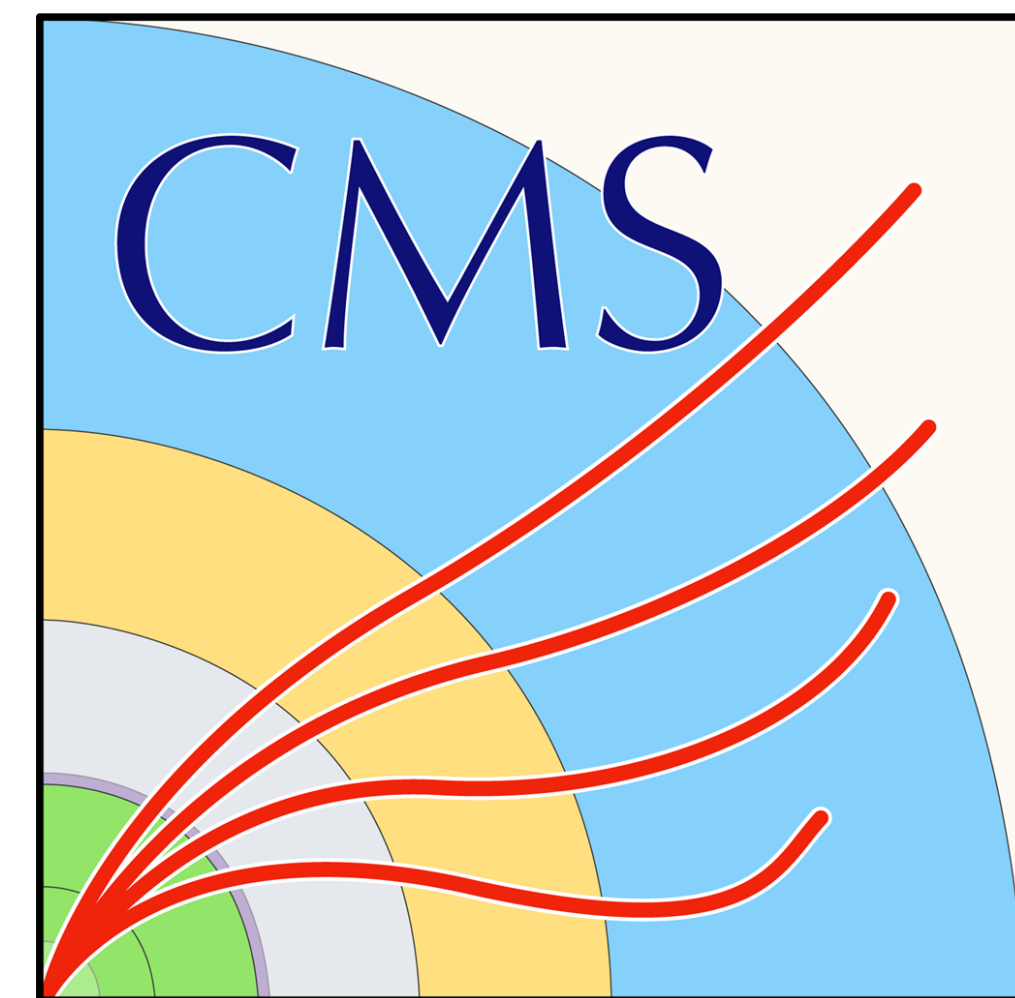


Beyond standard model searches: current status and prospects from the experiment side

Matteo Franchini on behalf of
the ATLAS and CMS collaborations



Introduction

- * The standard model (SM) is a highly predictive and well-tested theoretical framework that describes the electroweak and strong interactions
- * However, fundamental questions are left unanswered in the SM
- * Extensions of the SM are commonly referred to as new physics
- * As new physics has not been discovered (yet), searching for it becomes more and more challenging...
- * ... which boosts the creation of innovating ideas!

LHC experiments has established a rich program for searches for new physics

(not exhaustive) Overview of latest results!

- * BSM H/A \rightarrow tt [[ATLAS-CONF-2024-001](#)]
- * A \rightarrow ZH \rightarrow lltt [[CMS-PAS-B2G-23-006](#)]
- * A \rightarrow ZH \rightarrow 4l+jj/MET [<https://arxiv.org/abs/2401.04742>]
- * H/A \rightarrow 4top [[ATLAS-CONF-2024-002](#)]
- * HNL via WW scattering in ee, e μ final states [[EXOT-22-019](#)]
- * HNL in final states with e, μ , hadronic τ [[EXOT-22-011](#)]
- * Search for heavy long-lived charged particles [[CMS-PAS-EXO-18-002](#)]
- * light LLP with displaced vertices [[2403.15332](#) **[hep-ex]**]
- * LQ pair \rightarrow b μ b μ [[CERN-EP-2023-301](#)]
- * 3rd gen. LQ pair production [[CERN-EP-2023-288](#)]
- * Combination of heavy spin-1 resonances [[EXOT-2022-38](#)]
- * High-mass reso \rightarrow τ +MET [[EXOT-2018-37](#)]
- * Search for a resonance decaying to $W\gamma$ [[PAS-EXO-21-017](#)]
- * Search for resonances decaying to HH [[CERN-EP-2024-062](#)]
- * Mono-top [[EXOT-2022-40](#)]
- * Search for mass-degenerate Higgsinos [[2401.14046](#) [hep-ex]]
- * Model-agnostic search with dijet resonances [[CMS-PAS-EXO-22-026](#)]

HDMS

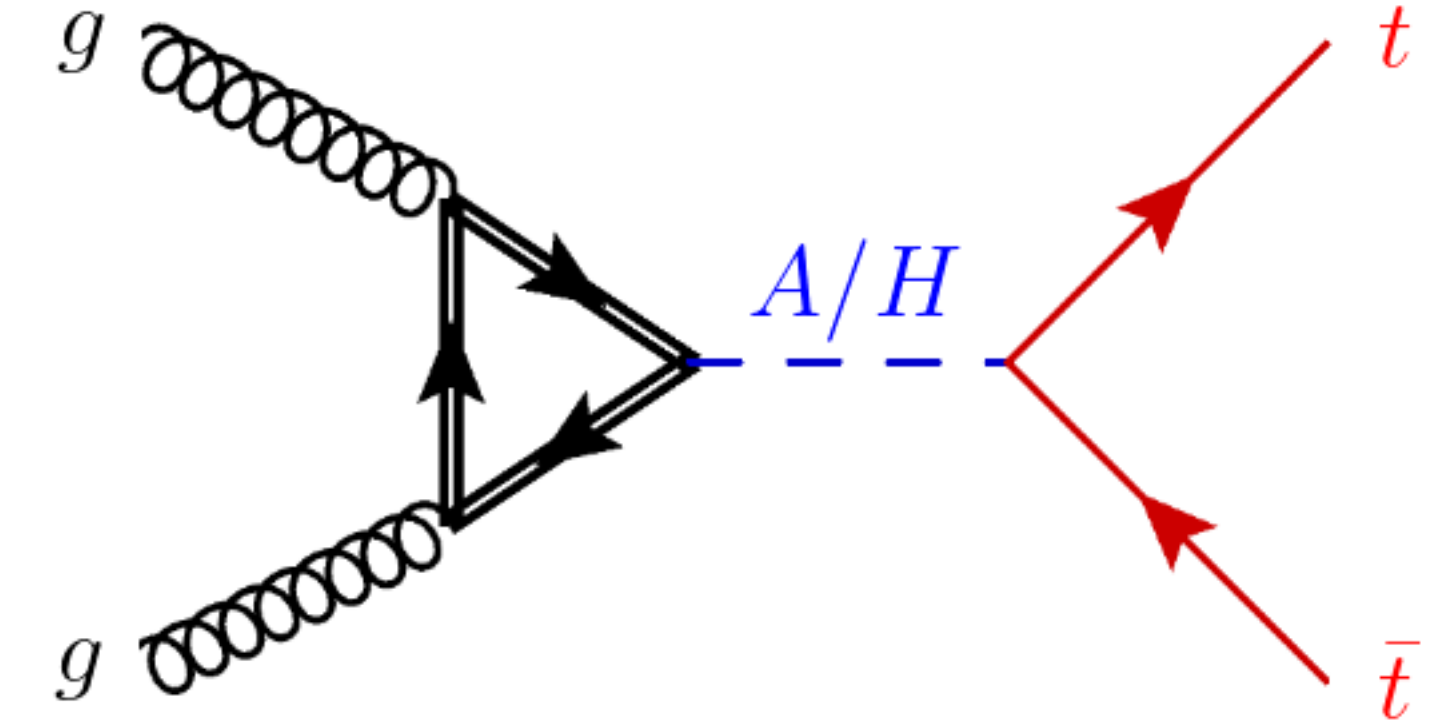
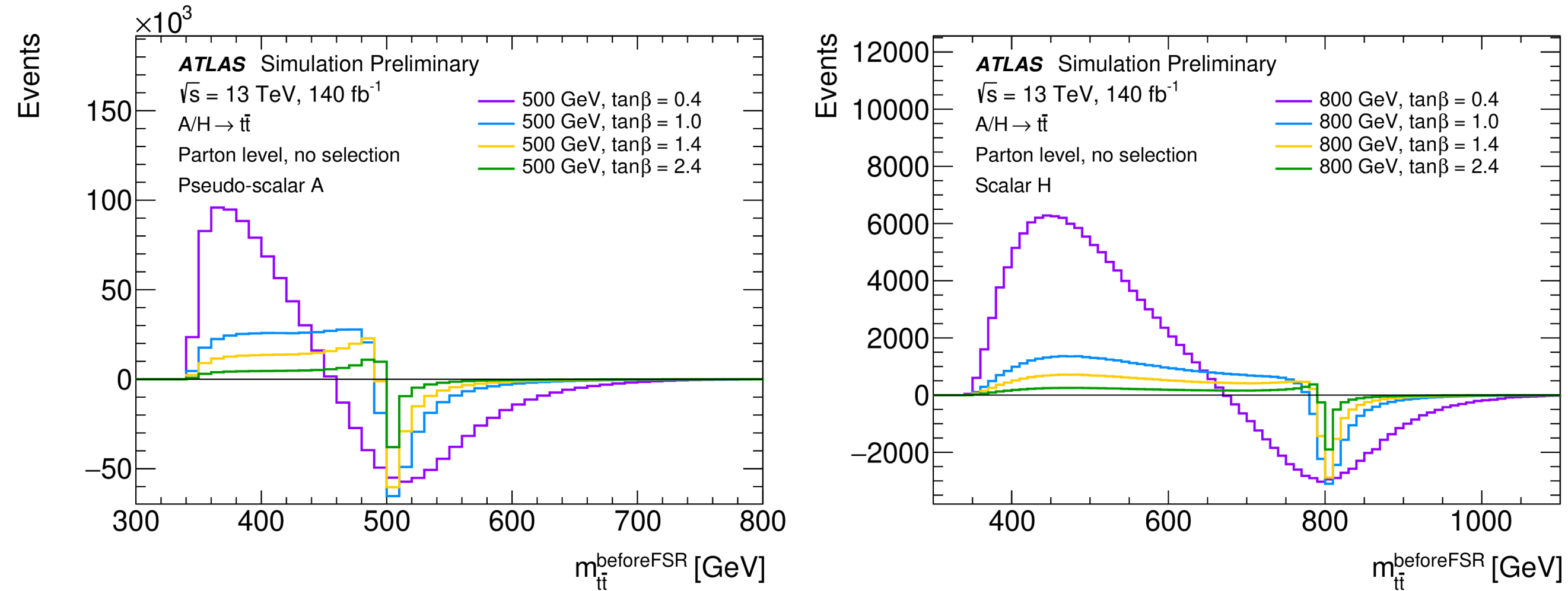
BSM H/A → tt

EXOT-2020-25

* Extensions to the SM Higgs sector can introduce additional fields that produce additional Higgs bosons.

• Two Higgs Doublet Model (2HDM, e.g. MSSM)

* Large interference effects with SM background.

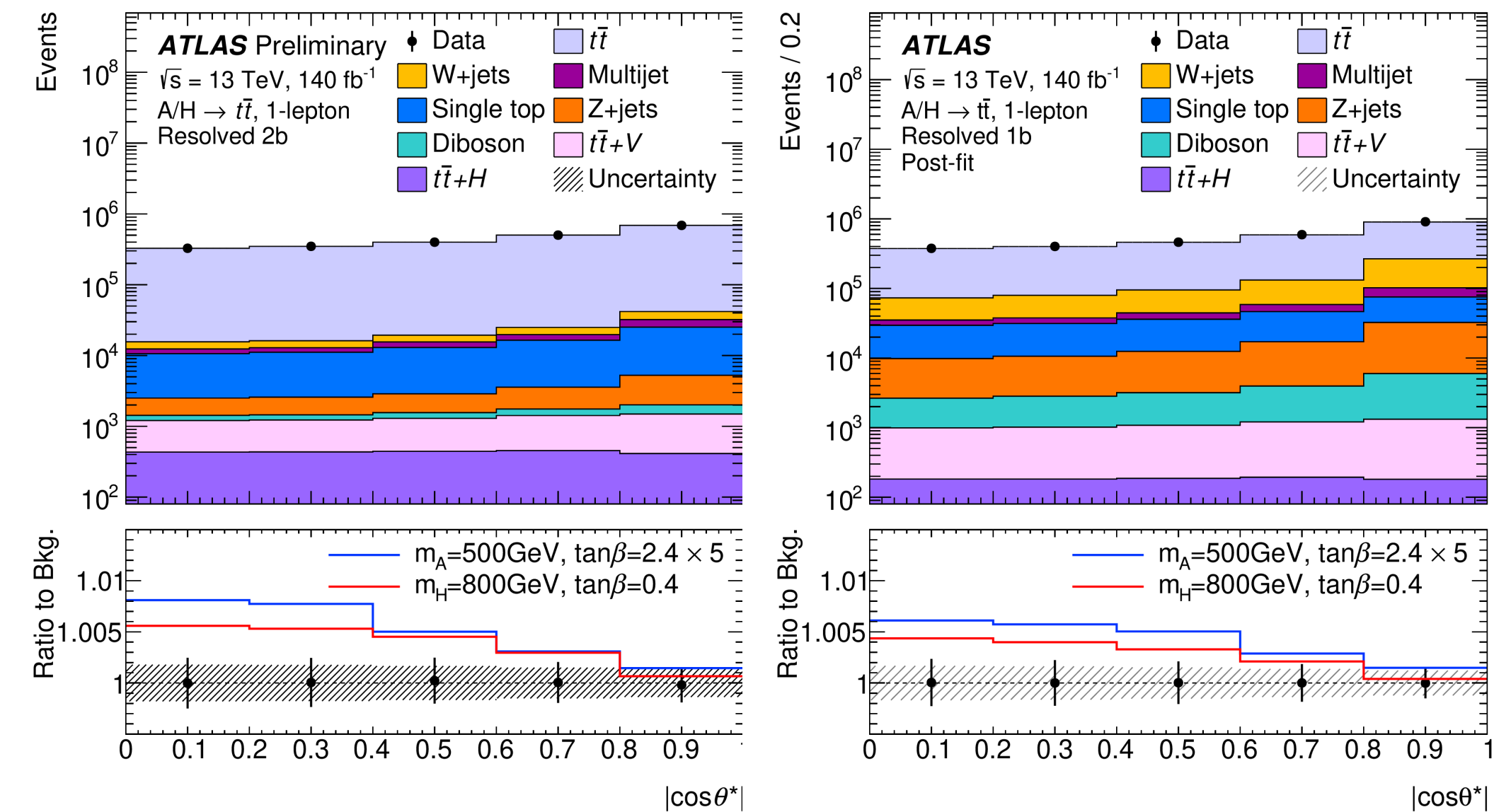


* Use resolved and merged b-jet categories as well as 1 and 2 lepton final states.

* The resolved events with 1-lepton are categorised in $\cos(\theta^*)$ and # b-jet bins.

* The 2-lepton events are categorised in $\Delta\phi_{ll}$ bins.

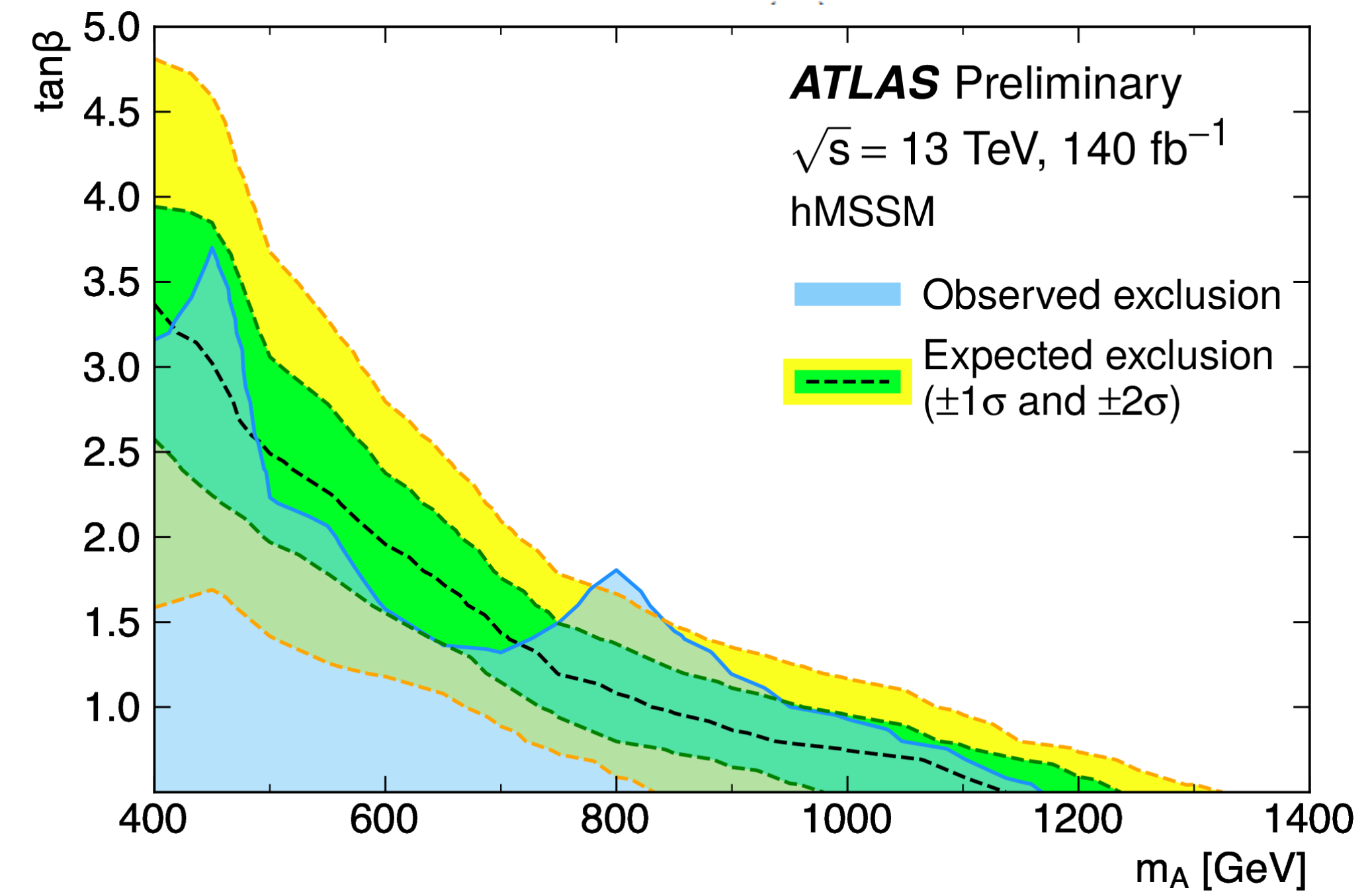
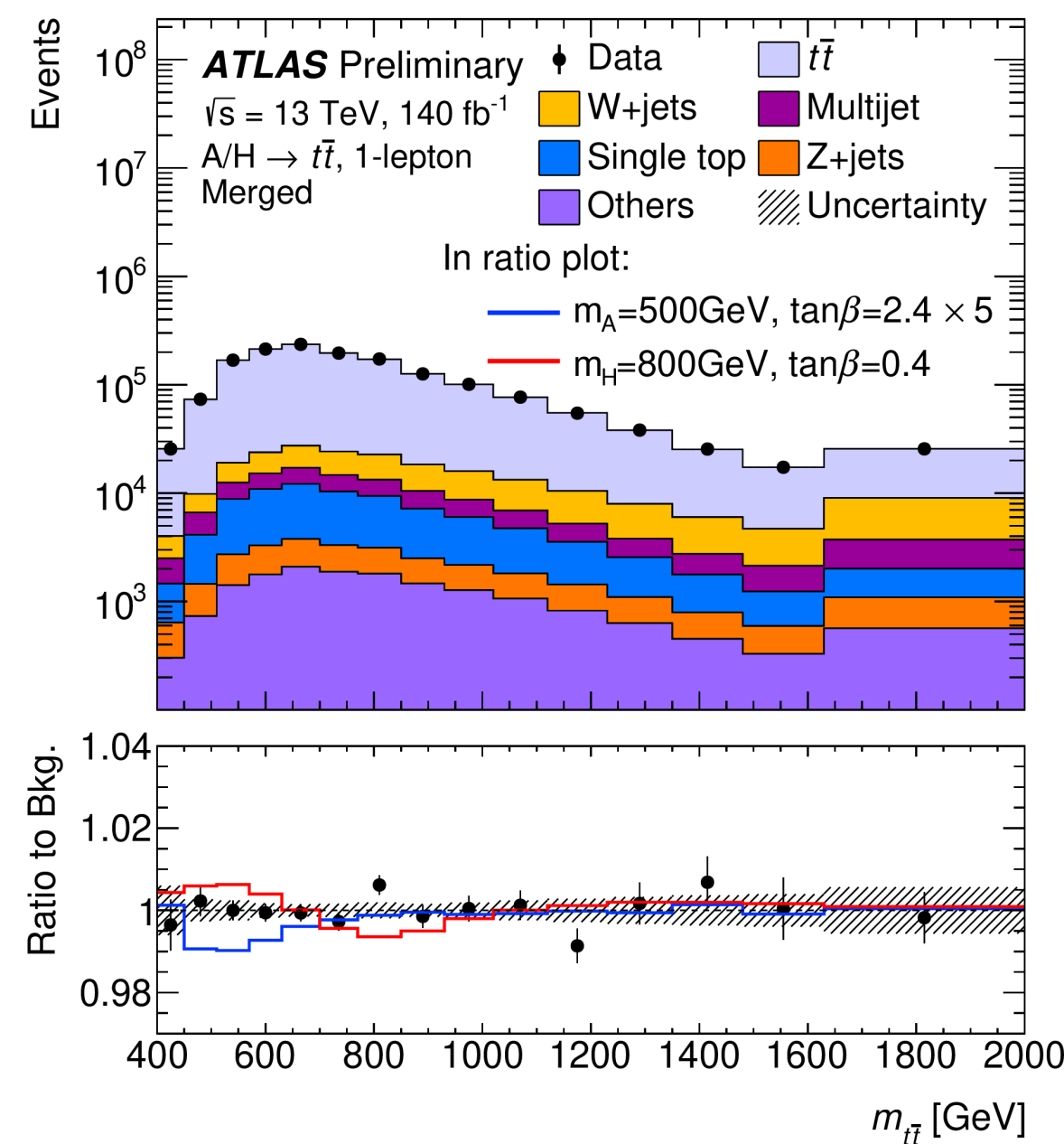
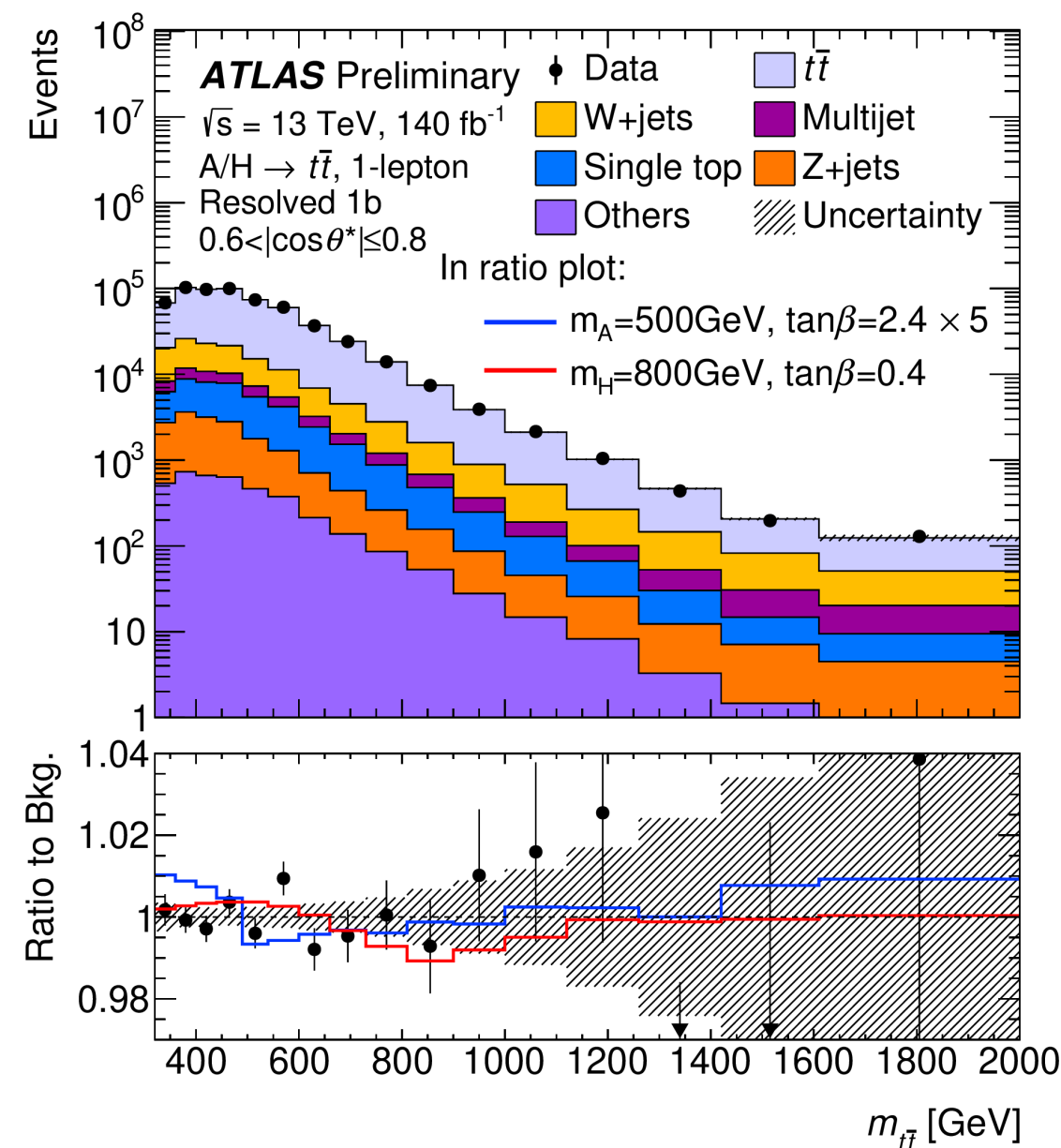
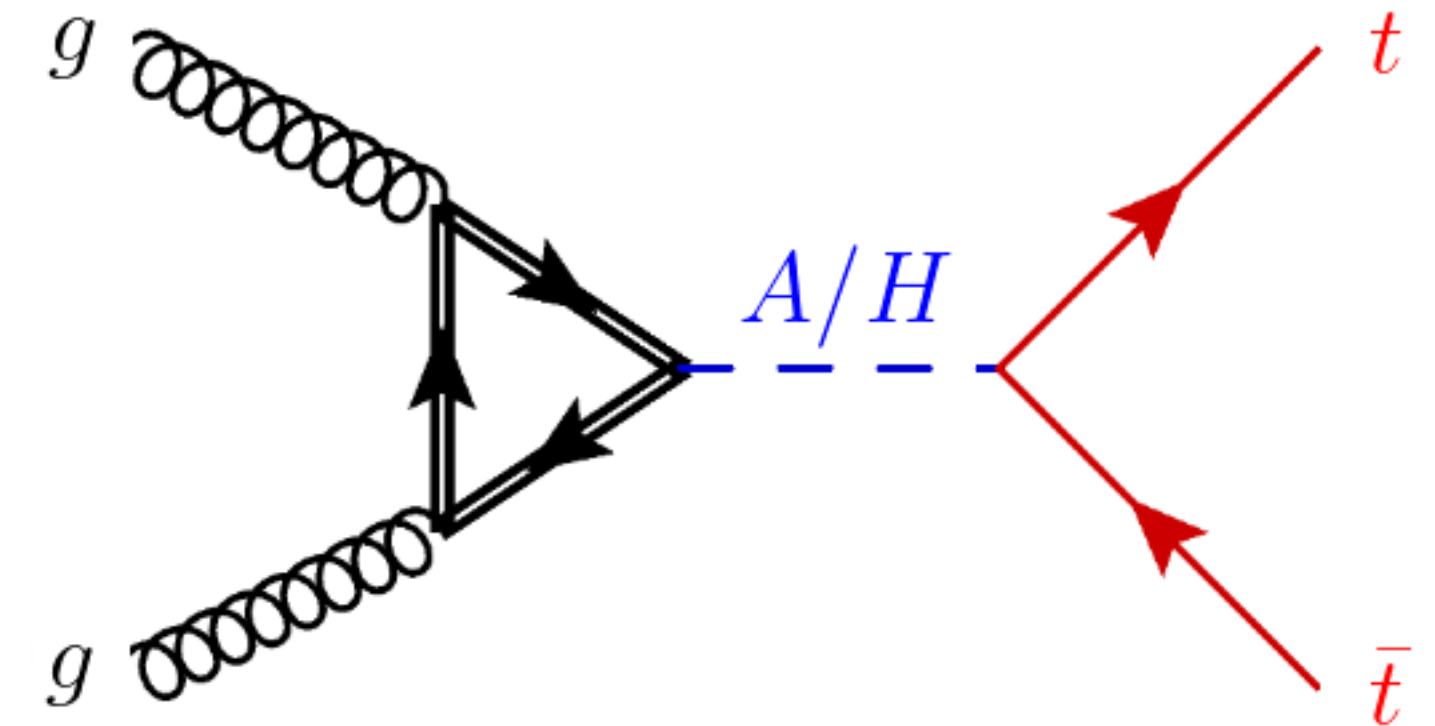
* Reconstructed H/A mass is used as the final discriminator.



BSM H/A \rightarrow $t\bar{t}$

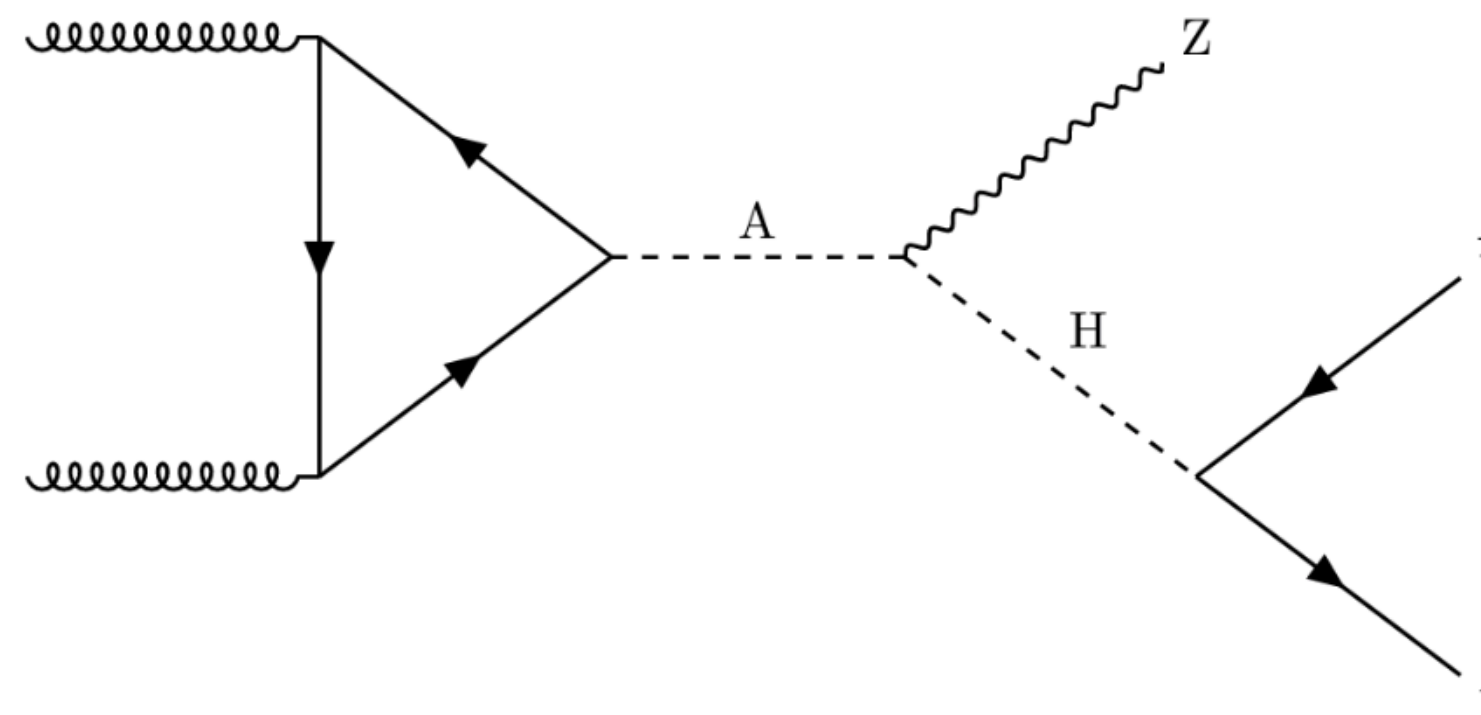
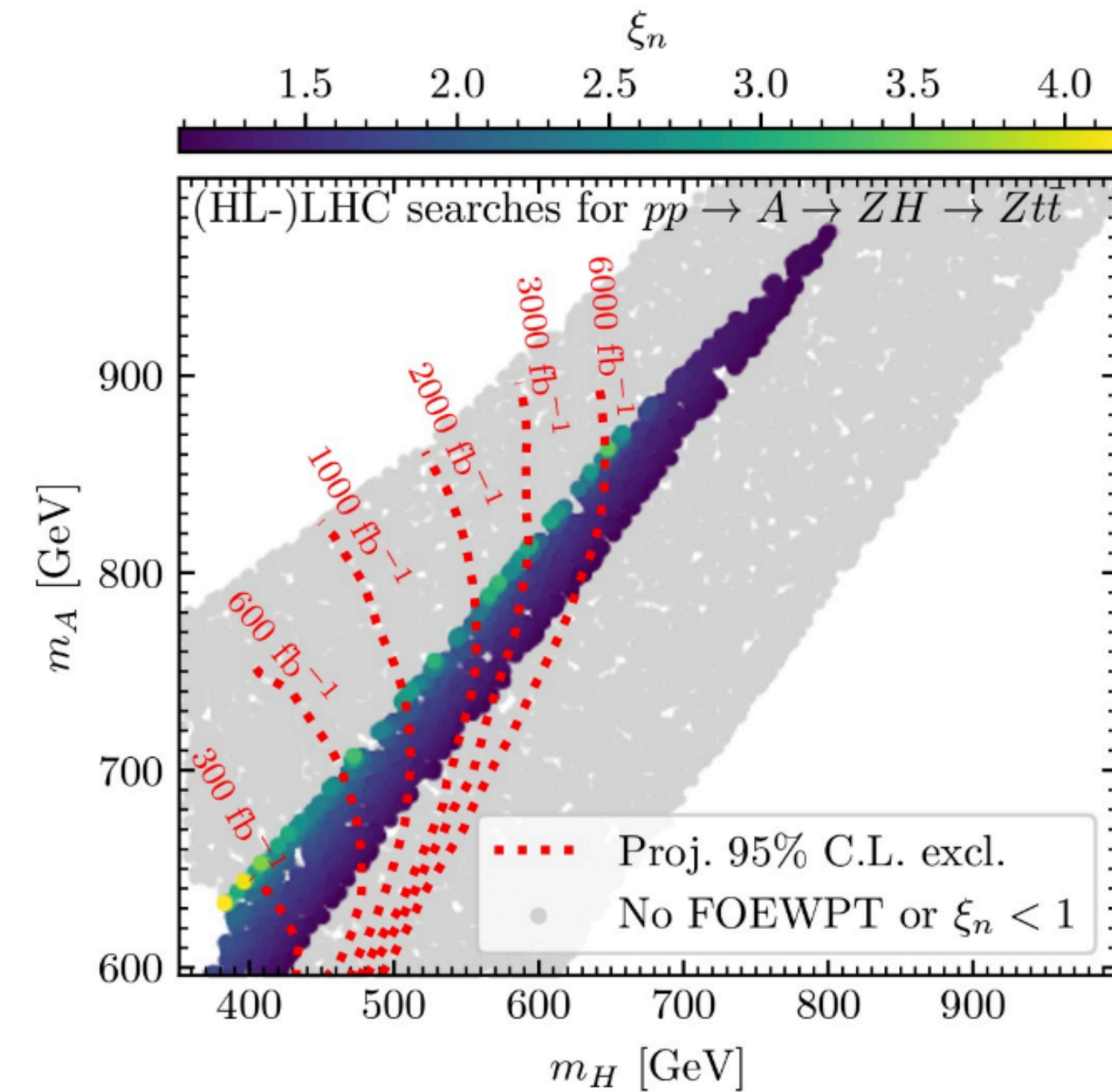
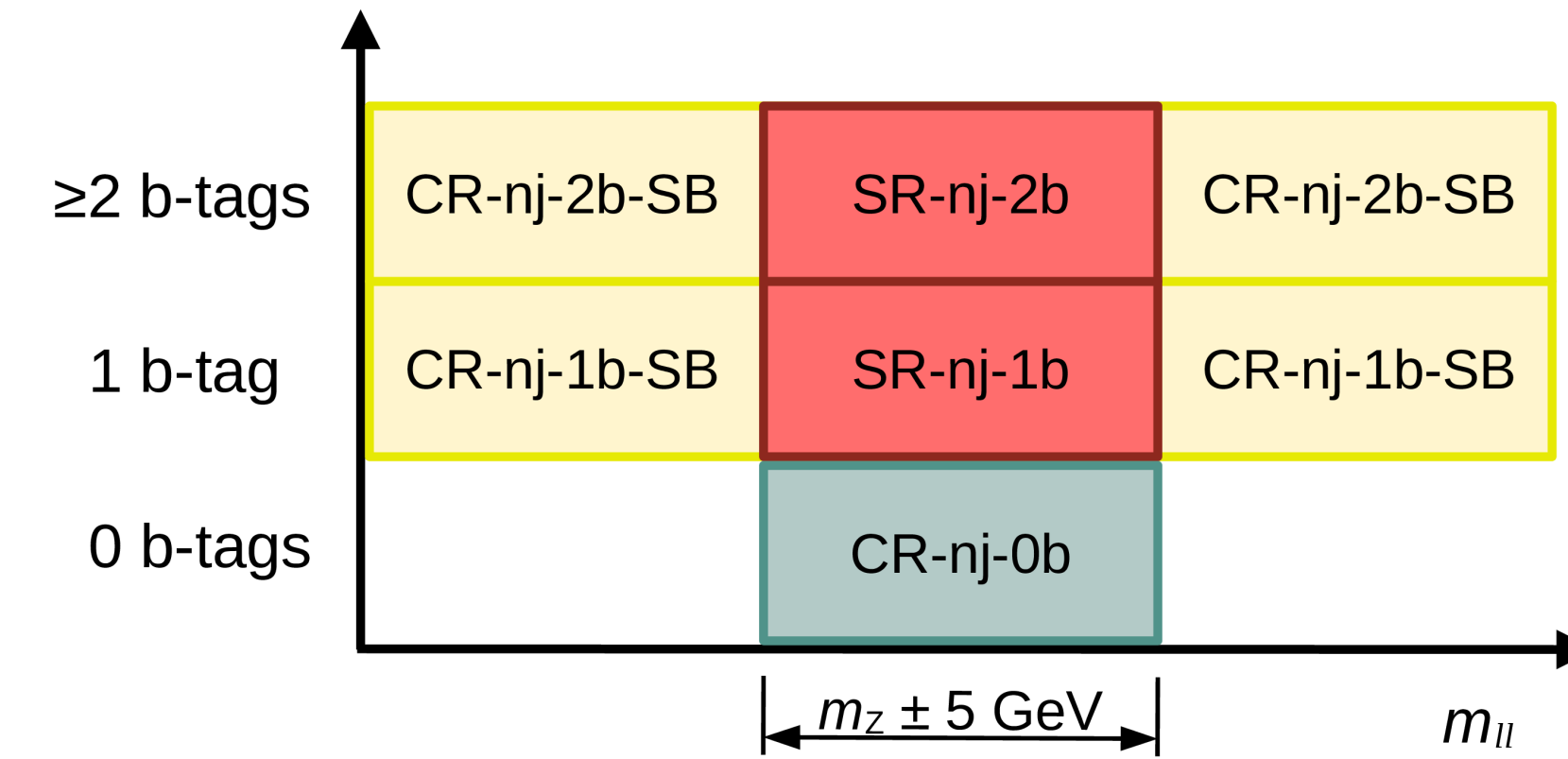
EXOT-2020-25

- * Results showed no statistically significant fluctuation away from the SM expectation.
- * Small deviation was observed at 800 GeV with a local significance of 2.3σ .
- * hMSSM exclusion limits range from $\tan\beta$ at 3.5 to 0.5 for A masses between 400 GeV and 1.1 TeV.

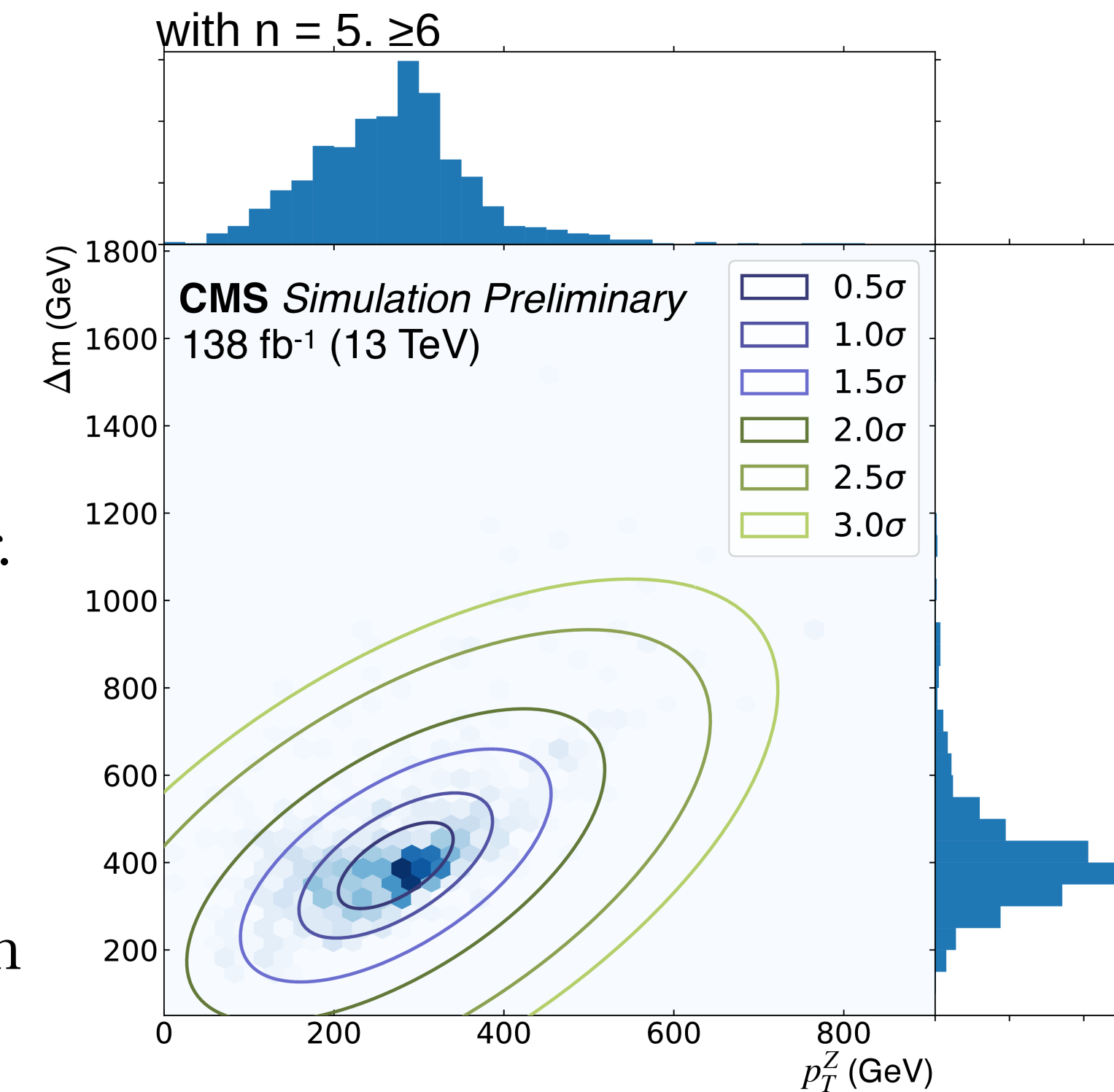


A → ZH → tt

* Possible “Smoking gun” channel for first-order electroweak phase transition in the 2HDM.



