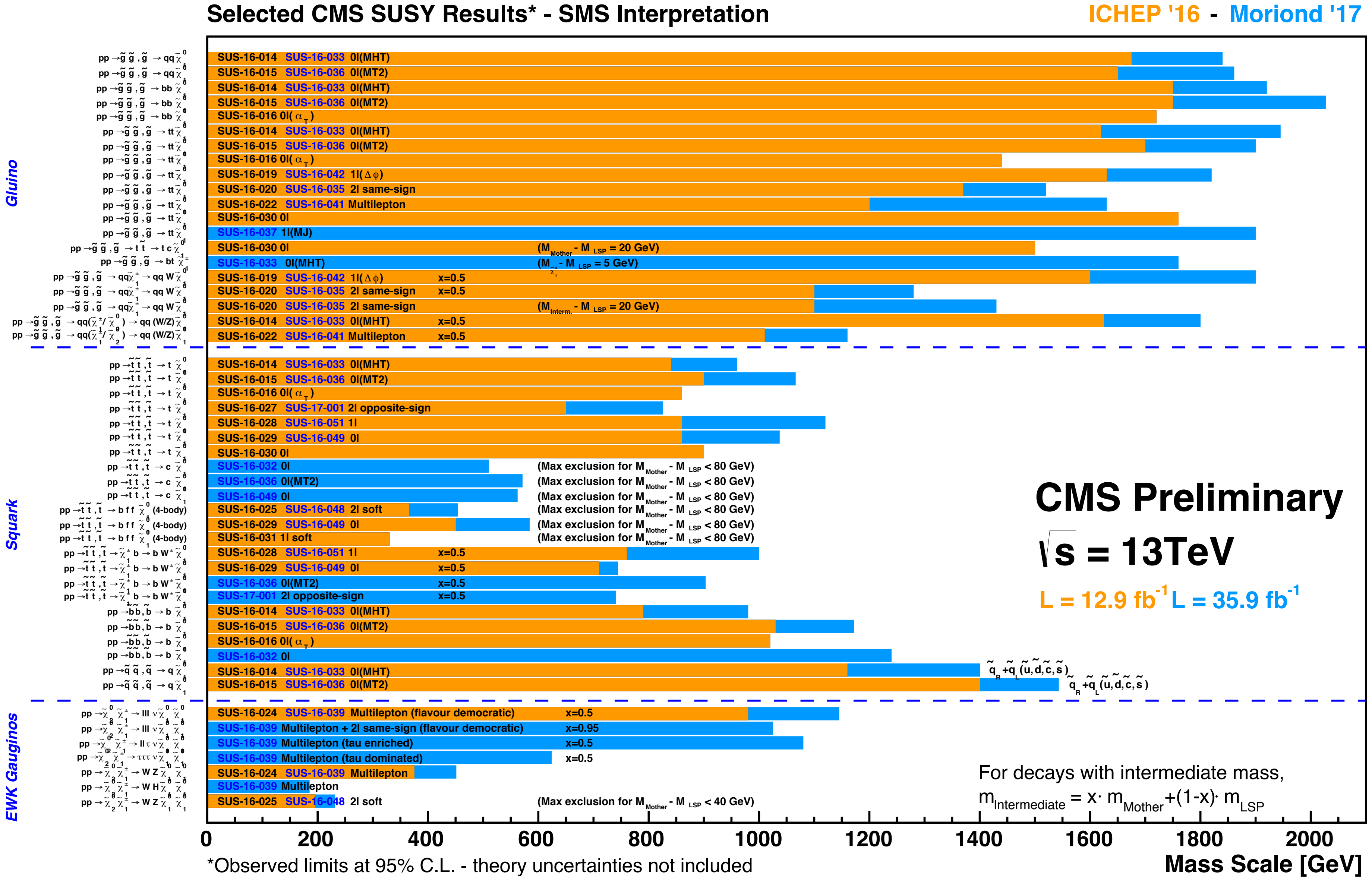
Experimental Results for BSM at the LHC

Christopher Rogan

Particle Physics on the Planes

October 13, 2018

Selected CMS SUSY Results* - SMS Interpretation



*Observed limits at 95% C.L. - theory uncertainties not included

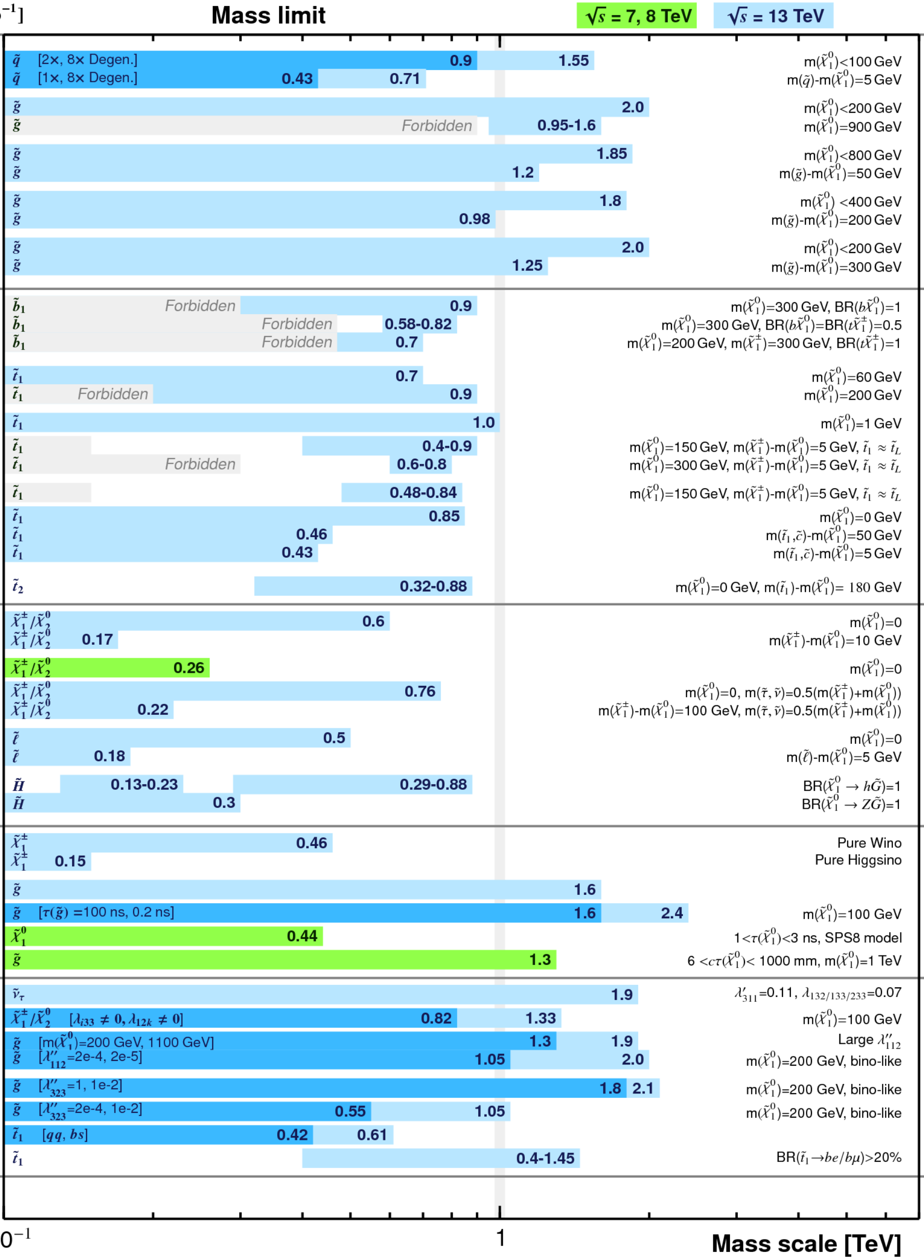
Only a selection of available mass limits. Probe *up to* the quoted mass limit for m_{LSP} ≈0 GeV unless stated otherwise

ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV



	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\text{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$ [2×, 8× Degen.] 0.9 1.55	m($\tilde{\chi}_1^0$)<100 GeV	1712.02332
		mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$ [1×, 8× Degen.] 0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.0	m($\tilde{\chi}_1^0$)<200 GeV	1712.02332
						$\tilde{g}$ Forbidden 0.95-1.6	m($\tilde{\chi}_1^0$)=900 GeV	1712.02332
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e,μ	4 jets	-	36.1	$\tilde{g}$ 1.85	m($\tilde{\chi}_1^0$)<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	Yes	36.1	$\tilde{g}$ 1.2	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$ 1.8	m($\tilde{\chi}_1^0$) <400 GeV	1708.02794
		3 e,μ	4 jets	-	36.1	$\tilde{g}$ 0.98	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	1706.03731
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	36.1	$\tilde{g}$ 2.0	m($\tilde{\chi}_1^0$)<200 GeV	1711.01901
		3 e,μ	4 jets	-	36.1	$\tilde{g}$ 1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1706.03731
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple		36.1	$\tilde{b}_1$ Forbidden 0.9	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.58-0.82	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=BR($t\tilde{\chi}_1^\pm$)=0.5	1708.09266
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.7	m($\tilde{\chi}_1^0$)=200 GeV, m($\tilde{\chi}_1^\pm$)=300 GeV, BR($t\tilde{\chi}_1^\pm$)=1	1706.03731
	$\tilde{b}_1\tilde{b}_1, \tilde{t}_1\tilde{t}_1$, $M_2 = 2\times M_1$		Multiple		36.1	$\tilde{t}_1$ 0.7	m($\tilde{\chi}_1^0$)=60 GeV	1709.04183, 1711.11520, 1708.03247
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.9	m($\tilde{\chi}_1^0$)=200 GeV	1709.04183, 1711.11520, 1708.03247
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	36.1	$\tilde{t}_1$ 1.0	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{H}$ LSP		Multiple		36.1	$\tilde{t}_1$ 0.4-0.9	m($\tilde{\chi}_1^0$)=150 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$	1709.04183, 1711.11520
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.6-0.8	m($\tilde{\chi}_1^0$)=300 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$ 0.48-0.84	m($\tilde{\chi}_1^0$)=150 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}_1^0$	0	$2c$	Yes	36.1	$\tilde{t}_1$ 0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
						$\tilde{t}_1$ 0.46	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.01649
		0	mono-jet	Yes	36.1	$\tilde{t}_1$ 0.43	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + h$	1-2 e,μ	4 b	Yes	36.1	$\tilde{t}_2$ 0.32-0.88	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 180 GeV	1706.03986
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	2-3 e,μ	-	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.6	m($\tilde{\chi}_1^0$)=0	1403.5294, 1806.02293
		$ee,\mu\mu$	≥ 1	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.17	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=10 GeV	1712.08119
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	$\ell\ell/\ell\gamma\gamma/\ell bb$	-	Yes	20.3	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.26	m($\tilde{\chi}_1^0$)=0	1501.07110
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$, $\tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.76	m($\tilde{\chi}_1^0$)=0, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1708.07875
						$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.22	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=100 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1708.07875
	$\tilde{\ell}_{\text{L,R}}\tilde{\ell}_{\text{L,R}}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	36.1	$\tilde{\ell}$ 0.5	m($\tilde{\chi}_1^0$)=0	1803.02762
		2 e,μ	≥ 1	Yes	36.1	$\tilde{\ell}$ 0.18	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=5 GeV	1712.08119
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0	$\geq 3b$	Yes	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88	BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0	Yes	36.1	$\tilde{H}$ 0.3	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^\pm$ 0.46	Pure Wino	1712.02118
						$\tilde{\chi}_1^\pm$ 0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron	SMP	-	-	3.2	$\tilde{g}$ 1.6		1606.05129
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$		Multiple		32.8	$\tilde{g}$ [$\tau(\tilde{g})$ =100 ns, 0.2 ns] 1.6 2.4	m($\tilde{\chi}_1^0$)=100 GeV	1710.04901, 1604.04520
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 0.44	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{g}$ 1.3	6 <$c\tau(\tilde{\chi}_1^0)$< 1000 mm, m($\tilde{\chi}_1^0$)=1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.82 1.33	m($\tilde{\chi}_1^0$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$ [m($\tilde{\chi}_1^0$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{g}\tilde{g}$, $\tilde{g}\to tbs$ / $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=1, 1e-2] 1.8 2.1	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	36.1	$\tilde{t}_1$ 0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544

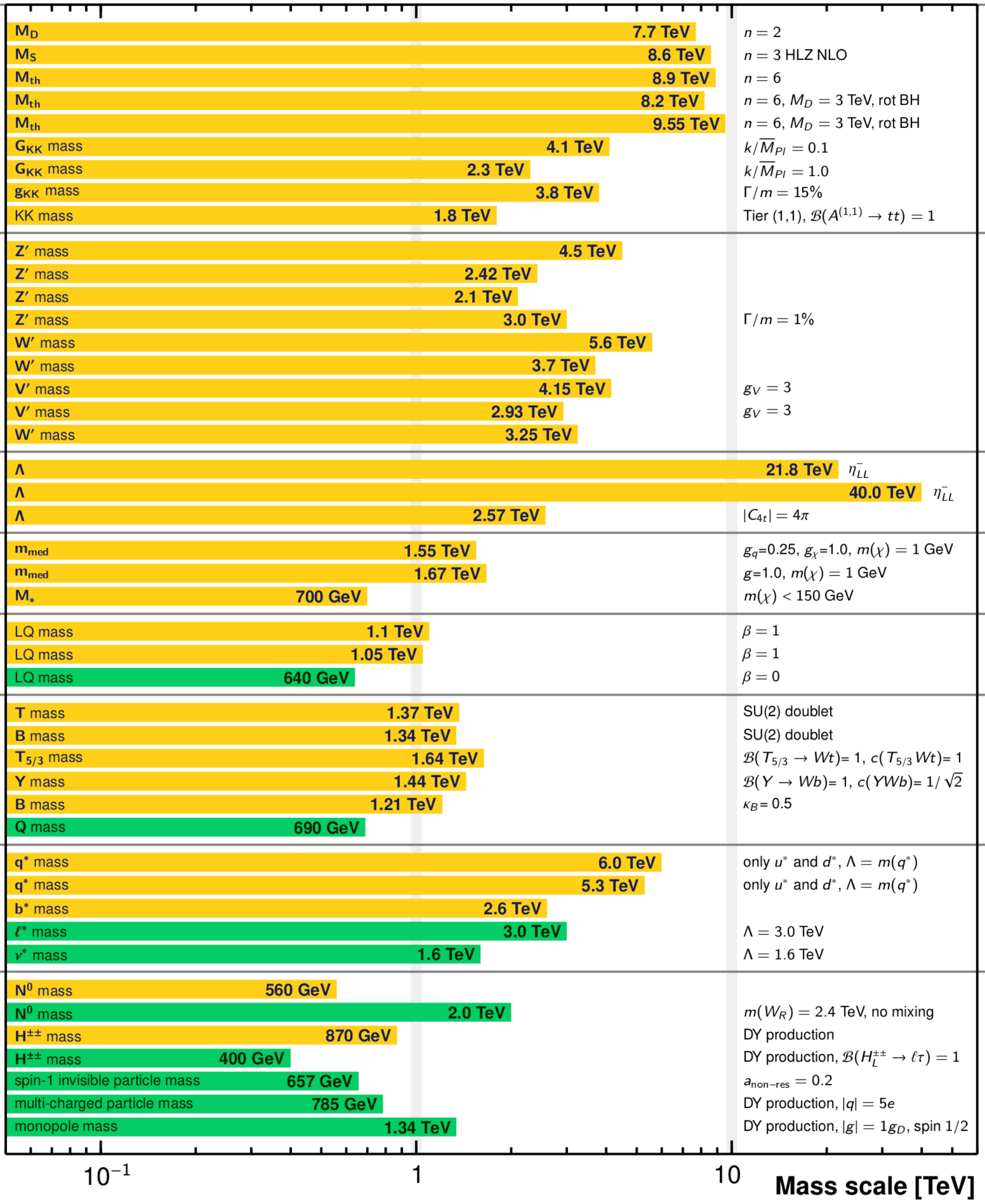
**Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.*

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

$\int\mathcal{L}\,dt$ = (3.2 – 79.8) fb^{-1} $\sqrt{s}$ = 8, 13 TeV

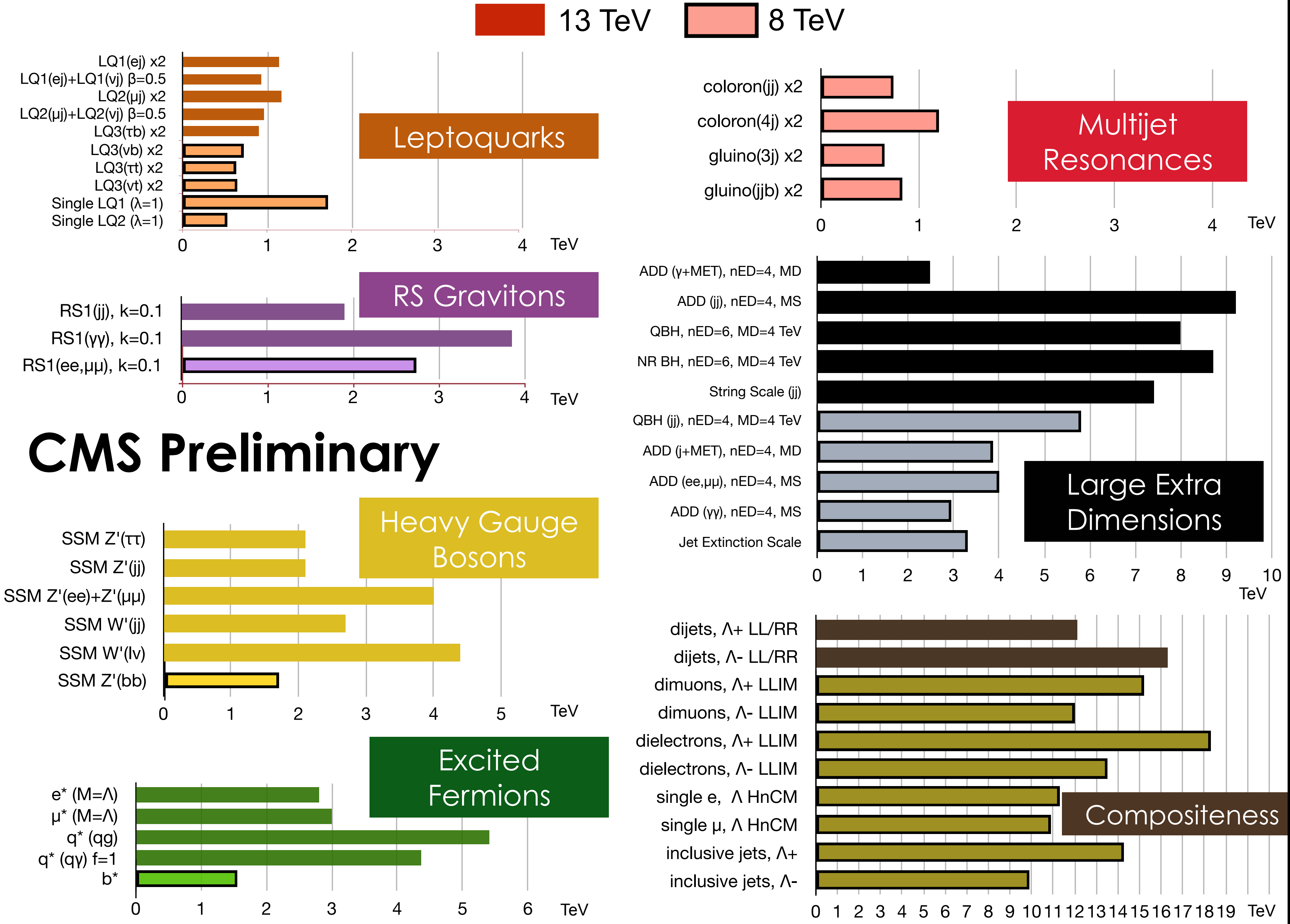


	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	🟨 M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	🟨 M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	🟨 M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 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 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	🟨 G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	🟨 G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	CERN-EP-2018-179
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	🟨 KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	36.1	🟨 Z' mass 4.5 TeV		1707.02424
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	🟨 Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	🟨 Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 Z' mass 3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	79.8	🟨 W' mass 5.6 TeV		ATLAS-CONF-2018-017
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	🟨 W' mass 3.7 TeV		1801.06992
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	79.8	🟨 V' mass 4.15 TeV	$g_V = 3$	ATLAS-CONF-2018-016
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	🟨 V' mass 2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W'_R \to tb$	multi-channel			36.1	🟨 W' mass 3.25 TeV		CERN-EP-2018-142
CI	CI $qqqq$	–	2 j	–	37.0	🟨 Λ 21.8 TeV	η^-_{LL}	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	🟨 Λ 40.0 TeV	η^-_{LL}	1707.02424
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	🟨 Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	CERN-EP-2018-174
DM	Axial-vector mediator (Dirac DM)	0 e, μ	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, μ	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, μ	1 J, ≤ 1 j	Yes	3.2	🟨 M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	🟨 LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	🟨 LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	🟩 LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	🟨 T mass 1.37 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	🟨 B mass 1.34 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $T_{5/3}T_{5/3} \vert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	🟨 $T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	CERN-EP-2018-171
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	3.2	🟨 Y mass 1.44 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c(YWb)$= $1/\sqrt{2}$	ATLAS-CONF-2016-072
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	🟨 B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	🟨 Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	🟨 q* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	🟨 q* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	🟨 b* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	🟩 ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	🟩 ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	🟨 N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	🟩 N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	🟨 $H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	🟩 $H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	🟩 spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	🟩 monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

🟩 $\sqrt{s}$ = 8 TeV 🟨 $\sqrt{s}$ = 13 TeV

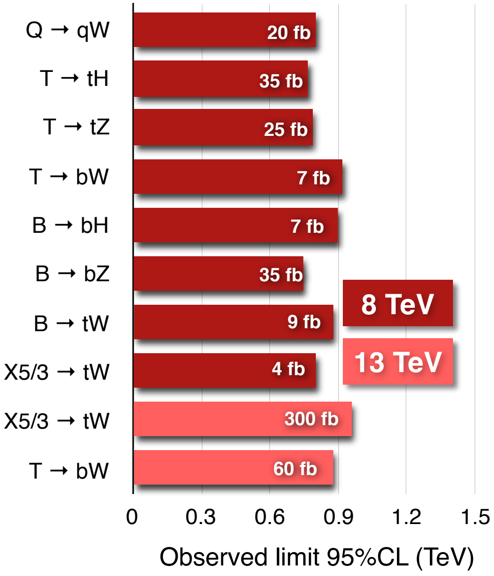
**Only a selection of the available mass limits on new states or phenomena is shown.*

†Small-radius (large-radius) jets are denoted by the letter j (J).

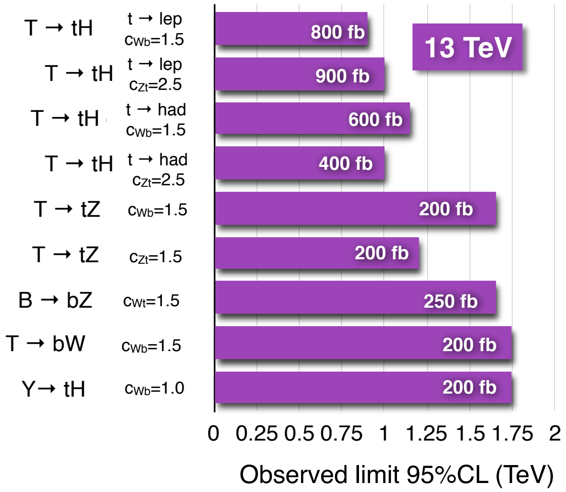


CMS Exotica Physics Group Summary – ICHEP, 2016

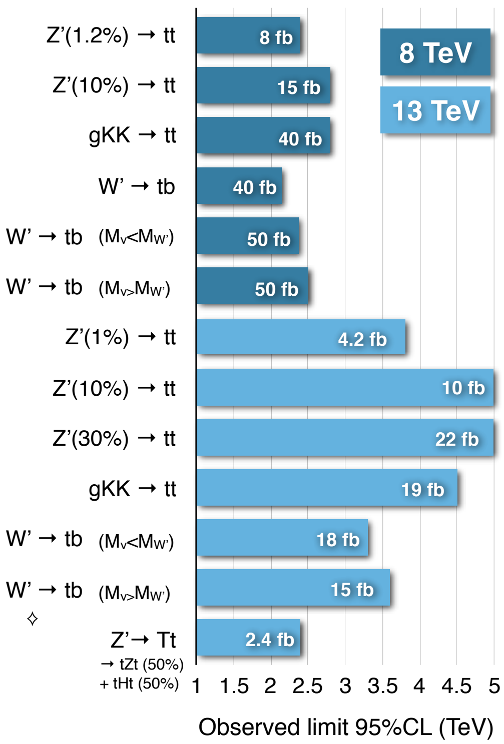
Vector-like quark pair production



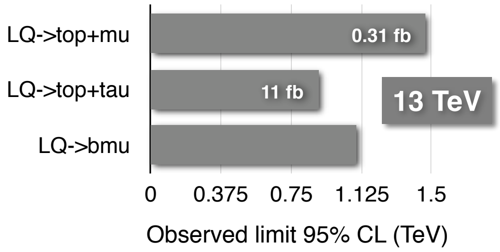
Vector-like quark single production



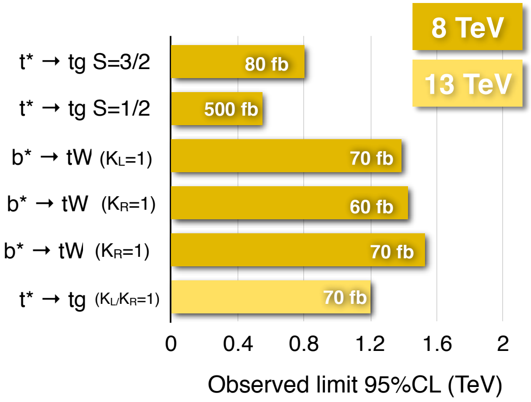
Resonances to heavy quarks



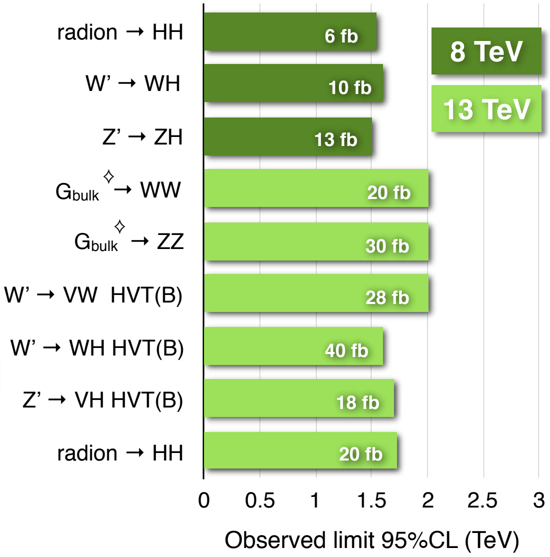
Leptoquarks



Excited quarks



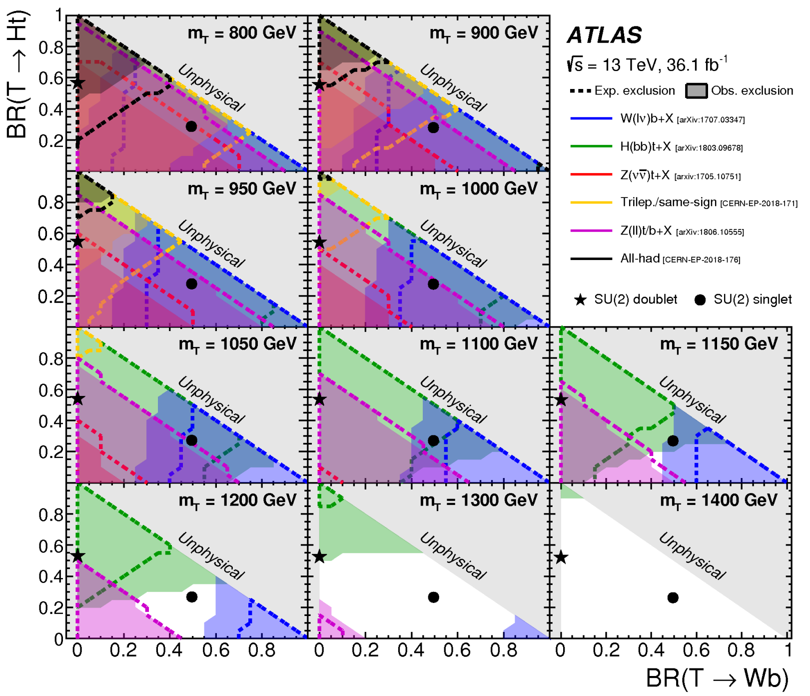
Resonances to dibosons

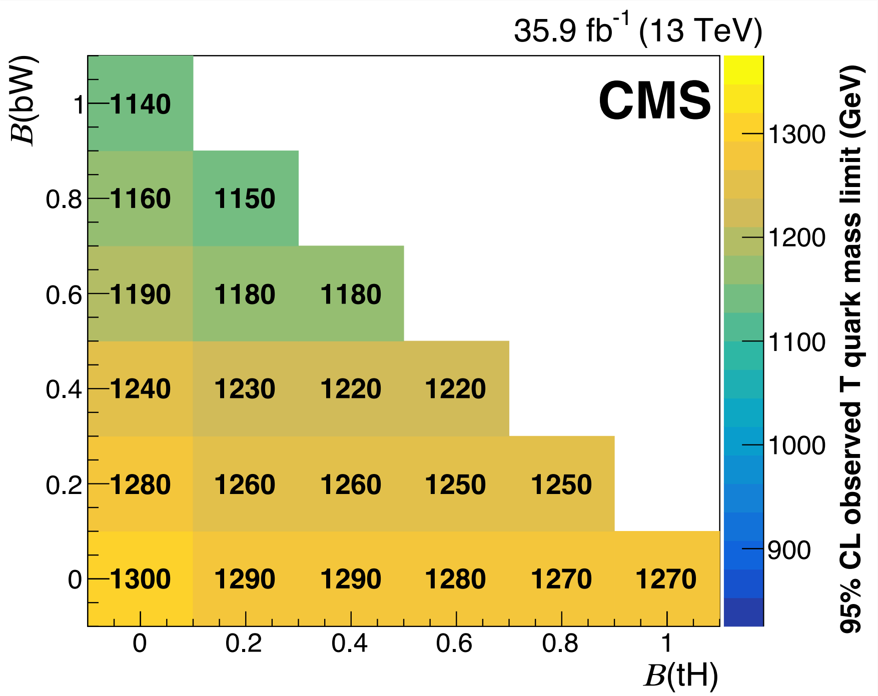


✧model-independent

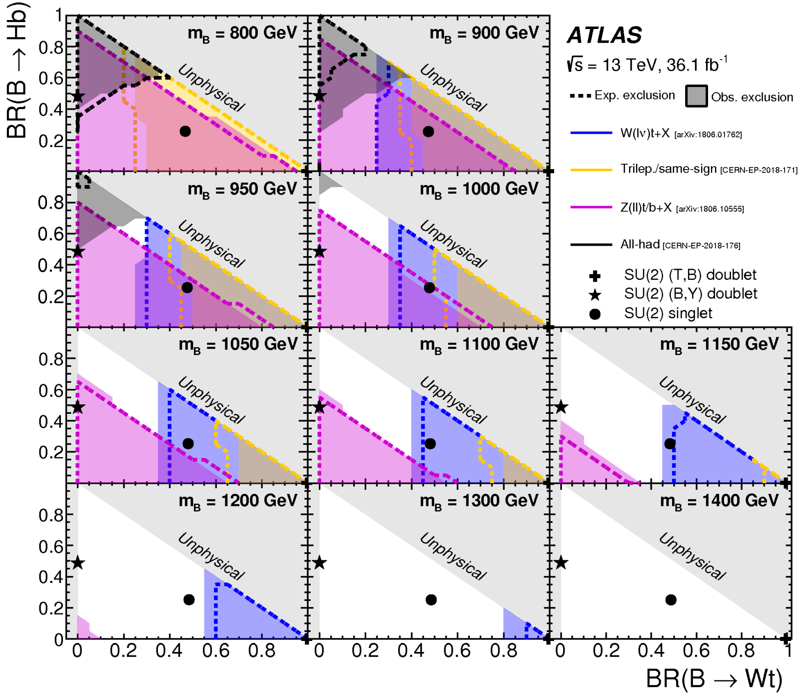
CMS

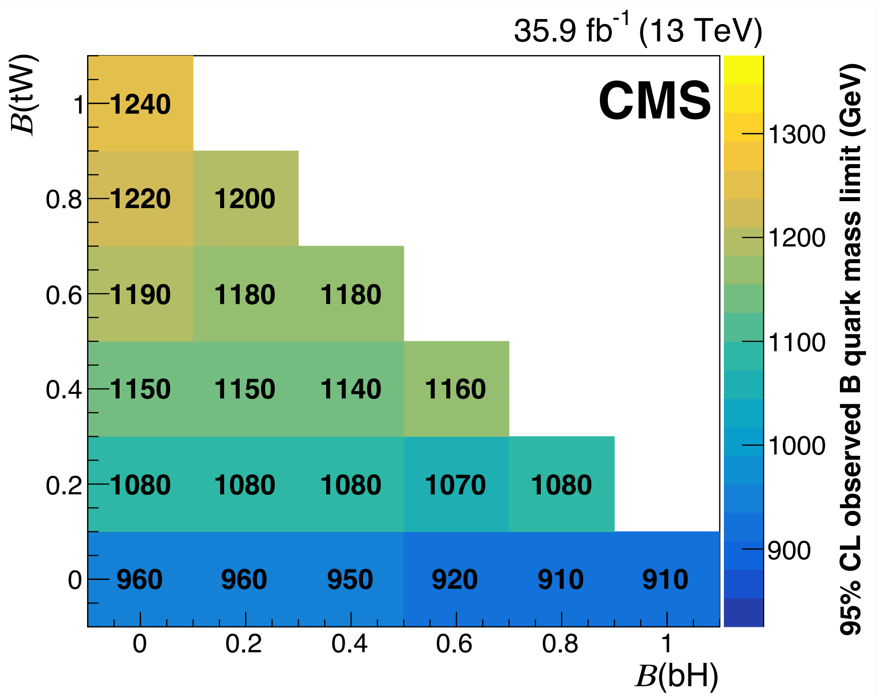
B2G
new physics searches with heavy SM particles





B(bW)						
1	1140					
0.8	1160	1150				
0.6	1190	1180	1180			
0.4	1240	1230	1220	1220		
0.2	1280	1260	1260	1250	1250	
0	1300	1290	1290	1280	1270	1270
	0	0.2	0.4	0.6	0.8	1
						B(tH)





B(tW)						
1	1240					
0.8	1220	1200				
0.6	1190	1180	1180			
0.4	1150	1150	1140	1160		
0.2	1080	1080	1080	1070	1080	
0	960	960	950	920	910	910
	0	0.2	0.4	0.6	0.8	1
						B(bH)

Fin

My personal perspective on LHC BSM searches, with some examples — *and caveats:*

My personal perspective on LHC BSM searches, with some examples — *and caveats:*

- Woefully incomplete

My personal perspective on LHC BSM searches, with some examples — *and caveats:*

- Woefully incomplete

- Surely biased

My personal perspective on LHC BSM searches, with some examples — *and caveats:*

- Woefully incomplete
- Surely biased
- Gratuitously self-indulgent

Continuing the latest phase of our **fantastic journey**…

Continuing the latest phase of our **fantastic journey**…

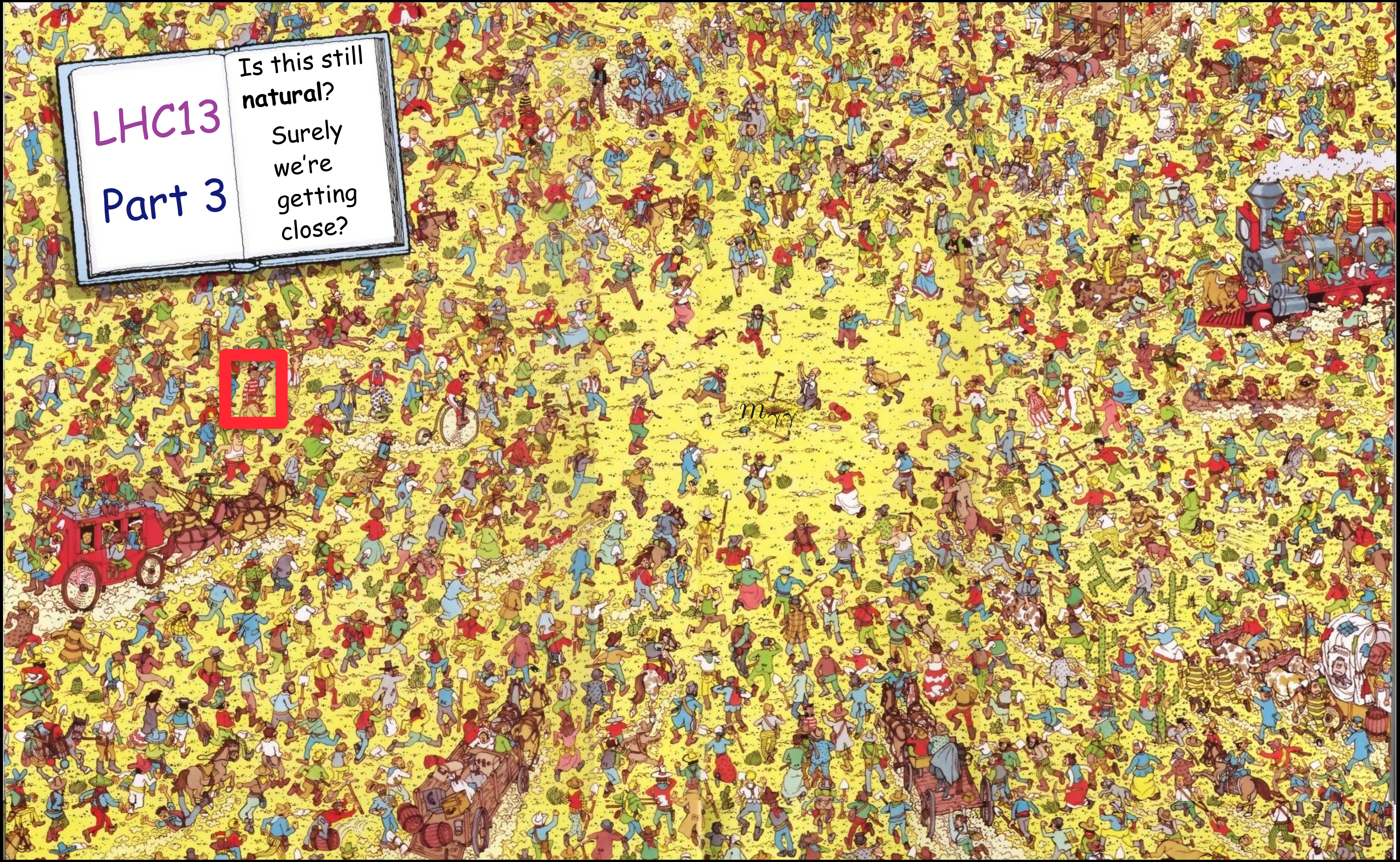
LHC13

Part 3

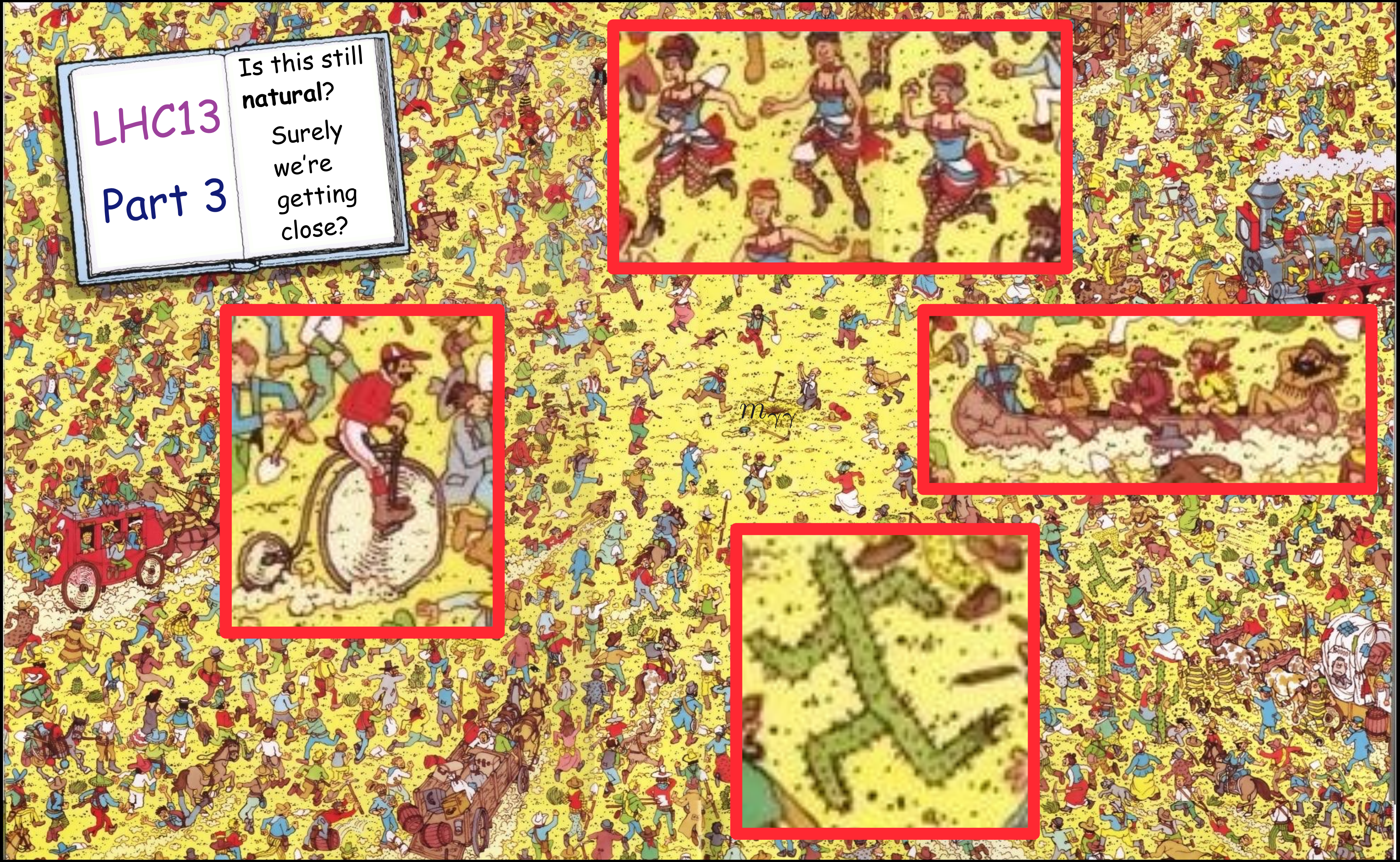
Is this still **natural**?

Surely we're getting close?

