Searching for Supersymmetry with ATLAS

WIN 2021 I University of Minnesota
09 June 2021

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On behalf of the ATLAS collaboration

UNIVERSITY OF CAMBRIDGE

ATLAS EXPERIMENT

Recent SUSY results from ATLAS: challenging scenarios

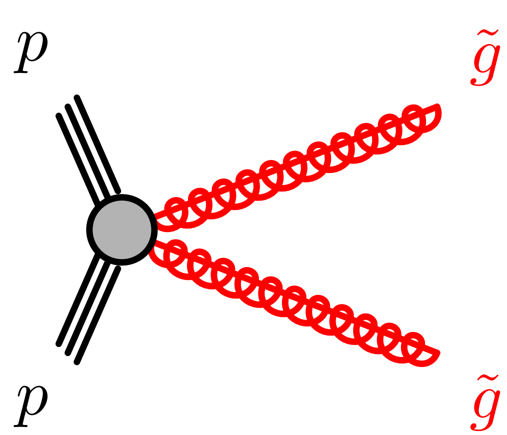
Electroweak SUSY
The 4 lepton search

Compressed SUSY spectra
The disappearing track search

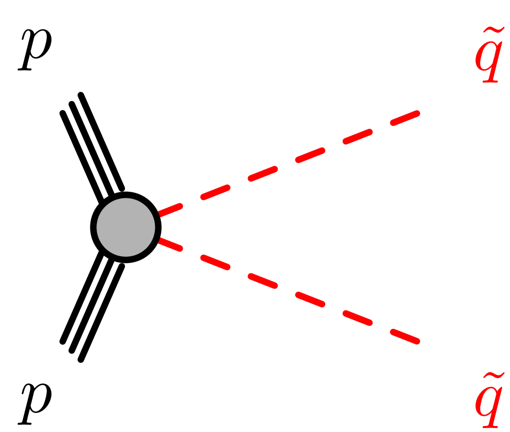
Better late than never
The long-lived stopped particle search

SUSY production mechanisms

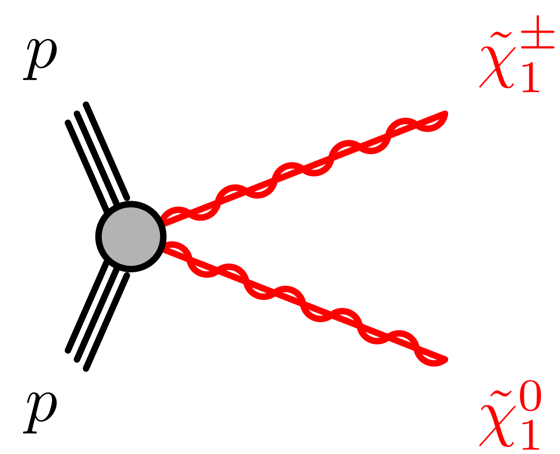
Gluinos



Squarks

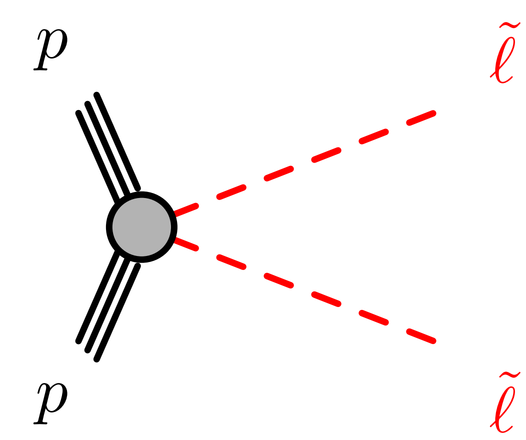


Electroweakinos



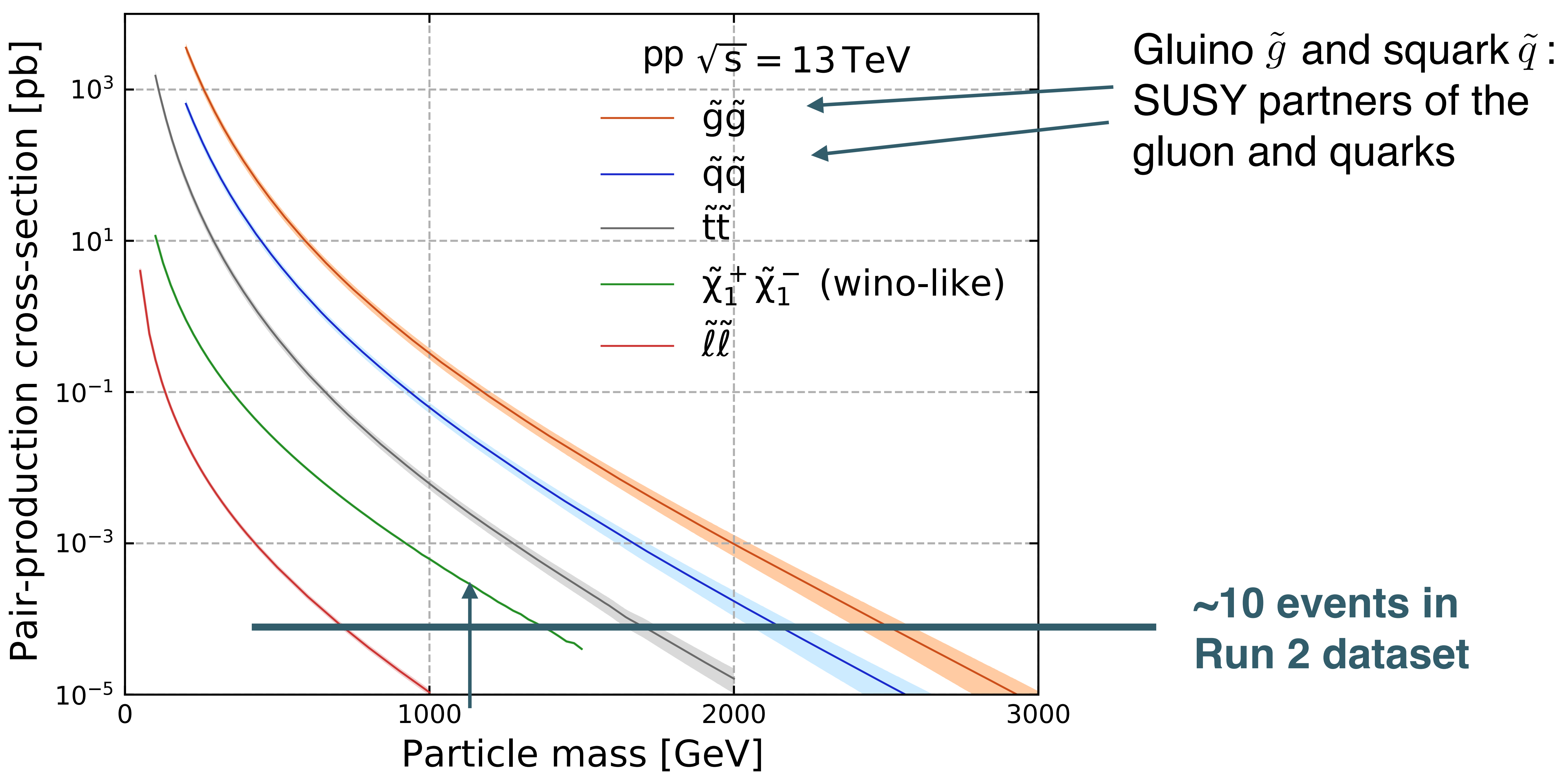
Partners of the charged and neutral Higgs bosons, and W/Z

Sleptons



- Each of these can decay in a variety of ways, giving a rich set of signatures to search for, not to mention keeping us busy!

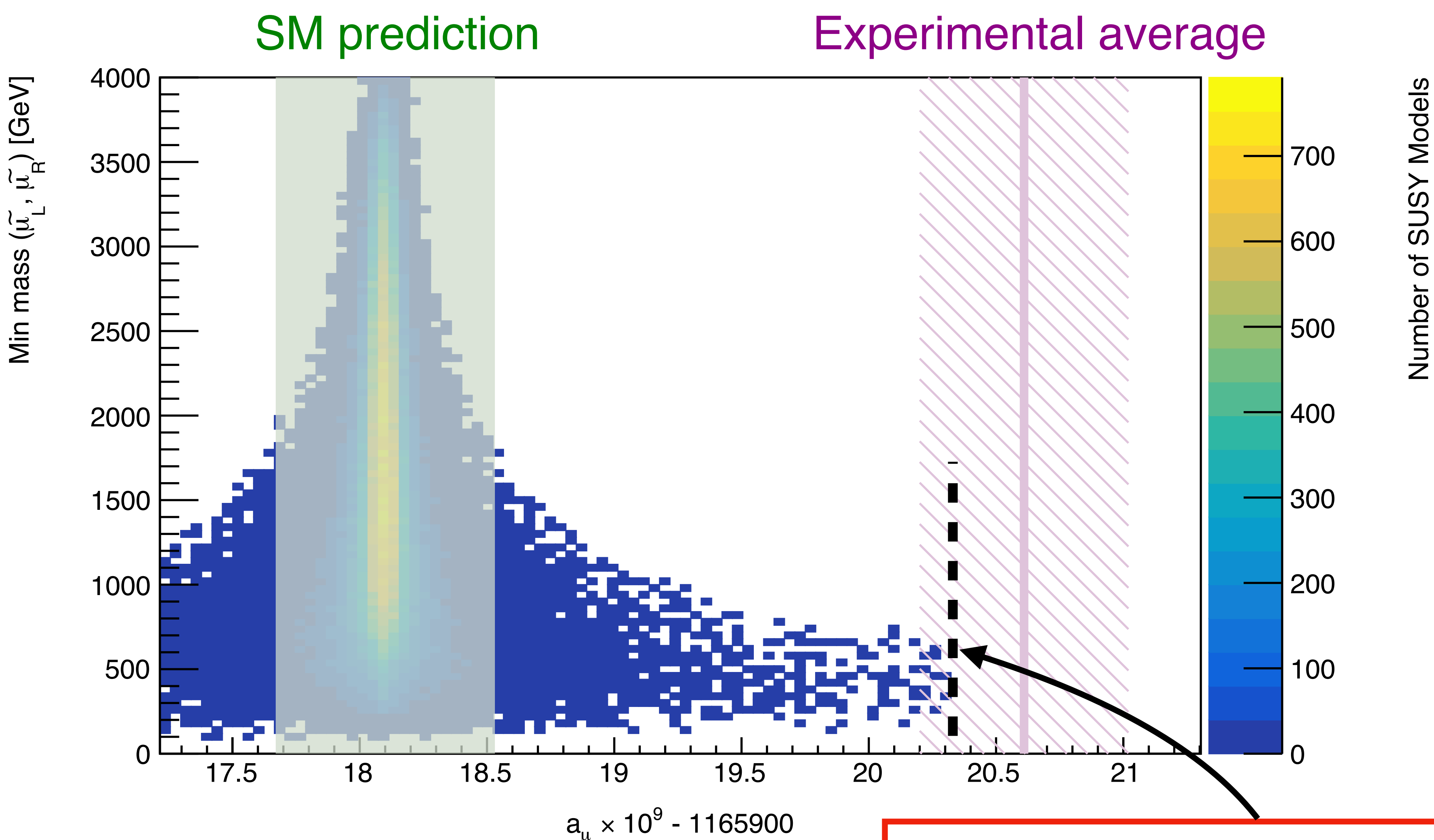
Electroweak scale SUSY



- Each sparticle has different decay phenomenology, giving a rich set of signatures
- ATLAS has dedicated groups targeting each of these production mechanisms

SUSY and g-2

G-2 predictions of SUSY models allowed by Run-1 ATLAS pMSSM scan



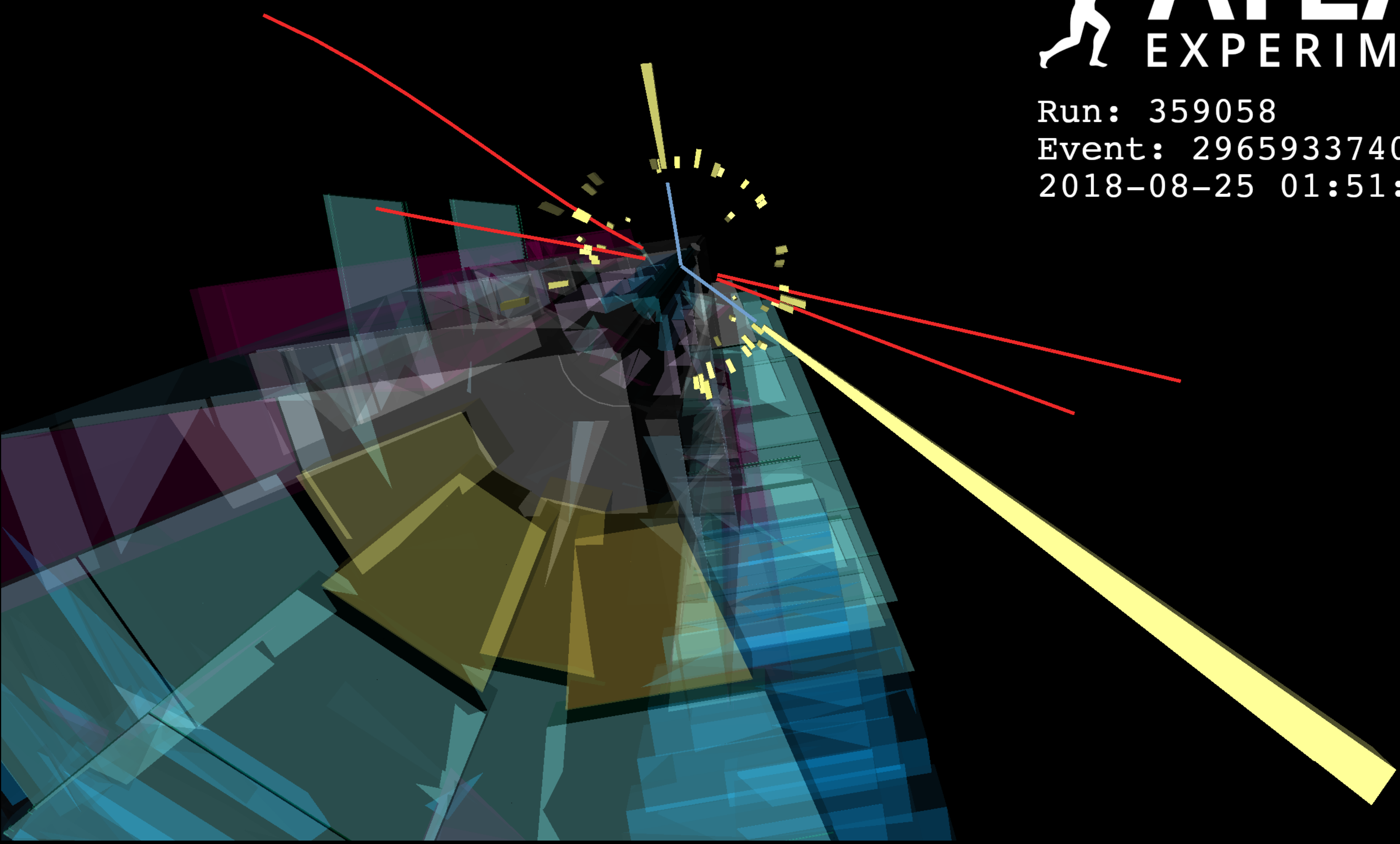
Limit of our simulation as it was 3σ beyond the previous experimental list!

