

SUSY/BSM Related Searches in ATLAS

Analyses & Anomalies

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on behalf of the ATLAS Collaboration



Overview

- ATLAS analyses and anomalies
 - Analyses and anomalies
 - SUSY analyses strategy
 - Other analyses
- Anomalies by final state
 - Di-lepton
 - Multi-lepton
 - Jet/b-jet
 - Di-photon
 - Long-lived particles
- Summary

Anomaly

- Anomaly - any deviation from the expectation
- Any new physics is a deviation from the Standard Model expectation, and represents an anomaly

In this talk ...

- ATLAS analyses using Run2 data, with emphasis on SUSY and other analyses and observed anomalies interesting for SUSY
- Final state oriented overview

Not in this talk ...

- Comprehensive SUSY analyses overview in ATLAS
- Sensitivity reach and exclusion limits
- Interpretations and statistical combinations

ATLAS Analyses & Anomalies

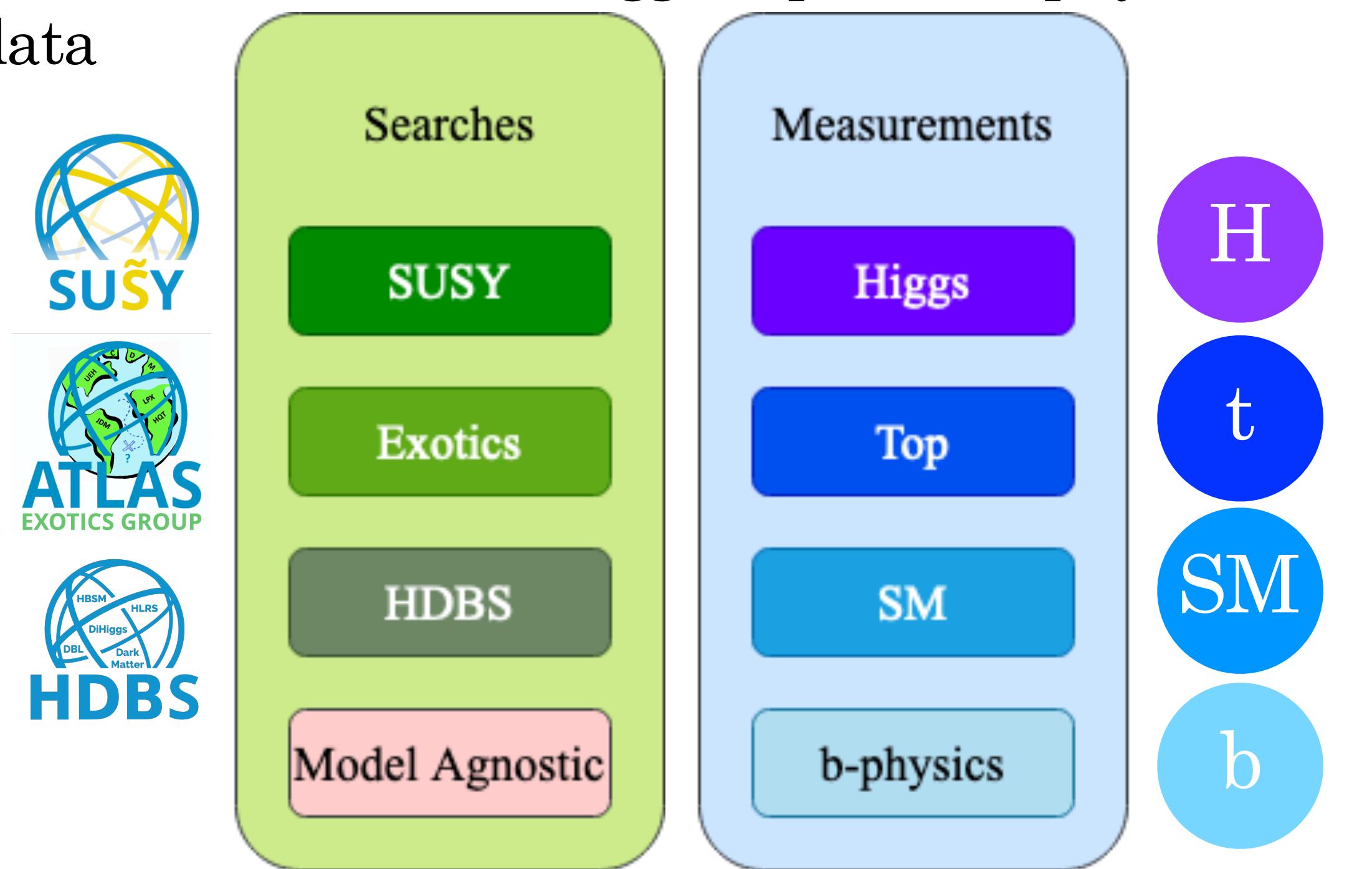
ATLAS analyses

Wide range of analyses in ATLAS:

- ATLAS SUSY/BSM physics **searches** are final state oriented (comparison on sensitivity presented as model dependent)
- Higgs/top/SM/b-physics **measurements** are performed for dedicated selections and compared to theory expectations

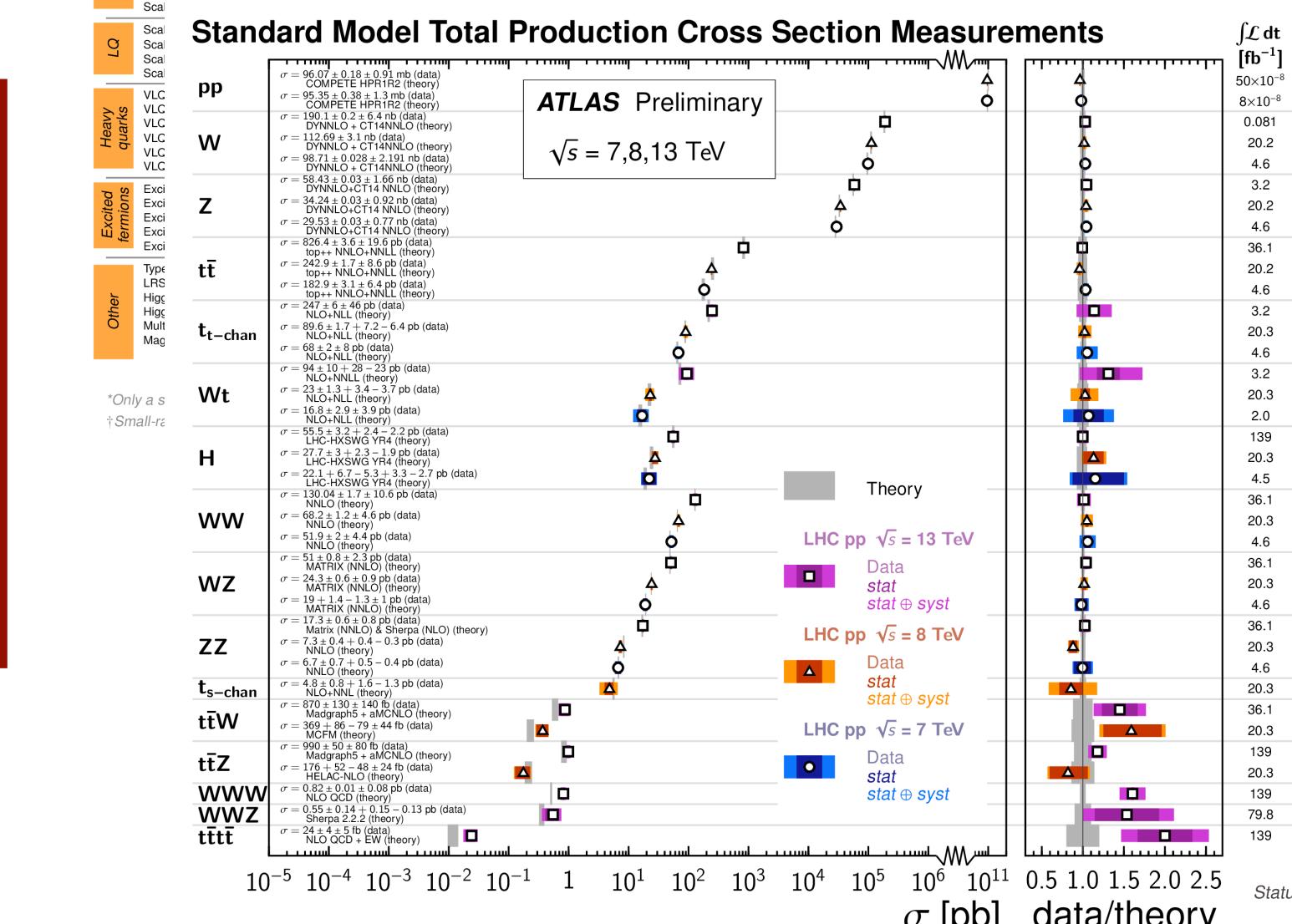
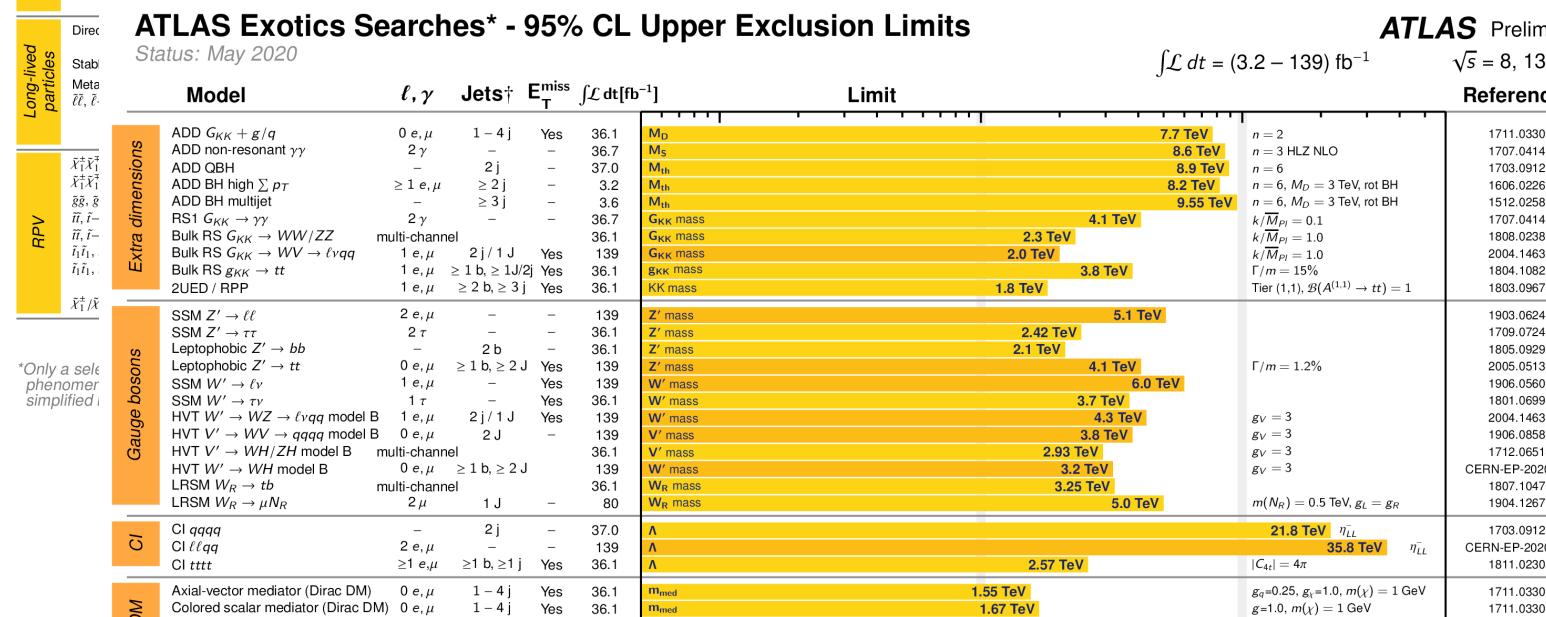
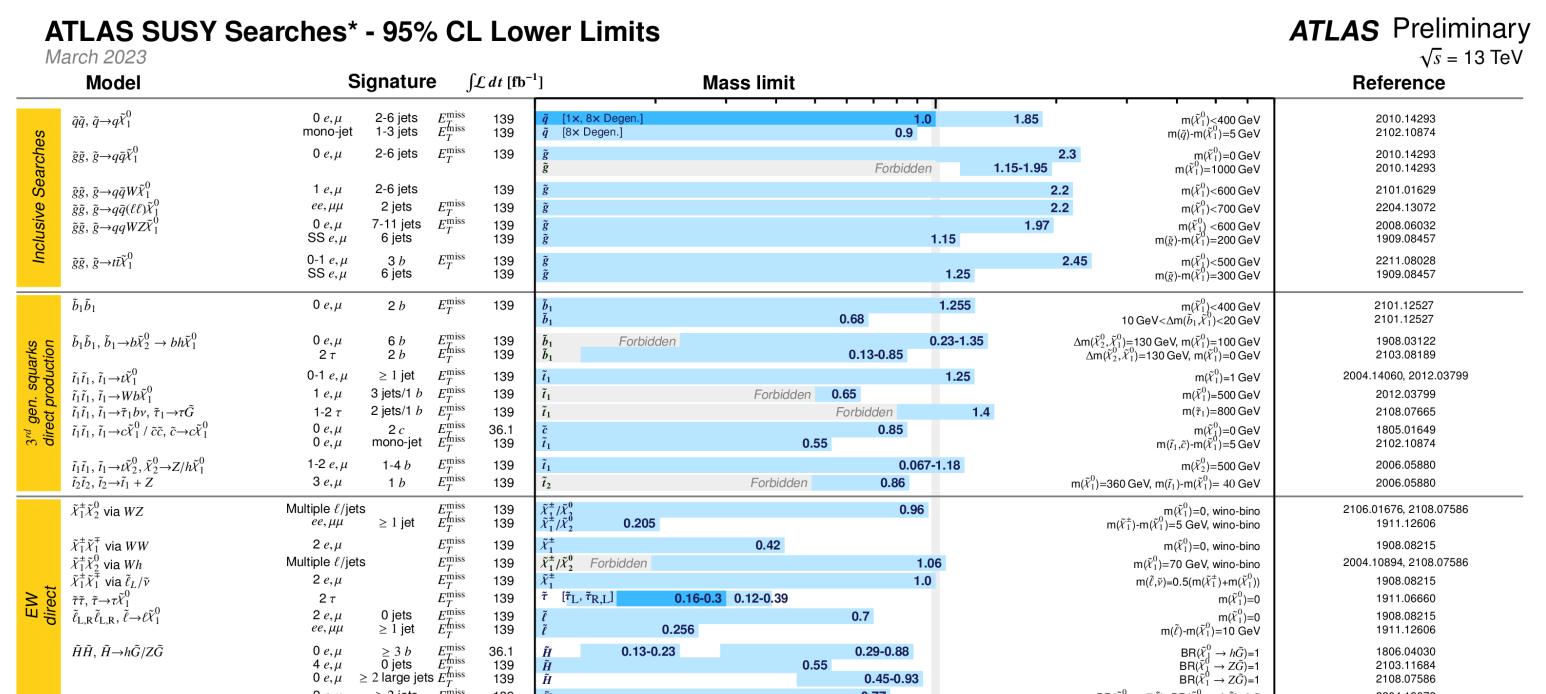
In this talk:

- Focus on statistically significant excesses seen in SUSY/BSM searches and tensions in the Higgs/top/SM/b-physics analyses in Run2 ATLAS data

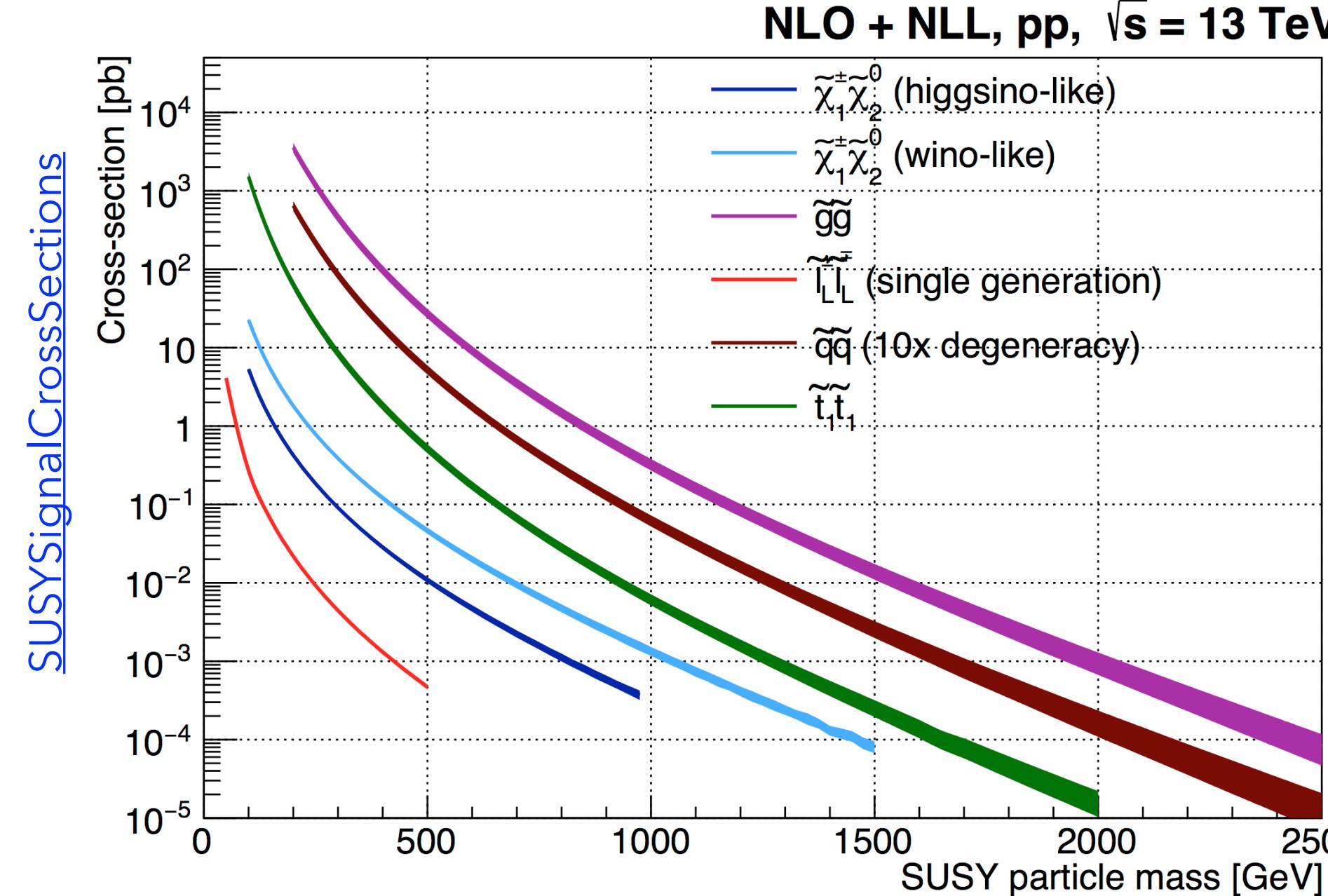


In this talk,
anomaly:

- Deviation higher than $\sim 2\sigma$ from the prediction



SUSY analyses strategy in ATLAS



SUSY Analyses grouped around production cross-sections (RPC):

- Strong production
- Third generation
- Electroweak



Study in addition:

- * RPV
- * Long Lived

Naturalness a useful (but not required) criterion on motivation for a given SUSY model

- Minimization condition for Higgs scalar potential

- Contributions must be tuned to achieve EWSB at the observed energy level, favor low fine tuning.

$$m_H^2 = (m_H^2)_{bare} + \delta m_H^2$$

$$\delta m_H^2 \sim -y_t^2 m_{\tilde{t}_1}^2 \log\left(\frac{\Lambda}{\text{TeV}}\right)$$

- Stops in the TeV range
- Maximal mixing

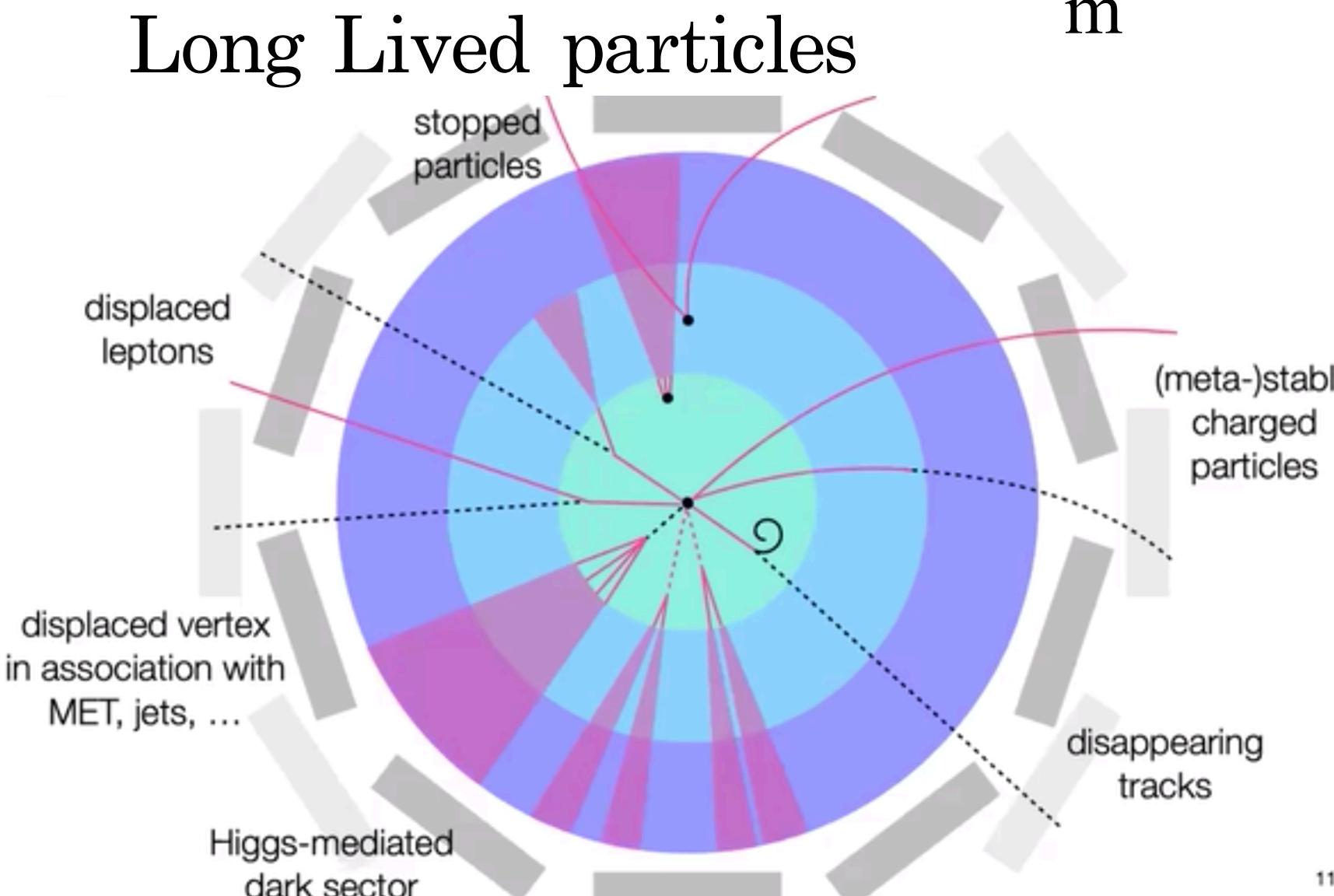
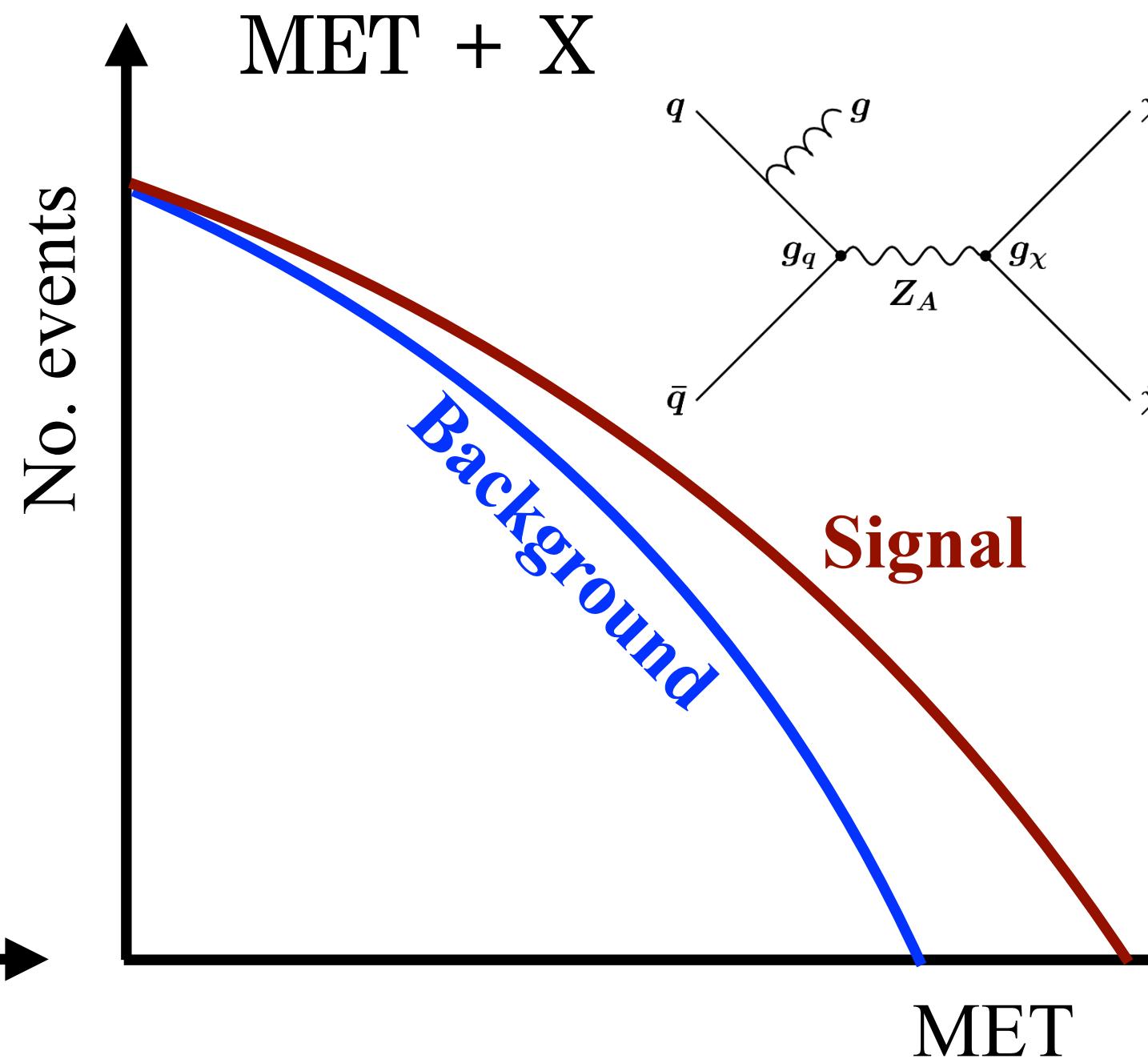
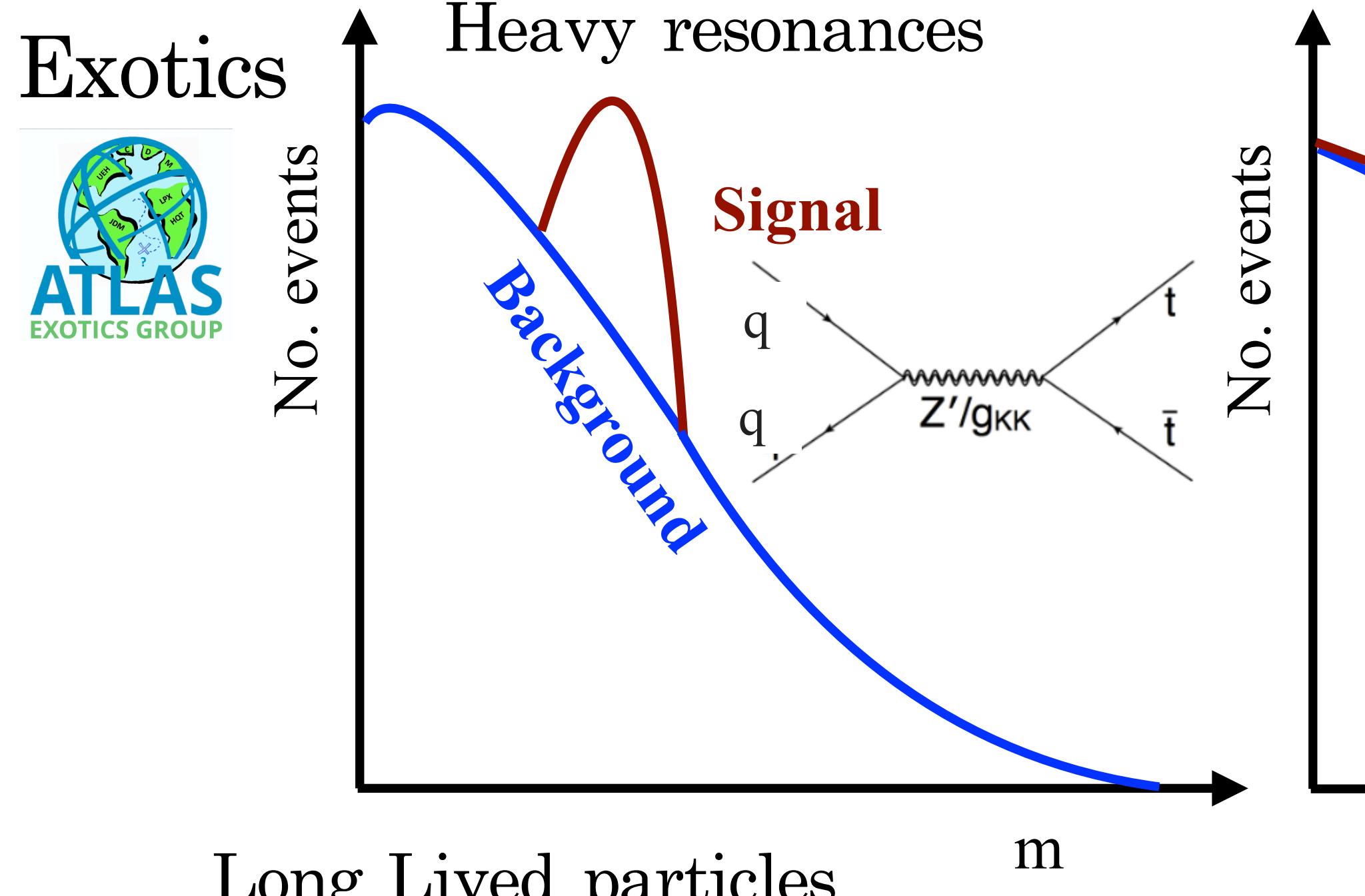
Search for light stop

