Searches for electroweak supersymmetry in ATLAS

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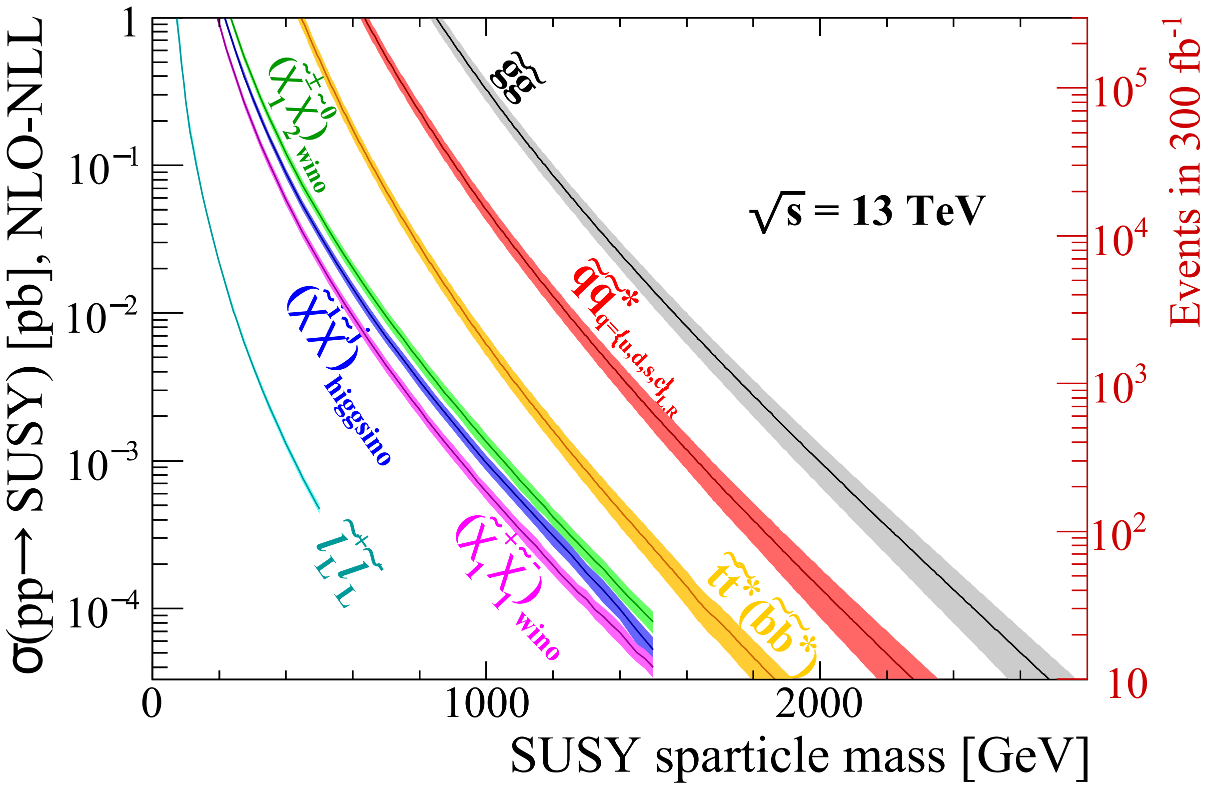
Electroweak Supersymmetry

TeV-range limits for strongly produced SUSY particles

Electroweak SUSY less constrained due to:
- Low cross sections
- Degenerate spectra
- Mixing

All results shown assume R-parity conservation
→ the lightest SUSY particle (LSP) is a Dark Matter (DM) candidate
→ < 3 TeV is allowed from thermal relic DM density

Exclusion plots are based on simplified models
- Only few SUSY particles considered
- All the others heavy
- 100% BR
- Usually stronger limits than for realistic models

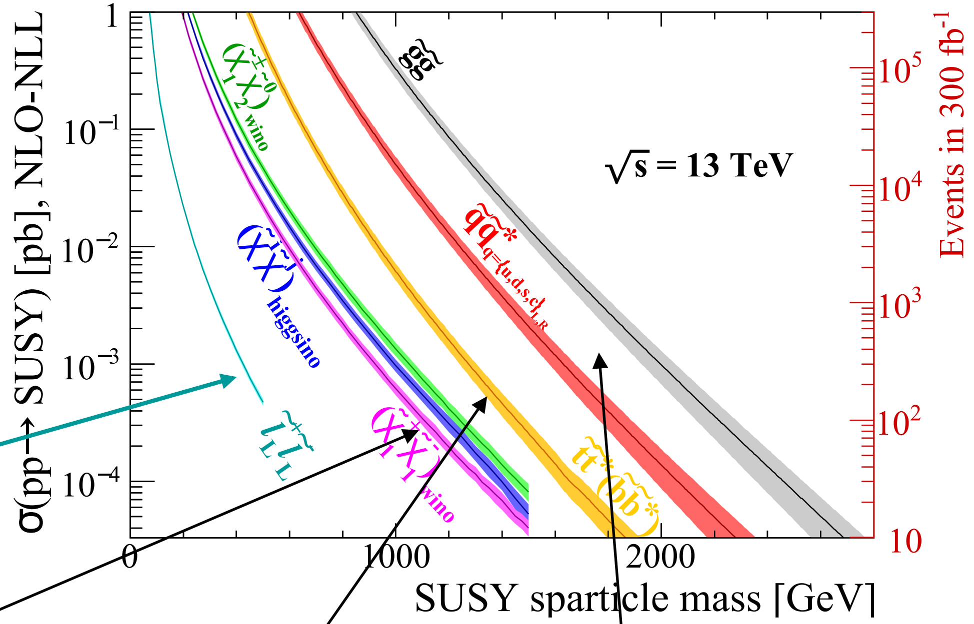


https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections

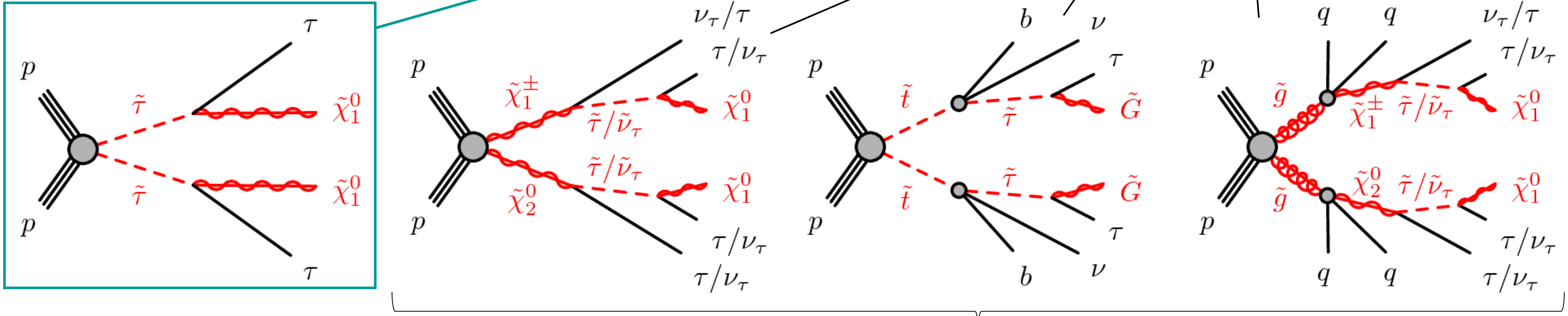
Search for slepton

- Direct productions have small cross sections
  - But important if other SUSY particles except LSP neutralino are heavy
- "in decay chain" analysis of 20-36 fb^{-1} for stau
  - Phys. Rev. D 99 (2019) 012009
  - Eur. Phys. J. C (2016) 76:81
  - Eur. Phys. J. C 78 (2018) 154

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections



139 fb^{-1} result!



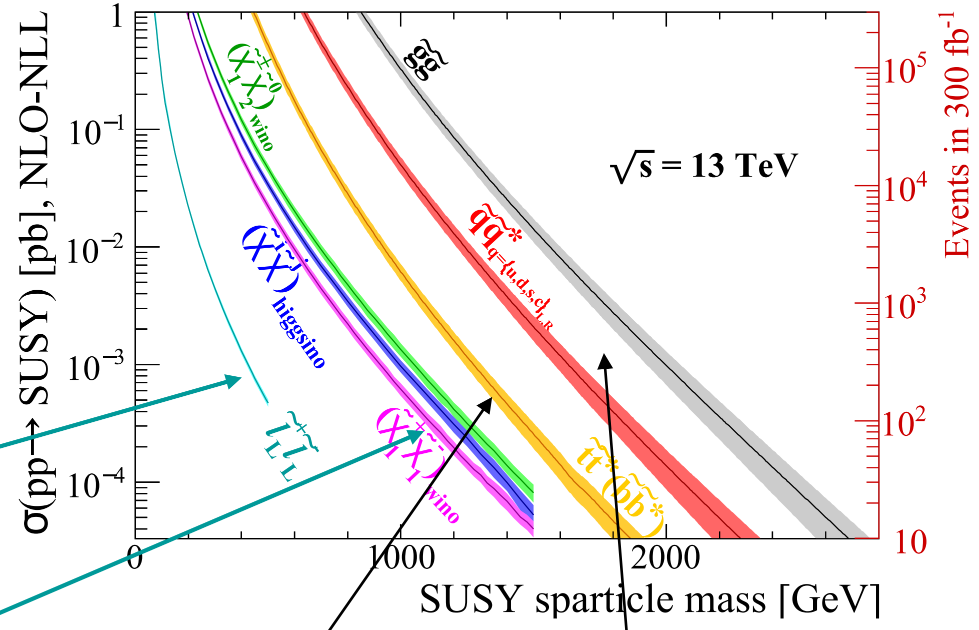
direct

in decay chain

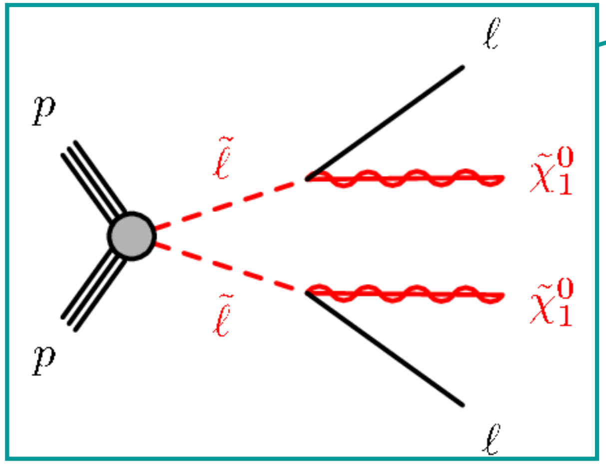
Search for slepton

- Direct productions have small cross sections
  - But important if other SUSY particles except LSP neutralino are heavy
- "in decay chain" analysis for other sleptons
  - Eur. Phys. J. C 78 (2018) 625
  - ATLAS-CONF-2019-008

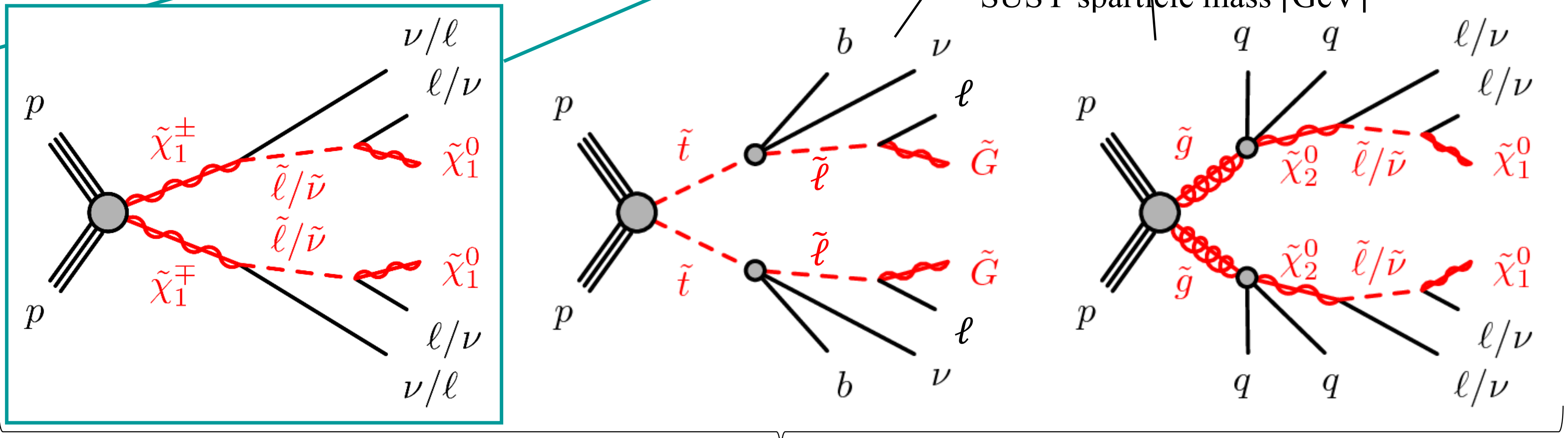
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections



139 fb-1 result!



