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

Matteo Franchini on behalf of
the ATLAS and CMS collaborations

CMS

ATLAS EXPERIMENT

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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

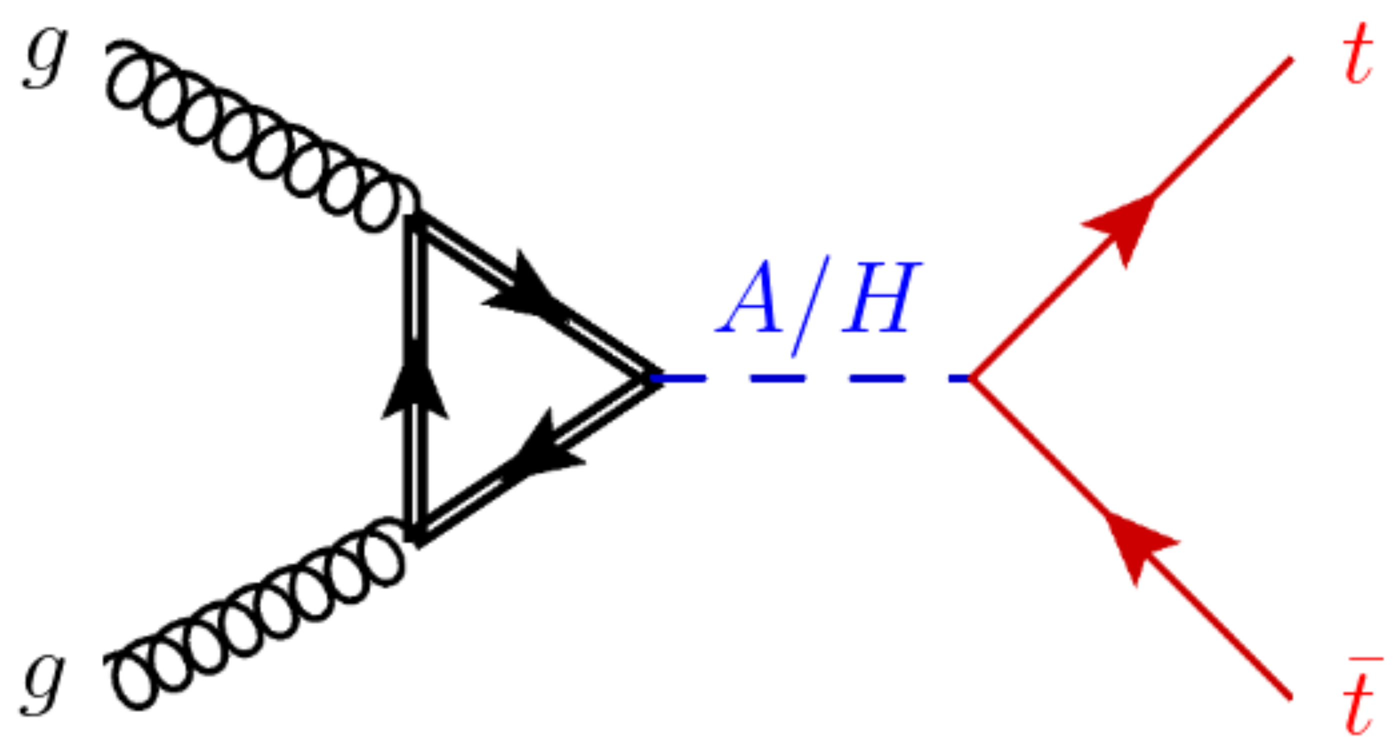
(not exhaustive) Overview of latest results!

* BSM H/A -> tt [ATLAS-CONF-2024-001]
* A-> ZH-> lltt [CMS-PAS-B2G-23-006]
* A-> ZH-> 4l+jj/MET [https://arxiv.org/abs/2401.04742]
* H/A -> 4top [ATLAS-CONF-2024-002]
* HNL via WW scattering in ee, eμ 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 —> b mu b mu [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 —> τ+MET [EXOT-2018-37]
* Search for a resonance decaying to Wγ [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

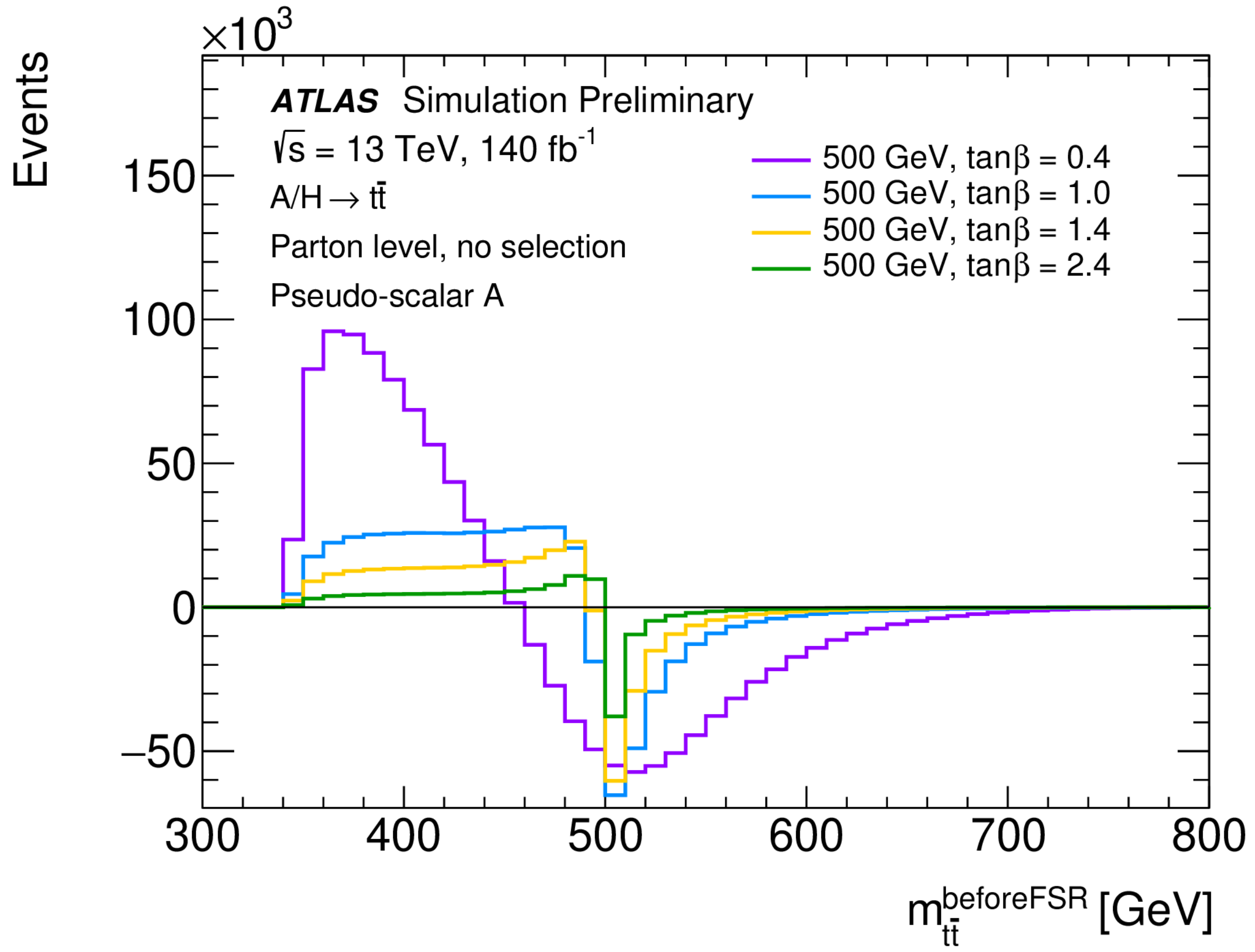
BSM H/A -> tt

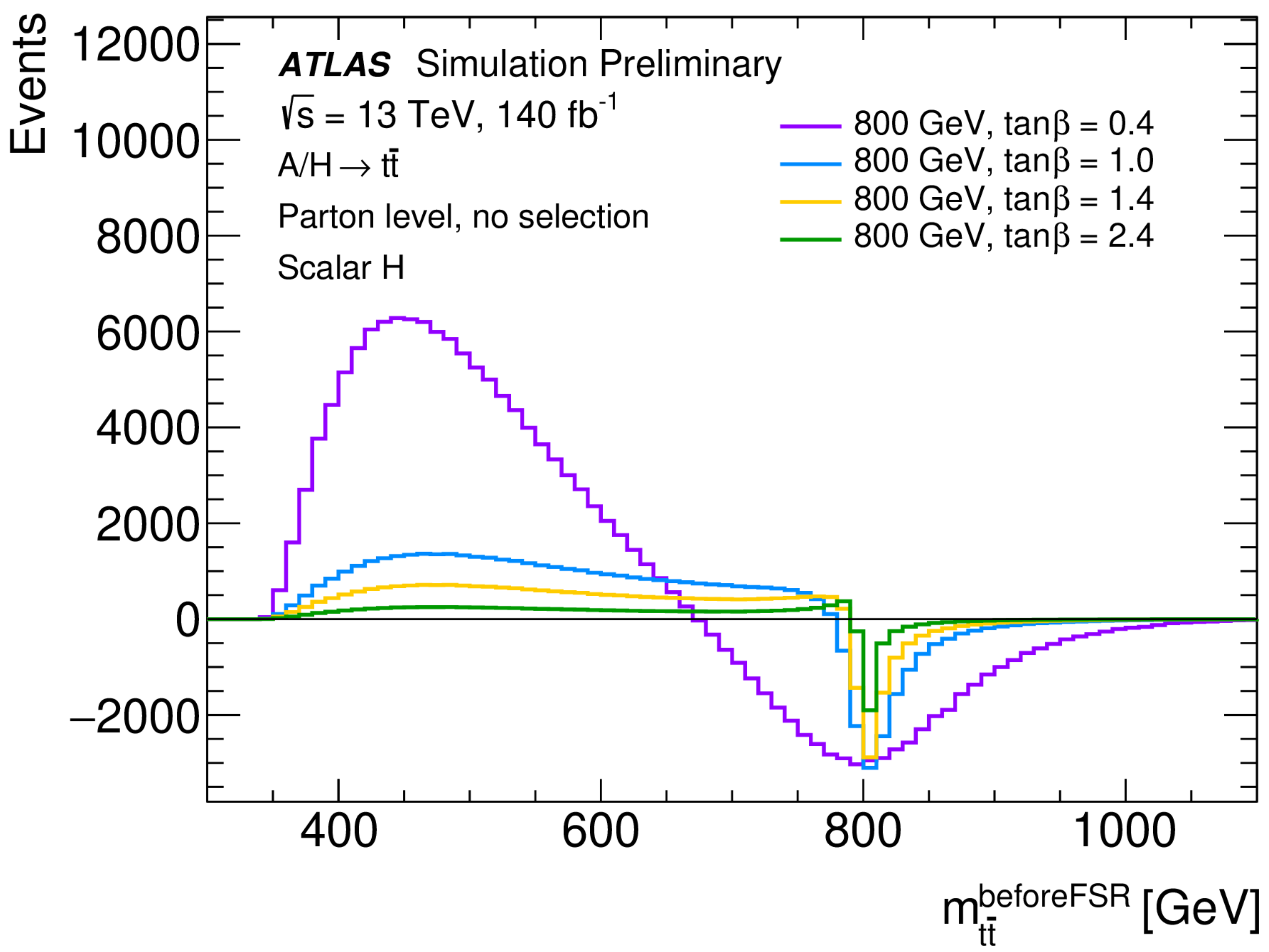
[EXOT-2020-25]



* 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.



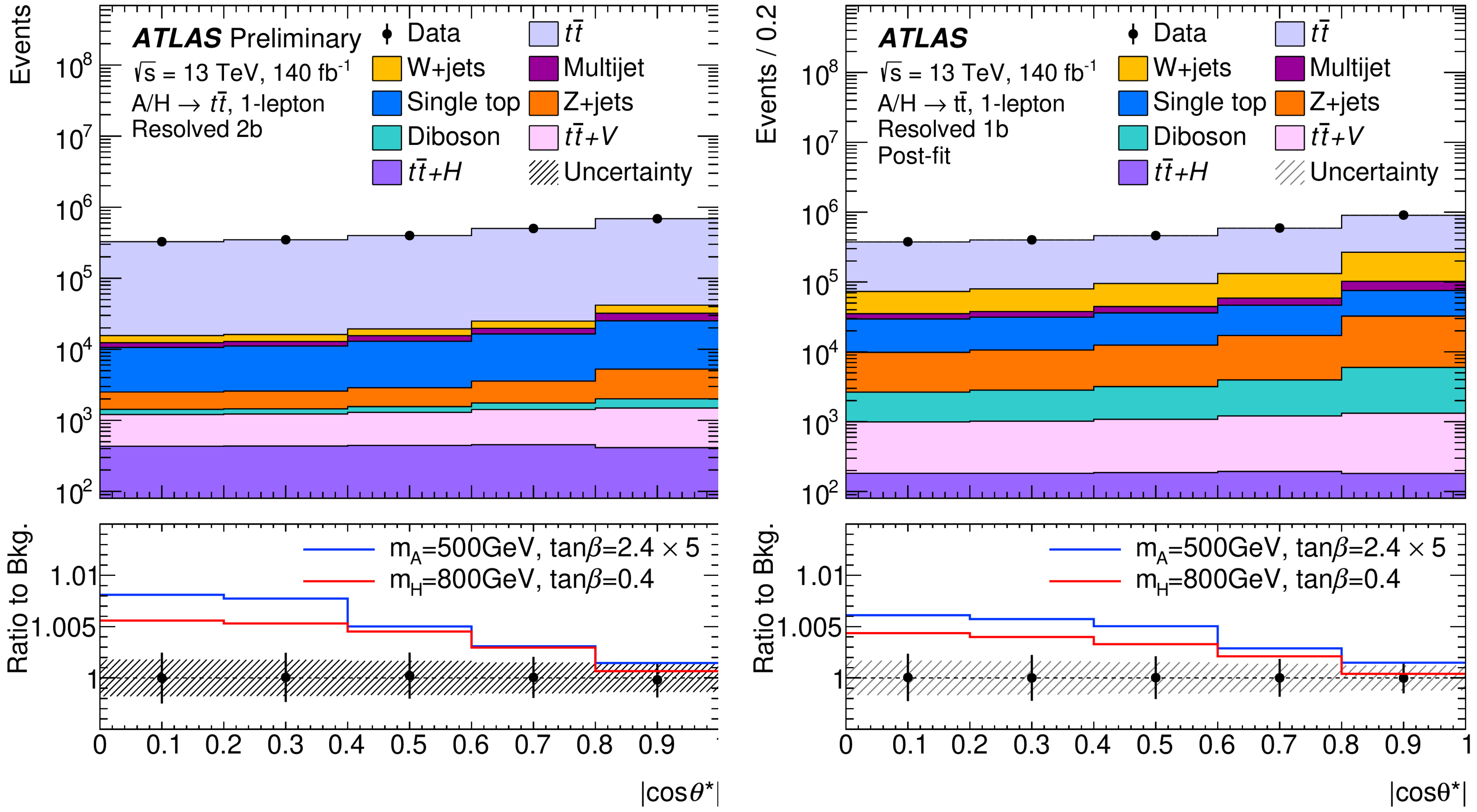


* Use resolved and merged b-jet categories as well as 1 and 2 lepton final states.

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

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

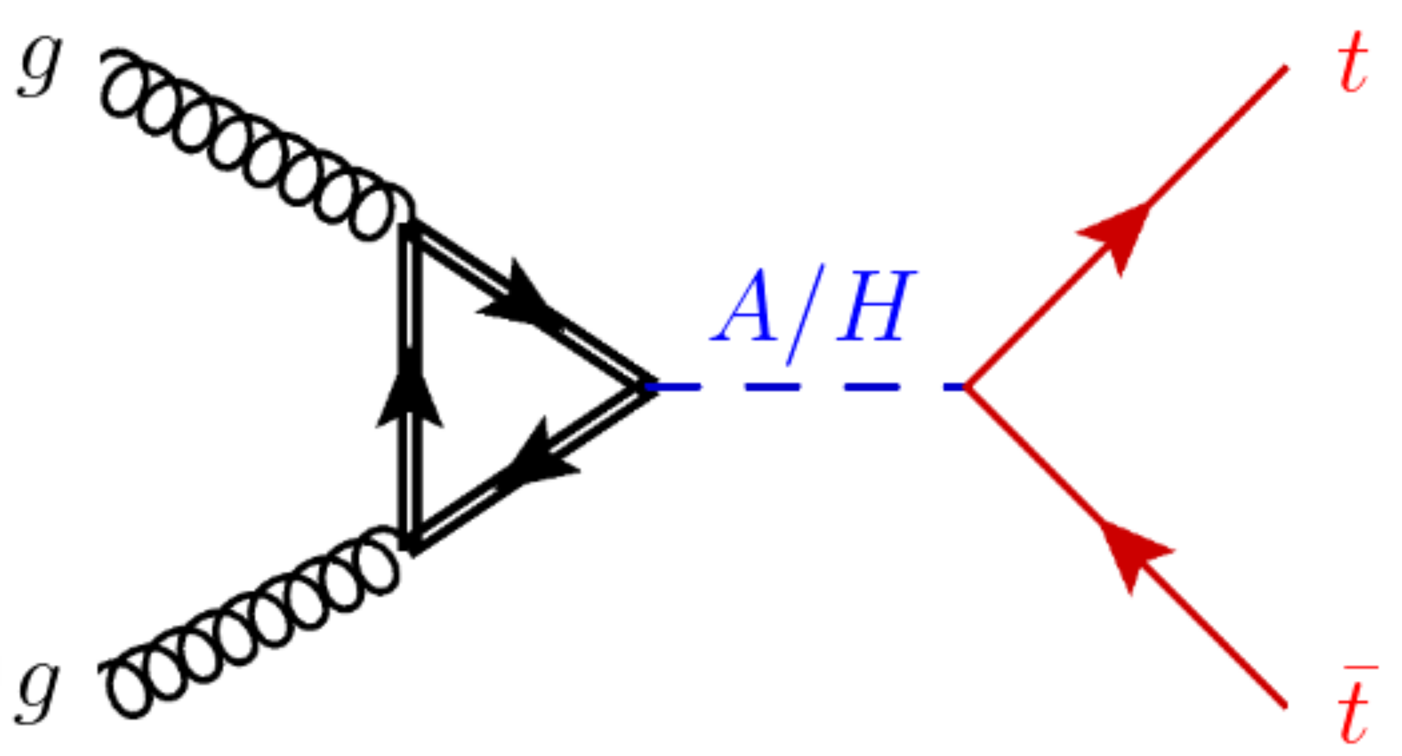
* Reconstructed H/A mass is used as the final discriminator.

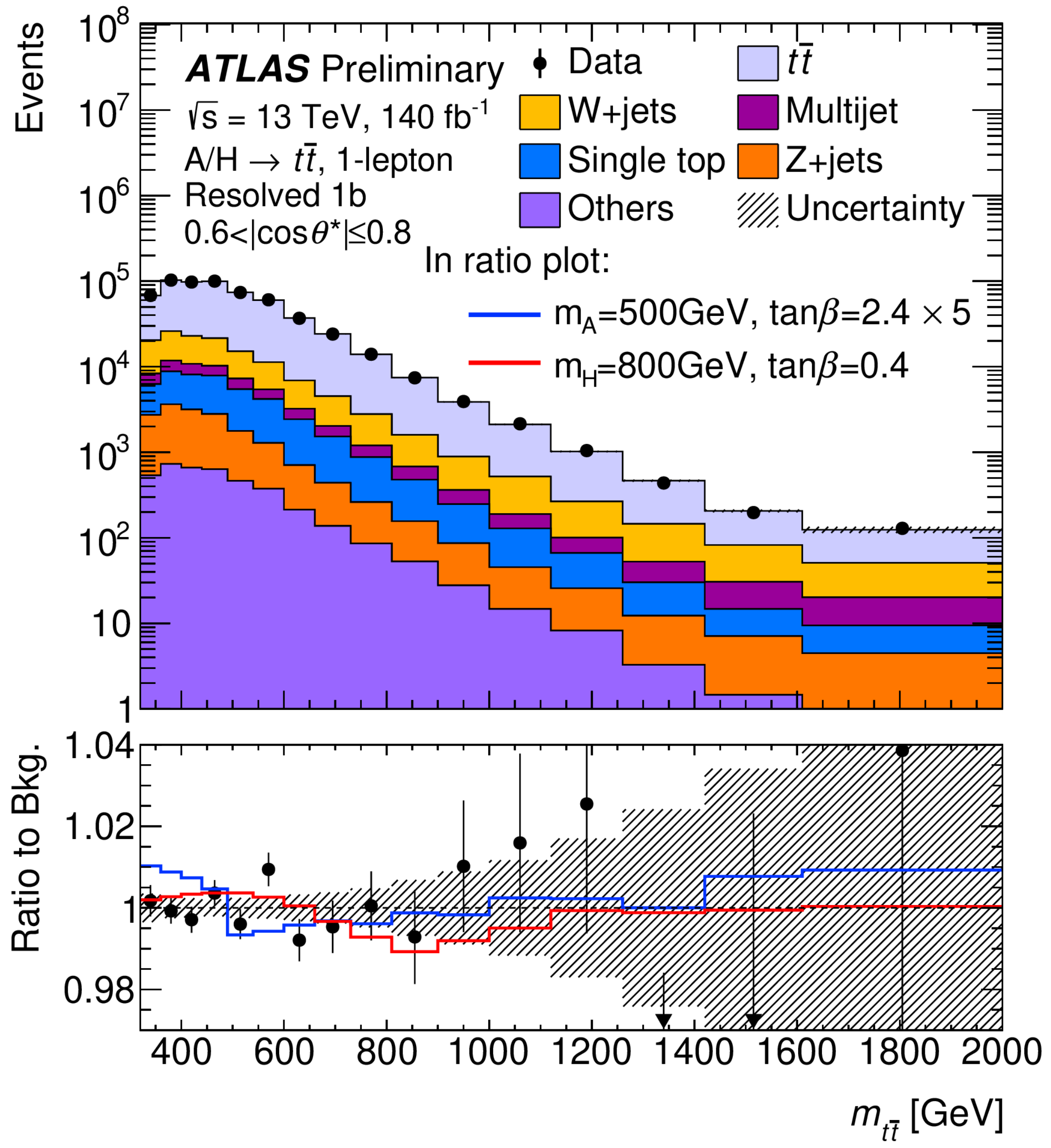


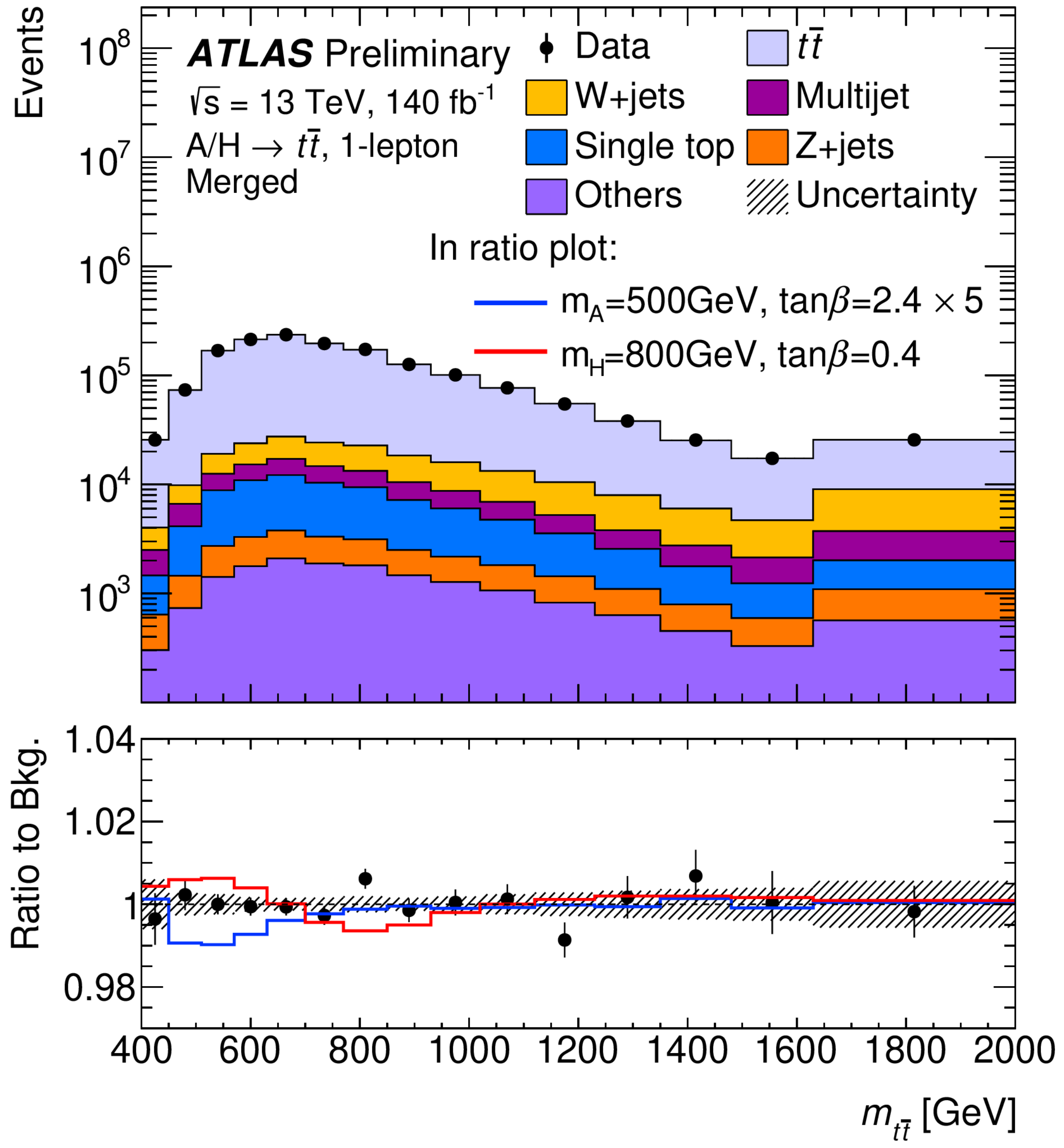
BSM H/A -> tt

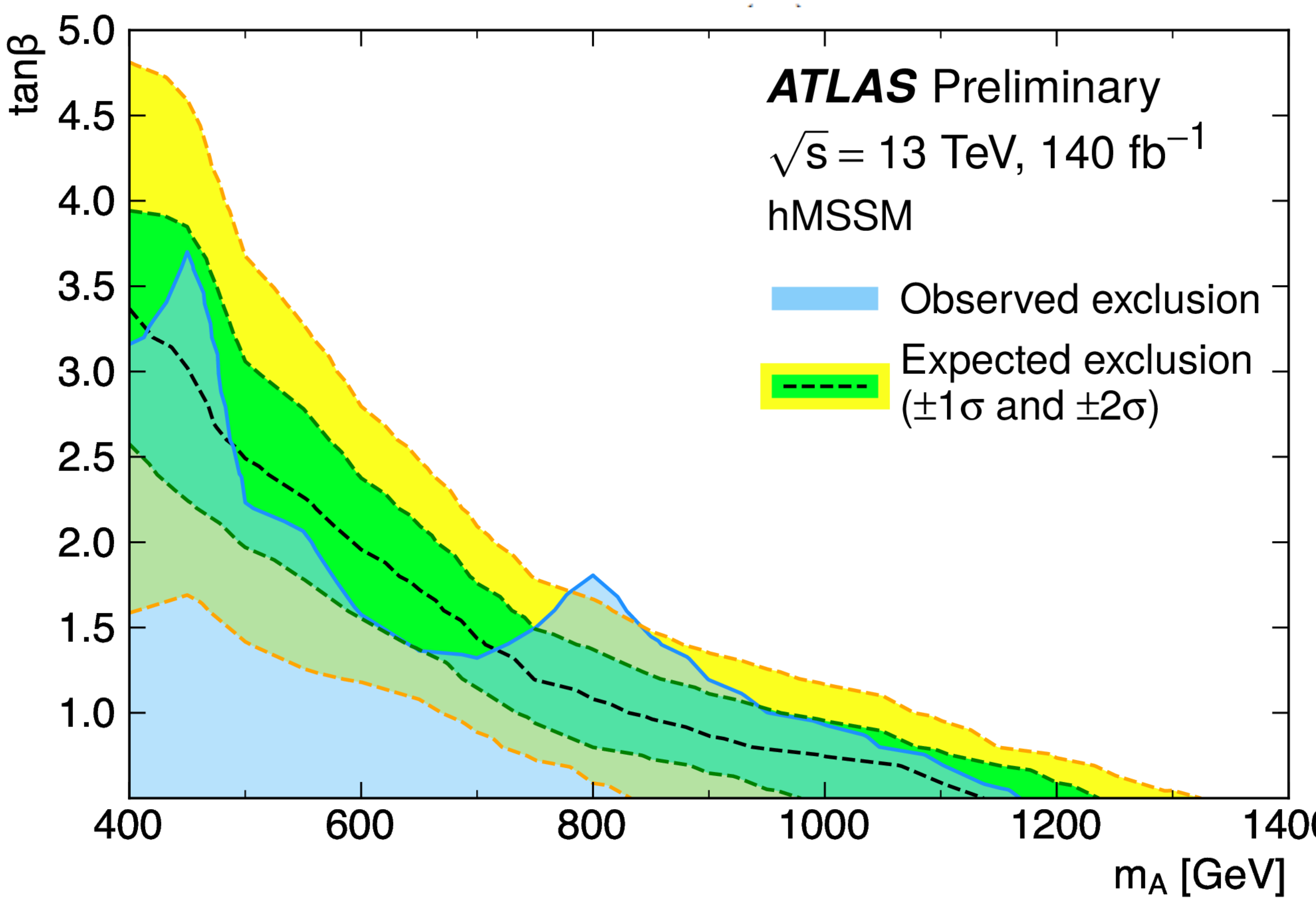
EXOT-2020-25

* 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.





