The Search for Physics Beyond the Standard Model

A Theorist Perspective

Gustavo Burdman

University of São Paulo, Brazil

TeVPA 2023, Napoli

IFUSP
Instituto de Física da USP

FAPESP

Outline

- The standard model of particle physics: the good
- The SM of particle physics: the bad and the ugly
- What do BSM searches imply ?
- BSM without New Particles: the transition from energy to precision
- Testing the Higgs sector at the LHC and beyond
- Making connections: the Higgs, Dark Matter and beyond
- Conclusions and Outlook

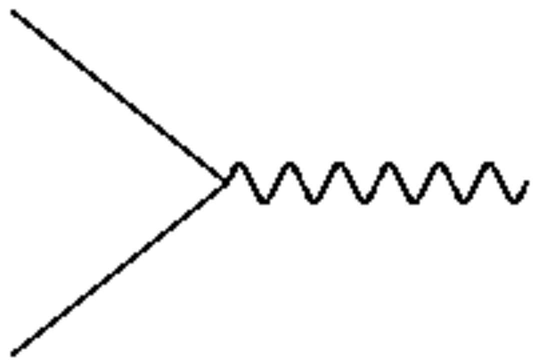
The Standard Model: The Good

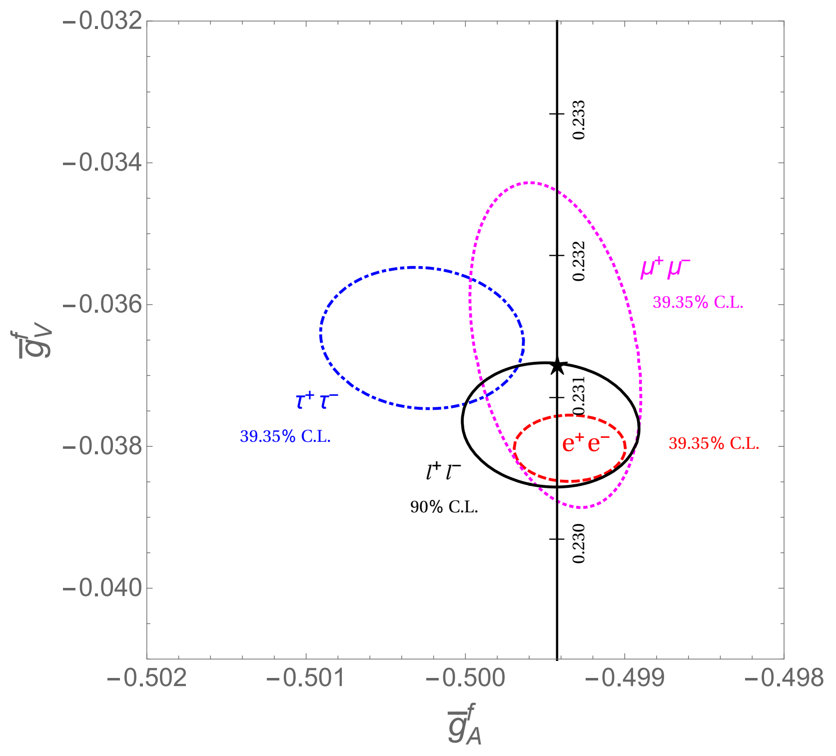
The SM is a gauge theory $SU(3)\times SU(2)_L \times U(1)_Y$

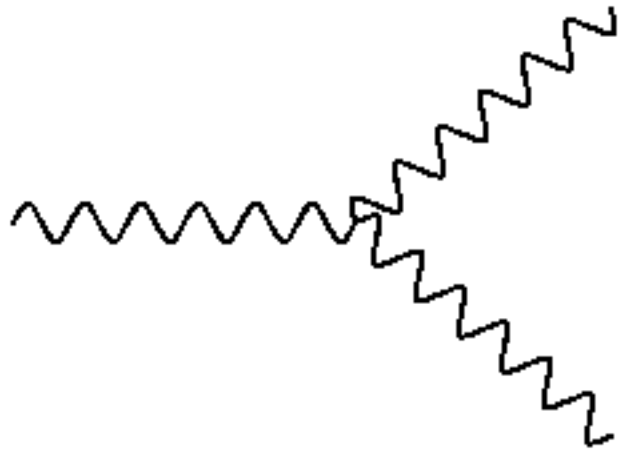
with O(1) dimensionless couplings $\underbrace{g_3}_{\text{Strong}} \quad \underbrace{g_2 \quad g_1}_{\text{Electroweak}}$

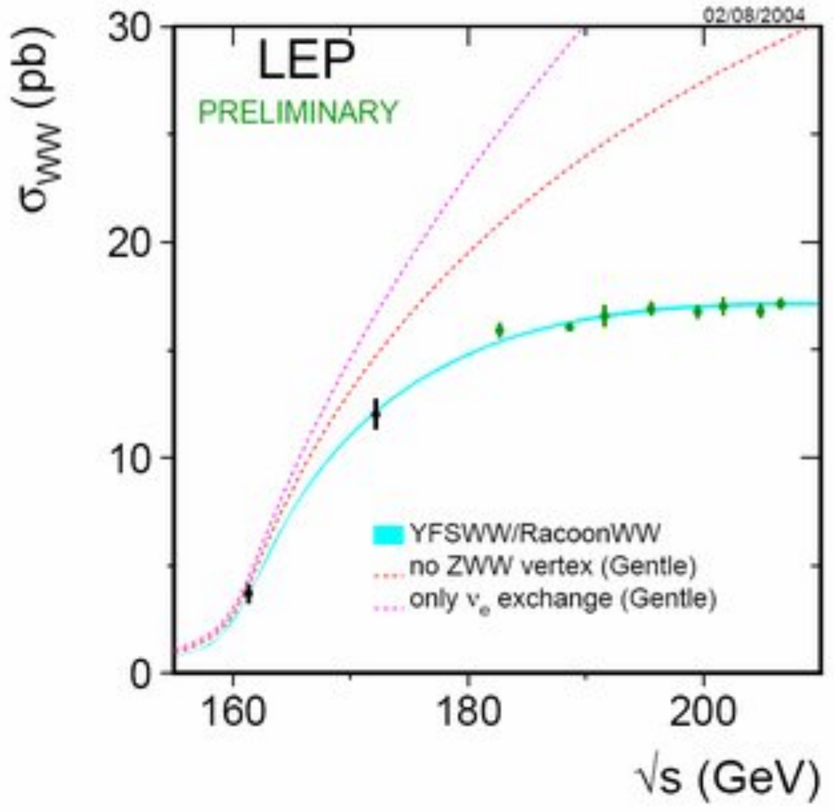
- Built with the input from experimental observations
- Some fermions feel the strong interactions (quarks). I.e. they transform under $SU(3)$
- All SM fermions transform under the electroweak gauge group $SU(2)_L \times U(1)_Y$
- It describes all the (gauge) interactions of all elementary particles

Gauge interactions tested with great precision at LEP, Tevatron, LHC, …









The Higgs Sector of the Standard Model

- Gauge invariance in the $\mathscr{L}_{\rm SM}$ *forbids* mass terms ! $\Rightarrow$ Massless gauge bosons and fermions!
- Masses in $\mathscr{L}_{\rm SM}$ break gauge invariance *explicitly*
- Introduce a scalar sector to spontaneously break the electroweak symmetry

$$SU(2)_L \times U(1)_Y \longrightarrow U(1)_{\rm EM} \qquad M_{W^\pm}, M_{Z^0} \neq 0 \quad M_\gamma = 0$$

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$ scalar $SU(2)_L$ doublet with $Y_\Phi = \frac{1}{2}$ Higgs doublet

Non-trivial minimum of $V(\Phi^\dagger\Phi) = -\, m^2\,(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$ $\Rightarrow$ $m_h = \sqrt{2}m = \sqrt{2\lambda}\,{\rm v}$

Experimentally $m_h \simeq 125~{\rm GeV}, \quad v \simeq 246~{\rm GeV}$

$\Rightarrow$ $m \simeq 89~{\rm GeV}$ is the one and only energy scale in all of $\mathscr{L}_{\rm SM}$!

(Only scale in fundamental physics together with $M_{\rm P}$ and $\Lambda_{\rm CC}$)

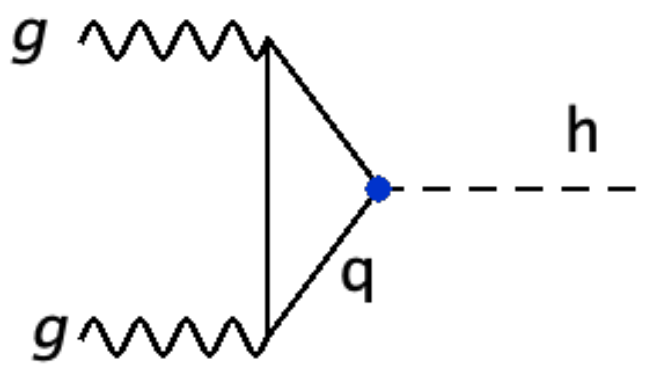
Higgs Couplings

To fermions

$$\lambda_f \, \bar{\psi}_L \psi_R + \text{h.c.}$$

with $$\lambda_f = \frac{\sqrt{2}\, m_f}{v}$$

- λ_t enters in production through ggF loop



and $t\bar{t}h$

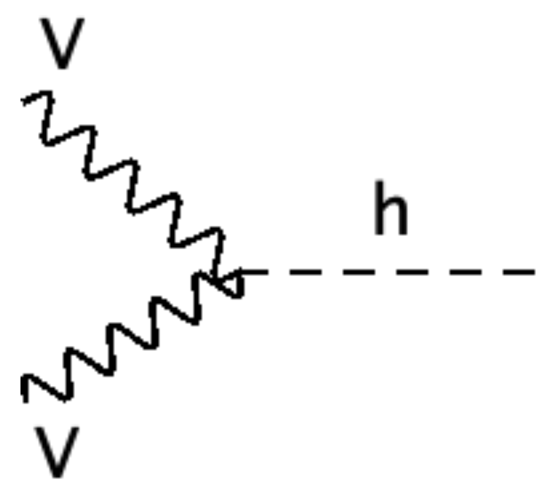
- λ_b ggF+VH+$t\bar{t}h$
- λ_τ VH+VBF+ggF
- λ_μ ggF+VBF

