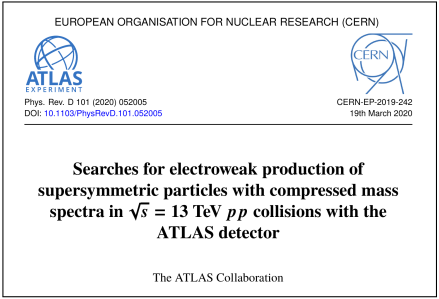
Searching for Compressed SUSY at the Energy Frontier

Mike Hance
UC Santa Cruz

September 16, 2020

Outline

1. Some Inspiration
2. The Tools
3. The Search
4. The Results →
5. The Future



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

CERN

Phys. Rev. D 101 (2020) 052005
DOI: 10.1103/PhysRevD.101.052005

CERN-EP-2019-242
19th March 2020

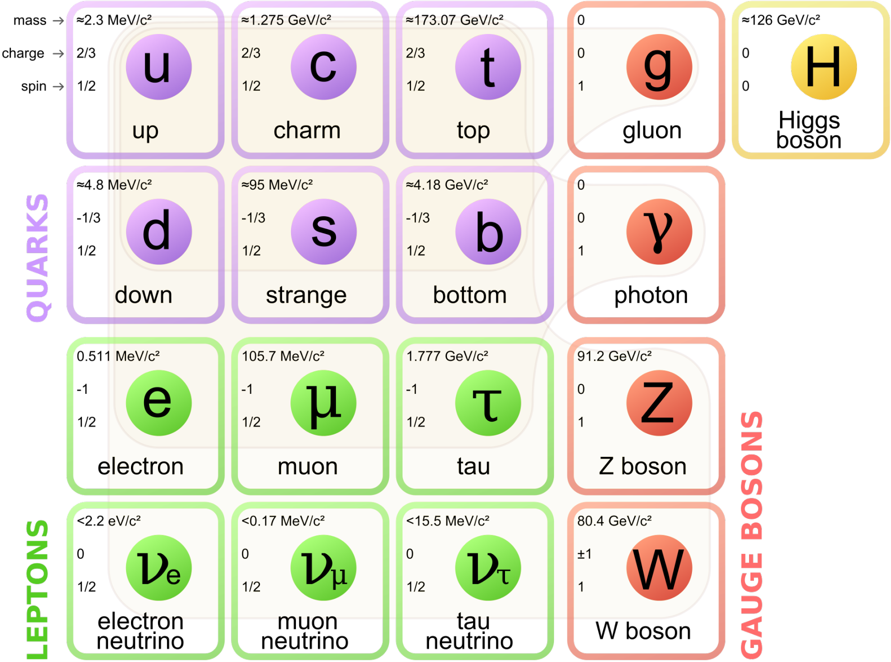
Searches for electroweak production of supersymmetric particles with compressed mass spectra in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector

The ATLAS Collaboration

Work done in collaboration with great students/postdocs including:

- Penn:Joana Machado Miguéns, Elodie Resseguie
- Santa Cruz: Jeff Shahinian
- Harvard: Julia Gonski, Stefano Zambito
- Milano: Lorenzo Rossini
- Pitt: Andy Aukerman, Ben Carlson
- MPI: Michael Holzbock
- Kyoto: Shun Akatsuka

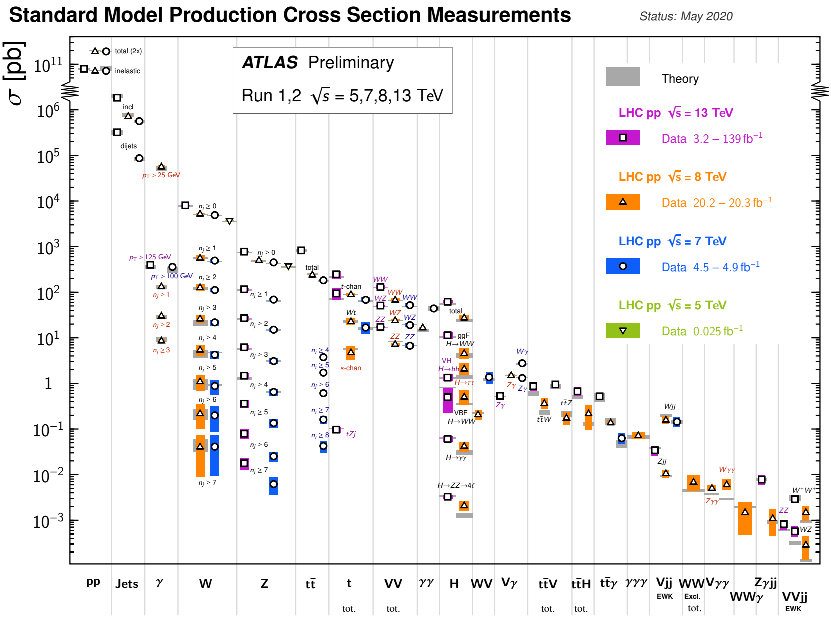
Some Inspiration



mass →
charge →
spin →

QUARKS	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson
	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
LEPTONS	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	GAUGE BOSONS
	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	

The Standard Model



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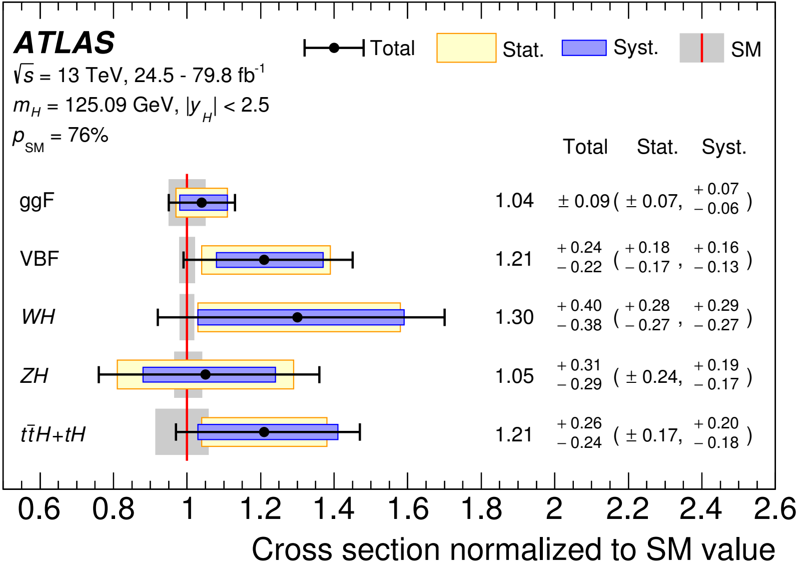

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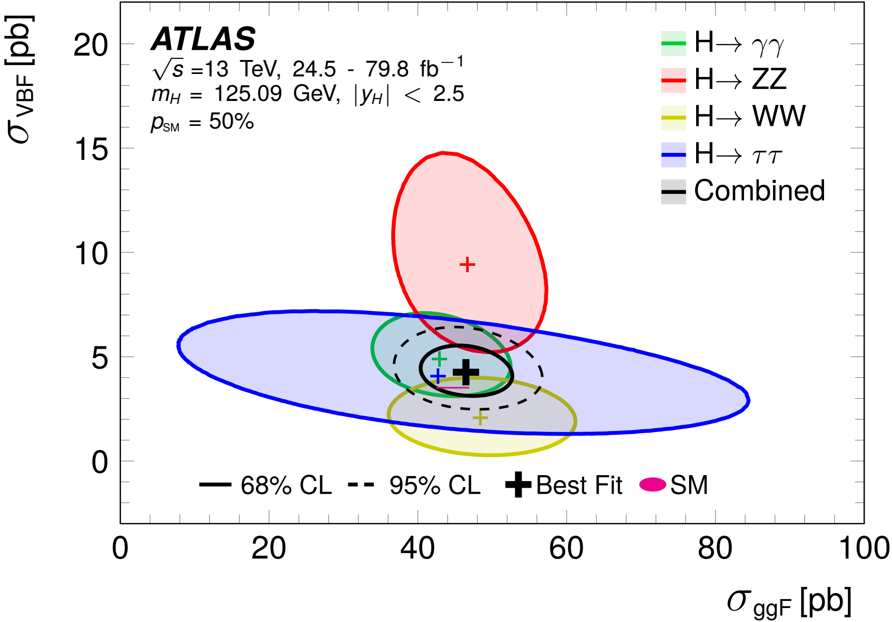
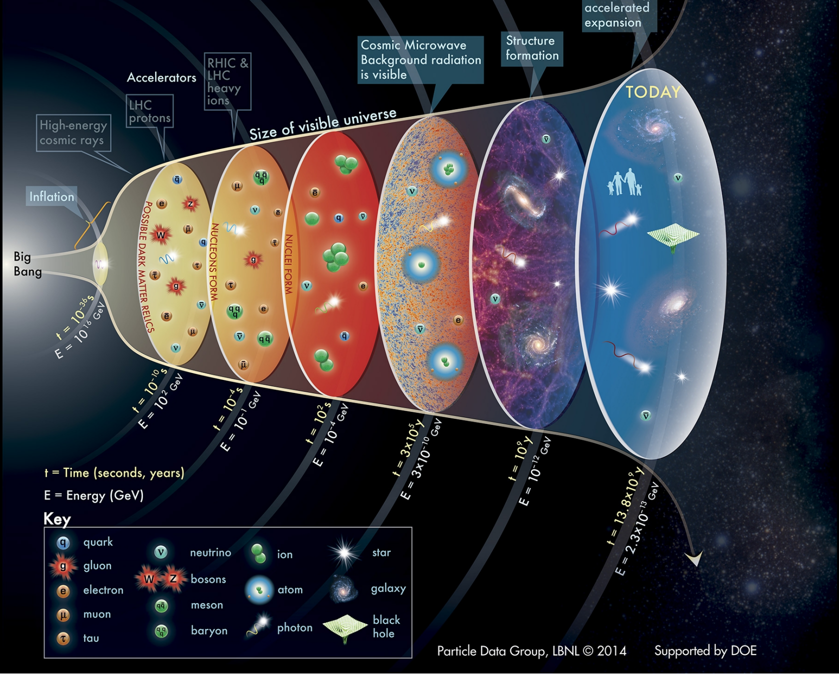


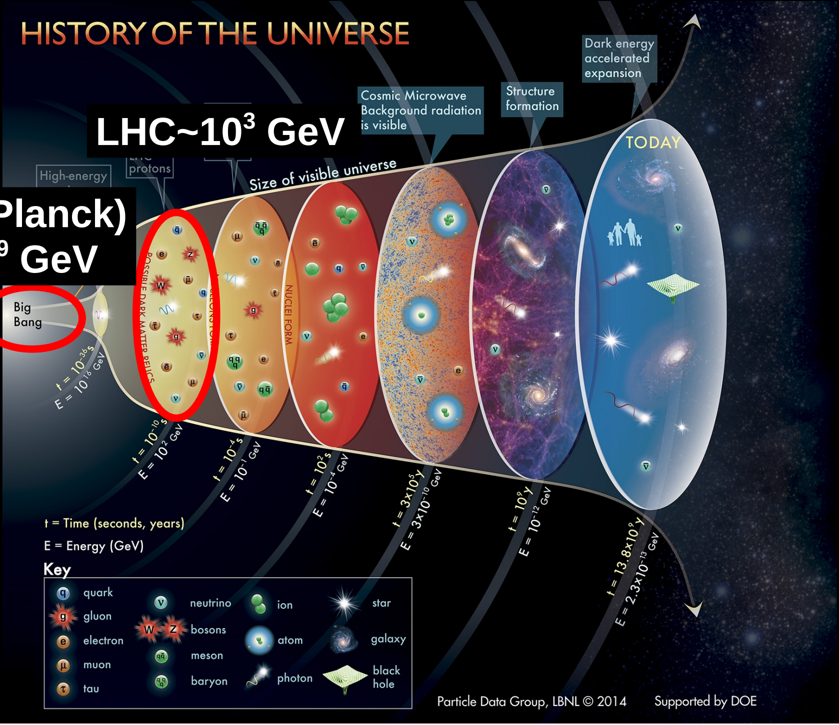
HISTORY OF THE UNIVERSE



Particle Data Group, LBNL © 2014 Supported by DOE

LHC~10^3 GeV

m(Planck)
10^{19} GeV



Particle Data Group, LBNL © 2014 Supported by DOE

A Minor Concern

The Higgs is particularly sensitive to the scale of the theory it's embedded in:

$$m_H^2 = m_{\text{bare}}^2 + \frac{y_t^2}{16\pi^2}\Lambda^2 + \delta\mathcal{O}(m_{\text{weak}}^2)$$

A "Naturalness" Problem

1. Either we just got lucky with a light Higgs, or
2. There is something new at rather low energy, or
3. There is something new at moderate energies with a mechanism for protecting the Higgs mass

Wells; arXiv:1603.06131
Many others.

