The fate of the Littlest Higgs Model with T-parity under 13 TeV LHC Data

Daniel Dercks, né Schmeier

in coll. with G. Moortgat-Pick, J. Reuter and S.Y. Shim

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(Re)interpreting the results of new physics searches at the LHC

CERN, 15 May 2018

Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676

Universität Hamburg
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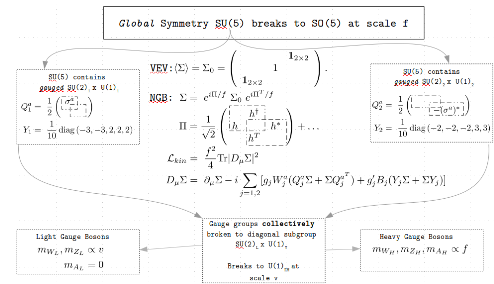

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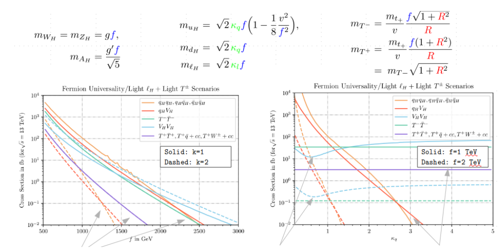

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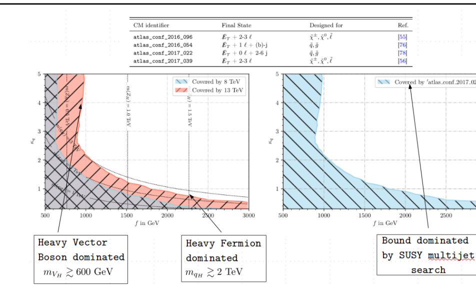

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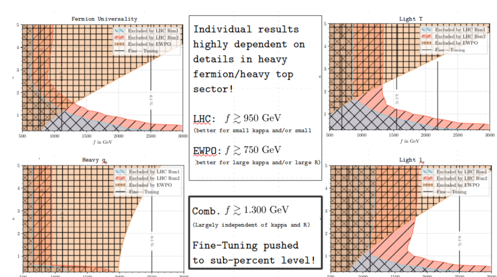
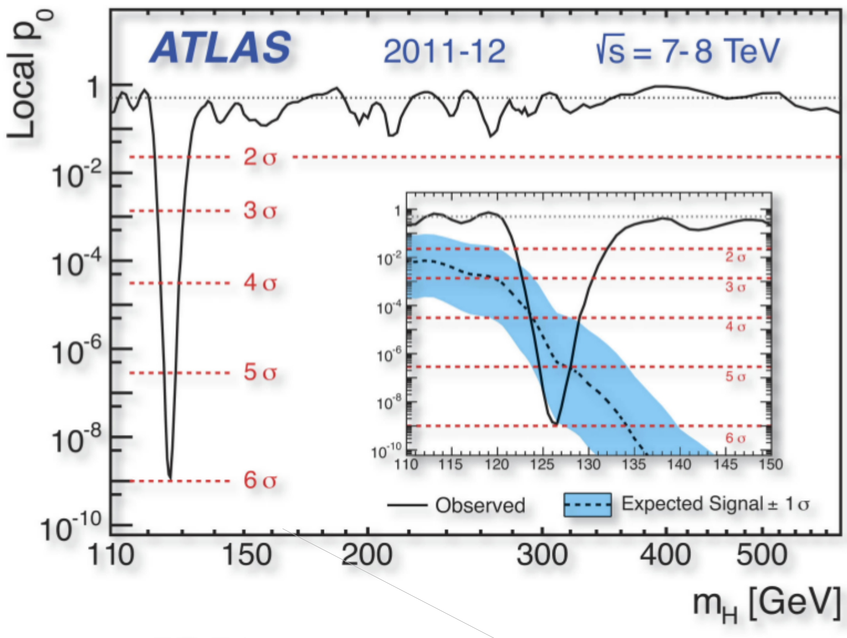
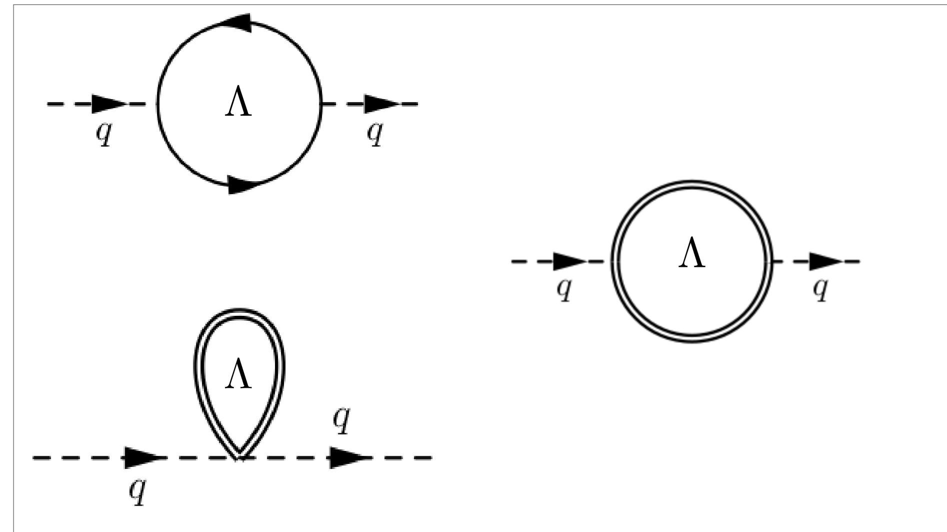


The Hierarchy Problem





$$m_h^2 = m_{h,0}^2 + \Lambda^2(loopfactor)$$

How can the Higgs mass be naturally light?

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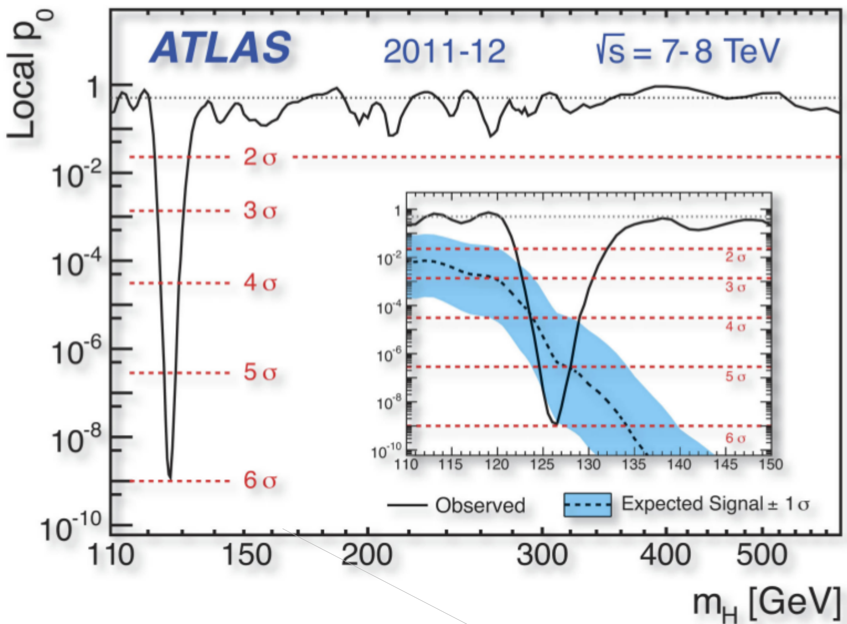

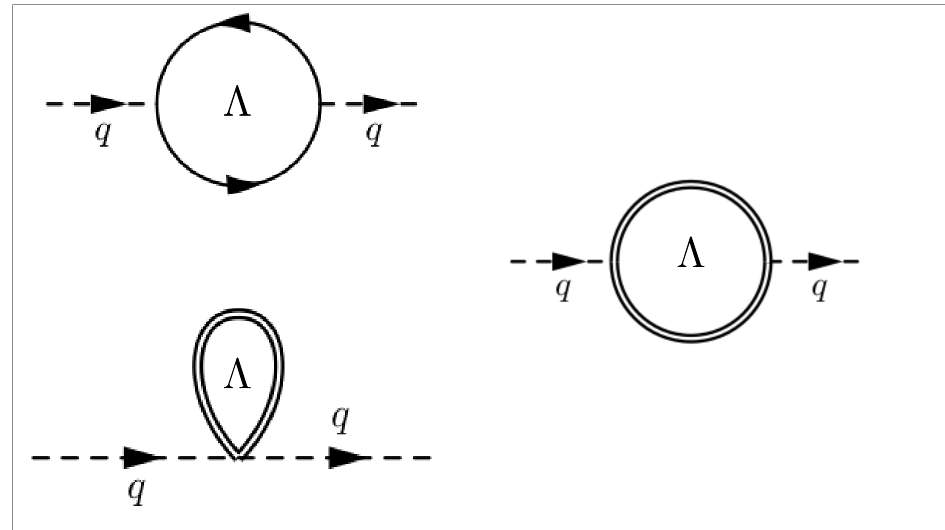

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Little Higgs: Make Higgs a Pseudo-Nambu-Goldstone Boson and protect its mass from loop corrections via "Collective Symmetry Breaking" of 2 groups!

Littlest Higgs Realisation

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

Global Symmetry SU(5) breaks to SO(5) at scale f

$$\texttt{VEV:}\langle\Sigma\rangle = \Sigma_0 = \begin{pmatrix} & & \mathbf{1}_{2\times 2} \\ & 1 & \\ \mathbf{1}_{2\times 2} & & \end{pmatrix}.$$

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Gauge groups **collectively** broken to diagonal subgroup $SU(2)_L$ x $U(1)_Y$

Breaks to $U(1)_{EM}$ at scale v

Light Gauge Bosons

$m_{W_L}, m_{Z_L} \propto v$

$m_{A_L} = 0$

Heavy Gauge Bosons

$m_{W_H}, m_{Z_H}, m_{A_H} \propto f$

Higgs mass corrections suppressed due to the simultaneous breaking of two gauge groups

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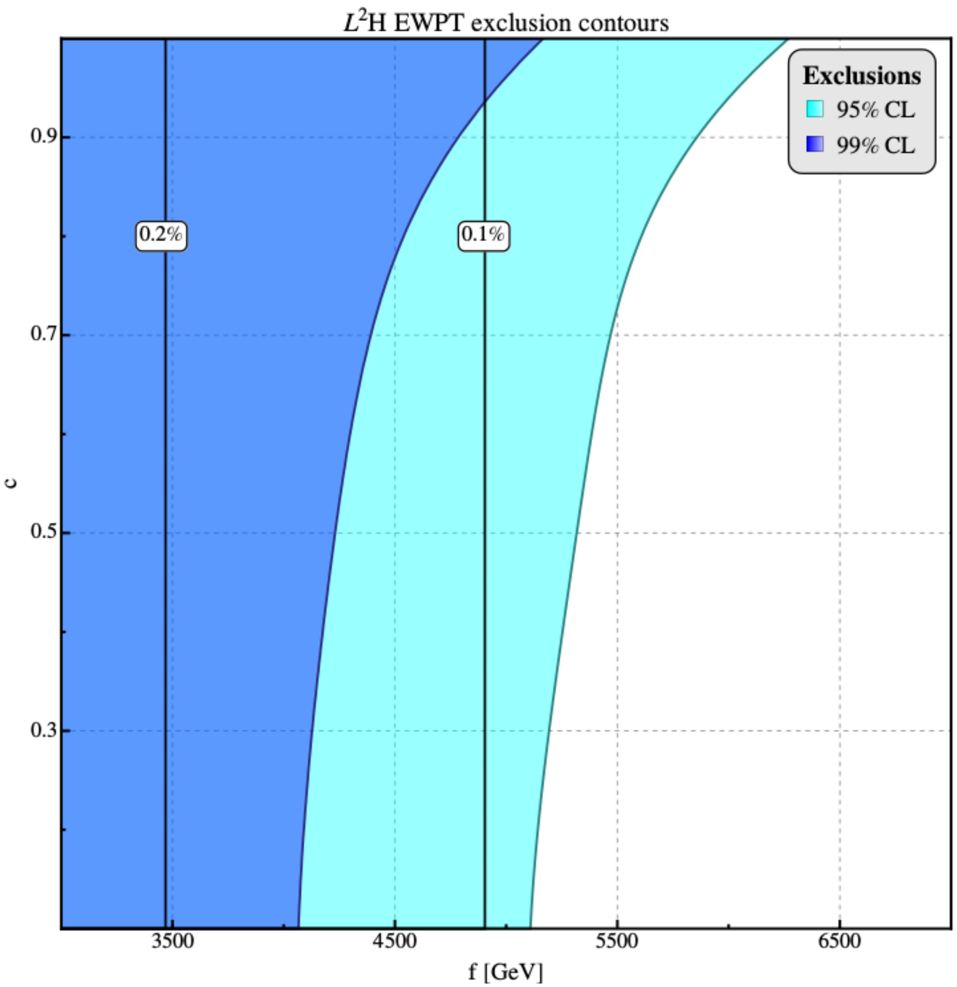
Hewett/Petriello/Rizzo, '02; Csáki/Hubisz/Kribs/Meade/Terning, '03; Kilian/Reuter, '03,...



