The fate of Little Higgs models with LHC Run 2 data

Jürgen R. Reuter, DESY

based on work with

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

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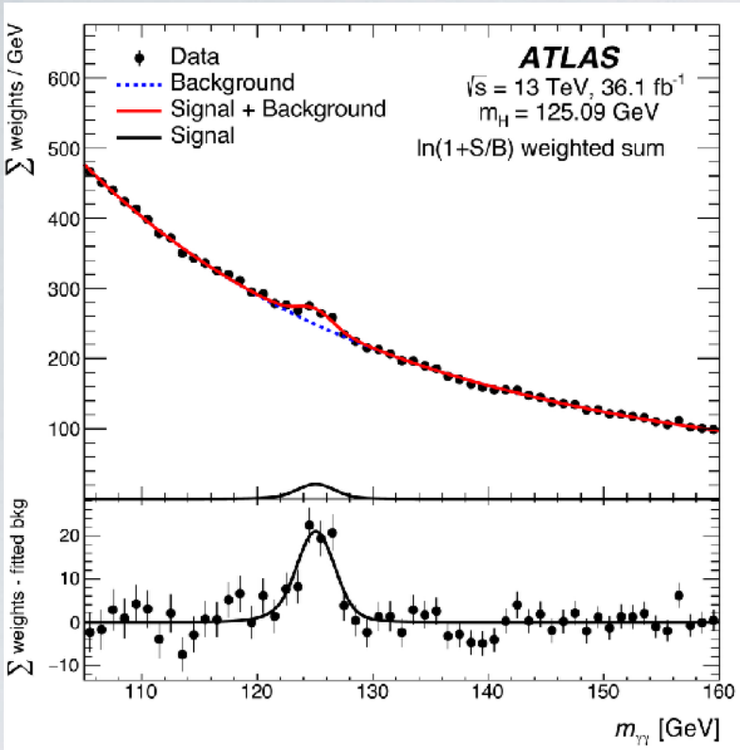
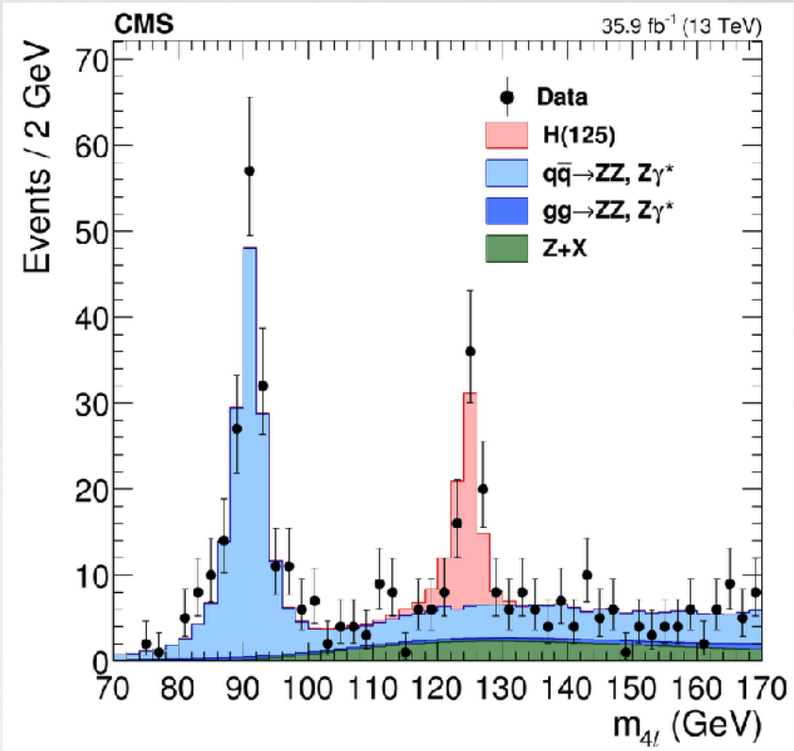
The Little Big Higgs boson



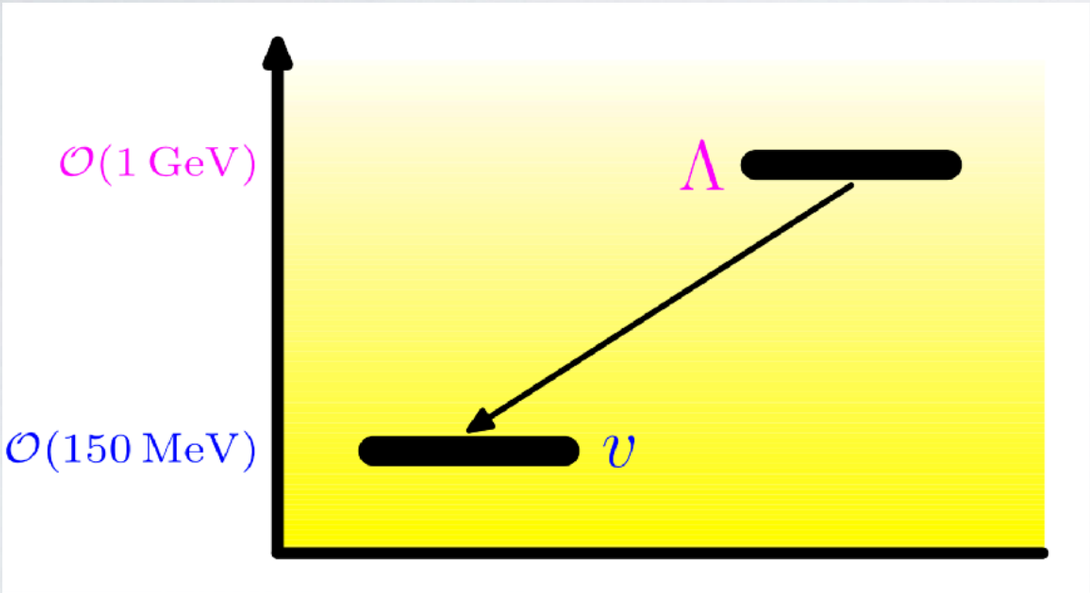


- Discovery of a light Higgs boson leaves still open questions:

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 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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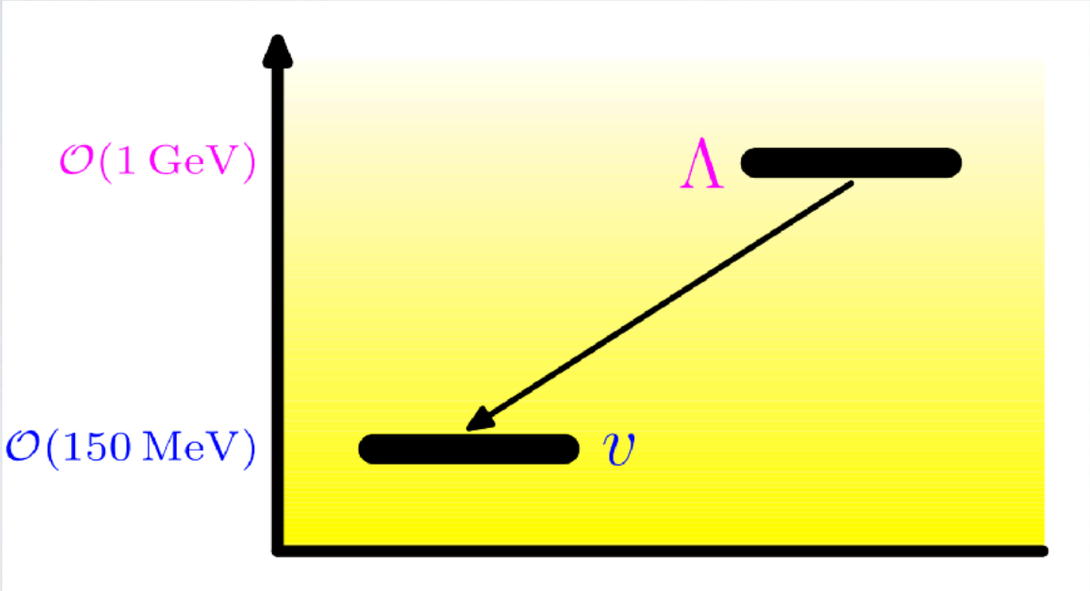

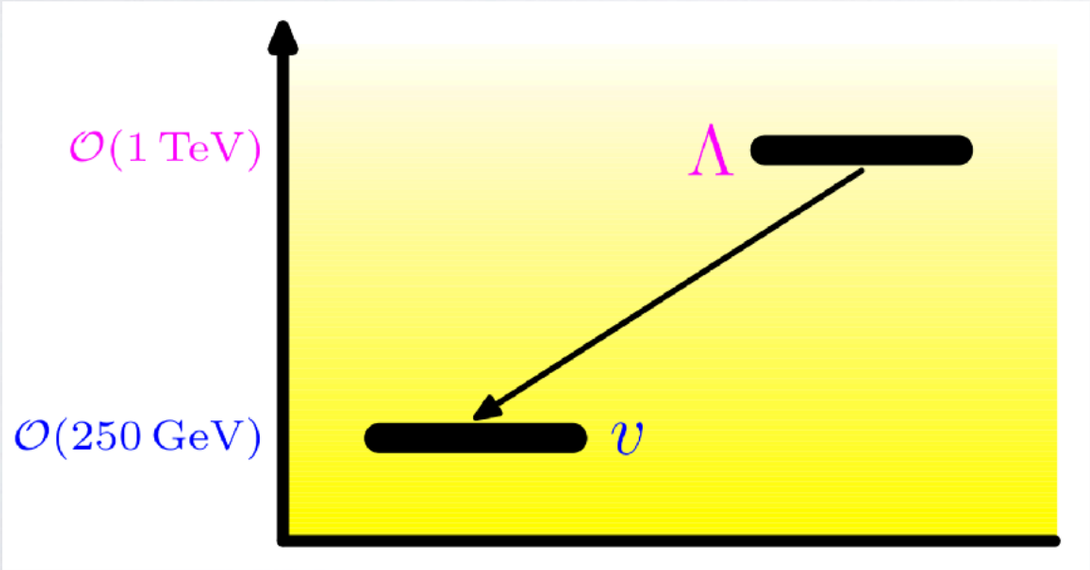

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Upscale: Technicolor (ruled out by EWPO/LHC)

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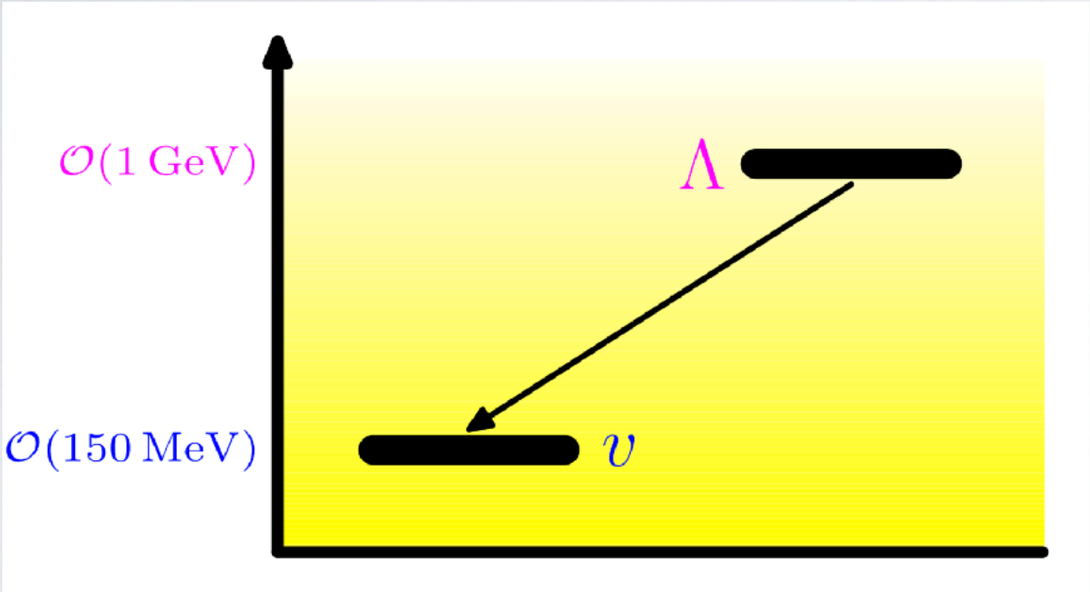

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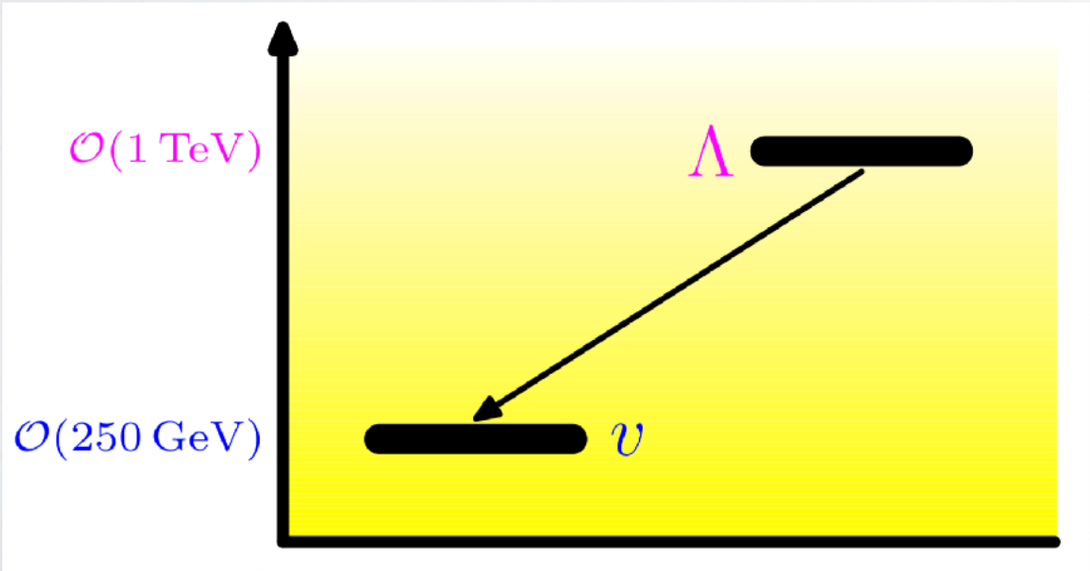
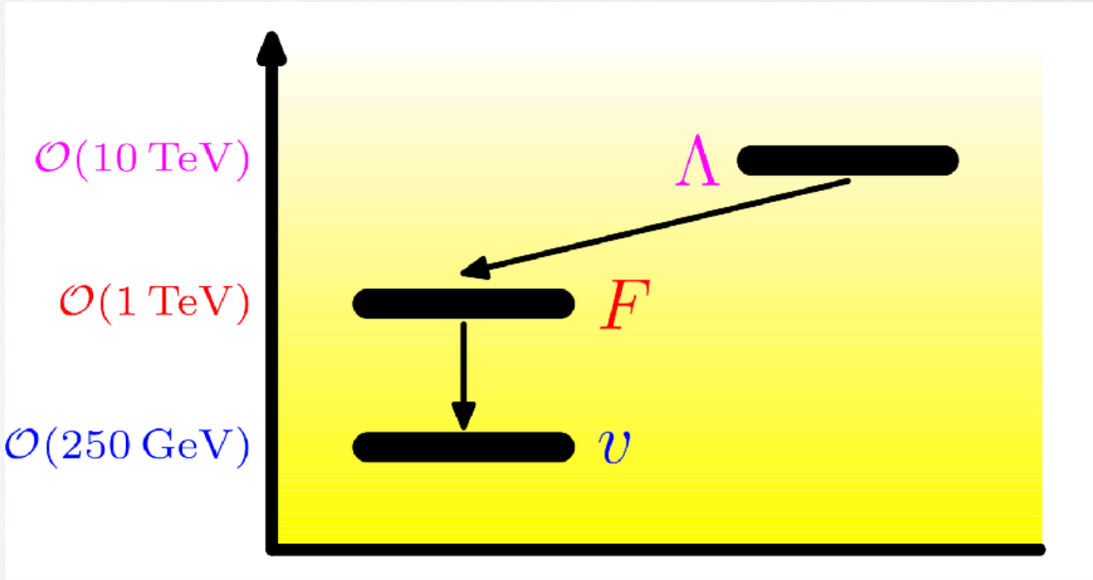
Collective Symmetry Breaking: 3-scale model

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

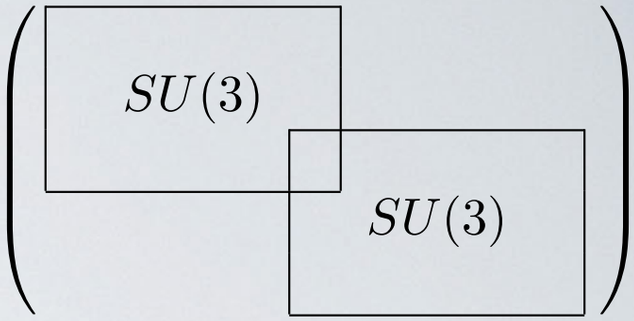




The Littlest Higgs Model

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

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



$$\Sigma(x) = e^{2i\Pi^a(x)X^a/f}\langle\Sigma\rangle$$

$$Q_1^a = \frac{1}{2}\left(\begin{array}{|c|c|}\hline \sigma^a & \\ \hline & \\ \hline\end{array}\right) \qquad Q_2^a = \frac{1}{2}\left(\begin{array}{|c|c|}\hline & \\ \hline & -\sigma^{a*} \\ \hline\end{array}\right)$$

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

Collective Symmetry Breaking

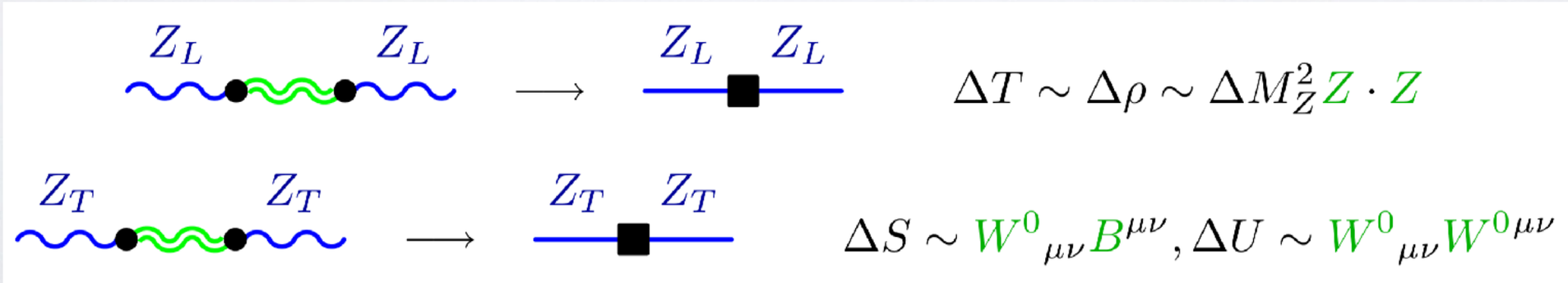
$$M_{W_H} \sim g\cdot f$$
$$M_{Z_H} \sim g\cdot f$$
$$M_{A_H} \sim g\cdot f$$
$$M_\Phi \sim f$$
$$m_h \sim \frac{f}{16\pi^2}$$

Local symmetry: $SU(2)_1 \otimes U(1)_1 \otimes SU(2)_2 \otimes U(1)_2 \rightarrow SU(2)_L \otimes U(1)_Y$
eats up 4 Nambu-Goldstones

Goldstone bosons:

$$\Pi^a X^a = \frac{1}{\sqrt{2}}\left(\begin{array}{|c|c|}\hline h^\dagger & \\ \hline h & h^* \\ \hline & h^T \\ \hline\end{array}\right) + \frac{1}{2}\left(\begin{array}{|c|c|}\hline & \Phi^\dagger \\ \hline \Phi & \\ \hline\end{array}\right)$$

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



T-parity: a discrete symmetry for EWPO

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

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

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

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

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

- (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
- Lightest *T*-odd particle (LTP) is stable → Dark Matter candidate

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- Assume *T*-parity violation: A_H heavily constrained as DM candidate
- 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

Signatures and constraints on the LHT model

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

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

Mirror fermions

- 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:

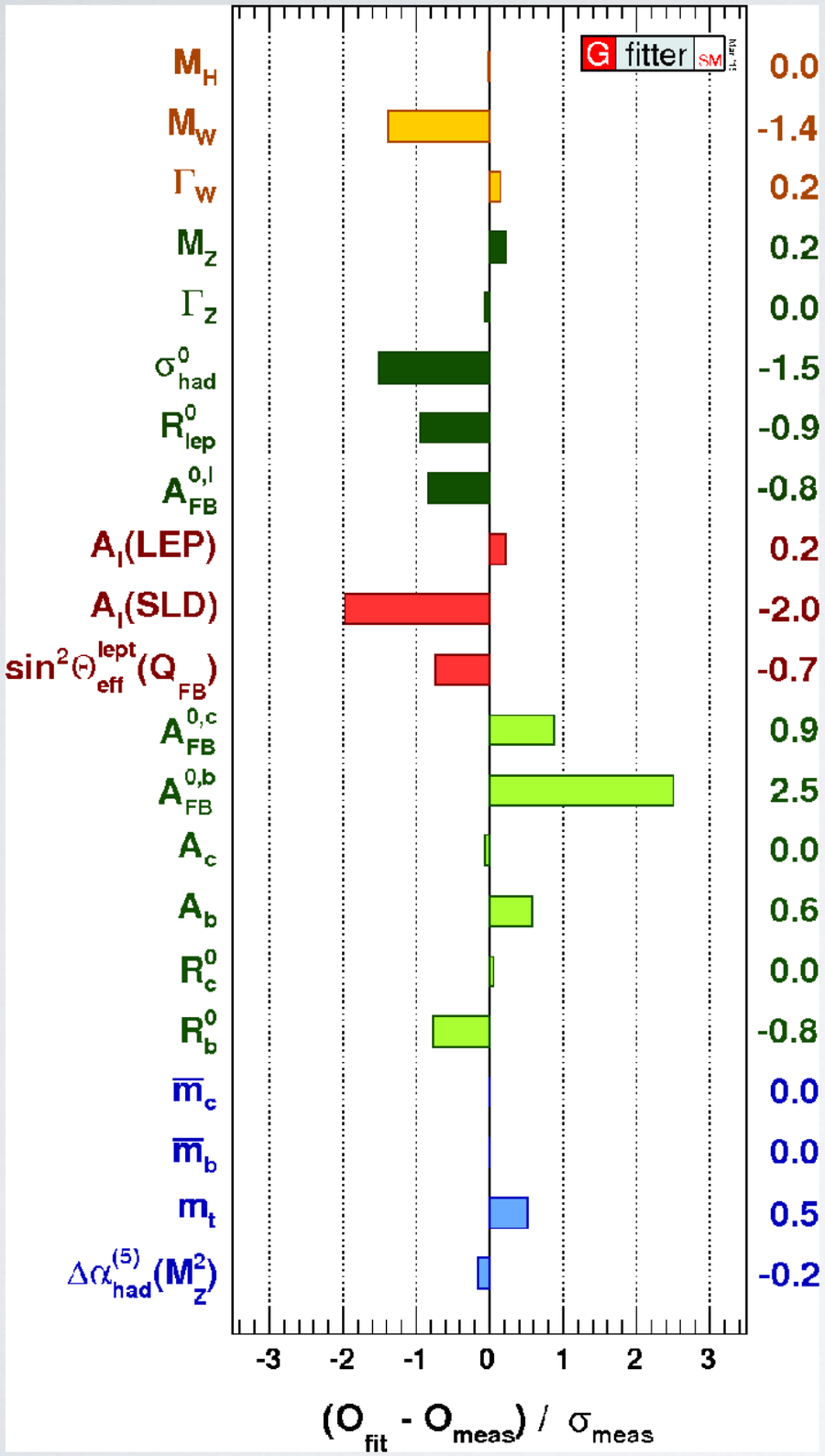
$$\frac{m_t^2}{v}\Big[\left(1+\mathcal{O}(v^2/f^2)\right)h\bar{t}t + \mathcal{O}(v^2/f^2)\,h\bar{t}\gamma^5 t\Big]$$

Modified *Vff* couplings:

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

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

Electroweak Precision Observables



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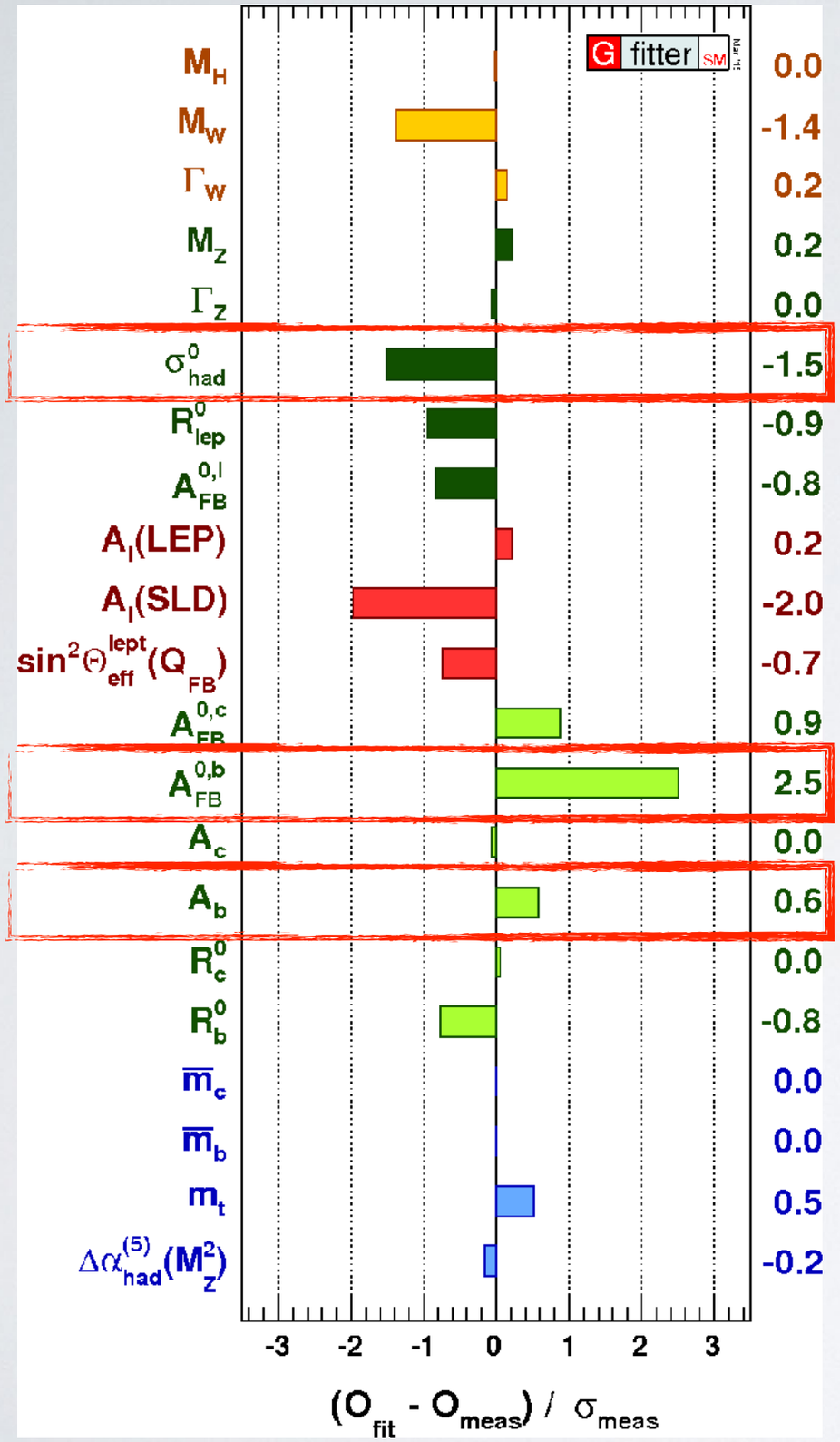