Not quite the right analogy…
…"BSM" isn't one signature that we simply look for



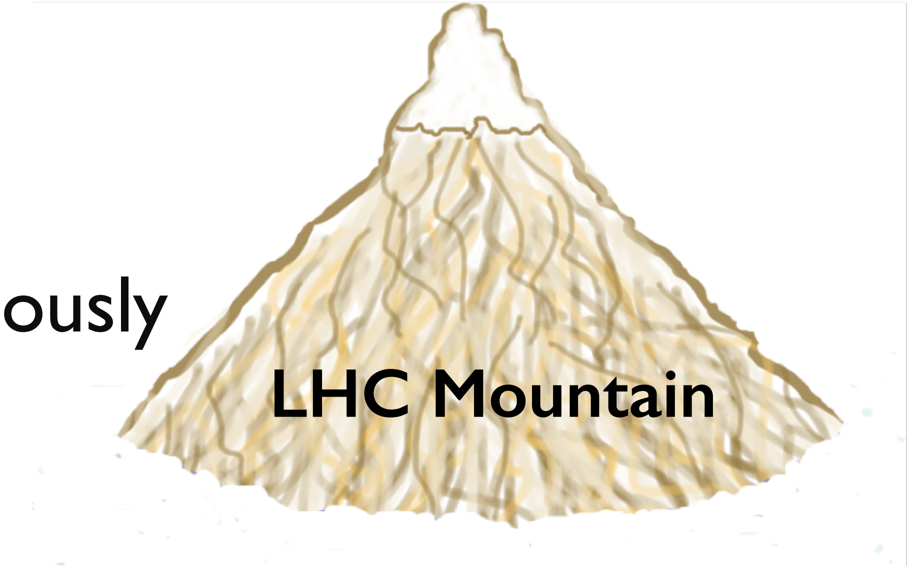
Rather: *Is this what the LHC13 is supposed to look like? Are our observations consistent with the SM?*



Searching Collider Phase Space for BSM

Less like searching
for a single person…

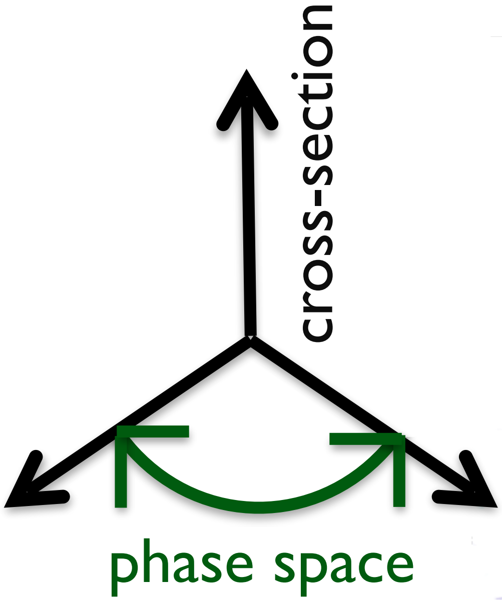
More like exploring a previously
unvisited landscape,
searching for new
flora/fauna/geographical features

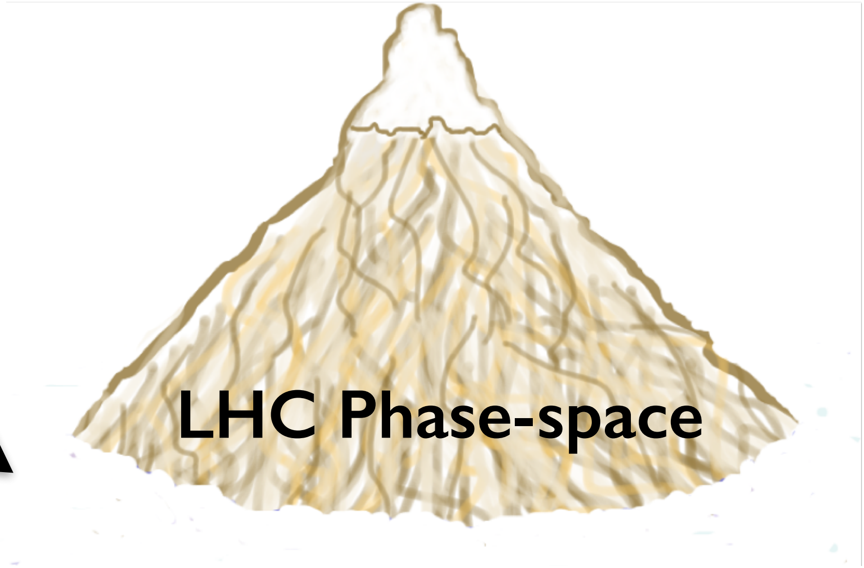


Searching Collider Phase Space for **BSM**

The elevation represents the rate of production of different types of collision events

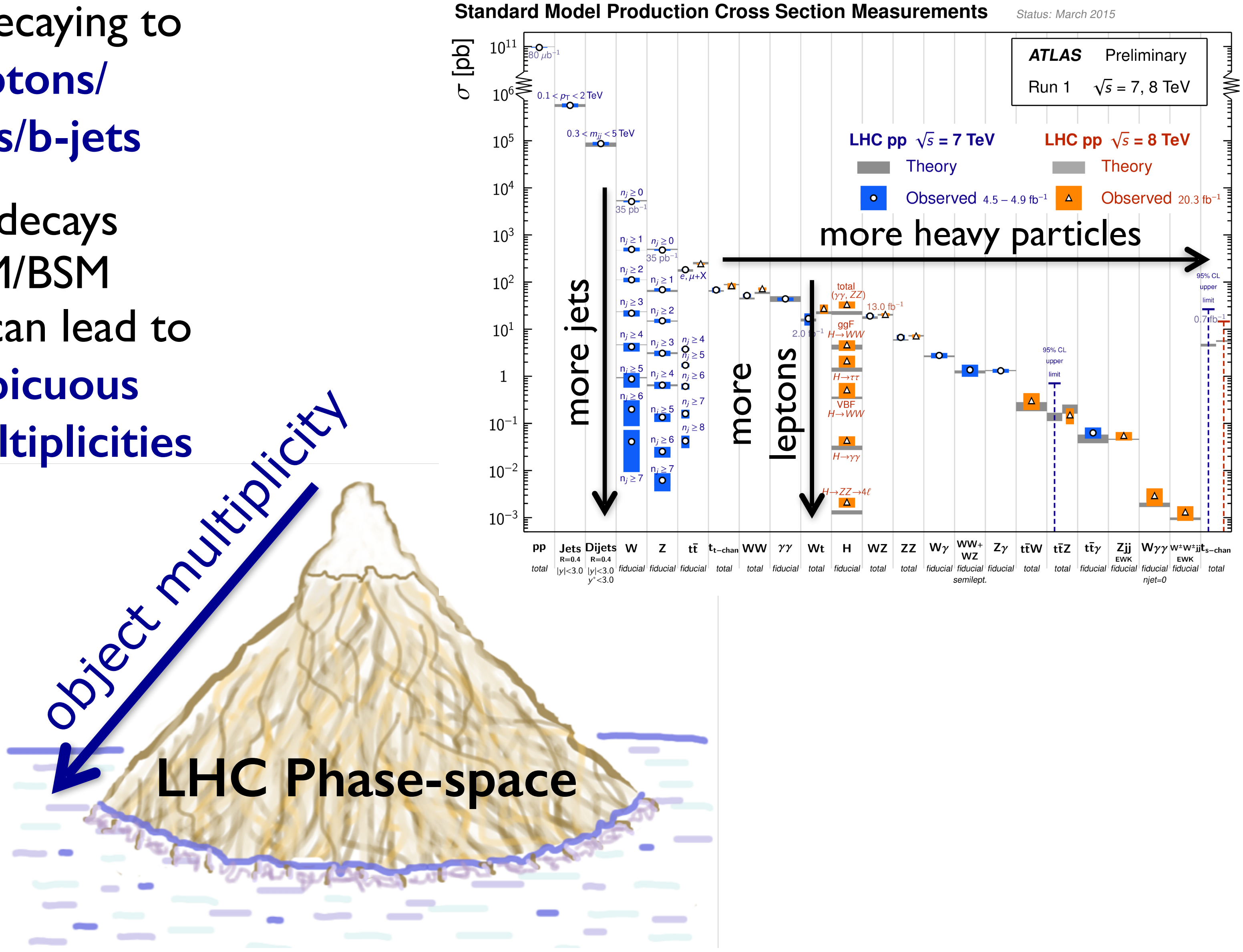
The lateral distance from the center of the mountain represents what's in those collision events, i.e. how rare they are



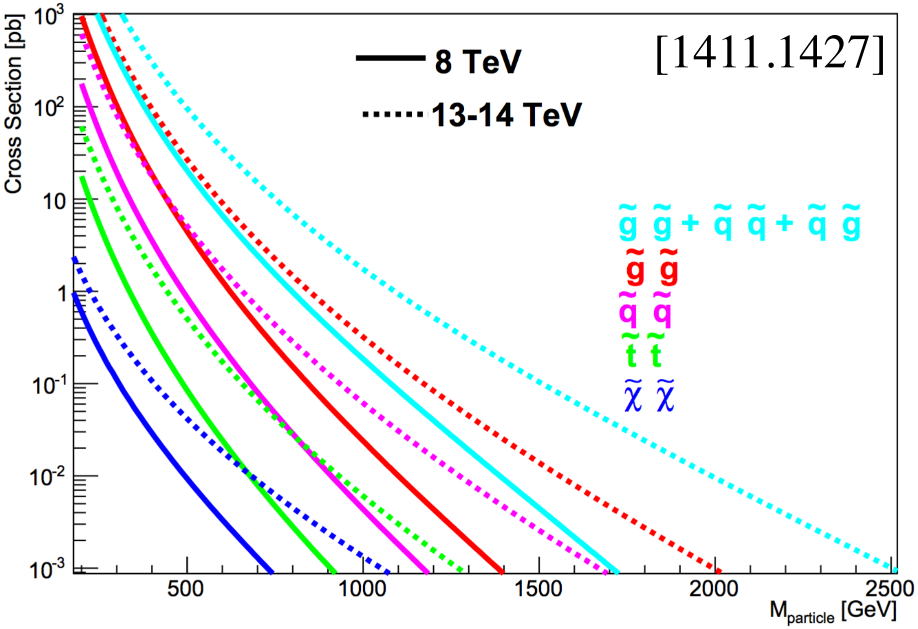


Searching Collider Phase Space for **BSM**

- Particles decaying to **W/Z/γ/leptons/ top quarks/b-jets**
- Cascading decays through SM/BSM spectrum can lead to **high/conspicuous object multiplicities**

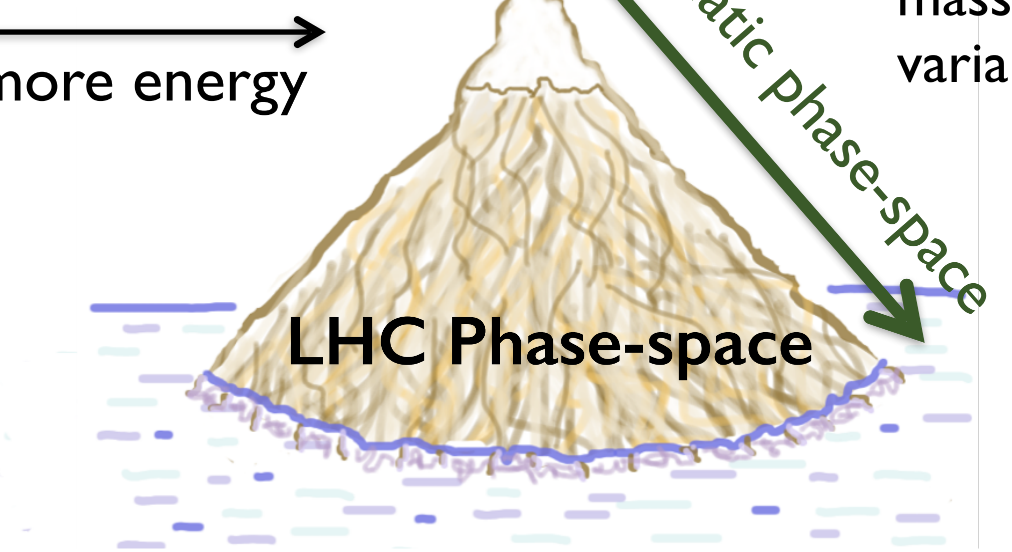


Searching Collider Phase Space for **BSM**



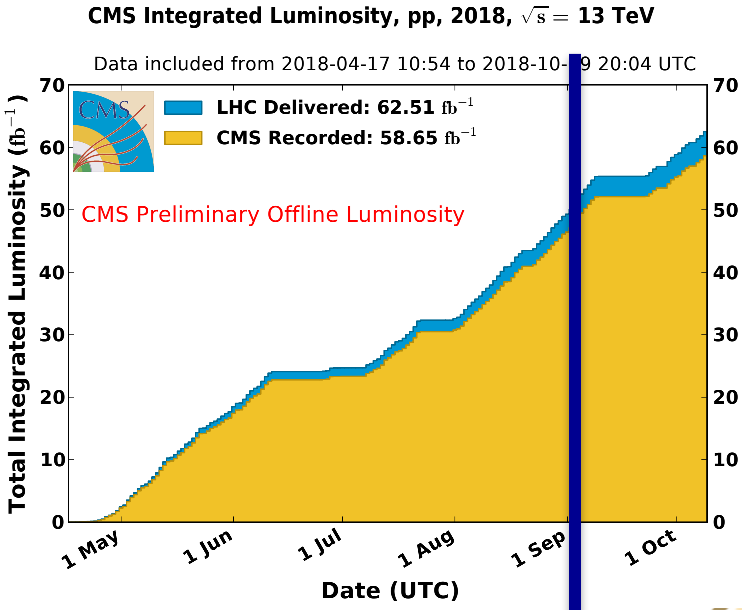
more mass ⇒ more energy

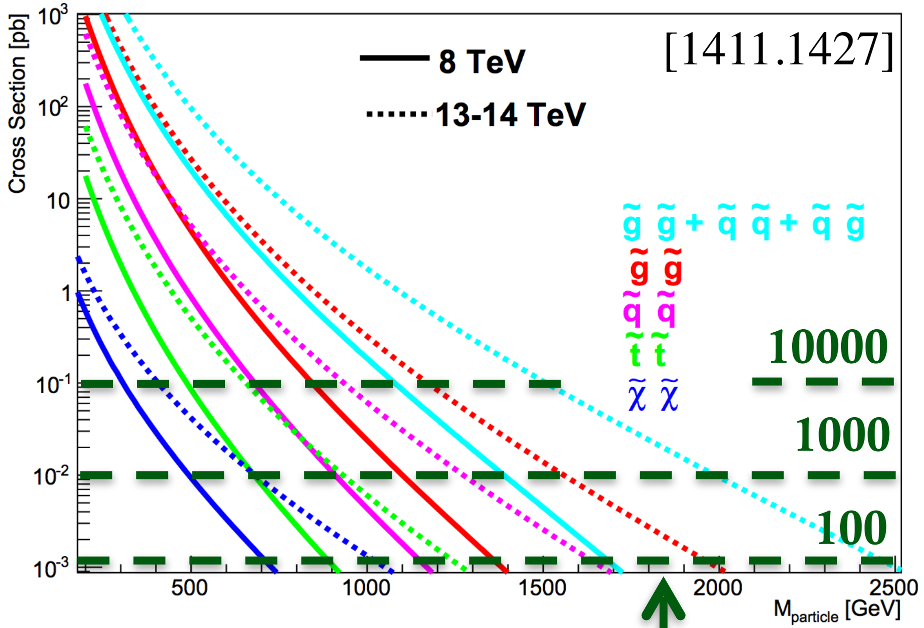
- Heavy BSM particles decaying to SM particles
  → **large visible momenta**
- New symmetry conservation
  → **large missing momenta**
- Resonances, kinematic edges, mass sensitive variables…



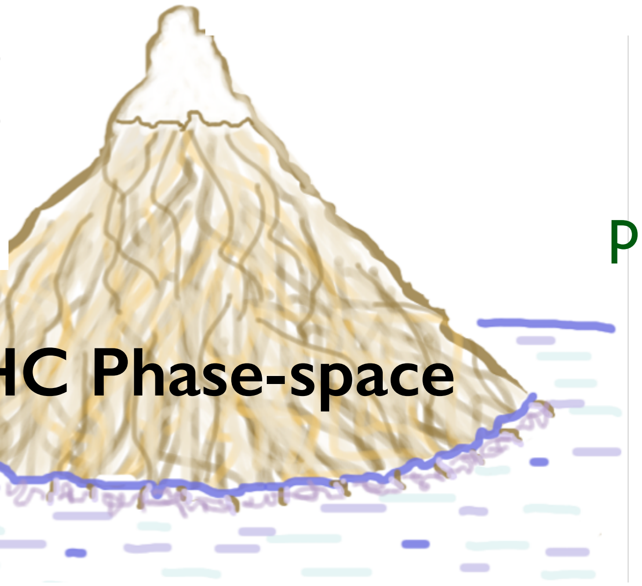
Searching Collider Phase Space for **BSM**

more integrated luminosity (more data) reveals more of the phase-space





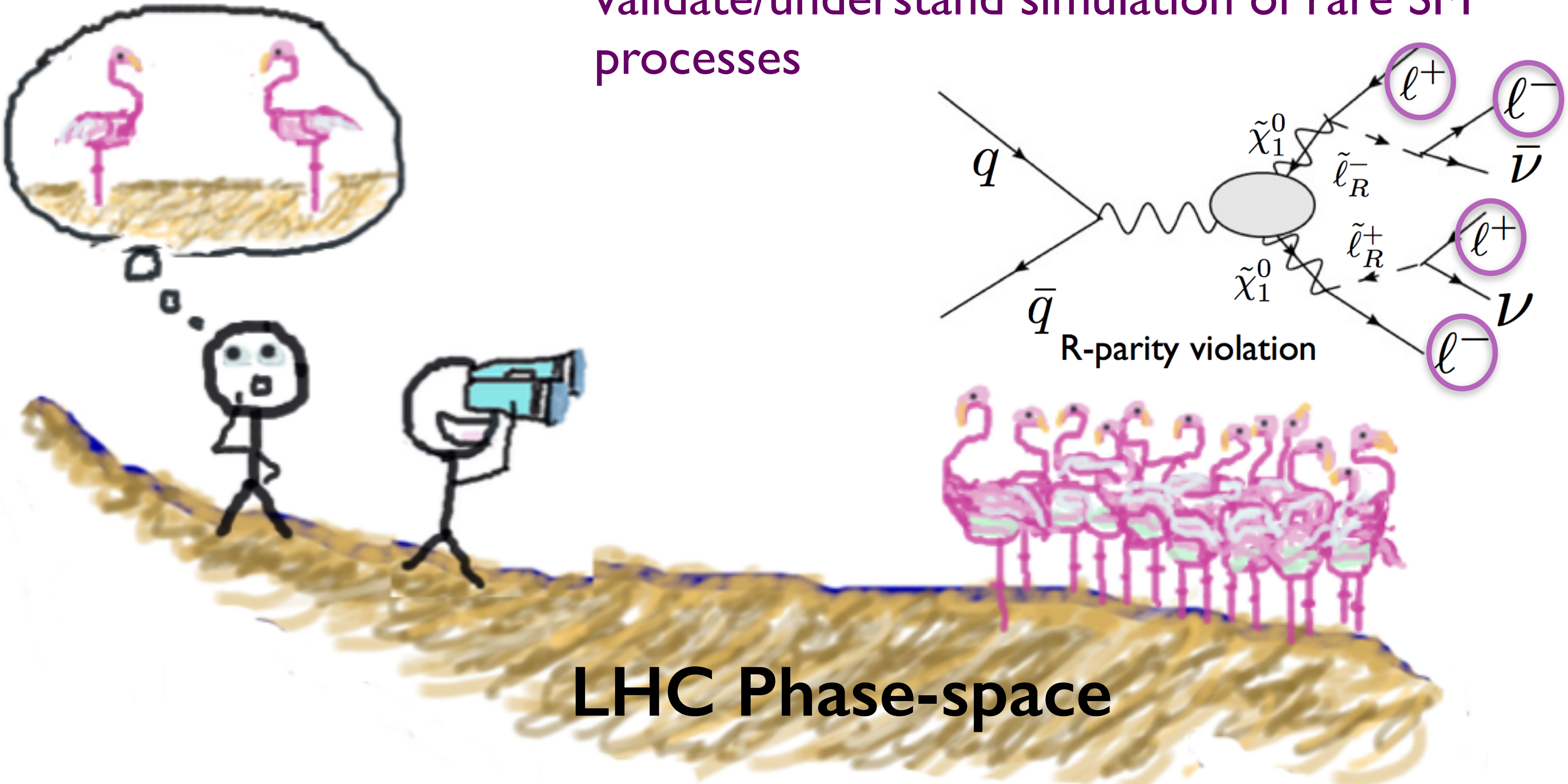
100 events produced / 100 fb^{-1}



Searching for rare BSM events

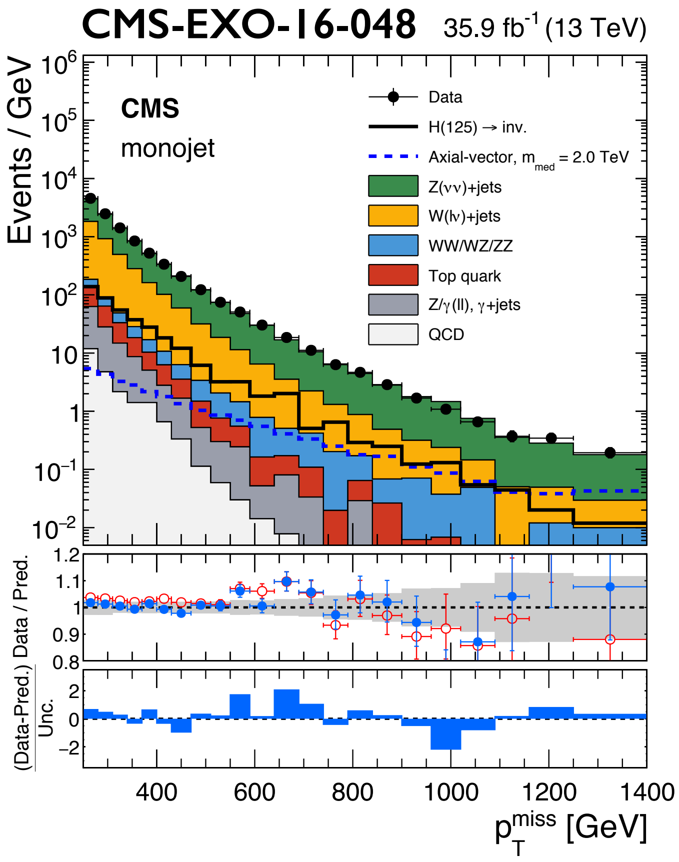
- BSM physics can potentially produce event topologies rarely seen in the SM
- Must control/measure object fake-rates and validate/understand simulation of rare SM processes

$Z + \text{jets}, ZZ, Z\gamma, WZ, \cdots$



Searching for general **BSM** excesses

- BSM can produce an excess of events with interesting kinematic features (large missing transverse energy, momentum, mass)
- Final states with non-interacting particles can lead to 'broad' excesses in the tails of these kinematic distributions



Searching for general **BSM** excesses

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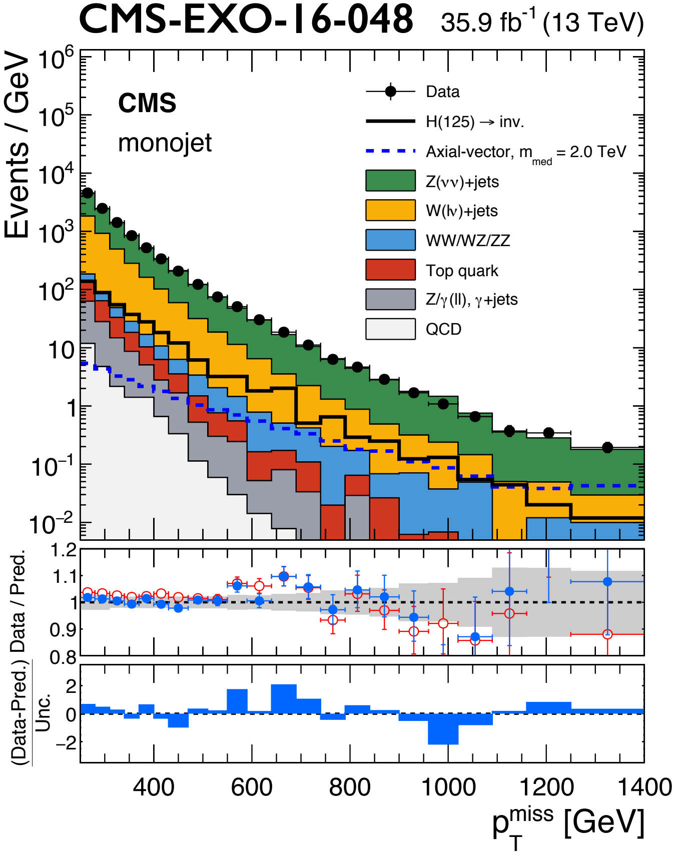
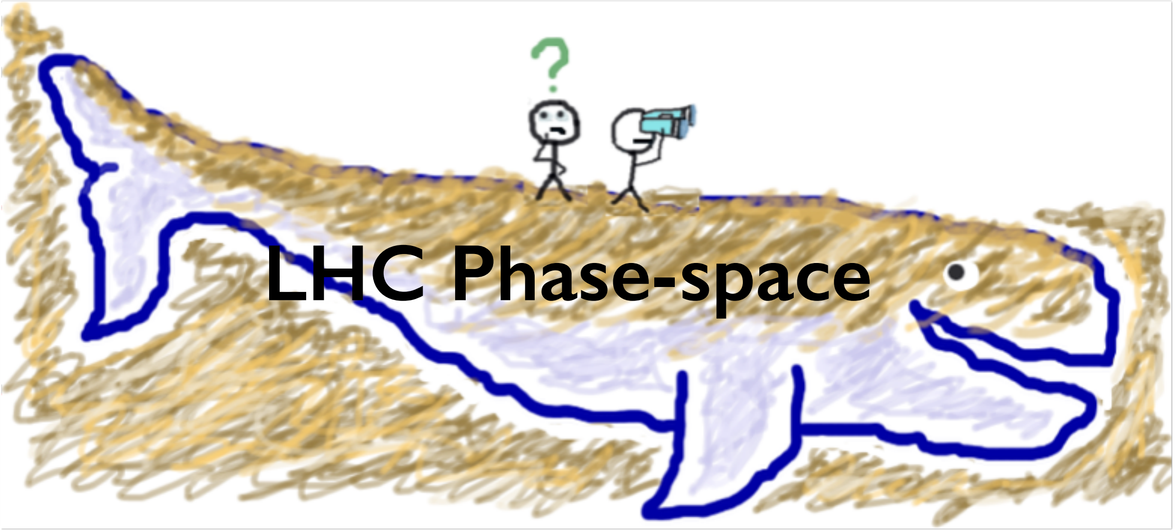
CMS-EXO-16-048



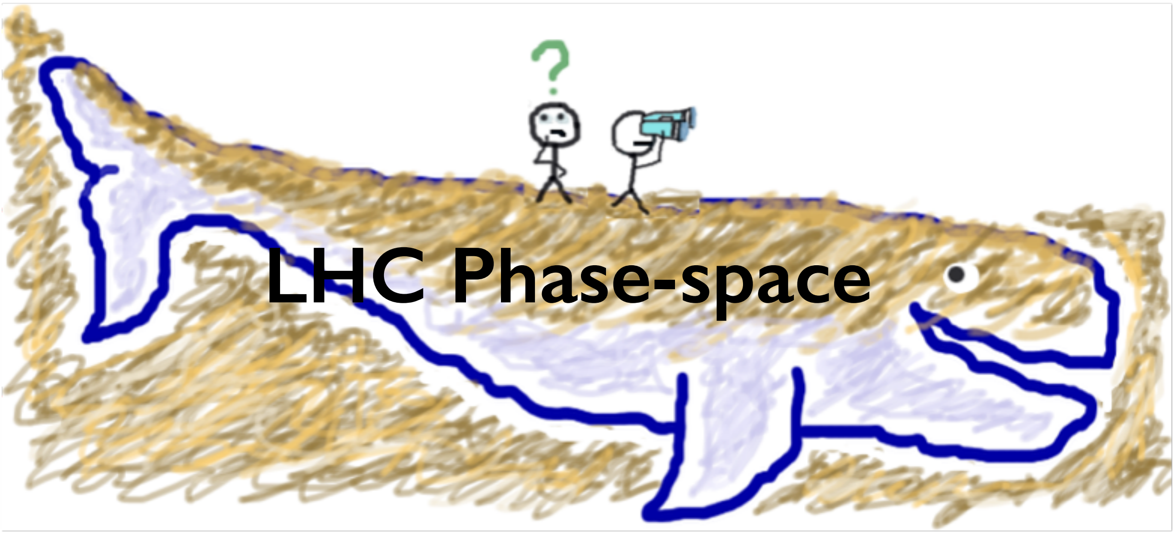
- Must have an accurate reference expectation for the SM to see subtle features!



Searching for general **BSM** excesses

Nearby regions of phase space are often necessary to contextualize our observations in signal sensitive regions

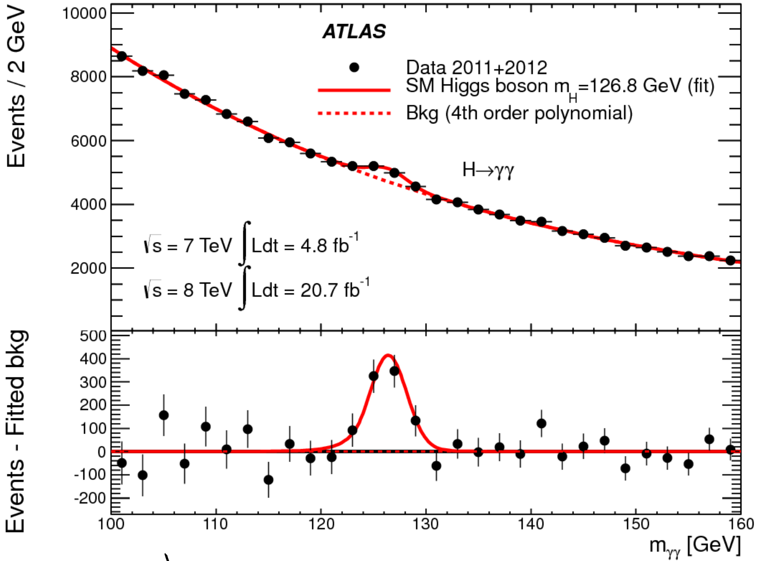
sidebands, control regions, …

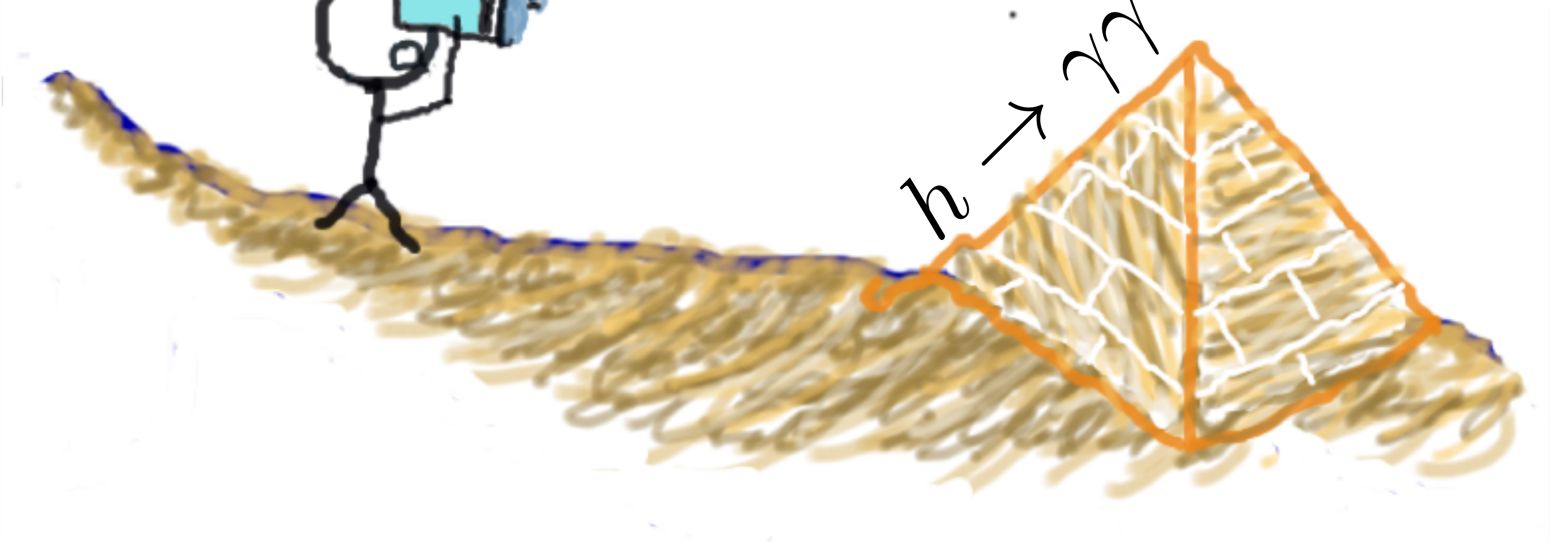


Searching for **BSM** kinematic features

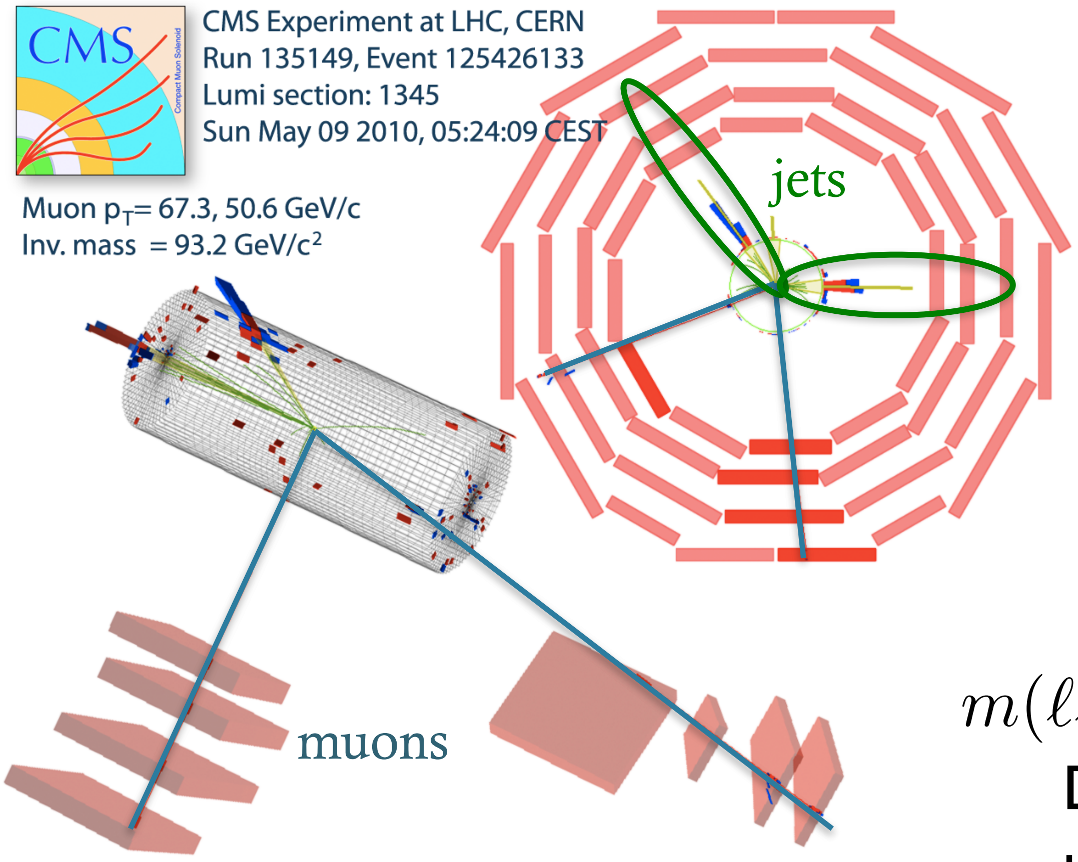
- New physics can produce kinematic features that are not expected in the SM – bumps, edges, kinks…
- Understanding/measuring/improving physics object reconstruction **essential for being able to resolve these features**

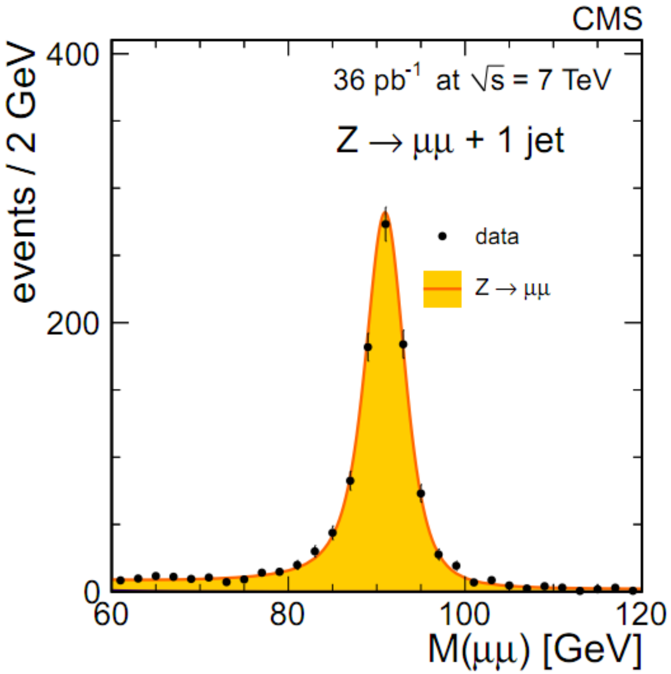
Phys. Lett. B 726 (2013), pp. 88-119





Standard Model Signposts $Z(\mu\mu)$





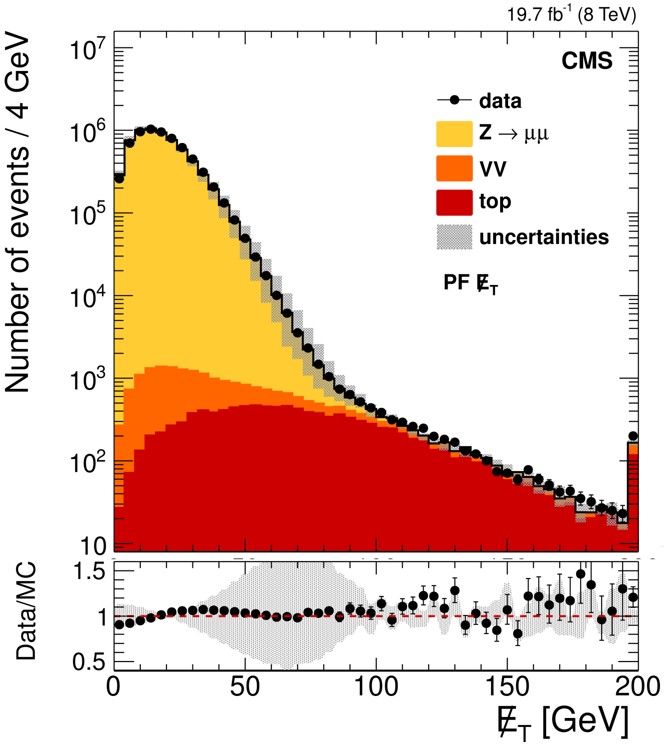
$m(\ell\ell)$ *peaks* at $m_Z \sim 91$ GeV

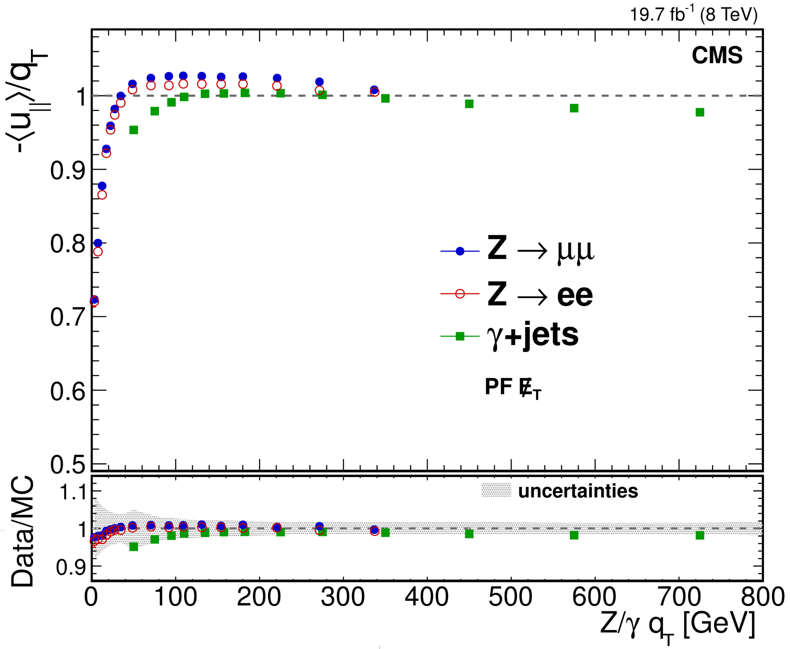
Di-lepton invariant mass is used to identify Z bosons

SM scale ‘candle’ used to calibrate detectors, commission object reconstruction and study backgrounds to new physics

The view from the pole(s)

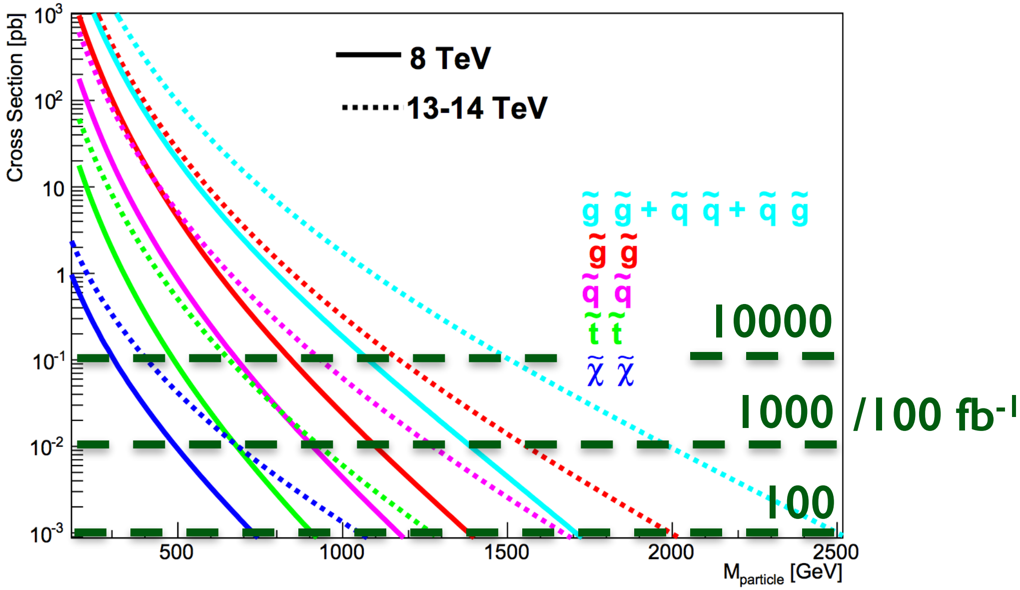
- LHC searches begin at **'the pole'**: W/Z bosons, tops, quarkonia candles
- Used to: select control samples of leptons, photons, b-jets, …
  calibrate/measure object reconstruction performance, fake-rates, energy scales
  validate our understanding of the SM in new phase-space