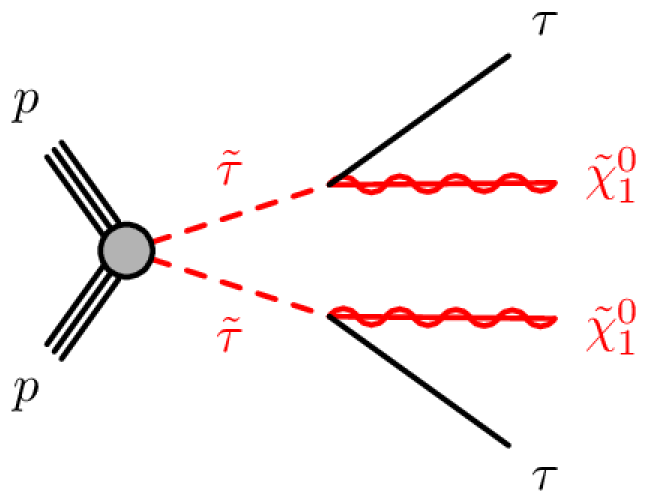
139 fb-1 result!



direct

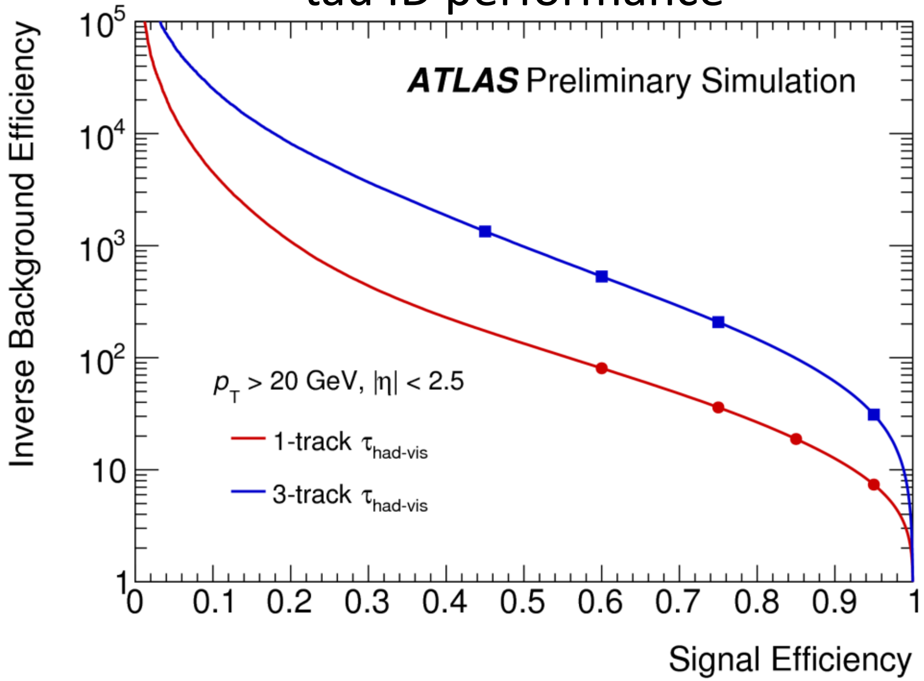
in decay chain

Direct stau production



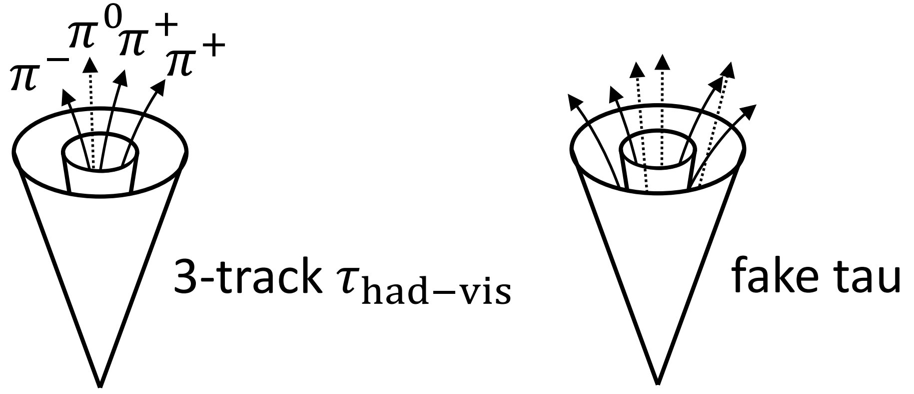
- Final state: 2 opposite sign taus + $E_{\mathrm{T}}^{\mathrm{miss}}$
  - taus are required to decay hadronically
- BDT based tau ID
  - jet shape + track multiplicity
- Backgrounds:
  - fake tau: multi-jet, W+jets
  - real tau: diboson, top and others

tau ID performance



tau branching fraction

1-track $\tau_{\mathrm{had-vis}}$	$\tau^- \to h^- \nu_\tau + N\pi^0\ (N = 0, 1, 2)$	~47 %
3-track $\tau_{\mathrm{had-vis}}$	$\tau^- \to h^- h^+ h^- \nu_\tau + N\pi^0\ (N = 0, 1)$	~15 %

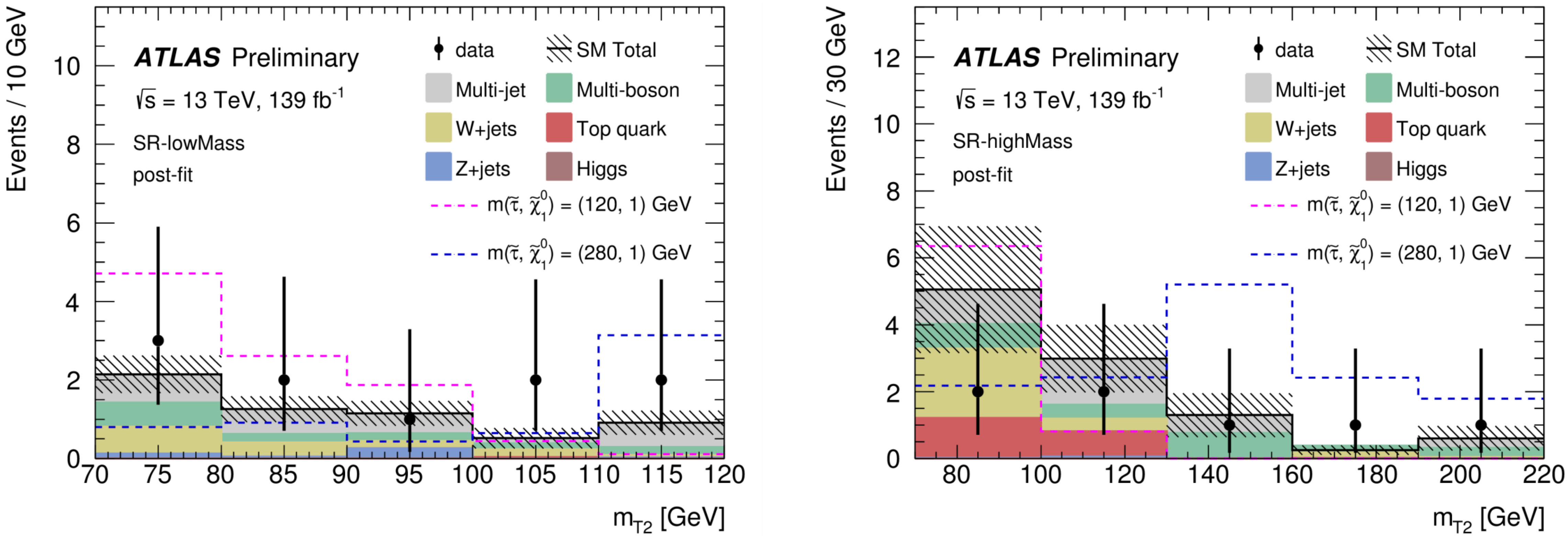


Direct stau production

- 2 signal regions (SRs), optimized for different stau masses
- Requiring large m_{T2}, calculate using 2 taus and $E_{\mathrm{T}}^{\mathrm{miss}}$
  - $m_{\mathrm{T2}} = \min_{q_{\mathrm{T}}}\{\max[m_{\mathrm{T}}(p_{\mathrm{T}}^{\tau 1}, q_{\mathrm{T}}), m_{\mathrm{T}}(p_{\mathrm{T}}^{\tau 2}, E_{\mathrm{T}}^{\mathrm{miss}} - q_{\mathrm{T}})]\}$
  - q_{T} is scanned all possibility region

low mass SR: $75 < E_{\mathrm{T}}^{\mathrm{miss}} < 150$ GeV

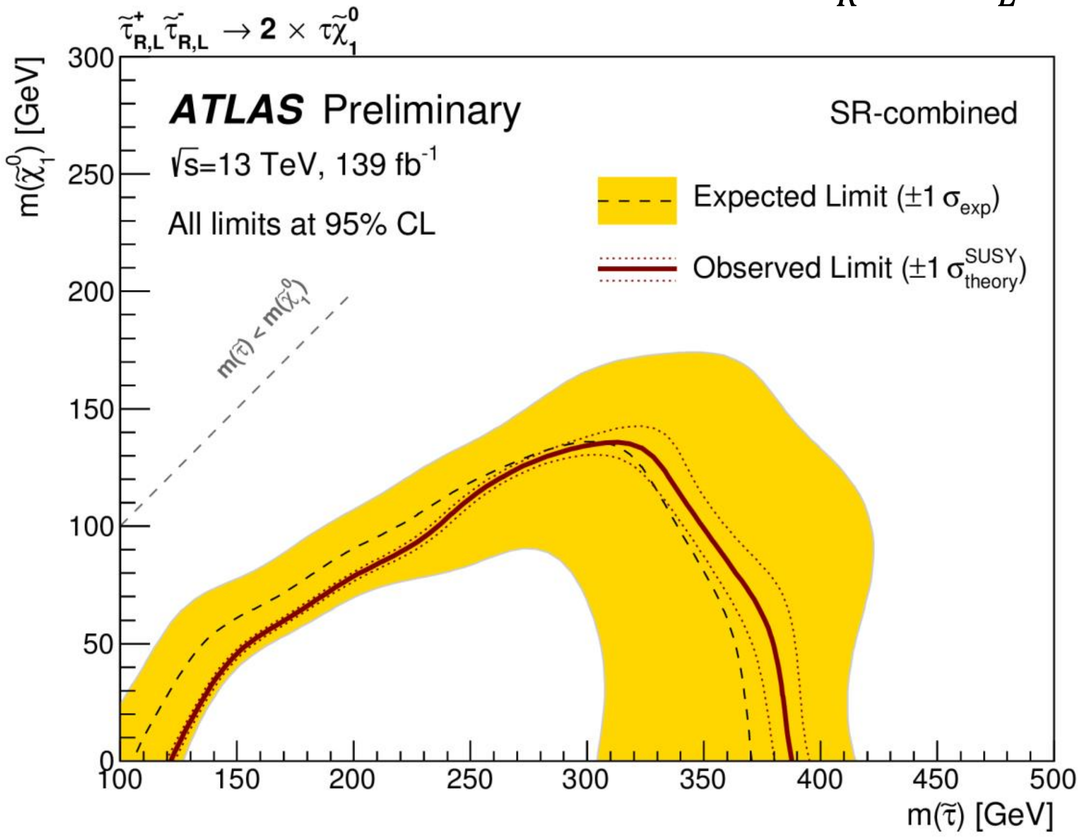
high mass SR: $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV



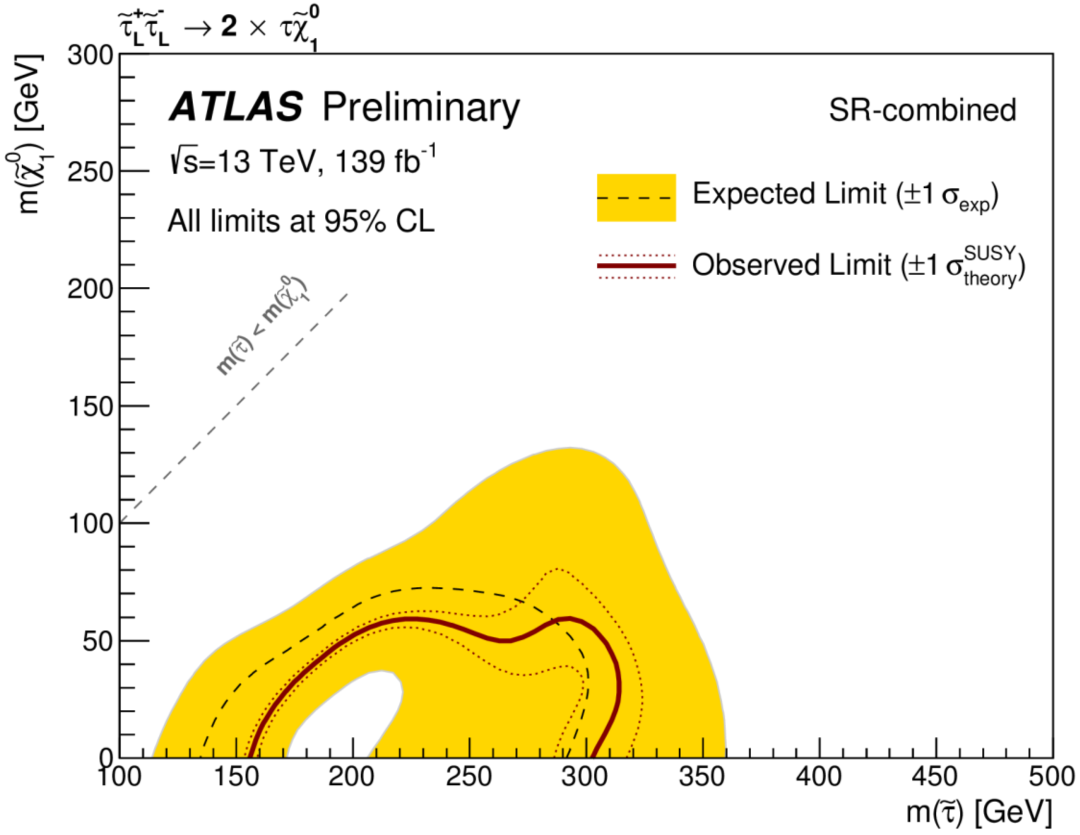
Direct stau production

- No significant excess was observed → exclusion limits
- Considering charginos/neutralinos except $\tilde{\chi}_1^0$ are very heavy

