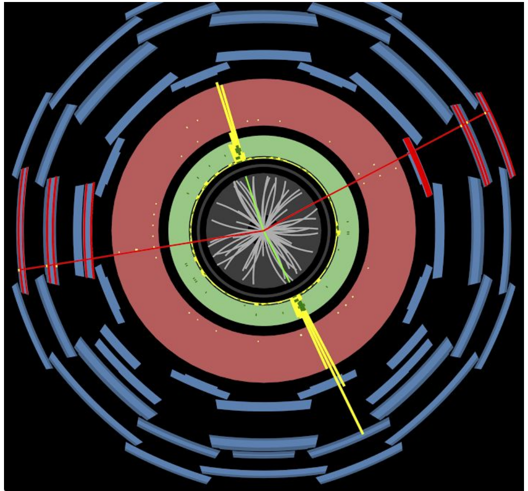
SEARCH FOR SUPERSYMMETRY IN EVENTS WITH FOUR OR MORE LEPTONS AT ATLAS

2017 February 20

Matt Klein



R-parity

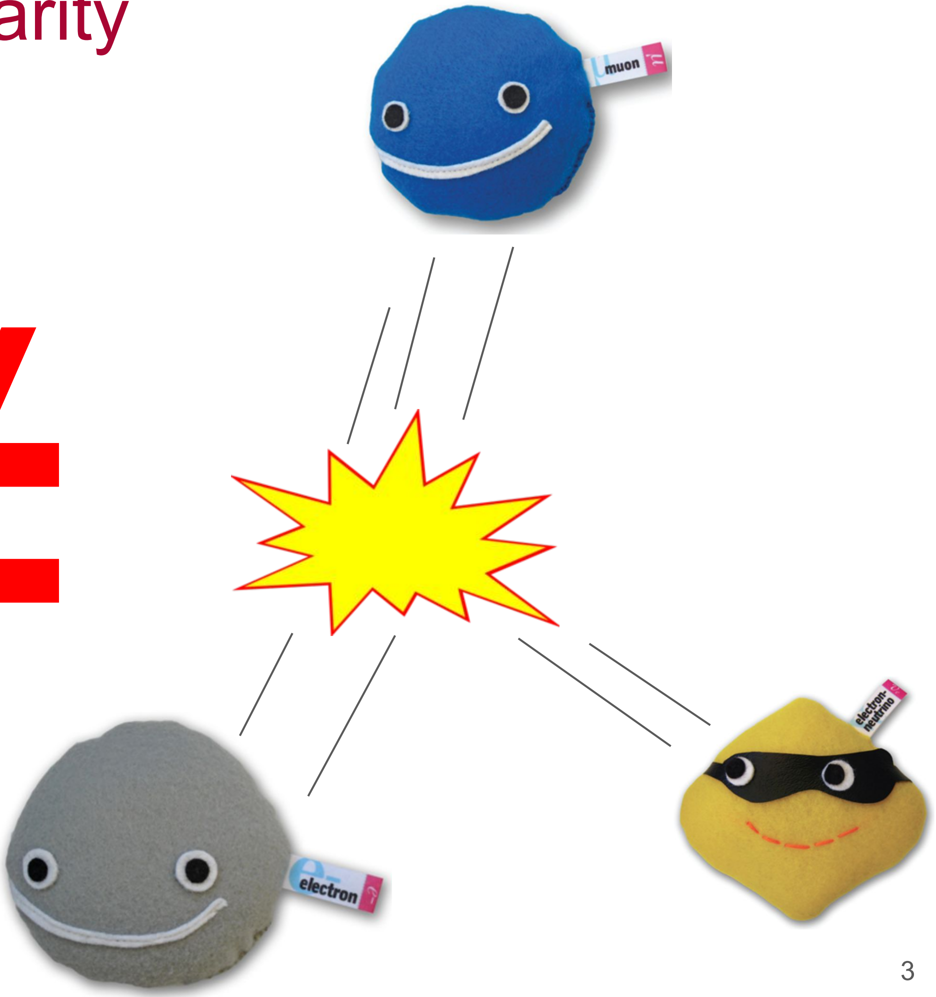
=

?

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

R-parity

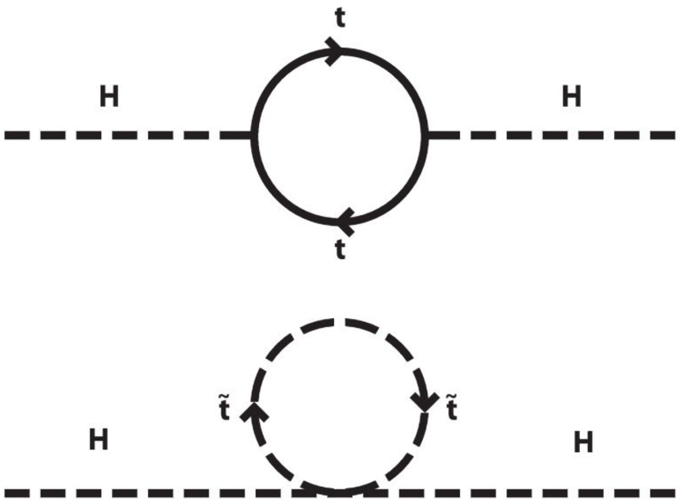
≠



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

R-parity

Why consider R-parity violating SUSY?



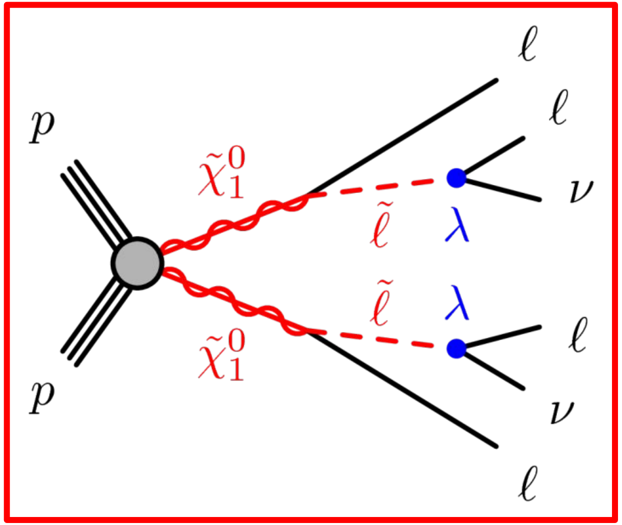
Better question: Why assume R-parity?

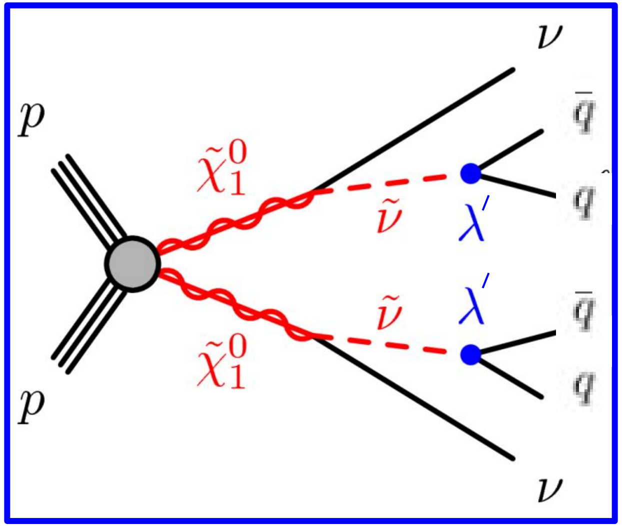
R-Parity Violation

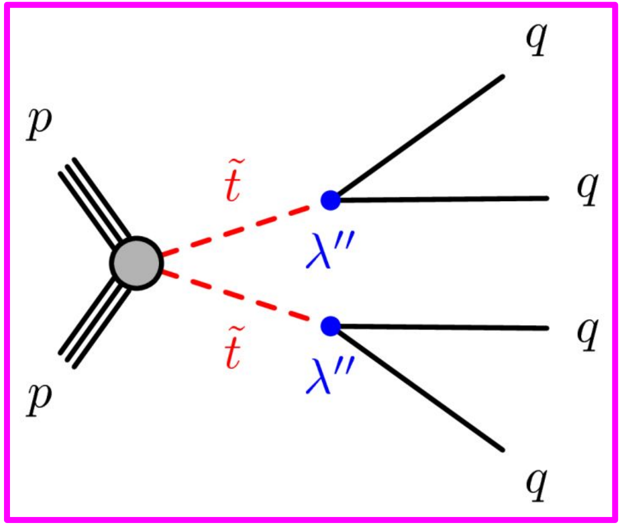
General MSSM RPV terms:

Can evade more inclusive searches

$$\frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_i L_i H_2$$





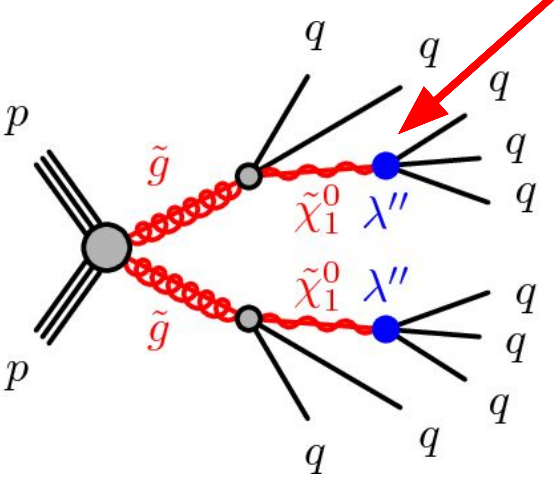


Distinctive Experimental Signatures

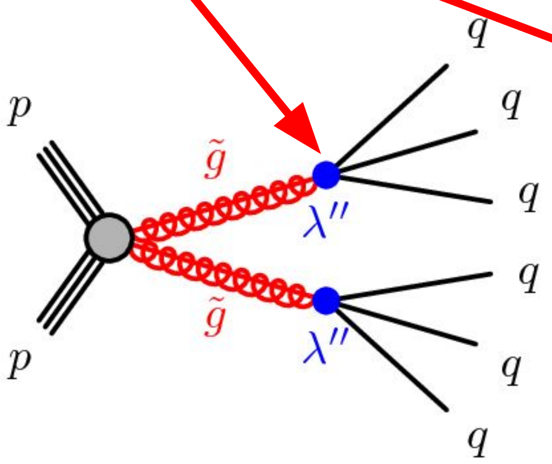
General MSSM RPV terms:

$$\frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_i L_i H_2$$

High jet multiplicity



ATLAS-CONF-2016-057
ATLAS-CONF-2016-094



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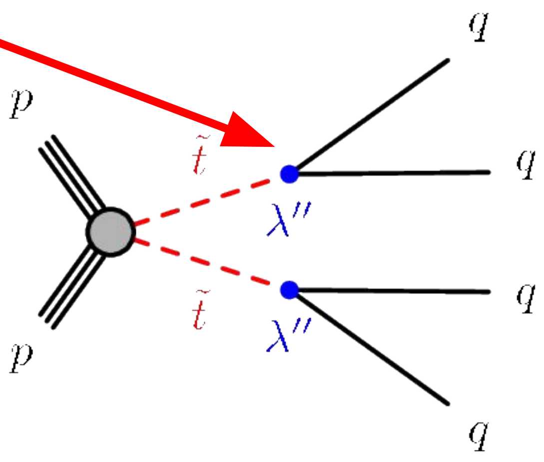

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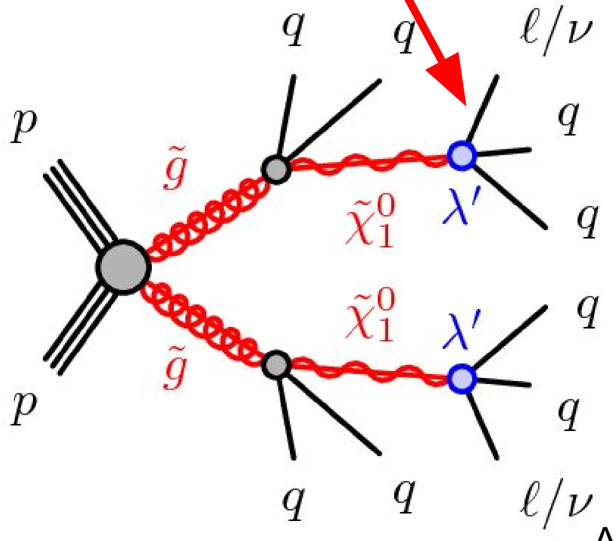
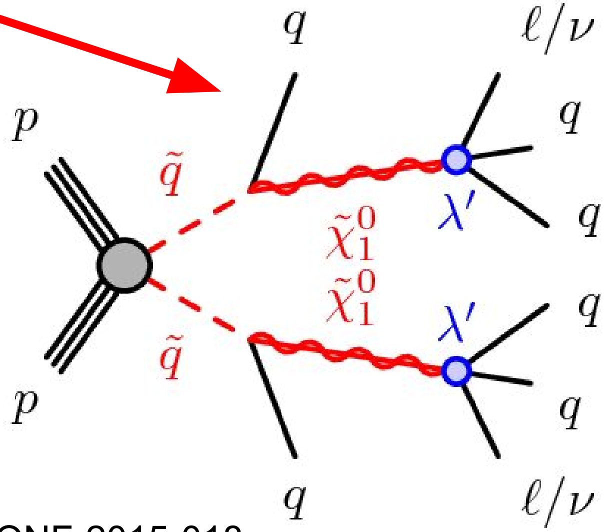
Distinctive Experimental Signatures

General MSSM RPV terms:

$$\frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_i L_i H_2$$

High jet multiplicity





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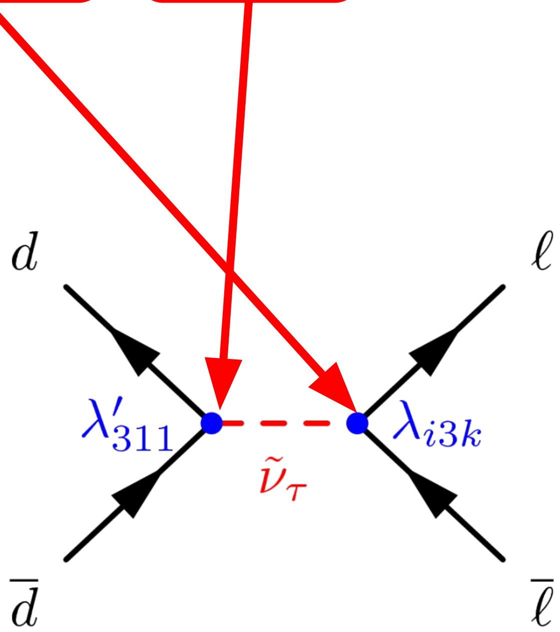
Distinctive Experimental Signatures

General MSSM RPV terms:

$$\frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_i L_i H_2$$

Possible resonance?



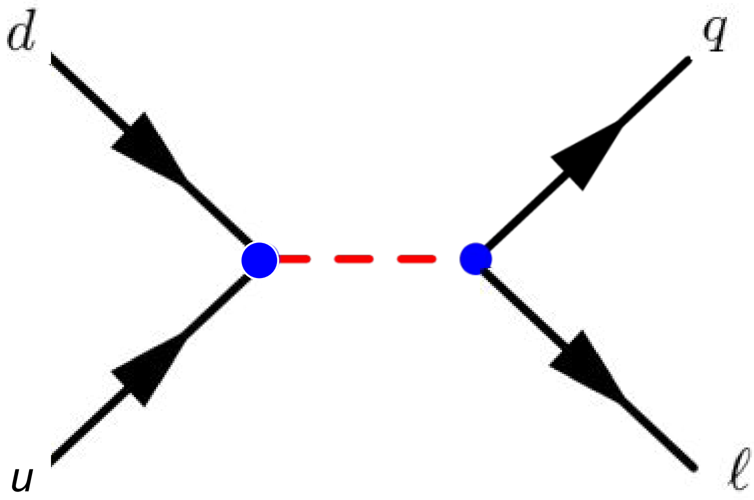
Phys. Rev. Lett. 115, 031801 (2015)

Distinctive Experimental Signatures

General MSSM RPV terms:

$$\frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_iL_iH_2$$

Proton decay -
Don’t need a collider for this one...



Distinctive Experimental Signatures

General MSSM RPV terms:

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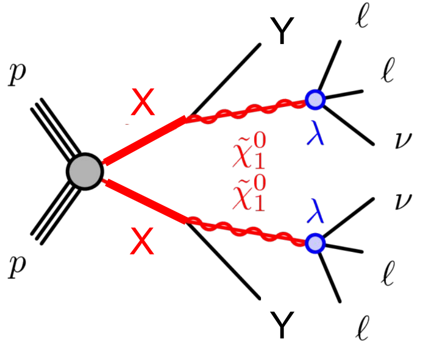
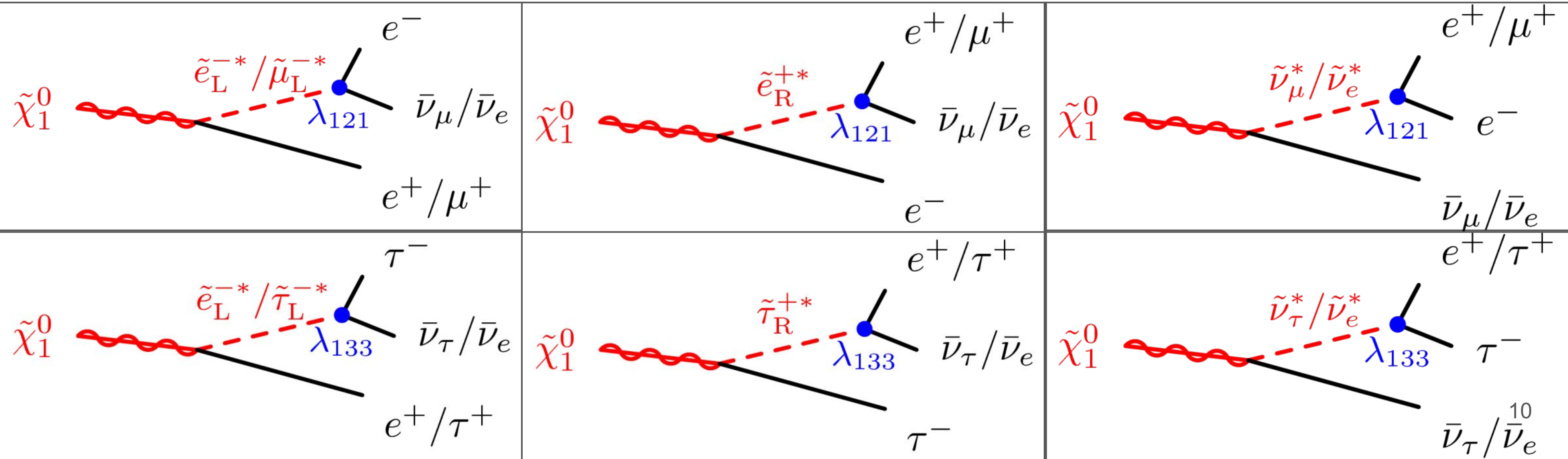
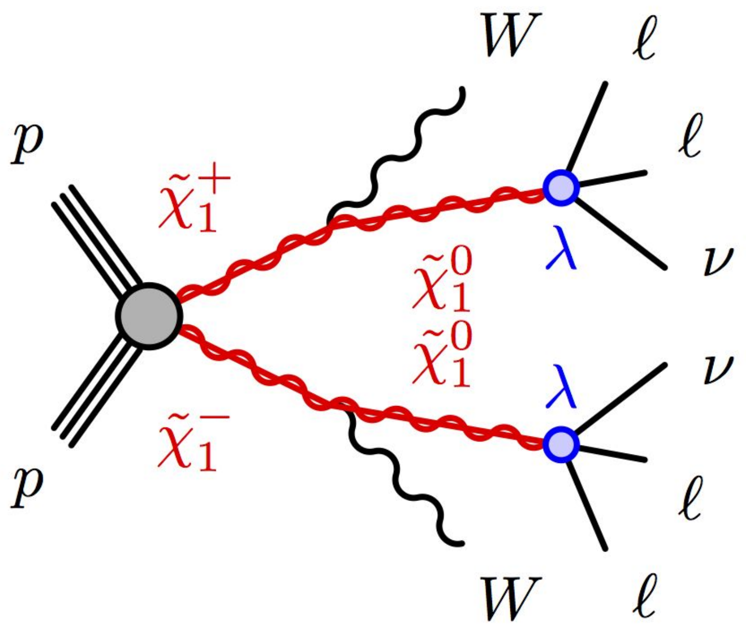
Focus of today's talk