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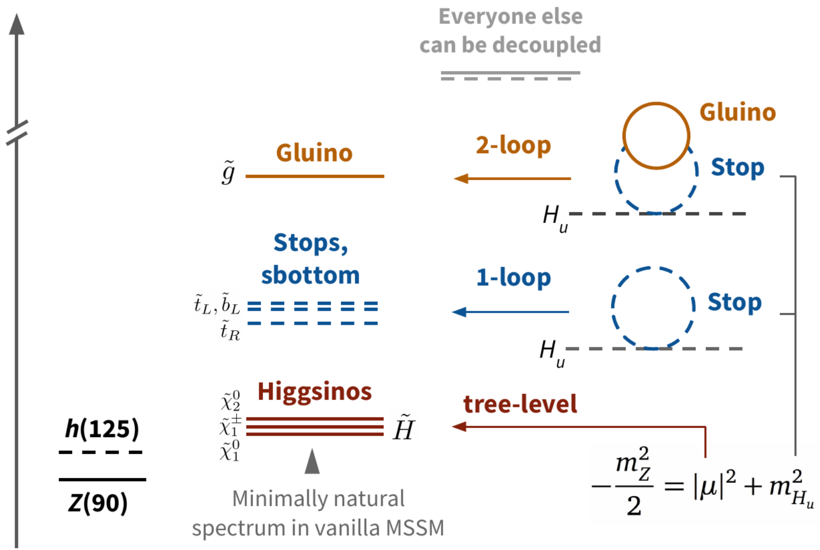
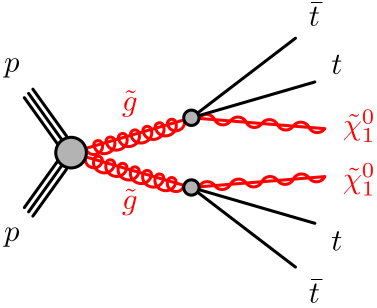
SUSY to the rescue!

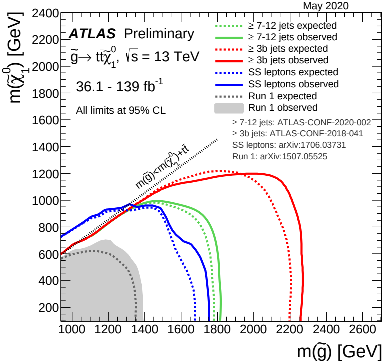


$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

Ben Hooberman, Jesse Liu
Papucci, Ruderman, Weiler; JHEP 1209 (2012) 035

Searches for Gluinos

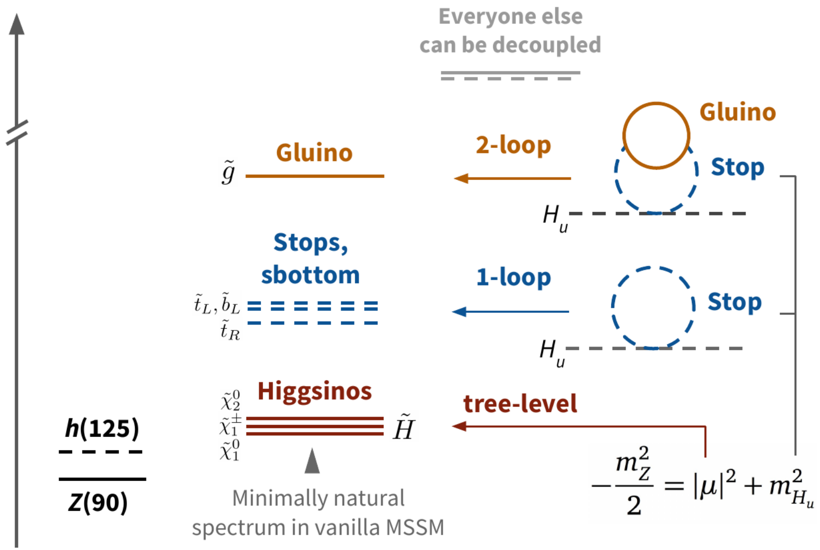




No signs so far of gluinos

- Limits go from 2150 GeV to ∼2450 GeV with 140 fb^{-1} (if no signal)
  - → limited opportunities for discovery.

SUSY to the rescue?

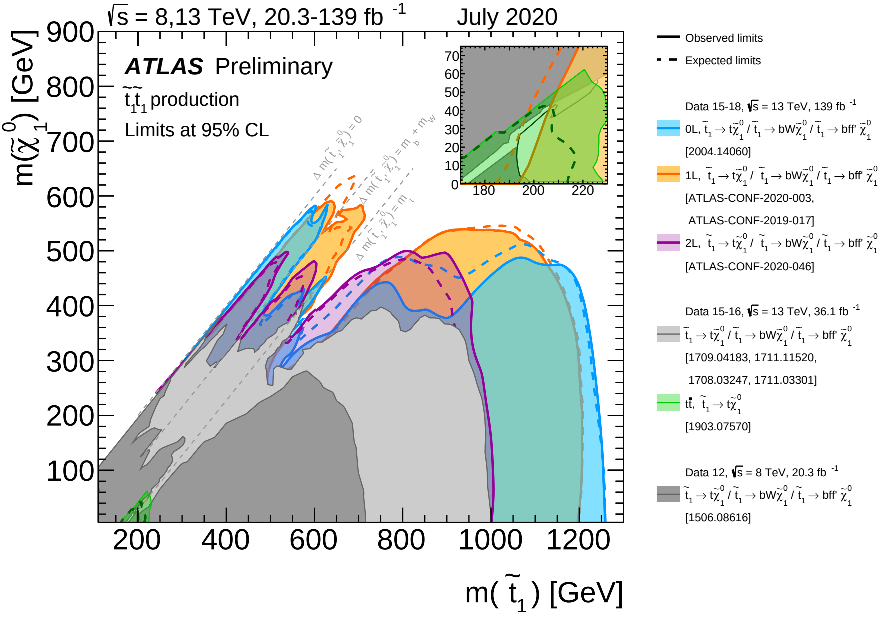


$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

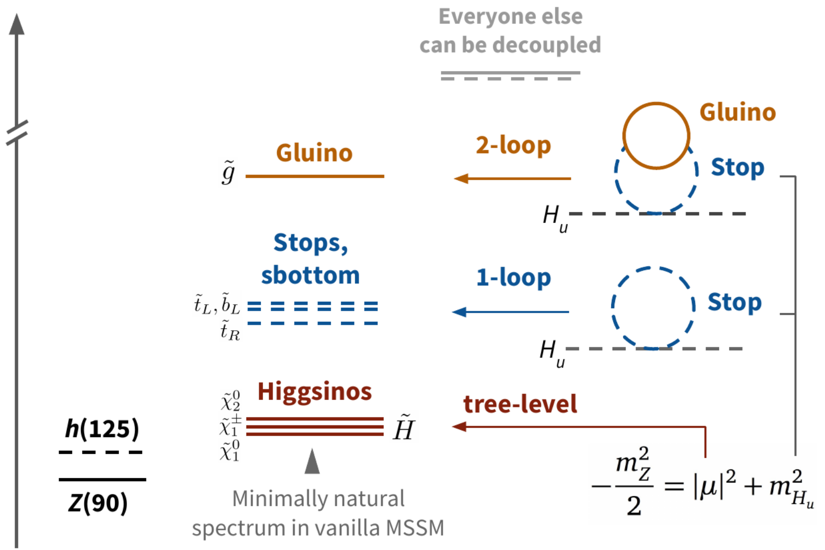
Ben Hooberman, Jesse Liu

Papucci, Ruderman, Weiler; JHEP 1209 (2012) 035

Searches for Stops



SUSY to the rescue??



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Electroweak SUSY Phenomenology

Electroweak masses in MSSM controlled by:

- M_1: “Bino” ($\widetilde{B}$) mass term
- M_2: “Wino” ($\widetilde{W}$) mass term
- μ: “Higgsino” mass term
- $\tan\beta$: ratio of VEV’s

Weak eigenstates mix into mass eigenstates ($\widetilde{\chi}^0_{1,2,3,4}$) by diagonalizing:

$$M_N = \begin{pmatrix} M_1 & 0 & M_Z\cos\beta\sin\theta_W & M_Z\sin\beta\sin\theta_W \\ 0 & M_2 & M_Z\cos\beta\cos\theta_W & M_Z\sin\beta\cos\theta_W \\ M_Z\cos\beta\sin\theta_W & M_Z\sin\beta\sin\theta_W & 0 & -\mu \\ M_Z\cos\beta\cos\theta_W & M_Z\sin\beta\cos\theta_W & -\mu & 0 \end{pmatrix}$$

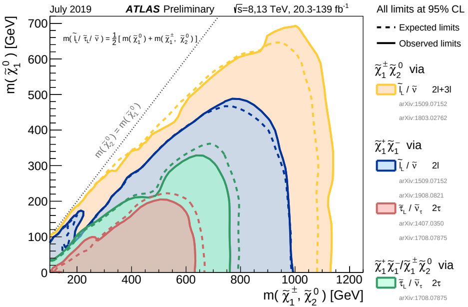
Similar procedure to find two charged states ($\widetilde{\chi}^\pm_1, \widetilde{\chi}^\pm_2$)

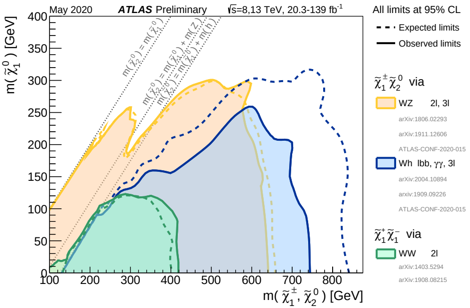
For a recent review, see Canepa, Han, Wang; arXiv:2003.05450

What do we know about EWK SUSY?

Constraints on Electroweak SUSY are... weak.

- Relatively-model-independent[1] constraints from LEP: $m(\tilde{\chi}_1^{\pm}) \gtrsim 100$ GeV
- Constraints from LHC are more model-dependent:





Still a lot of room for low-scale Electroweak SUSY!