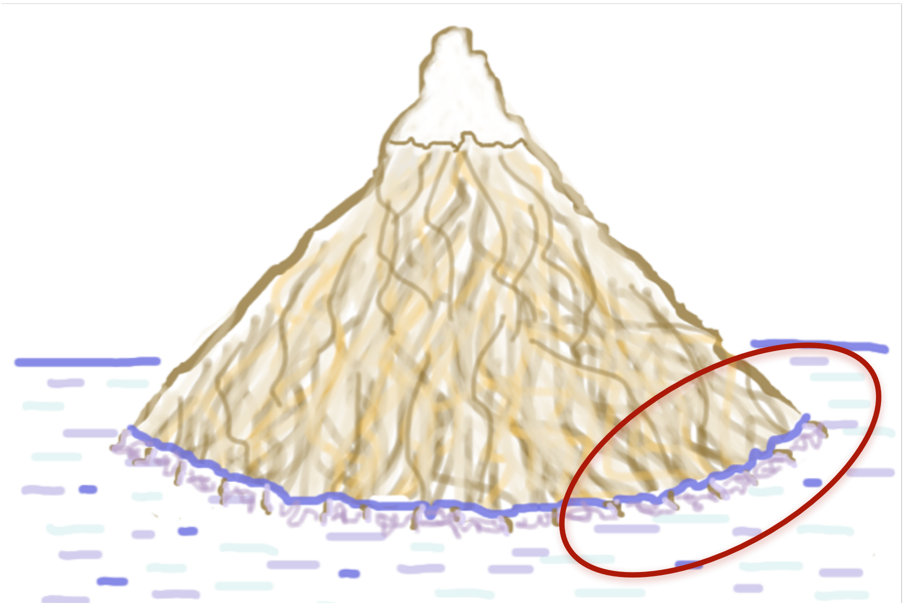




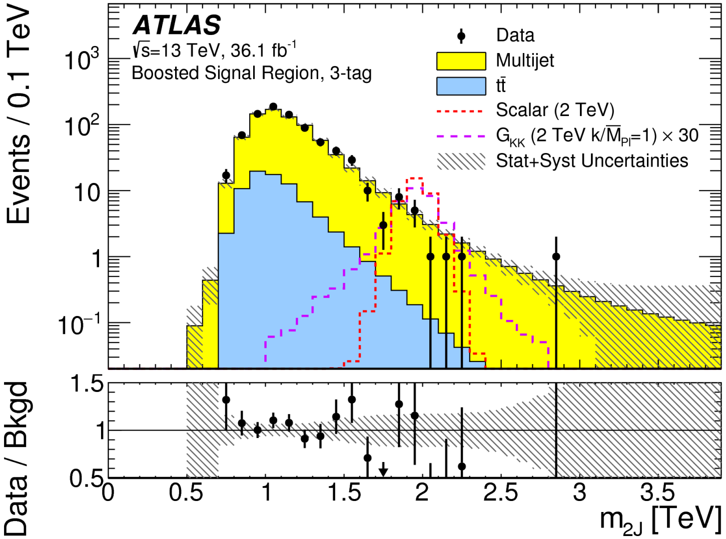
JINST 10 (2015) P02006

Searches at the shore



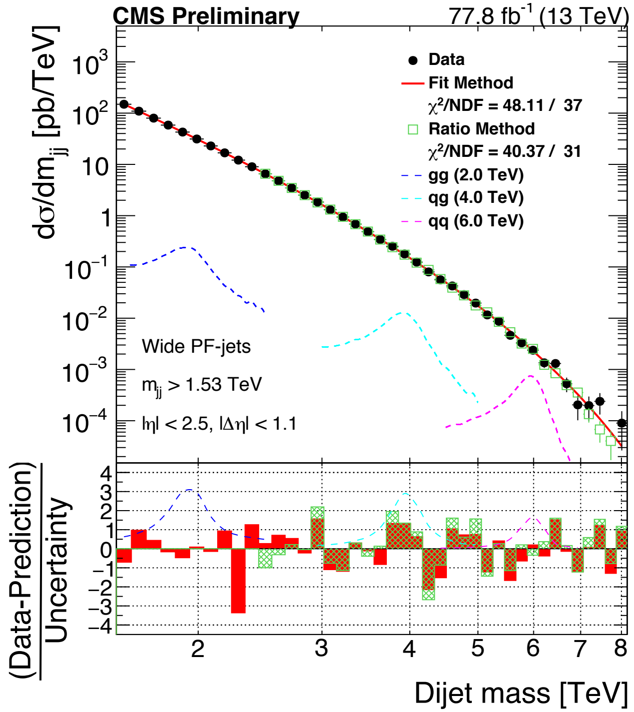


arXiv: 1804.06174



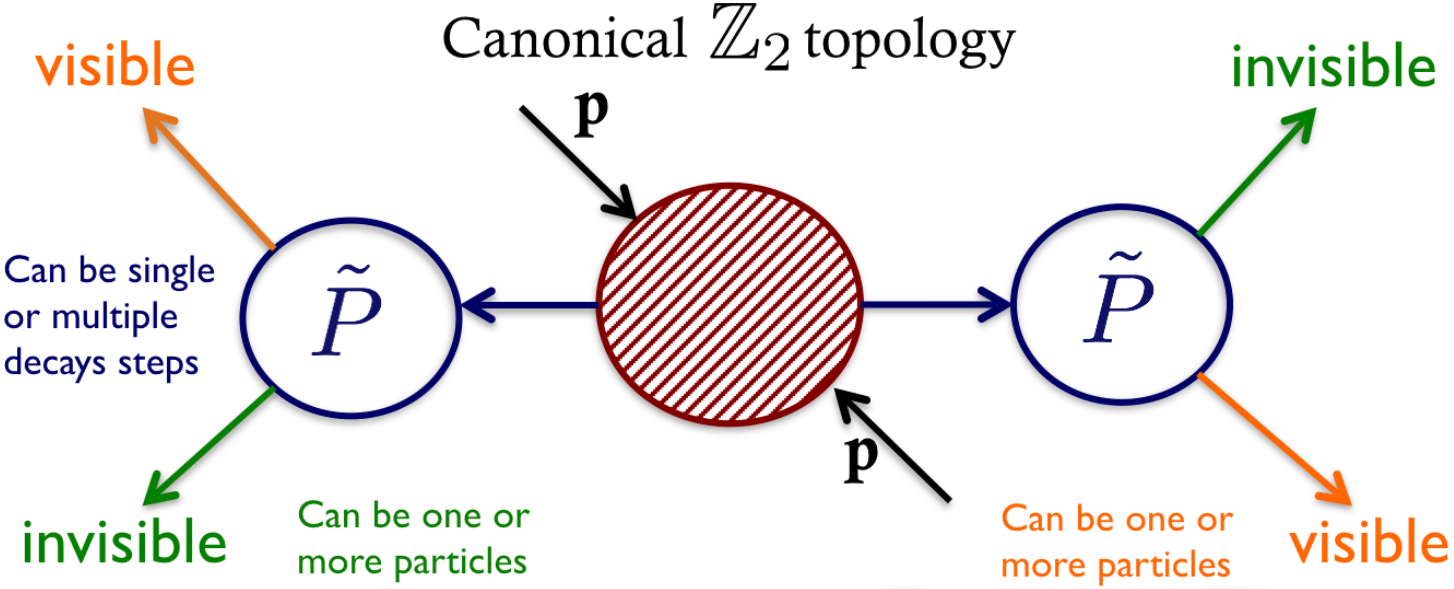
$X \to hh \to bbbb$

CMS-PAS-EXO-17-026

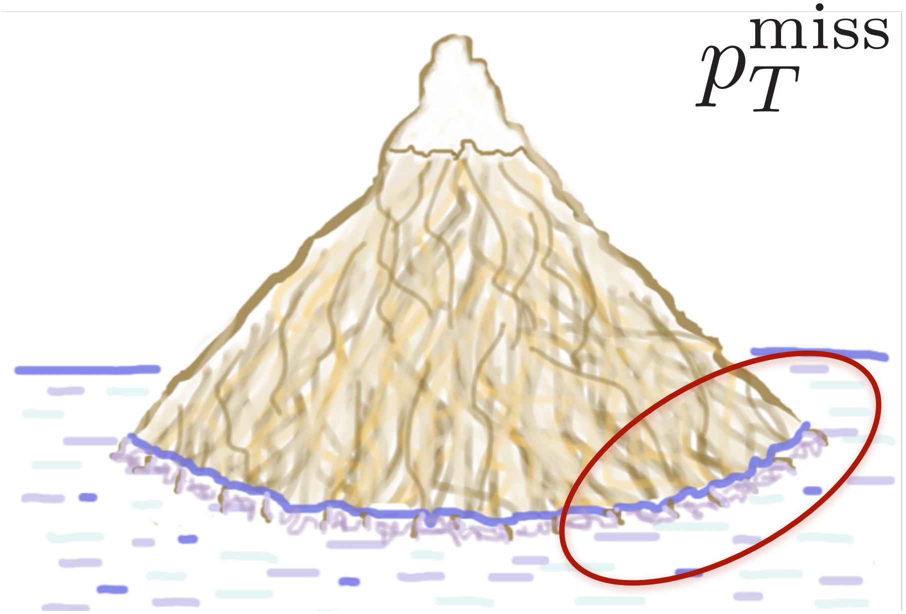


$X \to jj$

Searches at the shore



Canonical $\mathbb{Z}_2$ topology



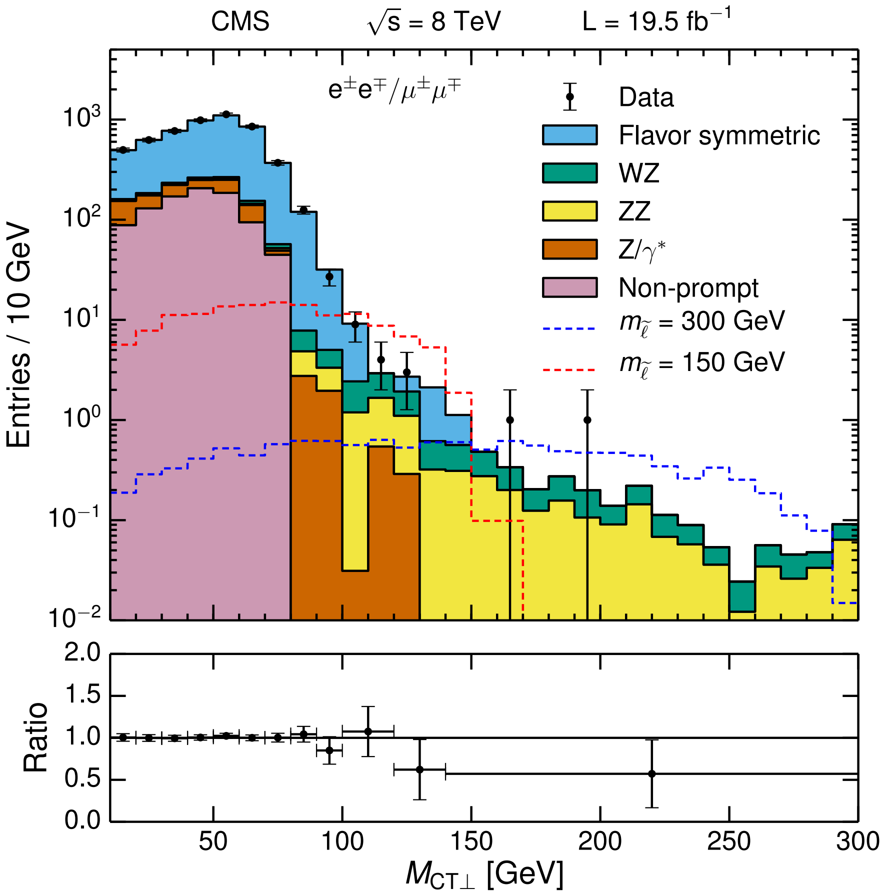
$$p_T^{\text{miss}} \sim m_{\tilde{P}} - \Sigma m_{\text{SM}} - m_{\tilde{\chi}}$$

Theory	$\mathbb{Z}_2$
SUSY	R-parity
Little Higgs	T-parity
UED	KK-parity

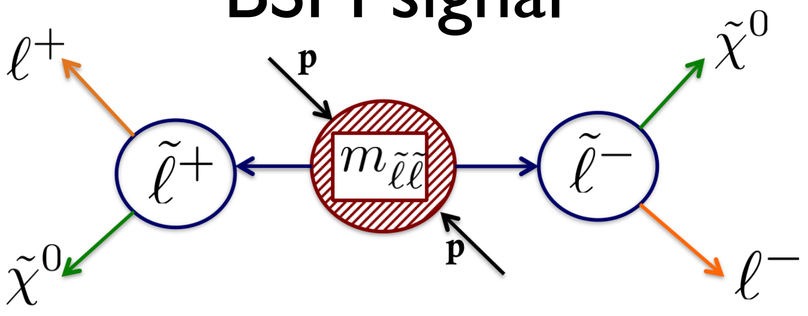
Searches at the shore

$$2\ell + E_T^{\mathrm{miss}}$$

EPJC 74 (2014) 3036 [1405.7570]

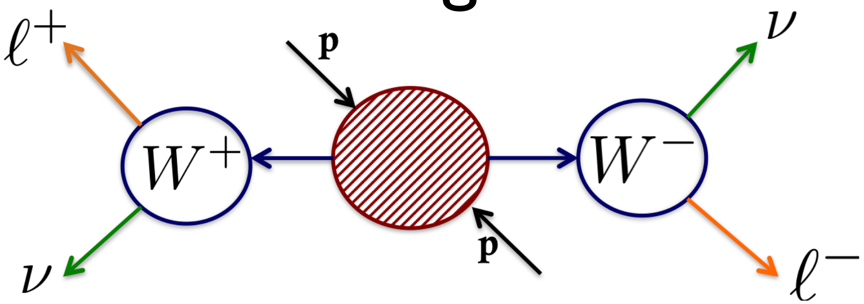


BSM signal



$$\max M_{\mathrm{CT}\perp} \sim \frac{m_{\tilde\ell}^2 - m_{\tilde\chi}^2}{m_{\tilde\ell}}$$

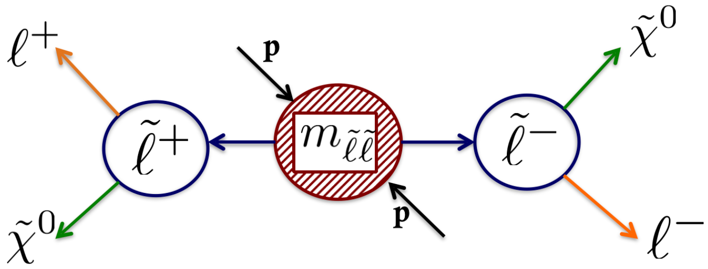
SM background

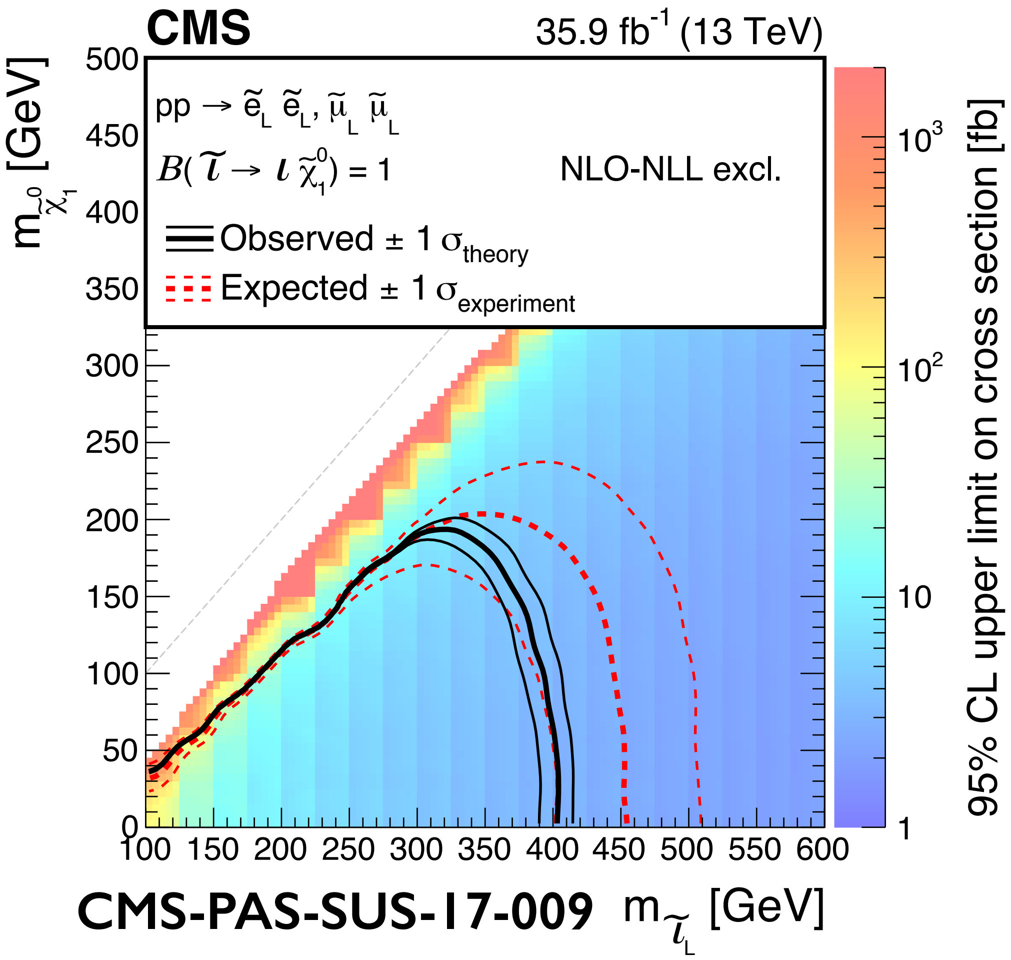


$$\max M_{\mathrm{CT}\perp} \sim \frac{m_W^2 - m_\nu^2}{m_W} \sim m_W$$

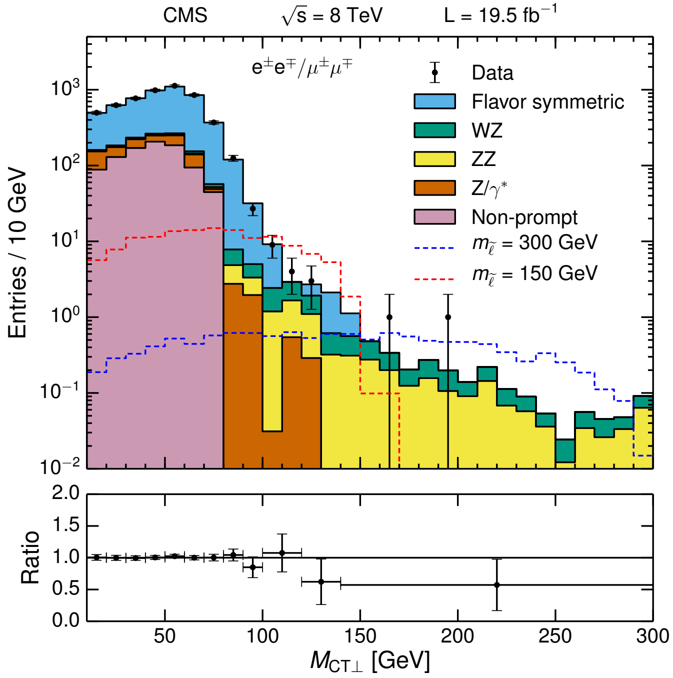
Searches at the shore

$2\ell + E_T^{\mathrm{miss}}$



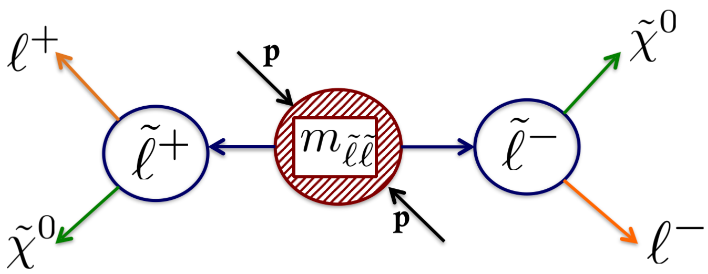


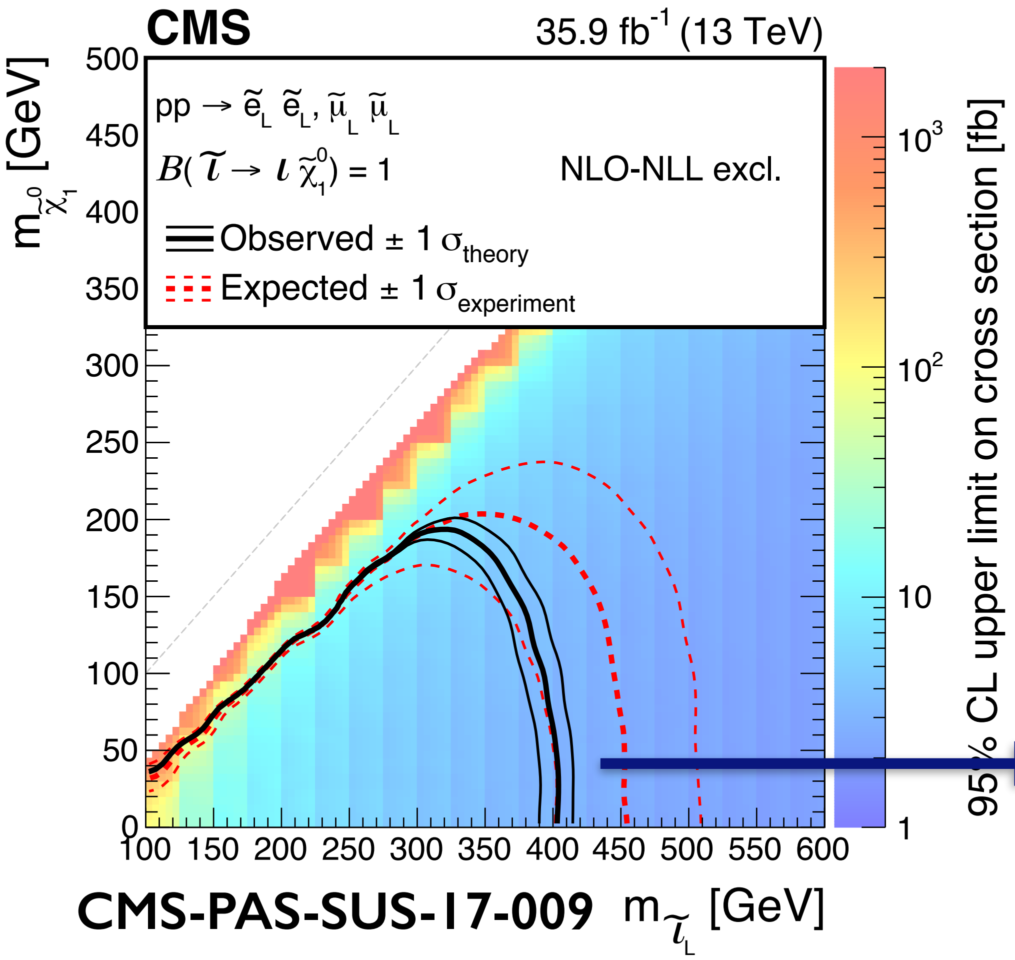
CMS-PAS-SUS-17-009



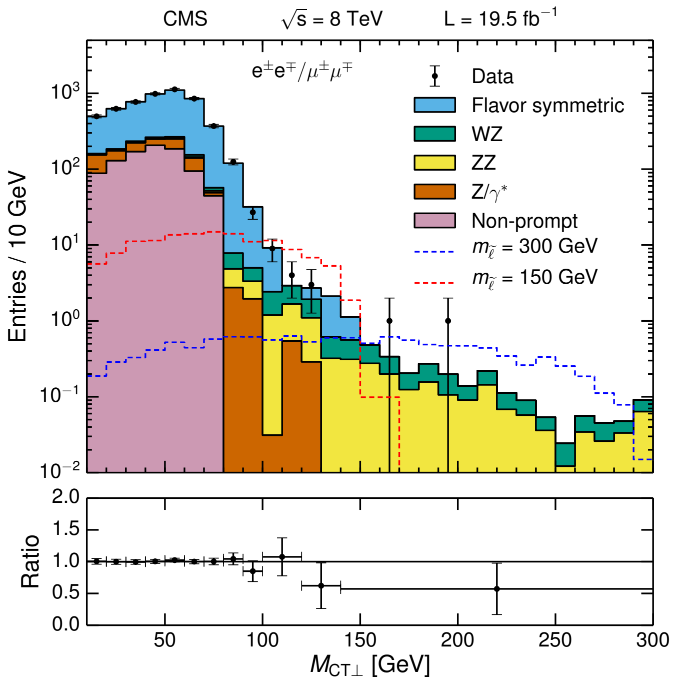
Searches at the shore

$2\ell + E_T^{\text{miss}}$





CMS-PAS-SUS-17-009

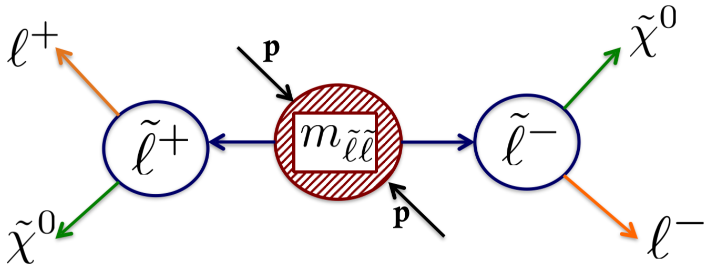


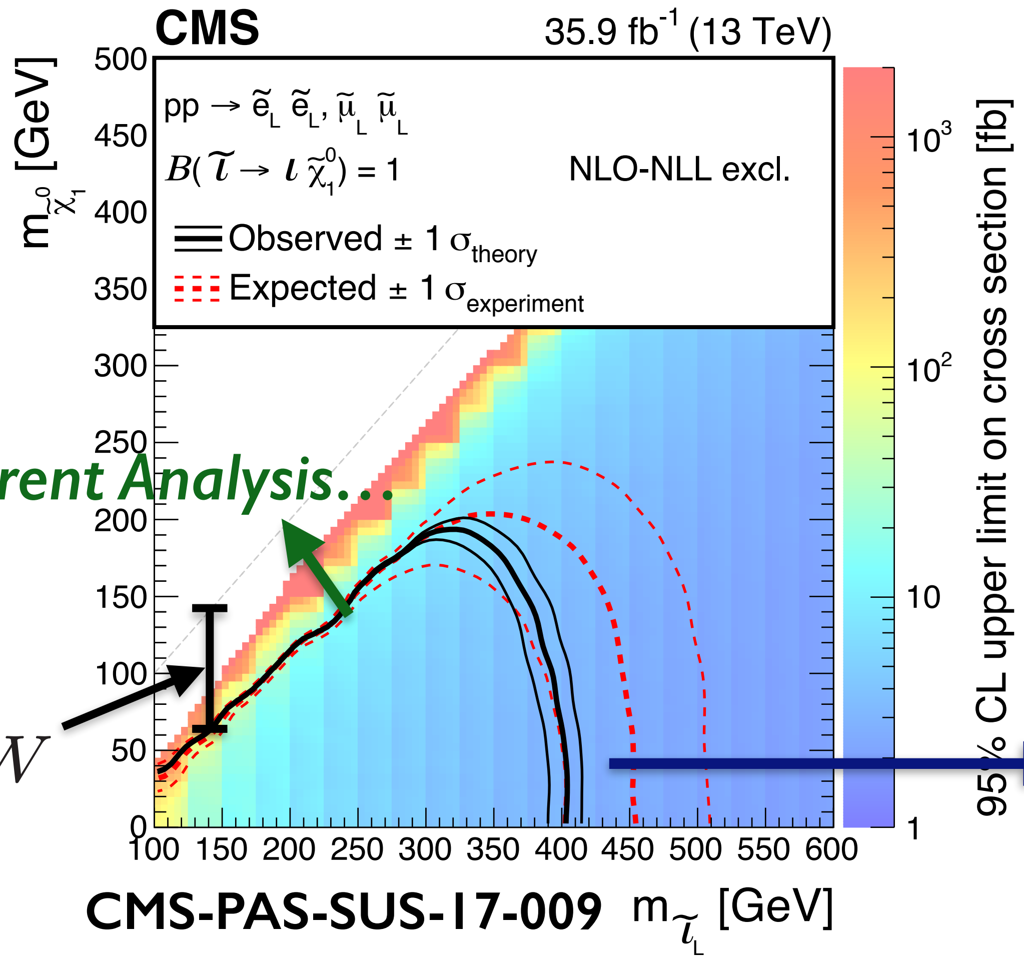
Higher collision energy

More data

Searches at the shore

$2\ell + E_T^{\rm miss}$

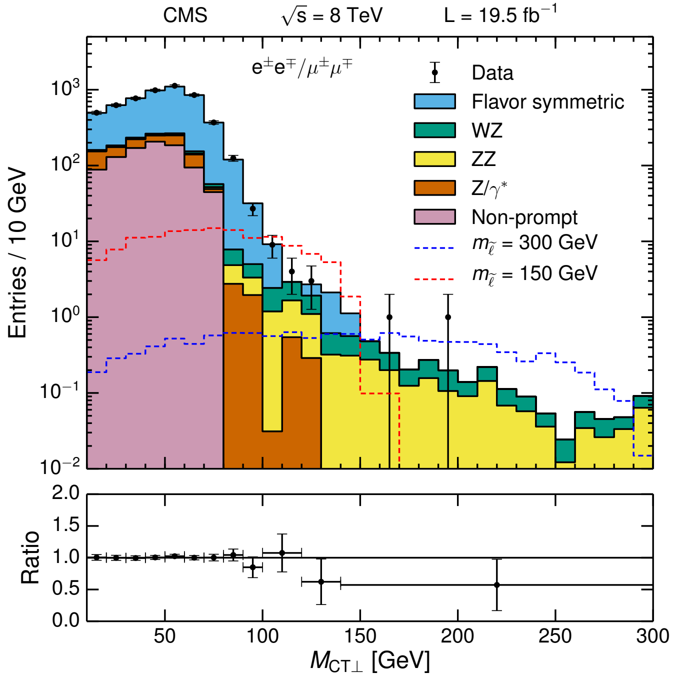




Different Analysis…

m_W

CMS-PAS-SUS-17-009



Higher collision energy

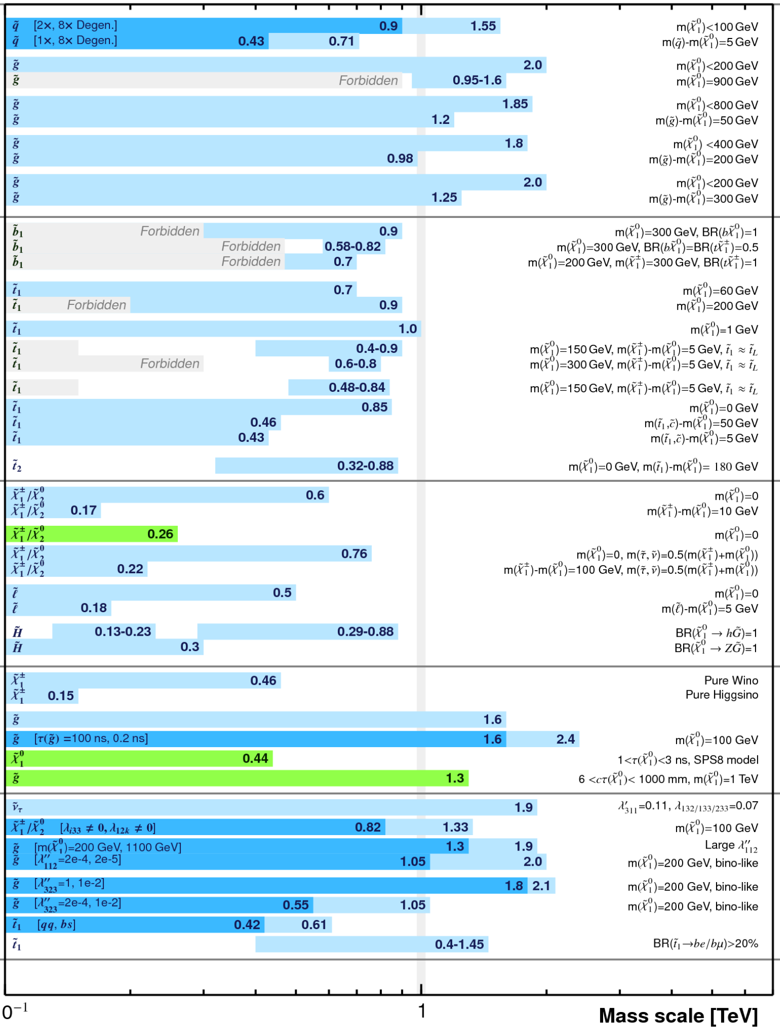
More data

ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

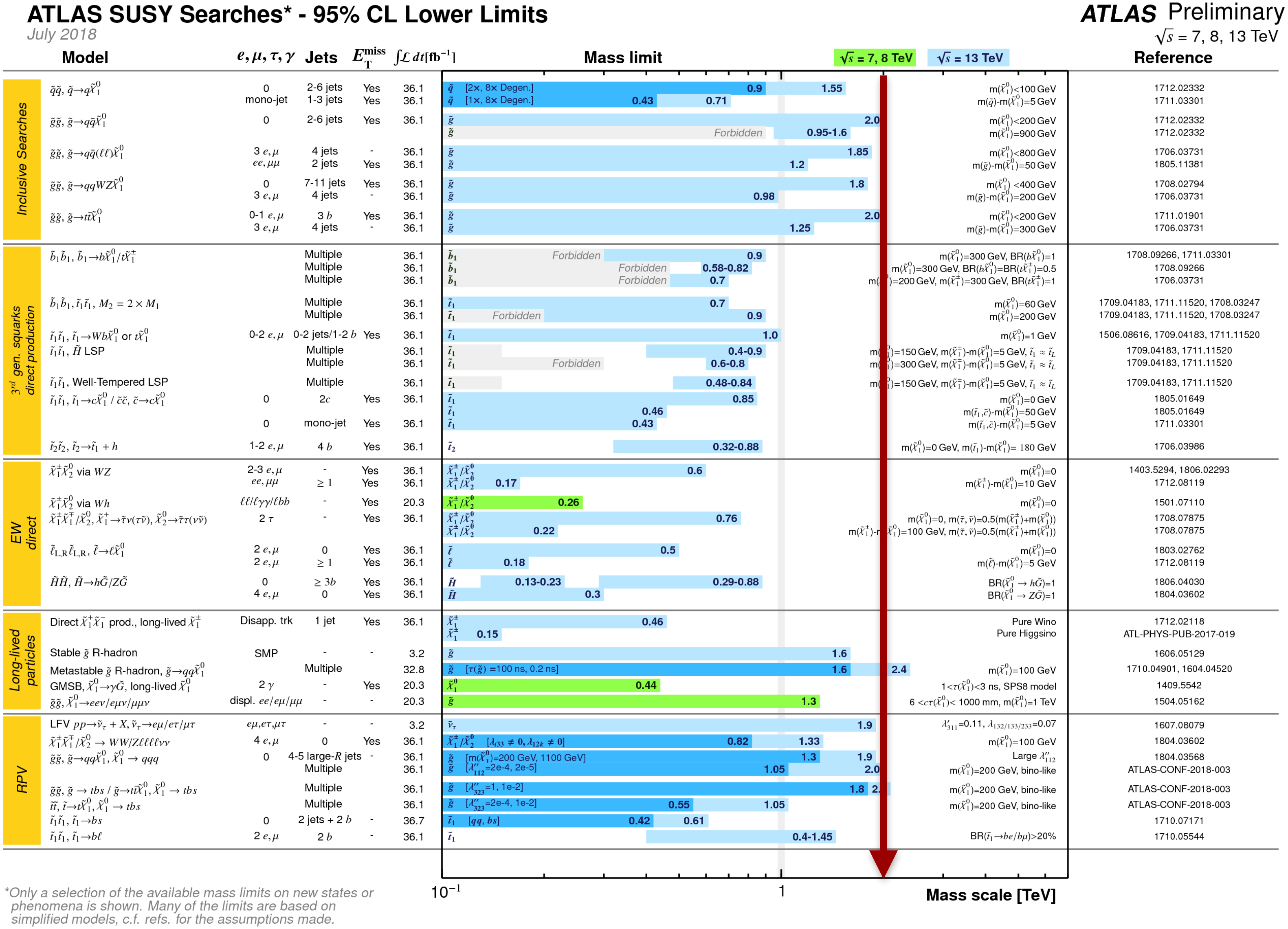
ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV



	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	$\tilde{q}$ [2×, 8× Degen.] 0.9 1.55	m($\tilde{\chi}^0_1$)<100 GeV	1712.02332
		mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$ [1×, 8× Degen.] 0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.0	m($\tilde{\chi}^0_1$)<200 GeV	1712.02332
						$\tilde{g}$ *Forbidden* 0.95-1.6	m($\tilde{\chi}^0_1$)=900 GeV	1712.02332
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	3 e, μ	4 jets	-	36.1	$\tilde{g}$ 1.85	m($\tilde{\chi}^0_1$)<800 GeV	1706.03731
		$ee, \mu\mu$	2 jets	Yes	36.1	$\tilde{g}$ 1.2	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	0	7-11 jets	Yes	36.1	$\tilde{g}$ 1.8	m($\tilde{\chi}^0_1$) <400 GeV	1708.02794
		3 e, μ	4 jets	-	36.1	$\tilde{g}$ 0.98	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV	1706.03731
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e, μ	3 b	Yes	36.1	$\tilde{g}$ 2.0	m($\tilde{\chi}^0_1$)<200 GeV	1711.01901
		3 e, μ	4 jets	-	36.1	$\tilde{g}$ 1.25	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV	1706.03731
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1/t\tilde{\chi}^\pm_1$		Multiple		36.1	$\tilde{b}_1$ *Forbidden* 0.9	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$ *Forbidden* 0.58-0.82	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=BR($t\tilde{\chi}^\pm_1$)=0.5	1708.09266
			Multiple		36.1	$\tilde{b}_1$ *Forbidden* 0.7	m($\tilde{\chi}^0_1$)=200 GeV, m($\tilde{\chi}^\pm_1$)=300 GeV, BR($t\tilde{\chi}^\pm_1$)=1	1706.03731
	$\tilde{b}_1\tilde{b}_1, \tilde{t}_1\tilde{t}_1$, $M_2 = 2 \times M_1$		Multiple		36.1	$\tilde{t}_1$ 0.7	m($\tilde{\chi}^0_1$)=60 GeV	1709.04183, 1711.11520, 1708.03247
			Multiple		36.1	$\tilde{t}_1$ *Forbidden* 0.9	m($\tilde{\chi}^0_1$)=200 GeV	1709.04183, 1711.11520, 1708.03247
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e, μ	0-2 jets/1-2 b	Yes	36.1	$\tilde{t}_1$ 1.0	m($\tilde{\chi}^0_1$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{H}$ LSP		Multiple		36.1	$\tilde{t}_1$ 0.4-0.9	m($\tilde{\chi}^0_1$)=150 GeV, m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
			Multiple		36.1	$\tilde{t}_1$ *Forbidden* 0.6-0.8	m($\tilde{\chi}^0_1$)=300 GeV, m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$ 0.48-0.84	m($\tilde{\chi}^0_1$)=150 GeV, m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}^0_1$	0	$2c$	Yes	36.1	$\tilde{t}_1$ 0.85	m($\tilde{\chi}^0_1$)=0 GeV	1805.01649
						$\tilde{t}_1$ 0.46	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.01649
		0	mono-jet	Yes	36.1	$\tilde{t}_1$ 0.43	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1	$\tilde{t}_2$ 0.32-0.88	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 180 GeV	1706.03986
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	2-3 e, μ	-	Yes	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.6	m($\tilde{\chi}^0_1$)=0	1403.5294, 1806.02293
		$ee, \mu\mu$	≥ 1	Yes	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.17	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=10 GeV	1712.08119
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	$\ell\ell/\ell\gamma\gamma/\ell bb$	-	Yes	20.3	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.26	m($\tilde{\chi}^0_1$)=0	1501.07110
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2$, $\tilde{\chi}^+_1\to\tilde{\tau}\nu(\tau\tilde{\nu})$, $\tilde{\chi}^0_2\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.76	m($\tilde{\chi}^0_1$)=0, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1708.07875
						$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.22	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=100 GeV, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1708.07875
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e, μ	0	Yes	36.1	$\tilde{\ell}$ 0.5	m($\tilde{\chi}^0_1$)=0	1803.02762
		2 e, μ	≥ 1	Yes	36.1	$\tilde{\ell}$ 0.18	m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=5 GeV	1712.08119
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0	$\geq 3b$	Yes	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88	BR($\tilde{\chi}^0_1 \to h\tilde{G}$)=1	1806.04030
		4 e, μ	0	Yes	36.1	$\tilde{H}$ 0.3	BR($\tilde{\chi}^0_1 \to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}^\pm_1$ 0.46	Pure Wino	1712.02118
						$\tilde{\chi}^\pm_1$ 0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron	SMP	-	-	3.2	$\tilde{g}$ 1.6		1606.05129
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$		Multiple		32.8	$\tilde{g}$ [$\tau(\tilde{g})$ =100 ns, 0.2 ns] 1.6 2.4	m($\tilde{\chi}^0_1$)=100 GeV	1710.04901, 1604.04520
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	20.3	$\tilde{\chi}^0_1$ 0.44	1<$\tau(\tilde{\chi}^0_1)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{g}$ 1.3	6 <$c\tau(\tilde{\chi}^0_1)$< 1000 mm, m($\tilde{\chi}^0_1$)=1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2 \to WW/Z\ell\ell\ell\ell\nu\nu$	4 e, μ	0	Yes	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ [$\lambda_{i33} \neq 0, \lambda_{12k} \neq 0$] 0.82 1.33	m($\tilde{\chi}^0_1$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1, \tilde{\chi}^0_1 \to qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$ [m($\tilde{\chi}^0_1$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{g}\tilde{g}$, $\tilde{g} \to tbs$ / $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1, \tilde{\chi}^0_1 \to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=1, 1e-2] 1.8 2.1	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}^0_1, \tilde{\chi}^0_1 \to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e, μ	2 b	-	36.1	$\tilde{t}_1$ 0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544

Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



ATLAS SUSY Searches* - 95% CL Lower Limits
July 2018

ATLAS Preliminary
$\sqrt{s}$ = 7, 8, 13 TeV

🟩 $\sqrt{s}$ = 7, 8 TeV 🟦 $\sqrt{s}$ = 13 TeV

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$ [2x, 8x Degen.] 0.9 1.55	m($\tilde{\chi}_1^0$)<100 GeV	1712.02332
		mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$ [1x, 8x Degen.] 0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.0	m($\tilde{\chi}_1^0$)<200 GeV	1712.02332
						$\tilde{g}$ Forbidden 0.95-1.6	m($\tilde{\chi}_1^0$)=900 GeV	1712.02332
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e,μ	4 jets	-	36.1	$\tilde{g}$ 1.85	m($\tilde{\chi}_1^0$)<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	Yes	36.1	$\tilde{g}$ 1.2	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$ 1.8	m($\tilde{\chi}_1^0$) <400 GeV	1708.02794
		3 e,μ	4 jets	-	36.1	$\tilde{g}$ 0.98	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	1706.03731
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	36.1	$\tilde{g}$ 2.0	m($\tilde{\chi}_1^0$)<200 GeV	1711.01901
		3 e,μ	4 jets	-	36.1	$\tilde{g}$ 1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1706.03731
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple		36.1	$\tilde{b}_1$ Forbidden 0.9	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.58-0.82	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=BR($t\tilde{\chi}_1^\pm$)=0.5	1708.09266
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.7	m( )=200 GeV, m($\tilde{\chi}_1^\pm$)=300 GeV, BR($t\tilde{\chi}_1^\pm$)=1	1706.03731
	$\tilde{b}_1\tilde{b}_1, \tilde{t}_1\tilde{t}_1$, $M_2 = 2\times M_1$		Multiple		36.1	$\tilde{t}_1$ 0.7	m($\tilde{\chi}_1^0$)=60 GeV	1709.04183, 1711.11520, 1708.03247
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.9	m($\tilde{\chi}_1^0$)=200 GeV	1709.04183, 1711.11520, 1708.03247
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	36.1	$\tilde{t}_1$ 1.0	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{H}$ LSP		Multiple		36.1	$\tilde{t}_1$ 0.4-0.9	m( )=150 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.6-0.8	m( )=300 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$ 0.48-0.84	m( )=150 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}_1^0$	0	$2c$	Yes	36.1	$\tilde{t}_1$ 0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
						$\tilde{t}_1$ 0.46	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.01649
		0	mono-jet	Yes	36.1	$\tilde{t}_1$ 0.43	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + h$	1-2 e,μ	4 b	Yes	36.1	$\tilde{t}_2$ 0.32-0.88	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 180 GeV	1706.03986
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	2-3 e,μ	-	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.6	m($\tilde{\chi}_1^0$)=0	1403.5294, 1806.02293
		$ee,\mu\mu$	≥ 1	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.17	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=10 GeV	1712.08119
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	$\ell\ell/\ell\gamma\gamma/\ell bb$	-	Yes	20.3	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.26	m($\tilde{\chi}_1^0$)=0	1501.07110
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$, $\tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.76	m($\tilde{\chi}_1^0$)=0, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1708.07875
						$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.22	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=100 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1708.07875
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	36.1	$\tilde{\ell}$ 0.5	m($\tilde{\chi}_1^0$)=0	1803.02762
		2 e,μ	≥ 1	Yes	36.1	$\tilde{\ell}$ 0.18	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=5 GeV	1712.08119
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0	$\geq 3b$	Yes	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88	BR($\tilde{\chi}_1^0 \to h\tilde{G}$)=1	1806.04030
		4 e,μ	0	Yes	36.1	$\tilde{H}$ 0.3	BR($\tilde{\chi}_1^0 \to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^\pm$ 0.46	Pure Wino	1712.02118
						$\tilde{\chi}_1^\pm$ 0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron	SMP	-	-	3.2	$\tilde{g}$ 1.6		1606.05129
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$		Multiple		32.8	$\tilde{g}$ [$\tau(\tilde{g})$ =100 ns, 0.2 ns] 1.6 2.4	m($\tilde{\chi}_1^0$)=100 GeV	1710.04901, 1604.04520
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 0.44	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to eev/e\mu v/\mu\mu v$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{g}$ 1.3	6 <$c\tau(\tilde{\chi}_1^0)$< 1000 mm, m($\tilde{\chi}_1^0$)=1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0 \to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33} \neq 0, \lambda_{12k} \neq 0$] 0.82 1.33	m($\tilde{\chi}_1^0$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$ [m($\tilde{\chi}_1^0$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{g}\tilde{g}$, $\tilde{g} \to tbs$ / $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=1, 1e-2] 1.8 2.	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	36.1	$\tilde{t}_1$ 0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Constraints on sparticle masses beyond ~2 TeV

Does this mean we've explored the entire LHC13 phase-space to this mass scale? … **NO!**

Compressed Mass Spectra

Generally, in scenarios with decays to invisible particles mass-sensitive observables scale as:

$$\sim m_{\tilde{P}} - m_{\tilde{\chi}}$$

parent sparticle mass

LSP mass

At large $m_{\tilde{P}} - m_{\tilde{\chi}}$, relevant SM backgrounds yields are falling quickly in the matching phase-space ⇒

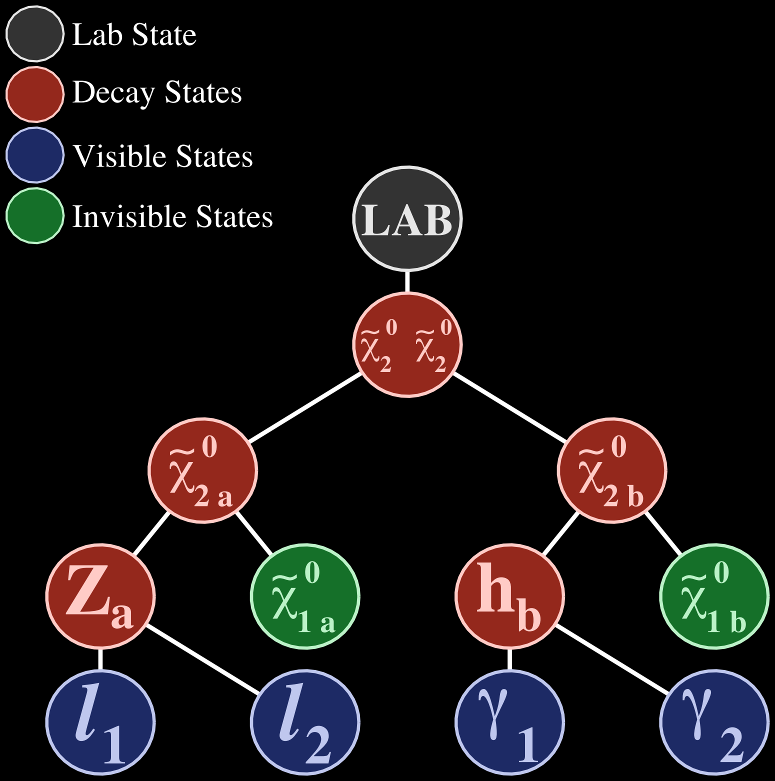
expect good S/B in the tails of mass-splitting-sensitive observables

