Search for R-parity violating supersymmetry

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Overview

Introduction

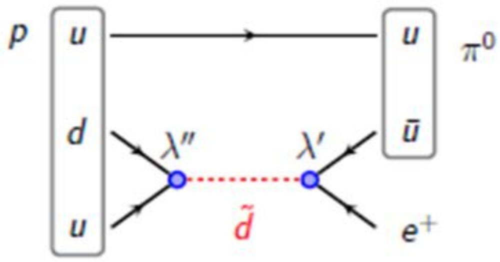
Recent ATLAS searches for R-parity violating SUSY

- First LHC search to obtain sensitivity to electroweak production of SUSY particles promptly decaying to quarks
    - Lightest supersymmetric particle (LSP) decays through UDD or LQD
    - Eur. Phys. J. C 81 (2021) 1023
- First search at 13 TeV for RPV models with a massive multi-track displaced vertex and multiple energetic jets
    - Long-lived LSP decays through UDD
    - JHEP 06 (2023) 200
- First search at 13 TeV for trilepton resonance
    - LSP decays to a Z boson and charged lepton in U(1) B-L model
    - PRD 103, (2021) 112003

Introduction

SUSY includes interactions that can change baryon (B) and lepton (L) number

Strength	Interaction	Description	RPC	RPV
λ''	UDD	Violates baryon number	╳	✔
λ'	LQD	Violates lepton number	╳	✔
λ	LLE	Violates lepton number	╳	✔
μ'	LH	Violates lepton number	╳	✔



$$R=(-1)^{3(B-L)+2s}$$

R-parity conservation (RPC) was introduced to prevent proton decay
R-parity is +1 for standard model particles and -1 for supersymmetric particles

- **RPC forbids production of single SUSY particles**
- **RPC forbids decay of SUSY particles to only standard model particles**
- **RPC forbids decay of lightest SUSY particle (LSP) ⇒ adds a new stable particle to universe ⇒ gives a candidate for dark matter**

Introduction

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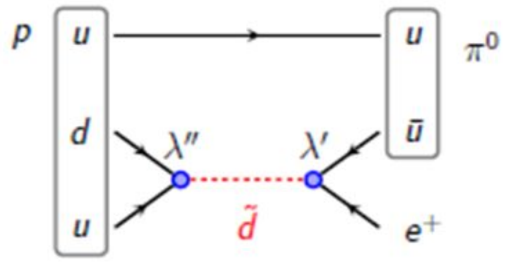


$$R=(-1)^{3(B-L)+2s}$$

R-parity violation (RPV) exists in less restrictive models where proton decay is prevented if some interaction strengths are very small or forbidden

- RPV allows production of single SUSY particles
- RPV allows SUSY particles to decay to standard model particles
- **RPV allows lightest SUSY particle (LSP) to decay ⇒ changes LHC searches**
- RPV candidates for dark matter can be axions and axinos or gravitinos

ATLAS search for leptons and many jets

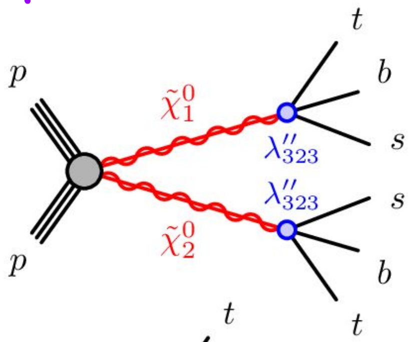
[Eur. Phys. J. C 81 (2021) 1023]

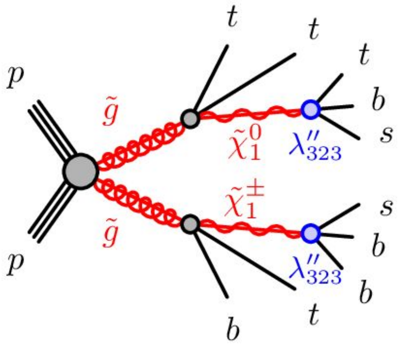
Models

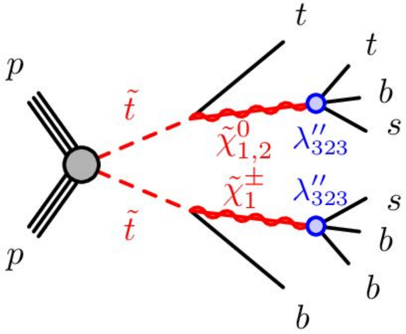
- Pair production of gluinos, top-squarks, and electroweakinos
- Minimal flavor violation model with λ'' 323 dominant (UDD)

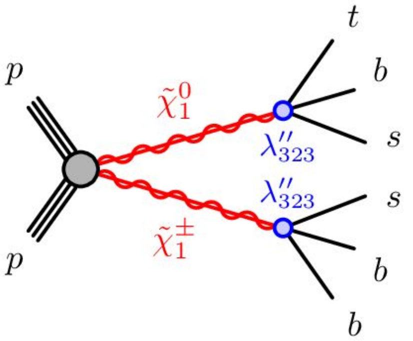
Selection: lepton(s) from top quark decay t →Wb→**e**νb or t →Wb→***μ***νb

- at least one isolated lepton or two-same-sign leptons
- at least four jets (anti-kT R=0.4) to 15+ jets
- 0,1,2,3, 4+ b-tagged jets (70% efficiency)
- no requirement on MET









ATLAS search for leptons and many jets

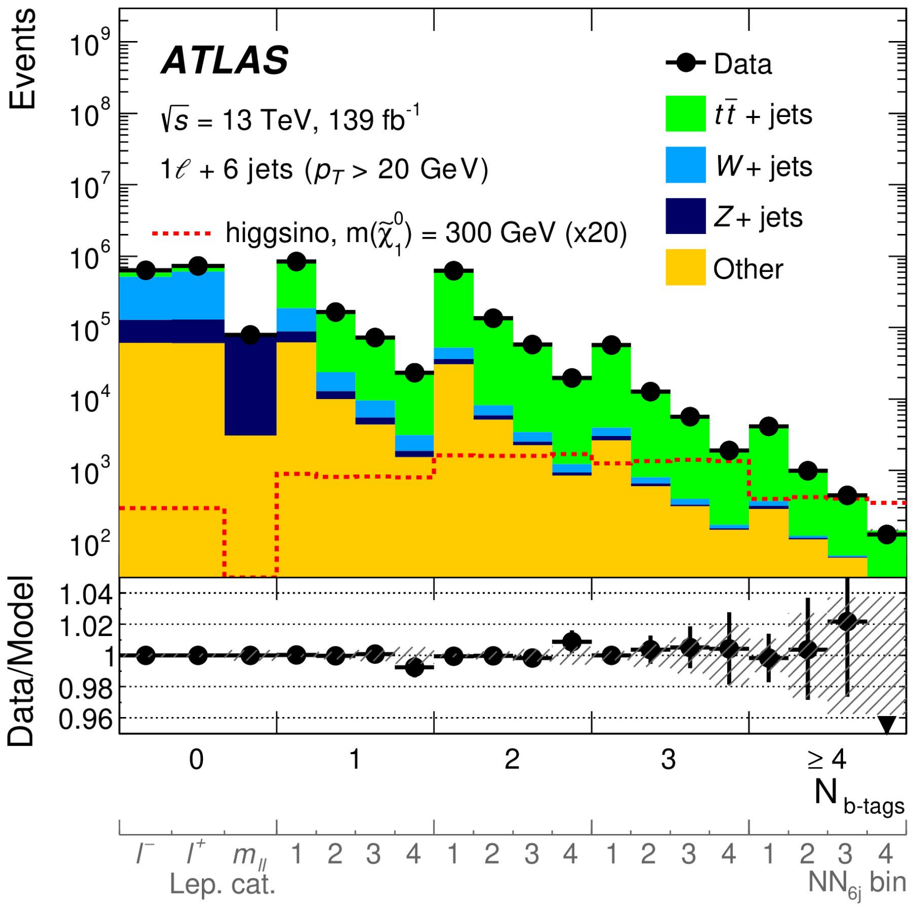
[Eur. Phys. J. C 81 (2021) 1023]

Data-driven model to **4,5,..,15+ jets,** based on observables at medium jet multiplicity, to predict b-tagged jet multiplicity distribution at higher jet multiplicities

- Fit parameters include bkg normalizations and ttbar b-tag multiplicity in 4-jets, jet scaling, extrapolation for b-tagged jets

Machine-learning techniques to reach sensitivity to electroweakinos

- Neural network trained so shape for ttbar is the same for each b-tagged jet multiplicity, so ttbar constrained by 1 and 2 b-tag regions



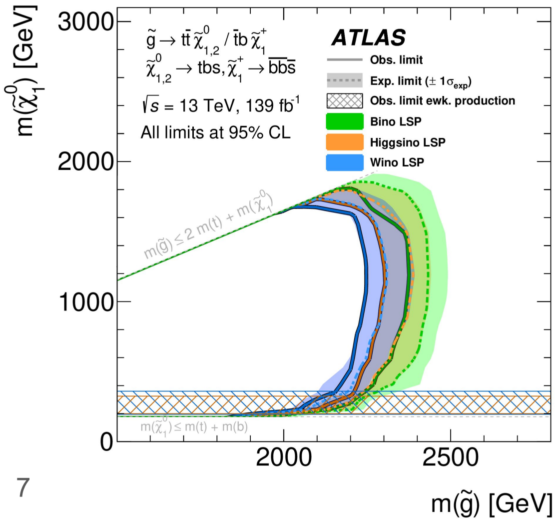
ATLAS search for leptons and many jets

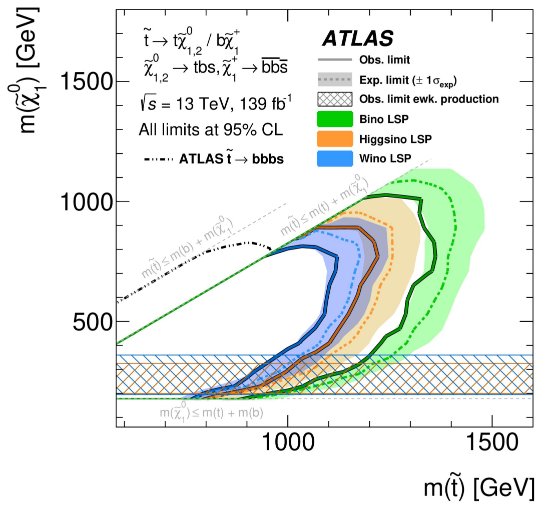
[Eur. Phys. J. C 81 (2021) 1023]