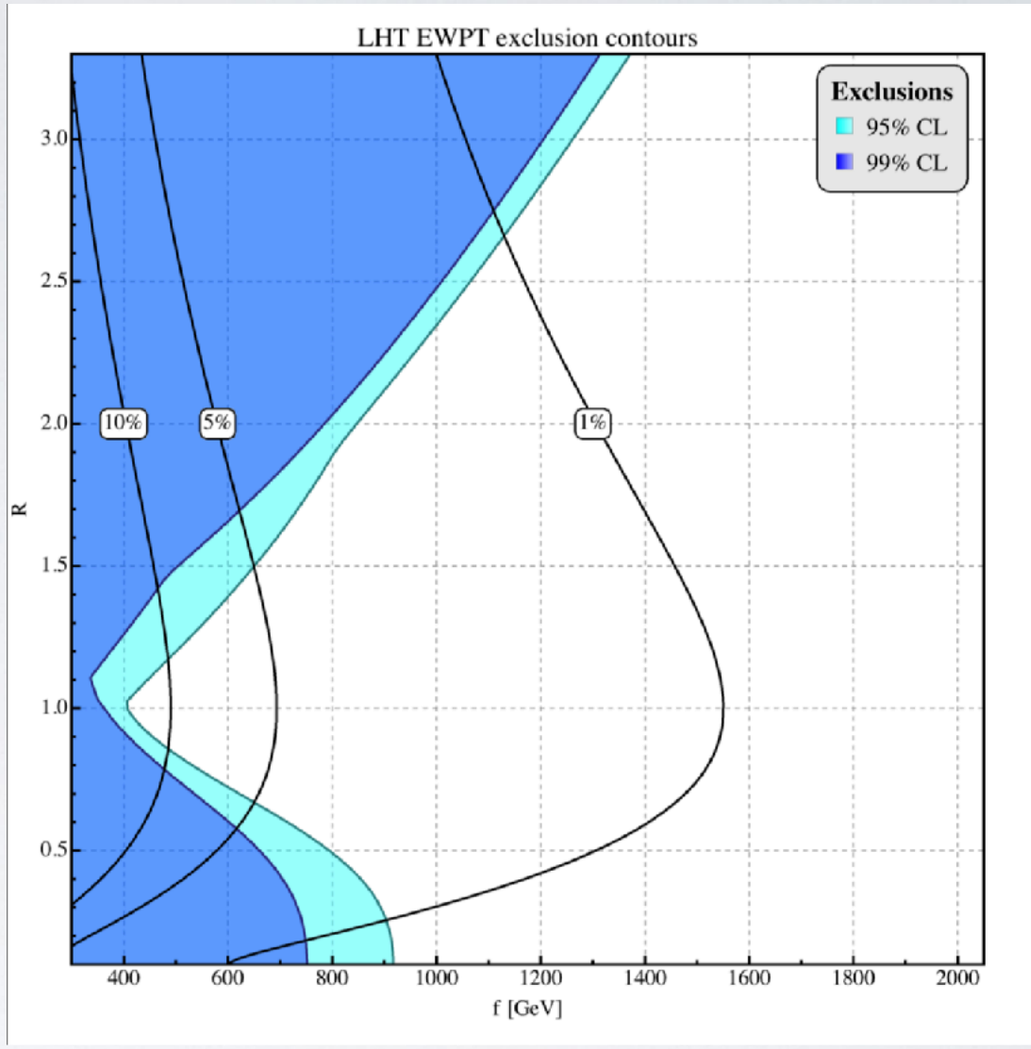

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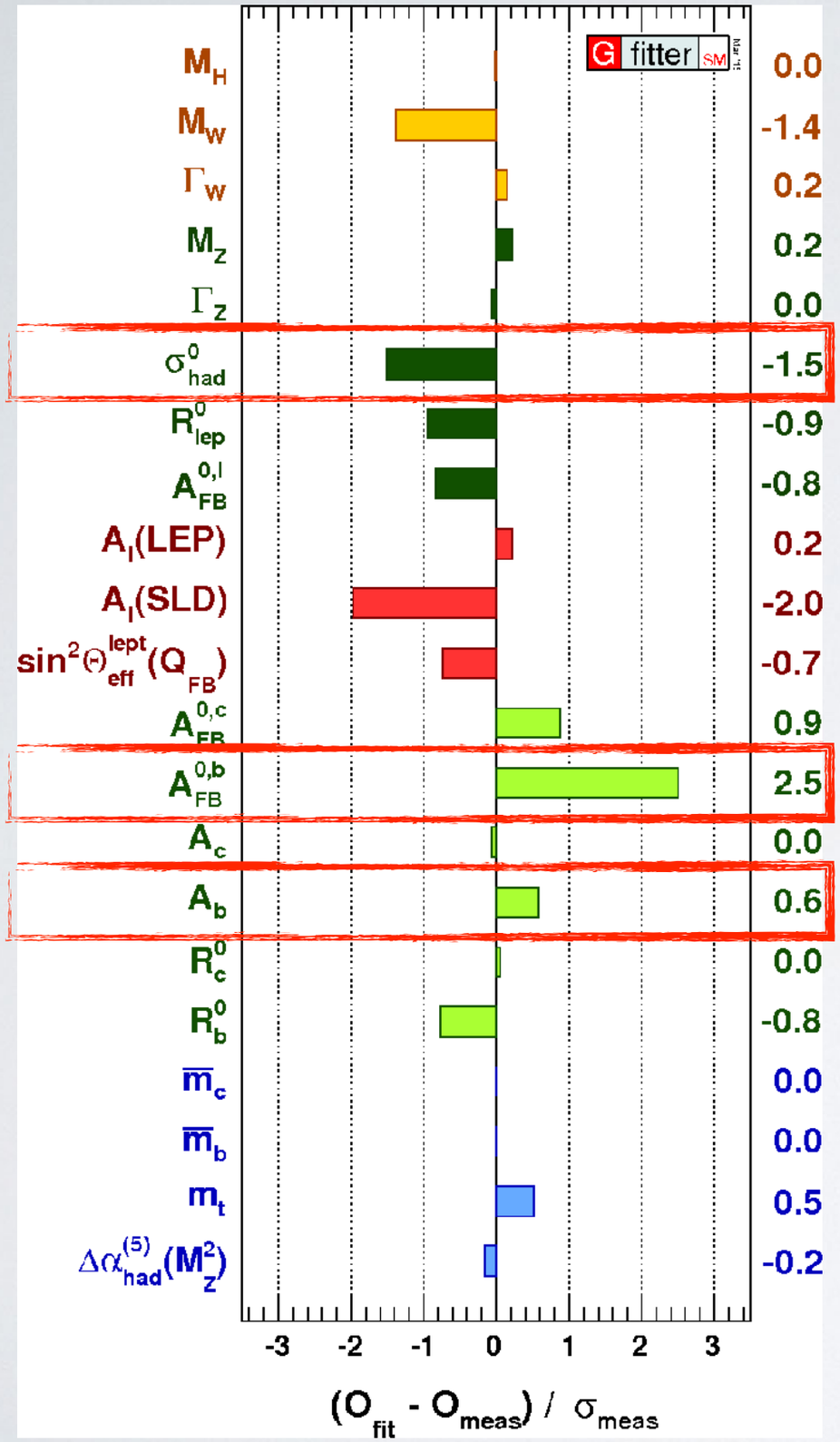
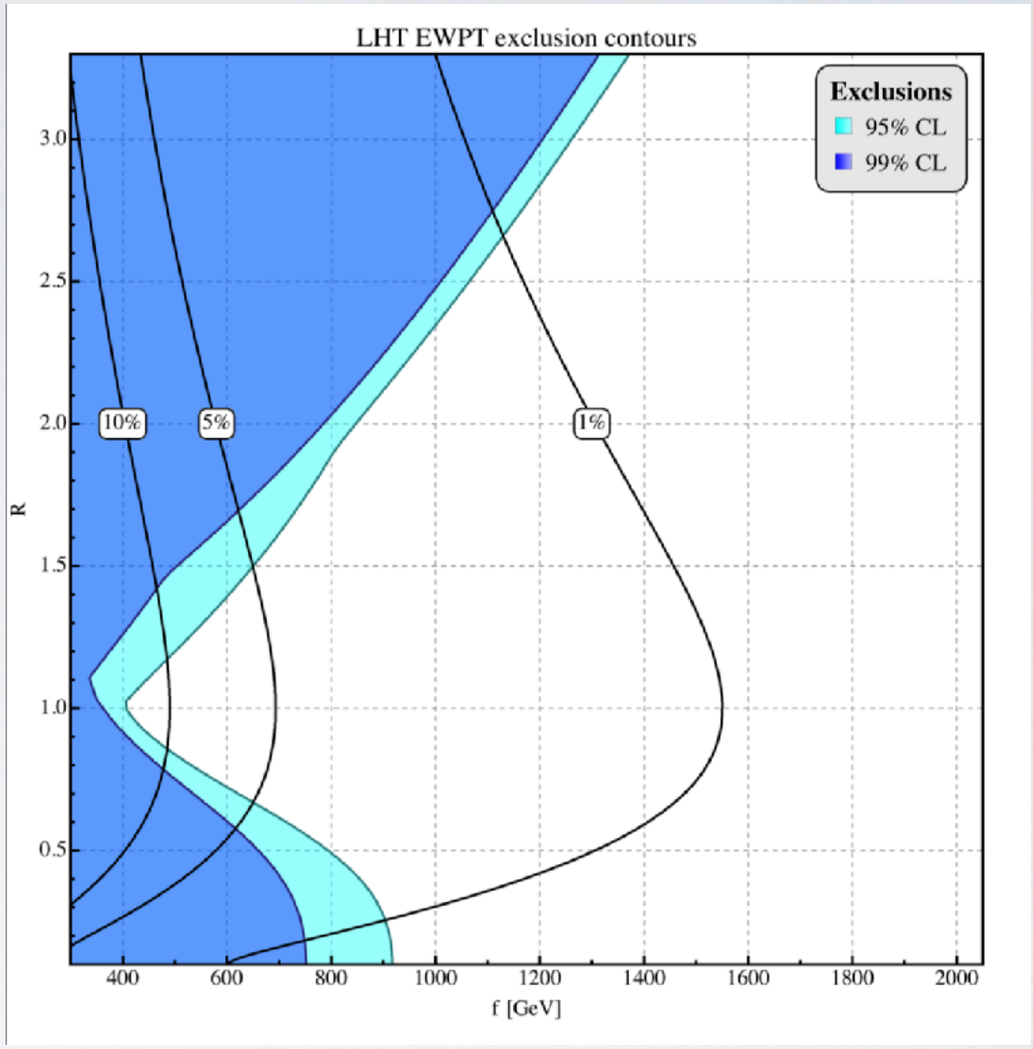




- Accidental cancellation to EWPO for $R \simeq 1$
- Bounds from 4-fermion contact interactions (later)
- Exclusion limits at 95% CL: $\boxed{f \gtrsim 405 \text{ GeV}}$

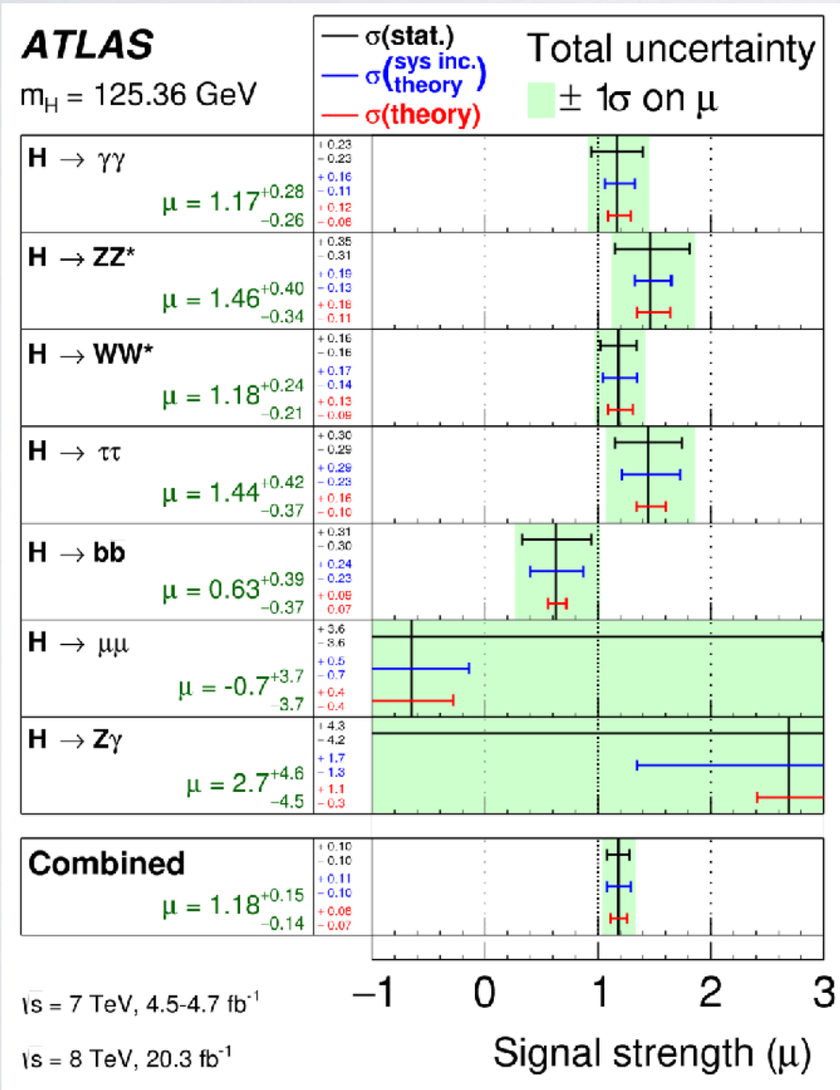
$$M_{W'} \gtrsim 270 \text{ GeV}$$
$$M_T \gtrsim 554 \text{ GeV}$$

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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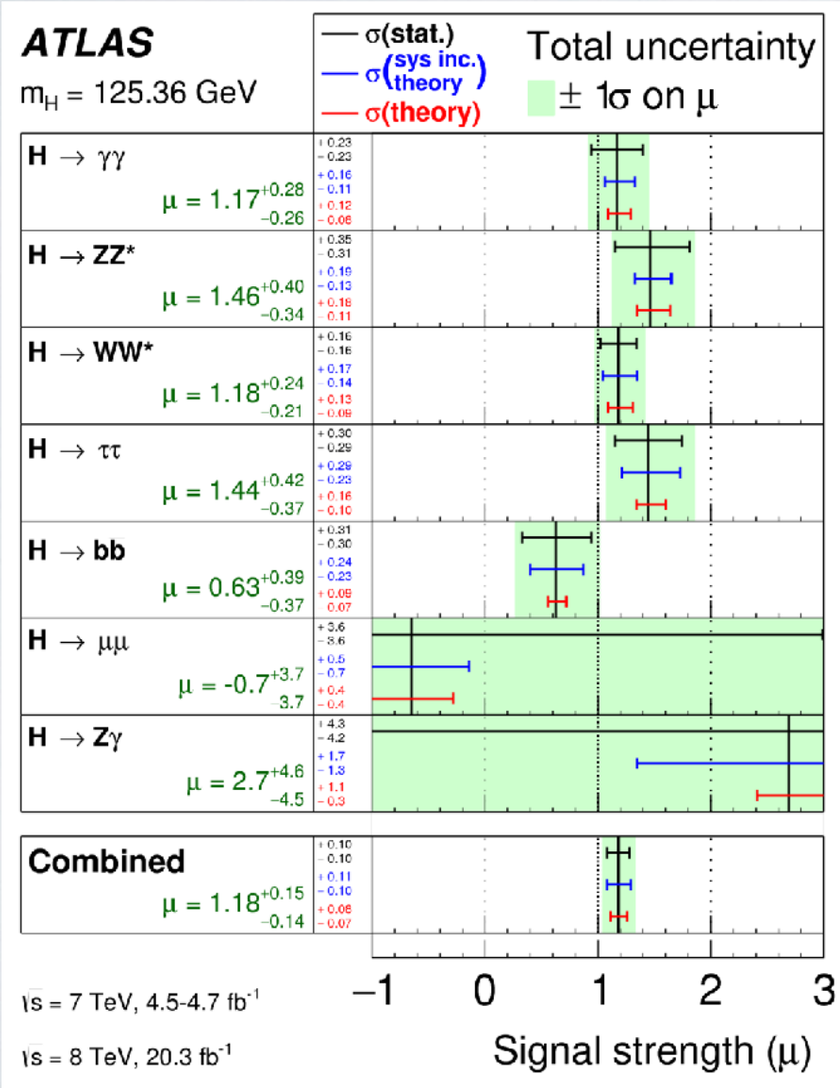

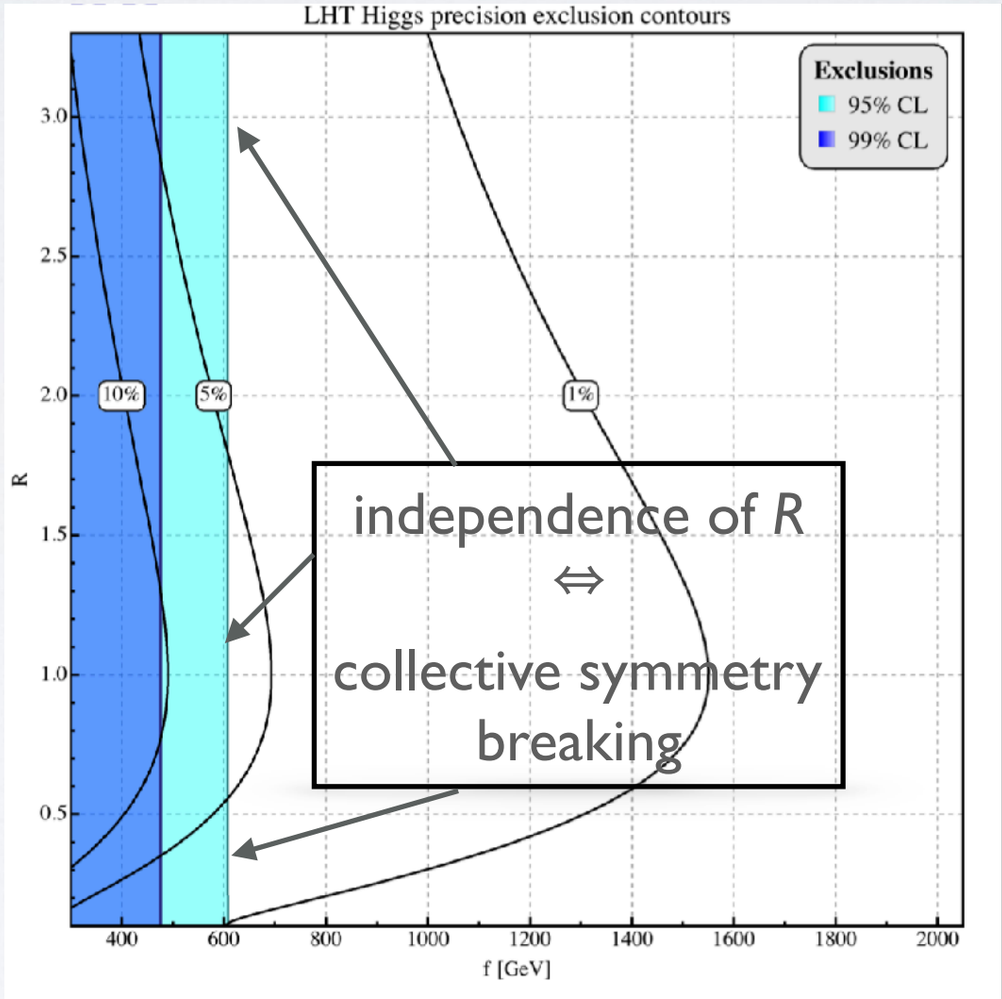

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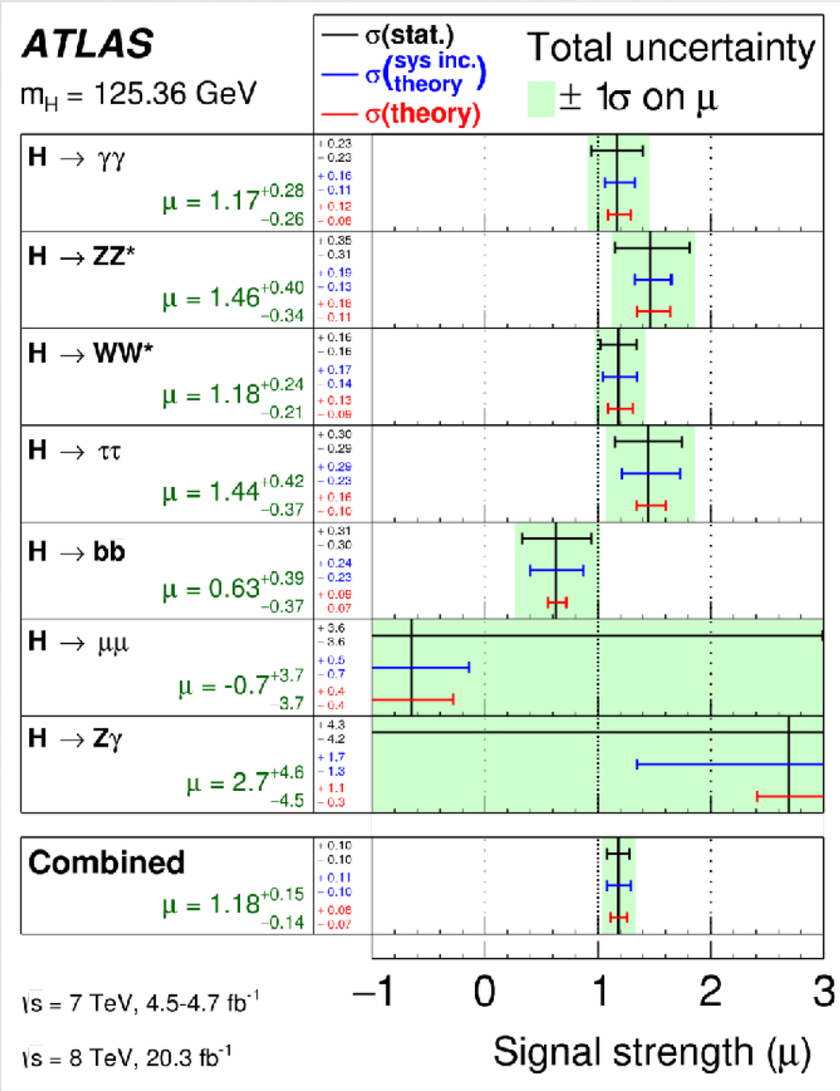

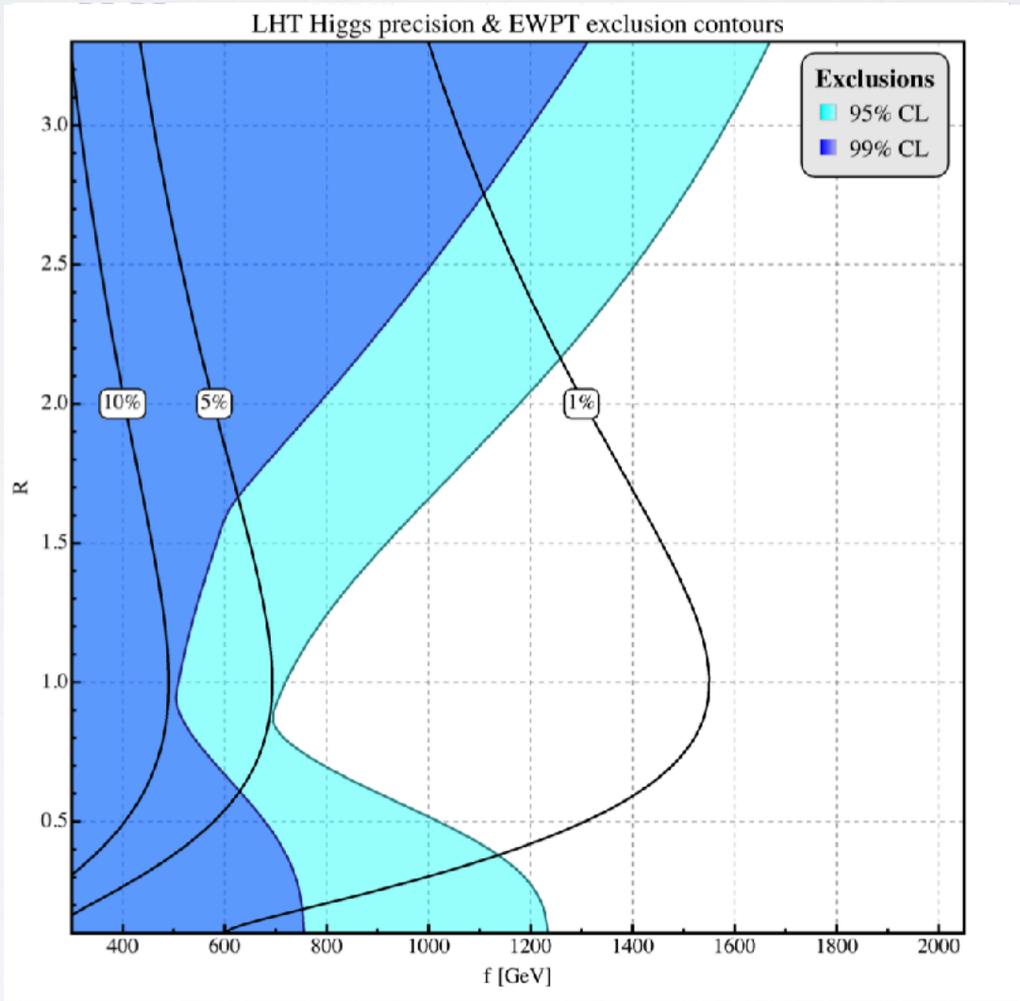

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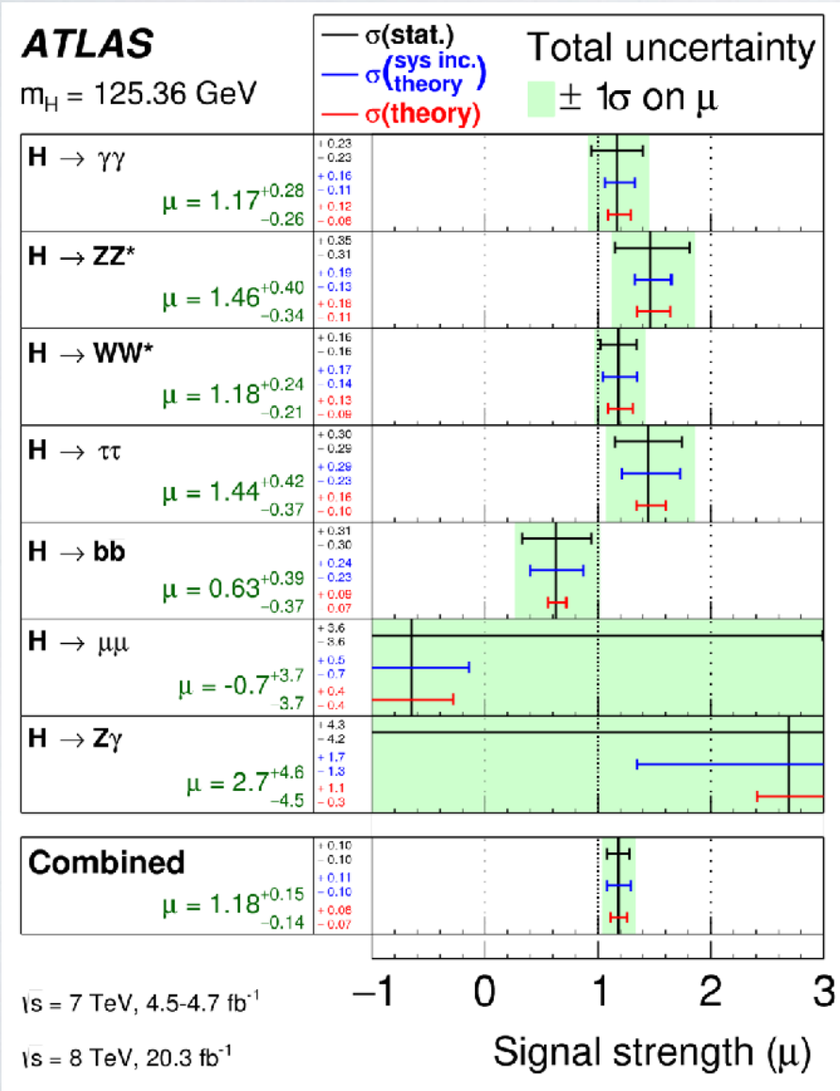

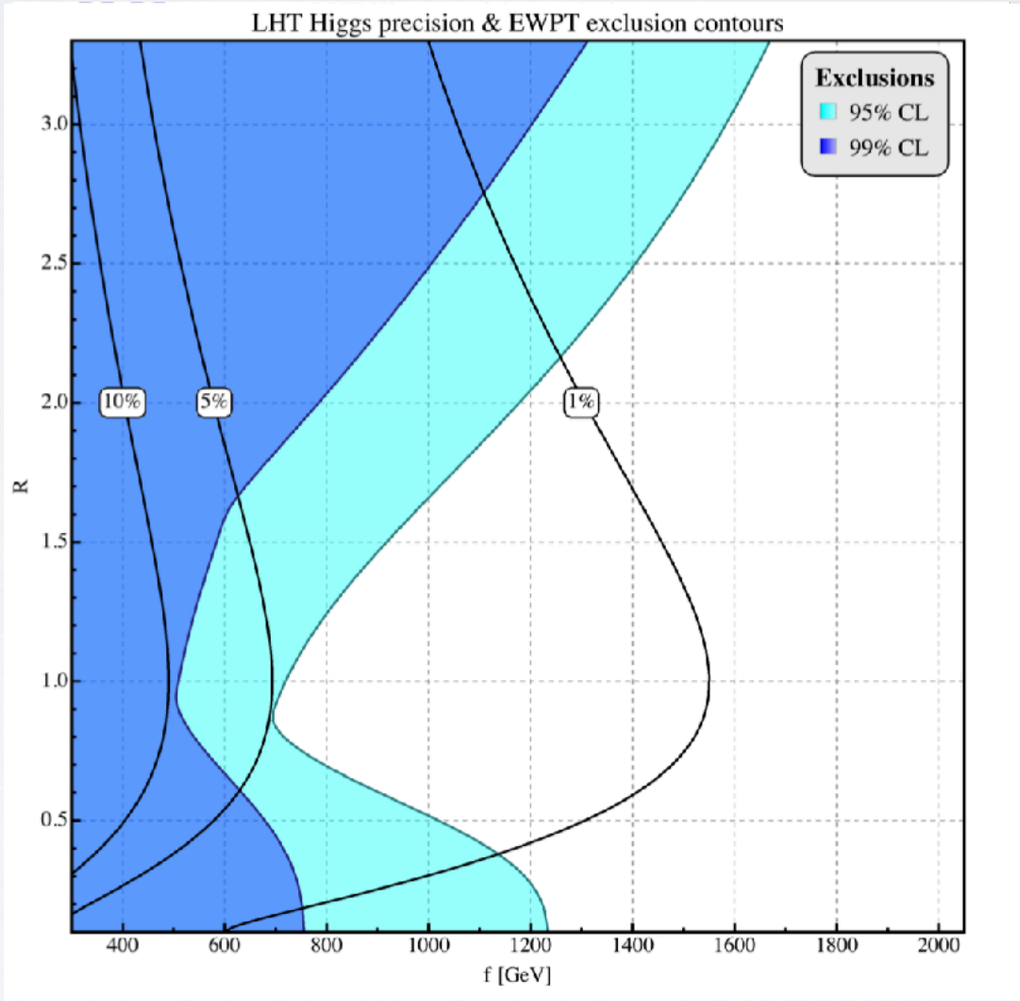

EWPT/Higgs data:

