New Physics searches at the LHC

WPI-next mini-workshop
"Hints for New Physics in Heavy Flavors"
Nagoya University, KMI

November
15th - 17th, 2018

KOBAYASHI-MASKAWA INSTITUTE FOR THE ORIGIN OF PARTICLES AND THE UNIVERSE

Paul Jackson

THE UNIVERSITY of ADELAIDE

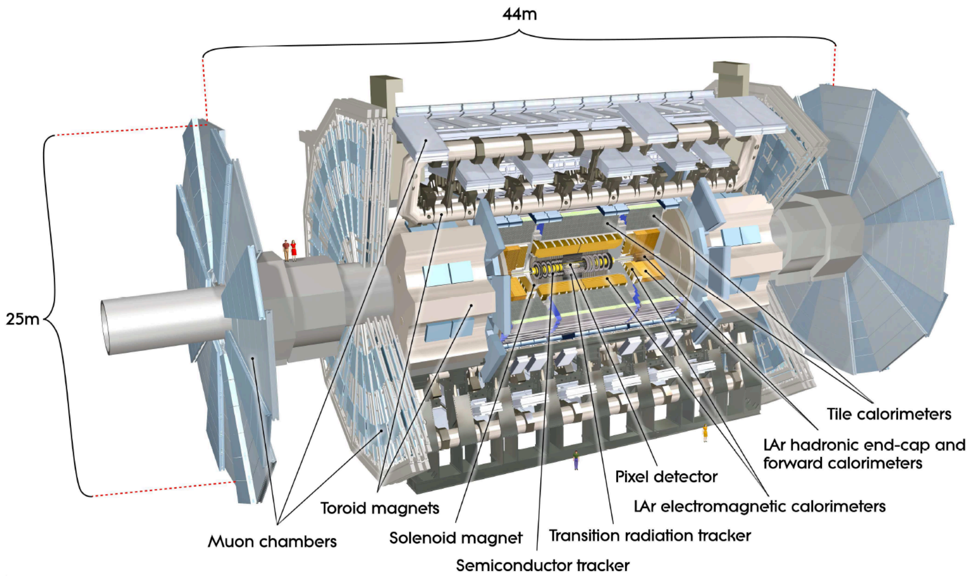
CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

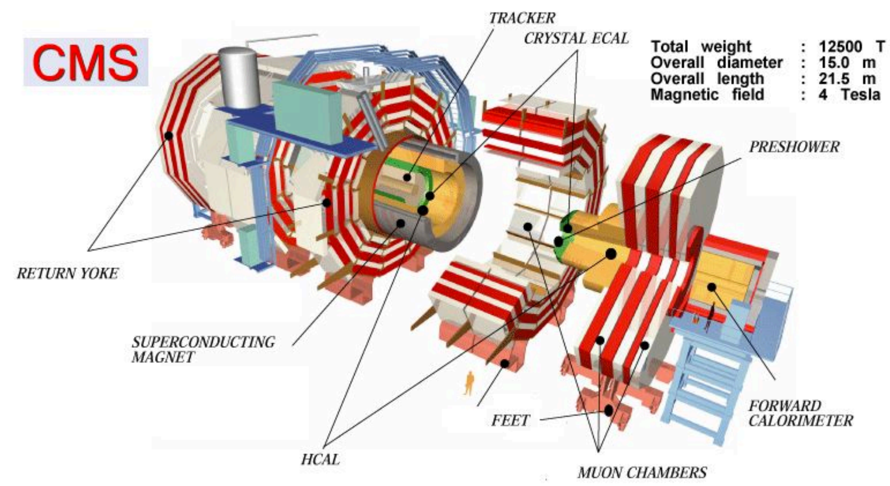
Outline

New physics search program at the LHC

- Status of Standard Model measurements
- Precision SM with indirect sensitivity to BSM
- New Physics searches:
  - Searches for Exotics and Supersymmetry
  - Selection of results showing excesses….that may be compatible with excesses in flavour physics
- Summary

The ATLAS and CMS experiments





- Solenoidal magnetic field (2T) in the central region – momentum measurement
- Energy meas. down to ~1° to the beamline

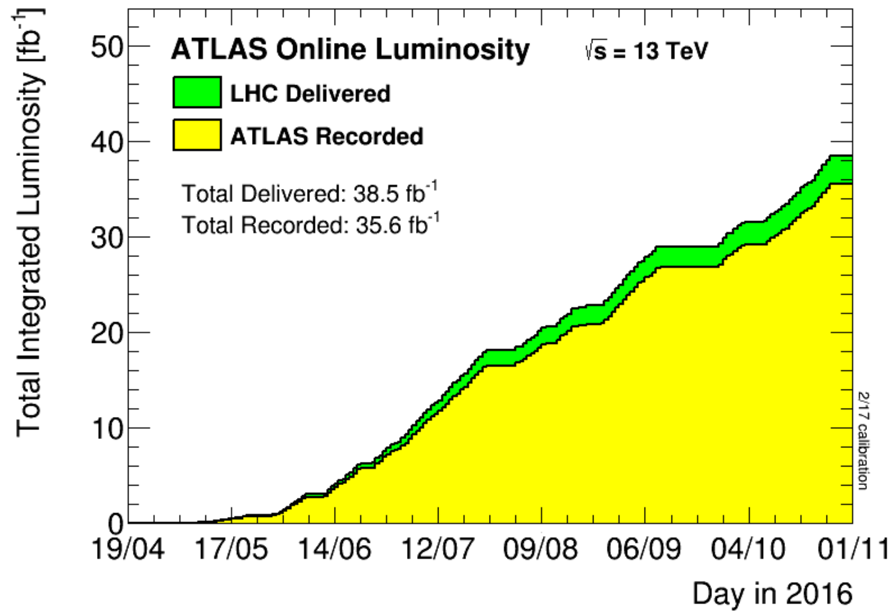
- High resolution silicon detectors
- Granular EM and Had calorimetry
- Independent muon spectrometer

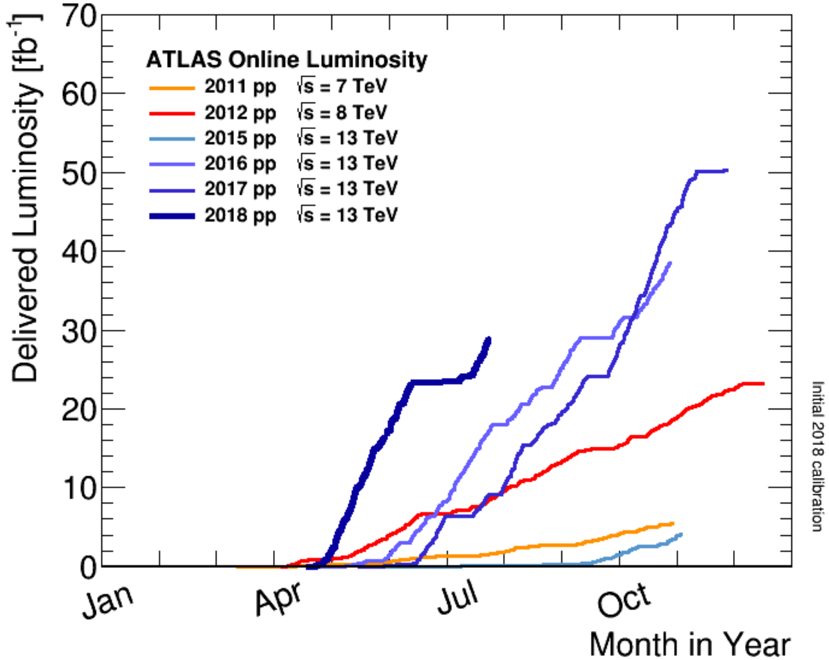
- Good coverage permits reconstruction of missing transverse momentum through object reconstruction

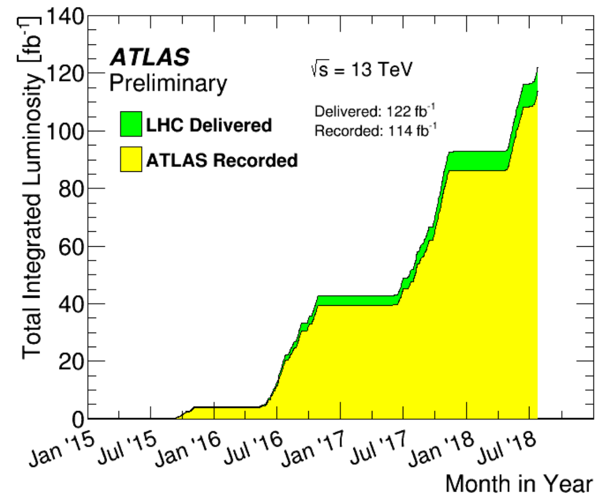
Data Samples – Run 2

Exceptional LHC performance in 2016 following 13 TeV commissioning in 2015
(2015: 4.2 fb^{-1} delivered, 3.9 fb^{-1} collected)

Collected by end of 2016 ~36 fb^{-1}







Run 2: Expect ~140 fb^{-1}

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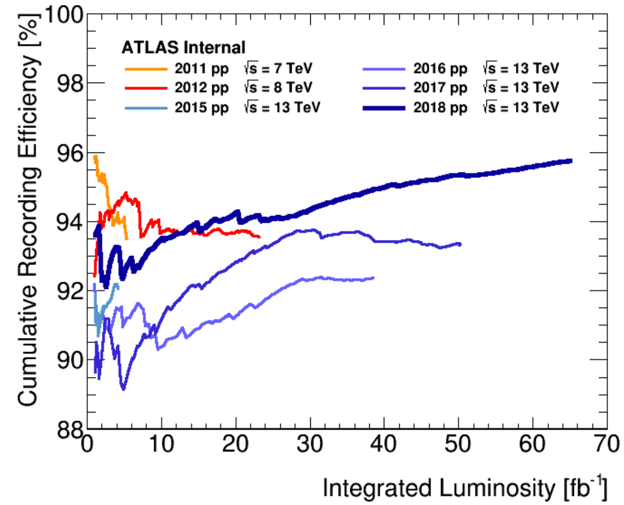
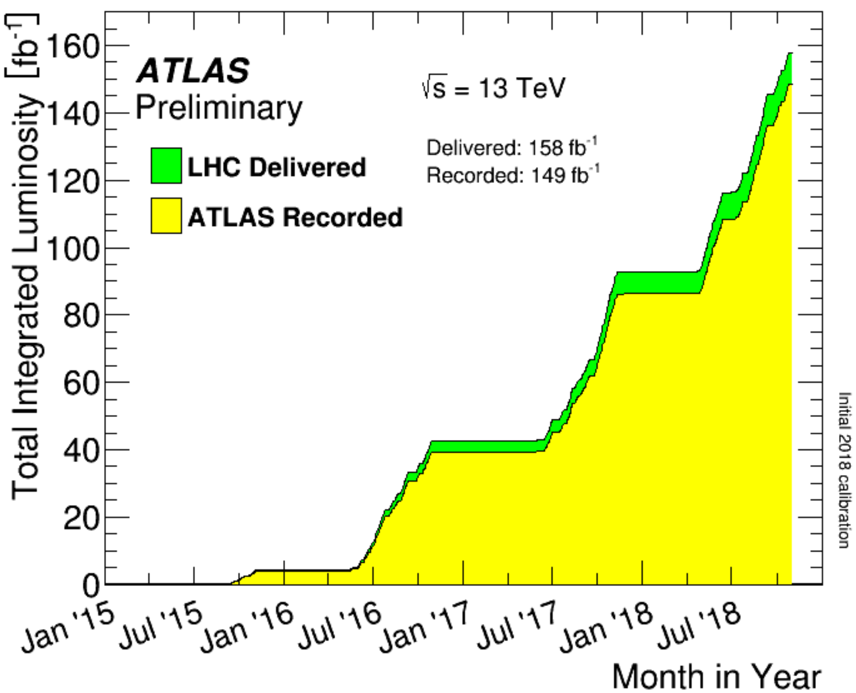
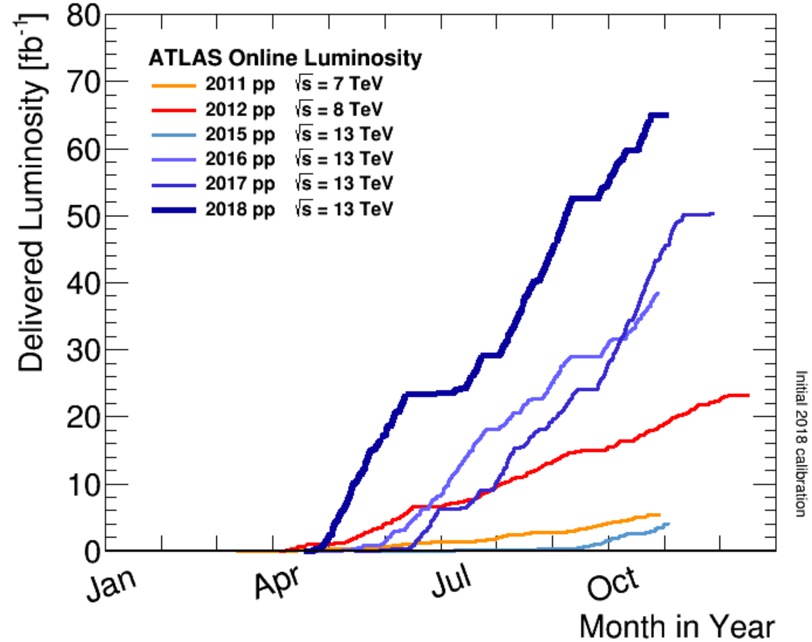
Data Samples – Run 2

Exceptional LHC performance in 2015-2018
Improved luminosity and recording efficiency throughout the run.

Integrated ~150 fb^{-1} at end of Run2 pp collisions







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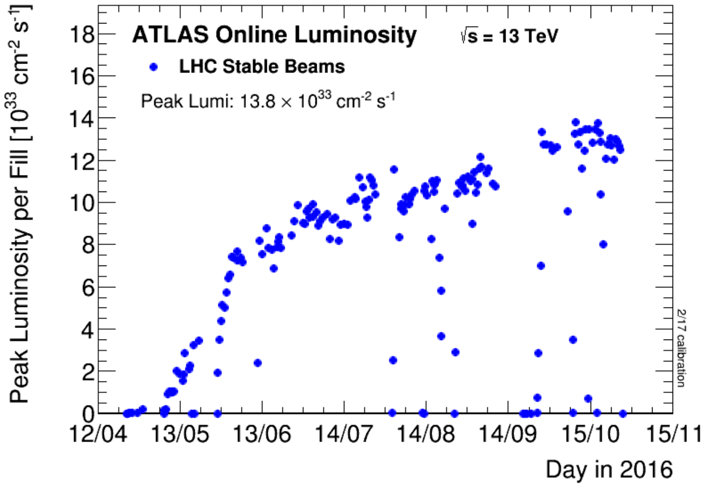
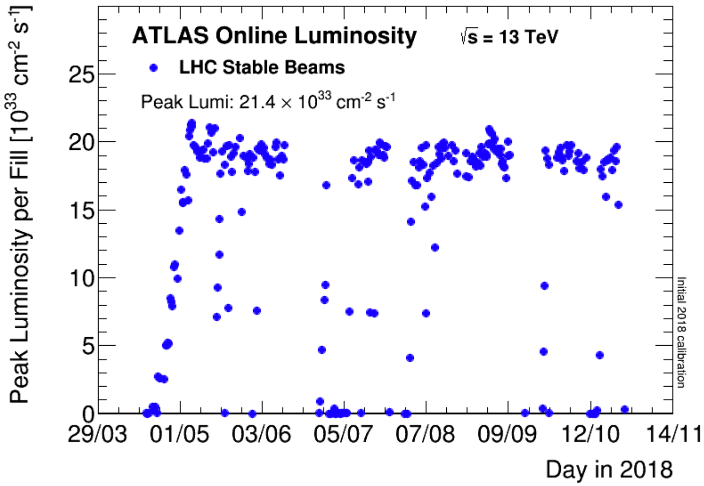
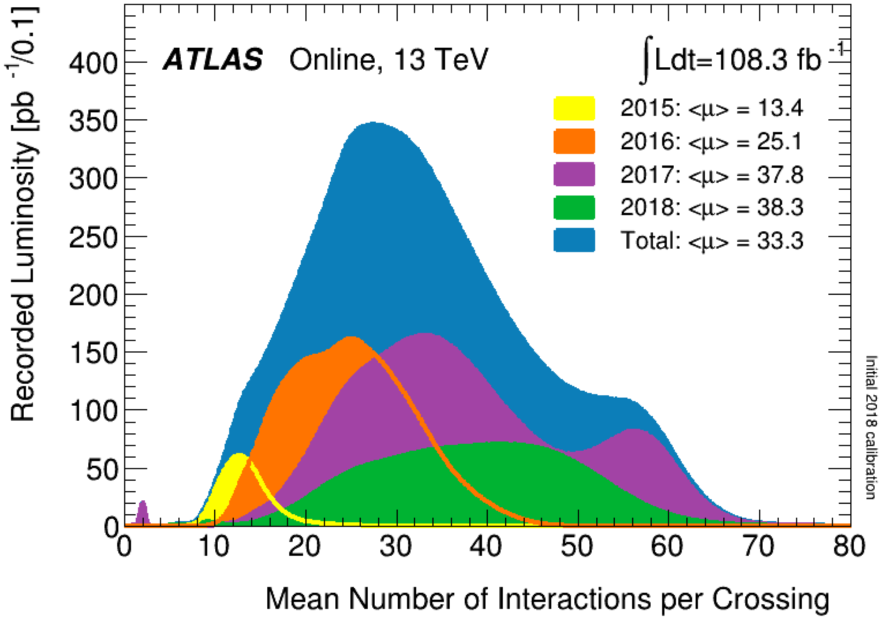
LHC: More than nominal Luminosity



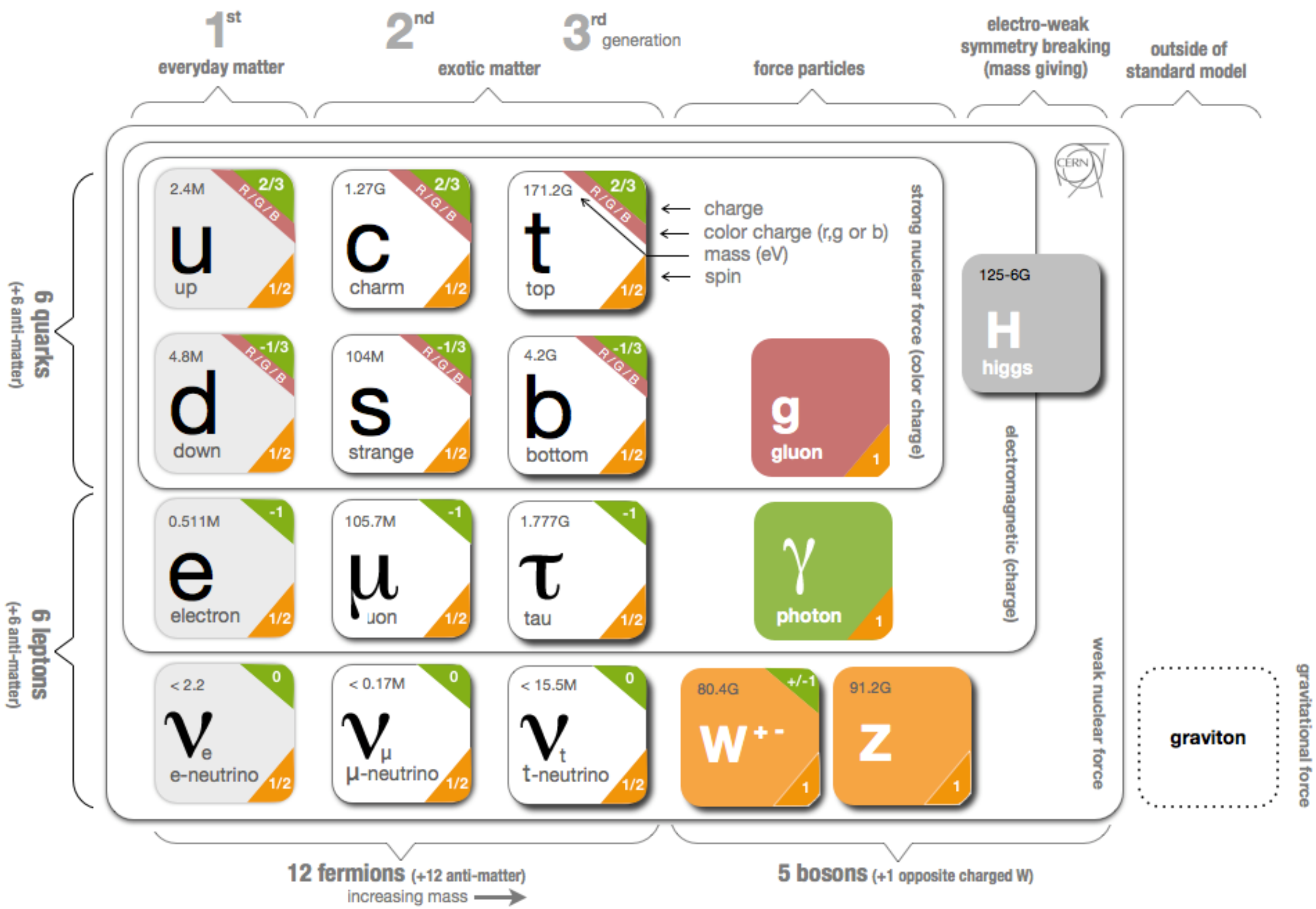


LHC design: $L = 1.0 \times 10^{34}$ cm^{-2} s^{-1}
Achieved (2016): $L = 1.4 \times 10^{34}$ cm^{-2} s^{-1}
Achieved (2018): $L = 2.1 \times 10^{34}$ cm^{-2} s^{-1}

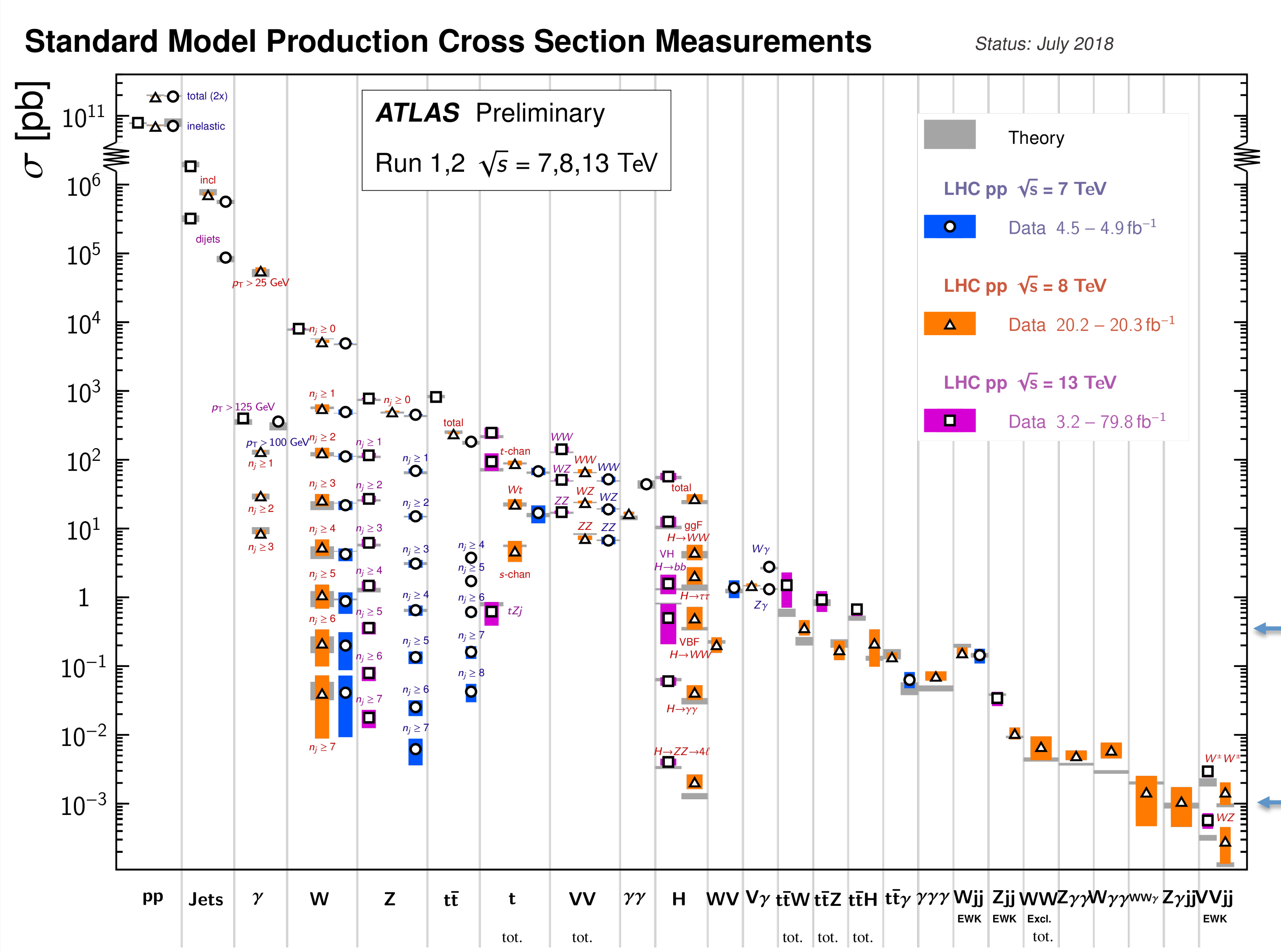
More lumi makes for a more challenging environment to extract results of interest



Measuring the Standard Model with ever increasing accuracy



Standard Model - Backgrounds to new physics searches



1 TeV gluino *

2 TeV gluino *

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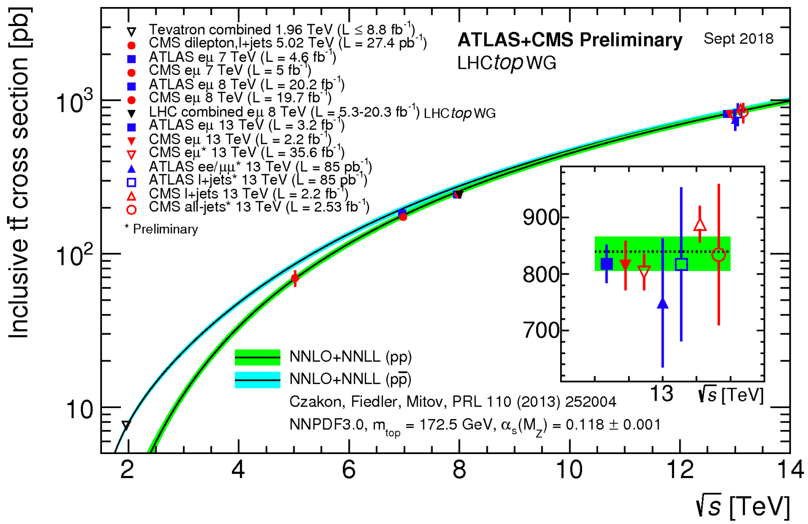
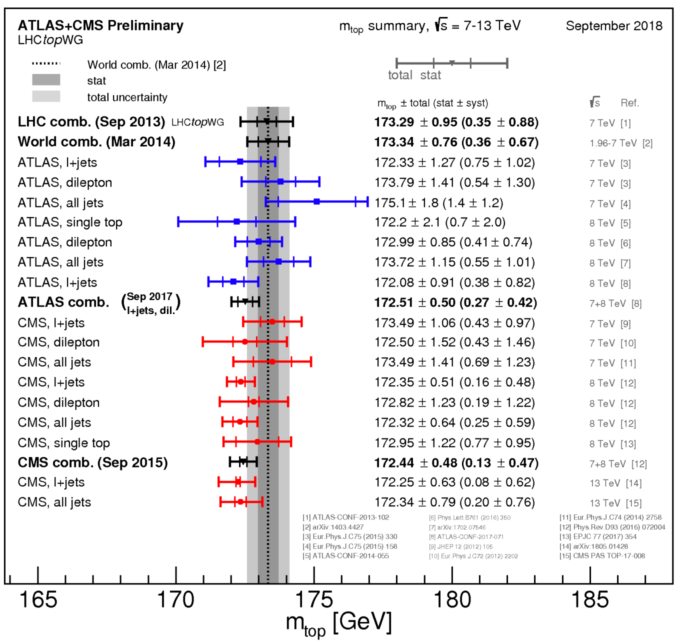
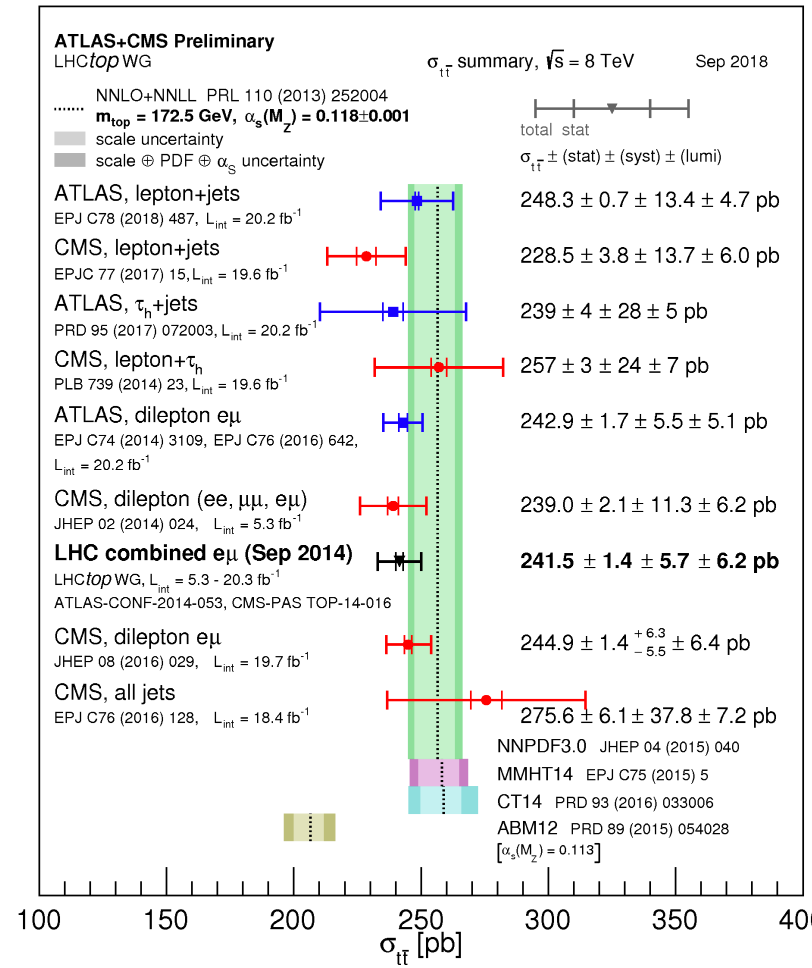
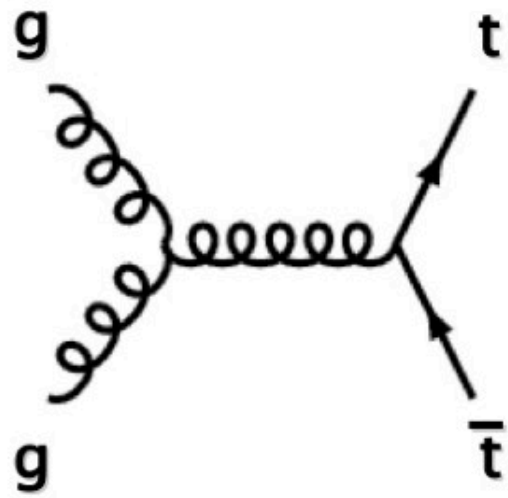
Top physics – hints for new physics in heavy flavor