- Address naturalness independently of the Higgs boson mass

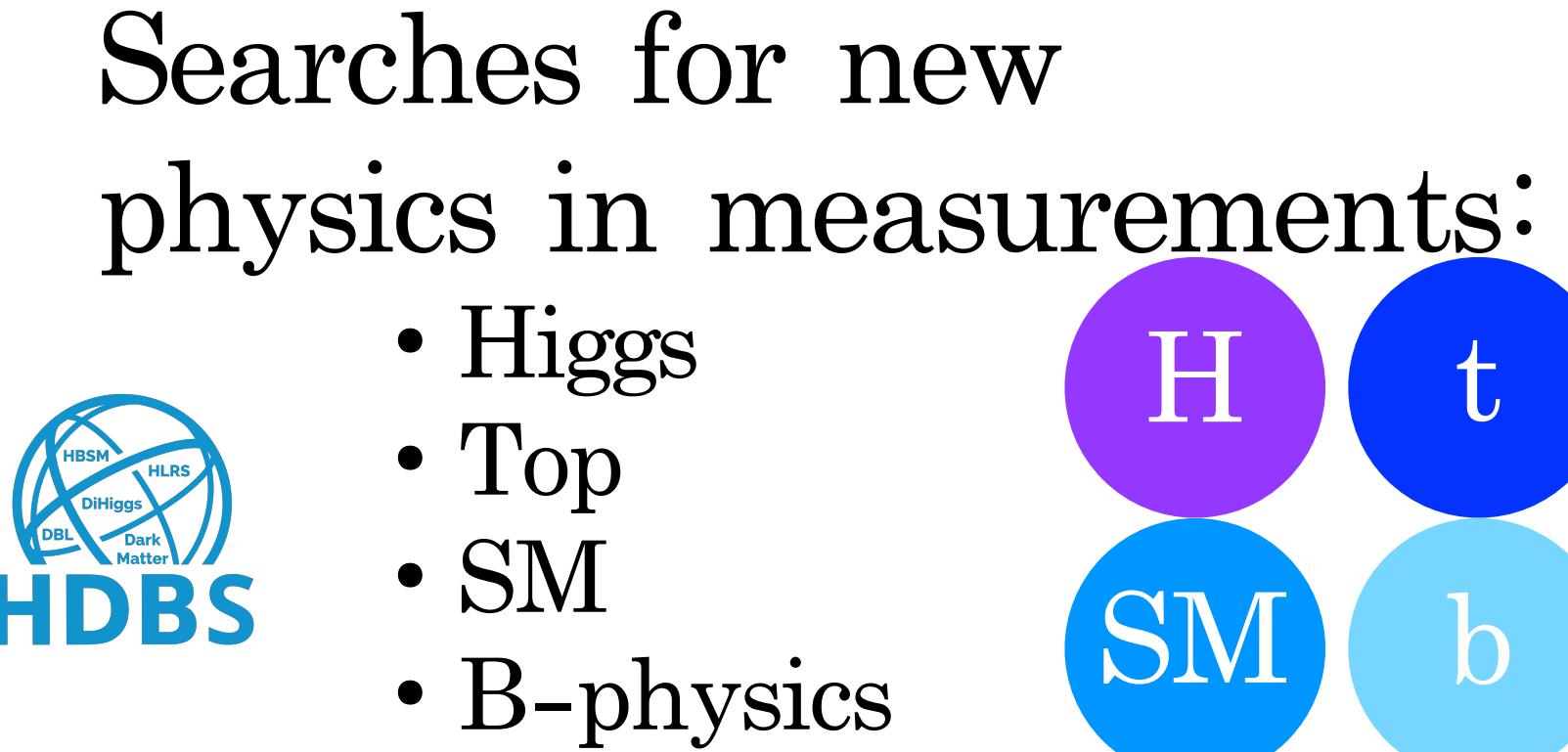
Search for low higgsino parameter

- Final state oriented, driven by cross-section and event topology
- Searches motivated to extend sensitivity for SUSY models
- Excess seen as deviation from the SM expectation

Other analyses in ATLAS



- Wide range of models and final states, **high diversity of analyses techniques**
- Searches motivated to extend sensitivity for Exotics models
- Anomaly seen as **deviation** from the SM expectation



- Final state oriented, driven by physics motivation and event topology
- Analyses motivated to target more final states and **improve analysis precision**
- Anomaly seen as a **tension** compared to SM theory prediction

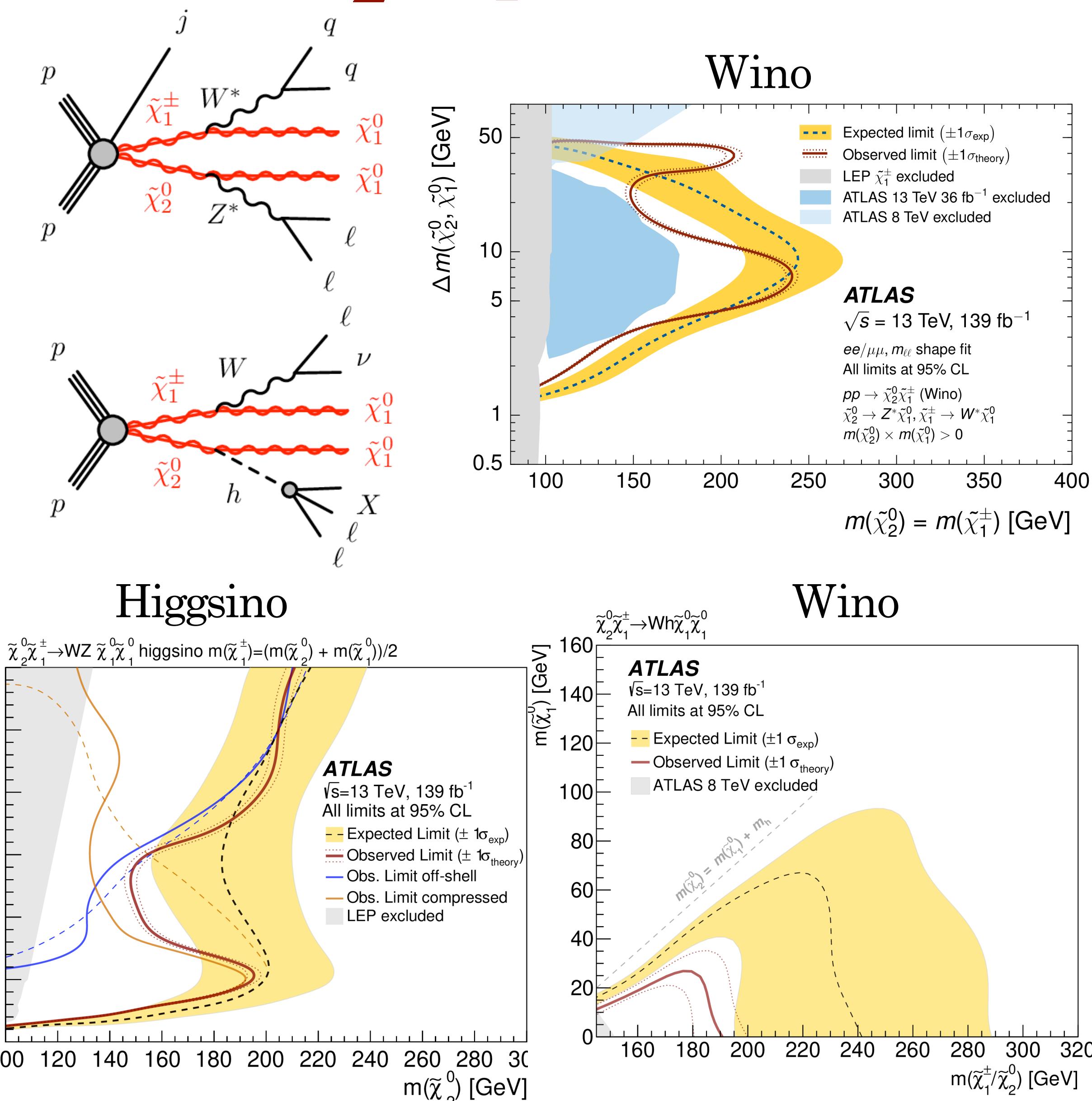
Anything else:

- Anomalies may appear in combined performance, trigger and validation regions of analyses
- Not covered in this talk

Di-lepton final states

SUSY: $2lOS/3l$ Wino/higgsino $\tilde{\chi}_2^0, \tilde{\chi}_1^\pm$

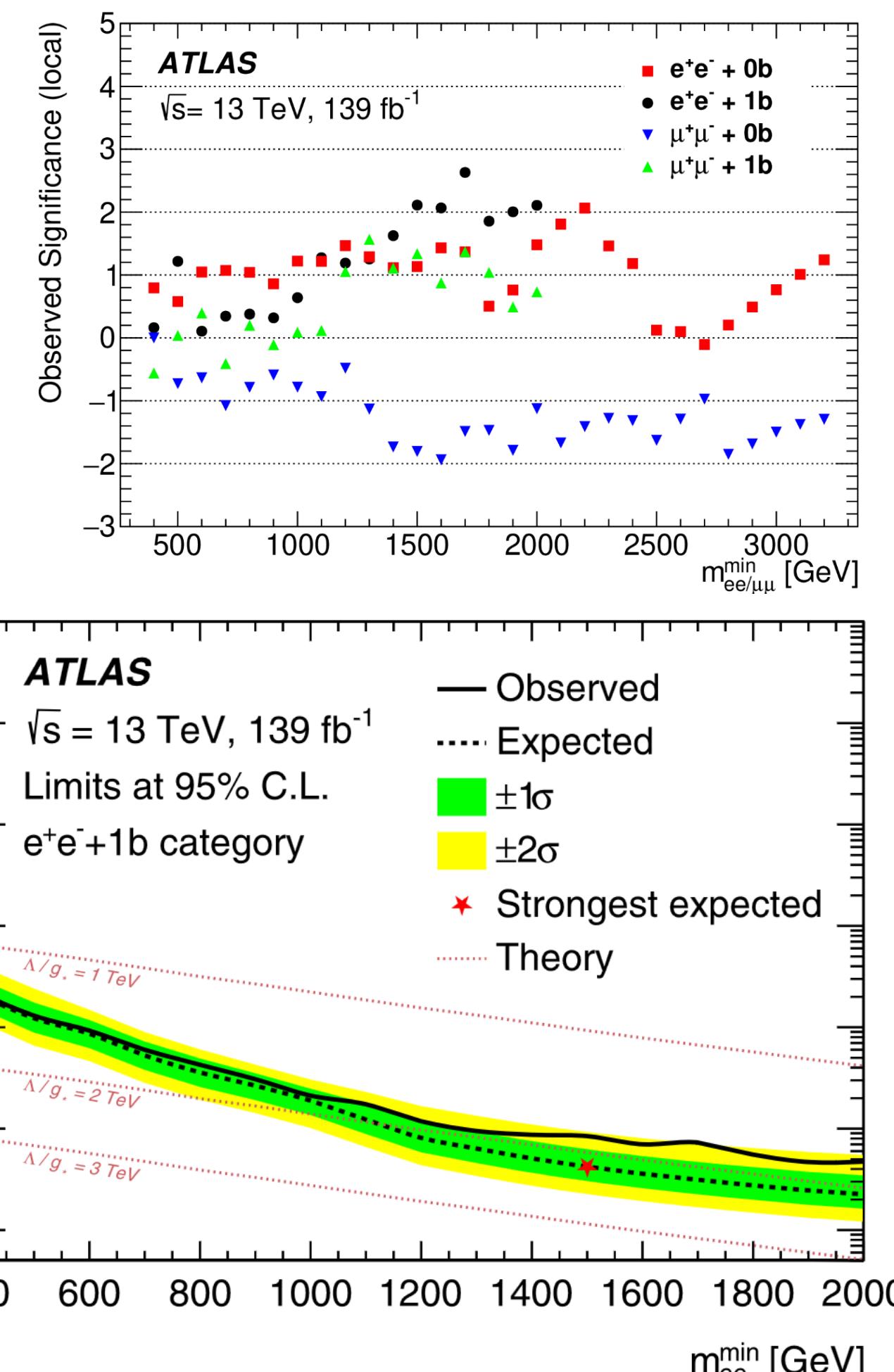
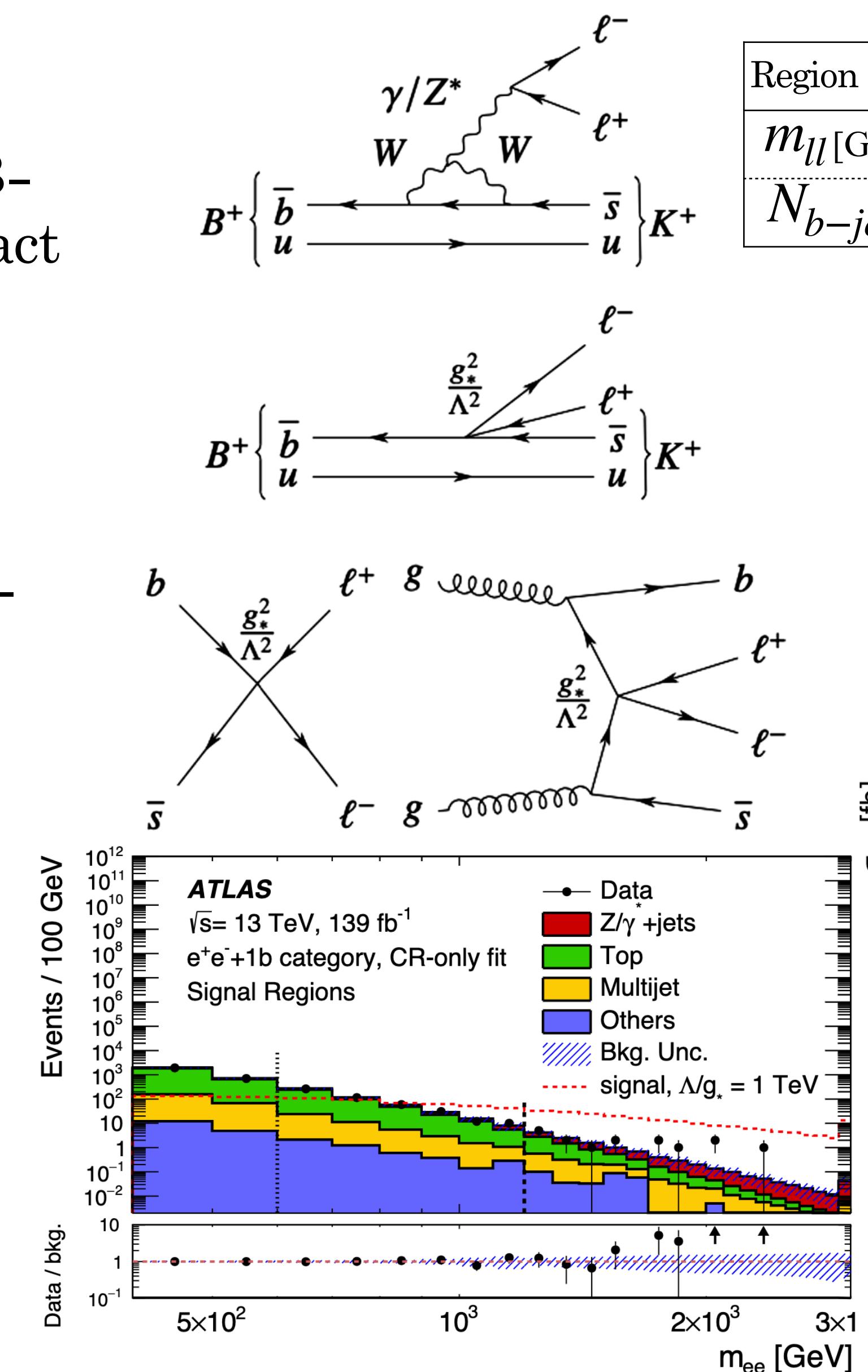
- Target:
 - Motivated by extending sensitivity to the wino/higgsino production of $\tilde{\chi}_2^0, \tilde{\chi}_1^\pm$ with decays into WZ^* and Wh
- Final state:
 - $2lOS + \text{jet} + E_T^{\text{miss}}$ (compressed)
[ATLAS SUSY-2018-16, PRD \(2020\)](#)
 - $3l + E_T^{\text{miss}}$ [ATLAS SUSY-2019-09, EPJC \(2021\)](#)
- Background:
 - Fake leptons from $W+\text{jets}$
- Strategy:
 - Multi-bin fit, cut and count
- Highest significance:
 - $2l$: $\sim 2\sigma$ for wino WZ $\Delta m = 20$ GeV
 - $3l$: $\sim 2\sigma$ for wino Wh DFOS
 - $2l + 3l$: $< 2\sigma$ for higgsino $\Delta m = 25$ GeV
 - CMS: $\sim 2\sigma$ for higgsino $\Delta m \sim 20$ GeV [CMS SUS-18-004, JHEP \(2022\)](#)



Exotics: bsl^+l^- Contact interaction

[ATLAS EXOT-2018-16, PRL \(2021\)](#)

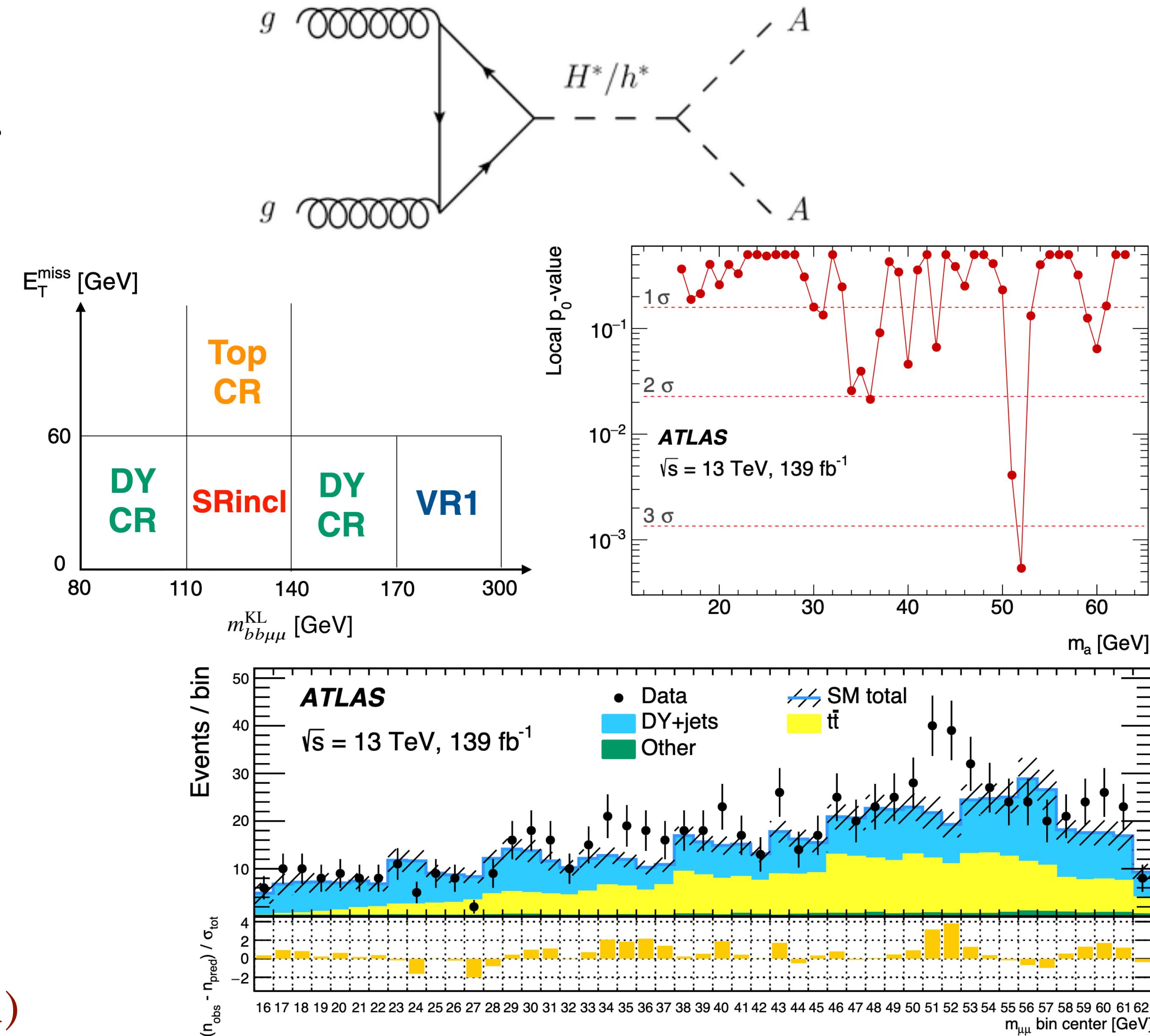
- Target:
 - Motivated by violation of LFU in B-meson decays. Using 4-fermion contact interaction between 2q and 2l as benchmark, characterized by energy scale Λ and coupling g_*
 - BSM interaction present between b-quark and s-quark with two same-flavor opposite-sign leptons
- Final state: bse^+e^- or $bs\mu^+\mu^-$
- Background:
 - Z+jets, di-leptonic $t\bar{t}$, data norm.
- Strategy:
 - CR-top and CR-Z orthogonal to SR by m_{ll} and b-jet multiplicity
- Highest significance:
 - $e^+e^- + 1b$ channel with 2.6σ local (1.5σ global)