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

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

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]
- Clustering, jet selection: `FastJet v3.3` [Cacciari/Salam/Soyez, '11]
- Parton shower and hadronization: `Pythia v8.2` [Sjöstrand/Mrenna/Skands, '08]
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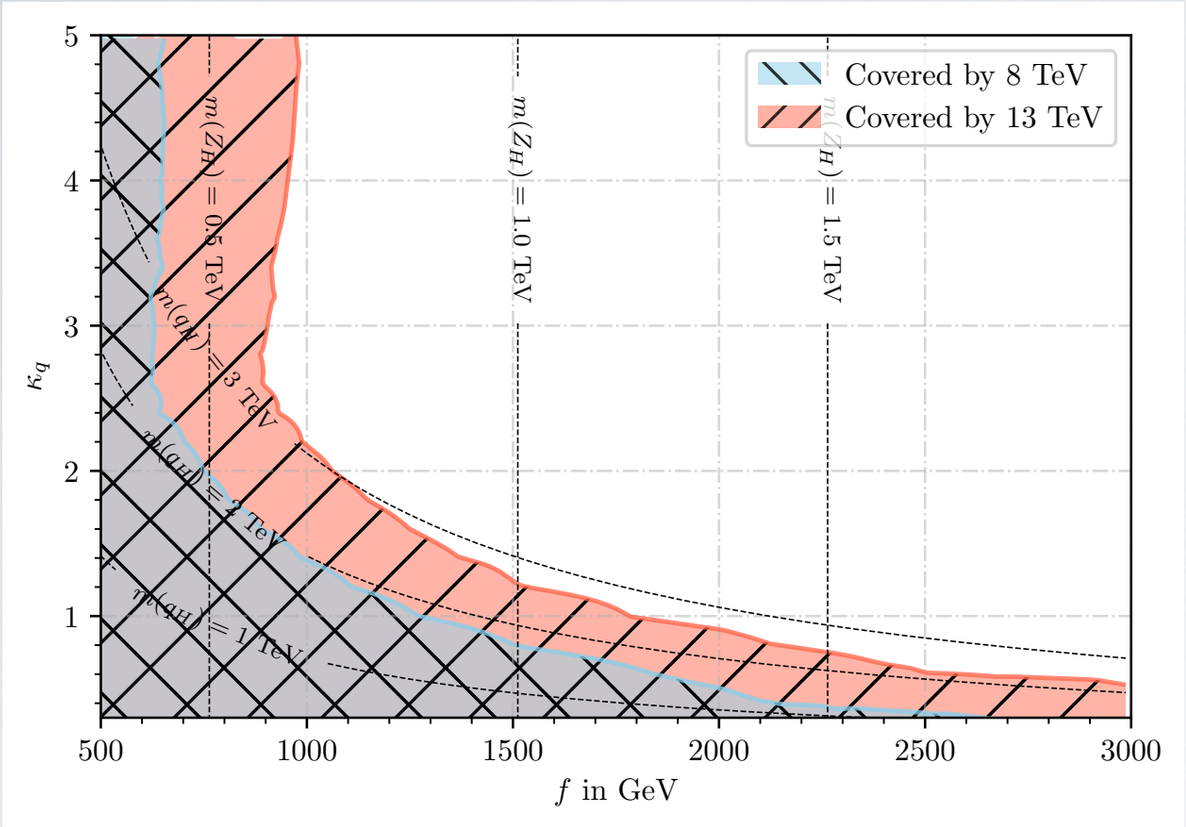
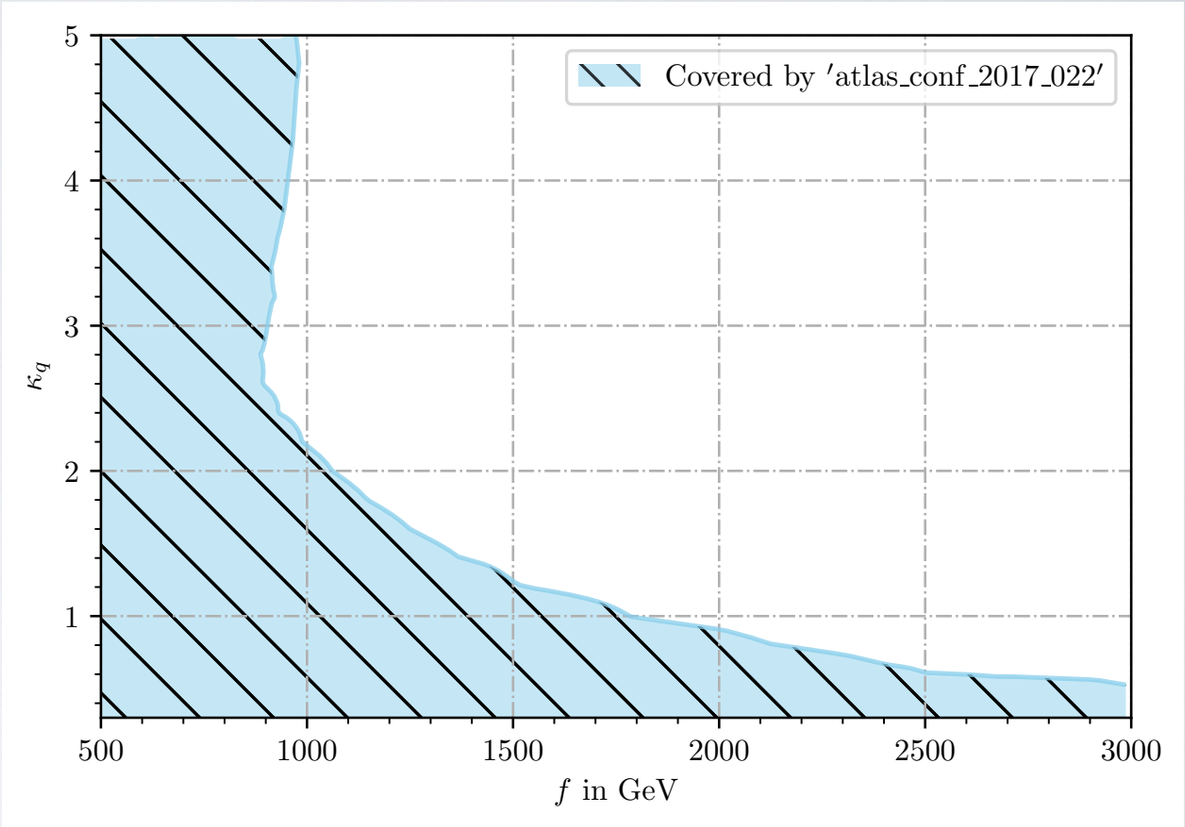
All used searches that have been recasted here:

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

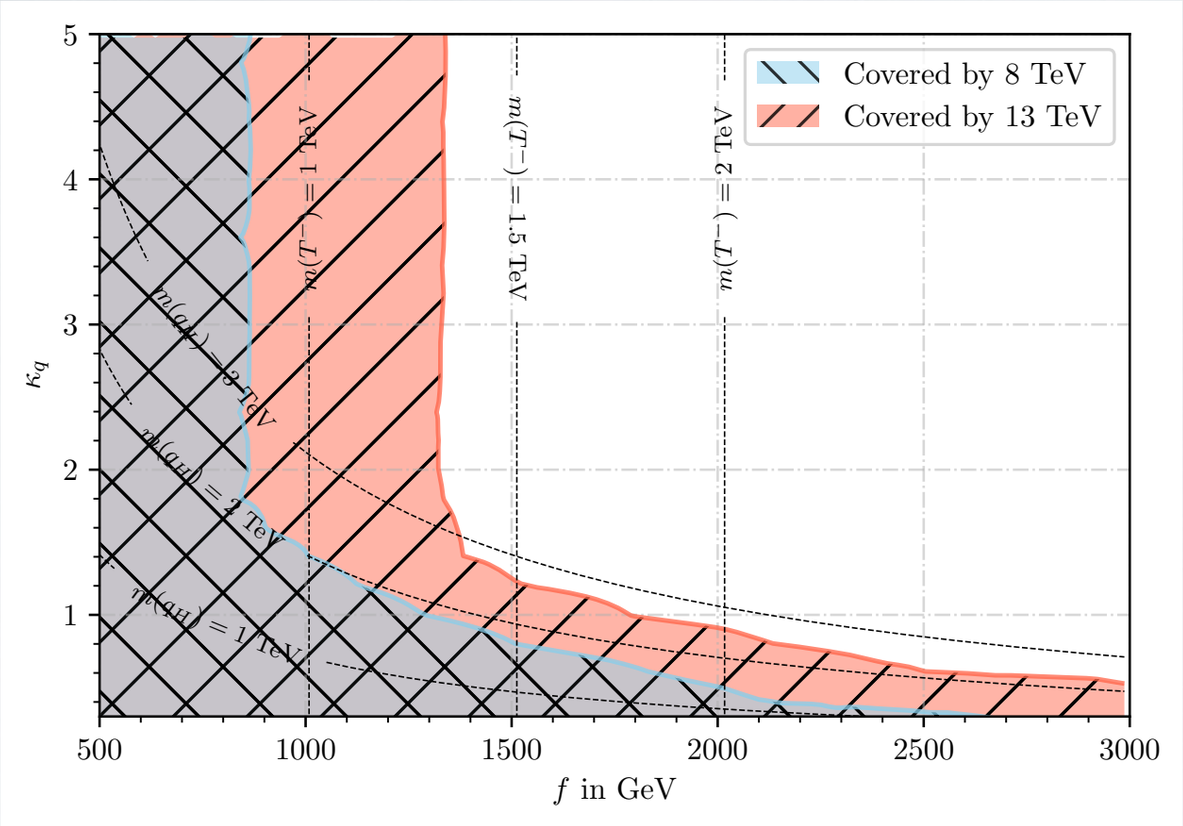
13 TeV recasting results: Fermion Universality

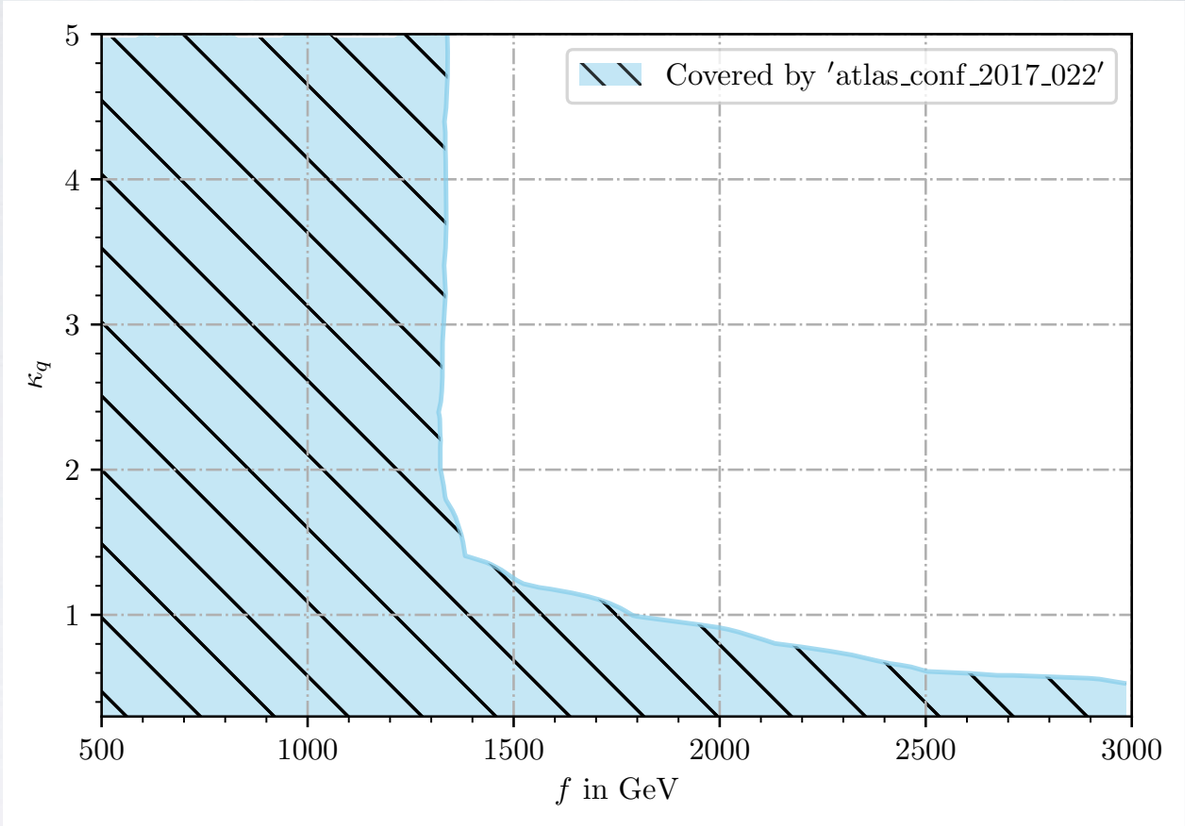




(Fermion Universality) ⊕ (Heavy $T^{\pm}$) ⊕ (TPC)

13 TeV recasting results: Fermion Universality





(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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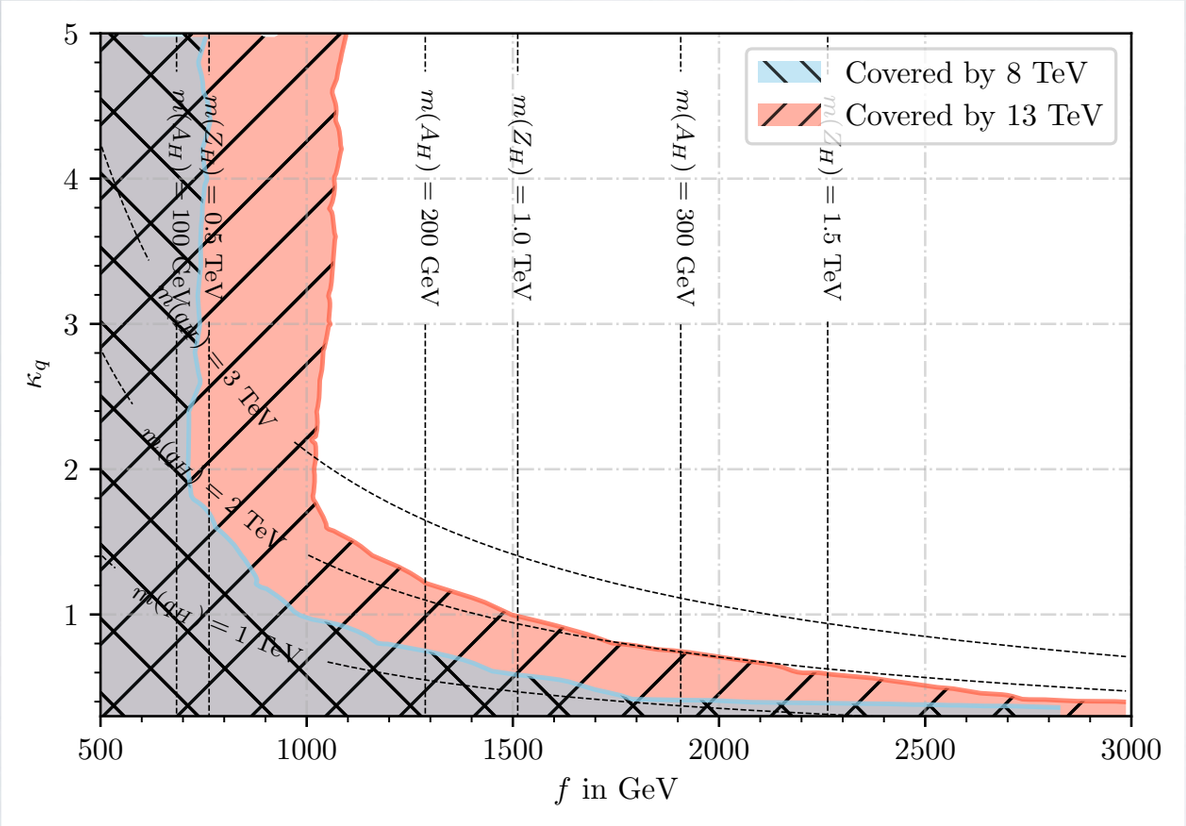

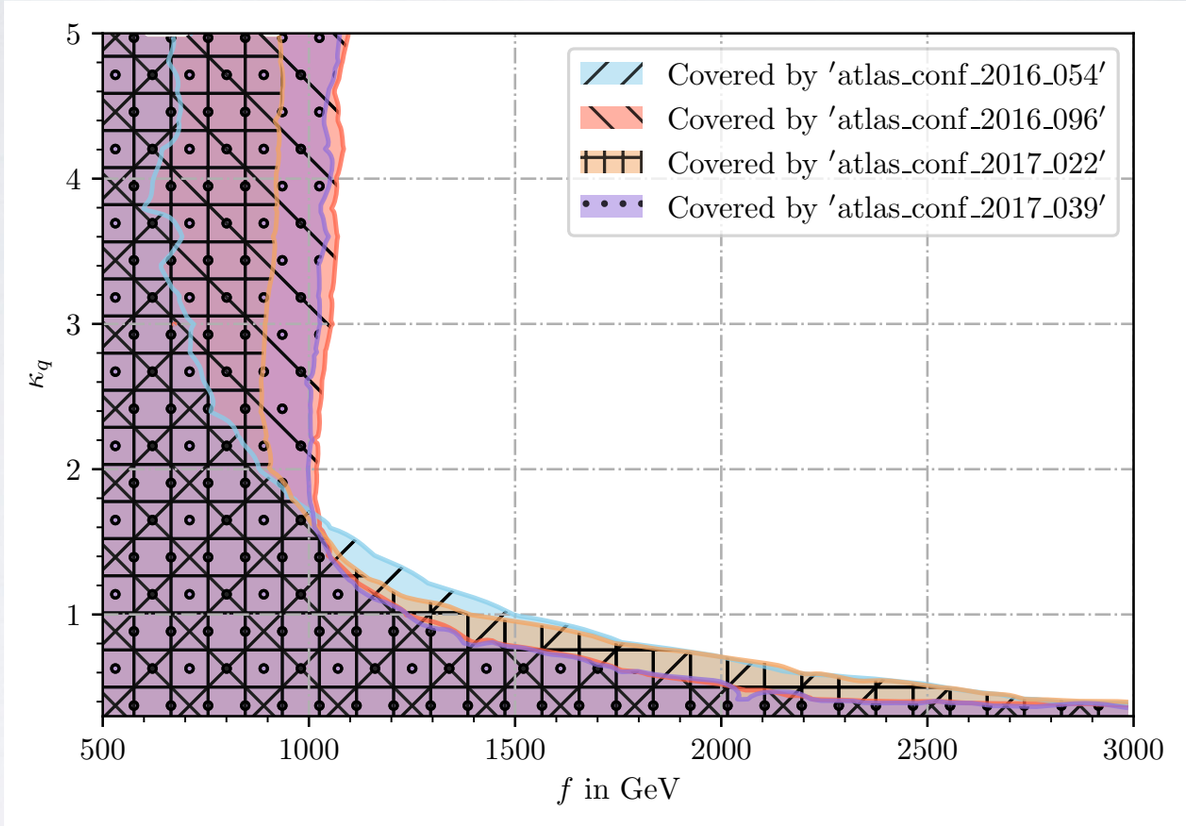

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Bounds from 4-fermion operators

- 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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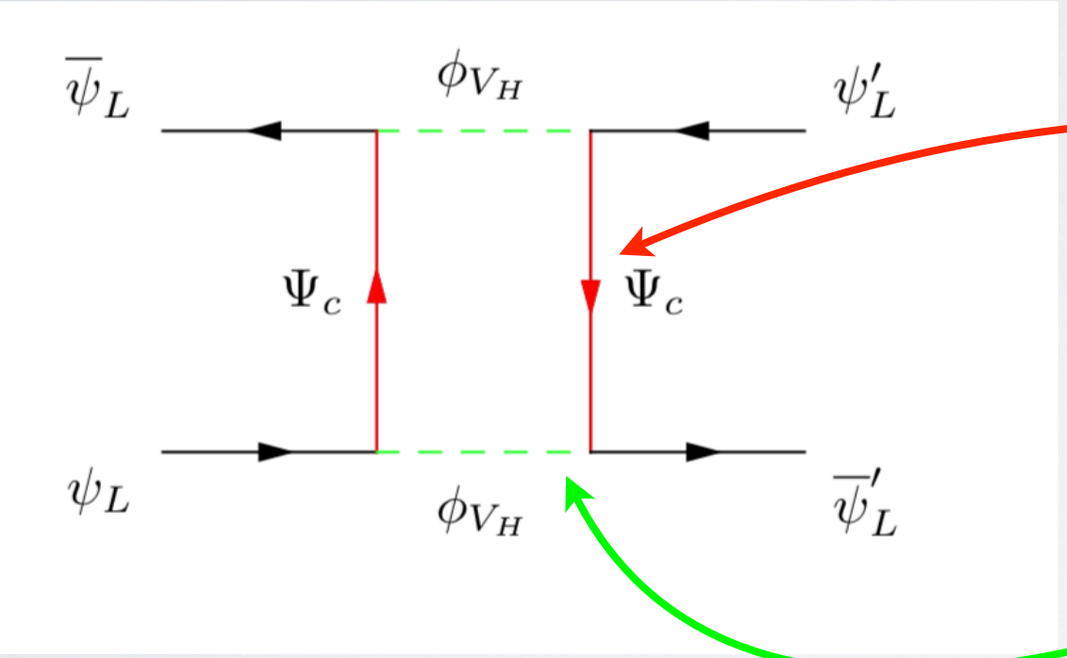

Mirror fermions

Goldstone bosons of heavy gauge bosons

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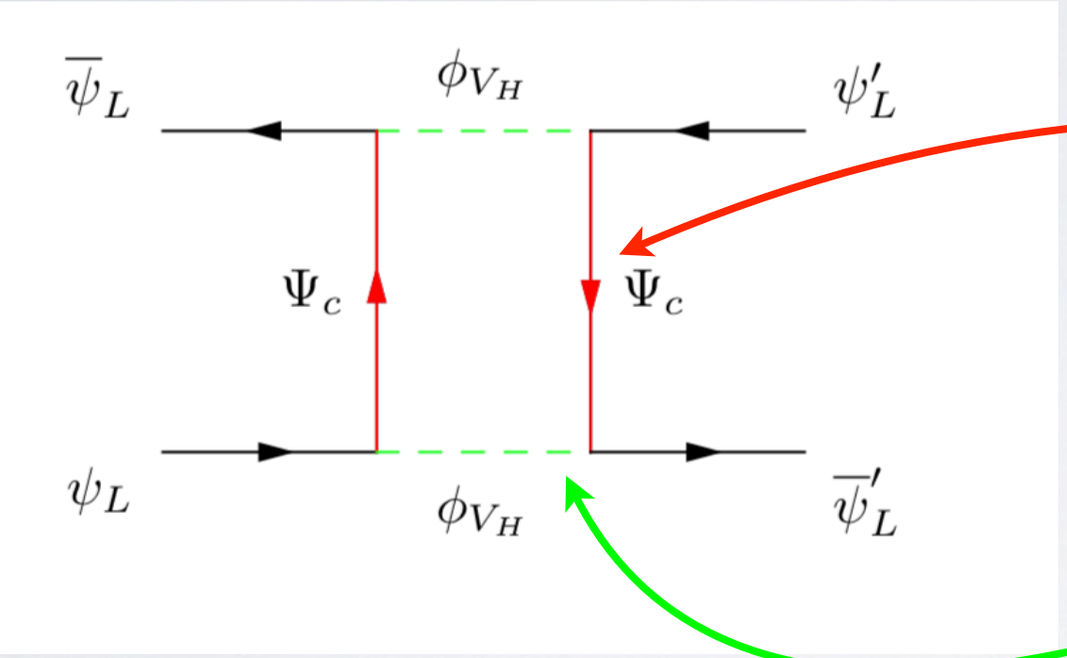

Mirror fermions

Goldstone bosons of heavy gauge bosons

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

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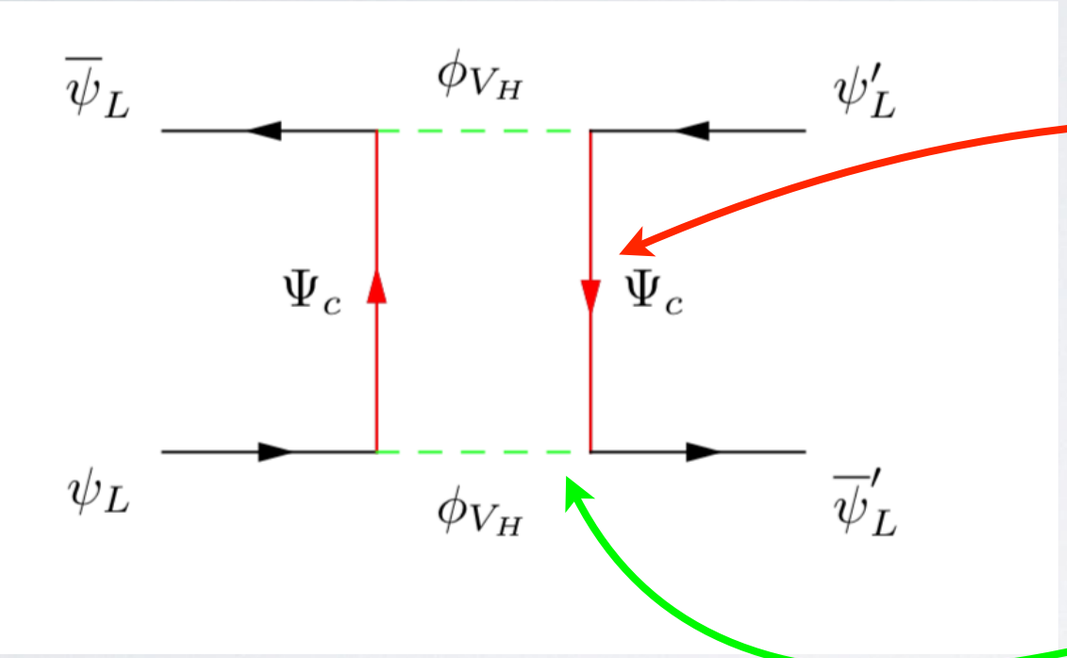

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Strongest constraints still from LEP:

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

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

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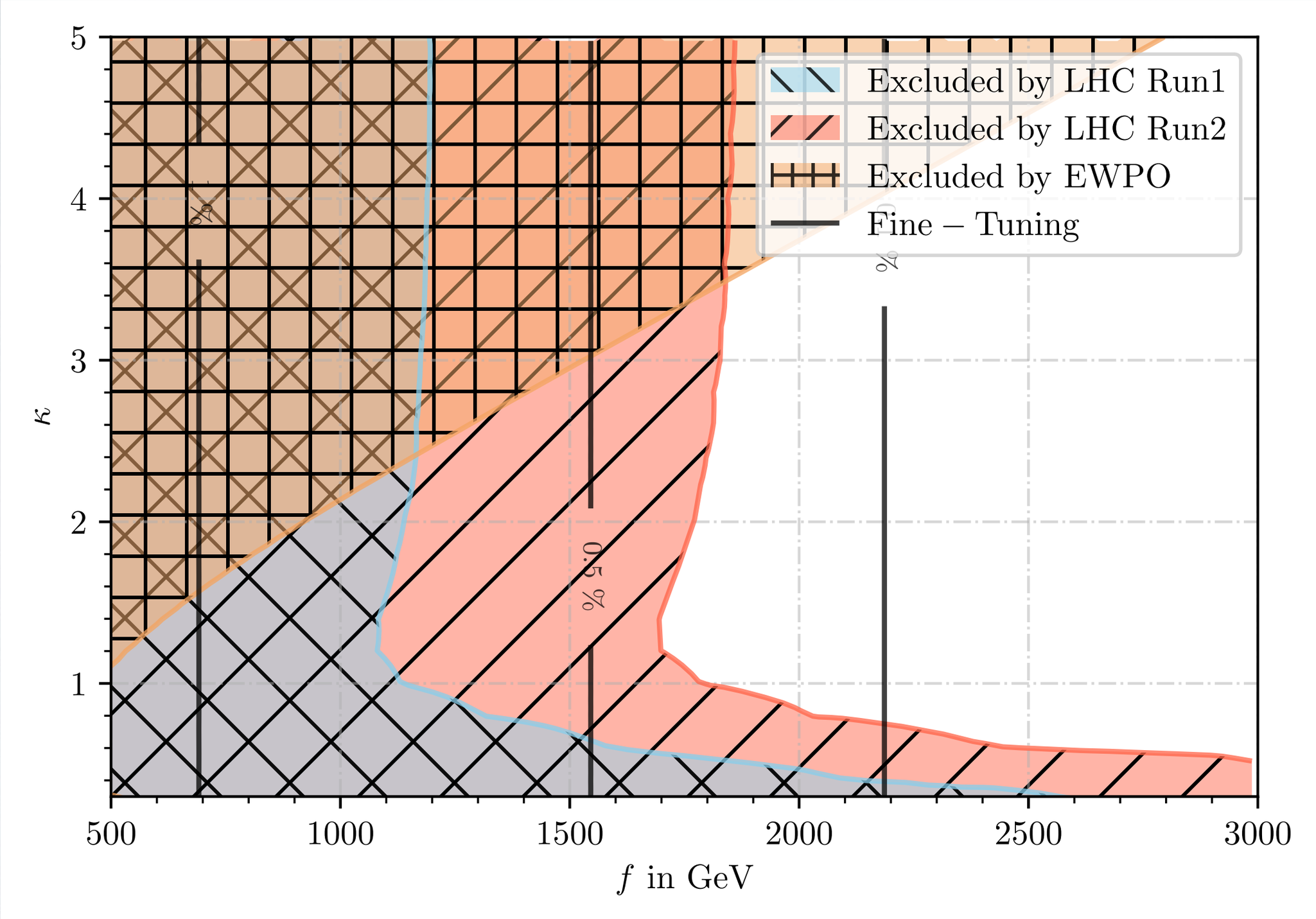
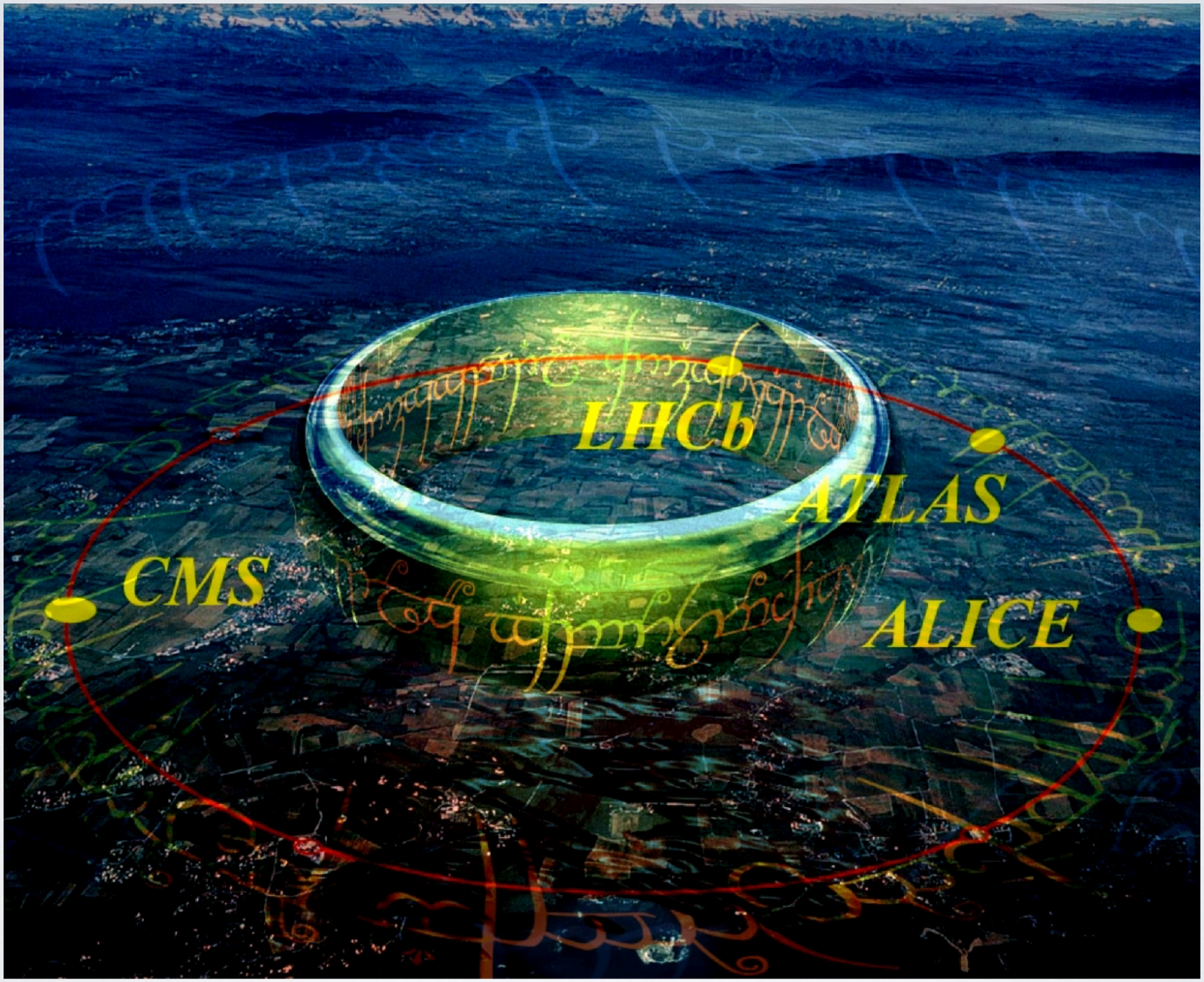


(Light ℓ_H) ⊕ (Light $T^{\pm}$) ⊕ (T-parity conservation)

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

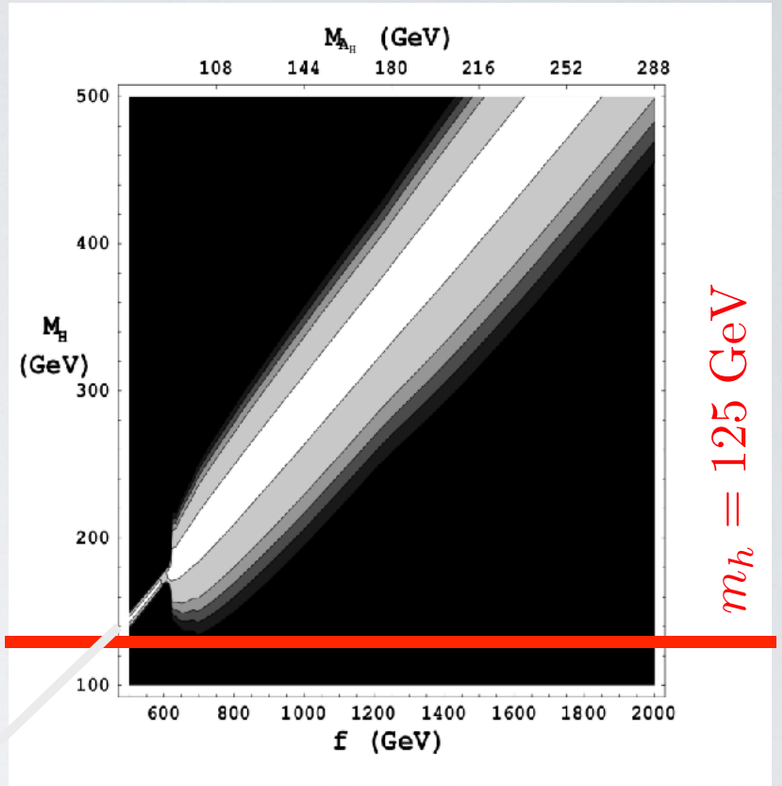
ONE RING TO FIND THEM ...
ONE RING TO RULE THEM OUT ?