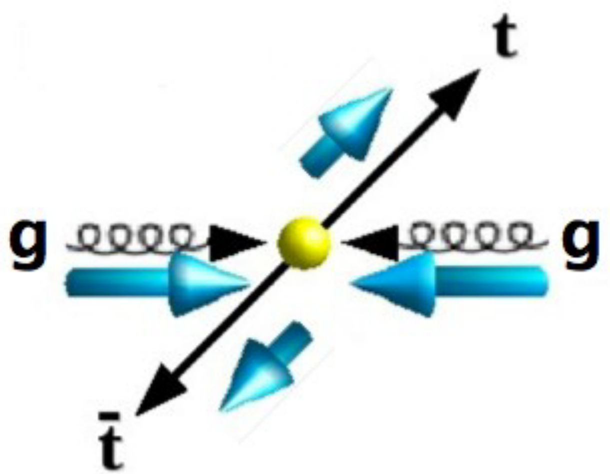




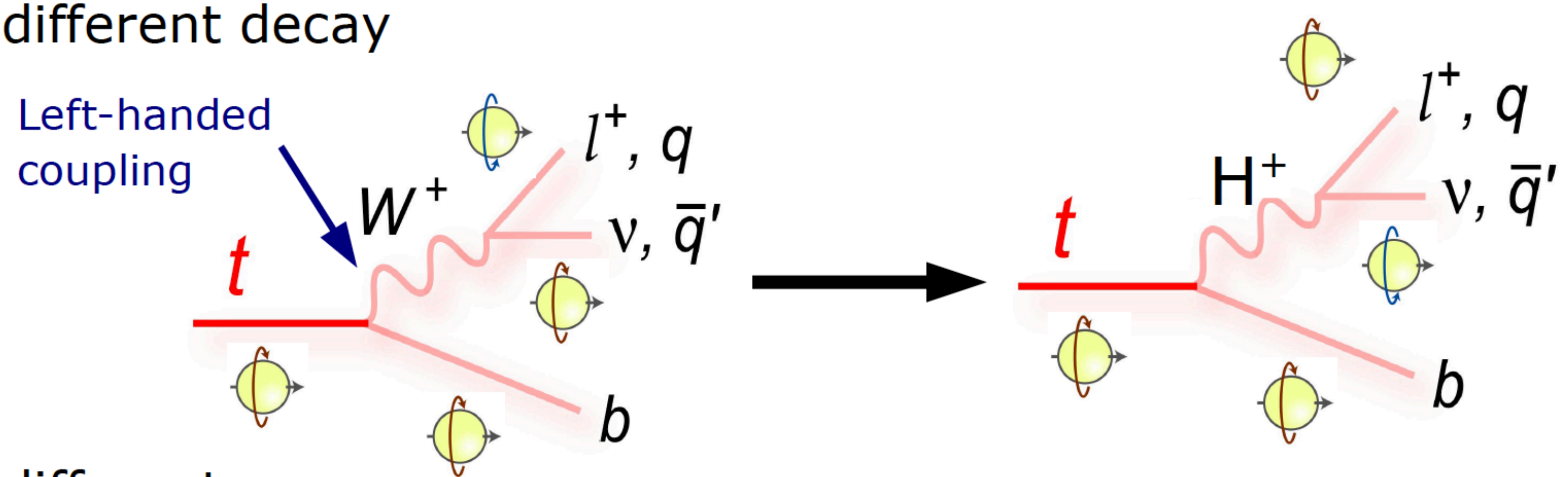


- Top quarks decay before fragmentation
  - Spin information is preserved
- Hadron colliders: top quarks are produced un-polarized, but
  - New physics (NP) could induce a polarization
    - e.g. NP causing forward-backward ttbar asymmetry leads ➔ more left-handed tops
  - Correlation between top and anti-top spin can be extracted

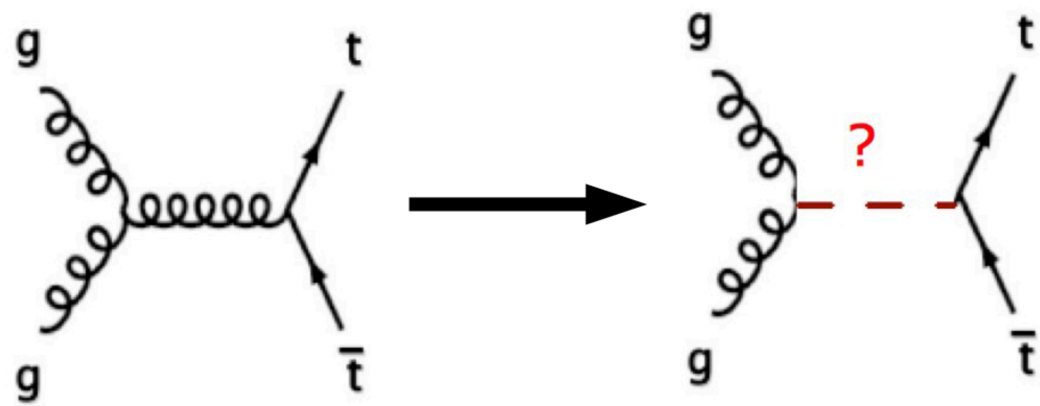




- Measured spin correlation can change
  - Due to different decay

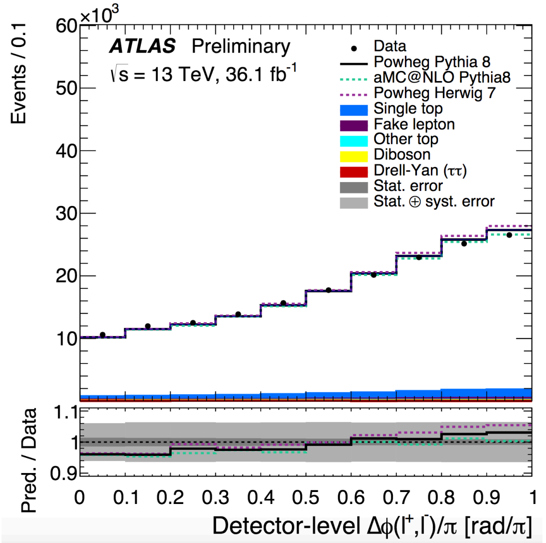


  - Due to different production

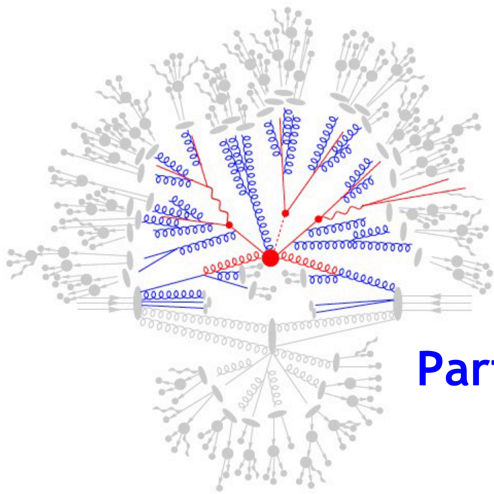


- Spin correlation: Test the full chain from production to decay!

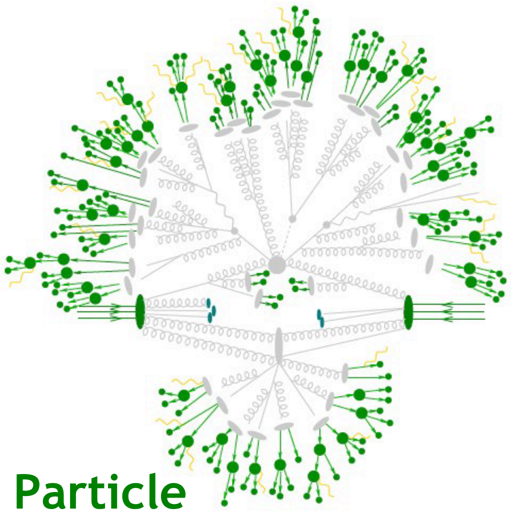
- Highest spin analysing power: leptons from top decays
  - Use dileptonic ttbar events (eμ)
  - Very clean samples
- Leverage Δϕ between the two leptons
  - No kinematic event reconstruction required
- Unfolded differential measurements:
  - Parton level and Particle level
  - Both inclusive and in bins of m(ttbar)



Full ttbar event reconstruction for m(ttbar)



Parton



Particle

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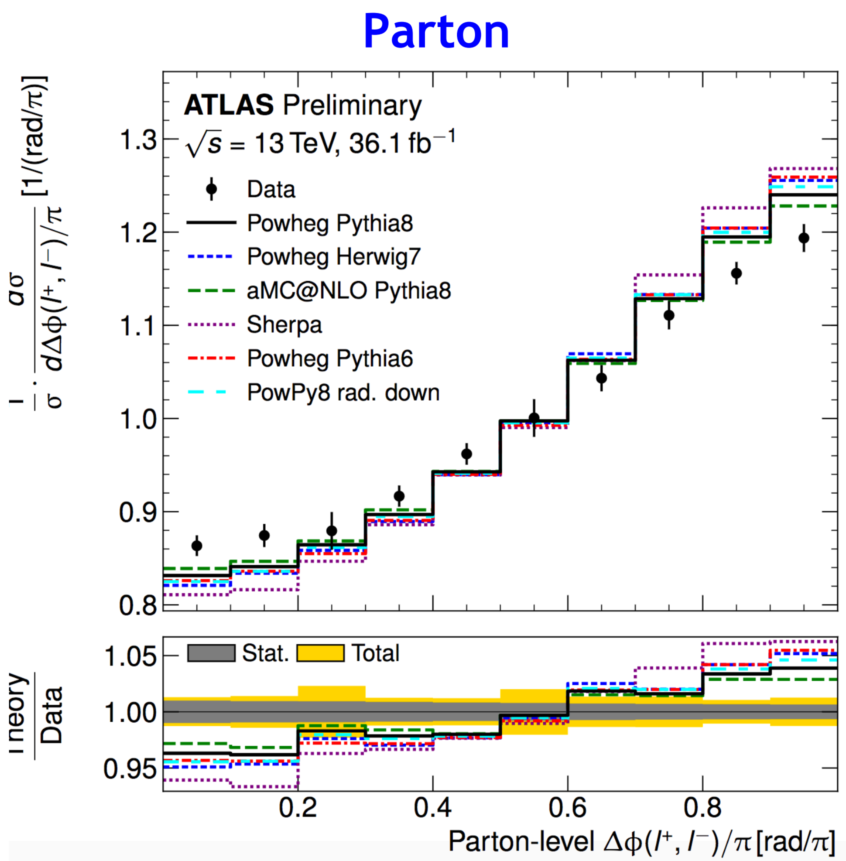
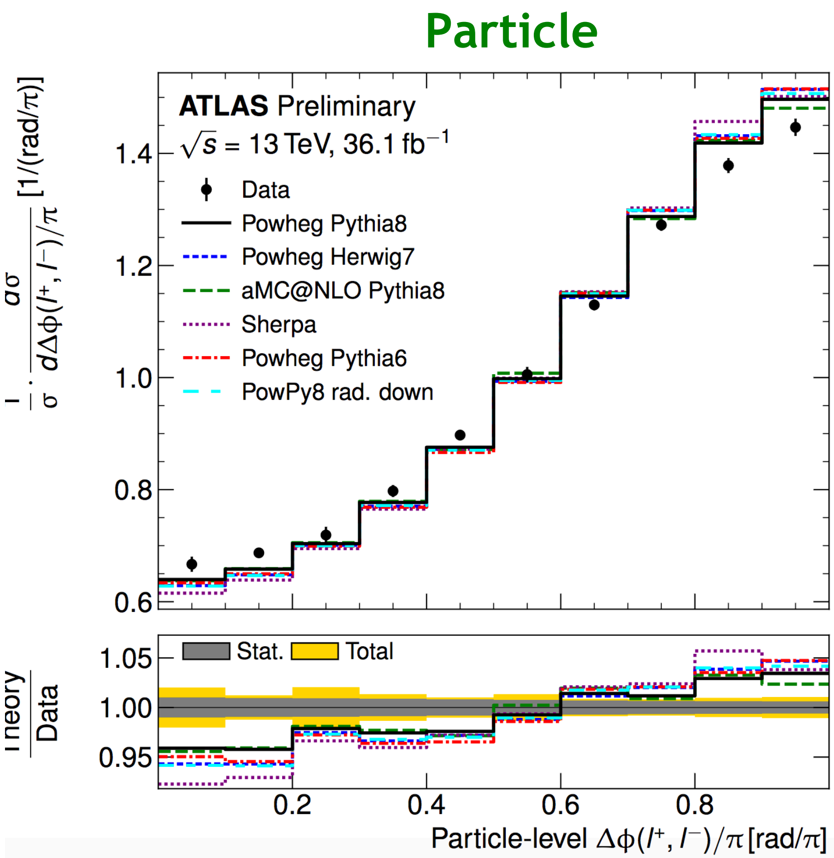
Unfolded distributions

- Unfolded distributions compared to different MC predictions

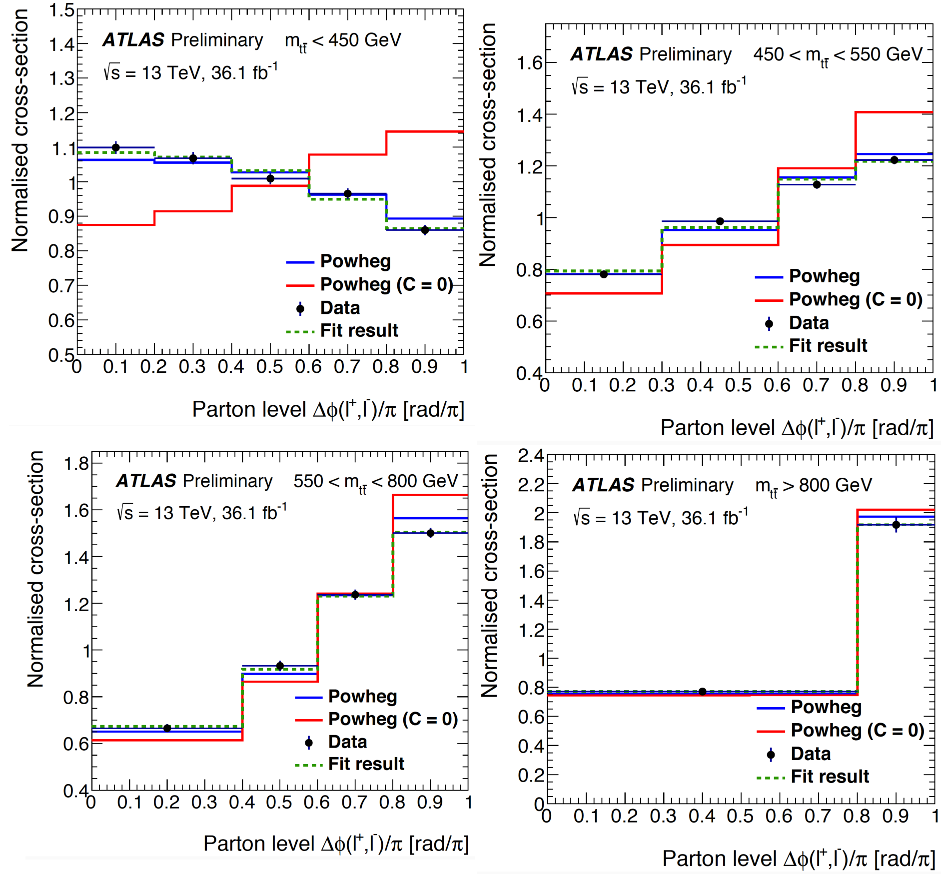




- Data shows a shallower slope than prediction

ATLAS-CONF-2018-027

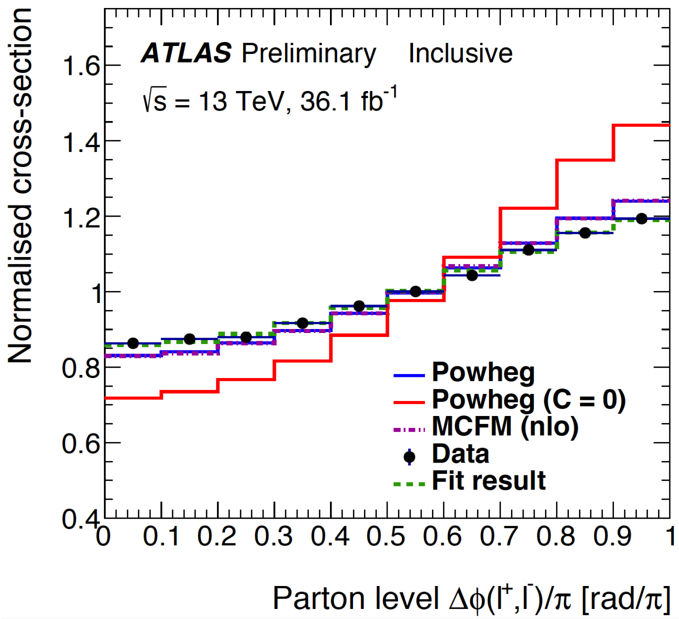
- Fitting spin and no-spin hypotheses to parton level distributions

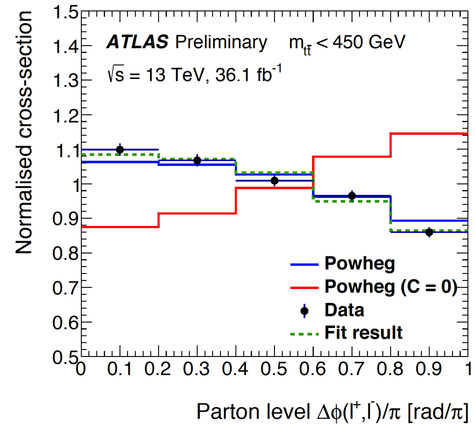


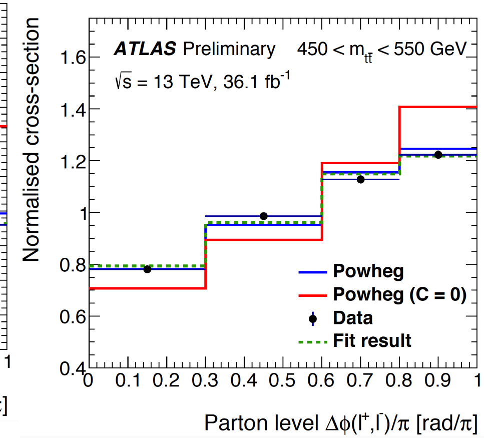
ATLAS-CONF-2018-027

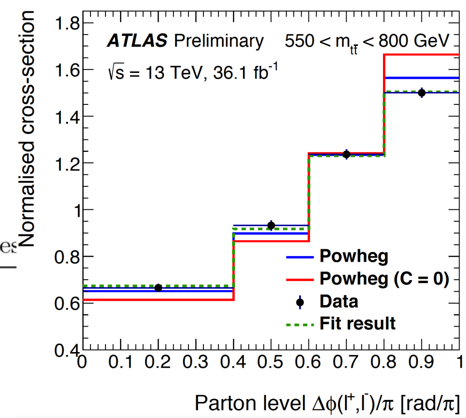
Template fit

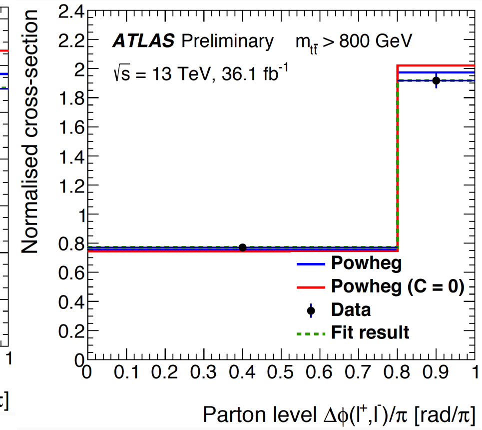
- Fitting spin and no-spin hypotheses to parton level distributions







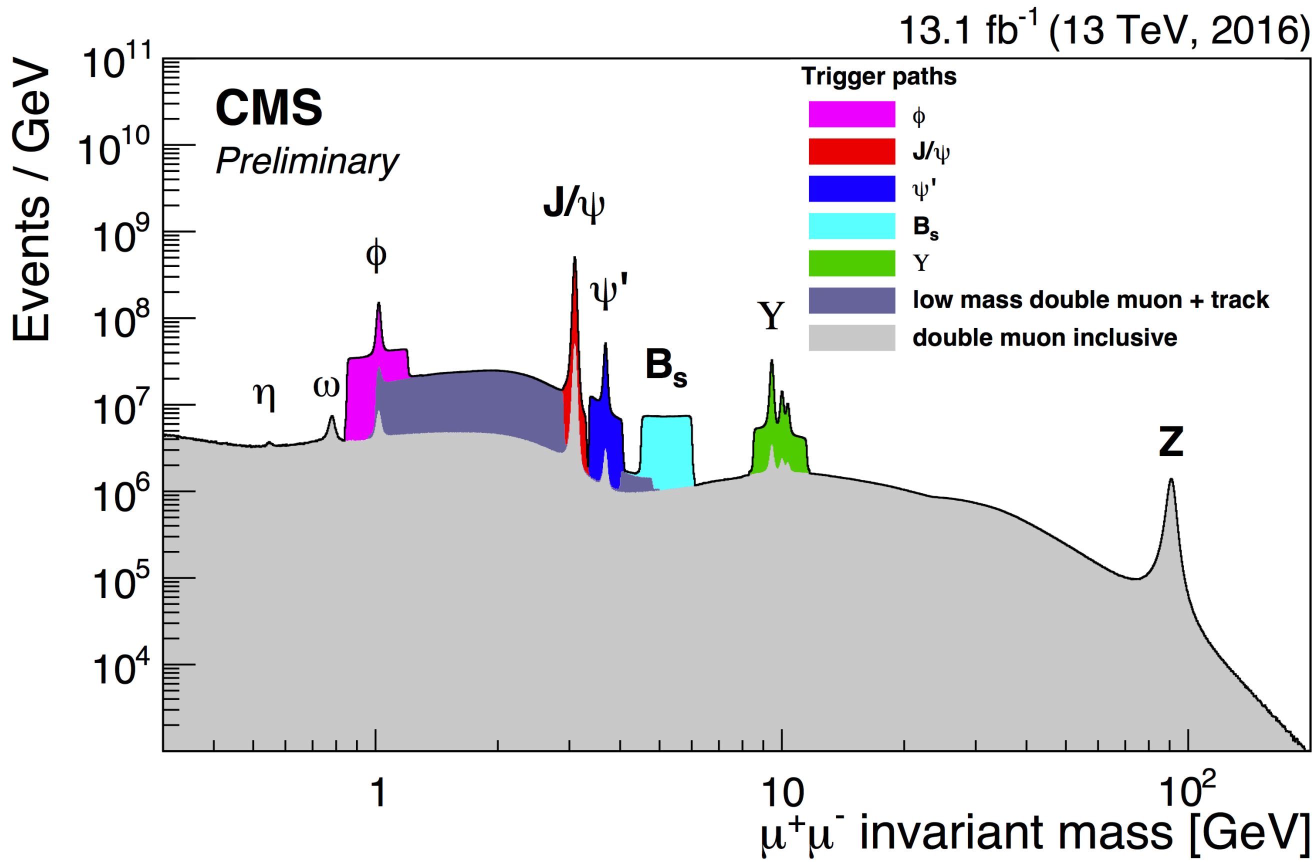




Region	f_{SM}	Significance (incl. theory uncertainties
$m_{t\bar{t}} < 450$ GeV	$1.11 \pm 0.04 \pm 0.13$	0.85 (0.84)
$450 < m_{t\bar{t}} < 550$ GeV	$1.17 \pm 0.09 \pm 0.14$	1.00 (0.91)
$550 < m_{t\bar{t}} < 800$ GeV	$1.60 \pm 0.24 \pm 0.35$	1.43 (1.37)
$m_{t\bar{t}} > 800$ GeV	$2.2 \pm 1.8 \pm 2.3$	0.41 (0.40)
inclusive	$1.250 \pm 0.026 \pm 0.063$	3.70 (3.20)

- Spin-correlations higher than SM prediction by 3.7σ (3.2σ including theory uncertainties)

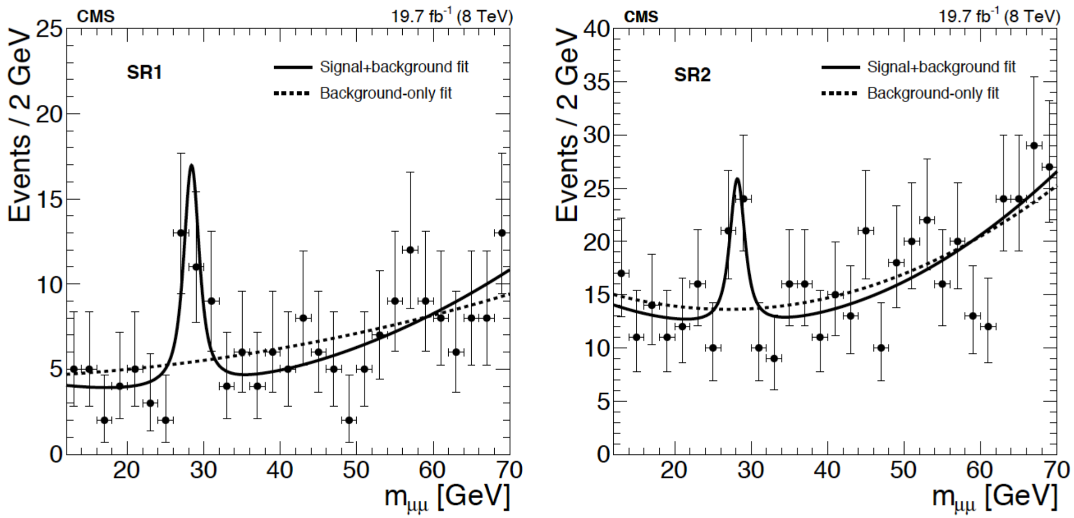
ATLAS-CONF-2018-027



A dimuon invariant mass plot contains much of the history of our field.

Could there be other objects lurking in the distribution?

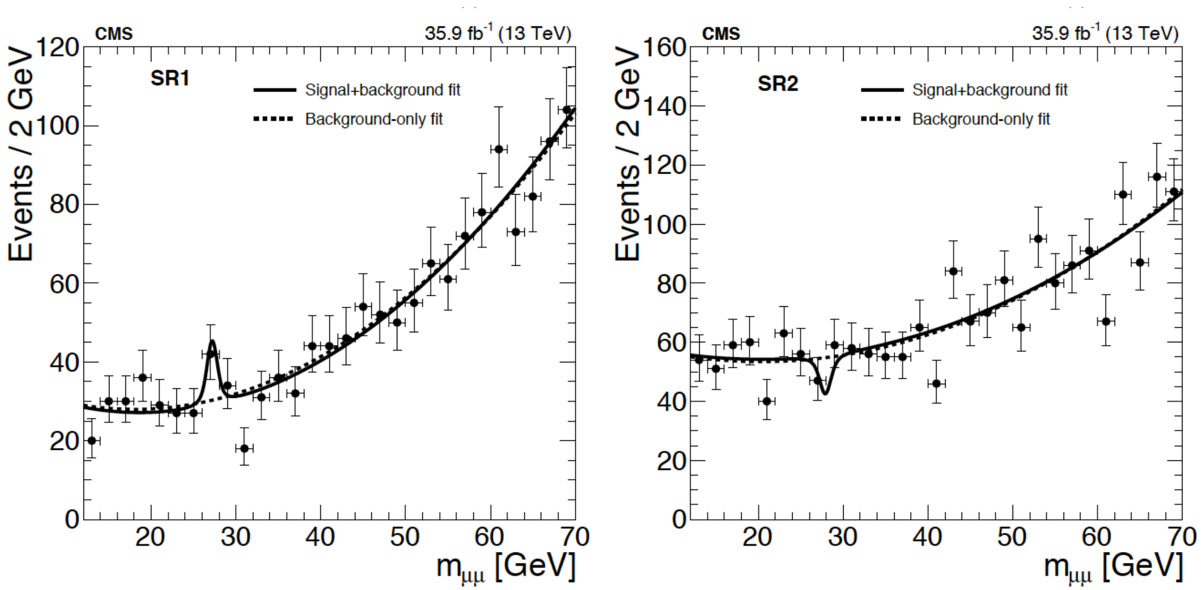
Di-muon resonance



arXiv:1808.01890
CERN-EP-2018-204

An excess of events above the background near a dimuon mass of 28 GeV is observed in the 8 TeV data, corresponding to local significances of 4.2 and 2.9 standard deviations in two event categories.