As $m_{\tilde{P}} - m_{\tilde{\chi}}$ becomes smaller, SM decay products become softer (more difficult to identify), while backgrounds are larger ⇒

no longer in the tails of mass-splitting-sensitive observables

Compressed Mass Spectra

Consider SUSY EWK-ino production

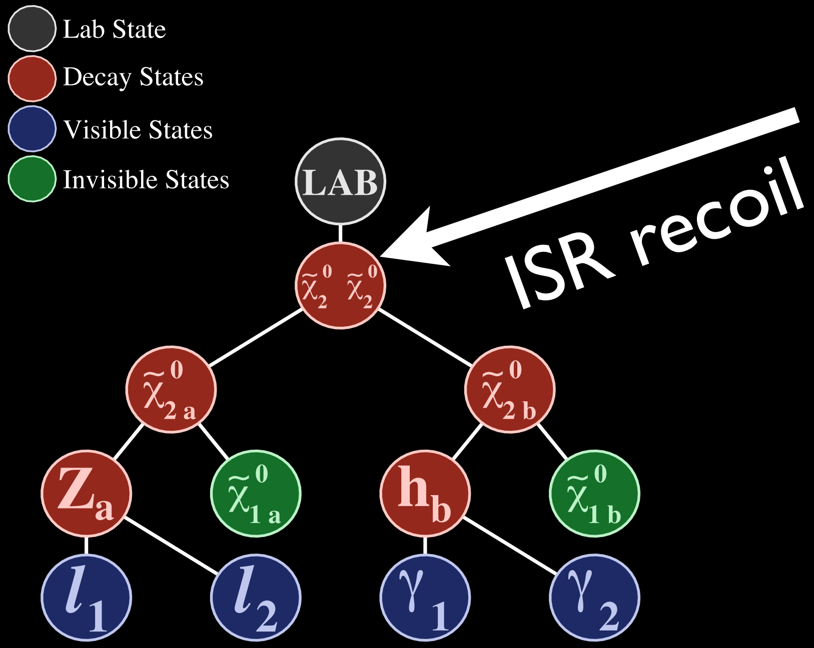


If the mass-splitting between sparticles, $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$, is small (compressed) then the decay products (both visible and invisible) will be soft

Can still calculate masses/ splittings, but they may not be distinctive from background…

Compressed Mass Spectra

We can instead consider observables sensitive to the **absolute mass** of missing sparticles

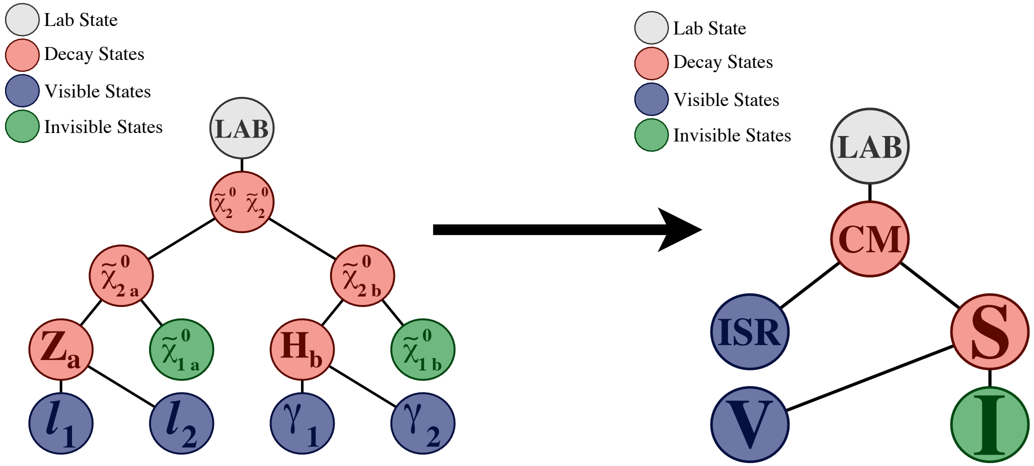


Identifying events with hard strong **initial-state radiation** means that soft particles will get momentum from recoil

$$E_T^{\text{miss}} \sim -\vec{p}_T^{\,\text{ISR}} \times \frac{m_{\tilde{\chi}}}{m_{\tilde{P}}}$$

In the limit of extreme compression the momentum of missing particles is sensitive to their mass

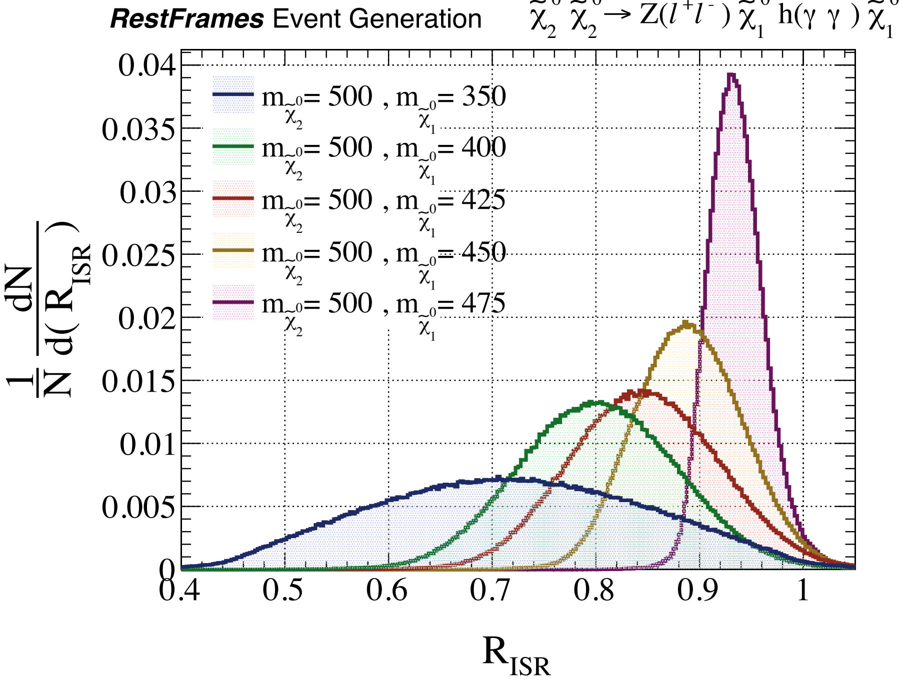
Compressed Mass Spectra



By analyzing each event in a simplified decay topology…

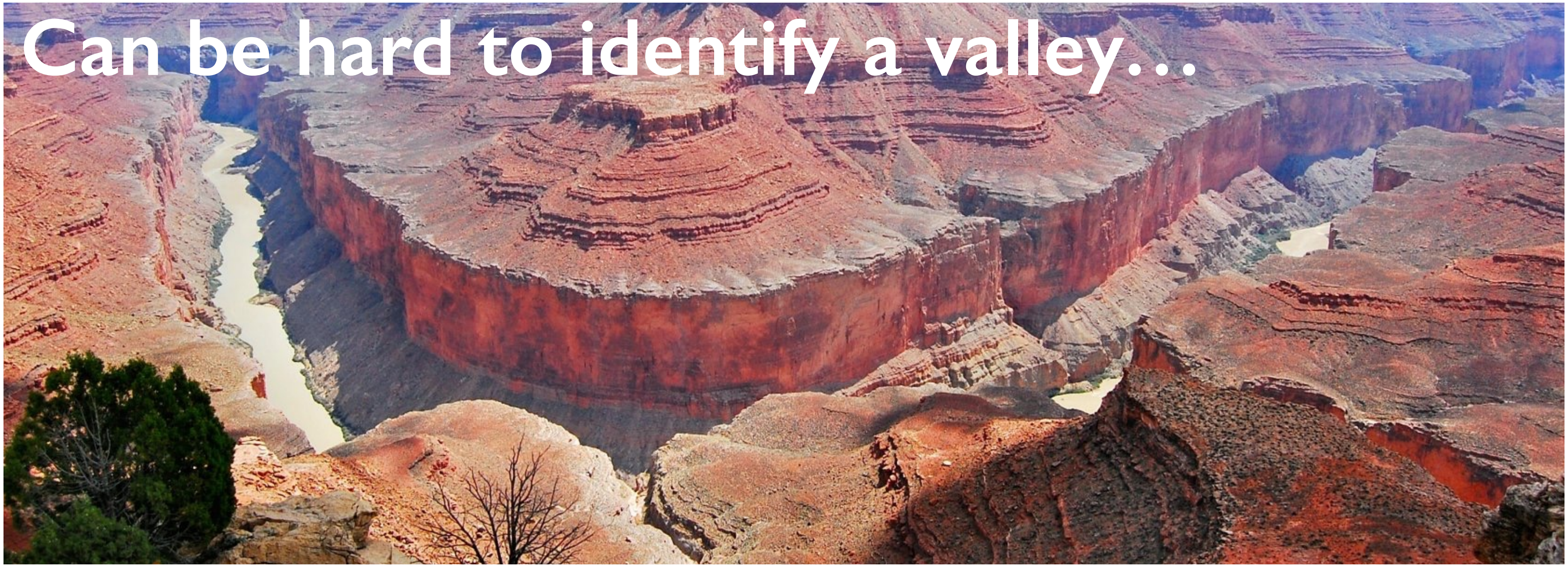
We can extract information about missing particle masses

$$R_{\mathrm{ISR}} \equiv \frac{\vec{p}_{\mathrm{I}}^{\;\mathrm{CM}} \cdot \hat{p}_{\mathrm{ISR}}^{\mathrm{CM}}}{p_{\mathrm{ISR}}^{\mathrm{CM}}} \sim \frac{m_{\tilde{\chi}}}{m_{\tilde{P}}}$$

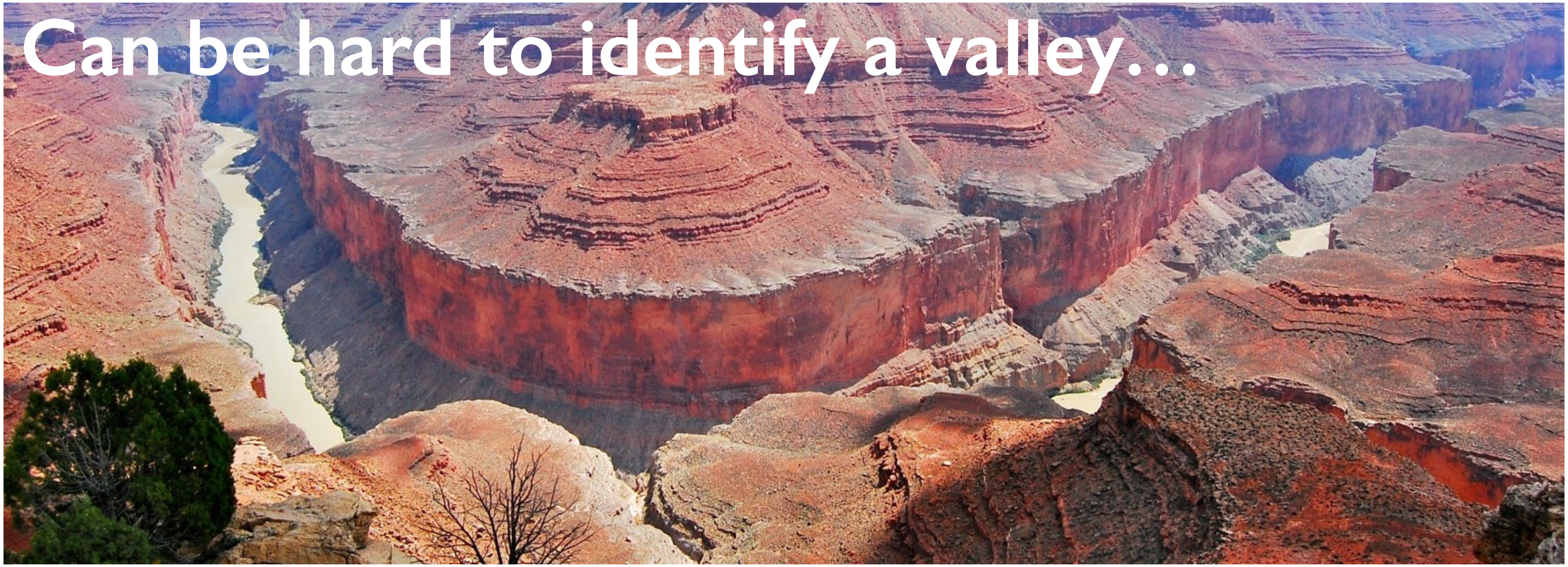


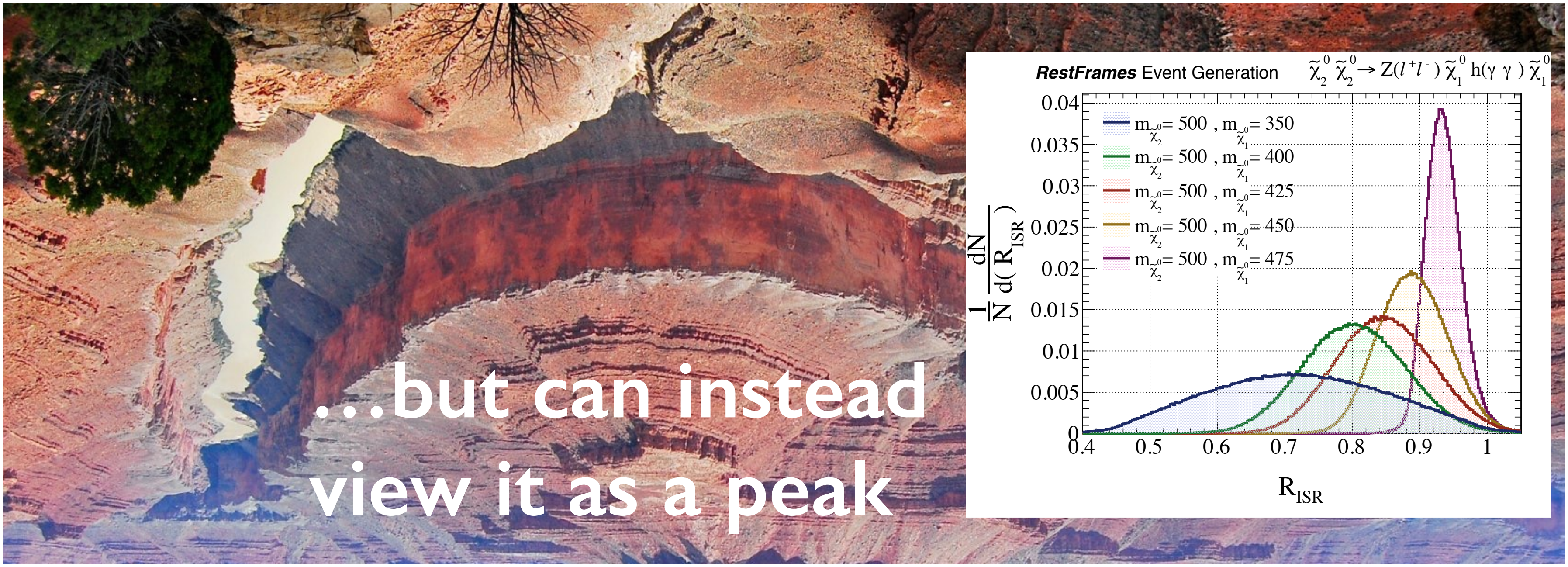
Recursive Jigsaw Reconstruction, PRD 95, 035031 [1607.08307]

Can be hard to identify a valley…



Can be hard to identify a valley…

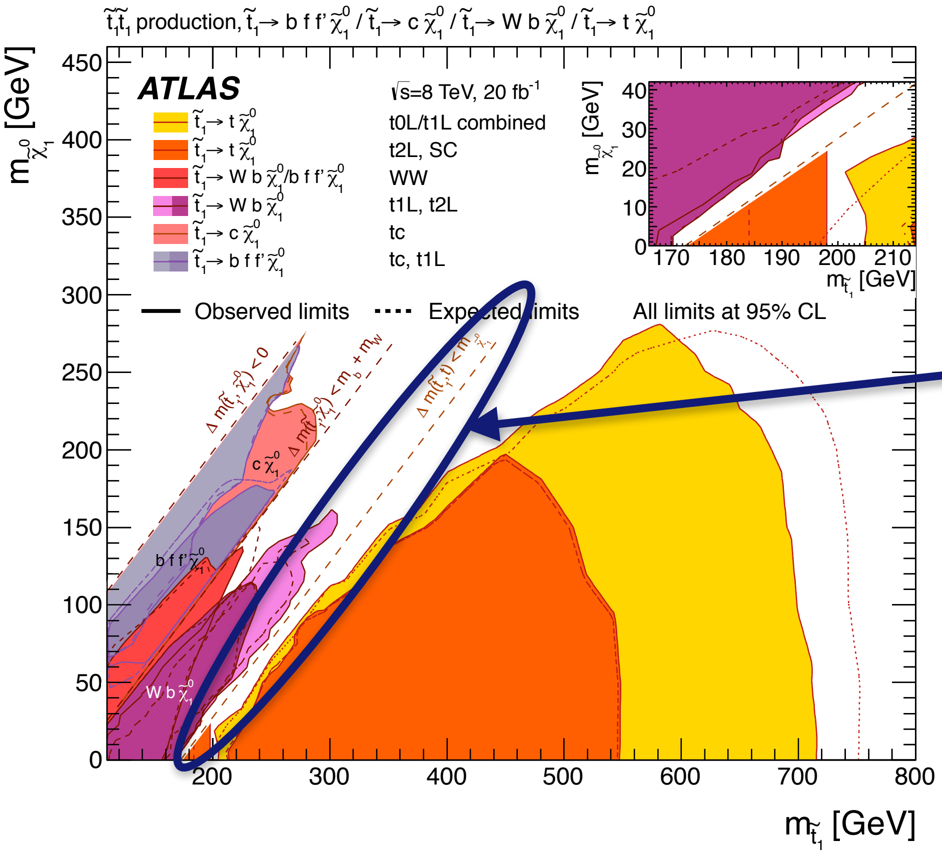




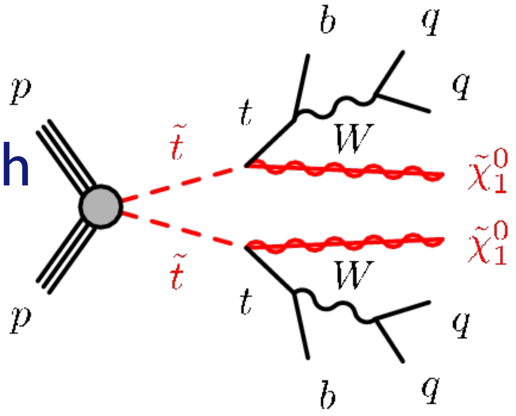
…but can instead view it as a peak

Compressed Stops

Constraints at the end of LHC Run I:



stop pair production with decays to top quarks



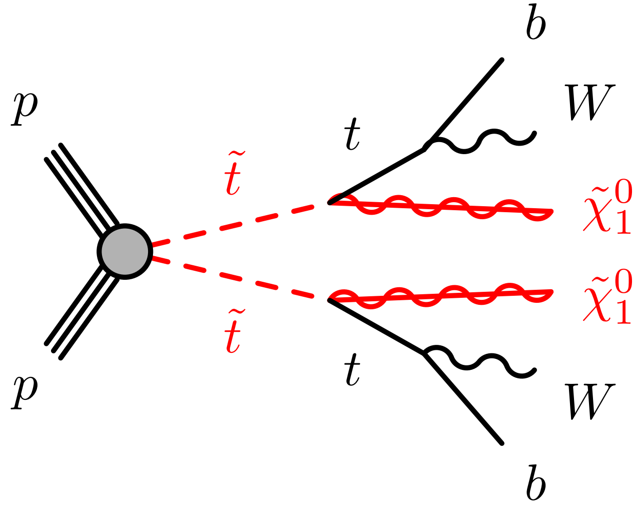
$$m_{\tilde{t}} \sim m_t + m_{\tilde{\chi}^0}$$

Lack of phase-space in stop decay generally leads to soft decay products, **including small missing momentum**

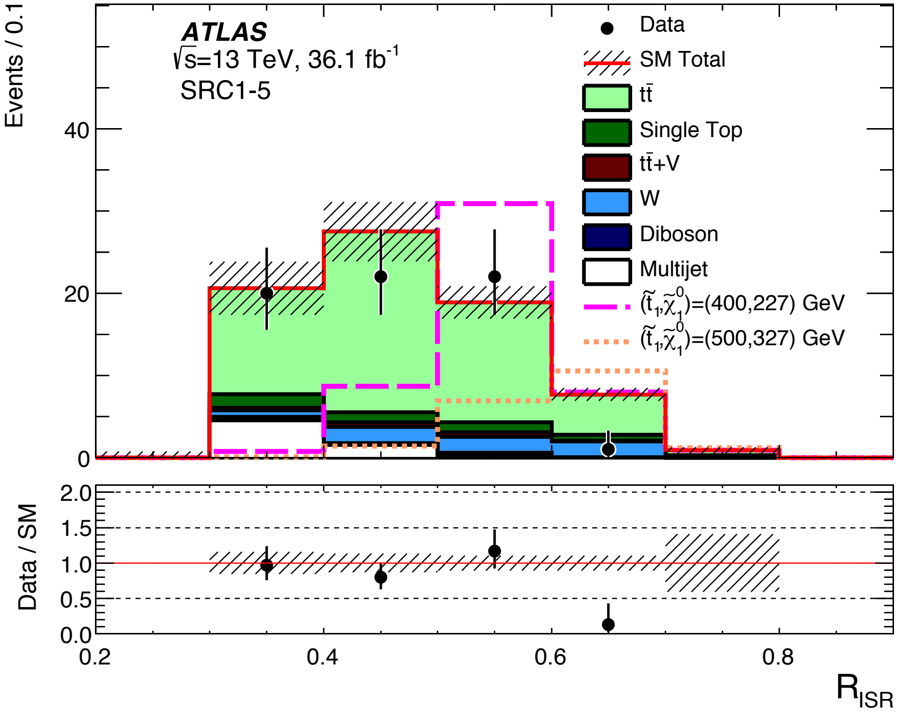
Difficult to distinguish potential signal events from large SM background

Compressed Stops

Can use this ISR-assisted compressed analysis technique to search for compressed decays of SUSY top partners



$$m_{\tilde{t}} - m_{\tilde{\chi}} \sim m_{top}$$



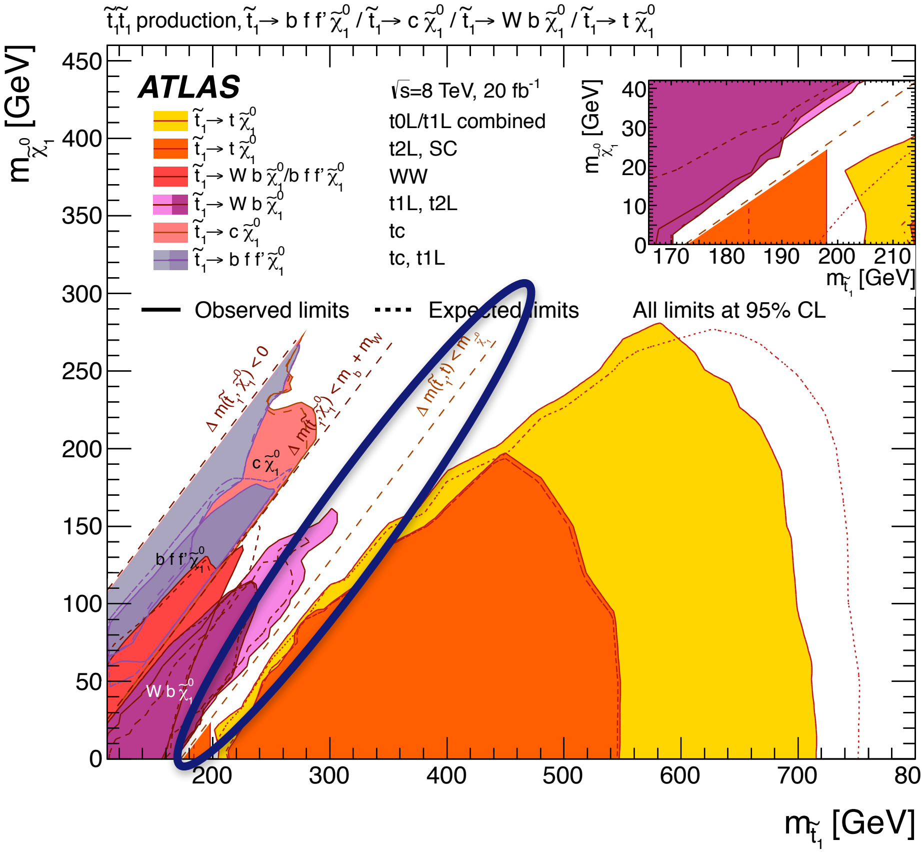
JHEP 12 (2017) 085 [1709.04183]

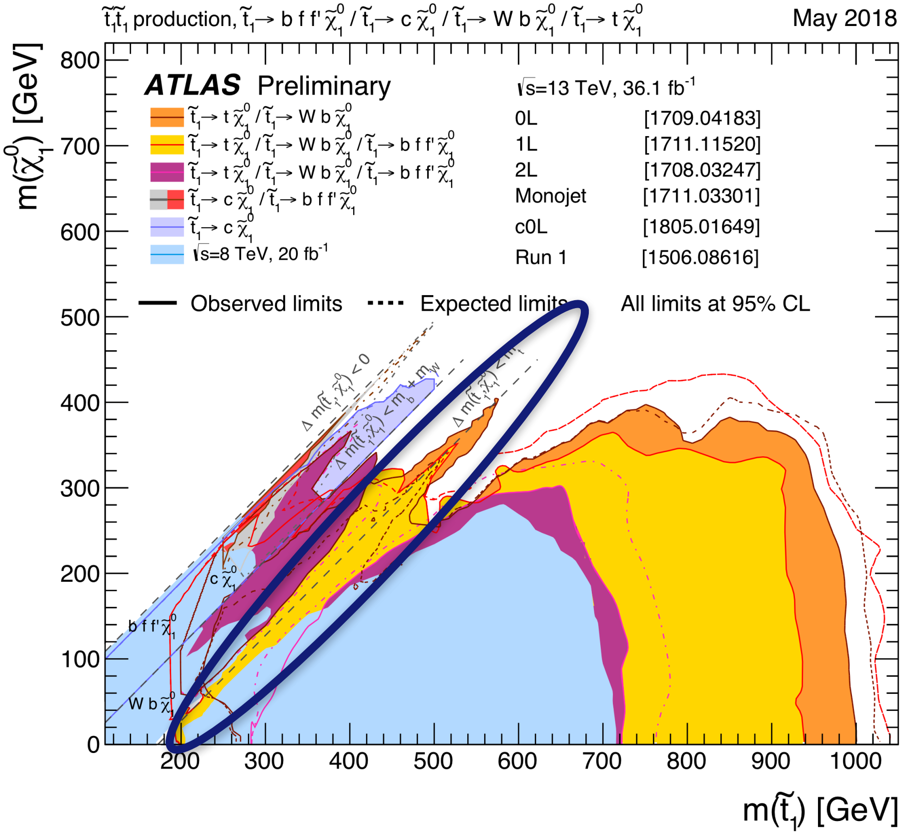
Compressed Stops

Can use this ISR-assisted compressed analysis technique to search for compressed decays of SUSY top partners

Constraints at the end of LHC Run I:

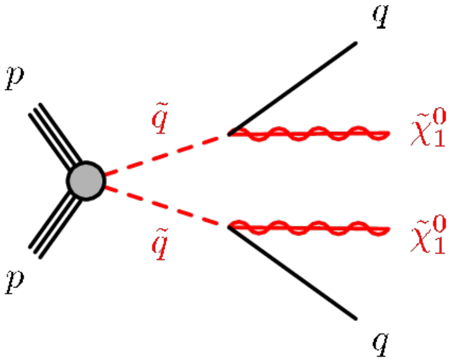
Now
JHEP 12 (2017) 085 [1709.04183]

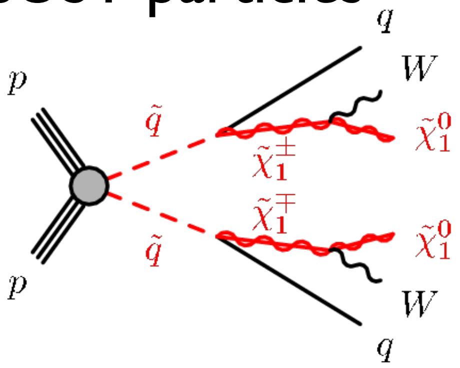




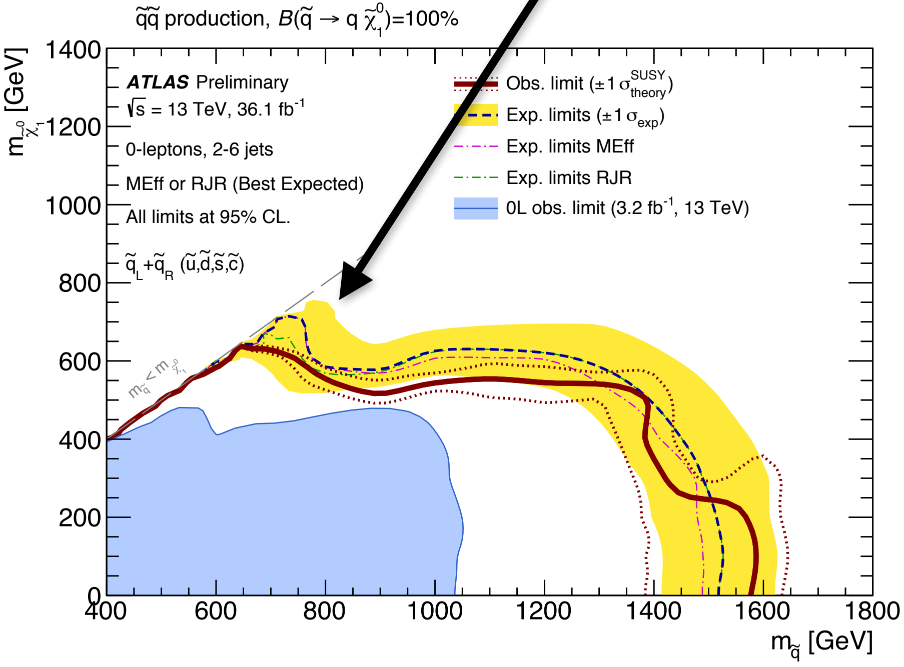
Compressed Squarks

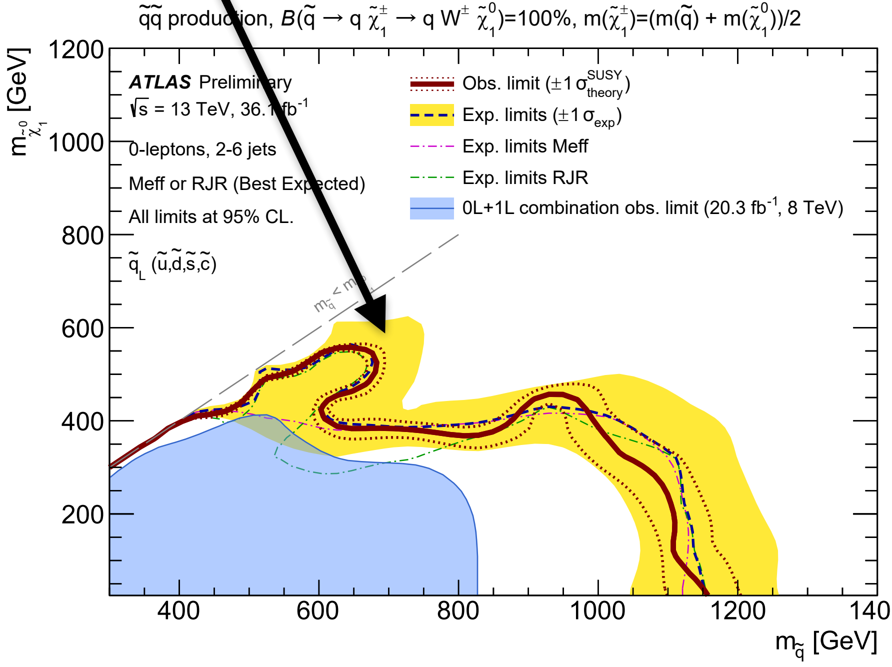
Can also use this ISR-assisted compressed analysis technique to search for compressed decays of other SUSY particles





small $m_{\tilde{q}} - m_{\tilde{\chi}}$

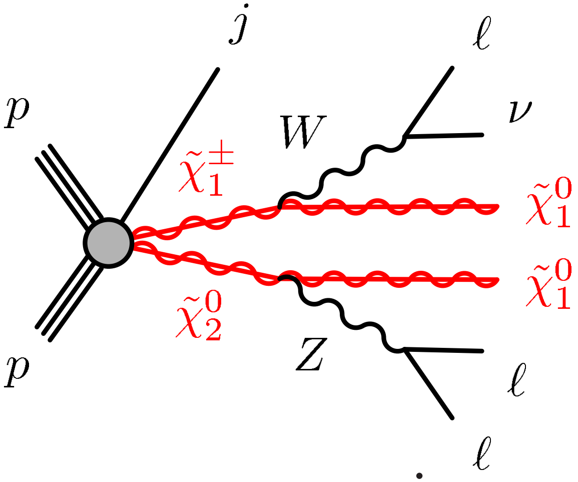




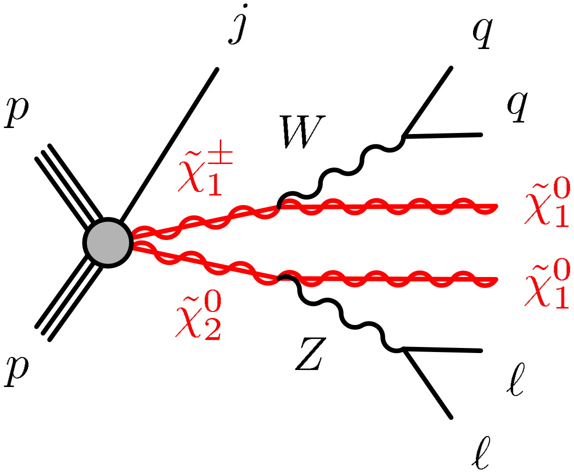
PRD 97, 112001 (2018) [1712.02332]

SUSY EWKinos

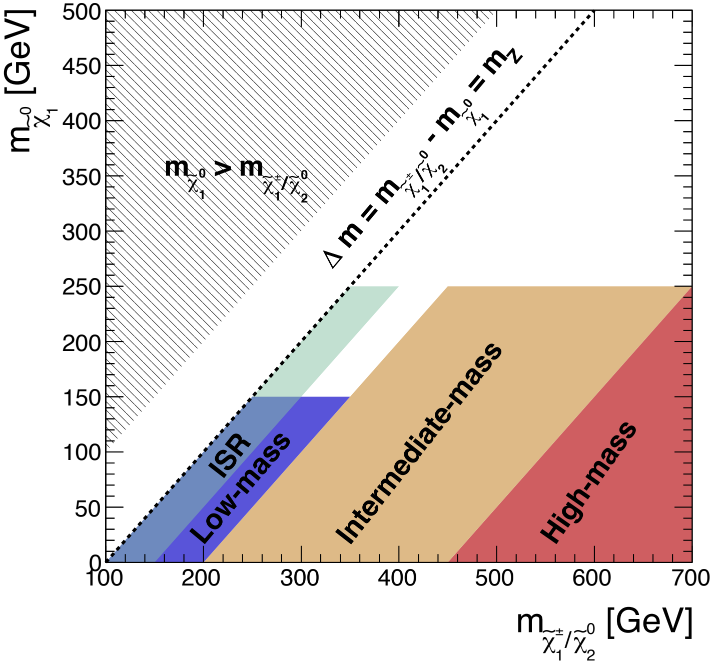
Can also use this ISR-assisted compressed analysis technique to search for EWKinos



$$3\ell + E_T^{\mathrm{miss}}$$



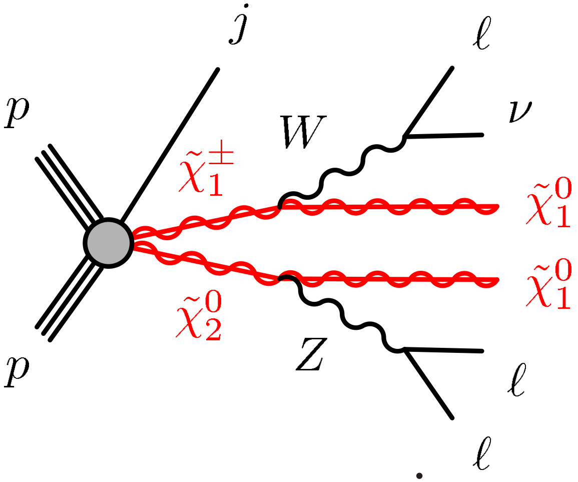
$$2\ell + 2\ \mathrm{jet} + E_T^{\mathrm{miss}}$$



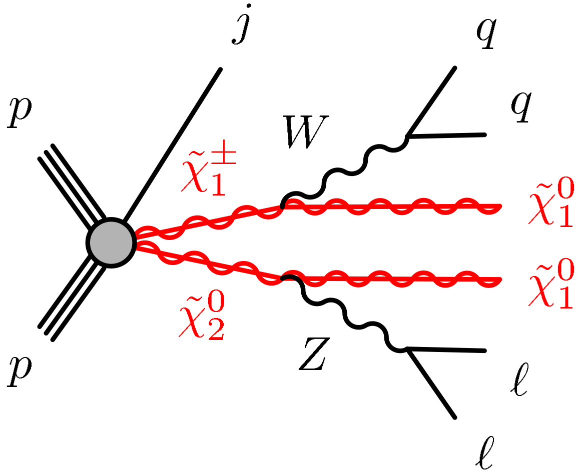
arXiv:1806.02293

SUSY EWKinos

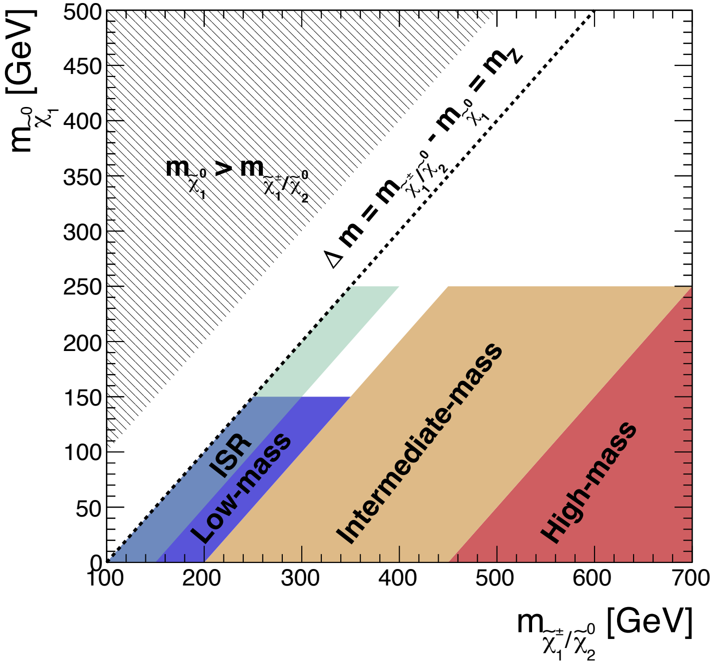
Can also use this ISR-assisted compressed analysis technique to search for EWKinos

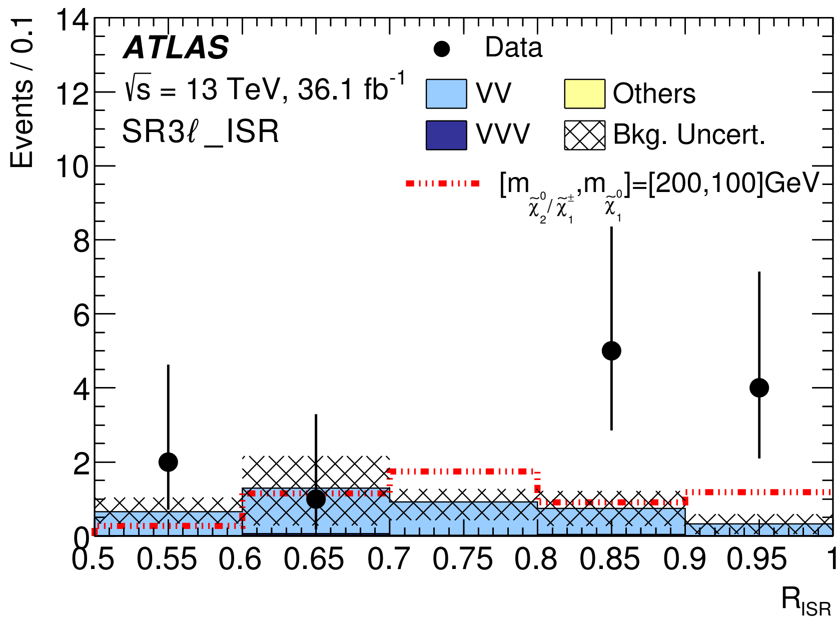


$3\ell + E_T^{\text{miss}}$



$2\ell + 2\ \text{jet} + E_T^{\text{miss}}$

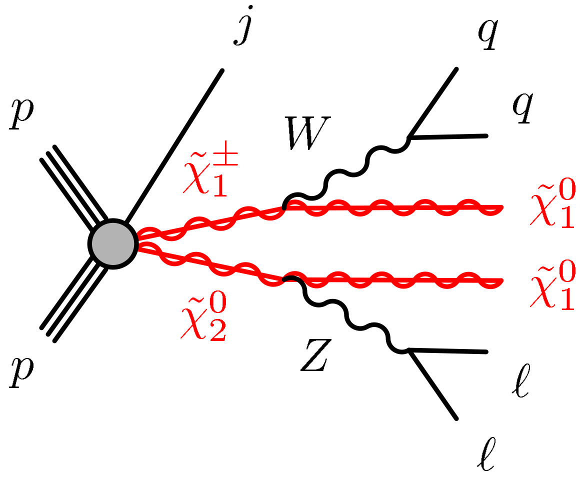




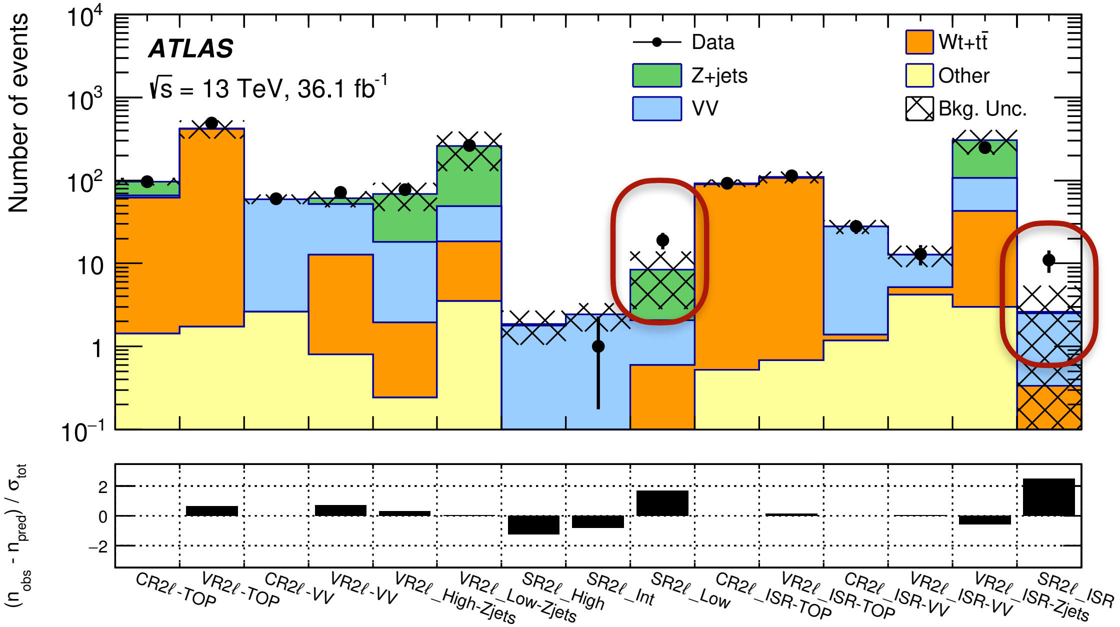
arXiv:1806.02293

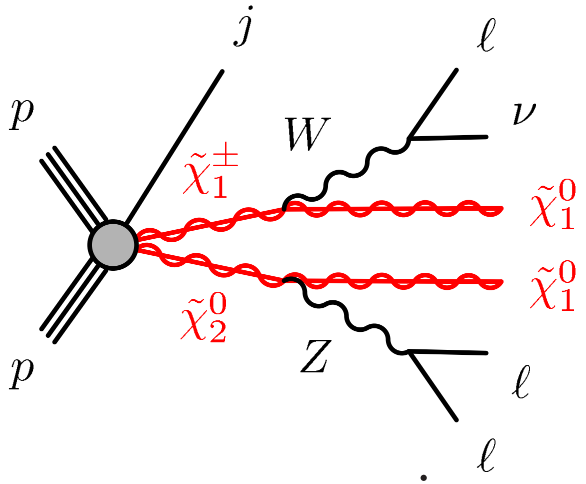
SUSY EWKinos

arXiv:1806.02293

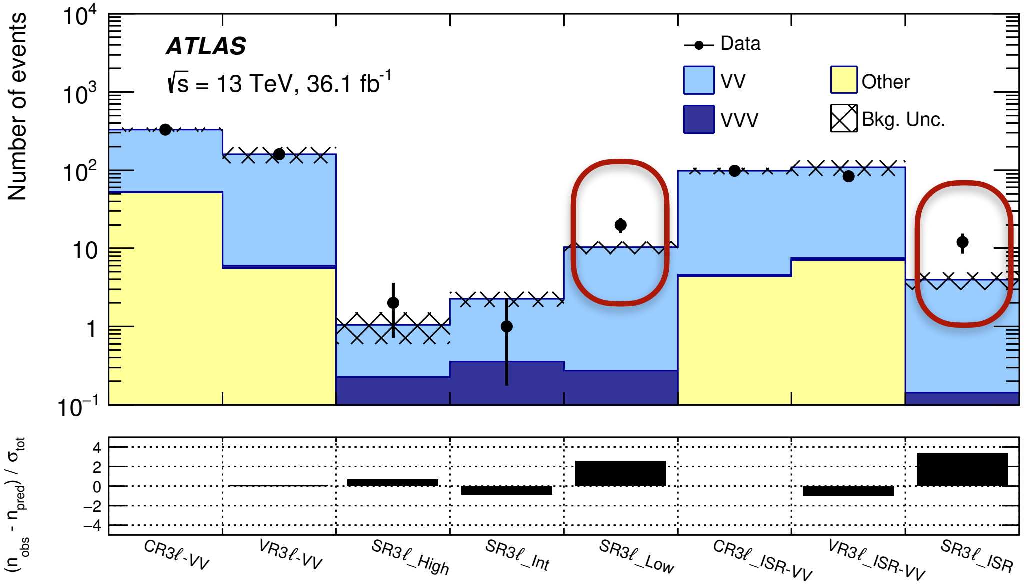


$$2\ell + 2\ \text{jet} + E_T^{\text{miss}}$$





$$3\ell + E_T^{\text{miss}}$$

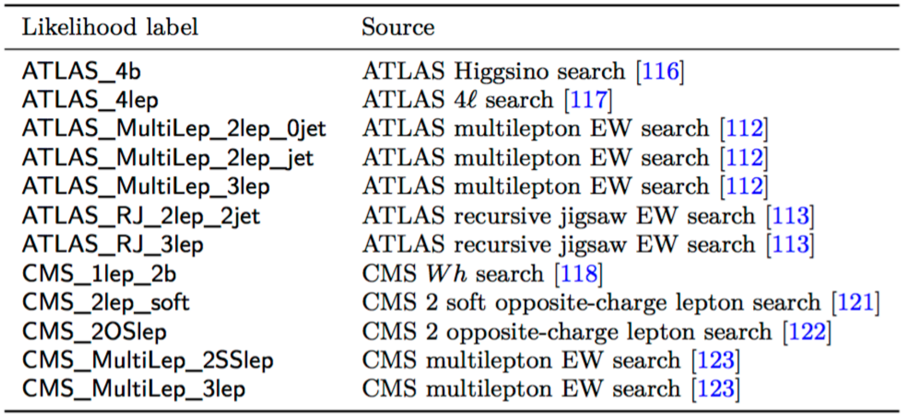


SUSY EWKinos Interpretation

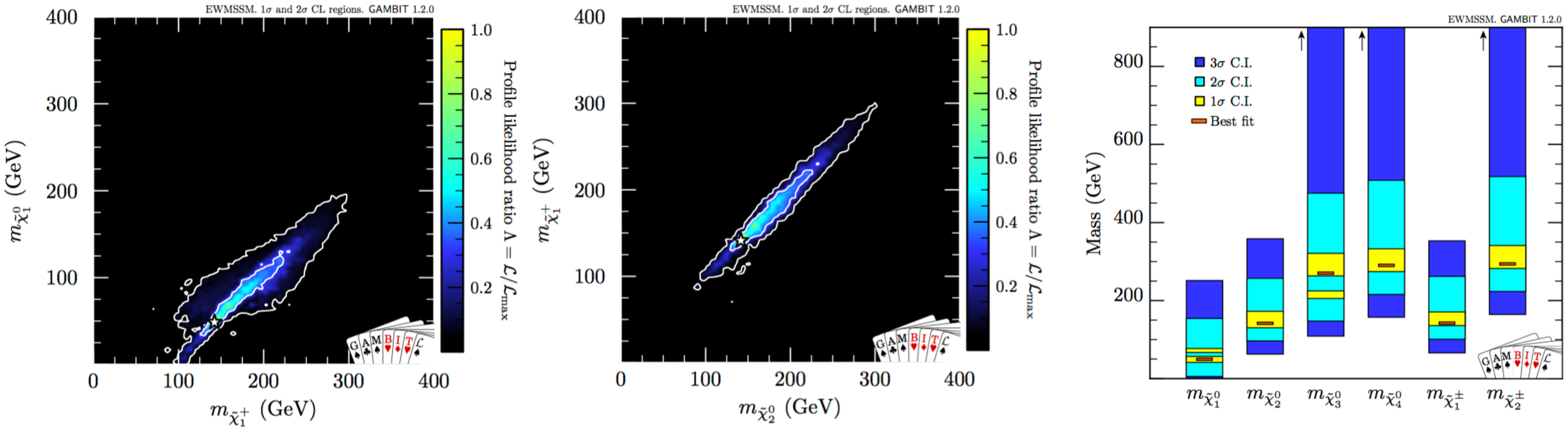
arXiv:1809.02097

Combined collider constraints on neutralinos and charginos

Global fit of EWMSSM by **GAMBIT collaboration** over parameters $M_1, M_2, \mu, \tan\beta$ including relevant LEP and 13 TeV LHC constraints