Combined Left/Right-handed ($m_{\tilde{\tau}_R} = m_{\tilde{\tau}_L}$)



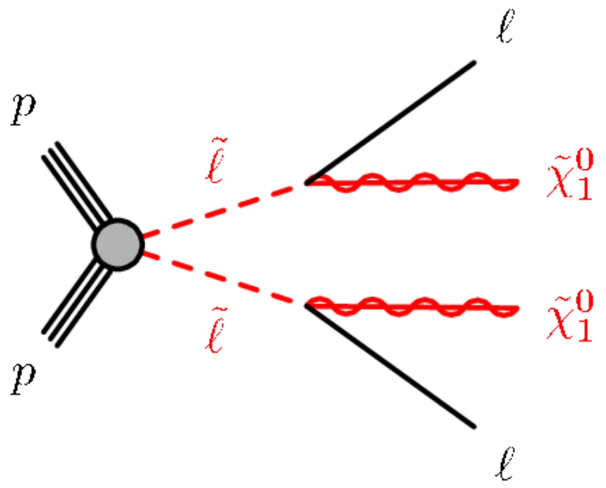
Left-handed only



Sensitivity from 120 to 390 GeV → significantly extend Run1/LEP results

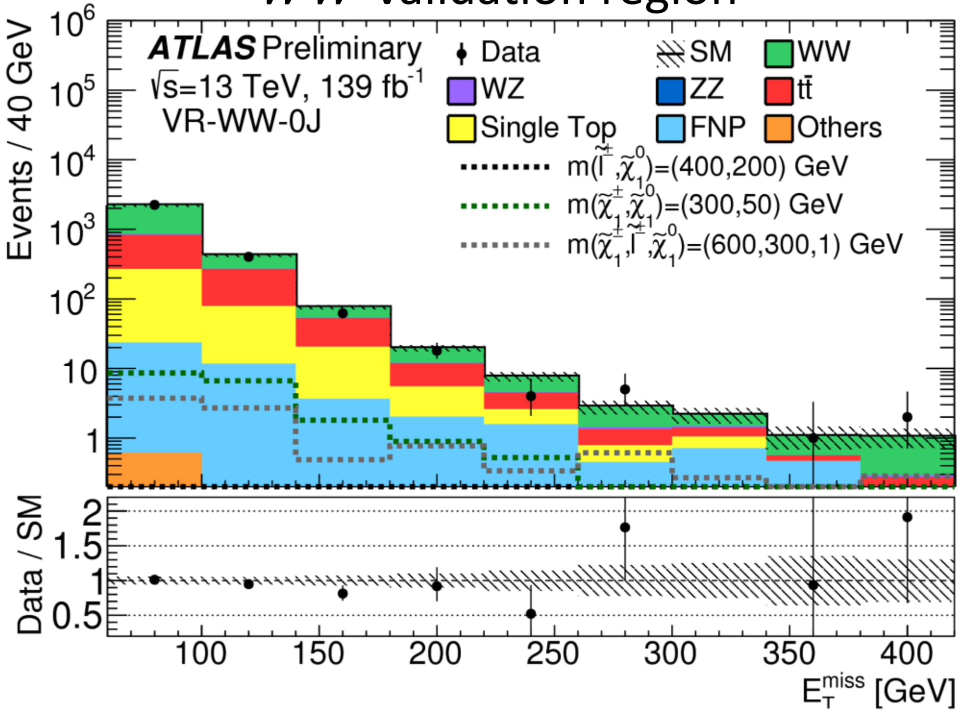
the first exclusion limit

Direct $\tilde{e}$ and $\tilde{\mu}$ production

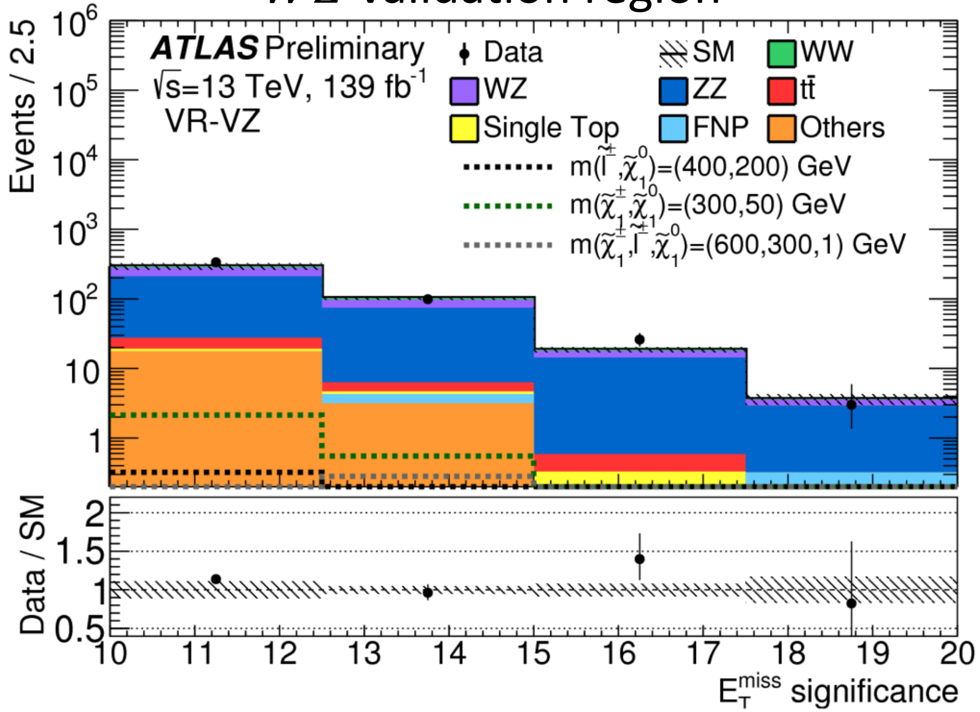


- Considering $m_{\tilde{e}_R} = m_{\tilde{e}_L} = m_{\tilde{\mu}_R} = m_{\tilde{\mu}_L}$
- Final state: 2 e or μ + $E_{\mathrm{T}}^{\mathrm{miss}}$
  - same flavor, opposite sign
- Backgrounds: WW, WZ
  - MC is normalized based on control regions
- Very clean signature: 0 or 1 ISR jet, b-jet veto

WW validation region



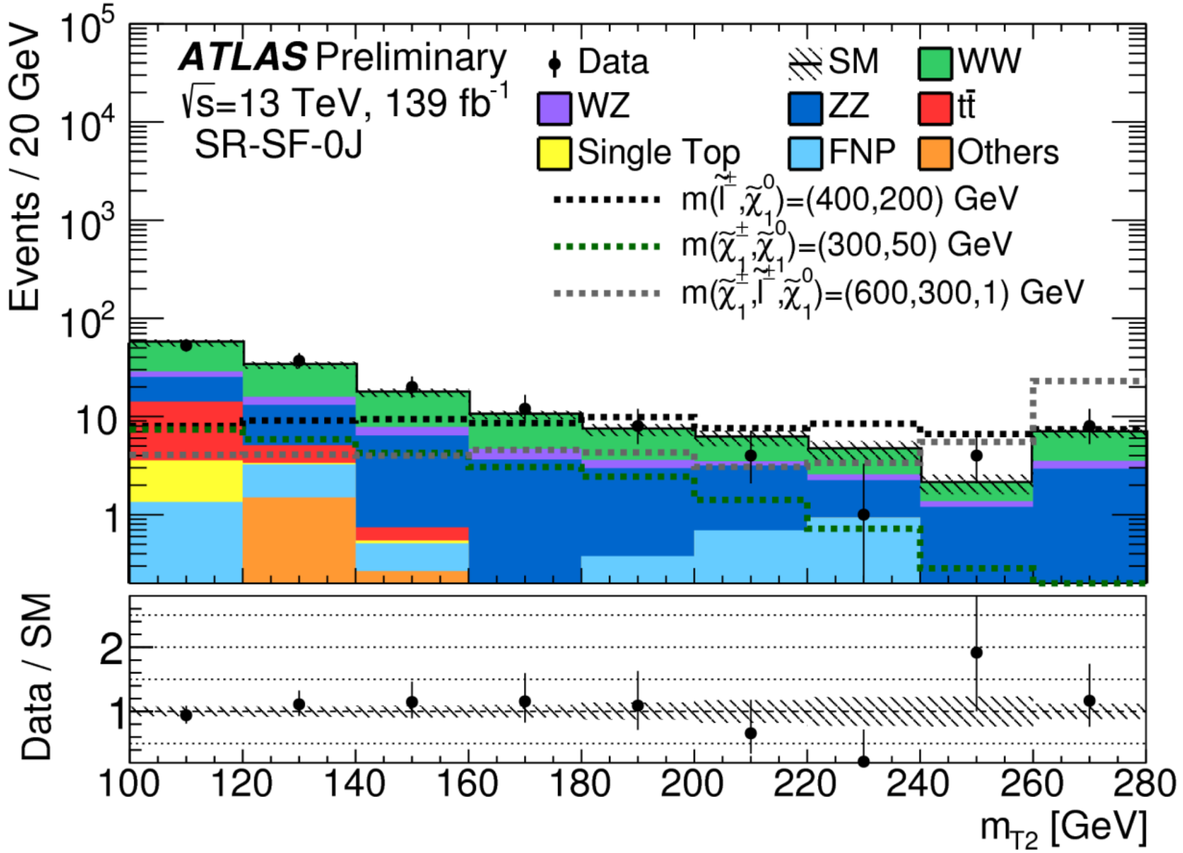
WZ validation region

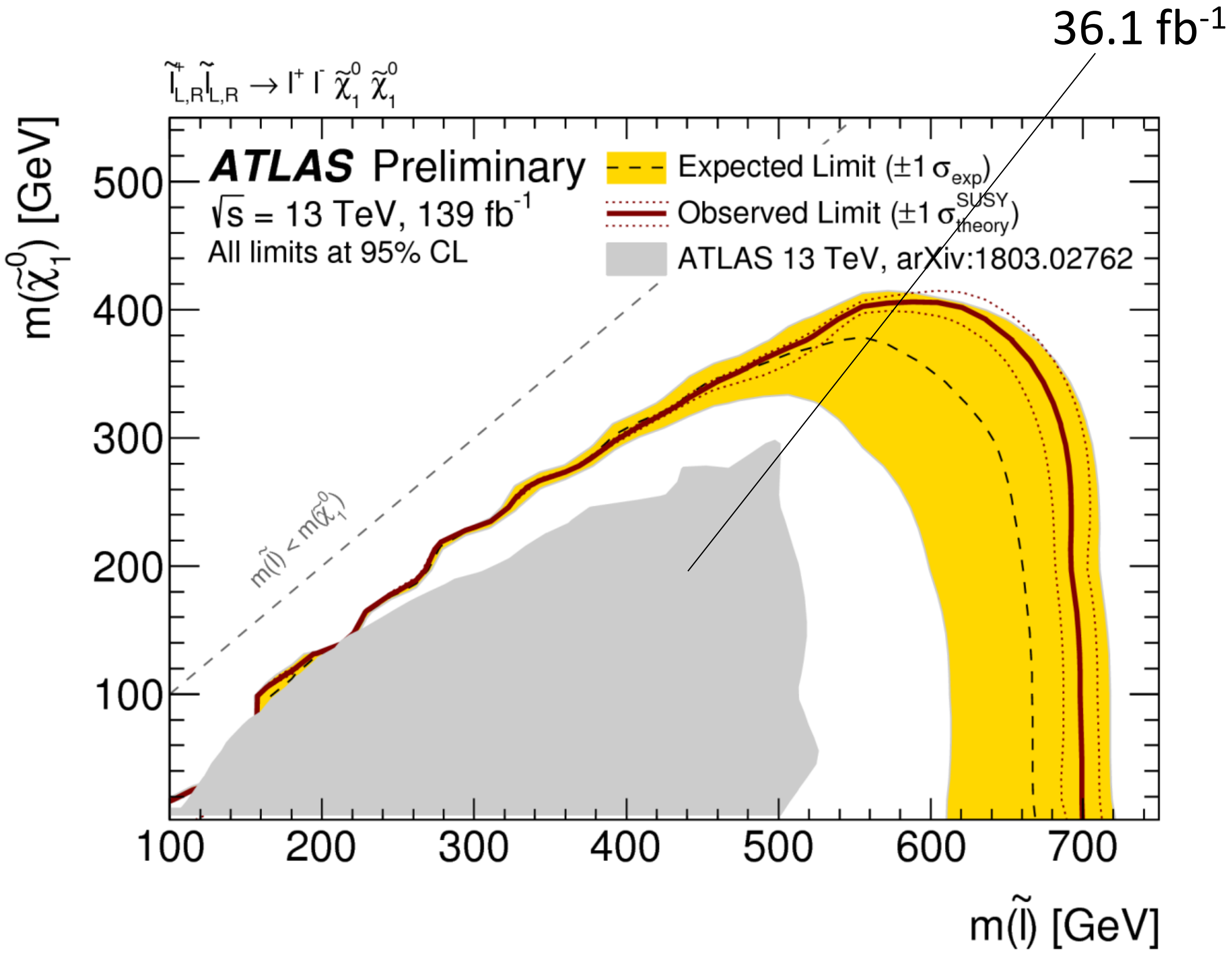


Good modeling

Direct $\tilde{e}$ and $\tilde{\mu}$ production

- m_{T2} is calculated with 2 leptons and $E_{\mathrm{T}}^{\mathrm{miss}}$
- No significant excess was observed → exclusion limits