Event category	SR1 Additional forward jet	SR2 Additional central jet
Muons	OS, $p_T > 25\,\text{GeV}, \lvert\eta\rvert < 2.1$	
$m_{\mu\mu}$	$m_{\mu\mu} > 12\,\text{GeV}$	
b-tagged jet	$p_T > 30\,\text{GeV}, \lvert\eta\rvert \leq 2.4$	
Additional jet	$p_T > 30\,\text{GeV}, 2.4 < \lvert\eta\rvert < 4.7$	$p_T > 30\,\text{GeV}, \lvert\eta\rvert \leq 2.4$
Jet veto	No other jets $p_T > 30\,\text{GeV}, \lvert\eta\rvert \leq 2.4$	No jets $p_T > 30\,\text{GeV}, 2.4 < \lvert\eta\rvert < 4.7$
p_T^{miss}	—	<40 GeV
$\Delta\phi(\mu\mu, \text{jj})$	—	>2.5 rad



arXiv:1808.01890
CERN-EP-2018-204

A mild excess of data over the background in the first event category is observed in 13 TeV data and corresponds to a local significance of 2.0 standard deviations, while the second category results in a deficit with a local significance of 1.4 standard deviations.

$\sqrt{s}$ (TeV)	8		13	
Event category	SR1	SR2	SR1	SR2
Local significance (s.d.)	4.2	2.9	2.0	1.4 deficit
N_S	22.0 ± 7.6	22.8 ± 9.5	14.5 ± 9.3	-14.9 ± 10.1


Event: 474587238
2015-10-21 06:26:57 CEST
breakyourownnews.com
LIVE
BREAKING NEWS
LHC DISCOVERS SUPERSYMMETRY
15:24
I KNEW IT WAS AT THAT MASS ALL ALONG, SAYS THEORIST

ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

ATLAS Preliminary

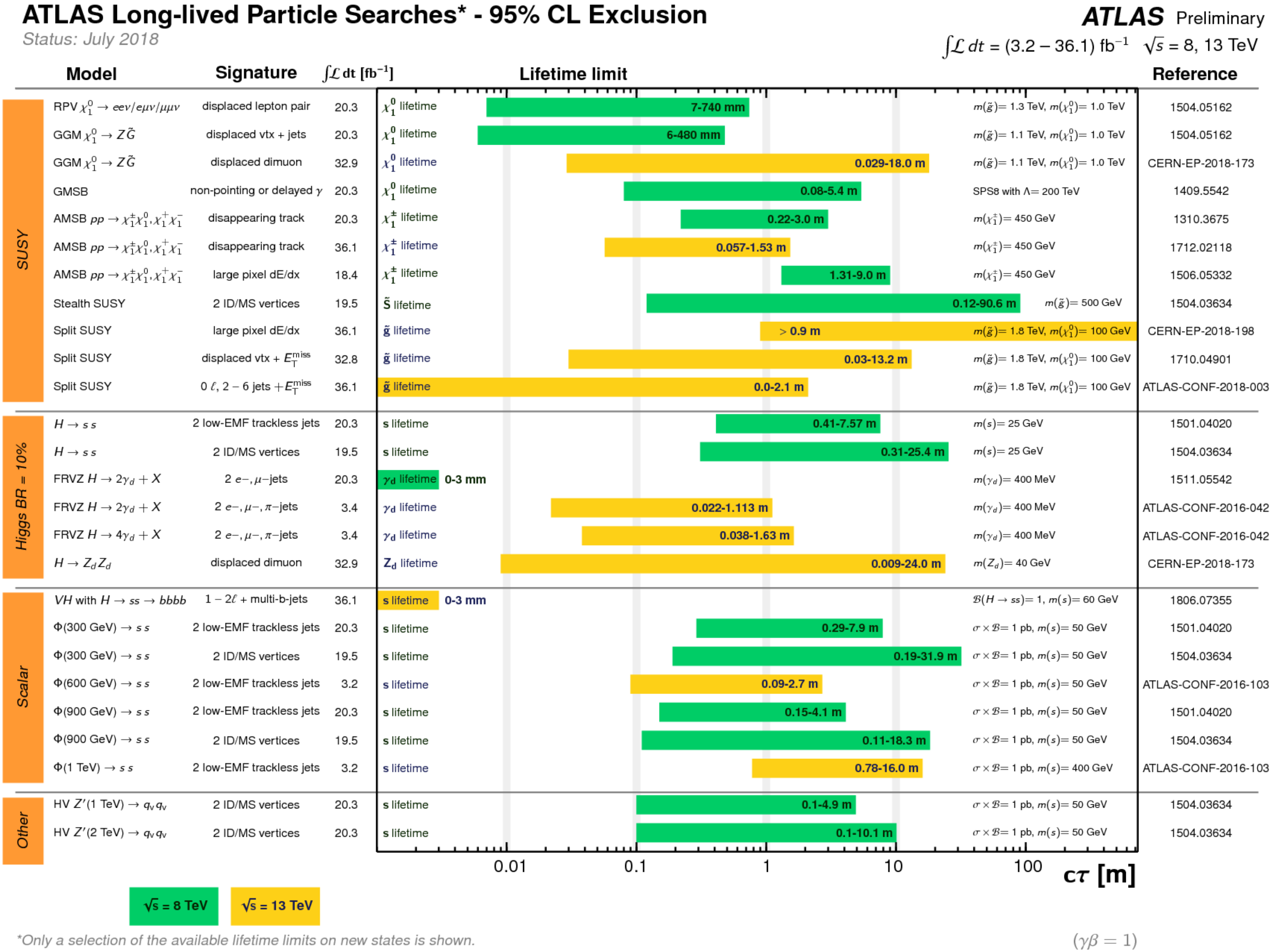
$\sqrt{s}$ = 7, 8, 13 TeV

$\sqrt{s}$ = 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	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	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
3rd 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

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

*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.



THE UNIVERSITY of ADELAIDE

CoEPP ARC Centre of Excellence for Particle Physics at the Terascale

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

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

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e,\mu$	$1-4$ j	Yes	36.1	M_D 7.7 TeV	$n=2$	1711.03301
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	M_S 8.6 TeV	$n=3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n=6$	1703.09127
	ADD BH high $\sum p_T$	$\geq 1\ e,\mu$	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n=6$, $M_D=3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n=6$, $M_D=3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	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 $g_{KK} \to tt$	$1\ e,\mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	$1\ e,\mu$	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt)=1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e,\mu$	–	–	36.1	Z' mass 4.5 TeV		1707.02424
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	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 $Z' \to tt$	$1\ e,\mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass 3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	$1\ e,\mu$	–	Yes	79.8	W' mass 5.6 TeV		ATLAS-CONF-2018-017
	SSM $W' \to \tau\nu$	$1\ \tau$	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $V' \to WV \to qqqq$ model B	$0\ e,\mu$	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 $\ell\ell qq$	$2\ e,\mu$	–	–	36.1	Λ 40.0 TeV	η_{LL}^-	1707.02424
	CI $tttt$	$\geq 1\ e,\mu$	≥ 1 b, ≥ 1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	CERN-EP-2018-174
DM	Axial-vector mediator (Dirac DM)	$0\ e,\mu$	$1-4$ j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi)=1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	$0\ e,\mu$	$1-4$ j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi)=1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	$0\ e,\mu$	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta=1$	1605.06035
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta=1$	1605.06035
	Scalar LQ 3rd gen	$1\ e,\mu$	≥ 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 $T_{5/3}T_{5/3} \lvert T_{5/3} \to Wt + X$	2(SS)/$\geq 3\ e,\mu$	≥ 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 $Y \to Wb + X$	$1\ e,\mu$	≥ 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 $B \to Hb + X$	$0\ e,\mu$, $2\ \gamma$	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	$1\ e,\mu$	≥ 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 $q^* \to q\gamma$	$1\ \gamma$	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^*	$3\ e,\mu$	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e,\mu,\tau$	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	$1\ e,\mu$	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	$2\ e,\mu$	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 $H^{\pm\pm} \to \ell\tau$	$3\ e,\mu,\tau$	–	–	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)	$1\ e,\mu$	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{non-res} = 0.2$	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 (green) $\sqrt{s}$ = 13 TeV (yellow)

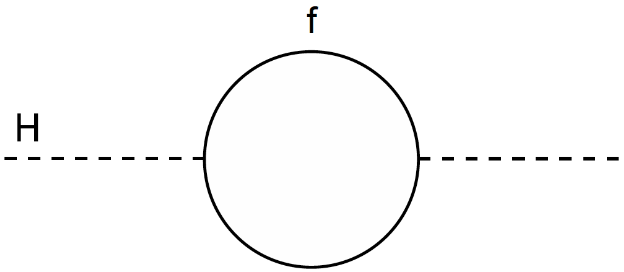
Mass scale [TeV] (10^{-1}, 1, 10)

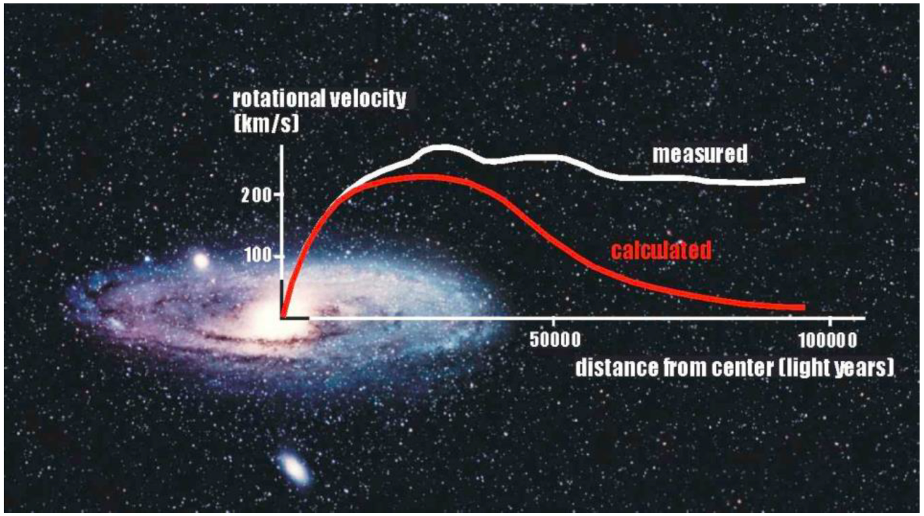
*Only a selection of the available mass limits on new states or phenomena is shown.

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

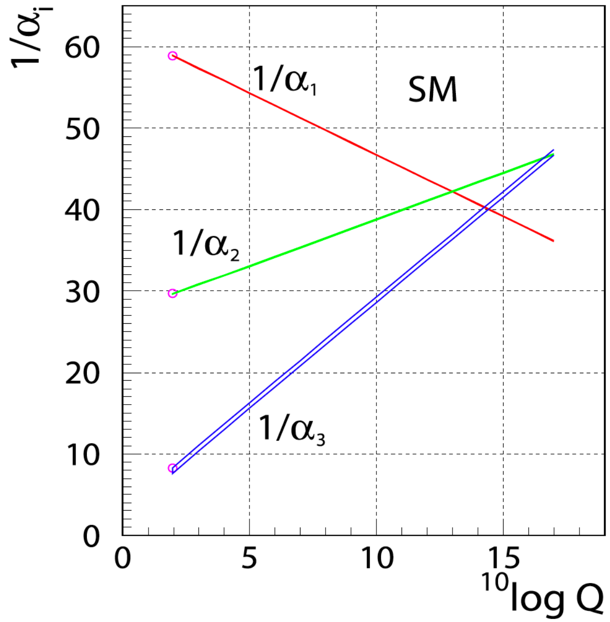
Why SUSY at all?

- **Hierarchy problem**: Higgs mass subject to quadratically divergent loop corrections.
  → Incredible fine-tuning





- **Dark matter:** Cosmological data suggest presence of dark matter → No explanation within Standard Model



- **Grand unification:** Standard Model coupling constants do not unify at high scales.
  → SM does not imply a Grand Unified Theory

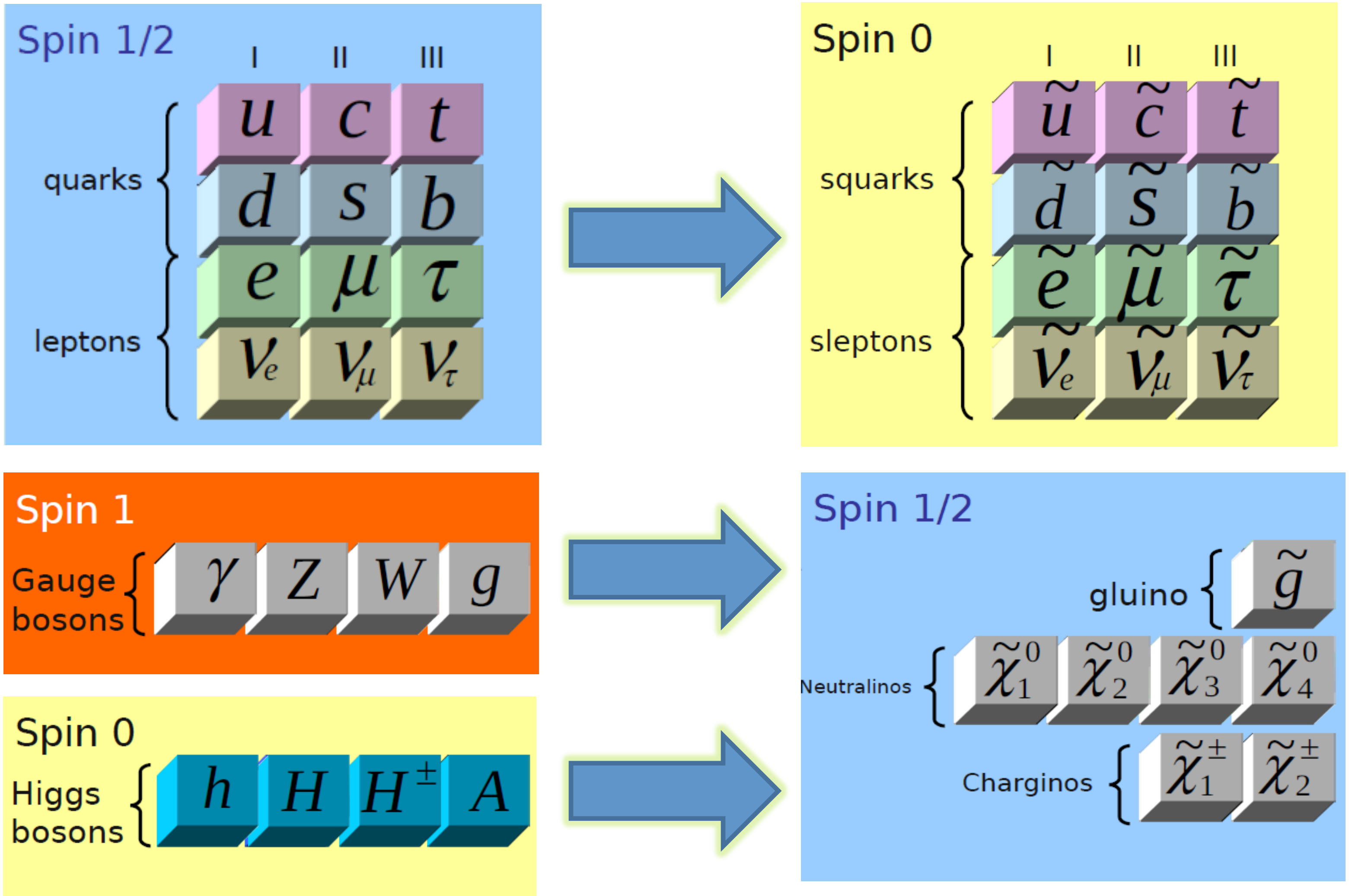
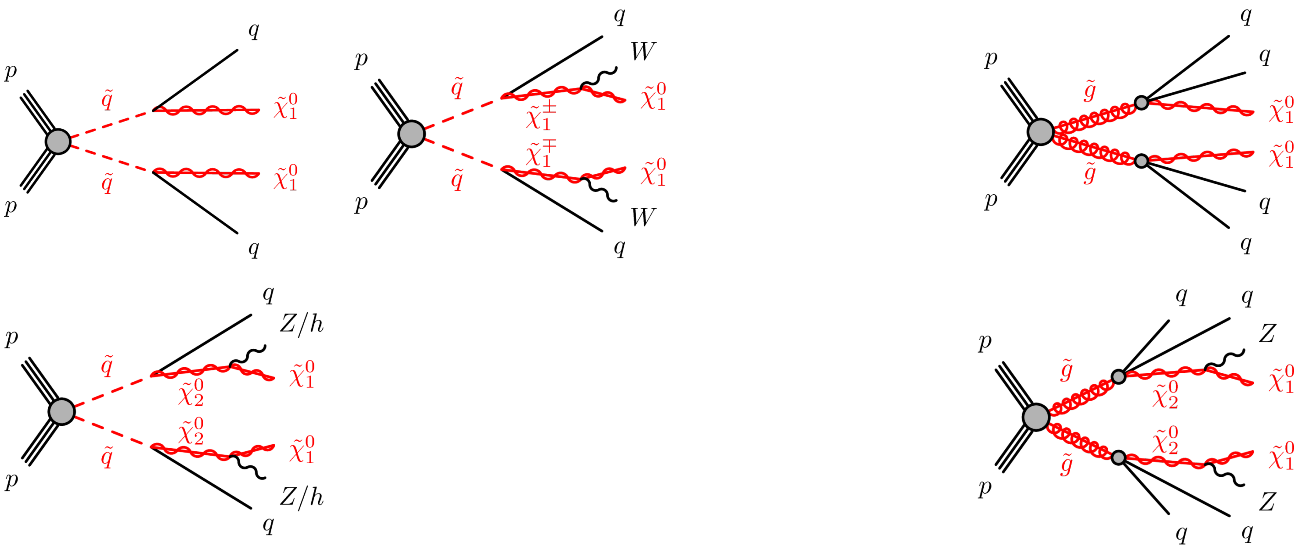


illustration by M-H Genest

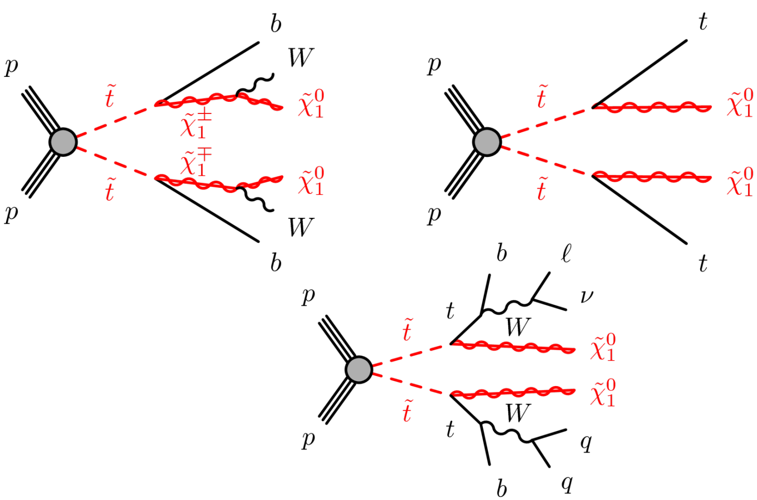
SUSY, this is what we often “claim” we’re searching for…

Squark and Gluino mediated light jets

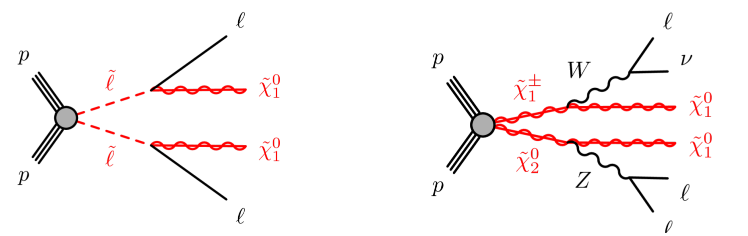


+ many more

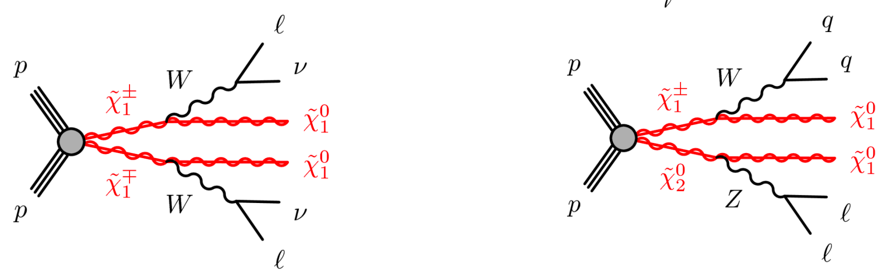
3rd generation squarks



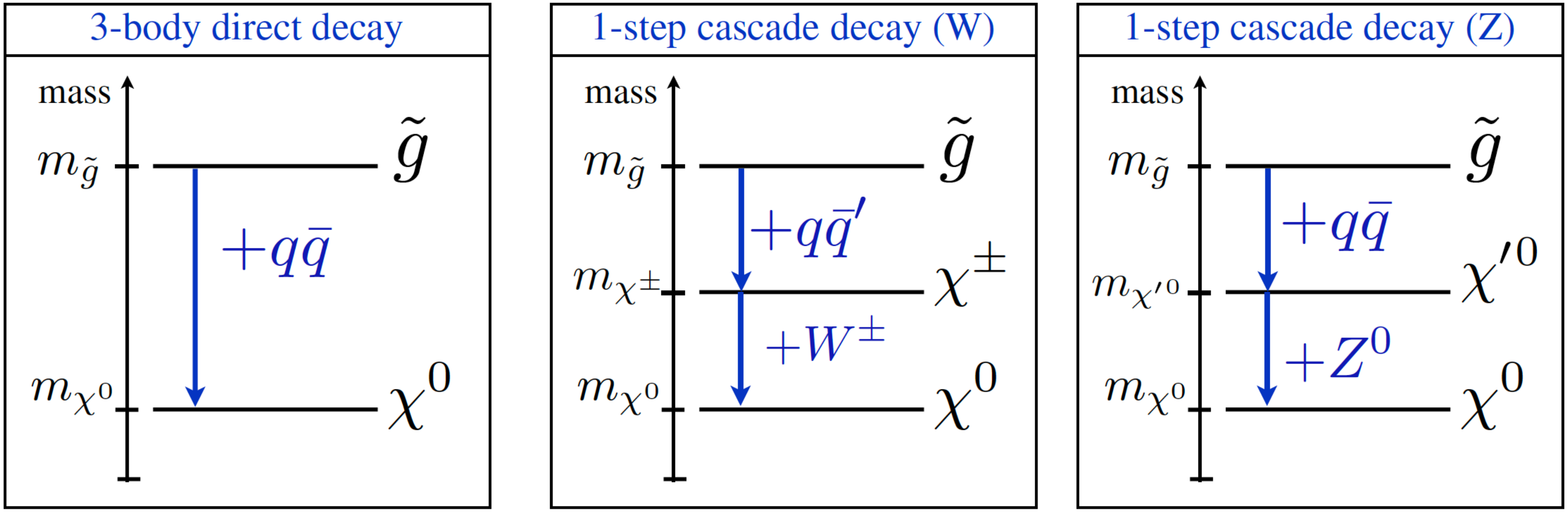
EWKino and slepton production



+ many more



Simplified Models

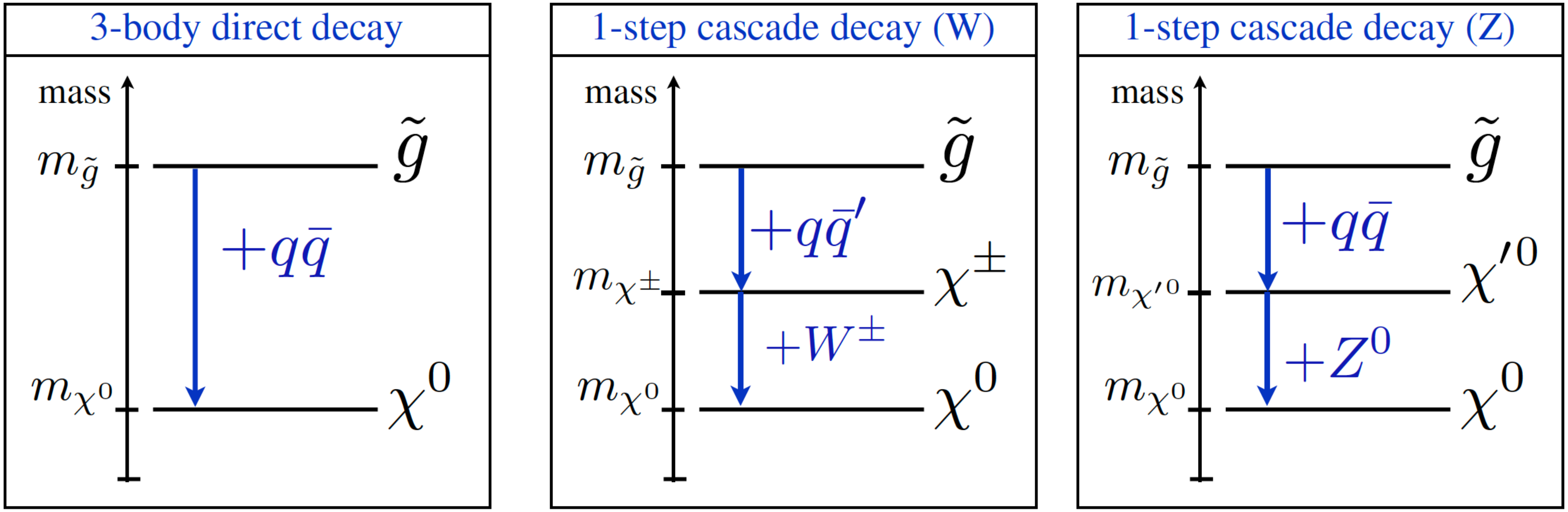


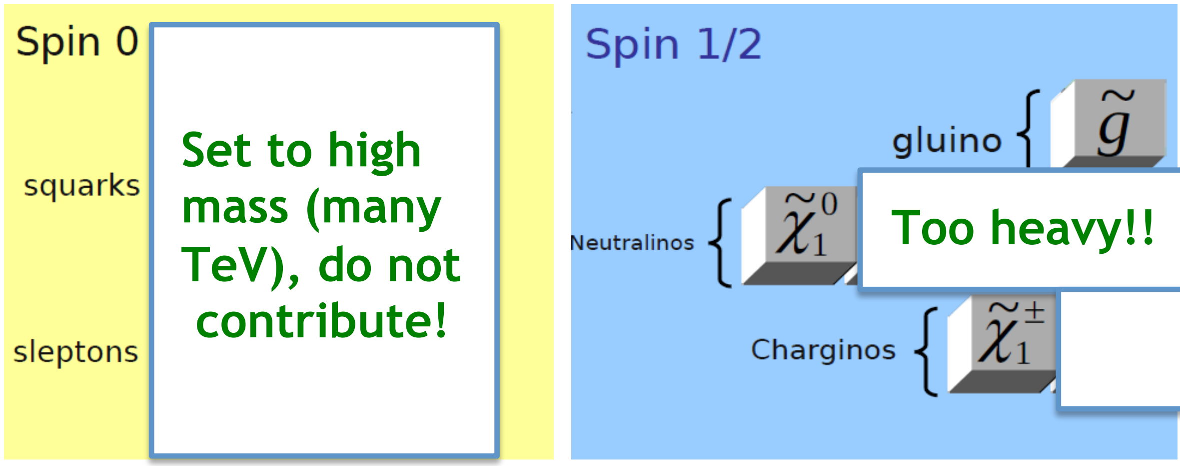
D. Alves et al J. Phys. G: Nucl. Part. Phys. 39 (2012) 105005

The way in which we design, *and optimize*, searches at LHC…..

…..not just an organising principle, this is what we search for!

