Pushing the boundaries - Standard Model and Beyond at LHC
18-20 September 2019, Institute for Particle Physics Phenomenology, Durham, UK

Search for chargino and neutralino production in final state with three leptons and missing transverse momentum, via intermediate SM bosons

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ATLAS EXPERIMENT

Outline

- Physics motivations and scenario of these searches
  - *What are the motivations?*
    - Where these analyses stand among all of the Beyond the Standard Model (BSM) searches
- Searches at Run2
  - *The state of the art*
    - First Run2 results of electroweak analyses with three leptons (3L) in the final state
      - Focus on W+h and W+Z mediated models
  - *Eye to the future*
    - Plans for the full Run2 analyses

On the quest for EWK SUSY

Physics scenario

Searching for New Physics with SUSY

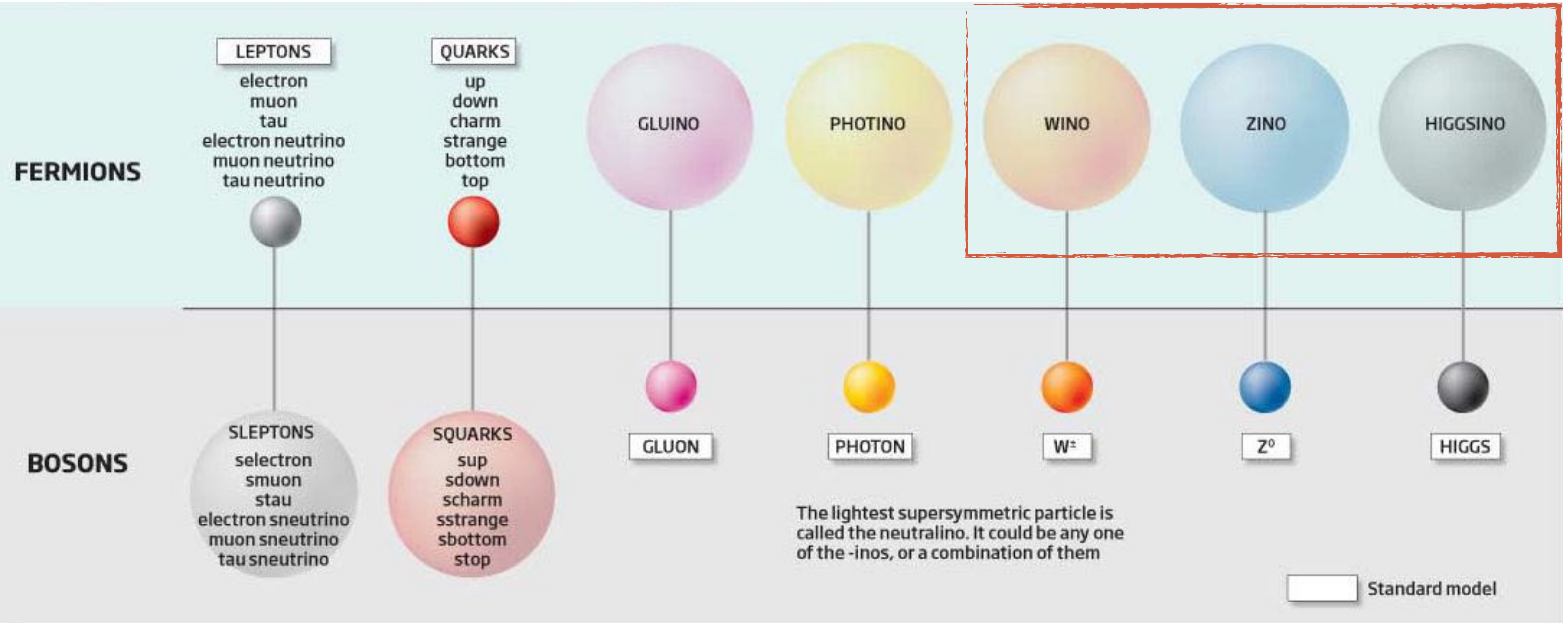
- Among all the possible BSM scenarios, SUSY is a ~~theory~~ principle which predicts a symmetry between fermions and bosons

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

B - baryonic number
L - leptonic number
s - spin

R-parity* conservation

- SUSY particles are produced in pairs and the Lightest SUSY Particle (LSP) is stable
- The weakly interacting lightest neutralino is often the stable LSP, hence it is a good Dark Matter candidate