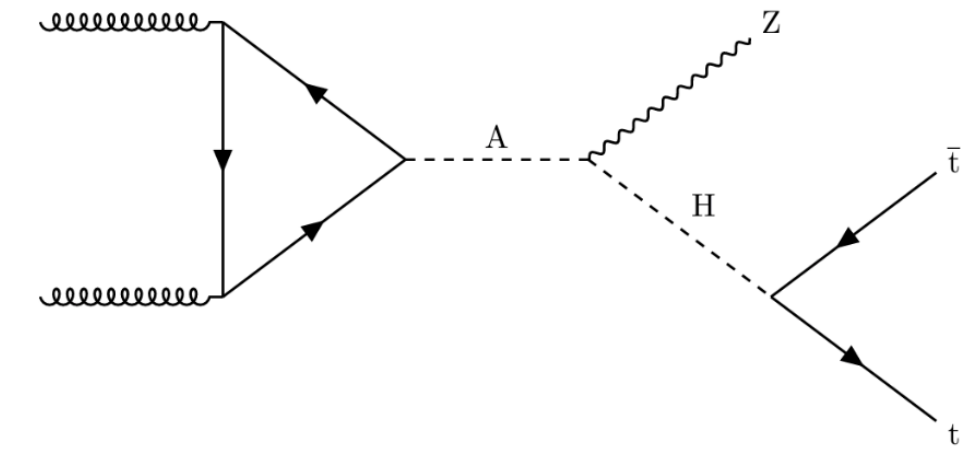
- * Use fully hadronic decays of the top quark pair.
- * The analysis uses signal categories binned in the number of jets and b-jets.
- * As a final discriminator, an unrolled distribution of p_T^Z and Δm is used.



$$\Delta m = m_{t\bar{t}Z} - m_{t\bar{t}} \approx m_A - m_H$$

Thomas Biekötter et al JCAP03(2023)031

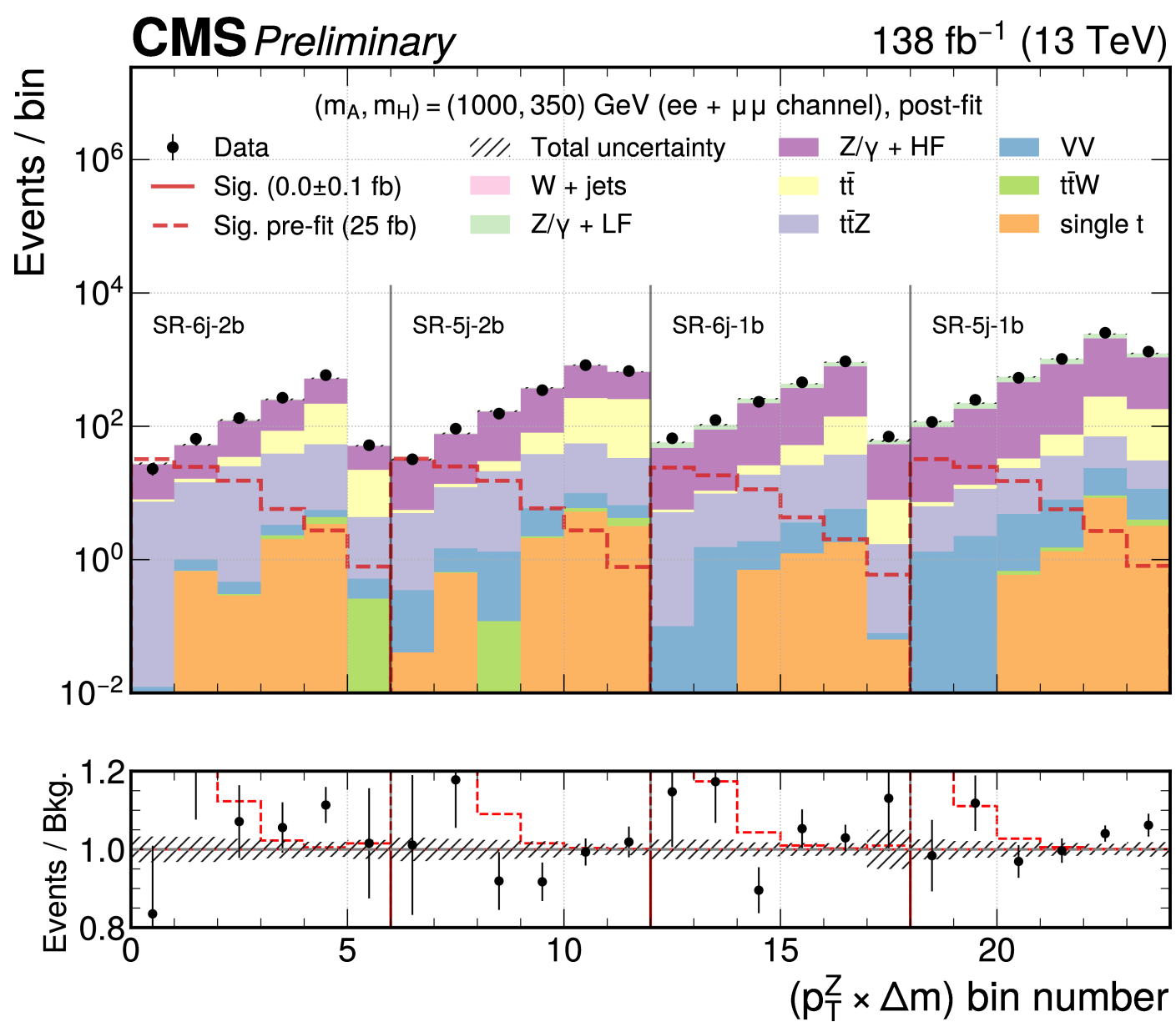
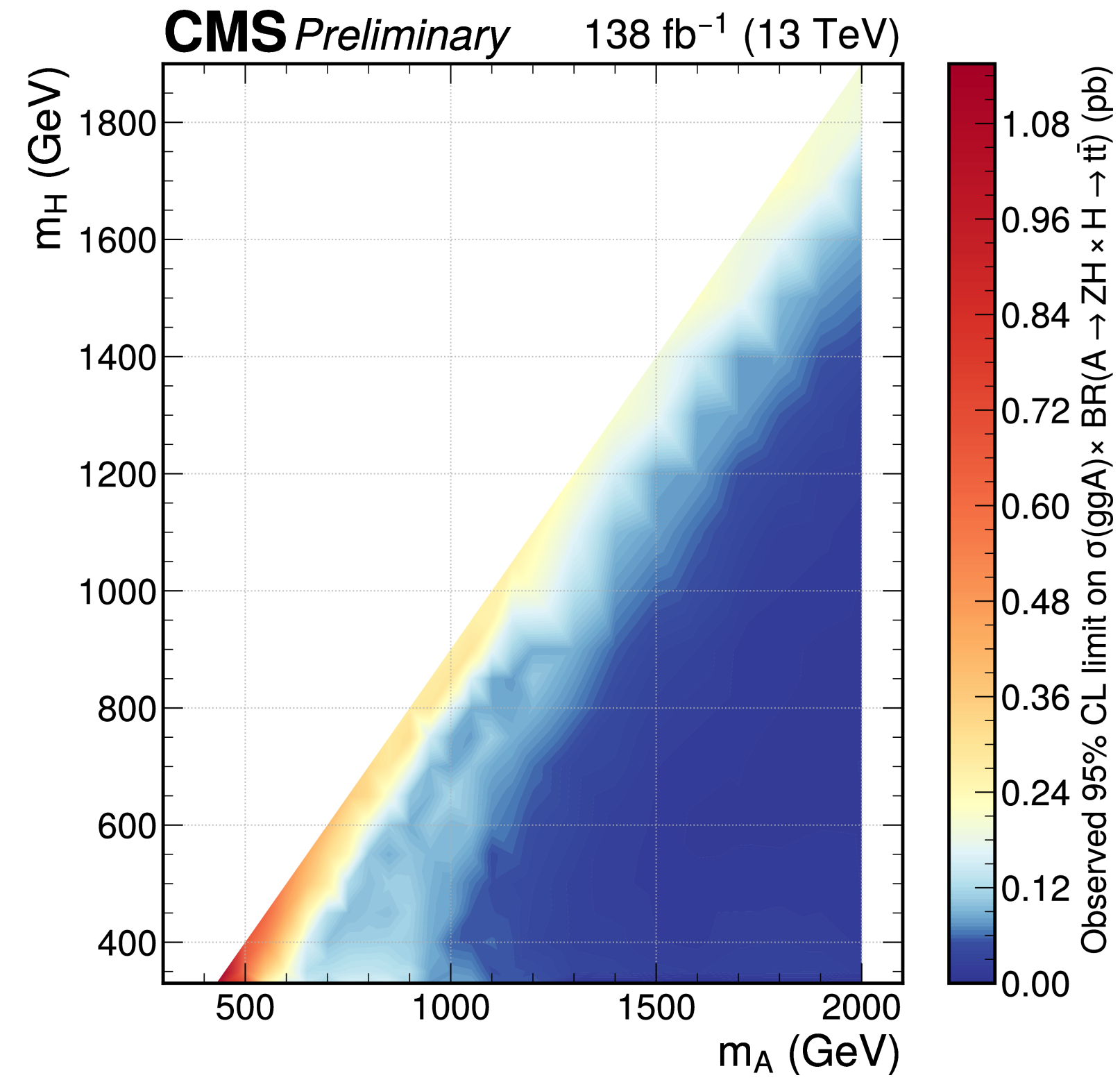
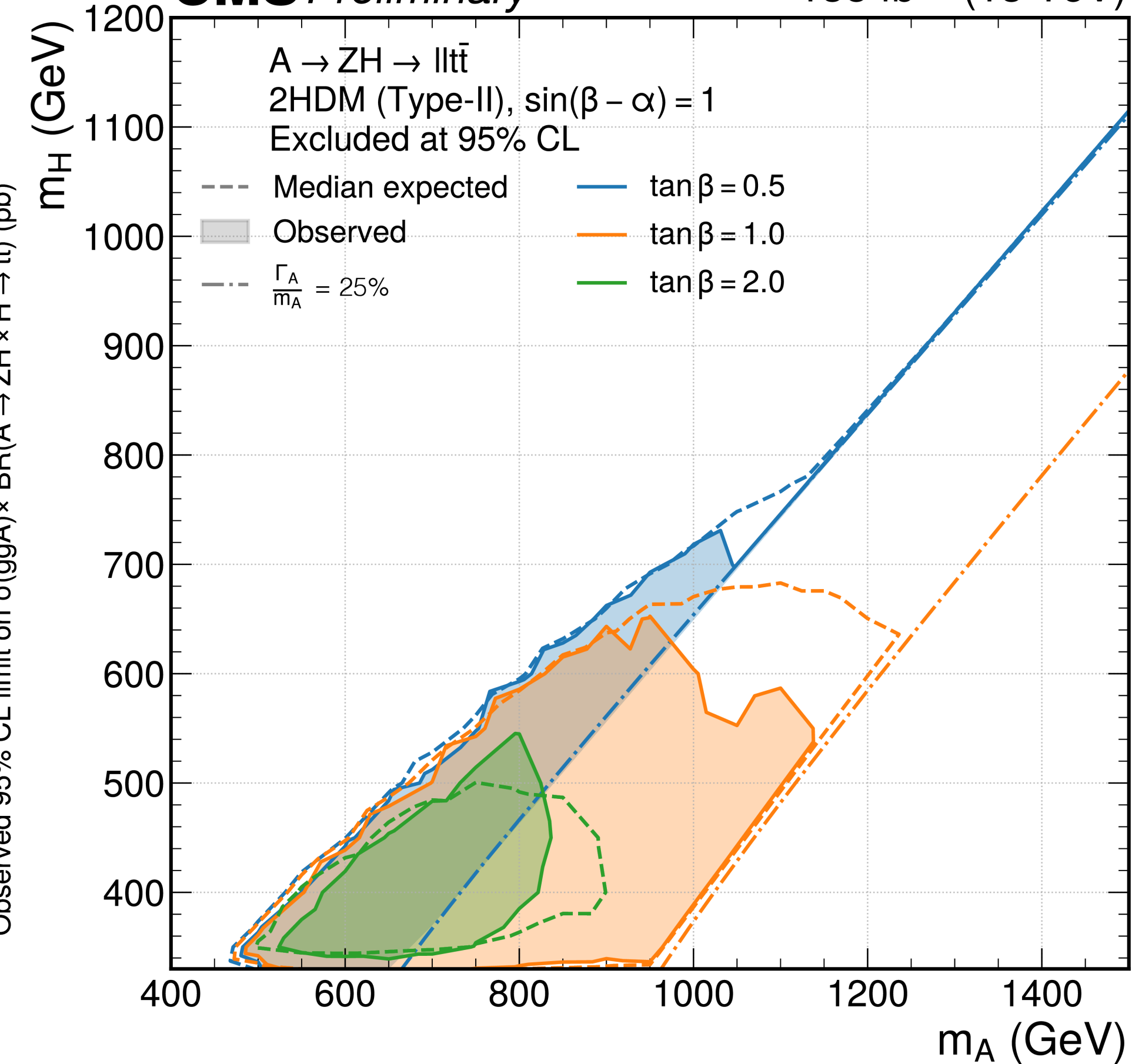
A → ZH → llt \bar{t}



* No statistically significant deviation from the SM expectation was observed.

* Type II 2HDM exclusions limits set at low $\tan\beta$ values.

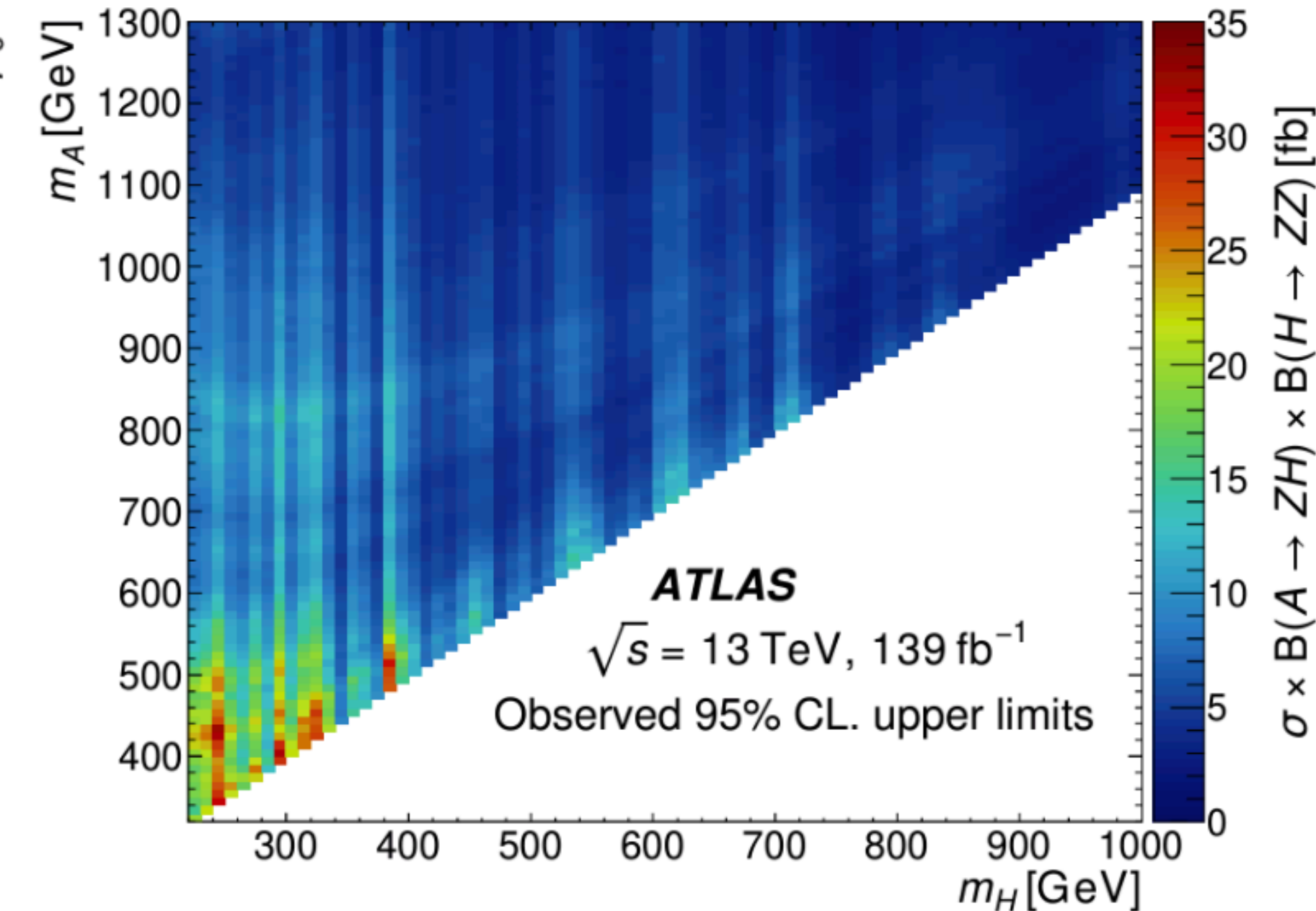
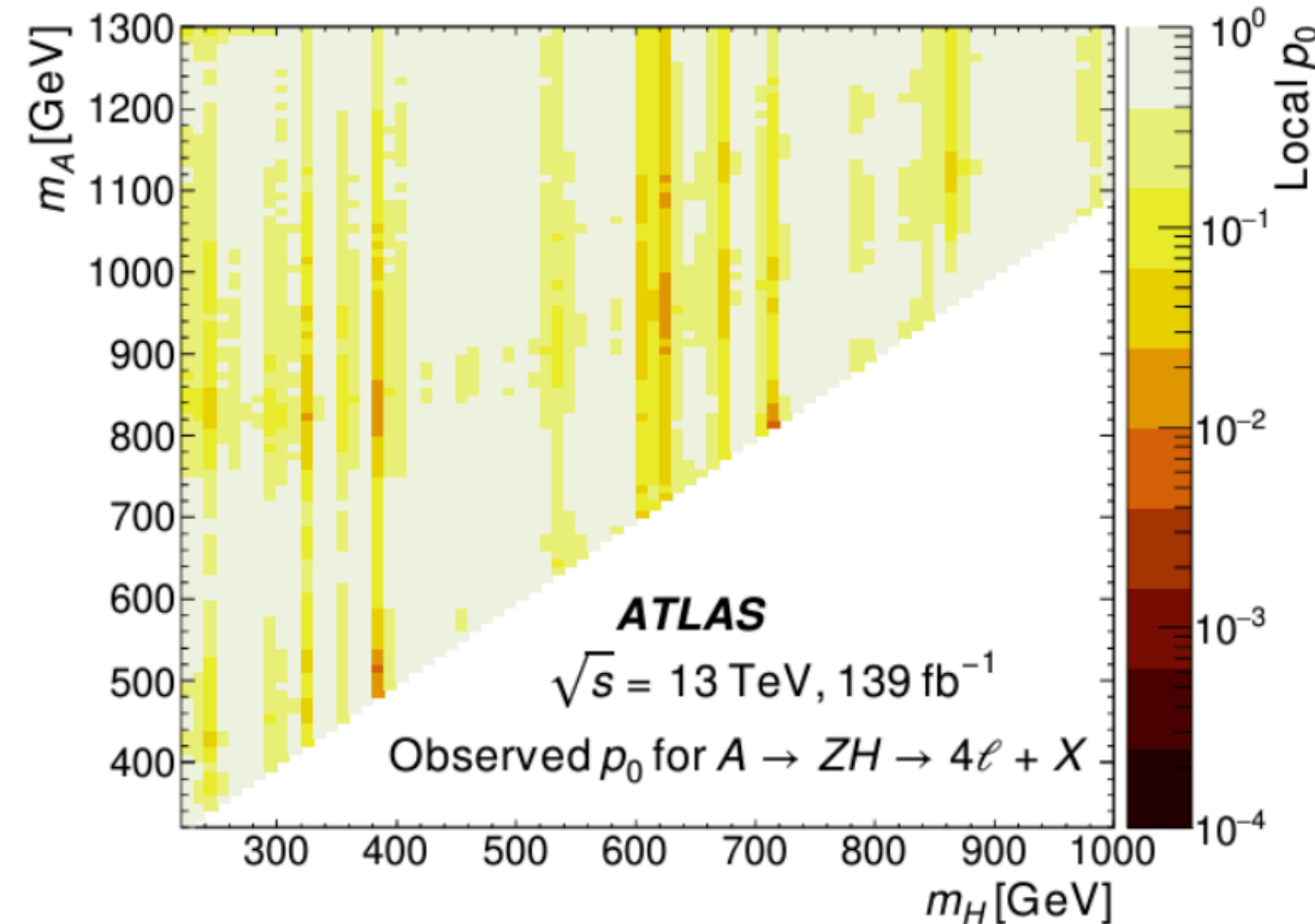
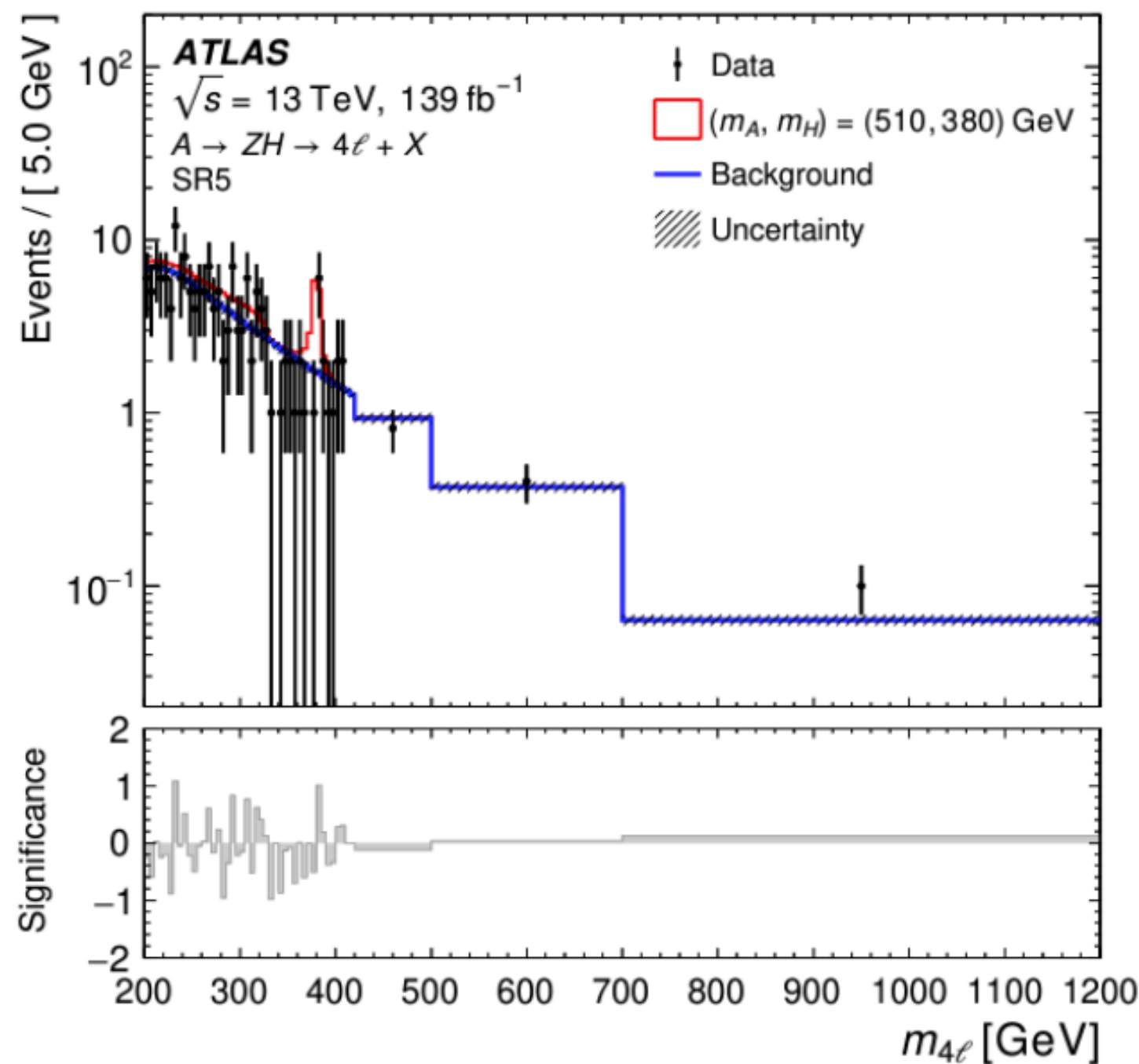
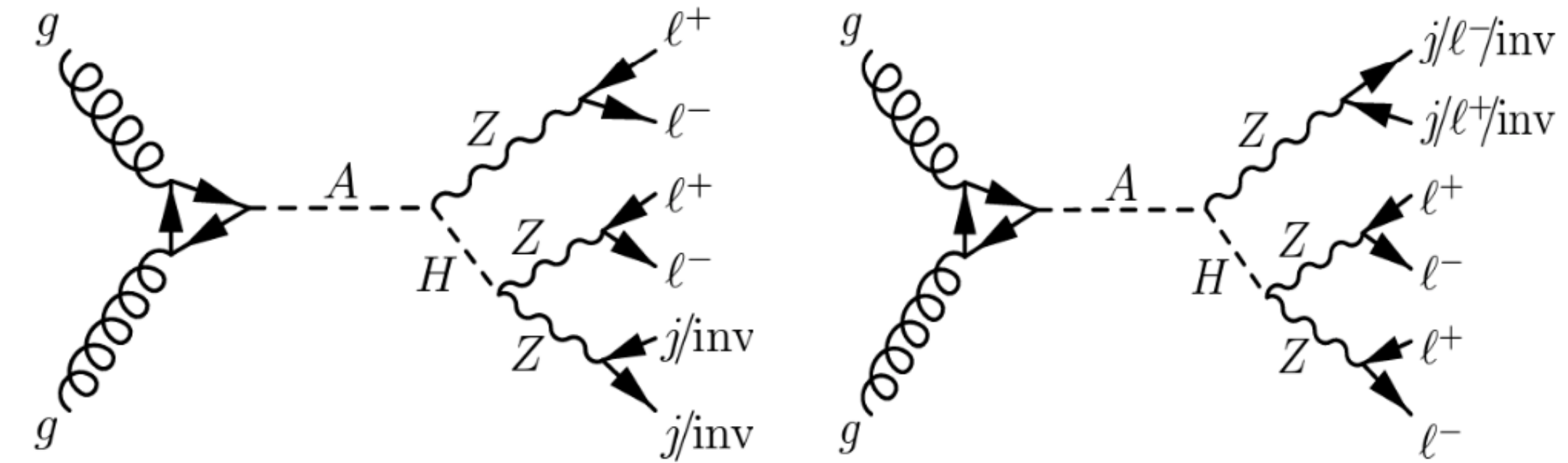
CMS Preliminary 138 fb⁻¹ (13 TeV)



ATLAS - $A \rightarrow ZH \rightarrow 4\ell + j\bar{j}/\text{MET}$

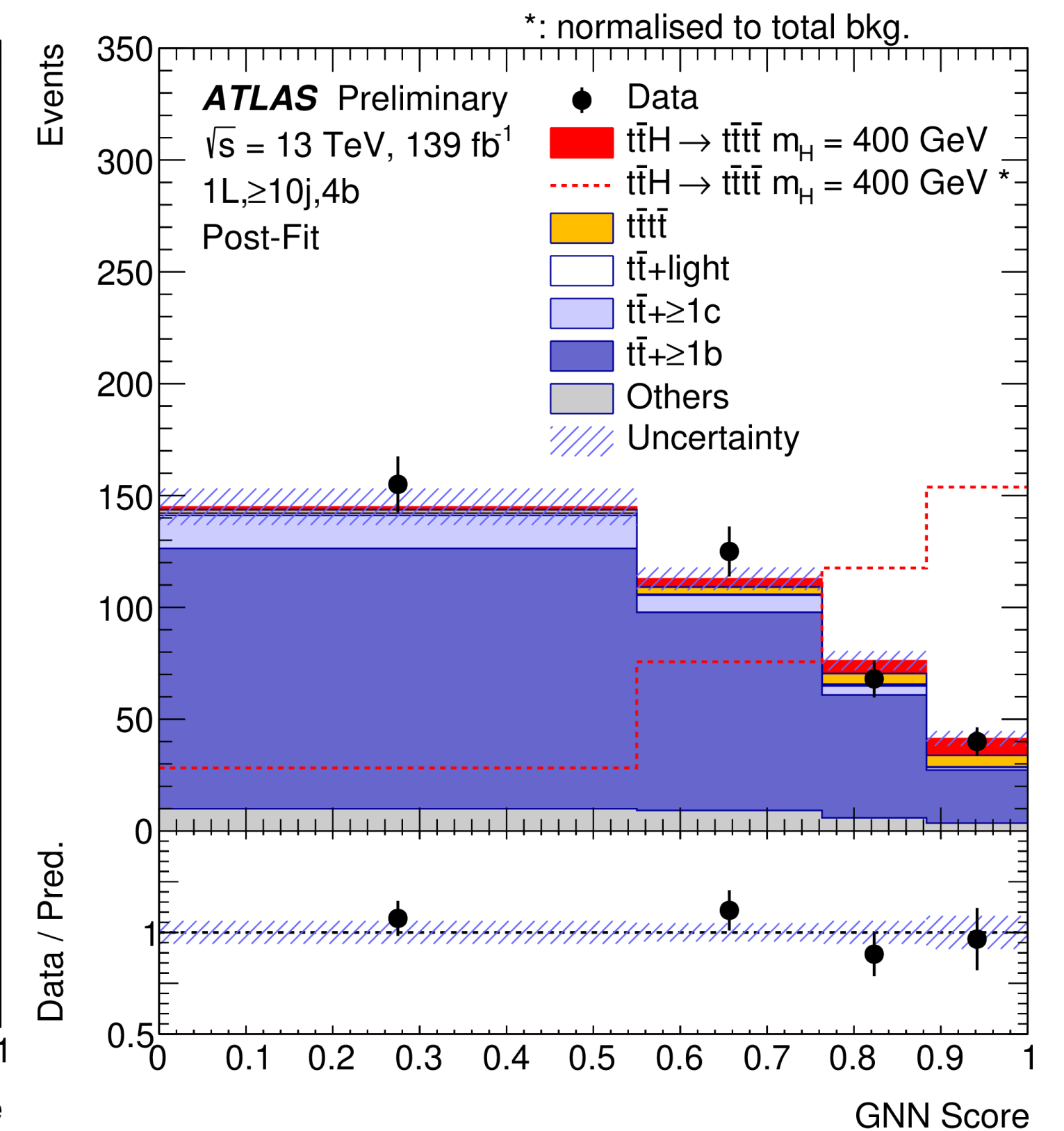
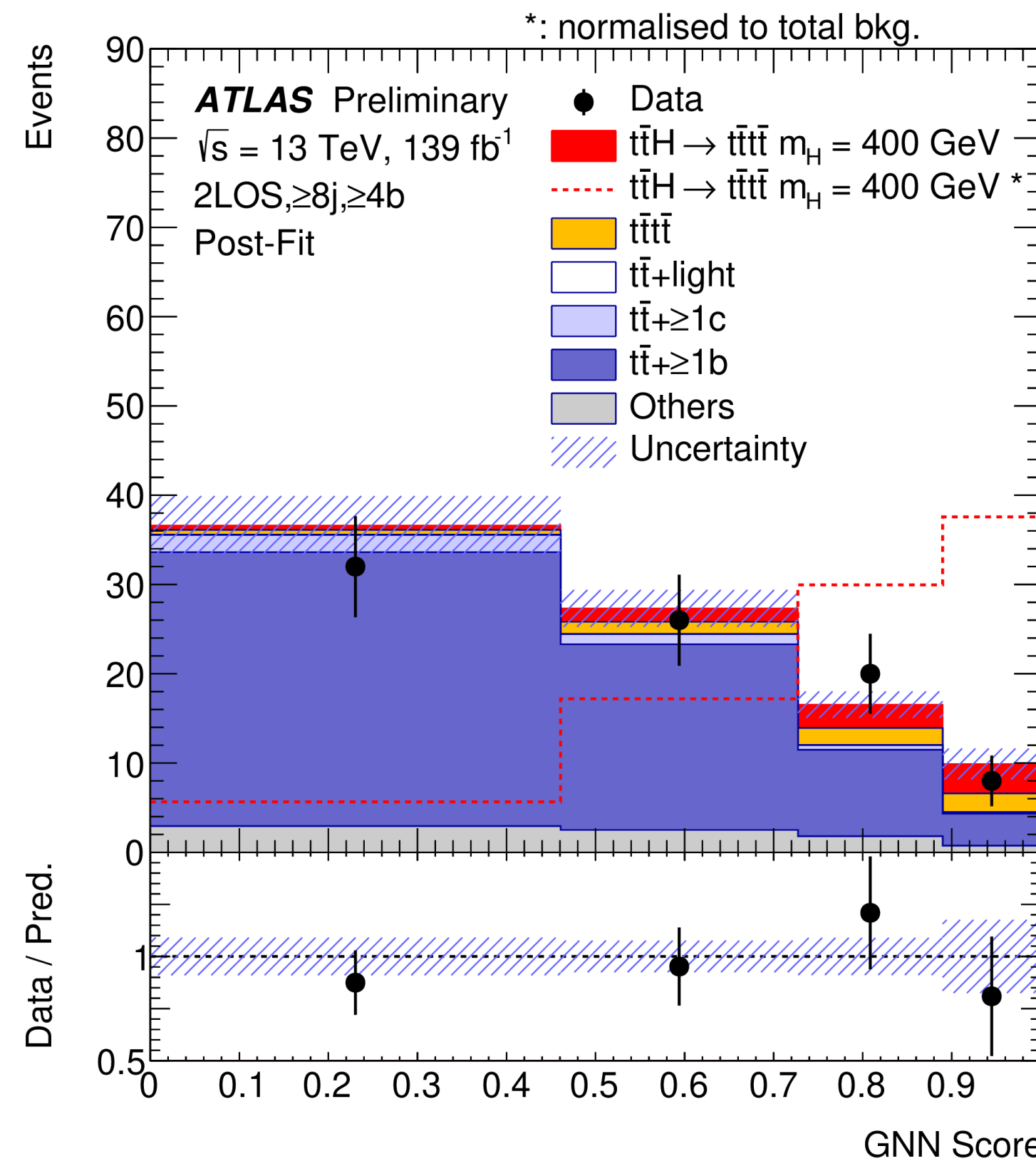
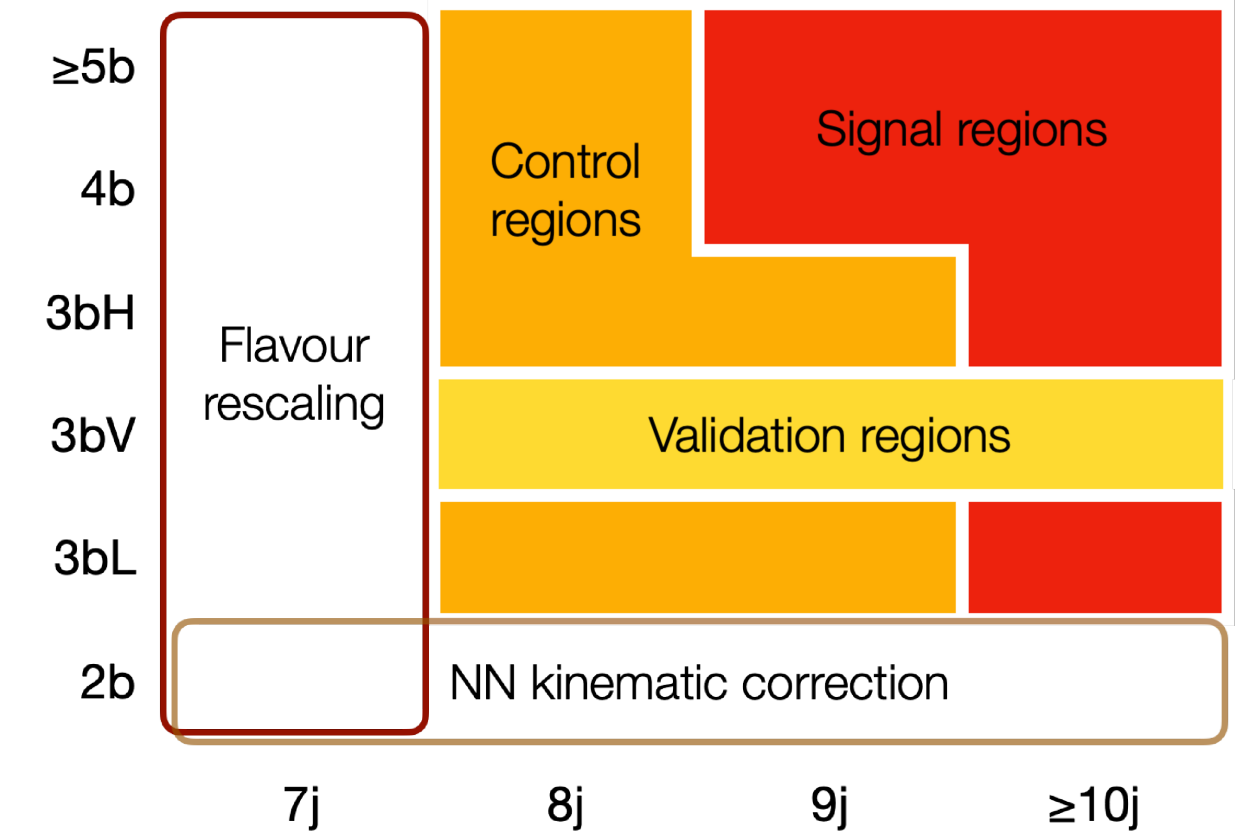
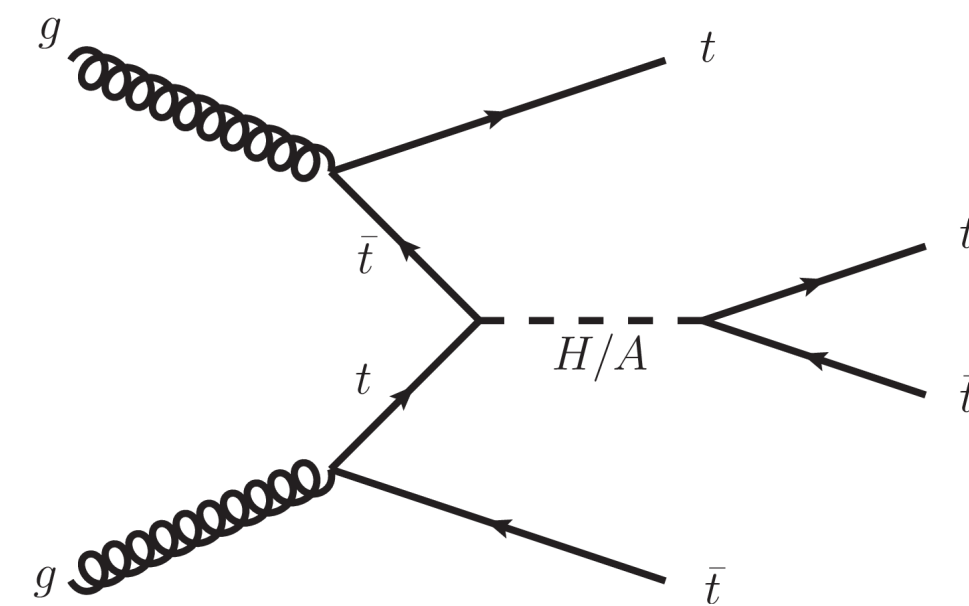
<https://arxiv.org/abs/2401.04742>

- * Motivated by the 2HDM and 2HDM+S.
- * Targets final states with 4 leptons (either from the Z or H) and one of two jets or some missing energy.
- * Search fits the 4-lepton mass spectrum with various categories to target the other final state object/MET.
- * No significant deviation is observed.



ttH/A \rightarrow 4top

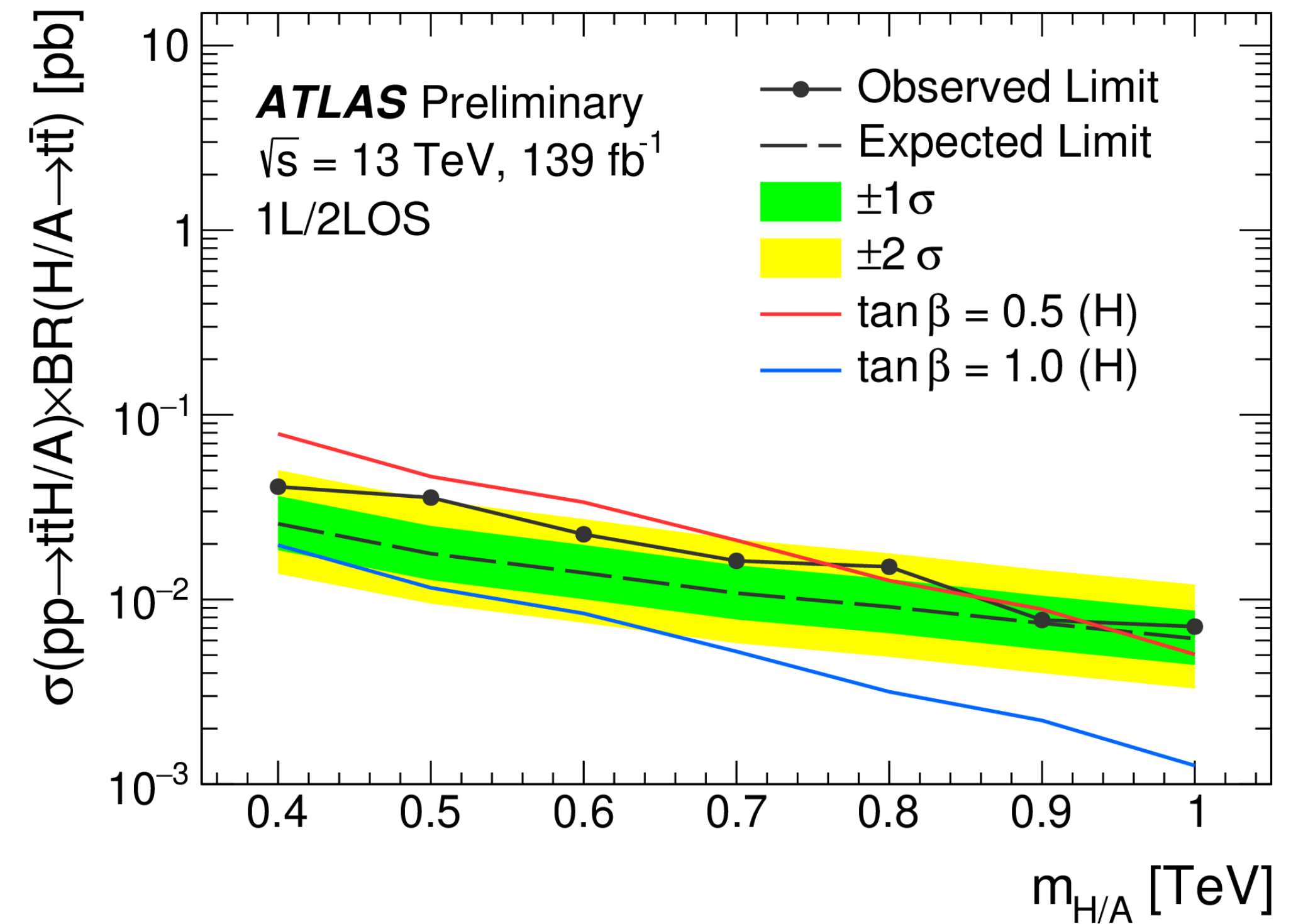
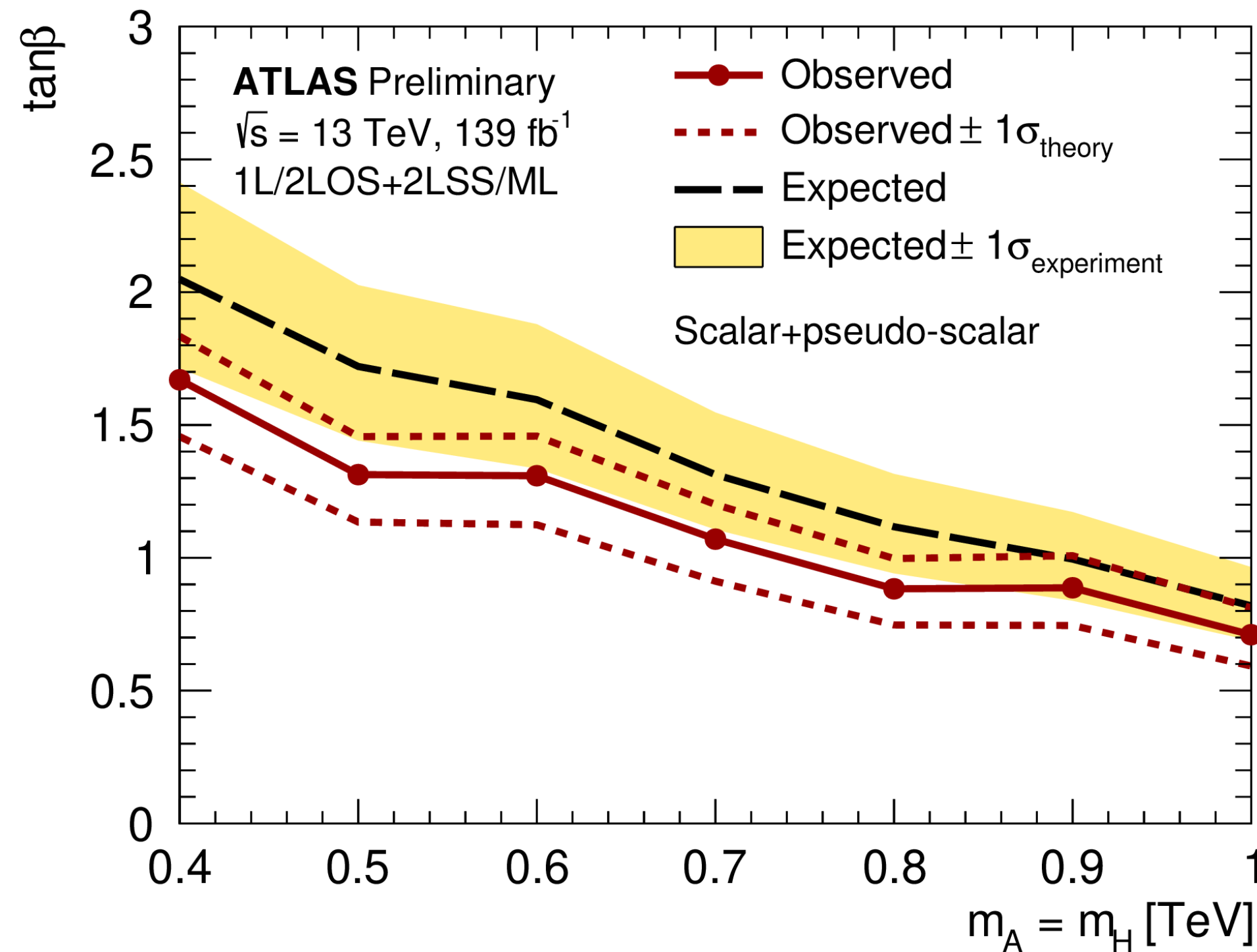
- * Heavy scalar (H) or pseudo-scalar (A) predicted by the Two-Higgs-Doublet-Model (2HDM)
- * Data-driven corrections applied to improve tt+jets modelling in high jet and b-jet multiplicities regime
- * Parametrised Graph Neural Network is trained to optimise the signal-to-background discrimination



H/A \rightarrow 4top

ATLAS-CONF-2024-002

- * Limits evaluated with respect to $\tan\beta$ VS $m(A/H)$
- * Results also used to constrain a model predicting pair production of a colour-octet scalar excluding $m(T) < 1.5\text{TeV}$
- * combination with a SSML search published before has been performed : <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2019-26>

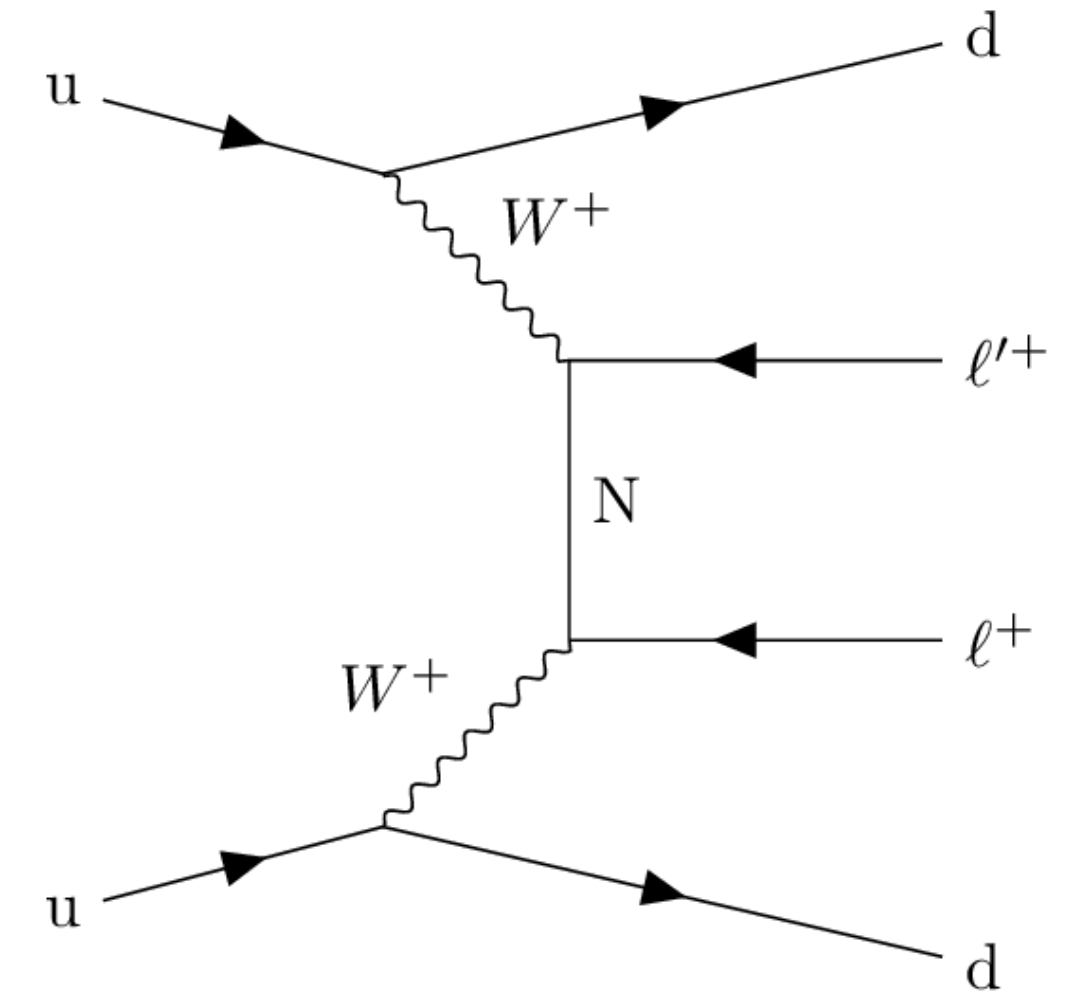


Heavy Neutrino

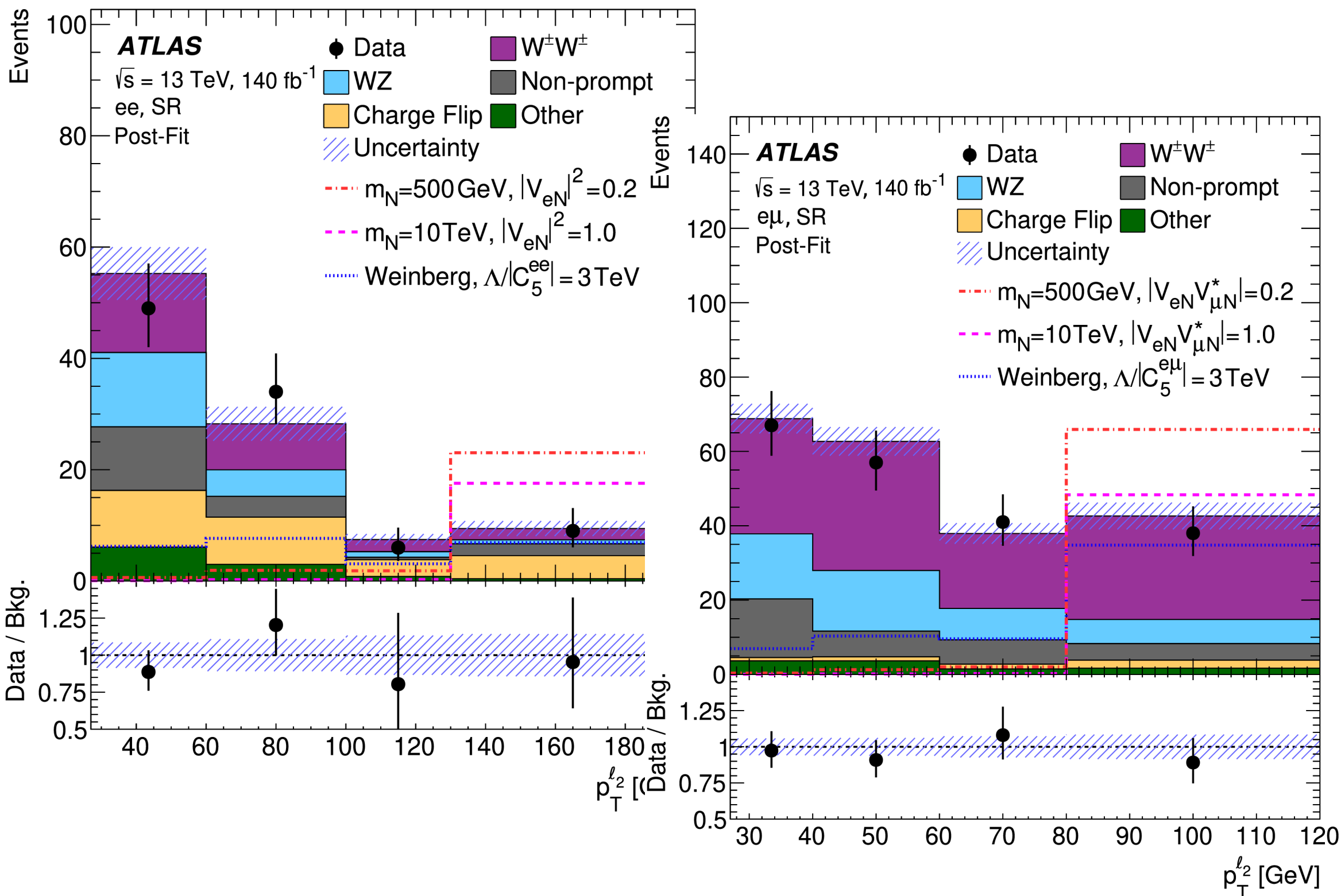
HNL via WW scattering in ee, eμ final states