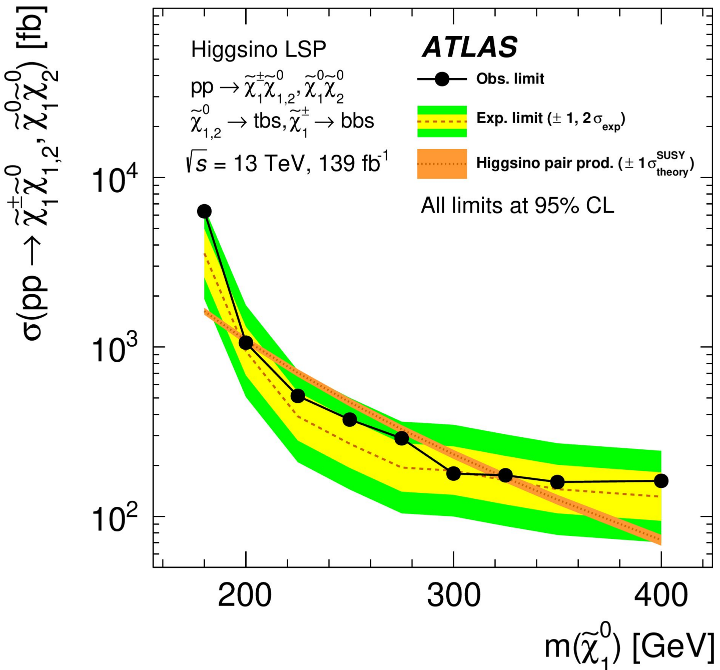
First LHC search to obtain sensitivity to electroweak production of SUSY particles promptly decaying to quarks. Also sensitive to SM four top quark production

No significant excess observed. Limits at 95% CL up to

- 2.4 TeV in gluino mass,
- 1.35 TeV in top-squark mass
- 320 (365) GeV in higgsino (wino) mass

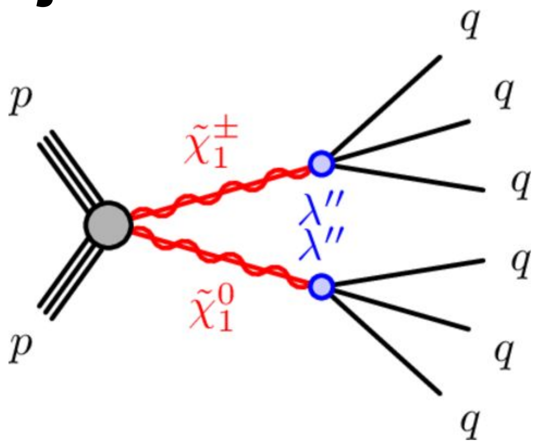






ATLAS search for displaced vertices and jets

JHEP 06 (2023) 200

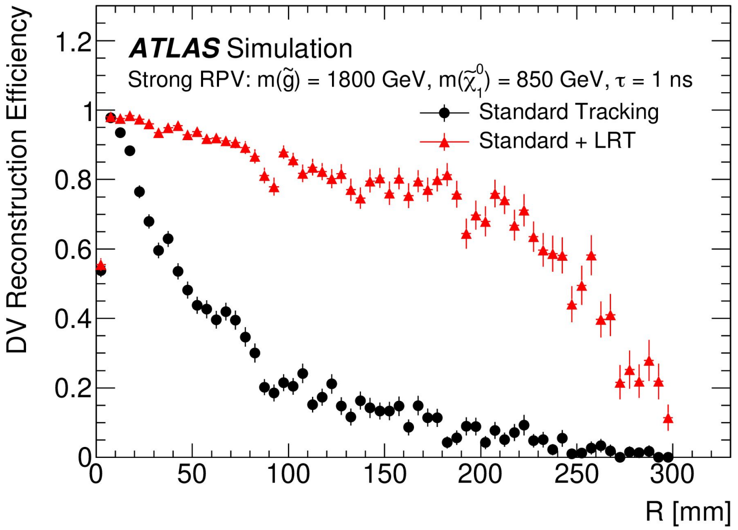


Models

- Pair production of gluinos and electroweakinos
- Small λ'' gives long-lived LSP decay to 3 quarks (UDD)

Selection/reconstruction

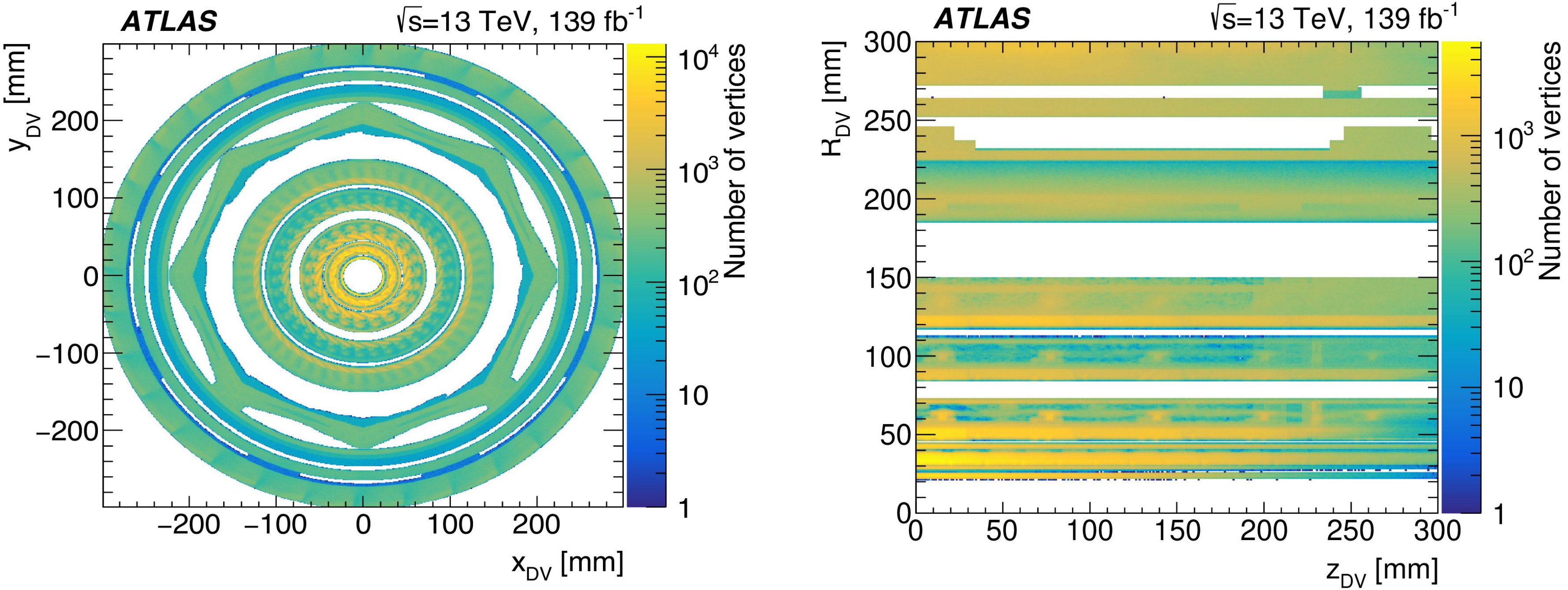
- Triggers: 4 jets p_T>100 GeV to 7 jets p_T>45 GeV
- Filters: "Trackless" jet(s) or high-p_T jets
- Large radius charged particle tracking
  - LRT (arXiv:2304.12867)
- Displaced vertex (DV) reconstruction



ATLAS search for displaced vertices and jets

JHEP 06 (2023) 200

Reconstructed displaced vertices vetoed by the material map in the analyzed data sample. The innermost area corresponds to the beampipe. This is surrounded by four pixel detector layers. The octagonal shape and outermost structures are due to support structures separating the pixel and SCT detectors.

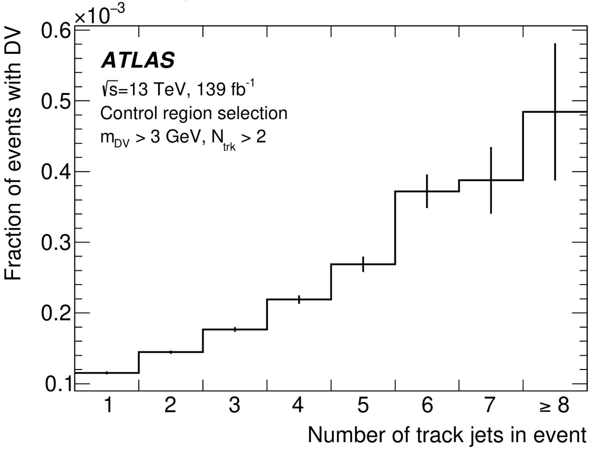


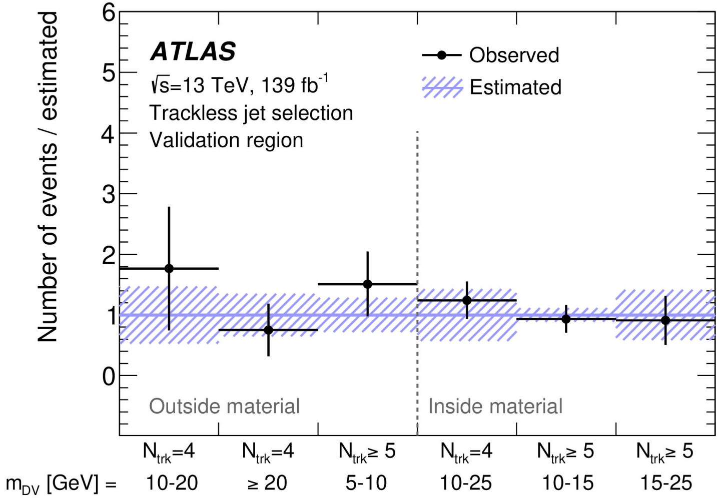
ATLAS search for displaced vertices and jets

