The fate of Little Higgs models with LHC Run 2 data

HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

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DESY

based on work with

D. Dercks, G. Moortgat-Pick, S.Y. Shim, M. Tonini, M. de Vries

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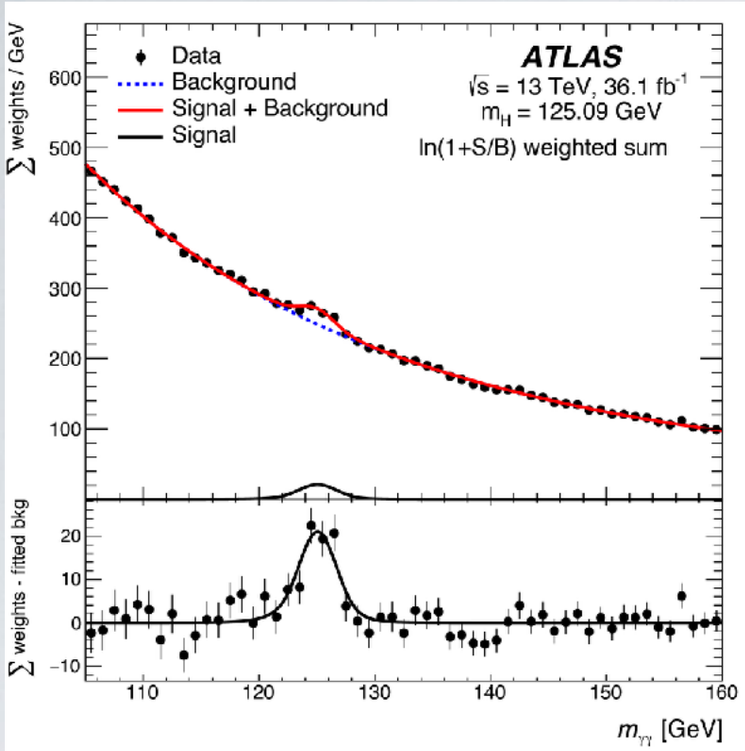
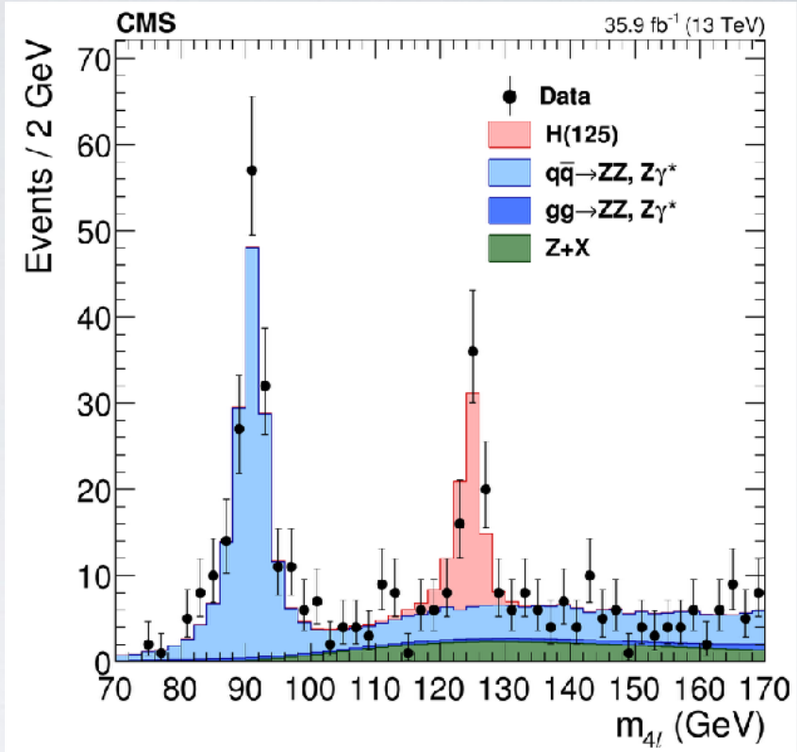
The Little Big Higgs boson



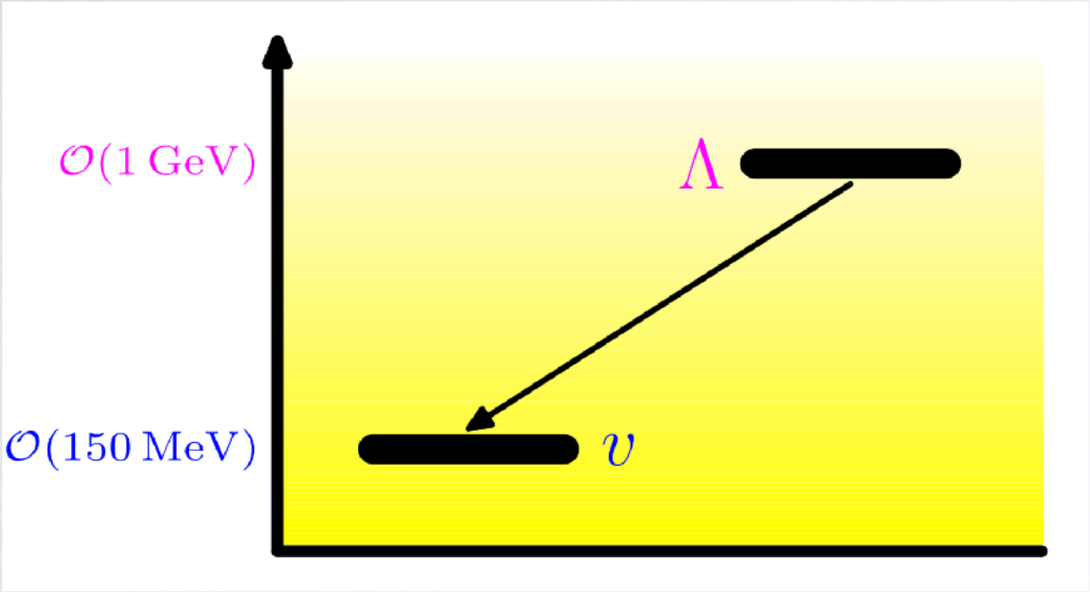


- Discovery of a light Higgs boson leaves still open questions:

1. Nature of Electroweak Symmetry Breaking
2. Higgs boson potential, all the way like the Standard Model!?
3. Does it fulfill the US-fermion/Europe-boson rule?
4. Is the 125 GeV state the only resonance in the system of EW vector bosons?
5. Is there something related to the Little Hierarchy problem (strong or weak)

Higgs as pNGB & Collective Symmetry Breaking

Old Idea: Light Higgs as a (pseudo-) Nambu-Goldstone boson of a spontaneously broken symmetry [Georgi/Pais, '75; Georgi/Kaplan, '84]



Analogy: chiral symmetry breaking in QCD

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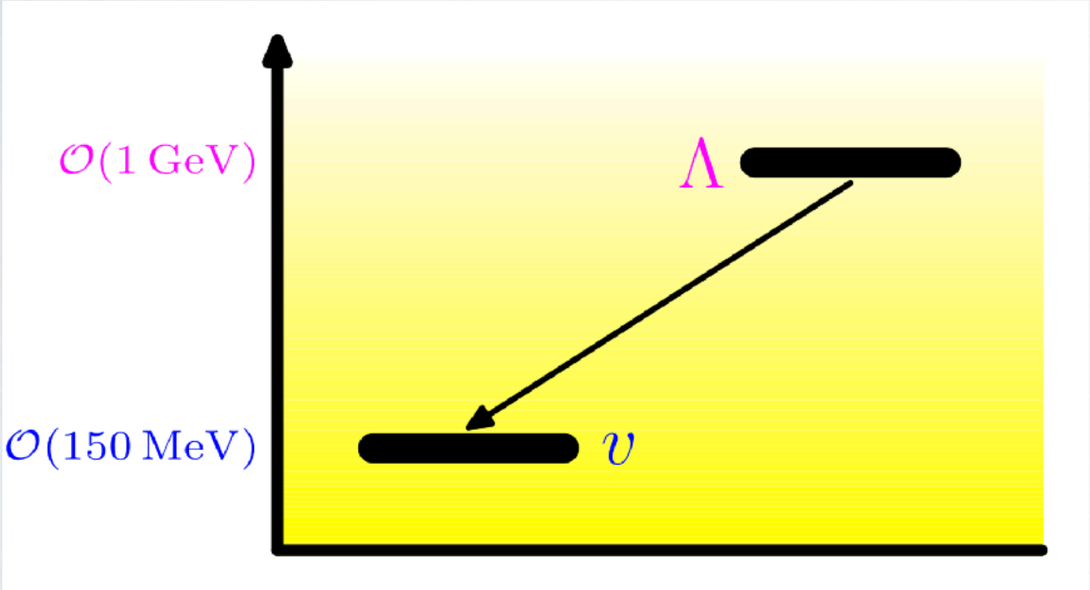

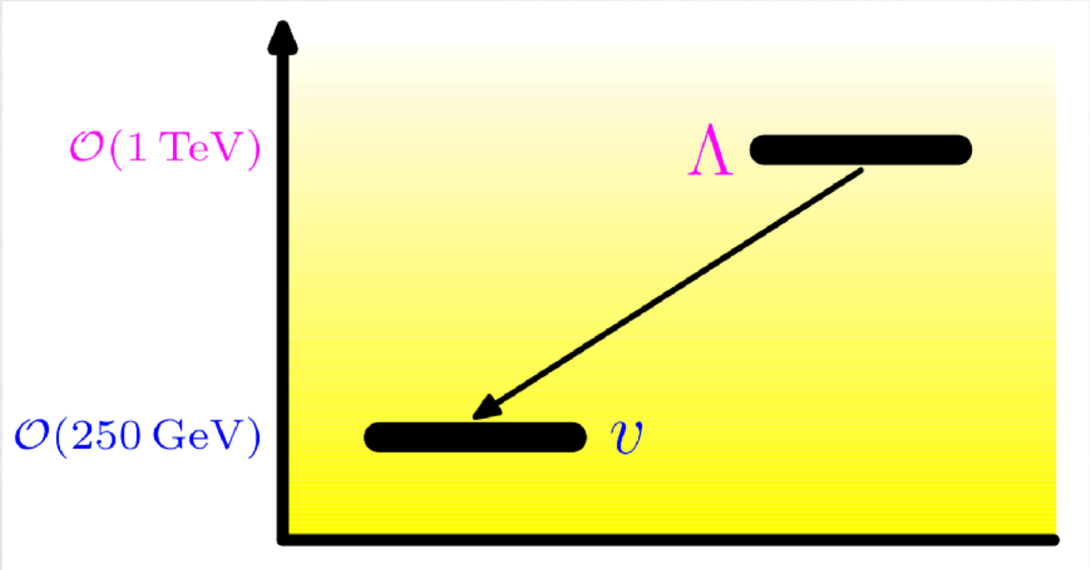

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Upscale: Technicolor (ruled out by EWPO/LHC)

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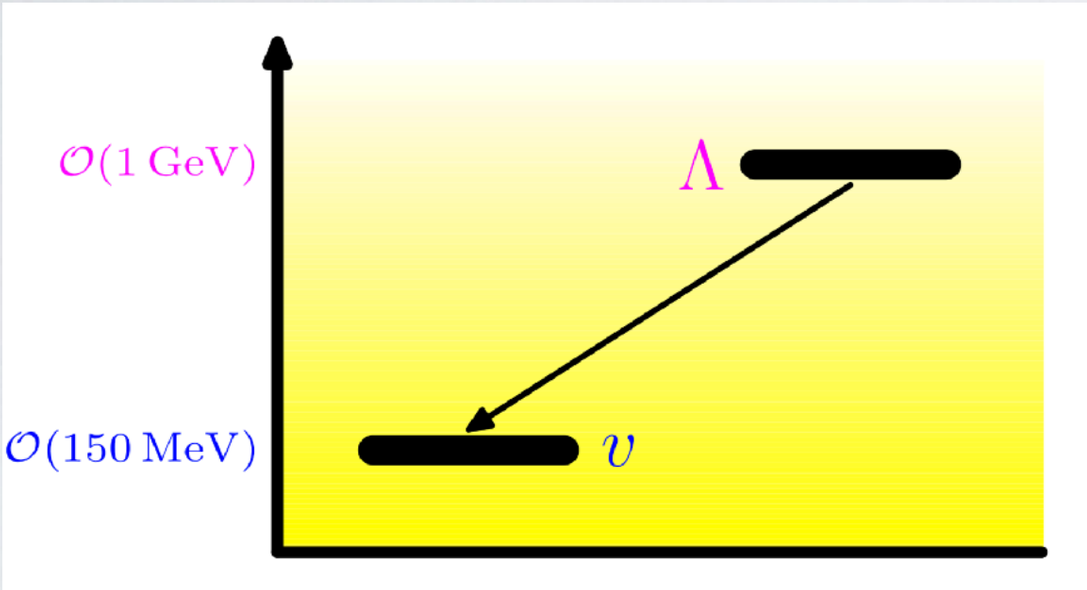

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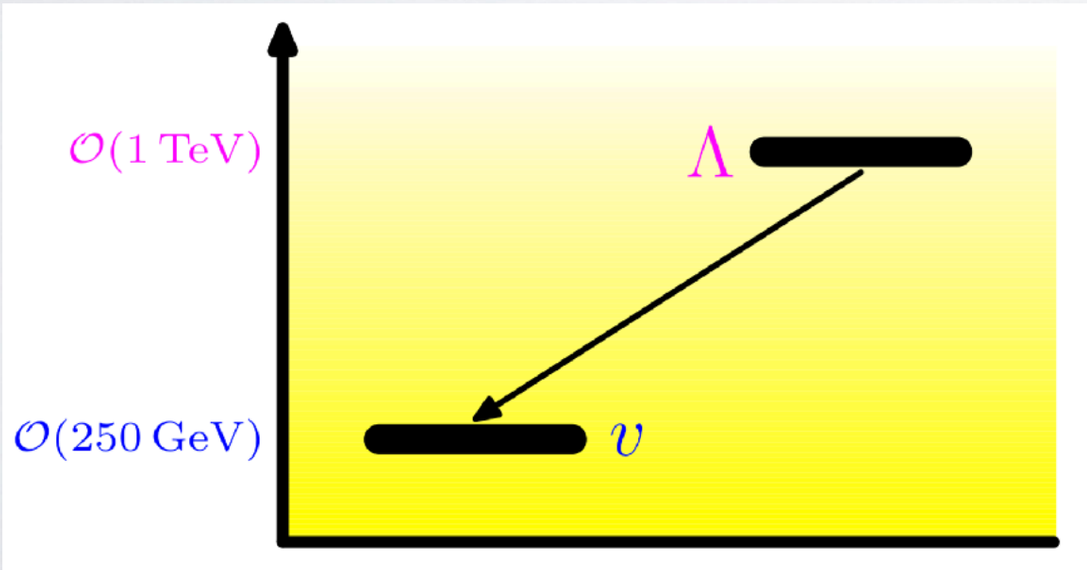
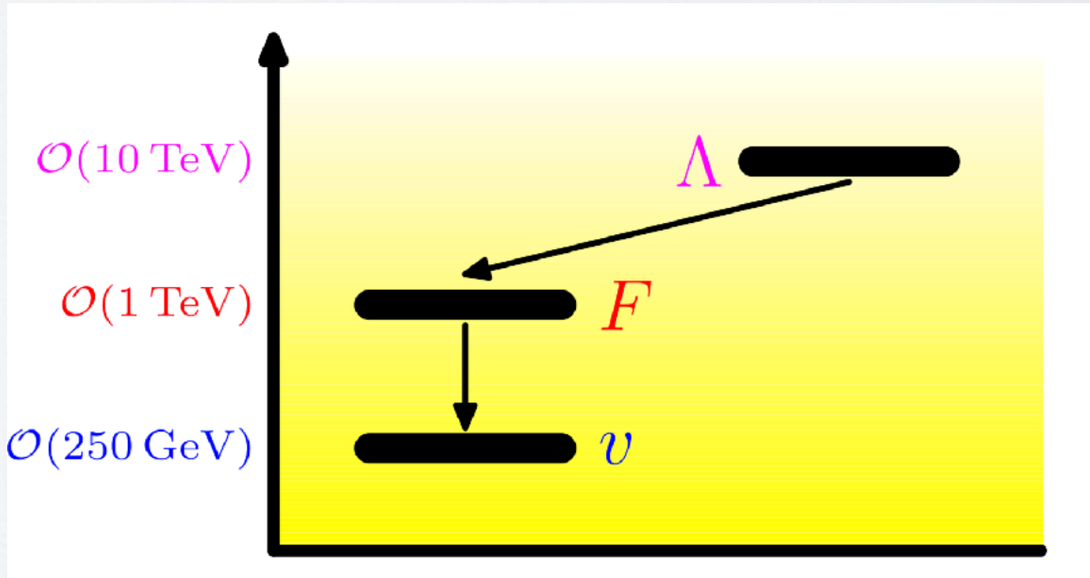
Upscale: Technicolor (ruled out by EWPO/LHC)

Collective Symmetry Breaking: 3-scale model

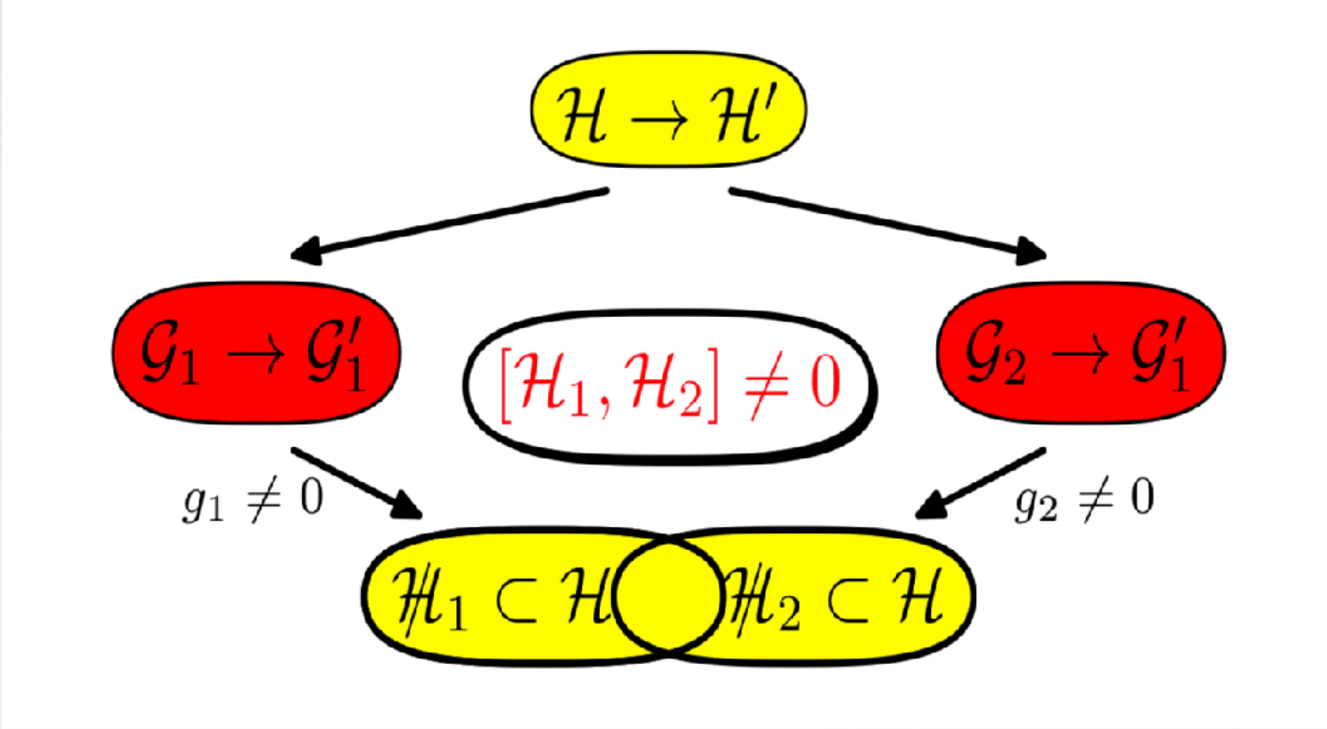
Arkani-Hamed/Cohen/Georgi, '01
Arkani-Hamed/Cohen/Gregoire/Wacker, '02

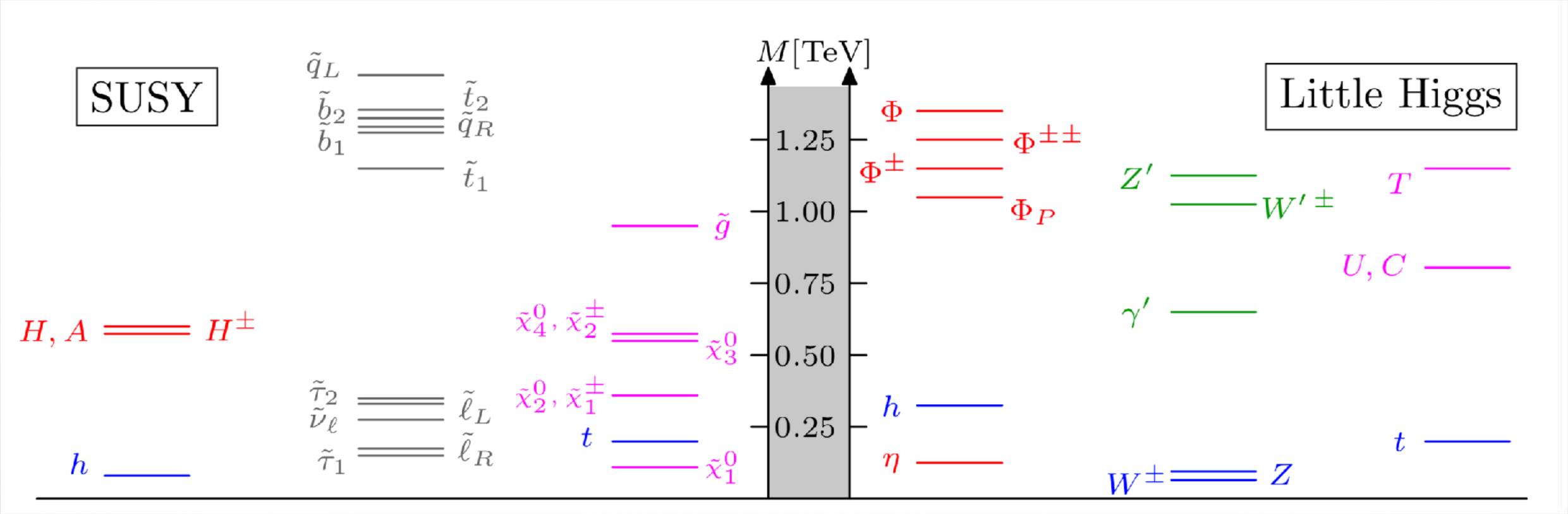




Characteristics and Spectra

- Extended global symmetry
- Radiative symmetry breaking (Coleman-Weinberg)
- Specific form of scalar potential
- Extended gauge symmetry
- New heavy gauge bosons
- New heavy (vector-like) fermions



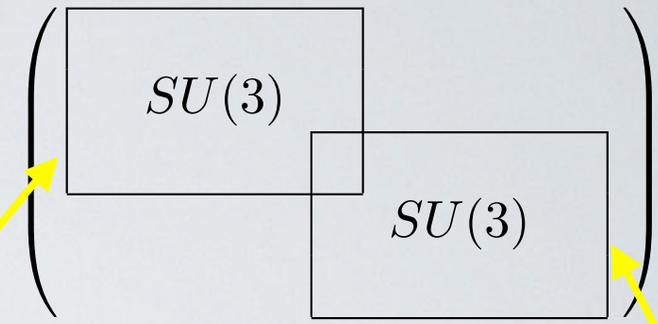


The Littlest Higgs Model

Arkani-Hamed/Cohen/Katz/Nelson, '02

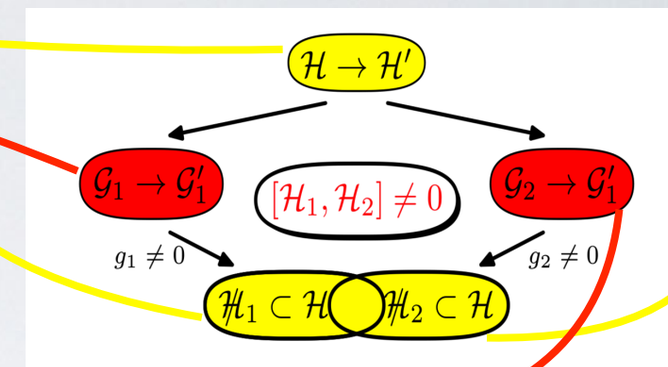
Based on *SU(5)/SO(5)* coset: Broken generators (24-10=14): X^a

$$\langle\Sigma\rangle = \begin{pmatrix} & & \mathbb{1} \\ & 1 & \\ \mathbb{1} & & \end{pmatrix} \qquad \Sigma(x) = e^{2i\Pi^a(x)X^a/f}\langle\Sigma\rangle$$



$$Q_1^a = \frac{1}{2}\begin{pmatrix} \sigma^a & \\ & \end{pmatrix} \qquad Q_2^a = \frac{1}{2}\begin{pmatrix} & \\ & -\sigma^{a*} \end{pmatrix}$$

$$Y_1 = \tfrac{1}{10}\mathrm{diag}\,(3,3,-2,-2,-2) \qquad Y_2 = \tfrac{1}{10}\mathrm{diag}\,(2,2,2,-3,-3)$$



Local symmetry: $SU(2)_l \otimes U(1)_l \otimes SU(2)_2 \otimes U(1)_2 \to SU(2)_L \otimes U(1)_Y$ eats up 4 Nambu-Goldstones

Covariant derivative:

$$D_\mu\Sigma = \partial_\mu\Sigma - i\sum_{j=1}^{2}\left[g_j W_j\left(Q_j\Sigma + \Sigma Q_j^T\right) + g_j' B_j\left(Y_j\Sigma + \Sigma Y_j^T\right)\right]$$

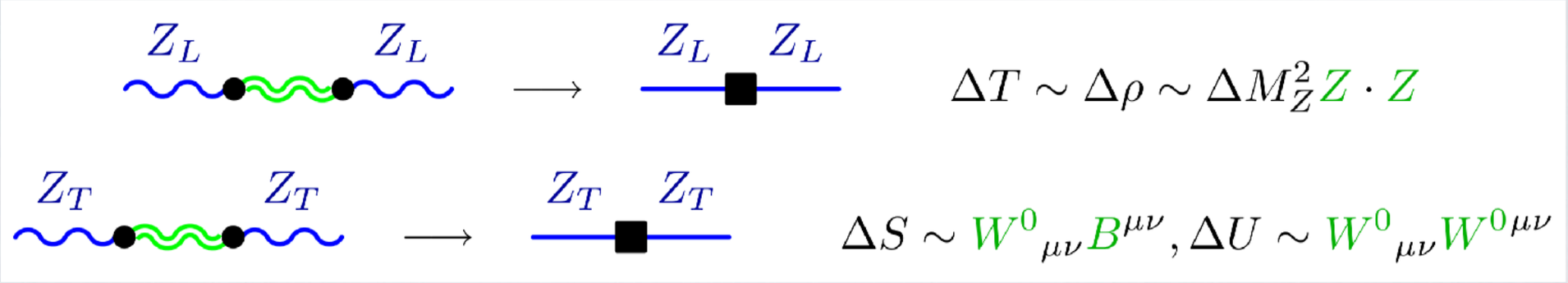
$$M_{W_H} \sim g\cdot f \qquad M_{Z_H} \sim g\cdot f \qquad M_{A_H} \sim g\cdot f \qquad M_\Phi \sim f \qquad m_h \sim \frac{f}{16\pi^2}$$

Goldstone bosons: $\mathbf{1}_0 \oplus \mathbf{3}_0 \oplus \mathbf{2}_{\pm\frac{1}{2}} \oplus \mathbf{3}_{\pm 1}$

$$\Pi^a X^a = \frac{1}{\sqrt{2}}\begin{pmatrix} & h^\dagger \\ h & h^* \\ h^T & \end{pmatrix} + \frac{1}{2}\begin{pmatrix} & \Phi^\dagger \\ \Phi & \end{pmatrix}$$

T-parity: a discrete symmetry for EWPO

Large contributions to EWPO Hewett/Petriello/Rizzo, '02; Csáki/Hubisz/Kribs/Meade/Terning, '03; Kilian/JRR, '03



Discrete symmetry: *T* (*TeV*)-Parity Cheng/Low, '03-'04

Involutary automorphism of symmetry algebra/coset space:

$$T : \Pi \mapsto -\Omega\Pi\Omega \qquad \Omega = \mathrm{diag}(1,1,-1,1,1) \qquad T^a \to T^a \quad X^a \to -X^a$$

$$M_\Phi = 1\,\mathrm{TeV}$$

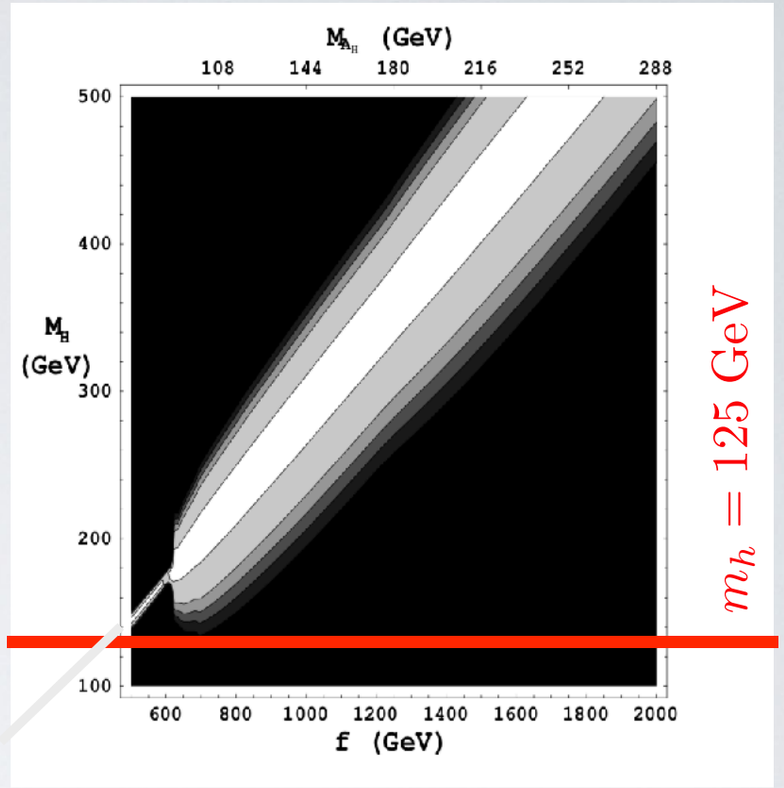
- (Almost) all new heavy particles *T*-odd
- Tree-level contributions to EWPO eliminated (also triplet Φ vev)
- Bounds on *f* relaxed from ca. 4-5 TeV to 500-600 GeV
- Only pair production of new particles at colliders
- Typical cascade decays
- Mixing angle 45° between $SU(2)_i$ and $U(1)_i$
- Lightest *T*-odd particle (LTP) is stable → Dark Matter candidate

$$M_{W_H} = M_{Z_H} = gf = 400 - 700\,\mathrm{GeV}$$

$$M_{A_H} = \frac{g' f}{\sqrt{5}} = 50 - 200\,\mathrm{GeV}$$

T-parity: a discrete symmetry for Dark Matter

- Lightest *T*-odd particle A_H (50-200 GeV)
- Dominant decay via *s*-channel Higgs exchange
  $A_H \rightarrow h \rightarrow WW, ZZ, hh$ Hubisz/Meade, '03
- Constraints from overclosure of universe
- Heavy lepton/quark coannihilation helps Yang/Wang/Shu, '13



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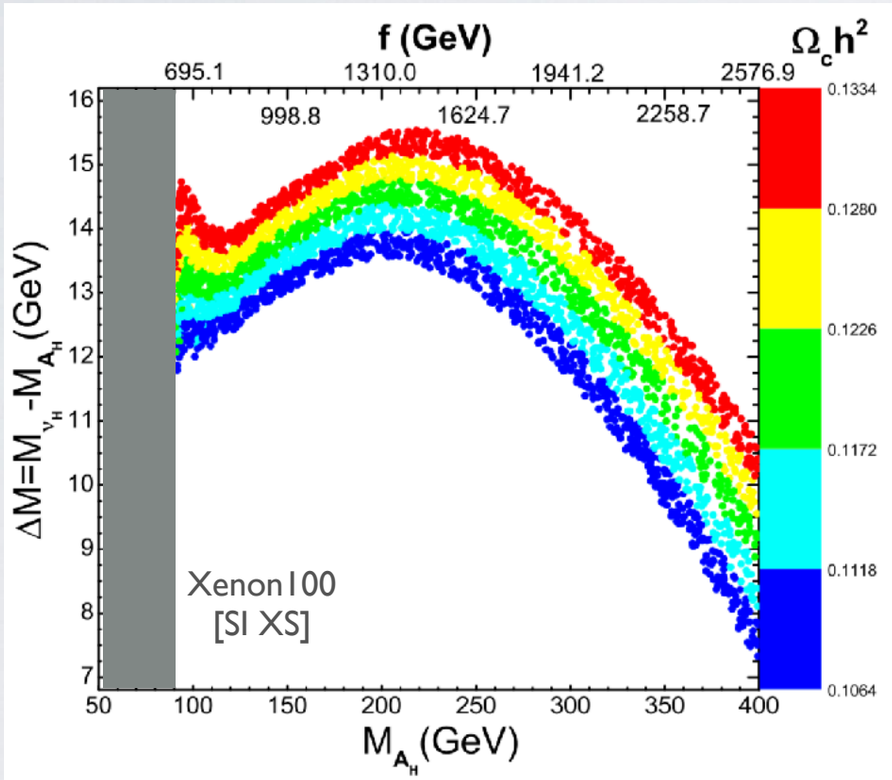

