Searches for electroweak production of supersymmetric particles involving the Higgs boson and the higgsinos with ATLAS

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ATLAS Collaboration

Motivations For Higgsinos Searches

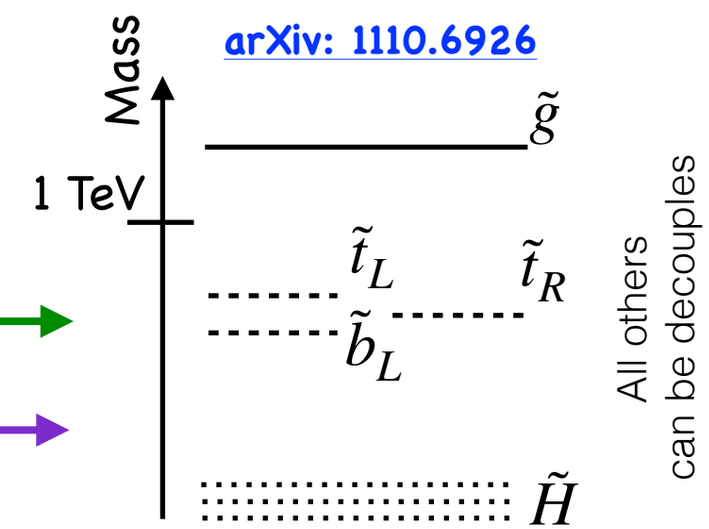
- **Higgsinos ($\tilde{H}$) are spin ½ partners of the Higgs bosons**
- **In natural SUSY models, Higgsinos *should* be light**

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

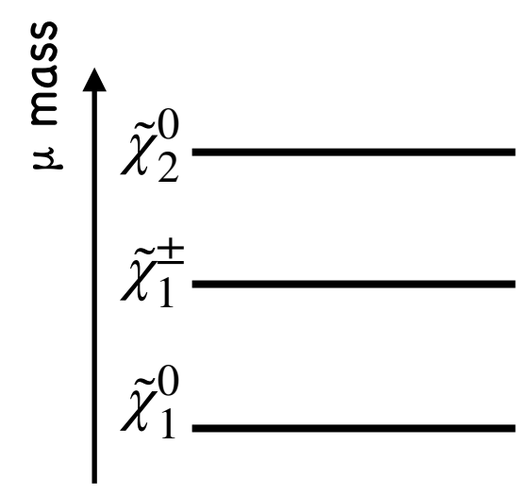
Naturalness in MSSM (tree level)

one (two) loops corrections to m_H from the stops (gluinos)

μ controls the Higgsino masses



- **Rich Electroweak SUSY sector**
  - **Many topologies determined by the composition of the mass eigenstates**



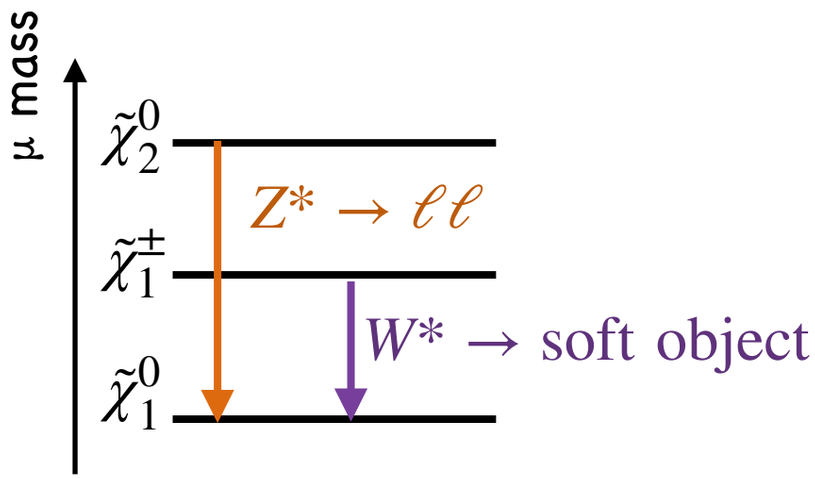
- **The mass splitting is determined by how dominant is the $\tilde{H}$ component**
  - **Pure $\tilde{H}$ could have very small splitting $\mathcal{O}$(100 MeV)**
  - **Moderate mixing could get to 1-10 GeV**

eg Higgsino LSP

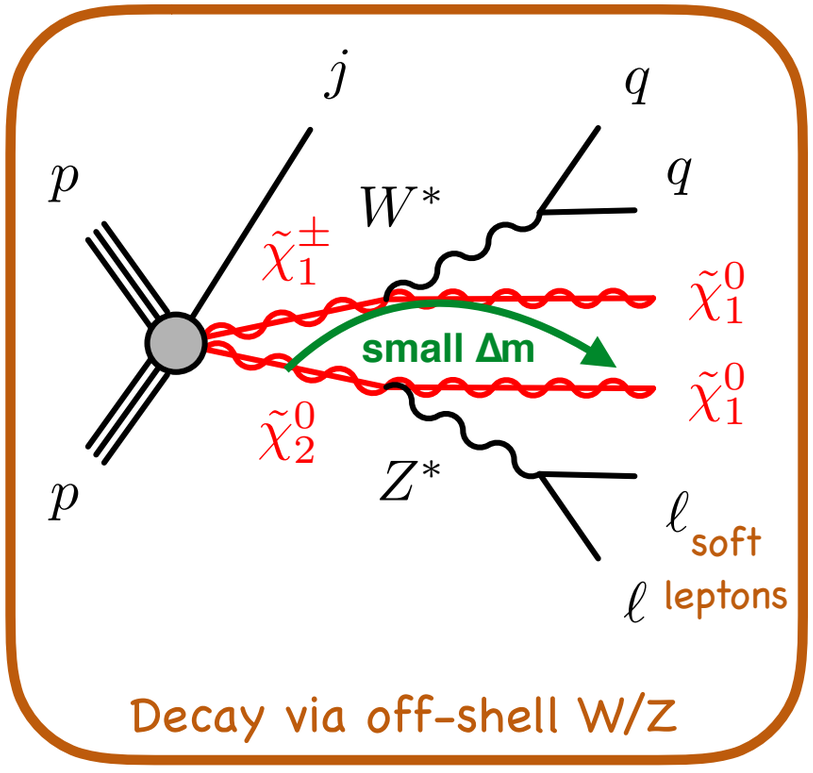
LSP: Lightest Supersymmetric Particle

Higgsinos Searches In ATLAS

Higgsino LSP



$\Delta m\left(\tilde{\chi}_2^0, \tilde{\chi}_1^\pm, \tilde{\chi}_1^0\right) \approx$ few GeV



arxiv:1712.08119

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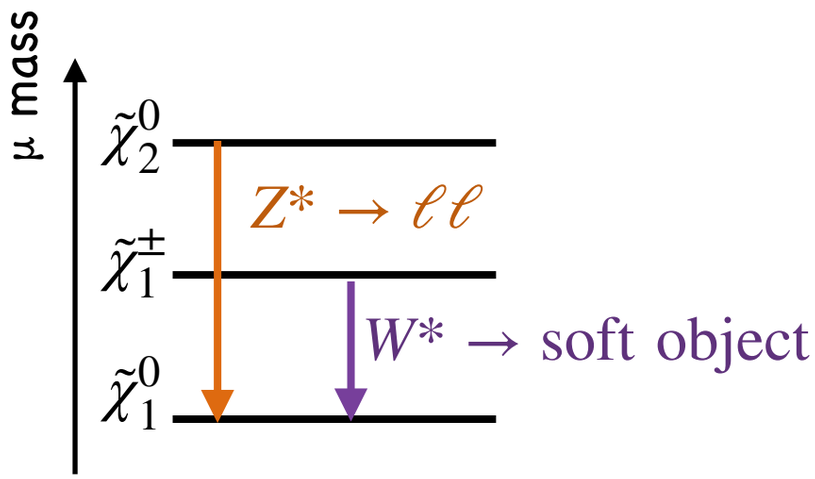

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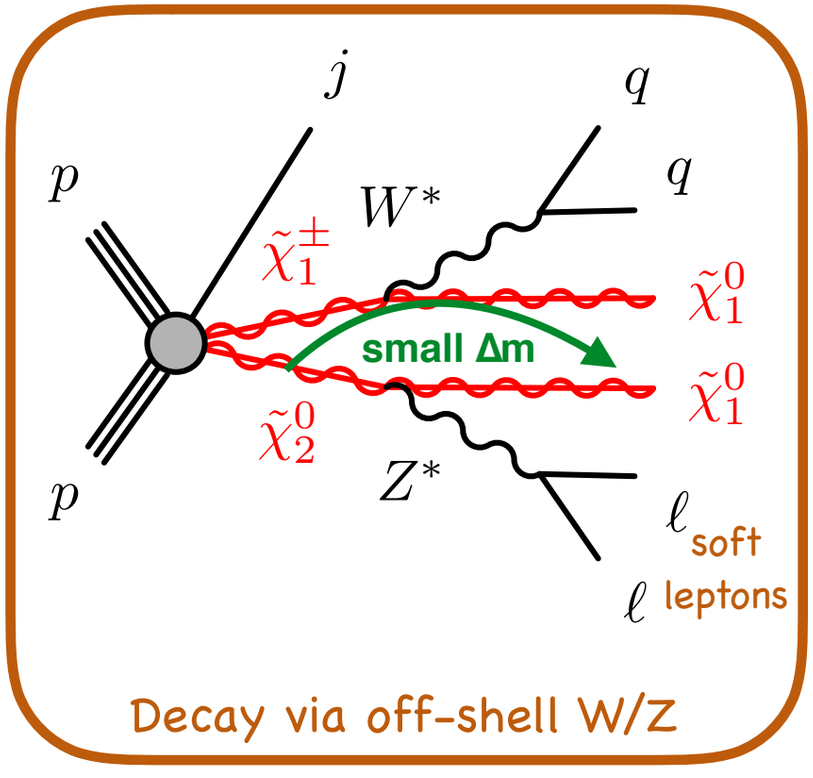

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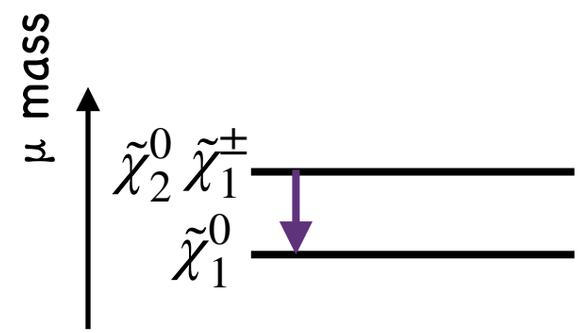
Ultra-compressed Higgsino LSP



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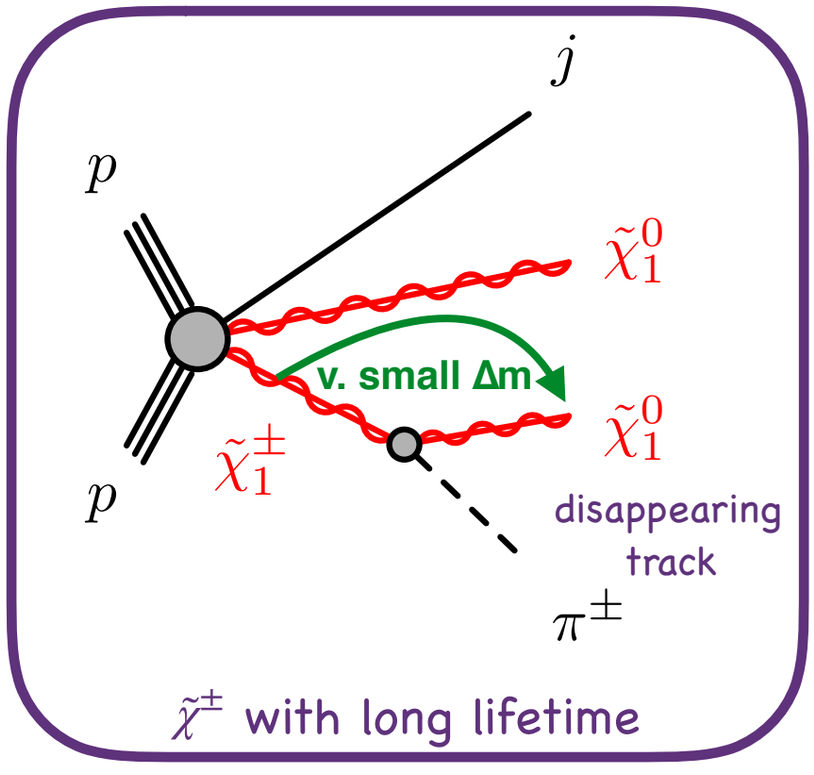

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Higgsinos Searches In ATLAS

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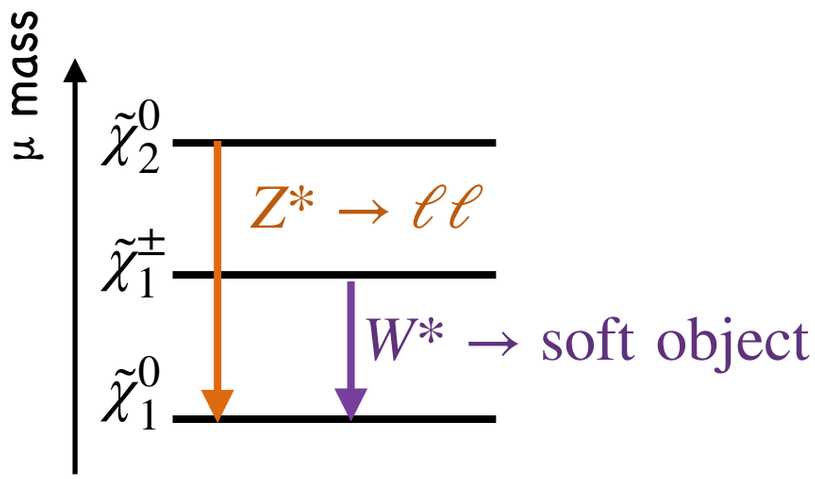

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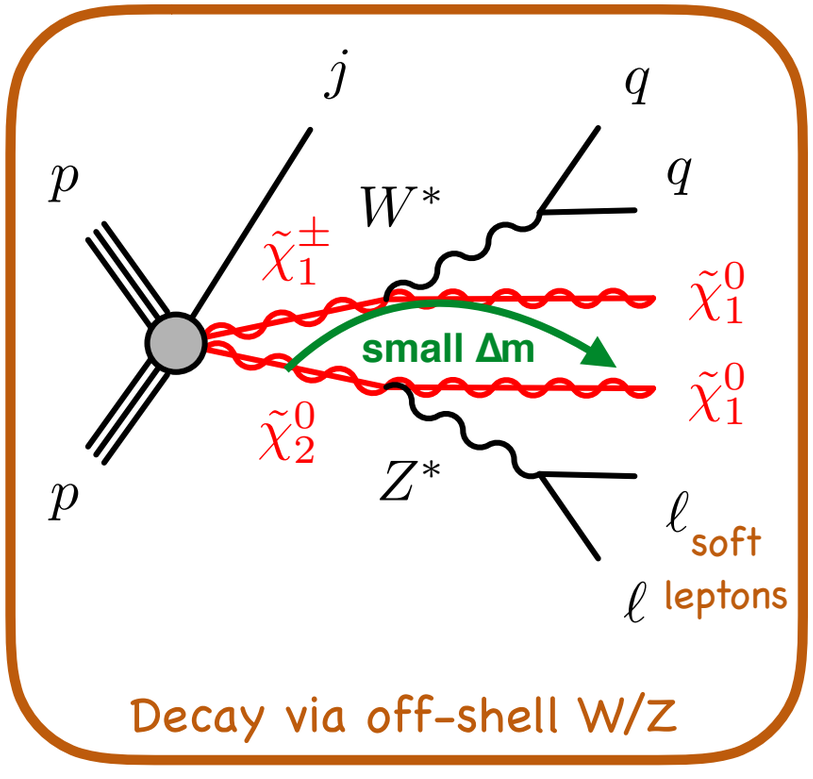

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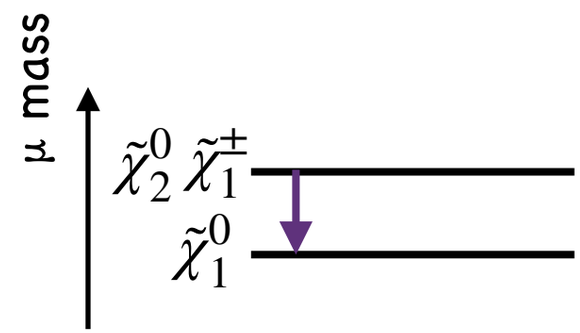

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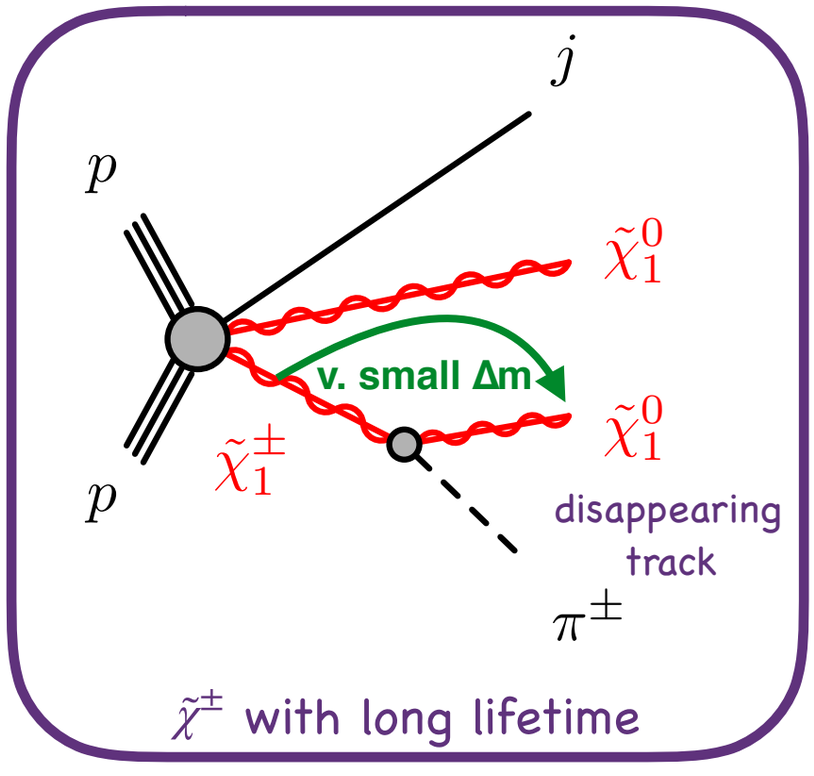