Simplified Models

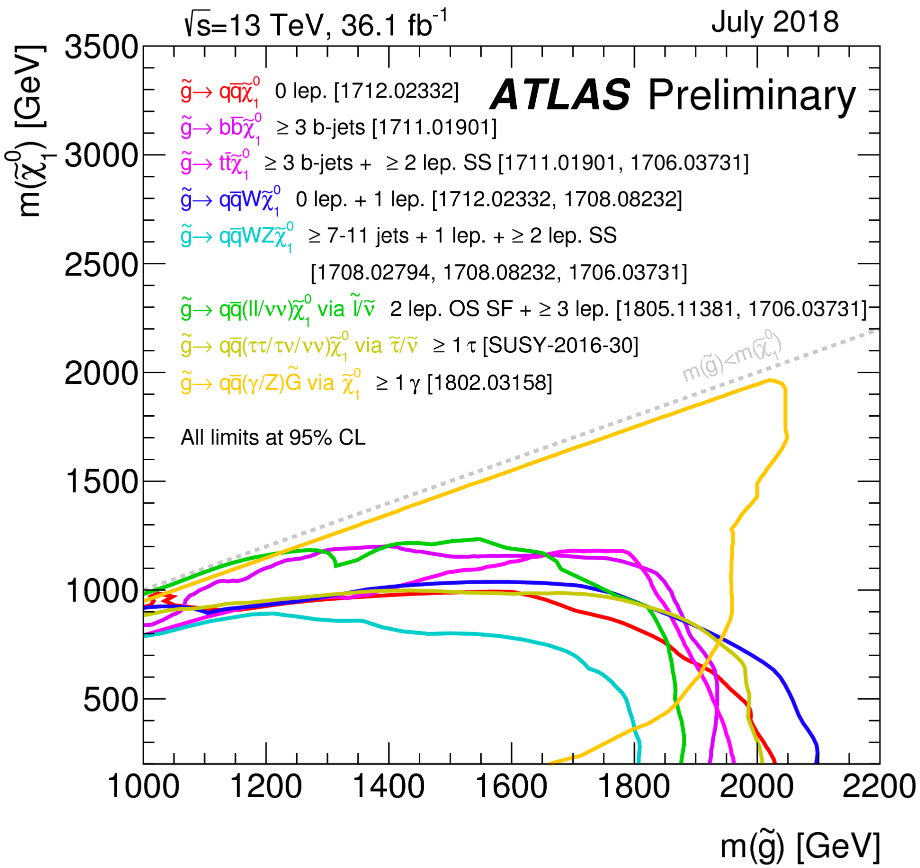


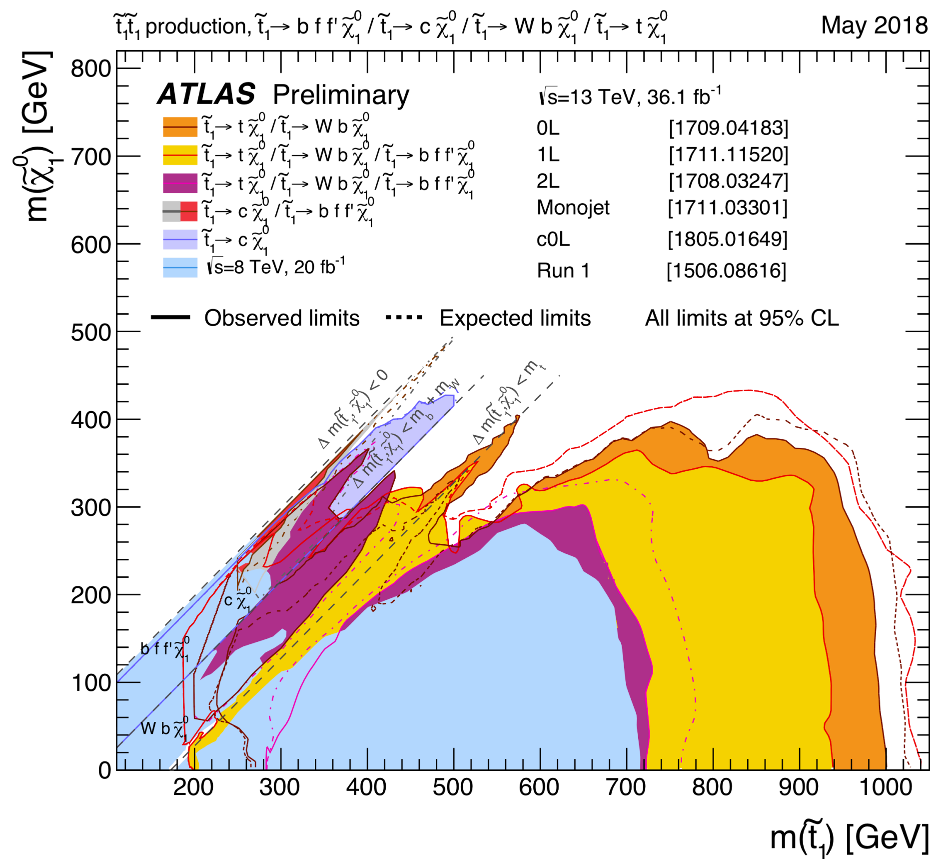


Set to high mass (many TeV), do not contribute!

Too heavy!!

What we usually show….





Experiments tend to show these plots as a summary of what has been excluded.

In all cases these limits are under very restricted conditions…

General philosophy

The general principle of the **approach for high and intermediate masses is the same.**

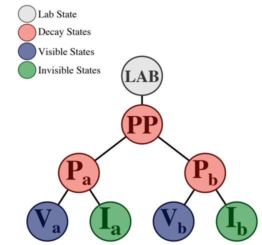
At much smaller mass splitting we need a different approach.

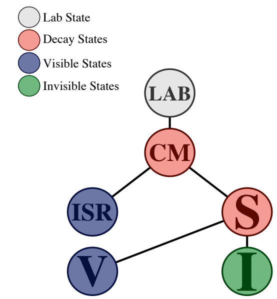
SRH – High Mass

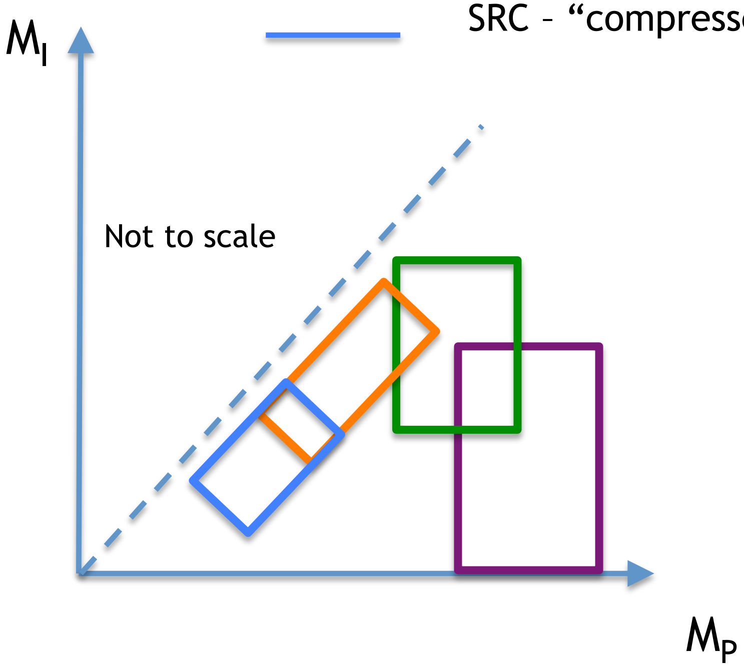
SRI - Intermediate Mass

SRL – Low Mass

SRC – “compressed” masses





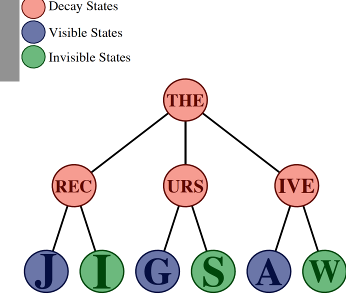


Need different cuts for different regions

All optimized using simplified models 😐

M_P = Parent mass
M_I = Invisible mass

Recursive Jigsaw Reconstruction



New(ish) approach to reconstructing open final states

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 according to particular rules defined for each topology (the topology relevant to each reference frame)

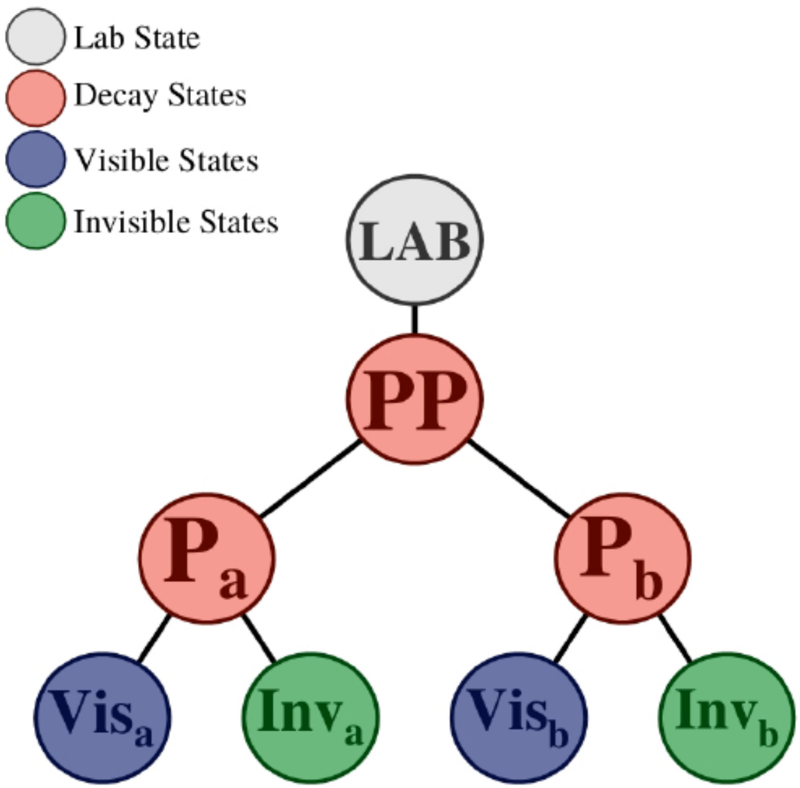
Jigsaw: Each of these rules is factorizable/customizable/interchangeable like jigsaw puzzle pieces

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

PJ, C. Rogan, Phys. Rev. D96 112007 (2017)
PJ, C. Rogan, M. Santoni, Phys. Rev. D95 035031 (2017)
M. Santoni, "Probing Supersymmetry with Recursive Jigsaw Reconstruction", PhD Thesis (2017)
M. Santoni, JHEP 1805 058 (2018)

Recursive Jigsaw Reconstruction technique

- Original method to **reconstructing** final states with weakly interacting particles.
- Transform observable momenta reference-frame to reference-frame
- **Jigsaw rules**: specify the unknown d.o.f. relevant to the transformation (customizable-interchangeable like jigsaw puzzle pieces)
- The procedure is repeated **recursively**, travelling through each of the reference frames relevant to the topology

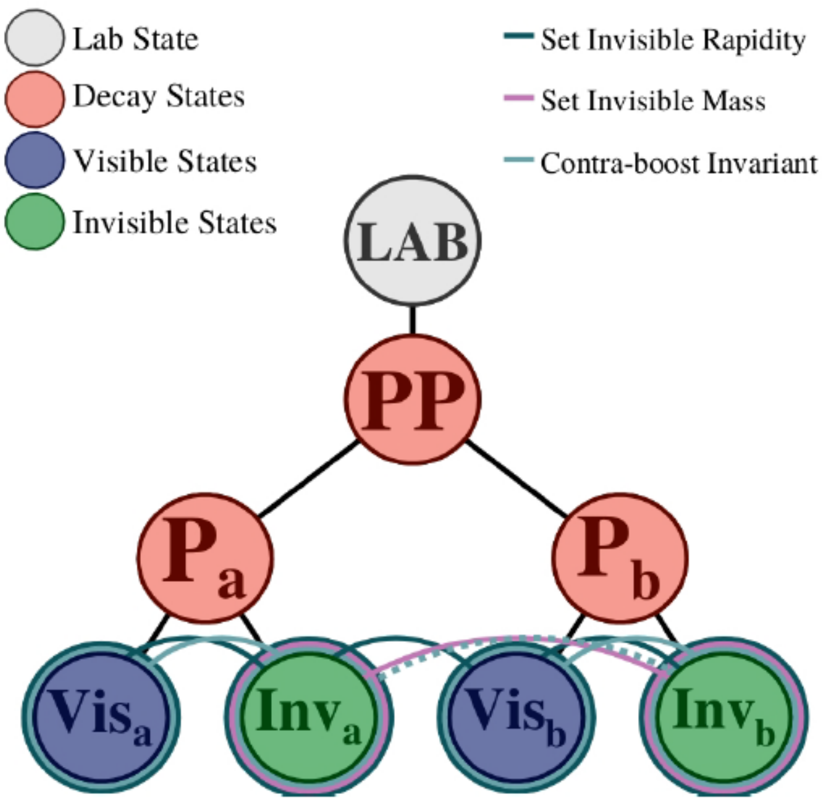


- Rather than obtaining one observable, get a complete basis of useful variables *diagonalized* with physical observable: angles, energies, masses ...

PJ, C. Rogan, Phys. Rev. D96 112007 (2017)
PJ, C. Rogan, M. Santoni, Phys. Rev. D95 035031 (2017)
M. Santoni, "Probing Supersymmetry with Recursive Jigsaw Reconstruction", PhD Thesis Uni. Adelaide (Dec 2017)
M. Santoni, JHEP 1805 058 (2018)

RJR technique

- Original method to **reconstructing** final states with weakly interacting particles.
- Transform observable momenta reference-frame to reference-frame
- **Jigsaw rules**: specify the unknown d.o.f. relevant to the transformation (customizable-interchangeable like jigsaw puzzle pieces)
- The procedure is repeated **recursively**, travelling through each of the reference frames relevant to the topology



- Rather than obtaining one observable, get a complete basis of useful variables *diagonalized* with physical observable: angles, energies, masses ...

PJ, C. Rogan, Phys. Rev. D96 112007 (2017)
PJ, C. Rogan, M. Santoni, Phys. Rev. D95 035031 (2017)
M. Santoni, "Probing Supersymmetry with Recursive Jigsaw Reconstruction", PhD Thesis Uni. Adelaide (Dec 2017)
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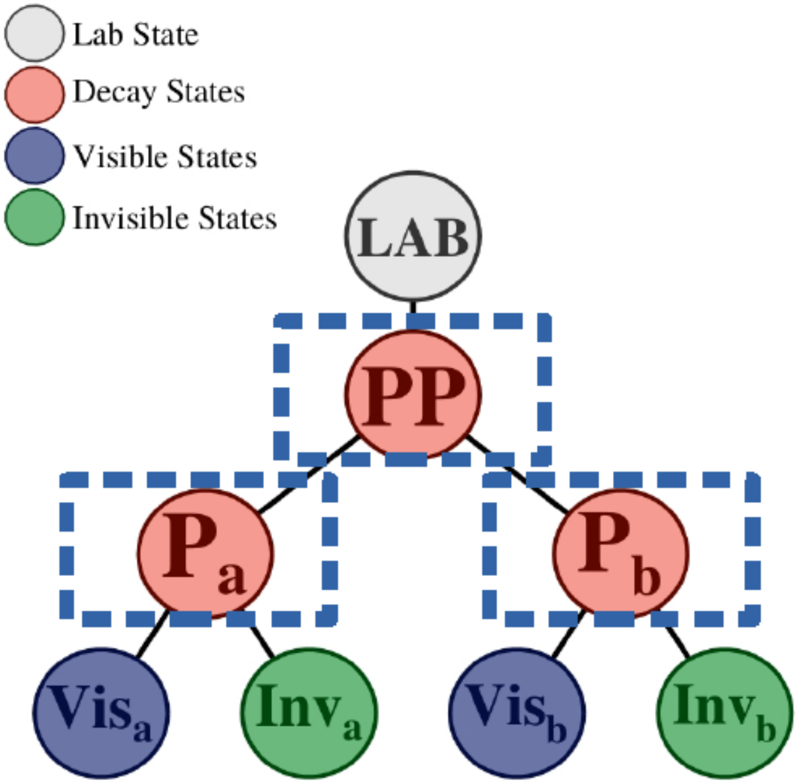

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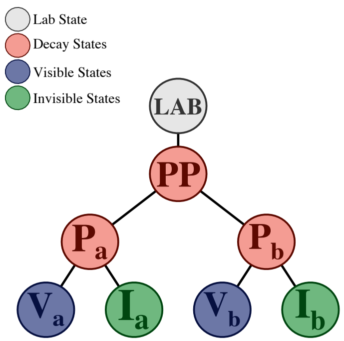
PJ, C. Rogan, Phys. Rev. D96 112007 (2017)
PJ, C. Rogan, M. Santoni, Phys. Rev. D95 035031 (2017)
M. Santoni, “Probing Supersymmetry with Recursive Jigsaw Reconstruction”, PhD Thesis Uni. Adelaide (Dec 2017)
M. Santoni, JHEP 1805 058 (2018)

ATLAS EXPERIMENT

Scale Variables



$$H^{\mathcal{F}}_{n,m} = \sum_{1}^{n} \vec{p}^{\,\mathcal{F}}_{vis,i} + \sum_{1}^{m} \vec{p}^{\,\mathcal{F}}_{inv,j}$$

where:

n : number of *visible ojects* considered as independent

m : number of *invisible ojects* considered as independent

$\mathcal{F}$: frame under examination (can be PP ($\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$) or P ($\tilde{\chi}_1^{\pm}$ or $\tilde{\chi}_2^0$))

Examples used in this analysis:

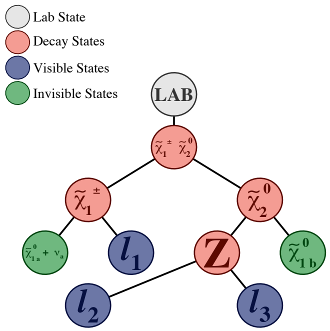
$$H^{PP}_{1,1} = (\ell_1 + \ell_2 + \ell_3)^{PP}.P() + (\tilde{\chi}^0_{1a} + \tilde{\chi}^0_{1b} + \nu_a)^{PP}.P()$$

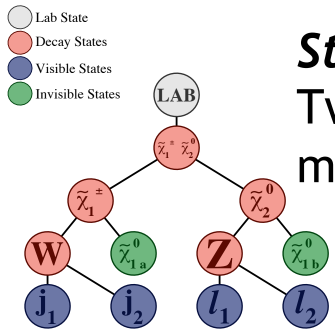
$$HT^{PP}_{4,1} = \ell_1^{PP}.Pt() + \ell_2^{PP}.Pt() + jet_1^{PP}.Pt() + jet_2^{PP}.Pt() + (\tilde{\chi}^0_{1a} + \tilde{\chi}^0_{1b})^{PP}.Pt()$$

$$H^{P_a}_{2,1} = \ell_1^{P_a}.P() + \ell_2^{P_a}.P() + \tilde{\chi}_1^{0\,P_a}.P()$$

$$H^{P_b}_{2,1} = jet_1^{P_b}.P() + jet_2^{P_b}.P() + \tilde{\chi}_1^{0\,P_b}.P()$$

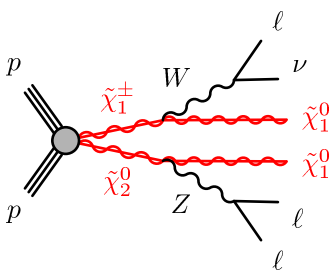
PJ, C. Rogan, Phys. Rev. D96 112007 (2017)

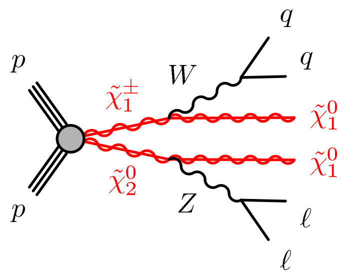


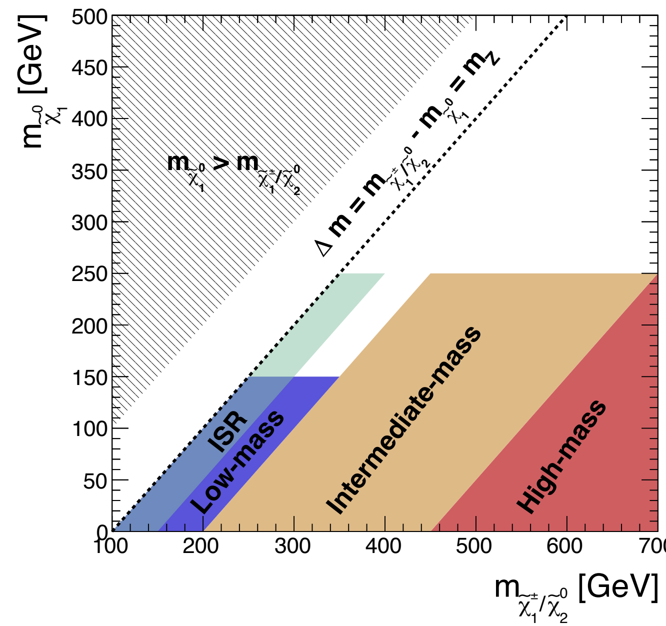


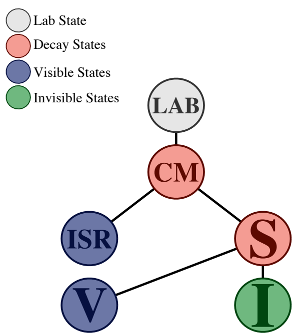
Standard Decay Tree

Two sets of SRs based on lepton multiplicity. High / Intermediate / Low



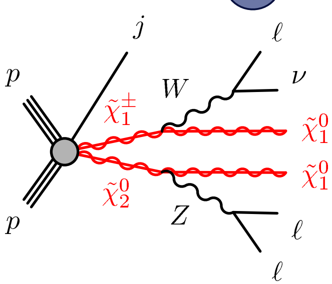


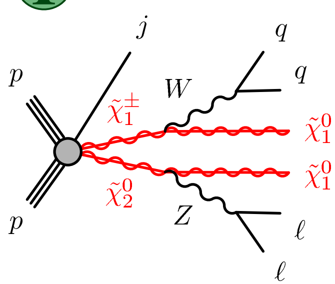




ISR Decay Tree

Requires a system of jet(s) to boost the signal





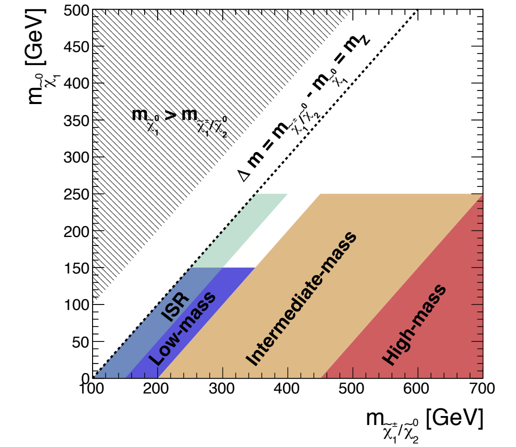
ISR and Low mass are designed to be orthogonal

3lepton Standard Tree Definitions

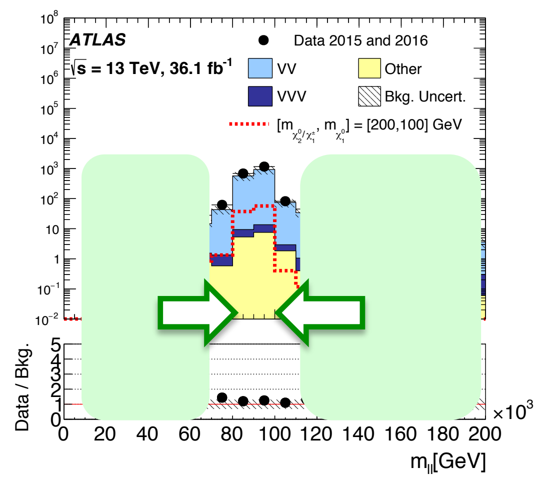
ATLAS EXPERIMENT

Region	n_{leptons}	n_{jets}	$n_{b\text{-tag}}$	$p_T^{\ell 1}$ [GeV]	$p_T^{\ell 2}$ [GeV]	$p_T^{\ell 3}$ [GeV]
CR3ℓ-VV	$= 3$	< 3	$= 0$	> 60	> 40	> 30
VR3ℓ-VV	$= 3$	< 3	$= 0$	> 60	> 40	> 30
SR3ℓ_High	$= 3$	< 3	$= 0$	> 60	> 60	> 40
SR3ℓ_Int	$= 3$	< 3	$= 0$	> 60	> 50	> 30
SR3ℓ_Low	$= 3$	$= 0$	$= 0$	> 60	> 40	> 30

Region	$m_{\ell\ell}$ [GeV]	m_T^W [GeV]	$H_{3,1}^{\text{PP}}$ [GeV]	$\frac{p_{T\,\text{PP}}^{\text{lab}}}{p_{T\,\text{PP}}^{\text{lab}}+H_{T\,3,1}^{\text{PP}}}$	$\frac{H_{T\,3,1}^{\text{PP}}}{H_{3,1}^{\text{PP}}}$	$\frac{H_{1,1}^{\text{P}_\text{b}}}{H_{2,1}^{\text{P}_\text{b}}}$
CR3ℓ-VV	$\in (75, 105)$	$\in (0, 70)$	> 250	< 0.2	> 0.75	–
VR3ℓ-VV	$\in (75, 105)$	$\in (70, 100)$	> 250	< 0.2	> 0.75	–
SR3ℓ_High	$\in (75, 105)$	> 150	> 550	< 0.2	> 0.75	> 0.8
SR3ℓ_Int	$\in (75, 105)$	> 130	> 450	< 0.15	> 0.8	> 0.75
SR3ℓ_Low	$\in (75, 105)$	> 100	> 250	< 0.05	> 0.9	–



Select events:
- with 3 high pT leptons
- l+l- pair at the Z-mass
- use RJ variables to define sensitive regions of phase space



Can leverage the behavior of the physics variables we design to target signals in a more natural way.

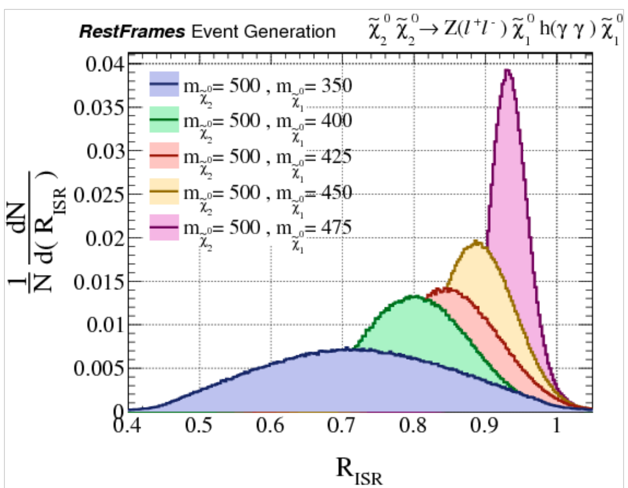
Similar selection optimization performed for 2lepton regions

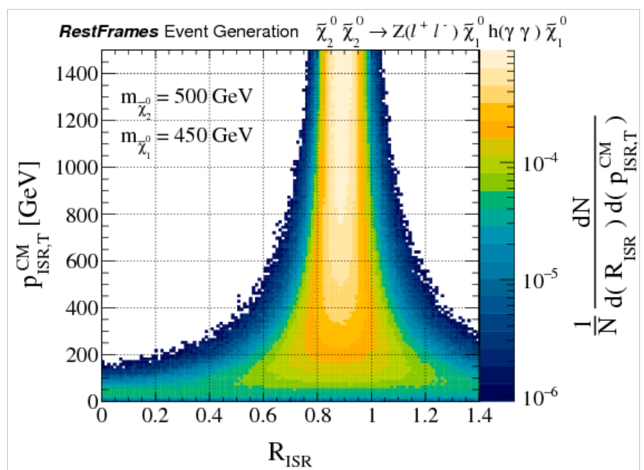
3lepton ISR Tree Definitions

ATLAS EXPERIMENT

Region	n_{leptons}	n_{jets}	$n_{b\text{-tag}}$	$p_{\mathrm{T}}^{\ell_1}$ [GeV]	$p_{\mathrm{T}}^{\ell_2}$ [GeV]	$p_{\mathrm{T}}^{\ell_3}$ [GeV]
CR3ℓ_ISR-VV	$= 3$	≥ 1	$= 0$	> 25	> 25	> 20
VR3ℓ_ISR-VV	$= 3$	≥ 1	$= 0$	> 25	> 25	> 20
SR3ℓ_ISR	$= 3$	$\in [1, 3]$	$= 0$	> 25	> 25	> 20

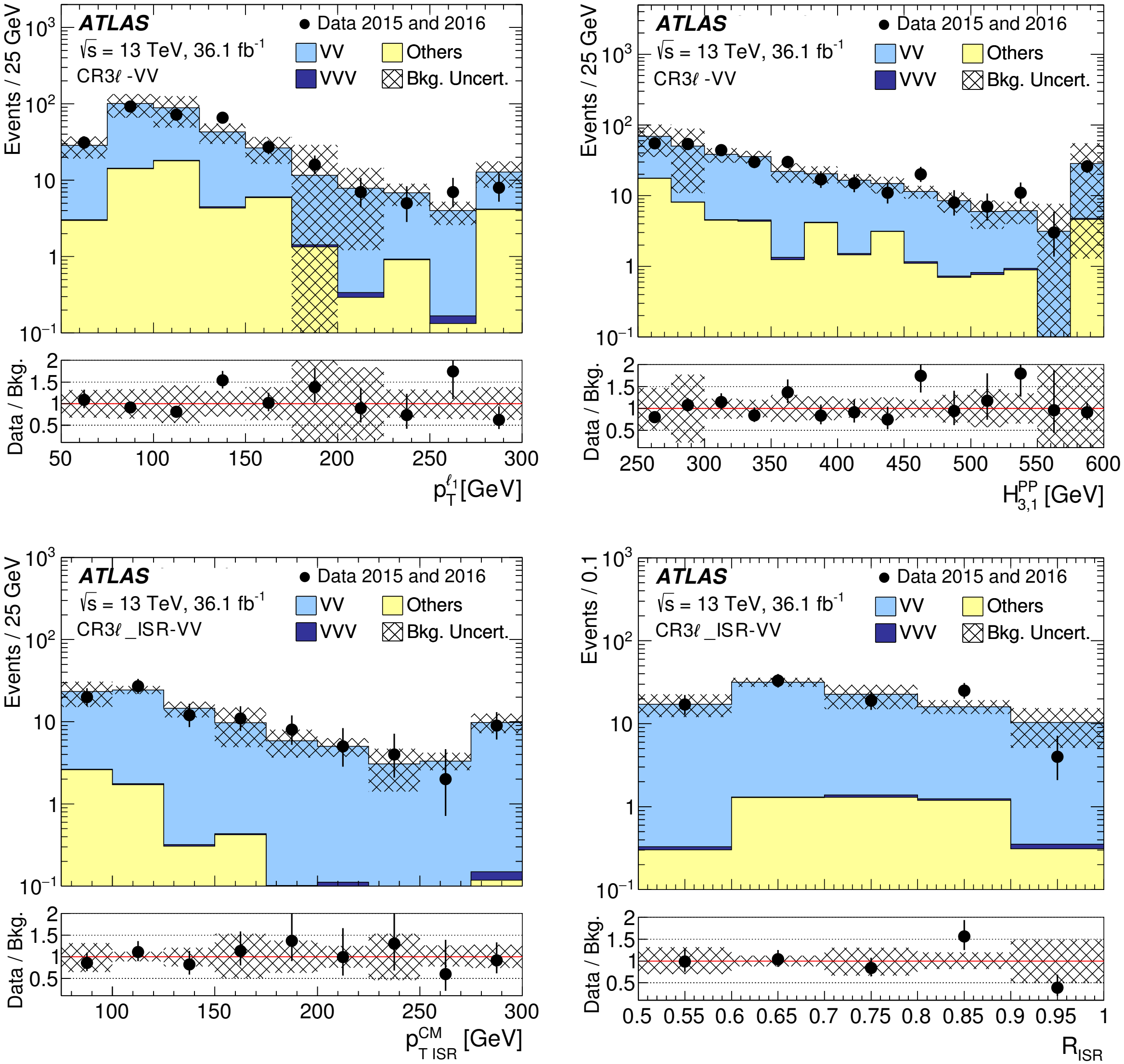
Region	$m_{\ell\ell}$ [GeV]	m_{T}^{W} [GeV]	$\Delta\phi_{\mathrm{ISR,I}}^{\mathrm{CM}}$	R_{ISR}	$p_{\mathrm{T\ ISR}}^{\mathrm{CM}}$ [GeV]	$p_{\mathrm{T\ I}}^{\mathrm{CM}}$ [GeV]	$p_{\mathrm{T}}^{\mathrm{CM}}$ [GeV]
CR3ℓ_ISR-VV	$\in (75, 105)$	< 100	> 2.0	$\in (0.55, 1.0)$	> 80	> 60	< 25
VR3ℓ_ISR-VV	$\in (75, 105)$	> 60	> 2.0	$\in (0.55, 1.0)$	> 80	> 60	> 25
SR3ℓ_ISR	$\in (75, 105)$	> 100	> 2.0	$\in (0.55, 1.0)$	> 100	> 80	< 25