HDBS: $b\bar{b}\mu\mu$ Higgs to pseudoscalars

[ATLAS HDBS-2021-03, PRD \(2022\)](#)

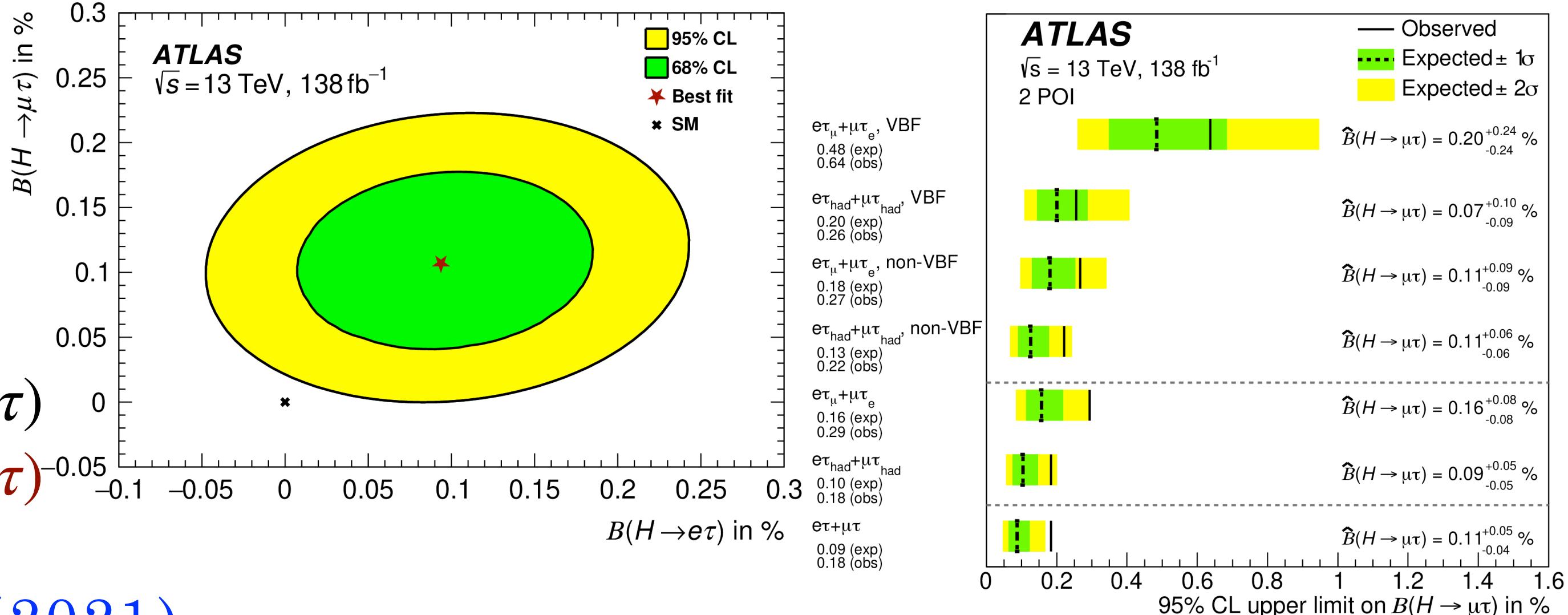
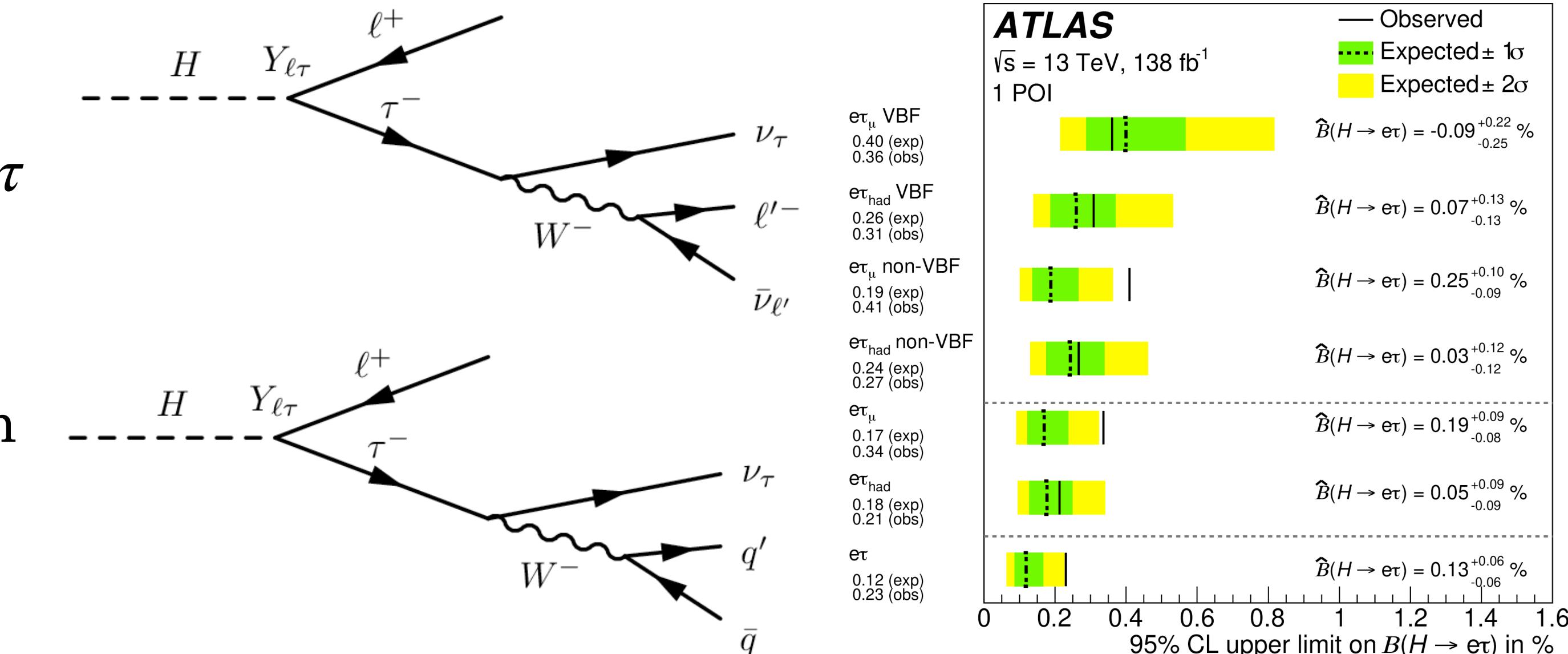
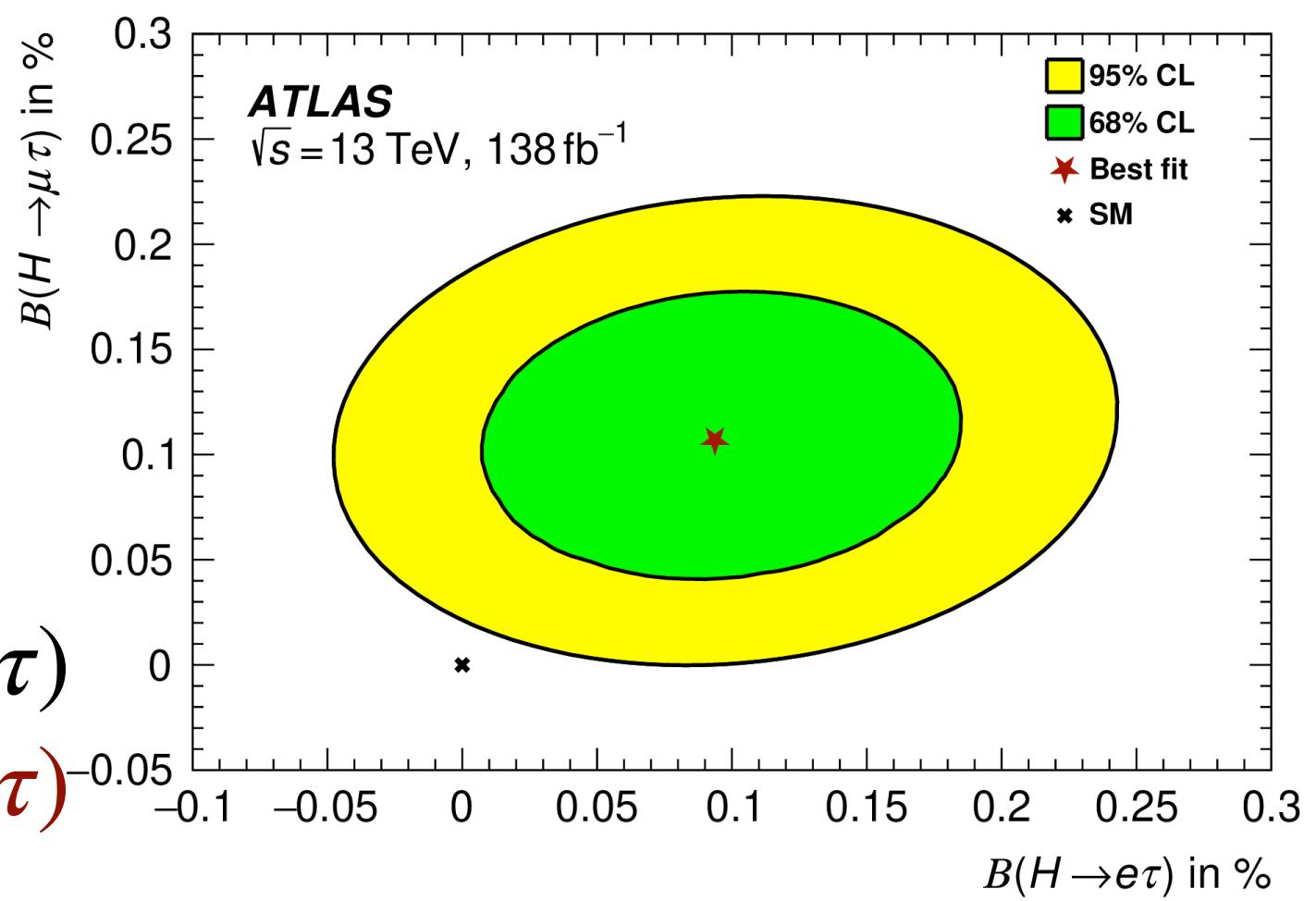
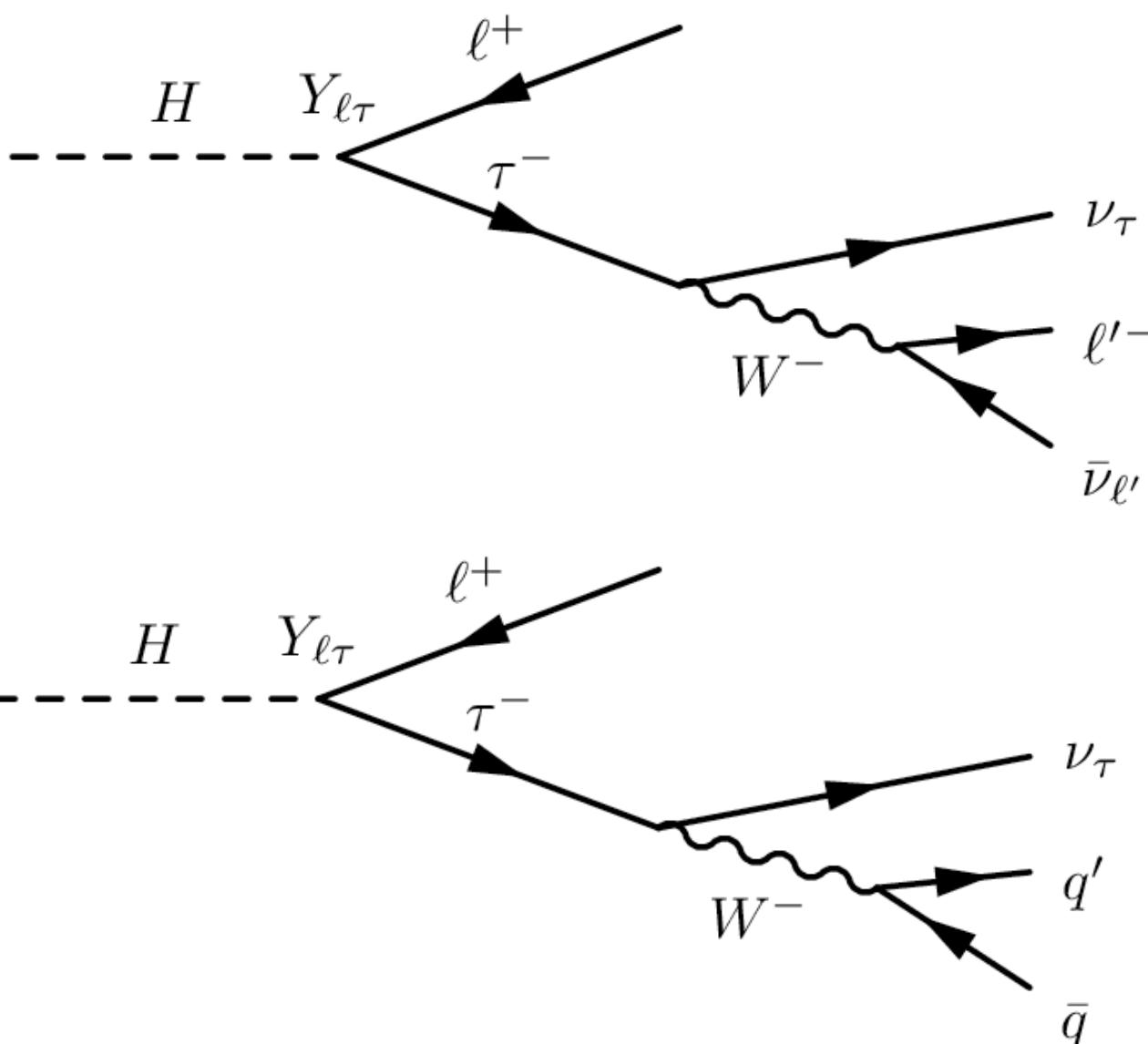
- Target:
 - Search for Higgs boson decay into a pair of pseudo scalars, $H \rightarrow aa \rightarrow b\bar{b}\mu\mu$
 - Narrow di-muon resonance $m_{\mu\mu} \in [16,62]$ GeV
- Final state:
 - $b\bar{b}\mu^+\mu^-$
- Background:
 - Z+jets and $t\bar{t}$, orthogonality obtained in E_T^{miss} and $m_{b\bar{b}\mu\mu}^{KL}$
- Strategy:
 - Use high branching ratio of $b\bar{b}$ and high mass-resolution of $\mu\mu$
 - BDT used to separate signal from SM background
- Highest significance:
 - For $m_{\mu\mu} = 52$ GeV 3.3σ local (1.7σ global)



Higgs: $e\tau, \mu\tau$ LFV Higgs decays

[ATLAS HIGG-2019-11 \(2023\)](#)

- Target:
 - Search for LFV decays of Higgs into $e\tau$ and $\mu\tau$
- Final state: $e\tau, \mu\tau$
- Background:
 - Fake lepton and tau: Data driven estimates in lep-lep and lep-had channels
 - Other smaller: From MC
- Strategy:
 - Two independent searches with $e\tau, \mu\tau$
 - Consider leptonic and hadronic tau decays
 - Multi-class NN classification for signal to background separation
- Highest significance:
 - 1POI fit: 2.2σ for $B(H \rightarrow e\tau)$, 1.9σ $B(H \rightarrow \mu\tau)$
 - 2POI fit: 1.6σ for $B(H \rightarrow e\tau)$, 2.5σ $B(H \rightarrow \mu\tau)$
 - Global compatibility with SM at 2.1σ
 - Seen also by CMS [CMS-HIG-20-009, PRD \(2021\)](#)

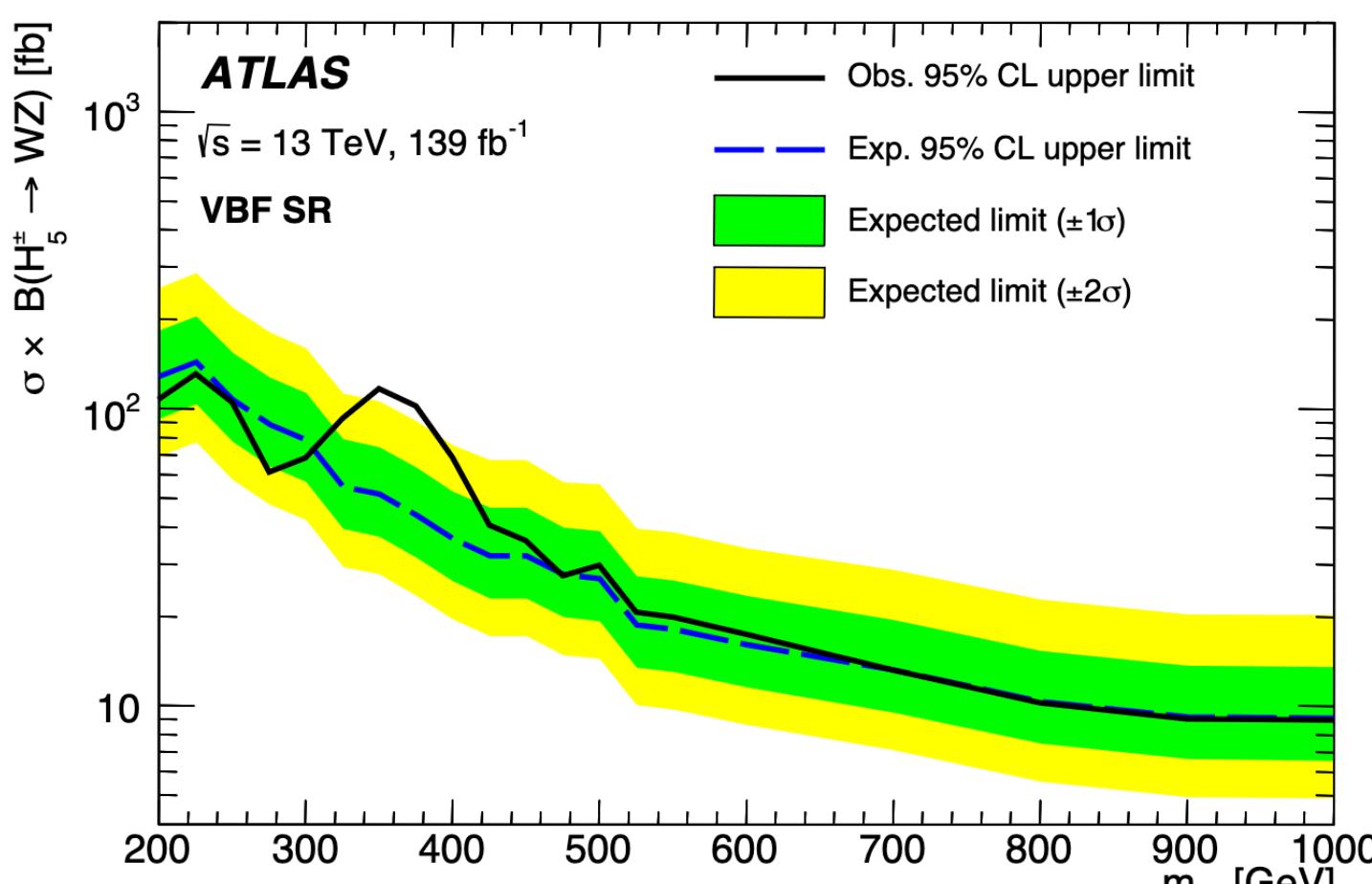
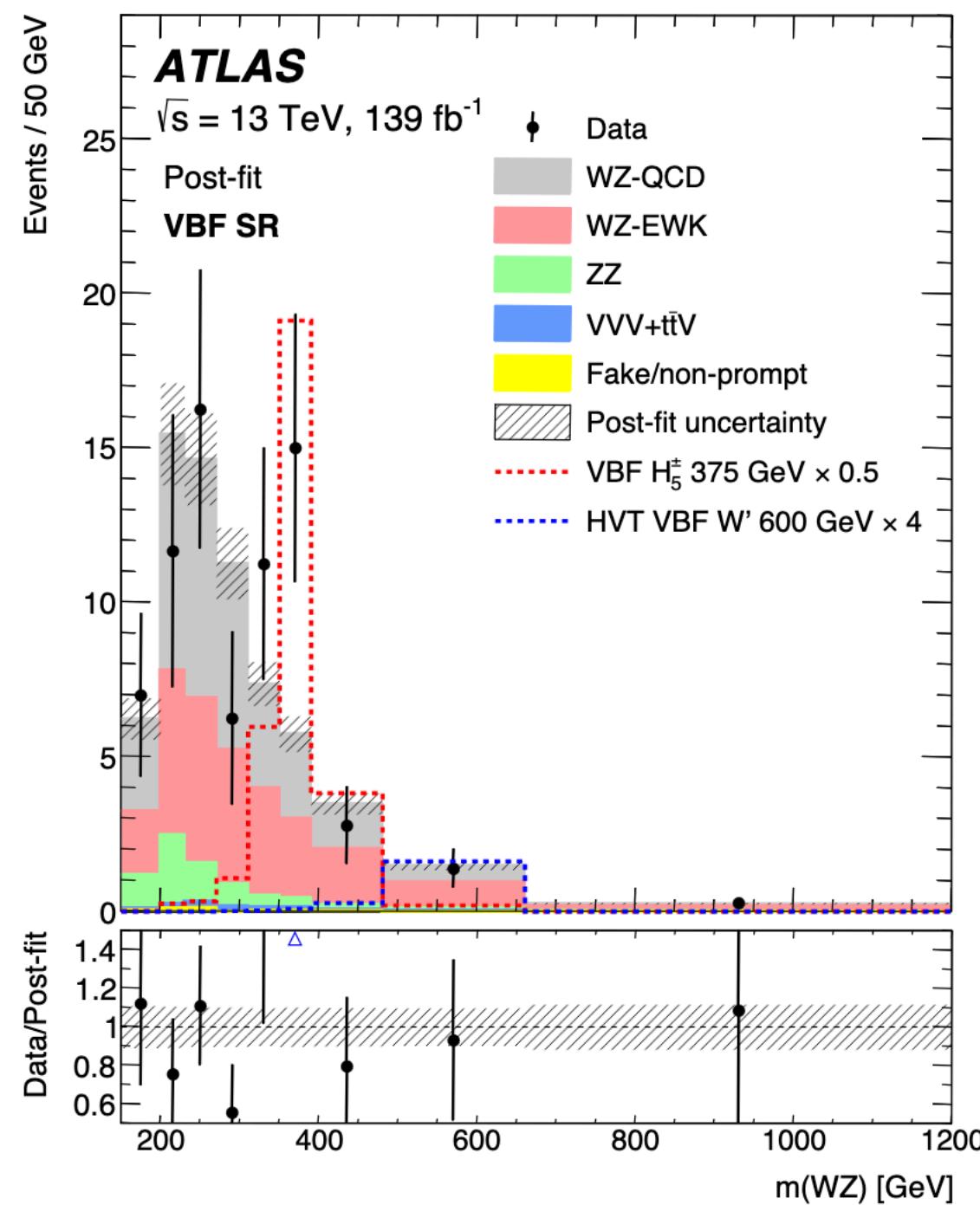
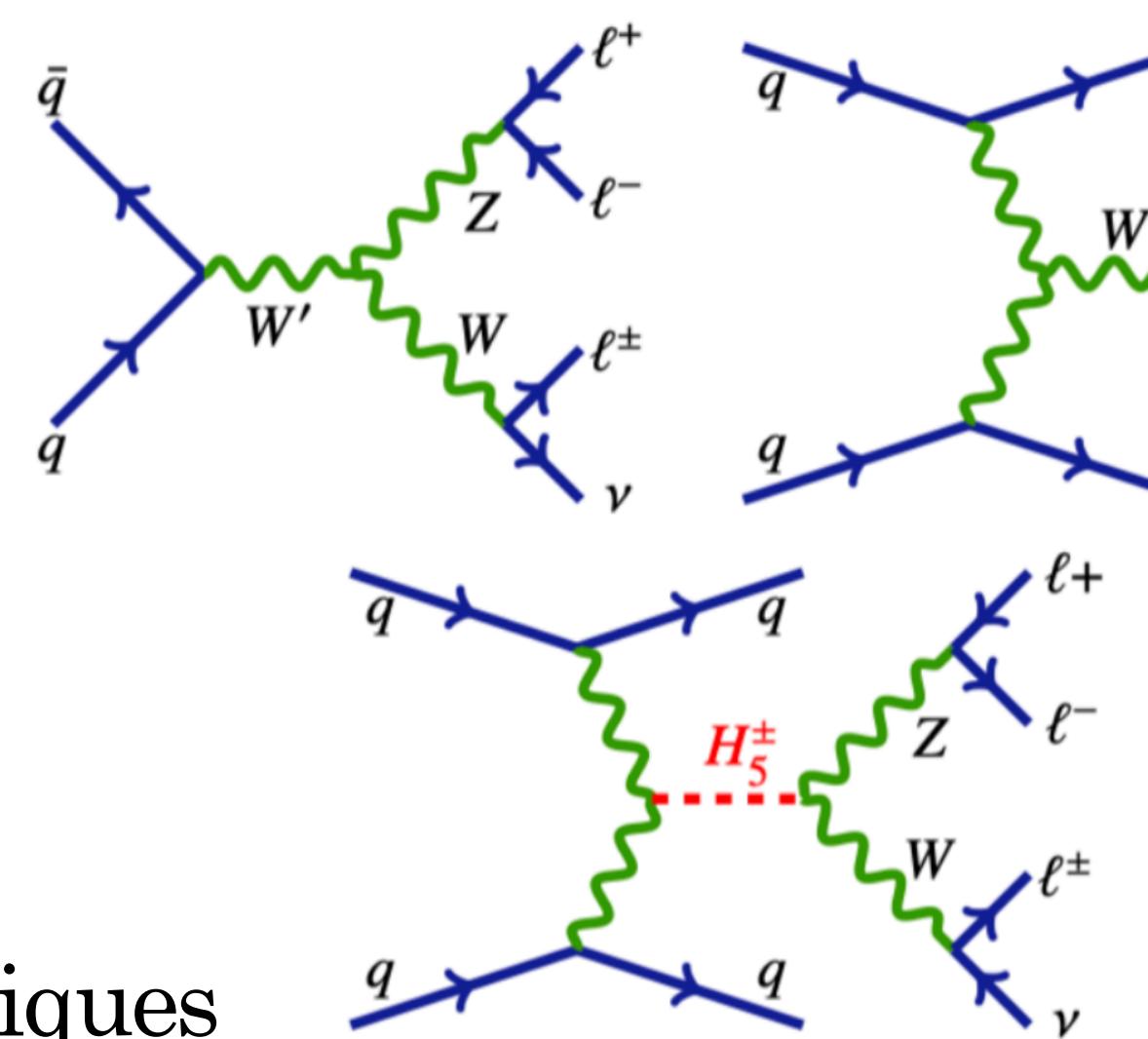