[EXOT-22-019](#)

- * Neutrino oscillations implies non-zero ν masses
- * Neutrinoless double β decay: probe Majorana mass terms
- * BSM theories: Type-I Seesaw, LRSM, GUT, dim-5 Weinberg operator



- $l^\pm l^\pm (ee, e\mu)$
- $m_{jj} > 500 \text{ GeV}, |\Delta y_{jj}| > 2$
- $p_T^{l_2}$ discriminating variable

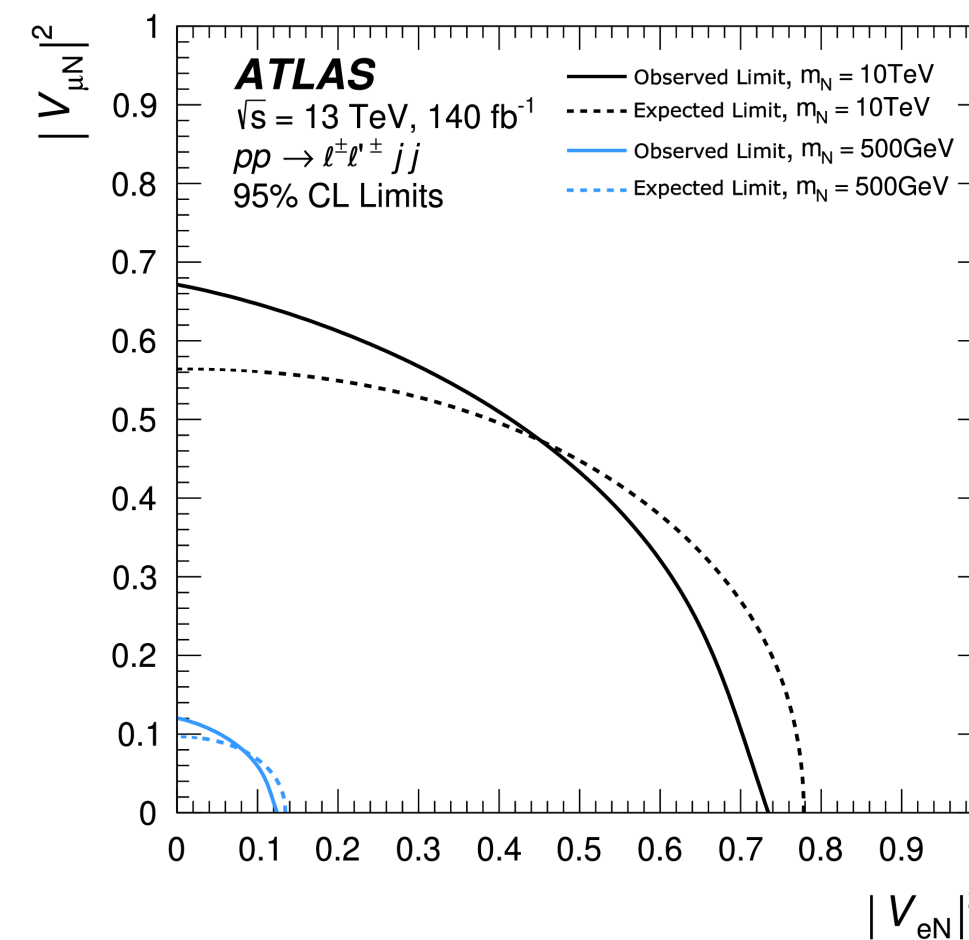
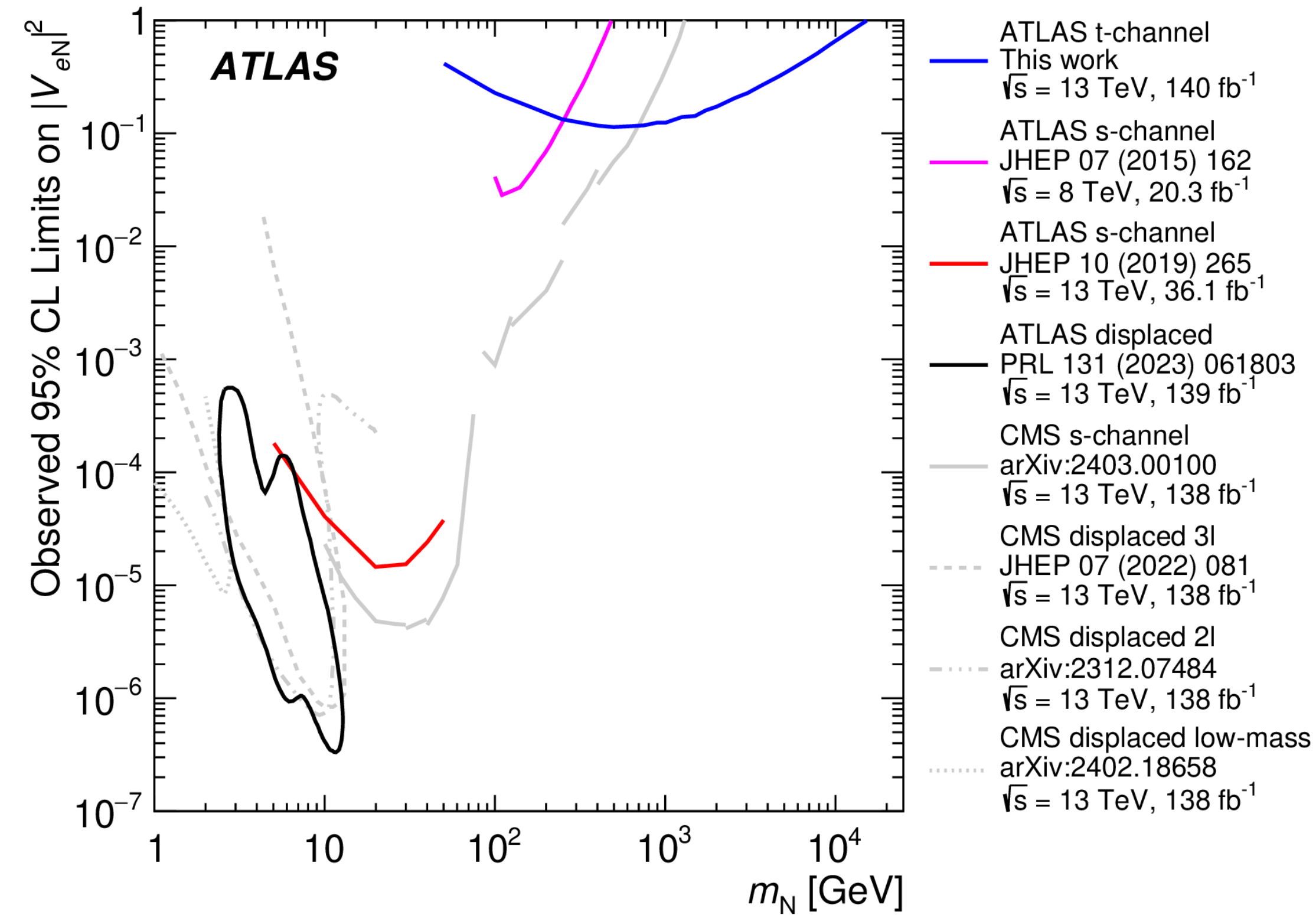
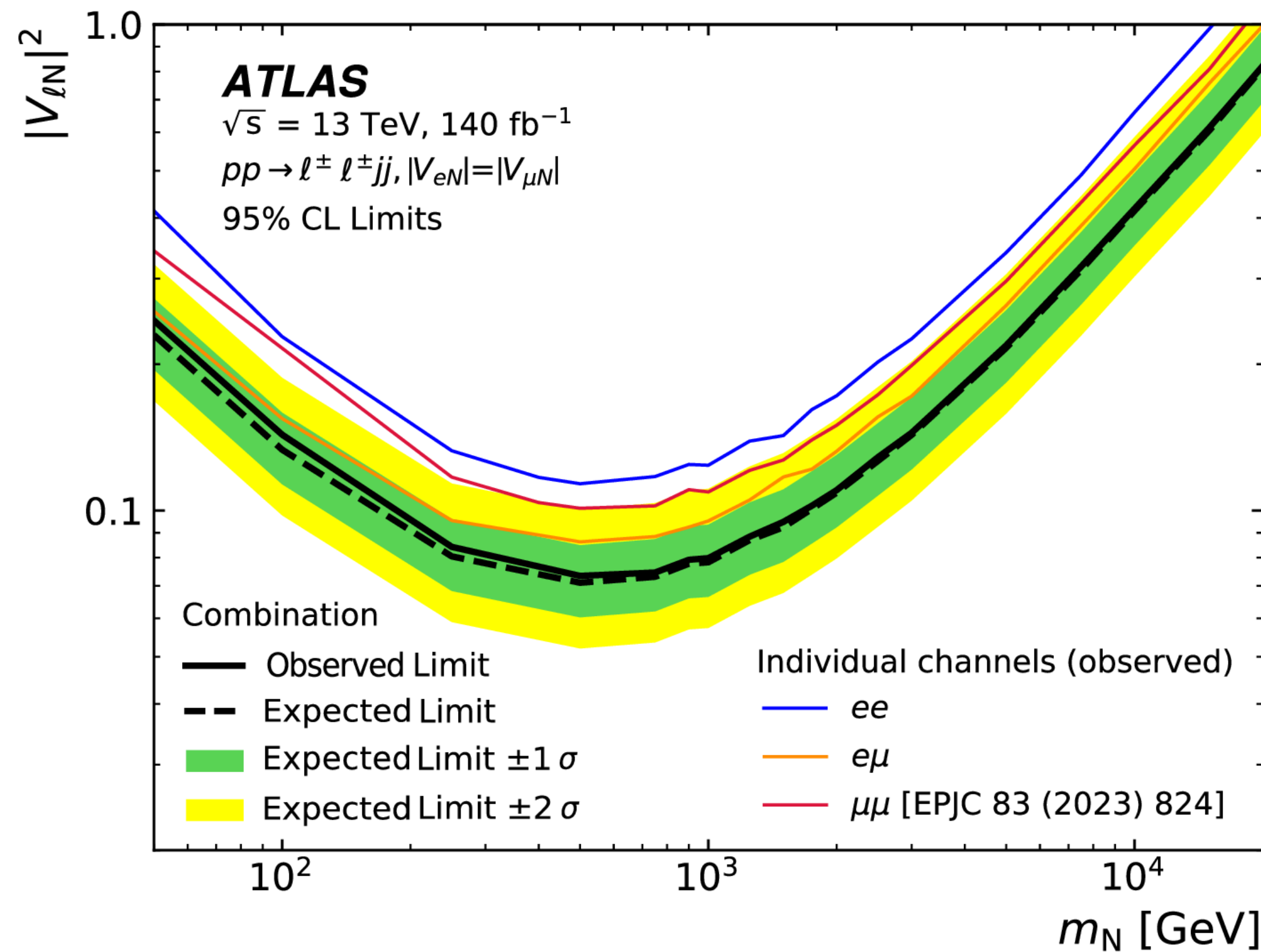


- * FIRST Search for Majorana N s in $0\nu\beta\beta$ -like W scattering process: $l^\pm l^\pm \pm jj$ in ee and (LFV!) $e\mu$ channels, complement existing & similar $\mu\mu$ channel [arXiv:2305.14931].
- * Cut-based event selection, binned fit in 2nd highest lepton p_T .
- * Dominant VBF $W^\pm W^\pm / WZ$ bkg Control Regions.
- * Data-driven fake lepton and electron charge mis-ID (Charge Flip) bkg.

HNL via WW scattering

EXOT-22-019

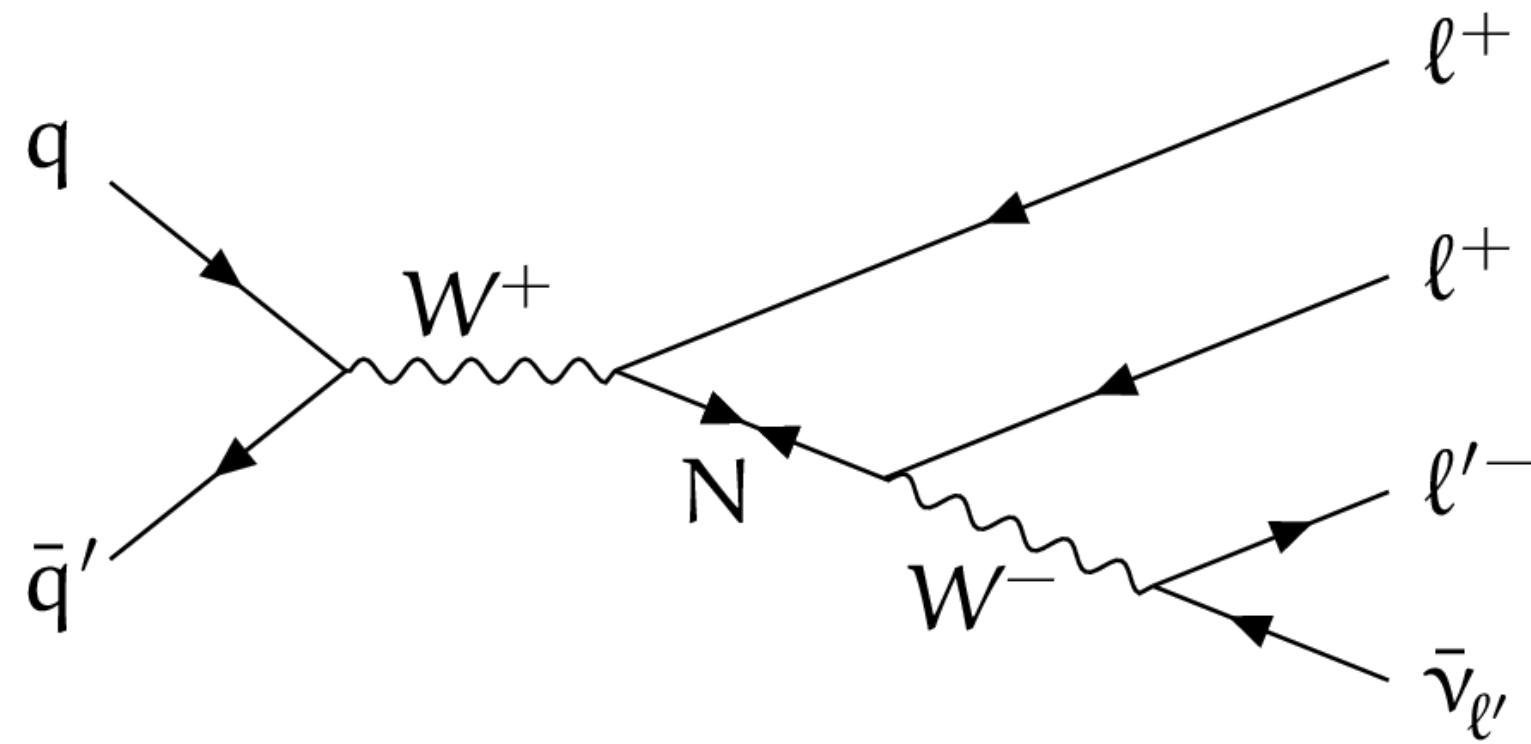
- * No significant excess, limits set on N couplings and masses. Best sensitivity in the $e\mu$ channel.
- * Also, statistical combination of 3 channels performed to constrain e and μ couplings simultaneously!



- * Limits on the mixing matrix elements $|V_{eN}|^2$, $|V_{eN}V_{\mu N}^*|$ and combined with
- * Limit Obs(Exp): $|m_{ee}| < 24.5(23.6)$, $|m_{e\mu}| < 12.5(14.8) \text{ GeV}$

HNL in final states with e, μ , hadronic τ

EXOT-22-011

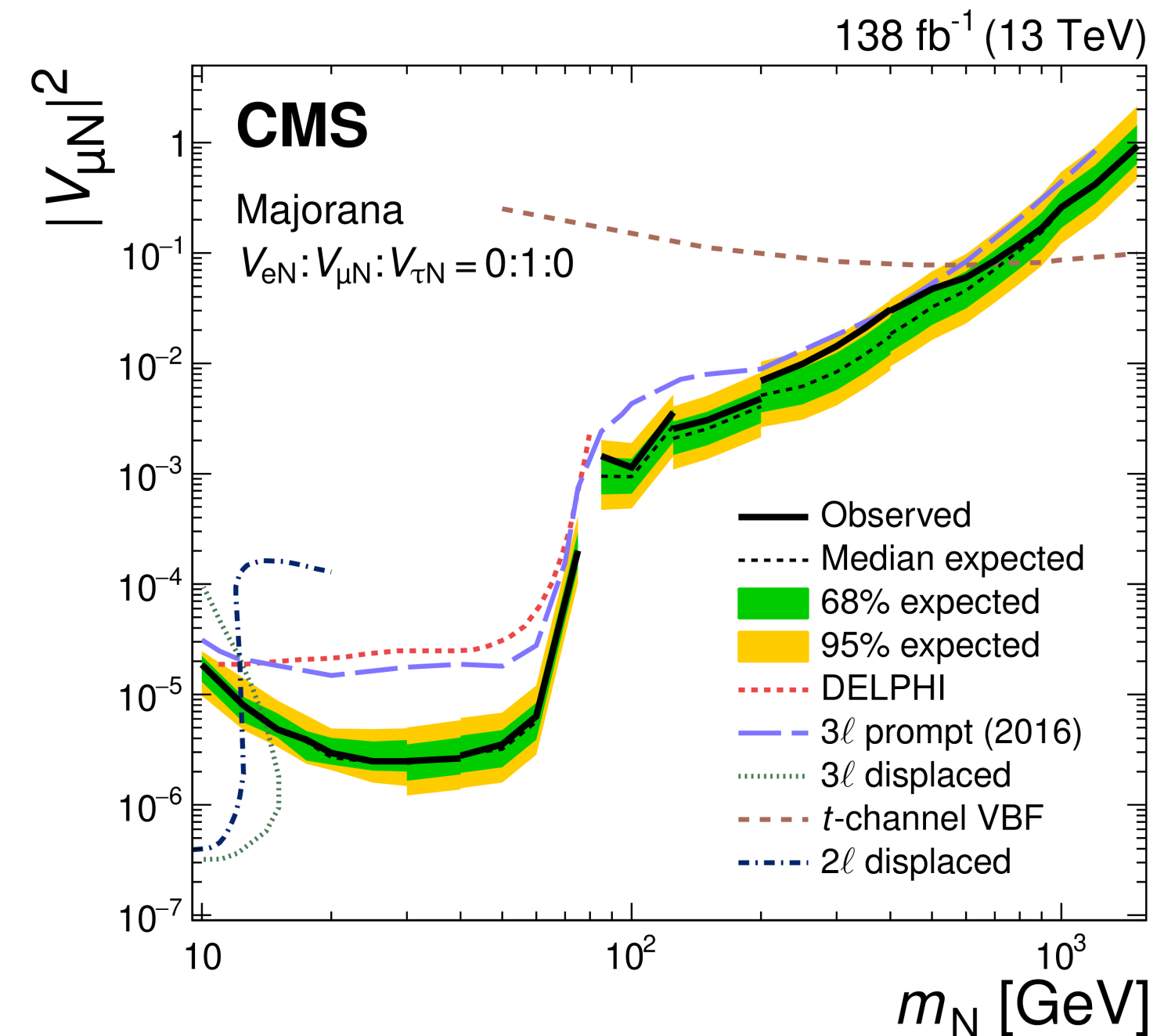
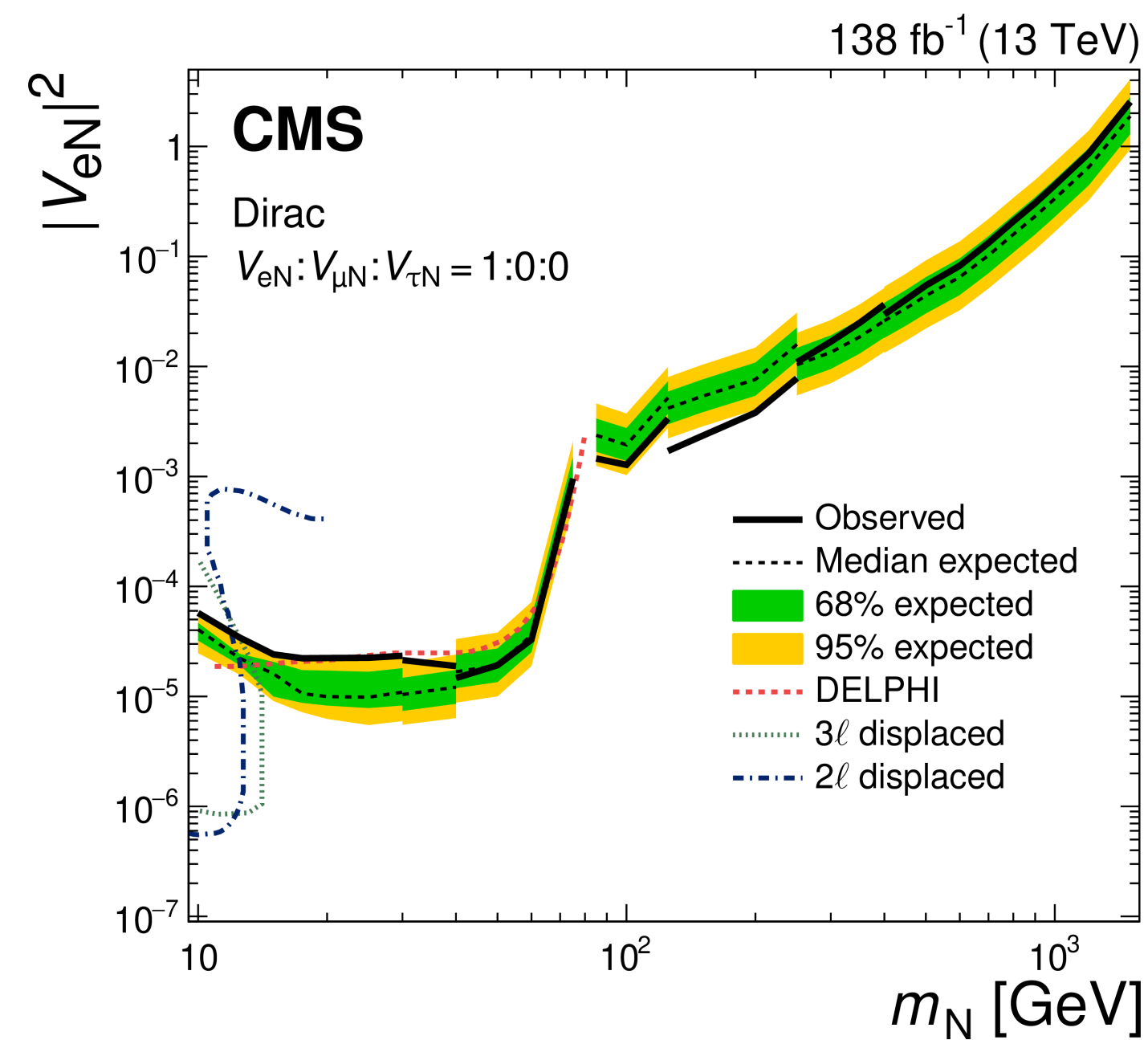


- * Heavy N: Majorana (LNV, LNC) or Dirac (LNC) type
- * Mixing matrix: exclusively to a single generation SM ν
- * Channels considering all combination of e, μ and τ_h

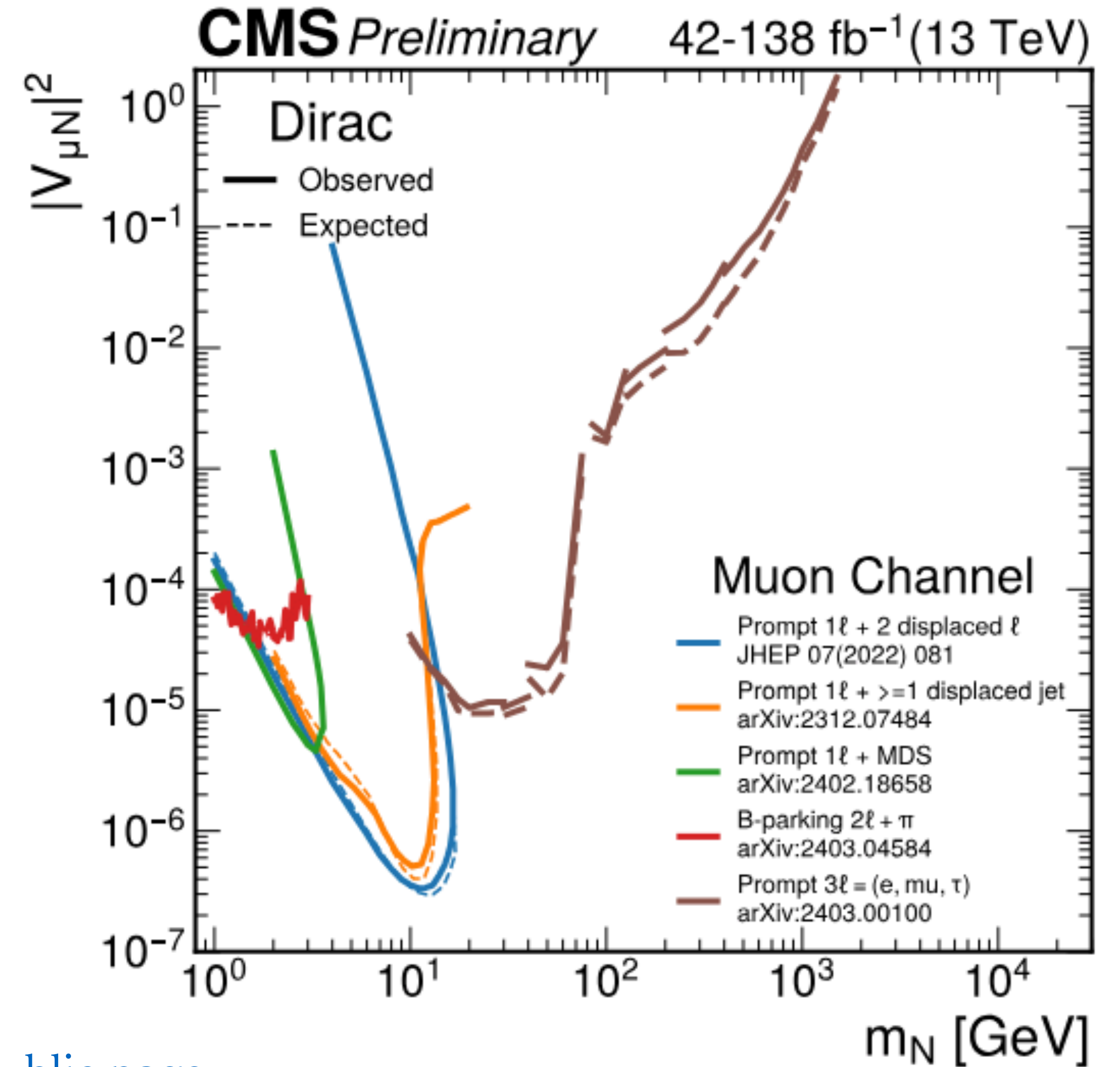
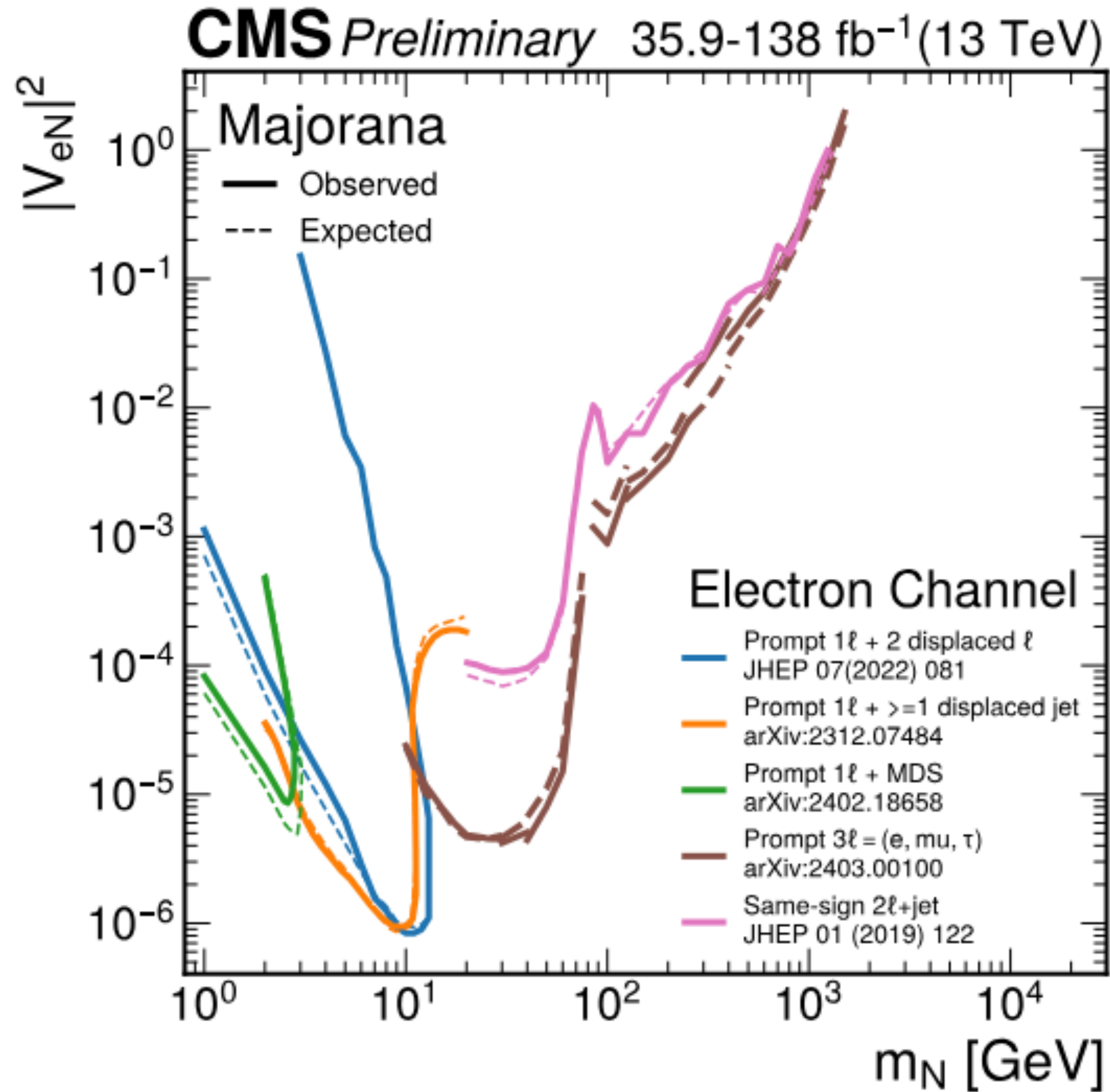
* Region defined on lepton p_T , 0-b-tag jets and using BDT discriminant

* Limits on mixing matrix elements $|V_{eN}|^2$, $|V_{\mu N}|^2$ and $|V_{\tau N}|^2$ (first time for $m_N > m_W$)

* Complementary to other searches, improved range of $(m_N, |V_{eN}|^2)$ exclusion limits



CMS Summary of neutrino exclusion limits



[Public page](#)

Long Lived Particle

Search for heavy long-lived charged particles

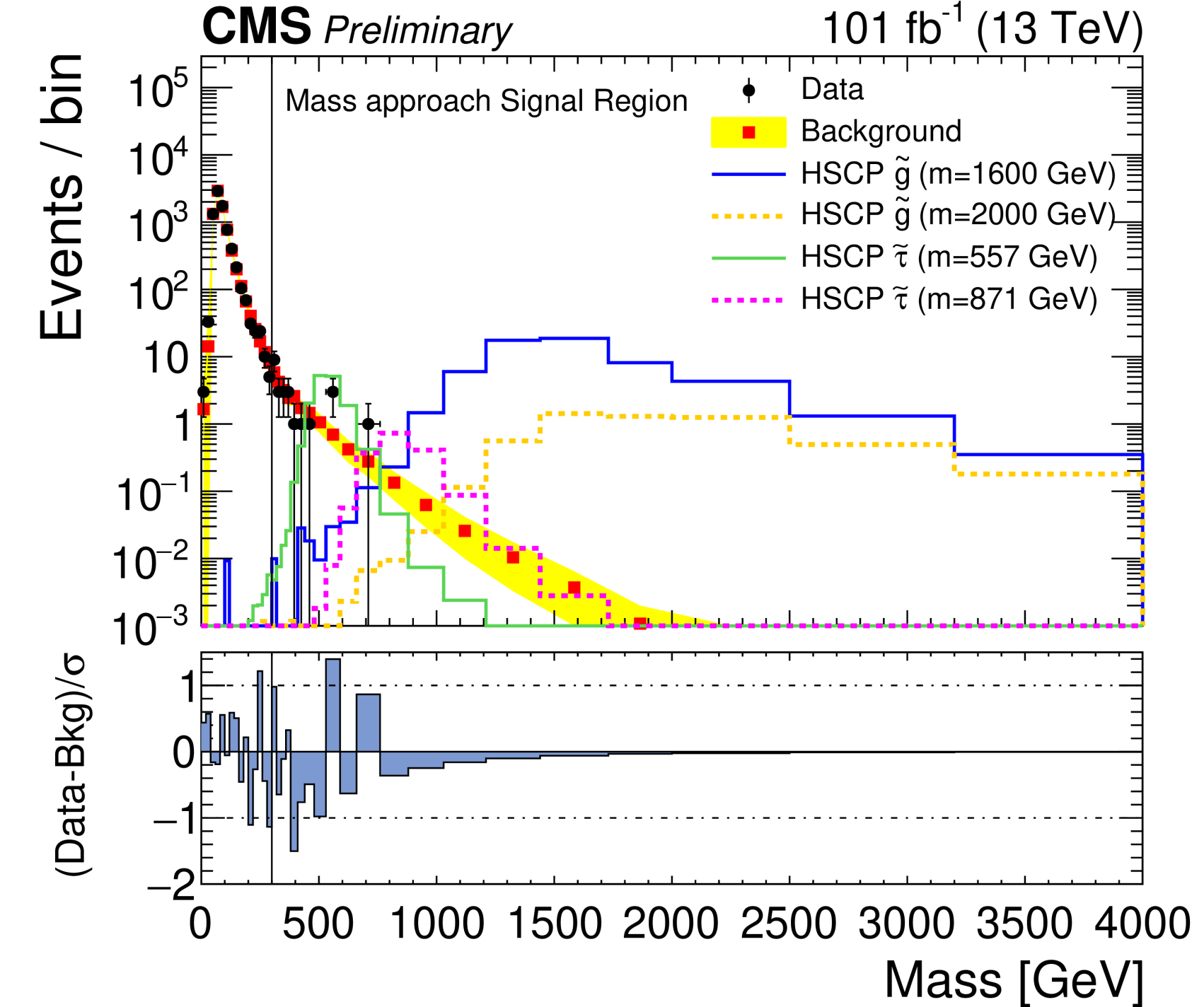
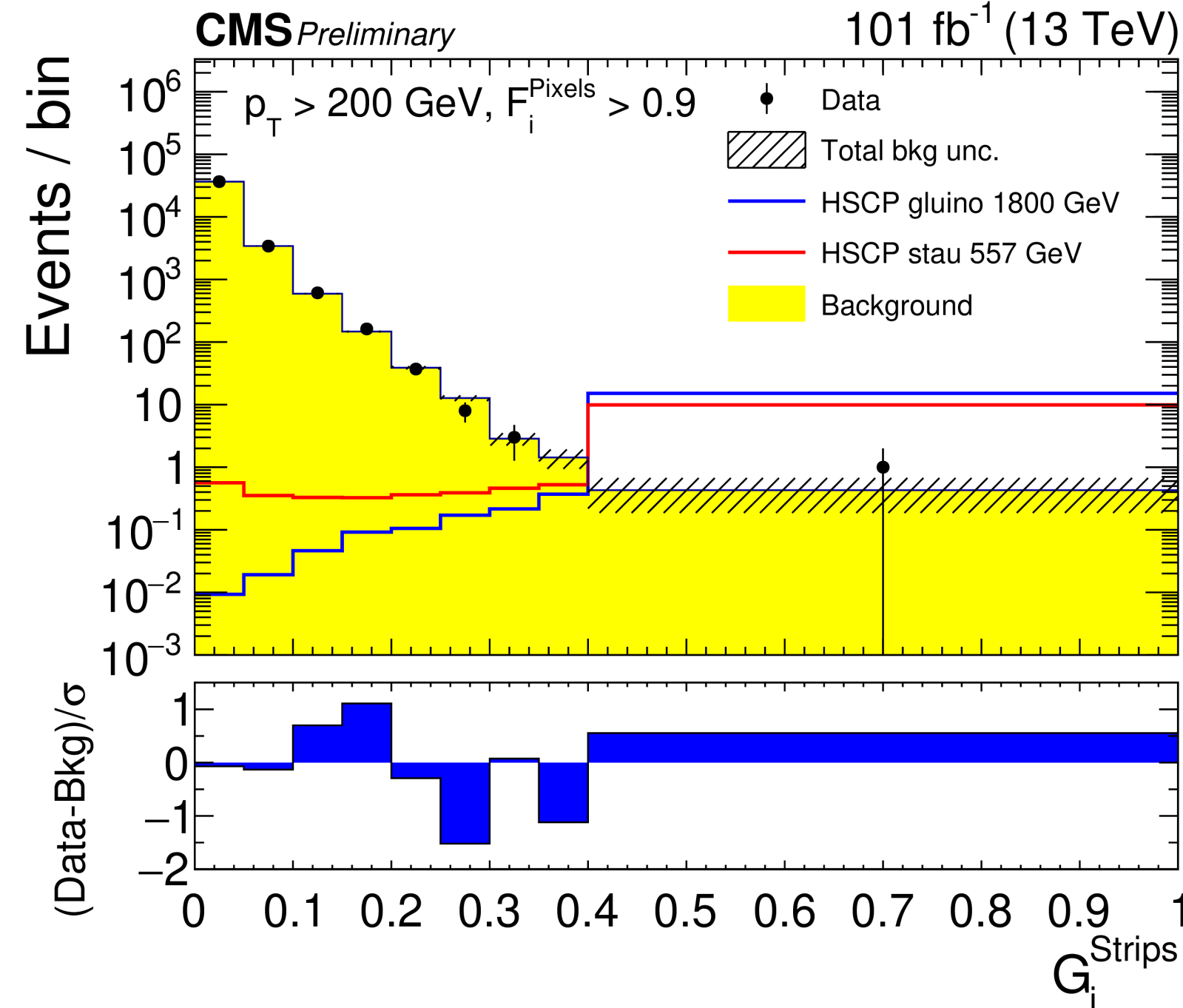
* **Signature:** An isolated track of high- p_T ($p_T > 55$ GeV, $|\eta| < 1$) with large dE/dx deposits in the tracker, selected in 2017-2018 data (101 fb^{-1}) with muon trigger.

[CMS-PAS-EXO-18-002](#)

* **Two approaches:**

- using independence of dE/dx in Pixel and Strip tracker for background recognition,
- using the mass spectrum.

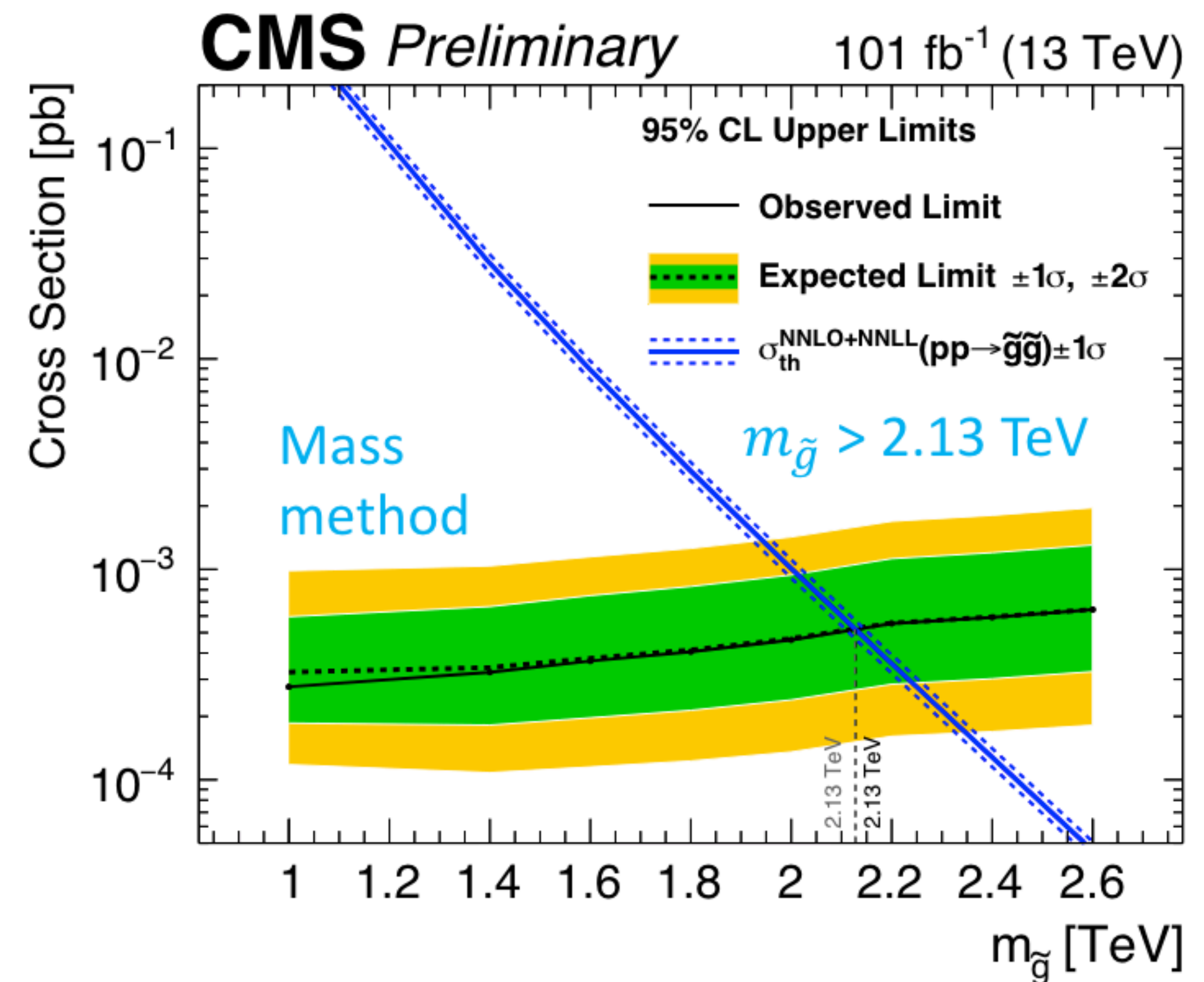
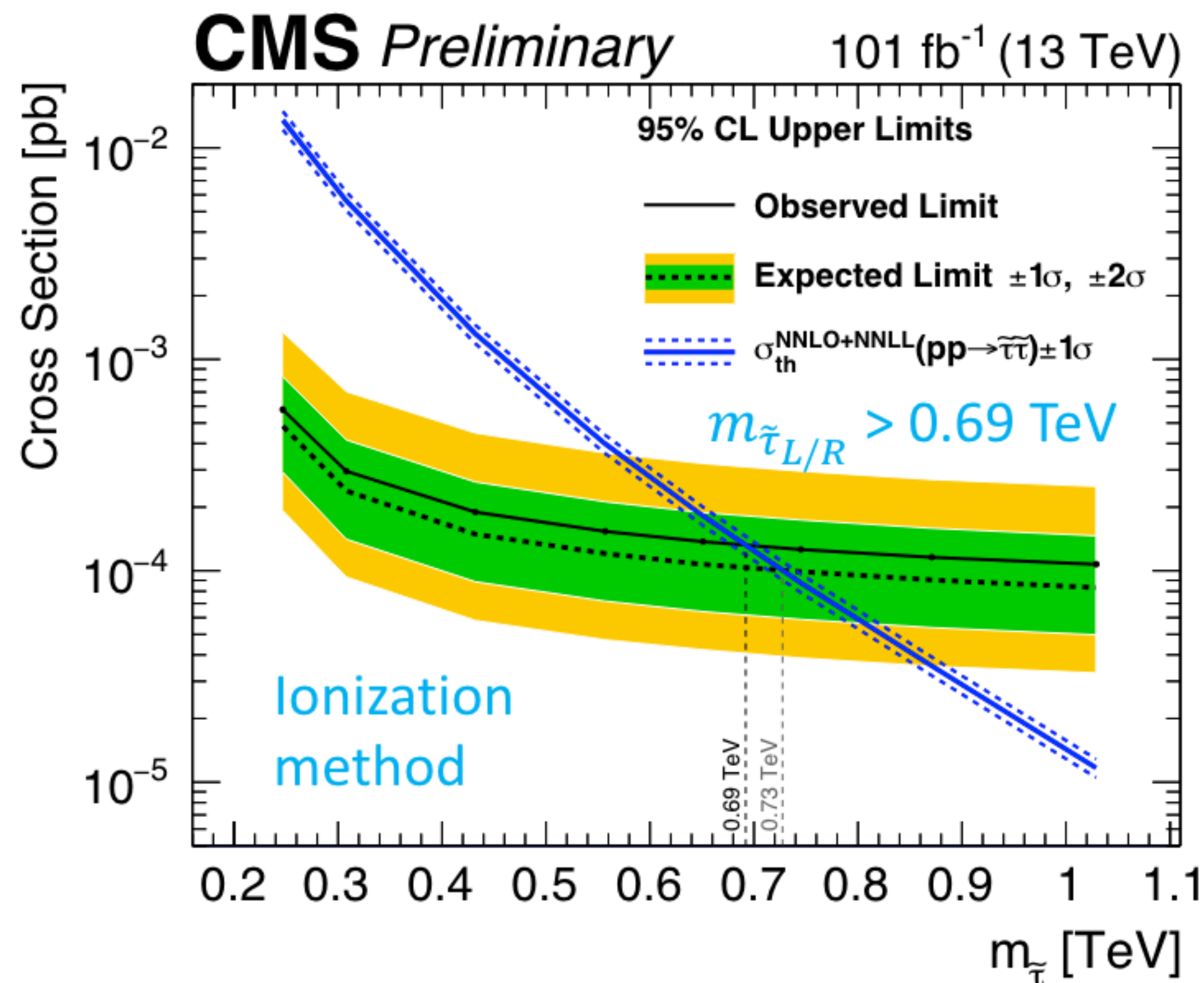
* Data-driven estimate in both cases



Search for heavy long-lived charged particles

[CMS-PAS-EXO-18-002](#)