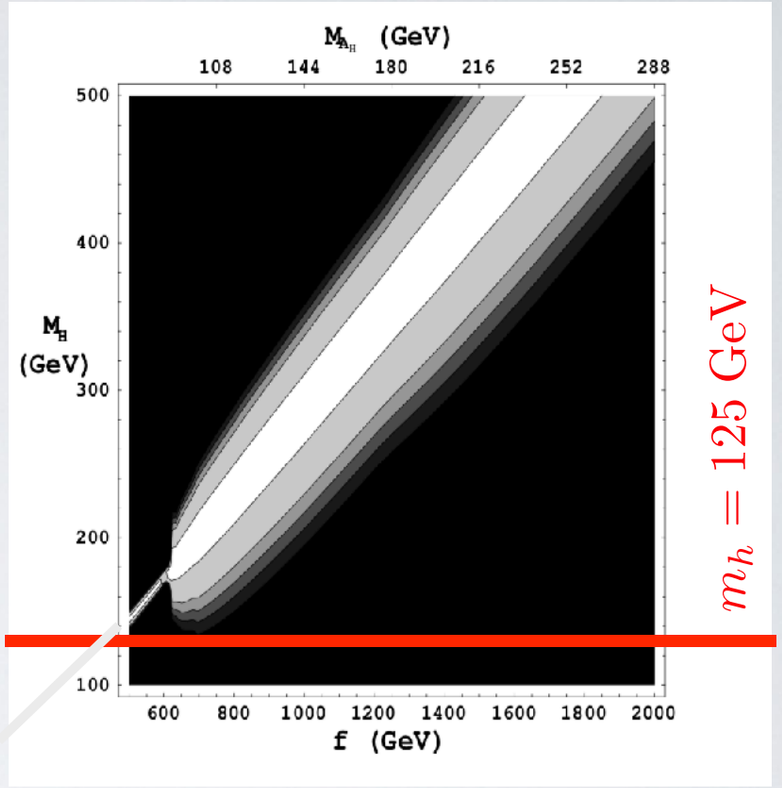

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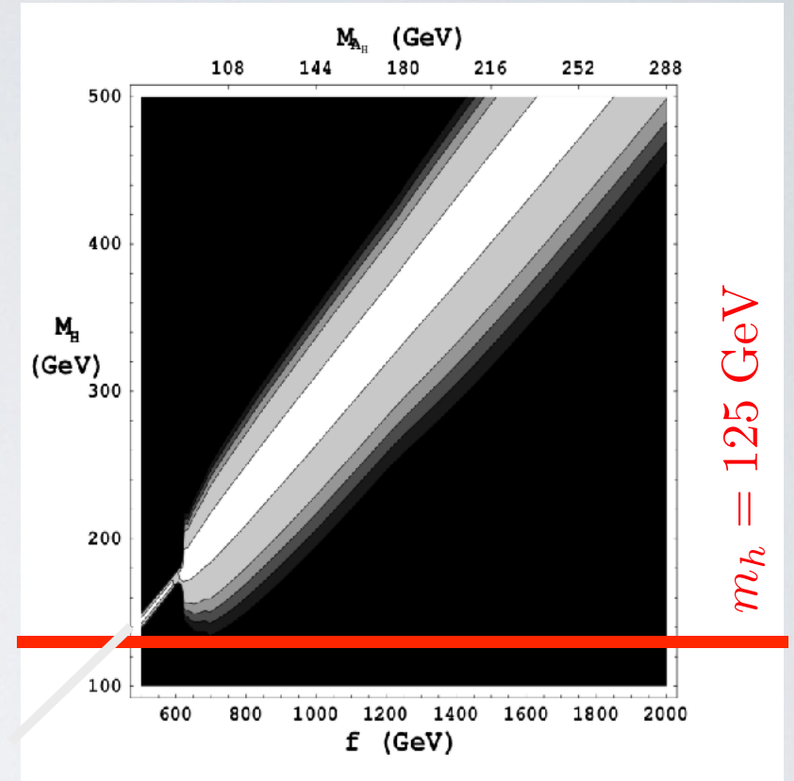

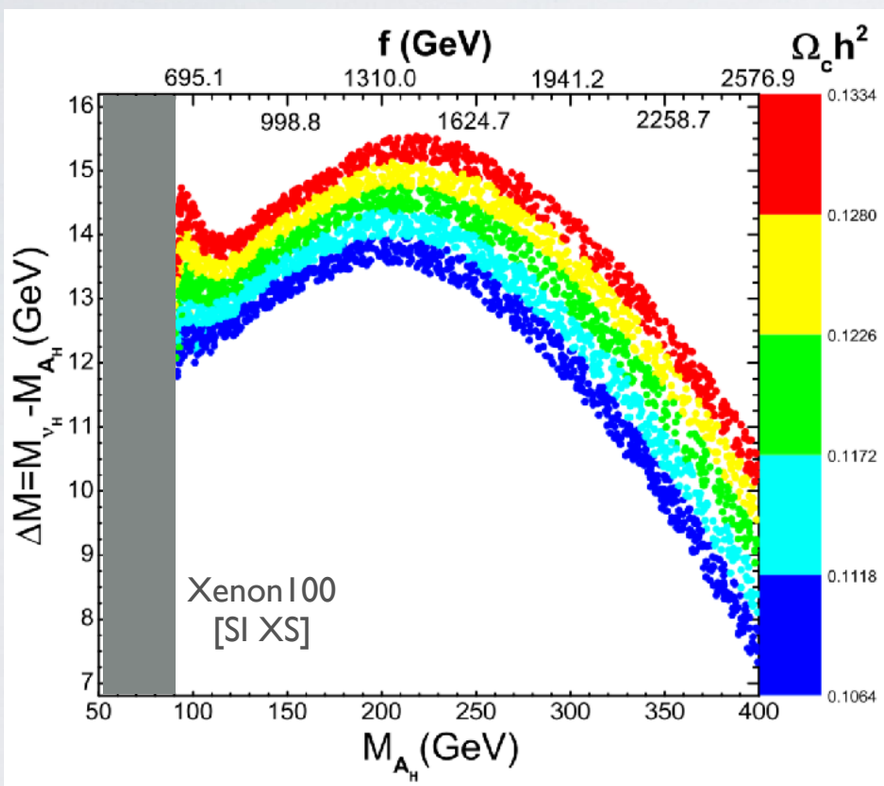

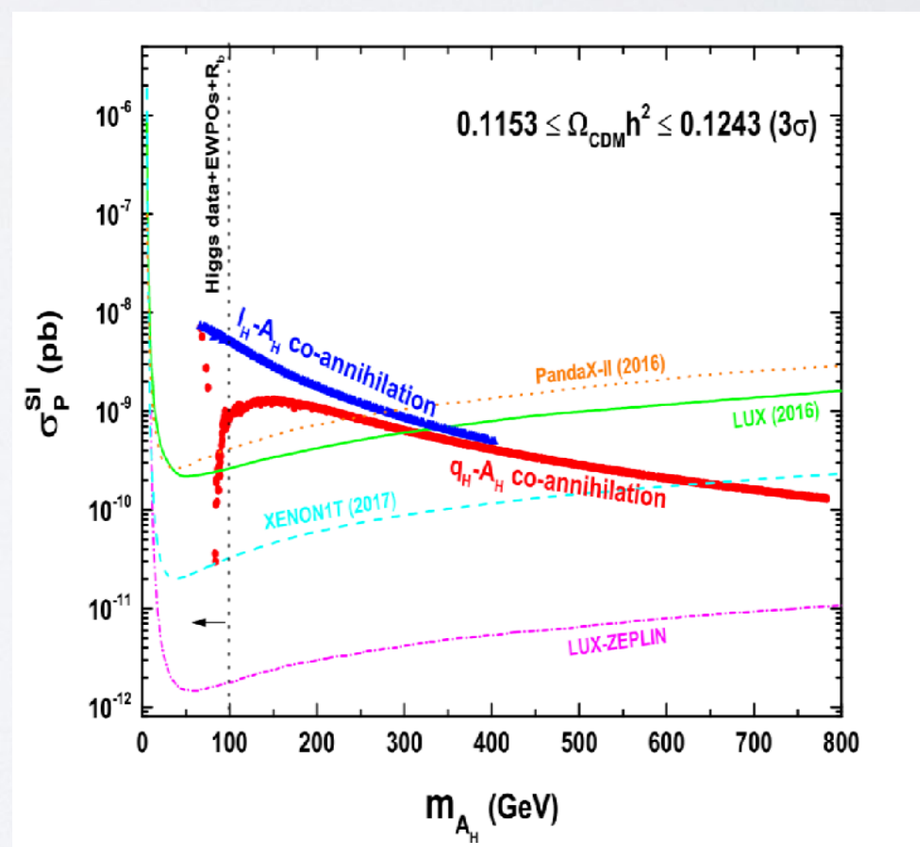

Severe constraints from direct detection
Yang/Wang/Shu, '13; Wu/Yang/Zhang, '16

T-parity violation

- Phenomenological motivation: A_H heavily constrained as DM candidate
- Assume *T*-parity violation
- DM candidate axion-like particle in mesonic sector of UV completion (+ QCD axion)
- *T*-parity violation: Wess/Zumino/Witten anomaly in UV sector Hill/Hill, '07
- In analogy to pion decays $\pi \to \gamma\gamma$ leads to $A_H \to WW, ZZ$

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- Consequences: DM bounds gone, collider phenomenology may change
- Decays to *WW*, *ZZ* (1-loop induced); to *ff* (2-loop induced) Freitas/Schwaller/Wyler, '08

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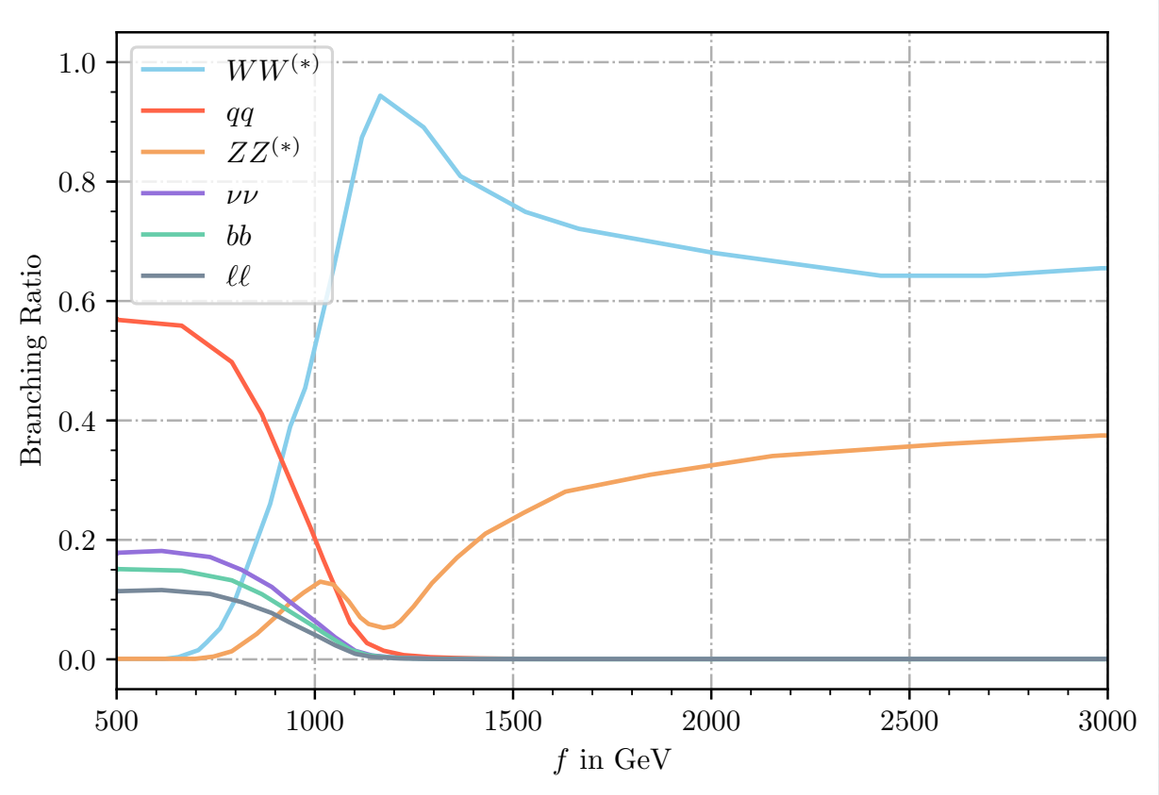
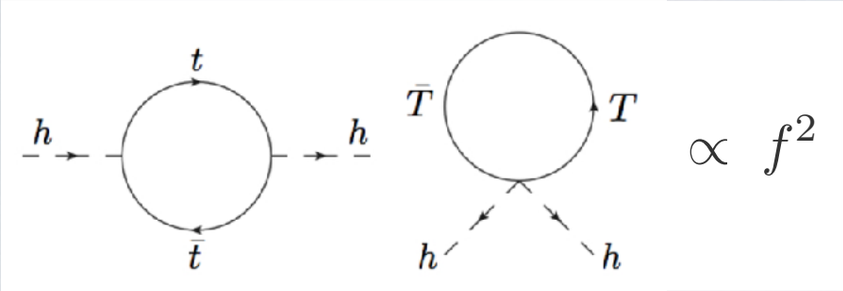
$$\Gamma(A_H \to ZZ) = \left(\frac{Ng'}{80\sqrt{3}\pi^3}\right)^2 \left(1 - \frac{4m_Z^2}{M_{A_H}^2}\right)^{\frac{5}{2}} \frac{M_{A_H}^3 m_Z^2}{f^4}$$

$$\Gamma(A_H \to W^+W^-) = \left(\frac{Ng'}{40\sqrt{3}\pi^3}\right)^2 \left(1 - \frac{4m_W^2}{M_{A_H}^2}\right)^{\frac{5}{2}} \frac{M_{A_H}^3 m_W^2}{f^4}$$

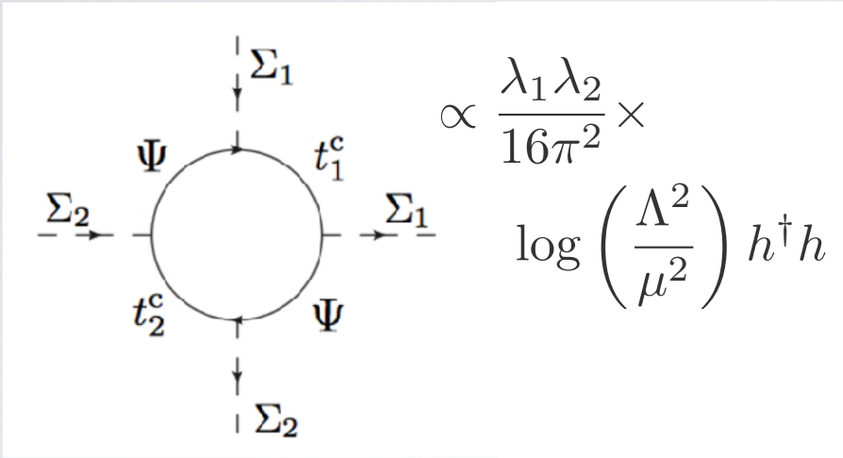
$$\Gamma(A_H \to ff) = \left(\frac{N_{C,f} M_{A_H}}{48\pi}\right) \left(1 - \frac{4m_f^2}{M_{A_H}^2}\right)^{\frac{1}{2}} \left[c_-^2 \left(1 - \frac{4m_f^2}{M_{A_H}^2}\right) + c_+^2 \left(1 + \frac{2m_f^2}{M_{A_H}^2}\right)\right]$$



Collective Symmetry Breaking / Fermion Masses



$\propto f^2$



$$\propto \frac{\lambda_1\lambda_2}{16\pi^2}\times \log\left(\frac{\Lambda^2}{\mu^2}\right) h^\dagger h$$

$\kappa_q \quad \kappa_\ell$ $\quad f \quad$ $R = \frac{\lambda_1}{\lambda_2}$

Top sector:

$$\Psi = \begin{pmatrix} ib_L \\ -it_{1L} \\ t_{2L} \\ \mathbf{0}_{2\times 1} \end{pmatrix} \qquad \Psi' = \begin{pmatrix} \mathbf{0}_{2\times 1} \\ t'_{2L} \\ ib'_L \\ -it'_{1L} \end{pmatrix} \qquad \Psi \overset{T}{\leftrightarrow} -\langle\Sigma\rangle\Psi'$$

$$\mathcal{L}_Y \supset \frac{\lambda_1 f}{2\sqrt{2}}\epsilon_{ijk}\epsilon_{xy}(\overline{\Psi}_i\Sigma_{jx}\Sigma_{ky} - (\overline{\Psi'})_i\tilde{\Sigma}_{jx}\tilde{\Sigma}_{ky})t_{1R}$$
$$+\lambda_2 f(\bar{t}_{2L}t_{2R} + \overline{t'}_{2L}t'_{2R}) + h.c.$$

$$i,j,k = 1,2,3 \quad x,y = 4,5 \qquad \tilde{\Sigma} = \Sigma_0\Omega\Sigma^\dagger\Omega\Sigma_0$$

1st/2nd generation quarks & leptons:

$$\mathcal{L}_Y \supset \frac{i\lambda_d f}{2\sqrt{2}}\epsilon_{ij}\epsilon_{xyz}(\overline{\Psi'}_x\Sigma_{jy}\Sigma_{jz}\Sigma_{33}^{\pm\frac{1}{4}} - (\overline{\Psi}\Sigma_0)_x\tilde{\Sigma}_{iy}\tilde{\Sigma}_{jz}\tilde{\Sigma}_{33}^{\pm\frac{1}{4}})d_R$$

$$\mathcal{L}_\kappa = -\kappa f(\overline{\Psi'}e^{i\Pi^a X^a/f}\Psi_c + \overline{\Psi}\Sigma_0\Omega e^{-i\Pi^a X^a/f}\Omega\Psi_c) + h.c.$$

$$m_t = \frac{\lambda_1\lambda_2}{\lambda_1^2+\lambda_2^2}v = \frac{\lambda_2 R}{\sqrt{1+R^2}}v$$
$$M_{T^-} = \lambda_2 f = \frac{m_t}{v}\frac{f\sqrt{1+R^2}}{R}$$
$$M_{T^+} = \frac{m_t}{v}\frac{f(1+R^2)}{R} = M_{T^-}\sqrt{1+R^2}$$

$$M_{u,-} = \sqrt{2}\,\kappa_q f\left(1 - \frac{1}{8}\frac{v^2}{f^2}\right)$$
$$M_{d,-} = \sqrt{2}\,\kappa_q f$$
$$M_{\ell/\nu,-} = \sqrt{2}\,\kappa_l f$$

$$\Psi_c = \begin{pmatrix} id_c, \\ -iu_c, \\ \chi_c, \\ i\tilde{d}_c, \\ -i\tilde{u}_c \end{pmatrix}$$

$$\Psi_c \overset{T}{\leftrightarrow} -\Psi_c$$

"mirror fermions"

Signatures and constraints on the LHT model

- New heavy particles: vector-like *T*-odd/even quarks, *T*-odd vectors, LTP (A_H)
- SUSY-like search signatures: mono-jets + MET, multi-jets (+MET), jets+leptons (+MET)
- Deviations in coupling constants at level of $\lesssim$ 5% (v^2/f^2)

Modified *HVV* couplings:

$$2\frac{m_V^2}{v}\left(1+\mathcal{O}(v^2/f^2)\right) hV\cdot V$$

Modified *ttH* couplings:

$$\frac{m_t^2}{v}\Big[\left(1+\mathcal{O}(v^2/f^2)\right) h\bar{t}t + \mathcal{O}(v^2/f^2)\, h\bar{t}\gamma^5 t\Big]$$

Modified *Vff* couplings:

$$\frac{g}{c_W}\sum_f \bar{f}\gamma^\mu\Big[\left(1+\mathcal{O}(v^2/f^2)\right) g_L^{\mathrm{SM}}\mathcal{P}_L + \left(1+\mathcal{O}(v^2/f^2)\right) g_R^{\mathrm{SM}}\mathcal{P}_R\Big] f Z_\mu$$

Electroweak Precision Observables, e.g. *T* or ρ parameter:

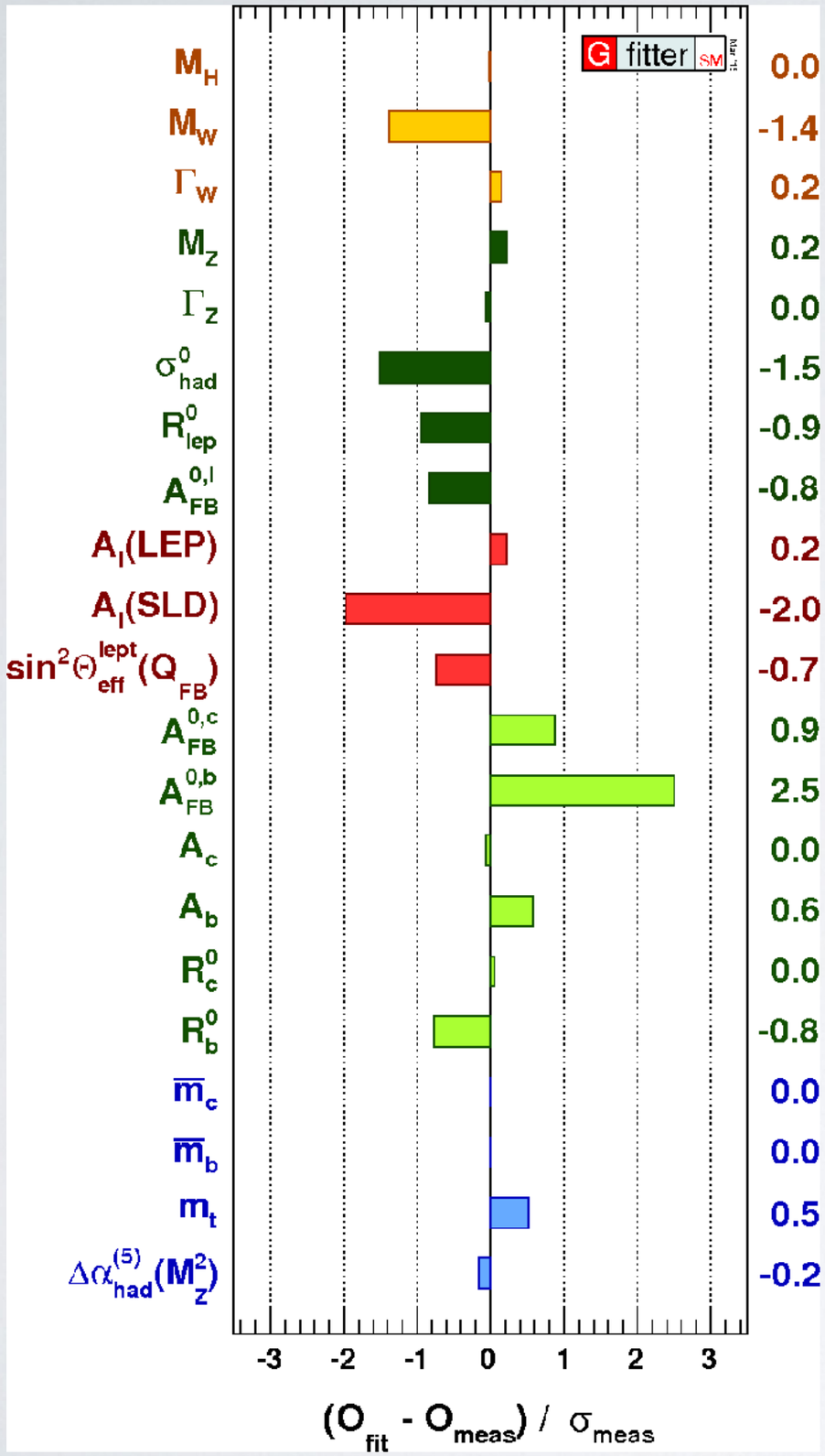
$$\Delta T = \underbrace{\frac{3}{16\pi}\frac{m_t^2}{m_Z^2}\mathcal{O}(1)}_{\Delta T_{T_+}} - \underbrace{\sum_{q_H,\ell_H}\frac{\kappa_{q,\ell}^2}{192\pi^2\alpha_W}\frac{v^2}{f^2}}_{\Delta T_{q_H,\ell_H}} + \underbrace{\frac{1}{8\pi c_W^2}\frac{v^2}{f^2}\log\frac{m_H}{\Lambda}}_{\Delta T_{HVV}} + \underbrace{\frac{m_W^2}{2\pi e^2 g^2 f^2}\mathcal{O}(1)}_{\Delta T_{\mathrm{UV}}}$$

only loop contributions (*T*-parity); partial cancellation of different terms

Fine tuning defined as Higgs mass squared ratio to radiative corrections:

$$\Delta := \frac{\mu_{\mathrm{exp.}}{}^2}{|\delta\mu^2|}$$

Electroweak Precision Observables



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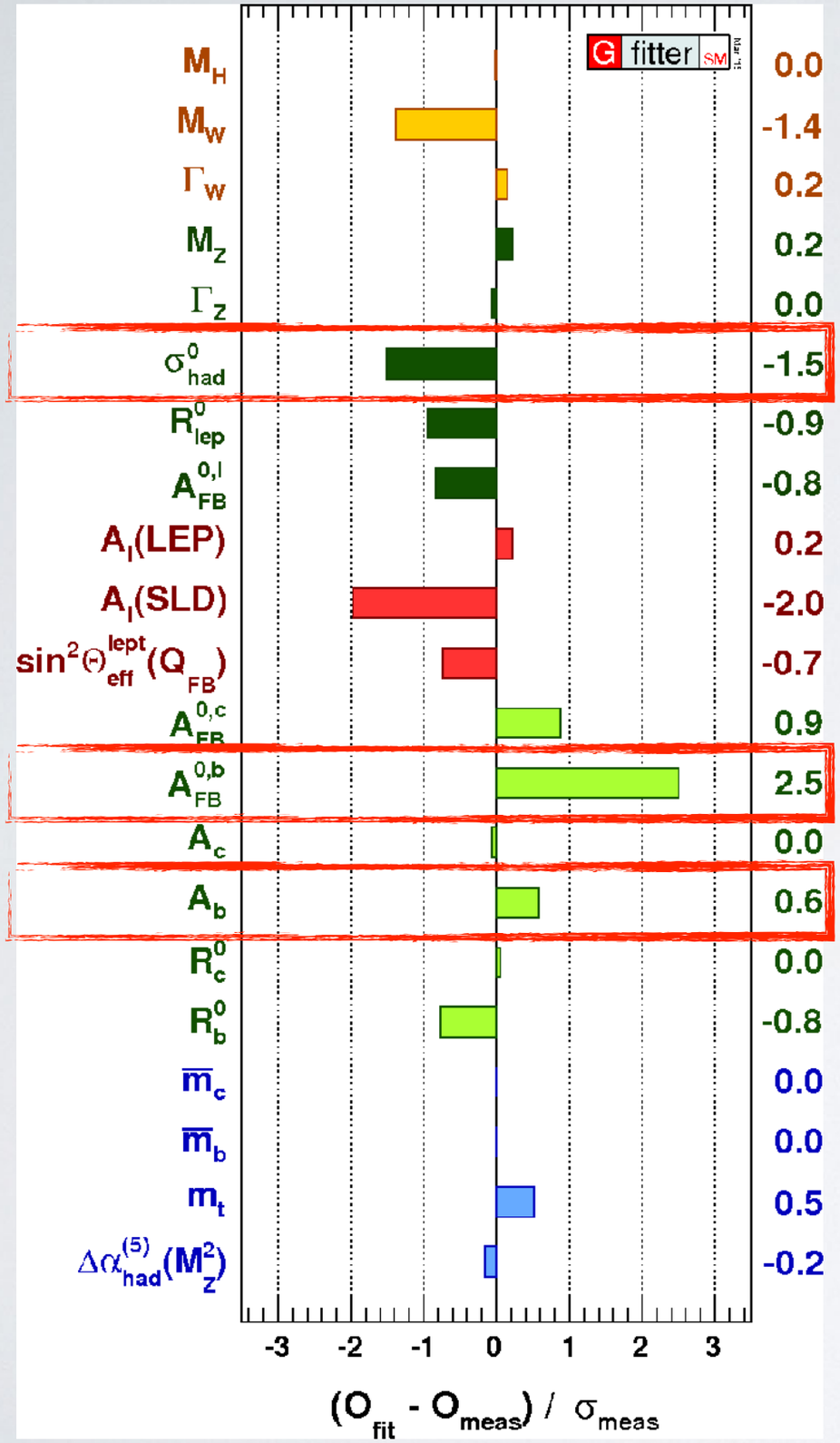