BACKUP SLIDES

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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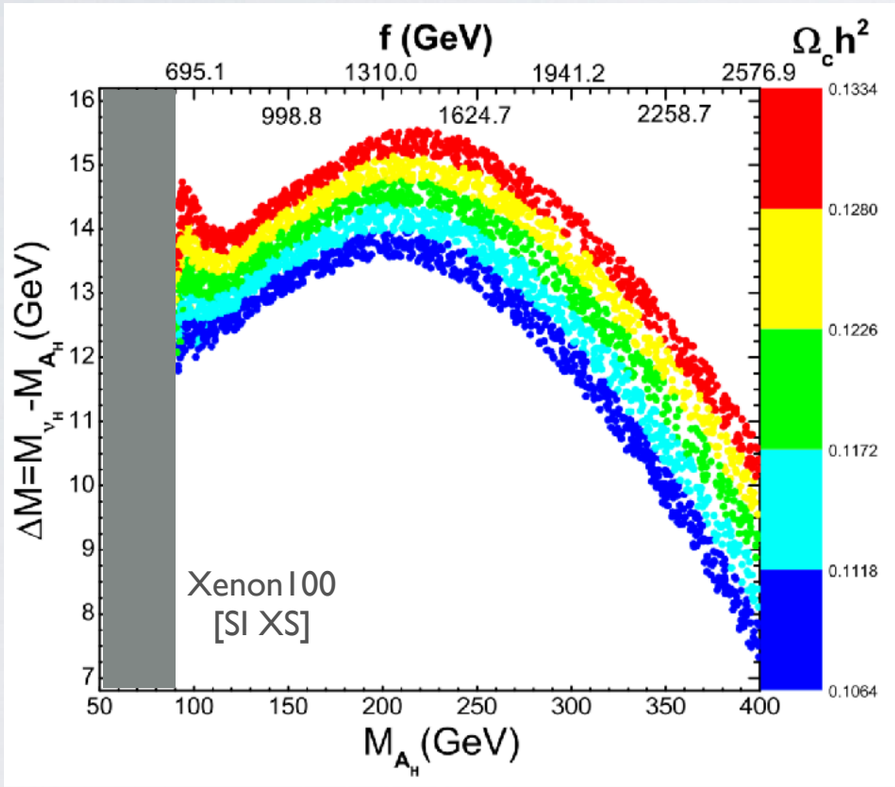

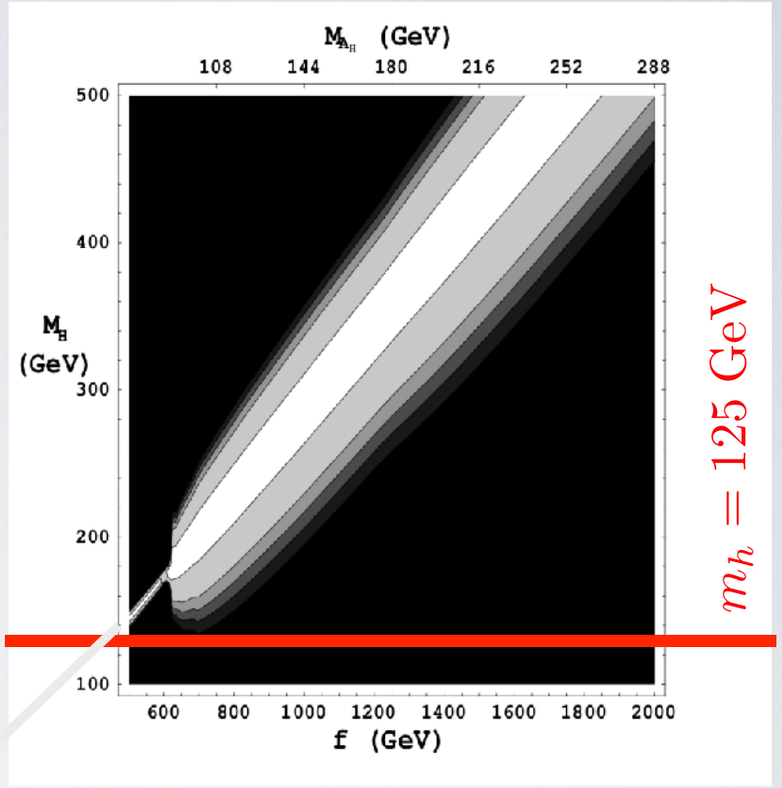

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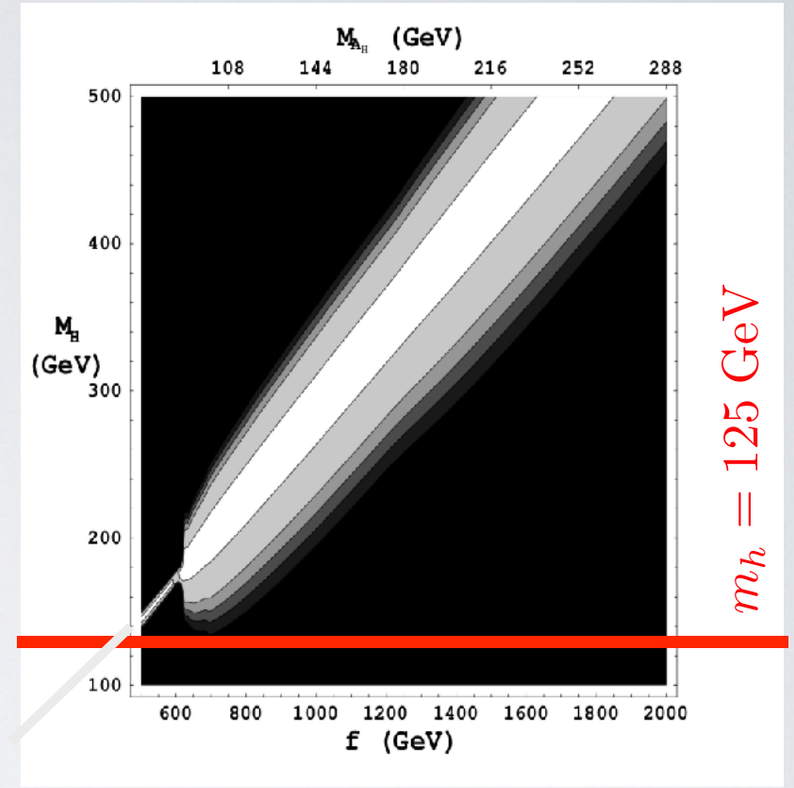
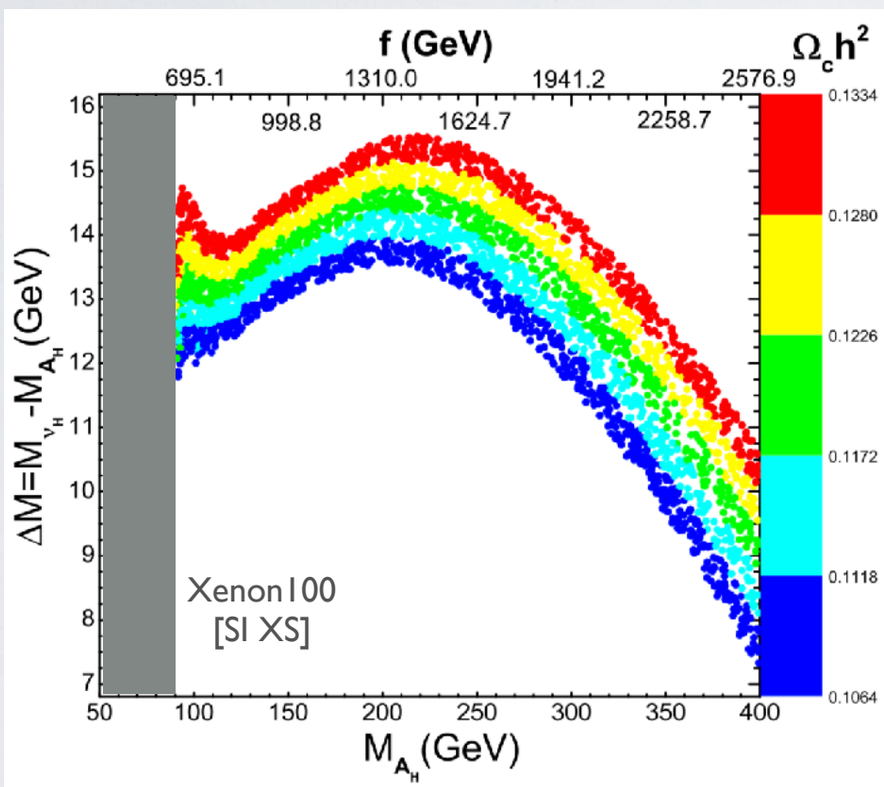
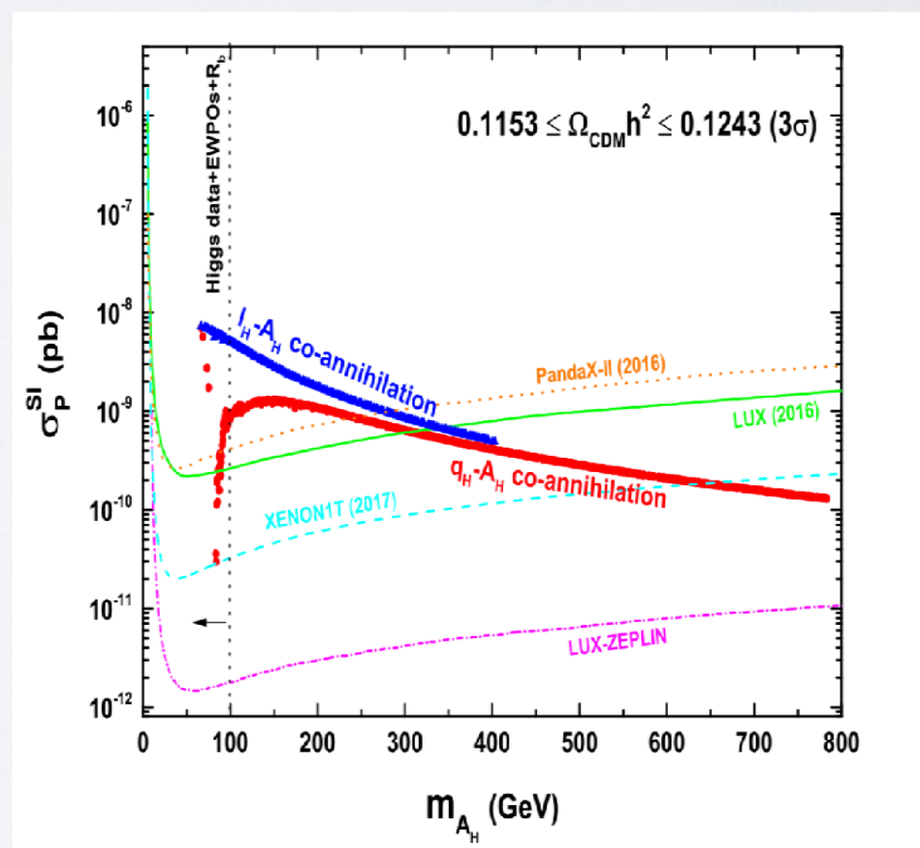






Severe constraints from direct detection
Yang/Wang/Shu, '13; Wu/Yang/Zhang, '16

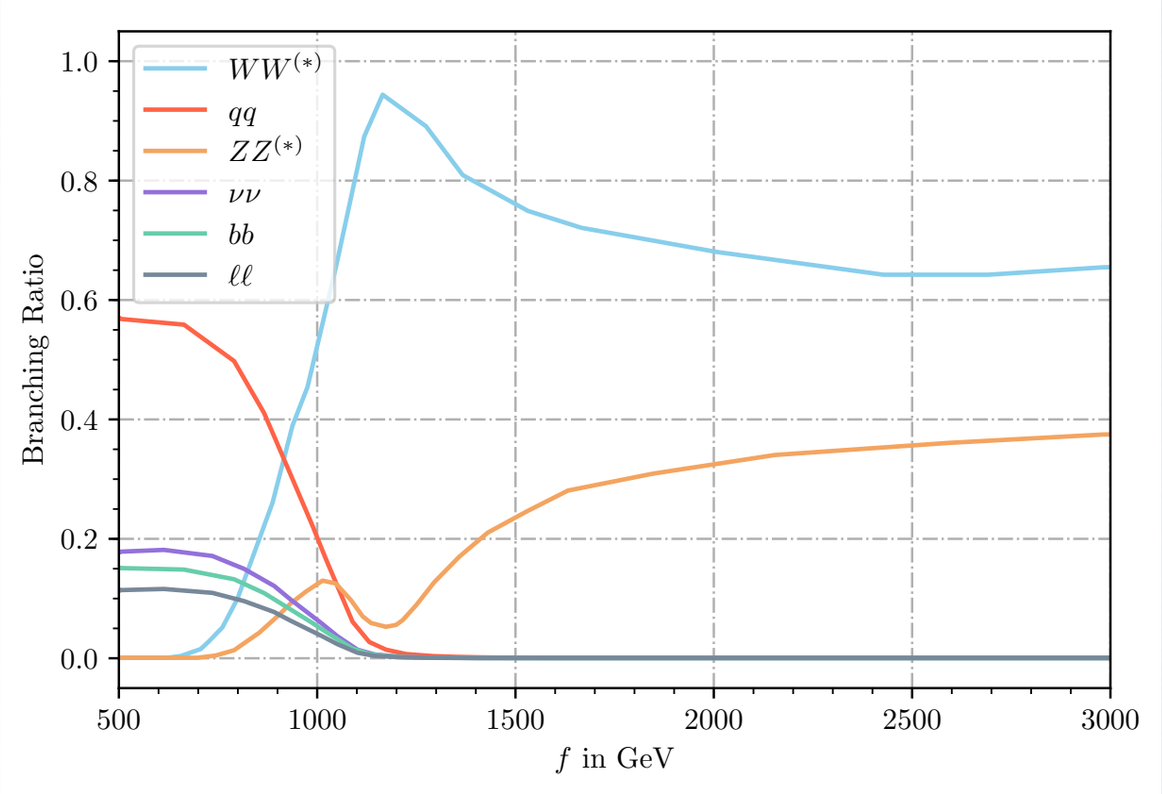
T-parity violation

T-parity violation

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

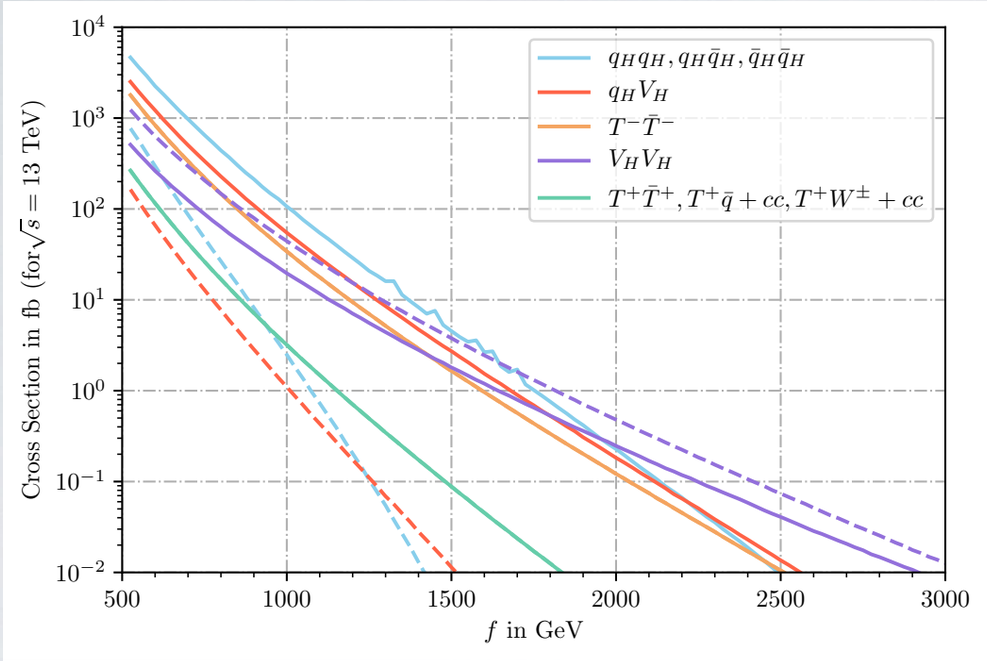
$$\Gamma(A_H \to W^+W^-) = \left(\frac{Ng'}{40\sqrt{3}\pi^3}\right)^2 \left(1 - \frac{4m_W^2}{M_{A_H}^2}\right)^{\frac{5}{2}} \frac{M_{A_H}^3 m_W^2}{f^4}$$

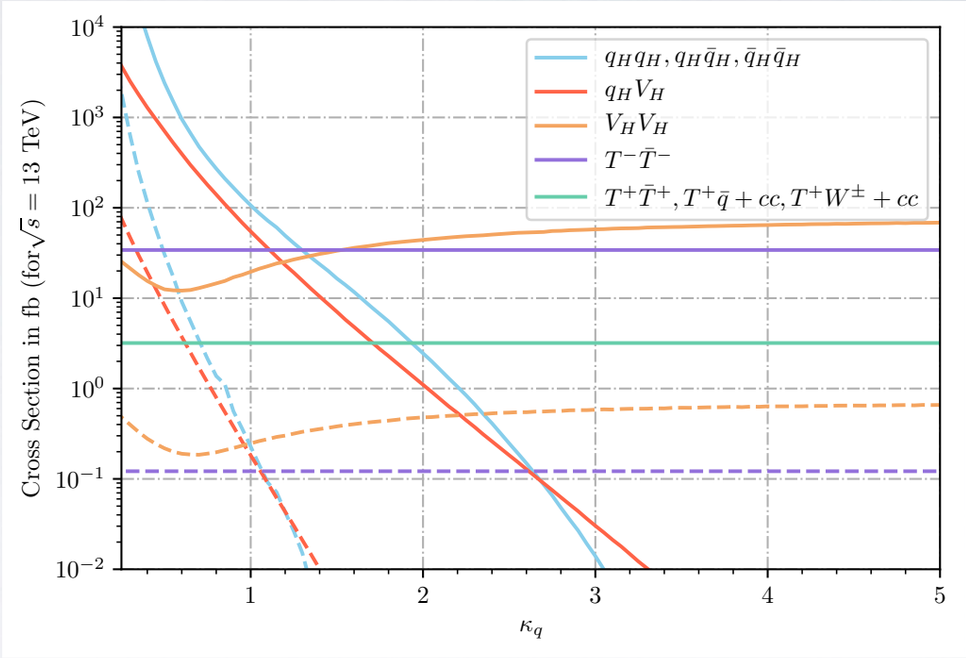
$$\Gamma(A_H \to ff) = \left(\frac{N_{C,f} M_{A_H}}{48\pi}\right) \left(1 - \frac{4m_f^2}{M_{A_H}^2}\right)^{\frac{1}{2}} \left[c_-^2 \left(1 - \frac{4m_f^2}{M_{A_H}^2}\right) + c_+^2 \left(1 + \frac{2m_f^2}{M_{A_H}^2}\right)\right]$$



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

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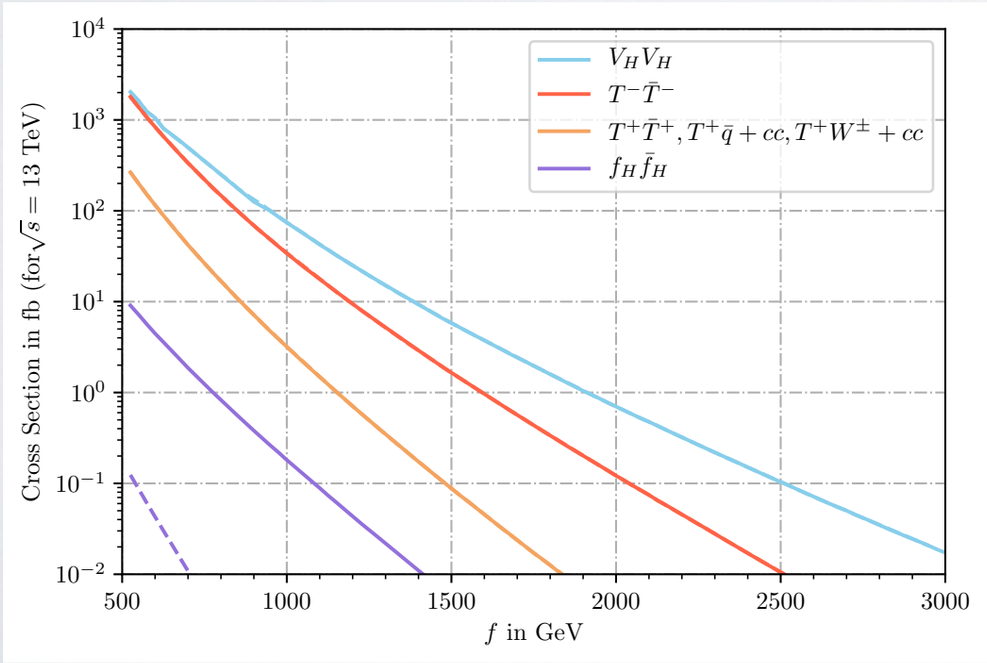
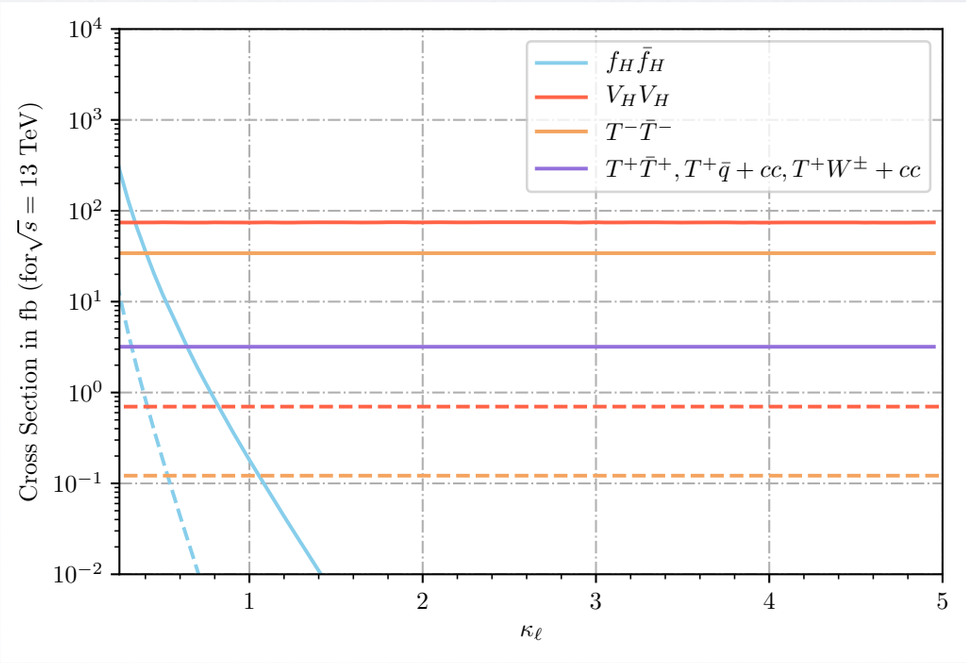
(Heavy q_H) ⊕ (Light $T^{\pm}$) 13 TeV





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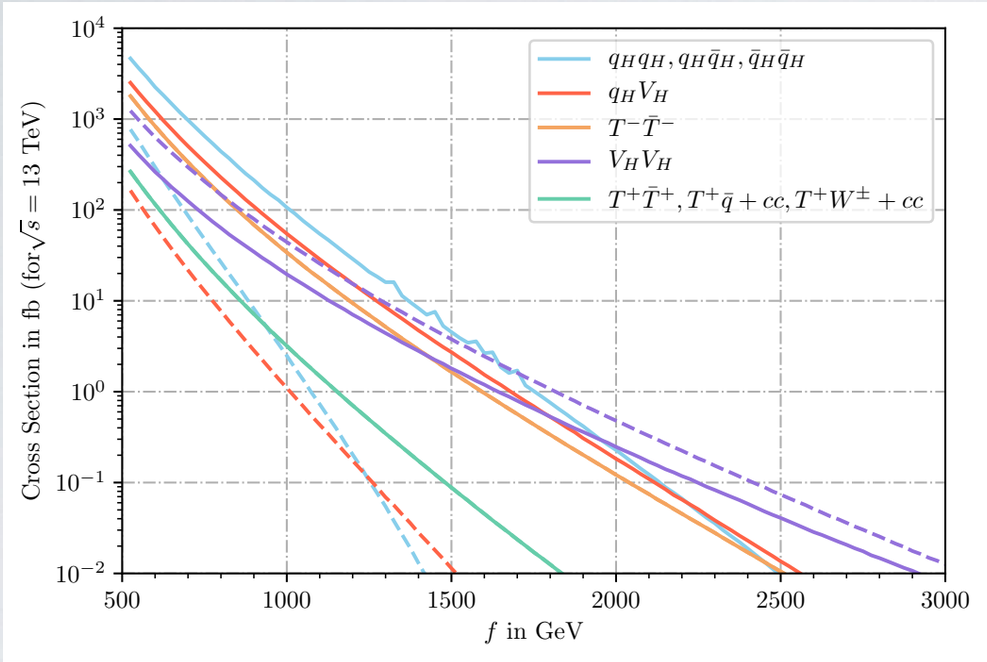