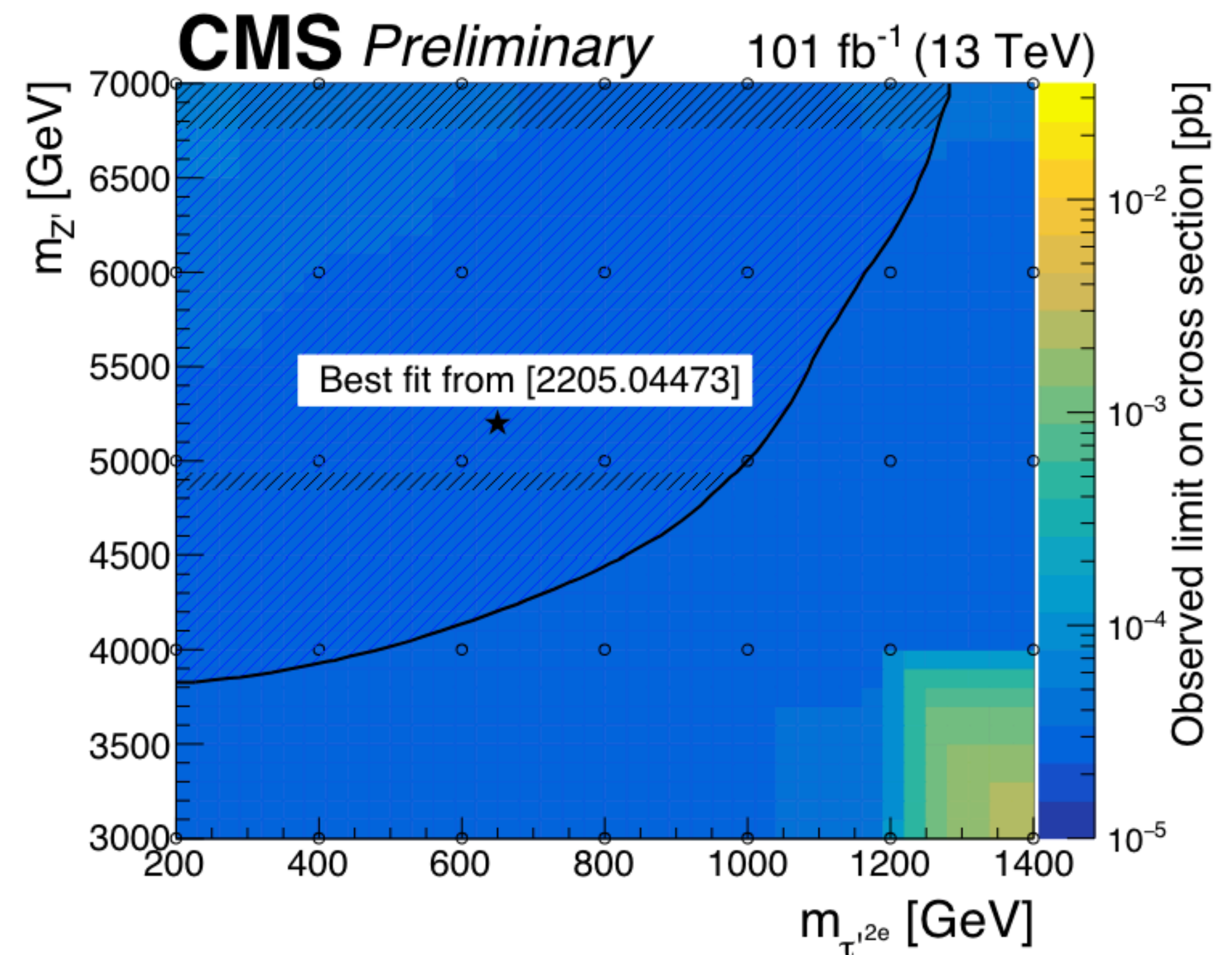
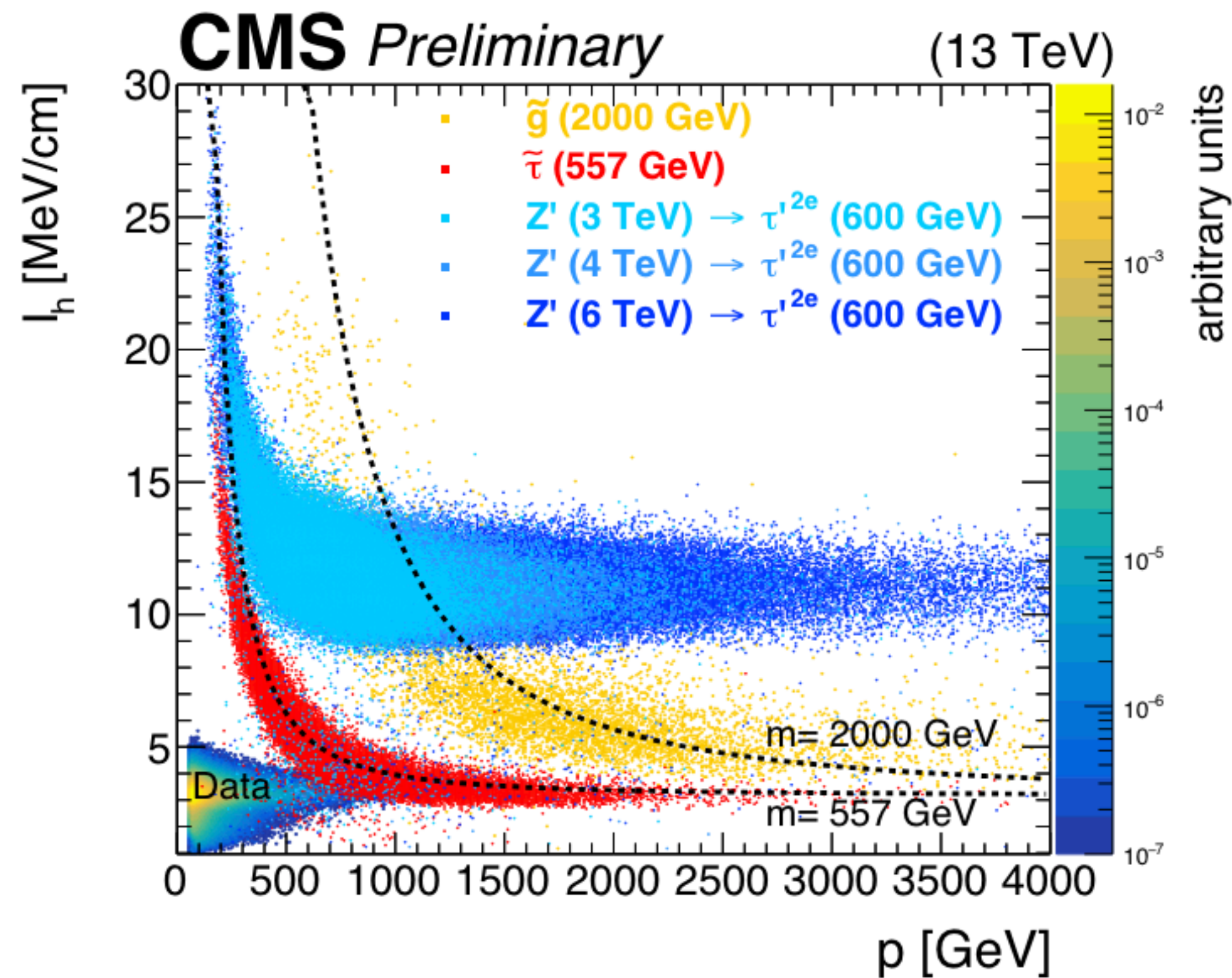
- * No excess \rightarrow Interpretation of many stable signals, considering $|Q|=1e$
- * The ionization method provides better limits at low signal masses while the mass method is more efficient at large masses



Search for heavy long-lived charged particles

CMS-PAS-EXO-18-002

- * No excess \rightarrow interpretation of many stable signals, considering $|Q|=1e$ or $2e$
- * Limits on the Z' model [Giudice, McCullough and Teresi, JHEP 08 (2022) 012] with $Z' \rightarrow \tau^{(2e)}\tau^{(2e)}$:
 - ☆ CMS data do not confirm any claim of signal excess

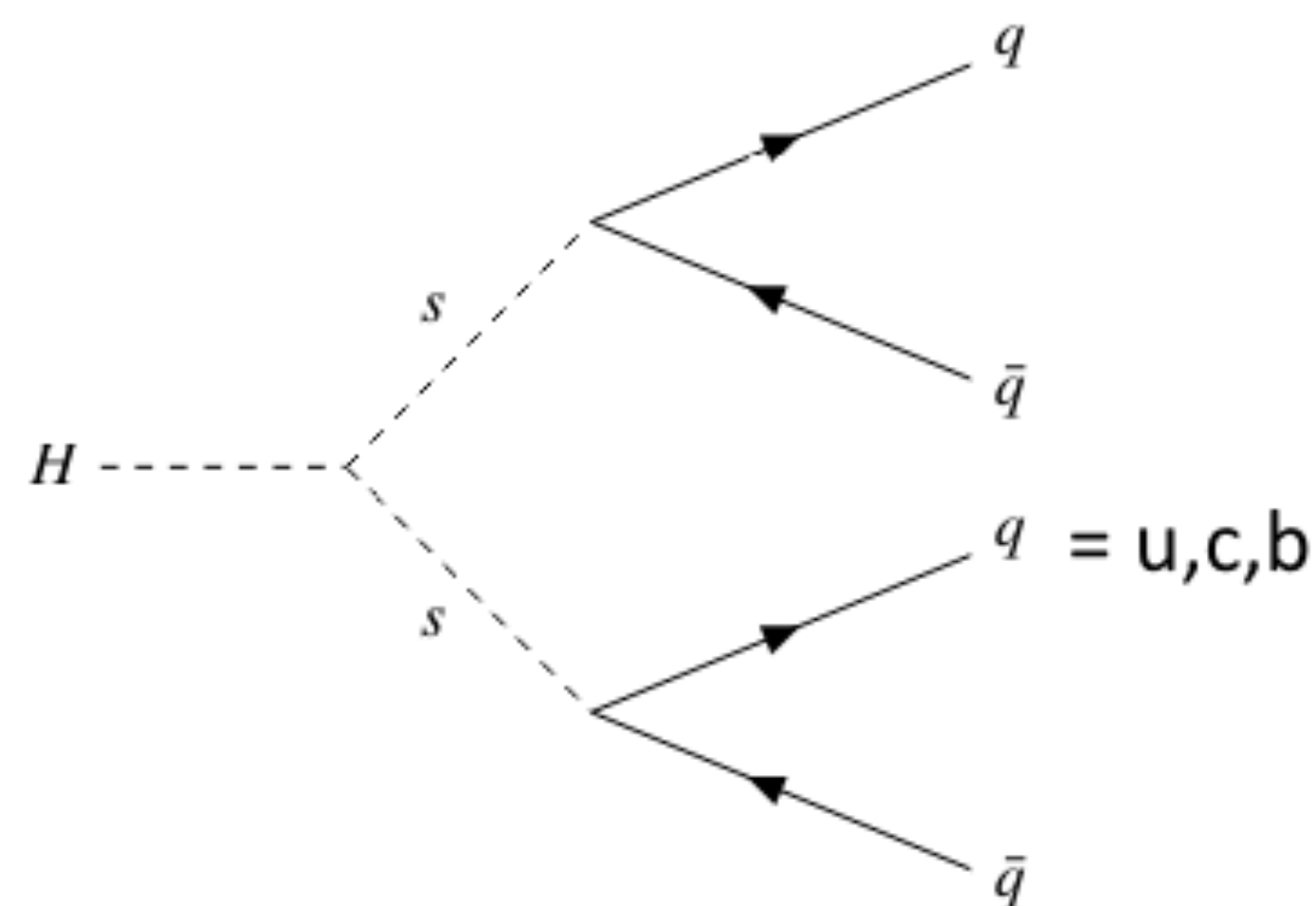


Light LLP with displaced vertices

[2403.15332](https://arxiv.org/abs/2403.15332) [hep-ex]

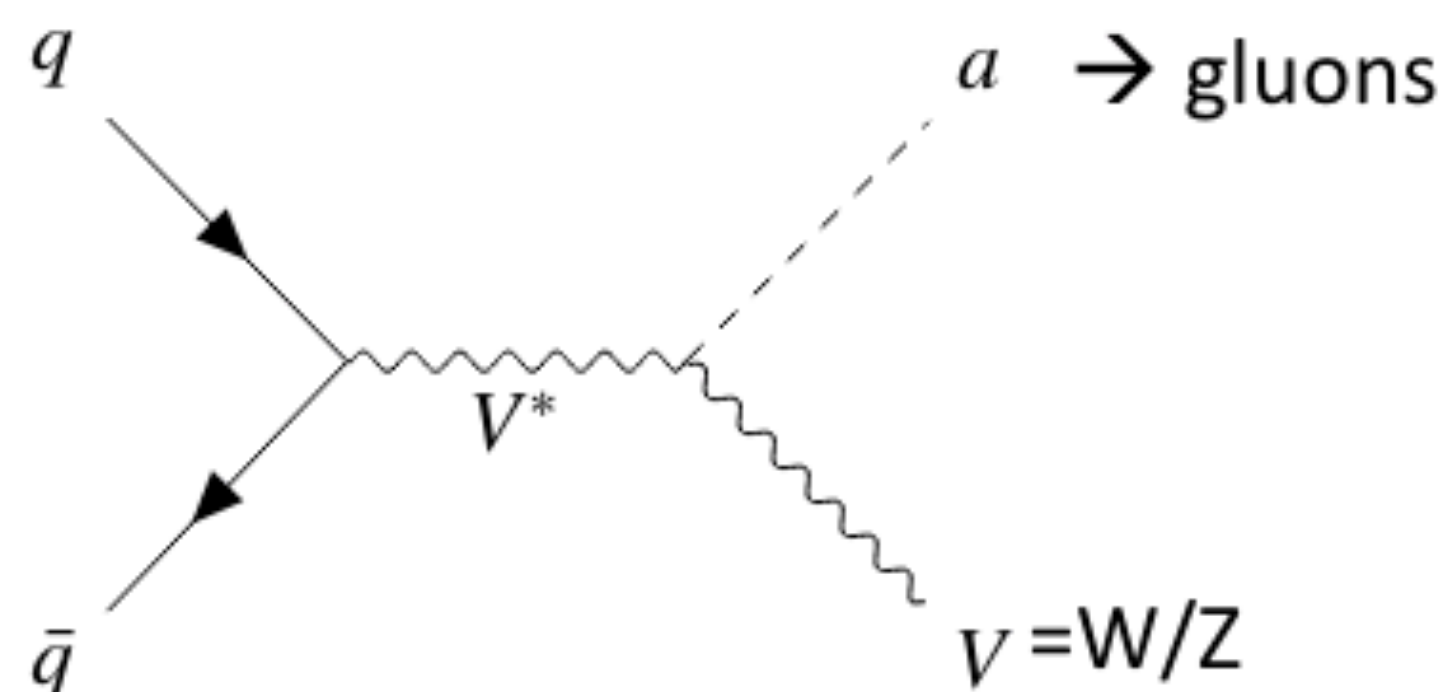
Pseudoscalar boson (s)

VH and VBF H production

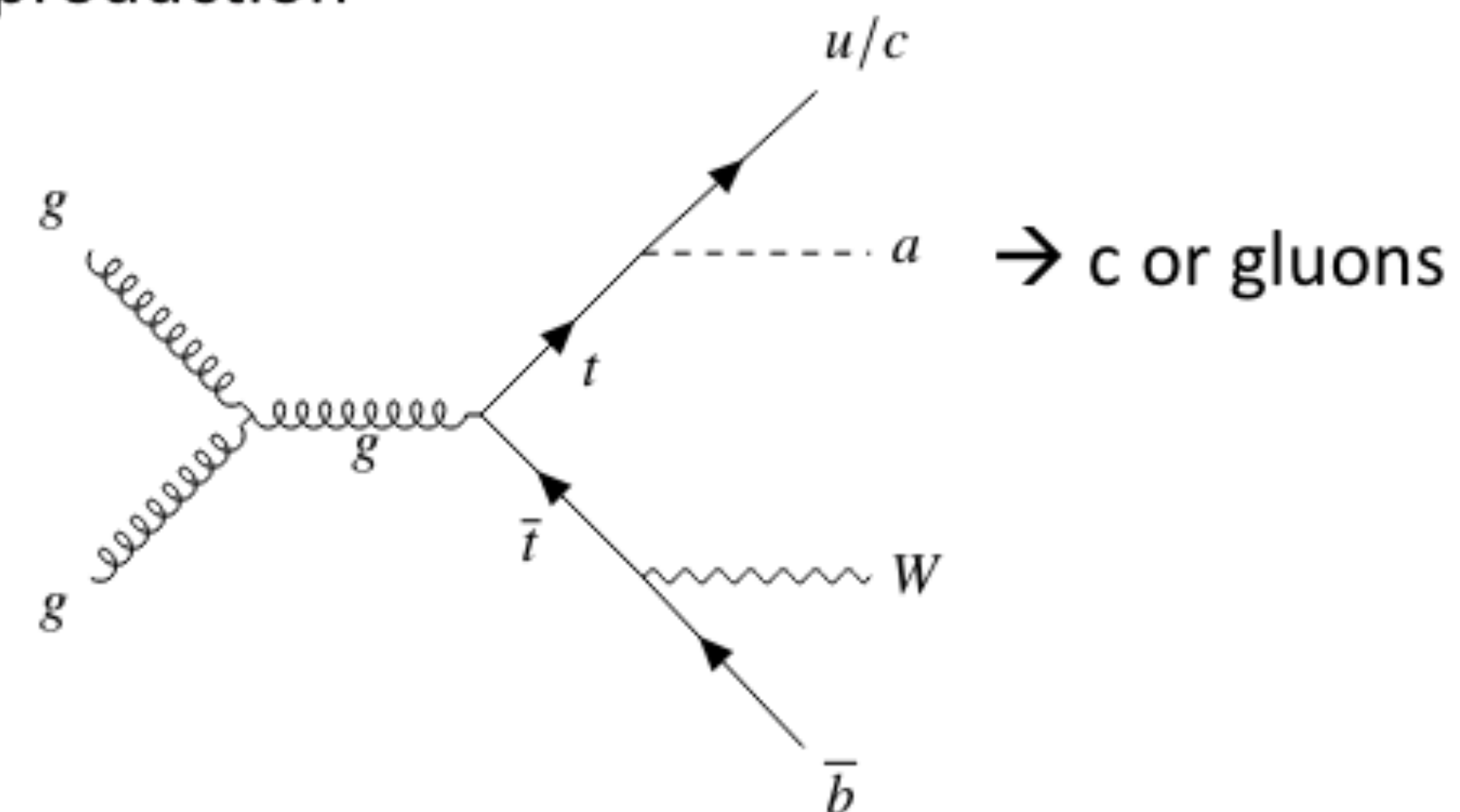


Pseudoscalar Axion-Like-Particle (a)

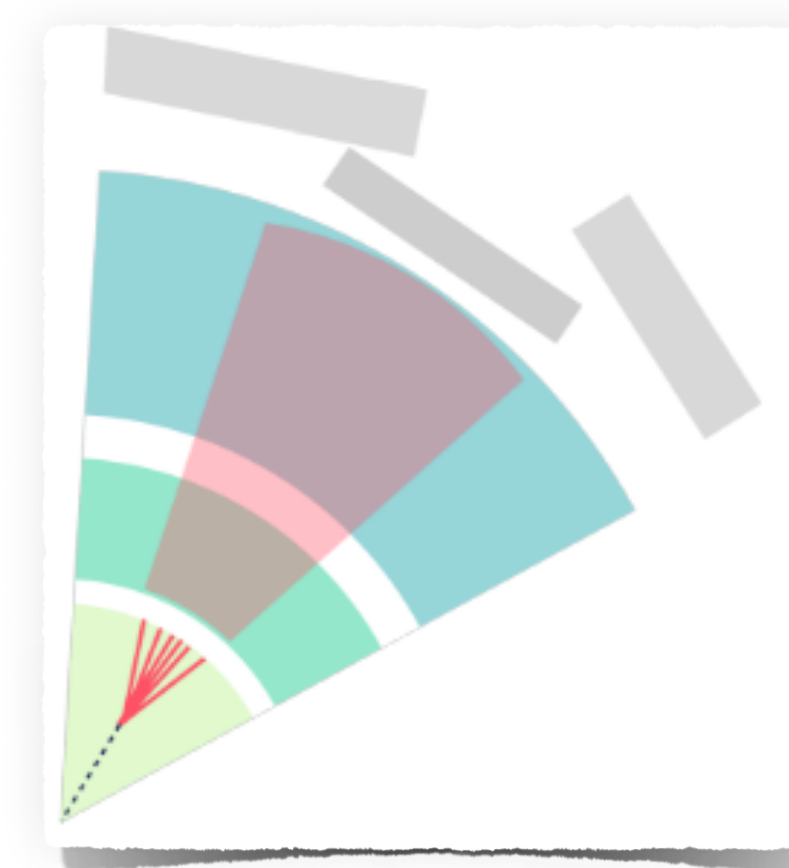
Va production



$t\bar{t}$ production



- * Signature: ≥ 2 displaced jets ($|\eta| < 2.5$), with ≥ 1 matched to a displaced vertex (DV), selected in 2015-2018 data (140 fb^{-1})
- * Newly improved displaced track reconstruction [[hep-ex](https://arxiv.org/abs/2304.12867)] [2304.12867](https://arxiv.org/abs/2304.12867)



Light LLP with displaced vertices

2403.15332 [hep-ex]

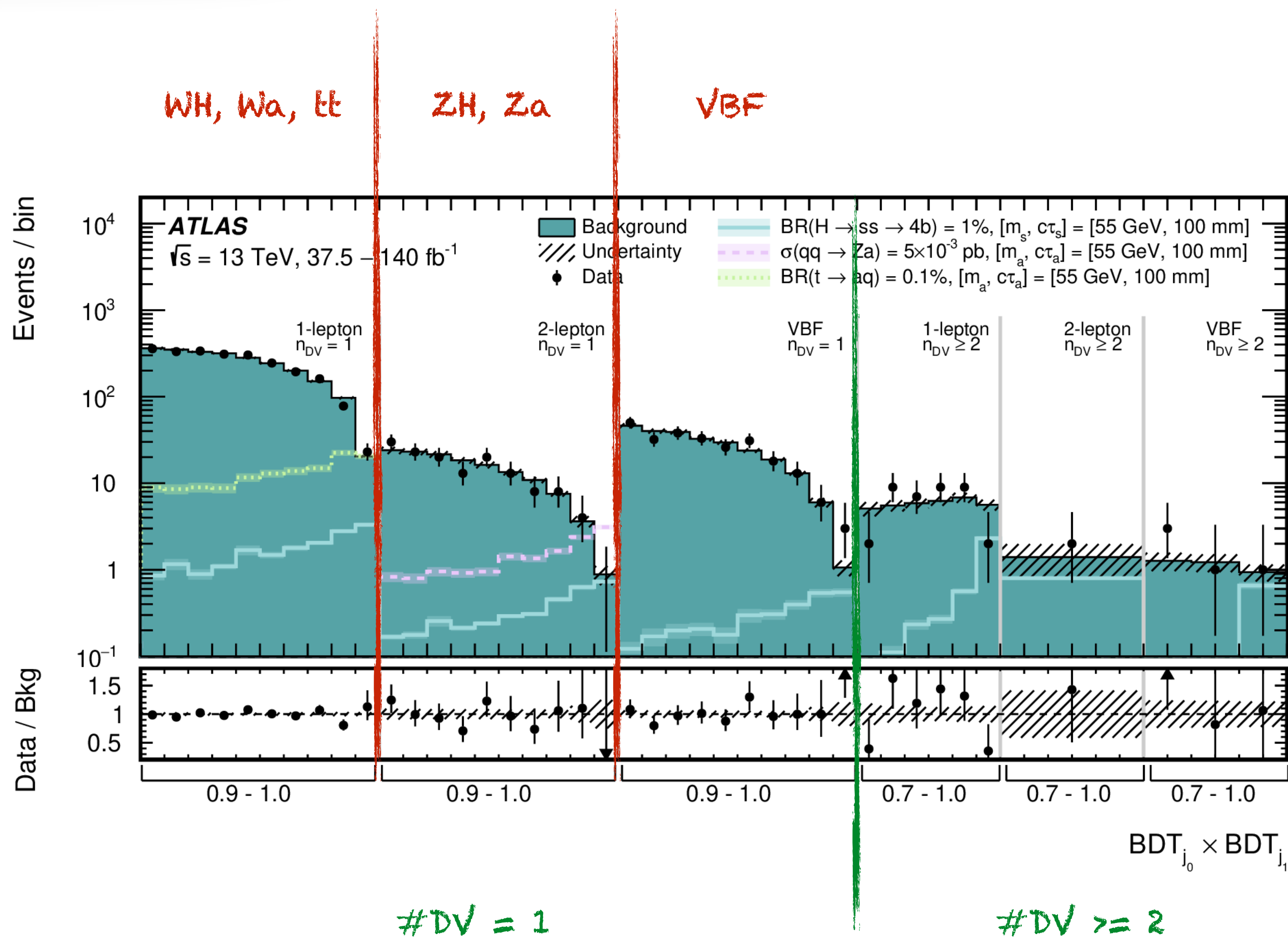
* Displaced jet tagger

using jet-level features that discriminate between prompt and displaced jets

- Event-level discriminant $BDT_{j0} \times BDT_{j1}$

* Data-driven

background estimate using the probability of a jet to be matched to a DV (depending on its p_T , flavour, BDT score) to determine a *per-event probability*

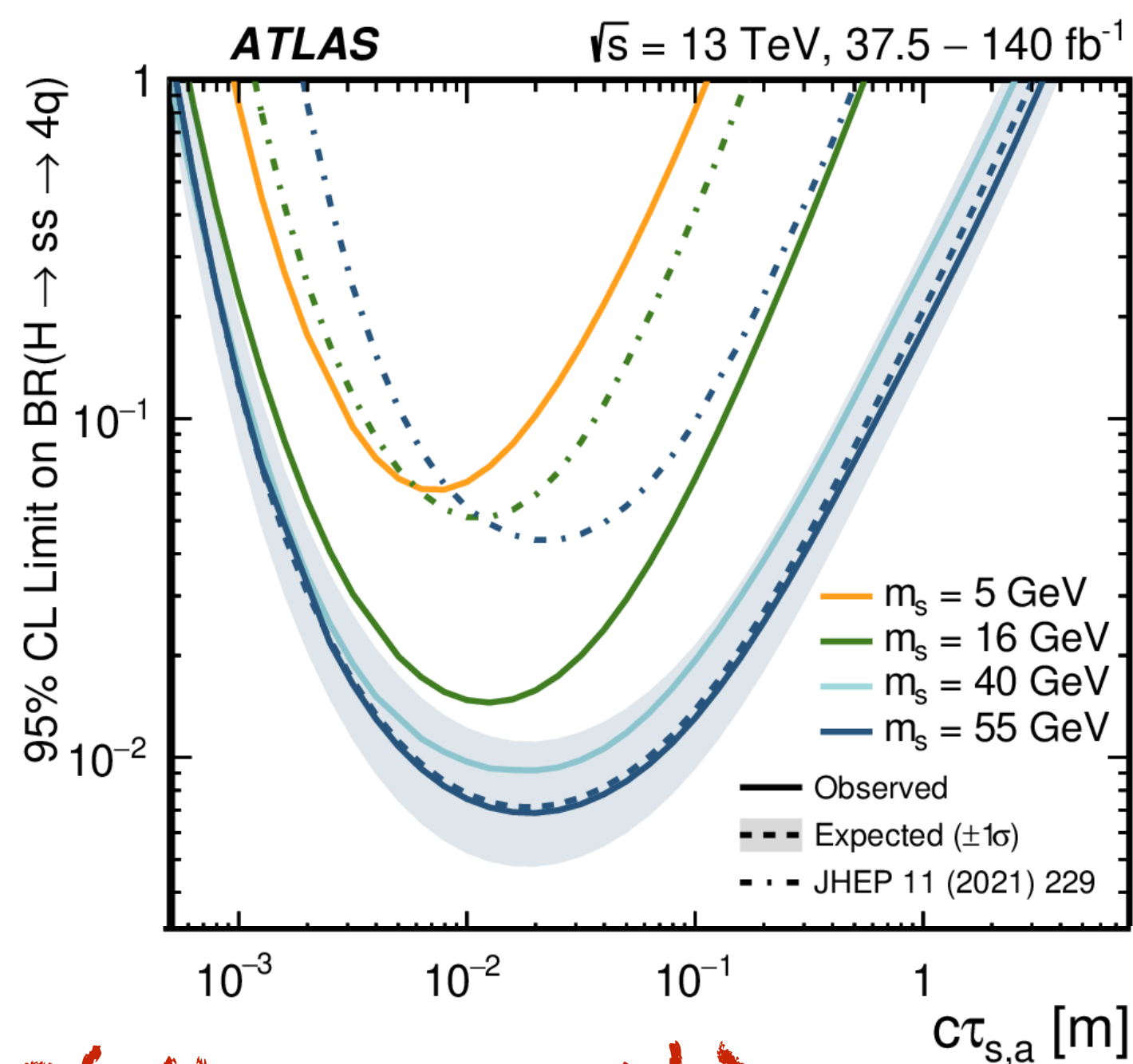


Light LLP with displaced vertices

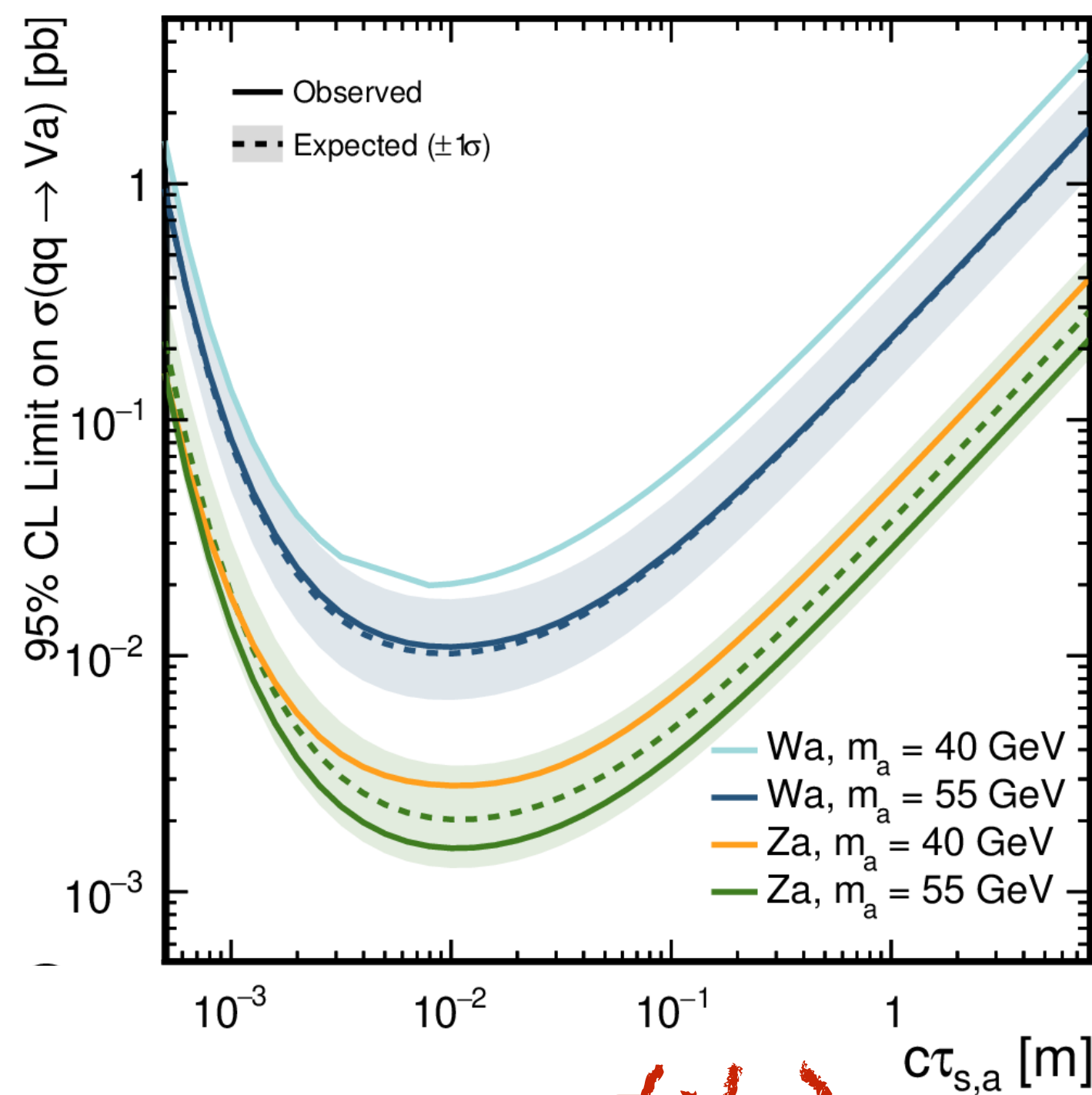
2403.15332 [hep-ex]

* No excess \rightarrow 95% CL limits:

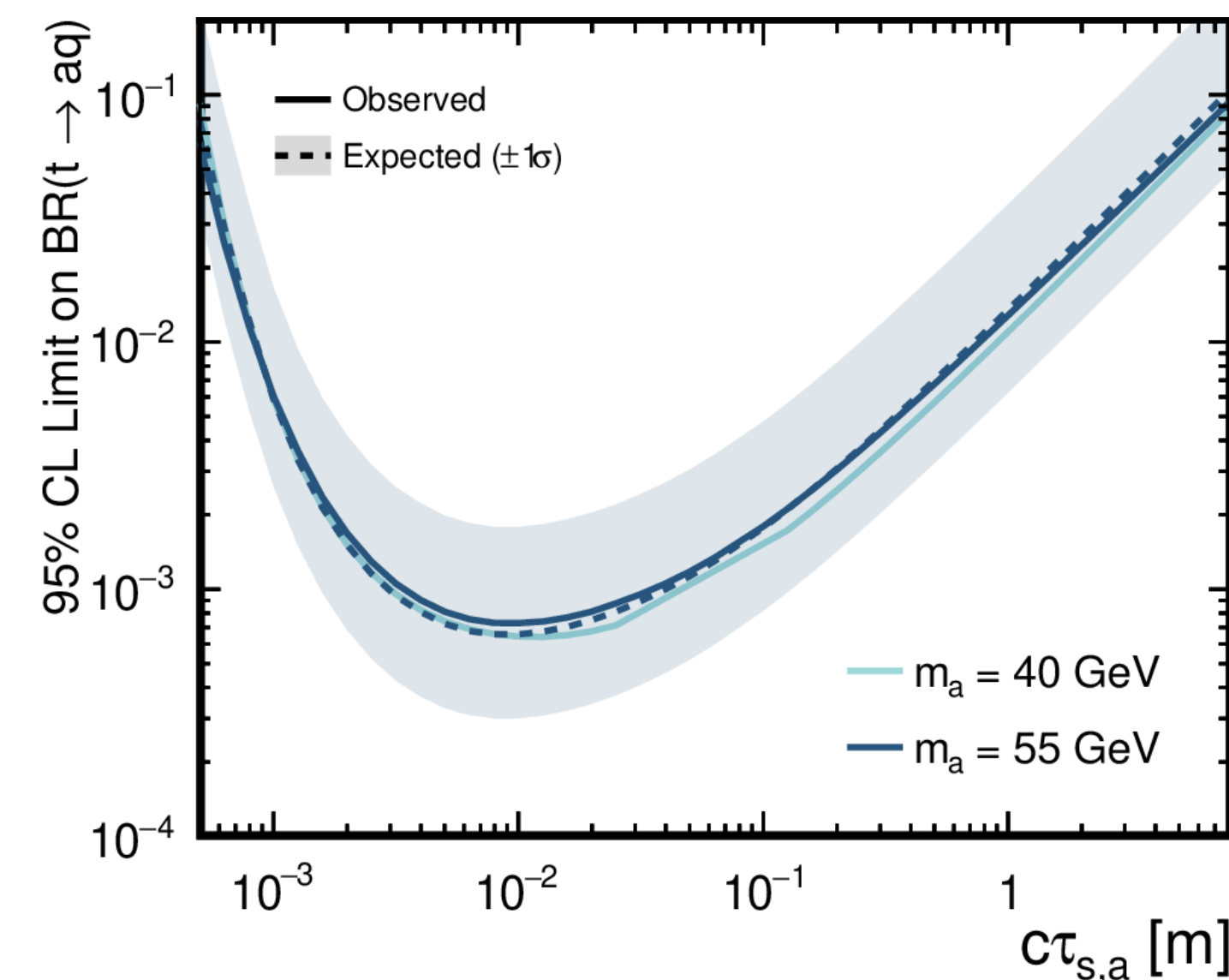
- on $B(H \rightarrow ss \rightarrow 4b)$ for $m_s \geq 16$ GeV and on $B(H \rightarrow ss \rightarrow 4c)$ for $m_s = 5$ GeV, improvements by as much as a factor of 20 for $m_s = 55$ GeV and $c\tau_s < 10$ mm.
- on $\sigma(Va)$ and $B(t \rightarrow aq)$ for the first time at LHC



$B(H \rightarrow ss \rightarrow 4b)$



$\sigma(Va)$

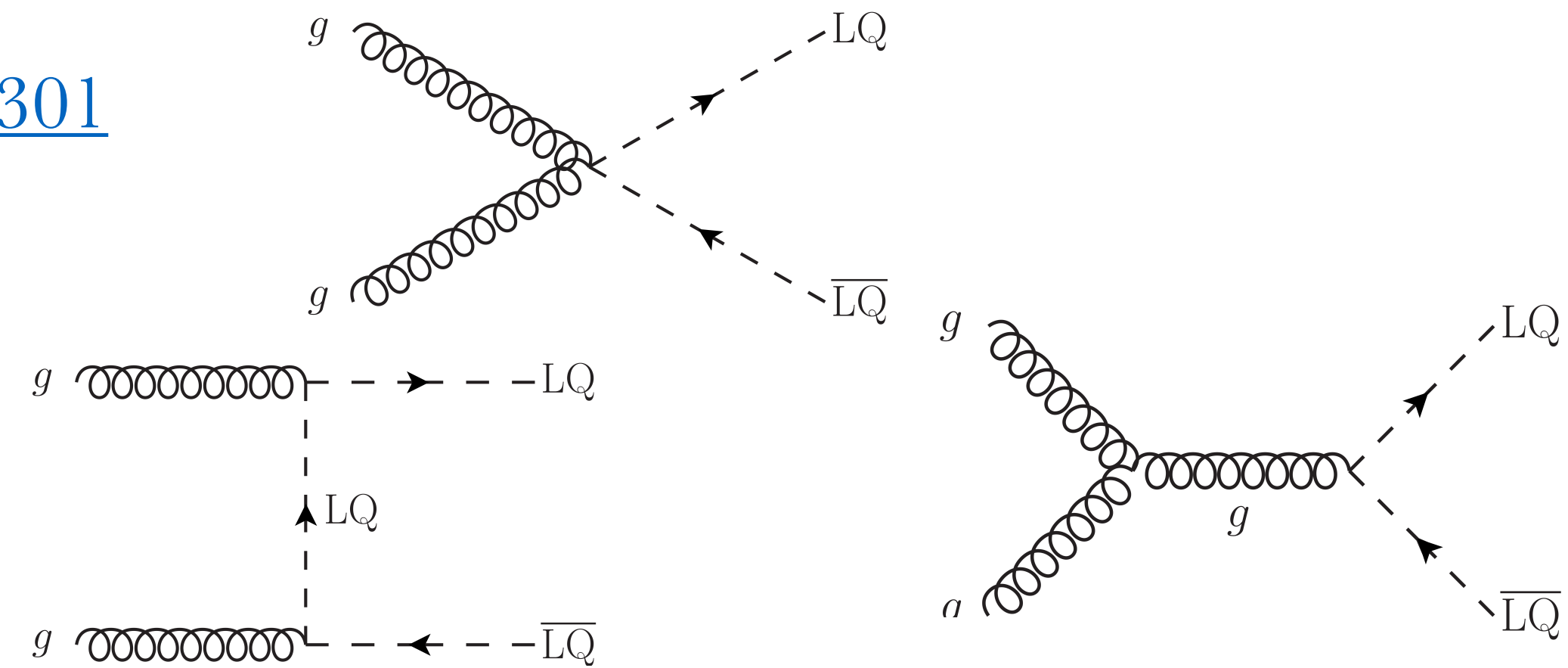


$B(t \rightarrow aq)$

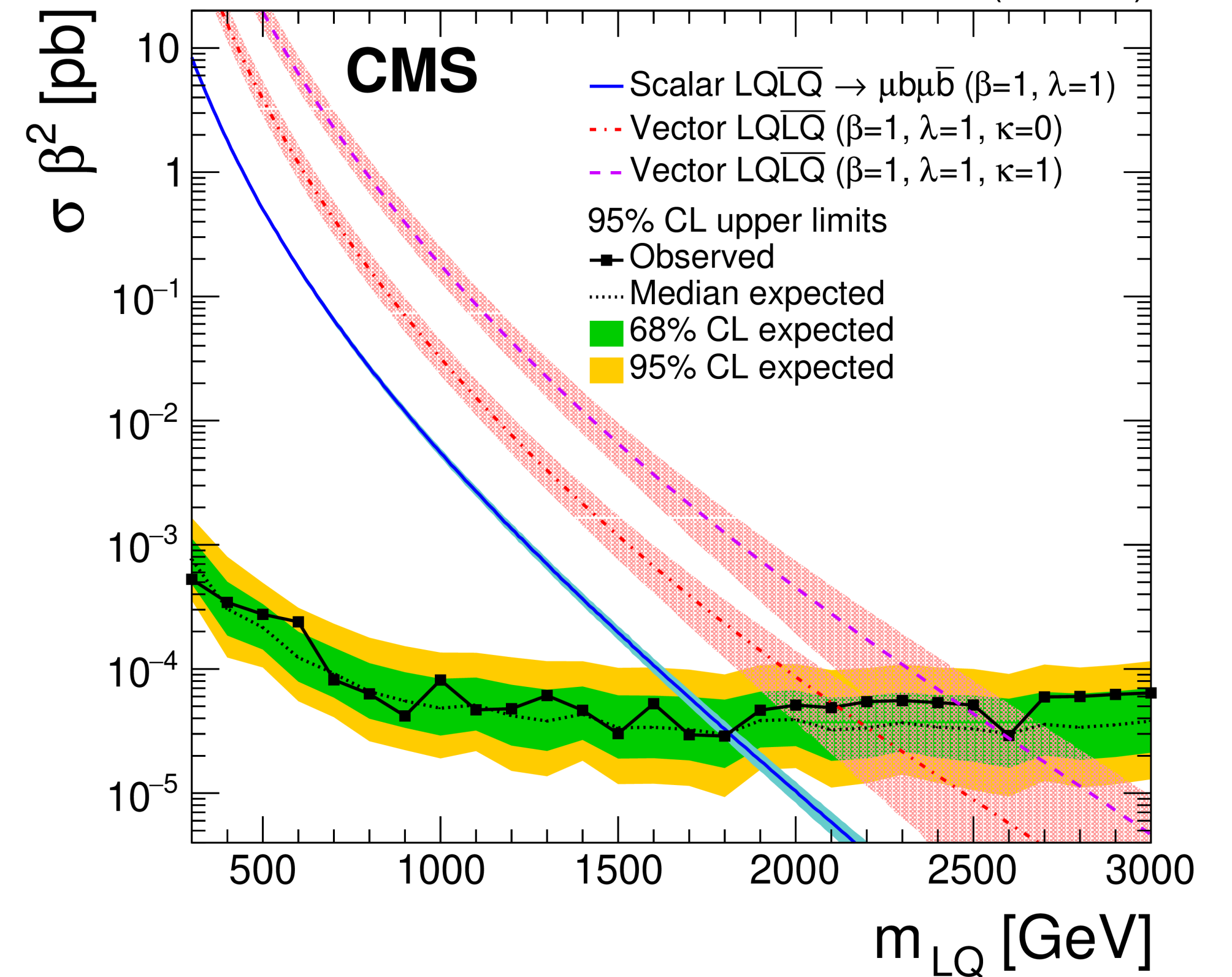
Lepto-Quarks

LQ pair $\rightarrow b\mu b\mu$

- * Full Run -2 search for Scalar/Vector LQ pair
- * Main bkg: drell-yan and tt estimated from MC normalised in dedicated regions “Control Region”.
- * SRs defined for each $m(LQ)$ hypothesis via cut on a dedicated BDT score.
- * No significant excess seen, most stringent limits to date!



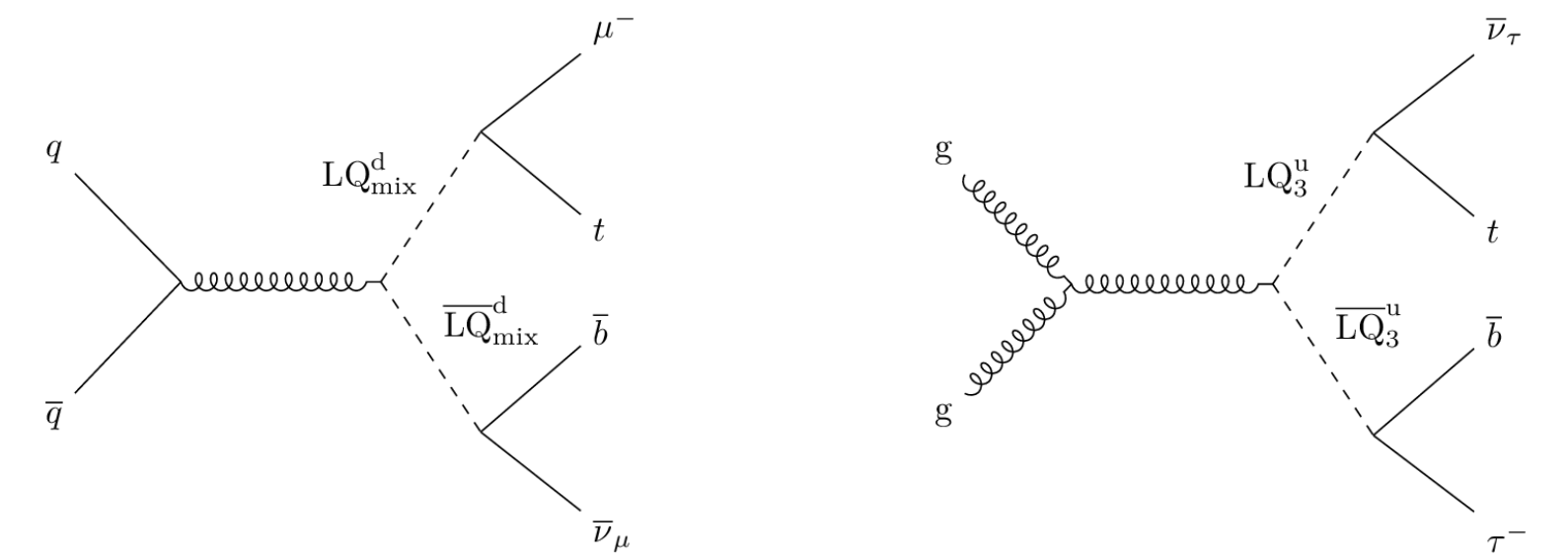
138 fb⁻¹ (13 TeV)



$m(LQ)$ upper bounds [TeV] @95%CL	Scalar LQ		Vector LQ ($\beta = 1$)	
	$\beta = 1$	$\beta = 0.5$	Minimal Coupling	Yang-Mills
ATLAS [arXiv.org:2210.04517]	1.5	1.3	1.5	1.8
CMS (this)	1.81	1.54	2.12	2.46

3rd gen. LQ pair production

CERN-EP-2023-288



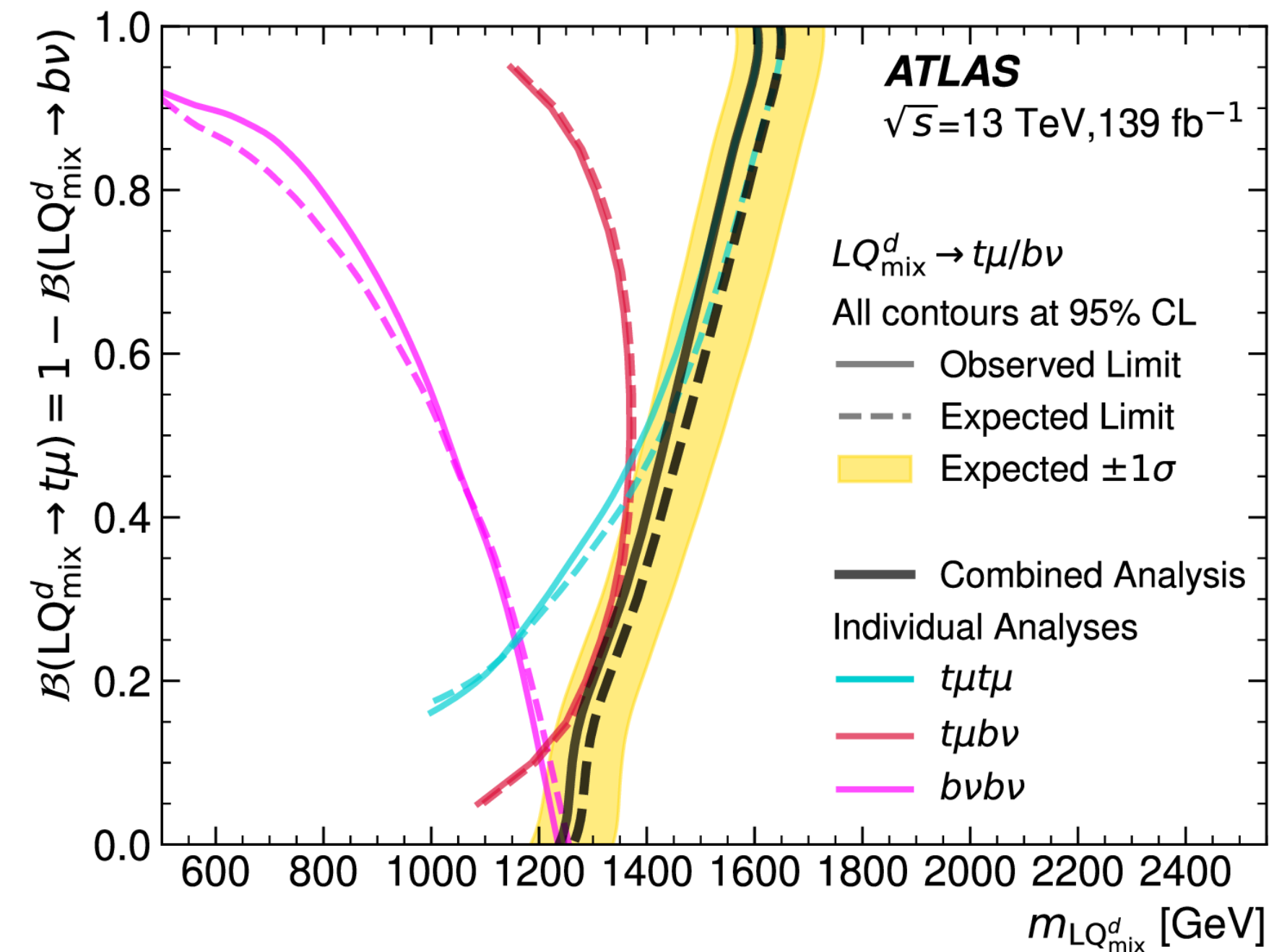
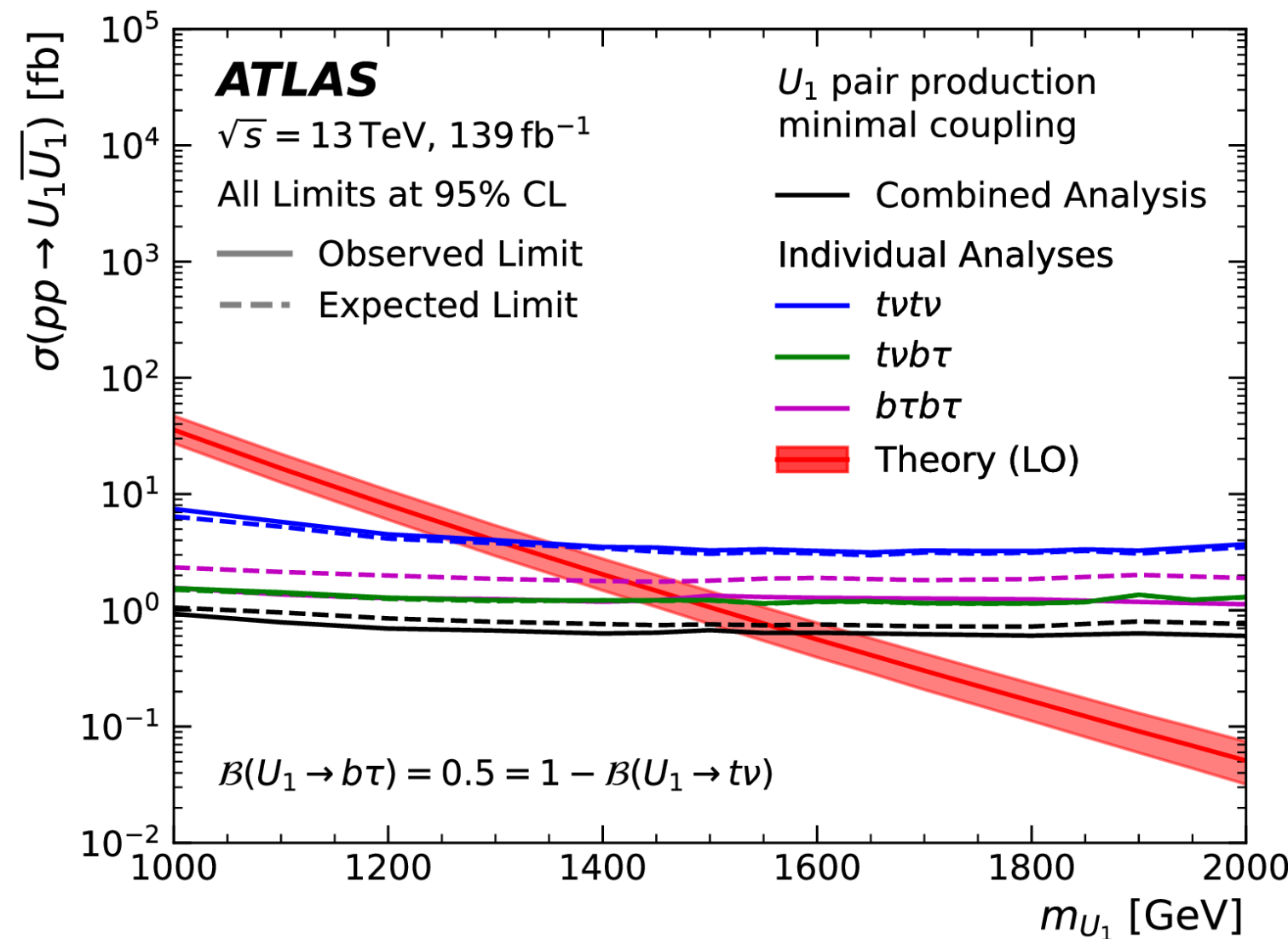
* Statistical combination of 9 ATLAS searches (6 LQ searches and 3 SUSY searches)

* Interpretations;

- Scalar/Vector LQs decaying to 3rd gen LQ or 1st/2nd gen mix LQ
- Limits on $m(LQ)$ and (B) branching fraction to l^\pm .