SUSY models will populate this area

Electroweak 4 lepton search

arXiv:2103.11684

ATLAS EXPERIMENT
Run: 359058
Event: 2965933740
2018-08-25 01:51:44 CEST



“The most beautiful 6 lepton event ever displayed”

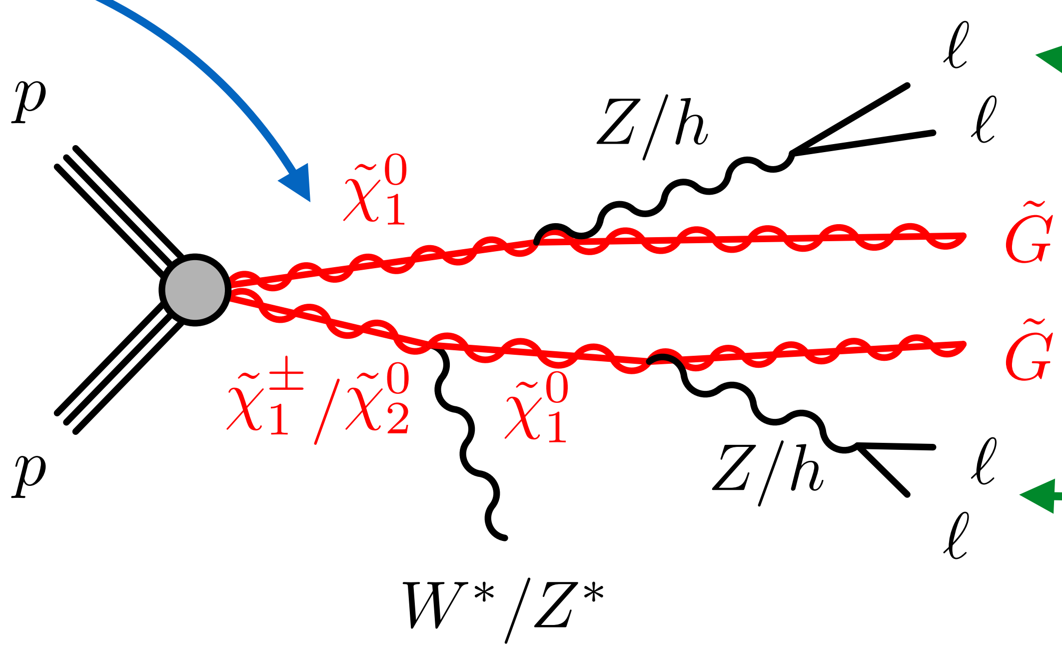
"Have you considered a 7 lepton signal region?"

4 leptons: R-Parity Conserving models

arXiv:2103.11684

- Searches for the Higgsino highly motivated from theory
- GGM offers an opportunity to search for the Higgsino without experimentally challenging low-pT leptons

Degenerate Higgsino
1 GeV mass splitting



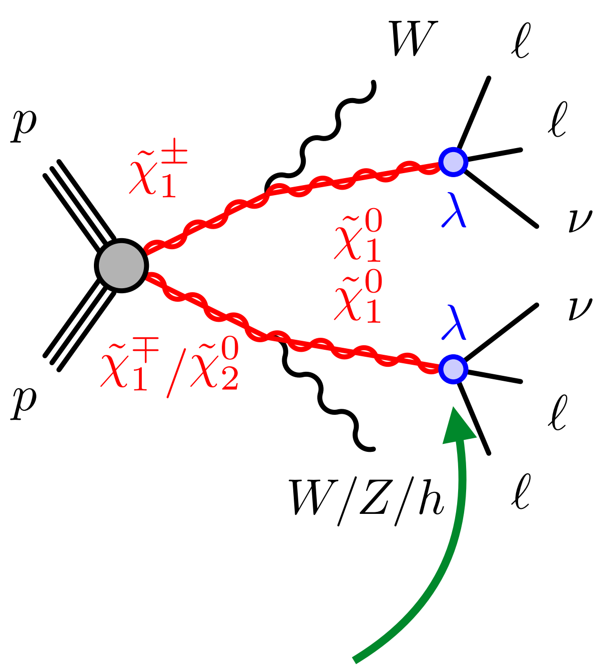
4 High pT leptons
Consistent with Z

Virtual bosons
Low pT decay products not reconstructed

Ultra-light Gravitino

- Signal regions: >=4 e or μ, m_{ll} close to Z mass for both lepton pairs, b-jet veto, $E_{\mathrm{T}}^{\mathrm{miss}}$ > 100 or 200 GeV

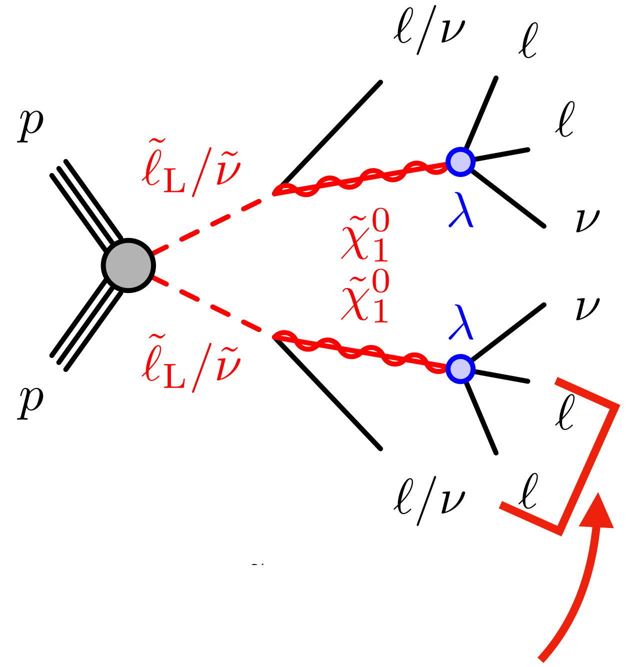
Wino production



RPV decay of Bino

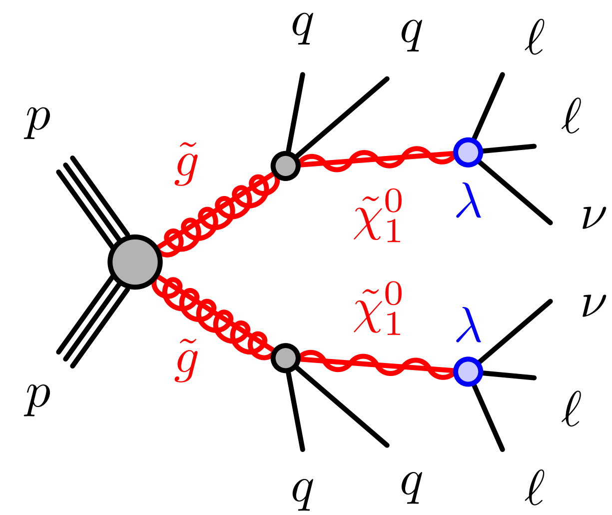
$$\tilde{\chi}_1^0 \rightarrow \ell\ell\nu$$

Slepton production



Z boson veto applied

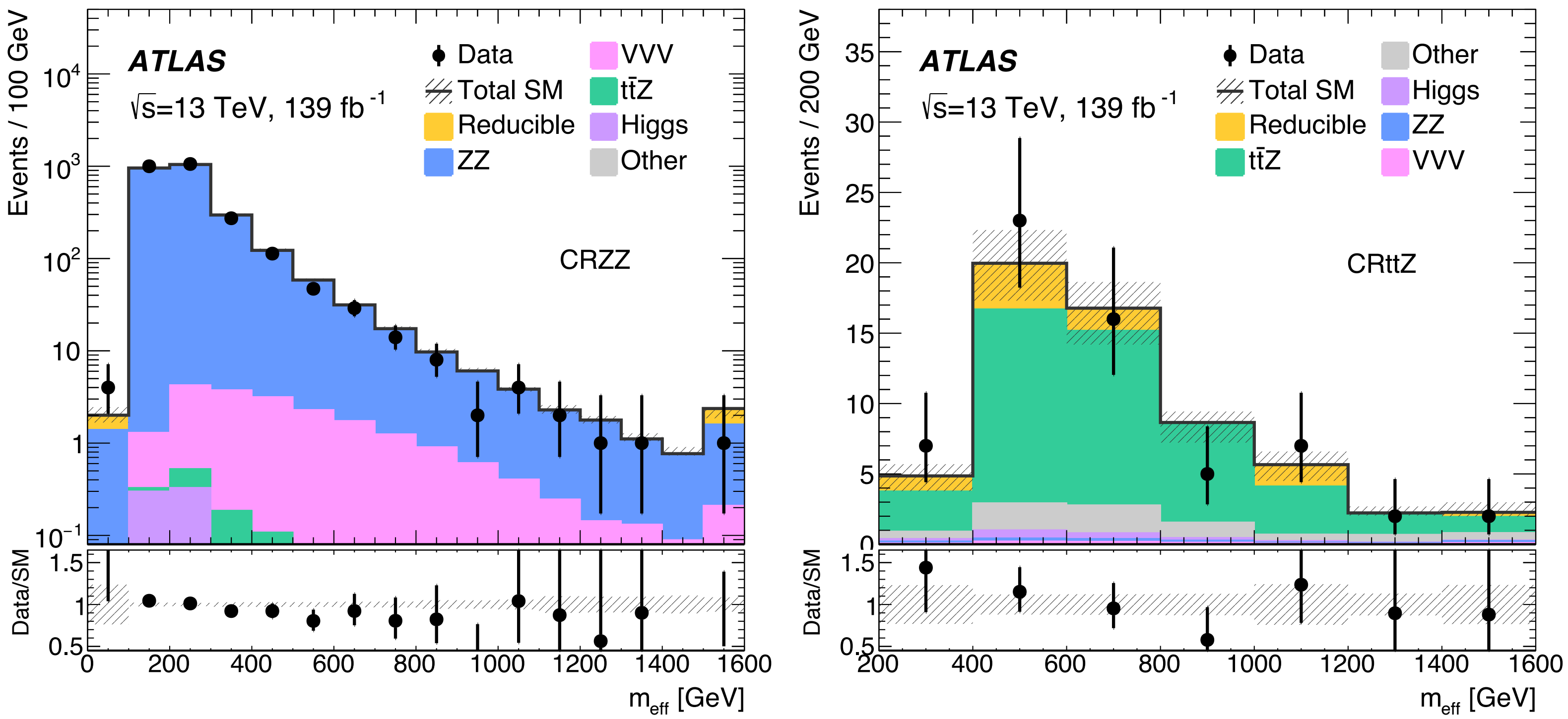
Gluino production



m_{eff} > 1000* GeV
Boost signal sensitivity
*** depending on SR**

- Two cases considered for RPV decay:
  - $\lambda_{12k} \neq 0$: e or μ
  - $\lambda_{i33} \neq 0$: τ or (e XOR μ)
- Signal regions (L is e or μ):
  - ≥4L ≥0τ
  - ≥3L ≥1τ
  - ≥2L ≥2τ

- "Reducible" backgrounds: ZZ, ttZ.
    - Estimated with Monte Carlo, normalised with control regions
- "Irreducible" backgrounds: W/Z+jets, ttbar where jet fakes one or more leptons
    - Estimated with fake factor method: a loose-to-tight method where the probability of a fake loose lepton to make it to the signal region is estimated in data

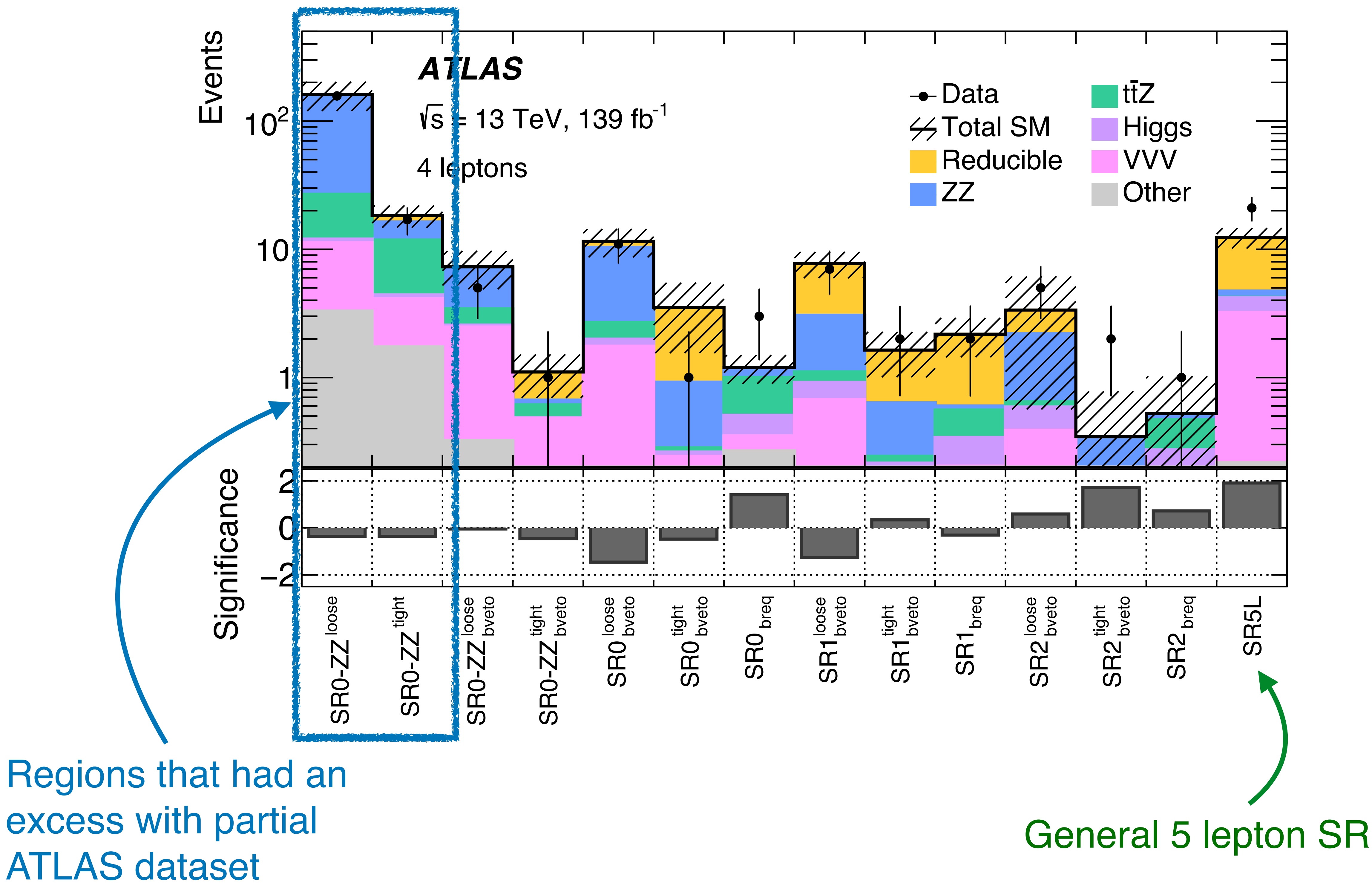


- ZZ and ttZ dominate ≥4L ≥0τ signal region
- Reducible backgrounds dominate ≥3L ≥1τ and ≥2L ≥2τ regions