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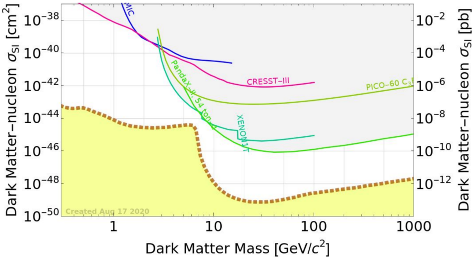
[1] : Ruderman *et al.* disagree; arXiv:1801.05432

Anything else?

> "OK, but what about dark matter?"
>
> –Greedy Physicist

Neutral LSP in R-parity conserving SUSY as WIMP dark matter:

- Under pressure from direct detection experiments
  - ...but those represent *upper* bounds
  - Possible that not *all* dark matter is the SUSY LSP!



Coannihilation can control overabundance (e.g. for $\tilde{\chi}_1^0 \sim \tilde{B}$)

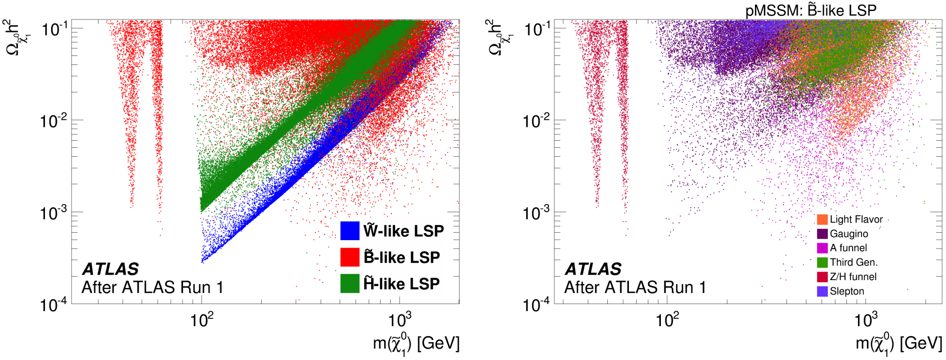
- Requires other particles (X) with similar abundance (mass)
- Freeze-out at temperature T:

$$T \sim \frac{m(\chi)}{25} \sim \Delta = \frac{m(X) - m(\chi_1)}{m(\chi_1)}$$

Griest and Seckel; Phys. Rev. D **43**, 3191
Bell *et al.*; Phys. Rev. D **89**, 115001
Baker *et al.*; JHEP 1512 (2015) 120

pMSSM Studies: post-Run1

We can use the parameterized MSSM (pMSSM) to get a sense for what scenarios are still viable given experimental constraints at the end of LHC Run-1:



- Higgsino LSP’s under some pressure from direct detection, but could form part of the DM
- Scenarios with Bino LSP’s survive due to annihilation

ATLAS; JHEP 10 (2015) 134

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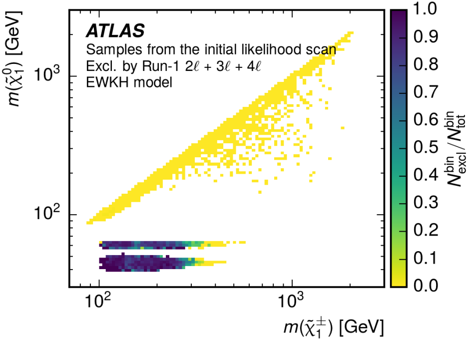
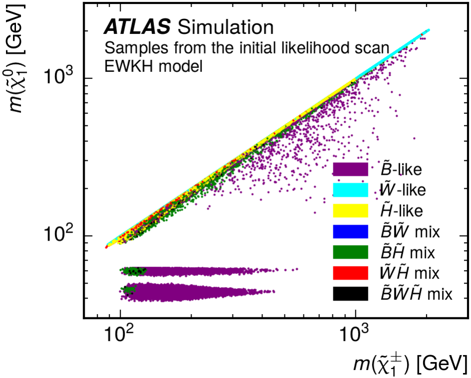


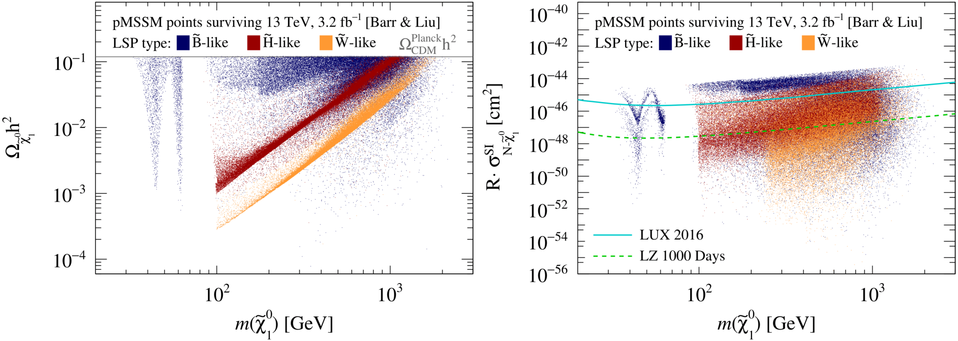


- Higgsino LSP’s cluster near “compressed” diagonal
- Larger splittings with Bino mixtures

ATLAS; JHEP 09 (2016) 175

pMSSM Studies: early-Run2

By the start of Run-2, more parameter space excluded by strong-SUSY searches:

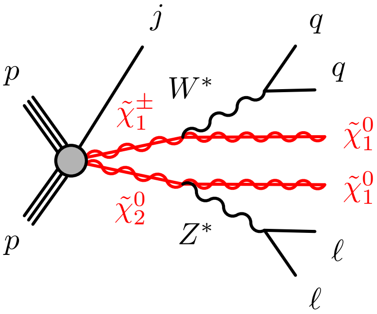


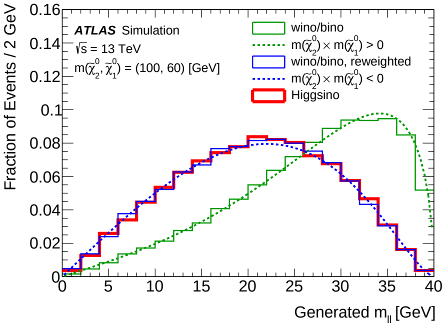
Still significant parameter space remaining!

- Either for (natural) Higgsino-like LSPs,
- Or for Bino-like LSP's with nearby annihilators/resonances/etc

Barr and Liu; Eur. Phys. J. C (2017) 77: 202

Our Challenge





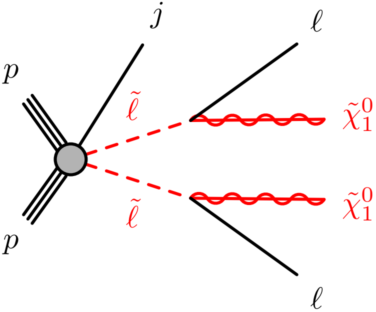
- Soft leptons: $p_T^\ell \sim \frac{1}{2}(m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}) \left[1 + \frac{p_{T,\mathrm{ISR}}}{m_{\tilde{\chi}_2^0}}\right]$
- Low $\sigma \times$ BR
- **Exploit endpoint in dilepton invariant mass $m_{\ell\ell}$**

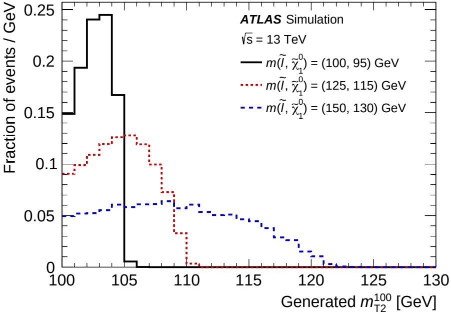
Han *et al.*; Phys. Rev. D 89, 075007 (2014)

Many others.

Our Challenge

Similar arguments (DM, $g-2$) inspire a companion search:





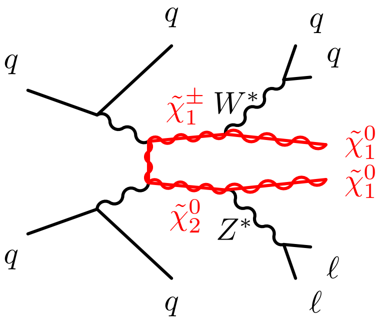
- Soft leptons: $p_T^\ell \sim (m_{\tilde{\ell}} - m_{\tilde{\chi}_1^0}) \left[1 + \frac{p_{T,ISR}}{m_{\tilde{\ell}}}\right]$
- Low σ
- **Exploit endpoint in "stransverse mass"** m_{T2}

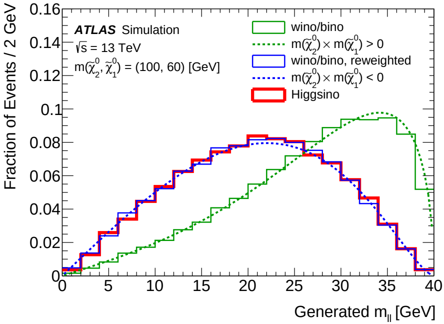
Barr and Scoville; JHEP 1504 (2015) 147

Han and Liu; Phys. Rev. D 92, 015010 (2015)

Our Challenge

...and a large dataset inspires us to reach for something really unique:





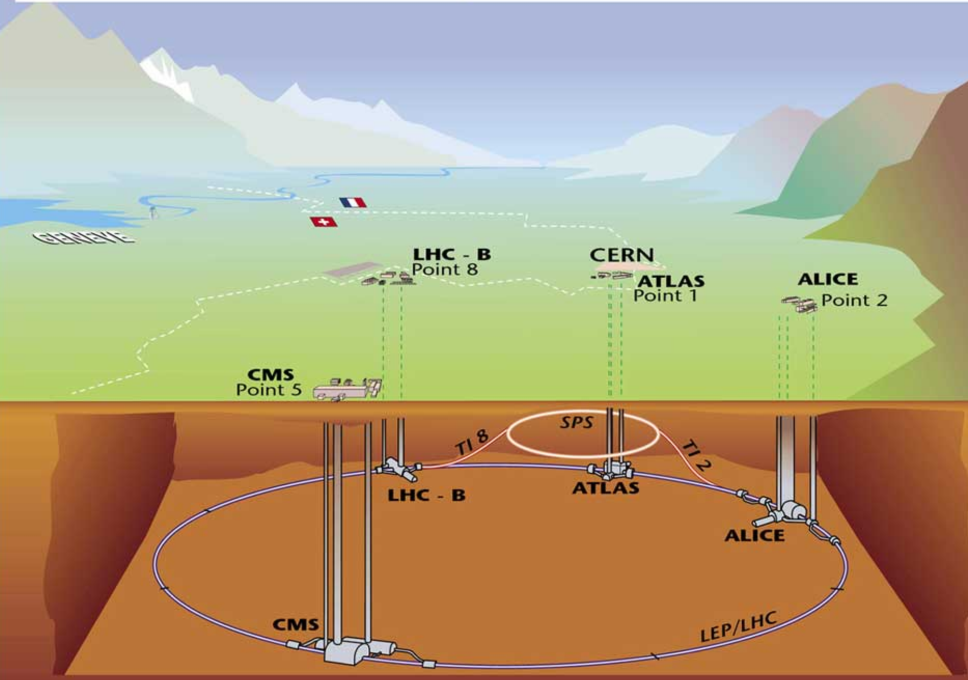
- *Extremely* low $\sigma \times$ BR
- Tools from electroweakino searches: $m_{\ell\ell}$, soft leptons
- **Further exploit the dijets:** $m_{jj}, \Delta\eta_{jj}$

Giudice, Han, Wang, Wang; Phys. Rev. D 81, 115011 (2010)