Reuter, Tonini, 1212.5930

Tree level mixing between heavy and light gauge bosons yields large contributions to electroweak precision observables

$$f > 4.7\ \text{TeV}@95\ \%\text{C.L.}$$

Fine Tuning of <0.1% would again introduce the hierarchy problem

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Cheng,Low, ’03

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Add automorphism which maps the two gauge groups

$$\Pi \to -\Omega\Pi\Omega$$

$$\Omega = \mathrm{diag}(1,1,-1,1,1)$$

$$g_1 = g_2 = g_{\mathrm{SM}}/\sqrt{2}$$

$$g_1' = g_2' = g_{\mathrm{SM}}'/\sqrt{2}$$

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LHT Particle Spectrum

- Standard Model particles are all T-parity even
- Heavy gauge bosons automatically T-parity odd

$$m_{W_H} = m_{Z_H} = gf,$$
$$m_{A_H} = \frac{g'f}{\sqrt{5}}$$

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  - → These mix to T-even Standard Model fermions + heavy T-odd partners + "decoupled rest"

$$m_{W_H} = m_{Z_H} = g f, \qquad m_{A_H} = \frac{g' f}{\sqrt{5}}$$

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$$m_{T^-} = \frac{m_{t_+}}{v}\frac{f\sqrt{1+R^2}}{R}, \qquad m_{T^+} = \frac{m_{t_+}}{v}\frac{f(1+R^2)}{R} = m_{T-}\sqrt{1+R^2}$$

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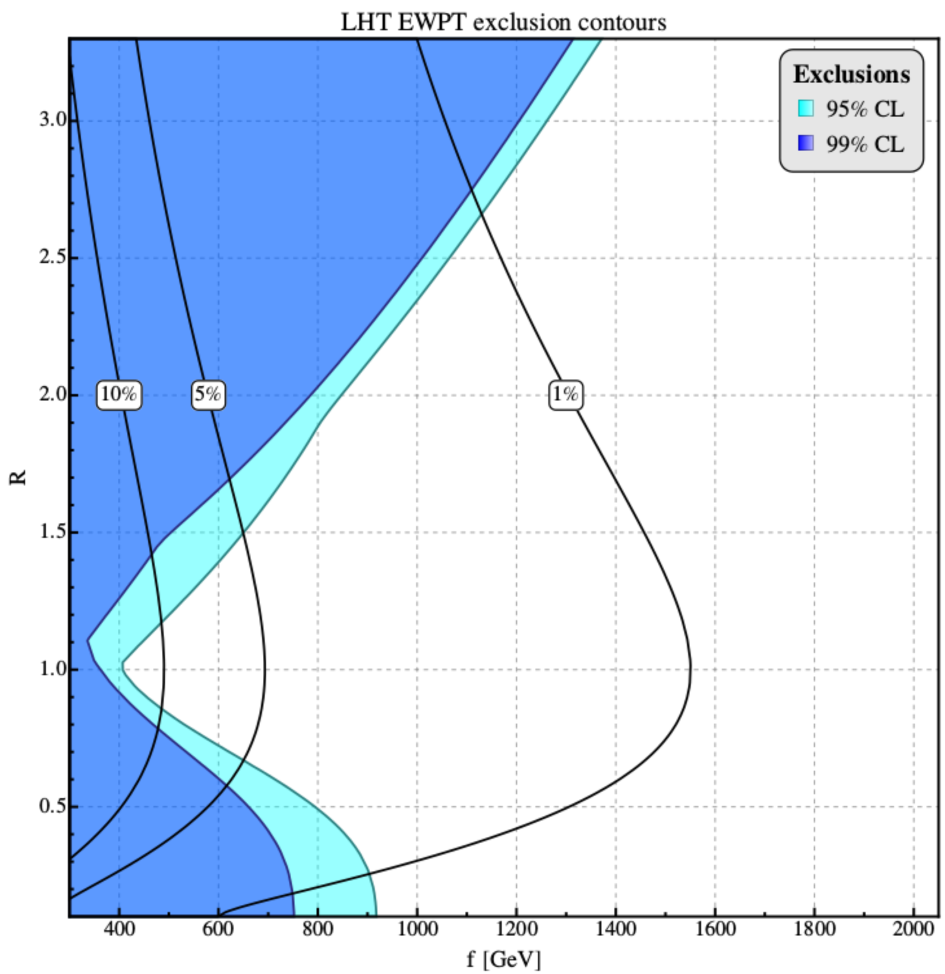
Little Higgs + T-Parity Constraints

Hewett/Petriello/Rizzo, ’02; Csáki/Hubisz/Kribs/Meade/Terning, ’03; Kilian/Reuter, ‘03,...



Reuter, Tonini, 1212.5930

Mixing is removed and EWPO contributions only appear at loop level

Heavy tops cancel contributions for R close to 1.

$$R = 1 : f \gtrsim 400 \text{ GeV@95 \%C.L.}$$
$$m_{W_H} \gtrsim 270 \text{ GeV}$$
$$m_T \gtrsim 550 \text{ GeV}$$

Model realisations with small fine tuning still possible!

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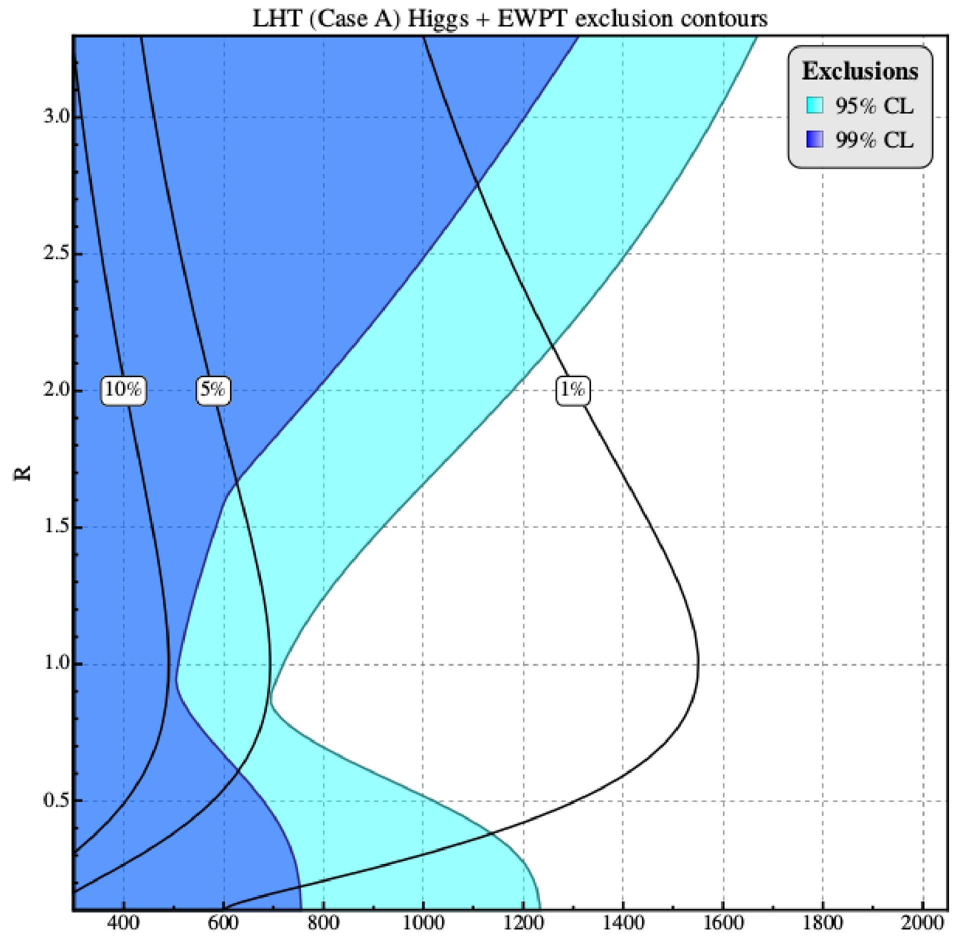

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Higgs constraints originate from deviations in production cross sections and branching ratios

$$R = 1 : f \gtrsim 700 \text{ GeV@95 \%C.L.}$$
$$m_{W_H} \gtrsim 470 \text{ GeV}$$
$$m_T \gtrsim 950 \text{ GeV}$$

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- Production of T-parity odd particles only in pairs
- T-parity conservation renders lightest T-odd particle stable
  - → Possible Dark Matter candidate, unless T-parity is violated

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Hill,Hill, ’07   Freitas/Schwaller/Wyler, ‘08

- Wess-Zumino-Witten-anomalies in the UV sector may create $A_H VV$ couplings

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

- For masses below 160 GeV, loop decays into fermions may become relevant

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

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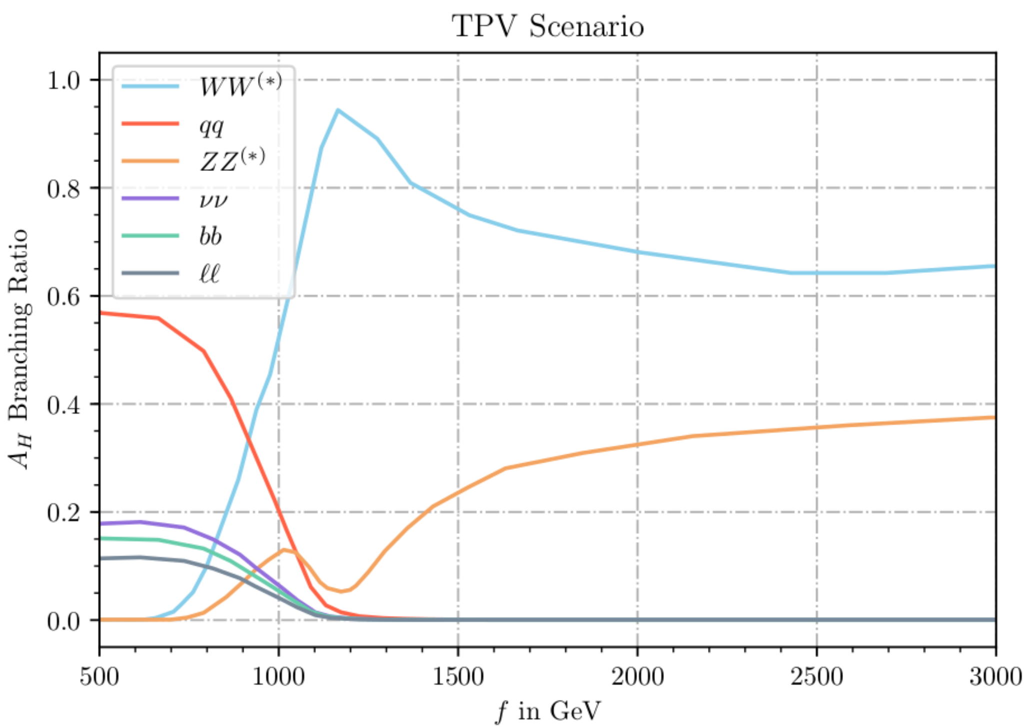

These decays may significantly change the expected collider phenomenology!
But: If N=0, T-Parity may still be unbroken!

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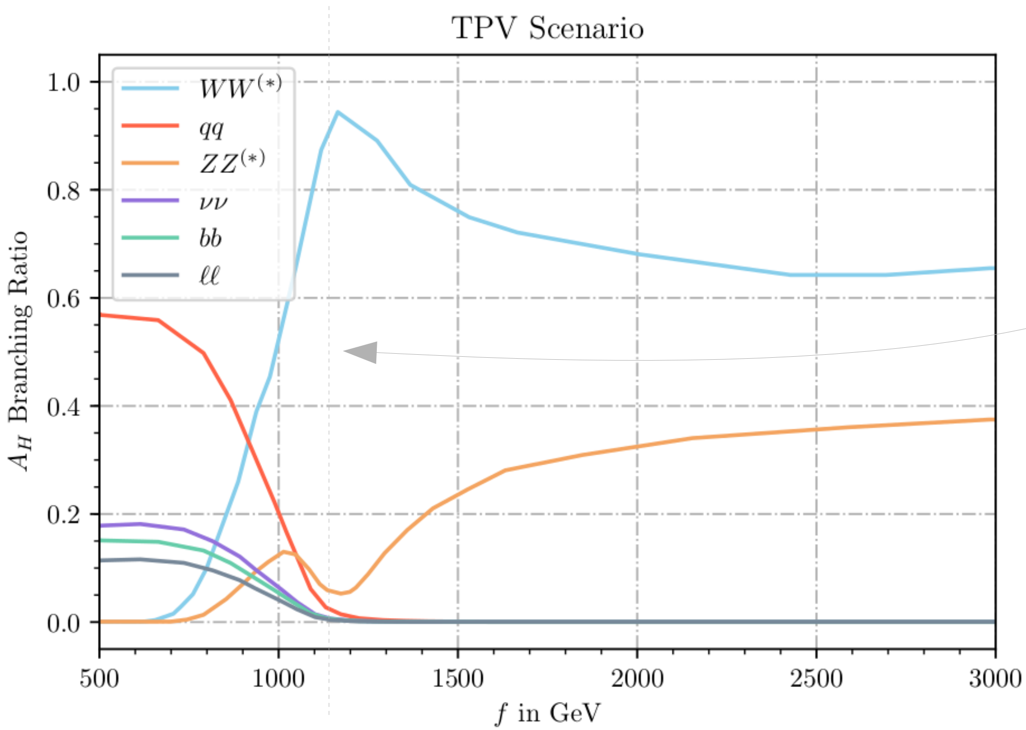
$$\Gamma(A_H \to W^+W^-) = 2\Gamma(A_H \to ZZ) = \left(\frac{N g'}{80\sqrt{3}\pi^3}\right)^2 \frac{M_{A_H}^3 m_V^2}{f^4}\left(1 - \frac{4m_V^2}{M_{A_H}^2}\right)^{\frac{5}{2}},$$

- For masses below 160 GeV, loop decays into fermions may become relevant

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



$m_{A_H} \approx 2m_V$

These decays may significantly change the expected collider phenomenology!
But: If N=0, T-Parity may still be unbroken!

LHT Scenarios

- 4 free parameters: $f, \kappa_q, \kappa_\ell, R$
- T-Parity may be conserved or broken

$$m_{W_H} = m_{Z_H} = gf,$$
$$m_{A_H} = \frac{g' f}{\sqrt{5}}$$

$$m_{u_H} = \sqrt{2}\,\kappa_q f\left(1 - \frac{1}{8}\frac{v^2}{f^2}\right),$$
$$m_{d_H} = \sqrt{2}\,\kappa_q f$$
$$m_{\ell_H} = \sqrt{2}\,\kappa_l f$$

$$m_{T^-} = \frac{m_{t_+}}{v}\frac{f\sqrt{1+R^2}}{R}$$
$$m_{T^+} = \frac{m_{t_+}}{v}\frac{f(1+R^2)}{R} = m_{T^-}\sqrt{1+R^2}$$

Sector	Model	Constraint	Phenomenology
f_H	*Fermion Universality*	$\kappa_l = \kappa_q$	• mass degeneracy of q_H, ℓ_H • ℓ_H production negligible
	Heavy q_H	$\kappa_q = 3.0$	• q_H decoupled • ℓ_H production relevant
	Light ℓ_H	$\kappa_l = 0.2$	• ℓ_H very light • V_H branching ratios change
$T^\pm$	*Light $T^\pm$*	$R = 1.0$	• $T^\pm$ are light/accessible
	Heavy $T^\pm$	$R = 0.2$	• $T^\pm$ are heavy/inaccessible
A_H	*TPC*	No TPV	• A_H is stable and invisible
	TPV	With TPV	• A_H is unstable

Expected LHC Topologies

$pp \to V_H V_H (\in W_H, Z_H, A_H)$

$W_H / Z_H \to \ell \ell_H \to \ell \ell A_H$ or

$W_H \to W A_H$,

$Z_H \to Z/h A_H$

$pp \to q_H q_H$,

$q_H \to q A_H$ or

$q_H \to q W_H / Z_H \to q A_H + X$

$pp \to q_H V_H$,

q_H and V_H decaying as above

$pp \to \ell_H \ell_H$

$\ell_H \to \ell A_H$

$pp \to T^{\pm} T^{\pm}$

$T^{\pm} \to t A_H$

Expected LHC Topologies

$pp \to V_H V_H (\in W_H, Z_H, A_H)$ $W_H/Z_H \to \ell \ell_H \to \ell \ell A_H$ or $W_H \to W A_H$, $Z_H \to Z/h A_H$	$pp \to \tilde{\chi}\tilde{\chi}$ $(\in \tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$, $\tilde{\chi}^{\pm}/\tilde{\chi}_2^0 \to \ell \tilde{\ell} \to \ell \ell \chi^0$ or $\tilde{\chi}_1^{\pm} \to W^{\pm} \tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \to Z/h \tilde{\chi}_1^0$	
$pp \to q_H q_H$, $q_H \to q A_H$ or $q_H \to q W_H/Z_H \to q A_H + X$	$pp \to \tilde{q}\tilde{q}$, $\tilde{q} \to q \tilde{\chi}_1^0$ or $\tilde{q} \to q \tilde{\chi}_2^0/\chi_1^{\pm} \to q \tilde{\chi}_1^0 + X$	Recasting SUSY analyses is expected to be very powerful here
$pp \to q_H V_H$, q_H and V_H decaying as above	$pp \to \tilde{q}\tilde{\chi}$, $\tilde{q}$ and $\tilde{\chi}$ decaying as above	
$pp \to \ell_H \ell_H$ $\ell_H \to \ell A_H$	$pp \to \tilde{\ell}\tilde{\ell}$, $\tilde{\ell} \to \ell \tilde{\chi}_1^0$	
$pp \to T^{\pm} T^{\pm}$ $T^{\pm} \to t A_H$	$pp \to \tilde{t}\tilde{t}$ $\tilde{t} \to t \tilde{\chi}_0$	