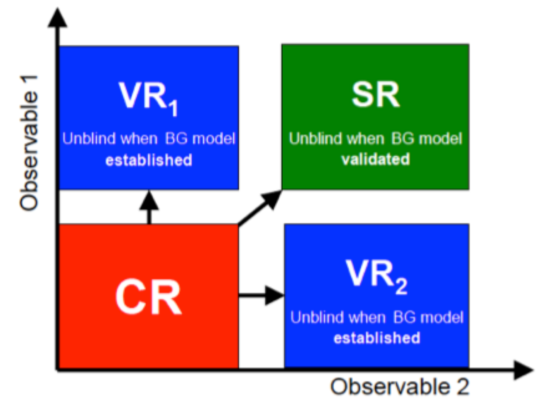




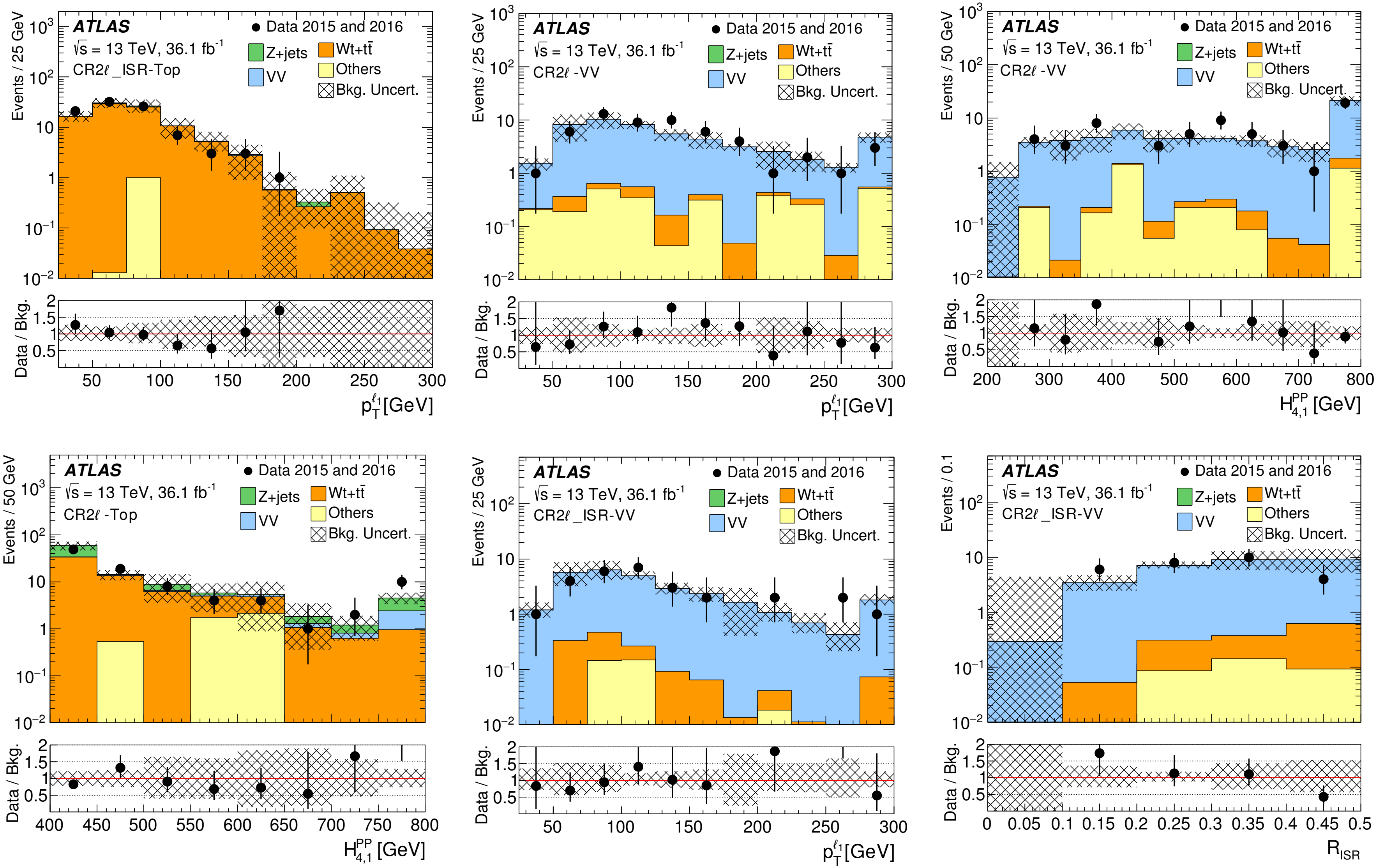
Complementarity between the R_{ISR} variable and $P_{\mathrm{T\ ISR}}$ outlined in detail in:
PJ, C. Rogan, M. Santoni, PRD 95 035013 (2017)

Control Regions – 3lepton

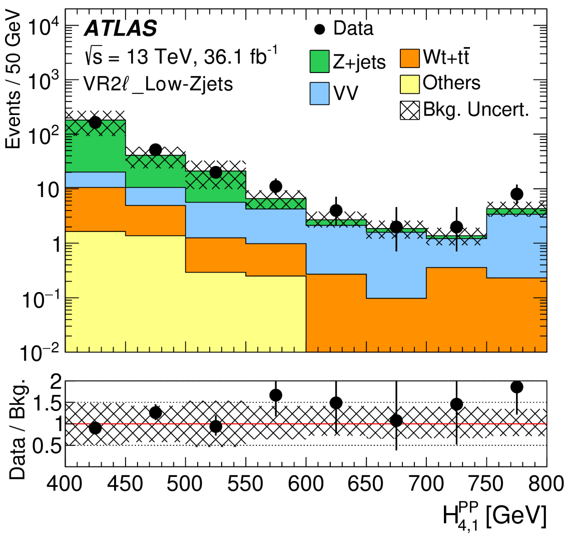


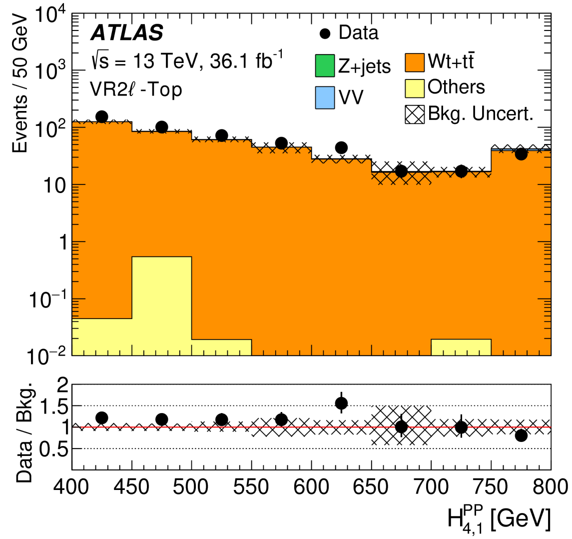


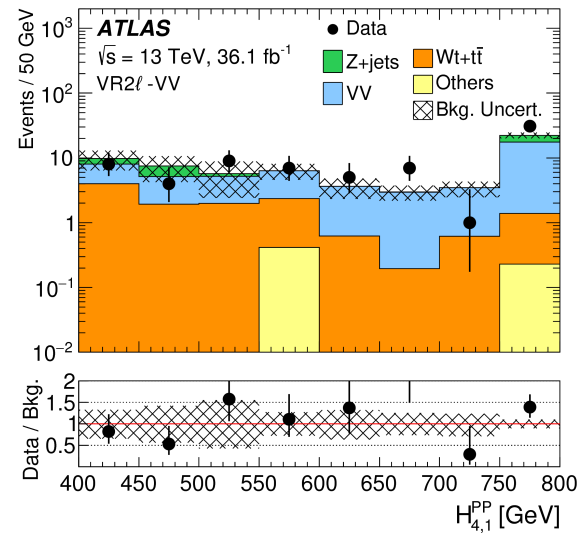
Control Regions – 2lepton

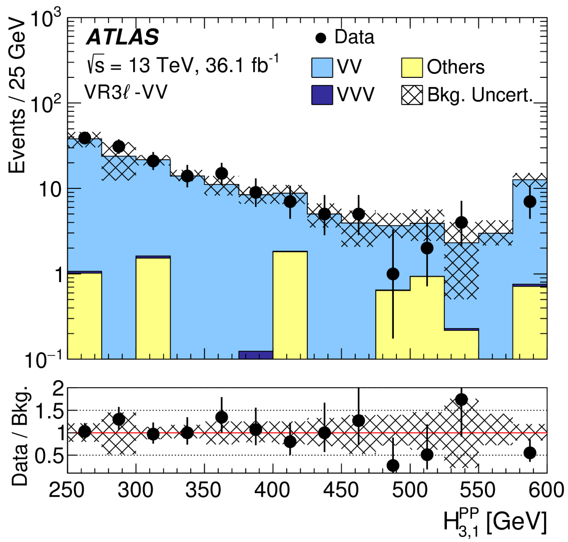


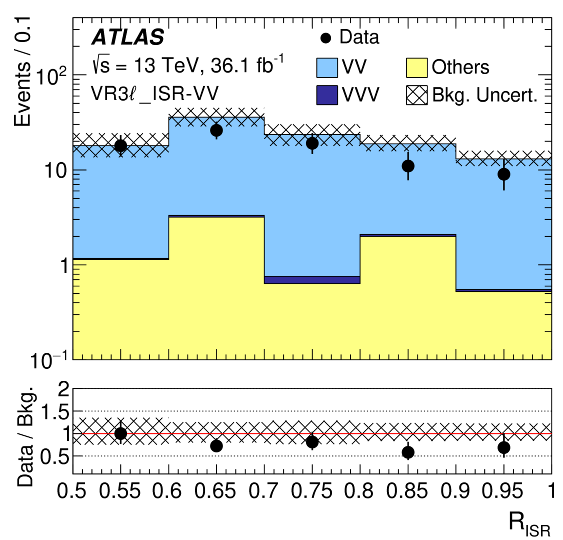
Validation Regions



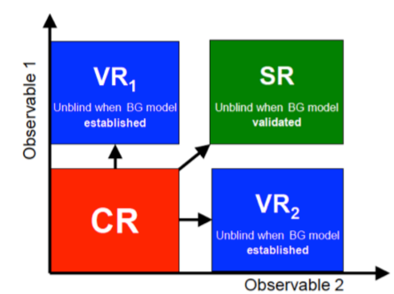






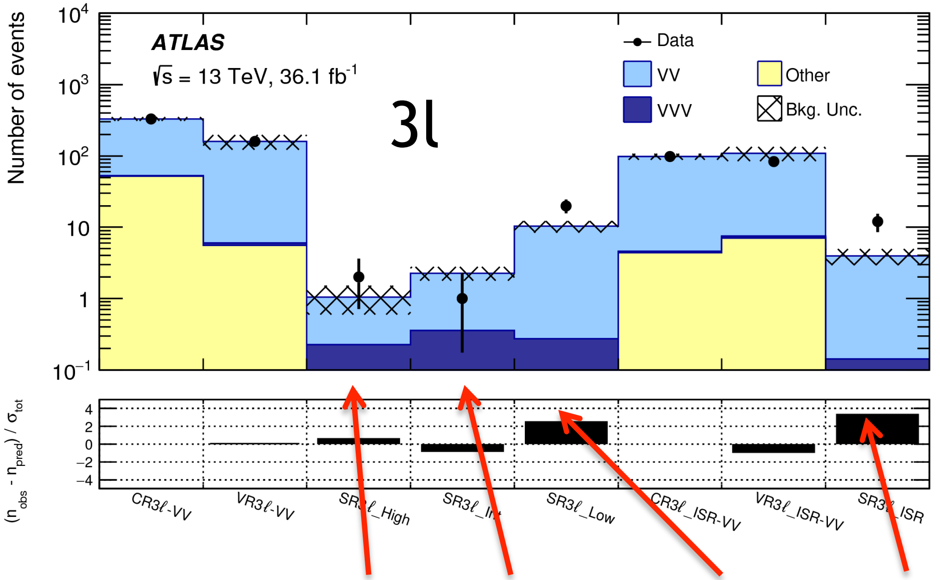


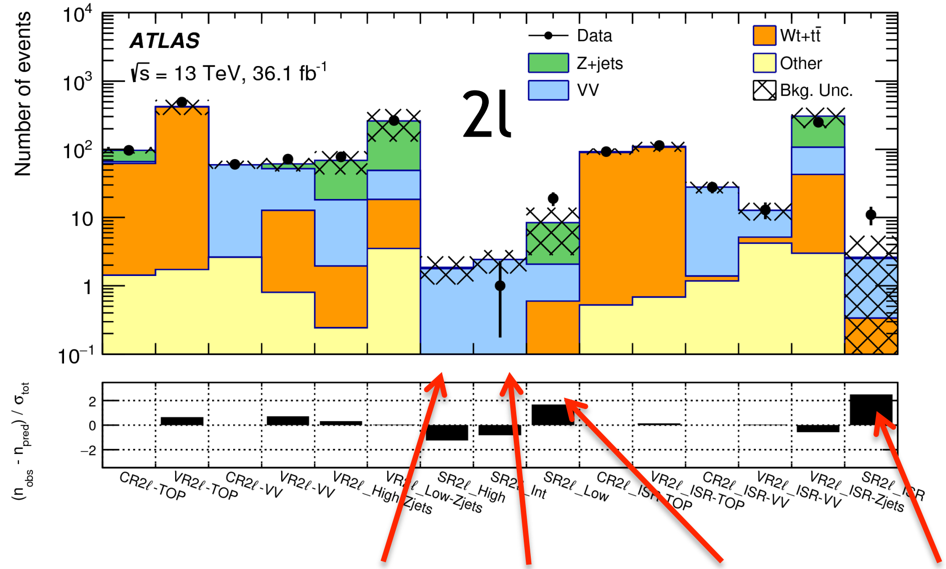
Study phase space even closer to the SR to check variables are well modelled.
All looks good.



Unblinded results

- Main background contribution is from VV (3l), VV and Z+jets (2l)
- Control and Validation Regions enriched in these processes demonstrate that the key backgrounds are well modeled
- Z+jets prediction from a dedicated photon template sample
- We see excesses, in 4 signal regions, all targeting the low mass splitting



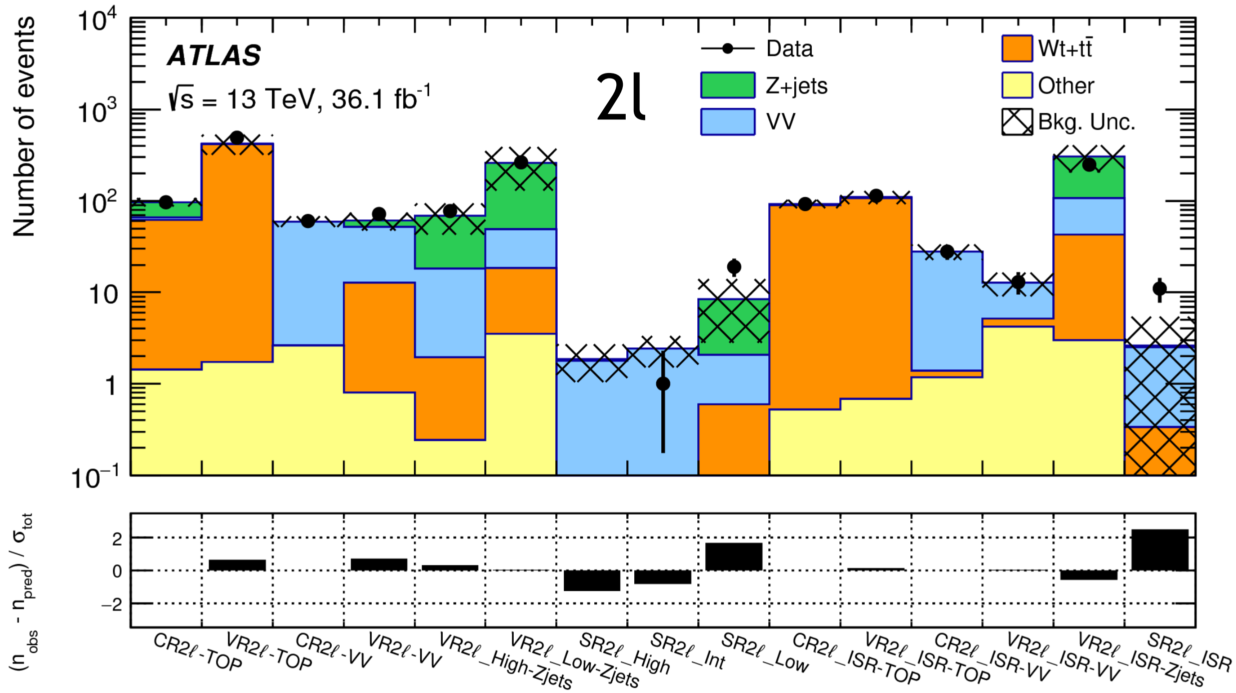


Signal Region	SR3ℓ_High	SR3ℓ_Int	SR3ℓ_Low	SR3ℓ_ISR
Total Observed events	2	1	20	12
Total Background events	1.1 ± 0.5	2.3 ± 0.5	10 ± 2	3.9 ± 1.0
Other	$0.03^{+0.07}_{-0.03}$	0.04 ± 0.02	$0.02^{+0.34}_{-0.02}$	$0.06^{+0.19}_{-0.06}$
Triboson	0.19 ± 0.07	0.32 ± 0.06	0.25 ± 0.03	0.08 ± 0.04
Fit output, VV	0.83 ± 0.39	1.9 ± 0.5	10 ± 2	3.8 ± 1.0
Fit input, VV	0.76	1.8	9.2	3.4

Signal Region	SR2ℓ_High	SR2ℓ_Int	SR2ℓ_Low	SR2ℓ_ISR
Total Observed events	0	1	19	11
Total Background events	1.9 ± 0.8	2.4 ± 0.9	8.4 ± 5.8	$2.7^{+2.8}_{-2.7}$
Other	0.02 ± 0.01	$0.05^{+0.12}_{-0.05}$	$0.02^{+1.07}_{-0.02}$	$0.06^{+0.33}_{-0.06}$
Fit output, $Wt + t\bar{t}$	0.00 ± 0.00	0.00 ± 0.00	0.57 ± 0.20	$0.28^{+0.34}_{-0.28}$
Fit output, VV	1.8 ± 0.7	2.4 ± 0.8	1.5 ± 0.9	2.3 ± 1.1
Z+jets	$0.07^{+0.78}_{-0.07}$	$0.00^{+0.74}_{-0.00}$	6.3 ± 5.8	$0.10^{+2.58}_{-0.10}$
Fit input, $Wt + t\bar{t}$	0.00	0.00	0.63	0.28
Fit input, VV	1.9	2.6	1.6	2.4

Results – 2lepton

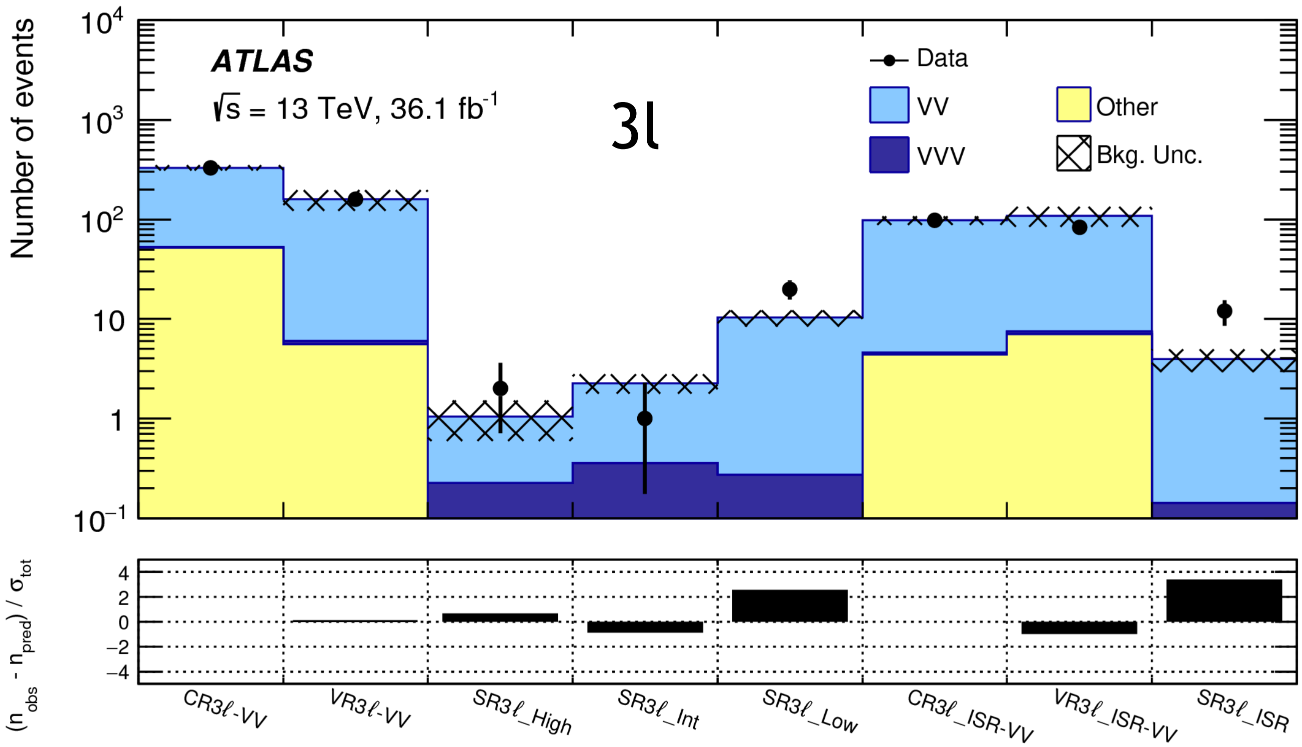
Signal region	SR2ℓ_High	SR2ℓ_Int	SR2ℓ_Low	SR2ℓ_ISR
Total observed events	0	1	19	11
Total background events	1.9 ± 0.8	2.4 ± 0.9	8.4 ± 5.8	$2.7^{+2.8}_{-2.7}$
Other	0.02 ± 0.01	$0.05^{+0.12}_{-0.05}$	$0.02^{+1.07}_{-0.02}$	$0.06^{+0.33}_{-0.06}$
Fit output, $Wt + t\bar{t}$	0.00 ± 0.00	0.00 ± 0.00	0.57 ± 0.20	$0.28^{+0.34}_{-0.28}$
Fit output, VV	1.8 ± 0.7	2.4 ± 0.8	1.5 ± 0.9	2.3 ± 1.1
Z+jets	$0.07^{+0.78}_{-0.07}$	$0.00^{+0.74}_{-0.00}$	6.3 ± 5.8	$0.10^{+2.58}_{-0.10}$
Fit input, $Wt + t\bar{t}$	0.00	0.00	0.63	0.28
Fit input, VV	1.9	2.6	1.6	2.4



arXiv:1806.02293

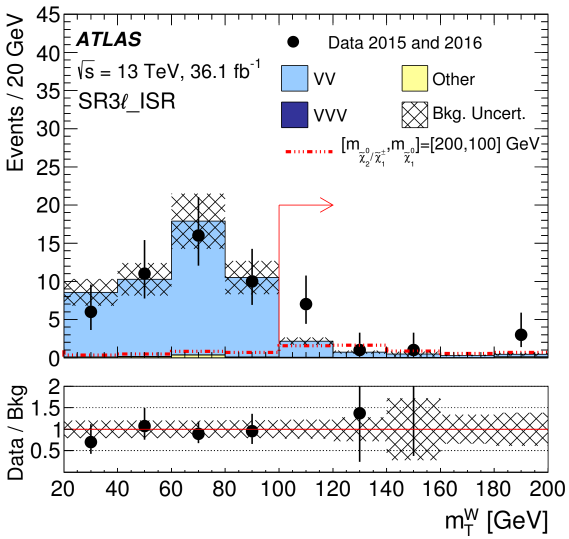
Results – 3lepton

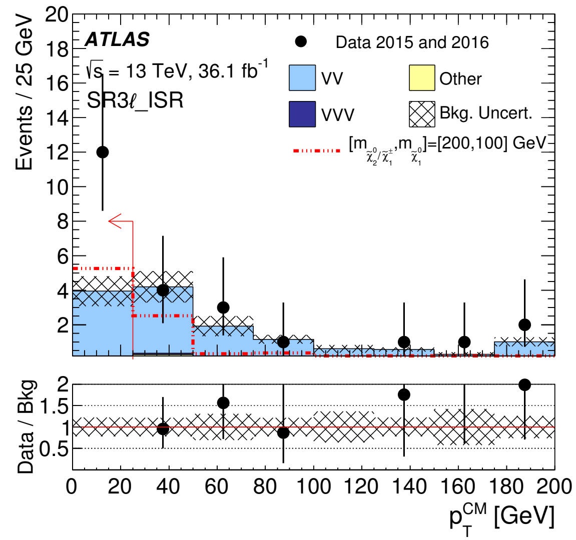
Signal region	SR3ℓ_High	SR3ℓ_Int	SR3ℓ_Low	SR3ℓ_ISR
Total observed events	2	1	20	12
Total background events	1.1 ± 0.5	2.3 ± 0.5	10 ± 2	3.9 ± 1.0
Other	$0.03^{+0.07}_{-0.03}$	0.04 ± 0.02	$0.02^{+0.34}_{-0.02}$	$0.06^{+0.19}_{-0.06}$
Triboson	0.19 ± 0.07	0.32 ± 0.06	0.25 ± 0.03	0.08 ± 0.04
Fit output, VV	0.83 ± 0.39	1.9 ± 0.5	10 ± 2	3.8 ± 1.0
Fit input, VV	0.76	1.8	9.2	3.4

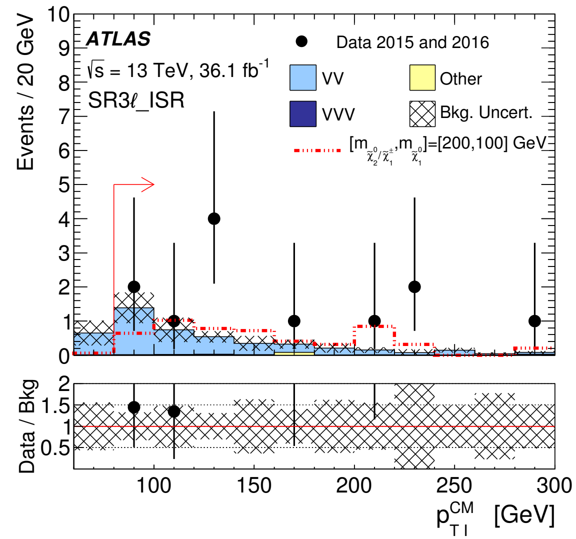


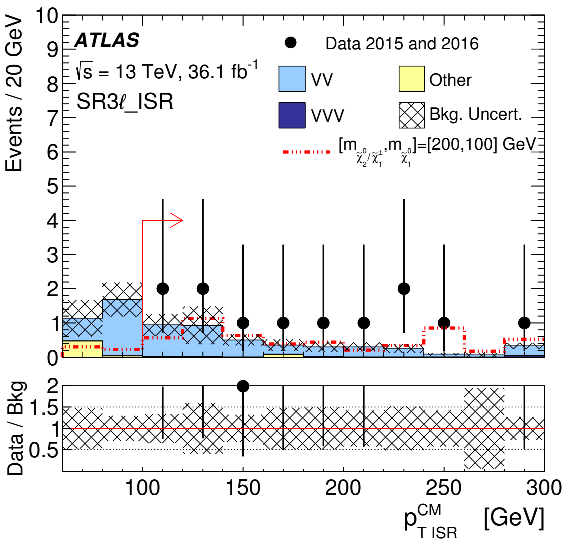
arXiv:1806.02293

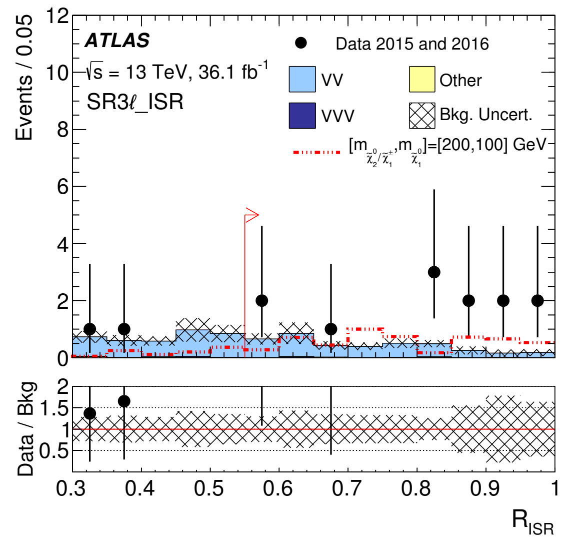
3lepton – ISR Signal Region





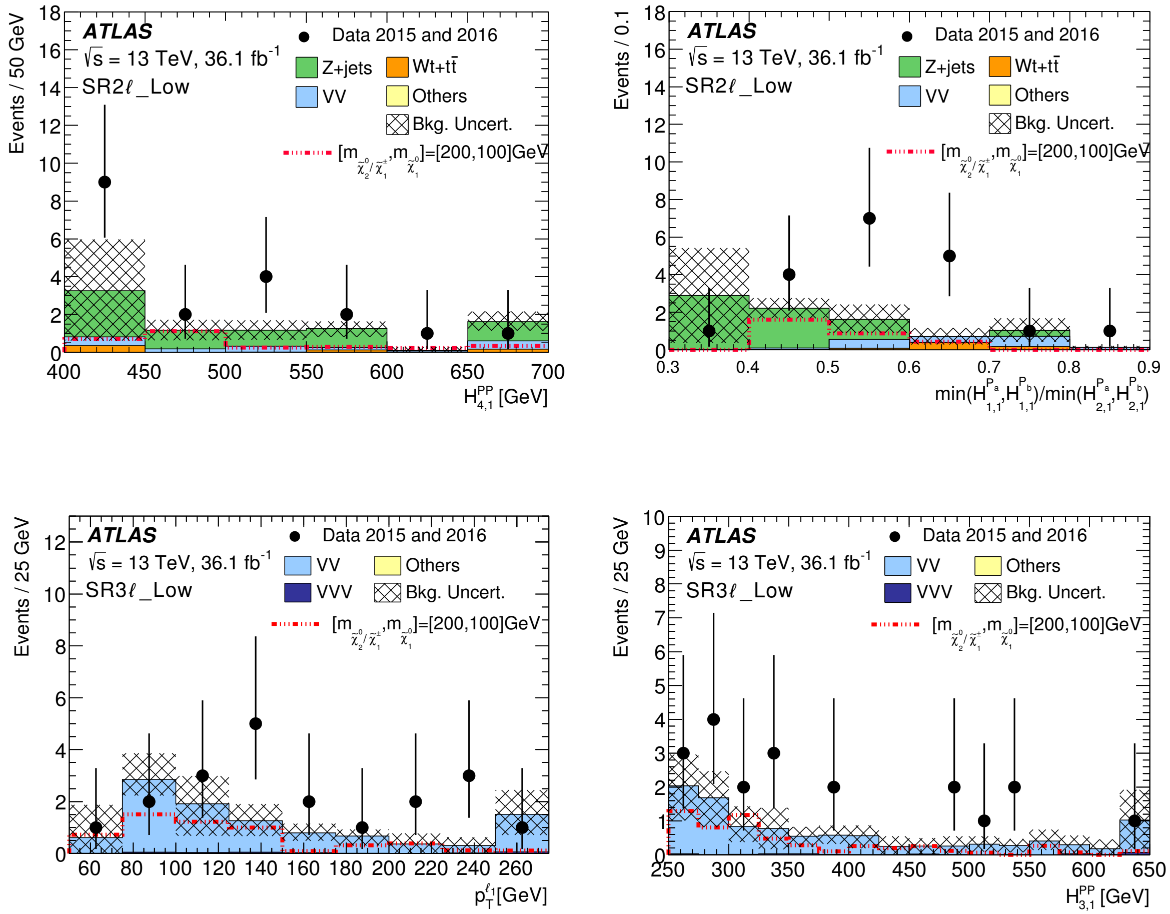






The shape of the excess events are similar to that predicted from the signal model used to optimize the search.

