Recent results from SUPERSYMMETRY searches with ATLAS

Jean-François Arguin (Université de Montréal)
On behalf of the ATLAS Collaboration

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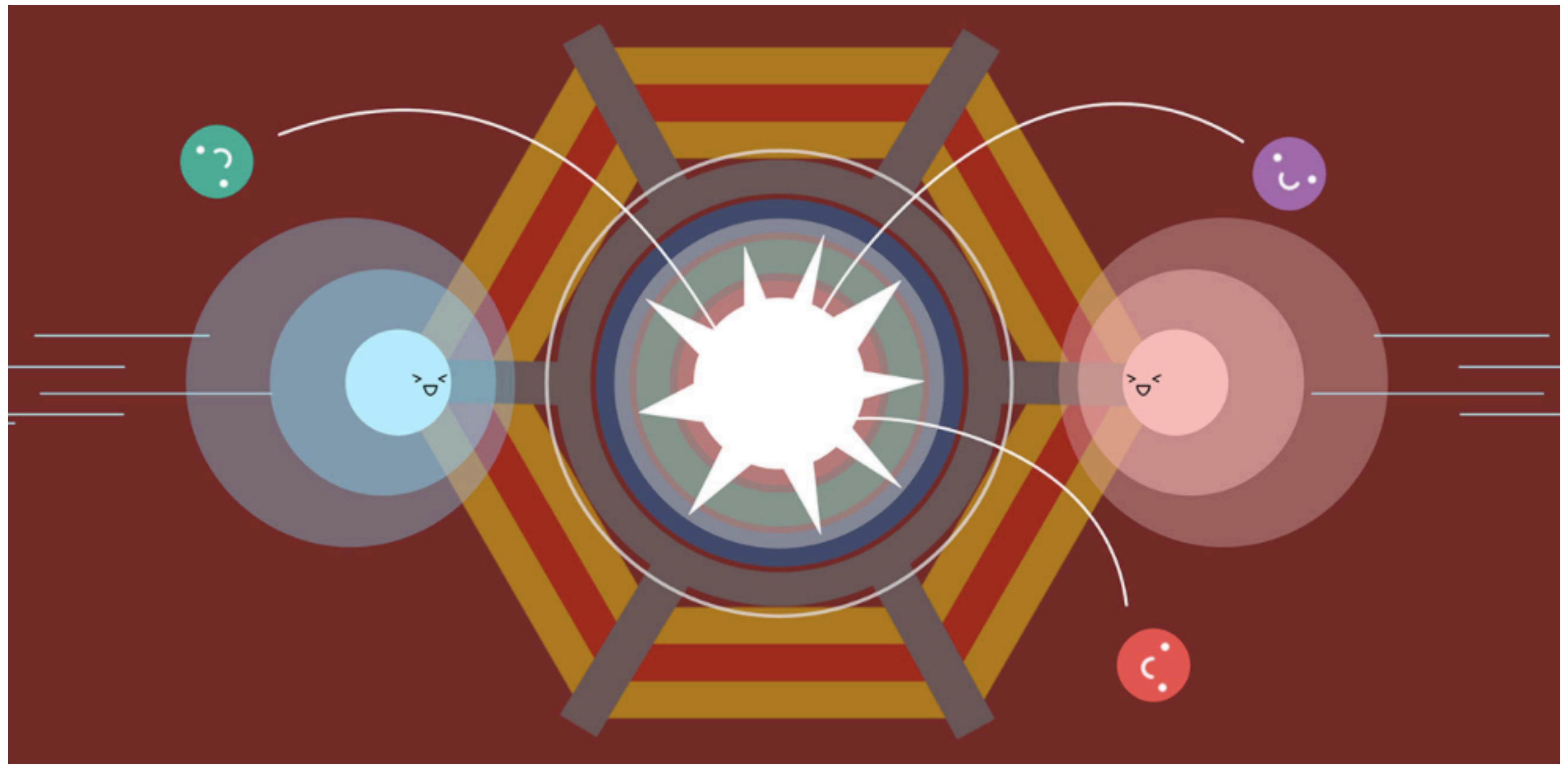
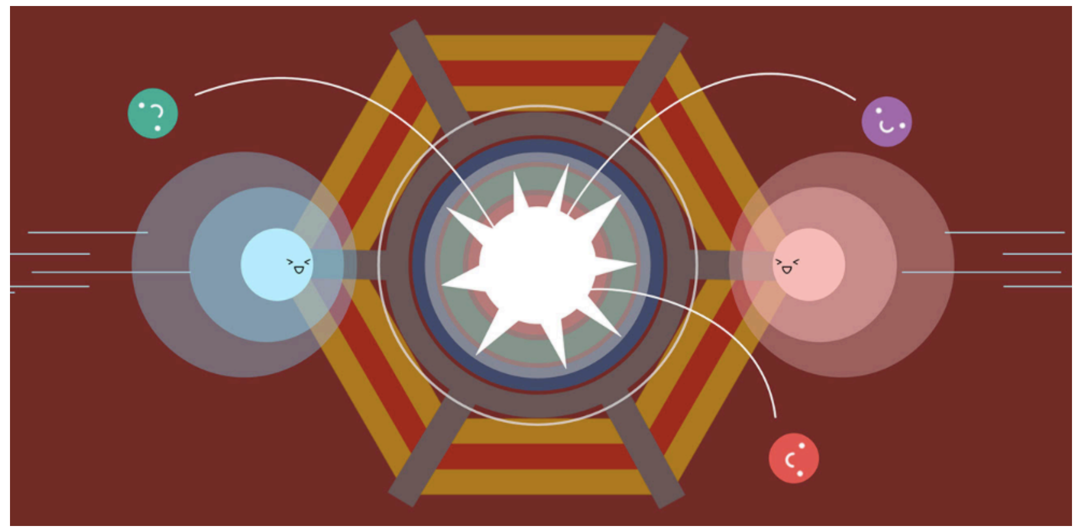
Picture from Symmetry Magazine

Outline

- Supersymmetry (SUSY): an attractive extension of the SM
- Searches for SUSY at ATLAS
  - Inclusive squarks/gluinos
  - stop/sbottom
  - Electroweakinos
  - Long-lived sparticles
- The way forward

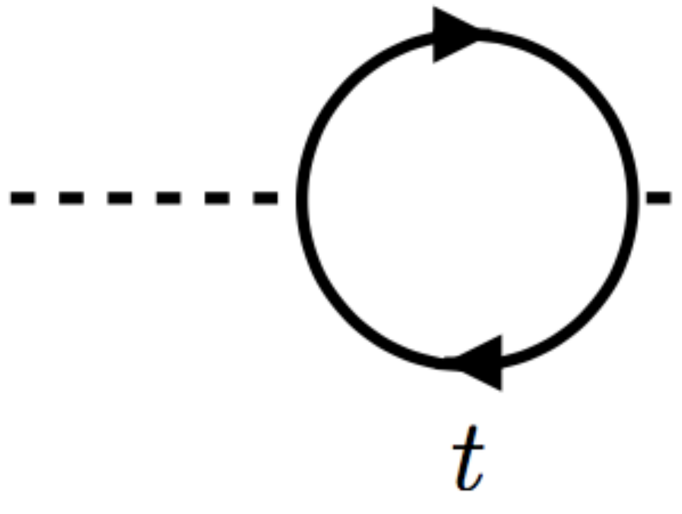




SUSY is an attractive theory

- Supersymmetry (SUSY): symmetry between bosons and fermions
    - Implies new superpartners with spin ½ difference from SM particles
    - Ex.: top quark → stop quark (spin 0), Higgs → Higgsino (spin ½)
- SUSY solves several problems/limitations of the SM at the same time
    - **Hierarchy problem**
    - Dark matter
    - Grand unification

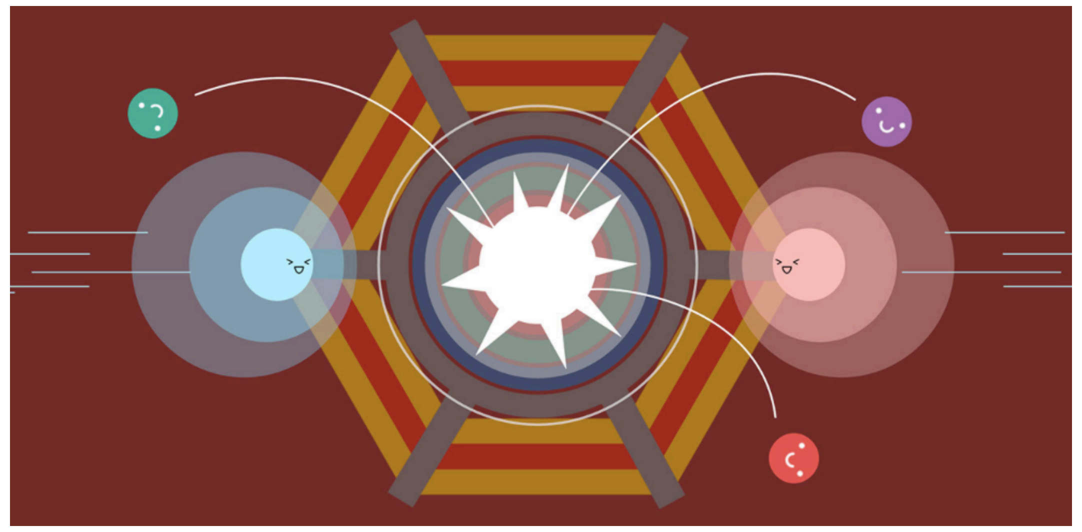
$\Delta m_h^2 \sim$



$\sim -\frac{3}{4\pi} y_t^2 \Lambda_{SM}^2 + \ldots$

$\sim 10^{38}\mathrm{GeV}^2$ if $\Lambda_{SM} = M_{Planck}$!

SUSY is an attractive theory



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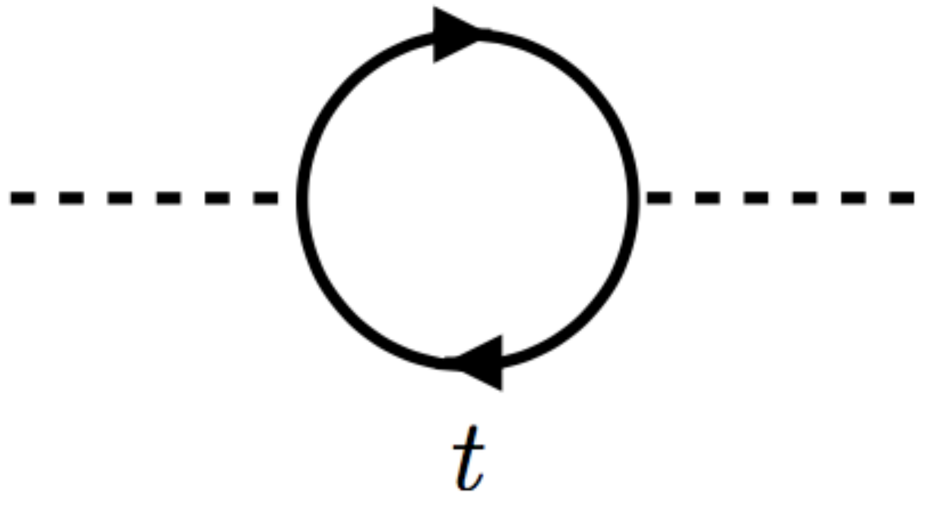
$\Delta m_h^2 \sim$  $\sim -\frac{3}{4\pi} y_t^2 \Lambda_{SM}^2 + \ldots$

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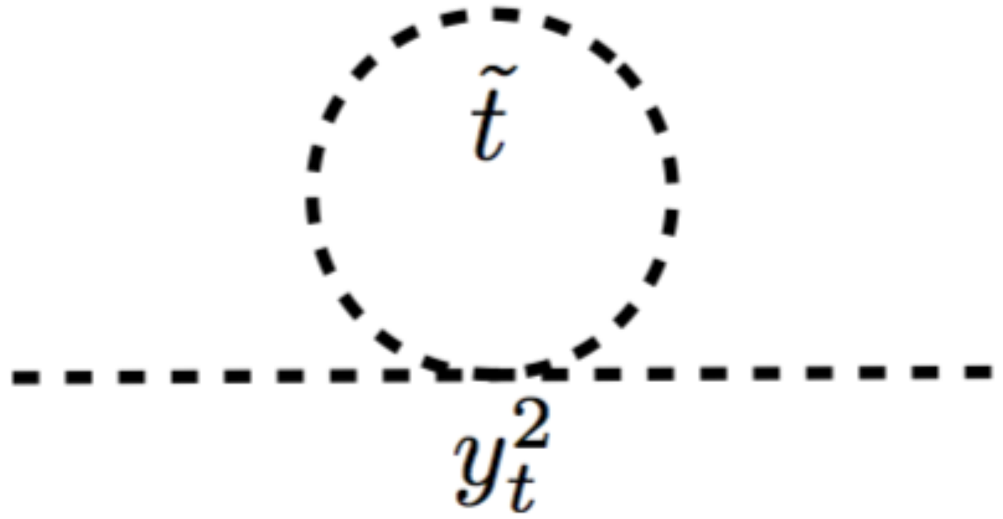
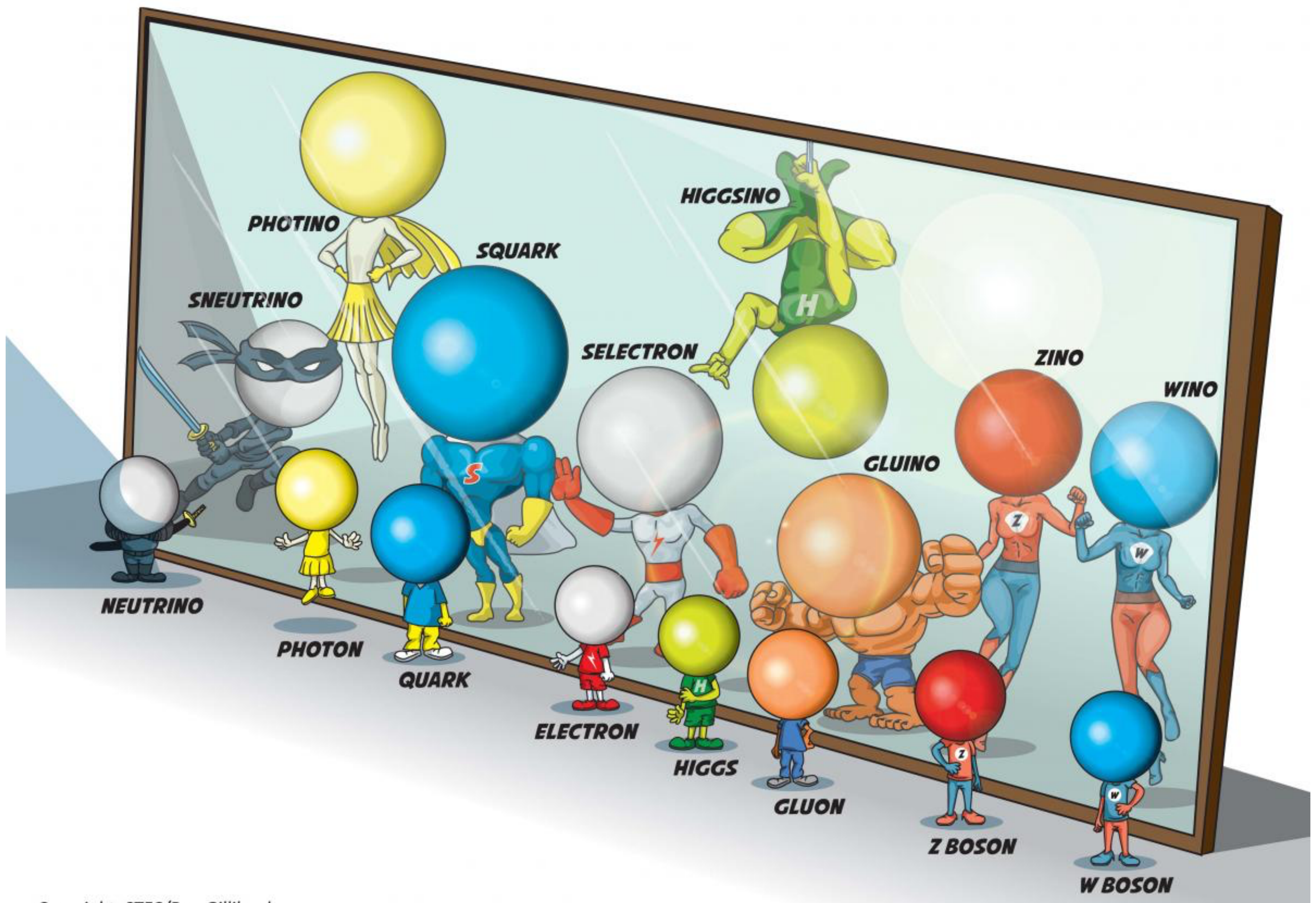
$\Delta m_h^2 \sim$  $\sim +\frac{3}{4\pi} y_t^2 \Lambda_{SM}^2 + \ldots$

Where are the superpartners?