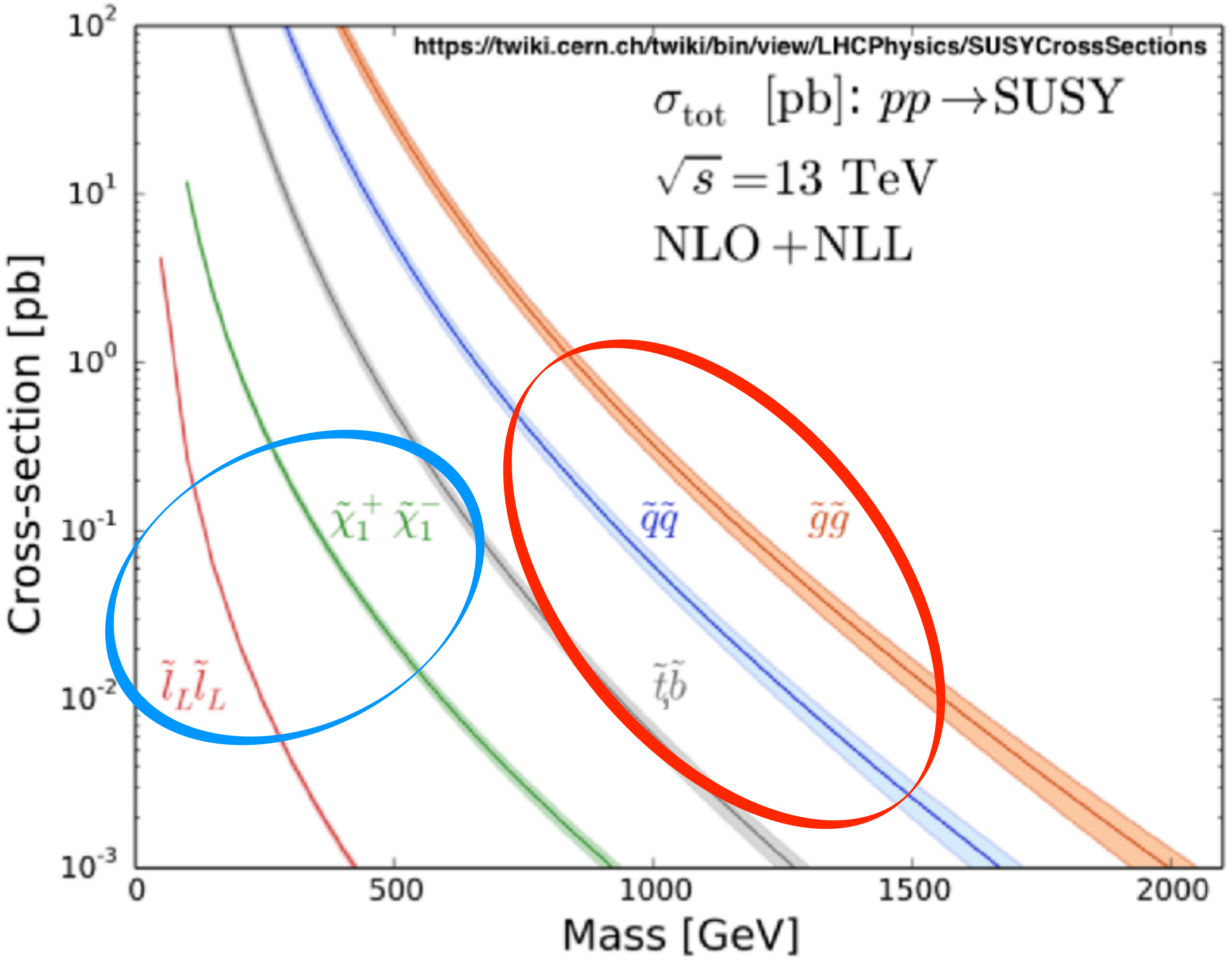


Winos, binos and higgsinos mix to form mass states charginos and neutralinos

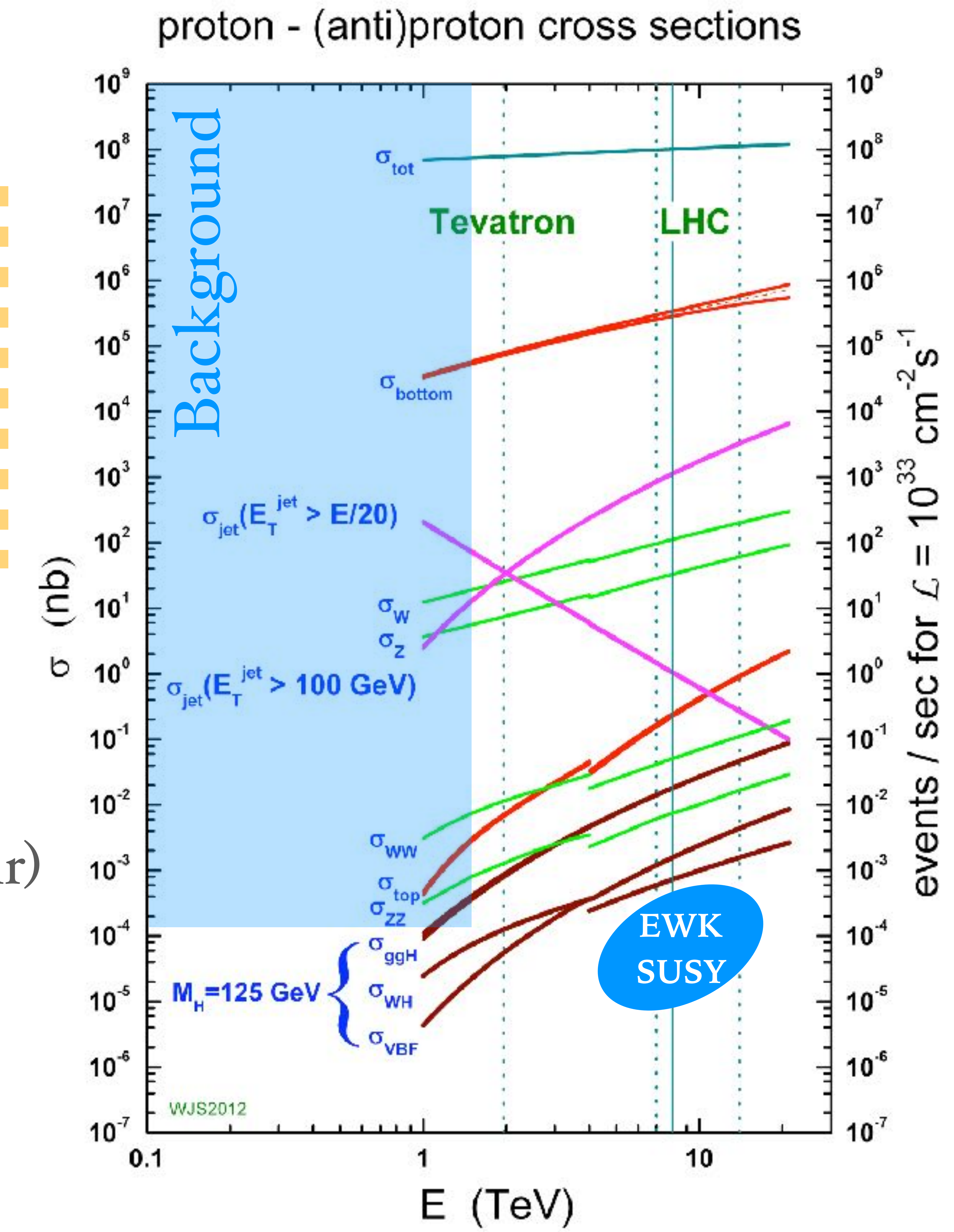
Why?

- SM hierarchy problem
- Dark matter
- Grand Unification
- It's beautiful!

Electroweak (EWK) SUSY al LHC and ATLAS



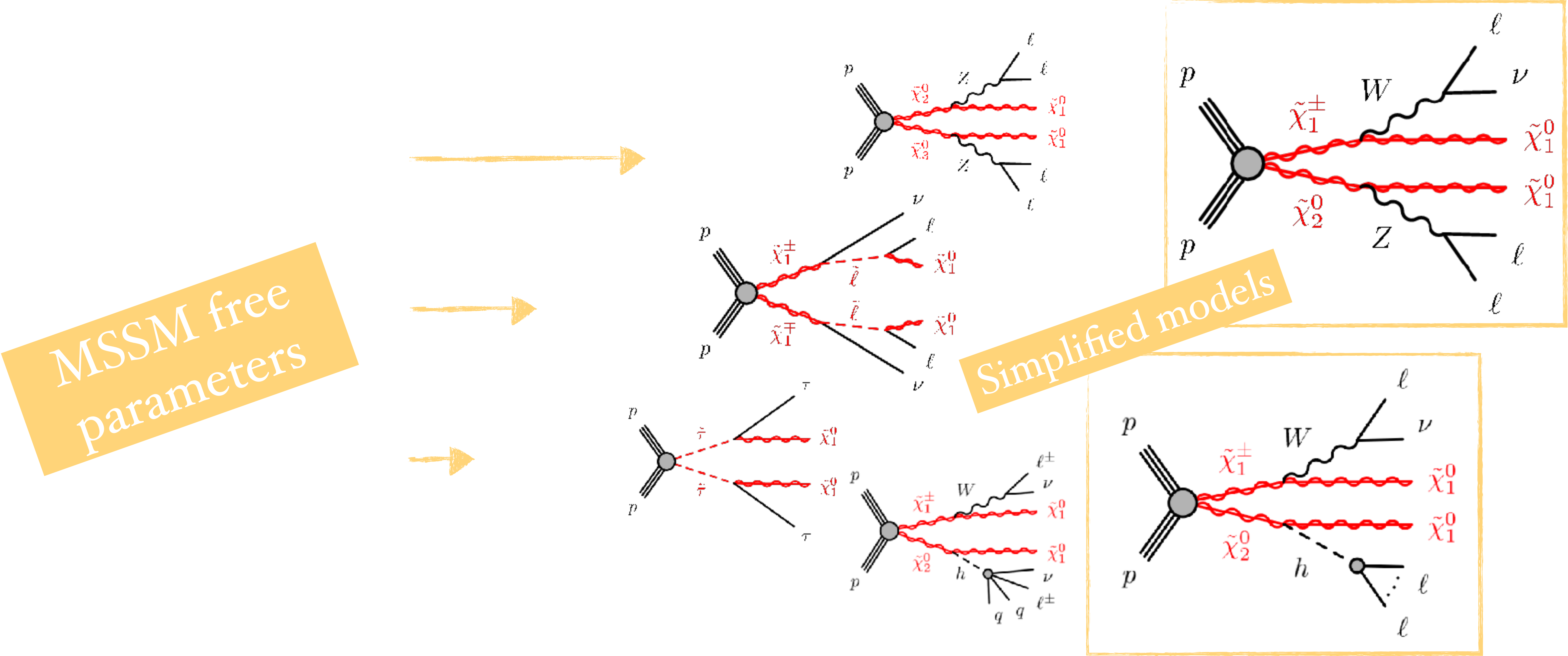
Control and suppression of Standard Model background processes is a crucial step in any SUSY analysis



- Electroweak production cross-section (e.g, chargino/neutralino pair) lower than for Strong production
- If squarks and gluinos are very heavy (as recent results suggest), EWK production becomes dominant if chargino and neutralinos masses around electroweak scale (naturalness considerations)

From MSSM to simplified models

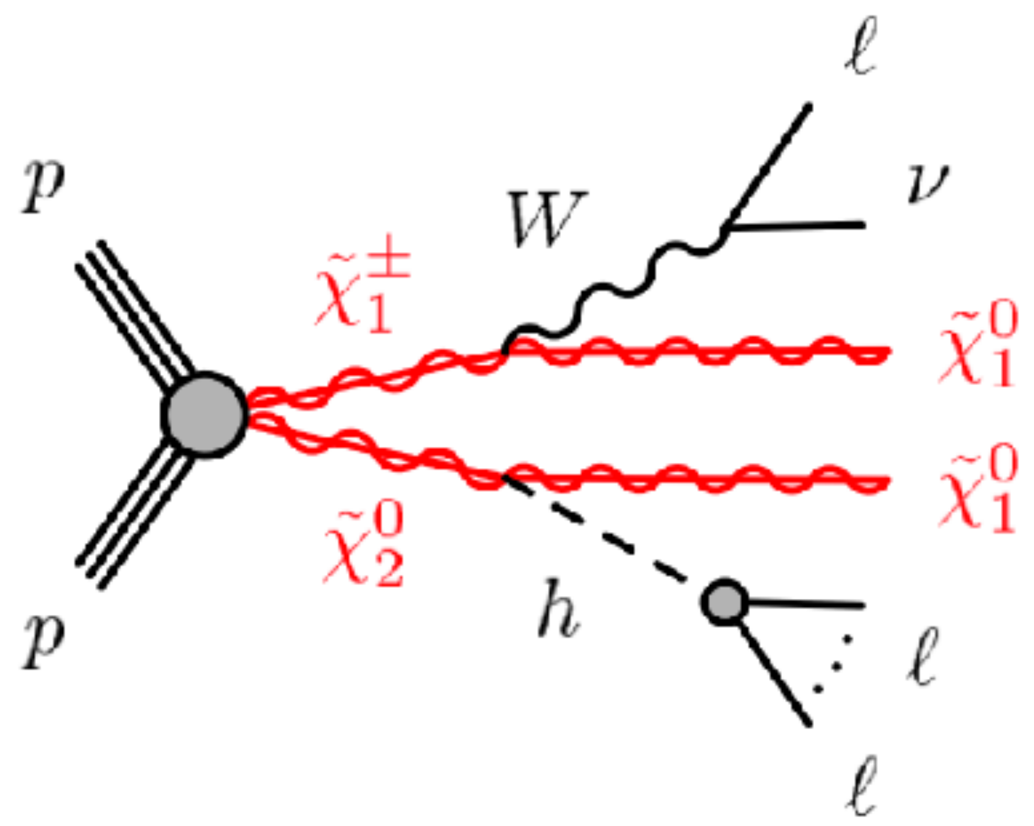
- In a simplified model, some parameters of the MSSM are fixed and others (some SUSY particle masses) are allowed to vary; individual channels are then explored one-by-one