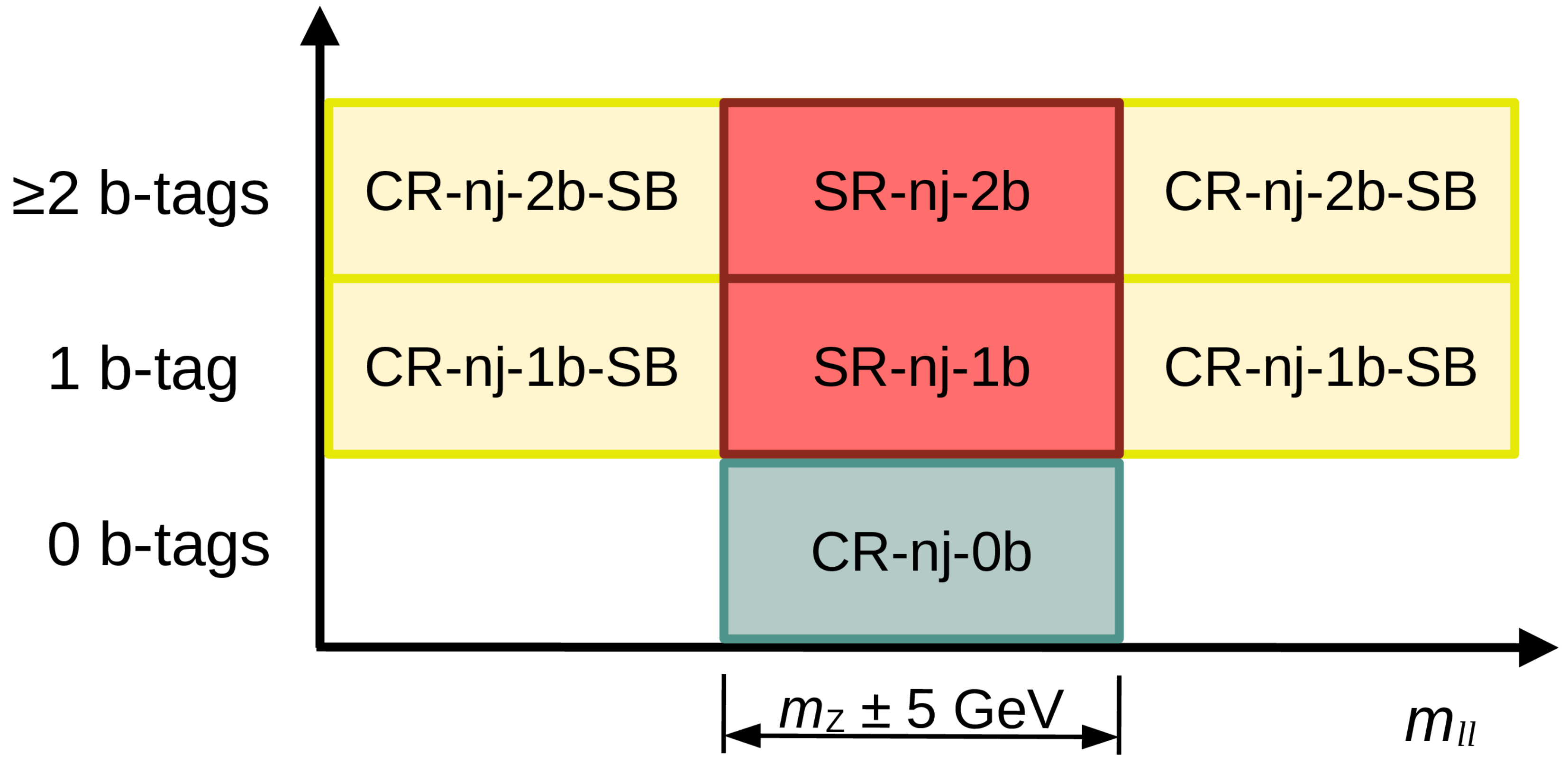


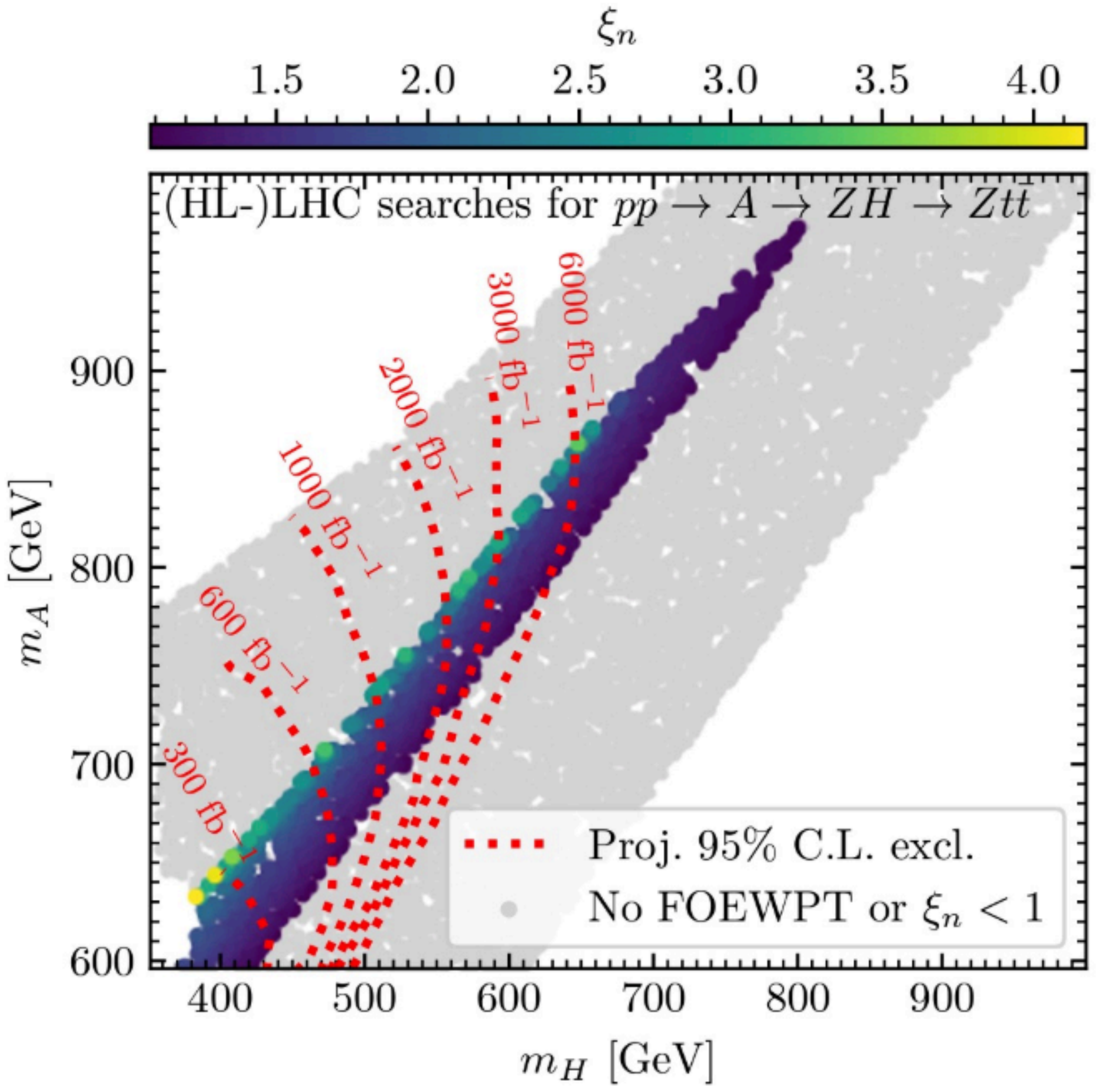


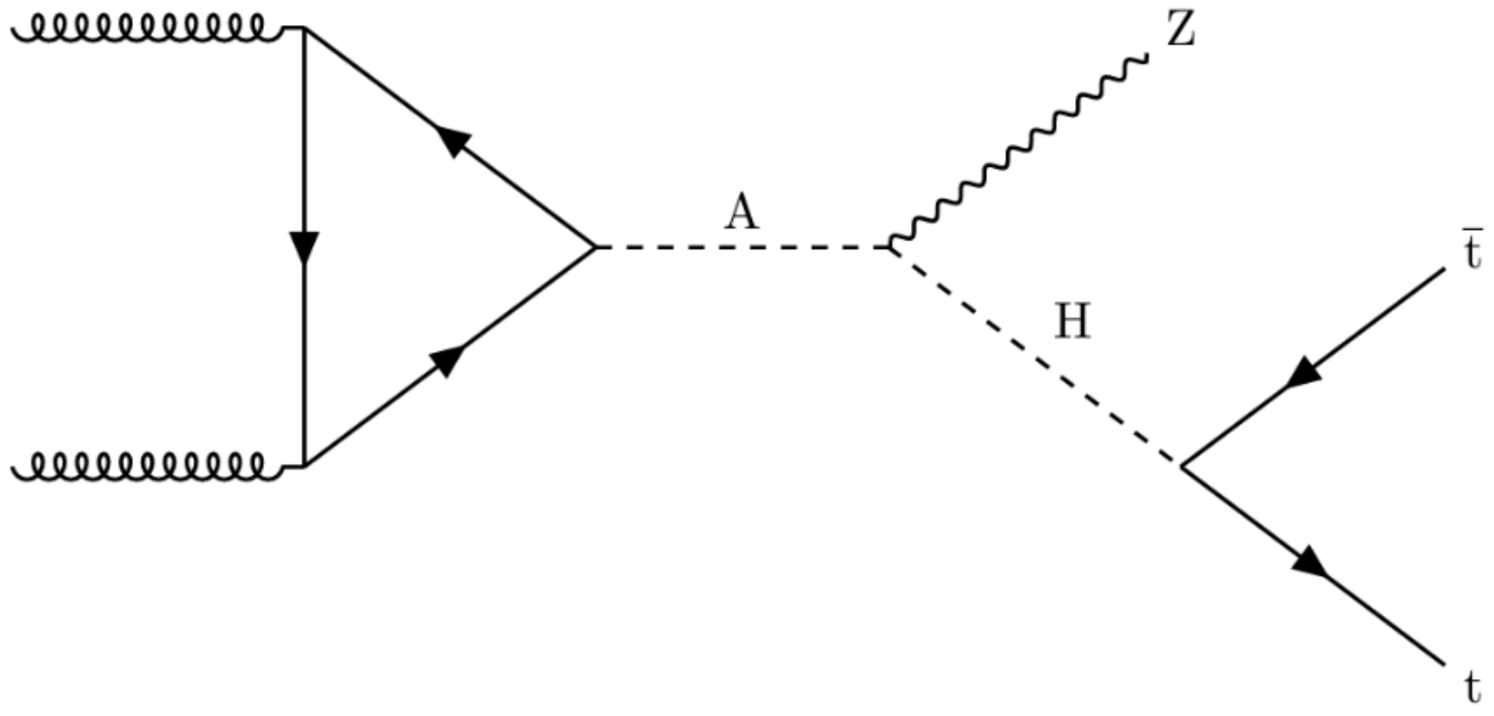
A-> ZH-> lltt

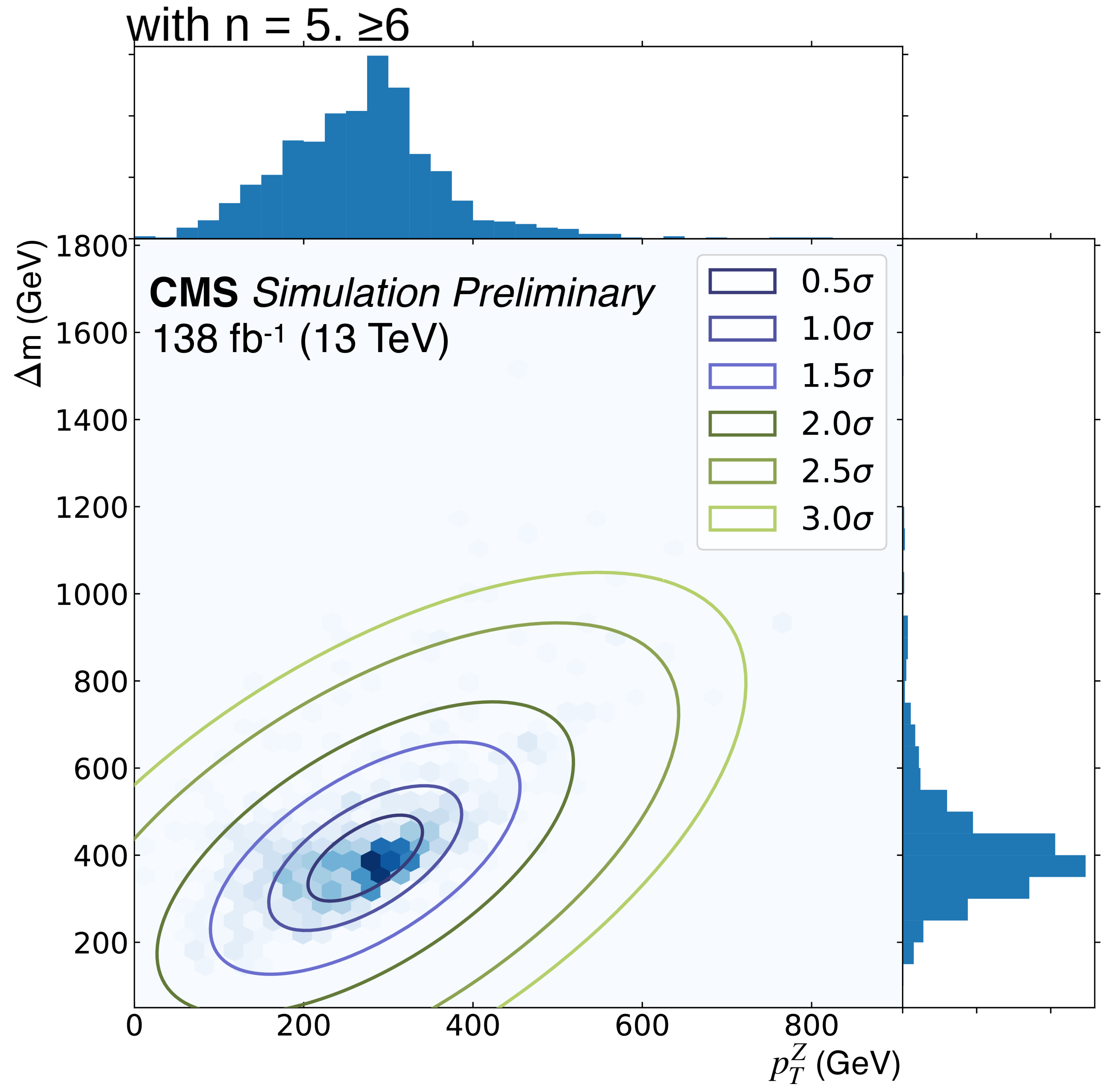
CMS-PAS-B2G-23-006

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









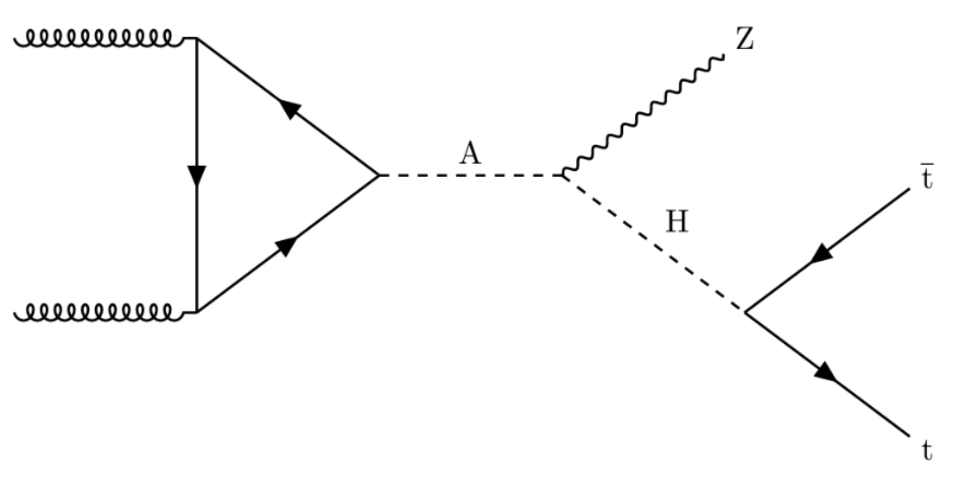
[Thomas Biekötter et al JCAP03(2023)031](#)

* 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.

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

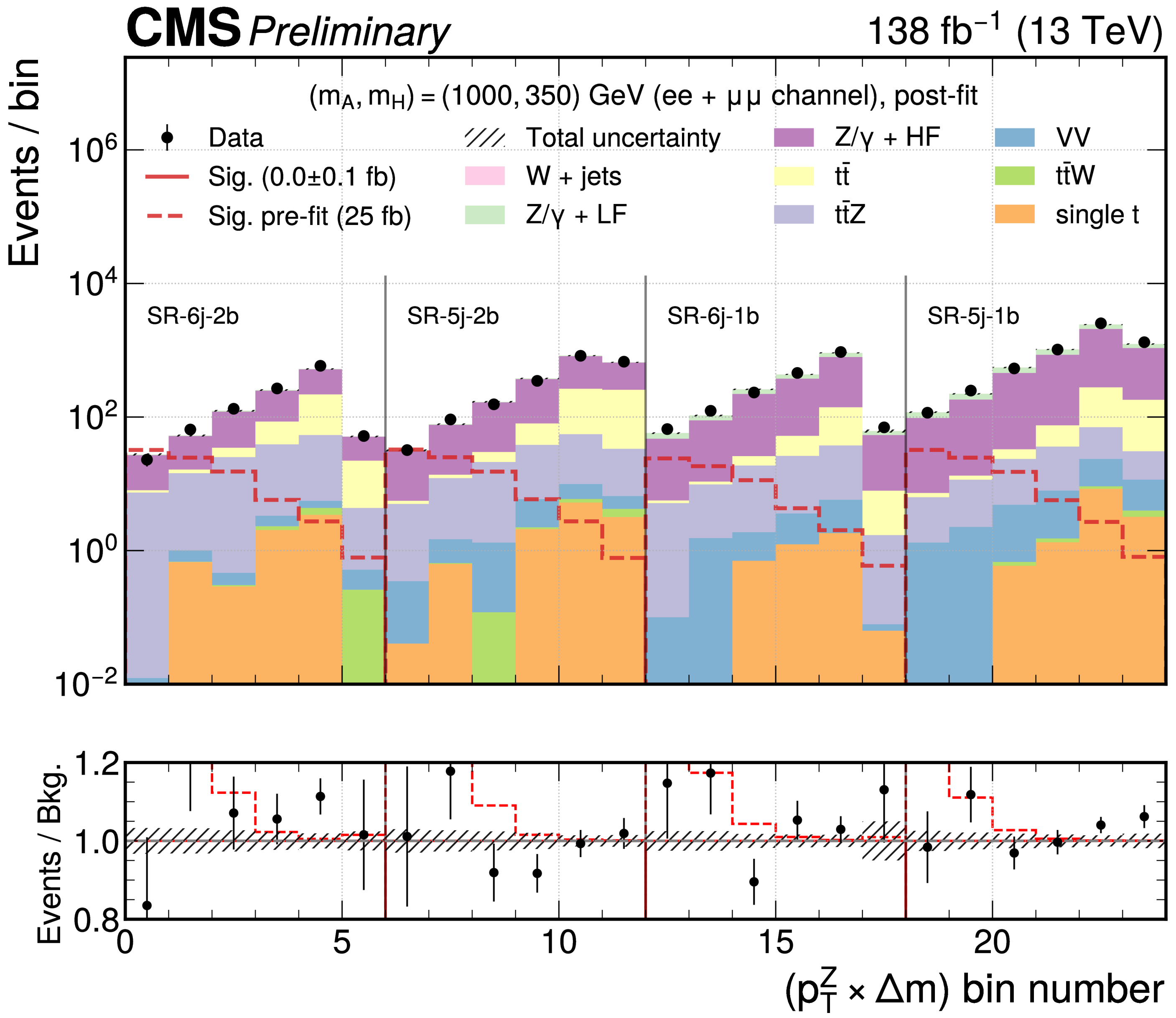
A-> ZH-> lltt

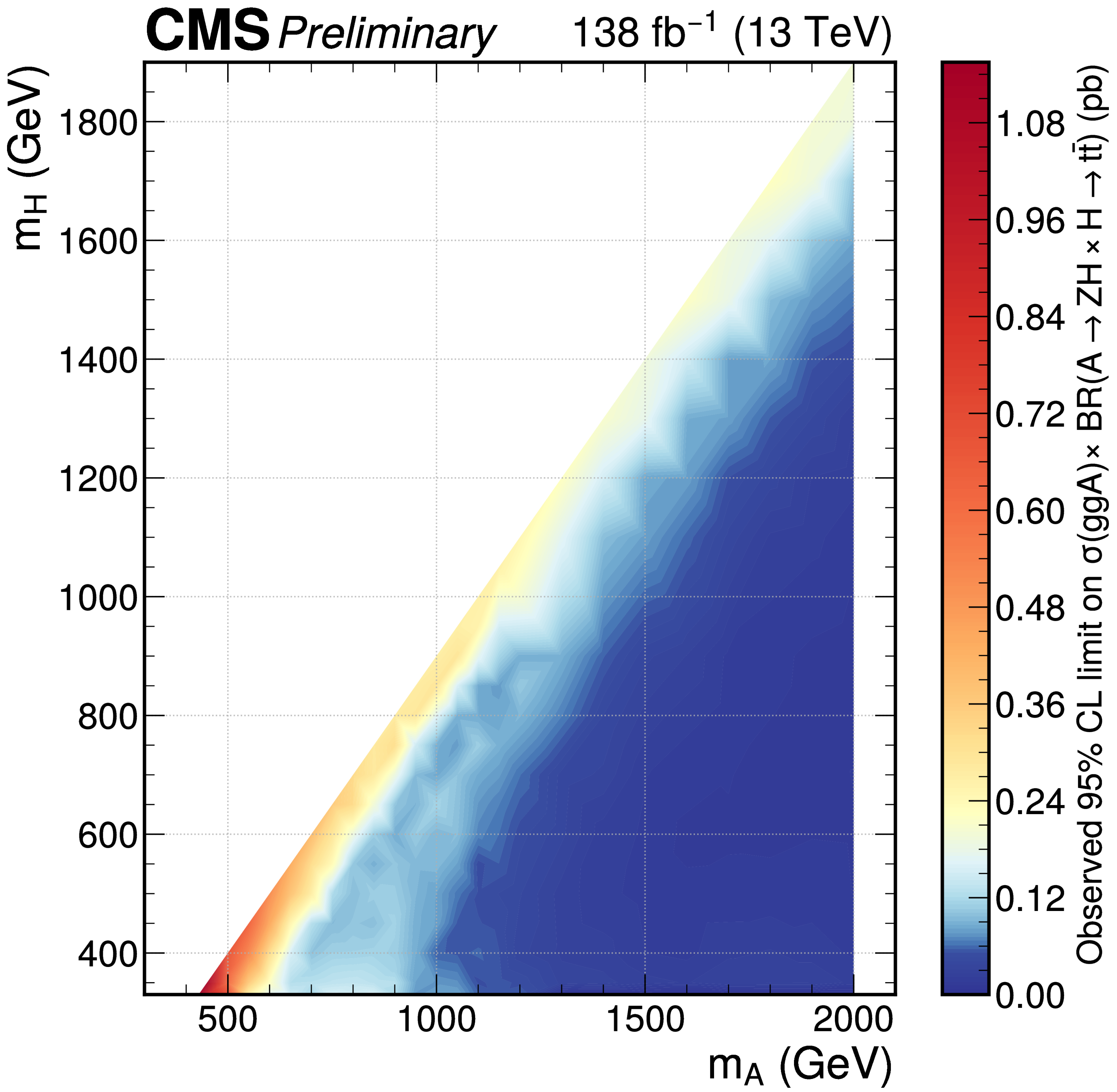
CMS-PAS-B2G-23-006

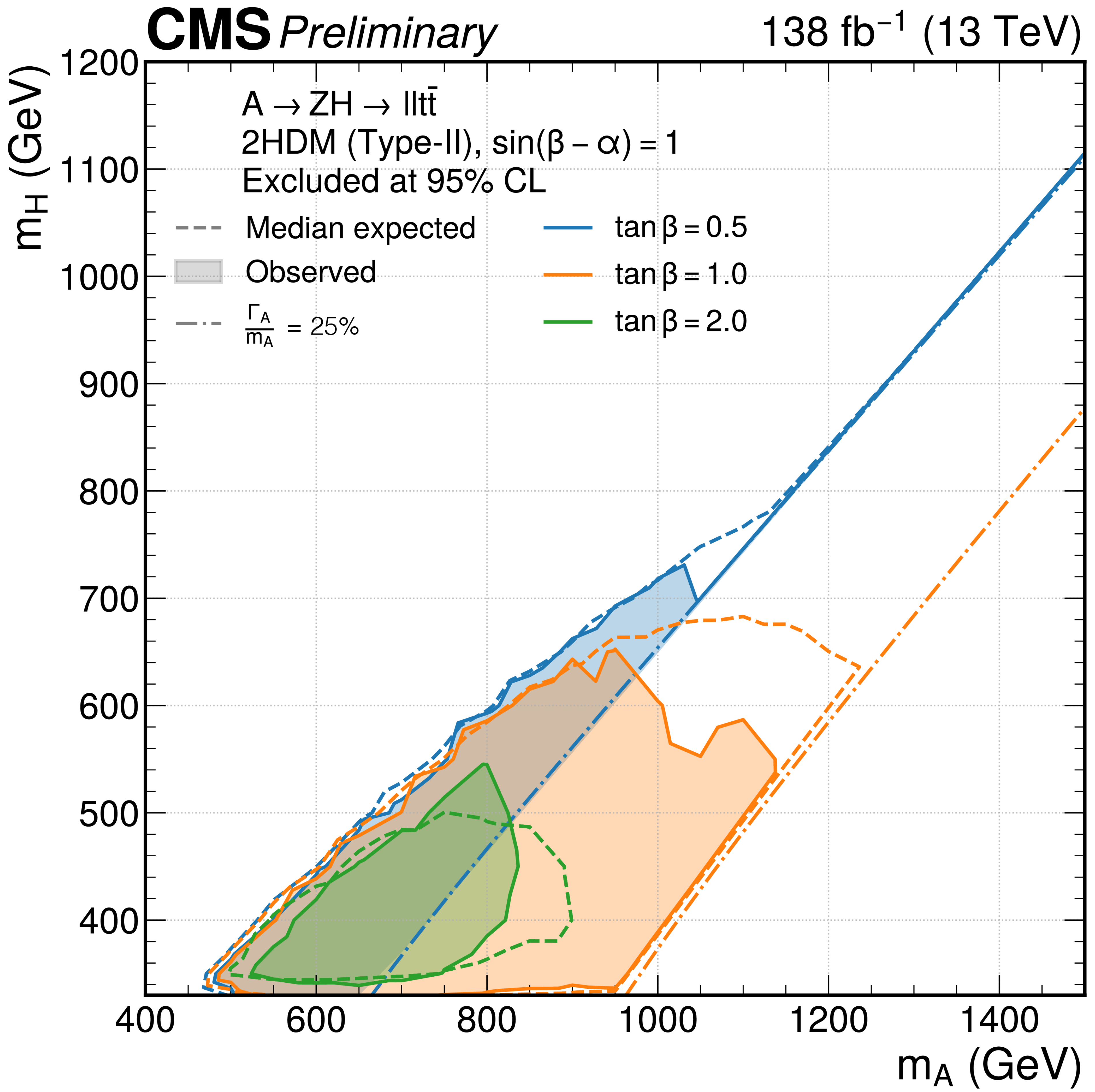


* No statistically significant deviation from the SM expectation was observed.

