The rise and fall of light stops in the LHC top quark sample

2312.09794 - Emanuele Bagnaschi, Gennaro Corcella, **Roberto Franceschini** and Dibyashree Sengupta

LHCtopWG

https://indico.cern.ch/event/1375202/ - April 25th 2024

ROMA TRE UNIVERSITÀ DEGLI STUDI
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Ministero dell'Università e della Ricerca
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LHC has excluded light new physics, period.

Has it?

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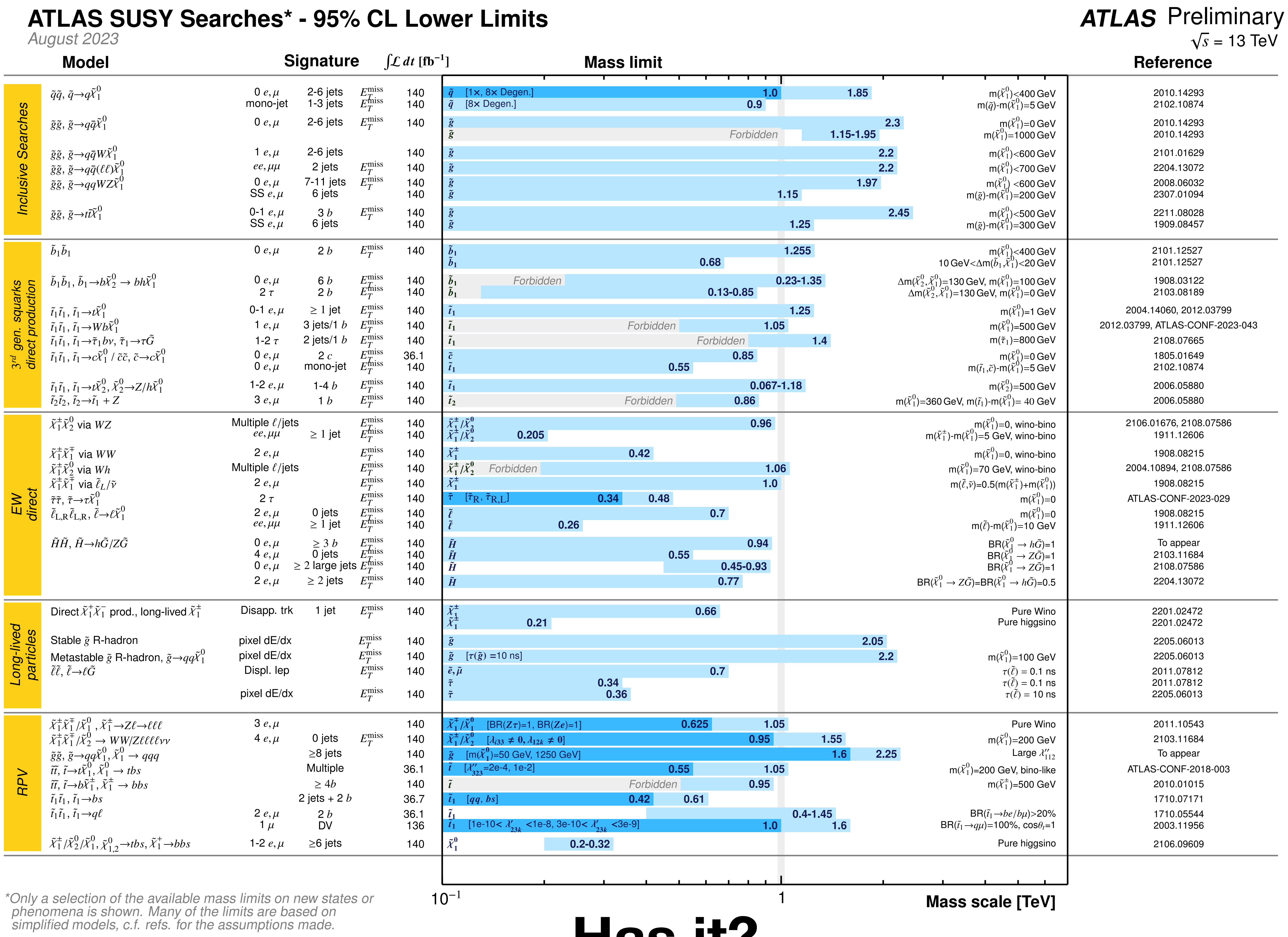

Has it?

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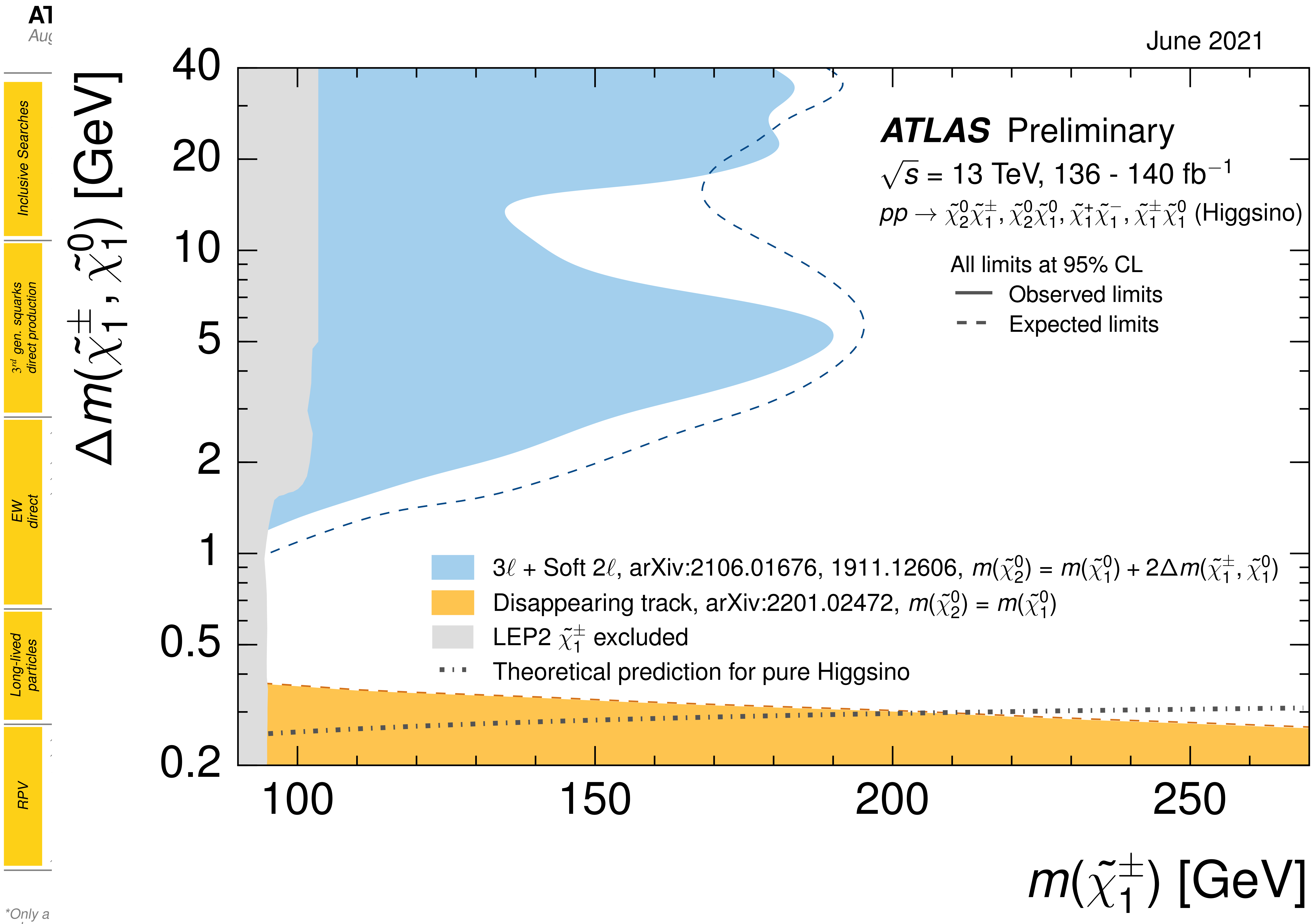

simplified models, c.f. refs. for the assumptions made.

Has it?

Eur. Phys. J. C (2023) 83:718
https://doi.org/10.1140/epjc/s10052-023-11508-9

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Experimental Physics

Measurements of W^+W^- production in decay topologies inspired by searches for electroweak supersymmetry

ATLAS Collaboration*

CERN, 1211 Geneva 23, Switzerland

Received: 1 July 2022 / Accepted: 9 October 2022

Abstract This paper presents a measurement of fiducial and differential cross-sections for W^+W^- production in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS experiment at the Large Hadron Collider using a dataset corresponding to an integrated luminosity of 139 fb^{-1}. Events with exactly one electron, one muon and no hadronic jets are studied. The fiducial region in which the measurements are performed is inspired by searches for the electroweak production of supersymmetric charginos decaying to two-lepton final states. The selected events have moderate values of missing transverse momentum and the 'stransverse mass' variable m_{T2}, which is widely used in searches for supersymmetry at the LHC. The ranges of these variables are chosen so that the acceptance is enhanced for direct W^+W^- production and suppressed for production via top quarks, which is treated as a background. The fiducial cross-section and particle-level differential cross-sections for six variables are measured and compared with two theoretical SM predictions from perturbative QCD calculations.

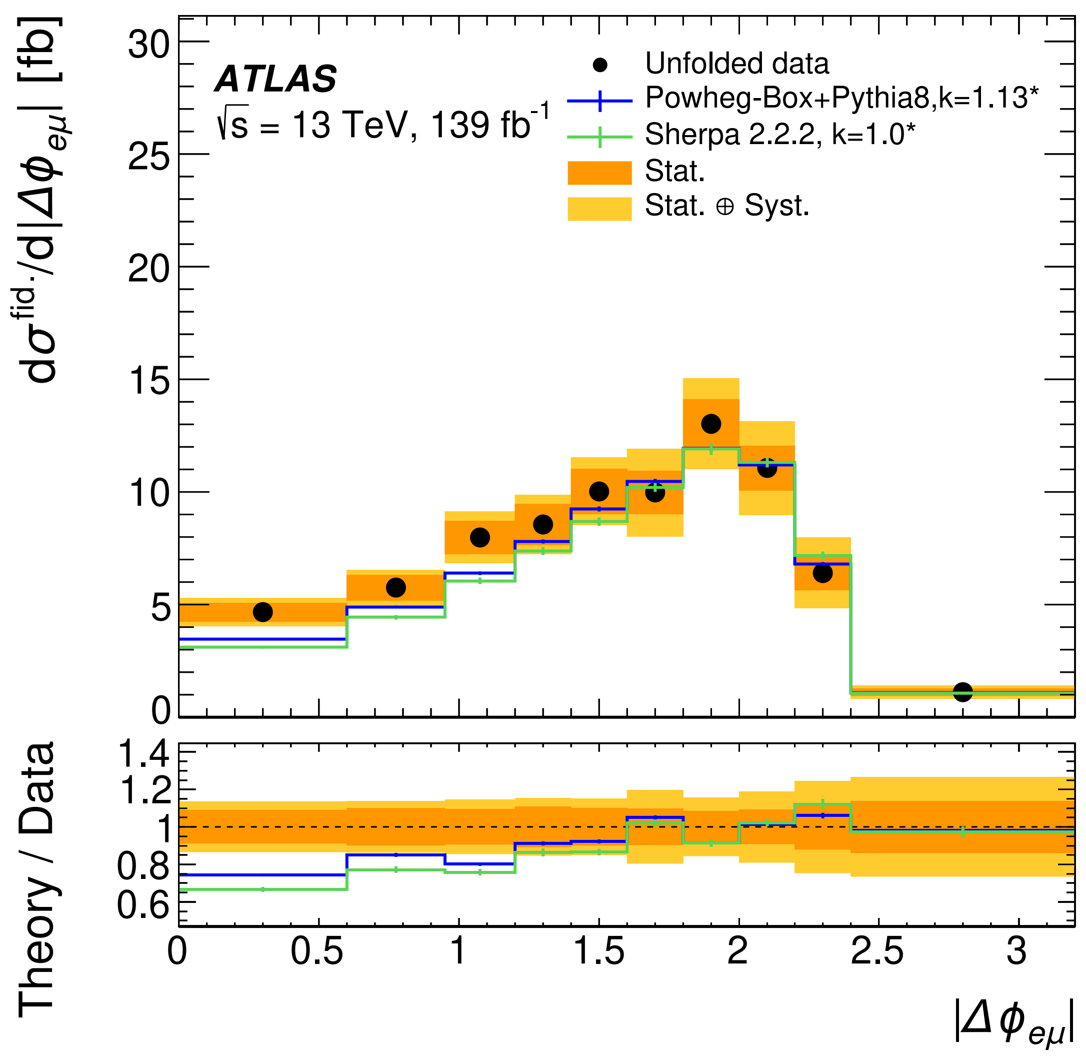

Table 4 Chi-squared per number of degrees of freedom χ^2/NDF for a comparison of unfolded distributions with different theory predictions. The calculation takes into account bin-by-bin correlations of systematic and statistical uncertainties. Uncertainties in the theory predictions are not considered

	$\|y_{e\mu}\|$	$\|\Delta\phi_{e\mu}\|$	$\cos\theta^*$	$p_T^{\text{lead}\,\ell}$	$m_{e\mu}$	$p_T^{e\mu}$
POWHEG BOX v2+PYTHIA 8 ($q\bar{q}$) and SHERPA 2.2.2+OPEN LOOPS (gg)	14.4/8	10.1/10	13.3/7	15.4/6	2.8/6	3.9/5
SHERPA 2.2.2 ($q\bar{q}$) and SHERPA 2.2.2+OPEN LOOPS (gg)	18.3/8	17.9/10	24.5/7	24.1/6	2.5/6	4.1/5

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Regular Article - Experimental Physics

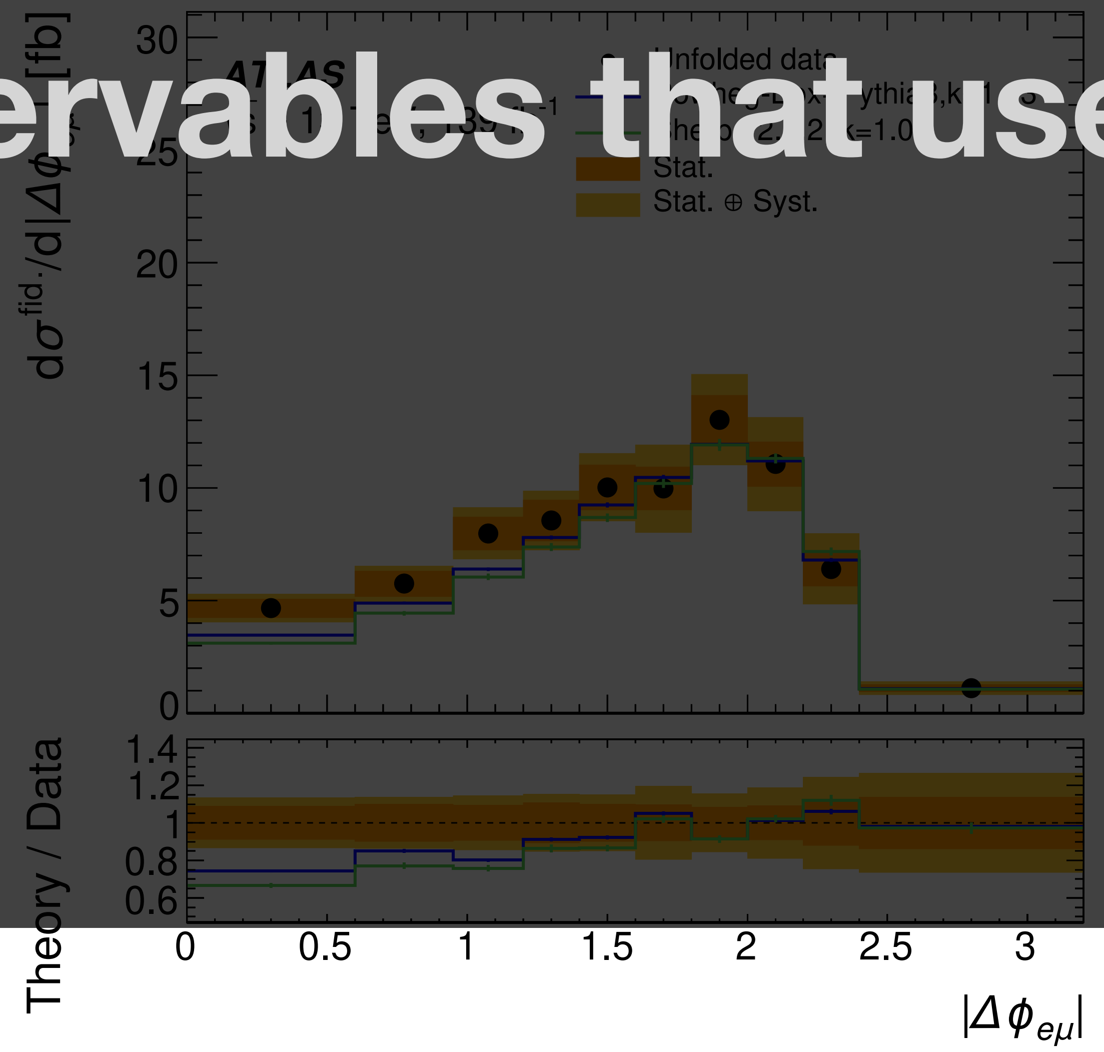
Measurements of W^+W^- production in decay topologies inspired by searches for electroweak supersymmetry

ATLAS Collaboration⋆

CERN, 1211 Geneva 23, Switzerland

This is one example of reaching the finest control and the highest scrutiny for a measurement of SM final states (in observables that useful for BSM searches)

Abstract This paper presents a measurement of fiducial and differential cross-sections for W^+W^- production in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS experiment at the Large Hadron Collider using a dataset corresponding to an integrated luminosity of 139 fb^{-1}. Events with exactly one electron, one muon and no hadronic jets are studied. The fiducial region in which the measurements are performed is inspired by searches for the electroweak production of supersymmetric charginos decaying to two-lepton final states. The selected events have moderate values of missing transverse momentum and the 'stransverse mass' variable m_{T2}, which is widely used in searches for supersymmetry at the LHC. The ranges of these variables are chosen so that the acceptance is enhanced for direct W^+W^- production and suppressed for production via top quarks, which is treated as a background. The fiducial cross-section and particle-level differential cross-sections for six variables are measured and compared with two theoretical SM predictions from perturbative QCD calculations.



The calculation takes into account bin-by-bin correlations of systematic uncertainties. Uncertainties in the theory predictions are

	$\|y_{e\mu}\|$	$\|\Delta\phi_{e\mu}\|$	$\cos\theta^*$	$p_T^{\text{lead}\,\ell}$	$m_{e\mu}$	$p_T^{e\mu}$
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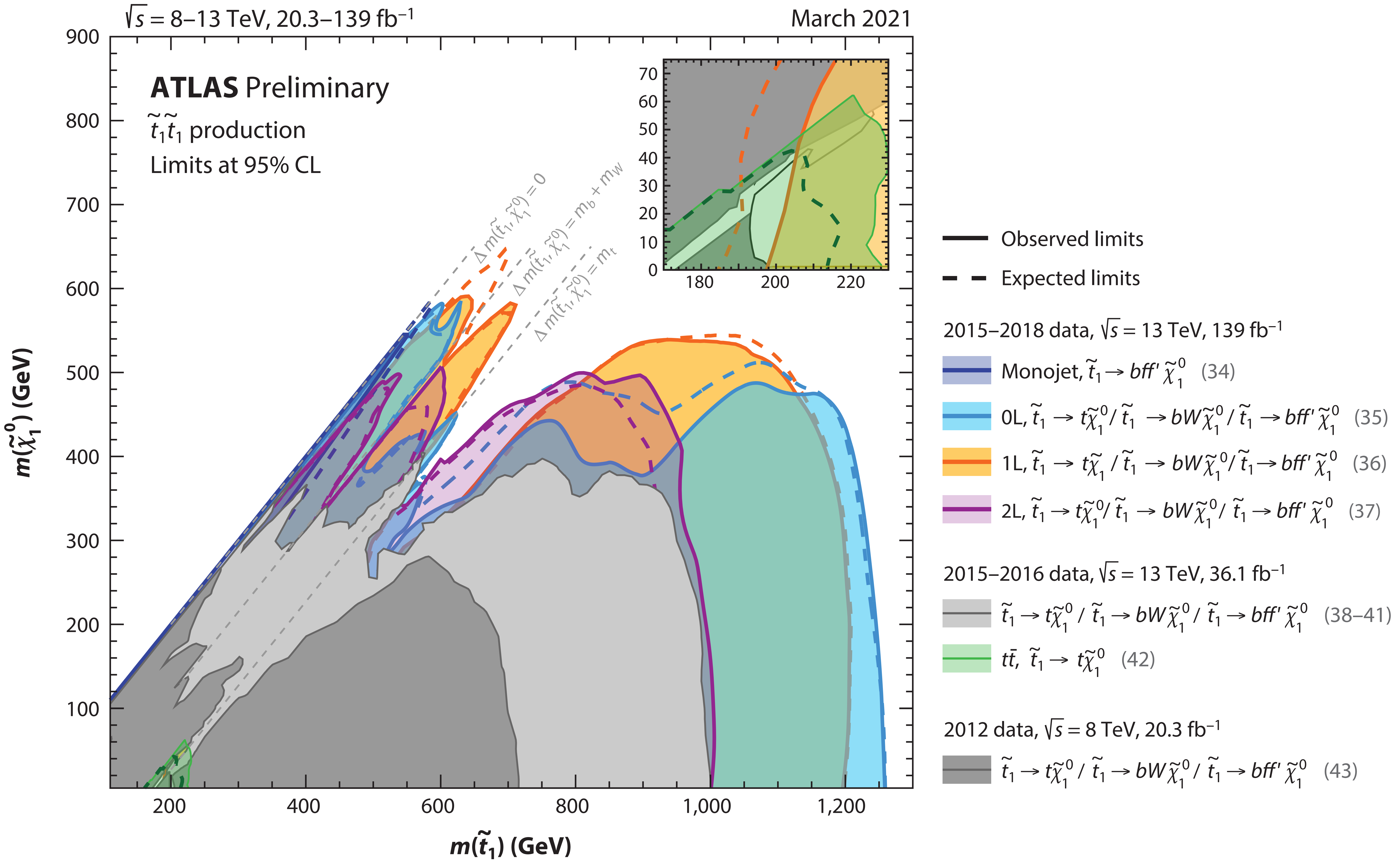
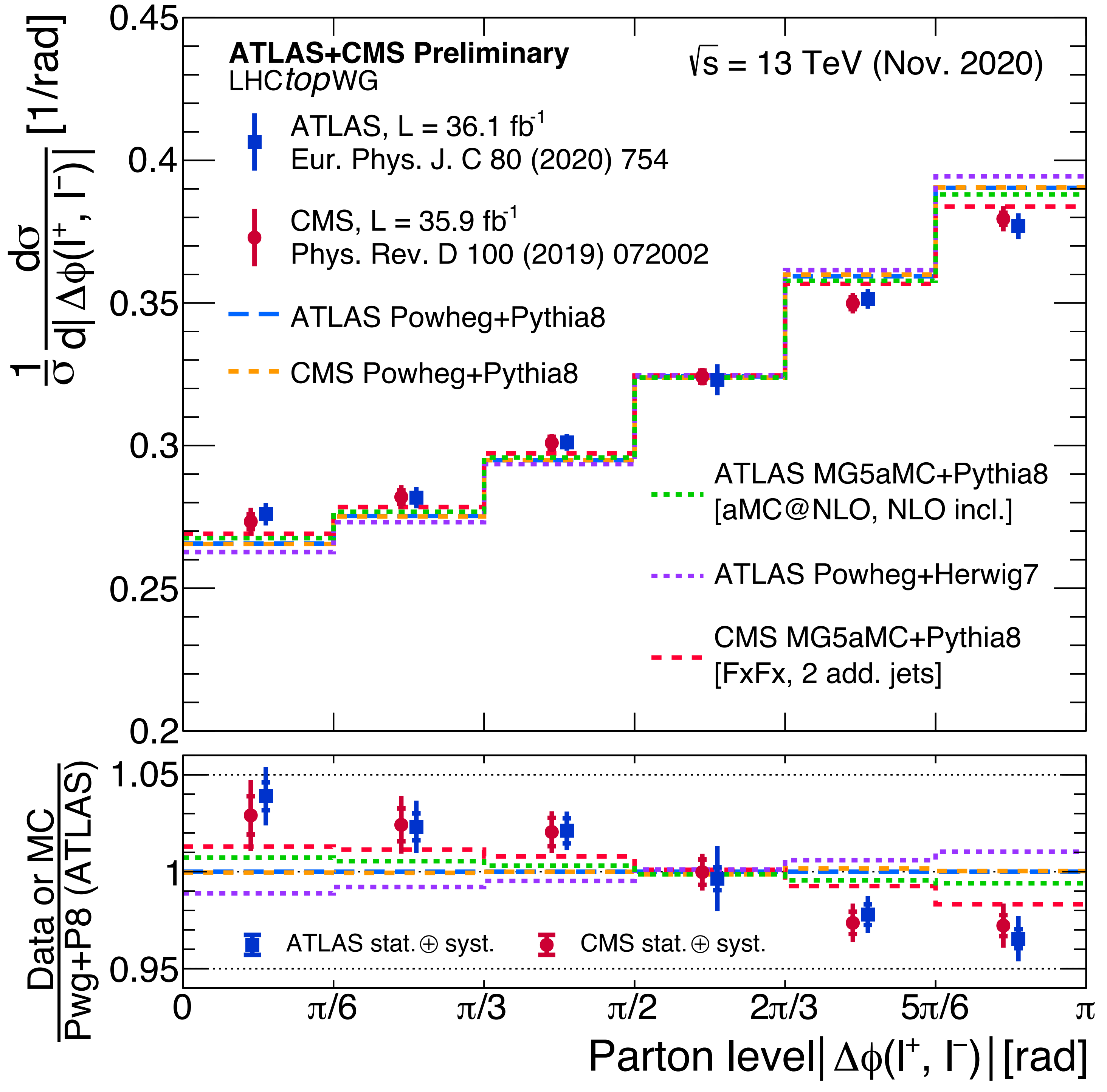
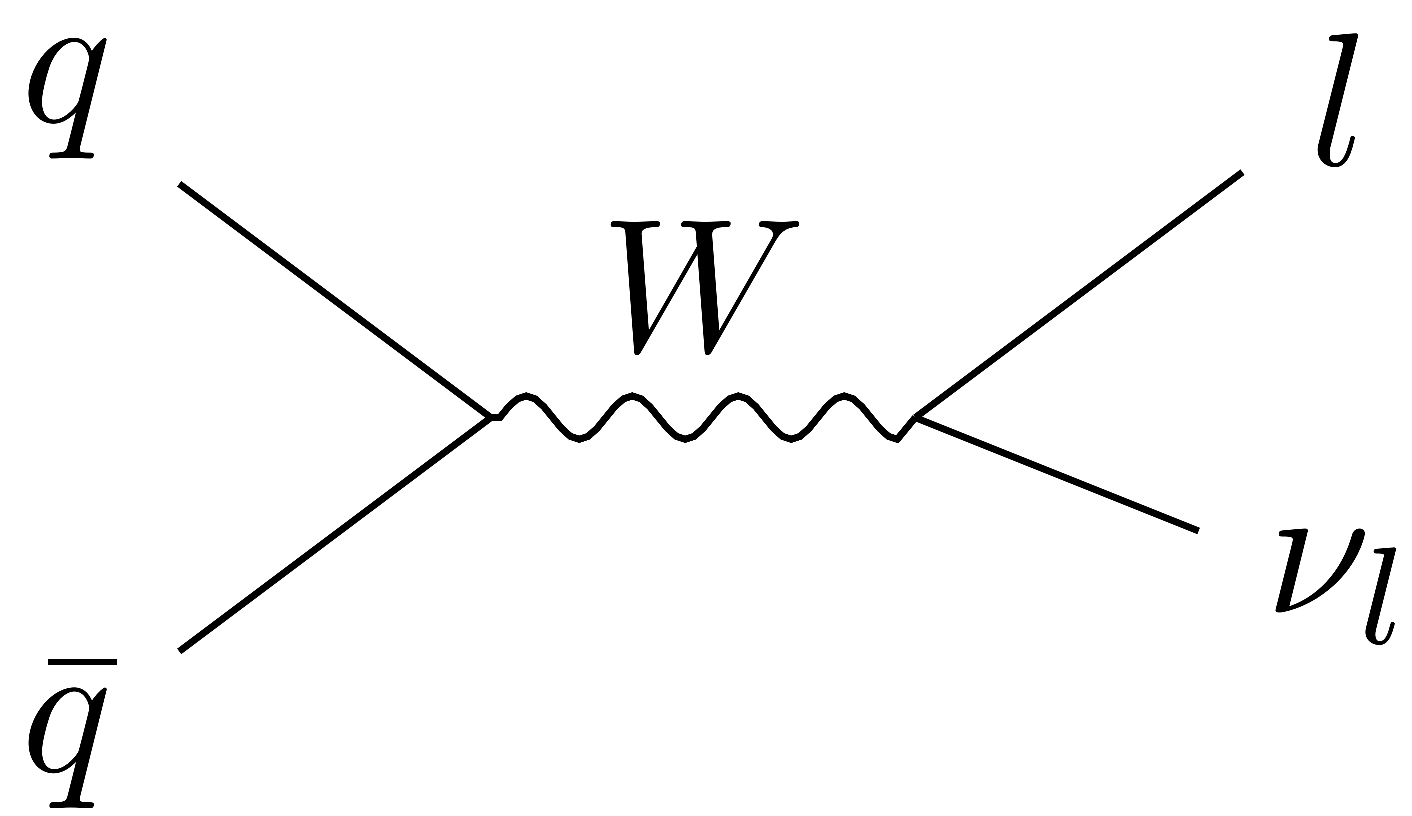
This is a valuable lesson.