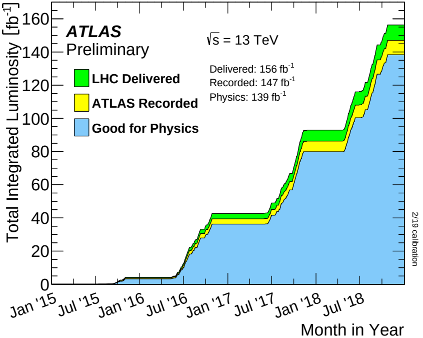
Nelson, Tanedo, Whiteson; Phys. Rev. D 93, 115029 (2016)

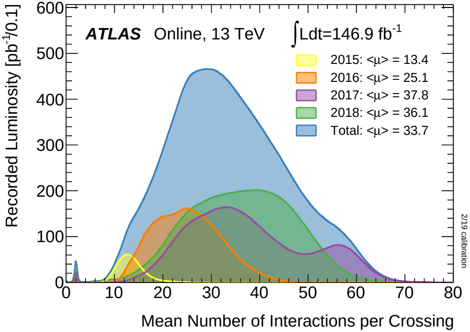
The Tools

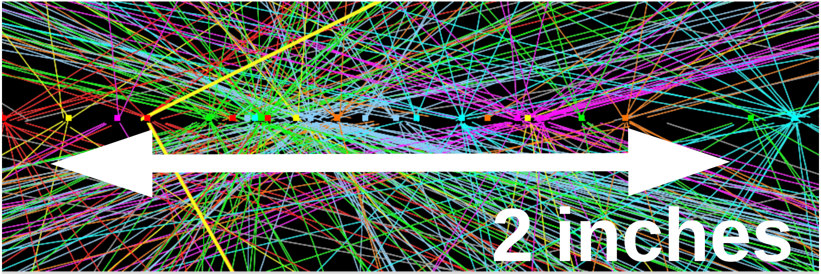
Overall view of the LHC experiments.



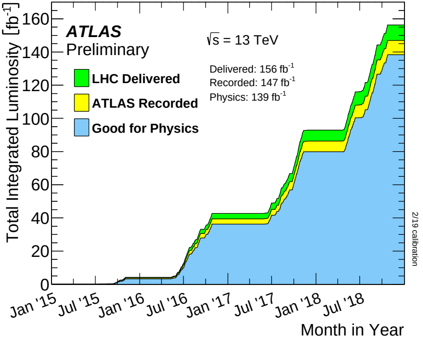
Data Taking


ATLAS
Preliminary
√s = 13 TeV
🟩 LHC Delivered
🟨 ATLAS Recorded
🟦 Good for Physics
Delivered: 156 fb^{-1}
Recorded: 147 fb^{-1}
Physics: 139 fb^{-1}
Total Integrated Luminosity [fb^{-1}]
0
20
40
60
80
100
120
140
160
Jan '15
Jul '15
Jan '16
Jul '16
Jan '17
Jul '17
Jan '18
Jul '18
Month in Year
2/19 calibration


ATLAS Online, 13 TeV
$\int$Ldt=146.9 fb^{-1}
2015: <μ> = 13.4
2016: <μ> = 25.1
2017: <μ> = 37.8
2018: <μ> = 36.1
Total: <μ> = 33.7
Recorded Luminosity [pb^{-1}/0.1]
0
100
200
300
400
500
600
0
10
20
30
40
50
60
70
80
Mean Number of Interactions per Crossing
2/19 calibration


2 inches

Data Taking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Jul '18
Month in Year
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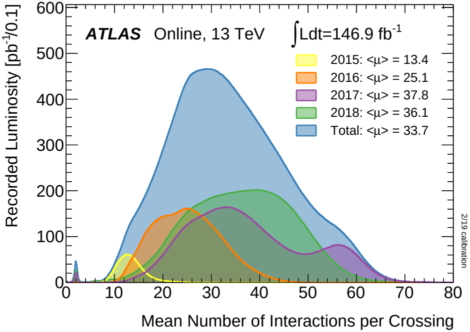
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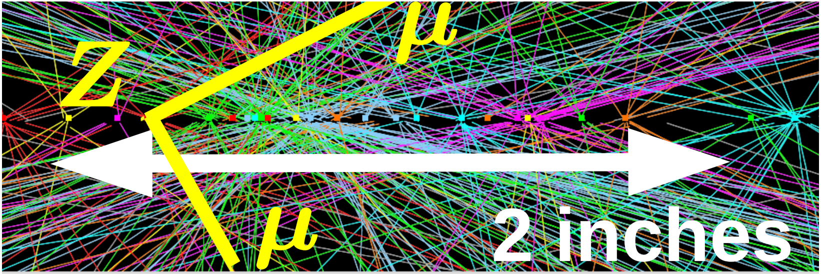
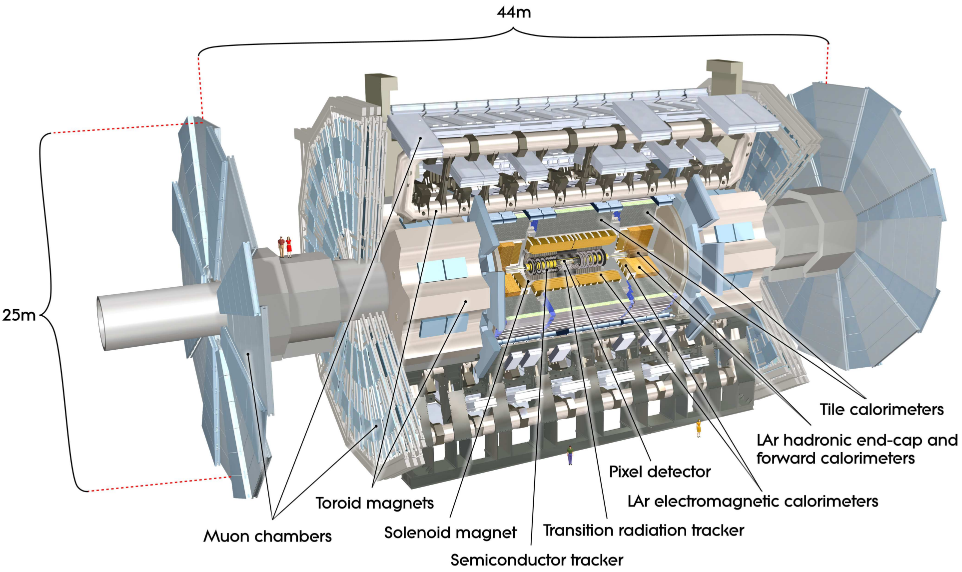
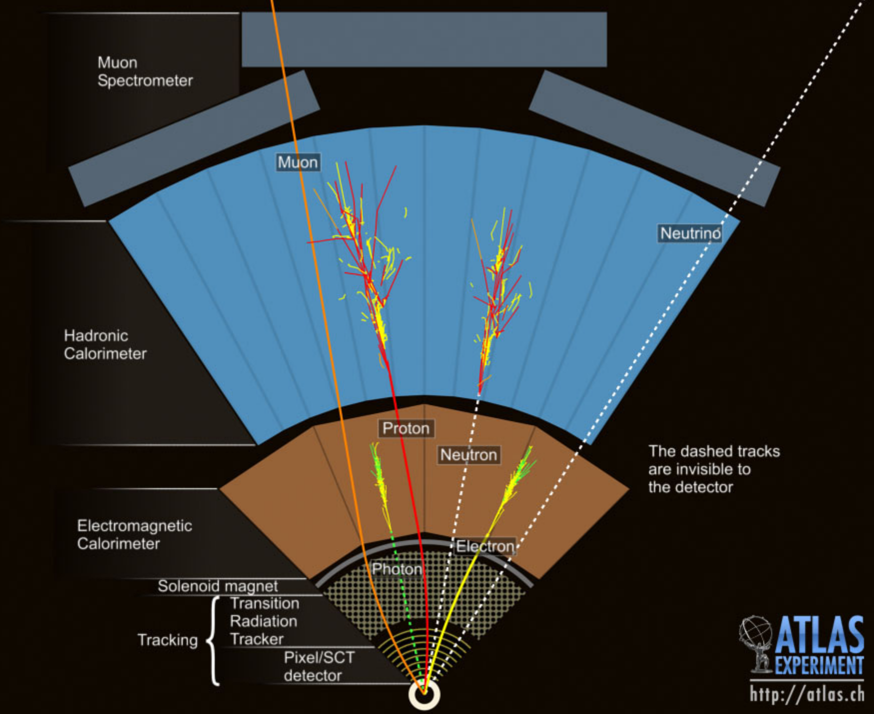

Z
μ
μ
2 inches

A **T**oroidal **L**HC **A**pparatu**S**

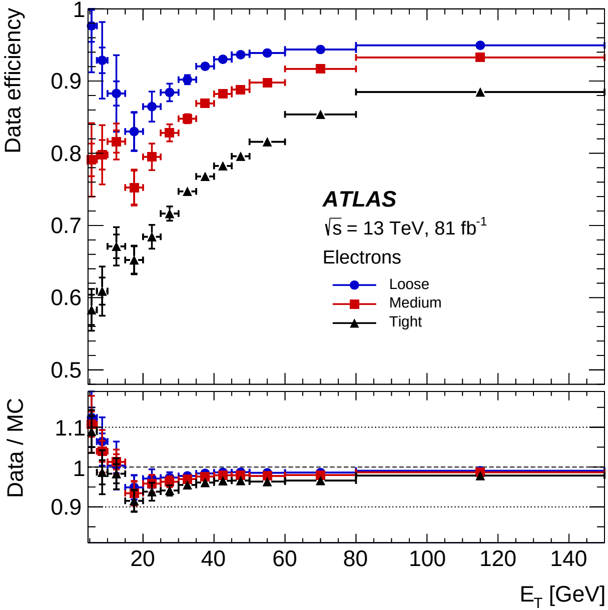




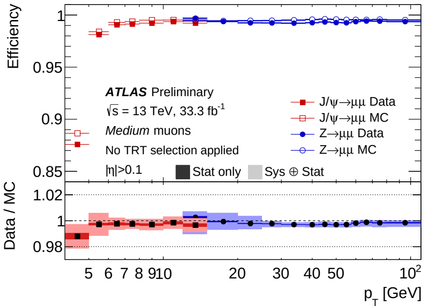
The dashed tracks are invisible to the detector