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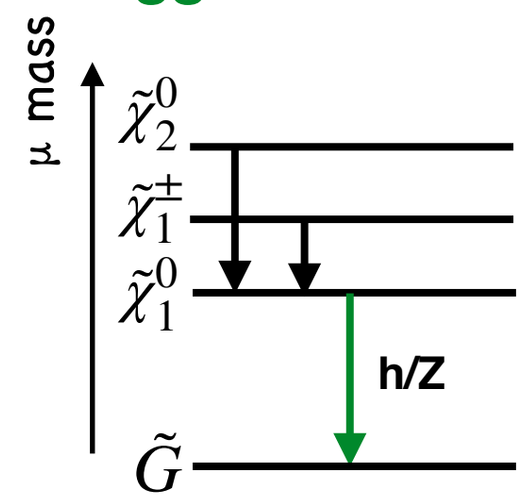
GMSB Higgsino NLSP



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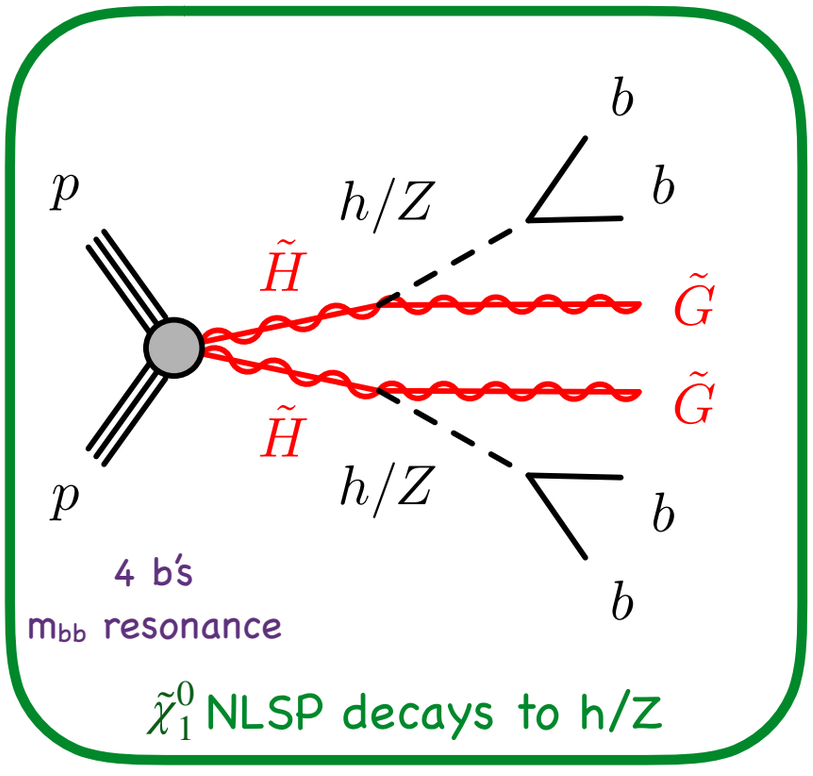

arXiv: 1806.04030
arXiv: 1804.03602

Higgsinos Searches In ATLAS

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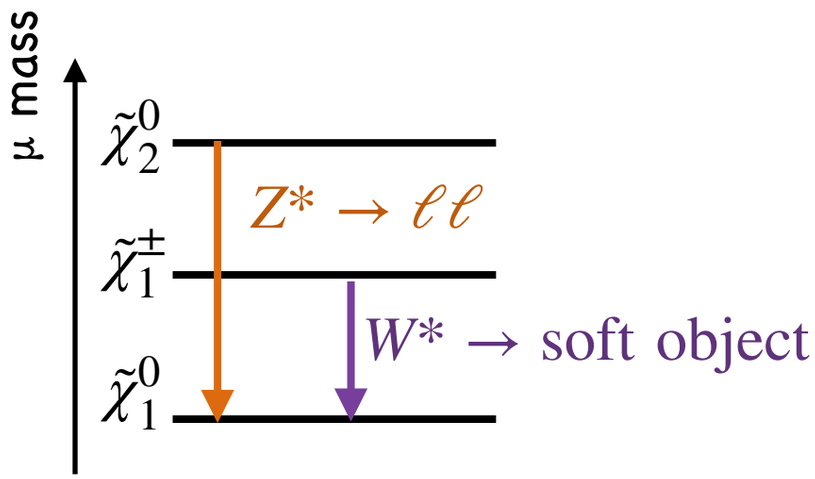

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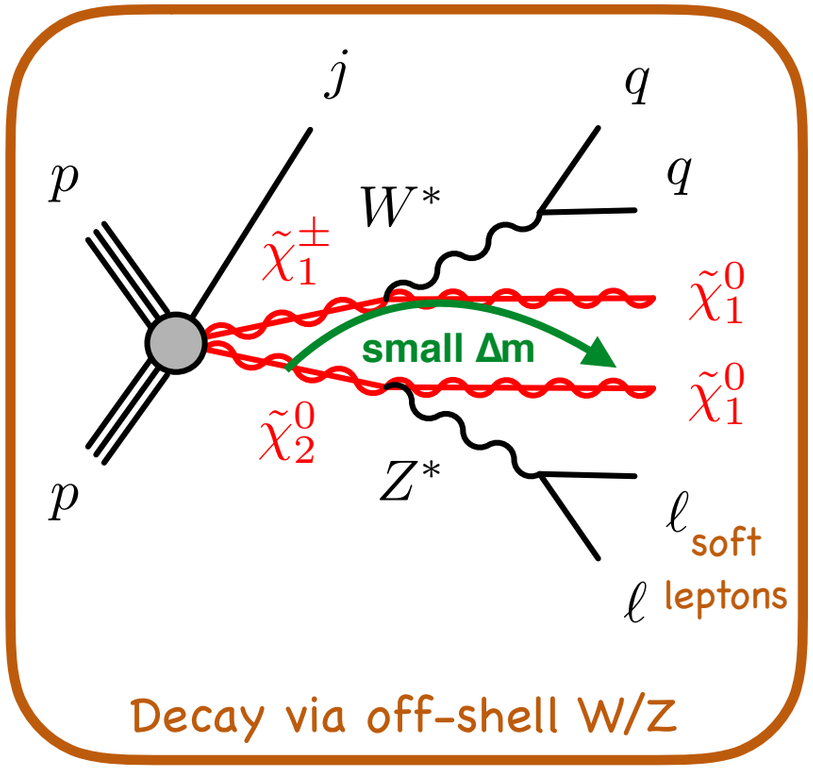

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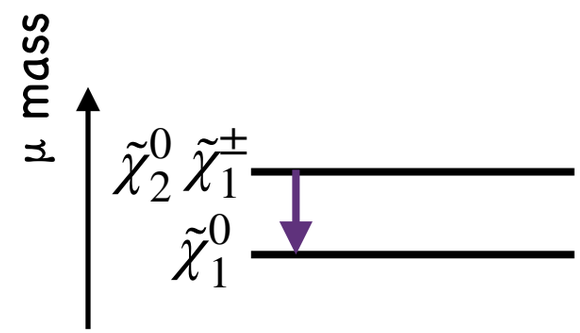

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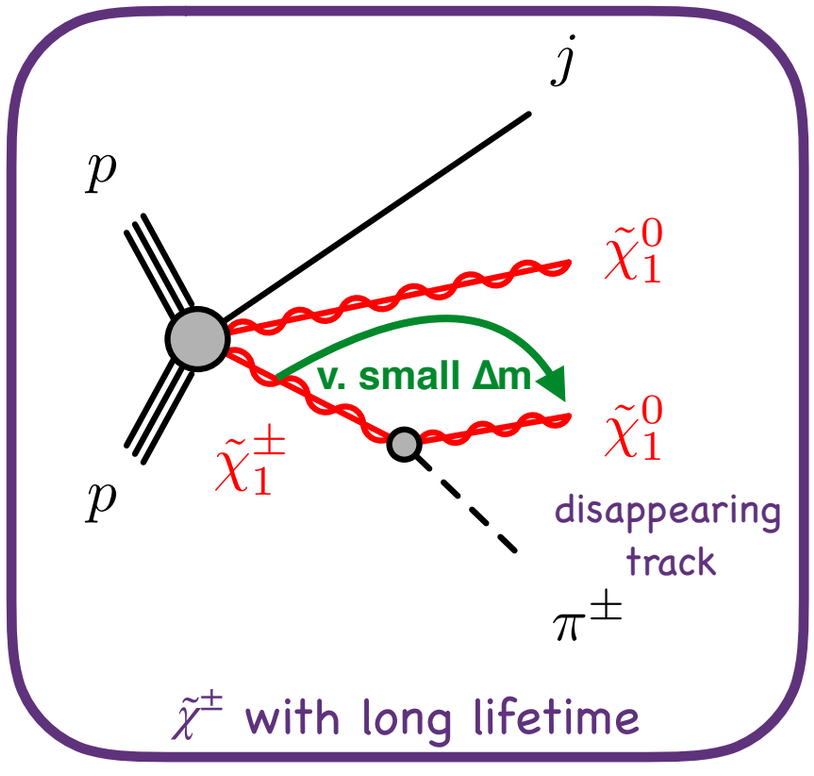

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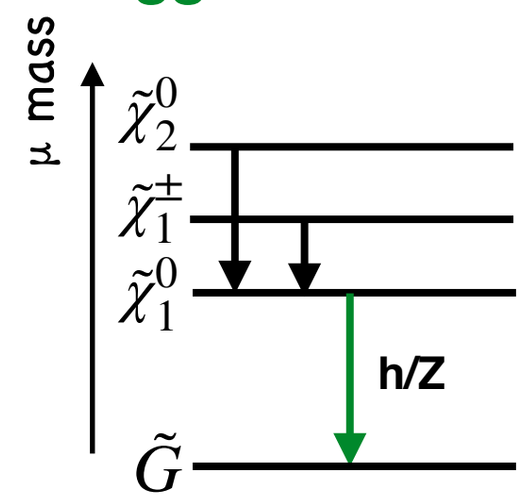

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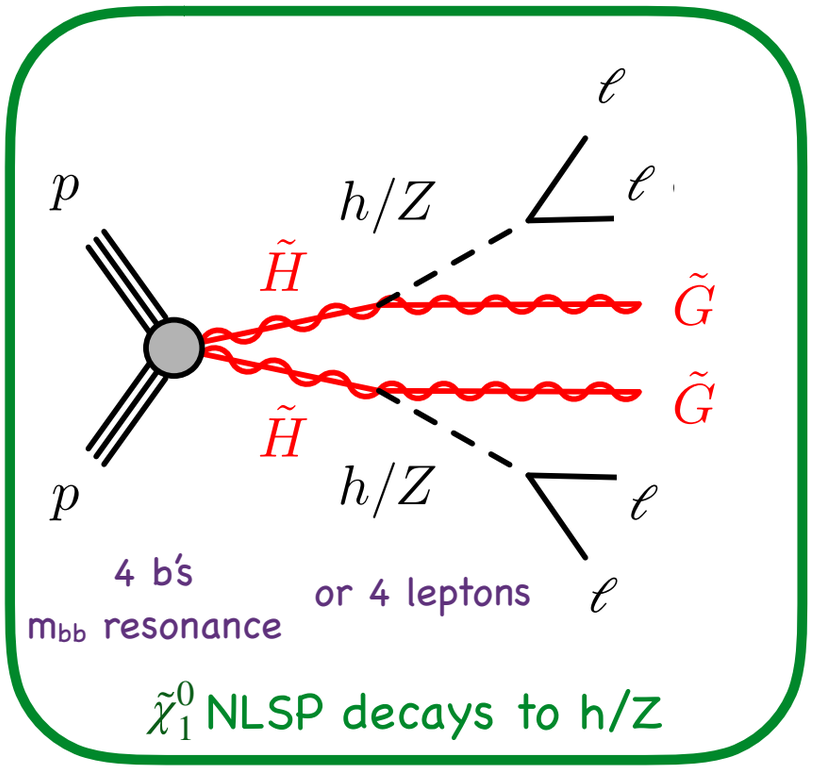

arXiv: 1806.04030
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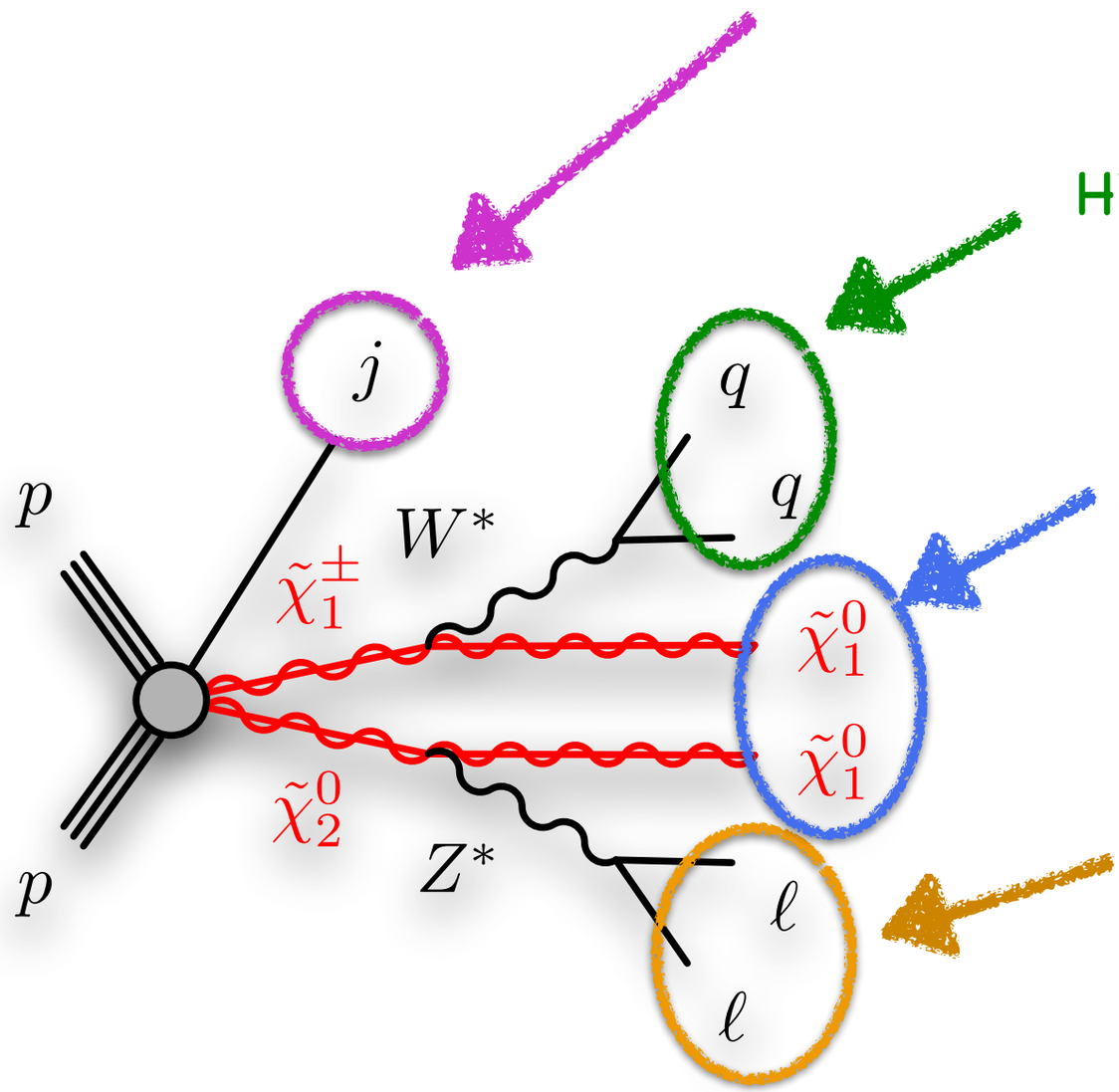
Higgsinos LSPs with Soft Leptons

Initial state radiation to boost the final state objects

High p_T jets, well separated from E_T^{miss}



Missing transverse momentum (E_T^{miss}) from $\tilde{\chi}_1^0$

Off-shell Z leads to soft-leptons and kinematic end point in m_{ll}

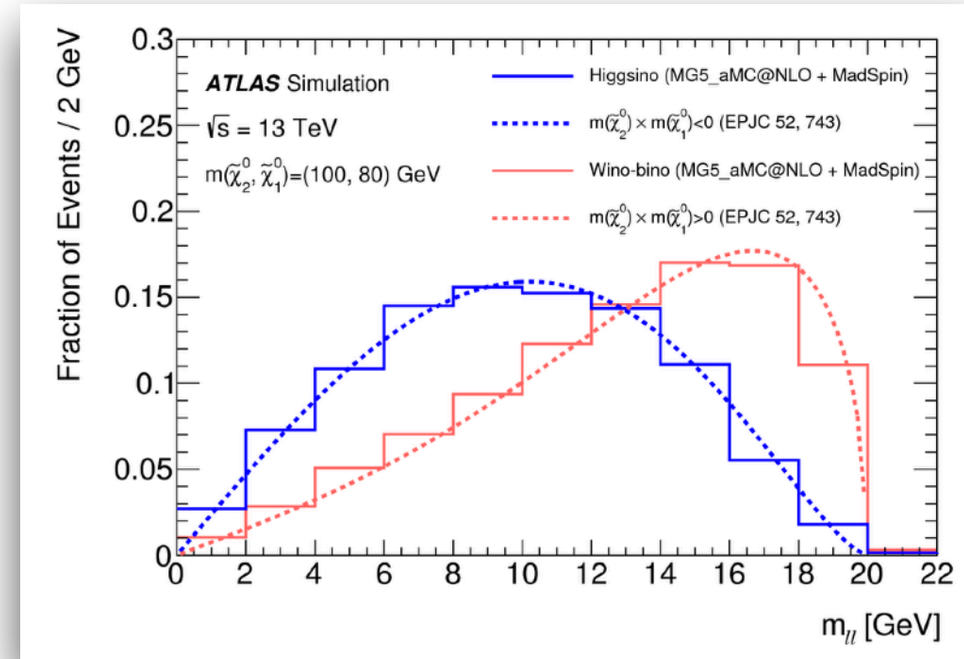
- 4 GeV muons
- 4.5 GeV electrons

Lower than any other ATLAS search !

arxiv:1712.08119

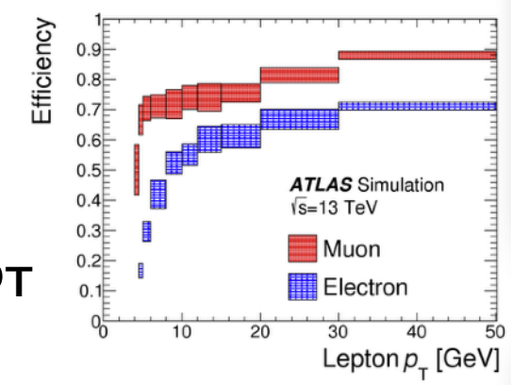
Analysis Challenges

- m_{ll} has a kinematic endpoint at $\Delta m\left(\tilde{\chi}_2^0, \tilde{\chi}_1^0\right)$
  - Different for Wino-Bino than Higgsino
  - Sensitivity driven by identification of soft leptons from off-shelf Z decays