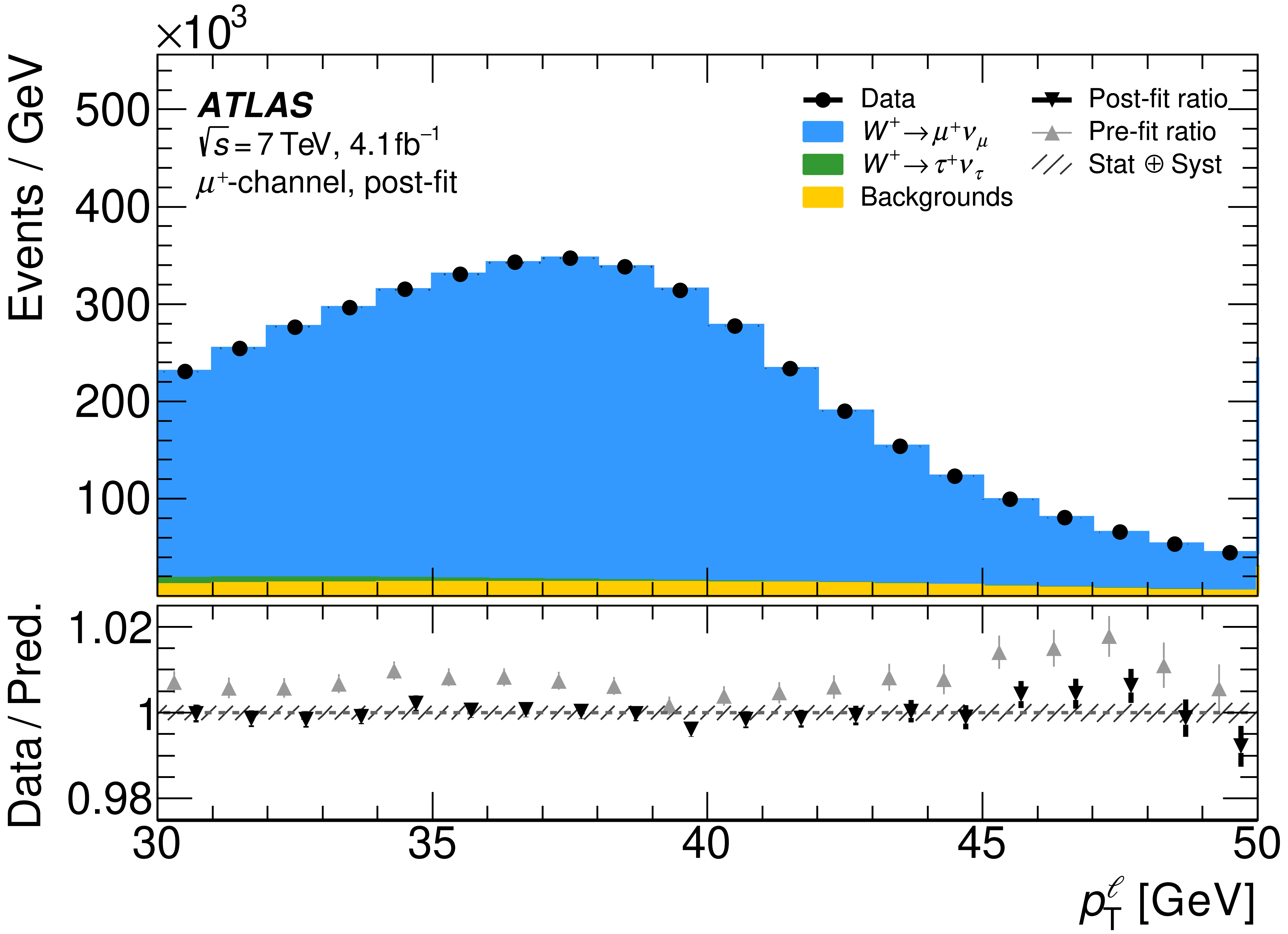


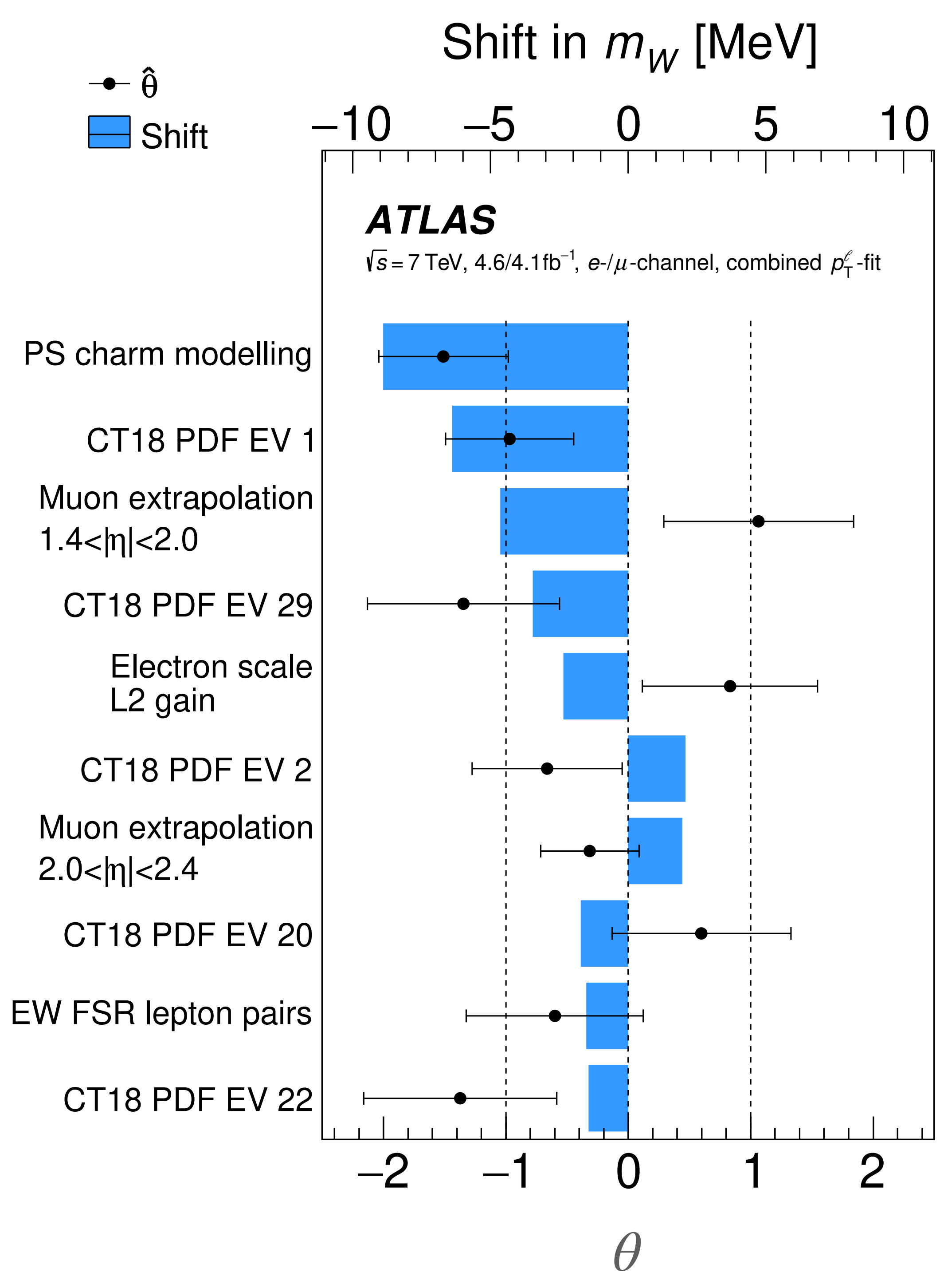


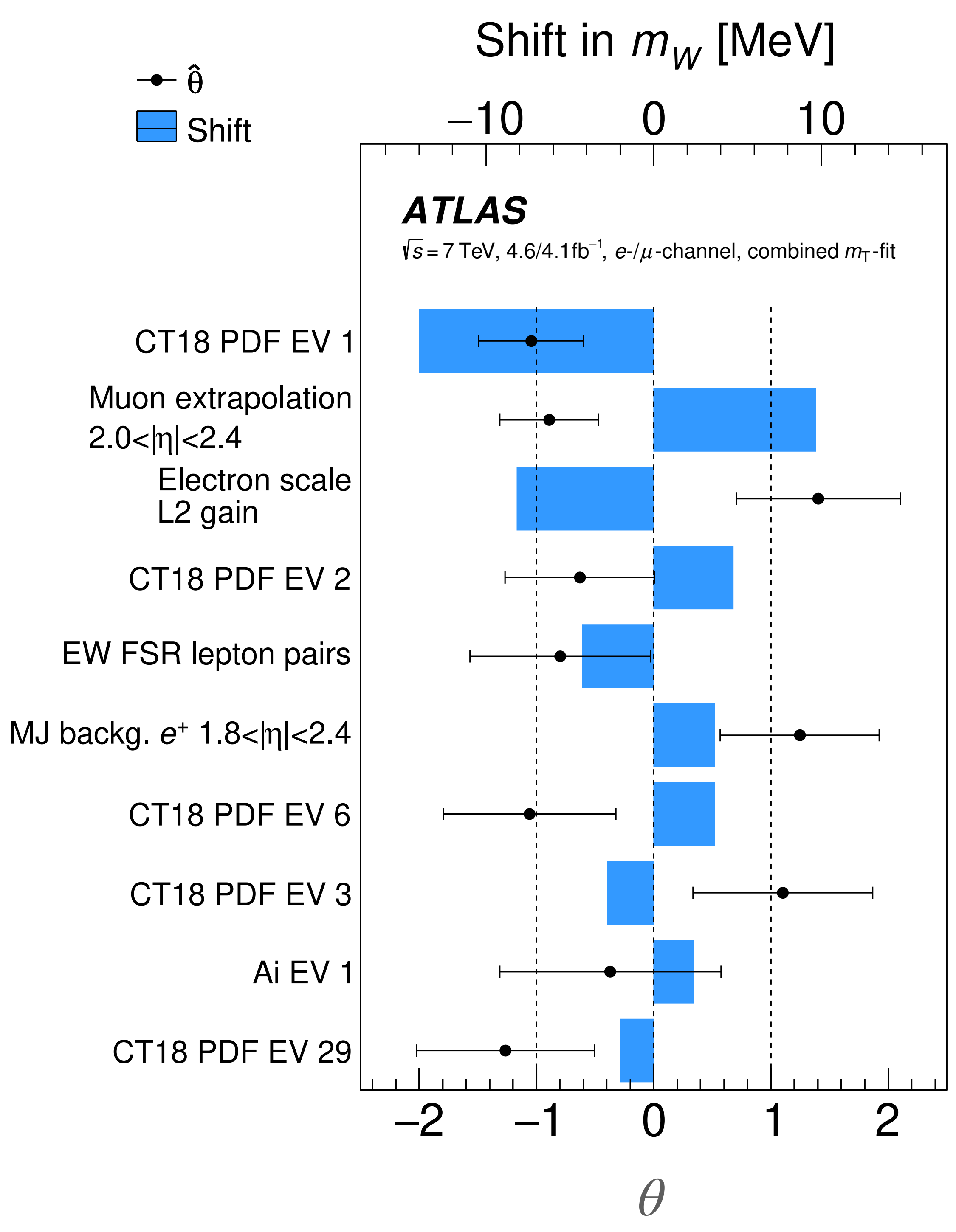
- Every SM measurement is a new physics search.
- Every BSM search is a SM measurement.

STANDARD MODEL







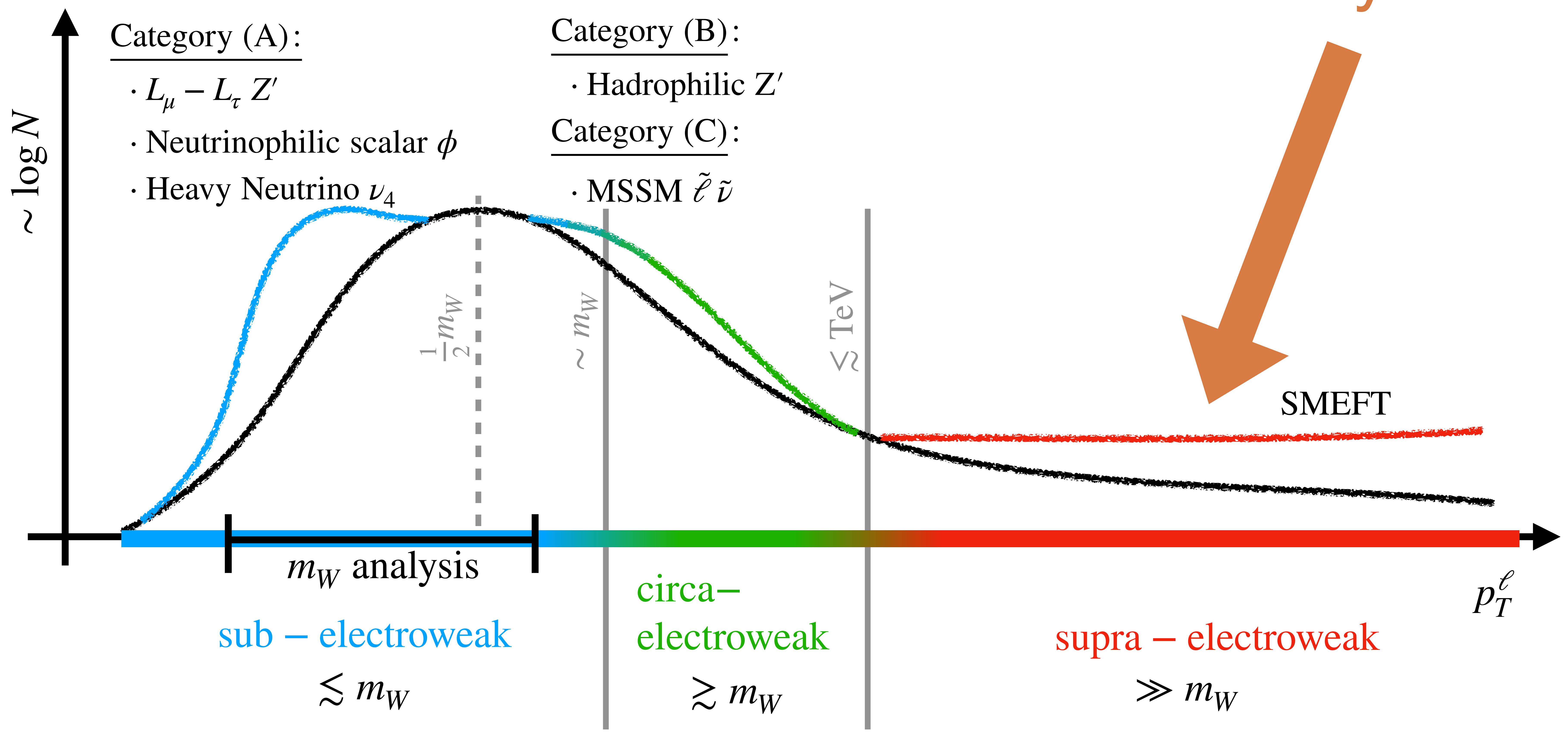


STANDARD & MODEL

SEARCH & MEASURE

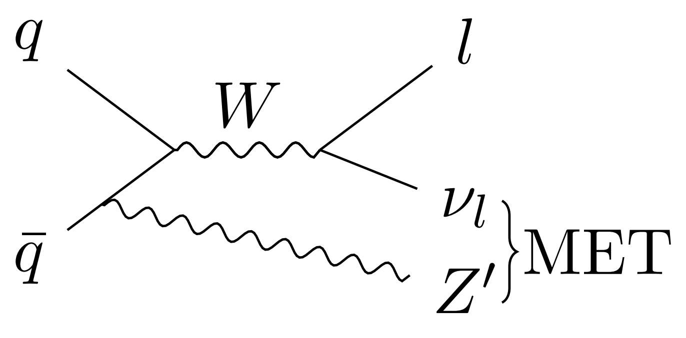
SEARCH & MEASURE

"hard" new physics
where everyone is looking

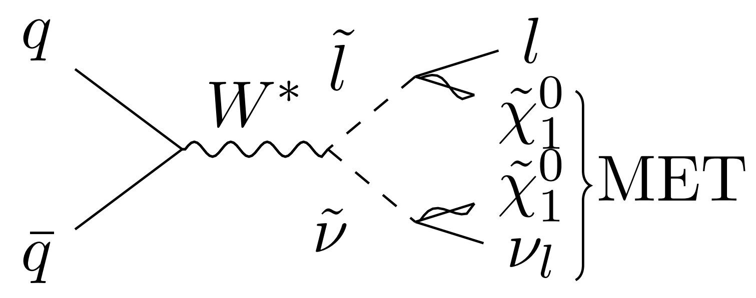


S&M

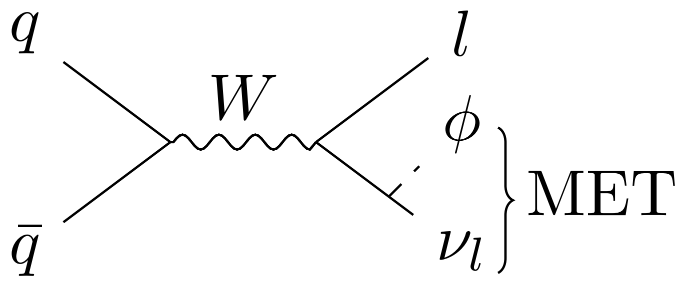
in ℓ + mET



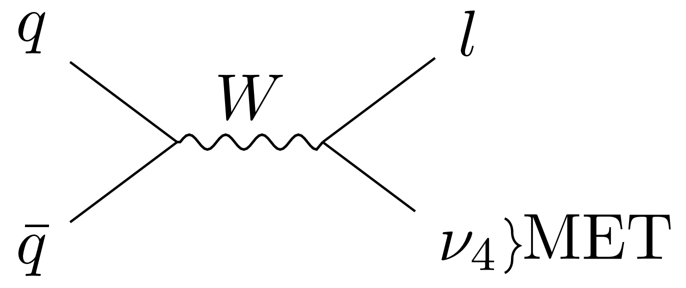
(a) Hadrophilic Z'



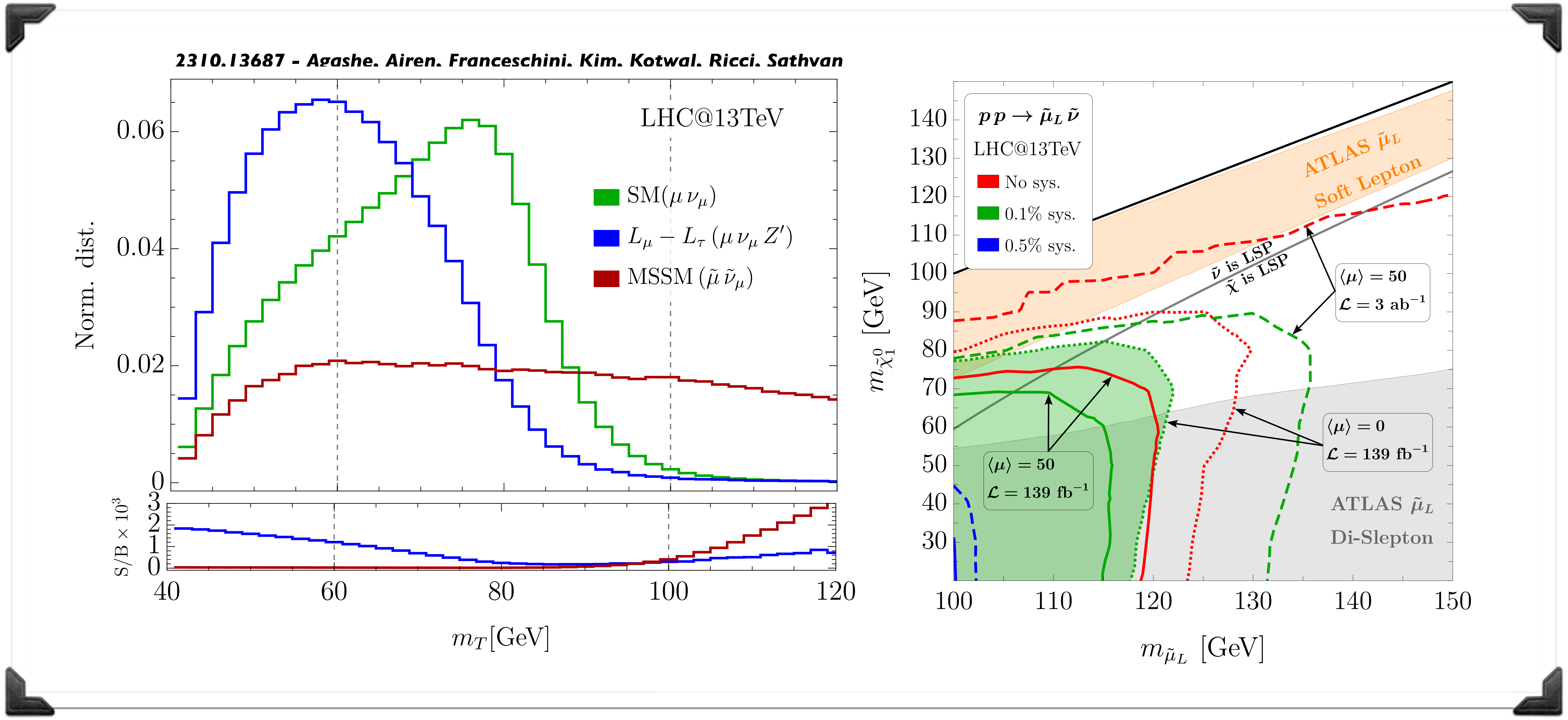
(b) MSSM slepton-sneutrino

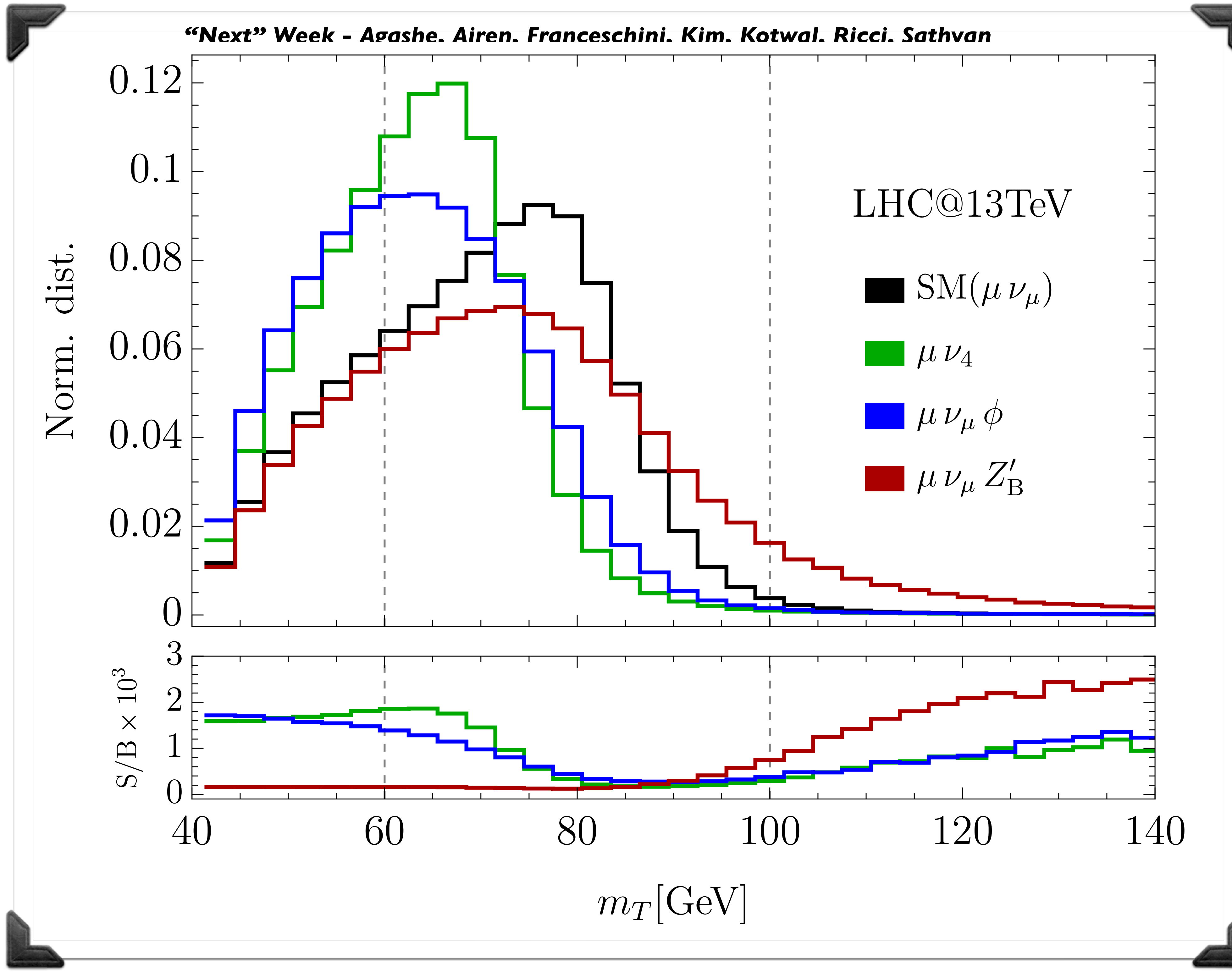


(c) Neutrinophilic scalar

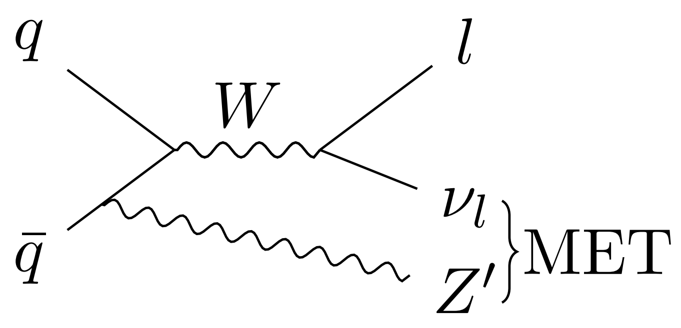


(d) Heavy neutrino





SEARCH & MEASURE in ℓ + mET



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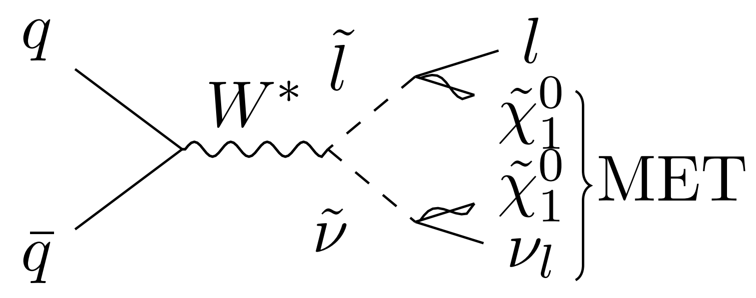