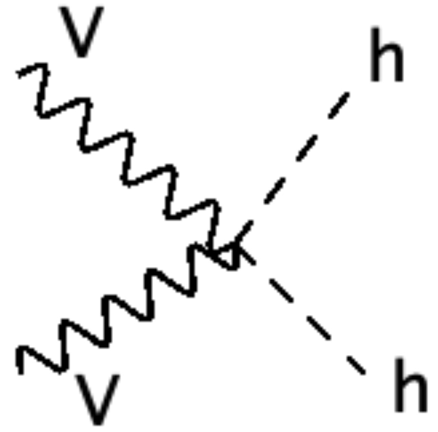
To gauge bosons

$$g_{hWW} = \frac{2M_W^2}{v} \qquad g_{hZZ} = \frac{2M_Z^2}{v}$$

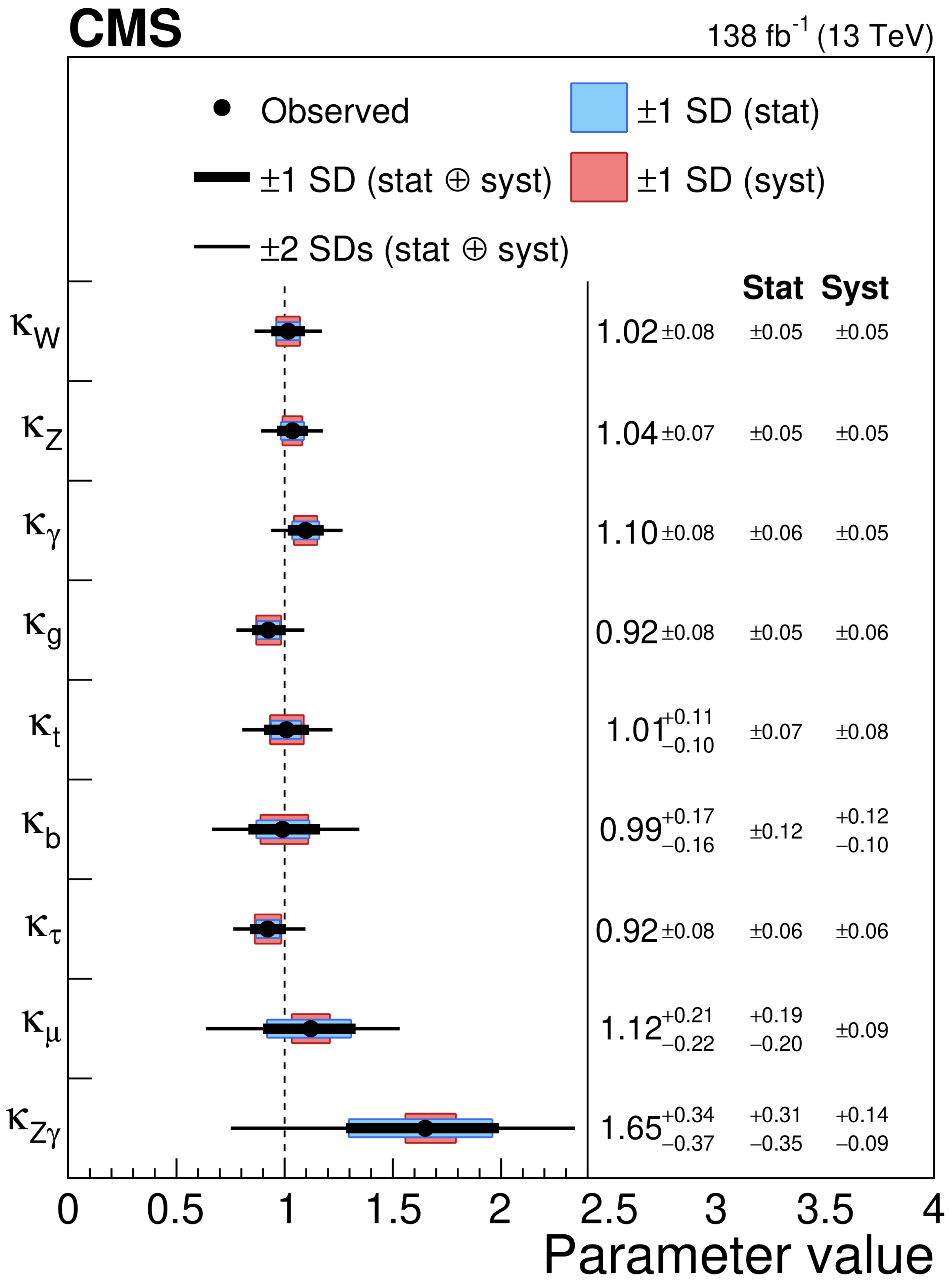
$$g_{hhWW} = \frac{2M_W^2}{v^2} \qquad g_{hhZZ} = \frac{2M_Z^2}{v^2}$$

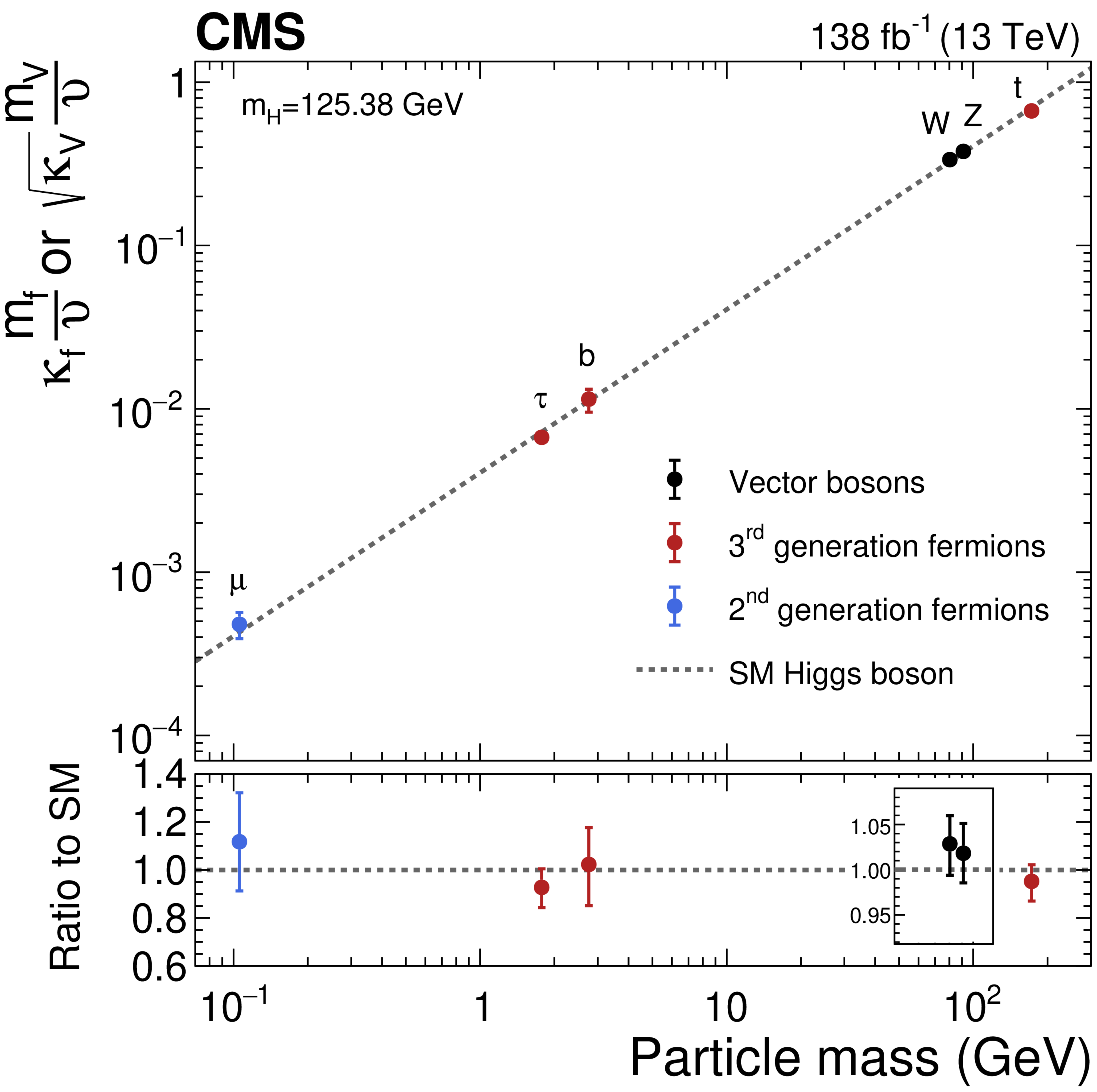
- Triple coupling tested in Higgs decays to both $\gamma\gamma$ and VV^* at the LHC
- g_{hhVV} accessible in double Higgs production



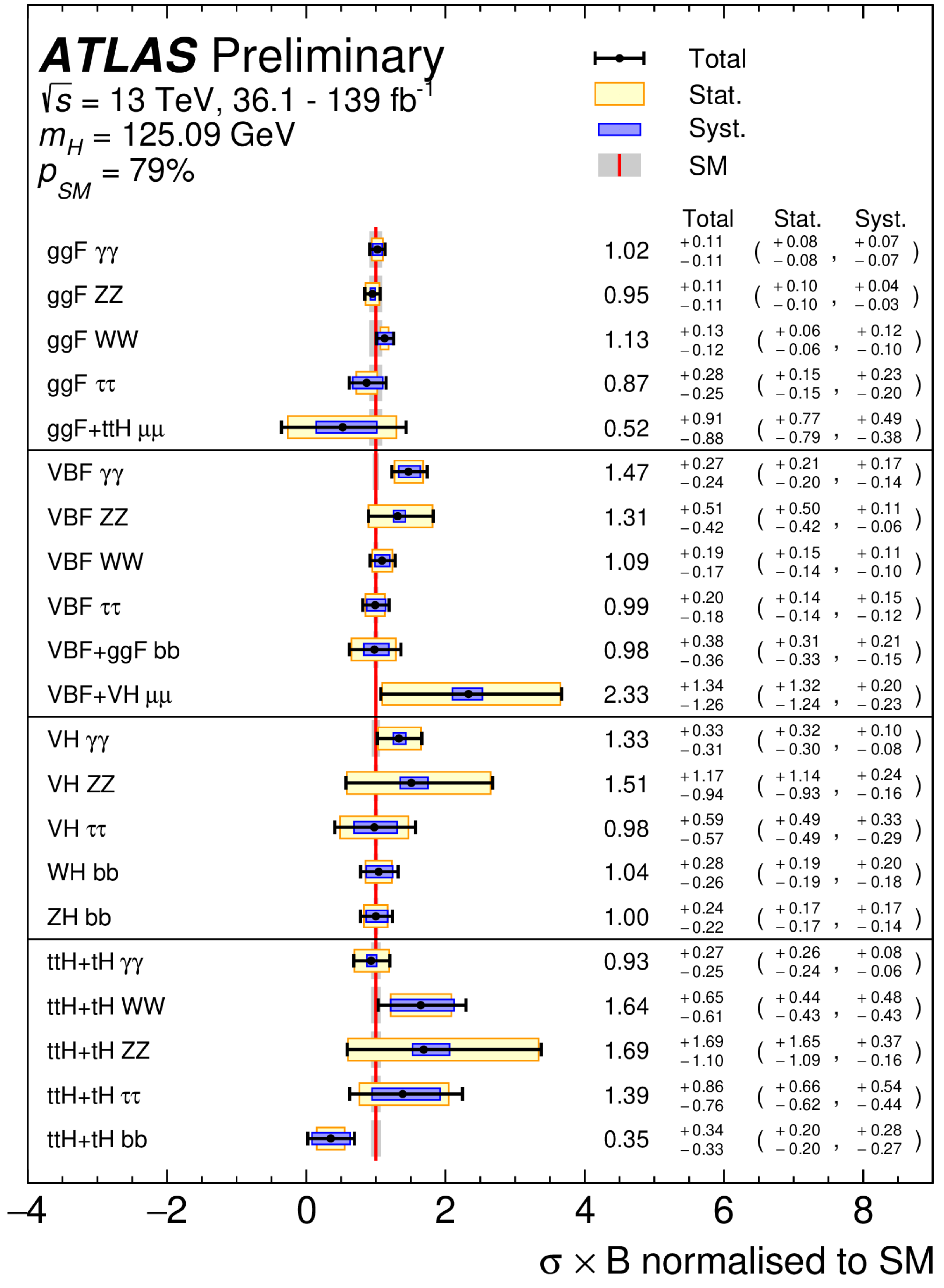


Testing the Higgs Couplings in the SM





Testing the Higgs Couplings in the SM



Parameter	(a) $B_{i.} = B_{u.} = 0$	(b) $B_{i.}$ free, $B_{u.} \geq 0$, $\kappa_{W,Z} \leq 1$
κ_Z	0.99 ± 0.06	$0.96\ ^{+\,0.04}_{-\,0.05}$
κ_W	1.06 ± 0.06	$1.00\ ^{+\,0.00}_{-\,0.03}$
κ_b	0.87 ± 0.11	0.81 ± 0.08
κ_t	0.92 ± 0.10	0.90 ± 0.10
κ_μ	$1.07\ ^{+\,0.25}_{-\,0.30}$	$1.03\ ^{+\,0.23}_{-\,0.29}$
κ_τ	0.92 ± 0.07	0.88 ± 0.06
κ_γ	1.04 ± 0.06	1.00 ± 0.05
$\kappa_{Z\gamma}$	$1.37\ ^{+\,0.31}_{-\,0.37}$	$1.33\ ^{+\,0.29}_{-\,0.35}$
κ_g	$0.92\ ^{+\,0.07}_{-\,0.06}$	$0.89\ ^{+\,0.07}_{-\,0.06}$
$B_{i.}$	-	< 0.09 at 95% CL
$B_{u.}$	-	< 0.16 at 95% CL