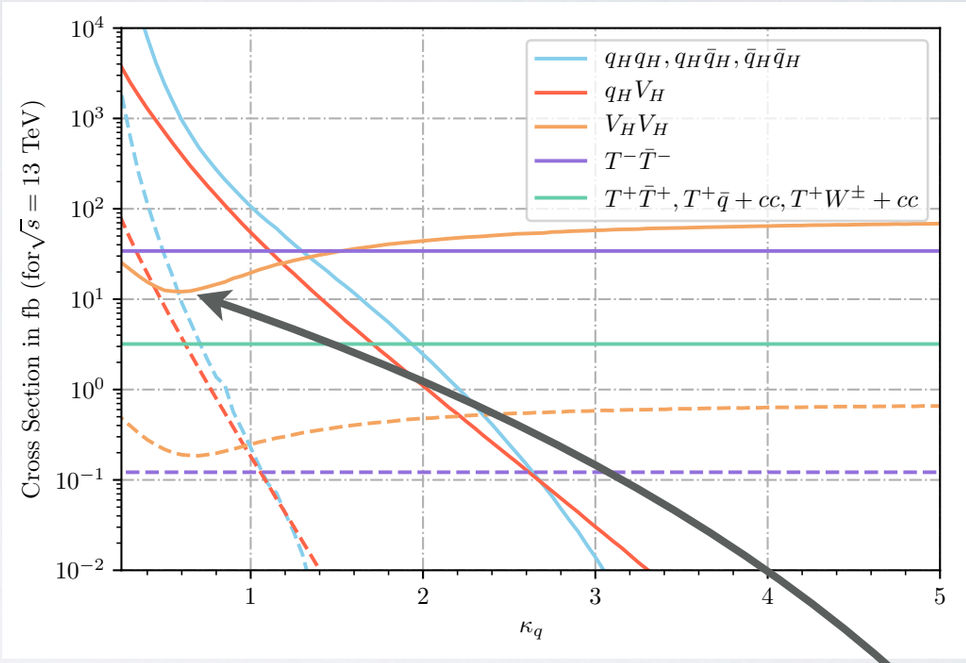

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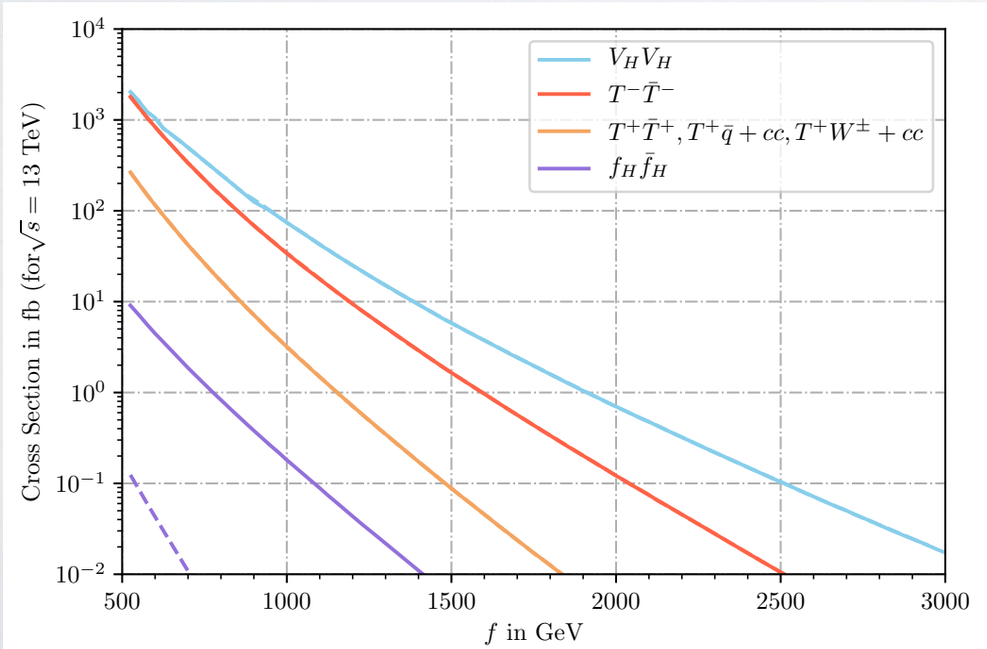
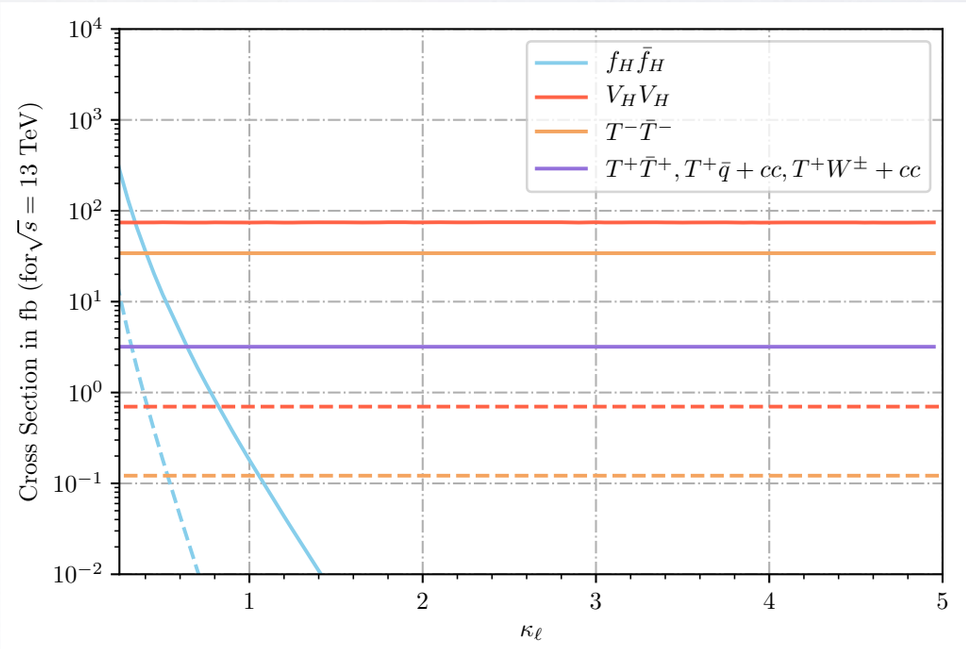
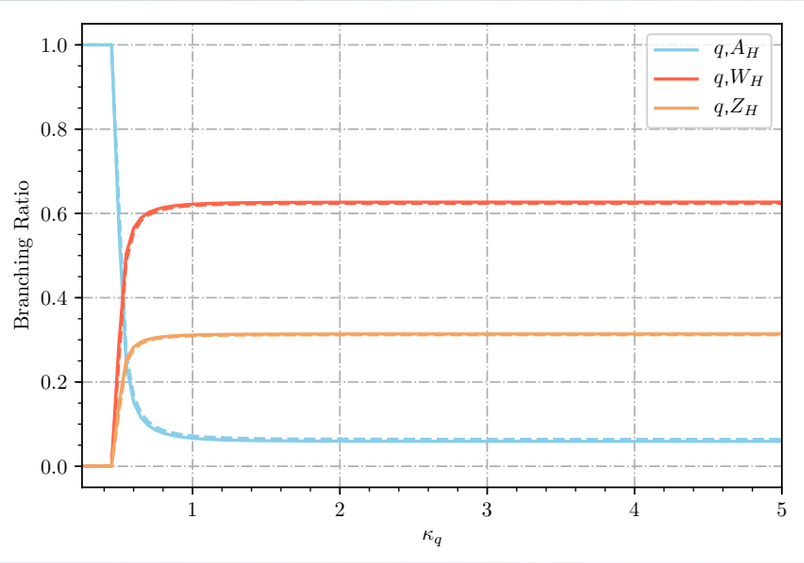


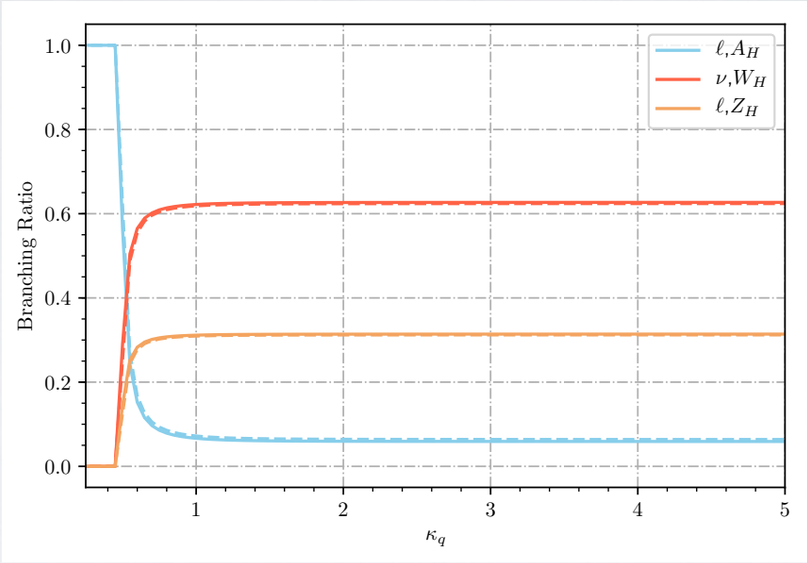


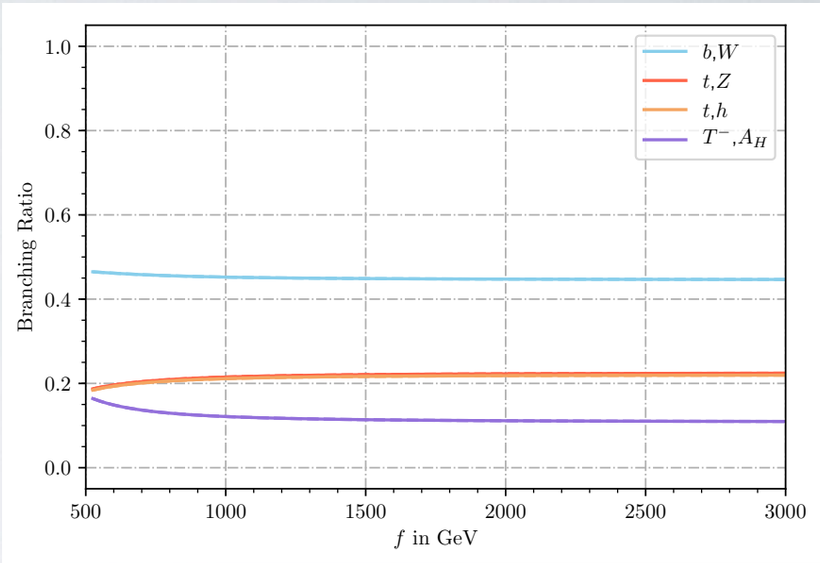
destructive t-q_H-channel interference w./ s-channel

Cross Sections & Branching ratios (II)

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



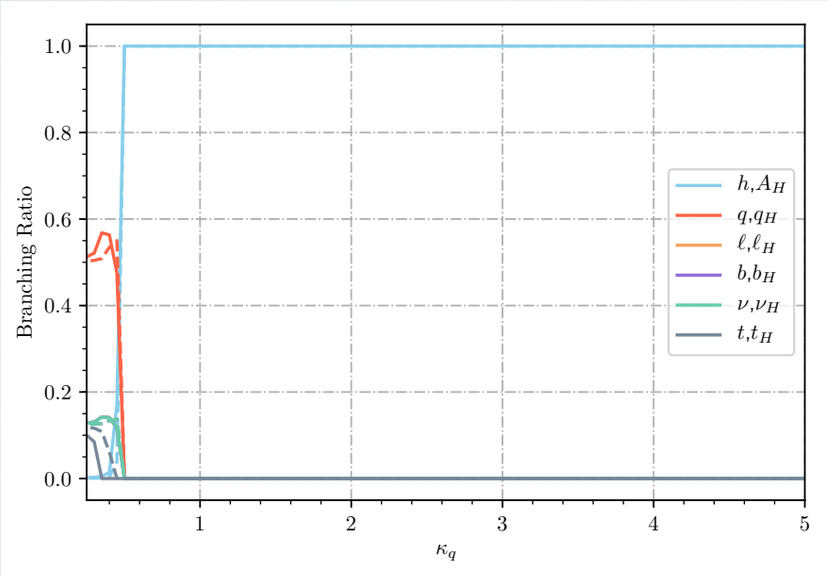


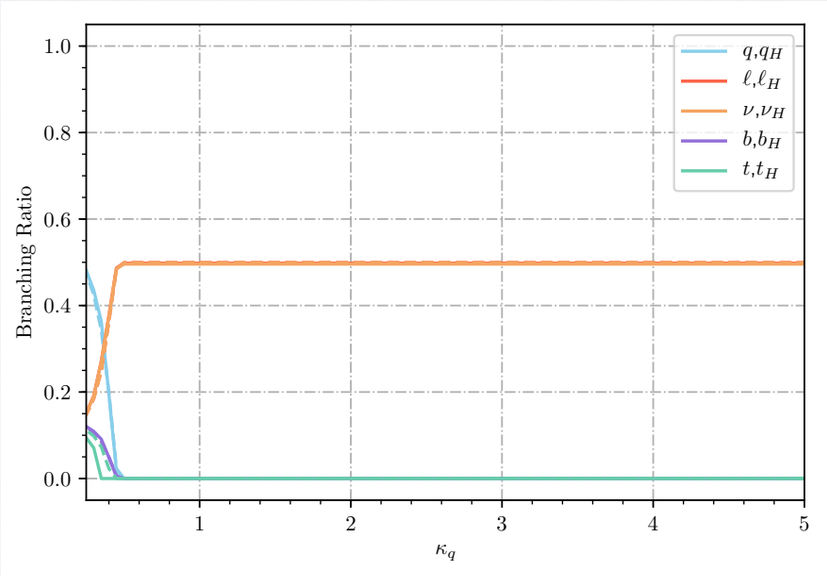


d_H, very similar: u_H [FU,Lℓ]

ℓ_H, very similar: ν_H [FU]

T^+ [Light T^-]





Light T^-:

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

Light ℓ_H:

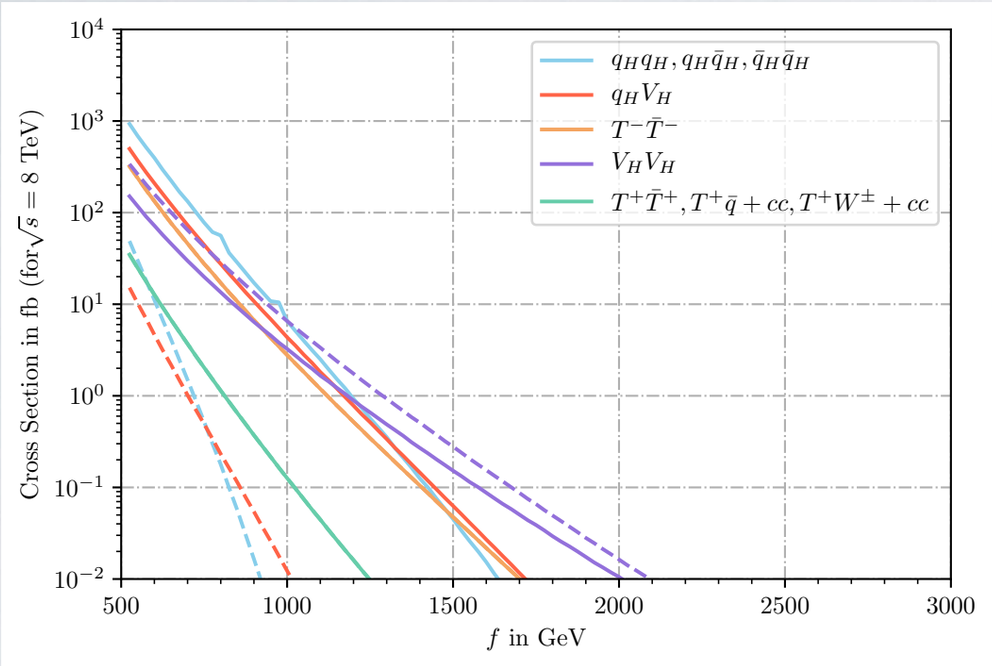
$$\mathrm{BR}(\ell_H/\nu_H \to \ell/\nu A_H) = 1$$

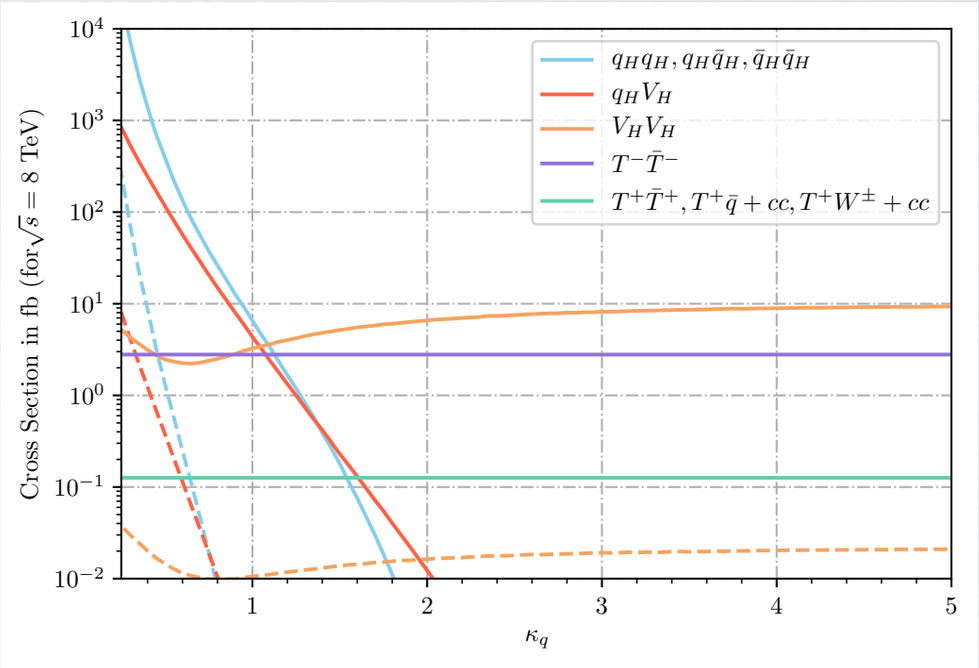
W_H, very similar: Z_H [FU,Hq]

W_H, very similar: Z_H [Lℓ]

Cross Sections 8 TeV

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





Left: fixed κ
Full line: f = 1 TeV
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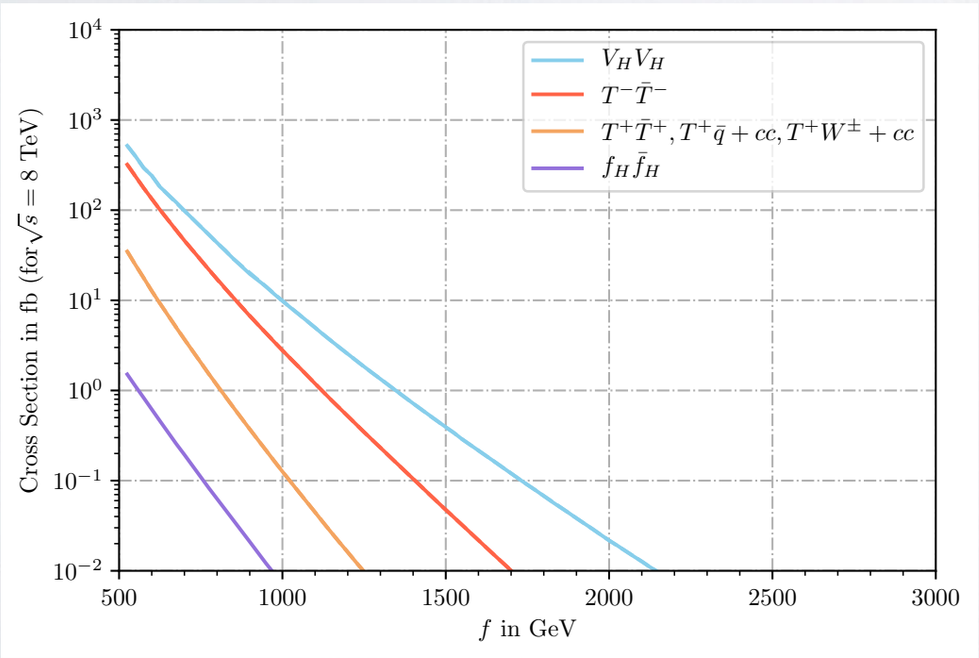
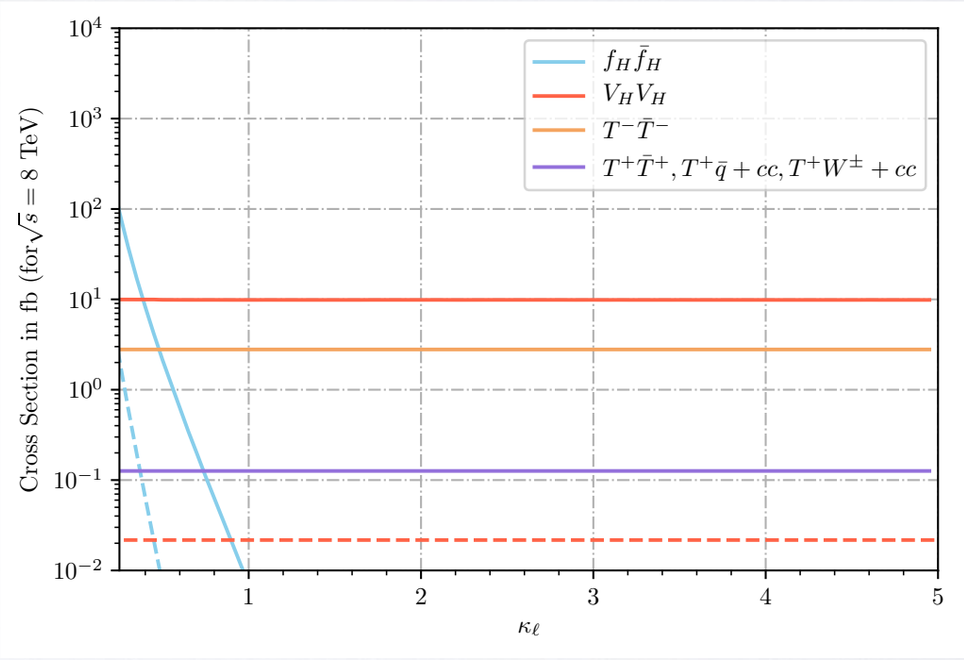
(Heavy q_H) ⊕ (Light $T^{\pm}$) 8 TeV





Cross Sections 14 TeV

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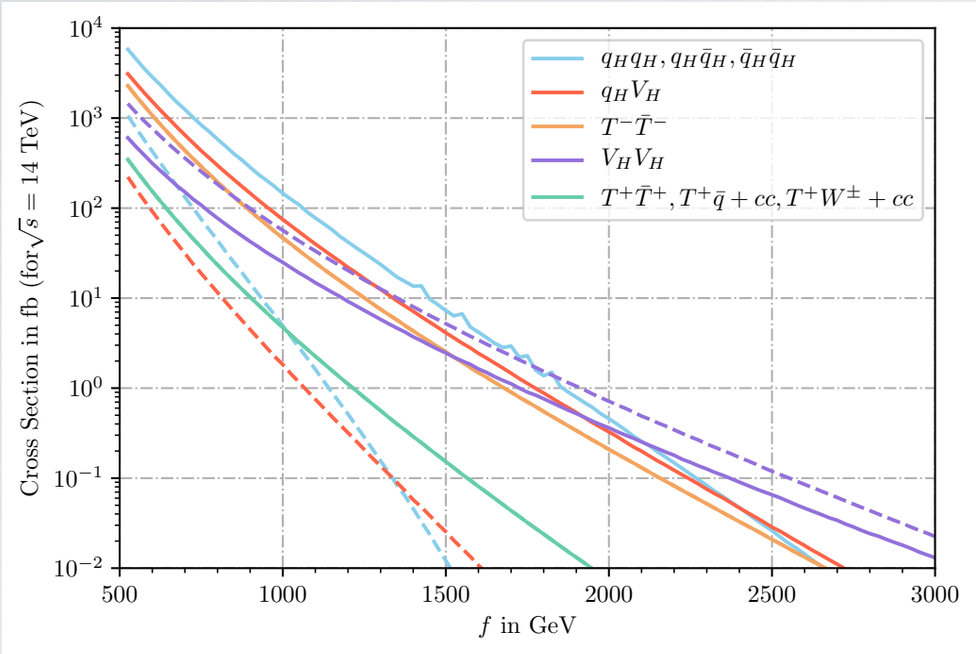

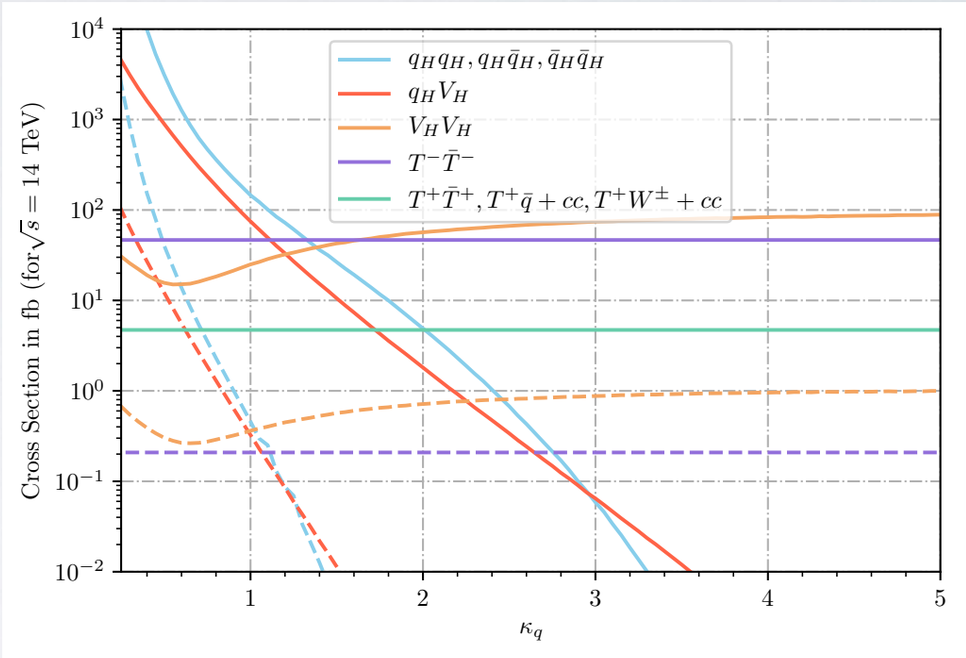

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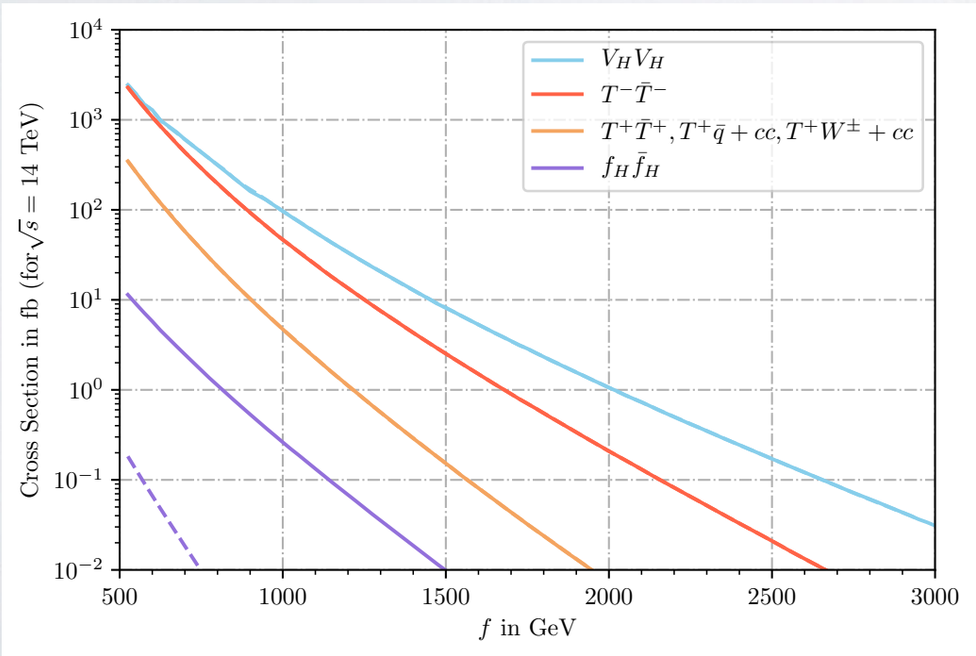
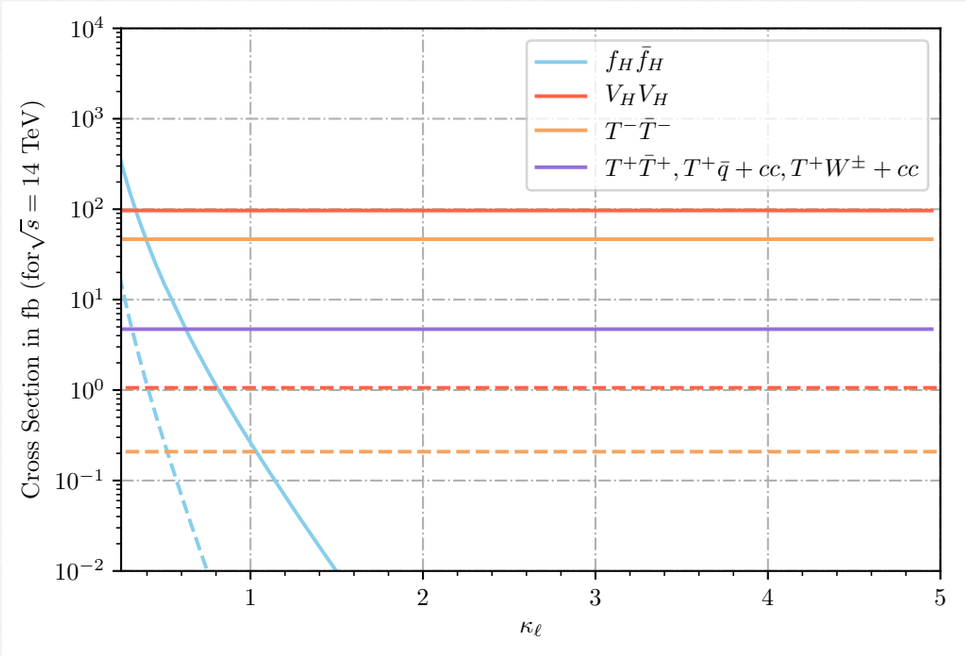
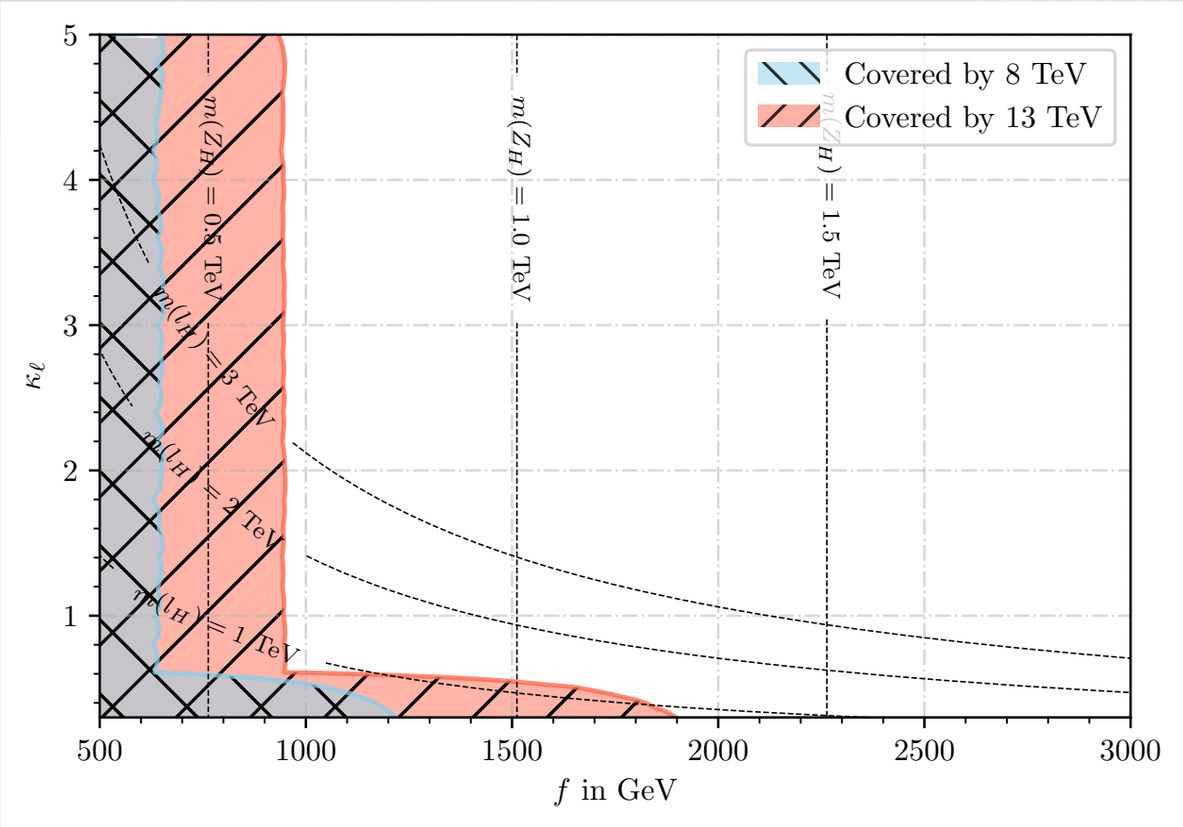
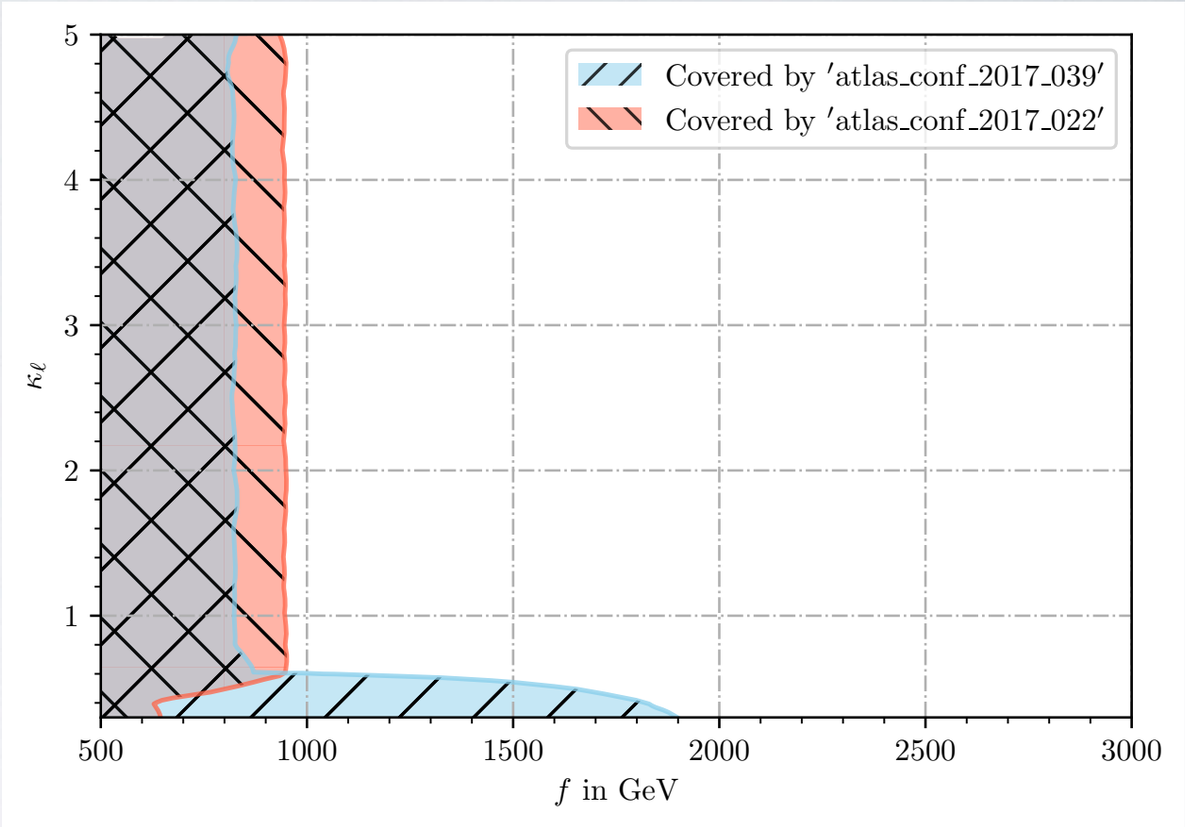
(Heavy q_H) ⊕ (Light $T^\pm$) 14 TeV