4 leptons: results

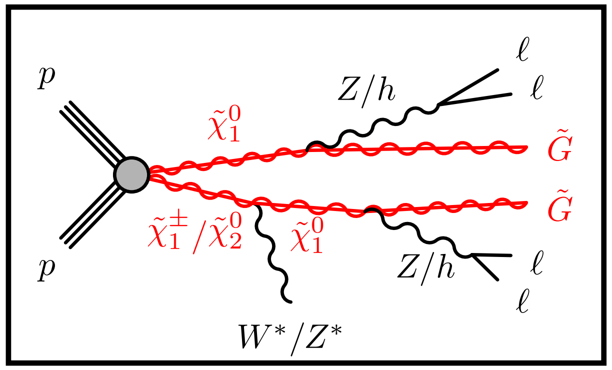
arXiv:2103.11684

*Full definition of signal regions in the backup

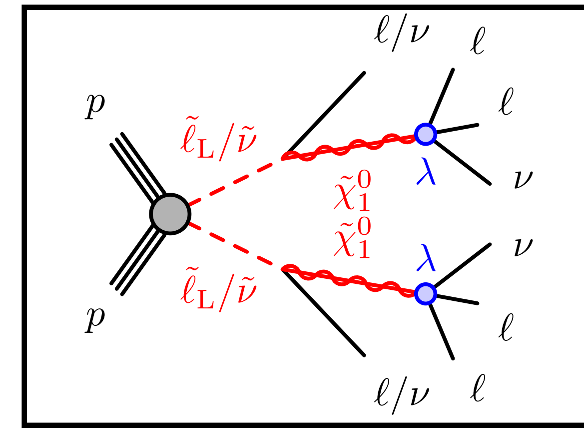


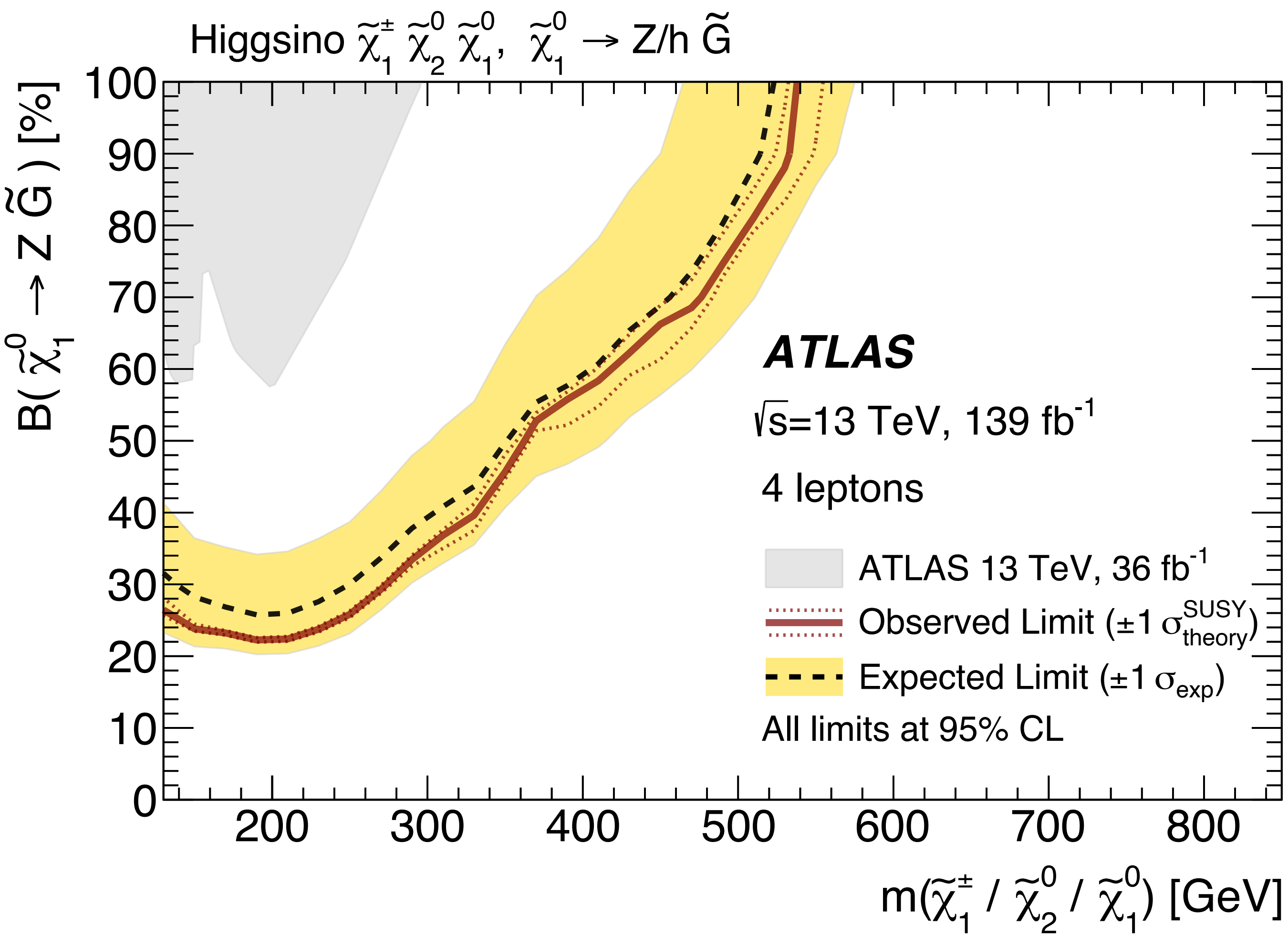
4 leptons: interpretation

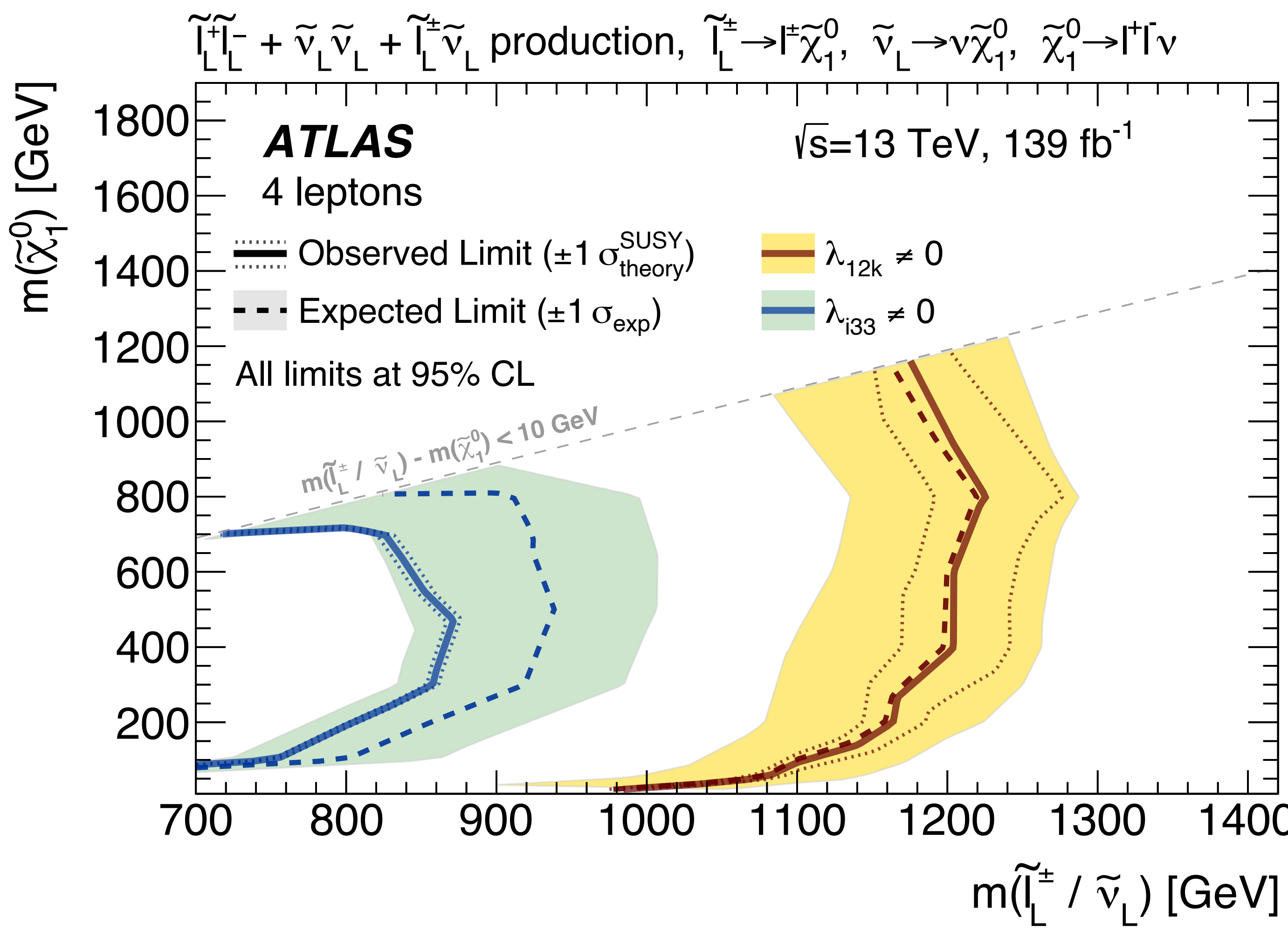
RPC model



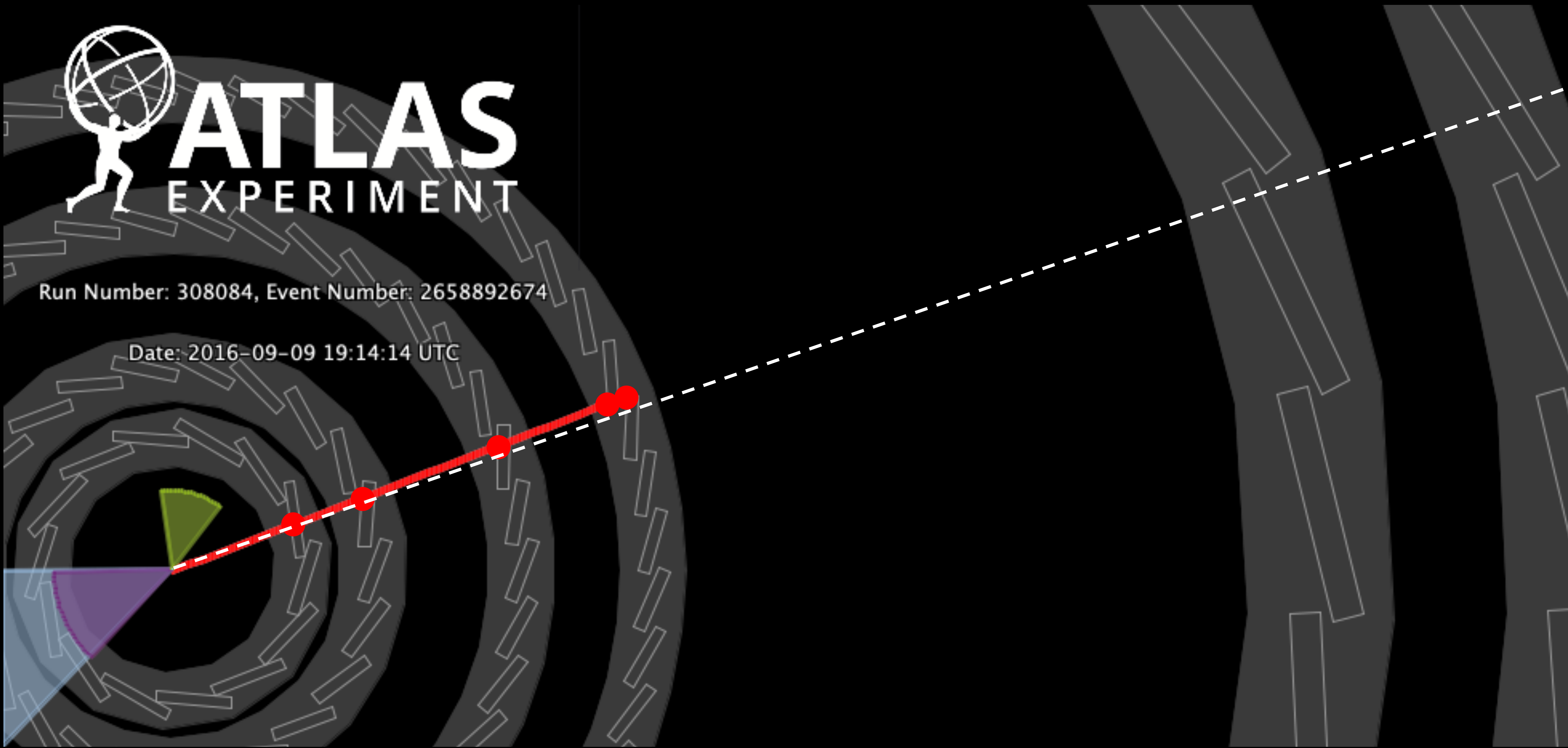
RPV model



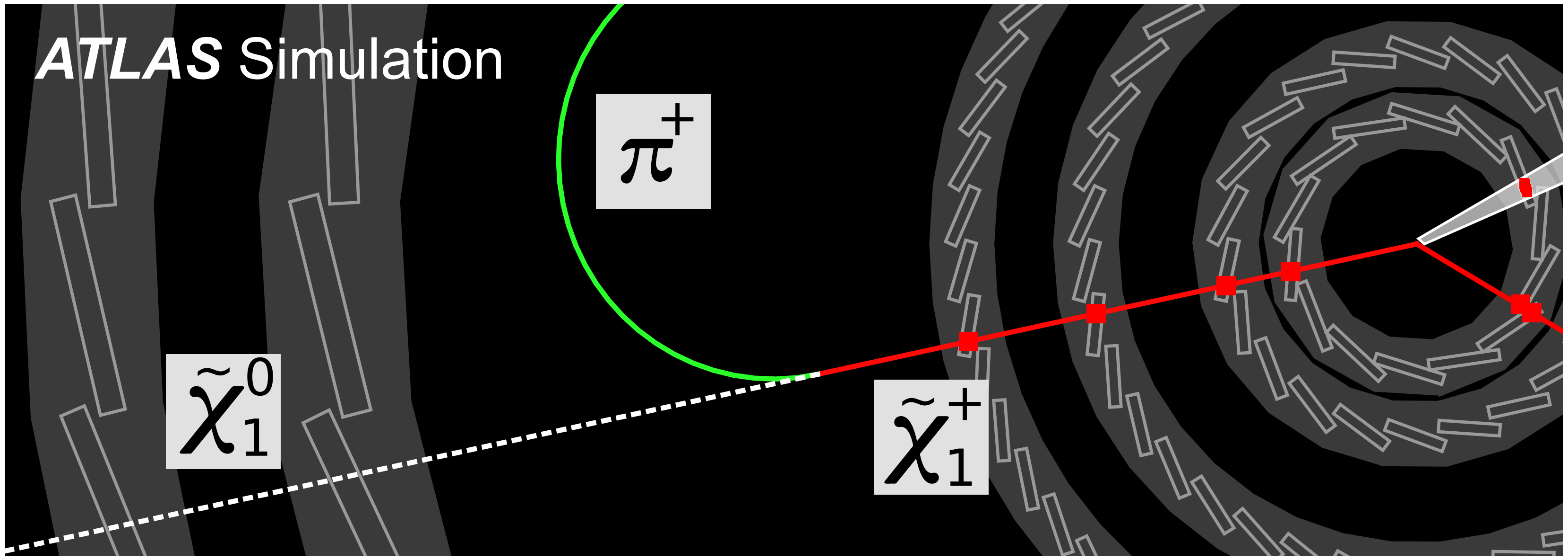




Disappearing tracks

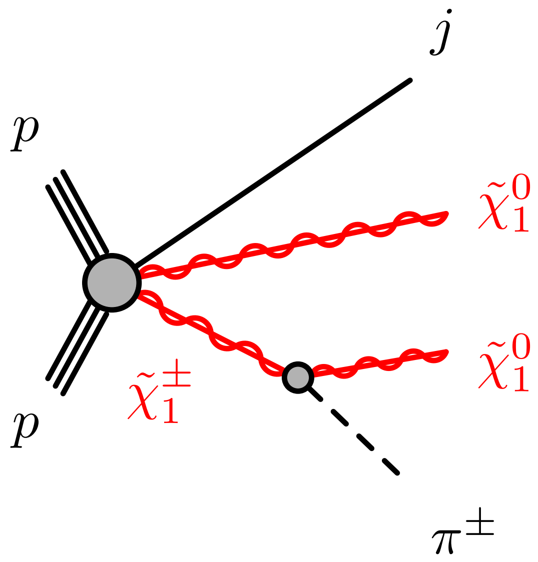


- Targets ultra-compressed **wino** or **Higgsino**
  - Either through electroweak production or gluino production
- Small mass splitting can make the chargino **long lived**
  - Typical lifetimes **0.02 ns** (Higgsino) to **0.2 ns** (wino)
- Chargino decays to a soft pion (not reconstructed) and LSP (MET)
- Gives rise to **disappearing track** signature

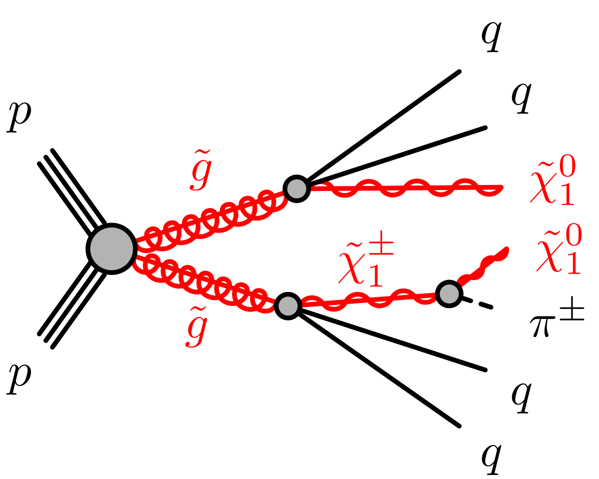


- Trigger on MET
- Target electroweak production with MET > 200 GeV, ≥1 jet
- Target strong production with MET > 250 GeV, ≥3 jets