- If supersymmetry was exact: the superpartners would be everywhere
- **SUSY must be broken**: heavy superpartners
  - Fortunately, SUSY can still solve the SM problems even though it's broken
- But, generally, **they can't be too heavy either**. $M_{\mathrm{SUSY}} \sim \mathcal{O}(\mathrm{TeV})$



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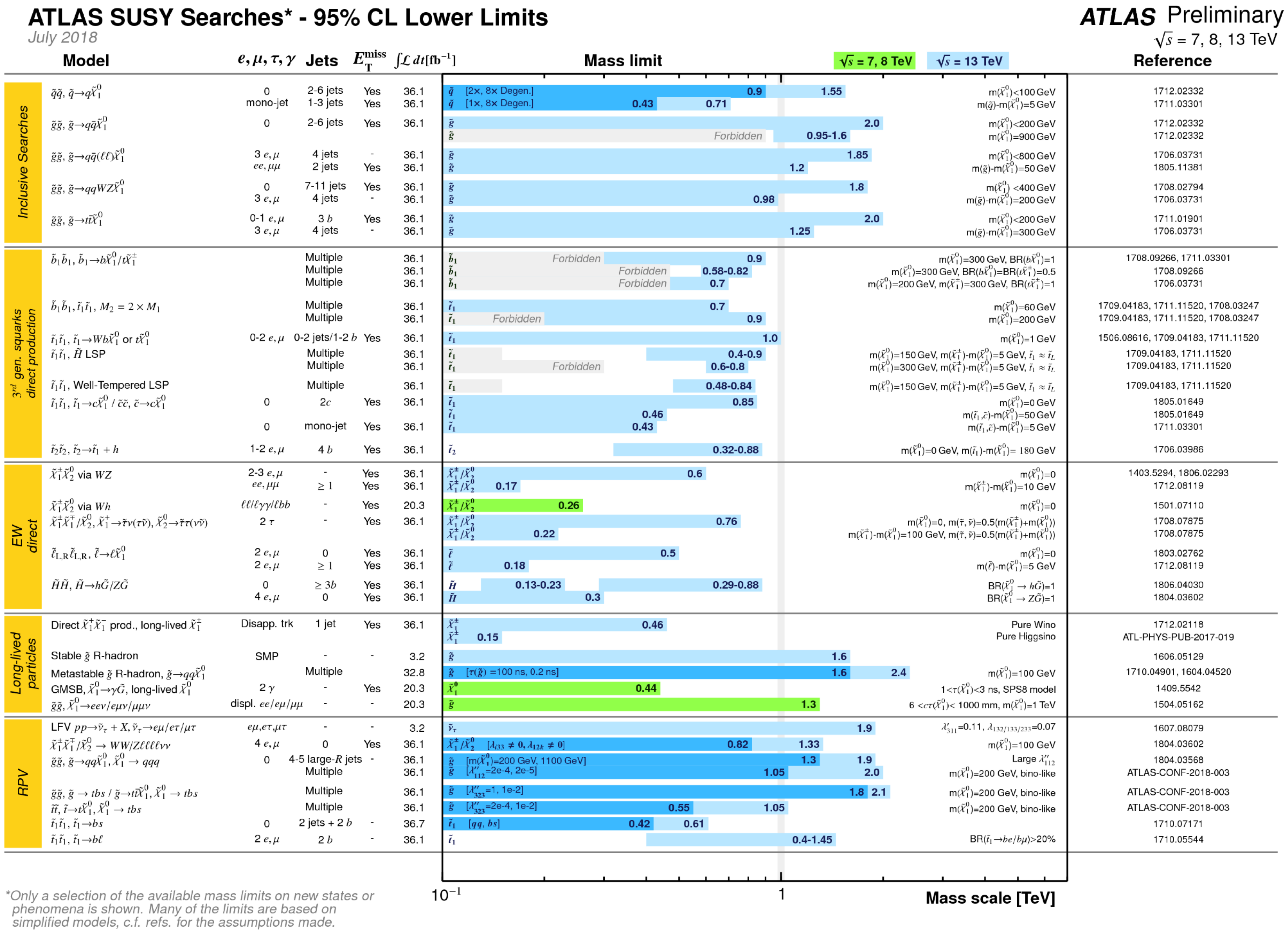
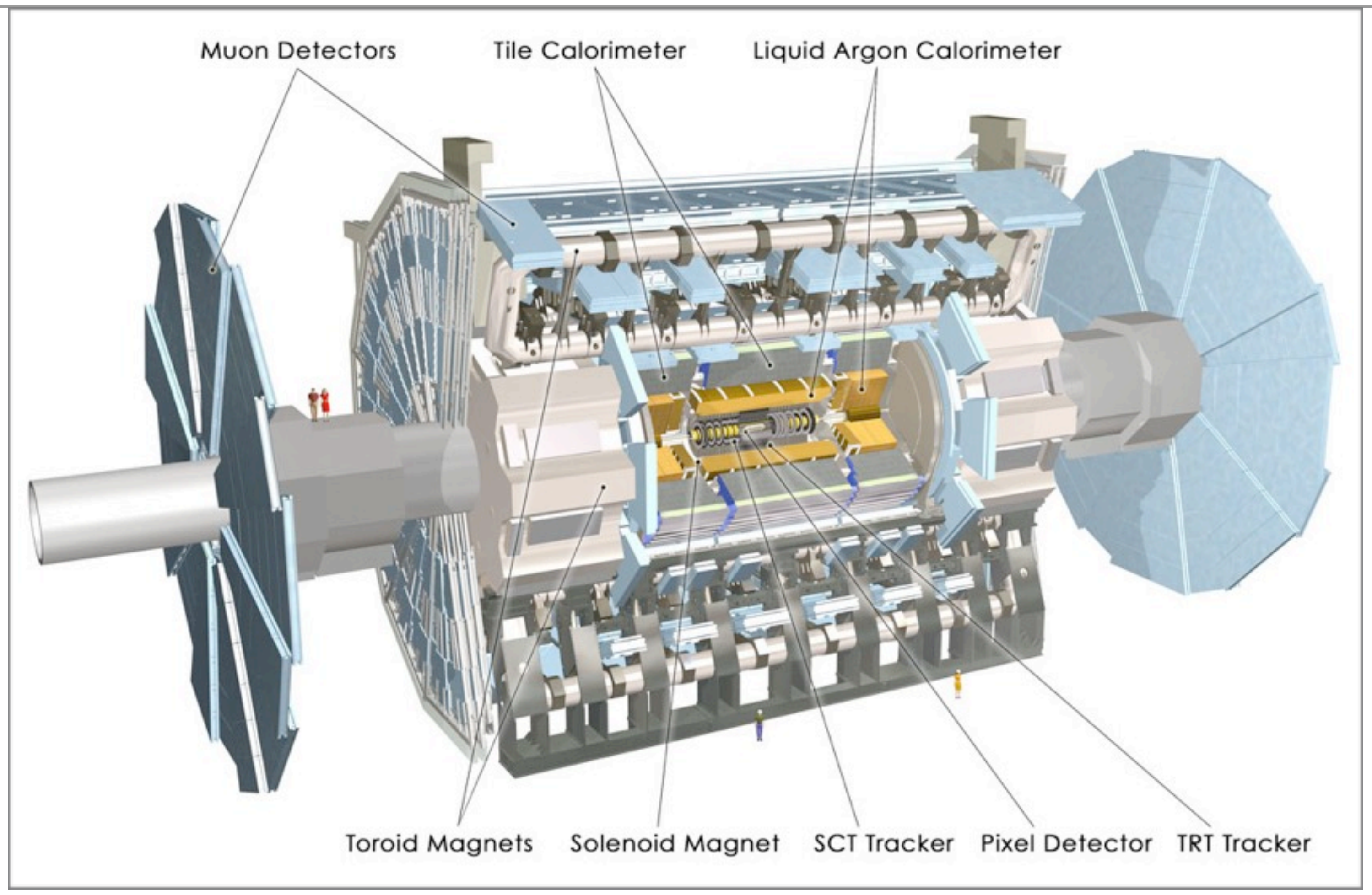
⇒ Superpartners could be discoverable at the LHC!

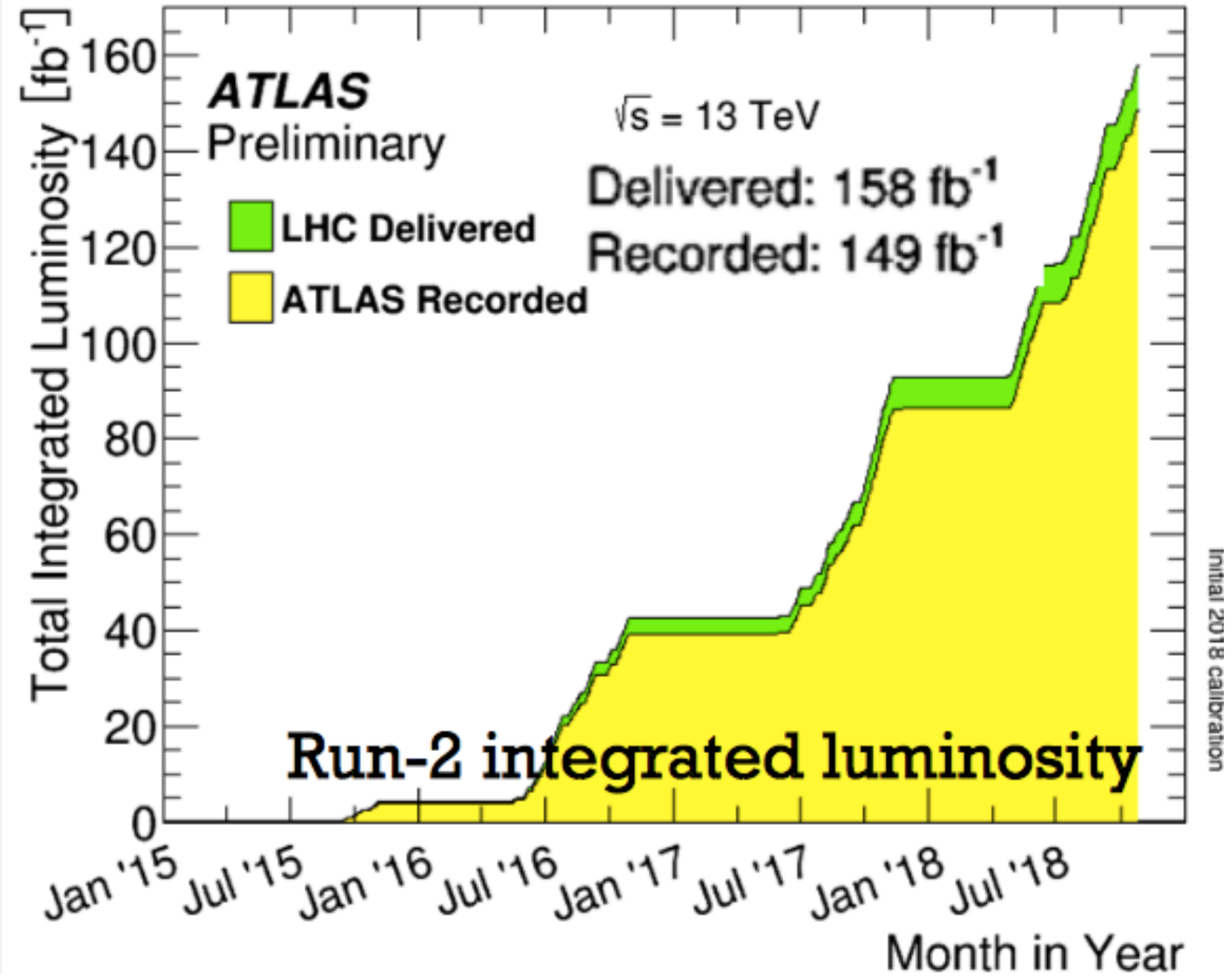
Large collective effort to discover SUSY at the LHC!



ATLAS detector is ideally suited for SUSY searches!

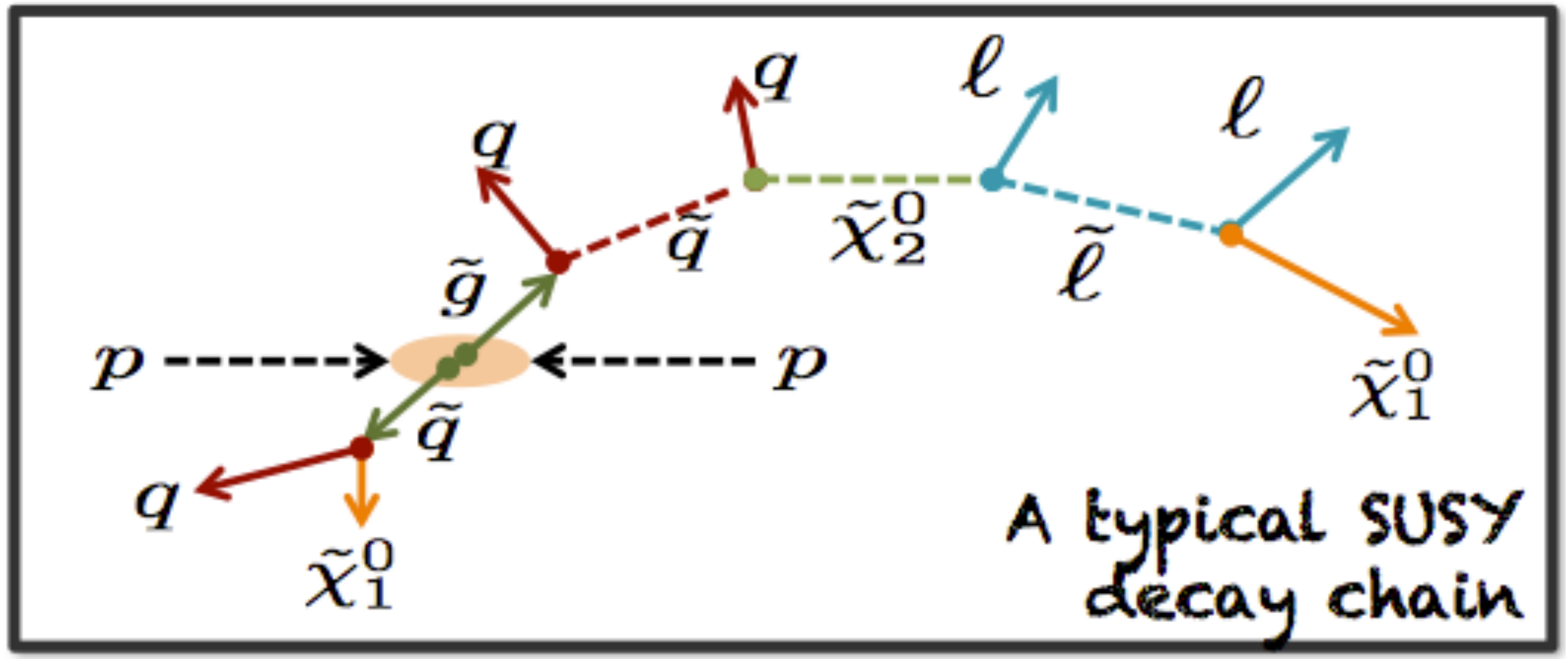
- Currently in LHC Run 2: $\sqrt{s}$ = 13 TeV
- Excellent LHC performance:
  - ~x2 higher luminosity than design
- Smooth operations for ATLAS
  - Collecting ~96% of LHC lumi
  - > 97% of detector channels operational
  - Manage to operate in high pile-up environment





What would superpartners production look like?

- **Strongly-interacting superpartners have highest production cross-section**
  - squarks, gluinos
- In most SUSY models: the number of superpartners is conserved in an interaction
  - Called R-parity conservation
  - Implies **SUSY particles are pair-produced**
- All SUSY particles (except one) decay promptly
  - A decay chain ensues

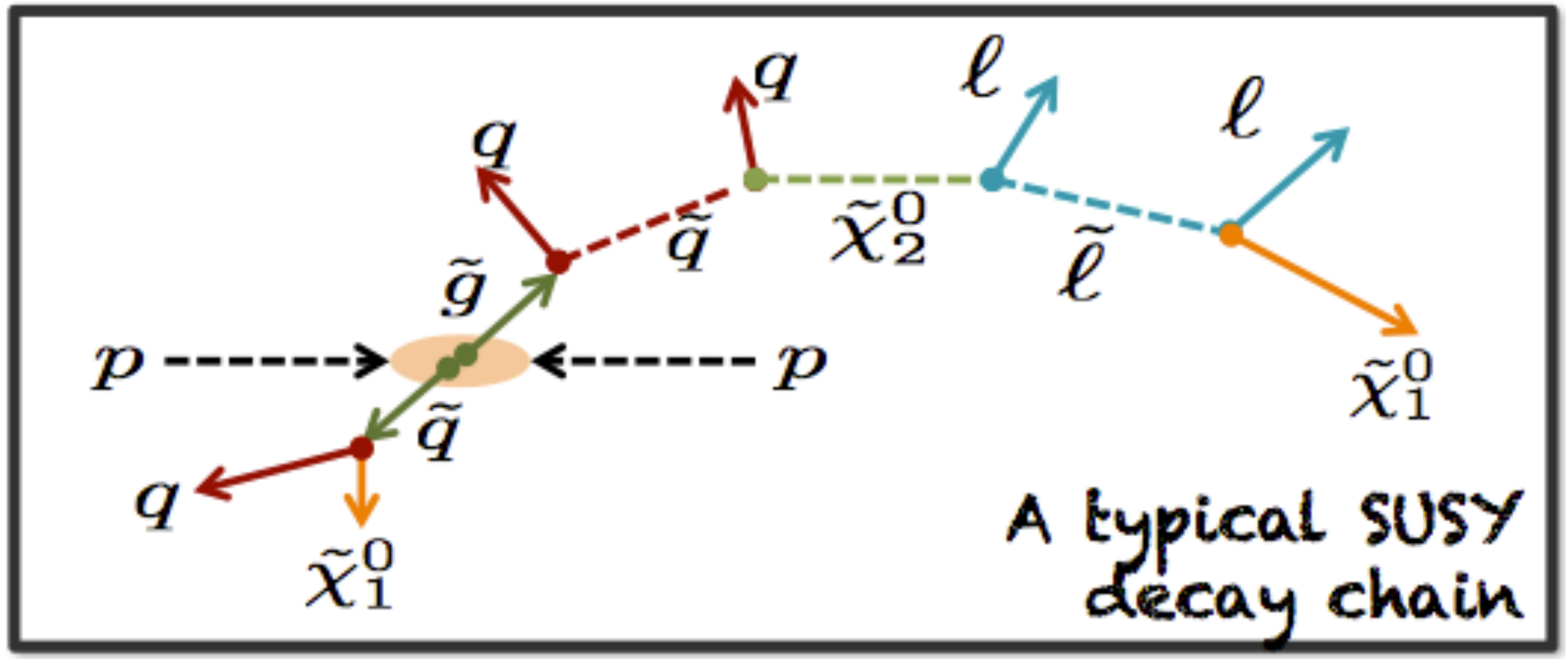


What would superpartners production look like?