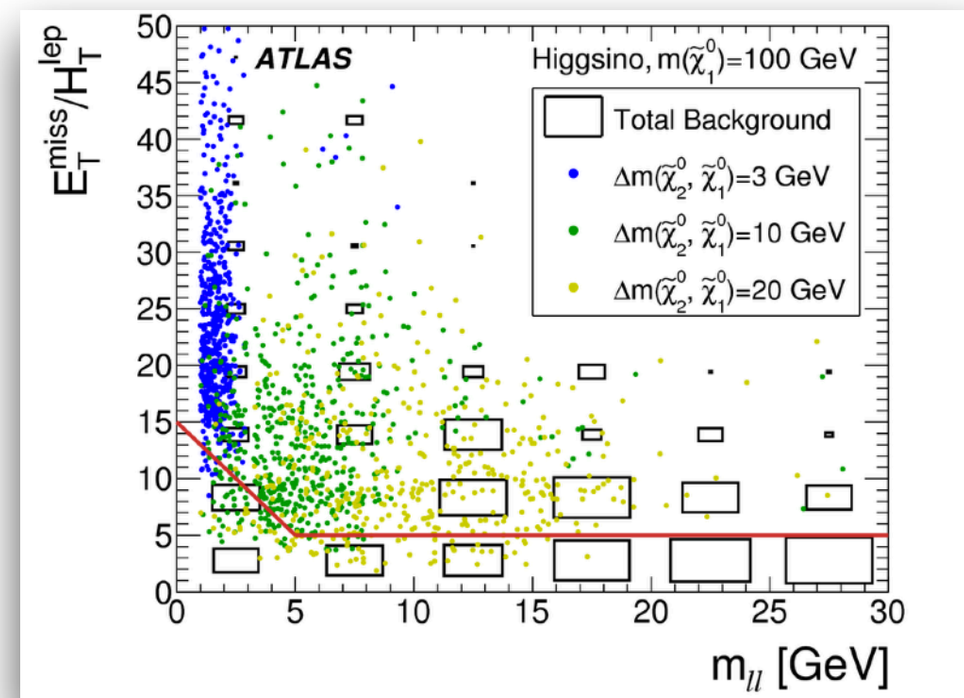
- Challenges:
  - Lepton identification at low p_T

    Checkout M. Hodgkinson's talk



  - Fake/non-prompt lepton background modeling
  - Low mass resonance

- Strategy:
  - $H_T^{\text{lep}} = p_T^{l_1} + p_T^{l_2}$ smaller in SUSY compressed region than in WW or WZ
  - $\dfrac{E_T^{\text{miss}}}{H_T^{\text{lep}}}$ higher in signal than background
    - ratio improves for lower mass splittings



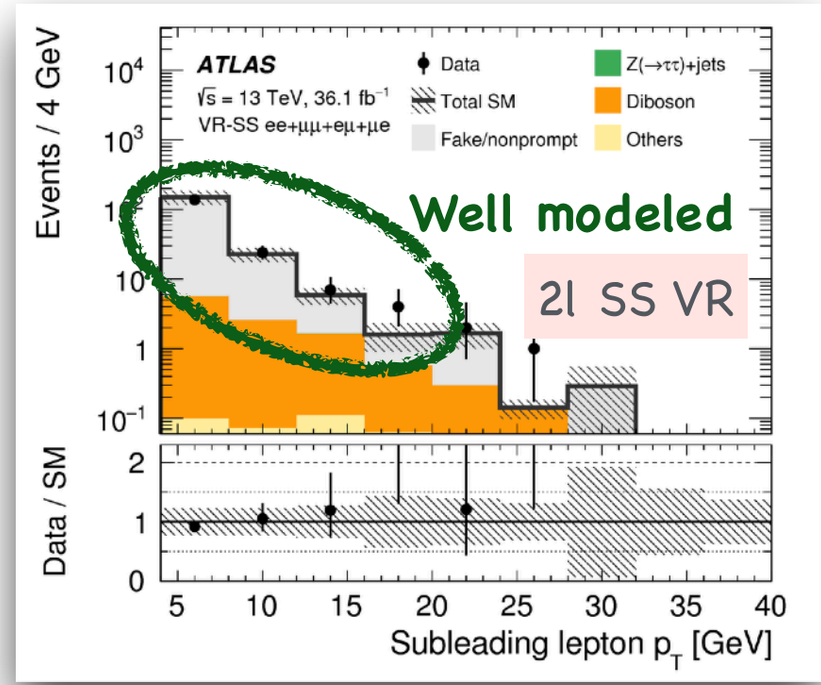
$$\frac{E_T^{\text{miss}}}{H_T^{\text{lep}}} > \max[5, 15 - 2m_{ll}/(1\ \text{GeV})]$$

Backgrounds

Use ee, μμ, eμ

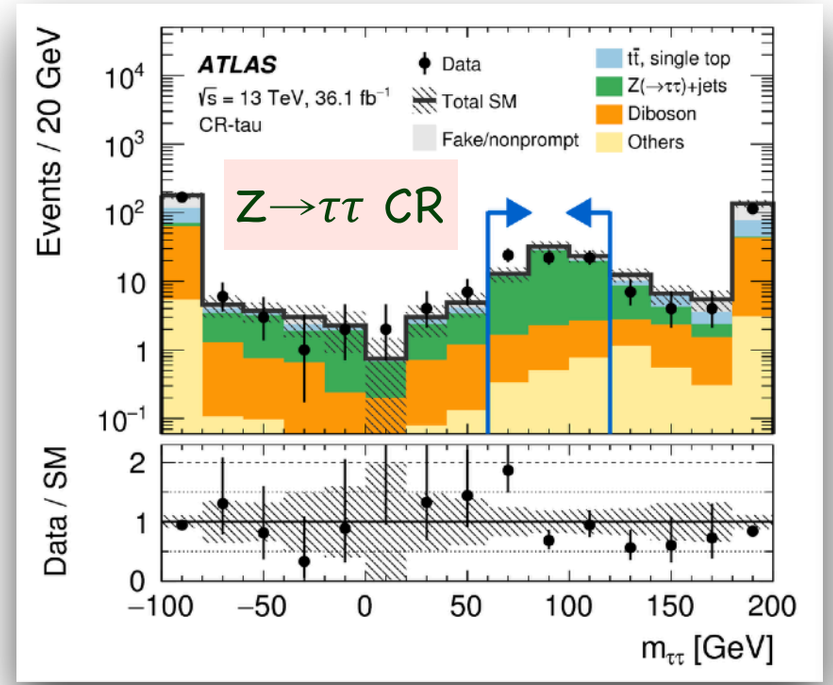
Fake Leptons

Dominant Background at low m_{ll}



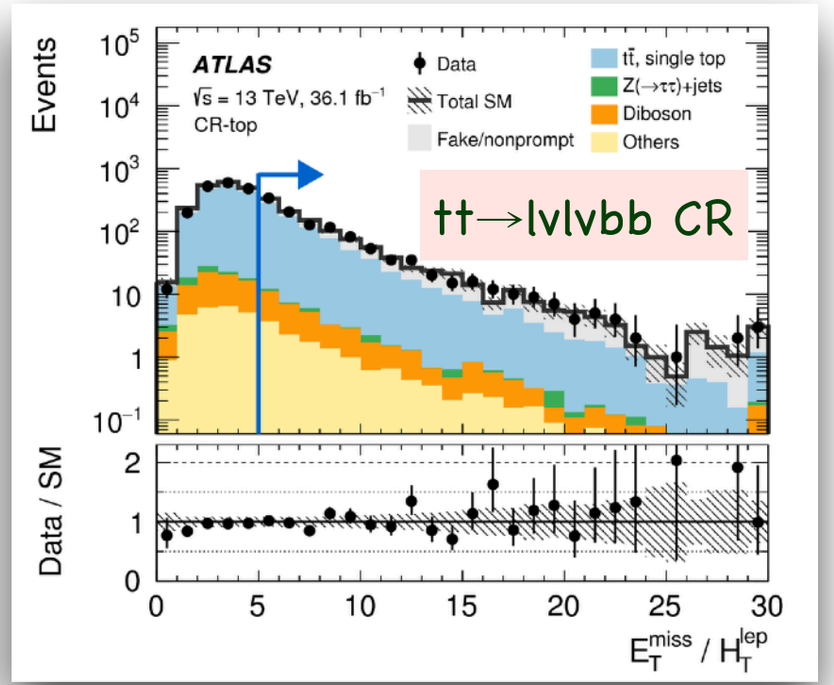
Leptonic Tau Decays

$Z \to \tau\tau$ minimized using di-tau mass proxy



Di-leptonic Top Decays

Reduced with b-jet veto



$$m_{\tau\tau} = \mathrm{sign}(\mathrm{m}^2_{\tau\tau})\sqrt{|\mathrm{m}^2_{\tau\tau}|}$$

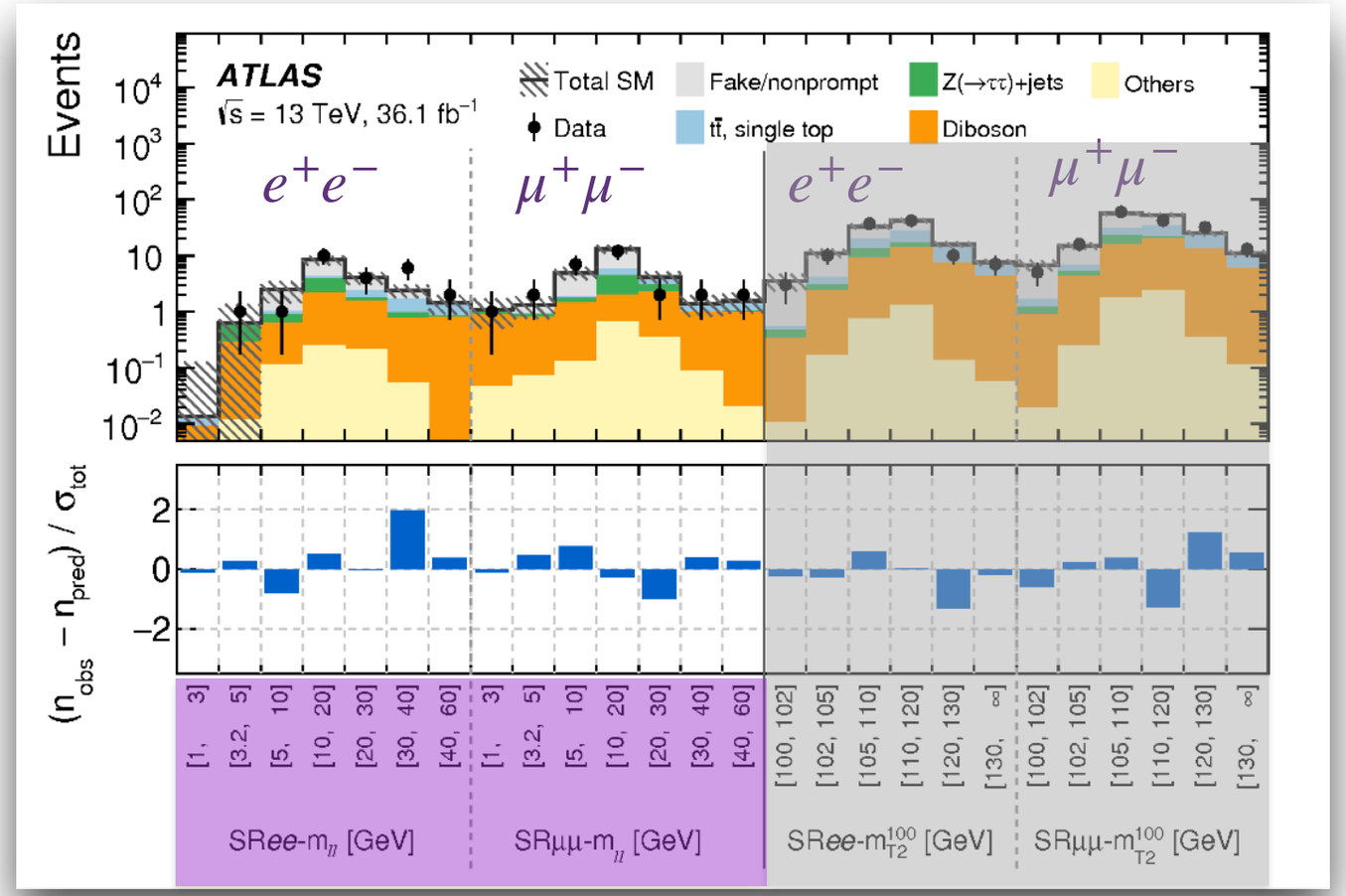
$$m^2_{\tau\tau} \equiv 2p_{\ell_1} \cdot p_{\ell_2}(1+\xi_1)(1+\xi_2)$$

- Estimated entirely from data using "Fake-Factor" method
- Validated in data in regions with same-sign leptons

- Estimated via controls regions (CRs)
- Scale MC prediction by data yield in background enriched regions

Results

SRs defined by cut on $\frac{E_T^{\mathrm{miss}}}{H_T^{\mathrm{lep}}}$ and fit the m_{ll} spectrum starting at 1GeV !



Higgsino Regions

Sleptons Regions

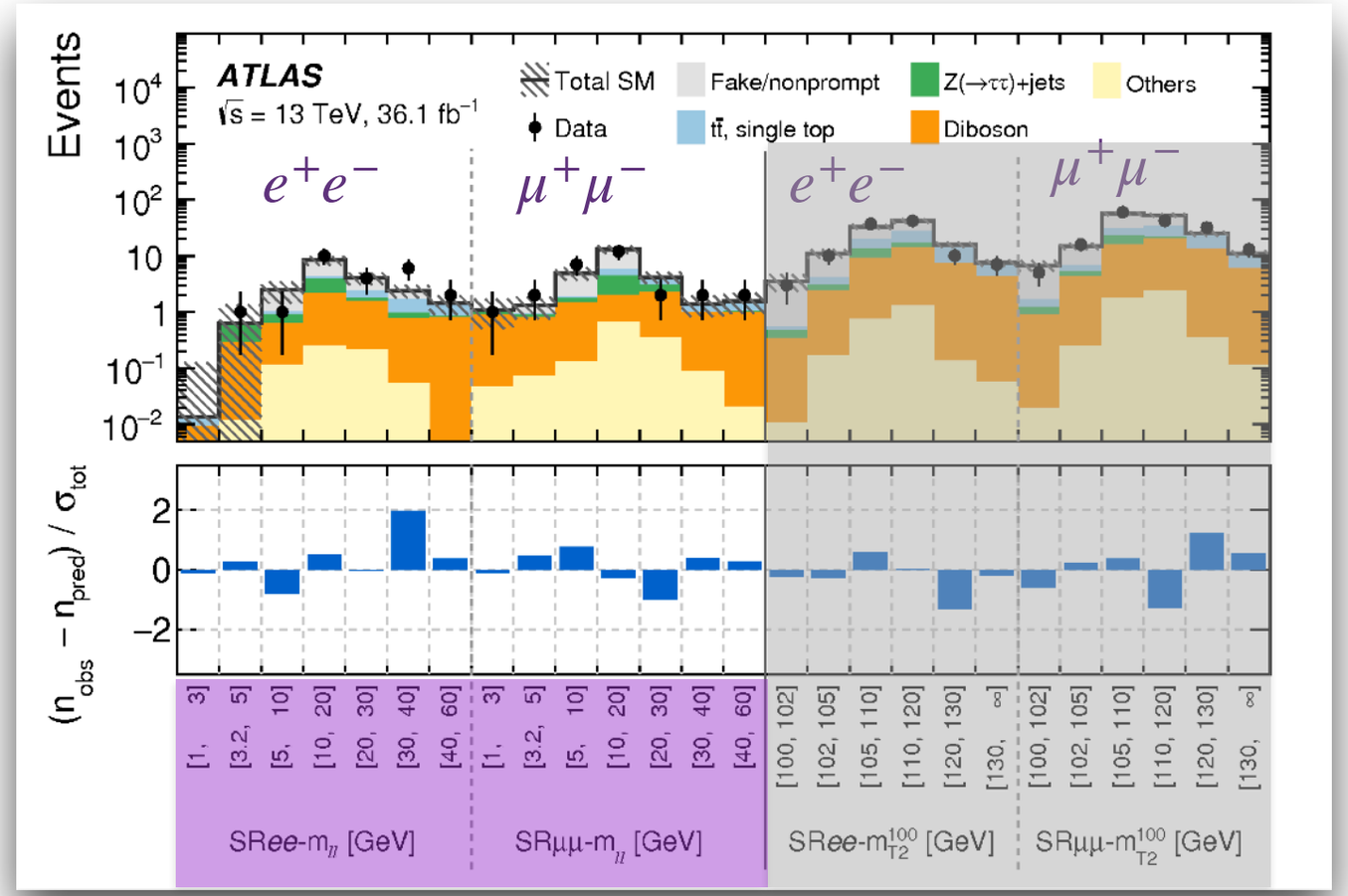
Checkout M. Primavera's talk

No significant excess observed

→ Set limits on simplified models

Results

SRs defined by cut on $\frac{E_T^{miss}}{H_T^{lep}}$ and fit the m_{ll} spectrum starting at 1GeV !



Higgsino Regions

Sleptons Regions

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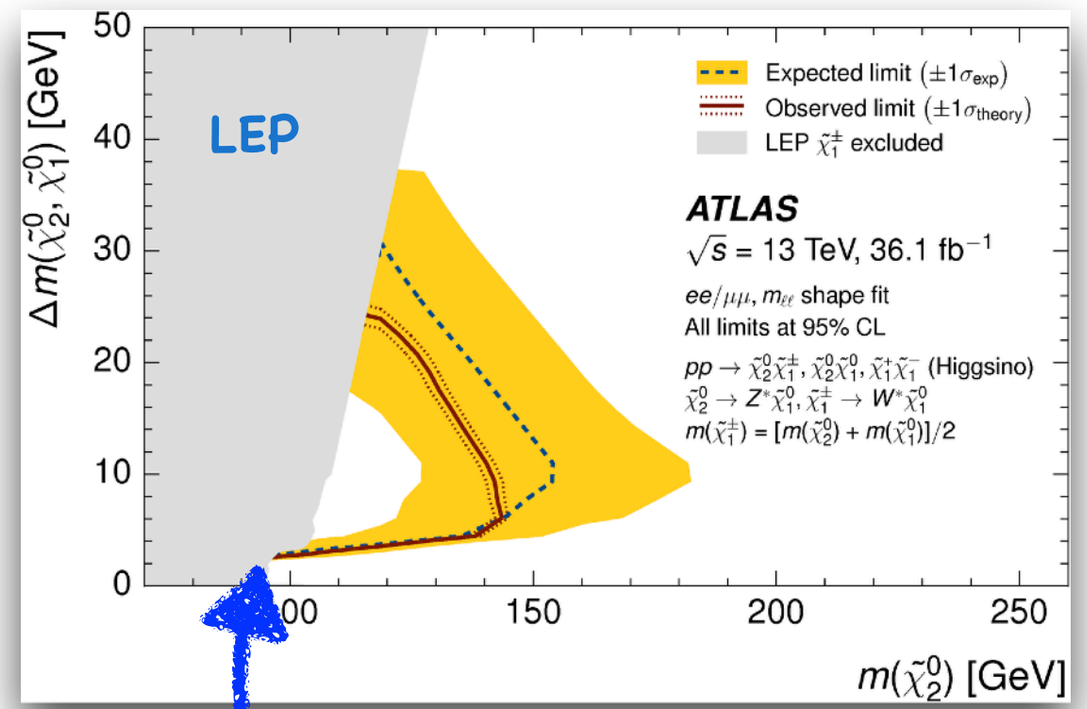
First ATLAS result on direct higgsinos production !