Multi-lepton final states

HDBS: $3l$ Resonant WZ

[ATLAS HDBS-2018-19 \(2022\)](#)

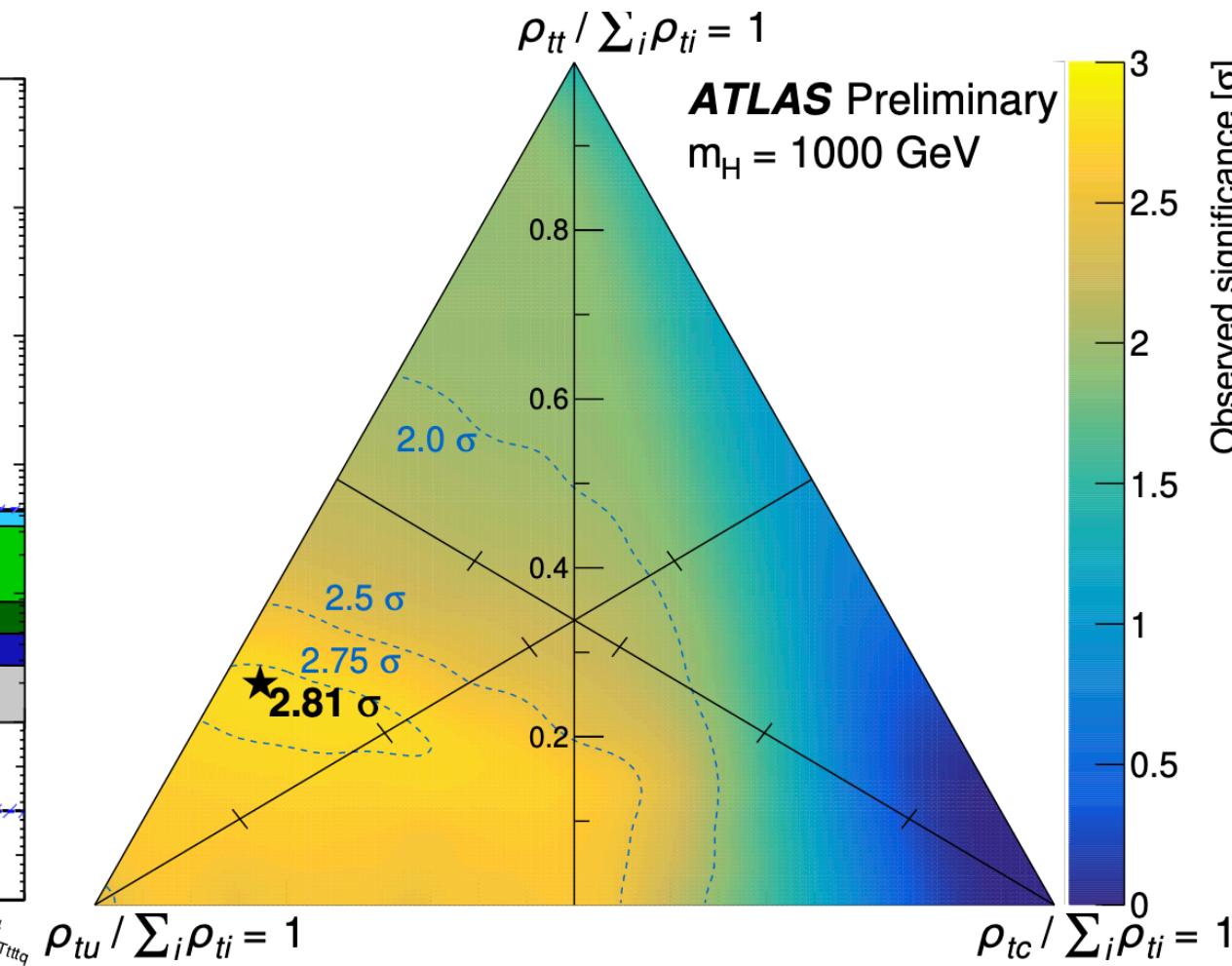
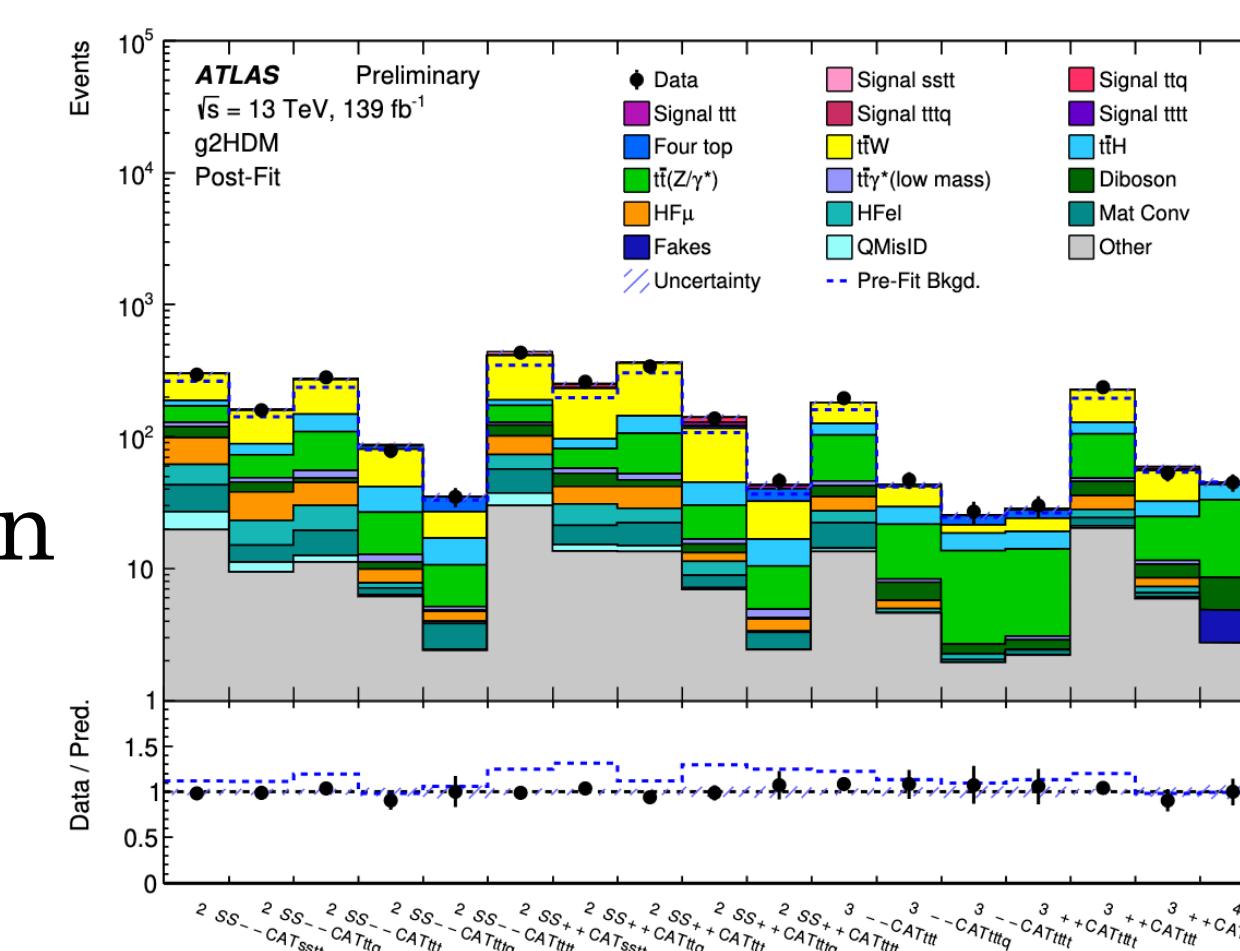
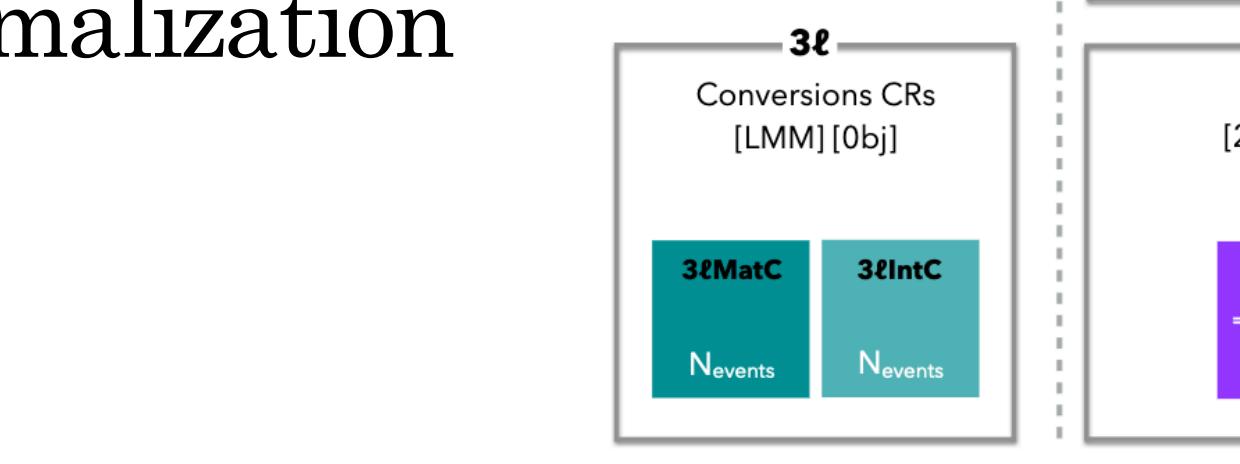
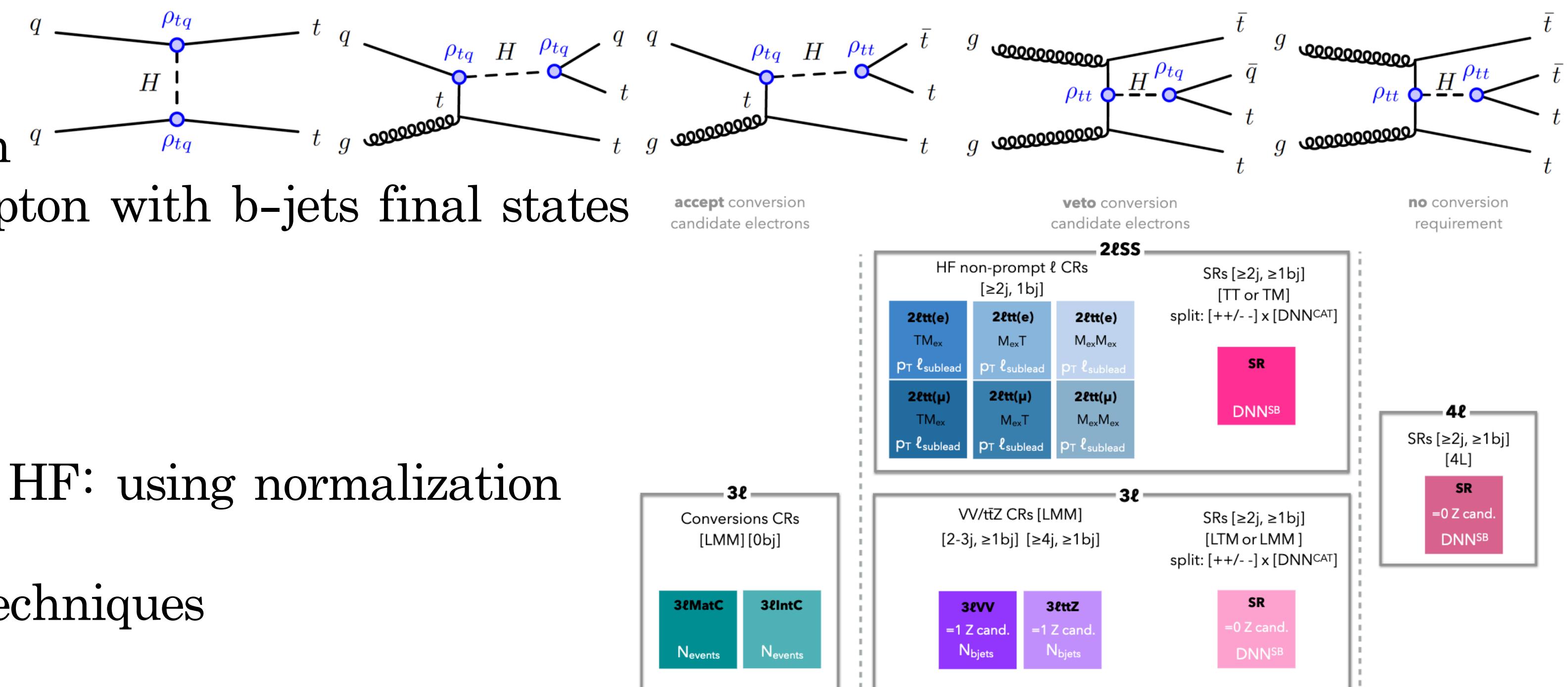
- Target:
 - Search for resonant WZ production with multi-leptons
- Final state:
 - $3l$
- Background:
 - WZ, ZZ: Normalization using CRs
 - Fake/non-prompt: Using data-driven techniques
 - Other SM: From MC
- Strategy:
 - SRs target different production modes: Drell-Yan (cut based), VBF (ANN)
 - Simultaneous CR and SR fit for m_{WZ} (separate DY and VBF fit)
- Highest significance:
 - SR VBF: $m_{WZ} \sim 375$ GeV 2.8σ for H_5^\pm , 2.5σ for HVT W' signal
 - Previous ATLAS: at 8 TeV $m_{WZ} \sim 375$ GeV 1.75σ [ATLAS EXOT-2013-07, PLB \(2014\)](#)
 - CMS: $m_{WZ} \sim 800$ GeV [CMS EXO-12-025, PLB \(2015\)](#)



HDBS: multi- l g2HDM

[ATLAS HDBS-2022-36 \(2022\)](#)

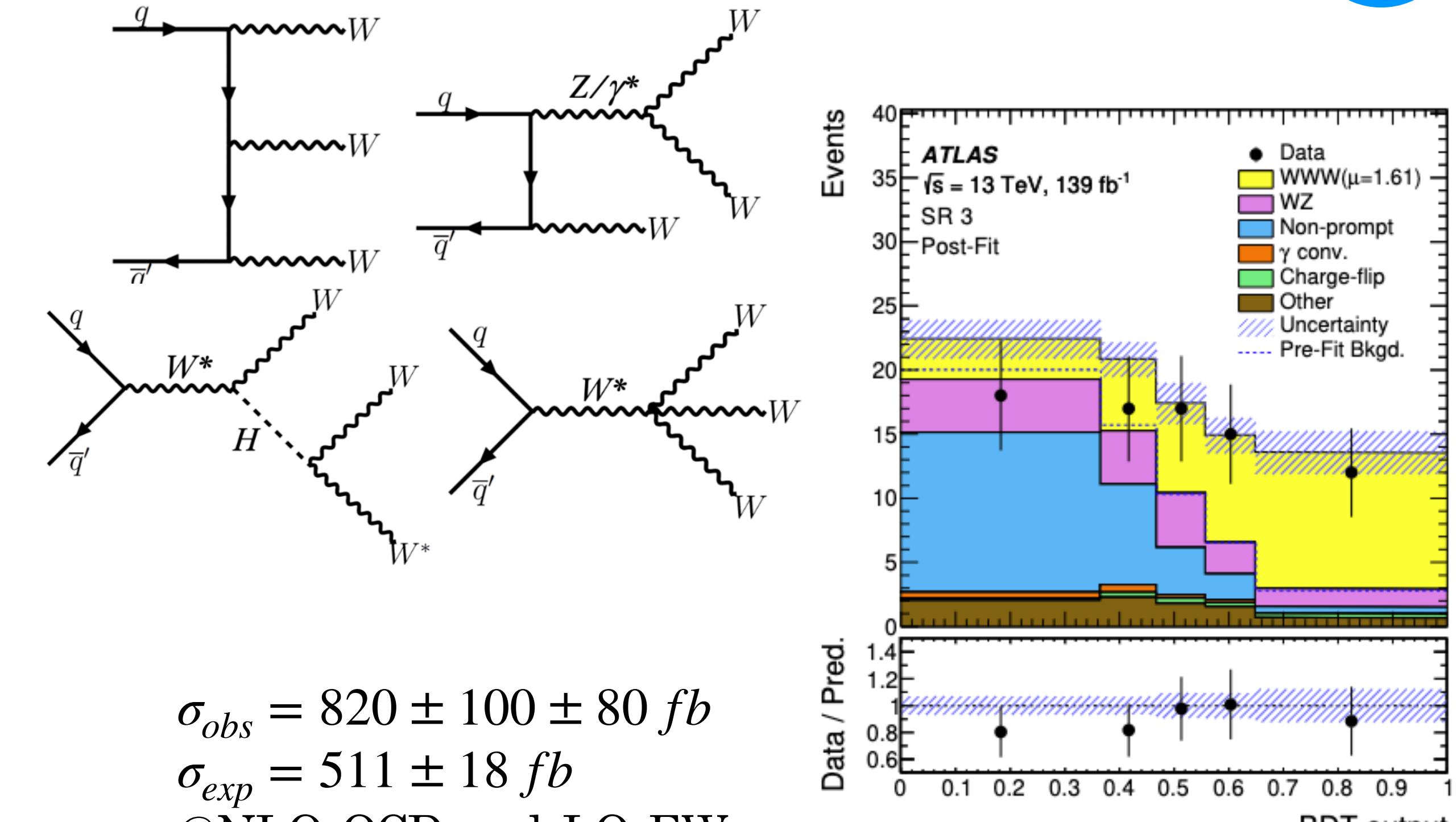
- Target:
 - Heavy Higgs boson general search in g2HDM model with multiple-lepton with b-jets final states
- Final state:
 - 2lSS, 3l and 4l
- Background:
 - $t\bar{t}W/Z$, VV , internal conversion, HF: using normalization to data in dedicated CRs
 - Charge-flip: Using data-driven techniques
 - Other SM: from MC
- Strategy:
 - SR/CR orthogonality obtained using lepton and b-jet multiplicity
 - SRs (17) categorization for lepton multiplicity, lepton charge and DNN signal to signal separation
 - Use DNN for signal to background separation
- Highest significance:
 - For $m_H = 1000$ GeV 2.81σ



SM: $2l, 3l$ Cross-section measurements

[ATLAS STDM-2019-09, PRL \(2022\)](#)

- Target:
 - Measure WWW production cross-section
- Final state: $2lSS, 3l$
- Background:
 - $WZ+jets$: Normalization in a simultaneous fit to SRs and CRs
 - Fake/non-prompt: Fake Factor method
 - Charge-flip: Data driven
 - Other SM: Taken from MC
- Strategy:
 - SRs: $e^\pm e^\pm, \mu^\pm \mu^\pm, e^\pm \mu^\pm, 3l$
 - BDT for signal from background separation
 - μ_{WWW} obtained from simultaneous fit in BDT score distributions of SRs and WZ CRs
- Highest significance:
 - Observed cross-section 2.6σ away from SM.
 - Background-only hypothesis rejected at 8.0σ observed (5.4σ expected). Excess mainly in $\mu^\pm \mu^\pm$ channel.



$$\begin{aligned}\sigma_{obs} &= 820 \pm 100 \pm 80 \text{ fb} \\ \sigma_{exp} &= 511 \pm 18 \text{ fb} \\ &\text{@NLO QCD and LO EW}\end{aligned}$$

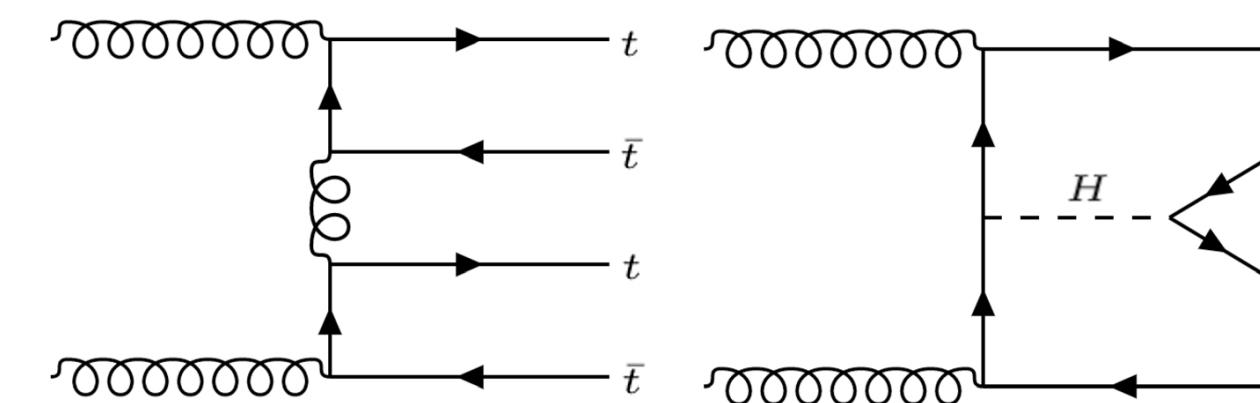
Fit	$\mu(WWW)$	Significance observed (expected)
$e^\pm e^\pm$	1.54 ± 0.76	$2.2 (1.4) \sigma$
$e^\pm \mu^\pm$	1.44 ± 0.39	$4.1 (3.0) \sigma$
$\mu^\pm \mu^\pm$	2.23 ± 0.46	$5.6 (2.7) \sigma$
2ℓ	1.75 ± 0.30	$6.6 (4.0) \sigma$
3ℓ	1.32 ± 0.37	$4.8 (3.8) \sigma$
Combined	1.61 ± 0.25	$8.0 (5.4) \sigma$

Top: $2lSS/3l$ Top precision measurements

t

[ATLAS TOPQ-2021-08, EPJC \(2023\)](#)

- Target:
 - Search for production of $4t$ in multi-leptons final state
- Final state: $2lSS/3l$
- Background:
 - $t\bar{t}W$: Data driven background estimate using N_j distribution
 - Fake/non-prompt: Template method
 - Charge-flip: Data driven
 - Other SM: Taken from MC
- Strategy:
 - One SR for $2lSS + 3l$, GNN to separate signal from background
 - Simultaneous fit in SR and CRs
- Highest significance:
 - Measured cross-section is 1.8σ away from SM
 - Background-only hypothesis rejected at 6.1σ observed (4.3 expected)