The Trouble(s) with the Standard Model

<u>The SM does not</u>

- Have a candidate for Dark Matter. Is m_{DM} a new fundamental scale ?
- Explain the Baryon Asymmetry of the universe.
- Adequately account for neutrino masses. Mechanisms point to new physics scale.
- Explain the enormous range of Yukawa couplings (Flavor Puzzle). Why is $\lambda_t/\lambda_u \simeq 10^5$?
- Have any symmetry preventing CPV in the strong interactions, i.e. explaining $\theta < 10^{-10}$
- Explain the origin of its only energy scale $m \simeq 89$ GeV
- Provide any reason why the Higgs boson mass is so light compared to the SM cutoff

The Trouble(s) with the Standard Model

The SM does not

- Have a candidate for Dark Matter. Is $m_{\rm DM}$ a new fundamental scale ? *Searches for DM particle(s).*
- Explain the Baryon Asymmetry of the universe. *Maybe some signals in HDV. Not guaranteed.*
- Adequately account for neutrino masses. Mechanisms point to new physics scale. *ν experiments.*
- Explain the enormous range of Yukawa couplings (Flavor Puzzle). Why is $\lambda_t/\lambda_u \simeq 10^5$? *Flavor physics.*
- Have any symmetry preventing CPV in the strong interactions, i.e. explaining $\theta < 10^{-10}$ *Axions.*
- Explain the origin of its only energy scale $m \simeq 89$ GeV
- Provide any reason why the Higgs boson mass is so light compared to the SM cutoff

} *TeV scale?*

The (In)Stability of the Electroweak Scale

The energy scale in the potential $V(\Phi^\dagger\Phi) = -\ m^2\,(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$ has a large UV sensitivity

Quantum corrections to the Higgs mass 

$\Rightarrow \quad \Delta m_h^2 \simeq \frac{c}{16\pi^2}\Lambda^2$

And Λ is a high energy scale, the highest considered in the loops

Not a problem in QFT. Yes, the renormalization condition condition is highly tuned

$(m_h^2)_{\rm phys.} = \Delta m_h^2 + \delta m_h^2$ But after removing Λ dependence by RC, $m_h^2(\mu)$ runs logarithmically

However, if heavy states of mass M couple to the Higgs with coupling y

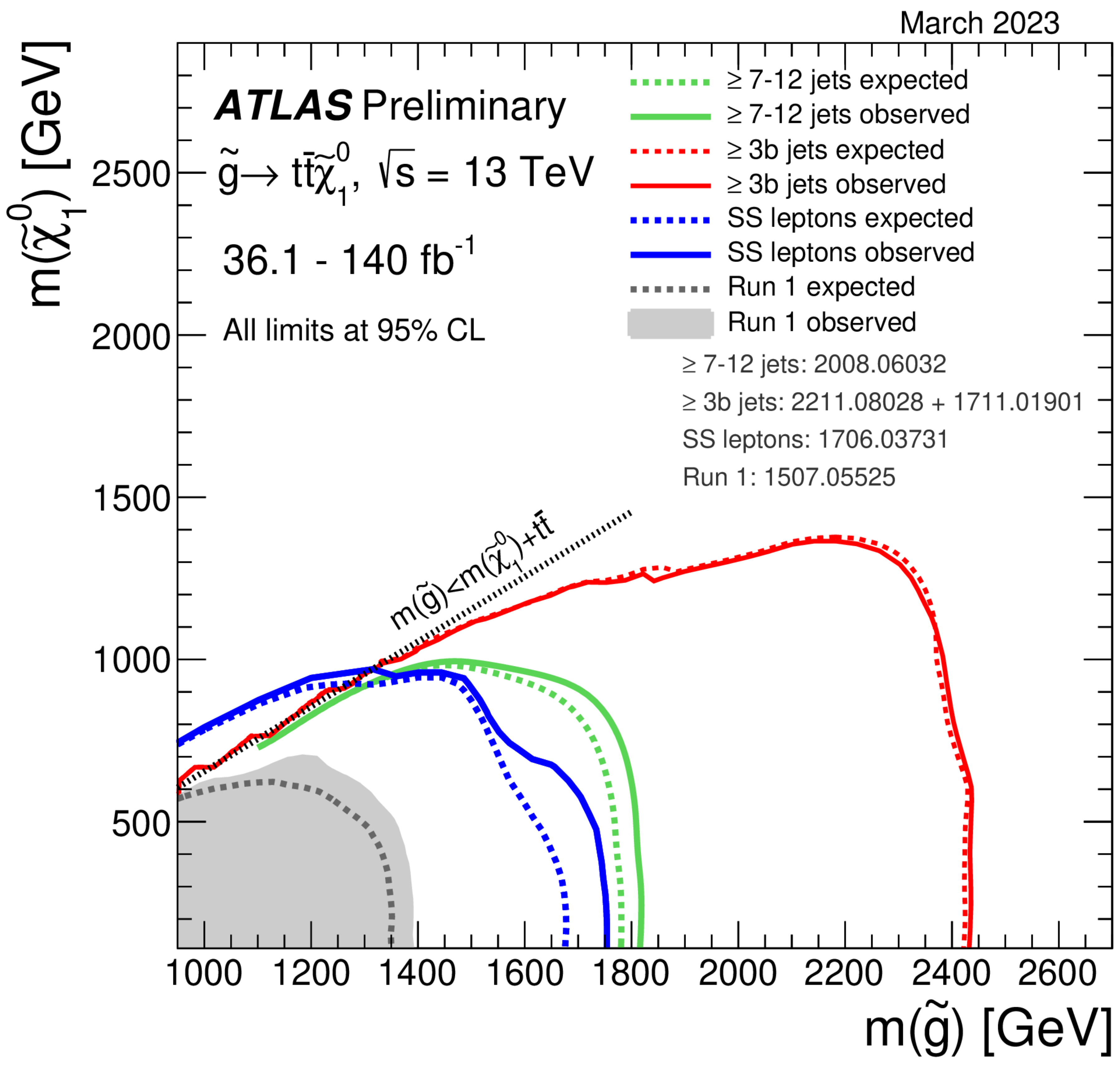
They result in large threshold corrections $\Delta m_h^2 \simeq \frac{y^2}{16\pi^2} M^2$ we recover the hierarchy problem

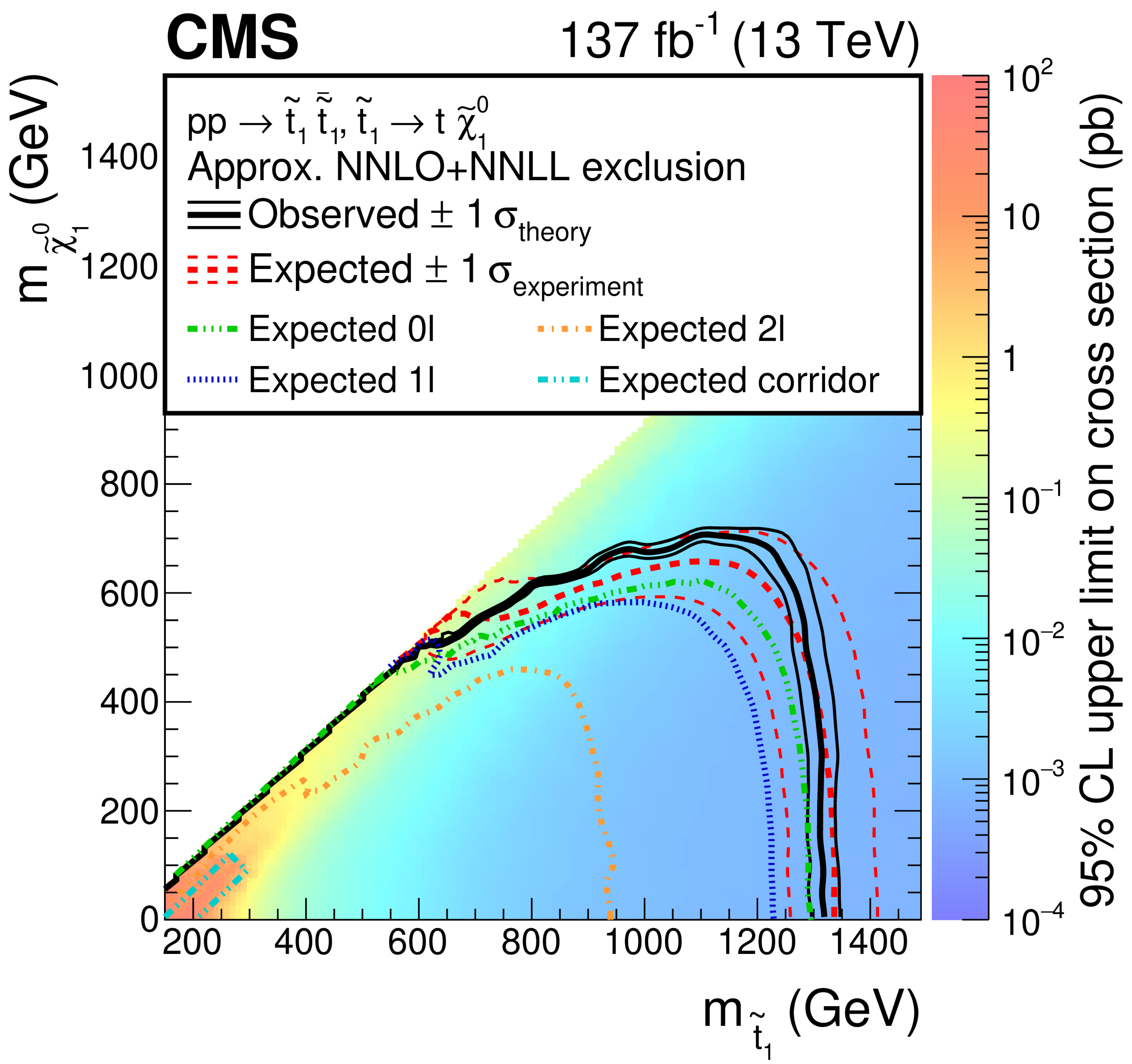
Motivation to have new physics either at Λ or M scales not too far above the electroweak scale