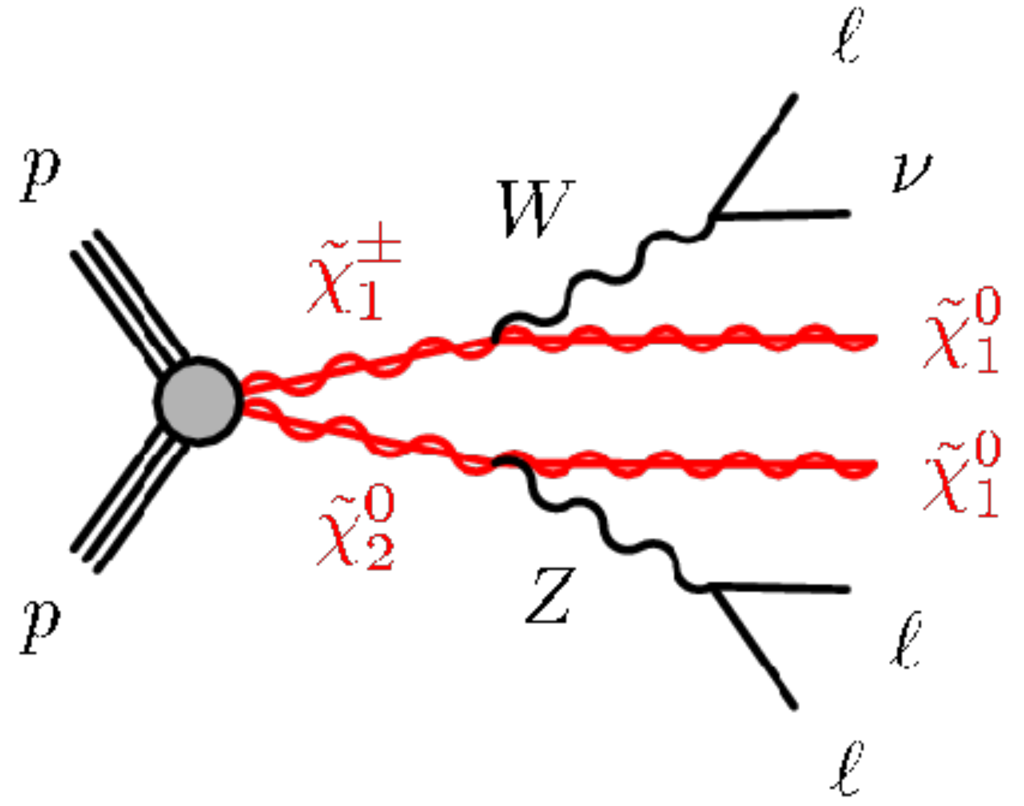
Chargino/neutralino decays via SM bosons

- RPC simplified model of production of mass degenerate chargino/neutralino, decaying to Standard Model bosons and lightest neutralinos (assumed 100% BR)

- Decays via Wh or WZ are dominant for various choices of SUSY parameters
  - If mass-splitting of the two lightest neutralinos allows Higgs boson mass to be on-shell, this becomes dominant
  - Chargino/neutralino are mostly winos



- Possible signatures depend on the SM particles the bosons decay into
  - e.g., multileptonic: such as 3L
    - Allow the exploration of lower mass-splittings for lower values of the transverse momenta of final-state leptons



Analysis strategy: "conventional" approach

Signal regions (SRs)

Cut-n-count **optimisation** of cuts that permit a good signal/background discrimination

Control regions (CRs)

Control of **irreducible background** in dedicated background-dominated regions

Fake/non-prompt (FNP)

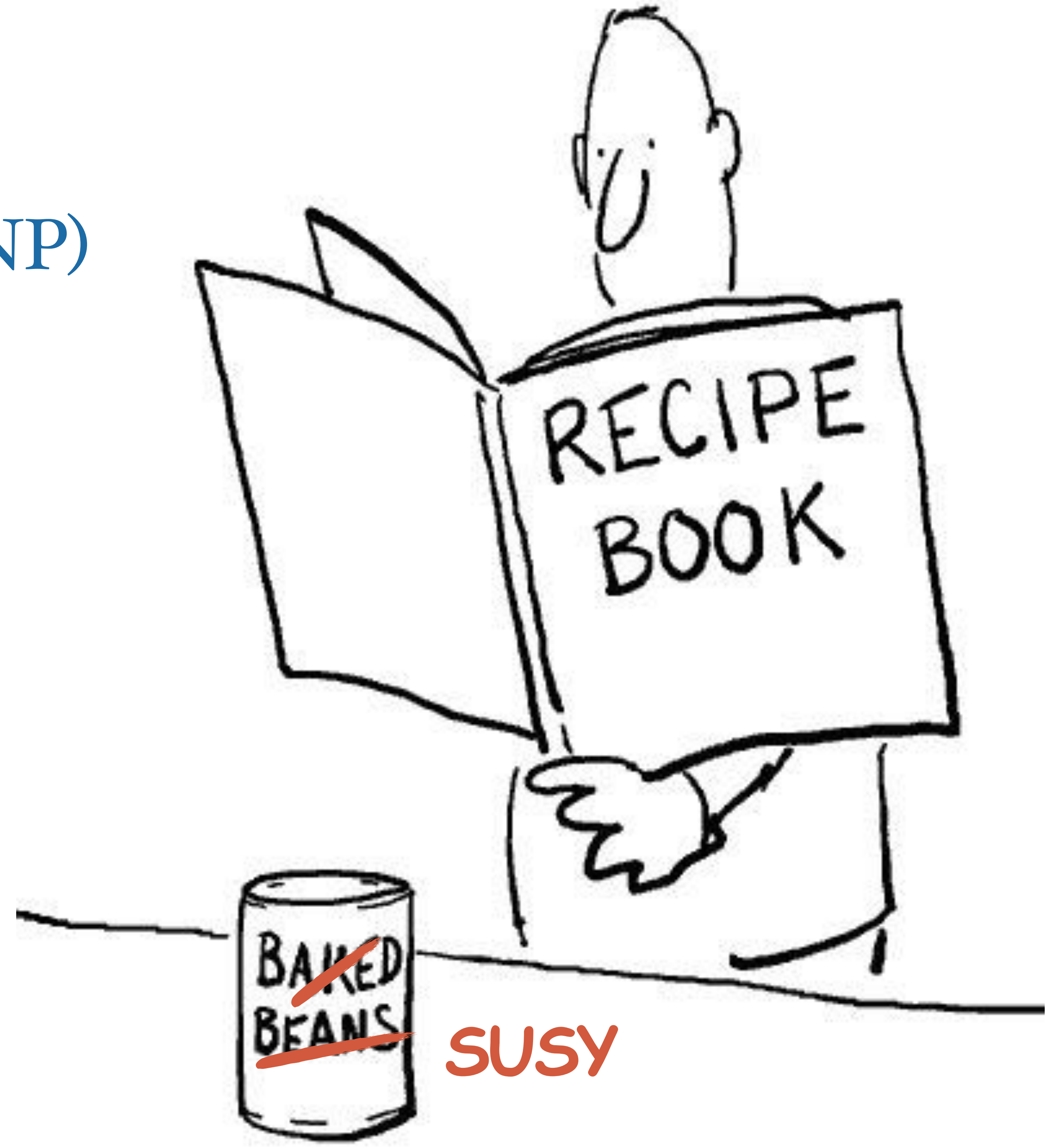
Estimation of **reducible background** with dedicated data-driven techniques

Validation regions (VRs)

Validation of background estimation

"**Unblinding**"

look for data excesses in the signal regions



The state of the art

First Run2 analyses results

Eur. Phys. J. C 78 (2018) 995

*Phys. Rev. D **100**, 012006*

WZ3L event selection

- Selection for the WZ analysis is the Same-Flavour Opposite-Sign (SFOS) flavour-sign combination
  - The invariant SFOS mass is selected in a 20 GeV window around the Z boson mass
  - Further binning using jet multiplicity, missing energy (MET) and transverse mass
- Main sources of SM background
  - Diboson WZ (dominant) → **Irreducible**
  - Z boson + jets → **Reducible**

Eur. Phys. J. C 78 (2018) 995

3ℓ exclusive signal region definitions

m_{SFOS} [GeV]	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$p_{\mathrm{T}}^{\ell_3}$ [GeV]	$n_{\text{non-}b\text{-tagged jets}}$	$m_{\mathrm{T}}^{\mathrm{min}}$ [GeV]	$p_{\mathrm{T}}^{\ell\ell\ell}$ [GeV]	$p_{\mathrm{T}}^{\mathrm{jet1}}$ [GeV]	Bins
81.2–101.2	60-120 120–170 > 170		0	> 110			SR3-WZ-0Ja SR3-WZ-0Jb SR3-WZ-0Jc
81.2-101.2	120–200 > 200	 > 35	≥ 1	> 110 110 160 > 160	< 120	> 70	SR3-WZ-1Ja SR3-WZ-1Jb SR3-WZ-1Jc

Background estimation for WZ3L

- Cross-section of irreducible background WZ is normalised in a dedicated CR
- FNP estimated with the Fake Factor (FF) Method, which relates the number of events with FNP leptons to the number of events with at least a "loose" lepton

Fake Factor Method

$$FF = \frac{N_{ID}}{N_{antiID}}$$

1) FF calculated in a fake-enriched region

$$N_{TTT}^{FNP} = FF_1(N_{LTT} - N_{LTT}^{MC\ prompt}) + FF_2(N_{TLT} - N_{TLT}^{MC\ prompt}) + FF_3(N_{TTL} - N_{TTL}^{MC\ prompt})$$
$$-FF_1FF_2(N_{LLT} - N_{LLT}^{MC\ prompt}) - FF_2FF_3(N_{TLL} - N_{TLL}^{MC\ prompt}) - FF_1FF_3(N_{LTL} - N_{LTL}^{MC\ prompt})$$
$$+FF_1FF_2FF_3(N_{LLL} - N_{LLL}^{MC\ prompt})$$

2) FF used to calculate fake contribution using events with at least one loose/antiID lepton