Expected LHC Topologies

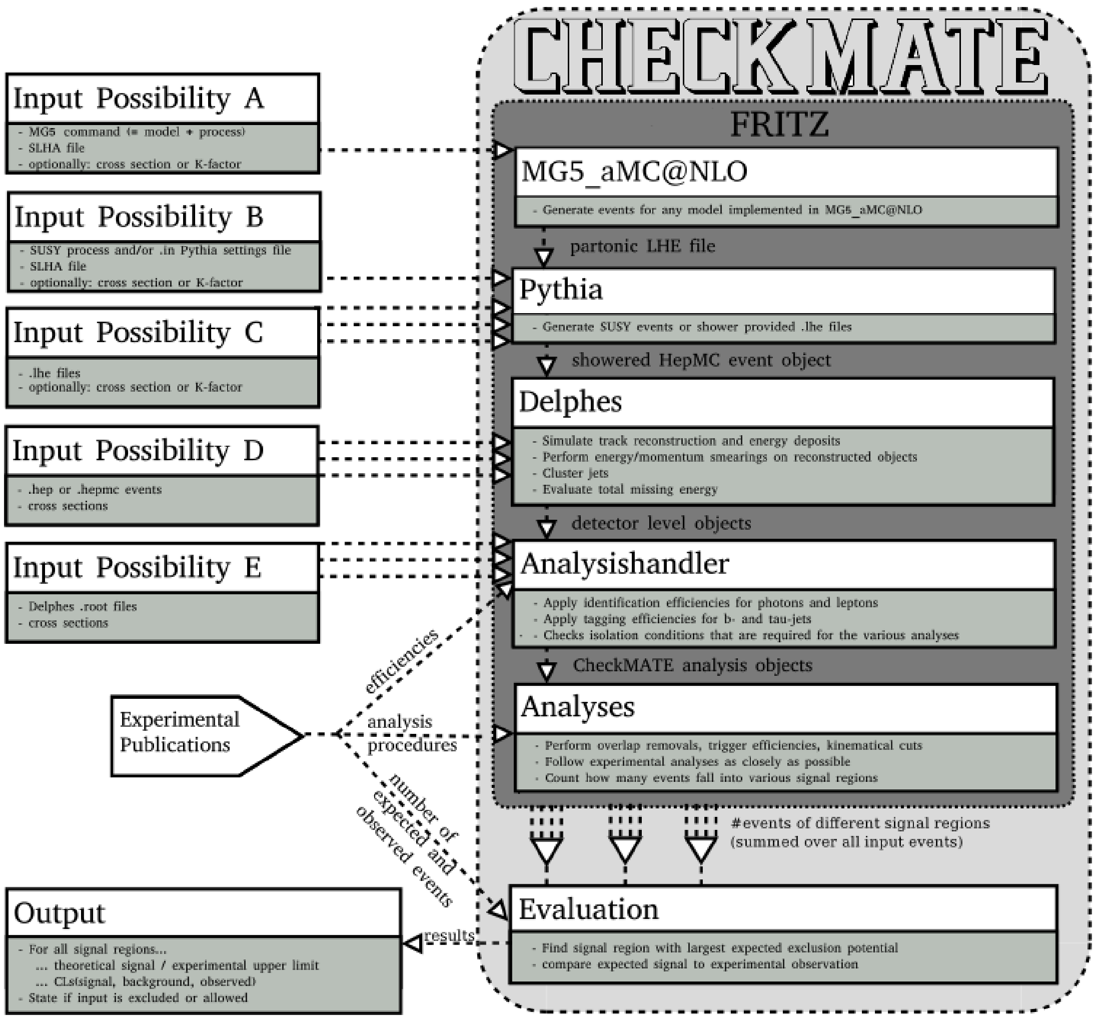
$pp \to V_H V_H (\in W_H, Z_H, A_H)$ $W_H/Z_H \to \ell\ell_H \to \ell\ell A_H$ or $W_H \to W A_H$, $Z_H \to Z/h A_H$	$pp \to \tilde{\chi}\tilde{\chi}$ $(\in \tilde{\chi}_1^\pm, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$, $\tilde{\chi}^\pm/\tilde{\chi}_2^0 \to \ell\tilde{\ell} \to \ell\ell\chi^0$ or $\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \to Z/h\tilde{\chi}_1^0$	
$pp \to q_H q_H$, $q_H \to q A_H$ or $q_H \to q W_H/Z_H \to q A_H + X$	$pp \to \tilde{q}\tilde{q}$, $\tilde{q} \to q\tilde{\chi}_1^0$ or $\tilde{q} \to q\tilde{\chi}_2^0/\chi_1^\pm \to q\tilde{\chi}_1^0 + X$	Recasting SUSY analyses is expected to be very powerful here
$pp \to q_H V_H$, q_H and V_H decaying as above	$pp \to \tilde{q}\tilde{\chi}$, $\tilde{q}$ and $\tilde{\chi}$ decaying as above	
$pp \to \ell_H \ell_H$ $\ell_H \to \ell A_H$	$pp \to \tilde{\ell}\tilde{\ell}$, $\tilde{\ell} \to \ell\tilde{\chi}_1^0$	
$pp \to T^\pm T^\pm$ $T^\pm \to t A_H$	$pp \to \tilde{t}\tilde{t}$ $\tilde{t} \to t\tilde{\chi}_0$	

$A_H A_H \to V_{\text{lep}} VVV (TPV)$

$V_{\text{lep}} \to$ MET ($> 70\%$ of all events)

T-Parity violation still covered by SUSY analyses due to leptonic gauge boson decays

Numerical Analysis



Use UFO implementation in MG5, validated with Whizard

Test the following processes against all implemented 8, 13 and high lumi 14 TeV results (only 13 TeV results discussed here)

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. $pp \to T_+ \bar{q}, \bar{T}_+ q, T_+ W^\pm, \bar{T}_+ W^\pm$

Results of LHC13 Recast

Fermion Universality x Heavy T x T-Parity Conserved

CM identifier	Final State	Designed for	Ref.
atlas_conf_2016_096	$\not{E}_T$ + 2-3 ℓ	$\tilde{\chi}^{\pm}, \tilde{\chi}^0, \tilde{\ell}$	[55]
atlas_conf_2016_054	$\not{E}_T$ + 1 ℓ + (b)-j	$\tilde{q}, \tilde{g}$	[76]
atlas_conf_2017_022	$\not{E}_T$ + 0 ℓ + 2-6 j	$\tilde{q}, \tilde{g}$	[78]
atlas_conf_2017_039	$\not{E}_T$ + 2-3 ℓ	$\tilde{\chi}^{\pm}, \tilde{\chi}^0, \tilde{\ell}$	[56]

Results of LHC13 Recast

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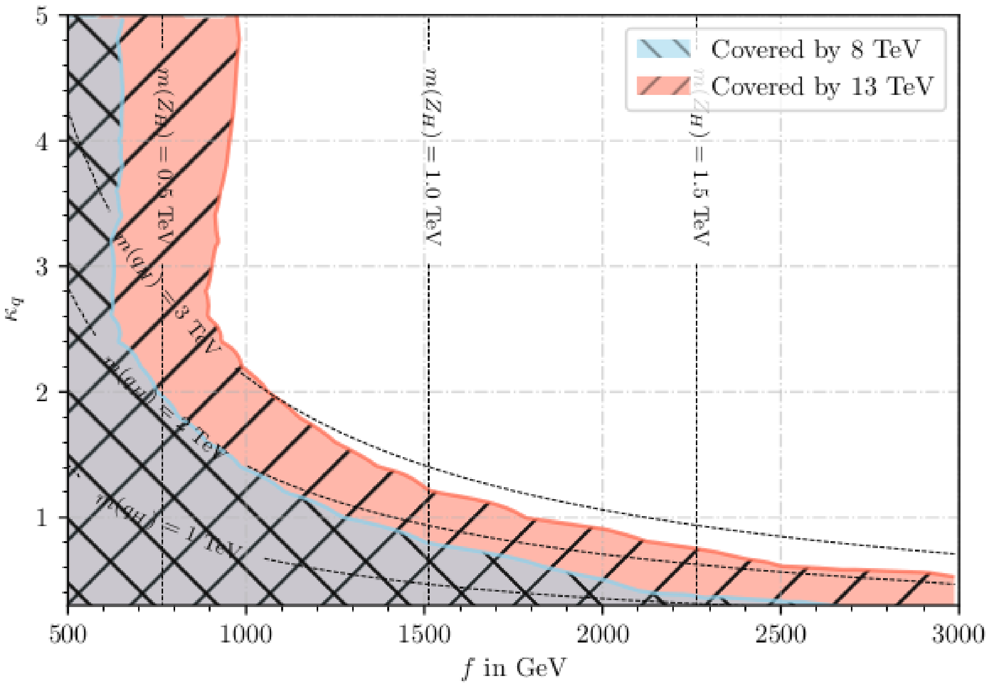
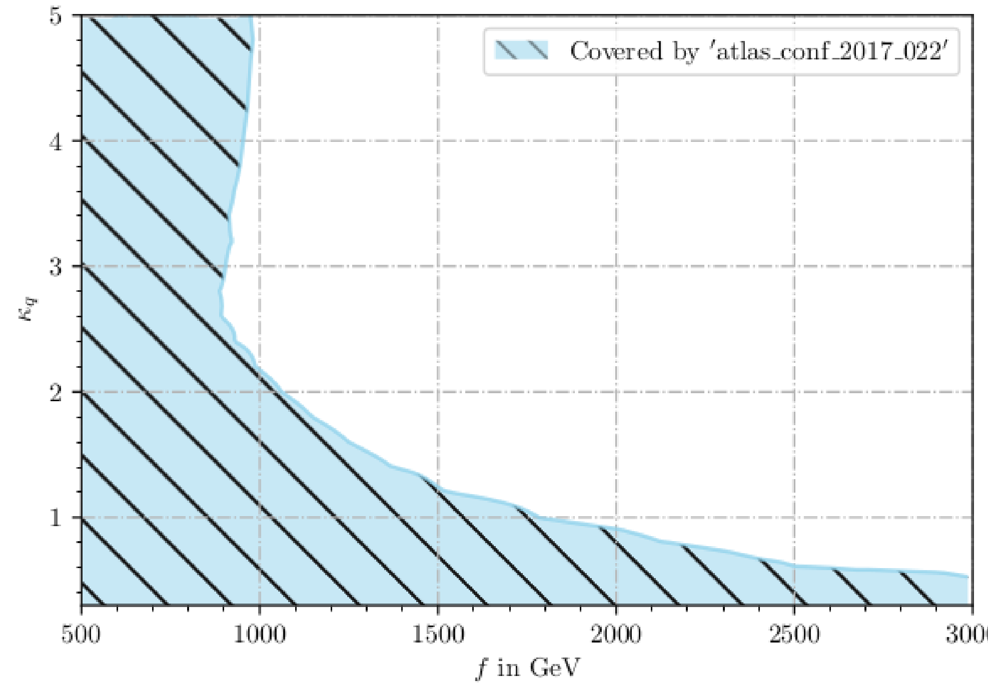
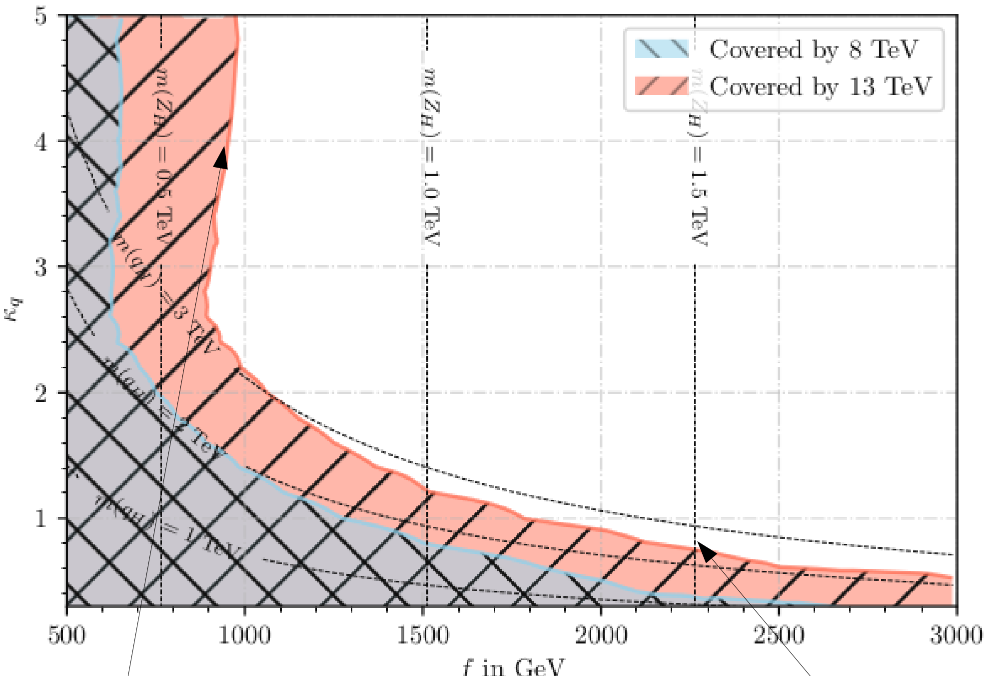