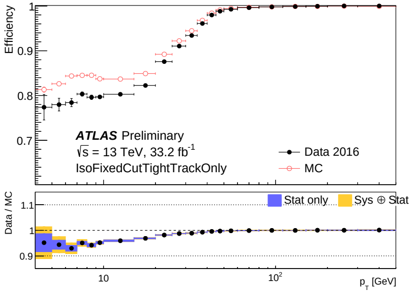
ATLAS EXPERIMENT
http://atlas.ch

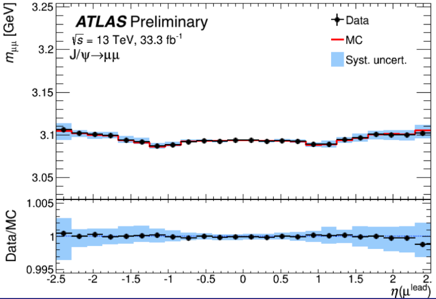
Performance – Electrons

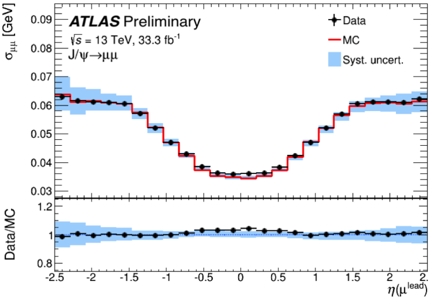


Performance – Muons

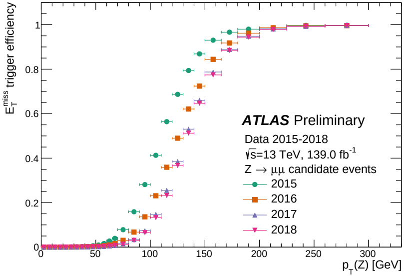


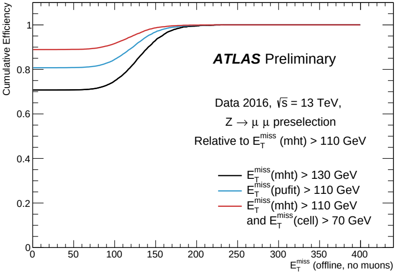


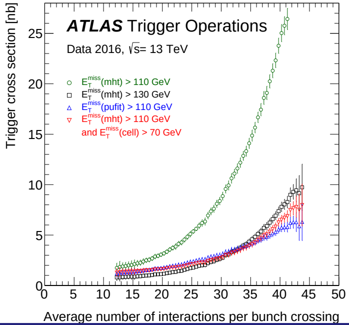




Performance – $E_{\mathrm{T}}^{\mathrm{miss}}$ and triggers





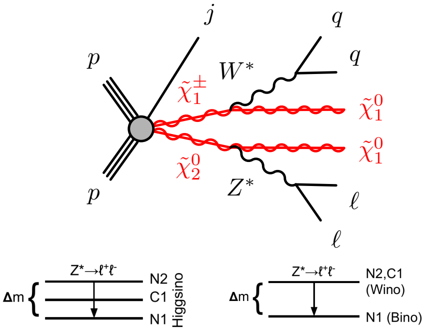


So far, we have kept up with pileup by:

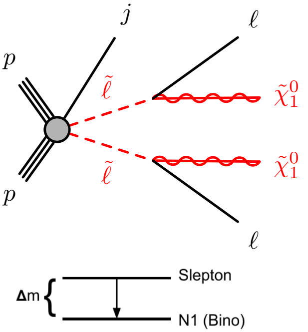
- Raising thresholds slightly
- Improving resolution (online and offline)
- New triggers in 2017+

The Search

Signal Modeling

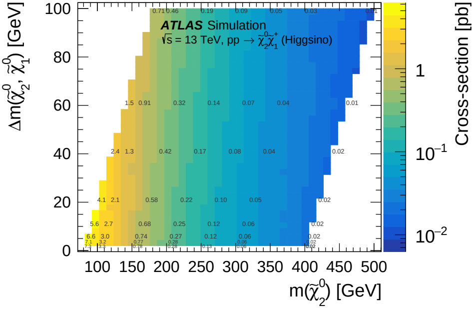


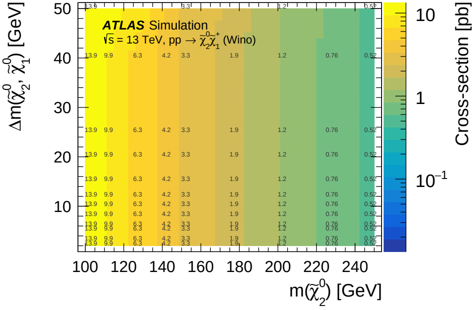
- MadGraph+MadSpin+Pythia8
- Higgsino, Wino-Bino
- $80 < m(\tilde{\chi}_1^0)/\mathrm{GeV} < 400$
- $2 < \Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)/\mathrm{GeV} < 60$

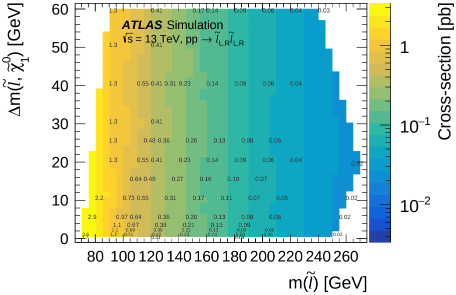


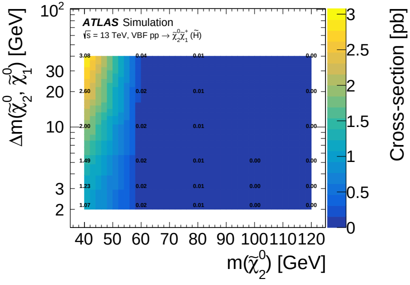
- MadGraph+Pythia8
- Degenerate flavor states
- $70 < m(\tilde{\chi}_1^0)/\mathrm{GeV} < 200$
- $0.5 < \Delta m(\tilde{\ell}, \tilde{\chi}_1^0)/\mathrm{GeV} < 50$

Cross sections









Background MC

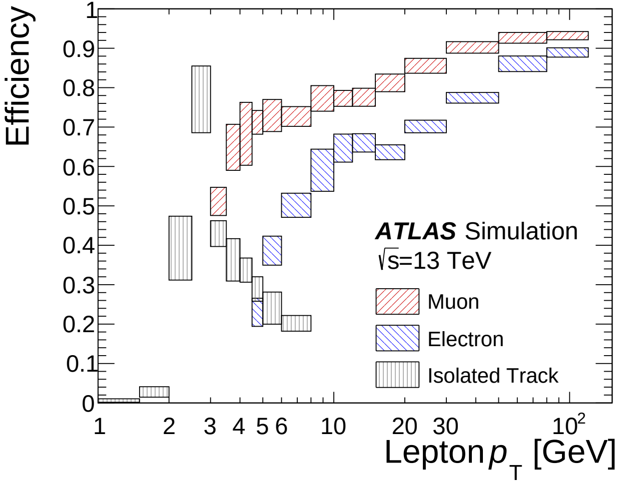
Process	Matrix element	Parton shower	PDF set	Cross-section
V+jets	SHERPA 2.2.1		NNPDF 3.0 NNLO [84]	NNLO [85]
VV	SHERPA 2.2.1/2.2.2		NNPDF 3.0 NNLO	Generator NLO
Triboson	SHERPA 2.2.1		NNPDF 3.0 NNLO	Generator LO, NLO
h (ggF)	POWHEG-BOX	PYTHIA 8.212	NLO CTEQ6L1 [86]	N^{3}LO [87]
h (VBF)	POWHEG-BOX	PYTHIA 8.186	NLO CTEQ6L1 [86]	NNLO + NLO [87]
$h + W/Z$	PYTHIA 8.186		NNPDF 2.3 LO [54]	NNLO + NLO [87]
$h + t\bar{t}$	MG5_aMC@NLO 2.2.3	PYTHIA 8.210	NNPDF 2.3 LO	NLO [87]
$t\bar{t}$	POWHEG-BOX	PYTHIA 8.230	NNPDF 2.3 LO	NNLO+NNLL [88,89,90,91,92]
t (s-channel)	POWHEG-BOX	PYTHIA 8.230	NNPDF 2.3 LO	NNLO+NNLL [93]
t (t-channel)	POWHEG-BOX	PYTHIA 8.230	NNPDF 2.3 LO	NNLO+NNLL [94,77]
$t + W$	POWHEG-BOX	PYTHIA 8.230	NNPDF 2.3 LO	NNLO+NNLL [95]
$t + Z$	MG5_aMC@NLO 2.3.3	PYTHIA 8.212	NNPDF 2.3 LO	NLO [53]
$t\bar{t}WW$	MG5_aMC@NLO 2.2.2	PYTHIA 8.186	NNPDF 2.3 LO	NLO [53]
$t\bar{t} + Z/W/\gamma^*$	MG5_aMC@NLO 2.3.3	PYTHIA 8.210/8.212	NNPDF 2.3 LO	NLO [87]
$t + WZ$	MG5_aMC@NLO 2.3.3	PYTHIA 8.212	NNPDF 2.3 LO	NLO [53]
$t + t\bar{t}$	MG5_aMC@NLO 2.2.2	PYTHIA 8.186	NNPDF 2.3 LO	LO [53]
$t\bar{t}t\bar{t}$	MG5_aMC@NLO 2.2.2	PYTHIA 8.186	NNPDF 2.3 LO	NLO [53]

- Background MC used to model events with ≥ 2 prompt leptons
- Special extensions for Z+jets, dibosons:
  - $m(\ell\ell) > 2m(\ell) + 250$ MeV
  - $p_{\mathrm{T}}^{\ell} > 2$ GeV

Lepton Selection

Select isolated, ∼tight electrons (muons) down to 4.5 (3) GeV

- Special treatment for nearby leptons from low-mass $Z^* \to \ell\ell$
- Include **isolated tracks** to increase efficiency at even lower p_{T}.



Event Pre-selection

- Common preselection removes some large backgrounds ($t\bar{t}$, $Z \to \tau\tau$) and enforces an ISR topology

	Preselection requirements	
Variable	2ℓ	$1\ell 1T$
Number of leptons (tracks)	$= 2$ leptons	$= 1$ lepton and ≥ 1 track
Lepton p_{T} [GeV]	$p_{\mathrm{T}}^{\ell_1} > 5$	$p_{\mathrm{T}}^{\ell} < 10$
$\Delta R_{\ell\ell}$	$\Delta R_{ee} > 0.30$, $\Delta R_{\mu\mu} > 0.05$, $\Delta R_{e\mu} > 0.2$	$0.05 < \Delta R_{\ell\mathrm{track}} < 1.5$
Lepton (track) charge and flavor	$e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$	$e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$
Lepton (track) invariant mass [GeV]	$3 < m_{ee} < 60$, $1 < m_{\mu\mu} < 60$	$0.5 < m_{\ell\mathrm{track}} < 5$
J/ψ invariant mass [GeV]	veto $3 < m_{\ell\ell} < 3.2$	veto $3 < m_{\ell\mathrm{track}} < 3.2$
$m_{\tau\tau}$ [GeV]	< 0 or > 160	no requirement
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 120	> 120
Number of jets	≥ 1	≥ 1
Number of b-tagged jets	$= 0$	no requirement
Leading jet p_{T} [GeV]	≥ 100	≥ 100
$\min(\Delta\phi(\text{any jet}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}))$	> 0.4	> 0.4
$\Delta\phi(j_1, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})$ †	≥ 2.0	≥ 2.0

Signal Region Selection

	Electroweakino SR Requirements			
Variable	SR–E–low	SR–E–med	SR–E–high	SR–E–$1\ell 1T$
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$[120, 200]$	$[120, 200]$	> 200	> 200
$E_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}}^{\mathrm{lep}}$	< 10	> 10	–	> 30
$\Delta\phi(\mathrm{lep}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})$	–	–	–	< 1.0
Lepton or track p_{T} [GeV]	$p_{\mathrm{T}}^{\ell_2} > 5 + m_{\ell\ell}/4$	–	$p_{\mathrm{T}}^{\ell_2} > \min(10, 2 + m_{\ell\ell}/3)$	$p_{\mathrm{T}}^{\mathrm{track}} < 5$
$M_{\mathrm{T}}^{\mathrm{S}}$ [GeV]	–	< 50	–	–
$m_{\mathrm{T}}^{\ell_1}$ [GeV]	$[10, 60]$	–	< 60	–
R_{ISR}	$[0.8, 1.0]$	–	$[\max(0.85, 0.98 - 0.02 \times m_{\ell\ell}),\ 1.0]$	–