- The superpartners of the **EWK gauge field mix** to produce **neutralinos** and **charginos**
  - bino, wino, higgsino →

$$\tilde{\chi}_1^0, \ldots \tilde{\chi}_4^0; \ \tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$$

- R-parity conservation: the **lightest SUSY particle (LSP) is typically stable**
  - ➡ **Dark matter candidate**!
  - Typically the $\tilde{\chi}_1^0$



<u>Experimental signature</u>:
- lots of missing momentum (dark matter)
- high-energy jets
- sometimes charged leptons

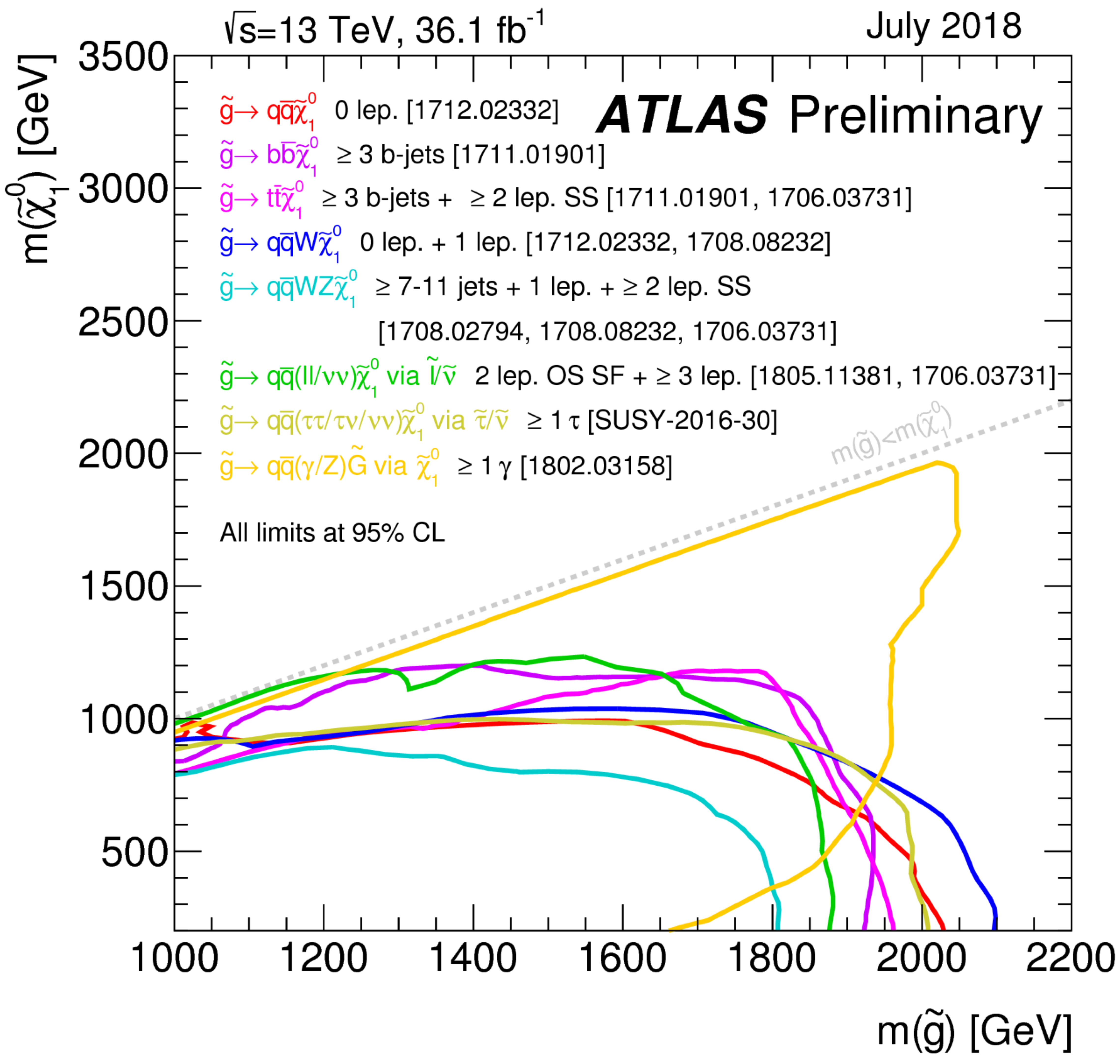
Searches for inclusive squarks and gluinos

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

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt [fb^{-1}]$	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$ [2×, 8× Degen.] 0.9 1.55	$m(\tilde{\chi}_1^0)$<100 GeV	1712.02332
		mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$ [1×, 8× Degen.] 0.43 0.71	$m(\tilde{q})$-$m(\tilde{\chi}_1^0)$=5 GeV	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.0	$m(\tilde{\chi}_1^0)$<200 GeV	1712.02332
						$\tilde{g}$ Forbidden 0.95-1.6	$m(\tilde{\chi}_1^0)$=900 GeV	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	$\tilde{g}$ 1.85	$m(\tilde{\chi}_1^0)$<800 GeV	1706.03731
		$ee, \mu\mu$	2 jets	Yes	36.1	$\tilde{g}$ 1.2	$m(\tilde{g})$-$m(\tilde{\chi}_1^0)$=50 GeV	1805.11381
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$ 1.8	$m(\tilde{\chi}_1^0)$ <400 GeV	1708.02794
		3 e, μ	4 jets	-	36.1	$\tilde{g}$ 0.98	$m(\tilde{g})$-$m(\tilde{\chi}_1^0)$=200 GeV	1706.03731
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	36.1	$\tilde{g}$ 2.0	$m(\tilde{\chi}_1^0)$<200 GeV	1711.01901
		3 e, μ	4 jets	-	36.1	$\tilde{g}$ 1.25	$m(\tilde{g})$-$m(\tilde{\chi}_1^0)$=300 GeV	1706.03731

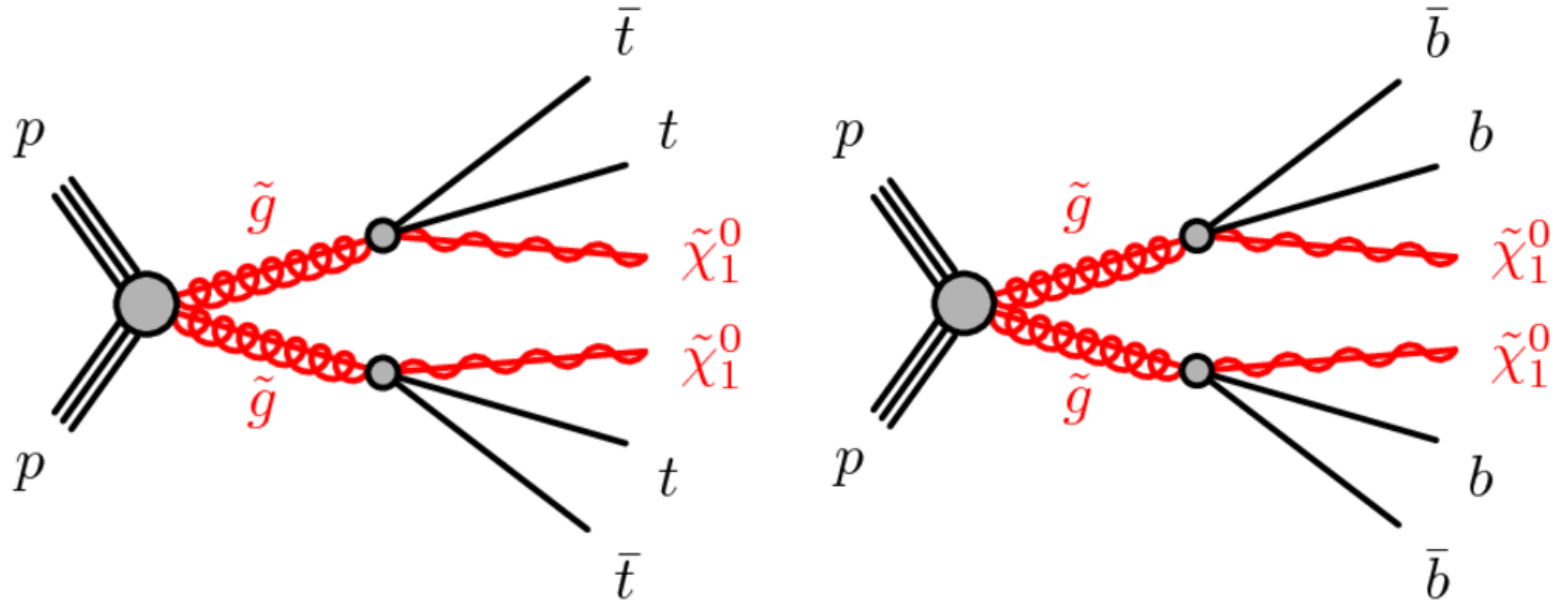
Summary of searches for inclusive squarks and gluinos

- Unfortunately no excess observed so far
- Limits on sparticle masses will improve only incrementally with luminosity
  - Moving toward complex techniques like machine learning



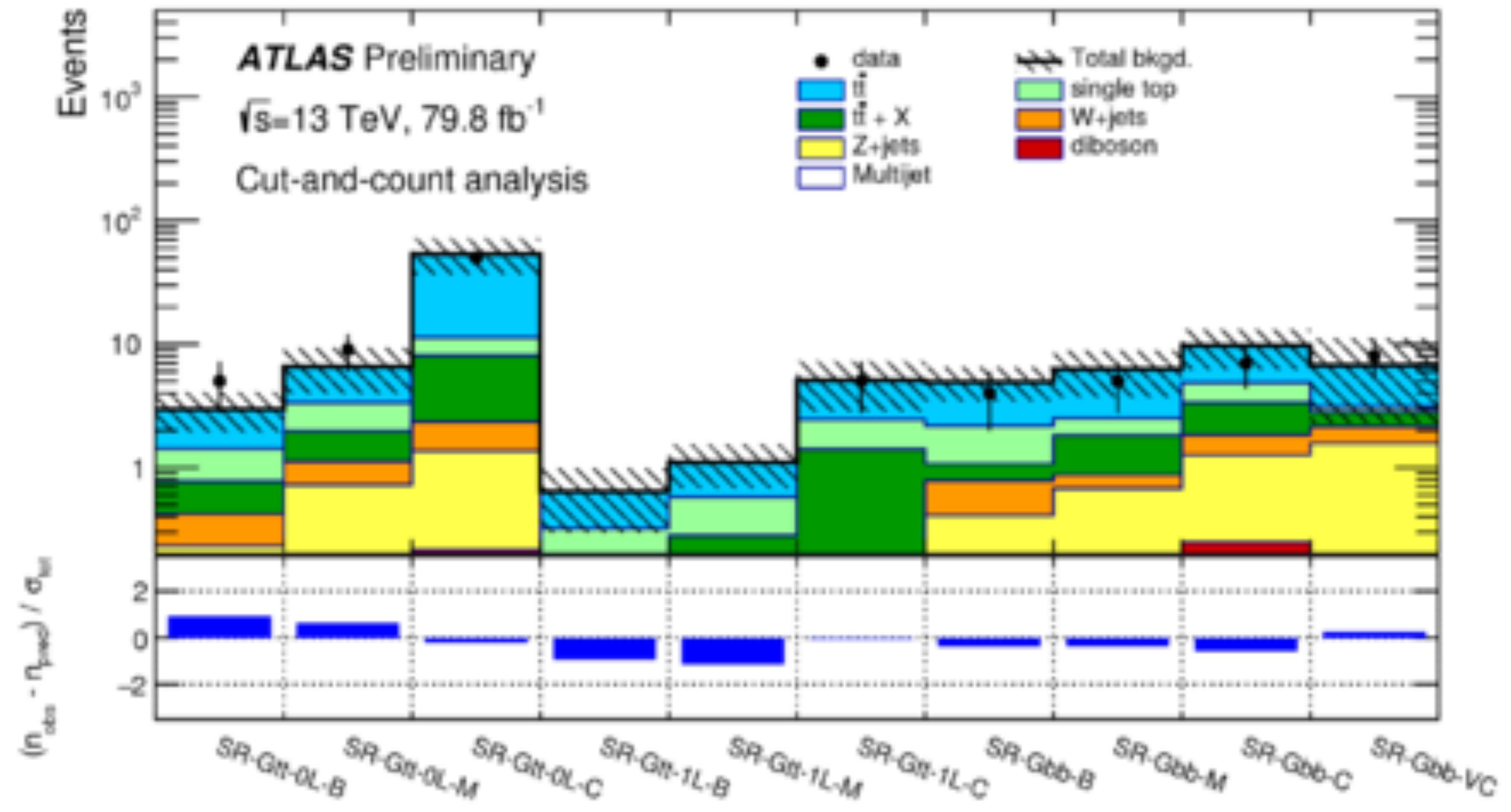
An example: gluino to stop/sbottom

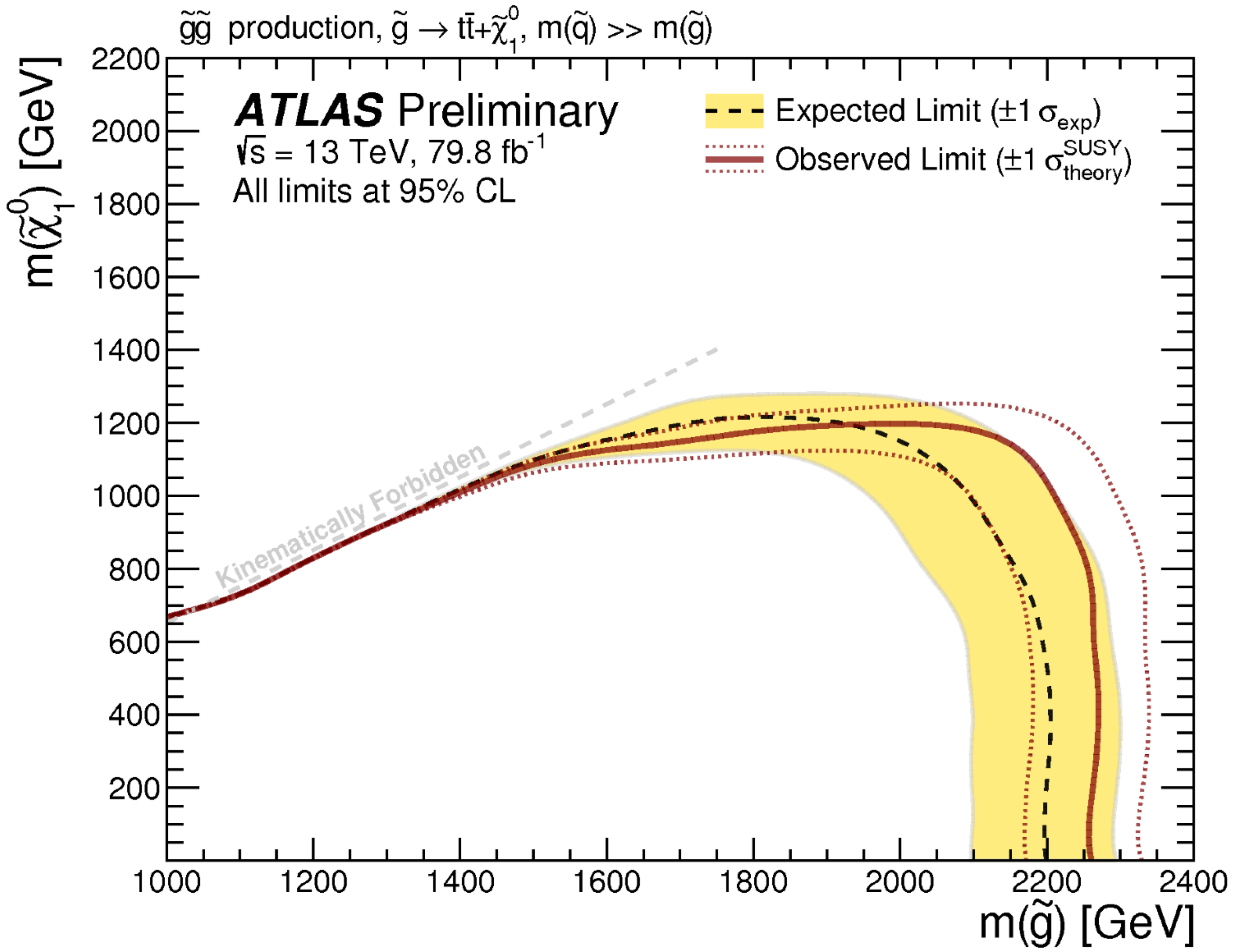
- $\tilde{g} \to \tilde{t}t, \;\; \tilde{g} \to \tilde{b}b$ well motivated by naturalness



- Several signal regions requiring ≥3 b-jets, lots of missing energy and hadronic activity

- Limits on gluino mass up-to 2.2 TeV





ATLAS-CONF-2018-041

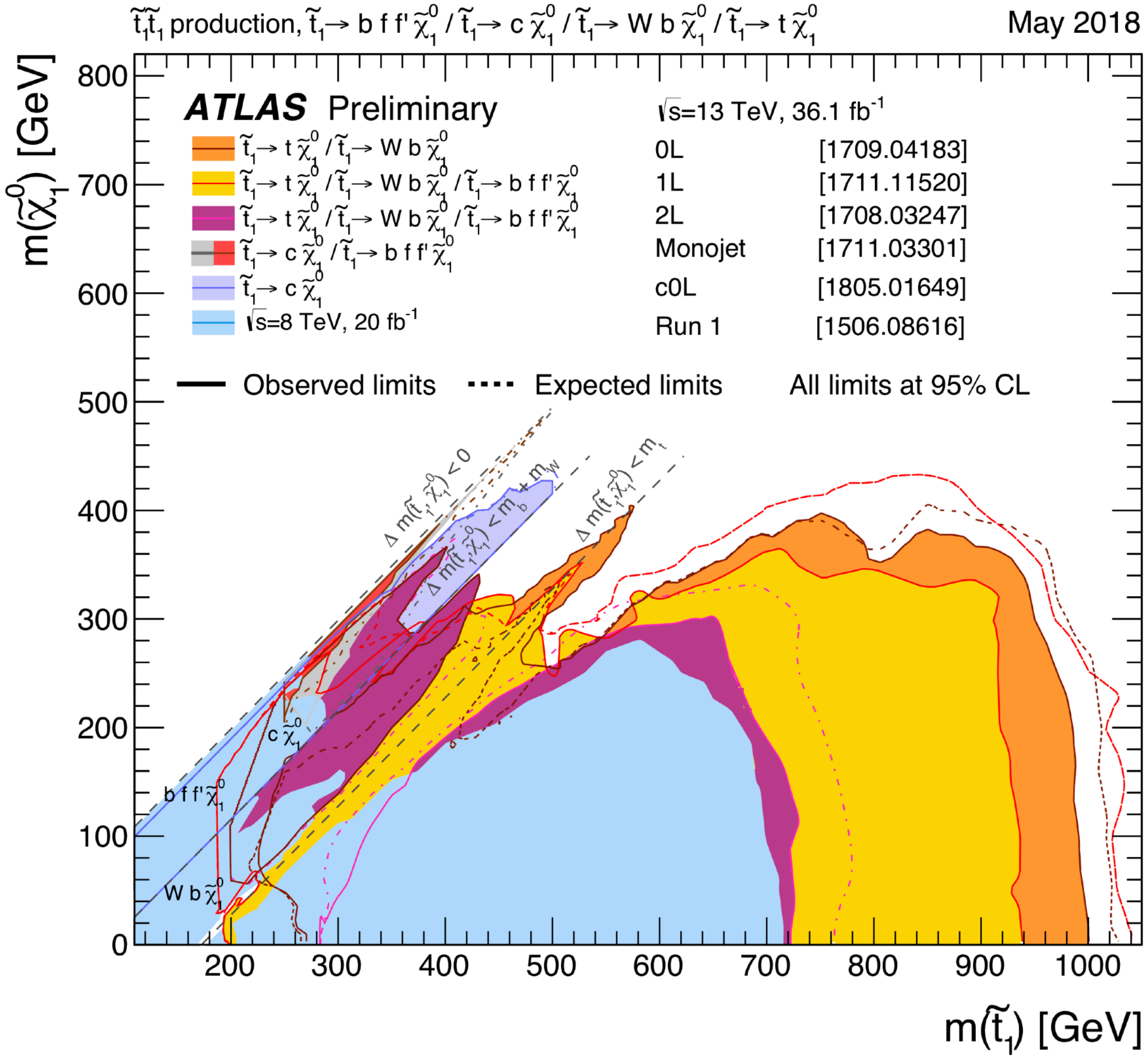
Searches for stop and sbottom

$\sqrt{s}$ = 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
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1,\ \tilde{b}_1 \to b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple		36.1	$\tilde{b}_1$ Forbidden 0.9	$m(\tilde{\chi}_1^0)$=300 GeV, BR$(b\tilde{\chi}_1^0)$=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.58-0.82	$m(\tilde{\chi}_1^0)$=300 GeV, BR$(b\tilde{\chi}_1^0)$=BR$(t\tilde{\chi}_1^\pm)$=0.5	1708.09266
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.7	$m(\tilde{\chi}_1^0)$=200 GeV, $m(\tilde{\chi}_1^\pm)$=300 GeV, BR$(t\tilde{\chi}_1^\pm)$=1	1706.03731
	$\tilde{b}_1\tilde{b}_1, \tilde{t}_1\tilde{t}_1,\ M_2 = 2 \times M_1$		Multiple		36.1	$\tilde{t}_1$ 0.7	$m(\tilde{\chi}_1^0)$=60 GeV	1709.04183, 1711.11520, 1708.03247
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.9	$m(\tilde{\chi}_1^0)$=200 GeV	1709.04183, 1711.11520, 1708.03247
	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1 \to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	36.1	$\tilde{t}_1$ 1.0	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1,\ \tilde{H}$ LSP		Multiple		36.1	$\tilde{t}_1$ 0.4-0.9	$m(\tilde{\chi}_1^0)$=150 GeV, $m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.6-0.8	$m(\tilde{\chi}_1^0)$=300 GeV, $m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$ 0.48-0.84	$m(\tilde{\chi}_1^0)$=150 GeV, $m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1 \to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c},\ \tilde{c} \to c\tilde{\chi}_1^0$	0	$2c$	Yes	36.1	$\tilde{t}_1$ 0.85	$m(\tilde{\chi}_1^0)$=0 GeV	1805.01649
						$\tilde{t}_1$ 0.46	$m(\tilde{t}_1,\tilde{c})$-$m(\tilde{\chi}_1^0)$=50 GeV	1805.01649
		0	mono-jet	Yes	36.1	$\tilde{t}_1$ 0.43	$m(\tilde{t}_1,\tilde{c})$-$m(\tilde{\chi}_1^0)$=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2,\ \tilde{t}_2 \to \tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1	$\tilde{t}_2$ 0.32-0.88	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$= 180 GeV	1706.03986