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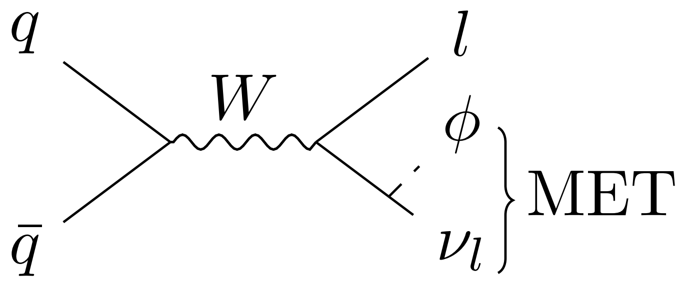
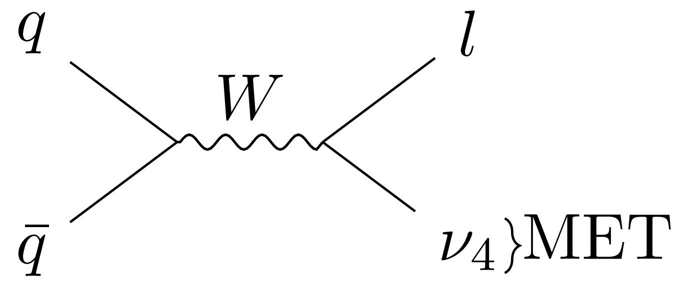


(c) Neutrinophilic scalar



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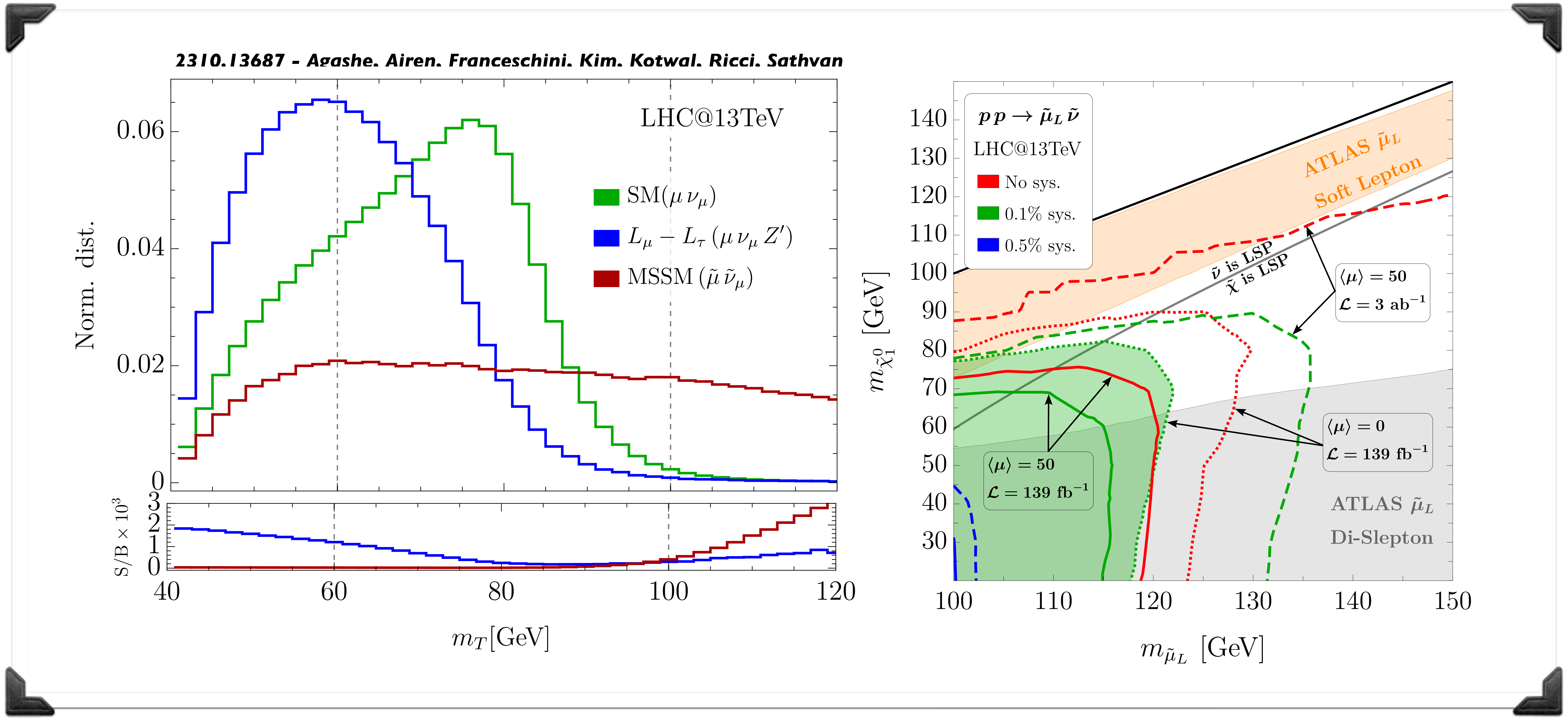
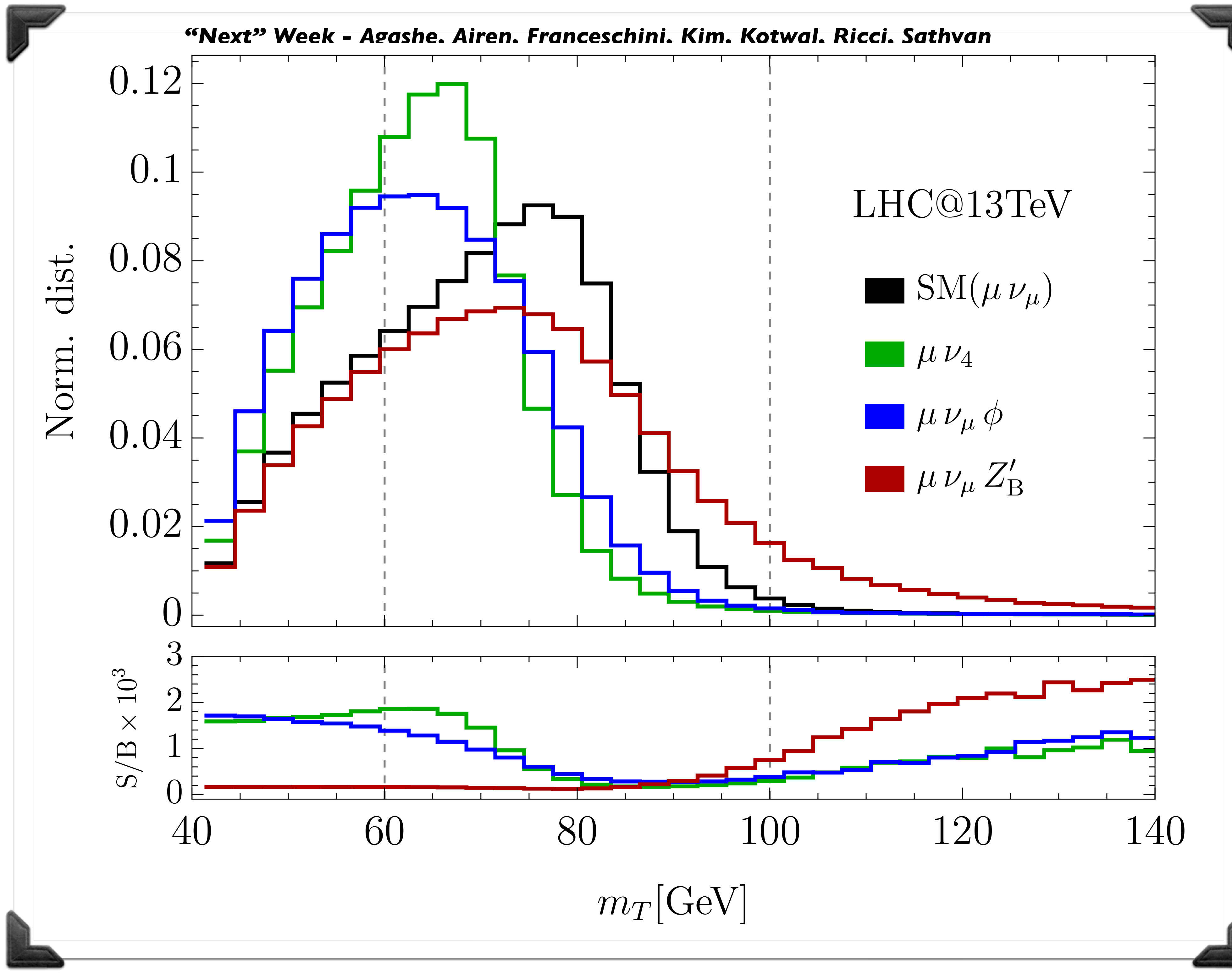
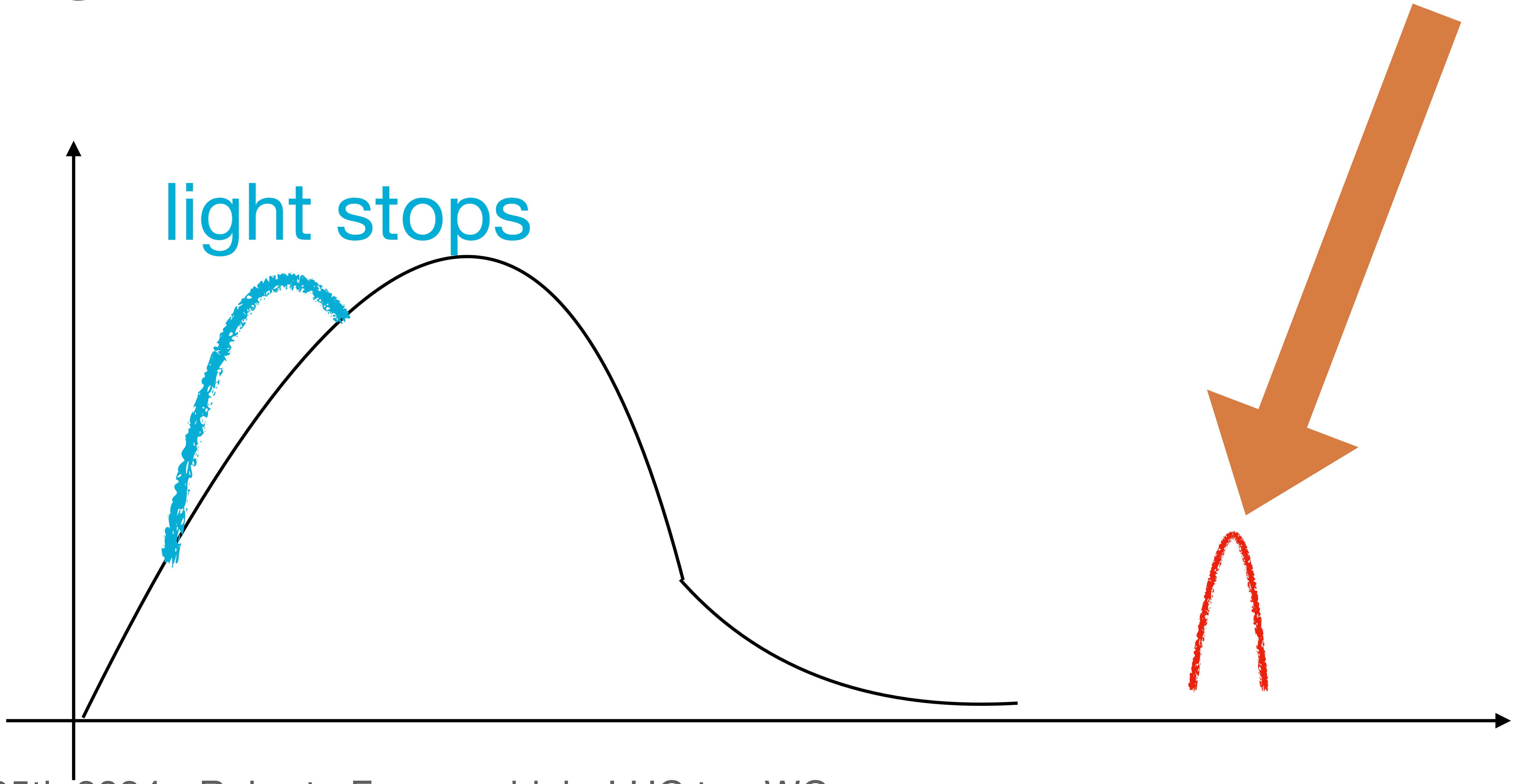




S&M in $t\bar{t}$

"hard" new physics where everyone is looking



SEARCH & MEASURE in $t\bar{t}$

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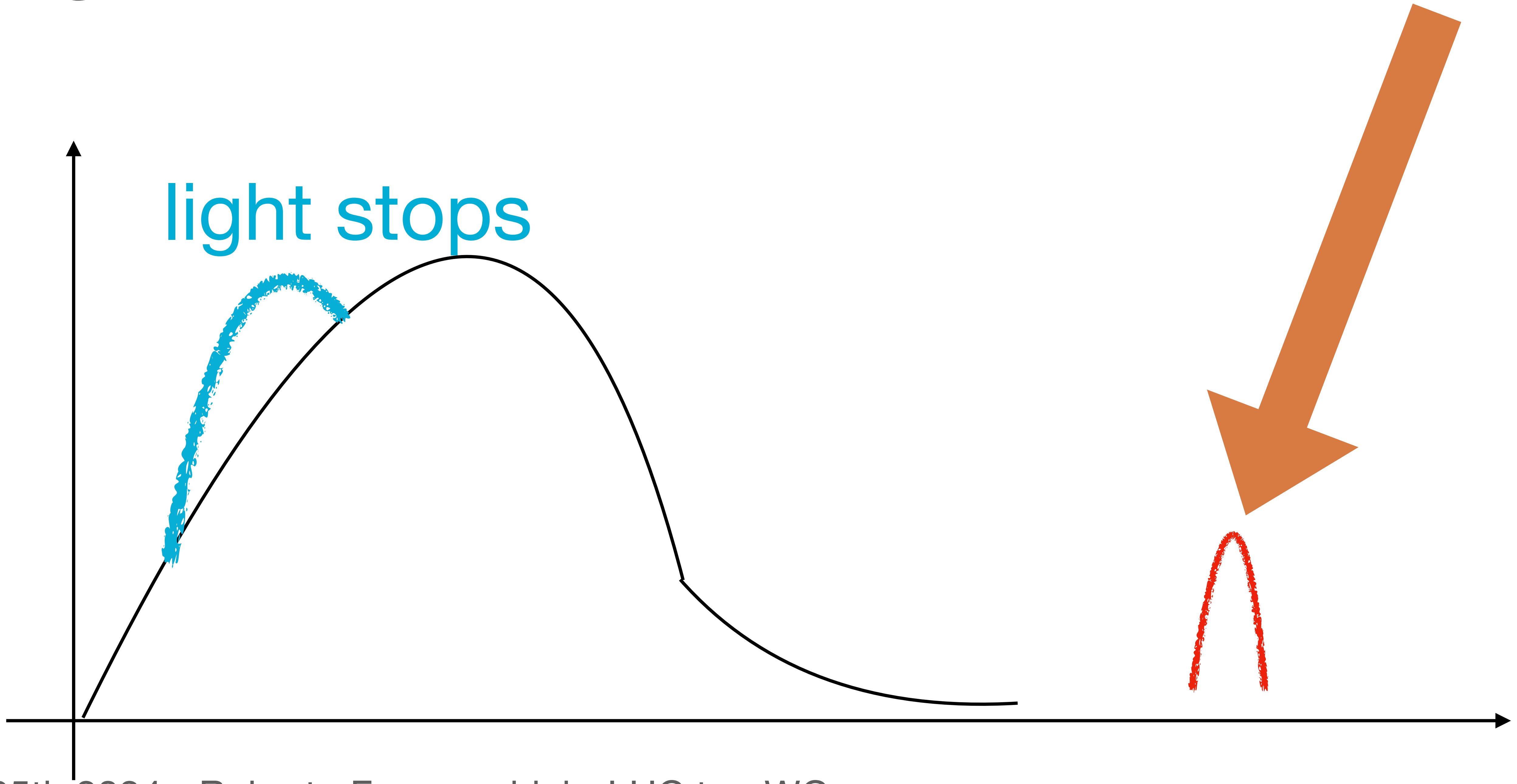
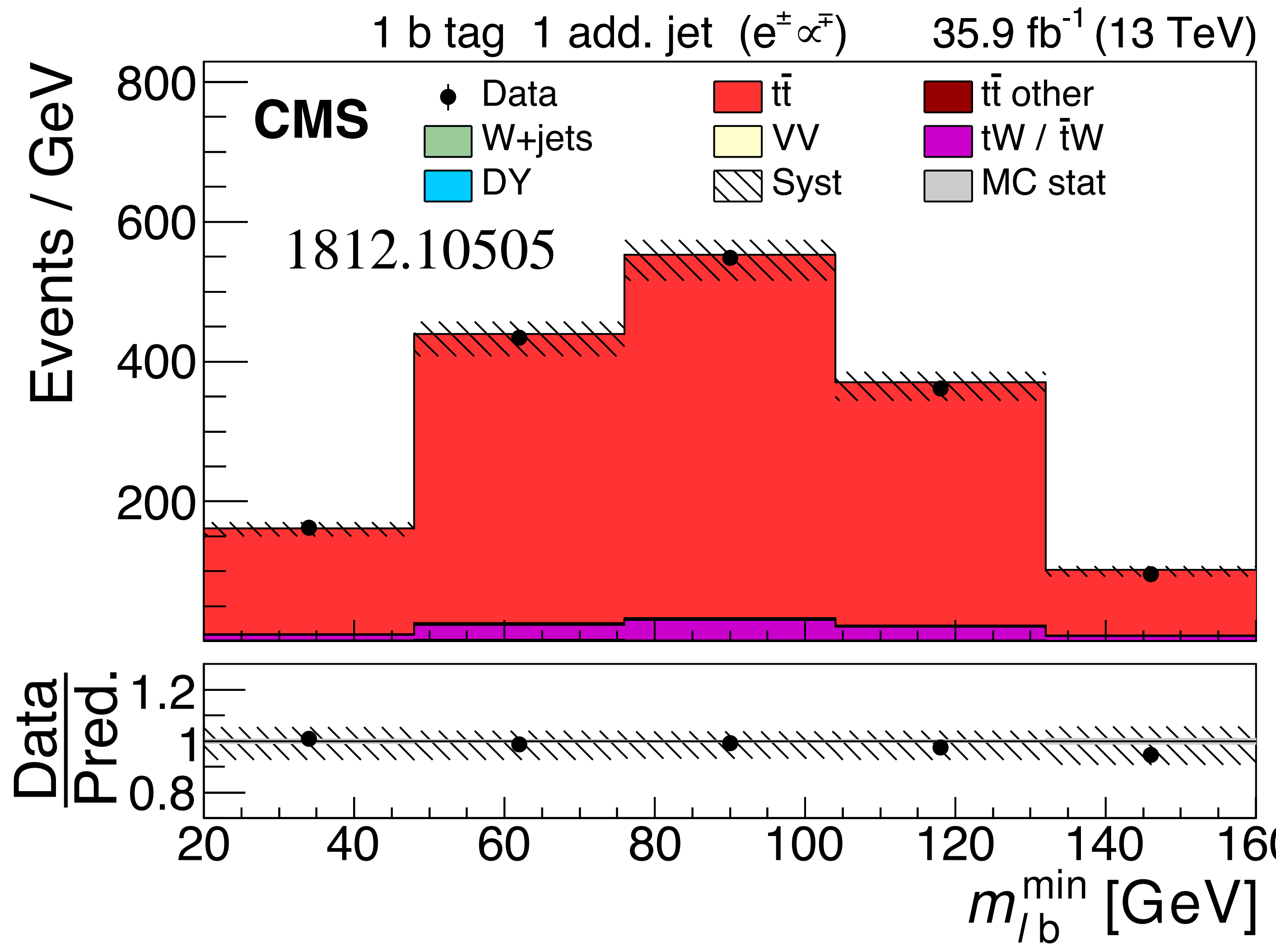
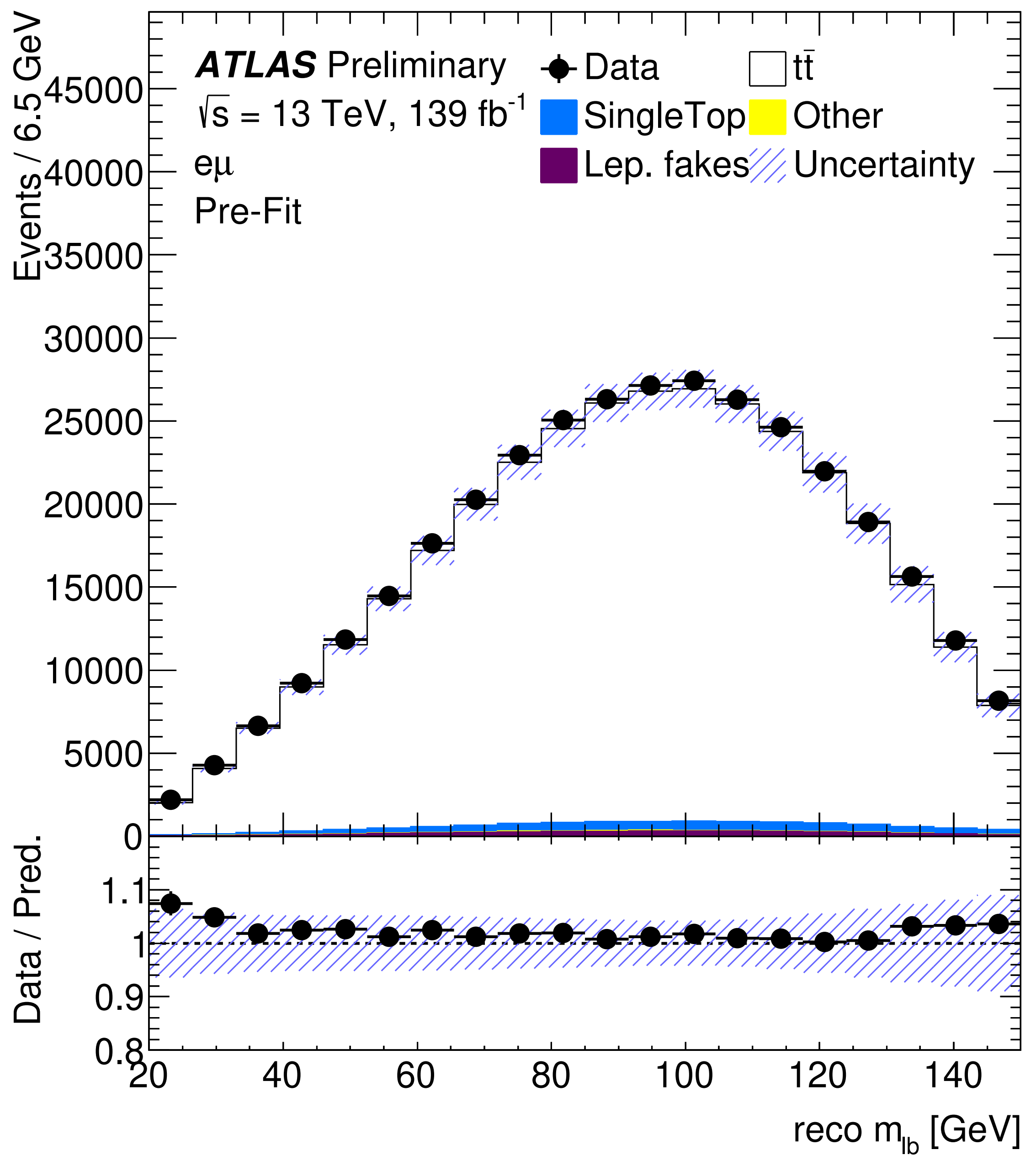
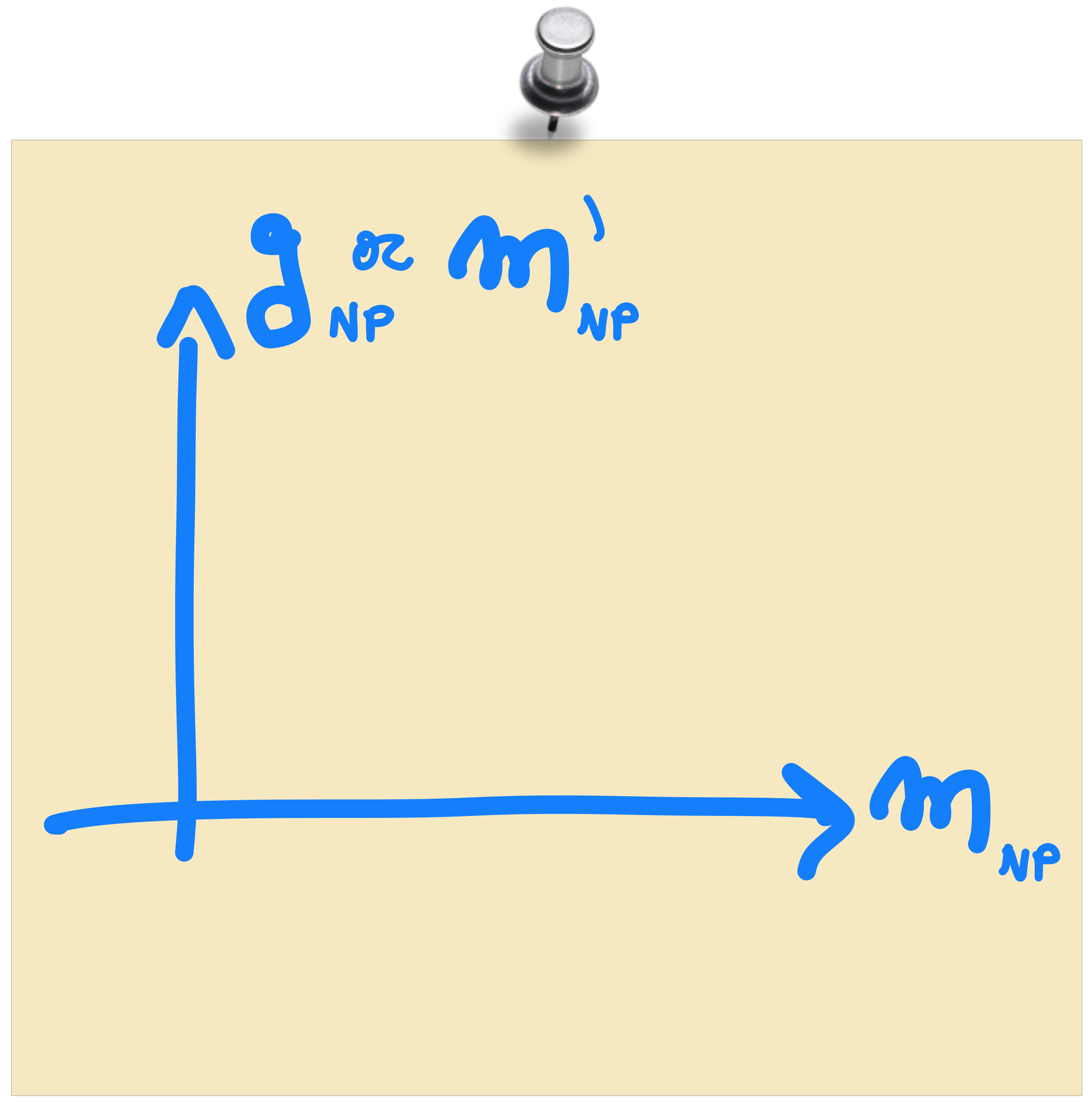


In this talk I will elaborate on this theme and provide directions on how to use the measurements of m_{bl} to test new physics scenarios



ATLAS-CONF-2019-038





The message can be spread to other observables: 1D distributions of $p_{T,\ell}, m_{T2}, E_b, \ldots$; 2D distributions as well; a full likelihood study in principle

Targeted new physics scenario

$\tilde{t} \to b\,\chi^{+} \to b\ell\nu\chi^{0}$

$t \to bW \to b\ell\nu$

Due to small mass differences between the NP states each energy release gives "soft" leptons and/or (b-)jets.

