Theory Perspective on Particle Searches at the LHC

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DPF2019, Boston July 31st, 2019

Where do we stand:

Just a few years ago…

SUSY right around the corner! **New W', Z', multiple Higgses!**

Very non-standard Higgs, or even no Higgs!

Dark Matter @ LHC, extra dimensions!

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2019

ATLAS Preliminary

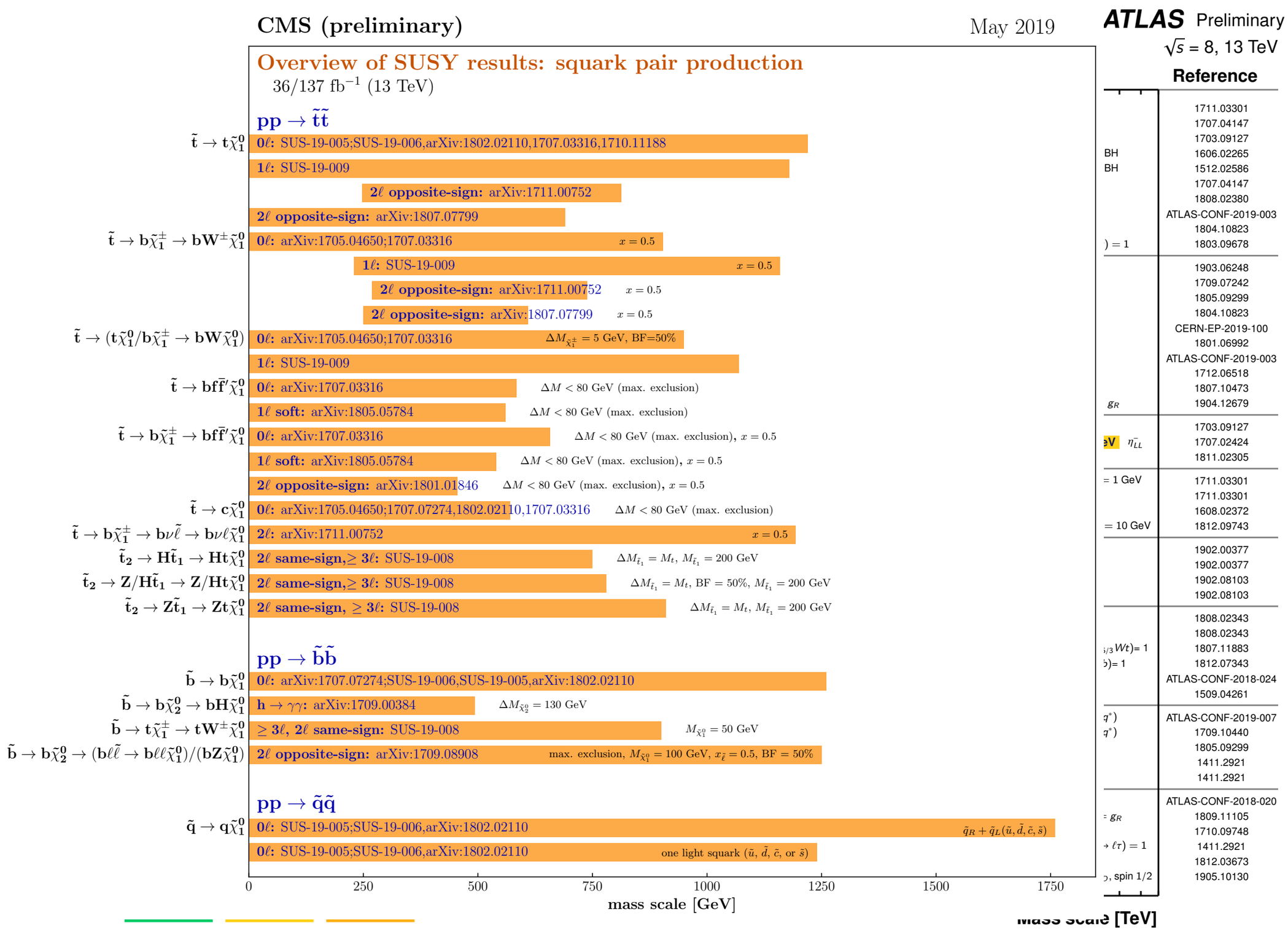
$\int \mathcal{L}\, dt = (3.2 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu$	$1-4$ j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2\ \gamma$	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qqqq$	$0\ e, \mu$	2 J	–	139	G_{KK} mass 1.6 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2019-003
	Bulk RS $g_{KK} \rightarrow tt$	$1\ e, \mu$	≥ 1 b, $\geq$ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2\ e, \mu$	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \rightarrow \tau\tau$	$2\ \tau$	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \rightarrow bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \rightarrow tt$	$1\ e, \mu$	≥ 1 b, $\geq$ 1J/2j	Yes	36.1	Z' mass 3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \rightarrow \ell\nu$	$1\ e, \mu$	–	Yes	139	W' mass 6.0 TeV		CERN-EP-2019-100
	SSM $W' \rightarrow \tau\nu$	$1\ \tau$	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $V' \rightarrow WZ \rightarrow qqqq$ model B	$0\ e, \mu$	2 J	–	139	V' mass 3.6 TeV	$g_V = 3$	ATLAS-CONF-2019-003
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W_R \rightarrow tb$	multi-channel			36.1	W_R mass 3.25 TeV		1807.10473
	LRSM $W_R \rightarrow \mu N_R$	$2\ \mu$	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	36.1	Λ 40.0 TeV	η_{LL}^-	1707.02424
	CI $tttt$	$\geq 1\ e, \mu$	≥ 1 b, ≥ 1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t} \rvert = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \rightarrow t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ 3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass 1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3rd gen	$2\ \tau$	2 b	–	36.1	LQ_3^u mass 1.03 TeV	$\mathcal{B}(LQ_3^u \rightarrow b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass 970 GeV	$\mathcal{B}(LQ_3^d \rightarrow t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \rightarrow Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3} \mid T_{5/3} \rightarrow Wt + X$	2(SS)/$\geq$3 e, μ	≥ 1 b, ≥ 1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \rightarrow Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \rightarrow Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 1j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \rightarrow Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \rightarrow Hb + X$	$0\ e, \mu, 2\ \gamma$	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \rightarrow WqWq$	$1\ e, \mu$	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \rightarrow qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2019-007
	Excited quark $q^* \rightarrow q\gamma$	$1\ \gamma$	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \rightarrow bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	$1\ e, \mu$	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	$2\ \mu$	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass 1.22 TeV	DY production, $\lvert q \rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g \rvert = 1g_D$, spin 1/2	1905.10130

$\sqrt{s}$ = 8 TeV | $\sqrt{s}$ = 13 TeV partial data | $\sqrt{s}$ = 13 TeV full data

10^{-1} 1 10 **Mass scale [TeV]**

Remarkable success of SM, through an incredible variety of tests/searches



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~~Dark Matter @ LHC, extra dimensions!~~

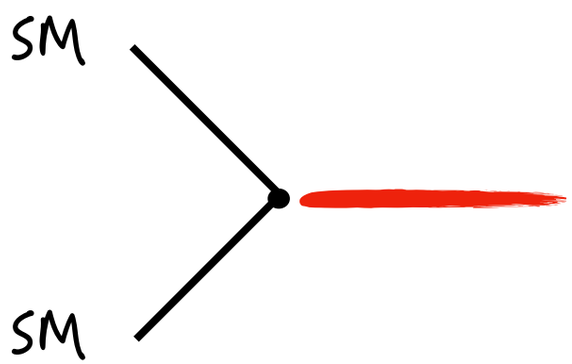
Still possible that one of these scenarios is lying just out of reach & will be dug up with more data. However, mass limits will increase very slowly in next phase of LHC

- **LHC as a precision machine, look for indirect effects of new physics**
- **leave no stone unturned**

Go heavy: Effective Field Theory (EFT) Approach

New physics may be too heavy to make on-shell at the LHC

instead, look for its indirect effects on SM processes



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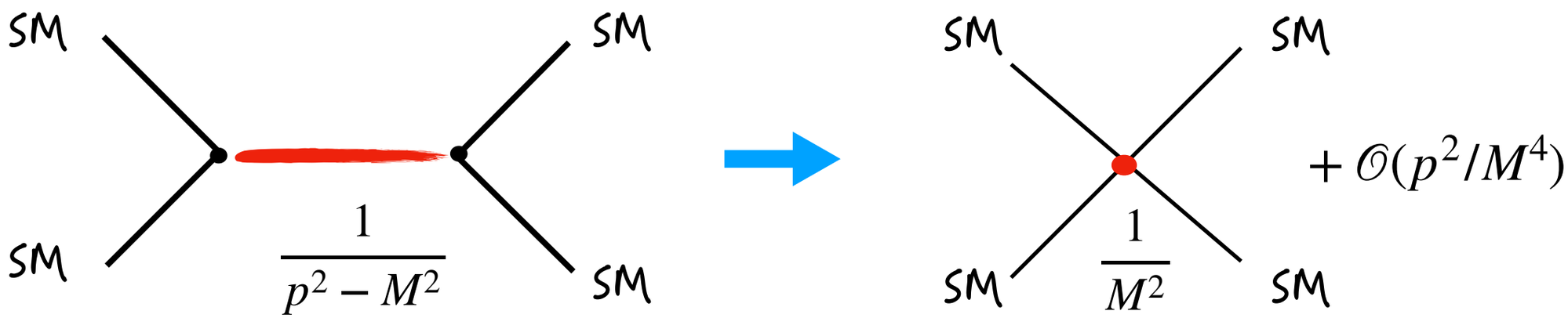

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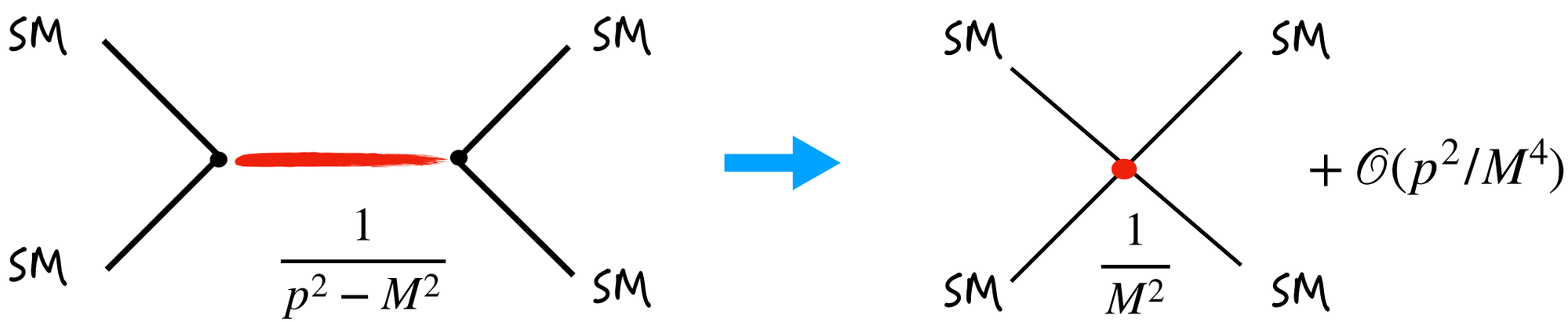