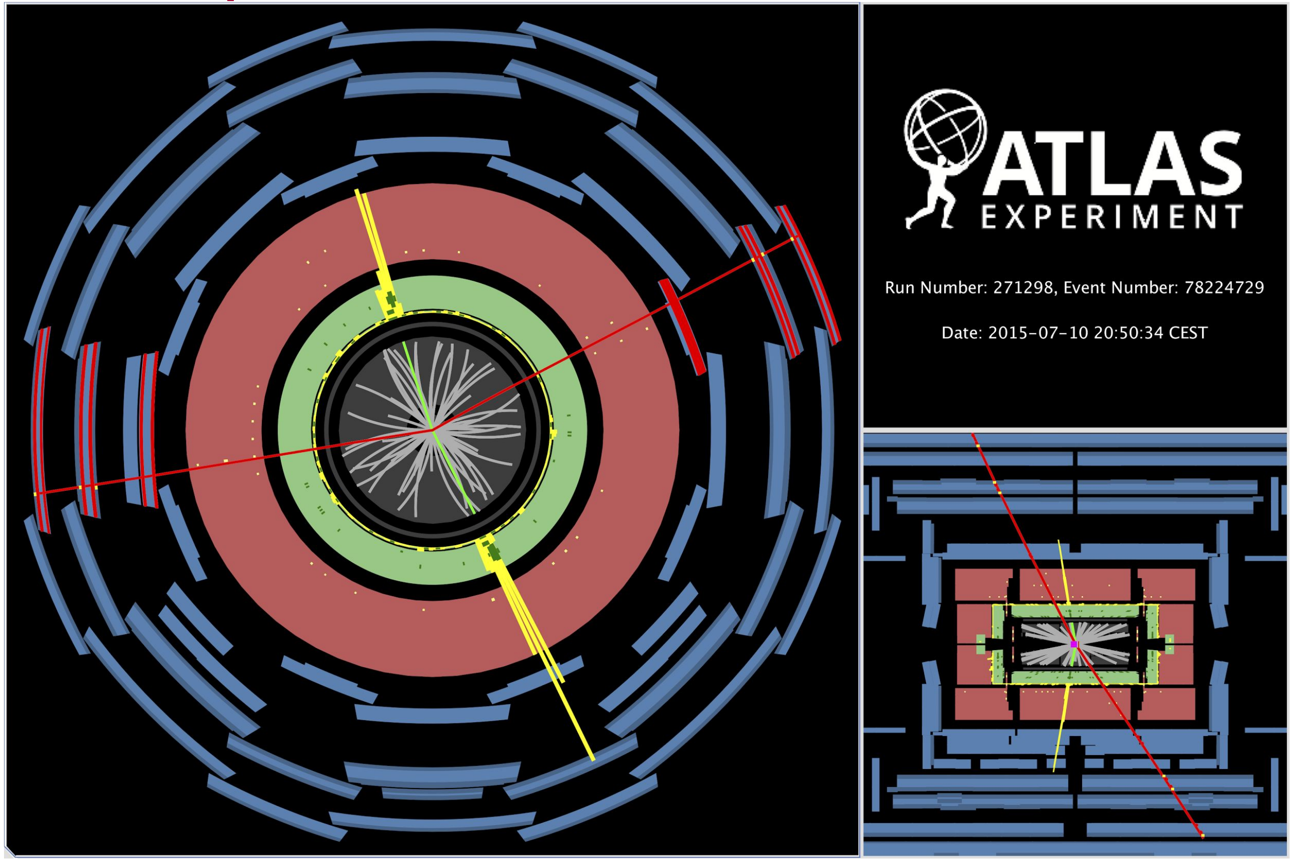
Benchmark Model

- 4-6 final state leptons, no dilepton resonance
- Considered masses:
  - 500 GeV ≤ $m_{chargino}$ ≤ 1200 GeV
  - 10 GeV ≤ $m_{neutralino}$ ≤ $m_{chargino}$ - 10 GeV
- Cross-sections range from ~22 fb^{-1} to 0.2 fb^{-1}

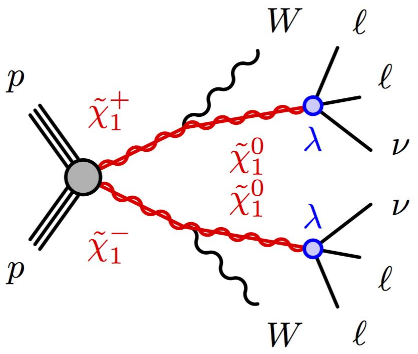


Four Lepton Selection

- Loose selection
  - $p_T > 7$ GeV
  - $|\eta| < 2.47$
- Loose selection
  - $p_T > 5$ GeV
  - $|\eta| < 2.7$

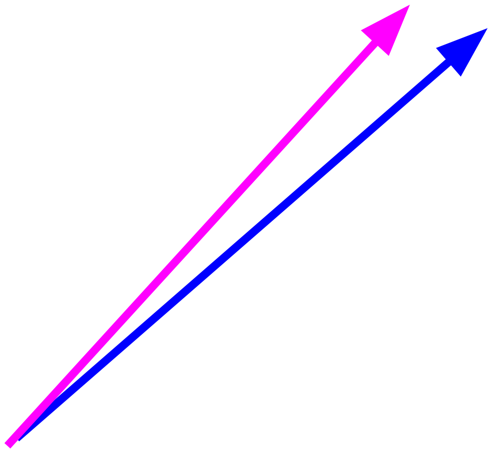


Resolving Nearby Leptons



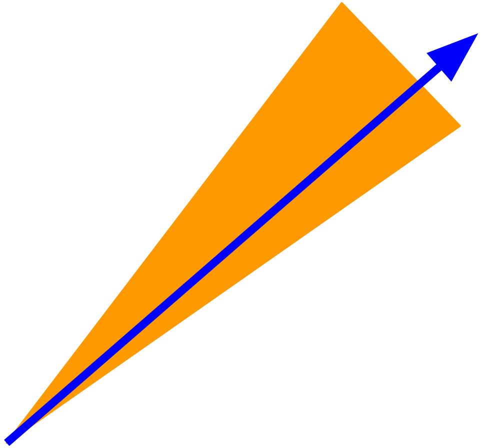
Must consider low mass lepton pairs, which introduces its own problems

Closeby muons:
25% of neutralino decays



Closeby electrons:
25% of neutralino decays

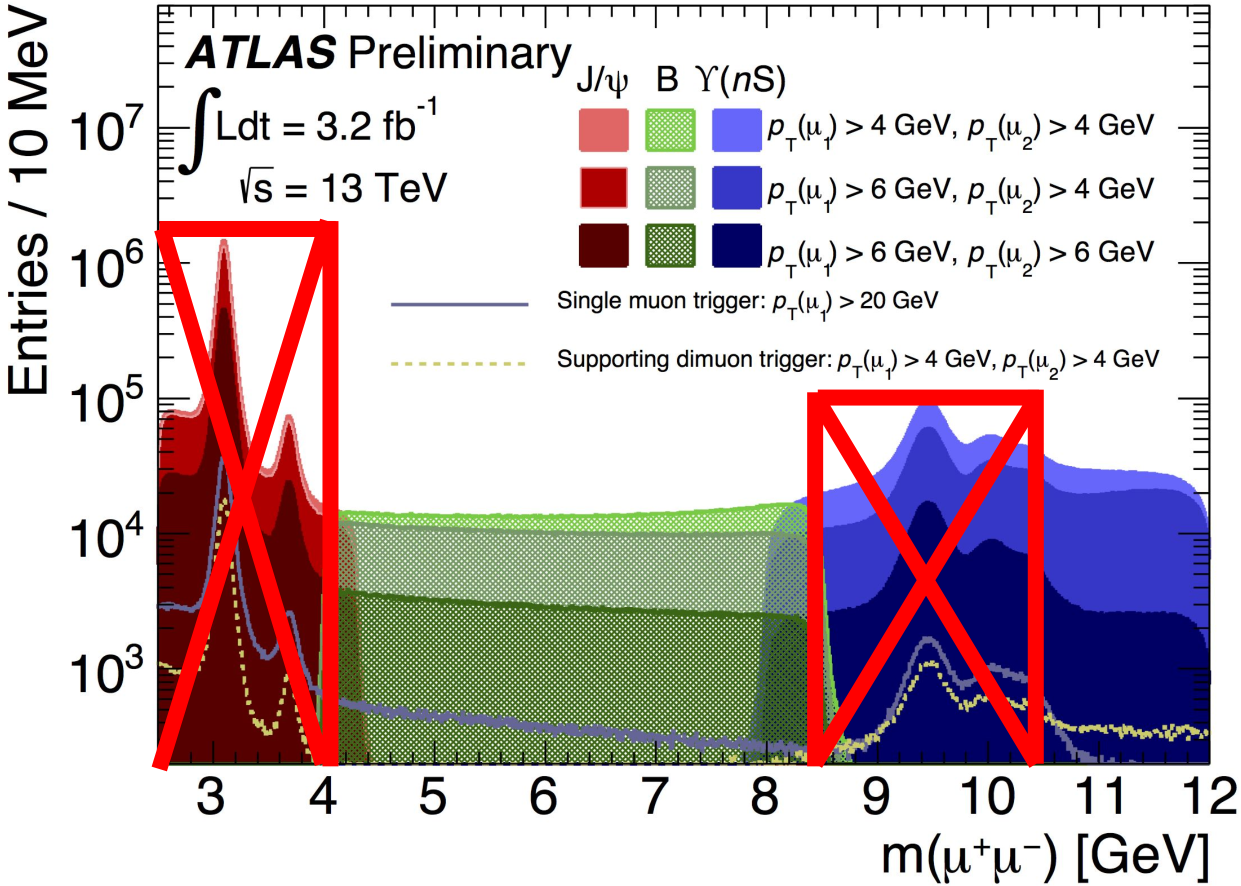
Closeby electron-muon:
50% of neutralino decays