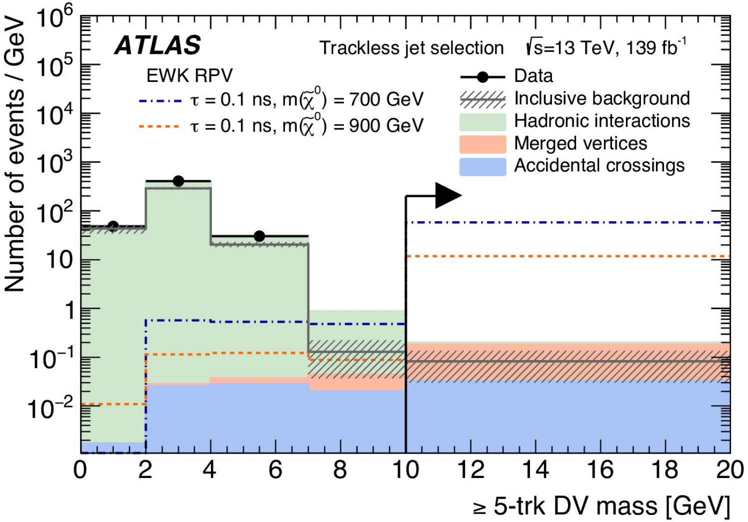
JHEP 06 (2023) 200

Inclusive data-driven background estimate

- Probability of DV correlated to jet multiplicity
    - Measure in control region (photon trigger)
- Test estimate in validation regions
- Cross-check with three source estimate



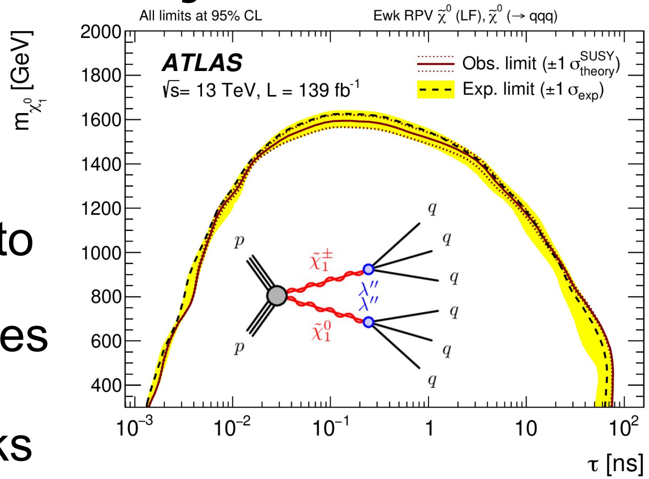




ATLAS search for displaced vertices and jets

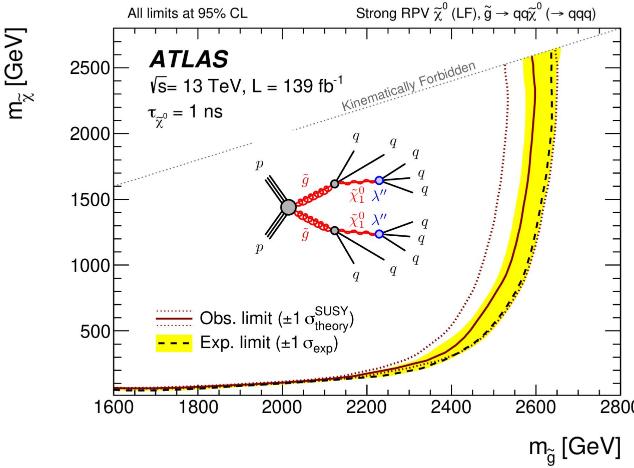
JHEP 06 (2023) 200

First search at 13 TeV with a massive multi-track displaced vertex and multiple energetic jets



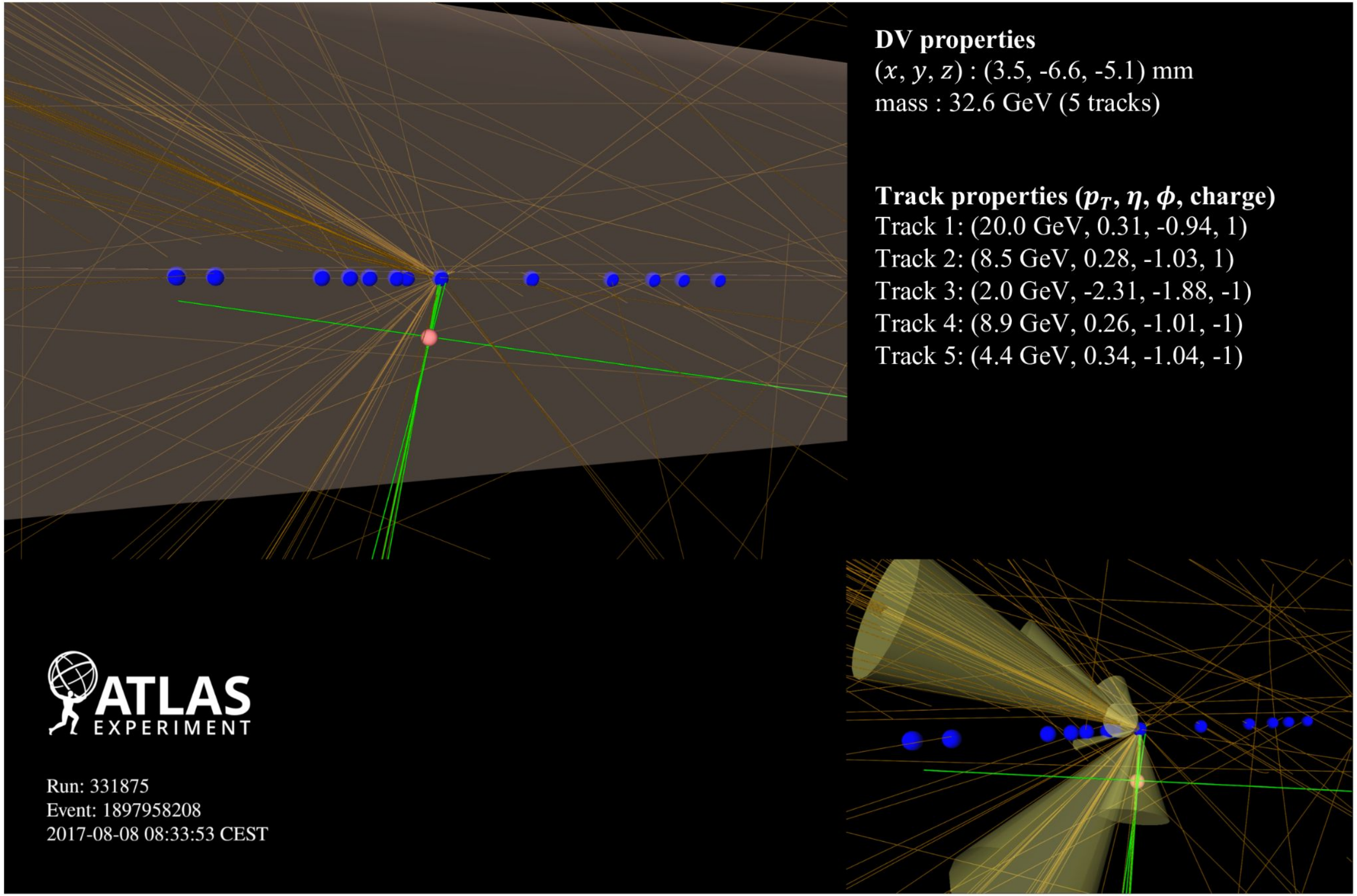
No significant excess observed. Limits at 95% CL up to

- 1500 GeV Higgsino mass for mean proper lifetimes in range 0.03 to 1 ns
- Even stronger limits for gluinos decaying to quarks and Higgsinos
- Model-independent limits at 0.02 fb level



Signal Region	Observed	Expected	S^{95}_{obs}	S^{95}_{exp}	$\langle\sigma_{vis}\rangle^{95}_{obs}$ [fb]
High-p_T jet SR	1	$0.46^{+0.27}_{-0.30}$	3.8	$3.1^{+1.0}_{-0.1}$	0.027
Trackless jet SR	0	$0.83^{+0.51}_{-0.53}$	3.0	$3.4^{+1.3}_{-0.3}$	0.022

1 displaced vertex with 5 tracks and mass 32.6 GeV



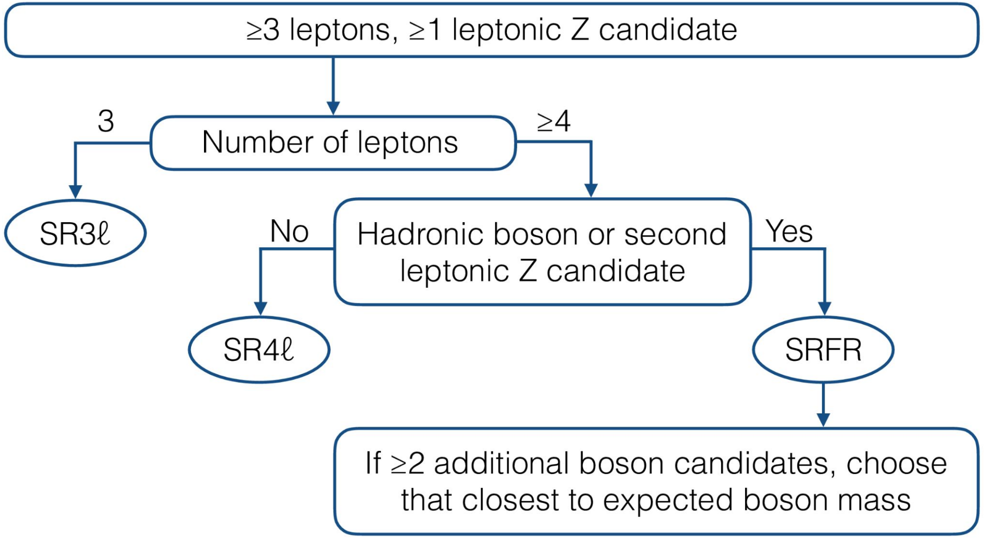
ATLAS search for trilepton resonance

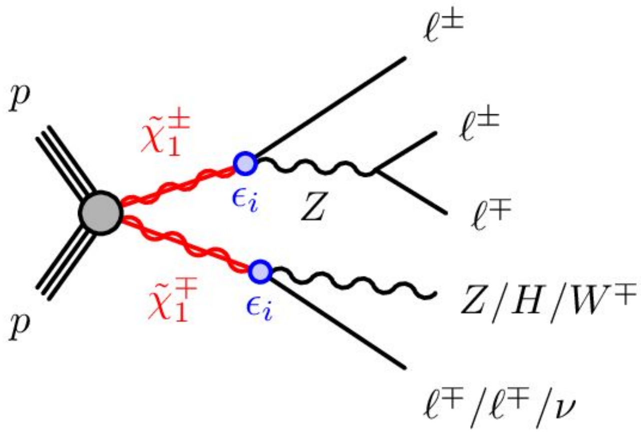
PRD 103, (2021) 112003

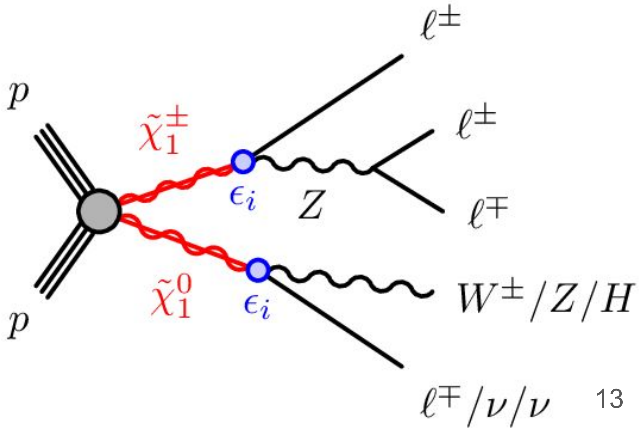
Model

- Add U(1) B-L gauge symmetry and RH neutrinos
- Symmetry spontaneously broken by sneutrino
- Wino LSP decay to Z/W/H boson and lepton