Effective vertices with only SM particles, expansion in derivatives = SMEFT

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i^{d=6} + \sum \frac{c_i}{\Lambda^4} \mathcal{O}_i^{d=8} + \ldots$$

BSM **SM particles**

Program: study SM final states, look for deviations. Clean processes usually the most sensitive: $h \to \gamma\gamma, pp \to 4\ell$, dibosons…

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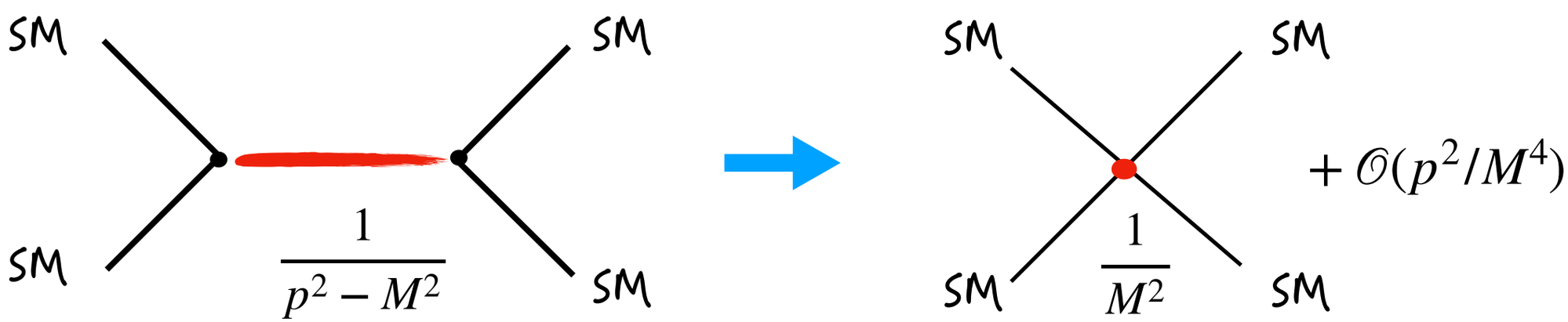


Including SMEFT terms:

$$|A|^2 = |A_{SM}|^2 + \frac{2\,E^2}{\Lambda^2} Re(A_{SM}^* A_6) + \frac{E^4}{\Lambda^4}|A_6|^2 + \frac{2\,E^4}{\Lambda^4} Re(A_{SM}^* A_8) \cdots$$

interference piece

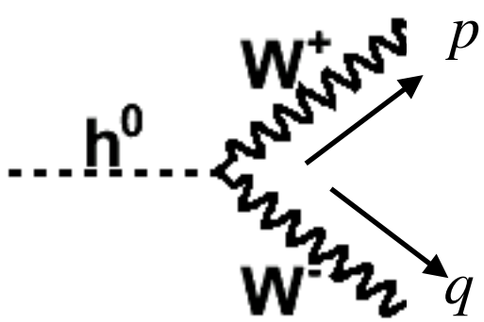
(new physics)^2

Go heavy: SMEFT

(* also CP structure)

Higher dimensional operators can have different Lorentz/derivative structure than SM!

ex.) $L_{EFT} \supset \frac{g_2^2\, c_{HW}}{\Lambda^2} H^\dagger H\, W^a_{\mu\nu} W^{a,\mu\nu} + \frac{c_{H\Box}}{\Lambda^2} H^\dagger H \Box (H^\dagger H)$

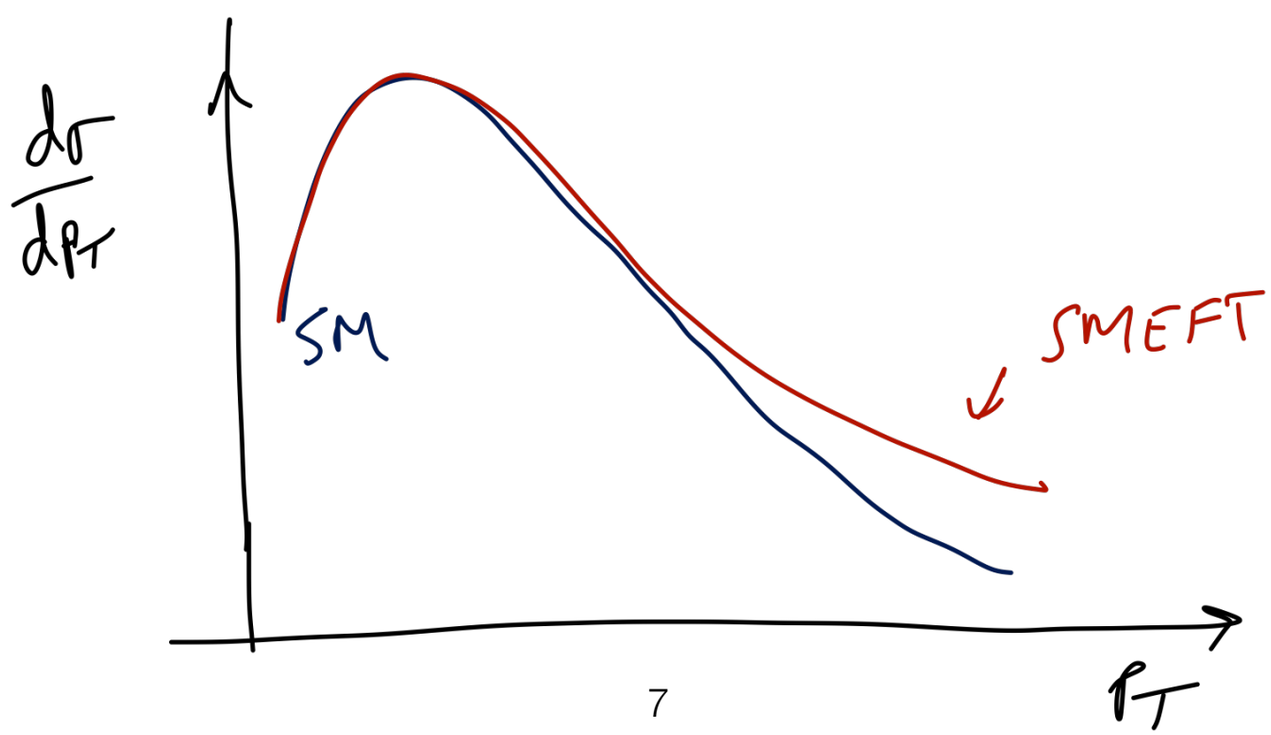


new momentum dependence

SM term

$$A_{hW(p)W(q)} \propto \frac{2\, m_W^2}{v} \left(g_{\mu\nu} \left(1 + \frac{c_{H\Box}\, v^2}{4\Lambda^2} \right) + (p \cdot q\, g_{\mu\nu} - q_\mu p_\nu) \frac{8\, c_{HW}}{\Lambda^2} \right)$$

For more handles to tease out new physics effects, look to differential distributions:
Higgs distributions are a natural target



Go heavy: SMEFT

Well defined mapping from UV theory → EFT → comparison with data

EFT

$$c_{3G} = \frac{g_s^2}{(4\pi)^2}\frac{1}{20}$$

$$c_{3W} = \frac{g^2}{(4\pi)^2}\frac{1}{20}$$

$$c_{2G} = \frac{g_s^2}{(4\pi)^2}\frac{1}{20}$$

$$c_{2W} = \frac{g^2}{(4\pi)^2}\frac{1}{20}$$

$$c_{2B} = \frac{g'^2}{(4\pi)^2}\frac{1}{20}$$

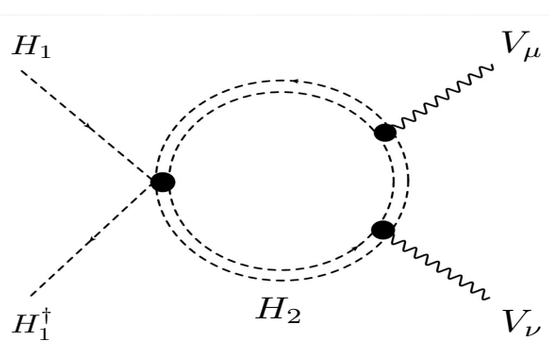
$$c_H = \frac{h_t^4}{(4\pi)^2}\frac{3}{4}\left[\left(1+\frac{1}{3}\frac{g'^2 c_{2\beta}}{h_t^2}+\frac{1}{12}\frac{g'^4 c_{2\beta}^2}{h_t^4}\right)-\frac{7}{6}\frac{X_t^2}{m_{\tilde{t}}^2}\left(1+\frac{1}{14}\frac{(g^2+2g'^2)c_{2\beta}}{h_t^2}\right)+\frac{7}{30}\frac{X_t^4}{m_{\tilde{t}}^2}\right]$$

$$c_T = \frac{h_t^4}{(4\pi)^2}\frac{1}{4}\left[\left(1+\frac{1}{2}\frac{g^2 c_{2\beta}}{h_t^2}\right)^2-\frac{1}{2}\frac{X_t^2}{m_{\tilde{t}}^2}\left(1+\frac{1}{2}\frac{g^2 c_{2\beta}}{h_t^2}\right)+\frac{1}{10}\frac{X_t^4}{m_{\tilde{t}}^4}\right]$$

$$c_R = \frac{h_t^4}{(4\pi)^2}\frac{1}{2}\left[\left(1+\frac{1}{2}\frac{g^2 c_{2\beta}}{h_t^2}\right)^2-\frac{3}{2}\frac{X_t^2}{m_{\tilde{t}}^2}\left(1+\frac{1}{12}\frac{(3g^2+g'^2)c_{2\beta}}{h_t^2}\right)+\frac{3}{10}\frac{X_t^4}{m_{\tilde{t}}^4}\right]$$