New physics that gives only "soft" leptons and (b-)jets is not the target of "*Search for …*"

Targeted new physics scenario

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$t \to bW \to b\ell\nu$

t $\tilde{t}$ $\chi^{\pm}$ χ^{0} W

Due to small mass differences between the NP states each energy release gives "soft" leptons and/or (b-)jets.

Ideally one would have to devise a search analysis that can deal with O(10) GeV p_T leptons and (bottom) jets

New physics that gives only "soft" leptons and (b-)jets is not the target for "Search for ..."

All the accurate work on these leptons and jets is already in place for the measurements of top quark properties!

Recast bounds on the NP scenario

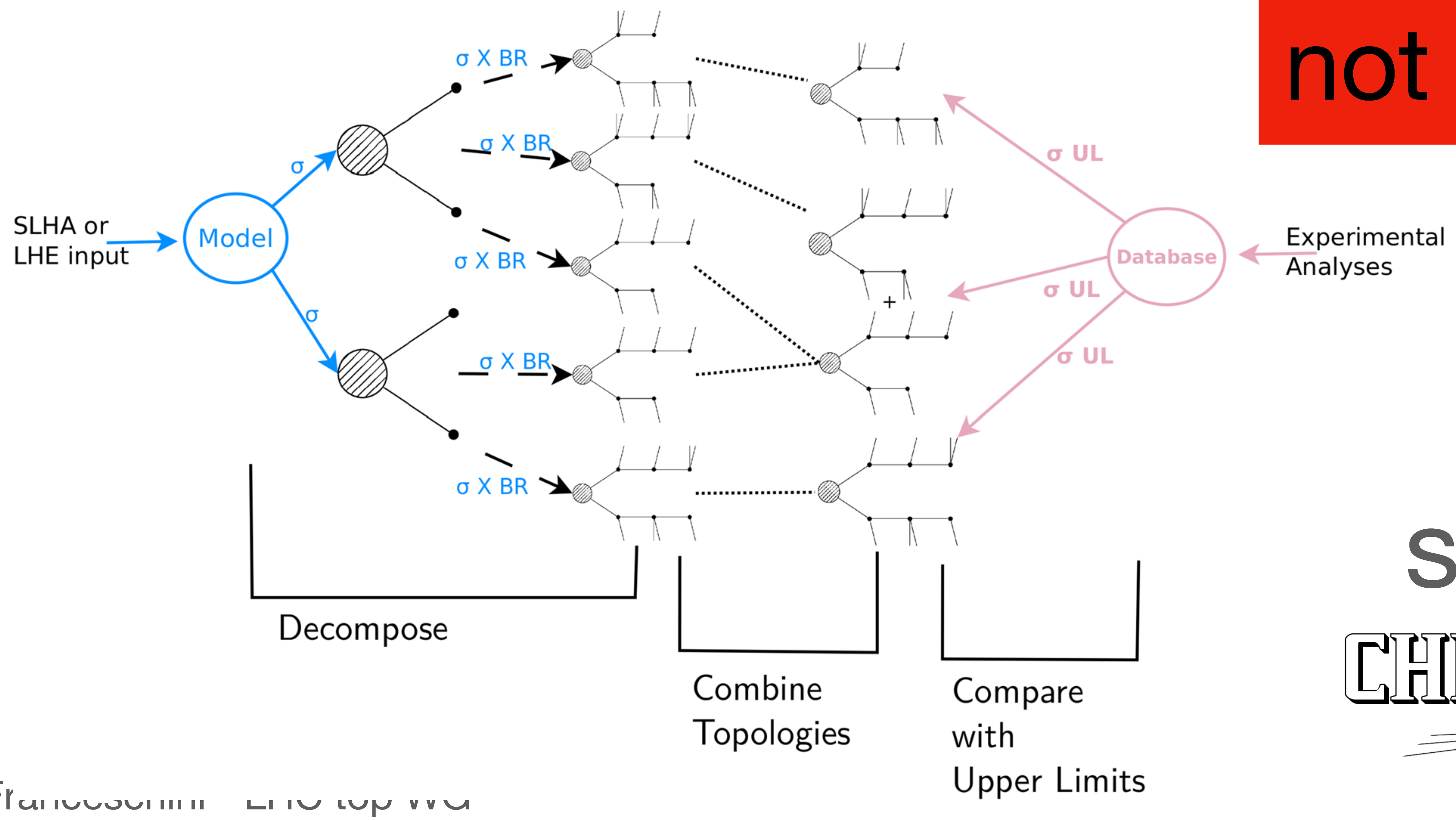
A point that made the development of this idea in practice very difficult for years is the objective difficulty to test if a new physics scenario is excluded by present searches that were not tailored for that scenario.

SModelS

2013 → 2023

1312.4175 → 2306.17676

v1.0 → v2.3



$r > 1$
excluded

$r < 1$
not excluded

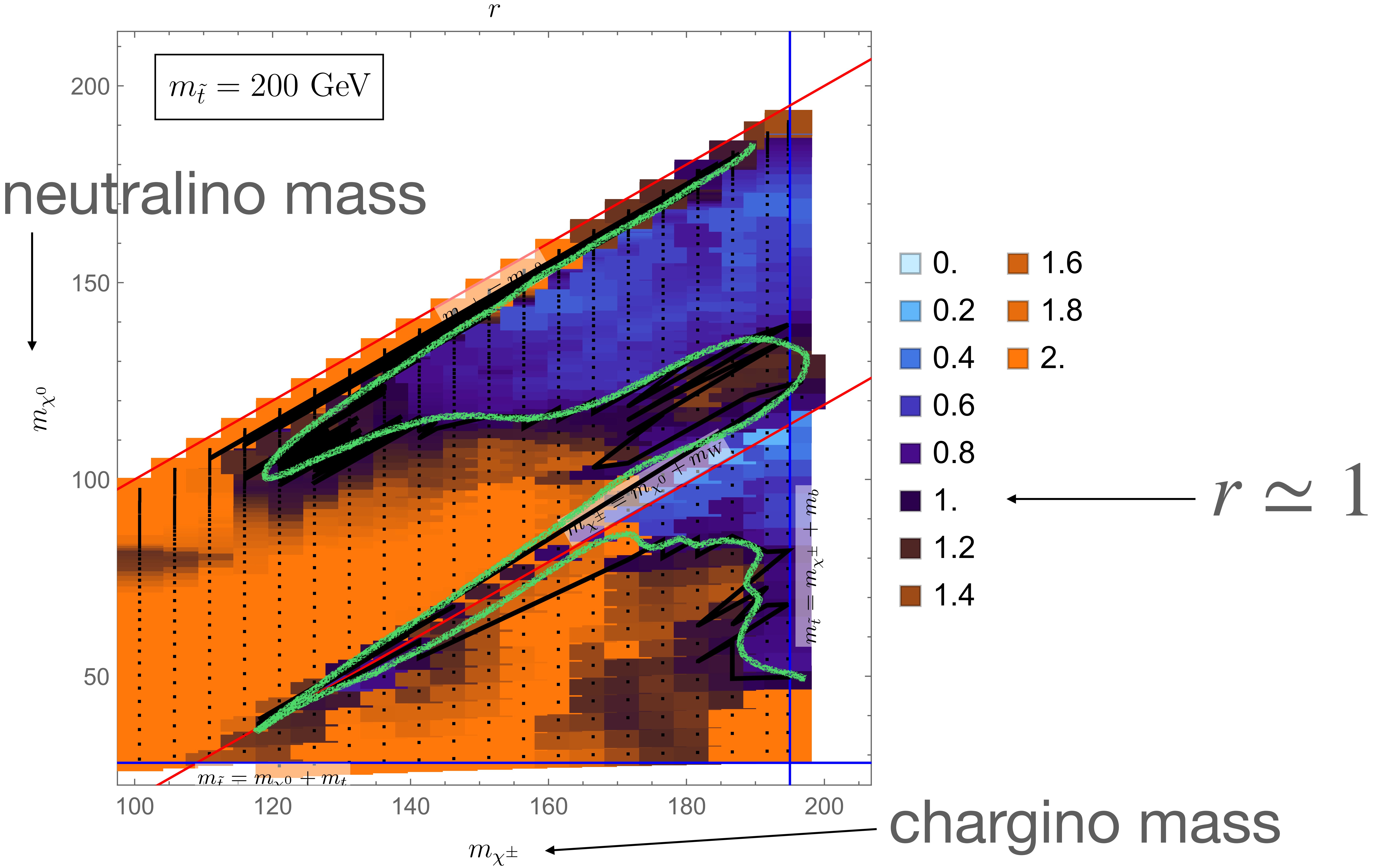
see also CHECKMATE

1312.2591

Recast bounds on the NP scenario

using all analyses included in SModelS

comprising 5744 individual maps from 1152 distinct signal regions, 100 different SMS topologies, from a total of 111 analyses



There are scenarios in the MSSM that cannot be excluded by the searches presently included in SModelS

(they even give the right Higgs boson mass at 1-loop, but never mind)

Recast bounds on the NP scenario

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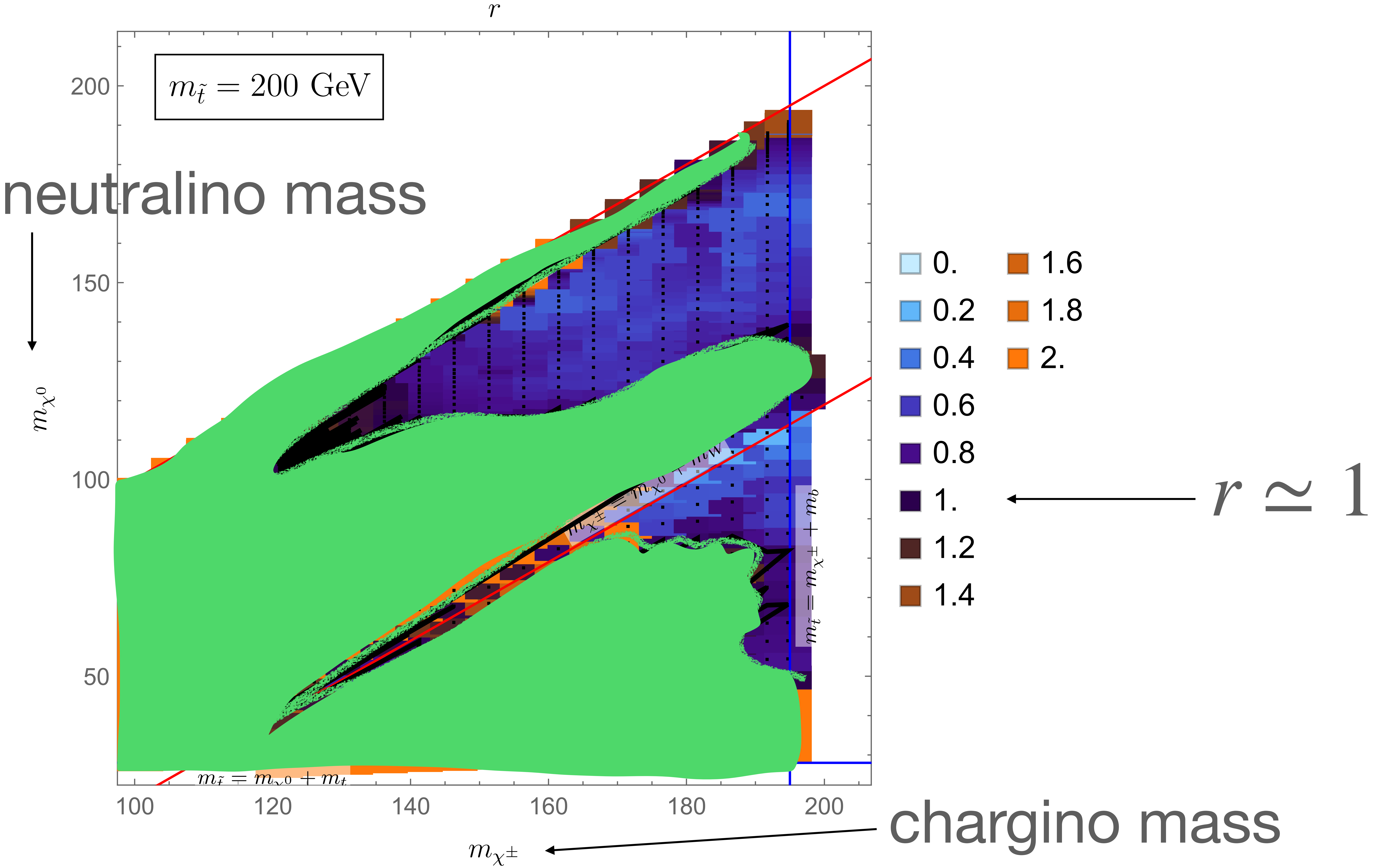

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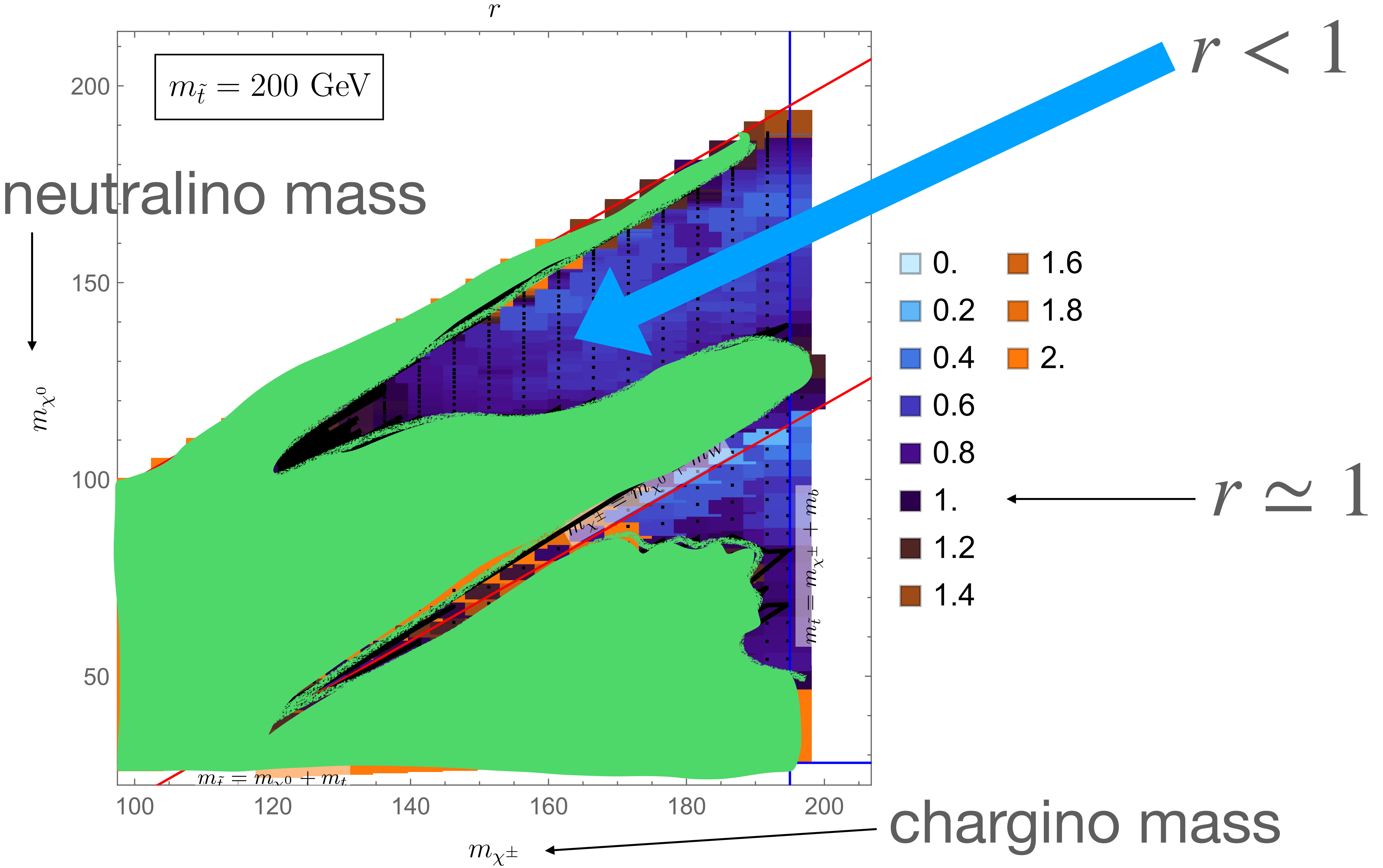


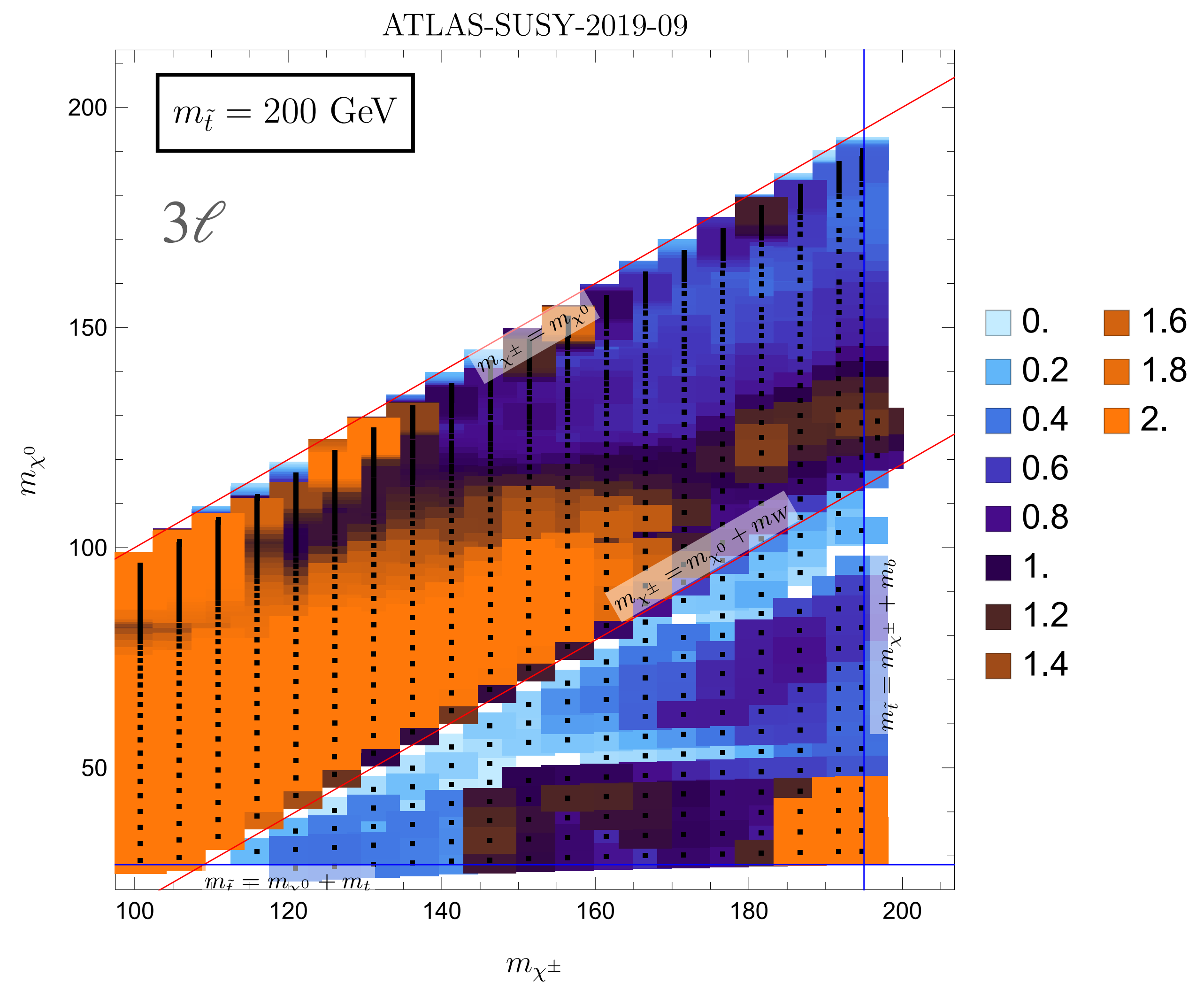
$m_{\tilde{t}} \simeq 200$ GeV
$m_{\chi^\pm} \simeq 170$ GeV
$m_{\chi^0} \simeq 130$ GeV

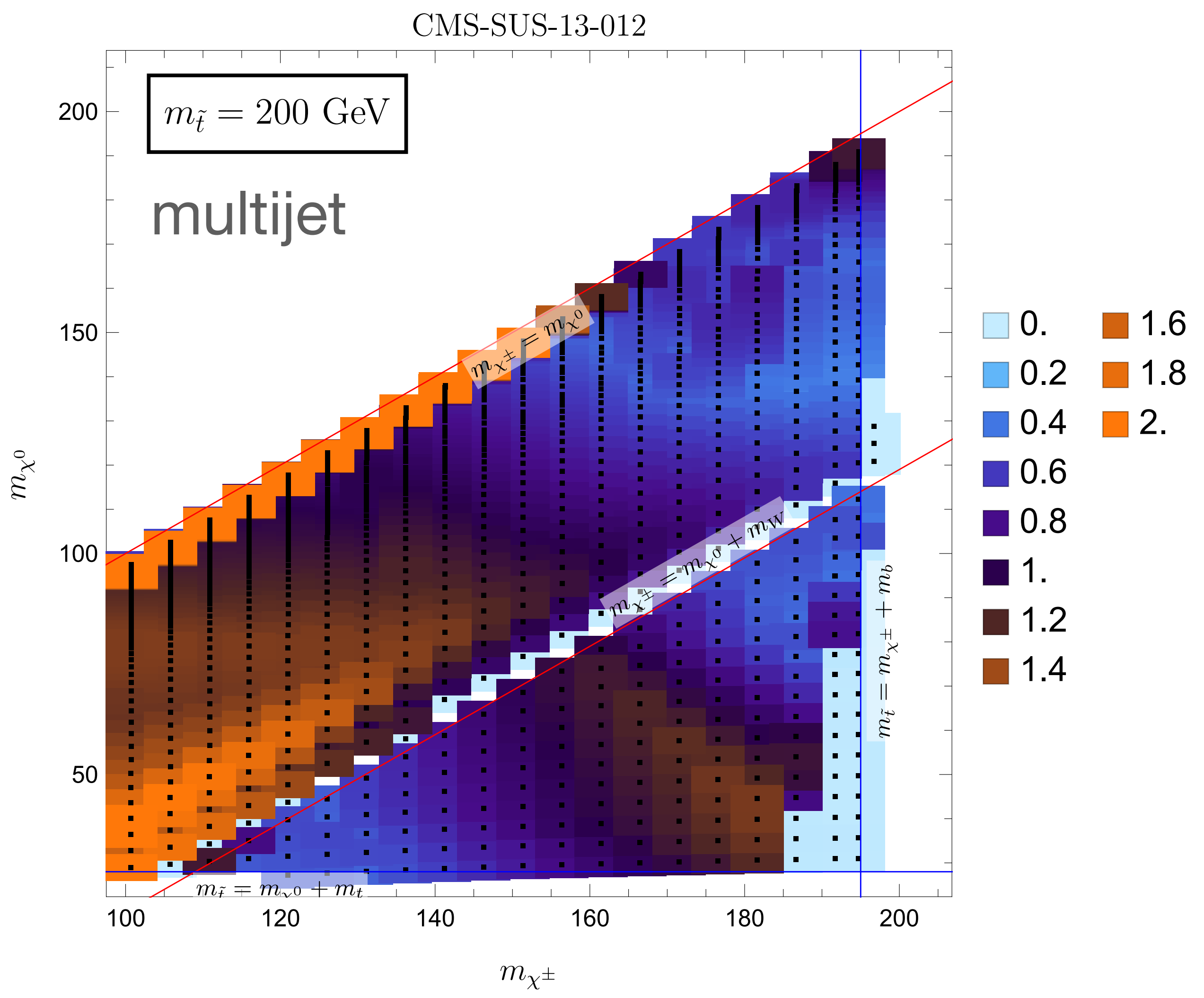
There are scenarios in the MSSM that cannot be excluded by the searches presently included in SModelS