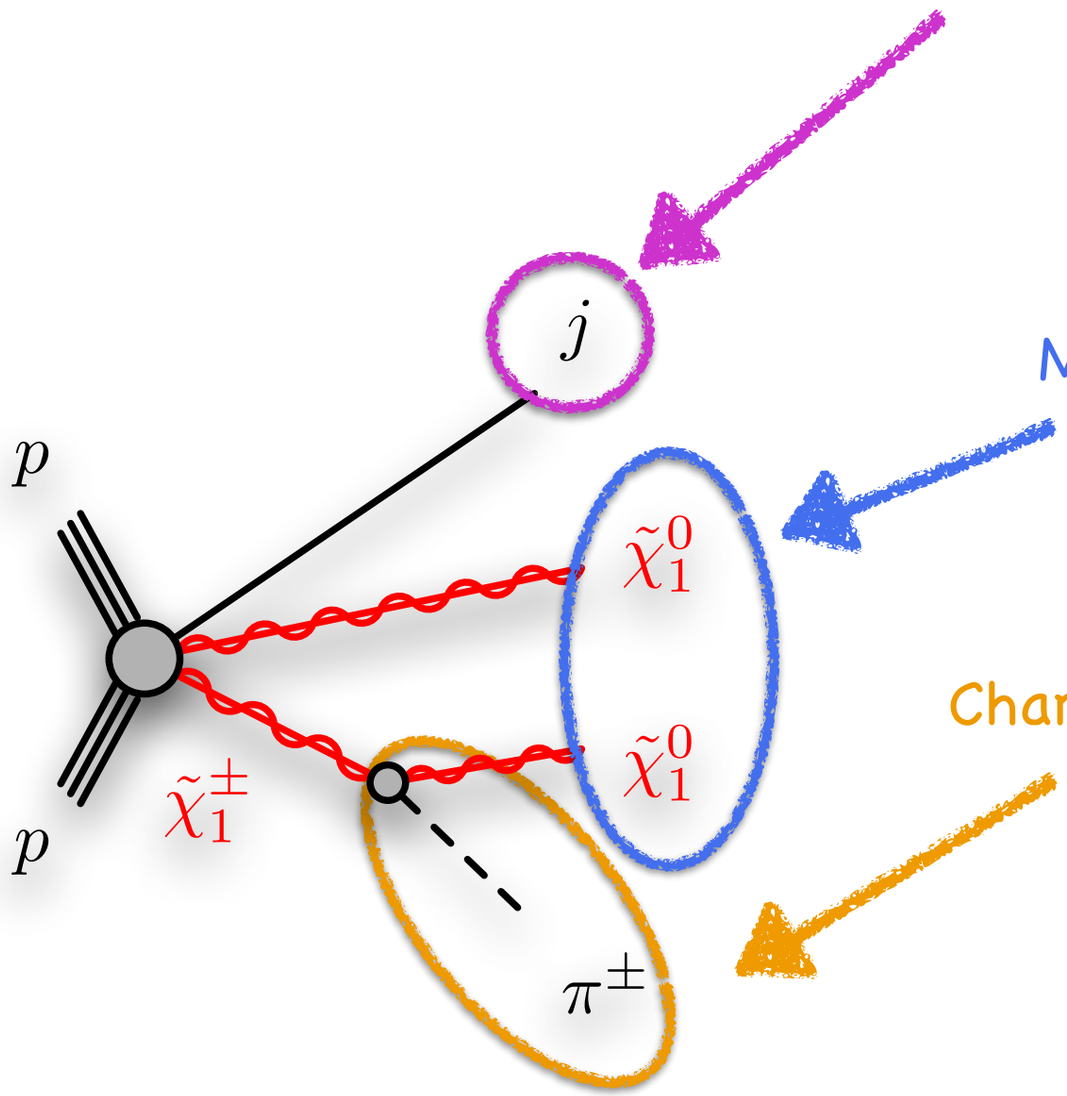
Mass splitting as low as 3 GeV have limits beyond LEP

No significant excess observed

→ Set limits on simplified models

Higgsinos LSPs with Disappearing Tracks

Initial state radiation to boost the final state objects



Missing transverse momentum (E_T^{miss}) from $\tilde{\chi}_1^0$

Chargino with long lifetime decays to low p_T pion + $\tilde{\chi}_1^0$

→ disappearing $\tilde{\chi}_1^\pm$ track(s)

Signal region selection:

≥1 jet (p_T > 140 GeV) and MET > 140 GeV

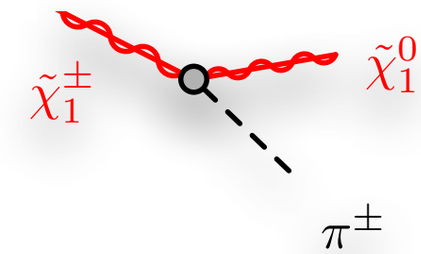
Well separated jets and MET

≥1 pixel tracklet

arxiv:1712.02118

ATL-PHYS-PUB-2017-019

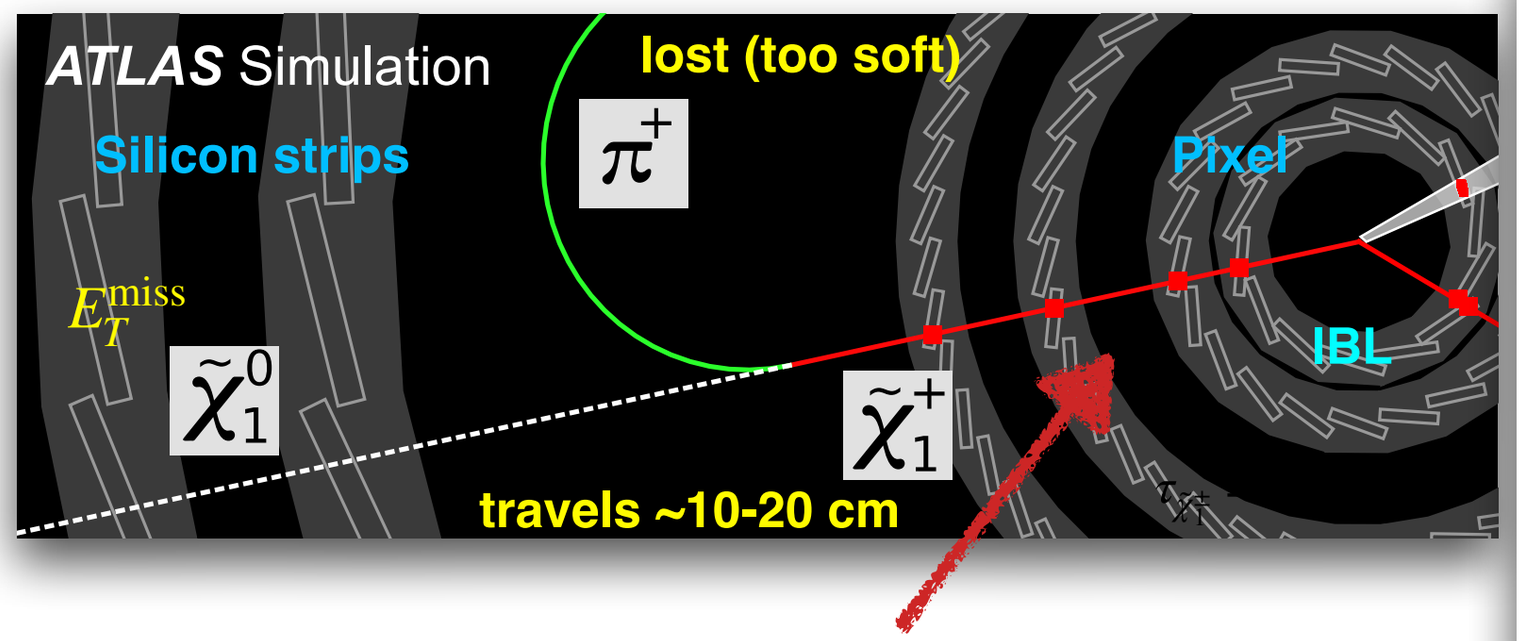
Analysis Strategy

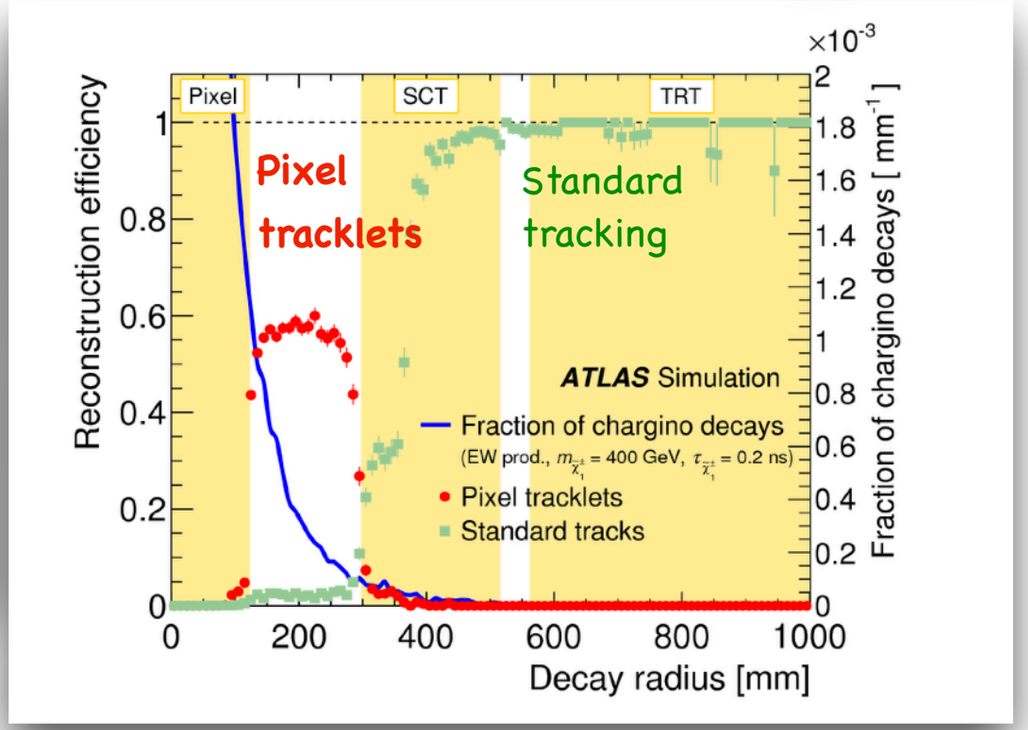


For ultra-compress Higgsino scenario:

$\tilde{\chi}_1^{\pm}$ can be long-lived

eg: $\tilde{\chi}_1^{\pm}$ lifetime of ~0.05 ns with $c\tau$~1.5cm γ~1





Look for "pixel tracklets" with few pixel hits, but no hits in the strip Si detector

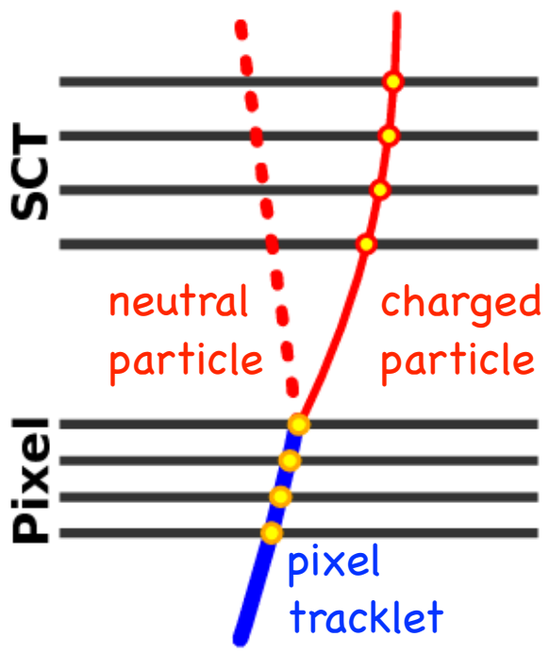
- **Unique signature requires non-standard methodologies:**
  - **Custom track reconstruction logic and algorithm**
    - **Standard track reconstruction → Unassociated hits → Tracklets**

