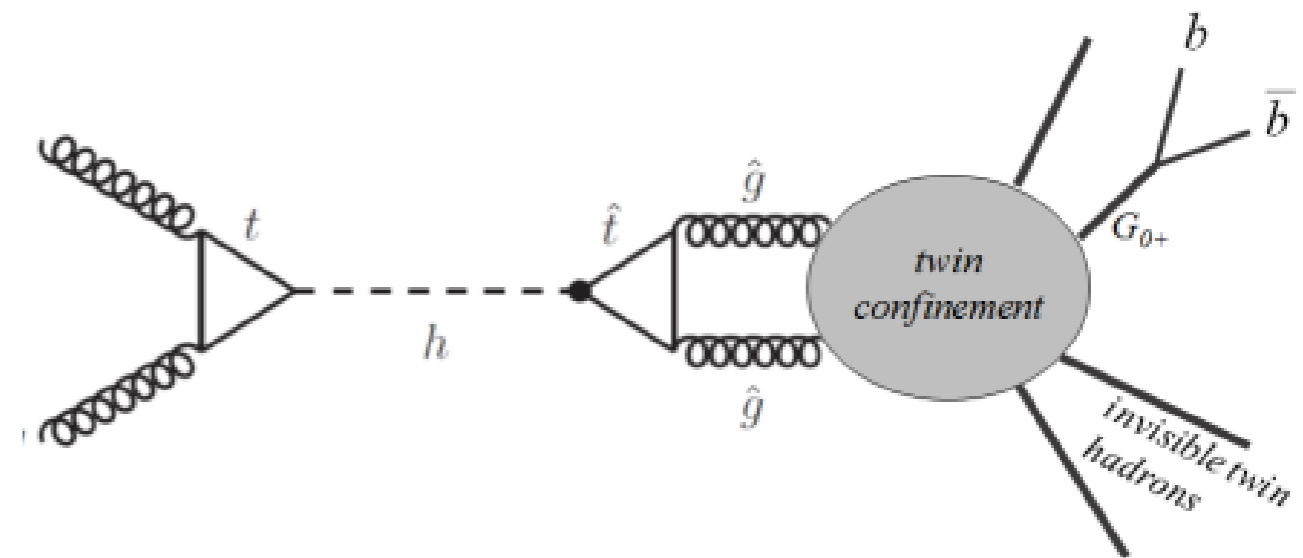
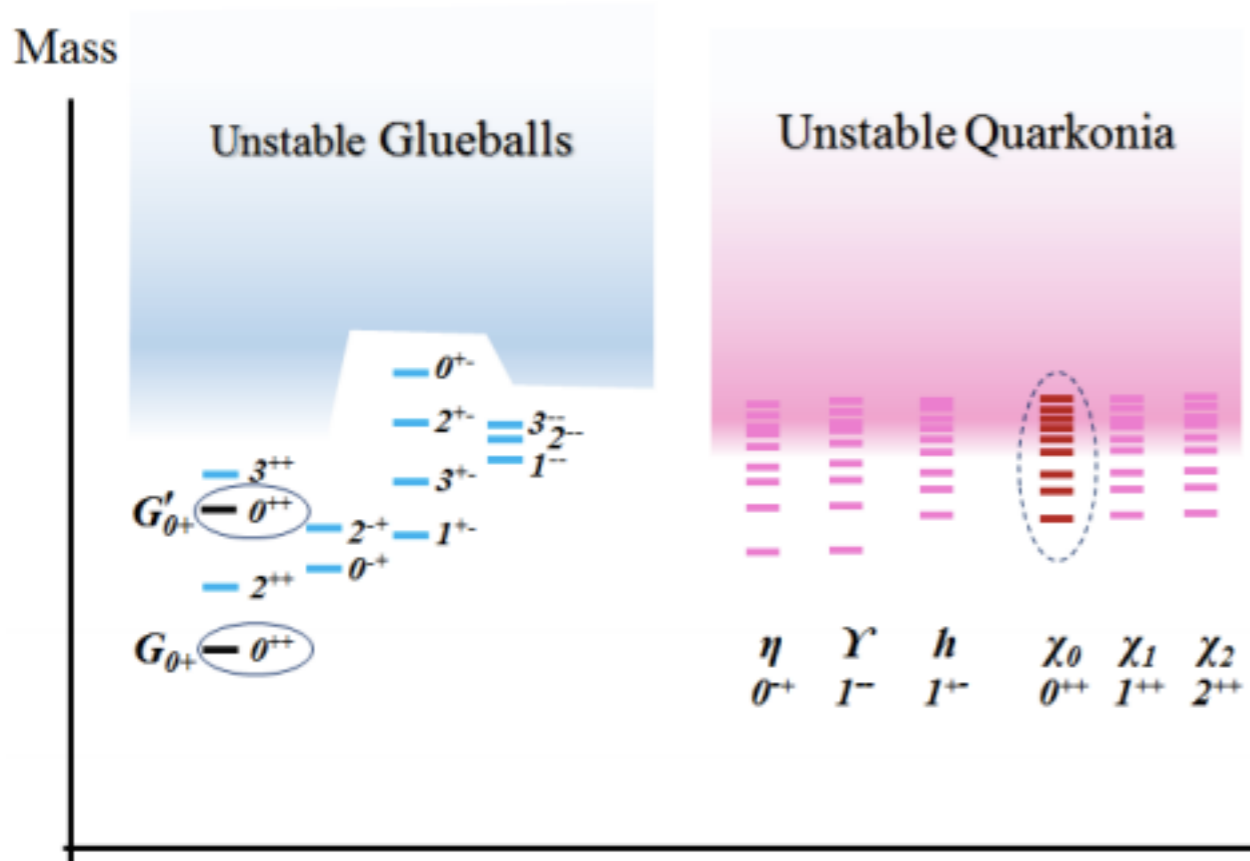
Phenomenology extremely rich and crucially depends on the value of  $g_*$  and the mechanism of  $Z_2$  breaking