Selection: leptons from Chargino decay to Z and lepton







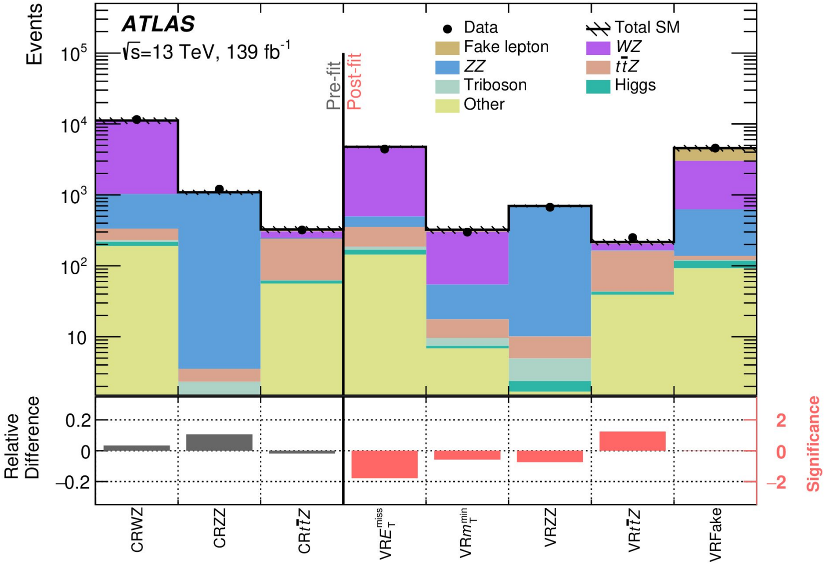
ATLAS search for trilepton resonance

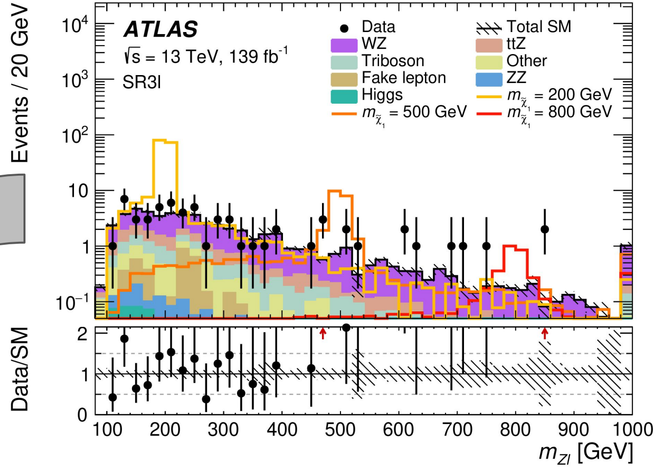
[PRD 103, (2021) 112003](#)

Optimize sensitivity over wide range of signal masses with a multi-bin fit in trilepton mass

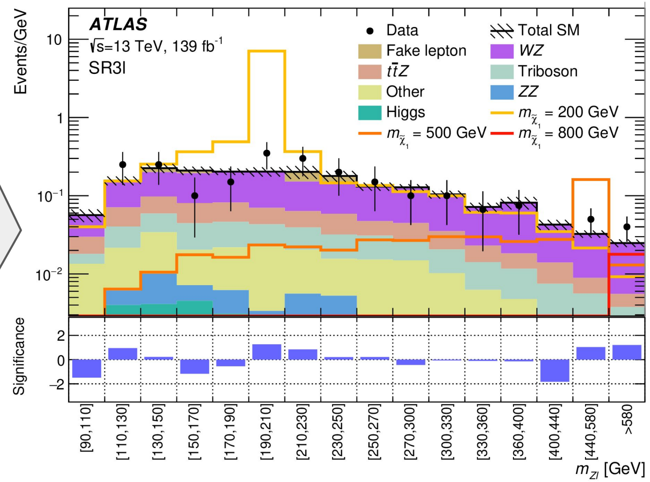
Background estimates

- Control regions for WZ, ZZ, ttZ
- Validation regions in good agreement





Optimal binning



ATLAS search for trilepton resonance

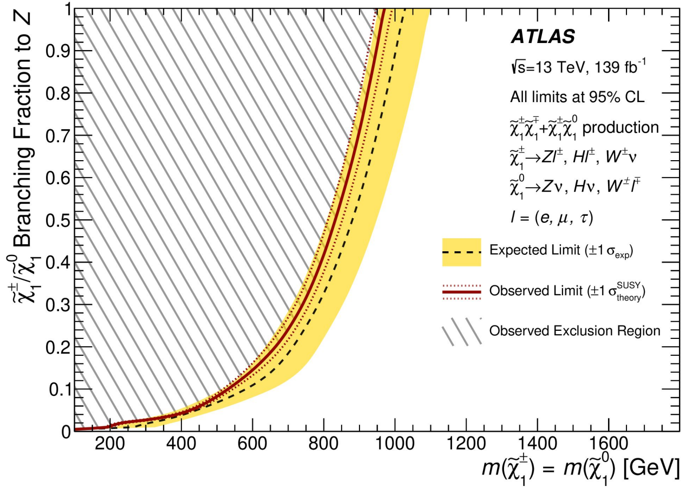
PRD 103, (2021) 112003

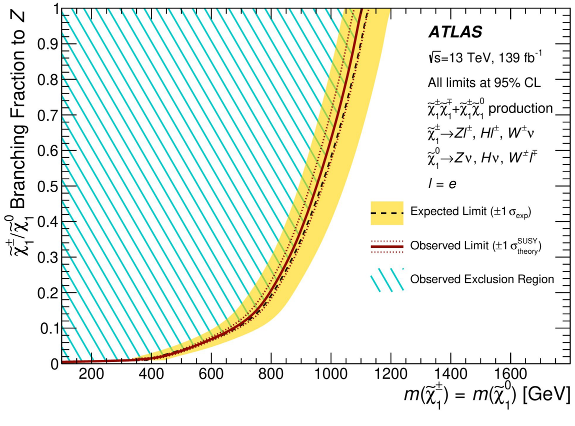
First search at 13 TeV for trilepton resonance

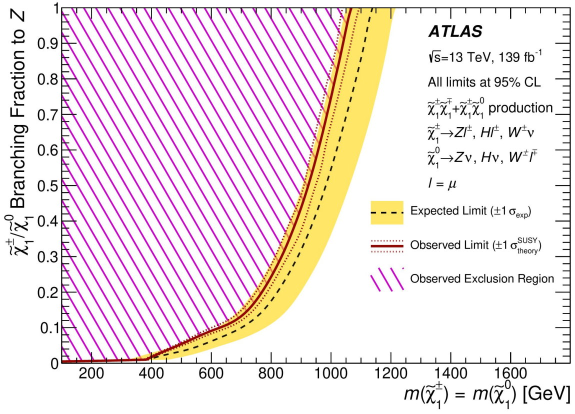
No significant excess observed.

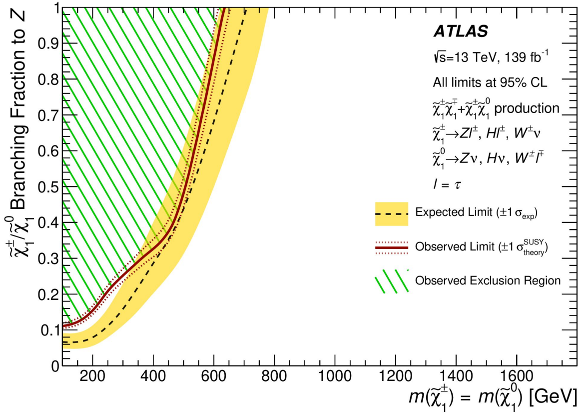
Combine 3 regions and set limits at 95% CL up to 1100 GeV in chargino or neutralino mass

- LSP branching fraction to Z lepton (y-axis)
- lepton flavor (electron, muon, tau)