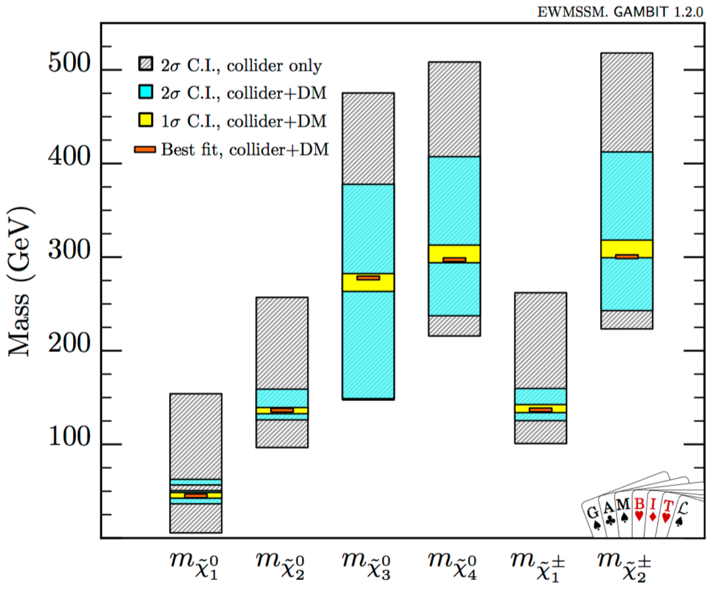
Likelihood label	Source
ATLAS_4b	ATLAS Higgsino search [116]
ATLAS_4lep	ATLAS 4ℓ search [117]
ATLAS_MultiLep_2lep_0jet	ATLAS multilepton EW search [112]
ATLAS_MultiLep_2lep_jet	ATLAS multilepton EW search [112]
ATLAS_MultiLep_3lep	ATLAS multilepton EW search [112]
ATLAS_RJ_2lep_2jet	ATLAS recursive jigsaw EW search [113]
ATLAS_RJ_3lep	ATLAS recursive jigsaw EW search [113]
CMS_1lep_2b	CMS Wh search [118]
CMS_2lep_soft	CMS 2 soft opposite-charge lepton search [121]
CMS_2OSlep	CMS 2 opposite-charge lepton search [122]
CMS_MultiLep_2SSlep	CMS multilepton EW search [123]
CMS_MultiLep_3lep	CMS multilepton EW search [123]



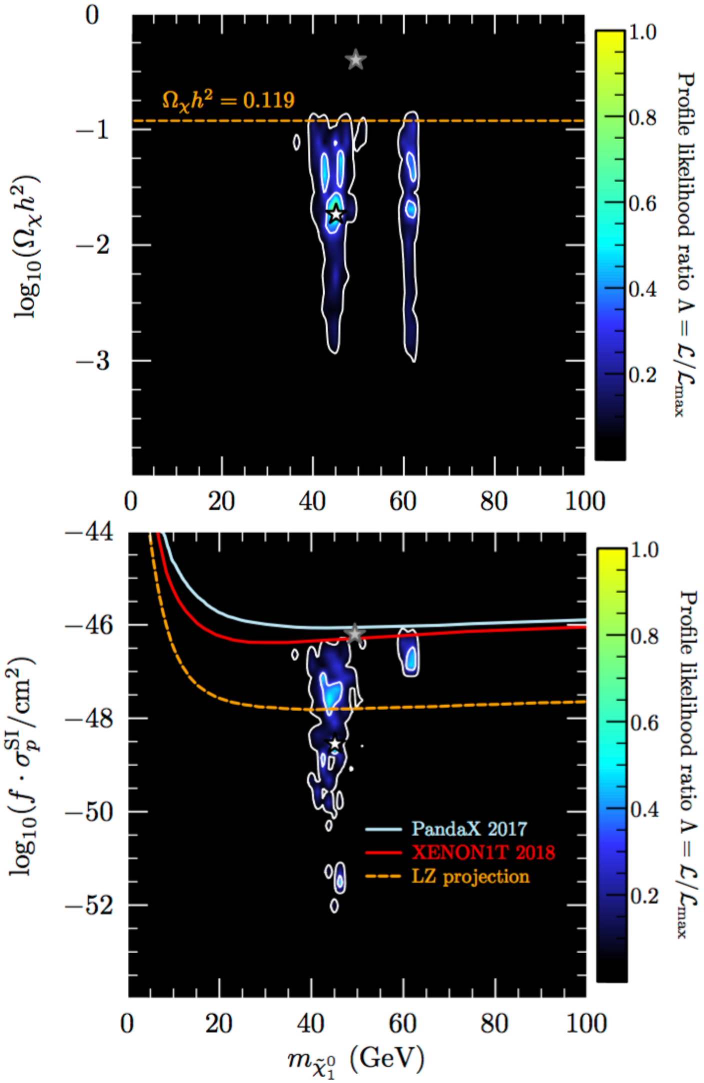
EWKino mass confidence intervals w/ collider constraints

best fit point with 3.5 σ local significance

SUSY EWKinos Interpretation



arXiv:1809.02097

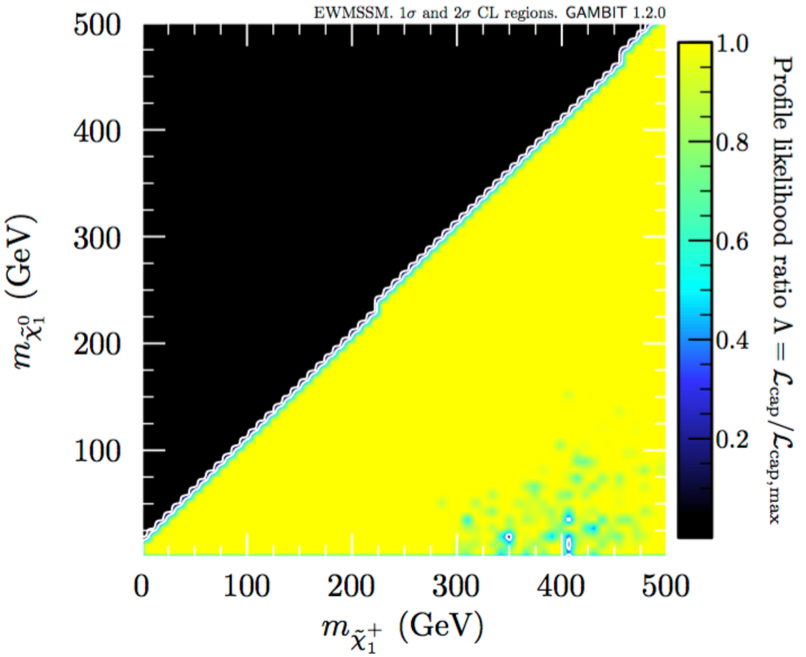


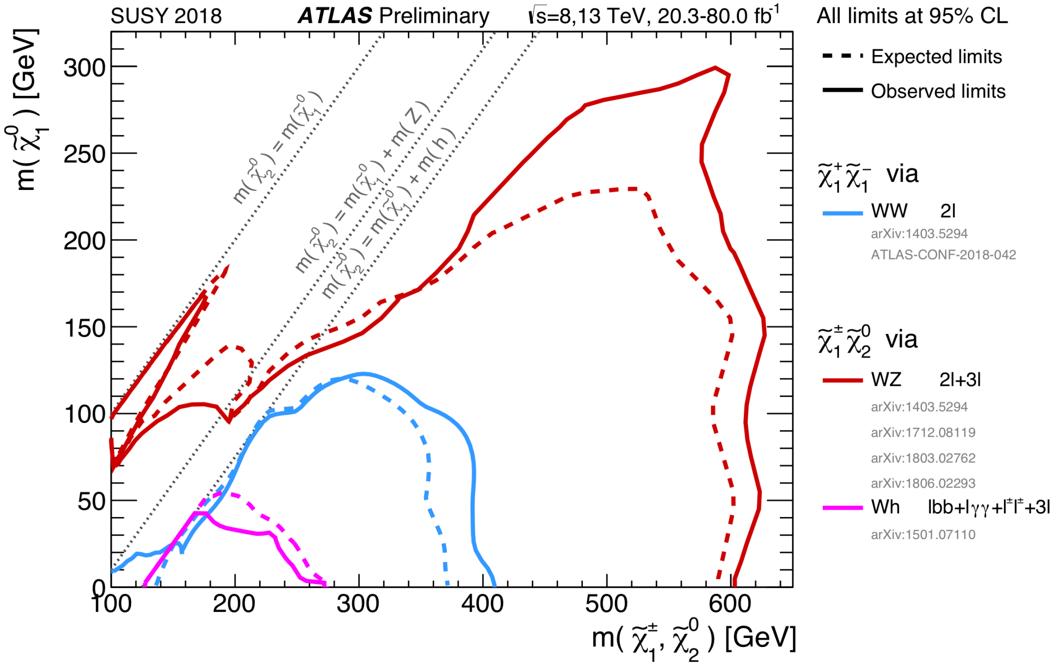
EWKino mass confidence intervals w/ collider + DM constraints, along with profile likelihood/confidence intervals including LSP relic density + SI direct detection xsection

arXiv:1809.11082: Excesses compatible with DM relic density, DM direct detection, and muon g-2

SUSY EWKinos Interpretation

arXiv:1809.02097





EWMSSM fit suggests very weak constraints from LHC 13 TeV analyses when considering the more comprehensive phenomenology of electroweak sector of MSSM

Due to, for example

- lower x-sections of non-wino dominated states
- reduced yields from additional production/decay modes relative to simplified models

Summary

- LHC BSM searches are probing many corners of accessible phase space, with sensitivity to new physics continuing to grow with more data

- As new 13 TeV phase space is revealed, new techniques are being deployed to target previously inaccessible signals ⇒

  Invisible particle final states in compressed scenarios and signatures characteristic of EWKinos, among other possibilities, could reveal something interesting

- Simplified model interpretations of null BSM search results reflect the sensitivity of these analyses but not the entirety of BSM possibilities ⇒

  New physics could be just around the corner, so stay tuned!

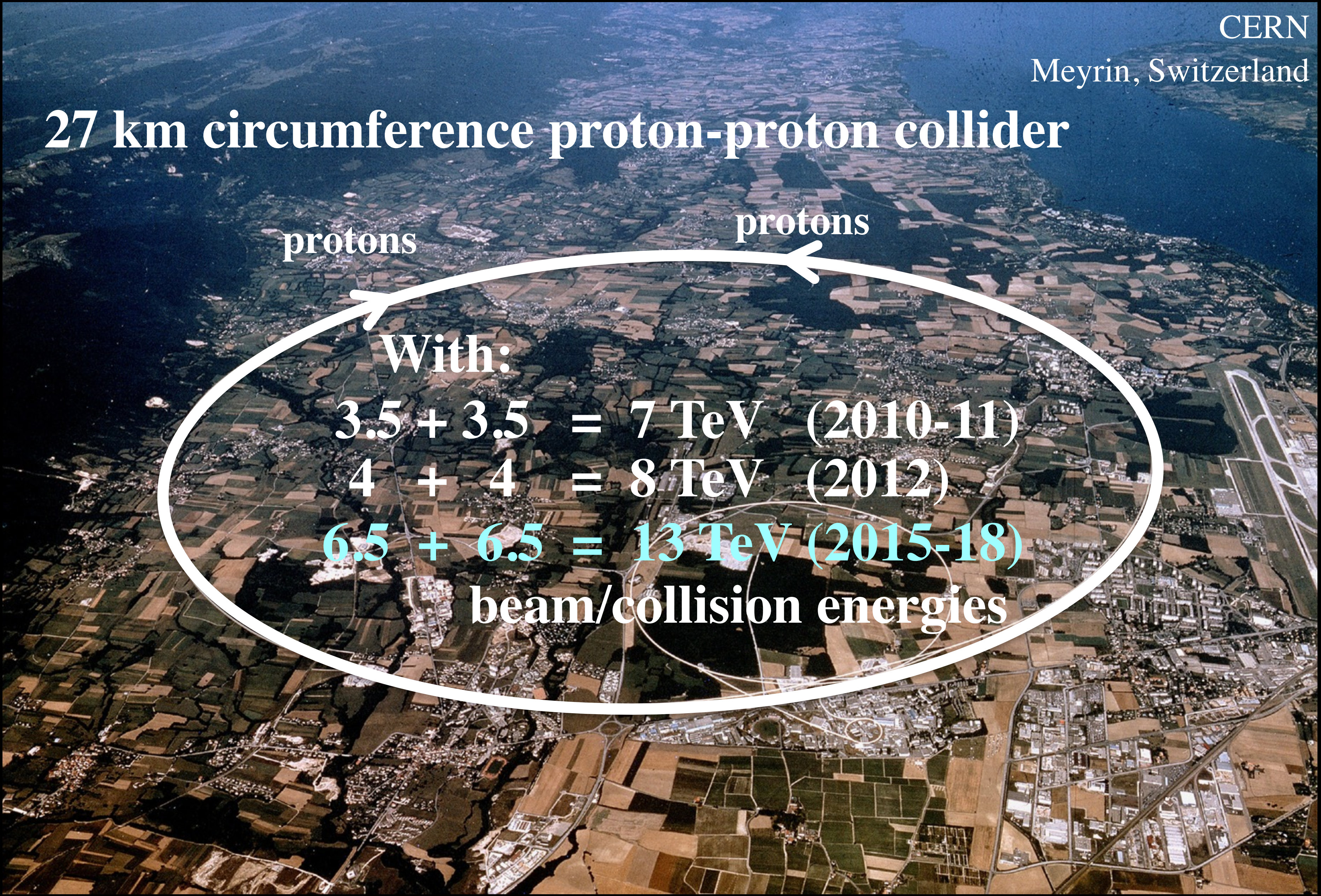
CMS and ATLAS BSM Results

- ATLAS Public Results [link]
  - SUSY [link]
  - Exotics [link]

- CMS Public Results [link]
  - SUSY [link]
  - Exotics [link]
  - Beyond 2 Generations [link]

Backup Slides

The Large Hadron Collider (LHC)



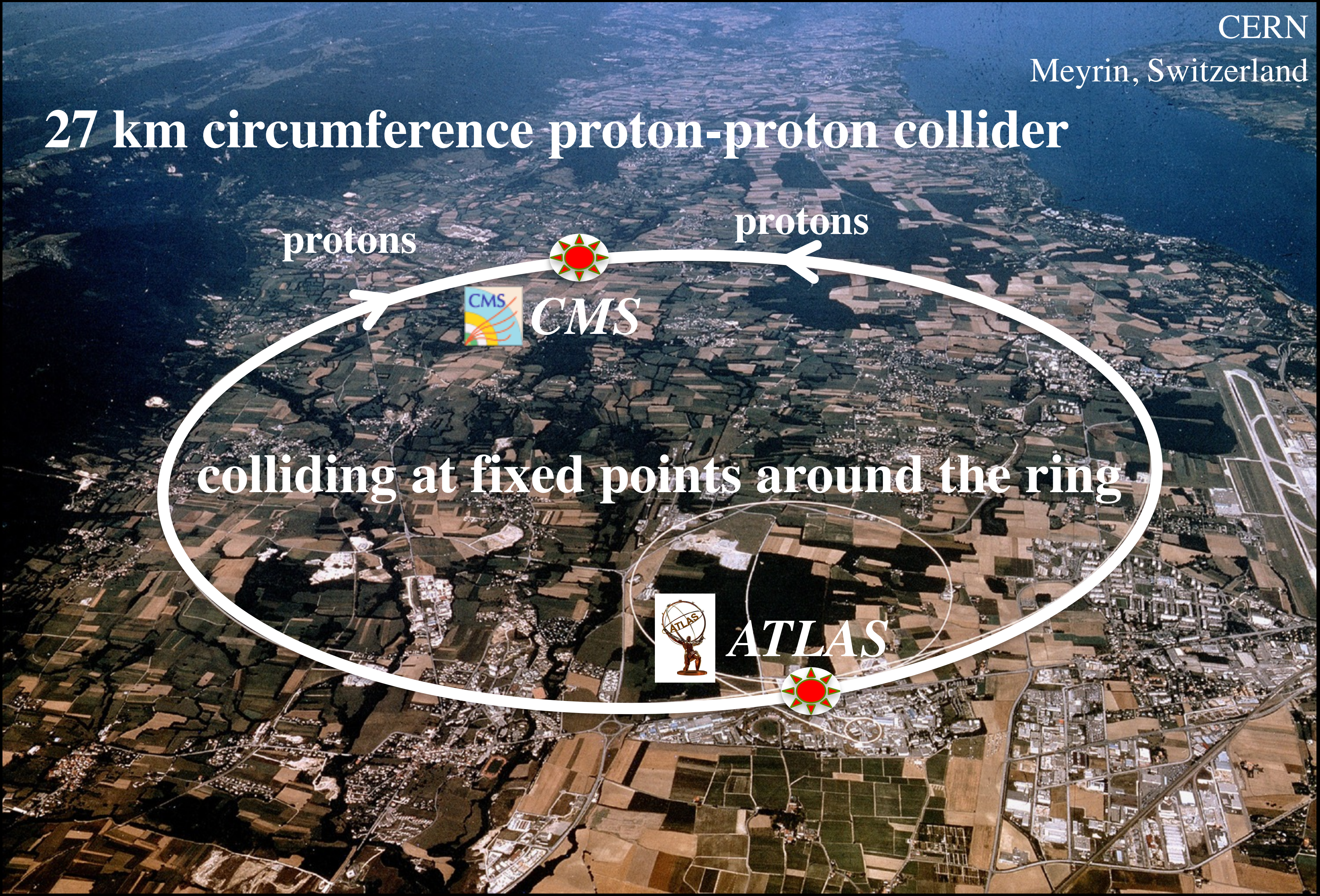
CERN
Meyrin, Switzerland

27 km circumference proton-proton collider

With:

3.5 + 3.5 = 7 TeV (2010-11)
4 + 4 = 8 TeV (2012)
6.5 + 6.5 = 13 TeV (2015-18)
beam/collision energies

The Large Hadron Collider (LHC)



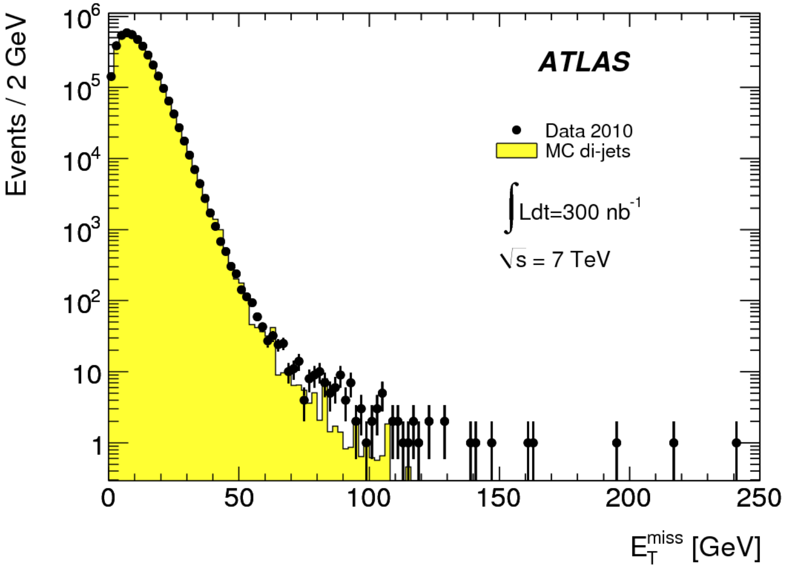
CERN
Meyrin, Switzerland

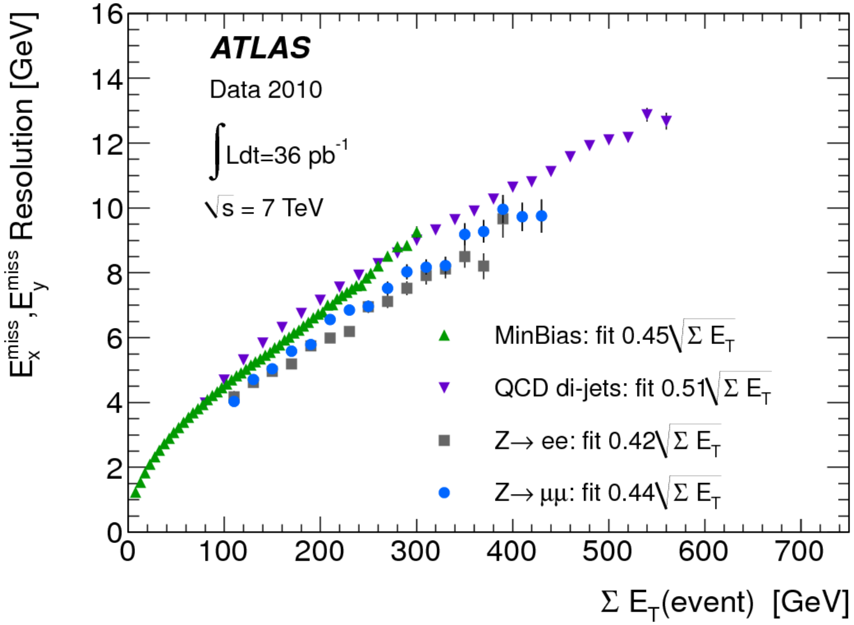
27 km circumference proton-proton collider

colliding at fixed points around the ring

The view from the peak

- LHC searches begin at **‘the rate peak’**: QCD multi-jet production
- Used to: select control samples of leptons, photons, b-jets, …
  calibrate/measure object reconstruction performance, fake-rates, energy scales
  validate our understanding of the SM in new phase-space





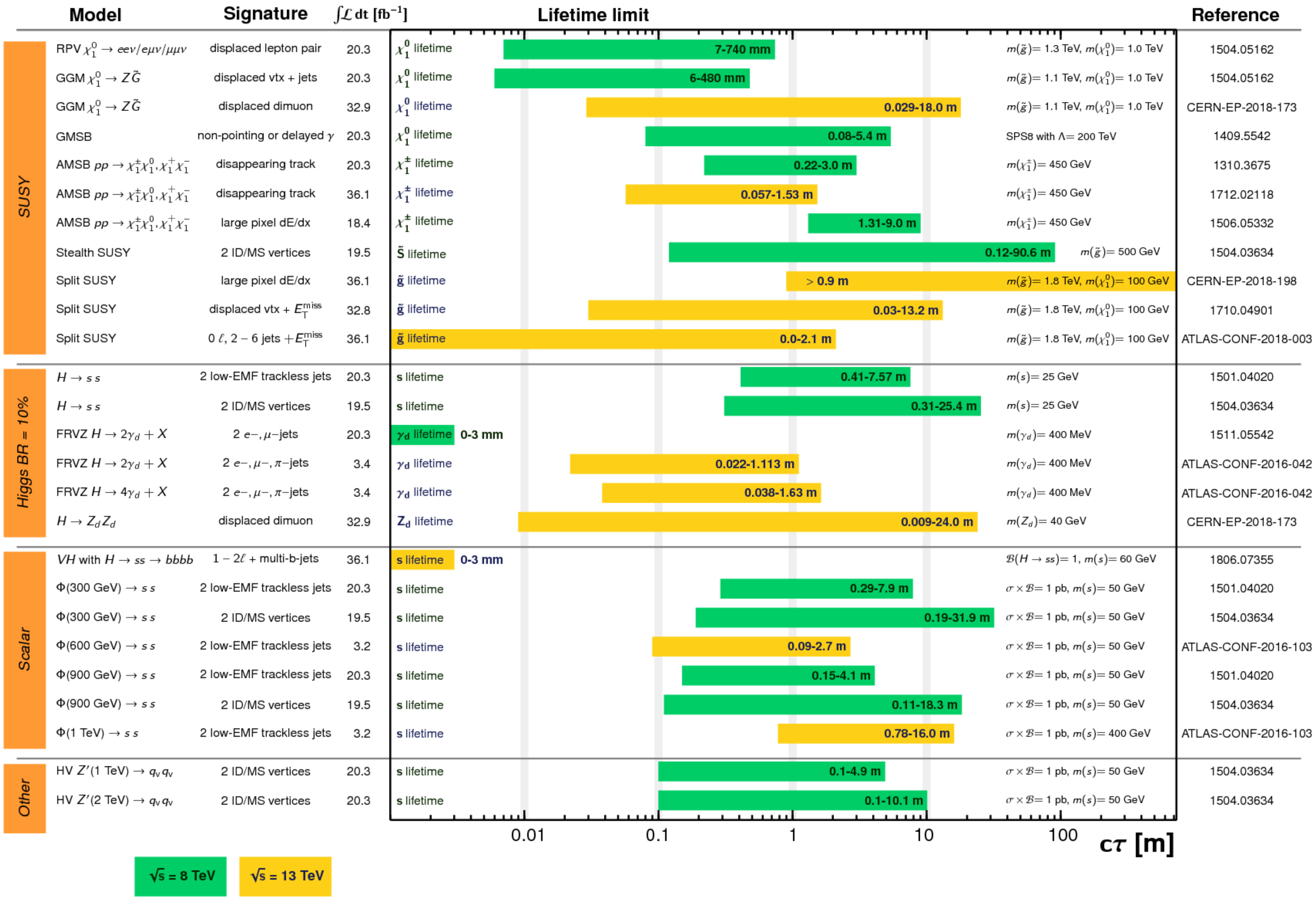
Eur.Phys.J. C72 (2012) 1844

ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Status: July 2018

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 36.1)\ \text{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

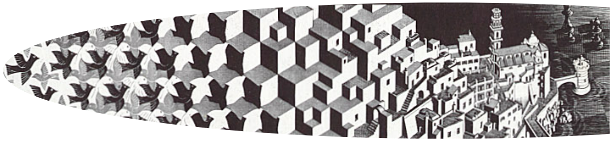


	Model	Signature	$\int \mathcal{L}\, dt\ [\text{fb}^{-1}]$	Lifetime limit			Reference
SUSY	RPV $\chi_1^0 \to ee\nu/e\mu\nu/\mu\mu\nu$	displaced lepton pair	20.3	χ_1^0 lifetime	🟩 7-740 mm	$m(\tilde{g})$= 1.3 TeV, $m(\chi_1^0)$= 1.0 TeV	1504.05162
	GGM $\chi_1^0 \to Z\tilde{G}$	displaced vtx + jets	20.3	χ_1^0 lifetime	🟩 6-480 mm	$m(\tilde{g})$= 1.1 TeV, $m(\chi_1^0)$= 1.0 TeV	1504.05162
	GGM $\chi_1^0 \to Z\tilde{G}$	displaced dimuon	32.9	χ_1^0 lifetime	🟨 0.029-18.0 m	$m(\tilde{g})$= 1.1 TeV, $m(\chi_1^0)$= 1.0 TeV	CERN-EP-2018-173
	GMSB	non-pointing or delayed γ	20.3	χ_1^0 lifetime	🟩 0.08-5.4 m	SPS8 with Λ= 200 TeV	1409.5542
	AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$	disappearing track	20.3	$\chi_1^\pm$ lifetime	🟩 0.22-3.0 m	$m(\chi_1^\pm)$= 450 GeV	1310.3675
	AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$	disappearing track	36.1	$\chi_1^\pm$ lifetime	🟨 0.057-1.53 m	$m(\chi_1^\pm)$= 450 GeV	1712.02118
	AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$	large pixel dE/dx	18.4	$\chi_1^\pm$ lifetime	🟩 1.31-9.0 m	$m(\chi_1^\pm)$= 450 GeV	1506.05332
	Stealth SUSY	2 ID/MS vertices	19.5	$\tilde{S}$ lifetime	🟩 0.12-90.6 m	$m(\tilde{g})$= 500 GeV	1504.03634
	Split SUSY	large pixel dE/dx	36.1	$\tilde{g}$ lifetime	🟨 $>$ 0.9 m	$m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV	CERN-EP-2018-198
	Split SUSY	displaced vtx + E_T^{miss}	32.8	$\tilde{g}$ lifetime	🟨 0.03-13.2 m	$m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV	1710.04901
	Split SUSY	$0\ \ell, 2-6$ jets $+E_T^{miss}$	36.1	$\tilde{g}$ lifetime	🟨 0.0-2.1 m	$m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV	ATLAS-CONF-2018-003
Higgs BR = 10%	$H \to s\, s$	2 low-EMF trackless jets	20.3	s lifetime	🟩 0.41-7.57 m	$m(s)$= 25 GeV	1501.04020
	$H \to s\, s$	2 ID/MS vertices	19.5	s lifetime	🟩 0.31-25.4 m	$m(s)$= 25 GeV	1504.03634
	FRVZ $H \to 2\gamma_d + X$	2 $e-, \mu-$jets	20.3	γ_d lifetime	🟩 0-3 mm	$m(\gamma_d)$= 400 MeV	1511.05542
	FRVZ $H \to 2\gamma_d + X$	2 $e-, \mu-, \pi-$jets	3.4	γ_d lifetime	🟨 0.022-1.113 m	$m(\gamma_d)$= 400 MeV	ATLAS-CONF-2016-042
	FRVZ $H \to 4\gamma_d + X$	2 $e-, \mu-, \pi-$jets	3.4	γ_d lifetime	🟨 0.038-1.63 m	$m(\gamma_d)$= 400 MeV	ATLAS-CONF-2016-042
	$H \to Z_d Z_d$	displaced dimuon	32.9	Z_d lifetime	🟨 0.009-24.0 m	$m(Z_d)$= 40 GeV	CERN-EP-2018-173
Scalar	VH with $H \to ss \to bbbb$	$1-2\ell$ + multi-b-jets	36.1	s lifetime	🟨 0-3 mm	$\mathcal{B}(H \to ss)$= 1, $m(s)$= 60 GeV	1806.07355
	Φ(300 GeV) $\to s\, s$	2 low-EMF trackless jets	20.3	s lifetime	🟩 0.29-7.9 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1501.04020
	Φ(300 GeV) $\to s\, s$	2 ID/MS vertices	19.5	s lifetime	🟩 0.19-31.9 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1504.03634
	Φ(600 GeV) $\to s\, s$	2 low-EMF trackless jets	3.2	s lifetime	🟨 0.09-2.7 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	ATLAS-CONF-2016-103
	Φ(900 GeV) $\to s\, s$	2 low-EMF trackless jets	20.3	s lifetime	🟩 0.15-4.1 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1501.04020
	Φ(900 GeV) $\to s\, s$	2 ID/MS vertices	19.5	s lifetime	🟩 0.11-18.3 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1504.03634
	Φ(1 TeV) $\to s\, s$	2 low-EMF trackless jets	3.2	s lifetime	🟨 0.78-16.0 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 400 GeV	ATLAS-CONF-2016-103
Other	HV Z'(1 TeV) $\to q_v q_v$	2 ID/MS vertices	20.3	s lifetime	🟩 0.1-4.9 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1504.03634
	HV Z'(2 TeV) $\to q_v q_v$	2 ID/MS vertices	20.3	s lifetime	🟩 0.1-10.1 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1504.03634

🟩 $\sqrt{s}$ = 8 TeV 🟨 $\sqrt{s}$ = 13 TeV

**Only a selection of the available lifetime limits on new states is shown.*

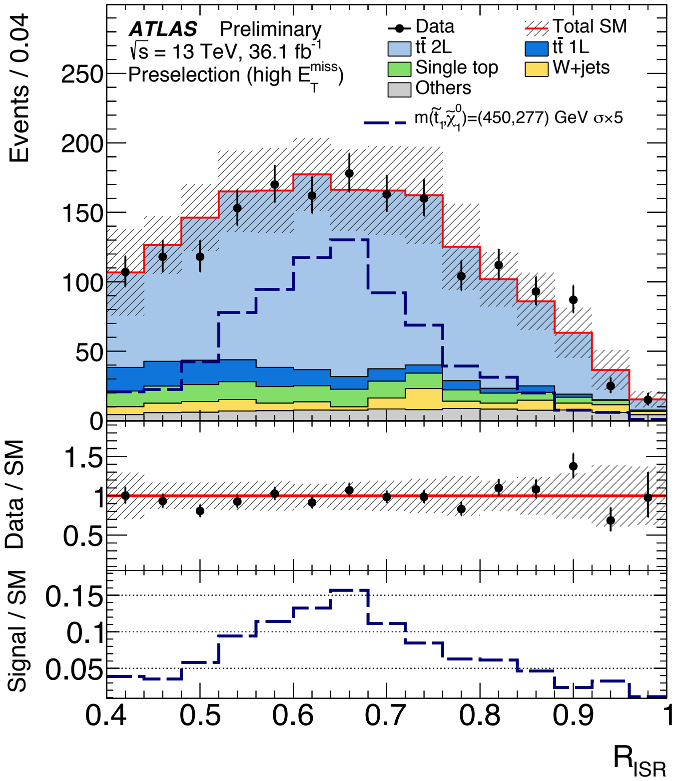
$(\gamma\beta = 1)$



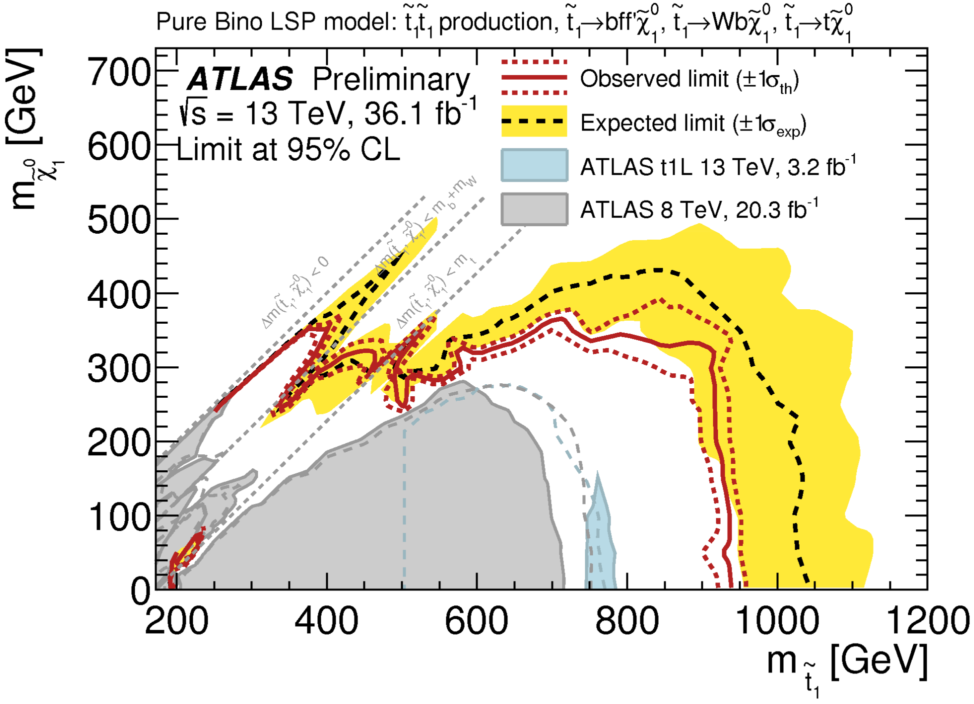
Sparticles In Motion

This ISR-assisted compressed analysis technique is already employed in ATLAS zero-lepton searches for SUSY top partners

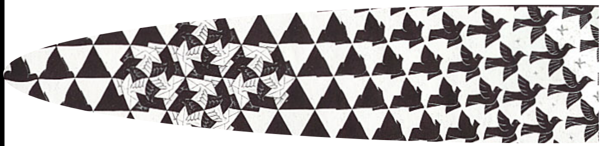
…and now also in one-lepton final states too



$$m_{\tilde{t}} - m_{\tilde{\chi}} \sim m_{top}$$

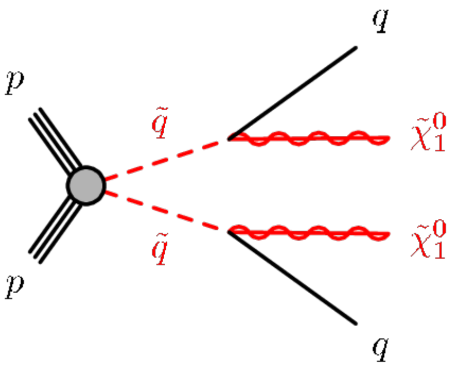


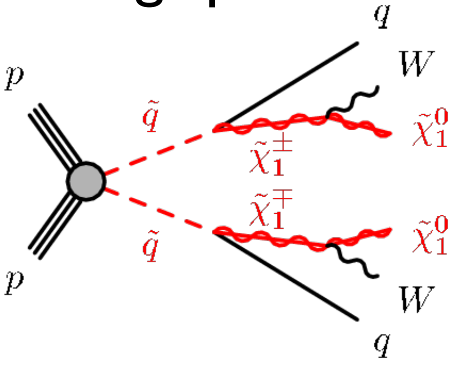
arXiv:1711.11520 [hep-ex]