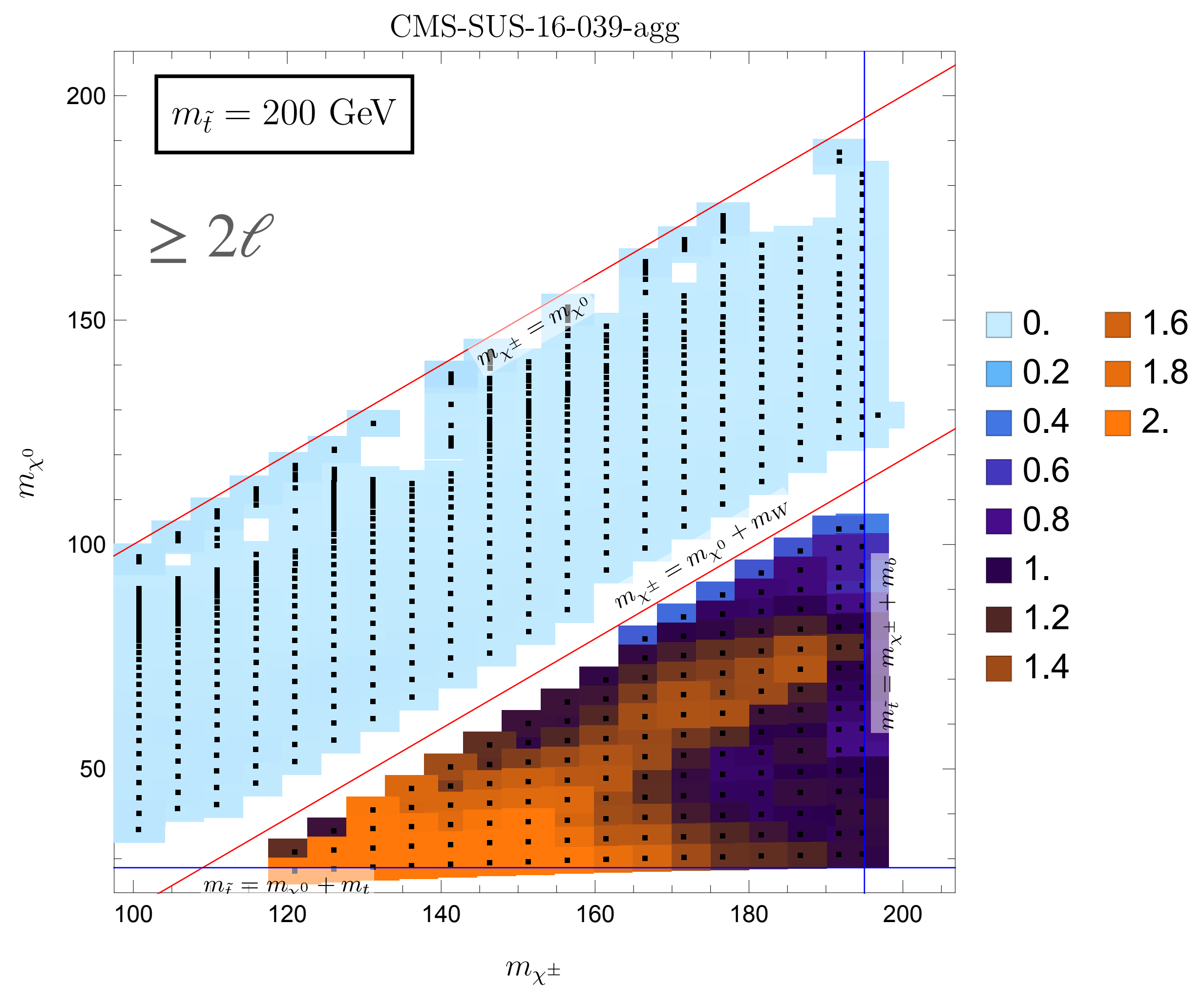
(they even give the right Higgs boson mass at 1-loop, but never mind)

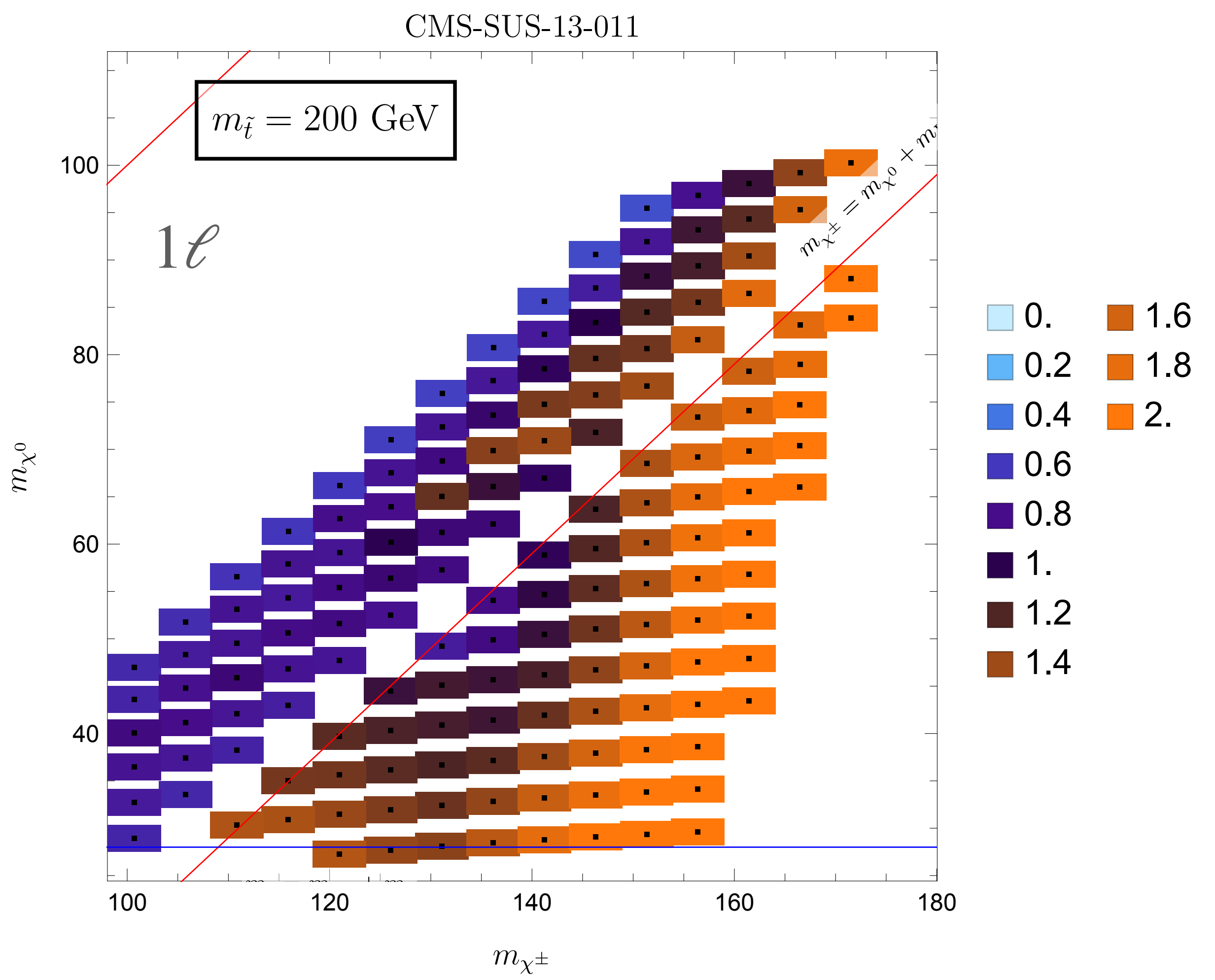
Recast bounds on the NP scenario

analysis by analysis









ATLAS SUSY-2019-09

Table 8: Summary of the preselection criteria applied in the SRs of the off-shell *WZ* selection. In rows where only one value is given it applies to all regions. '-' indicates no requirement is applied for a given variable/region.

Variable	$SR^{offWZ}_{lowE_T^{miss}}$-0j	$SR^{offWZ}_{lowE_T^{miss}}$-nj	$SR^{offWZ}_{highE_T^{miss}}$-0j	$SR^{offWZ}_{highE_T^{miss}}$-nj
	Preselection requirements			
$n_{lep}^{baseline}, n_{lep}^{signal}$	= 3			
n_{SFOS}	≥ 1			
$m_{\ell\ell}^{max}$ [GeV]	< 75			
$m_{\ell\ell}^{min}$ [GeV]	∈ [1, 75]			
$n_{b\text{-jets}}$	= 0			
min $\Delta R_{3\ell}$	> 0.4			
Resonance veto $m_{\ell\ell}^{min}$ [GeV]	∉ [3, 3.2], ∉ [9, 12]			-
Trigger	(multi-)lepton		((multi-)lepton ‖ E_T^{miss})	
$n_{jets}^{30\ GeV}$	= 0	≥ 1	= 0	≥ 1
E_T^{miss} [GeV]	< 50	< 200	> 50	> 200
E_T^{miss} significance	> 1.5	> 3.0	> 3.0	> 3.0
$p_T^{\ell_1}, p_T^{\ell_2}, p_T^{\ell_3}$ [GeV]	> 10			> 4.5(3.0) for $e(\mu)$
$\lvert m_{3\ell} - m_Z \rvert$ [GeV]	> 20 ($\ell_W = e$ only)		-	
min ΔR_{SFOS}	[0.6, 2.4] ($\ell_W = e$ only)		-	

Table 2: Summary of the preselection criteria applied in the SRs of the on-shell *WZ* and *Wh* selections. In rows where only one value is given it applies to all regions. '-' indicates no requirement is applied for a given variable/region.

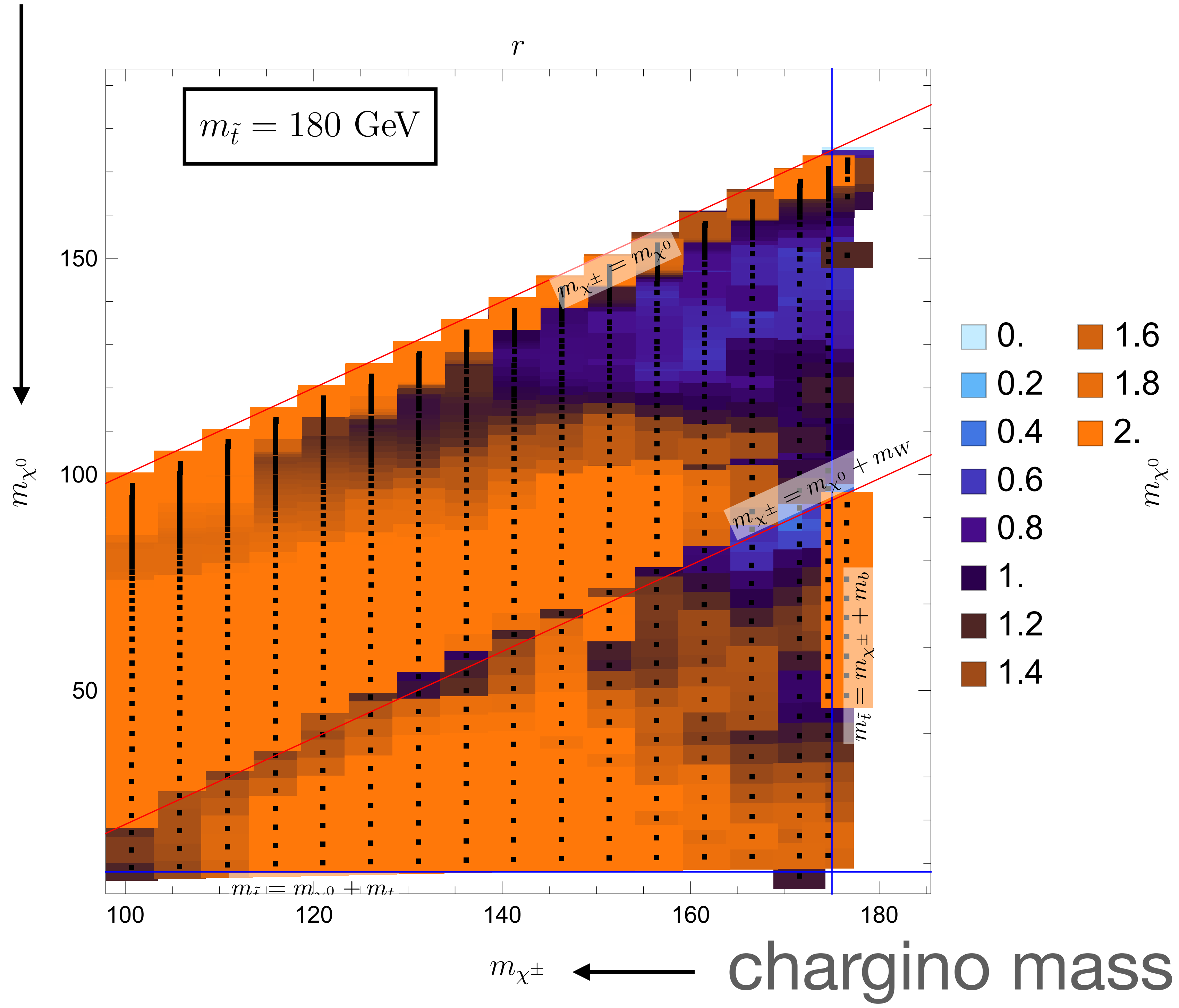
Variable	SR^{WZ}	SR^{Wh}_{SFOS}	SR^{Wh}_{DFOS}
	Preselection requirements		
$n_{lep}^{baseline}, n_{lep}^{signal}$	= 3		
Trigger	dilepton		
$p_T^{\ell_1}, p_T^{\ell_2}, p_T^{\ell_3}$ [GeV]	> 25, 20, 10		
E_T^{miss} [GeV]	> 50		
$n_{b\text{-jets}}$	= 0		
Resonance veto $m_{\ell\ell}$ [GeV]	> 12	> 12	-
n_{SFOS}	≥ 1	≥ 1	= 0
$m_{\ell\ell}$ [GeV]	∈ [75, 105]	∉ [75, 105]	-
$\lvert m_{3\ell} - m_Z \rvert$ [GeV]	> 15	> 15	-