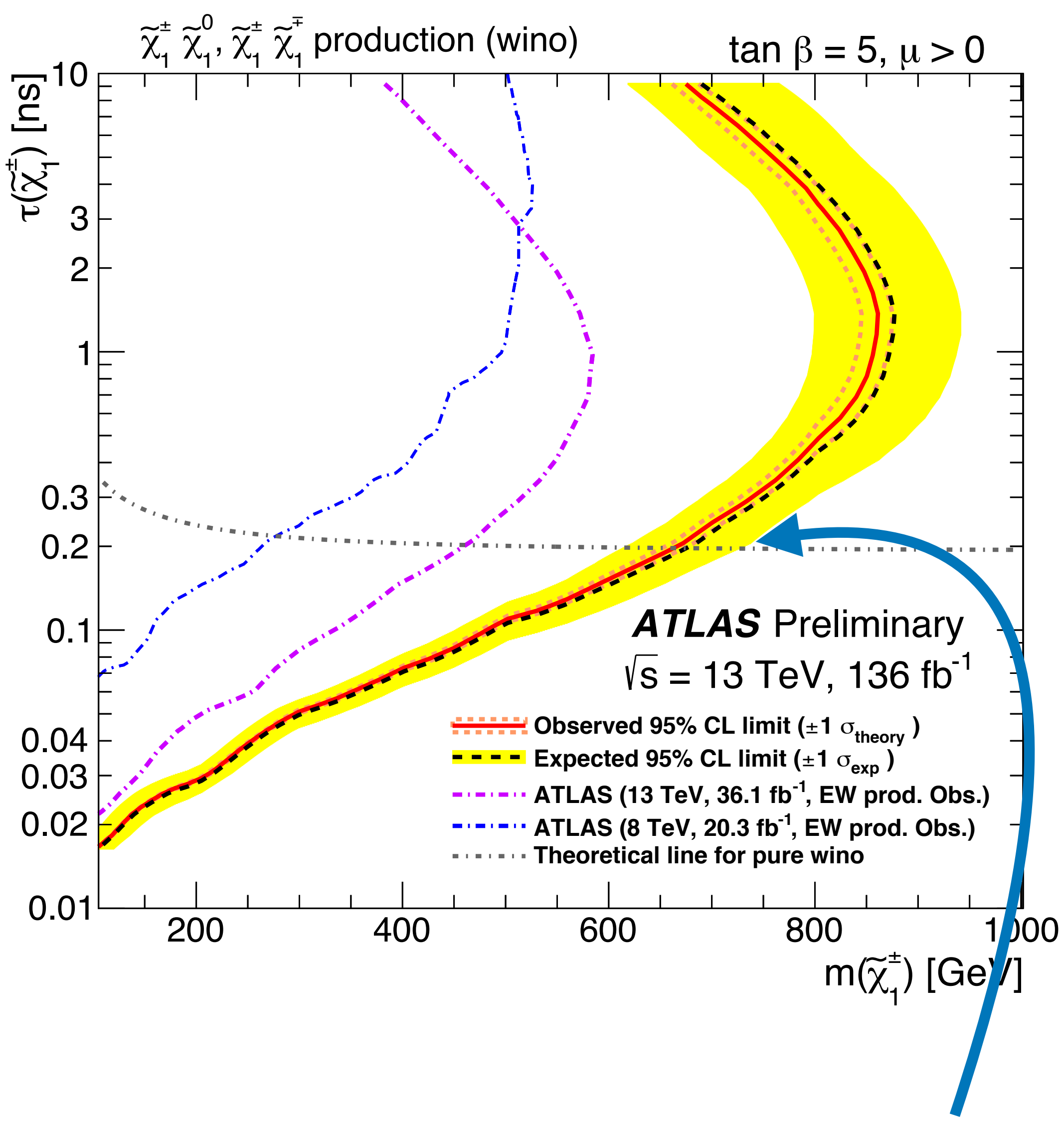
Electroweak



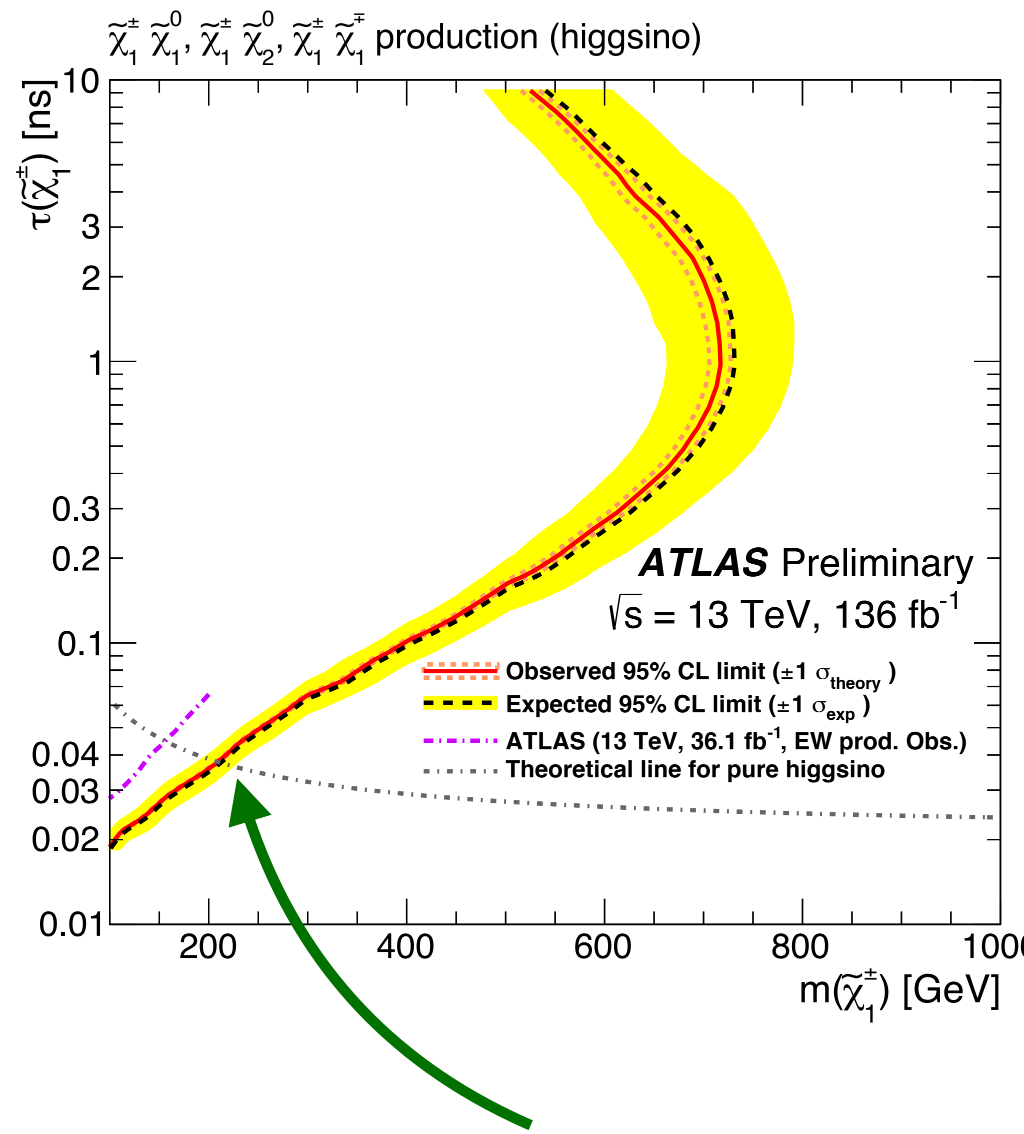
Strong



Grey dashed line is theoretical line for pure wino/Higgsino

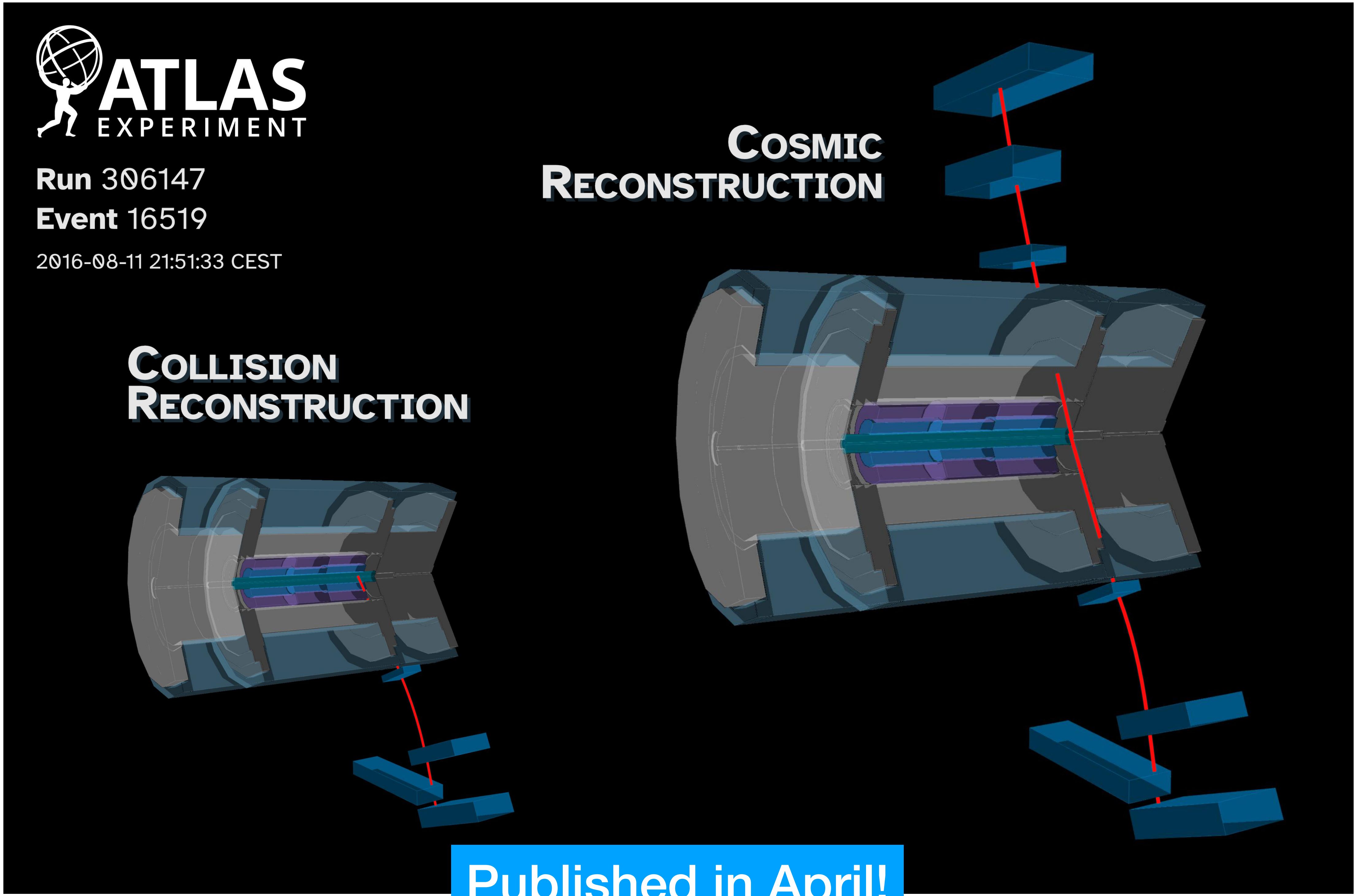


Limit on pure wino at 660 GeV



Limit on pure Higgsino at 210 GeV

arXiv:2104.03050

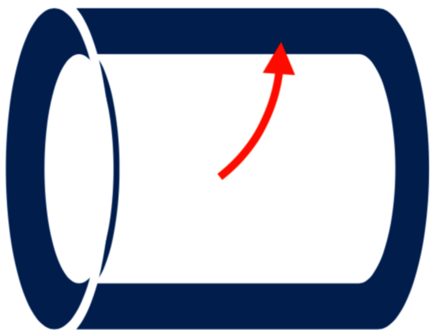


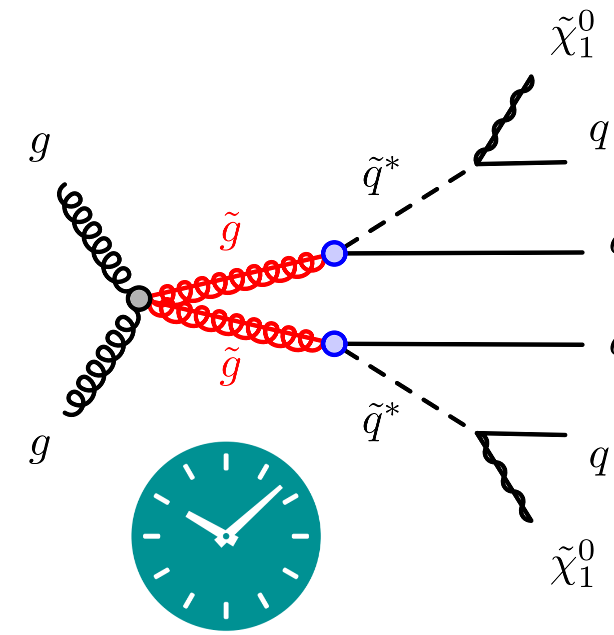
Published in April!

Stopped long-lived particles

arXiv:2104.03050

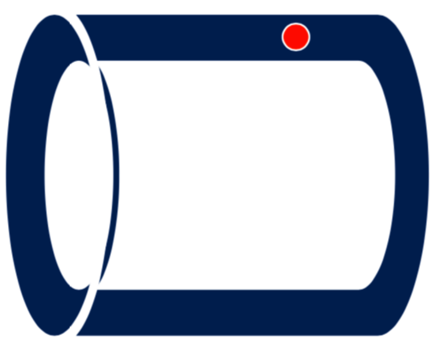
- Search for BSM long-lived particles carrying SM charge





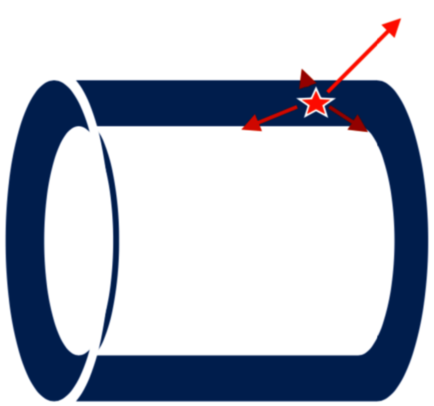
LLP produced in *pp* collisions

Bonds with SM quarks