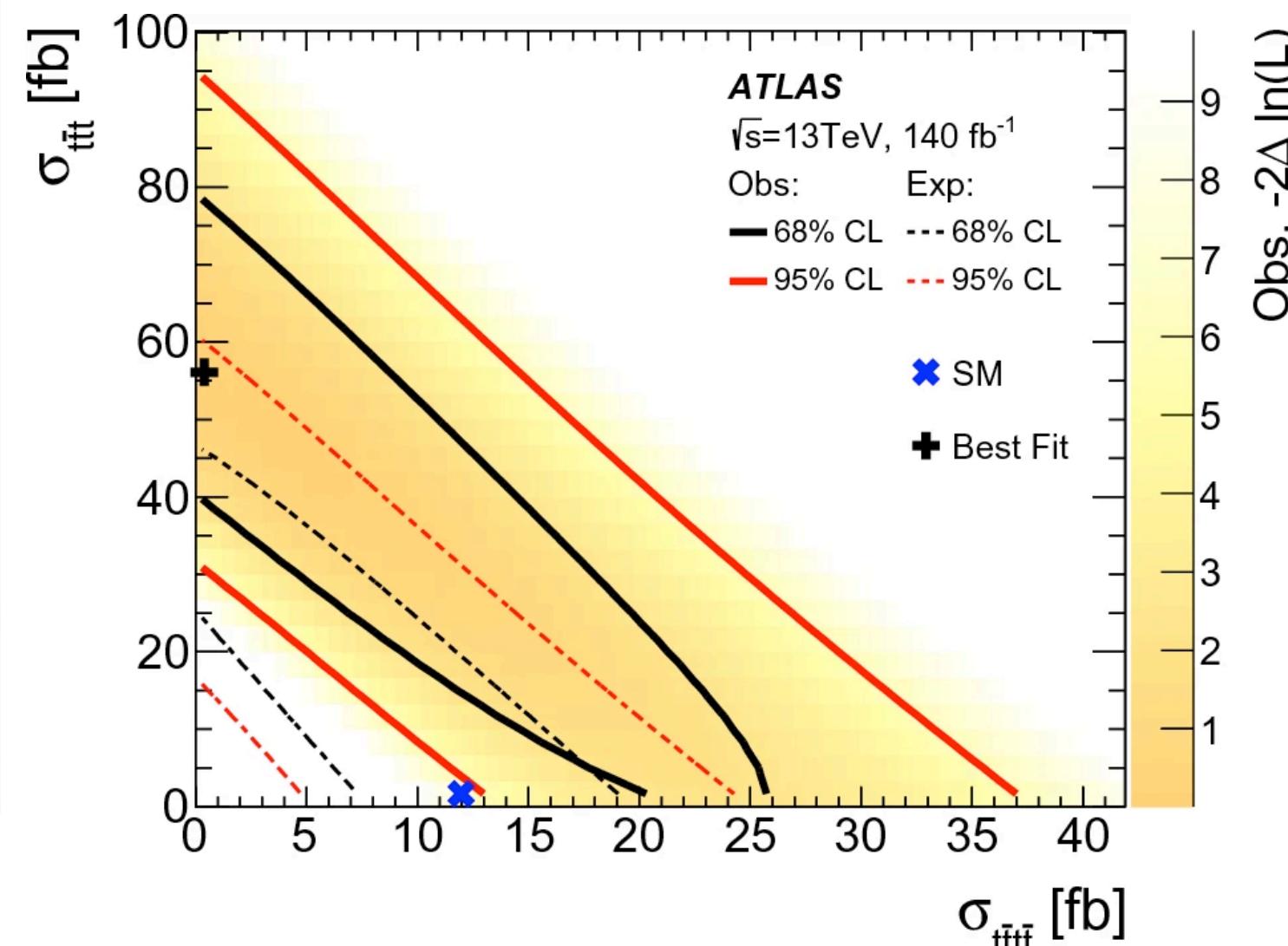
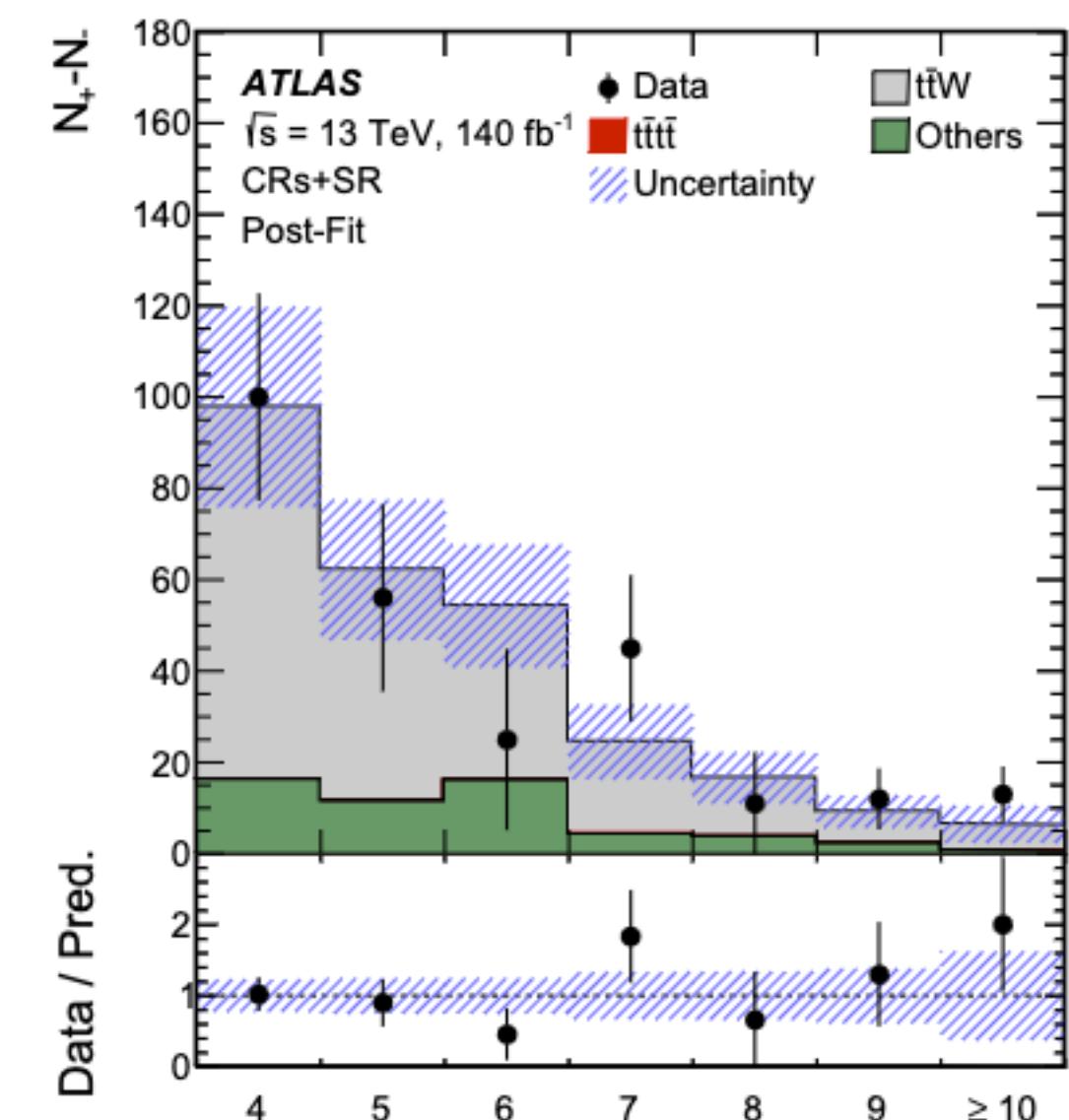
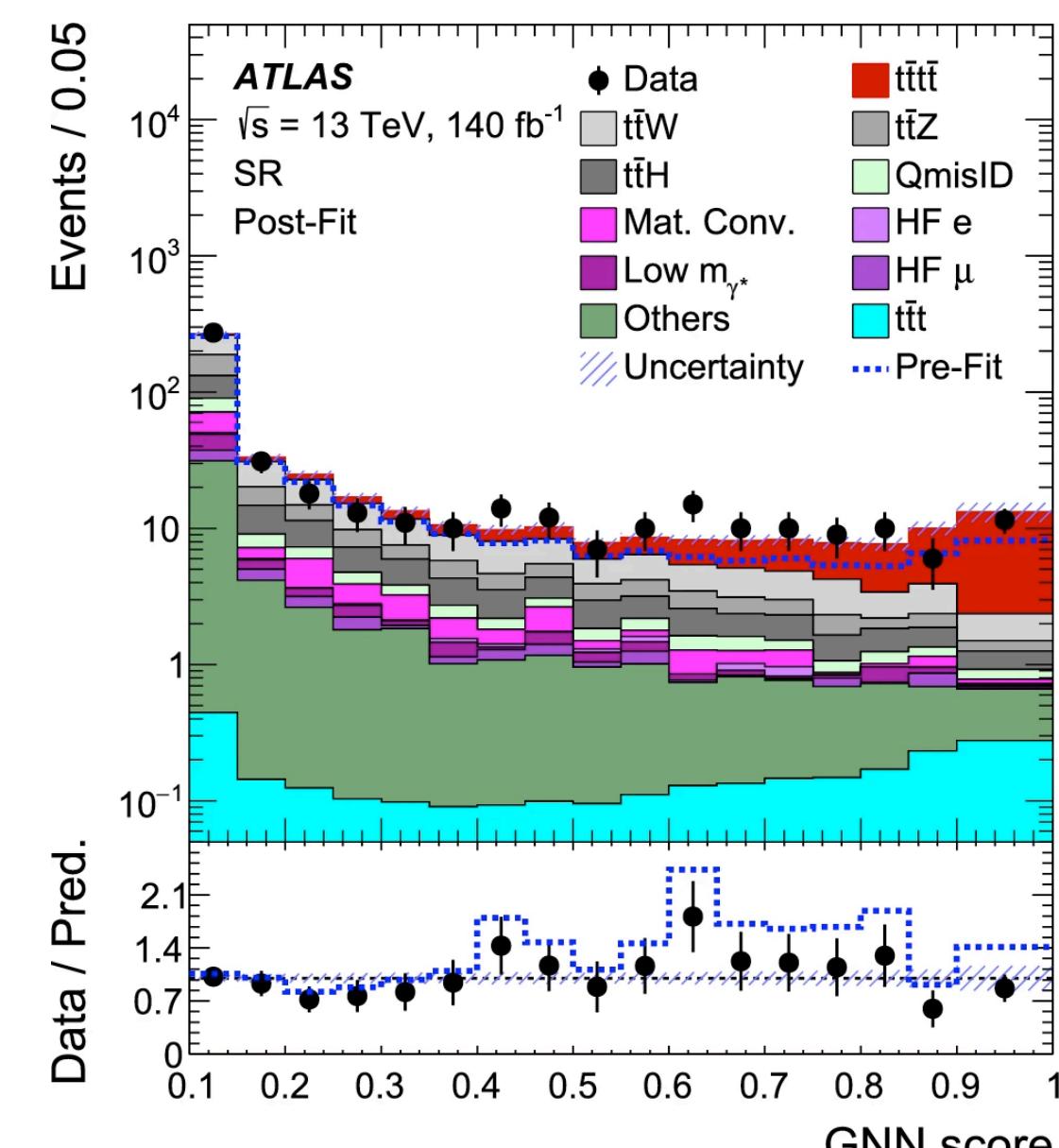


$$NF_{t\bar{t}W^+(4jet)} = 1.27^{+0.25}_{-0.22}$$

$$NF_{t\bar{t}W^-(4jet)} = 1.11^{+0.31}_{-0.28}$$

$$\sigma_{obs} = 22.4^{+6.6}_{-5.5} fb$$

$$\sigma_{exp} = 12.0 \pm 2.4 fb$$

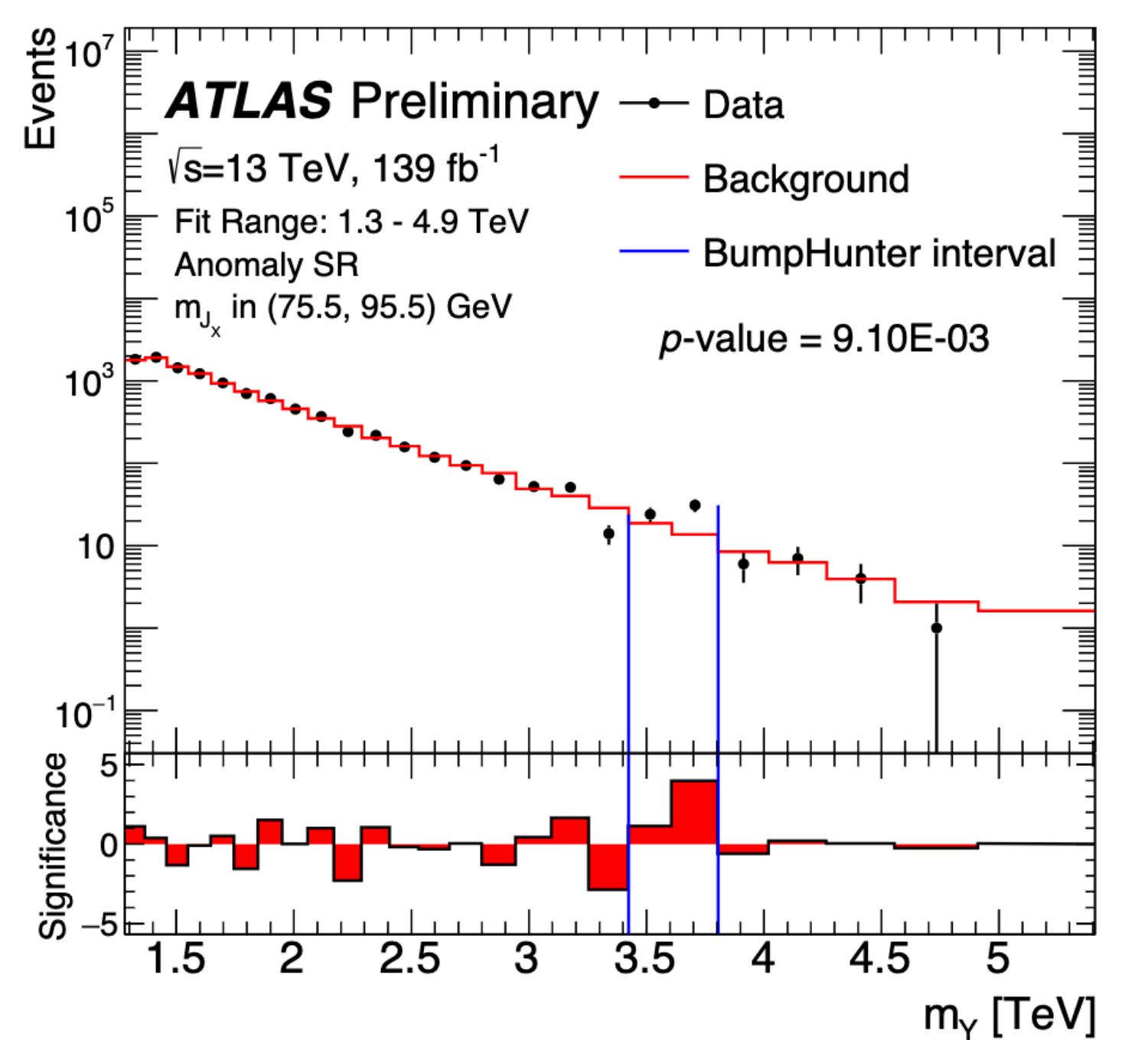
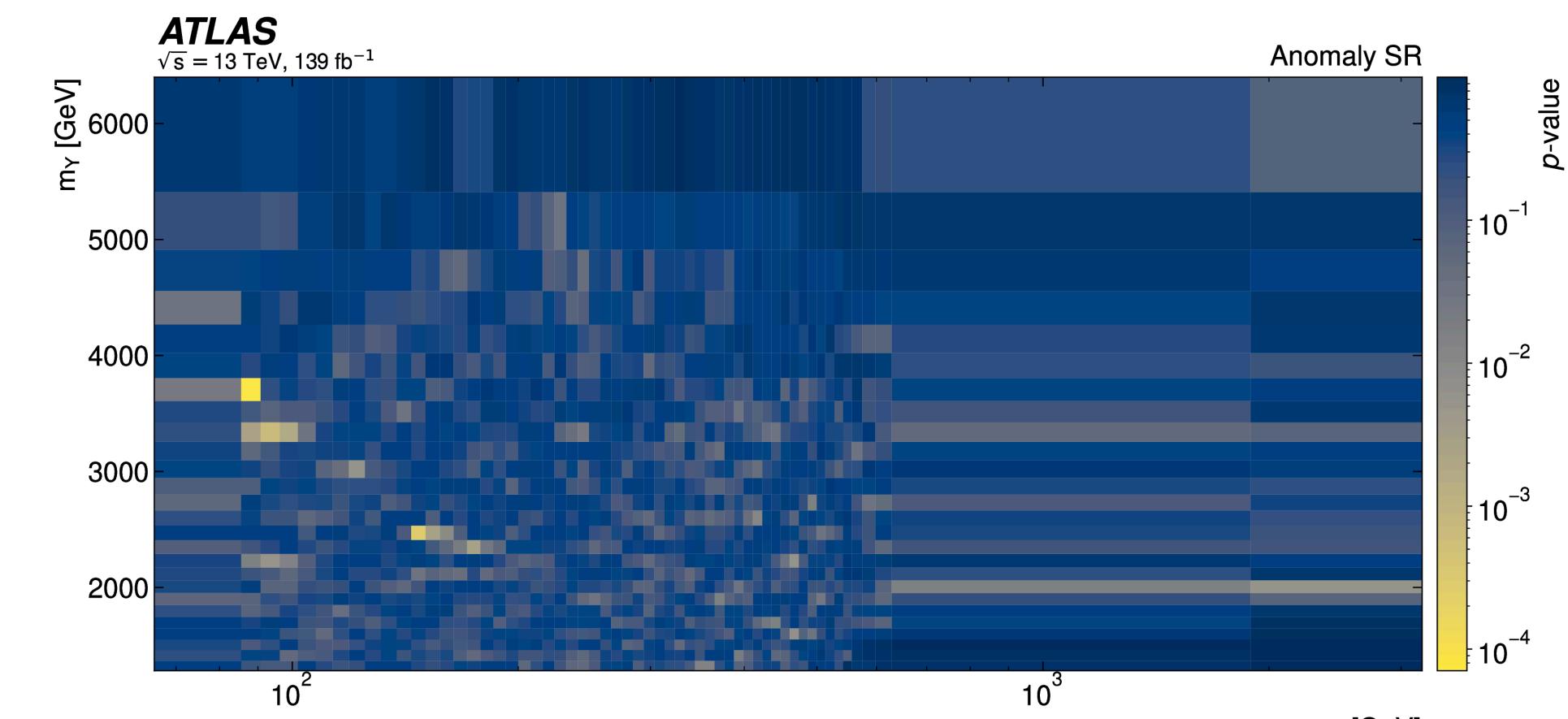
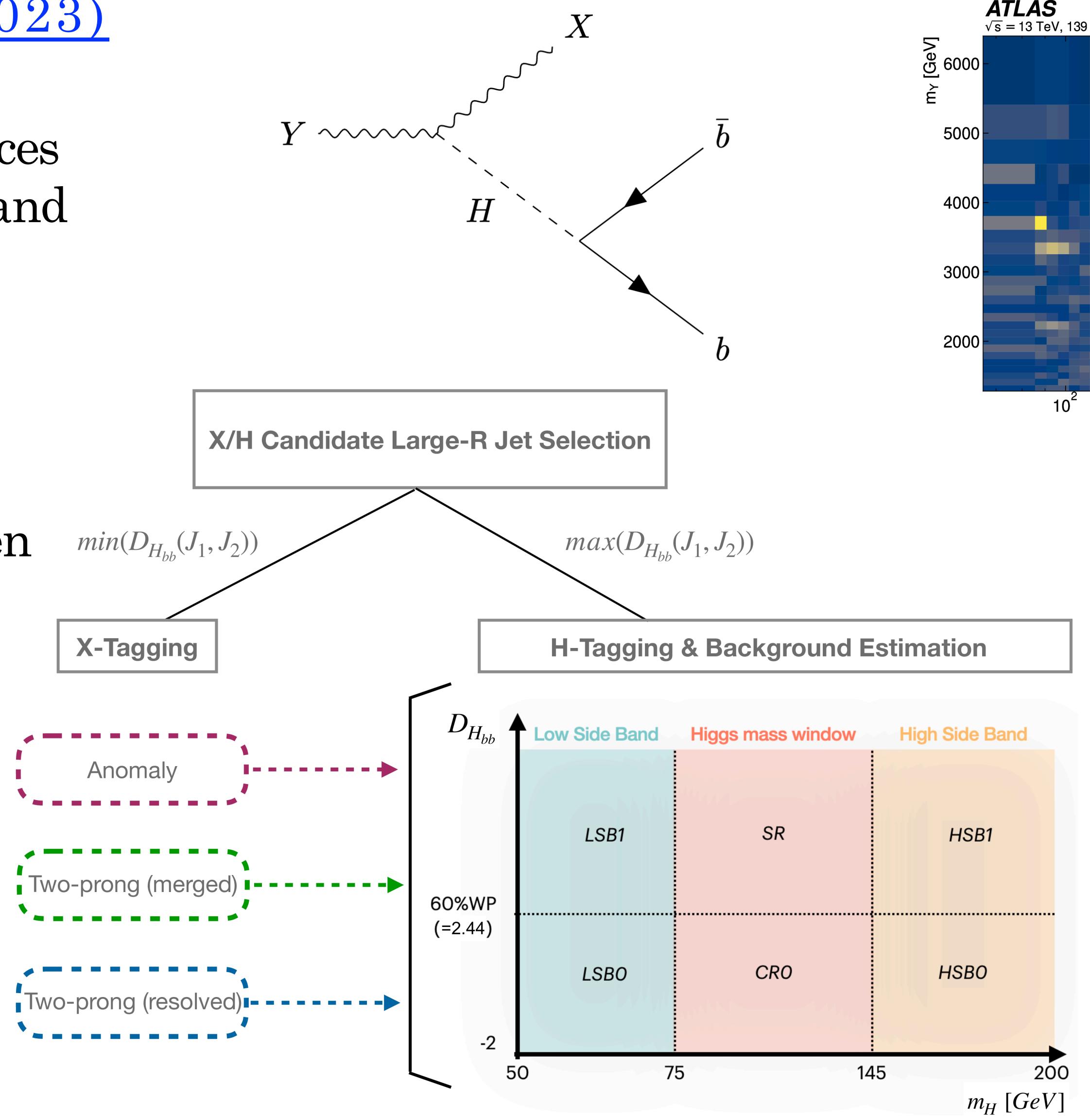


Jet/b-jet final states

HDBS: $qqbb \rightarrow Xh$ Anomaly detection

[ATLAS HDBS-2019-23 \(2023\)](#)

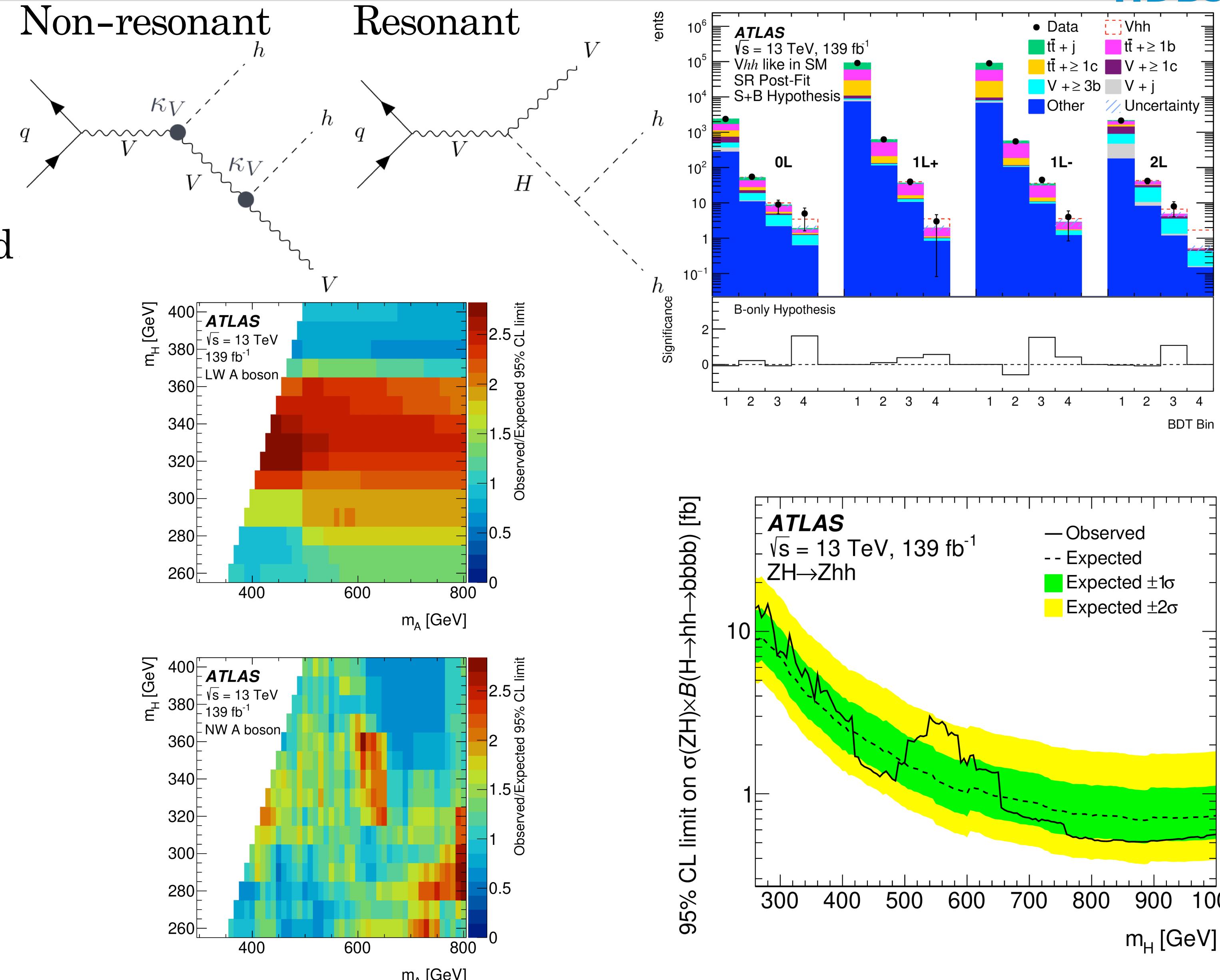
- Target:
 - Search for new resonances decaying to Higgs boson and a generic new particle X
$$Y \rightarrow Xh \rightarrow qqbb$$
- Final state: $qqbb$
- Background:
 - Multi-jet, data driven analysis
- Strategy:
 - Bump-hunt using the Large-R jet and NN anomaly detection algorithm
- Highest significance:
 - At $m_Y = 3.7$ TeV
 - 3.8σ local (1.5σ global)