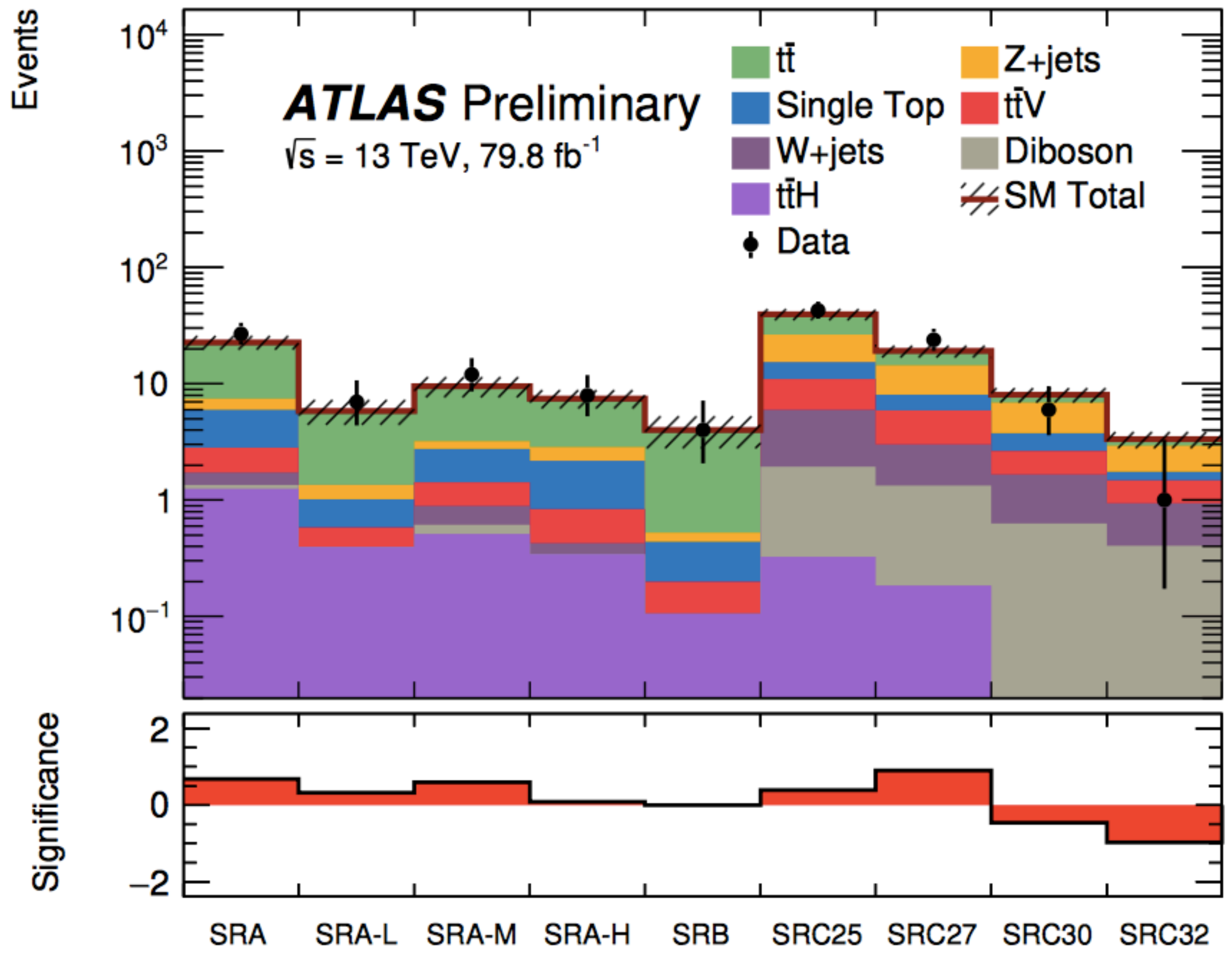
Summary of searches for stop and sbottom

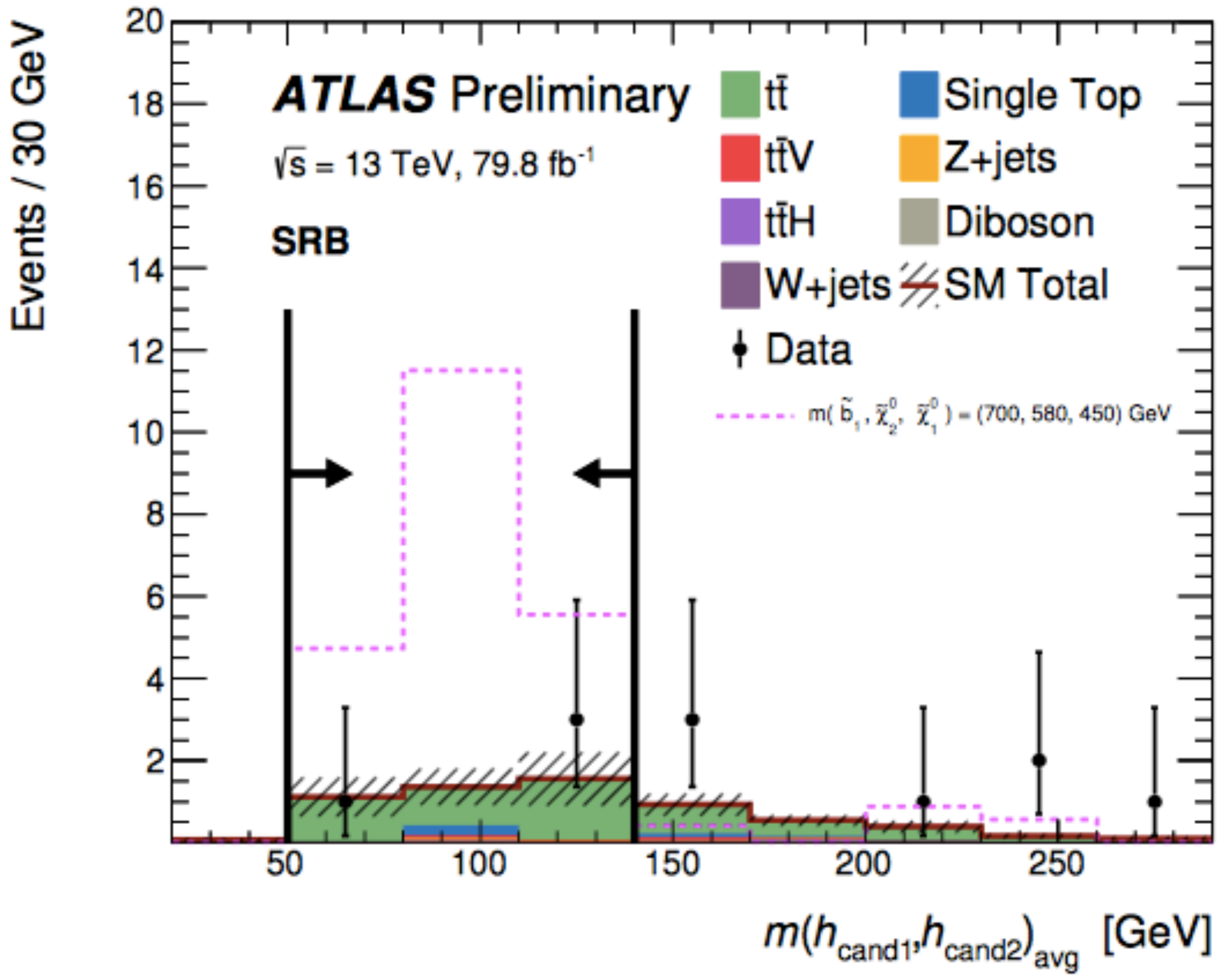
- Maybe the gluinos/squarks are too heavy to be seen at the LHC?
- **stop/sbottom are well motivated to by light by naturalness**
  - ➡ Very important focus at the LHC
- But again unfortunately no excess so far
  - Limits on stop mass up-to ~1 TeV

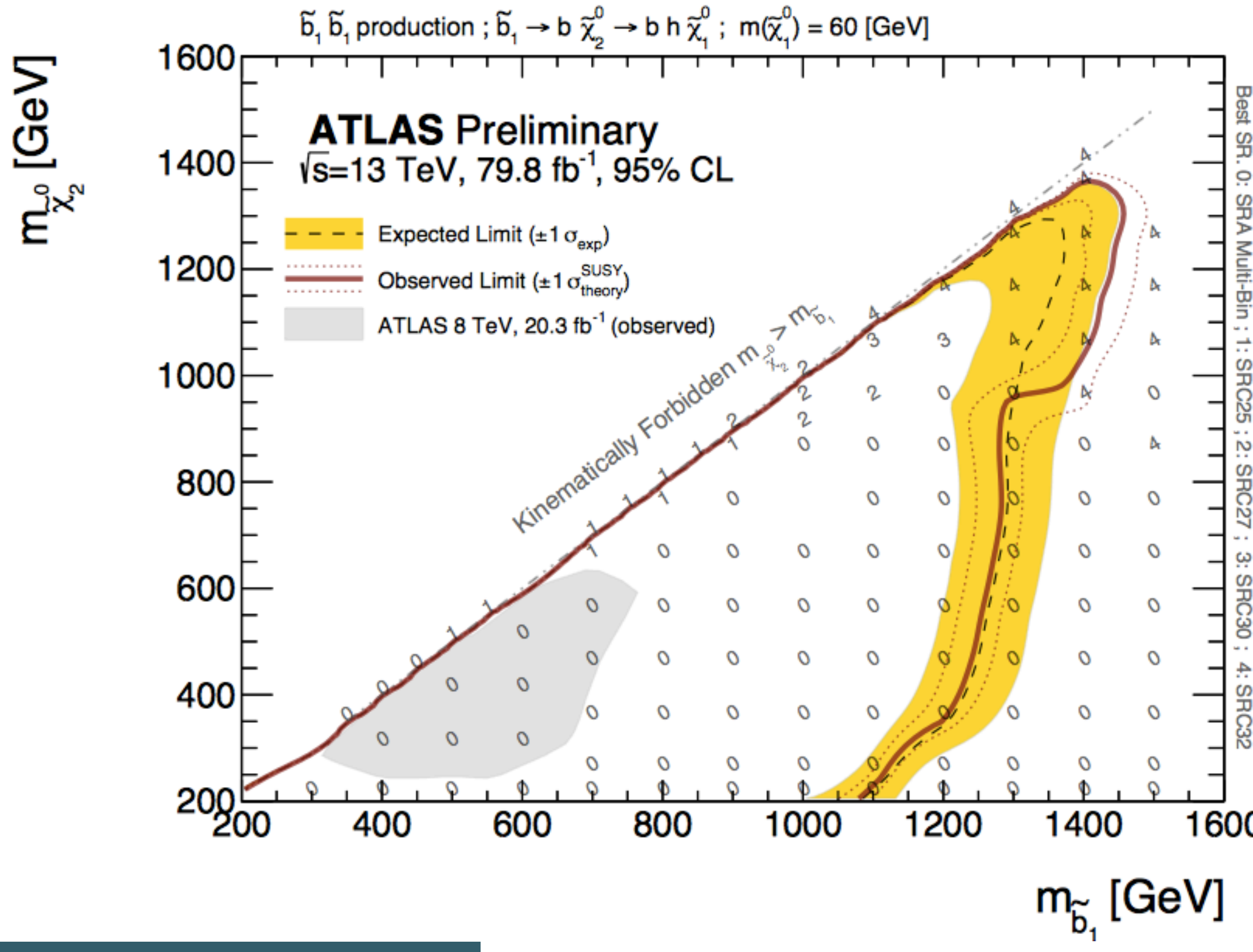


An example: $\tilde{b} \to b\tilde{\chi}_2^0,\ \tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$

- Well motivated by naturalness
- Targeting $h \to b\bar{b}$ (60%) → final state with 6 b-jets!
- Several signal regions targeting ≥4 b-jets, large E_T^{miss} and hadronic activity, and reconstructed $h \to b\bar{b}$ candidate(s)
- Limits on sbottom mass up-to 1.4 TeV







ATLAS-CONF-2018-040

Searches for electroweakinos

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

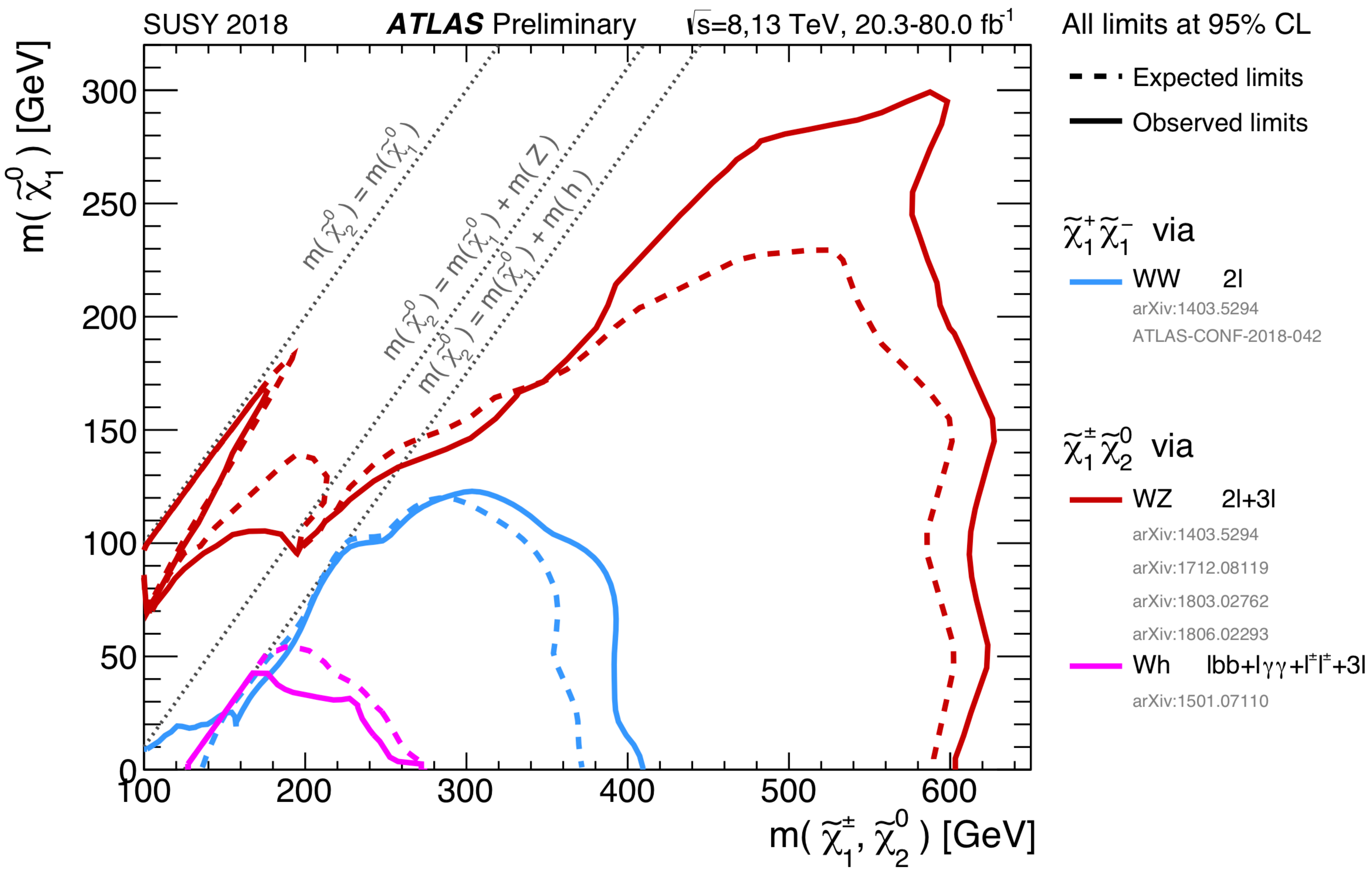
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[fb^{-1}]$	Mass limit			Reference
EW direct	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ	2-3 e, μ	-	Yes	36.1	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	0.6	$m(\tilde{\chi}_1^0)$=0	1403.5294, 1806.02293
		$ee, \mu\mu$	≥ 1	Yes	36.1	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	0.17	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$=10 GeV	1712.08119
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh	$\ell\ell/\ell\gamma\gamma/\ell bb$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	0.26	$m(\tilde{\chi}_1^0)$=0	1501.07110
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0, \tilde{\chi}_1^{+}\to\tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	0.76	$m(\tilde{\chi}_1^0)$=0, $m(\tilde{\tau}, \tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1708.07875
						$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	0.22	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$=100 GeV, $m(\tilde{\tau}, \tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1708.07875
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	36.1	$\tilde{\ell}$	0.5	$m(\tilde{\chi}_1^0)$=0	1803.02762
		2 e, μ	≥ 1	Yes	36.1	$\tilde{\ell}$	0.18	$m(\tilde{\ell})$-$m(\tilde{\chi}_1^0)$=5 GeV	1712.08119
	$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$	0	$\geq 3b$	Yes	36.1	$\tilde{H}$	0.13-0.23, 0.29-0.88	BR($\tilde{\chi}_1^0 \to h\tilde{G}$)=1	1806.04030
		4 e, μ	0	Yes	36.1	$\tilde{H}$	0.3	BR($\tilde{\chi}_1^0 \to Z\tilde{G}$)=1	1804.03602

Summary of searches for direct electroweakino production

- Pure $\chi_1^0 \chi_1^0$ cross-section tiny
- Better to search for $\chi_1^+ \chi_2^0$ or $\chi_1^+ \chi_1^+$
- Which then typically decay to χ_1^0 via emitting a SM boson (W, Z, h)

$$\chi_2^0 \rightarrow h\chi_1^0 \qquad \chi_2^0 \rightarrow Z\chi_1^0$$
$$\chi_1^+ \rightarrow W^+\chi_1^0$$

- **Room for $m(\chi_1^0)$ down-to ~100 GeV**, **not as constrained as squark/gluino searches!**