Conclusion & Outlook

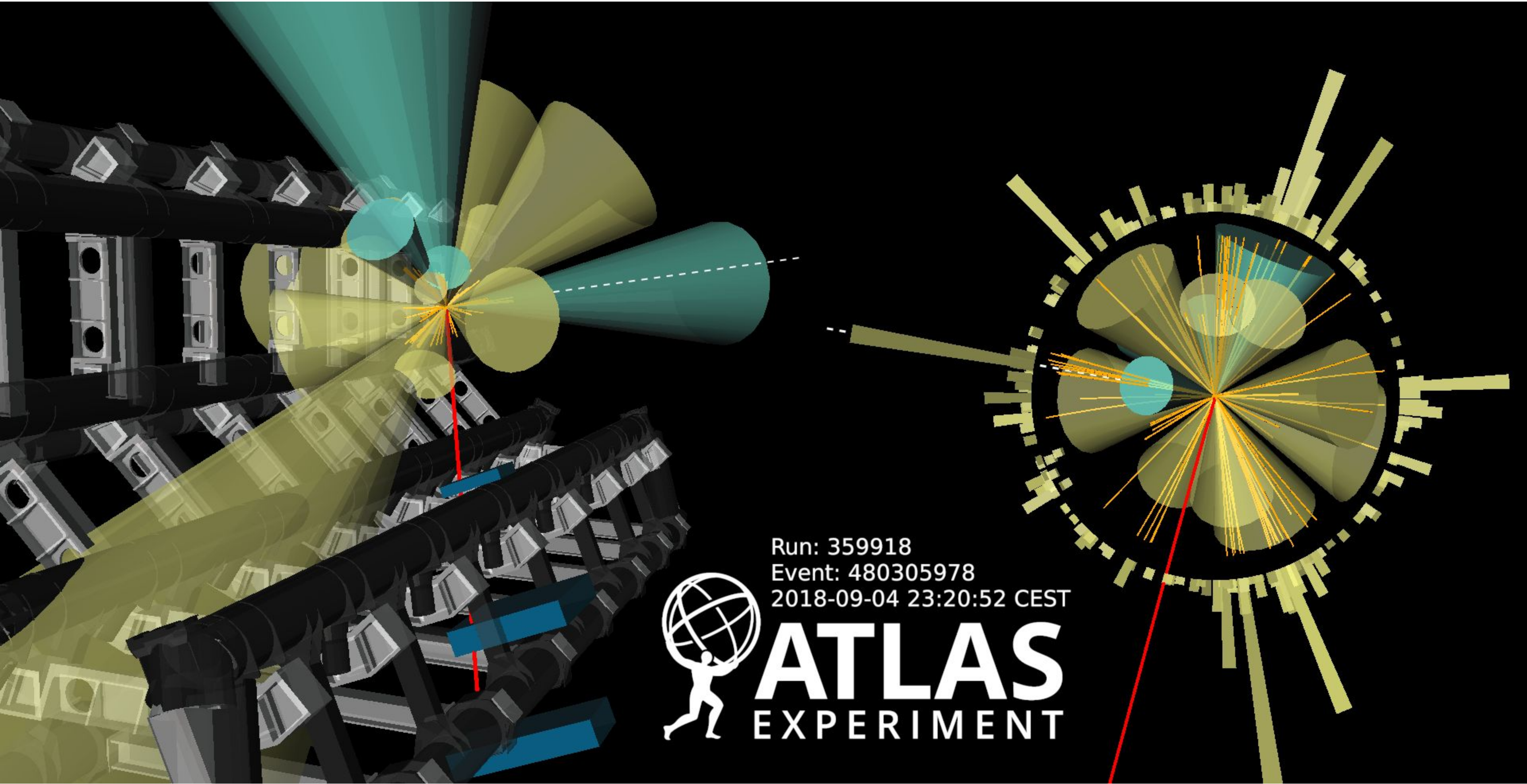
Many firsts even in 2020’s in recent ATLAS searches for RPV SUSY signatures

- First LHC search to obtain sensitivity to electroweak production of SUSY particles promptly decaying to quarks
- First search at 13 TeV for RPV models with a massive multi-track displaced vertex and multiple energetic jets
- First search at 13 TeV for trilepton resonance in RPV U(1) B-L model

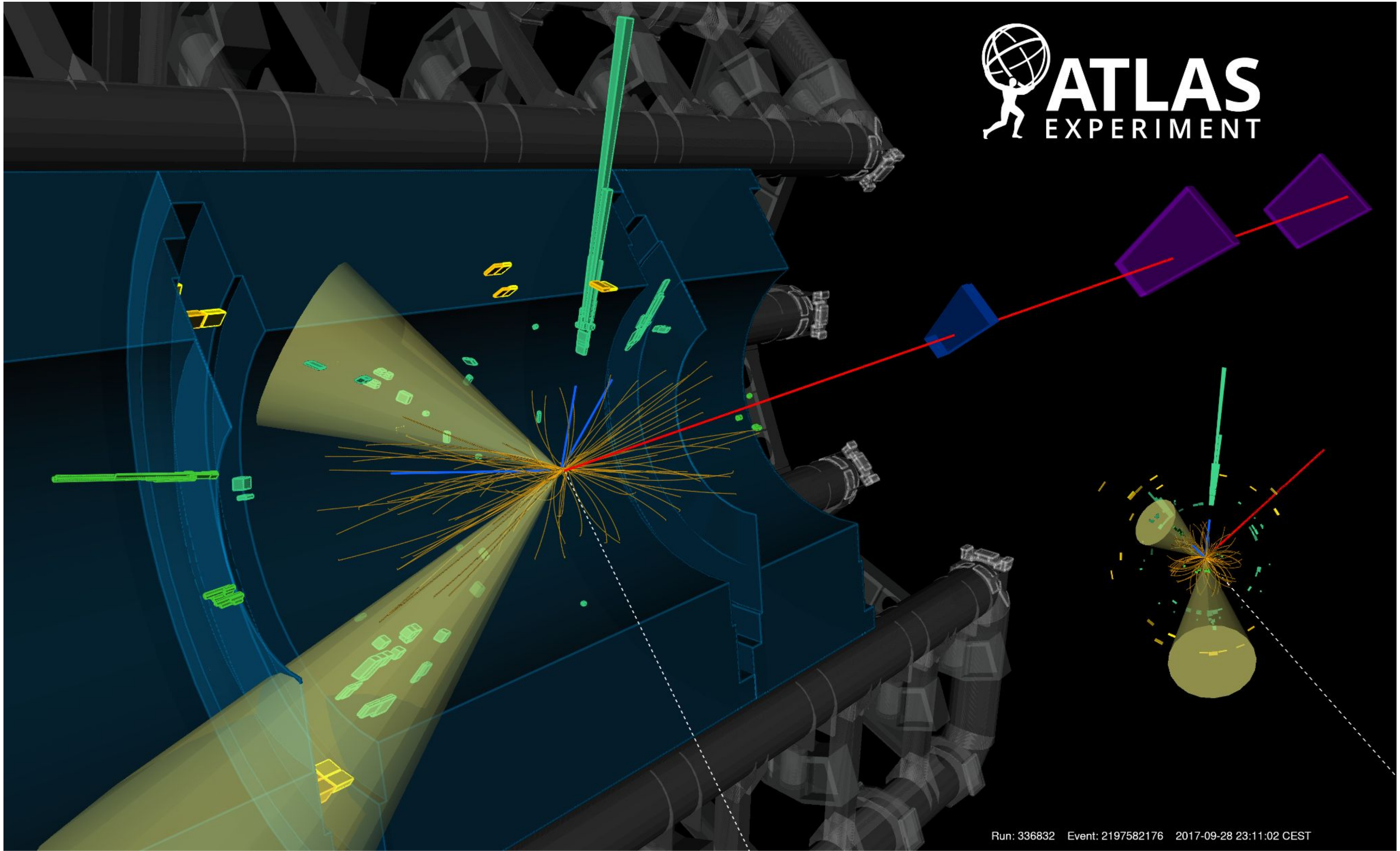
Several more results in preparation with full Run 2 dataset

Looking forward to developing new searches and extending previous searches for RPV SUSY with more data and new triggers in Run 3

2 leptons with same electric charge, 15 jets, and 4 b-jets



3 electrons, 1 muon, and di-jet mass 93 GeV



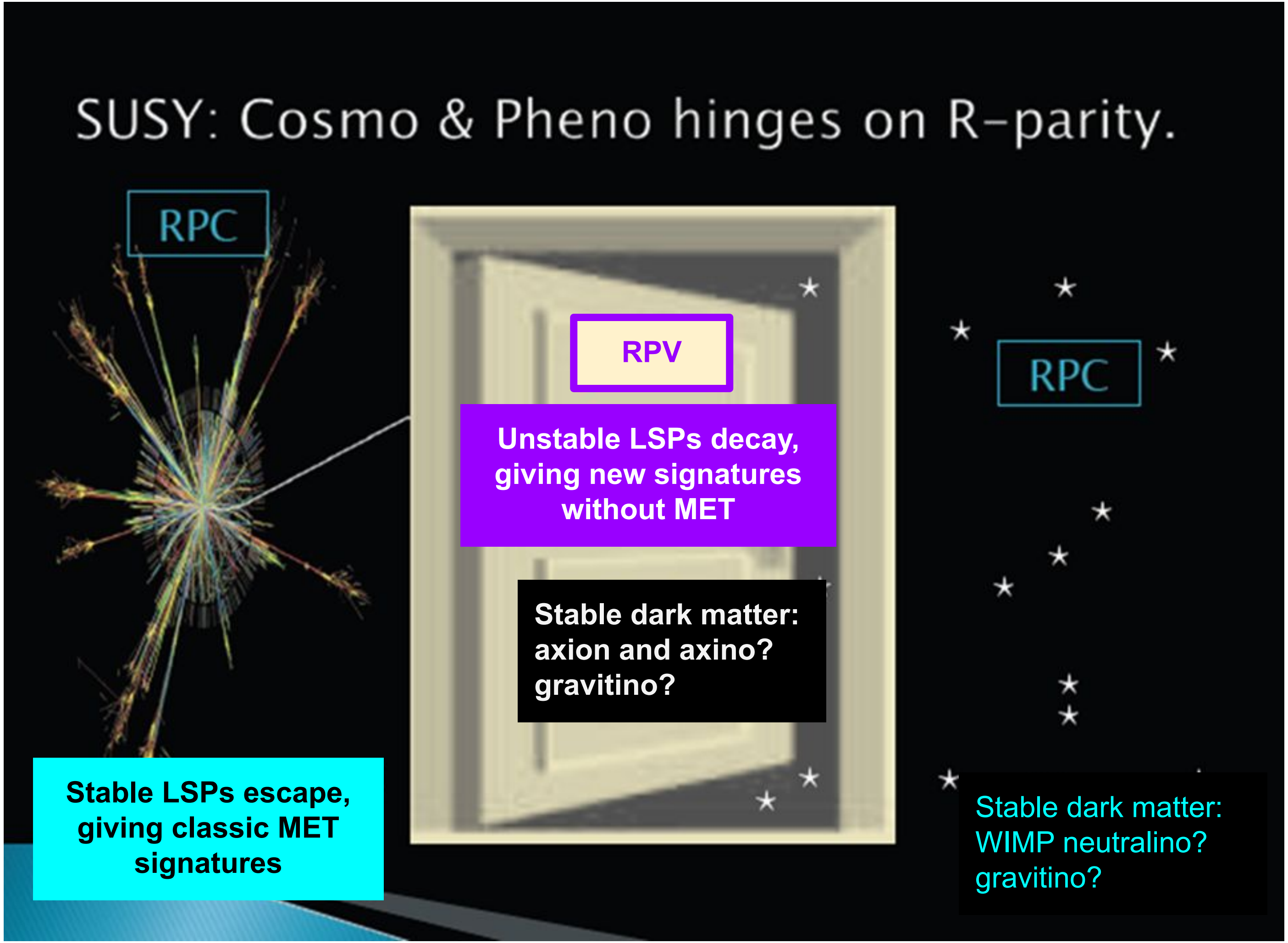


Figure credit: S. Spinner

Leptons and many jets - why LSP type matters?