HDBS: $bbbb + 0l/1l/2l$ BSM Vhh

[ATLAS HDBS-2019-31, EPJC \(2023\)](#)

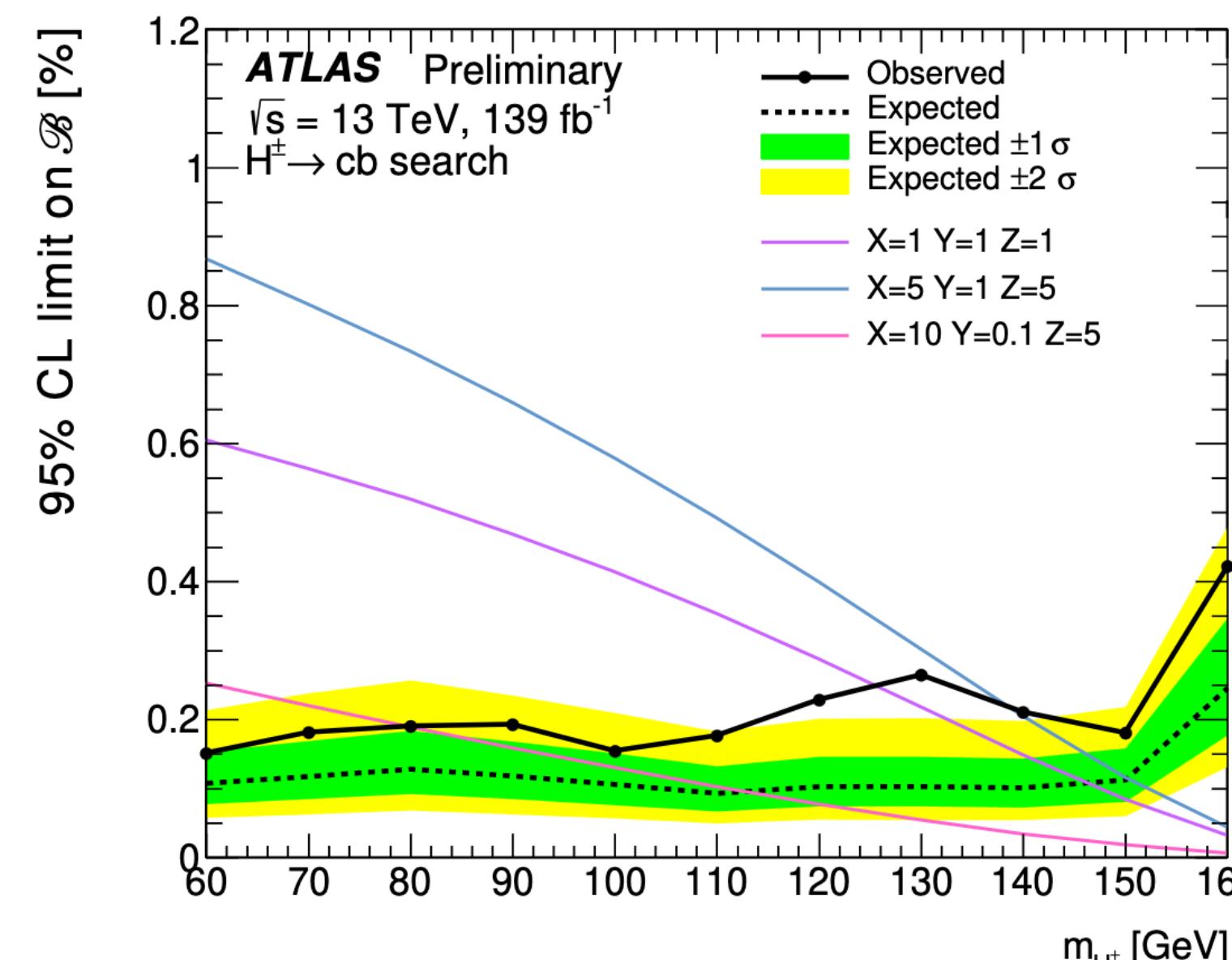
- Target:
 - Search for H boson pair production with W or Z (leptonic decays)
 - Resonant and non-resonant hh prod
- Final state: $bbbb + 0l/1l/2l$
- Background:
 - $t\bar{t}$ and V+jets
- Strategy:
 - Using parametrized NN for optimal discriminant across all signal masses
- Highest significance:
 - ZH: At $m_H = 550$ GeV 2.7σ local (1.4σ global)
 - AZH Large-width: $m_H, m_A = 320, 420$ GeV 3.8σ local (3.0σ global)
 - AZH Narrow-width: $m_H, m_A = 300, 800$ GeV 3.6σ local (1.4σ global)



HDBS: cbb BSM top and $bb + \tau\tau/\gamma\gamma/bb$ Resonant hh

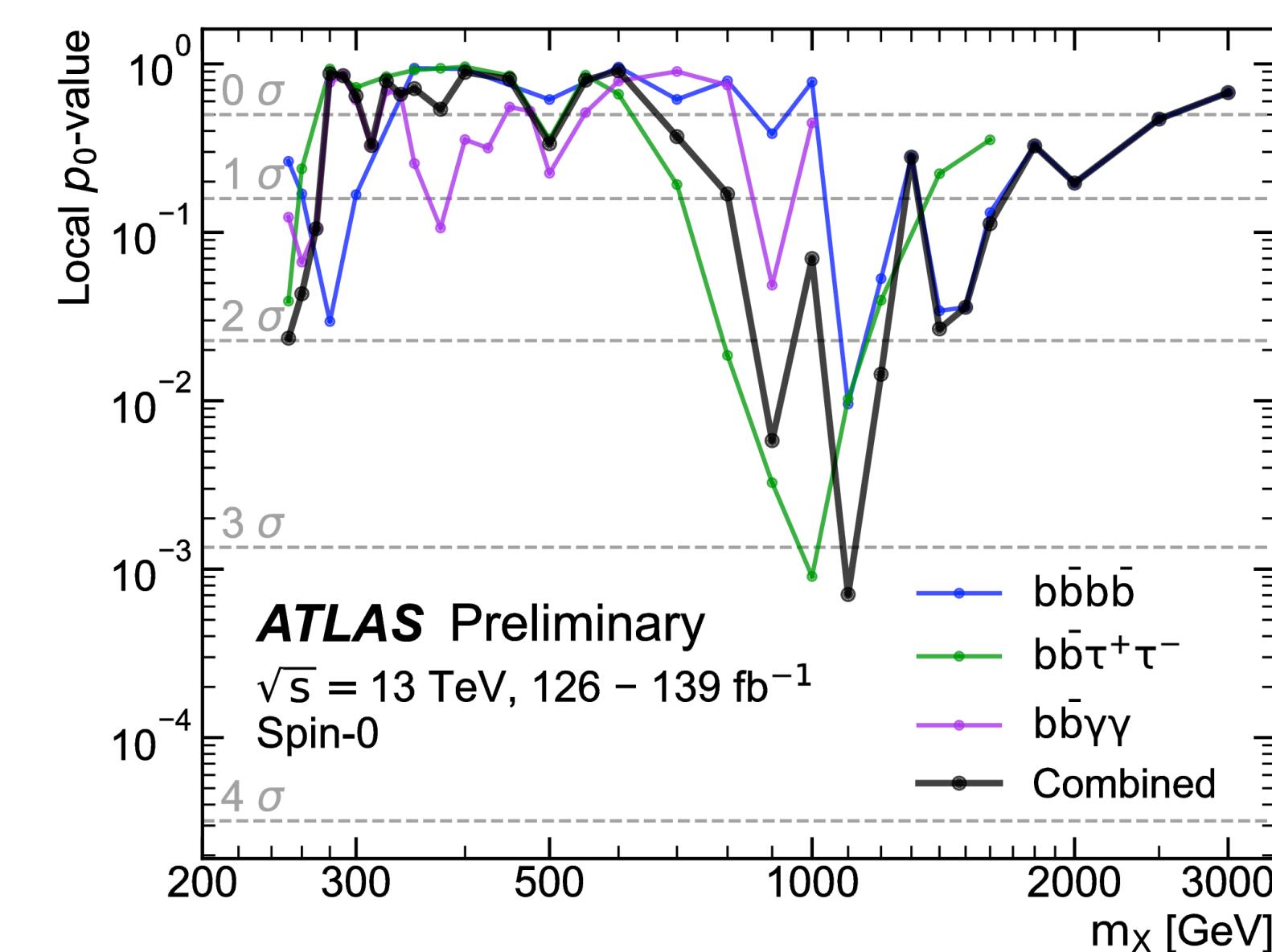
[ATLAS HDBS-2019-24 \(2023\)](#)

- Target:
 - Search for $t \rightarrow H^+ b \rightarrow cbb$ in $t\bar{t}$
- Final state: cbb
- Strategy:
 - Using parametrized NN for optimal discriminant across all signal masses
- Highest significance:
 - At $m_{H^\pm} = 130$ GeV 3.0σ local (1.6σ global)



[ATLAS-CONF-2021-052 \(2021\)](#)

- Target:
 - Search for resonant hh peak
- Final state: $bb\tau\tau$, $bb\gamma\gamma$, $bbbb$
- Strategy:
 - Using parameterized NN for optimal discriminant across all signal masses
- Highest significance:
 - At $m_X = 1.1$ TeV 3.2σ local (2.1σ global)



Di-photon final states

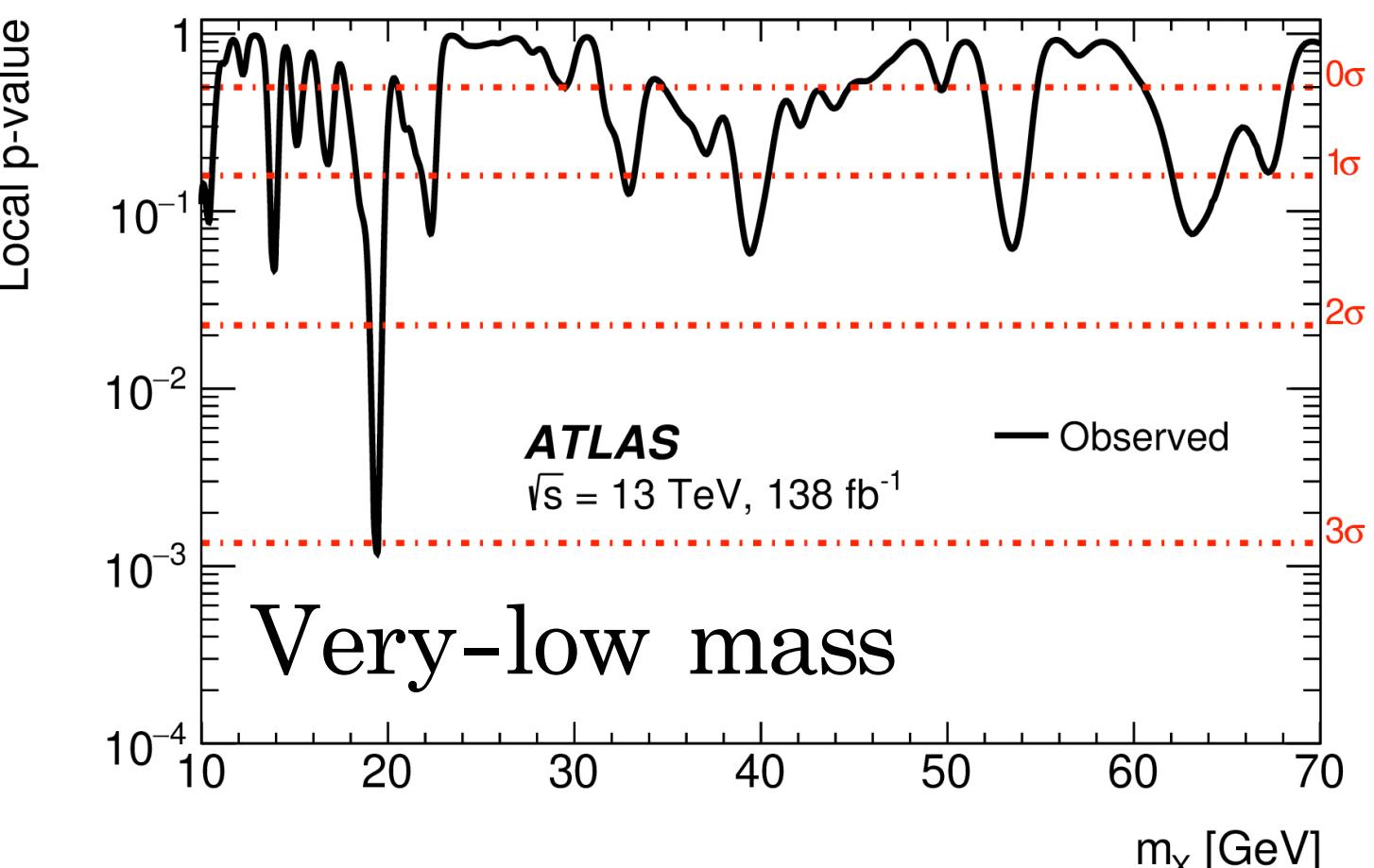
Higgs: $\gamma\gamma$ in $X \rightarrow \gamma\gamma$



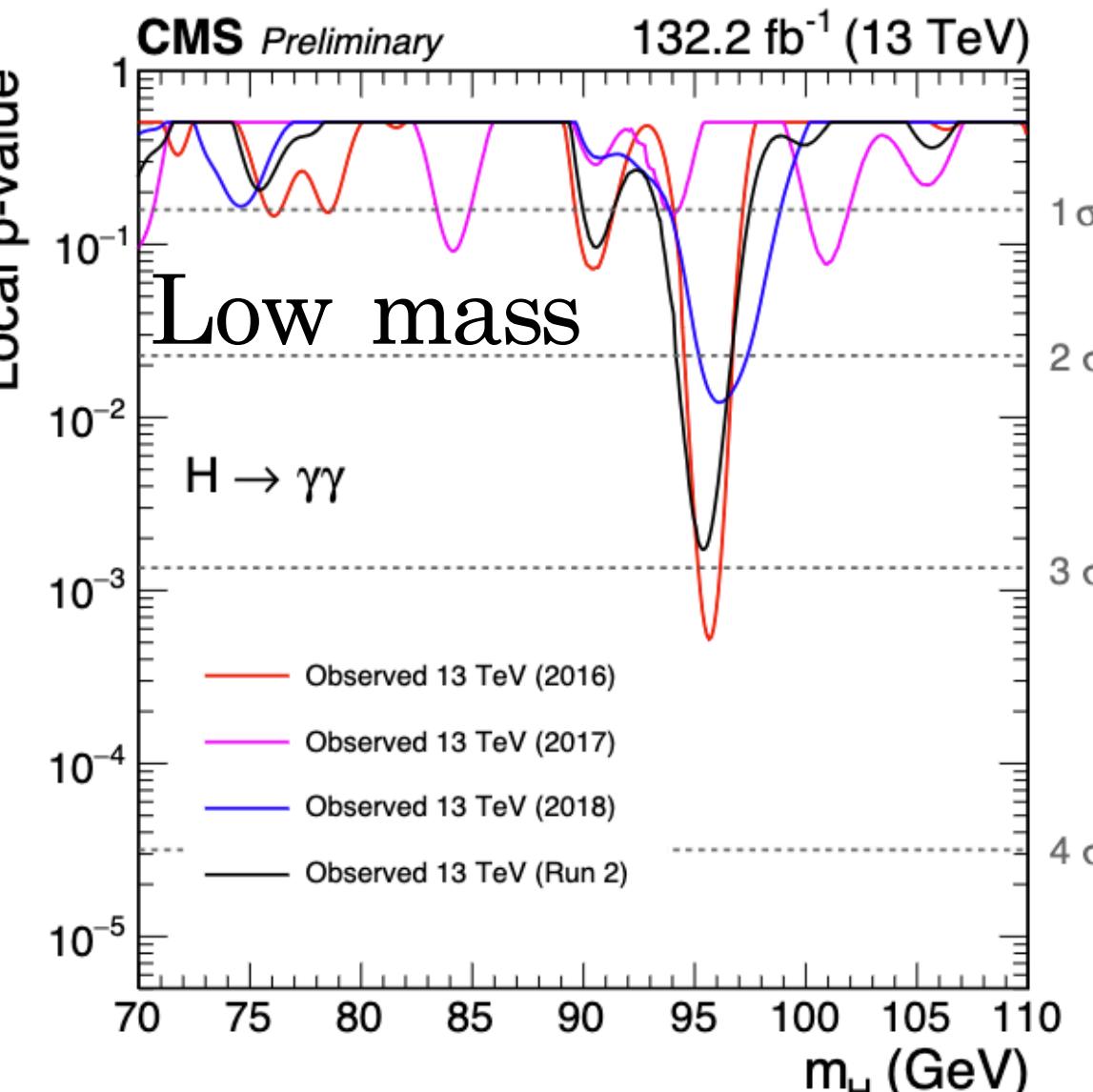
Very-low mass
 < 70 GeV Low mass
 65-110 GeV High mass
 > 150 GeV

- Target:
 - Search for $X \rightarrow \gamma\gamma$ decays motivated by 2HDM and Axion-like particle models
- Final state: $\gamma\gamma$
- Background:
 - $Z \rightarrow ee$: Modeled by DSCB func, DD norm.
 - Non-resonant: $\gamma\gamma$ from MC, jets faking γ , shape from MC and normalization in CRs
- Strategy:
 - Bump hunt in the $m_{\gamma\gamma}$
- Highest significance:
 - Very low mass: $m_{\gamma\gamma} = 19.4 \text{ GeV}$ 3.1σ local
 (1.5σ global)
 - Low mass: $m_{\gamma\gamma} = 71.8 \text{ GeV}$ 2.2σ local (mod.in.)
 - High mass: $m_{\gamma\gamma} = 684 \text{ GeV}$ 3.29σ local
 (1.36σ global)
 - CMS: $m_{\gamma\gamma} = 95.4 \text{ GeV}$ 2.9σ local (1.3σ global)

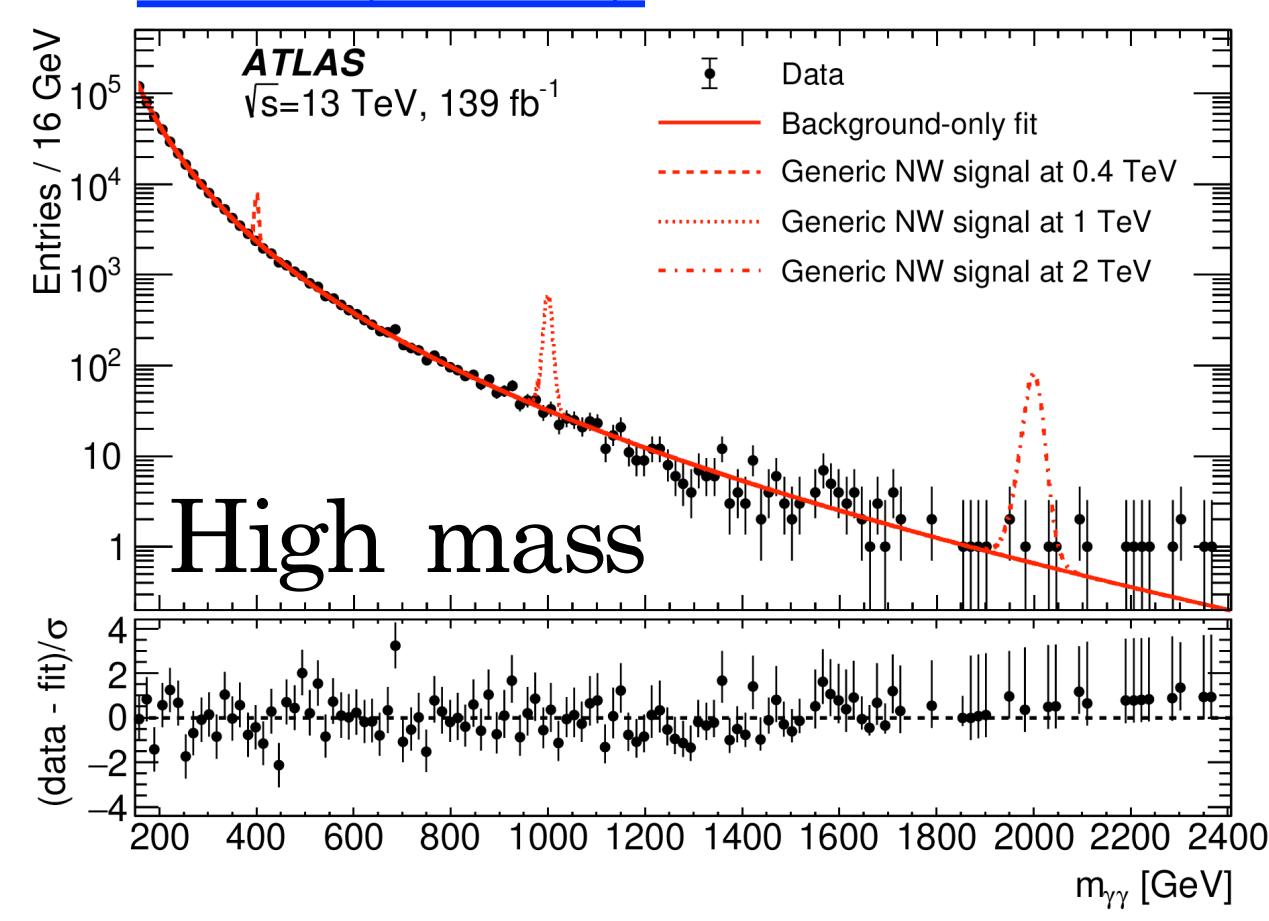
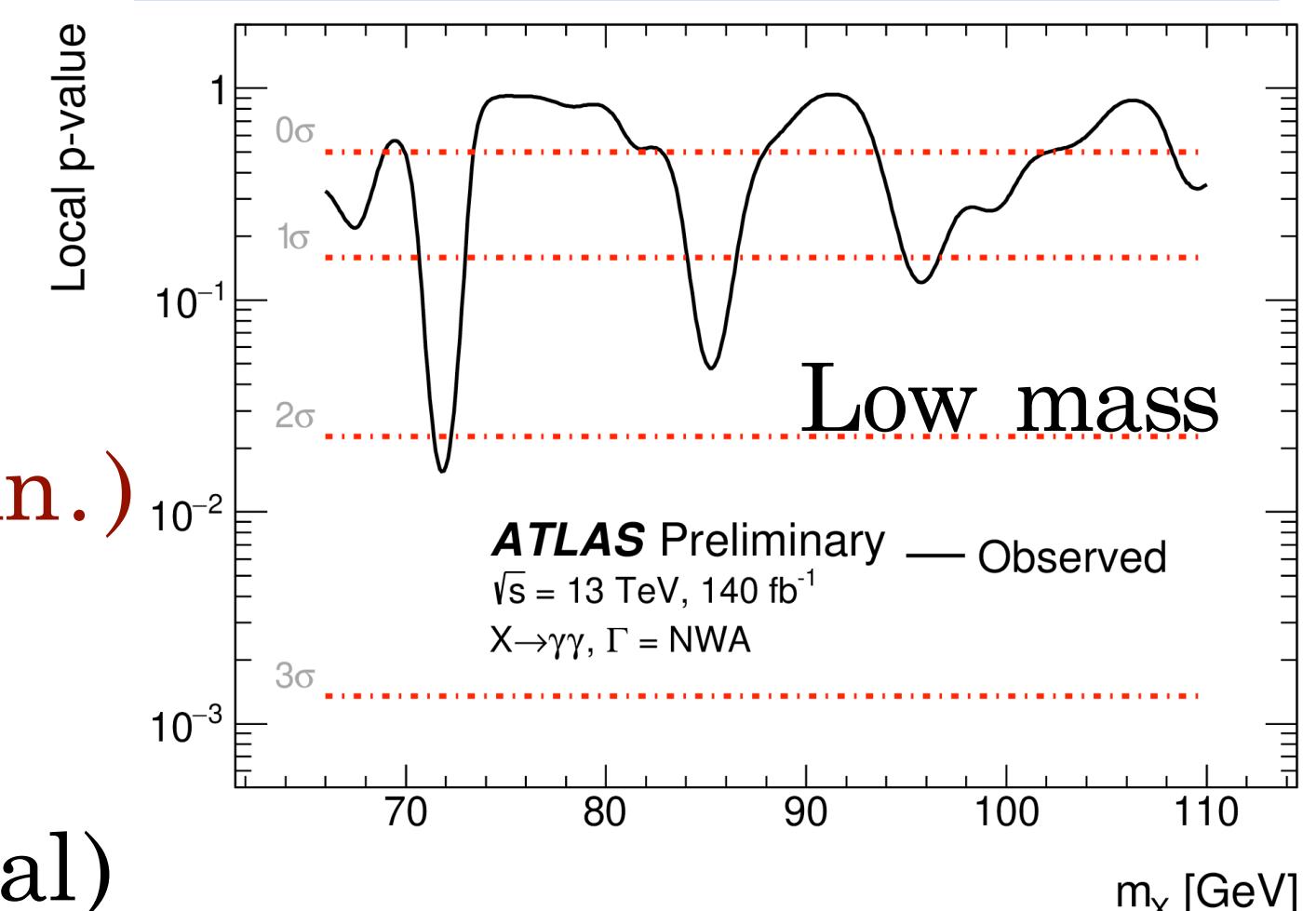
[ATLAS HIGG-2019-23 \(2022\)](#)



[CMS HIG-20-002 \(2023\)](#)



Prev.: [ATLAS-CONF-2018-025](#)
[ATLAS-CONF-2023-035](#)