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



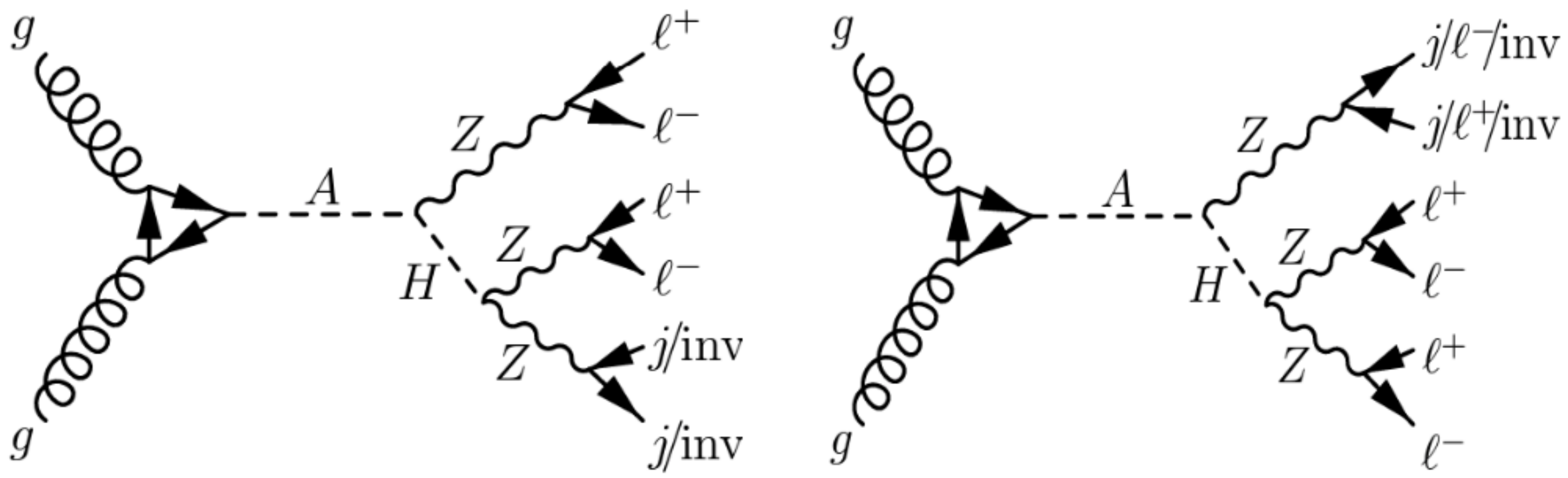


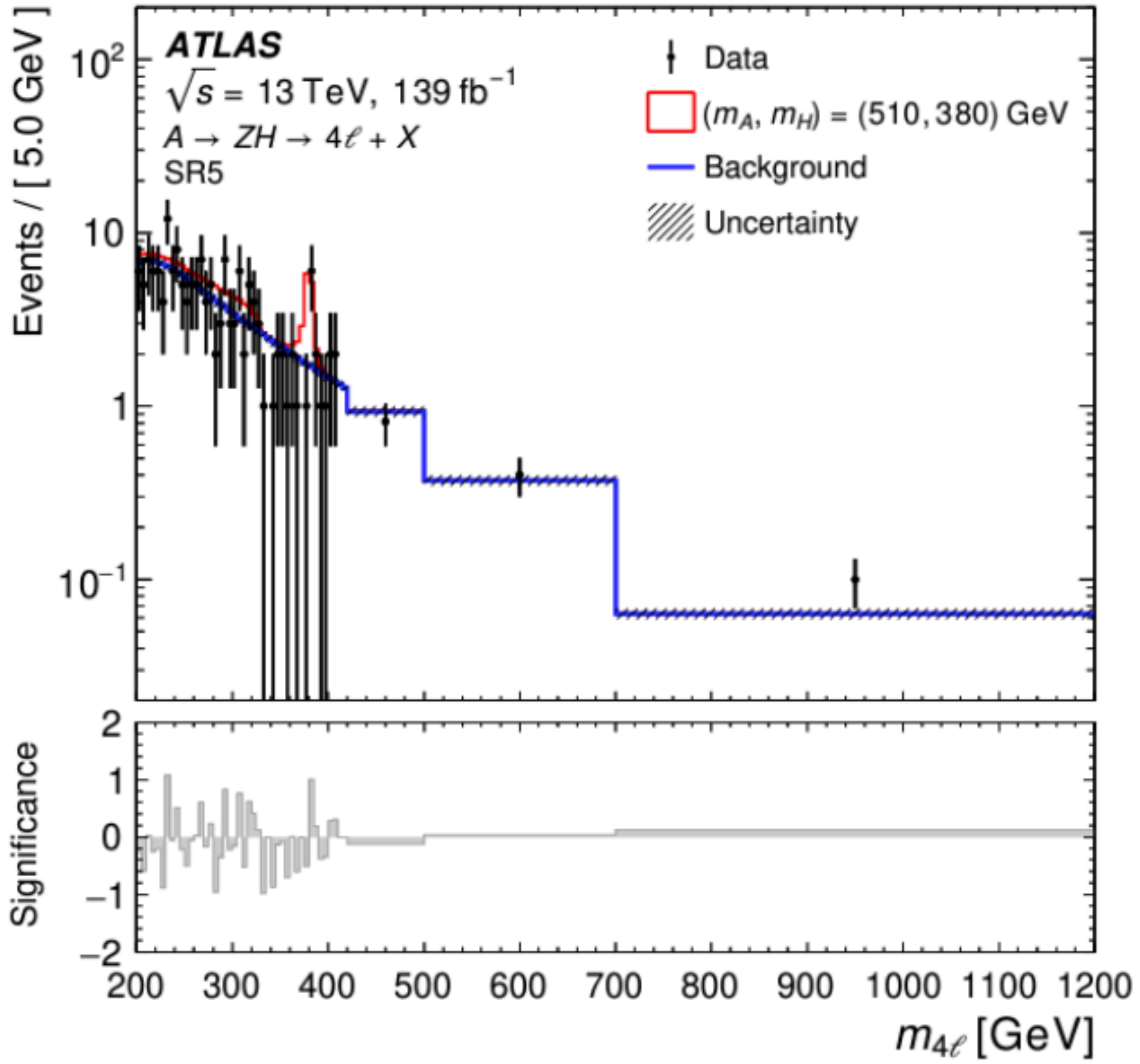


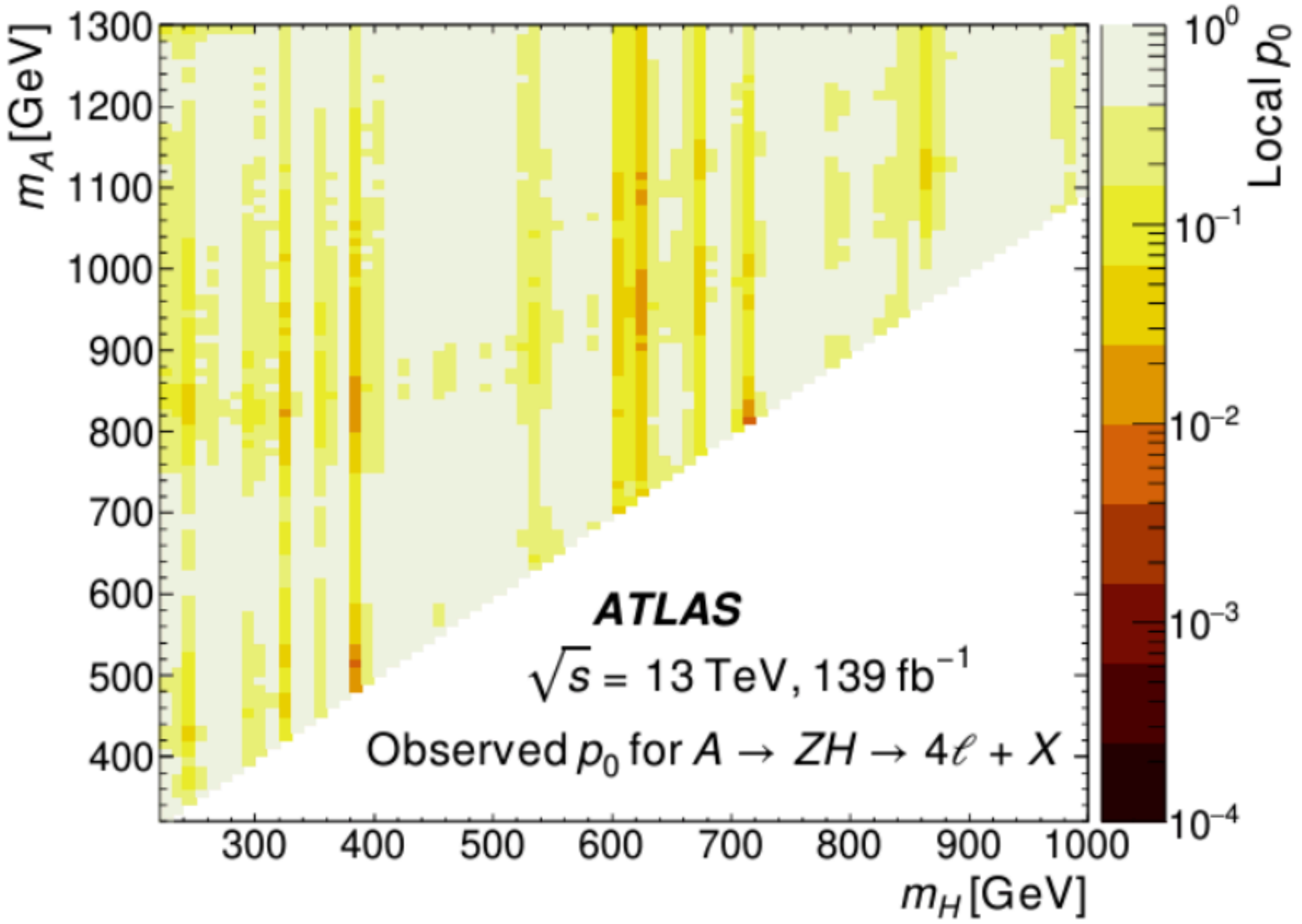
ATLAS - A-> ZH-> 4l+jj/MET

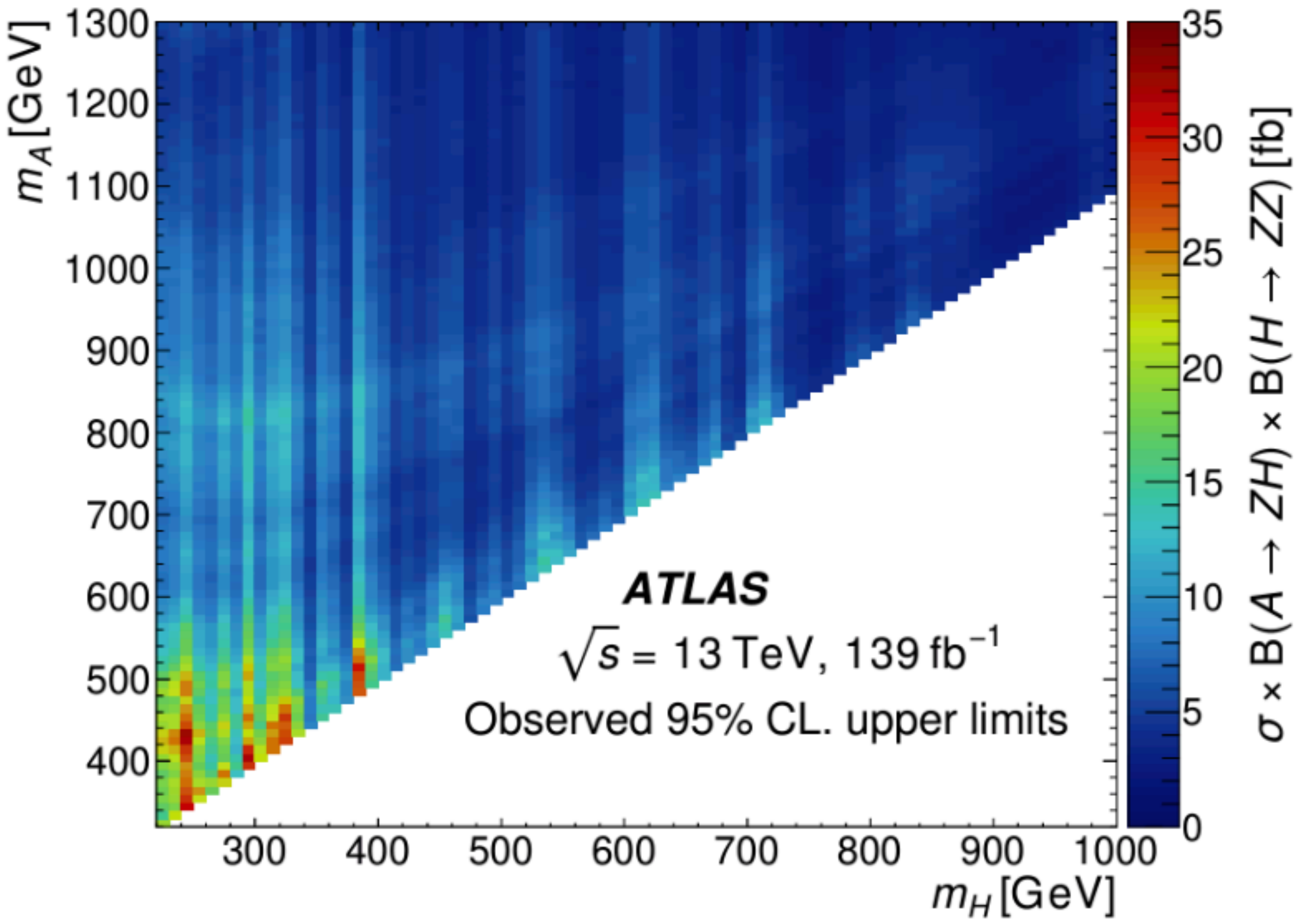
https://arxiv.org/abs/2401.04742

- 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.