Minimal flavor violation model with λ'' 323 dominant

- Neutralino 100% decay to tbs (lepton from either t →Wb→**e**νb or t →Wb→$\boldsymbol{\mu}\nu$b)
- Chargino 100% decay to bbs (no lepton!)

Higher fraction of neutral LSP states ⇒ more leptons ⇒ better sensitivity

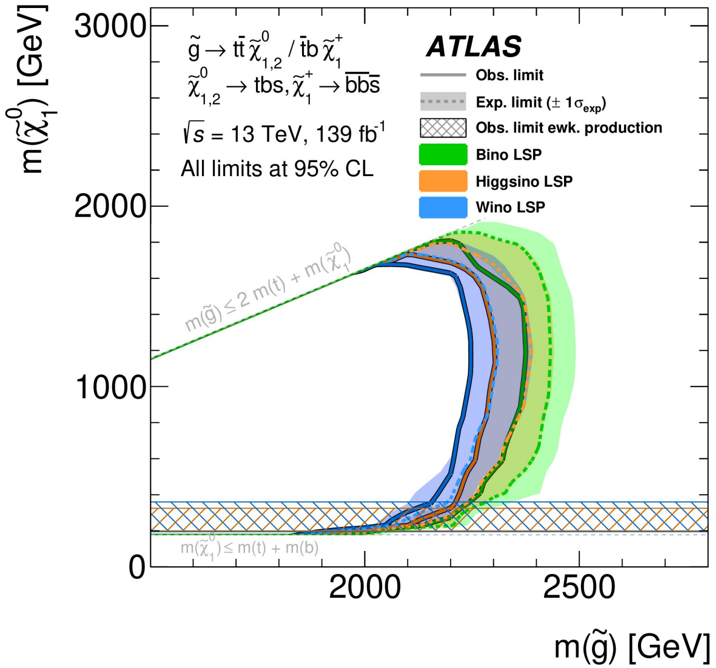
- LSP type: Wino (N1,+C1,-C1), Higgsino (N1, N2, +C1, -C1), Bino (N1)
- Explains limits Wino < Higgsino < Bino

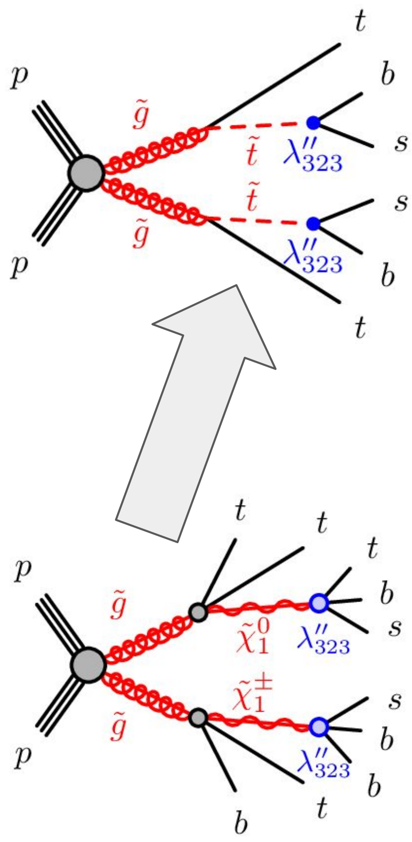
LSP type	Branching ratios: stop $t\tilde{\chi}^0_{1,2}$	stop $b\tilde{\chi}^\pm_1$	gluino $tt\tilde{\chi}^0_{1,2}$	gluino $bb\tilde{\chi}^0_{1,2}$	gluino $tb\tilde{\chi}^\pm_1$	Cross-section [fb] for direct production $\tilde{\chi}^\pm_1\tilde{\chi}^0_1$	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$	$\tilde{\chi}^0_2\tilde{\chi}^0_1$
Bino	100%	0%	100%	0%	0%	0	0	0
Wino	33%	67%	17%	17%	66%	387	0	0
Higgsino	50%	50%	50%	0%	50%	91	91	52

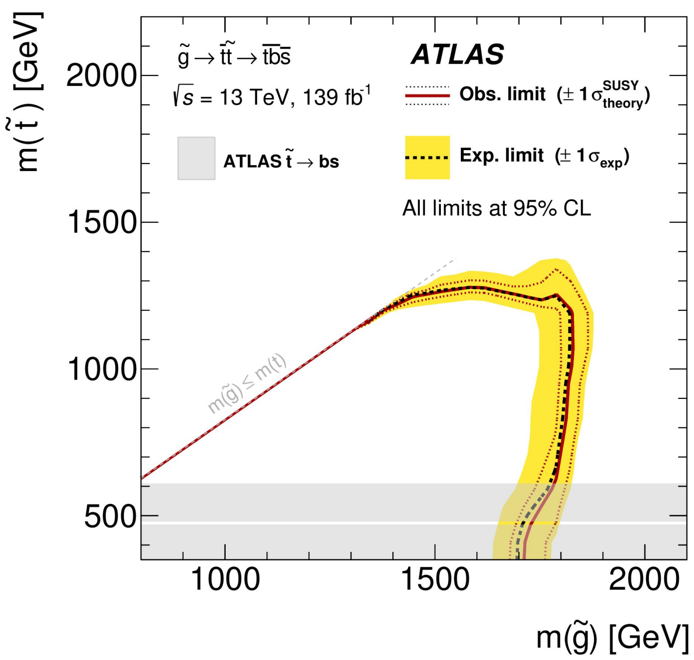
(If LSP mass 300 GeV)

Leptons and many jets - larger value for RPV?

Larger value for λ'' 323 allows direct stop decay, but more difficult since fewer b-jets



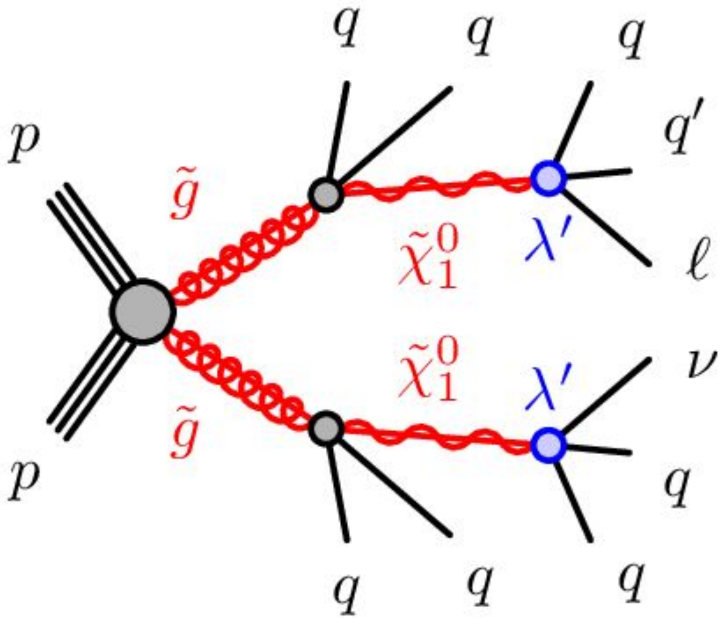


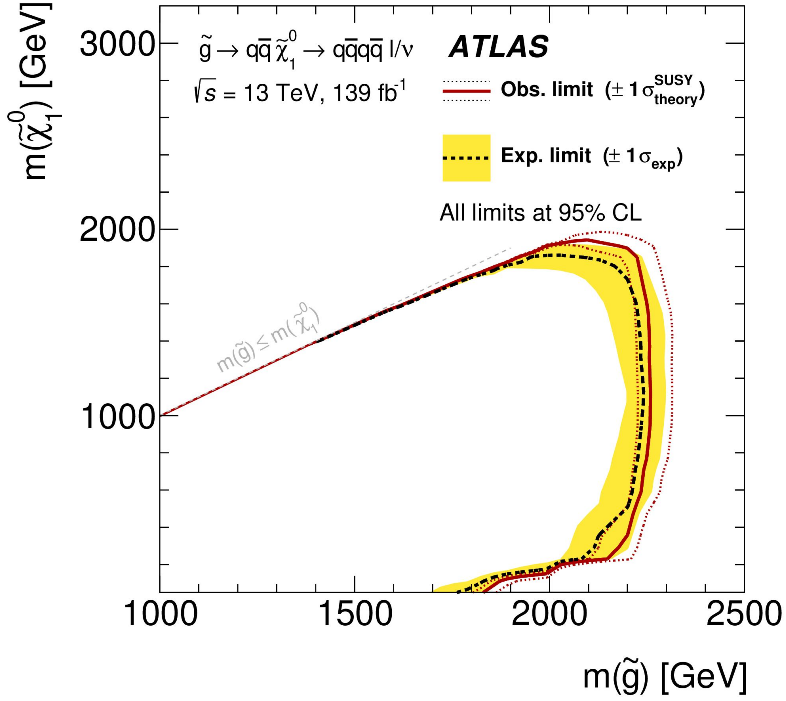


Leptons and many jets - other model with LQD RPV

LQD model with λ’ for first and/or second generation for electrons and/or muons

Selection with zero b-jets and eight or more jets, one isolated lepton





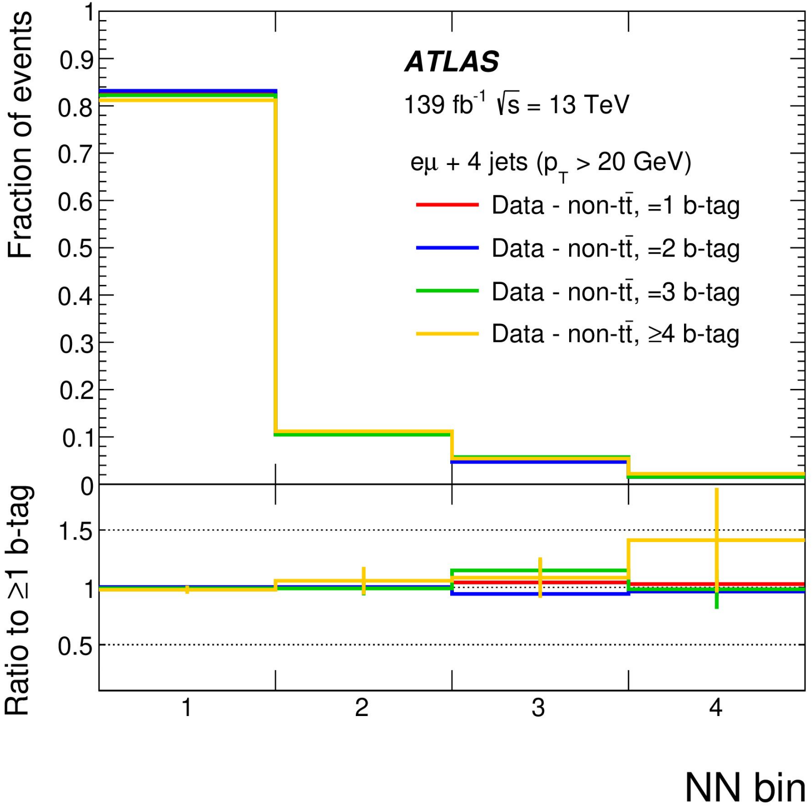
Leptons and many jets - NN shape

Test in data that NN shape is invariant with b-tagged jet multiplicity

Non-ttbar backgrounds subtracted

See excellent agreement

(stat limited for >= 4 b-tags)