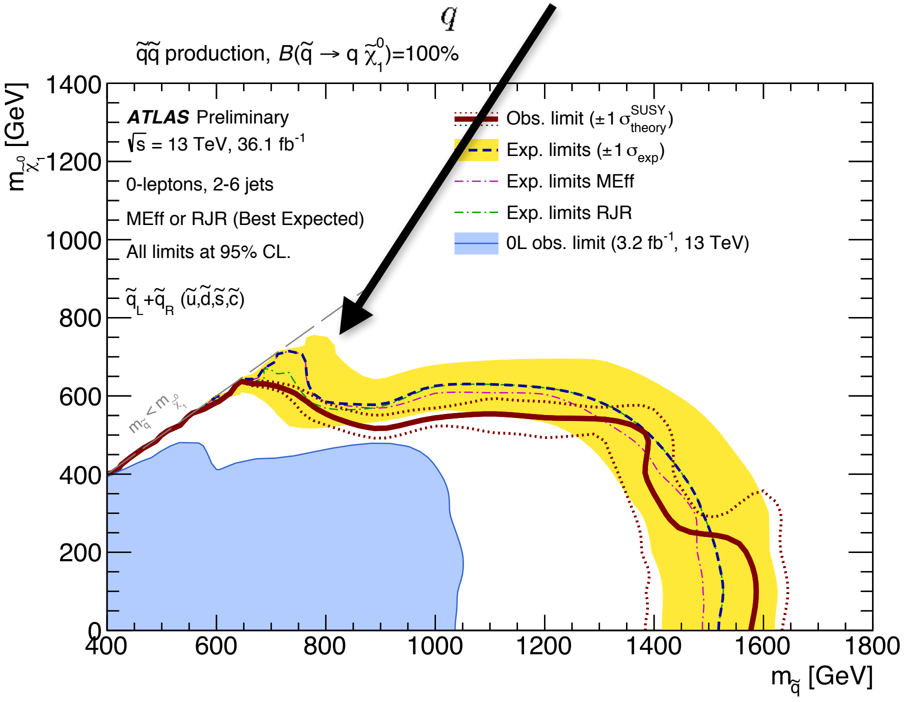
Sparticles In Motion

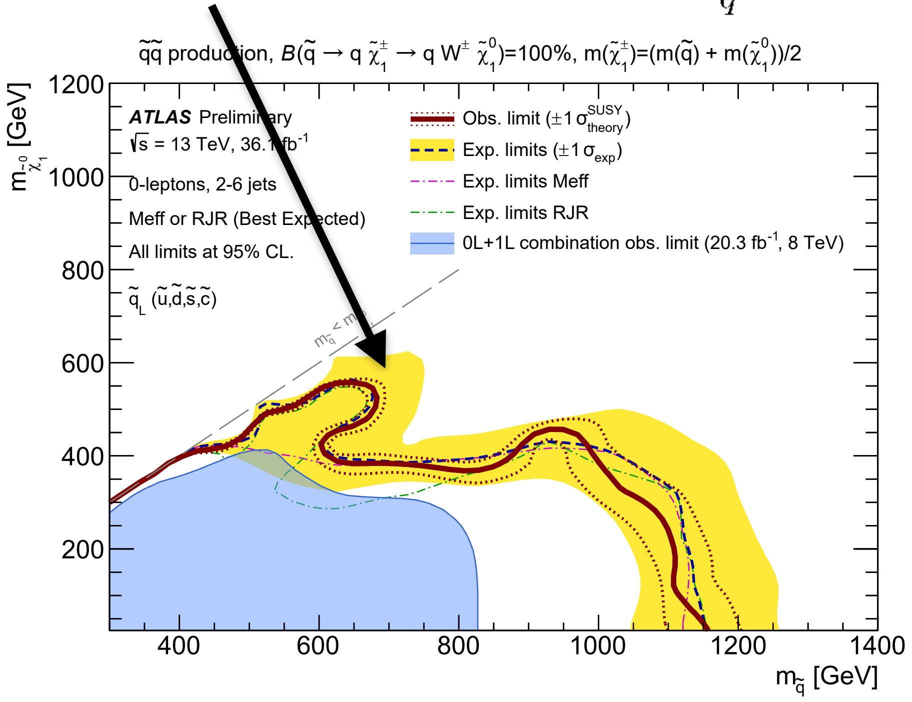
This ISR-assisted compressed analysis technique is also used in ATLAS zero-lepton searches for strongly-interacting sparticles:





small $m_{\tilde{q}} - m_{\tilde{\chi}}$





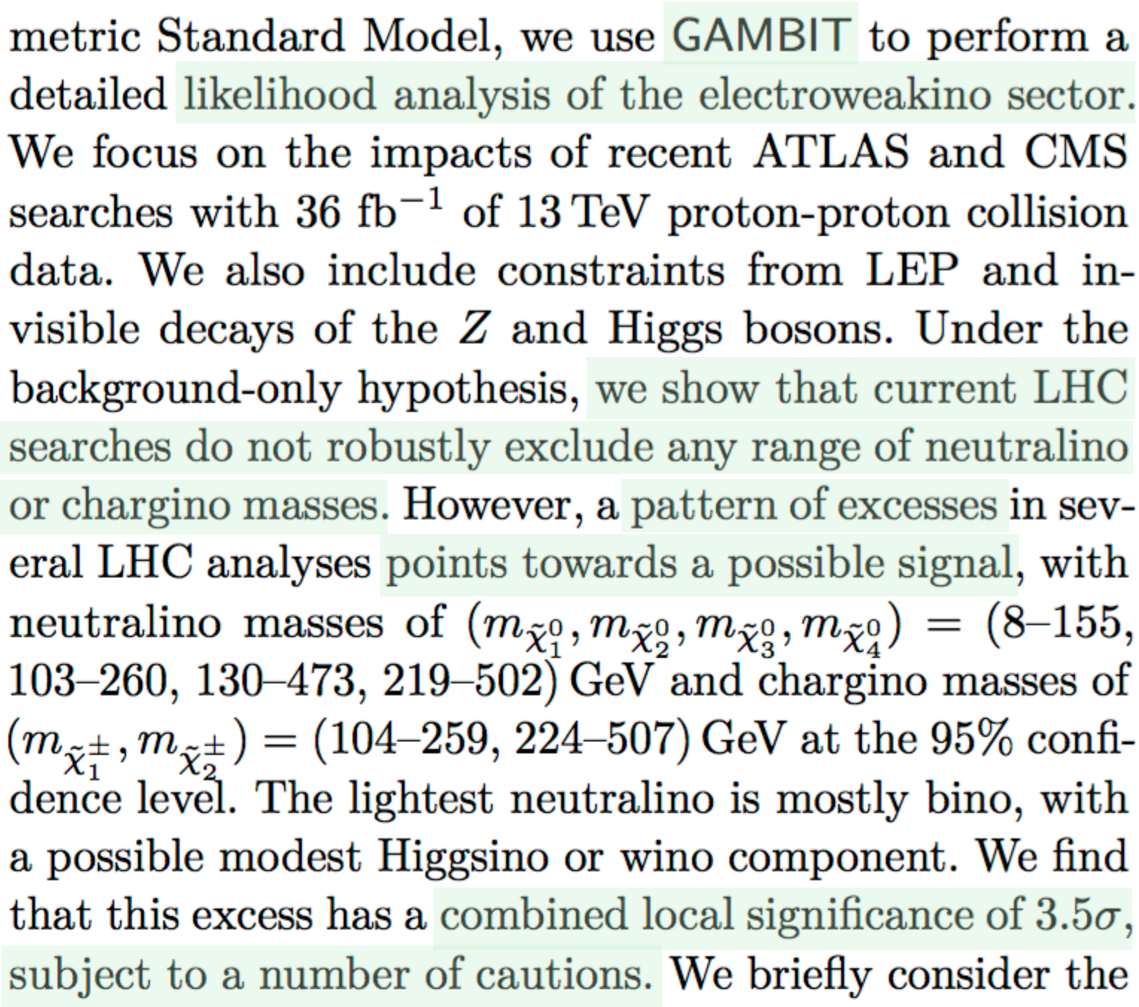
arXiv:1712.02332 [hep-ex]

SUSY EWKinos Interpretation

arXiv:1809.02097

Combined collider constraints on neutralinos and charginos

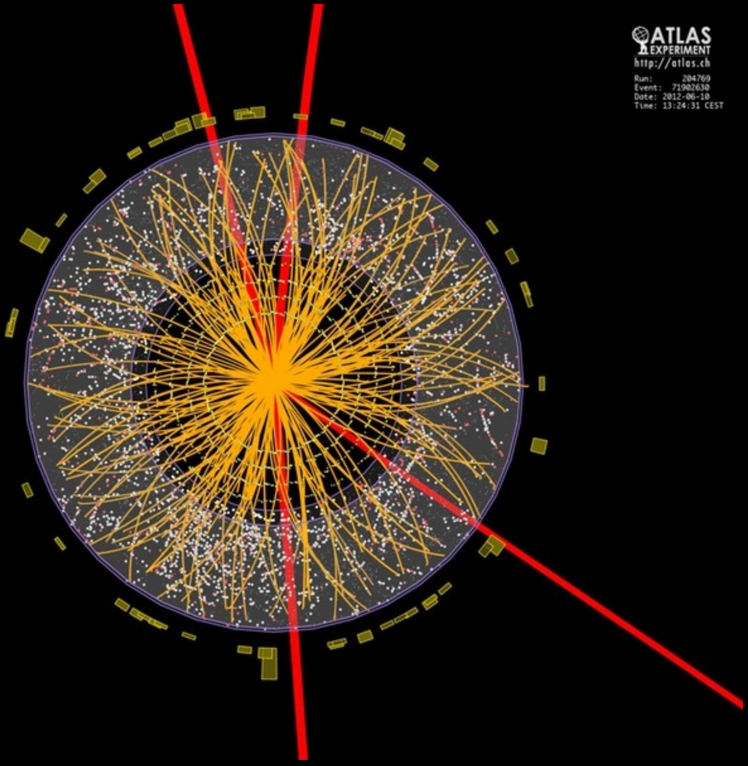
abstract excerpt:



metric Standard Model, we use GAMBIT to perform a detailed likelihood analysis of the electroweakino sector. We focus on the impacts of recent ATLAS and CMS searches with 36 fb^{-1} of 13 TeV proton-proton collision data. We also include constraints from LEP and invisible decays of the Z and Higgs bosons. Under the background-only hypothesis, we show that current LHC searches do not robustly exclude any range of neutralino or chargino masses. However, a pattern of excesses in several LHC analyses points towards a possible signal, with neutralino masses of $(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0}) =$ (8–155, 103–260, 130–473, 219–502) GeV and chargino masses of $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^\pm}) =$ (104–259, 224–507) GeV at the 95% confidence level. The lightest neutralino is mostly bino, with a possible modest Higgsino or wino component. We find that this excess has a combined local significance of 3.5σ, subject to a number of cautions. We briefly consider the

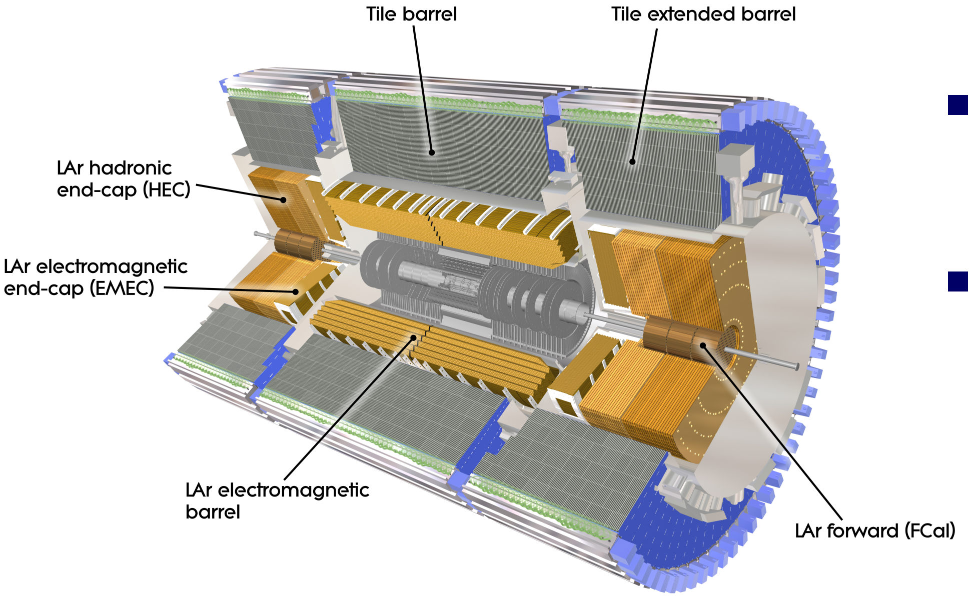
Event Reconstruction

How can we *interpret* the information we measure in each event?



Invisible Particle Reconstruction

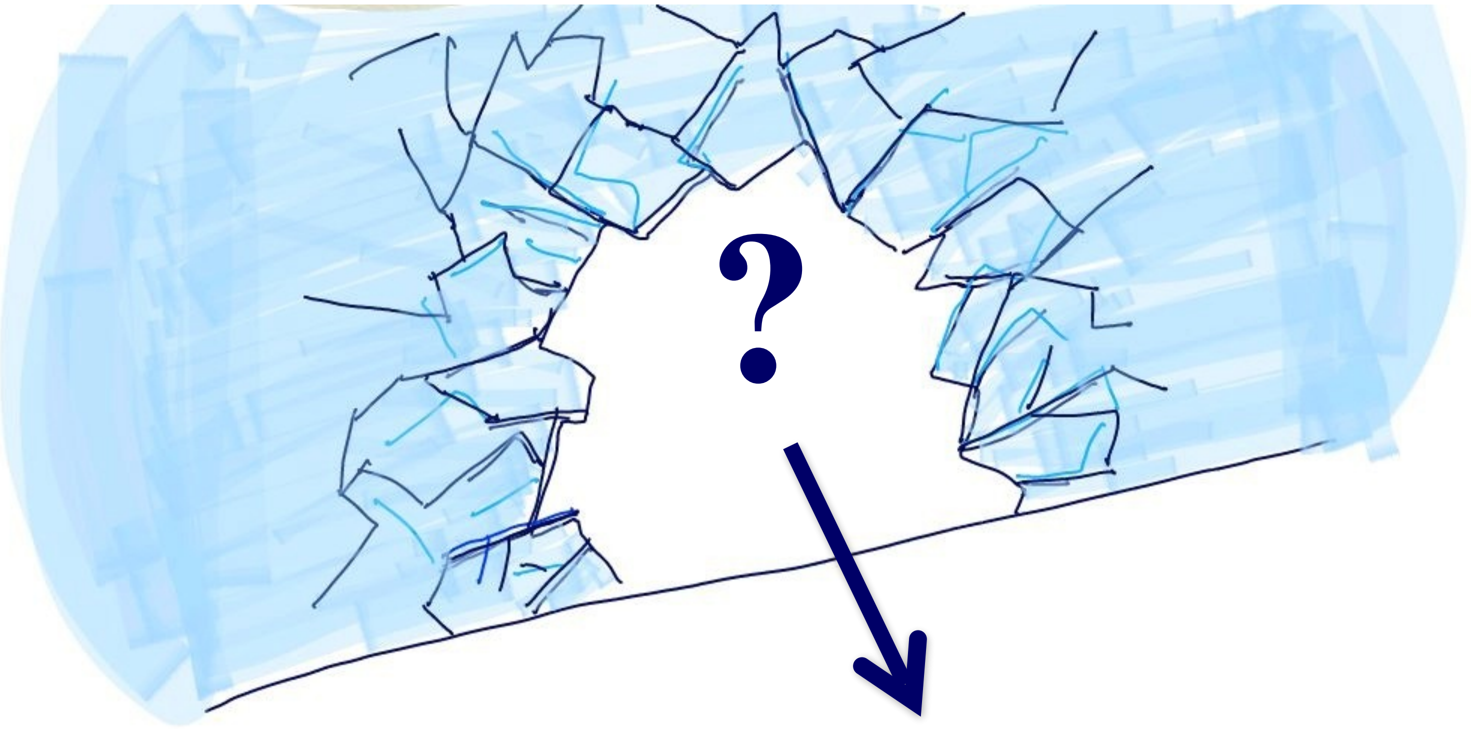
- **How do we study weakly interacting particles?**
  - Can infer their presence through ***missing transverse energy***
  - Hermetic design of LHC experiments allows us to infer ***'what's missing'***
    - full azimuthal coverage, up to |η| of ~5
    - stopping power of ~12-20 interaction lengths
    - ECAL+HCAL components with segmentation comparable to lateral shower sizes



LHC Calorimeters

$$\vec{E}_T^{miss} = -\sum_i^{cells} \vec{E}_T$$

Missing Transverse Energy



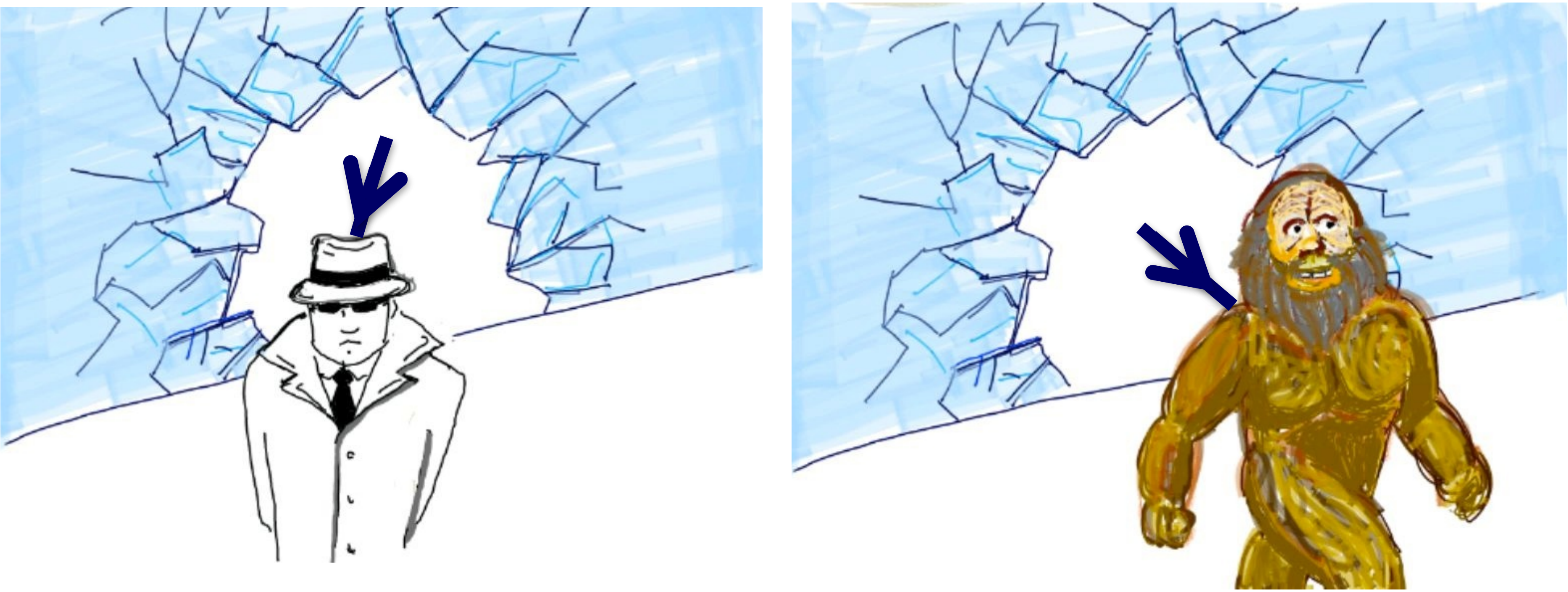
$\vec{E}_T^{miss}$

Missing transverse energy only tells us about the momentum of weakly interacting particles in an event…

Missing Transverse Energy

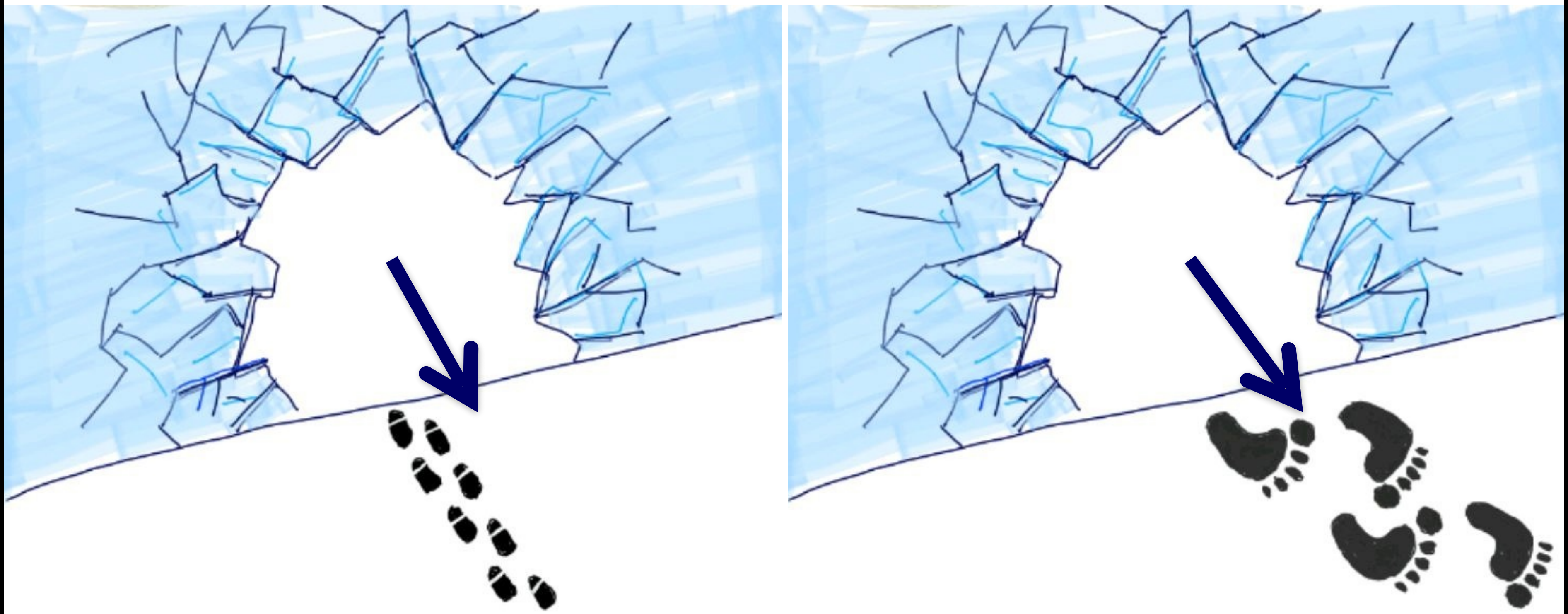
…not about the identity or mass of weakly interacting particles, or about the particle(s) they may decay from…

Missing Transverse Energy



…not about the identity or mass of weakly interacting particles, or about the particle(s) they may decay from…

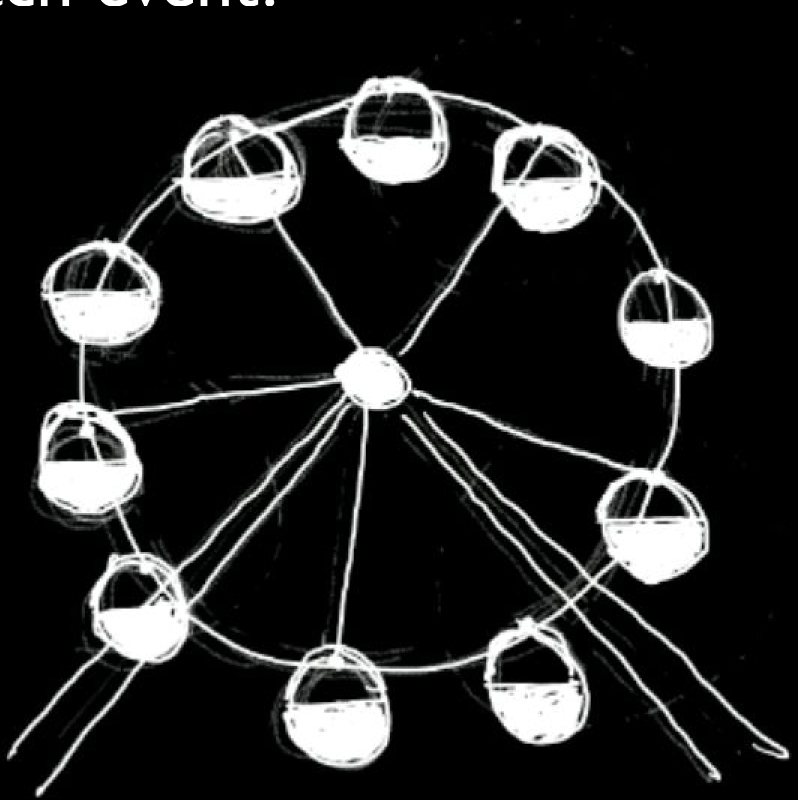
Missing Transverse Energy



We can learn more by using other information in an event to **contextualize the missing transverse energy** and **resolve additional information**

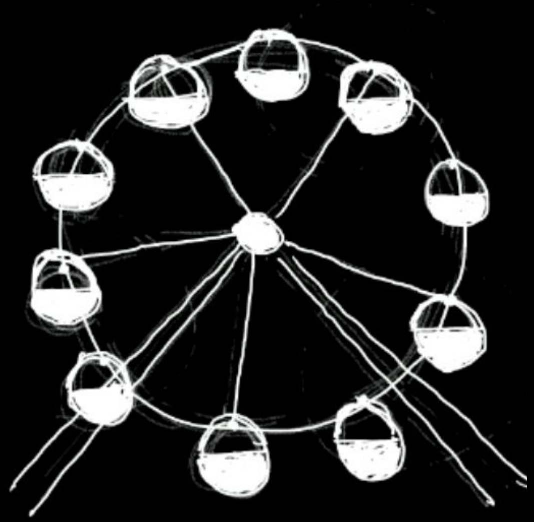
Event Reconstruction

How can we *interpret* the information
we measure in each event?



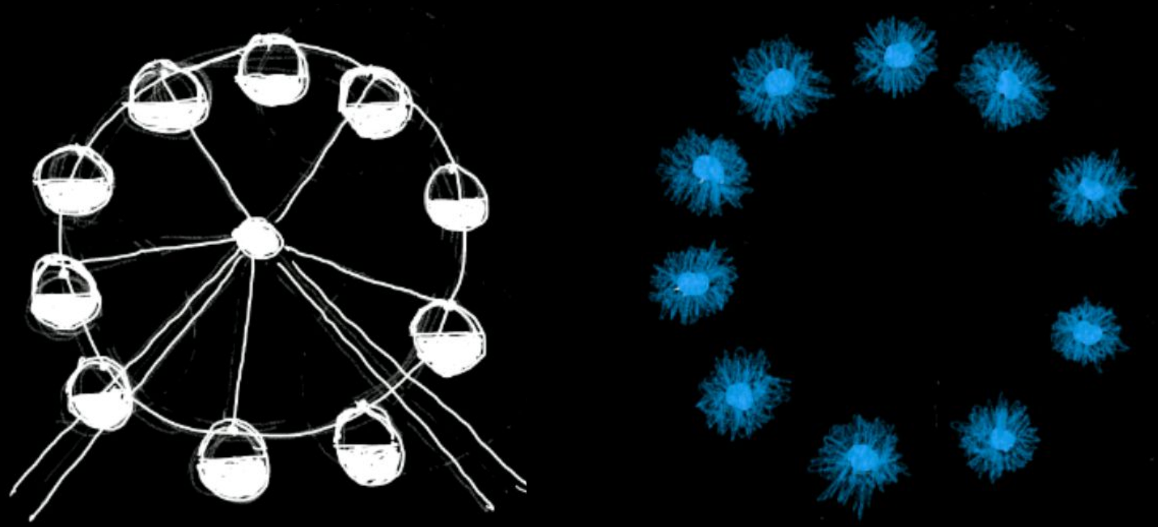
Suppose I'm interested in Ferris wheels,
particularly their *size*…

Event Reconstruction



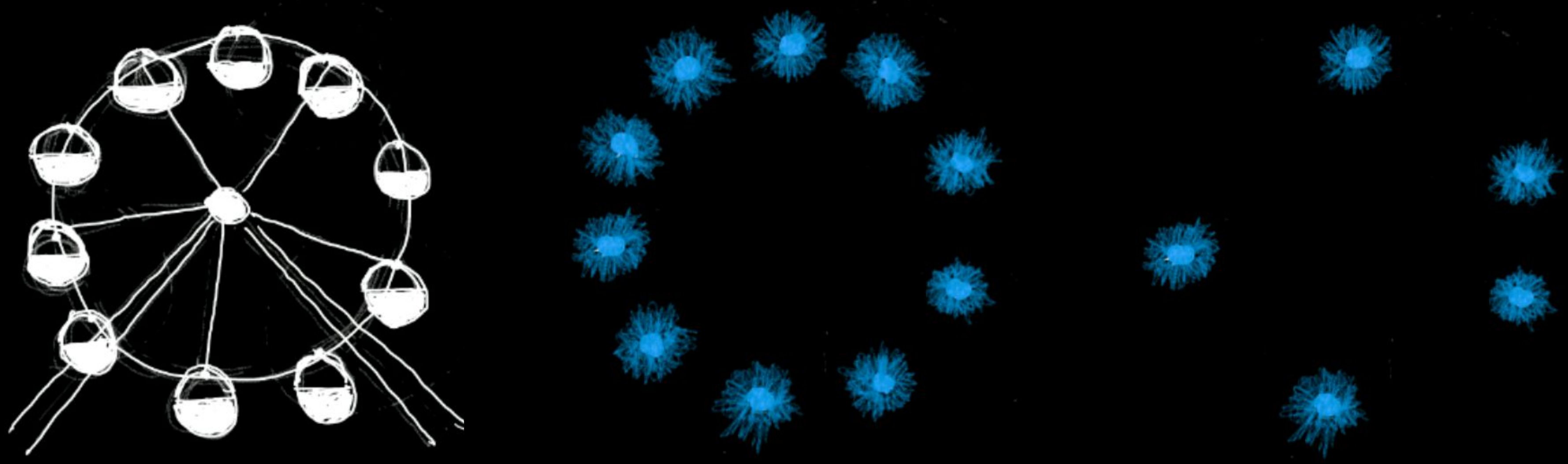
I can clearly infer the wheel radius from this image…

Event Reconstruction



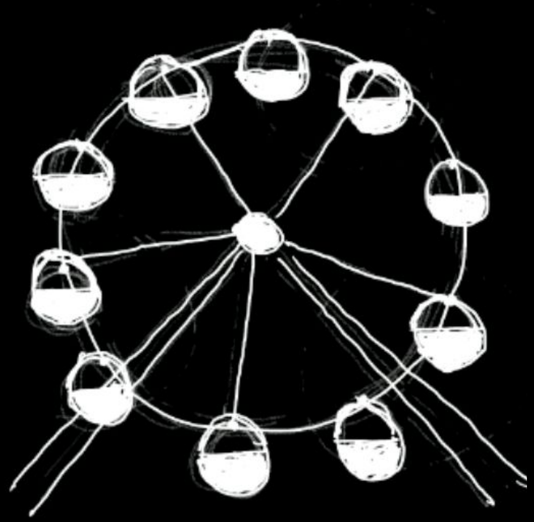
…and in the dark with only each cabin lit?…

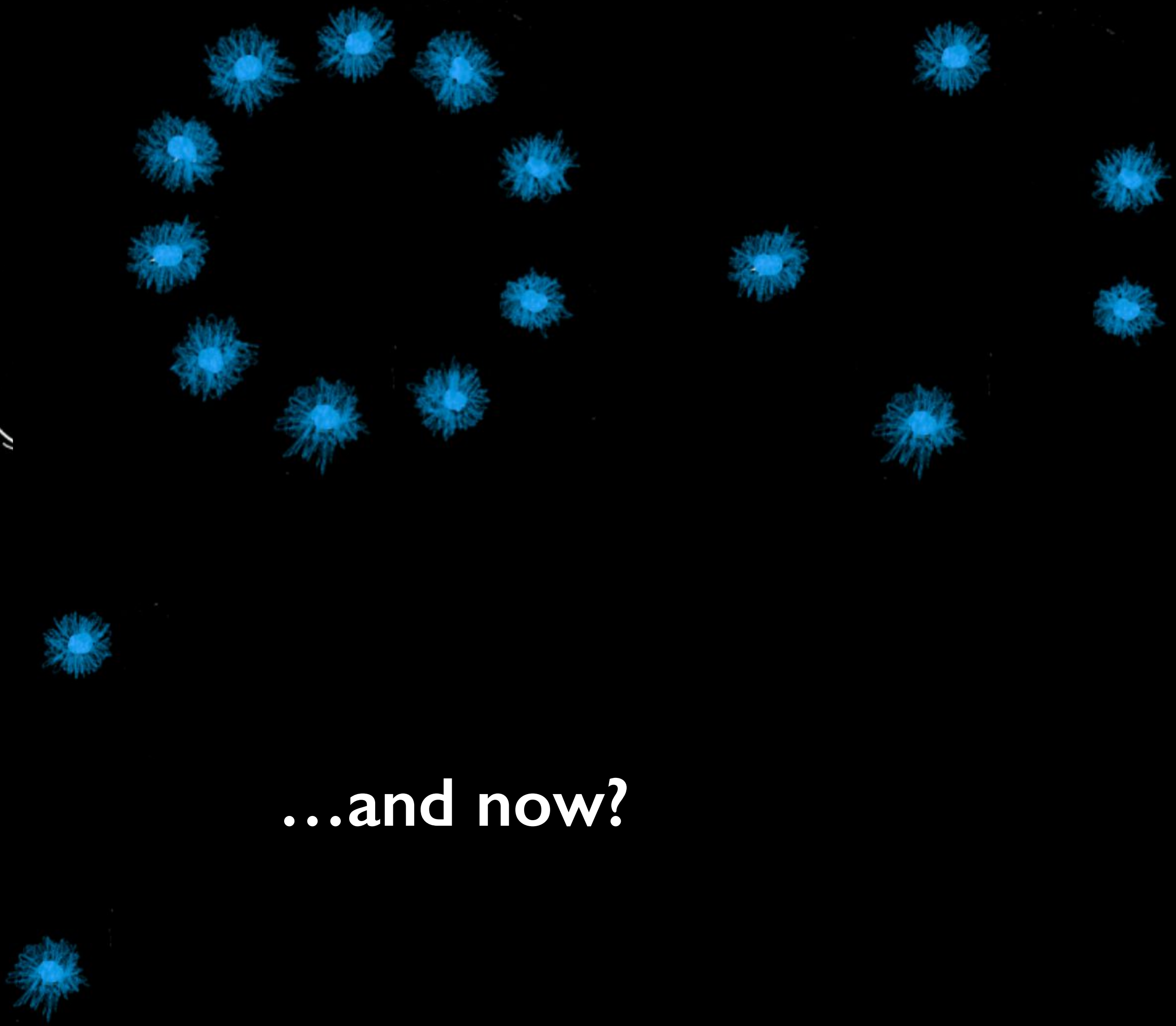
Event Reconstruction



…and with only some of the cabins lit?…

Event Reconstruction

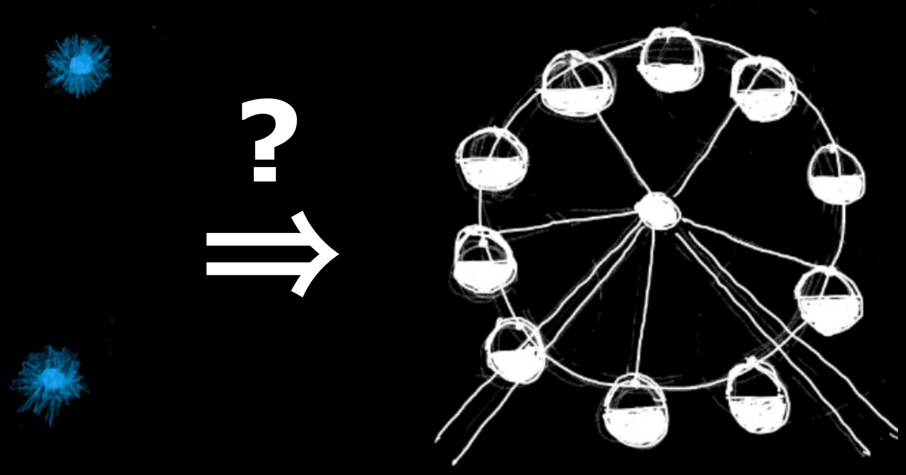




…and now?

Event Reconstruction

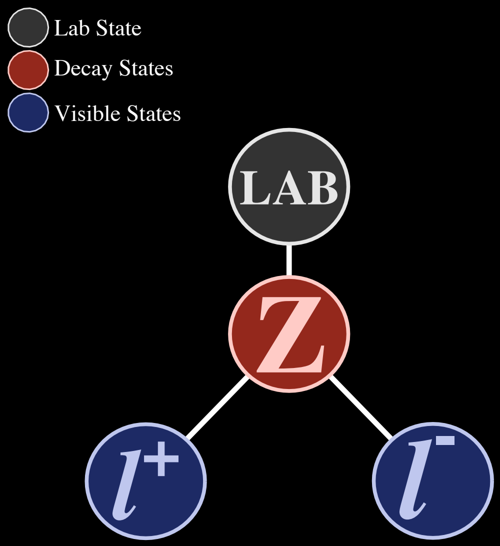
How can we *interpret* the information we measure in each event?

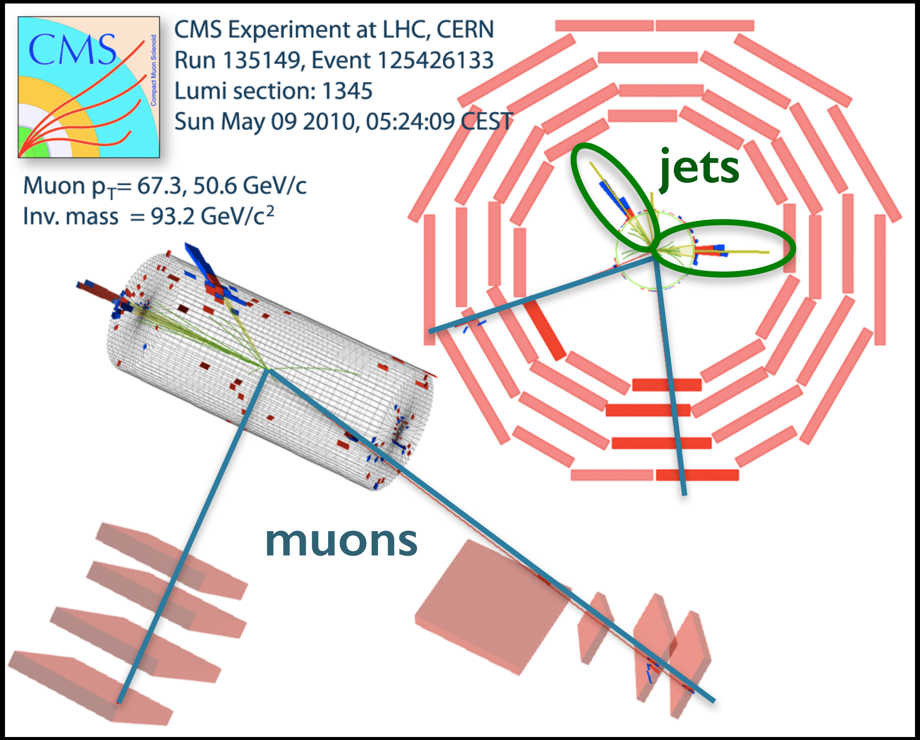


- Seeing only lights, we must first *assume* we are looking at a Ferris wheel to make inferences
- With only two lights, we can only infer its *minimum* radius
- What if we…
  - *knew how many equidistant cabins there were?*
  - *assumed that the two lit cabins were opposite each other?*

Event Reconstruction

Suppose we want to study events with a *Z* boson decaying to two leptons

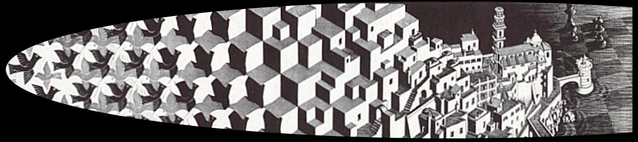




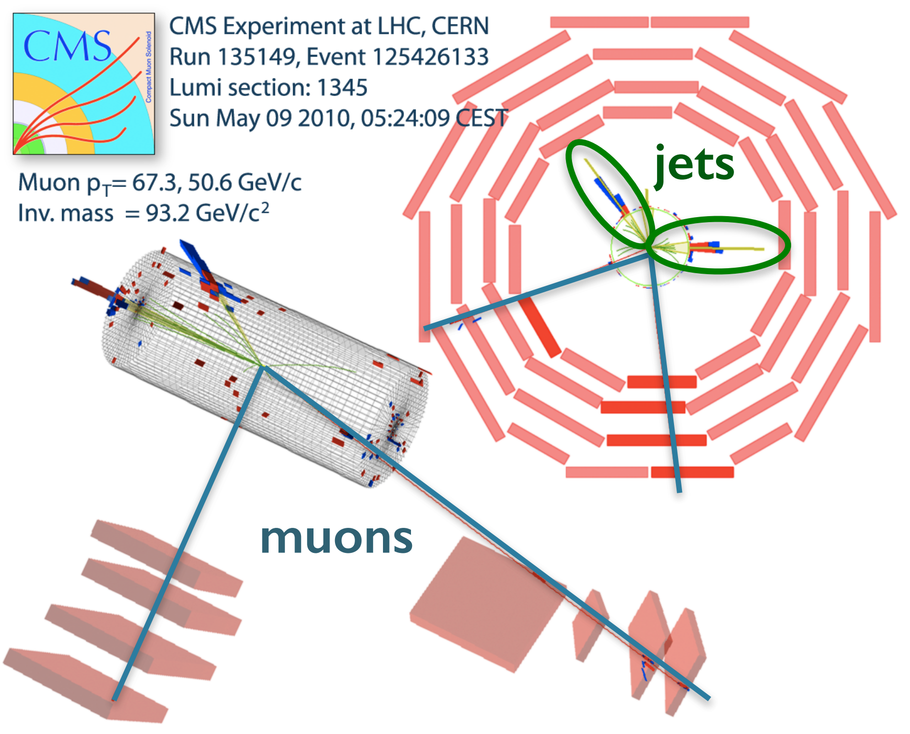
CMS Experiment at LHC, CERN
Run 135149, Event 125426133
Lumi section: 1345
Sun May 09 2010, 05:24:09 CEST

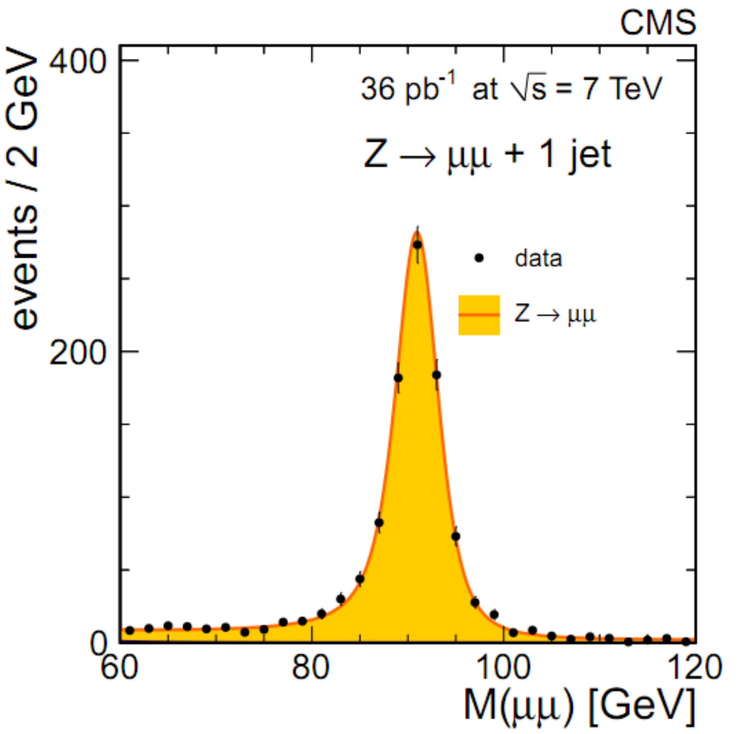
Muon p_T= 67.3, 50.6 GeV/c
Inv. mass = 93.2 GeV/c^2

We reconstruct the particle candidates in each collision, keeping events with two opposite sign, same-flavor leptons. *How do we interpret their measured momentum?*



Event Reconstruction



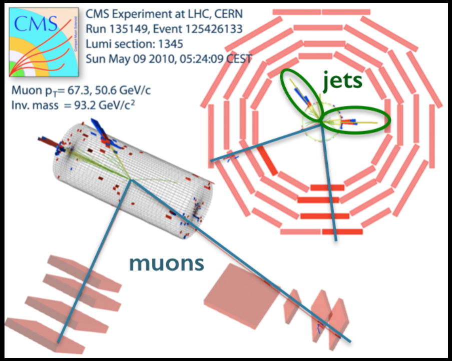


We can calculate the invariant mass of the two leptons

$$M(\ell\ell)^2 = (p_{\ell 1} + p_{\ell 2})^2 = (E_{\ell 1} + E_{\ell 2})^2 - |\vec{p}_{\ell 1} + \vec{p}_{\ell 2}|^2$$

Reveals the resonant structure of the *Z* boson decay

Event Reconstruction



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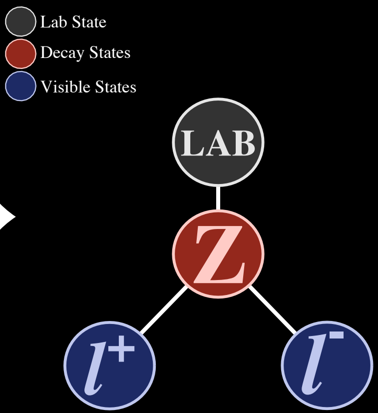
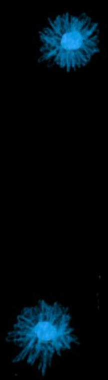


From the two leptons, we can make inferences about the mass of the *Z* boson, just like the wheel radius from opposite lights



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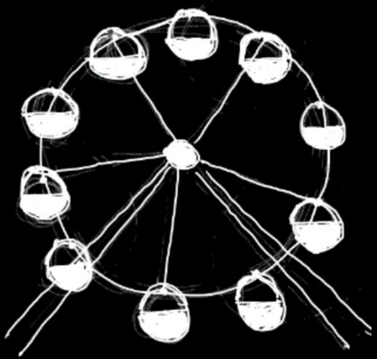
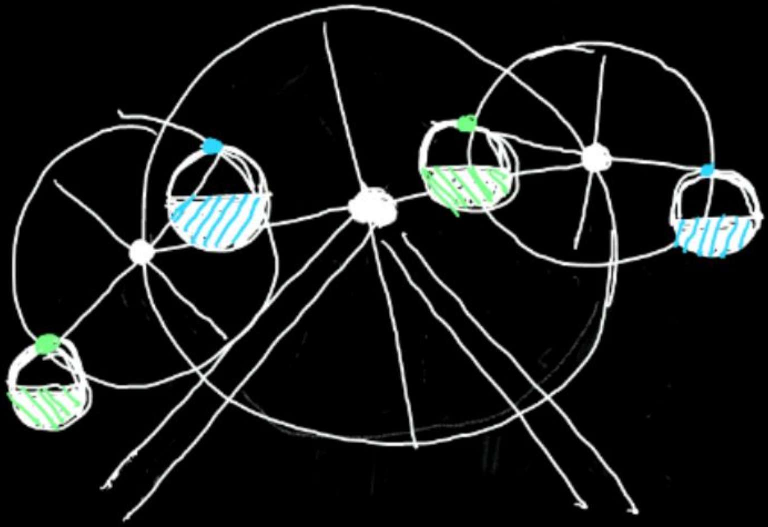