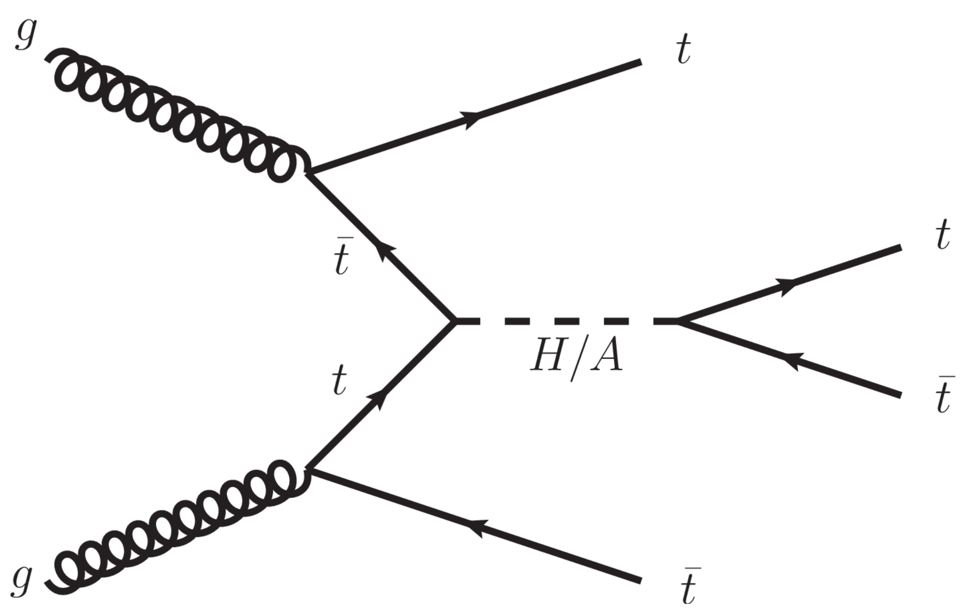


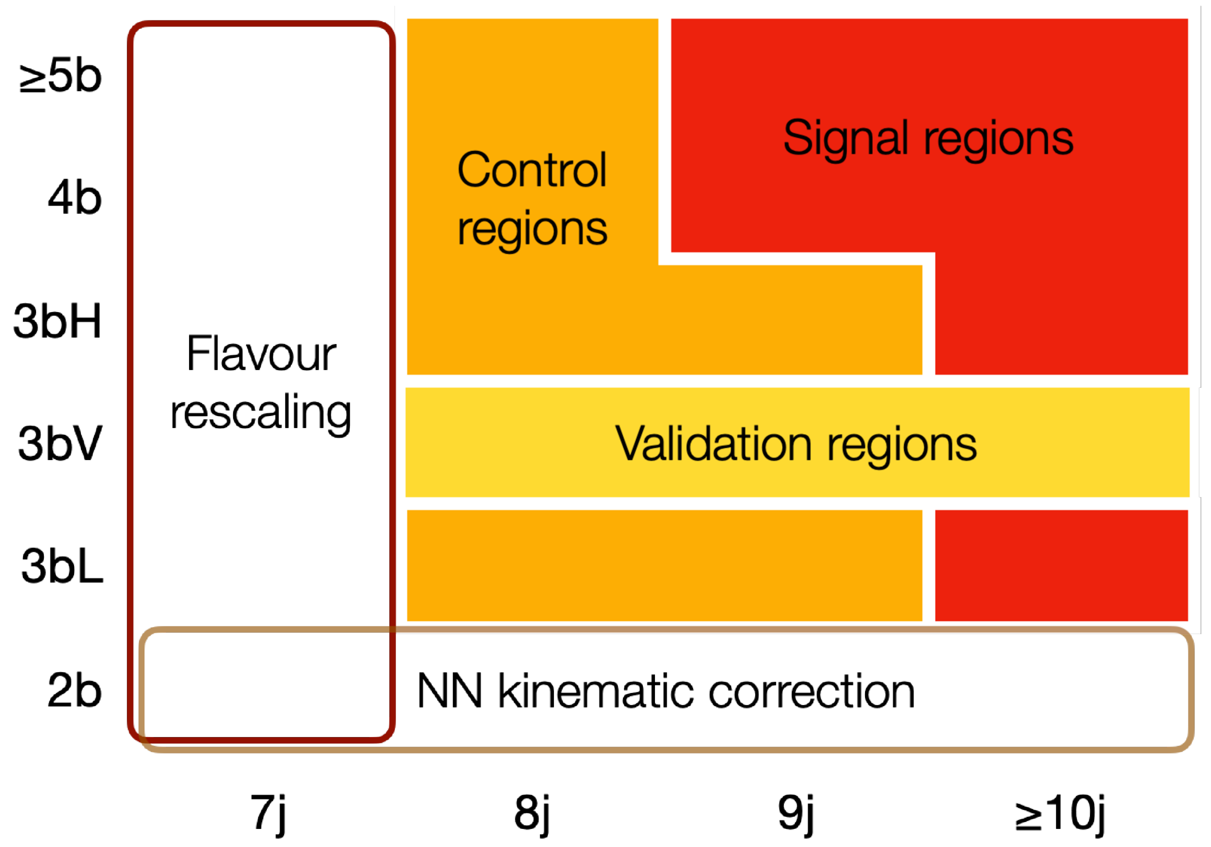




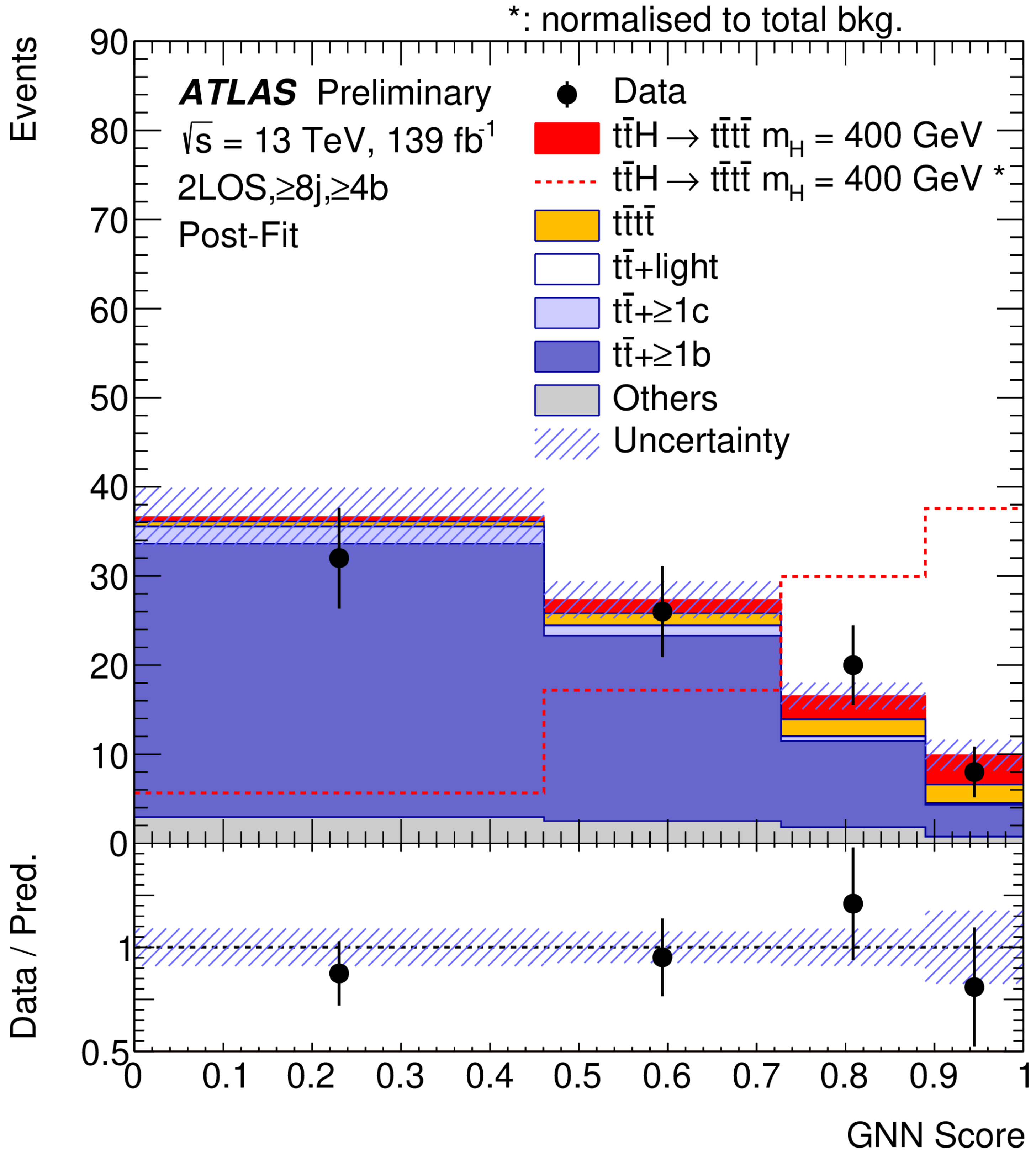
ttH/A -> 4top

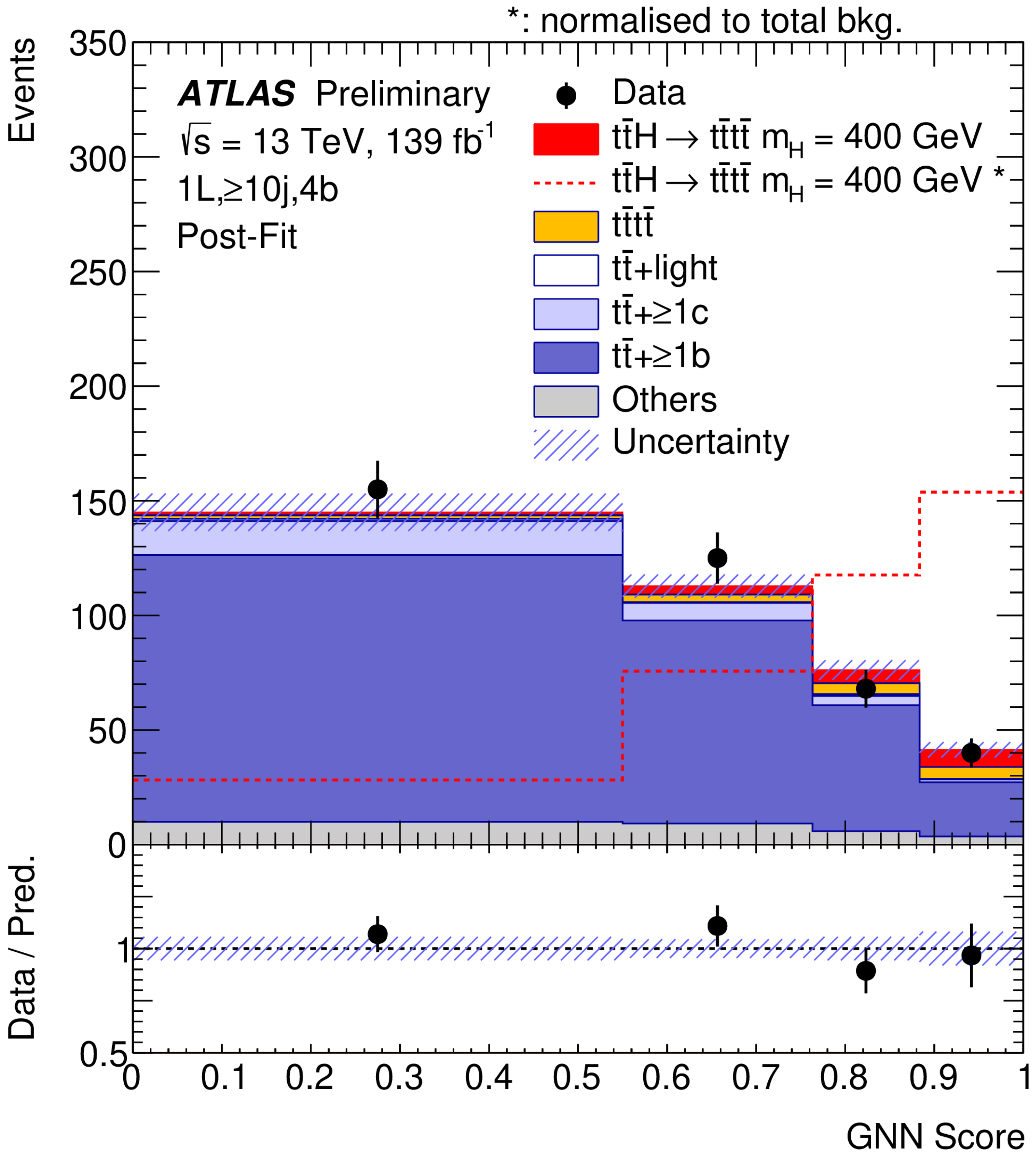
ATLAS-CONF-2024-002





- 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

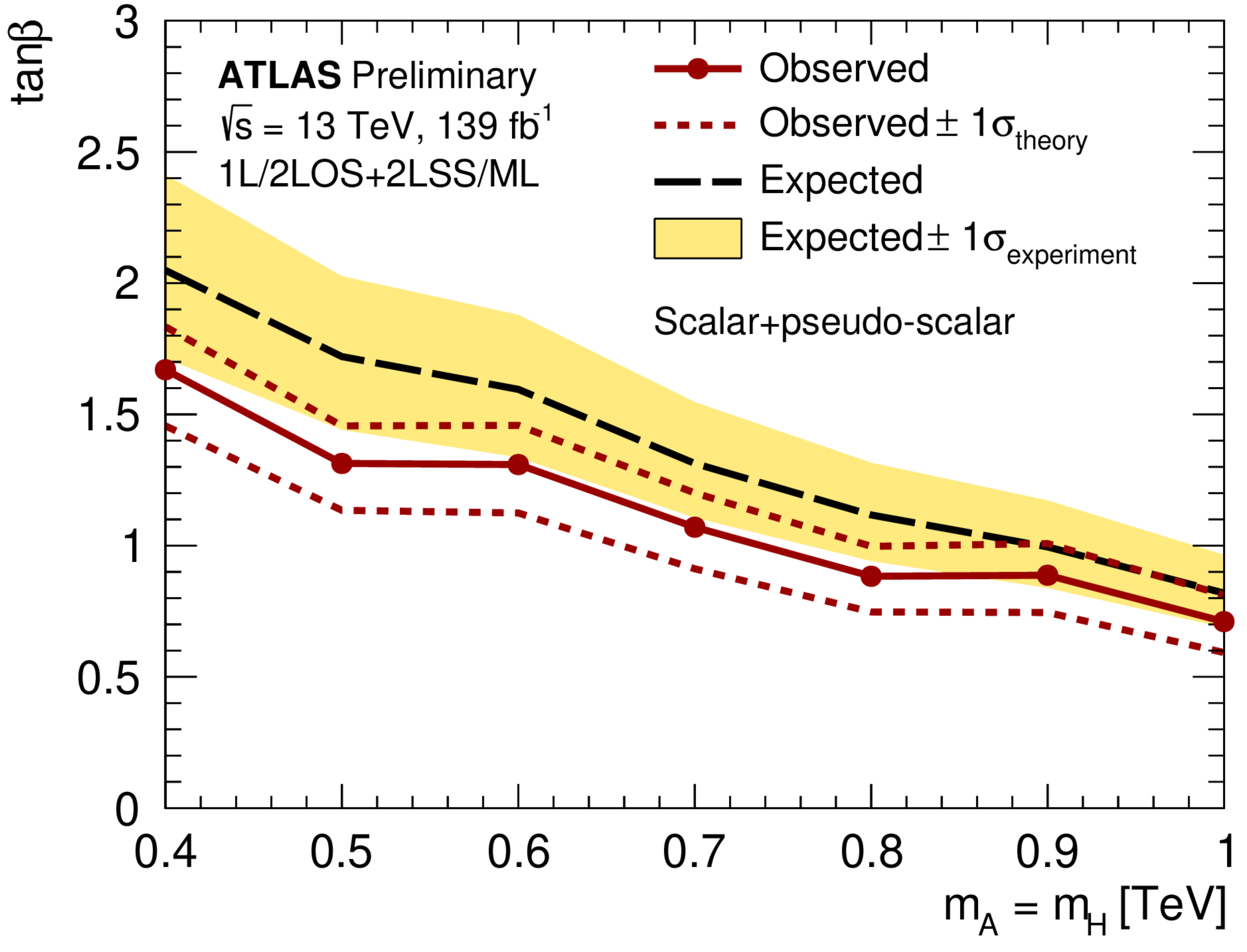


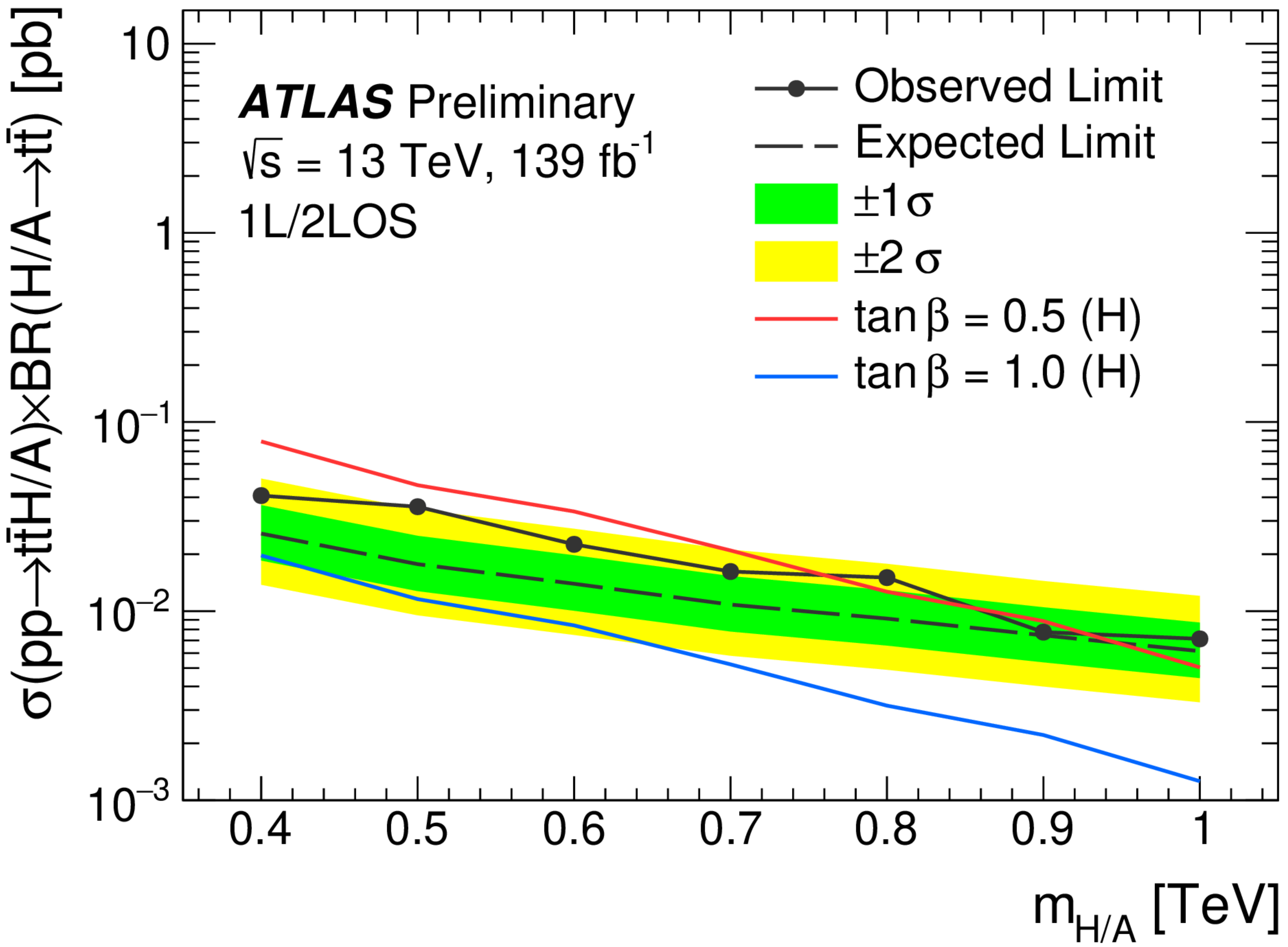


H/A -> 4top

ATLAS-CONF-2024-002

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



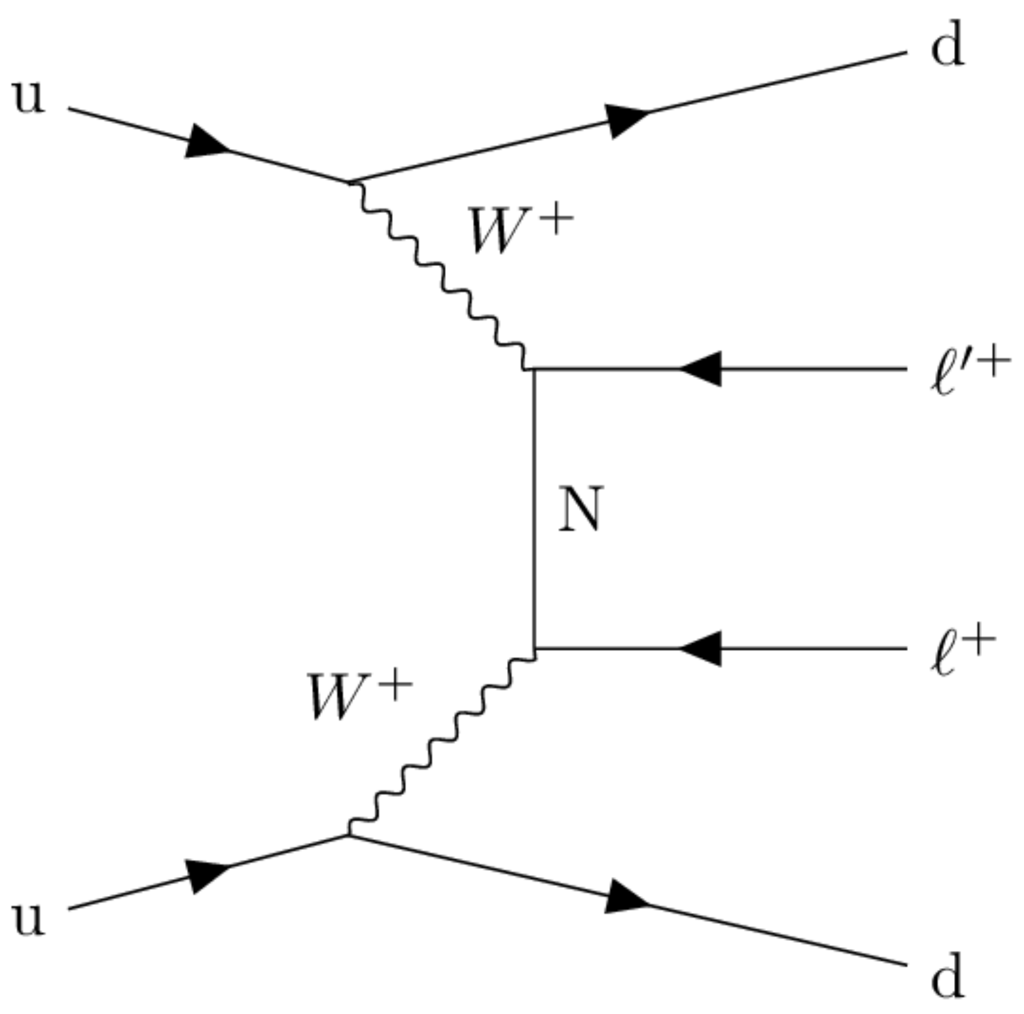


Heavy Neutrino

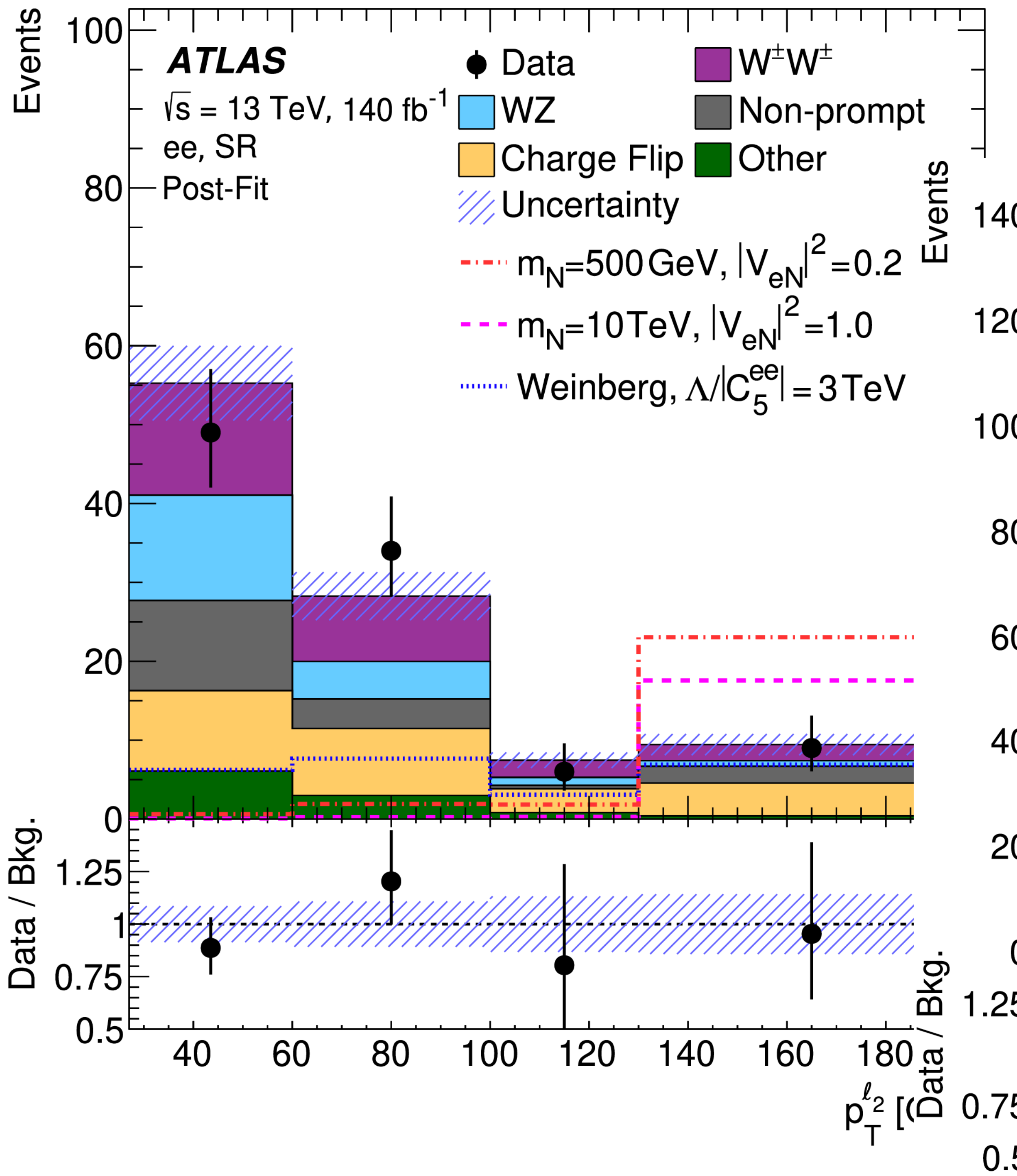
HNL via WW scattering in ee, eμ final states

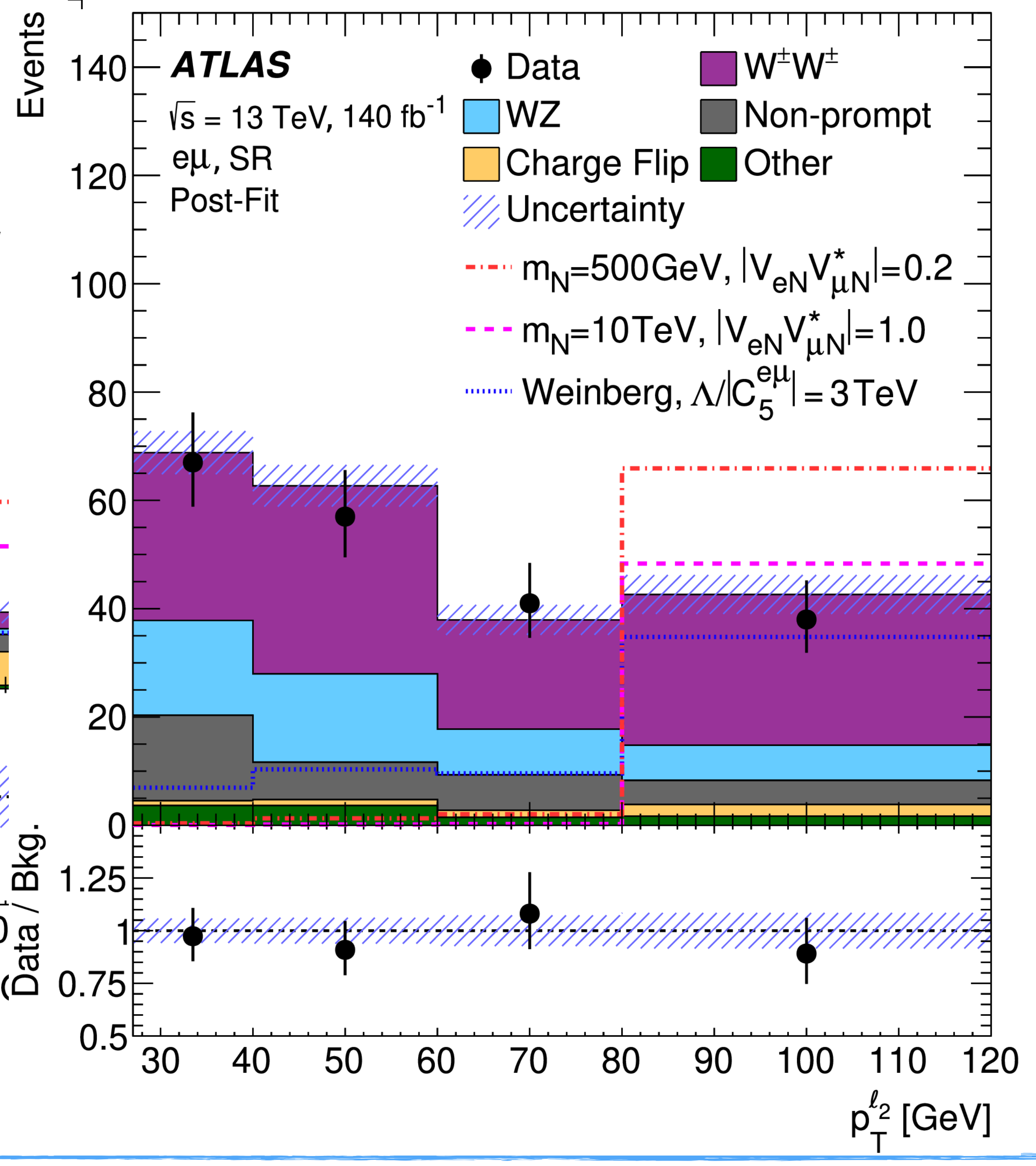
* Neutrino oscillations implies non-zero ν masses
* Neutrinoless double β decay: probe Majorana mass terms
* BSM theories: Type-I Seesaw, LRSM, GUT, dim-5 Weinberg operator

EXOT-22-019



- $\ell^\pm\ell^\pm(ee, e\mu)$
- $m_{jj} > 500$ GeV, $|\Delta y_{jj}| > 2$
- $p_T^{\ell_2}$ discriminating variable



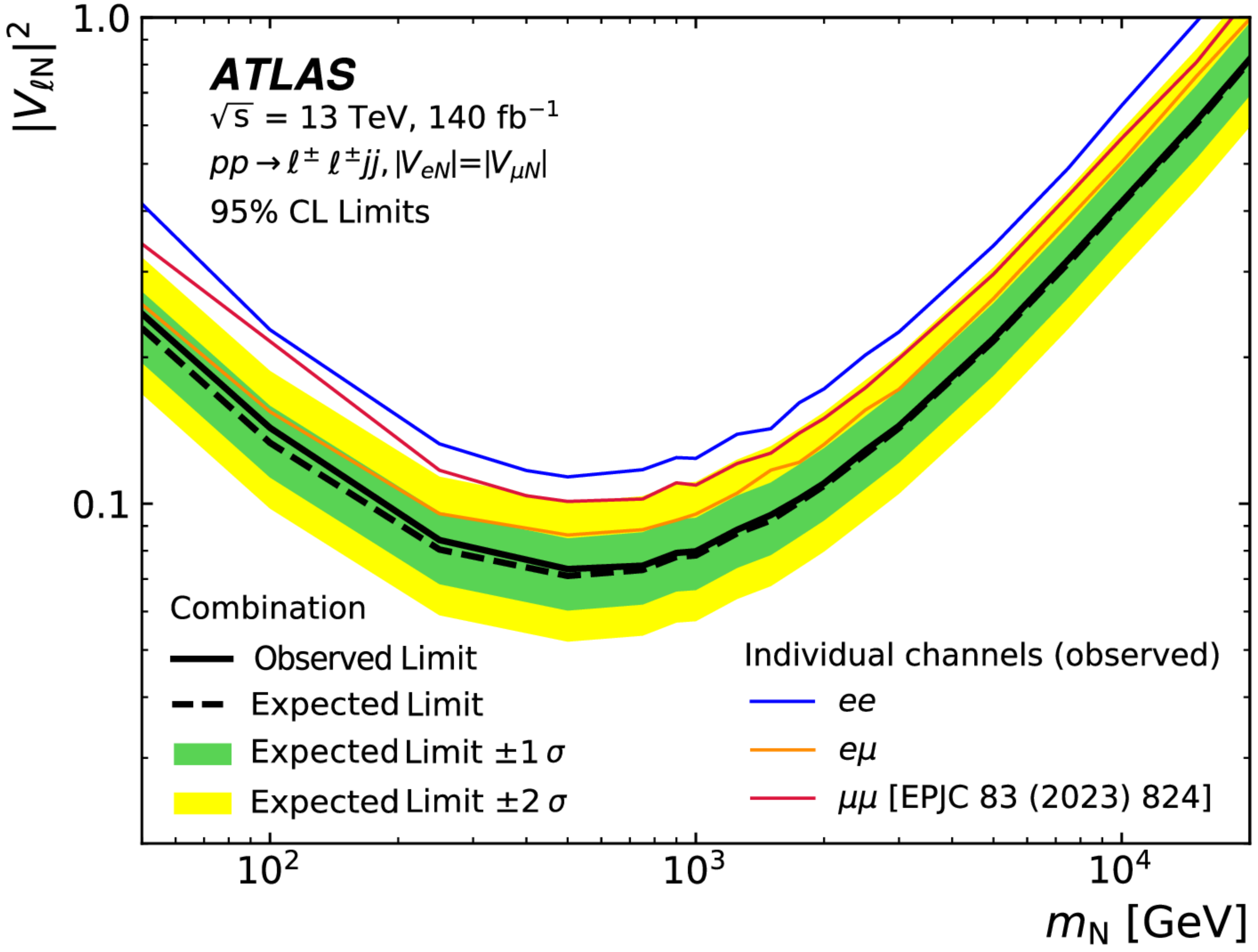


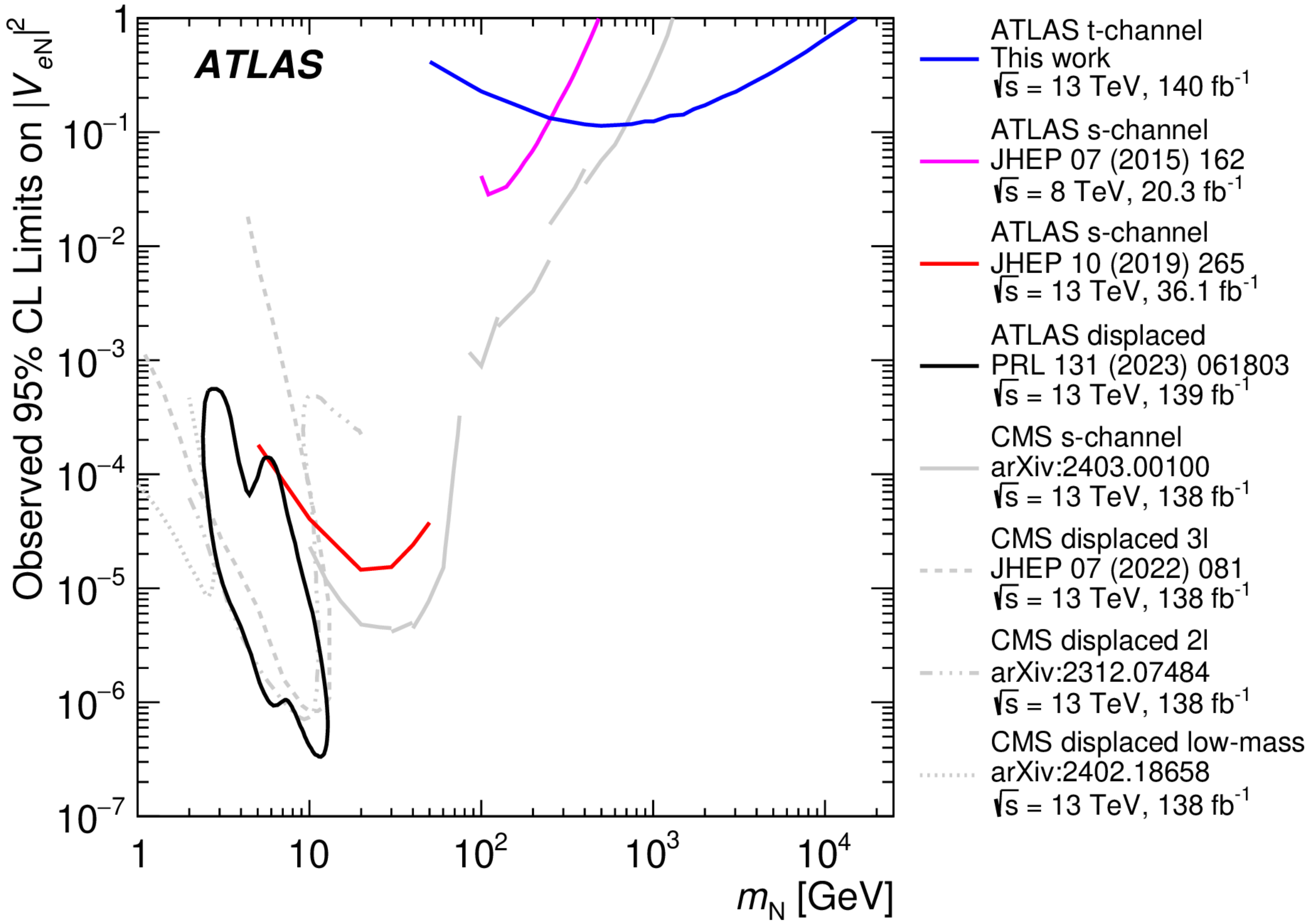
* FIRST Search for Majorana *N*s in $0\nu\beta\beta$-like *W* scattering process: $l \pm l \pm jj$ in ee and (LFV!) **e*μ*** channels, complement existing & similar *μμ* channel [arXiv:2305.14931].
* Cut-based event selection, binned fit in 2nd highest lepton *pT*.
* Dominant VBF $W\pm W\pm/WZ$ bkgs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

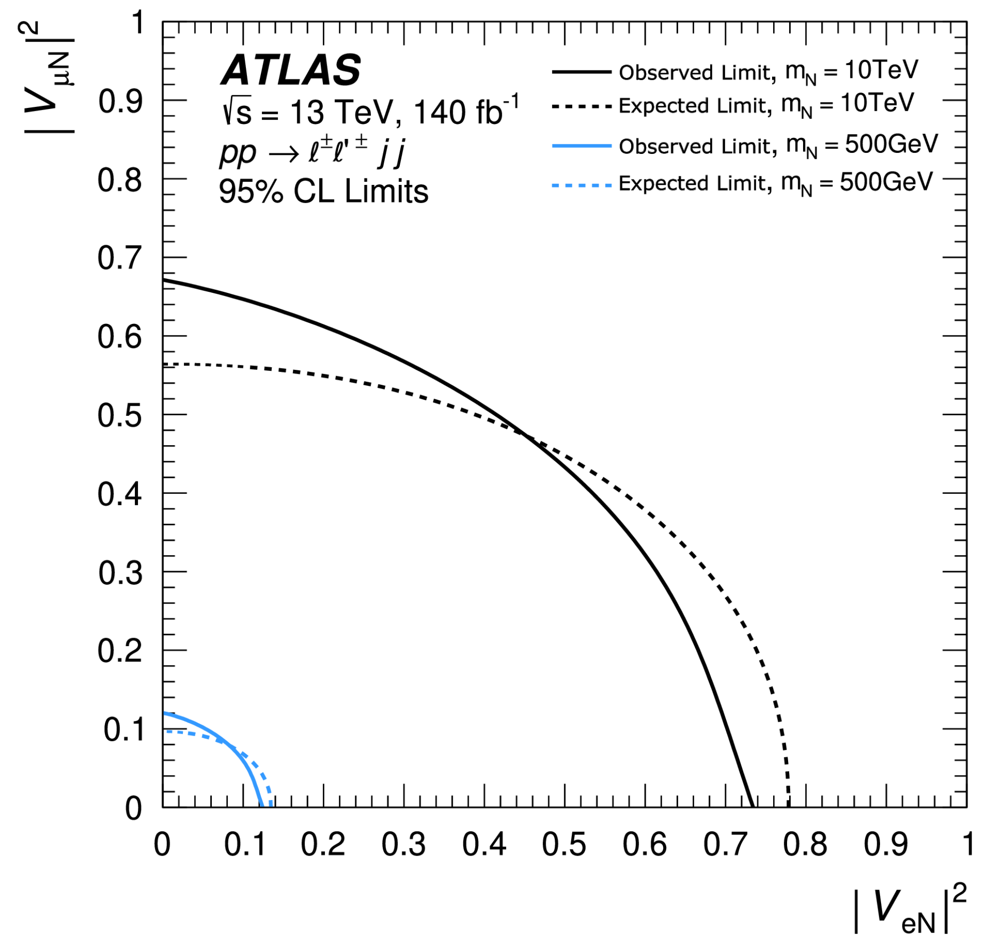
HNL via WW scattering

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!



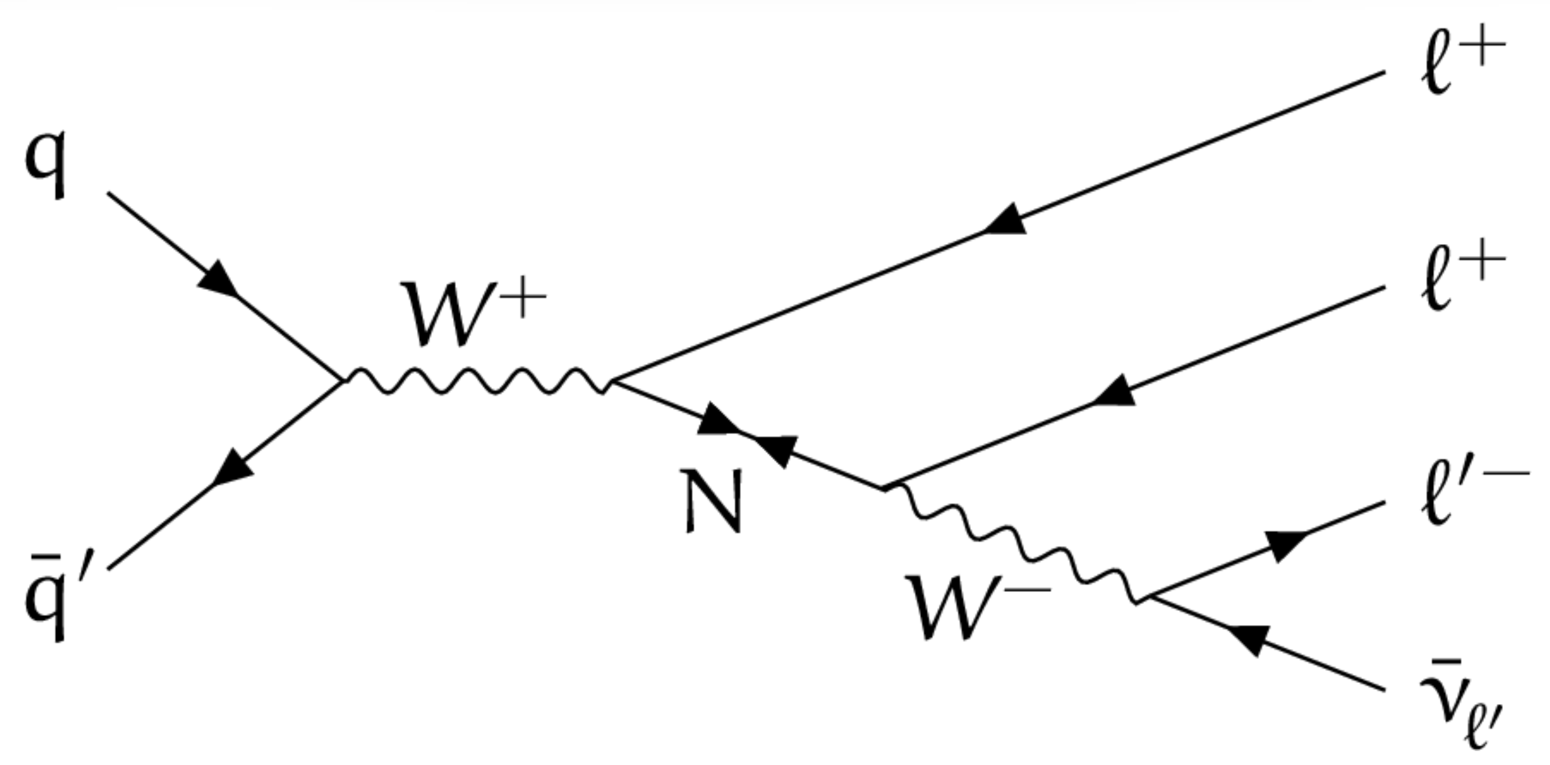




- Limits on the mixing matrix elements $|V_{eN}|^2$, $|V_{eN}V^*_{\mu N}|$ and combined with
- Limit Obs(Exp): $|m_{ee}|<24.5(23.6)$, $|m_{e\mu}|<12.5(14.8)$ GeV

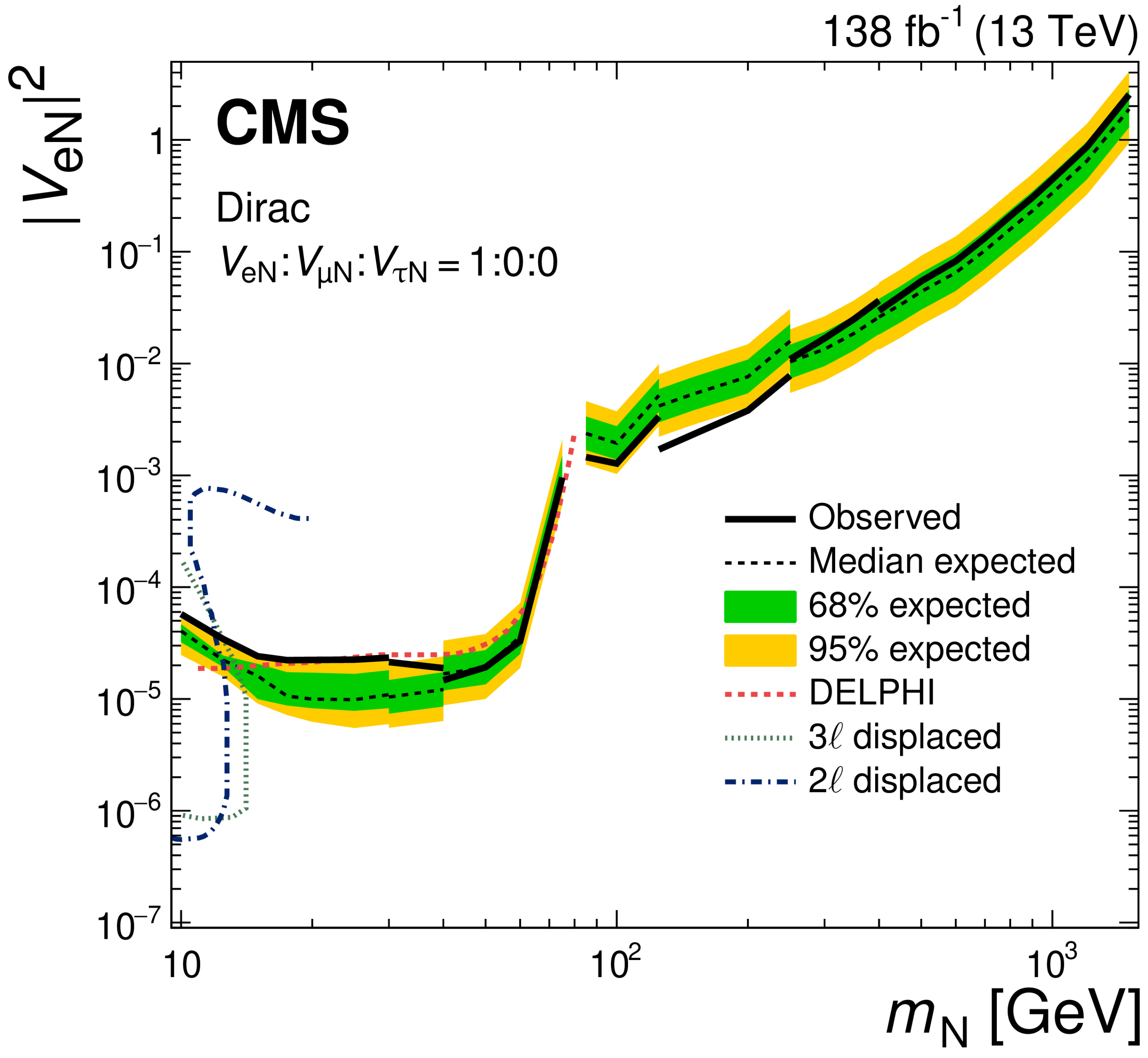
HNL in final states with e, μ, hadronic τ