New IBL pixel layer in Run 2 allows for shorter tracks

Increases sensitivity to shorter lifetime compared to Run 1

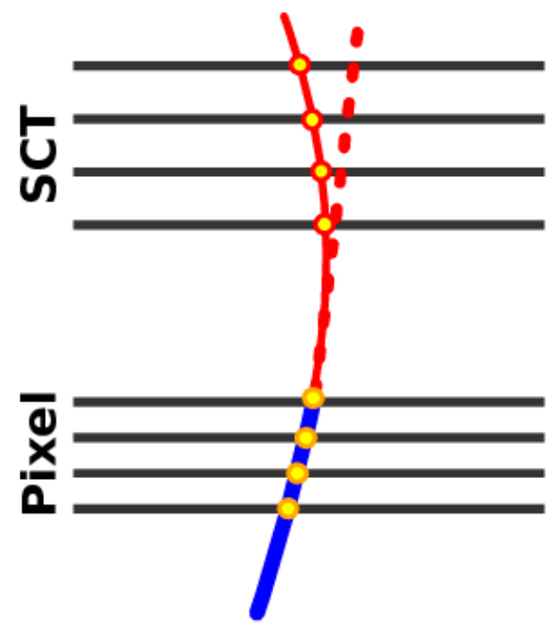
Backgrounds

Hadron undergoing hard scattering

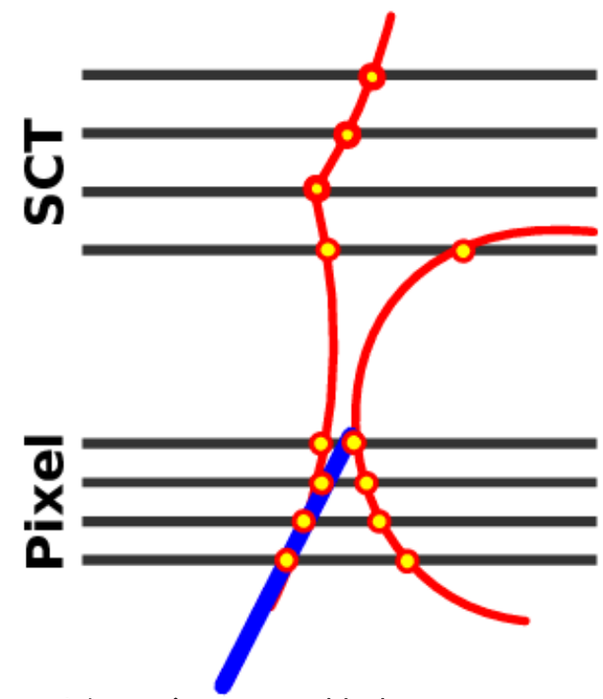


Pixel and SCT hits not associated to the same track

Lepton emitting hard γ



Random combinations

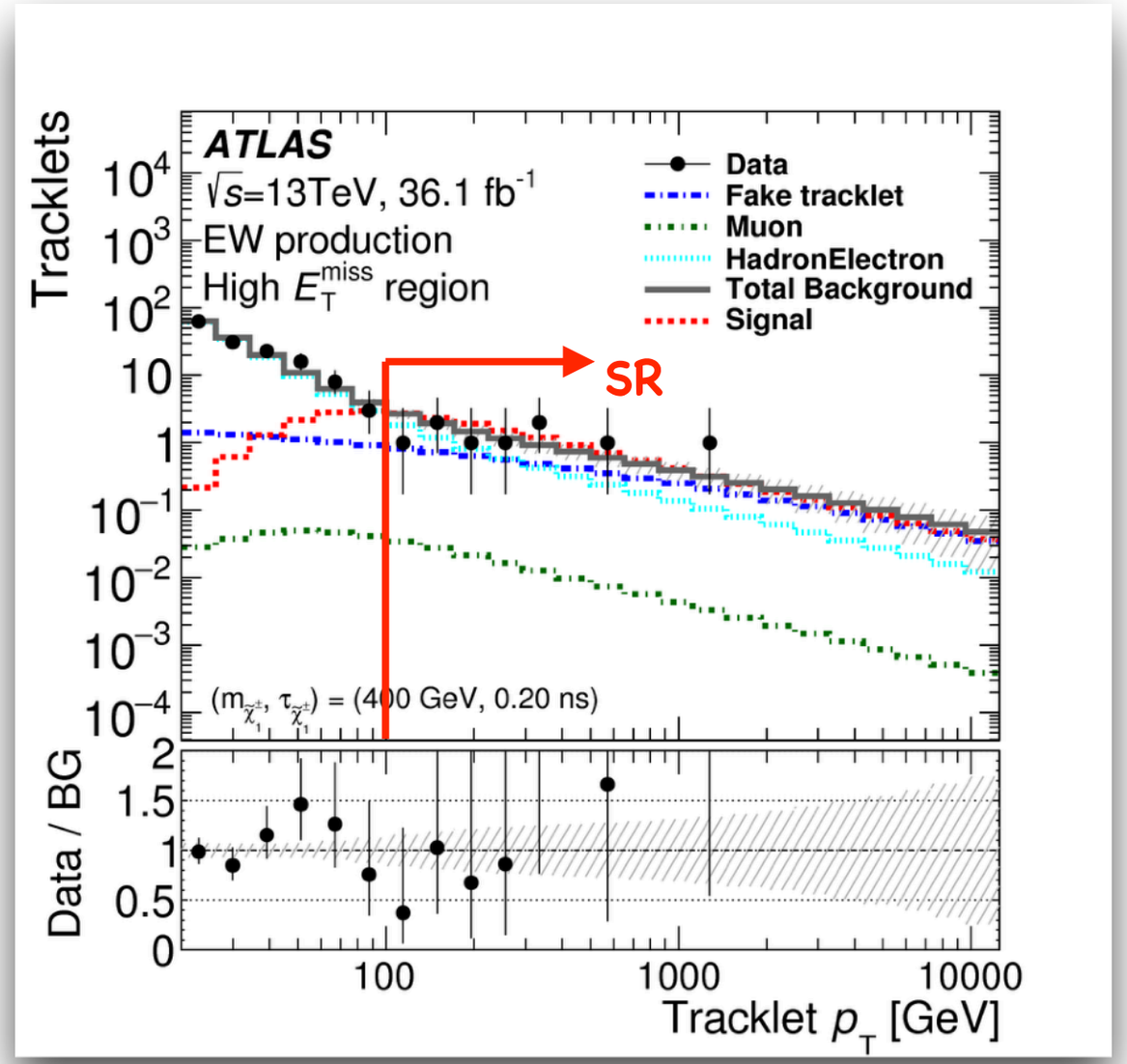


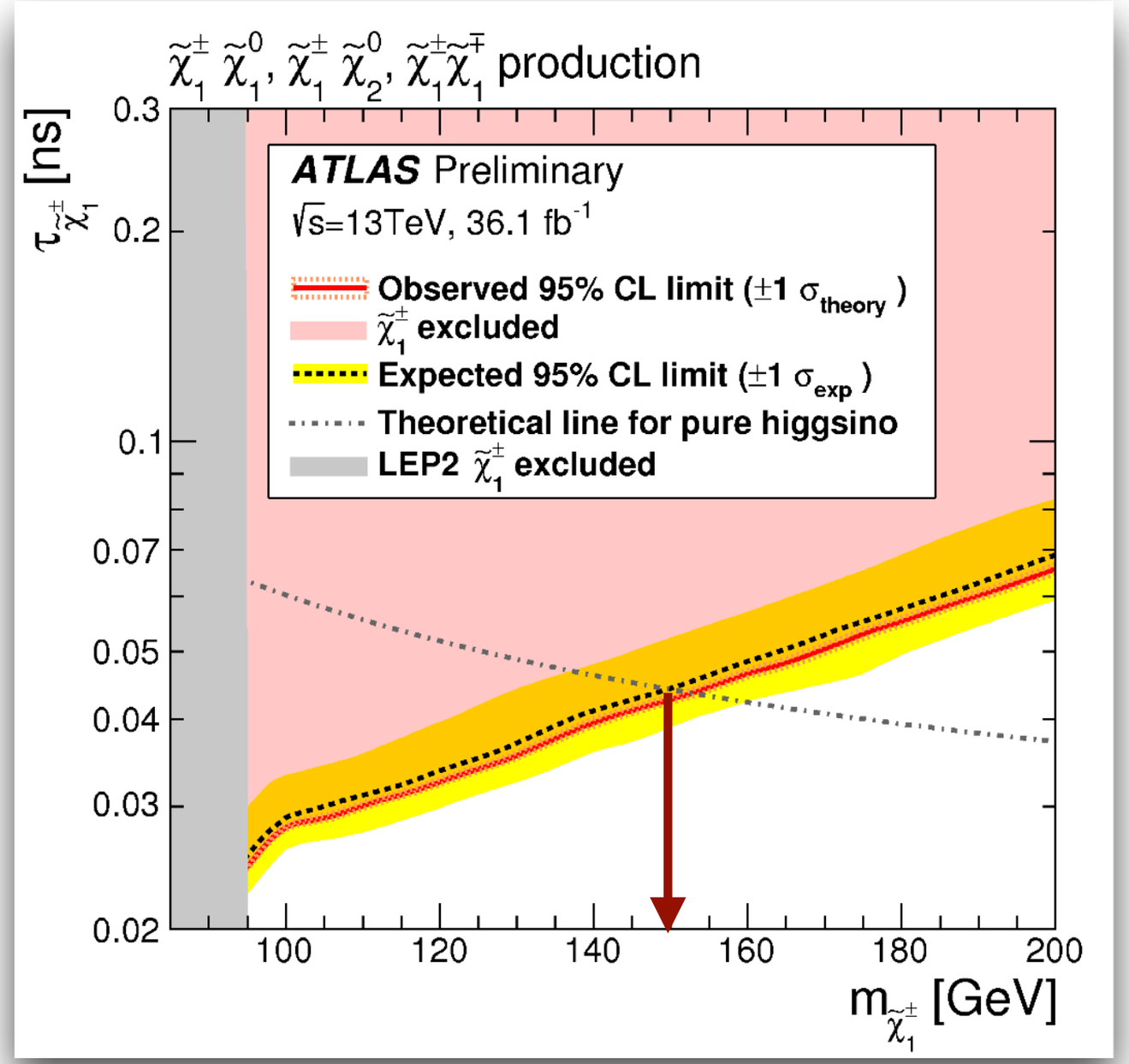
Nearby particles generate random combinations

- **Backgrounds suppressed with isolation, impact parameter cuts, and quality requirement for the tracklets**

- **Backgrounds estimated from data by building templates of tracklets p_T spectrum from each source and smearing/likelihood fitting to control samples**

Results





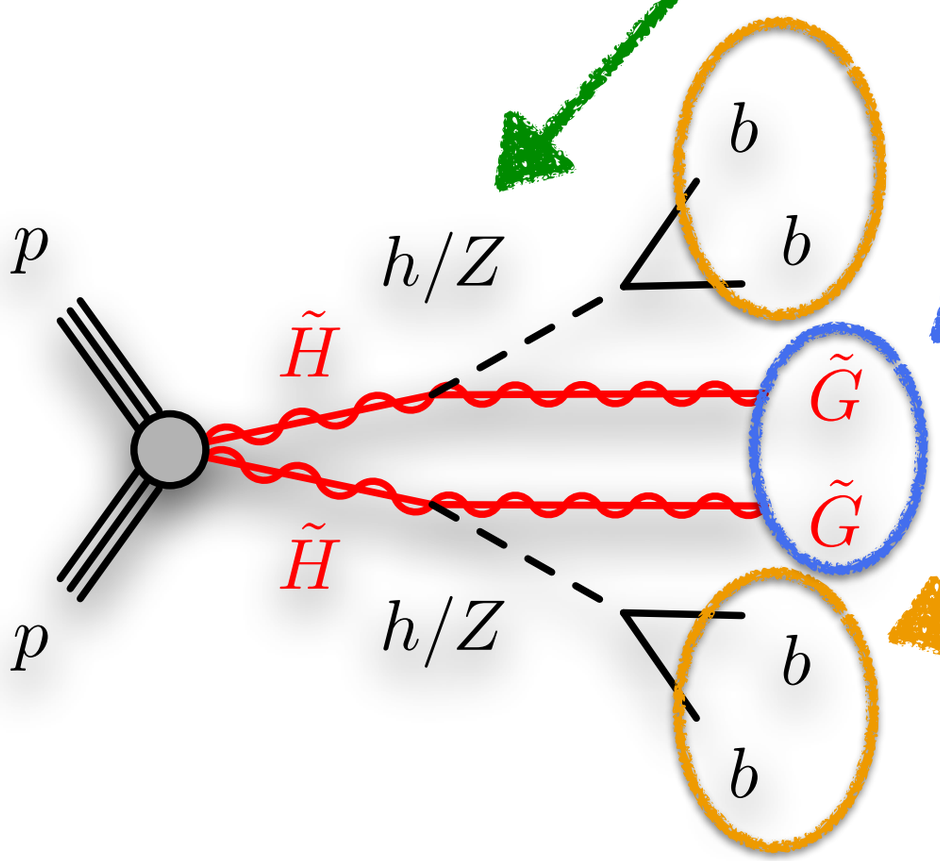
No significant excess observed

→ Set limits on higgsinos masses below 150 GeV

Higgsinos NLSPs with Higgs Decays

In GMSB, LSP is a nearly massless gravitino

- Allows NLSP $\tilde{\chi}_1^0$ (higgsino dominated $m_{\tilde{H}} > m_h$) to decay to on-shell h/Z



Missing transverse momentum (E_T^{miss}) from $\tilde{G}$

$h/Z \to b\bar{b}$ gives powerful 4b's final state with large branching ratio & $m_{bb} \sim m_h$

arXiv: 1806.04030

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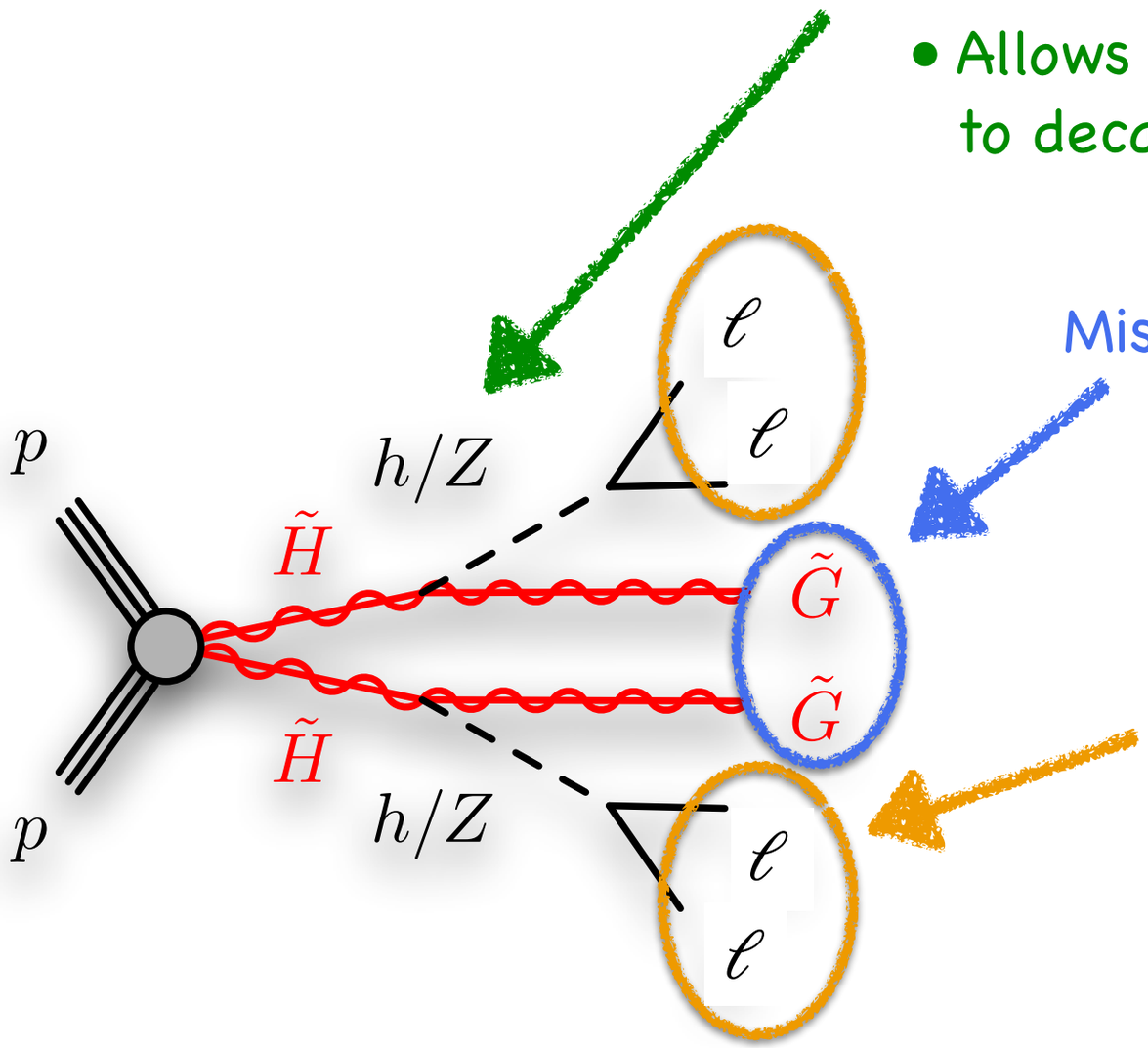


Missing transverse momentum (E_T^{miss}) from $\tilde{G}$

$h/Z \to b\bar{b}$ gives powerful 4b's final state with large branching ratio & $m_{bb} \sim m_h$

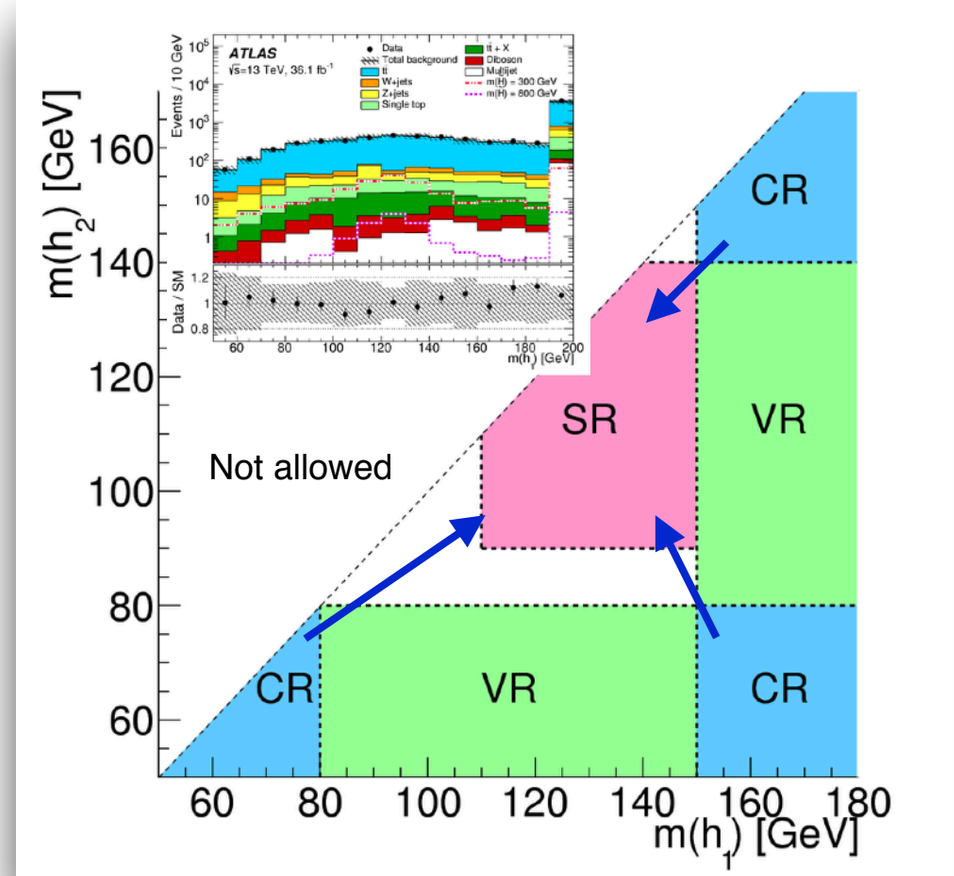
$Z \to \ell\ell$ gives a powerful 4L's final state with small branching ratio but very small SM backgrounds & $m_{ll} \sim m_Z$

arXiv: 1806.04030

arXiv: 1804.03602

Analysis strategy (4b's)

- **High-mass:** $m_{\tilde{H}} > 300$ GeV
  - **Use E_T^{miss} triggers ($E_T^{\text{miss}} > 200$ GeV)**
  - **4 jets (≥3 b-jets) from the Higgs bosons**
    - **Paired based on ΔR_{max}^{bb} (captures both h/Z)**
    - **Use minimum $\Delta\phi^{4j}$ and $\vec{p}_T^{\text{miss}}$ to reduce multi jet background**
  - **Top background dominant**



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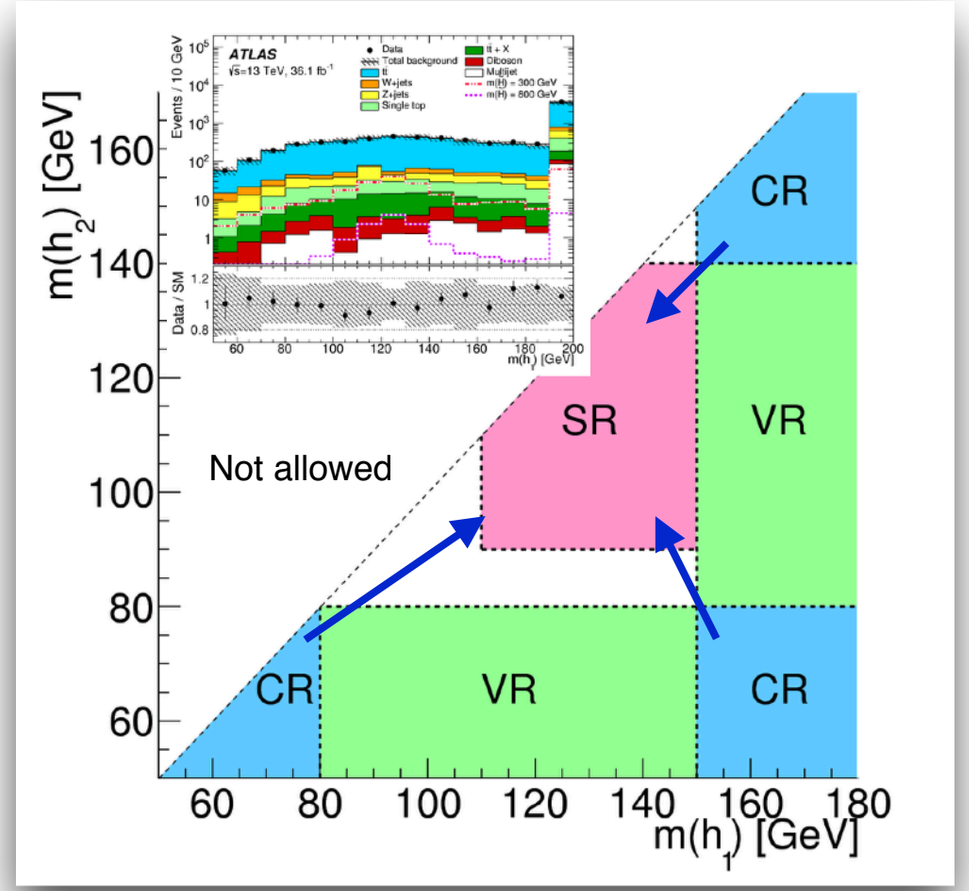
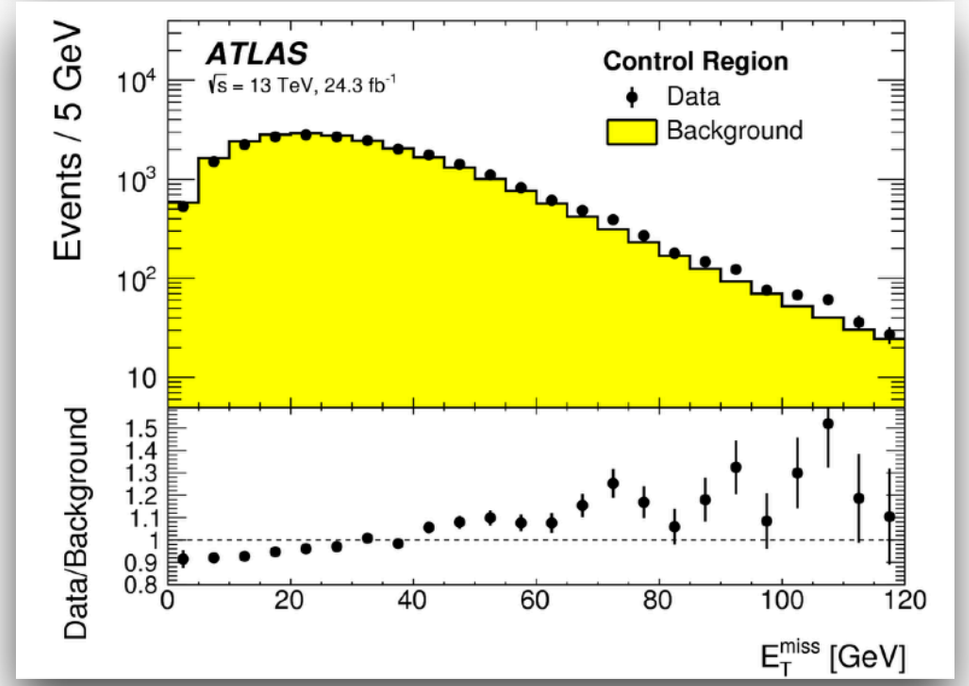
  - Top background dominant