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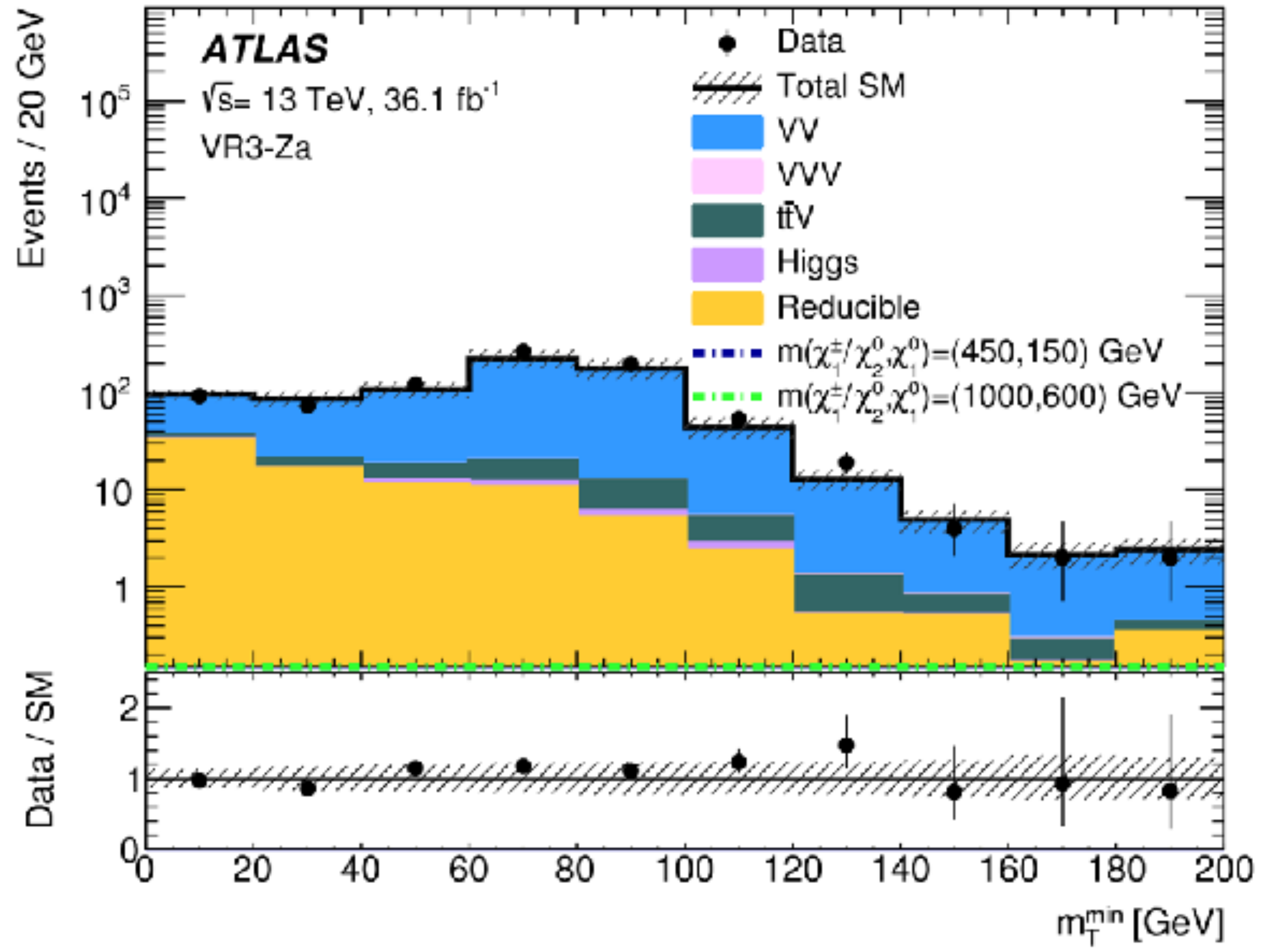

3) Validation again data in VRs close to SRs

Results for WZ3L analysis

- No excess observed with respect to SM prediction :(

SR3-	WZ-0Ja	WZ-0Jb	WZ-0Jc	WZ-1Ja	WZ-1Jb	WZ-1Jc
Observed	21	1	2	1	3	4
Total SM	21.7 ± 2.9	2.7 ± 0.5	1.56 ± 0.33	2.2 ± 0.5	1.82 ± 0.26	1.26 ± 0.34
WZ	19.5 ± 2.9	2.5 ± 0.5	1.33 ± 0.31	1.8 ± 0.5	1.49 ± 0.22	0.92 ± 0.28
ZZ	0.81 ± 0.23	0.06 ± 0.03	0.05 ± 0.01	0.05 ± 0.02	0.02 ± 0.01	
VVV	0.31 ± 0.07	0.13 ± 0.04	0.13 ± 0.03	0.11 ± 0.02	0.12 ± 0.03	0.23 ± 0.05
$t\bar{t}V$	0.04 ± 0.02	0.01 ± 0.01	0.01 ± 0.01	0.14 ± 0.04	0.12 ± 0.02	0.08 ± 0.02
Higgs	–	–	–	0.01 ± 0.00	–	–
FNP	1.1 ± 0.5	0.02 ± 0.01	0.04 ± 0.02	0.11 ± 0.06	0.07 ± 0.04	0.01 ± 0.00

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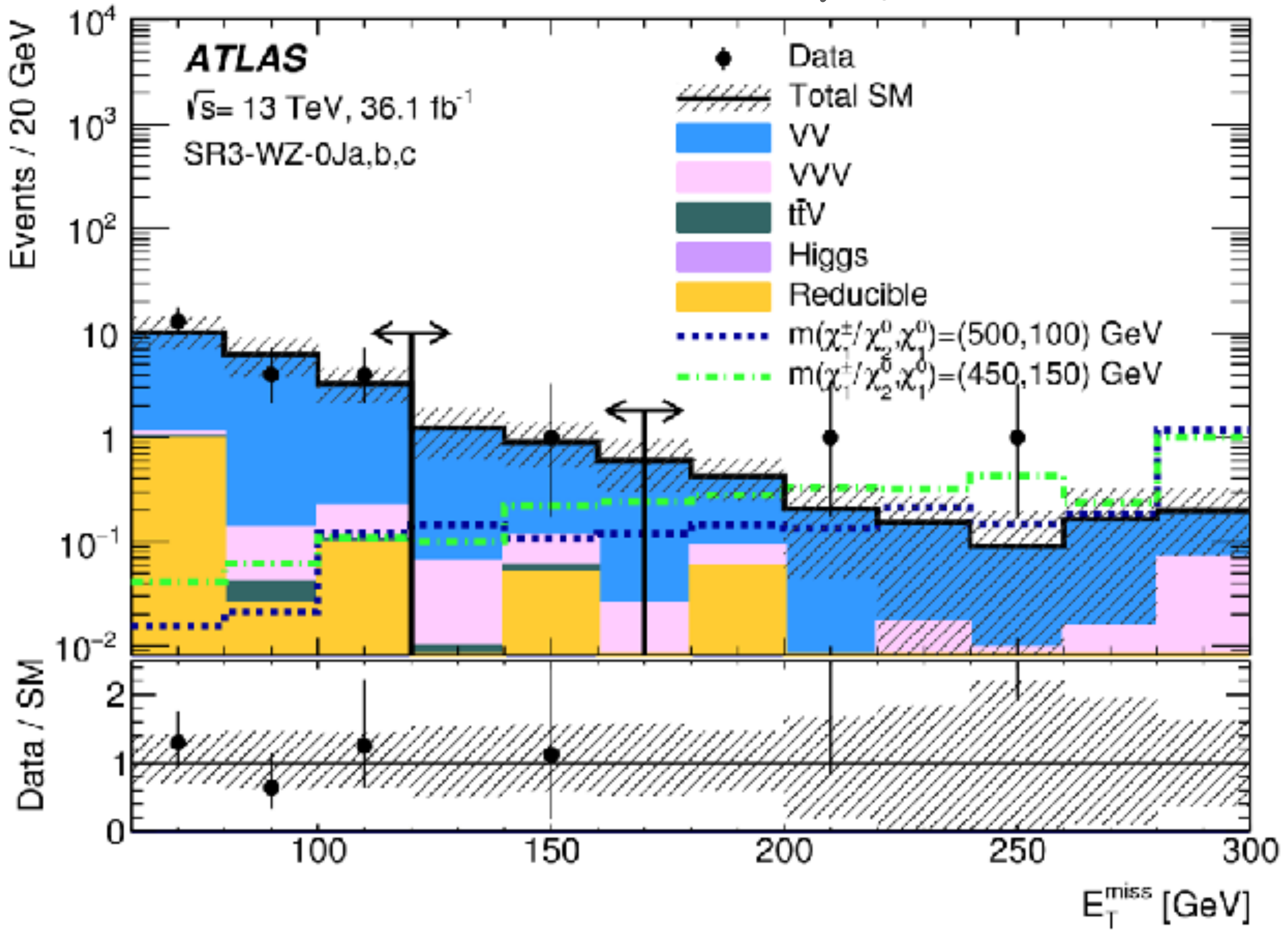

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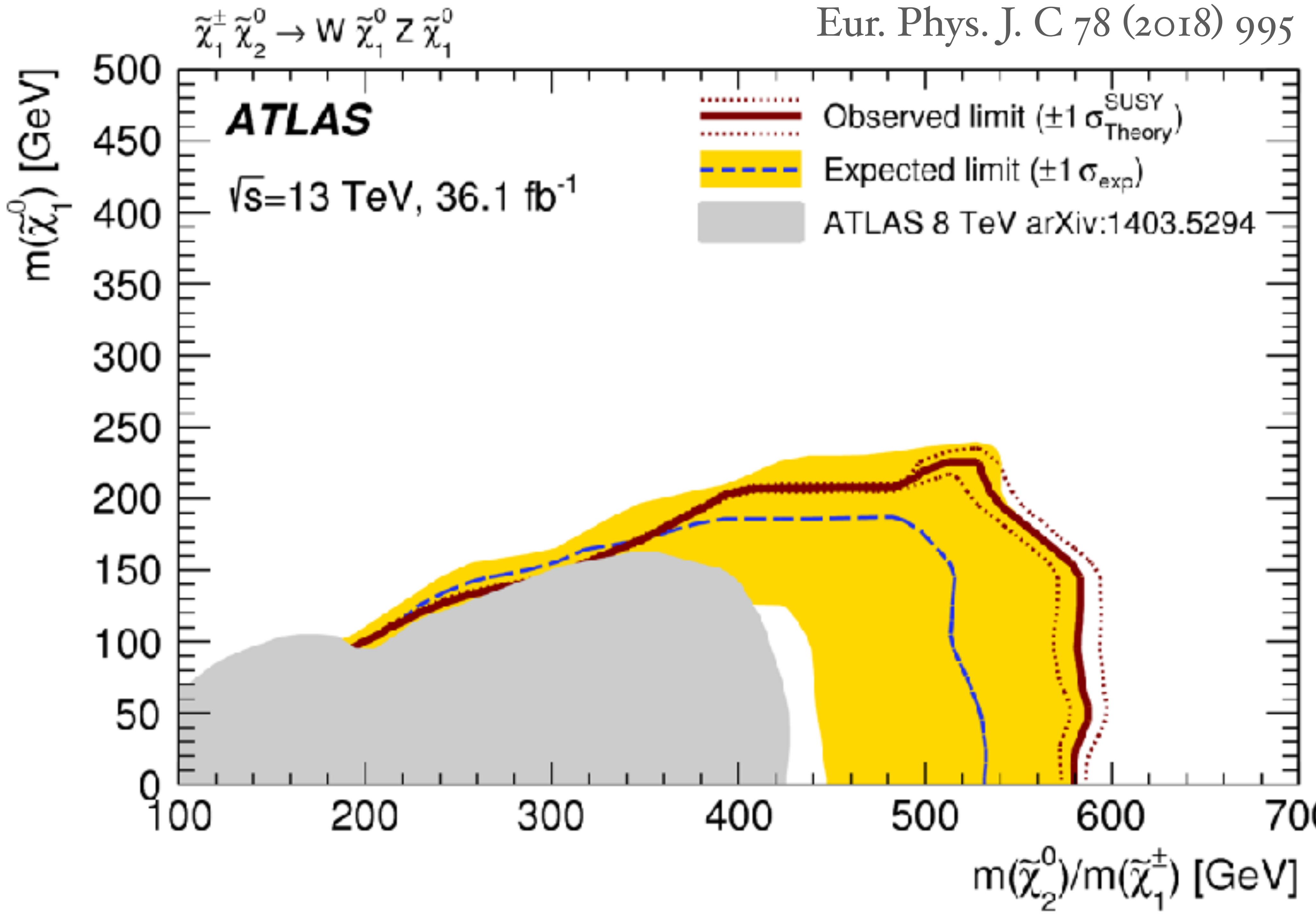