Low Mass Resonances

Low mass resonances form large, poorly modeled background

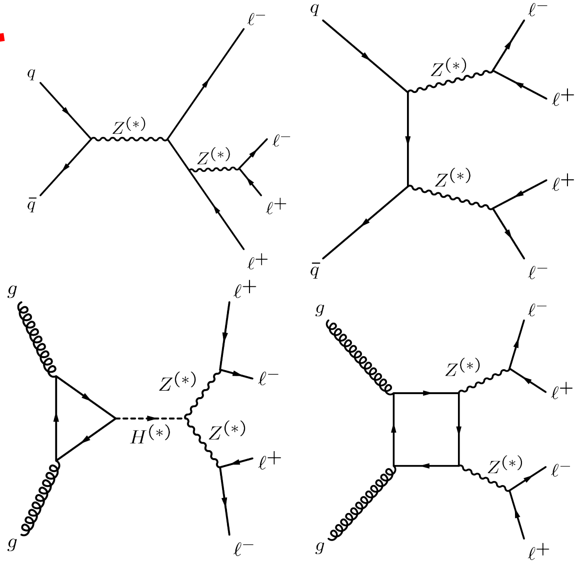
Reject low mass regime for all lepton pairs and the upsilon window for same-flavor pairs



ATL-COM-DAQ-2016-005

Motivation for Further Selection

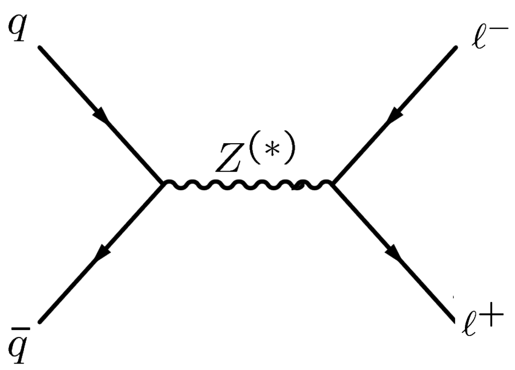
- Low cross-sections - must consider many rare Standard Model processes
- In rough order of importance:
  - ttZ
  - ZZ
  - ttbar
  - Z+jets
  - VH
  - ttH
  - WZ
  - ttW
  - tWZ
  - VVV
  - tttt/ttt



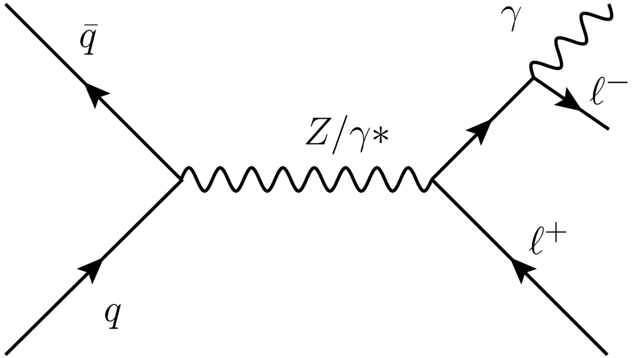
Physics Letters B 753 (2016) 552-572

Event Selection:
- Z-veto
- M_{eff} cut

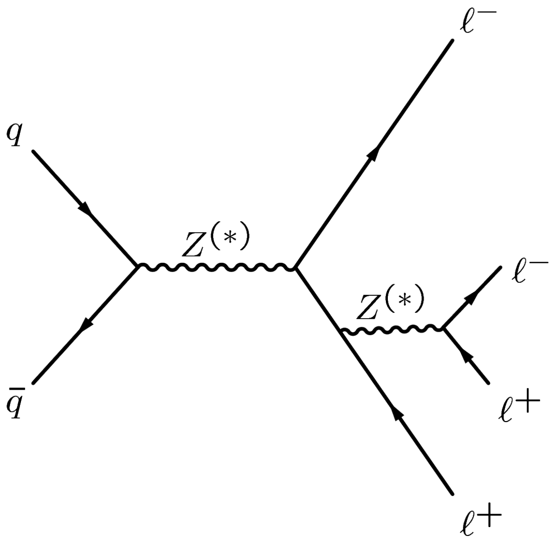
Event Selection: Z-veto



$$|m(\ell^+\ell^-) - m_Z| < 10\,\mathrm{GeV}$$



$$|m(\ell^+\ell^-\ell'^{\pm}) - m_Z| < 10\,\mathrm{GeV}$$



$$|m(\ell^+\ell^-\ell'^+\ell'^-) - m_Z| < 10\,\mathrm{GeV}$$

Phys. Rev. D 93, 112002 (2016)

Signal Regions

Sample	$N(e,\mu)$ signal	$N(e,\mu)$ loose	Z boson	m_{eff} [GeV]
SRA	>= 4	>= 0	veto	> 600
CR-SRA	= 2	>= 2	veto	> 600
SRB	>= 4	>= 0	veto	> 900
CR-SRB	= 2	>= 2	veto	> 900
VR	>= 4	>= 0	veto	< 600
CR-VR	= 2	>= 2	veto	< 600

→ More general 4L region (SRA)

→ Optimized for benchmark model (SRB)

$$m_{\text{eff}} = \sum_{\ell=e,\mu} p_{\text{T}}(\ell) + \sum_{p_{\text{T}}(j)>40\,\text{GeV}} p_{\text{T}}(j) + E_{\text{T}}^{\text{miss}}$$

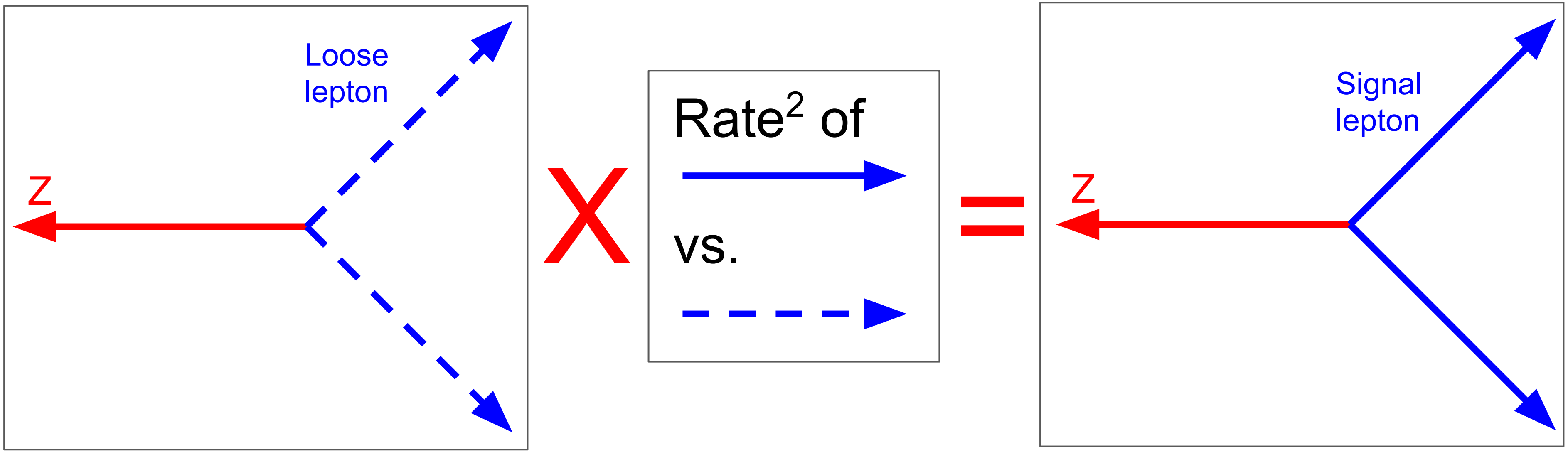
Signal Regions

Sample	$N(e,\mu)$ signal	$N(e,\mu)$ loose	Z boson	m_{eff} [GeV]
SRA	>= 4	>= 0	veto	> 600
CR-SRA	= 2	>= 2	veto	> 600
SRB	>= 4	>= 0	veto	> 900
CR-SRB	= 2	>= 2	veto	> 900
VR	>= 4	>= 0	veto	< 600
CR-VR	= 2	>= 2	veto	< 600

Used in background estimation

$$m_{\text{eff}} = \sum_{\ell=e,\mu} p_{\text{T}}(\ell) + \sum_{p_{\text{T}}(j)>40\,\text{GeV}} p_{\text{T}}(j) + E_{\text{T}}^{\text{miss}}$$