**Large**  $\lambda_{\mathcal{H}} \sim g_*^2 \implies$  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]*

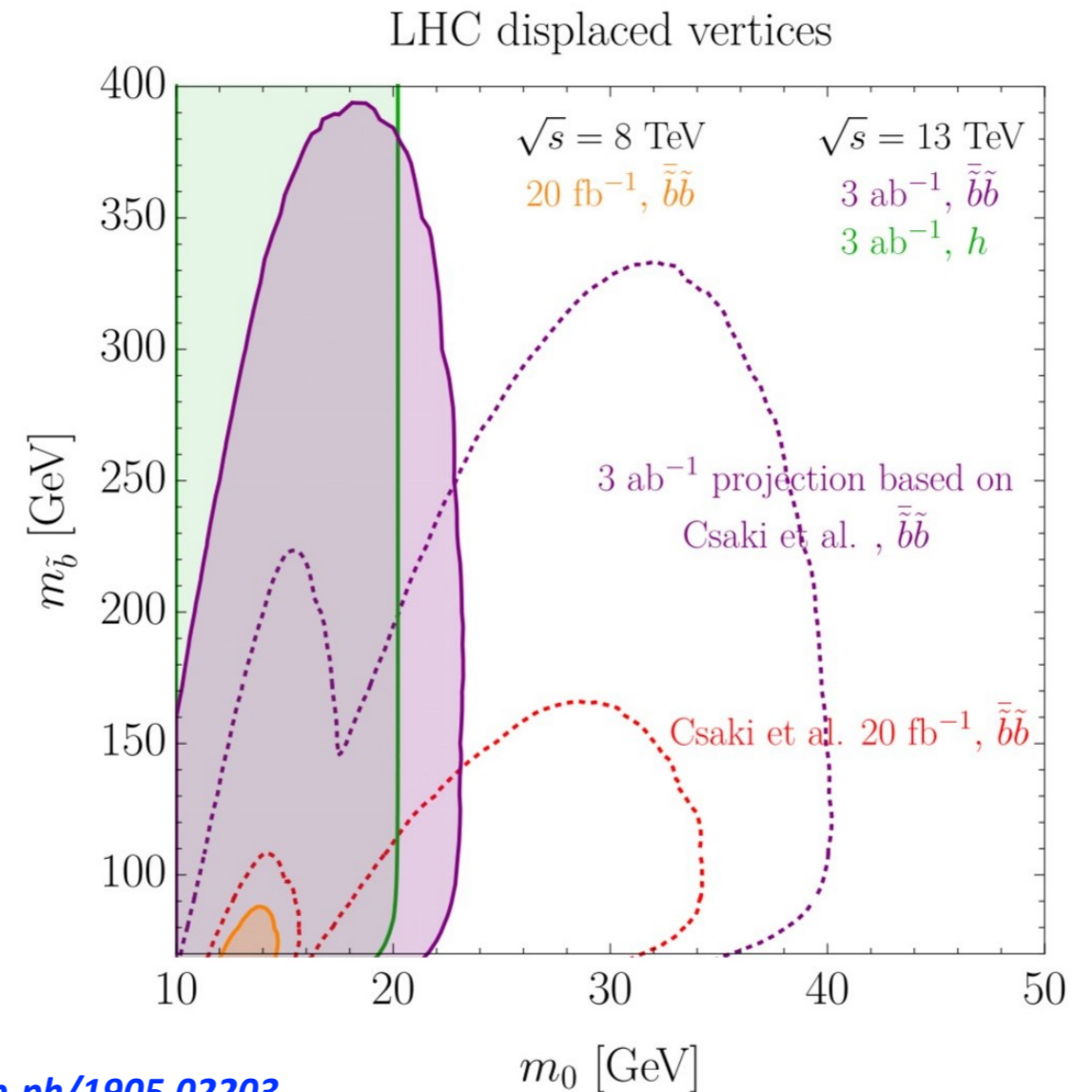
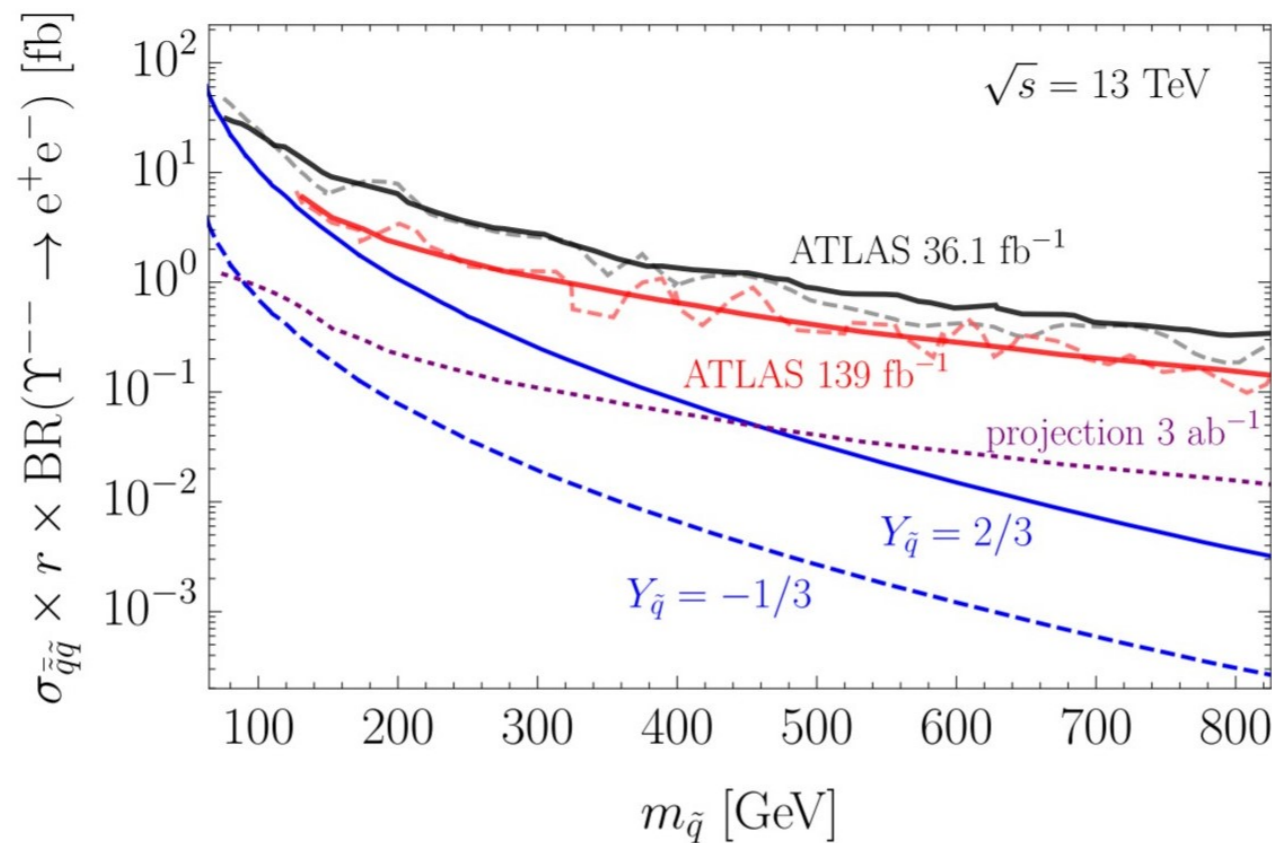
*Farina, Monteux, Shin, 1604.08211 [hep-ph]*

# Phenomenology

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

**Large  $\lambda_{\mathcal{H}} \sim g_*^2 \implies$**  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