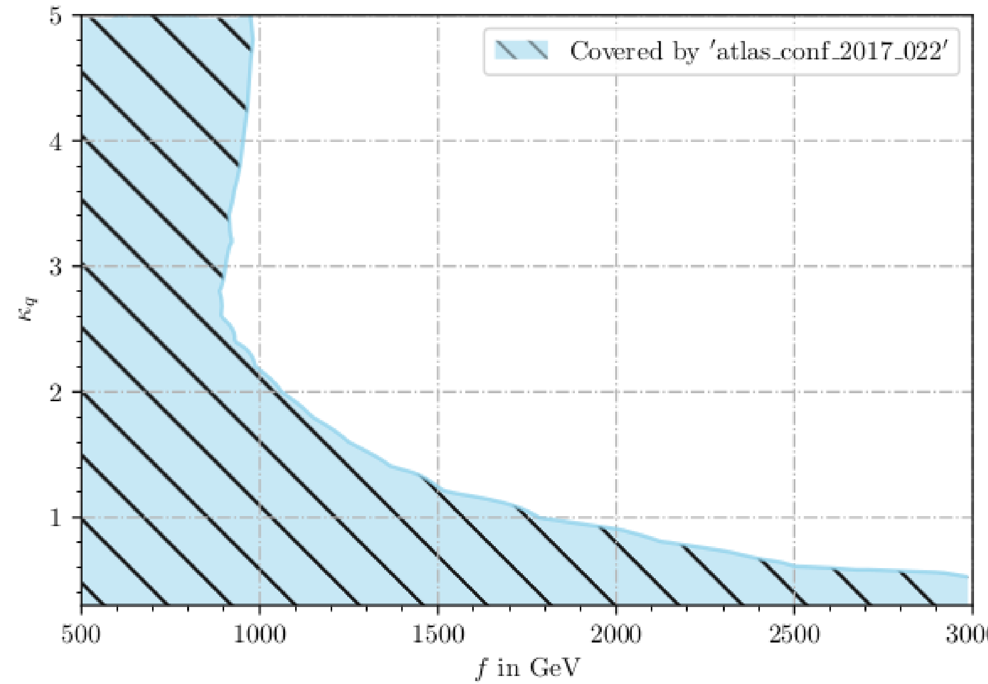


Results of LHC13 Recast

Fermion Universality x Heavy T x T-Parity Conserved

CM identifier	Final State	Designed for	Ref.
atlas_conf_2016_096	$\not{E}_T$ + 2-3 ℓ	$\tilde{\chi}^{\pm}, \tilde{\chi}^0, \tilde{\ell}$	[55]
atlas_conf_2016_054	$\not{E}_T$ + 1 ℓ + (b)-j	$\tilde{q}, \tilde{g}$	[76]
atlas_conf_2017_022	$\not{E}_T$ + 0 ℓ + 2-6 j	$\tilde{q}, \tilde{g}$	[78]
atlas_conf_2017_039	$\not{E}_T$ + 2-3 ℓ	$\tilde{\chi}^{\pm}, \tilde{\chi}^0, \tilde{\ell}$	[56]





Heavy Vector Boson dominated

$m_{V_H} \gtrsim 600$ GeV

$$m_{W_H} = m_{Z_H} = g f, \quad m_{A_H} = \frac{g' f}{\sqrt{5}}$$

Heavy quark dominated

$m_{q_H} \gtrsim 2$ TeV

$$m_{u_H} = \sqrt{2}\kappa_q f\left(1 - \frac{1}{8}\frac{v^2}{f^2}\right),$$
$$m_{d_H} = \sqrt{2}\kappa_q f$$
$$m_{\ell_H} = \sqrt{2}\kappa_l f$$

Results of LHC13 Recast

Fermion Universality x Heavy T x T-Parity Conserved

CM identifier	Final State	Designed for	Ref.
atlas_conf_2016_096	$\not{E}_T$ + 2-3 ℓ	$\tilde{\chi}^{\pm}, \tilde{\chi}^0, \tilde{\ell}$	[55]
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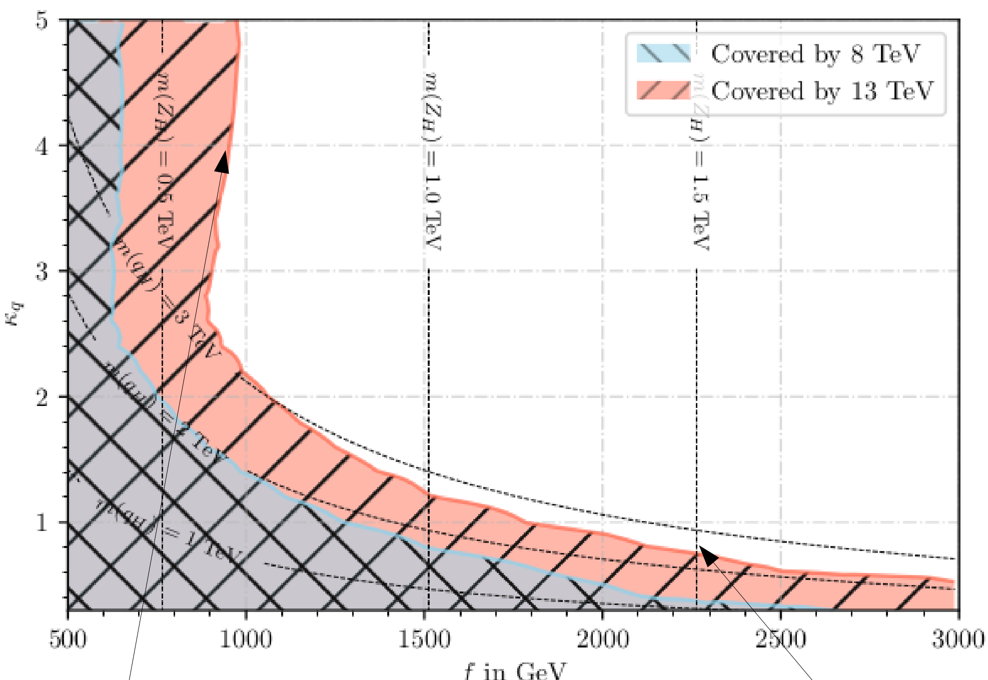

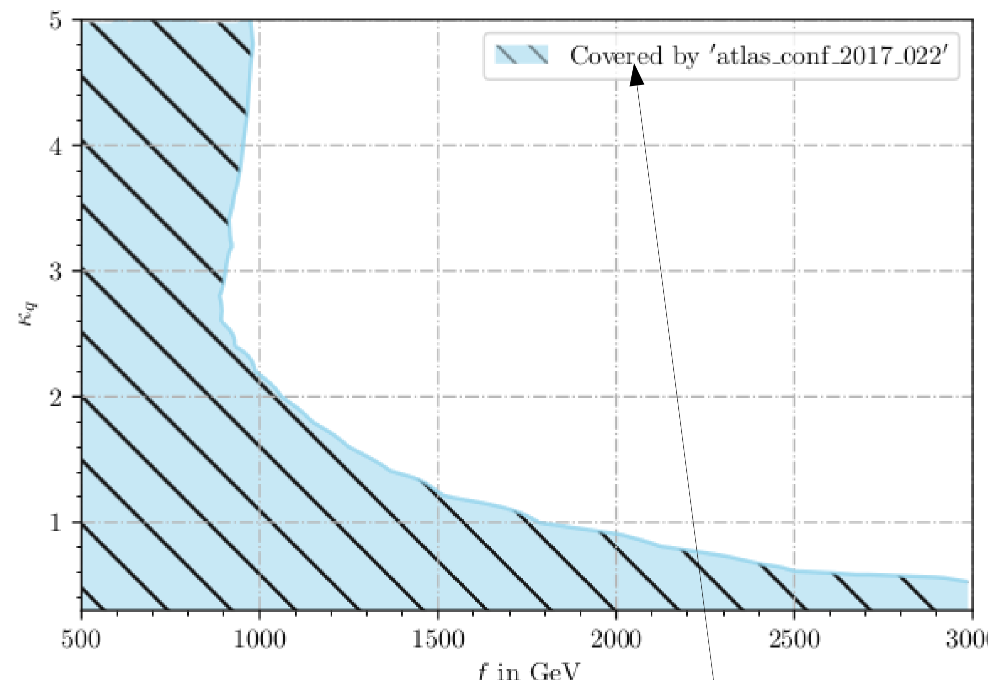

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Heavy quark dominated

$m_{q_H} \gtrsim 2$ TeV

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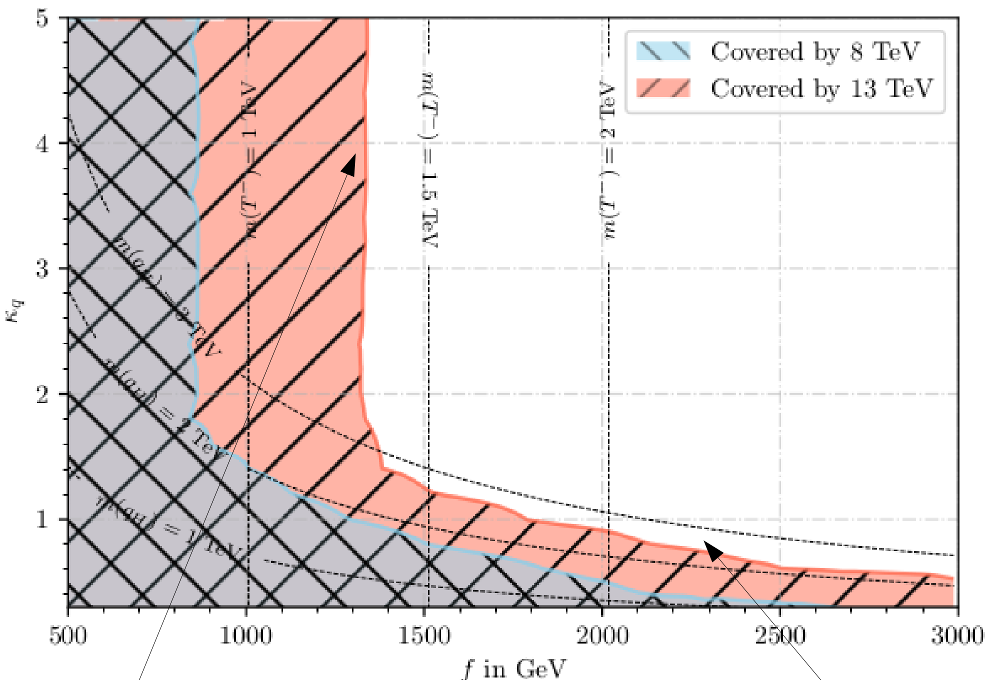
$$m_{d_H} = \sqrt{2}\kappa_q f$$
$$m_{\ell_H} = \sqrt{2}\kappa_l f$$

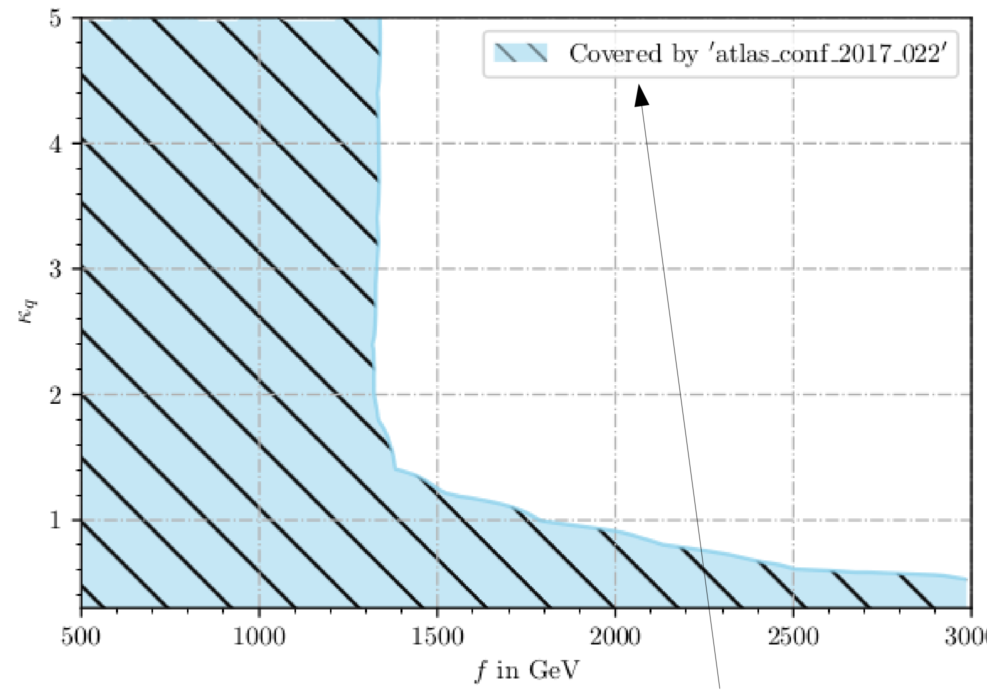
Bound dominated by SUSY multijet search

Results of LHC13 Recast

Fermion Universality x Light T x T-Parity Conserved

CM identifier	Final State	Designed for	Ref.
atlas_conf_2016_096	$\not{E}_T$ + 2-3 ℓ	$\tilde{\chi}^{\pm}, \tilde{\chi}^0, \tilde{\ell}$	[55]
atlas_conf_2016_054	$\not{E}_T$ + 1 ℓ + (b)-j	$\tilde{q}, \tilde{g}$	[76]
atlas_conf_2017_022	$\not{E}_T$ + 0 ℓ + 2-6 j	$\tilde{q}, \tilde{g}$	[78]
atlas_conf_2017_039	$\not{E}_T$ + 2-3 ℓ	$\tilde{\chi}^{\pm}, \tilde{\chi}^0, \tilde{\ell}$	[56]





Heavy Top partner dominated
$m_{T^-} \gtrsim 1.3$ TeV

Heavy Fermion dominated
$m_{q_H} \gtrsim 2$ TeV

Bound still dominated by SUSY multijet search
(Most recent SUSY stop search wasn't impl. yet)

Results of LHC13 Recast

Heavy q_H x Light T x T-Parity Conserved

CM identifier	Final State	Designed for	Ref.
atlas_conf_2016_096	$\not{E}_T$ + 2-3 ℓ	$\tilde{\chi}^{\pm}, \tilde{\chi}^0, \tilde{\ell}$	[55]
atlas_conf_2016_054	$\not{E}_T$ + 1 ℓ + (b)-j	$\tilde{q}, \tilde{g}$	[76]
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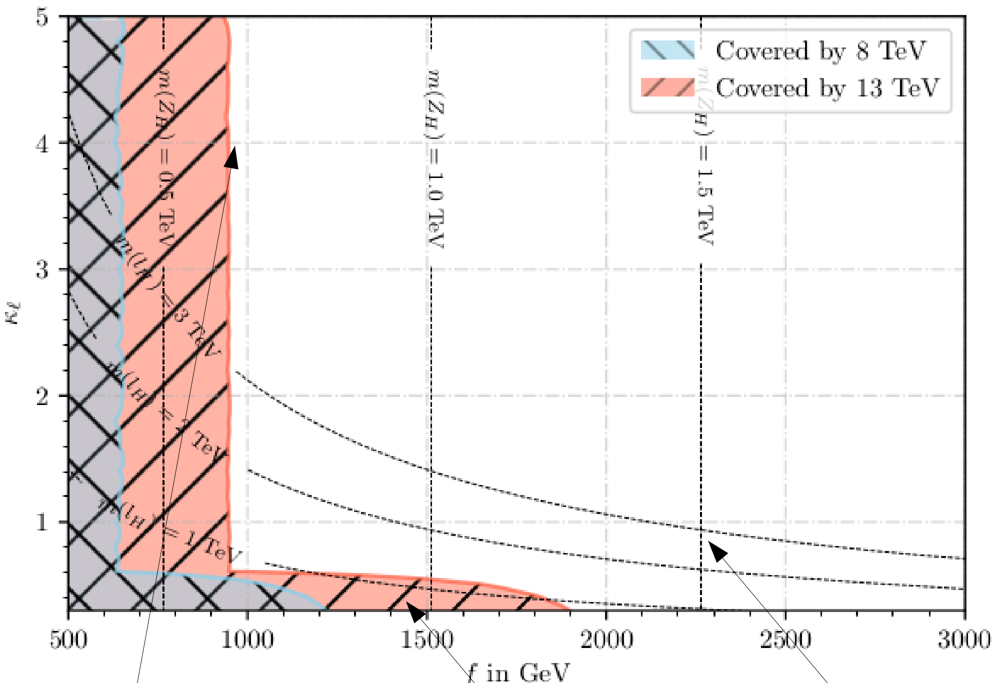