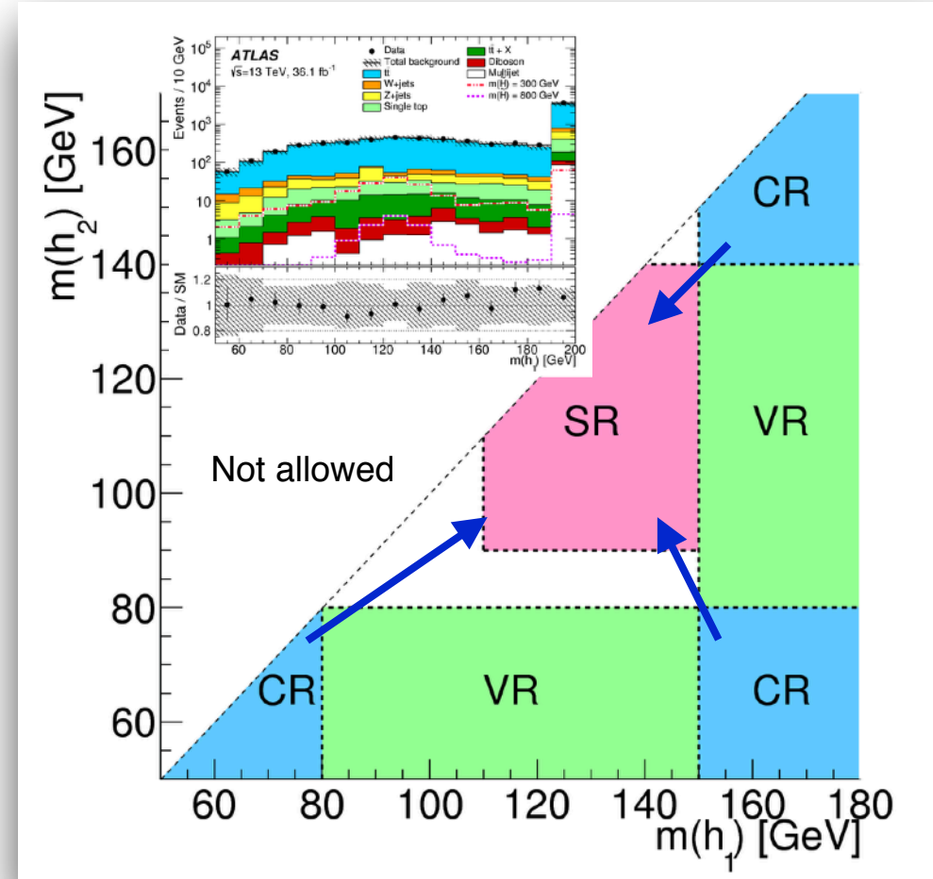
- **Low-mass:** $m_{\tilde{H}} < 300$ GeV
  - Uses b-jet triggers to recover efficiency at low E_T^{miss}
  - ≥4 b-jets (use 4 w/ highest b-tag score)
    - Paired based on ΔR^{bb} and m_{bb} consistent with two Higgs bosons of roughly the same mass
  - Main background from multi jet events.
    - Design BDT to reweigh data from 2 b-tags regions to 4 b-tags region

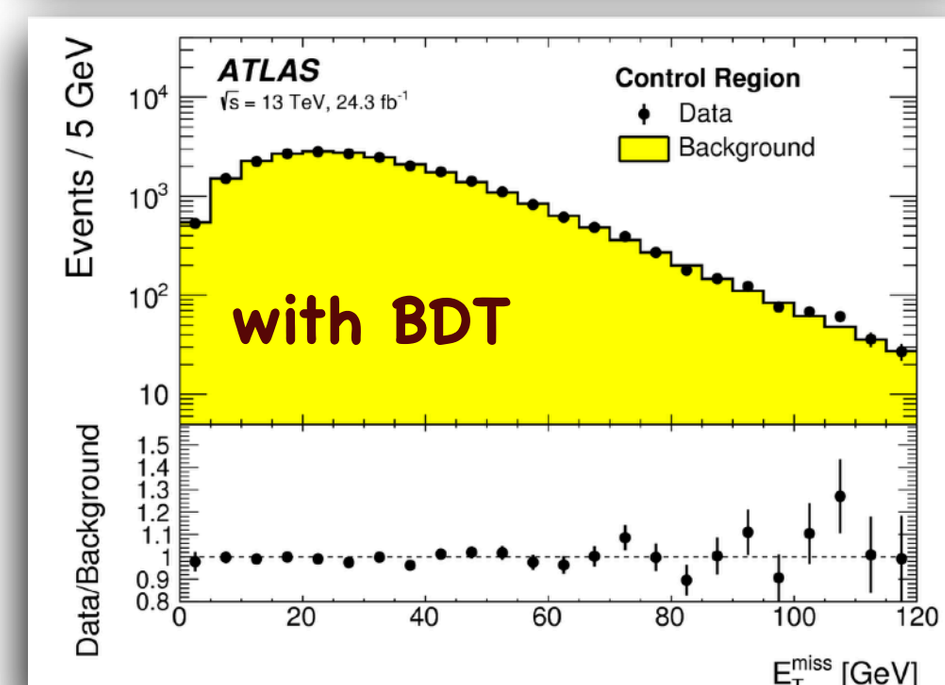


Analysis strategy (4b's)

- **High-mass:** $m_{\tilde{H}} > 300$ GeV
  - Use E_T^{miss} triggers ($E_T^{\text{miss}} > 200$ GeV)
  - 4 jets (≥3 b-jets) from the Higgs bosons
    - Paired based on ΔR_{max}^{bb} (captures both h/Z)
    - Use minimum $\Delta\phi^{4j}$ and $\vec{p}_T^{\text{miss}}$ to reduce multi jet background
  - Top background dominant

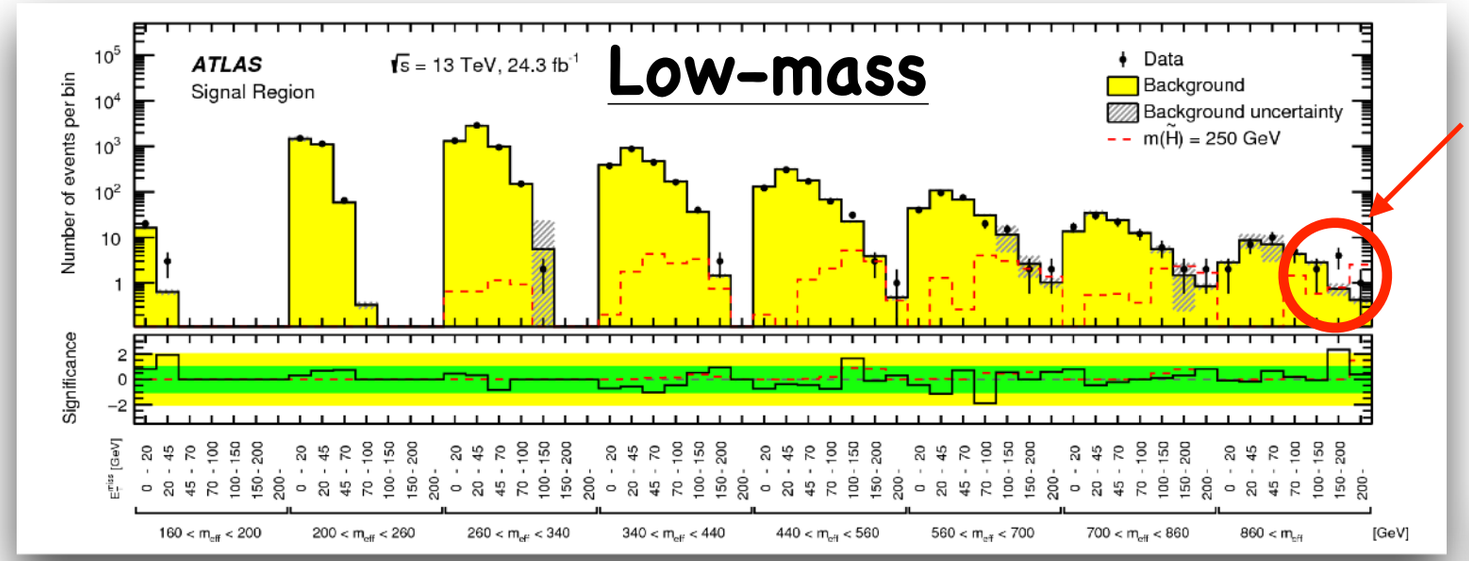
- **Low-mass:** $m_{\tilde{H}} < 300$ GeV
  - Uses b-jet triggers to recover efficiency at low E_T^{miss}
  - ≥4 b-jets (use 4 w/ highest b-tag score)
    - Paired based on ΔR^{bb} and m_{bb} consistent with two Higgs bosons of roughly the same mass
  - Main background from multi jet events.
    - Design BDT to reweigh data from 2 b-tags regions to 4 b-tags region





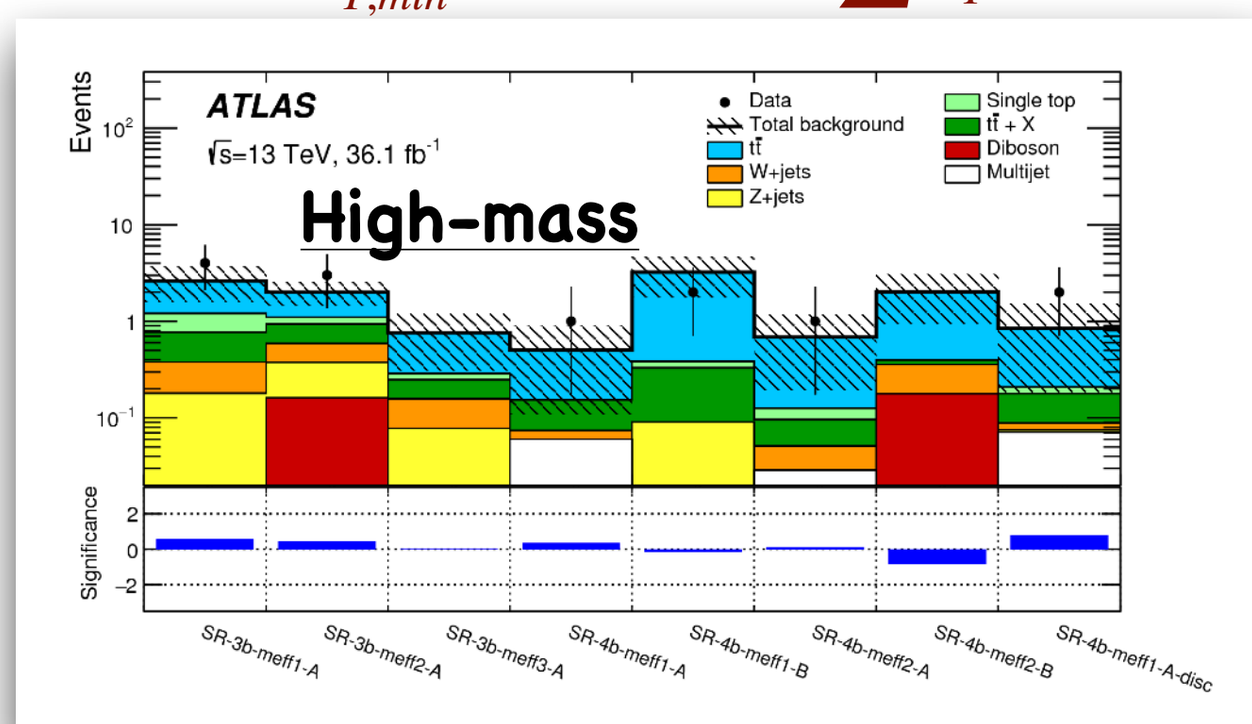
Results

Signal regions based on 6 E_T^{miss} bins within 8 m_{eff} bins

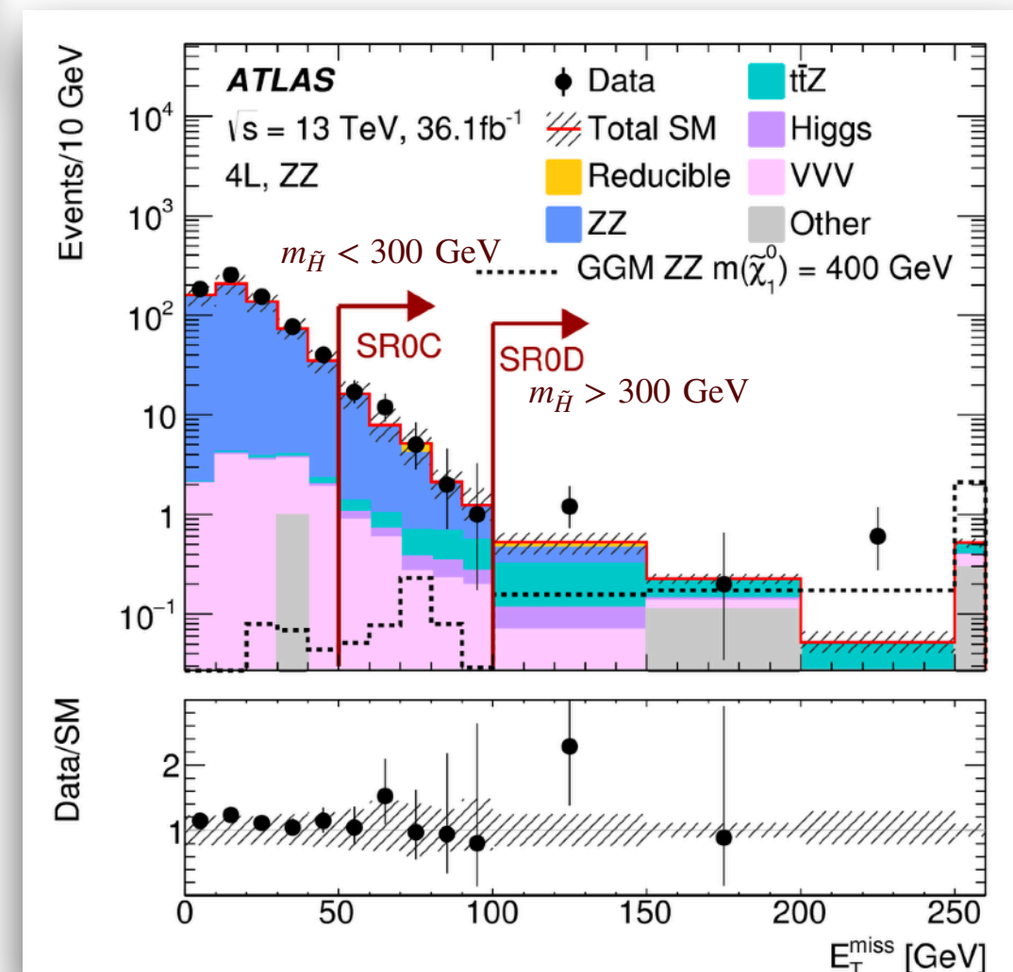


max excess
4 -vs- 1.0±0.2

8 signal regions based on $N_{\text{b-jets}}$, N_{jets}, ΔR_{max}^{bb} , $m_{T,min}^{b-jets}$ and $m_{\text{eff}} = \sum p_T^j + E_T^{miss}$

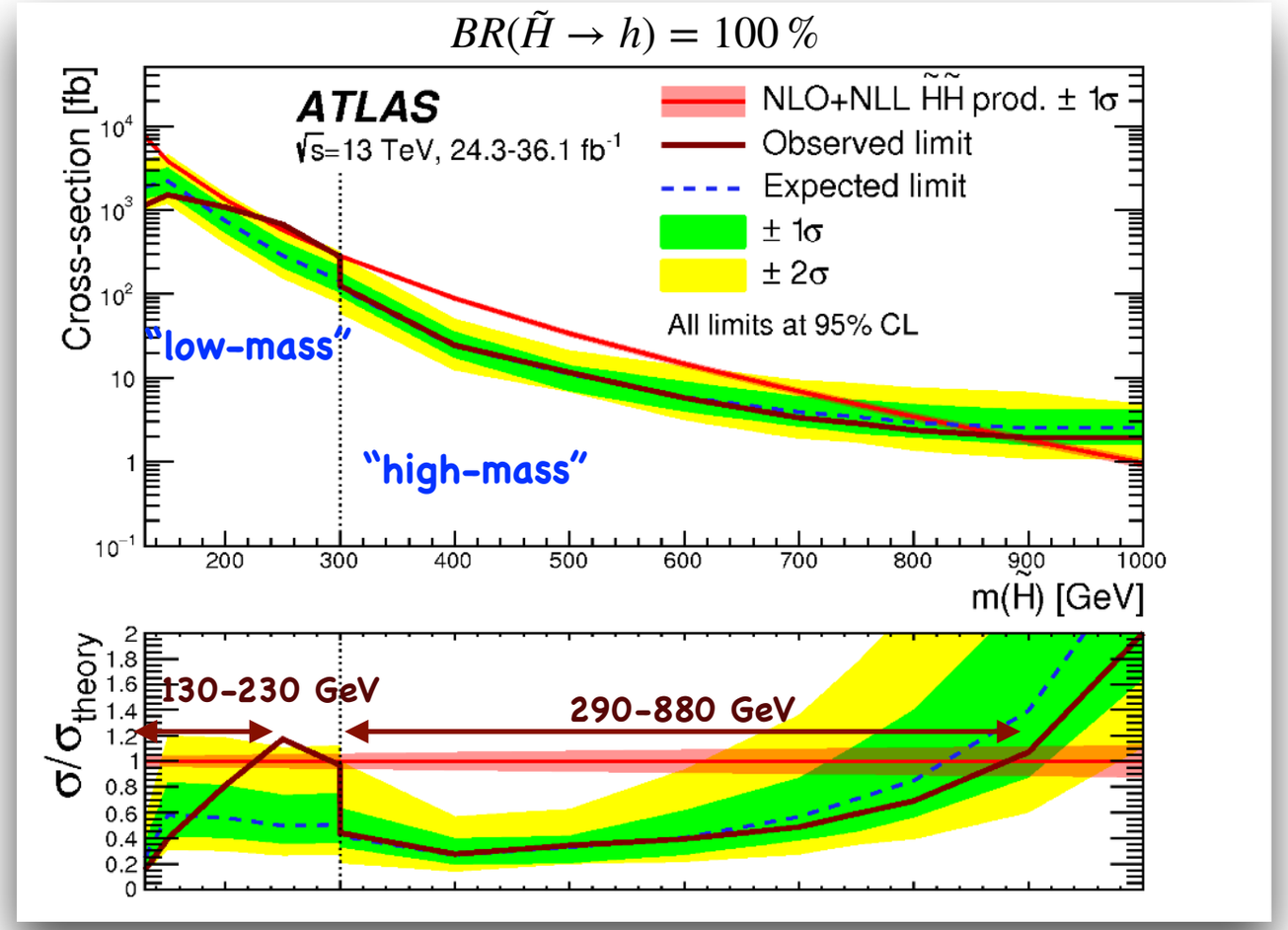


4 leptons with $m_{\ell\ell}$ consistent with 2 Z's.