* Most stringent results to date for majority of the models

Search	Final State	Citation	Interpretation				Signal Region				
			Scalar	Vector	Signal Region						
			LQ_3^u	LQ_3^d	LQ_{mix}^u	LQ_{mix}^d	$U_1^{YM/MC}$	$\tilde{U}_1^{YM/MC}$	N_ℓ	$N_{\tau had}$	N_{bjets}
$t\nu b\tau$			✓	✓	-	-	✓	-	0	1	≥ 2
$b\tau b\tau$			✓	-	-	-	✓	-	{0, 1}	{1, 2}	{1, 2}
$t\tau t\tau$			-	✓	-	-	-	✓	{1, 2, 3}	≥ 1	≥ 1
$t\nu b\ell$			-	-	✓	✓	-	-	1	-	≥ 1
$blb\ell$			-	-	✓	-	-	-	2	-	{0, 1, 2}
$t\ell t\ell$ (2 ℓ)			-	-	-	✓	-	-	2	-	-
$t\ell t\ell$ ($\geq 3\ell$)			-	-	-	✓	-	-	{3, 4}	-	≥ 2
$t\nu t\nu$			✓	-	✓	-	✓	-	0	0	≥ 2
$b\nu b\nu$			-	✓	-	✓	-	-	0	-	≥ 2

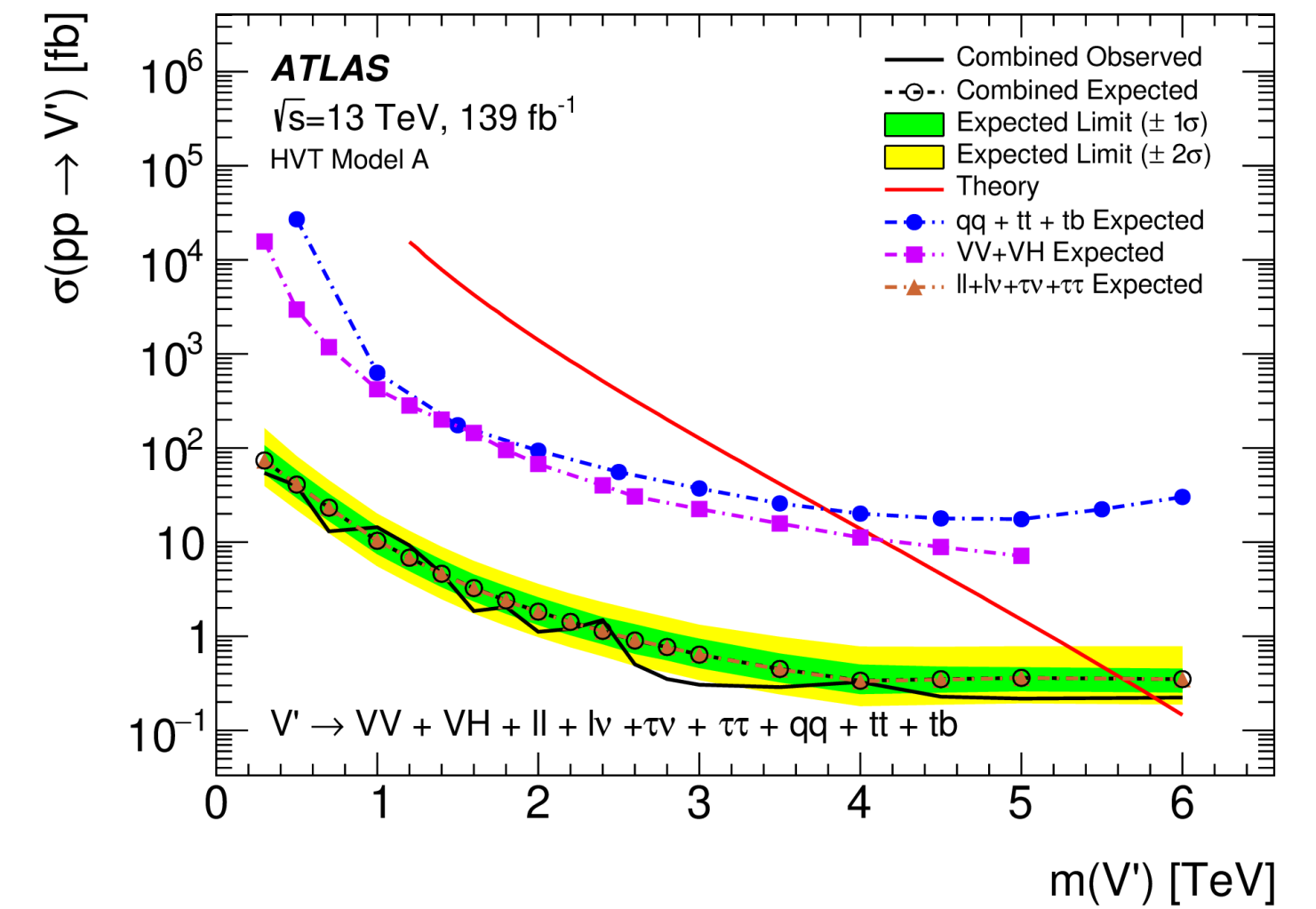


Resonances

Combination of heavy spin-1 resonances

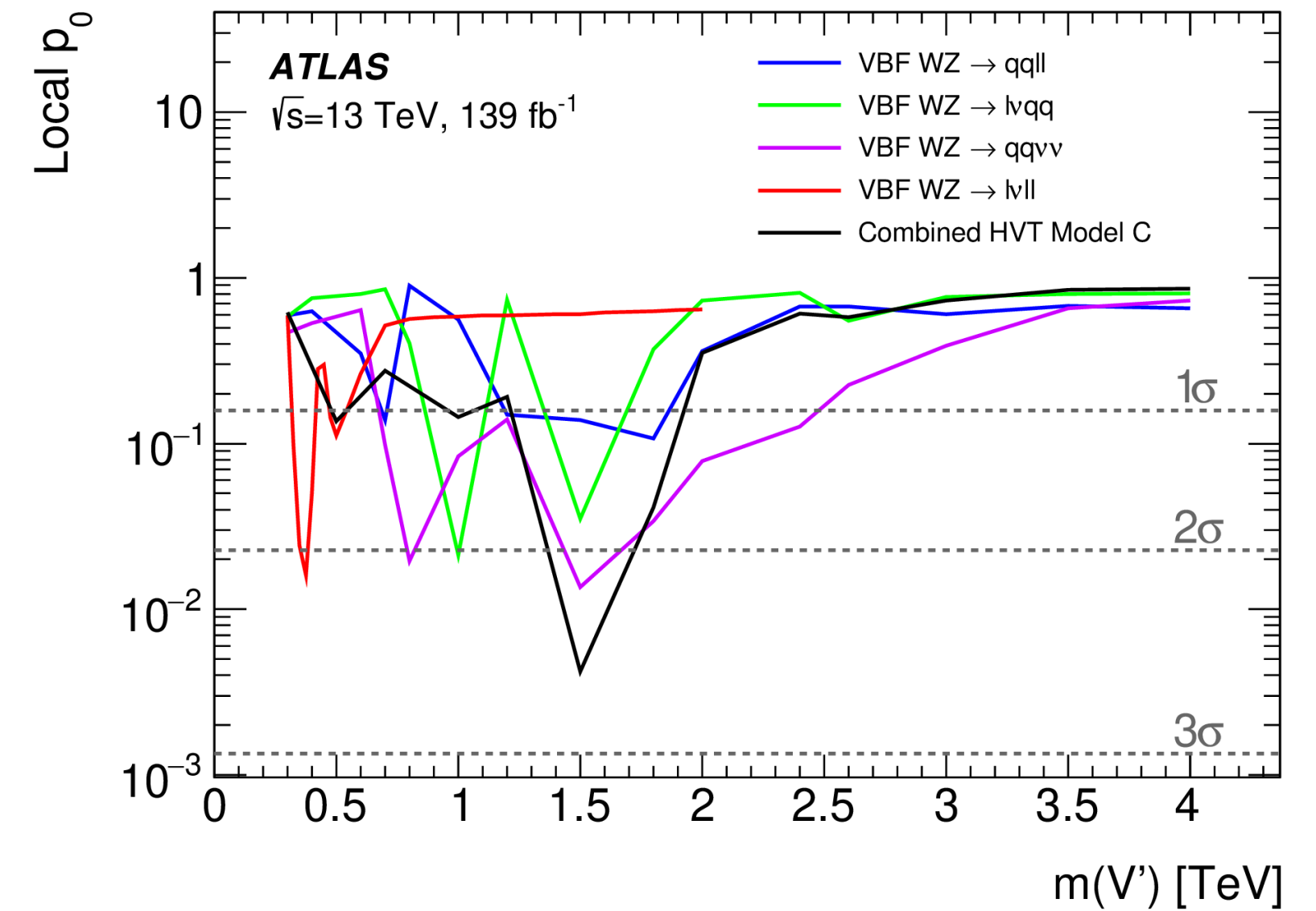
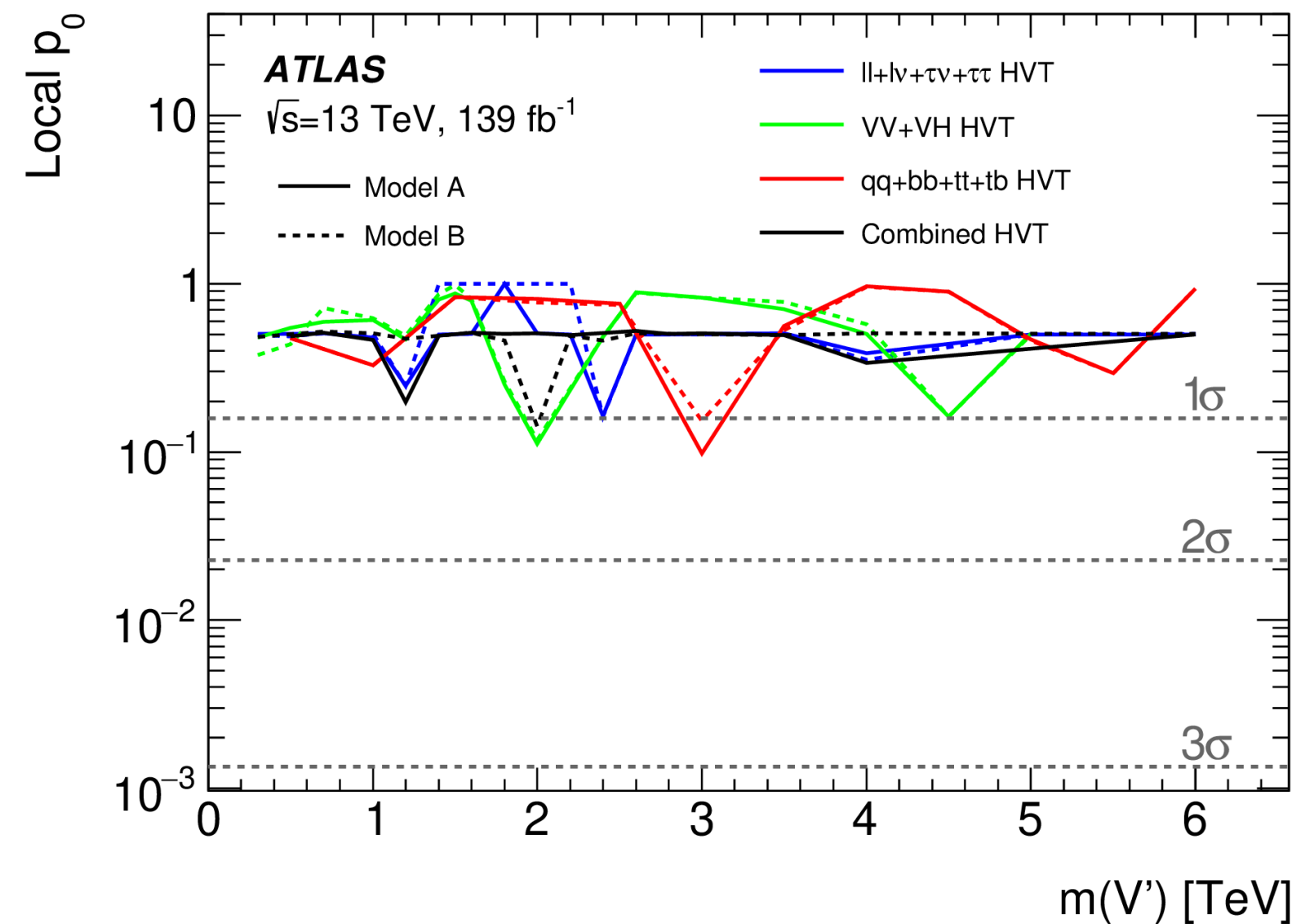
EXOT-2022-38

- * Combination of searches for new heavy spin-1 resonances decaying into different pairings of W , Z , or Higgs bosons selecting quark pairs (qq , bb , tt , and tb) or third-generation leptons ($\tau\nu$ and $\tau\tau$)
- * Analyses complementarity increases sensitivity to new physics and makes resulting constraints stronger



* Data exclude:

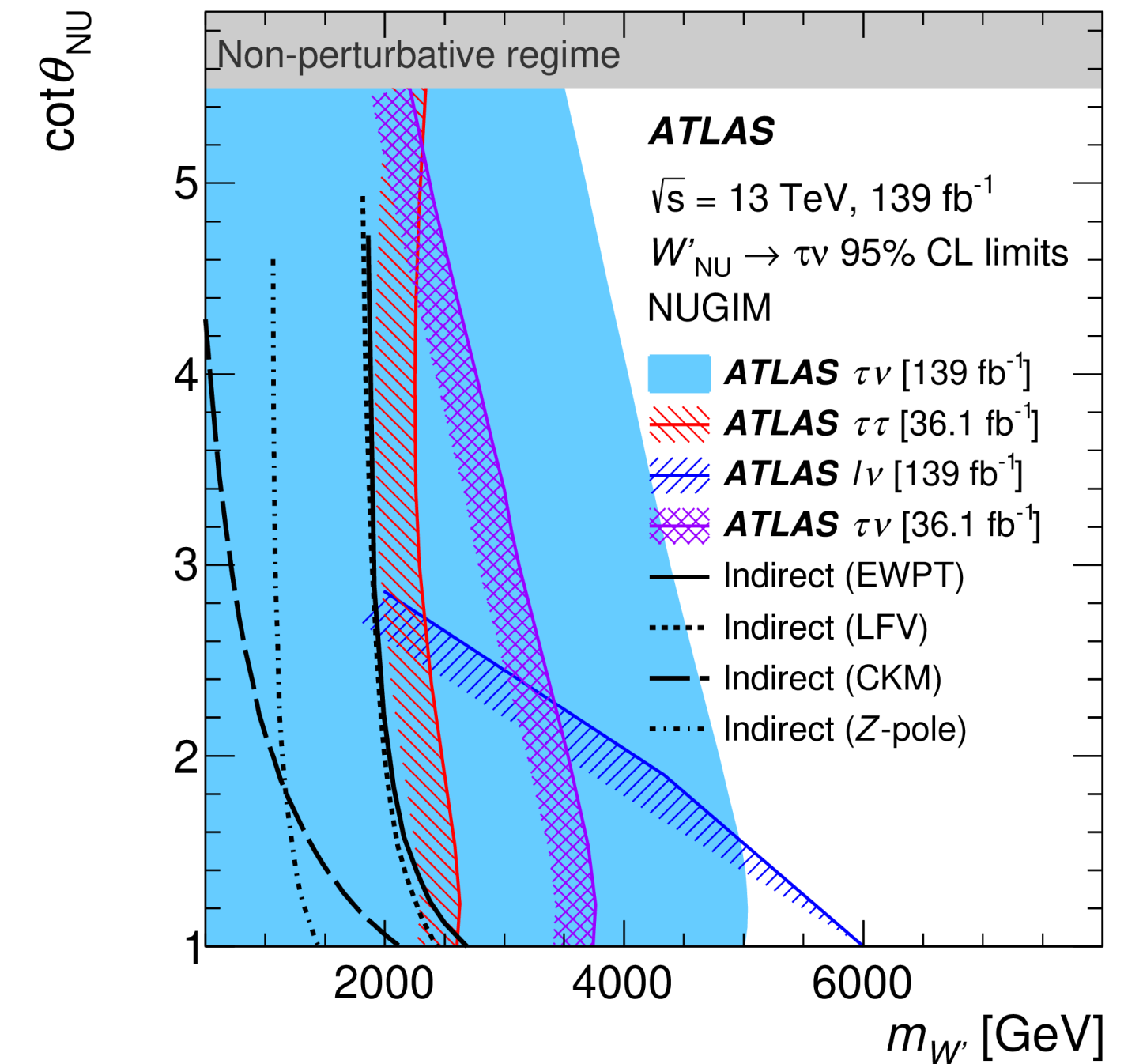
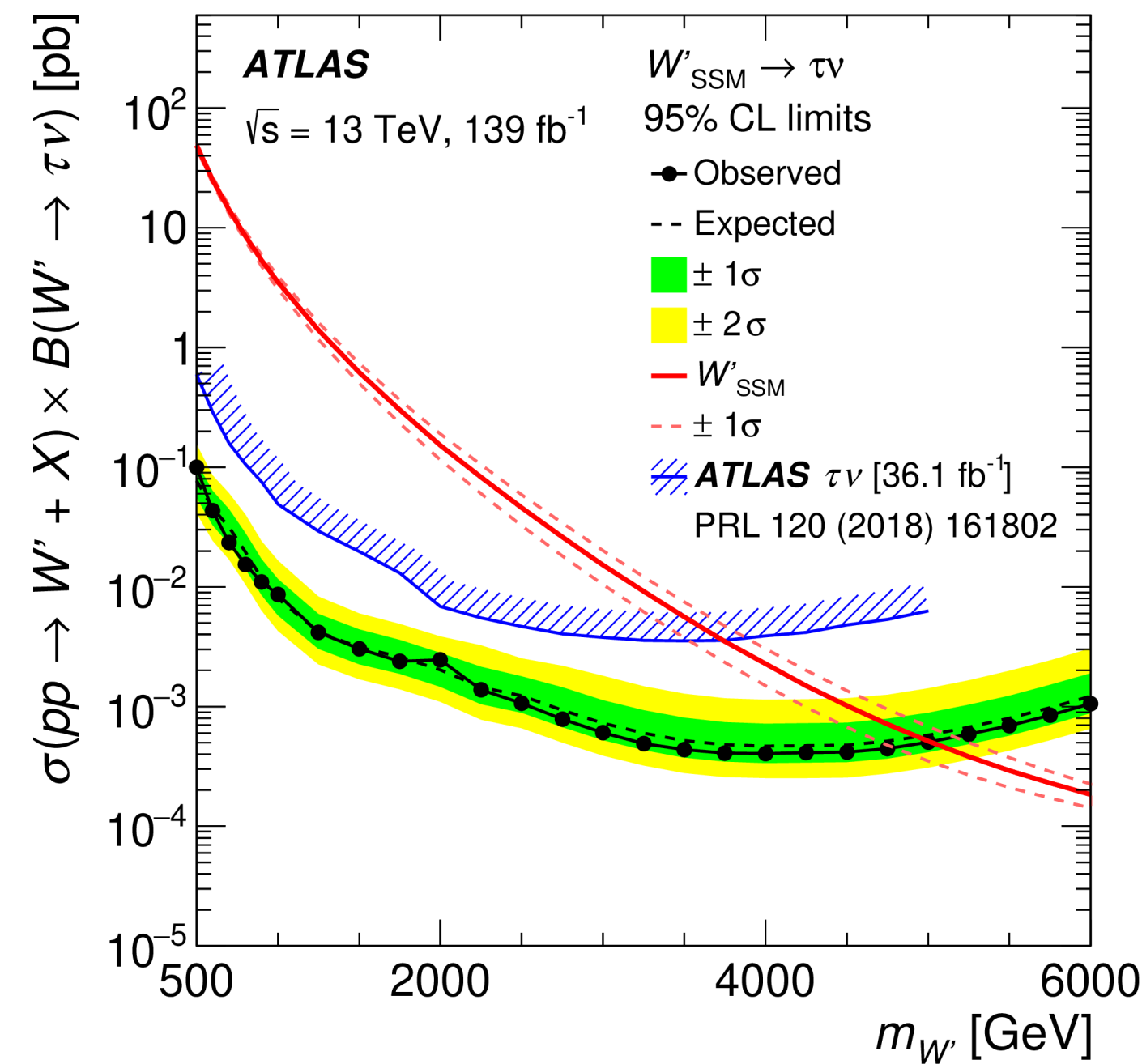
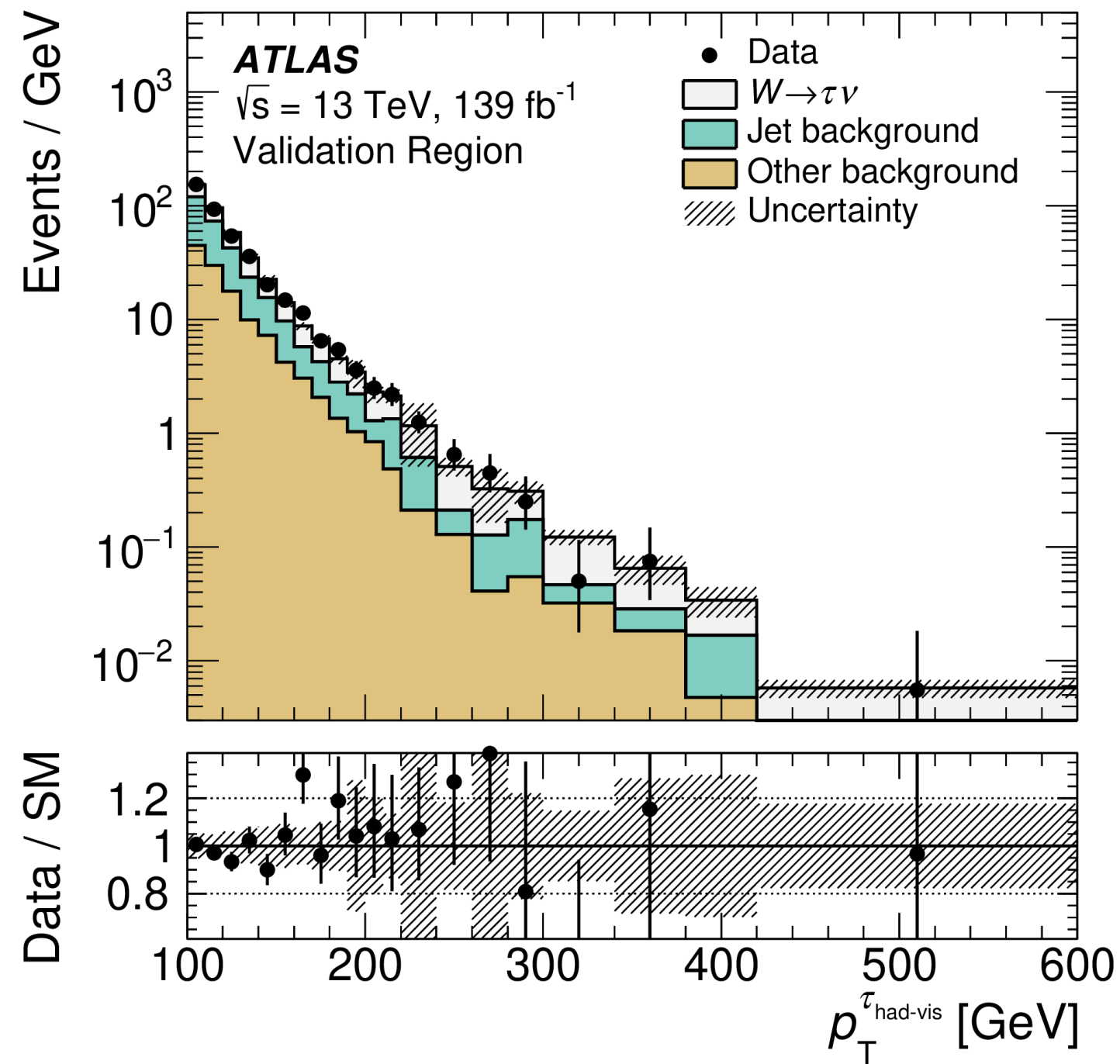
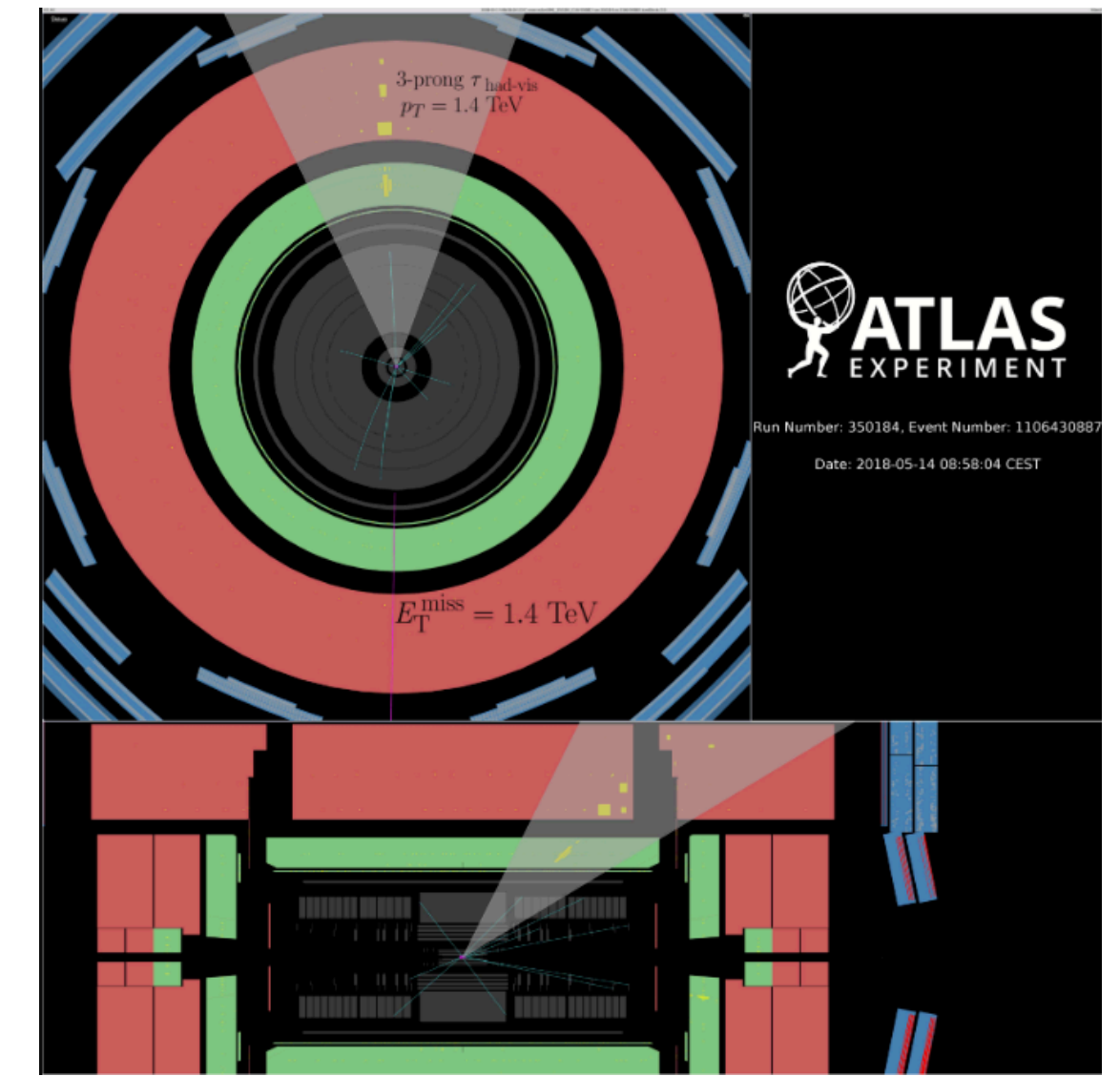
- ☆ a heavy vector-boson triplet with mass below 5.8 TeV in a weakly coupled scenario,
- ☆ below 4.4 TeV in a strongly coupled scenario,
- ☆ up to 1.5 TeV in the case of production via vector-boson fusion.



High-mass reso \rightarrow $T+MET$

EXOT-2018-37

- * τ_h reconstructed in hadronic decay modes, the total $p_T(\nu)$ inferred from reconstructed missing transverse momentum
- * **No excess of events** above the Standard Model
 - ☆ Heavy W' vector bosons with masses up to 5.0 TeV are excluded
 - ☆ Considering non-universal couplings, W' bosons are excluded for masses less than 3.5 - 5.0 TeV



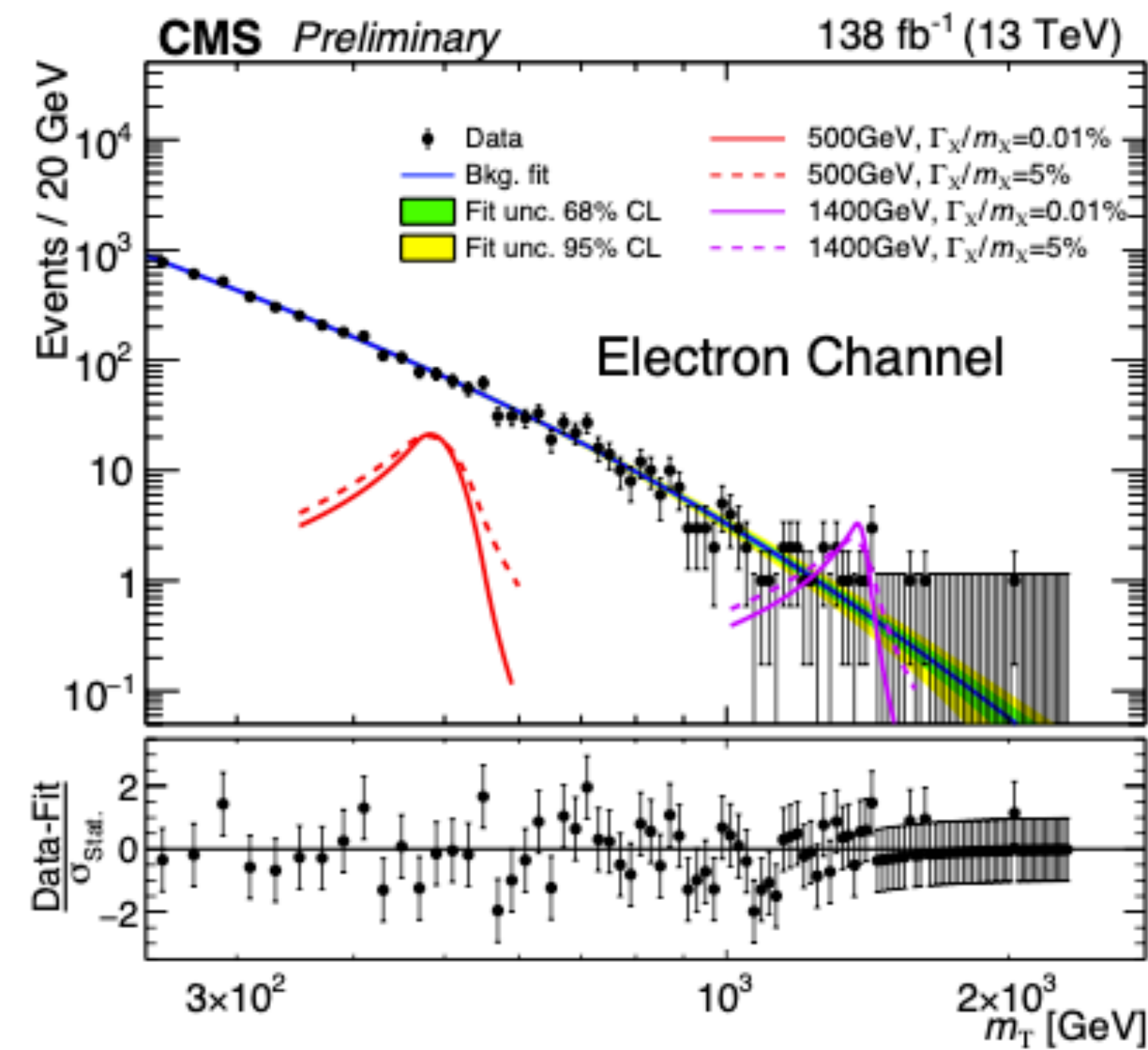
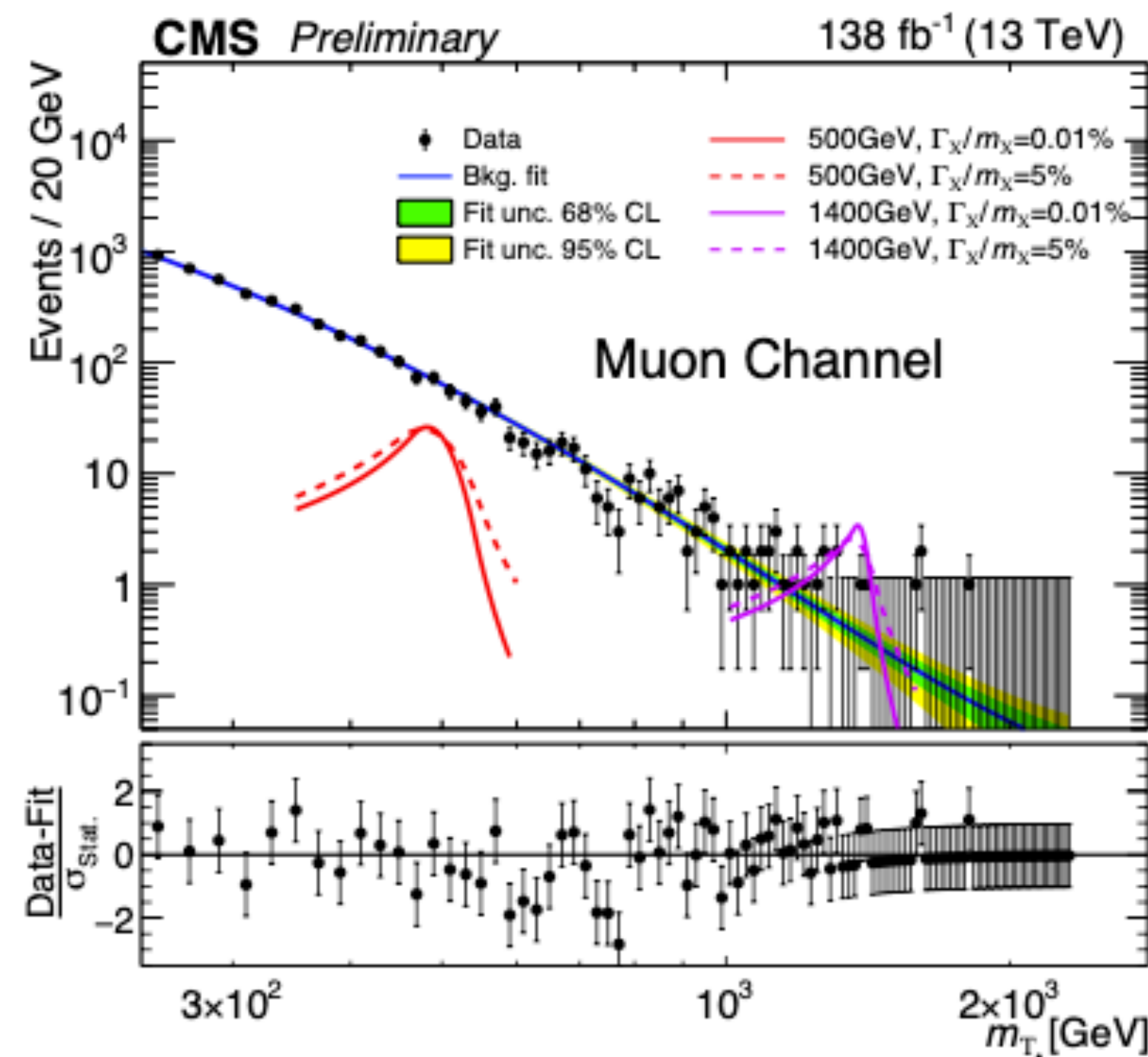
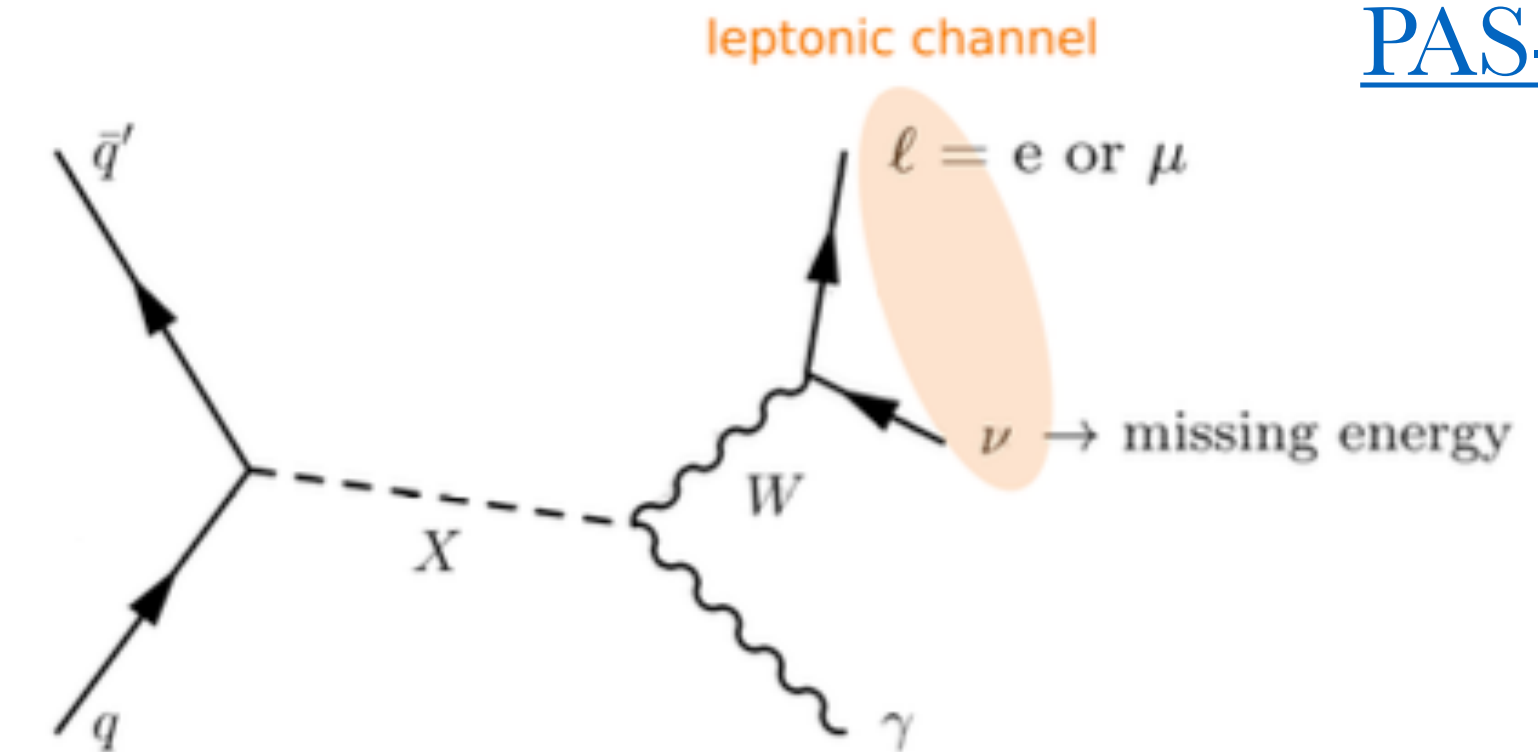
Search for a resonance decaying to $W\gamma$

PAS-EXO-21-017

- * W boson decays leptonically (e or μ)
- * Bump hunt in the transverse mass m_T spectrum

$$(m_T)^2 = (E_T(\gamma) + E_T(\ell) + p_T^{\text{miss}})^2 - |\vec{p}_T(\gamma) + \vec{p}_T(\ell) + \vec{p}_T^{\text{miss}}|^2$$

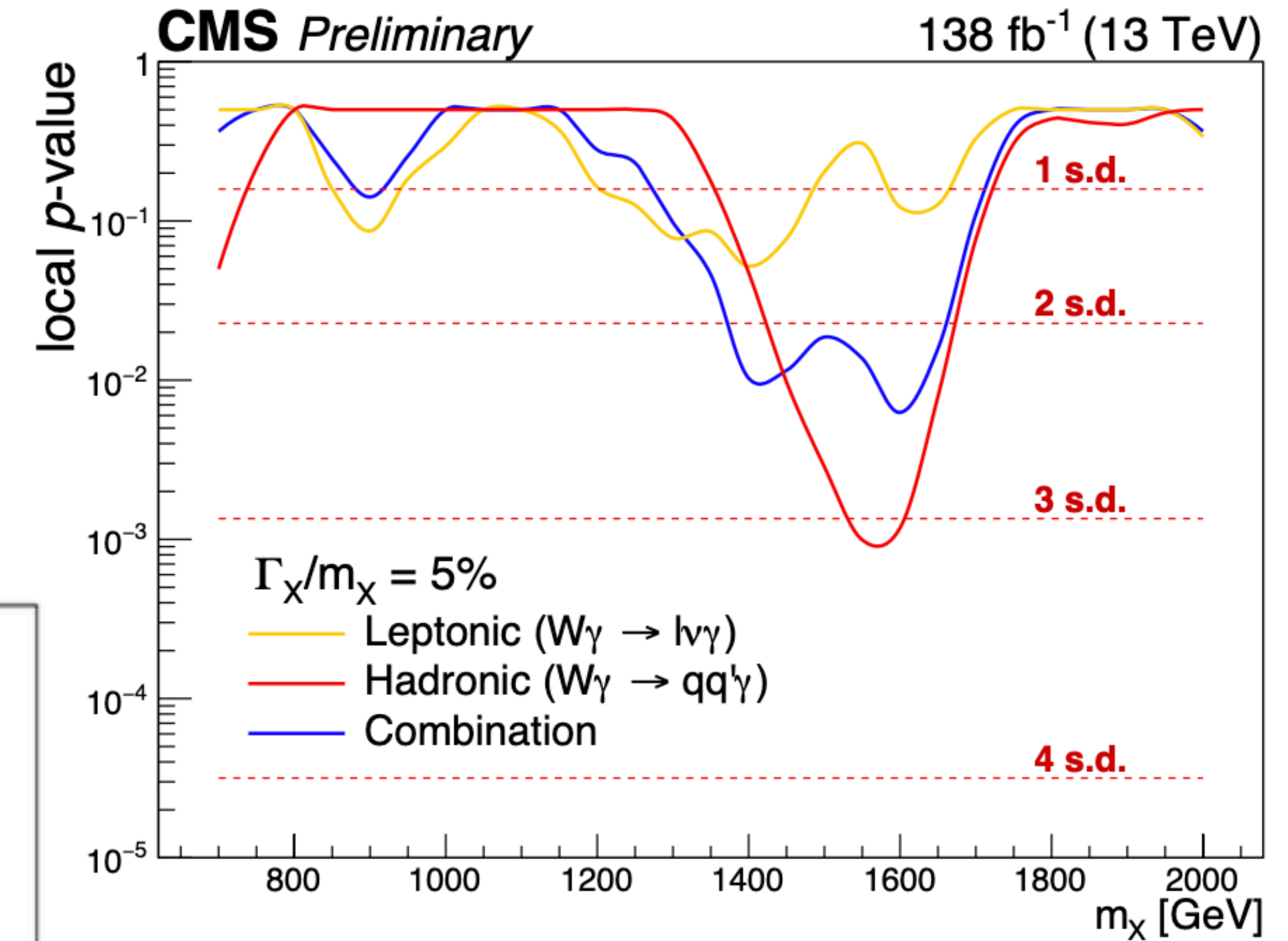
- * Parametric fit to the data using signal shape templates