Reducible Background Estimation



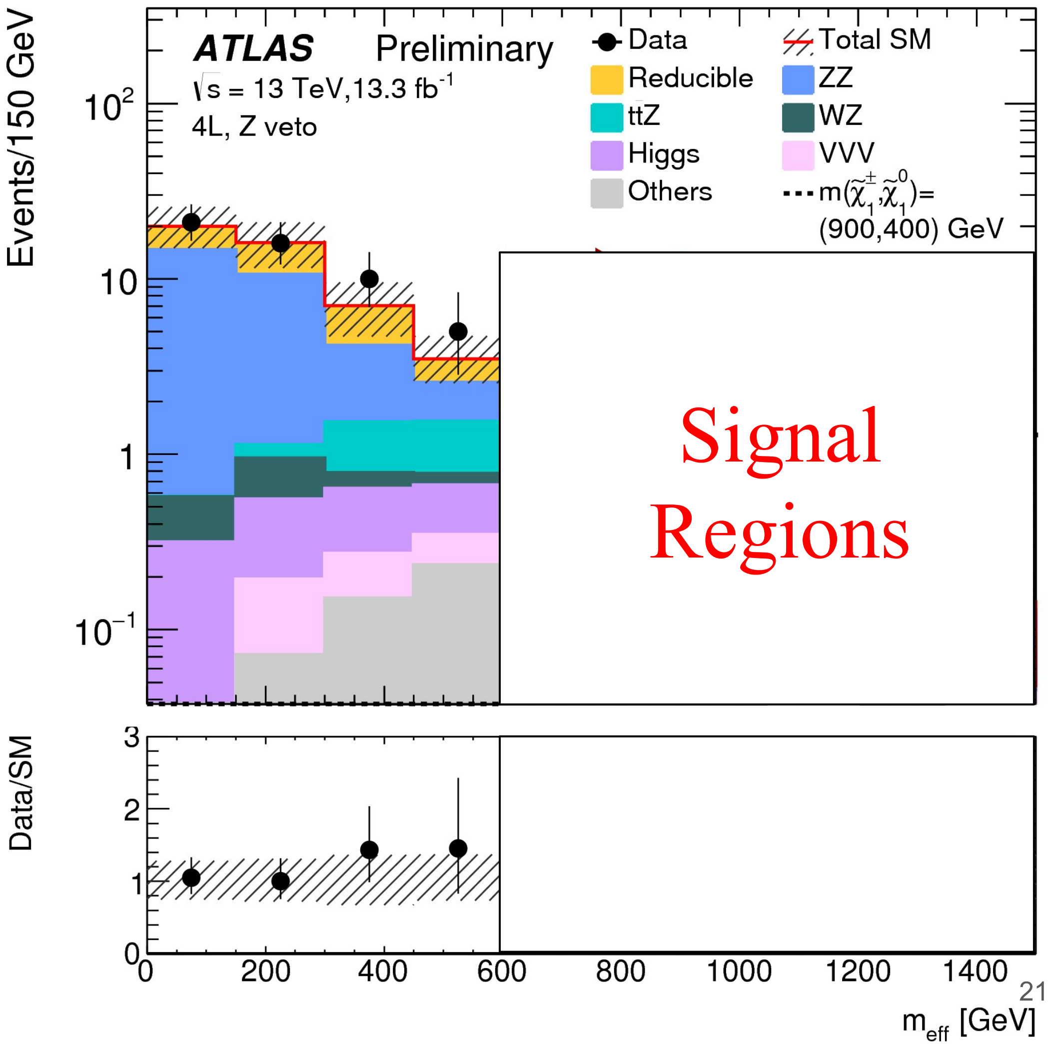
Irreducible Background Estimation

- Many rare backgrounds - MC based estimation method
- High theoretical background uncertainties

Experimental (% of total SM)		Theoretical (% of each process)	
e efficiency	3.9%	σ: $t\bar{t}Z$	12%
μ efficiency	1.9–2.8%	σ: $t\bar{t}W$	13%
Jet energy scale	3.0–3.4%	σ: ZZ,WZ	6%
Luminosity	2.9%	σ: VVV/tWZ	20%
MC statistics	2.7–2.5%	$A\epsilon$: ZZ	56–80%
CR statistics	4.5–6.4%	$A\epsilon$: $t\bar{t}Z$	9–12%
		$\sigma A\epsilon$: VH/VBF H	20%
		$\sigma A\epsilon$: ggF H/ $t\bar{t}$H	100%

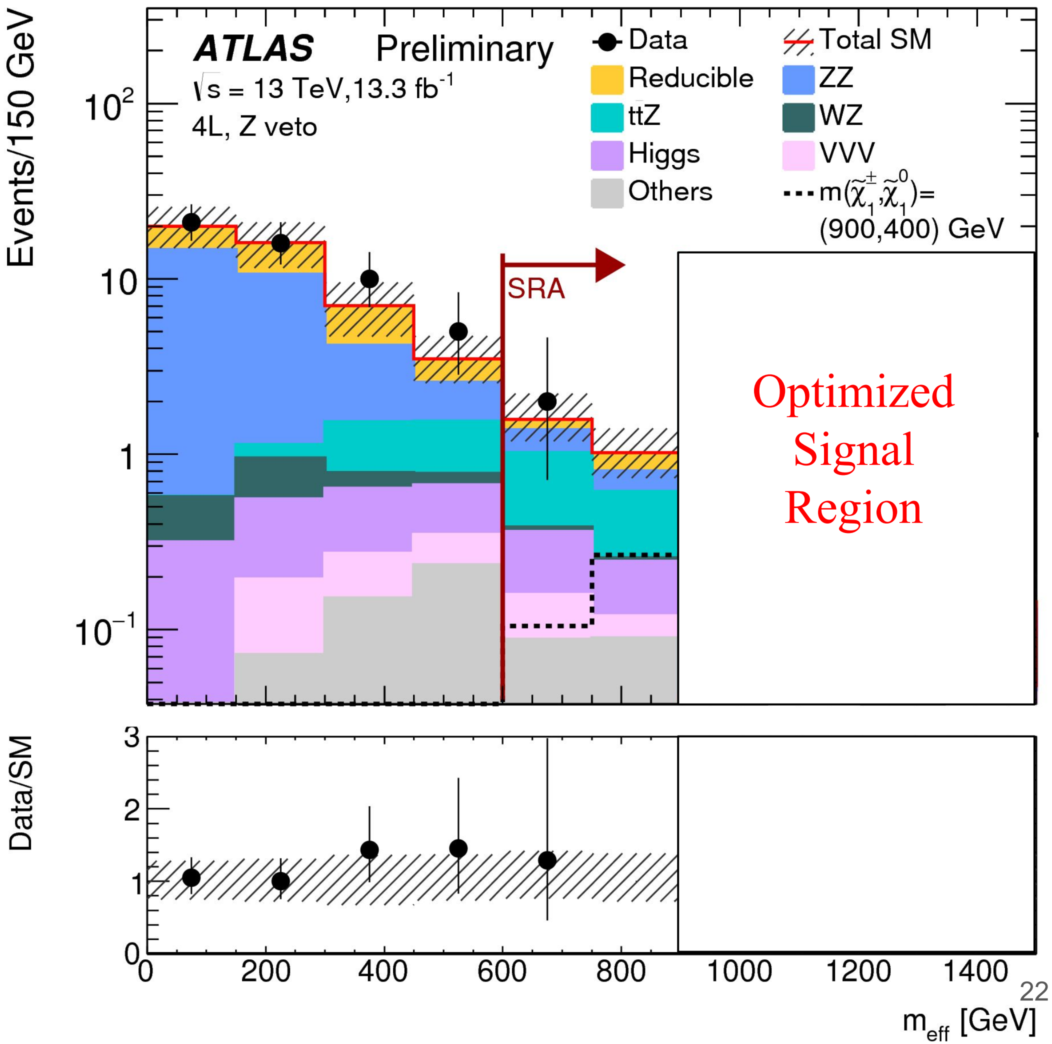
Validation Region

Sample	VR
Irreducible	
ZZ	29 ± 5
$t\bar{t}Z$	2.05 ± 0.24
Higgs	1.7 ± 1.4
VVZ	0.72 ± 0.14
Others	0.28 ± 0.07
1-fake ℓ reducible	1.14 ± 0.07
2-fake ℓ reducible	16 ± 6
Σ SM	51 ± 6
Data	53
p_0	—
S^{95}_{obs}	—
S^{95}_{exp}	—
$\langle\epsilon\sigma\rangle^{95}_{\text{obs}}$ [fb]	—
CL_b	—