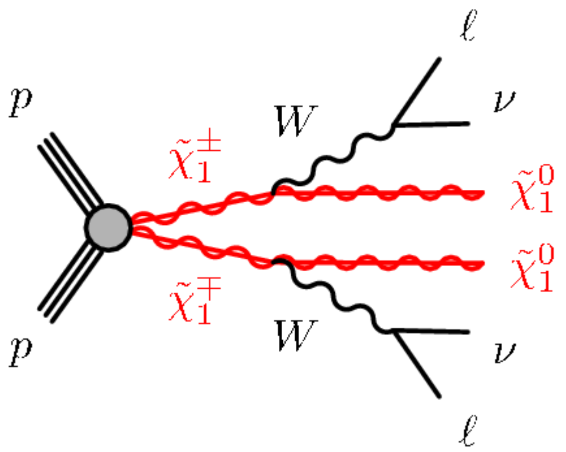


exclude up to 700 GeV

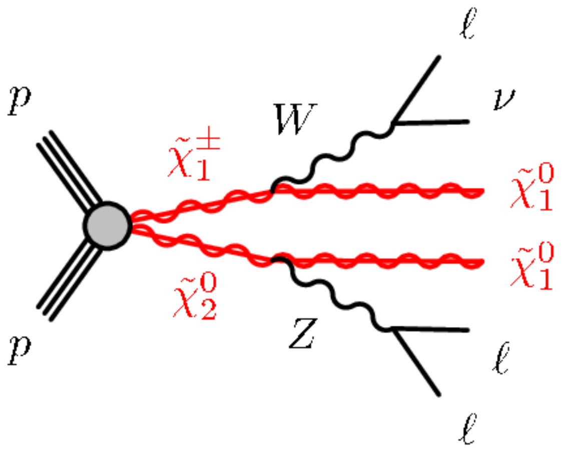
Direct chargino/neutralino production

Several full Run-2 results (139 fb^{-1})

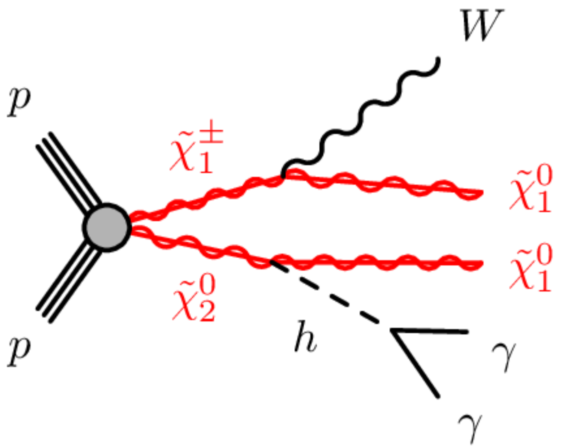
ATLAS-CONF-2019-008: 2-lepton



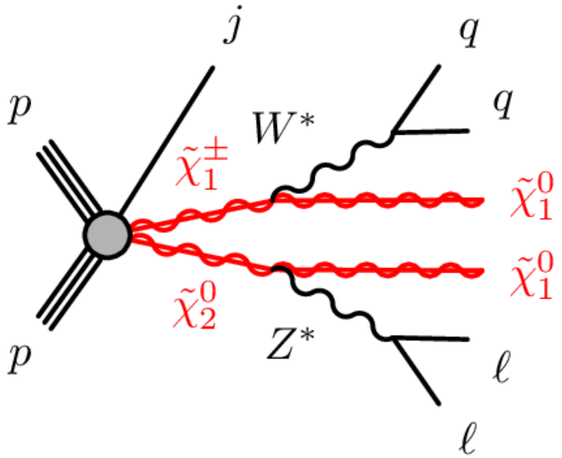
ATLAS-CONF-2019-020: 3-lepton



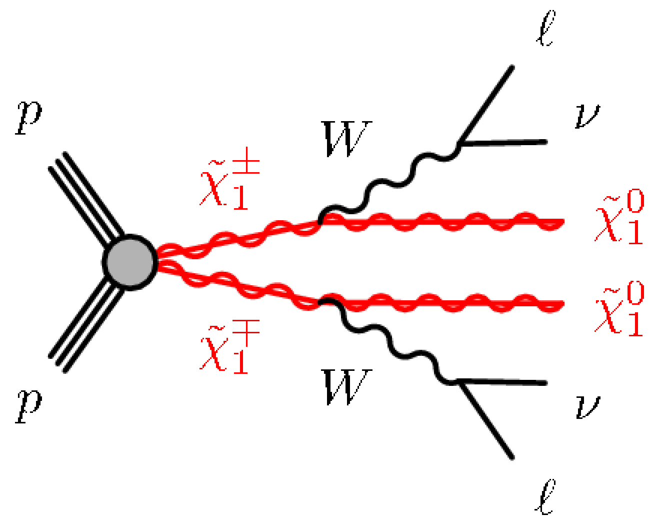
ATLAS-CONF-2019-019: $h \to \gamma\gamma$

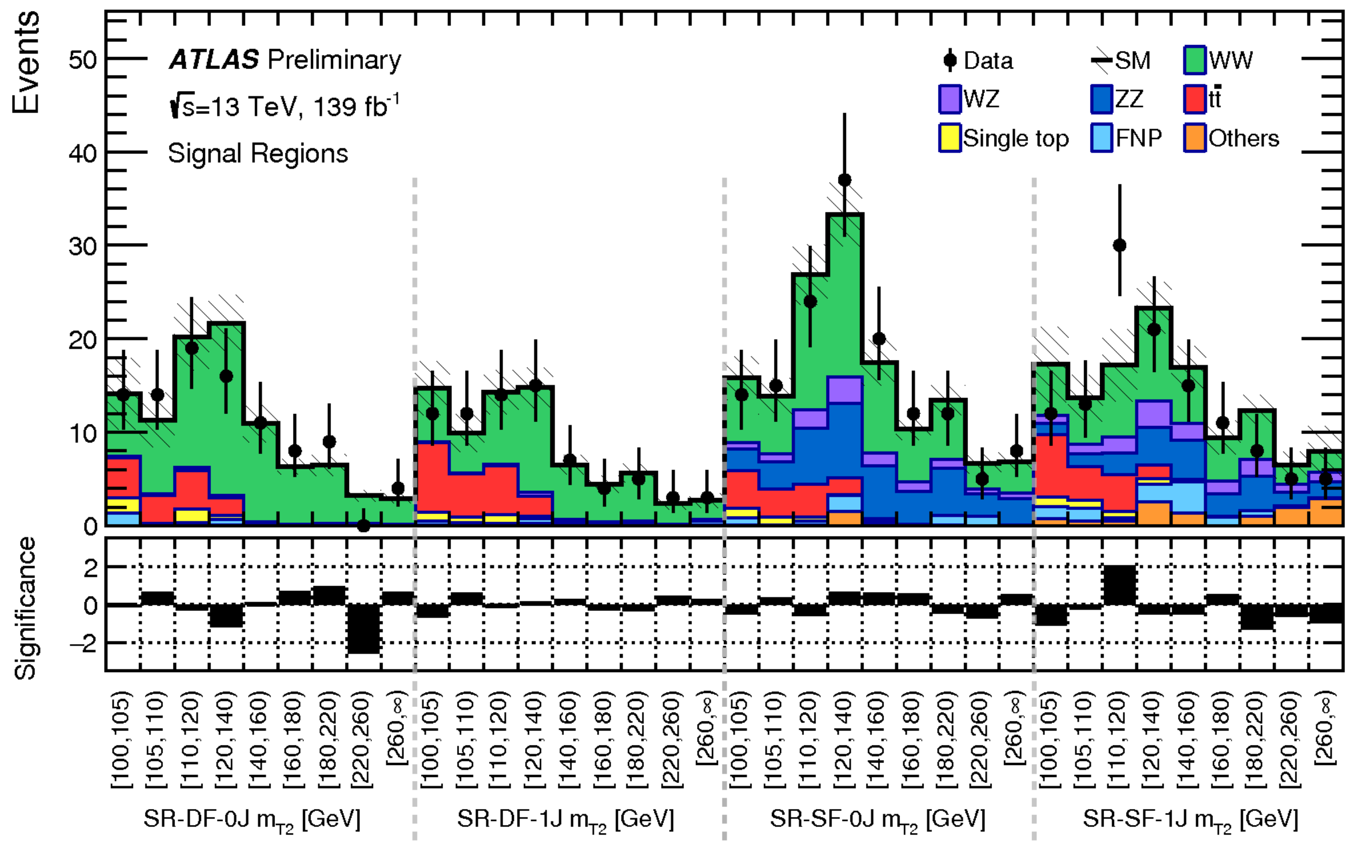


ATLAS-CONF-2019-014: Compressed EWK



2-lepton





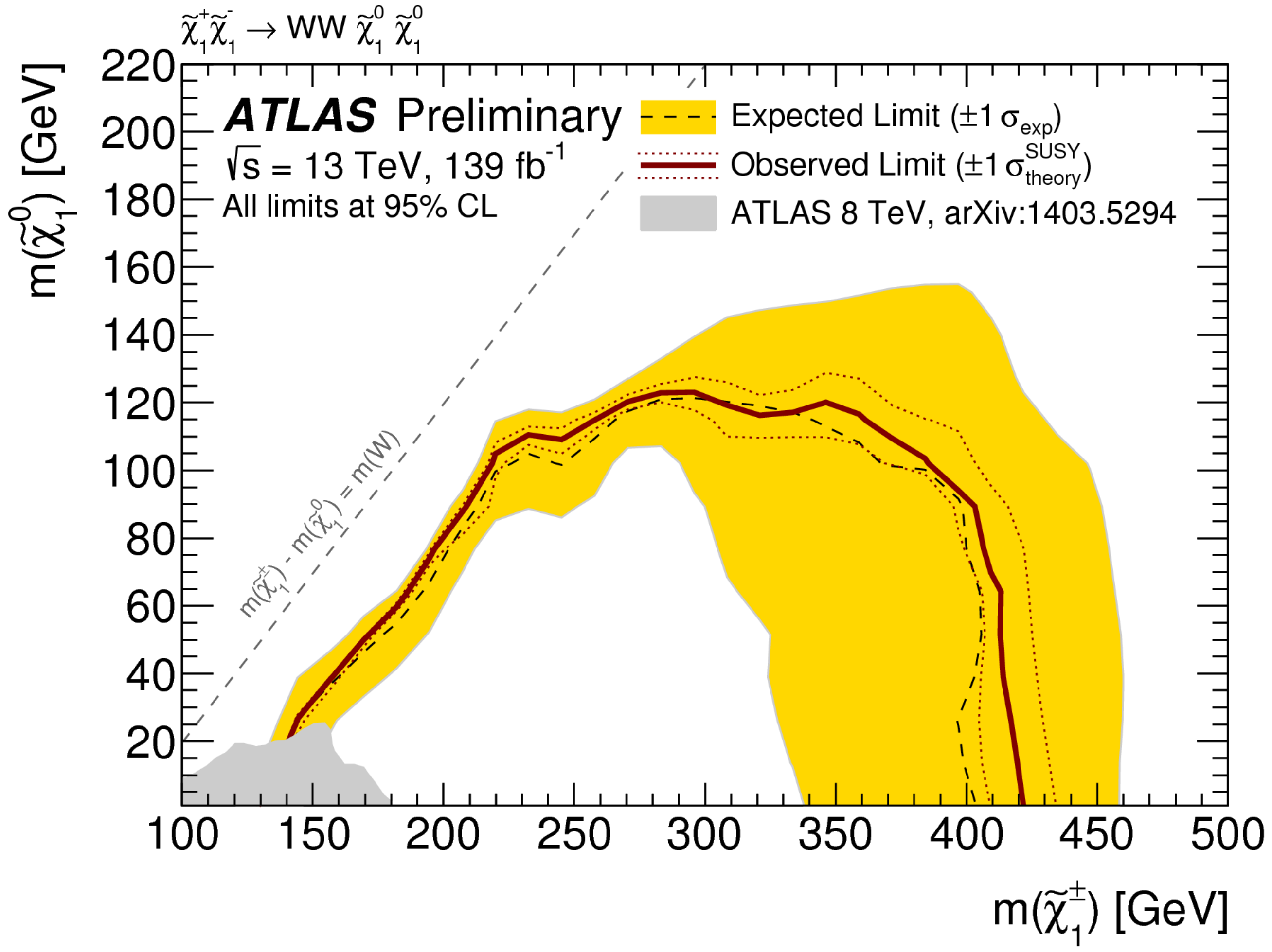
- Direct $\chi_1^\pm$ production with leptonic W decays
- Similar final state as the search for $\tilde{e}$ and $\tilde{\mu}$
  - using m_{T2} as well
  - but different flavor lepton regions are included
- main BG: WW, WZ