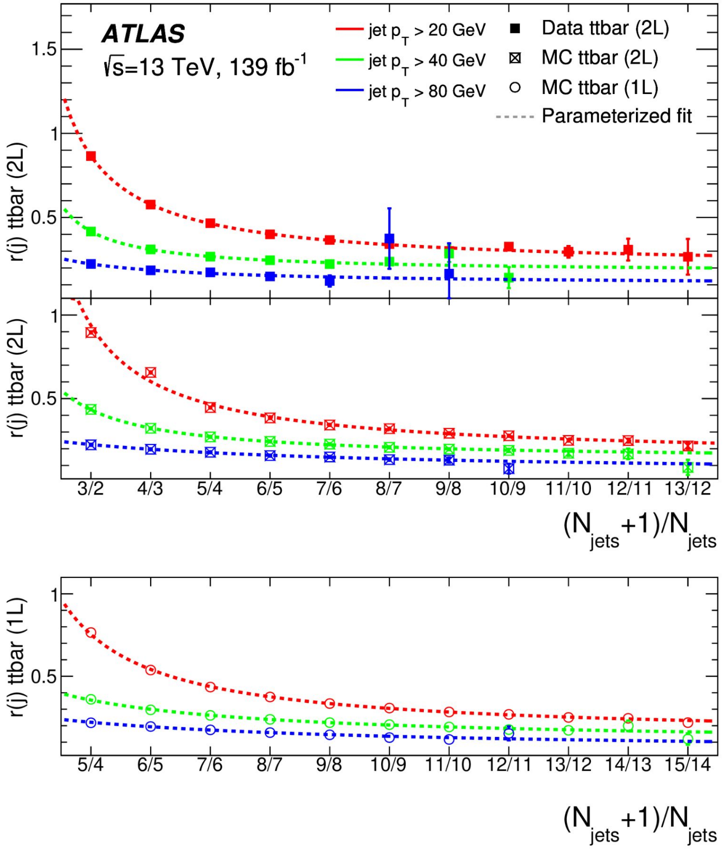
Leptons and many jets - Fit information on jets

Jet multiplicity

- Staircase scaling + Poisson scaling
- Extrapolation for 4 backgrounds, validate in photon+jets and dilepton ttbar

$$r^X(j) = c_0^X + c_1^X/(j + c_2^X)$$

$$N_j^X = N_4^X \cdot \prod_{j'=4}^{j'=j-1} r^X(j')$$



Leptons and many jets - Fit information on b-tagged jets

For each jet multiplicity, b-tagged jet multiplicity $N^X_{j,b} = f^X_{j,b} \cdot N^X_j$

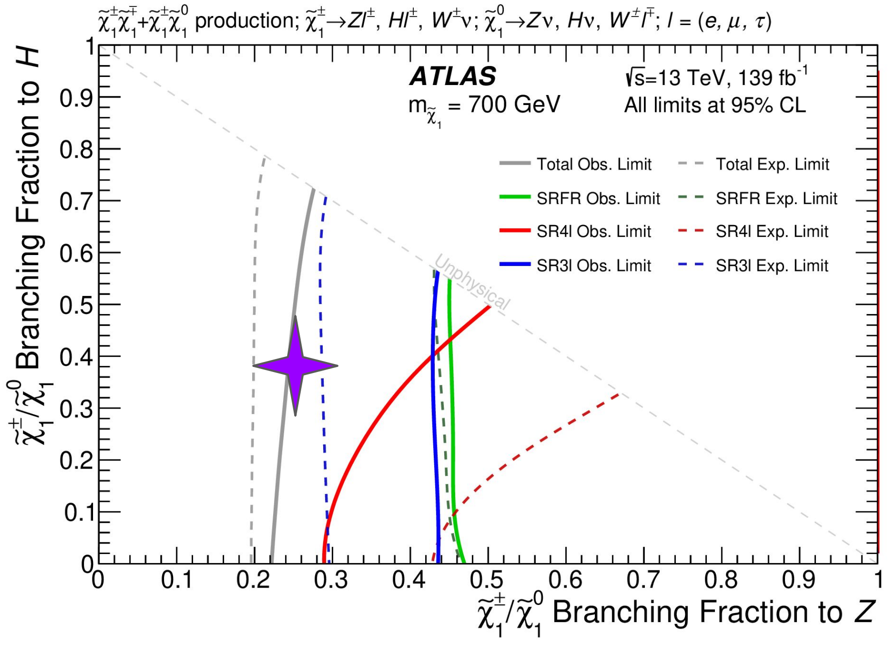
- For ttbar, determine fractions in 4 jet region and extrapolate to higher jet multiplicities assuming one additional jet to be
  - not b-tagged ($x0$)
  - b-tagged ($x1$)
  - b-tagged and causing a second jet to be b-tagged ($x2$)
- Include correlation for gluon splitting

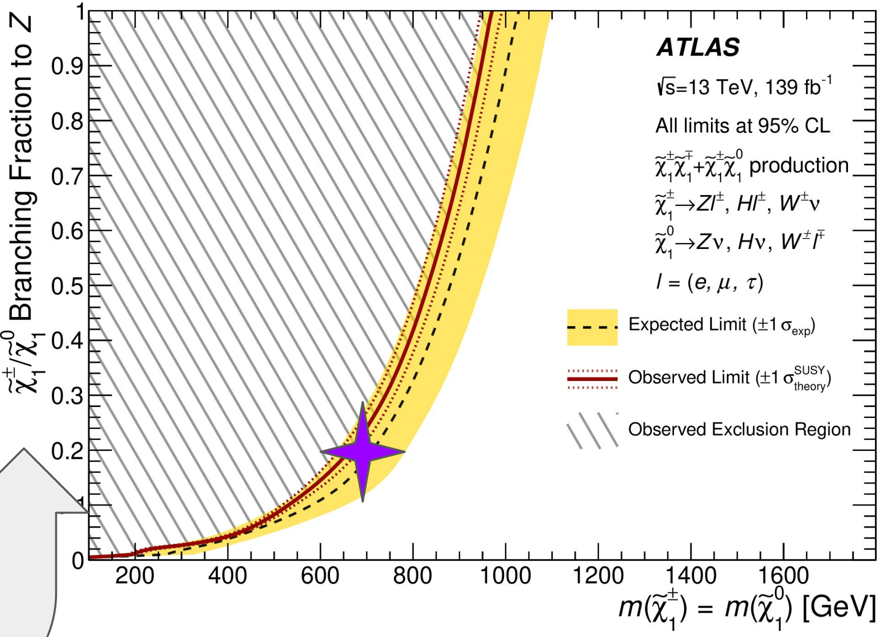
$$f_{(j+1),b} = f_{j,b} \cdot x_0 + f_{j,(b-1)} \cdot x_1 + f_{j,(b-2)} \cdot x_2$$

Parameters	$t\bar{t}$ +jets	$t\bar{t}X^{\rm sc}$	W+jets	Z+jets	VV+jets	Constraints
Normalization	$N_4^{t\bar{t}}$	$N_4^{t\bar{t}X^{\rm sc}}$	N_4^W	N_4^Z	N_4^{VV}	–
Jet scaling, $i \in \{0, 1, 2\}$	$c_i^{t\bar{t}}$	$c_i^{t\bar{t}X^{\rm sc}}$	$c_i^{W/Z}$		c_i^{VV}	$c_2^{W/Z} = c_2^{VV} = 1$
Initial b-jet fractions, $i \in \{0 \dots 4\}$	$f_{4,i}^{t\bar{t}}$	$f_{4,i}^{t\bar{t}X^{\rm sc}}$	–	–	–	$\sum_i f_{4,i} = 1$
Extra heavy-flavour jets, $i \in \{0, 1, 2\}$	x_i, ρ_{11}		–	–	–	$\sum_i x_i = 1$
NN shape, $i \in \{1 \dots 4\}$, $j \in \{4 \dots 8\}$	$n_{j,i}$	–	–	–	–	$\sum_i n_{j,i} = 1$

ATLAS search for trilepton resonance

PRD 103, (2021) 112003





Combine 3 orthogonal channels

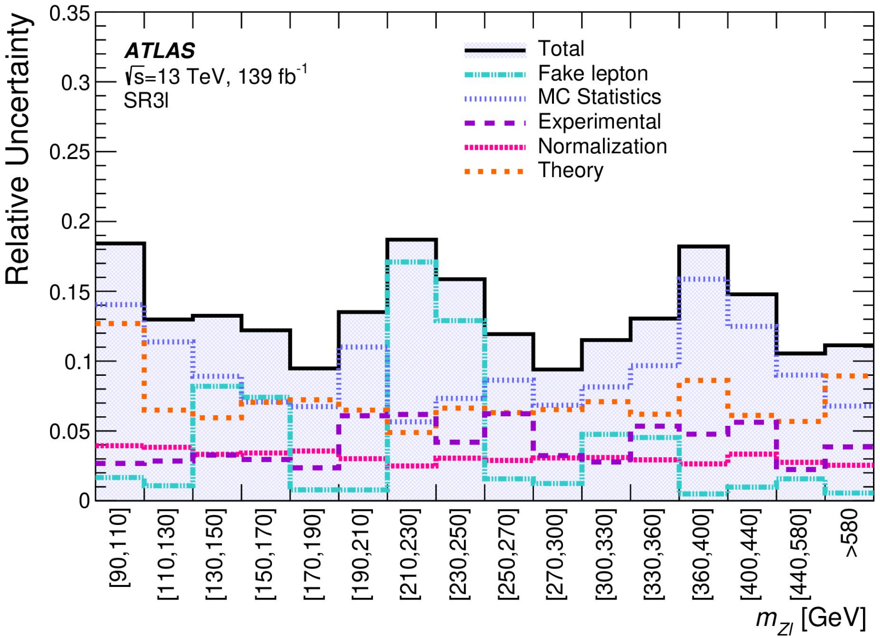
Limit reported has remainder equally split between decays to H and W, e.g. if C1->Zl =0.2, then report limit with C1->Hl=0.4, C1->Wv=0.4