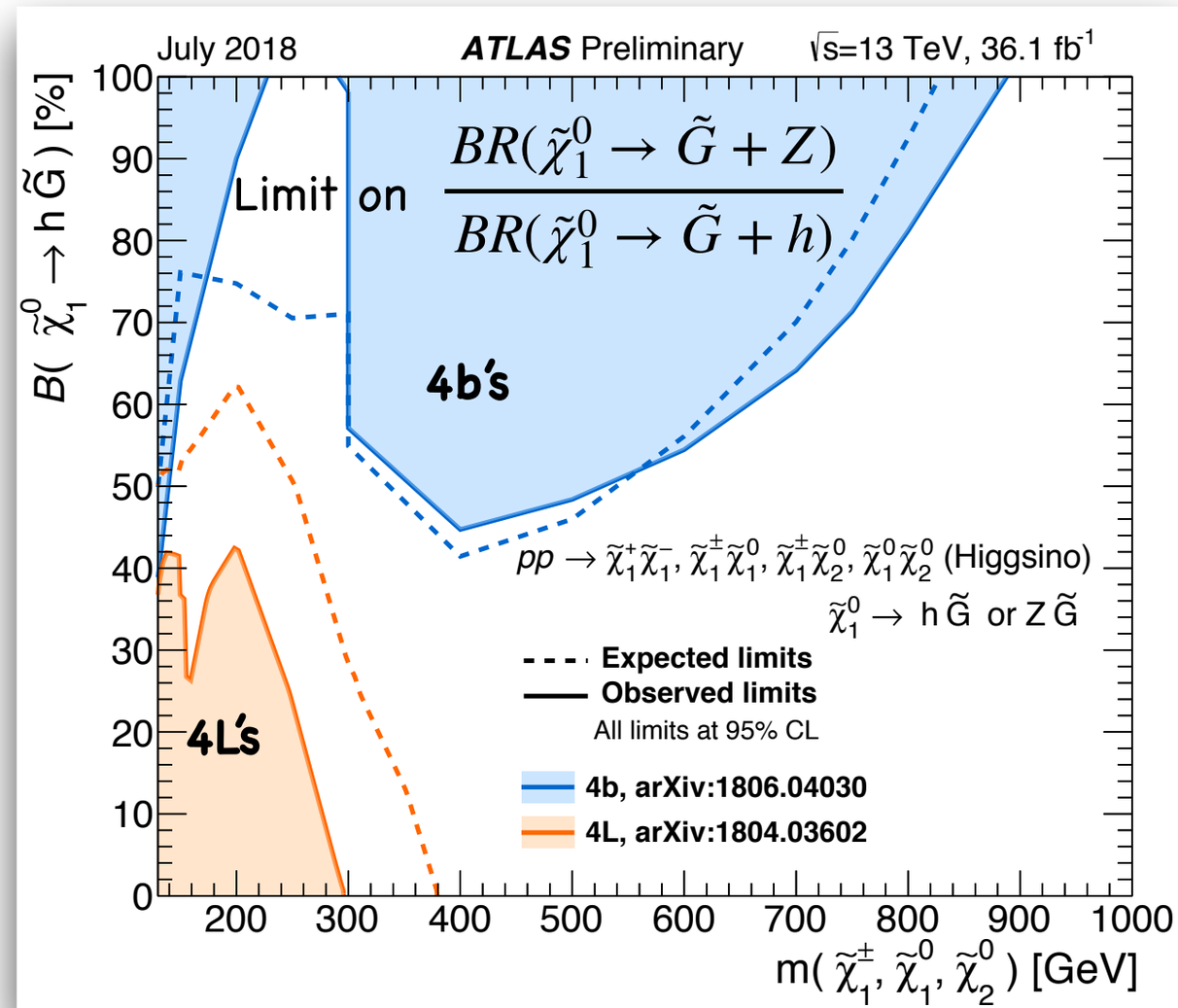


Interpretations

Pure Higgs decay

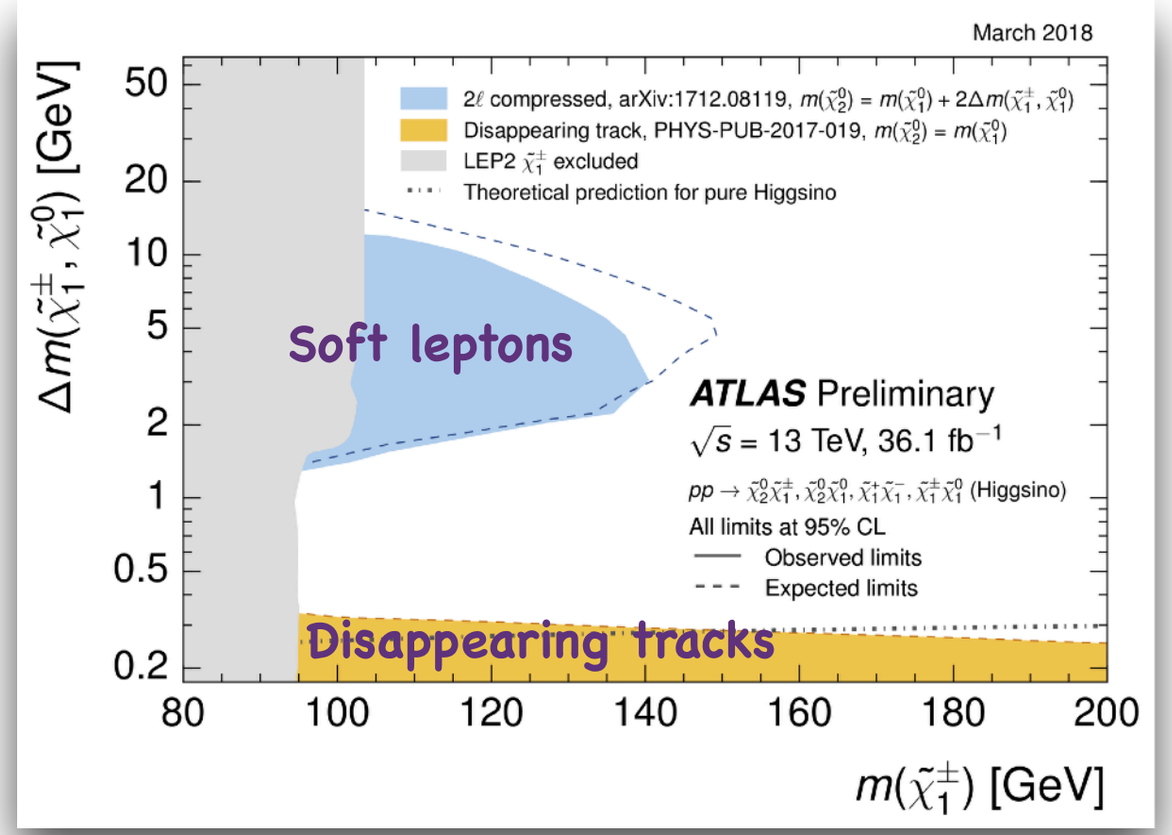


Variable Higgs/Z decay



Summary

- Light Higgsino searches well motivated by naturalness
- ATLAS has a strong program to search for Higgsino
- Multi-pronged approach with very challenging channels
  - Compress scenarios with very soft leptons, disappearing tracks
  - GMSB models sensitive to $BR(\tilde{\chi}_1^0 \to \tilde{G} + h)$
- With the LHC growing dataset, we now have exclusion starting to push beyond LEP limit from over a decay ago!




Thank You !
LOTTE WORLD

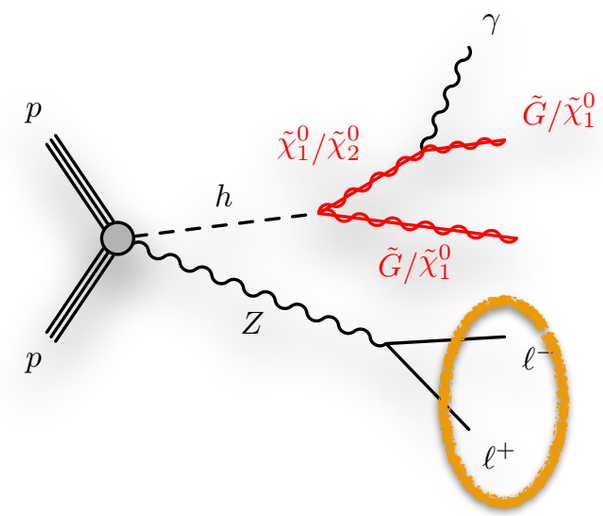
BACKUP

Search for Exotics Higgs Decays

- Bino LSP has no generic collider limit when wino/higgsino are decoupled
  Since it cannot be directly produced.
- But it can be generated from EWK higgs decay when it lighter than 125 GeV

GMSB/nMSSM decay of EWK higgs to NSLP+LSPs

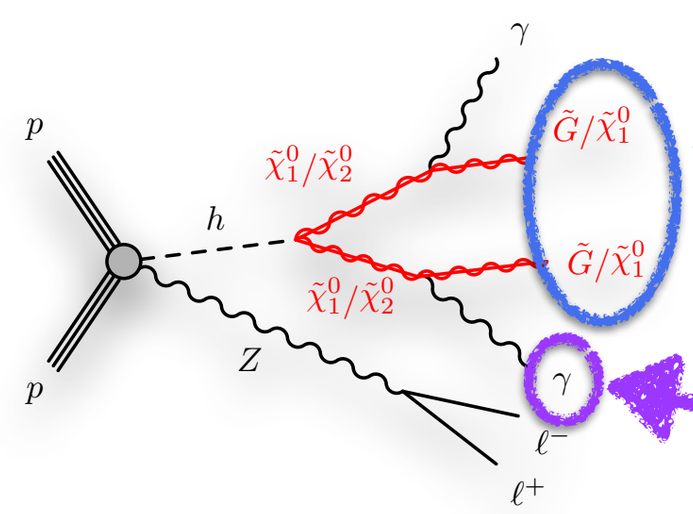
1 photon signature $m_h/2 < m_{\tilde{\chi}_1^0}\ (m_{\tilde{\chi}_2^0})$



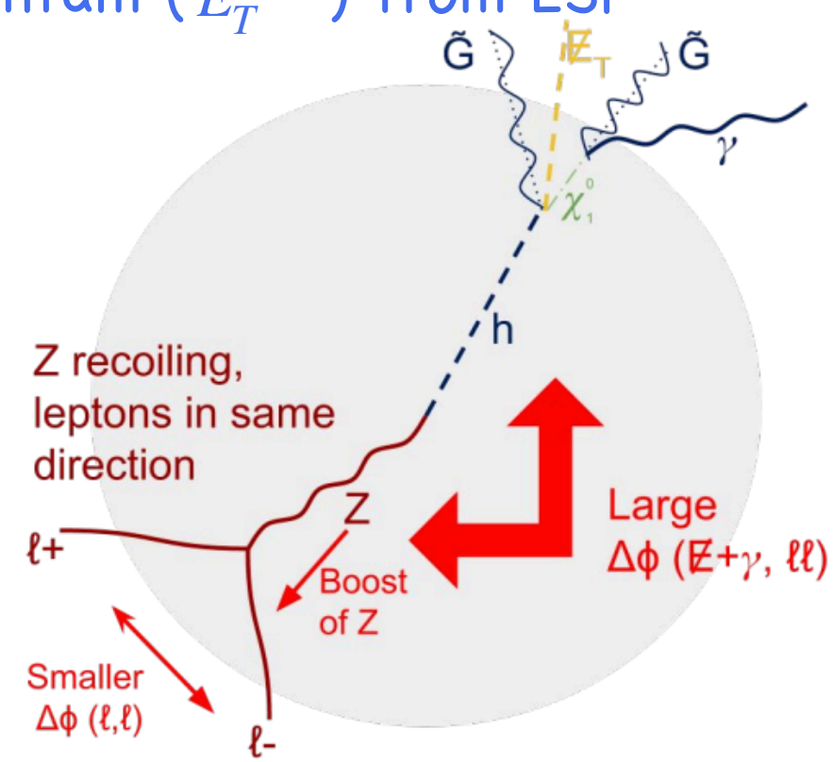
On-shell Z balancing the $\gamma + E_T^{\text{miss}}$ system

2 photons signature $m_{\tilde{\chi}_1^0}\ (m_{\tilde{\chi}_2^0}) < m_h/2$

Missing transverse momentum (E_T^{miss}) from LSP



At least 1 photon
No jet activity



NLSP neutralinos (bino-like neutralinos)
LSP gravitino (singlino-like neutralino)

ATLAS-CONF-2018-019

Backgrounds

- **95% of the background originate from fake photon**
  - **Data driven estimate**

Electron faking photon (~70%)

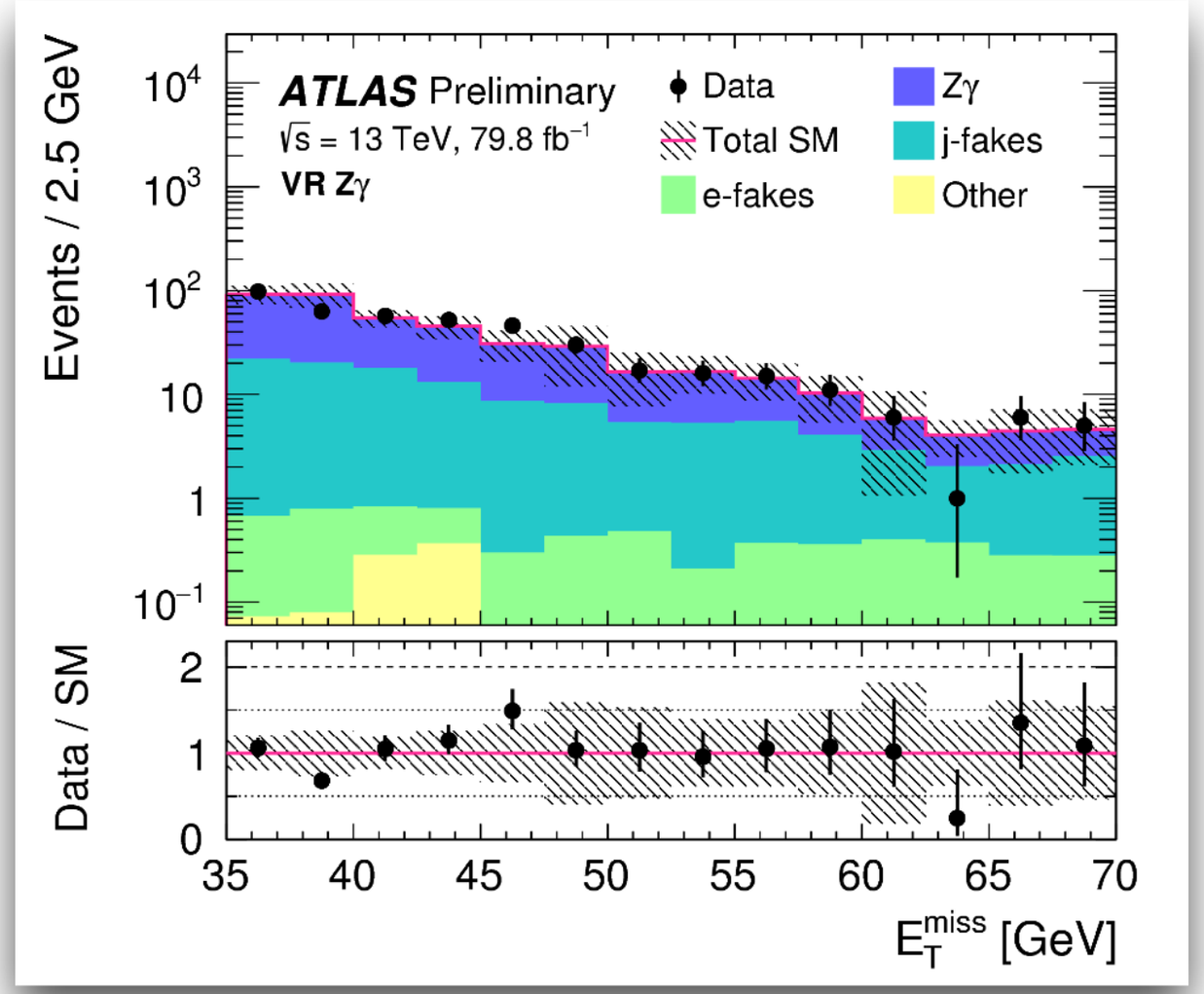
- Source: WZ→eνll
- Fake factor method using Z→ee data events

Jet faking photon (~30%)

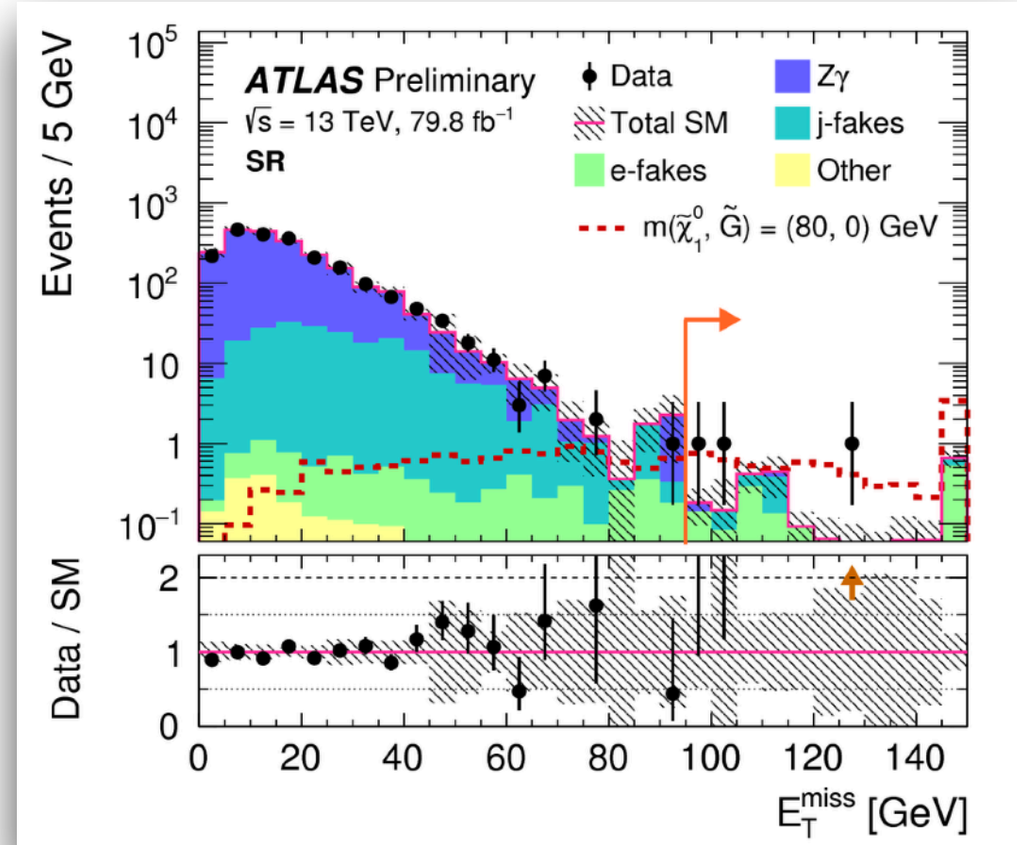
- Source: Z+jets (VV+jets, ttbar)
- ABCD method using loosely ID-ed or non-isolated photons