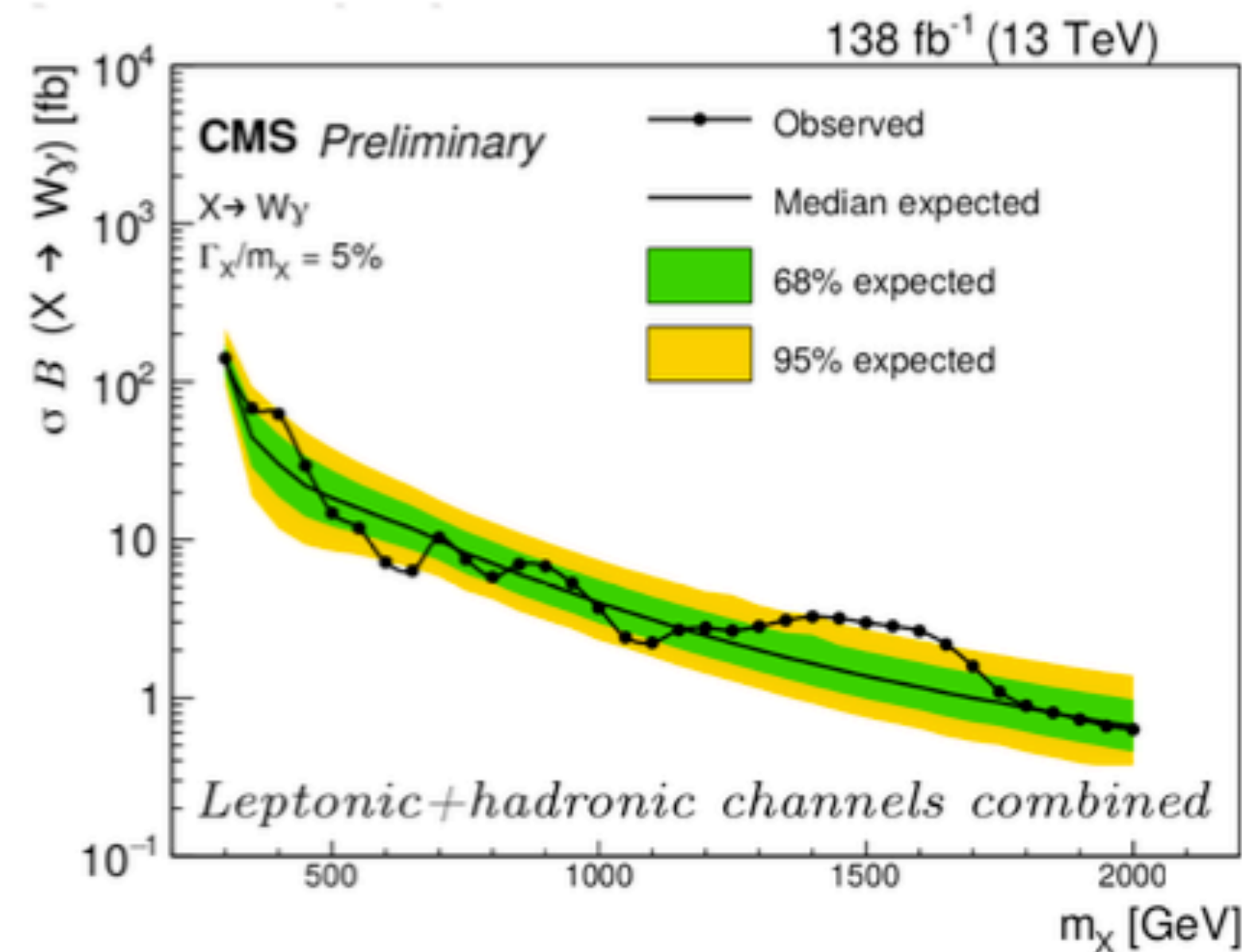
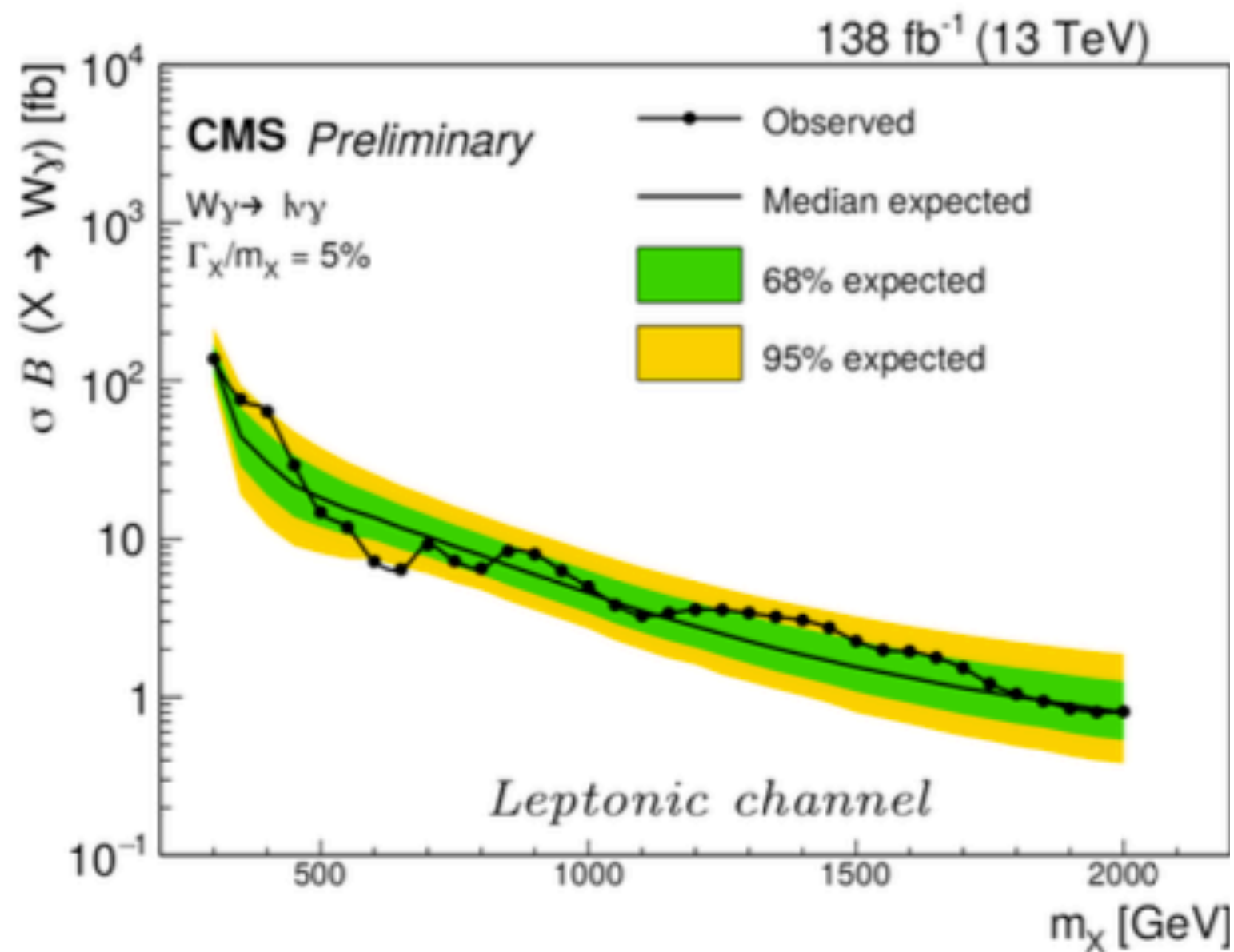
Search for a resonance decaying to $W\gamma$

PAS-EXO-21-017

- * **No significant deviation** from the background-only expectation is observed
- * **Combination** with search using hadronic channel [doi:10.1016/j.physletb.2022.136888](https://doi.org/10.1016/j.physletb.2022.136888)
- * **Most stringent limits** to date in the probed mass range

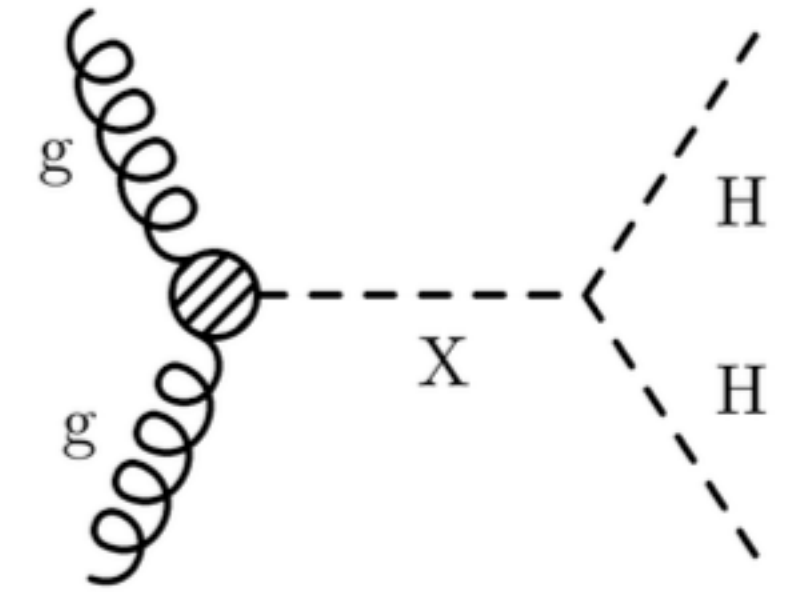


Local excess of 3.1σ in the hadronic analysis reduced to 2.5σ with the two channels combined

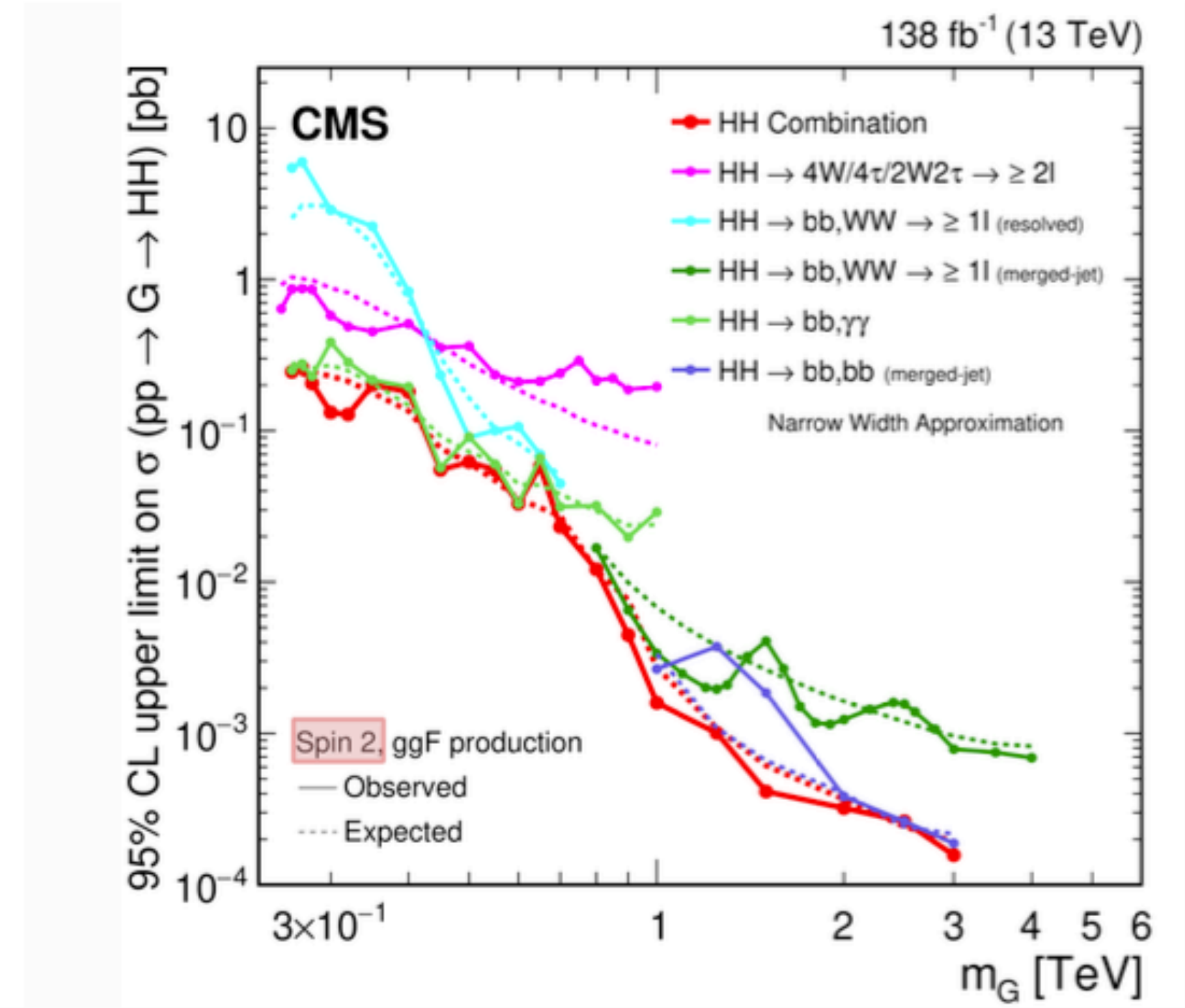
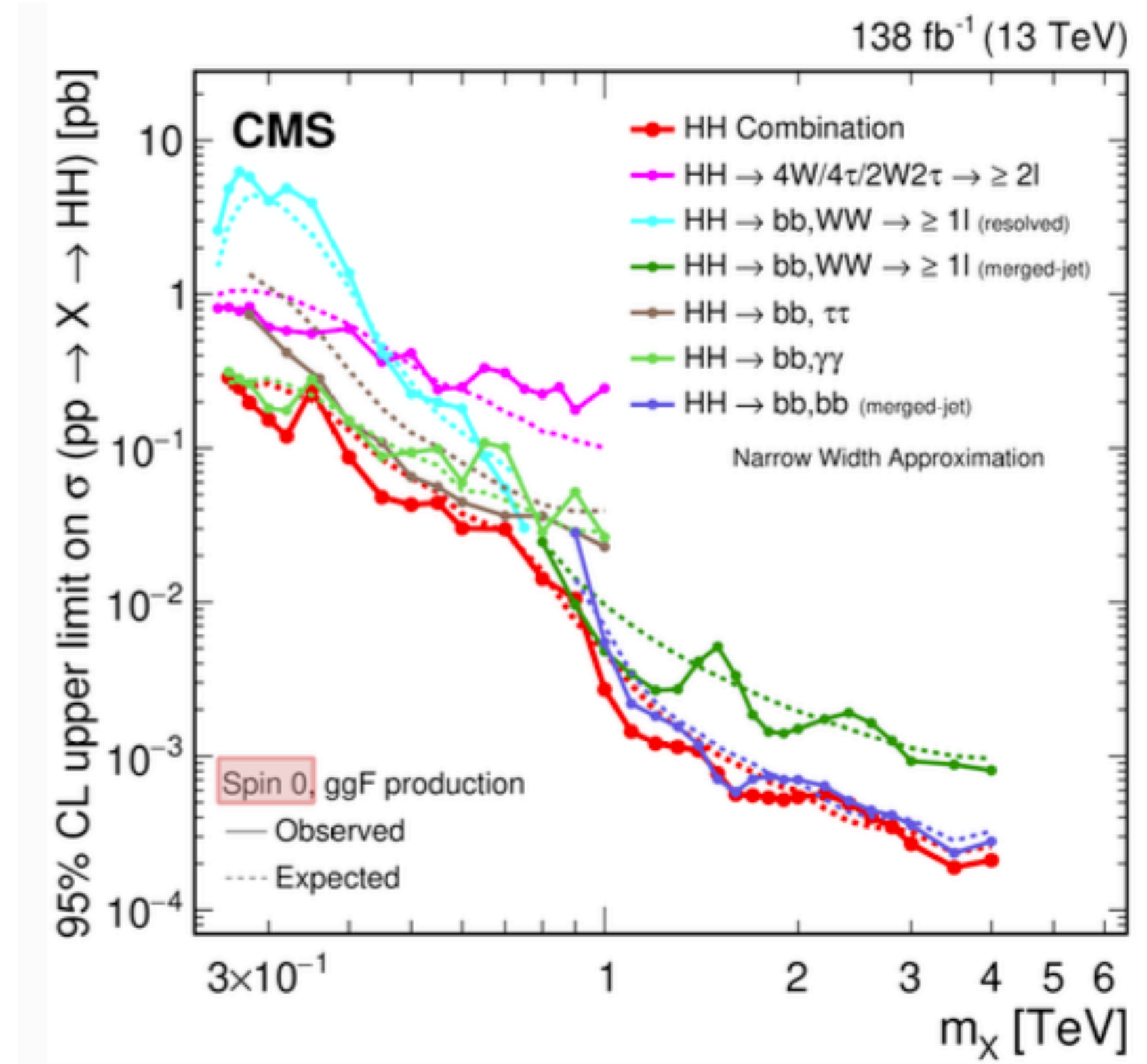


Search for resonances decaying to HH

- * Resonances decaying to 2-Higgs bosons predicted in many new physics models (extended Higgs sector, extra dimensions, etc)
- * Several searches have been performed with different final states (all summarised in the review paper!)



- * $X \rightarrow HH$ searches are statistically combined
 - ☆ I For both cases where X is a spin 0 or spin 2 particle
 - ☆ I Best limits for masses below 320 GeV and above 800 GeV



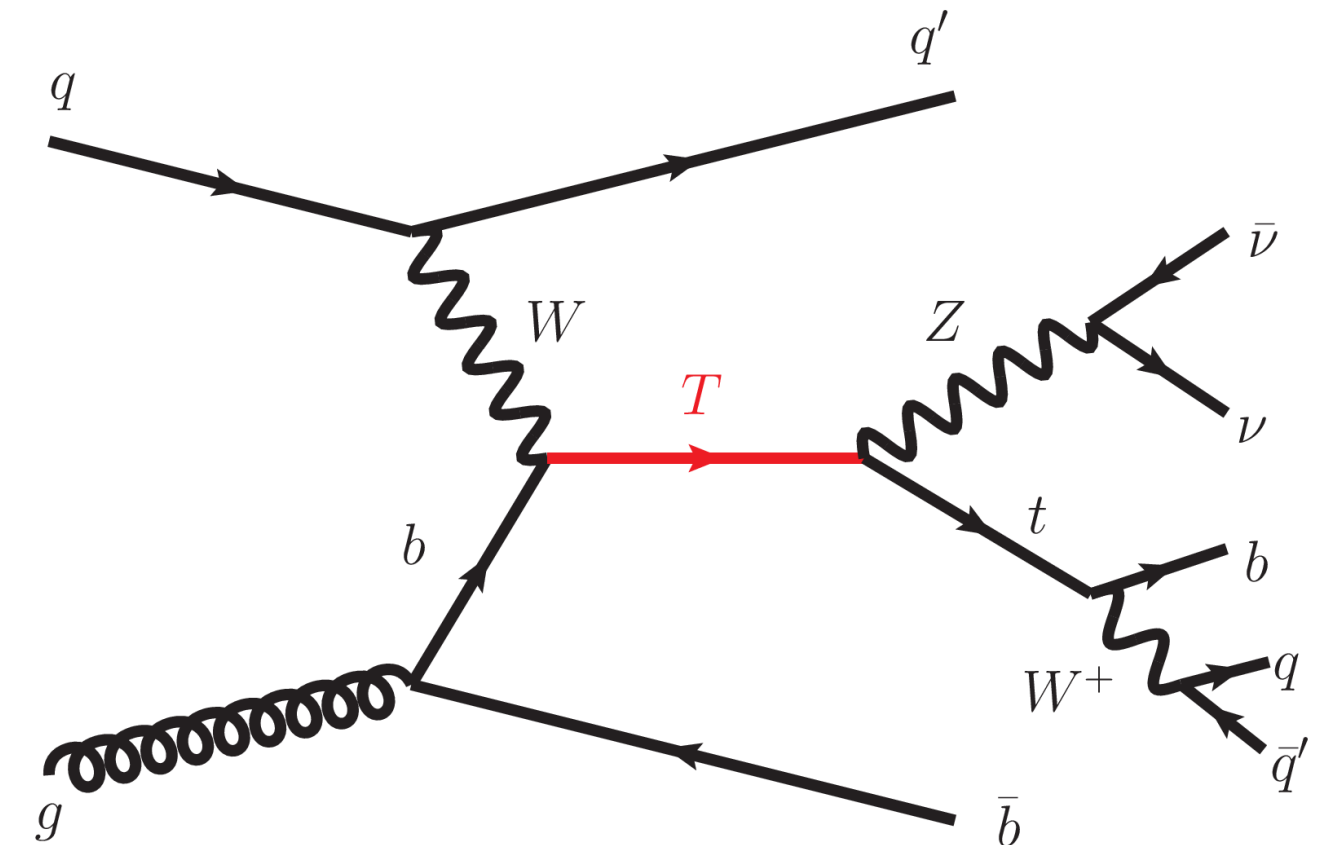
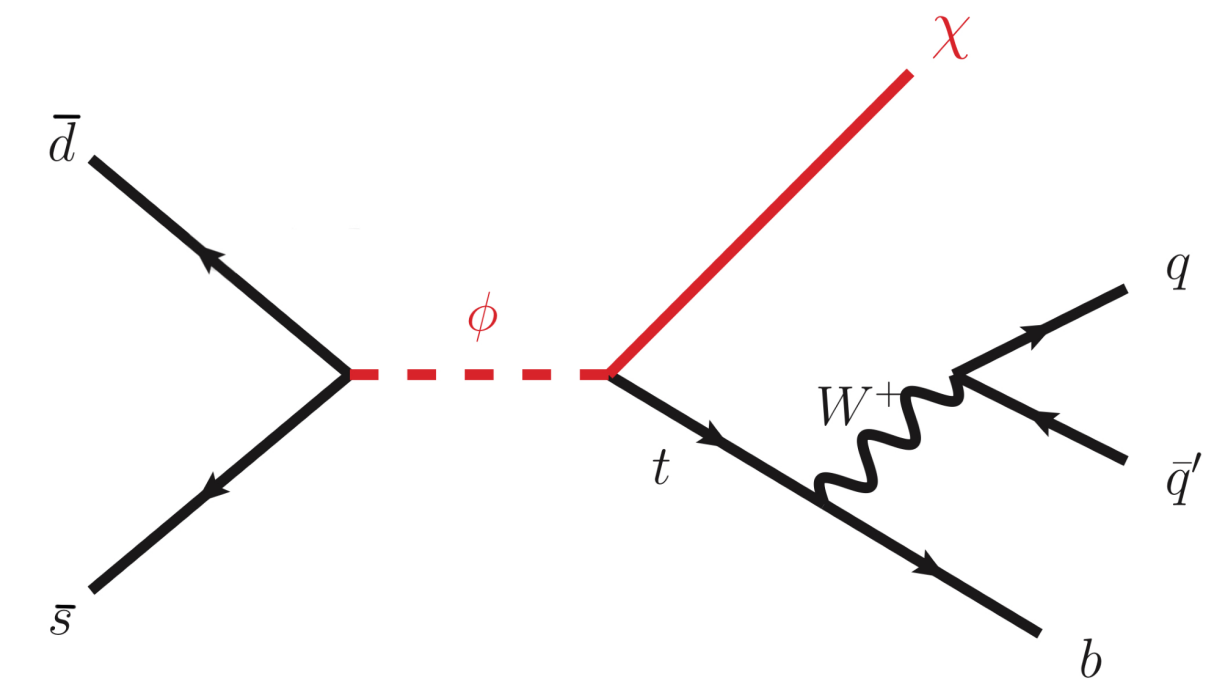
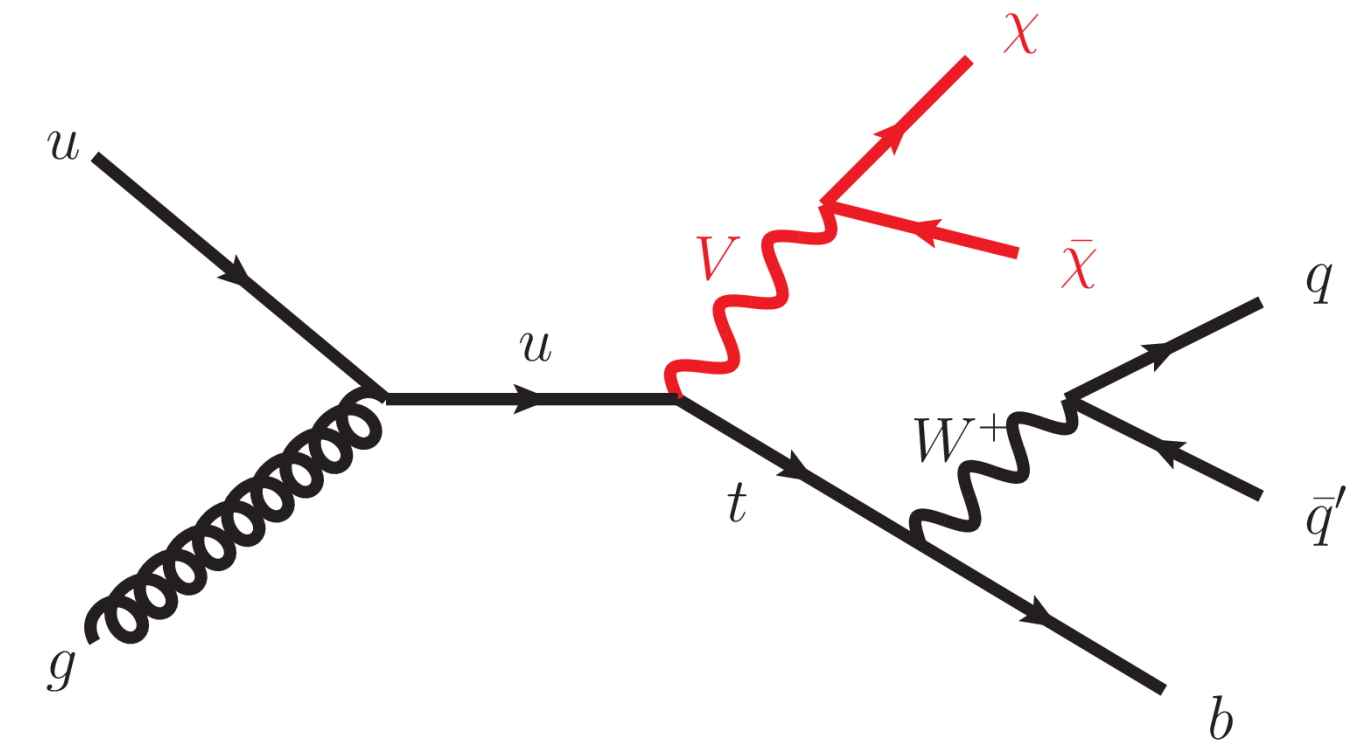
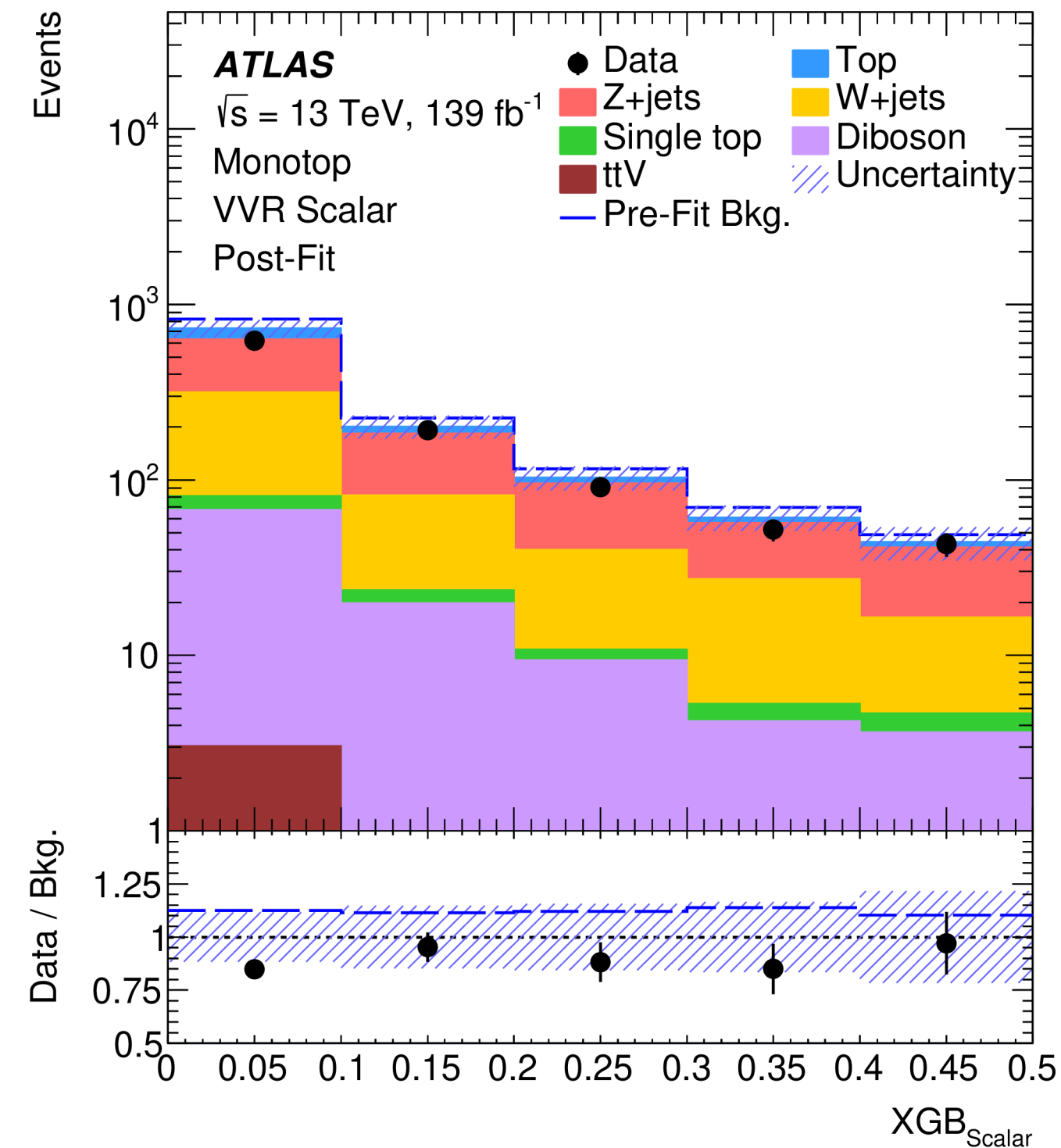
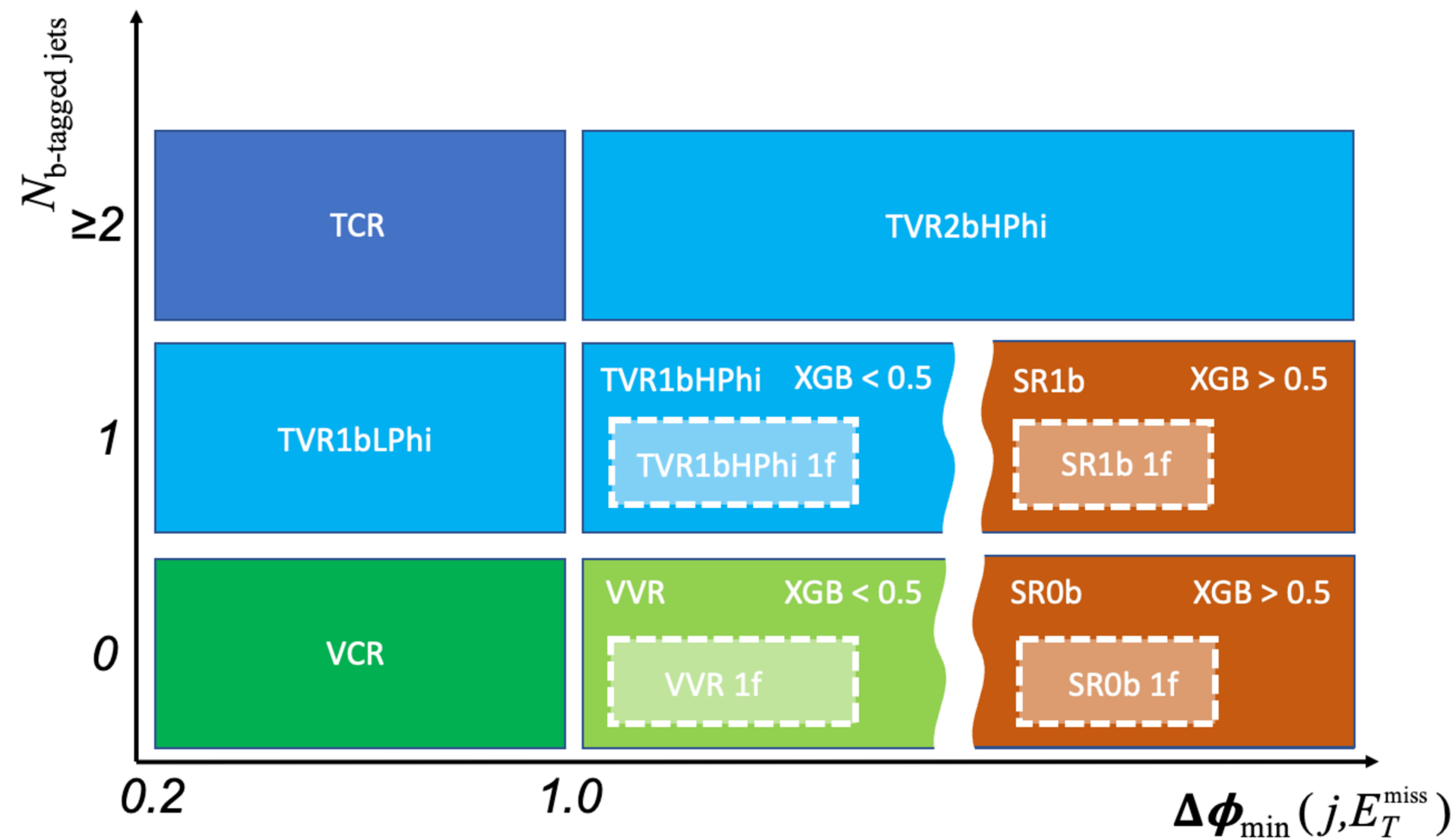
[CERN-EP-2024-062](https://arxiv.org/abs/2406.12345)

Outliers

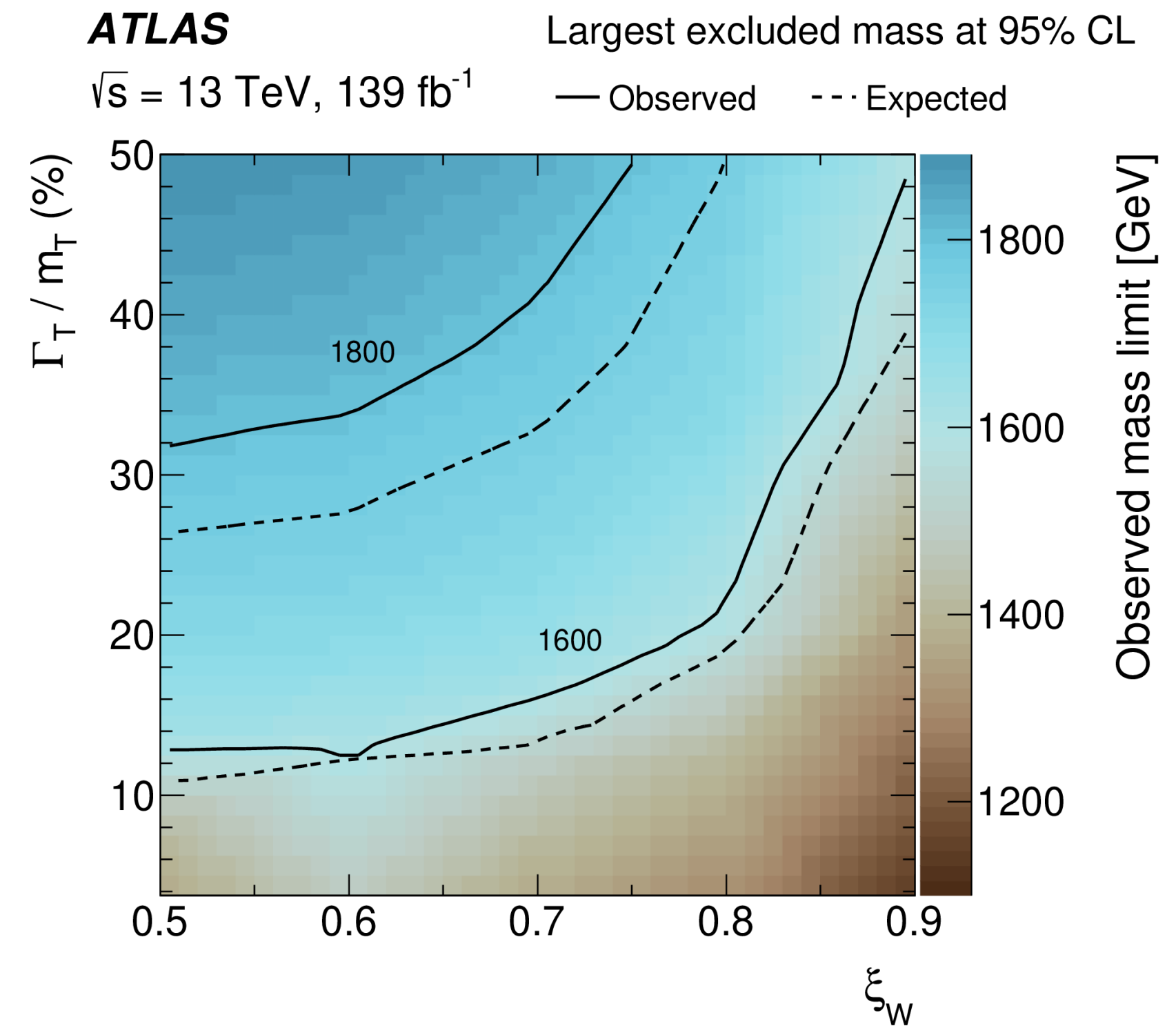
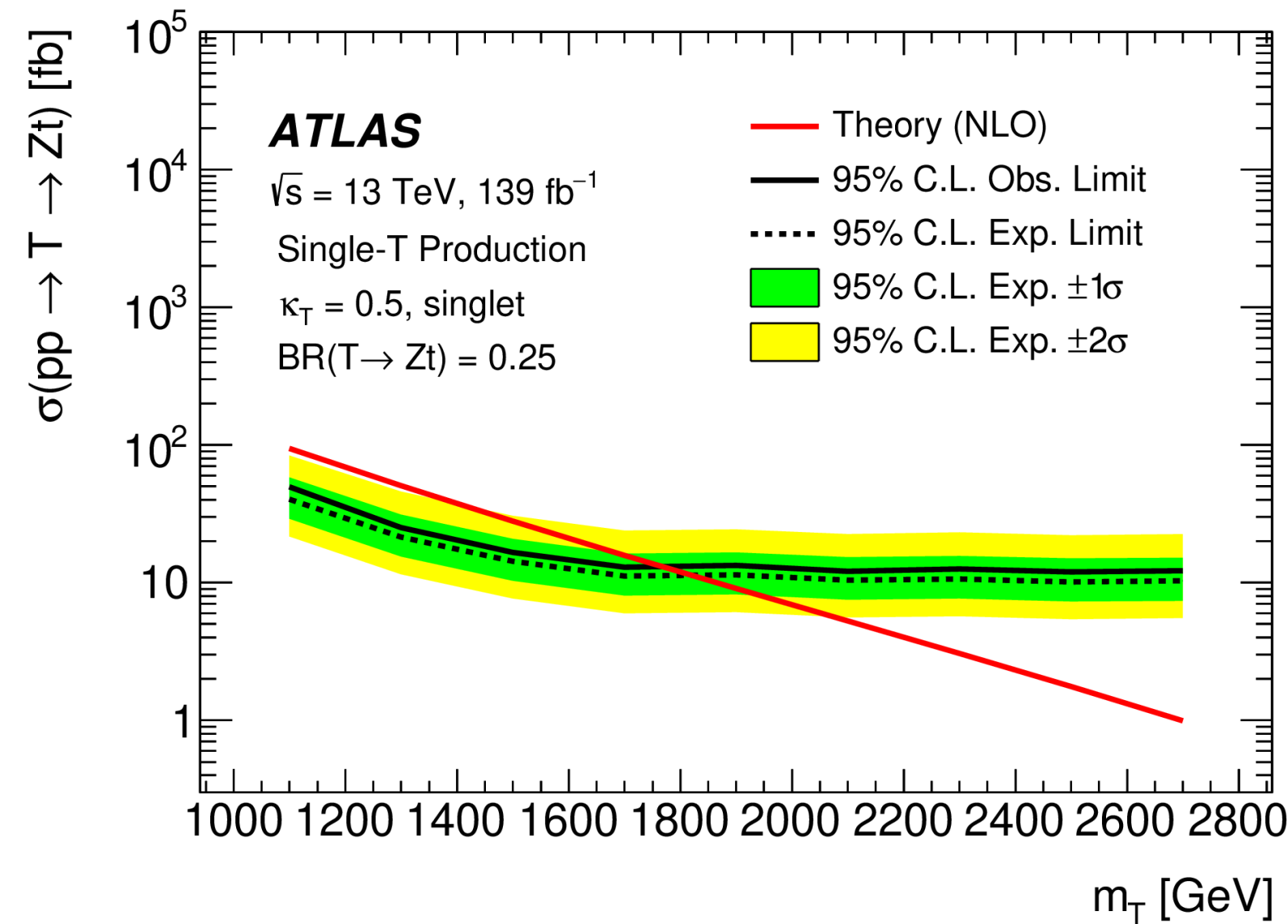
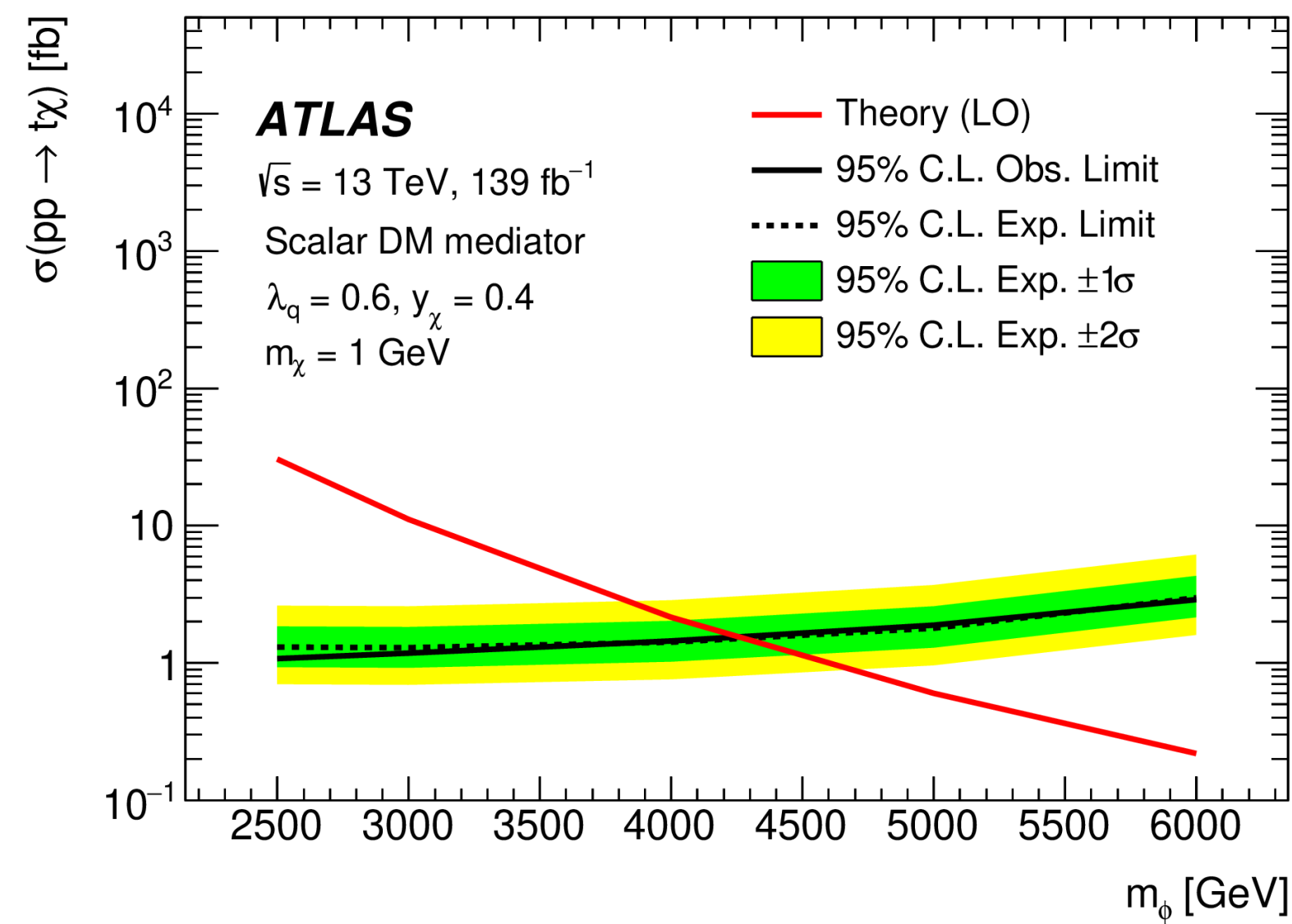
Mono-top

EXOT-2022-40

- * New particles in final states with a boosted top+MET
- * Results are interpreted in the context of simplified models for **Dark Matter particle** production and the single production of a **vector-like T quark**

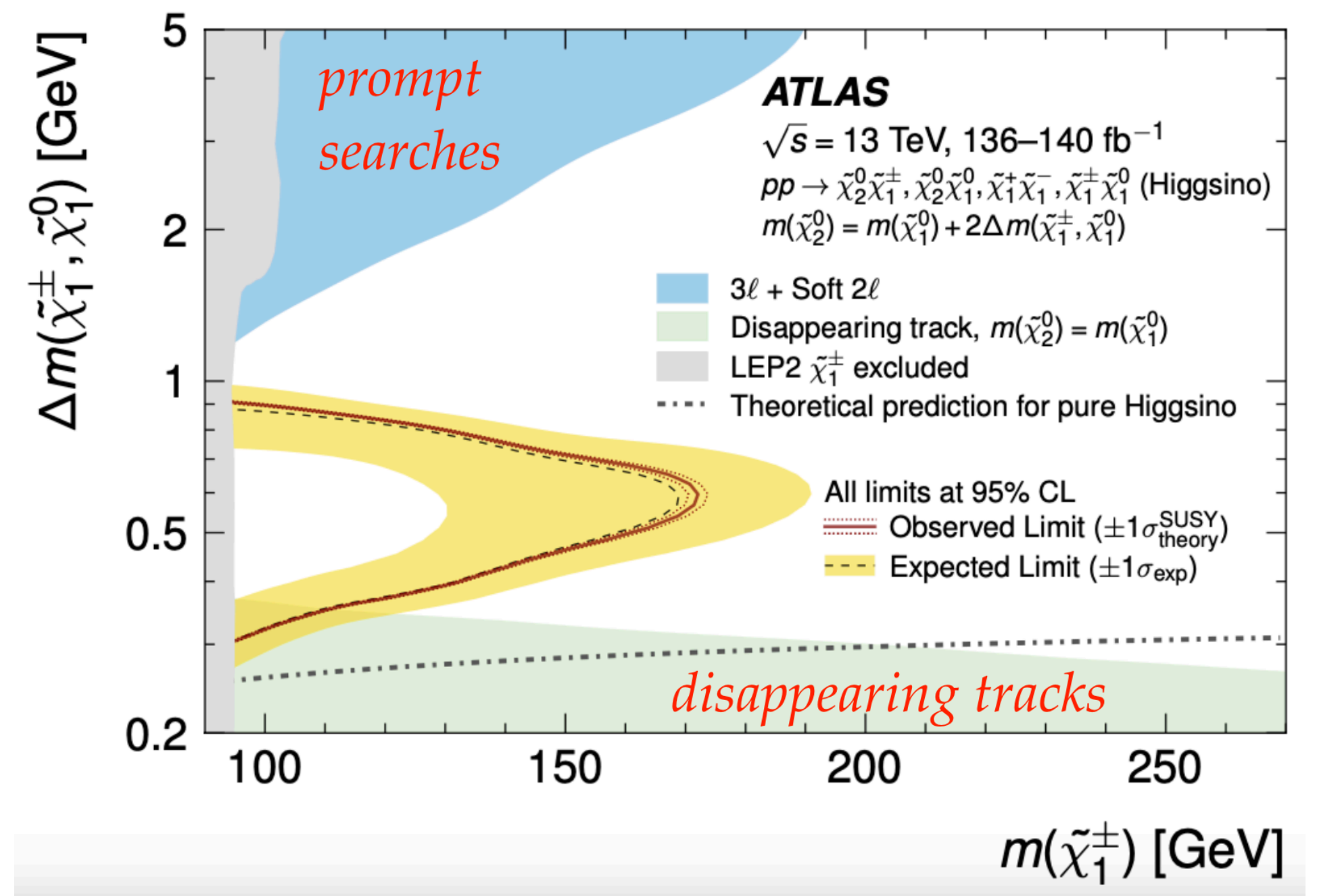
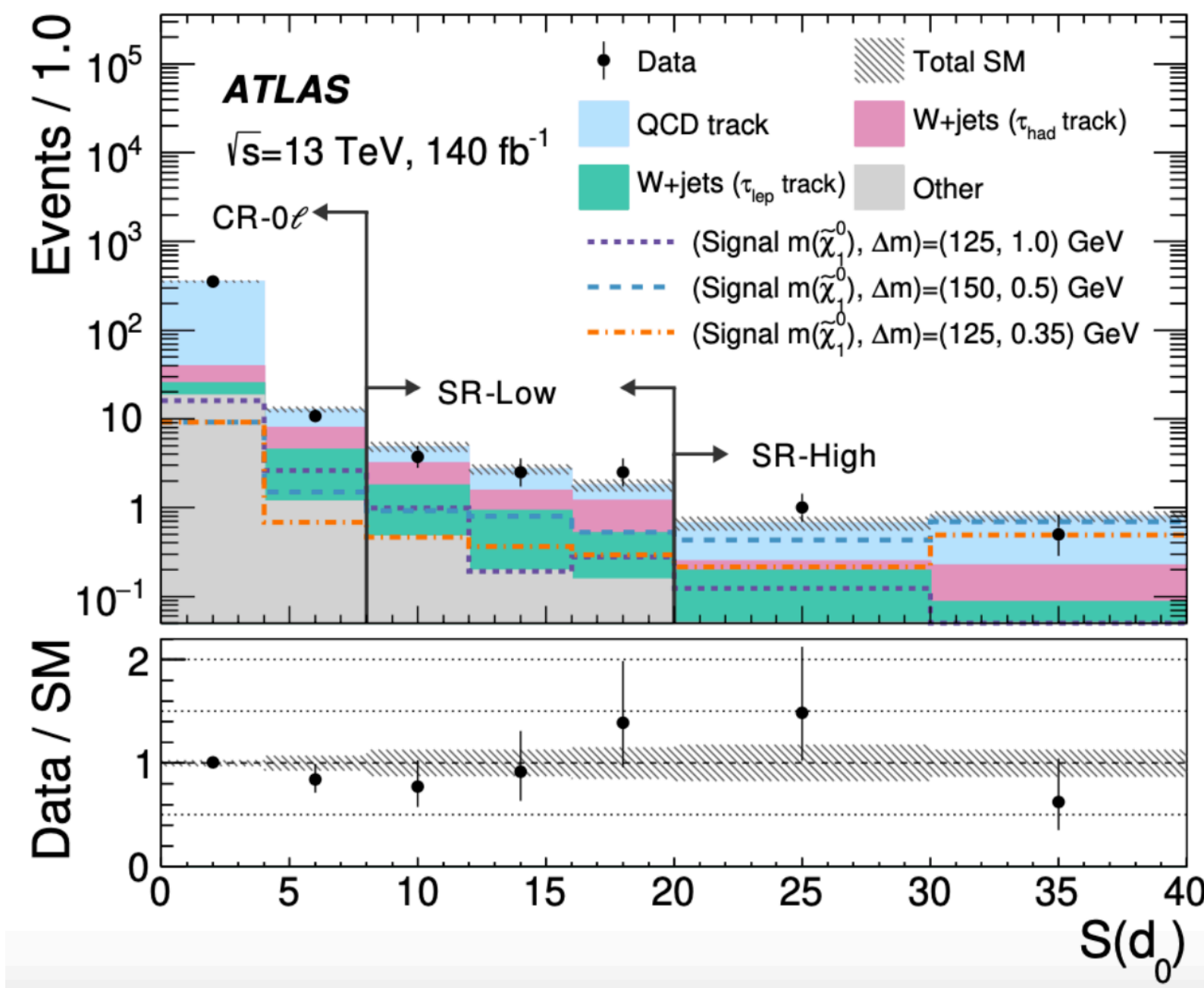
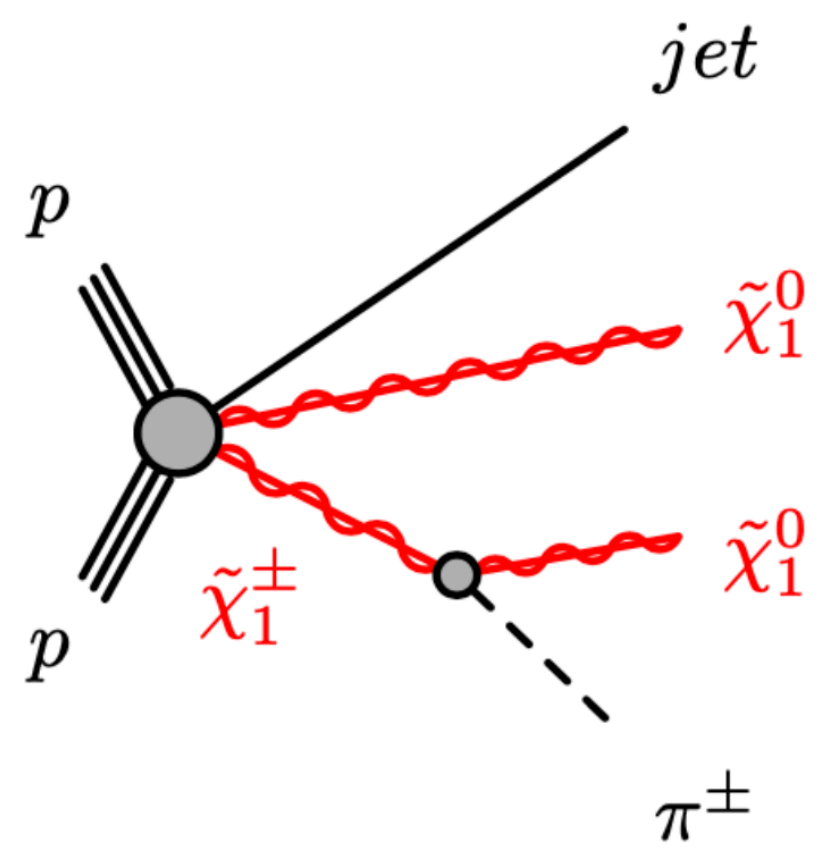