ATLAS EXPERIMENT



Similarly, there are excess events in data compared to our prediction in the Low mass SRs. The upper right distribution ***was not used*** in the event selection.

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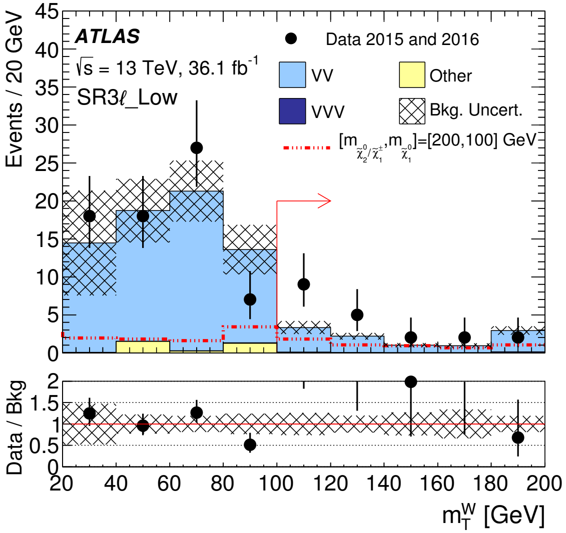
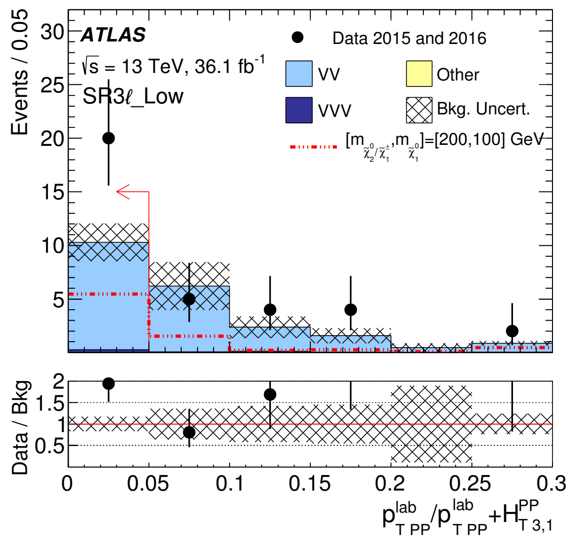
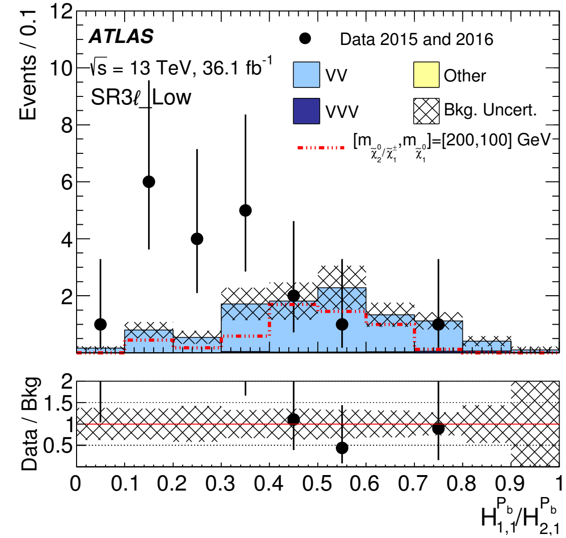
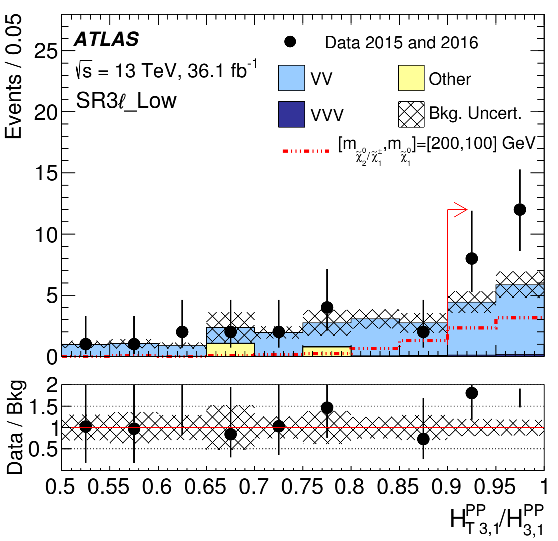
CoEPP ARC Centre of Excellence for Particle Physics at the Terascale

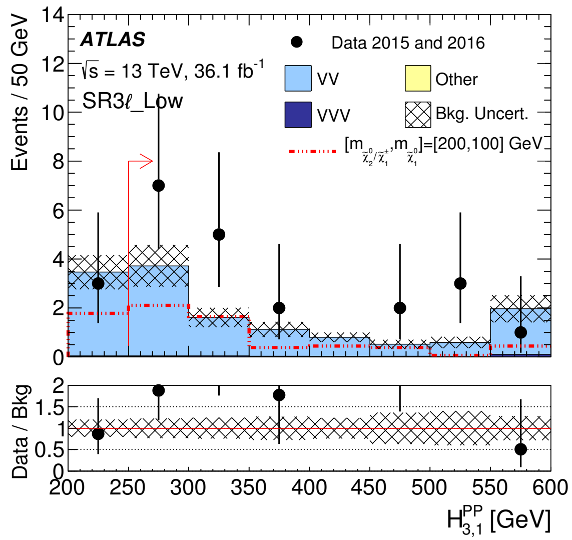
3lepton – Low Mass Signal Region









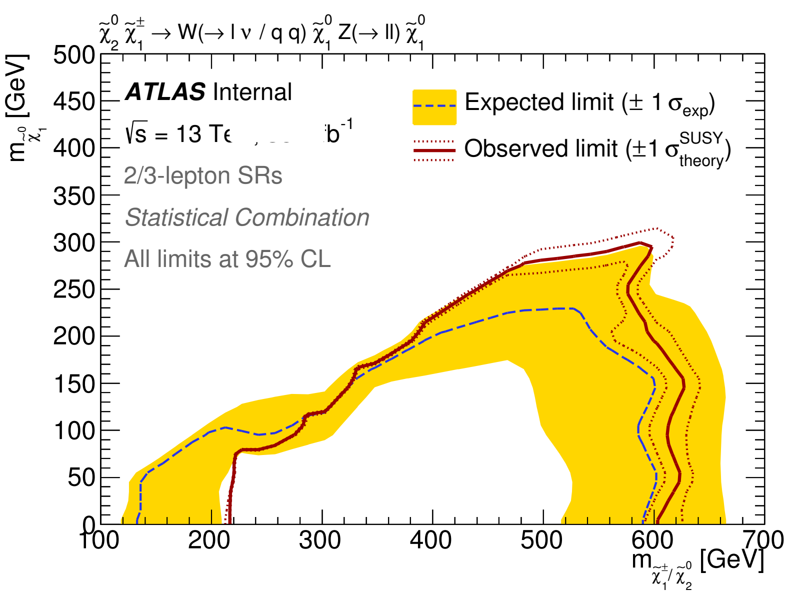


In this region, there are variables where the excess events clearly differ in shape from that predicted by the signal model.

ATLAS EXPERIMENT

Signal region	$\langle\epsilon\sigma\rangle^{95}_{\rm obs}$[fb]	$S^{95}_{\rm obs}$	$S^{95}_{\rm exp}$	p_0 (Z)
SR3ℓ_ISR	0.42	15.3	$6.9^{+3.1}_{-2.2}$	0.001 (3.02)
SR2ℓ_ISR	0.43	15.4	$9.7^{+3.6}_{-2.5}$	0.02 (1.99)
SR3ℓ_Low	0.53	19.1	$9.5^{+4.2}_{-1.8}$	0.016 (2.13)
SR2ℓ_Low	0.66	23.7	$16.1^{+6.3}_{-4.3}$	0.08 (1.39)
SR3ℓ_Int	0.09	3.3	$4.4^{+2.5}_{-1.5}$	0.50 (0.00)
SR2ℓ_Int	0.09	3.3	$4.6^{+2.6}_{-1.5}$	0.50 (0.00)
SR3ℓ_High	0.14	5.0	$3.9^{+2.2}_{-1.3}$	0.23 (0.73)
SR2ℓ_High	0.09	3.2	$4.0^{+2.3}_{-1.2}$	0.50 (0.00)

To remain as conservative as possible, and to avoid model dependent statements, *we do not combine the significances*



arXiv:1806.02293

Excesses of 3.0σ, 2.0σ, 2.1σ and 1.4σ in the four regions targeting moderately compressed EWK SUSY.

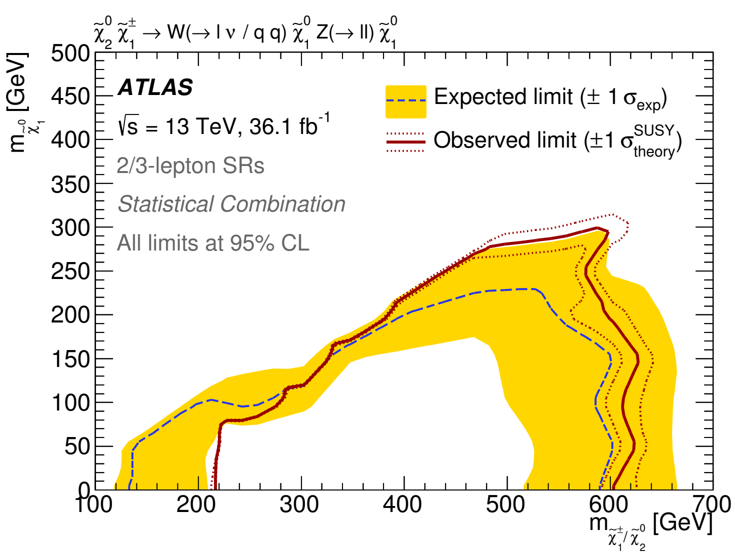
This is **the largest excess** seen in an ATLAS search for Supersymmetry

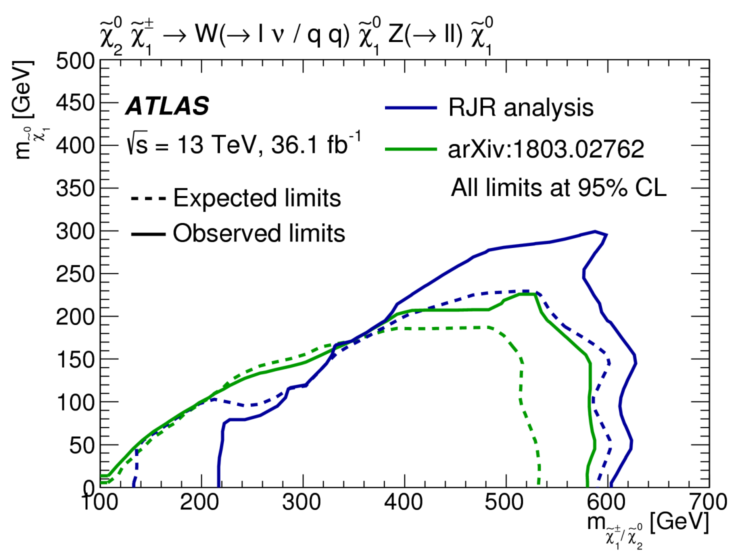
Statistical interpretation

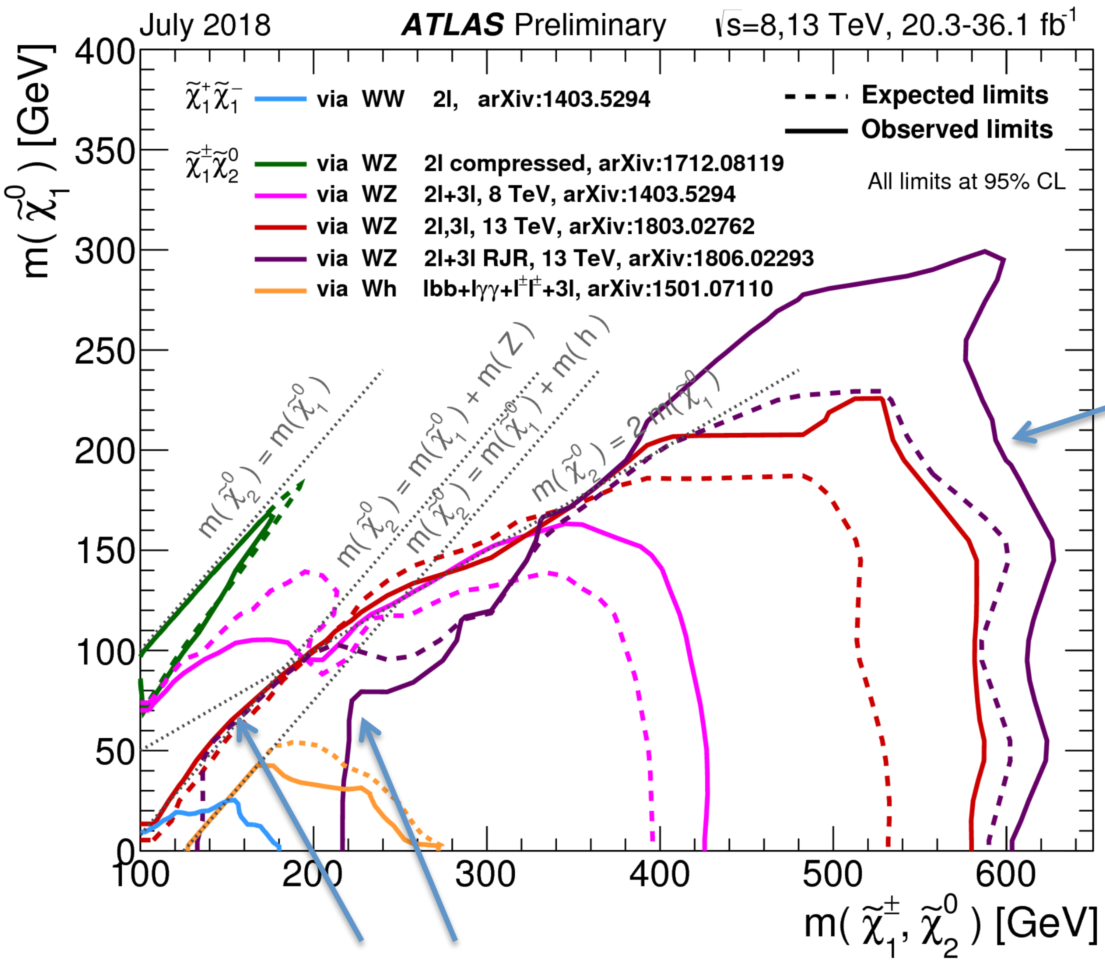
Signal region	SR2ℓ_Low	SR2ℓ_ISR
ee	9 (4.5±3.9)	3 (1.2±1.2)
$\mu\mu$	10 (3.9±2.6)	8 (1.5±1.5)
Signal region	**SR3ℓ_Low**	**SR3ℓ_ISR**
eee	6 (3.5±0.7)	3 (1.1±0.3)
$ee\mu$	6 (2.0±0.4)	3 (0.9±0.3)
$\mu\mu\mu$	7 (2.7±0.6)	4 (1.5±0.4)
$\mu\mu e$	1 (1.9±0.4)	2 (0.4±0.1)

The four signal regions with excesses were studied in terms of their flavour composition – looks as expected.
MANY other cross-checks performed.

Improved limits at high mass compared to previous analysis…...with weaker limits at low mass due to excesses observed.



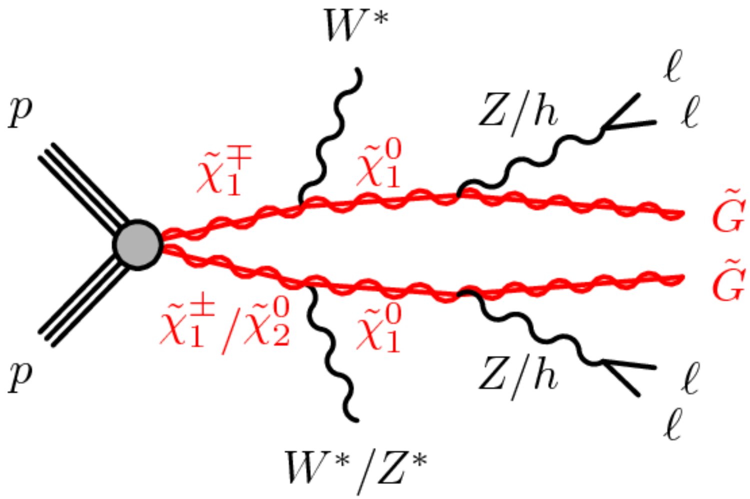


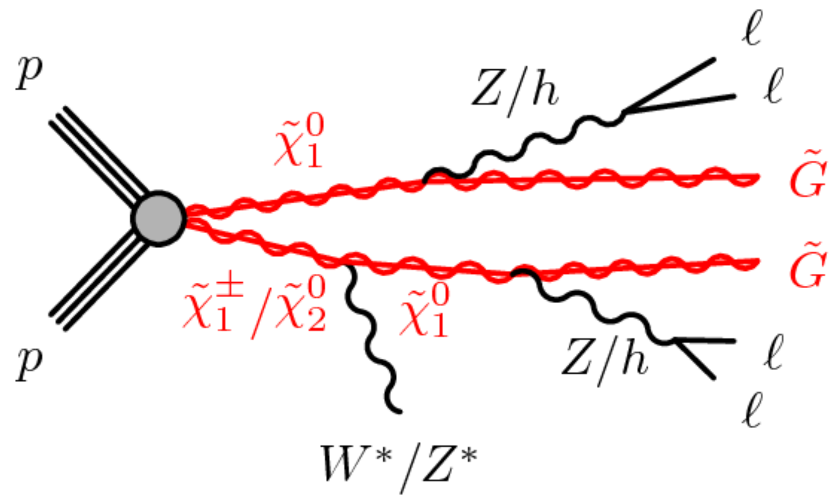


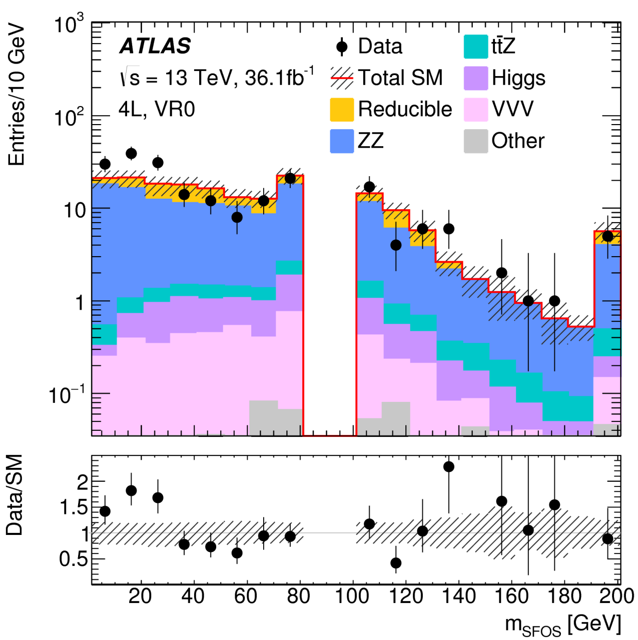
Analysis with the best reach in Electroweak searches with intermediate W/Z bosons.

Largest excess (≥ 3σ) in any SUSY search!

ATLAS – 4 lepton







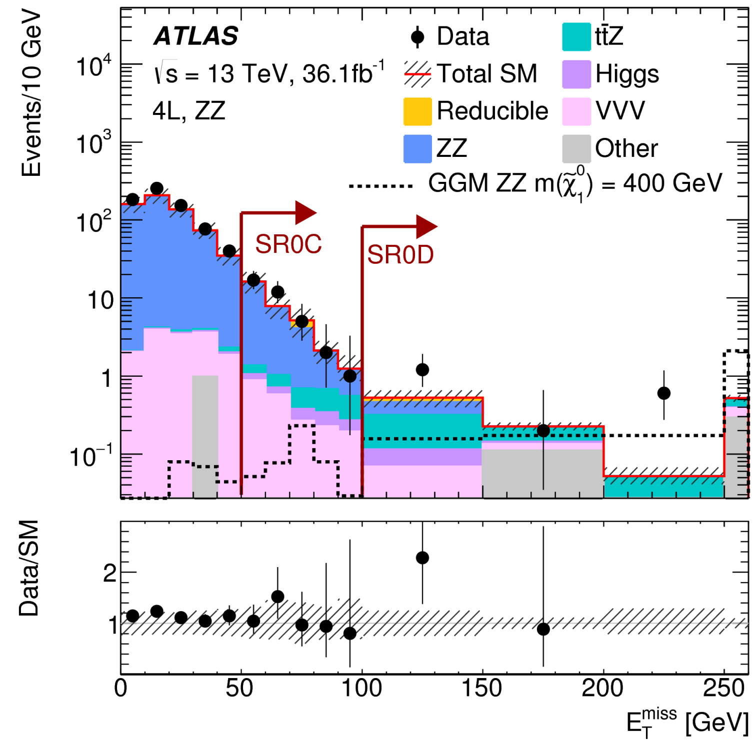
Hints in some EWK SUSY channels would suggest we should see excesses in similar phase space.

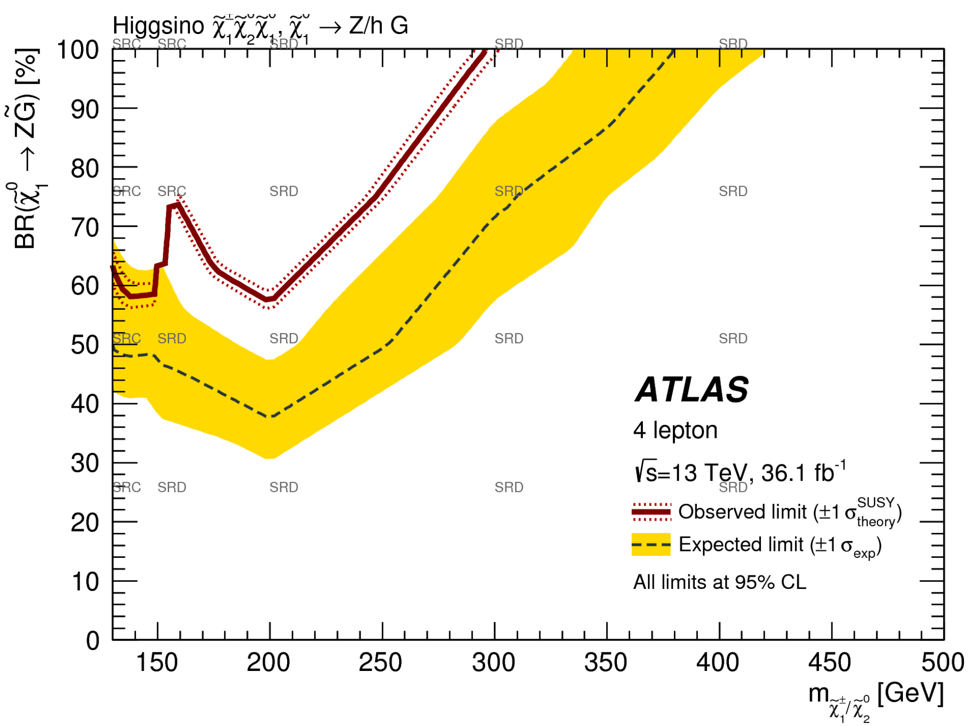
Region	$N(e,\mu)$	$N(\tau_{\text{had-vis}})$	$p_T\,(\tau_{\text{had-vis}})$	Z boson	Selection	Target
SR0A	≥ 4	$= 0$	> 20 GeV	veto	$m_{\text{eff}} > 600$ GeV	General
SR0B	≥ 4	$= 0$	> 20 GeV	veto	$m_{\text{eff}} > 1100$ GeV	RPV $LL\bar{E}12k$
SR0C	≥ 4	$= 0$	> 20 GeV	require 1st & 2nd	$E_T^{\text{miss}} > 50$ GeV	higgsino GGM
SR0D	≥ 4	$= 0$	> 20 GeV	require 1st & 2nd	$E_T^{\text{miss}} > 100$ GeV	higgsino GGM
SR1	$= 3$	≥ 1	> 30 GeV	veto	$m_{\text{eff}} > 700$ GeV	RPV $LL\bar{E}i33$
SR2	$= 2$	≥ 2	> 30 GeV	veto	$m_{\text{eff}} > 650$ GeV	RPV $LL\bar{E}i33$

arXiv:1804.03602, Phys. Rev. D 98, 032009 (2018)

New Physics interpretation

Sample	SR0A	SR0B	SR0C	SR0D	SR1	SR2
Observed	13	2	47	10	8	2
SM Total	10.2 ± 2.1	1.31 ± 0.24	37 ± 9	4.1 ± 0.7	4.9 ± 1.6	2.3 ± 0.8
ZZ	2.7 ± 0.7	0.33 ± 0.10	28 ± 9	0.84 ± 0.34	0.35 ± 0.09	0.33 ± 0.08
$t\bar{t}Z$	2.5 ± 0.6	0.47 ± 0.13	3.2 ± 0.4	1.62 ± 0.23	0.54 ± 0.11	0.31 ± 0.08
Higgs	1.2 ± 1.2	0.13 ± 0.13	0.9 ± 0.8	0.28 ± 0.25	0.5 ± 0.5	0.32 ± 0.32
VVV	0.79 ± 0.17	0.22 ± 0.05	2.7 ± 0.6	0.64 ± 0.14	0.18 ± 0.04	0.20 ± 0.06
Reducible	2.4 ± 1.4	$0.000^{+0.005}_{-0.000}$	$0.9^{+1.4}_{-0.9}$	$0.23^{+0.38}_{-0.23}$	3.1 ± 1.5	1.1 ± 0.7
Other	0.53 ± 0.06	0.165 ± 0.018	0.85 ± 0.19	0.45 ± 0.10	0.181 ± 0.022	0.055 ± 0.012
$\langle\epsilon\sigma\rangle^{95}_{obs}$ fb	0.32	0.14	0.87	0.36	0.28	0.13
S^{95}_{obs}	12	4.9	31	13	10	4.6
S^{95}_{exp}	$9.3^{+3.6}_{-2.3}$	$3.9^{+1.6}_{-0.8}$	23^{+8}_{-5}	$6.1^{+2.1}_{-1.3}$	$6.5^{+3.5}_{-1.3}$	$4.7^{+2.0}_{-1.3}$
CL_b	0.76	0.74	0.83	0.99	0.86	0.47
$p_{s=0}$	0.23	0.25	0.15	0.011	0.13	0.61
Z	0.75	0.69	1.0	2.3	1.2	0



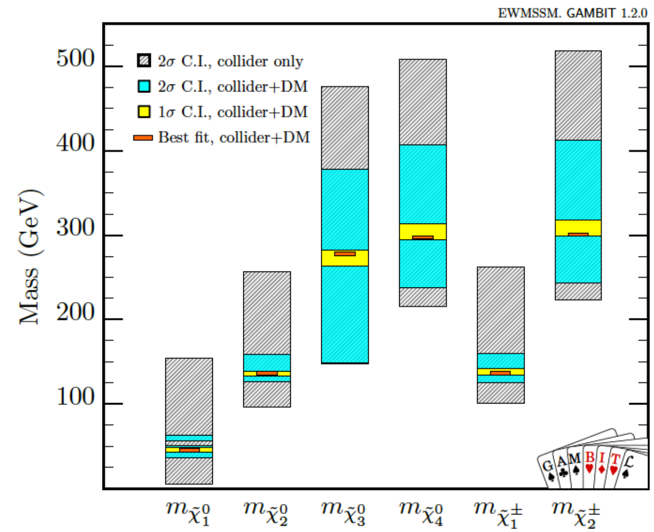


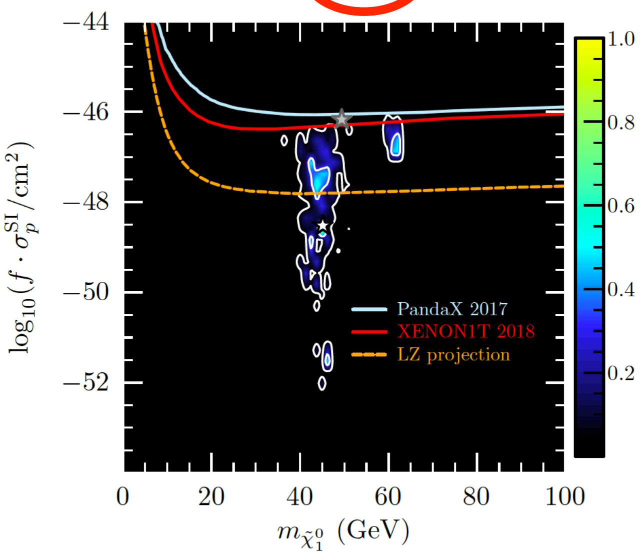
2.3σ deviation from SM in 4lepton EWKino search in region sensitive to ≈200GeV

Still to be updated with 4x more data!