$$c_D = \frac{h_t^2}{(4\pi)^2}\frac{1}{20}\frac{X_t^2}{m_{\tilde{t}}^2}$$

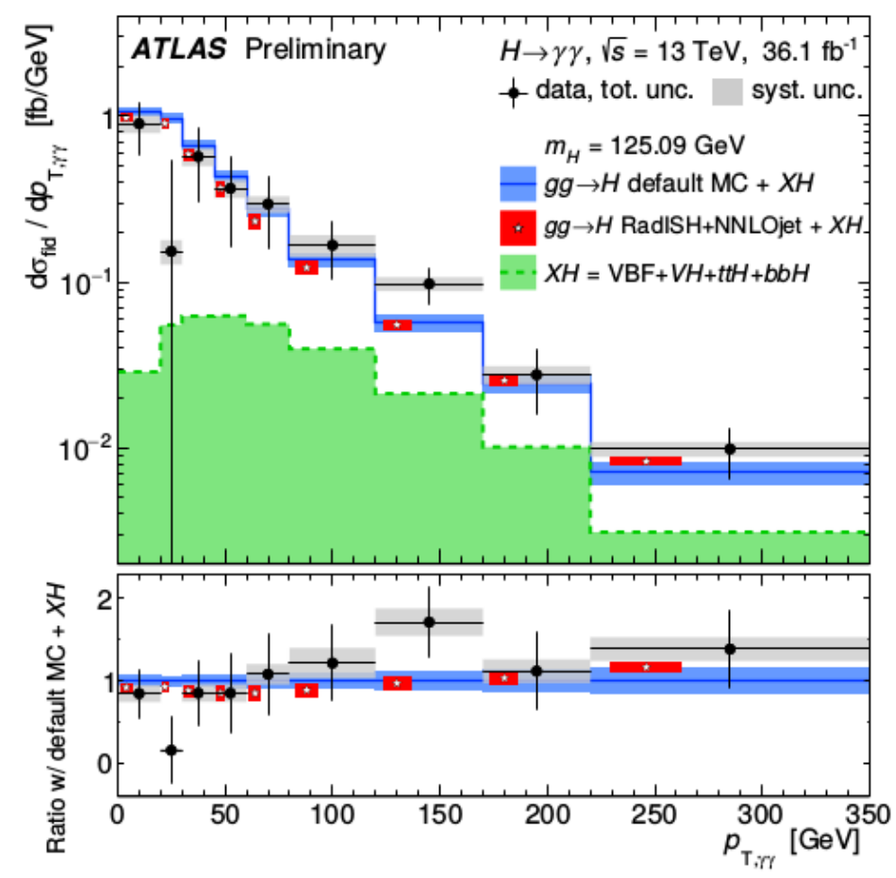
Models



...

[Gaillard '86,Henning et al 1412.1837,1604.01019, de Blas et al1711.10391]

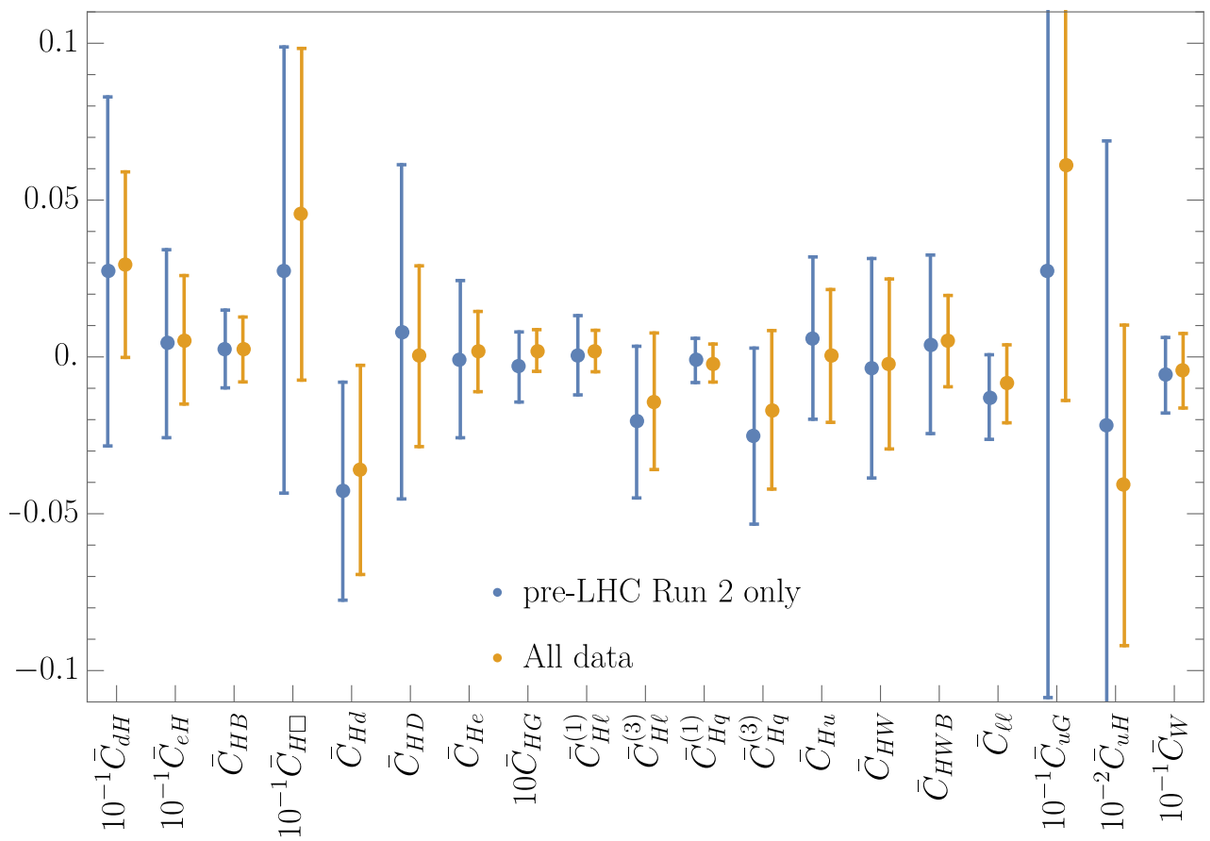
Observables



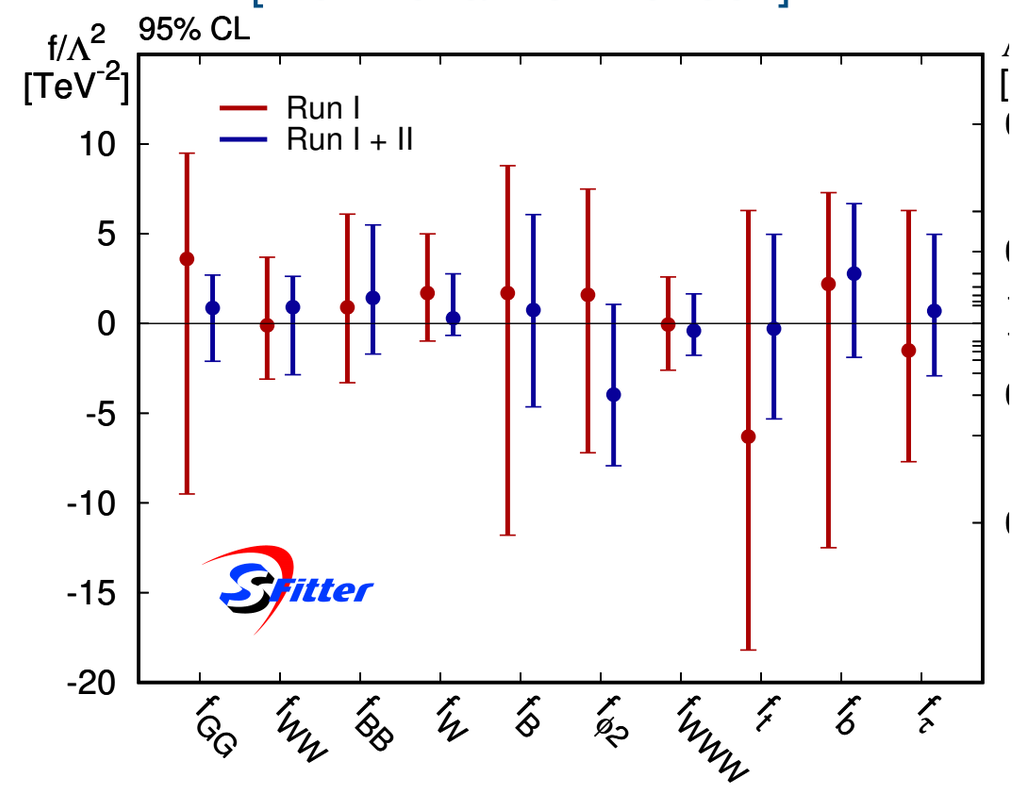
Go heavy: SMEFT

Recent results: global fits to Higgs data + LEP I/II

[Ellis et al 1803.03252]



[Plehn et al 1812.07587]



[see talk by Tian]

What's next?

Λ = NP scale = where you want to put the next collider, so knowing the uncertainty is important

May require EFT + NLO SM, or dim-8 EFT

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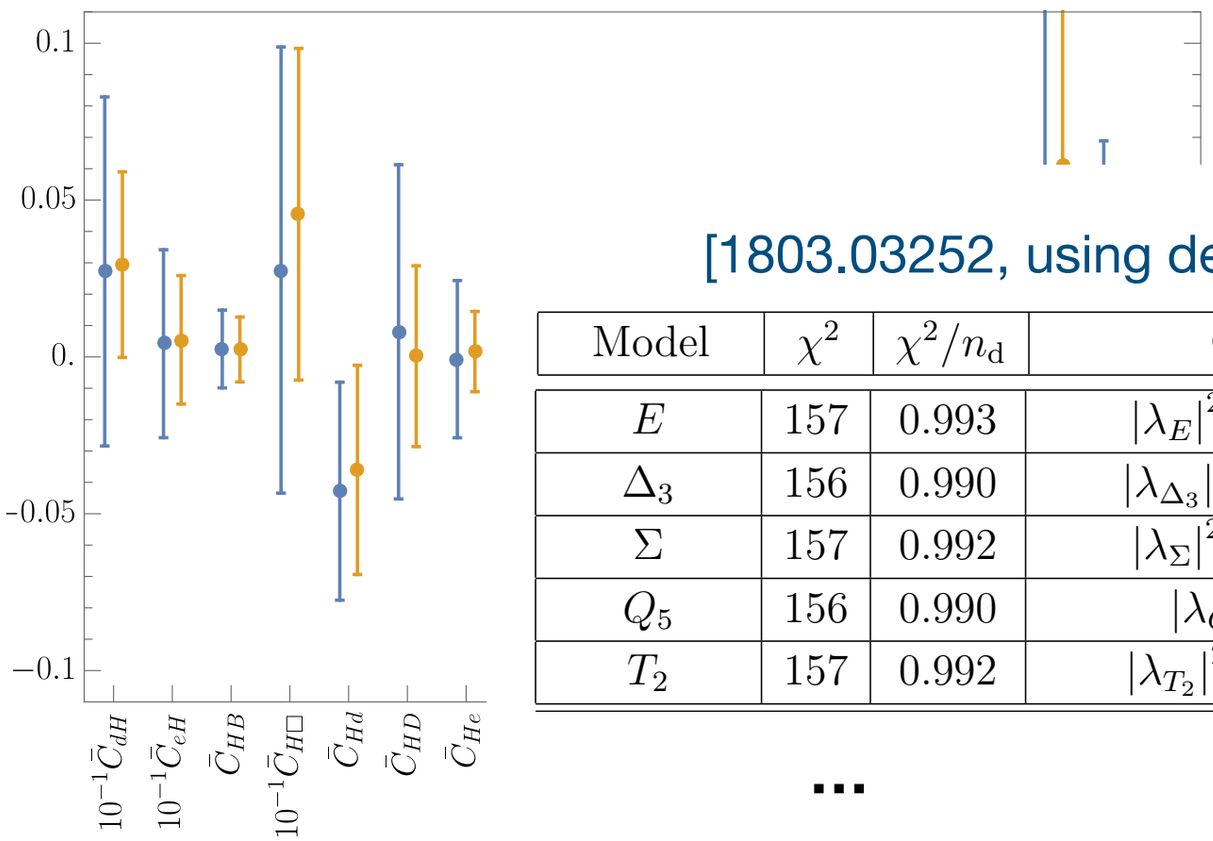