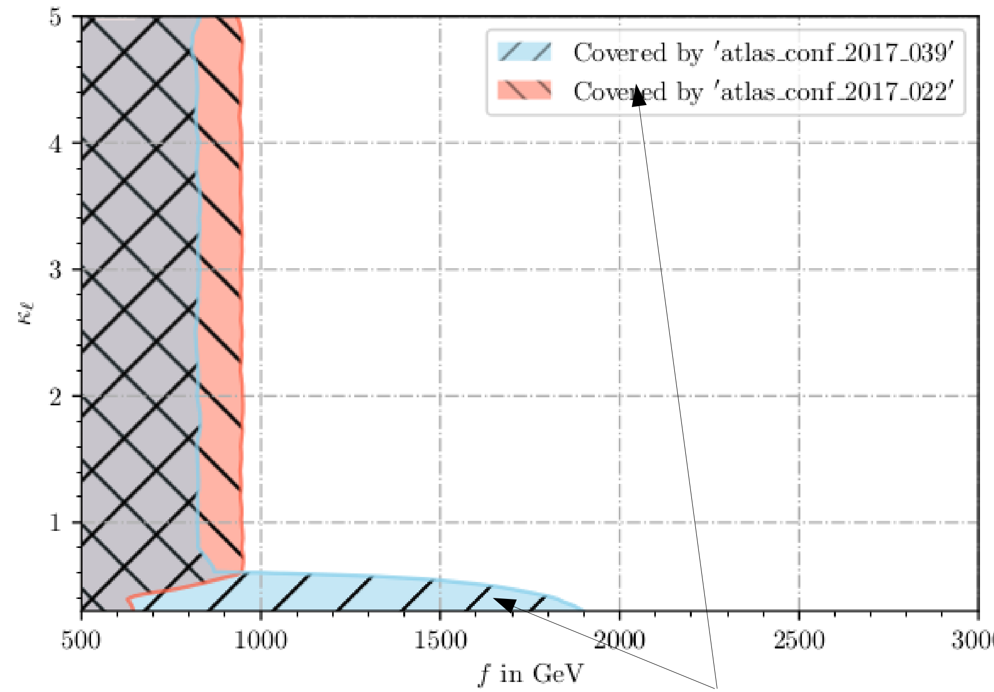

Pure gauge boson bound

$V_H \to \ell_H \ell$ opens

Heavy Fermion bound disappears

Multilepton analysis relevant for small kappa

Results of LHC13 Recast

Light l_H x Light T x T-Parity Conserved

CM identifier	Final State	Designed for	Ref.
atlas_conf_2016_096	$\not{E}_T$ + 2-3 ℓ	$\tilde{\chi}^{\pm}, \tilde{\chi}^0, \tilde{\ell}$	[55]
atlas_conf_2016_054	$\not{E}_T$ + 1 ℓ + (b)-j	$\tilde{q}, \tilde{g}$	[76]
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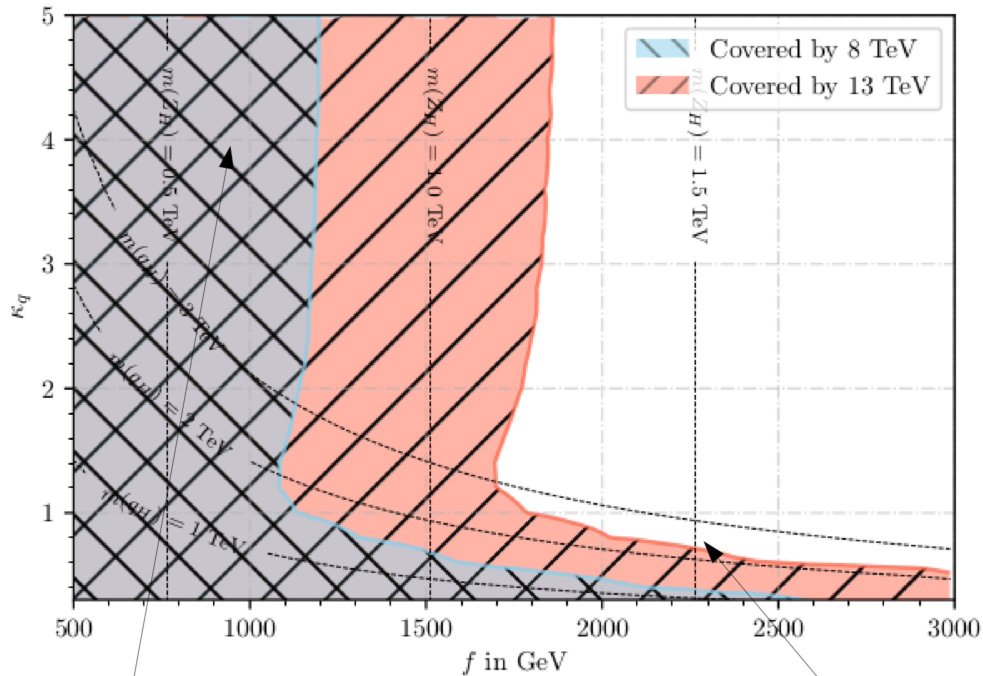
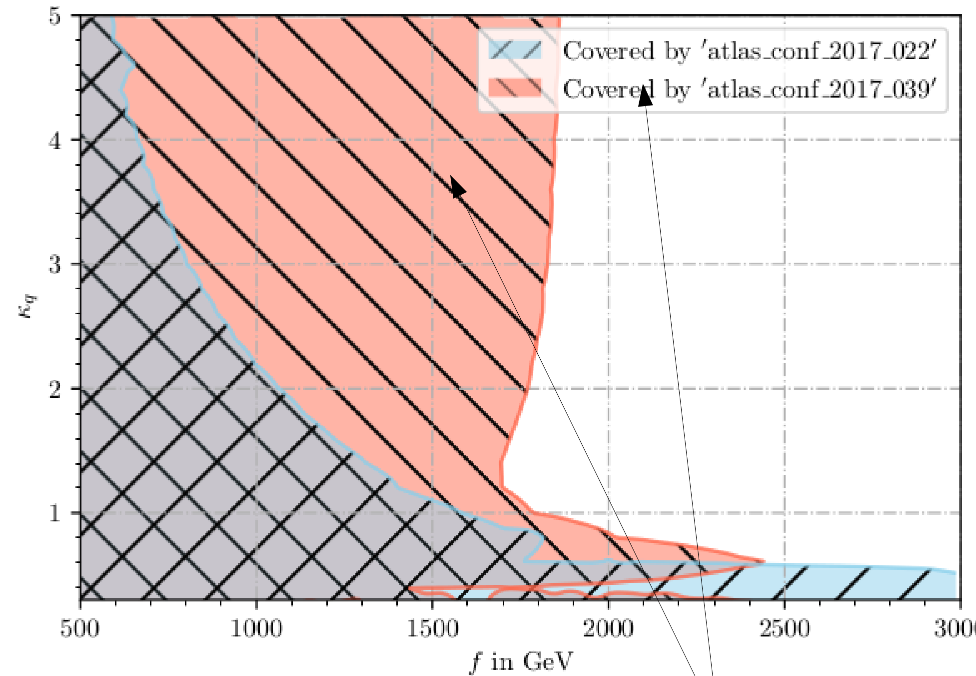




Gauge boson dominated $m_{V_H} \gtrsim 1.2$ TeV

$V_H \to \ell_H \ell$ open everywhere

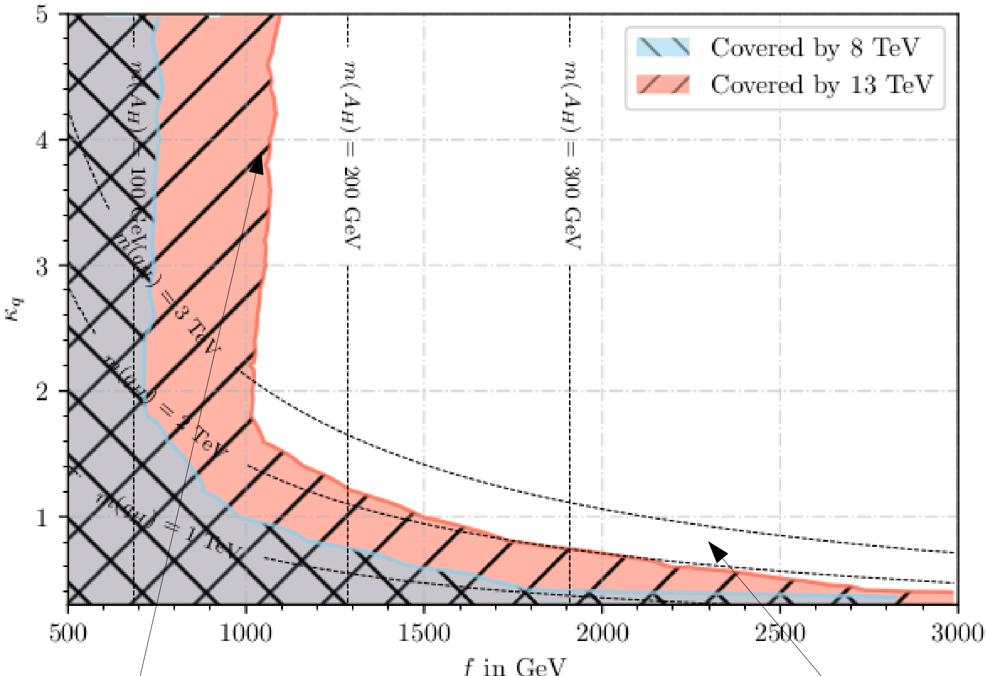
Heavy Quark dominated $m_{q_H} \gtrsim 2$ TeV

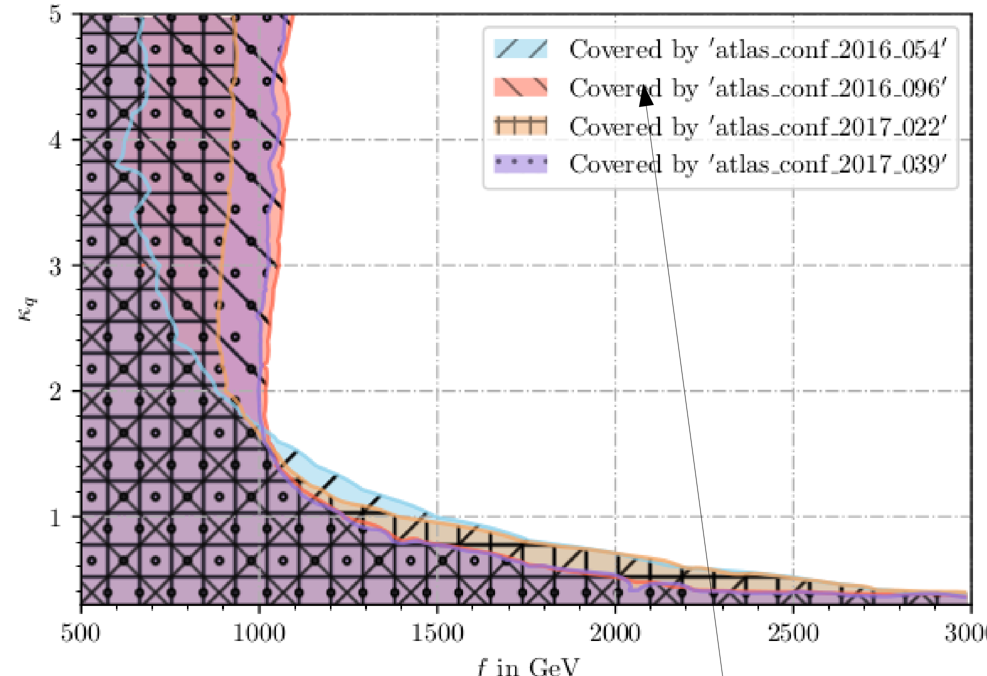
Multilepton analysis relevant everywhere

Results of LHC13 Recast

Fermion Universality x Heavy T x T-Parity Violated

CM identifier	Final State	Designed for	Ref.
atlas_conf_2016_096	$\not{E}_T$ + 2-3 ℓ	$\tilde{\chi}^{\pm}, \tilde{\chi}^0, \tilde{\ell}$	[55]
atlas_conf_2016_054	$\not{E}_T$ + 1 ℓ + (b)-j	$\tilde{q}, \tilde{g}$	[76]
atlas_conf_2017_022	$\not{E}_T$ + 0 ℓ + 2-6 j	$\tilde{q}, \tilde{g}$	[78]
atlas_conf_2017_039	$\not{E}_T$ + 2-3 ℓ	$\tilde{\chi}^{\pm}, \tilde{\chi}^0, \tilde{\ell}$	[56]

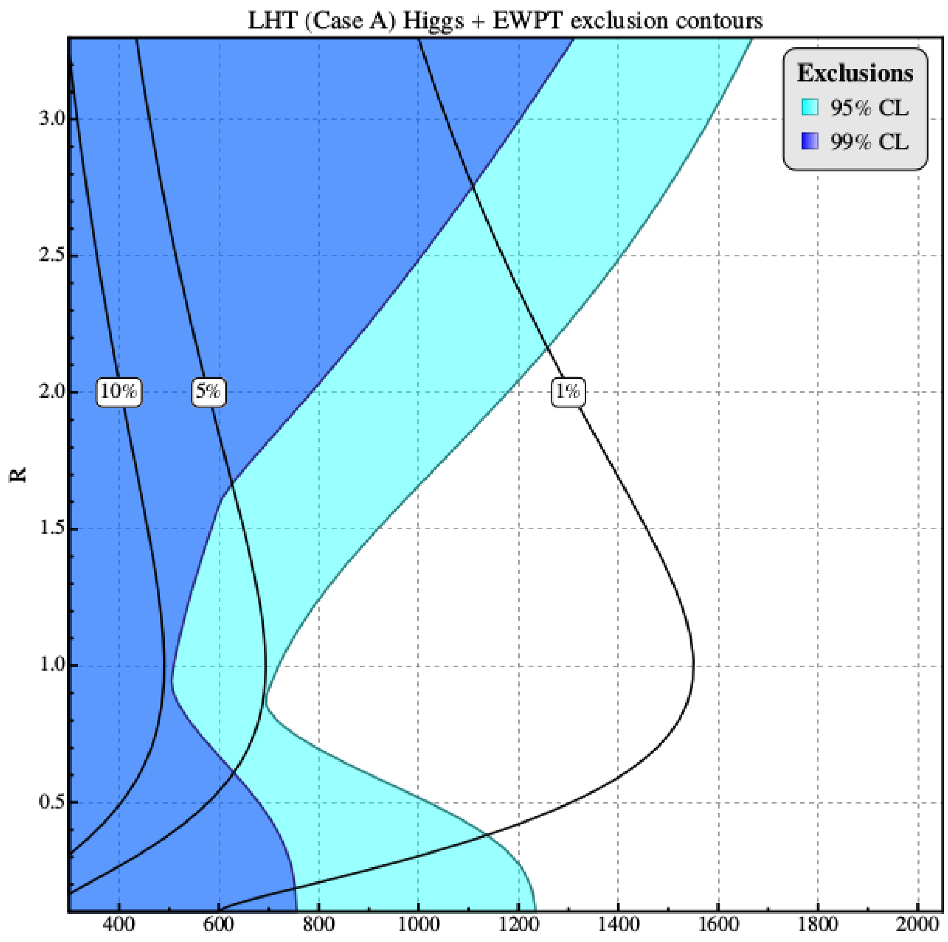




Bound hardly affected

Multiple topologies appearing due to many possibilities in $A_H \to VVVV$

Combine with EWPO + Higgs



Here: R-vs-f favours R=1 to achieve cancellation effects of heavy top and SM top sector

Kappa-dependence not shown

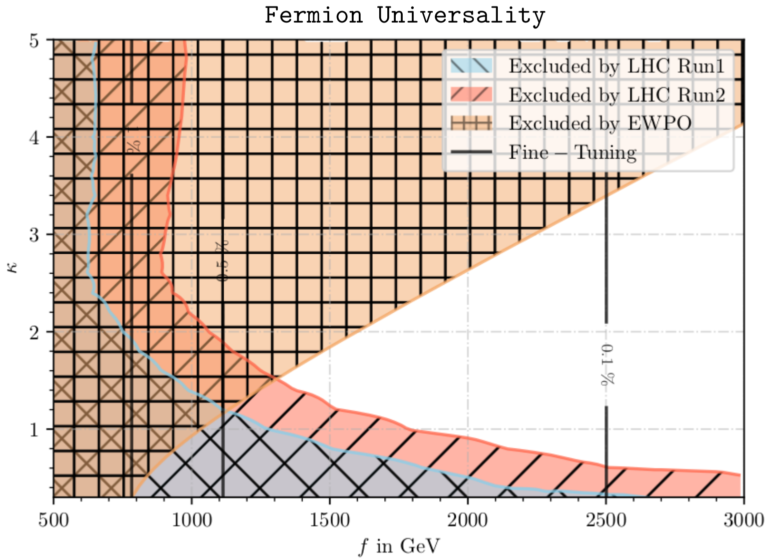
Interestingly, heavy fermions contributions (box diagrams) do not decouple at high mass values!