dedicated analyses for compressed scenarios are included in the recast

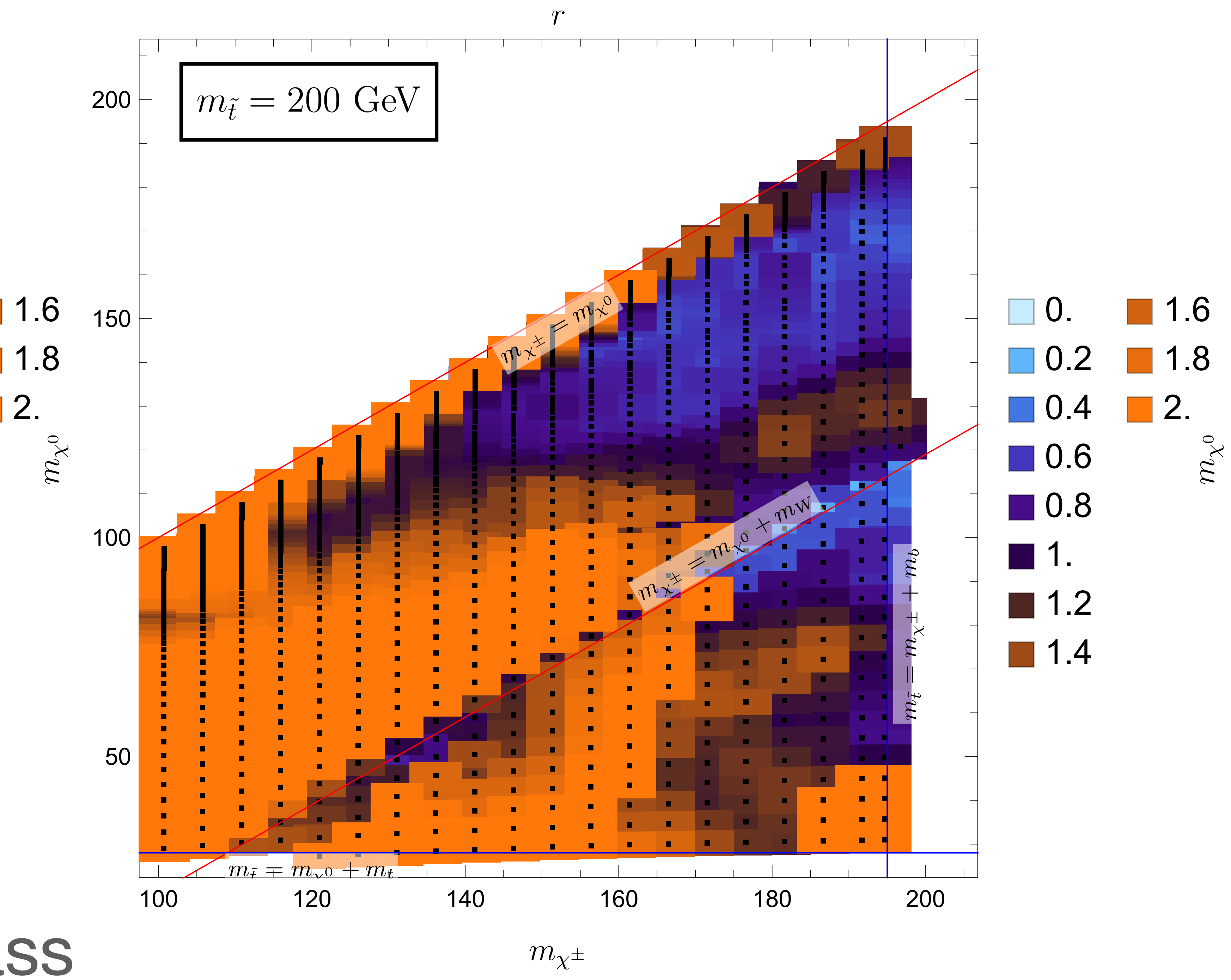
Recast bounds on the NP scenario

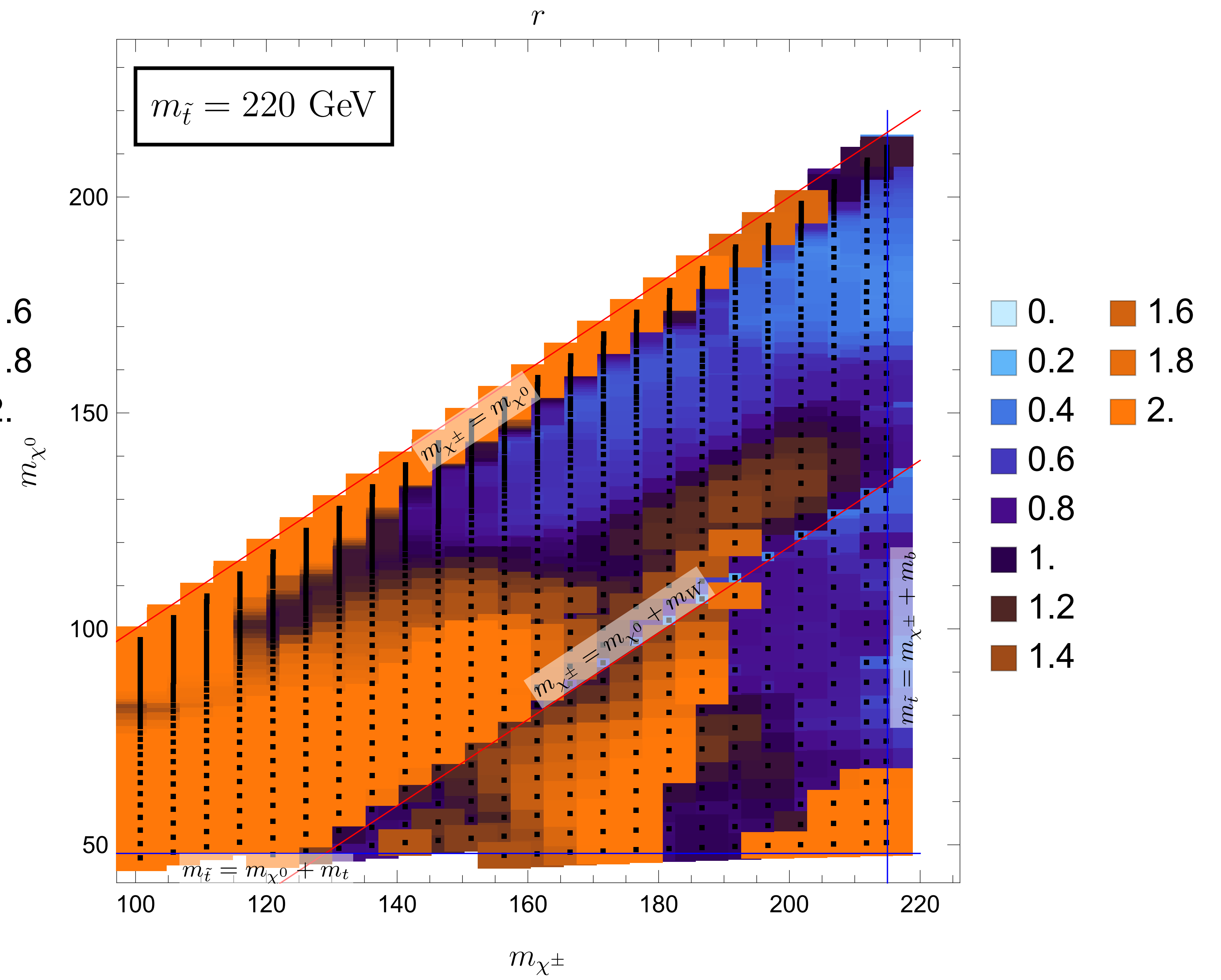
at several stop quark mass values

neutralino mass



chargino mass





$m_{\tilde{t}} \simeq 180$ GeV

$m_{\tilde{t}} \simeq 200$ GeV

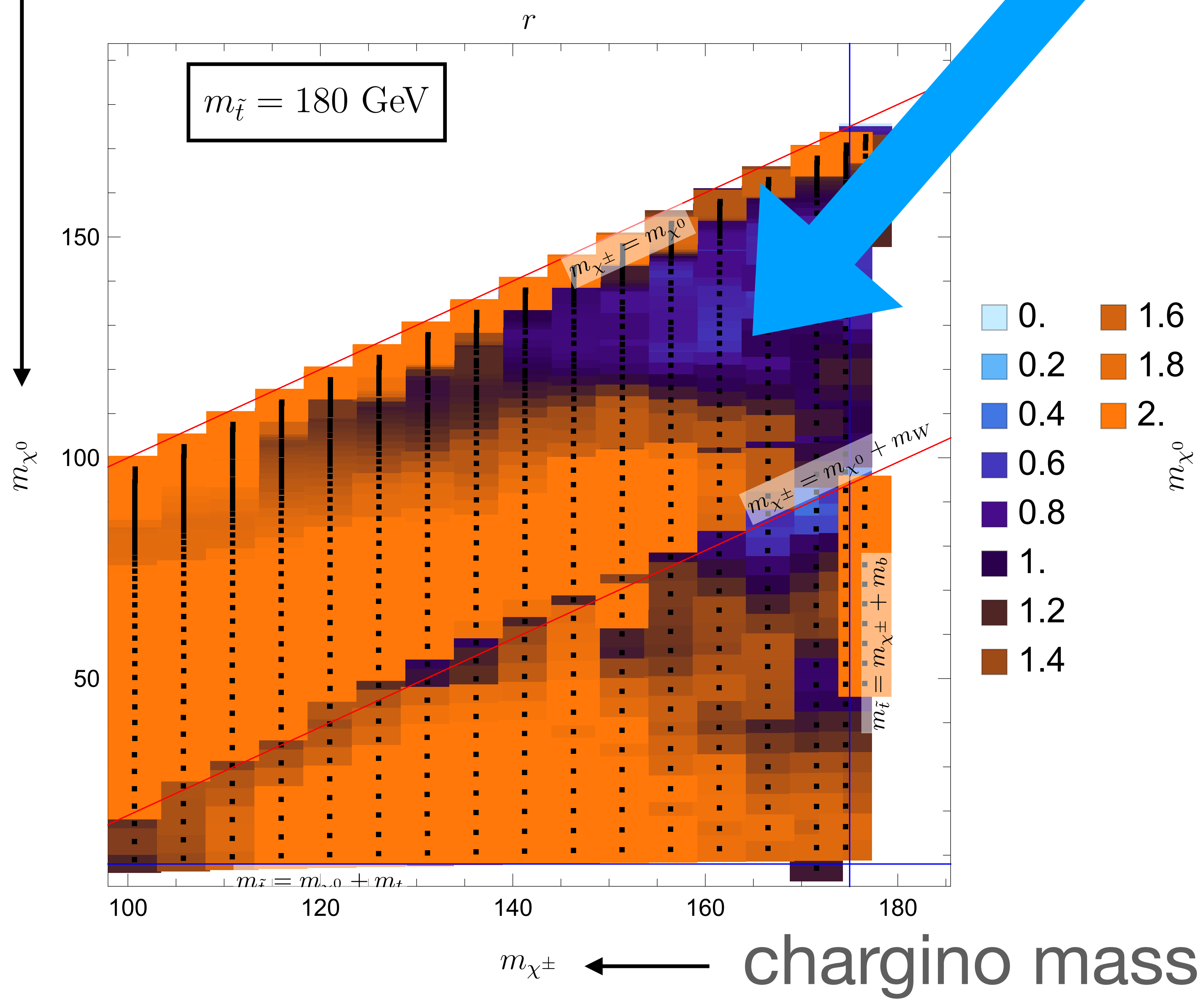
$m_{\tilde{t}} \simeq 220$ GeV

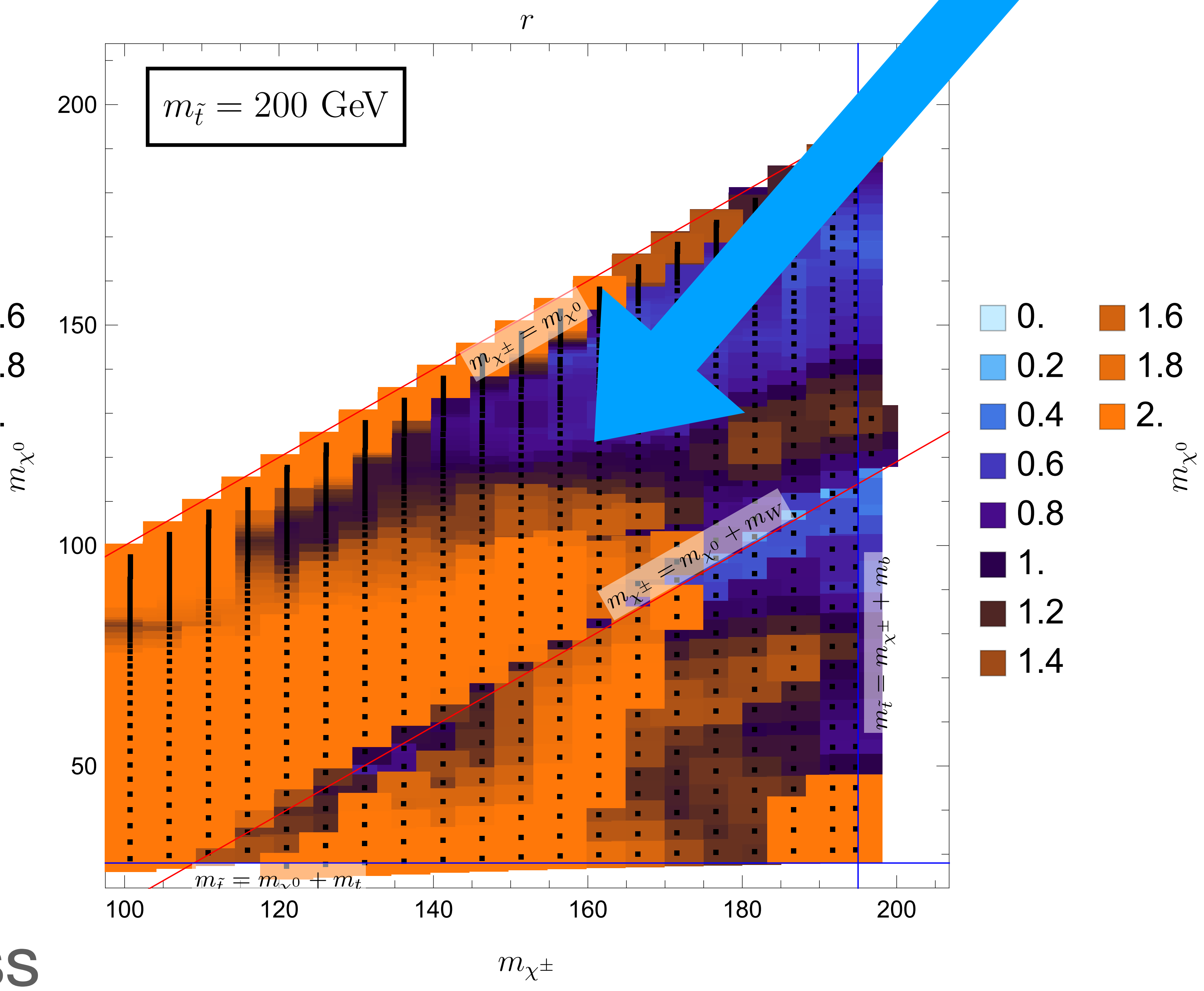
Recast bounds on the NP scenario

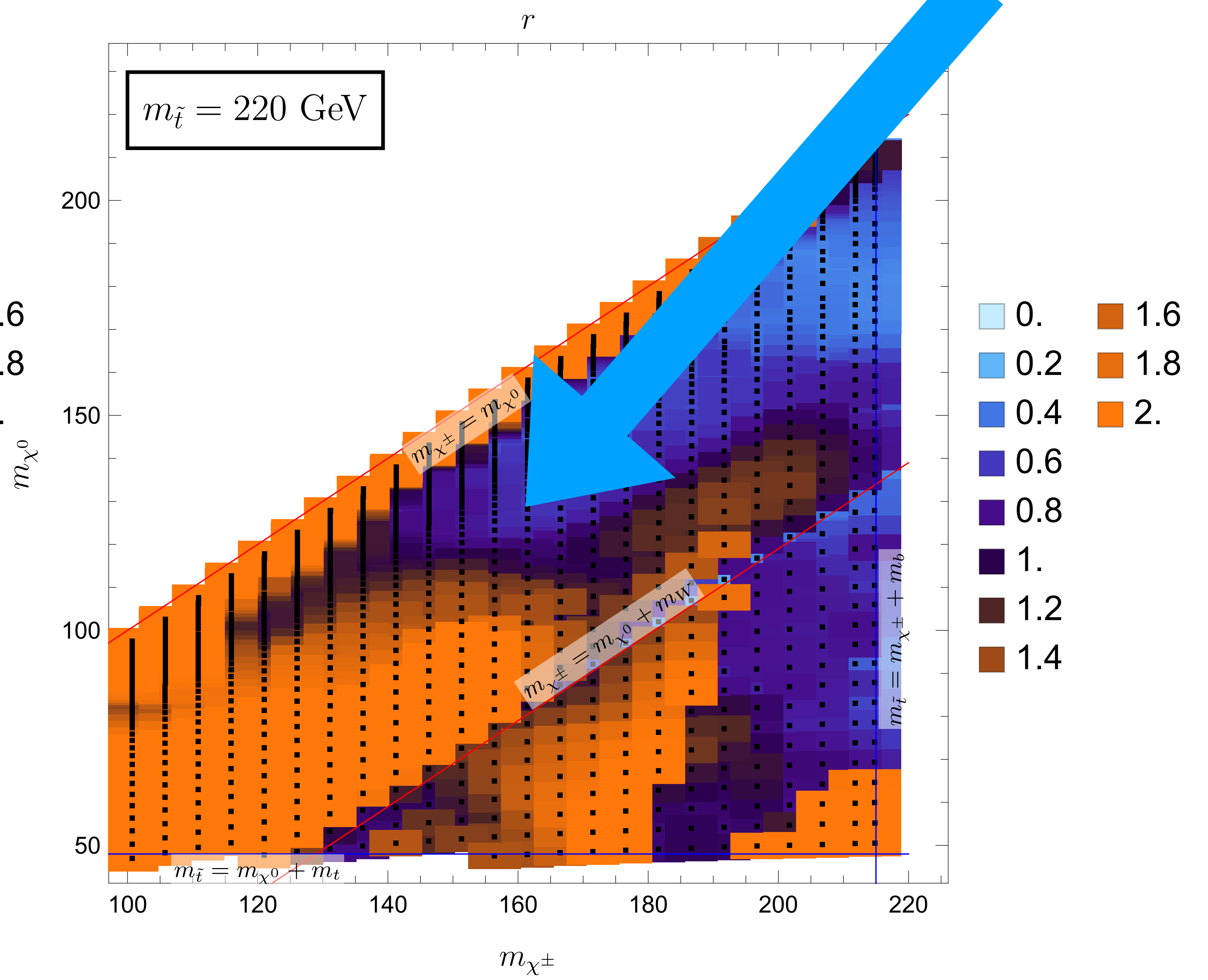
at several stop quark mass values

$r < 1$ $r < 1$ $r < 1$

neutralino mass





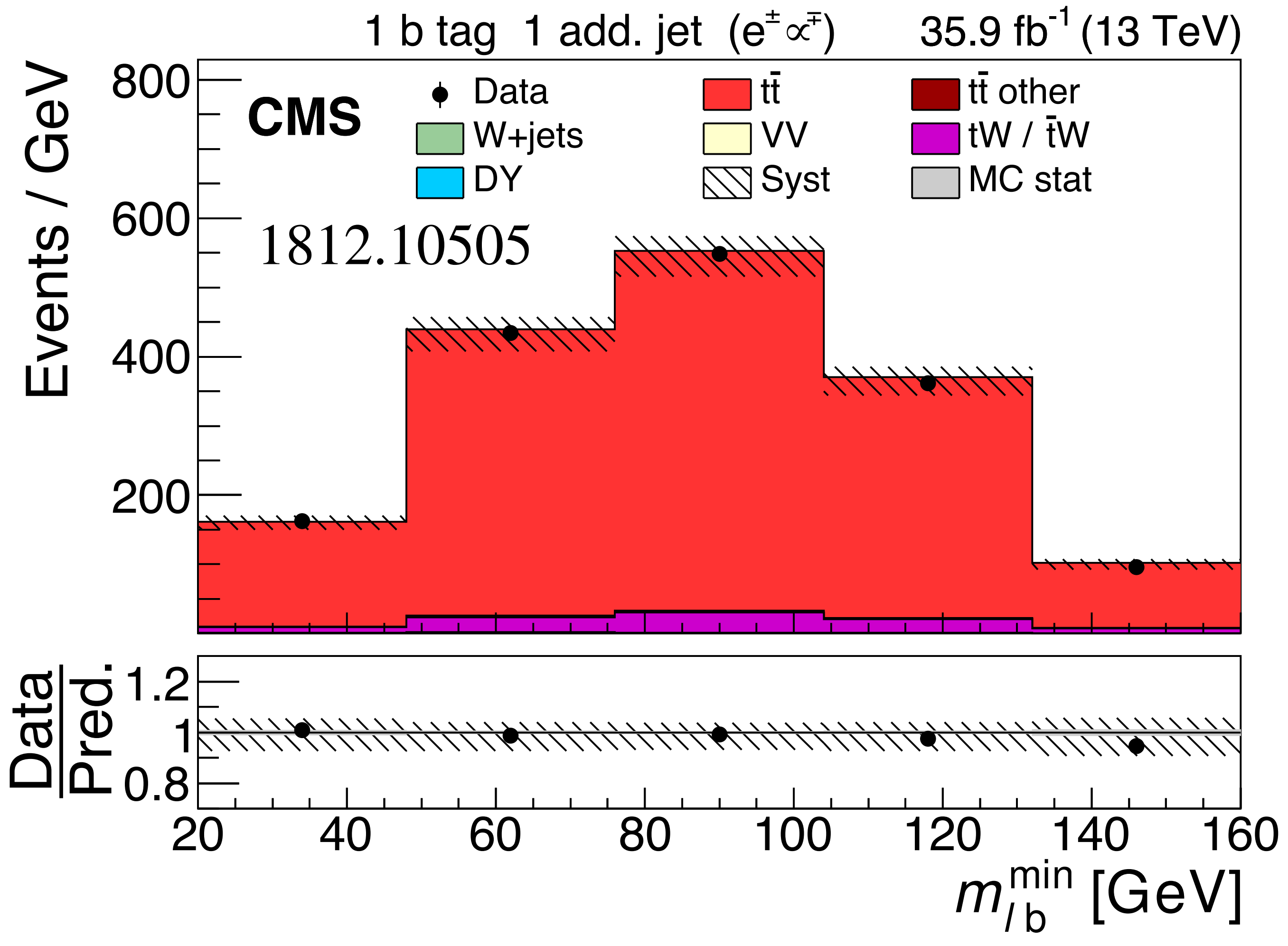


chargino mass

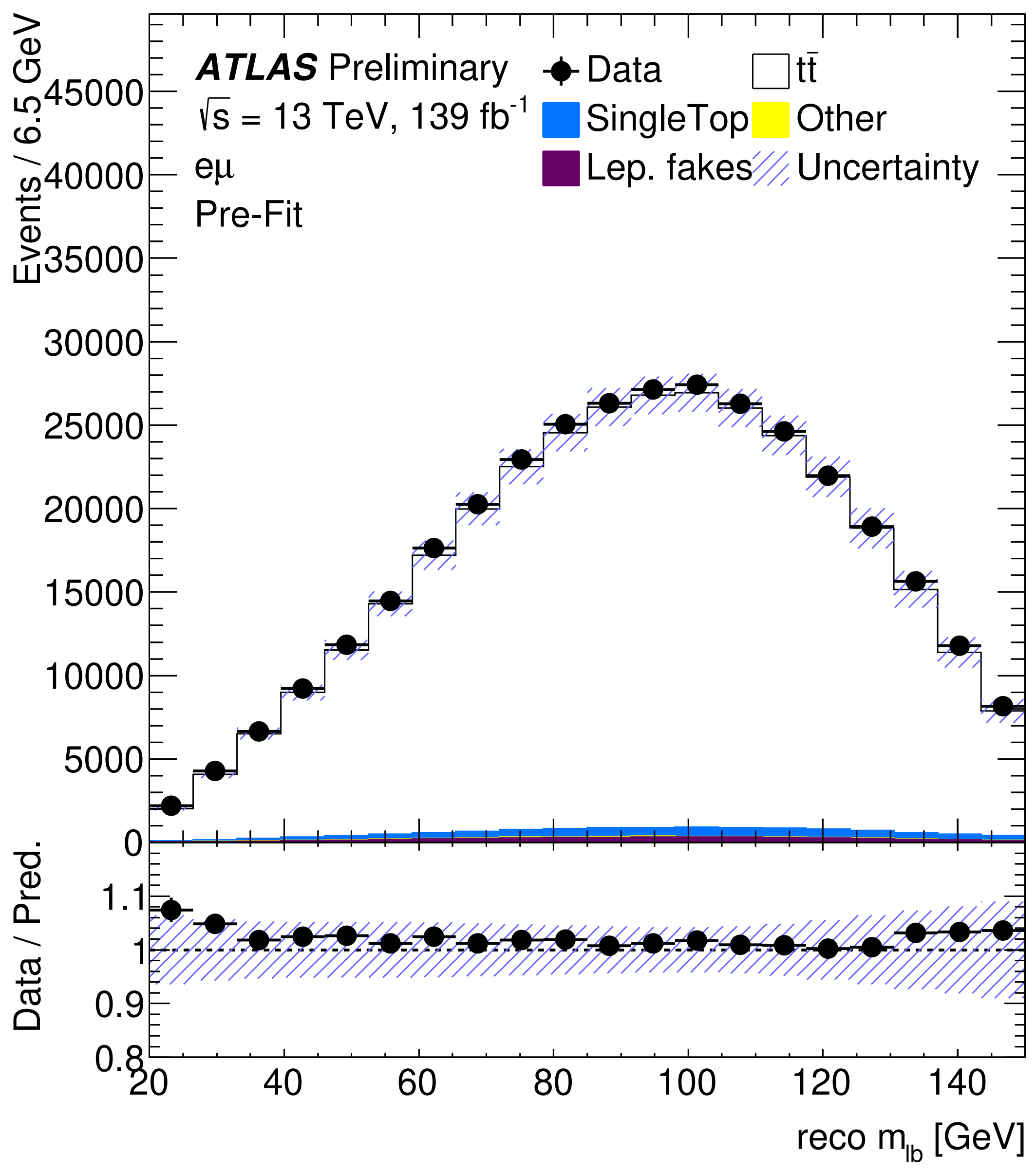
$m_{\tilde{t}} \simeq 180$ GeV $m_{\tilde{t}} \simeq 200$ GeV $m_{\tilde{t}} \simeq 220$ GeV

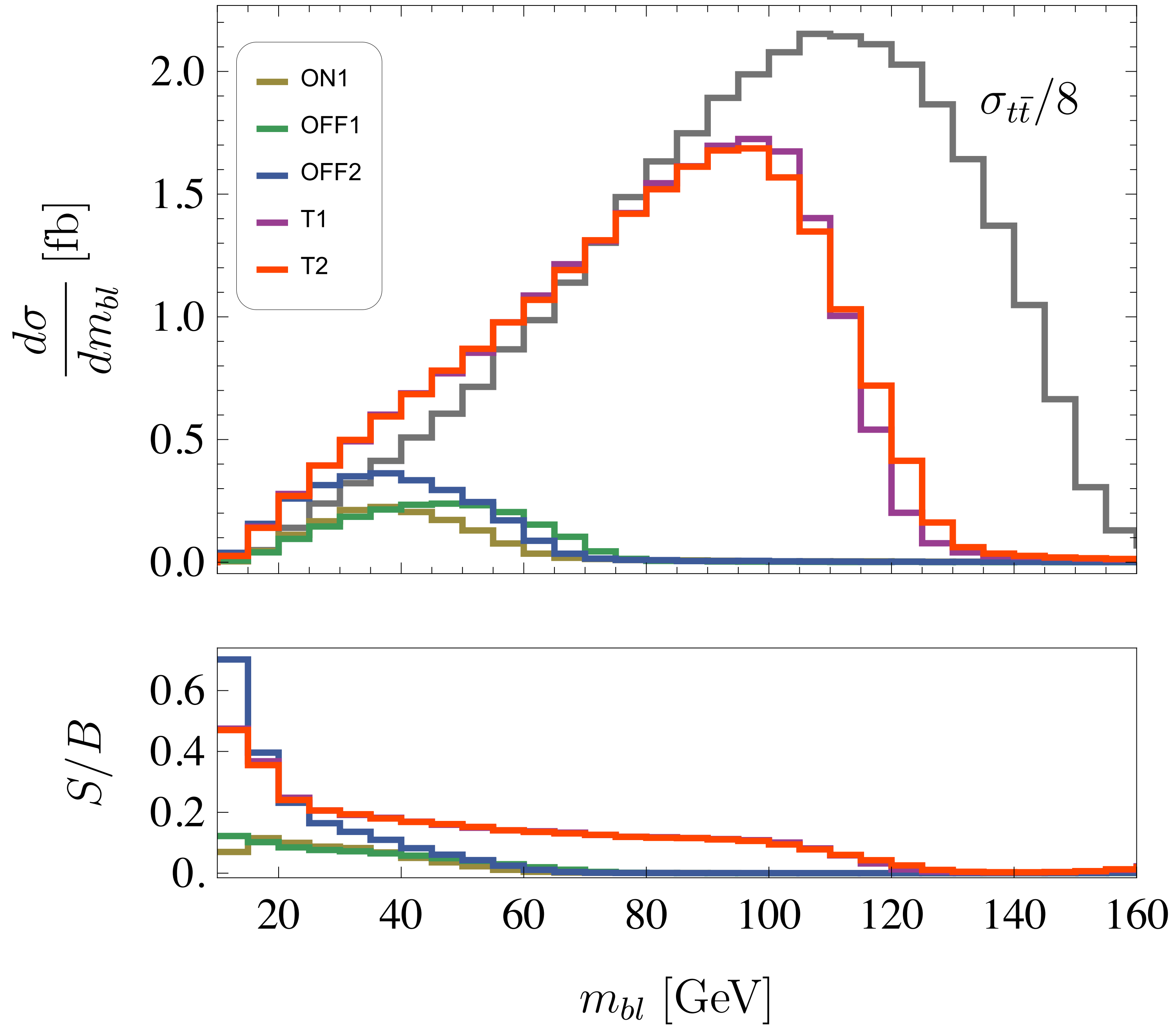
Compute the sensitivity for the NP scenario

- **find two analyses measuring the $m_{b\ell}$ distribution** *<u>with published uncertainty</u>*
- **compute the expected $m_{b\ell}$ shape and rate from the NP scenario using the** <u>same selection as the experimental paper</u>
- **use the published uncertainty to compute the expected significance for the putative NP signal with a template χ^2 analysis**



ATLAS-CONF-2019-038





Workflow **Easily reproducible with well known codes.**

SLHA-based → can be injected in Pythia in your experiment software framework(!)

- Generate MSSM model in SPheno 4.0.1 → SLHA file
- Elaborate the SLHA file with SModelS 2.3.3 (using SR combination)
- Find $r < 1$ or $r > 1$ (soon available on Zenodo for those who want to inject signals in their top quark property measurements)
- Run Pythia 8.3 to generate SM $t\bar{t}$ "background" and $pp \to \tilde{t}\tilde{t}$ signal events (relies on Pythia SLHA interface) → compute any distribution after selection cuts
- For simplicity we compute the correctly paired $m_{b\ell}$, which is different from CMS and ATLAS choices (interesting question to find out what is the best pairing strategy)

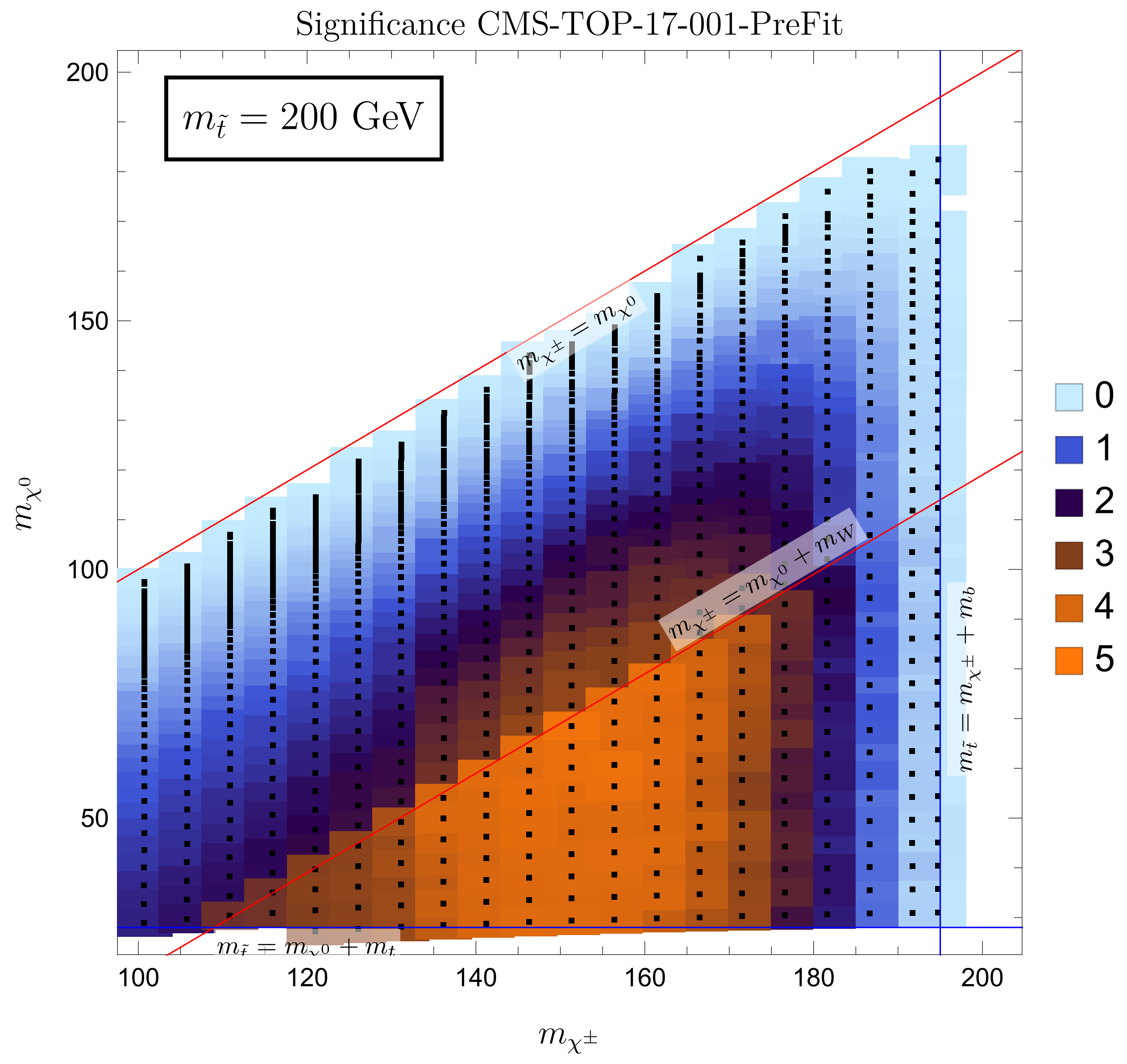
Significance estimator

$m_{\tilde{t}} \simeq 200$ GeV

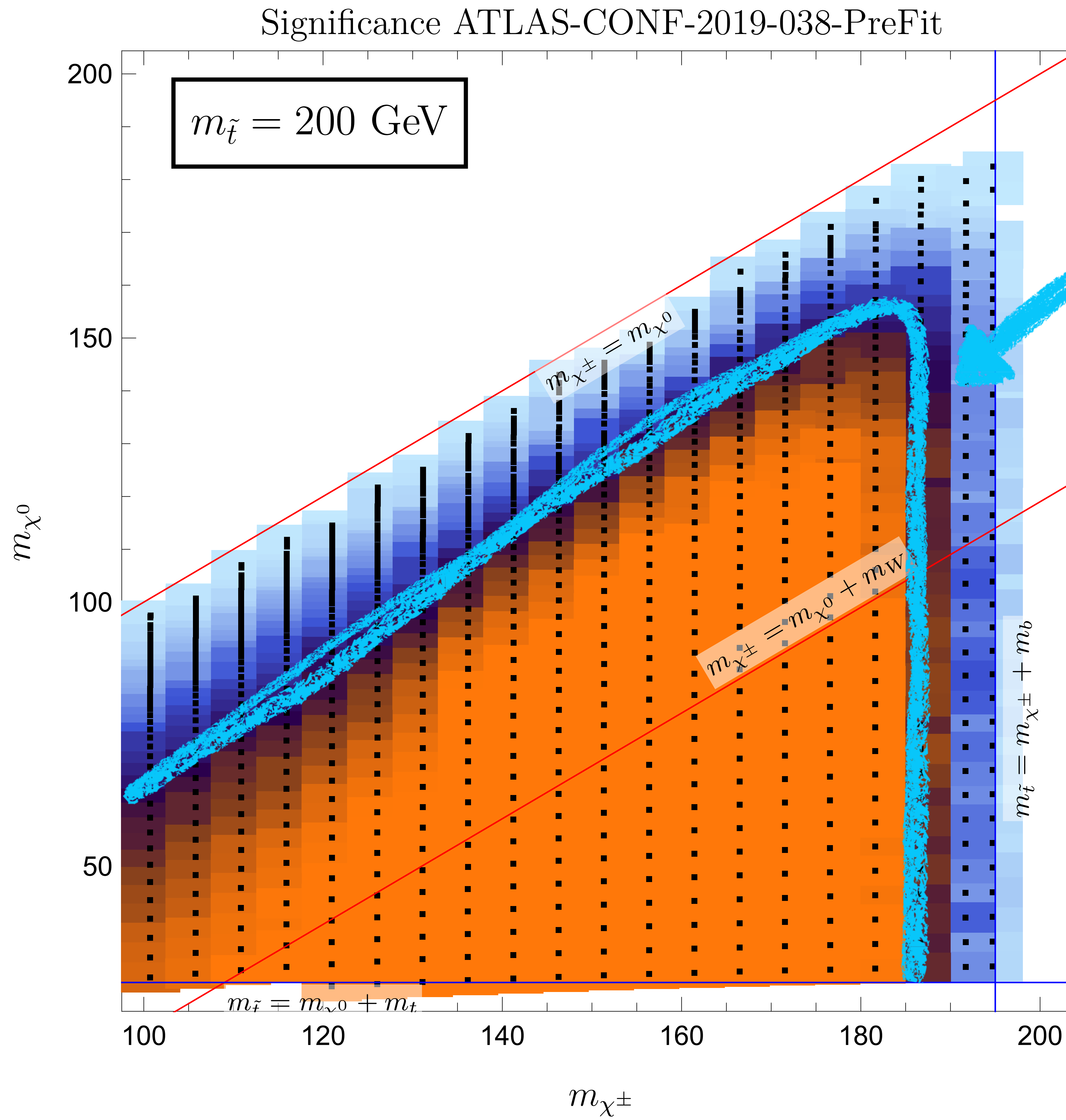
$$z = \sqrt{\sum_i \left(\frac{S_i}{\delta B_i}\right)^2},$$

$$m_{b\ell}^{max}\Big|_{m_b=0} = \sqrt{\frac{(m_{\tilde{t}}^2 - m_{\chi^+}^2)(m_{\chi^+}^2 - m_{\chi^0}^2)}{m_\chi}}$$