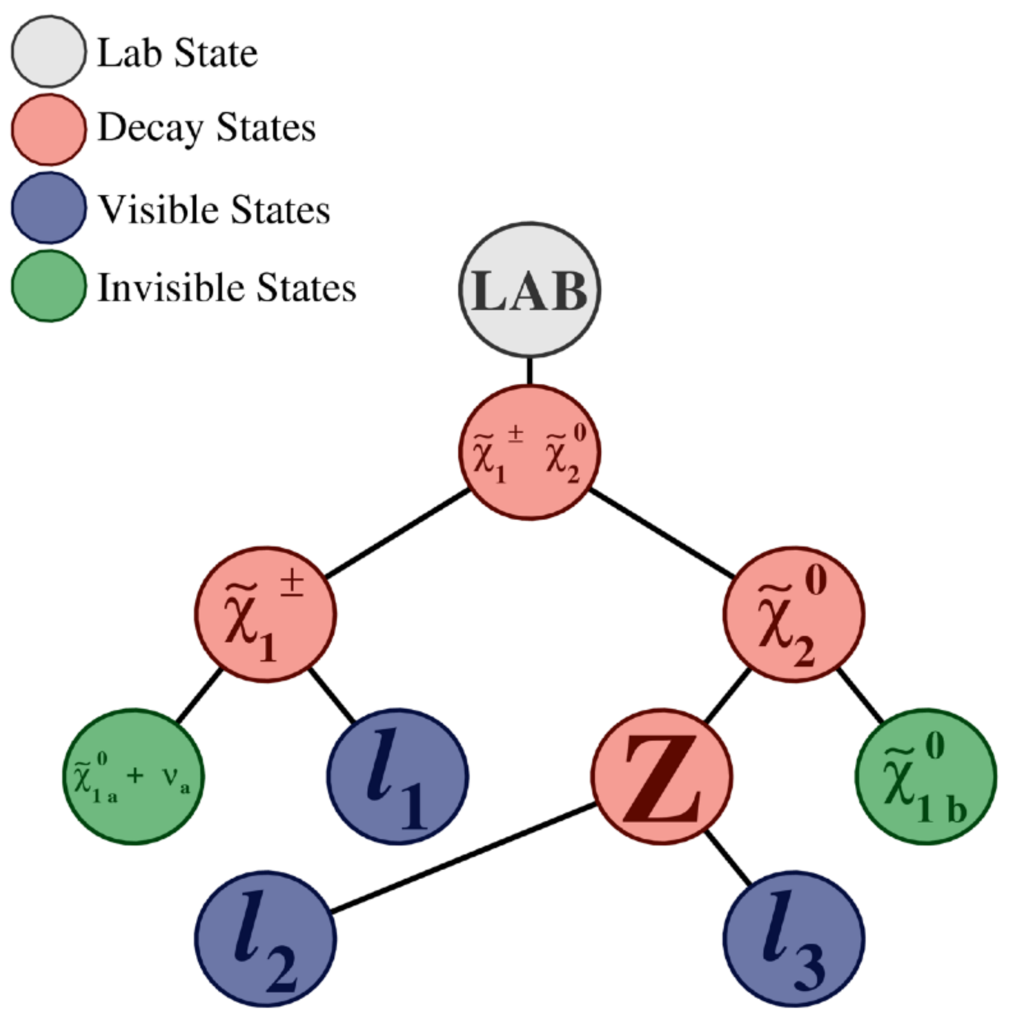
An example: Search for electroweakinos with recursive jigsaw reconstruction

arXiv:1806.02293

- Search for $\chi_1^+ \chi_2^0$ production in the 2/3-lepton channels

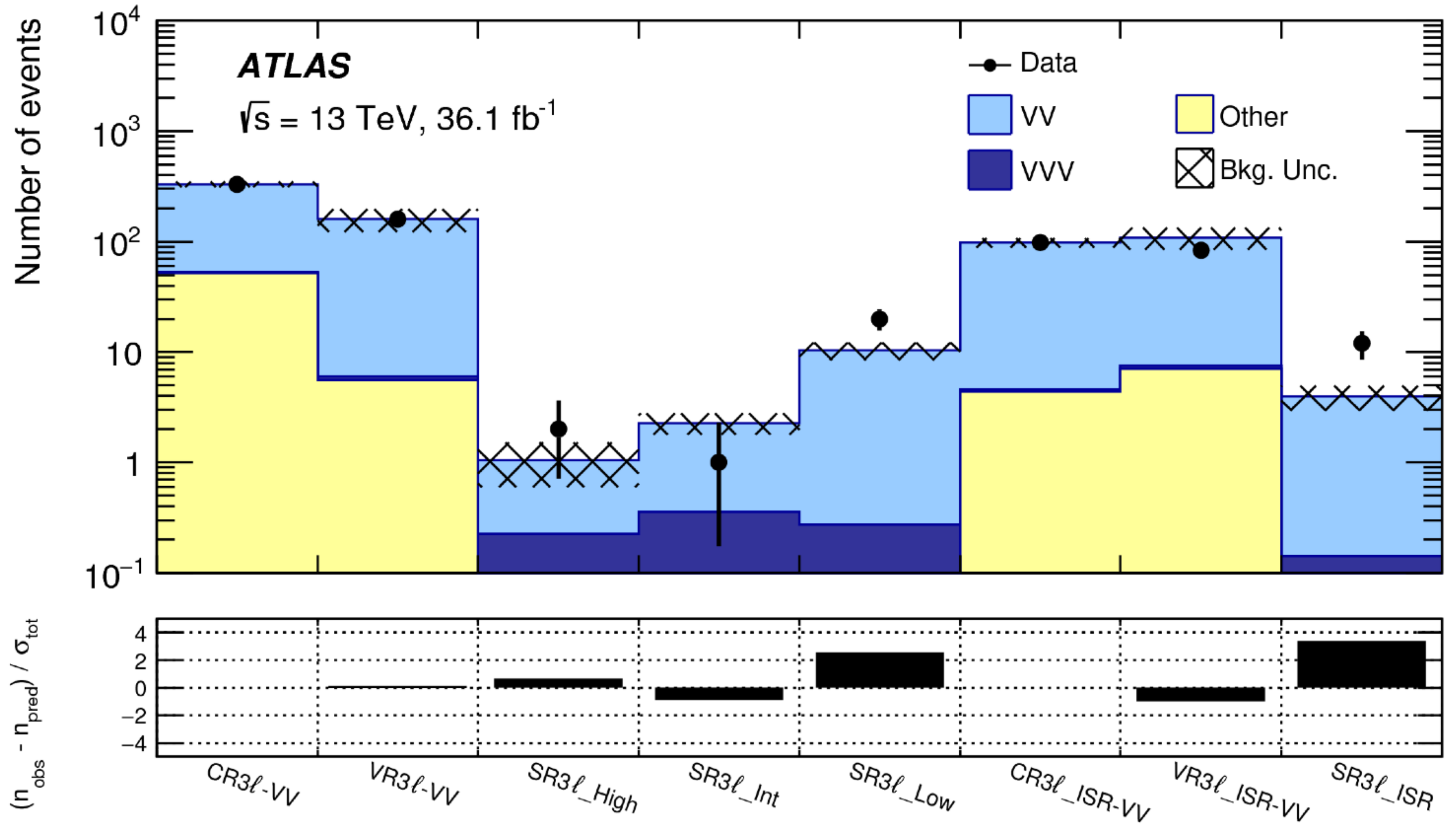
$$m(\chi_2^0/\chi_1^+) - m(\chi_1^0) \gtrsim 100 \text{ GeV}$$

- Attempt to reconstruct the sparticles decay tree

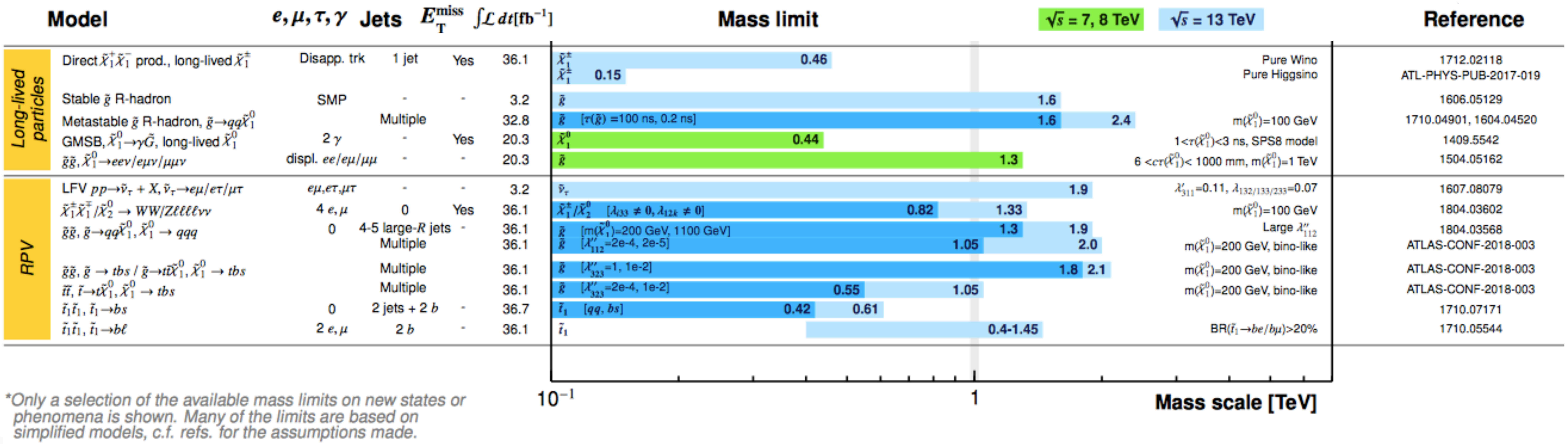


- Four signal regions with excesses ~1.4 - 3.0σ

- Using only 2015-16 data → looking forward to adding 2017-18 data

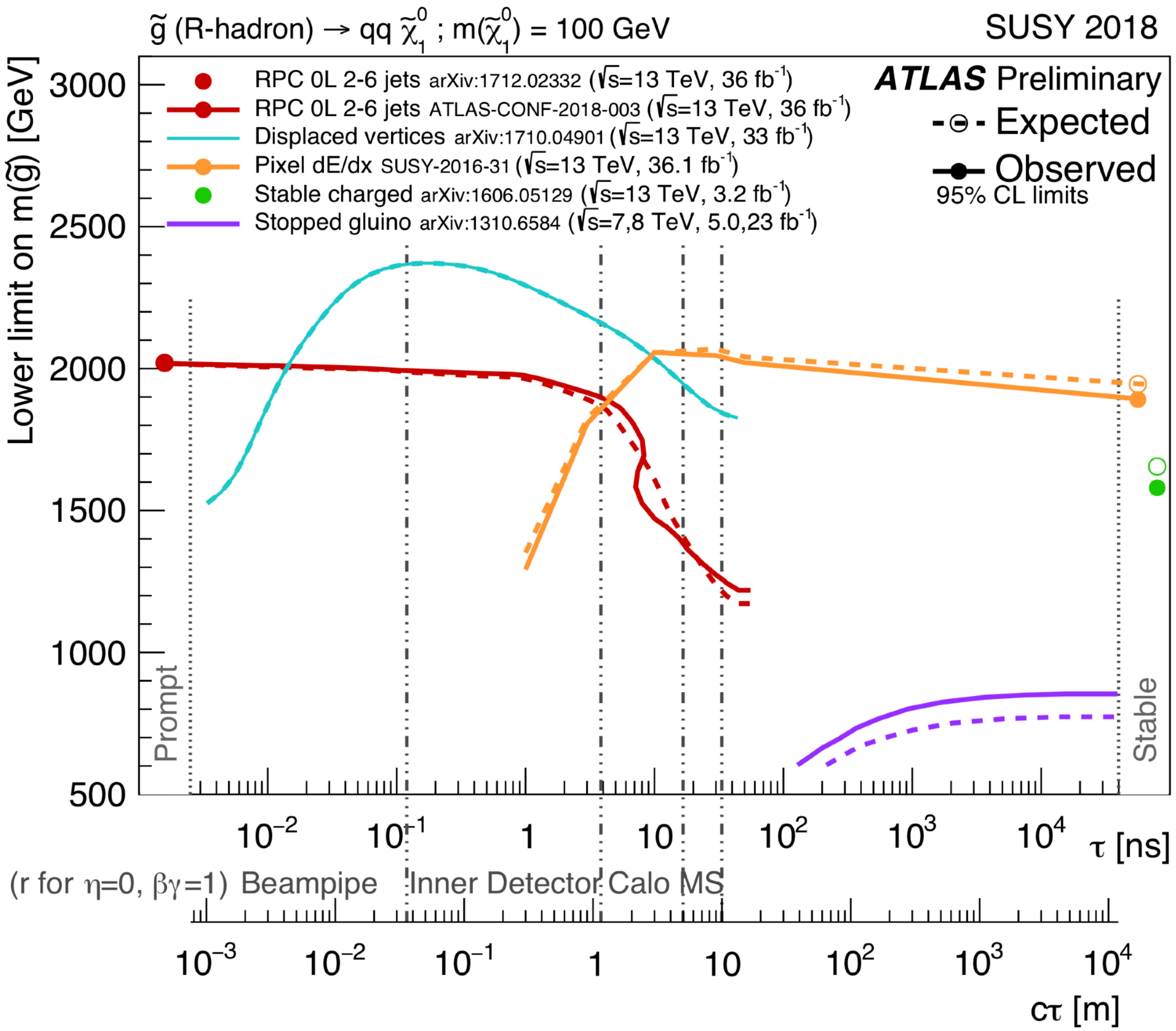


Searches for SUSY long-lived particles and RPV



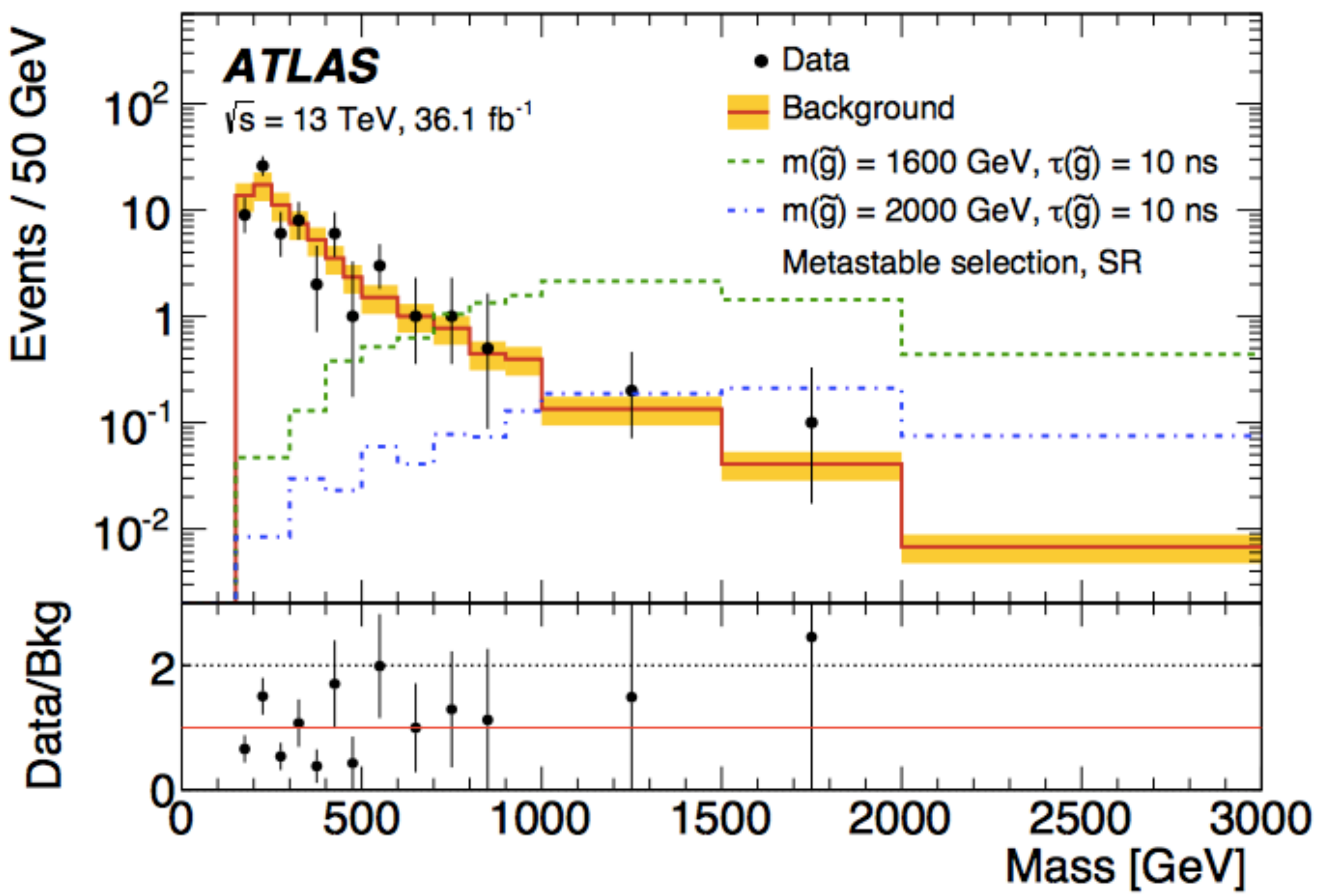
Searches for SUSY long-lived particles

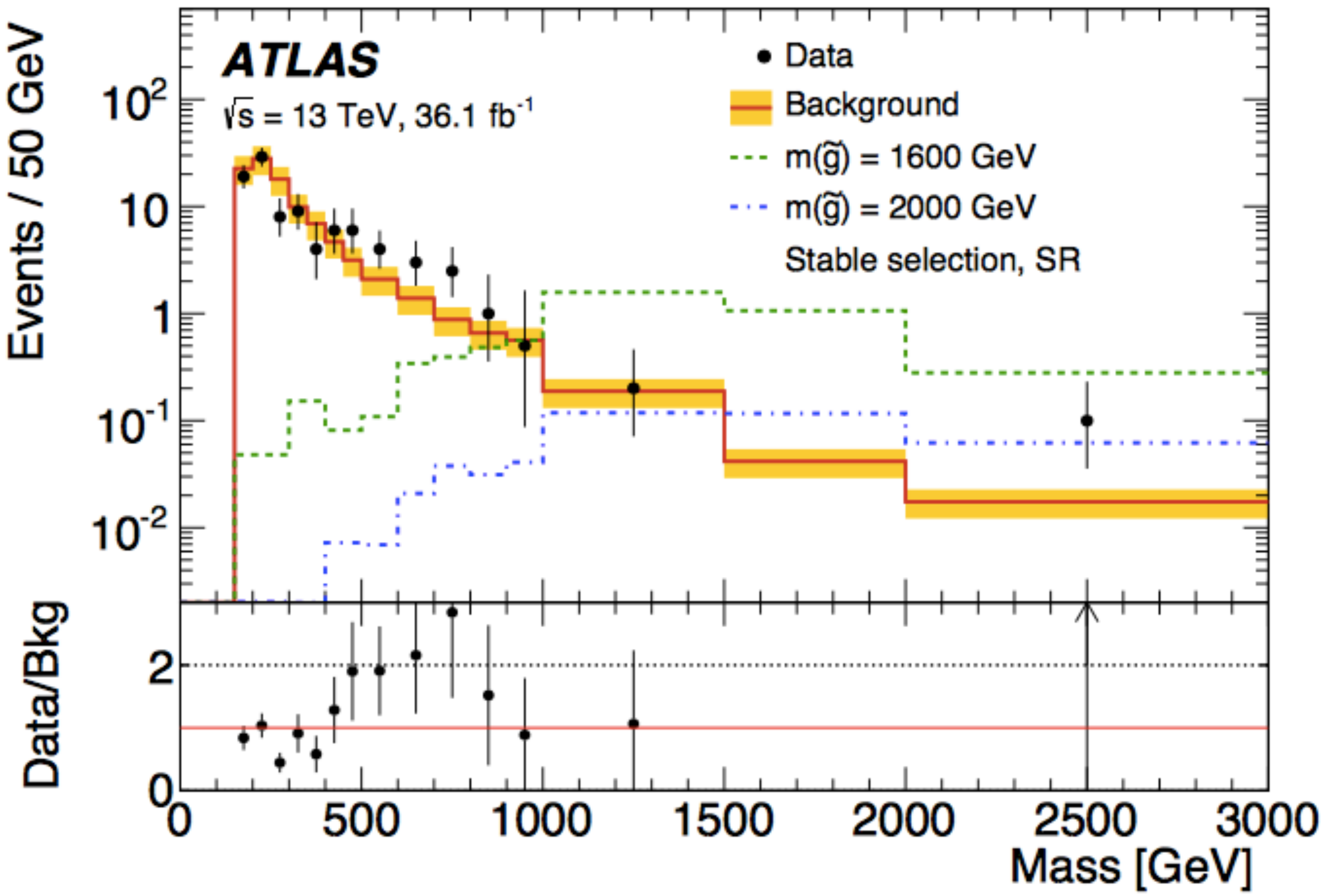
- What if the accessible sparticles are long-lived?
- Well motivated by naturalness and dark matter
  - Predicts compressed mass spectra of sparticles
- More and more focus on these searches
- Exotic, almost background-free signatures
  - Massive stable particle, disappearing tracks



An example: pixel detector dE/dx

- ATLAS pixel detector: 4 layers that can measure dE/dx
    - dE/dx ⇒ mass, if momentum is measured
- SUSY particles can sometimes be (meta)stable
    - E.g. R-hadron in split-SUSY
- Stable R-hadrons excluded with mass below 1890 GeV
    - Local 2.4σ excess at ~600 GeV





arXiv:1808.04095

Conclusions

- No signs of SUSY so far at the LHC
- “Vanilla” natural SUSY significantly constrained
  - But still room left → very important to keep looking!
- Constraints can be weakened in more complex SUSY models
  - NMSSM, RPV, stealth SUSY, hidden valley, twin higgs, etc
- And experimental constraints on electroweakinos are weaker
  - High-Luminosity LHC (2026+) will significantly improve the sensitivity to electroweakinos!