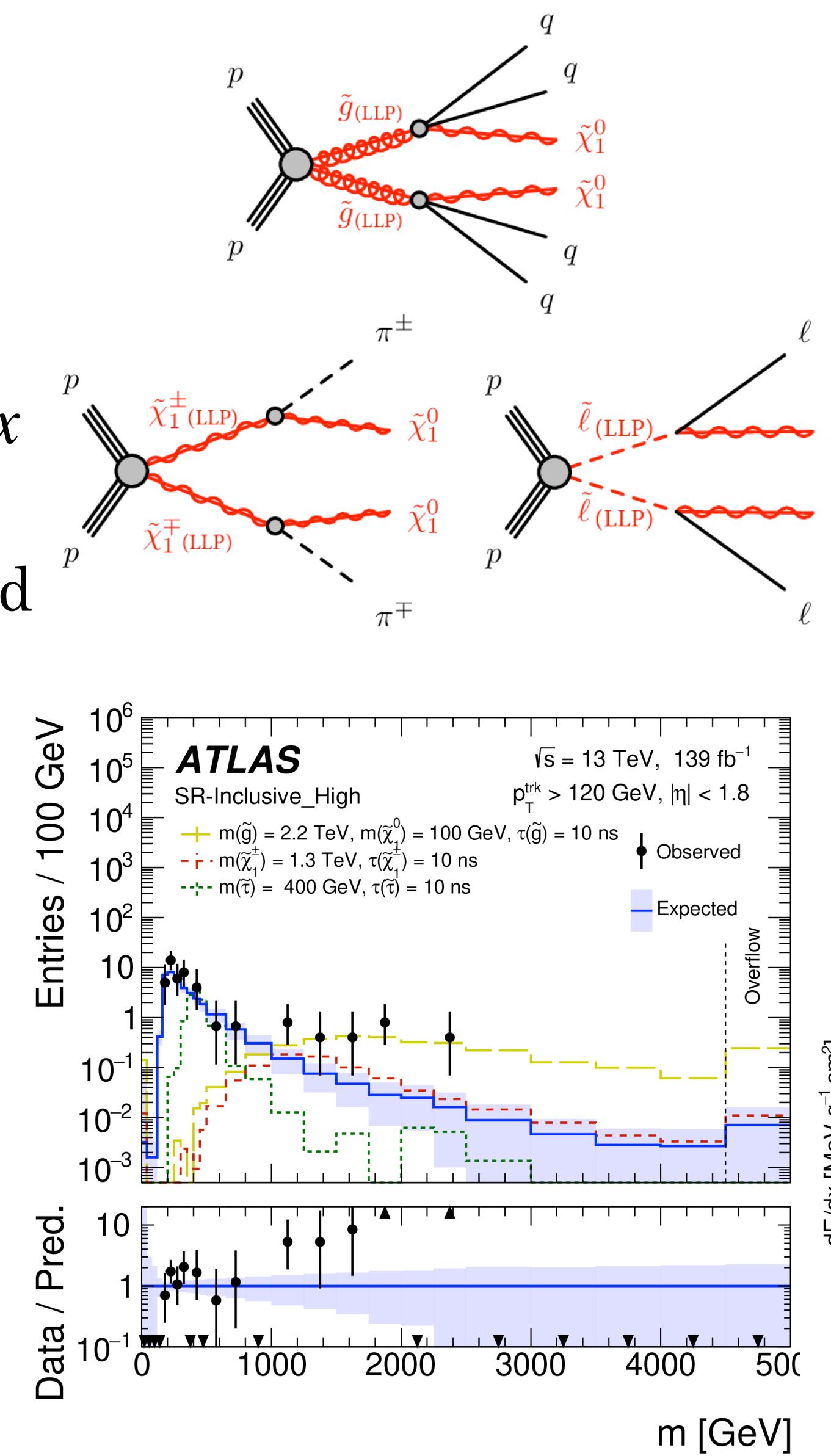


Long-lived particle searches

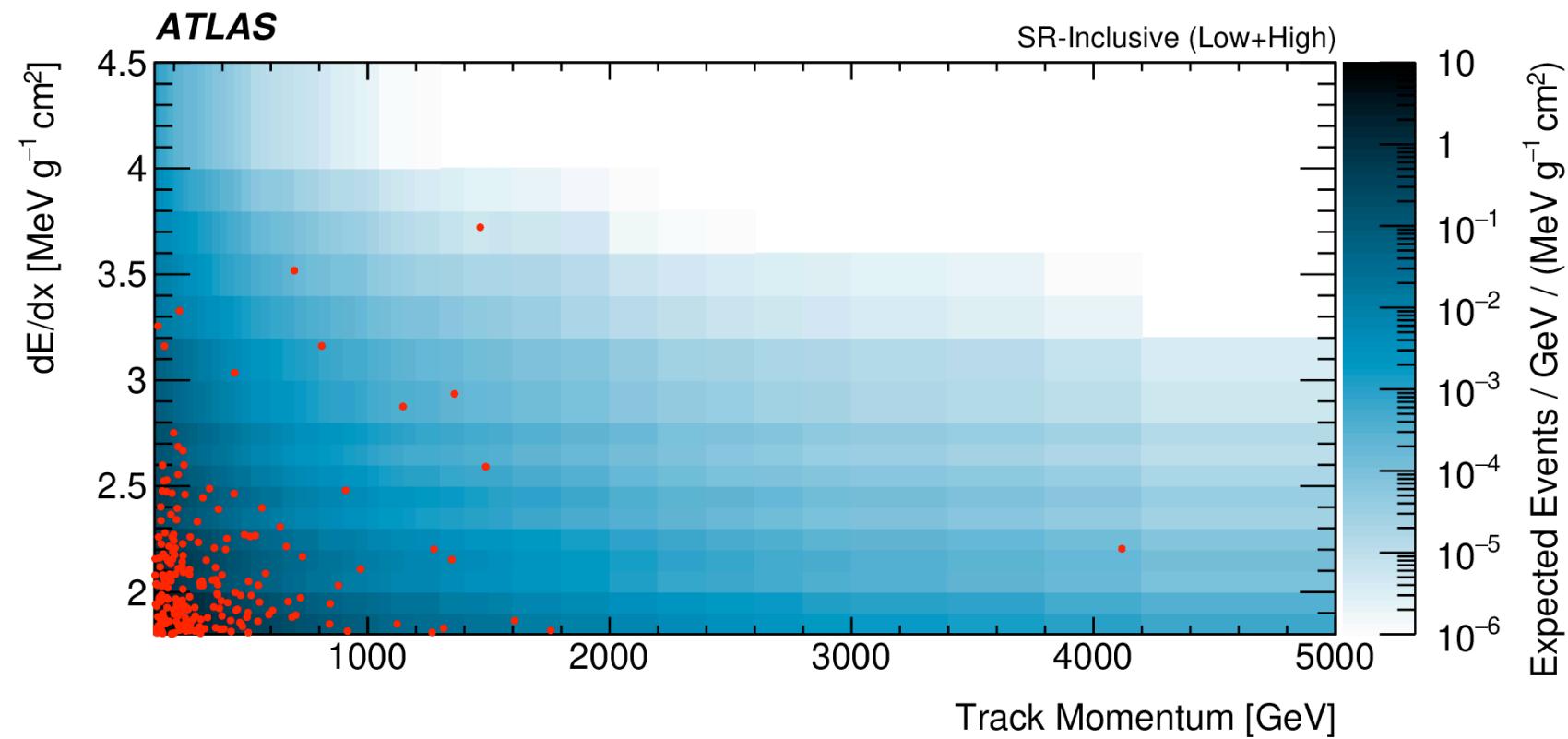
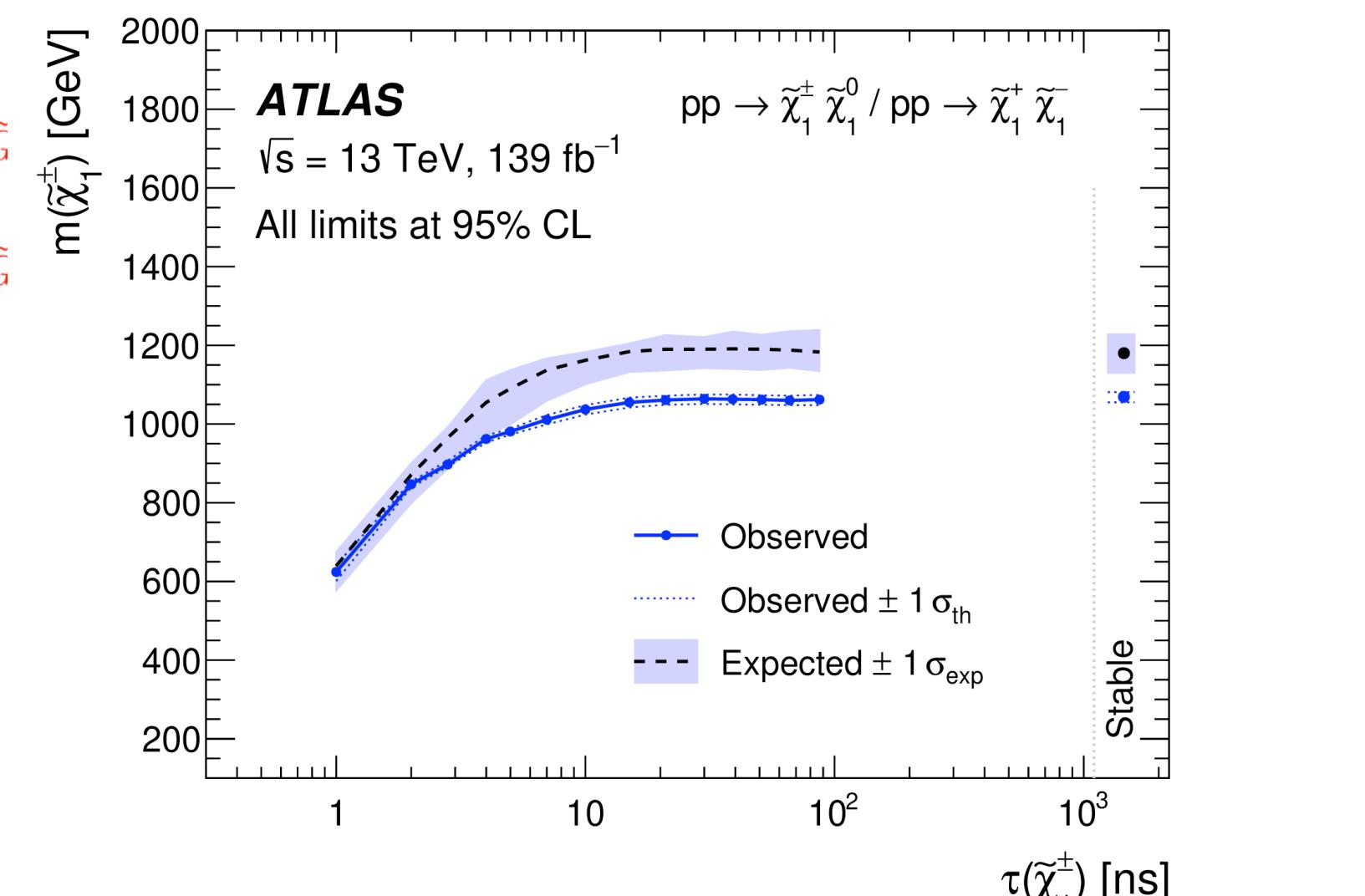
SUSY: Long-lived, pixel dE/dx

[ATLAS SUSY-2018-42, JHEP \(2023\)](#)

- Target:
 - Search for massive, charged, long-lived particle, with high ionization
- Final state:
 - High p_T track with high pixel dE/dx
- Background:
 - LL particles much slower than speed of flight, have high transverse momenta and large ionization loss
- Strategy:
 - SR/CR orthogonality obtained via lepton p_T cut
- Highest significance:
 - For target mass 1400 GeV 3.6σ local (3.3σ global)
 - In the ToF check excess not compatible with the slow moving particle hypothesis



SR name	Discovery	Limit setting	Track category	IBL overflow	dE/dx [MeV g $^{-1}$ cm 2]
SR-Inclusive_Low	✓		inclusive	yes or no	[1.8, 2.4]
SR-Inclusive_High	✓				> 2.4
SR-Trk-IBL0_Low		✓	track	no	[1.8, 2.4]
SR-Trk-IBL0_High		✓		no	> 2.4
SR-Trk-IBL1		✓		yes	> 1.8
SR-Mu-IBL0_Low		✓	muon tracks	no	[1.8, 2.4]
SR-Mu-IBL0_High		✓		no	> 2.4
SR-Mu-IBL1		✓		yes	> 1.8



Summary

	SUSY	Other BSM	Higgs/top/SM/b
Di-lepton	2l+jet+MET: wino/higgsino 2σ PRD 2020 3l + MET: wino/higgsino 2σ EPJC 2021	bsll: Contact interaction 2.6σ PRL 2021 bbmm: H to aa 3.3σ PRD 2022	$e\tau, \mu\tau$: LFV Higgs 2.5σ ATLAS-HIGG 2023
Multi-lepton		3l: Resonant WZ 2.8σ local ATLAS-HDBS 2022 2lSS, 3l, 4l: g2HDM 2.81σ local ATLAS-HDBS 2022	2lSS, 3l: WWW cross-section 2.6σ PRL 2022 . 2lSS, 3l, 4l: tt tt 1.8σ EPJC 2023
Jets/b-jets		qqbb: Y to Xh 3.8σ ATLAS-HDBS 2023 bbbb +1/2/3l: BSM Vhh 3.8σ EPJC 2023 cbb: BSM top 3.0σ ATLAS-HDBS 2023 bb $\tau\tau$, bb $\gamma\gamma$, bbbb: Resonant hh 3.2σ ATLAS-HDBS 2021	
Di-photon			$\gamma\gamma$: Very low mass 3.1σ ATLAS-HIGG 2022 $\gamma\gamma$: Low mass 2.2σ ATLAS-HIGG 2023 $\gamma\gamma$: High mass 3.29σ PLB 2021
Long-lived	dE/dx: Long-lived 3.3σ global JHEP 2023		



Thank you for your attention!

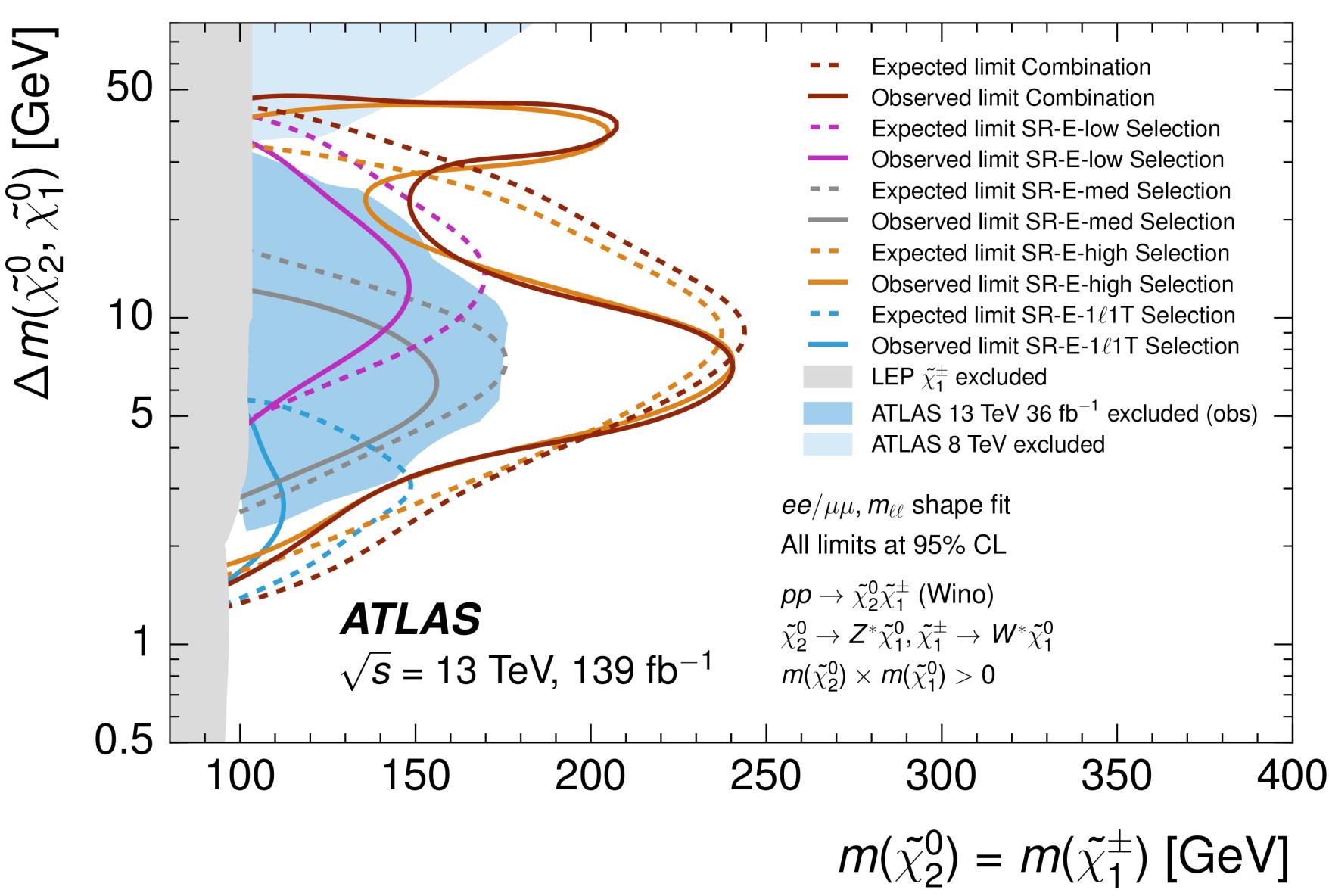
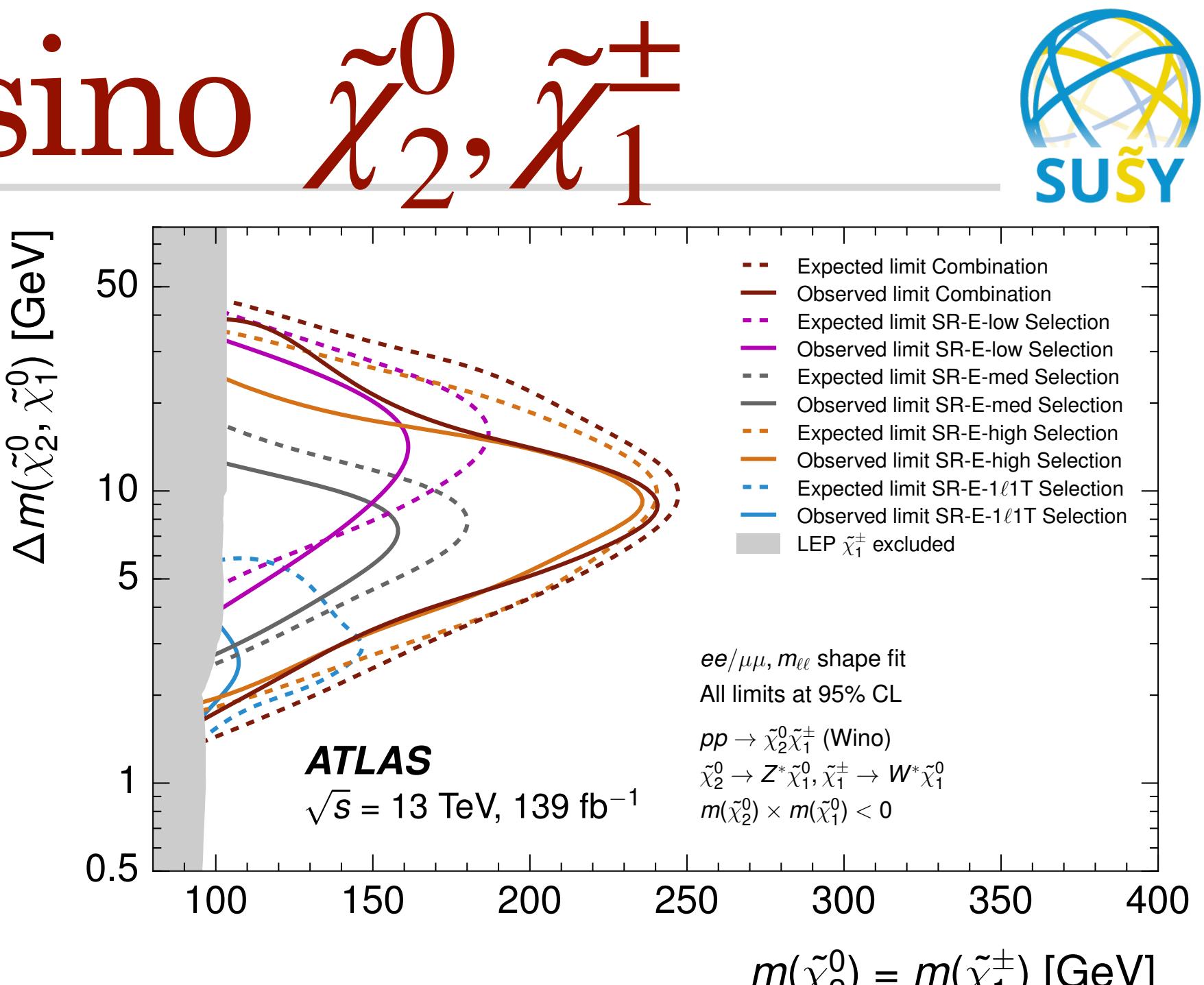
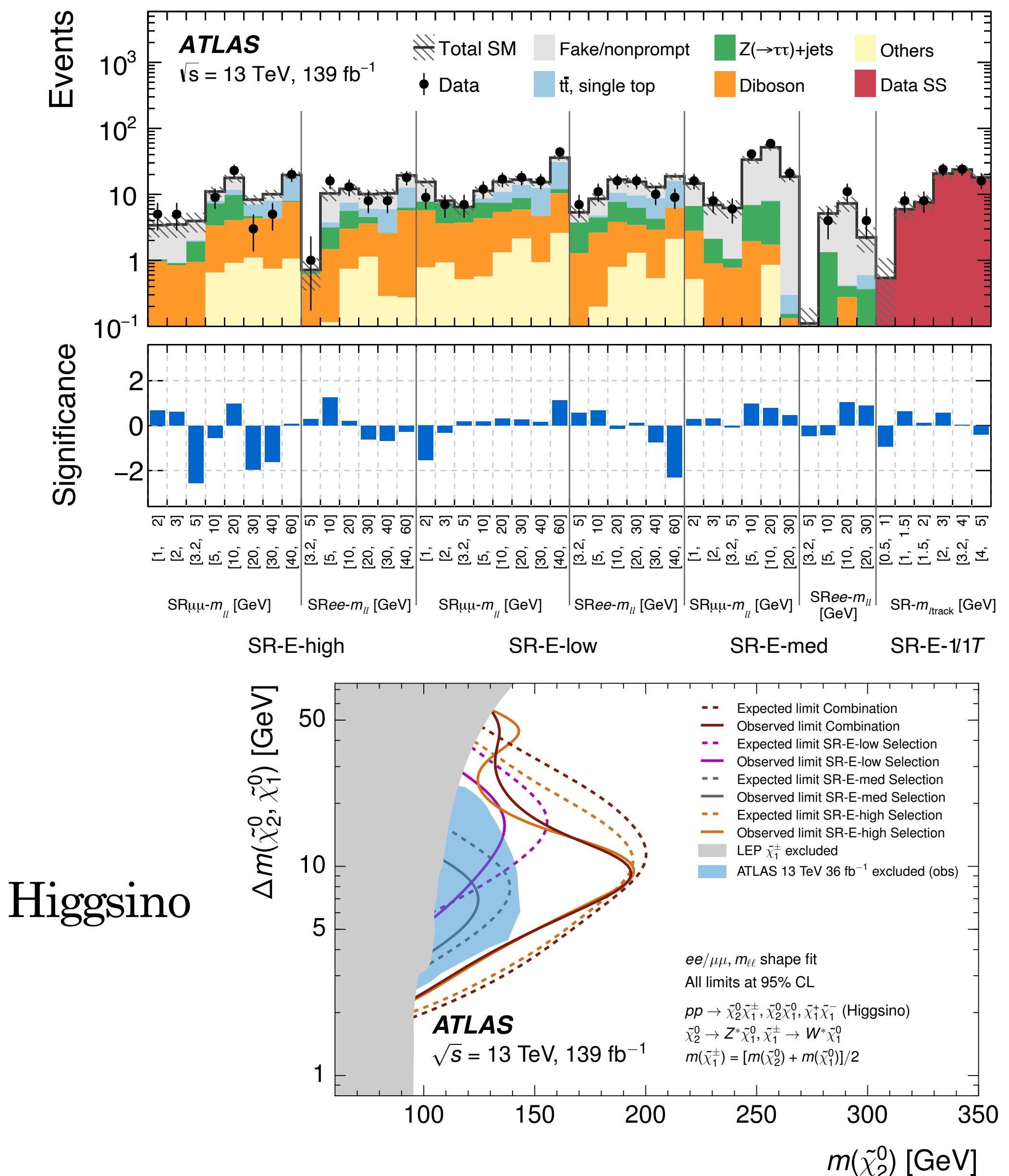


Backup

SUSY: 2lOS comp. Wino/higgsino $\tilde{\chi}_2^0, \tilde{\chi}_1^\pm$



ATLAS SUSY-2018-16, PRD (2020)