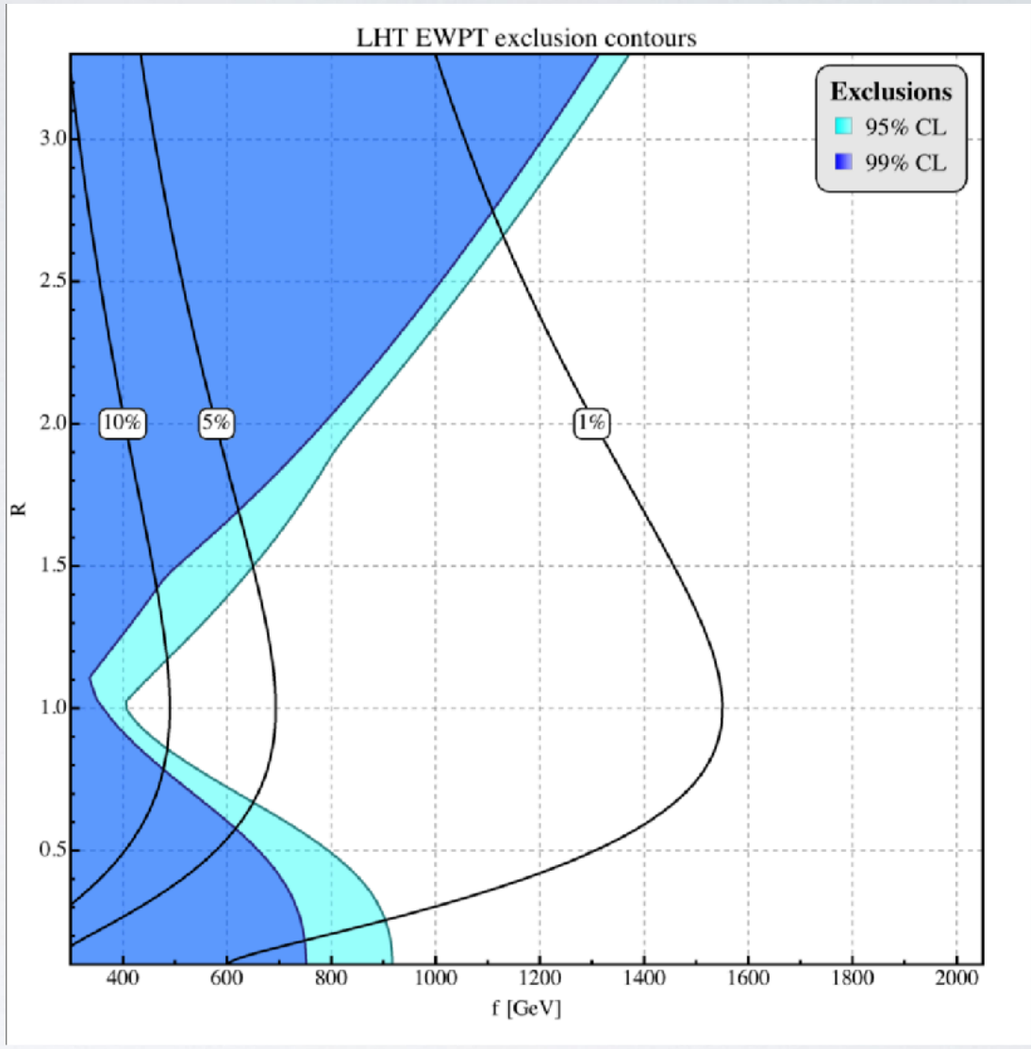

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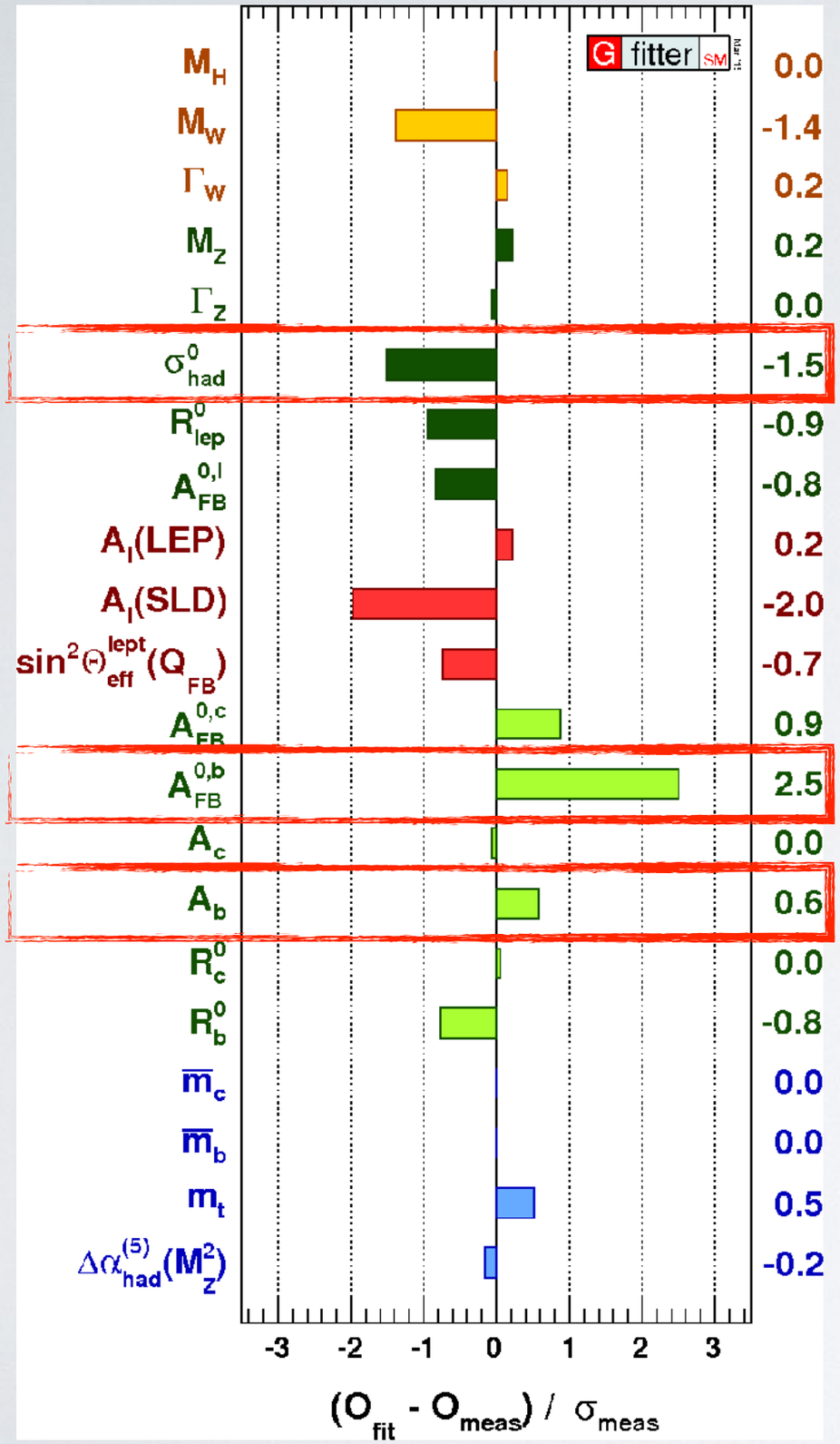
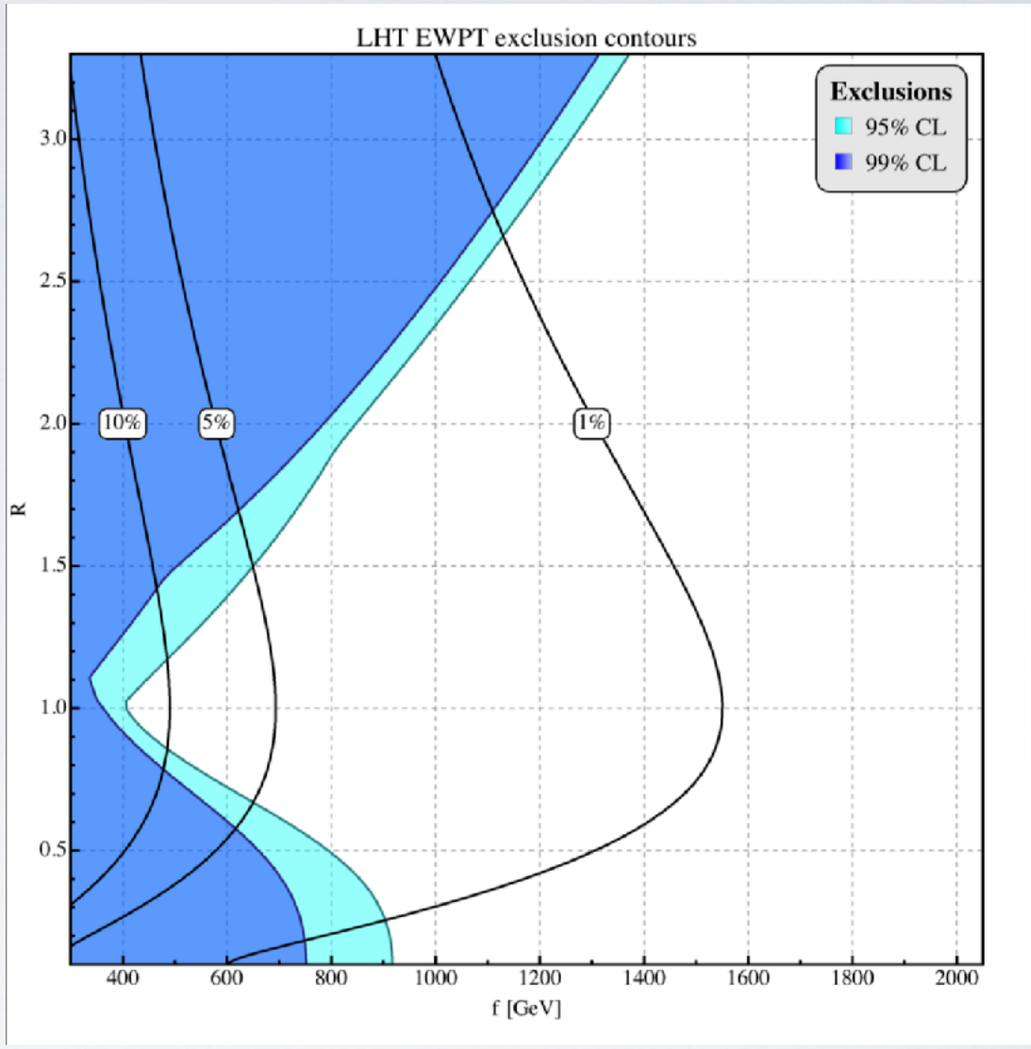




- Accidental cancellation to EWPO for $R \simeq 1$
- Bounds from 4-fermion contact interactions (later)
- Exclusion limits at 95% CL: $\boxed{f \gtrsim 405 \text{ GeV}}$

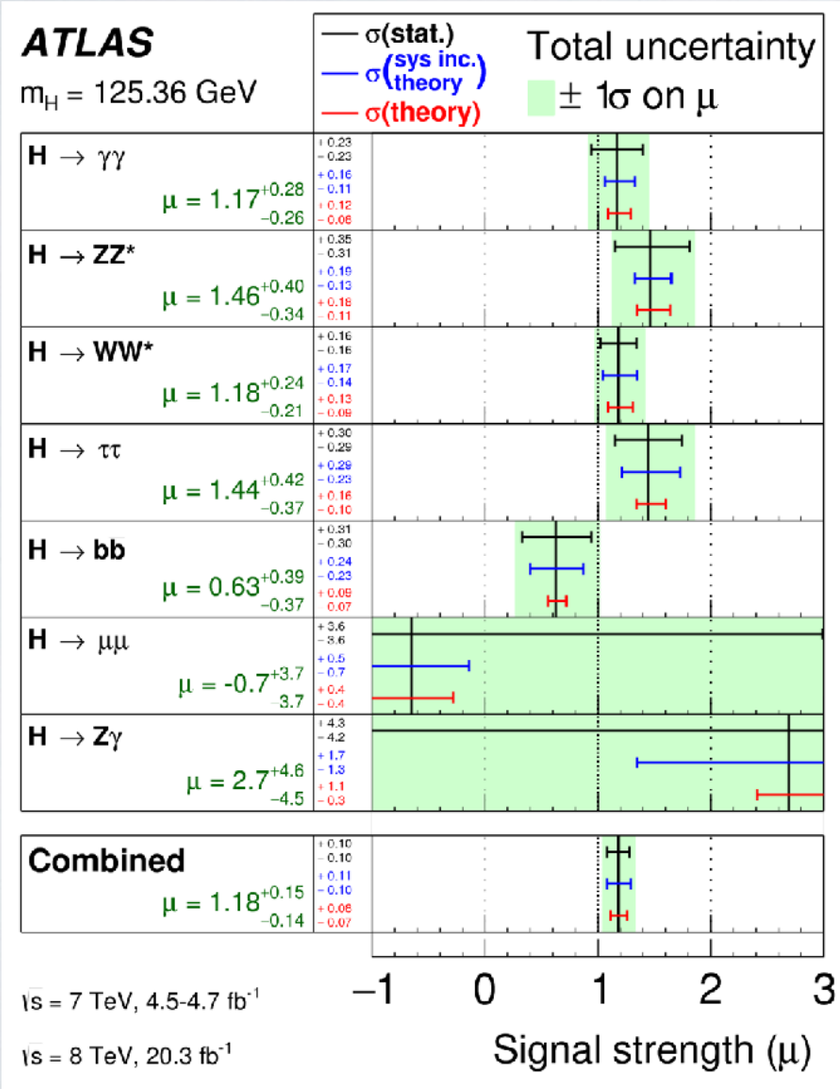
$$M_{W'} \gtrsim 270 \text{ GeV}$$
$$M_T \gtrsim 554 \text{ GeV}$$

Constraints from Higgs measurements

- Main driver of constraints from Higgs data: invisible decay channel $H \to A_H A_H$
- Modifications of gluon fusion, vector boson fusion, top-associated production
- Minor effect: modifications in branching ratios (LHC cannot disentangle these!)

Signal strength modifier in channel *i*

$$\mu^i = \frac{n_S^i}{n_S^{\mathrm{SM},i}} = \sum_{prod.} \frac{n_{S,p}^i \zeta_p^i}{\sigma_p^{\mathrm{SM}} \mathrm{BR}_i^{\mathrm{SM}}} \longrightarrow \left[c_g \zeta_g^i + c_V^2 \zeta_V^i + c_t^2 \zeta_t^i\right] \frac{\mathrm{BR}_i}{\mathrm{BR}_i^{\mathrm{SM}}}$$



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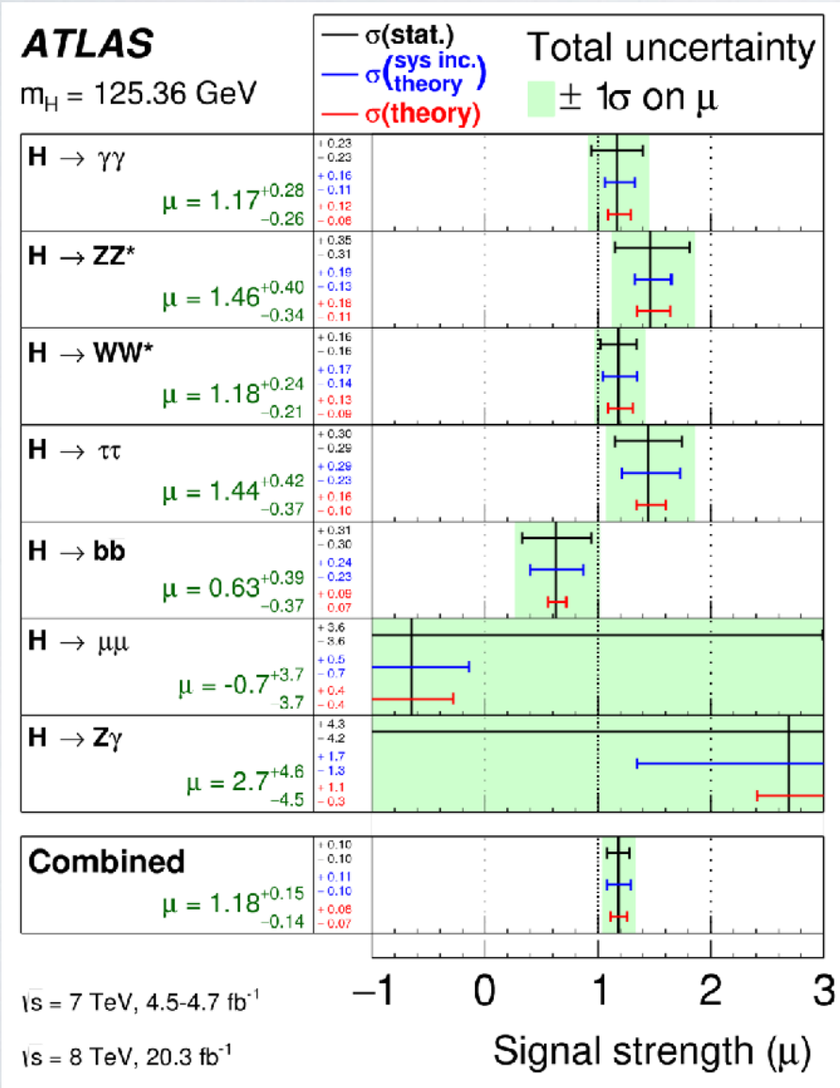
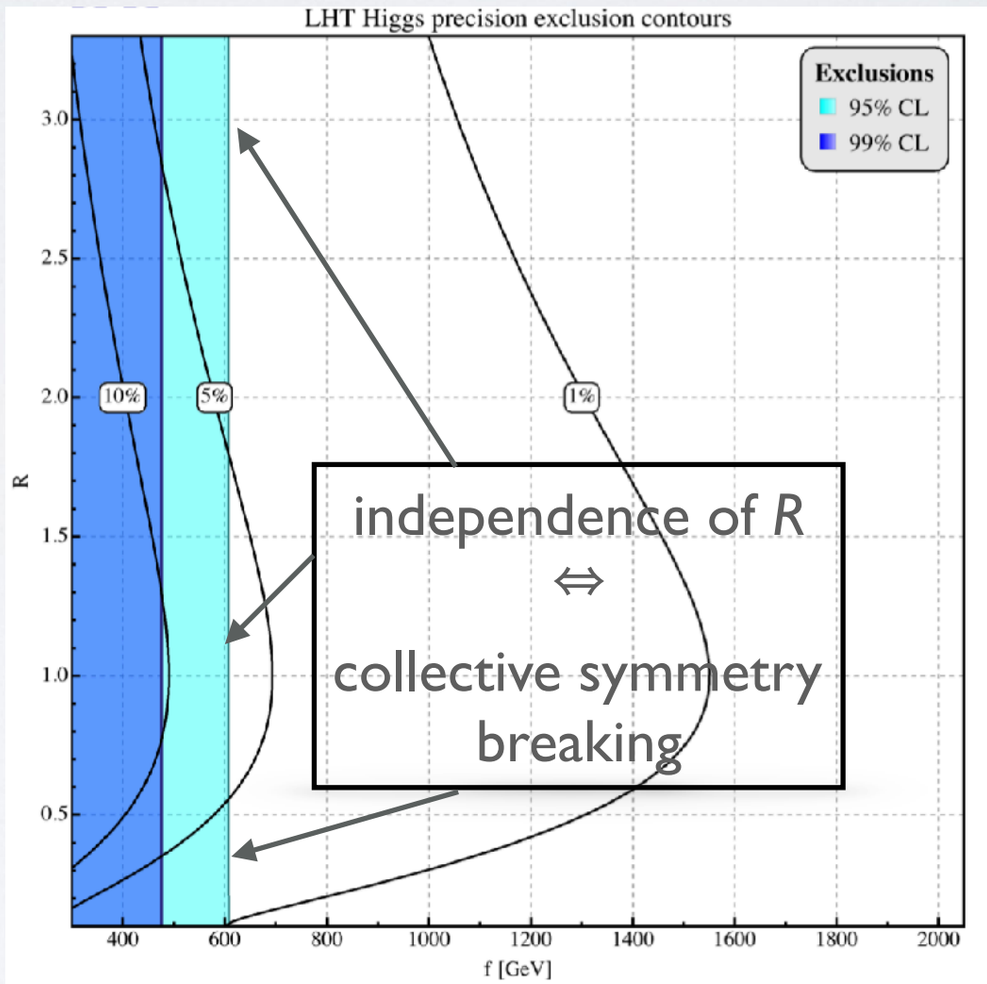
Signal strength modifier in channel *i* $\mu^i = \frac{n_S^i}{n_S^{\mathrm{SM},i}} = \sum_{prod.} \frac{n_{S,p}^i \zeta_p^i}{\sigma_p^{\mathrm{SM}} \mathrm{BR}_i^{\mathrm{SM}}} \longrightarrow \left[c_g \zeta_g^i + c_V^2 \zeta_V^i + c_t^2 \zeta_t^i\right] \frac{\mathrm{BR}_i}{\mathrm{BR}_i^{\mathrm{SM}}}$





Constraints from Higgs measurements

- Main driver of constraints from Higgs data: invisible decay channel $H \to A_H A_H$
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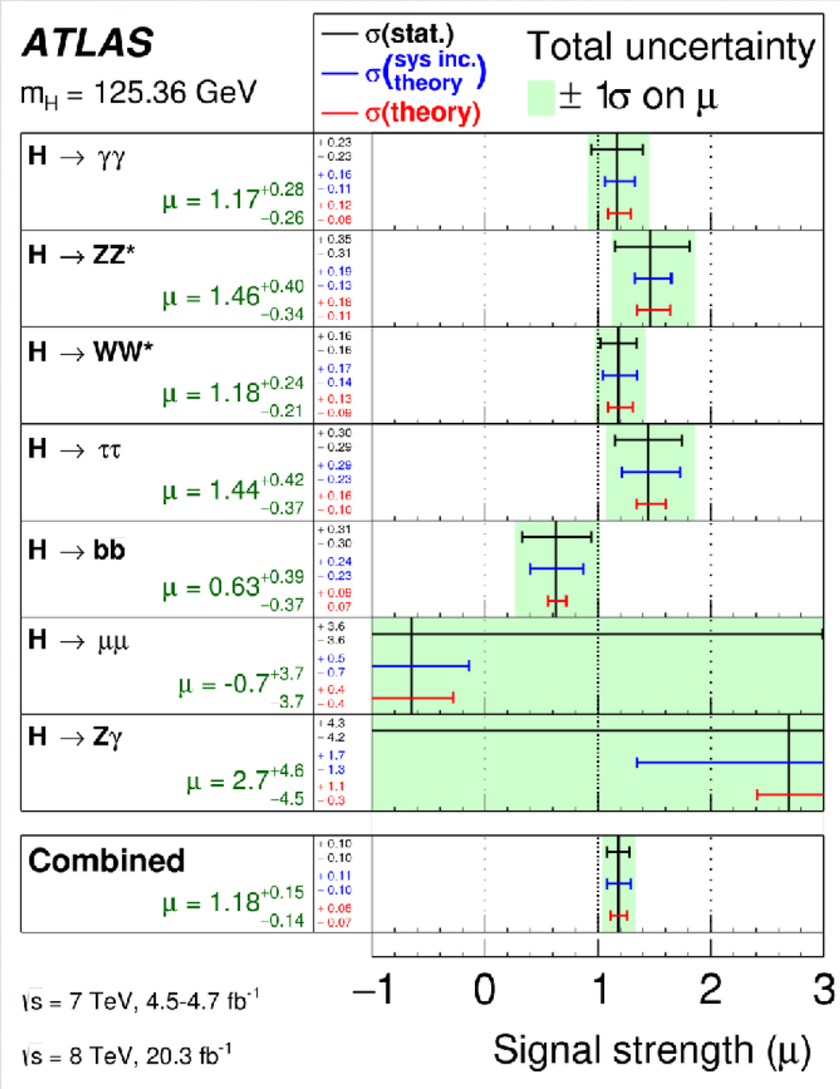

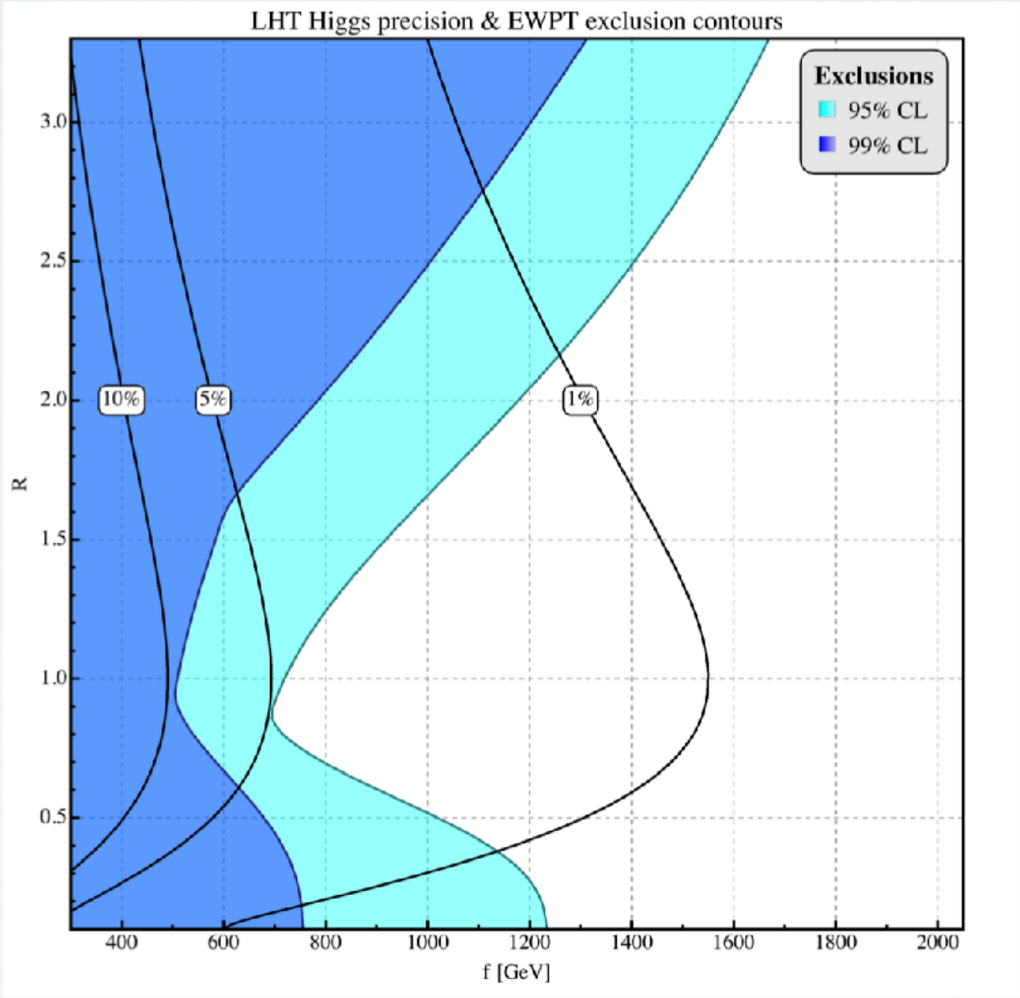

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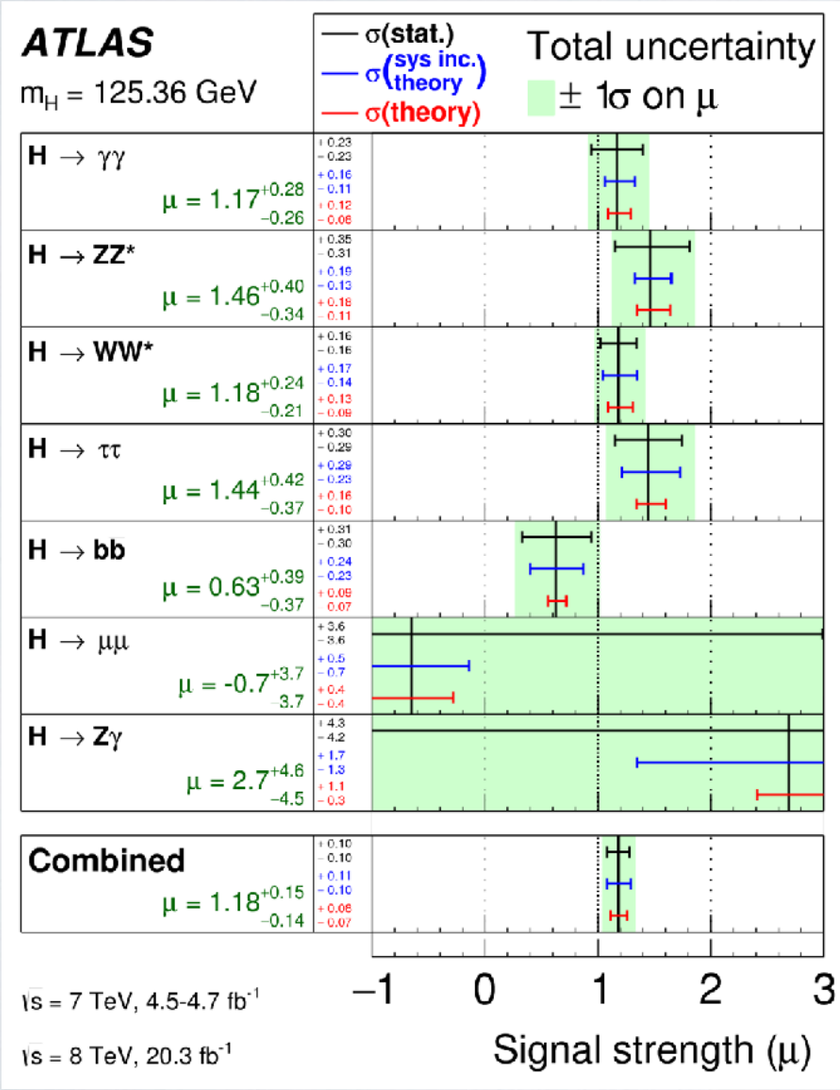
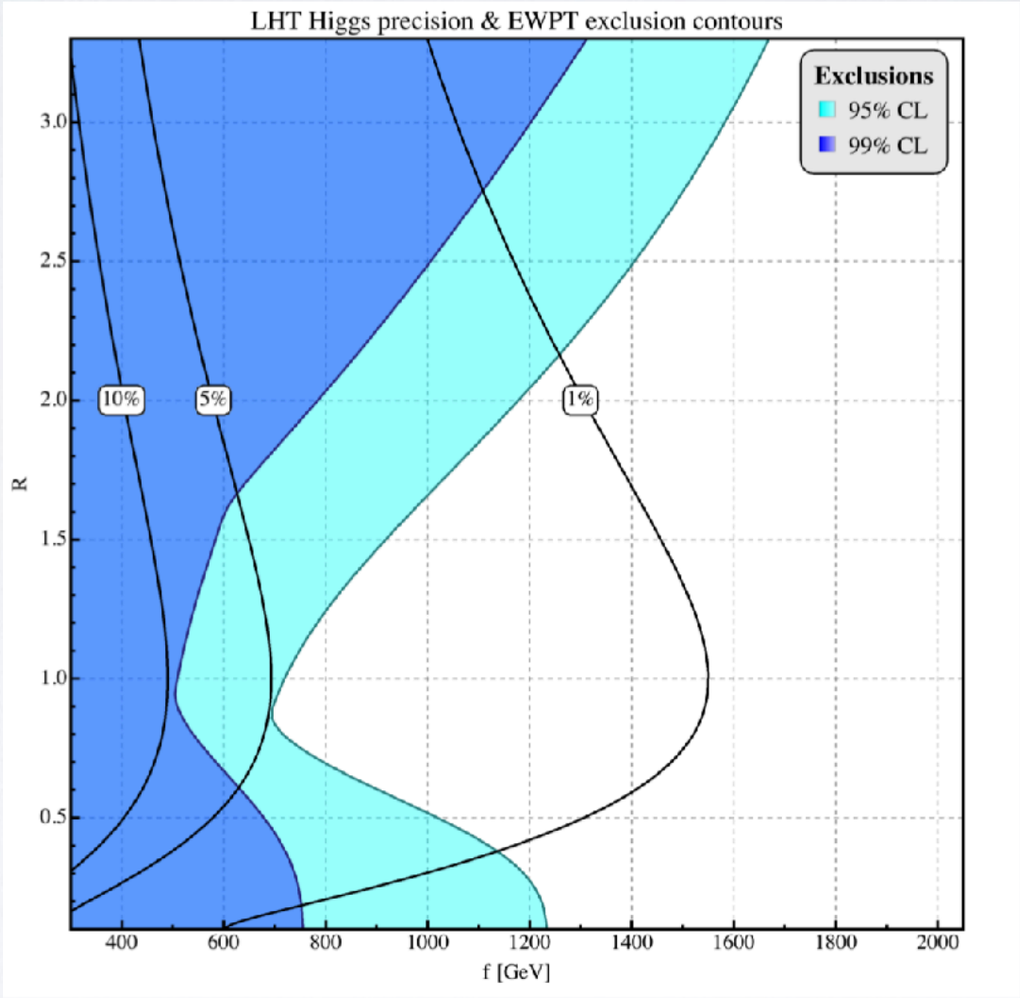




EWPT/Higgs data:

$$f \gtrsim 694 \text{ GeV}$$

Direct searches: Topologies & Benchmarks

Notation:

$q_H := \{d_H, u_H, s_H, c_H, b_H, t_H\}$

$\ell_H := \{e_H, \mu_H, \tau_H, \nu_{eH}, \nu_{\mu H} \nu_{\tau H}\}$

$V_H := \{W_H, Z_H, A_H\}$

$T^\pm :=$ *T*-even/odd top partners

Production processes:

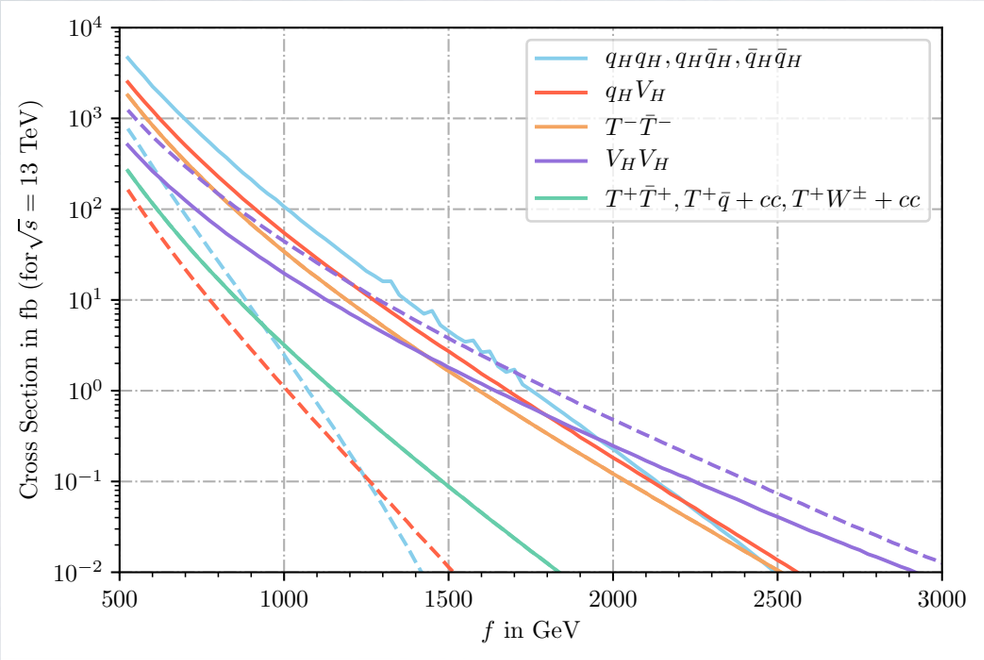
1. $pp \to q_H q_H, q_H \bar{q}_H, \bar{q}_H \bar{q}_H$
2. $pp \to q_H V_H$
3. $pp \to \ell_H \bar{\ell}_H$
4. $pp \to V_H V_H$
5. $pp \to T^+ \bar{T}^+, T^- \bar{T}^-$
6. $pp \to T_+ \bar{q}, \bar{T}_+ q, T_+ W^\pm, \bar{T}_+ W^\pm$

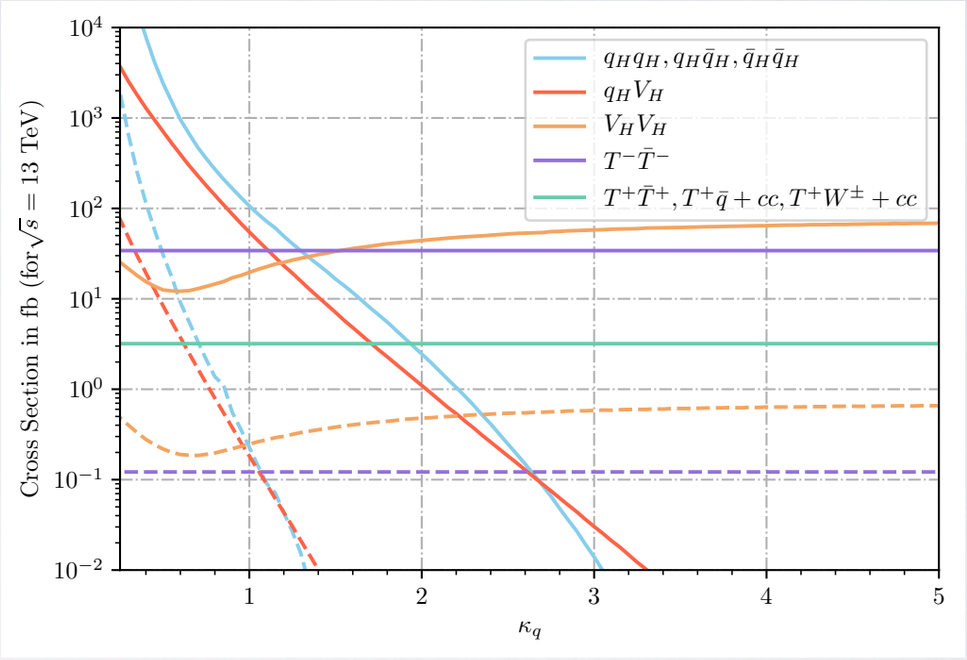
2 x 2 x 3 different benchmark scenarios:

Sector	Model	Constraint	Phenomenology	Considered Topology
f_H	*Fermion Universality*	$\kappa_l = \kappa_q$	• mass degeneracy of q_H, ℓ_H • ℓ_H production negligible	Exclude process 3
	Heavy q_H	$\kappa_q = 3.0$	• q_H decoupled • ℓ_H production relevant	Exclude processes 1, 2
	Light ℓ_H	$\kappa_l = 0.2$	• ℓ_H very light • V_H branching ratios change	Exclude process 3
$T^\pm$	*Light $T^\pm$*	$R = 1.0$	• $T^\pm$ are light/accessible	Include process 4, 5
	Heavy $T^\pm$	$R = 0.2$	• $T^\pm$ are heavy/inaccessible	Exclude process 4, 5
A_H	*TPC*	No TPV	• A_H is stable and invisible	A_H stable
	TPV	With TPV	• A_H is unstable	$A_H \to VV$ decays