Wh3L event selection strategy

- Events with exactly three leptons are categorised into flavour and sign combinations
  - At least one pair of SFOS leptons, invariant mass outside a 20 GeV window around the Z boson mass
    - Diboson WZ (dominant) → **Irreducible**
    - Z boson + jets → **Reducible**
  - A pair of same-flavour and same-sign leptons, plus an additional lepton different-flavour and opposite sign (DFOS)
    - Pair production of top quarks → **Reducible**
    - Diboson WZ (not dominant) → **Irreducible**

Wh3L signal regions definition

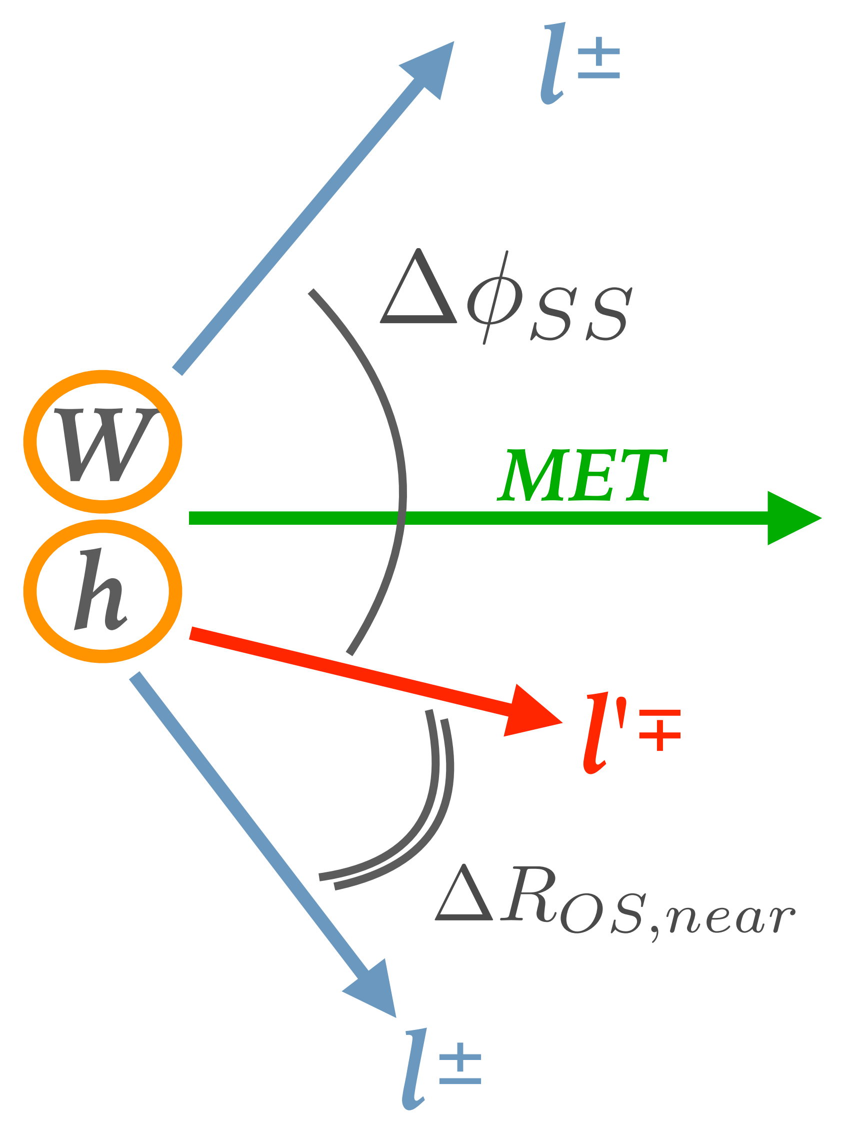
- Further binning is applied considering jet multiplicity and MET
  - For DFOS selection angular variables are used
  - For SFOS the transverse mass of the third lepton not in the SFOS pair is minimised

Phys. Rev. D 100 (2019) 12006

Variable	SR3L-DFOS-0J	SR3L-DFOS-1Ja	SR3L-DFOS-1Jb
N_{jet} ($p_{\text{T}} > 20\ GeV$)	$= 0$	> 0	> 0
$N_{b\text{-jet}}$	$= 0$	$= 0$	$= 0$
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 60	$\in [30, 100]$	> 100
$m_{\ell_{\text{DFOS}}+\ell_{\text{near}}}$ [GeV]	< 90	< 60	< 70
$\Delta R_{\text{OS,near}}$	-	< 1.4	< 1.4
$\Delta\phi_{\text{SS}}$	-	-	< 2.8

Phys. Rev. D 100 (2019) 12006

Variable	SR3L-SFOS-0Ja	SR3L-SFOS-0Jb	SR3L-SFOS-1J
N_{jet} ($p_{\text{T}} > 20\ GeV$)	$= 0$	$= 0$	> 0
$N_{b\text{-jet}}$	$= 0$	$= 0$	$= 0$
$E_{\text{T}}^{\text{miss}}$ [GeV]	$\in [80, 120]$	> 120	> 110
$m_{\text{T}}^{\text{min}}$ [GeV]	> 110	> 110	> 110
$m_{\text{SFOS}}^{\text{min}}$	$> 20\ GeV, \notin [81.2, 101.2]$	$> 20\ GeV, \notin [81.2, 101.2]$	$> 20\ GeV, \notin [81.2, 101.2]$



Background estimation for Wh3L

- Rate of irreducible background WZ is normalised in a dedicated CR
- Fakes are estimated with a data-driven technique (Dynamic Matrix Method), which relates the number of FNP leptons to the number of leptons which pass a specific tight or loose selection
  - Data-driven estimate is then validated in a dedicated fake enriched VR

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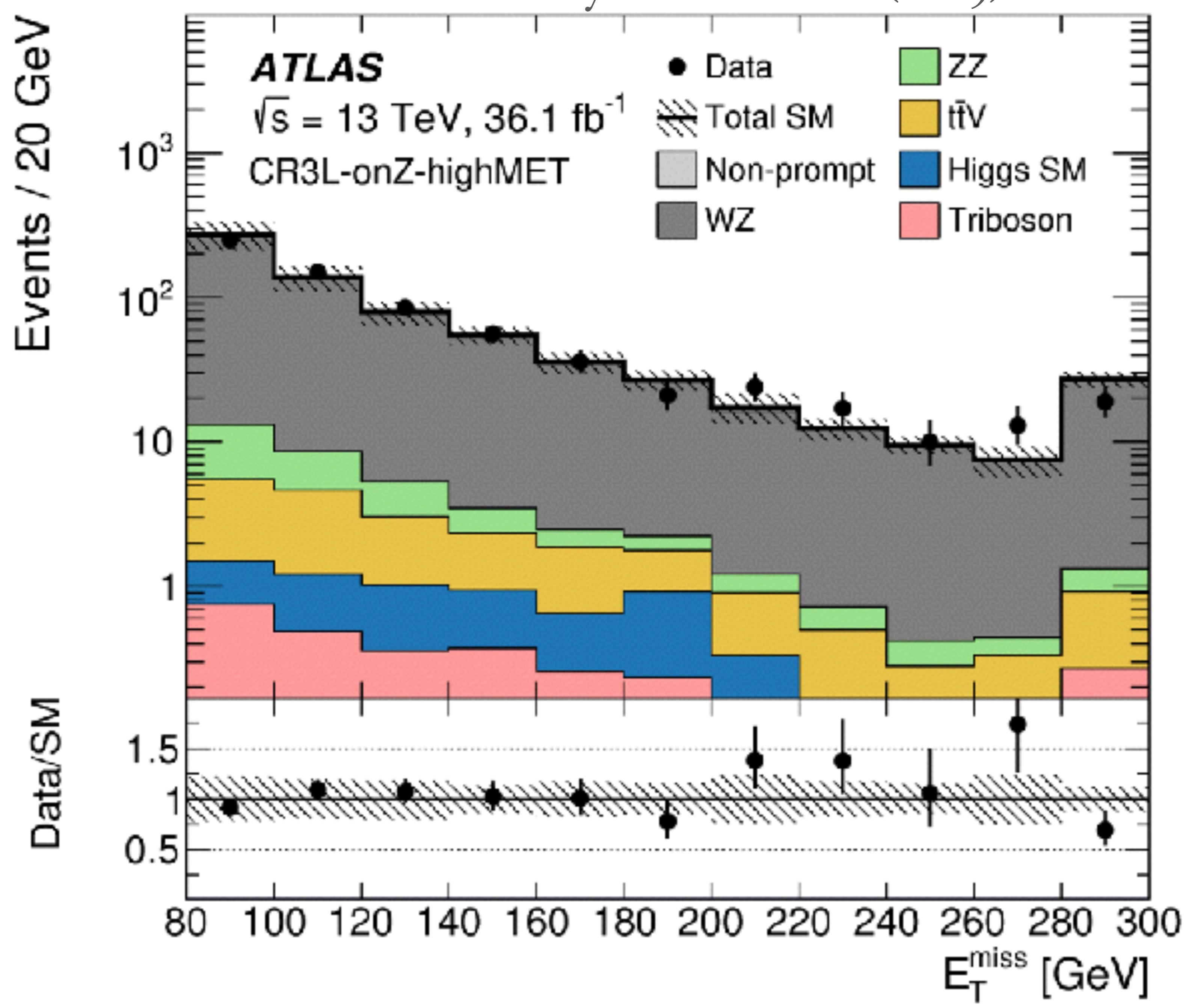