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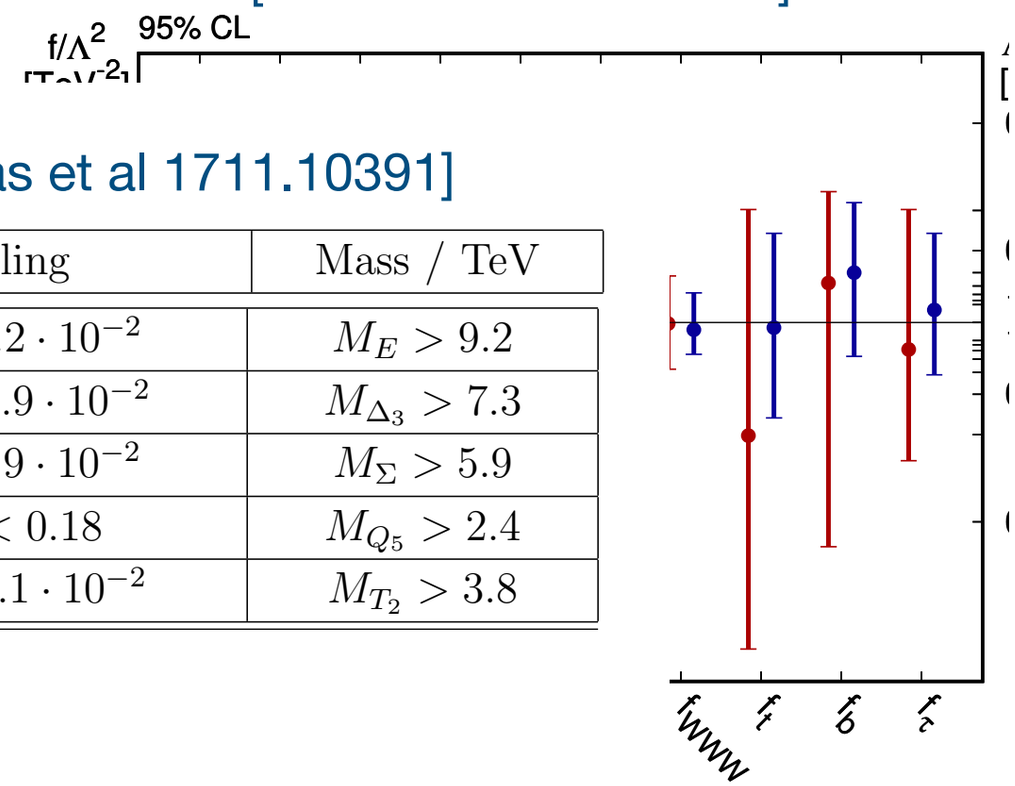

[1803.03252, using de Blas et al 1711.10391]

Model	χ^2	χ^2/n_d	Coupling	Mass / TeV
E	157	0.993	$\lvert\lambda_E\rvert^2 < 1.2 \cdot 10^{-2}$	$M_E > 9.2$
Δ_3	156	0.990	$\lvert\lambda_{\Delta_3}\rvert^2 < 1.9 \cdot 10^{-2}$	$M_{\Delta_3} > 7.3$
Σ	157	0.992	$\lvert\lambda_\Sigma\rvert^2 < 2.9 \cdot 10^{-2}$	$M_\Sigma > 5.9$
Q_5	156	0.990	$\lvert\lambda_{Q_5}\rvert^2 < 0.18$	$M_{Q_5} > 2.4$
T_2	157	0.992	$\lvert\lambda_{T_2}\rvert^2 < 7.1 \cdot 10^{-2}$	$M_{T_2} > 3.8$

...

[see talk by Tian]

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May require EFT + NLO SM, or dim-8 EFT

Go color neutral:

LHC is great at producing of colored states = fit well with naturalness solutions with colored `top-partners', etc. close to TeV scale

Much weaker limits for uncolored states: squark limits ~ 1.5 TeV vs. electroweakino limits ~ 300 GeV)

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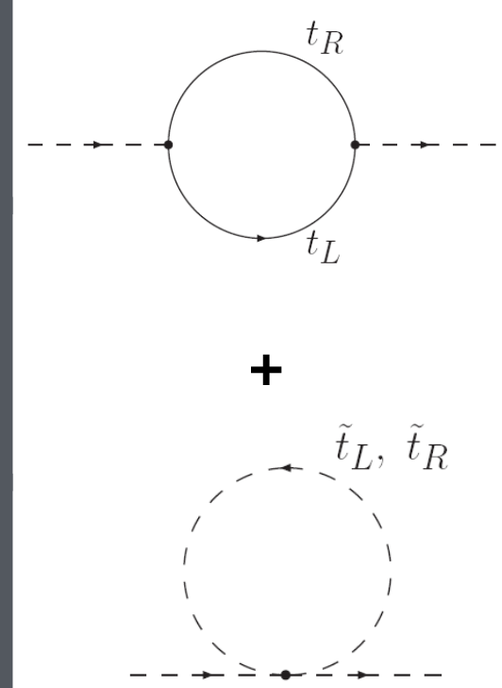
Lots of model building recently working to solve hierarchy problem using color neutral partners = `neutral naturalness'.

	Scalar Top Partner	Fermionic Top Partner
Colored Top Partner	Supersymmetry	Compositeness/Warped Extra Dimensions
EW-charged Top Partner	Folded SUSY [Chacko, Harnik, Goh, Burdman]	Quirky Little Higgs [Cai, Cheng, Terning]
Neutral Top Partner	Hyperbolic Higgs [Cohen, Craig, Giudice, McCullough] Tripled Top [Cheng, Li, Salvioni, Verhaaren]	Twin Higgs [Chacko, Harnik, Goh] [Barbieri, Gregoire, Hall]

Table from B. Batell

[Table inspiration from Curtin, Verhaaren]



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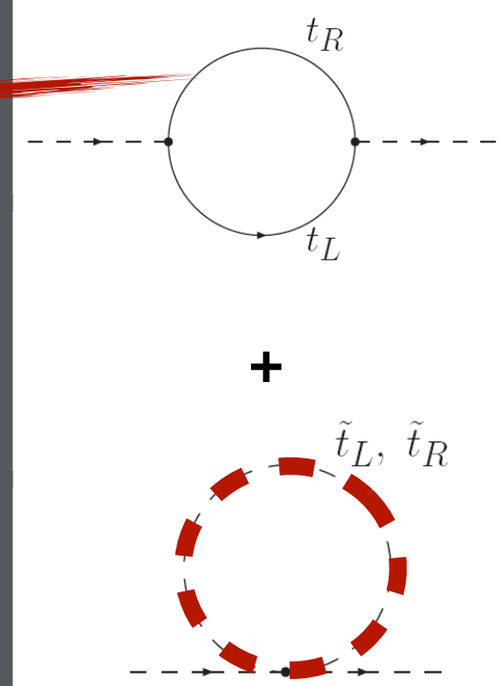

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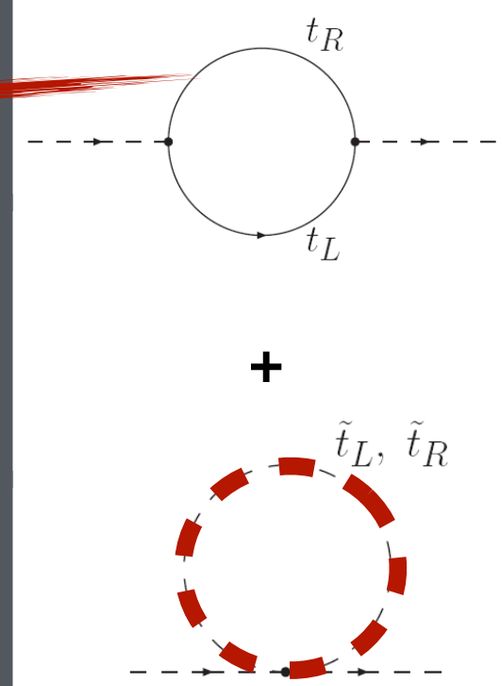


+ extra Higgs, mixes with SM Higgs

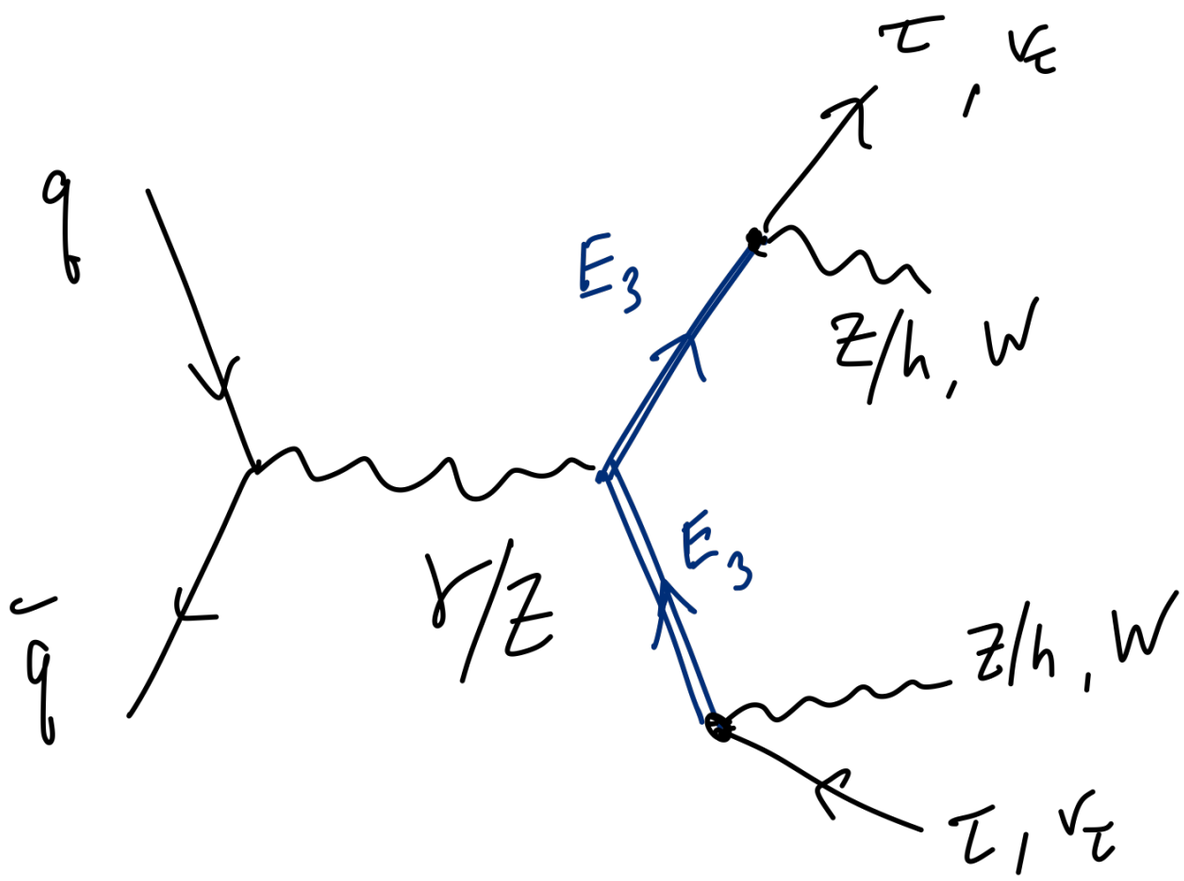
$$y_A Q_A H_A u_A + y_B Q_B H_B u_B + \lambda |H|_A^2 |H_B|^2$$