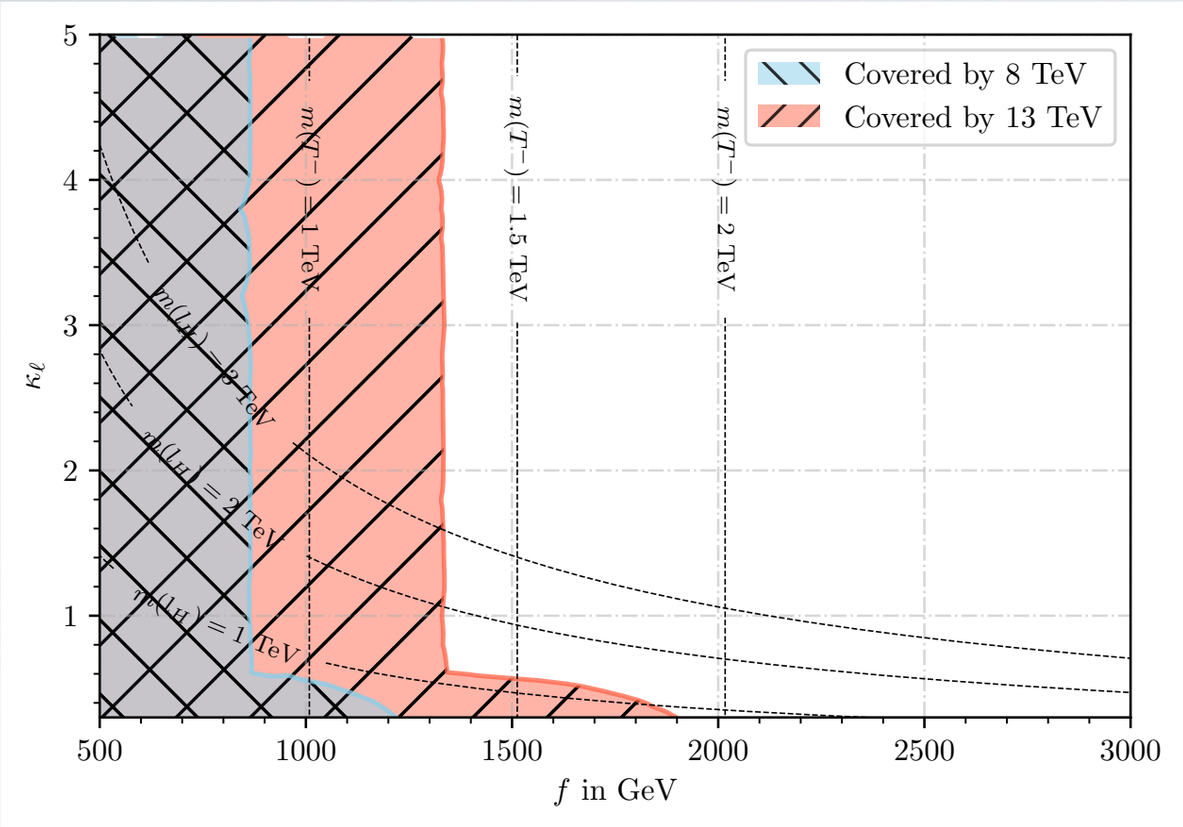
13 TeV recasting results: Heavy q_H

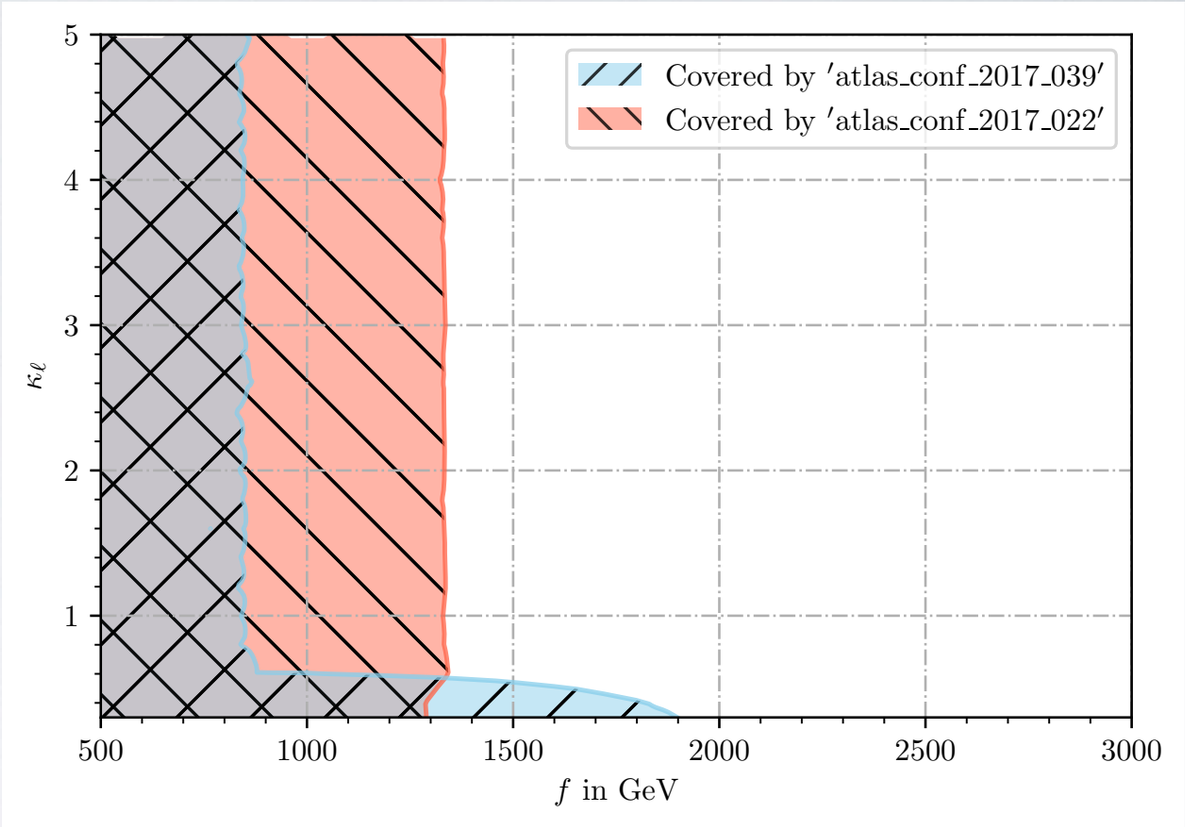




(Heavy q_H) ⊕ (Heavy $T^{\pm}$) ⊕ (TPC)

13 TeV recasting results: Heavy q_H

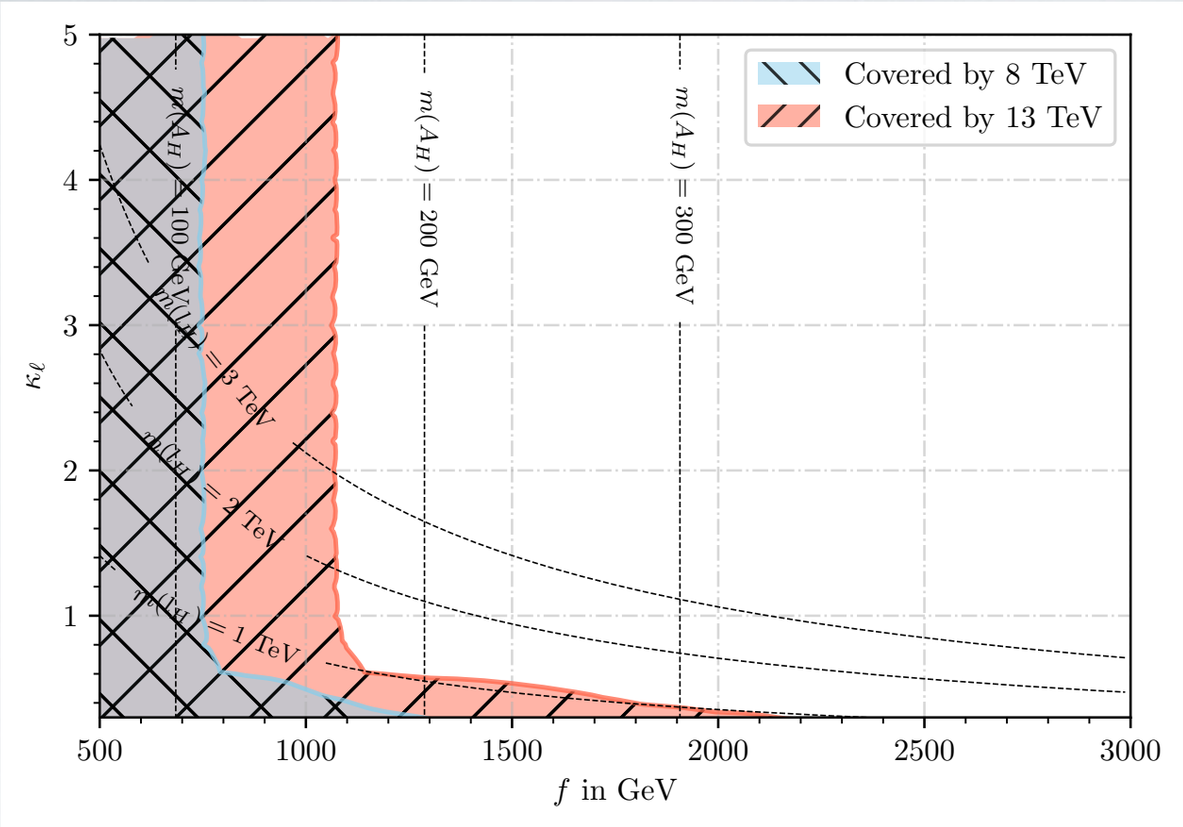


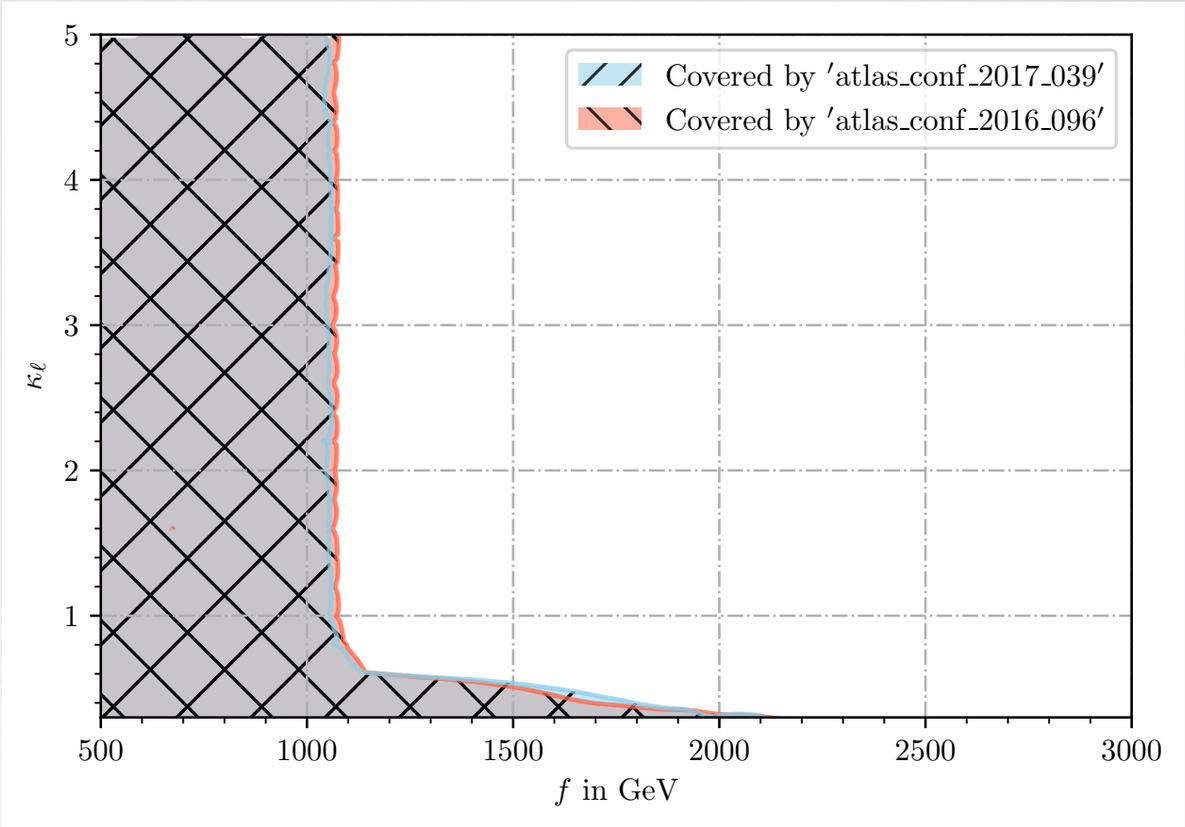


(Heavy q_H) ⊕ (Light $T^\pm$) ⊕ (TPC)

- $q_H \to q V_H \Longrightarrow \ell_H \to \ell V_H$; 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

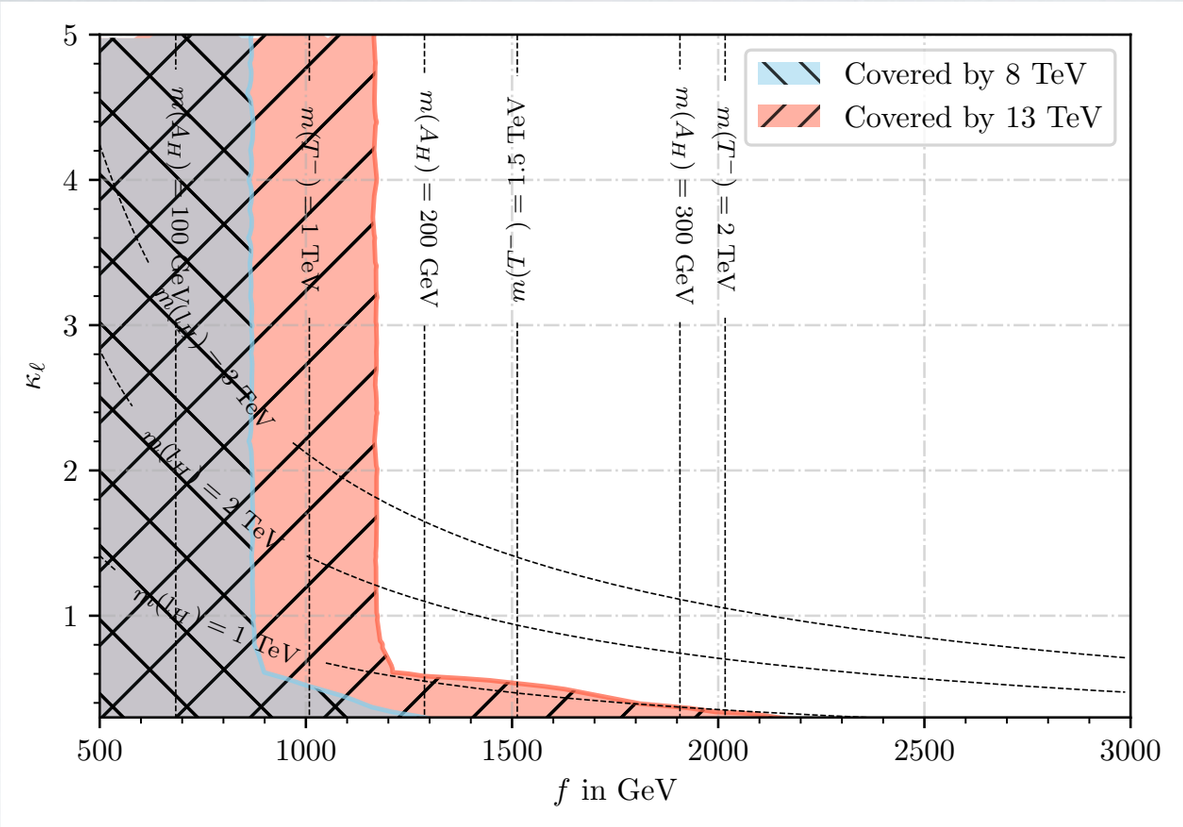


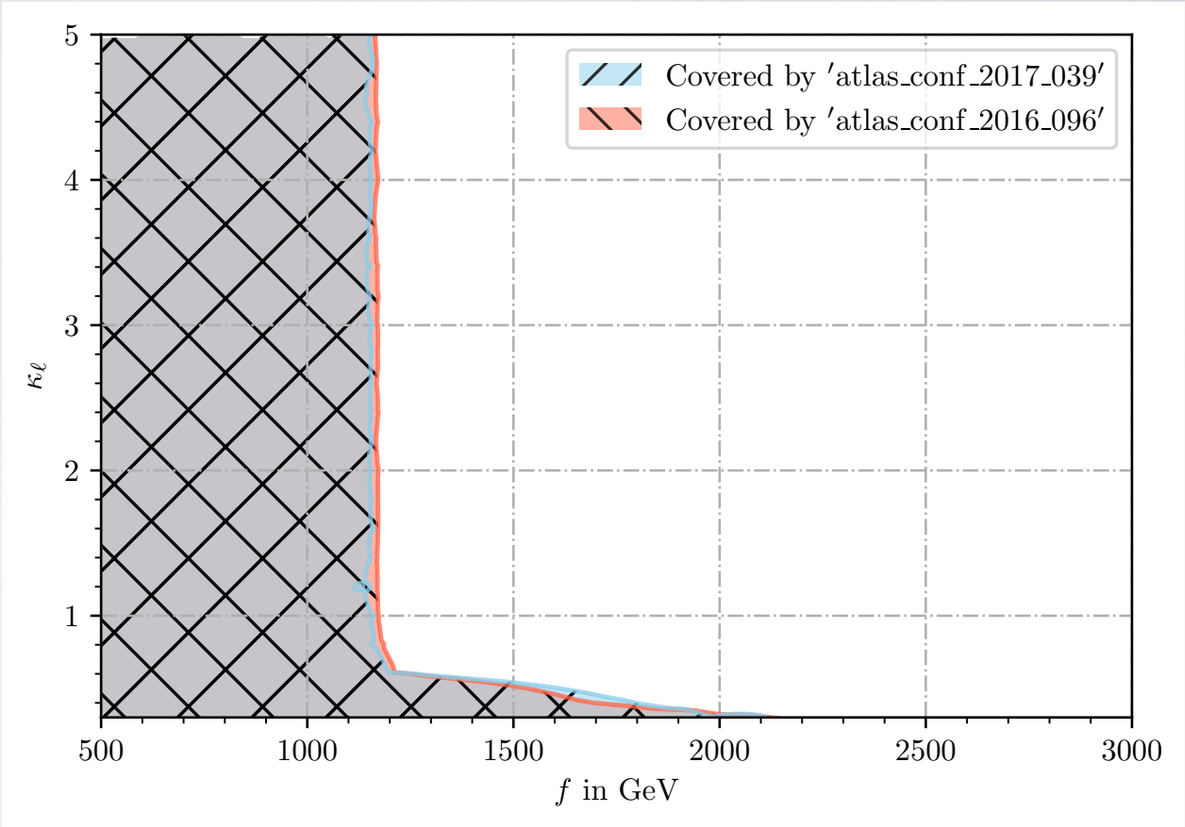


(Heavy q_H) ⊕ (Heavy $T^\pm$) ⊕ (TPV)

- $q_H \to q V_H \Longrightarrow \ell_H \to \ell V_H$; 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





(Heavy q_H) ⊕ (Light $T^\pm$) ⊕ (TPV)

- $q_H \to q\,V_H \Longrightarrow \ell_H \to \ell\,V_H$; 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 $T^\pm$)
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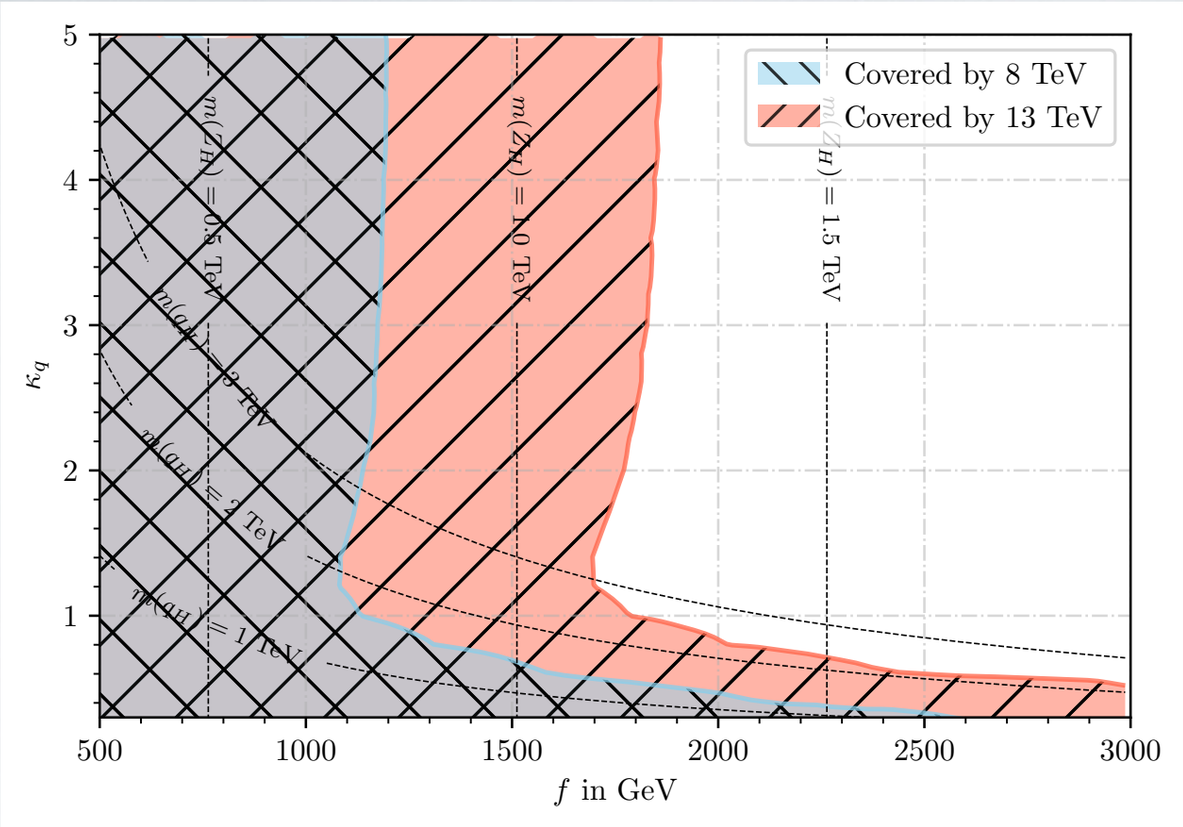
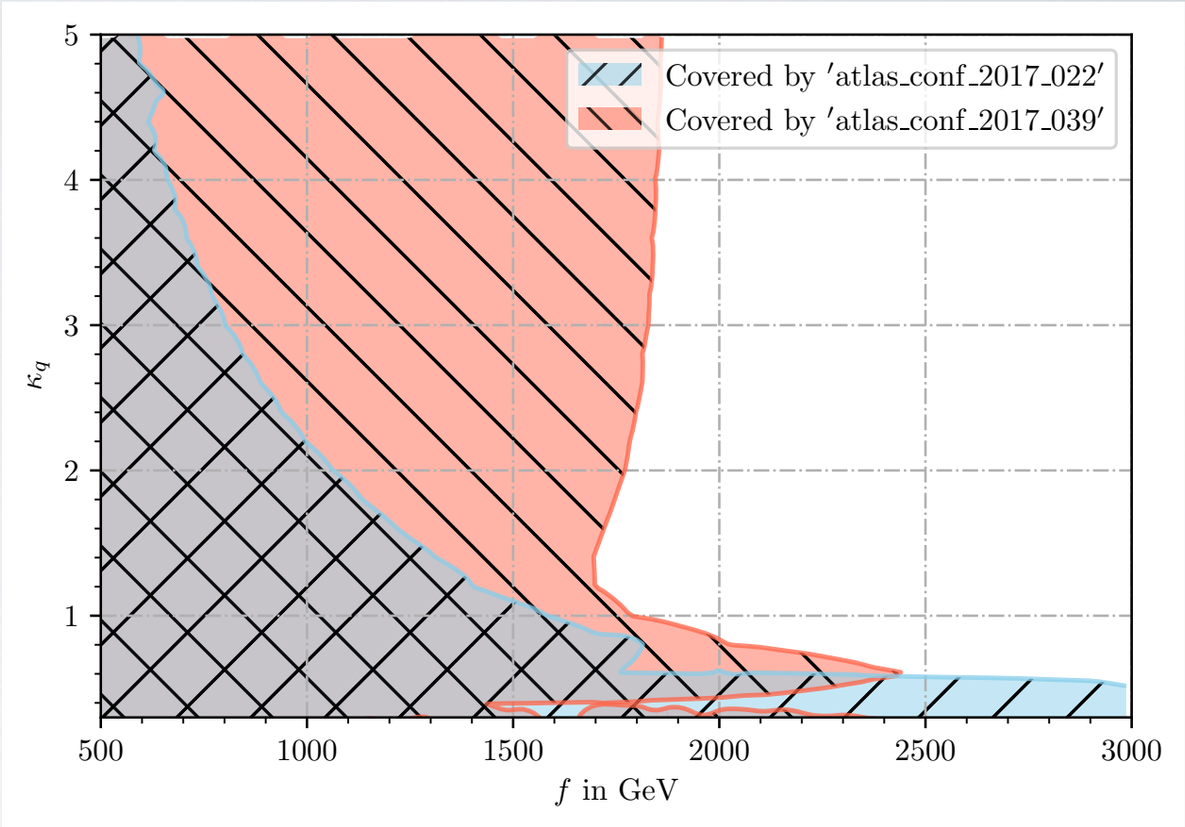
- Only very tiny changes for TPV