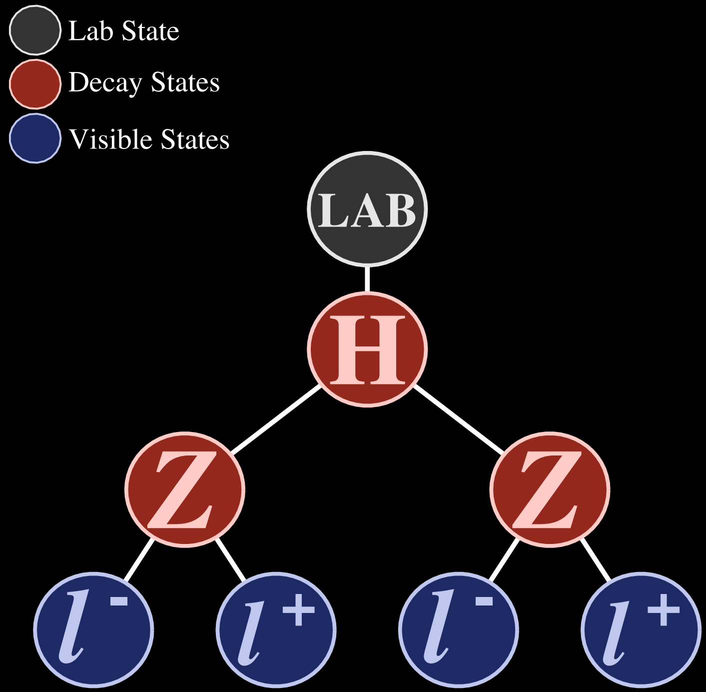
The invariant mass is part of a complete *basis* of observables

Instead of considering the individual lepton momenta,
we can look at the *Z* boson’s four vector, *its* decay angle,
and the orientation of its decay plane

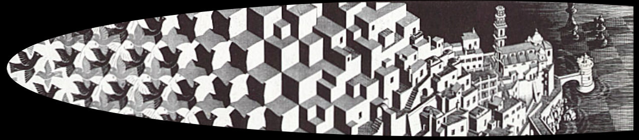
Event Reconstruction

Just as one can imagine more involved Ferris wheels…

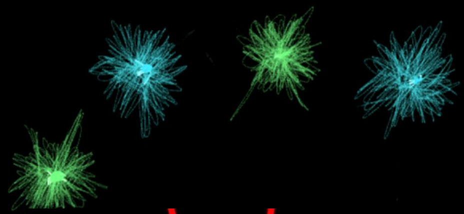




…Nature also realizes more complicated decays in collision events



Event Reconstruction



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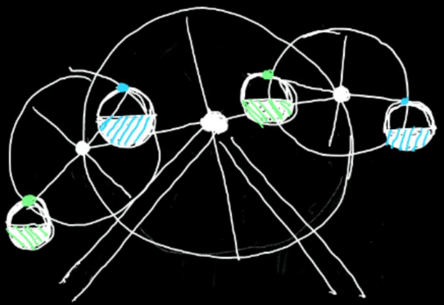
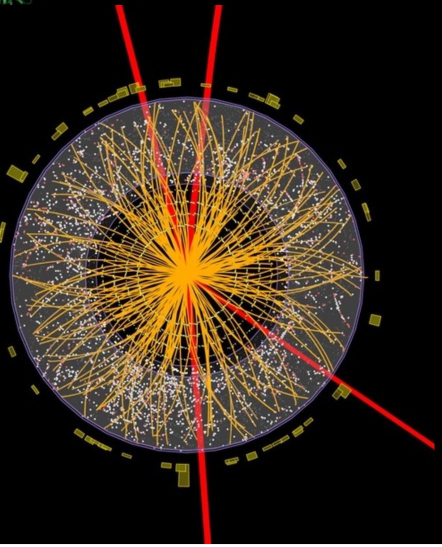


These events can be analyzed in the same way as the simpler case:



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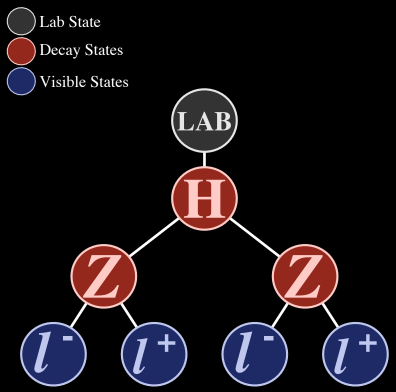
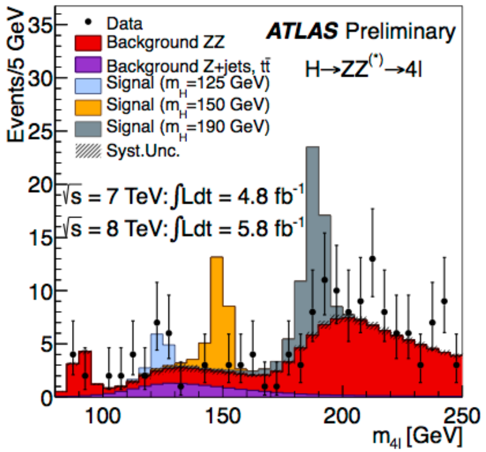
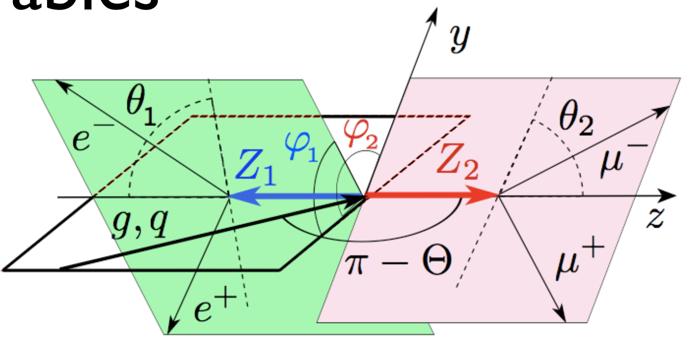
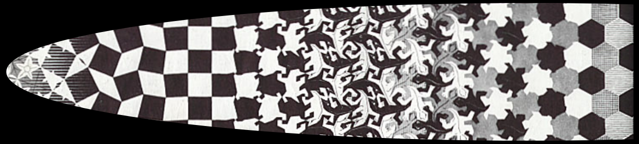


(a) Assume a decay topology describing the event

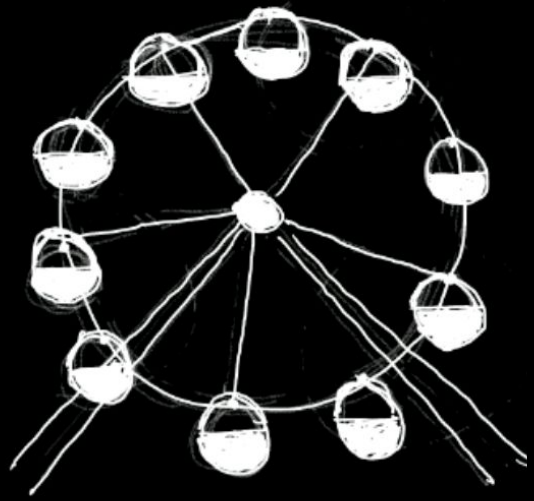


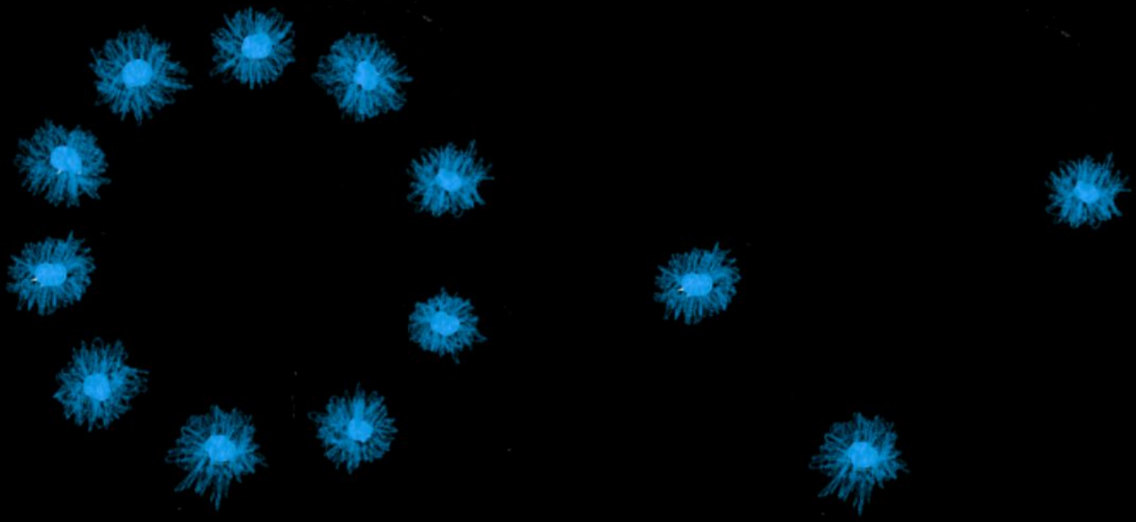
(b) Calculate observables according to the decay tree — *particle masses and decay angles*

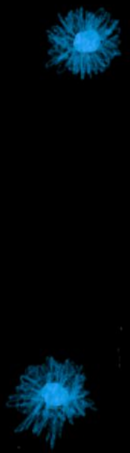




Event Reconstruction



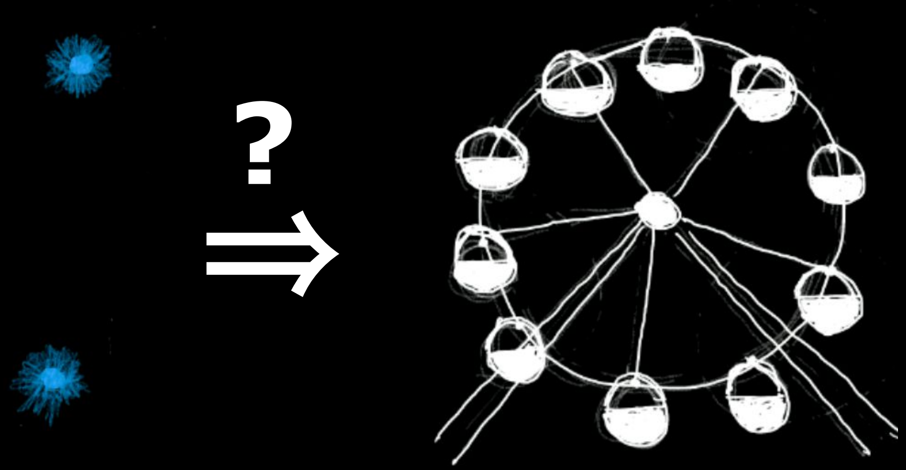




…and now?

Event Reconstruction

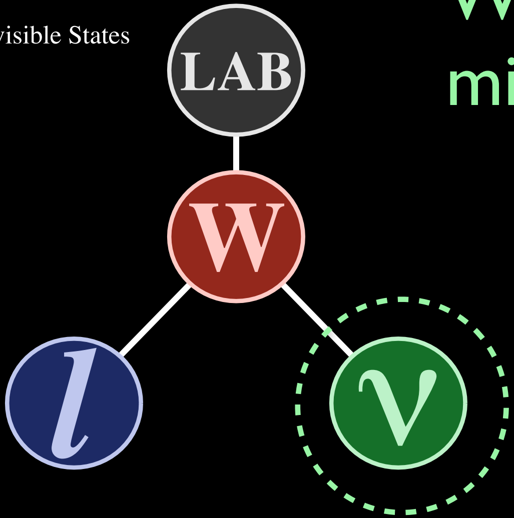
How can we *interpret* the information we measure in each event?



- Seeing only lights, we must first *assume* we are looking at a Ferris wheel to make inferences
- With only two lights, we can only infer its *minimum* radius

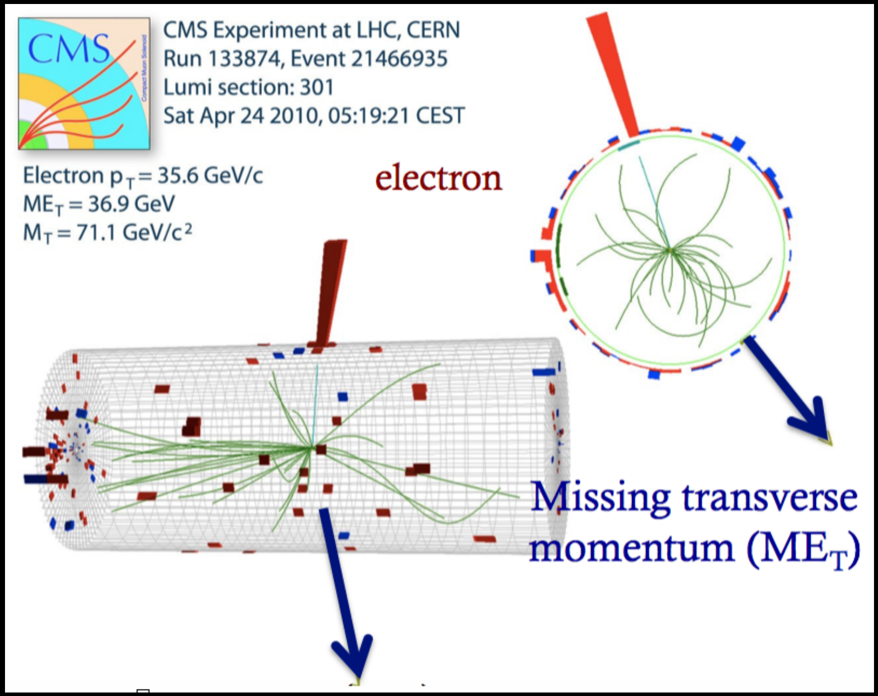
Invisible Particles

● Lab State
● Decay States
● Visible States
● Invisible States



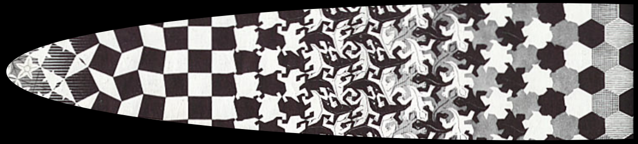
What about events with missing *invisible* particles?

As the invisible particle escapes undetected, it carries with it important, irrecoverable information describing the event



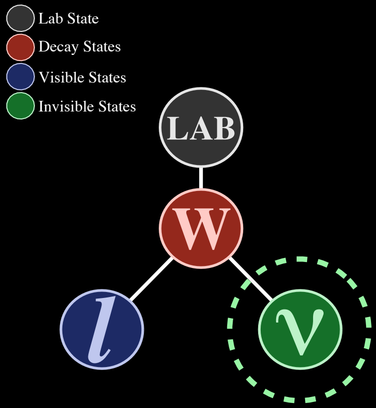
CMS Experiment at LHC, CERN
Run 133874, Event 21466935
Lumi section: 301
Sat Apr 24 2010, 05:19:21 CEST

Electron $p_T = 35.6$ GeV/c
$ME_T = 36.9$ GeV
$M_T = 71.1$ GeV/c^2



Invisible Particles

What information are we missing?



four unknown d.o.f. associated with the neutrino

$$\left(\vec{p}_{\nu,\mathrm{T}},\ p_{\nu,z},\ m_\nu\right)$$

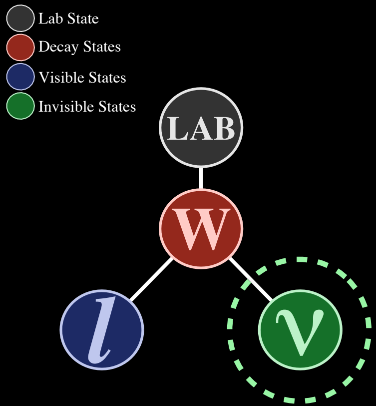
subject to three constraints

$$\vec{p}_{\nu,\mathrm{T}} = \vec{E}_{\mathrm{T}}^{\mathrm{miss}} \qquad m_\nu = 0$$

leaving one under-constrained unknown: $p_{\nu,z}$

Invisible Particles

What information are we missing?



four unknown d.o.f. associated with the neutrino

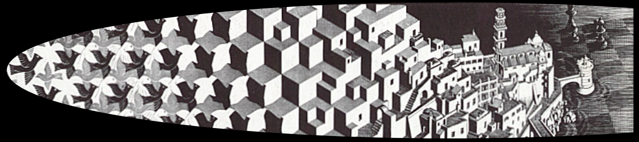
$$\left(\vec{p}_{\nu,\mathrm{T}},\ p_{\nu,z},\ m_{\nu}\right)$$

subject to three constraints

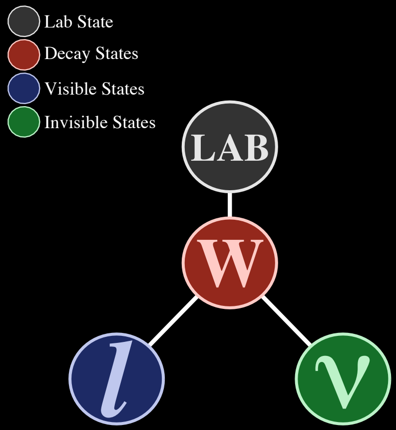
$$\vec{p}_{\nu,\mathrm{T}} = \vec{E}_{\mathrm{T}}^{\mathrm{miss}} \qquad m_{\nu} = 0$$

leaving one under-constrained unknown: $p_{\nu,z}$

Unfortunately, most of the desired observables (W mass, decay angles) all depend on $p_{\nu,z}$



Invisible Particles



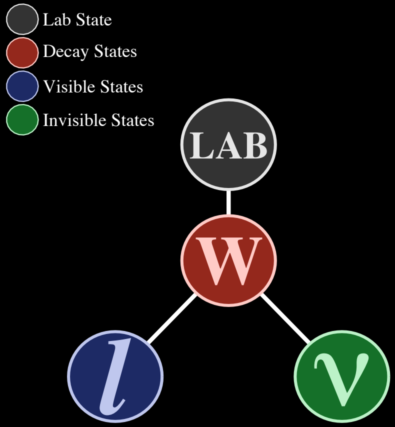
Crucial observation for RJR:
despite decaying to both a visible and invisible particle, knowing only the velocity relating the W rest frame to the lab frame gives us all the information we need

Knowing this velocity ($\vec{\beta}_W^{\,\mathrm{lab}}$), we can boost the measured lepton from the lab frame to the W rest frame

The angle between $\vec{\beta}_W^{\,\mathrm{lab}}$ and $\vec{p}_\ell^{\,W}$ gives the W decay angle, and their cross-product the decay plane orientation

The W mass can be calculated from the lepton's energy, as in this reference frame $M_W = 2E_\ell^{\,W}$

Invisible Particles



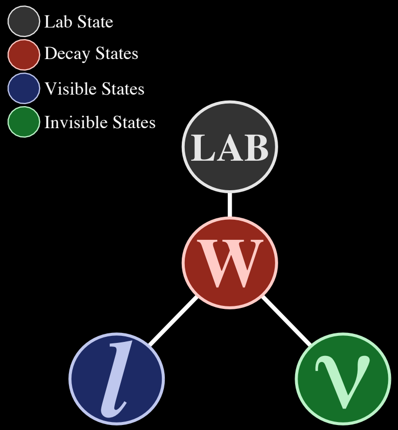
Crucial guess/choice:

interpret the event with $p_{\nu,z}$ *chosen to satisfy*

$$\frac{\partial M_W(\beta_{W,z}^{\rm lab})}{\partial\beta_{W,z}^{\rm lab}} = 0$$

What are the implications of this choice?

Invisible Particles



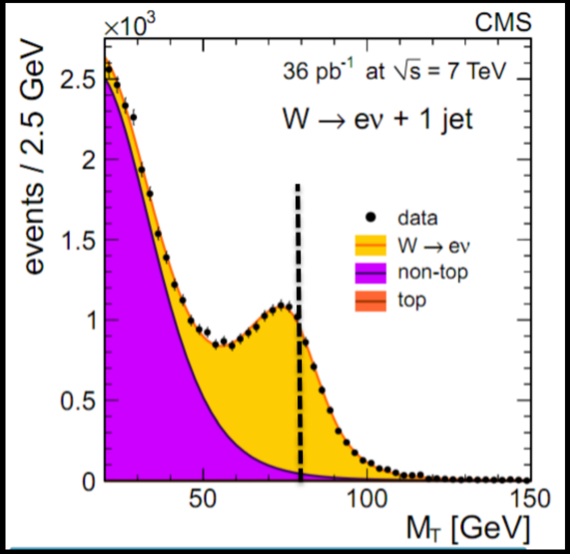
Crucial guess/choice:

interpret the event with $p_{\nu,z}$ *chosen to satisfy*

$$\frac{\partial M_W\left(\beta_{W,z}^{\text{lab}}\right)}{\partial \beta_{W,z}^{\text{lab}}} = 0$$

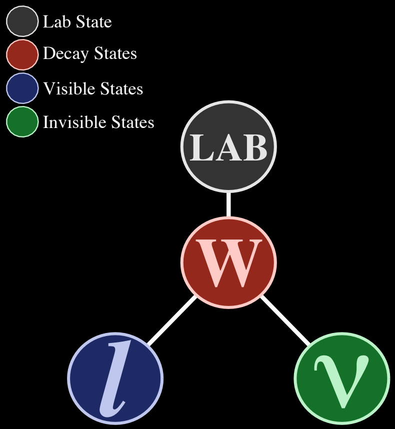
(a) Our W mass estimator can be expressed as

$$M_W^2 = m_\ell^2 + 2\left(|\vec{p}_{\nu,T}^{\,\text{lab}}|\sqrt{m_\ell^2 + |\vec{p}_{\ell,T}^{\,\text{lab}}|^2} - \vec{p}_{\ell,T}^{\,\text{lab}} \cdot \vec{p}_{\ell,T}^{\,\text{lab}}\right)$$



The resulting observable is the well-known transverse mass, and is equivalent to minimizing the W mass w.r.t. $p_{\nu,z}$

Invisible Particles



Crucial guess/choice:

interpret the event with $p_{\nu,z}$ *chosen to satisfy*

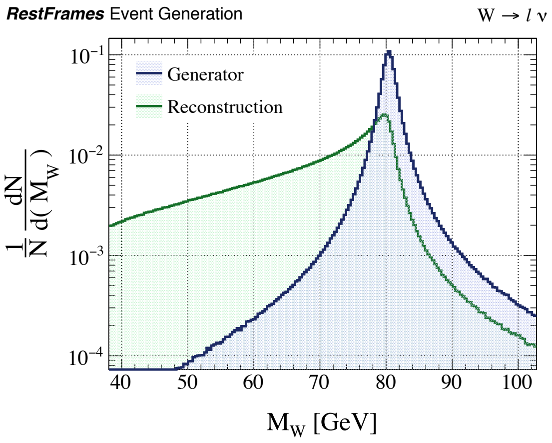
$$\frac{\partial M_W(\beta_{W,z}^{\rm lab})}{\partial \beta_{W,z}^{\rm lab}} = 0$$

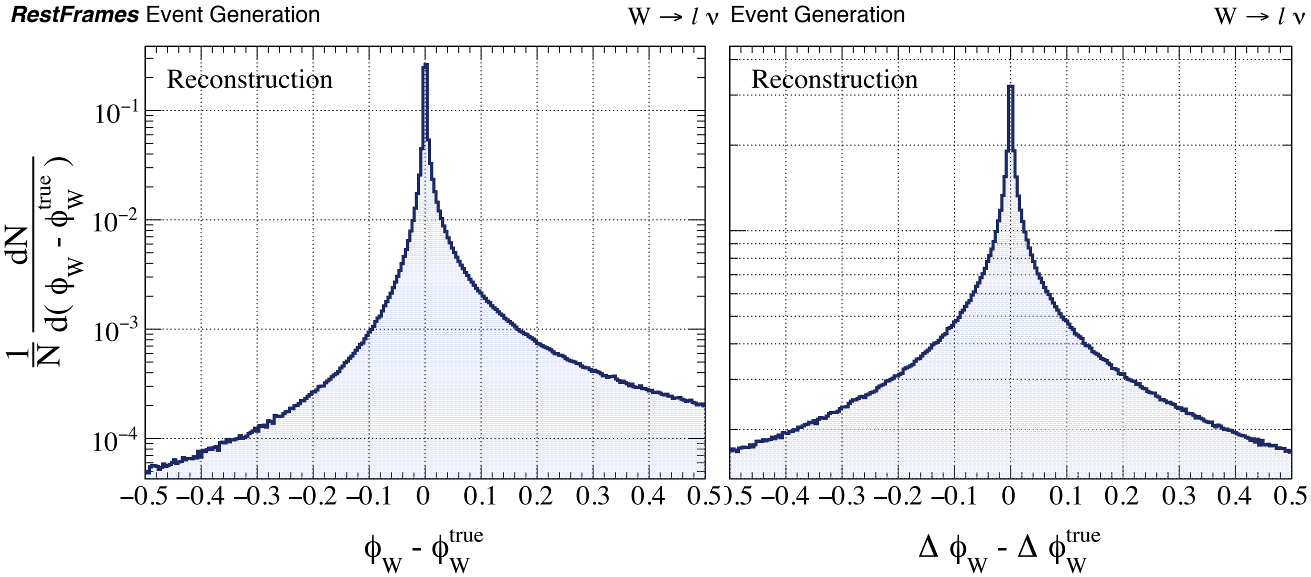
(b) The partial derivative ensures that all kinematic observables we calculate will be independent of the true value of $\beta_{W,z}^{\rm lab}$, ex. the W mass estimator is *invariant under longitudinal boosts*

$$M_W^2 = m_\ell^2 + 2\left(|\vec{p}_{\nu,T}^{\,\rm lab}|\sqrt{m_\ell^2 + |\vec{p}_{\ell,T}^{\,\rm lab}|^2} - \vec{p}_{\ell,T}^{\,\rm lab} \cdot \vec{p}_{\ell,T}^{\,\rm lab}\right)$$

Invisible Particles

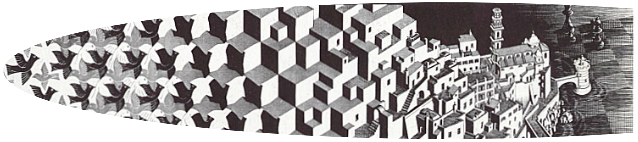
Choosing $p_{\nu,z}$ according to this prescription results in a *basis* of observables, each *accurately* estimating physical quantities of interest related to the *W* boson:





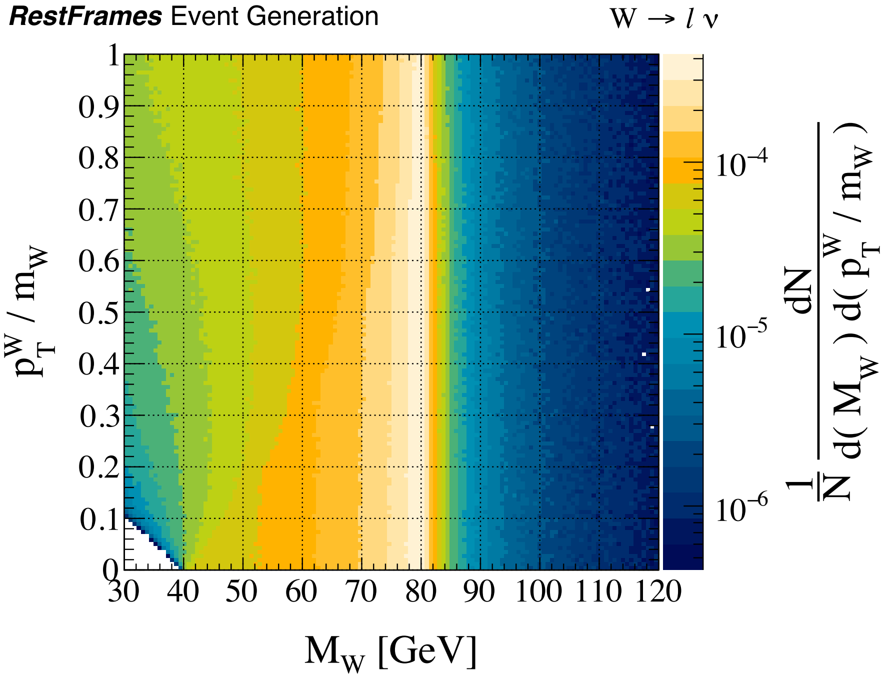
transverse part
of *W* decay angle

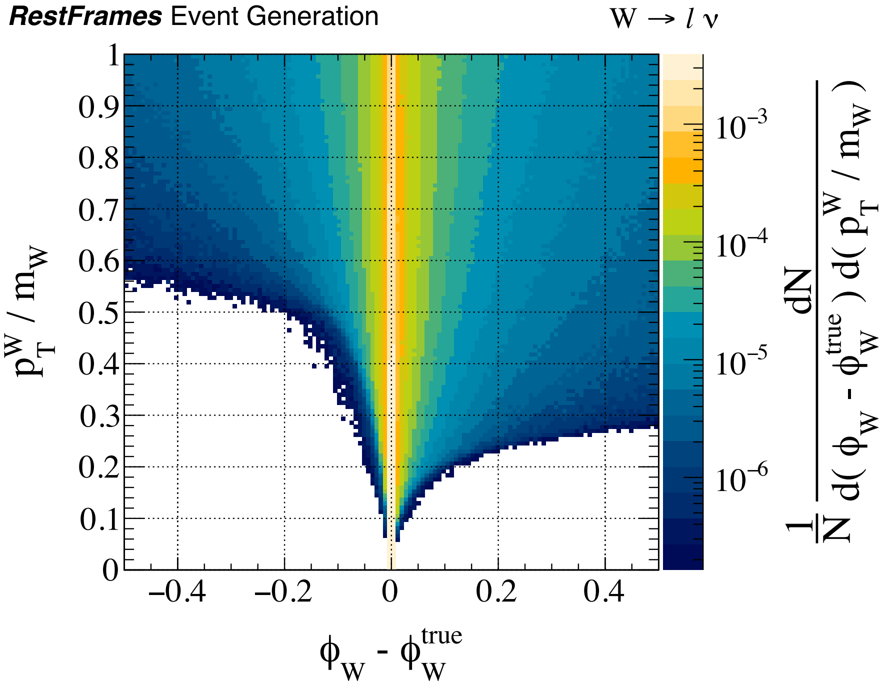
azimuthal angle
between W decay plane
and $\vec{p}_{W,T}/\hat{n}_z$ plane



Invisible Particles

While perfectly invariant under *longitudinal* boosts, these observables are also invariant to order β^2 in *transverse* boosts





In a sense, our approximation of the *W* rest frame in each event has these invariance properties

Recursive Jigsaw Reconstruction

A new approach to reconstructing final states with missing information

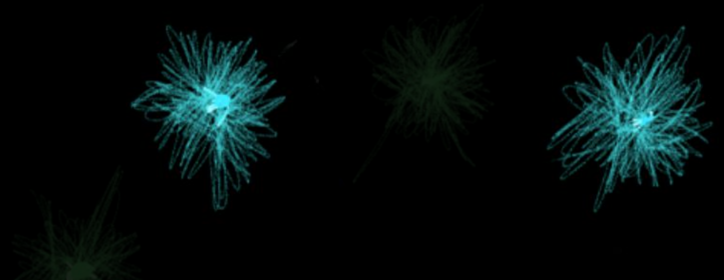
- PRD 96, 112007 (2017) [1705.10733]

- The strategy is to transform observable momenta iteratively *reference-frame to reference-frame*, traveling through each of the reference frames relevant to the topology
  - **Recursive:** At each step, specify *only the relevant d.o.f. related to that transformation ⇒ apply a Jigsaw Rule*

    Repeat procedure recursively, using the visible momenta encountered in each reference frame
  - **Jigsaw:** each of these rules is factorizable/customizable/interchangeable like a (strange) jigsaw puzzle pieces

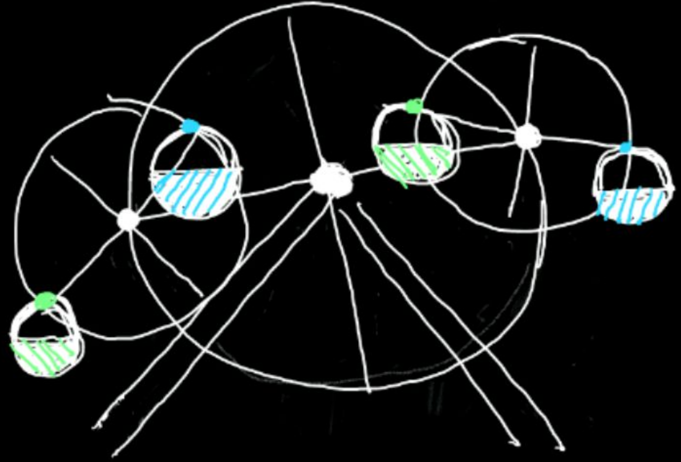
- **Rather than obtaining one observable, get a *complete basis* of useful observables for each event**

Two Invisible Particles



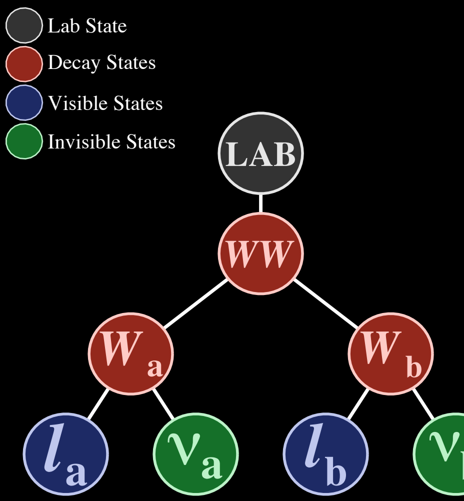
?

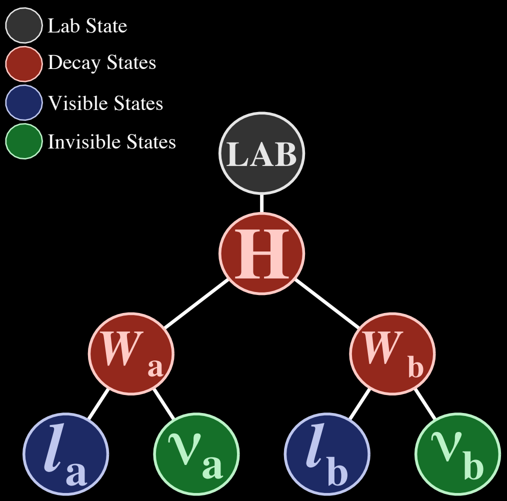
⇒

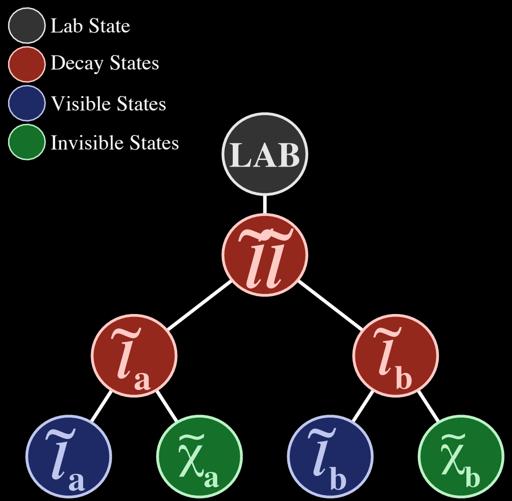


What if there is more than one missing particle in an event?

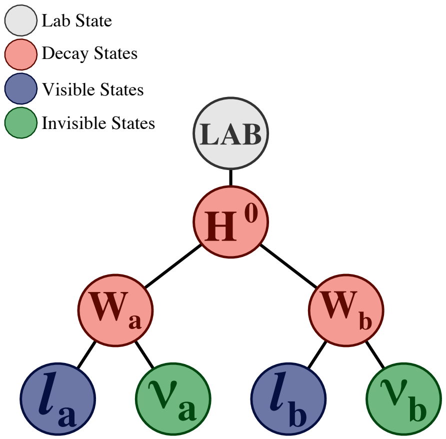
We consider examples in the di-lepton and missing momentum final state:

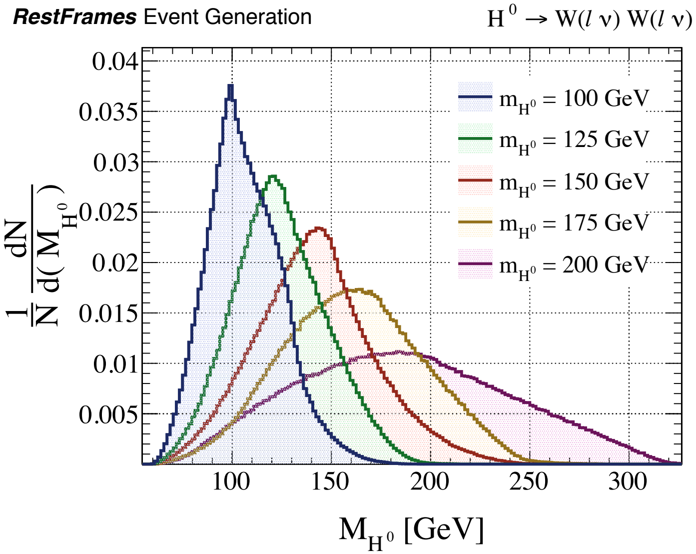


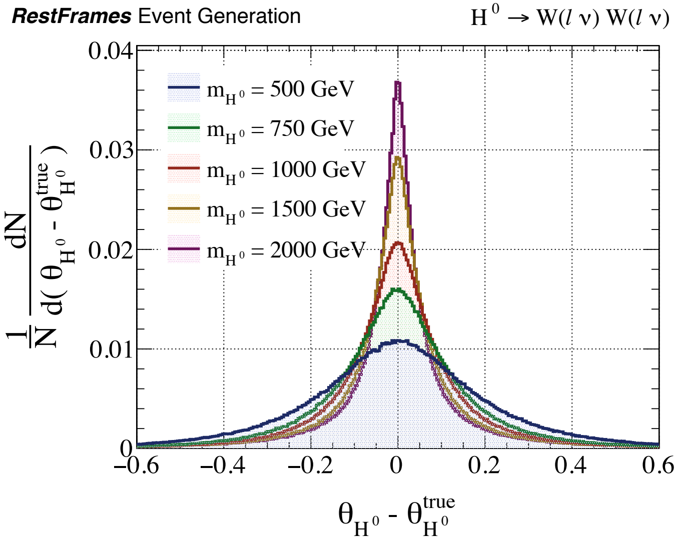




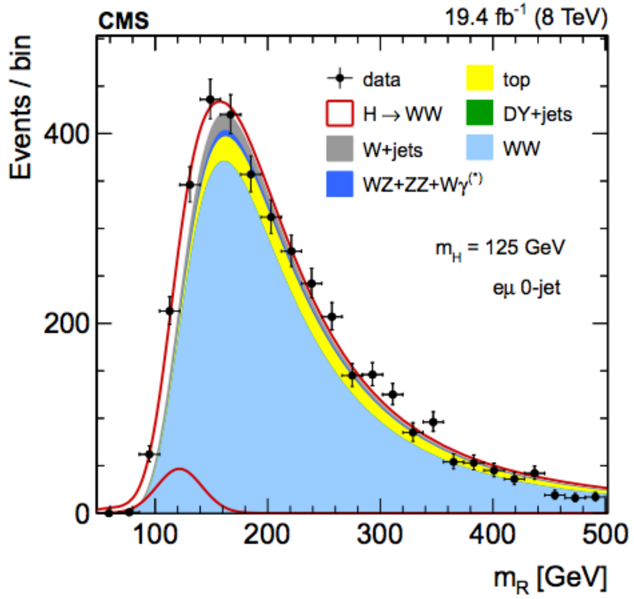
RJR & Two Invisible Particles



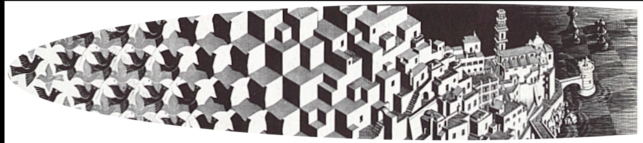




For resonant W production, observables in the same basis are sensitive to the Higgs

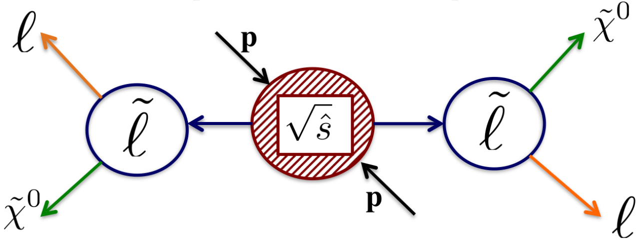


Already used in CMS measurement of Higgs mass in this channel
[JHEP 01 (2014) 096, arXiv:1312.1129]

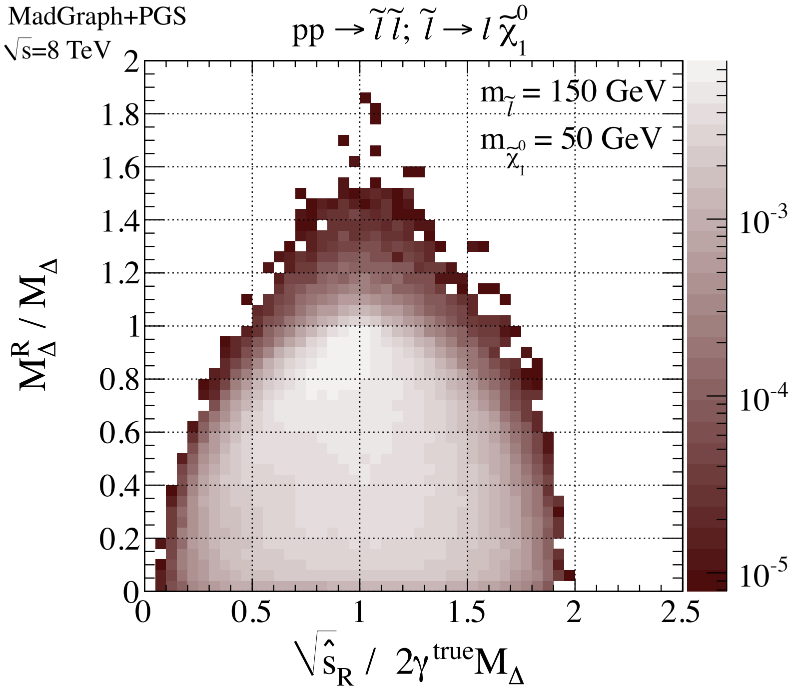


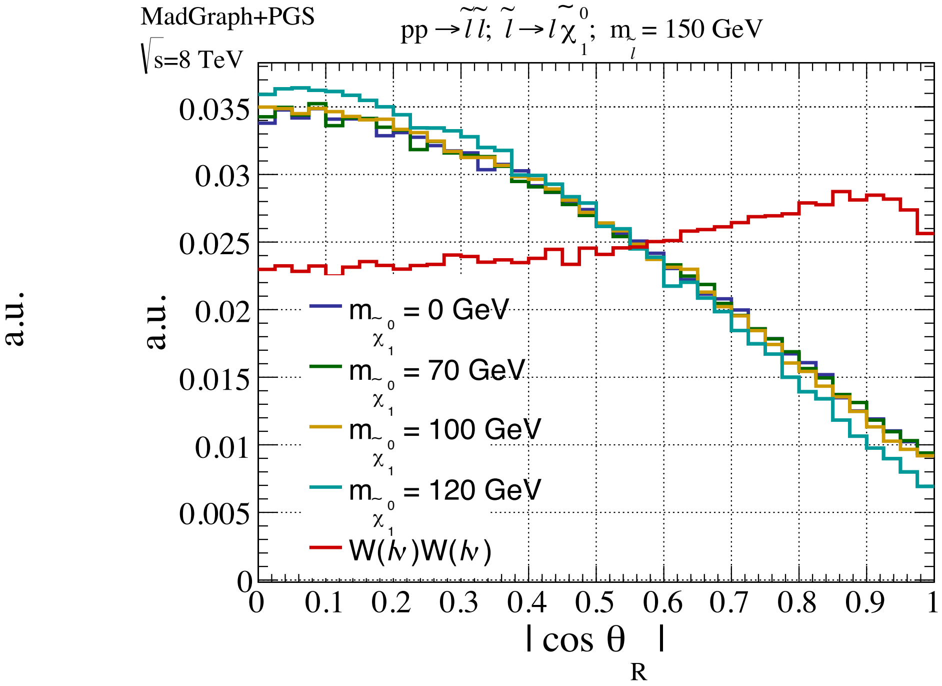
RJR & Two Invisible Particles

Example: di-sleptons



Resulting basis of observables are the *super-razor variables* [PRD 89, 055020 (2014)]

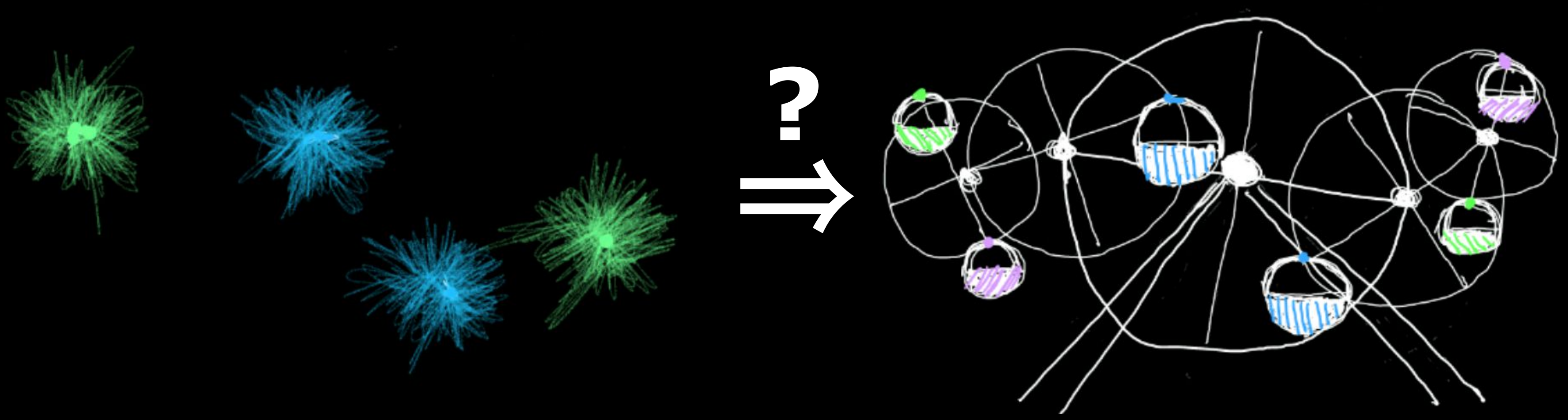




extracts ~uncorrelated mass peaks and edges

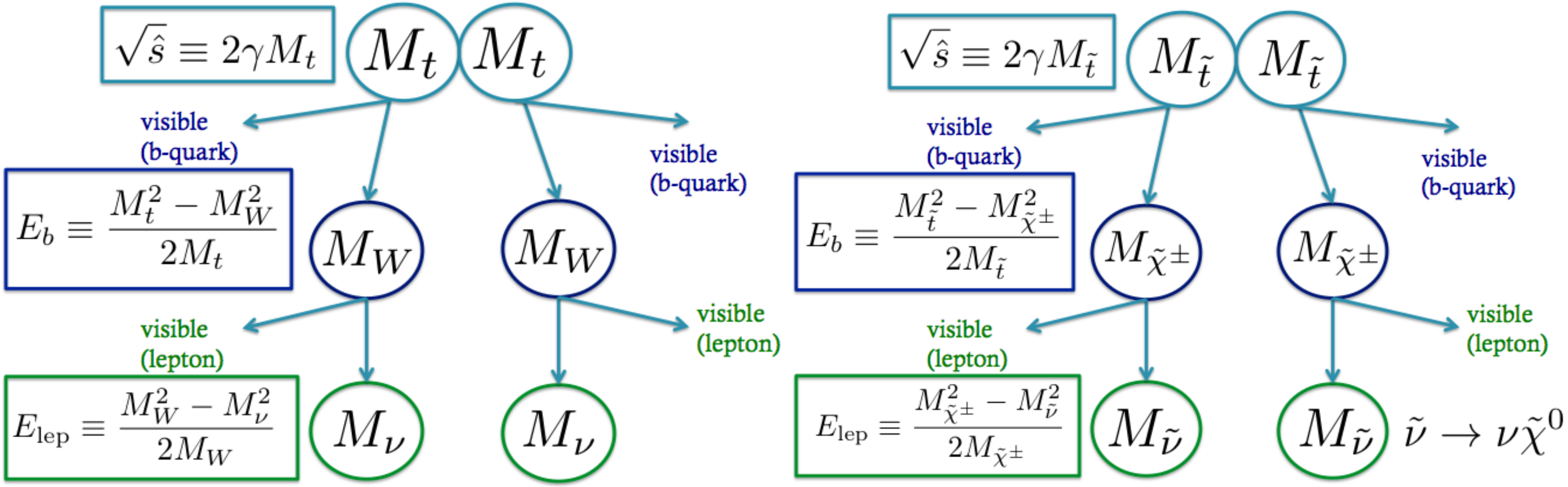
along with complete basis of other observables

More Particles



What if there are even more particles expected in the decays in an event?