Forms R-hadron



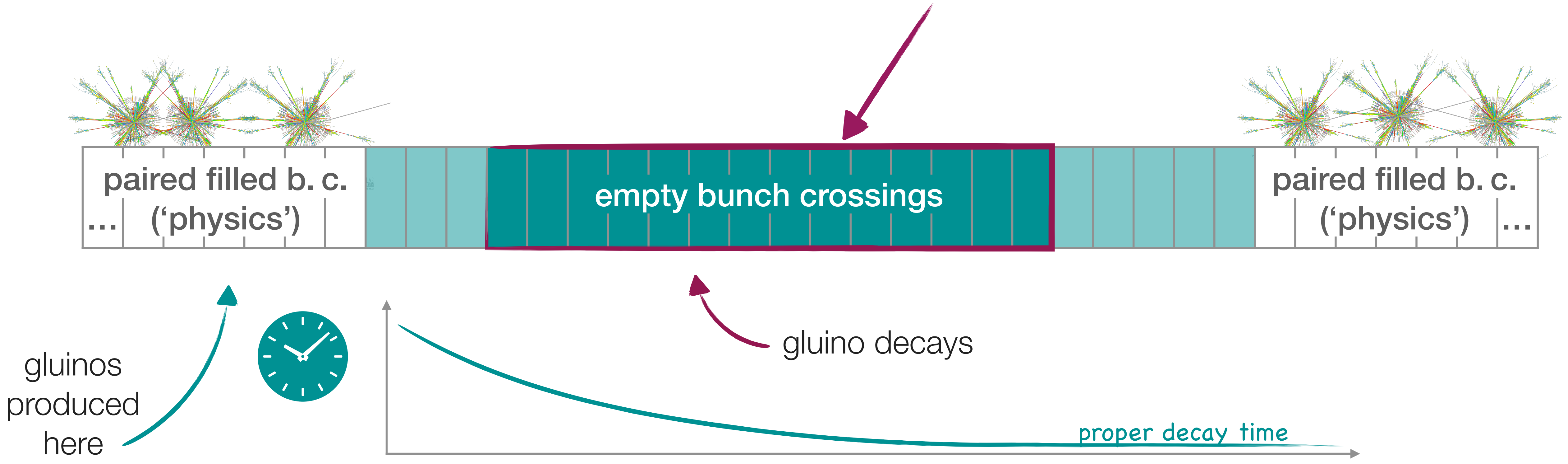
Loses momentum through
interactions with detector material

If LLP is long-lived enough, some will **stop**
inside the detector before decaying



Look for late decays to hadronic jets
Target lifetimes from μs to years

Search strategy: trigger on jets produced in **empty bunch crossings**



Signal region requirements

Jet pT > 150 GeV

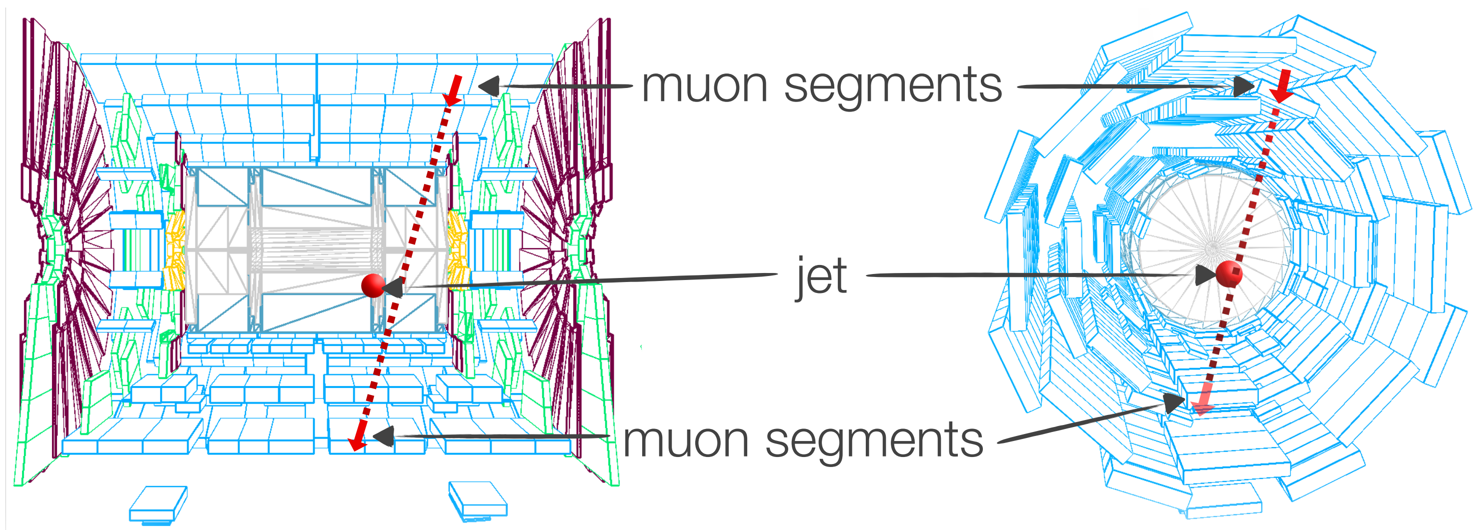
Primary vertex veto, muon veto

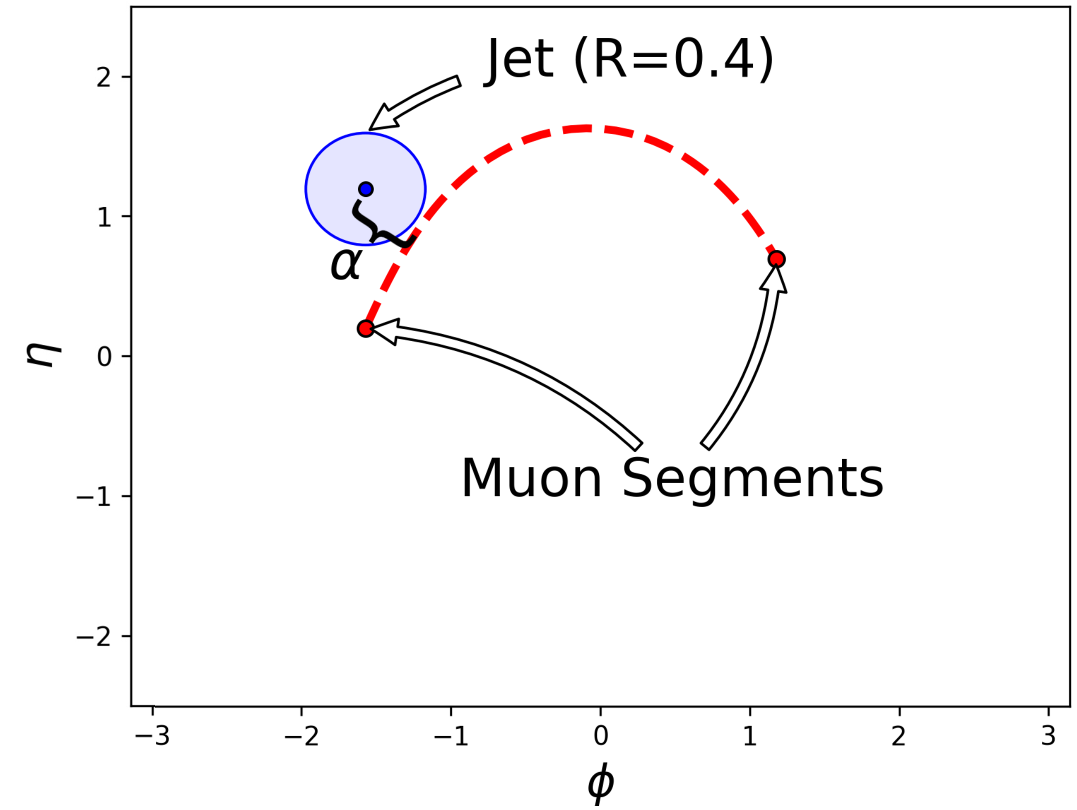
x2 SRs split by jet η:

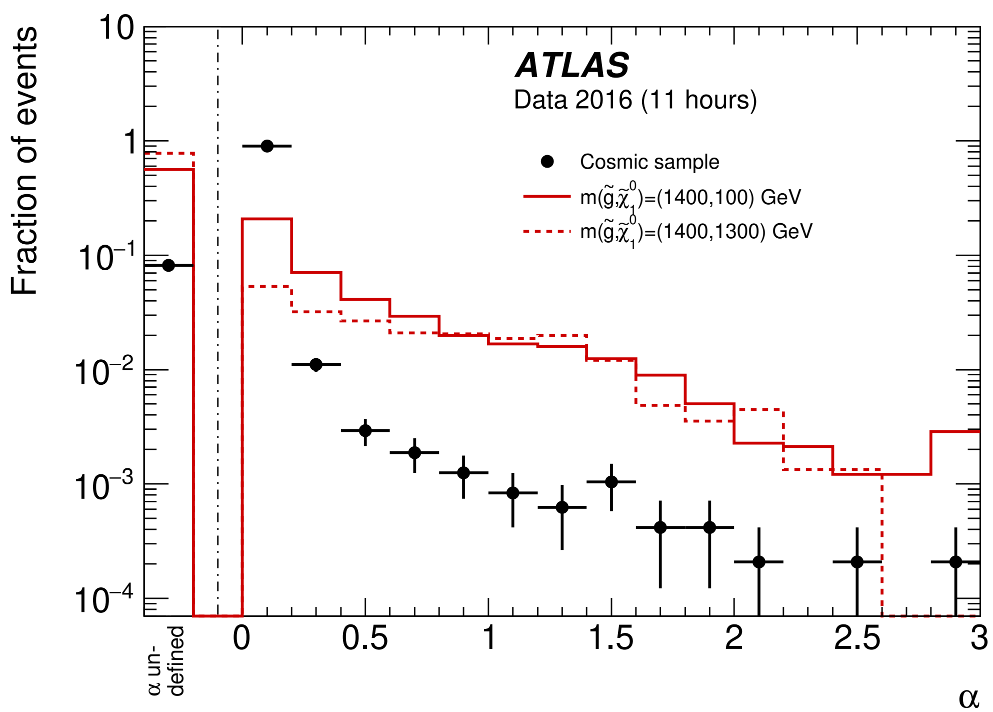
- Jet |η| <0.8 “SR C”
- Jet |η| <2.4 “SR inclusive”