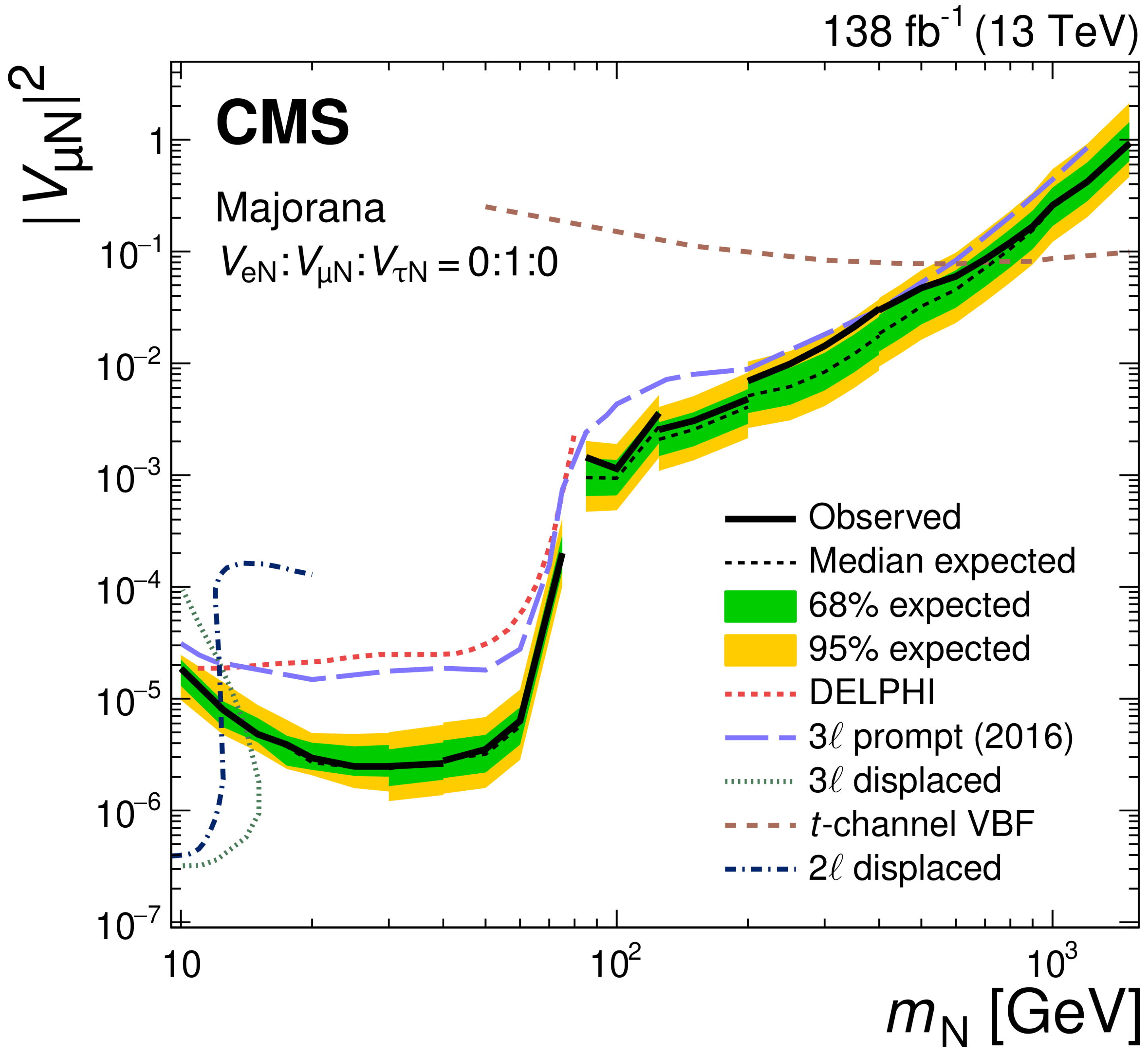
EXOT-22-011



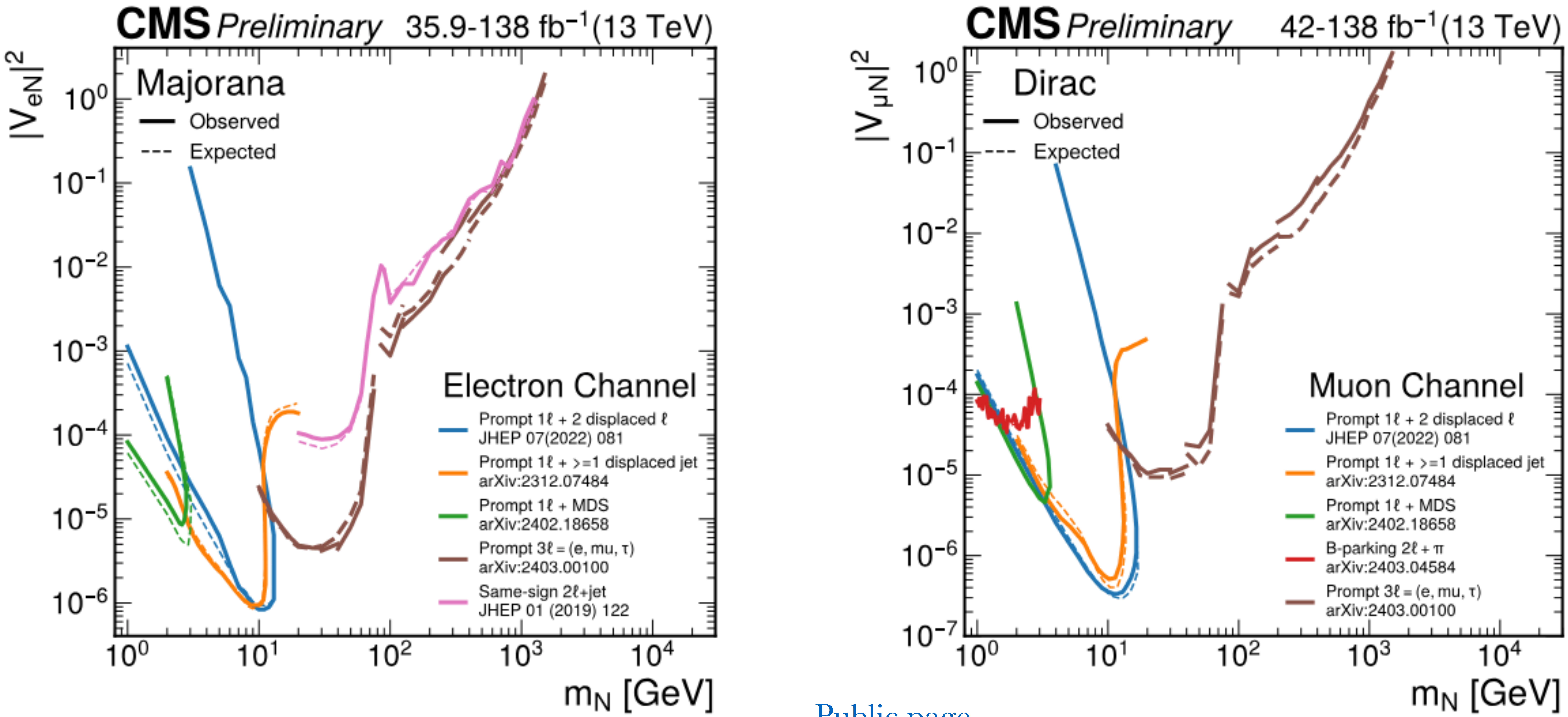
* Heavy N: Majorana (LNV, LNC) or Dirac (LNC) type
* Mixing matrix: exclusively to a single generation SM ν
* Channels considering all combination of e, μ and τ_h

* 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

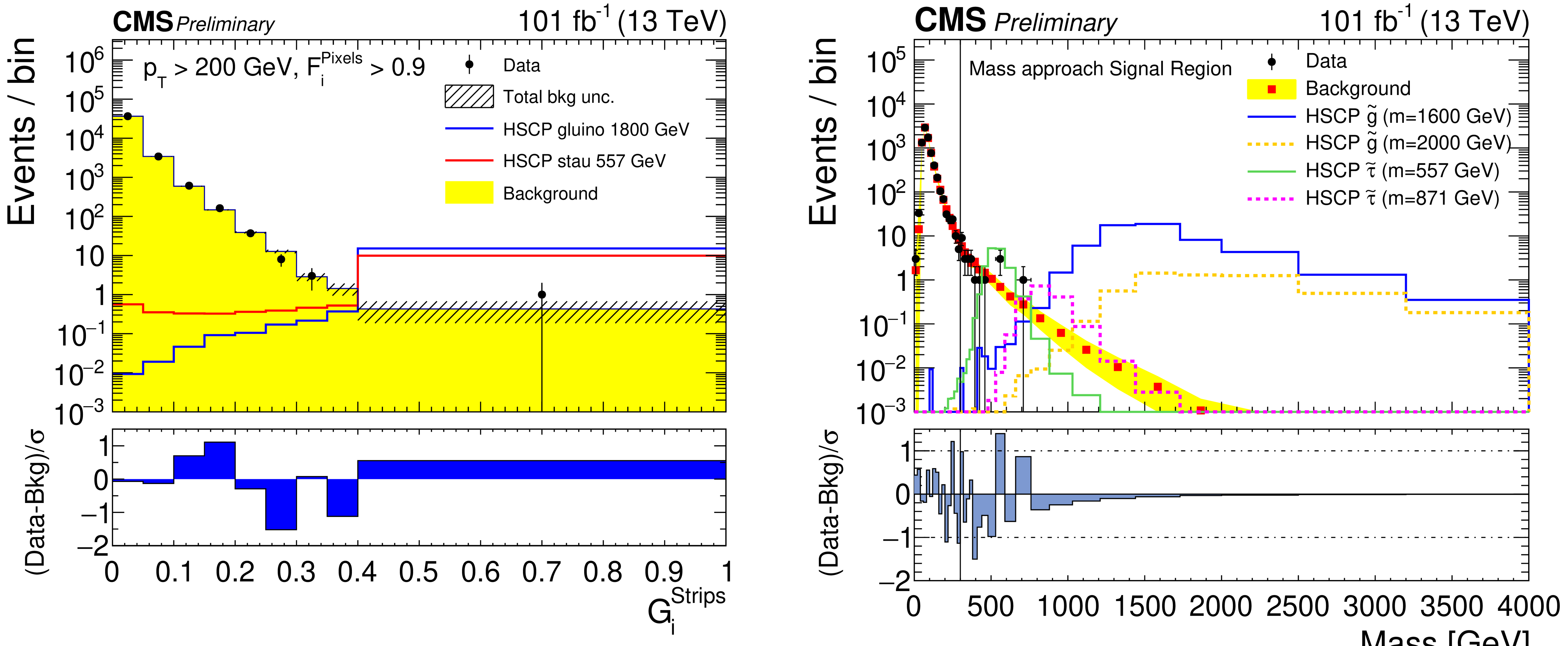
Long Lived Particle

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

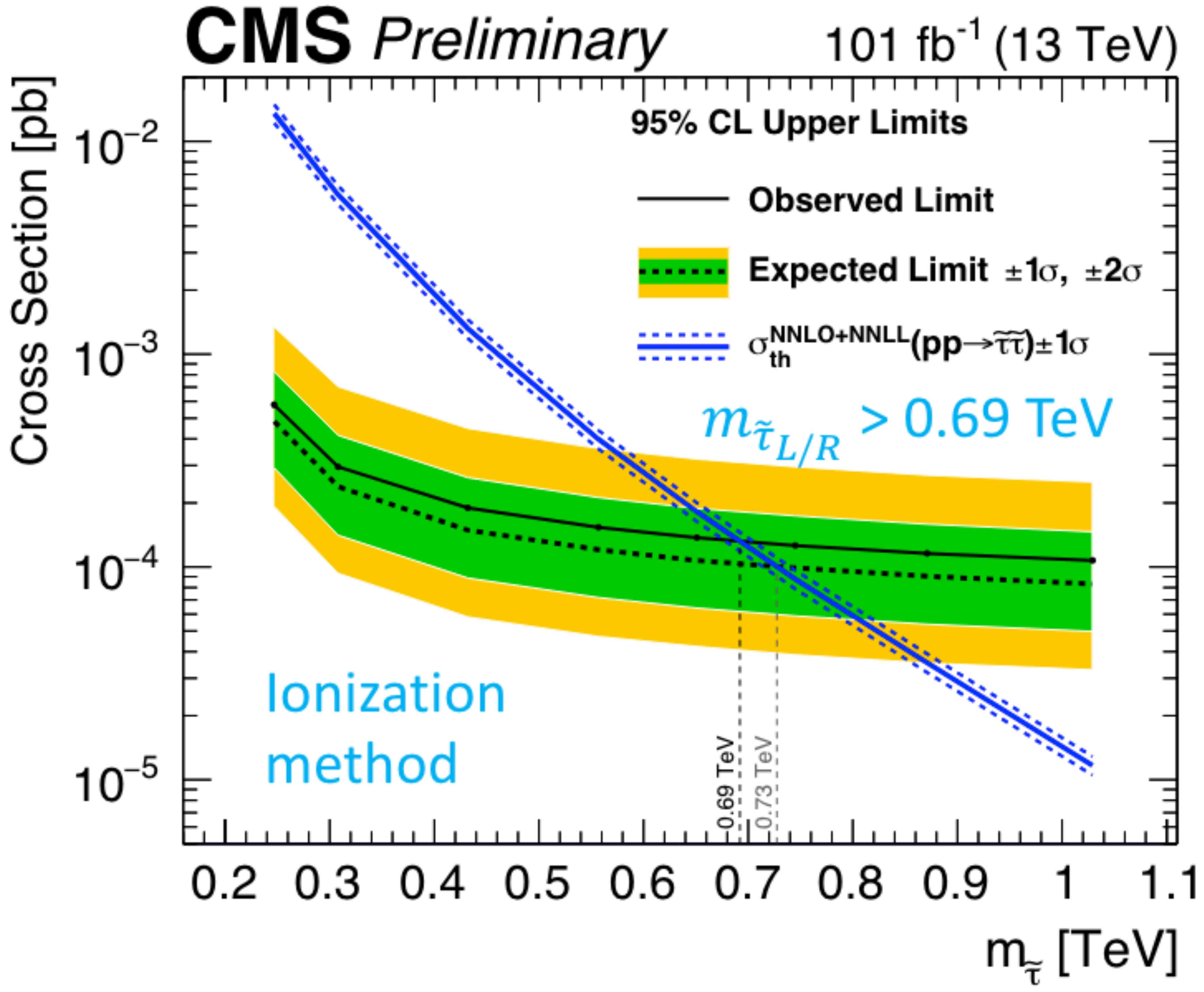
* **Two approaches:**
    - using independence of dE/dx in Pixel and Strip tracker for background recognition,
    - using the mass spectrum.
* Data-driven estimate in both cases

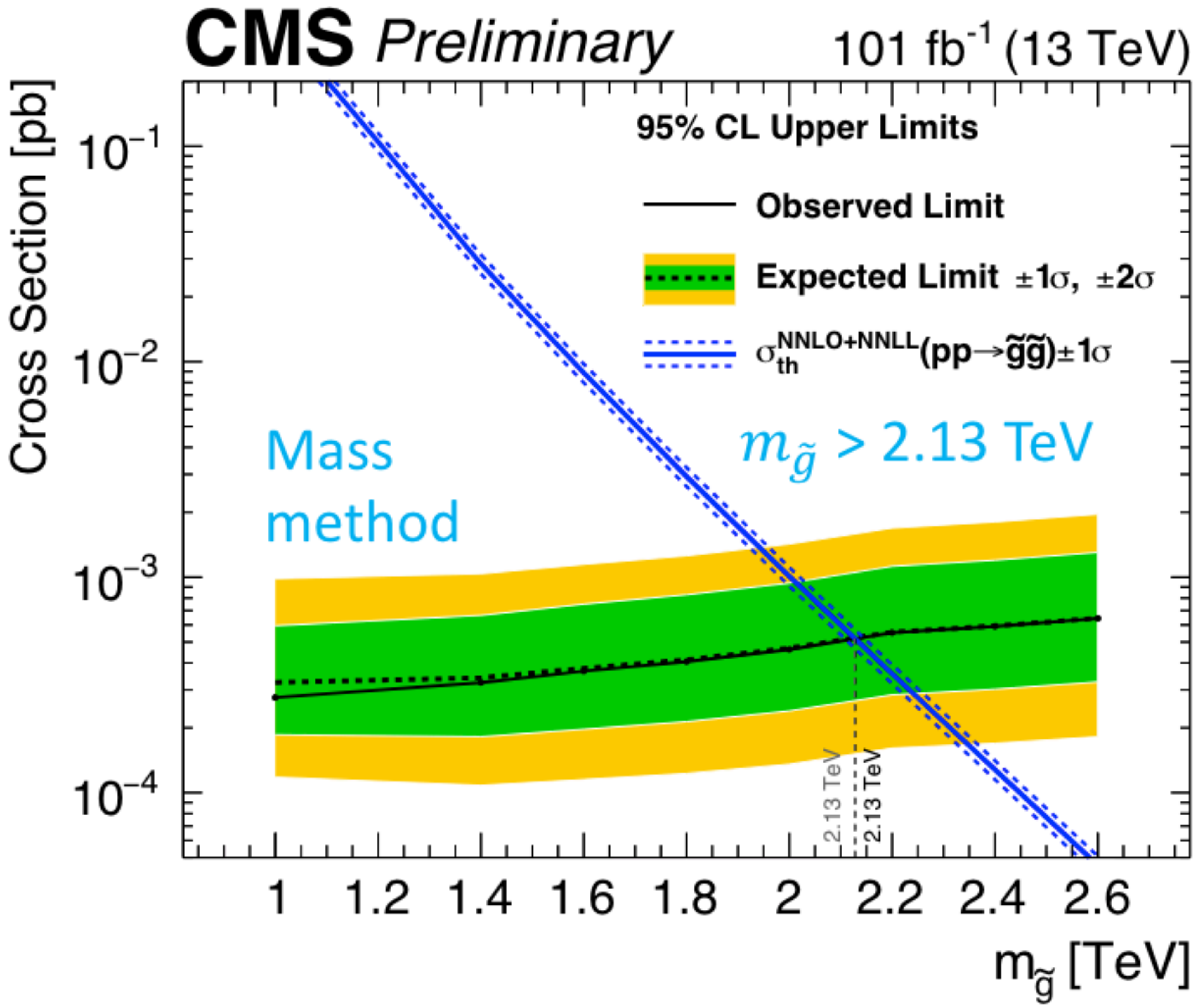


Search for heavy long-lived charged particles

CMS-PAS-EXO-18-002

* No excess —> 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

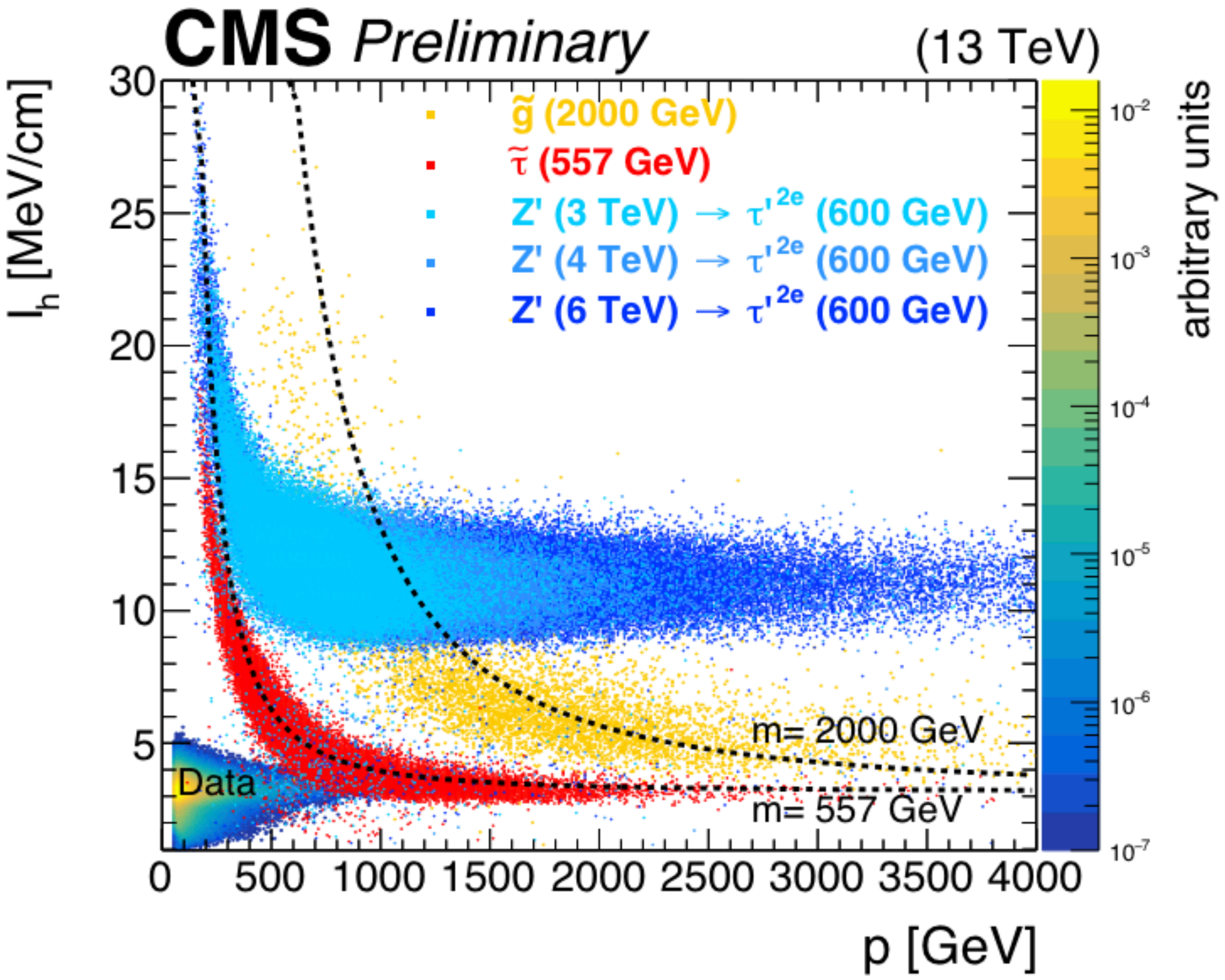


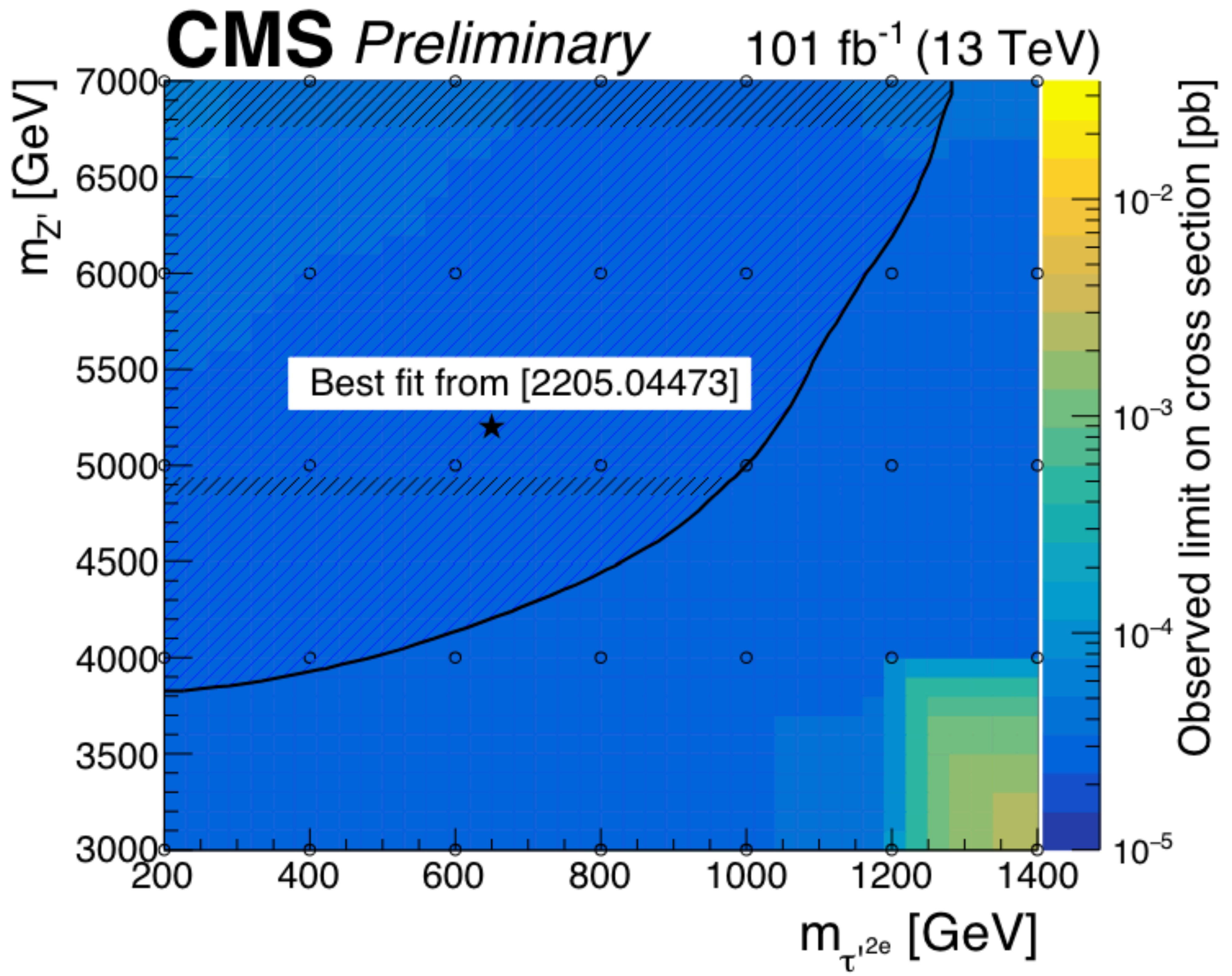


Search for heavy long-lived charged particles

CMS-PAS-EXO-18-002

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



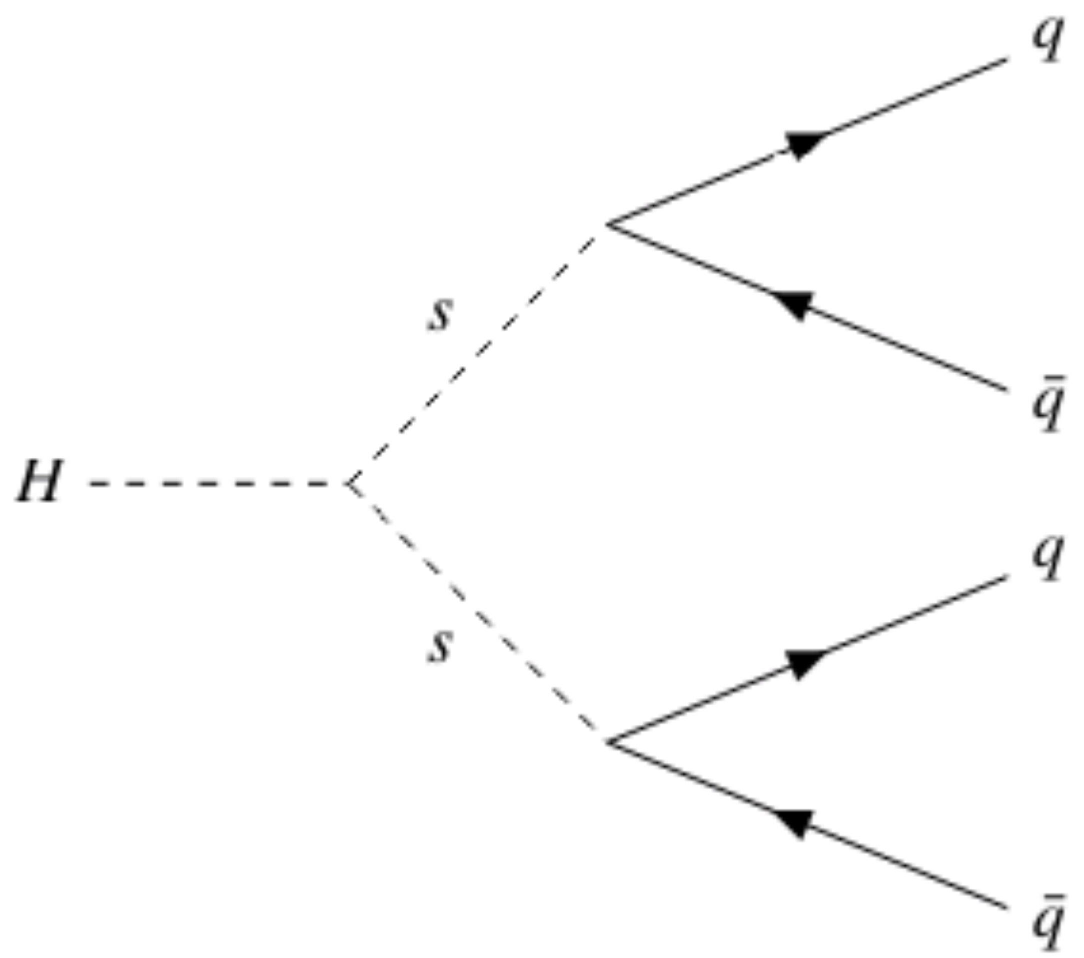


Light LLP with displaced vertices

2403.15332 [hep-ex]

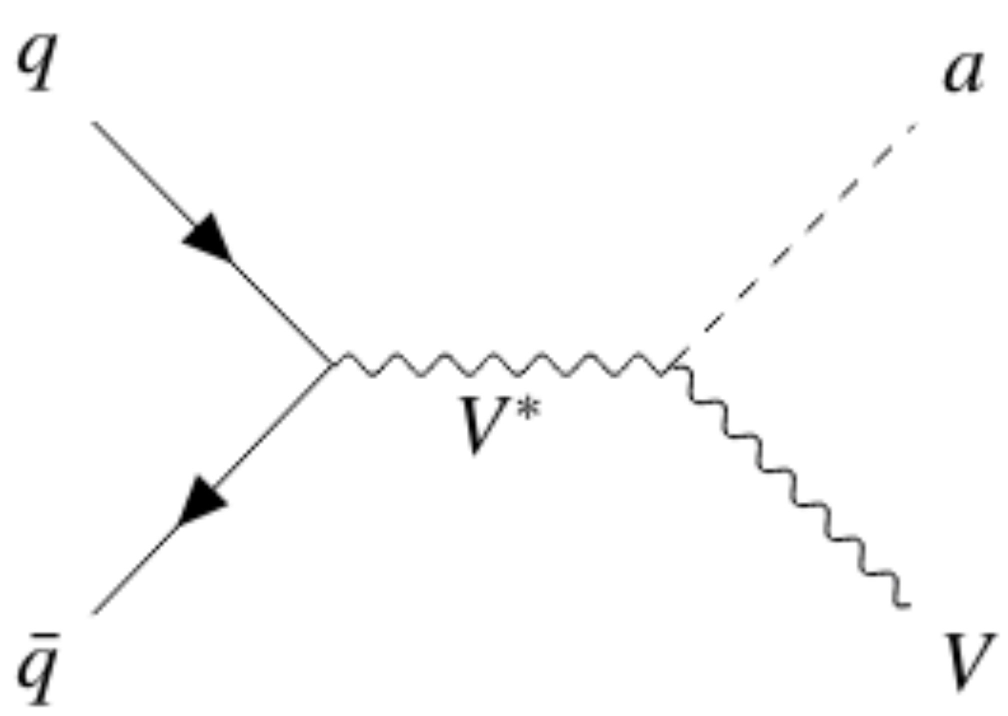
Pseudoscalar boson (s)