different flavor:
adding for this search

same flavor:
sharing with $\tilde{e}$ and $\tilde{\mu}$ search

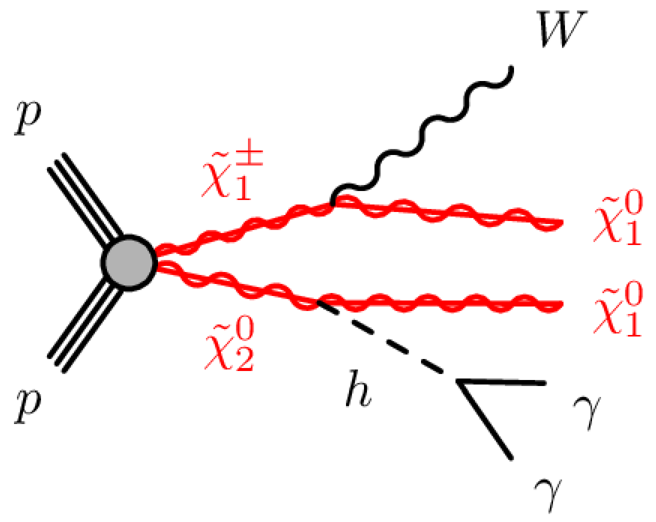
2-lepton

- No significant excess was observed → exclusion limits

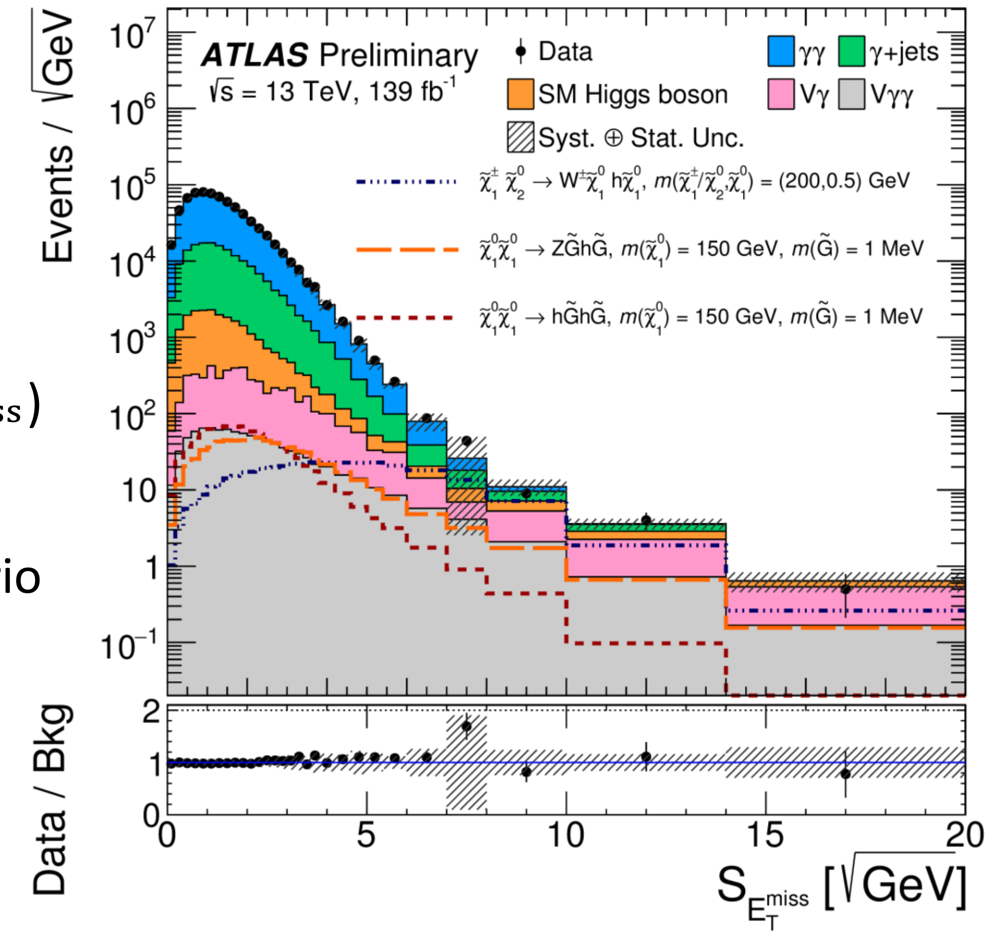


exclude up to 420 GeV

$h \to \gamma\gamma$



- Considering $m_{\tilde{\chi}_1^{\pm}} = m_{\tilde{\chi}_2^0}$
- Final state: $h \to \gamma\gamma + W$
  - 36 fb^{-1} analysis: $W \to \ell\nu$ only
  - 139 fb^{-1} analysis: $W \to jj$ was newly added



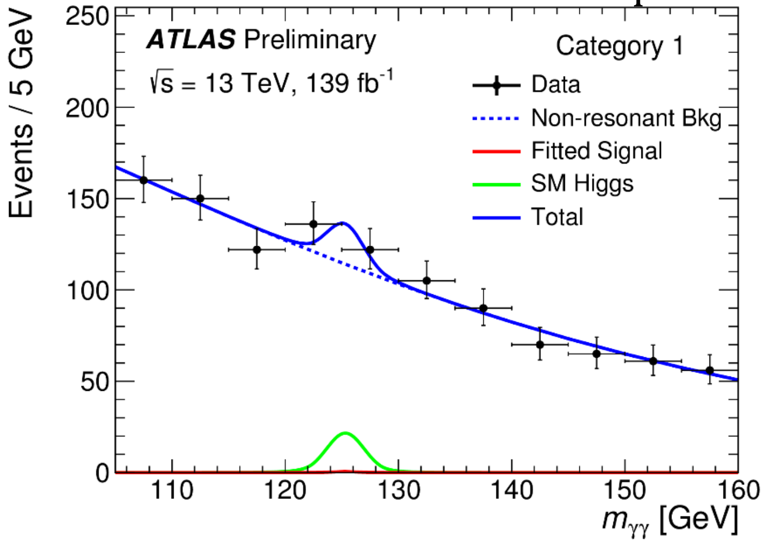
- Signal regions are separated based on $E_{\mathrm{T}}^{\mathrm{miss}}$ significance ($S_{E_{\mathrm{T}}^{\mathrm{miss}}}$)
  - $S_{E_{\mathrm{T}}^{\mathrm{miss}}} = E_{\mathrm{T}}^{\mathrm{miss}} / \sqrt{\sum E_{\mathrm{T}}}$
  - low $E_{\mathrm{T}}^{\mathrm{miss}}$ region is important for small $m_{\tilde{\chi}_1^{\pm}} - m_{\tilde{\chi}_1^0}$ scenario
- Dominant BG: SM $h \to \gamma\gamma$, non-resonant process

$\gamma\gamma, \gamma + \mathrm{jet}, \mathrm{V}\gamma, \mathrm{V}\gamma\gamma$

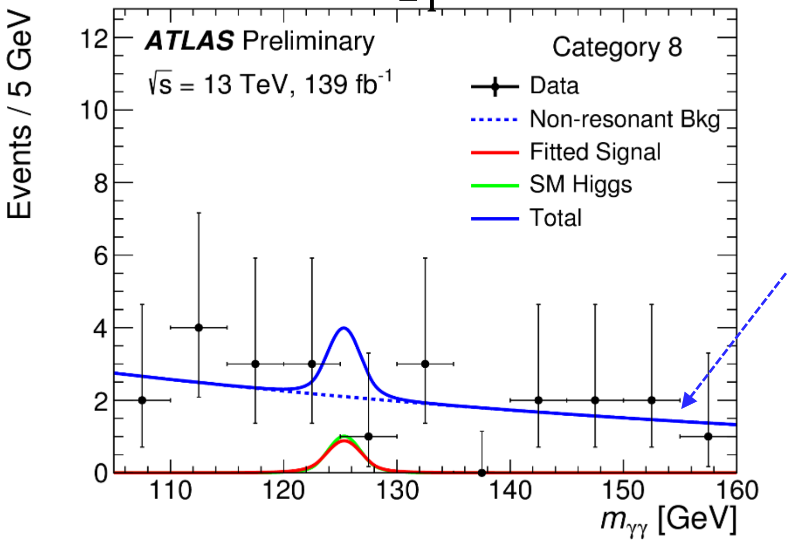
ATLAS-CONF-2019-019

$h \rightarrow \gamma\gamma$

$m_{\gamma\gamma}$ distribution in a leptonic low $S_{E_T^{miss}}$ signal region

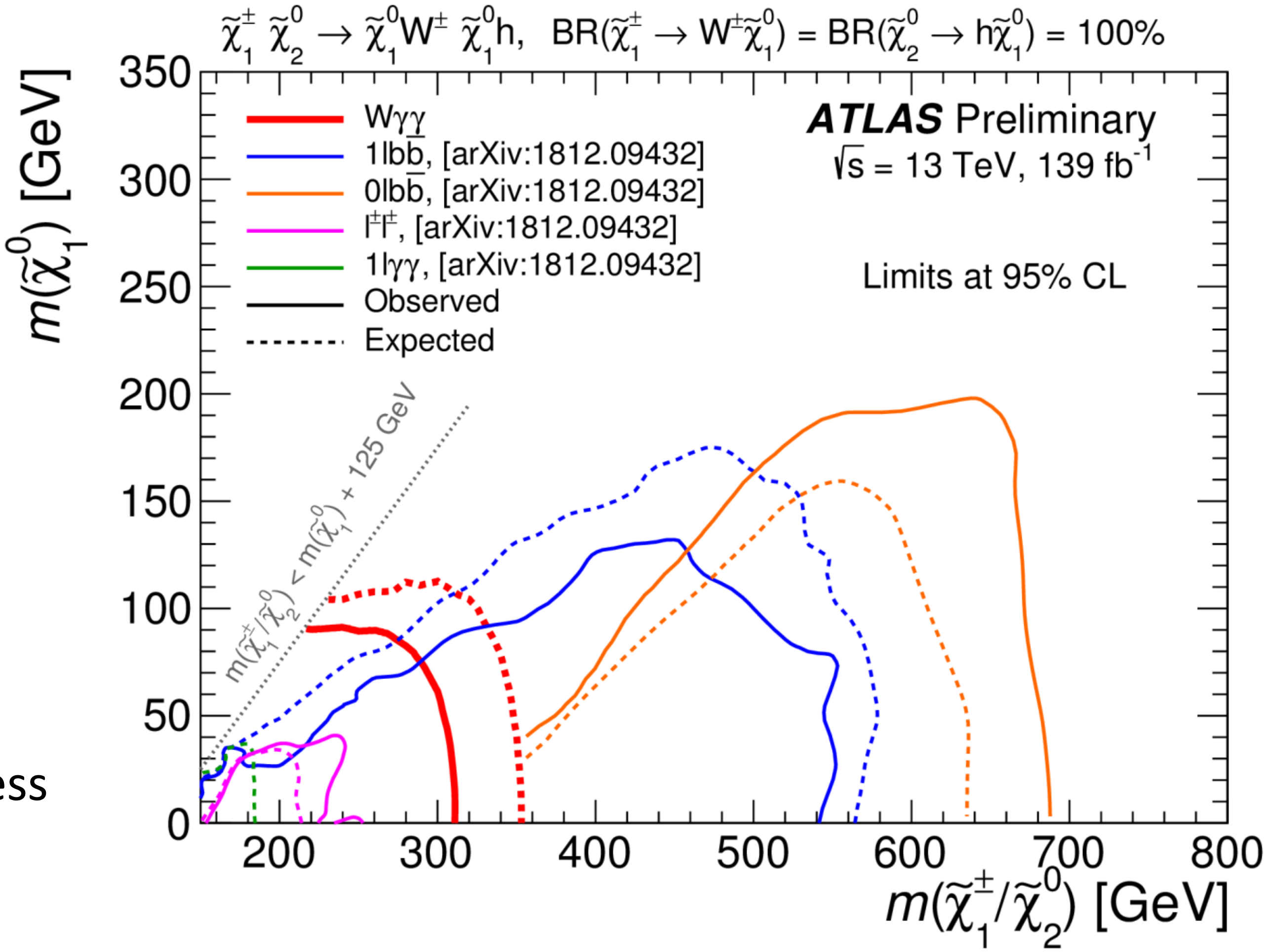


hadronic high $S_{E_T^{miss}}$ signal region



non-resonant process are estimated by sidebands

No significant excess was observed → exclusion limits

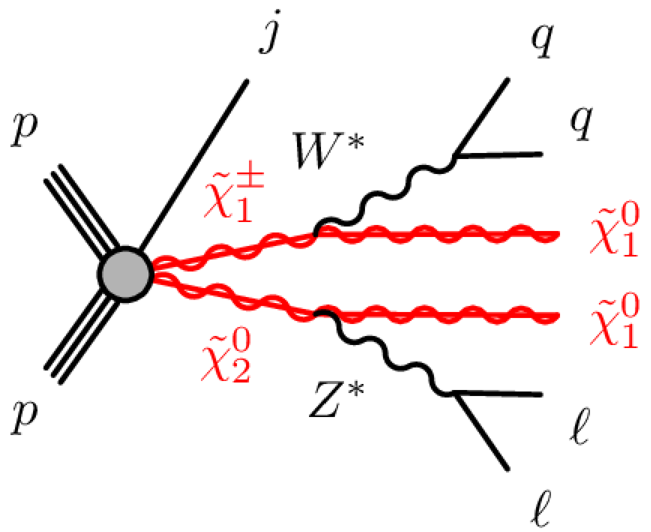


thanks to the clean signature of $h \rightarrow \gamma\gamma$,

extend limit to small $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ region

Compressed EWK

Considering nearly-degenerate masses: "compressed"

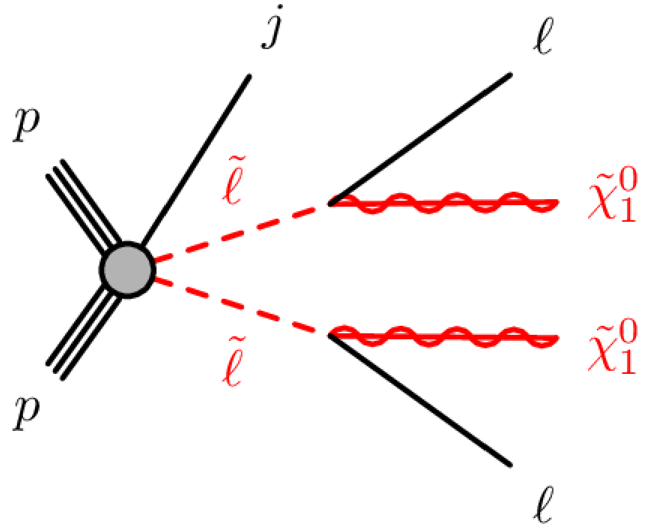


Scenario 1: $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^0$, $\tilde{\chi}_1^0$ are a triplet of Higgsino-like states