Searches for Physics Beyond the SM

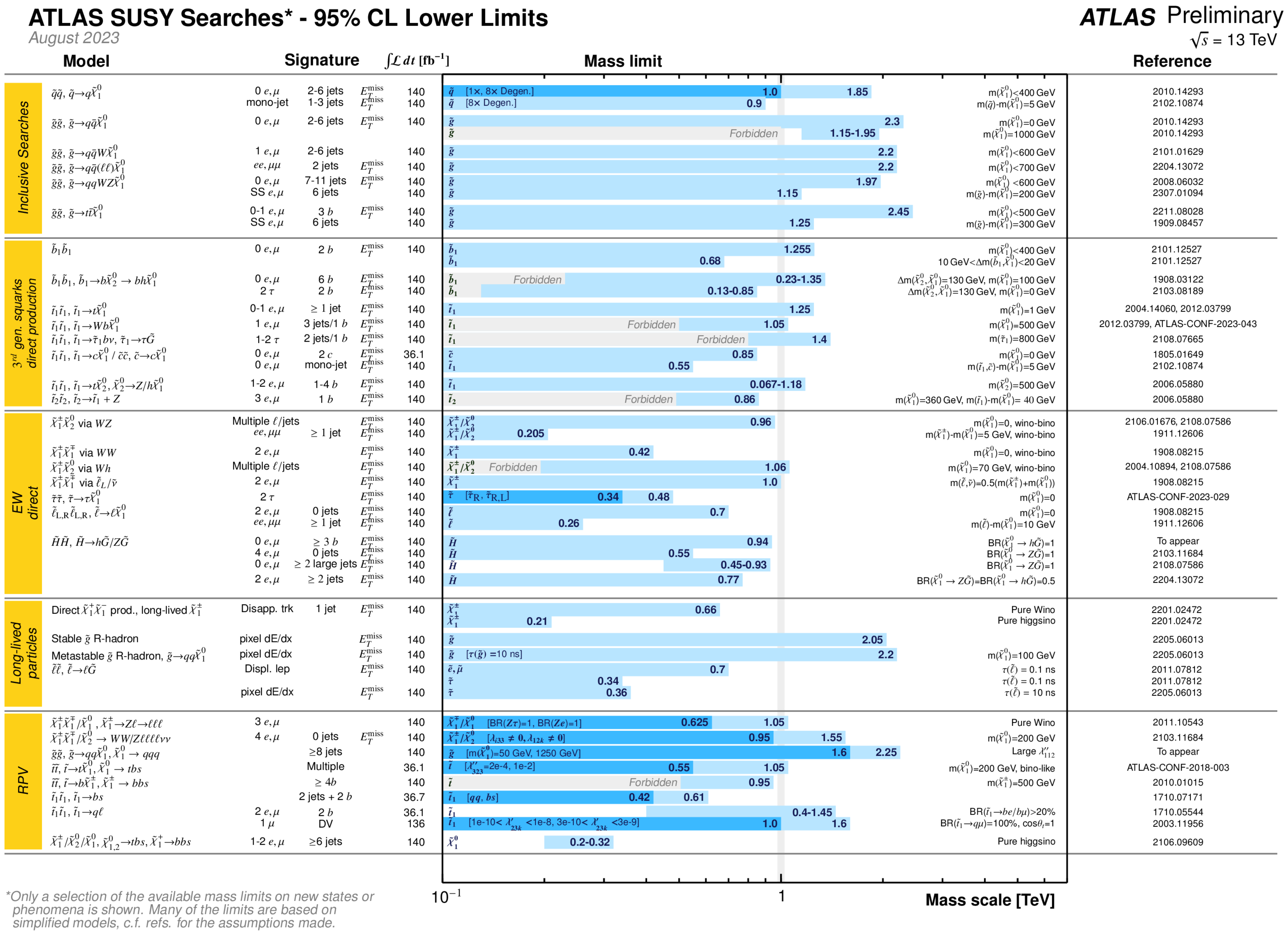
New Particles enter in the quantum corrections so as to diminish the UV sensitivity of m_h^2

SUSY





SUSY Searches



Difficult to avoid bounds on stops and sbottoms from reaching 600-700 GeV

This makes the SUSY solution to the UV sensitivity of m_h, fine tuned typically $\ll 1\%$.

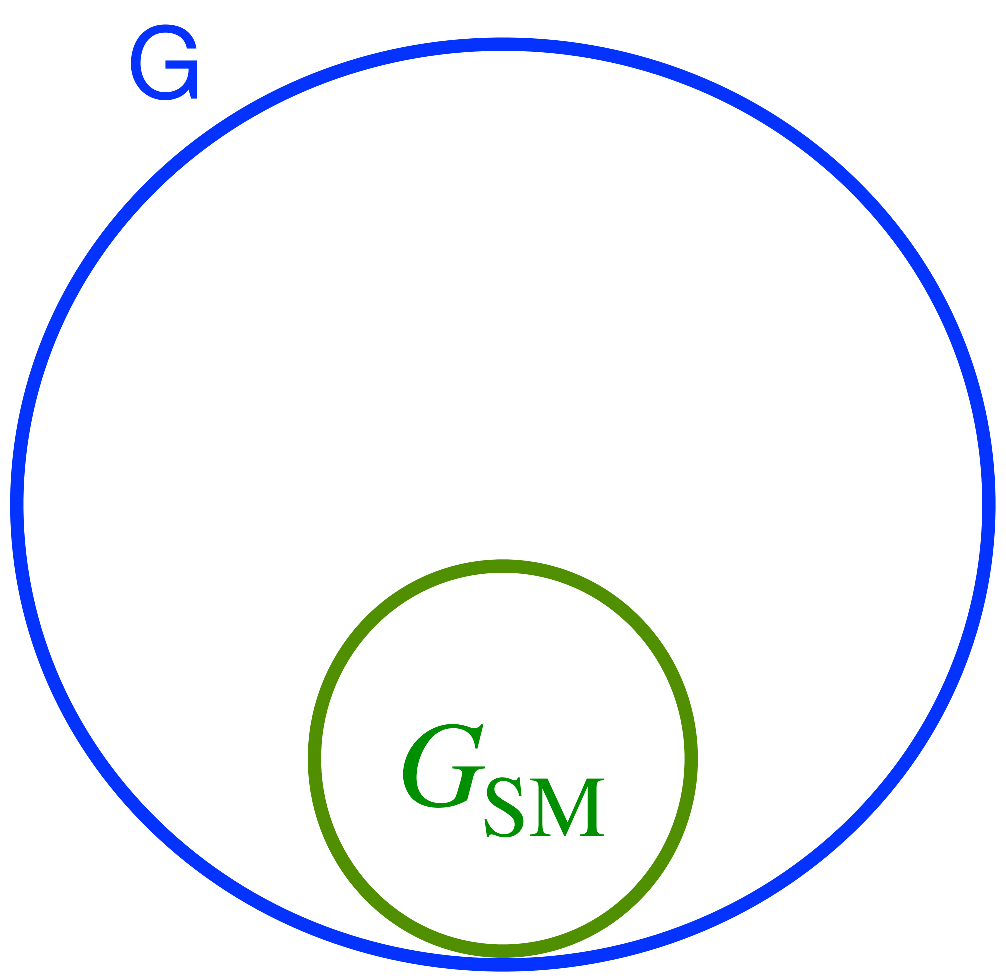
However, this is what SUSY needs to get $m_h \simeq 125$ GeV correctly

Composite Higgs Models

- Long history of non-elementary Higgs boson
  - Technicolor. Many problems. Plus: no Higgs! ✗
  - Topcolor. Main problem: heavier Higgs. ✗
  - Modern CHMs: Higgs is a (pseudo) Nambu-Goldstone boson ✓

K. Agashe, R. Contino, A. Pomarol, 2005

$m_h \ll \Lambda_{\rm BSM} \simeq {\rm TeV}$ analogous to $m_\pi \ll \Lambda_{\rm hadronic} \simeq {\rm GeV}$



G is a global symmetry *spontaneously* broken at f ⇒ massless Higgs

SM interactions *explicitly* break G ⇒ Generate $V(H)$ and m_h

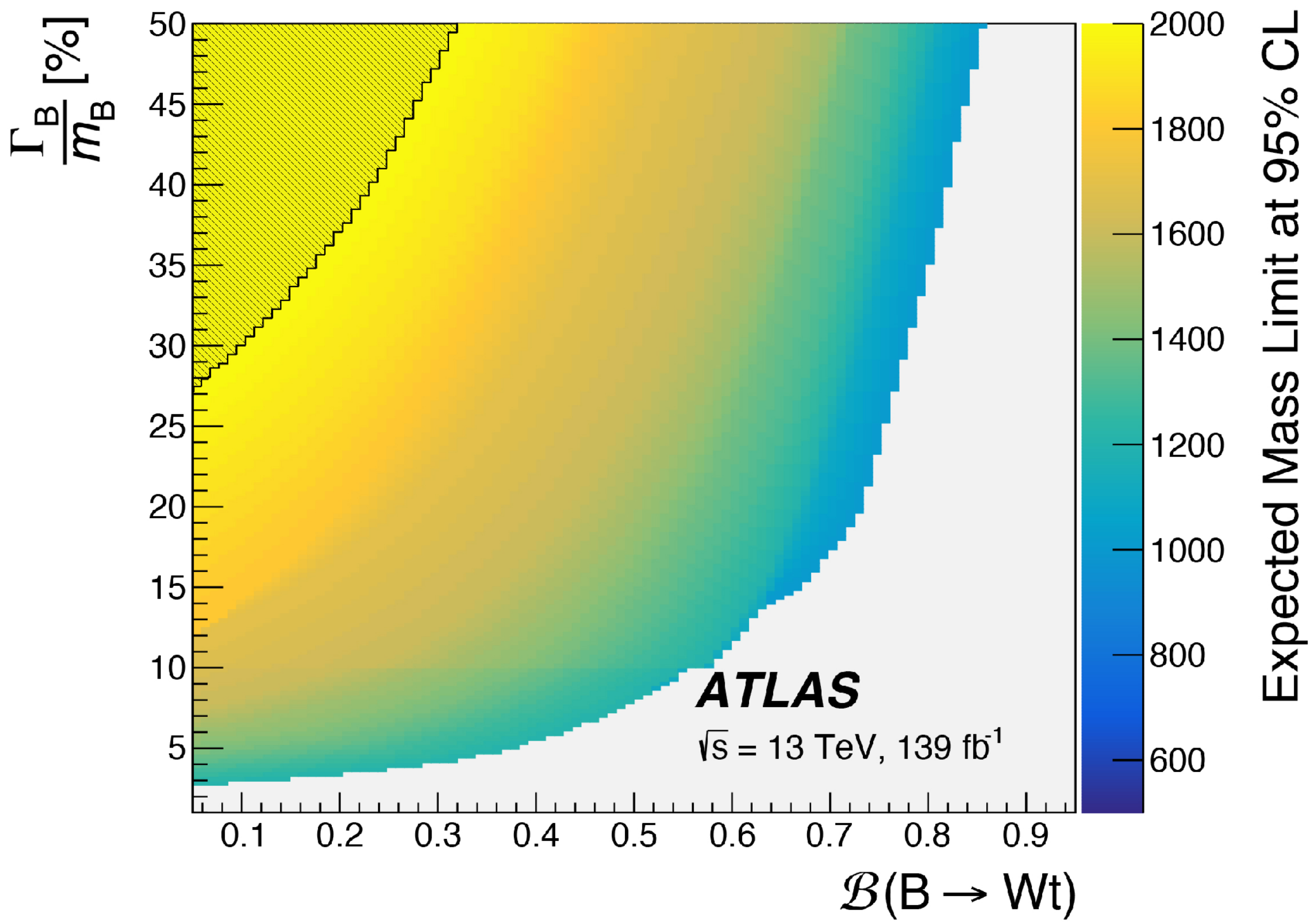
Minimal model: just enough pNGBs to make a H doublet