Cross Sections & Branching ratios (I)

(Fermion Universality/Light ℓ_H) ⊕ (Light $T^\pm$) 13 TeV

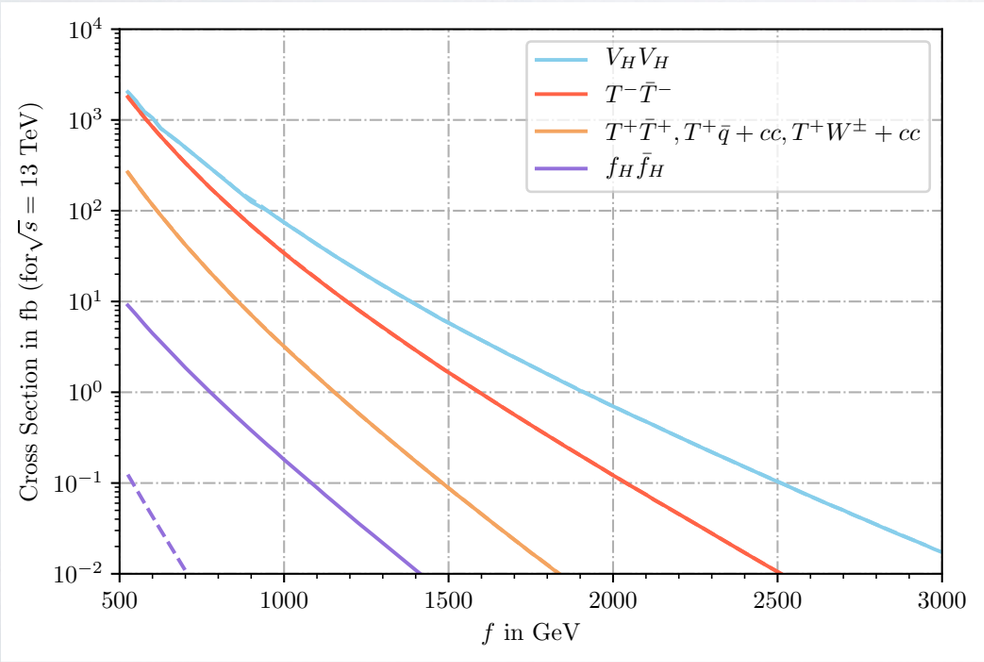


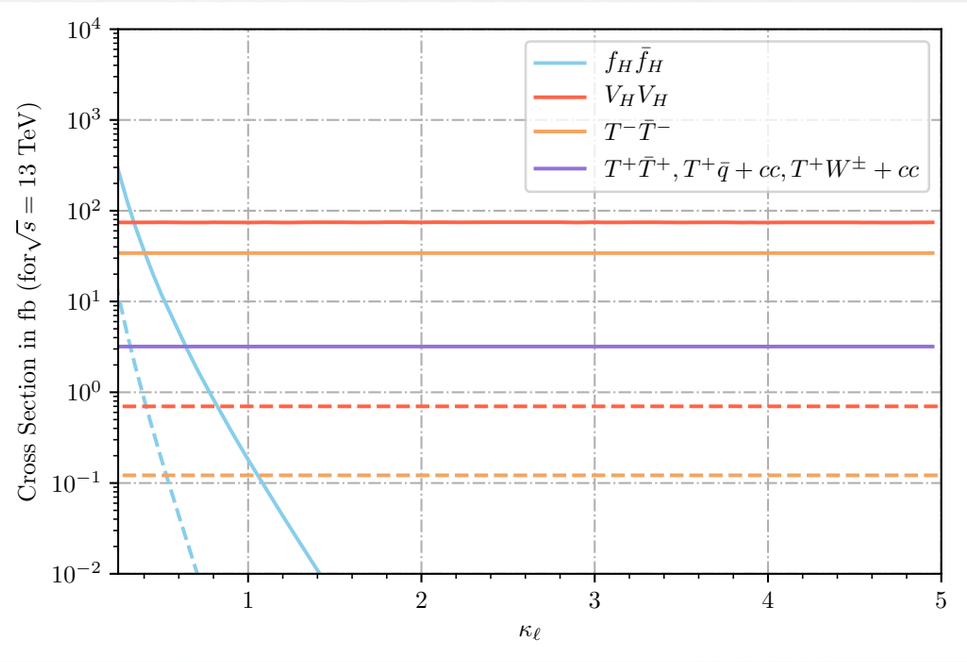


Left: fixed κ
Full line: f = 1 TeV
Dashed: f = 2 TeV

Right: fixed f
Full line: κ = 1 TeV
Dashed: κ = 2 TeV

(Heavy q_H) ⊕ (Light $T^\pm$) 13 TeV





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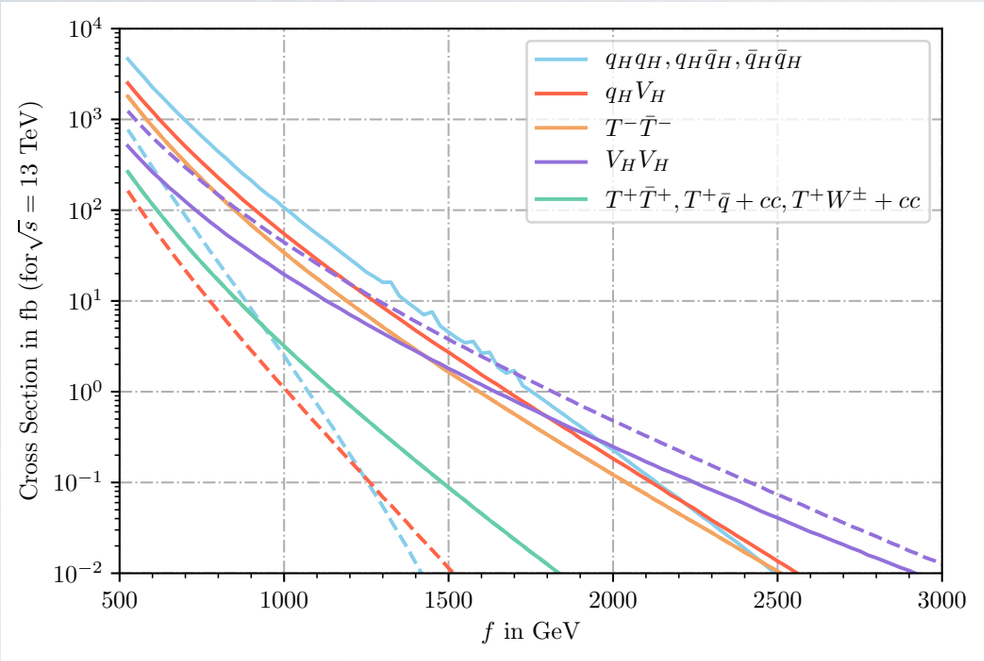

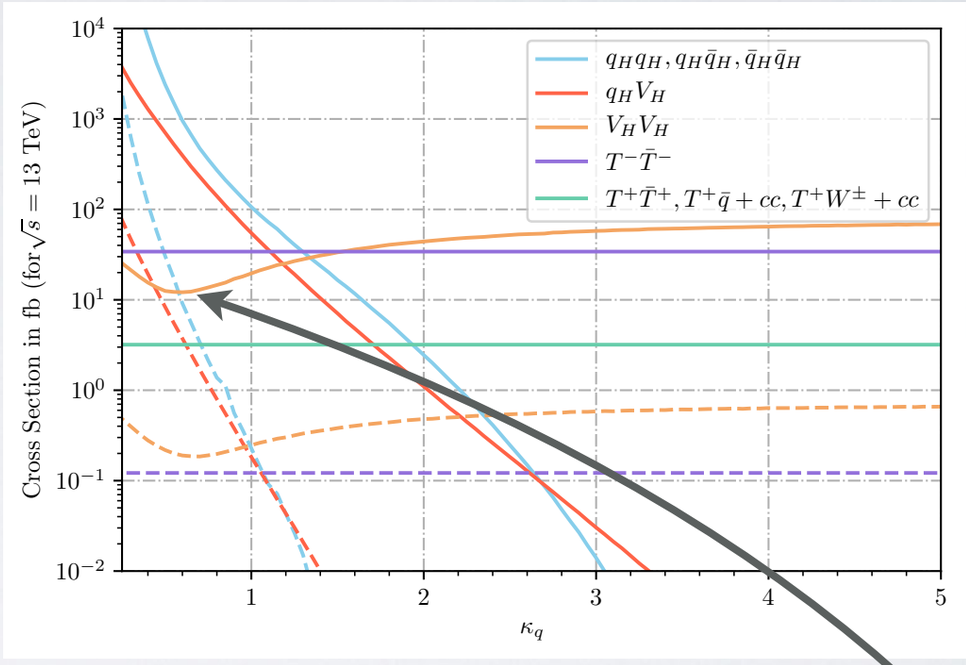

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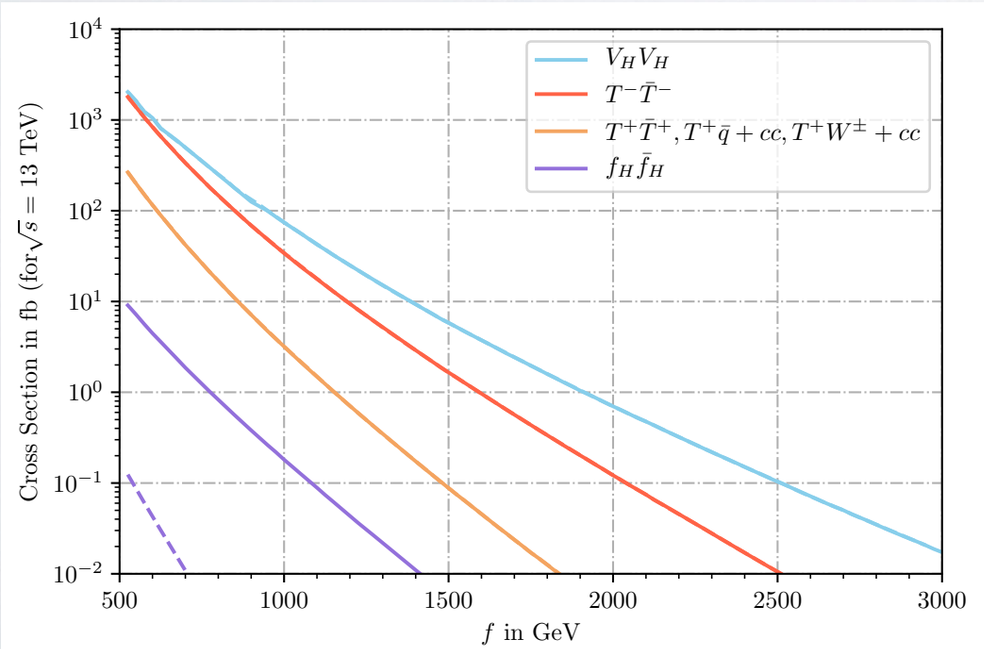
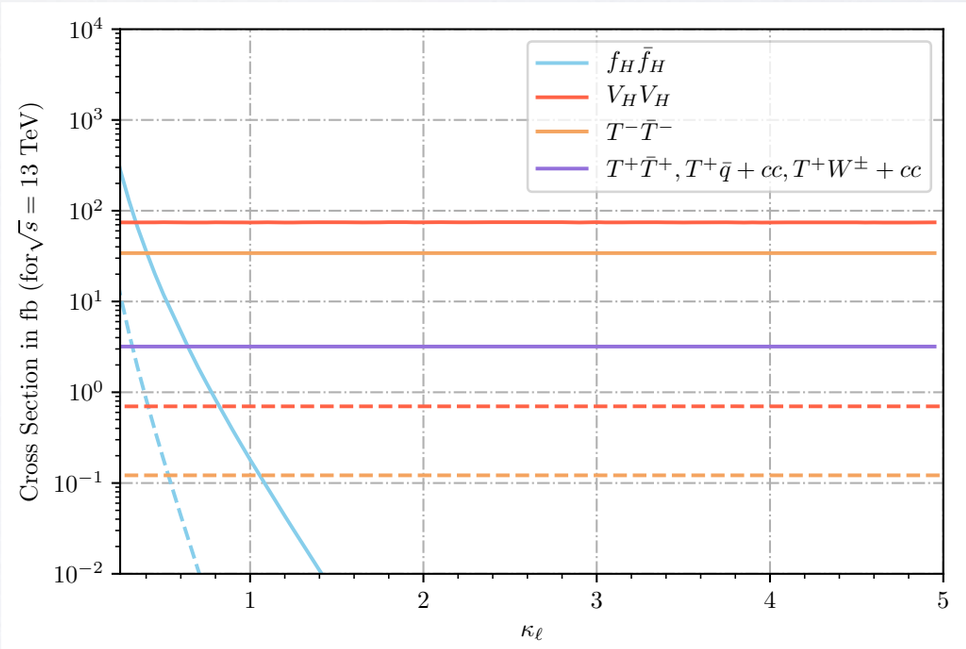
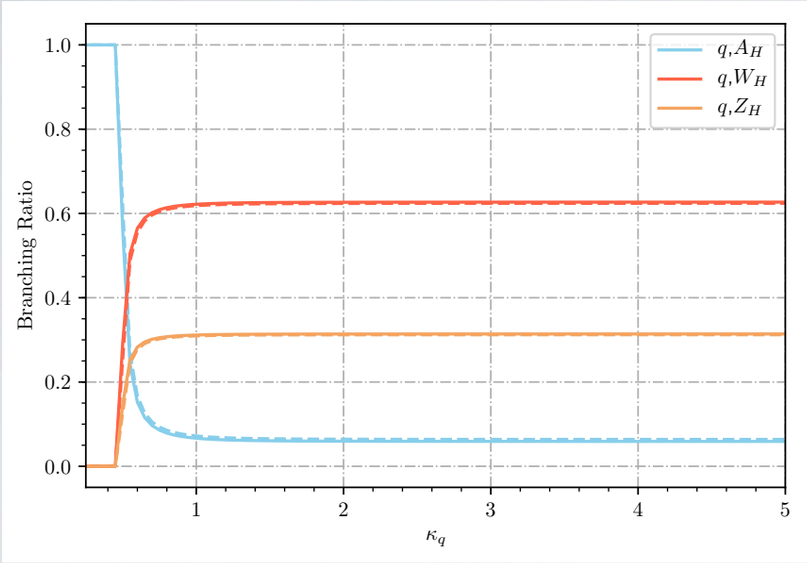


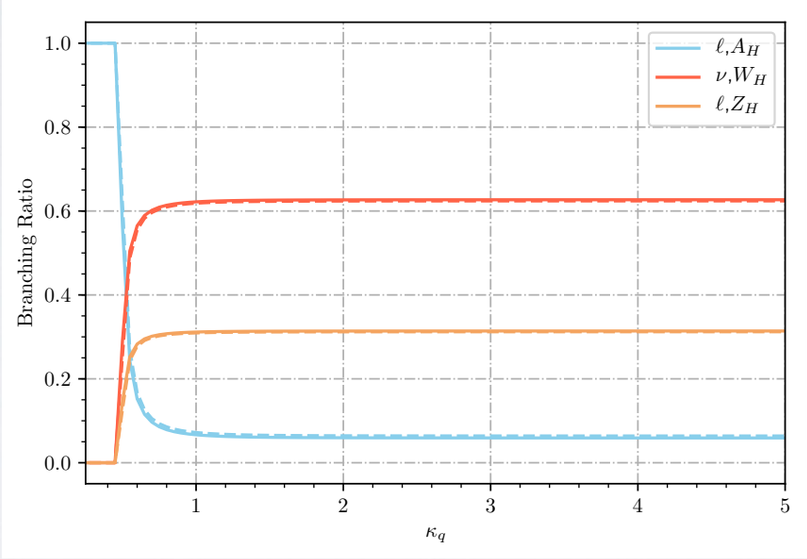


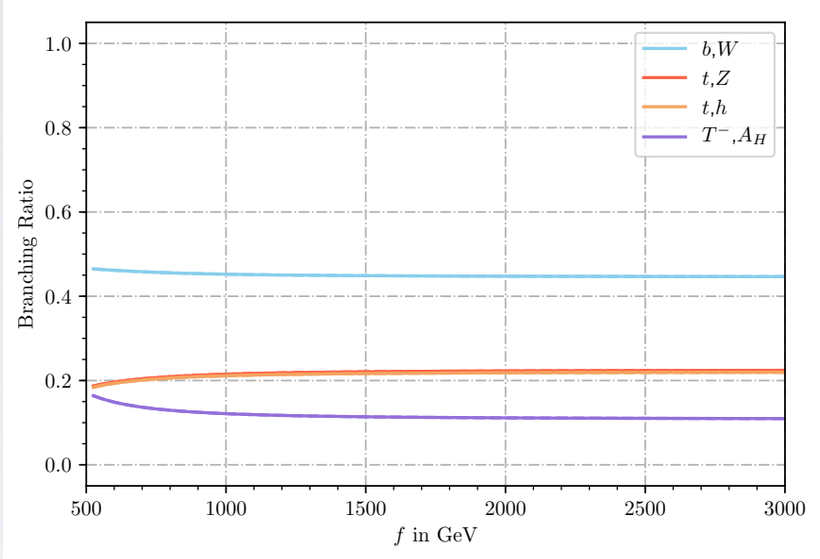
destructive t-q_H-channel interference w./ s-channel

Cross Sections & Branching ratios (II)

Branching ratios have very small *f* dependence (only small *f*, mass effects)



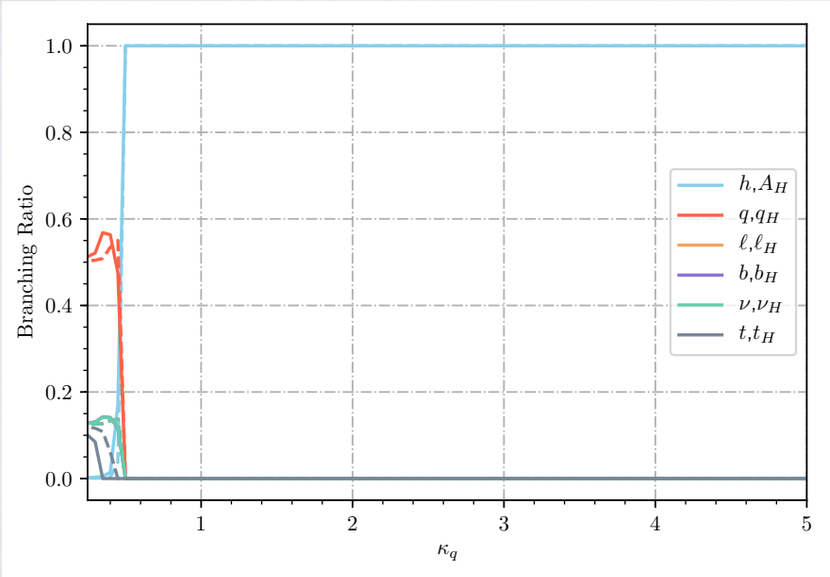


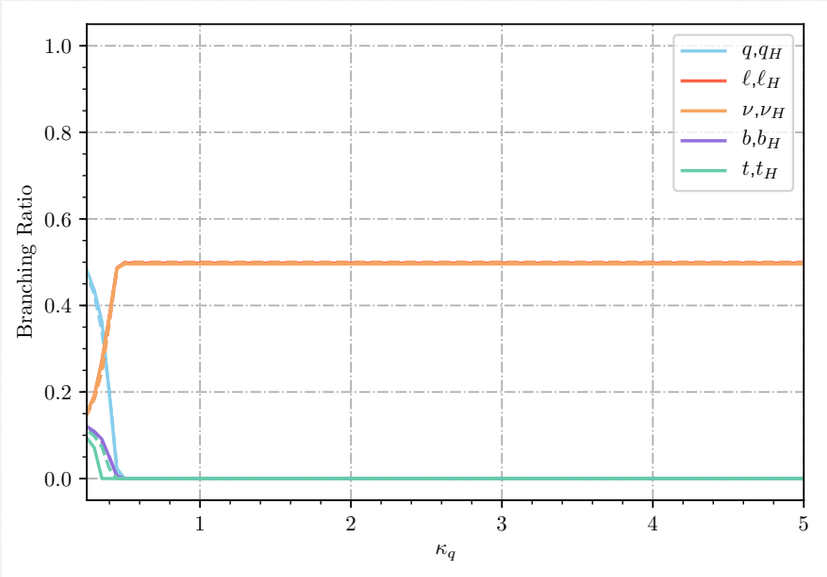


d_H, very similar: u_H [FU,Lℓ]

ℓ_H, very similar: ν_H [FU]

T^+ [Light T^-]





Light T^-:

$$\mathrm{BR}(T^- \to tA_H) = 1$$

Light ℓ_H:

$$\mathrm{BR}(\ell_H/\nu_H \to \ell/\nu A_H) = 1$$

W_H, very similar: Z_H [FU,Hq]

W_H, very similar: Z_H [Lℓ]

Toolchain for event simulation and recasting

- Steering program and Recasting tool: `CheckMate2` [Dercks/Desai/Kim/Rolbiecki/Tattersall/Weber, '16]
- Model file for LHT model via UFO format [Degrande *et al.*, '12]
- Partonic events: `MG5_aMC@NLO` [Alwall *et al.*, '10] and `WHIZARD v2.5` [Kilian/Ohl/JRR, '10]
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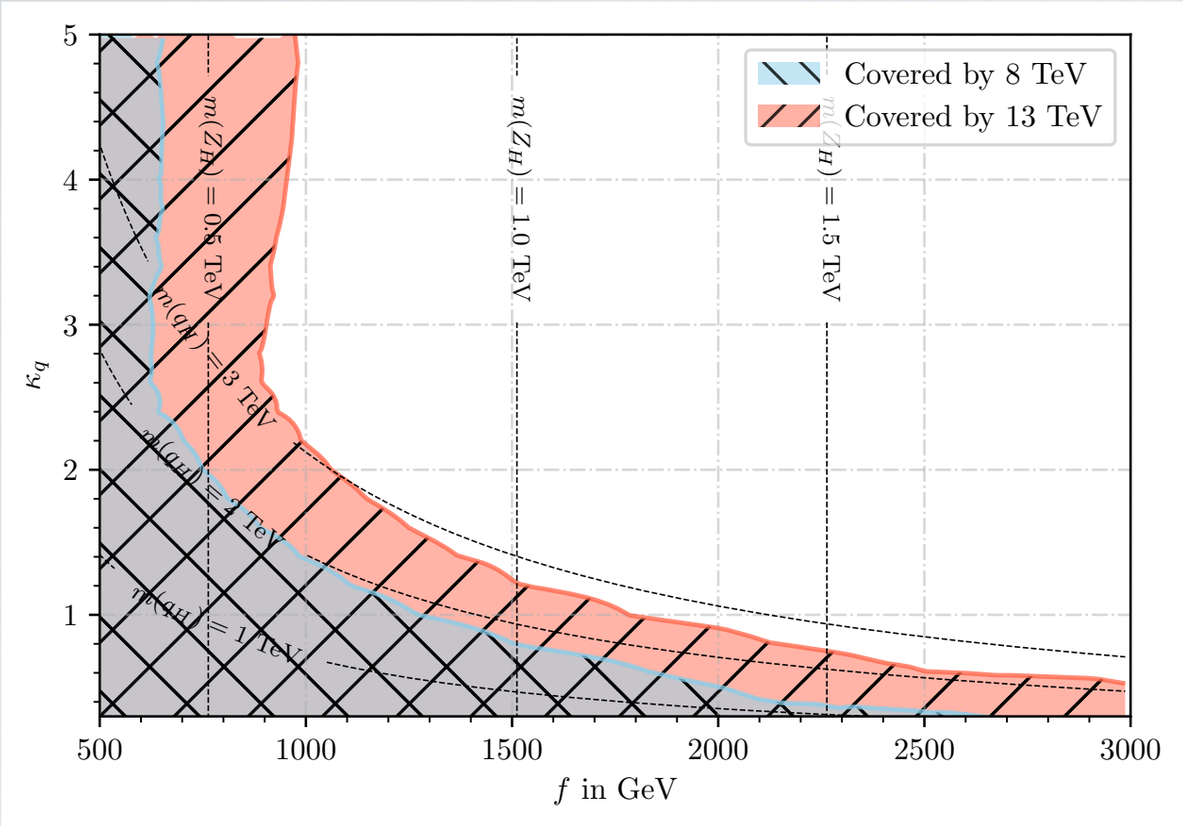
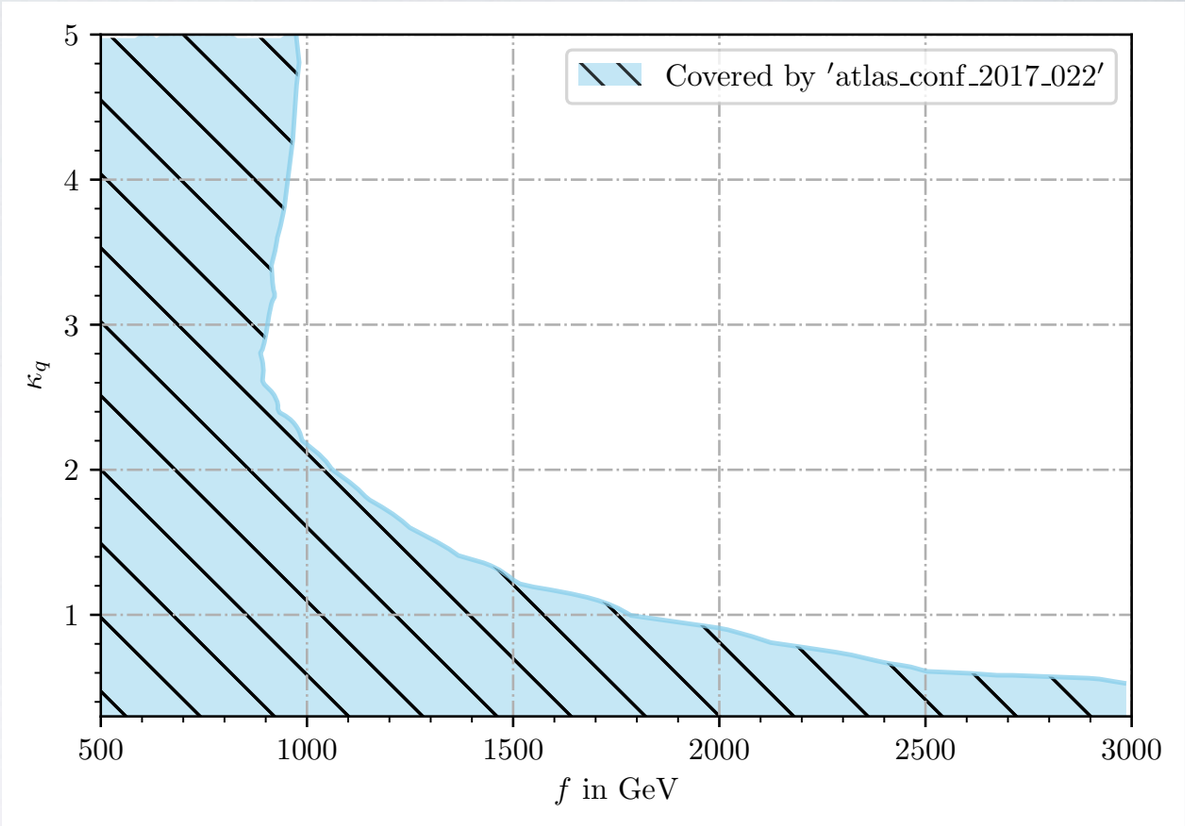
All used searches that have been recasted here:

CM identifier	Final State	Designed for	Lum.	SR	Ref.
atlas_conf_2016_096	$\not{E}_T + 2\text{-}3\ \ell$	$\tilde{\chi}^\pm, \tilde{\chi}^0, \tilde{\ell}$	13.3	8	ATLAS-CONF-2016-096
atlas_conf_2016_054	$\not{E}_T + 1\ \ell + (\mathrm{b})\text{-j}$	$\tilde{q}, \tilde{g}$	14.8	10	ATLAS-CONF-2016-054
atlas_conf_2017_022	$\not{E}_T + 0\ \ell + 2\text{-}6\ \mathrm{j}$	$\tilde{q}, \tilde{g}$	36.1	24	ATLAS-CONF-2017-022
atlas_conf_2017_039	$\not{E}_T + 2\text{-}3\ \ell$	$\tilde{\chi}^\pm, \tilde{\chi}^0, \tilde{\ell}$	36.1	37	ATLAS-CONF-2017-039

13 TeV recasting results: Fermion Universality





(Fermion Universality) ⊕ (Heavy $T^{\pm}$) ⊕ (TPC)

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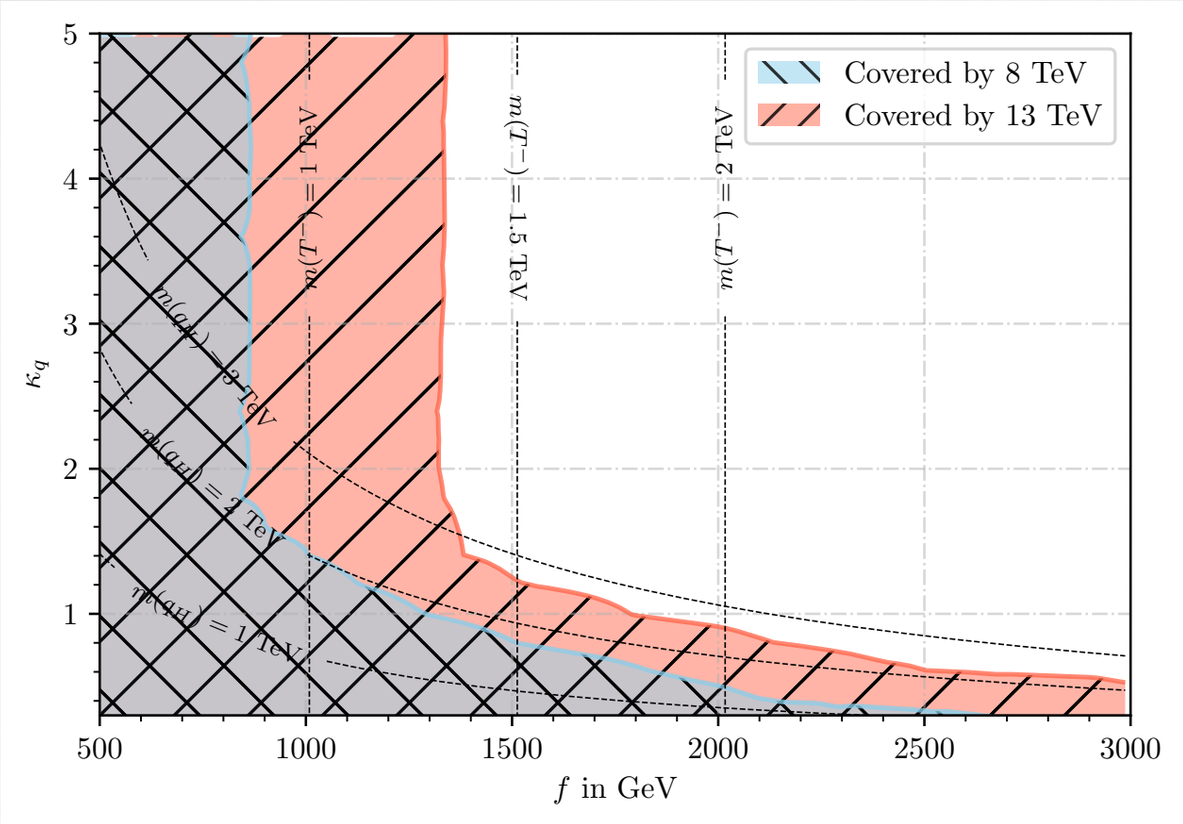

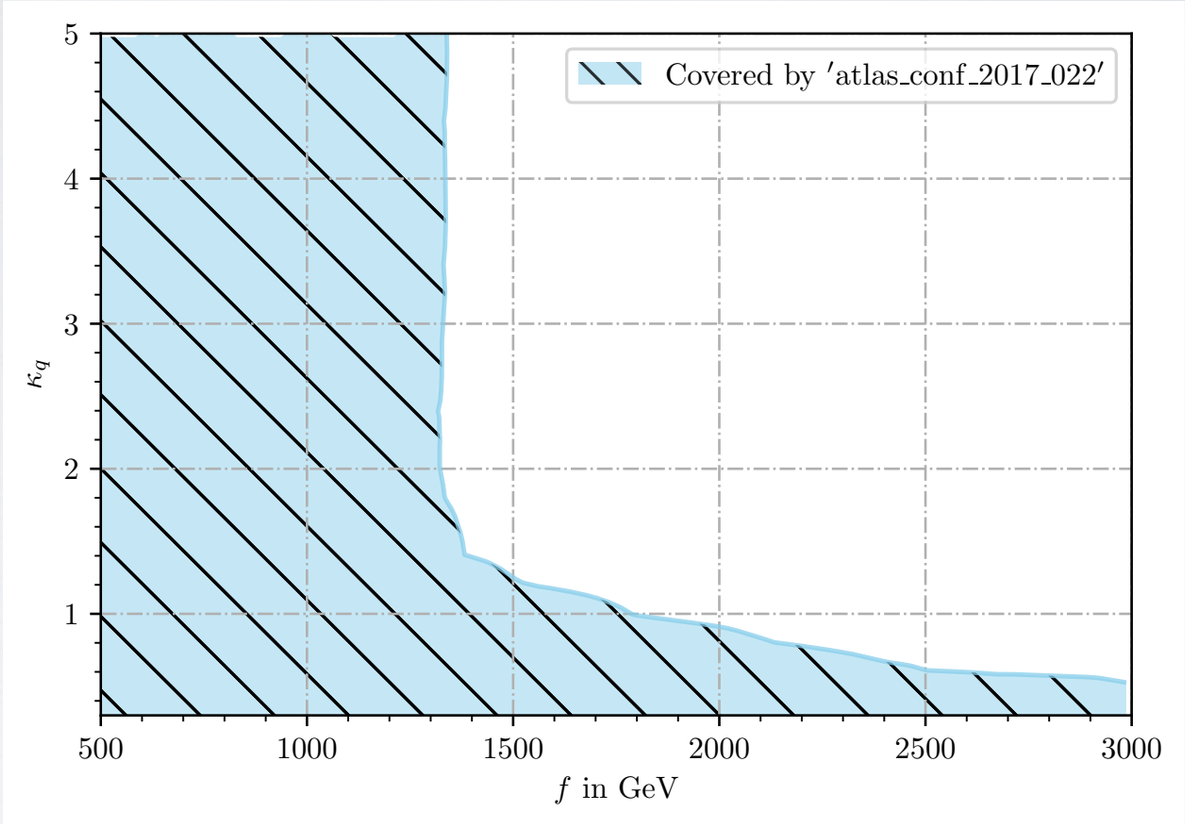

(Fermion Universality) ⊕ (Light $T^{\pm}$) ⊕ (TPC)