- motivated by naturalness
- discriminant: $m_{\ell\ell}$

Scenario 2: $\tilde{\chi}_1^0$ is a pure bino state, $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^0$ are pure wino states

- motivated by the observed DM density
- discriminant: $m_{\ell\ell}$



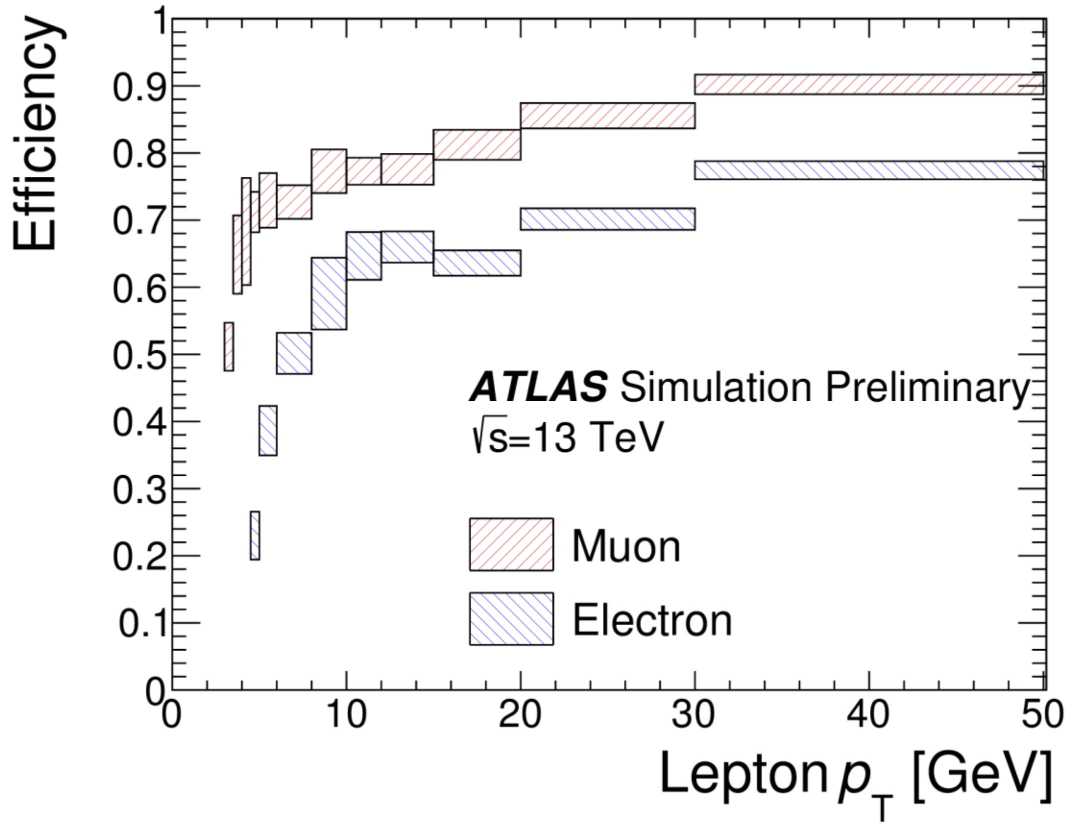
Scenario 3: $\tilde{\chi}_1^0$ is a pure bino state, sleptons are slightly heavy

- motivated by DM thermal relic densities, $g-2$ anormaly
- discriminant: m_{T2}

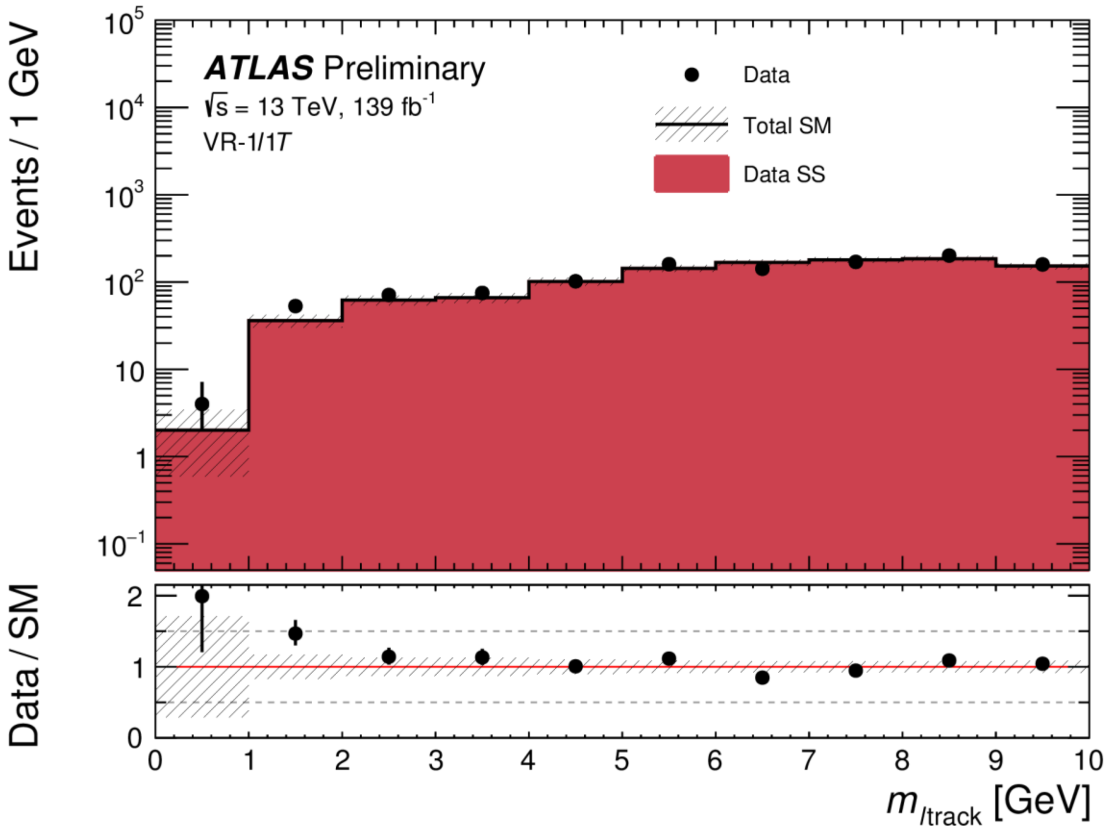
- Final state: 2 opposite sign same flavor low p_T leptons + E_T^{miss} + ISR jet
- Backgrounds: top, diboson, fake lepton

Compressed EWK

low p_{T} lepton reconstruction



Validation region of 1 lepton + 1 signal track



Signal leptons have low efficiency at very low p_{T}
→ Define complementary signal region: 1 lepton + 1 “signal track”
signal track: $p_{\mathrm{T}} > 1$ GeV, isolated, matched to lepton candidates

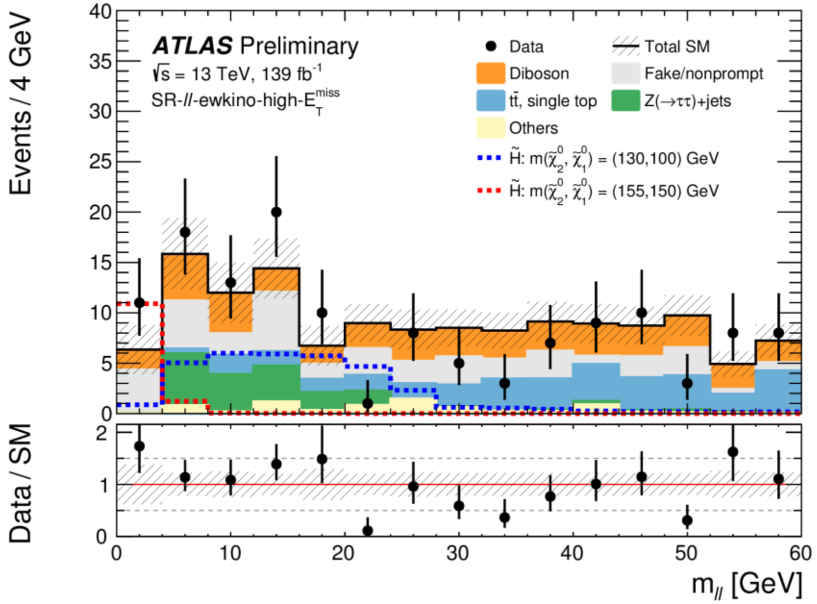
signal track is well modelled

Compressed EWK

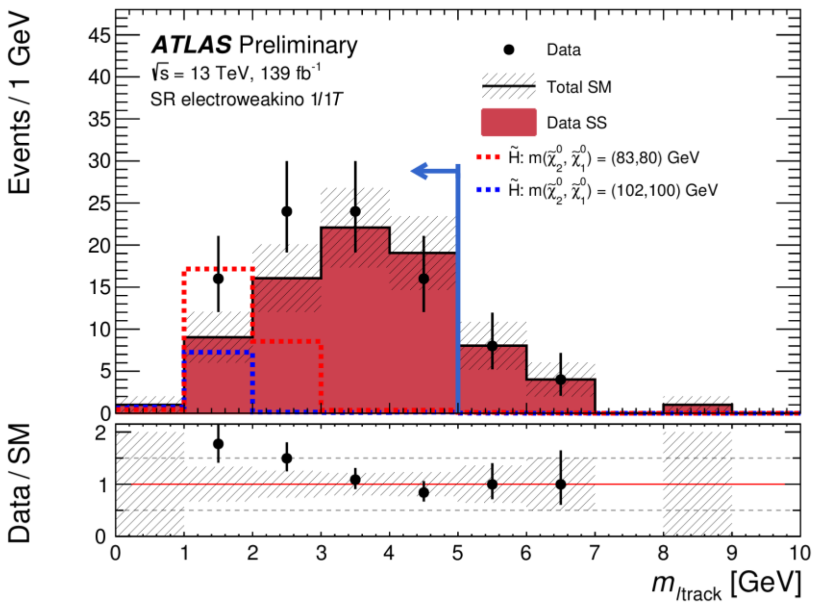
Background estimation:

- 1 lepton + 1 signal track: data-driven using same sign control region
- Fake leptons in 2-lepton regions: data-driven (fake factor method)
- Real leptons in 2-lepton regions: MC is normalized based on control regions

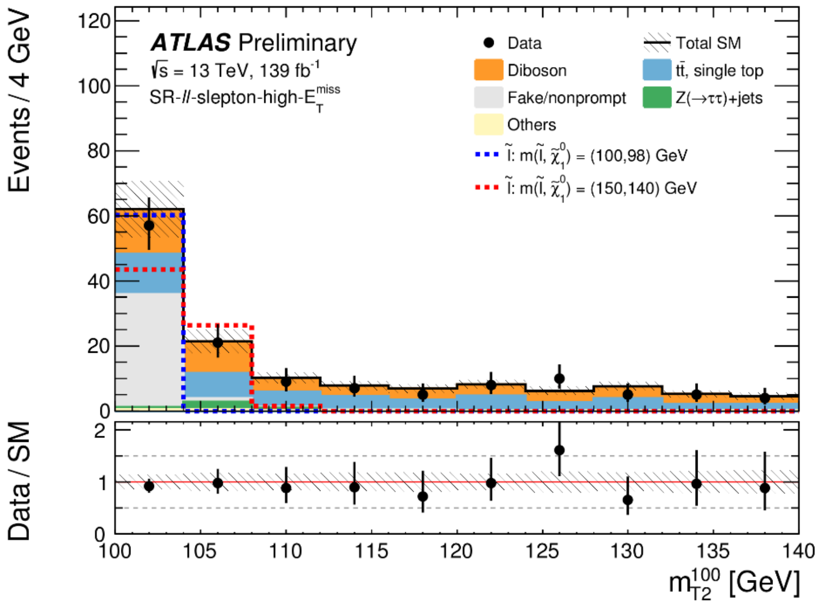
2-lepton for scenario 1, 2



1 lepton + 1 signal track



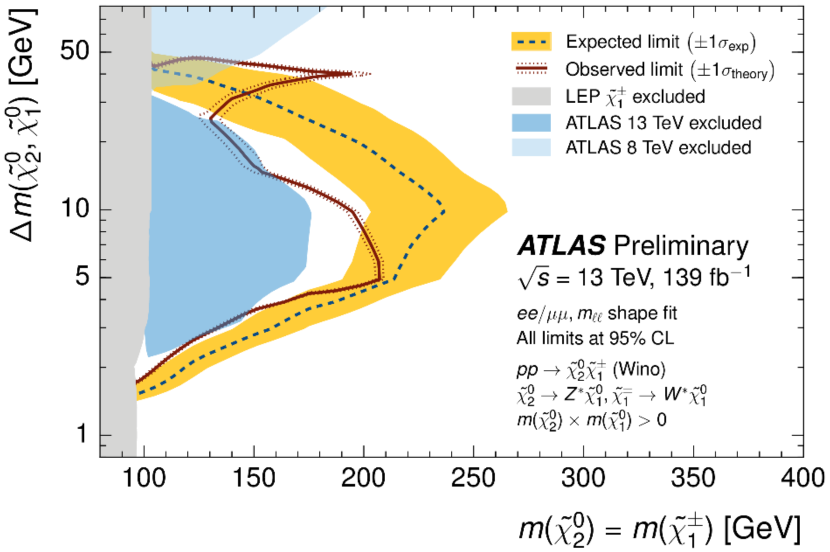
2-lepton for scenario 3



No significant excess was observed → exclusion limits

Compressed EWK

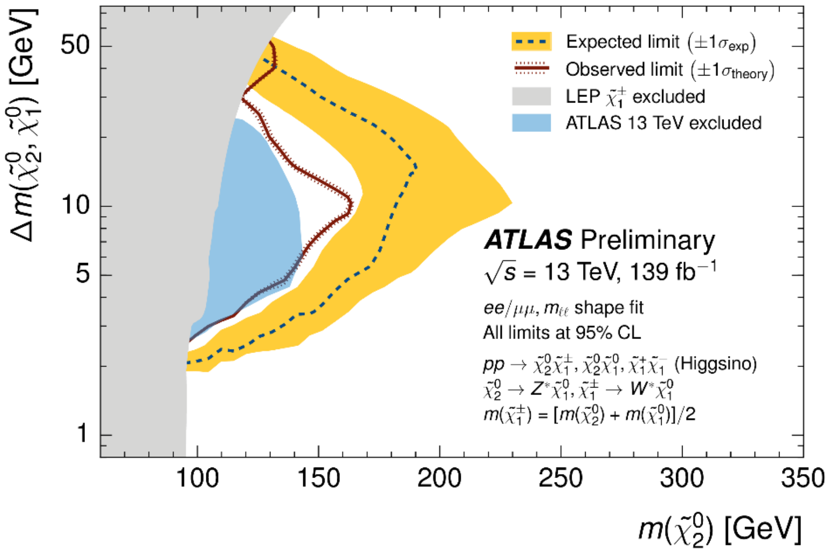
scenario 1



Considering

- $m_{\tilde{\chi}_1^{\pm}} = m_{\tilde{\chi}_2^0}$
- $m_{\tilde{\chi}_2^0} \times m_{\tilde{\chi}_1^0} > 0$