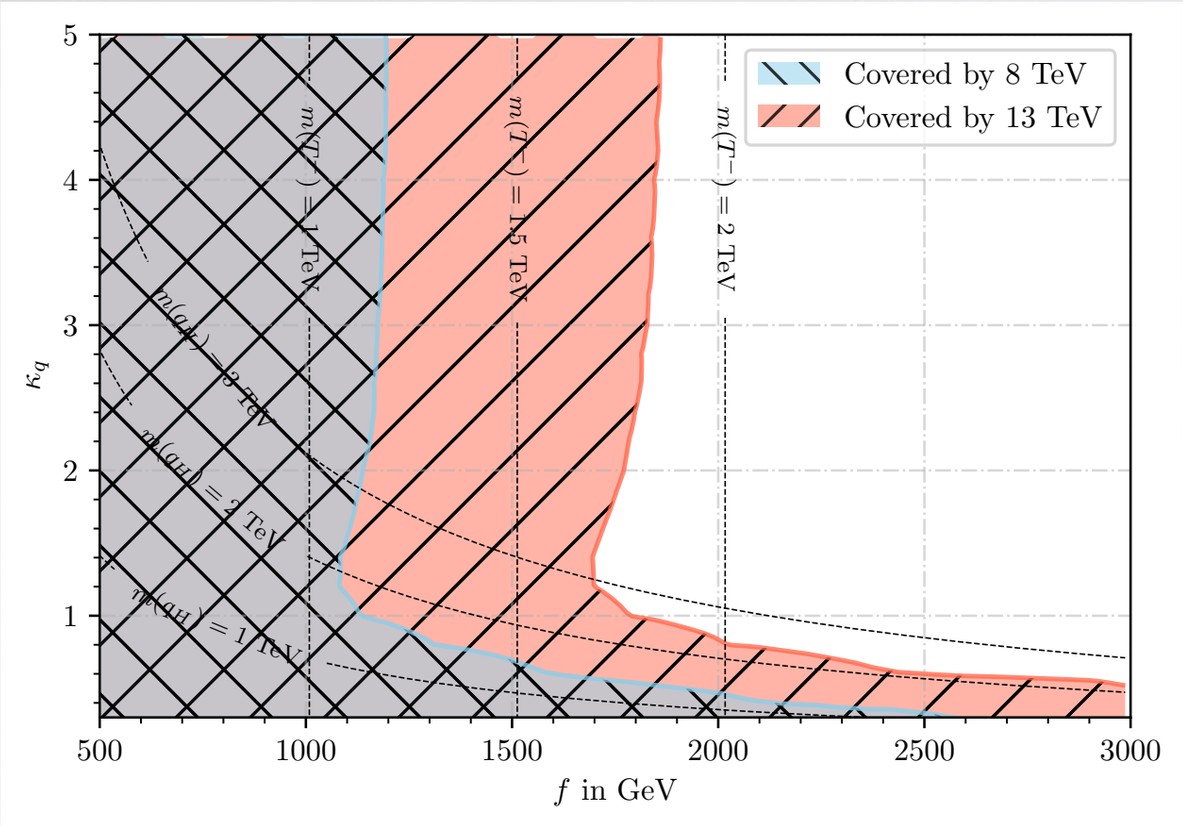
13 TeV recasting results: Light ℓ_H

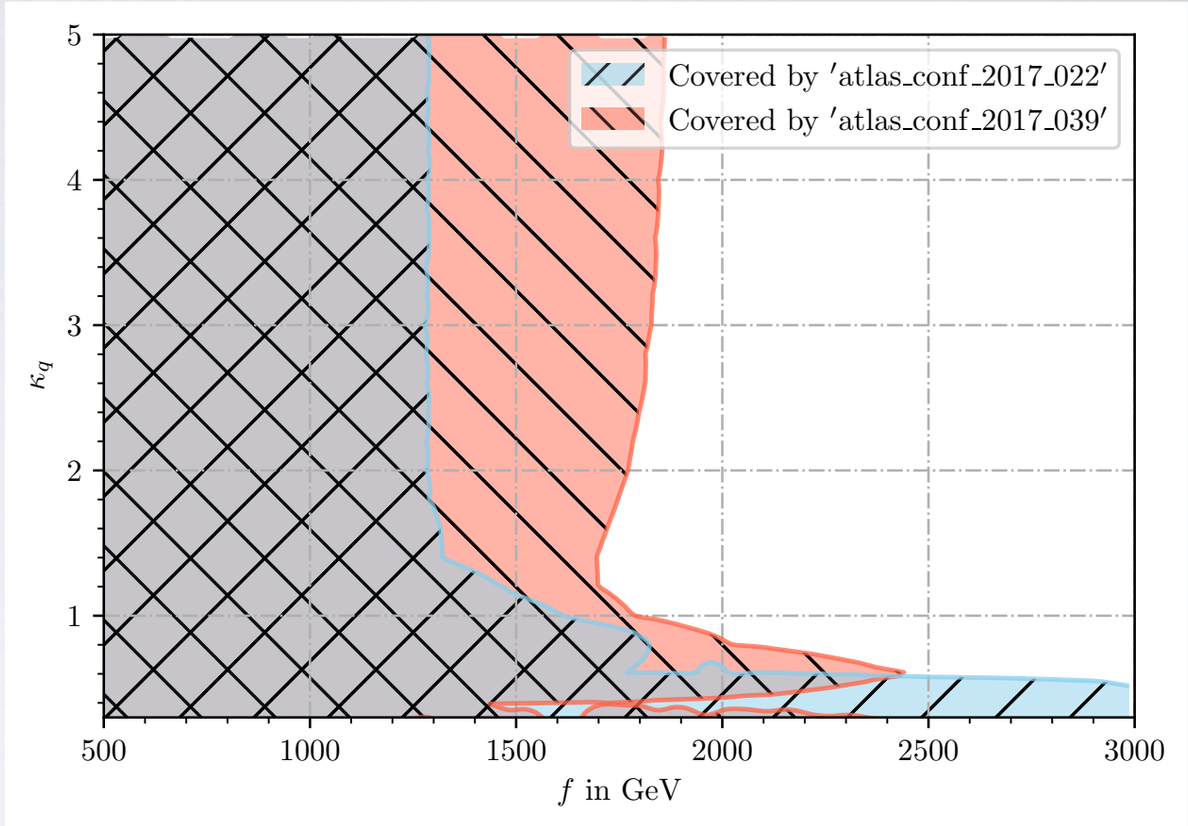




(Light ℓ_H) ⊕ (Heavy $T^{\pm}$) ⊕ (TPC)

13 TeV recasting results: Light ℓ_H

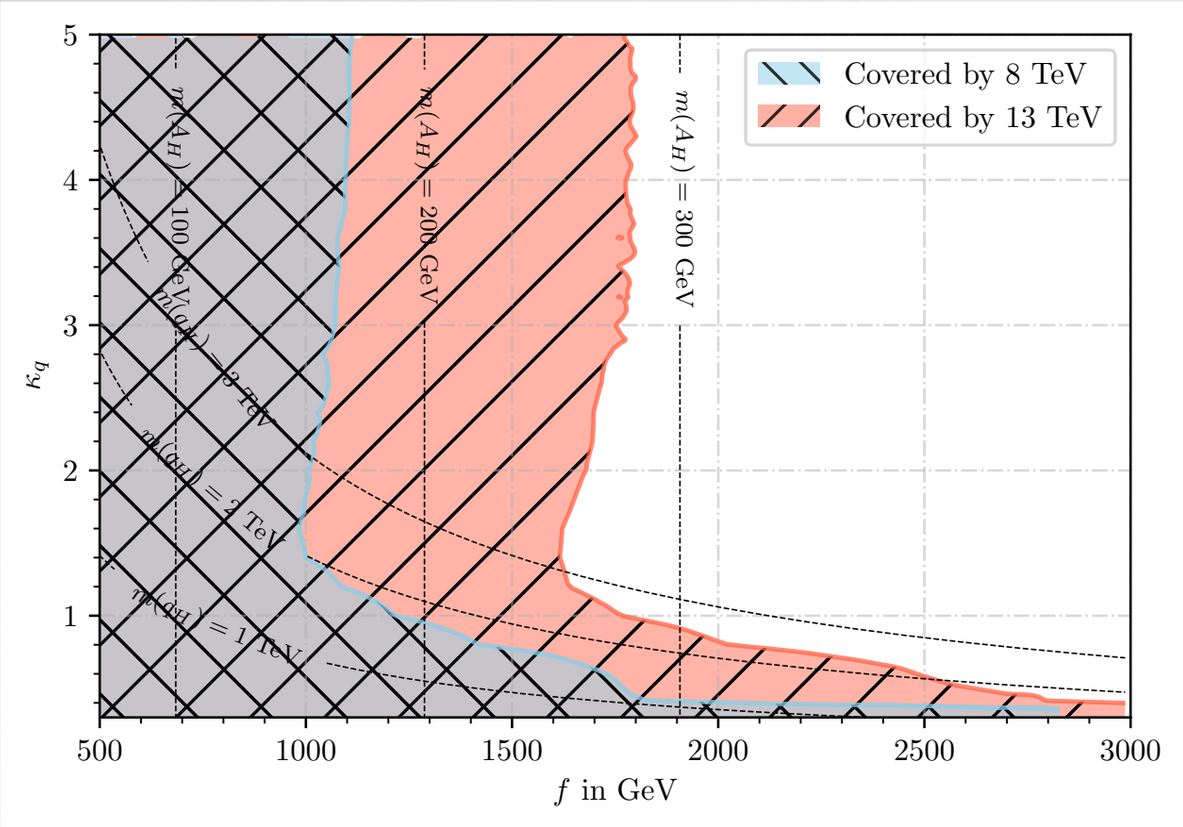


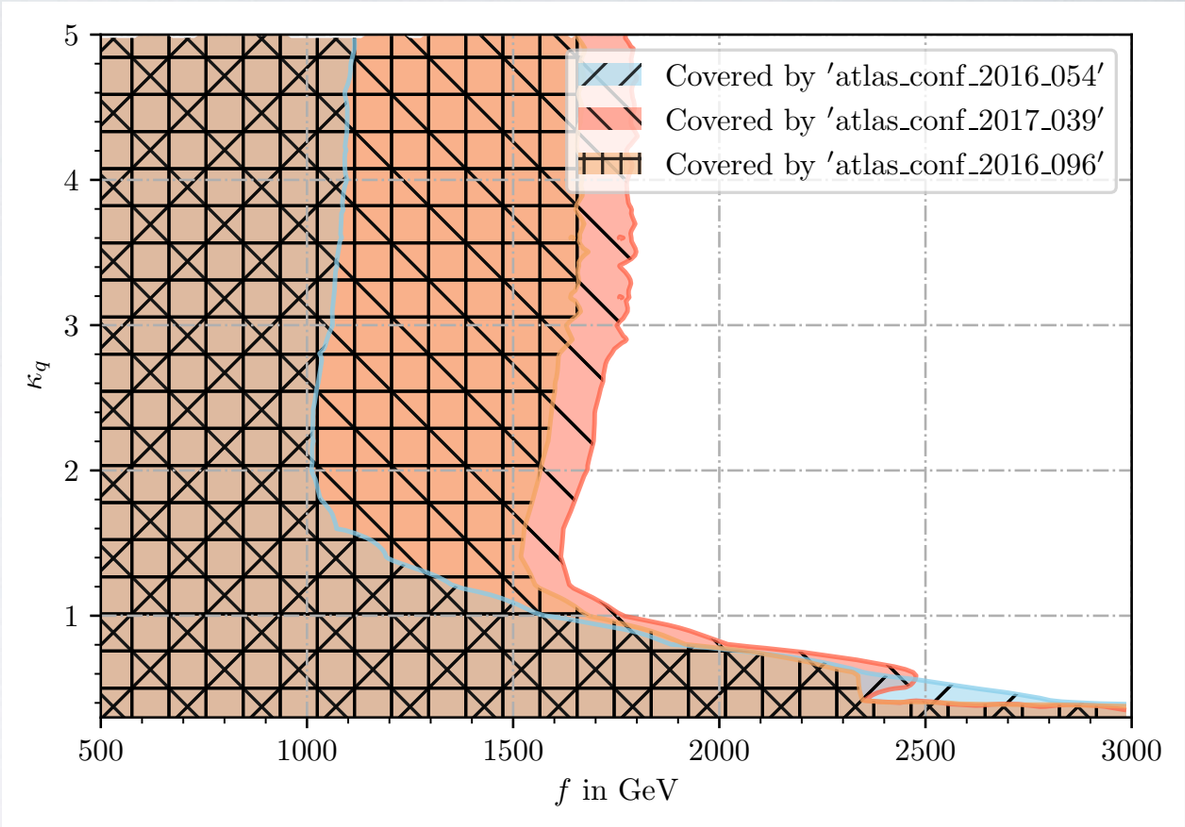


(Light ℓ_H) ⊕ (Light $T^\pm$) ⊕ (TPC)

- 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
- TPV: bounds slightly weakened due to smaller MET cut efficiency

13 TeV recasting results: Light ℓ_H





(Light ℓ_H) ⊕ (Heavy $T^\pm$) ⊕ (TPV)

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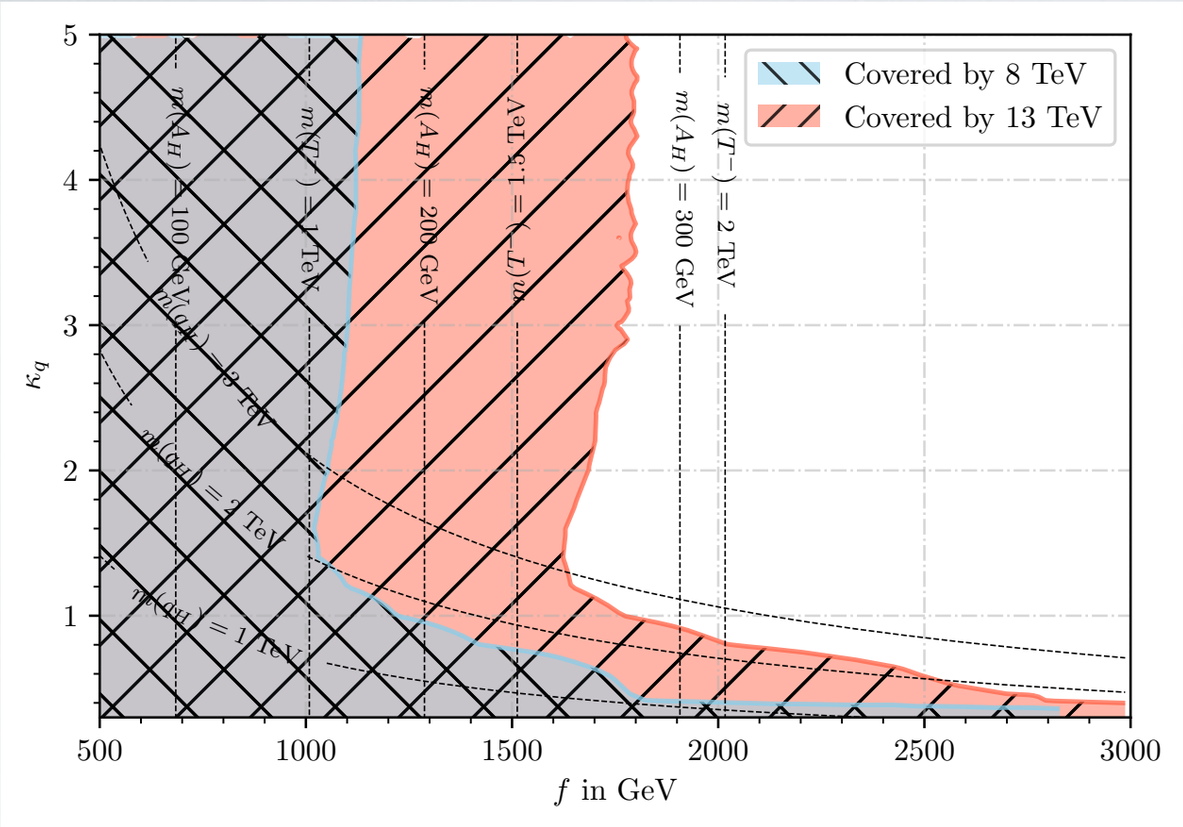
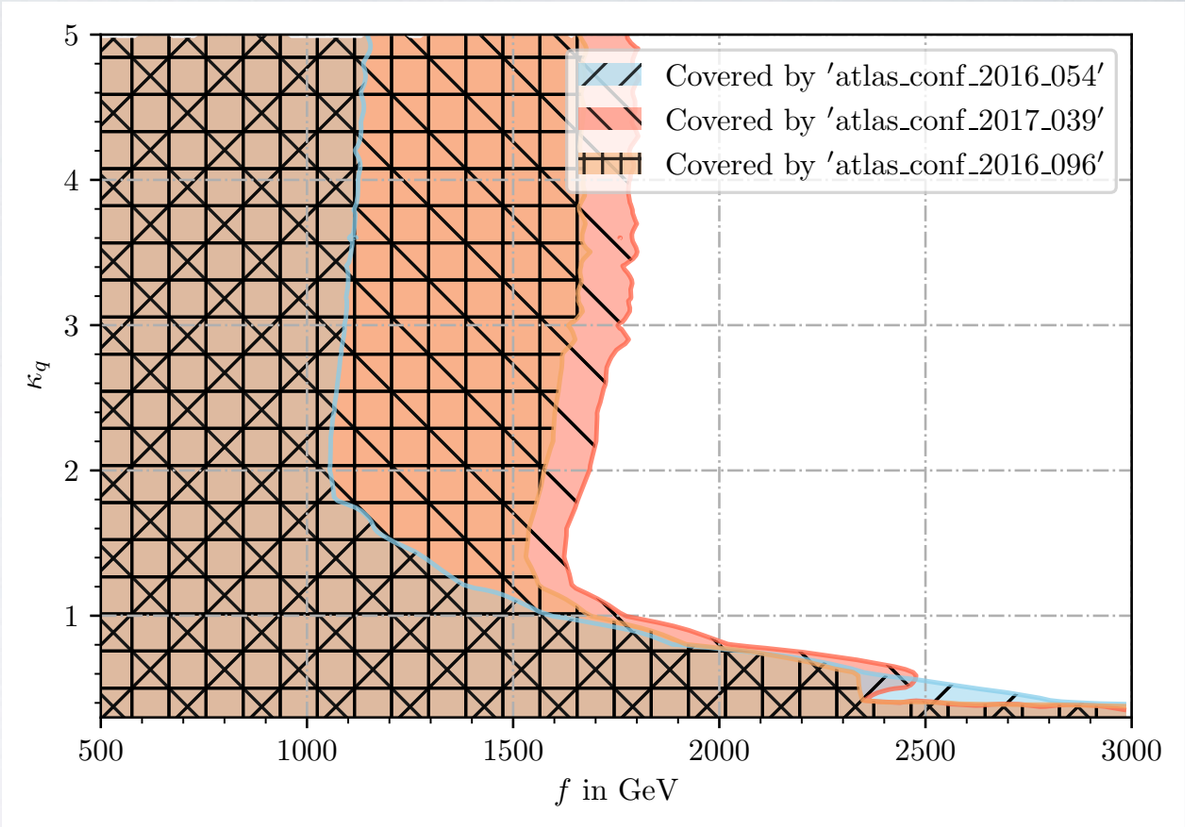
13 TeV recasting results: Light ℓ_H





(Light ℓ_H) ⊕ (Light $T^\pm$) ⊕ (TPV)

- 2 main exclusion regions, intersect at $f \approx 1.6$ TeV and $\kappa_q \approx 1.2$
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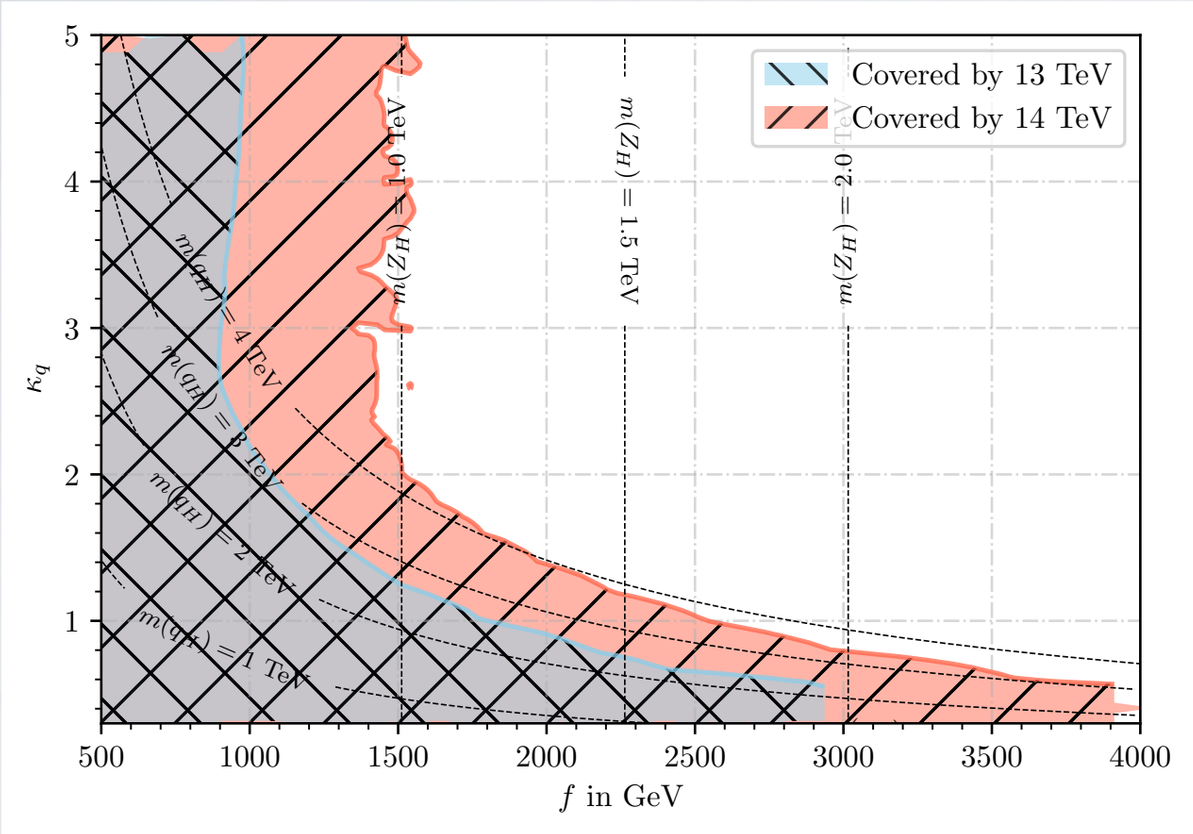
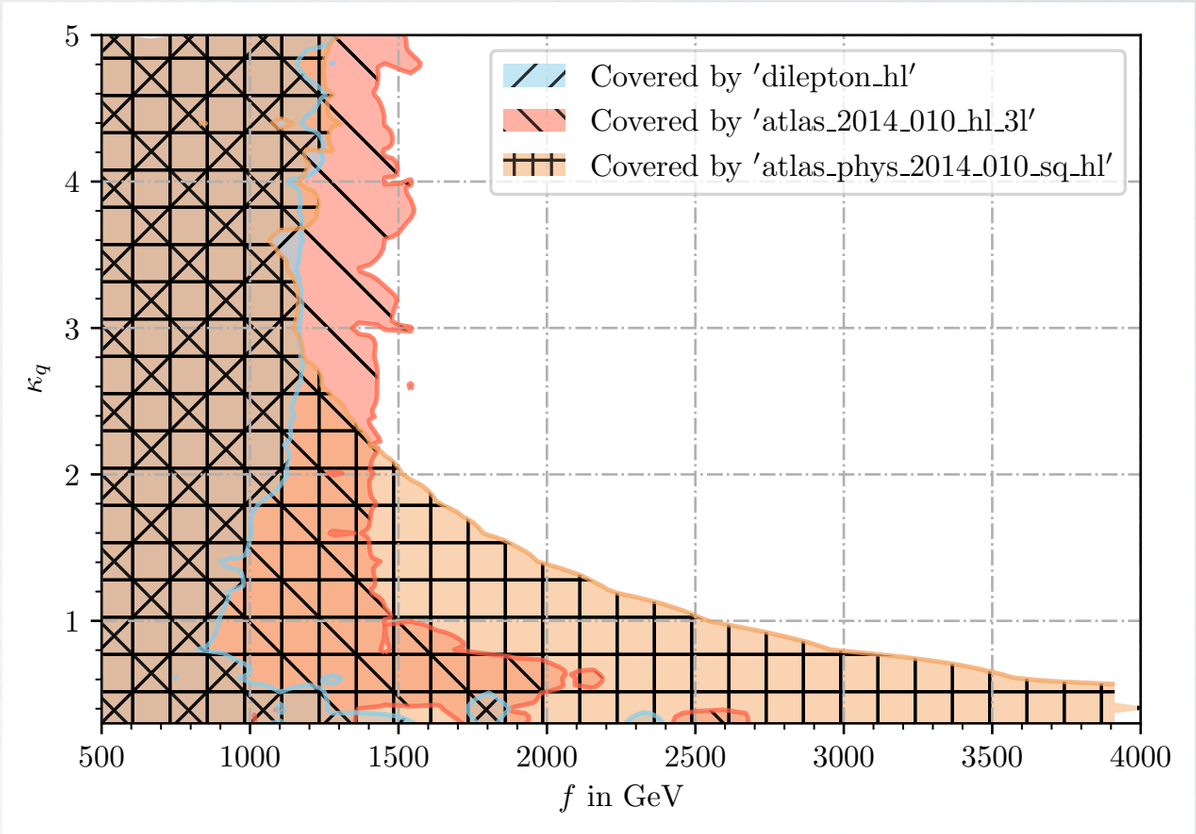
- TPV: bounds slightly weakened due to smaller MET cut efficiency

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



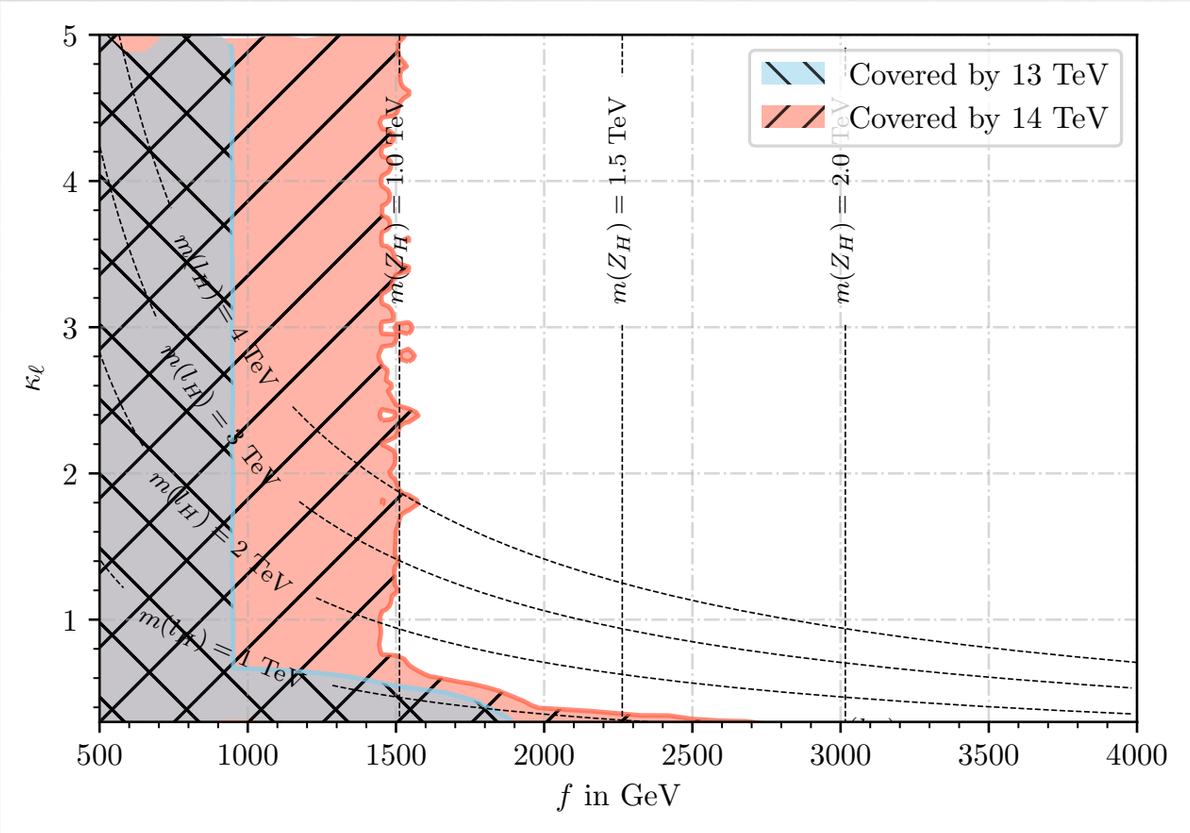


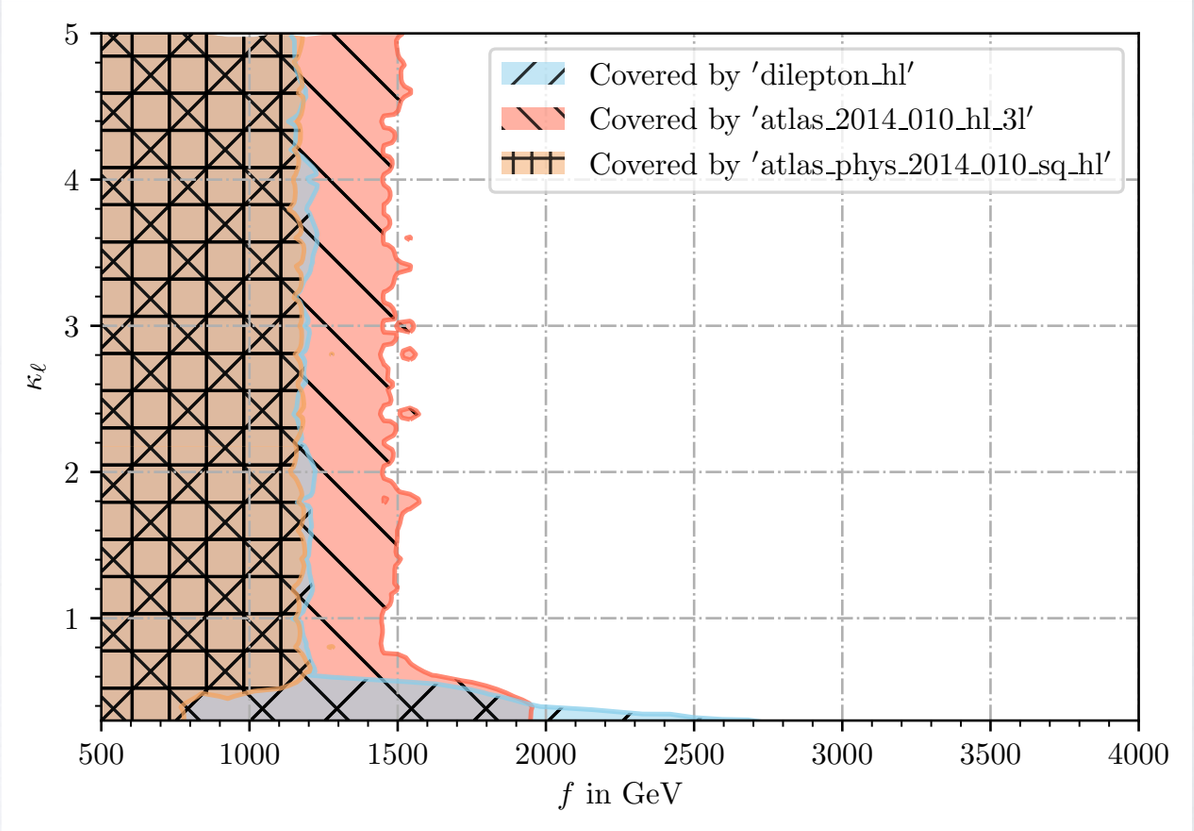
(Fermion Universality) ⊕ (Heavy $T^{\pm}$) ⊕ (TPC) 14 TeV 3,000 / fb