- High f: bounds follow $M(q_H)$ isocontours, $f \times \kappa < f\,\kappa_{\max}$, with $f\,\kappa_{\max} \sim 1.5/2$ TeV (Run 1/Run 2)
- Most effective analysis: search for 2 Jets + MET from $pp \to q_H\, q_H \to j\, j\, A_H\, A_H + X$
- Low f: independent of κ, large κ: q_H too heavy; V_H production, $M(V_H) \gtrsim 600$ GeV, $f \gtrsim 900$ GeV
- Light $T^{\pm}$: if kinematically accessible improve f-bound to $f \gtrsim 1.3$ TeV
- TPV: q_H isocontours slightly weakened (more V), f-bound improved (!) [ℓ take over j analyses]

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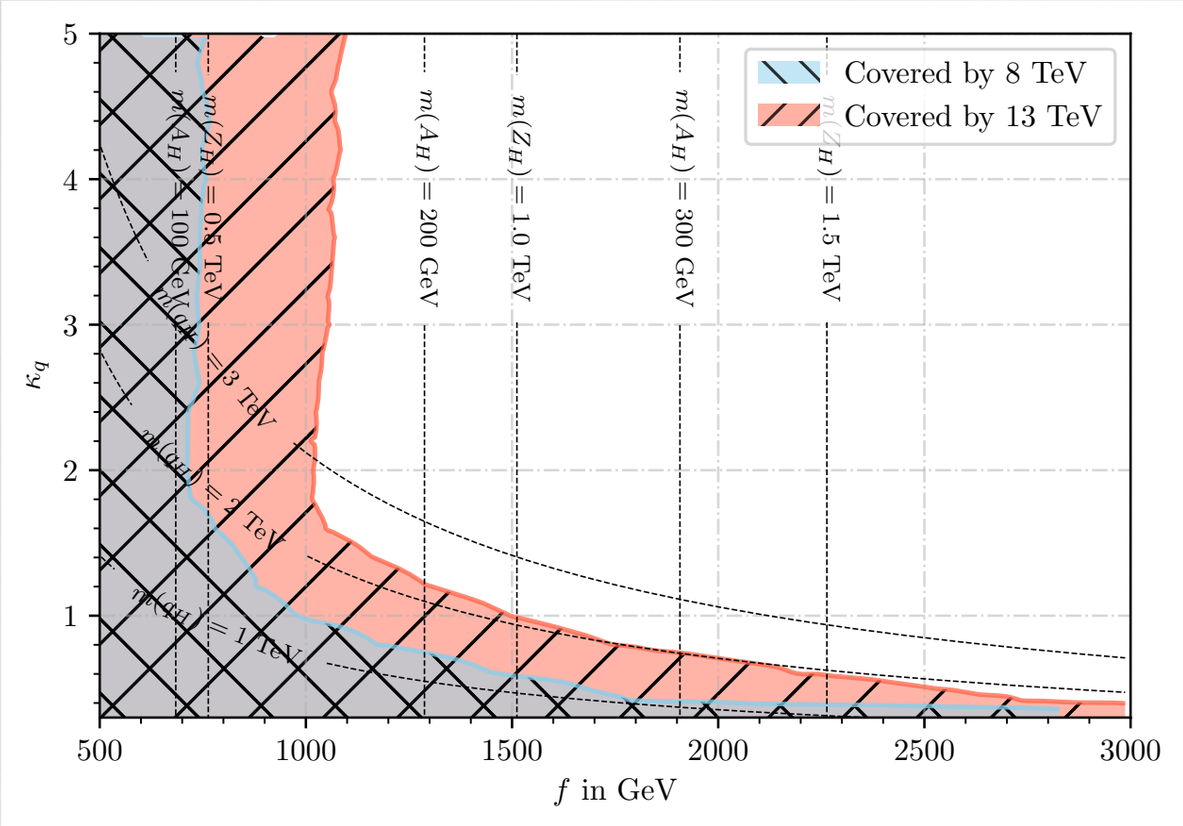

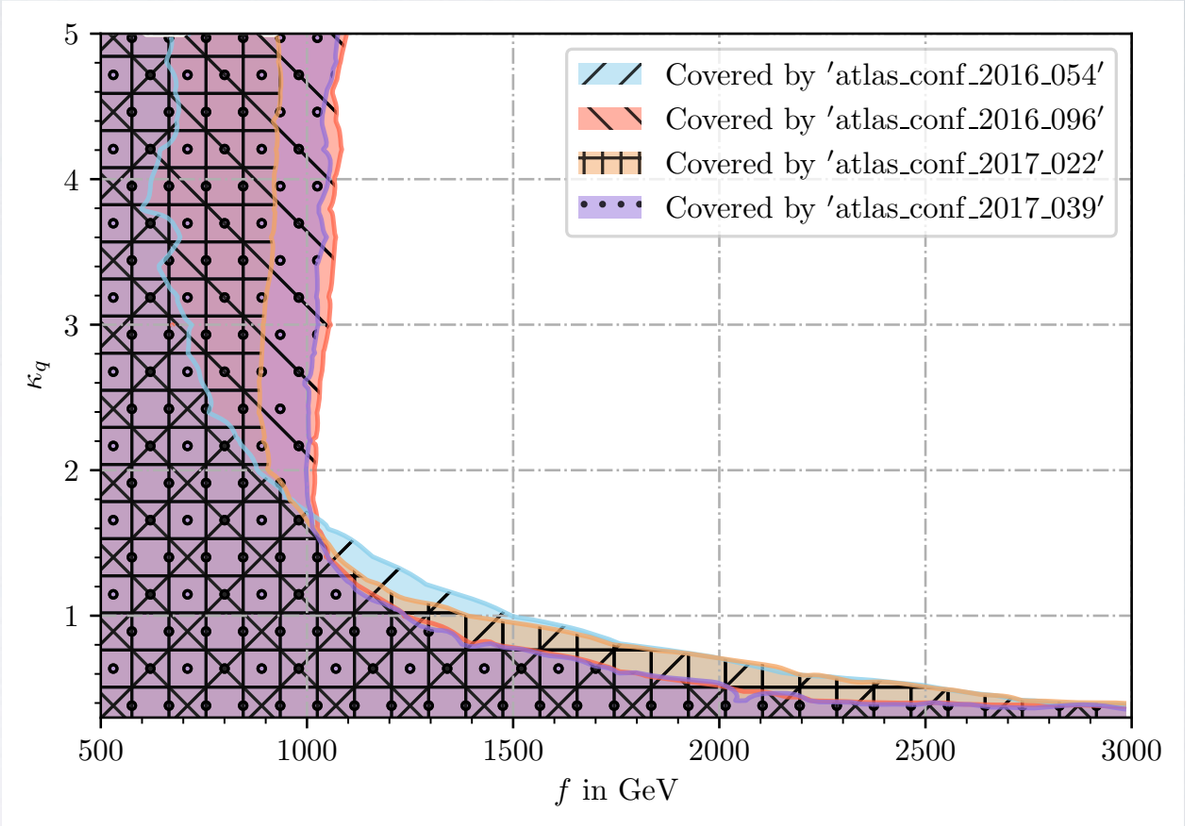

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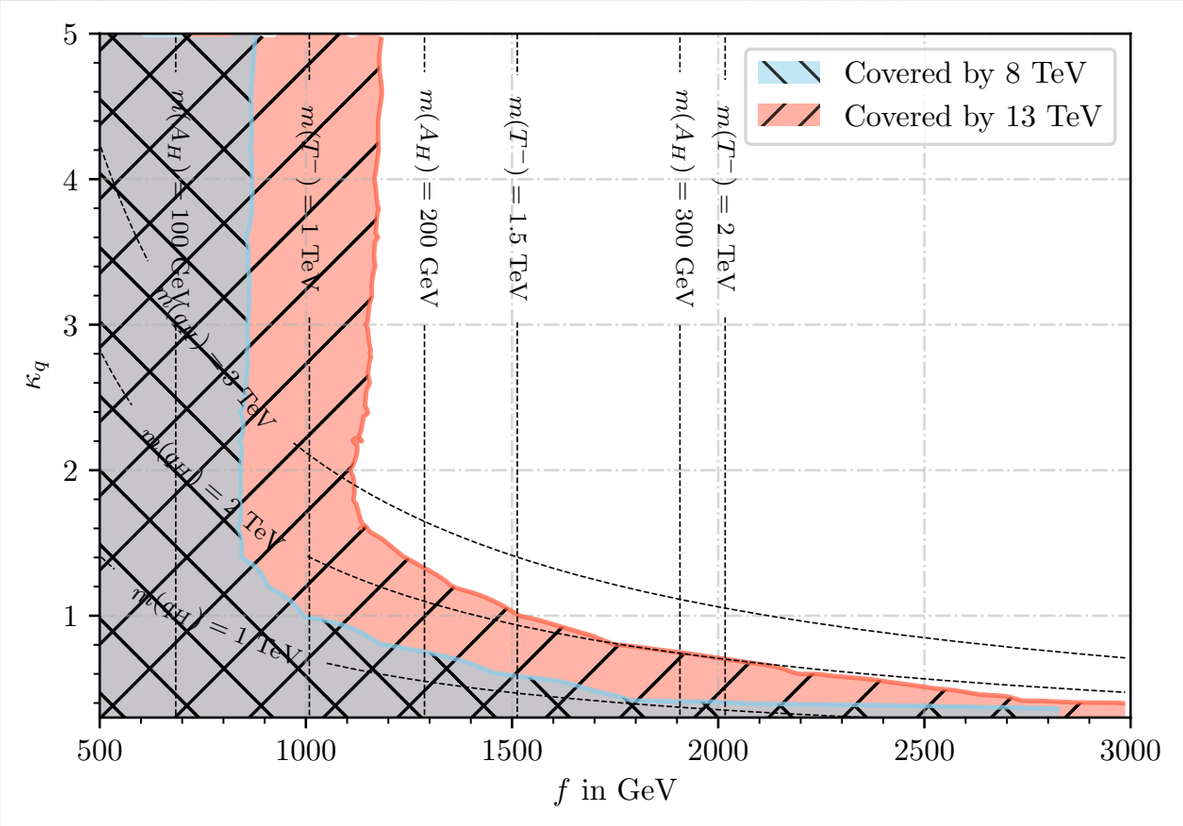

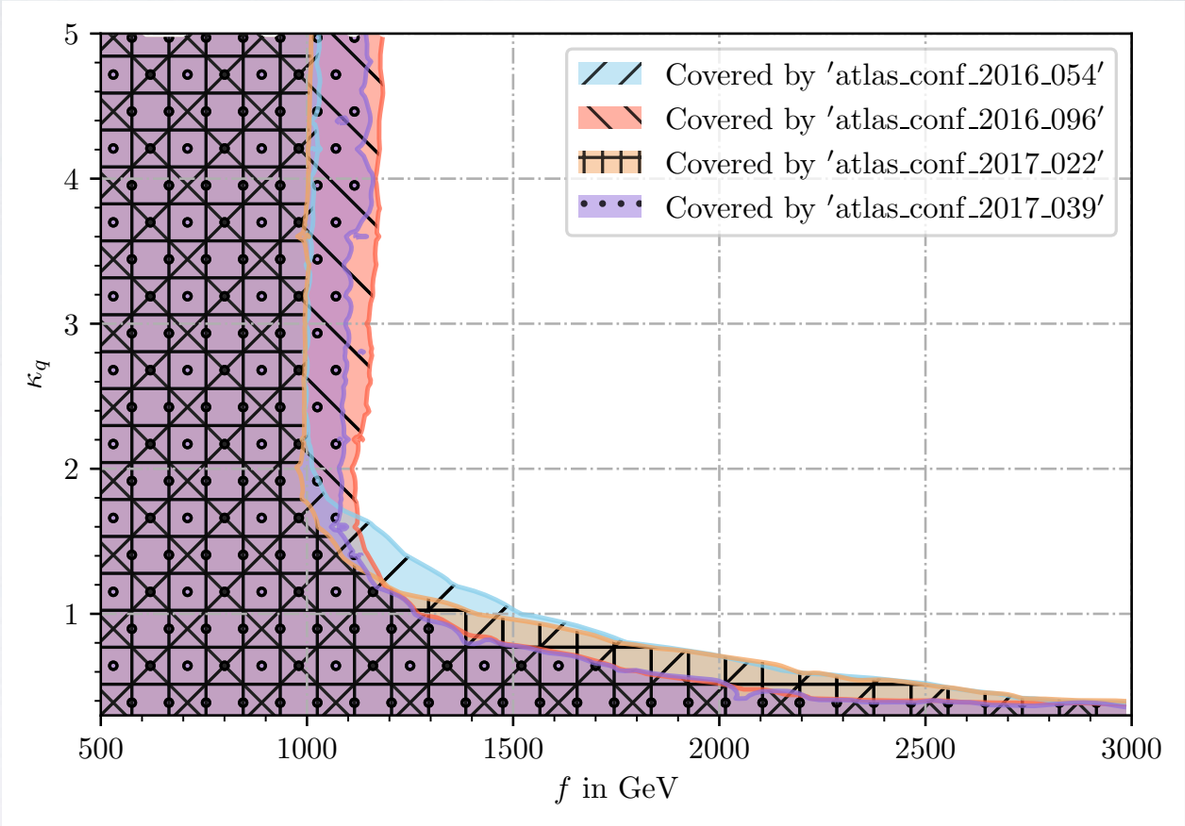

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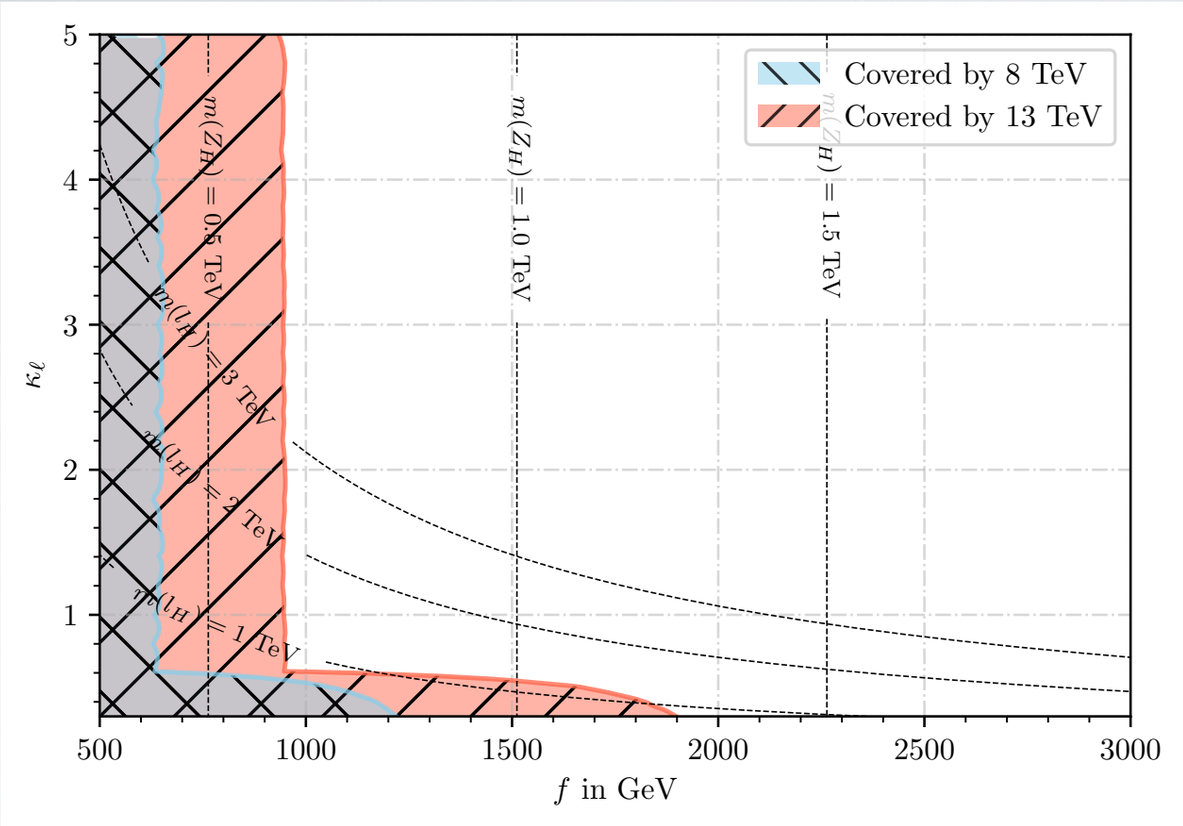
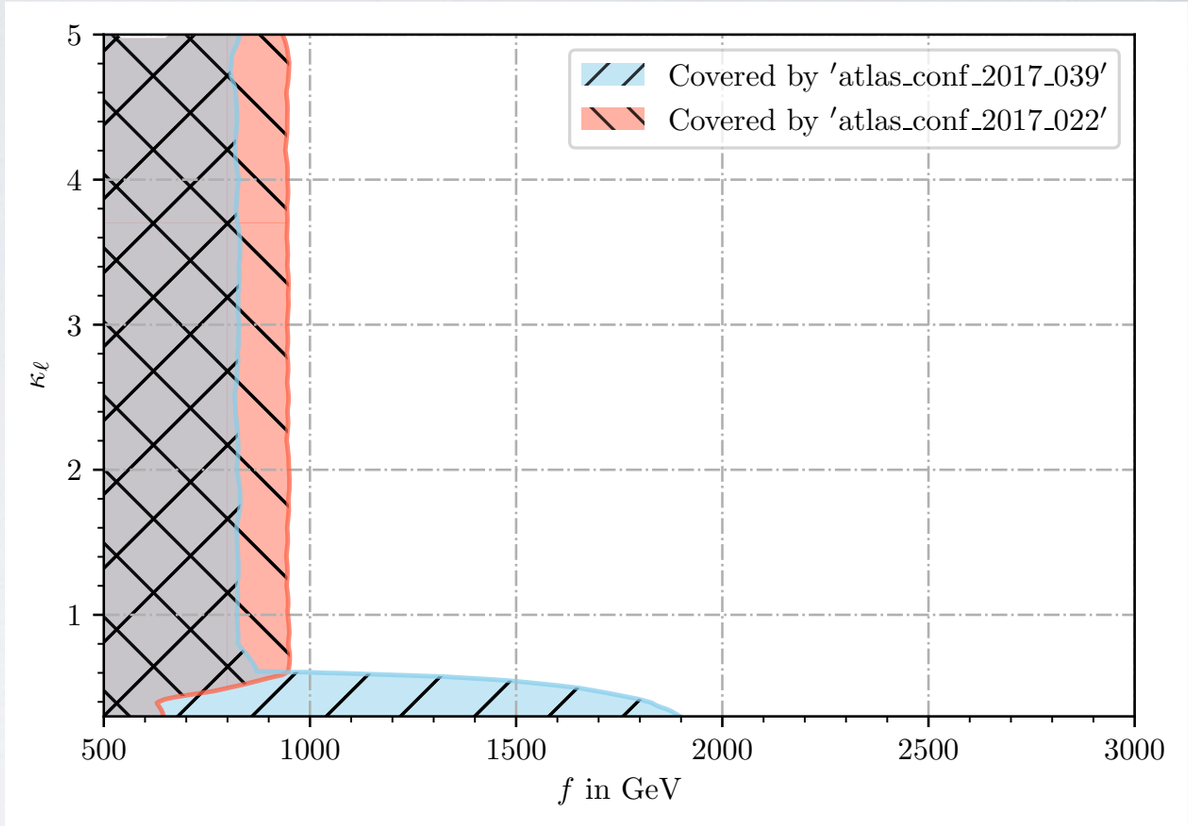
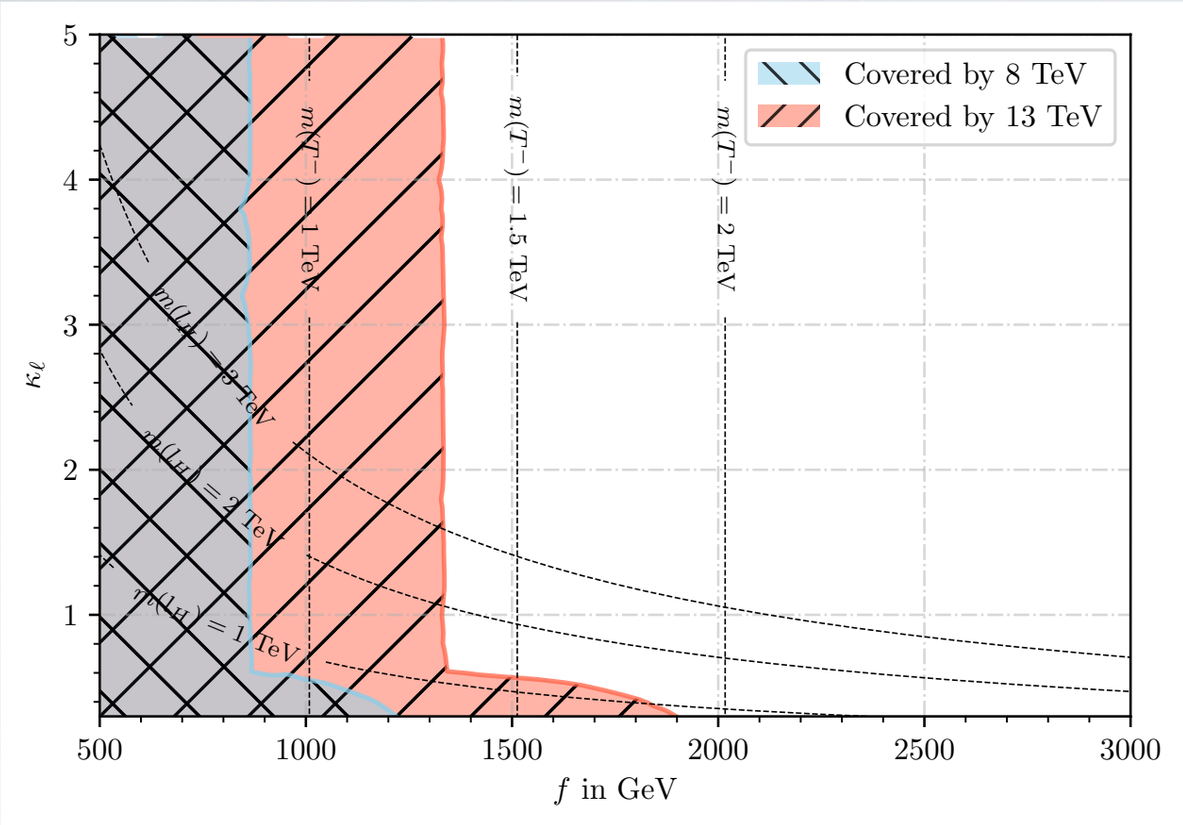
13 TeV recasting results: Heavy q_H

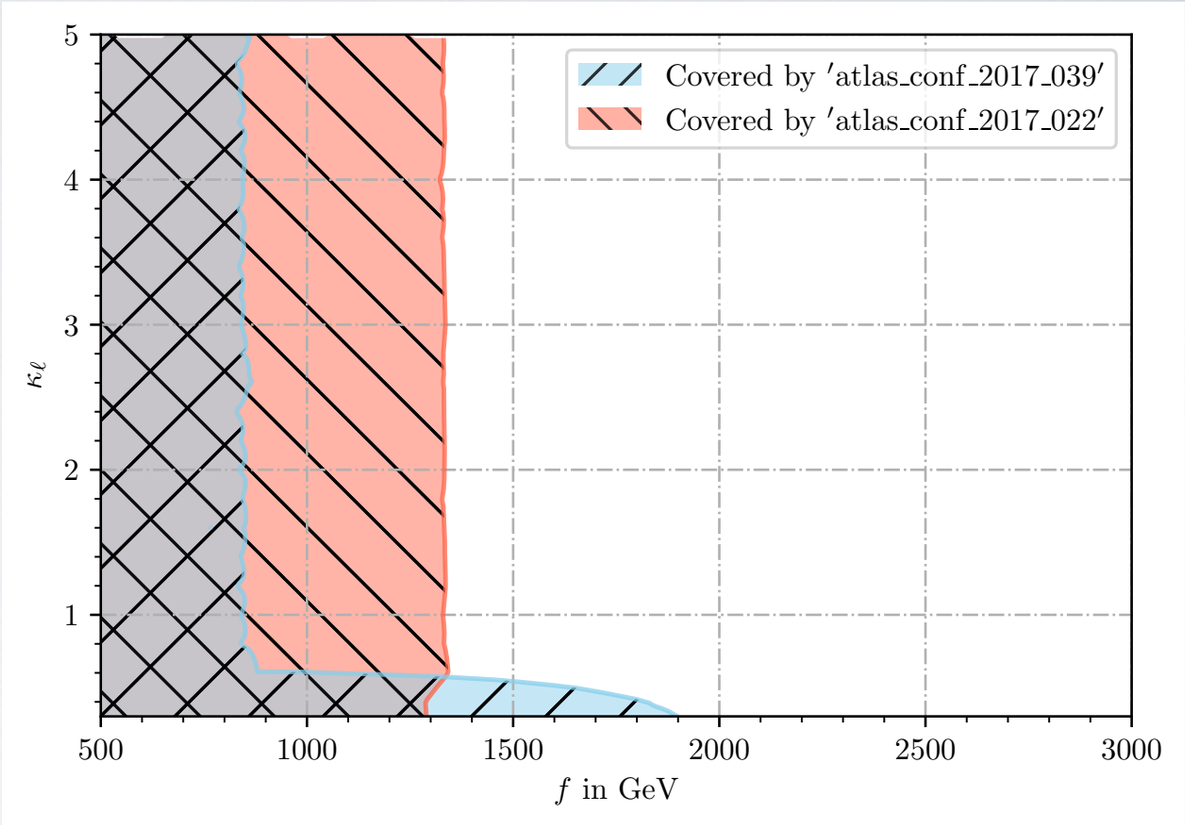




(Heavy q_H) ⊕ (Heavy $T^{\pm}$) ⊕ (TPC)

13 TeV recasting results: Heavy q_H

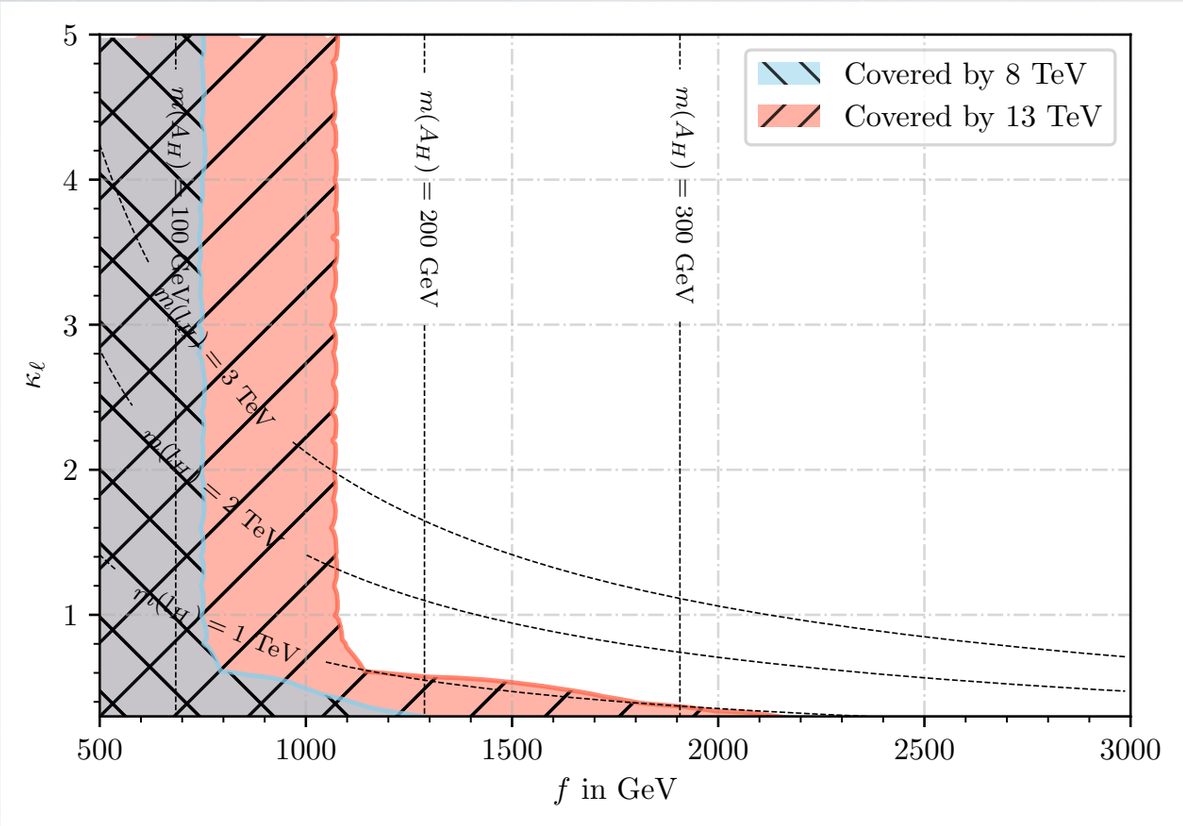


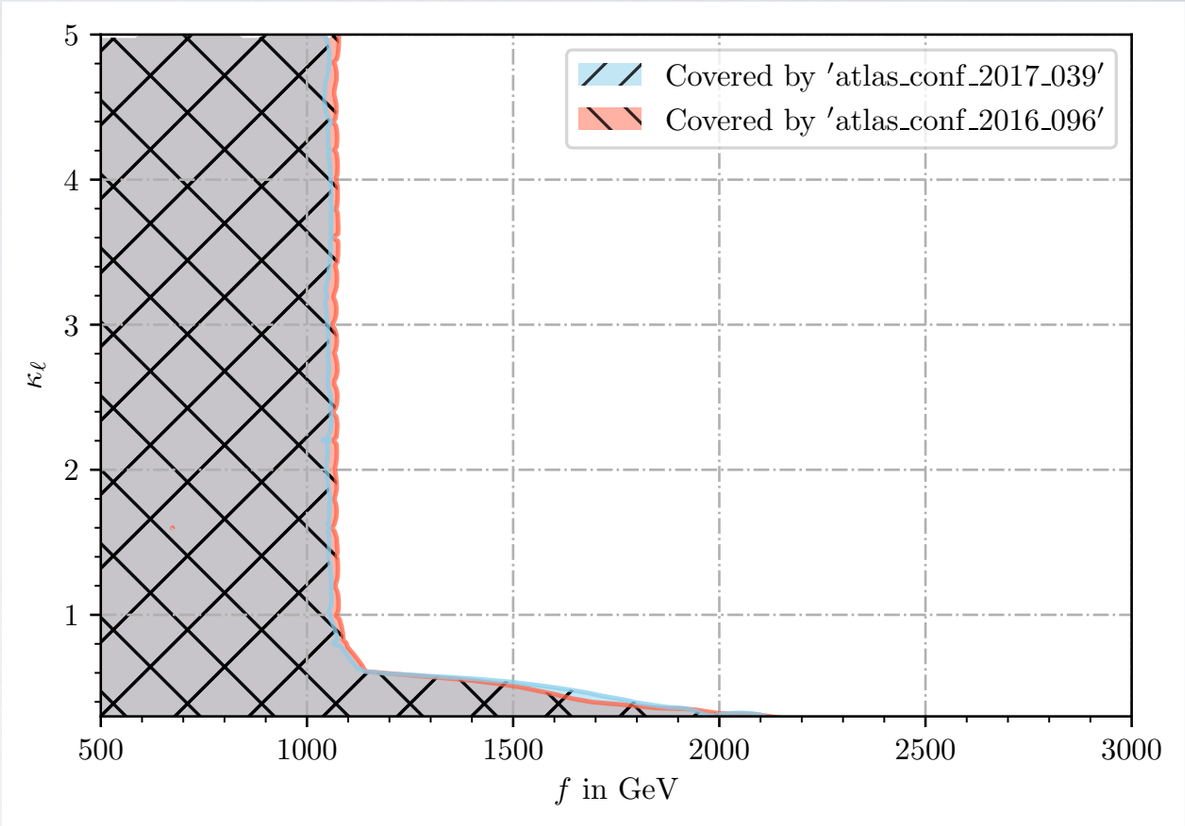


(Heavy q_H) ⊕ (Light $T^\pm$) ⊕ (TPC)