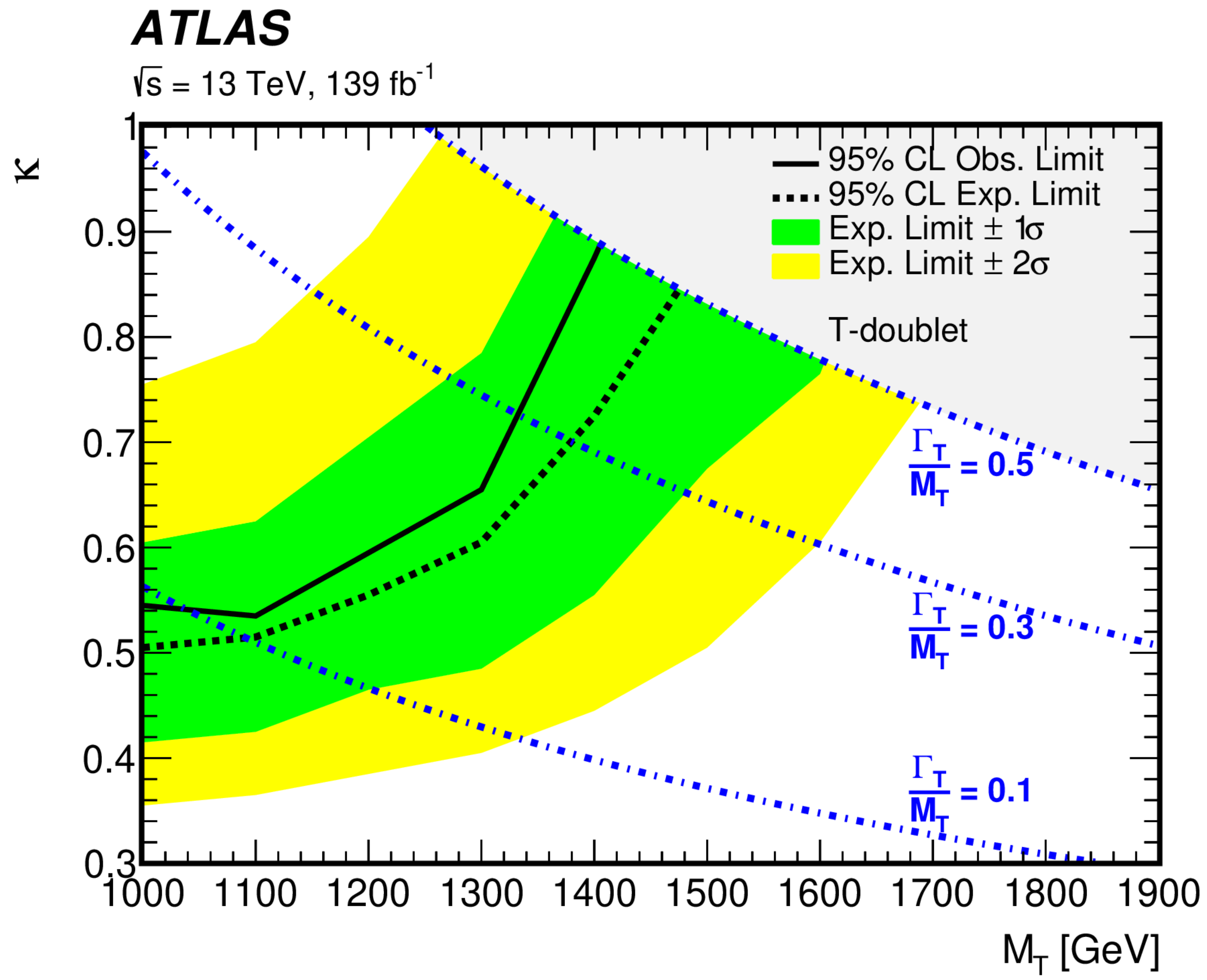
<u>MCHM</u>: $SO(5)/SO(4)$

Searches in CHMs

In CHMs vector and fermion resonances responsible for taming the UV sensitivity in m_h

Fermion resonances:





Resonance bounds are typically above 1 TeV.   Similarly for vector resonances.

Still not as fined tuned as SUSY since H is a pNGB.

BSM without New Particles

- The energy frontier will stay at the LHC for some time. HL-LHC up to 2030s.
- Look for hidden/dark sectors: dark sector/DM searches at various energies
- Test the SM with precision, low(er) energies: Flavor Physics, Electroweak tests
- Precision Tests of the Higgs Sector: Higgs Couplings to everything

Higgs as a window to new dynamics BSM
+
Energy Frontier: at $\sqrt{s} \simeq 14 \text{ TeV}$ for a while

$\Bigg\} \Rightarrow$ Understand Higgs couplings at the LHC/HL-LHC

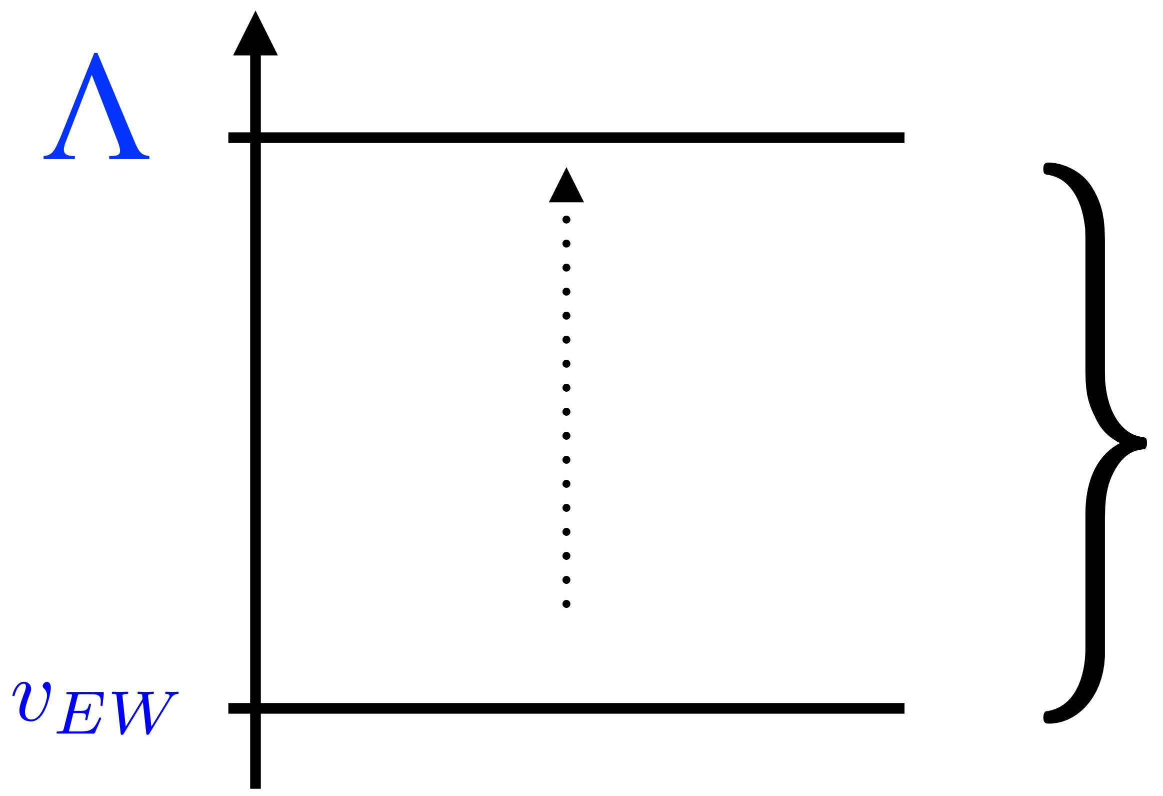
Effective Field Theory Approach

- New physics encoded in expansion in local HDOs suppressed by a cutoff Λ

$$\mathcal{L}_{\rm SM} + \sum_{i,n>4} \frac{c_i^{(n)}}{\Lambda^{n-4}} \mathcal{O}_i^{(n)}$$

SMEFT *Brivio and Trott (2019)*

- Model Independent requires 59 operators up to dimension 6.
- Correlated constraints from EW and Higgs data.



No BSM found really means

$$\Lambda \gg v_{\rm EW}$$

- Contradicts expectation from m_h UV sensitivity.

The Higgs Potential

In the SM we have

$$V(\Phi^\dagger\Phi) = -m^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$ and using $$v = \sqrt{\frac{m^2}{\lambda}}$$ from minimization

$$\mathcal{L}_h = -\frac{1}{2}m_h^2\, h^2 - \frac{g_{h^3}}{3!}\, h^3 - \frac{g_{h^4}}{4!}$$

with
$$\begin{cases} m_h = \sqrt{2\lambda}\, v \\ g_{h^3} = \dfrac{3m_h^2}{v} \\ g_{h^4} = \dfrac{3m_h^2}{v^2} \end{cases}$$

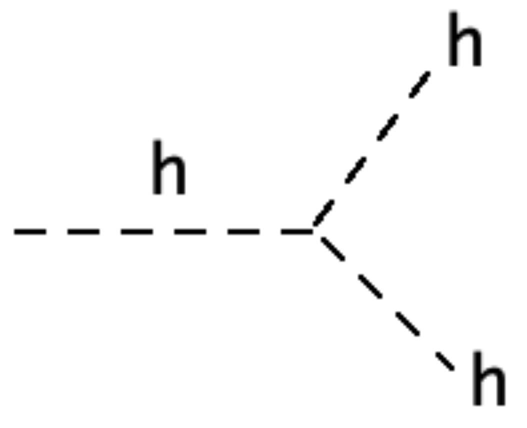
But HDOs could be present

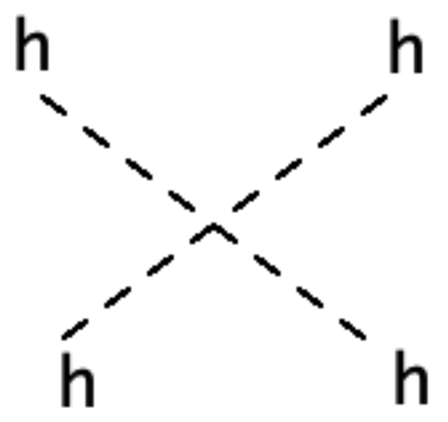
$$V(\Phi^\dagger\Phi) = -m^2\left(\Phi^\dagger\Phi\right) + \lambda\left(\Phi^\dagger\Phi\right)^2 + \frac{c}{\Lambda^2}\left(\Phi^\dagger\Phi\right)^3 + \frac{d}{\Lambda^4}\left(\Phi^\dagger\Phi\right)^4 + \cdots$$

Test the “shape”of the Higgs potential.

The Higgs Potential

Require experimental access to (at least) double Higgs production





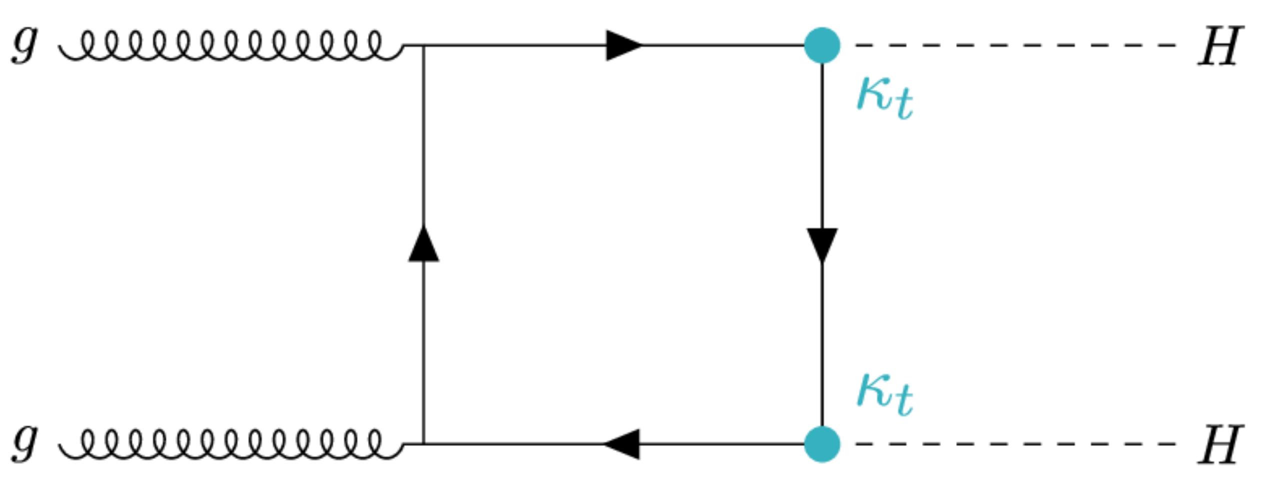
Fundamental question: is the coupling extracted from the measurement of m_h really the Higgs self-coupling ? We will begin attacking this question at the HL-LHC.