- * Production of **single vector-like T quark** excluded for masses below 1.8 TeV
- * **Dark Matter particles** + single top quark excluded for masses of a scalar (vector) mediator up to 4.3 (2.3) TeV
- * Exclusion limits on the T quark mass in the singlet SU(2) scenario



Search for mass-degenerate Higgsinos

- * RPC SUSY: higgsino-like DM can be almost mass degenerate with charged NLSP ($\Delta(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) \sim 250\text{--}400\text{ MeV}$) \rightarrow disappearing track signature
- * For Δm of few GeV \rightarrow prompt soft lepton searches via $m_{\tilde{\chi}_1^\pm} \rightarrow Z^*(\ell\ell)m_{\tilde{\chi}_1^0}$ are sensitive
- * “Mildly” displaced soft track (hit in first layer, $2\text{ GeV} < p_T < 5\text{ GeV}$) **targets mass gap from 0.3 to 1 GeV** (veto if track compatible with K_s or Λ decay)
- * No excess over bkg prediction \rightarrow limits exceeding LEP results for first time

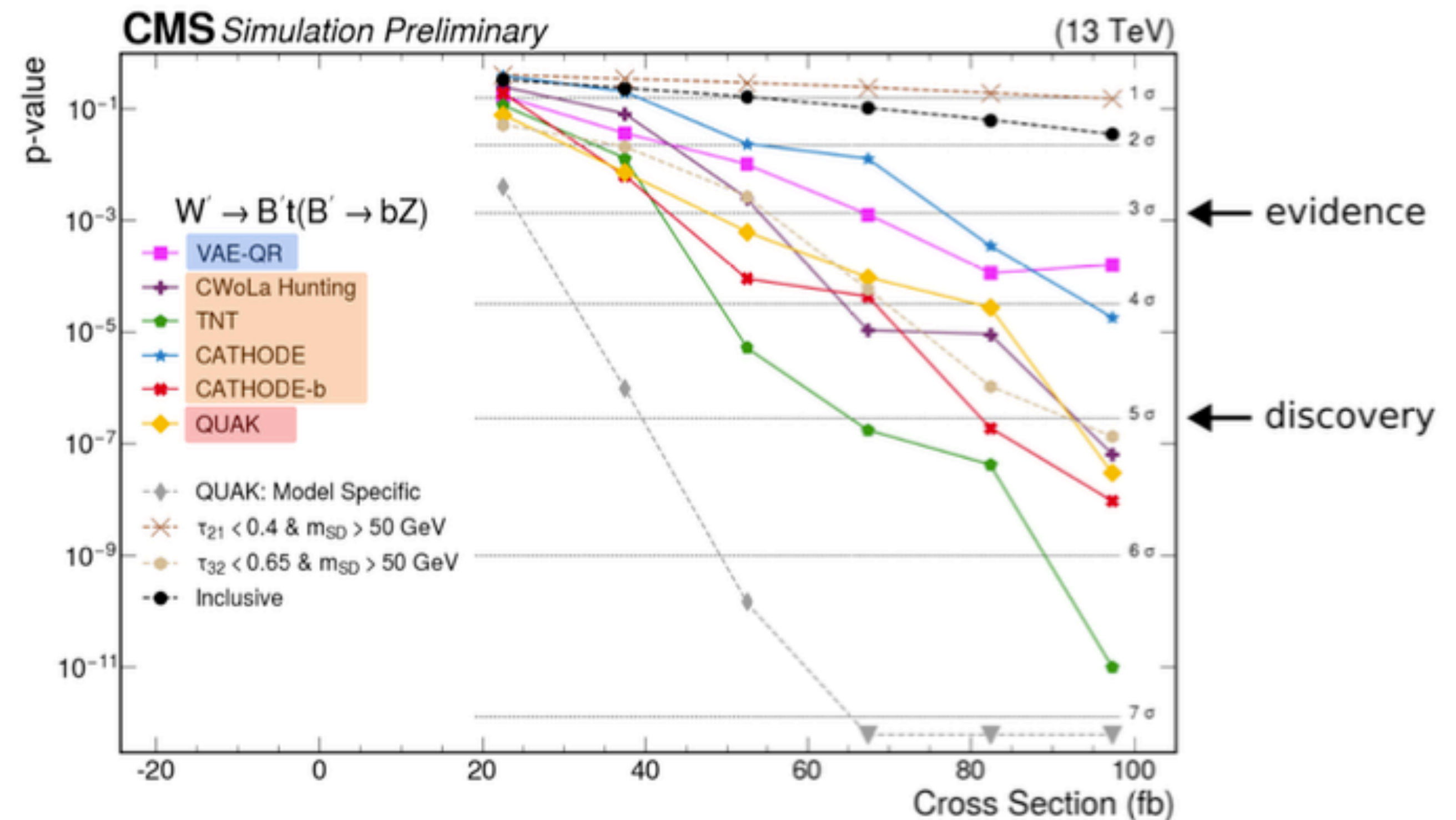
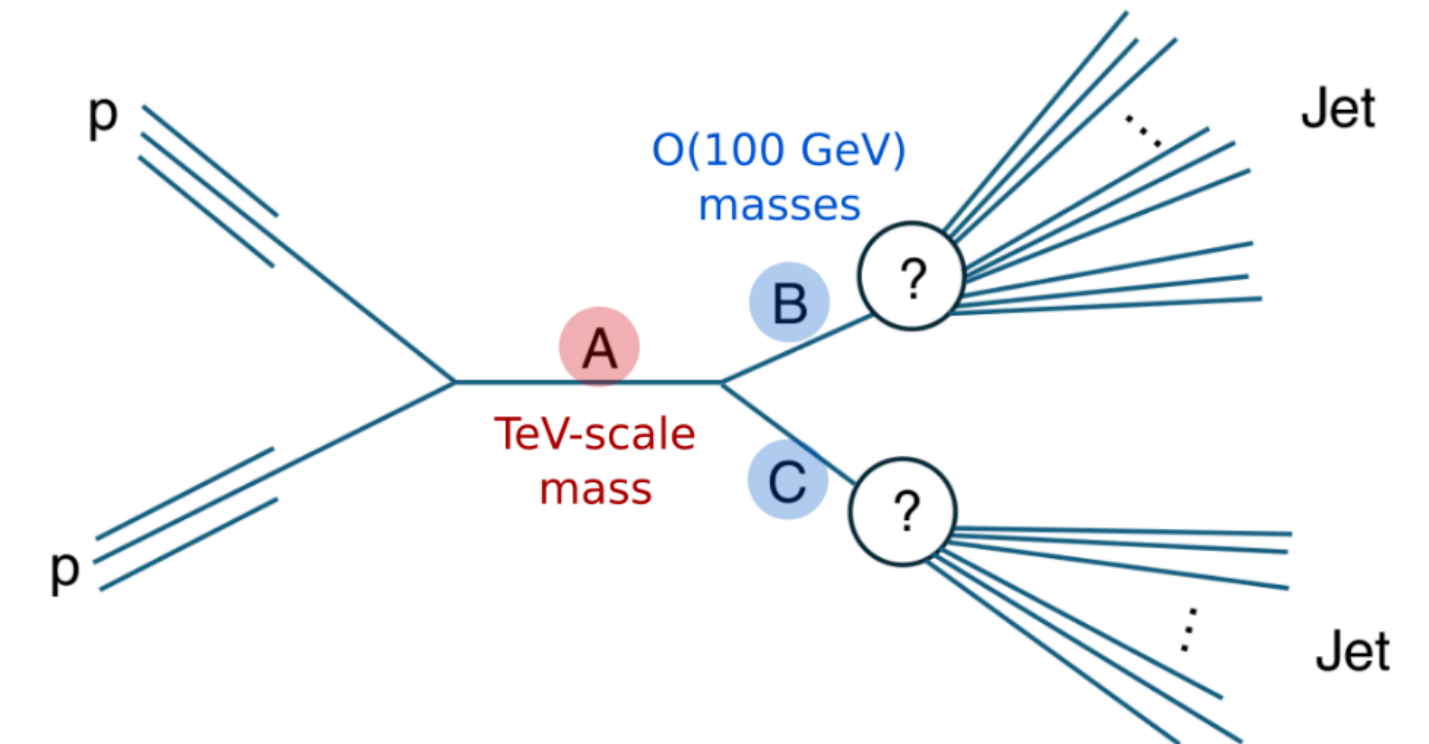


2401.14046 [hep-ex]

Model-agnostic search with dijet resonances

CMS-PAS-EXO-22-026

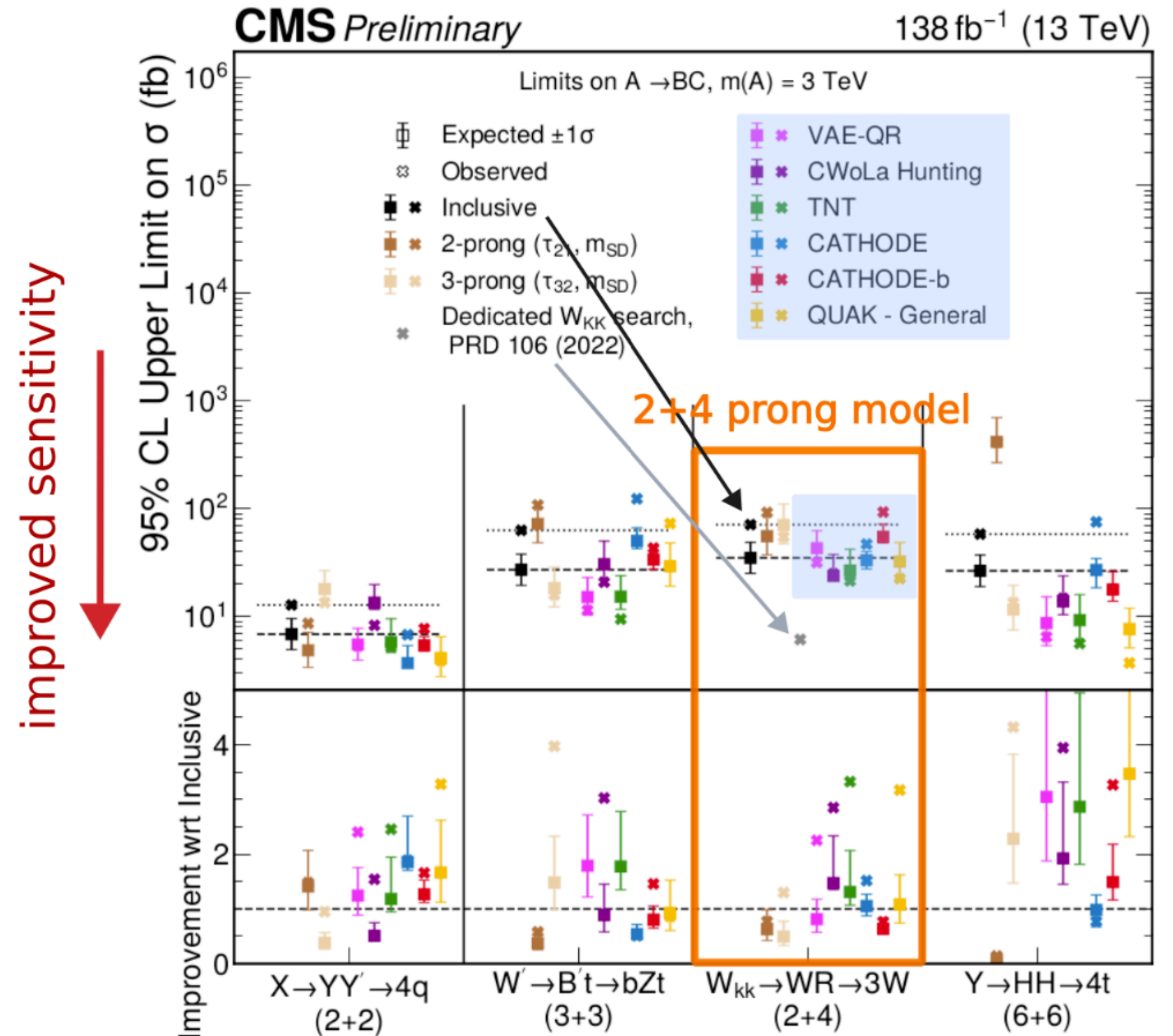
- * Search for new physics in di-jet final states in a model-agnostic manner
- * Based on anomaly detection
 - ☆ Identify jets with non-QCD-like substructure
 - ☆ Maximisation of the sensitivity to unknown new physics signatures
- * First results derived with anomaly detection at CMS!
- * Five machine learning methods designed to identify anomalous jets
 - ☆ Unsupervised algorithm
 - ☆ Weakly-supervised algorithms
 - ☆ Semi-supervised algorithm
- * Signal injection studies show the promising discovery power of the methods



Model-agnostic search with dijet resonances

CMS-PAS-EXO-22-026

- * Events selected based on the anomaly score
- * Bump hunt in the di-jet mass spectrum
- * Sensitivity evaluated on benchmark models
 - ☆ For most of the models, these are the first limits ever presented
- * Sensitivity improved up to a factor 4 compared to "inclusive" case (no cut on anomaly score)
- * Sensitivity not as good as a dedicated search, but the range of models constrained is broader



Summary

- * Extensive and diverse research program from both ATLAS and CMS
- * New taggers, triggers and techniques to improve sensitivity and constrain previously non-accessible parameter space
- * So far, no conclusive hints for physics Beyond the SM at the current energy

Much more results still to come from Run2 and Run3 and waiting for High-Luminosity LHC



ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2023

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$$

$$\sqrt{s} = 13 \text{ TeV}$$

Model	ℓ, γ	Jets†	E_{T}^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimen.	ADD $G_{KK} + g/g$	$0, e, \mu, \tau, \gamma$	$1-4$	Yes	139	M_{KK}
	ADD non resonant $\gamma\gamma$	2γ	-	-	36.7	M_{KK}
	ADD OBH	-	$2j$	-	139	M_{KK}
	ADD BH multijet	-	$\geq 3j$	-	3.6	M_{KK}
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	139	G_{KK} mass
Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	-	36.1	G_{KK} mass
	$1, e, \mu$	$\geq 2b, \geq 3j$	Yes	36.1	2.3 TeV	G_{KK} mass
2UED / RPP	$1, e, \mu$	$\geq 2b, \geq 3j$	Yes	36.1	3.8 TeV	KK mass
	$1, e, \mu$	$\geq 2b, \geq 3j$	Yes	36.1	1.8 TeV	KK mass
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2, e, \mu$	-	-	139	Z' mass
	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	36.1	Z' mass
	Leptophobic $Z' \rightarrow bb$	$0, e, \mu$	$\geq 1b, \geq 2j$	Yes	139	Z' mass
	Leptophobic $Z' \rightarrow \tau\tau$	$0, e, \mu$	$\geq 1b, \geq 2j$	Yes	139	Z' mass
	SSM $W' \rightarrow \ell\nu$	$1, e, \mu$	-	Yes	139	W' mass
	SSM $W' \rightarrow \tau\nu$	1τ	-	Yes	139	W' mass
	SSM $W' \rightarrow b\bar{b}$	-	$\geq 1b, \geq 1j$	Yes	139	W' mass
	HVT $W' \rightarrow WZ$ model B	$0, 2, e, \mu$	$2j / 1j$	Yes	139	W' mass
	HVT $W' \rightarrow WZ$ model C	$3, e, \mu$	$2j$ (VBF)	Yes	139	W' mass
	HVT $Z' \rightarrow WW$ model B	$1, e, \mu$	$2j / 1j$	Yes	139	Z' mass
LRSM $W_R \rightarrow \mu N_R$	2μ	$1j$	-	80	W_R mass	
CI	CI $qqqq$	$2, e, \mu$	-	-	37.0	A
	CI $\ell\ell qq$	$2, e, \mu$	-	-	139	A
	CI $e\bar{e}bb$	$2, e$	-	-	139	A
	CI $\mu\bar{\mu}bb$	$2, \mu$	$1b$	-	139	A
CI $tttt$	$\geq 1, e, \mu$	$\geq 1b, \geq 1j$	Yes	36.1	A	
DM	Axial-vector med. (Dirac DM)	-	$2j$	-	139	m_{DM}
	Pseudo-scalar med. (Dirac DM)	$0, e, \mu, \tau, \gamma$	$1-4$	Yes	139	m_{DM}
	Vector med. Z' -2HDM (Dirac DM)	$0, e, \mu$	$2b$	Yes	139	m_{DM}
Pseudo-scalar med. 2HDM+a	multi-channel	-	-	-	139	m_{DM}
LO	Scalar LQ 1 st gen	$2, e$	$\geq 2j$	Yes	139	LQ mass
	Scalar LQ 2 nd gen	$2, \mu$	$\geq 2j$	Yes	139	LQ mass
	Scalar LQ 3 rd gen	$1, \tau$	$2b$	Yes	139	LQ mass
	Scalar LQ 3 rd gen	$0, e, \mu$	$\geq 2j, \geq 2b$	Yes	139	LQ mass
	Scalar LQ 3 rd gen	$\geq 2, e, \mu$	$\geq 1j, \geq 1b$	Yes	139	LQ mass
	Scalar LQ 3 rd gen	$0, e, \mu$	$\geq 1\tau, 0-2j, 2b$	Yes	139	LQ mass
	Vector LQ mix gen	multi-channel	$\geq 1j, \geq 1b$	Yes	139	LQ mass
Vector LQ 3 rd gen	$2, e, \mu, \tau$	$\geq 1b$	Yes	139	LQ mass	
Vector-like fermions	VLO $TT \rightarrow Zt + X$	$2e/2\mu/2e, \mu$	$\geq 1b, \geq 1j$	-	139	T mass
	VLO $BB \rightarrow W\tau/Zb + X$	multi-channel	-	-	36.1	B mass
	VLO $T_{3/2} T_{3/2} \rightarrow W\tau + X$	$2(SS)/2(S, \mu)$	$\geq 1b, \geq 1j$	Yes	36.1	$T_{3/2}$ mass
	VLO $T \rightarrow H/Zt$	$1, e, \mu$	$\geq 1b, \geq 3j$	Yes	139	T mass
	VLO $Y \rightarrow Wb$	$1, e, \mu$	$\geq 1b, \geq 1j$	Yes	36.1	Y mass
	VLO $B \rightarrow Hb$	$0, e, \mu$	$\geq 2b, \geq 1j, \geq 1b$	Yes	139	B mass
VLL $\tau \rightarrow Z\tau/H\tau$	multi-channel	$\geq 1j$	Yes	139	τ' mass	
Exotic ferm.	Excited quark $q^* \rightarrow qg$	-	$2j$	-	139	q^* mass
	Excited quark $q^* \rightarrow q\gamma$	1γ	-	-	36.7	q^* mass
	Excited quark $b^* \rightarrow bg$	-	$1b, 1j$	-	139	b^* mass
	Excited lepton τ^*	2τ	$\geq 2j$	-	139	τ^* mass
	Type III Seesaw	$2, 3, 4, e, \mu$	$\geq 2j$	Yes	139	N^c mass
LRSM Majorana ν	$2, \mu$	$2j$	-	36.1	N_{μ} mass	
Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm} W^{\pm}$	$2, 3, 4, e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass	
Higgs triplet $H^{\pm} \rightarrow \ell\ell$	$2, 3, 4, e, \mu$ (SS)	-	Yes	139	H^{\pm} mass	
Multi-charged particles	-	-	-	139	multi-charged particle mass	
Magnetic monopoles	-	-	-	34.4	magnetic monopole mass	
Other	Type I Seesaw	$2, 3, 4, e, \mu$	$\geq 2j$	Yes	139	$m(W_2) = 4.1 \text{ TeV}, g_L = g_R$
	LRSM Majorana ν	$2, \mu$	$2j$	-	36.1	N_{μ} mass
	Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm} W^{\pm}$	$2, 3, 4, e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass
	Higgs triplet $H^{\pm} \rightarrow \ell\ell$	$2, 3, 4, e, \mu$ (SS)	-	Yes	139	H^{\pm} mass

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter J (J).

- Multijet
- Displaced jets
- Fully hadronic
- Displaced
- VBF

ν MSM, $|V_{\mu\mu}|^2 = 1.0$, $|V_{\mu\tau}|^2 = 1.0$
 Type-III Seesaw Heavy Fermions, Flavor Democratic
 Type-III Seesaw Heavy Fermions, $B_\mu = 1.0, B_\tau = B_\nu = 0.0$
 Type-III Seesaw Heavy Fermions, $B_\mu = 1.0, B_\tau = B_\nu = 0.0$
 ν MSM, $|V_{\mu\mu}|^2 = 1.0$, $|V_{\mu\tau}|^2 = 0.0$

LRSM $W_L(\nu N_L)$, $M_{N_L} < M_{W_L} = 200 \text{ GeV}$
 LRSM $W_L(\nu N_L)$, $M_{N_L} < 0.5 M_{W_L}$
 LRSM $W_L(\nu N_L)$, $M_{N_L} < M_{W_L} = 200 \text{ GeV}$
 LRSM $W_L(\nu N_L)$, $M_{N_L} < 0.5 M_{W_L}$
 LRSM $Z_L(\nu N_L)$, $M_{N_L} < 0.5 M_{W_L} = 100 \text{ GeV}$
 LRSM $Z_L(\nu N_L)$, $M_{N_L} < 0.25 M_{W_L}$
 LRSM $Z_L(\nu N_L)$, $M_{N_L} < 0.5 M_{W_L} = 100 \text{ GeV}$
 LRSM $Z_L(\nu N_L)$, $M_{N_L} < 0.25 M_{W_L}$
 Composite Fermions $N_L, M_{N_L} < \Lambda$
 Composite Fermions $N_L, M_{N_L} < \Lambda$

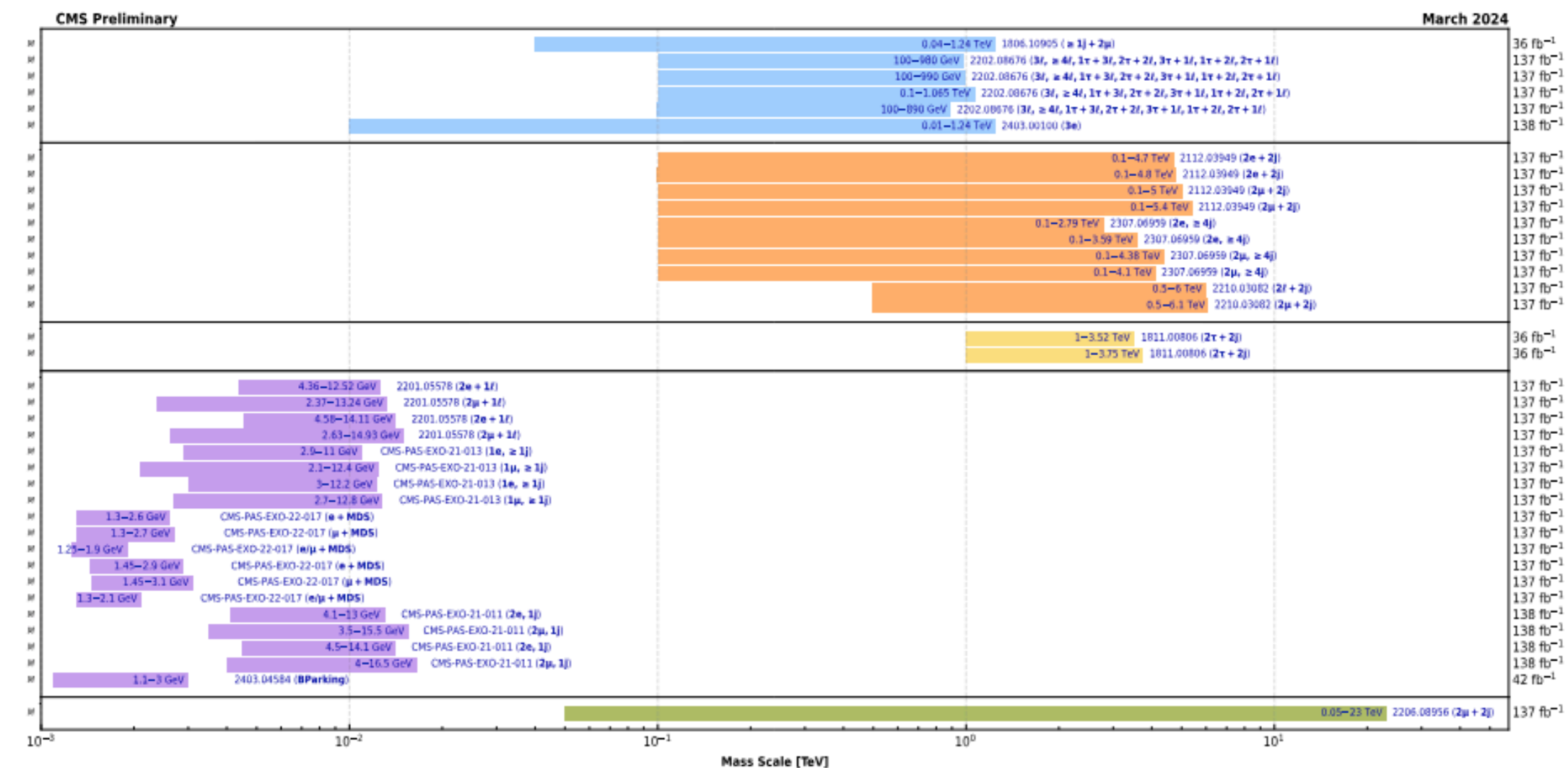
LRSM $W_R(\nu N_R)$, $M_{N_R} = 0.8 M_{W_R}$
 LRSM $W_R(\nu N_R)$, $M_{N_R} = 0.2 M_{W_R}$

Displaced Majorana HNL, $|V_{\mu\mu}|^2 = 1.0 \times 10^{-2}$
 Displaced Majorana HNL, $|V_{\mu\mu}|^2 = 1.0 \times 10^{-2}$
 Displaced Dirac HNL, $|V_{\mu\mu}|^2 = 1.0 \times 10^{-2}$
 Displaced Dirac HNL, $|V_{\mu\mu}|^2 = 1.0 \times 10^{-2}$
 Displaced Majorana HNL, $|V_{\mu\mu}|^2 = 1.0 \times 10^{-2}$
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 Displaced Dirac HNL, $|V_{\mu\mu}|^2 = 1.0 \times 10^{-2}$
 Displaced Dirac HNL, $|V_{\mu\mu}|^2 = 1.0 \times 10^{-2}$
 Displaced Majorana HNL, $|V_{\mu\mu}|^2 = 1.0 \times 10^{-2}$
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 Displaced Majorana HNL, $|V_{\mu\mu}|^2 = 1.0 \times 10^{-2}$
 Displaced Majorana HNL, $|V_{\mu\mu}|^2 = 1.0 \times 10^{-2}$
 Displaced Dirac HNL, $|V_{\mu\mu}|^2 = 1.0 \times 10^{-2}$
 Displaced Majorana HNL, $|V_{\mu\mu}|^2 = 1.0 \times 10^{-2}$
 Displaced Dirac HNL, $|V_{\mu\mu}|^2 = 1.0 \times 10^{-2}$
 Displaced HNL from B meson decay, $|V_{\mu\mu}|^2 = 5.0 \times 10^{-2}$

Type I Seesaw VBF SSWW, $|V_{\mu\mu}|^2 = 1.0$

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

Overview of CMS HNL results



Backup

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2023

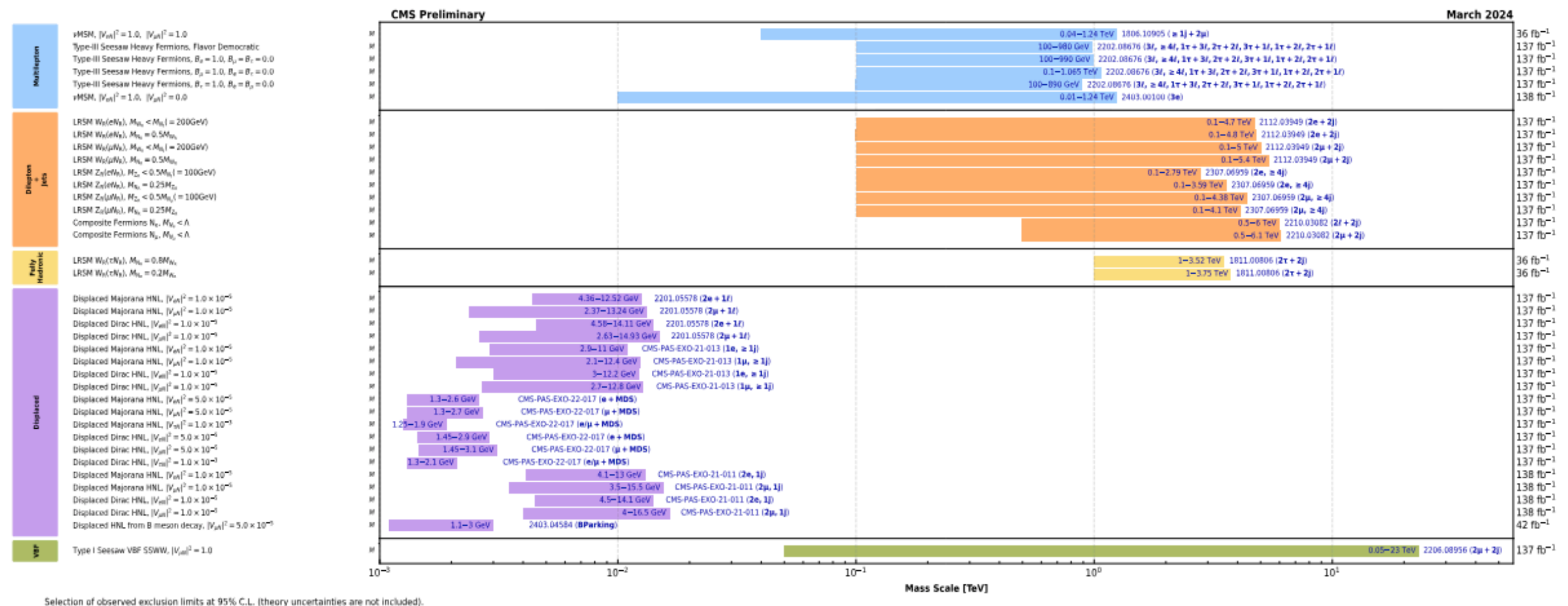
ATLAS Preliminary

$$\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$$

$$\sqrt{s} = 13 \text{ TeV}$$

Model	ℓ, γ	Jets†	$E_{\text{miss}}^{\text{T}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimen.	ADD $G_{KK} + g/q$	$0 e, \mu, \tau, \gamma$	$1-4 j$	Yes	139	M_{pl} 11.2 TeV $n=2$
	ADD non resonant $\gamma\gamma$	2γ	-	-	36.7	M_{pl} 8.6 TeV $n=3$ HLZ NLO
	ADD OBH	-	$2j$	-	139	M_{pl} 9.4 TeV $n=6$
	ADD BH multijet	-	$\geq 3j$	-	3.6	M_{pl} 9.55 TeV $n=6, M_{\text{pl}} = 3 \text{ TeV, rot BH}$
Gauge bosons	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	139	$G_{KK} \text{ mass}$ 2.3 TeV $k/\bar{M}_{\text{pl}} = 0.1$
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	$G_{KK} \text{ mass}$ 2.3 TeV $k/\bar{M}_{\text{pl}} = 1.0$
	Bulk RS $G_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2$	Yes	36.1	$G_{KK} \text{ mass}$ 3.8 TeV $f/m = 15\%$
	2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	$KK \text{ mass}$ 1.8 TeV $\text{Tier (1,1), } \mathcal{R}(A^{(1,1)} \rightarrow t\bar{t}) = 1$
CI	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	139	$Z' \text{ mass}$ 2.42 TeV
	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	36.1	$Z' \text{ mass}$ 2.1 TeV
	Leptophobic $Z' \rightarrow bb$	$0 e, \mu$	$\geq 1 b, \geq 2 J$	Yes	139	$Z' \text{ mass}$ 4.1 TeV $f/m = 1.2\%$
	Leptophobic $Z' \rightarrow t\bar{t}$	$0 e, \mu$	$\geq 1 b, \geq 2 J$	Yes	139	$Z' \text{ mass}$ 4.1 TeV
DM	Scalar LQ 1 st gen	$2 e$	$\geq 2 j$	Yes	139	$LQ \text{ mass}$ 1.8 TeV
	Scalar LQ 2 nd gen	2μ	$\geq 2 j$	Yes	139	$LQ \text{ mass}$ 1.7 TeV
	Scalar LQ 3 rd gen	1τ	$2 b$	Yes	139	$LQ \text{ mass}$ 1.49 TeV
	Scalar LQ 3 rd gen	$0 e, \mu$	$\geq 2 j, \geq 2 b$	Yes	139	$LQ \text{ mass}$ 1.24 TeV
Vector-like fermions	Scalar LQ 3 rd gen	$2 e, \mu$	$\geq 1 \tau, \geq 1 b$	Yes	139	$LQ \text{ mass}$ 1.43 TeV
	Scalar LQ 3 rd gen	$0 e, \mu$	$\geq 1 \tau, 0-2 j, 2 b$	Yes	139	$LQ \text{ mass}$ 1.26 TeV
	Vector LQ mix gen	multi-channel	$\geq 1 j, \geq 1 b$	Yes	139	$LQ \text{ mass}$ 2.0 TeV
	Vector LQ 3 rd gen	$2 e, \mu, \tau$	$\geq 1 b$	Yes	139	$LQ \text{ mass}$ 1.96 TeV
Other	VLLQ $TT \rightarrow Zt + X$	$2e/2\mu/2e, \mu$	$\geq 1 b, \geq 1 j$	-	139	$T \text{ mass}$ 1.46 TeV
	VLLQ $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	$B \text{ mass}$ 1.34 TeV
	VLLQ $T_3, T_3 \rightarrow Wt/Zb + X$	$2(SS)/2(e, \mu)$	$\geq 1 b, \geq 1 j$	Yes	36.1	$T_{3,3} \text{ mass}$ 1.64 TeV
	VLLQ $T \rightarrow Ht/Zt$	$1 e, \mu$	$\geq 1 b, \geq 3 j$	Yes	139	$T \text{ mass}$ 1.8 TeV
Excited ferm.	VLLQ $Y \rightarrow Wb$	$1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$Y \text{ mass}$ 1.85 TeV
	VLLQ $B \rightarrow Hb$	$0 e, \mu$	$\geq 2b, \geq 1 j, \geq 1 J$	-	139	$B \text{ mass}$ 2.0 TeV
	VLLQ $\tau \rightarrow Z\tau/H\tau$	multi-channel	$\geq 1 j$	Yes	139	$\tau' \text{ mass}$ 898 GeV
	Excited quark $q^* \rightarrow qg$	$2 j$	-	-	139	$q^* \text{ mass}$ 6.7 TeV
Type III Seesaw	Excited quark $q^* \rightarrow q\gamma$	$1 j$	-	-	36.7	$q^* \text{ mass}$ 1.1 TeV
	Excited quark $b^* \rightarrow bg$	$1 b, 1 j$	-	-	139	$b^* \text{ mass}$ 3.2 TeV
	Excited lepton τ^*	2τ	$\geq 2 j$	-	139	$\tau^* \text{ mass}$ 4.6 TeV
	Type III Seesaw	$2.3, 4 e, \mu$	$\geq 2 j$	Yes	139	N^{e} mass 910 GeV
Higgs triplet	LFSM Majorana ν	2μ	$2 j$	-	36.1	N_{u} mass 3.2 TeV
	Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm} W^{\pm}$	$2.3, 4 e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm} \text{ mass}$ 350 GeV
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2.3, 4 e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm} \text{ mass}$ 1.08 TeV
	Multi-charged particles	-	-	-	139	$H^{\pm\pm} \text{ mass}$ 1.59 TeV
Magnetic monopoles	Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV

Overview of CMS HNL results



*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter J (J).

More ATLAS

results overview

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2023-008/>

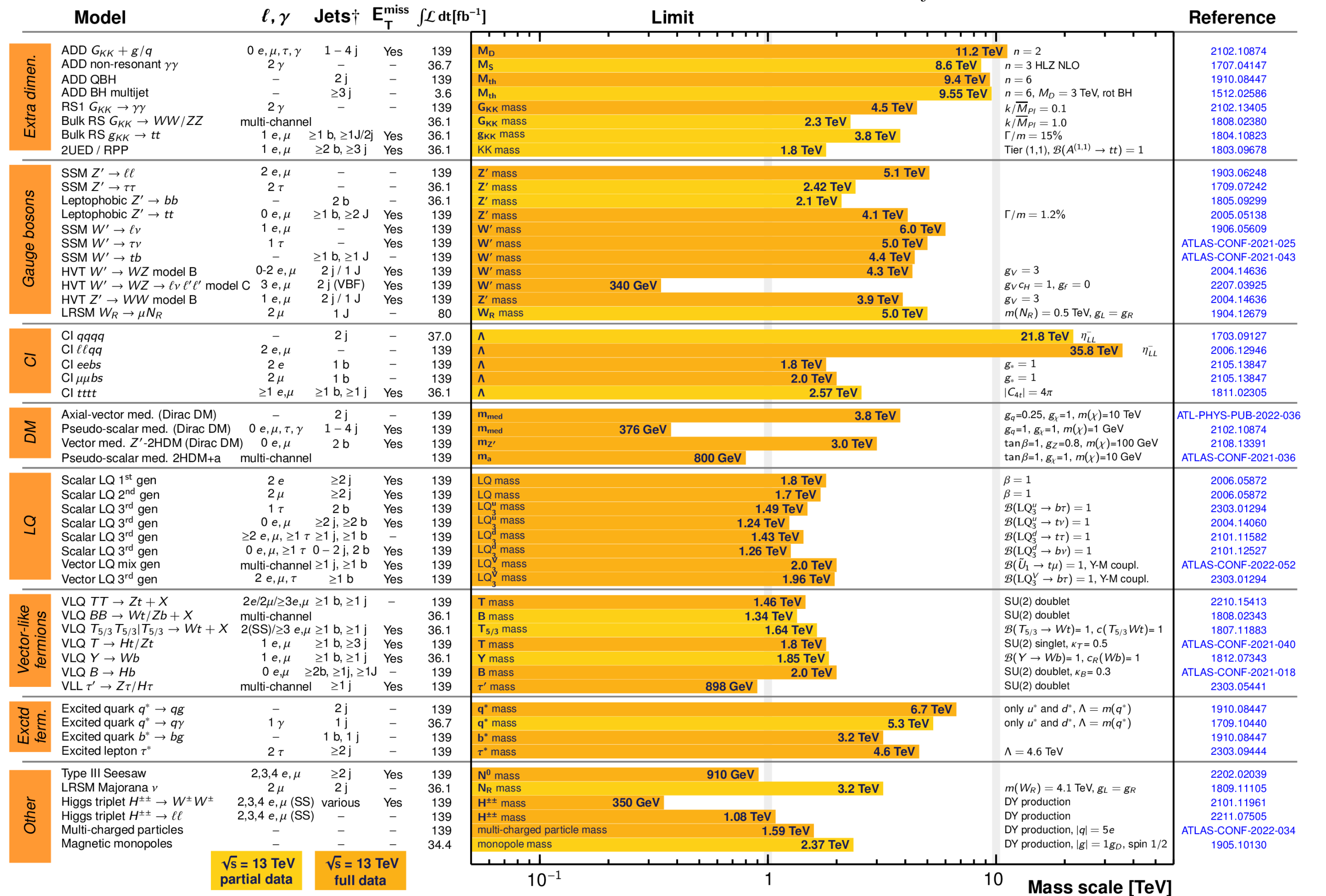
ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2023

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$$

$$\sqrt{s} = 13 \text{ TeV}$$



*Only a selection of the available mass limits on new states or phenomena is shown.

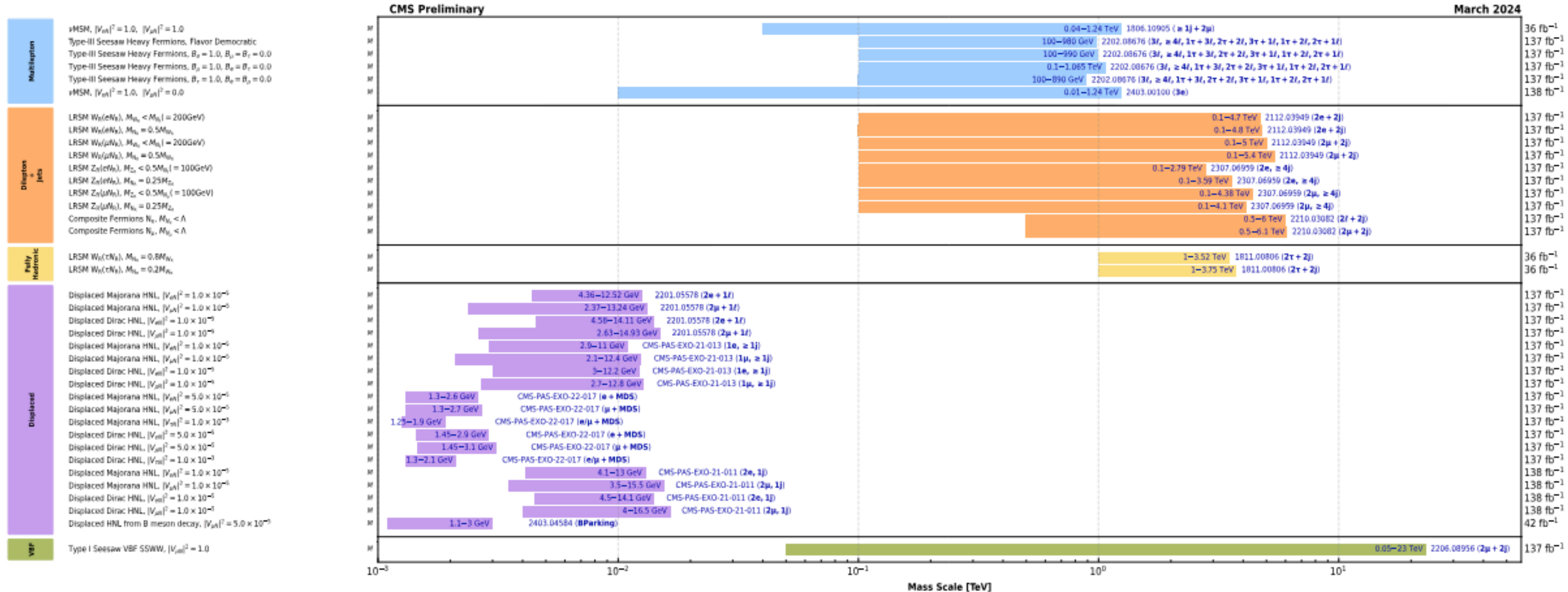
†Small-radius (large-radius) jets are denoted by the letter j (J).