VH and VBF H production

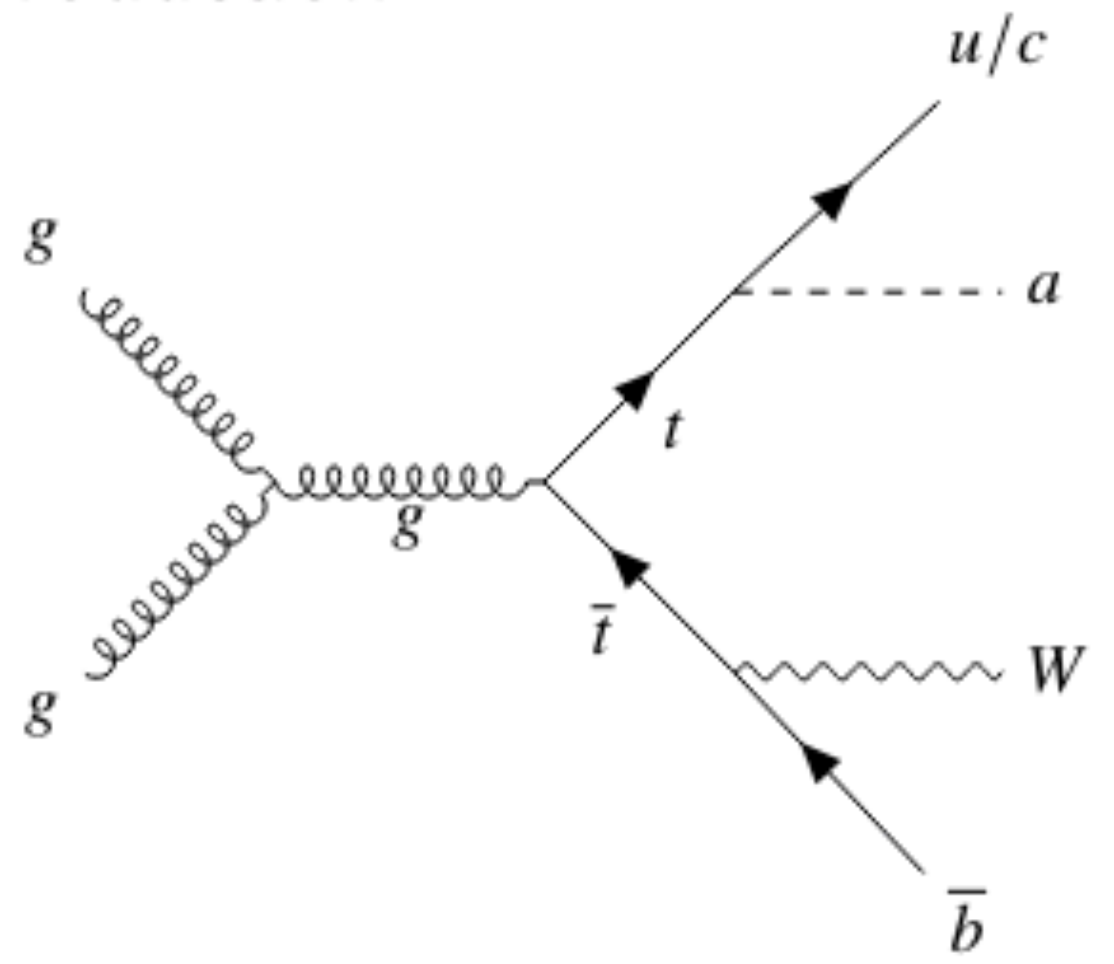


Pseudoscalar Axion-Like-Particle (a)

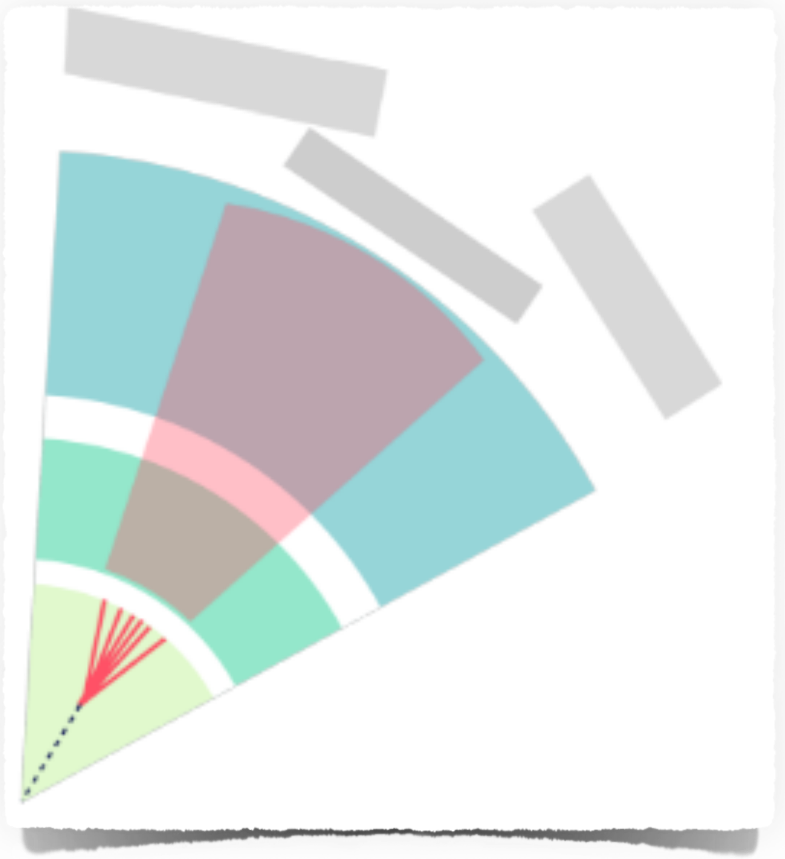
Va production



$t\bar{t}$ 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] 2304.12867

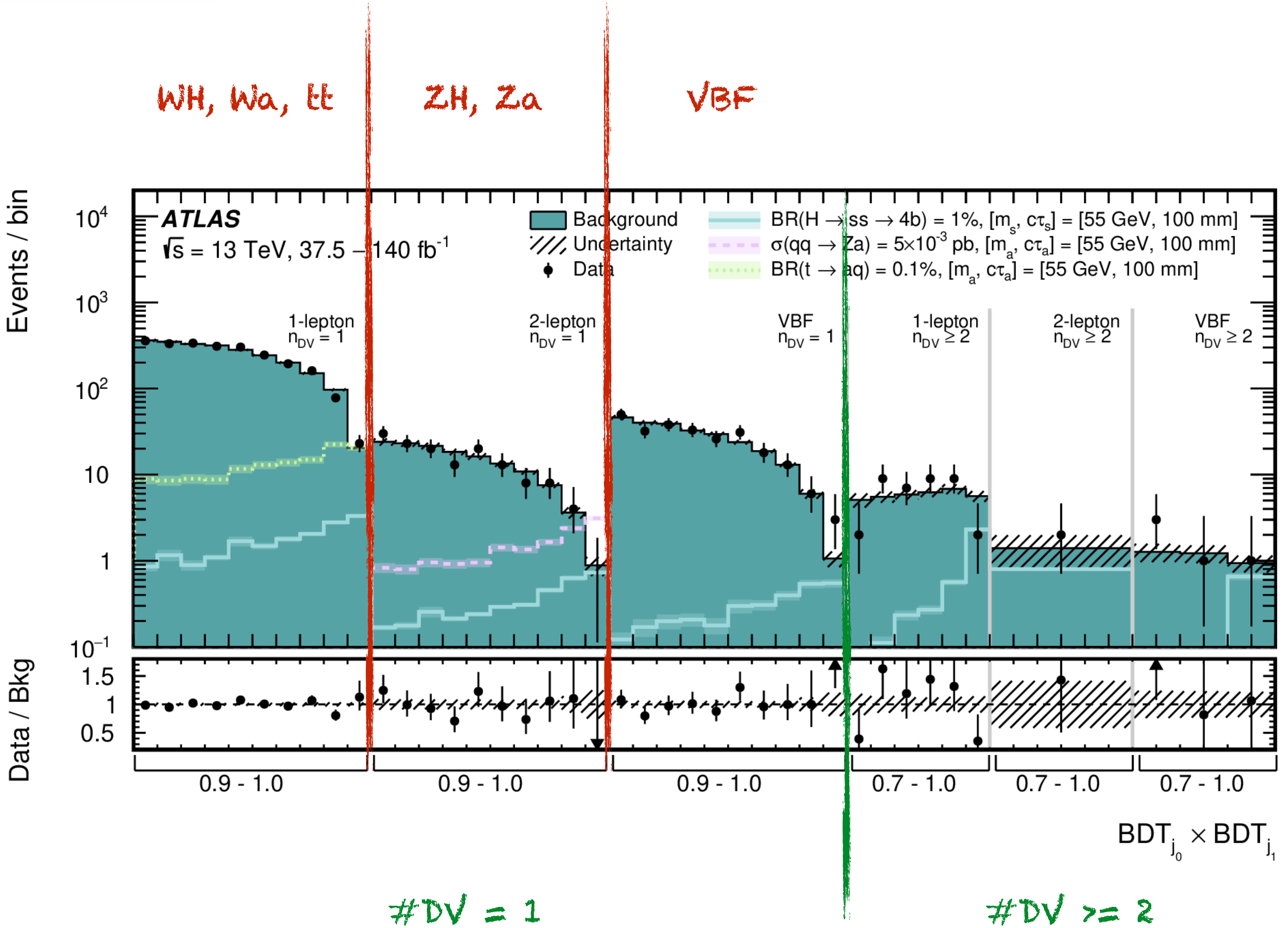


Light LLP with displaced vertices

2403.15332 [hep-ex]

* **Displaced jet tagger** using jet-level features that discrimate between prompt and displaced jets
  - Event-level discriminant $BDT_{j0} \times BDT_{j1}$

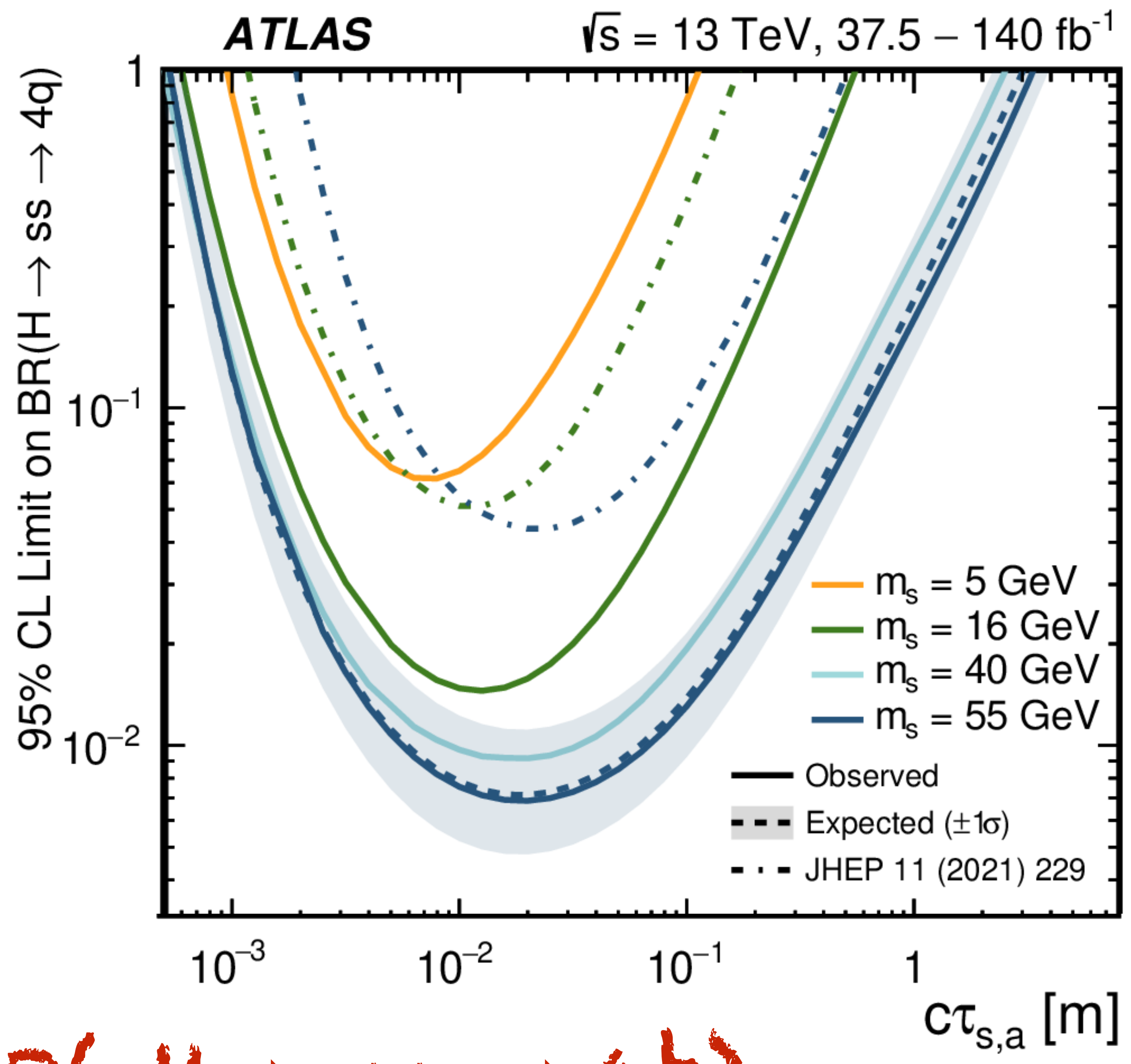
* **Data-driven background** estimate using the probability of a jet to be matched to a DV (depending on its p_T, flavour, BDT score) to determine a *per-event probability*



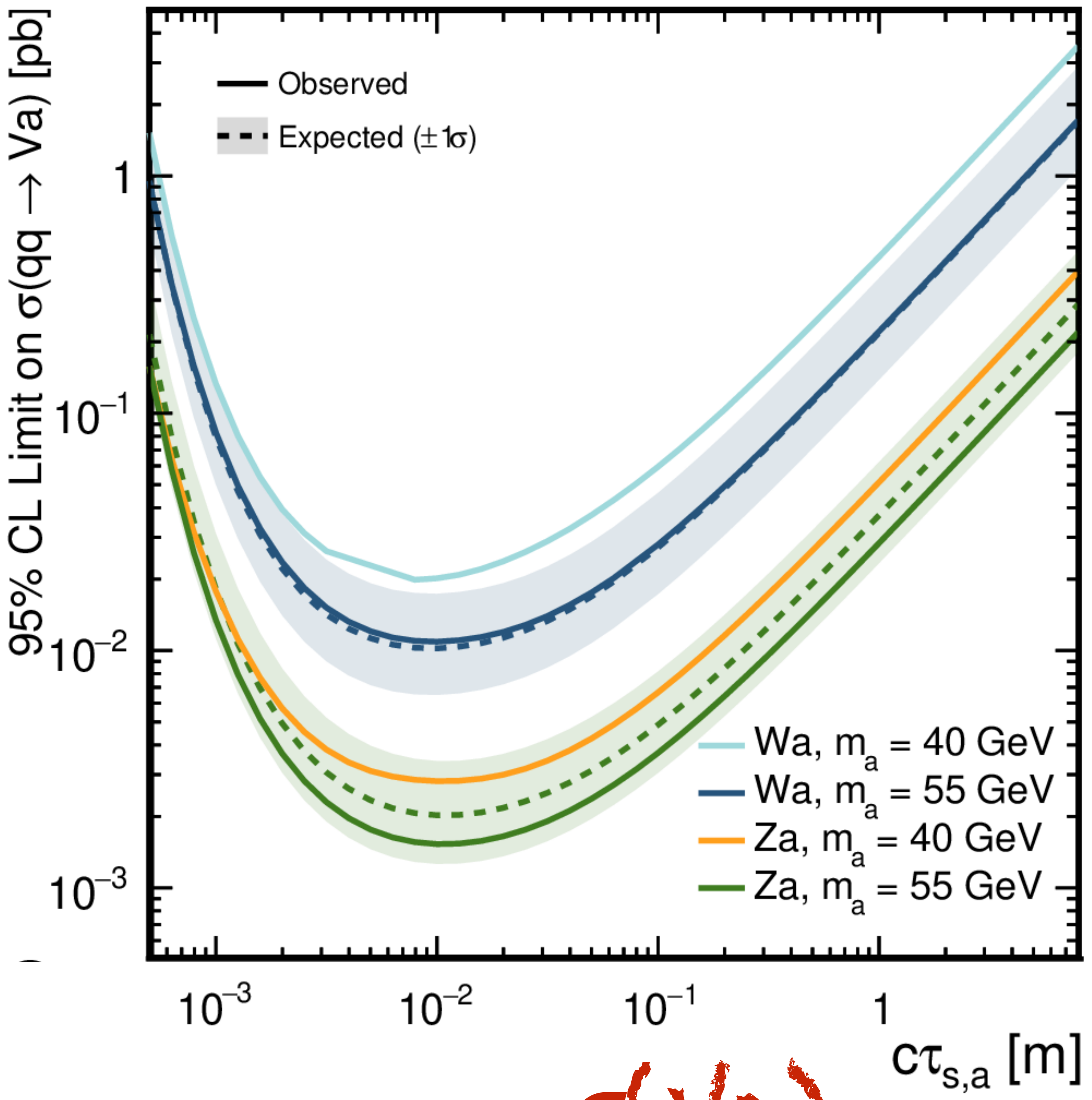
Light LLP with displaced vertices

2403.15332 [hep-ex]

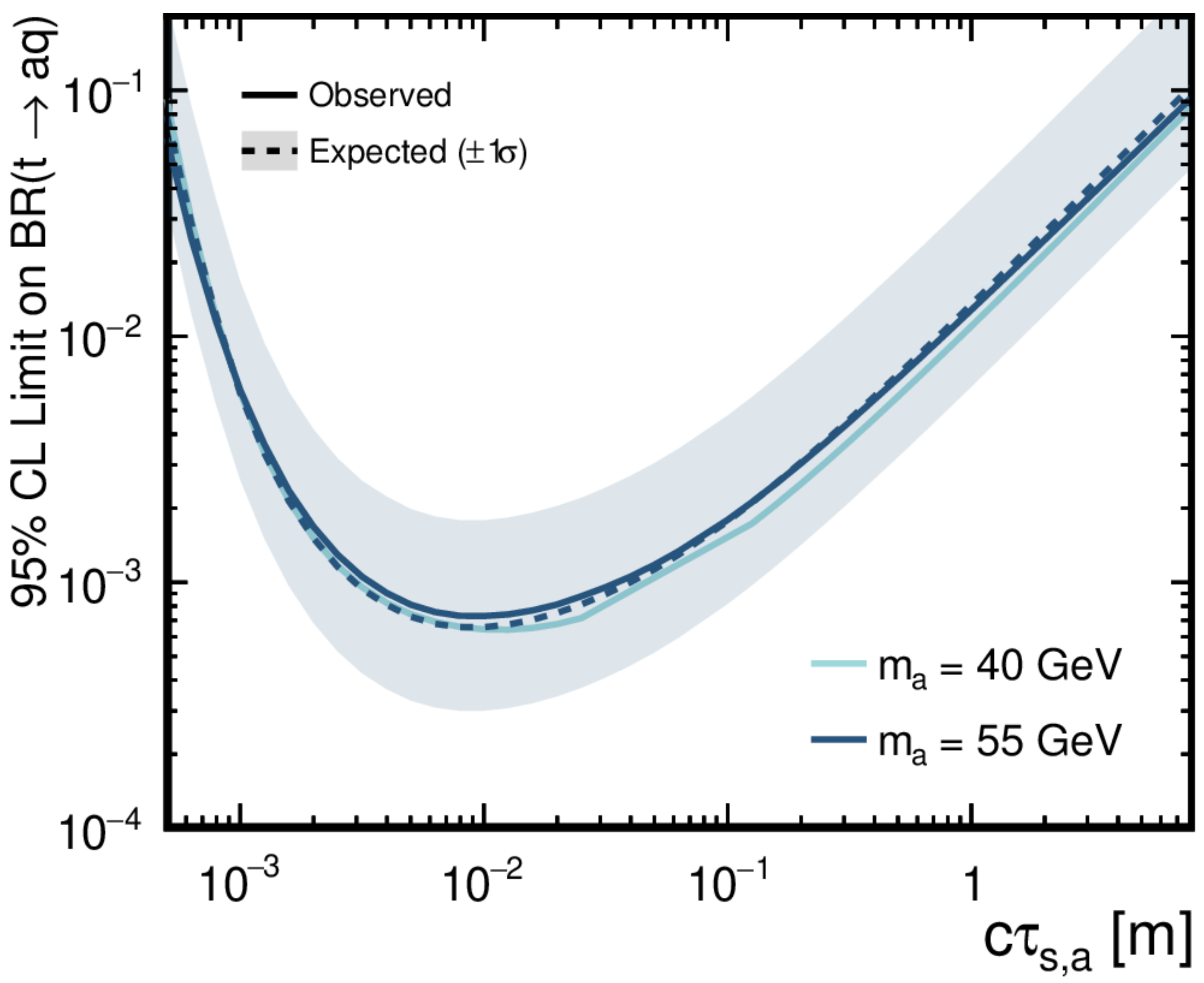
* No excess —> 95% CL limits:
    - on B(H→ ss →4b) for $m_s \geq 16$ GeV and on B(H→ ss →4c) for $m_s = 5$ GeV, improvements by as much as a factor of 20 for $m_s = 55$ GeV and $c\tau_s < 10$ mm.
    - on σ(Va) and B(t → aq) for the first time at LHC



B(H→ ss →4b)



σ(Va)

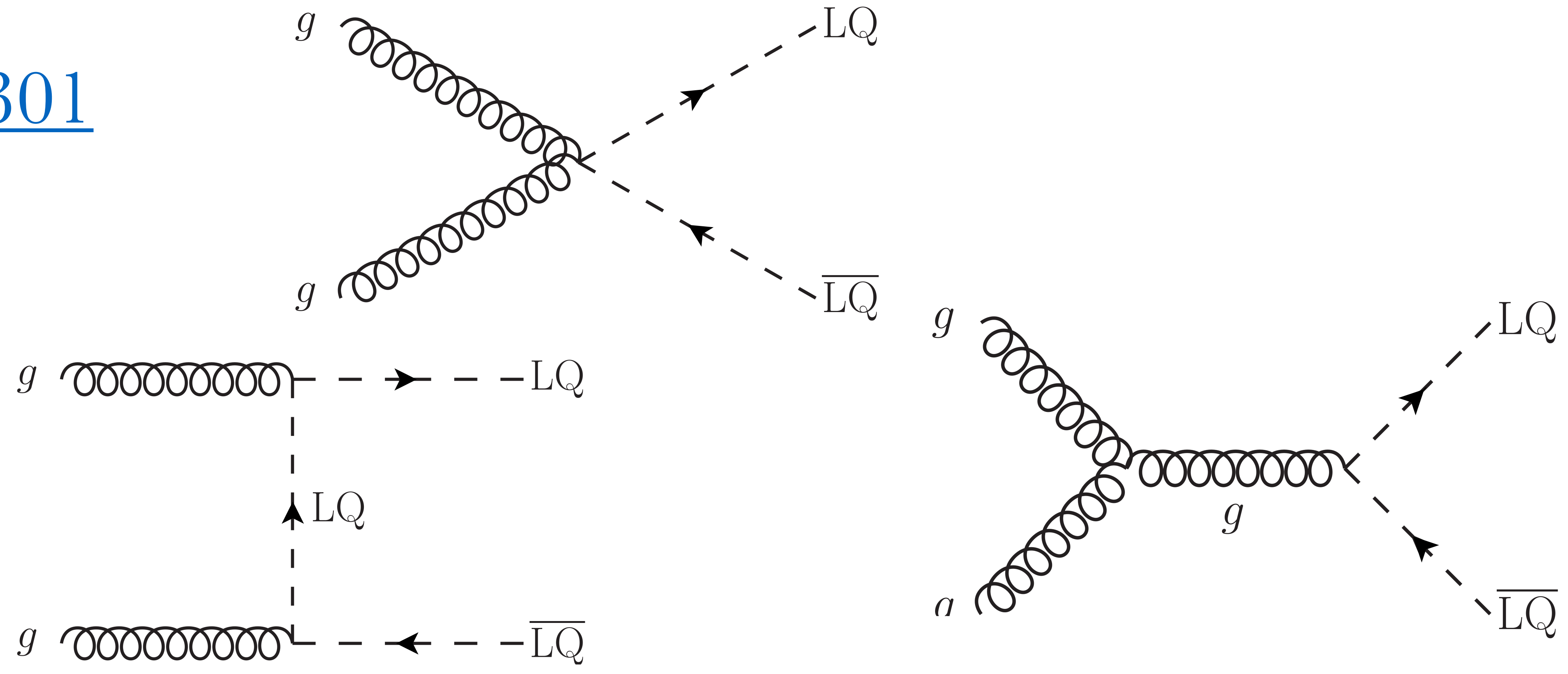


B(t → aq)

Lepto-Quarks

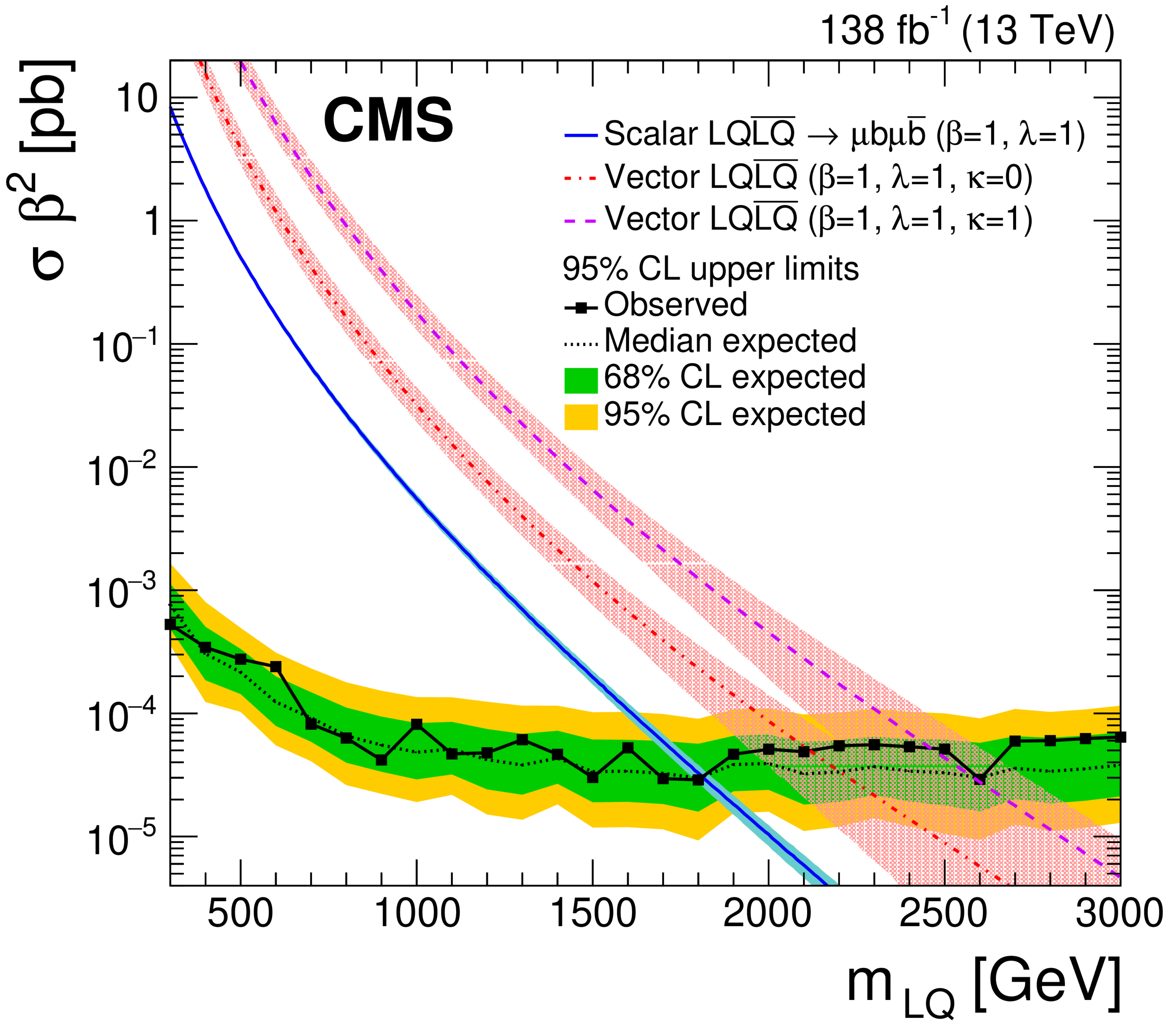
LQ pair → bμbμ

[CERN-EP-2023-301]



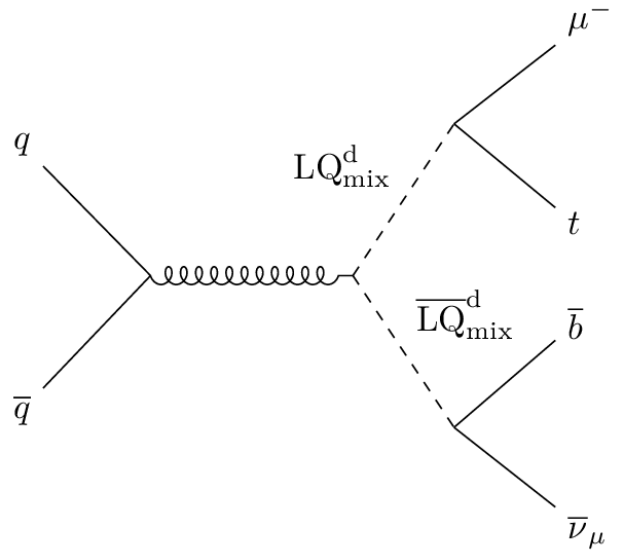
- Full Run -2 search for Scalar/Vector LQ pair
- Main bkgs: drell-yan and tt estimated from MC normalised in dedicated regions "Control Region".
- SRs defined for each $m\ (LQ\ )$ hypothesis via cut on a dedicated BDT score.
- No significant excess seen, most stringent limits to date!