Cosmic rays inducing an energetic jet

- Highly energetic bremsstrahlung photon from the cosmic muon
- Removed with impact-parameter style geometrical requirements between the jet and the muon spectrometer segments (remove $|\alpha| < 0.2$)





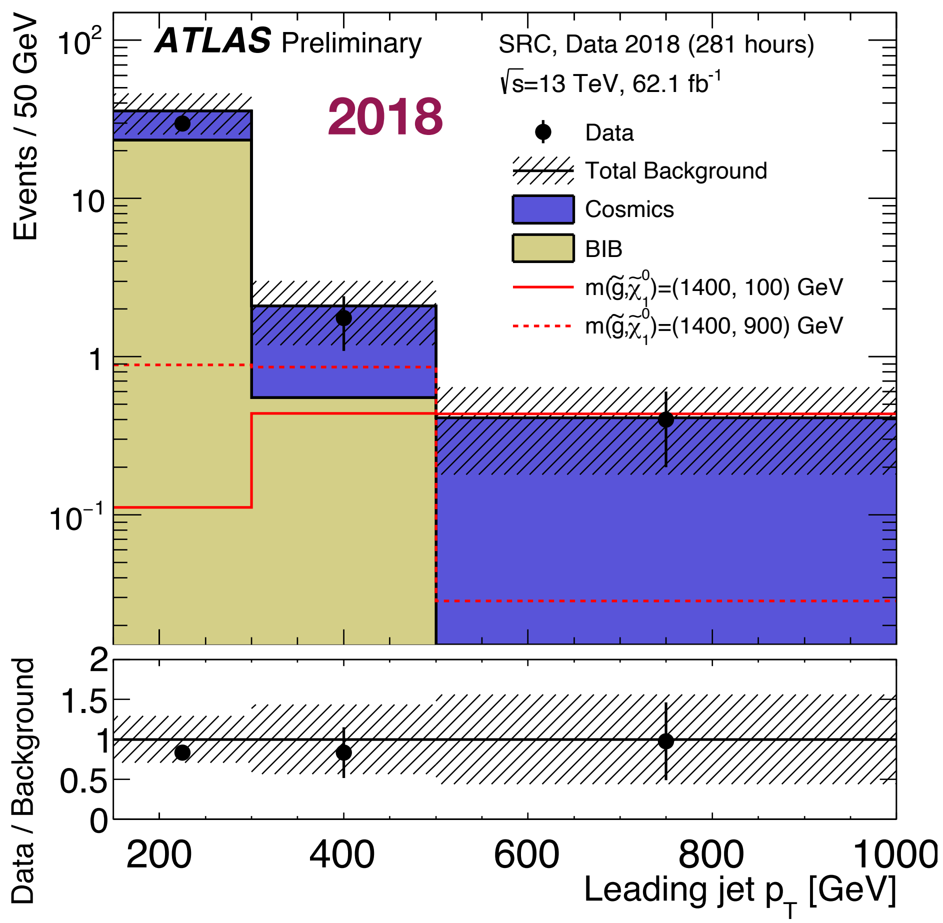


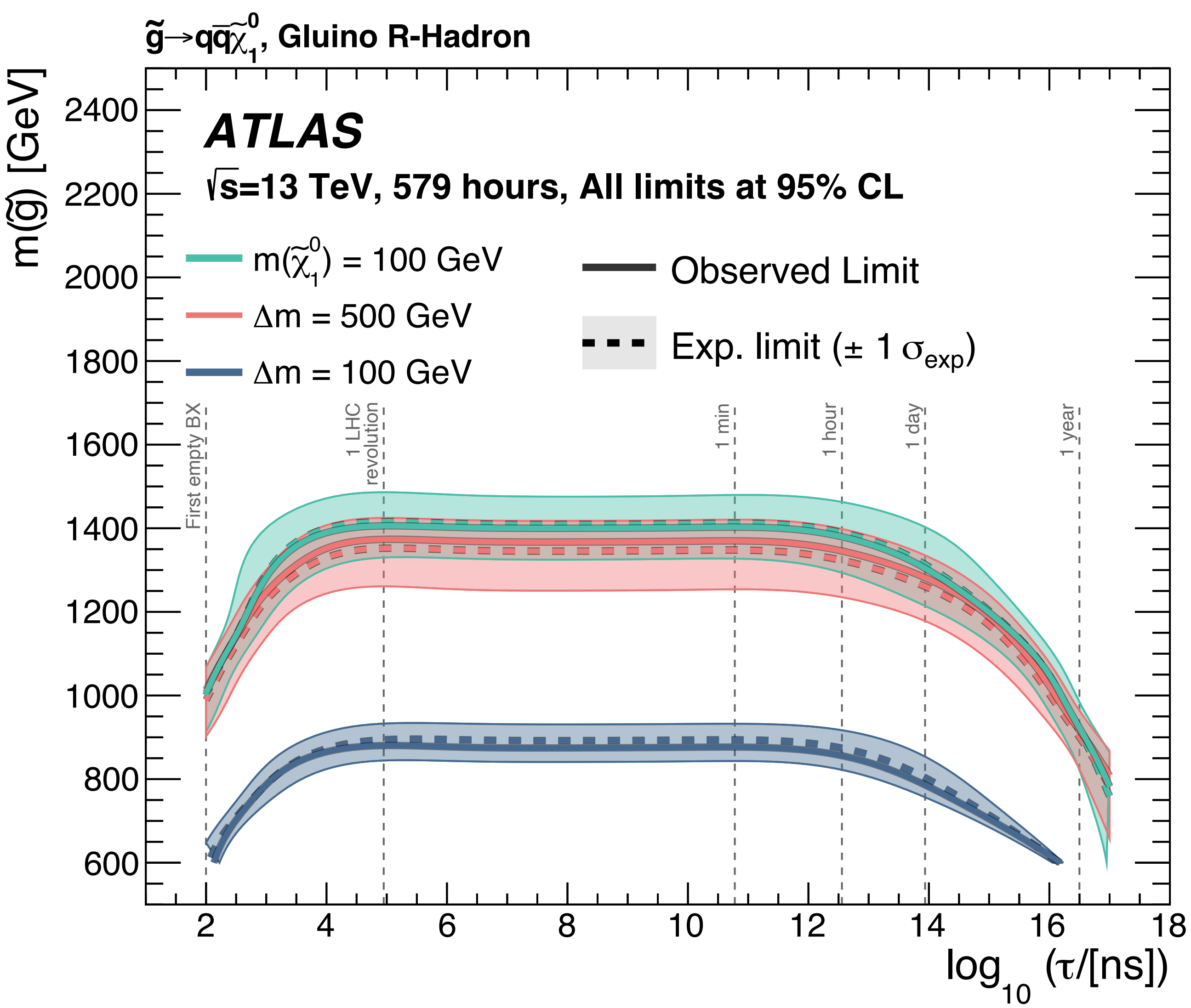
Other backgrounds

- **Beam-induced backgrounds:** stray protons interacting with residual beam gas or LHC collimators/beam pipe
- calorimeter noise, cavern background

Stopped long-lived particles: results

arXiv:2104.03050





- Sensitive to gluino masses up to **1.4 TeV** in the lifetime plateau (10^{-5} to 10^{3}s),
  - and up to **1.0 TeV** for lifetimes of 100 ns and up to 10^{7}s
- See this wonderful CERN Physics Briefing for more on this search!

Recent ATLAS SUSY results

Check out these other full run2 publications released in the last 2 months!

Search for sbottoms with b-jets and hadronic taus	arXiv:2103.08189
The mono-jet search	arXiv:2102.10874
Stop pair or leptoquarks to taus	ATLAS-CONF-2021-008
RPV gluinos or stops to at least 1 lepton	ATLAS-CONF-2021-007

Summary: the search continues

- No hints of SUSY at the LHC so far!
- Lots of room still to cover
- Full spectrum of production mechanisms covered
- Challenging Higgsino targeted with GGM scenario
- Ultra-compressed wino and Higgsino with disappearing tracks
- Innovative stopped particle search with custom dataset ruling out many BSM theories
- Stay tuned for more searches to come!

Thank you!

Backup

4 leptons: signal regions

Name	Signal Region	$N(e,\mu)$	$N(\tau_{had})$	N (b-tagged jets)	Z boson	Selection	Target
$4L0T$	$\mathtt{SR0\text{-}ZZ}^{loose}_{bveto}$	≥ 4	≥ 0	$= 0$	require 1st & 2nd	$E_T^{miss} > 100$ GeV	higgsino GGM
	$\mathtt{SR0\text{-}ZZ}^{tight}_{bveto}$	≥ 4	≥ 0	$= 0$	require 1st & 2nd	$E_T^{miss} > 200$ GeV	higgsino GGM
	$\mathtt{SR0\text{-}ZZ}^{loose}$	≥ 4	≥ 0	≥ 0	require 1st & 2nd	$E_T^{miss} > 50$ GeV	Excess from Ref. [18]
	$\mathtt{SR0\text{-}ZZ}^{tight}$	≥ 4	≥ 0	≥ 0	require 1st & 2nd	$E_T^{miss} > 100$ GeV	Excess from Ref. [18]
	$\mathtt{SR0}^{loose}_{bveto}$	≥ 4	≥ 0	$= 0$	veto	$m_{eff} > 600$ GeV	General
	$\mathtt{SR0}^{tight}_{bveto}$	≥ 4	≥ 0	$= 0$	veto	$m_{eff} > 1250$ GeV	RPV $LL\bar{E}12k$
	$\mathtt{SR0}_{breq}$	≥ 4	≥ 0	≥ 1	veto	$m_{eff} > 1300$ GeV	RPV $LL\bar{E}12k$
$3L1T$	$\mathtt{SR1}^{loose}_{bveto}$	$= 3$	≥ 1	$= 0$	veto	$m_{eff} > 600$ GeV	General
	$\mathtt{SR1}^{tight}_{bveto}$	$= 3$	≥ 1	$= 0$	veto	$m_{eff} > 1000$ GeV	RPV $LL\bar{E}i33$
	$\mathtt{SR1}_{breq}$	$= 3$	≥ 1	≥ 1	veto	$m_{eff} > 1300$ GeV	RPV $LL\bar{E}i33$
$2L2T$	$\mathtt{SR2}^{loose}_{bveto}$	$= 2$	≥ 2	$= 0$	veto	$m_{eff} > 600$ GeV	General
	$\mathtt{SR2}^{tight}_{bveto}$	$= 2$	≥ 2	$= 0$	veto	$m_{eff} > 1000$ GeV	RPV $LL\bar{E}i33$
	$\mathtt{SR2}_{breq}$	$= 2$	≥ 2	≥ 1	veto	$m_{eff} > 1100$ GeV	RPV $LL\bar{E}i33$
$5L0T$	SR5L	≥ 5	≥ 0	≥ 0	–	–	General

Ref 18: arXiv:1804.03602

Disappearing track: signal regions

Signal region	Electroweak production	Strong production
Number of electrons and muons	0	
Number of pixel tracklets	≥ 1	
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 200	> 250
Number of jets ($p_{\mathrm{T}} > 20$ GeV)	≥ 1	≥ 3
Leading jet p_{T} [GeV]	> 100	> 100
Second and third jet p_{T} [GeV]	–	> 20
$\Delta\phi_{min}^{\mathrm{jet}-E_{\mathrm{T}}^{\mathrm{miss}}}$	> 1.0	> 0.4

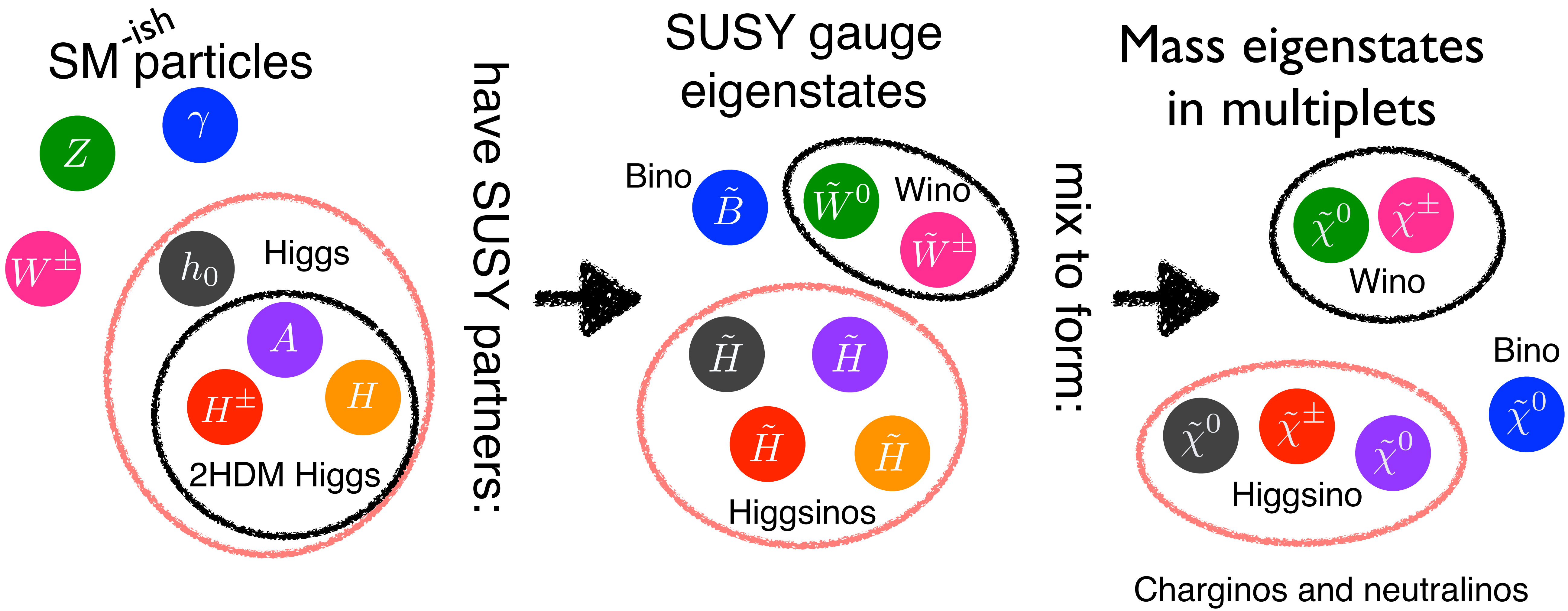
Stopped long-lived particles: signal regions

Region	Data sample	Number of muons	Leading jet p_T [GeV]	α	Leading jet w_ϕ	Leading jet $\|\eta\|$
Central signal region						
SRC	Search sample	0	150–300 300–500 > 500	> 0.2	> 0.02	< 0.8
Inclusive signal region						
SRIncl	Search sample	0	150–300 300–500 > 500	> 0.2	> 0.02	< 2.4
Central discovery regions						
DRC-150 DRC-300 DRC-500	Search sample (2018 data only)	0	> 150 > 300 > 500	> 0.2	> 0.02	< 0.8
Inclusive discovery regions						
DRIncl-150 DRIncl-300 DRIncl-500	Search sample (2018 data only)	0	> 150 > 300 > 500	> 0.2	> 0.02	< 2.4

Stopped long-lived particles: other regions

Data sample (purpose)	**Bunch structure**	**Trigger requirements**	**Offline requirements**
Search sample	Empty	HLT jet $p_T > 55$ GeV HLT $E_T^{miss} > 50$ GeV HLT jet $\lvert\eta\rvert < 2.4$	Leading jet $p_T > 90$ GeV Leading jet $\lvert\eta\rvert < 2.4$
Cosmic sample	–	L1 jet $p_T > 12$ GeV	Leading jet $p_T > 90$ GeV Leading jet $\lvert\eta\rvert < 2.4$
Beam-induced background sample	Unpaired	L1 jet $p_T > 12$ GeV or L1 jet $p_T > 50$ GeV	Leading jet $p_T > 90$ GeV Leading jet $\lvert\eta\rvert < 2.4$
Cavern background sample	Empty	Random	–

Electroweak SUSY



[Picture credit: Max Swiatlowski]

- Charginos and neutralinos labelled in mass order from lightest to heaviest

$$\tilde{\chi}^0_{1,2,3,4} \qquad \tilde{\chi}^{\pm}_{1,2}$$

A closer look at their decays

Higgsino

$$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z^*, Z^* \to \ell\ell$$

Bino+compressed slepton

$$\tilde{\ell} \to \tilde{\chi}_1^0 \ell$$ **x 2**

- Coannihilation "natural" for higgsinos
- Bino requires another SUSY particle to be compressed, e.g. the slepton
- Both leave the same signature: a pair of soft leptons
- Can search for Binos and Higgsinos at the same time

The Higgsino: a special particle in SUSY

Why higgsinos?