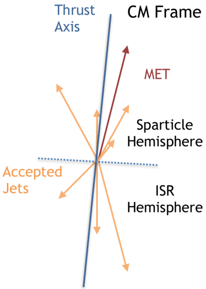
	Slepton SR Requirements	
Variable	SR–S–low	SR–S–high
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$[150, 200]$	> 200
m_{T2}^{100} [GeV]	< 140	< 140
$p_{\mathrm{T}}^{\ell_2}$ [GeV]	$> \min(15, 7.5 + 0.75 \times (m_{\mathrm{T2}} - 100))$	$> \min(20, 2.5 + 2.5 \times (m_{\mathrm{T2}} - 100))$
R_{ISR}	$[0.8,\ 1.0]$	$[\max(0.85, 0.98 - 0.02 \times (m_{\mathrm{T2}} - 100)),\ 1.0]$

Variable	VBF SR Requirements	
$m_{\ell\ell}$ [GeV]	< 40	
Number of jets	≥ 2	
$p_{\mathrm{T}}^{j_2}$ [GeV]	> 40	
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 150	
$E_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}}^{\mathrm{lep}}$	> 2	
$p_{\mathrm{T}}^{\ell_2}$ [GeV]	$> \min(10, 2 + m_{\ell\ell}/3)$	
$m_{\mathrm{T}}^{\ell_1}$ [GeV]	< 60	
R_{VBF}	$[\max(0.6, 0.92 - m_{\ell\ell}/60),\ 1.0]$	
$\eta_{j_1} \cdot \eta_{j_2}$	< 0	
m_{jj} [GeV]	> 400	
$\Delta\eta_{jj}$	> 2	
	SR–VBF–low	SR–VBF–high
$\Delta\eta_{jj}$	< 4	> 4

Extensive signal region optimization:

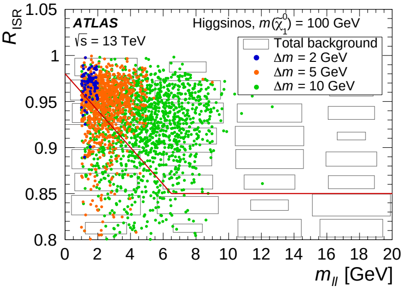
- Eight distinct selections
- Regions within a colored box designed to be orthogonal (combinations!)
- This looks over-optimized?
  - → compressed scenarios have constrained phase space that make many requirements model independent

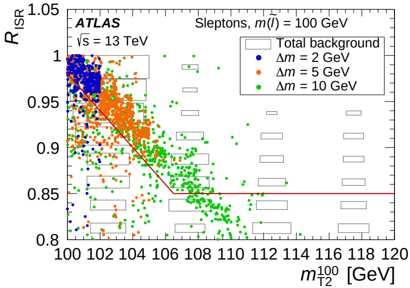
Event Selection example: Recursive Jigsaw Variables



Recursive Jigsaw Reconstruction boosts the event back to the SUSY rest frame:

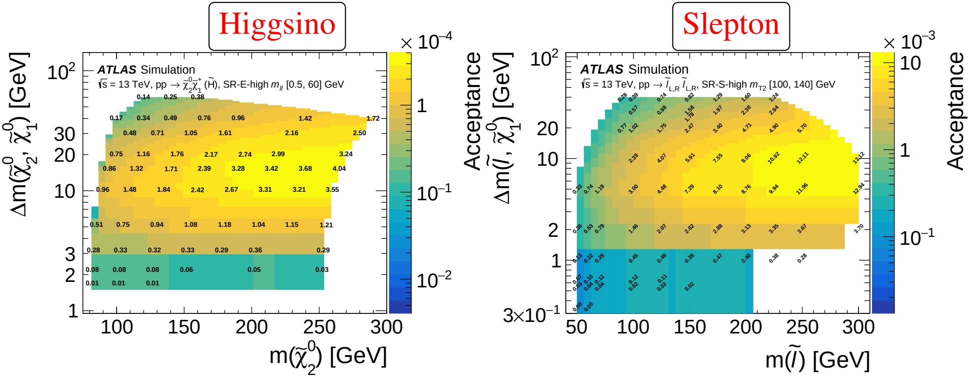
- Efficient background rejection
- Sensitive to SUSY mass spectrum, especially compressed scenarios!





Jackson and Rogan; Phys. Rev. D 96, 112007

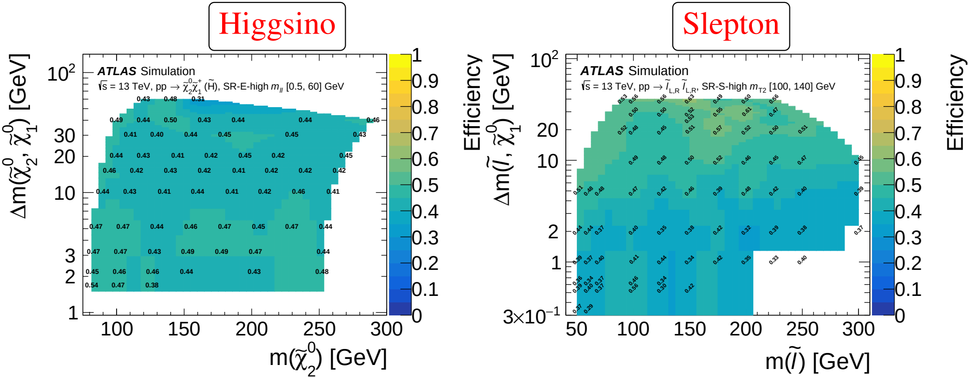
Event Selection: Acceptance



Low acceptances driven by hard-$E_{\mathrm{T}}^{\mathrm{miss}}$ requirement

- EWKino acceptances also include branching ratio
- Drop at low-Δm from soft leptons

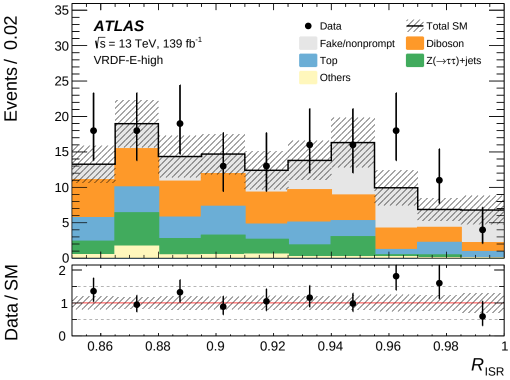
Event Selection: Efficiency



Efficiencies mostly due to lepton ID:

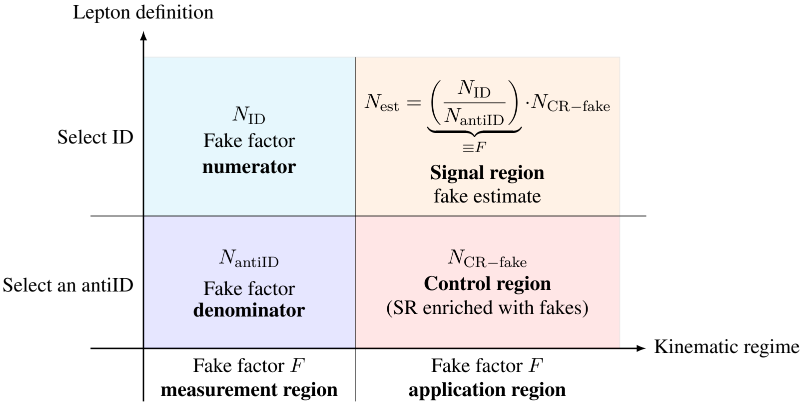
- Tight ID/isolation requirements to reduce fakes
- Room for improvement!

Background Strategy



- Data-driven approach for fake/non-prompt leptons (Fake Factors)
- MC used for events with ≥ 2 prompt leptons
  - $t\bar{t}$ and $Z \rightarrow \tau\tau$ scaled in signal-free **control regions**
  - All others scaled to predicted cross sections
- All estimates checked in signal-free **validation regions**

Data-driven fake lepton backgrounds



Lepton definition

Select ID

N_{ID}
Fake factor
numerator

$$N_{\mathrm{est}} = \underbrace{\left(\frac{N_{\mathrm{ID}}}{N_{\mathrm{antiID}}}\right)}_{\equiv F} \cdot N_{\mathrm{CR-fake}}$$

Signal region
fake estimate

Select an antiID

N_{antiID}
Fake factor
denominator

$N_{\mathrm{CR-fake}}$
Control region
(SR enriched with fakes)

Kinematic regime

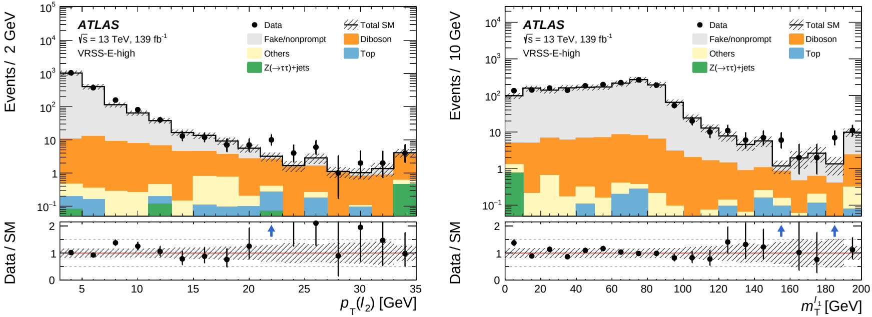
Fake factor F
measurement region

Fake factor F
application region

1. **Estimate** fake factors in dijet region
2. **Apply** fake factors in VR/CR/SR

Same-sign validation region

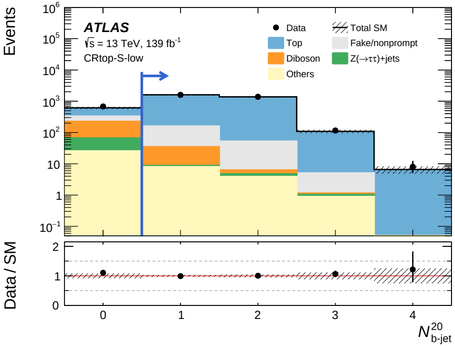
$\ell^{\pm}\ell^{\pm}$ events often from W+jets with jet→fake/non-prompt lepton:

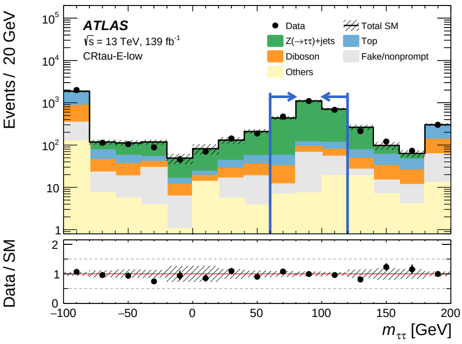


Systematics on fake-factor estimates typically $\sim 30\%$, based on:

- Modeling of kinematic variables
- Non-closure in `VRSS`

Control Regions



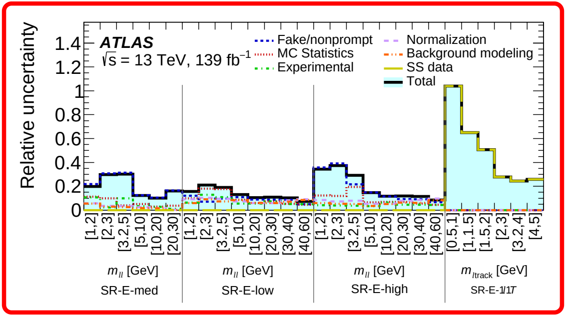


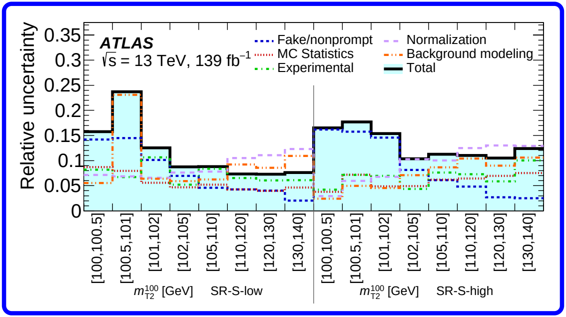
Control regions are used to scale $t\bar{t}$ and $Z \to \tau\tau$