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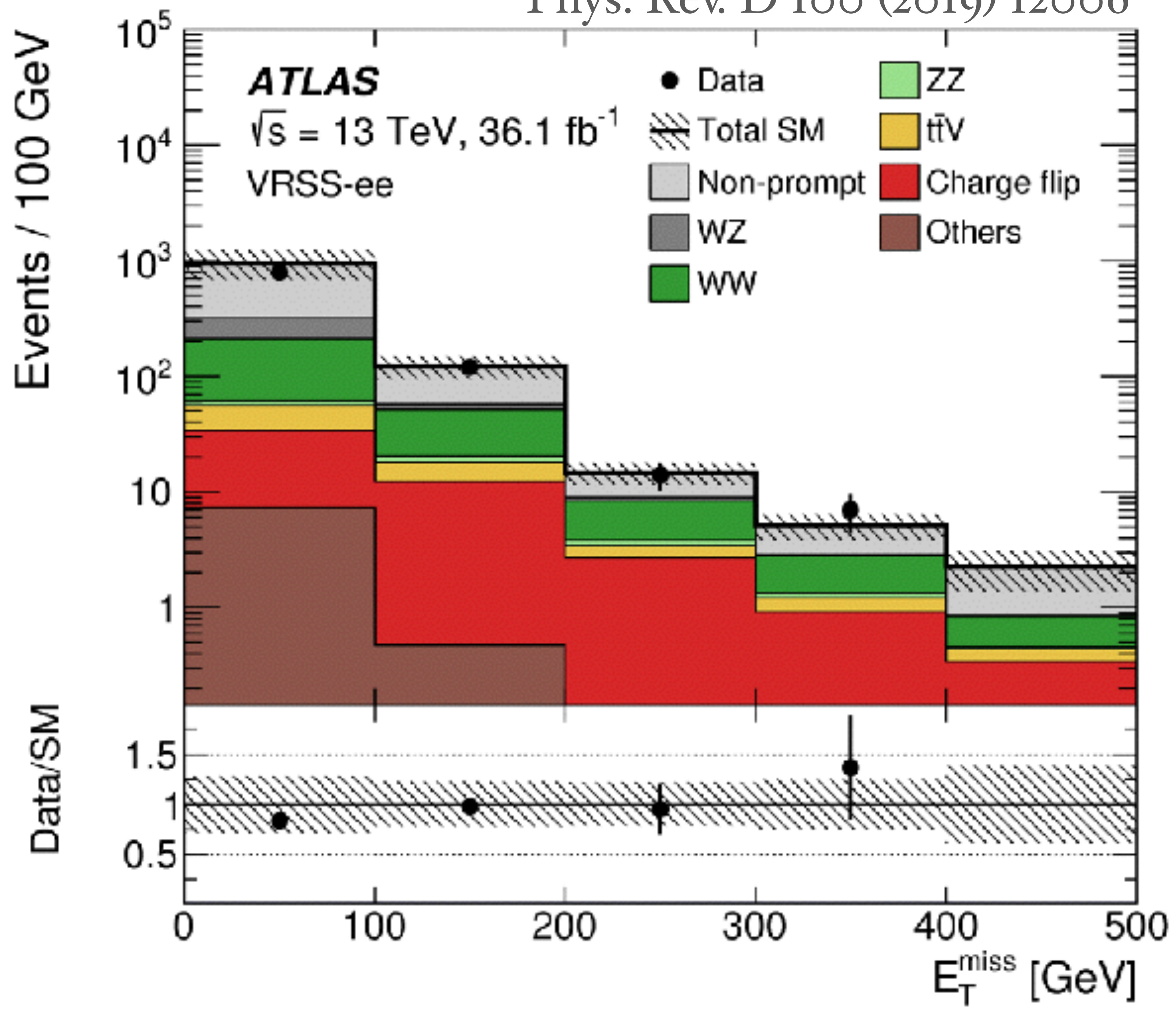

Results for Wh3L analysis

- No significant deviations from SM expectation found :(

SR channels	SR3L-DFOS-1Jb	SR3L-SFOS-1J
Observed events	1	11
Fitted bkg events	1.7 ± 0.7	11.5 ± 2.6
WZ	0.54 ± 0.16	7.4 ± 2.3
ZZ	0.03 ± 0.01	0.29 ± 0.09
$t\bar{t} + V$	0.43 ± 0.16	1.9 ± 0.5
Tribosons	0.23 ± 0.08	1.4 ± 0.4
Higgs SM	0.05 ± 0.04	1.4 ± 0.4
FNP	$0.4^{+0.6}_{-0.4}$	$0.4^{+0.5}_{-0.4}$

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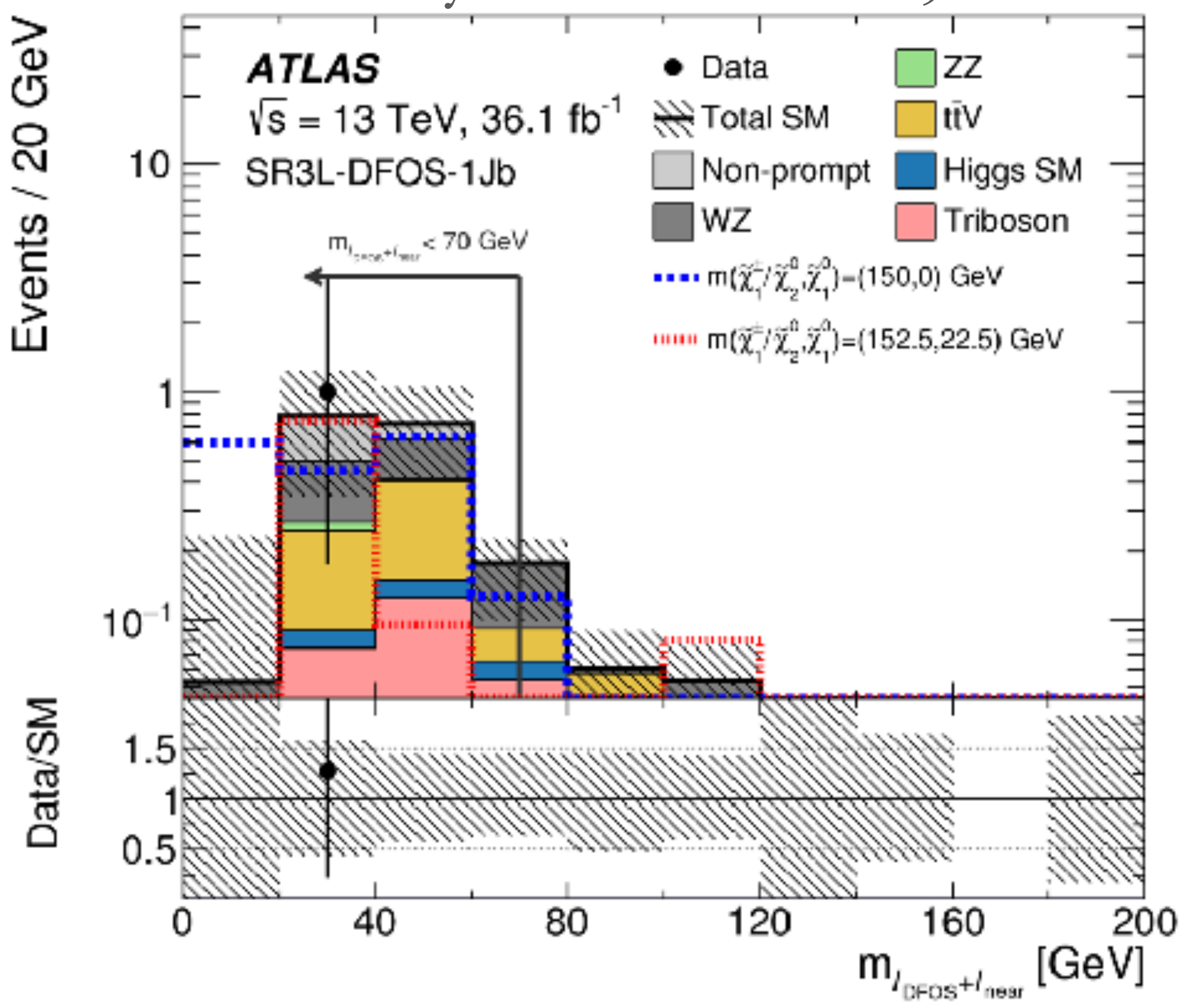