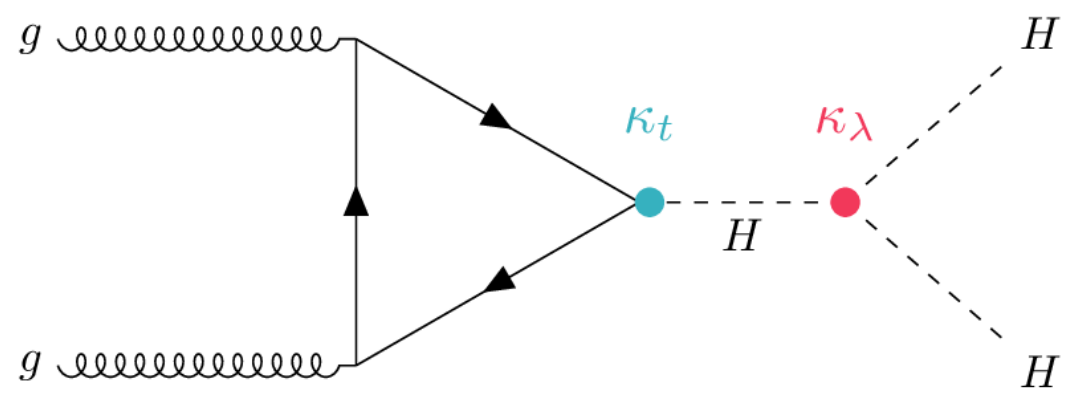
From $m_h \simeq 125\,\mathrm{GeV}$ using $m_h = \sqrt{2\lambda}\,v$ and $v \simeq 246\,\mathrm{GeV}$

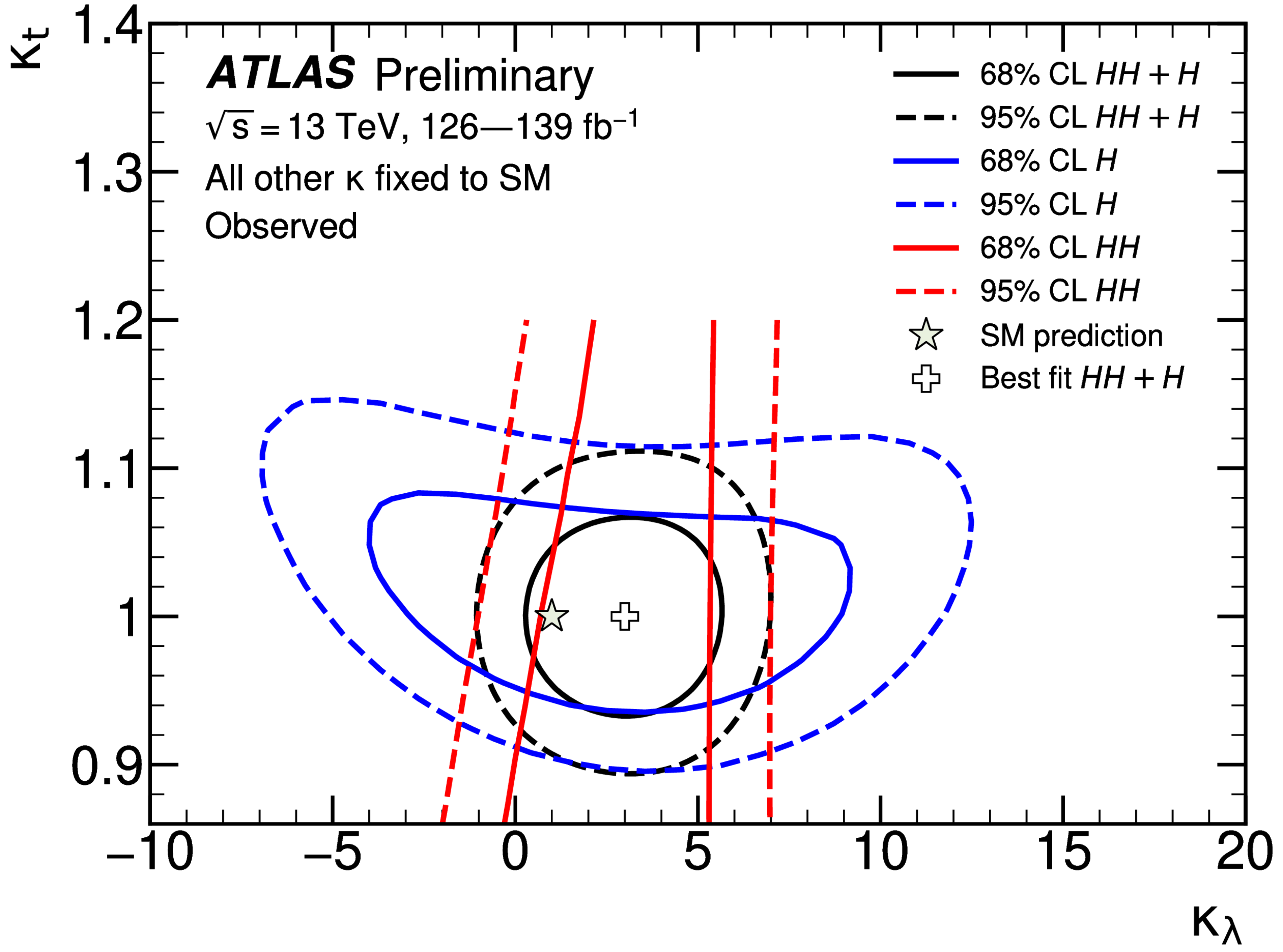
We arrive at $\lambda \simeq 0.13$

Measurements of λ in multi-Higgs production directly test the shape of the Higgs potential

Higgs Self-Coupling from Di-Higgs Production







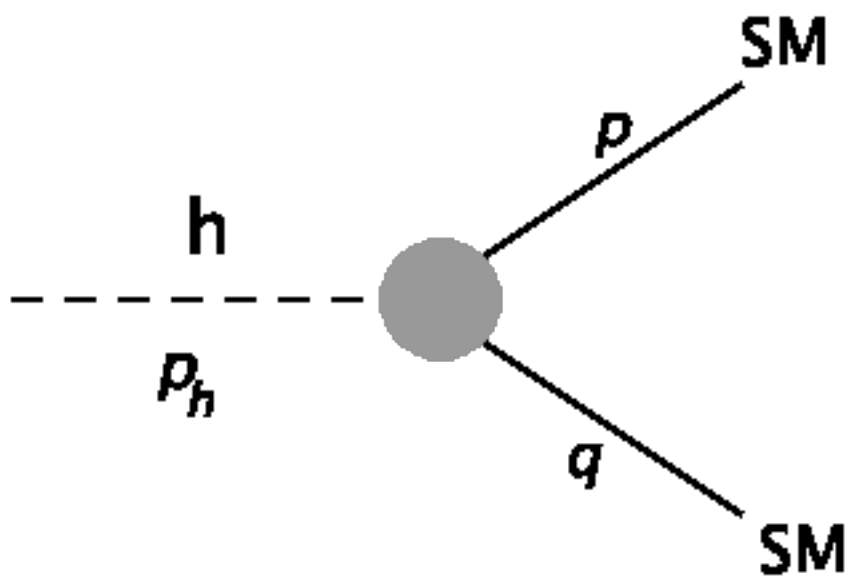
A long way to go for the HL-LHC and beyond

5% measurement of λ only at the FCC-ee

Searching for BSM through the Higgs

Higgs Couplings as a window to BSM physics

New physics can generate momentum dependence in couplings



Requires off shell momentum

$\Rightarrow$ Form factor in Higgs couplings $\left\{ \right.$

Isidori, Trott (2014)

Bellazzini, Csaki, et al. (2016)

Gonçalves, Han, Mukhopadhyay (2018)

Off-Shell Higgs and BSM Effects

Model dependent approach

Pedro Bittar, GB, 2022

Compute the Higgs form factors in a specific model → full momentum dependence

Matching with EFT may require operators of dim > 6 to capture full non-local features

Loose generality, **Gain** in power of data to constrain specific BSM not directly accessible

“Scan" over models so as to cover all signals : where is the momentum dependence coming from ?

- Higgs line
- Gauge boson line
- Fermion line

Example: Mixing with an Unparticle Scalar Sector

Scalar unparticle operator $\phi(x)$ of dimension d $\quad 1 < d < 2$

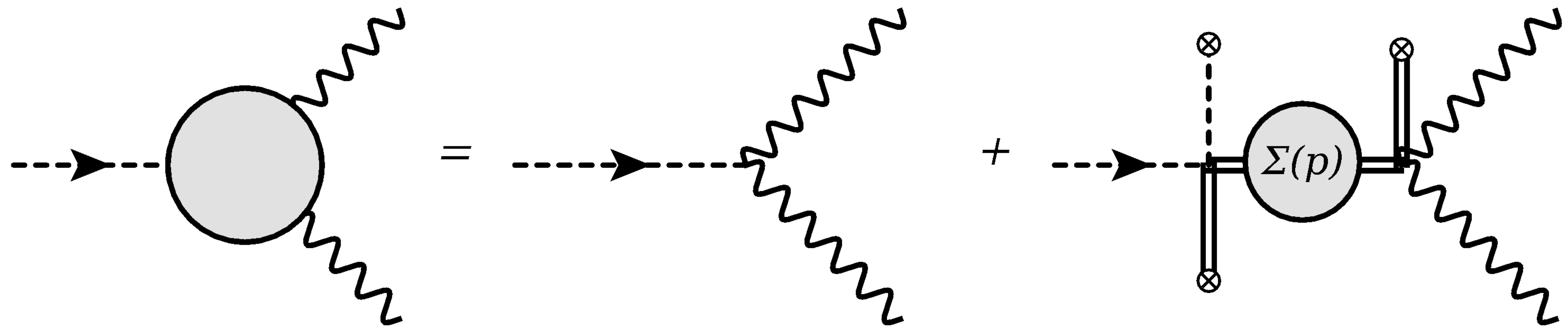
Fox, Rajaraman, Shirman (2007)

Cacciapaglia, Marandella, Terning (2008)

2-point function with IR cutoff μ

$$\Delta(p,\mu,d) = \int d^4x \langle 0|\mathcal{T}\phi(x)\phi^\dagger(0)|0\rangle = \frac{A_d}{2\pi}\int_{\mu^2}^{\infty} ds (s-\mu^2)^{d-2}\frac{i}{p^2 - s + i\epsilon},$$

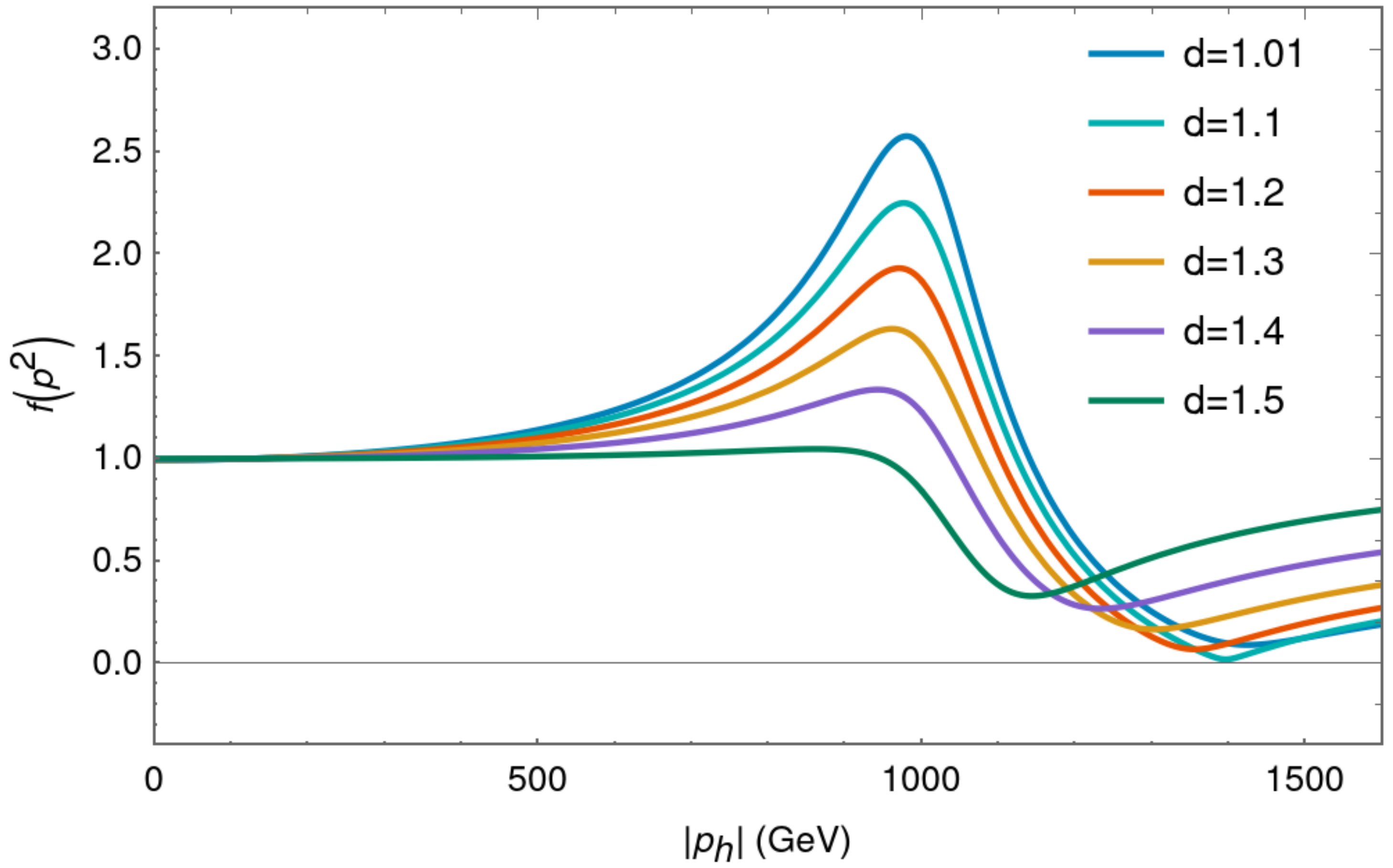
Non-local action $$S_{\rm NL} = \int d^4x \left\{ \phi^\dagger (D^2-\mu^2)^{2-d}\phi + \alpha |H|^2 \frac{|\phi|^2}{\Lambda^{2(d-1)}} \right\}$$