Di-leptonic (s)top Pairs



$$\sqrt{\hat{s}} \equiv 2\gamma M_t$$

$$E_b \equiv \frac{M_t^2 - M_W^2}{2M_t}$$

$$E_{\rm lep} \equiv \frac{M_W^2 - M_\nu^2}{2M_W}$$

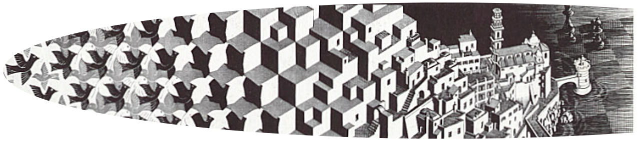
$$\sqrt{\hat{s}} \equiv 2\gamma M_{\tilde{t}}$$

$$E_b \equiv \frac{M_{\tilde{t}}^2 - M_{\tilde{\chi}^\pm}^2}{2M_{\tilde{t}}}$$

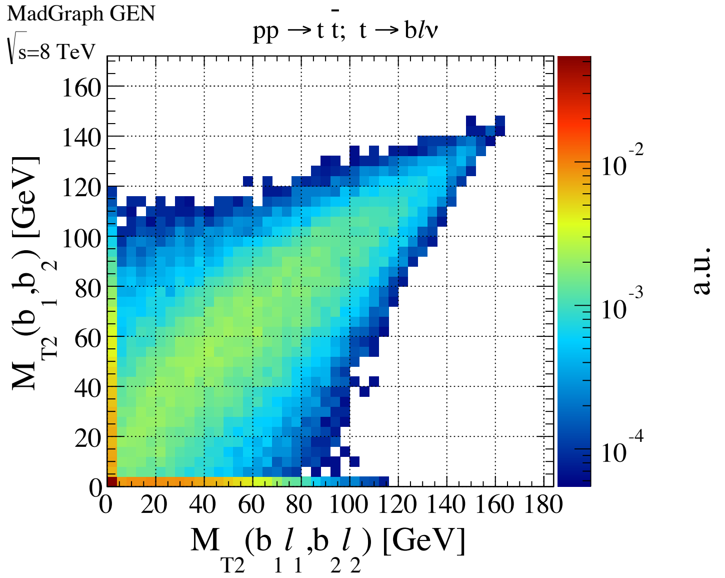
$$E_{\rm lep} \equiv \frac{M_{\tilde{\chi}^\pm}^2 - M_{\tilde{\nu}}^2}{2M_{\tilde{\chi}^\pm}}$$

$$\tilde{\nu} \to \nu\tilde{\chi}^0$$

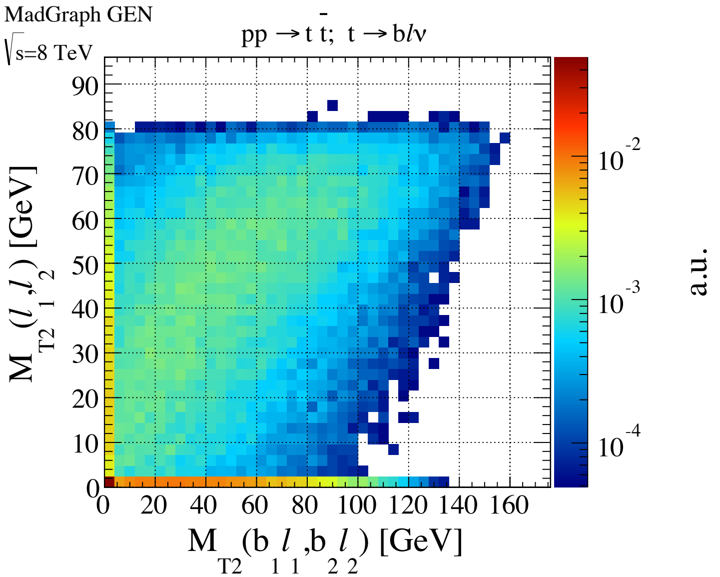
In more complicated decay topologies there can be many masses/mass-splittings, spin-sensitive angles and other observables of interest that can be used to study the SM and distinguish it from SUSY signals

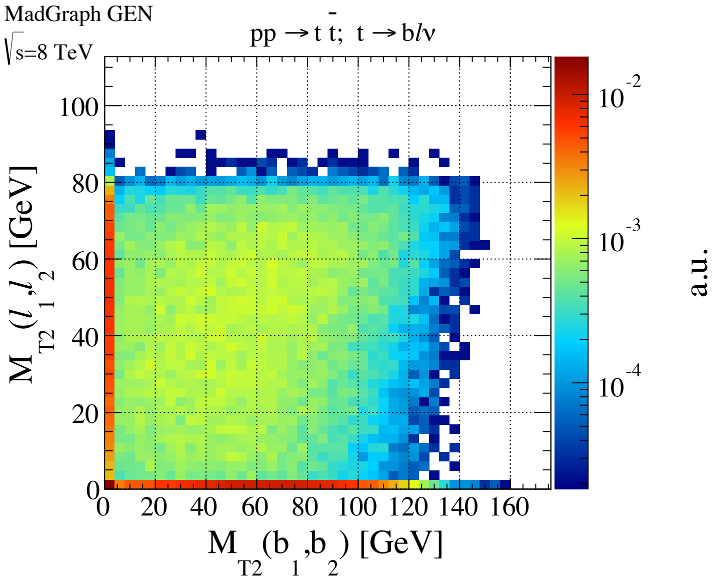


Di-leptonic (s)top Pairs

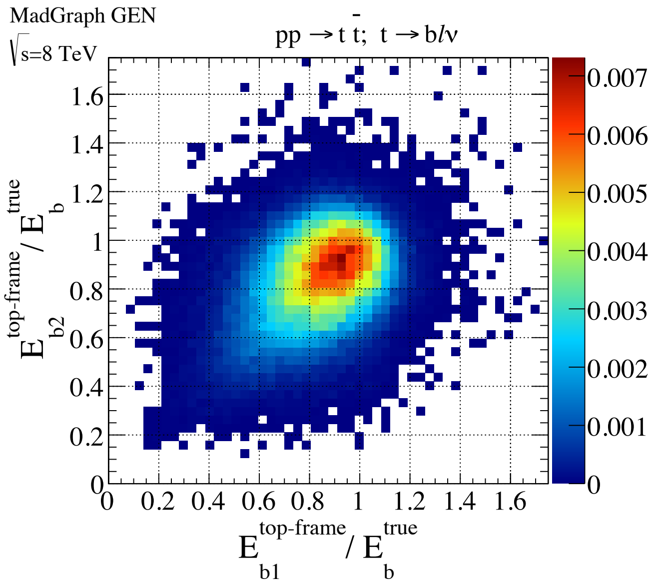


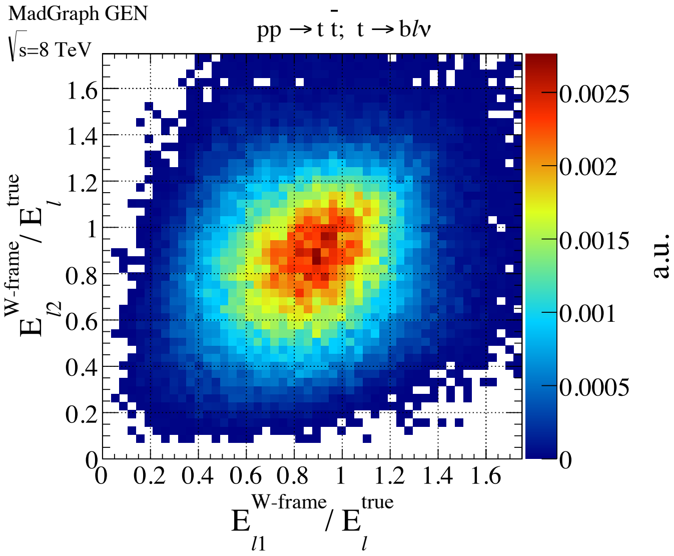
Mass-sensitive singularity variables are sensitive to mass splittings through end-points, but are not necessarily *independent*



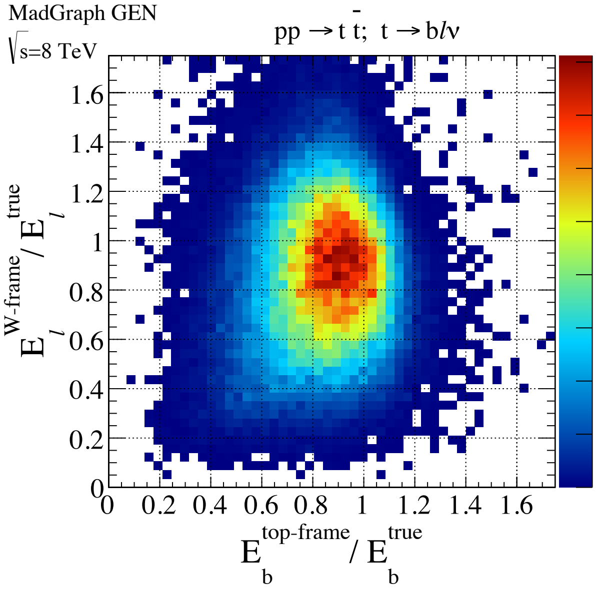


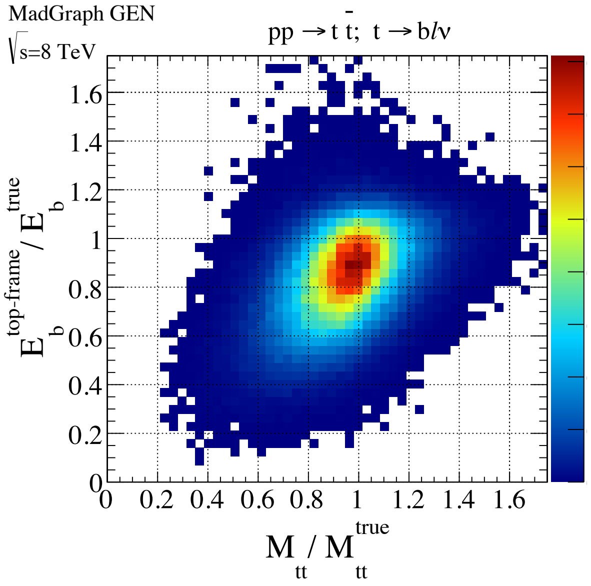
Di-leptonic (s)top Pairs

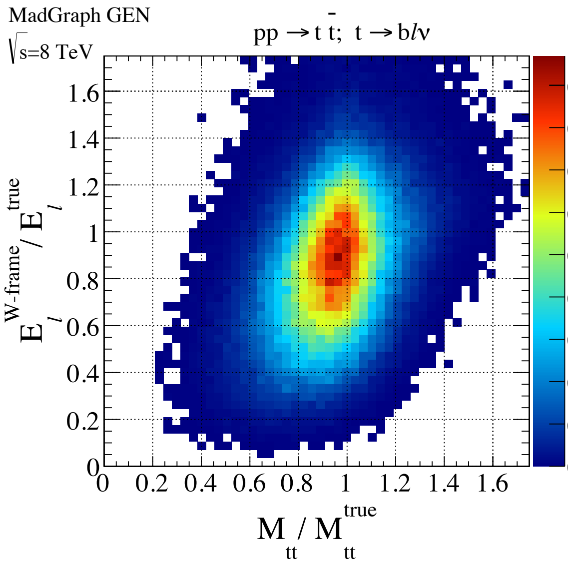


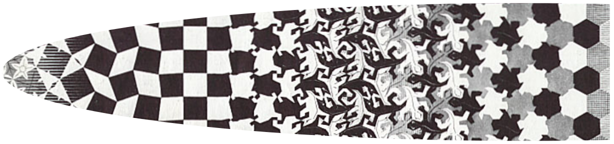


RJR provides *independent* information about five different masses, and decay angles



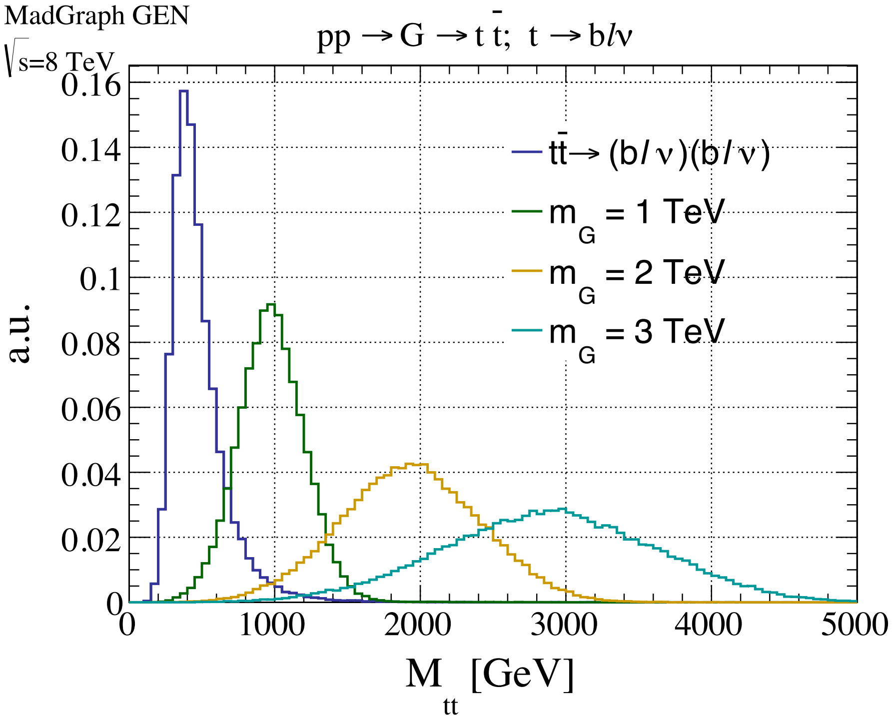


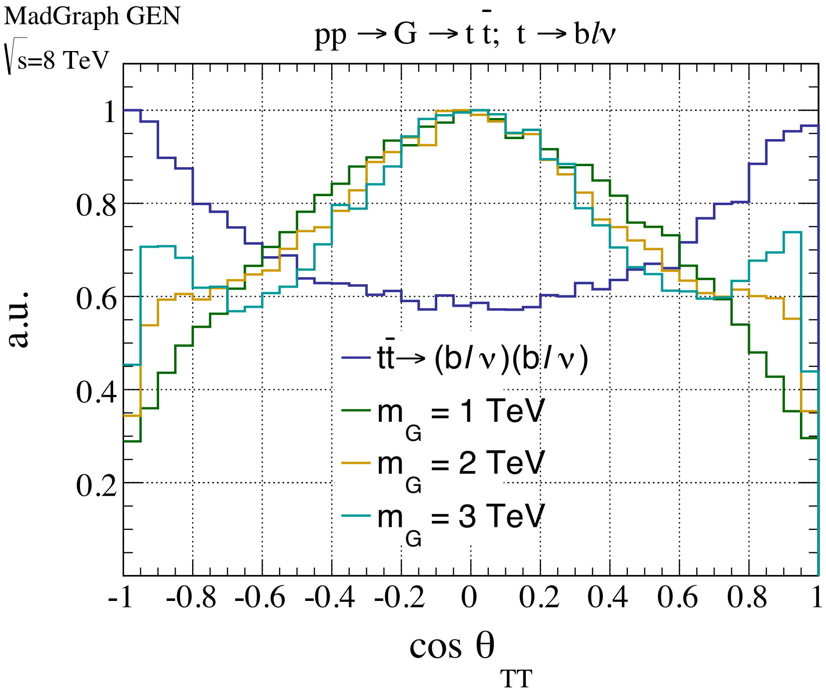




Di-leptonic (s)top Pairs

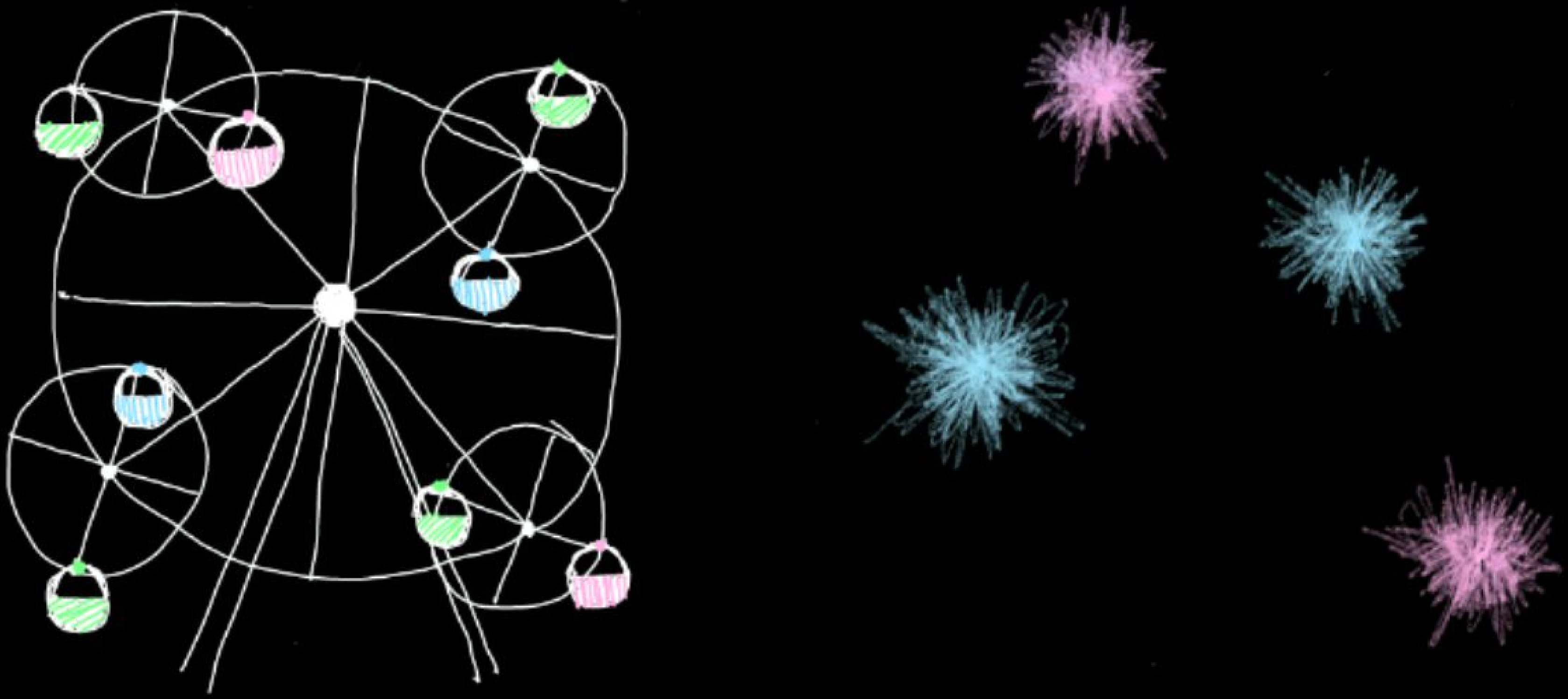
largely independent information about decay angles



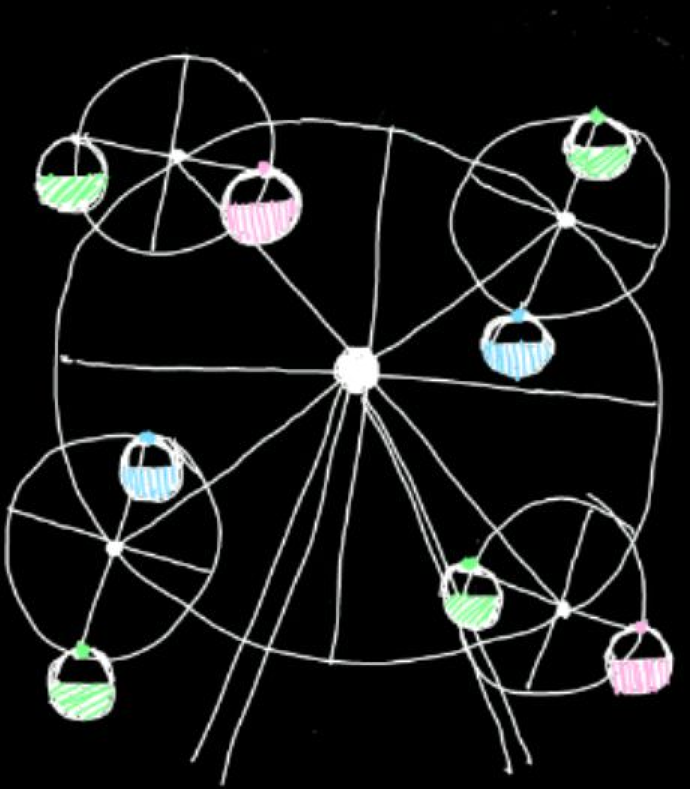


Here, the decay angle of the top/anti-top system can be used to study resonance structure in Graviton production, along with di-top mass

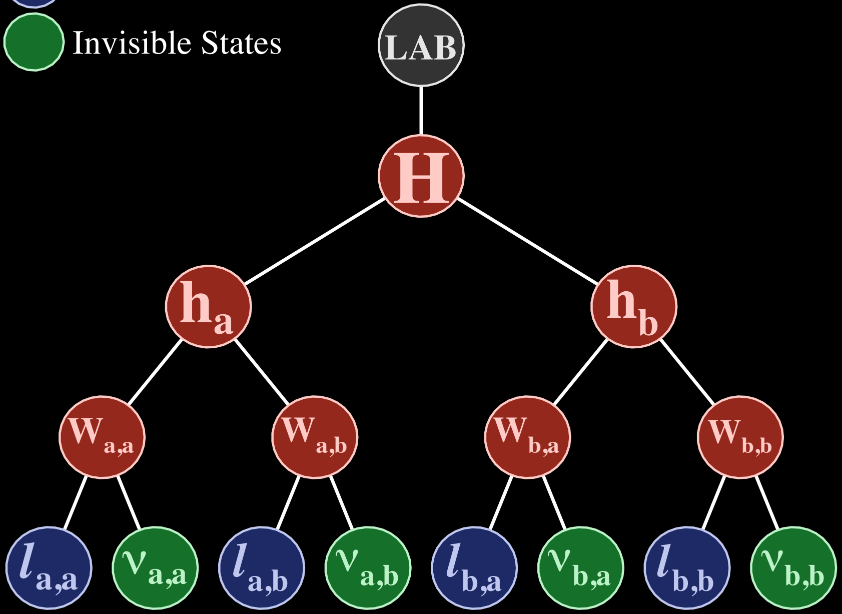
More Invisible Particles



More Invisible Particles



● Lab State
● Decay States
● Visible States
● Invisible States



LAB

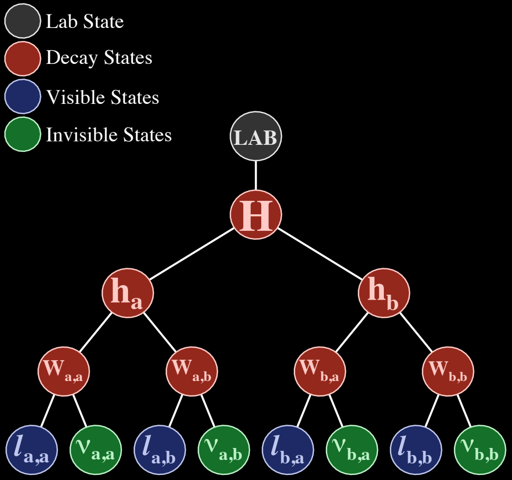
H

h_a h_b

$W_{a,a}$ $W_{a,b}$ $W_{b,a}$ $W_{b,b}$

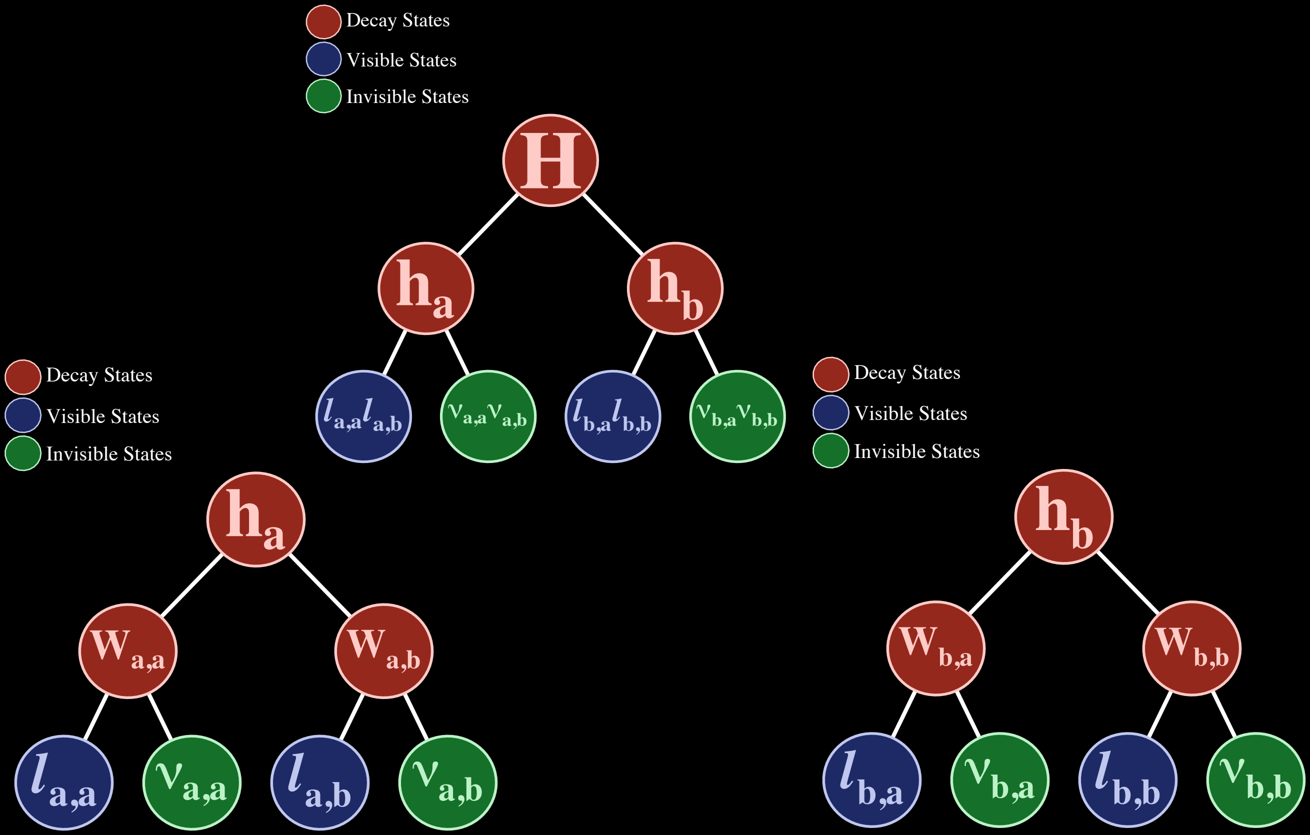
$l_{a,a}$ $\nu_{a,a}$ $l_{a,b}$ $\nu_{a,b}$ $l_{b,a}$ $\nu_{b,a}$ $l_{b,b}$ $\nu_{b,b}$

More Invisible Particles



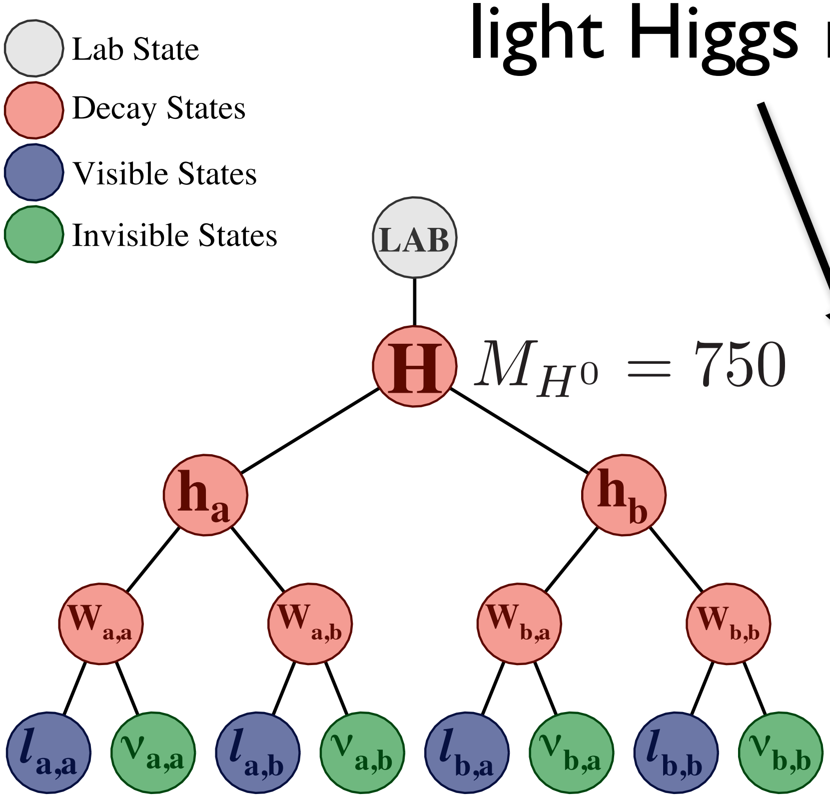
By factorizing our choices for kinematic unknowns we can extract more independent information

We apply three Jigsaw Rules according to three different two-body decays

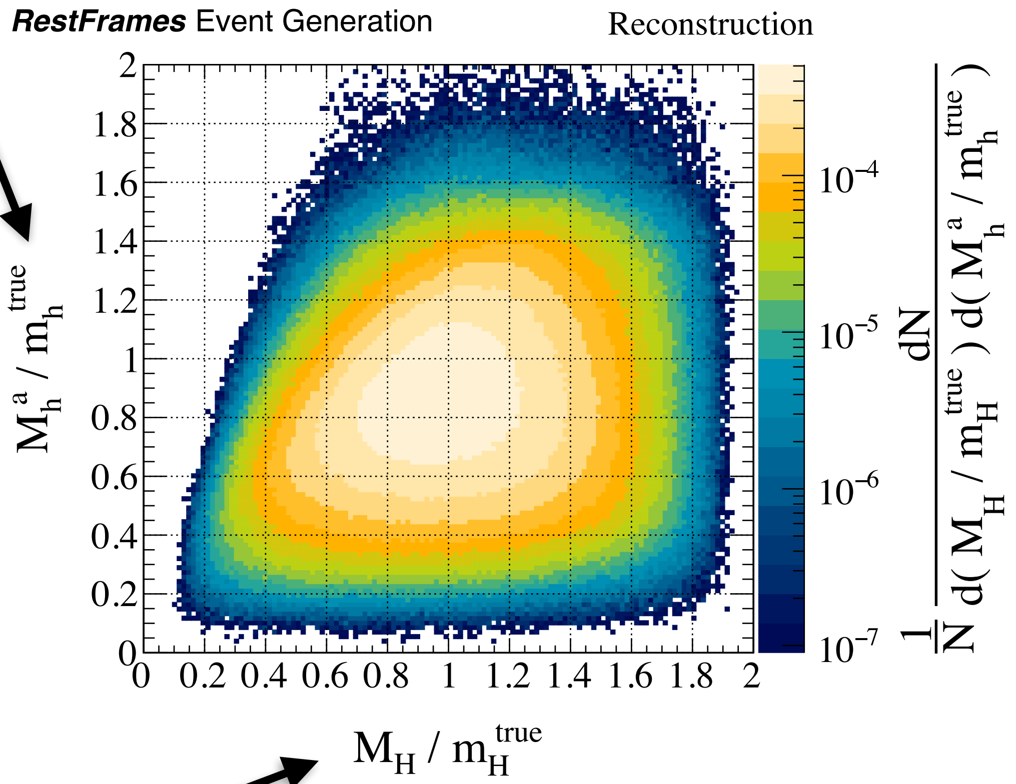


More Invisible Particles

light Higgs mass

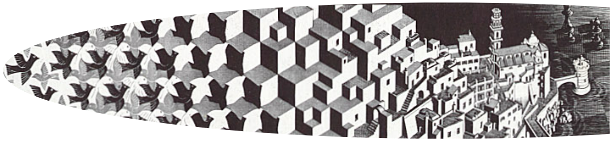


$M_{H^0} = 750$

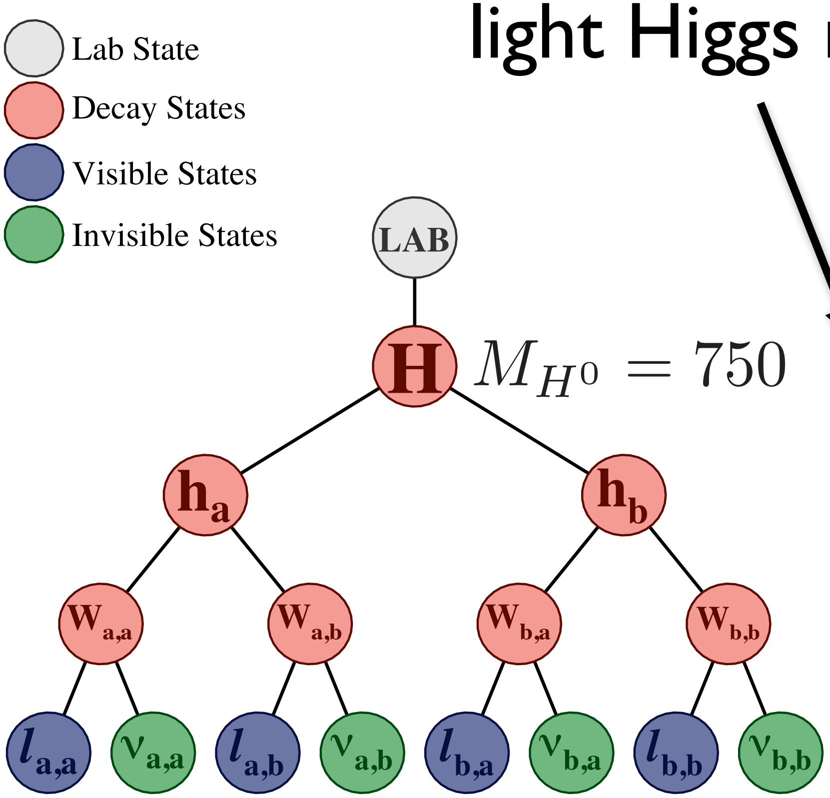


heavy Higgs mass

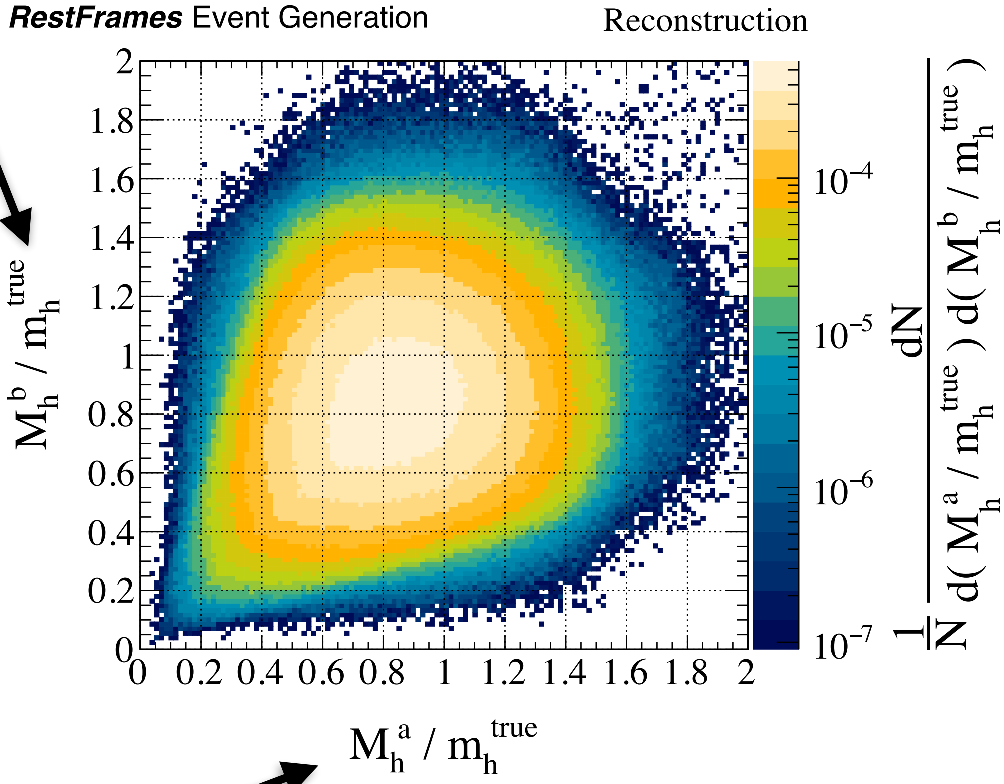
PRD 96, 112007 (2017) [1705.10733]



More Invisible Particles



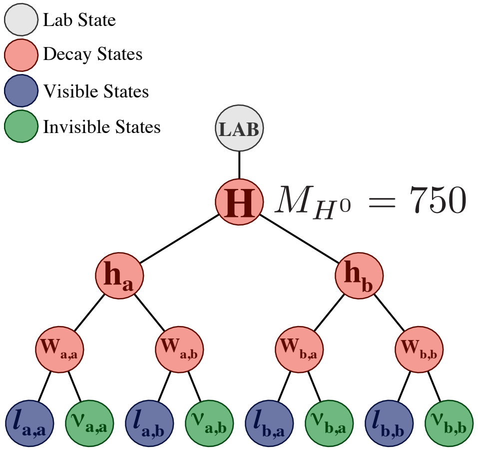
light Higgs mass

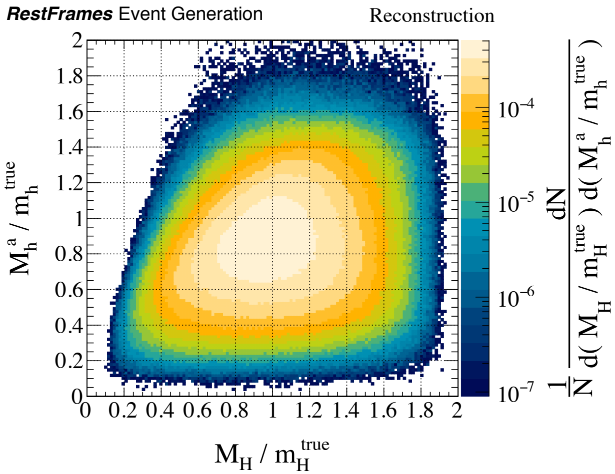


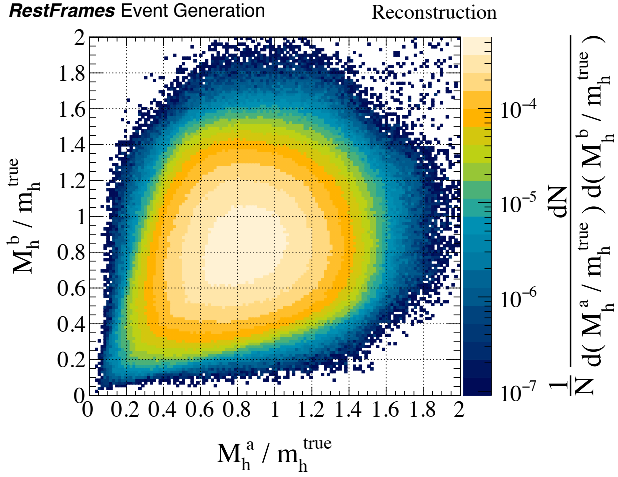
light Higgs mass

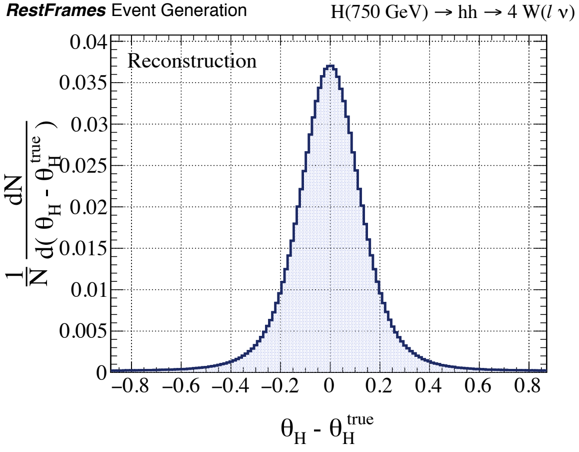
PRD 96, 112007
(2017) [1705.10733]

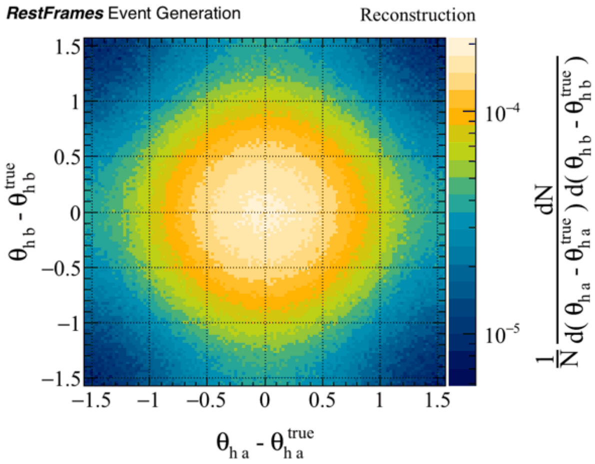
More Invisible Particles

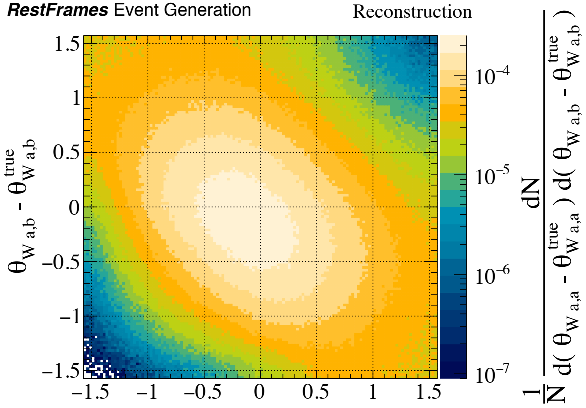












The factorized RJR approach resolves the intermediate particles and decays appearing in the tree