Validation:

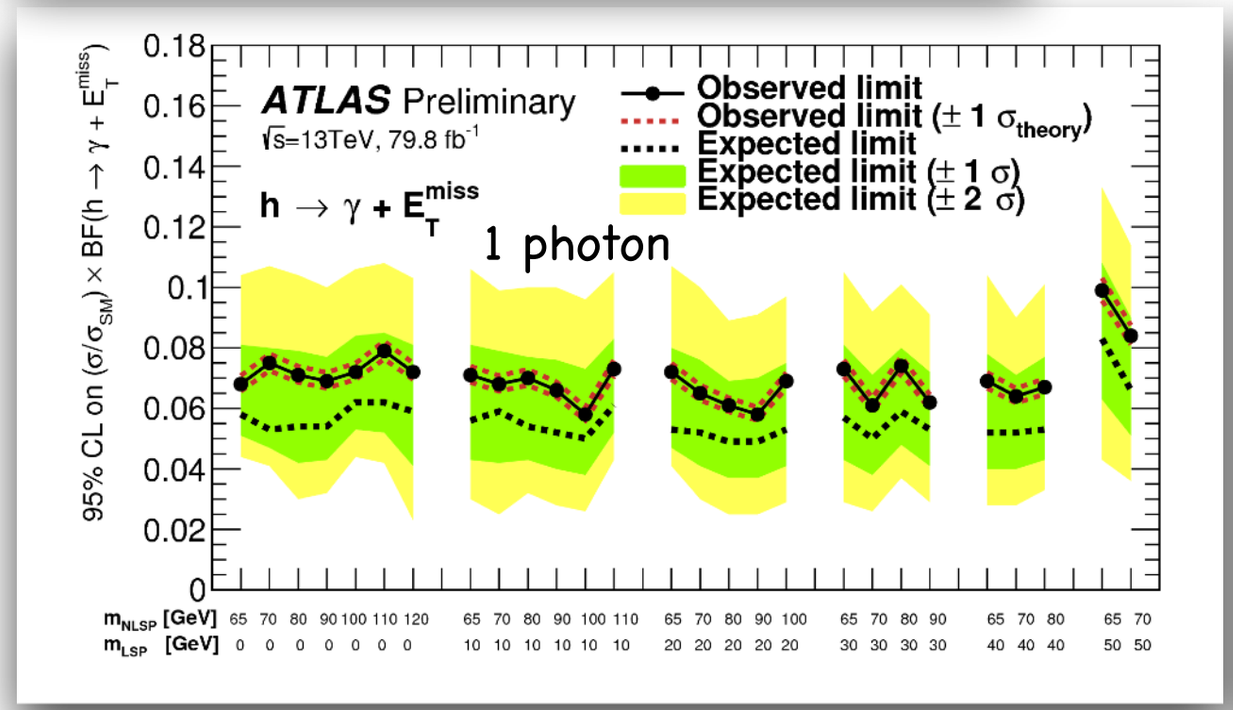
- e→γ estimation validated using WZ CR and MC closure test
- Other background (<5%) are tested in Vars

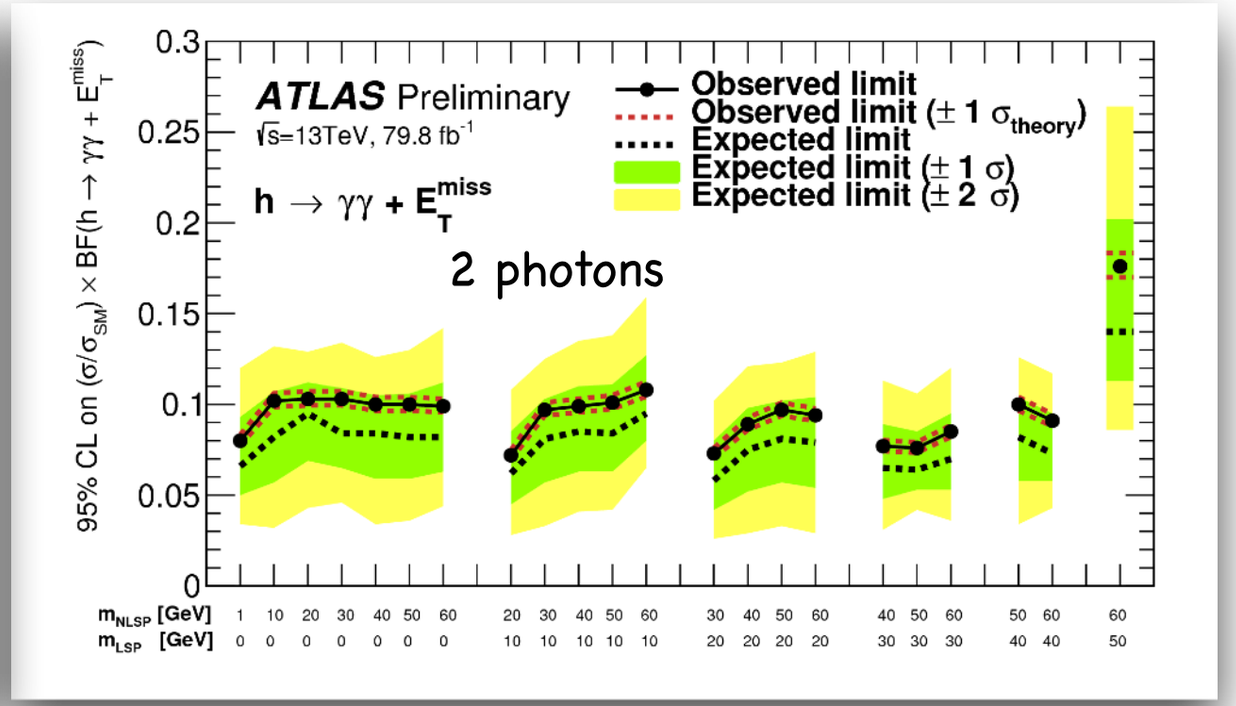


Results

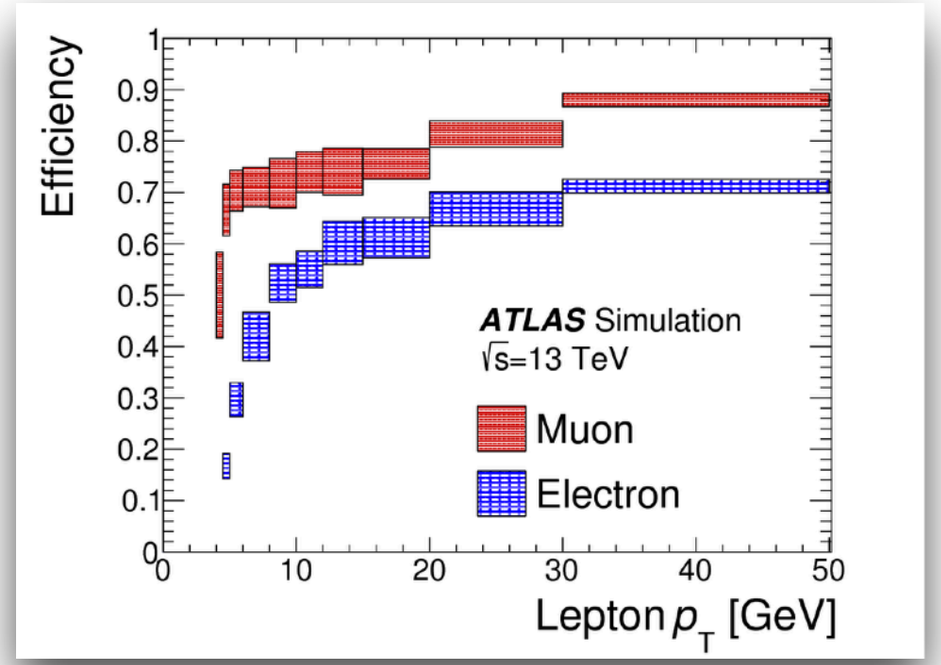


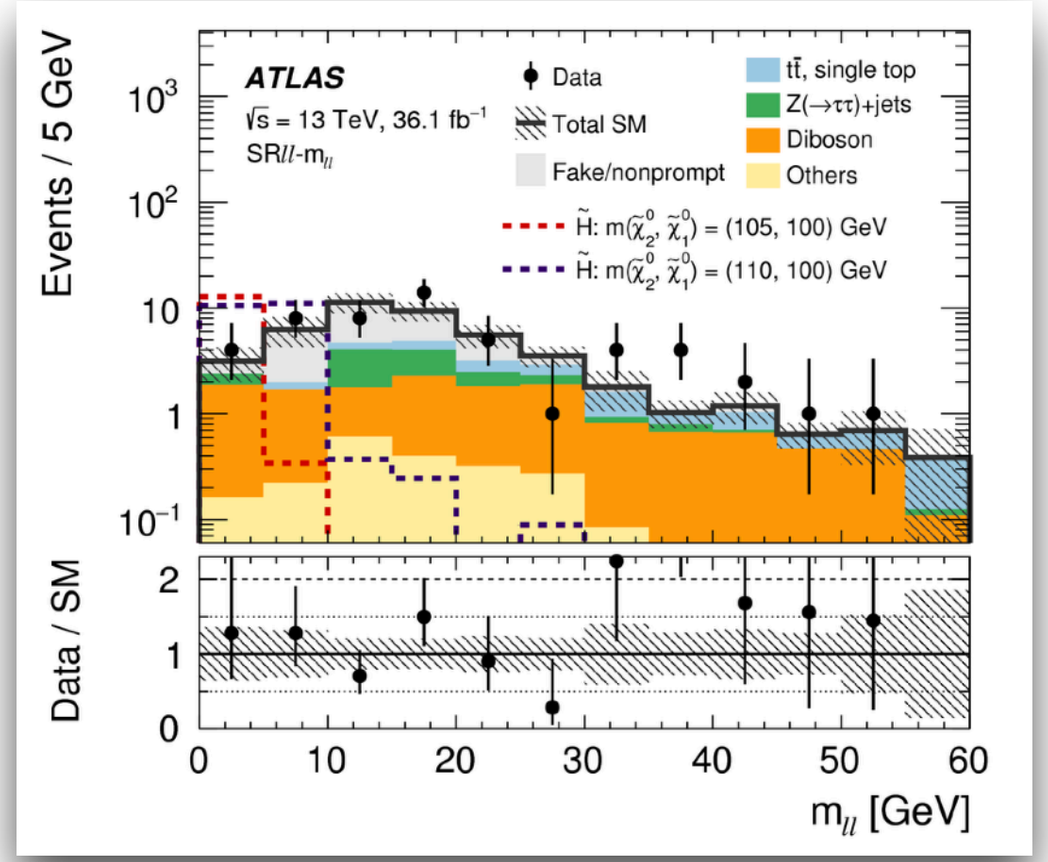
- No significant excess observed
- Setting limit on higgs branching ratio
  - Assume GMSB kinematics for signal
  - Constraint down to 7-10%
  - Significant improvement from Run1 (10-60%)



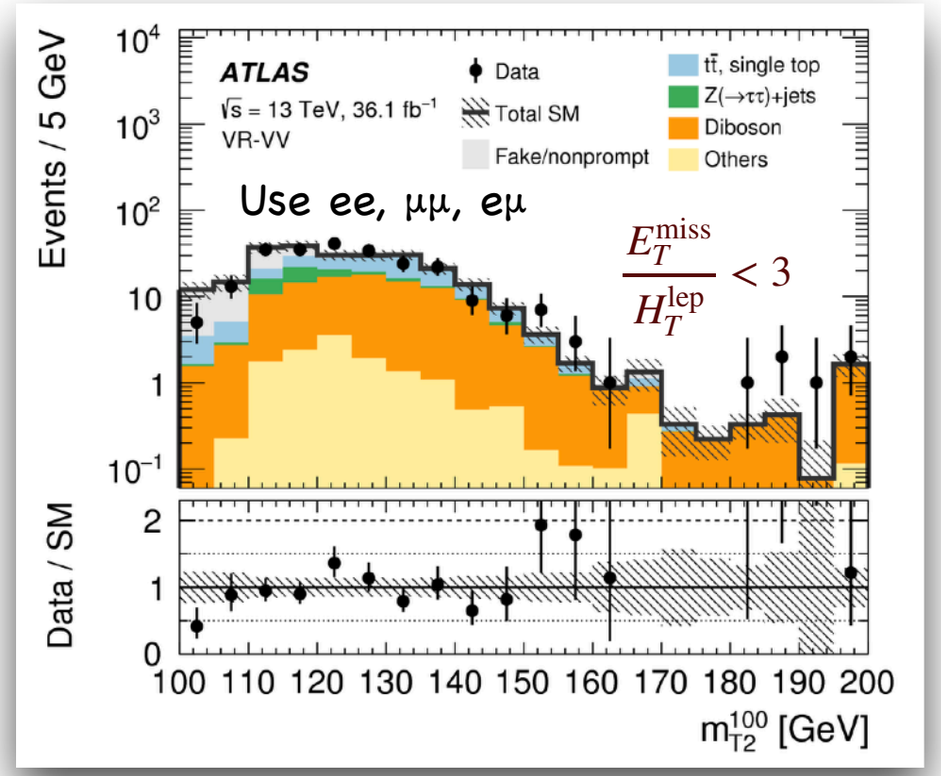


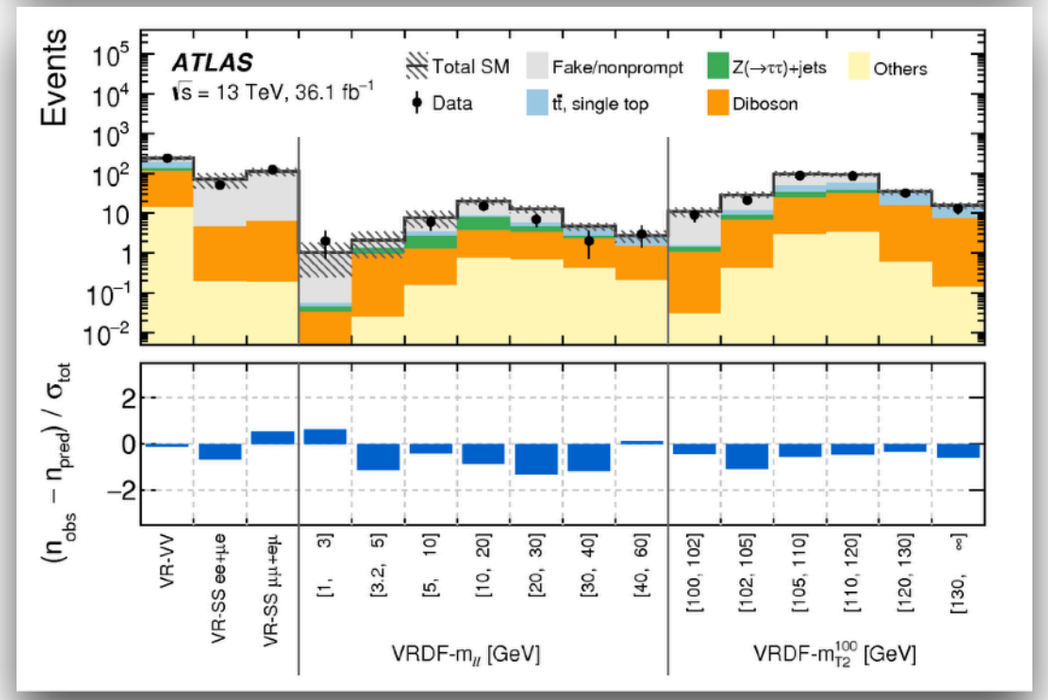
Soft Leptons





Dibosons: Validation regions (VRs) only

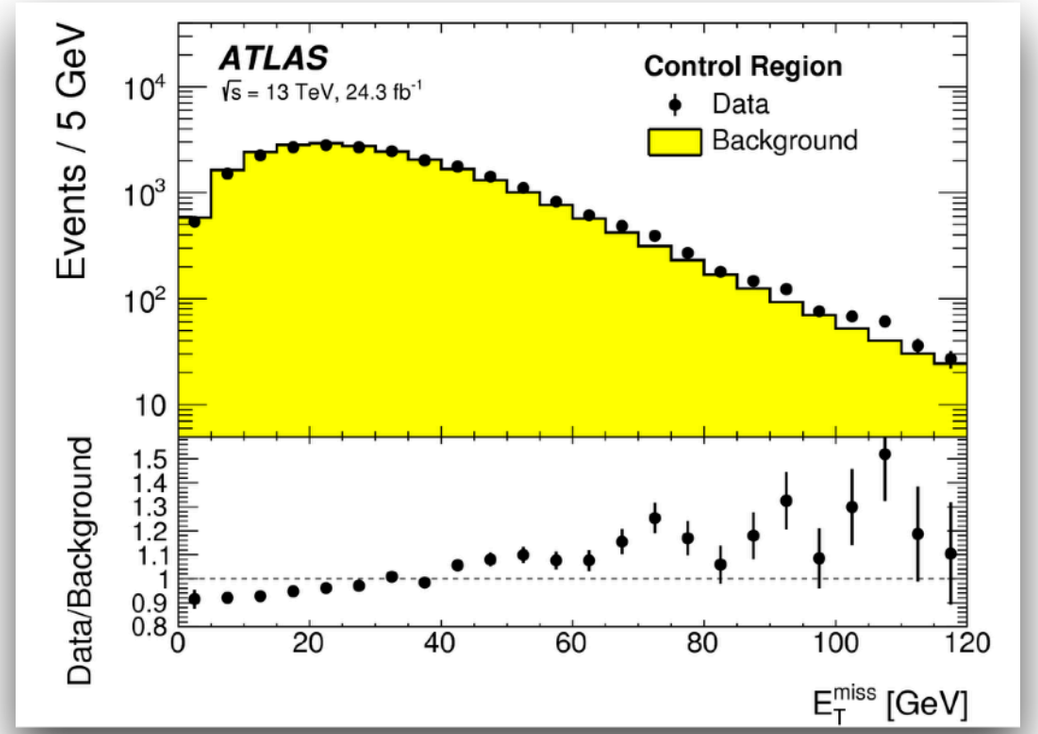




Analysis strategy: "Low-mass"

$m_{\tilde{H}} < 300$ GeV

- **Main background from multi jet events. Use fully data driven method**
- **Design BDT to reweigh data from 2 b-tags regions to 4 b-tags regions**
  - **Differences arises due to b-tag efficiency, c/LF jet mistag, multi jet processes composition and trigger**
  - **Trained in 2 & 4 b-tags CRs and validated in VRs**
  - **Background in the 4 b-tags SR determined from data in 2 b-tag "SR" and using reweighting BDT**



BDT