GAMBIT collaboration performed a global electroweak fit using available collider and direct DM constraints

	Best expected SRs				All SRs; neglect correlations			
Analysis	Local signif. (σ)	SM fit (σ)	EWMSSM fit (σ)	#SRs	Local signif. (σ)	SM fit (σ)	EWMSSM fit (σ)	#SRs
Higgs invisible width	0.9	0.3	0.2	1	0.9	0.3	0.2	1
Z invisible width	0	1.3	1.3	1	0	1.3	1.3	1
ATLAS_4b	0.7	0	0	1	2.1	0	0	2*
ATLAS_4lep	2.3	2.0	0	1	2.5	1.0	0	4
ATLAS_MultiLep_2lep_0jet	0.9	0.3	0.1	1	1.3	0	0	6
ATLAS_MultiLep_2lep_jet	0	0	0.5	1	0.8	0.5	0.3	3
ATLAS_MultiLep_3lep	1.8	1.6	0.6	1	1.2	0.4	0.3	11
ATLAS_RJ_2lep_2jet	0	0.3	0.5	1	1.5	1.8	1.5	4
ATLAS_RJ_3lep	2.8	2.4	1.0	1	3.5	2.6	0.5	4
CMS_1lep_2b	0.9	0.3	0.3	1	0	0	0	2
CMS_2lep_soft	0.4	0.2	0.2	12	0.4	0.2	0.2	12
CMS_2OSlep	0	0.4	0.6	7	0	0.4	0.6	7
CMS_MultiLep_2SSlep	0.2	0	0	1	0.2	0	0	2
CMS_MultiLep_3lep	0	0	0.5	1	0	0	0	6
Combined	3.5	1.5	0.3	31	4.2	1.3	0	65

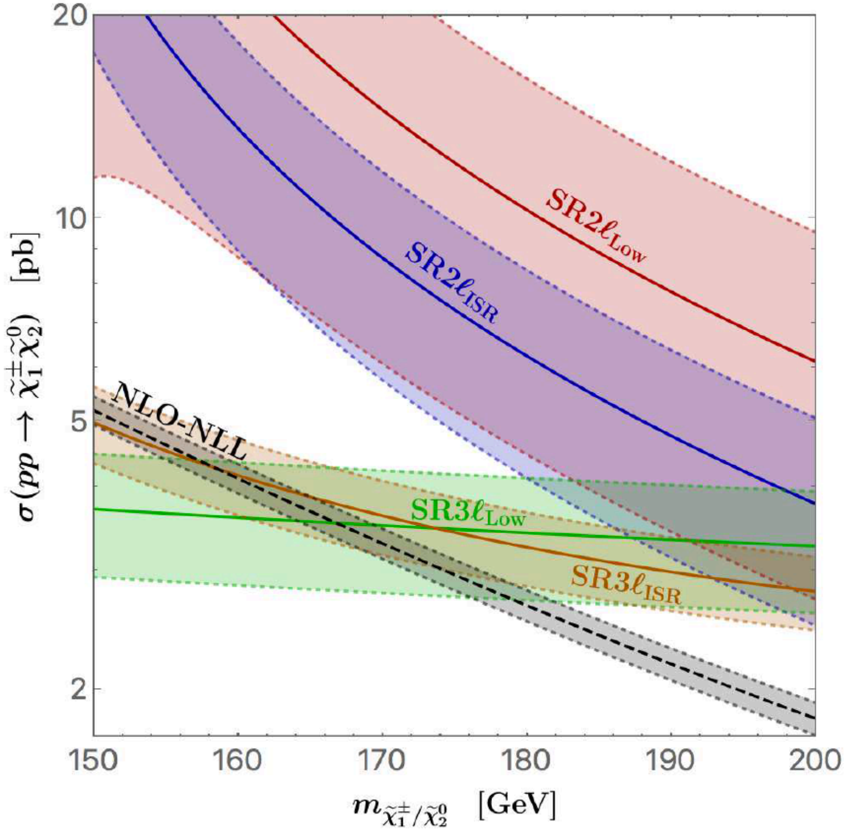




Our best-fit point has neutralino masses of $(m_{\tilde\chi_1^0}, m_{\tilde\chi_2^0}, m_{\tilde\chi_3^0}, m_{\tilde\chi_4^0}) \approx (49.4, 141.6, 270.3, 290.2)$ GeV, and chargino masses of $(m_{\tilde\chi_1^\pm}, m_{\tilde\chi_2^\pm}) \approx (142.1, 293.9)$ GeV. We find a local significance of 3.5σ for this excess. If there is indeed a supersymmetric signal resembling these properties the ATLAS and CMS experiments should be sensitive to it using the full LHC Run 2 dataset.

* GAMBIT: The Global and Modular Beyond-the-Standard-Model Inference Tool, Eur. Phys. J. C 77 (2017) 784, [arXiv:1705.07908].

Carena et al, arXiv:1809:11082



Reproduced ATLAS excesses, they show consistency with muon g-2 and DM direct detection results.

The benchmark parameter point found is very similar to the GAMBIT result.

Summary

- **The search for new physics at the LHC continues, but:**
  - There are a few ≈3σ excesses in the data.
  - With the invention of powerful new methods we're seeing that analyses can be designed to be sensitive to events that were previous inaccessible - exciting for future searches.
  - Results from recent GAMBIT work, and other interesting pheno studies, show hints of tension between LHC results and SM prediction, may agree with flavour anomalies.
  - 150 fb^{-1} of Run2 promises a bounty of new results!!!

CHEP 2019 – Computing in High-Energy and Nuclear Physics Conference

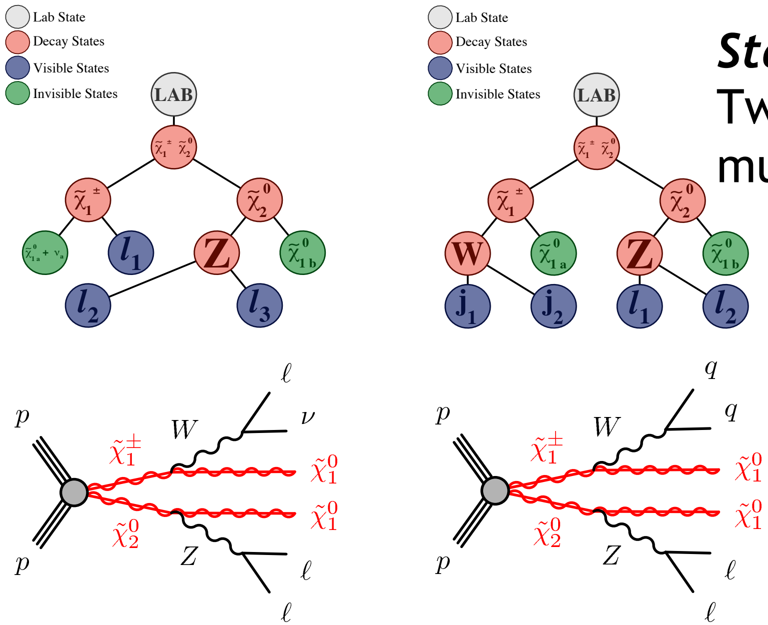
4-8 November, 2019
Adelaide, Australia

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

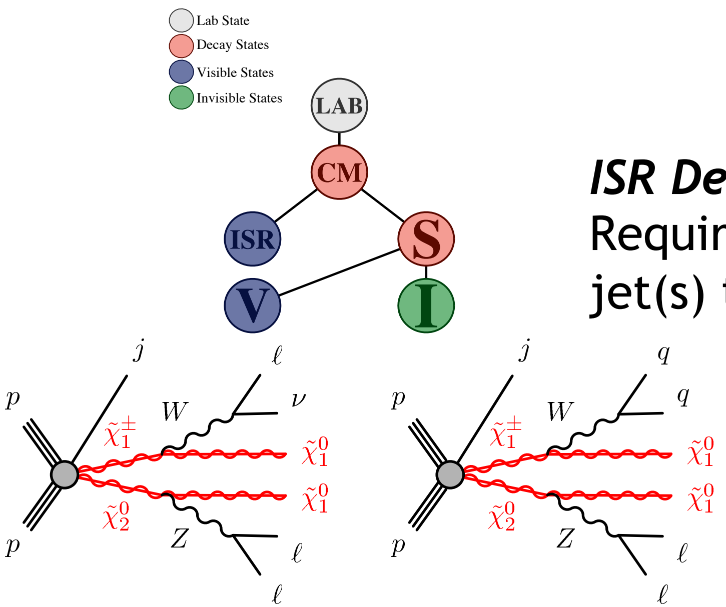
Thanks! Some backup slides may follow

p.jackson@adelaide.edu.au



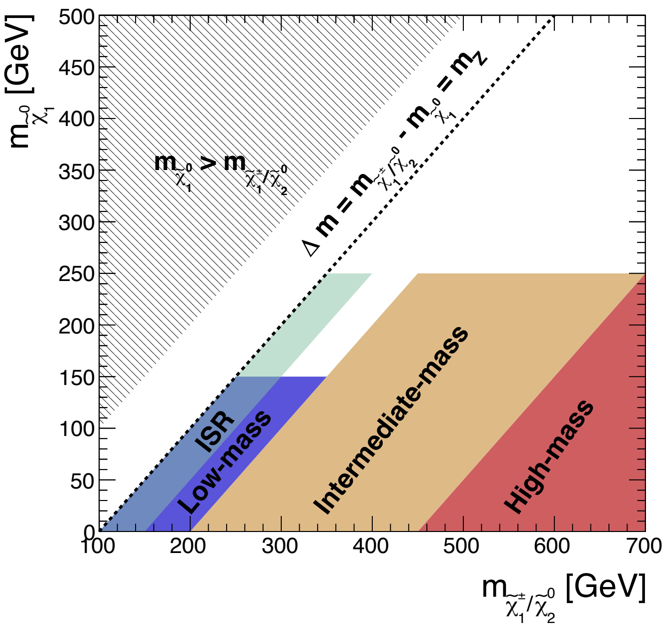
Standard Decay Tree

Two sets of SRs based on lepton multiplicity. High / Intermediate / Low



ISR Decay Tree

Requires a system of jet(s) to boost the signal



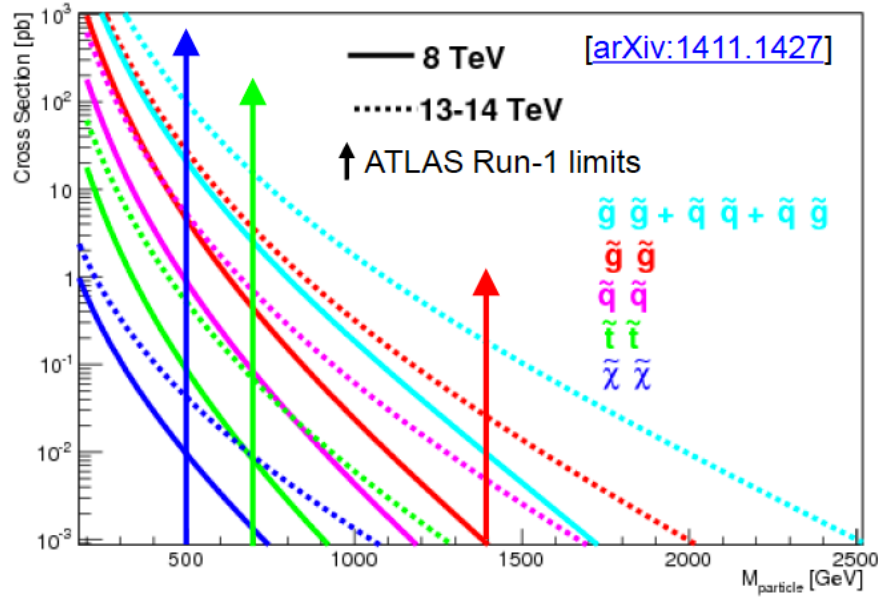
ISR and Low mass are designed to be orthogonal

HOWTO search for SUSY

- If SUSY particles exist at LHC accessible energies:
  ① **R-parity conservation**
    - Pair-production via strong / EW interaction
    - Direct or cascade decays to the stable lightest SUSY particle (LSP).
    - Many high p_T SM decay products + large $E_{T,miss}$ (depending on the mass spectrum)

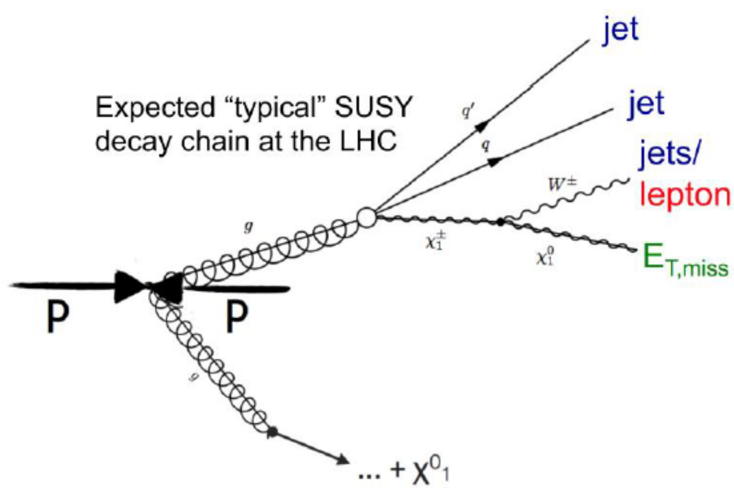
  ② **R-parity violation**
    - Multi-jets / multi-leptons signatures from LSP decay to SM particles
    - Displaced vertices from late LSP decays

  ③ **Long-lived particles**
    - Sparticles produced with long lifetimes due to mass degeneracy, small couplings, virtuality
    - Secondary decay vertex



- Search strategy @ 13 TeV:
  → Early data: **Gluino & 1st/2nd generation squark** searches have the largest potential due to enhanced cross-sections

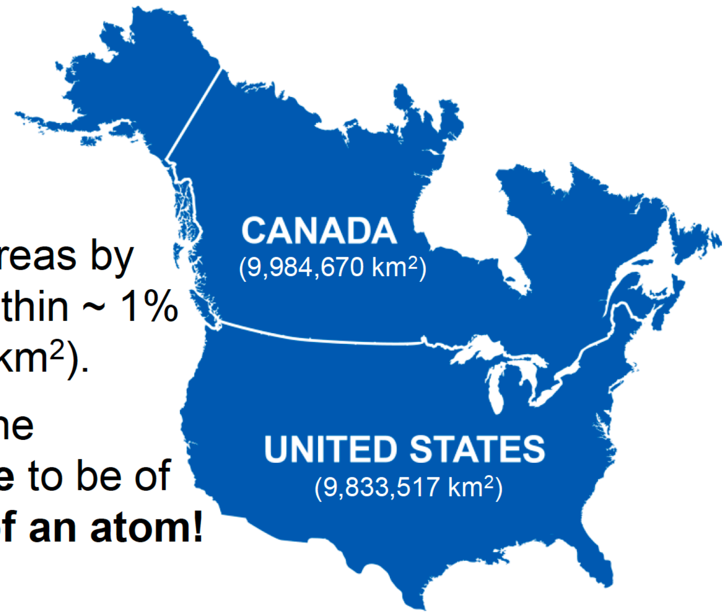
  → Beyond ~10 fb^{-1}: Searches for **3rd generation squarks** and **EW production** start to exceed Run-1 sensitivity



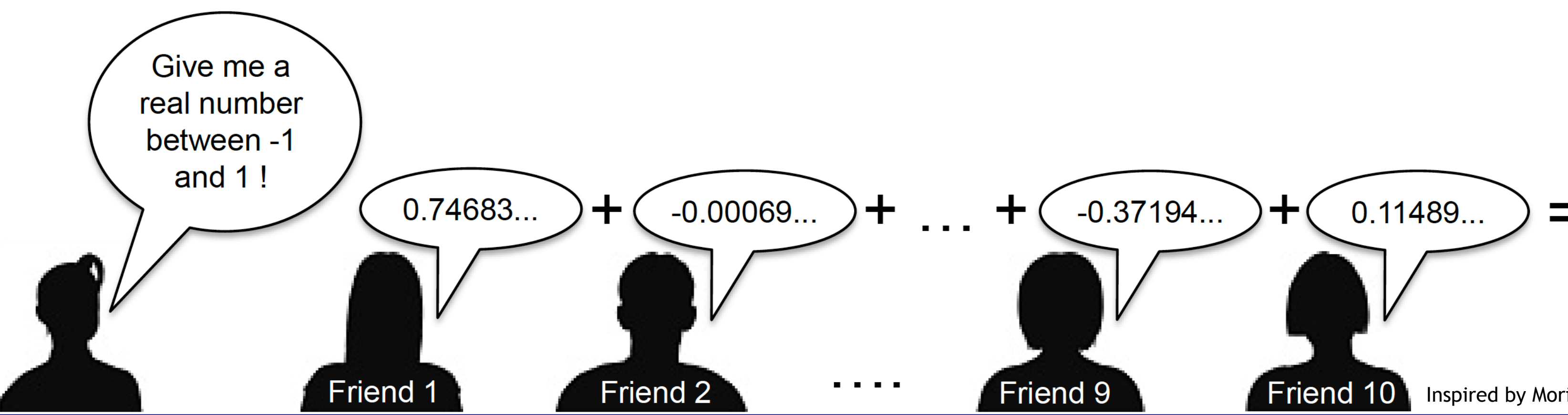
SM has a snowman's chance in hell

Surface areas by chance within ~ 1% (151,153 km²).

Imagine the **difference** to be of the **size of an atom!**



Analogies only for illustration. No liability for quantitative interpretation.



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Inspired by Moritz Backes [source: link]

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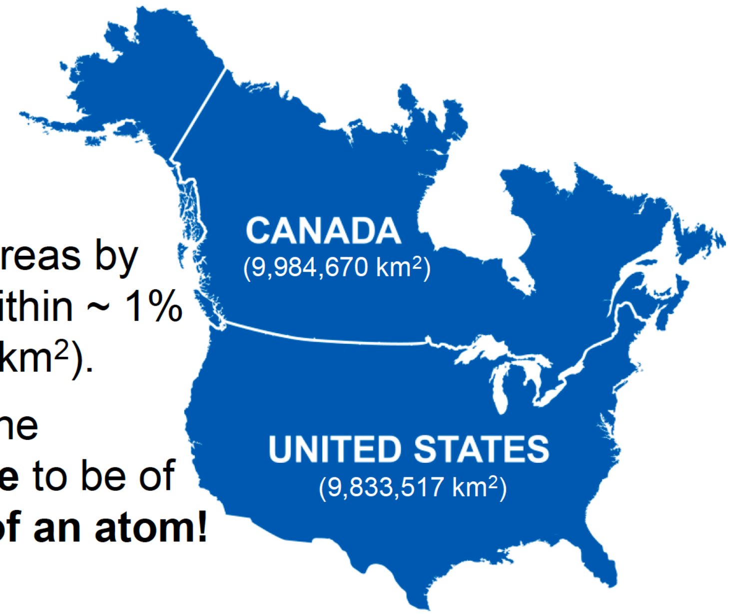
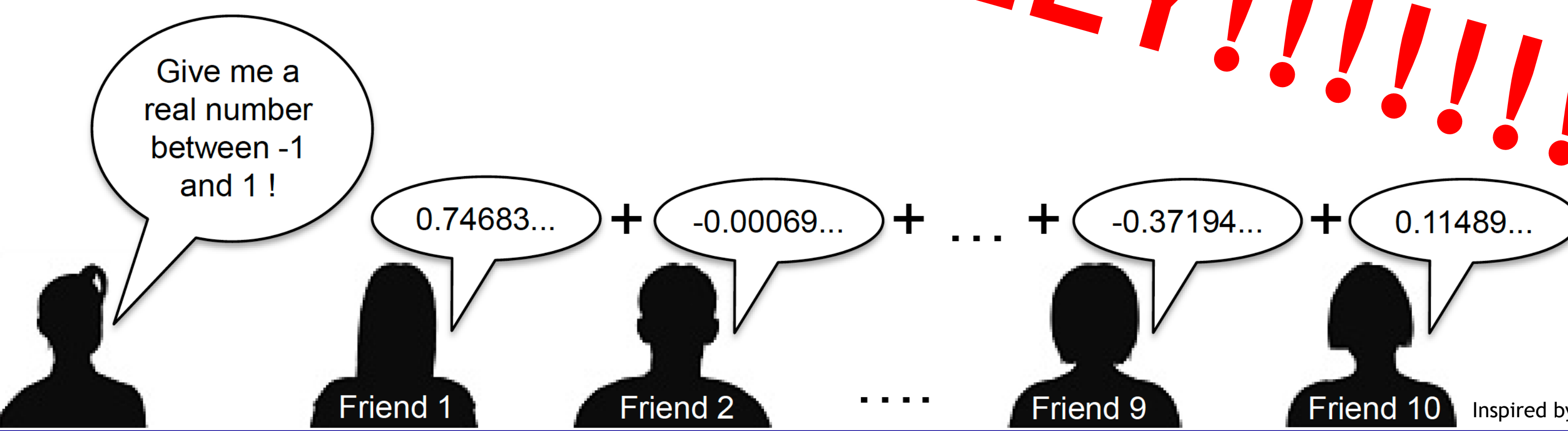
Surface areas by chance within ~ 1% (151,153 km²).

Imagine the **difference** to be of the **size of an atom!**



UNLIKELY!!!!!!!

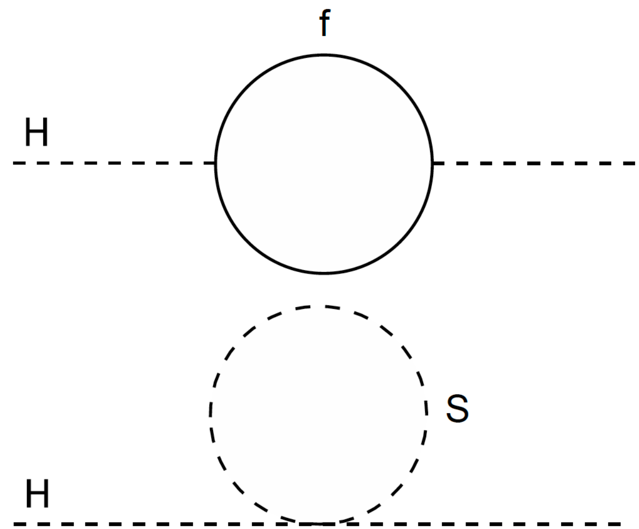


0.74683... + -0.00069... + ... + -0.37194... + 0.11489... = 0.000000000 00000000000 00000000000 0001

Inspired by Moritz Backes [source: link]

Analogies only for illustration. No liability for quantitative interpretation.

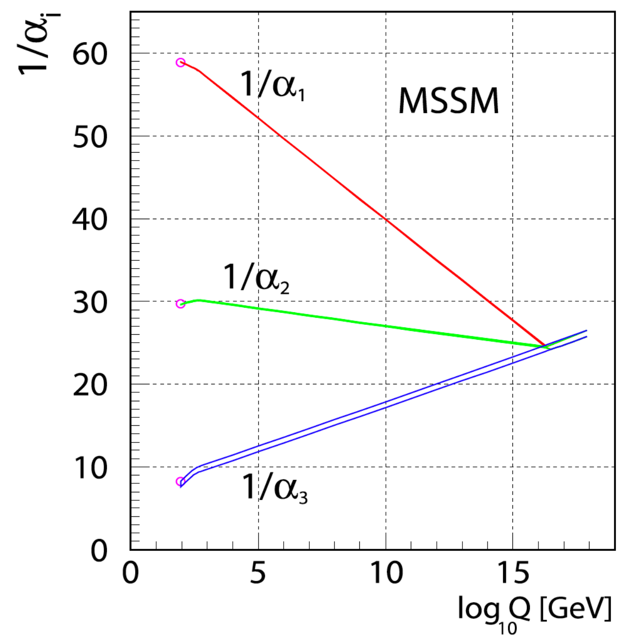
- Fundamental symmetry between fermions and bosons introducing a set of new partner particles to the SM particles with half-spin difference.



✓ Opposite-sign loop corrections from SUSY particles. Quadratic divergencies cancel. → No (little) fine-tuning.

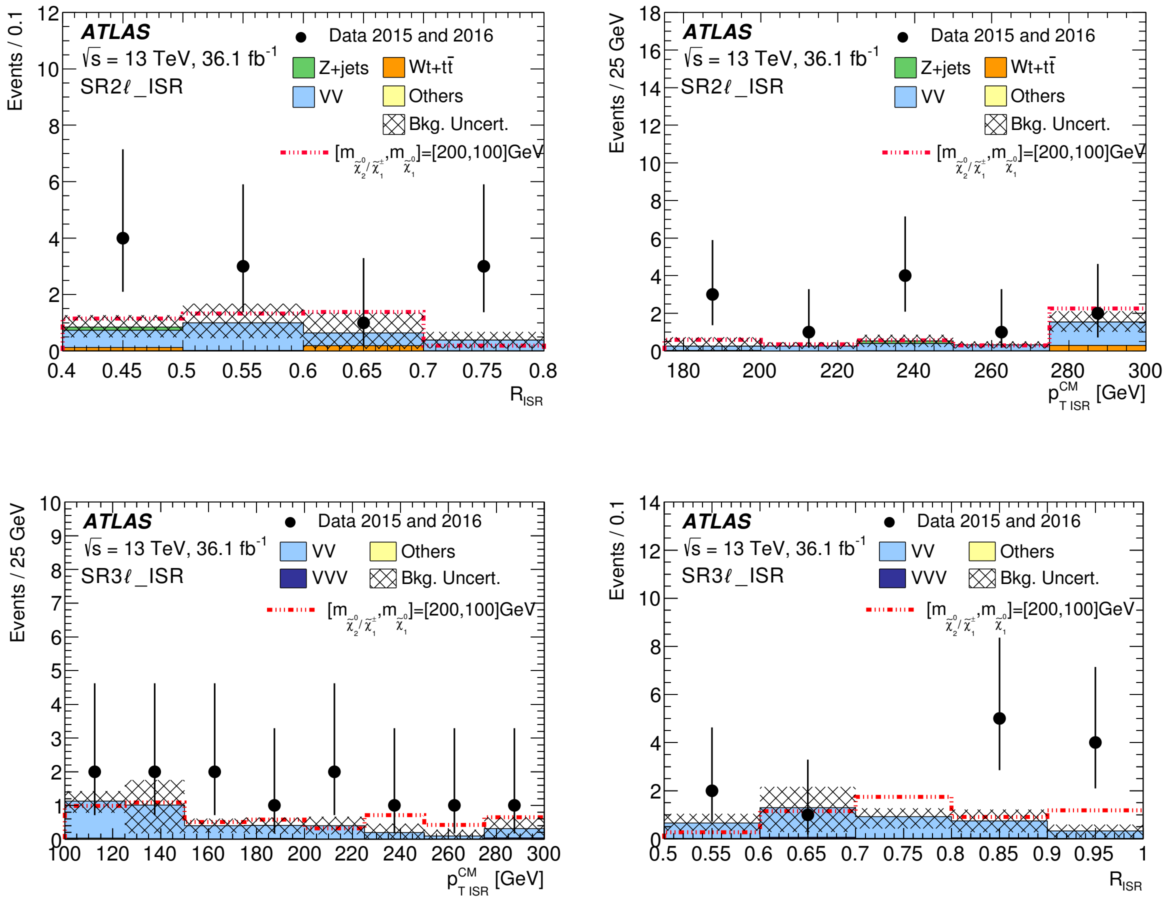
✓ If R-parity conserved: Lightest SUSY Particle (LSP) stable. → Natural candidate for dark matter.