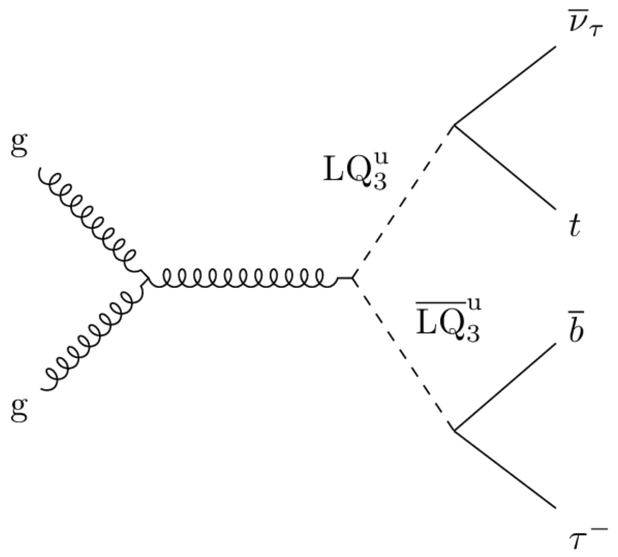
$m(LQ)$ upper bounds [TeV] @95%CL	Scalar LQ		Vector LQ $(\beta = 1)$	
	$\beta = 1$	$\beta = 0.5$	Minimal Coupling	Yang-Mills
ATLAS [arXiv.org:2210.04517]	1.5	1.3	1.5	1.8
CMS (this)	1.81	1.54	2.12	2.46



3rd gen. LQ pair production

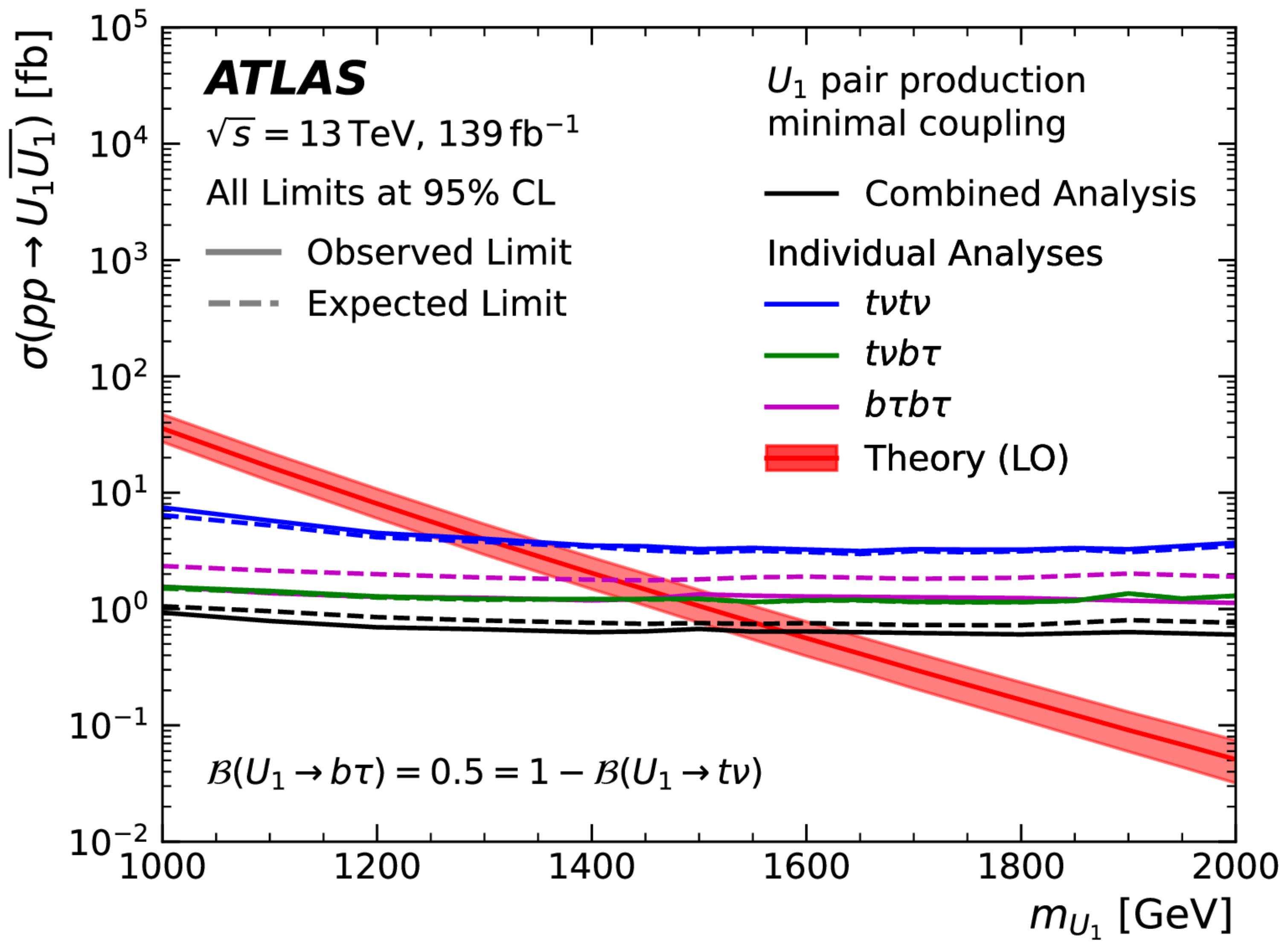
CERN-EP-2023-288

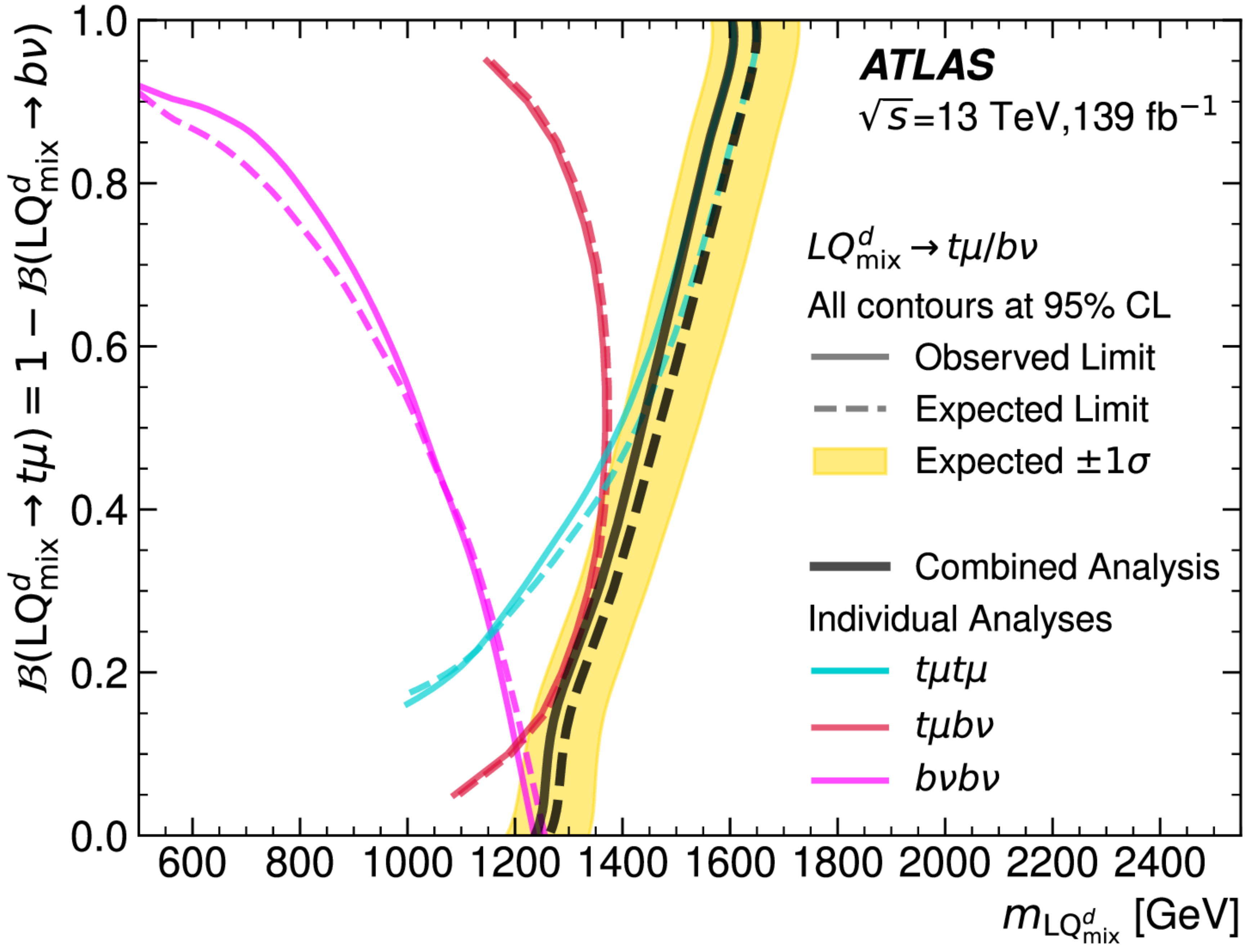




* Statistical combination of 9 ATLAS searches (6 *LQ* searches and 3 SUSY searches)
* Interpretations;
  - Scalar/Vector *LQ*s decaying to 3rd gen LQ or 1st/2nd gen mix LQ
  - Limits on $m(LQ)$ and (B) branching fraction to $l^{\pm}$.
* Most stringent results to date for majority of the models

Search		Interpretation						Signal Region		
		Scalar				Vector				
Final State	Citation	LQ^u_3	LQ^d_3	LQ^u_{mix}	LQ^d_{mix}	$U_1^{YM/MC}$	$\tilde{U}_1^{YM/MC}$	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
$b\ell b\ell$		–	–	✓	–	–	–	2	–	$\{0,1,2\}$
$t\ell t\ell$ $(2\ell))$		–	–	–	✓	–	–	2	–	–
$t\ell t\ell$ $(\geq 3\ell)$		–	–	–	✓	–	–	$\{3,4\}$	–	≥ 2
$t\nu t\nu$		✓	–	✓	–	✓	–	0	0	≥ 2
$b\nu b\nu$		–	✓	–	✓	–	–	0	–	≥ 2





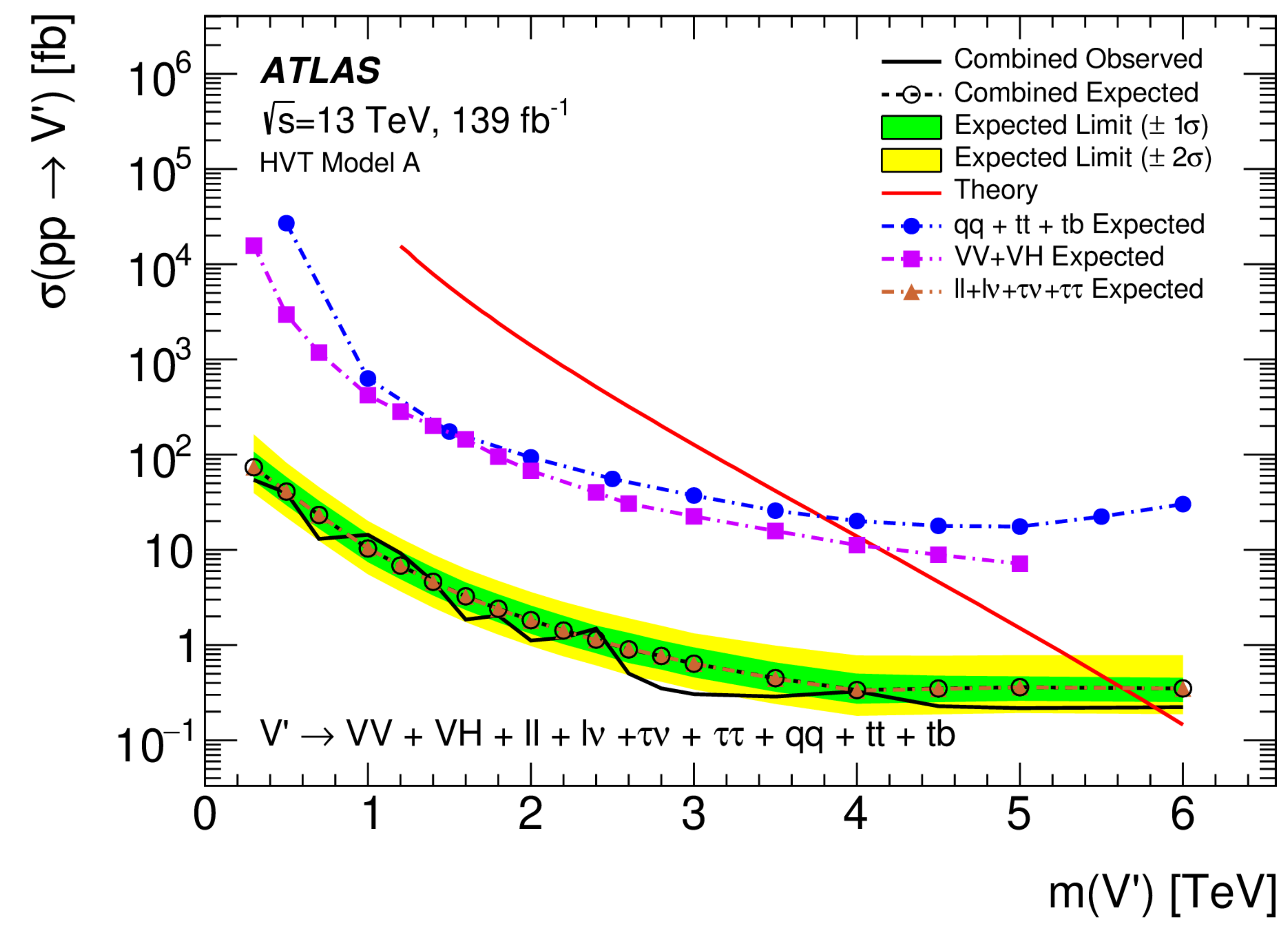
Resonances

Combination of heavy spin-1 resonances

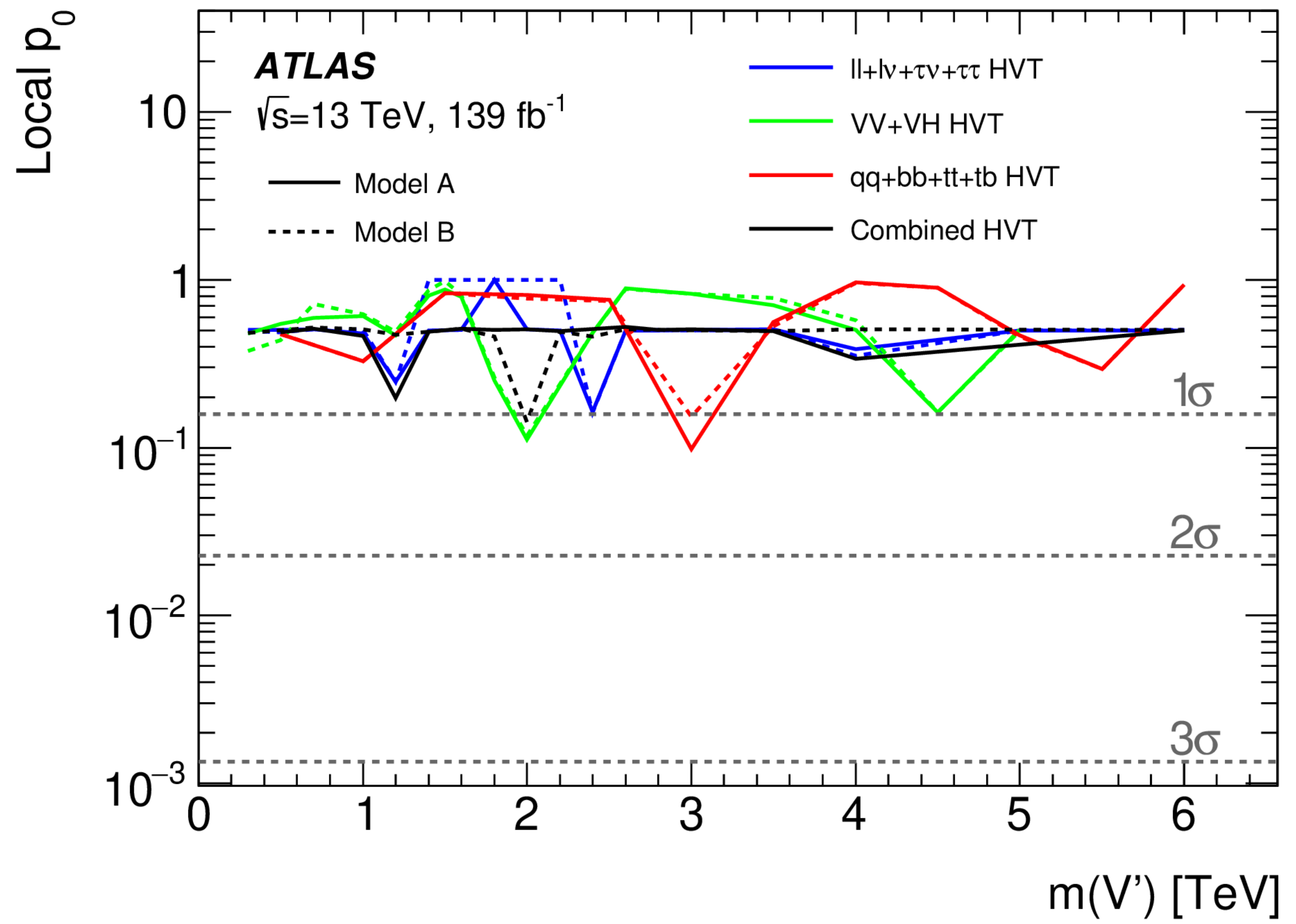
EXOT-2022-38

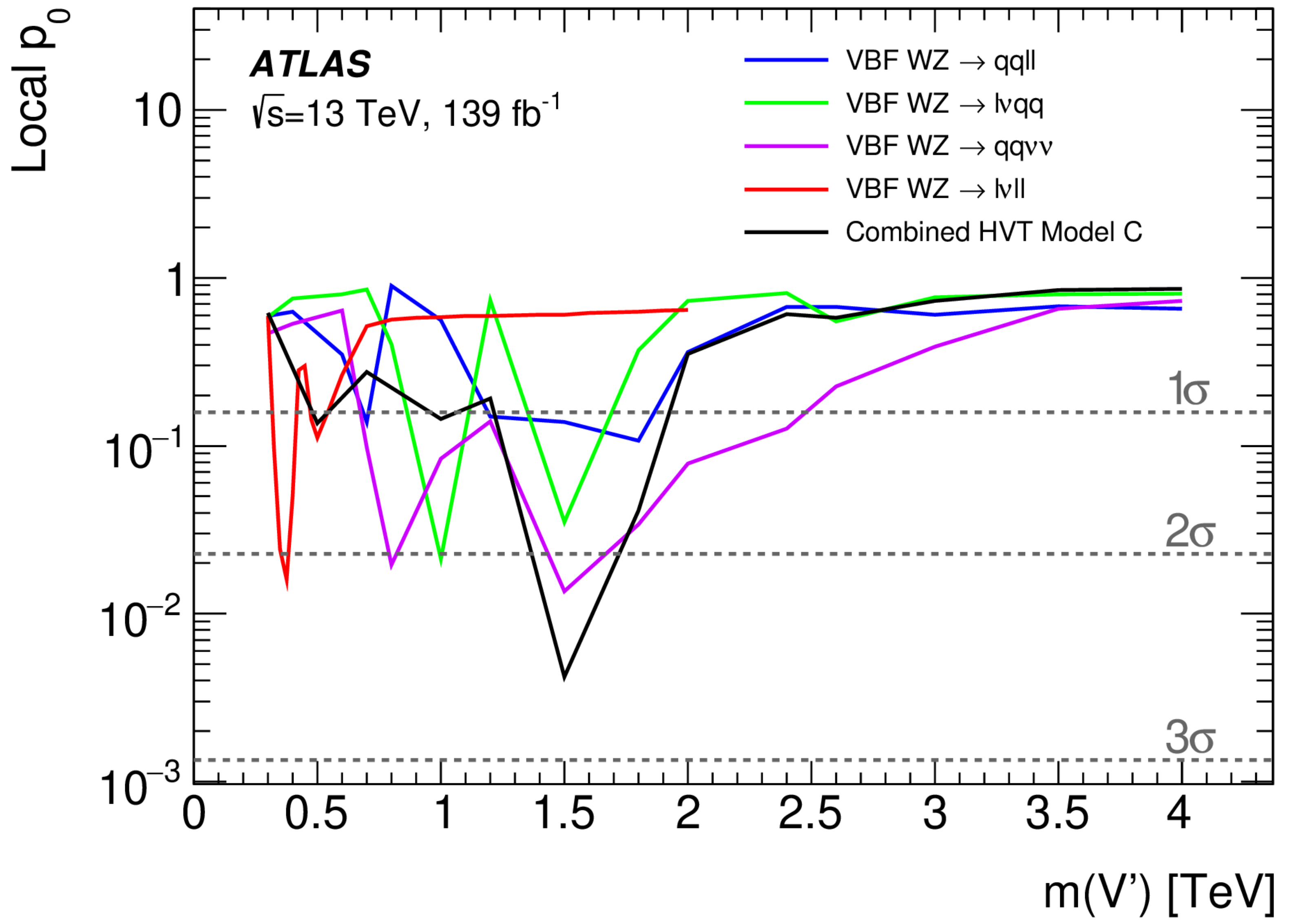
- Combination of searches for new heavy spin-1 resonances decaying into different pairings of W, Z, or Higgs bosons selecting quark pairs (qq, bb, $t\bar{t}$, and tb) or third-generation leptons ($\tau\nu$ and $\tau\tau$)

- Analyses complementarity increases sensitivity to new physics and makes resulting constraints stronger



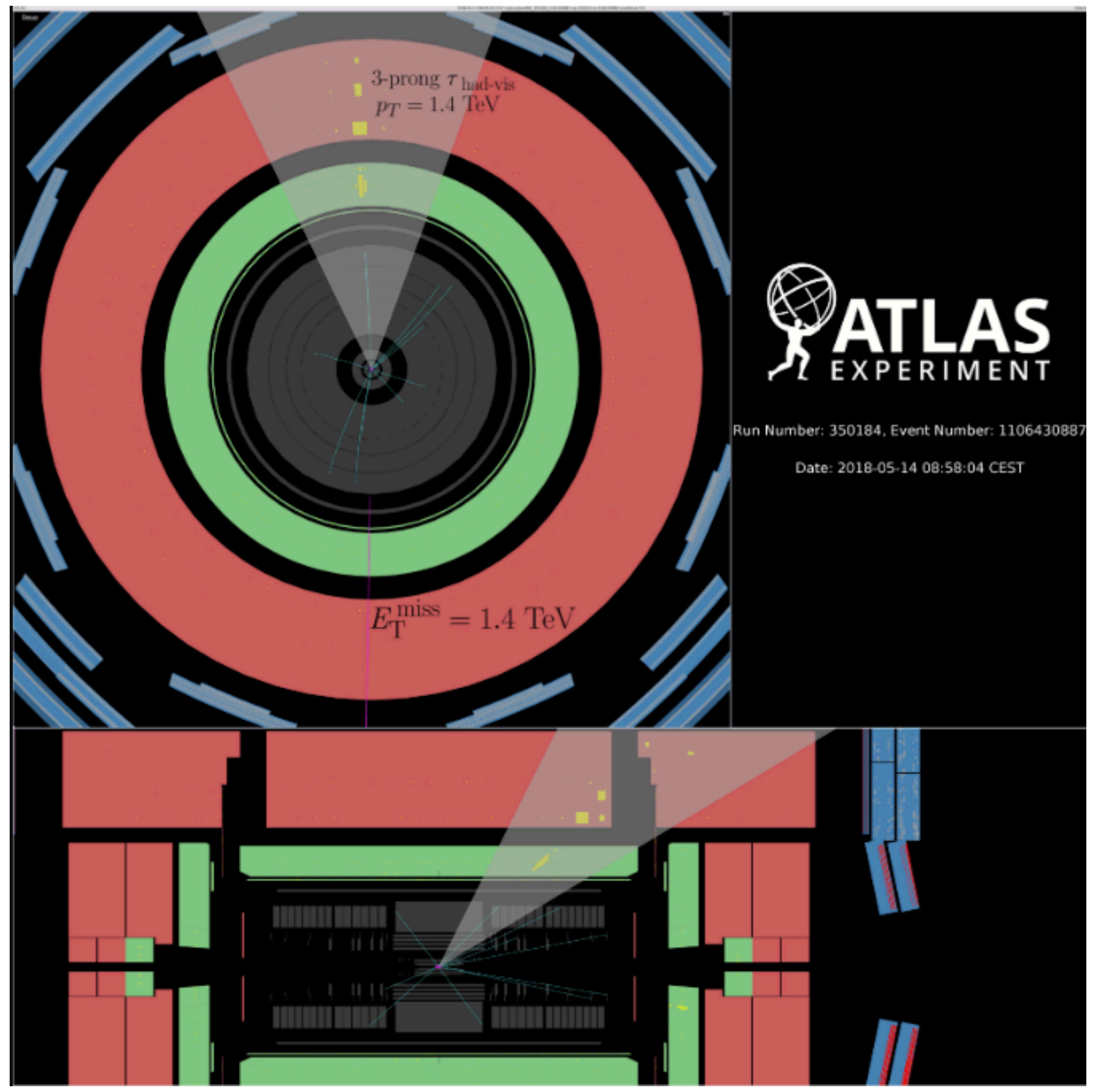
- Data exclude:
  - a heavy vector-boson triplet with mass below 5.8 TeV in a weakly coupled scenario,
  - below 4.4 TeV in a strongly coupled scenario,
  - up to 1.5 TeV in the case of production via vector-boson fusion.