- $q_H \to q\,V_H \Longrightarrow \ell_H \to \ell\,V_H$; multijets $\Longrightarrow$ multileptons
- $\sigma(pp \to q_H q_H)$ 2-3 orders of magnitudes larger than $\sigma(pp \to \ell_H \ell_H)$
- Limits for large f similar to FU: exclusions $f \gtrsim 950$ GeV (1350 GeV with $T^\pm$)
- $\kappa \lesssim 0.5$: $V_H \to \ell_H \ell$ now open; covered by multilepton analysis; $f \gtrsim 1.9$ TeV
- Only very tiny changes for TPV

13 TeV recasting results: Heavy q_H





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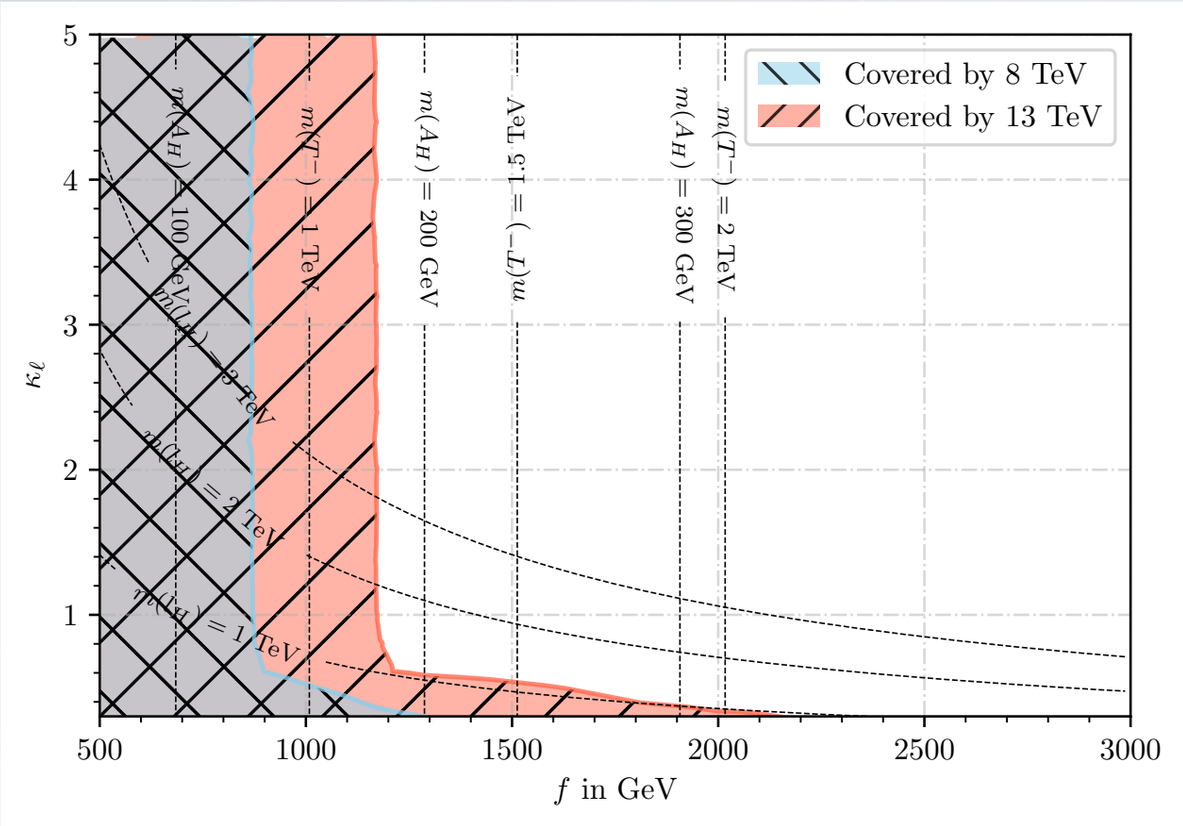

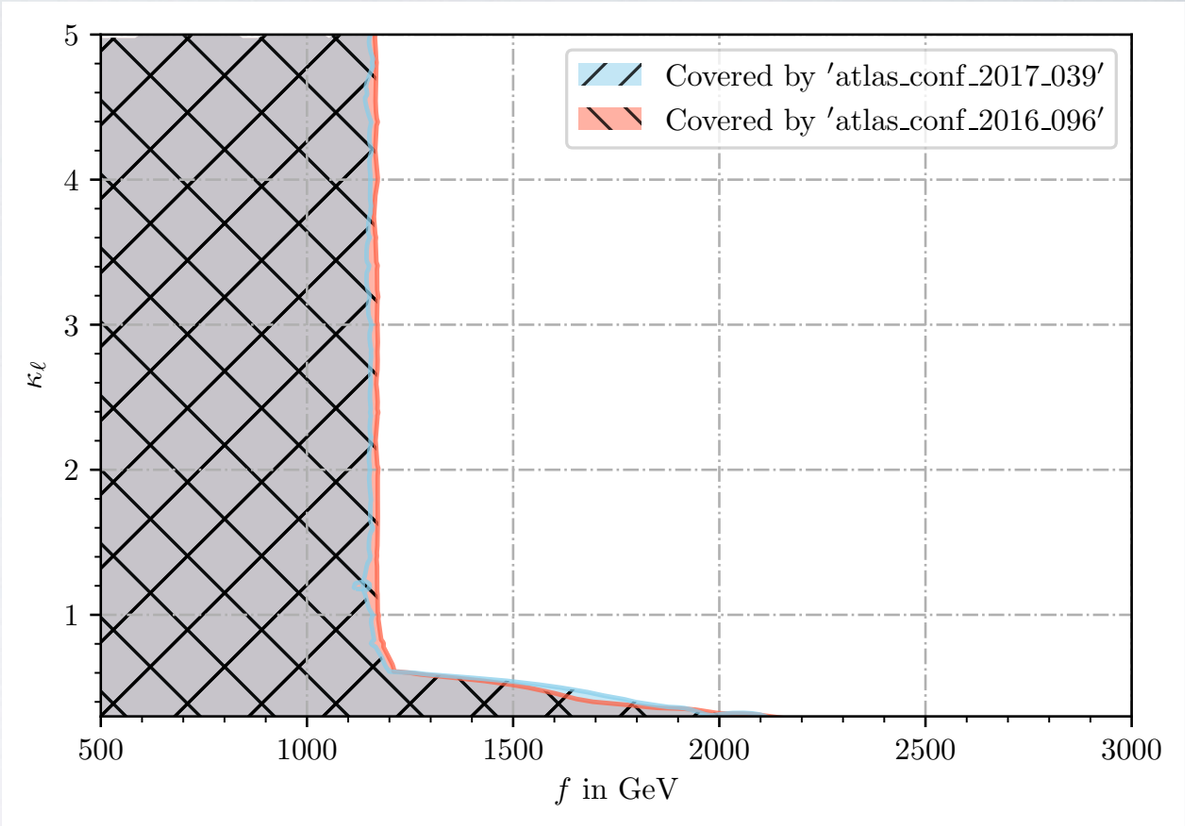

(Heavy q_H) ⊕ (Light $T^\pm$) ⊕ (TPV)

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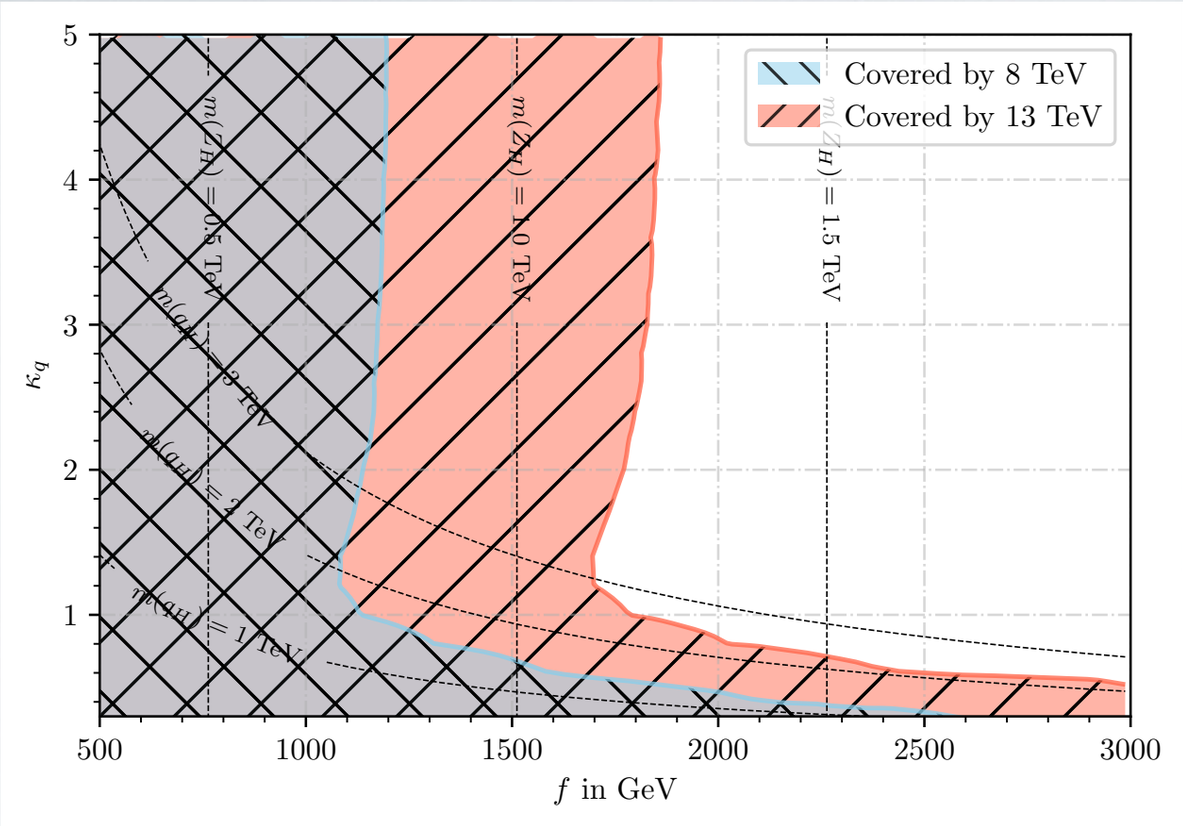
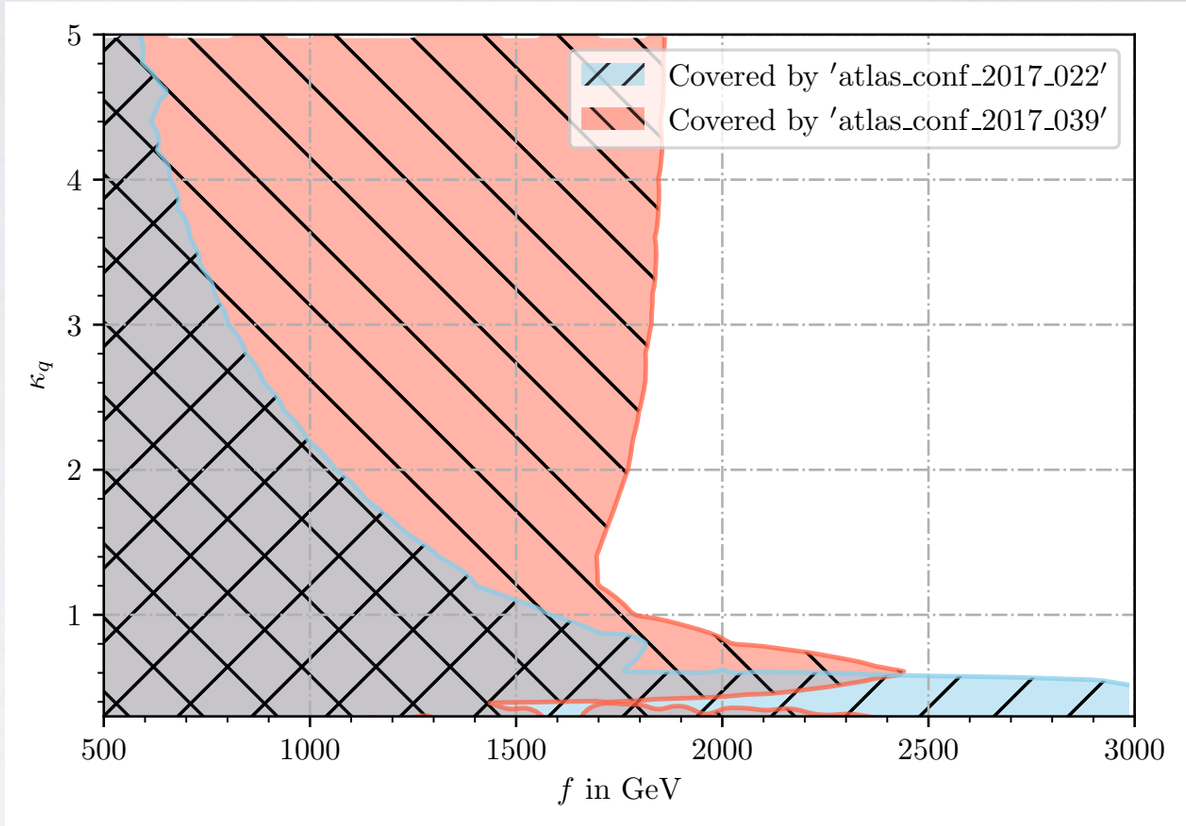
- Only very tiny changes for TPV

13 TeV recasting results: Light ℓ_H





(Light ℓ_H) $\oplus$ (Heavy $T^{\pm}$) $\oplus$ (TPC)

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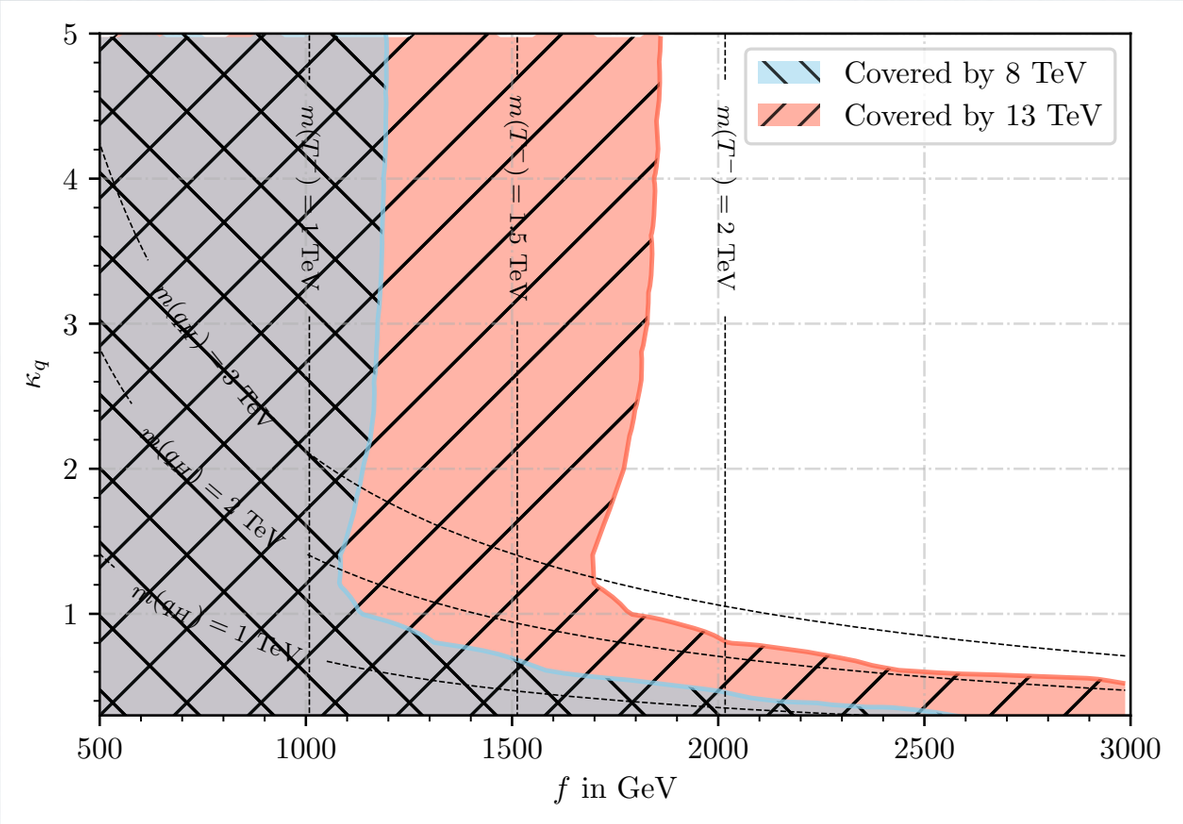

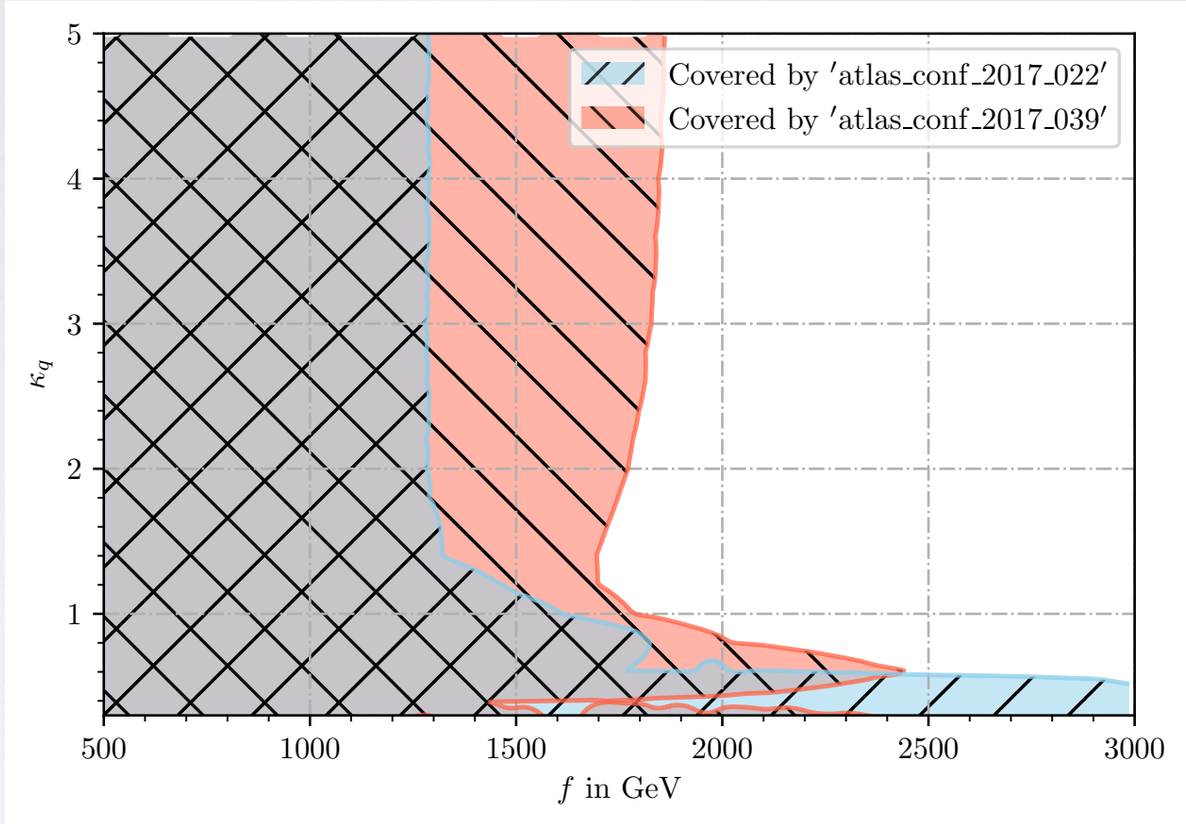

(Light ℓ_H) ⊕ (Light $T^\pm$) ⊕ (TPC)

- 2 main exclusion regions, intersect at $f \approx 1.6$ TeV and $\kappa_q \approx 1.2$
- $\kappa_q > 0.5$: 3ℓ search, $pp \to q_H q_H \to j\,j\,V_H V_H \to j\,j\,\ell\ell\ell\ell\,A_H A_H$
- $\kappa_q < 0.5$: V_H have hadronic decays, multi-jet analyses dominate
- Large-κ bound stronger due to leptons compared to *Fermion Universality*
- Presence of $T^\pm$ leads only to marginal changes
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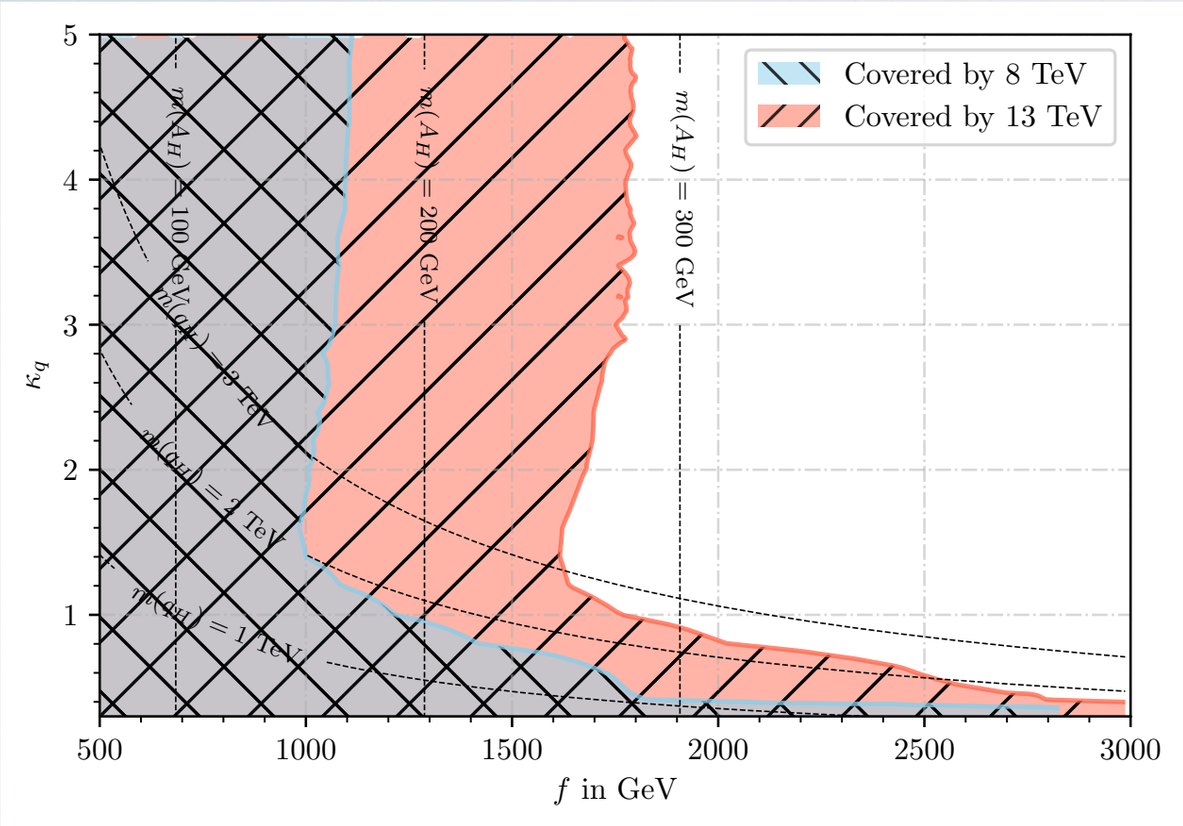

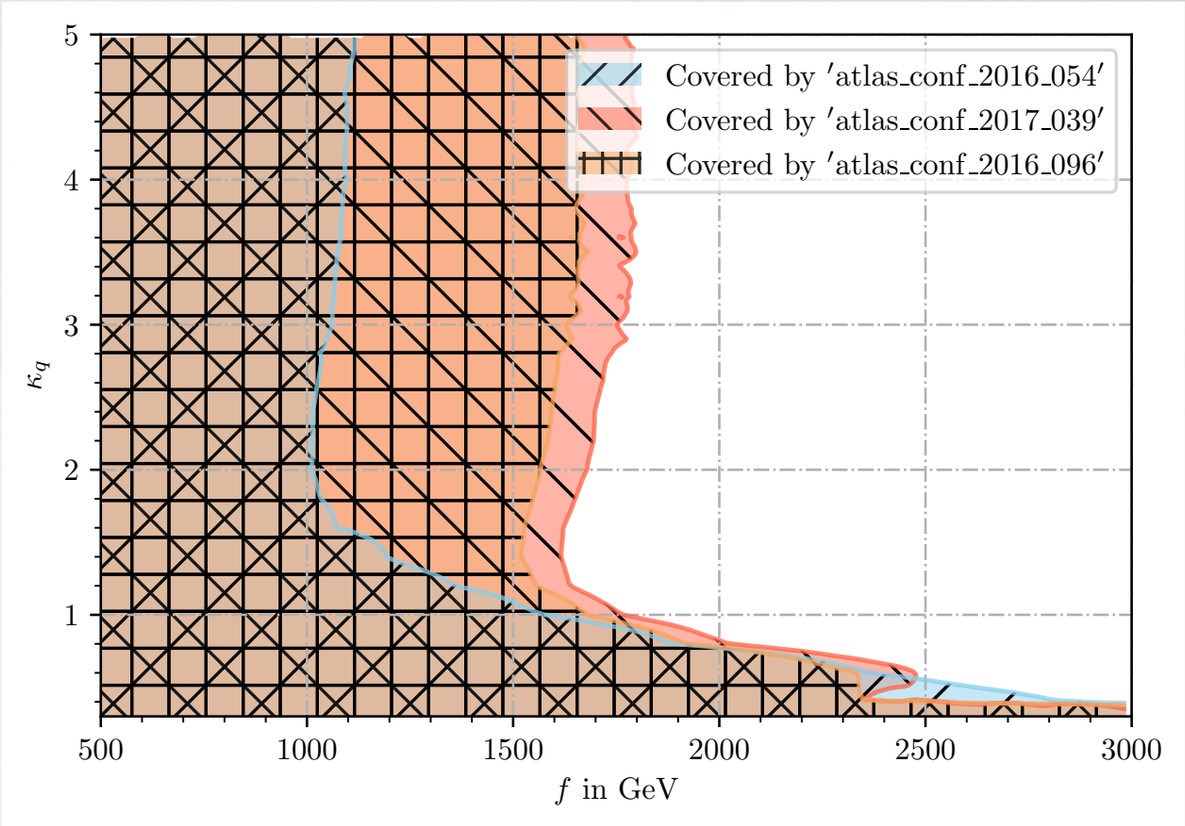

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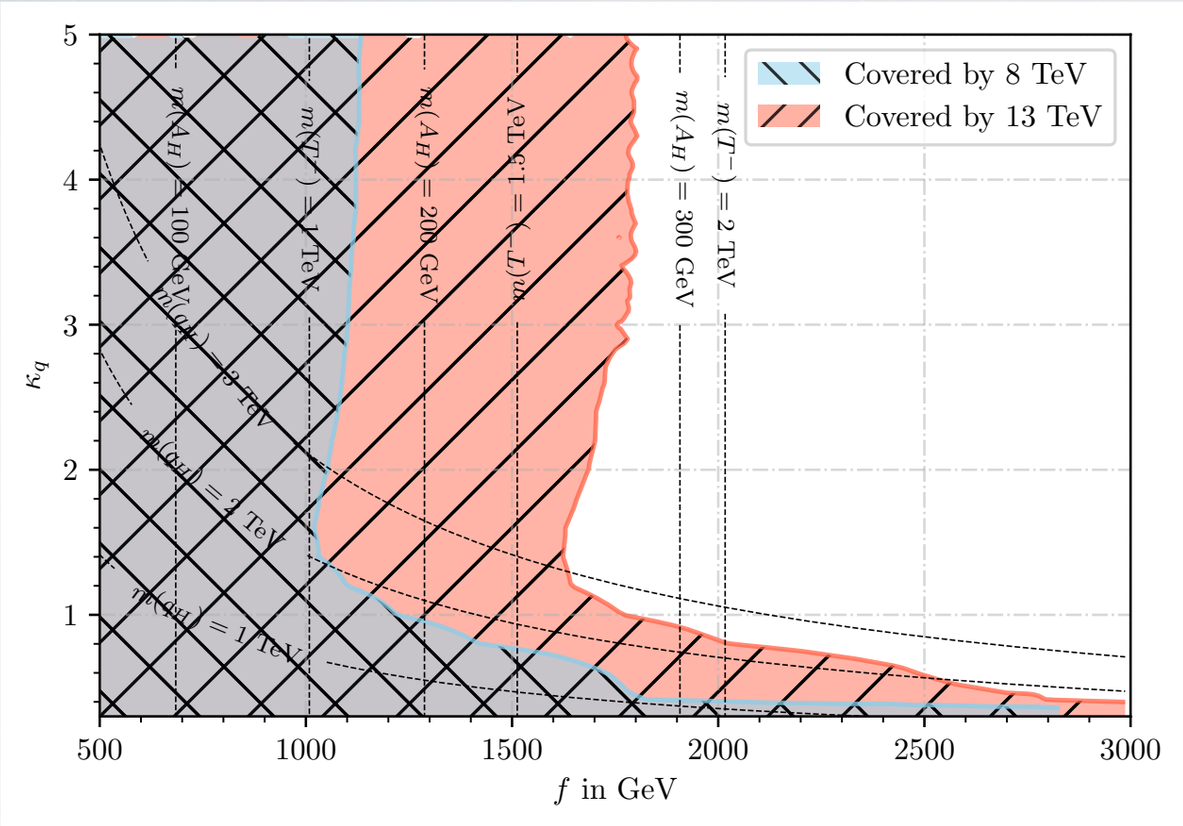

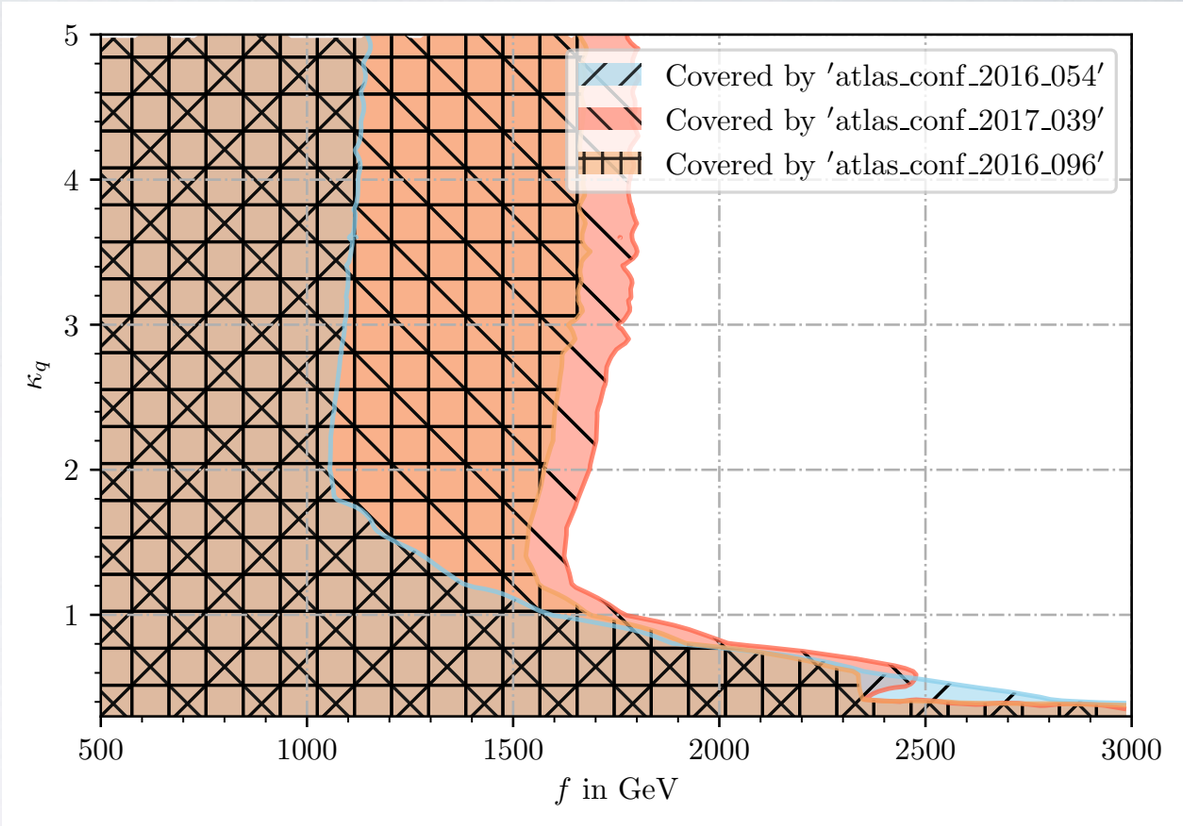

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Bounds from 4-fermion operators

- Low-energy bounds: flavor observables (kaon, *D*-, *B*-physics) [Blanke *et al.*, '06, '15]
- Mirror fermions generate 4-fermion operators via box diagrams

[Hubisz/Meade/Noble/Perelstein, '06]