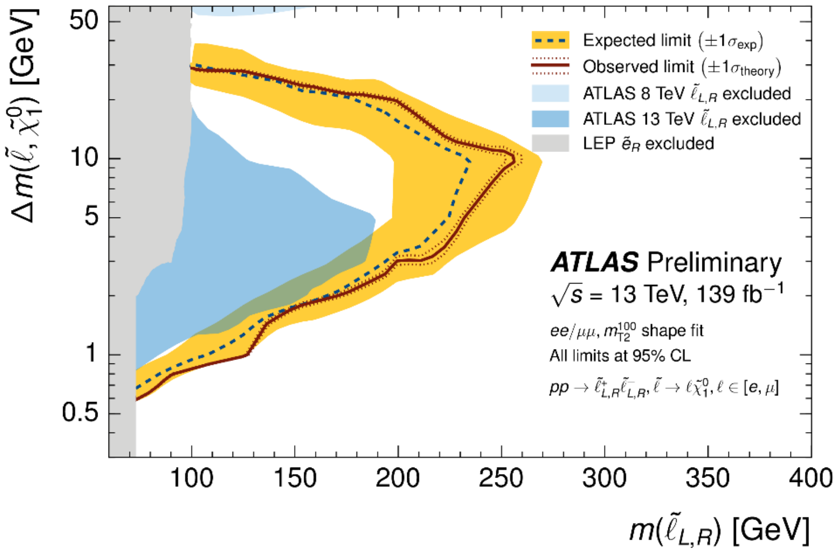
scenario 2



Considering

- charginos are very heavy
- $m_{\tilde{\chi}_1^{\pm}} = \left(m_{\tilde{\chi}_2^0} + m_{\tilde{\chi}_1^0}\right)/2$

scenario 3

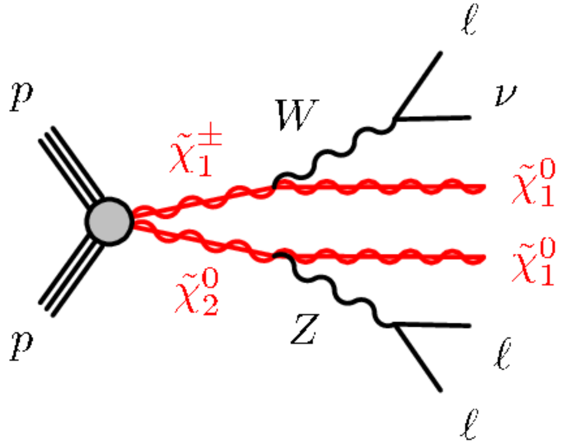


Considering

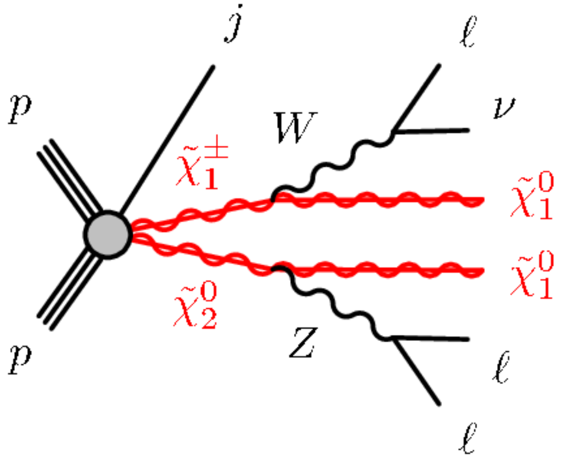
- $m_{\tilde{e}_R} = m_{\tilde{e}_L} = m_{\tilde{\mu}_R} = m_{\tilde{\mu}_L}$

3-lepton

without ISR



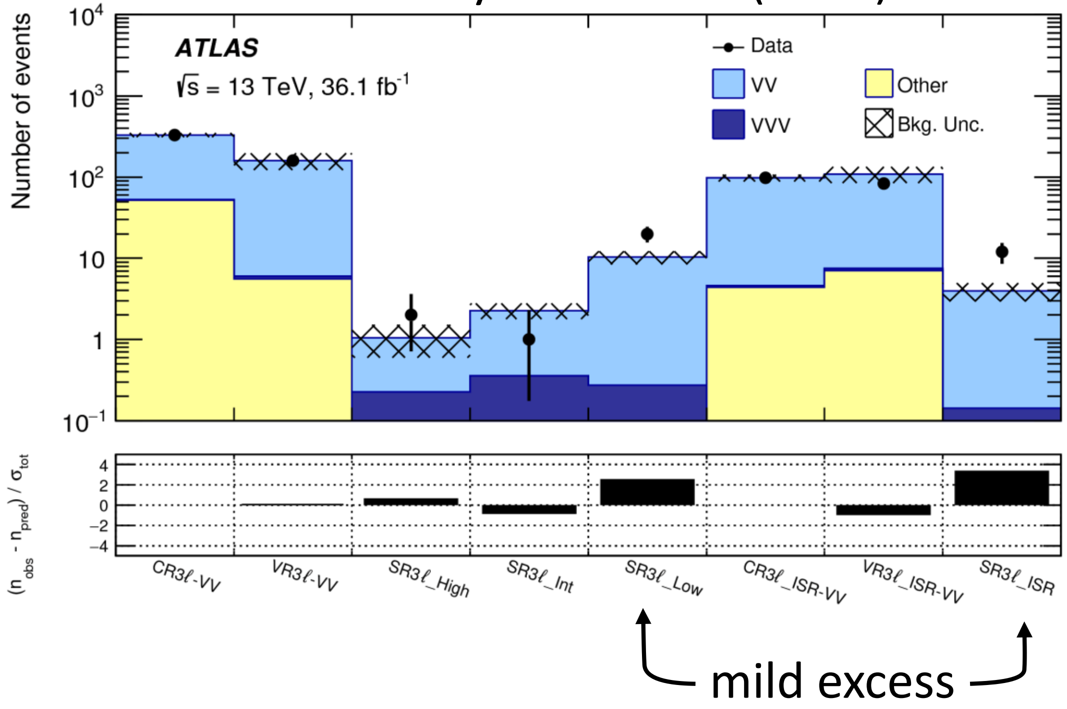
with ISR



- Final state: 3-lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$
- Emulated Recursive Jigsaw Reconstruction: eRJR
- backgrounds: fully leptonic WZ

RJR used in 36 fb^{-1} analysis:

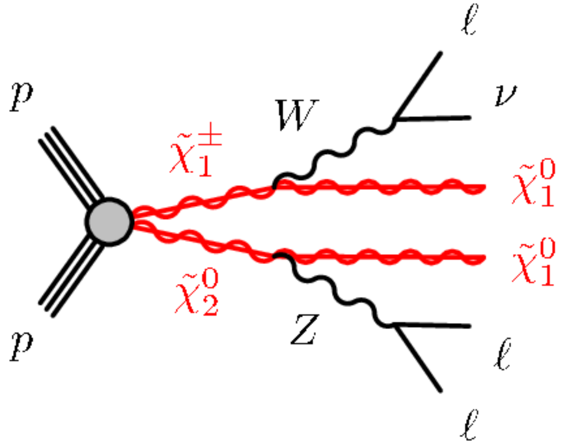
Phys. Rev. D 98 (2018) 092012



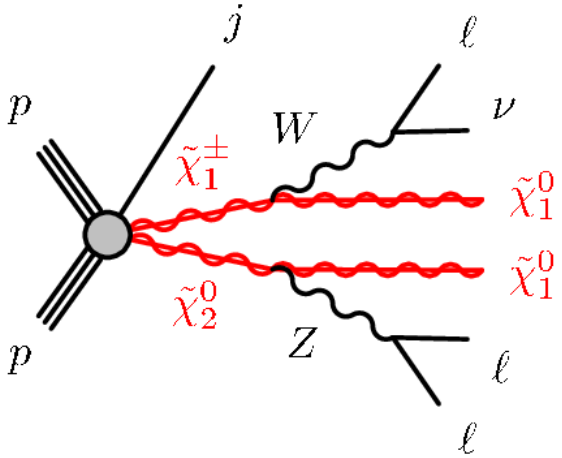
ATLAS-CONF-2019-020

3-lepton

without ISR



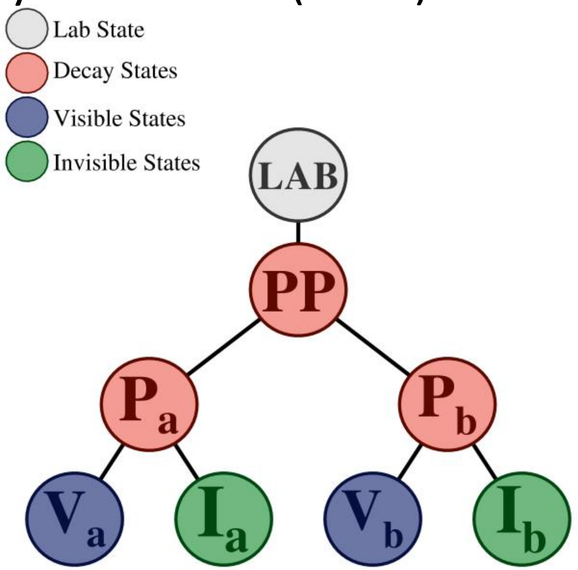
with ISR



- Final state: 3-lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$
- Emulated Recursive Jigsaw Reconstruction: eRJR
- backgrounds: fully leptonic WZ

RJR used in 36 fb^{-1} analysis:
Decompose events according to assumption of particular decays and rest frames to estimate missing degrees of freedom

Phys. Rev. D 98 (2018) 092012



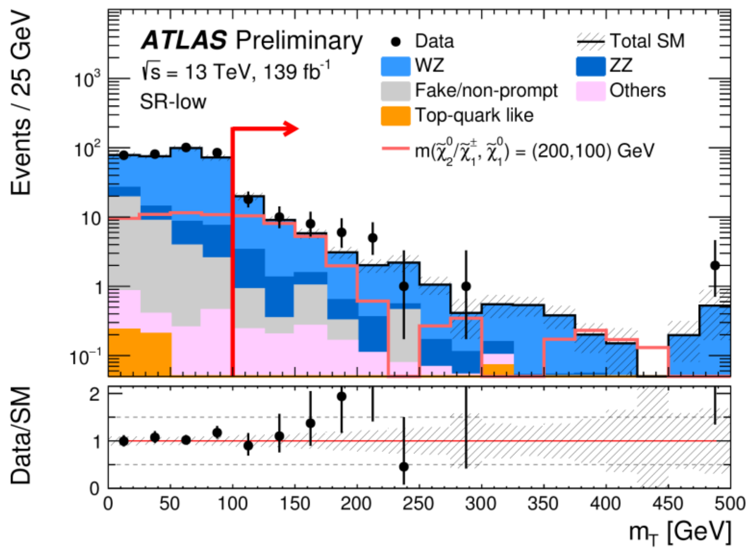
newly developed

eRJR:
Simplified technique, using lab frame variables
→ try with more conventional variables

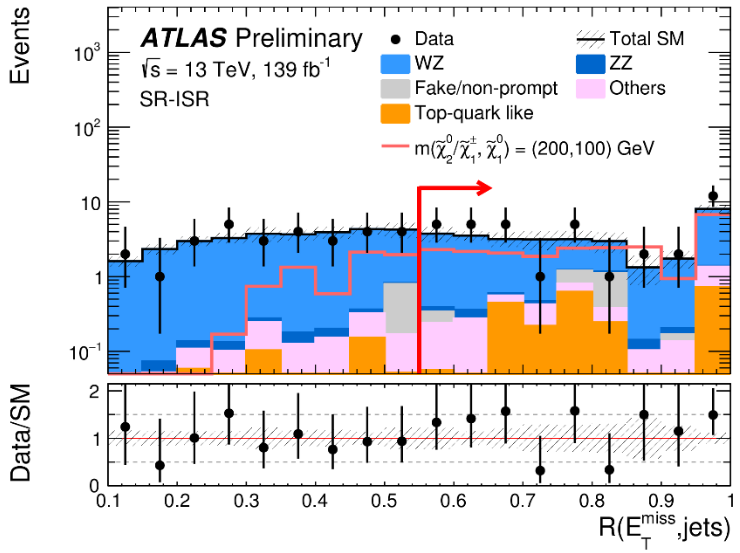
3-lepton

reproduce the RJR result with 36 fb^{-1} dataset
BUT no significant excess with the full Run2 dataset
→ exclusion limits