Stolen from John Ellis
(SUSY 2018)
We still believe in supersymmetry
You must be joking

Back–up slides

Multi-b: MC generators

Process	Generator + fragmentation/hadronization	Tune	PDF set	Cross-section order
Gbb/Gtb/Gtt	MadGraph5_aMC@NLO-2.2.2 + Pythia v8.186	A14	NNPDF2.3	NLO+NLL [30–35]
$t\bar{t}$	Powheg-Box v2 + Pythia-8.230	A14	NNPDF3.0	NNLO+NNLL [36]
Single top Wt-channel (s/t)	Powheg-Box v1 (v2) + Pythia-6.428 (-8.230)	PERUGIA2012	CT10	NNLO+NNLL [37–39]
$t\bar{t}W/t\bar{t}Z$	MadGraph5_aMC@NLO-2.2.2 + Pythia-8.186	A14	NNPDF2.3	NLO [40]
4-tops	MadGraph-2.2.2 + Pythia-8.186	A14	NNPDF2.3	NLO [40]
$t\bar{t}H$	MadGraph5_aMC@NLO-2.2.1 + Herwig++-2.7.1	UEEE5	CT10	NLO [41]
Dibosons WW, WZ, ZZ	Sherpa-2.2.1	Default	NNPDF3.0	NLO [42, 43]
W/Z+**jets**	Sherpa-2.2.1	Default	NNPDF3.0	NNLO [44]

Multi-b: Signal and control regions: cut&count

Gtt 1-lepton

Criteria common to all regions: ≥ 1 signal lepton, $N_{b\text{-jets}} \geq 3$

Targeted kinematics	Type	N_{jet}	m_{T}	$m_{\text{T,min}}^{b\text{-jets}}$	$E_{\text{T}}^{\text{miss}}$	$m_{\text{eff}}^{\text{incl}}$	M_J^{Σ}
Region B (Boosted, Large Δm)	SR	≥ 5	> 150	> 120	> 500	> 2200	> 200
	CR	$= 5$	< 150	–	> 300	> 1700	> 150
Region M (Moderate Δm)	SR	≥ 6	> 150	> 160	> 450	> 1800	> 200
	CR	$= 6$	< 150	–	> 400	> 1500	> 100
Region C (Compressed, small Δm)	SR	≥ 7	> 150	> 160	> 350	> 1000	–
	CR	$= 7$	< 150	–	> 350	> 1000	–

Gtt 0-lepton

Targeted kinematics	Type	N_{lepton}	$N_{b\text{-jets}}$	N_{jet}	$\Delta\phi_{\text{min}}^{4\text{j}}$	m_{T}	$m_{\text{T,min}}^{b\text{-jets}}$	$E_{\text{T}}^{\text{miss}}$	$m_{\text{eff}}^{\text{incl}}$	M_J^{Σ}
Region B (Boosted, Large Δm)	SR	$= 0$	≥ 3	≥ 7	> 0.4	–	> 60	> 350	> 2600	> 300
	CR	$= 1$	≥ 3	≥ 6	–	< 150	–	> 275	> 1800	> 300
Region M (Moderate Δm)	SR	$= 0$	≥ 3	≥ 7	> 0.4	–	> 120	> 500	> 1800	> 200
	CR	$= 1$	≥ 3	≥ 6	–	< 150	–	> 400	> 1700	> 200
Region C (Compressed, moderate Δm)	SR	$= 0$	≥ 4	≥ 8	> 0.4	–	> 120	> 250	> 1000	> 100
	CR	$= 1$	≥ 4	≥ 7	–	< 150	–	> 250	> 1000	> 100

Multi-b: Signal and control regions: cut&count

Gbb

Criteria common to all regions: $N_{\text{jet}} \geq 4$

Targeted kinematics	Type	N_{lepton}	$N_{b\text{-jets}}$	$\Delta\phi^{4j}_{\text{min}}$	m_T	$m^{b\text{-jets}}_{T,\text{min}}$	E_T^{miss}	m_{eff}	Others
Region B (Boosted, Large Δm)	SR	= 0	≥ 3	> 0.4	–	–	> 400	> 2800	–
	CR	= 1	≥ 3	–	< 150	–	> 400	> 2500	–
Region M (Moderate Δm)	SR	= 0	≥ 4	> 0.4	–	> 90	> 450	> 1600	–
	CR	= 1	≥ 4	–	< 150	–	> 300	> 1600	–
Region C (Compressed, small Δm)	SR	= 0	≥ 4	> 0.4	–	> 155	> 450	–	–
	CR	= 1	≥ 4	–	< 150	–	> 375	–	–
Region VC (Very Compressed, very small Δm)	SR	= 0	≥ 3	> 0.4	–	> 100	> 600	–	$p_T^{j_1} > 400$, $j_1 \neq b$, $\Delta\phi^{j_1} > 2.5$
	CR	= 1	≥ 3	–	< 150	–	> 600	–	

Multi-b: Signal and control regions: multi-bin

High-N_{jet} regions

Criteria common to all regions: $N_{b\text{-jets}} \geq 3$

Targeted kinematics	Type	N_{lepton}	$\Delta\phi^{4j}_{min}$	m_T	N_{jet}	$m^{b\text{-jets}}_{T,min}$	M^{Σ}_{J}	E^{miss}_{T}	m_{eff}
High-m_{eff} (HH) (Large Δm)	SR-0L	= 0	> 0.4	–	≥ 7	> 100	> 200	> 400	> 2500
	SR-1L	≥ 1	–	> 150	≥ 6	> 120	> 200	> 500	> 2300
	CR	≥ 1	–	< 150	≥ 6	> 60	> 150	> 300	> 2100
Intermediate-m_{eff} (HI) (Intermediate Δm)	SR-0L	= 0	> 0.4	–	≥ 9	> 140	> 150	> 300	[1800, 2500]
	SR-1L	≥ 1	–	> 150	≥ 8	> 140	> 150	> 300	[1800, 2300]
	CR	≥ 1	–	< 150	≥ 8	> 60	> 150	> 200	[1700, 2100]
Low-m_{eff} (HL) (Small Δm)	SR-0L	= 0	> 0.4	–	≥ 9	> 140	–	> 300	[900, 1800]
	SR-1L	≥ 1	–	> 150	≥ 8	> 140	–	> 300	[900, 1800]
	CR	≥ 1	–	< 150	≥ 8	> 130	–	> 250	[900, 1700]

Intermediate-N_{jet} regions

Criteria common to all regions: $N_{b\text{-jets}} \geq 3$

Targeted kinematics	Type	N_{lepton}	$\Delta\phi^{4j}_{min}$	m_T	N_{jet}	$j_1 = b$ or $\Delta\phi^{j_1} \leq 2.9$	$m^{b\text{-jets}}_{T,min}$	M^{Σ}_{J}	E^{miss}_{T}	m_{eff}
Intermediate-m_{eff} (II) (Intermediate Δm)	SR-0L	= 0	> 0.4	–	[7, 8]	✓	> 140	> 150	> 300	[1600, 2500]
	SR-1L	≥ 1	–	> 150	[6, 7]	–	> 140	> 150	> 300	[1600, 2300]
	CR	≥ 1	–	< 150	[6, 7]	✓	> 100	> 150	> 300	[1600, 2100]
Low-m_{eff} (IL) (Low Δm)	SR-0L	= 0	> 0.4	–	[7, 8]	✓	> 140	–	> 300	[800, 1600]
	SR-1L	≥ 1	–	> 150	[6, 7]	–	> 140	–	> 300	[800, 1600]
	CR	≥ 1	–	< 150	[6, 7]	✓	> 130	–	> 300	[800, 1600]

Multi-b: Signal and control regions: multi-bin

Low-N_{jet} regions

Criteria common to all regions: $N_{b\text{-jets}} \geq 3$

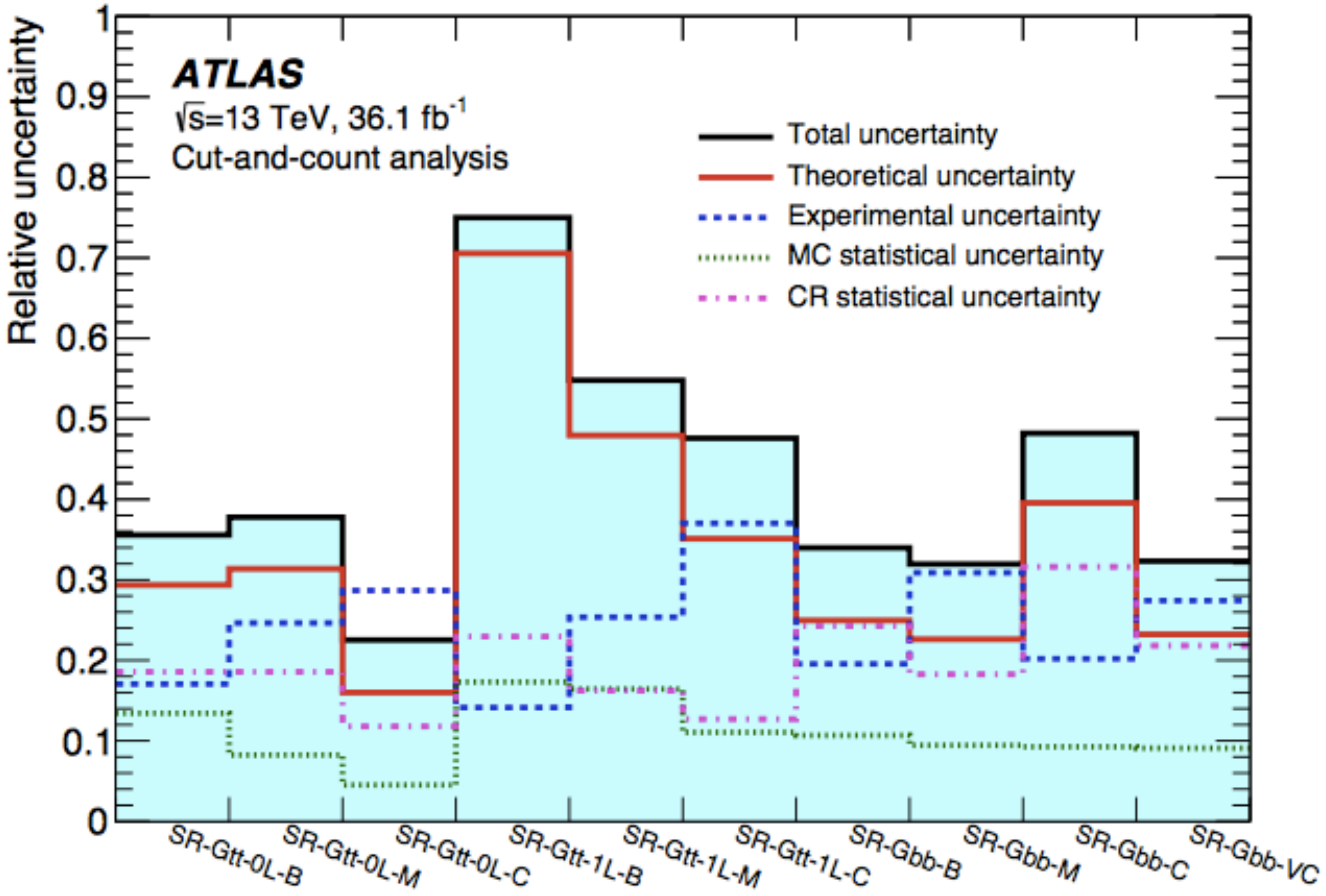
Targeted kinematics	Type	N_{lepton}	$\Delta\phi^{4j}_{\text{min}}$	m_{T}	N_{jet}	$j_1 = b$ or $\Delta\phi^{j_1} \leq 2.9$	$p_{\text{T}}^{j_4}$	$m_{\text{T,min}}^{b\text{-jets}}$	$E_{\text{T}}^{\text{miss}}$	m_{eff}
High-m_{eff} (LH) (Large Δm)	SR	$= 0$	> 0.4	–	[4, 6]	–	> 90	–	> 300	> 2400
	CR	≥ 1	–	< 150	[4, 5]	–	-	–	> 200	> 2100
Intermediate-m_{eff} (LI) (Intermediate Δm)	SR	$= 0$	> 0.4	–	[4, 6]	✓	> 90	> 140	> 350	[1400, 2400]
	CR	≥ 1	–	< 150	[4, 5]	✓	> 70	–	> 300	[1400, 2000]
Low-m_{eff} (LL) (Low Δm)	SR	$= 0$	> 0.4	–	[4, 6]	✓	> 90	> 140	> 350	[800, 1400]
	CR	≥ 1	–	< 150	[4, 5]	✓	> 70	–	> 300	[800, 1400]

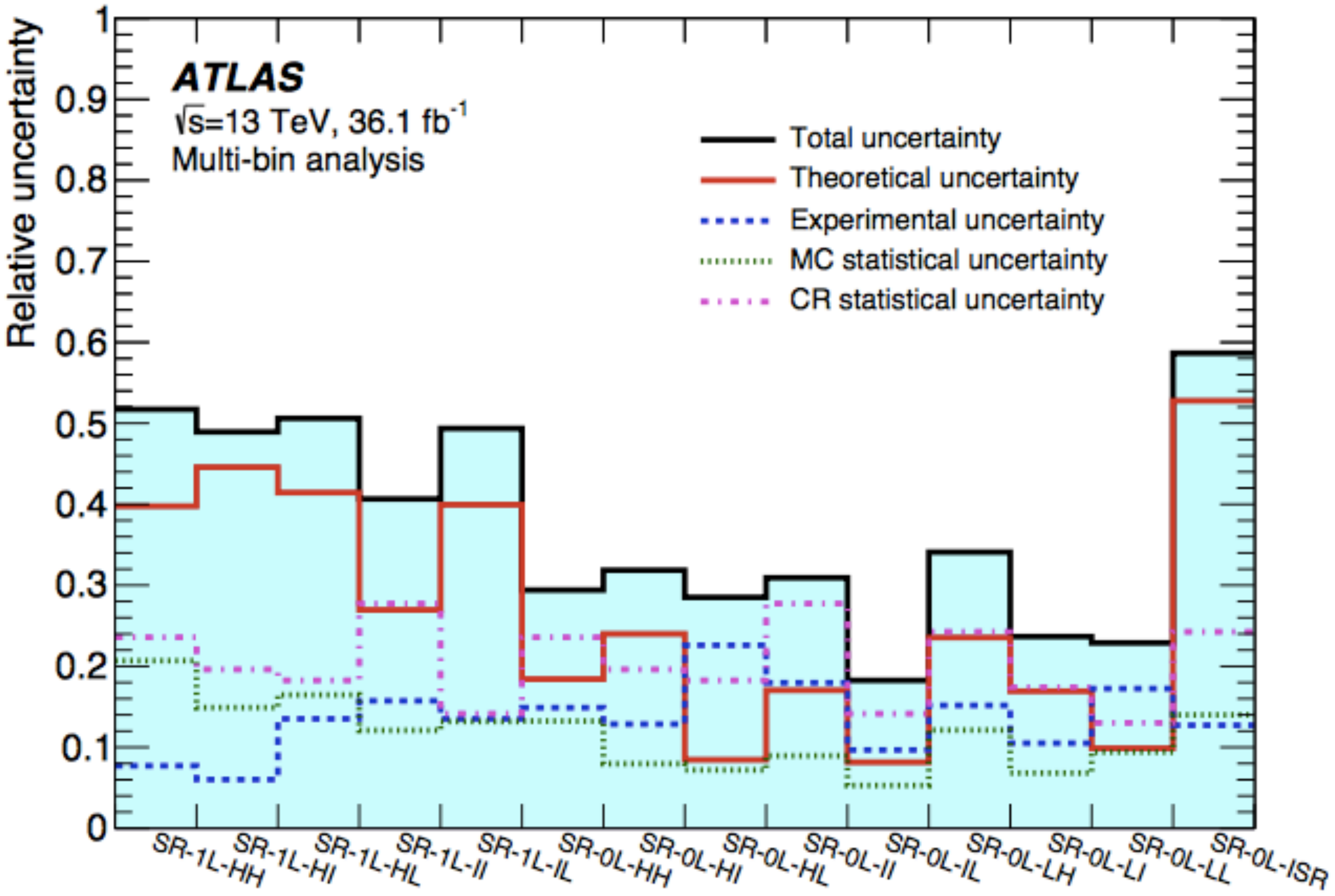
ISR regions

Criteria common to all regions: $N_{b\text{-jets}} \geq 3$, $\Delta\phi^{j_1} > 2.9$, $p_{\text{T}_1}^{j} > 400$ GeVand $j_1 \neq b$