Go color neutral:

LHC limits weaken even further if we have **no BSM MET**

ex.) new lepton with vector-like charge assignments under $U(1)_Y$, talks primarily to tau

[Bhattiprolu, S. Martin 1905.00498]



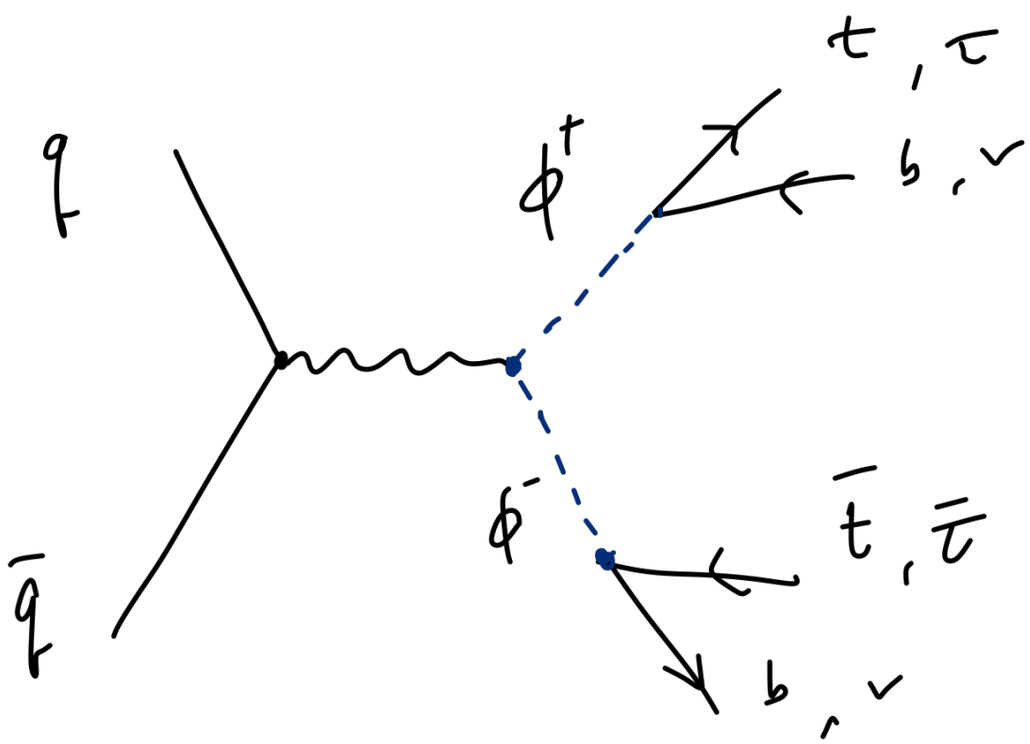
Best limit: LEP II

Could be: the lightest stuff from heavy SUSY/compositeness

Go color neutral:

ex .) new $SU(2)_w$ triplet scalar, talks to SM fermions via higher dimensional operators

[Kribs, AM, Ostdiek, Tong 1809.10184]



$$\mathscr{L}_{decay} \supset \frac{y_u Q \tau^A H u_c \phi^A}{\Lambda} + \frac{y_\ell L \tau^A H e_c \phi^A}{\Lambda} + \cdots$$

* ($pp \to \phi^\pm \phi^0$ too)

Could be… a remnant from solutions to other SM shortcoming (DM)

8 TeV limits > 13 TeV limits, as 13 TeV analyses focus on heavier stuff with BSM MET

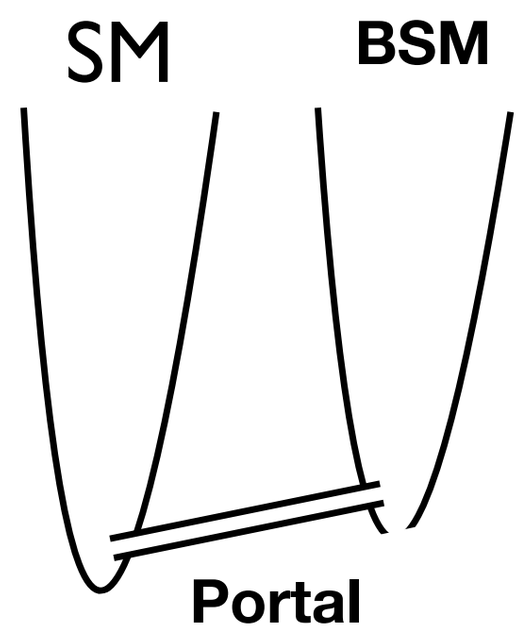
Model independent, multi-lepton searches at 8 TeV (ATLAS 1411.2921, CMS 1404.5801) are great & extremely powerful — would be great to have 13 TeV versions

Go long lived:

$\epsilon F^{\mu\nu} X_{\mu\nu}$ $\qquad$ $\dfrac{(SM)(BSM)}{M_{mediator}}$

Even weaker connections: Higgs 'portal', photon portal, heavy mediator portal, etc.

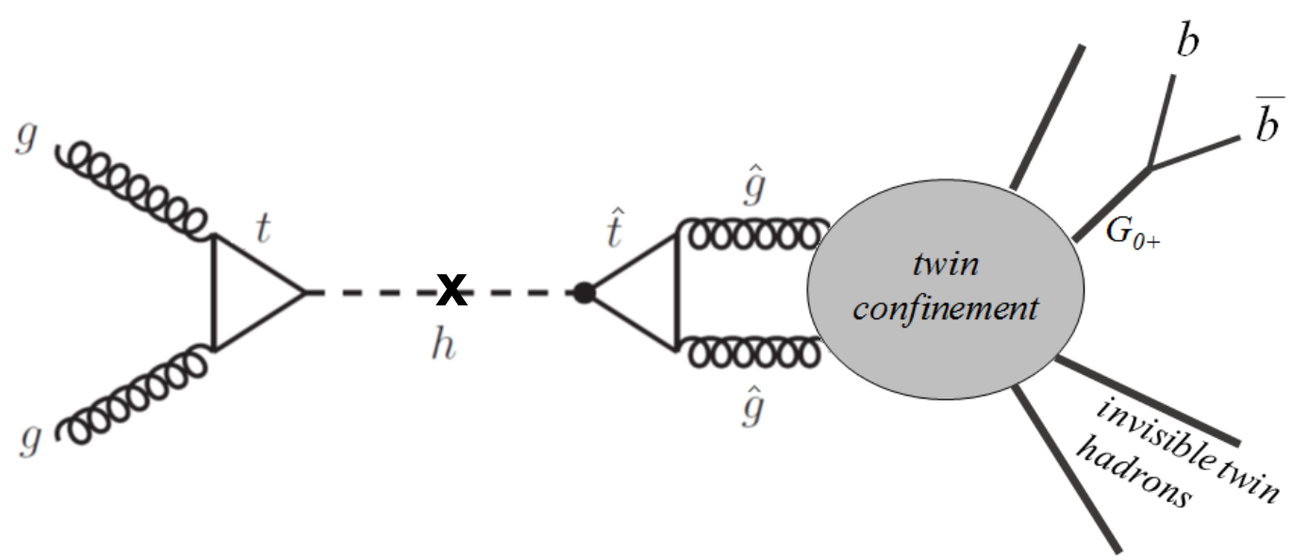
$\lambda |H|^2 \phi^2$



hidden by weak coupling rather than high mass

If SM <-> BSM connection is sufficiently weak → **long lived particles (LLP)**!
Show up as exotic decays of SM particles and/or displaced vertices.

ex.)



Neutral naturalness signal!