$\sqrt{s} = 13 \text{ TeV}$
partial data full data

10⁻¹ 1 10 Mass scale [TeV]

More CMS results overview

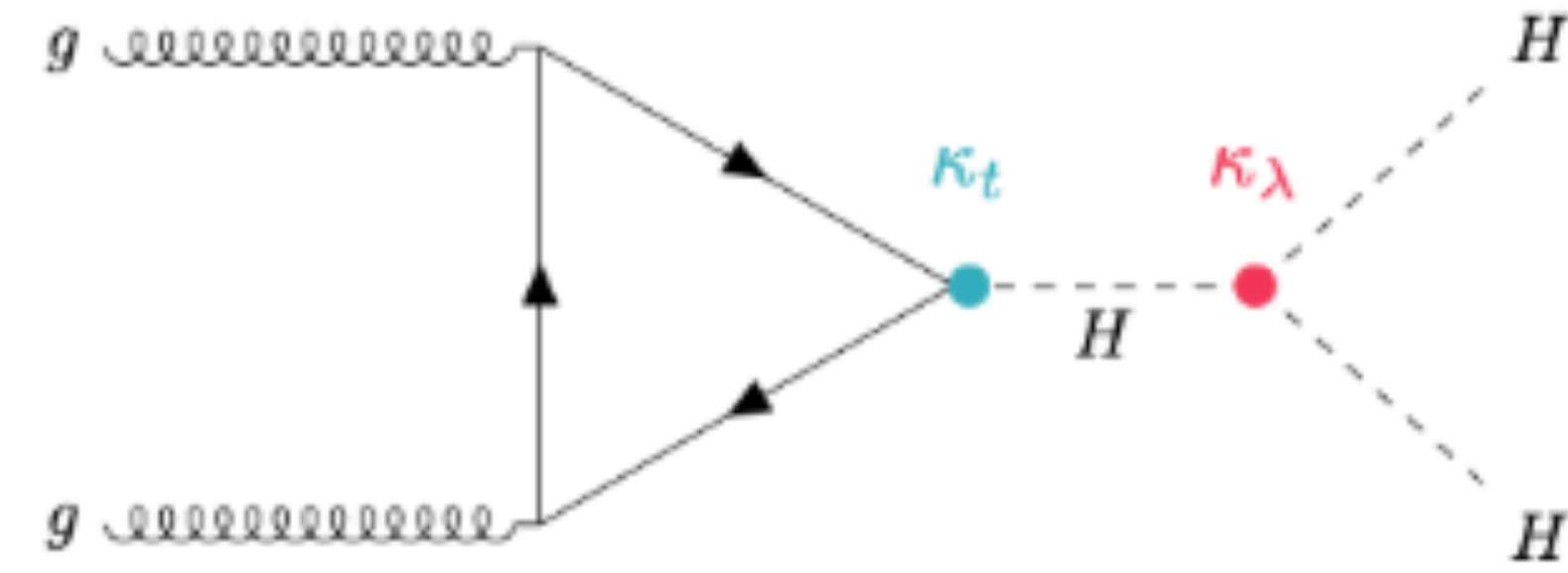
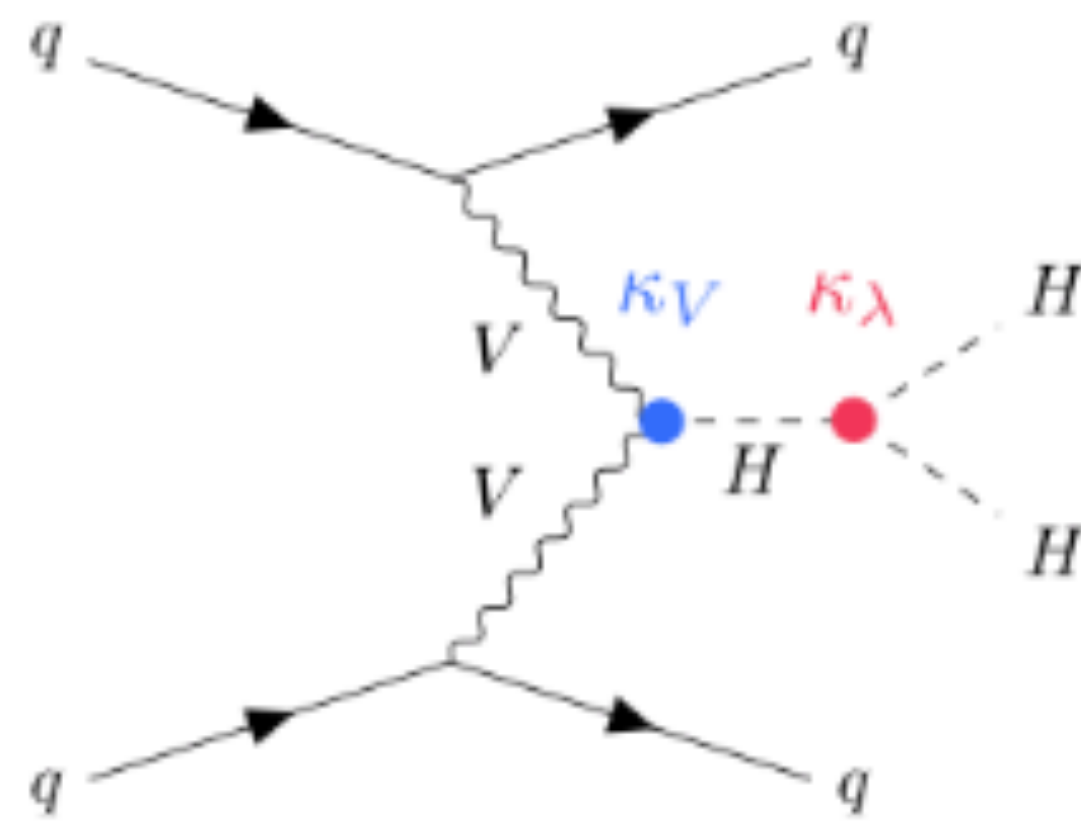
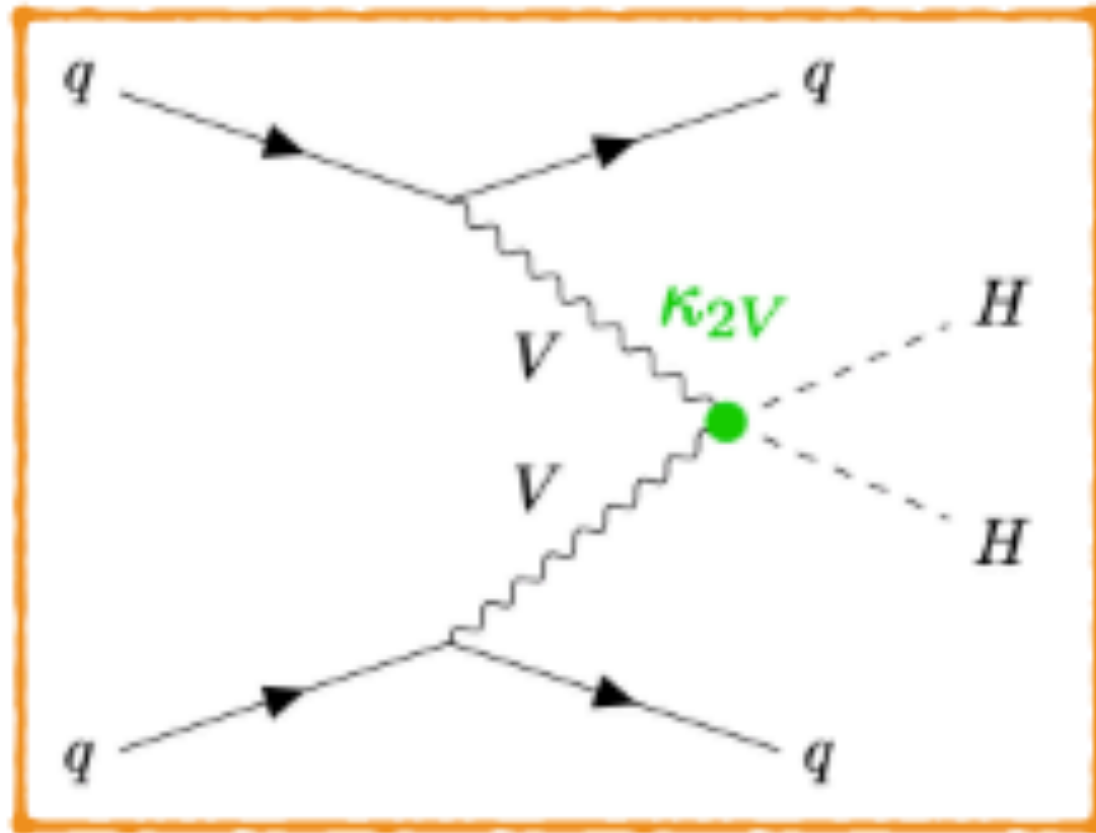
Overview of CMS HNL results



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

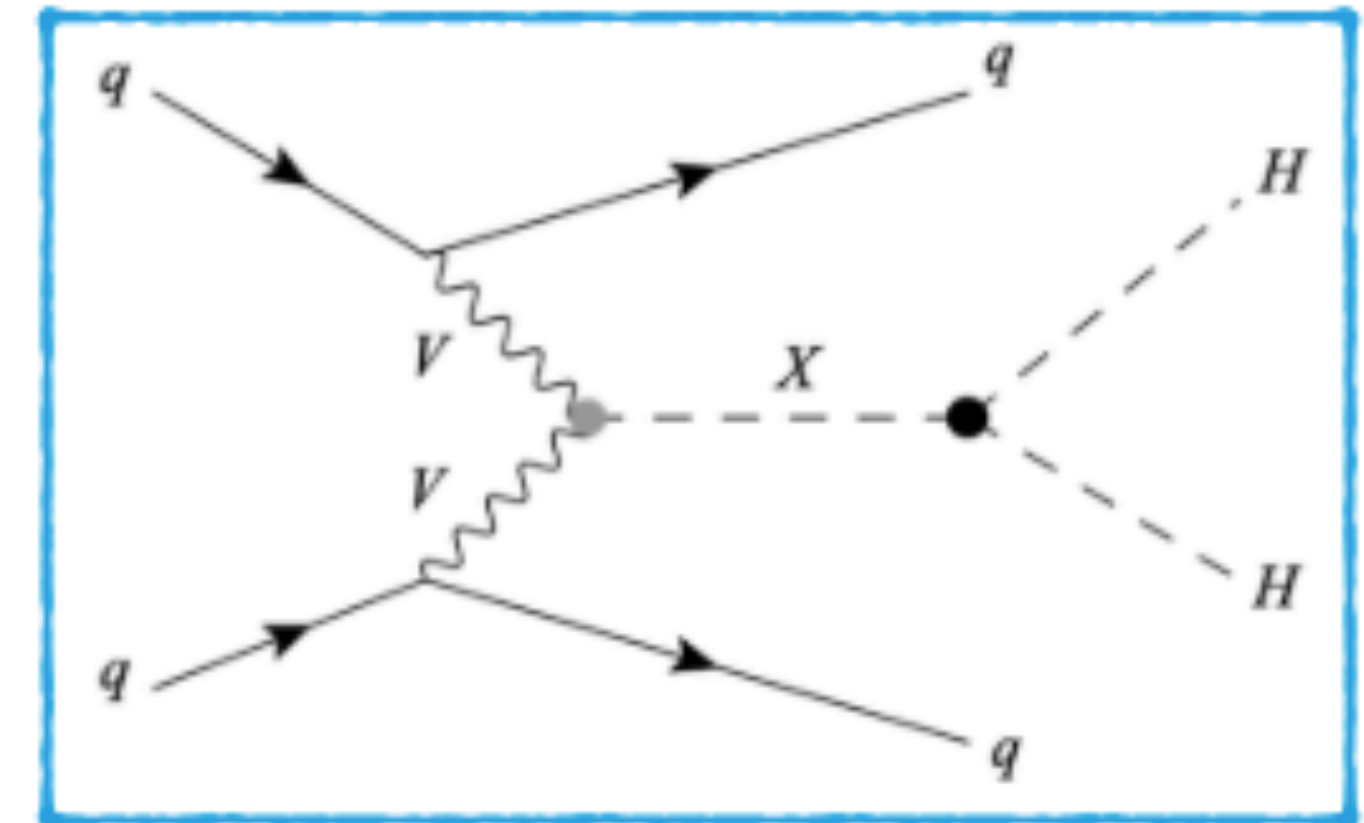
<https://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/>

Di-Higgs \rightarrow $b\bar{b}b\bar{b}$



Some example diagrams for di-Higgs production

- κ_{2V} and κ_λ remain experimentally less constrained
- Di-Higgs final states depend also on κ_V and κ_t
- Dedicated search for $H \rightarrow b\bar{b}b\bar{b}$ using large- R jets aiming to
 - **constrain κ_{2V}**
 - **and search for new heavy scalar mediator**
- $H(b\bar{b})$ candidates identified by dedicated NN double- b tagging for large- R jets



Also covered in talk by Torben on Higgs cross sections from CMS and ATLAS

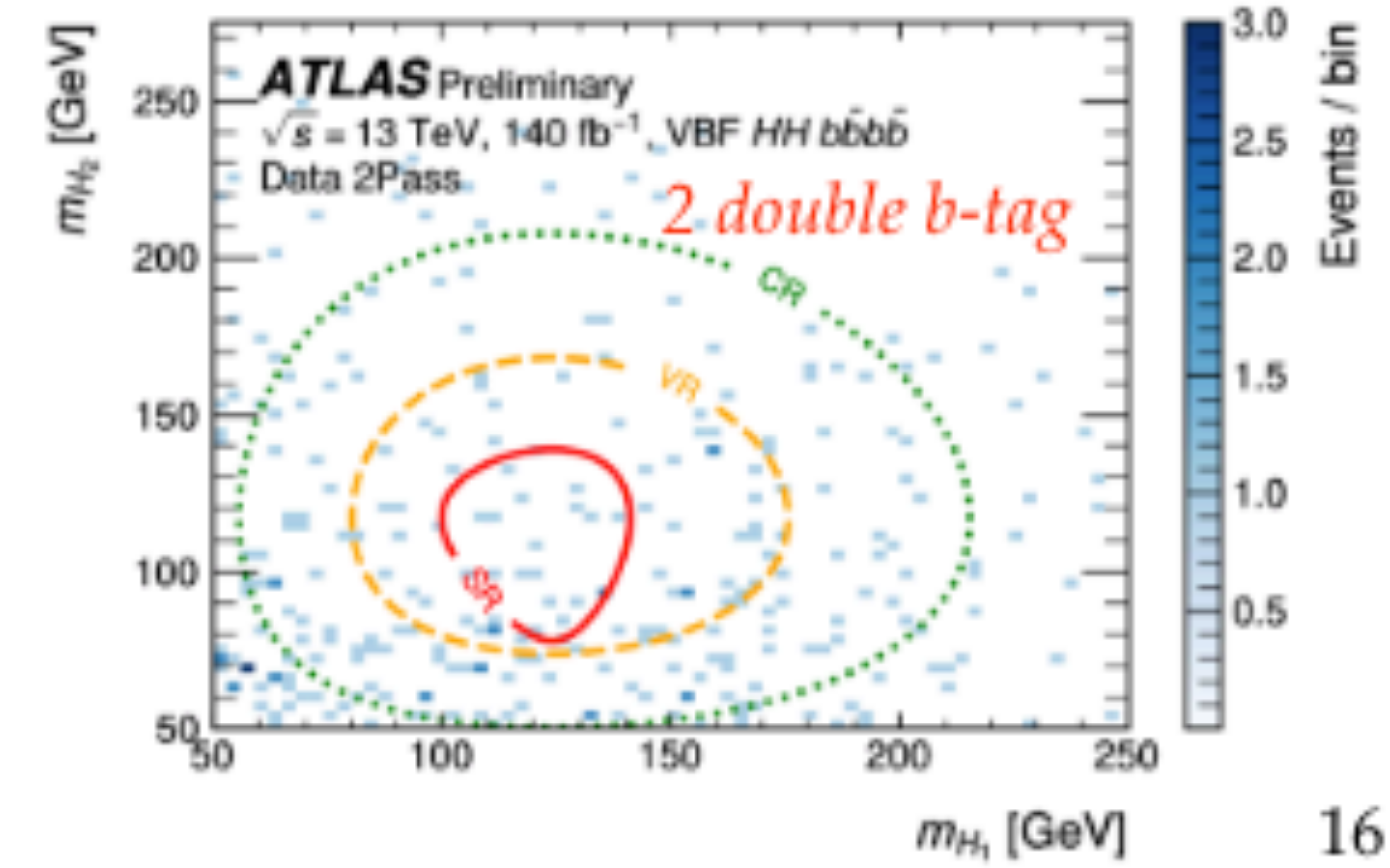
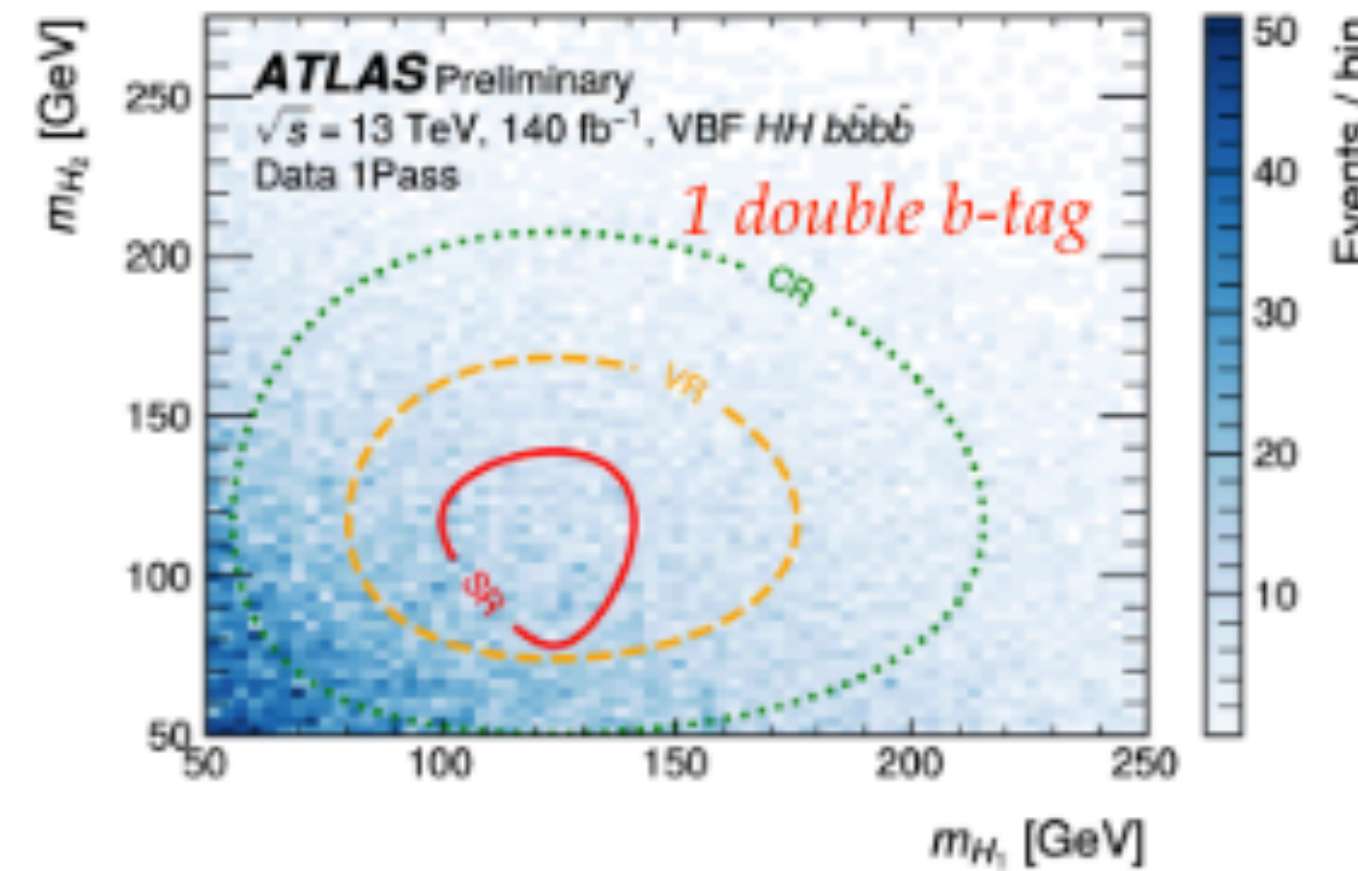
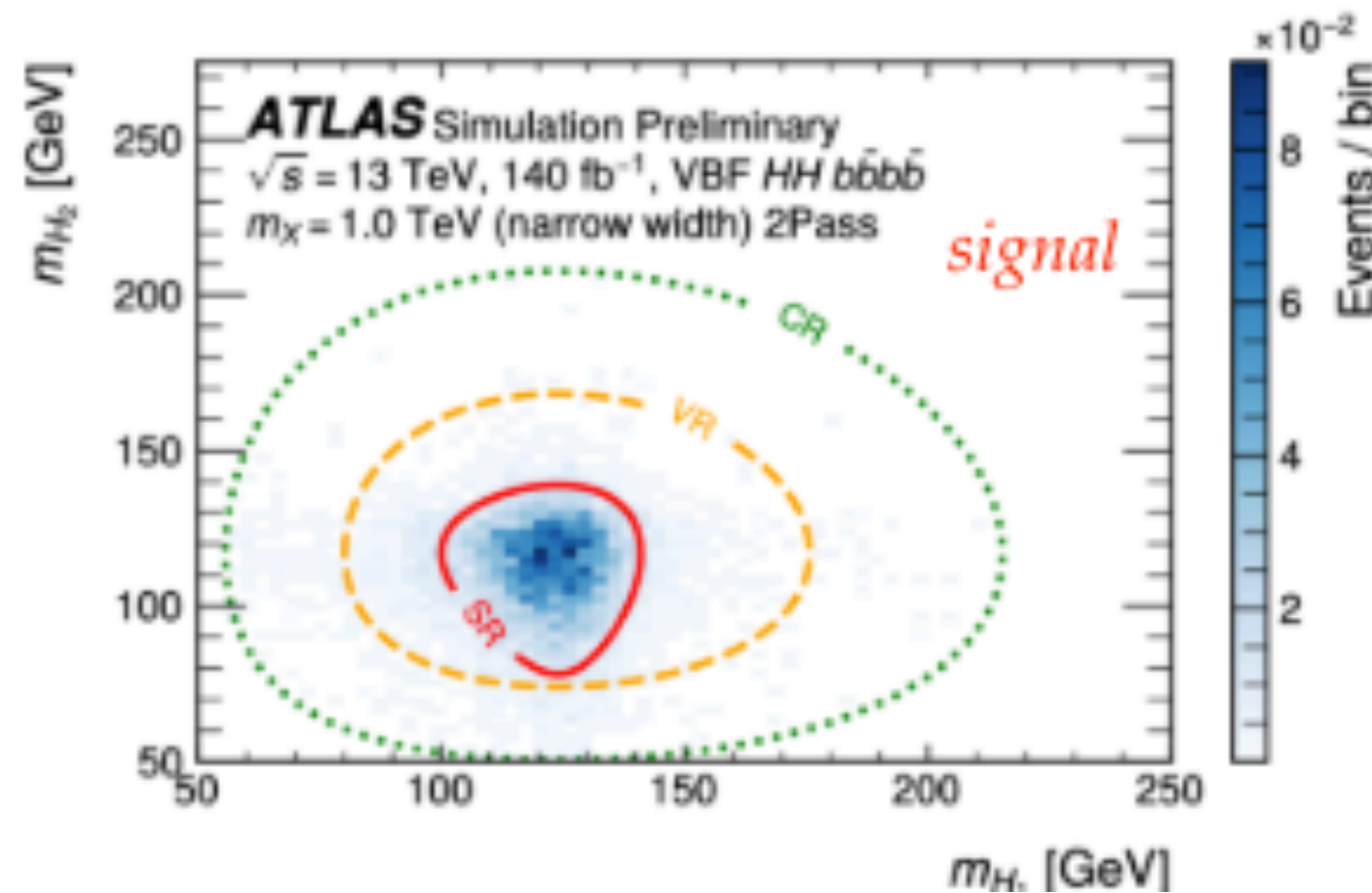
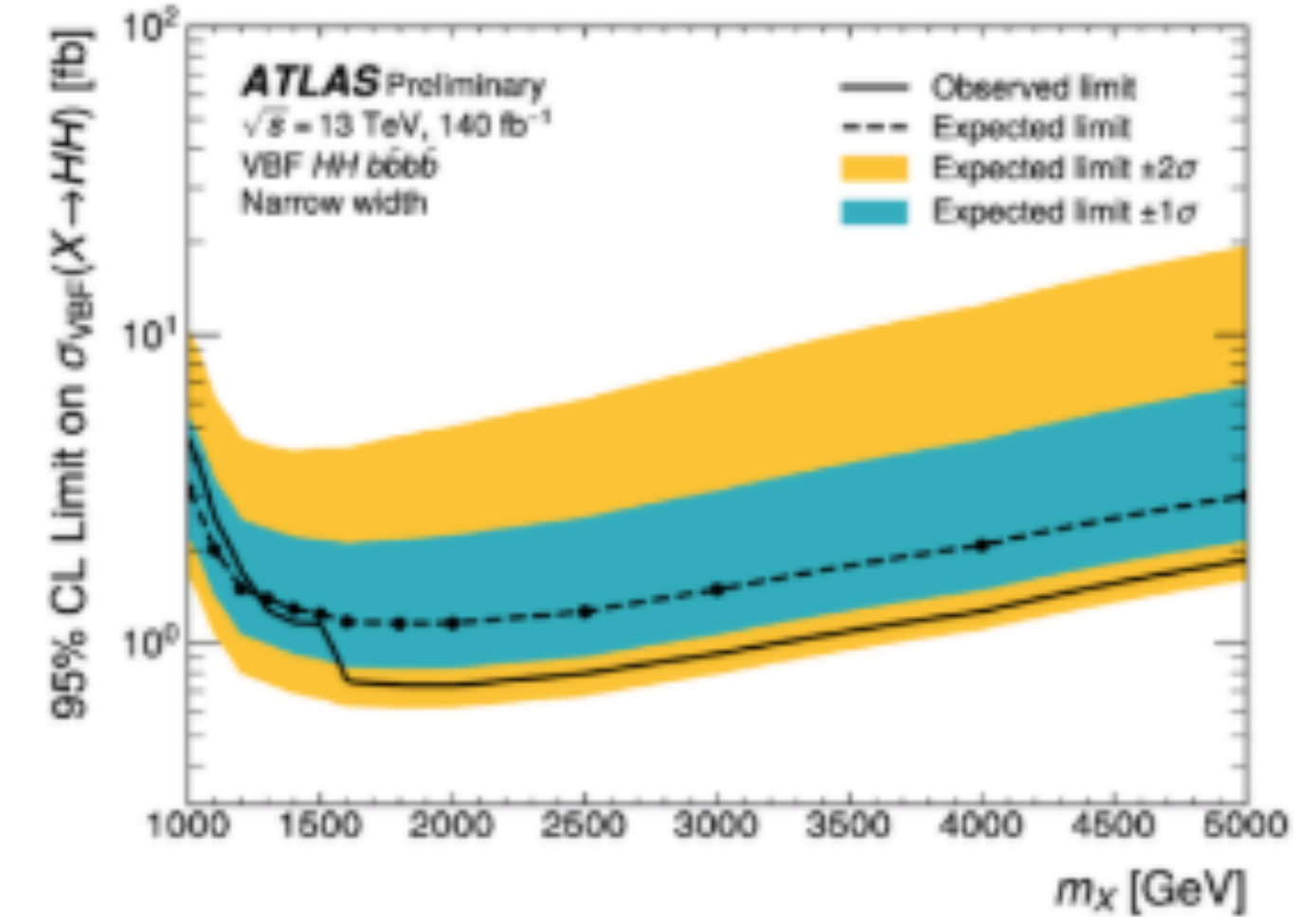
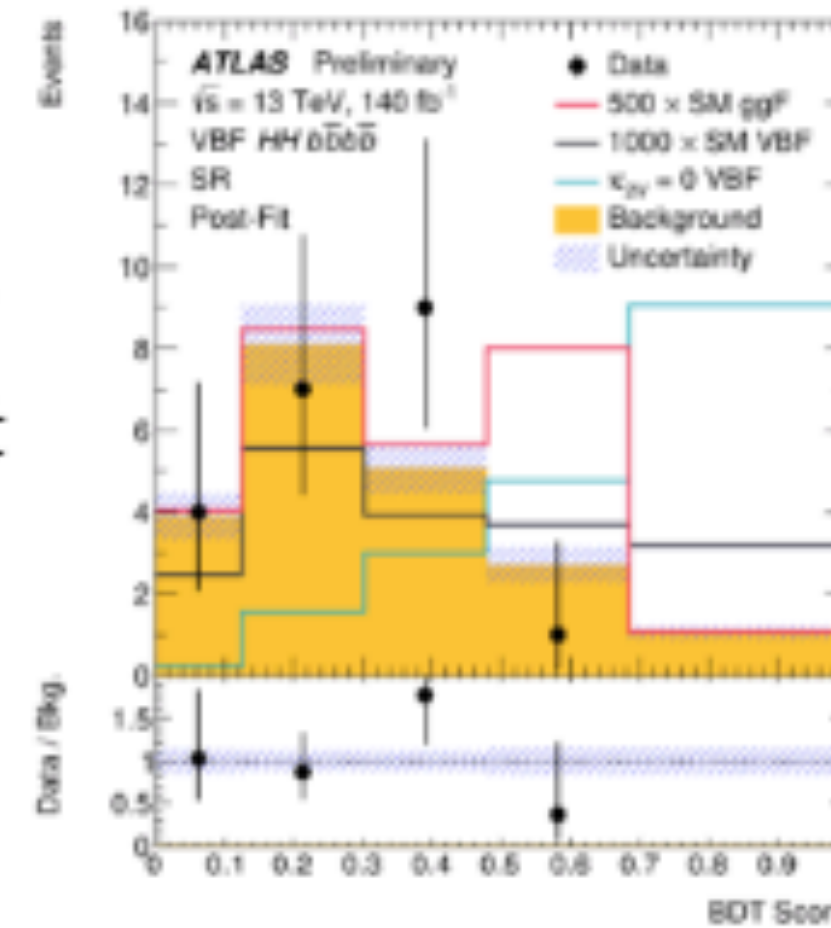
Di-Higgs \rightarrow $bbbb$

- Bkg. from events with 1 double- b tag normalised in CR with 2 double- b tags
- BDT trained to separate sig. ($\kappa_{2V} = 0$) from bkg.
- No, excess \rightarrow combination with resolved result [[PRD 108 \(052003\)](#)]:

$\kappa_{2V} = 0$ excluded with 3.8σ (3.3σ)

$0.6 < \kappa_{2V} < 1.5$ ($0.4 < \kappa_{2V} < 1.7$) at 95% CL

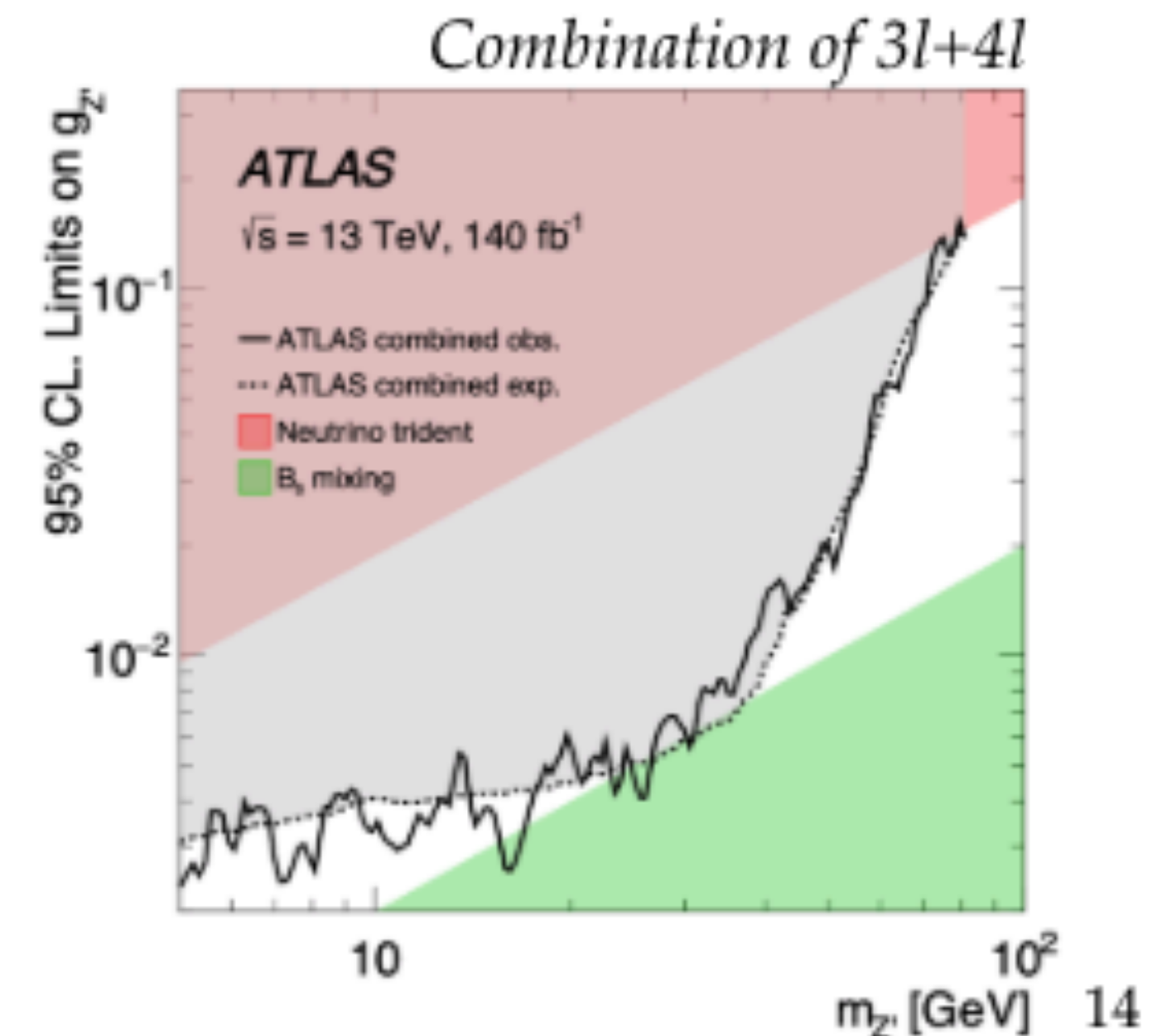
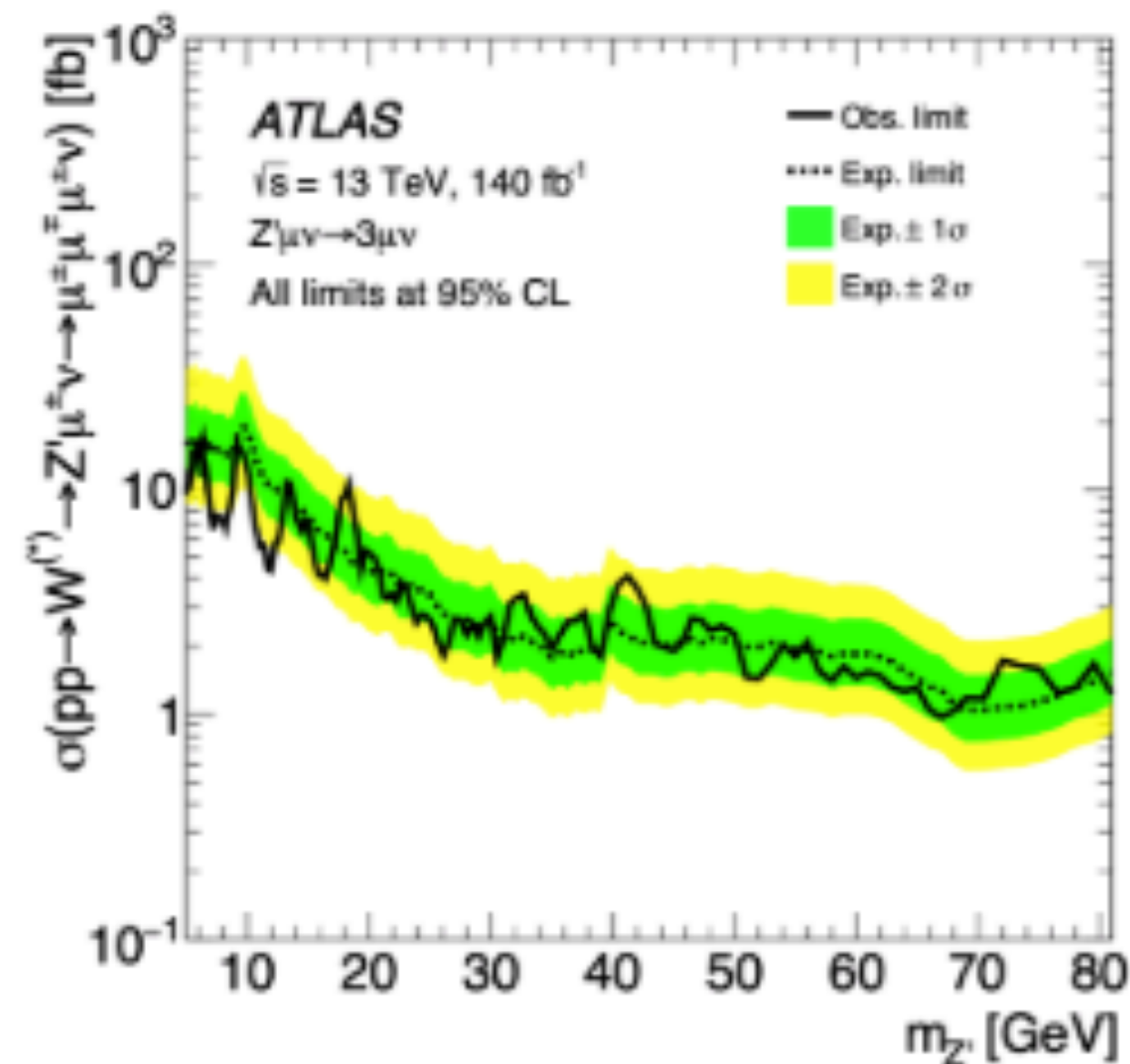
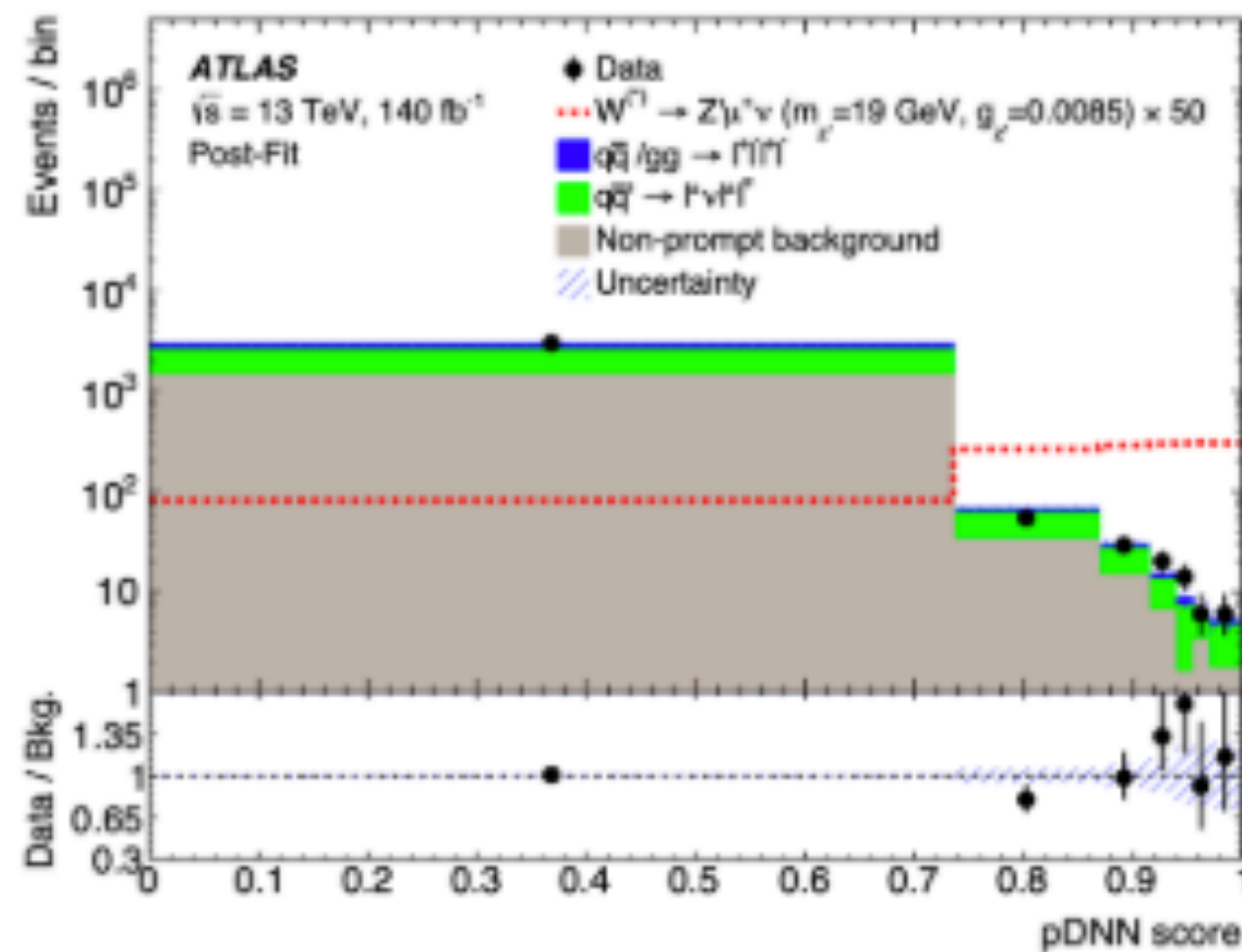
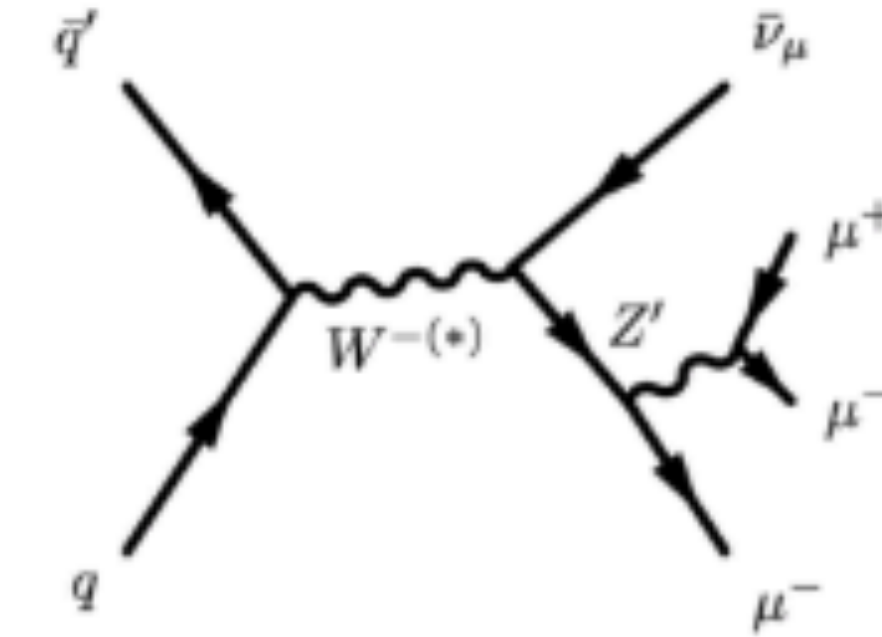
- Cross section limits on heavy scalar mediator



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$Z' \rightarrow 3\mu$

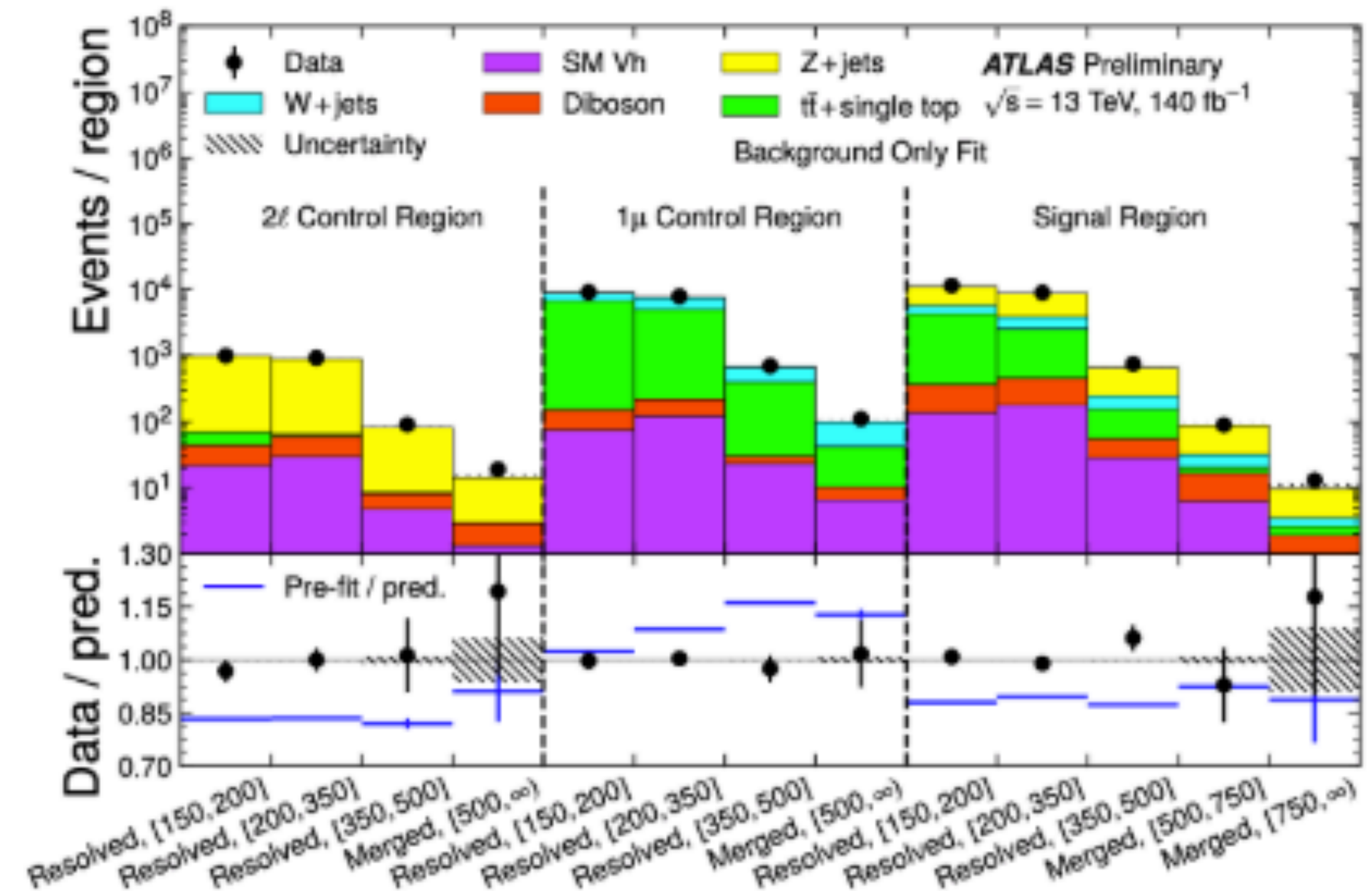
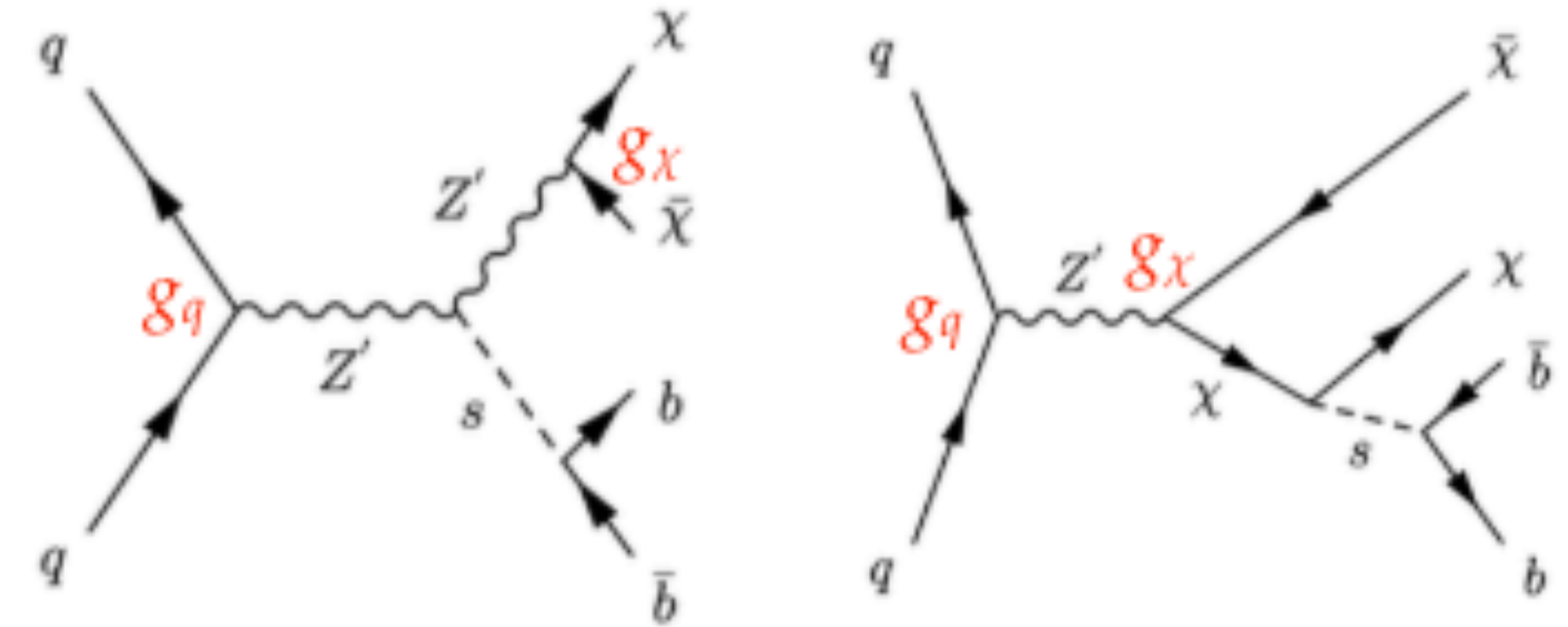
- Target: Z' from $U(1)_{L\mu-L\tau}$ only coupling to 2nd and 3rd gen. leptons
- Dominant bkg: $q\bar{q}' \rightarrow W(Z/\gamma^*) \rightarrow l^\pm \nu l^\mp l^\pm$
- Single parameterised Deep NN trained for various mass hypotheses
- Combination with ATLAS result from 4-lep (slightly better limits for $m_{Z'} < 65$ GeV) [\[JHEP07 \(2023\) 090\]](#) \rightarrow most stringent limits on $U(1)_{L\mu-L\tau}$ models



Mono $s(bb)$

- Target: DM production via Z' (couplings g_q and g_χ) mediator in association with scalar s (with mixing $\sin \theta$ to SM-like Higgs) decaying to $b\bar{b}$
- Resolved ($150 < \text{MET} < 500 \text{ GeV}$) and merged ($\text{MET} > 500 \text{ GeV}$) SRs
- Using **optimised $X \rightarrow bb$ tagging** [[ATL-PHYS-PUB-2020-019](#)] in boosted SR (for $m_{bb} > 50 \text{ GeV}$) ... and DL1r for resolved and boosted SR ($m_{bb} < 50 \text{ GeV}$)
- Control bkg in 1- and 2-lepton CRs
- No excess: Limits in three different scenarios ...

$\text{MET bins} \rightarrow$



Mono $S(bb)$

Scenario 1 ("conventional")

- $m_{Z'}-m_s$ plane
- $m_\chi = 200$ GeV (no $s \rightarrow \chi\chi$)
- $g_q = 0.25; g_\chi = 1$
- $\sin \theta = 0.01$

Scenario 2

- $m_{Z'}-m_s$ plane
- $m_\chi = 900$ GeV
- $g_q = 0.25; \sin \theta = 0.01$

Scenario 3

- $m_{Z'}-m_\chi$ plane
- $m_s = 70$ GeV
- $g_q = 0.25; \sin \theta = 0.01$

Tune g_χ to get $\Omega h^2 = 0.12$