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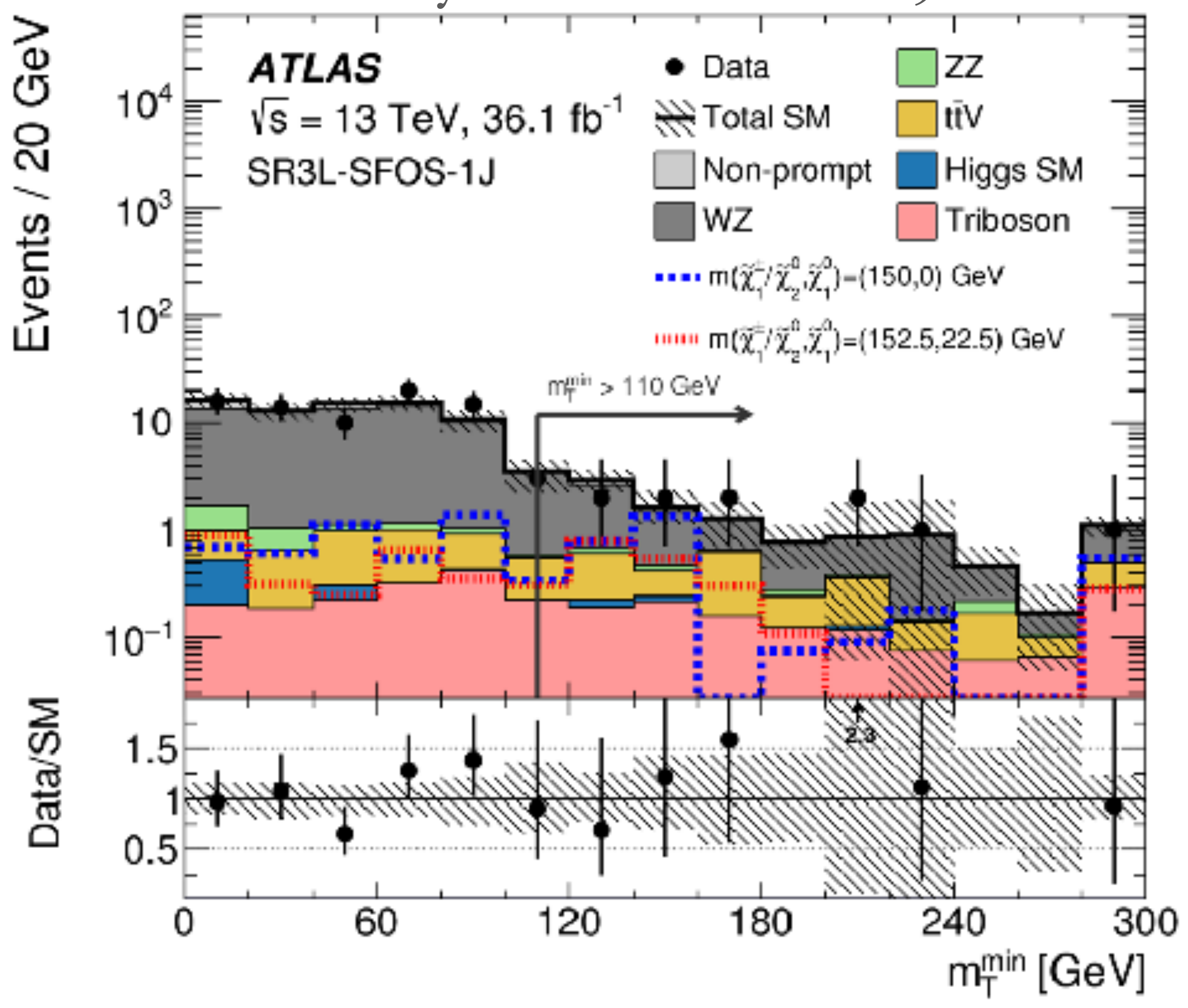

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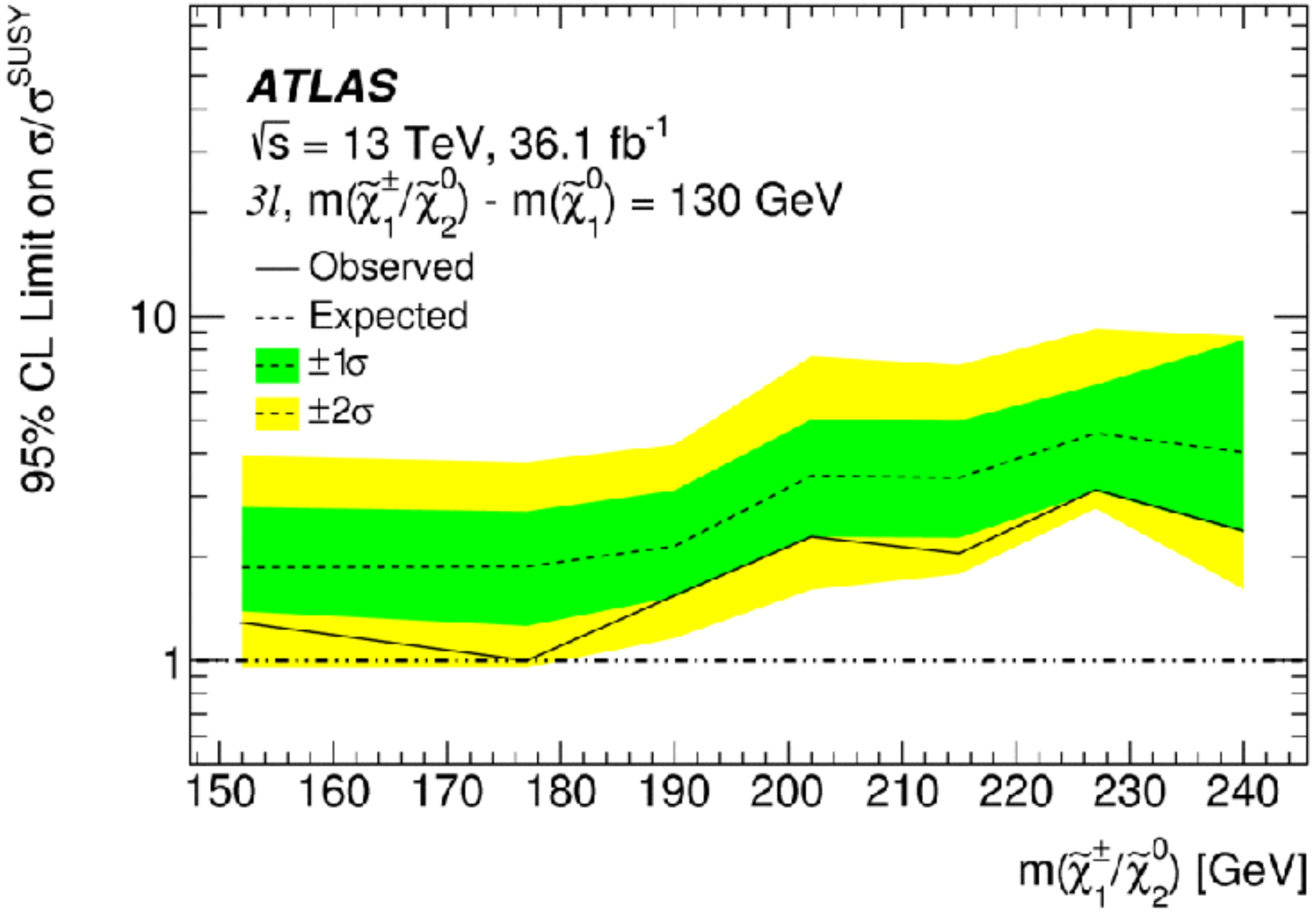
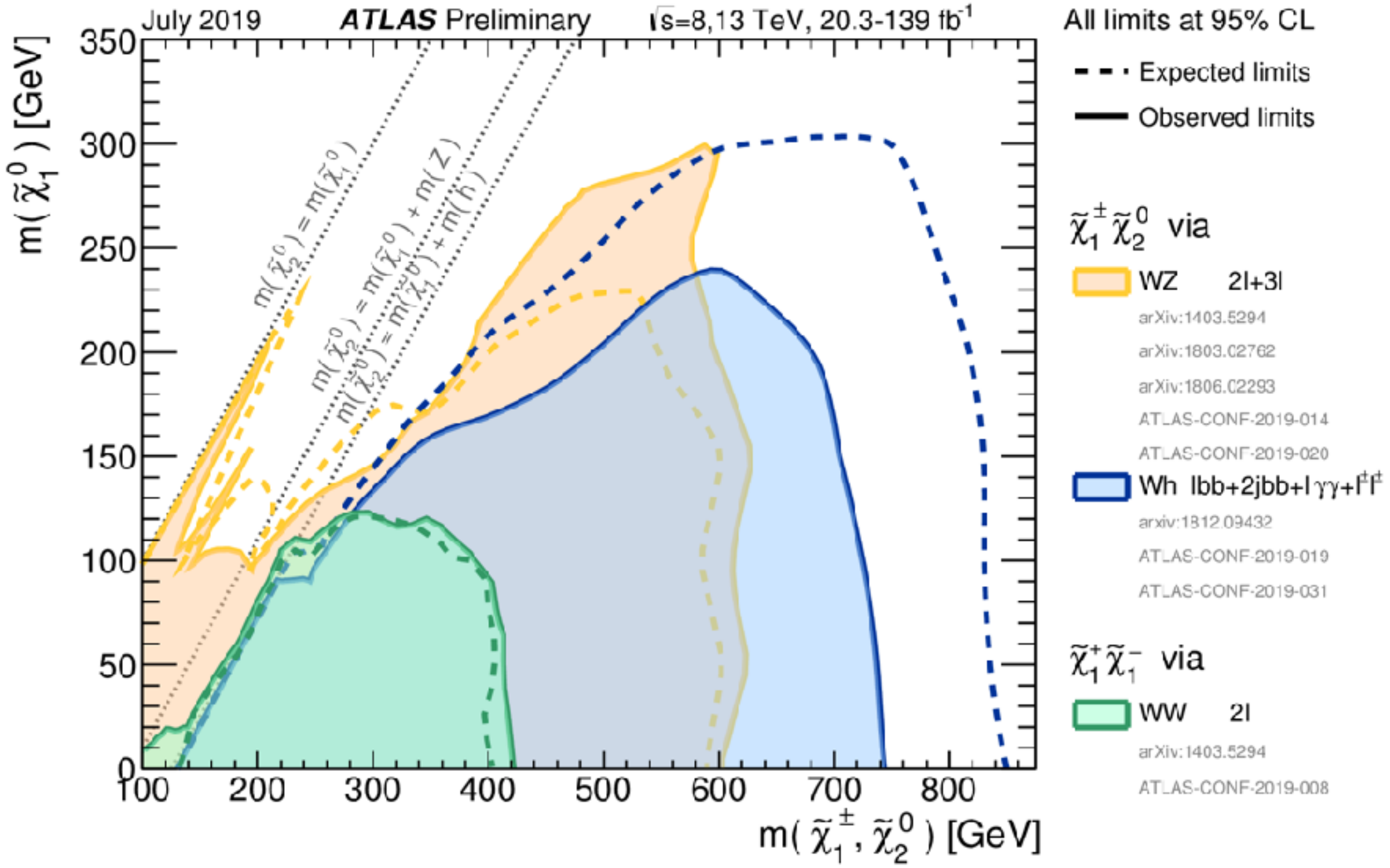