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

Prospects for 14 TeV HL-LHC

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



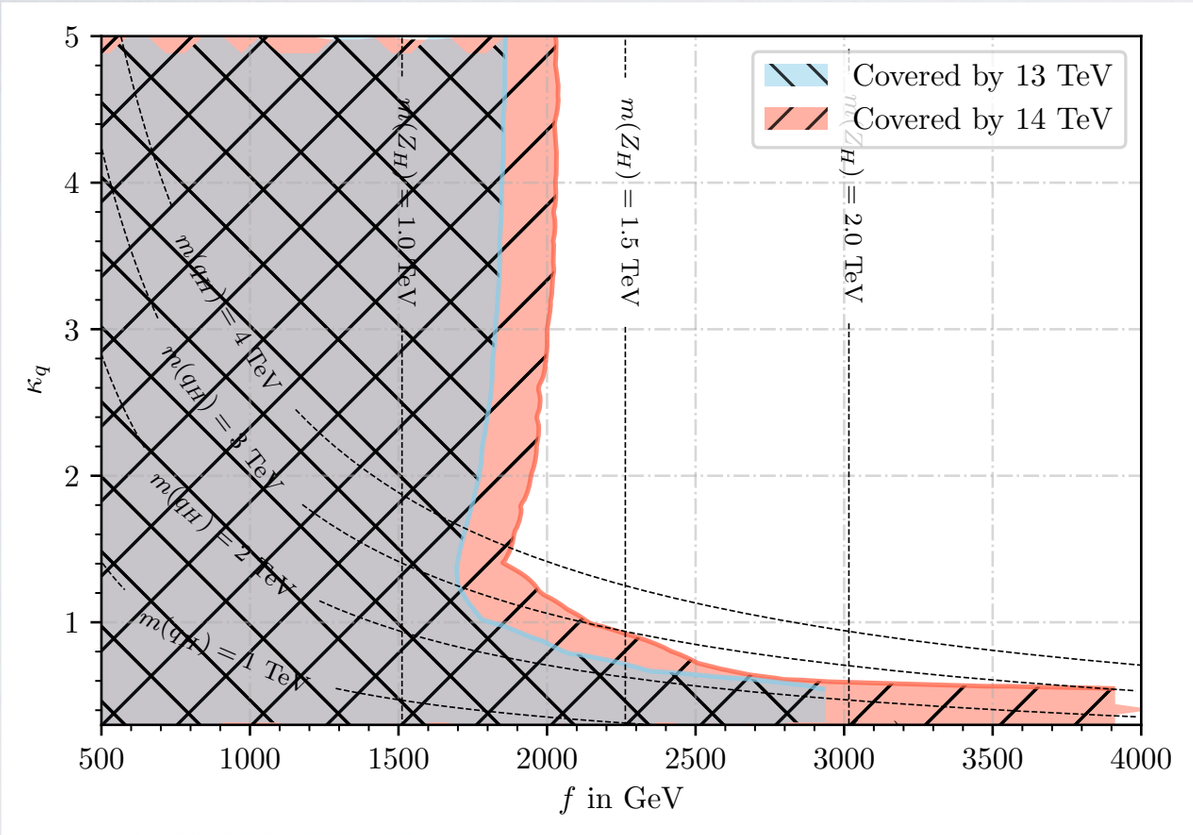


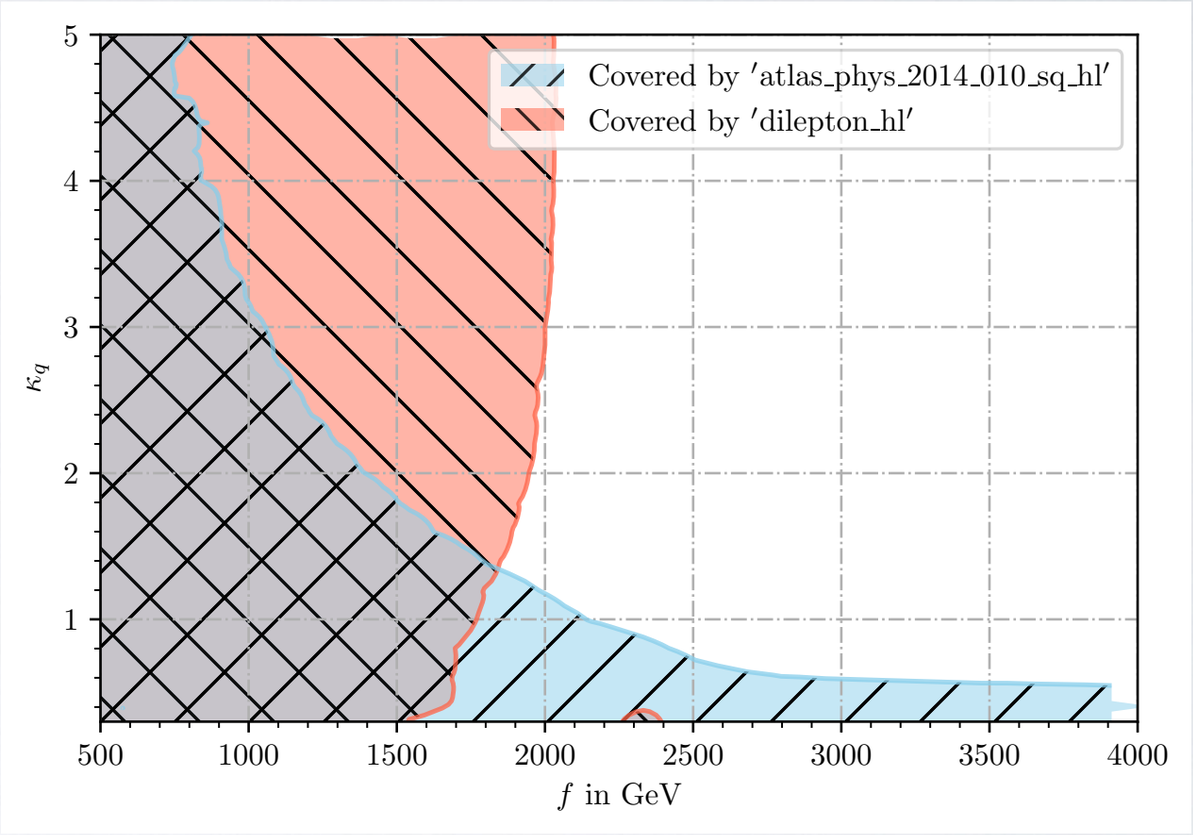
(Heavy q_H) ⊕ (Heavy $T^{\pm}$) ⊕ (TPC) 14 TeV 3,000 / fb

Relatively moderate improvements for ℓ_H mass bounds

Prospects for 14 TeV HL-LHC

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

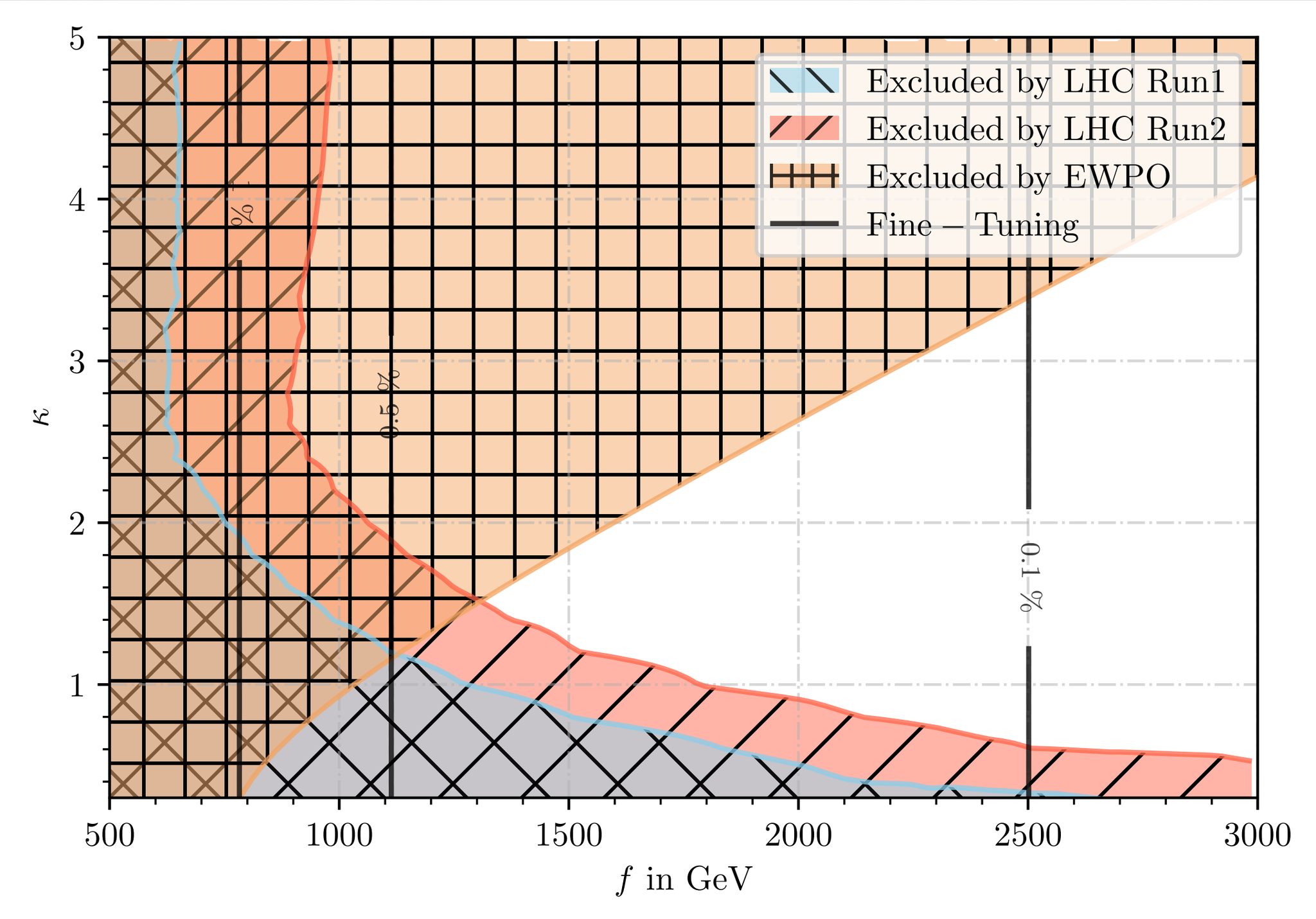




(Light ℓ_H) $\oplus$ (Heavy $T^{\pm}$) $\oplus$ (TPC) 14 TeV 3,000 / fb

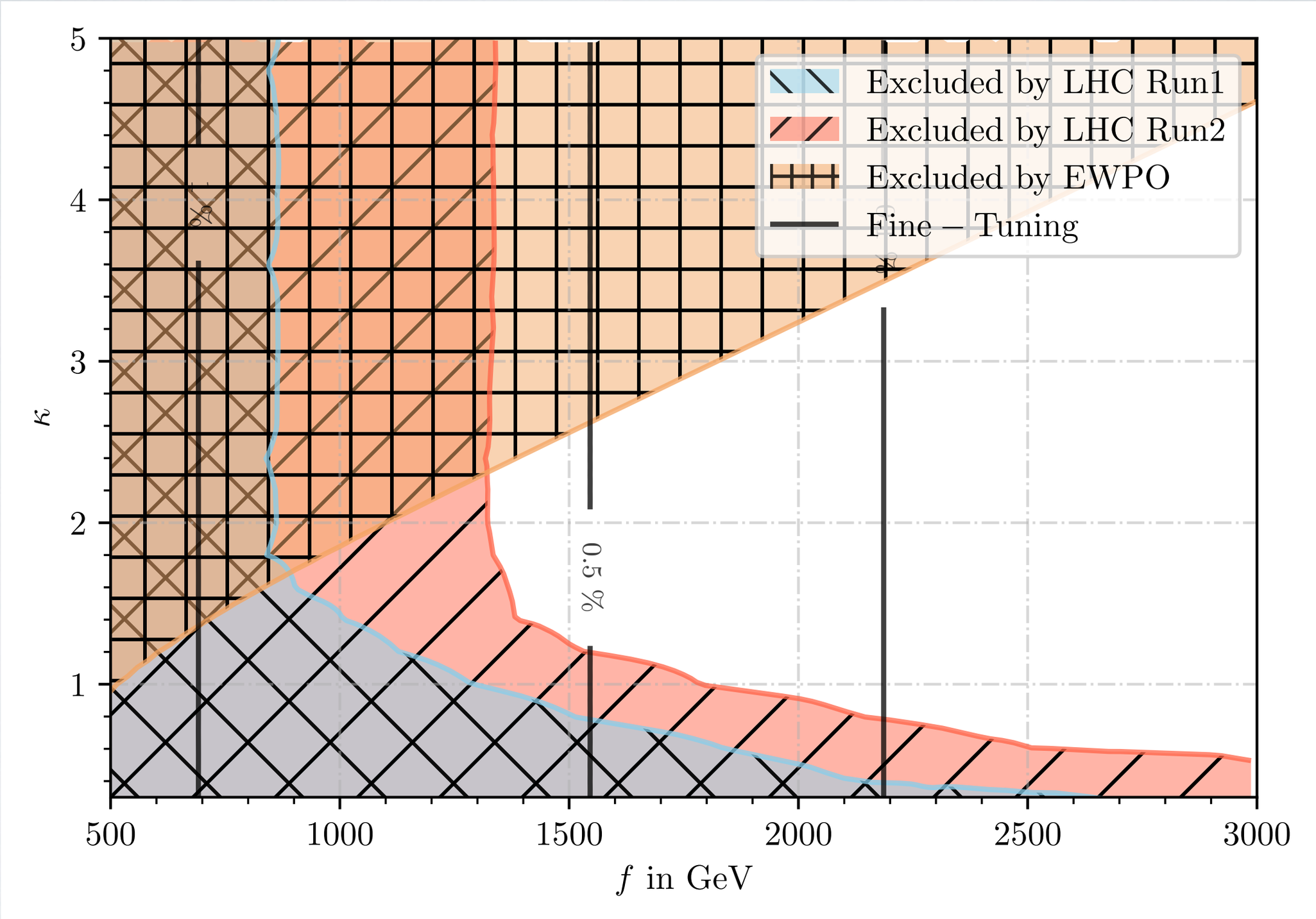
Little improvement compared to 13 TeV

LHC Run 2 and EWPO/Higgs Results



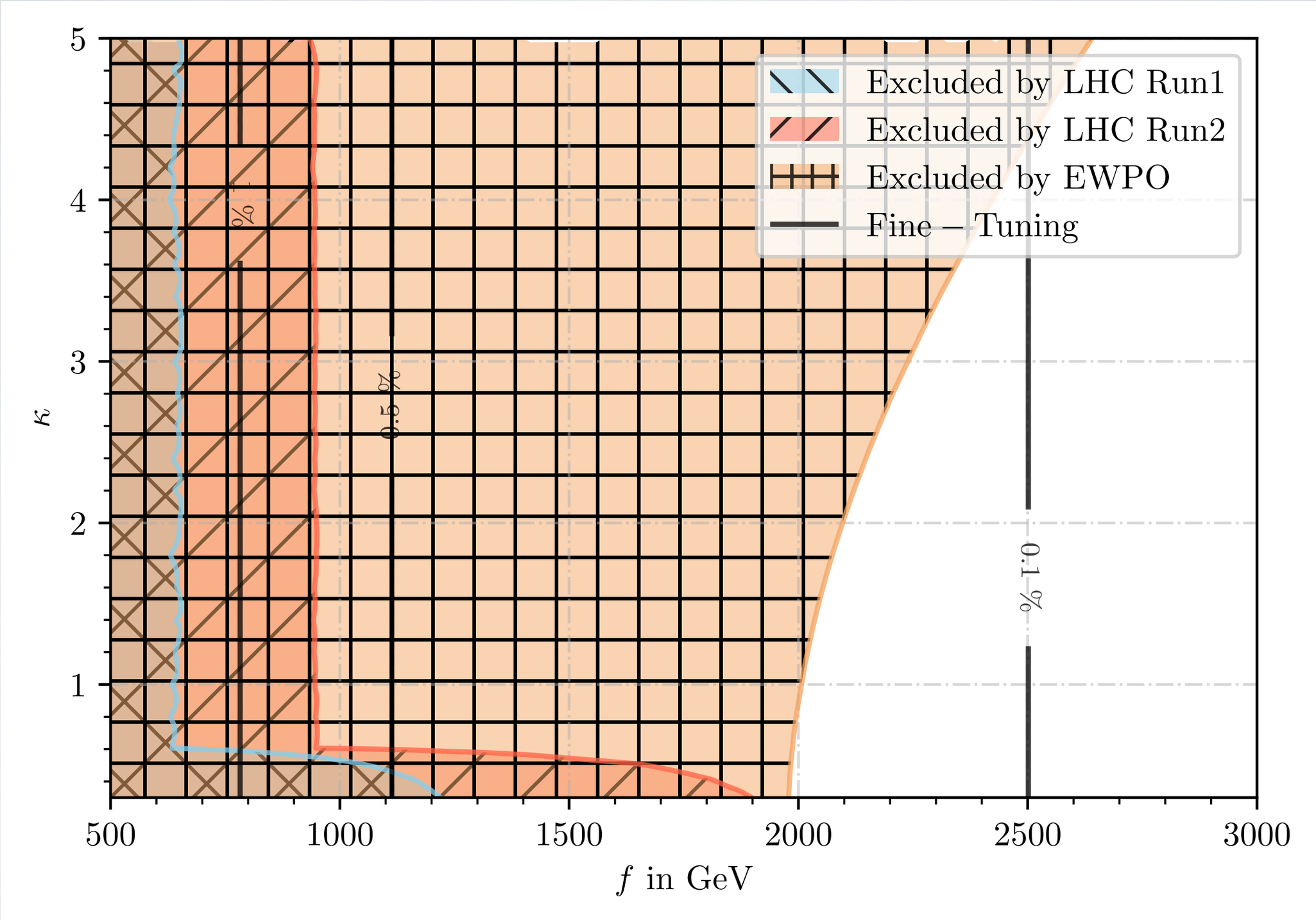
(Fermion Universality) ⊕ (Heavy $T^{\pm}$) ⊕ (T-parity conservation)

LHC Run 2 and EWPO/Higgs Results



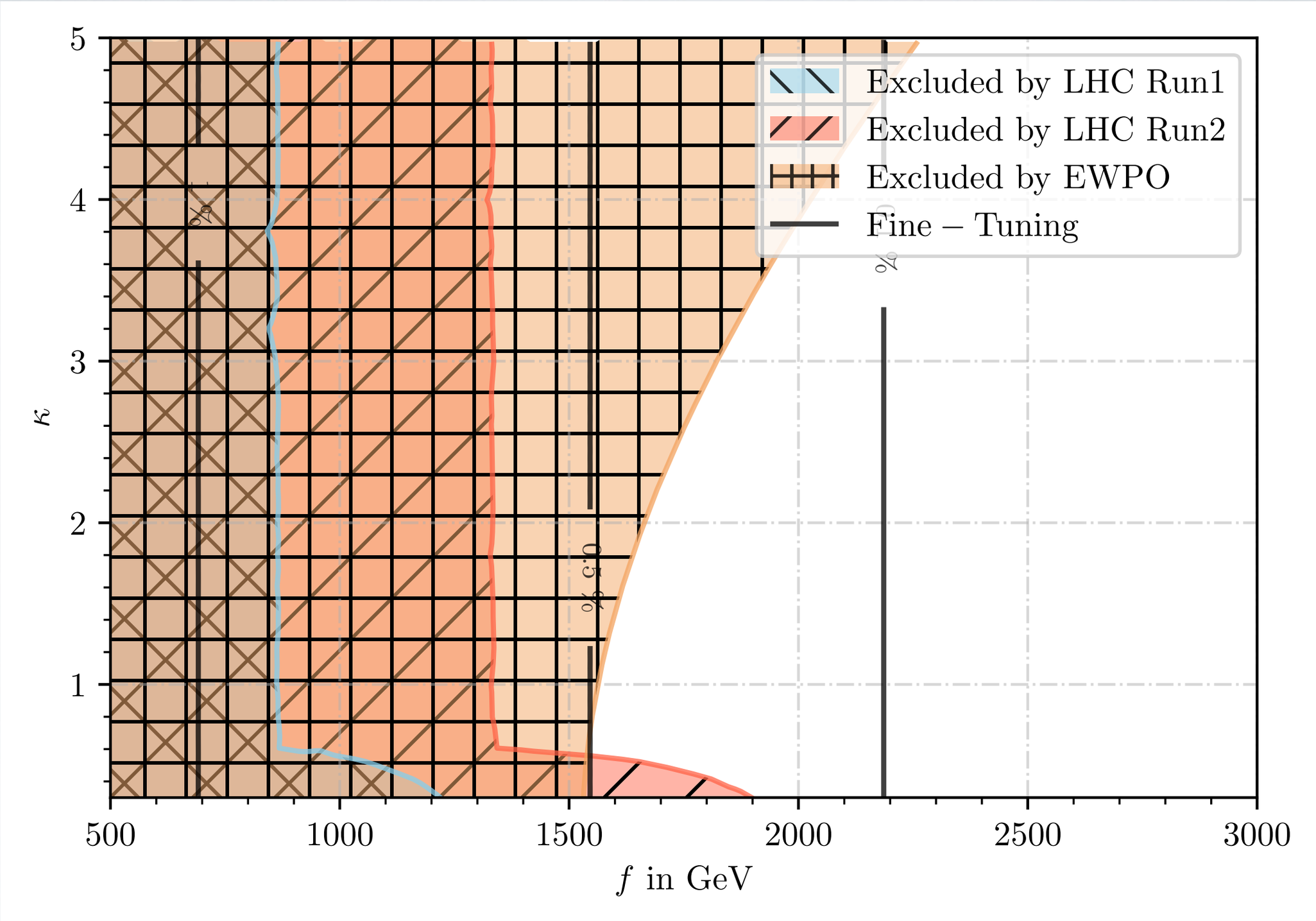
(Fermion Universality) ⊕ (Light $T^{\pm}$) ⊕ (T-parity conservation)

LHC Run 2 and EWPO/Higgs Results



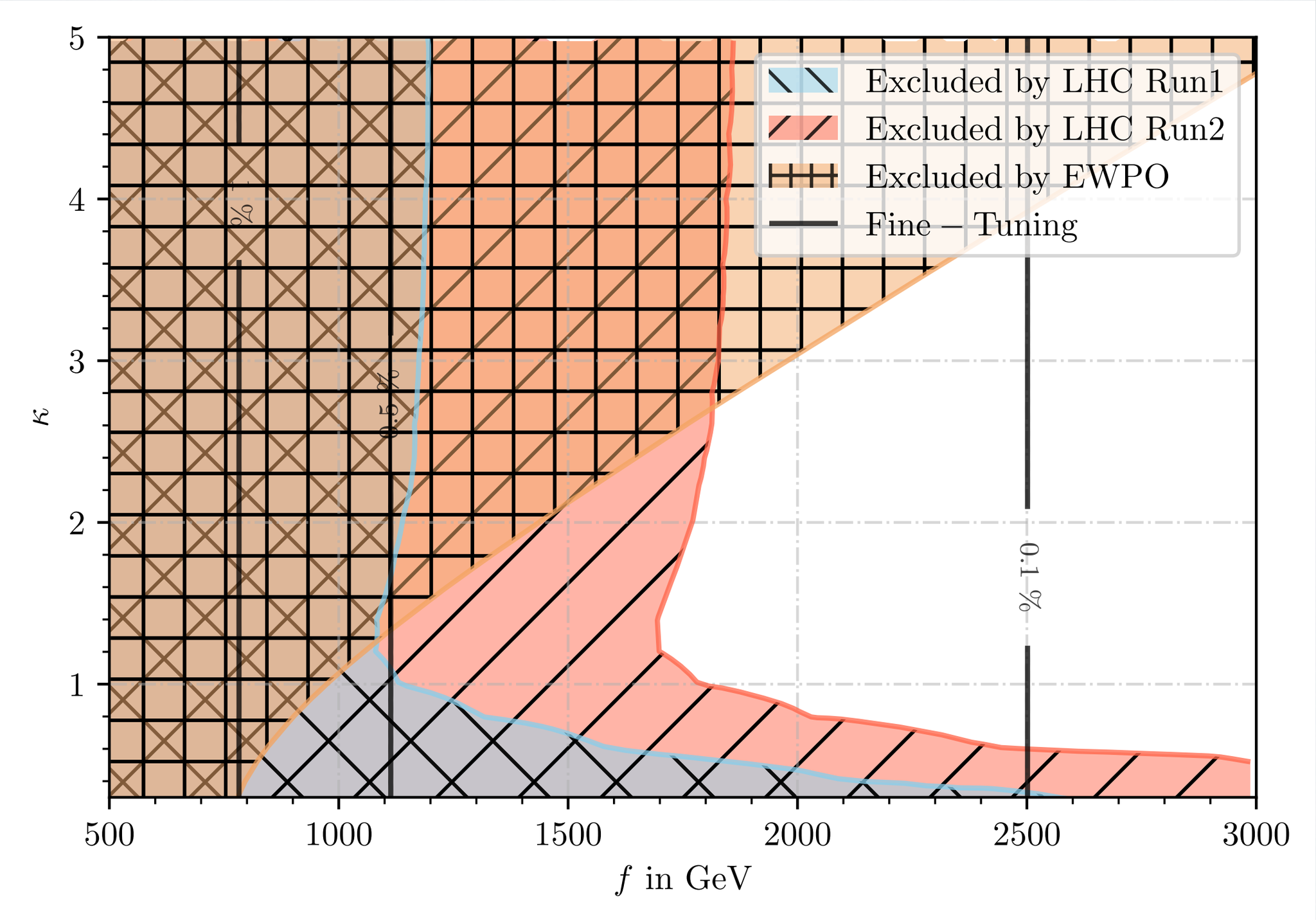
(Heavy q_H) ⊕ (Heavy $T^{\pm}$) ⊕ (T-parity conservation)

LHC Run 2 and EWPO/Higgs Results



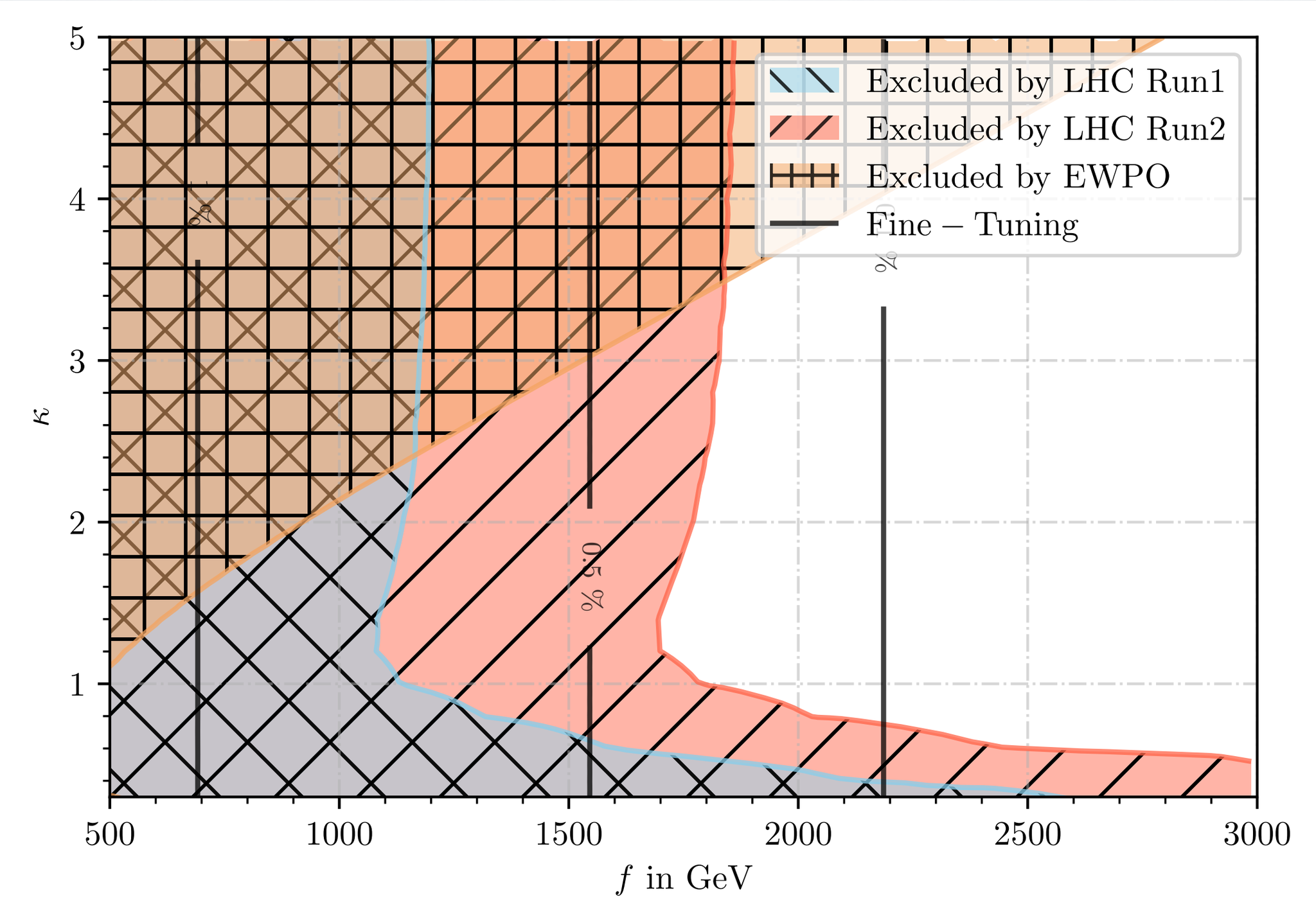
(Heavy q_H) ⊕ (Light $T^{\pm}$) ⊕ (T-parity conservation)

LHC Run 2 and EWPO/Higgs Results



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

LHC Run 2 and EWPO/Higgs Results



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