$z \simeq 2$



CMS pre-fit



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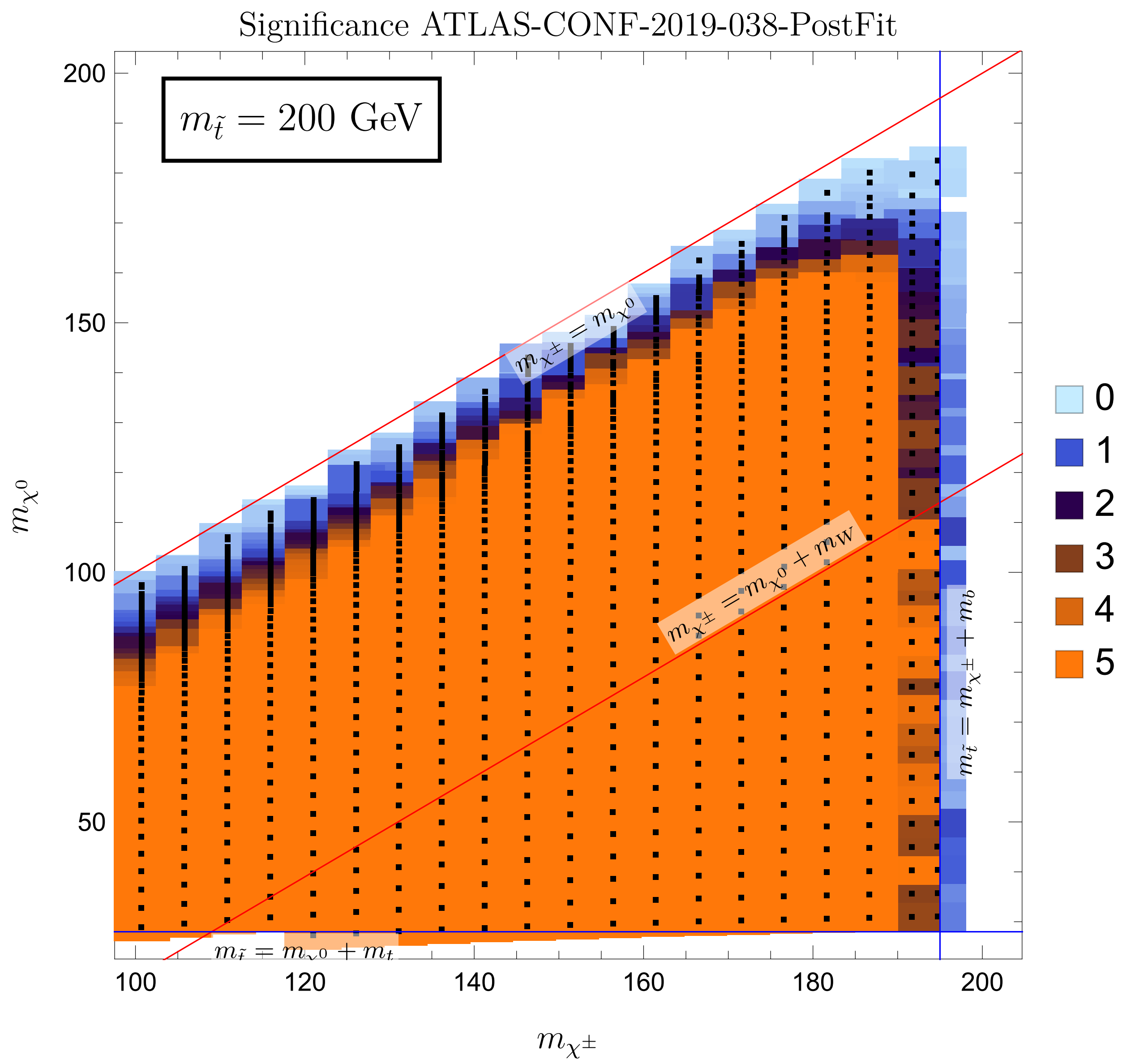

ATLAS post-fit

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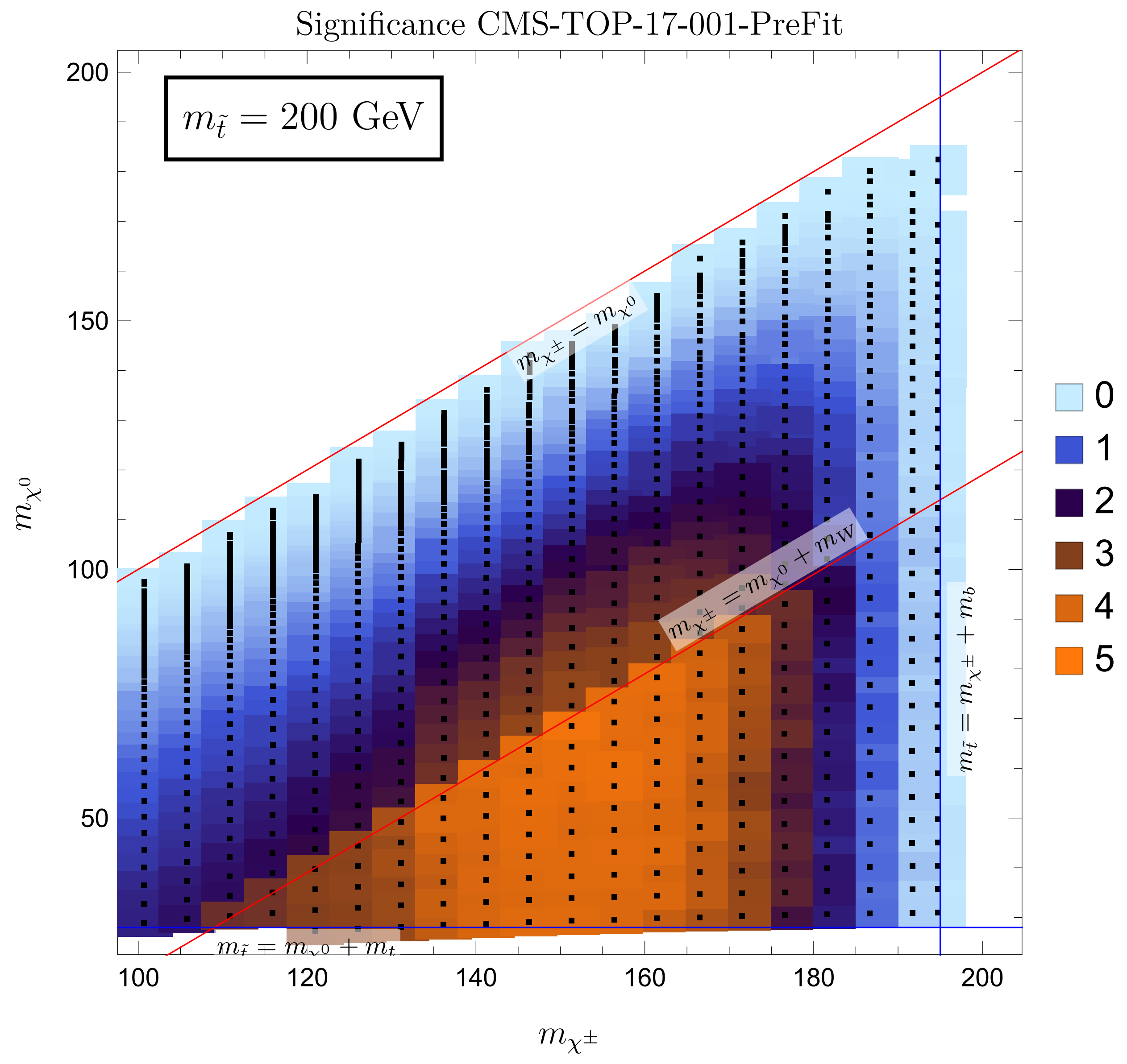

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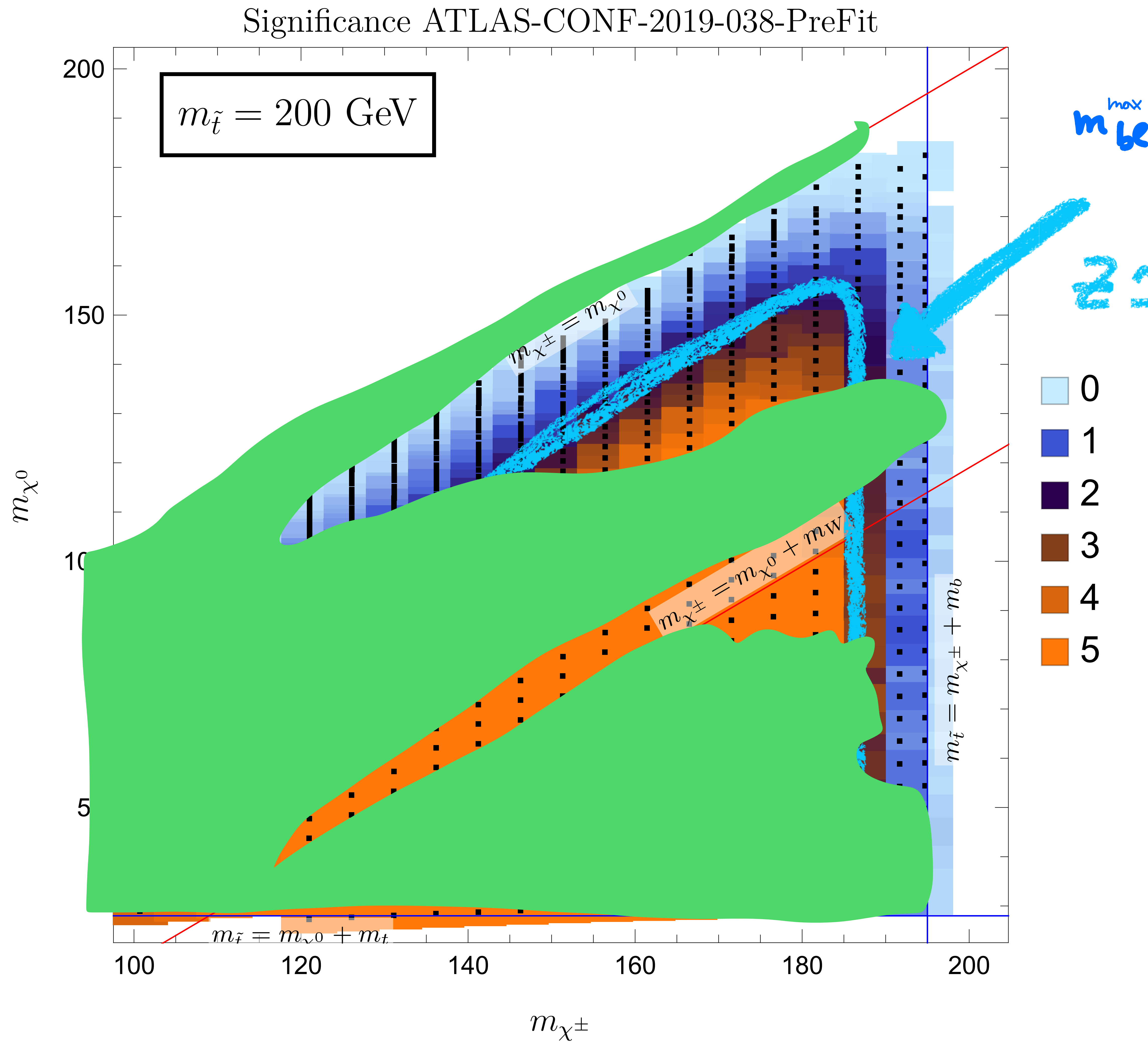

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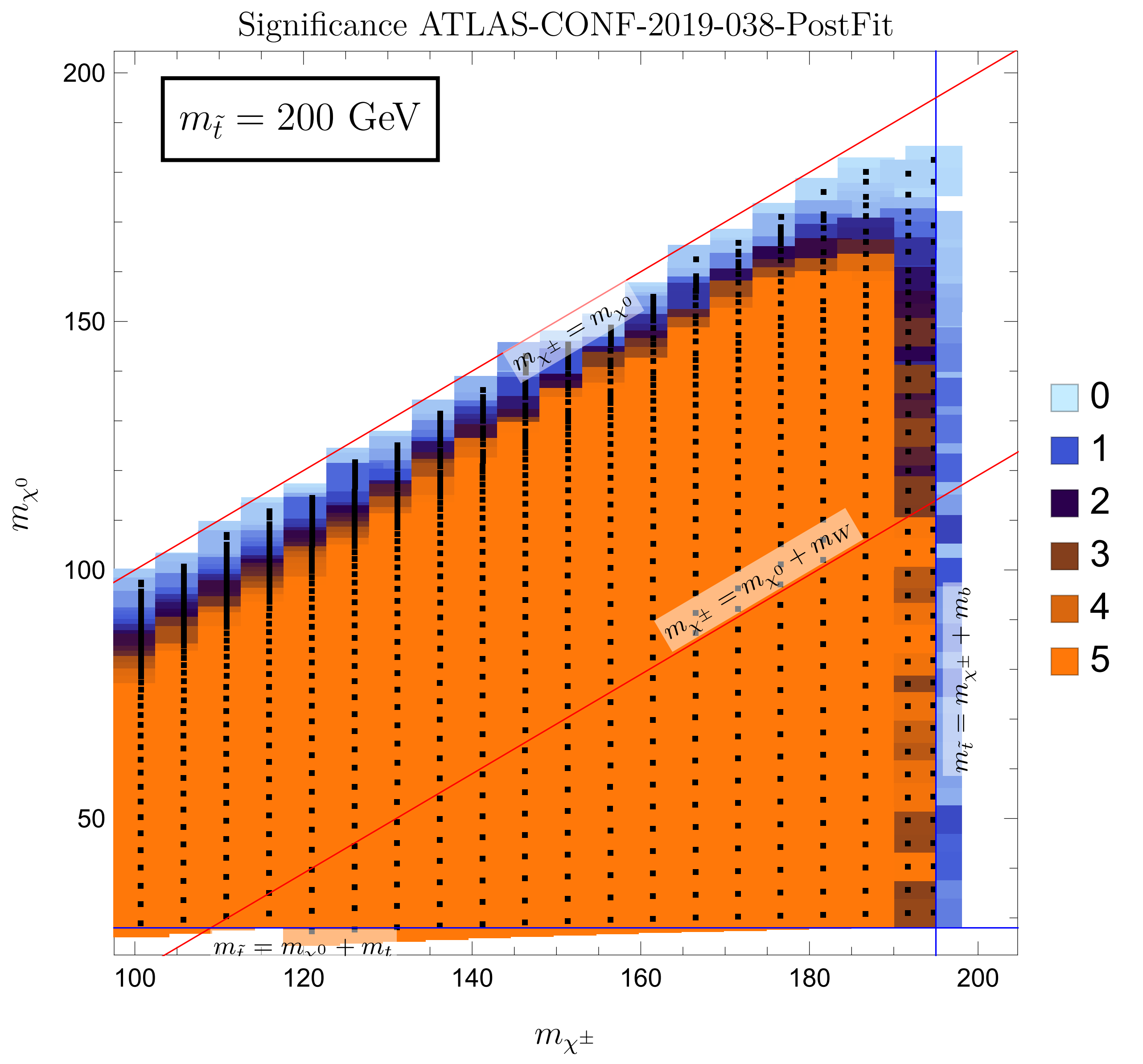

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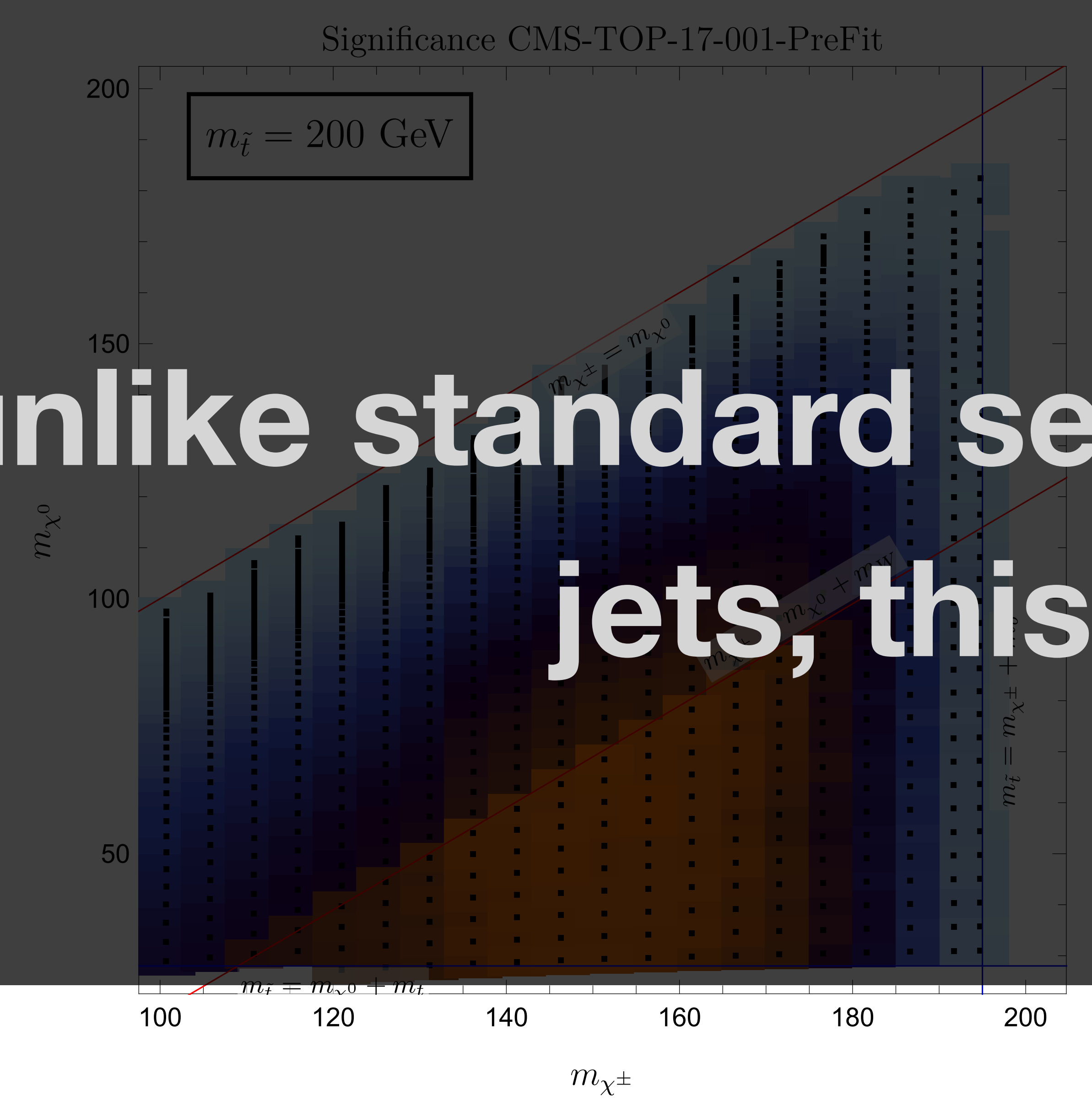

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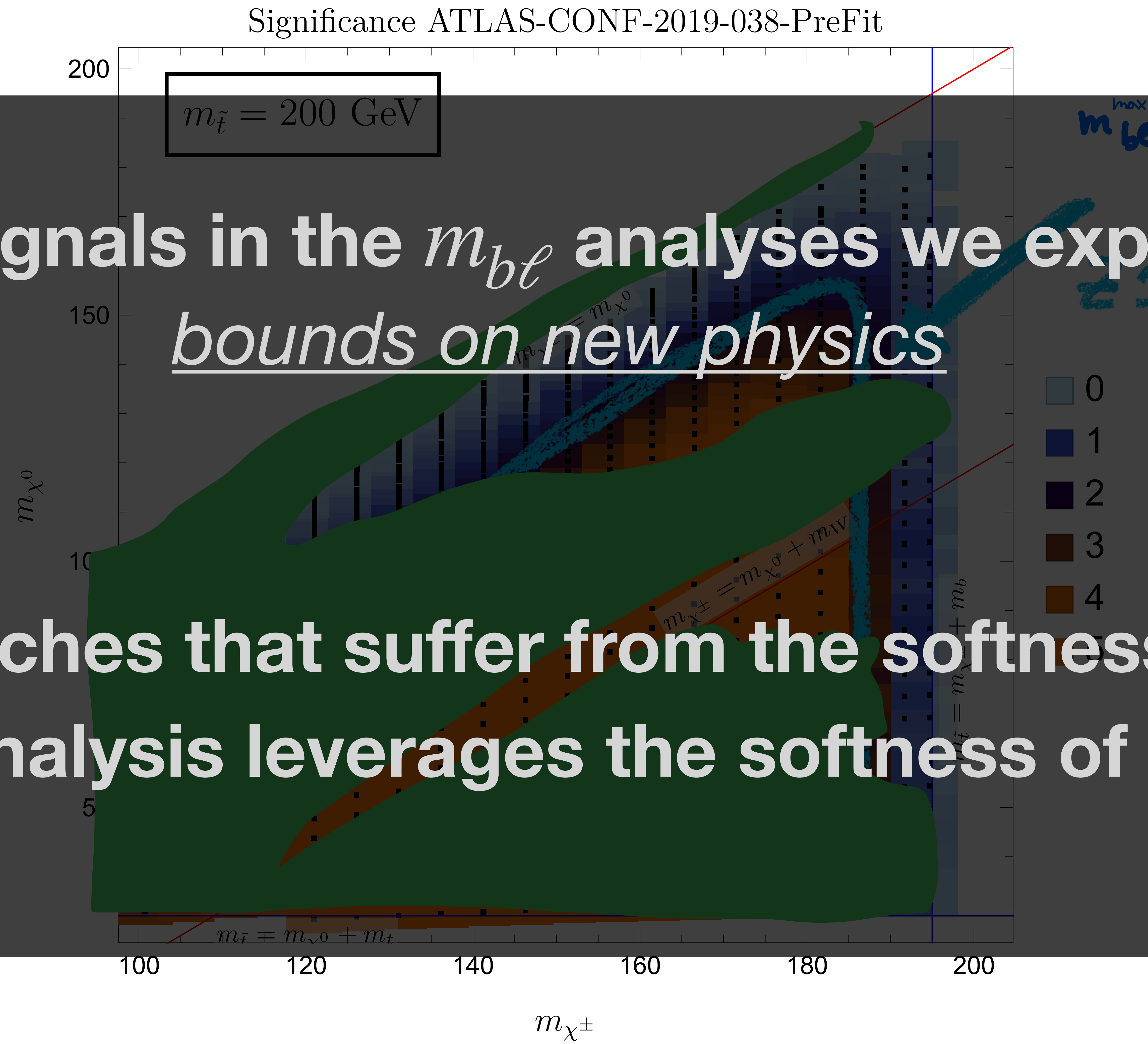

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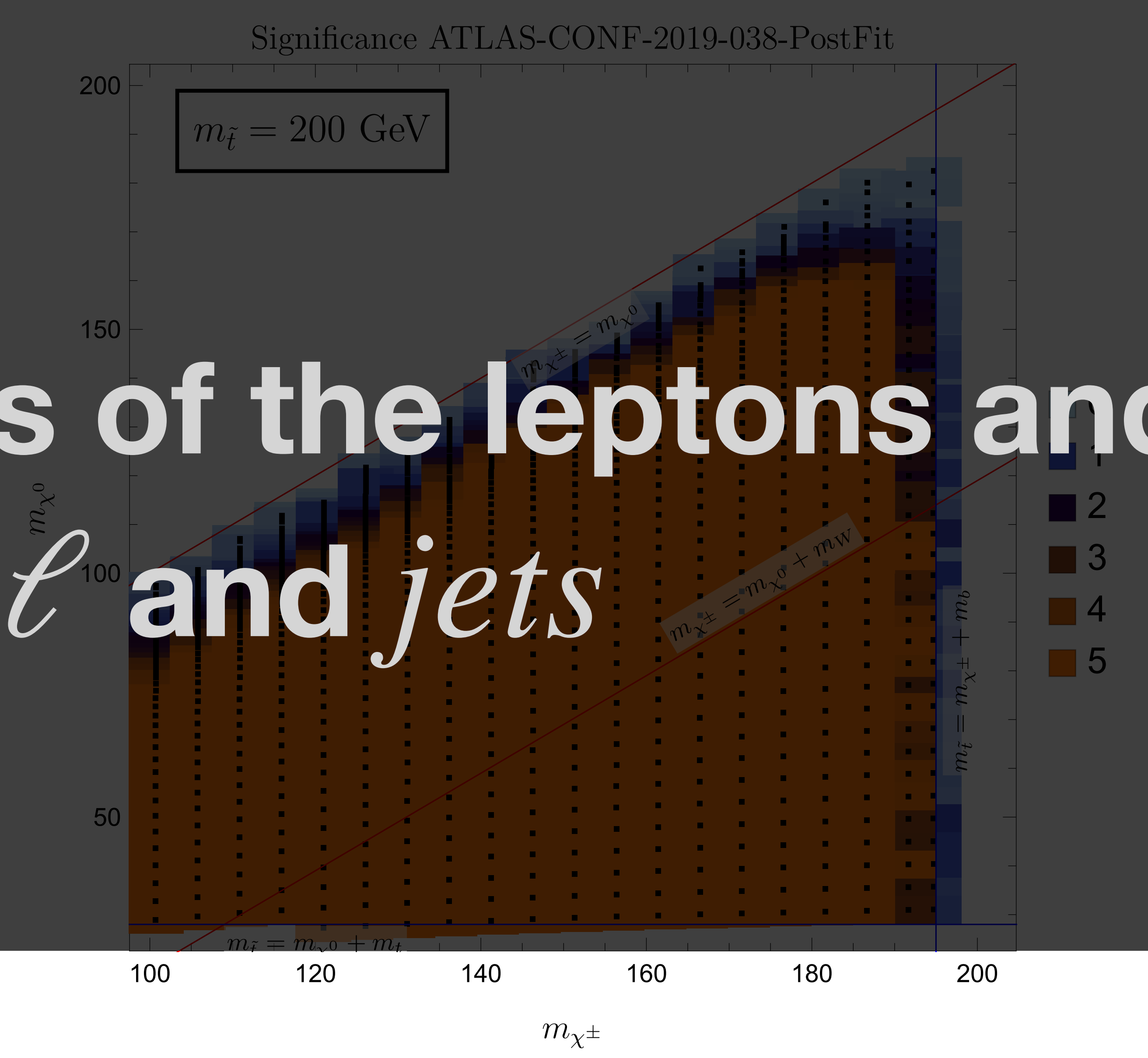


ATLAS post-fit

injecting MSSM signals in the $m_{b\ell}$ analyses we expect to obtain *new bounds on new physics*