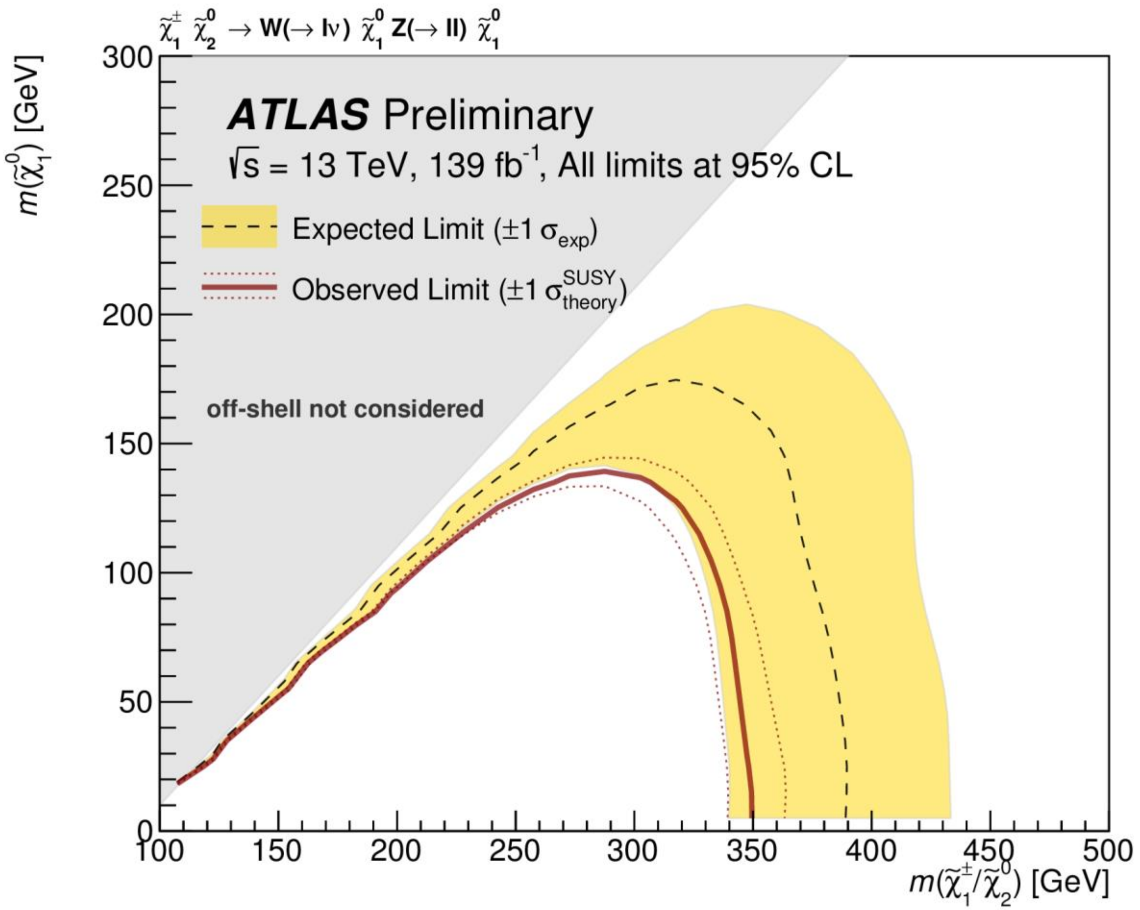
without ISR



with ISR



an emulated RJ variable



exclude up to 350 GeV

Conclusion

Starting to release papers for electroweak SUSY with the full Run-2 dataset

- almost sensitive to 1 TeV

Significance was highly increased with using hadronic final states

- direct stau production
- hadronic $W + h \rightarrow \gamma\gamma$

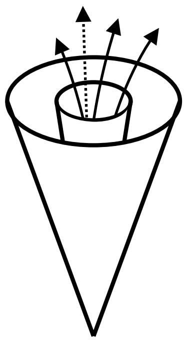
Increasing detector performance is one of the key words

- soft lepton reconstruction

Many more results with the full Run-2 dataset will come!!

backup

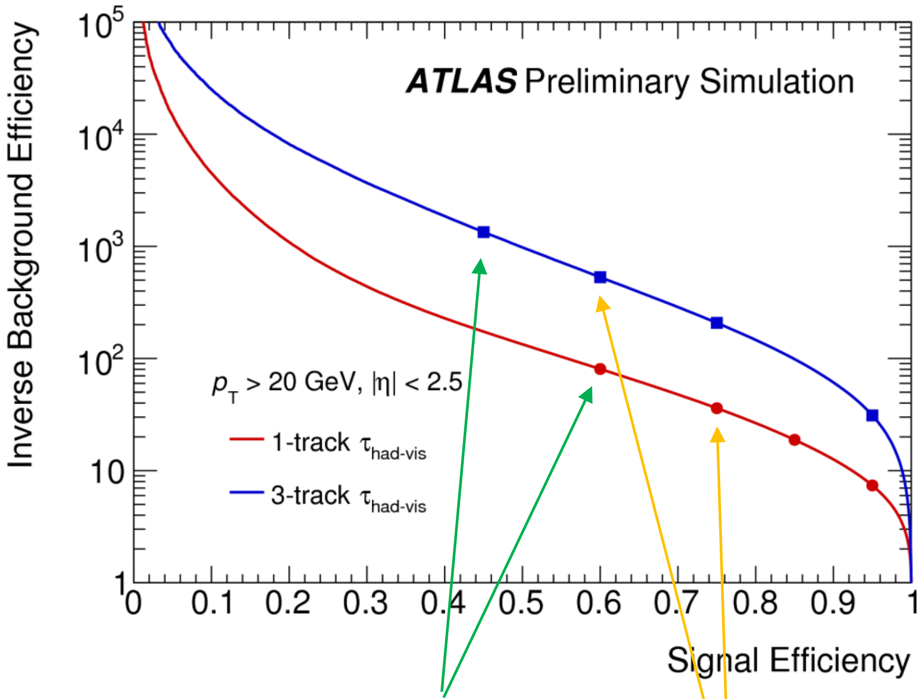
hadronic tau



- Reconstruction seeded by calorimeter jets
- 1 or 3 tracks with in the jet
- isolation cone is defined as $0.2 < \Delta R < 0.4$

Identification BDT is trained for 1-prong and 3-prong separately

- collimation of calorimeter cells and tracks
- secondary vertex
- impact parameter
- $E_{\mathrm{calo}}/p_{\mathrm{track}}$ fraction



the low mass SR is using

the high mass SR is using

stau direct search

Background estimation
- multi-jet: fully data-driven (ABCD method)
- W+jets: MC is normalized based on W+jets control region

Systematic uncertainties

Source of systematic uncertainty	SR-lowMass (%)	SR-highMass (%)
Statistical uncertainty of MC samples	11	21
Tau identification and energy scale	19	10
Normalisation uncertainties of the multi-jet background	13	9
Multi-jet estimation	6	11
W+jets theory uncertainty	5	8
Diboson theory uncertainty	5	6
Jet energy scale and resolution	5	8
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft-term resolution and scale	2	2
Total	28	33

Source of systematic uncertainty m $(\tilde{\tau},\tilde{\chi}_1^0)$ GeV	SR-lowMass (%) (120, 1)	SR-highMass (%) (280, 1)
Tau identification and energy scale	29	14
Statistical uncertainty of MC samples	6	10
Signal cross section uncertainty	4	6
Jet energy scale and resolution	3	2
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft-term resolution and scale	3	< 1
Total	31	18

$h \to \gamma\gamma$ categorization

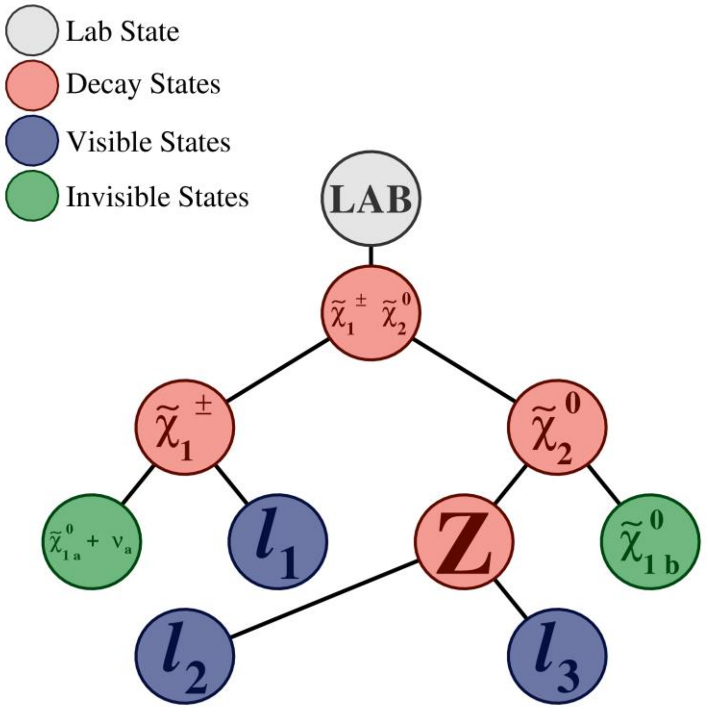
Channels	Names	Selection
Leptonic	Category 1	$0 < S_{E_T^{miss}} \leq 2,\ N_\ell \geq 1$
	Category 2	$2 < S_{E_T^{miss}} \leq 4,\ N_\ell \geq 1$
	Category 3	$4 < S_{E_T^{miss}} \leq 6,\ N_\ell \geq 1$
	Category 4	$S_{E_T^{miss}} > 6,\ N_\ell \geq 1$
Hadronic	Category 5	$5 < S_{E_T^{miss}} \leq 6,\ N_\ell = 0,\ N_j \geq 2,\ M_{jj} \in [40, 120]\ GeV$
	Category 6	$6 < S_{E_T^{miss}} \leq 7,\ N_\ell = 0,\ N_j \geq 2,\ M_{jj} \in [40, 120]\ GeV$
	Category 7	$7 < S_{E_T^{miss}} \leq 8,\ N_\ell = 0,\ N_j \geq 2,\ M_{jj} \in [40, 120]\ GeV$
	Category 8	$S_{E_T^{miss}} > 8,\ N_\ell = 0,\ N_j \geq 2,\ M_{jj} \in [40, 120]\ GeV$
Rest	Category 9	$6 < S_{E_T^{miss}} \leq 7,\ N_\ell = 0,\ N_j < 2$ or $(\ N_j \geq 2,\ M_{jj} \notin [40, 120]\ GeV)$
	Category 10	$7 < S_{E_T^{miss}} \leq 8,\ N_\ell = 0,\ N_j < 2$ or $(\ N_j \geq 2,\ M_{jj} \notin [40, 120]\ GeV)$
	Category 11	$8 < S_{E_T^{miss}} \leq 9,\ N_\ell = 0,\ N_j < 2$ or $(\ N_j \geq 2,\ M_{jj} \notin [40, 120]\ GeV)$
	Category 12	$S_{E_T^{miss}} > 9,\ N_\ell = 0,\ N_j < 2$ or $(\ N_j \geq 2,\ M_{jj} \notin [40, 120]\ GeV)$

RJR

- Assume a pair-production of particles with specific decay trees
- Transform observable momenta to a reference-frame like $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ frame
- Determine the momenta of invisible states corresponding to the frame
- Repeat procedure recursively

- Using the decay trees, construct kinematic variables within the defined reference frames

$$H_{n,m}^{\mathrm{F}} = \sum_{i=1}^{n} |\vec{p}_{\mathrm{vis},\ i}^{\,\mathrm{F}}| + \sum_{j=1}^{m} |\vec{p}_{\mathrm{inv},\ j}^{\,\mathrm{F}}|$$



RJR → eRJR

- Low variables
  - $p_T^{PP} \approx (lep1 + lep2 + lep3 + MET).Pt() \equiv p_{\mathrm{T}}^{\mathrm{soft}}$
  - $HT_{3,1}^{PP} \approx (\ell_1).\mathrm{Pt}() + (\ell_2).\mathrm{Pt}() + (\ell_3).\mathrm{Pt}() + (\mathrm{met}).\mathrm{Pt}() \equiv m_{\mathrm{eff}}^{3\ell}$
  - $H_{3,1}^{PP} \approx (\ell_1).\mathrm{P}() + (\ell_2).\mathrm{P}() + (\ell_3).\mathrm{P}() + (\mathrm{met}).\mathrm{P}() \equiv H^{\mathrm{boost}}$
    - Contains z-component of missing energy vector
    - Contains boost
- ISR variables
  - $p_T^I \approx E_{\mathrm{T}}^{\mathrm{miss}}$
  - $p_T^{CM} \approx p_T$ of $\sum$ of the (4-momenta of leptons + 4-momenta of signal jets + MET vector) $\equiv p_{\mathrm{T}}^{\mathrm{soft}}$
  - $p_T^{ISR} = \overrightarrow{ISR}.\mathrm{Pt}() \approx p_T$ of $\sum \overrightarrow{\text{signal jets}} \equiv p_{\mathrm{T}}^{\mathrm{jets}}$
  - $d\phi_{ISR,I} = |\Delta\phi_{\overrightarrow{ISR},MET}| \approx |\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jets})|$
  - $R_{ISR} = \frac{|\overrightarrow{MET} \cdot \overrightarrow{ISR}|}{(p_T^{ISR})^2} \approx \frac{|\overrightarrow{MET} \cdot \widehat{jets}|}{p_{\mathrm{T}}^{\mathrm{jets}}} \equiv \mathrm{R}(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jets})$