R-parity = $(-1)^{3(B-L)+2s}$
- SM particles: +1
- SUSY particles: -1

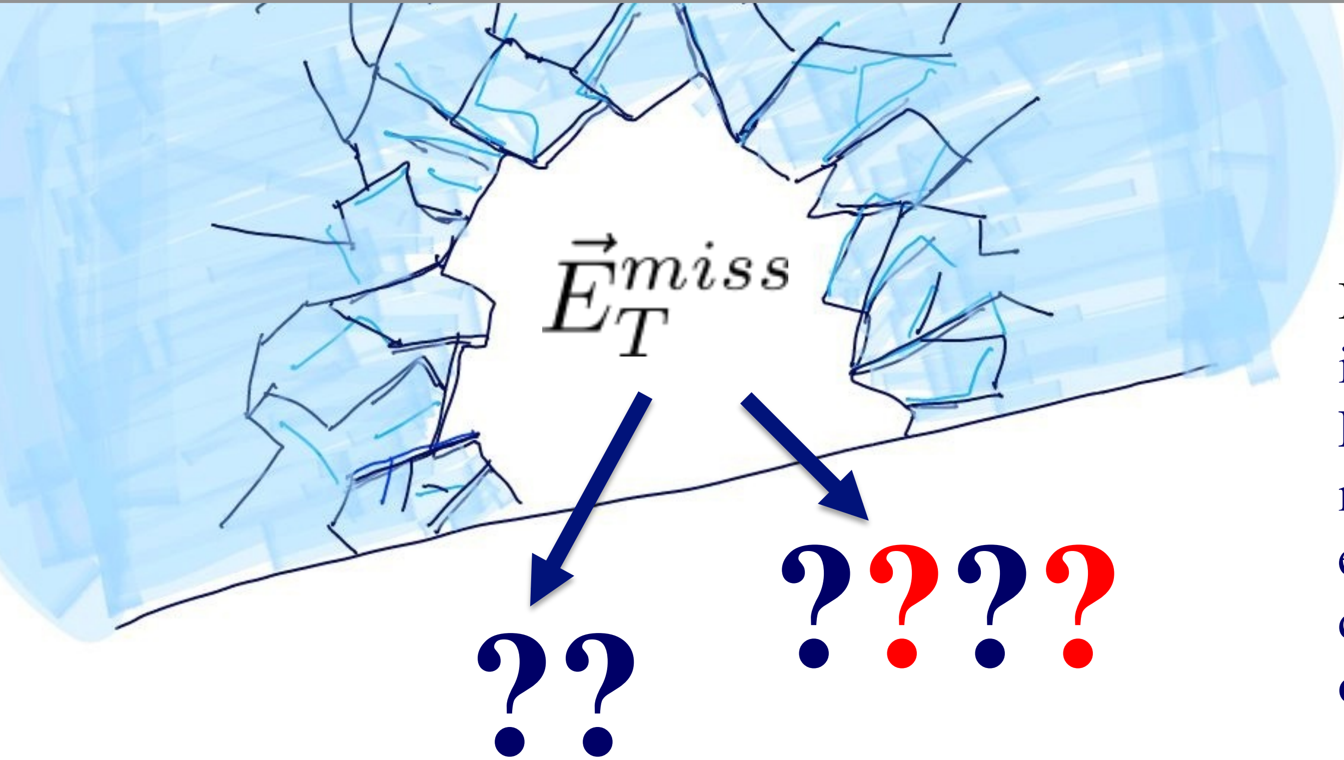


✓ Unification of gauge couplings at $M_{GUT} \approx 10^{16}$ GeV

Results – ISR Signal Regions



We see different yields in data compared to our prediction in the ISR SRs, most prominently in the 3 lepton region (lower plots).

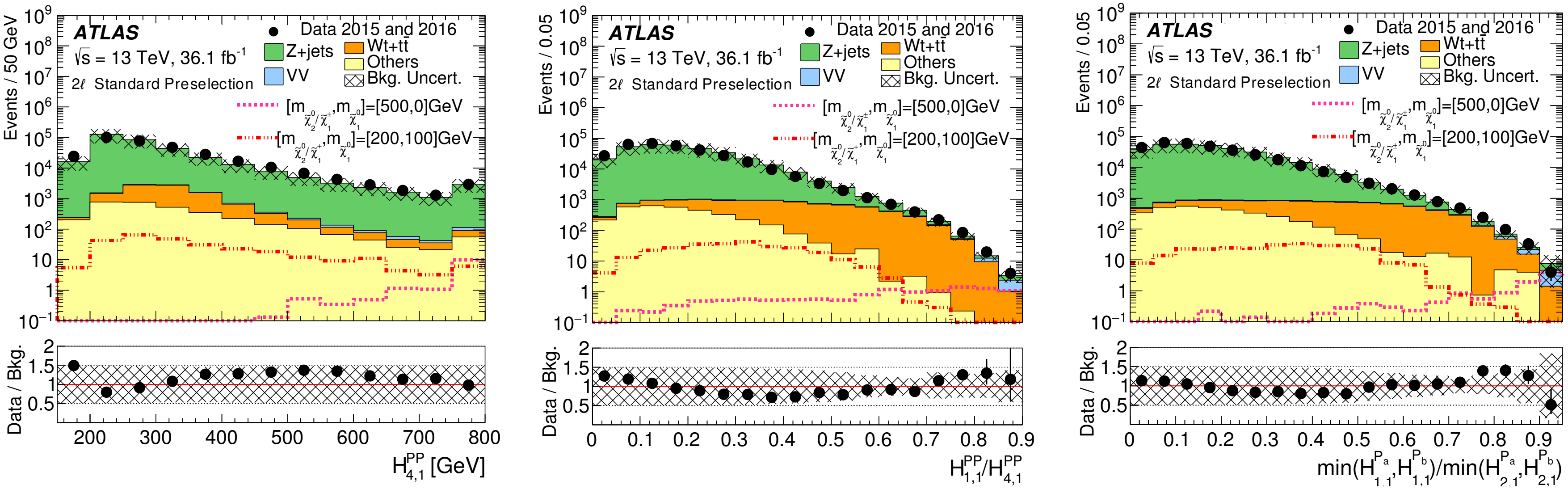


$$\vec{E}_T^{miss} \equiv -\sum_{i}^{\text{calo}} \vec{E}_T^{\,i}$$

Infer presence of weakly interacting particles in LHC events by looking for missing transverse energy…..may be composed of one or more objects, which may differ

We can learn more by using other information in an event to contextualize the missing transverse momentum ⇒
multiple weakly interacting particles?

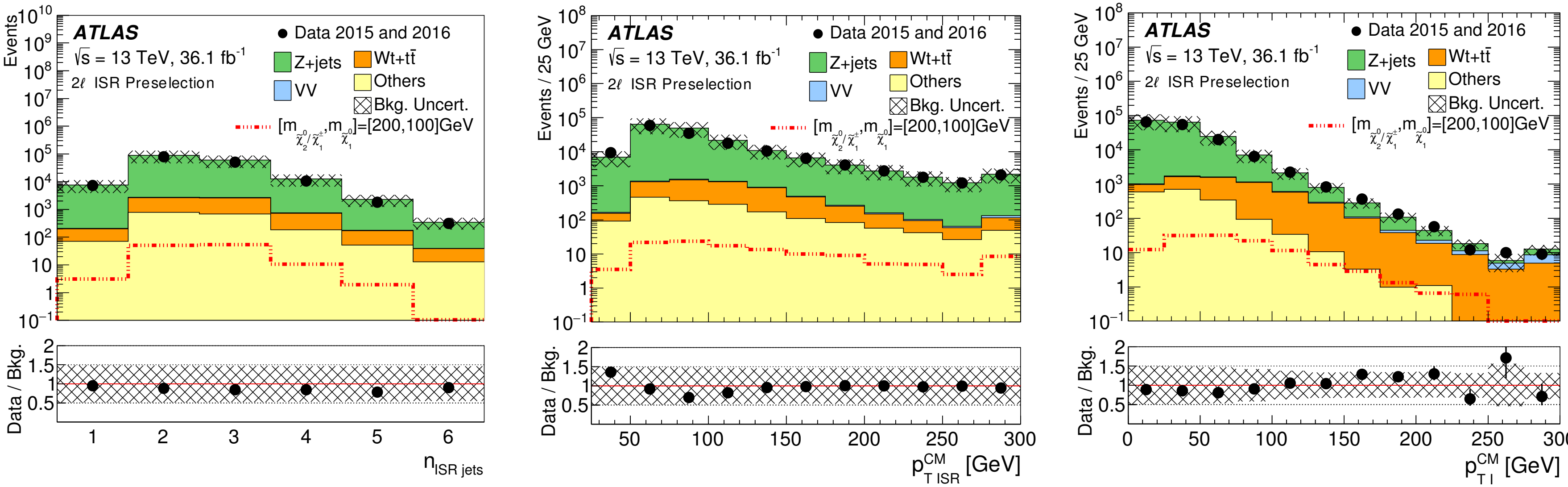
Preselection for the 2lepton Standard tree



The different shapes of these variables in the signal models as compared to the major backgrounds can be used in a more targeted way.

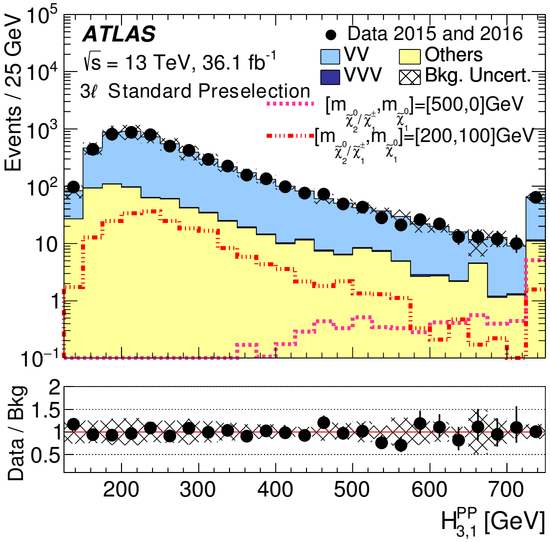
The interplay between the variables is also key – if we require one ratio to be large (for instance) it may make it **increasingly hard** for a complementary variable to have background events looking like signal events

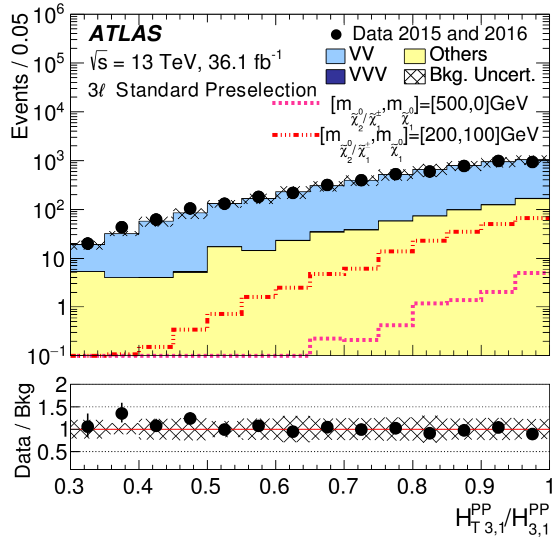
Preselection for the 2lepton ISR tree

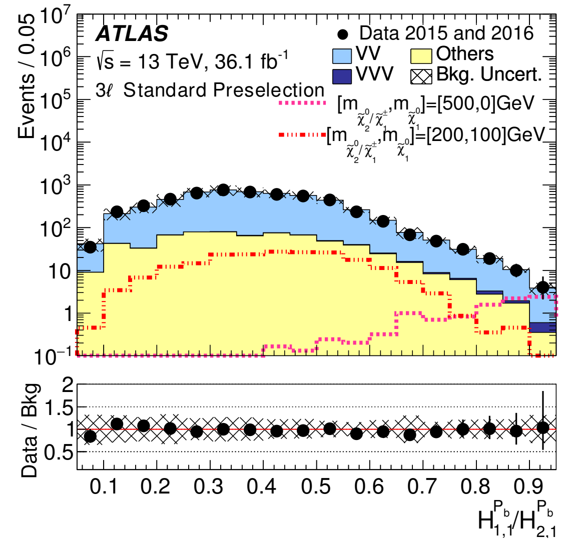


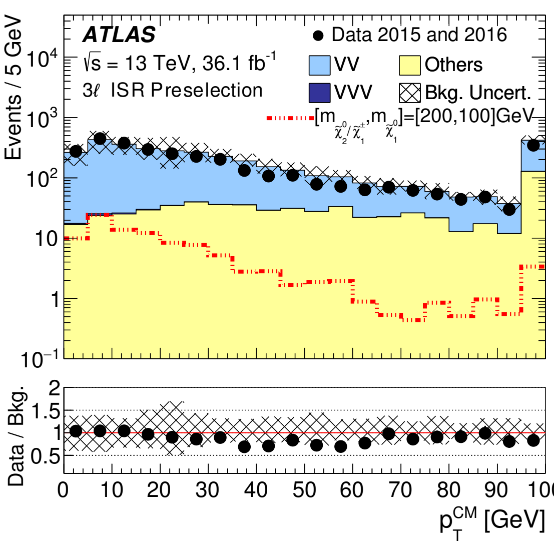
Similarly, where we require initial-state radiation, we need complementary variables to tease out sensitivity to a signal

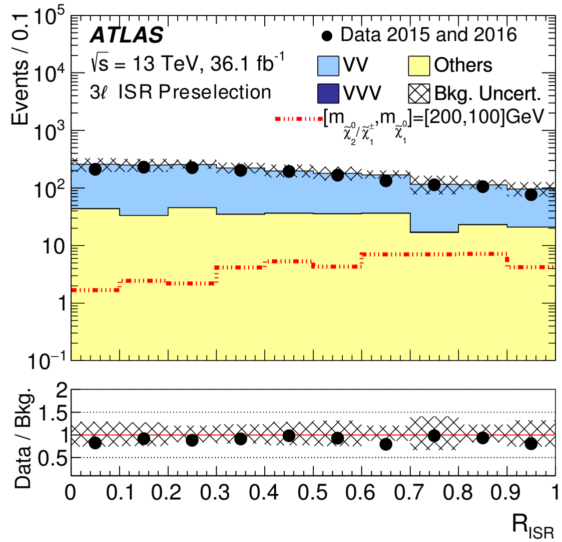
Preselection for the 3lepton Standard and ISR trees



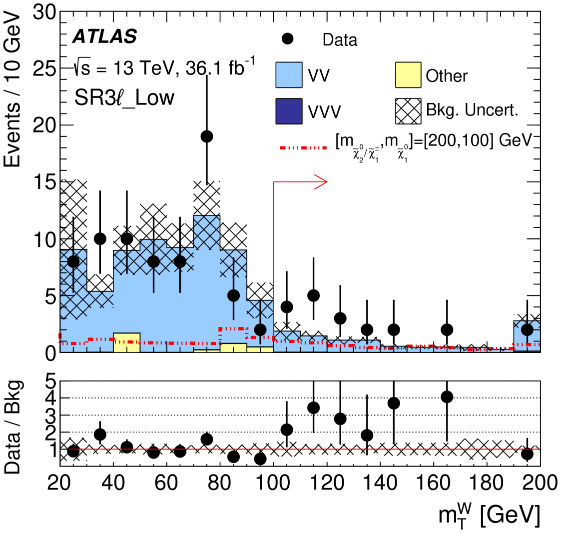




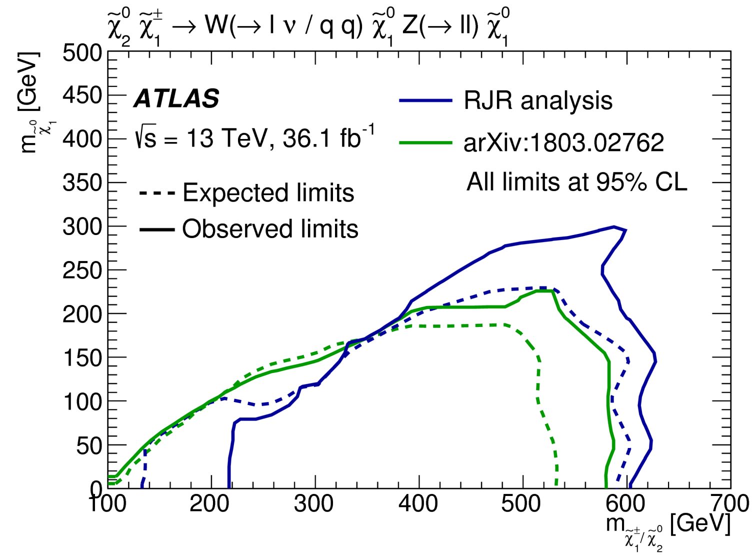




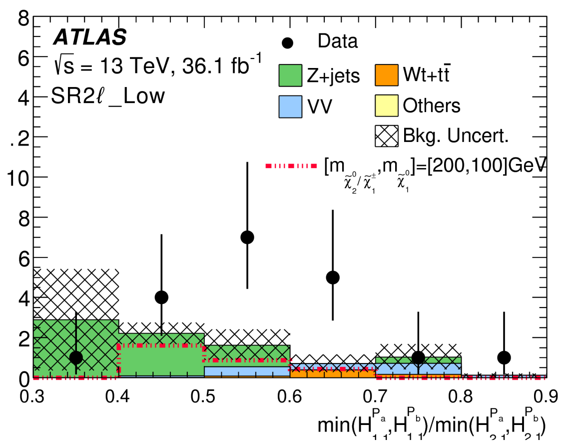
3 lepton selection is a similar story!



Excesses of 3.0, 2.0, 2.1 and 1.4 σ in the 3L ISR, 2L ISR, 3L low mass and 2L low mass respectively

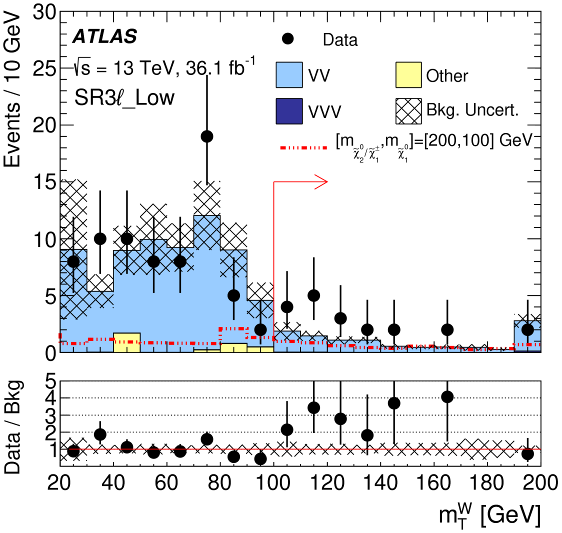


Largely unique selection of events compared to earlier analysis on same dataset



Exclusions for high mass reach 600 GeV and low mass points cannot be excluded due to excesses

Signal Region	$\langle\epsilon\sigma\rangle^{95}_{\rm obs}$ [fb]	$S^{95}_{\rm obs}$	$S^{95}_{\rm exp}$	$p(s=0)$ (Z)
SR3ℓ_ISR	0.42	15.3	$6.9^{+3.1}_{-2.2}$	0.001 (3.02)
SR2ℓ_ISR	0.43	15.4	$9.7^{+3.6}_{-2.5}$	0.02 (1.99)
SR3ℓ_Low	0.53	19.1	$9.5^{+4.2}_{-1.8}$	0.016 (2.13)
SR2ℓ_Low	0.66	23.7	$16.1^{+6.3}_{-4.3}$	0.08 (1.39)



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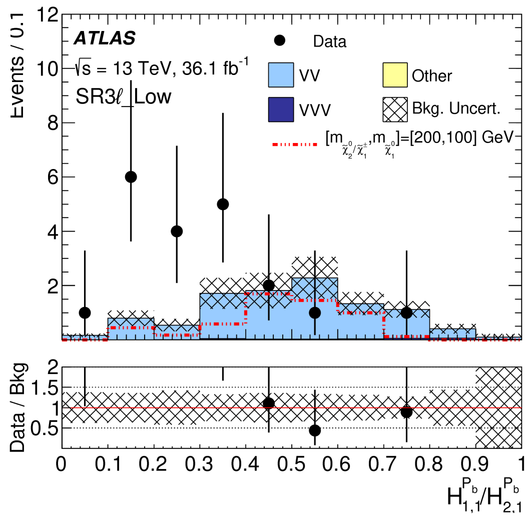

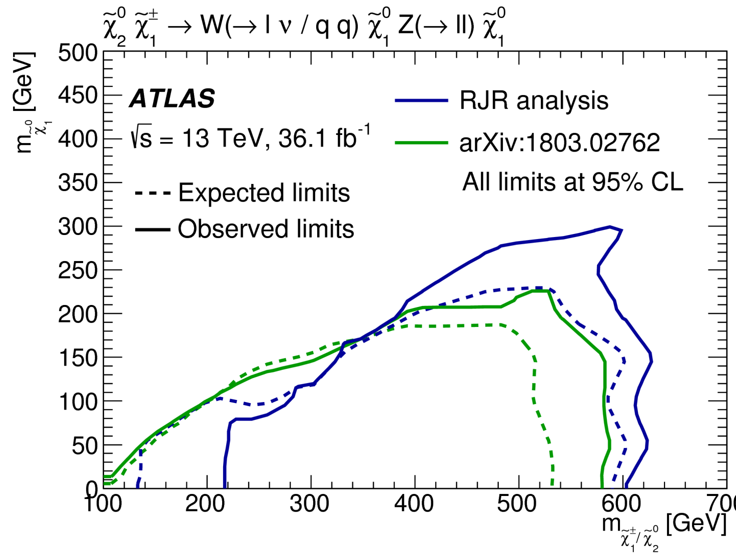

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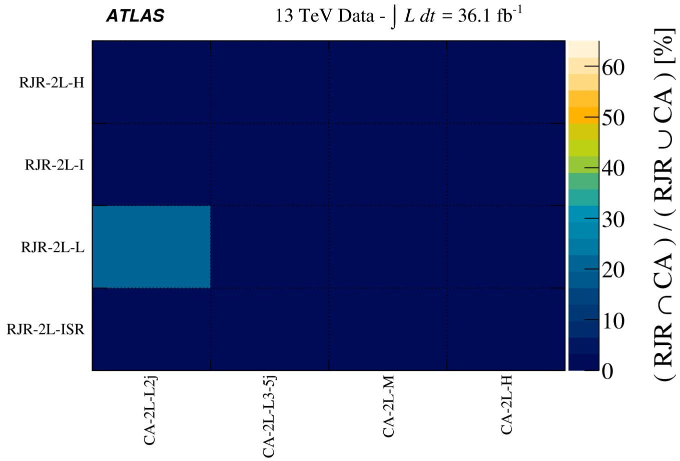
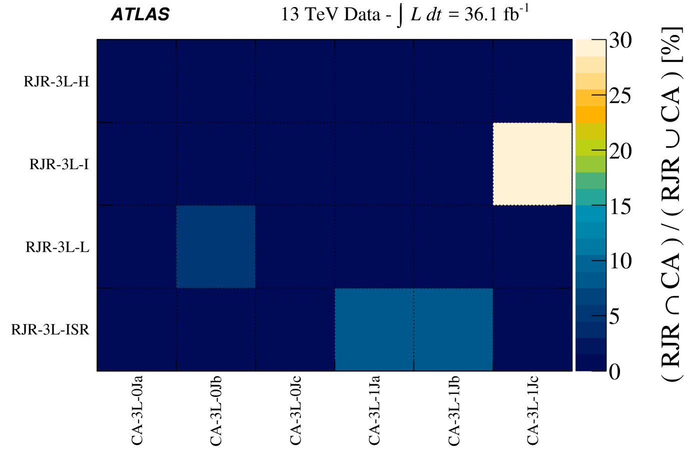
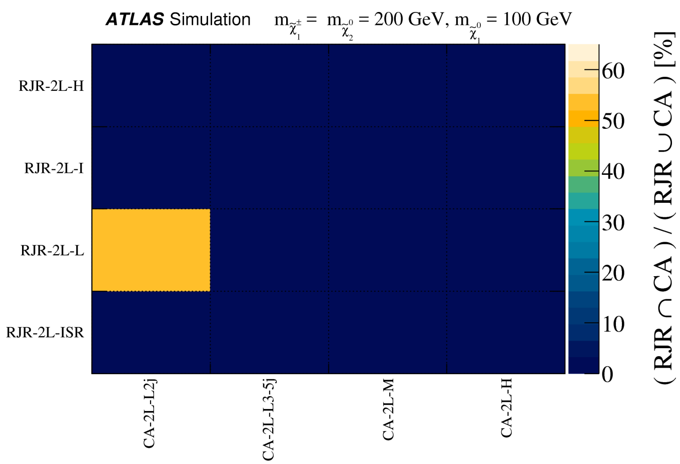
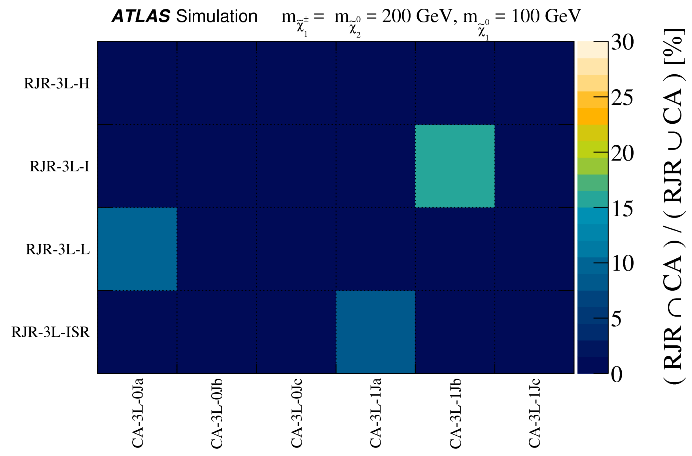
Overlap Plots in 2l and 3l searches

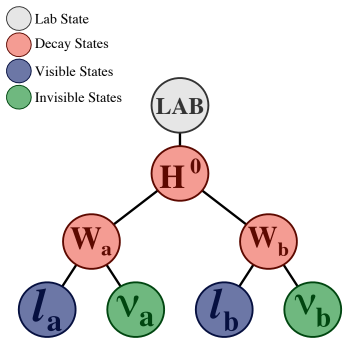


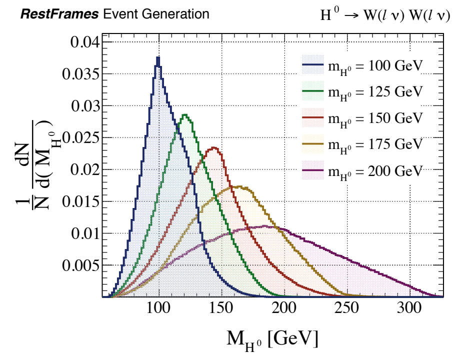


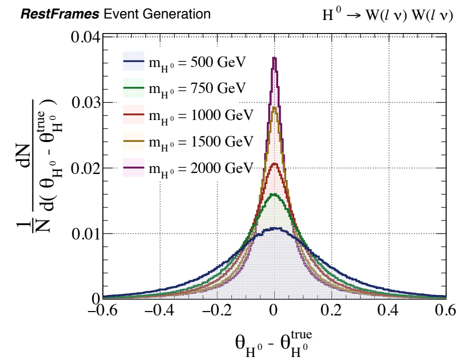




Recursive Jigsaw Reconstruction

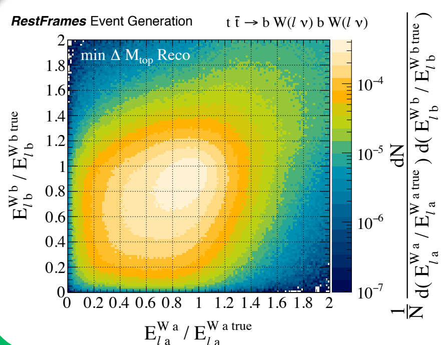


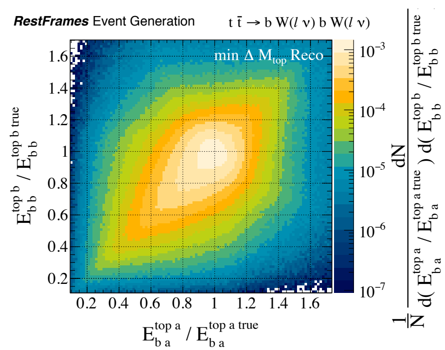


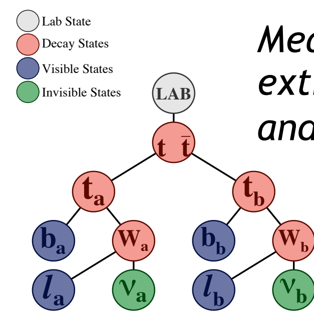


Reconstruct approx. of masses and decay angles in resonant final states (e.g. H->WW)

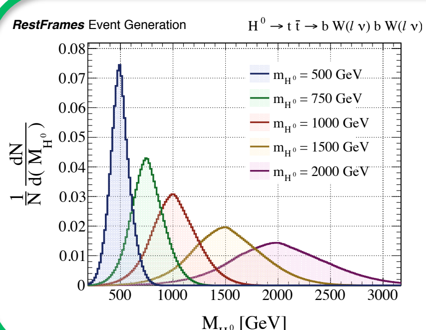
PJ, C. Rogan
arXiv:1705.10733

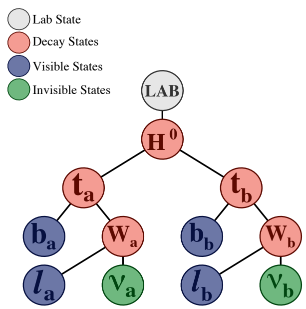




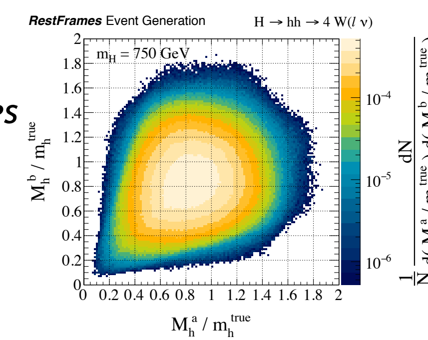


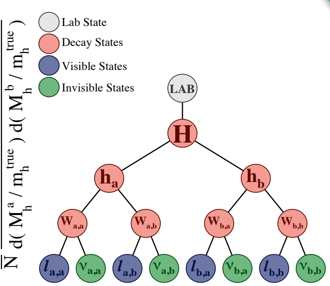
Measure mass splitting and energies, extracting a basis for dileptonic ttbar and sparticle pair production





Bump hunt for parent masses and retain sensitivity to properties in open final states enriched with further decay tree structure





HOWTO search for SUSY

① Build signal regions (**SR**s) based on requirements on signal / background discriminating variables to target specific SUSY event topologies. Optimised for discovery & exclusion.

② Determine Standard Model background in the SRs:

Irreducible Backgrounds

- Dominant processes:
  - MC normalised to data in process-enhanced control regions (**CR**s)
  - Extrapolation to validation regions (**VR**s) & **SR**s
- Subdominant processes: Pure MC predictions

Reducible Backgrounds

- Fake $E_{T,miss}$, fake leptons backgrounds: Pure data-driven estimates
- Validation in **VR**s

Combined Fit

- Simultaneous fit of all components in **CR**s (and **SR**s for exclusion)