Go long lived:

LLPs are an ingredient in many `motivated' UV scenarios

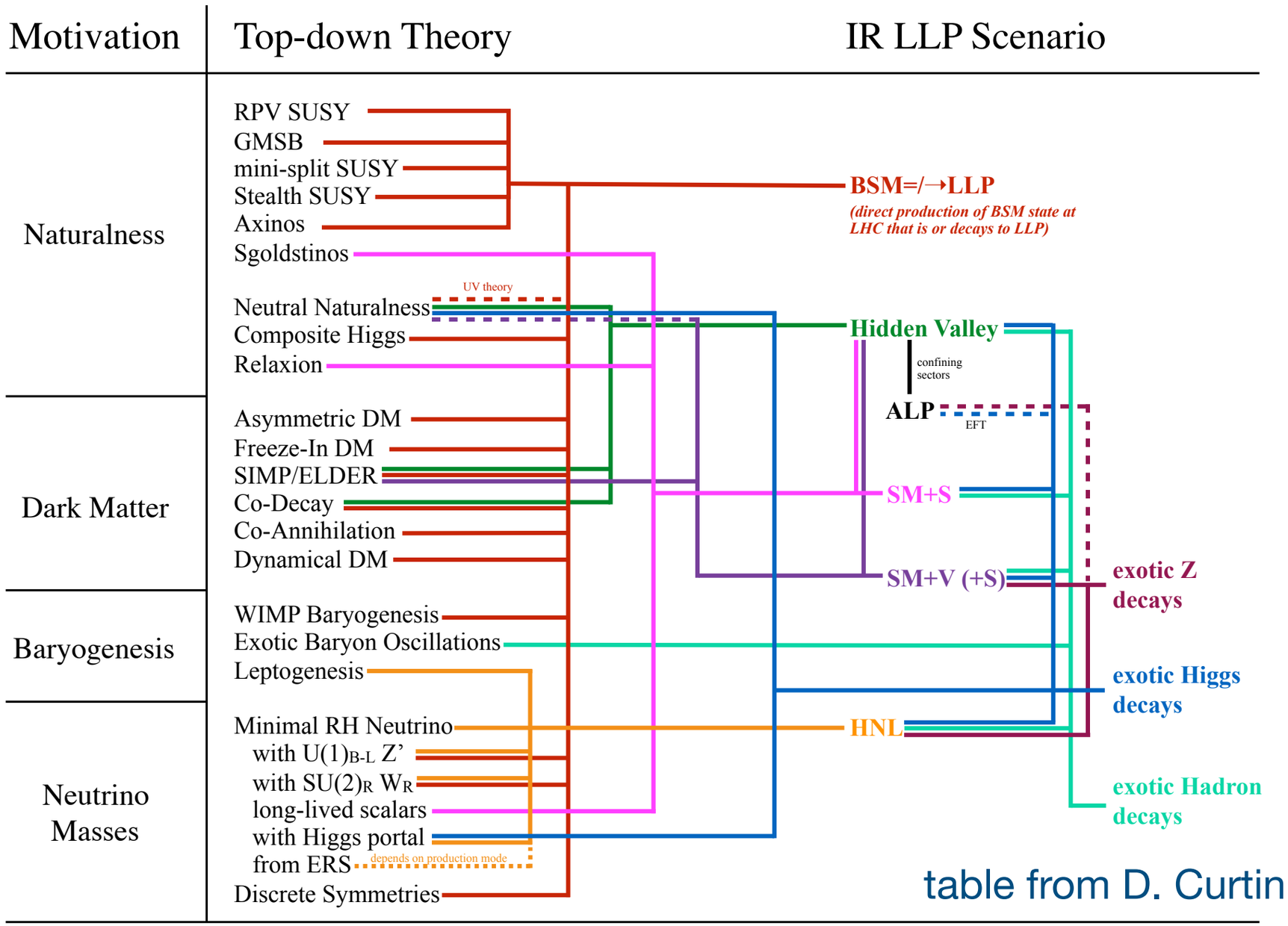


table from D. Curtin

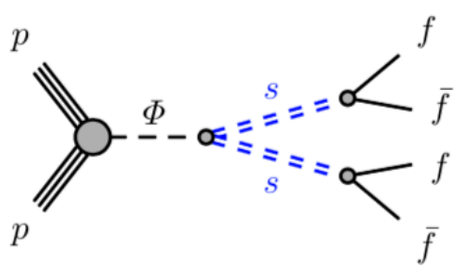
Go long lived:

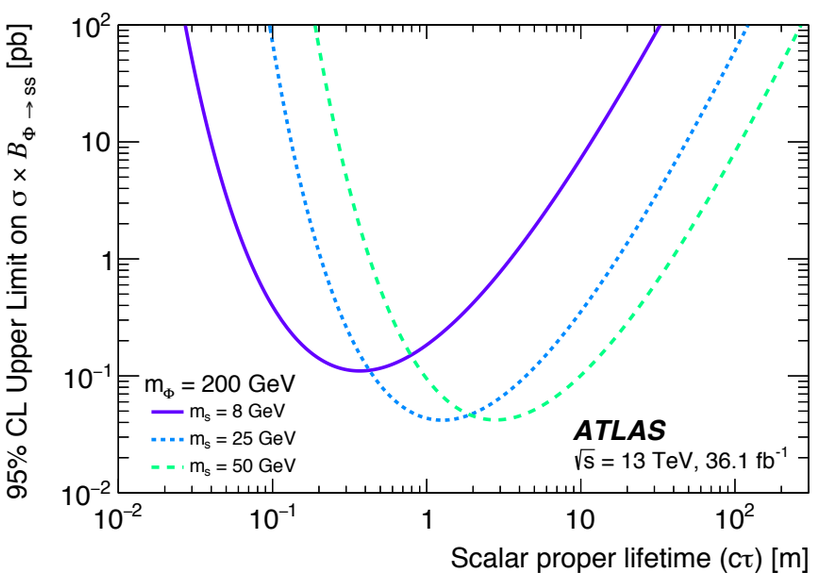
Neutral LLPs: often difficult to trigger on and with hard to predict backgrounds, but lots of attention recently

(see talks by Proffitt, Adams, Rifki, Gan,..)

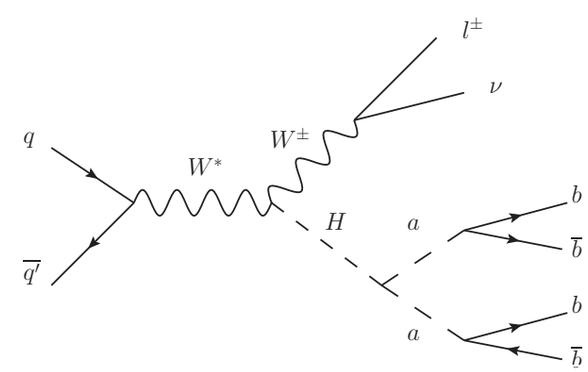
ex.)

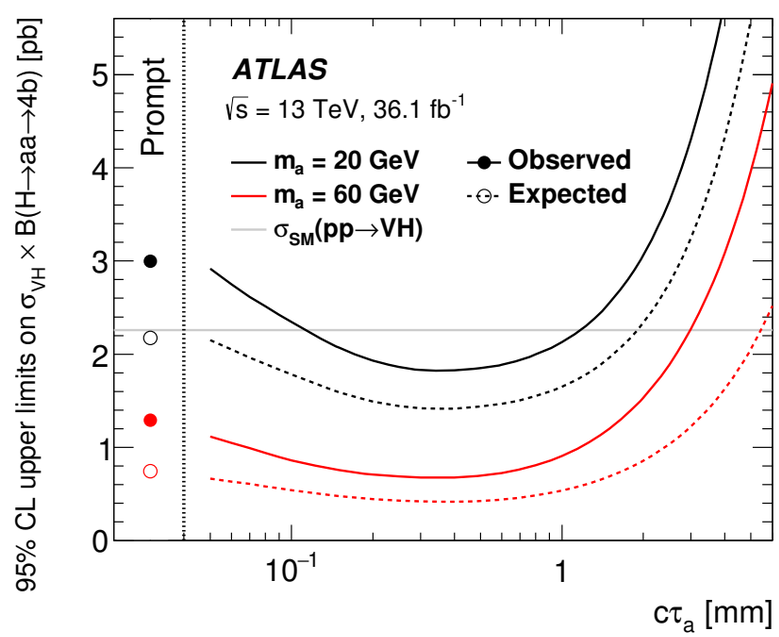
ATLAS displaced jets 1811.07370



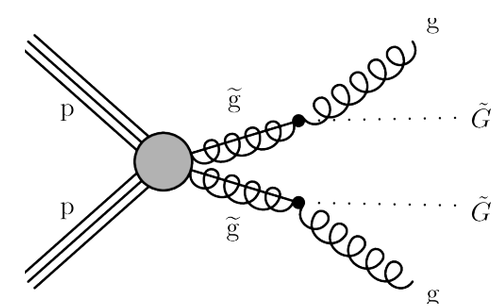


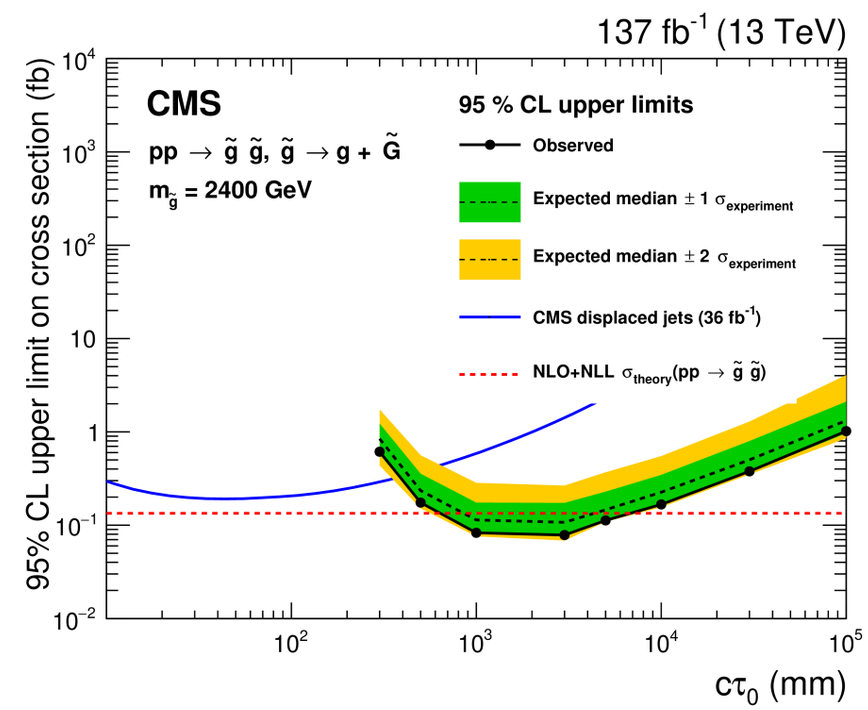
ATLAS VH, H-> 2a -> 4b
1806.07355





CMS non-prompt jets 1906.06441





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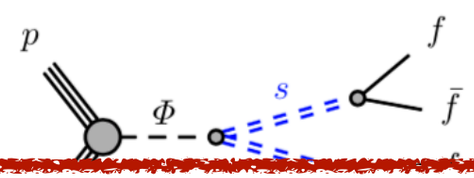
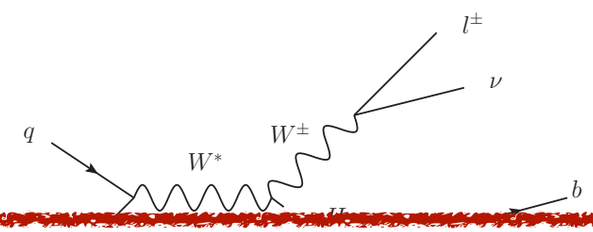
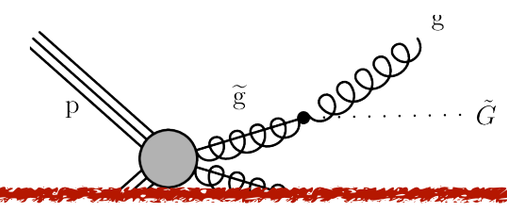
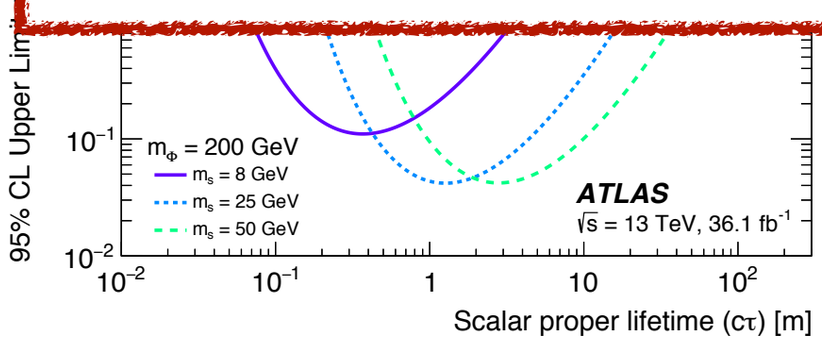