Eye to the future

Conclusions and outlook

Conclusions and outlook

- Wh3L and WZ3L analys2s published with 36.1 fb⁻¹ Run2 dataset (Phys. Rev. D 100, 012006 and Eur. Phys. J. C 78 (2018) 995)
  - First stringent limits are provided with partial dataset
- The analyses to full Run2 dataset is on-going. In addition to larger dataset, improvements have been worked on
  - Further optimisation of SRs
  - Revised background estimation
  - Treatment of Wh and WZ searches as focus on a 3L signature analysis
  - The two analyses will be essential to explore challenging SUSY scenarios at the electroweak cross-sections



Any questions?

Thank you!

Backup

MSSM mass states

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	(same)
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	(same)
			$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\widetilde{G}$	(same)

CR and VR definitions

3ℓ control and validation region definitions	$p_T^{\ell_3}$ [GeV]	$m_{\ell\ell\ell}$ [GeV]	m_{SFOS} [GeV]	E_T^{miss} [GeV]	m_T^{min} [GeV]	$n_{non\text{-}b\text{-}tagged\ jets}$	$n_{b\text{-}tagged\ jets}$
CR3-WZ-inc	> 20	–	81.2–101.2	> 120	< 110	–	0
CR3-WZ-0j	> 20	–	81.2–101.2	> 60	< 110	0	0
CR3-WZ-1j	> 20	–	81.2–101.2	> 120	< 110	> 0	0
VR3-Za	> 30	$\notin [81.2, 101.2]$	81.2 101.2	40 60			
VR3-Zb	> 30		81.2–101.2	>60	–	–	> 0
VR3-offZa	> 30	$\notin [81.2, 101.2]$	$\notin [81.2, 101.2]$	40–60	–	–	–
VR3-offZb	> 20			> 40	–	–	> 0
VR3-Za-0J	> 20	$\notin [81.2, 101.2]$	81.2–101.2	40 60		0	0
VR3-Za-1J				40–60	–	> 0	0

CR definition

	CR3L-onZ-highMET
Baseline leptons	=3
Signal leptons	=3
Flavour/sign	SFOS
b-tagged jets	=0 ($p_T > 20$ GeV)
p_T $^{3rd\ \ell}$	> 25 GeV
E_T^{miss}	>80 GeV
$m_{\ell\ell\ell}$	> 20 GeV
m_{SFOS}^{min}	> 20, $\in$ [81.2, 101.2] GeV

VR definition

	VR3L-offZ-highMET
Baseline leptons	=3
Signal leptons	=3
Flavour/sign	SFOS
b-tagged jets	=0
$p_T^{3rd\ \ell}$	> 25 GeV
MET	>80 GeV
$m_{\ell\ell\ell}$	> 20 GeV
m_{SFOS}^{min}	> 20, $\notin$ [81.2, 101.2] GeV
m_T^{min}	<110

Wh3L results: SR pulls

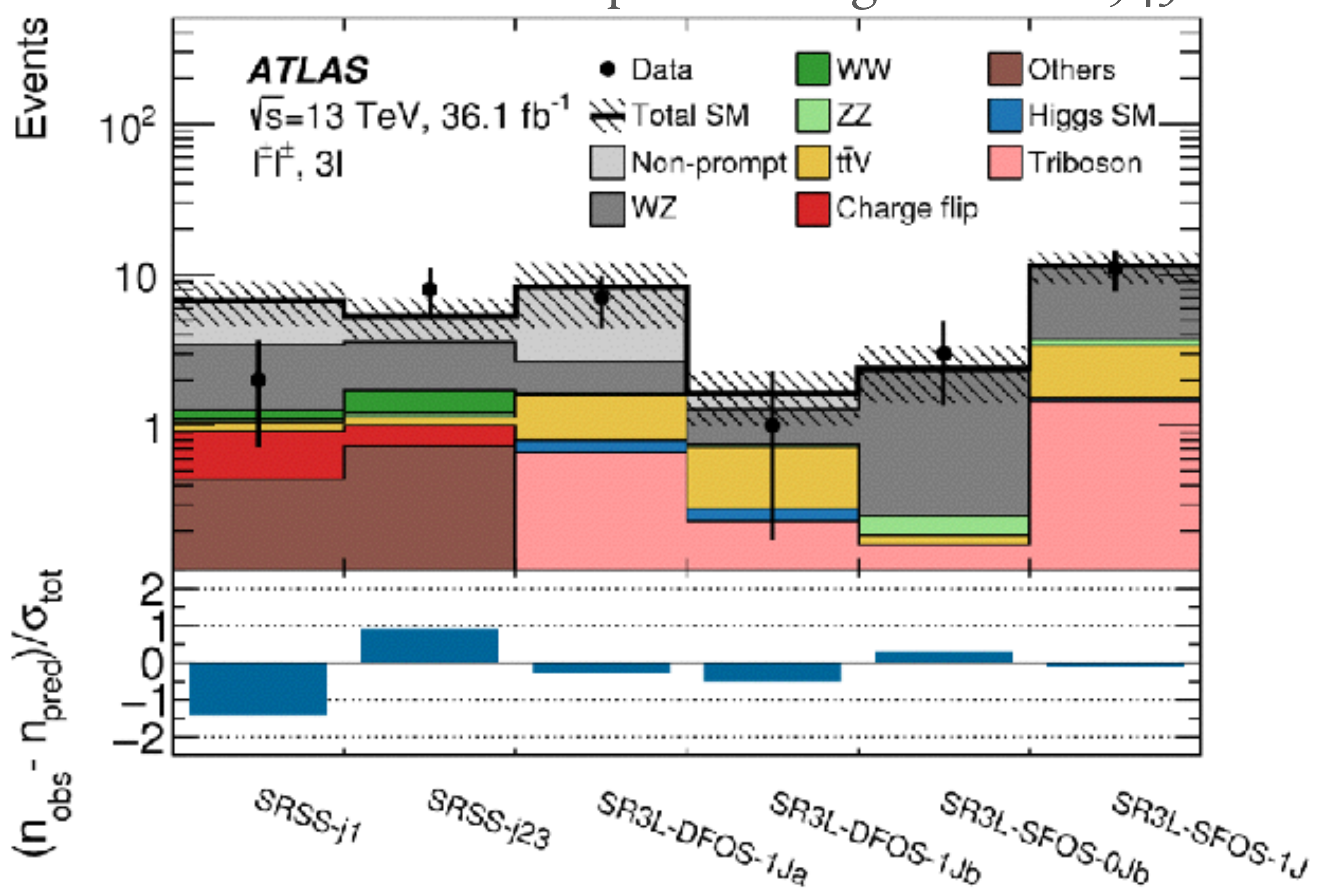
https://arxiv.org/abs/1812.09432

SR channels	SR3L-DFOS-0J	SR3L-DFOS-1Ja	SR3L-DFOS-1Jb
Observed events	0	7	1
Fitted bkg events	2.1 ± 1.0	8.3 ± 3.8	1.7 ± 0.7
WZ	0.18 ± 0.13	1.01 ± 0.27	0.54 ± 0.16
ZZ	0.0017 ± 0.0012	0.06 ± 0.02	0.03 ± 0.01
$t\bar{t}+V$	0.0013 ± 0.0013	0.79 ± 0.29	0.43 ± 0.16
Tribosons	0.52 ± 0.28	0.66 ± 0.22	0.23 ± 0.08
Higgs SM	0.39 ± 0.15	$0.1^{+0.5}_{-0.1}$	0.05 ± 0.04
FNP	1.0 ± 0.9	5.6 ± 3.8	$0.4^{+0.6}_{-0.4}$

https://arxiv.org/abs/1812.09432

SR channels	SR3L-SFOS-0Ja	SR3L-SFOS-0Jb	SR3L-SFOS-1J
Observed events	0	3	11
Fitted bkg events	3.8 ± 1.7	2.4 ± 1.0	11.5 ± 2.6
WZ	2.5 ± 1.2	2.0 ± 0.9	7.4 ± 2.3
ZZ	0.10 ± 0.04	0.07 ± 0.02	0.29 ± 0.09
$t\bar{t}+V$	0.09 ± 0.03	0.02 ± 0.01	1.9 ± 0.5
Tribosons	0.57 ± 0.29	0.16 ± 0.08	1.4 ± 0.4
Higgs SM	$0.24^{+0.25}_{-0.24}$	0.07 ± 0.07	0.07 ± 0.04
FNP events	$0.27^{+0.31}_{-0.27}$	$0.11^{+0.20}_{-0.11}$	$0.4^{+0.5}_{-0.4}$

https://arxiv.org/abs/1812.09432



Wh3L results: limits

https://arxiv.org/abs/1812.09432