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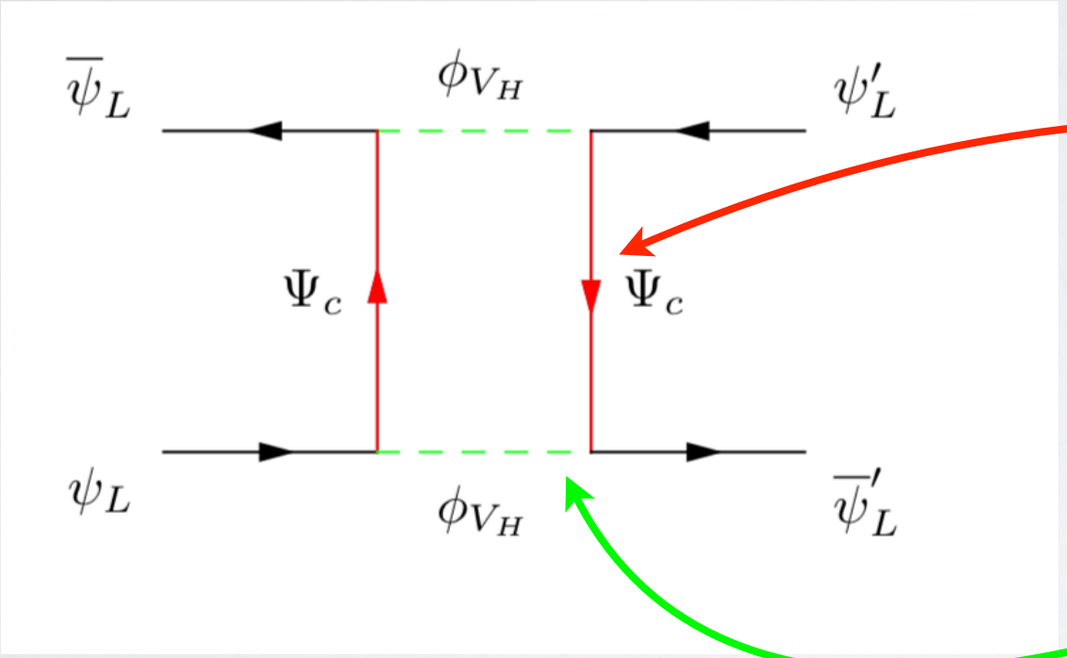

Mirror fermions

Goldstone bosons of heavy gauge bosons

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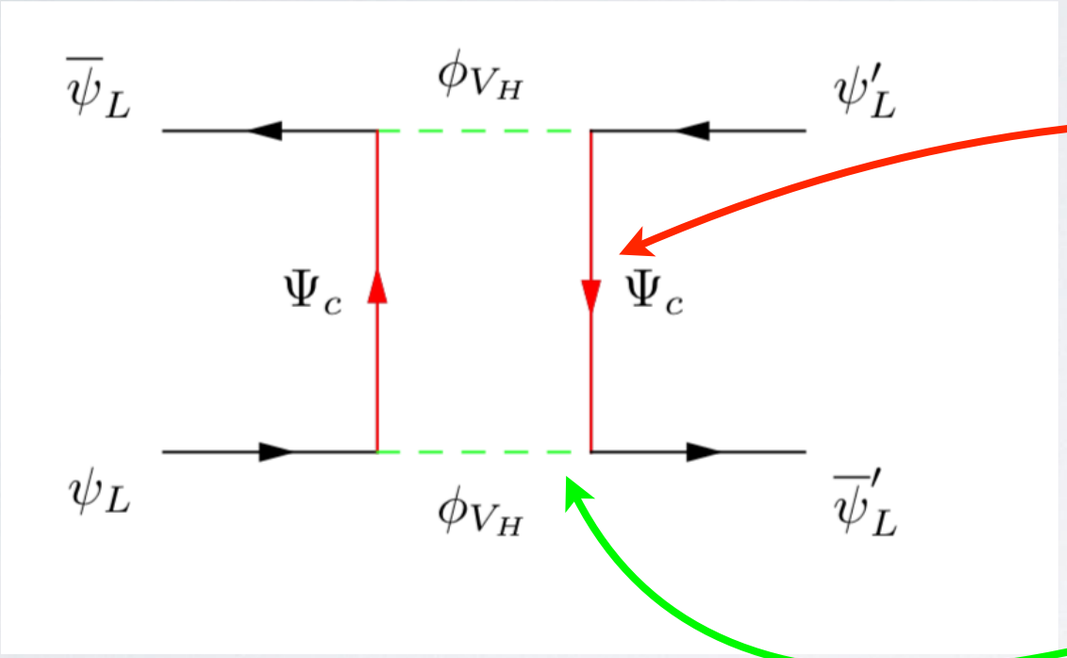

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$$\mathcal{O}_{4-\text{ferm.}} = -\frac{\kappa_{q,\ell}^2}{128\pi^2 f^2}\left(\overline{\psi}_L\gamma^\mu\psi_L\right)\left(\overline{\psi}'_L\gamma_\mu\psi'_L\right)$$

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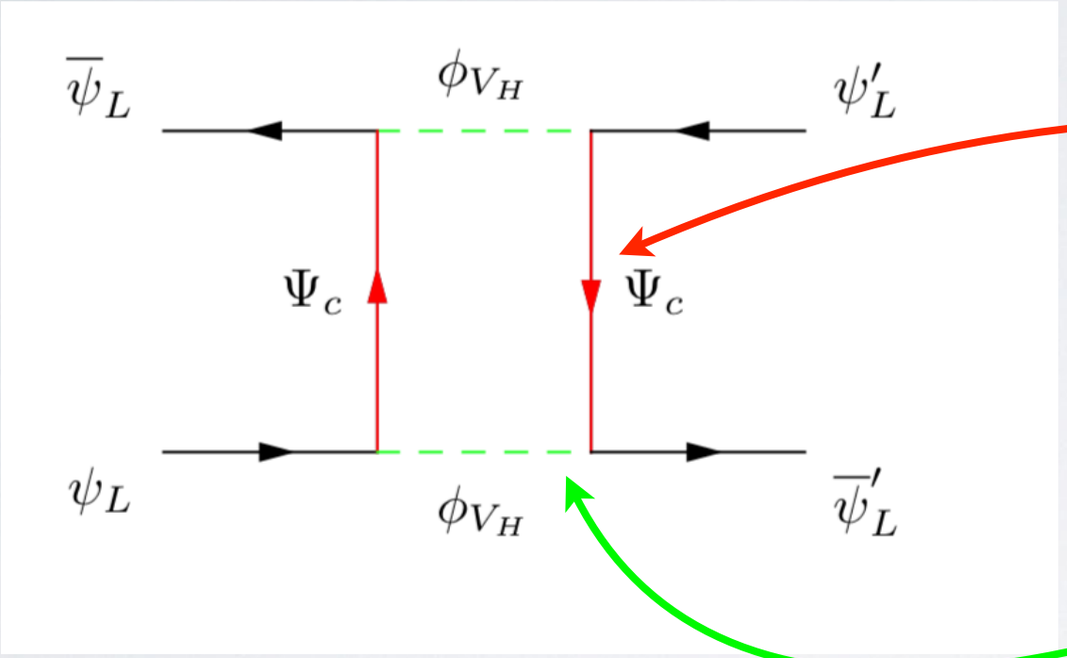

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Strongest constraints still from LEP:

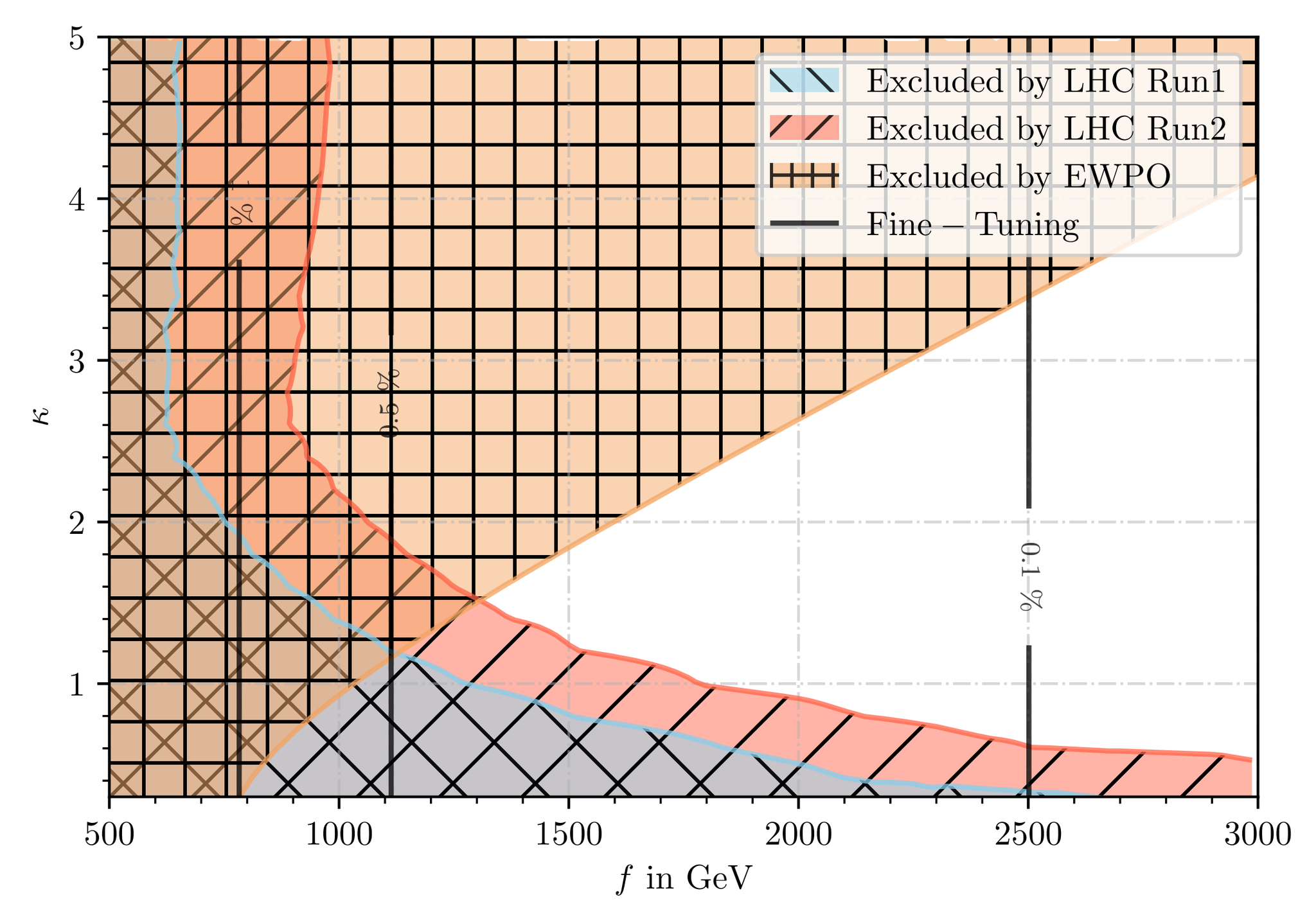
$$\Lambda\left[(\overline{e}e)(\overline{q}q)\right] \gtrsim 26.4\,\text{TeV}$$

LHC Dijet Bounds:

$$\Lambda\left[(\overline{q}q)(\overline{q}q)\right] \gtrsim 15.7\,\text{TeV}$$

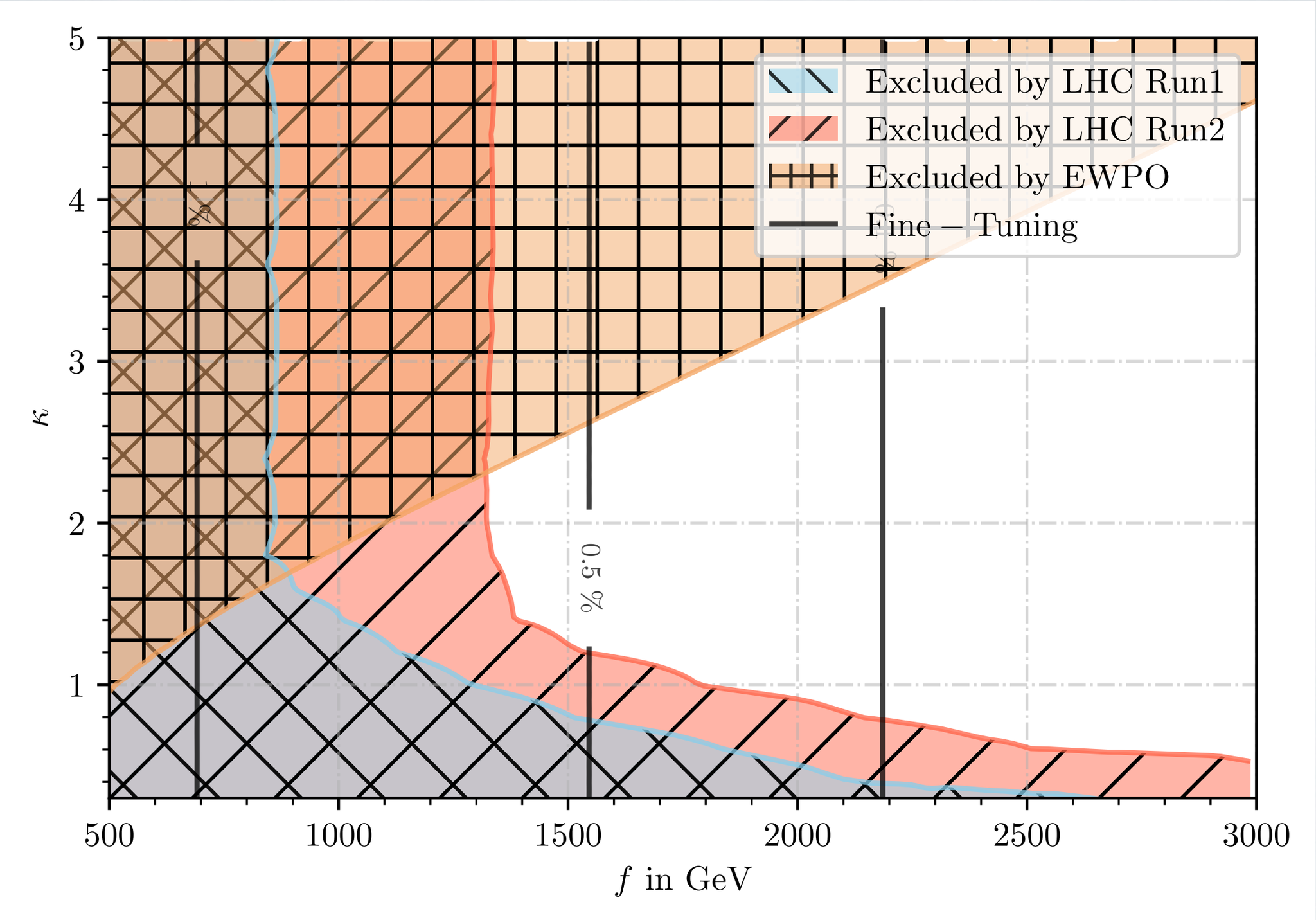
$\Longrightarrow$ EWPO

LHC Run 2 and EWPO/Higgs Results



(Fermion Universality) ⊕ (Heavy $T^{\pm}$) ⊕ (T-parity conservation)

LHC Run 2 and EWPO/Higgs Results



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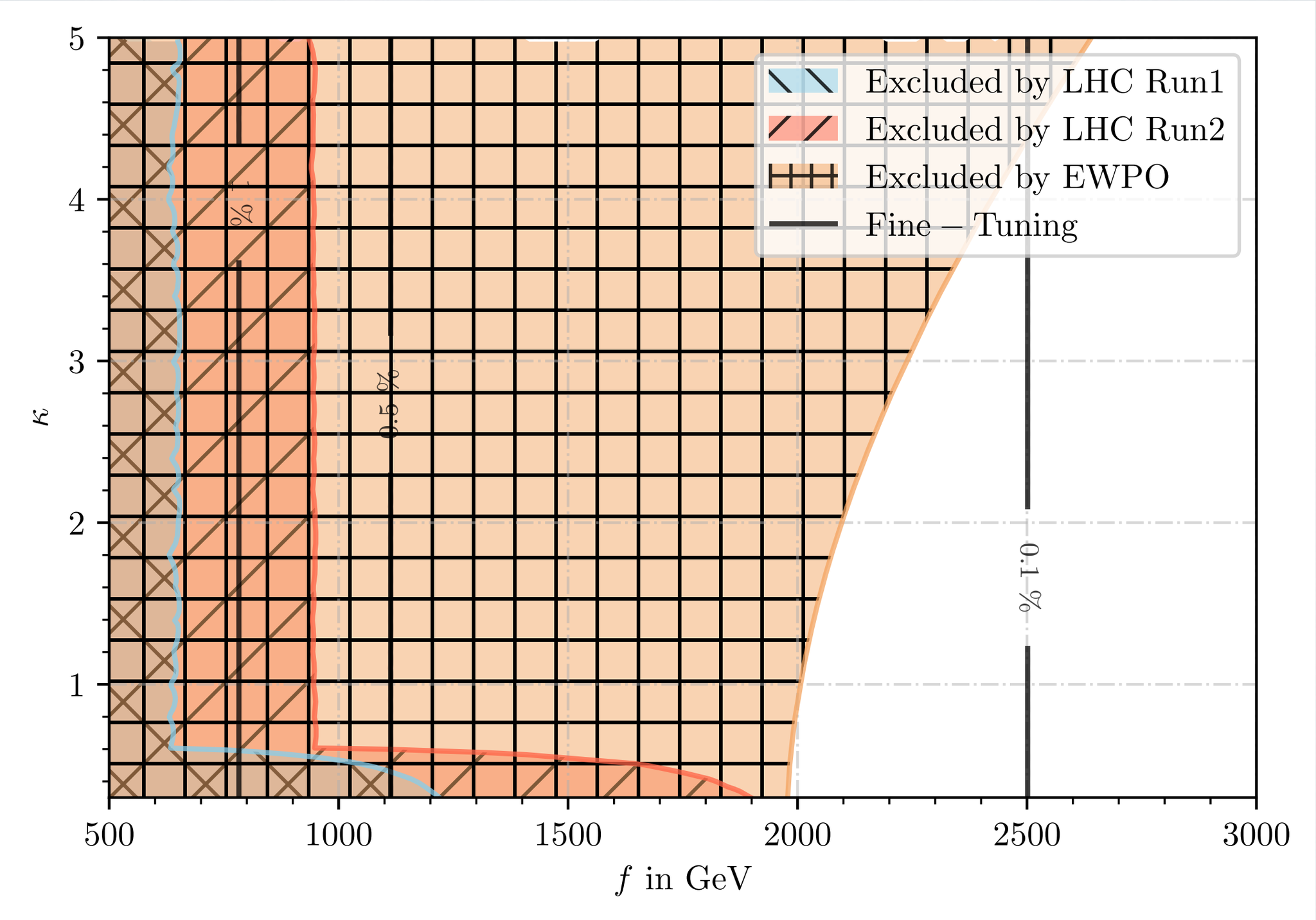
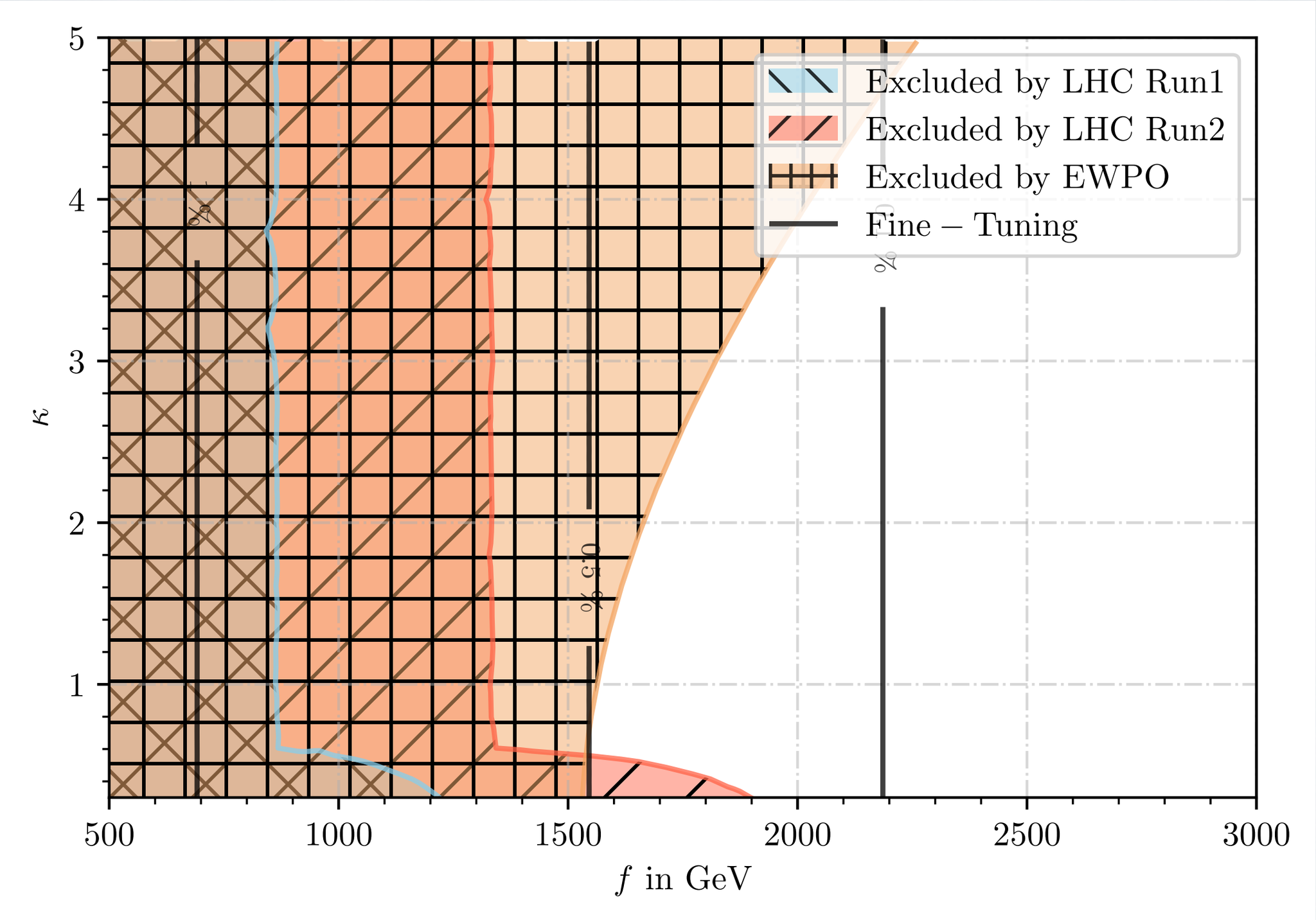
LHC Run 2 and EWPO/Higgs Results



(Heavy q_H) ⊕ (Heavy $T^{\pm}$) ⊕ (T-parity conservation)

LHC Run 2 and EWPO/Higgs Results



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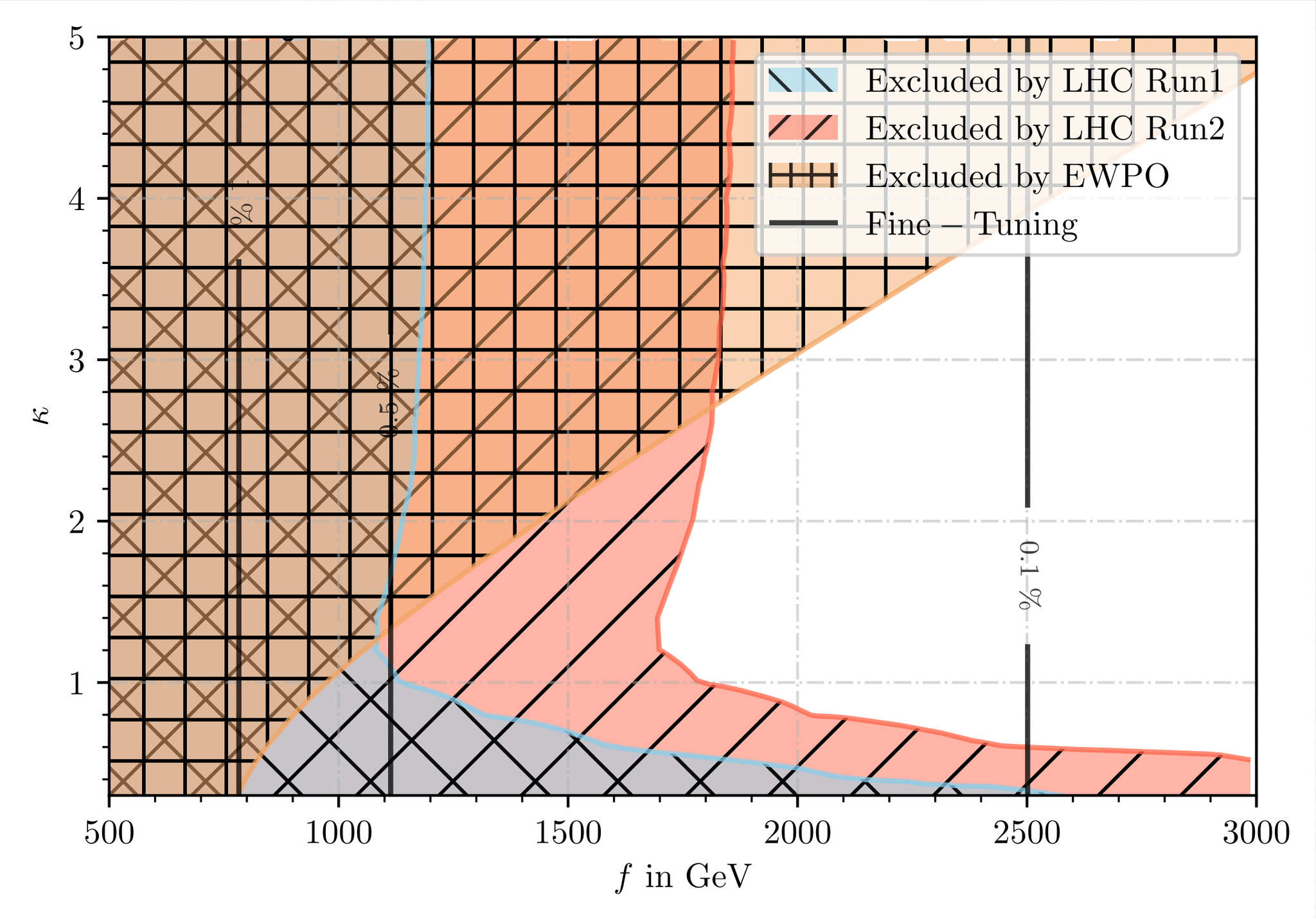

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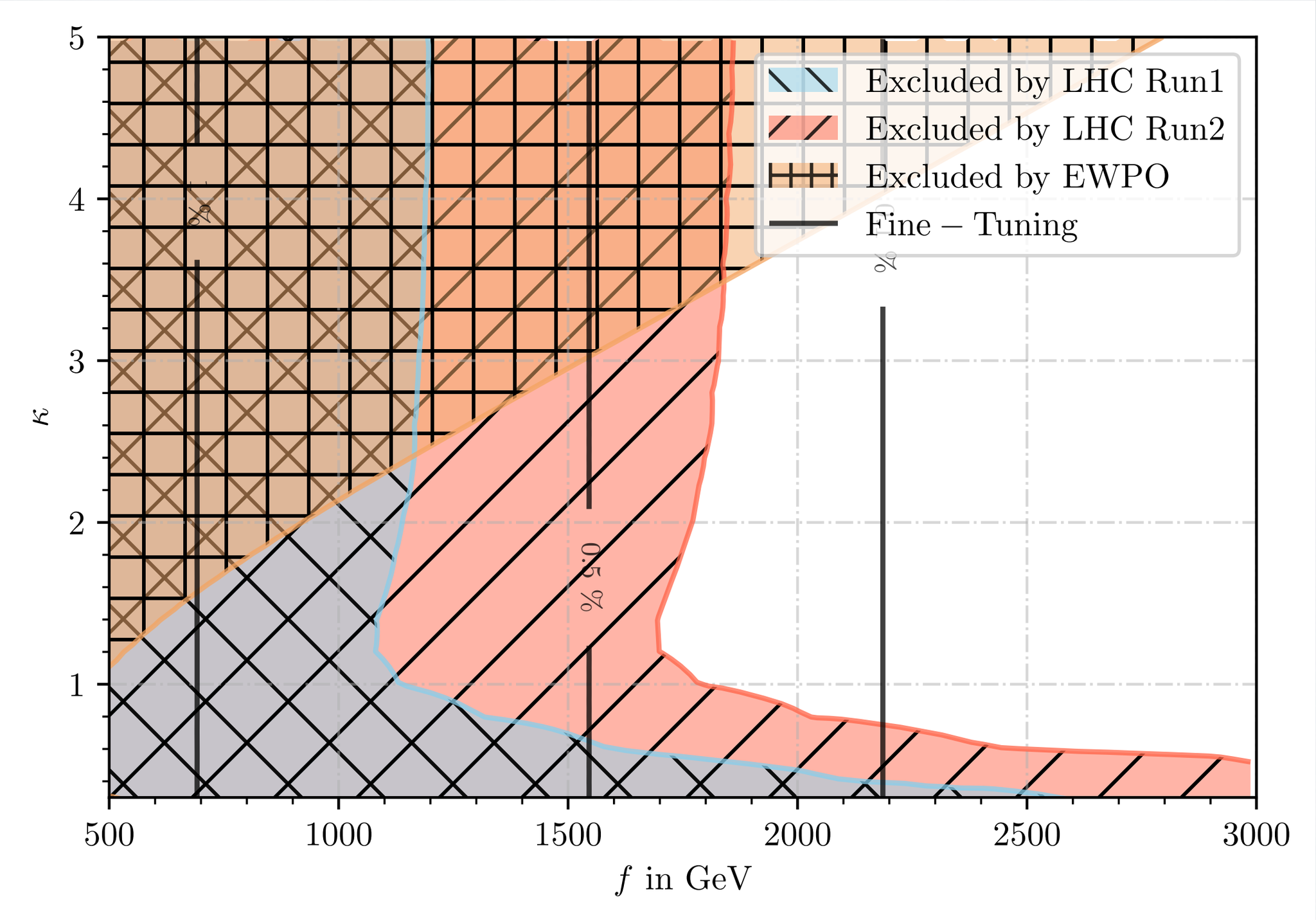
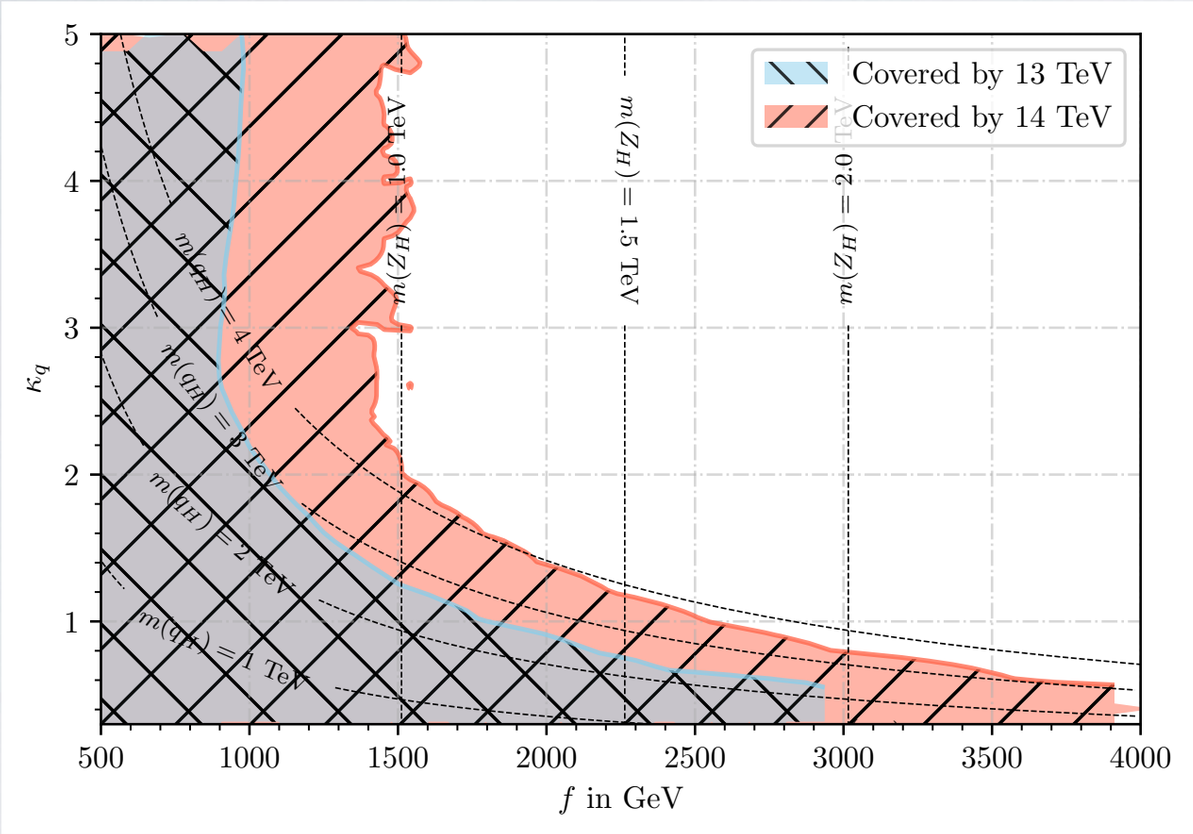
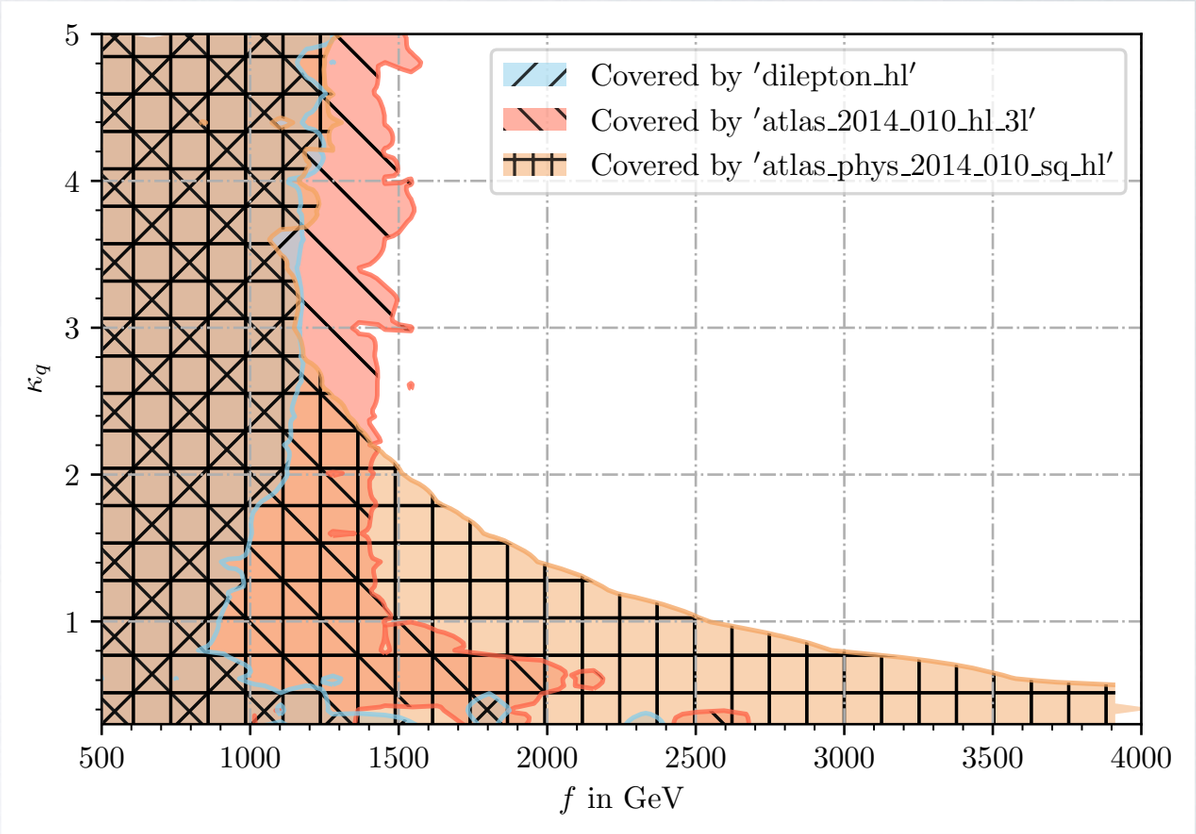