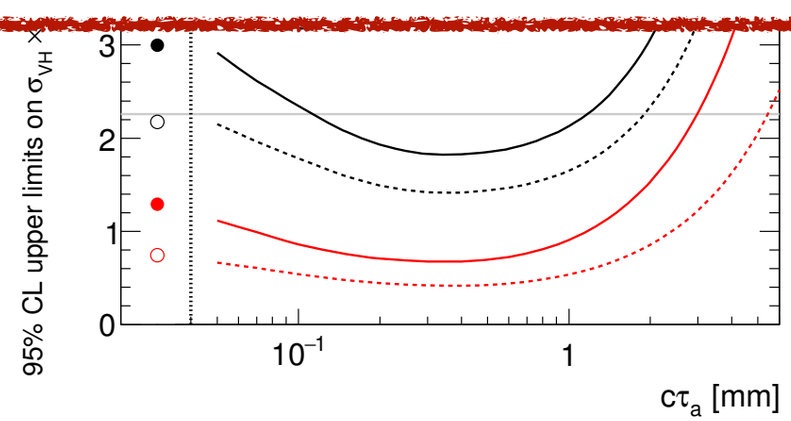


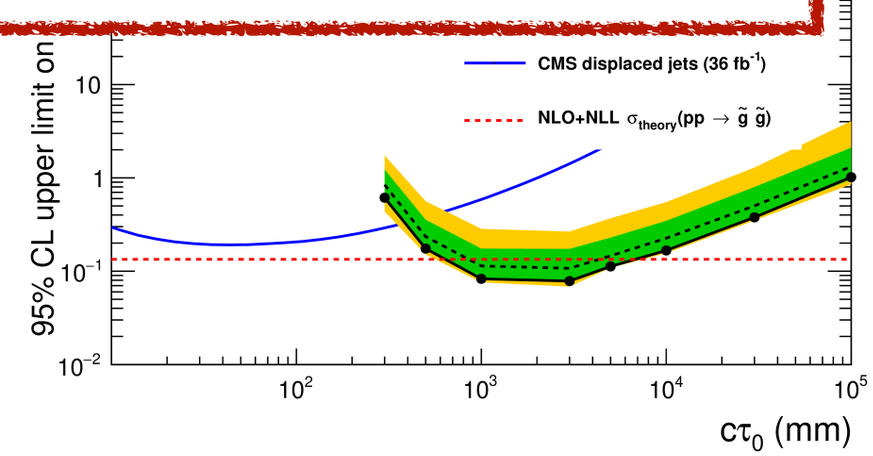


LHC upgrades to trigger/timing could have a big impact — see 1903.04497
(talk by Flowers)

Complementarity between ATLAS/CMS detectors & new dedicated LLP experiments/ proposals: MATHUSLA, CODEX-B, FASER…







Conclusions

- SUSY/Composite Higgs extensions of SM still well motivated, worth pursuing with full force .. however increasingly strained by null results

- **SMEFT**: model independent parameterization of physics too heavy to make on shell. Well defined, systematic. Lots of directions to pursue, power in differential distributions

- **Keep the net wide:**

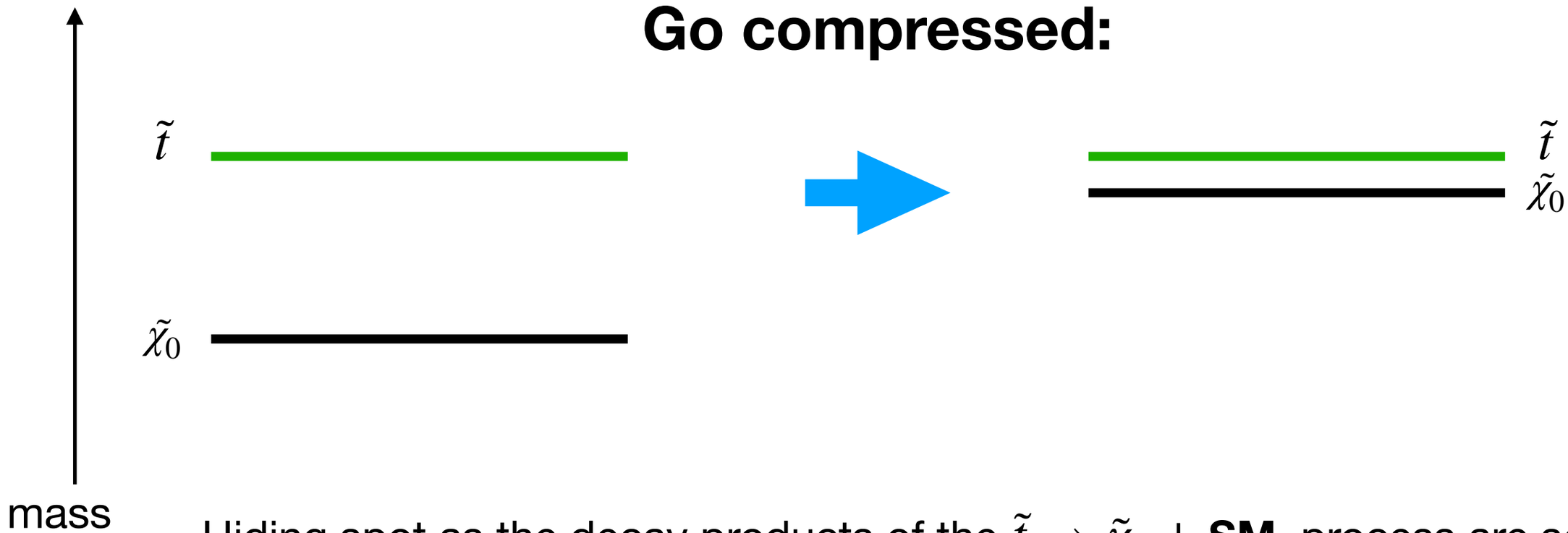
Color neutral states, especially with no BSM MET could still be lurking at light scales. Keep the model independent searches coming!

Long lived particles: generic feature in many models, including `neutral natural' setups. New frontier! Many innovative ideas but lots of space left to explore

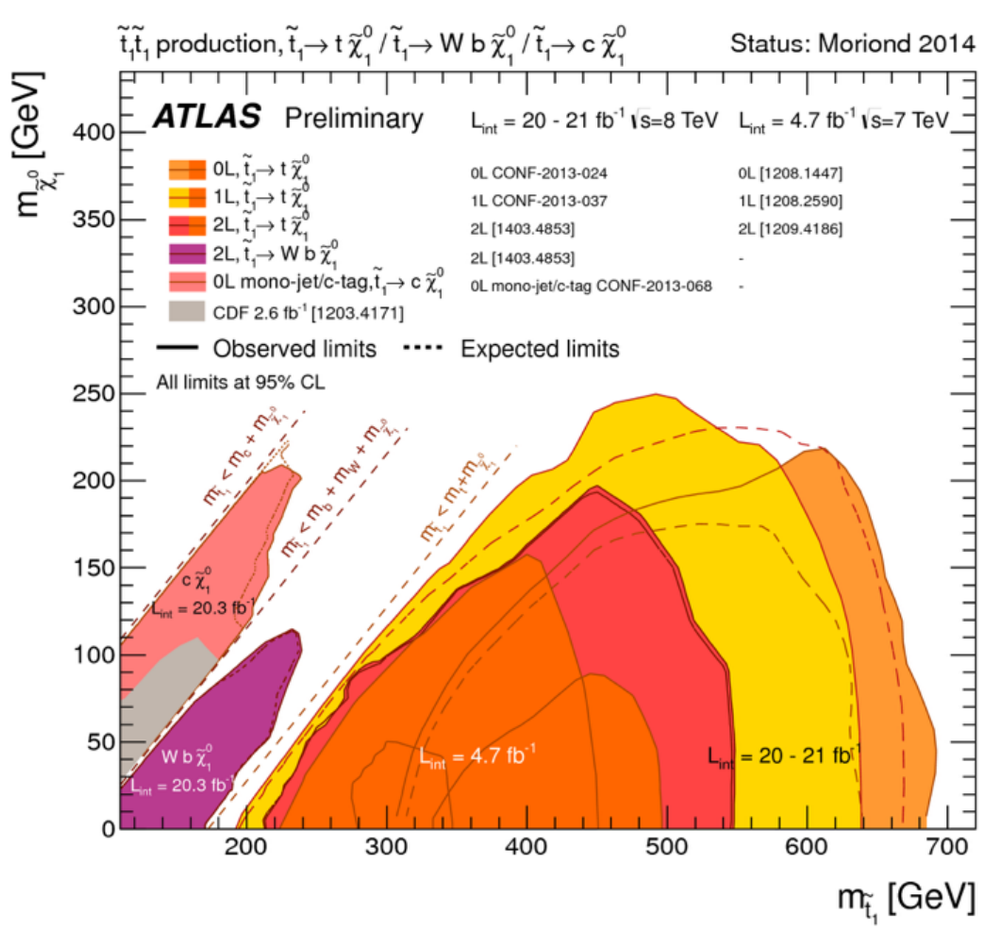
Looking forward to more data & results! Thank you!