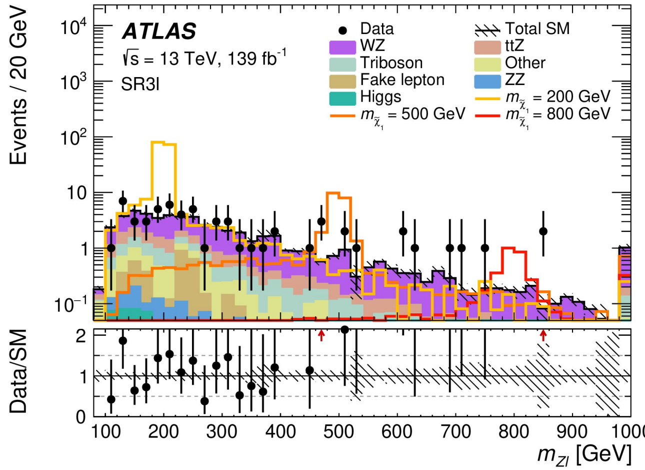
ATLAS search for trilepton resonance - SR3l

PRD 103, (2021) 112003

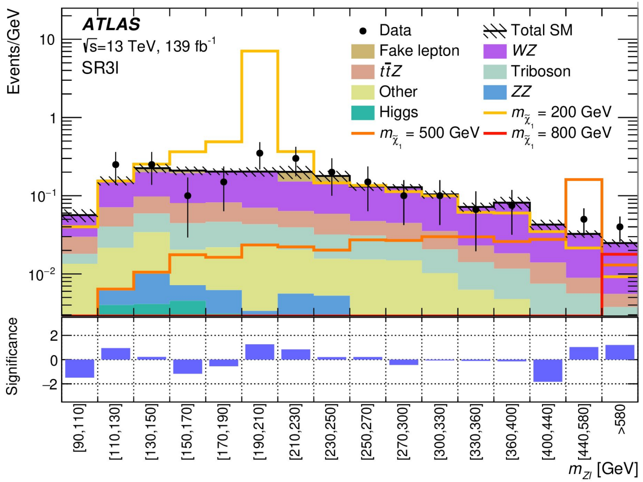
Optimize sensitivity over wide range of signal masses with a multi-bin fit in trilepton mass

Balance between detector resolution and ability to estimate systematic uncertainties





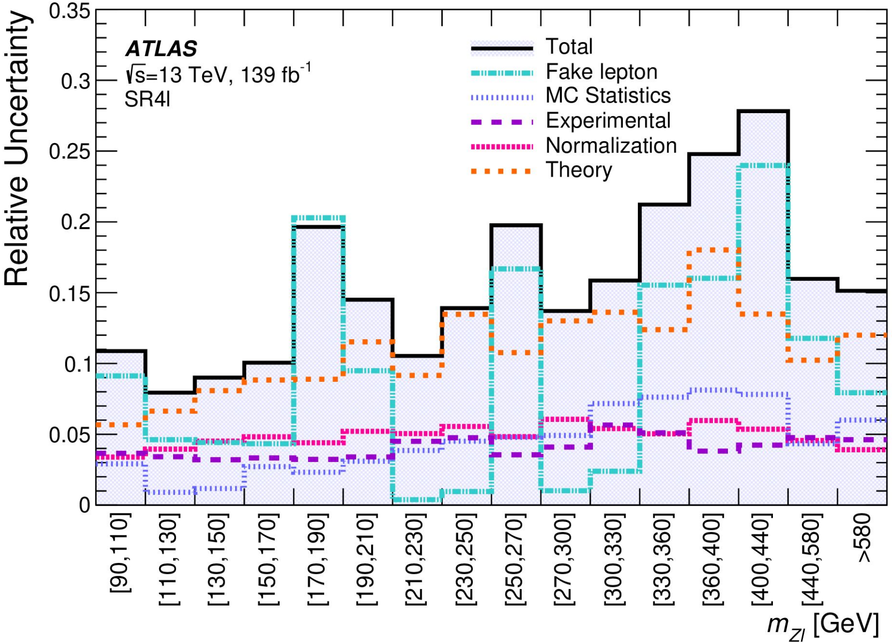
Optimal binning

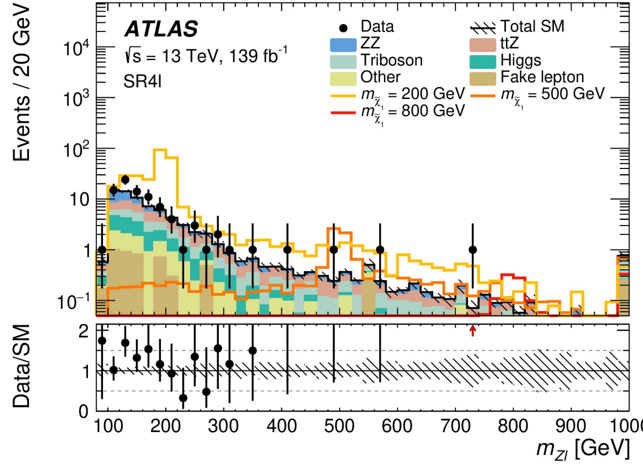


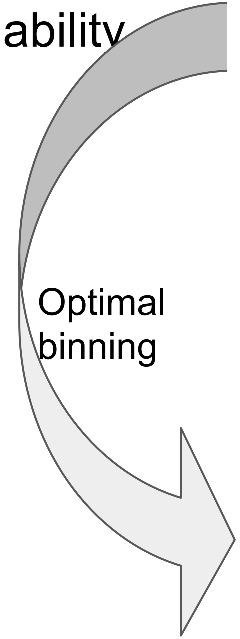
ATLAS search for trilepton resonance - SR4l

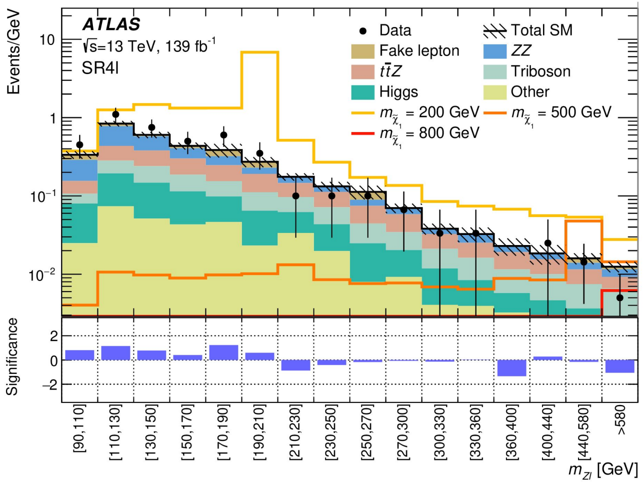
Optimize sensitivity over wide range of signal masses with a multi-bin fit in trilepton mass

Balance between detector resolution and ability to estimate systematic uncertainties









ATLAS search for trilepton resonance - SRFR

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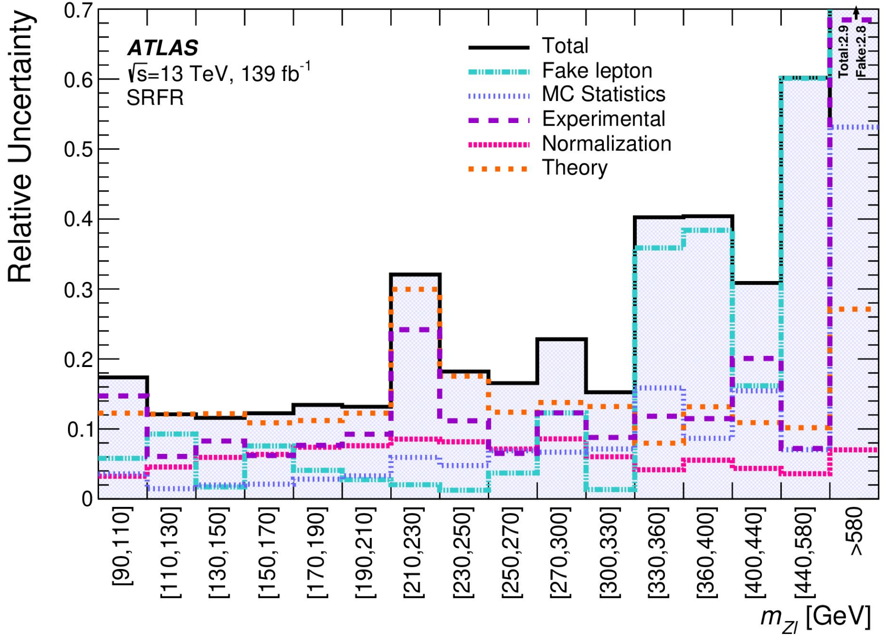

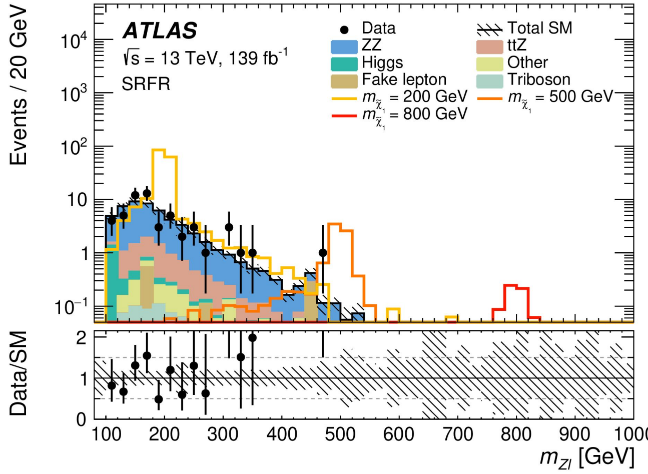

Optimal binning