SUSY: dE/dx

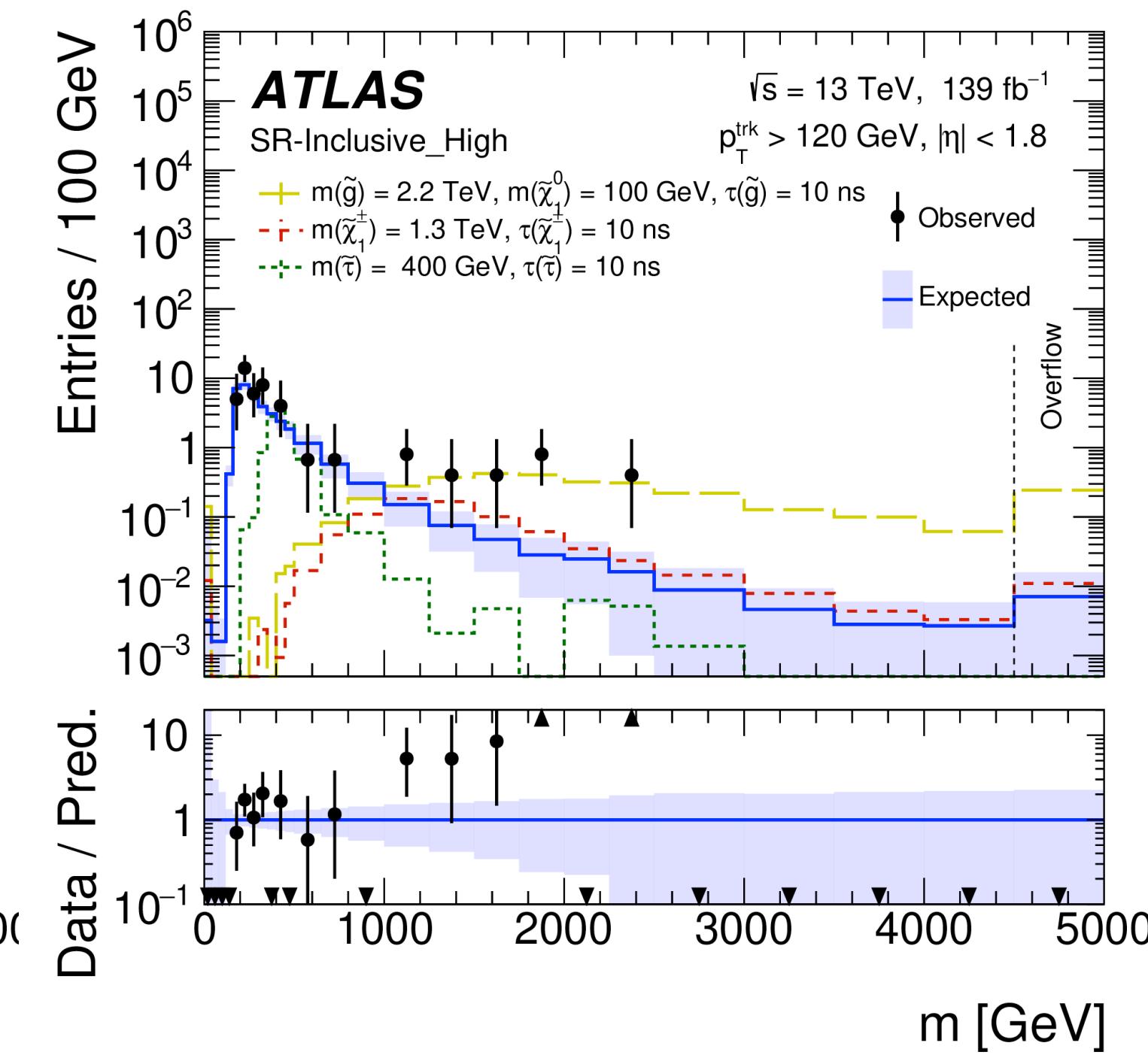
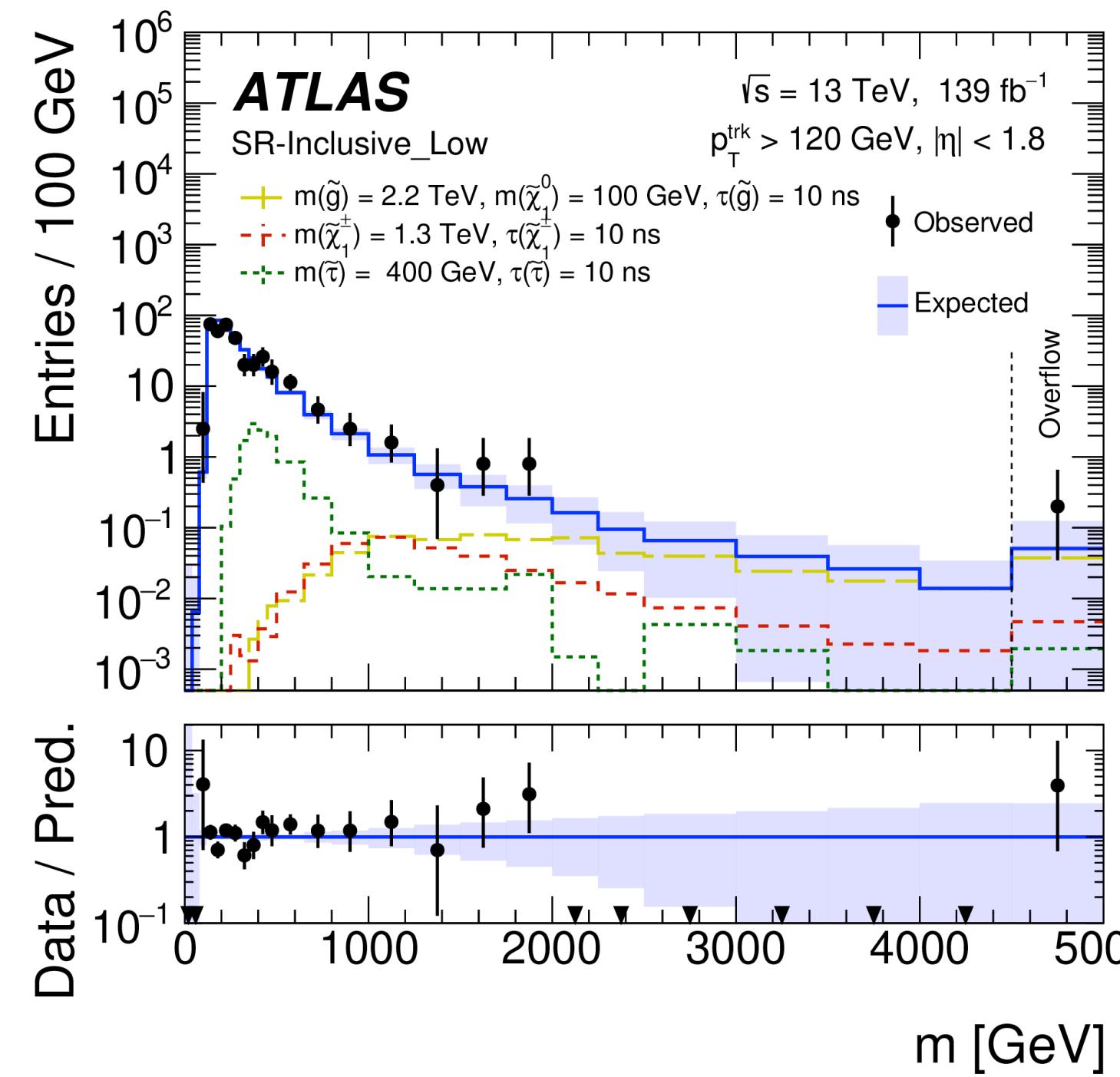
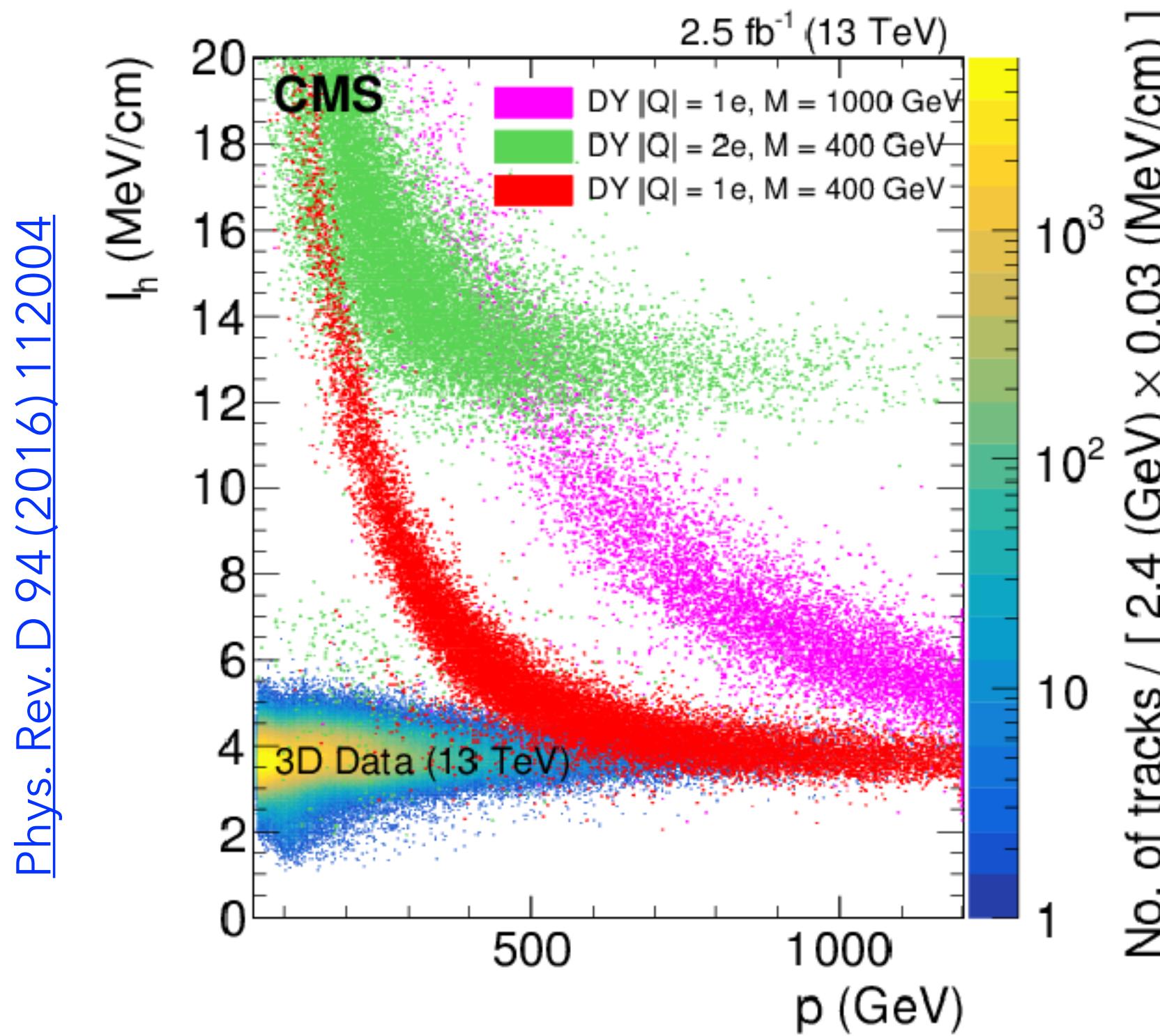
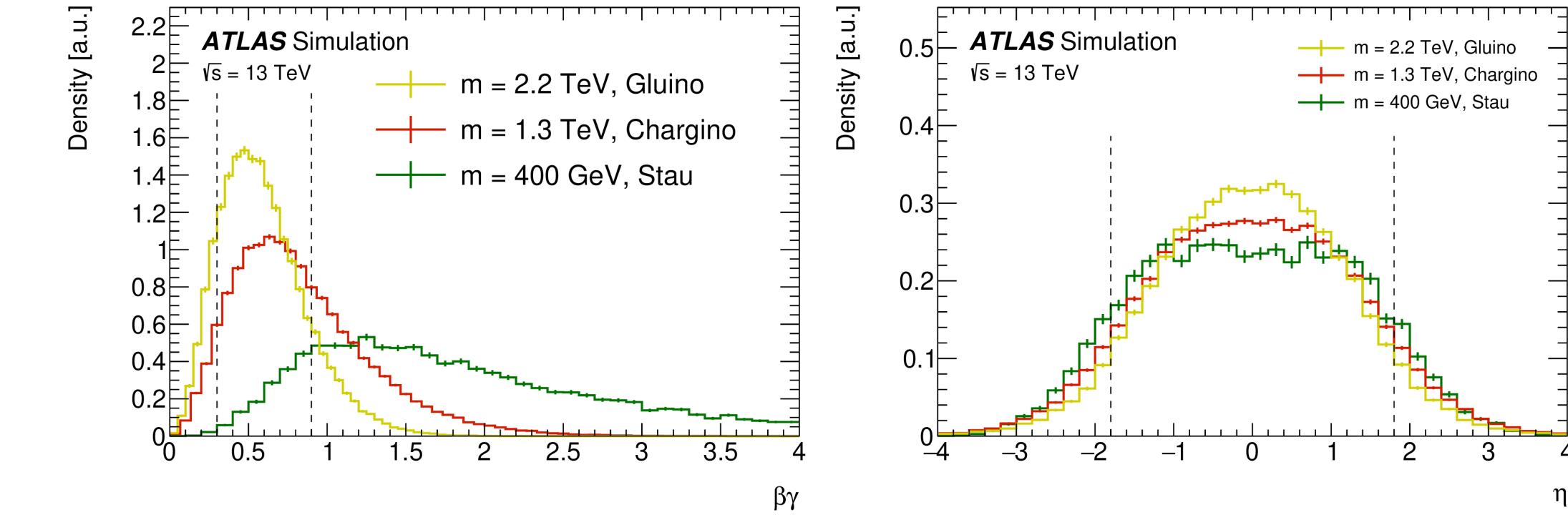
Bethe-Bloch, energy loss per path length via ionization:

$$-\left\langle \frac{dE}{dx} \right\rangle^{\text{charge}} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

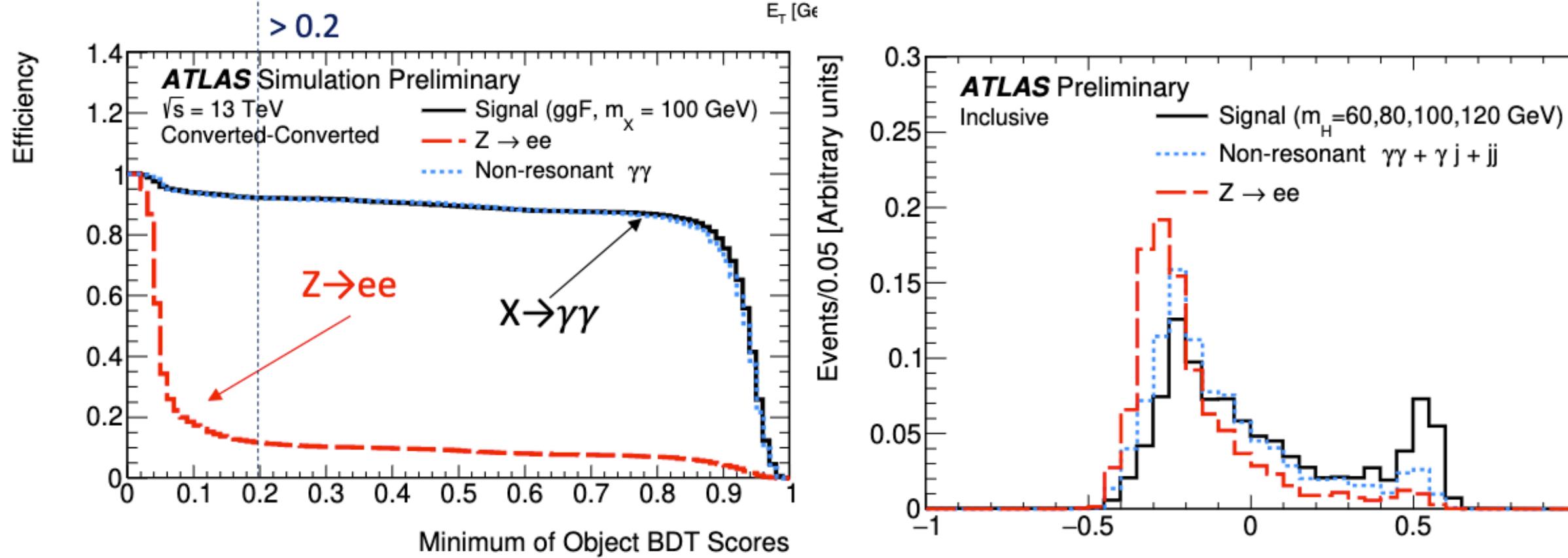
$0.1 \lesssim \beta\gamma \lesssim 1000$ $\beta = \frac{v}{c}$

charge **velocity**

- Pixel detector ionization (sensitive to shorter life times).
- High dE/dx for slow moving and heavy charged particles.

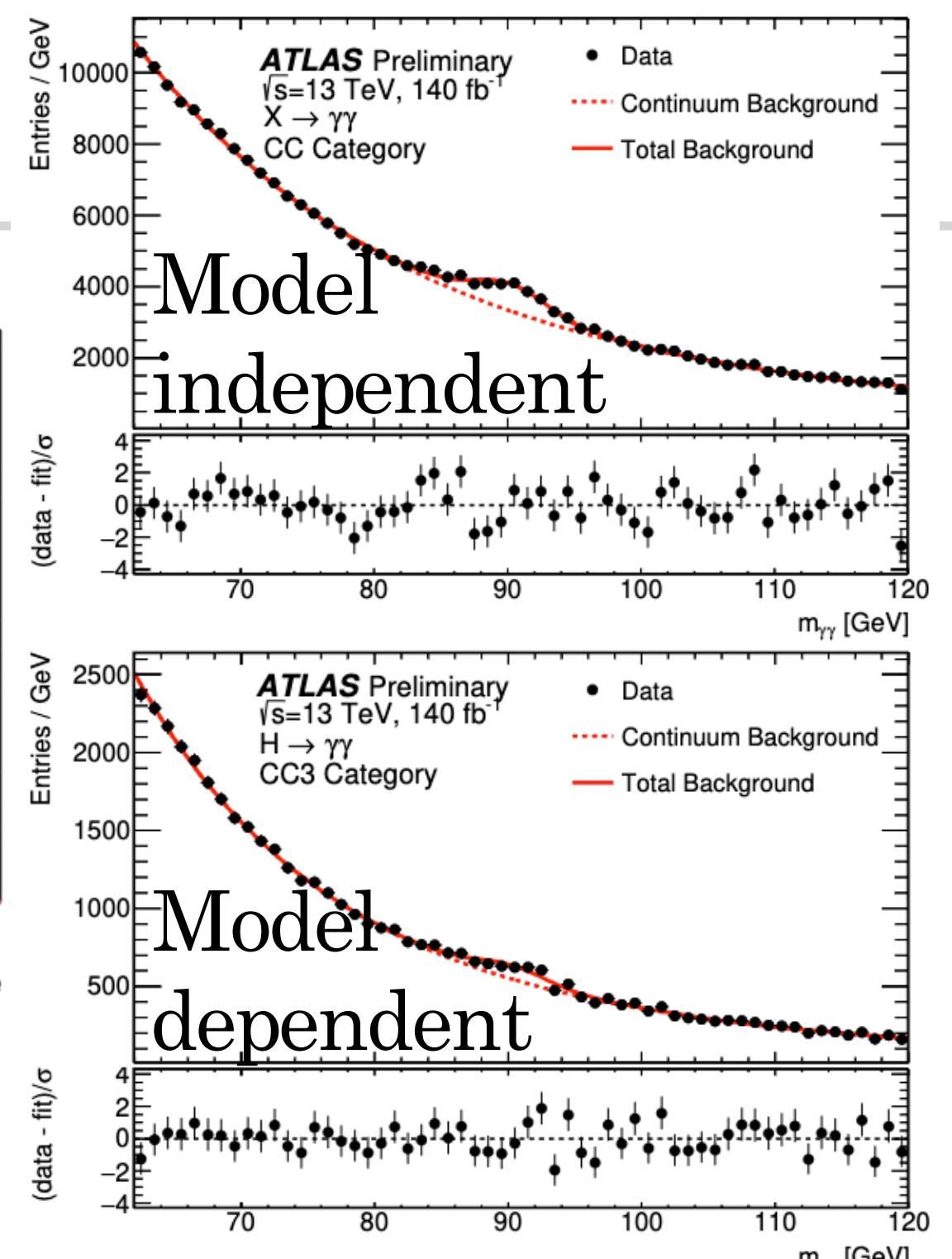


HIGG: Low mass $Y \rightarrow$

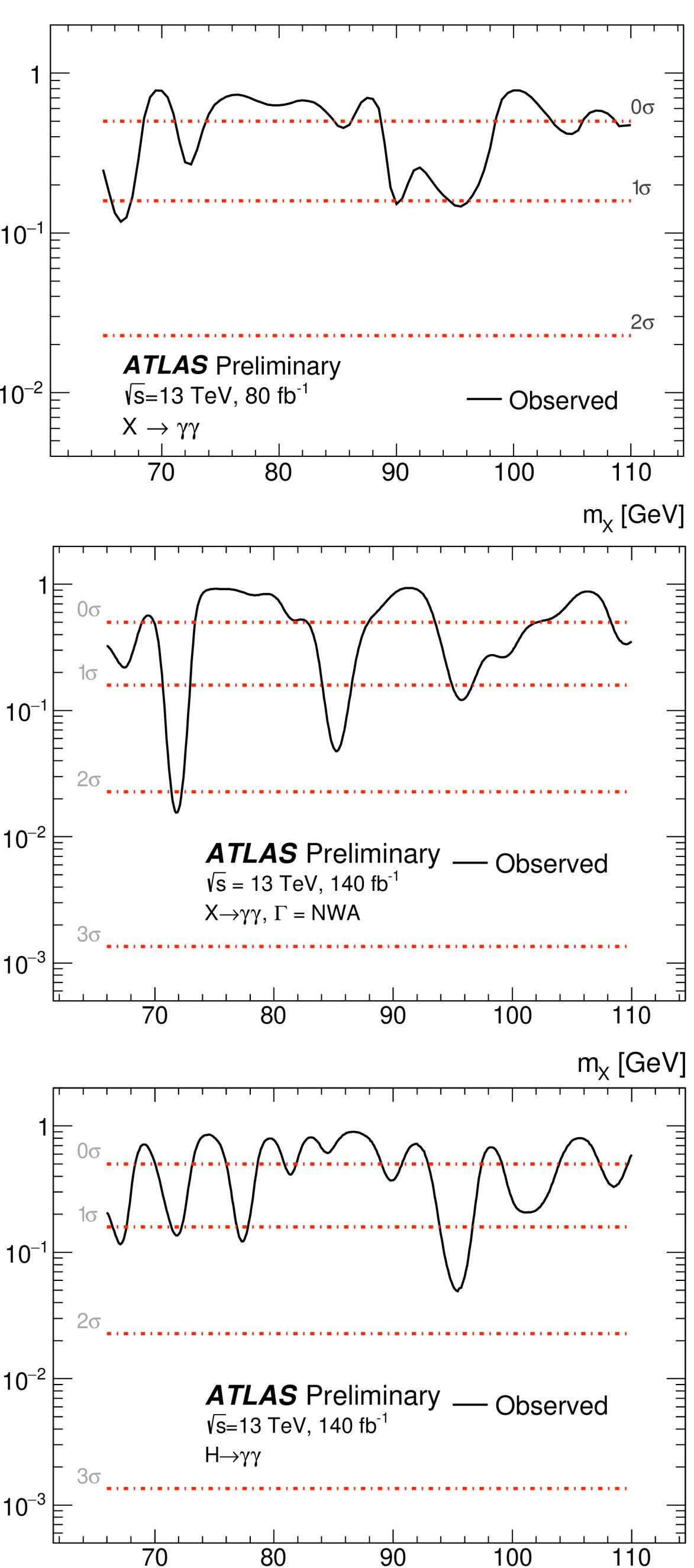


[ATLAS-CONF-2023-035](#)

- Events with 2 high energy photons, $E_T > 33 \text{ GeV}$
- Photon isolation
- e/γ BDT classifier, large $Z \rightarrow ee$ background rejection (90% fake rejection)
- $\gamma\gamma$ conversion categories: converted and unconverted (UU, UC/CU, CC)
- Use BDT di-photon classifier, 9 categories
- Signal modeling: Double-Sided Cristal Ball
- Background:
 - Non-resonant: Irreducible $\gamma\gamma$ shape from MC, Reducible jets faking photons $\gamma j + jj$ shape from MC, reweighting in CR
 - Resonant: $Z \rightarrow ee$ modeling by DSCB, shape from di-electron data, normalization from $e \rightarrow \gamma$ fake rate from data
- Results: model independent and model dependent, correct for detector effects



Model independent
Model dependent



SM: WWW

[ATLAS STDM-2019-09, PRL \(2022\)](#)

- Dominant backgrounds:
 - $WZ + jets$: using normalization and 3 CRs for +0/1/2j
 - Fake/non-prompt leptons: DD method
 - γ conversion, charge-flip: DD method
 - Other: from MC
- Signal to background separation using BDT for $2l$ and $3l$ SRs
- Binned maximum likelihood fit in $2l, 3l$ SRs score and m_{lll} of CRs distributions to determine μ_{WWW}

	Post fit			
	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	3ℓ
WWW signal	28.4 ± 4.3	124 ± 19	82 ± 12	34.8 ± 5.2
WZ	81.1 ± 5.7	346 ± 22	170 ± 10	16.4 ± 1.5
Charge-flip	31.1 ± 7.3	19 ± 5	...	1.7 ± 0.4
γ conversions	60.8 ± 8.5	139 ± 15	...	1.5 ± 0.1
Nonprompt	17.0 ± 4.0	145 ± 23	104 ± 21	26.6 ± 2.9
Other	22.3 ± 2.4	100 ± 10	58 ± 6	8.0 ± 0.9
Total predicted	241 ± 11	873 ± 22	415 ± 17	89.0 ± 5.4
Data	242	885	418	79