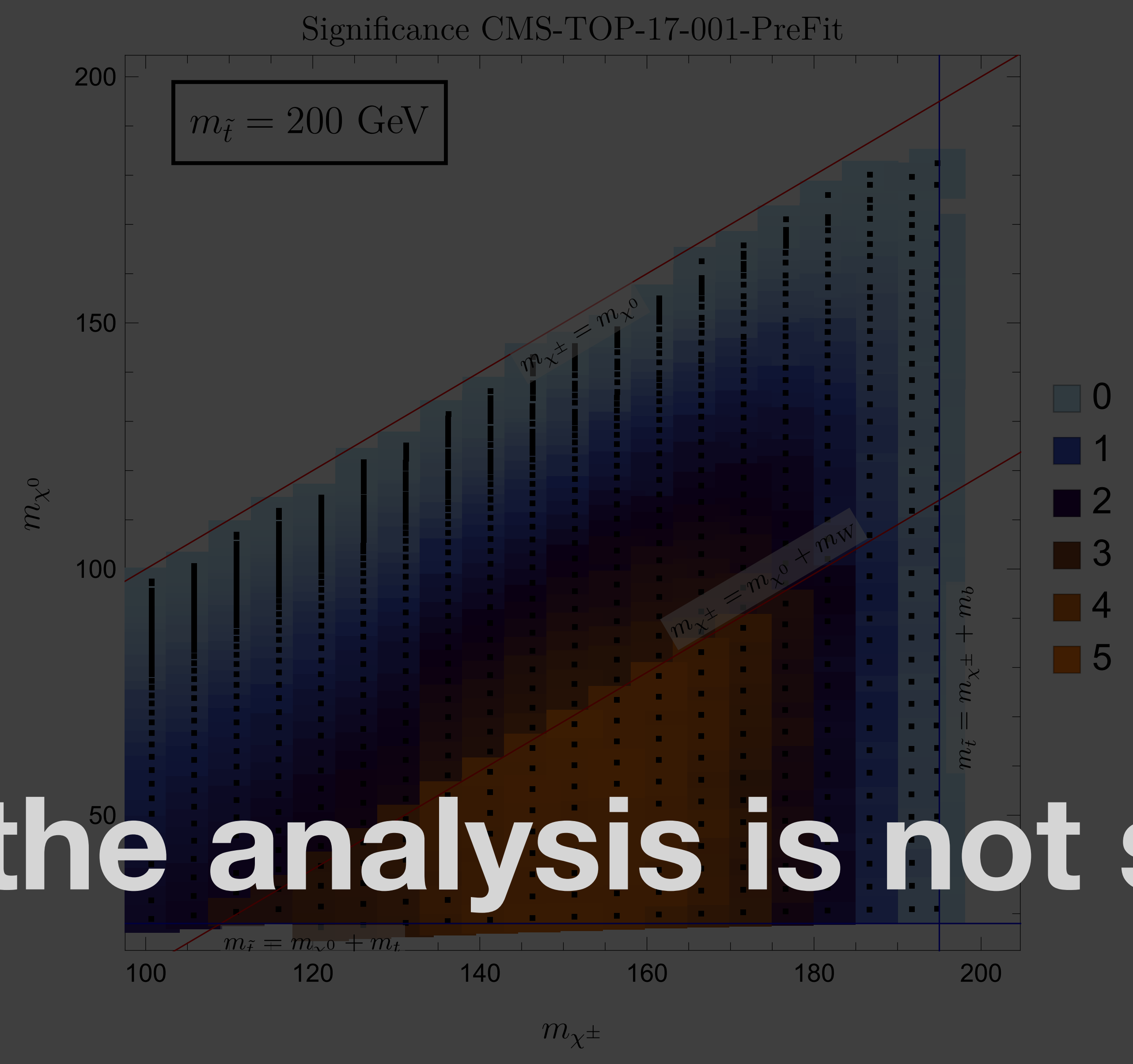
unlike standard searches that suffer from the softness of the leptons and jets, this analysis leverages the softness of ℓ and *jets*

Significance estimator

$$z = \sqrt{\sum_i \left(\frac{S_i}{\delta B_i}\right)^2},$$

$m_{\tilde{t}} \simeq 200$ GeV

the presence of the BSM signal is in general limited to low $m_{b\ell}$, because of the massive invisible χ^0 (or other invisibile state)



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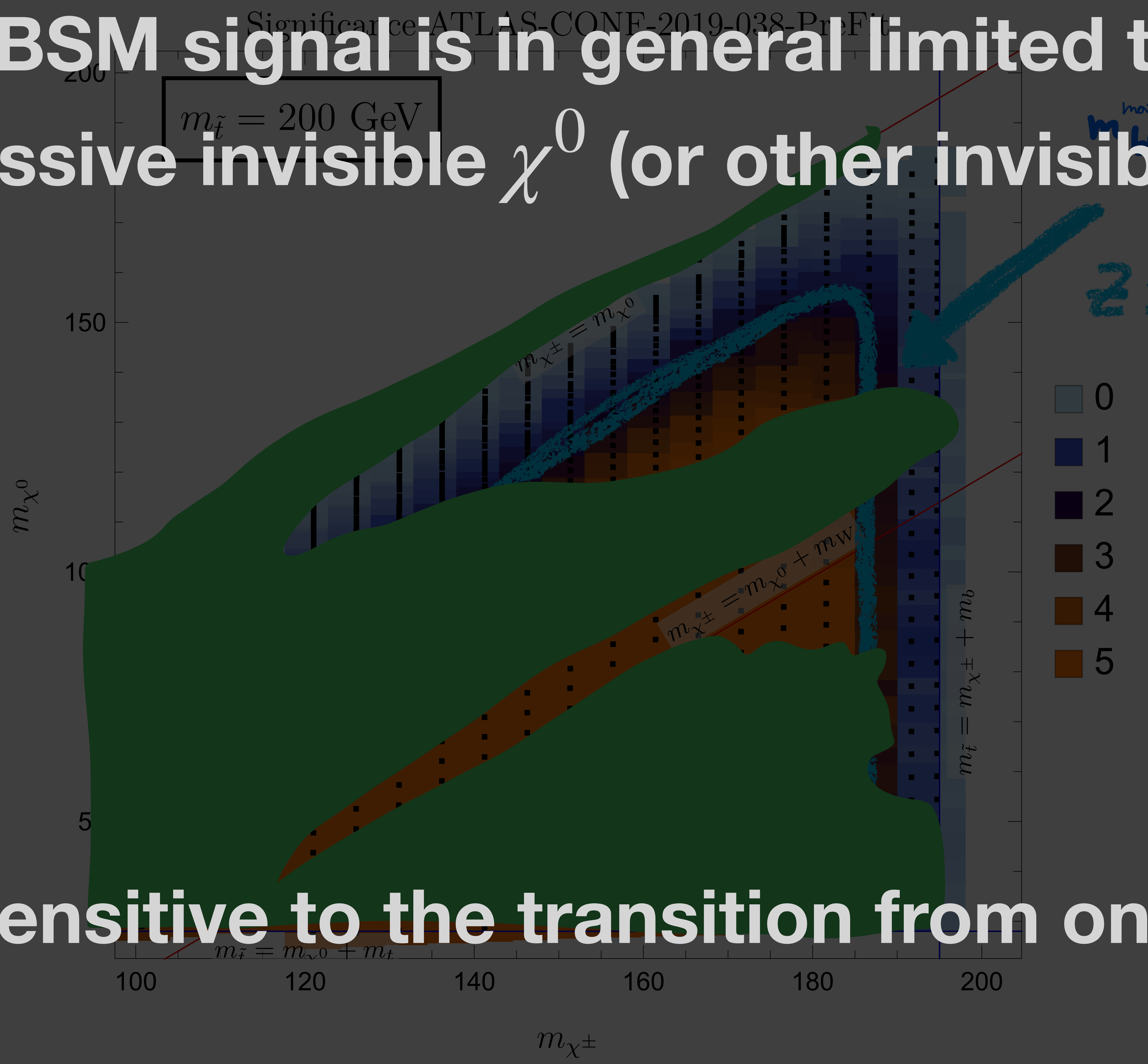

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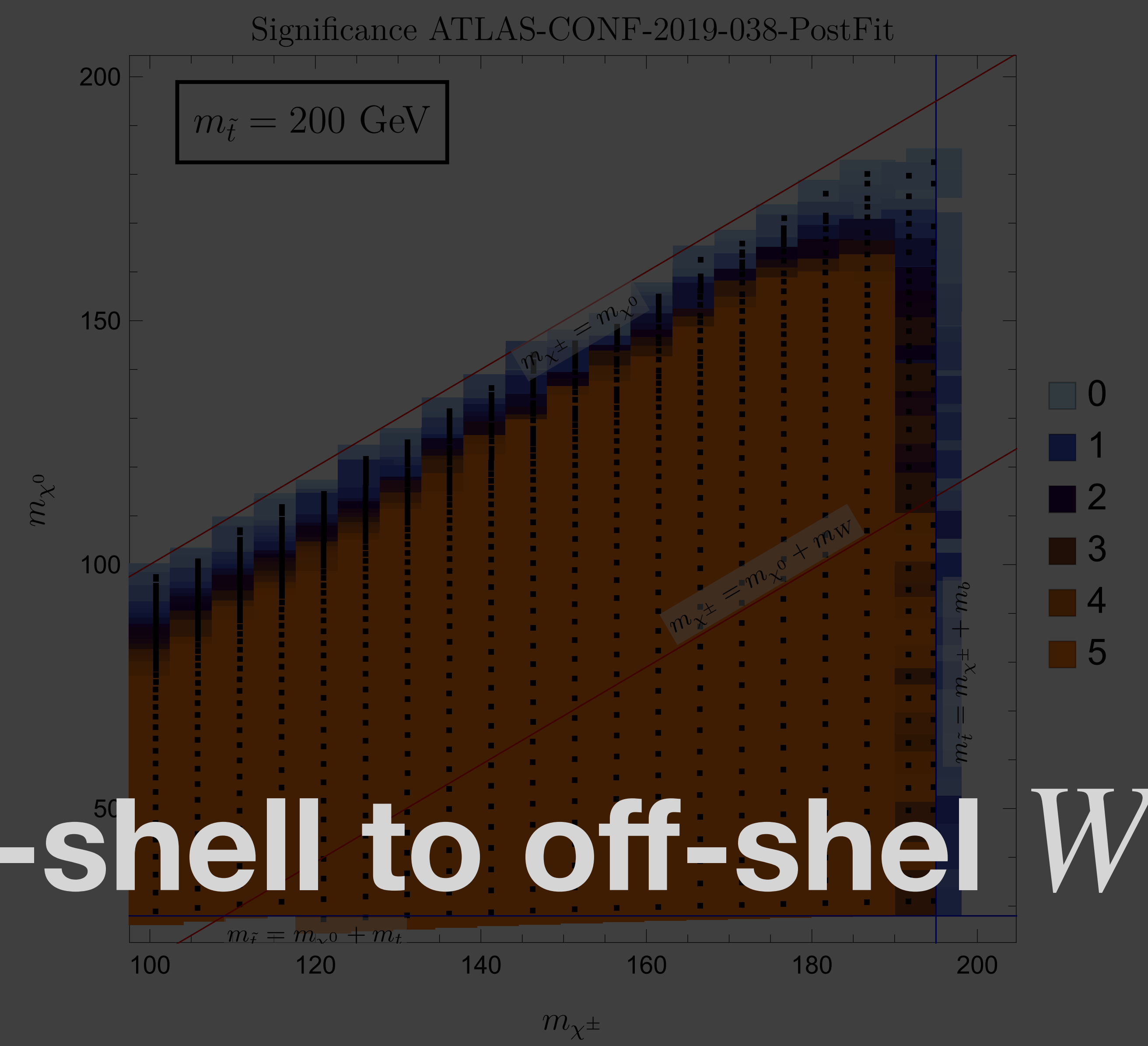

ATLAS post-fit

the analysis is not sensitive to the transition from on-shell to off-shel W

Significance estimator $z = \sqrt{\sum_i \left(\frac{S_i}{\delta B_i}\right)^2}$,

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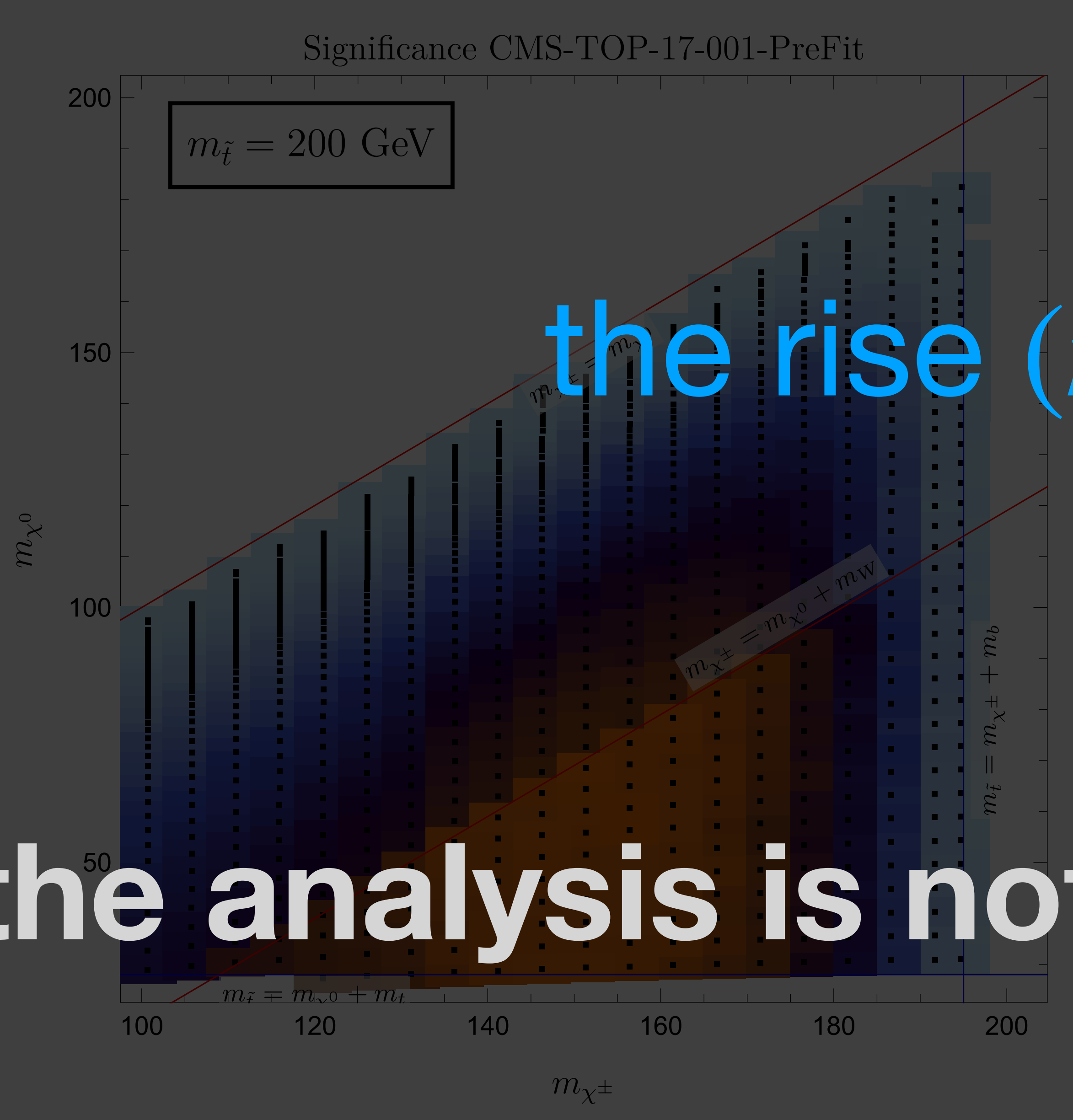

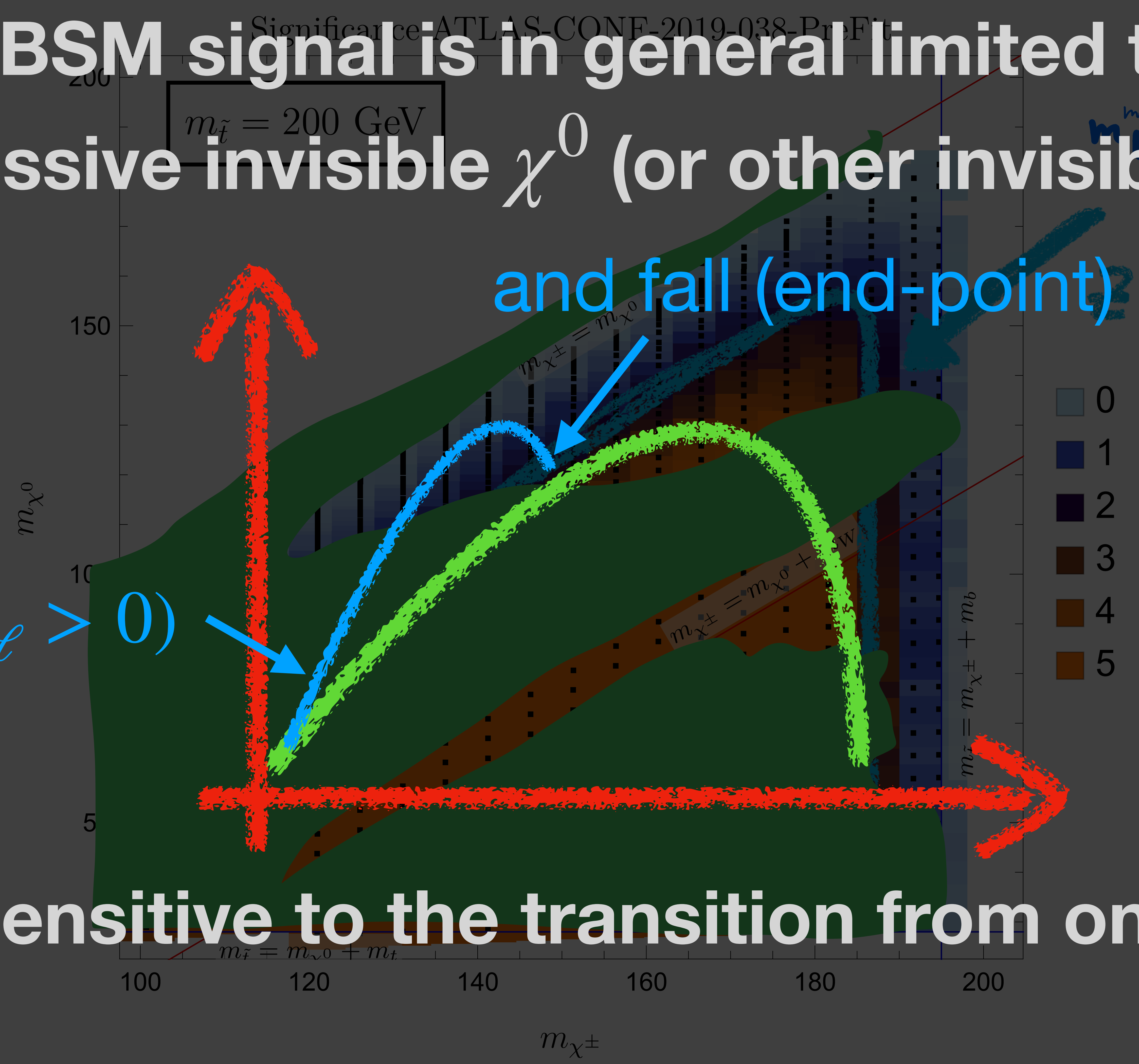

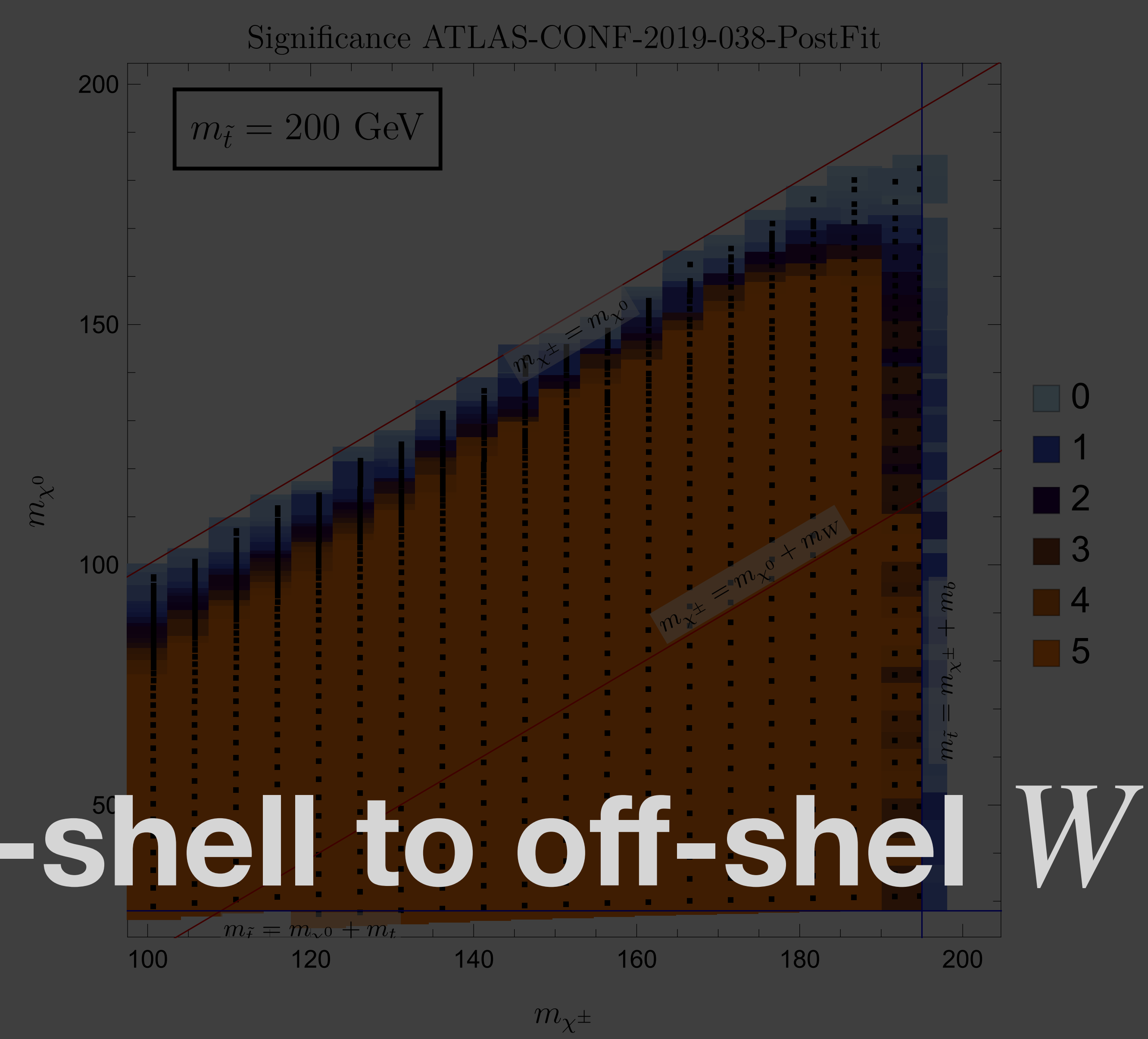

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CMS pre-fit | ATLAS pre-fit | ATLAS post-fit

Conclusion
and outlook

The (HL)LHC will give us more and more data.
If we want to exploit them at best we need to

- **make the result available in a most reusable way**
    - **Recast Exercises are very useful!**
- **start leveraging the strategies not pursed much so far**
    - **measure SM in places we had not traditionally done it**
    - **search BSM where is not usually sought for**

- m_{bl} **is a clear example where a** *Search&Measure* **approach works that brings new BSM models under the scope, plus it strengthens the "precision" of the SM measurement carried out with the same data**
- **more precision observables can be used**

Thank you

Backup slides

Next we simulate the contribution to $m_{b\ell}$ for each parameter space point using `Pythia` 8.3 [42] in the region of phase space identified by the following selection:

$$\begin{aligned} p_T(\ell) &\geq 25\ \text{GeV},\ \ |\eta(\ell)| < 2.5, \\ p_T(j) &\geq 25\ \text{GeV},\ \ |\eta(j)| < 2.5, \end{aligned} \qquad (1)$$

for jets made with anti-kT [43] algorithm with $R = 0.4$ and separations between jets and leptons $\Delta R(\ell, j) > 0.2$, $\Delta R(j, j) > 0.4$ and $\Delta R(\ell, \ell) > 0.1$. This is a selection closely following that of the experimental collaborations, e.g. [16, 18, 36], except for minor differences in the selection for $\ell = e$ and $\ell = \mu$ that we do not pursue. We have considered variations of the cuts and found

BM	μ	M_1	A_t	m_{χ^+}	m_{χ^0}	z [31]	z [16]	r
	$m_{\tilde{t}} = 200$ GeV							
ON1	185	95	2820.5	186.6	85.6	[0.8,1.7]	[2.7,14.3]	0.9
OFF1	155	160	2857.5	156.4	123.3	[0.9,1.8]	[2.6,14.8]	0.7
OFF2	175	145	2839.5	176.6	123.5	[1.5,3.]	[5.1,25.5]	0.8
T1	135	65	2895.5	136.2	54.	[4.,7.7]	[10.7,61.3]	0.8
T2	135	60	2895.5	136.2	49.9	[4.1,7.9]	[10.8,60.6]	0.8
	$m_{\tilde{t}} = 220$ GeV							
OFF3	155	150	3140.5	156.4	118.6	[0.7,1.4]	[1.9,10.9]	0.8
OFF4	170	160	3122	171.5	130.8	[0.9,1.8]	[2.5,13.7]	0.6
ON2	190	95	3104	191.7	86.1	[2.1,4.3]	[6.1,32.8]	0.7
OFF5	190	145	3104	191.7	127.7	[1.4,2.8]	[4.2,22.5]	0.6
ON3	190	65	3104	191.7	58.9	[1.9,3.7]	[5.3,28.7]	0.8
	$m_{\tilde{t}} = 180$ GeV							
OFF6	165	115	2570.5	166.5	99.2	[1.2,2.5]	[4.8,22.9]	0.8
OFF7	160	105	2580	161.5	90.4	[2.2,4.5]	[7.2,36.3]	0.8
OFF8	160	170	2570	161.5	130.3	[0.6,1.2]	[2.4,11.2]	0.6
OFF9	155	150	2579.5	156.4	118.5	[1.6,3.2]	[5.3,27.2]	0.8
OFF10	145	175	2598.5	146.3	122.2	[0.8,1.6]	[2.4,12.7]	0.8

TABLE I. Chargino and neutralino masses, input parameters μ, M_1 and A_t, all given in GeV for few benchmarks (BM). Resulting value of r computed from `SModelS` 2.2.1 and the range of the significance eq. (2) expected from the $m_{b\ell}$ spectrum analysis using ATLAS [16] or CMS [31] measurements. The low (high) end the significance range corresponds to uncertainties on the $m_{b\ell}$ spectrum before(after) a fit using SM predictions for the known backgrounds.

$$z = \sqrt{\sum_i \left(\frac{S_i}{\delta B_i}\right)^2},$$