- Scale factors are near unity

Backgrounds	$E_{\mathrm{T}}^{\mathrm{miss}}$ region	Normalization Parameters electroweakino	slepton	VBF
$t\bar{t}/Wt$	high	1.08 ± 0.20	1.05 ± 0.20	1.04 ± 0.04
	low	1.08 ± 0.18	1.09 ± 0.19	
$Z^{(*)}/\gamma^{*}(\to \tau\tau)$ + jets	high	0.96 ± 0.14	0.80 ± 0.17	0.97 ± 0.13
	low	1.02 ± 0.15	1.08 ± 0.17	
VV	high	0.89 ± 0.27	0.85 ± 0.28	–
	low	0.69 ± 0.22	0.71 ± 0.23	

Systematics

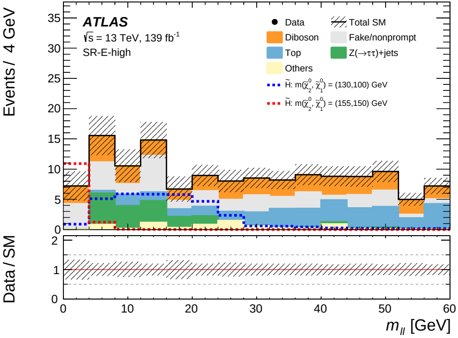


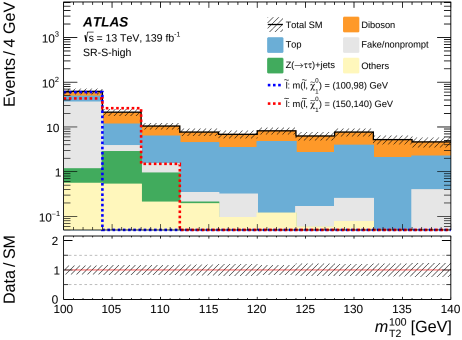


Large uncertainties from fake factors, statistics

- Some will improve with more data, especially $1\ell 1T$
- Non-trivial ISR modeling systs, mitigated by studies of $Z \to \mu\mu$ in data
- Jet, lepton, calibration systs are $\sim$negligible here

Blinded Signal Regions: Final Discriminants





Search Strategy

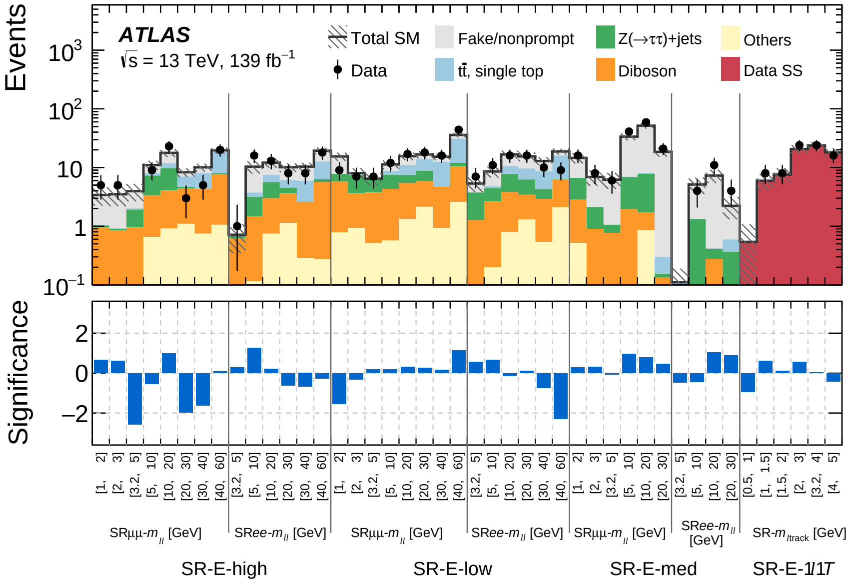
- Model-independent, cut-and-count SR's for *discovery*
- If no significant excess, use a model-dependent shape fit for *exclusion*
- Also include medium/low-E_T^{miss} regions (not shown)

The Results

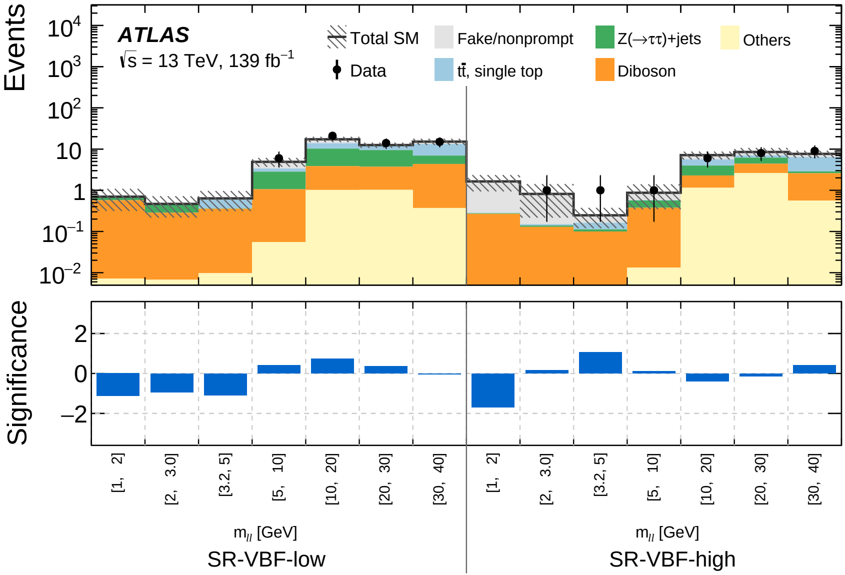
Results! Model-independent “discovery” regions

	Signal Region	N_{obs}	N_{exp}	$\langle\epsilon\sigma\rangle^{95}_{\text{obs}}$ [fb]	S^{95}_{obs}	S^{95}_{exp}	$p(s=0)$
SR–E	$m_{\ell\ell} < 1$	0	1.0 ± 1.0	0.022	3.0	$3.0^{+1.3}_{-0.0}$	0.50
	$m_{\ell\ell} < 2$	46	44 ± 6.8	0.15	21	19^{+7}_{-5}	0.38
	$m_{\ell\ell} < 3$	90	77 ± 12	0.29	41	31^{+11}_{-9}	0.18
	$m_{\ell\ell} < 5$	151	138 ± 18	0.38	52	43^{+16}_{-11}	0.24
	$m_{\ell\ell} < 10$	244	200 ± 19	0.62	86	49^{+26}_{-13}	0.034
	$m_{\ell\ell} < 20$	383	301 ± 23	0.95	132	61^{+22}_{-16}	0.0034
	$m_{\ell\ell} < 30$	453	366 ± 27	1.04	144	70^{+26}_{-20}	0.0065
	$m_{\ell\ell} < 40$	492	420 ± 30	0.96	134	74^{+29}_{-20}	0.027
	$m_{\ell\ell} < 60$	583	520 ± 35	0.97	135	84^{+32}_{-23}	0.063
SR–VBF	$m_{\ell\ell} < 2$	0	2.8 ± 1.6	0.022	3.0	$3.9^{+1.6}_{-0.9}$	0.50
	$m_{\ell\ell} < 3$	1	3.1 ± 1.7	0.030	3.6	$4.4^{+2.0}_{-1.0}$	0.50
	$m_{\ell\ell} < 5$	2	3.3 ± 1.7	0.035	4.8	$5.2^{+2.1}_{-1.1}$	0.50
	$m_{\ell\ell} < 10$	9	8.4 ± 2.7	0.068	9.5	$8.8^{+3.2}_{-2.2}$	0.43
	$m_{\ell\ell} < 20$	36	32 ± 5	0.14	20	16^{+6}_{-4}	0.27
	$m_{\ell\ell} < 30$	58	52 ± 7	0.19	26	21^{+8}_{-6}	0.28
	$m_{\ell\ell} < 40$	82	74 ± 10	0.24	33	27^{+10}_{-7}	0.27
SR–VBF–high	$m_{\ell\ell} < 2$	0	2.4 ± 1.1	0.022	3.0	$4.0^{+1.6}_{-0.9}$	0.50
	$m_{\ell\ell} < 3$	1	3.0 ± 1.4	0.025	3.5	$4.6^{+1.8}_{-1.2}$	0.50
	$m_{\ell\ell} < 5$	2	3.0 ± 1.4	0.034	4.7	$5.1^{+2.0}_{-1.3}$	0.50
	$m_{\ell\ell} < 10$	3	3.8 ± 1.7	0.041	5.6	$5.8^{+2.1}_{-1.3}$	0.50
	$m_{\ell\ell} < 20$	9	11.7 ± 2.8	0.055	8	$9^{+4}_{-2.3}$	0.50
	$m_{\ell\ell} < 30$	17	20 ± 5	0.079	11	$13^{+5}_{-3.2}$	0.50
	$m_{\ell\ell} < 40$	26	28 ± 6	0.10	14	15^{+6}_{-4}	0.50
SR–S	$m^{100}_{\text{T2}} < 100.5$	24	27 ± 4.8	0.09	13	14^{+5}_{-4}	0.50
	$m^{100}_{\text{T2}} < 101$	41	46 ± 6.5	0.11	16	18^{+7}_{-5}	0.50
	$m^{100}_{\text{T2}} < 102$	91	82 ± 10	0.25	35	28^{+10}_{-8}	0.25
	$m^{100}_{\text{T2}} < 105$	158	158 ± 17	0.30	41	41^{+16}_{-11}	0.50
	$m^{100}_{\text{T2}} < 110$	243	242 ± 21	0.38	52	52^{+19}_{-14}	0.36
	$m^{100}_{\text{T2}} < 120$	328	312 ± 24	0.51	71	60^{+22}_{-17}	0.26
	$m^{100}_{\text{T2}} < 130$	419	388 ± 28	0.66	92	68^{+27}_{-18}	0.17
	$m^{100}_{\text{T2}} < 140$	472	443 ± 31	0.69	95	74^{+28}_{-21}	0.19

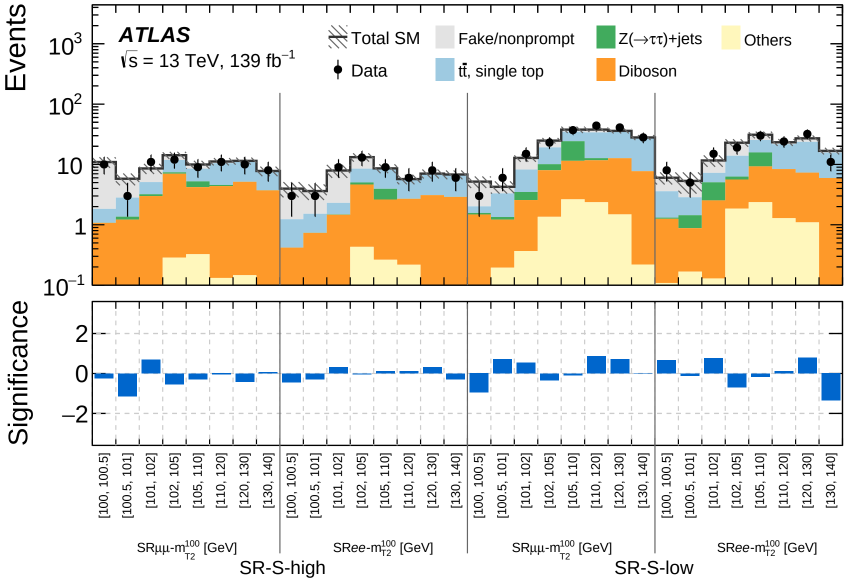
Results! Shape-fit “exclusion” regions: EWKinos