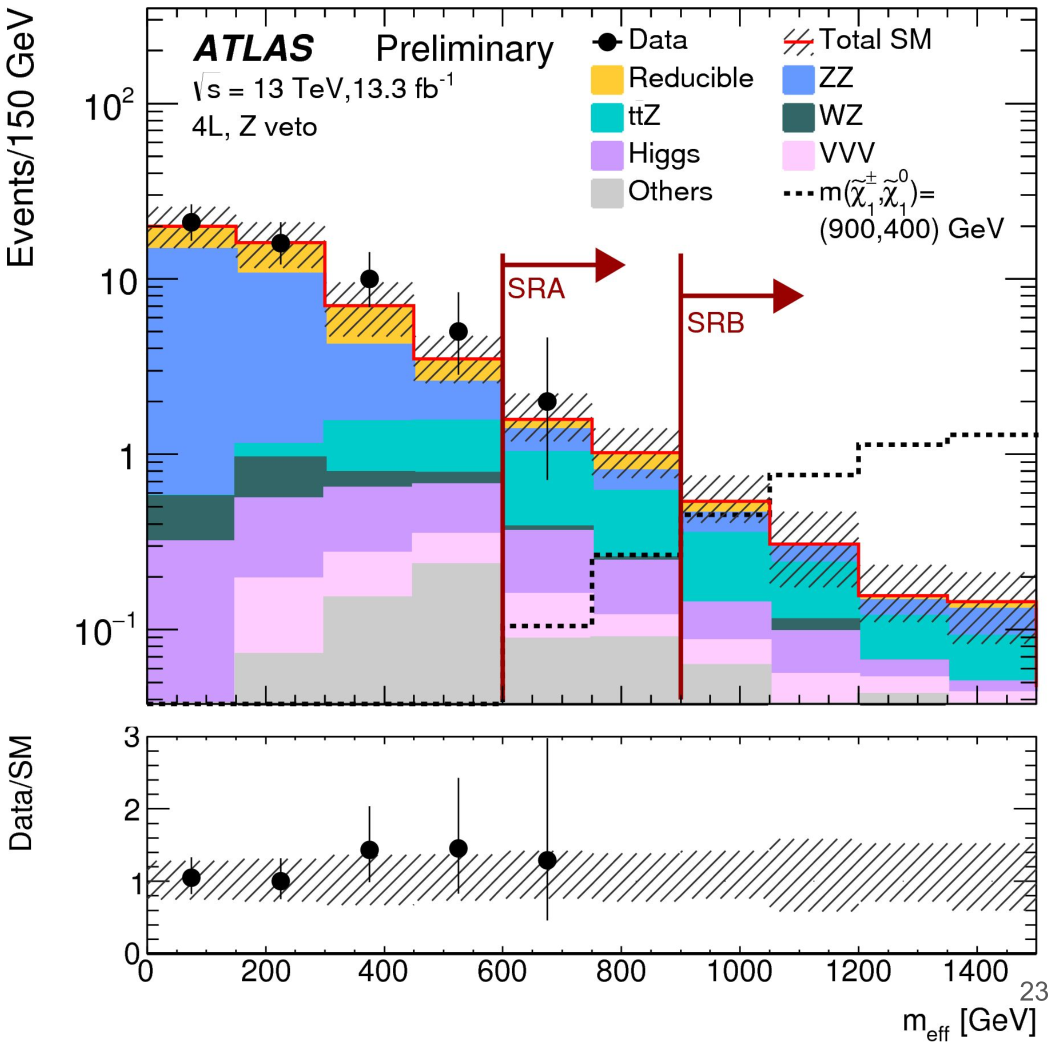
Loose Signal Region

Sample	SRA
Irreducible	
ZZ	0.6 ± 0.4
$t\bar{t}Z$	1.43 ± 0.23
Higgs	0.4 ± 0.4
VVZ	0.31 ± 0.06
Others	0.32 ± 0.04
1-fake ℓ reducible	0.168 ± 0.018
2-fake ℓ reducible	0.48 ± 0.24
Σ SM	3.6 ± 0.6
Data	2
p_0	0.64
S^{95}_{obs}	4.3
S^{95}_{exp}	$5.4^{+1.6}_{-1.3}$
$\langle\epsilon\sigma\rangle^{95}_{obs}$ [fb]	0.32
CL_b	0.21



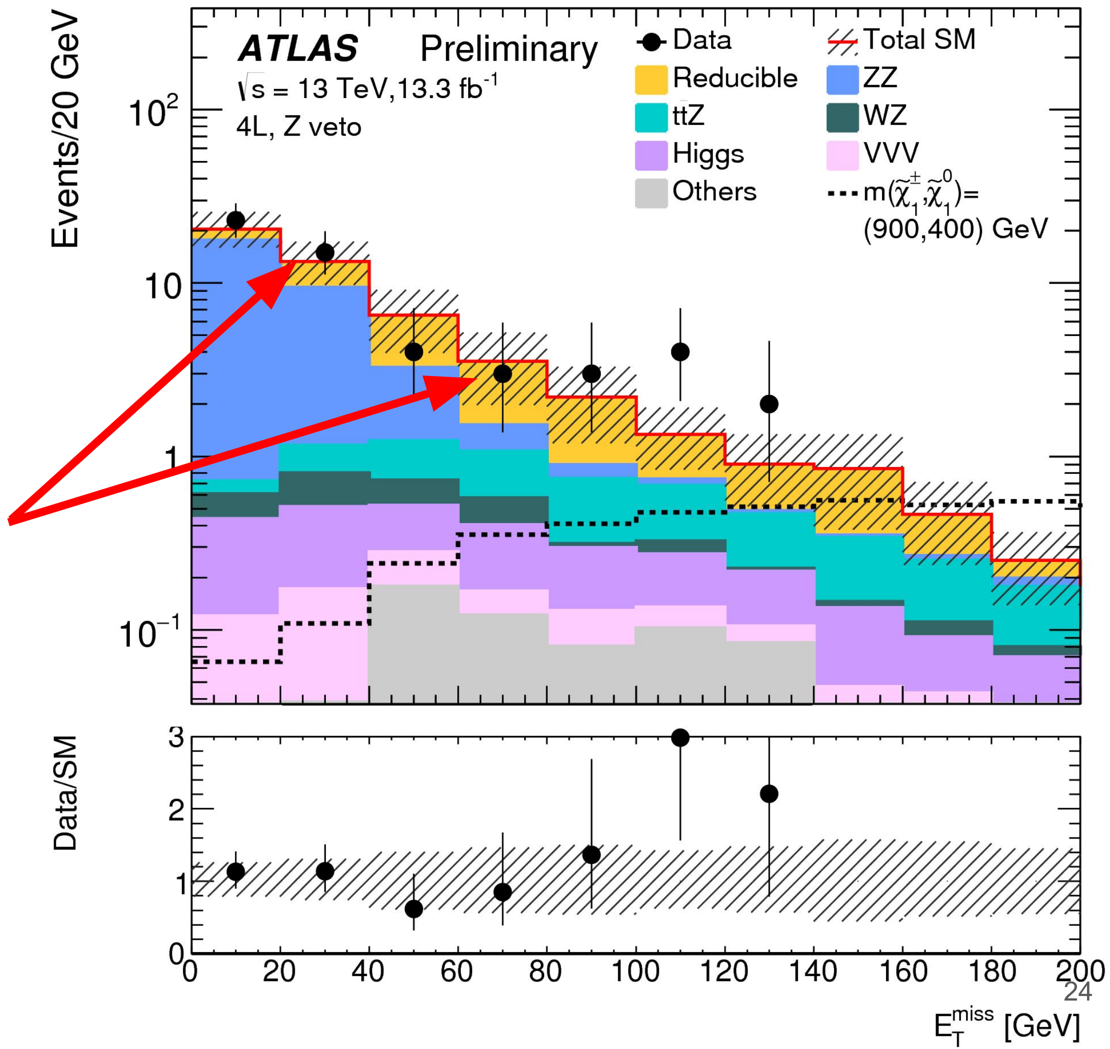
Tight Signal Region

Sample	SRB
Irreducible	
ZZ	0.20 ± 0.19
$t\bar{t}Z$	0.47 ± 0.09
Higgs	0.11 ± 0.11
VVZ	0.123 ± 0.027
Others	0.181 ± 0.022
1-fake ℓ reducible	0.069 ± 0.014
2-fake ℓ reducible	0.11 ± 0.05
Σ SM	1.26 ± 0.26
Data	0
p_0	0.80
S^{95}_{obs}	3.0
S^{95}_{exp}	$3.8^{+1.3}_{-0.8}$
$\langle\epsilon\sigma\rangle^{95}_{\text{obs}}$ [fb]	0.22
CL_b	0.15

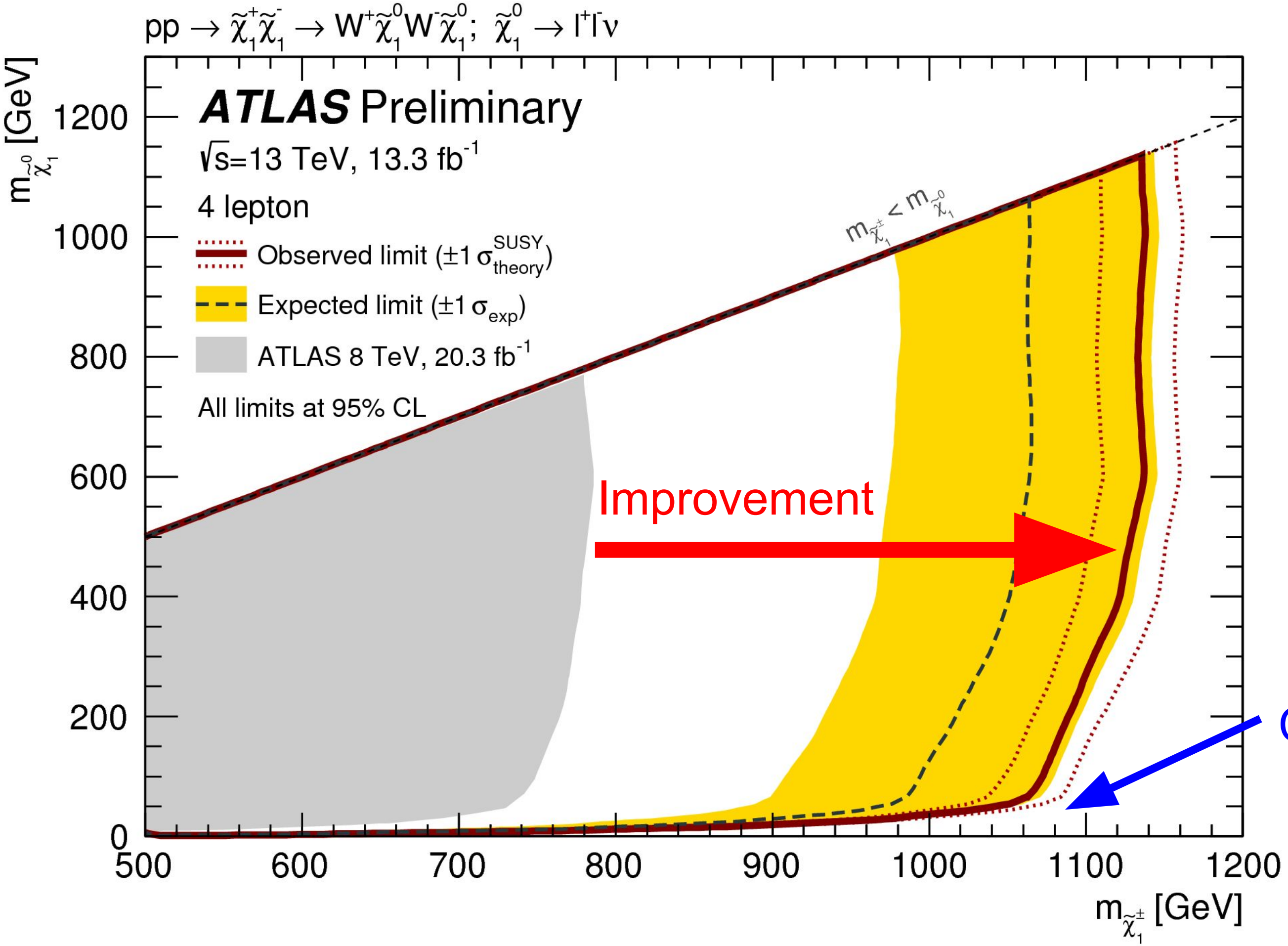


E_T^{miss} Distribution

- No high E_T^{miss} signal
- 2 signal region events:

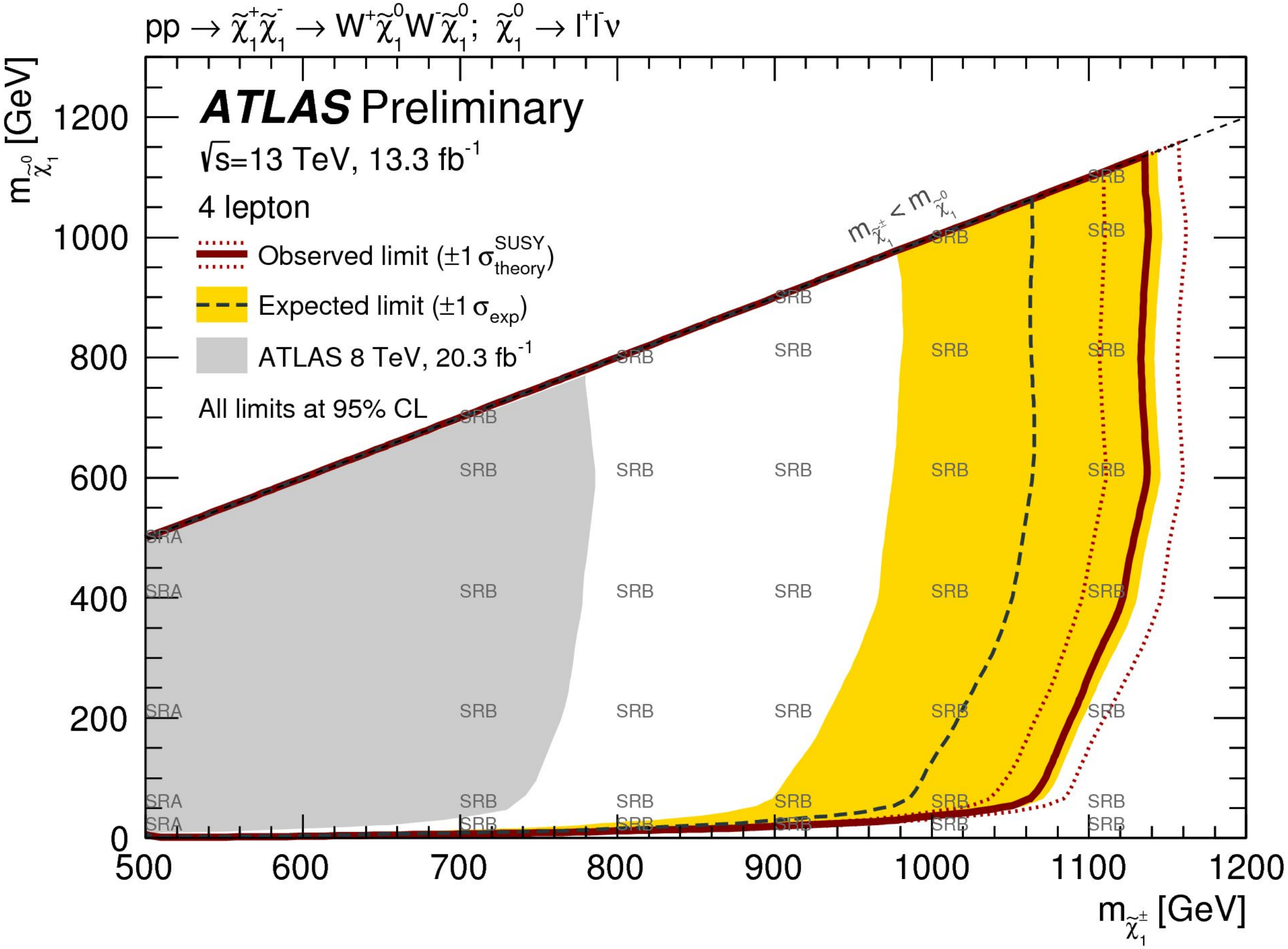


Limits



Search very sensitive to √s - limits extended with-respect-to previous limits

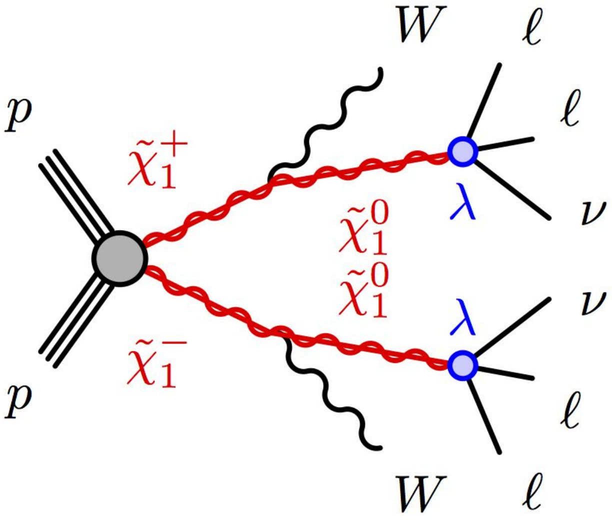
Limits



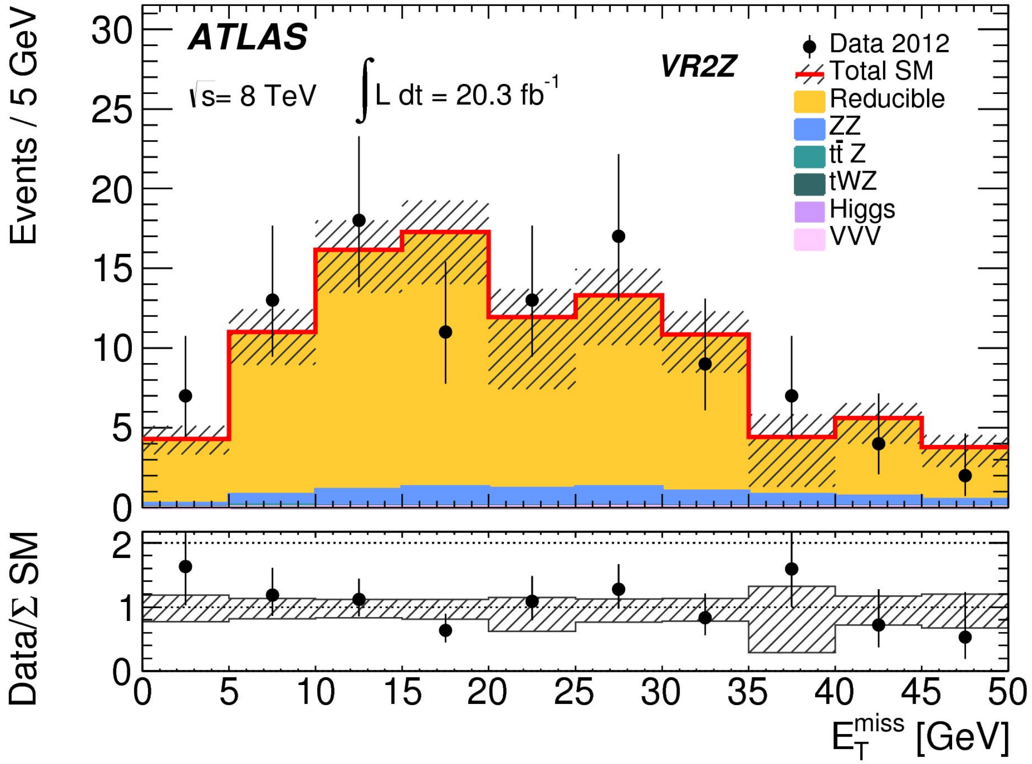
Optimized SR used to set limits in all grid points except lowest chargino masses