1. In "natural" SUSY models, higgsinos should be light

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

- μ (which controls all higgsino masses) and $m_{H_u}^2$ (set by stop and gluino masses) should both be small for fine-tuning to be minimal

- Higgsino masses affect fine-tuning at tree-level!

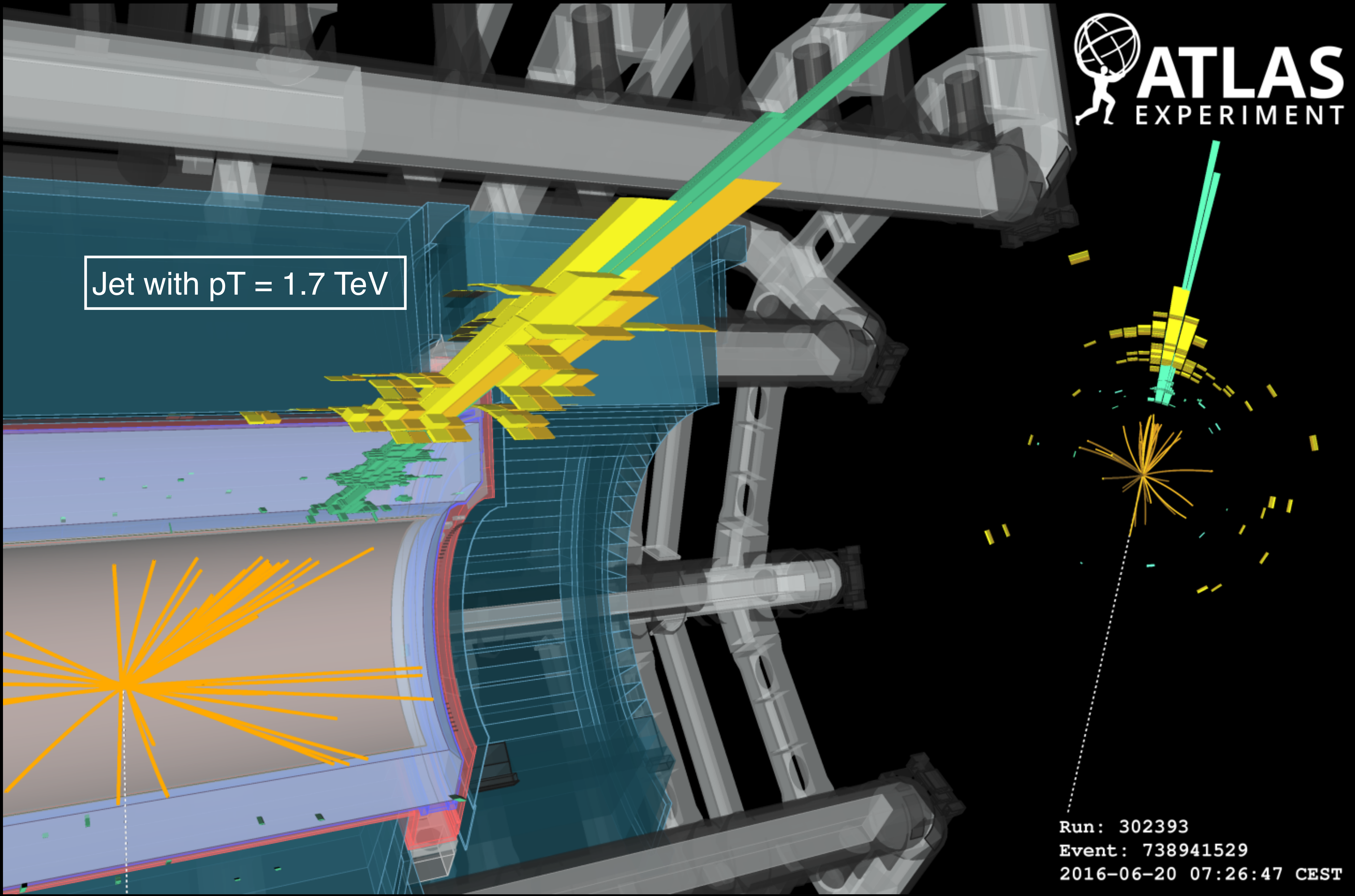
Why compressed?

2. If the lightest neutralinos and charginos are dominated by the higgsino, the mass splitting between them will be small: O(100 MeV - several GeV)

- The mass splitting is determined by how dominant the higgsino component is

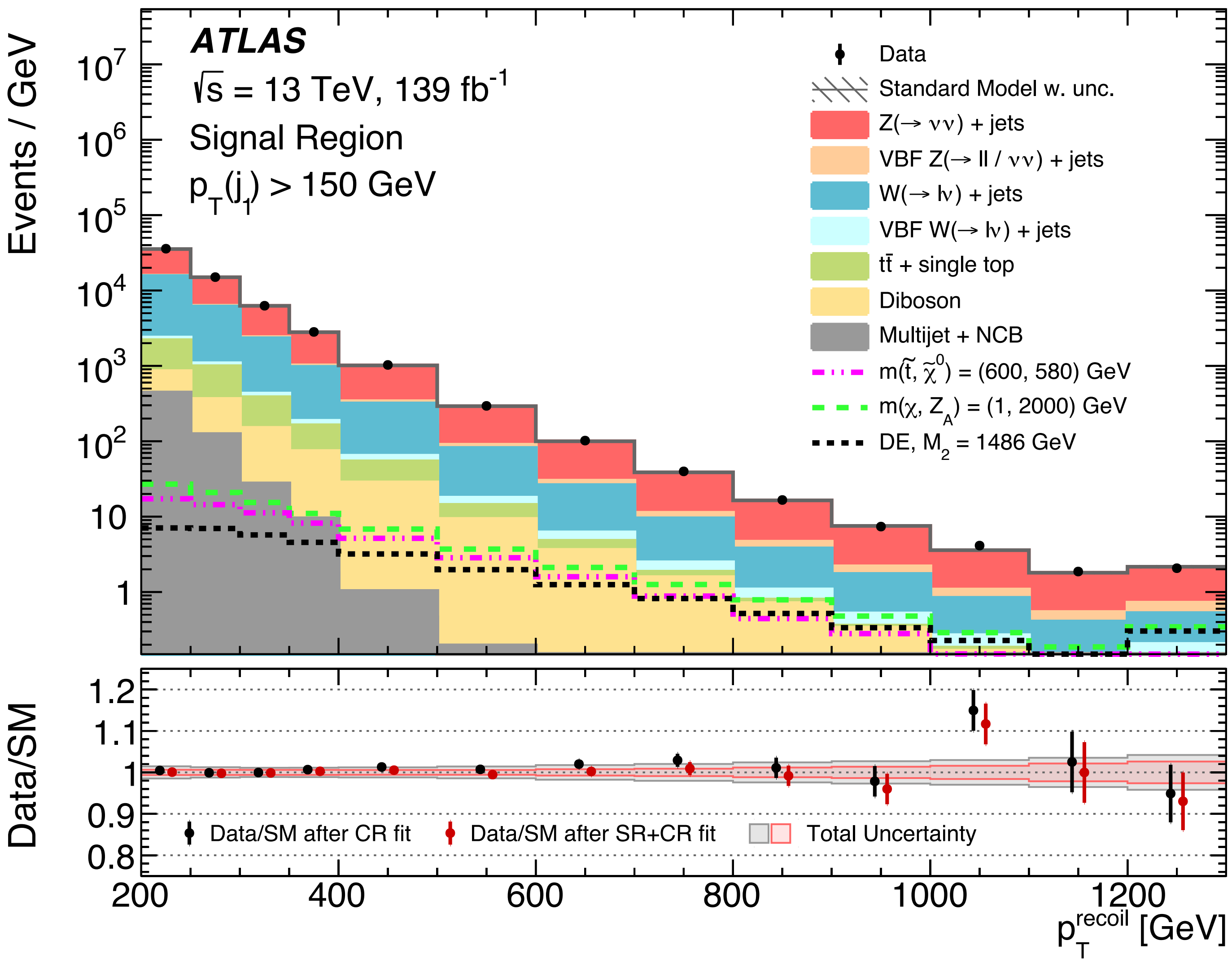
3. Large datasets at the LHC mean we are finally competitive with LEP limits!

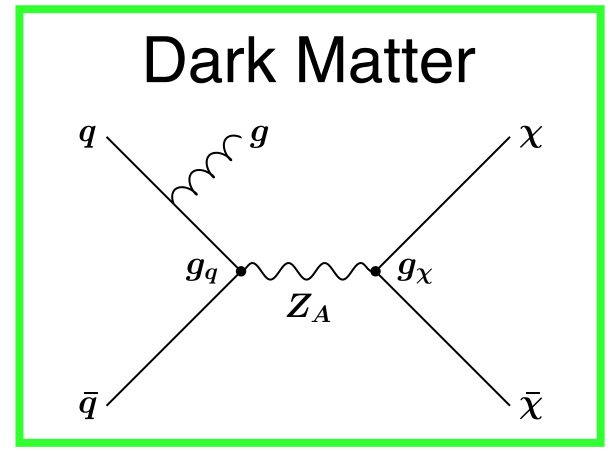
Mono-jet: dark matter signatures = SUSY signatures arXiv:2102.10874