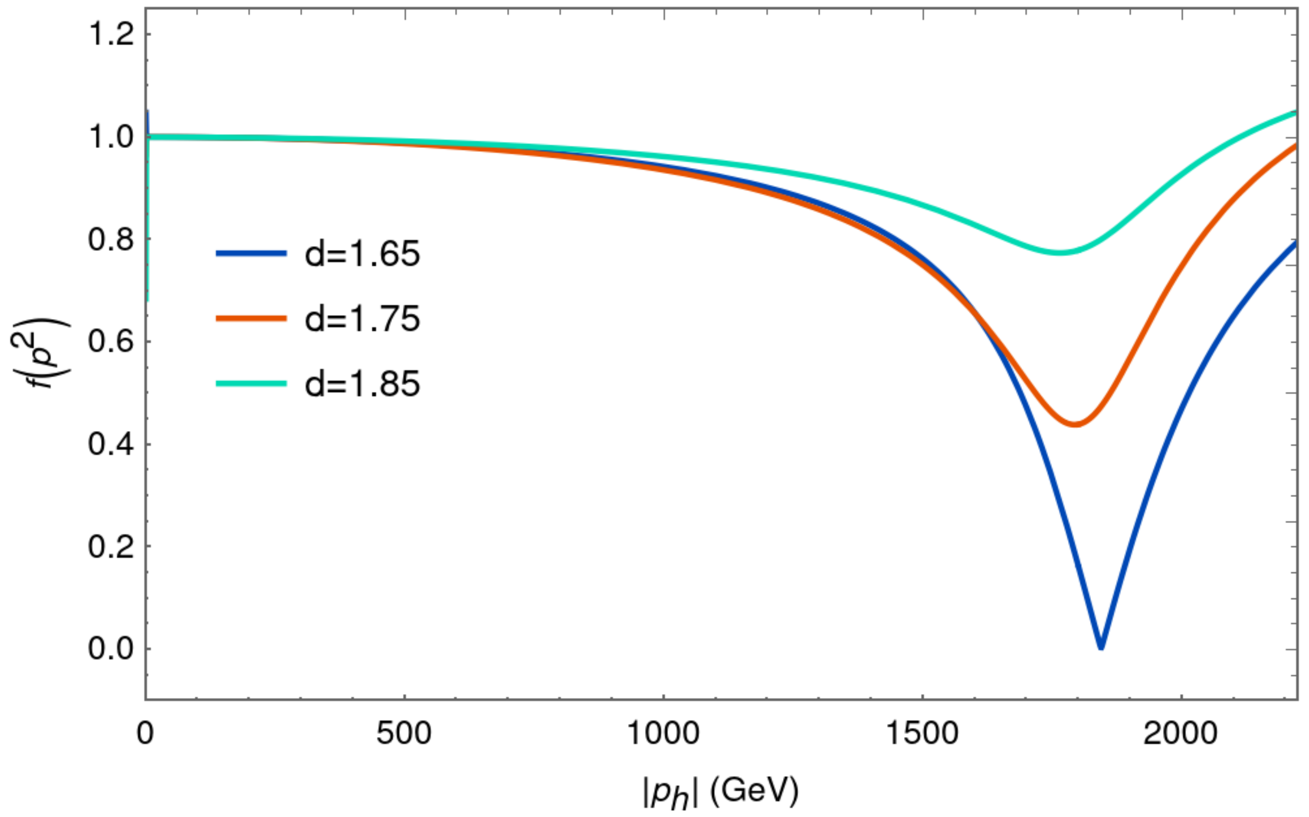


Form Factor from an Unparticle Scalar Sector

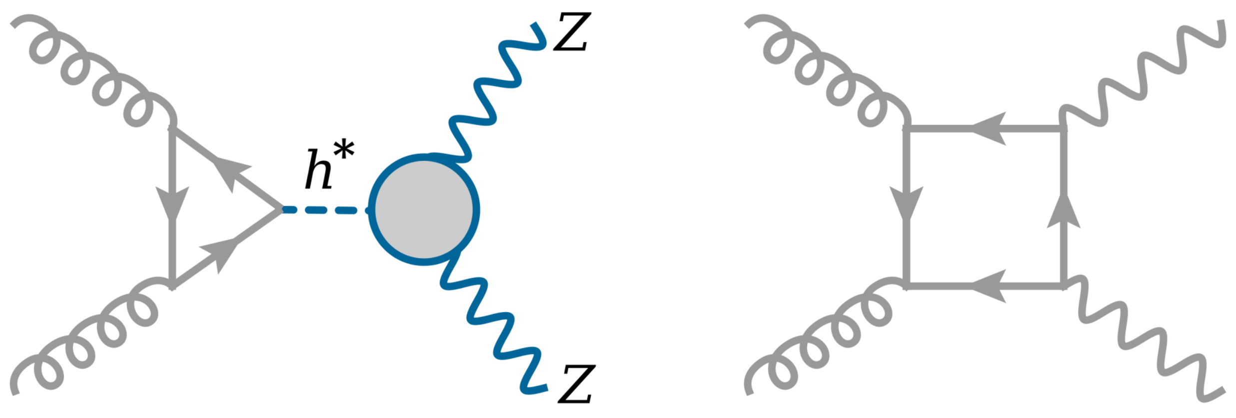
Results for $f_{hVV}(q^2)$ with off shell Higgs, on shell gauge bosons *P. Bittar, G.B. 2022*