Future Plans: Taus

- Tau decays?
- Extra difficulty of fake taus



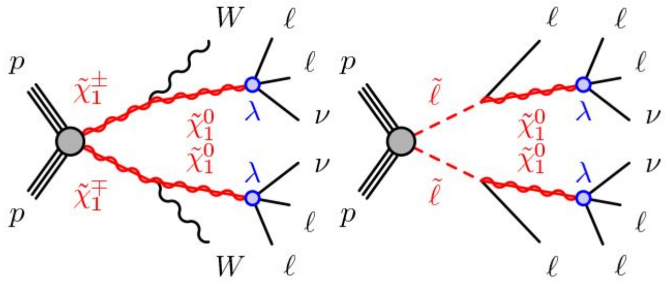
Same model, different couplings



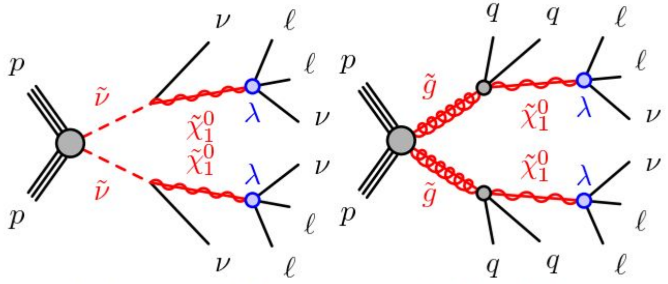
SUSY-2013-13

Future Plans: Signal Models

Summary of simplified RPV models

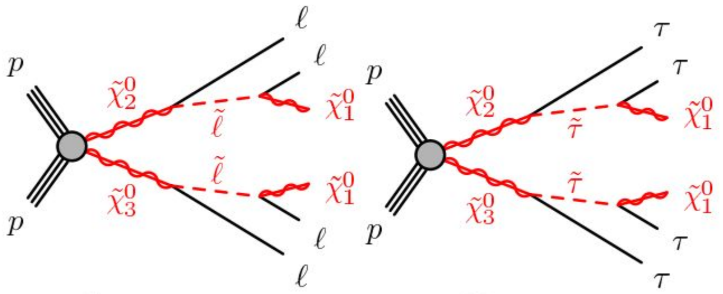


(a) Chargino NLSP (b) R(L)-slepton NLSP

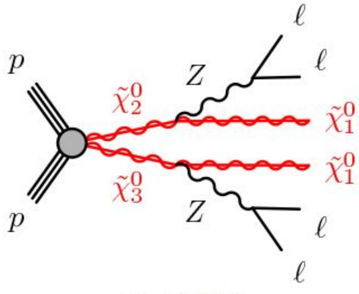


(c) Sneutrino NLSP (d) Gluino NLSP

Summary of simplified RPC models

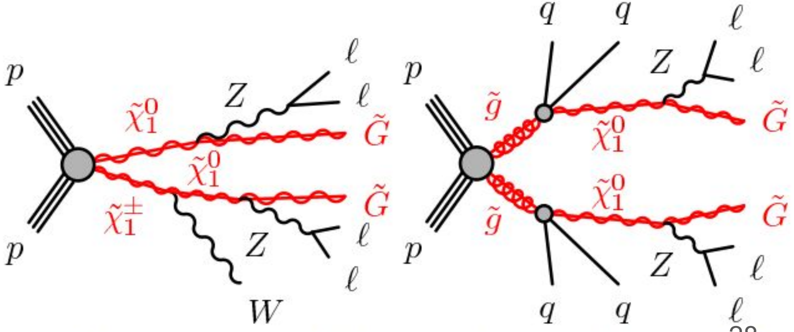


(a) R-slepton RPC (b) Stau RPC



(c) Z RPC

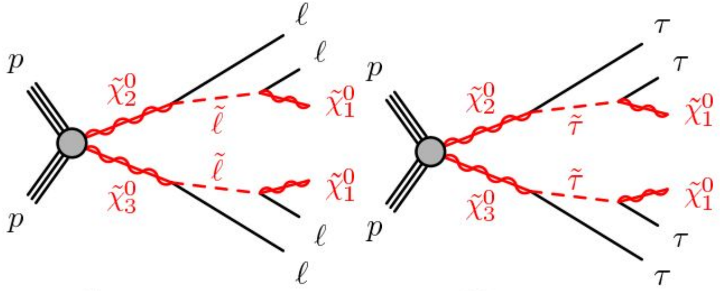
Summary of GGM models



(a) Weak production GGM (b) Strong production GGM

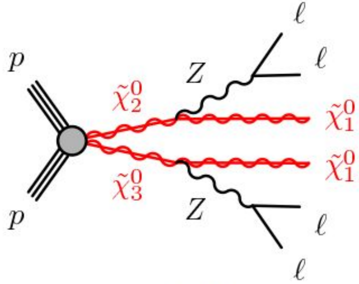
Future Plans: Signal Models

- Beyond RPV models, the 4-lepton final state is useful in detecting many types of models
- E_T^{miss} based identification



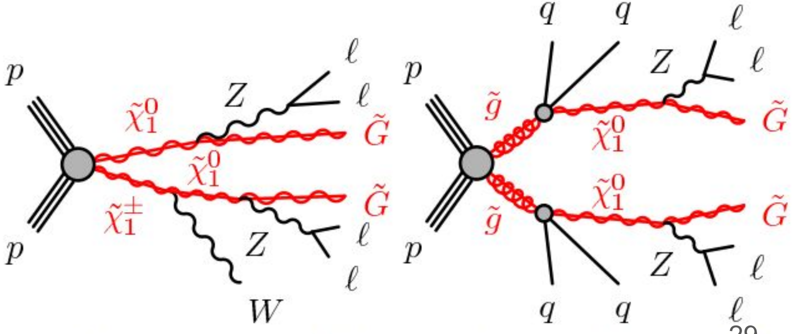
(a) R-slepton RPC (b) Stau RPC

Summary of simplified RPC models

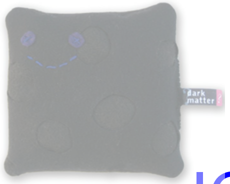


(c) Z RPC

Summary of GGM models



(a) Weak production GGM (b) Strong production GGM



Conclusion

- ICHEP 2016 four lepton SUSY search did not find SUSY
- Moriond 2017 search currently underway with 2016 data
- Future searches will allow for probing models with lower cross-sections but will require more innovative techniques for removing and understanding rare background processes.

Backup

Four Lepton Selection Summary

- Red items optimized specifically for this search

Electron	Muon	Jet	Pile-up jet
Preselected			
$p_T > 7$ GeV $\lvert\eta_{\text{cluster}}\rvert < 2.47$ VeryLooseLH	$p_T > 5$ GeV $\lvert\eta\rvert < 2.7$ Medium	$p_T > 20$ GeV $\lvert\eta\rvert < 4.9$	$p_T < 60$ GeV $\lvert\eta\rvert < 2.4$ JVT < 0.59
		AntiKt4EMTopo, anti-k_t, $R = 0.4$	
Overlap Removal see Table 4			
Signal			
MediumLH $d_0/\sigma(d_0) < 5$	$d_0/\sigma(d_0) < 3$	$\lvert\eta\rvert < 2.8$ not pile-up jet	
$z_0 \sin\theta < 0.5$ mm GradientLoose isolation modified for close-by leptons			

	overlap	discard	comment
1.	e, calo-μ sharing track	μ	
2.	e, μ sharing track	e	
3.	$\Delta R(e, \text{jet}) < 0.2$	jet	We do not give priority to b-jets.
	$\Delta R(e, \text{jet}) < 0.4$	e	
4.	μ,jet*	jet*	$\Delta R(\mu, \text{jet}) < 0.2$ or the jet is ghost-matched to a muon *jet must have either fewer than two associated tracks from the PV or $p_T^{\mu}/p_T^{\text{jet}} > 0.5$ and $p_T^{\mu}/\sum p_T^{\text{jet tracks}} > 0.7$. We do not give priority to b-jets.
	$\Delta R(\mu, \text{jet}) < 0.4$	μ	

Standard Model Background Simulation

Process	Generator(s)	Full/fast sim	Cross-section calculation	UE tune	PDF set
$t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}WW$	MadGraph 5_aMC@NLO [39] + Pythia 8 [40]	Fullsim	NLO	A14	NNPDF23LO
$t\bar{t}Z^{\dagger}$	Sherpa [41]	AF-II	NLO	Default	CT10
tWZ	aMC@NLO [42] + Pythia 8	Fullsim	NLO	A14	NNPDF23LO
ZZ, WZ, WW	Powheg [43] + Pythia 8	Fullsim	NLO	AZNLO	CTEQ6L1
$ZZ^{\dagger}$	Sherpa	AF-II	NLO	Default	CT10
$t\bar{t}$	Powheg + Pythia 6 [44]	Fullsim	NNLO+NNLL	Perugia2012	CT10
Z+jets, W+jets	MadGraph 5_aMC@NLO + Pythia 8	Fullsim	NNLO	A14	NNPDF23LO
Higgs (ggF, VH, VBF H)	Powheg + Pythia 8	Fullsim	NNLO+NNLL	Perugia2012	CT10
$t\bar{t}$H	aMC@NLO + Pythia 8	Fullsim	NLO	UE EE5	CTEQ6L1 (CT10ME)
VVV	Sherpa	Fullsim	NLO	Default	CT10
$tt\bar{t}$, $t\bar{t}t\bar{t}$	MadGraph 5_aMC@NLO + Pythia 8	Fullsim	NLO	A14	NNPDF23LO
$b\bar{b}$, $c\bar{c}$	Pythia 8	Fullsim	NLO	A14	NNPDF23LO
SUSY signal	MadGraph 5 [45] + Pythia 8	AF-II	NLO	A14	NNPDF23LO

Reducible Background Estimation

$$F = \frac{N_{\text{signal}}}{N_{\text{loose}}}$$

Measured in MC, validated in data

Full background Calculation:

$$N_{\text{SR}}^{\text{SM}} = N_{\text{SR}}^{\text{SM,irreducible}} + \left(N_{\text{CR1}}^{\text{data}} - N_{\text{CR1}}^{\text{SM,irreducible}}\right) \cdot F - \left(N_{\text{CR2}}^{\text{data}} - N_{\text{CR2}}^{\text{SM,irreducible}}\right) \cdot F_1 F_2$$

Control region events

Rate at which events lie in the signal region vs. control region

Simplified background Calculation:

$$N_{\text{red}}^{\text{SR}} = [N_{\text{data}}^{\text{CR}} - N_{\text{irr,1-fake}}^{\text{CR}}] \times F_{w,1} \times F_{w,2}$$

Assuming ttbar/Z+jets dominate over WZ/ttW

Calculating Fake Factors

- Fake factor expressed as

$$F^{\ell}_{XR} = \sum_{i,j} \left(f^{ij}_{XR} \times sf^{i} F^{ij} \right)$$

Fake factor, calculated from MC for each truth source (HF, conversion, or LF)

Fraction of leptons originating from each truth source in MC

Scale factor accounting for data/MC differences in fake factor