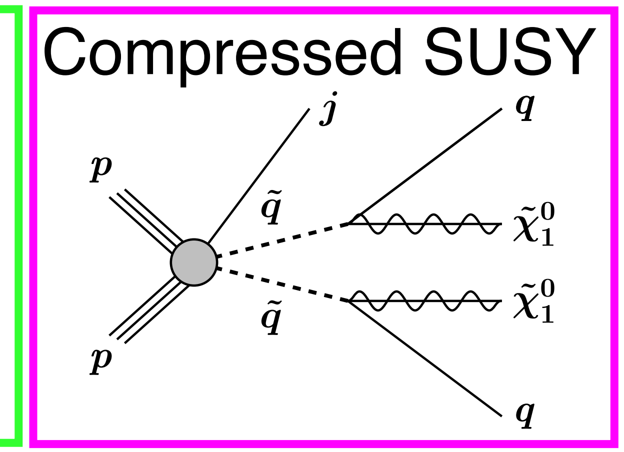


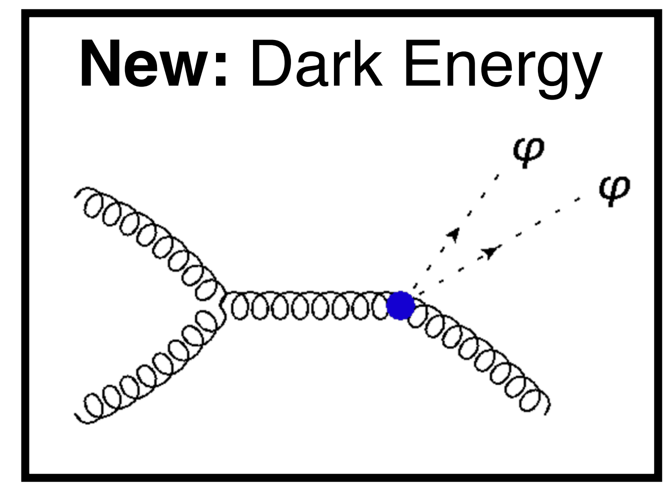
Mono-jet: search strategy

arXiv:2102.10874

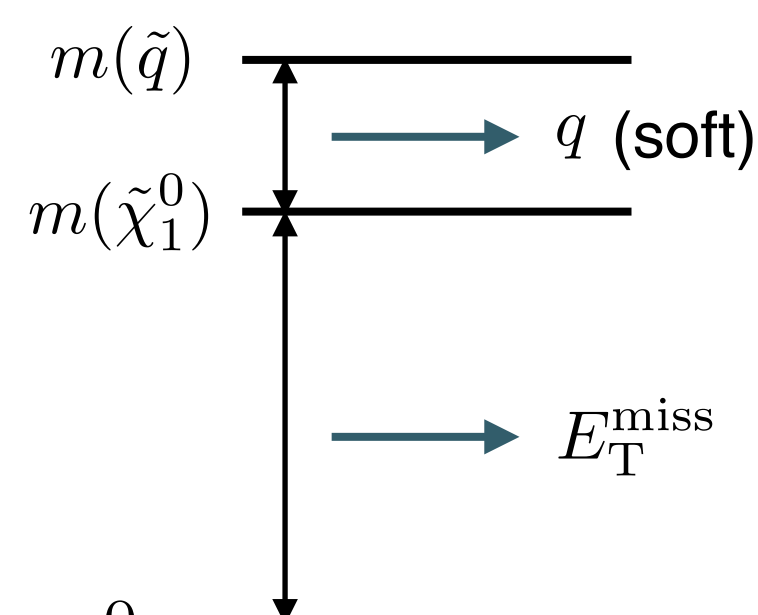






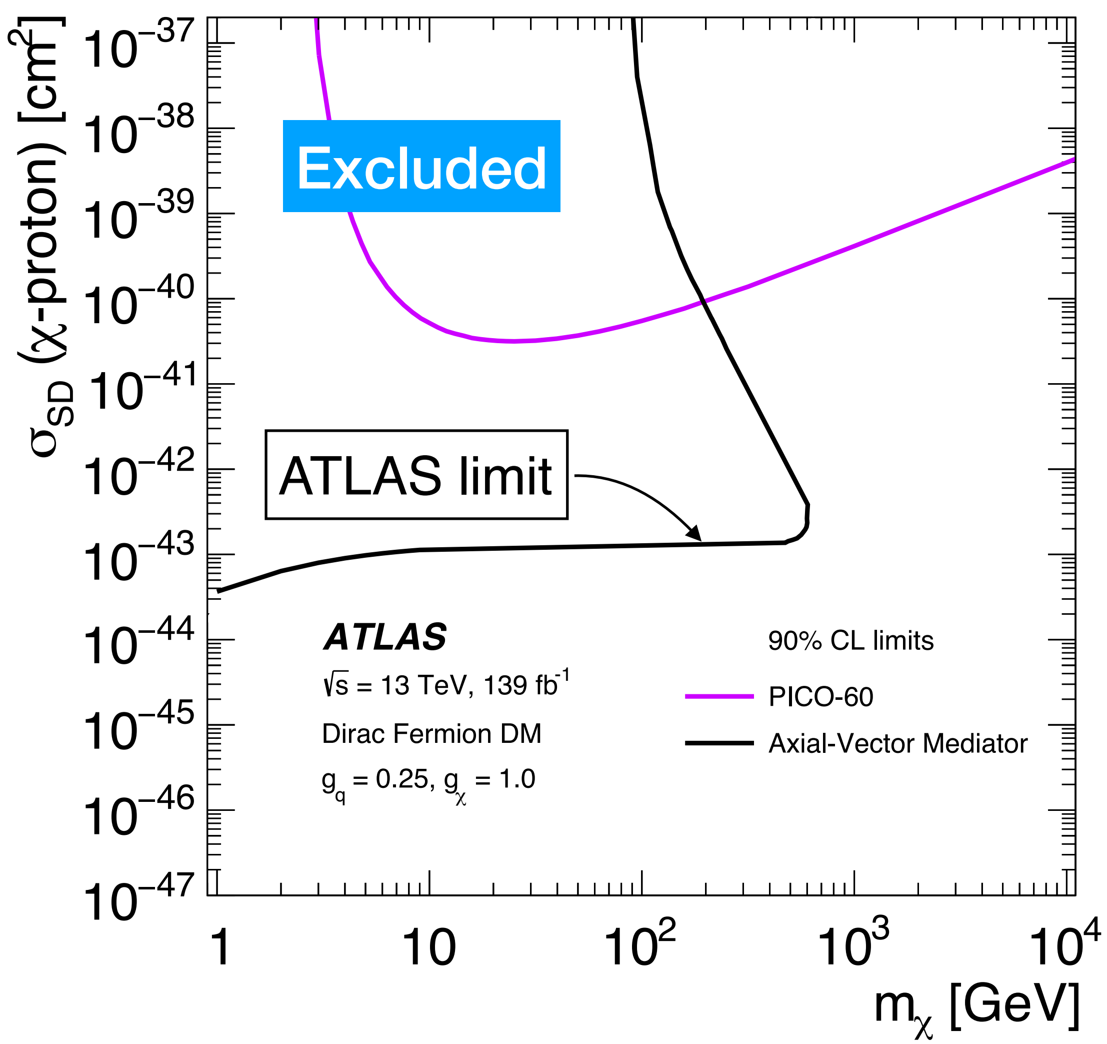


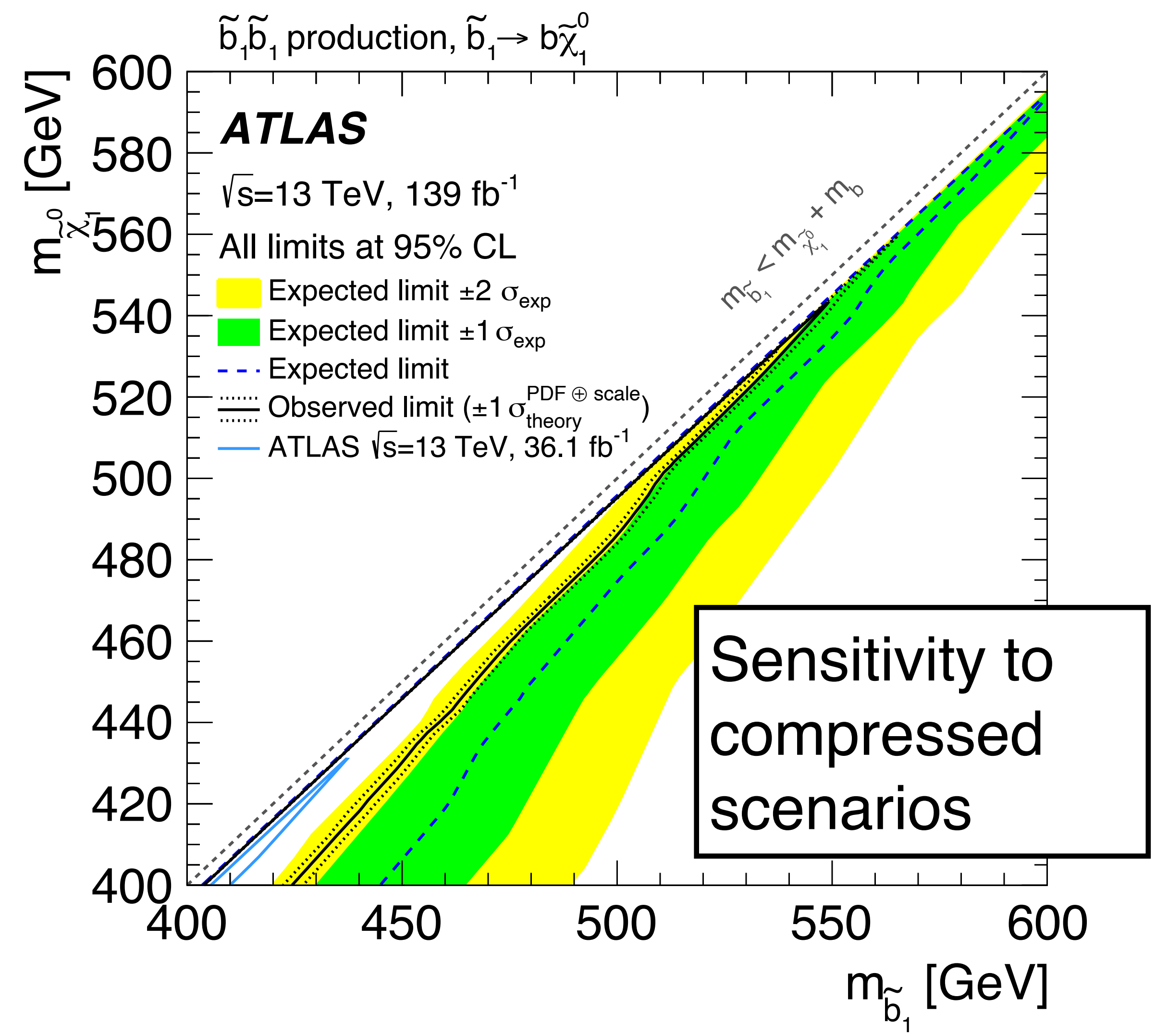
- Select events with at least 1 energetic jet, no leptons or photons
- Leading jet $p_{\mathrm{T}} > 250$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV
- Seek increase in events at high “recoil pT”
- Can search for direct DM production, SUSY or Dark Energy!



Mono-jet: Results

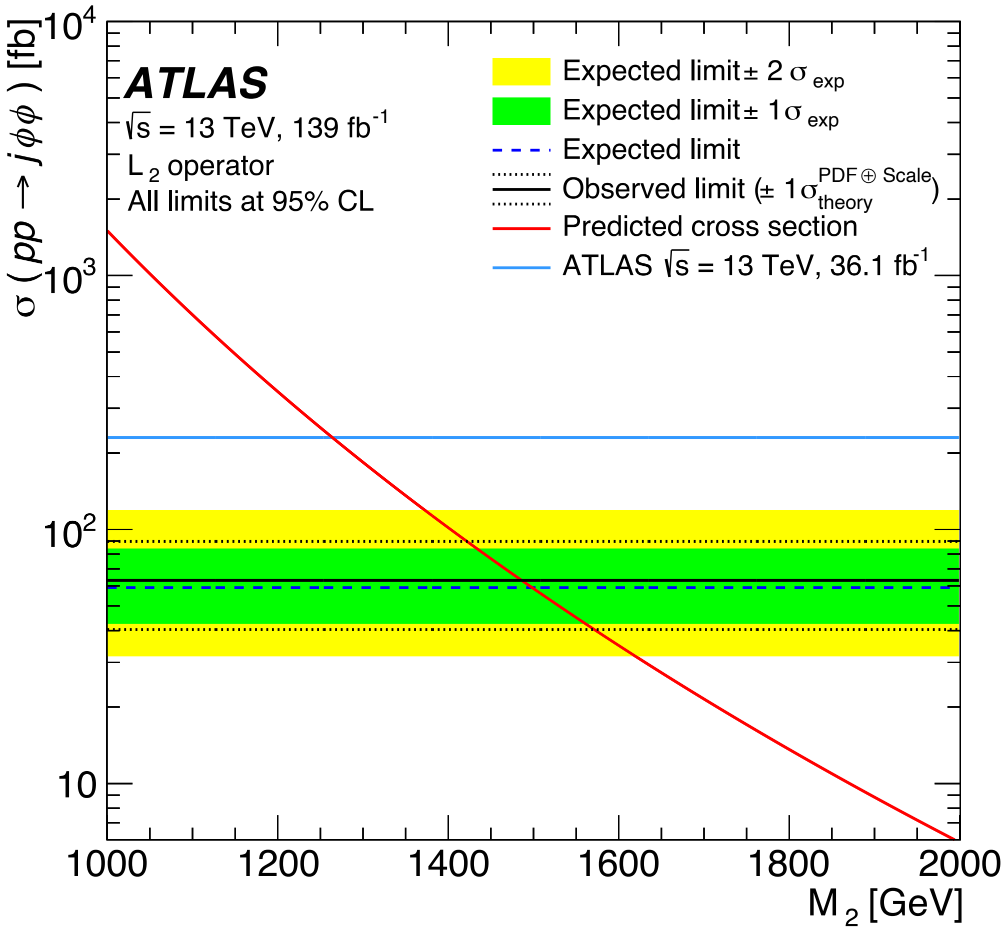
arXiv:2102.10874

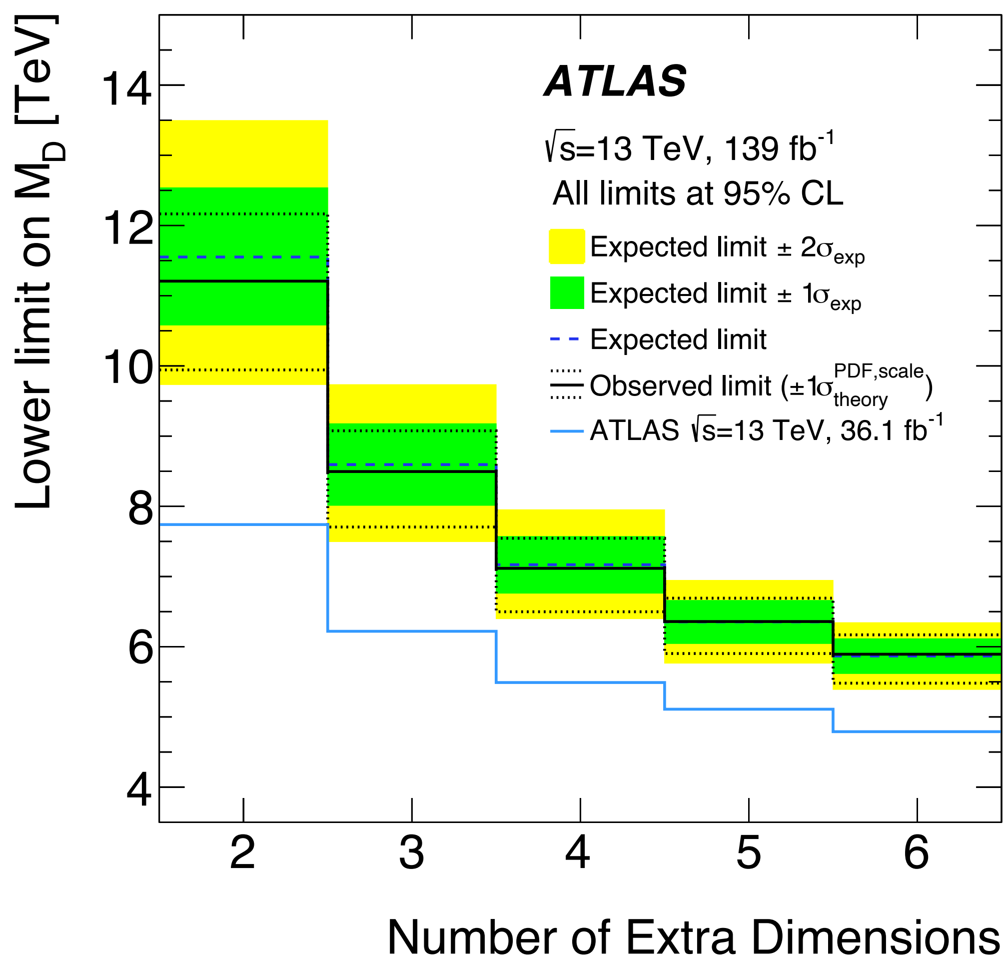




- No excess in high recoil pT events found.
- Can translate this into WIMP-proton scattering cross-section.
- Complementary to direct-detection searches e.g. PICO experiment.
- Also can constrain SUSY models, does particularly well in compressed scenario.

More interpretations of the mono-jet search





ATLAS p(henomenological) MSSM summary paper

Scan 19-parameter pMSSM
(R-parity conserving, neutralino LSP, minimal flavour violation, no new CP phases)

DM relic density

Z width

LEP searches

500 million
pMSSM points

Muon g-2

DM direct detection

B Physics

Higgs mass

non-LHC constraints

310.3k points viable before LHC Run 1

Test sensitivity: 22 ATLAS 7+8 TeV (up to 20/fb) searches