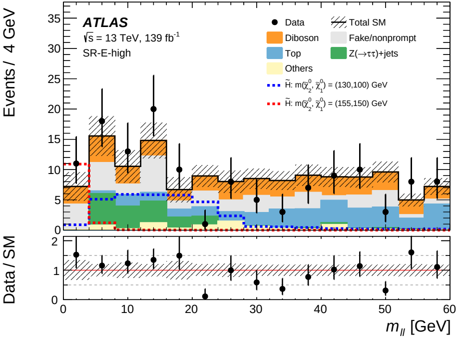
Results! Shape-fit “exclusion” regions: VBF

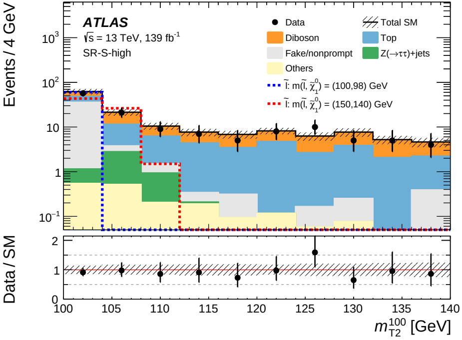


Results! Shape-fit “exclusion” regions: Sleptons



Results! Shape-fit “exclusion” regions

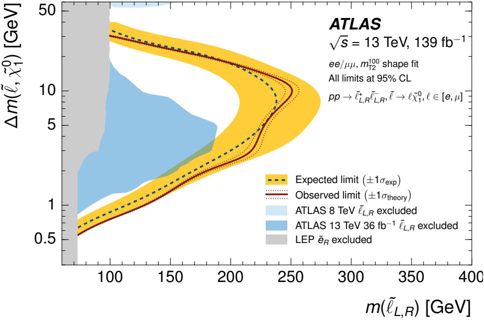


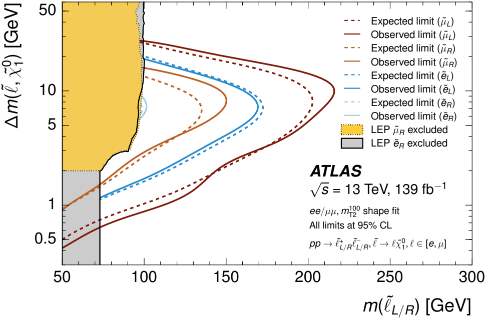


No significant excesses.

- Interpret results as limits on simplified models
- Extend fits to separate ee, $\mu\mu$ channels, modified binning...

Slepton Interpretation

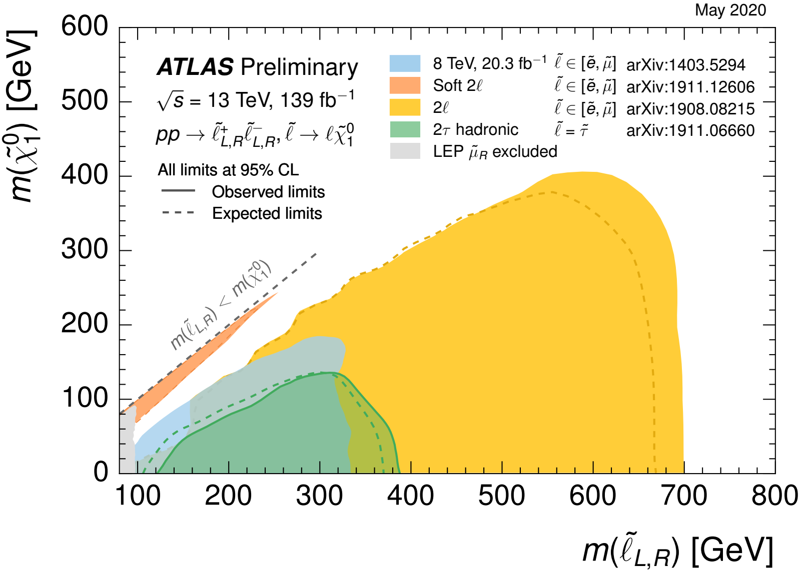




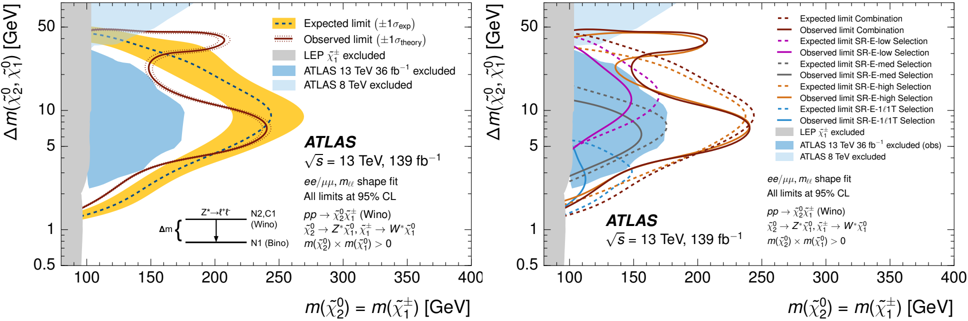
Limits on Compressed Sleptons

- Constraints on fully-degenerate sleptons up to 250 GeV
- Separate interpretations for left/right selectrons/smuons
  - Compressed smuons of particular interest due to $g-2$ and DM/coannihilation models, LEP coverage only down to $\Delta m = 2$ GeV, extended for the first time here

Slepton Interpretation, In Context

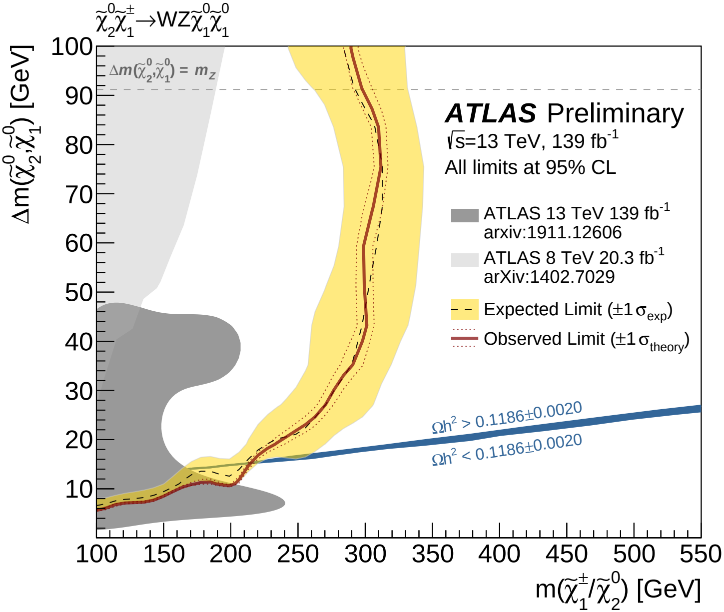


Wino-Bino Interpretation

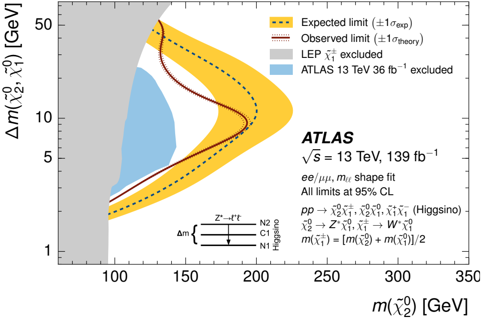


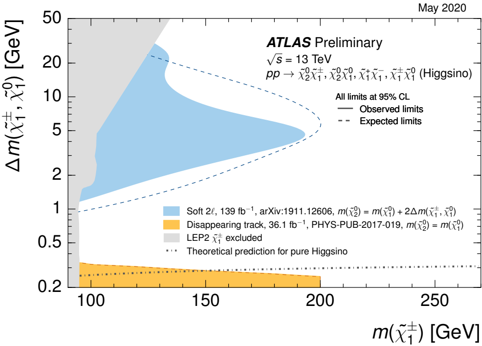
- Pushed constraints in all directions relative to 36/fb paper
- All signal regions contribute, $1\ell 1T$ selection particularly powerful at low splittings!

Wino-Bino Interpretation, In Context



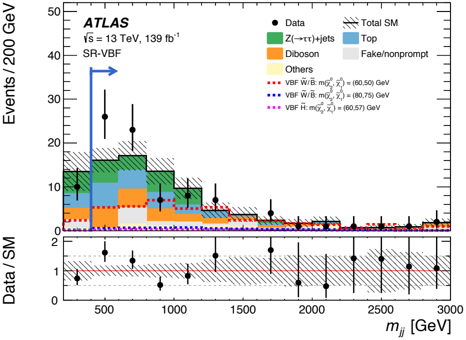
Higgsino Interpretation

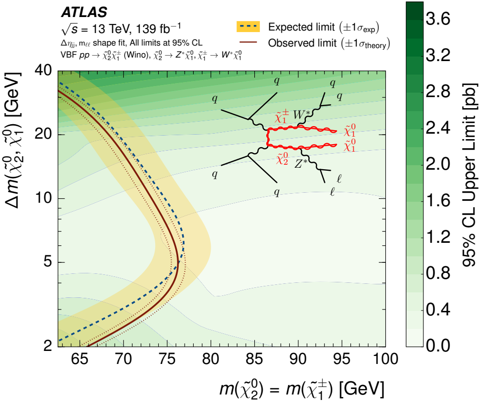




- Similar story for Higgsinos, which assume a slightly different mass spectrum
- Closing the gap between Disappearing Track searches and prompt-2ℓ searches

VBF Production



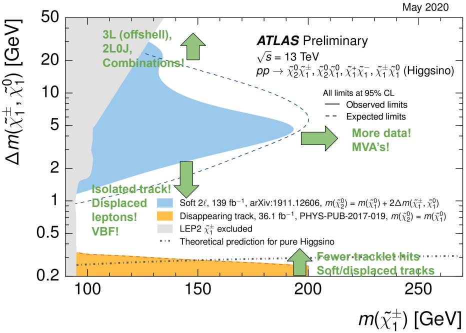


- Low cross section for VBF SUSY along with small $Z \to \ell\ell$ BR makes this a challenging search
- Pioneered by Andy Aukerman and the Pitt team
- Will become much more interesting at high-lumi!

The Future

Prospects

First steps in a longer program:



Extrapolating our limits (assuming no signal):

	95% CL Limits	
	140 fb^{-1}	3 ab^{-1}
Higgsino	193 GeV	456 GeV
Wino/Bino	240 GeV	551 GeV
Slepton	251 GeV	573 GeV

Collider Reach: scaling by parton luminosities

Additional gains from:

- Using larger data samples to reduce systematics (especially on fake/non-prompt estimates)
- Improvements in lepton reconstruction and ID efficiency (especially at low-p_T)
- Many other ideas

CMS; JHEP 08 (2019)150

Fukuda et al.;Phys. Rev. Lett. 124, 101801 (2020)

Conclusion

Low-scale SUSY is an attractive extension of the Standard Model.

- Light, electroweak SUSY states mitigate **naturalness** concerns and provide a viable dark matter candidate
    - **Compressed** mass spectra are *especially* well-motivated
- Searches for **direct production** of EWK SUSY states are *finally extending LEP limits*, providing exciting opportunities for discovery at the LHC