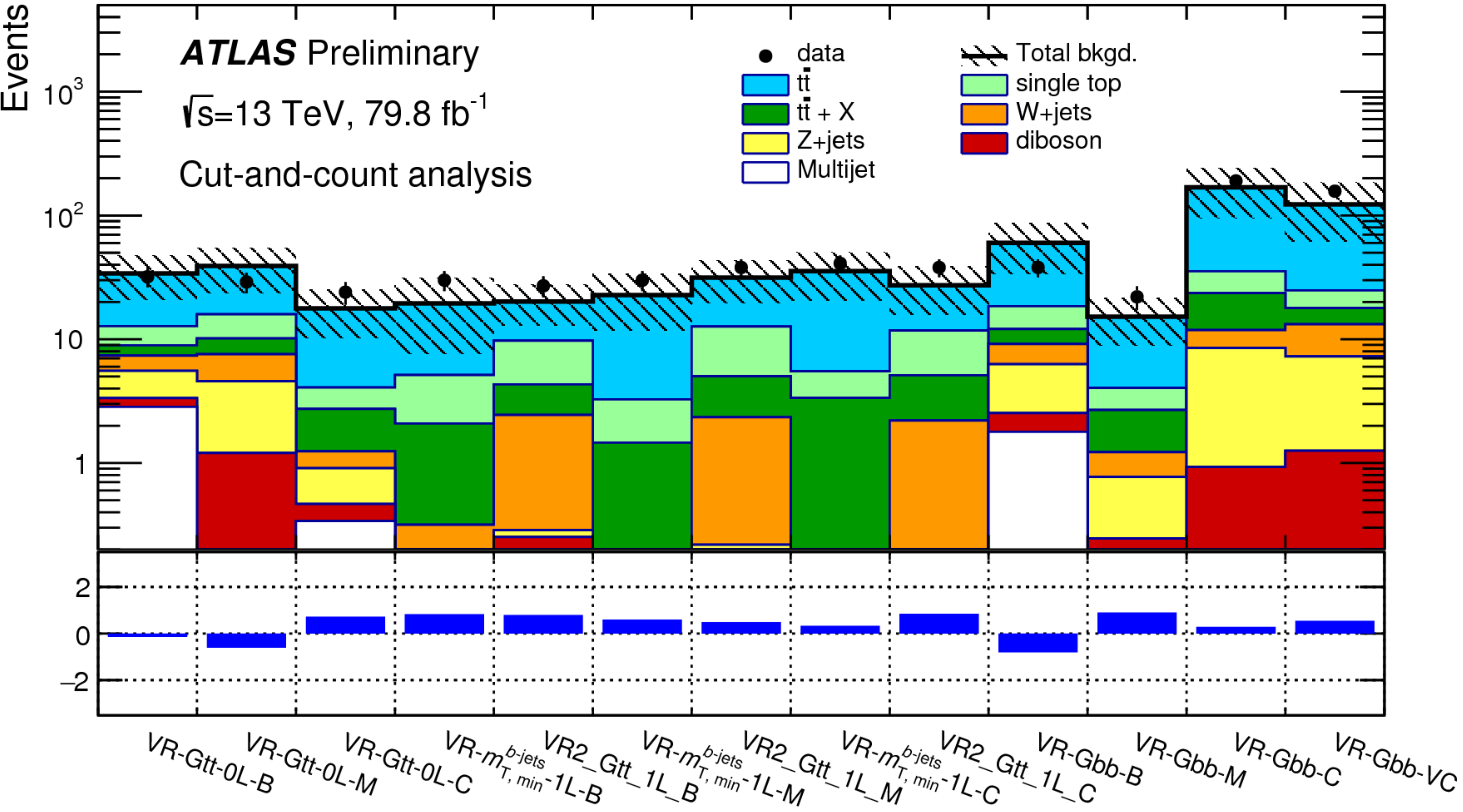
Type	N_{lepton}	$\Delta\phi^{4j}_{\text{min}}$	m_{T}	N_{jet}	$m_{\text{T,min}}^{b\text{-jets}}$	$E_{\text{T}}^{\text{miss}}$	m_{eff}
SR	$= 0$	> 0.4	–	[4, 8]	> 100	> 600	< 2200
CR	≥ 1	–	< 150	[4, 7]	–	> 400	< 2000