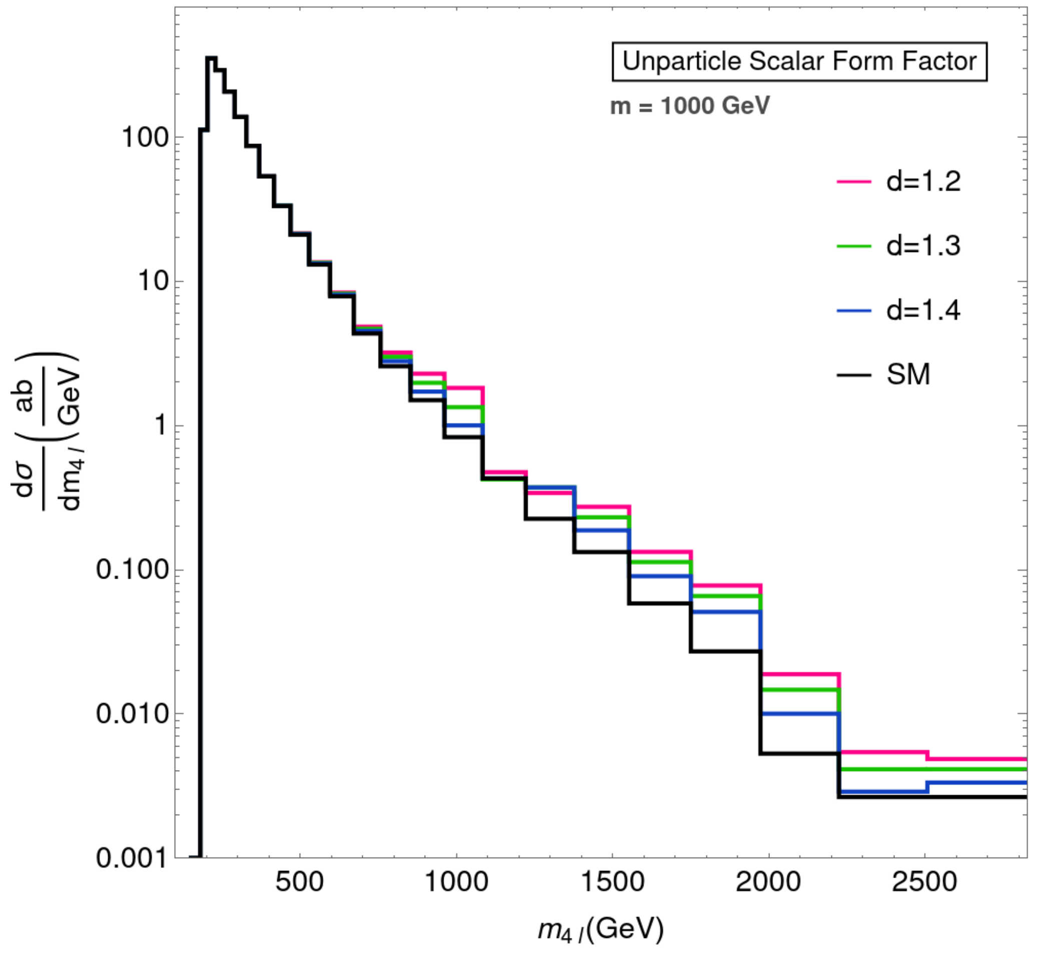
$\mu = 1\ \text{TeV}$

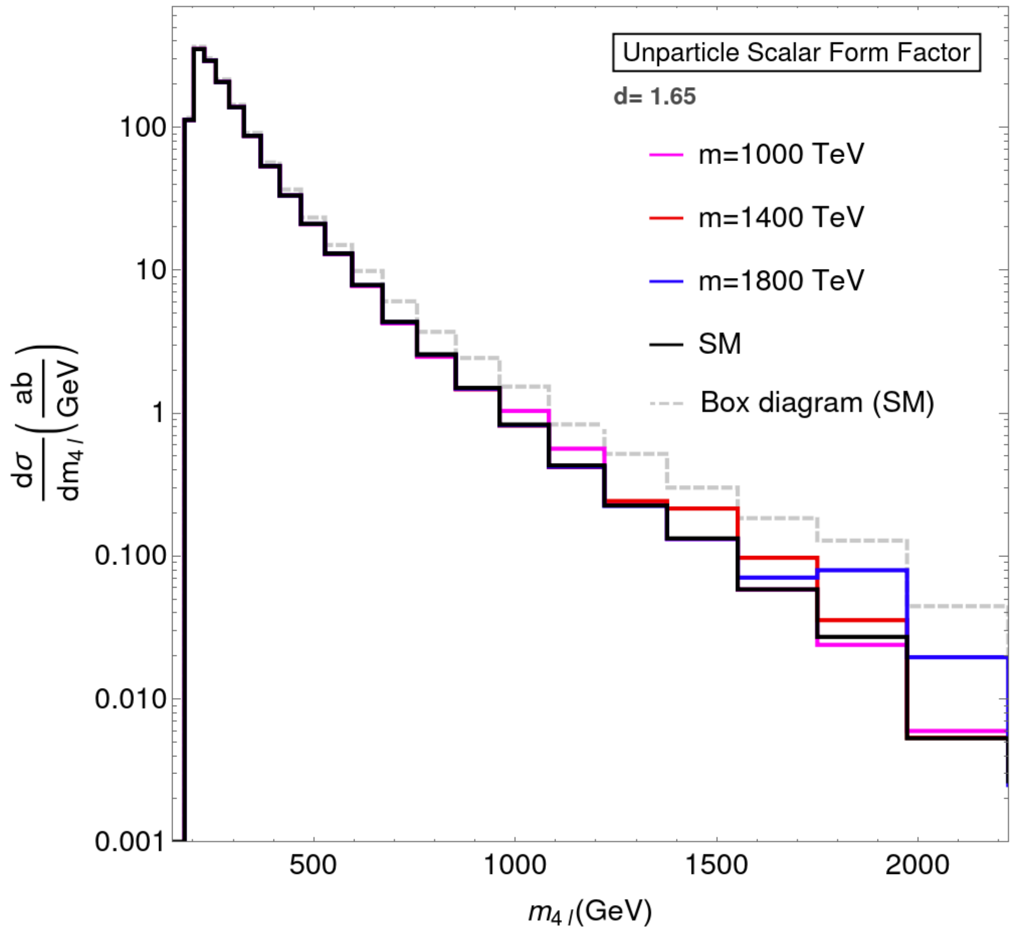




$pp \to h^* \to 4\ell$







Another Example: the Twin Higgs

Z. Chacko, H. Goh and R. Harnik, 2005

- The Higgs is a pNGB, just as in CHMs
- New states controlling the UV sensitivity in m_h are in an invisible (twin) sector
- In the Mirror Twin Higgs, two copies of the SM are related by a Z_2 symmetry
- Exact Z_2 means $f = \mathrm{v}$. Excluded by Higgs phenomenology (invisible decays, couplings)
- Need soft Z_2 breaking so that $\frac{f}{v} \gtrsim 3$ $\Rightarrow$ Twin particles somewhat heavier than SMs

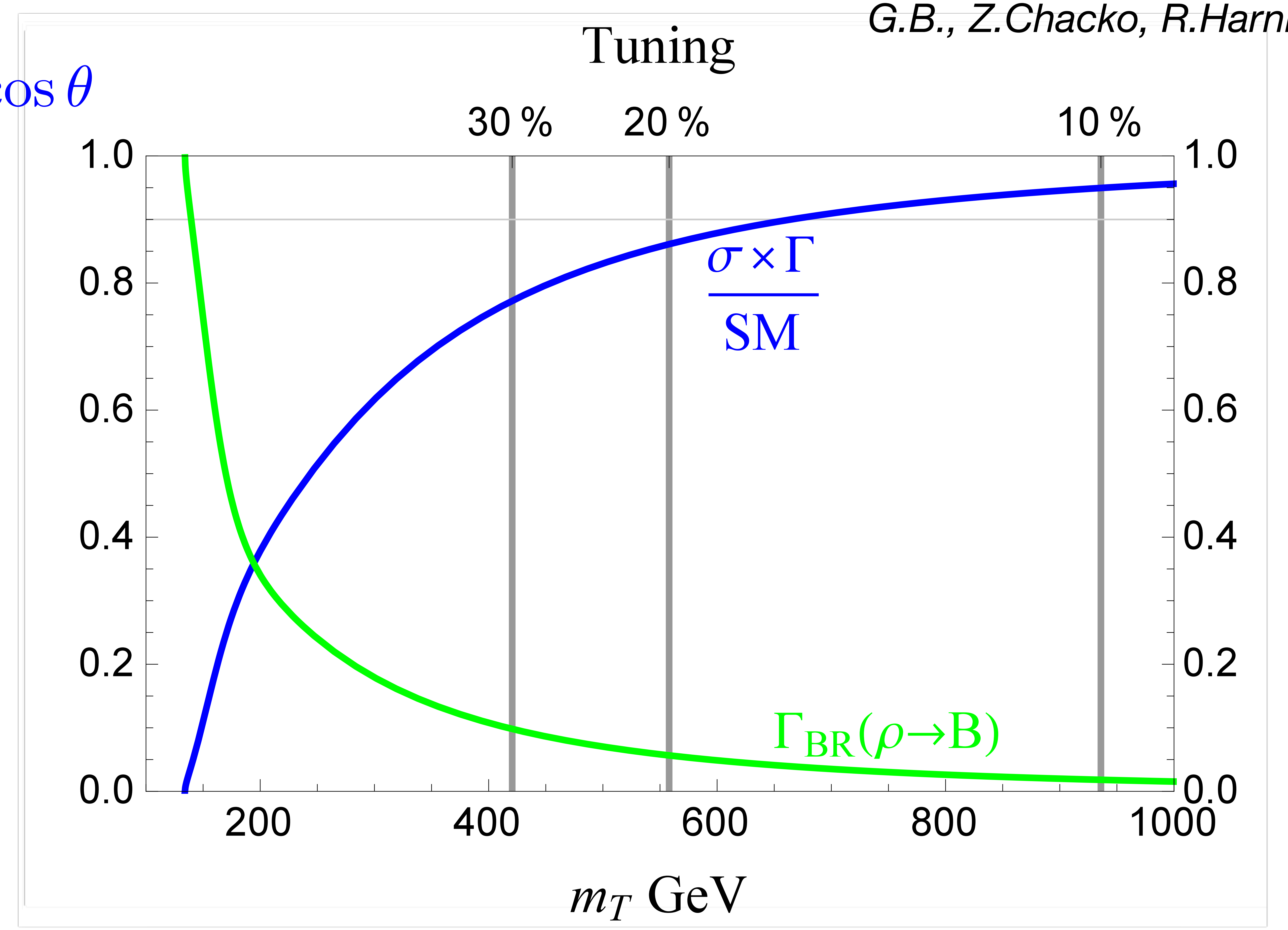
All Higgs couplings to SM are suppressed by a factor of $\cos\left(\frac{v}{\sqrt{2}f}\right)$

Future Bounds on the Twin Higgs

It is hard to constraint the MTH at the LHC

G.B., Z.Chacko, R.Harnik, L. Lima, C. Verhaaren, 2014

Here $m_T = \lambda_t \, f \, \cos\theta$



⇒ MTH to remain natural well into the HL-LHC

Other aspects of the Mirror Twin Higgs

Cosmology:

- Potentially large contribution to $\Delta N_{\rm eff.}$ from twin neutrinos and photon
- Many possible solutions: give twin ν's large masses, asymmetric reheating, …

Dark Matter:

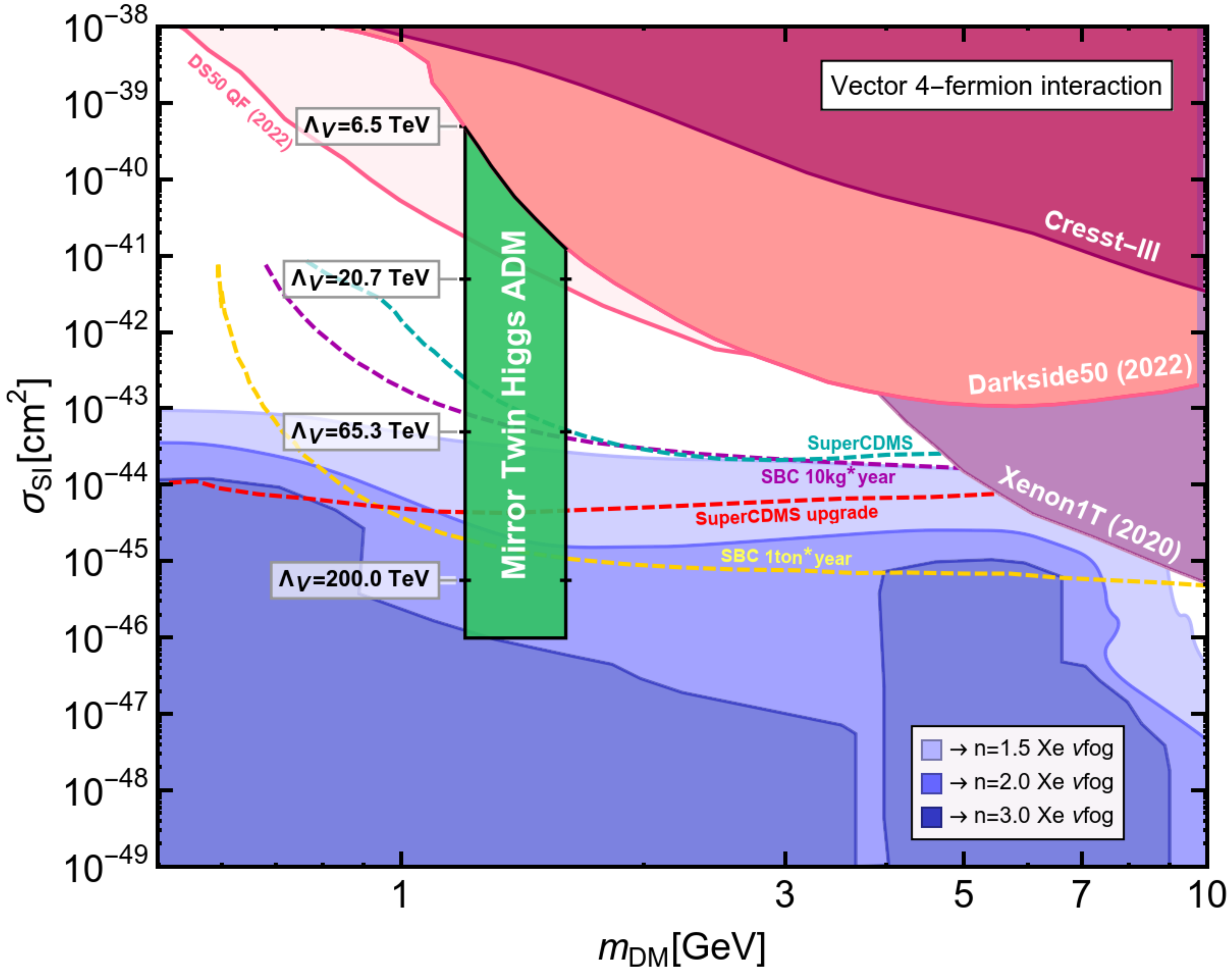
- Mirror standard model playground for DM model building
- Thermal relic, asymmetric DM, …
- Details depend on twin matter content (e.g. Mirror vs. Fraternal), on Z_2 breaking, …

Asymmetric Dark Matter in the Mirror Twin Higgs

Pedro Bittar, G.B, Larissa Pastrello, 2023

ADM in the MTH naturally just around $O(1)$ GeV

Twin quarks heavier $\Rightarrow \tilde{\Lambda}_{\rm QCD} \gtrsim \Lambda_{\rm QCD} \Rightarrow m_{\rm DM} \simeq 1.4\, m_N$



Summary and Outlook

- No evidence for BSM in direct searches at the LHC, or in flavor physics.

- Next BSM frontier: precision measurements involving the Higgs boson

  - Energy frontier closing for sometime. HL-HLC → 2030s-2040

- Future accelerators:

  - Higgs factory. FCC-ee great reach in precision, including 5% in λ. (Would start 2048!?)
  - FCC-hh 100 TeV (same tunnel as FCC-ee at CERN ⇒2070s !)
  - Muon Collider: 3 TeV, 10 TeV ? (Off real axis right now, but …)

- A lot of interesting correlations between DM searches and accelerator physics still happening
  This will continue throughout the HL-LHC lifetime.
  These include new experiments coming on line for highly displaced vertices: Dark Sectors, BAU, …