EXTRA

Go compressed:

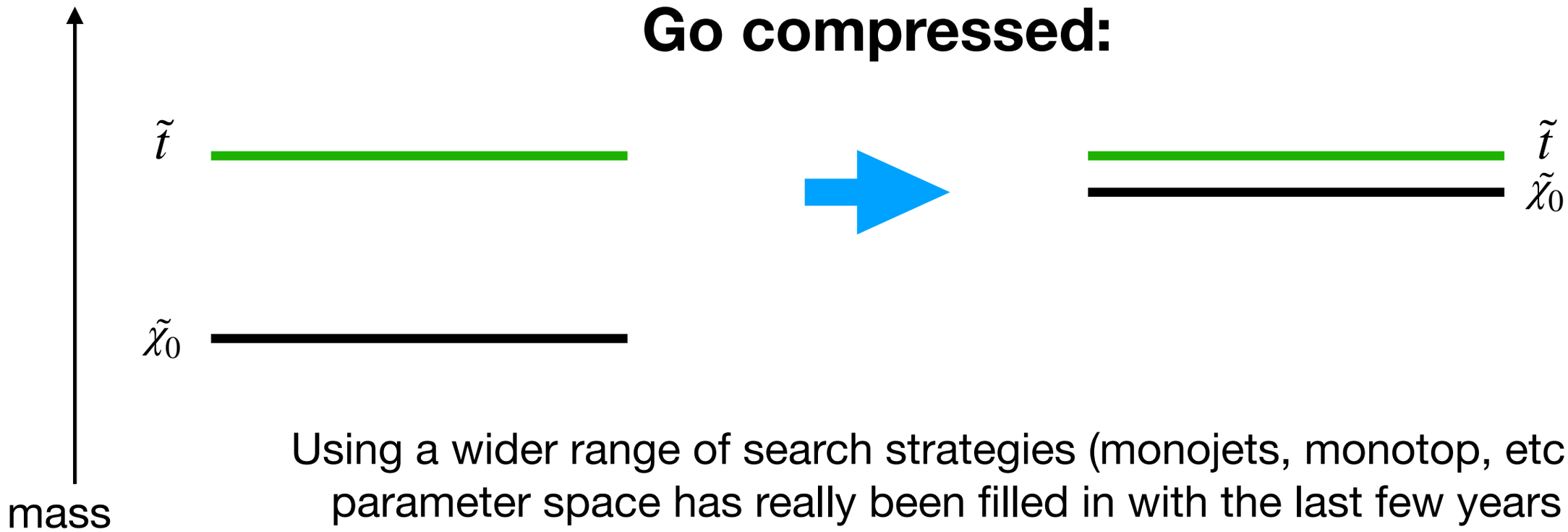


Hiding spot as the decay products of the $\tilde{t} \to \tilde{\chi}_0 + \mathbf{SM}$ process are soft

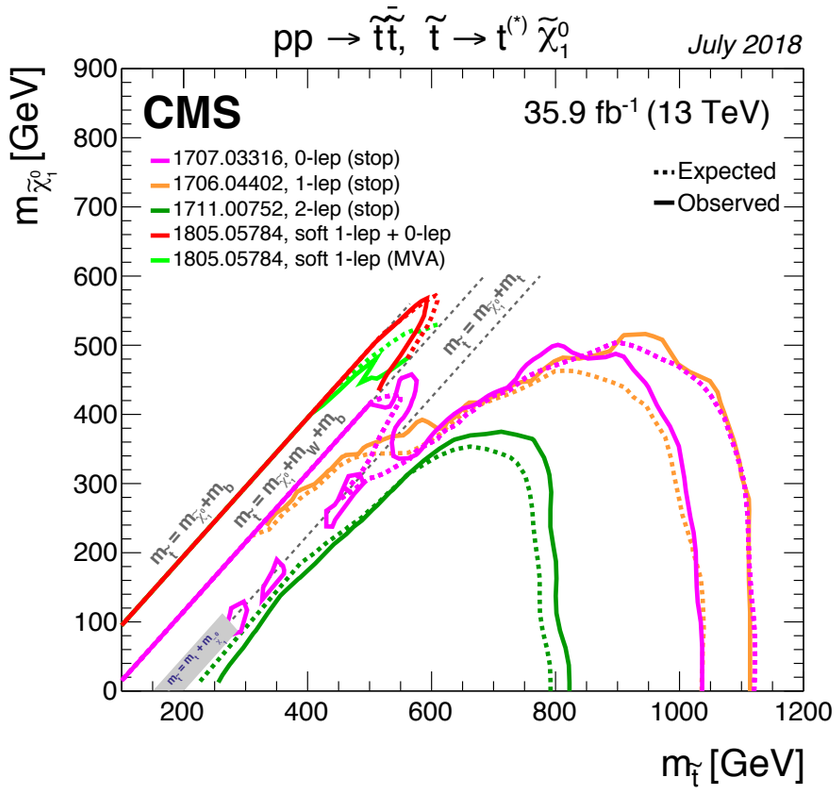


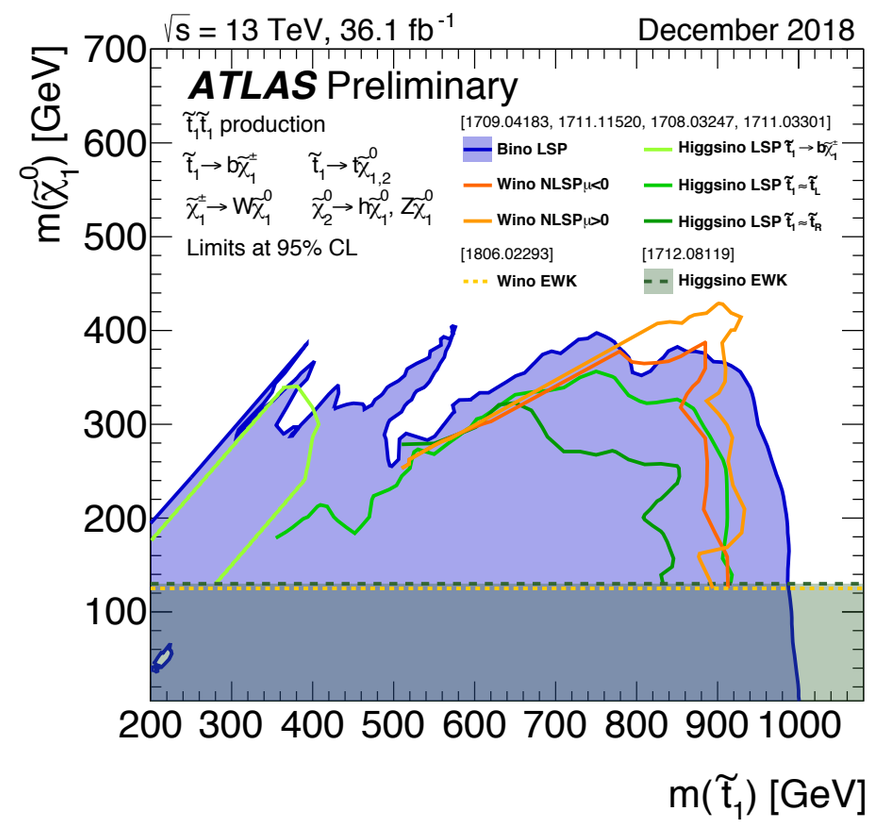
Plenty of other examples, e.g. degenerate chargino-neutralio

Go compressed:



Using a wider range of search strategies (monojets, monotop, etc.), parameter space has really been filled in with the last few years





Hiding spots remain, but it's getting a lot tougher

(talk by Chen)

Twin Higgs done more correctly…

not SM colored

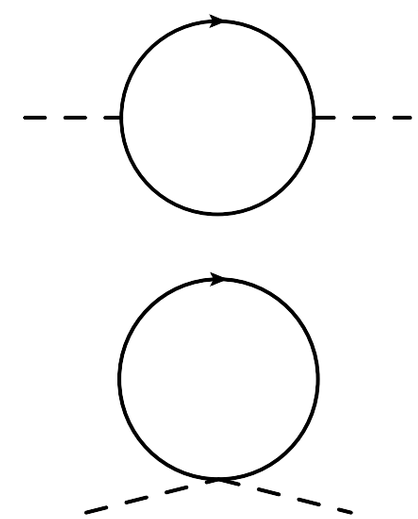
$$y_t Q_A H_A u_A + y_t Q_B H_B u_B$$

A <-> B related by Z_2

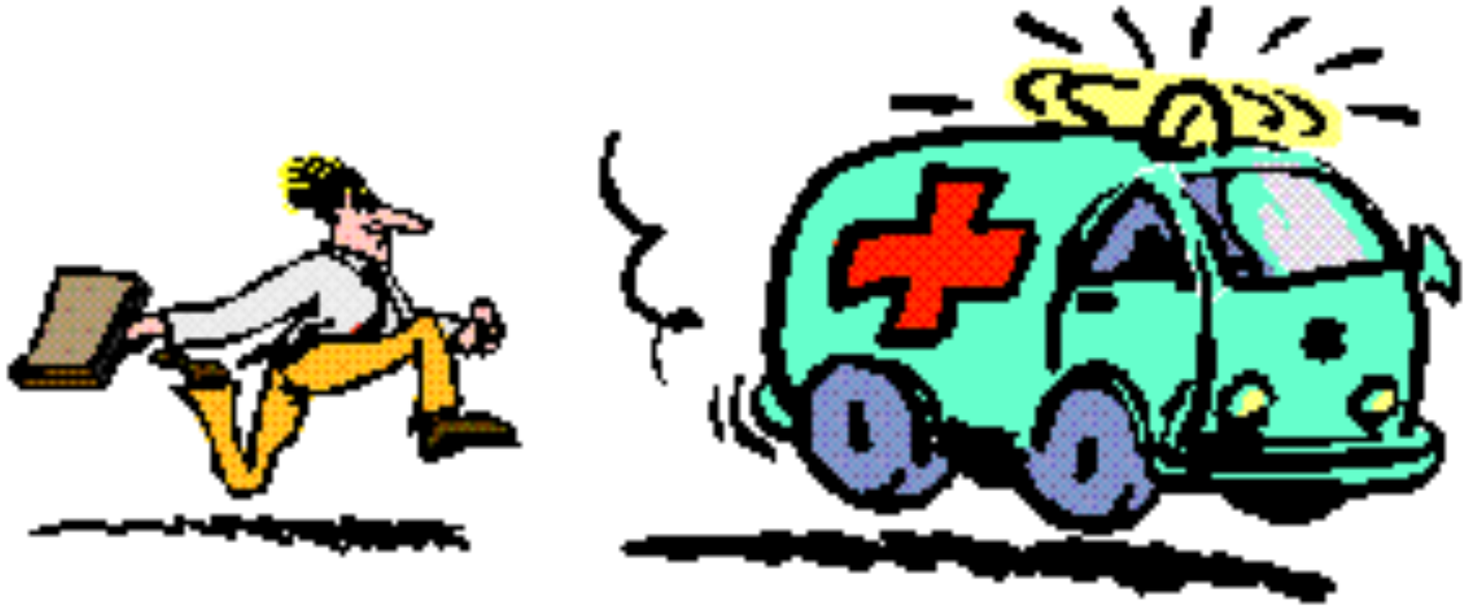
Combine H_A, H_B, they have a SU(4) global symmetry that breaks at f

SM h is Goldstone from SU(4) breaking

$$y_t Q_A h u_A - y_t Q_B \frac{h^2}{f} u_B$$



Chase the anomalies!



- For the theorists: ’motivated’ models haven’t shown up, so keep broadening our scope

- For the experimenters: Don’t let “no theory paper exists with that particle/final state” stop you

Even if anomaly fades, creative efforts lead to new models/revitalize old models/ point out issues in search strategies!