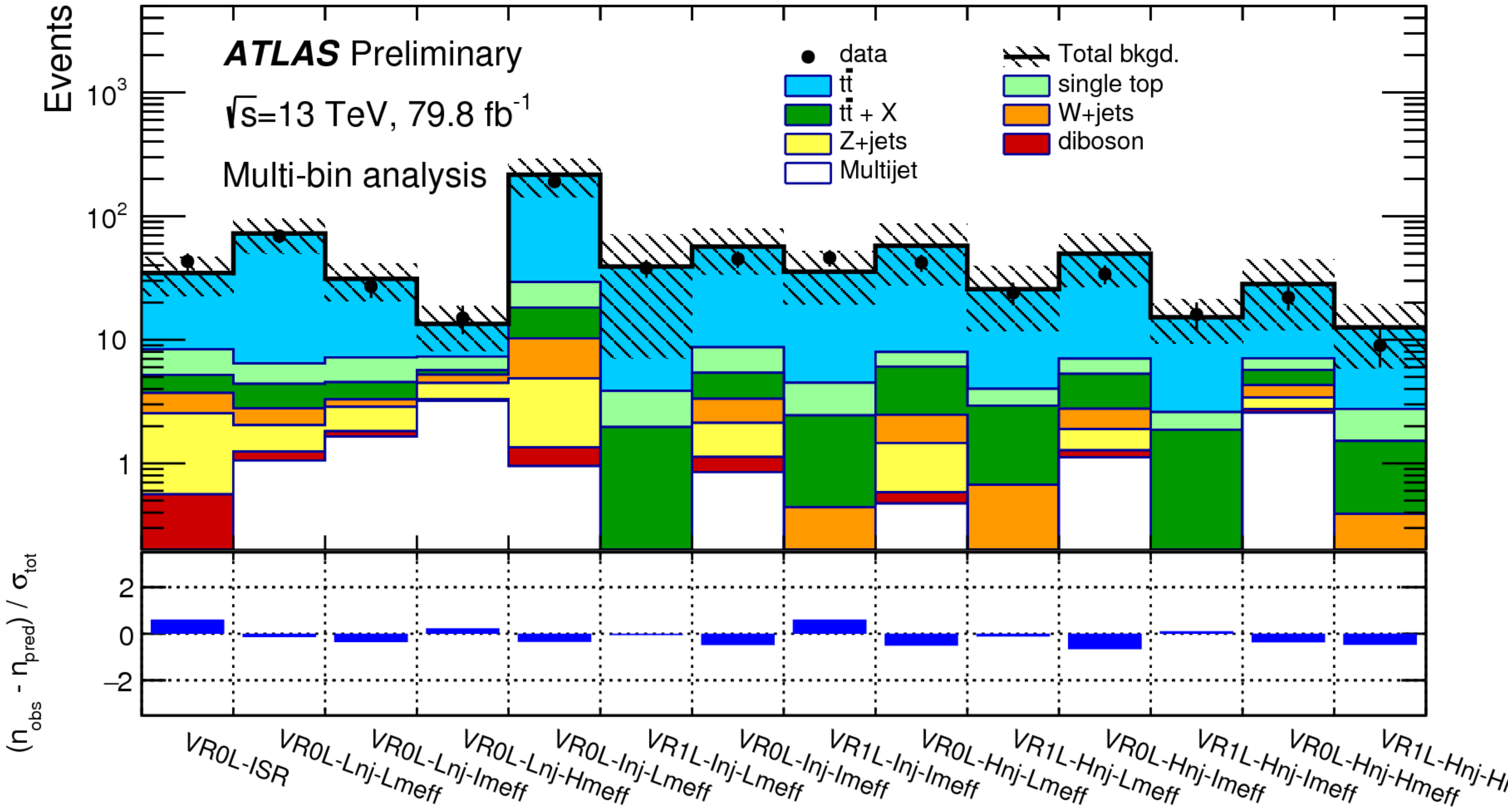
Multi-b: Systematic uncertainties



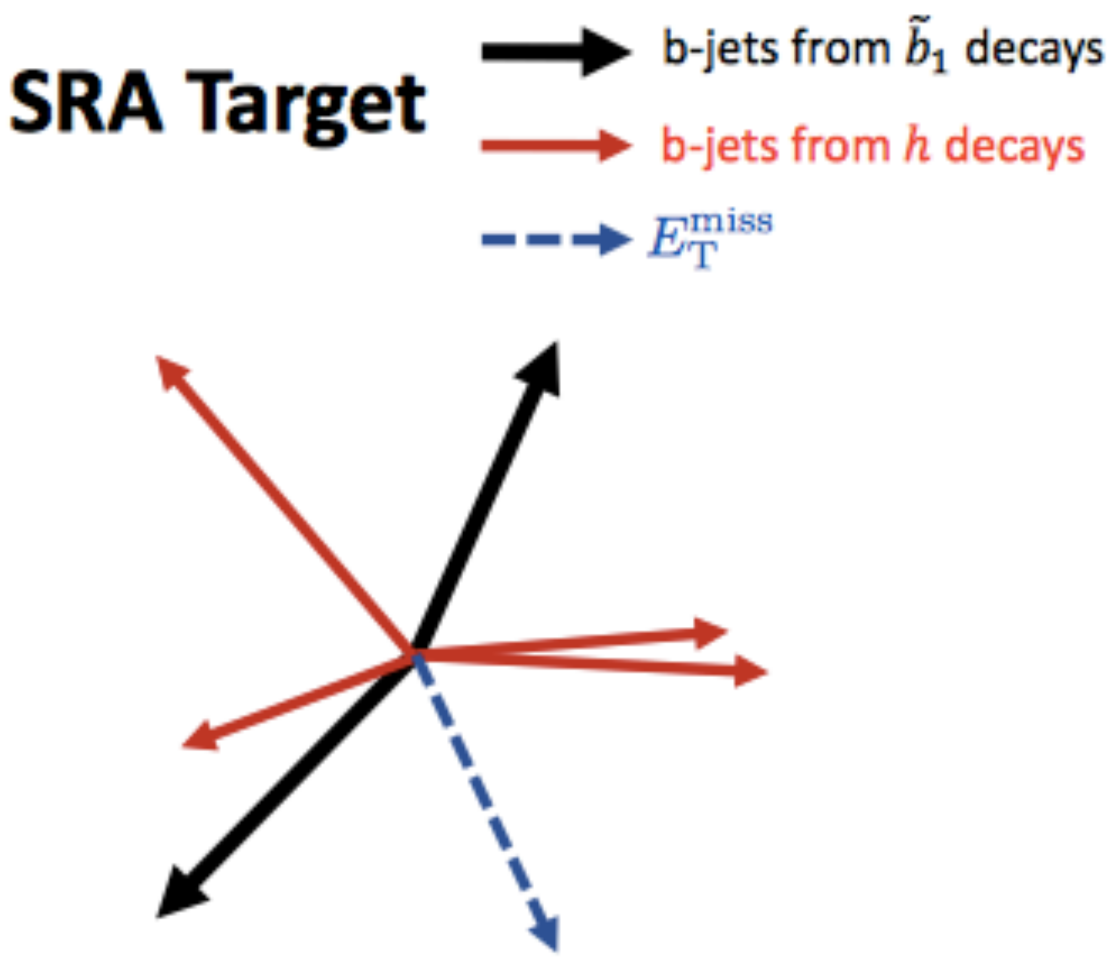


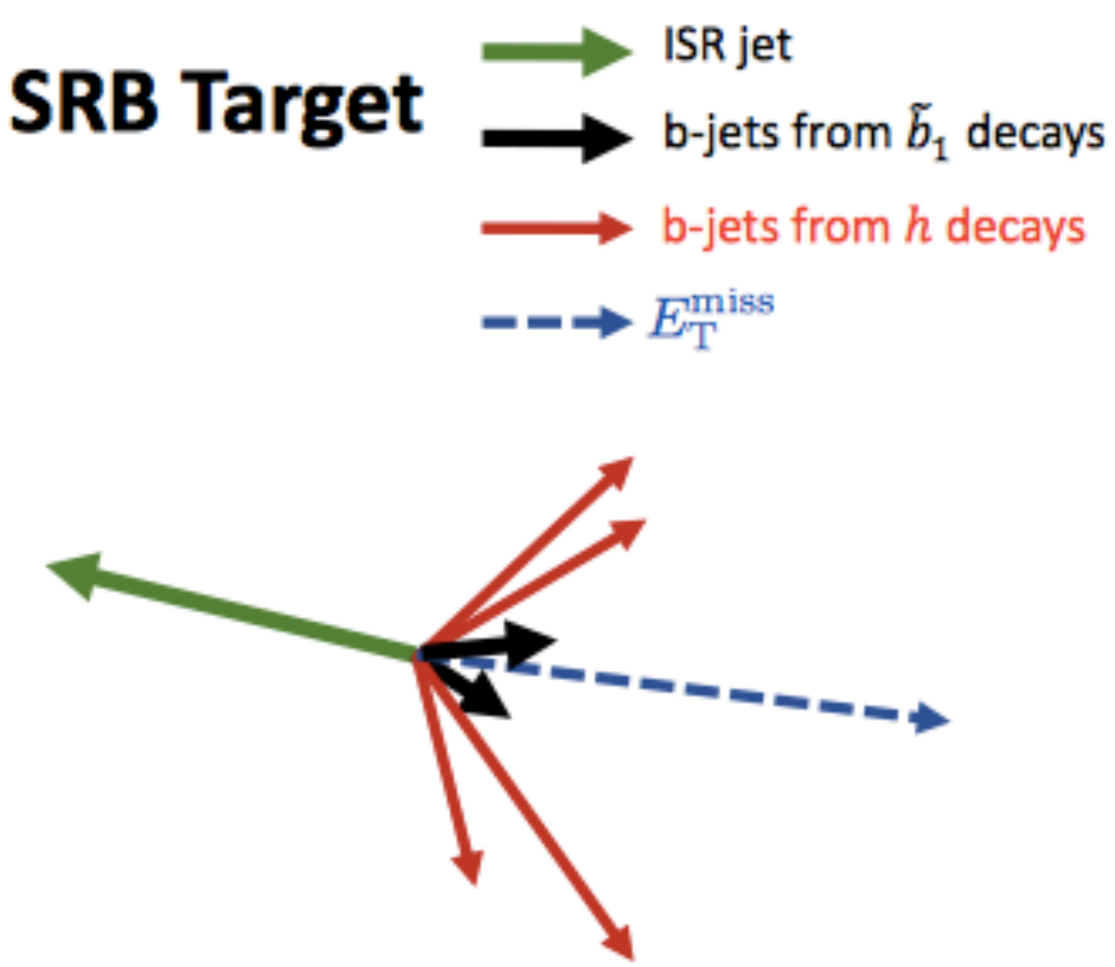
Multi-b: Validation regions

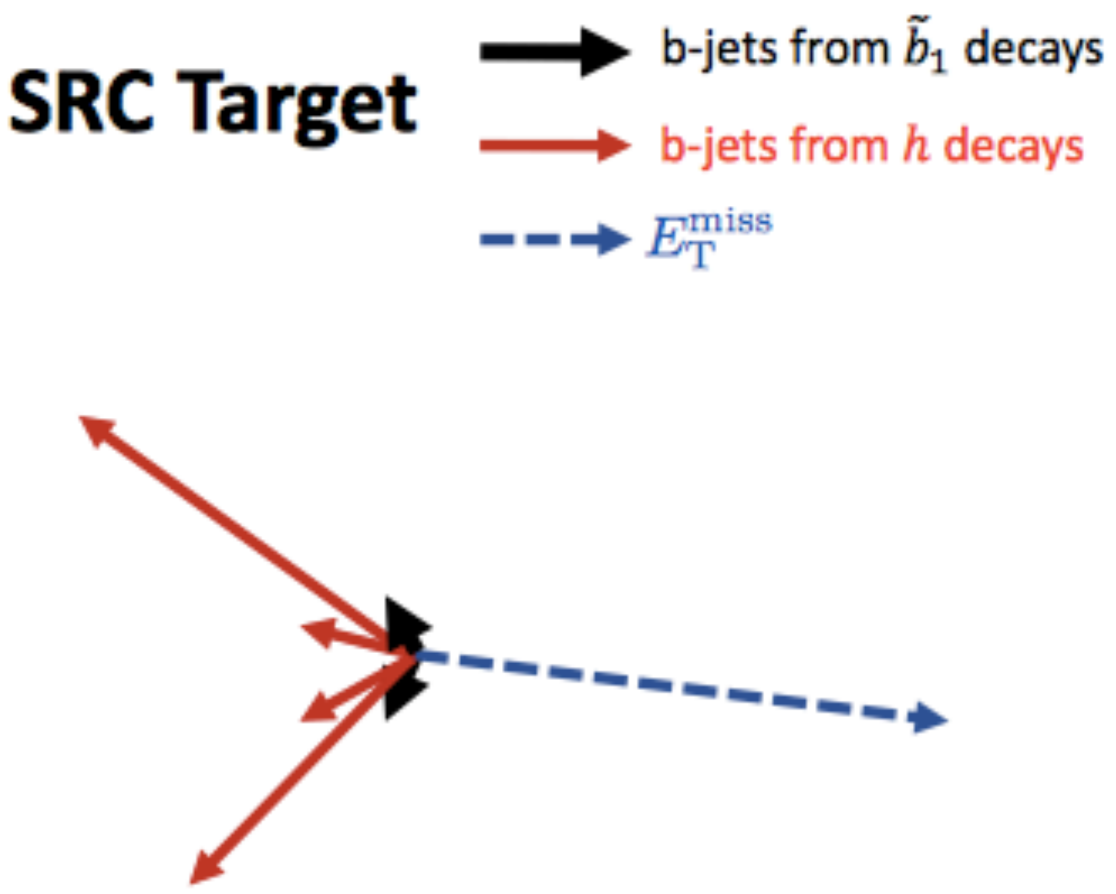




Sbottom analysis







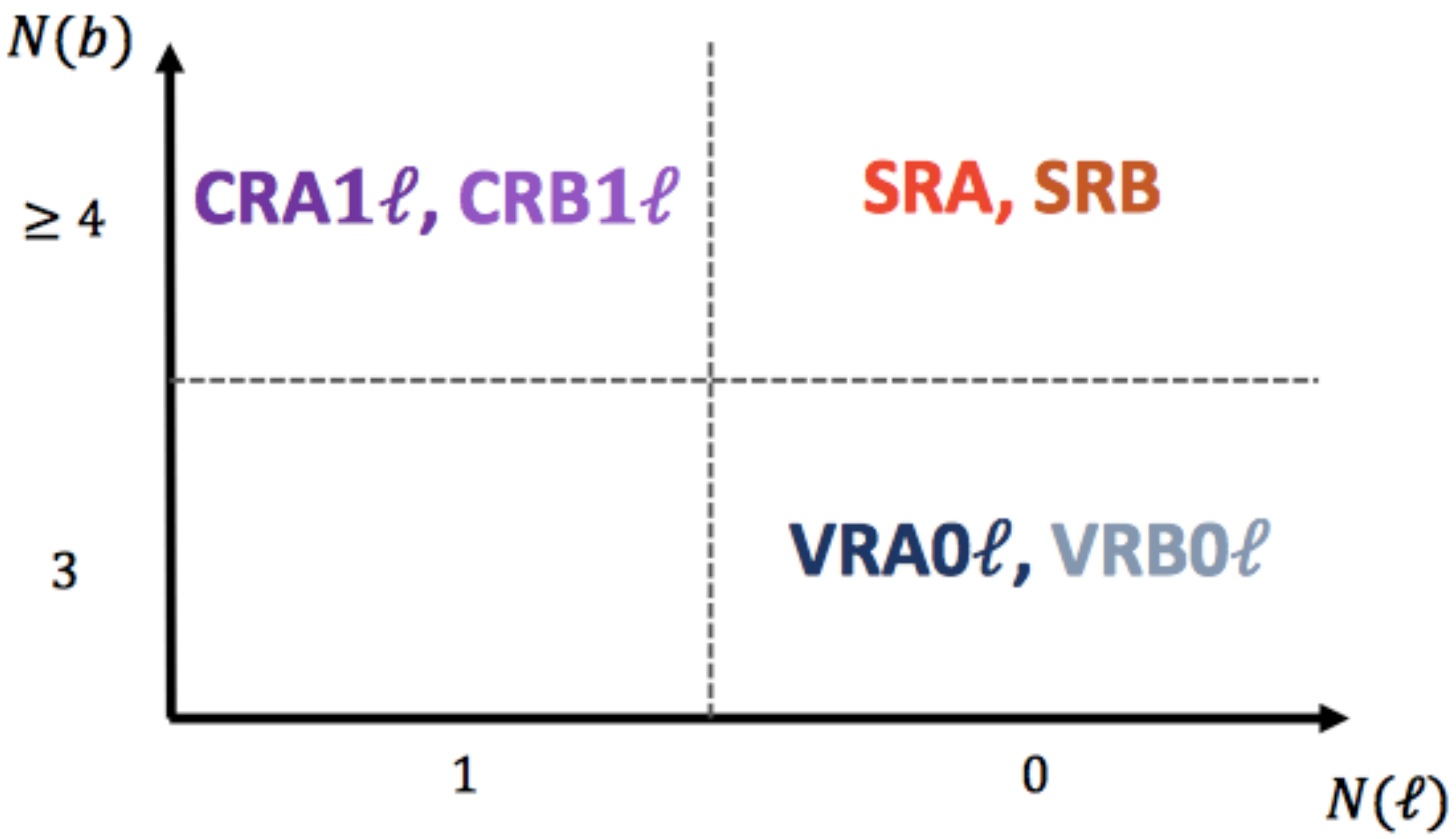
Variable	SRA	SRA-L	SRA-M	SRA-H
$N_{leptons}$ (baseline)	$= 0$			
N_{jets}	≥ 6			
N_{b-jets}	≥ 4			
E_T^{miss} [GeV]	> 250			
$\min \Delta\phi(\text{jet}_{1-4}, \mathbf{p}_T^{miss})$ [rad]	> 0.4			
τ veto	Yes			
$p_T(b_1)$ [GeV]	> 200			
$\Delta R_{max}(b, b)$	> 2.5			
$\Delta R_{max-min}(b, b)$	< 2.5			
$m(h_{cand})$ [GeV]	> 80			
m_{eff} [TeV]	> 1.0	$\in [1.0, 1.2]$	$\in [1.2, 1.5]$	> 1.5

Table 2: Selections for SRB.

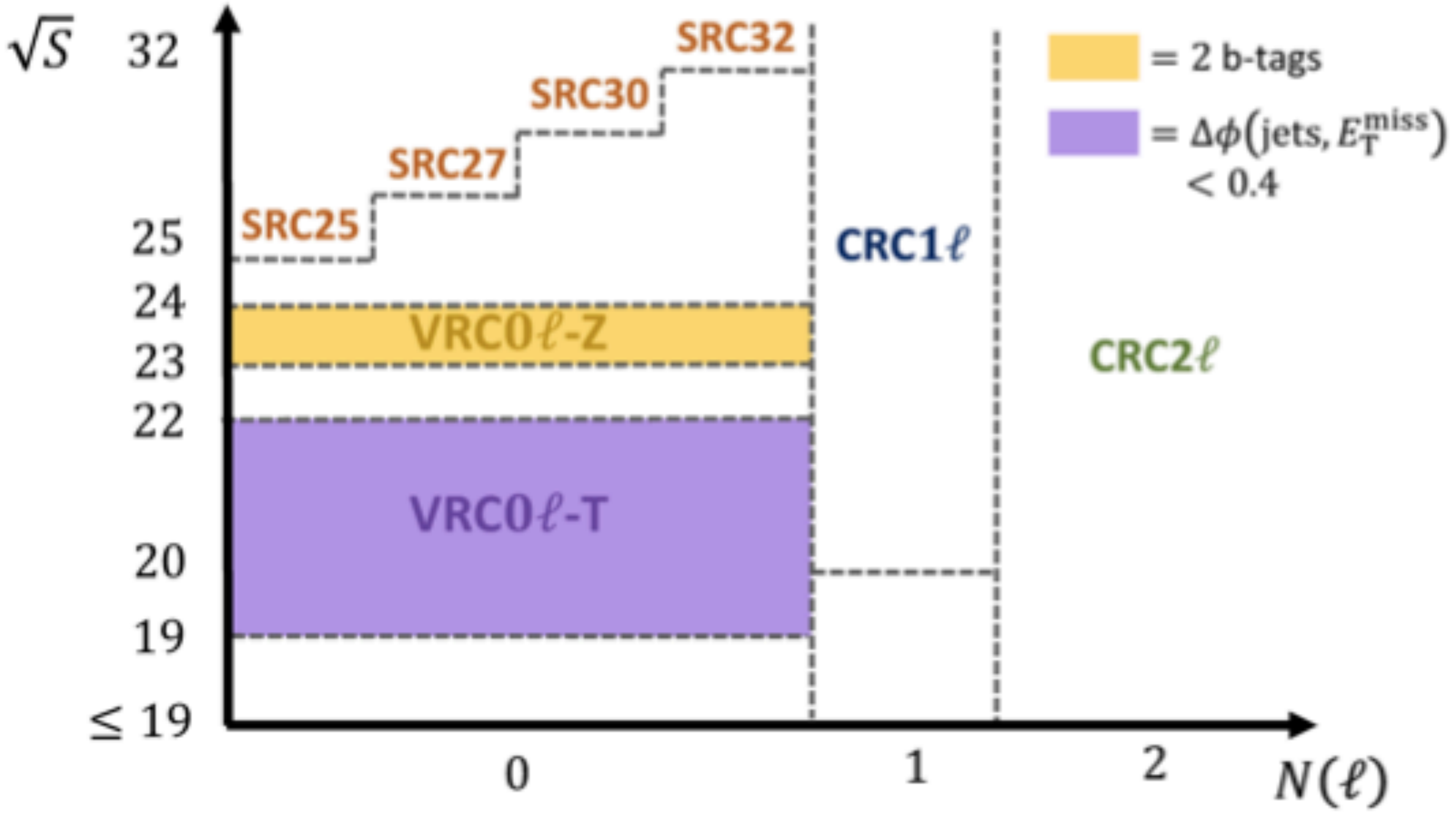
Variable	SRB
$N_{leptons}$ (baseline)	$= 0$
N_{jets}	≥ 5
N_{b-jets}	≥ 4
E_T^{miss} [GeV]	> 300
$\min \Delta\phi(\text{jet}_{1-4}, \mathbf{p}_T^{miss})$ [rad]	> 0.4
τ veto	Yes
$m(h_{cand1}, h_{cand2})_{avg}$ [GeV]	$\in [50, 140]$
non-b leading jet	Yes
$p_T(j_1)$ [GeV]	> 300
$\lvert\Delta\phi(j_1, E_T^{miss})\rvert$ [rad]	> 2.8
m_{eff} [TeV]	> 1

Variable	SRC25	SRC27	SRC30	SRC32
$N_{leptons}$ (baseline)	$= 0$			
N_{jets}	≥ 4			
N_{b-jets}	≥ 3			
E_T^{miss} [GeV]	> 250			
$\min \Delta\phi(\text{jet}_{1-4}, \mathbf{p}_T^{miss})$ [rad]	> 0.4			
$\mathcal{S}$	> 25	> 27	> 30	> 32

Sbottom analysis

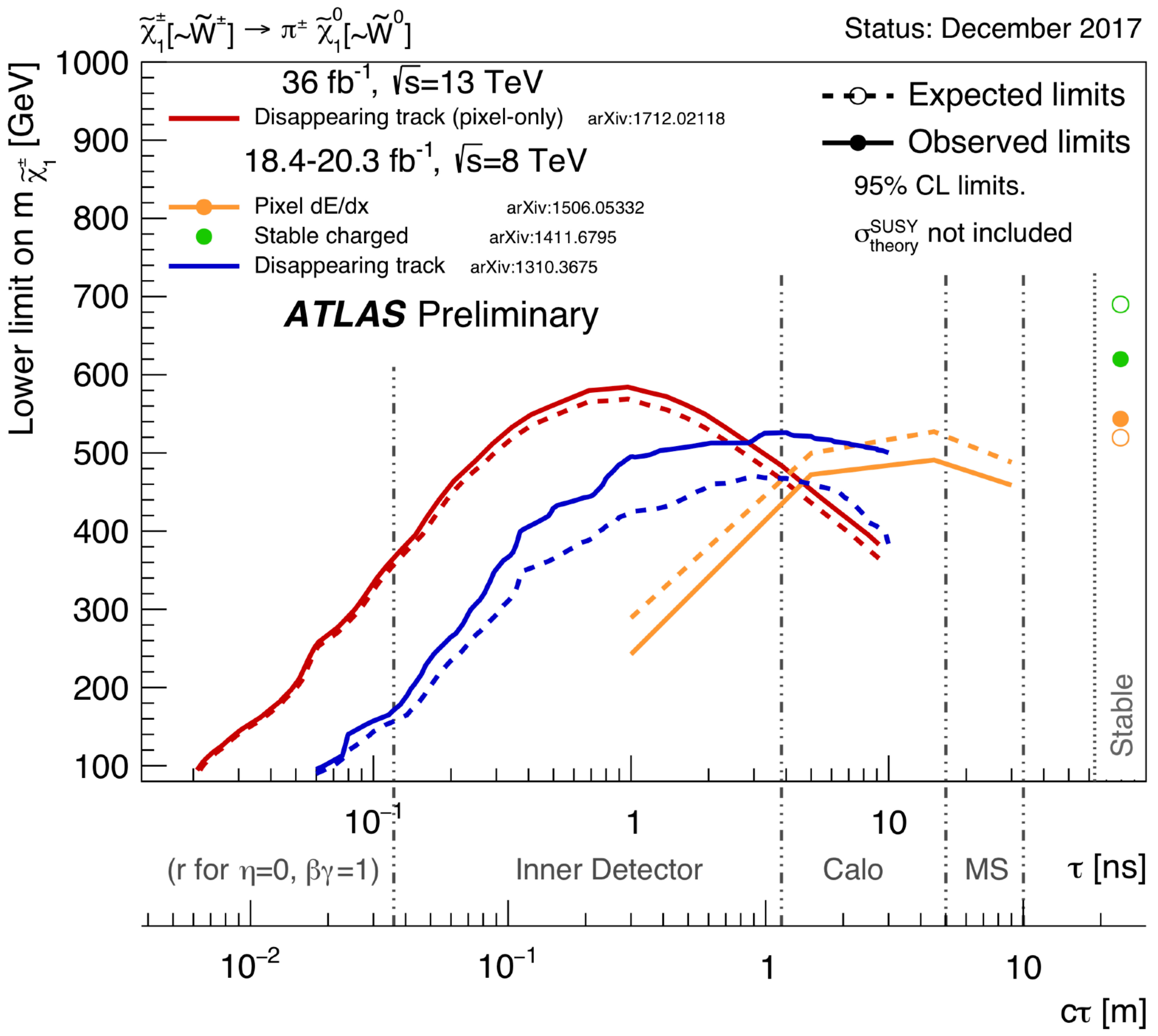


(a) A- and B-type fit strategy



(b) C-type fit strategy

Long-lived particles



Pixel dE/dx

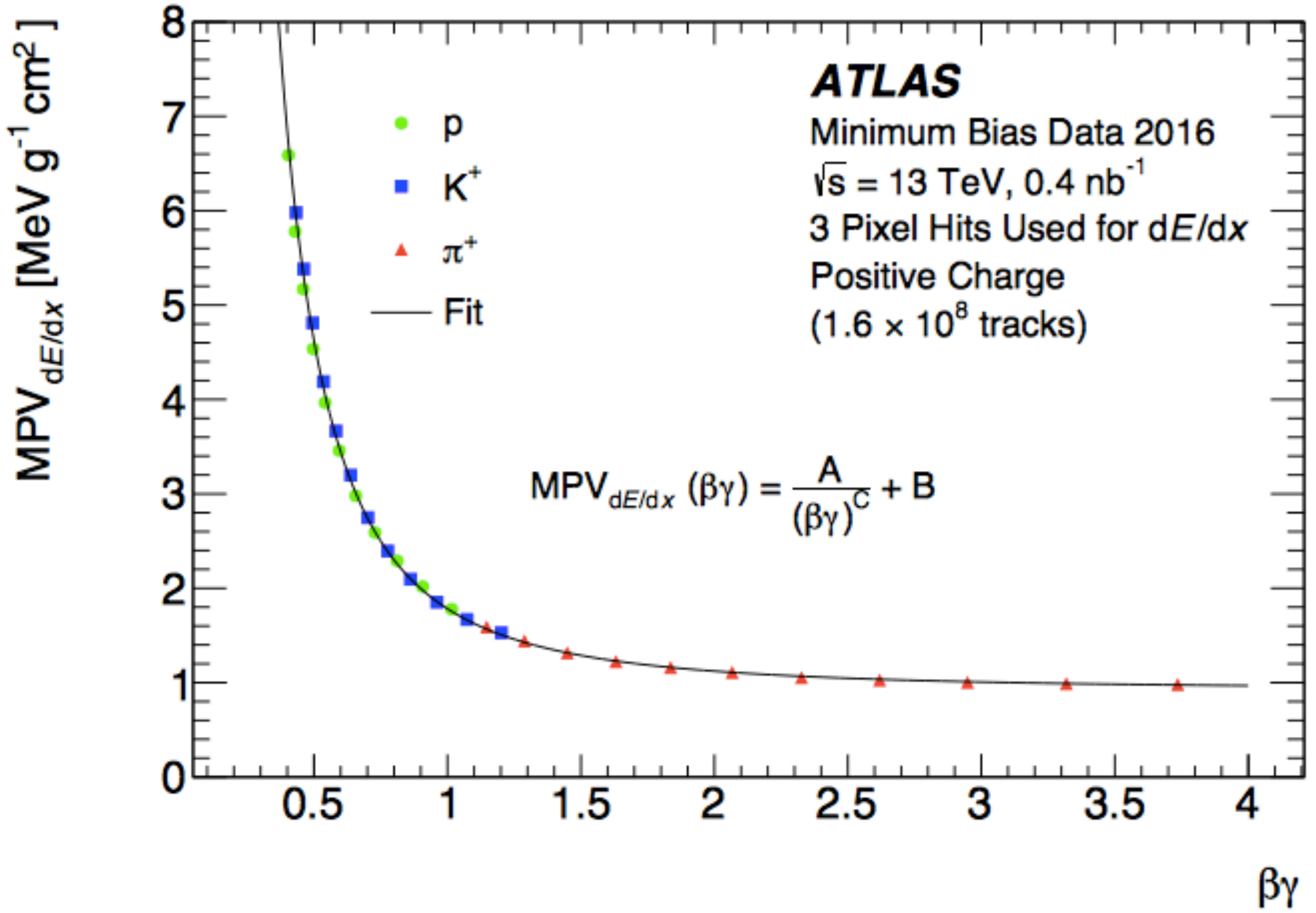
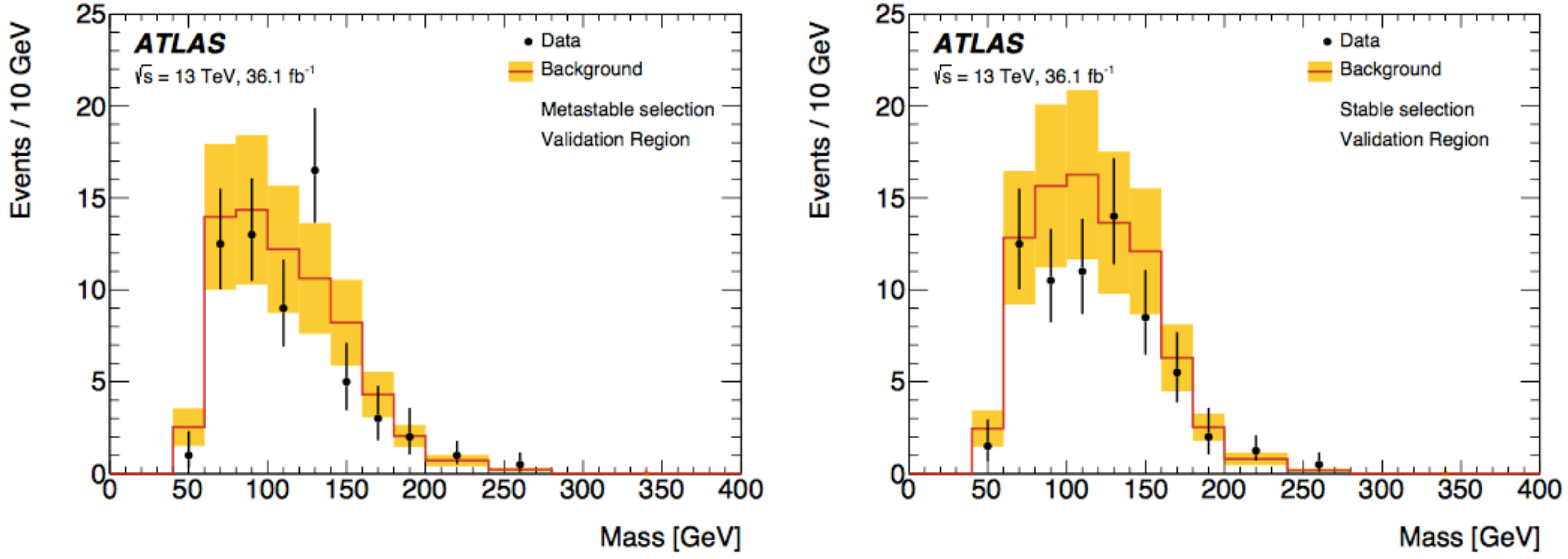


Table 1: Summary of the different selection requirements applied to the signal region (SR), the validation region (VR), and the control regions (CR).

	SR	VR	p-CR		dE/dx-CR	
			for SR	for VR	for SR	for VR
Track Momentum [GeV]	>150	50–150	>150	50–150	>150	50–150
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	>170		>170		<170	
Ionisation [MeV g^{-1} cm^2]	> 1.8		< 1.8		–	

Pixel dE/dx



ATLAS
√s = 13 TeV, 36.1 fb⁻¹
Data
Background
Metastable selection
Validation Region
Events / 10 GeV
Mass [GeV]
ATLAS
√s = 13 TeV, 36.1 fb⁻¹
Data
Background
Stable selection
Validation Region
Events / 10 GeV
Mass [GeV]