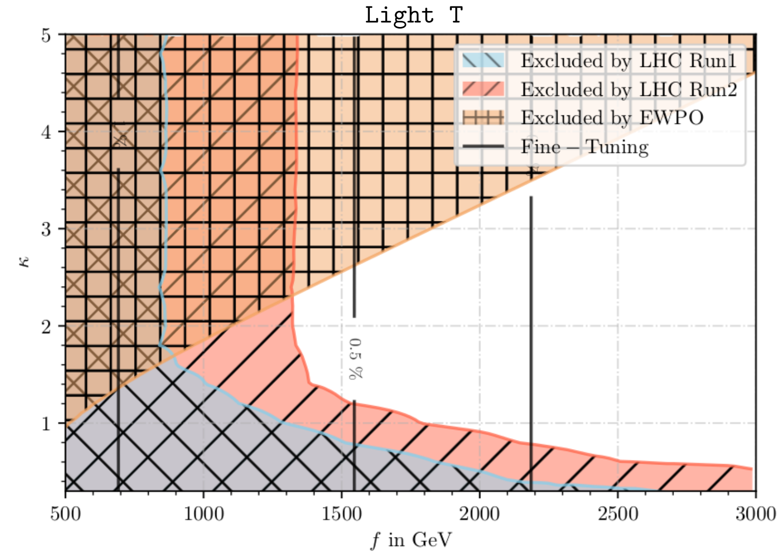
$$\Delta T_{q_H,\ell_H} = -\sum_{q_H,l_H} \frac{\kappa_{q,\ell}^2}{192\pi^2\alpha_w}\frac{v^2}{f^2}$$

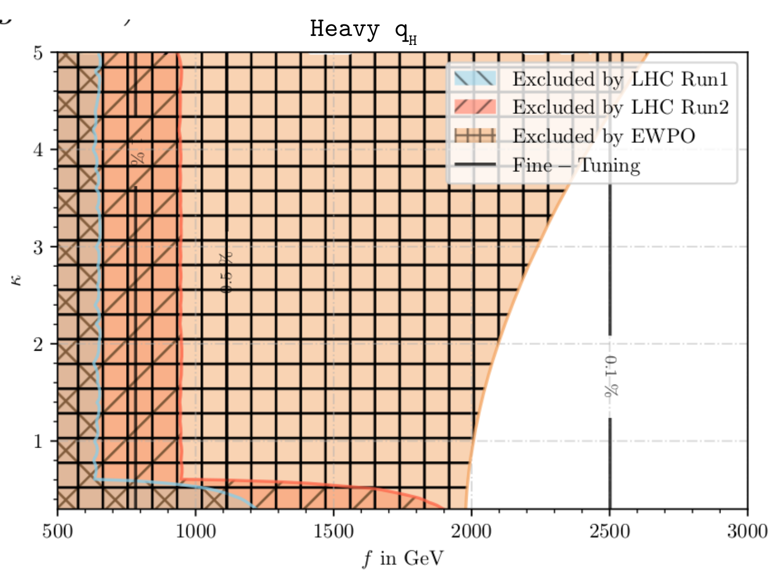
$$= -\sum_{q_H,l_H} \frac{m_{q_H,\ell_H}^2}{192\pi^2\alpha_w}\frac{v^2}{f^4}$$

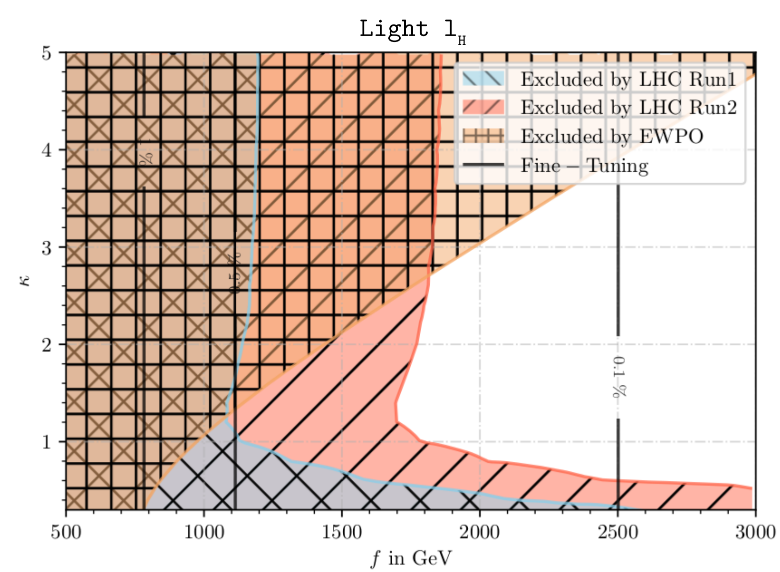
Strong complementarity to LHC expected!

Combined Results

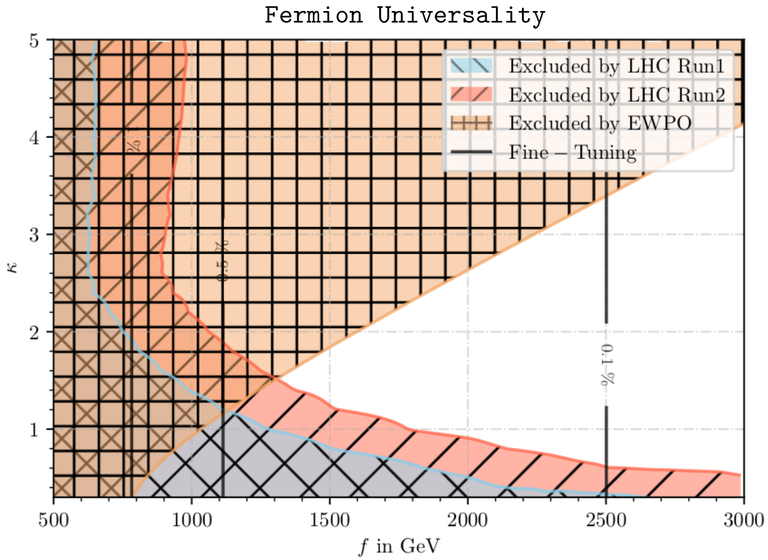








Combined Results



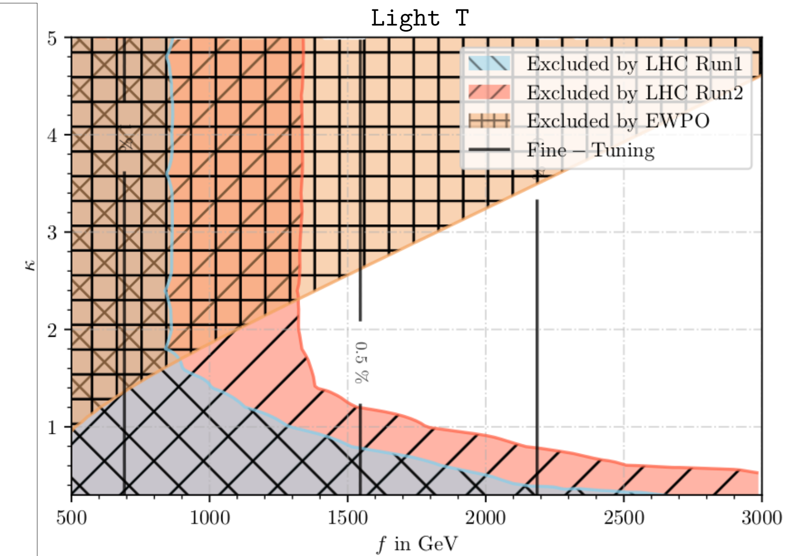
Individual results highly dependent on details in heavy fermion/heavy top sector!

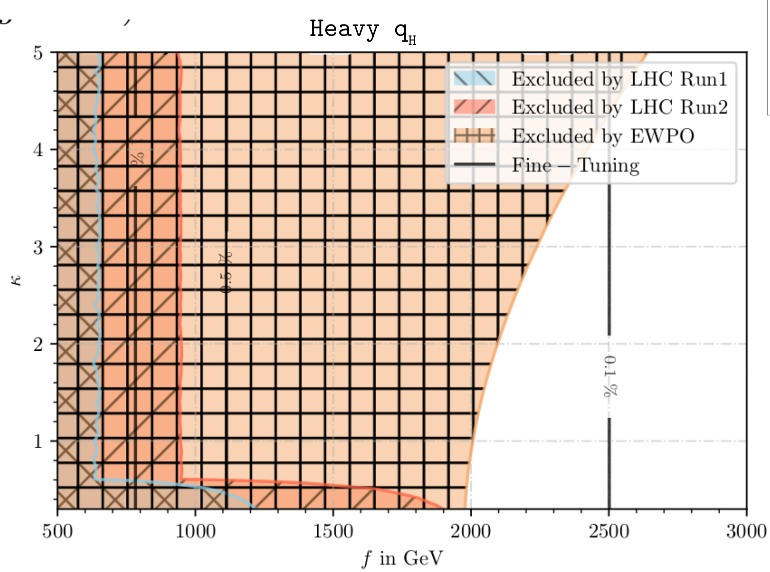
LHC: $f \gtrsim 950$ GeV

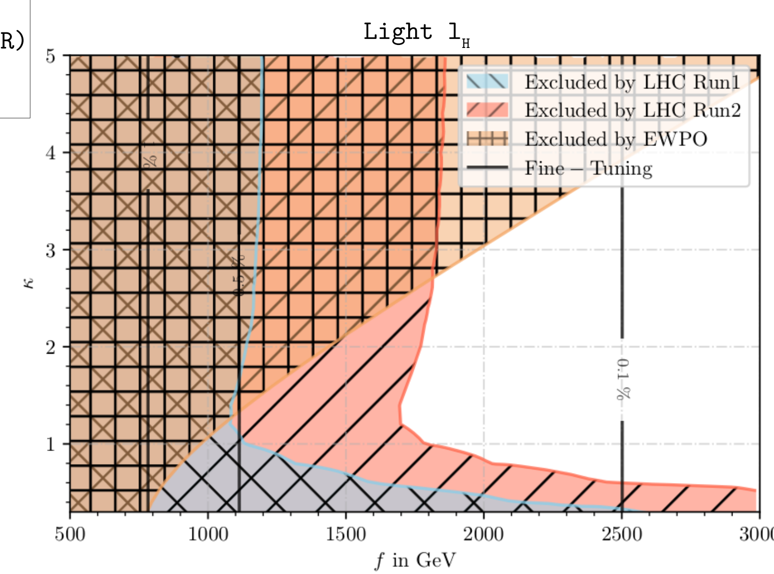
(better for small kappa and/or small

EWPO+H: $f \gtrsim 700$ GeV

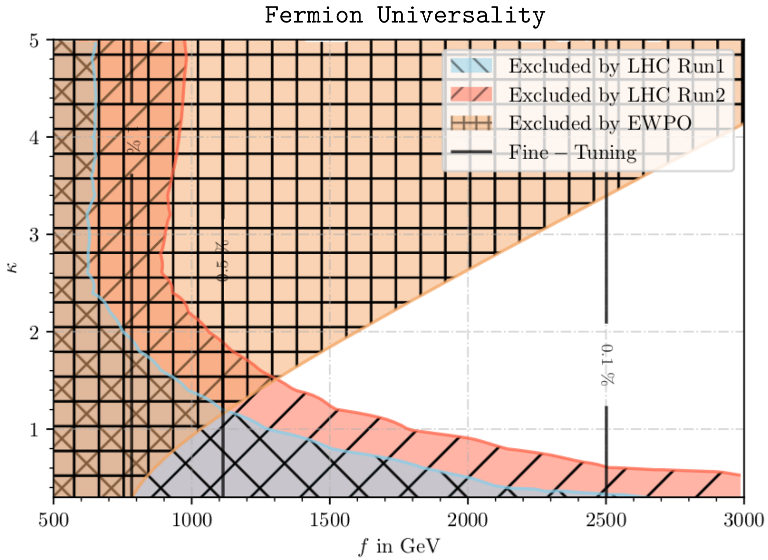
(better for large kappa and/or large R)







Combined Results



Individual results highly dependent on details in heavy fermion/heavy top sector!