(Light ℓ_H) ⊕ (Light $T^{\pm}$) ⊕ (T-parity conservation)

Prospects for 14 TeV HL-LHC

CM identifier	Final State	Designed for	Ref.
atlas_2014_010_hl_3l	$\not{E}_T + 3\ \ell$	$\tilde{\chi}^{\pm}, \tilde{\chi}^0$	ATL-PHYS-PUB-2014-010
atlas_phys_2014_010_sq_hl	$\not{E}_T + 0\ \ell + 2\text{-}6\ \mathrm{j}$	$\tilde{q}, \tilde{g}$	ATL-PHYS-PUB-2014- 010
dilepton_hl	$\not{E}_T + 2\ \ell$	$\tilde{\chi}^{\pm}, \tilde{\ell}$	based on 1403.5294





(Fermion Universality) ⊕ (Heavy $T^{\pm}$) ⊕ (TPC) 14 TeV 3,000 / fb

q_H mass bounds improves by 1.0-1.5 TeV: $M(q_H) \gtrsim$ 3-4 TeV

Prospects for 14 TeV HL-LHC

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atlas_2014_010_hl_3l	$\not{E}_T + 3\ \ell$	$\tilde{\chi}^{\pm}, \tilde{\chi}^0$	ATL-PHYS-PUB-2014-010
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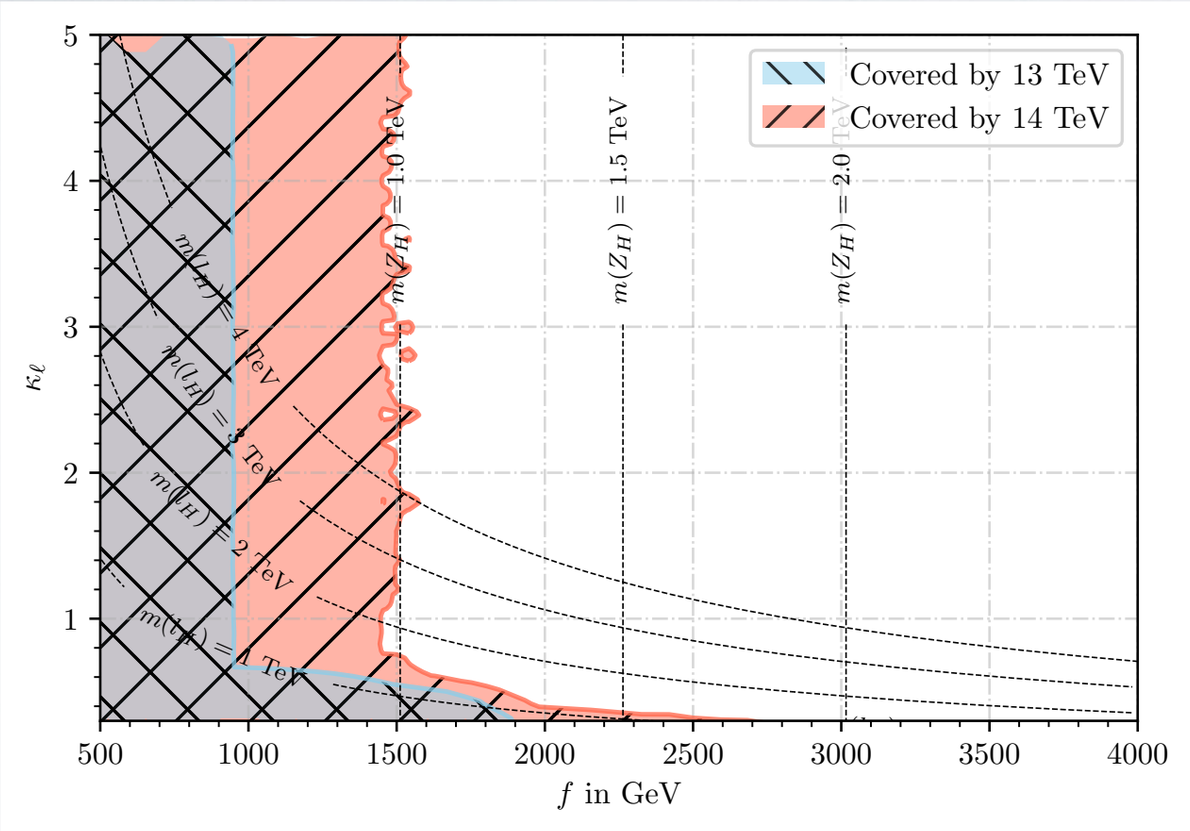

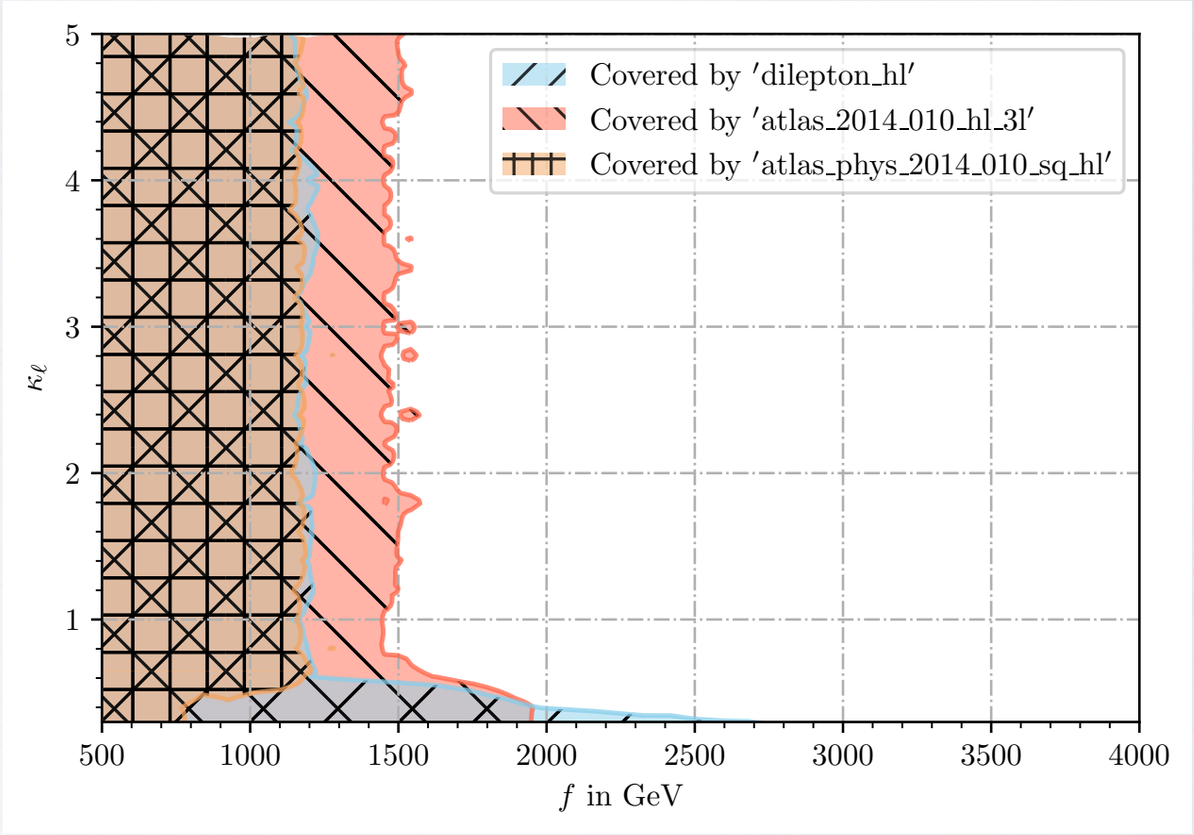

(Heavy q_H) ⊕ (Heavy $T^{\pm}$) ⊕ (TPC) 14 TeV 3,000 / fb

Relatively moderate improvements for ℓ_H mass bounds

Prospects for 14 TeV HL-LHC

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atlas_2014_010_hl_3l	$\not{E}_T + 3\ \ell$	$\tilde{\chi}^{\pm}, \tilde{\chi}^0$	ATL-PHYS-PUB-2014-010
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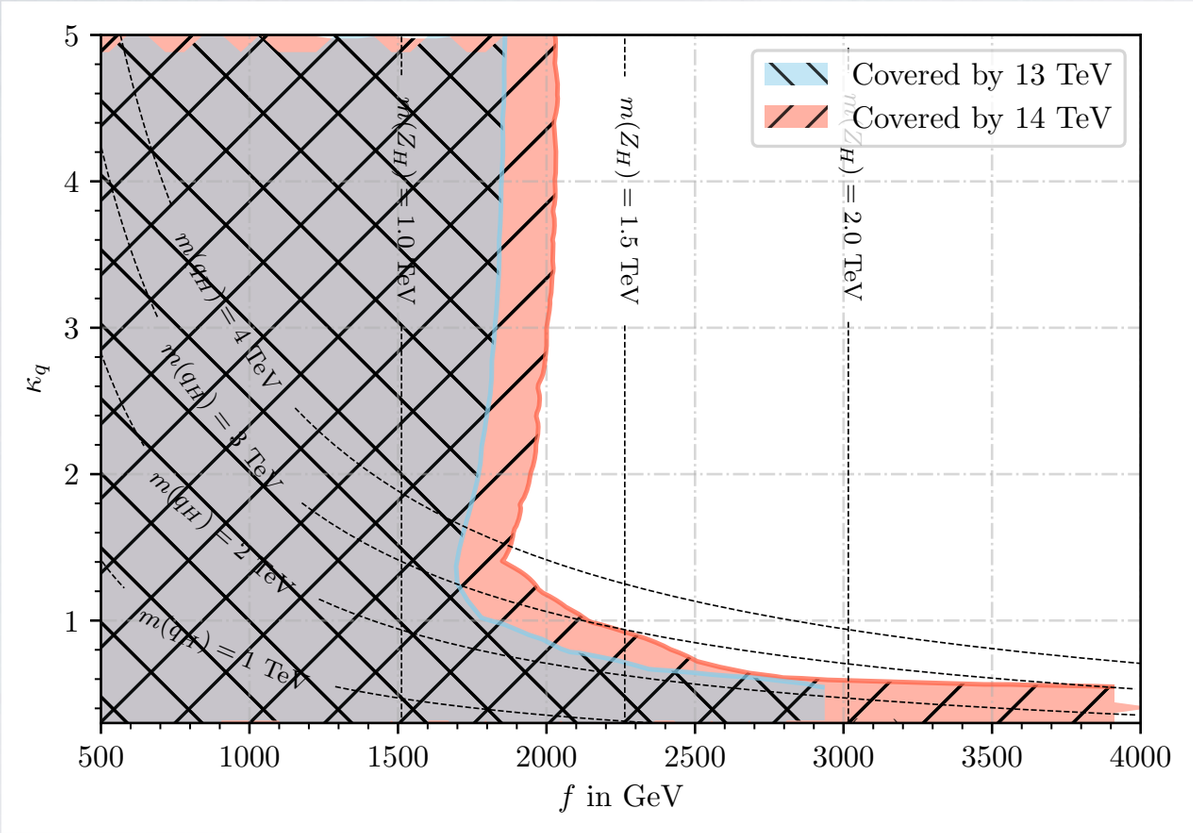
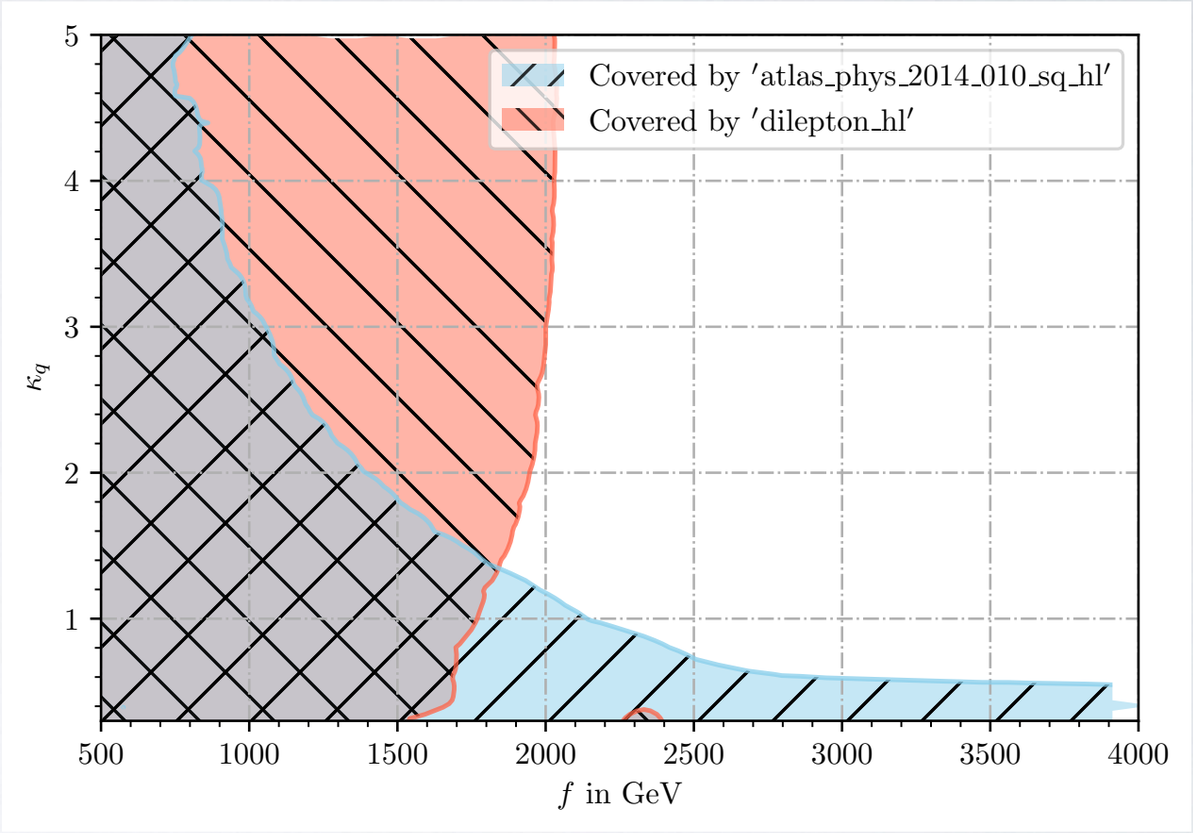




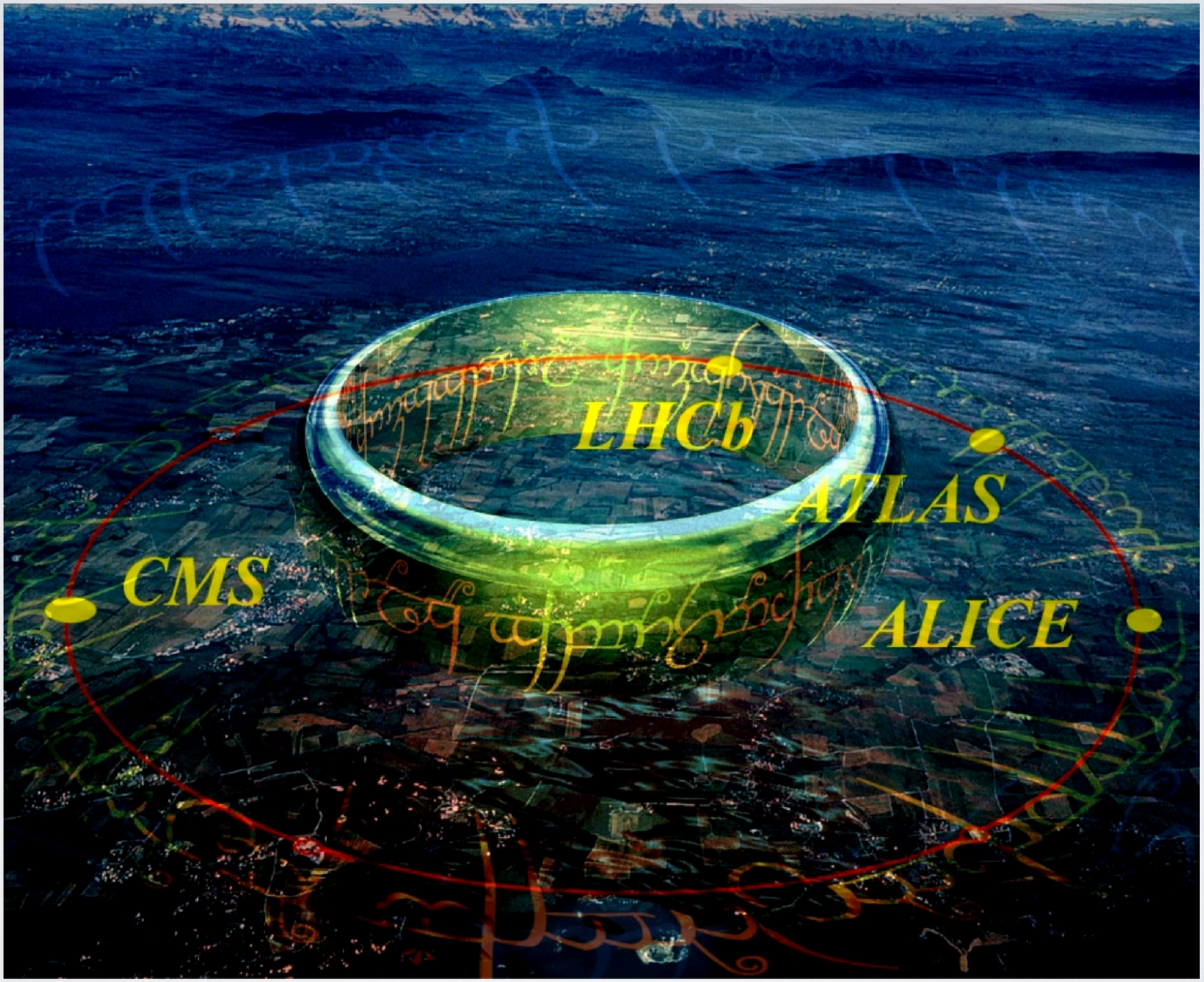
(Light ℓ_H) ⊕ (Heavy $T^{\pm}$) ⊕ (TPC) 14 TeV 3,000 / fb

Little improvement compared to 13 TeV

Conclusions / Summary

- Little Higgs models explain light Higgs as (pseudo-)Nambu-Goldstone boson
- Solves (little) hierarchy breaking by collective symmetry breaking
- EFT description of coset space, most commonly embedded in Composite Model
- Inclusion of discrete symmetry (*T*-parity) for EWPO and DM
- Constraints on parameter space from EWPO / Higgs data / direct searches
- 4-fermion operators give strict bounds (complimentary to direct searches)
- With LHC Run 2 scales go up into TeV range: $f \gtrsim 1.3$ TeV
- LHC bounds & LUX / Xenon direct detection (almost) rule LHT DM
- Prospects for 14 TeV HL-LHC: exclusion 1.5-1.8 TeV [preliminary]
- Higgs data (except for $H \to A_H A_H$) irrelevant $\Rightarrow$ need for a lepton collider

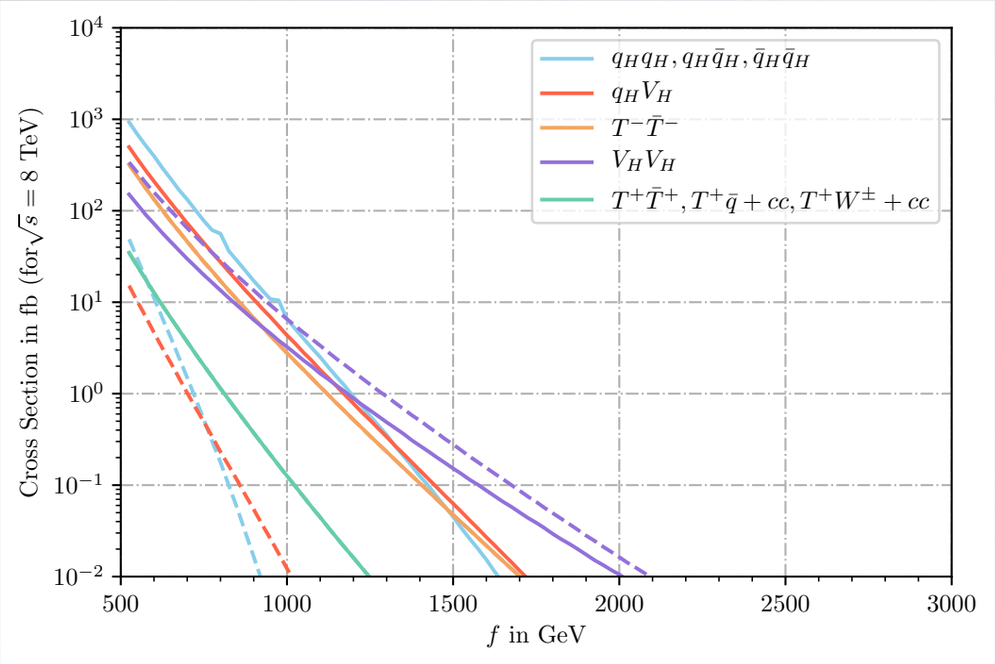
ONE RING TO FIND THEM ...
ONE RING TO RULE THEM OUT ?

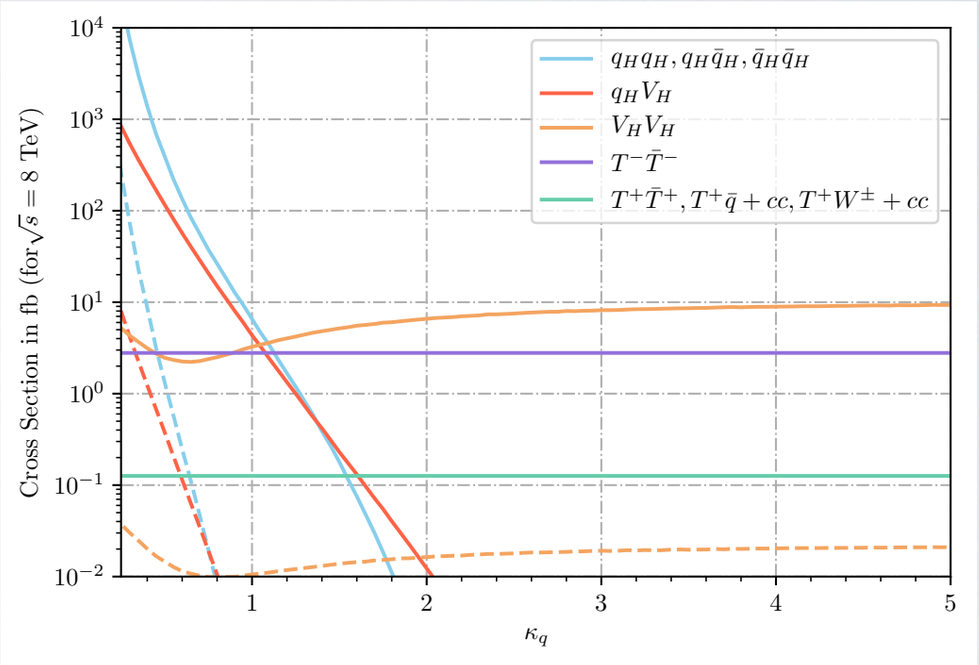


BACKUP SLIDES

Cross Sections 8 TeV

(Fermion Universality/Light ℓ_H) ⊕ (Light $T^\pm$) 8 TeV

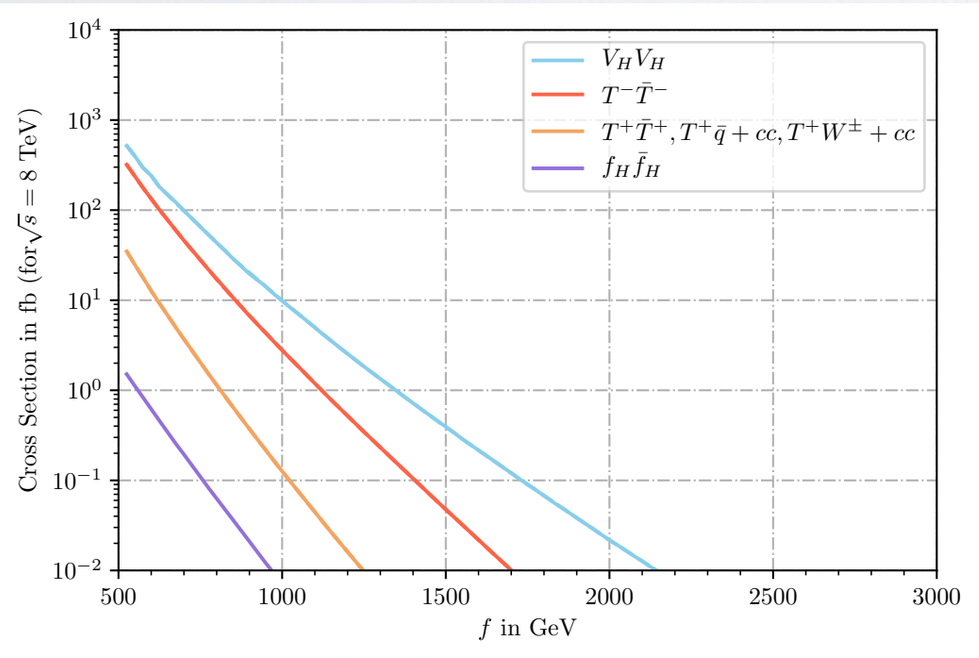


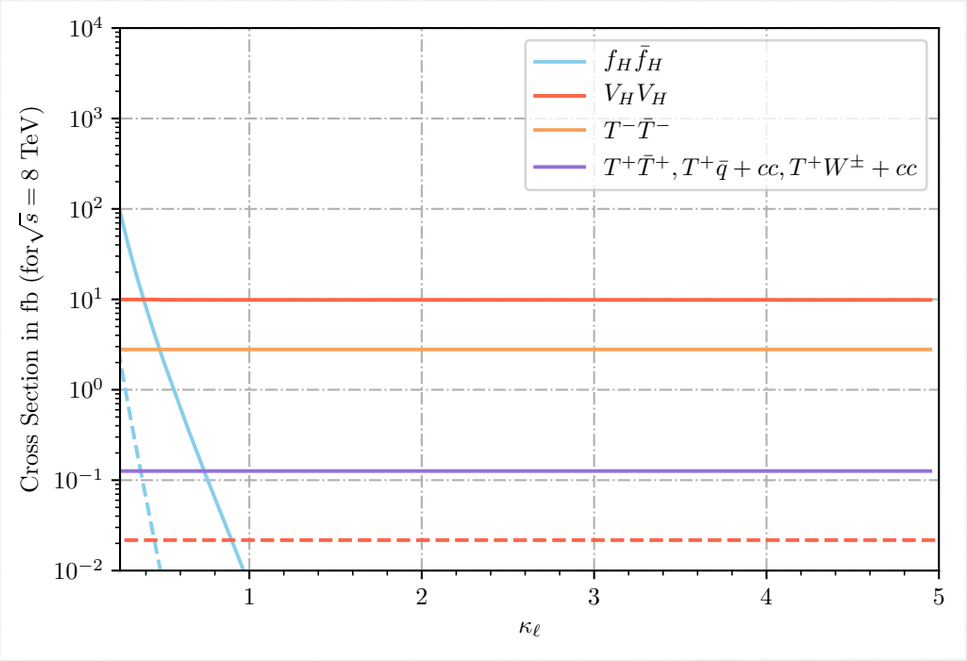


Left: fixed κ
Full line: f = 1 TeV
Dashed: f = 2 TeV

Right: fixed f
Full line: κ = 1 TeV
Dashed: κ = 2 TeV

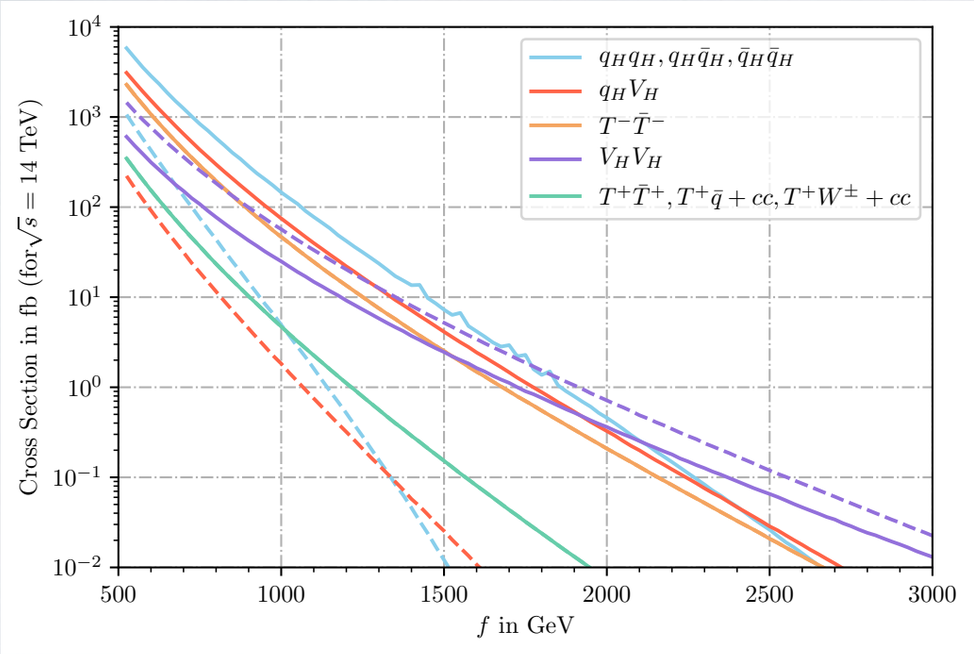
(Heavy q_H) ⊕ (Light $T^\pm$) 8 TeV

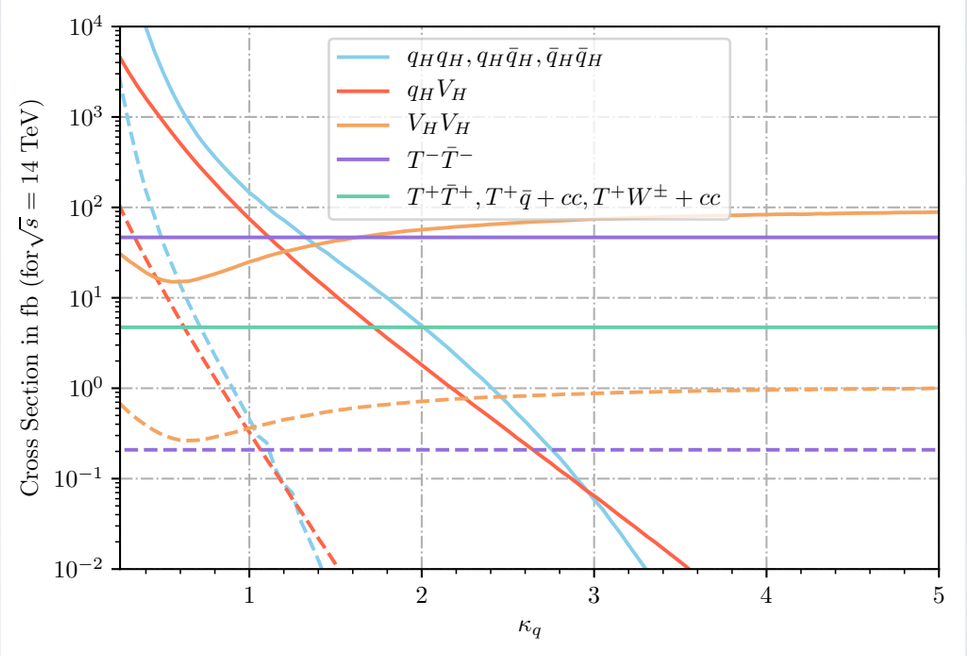




Cross Sections 14 TeV

(Fermion Universality/Light ℓ_H) ⊕ (Light $T^\pm$) 14 TeV





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(Heavy q_H) ⊕ (Light $T^\pm$) 14 TeV