LHC: $f \gtrsim 950$ GeV

(better for small kappa and/or small

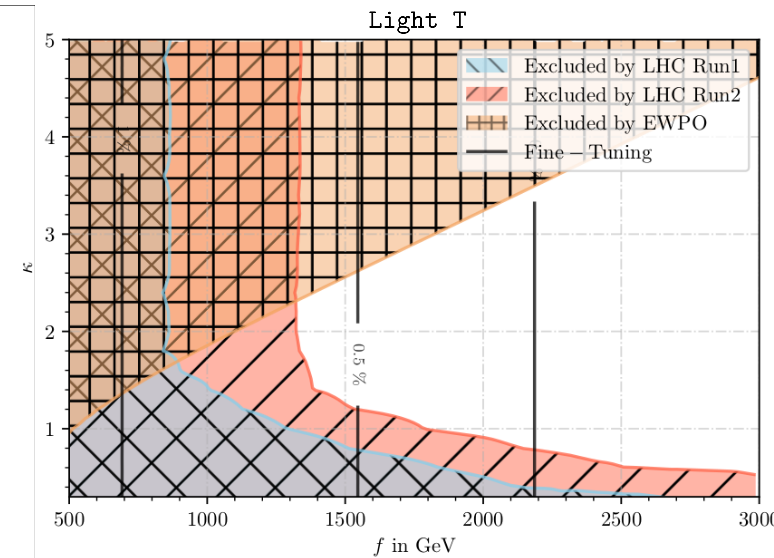
EWPO+H: $f \gtrsim 700$ GeV

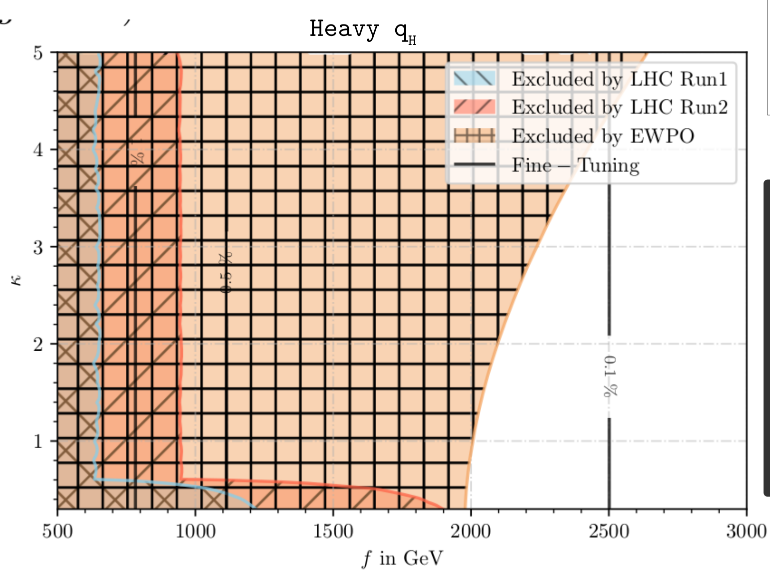
(better for large kappa and/or large R)

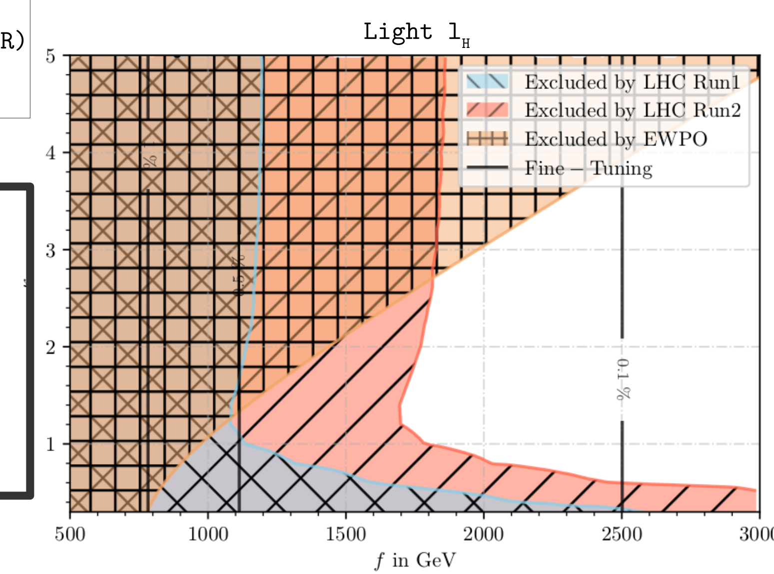
Comb. $f \gtrsim 1.300$ GeV

(Largely independent of kappa and R)

Fine-Tuning pushed to sub-percent level!







Conclusions

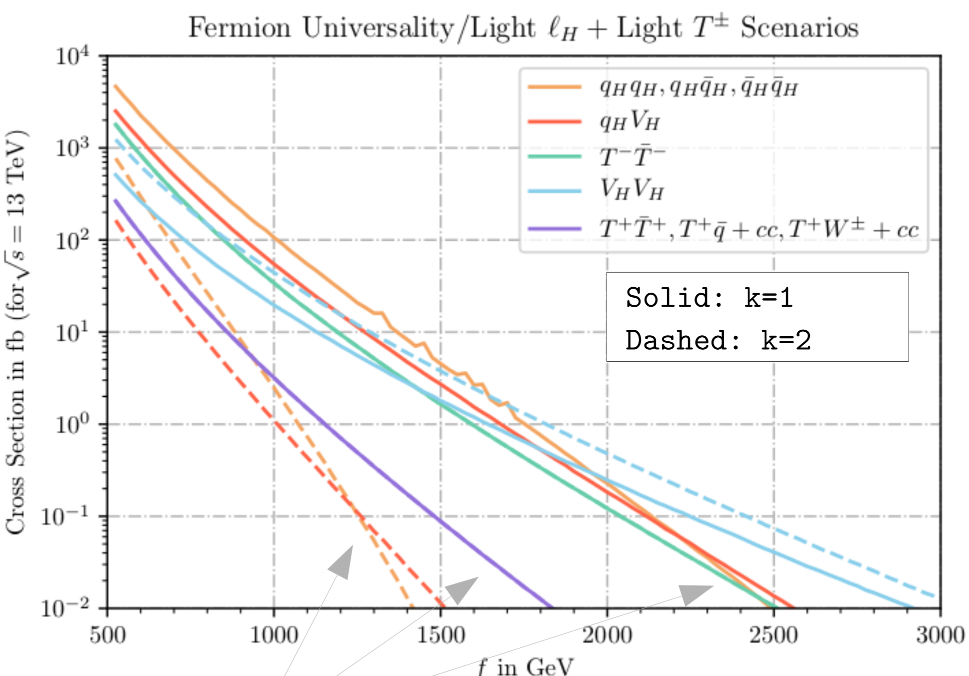
- Little Higgs theories provide interesting solution to hierarchy problem and predict global symmetry broken at scale f.
- Littlest Higgs + T-Parity weakly constrained by EWPO + Higgs constraints
- Collider phenomenology shares many similarities with Supersymmetry
- Bounds on parameters strongly dependent on details of heavy fermion and heavy top sector but complementary to EWPO + Higgs
- Combination yields "model-independent" bound of $f > 1.3$ TeV and requires sub-percent fine-tuning, hence weakening the motivation for the Littlest Higgs as a solution to the hierarchy problem

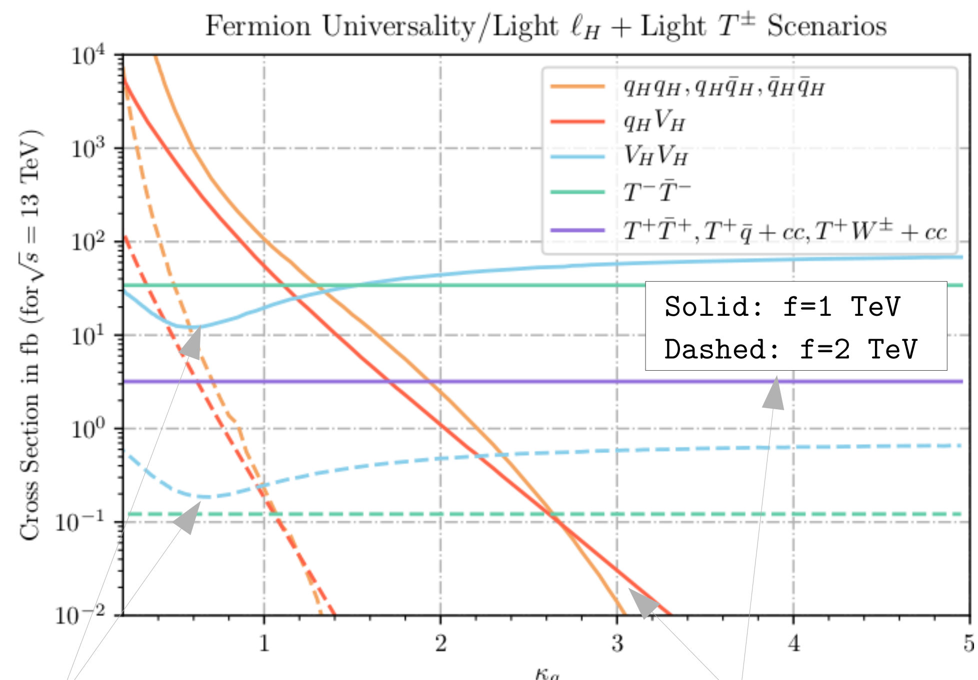
LHC Run2 Production Cross Sections

$$m_{W_H} = m_{Z_H} = g f,$$
$$m_{A_H} = \frac{g' f}{\sqrt{5}}$$

$$m_{u_H} = \sqrt{2}\,\kappa_q f \left(1 - \frac{1}{8}\frac{v^2}{f^2}\right),$$
$$m_{d_H} = \sqrt{2}\,\kappa_q f$$
$$m_{\ell_H} = \sqrt{2}\,\kappa_l f$$

$$m_{T^-} = \frac{m_{t_+}}{v}\frac{f\sqrt{1+R^2}}{R}$$
$$m_{T^+} = \frac{m_{t_+}}{v}\frac{f(1+R^2)}{R} = m_{T_-}\sqrt{1+R^2}$$





All masses increase with f
→ cross sections decrease

Destructive interference from t-channel q_H

Only heavy fermion masses depend on k

LHC Run2 Production Cross Sections

$$m_{W_H} = m_{Z_H} = g f,$$
$$m_{A_H} = \frac{g' f}{\sqrt{5}}$$

$$m_{u_H} = \sqrt{2}\,\kappa_q f \left(1 - \frac{1}{8}\frac{v^2}{f^2}\right),$$
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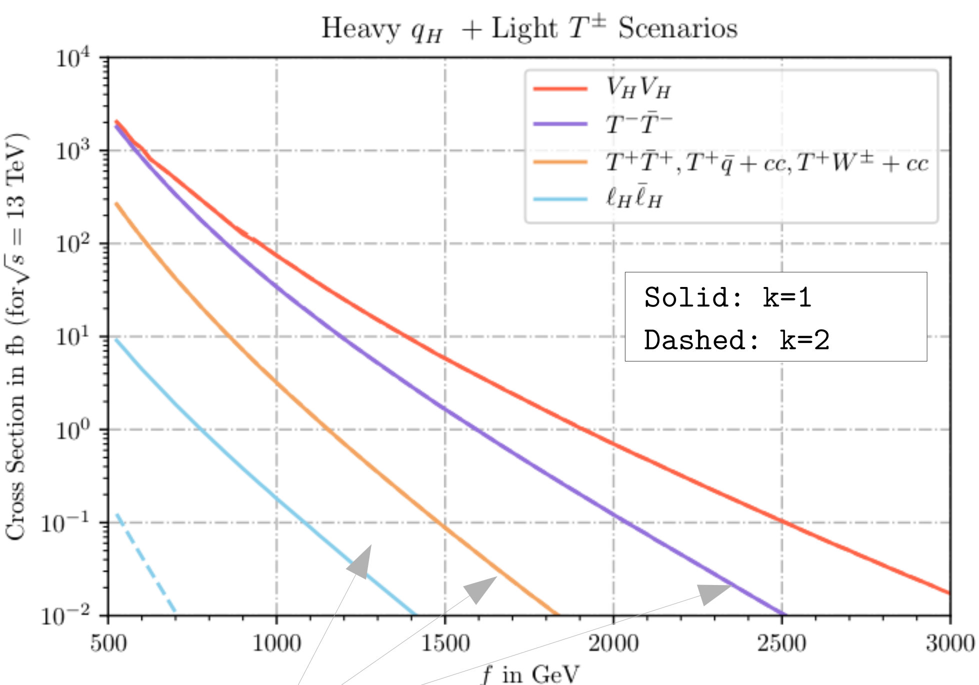

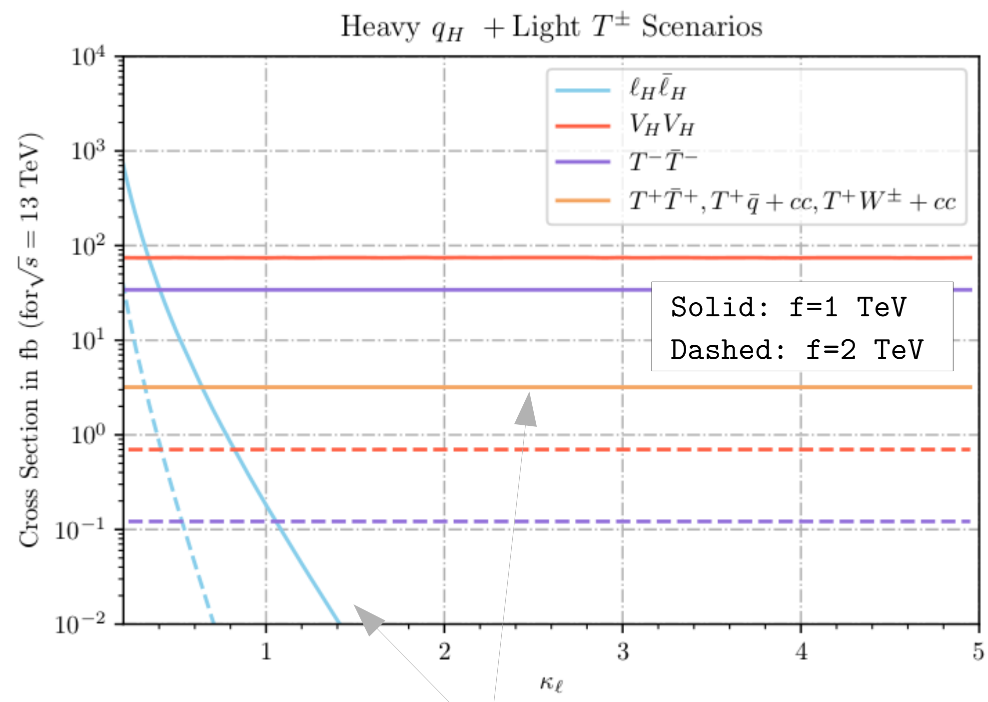

Heavy lepton production
Almost negligible

Only heavy fermion
masses depend on k

Relevant Decays

$$m_{W_H} = m_{Z_H} = g f,$$
$$m_{A_H} = \frac{g' f}{\sqrt{5}}$$

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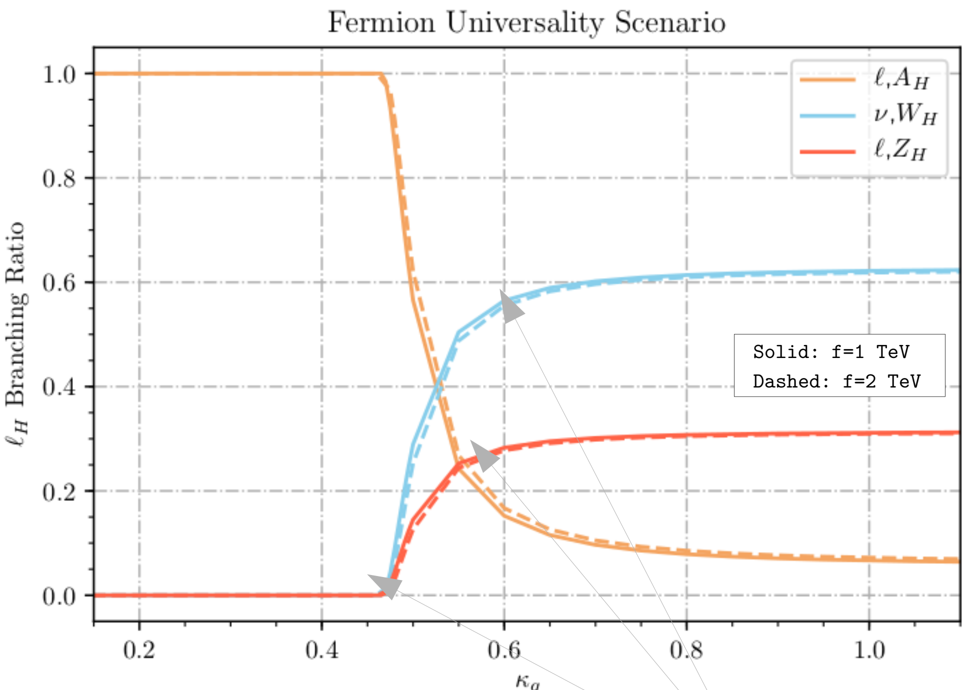
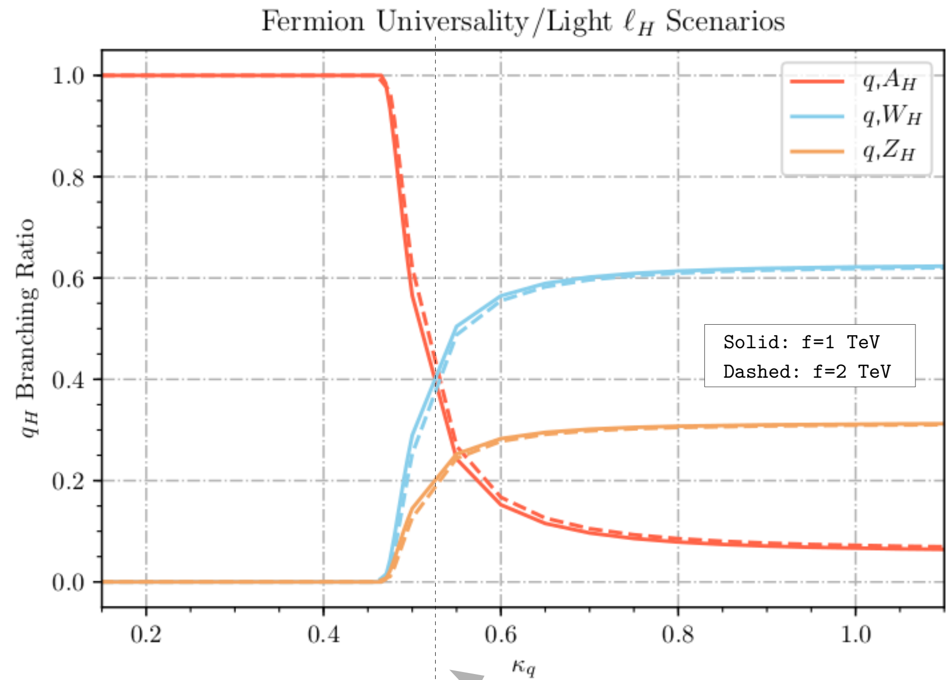
$$= m_{T^-}\sqrt{1+R^2}$$





Heavy fermion branching ratios nearly constant, except for very small kappa

$m_{q_H} < m_{V_H}$

Relevant Decays

$$m_{W_H} = m_{Z_H} = g f,$$
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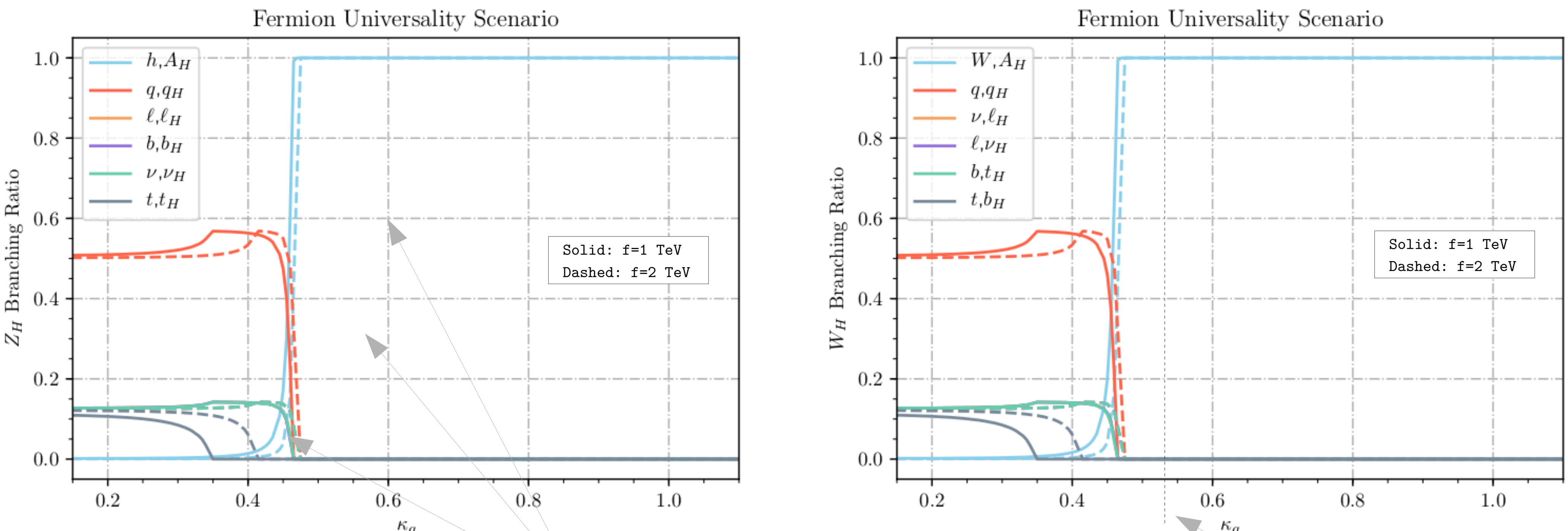

Heavy quark branching ratios nearly fixed, except for very small kappa (similar for l_H)

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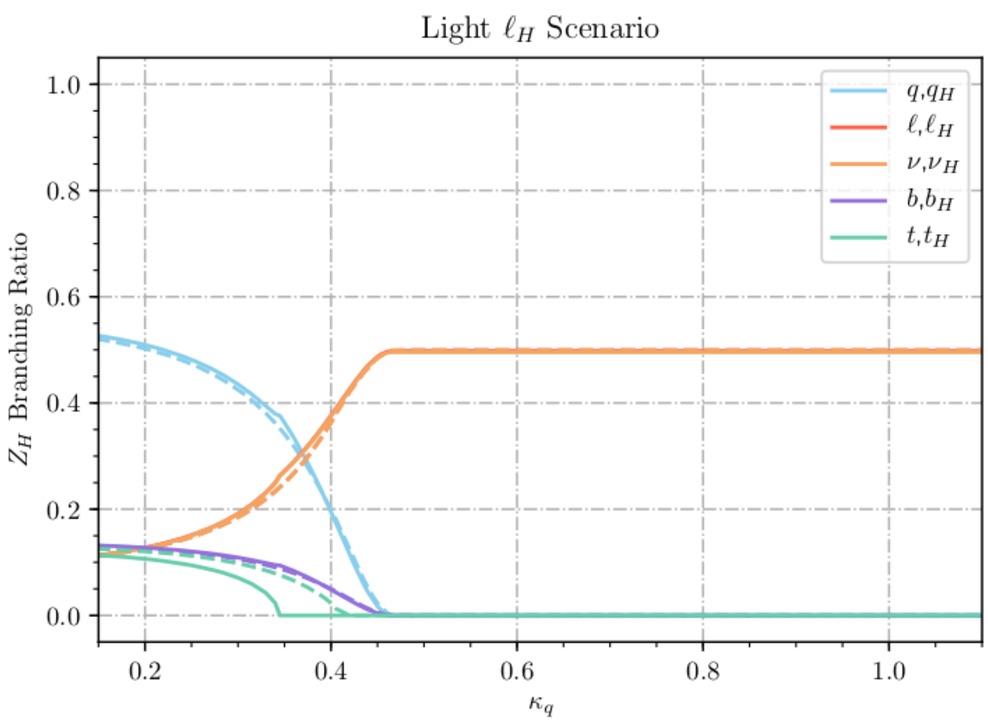

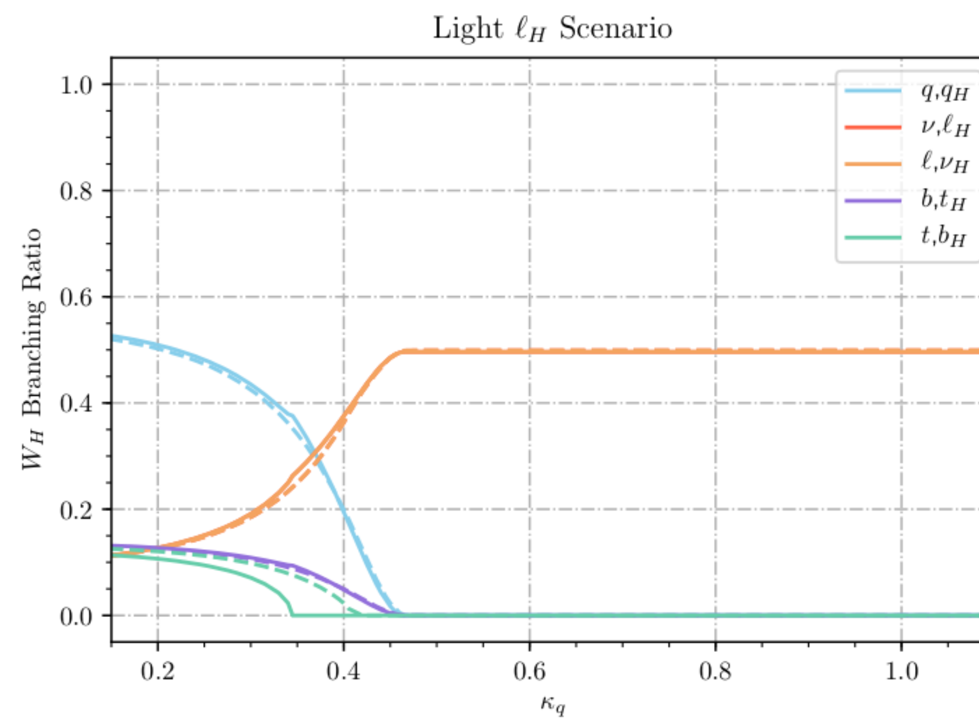

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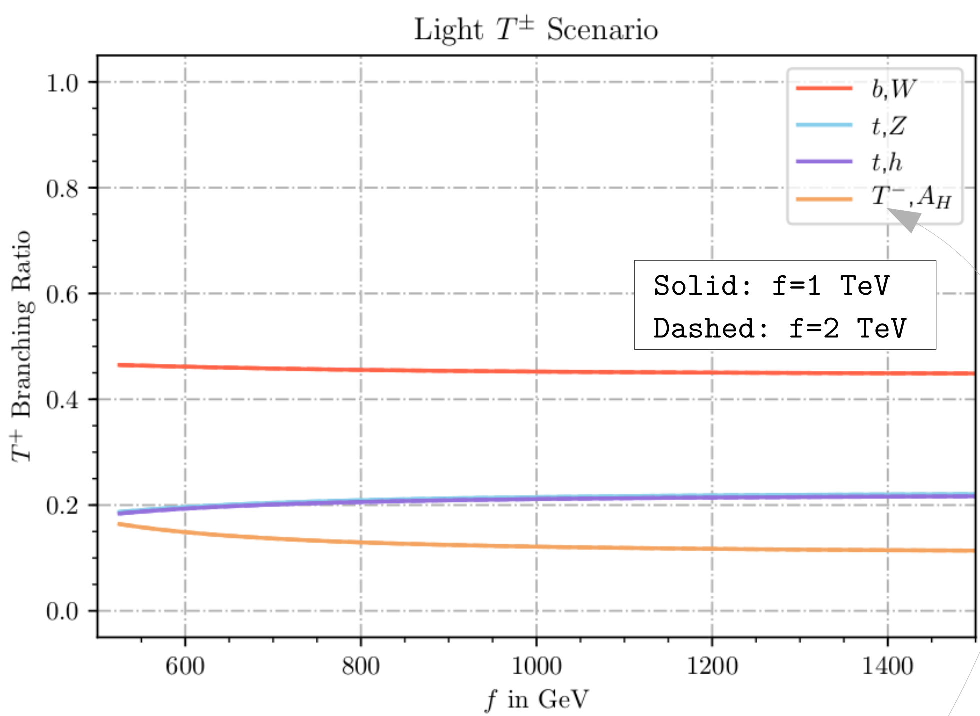

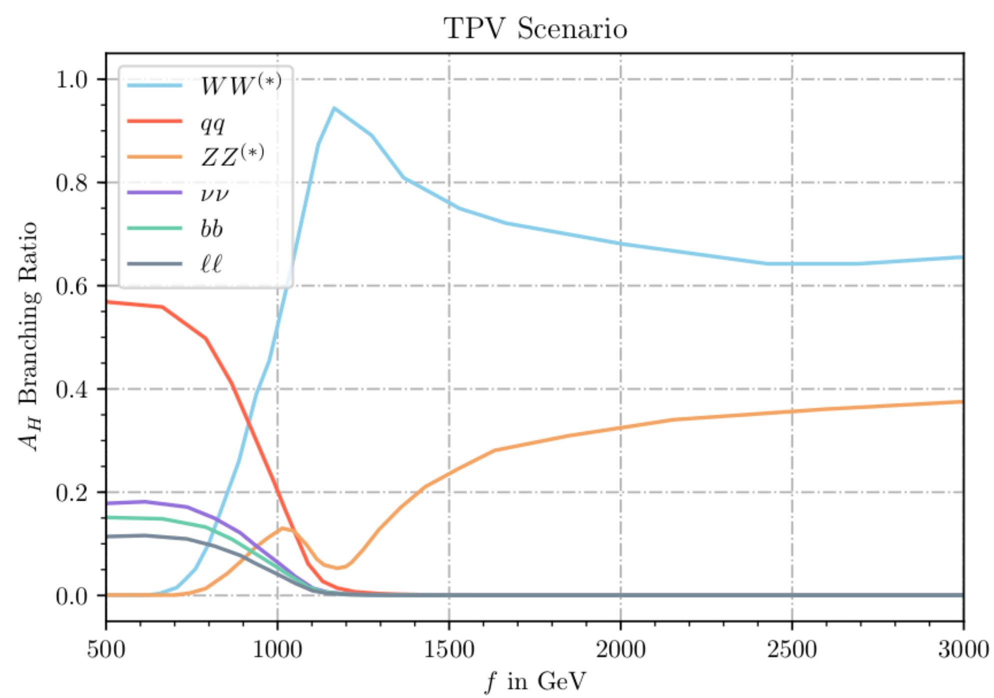

T^- always decays into A_H + top

T^+ may decay into SM particles