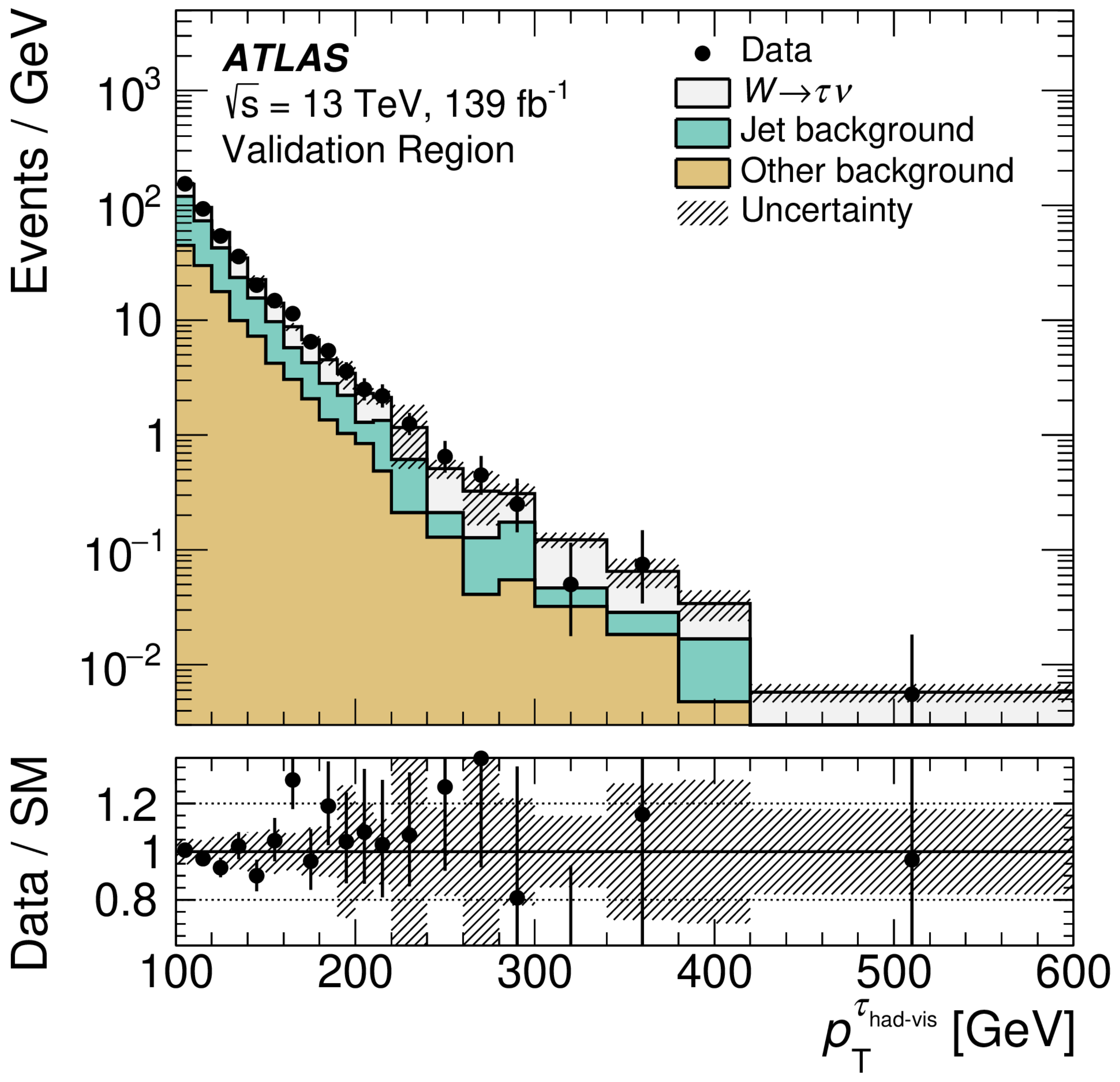
High-mass reso -> τ+MET

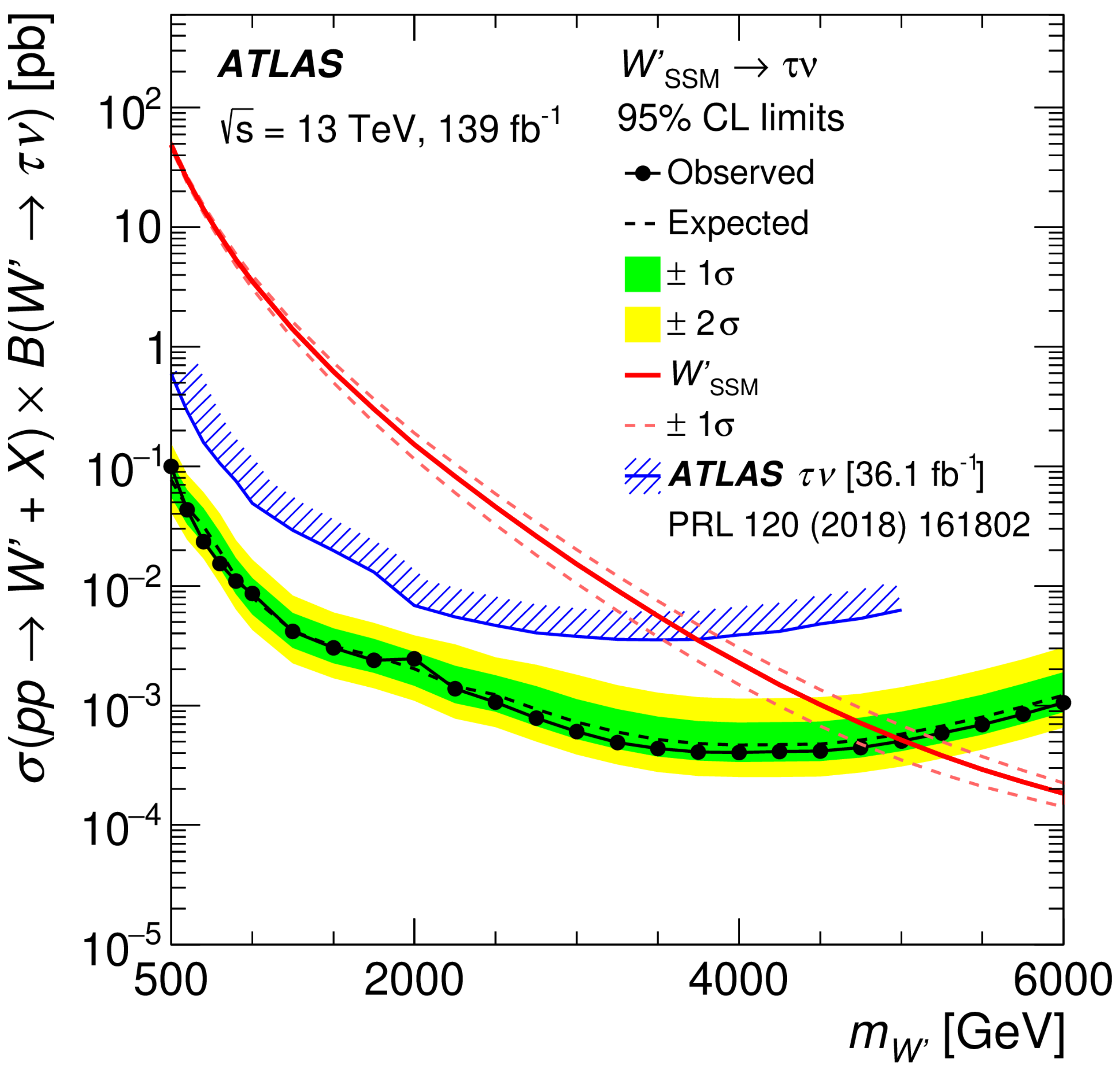
EXOT-2018-37

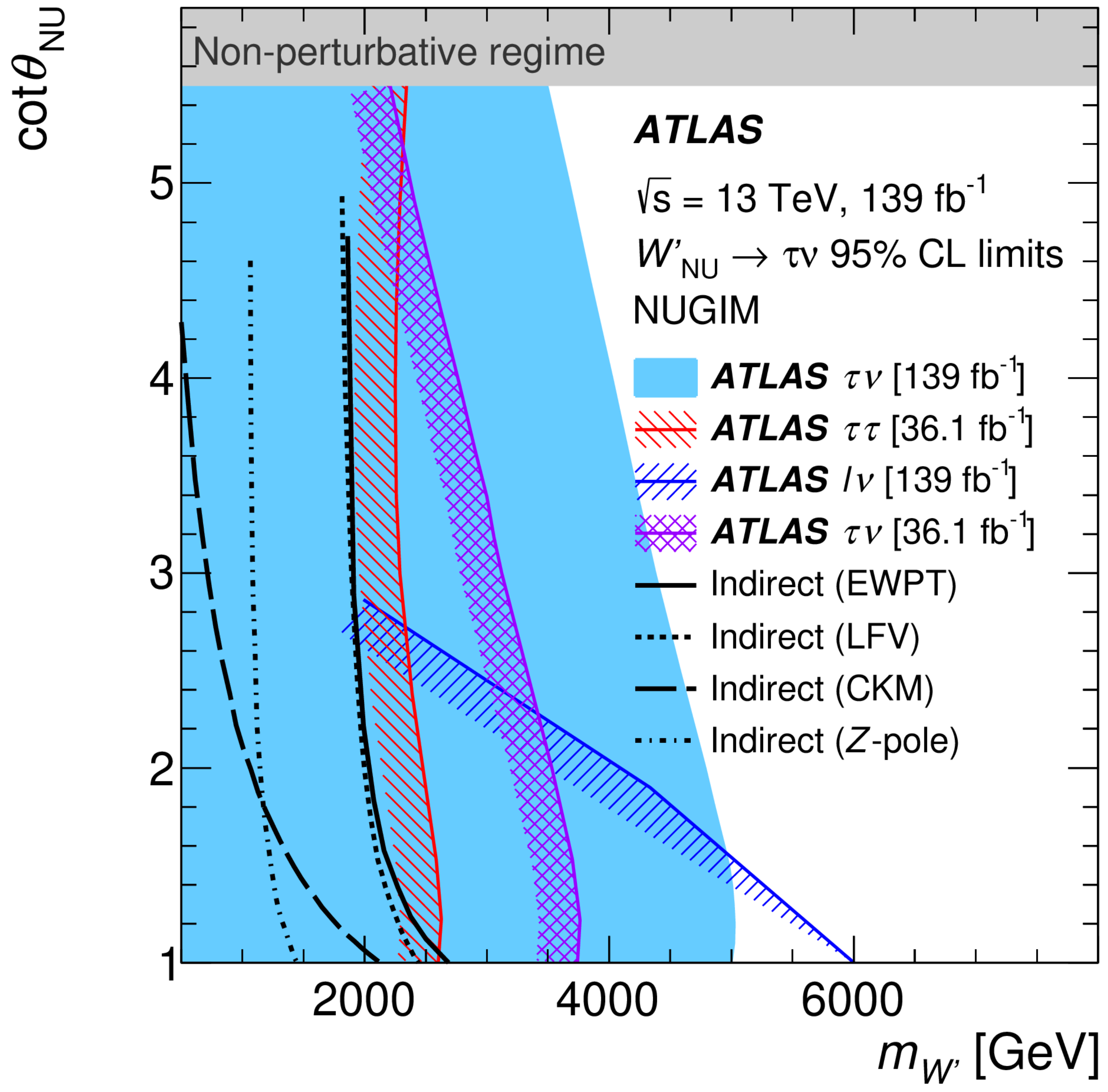


* τ_h reconstructed in hadronic decay modes, the total $p_T(\nu)$ inferred from reconstructed missing transverse momentum

* **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







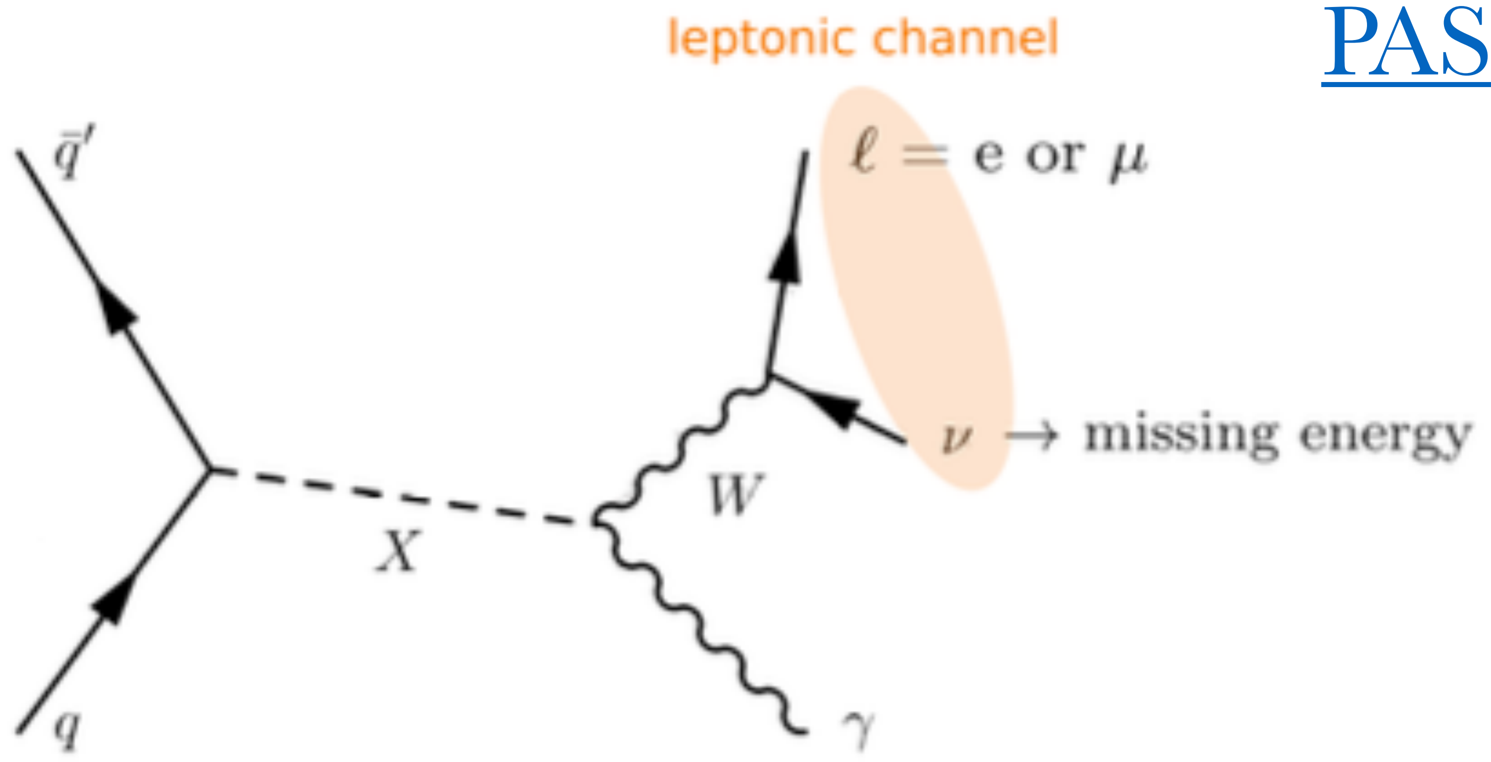
Search for a resonance decaying to Wγ

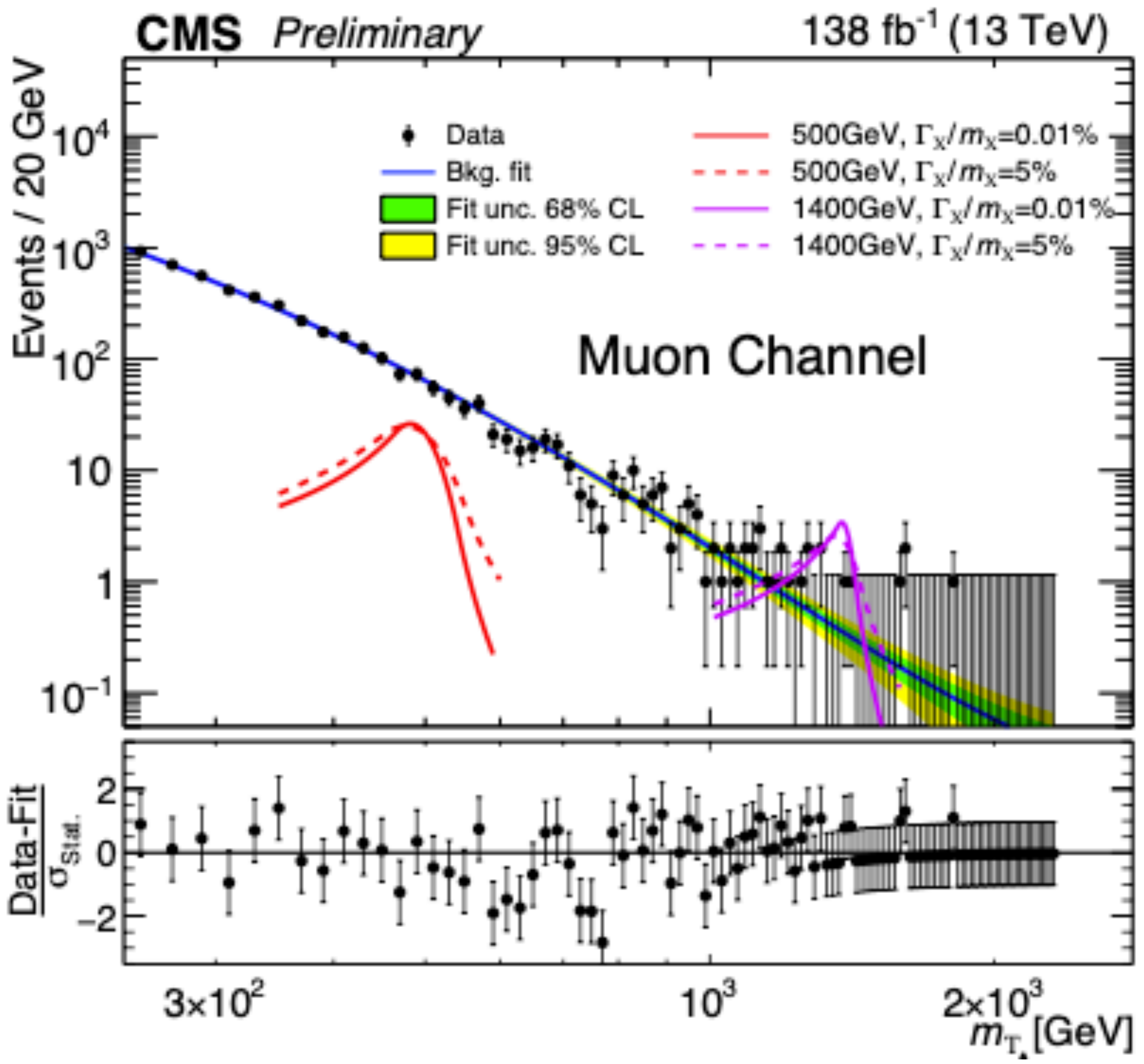
[PAS-EXO-21-017]

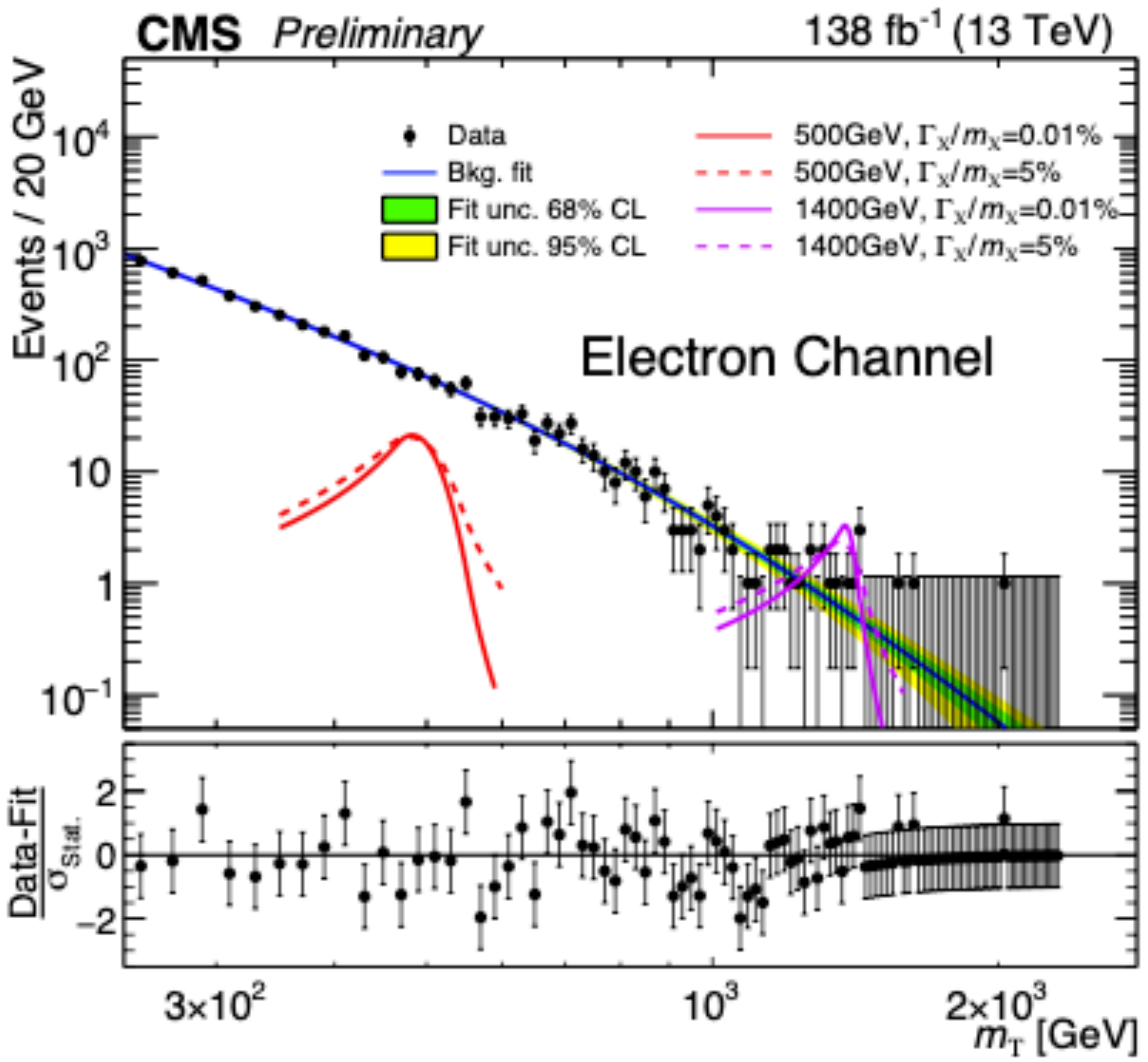
* W boson decays leptonically (e or μ)
* Bump hunt in the transverse mass mT spectrum

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

* Parametric fit to the data using signal shape templates







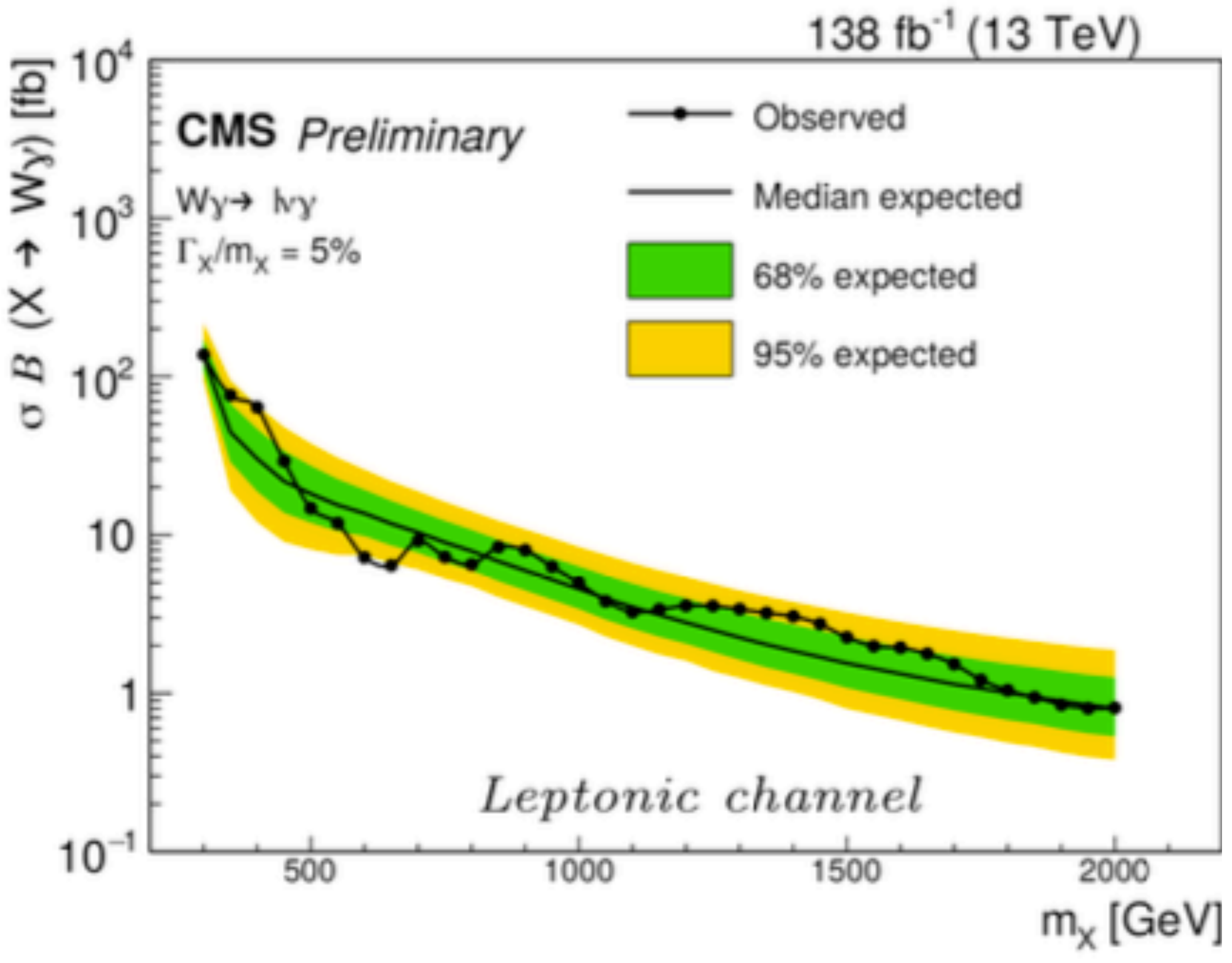
Search for a resonance decaying to Wγ

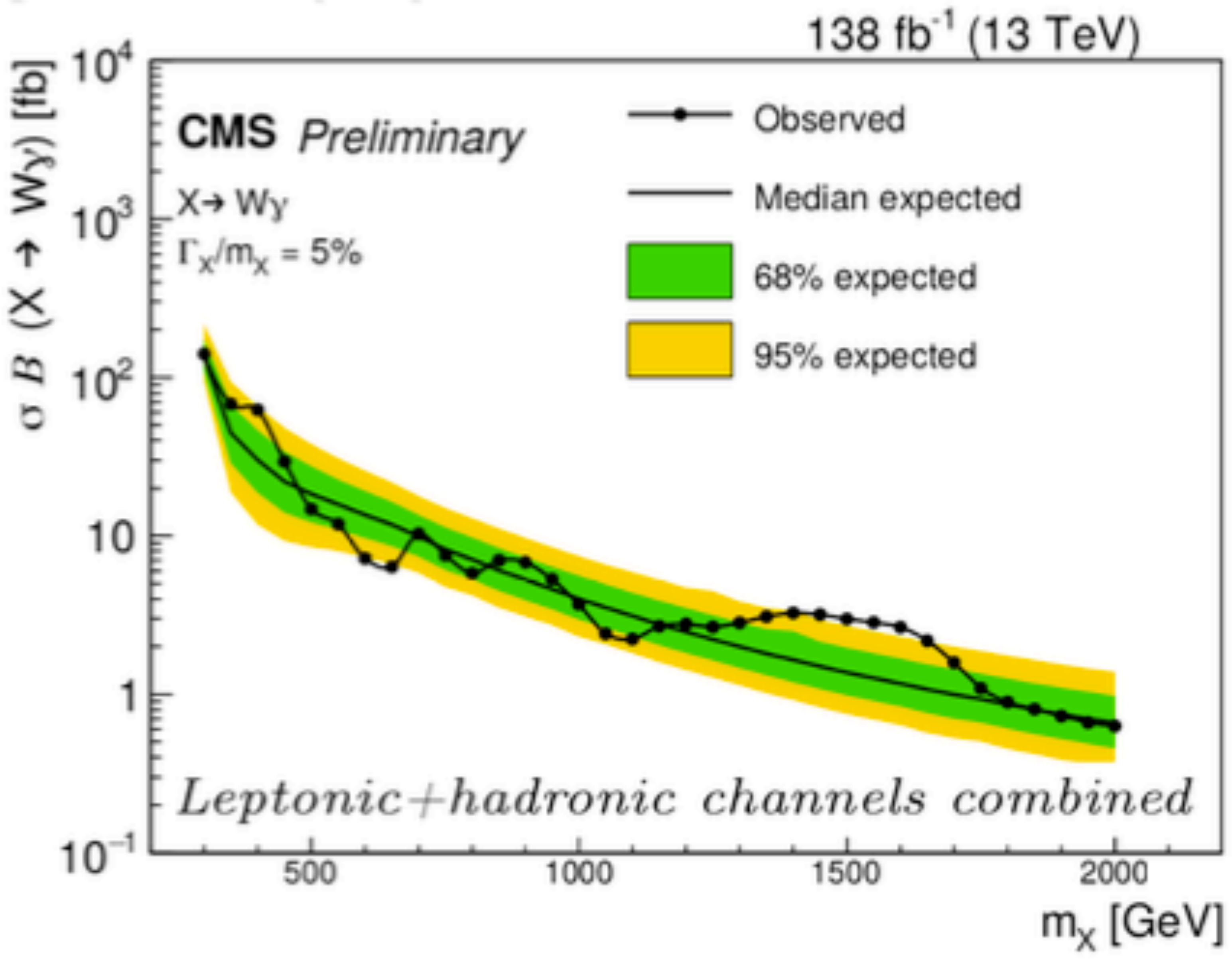
PAS-EXO-21-017

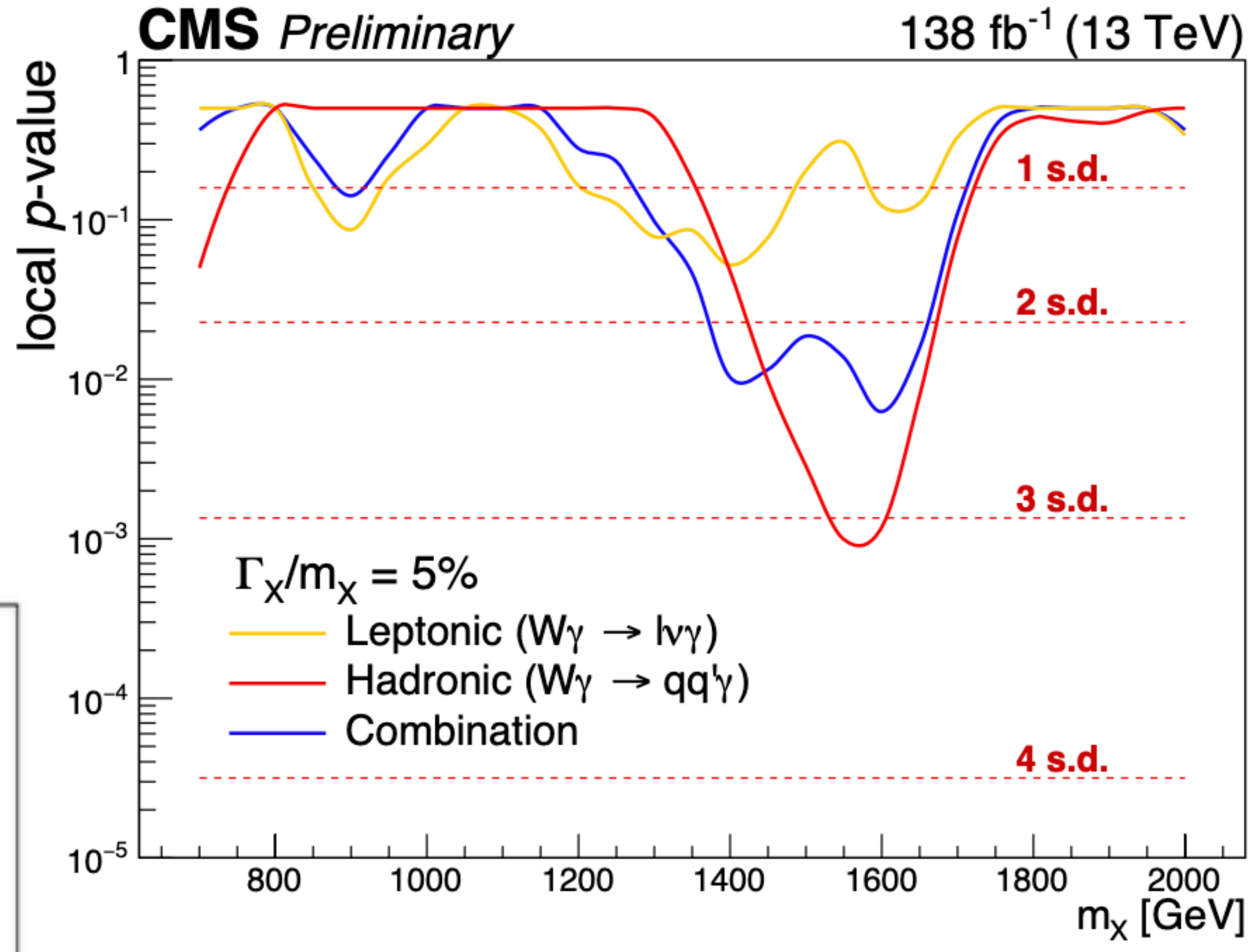
* **No significant deviation** from the background-only expectation is observed

* **Combination** with search using hadronic channel doi:10.1016/j.physletb.2022.136888

* **Most stringent limits** to date in the probed mass range



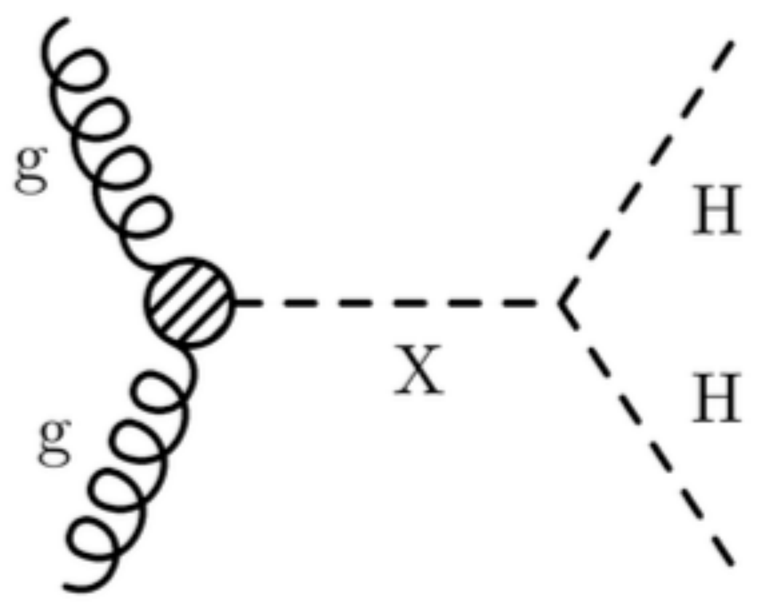




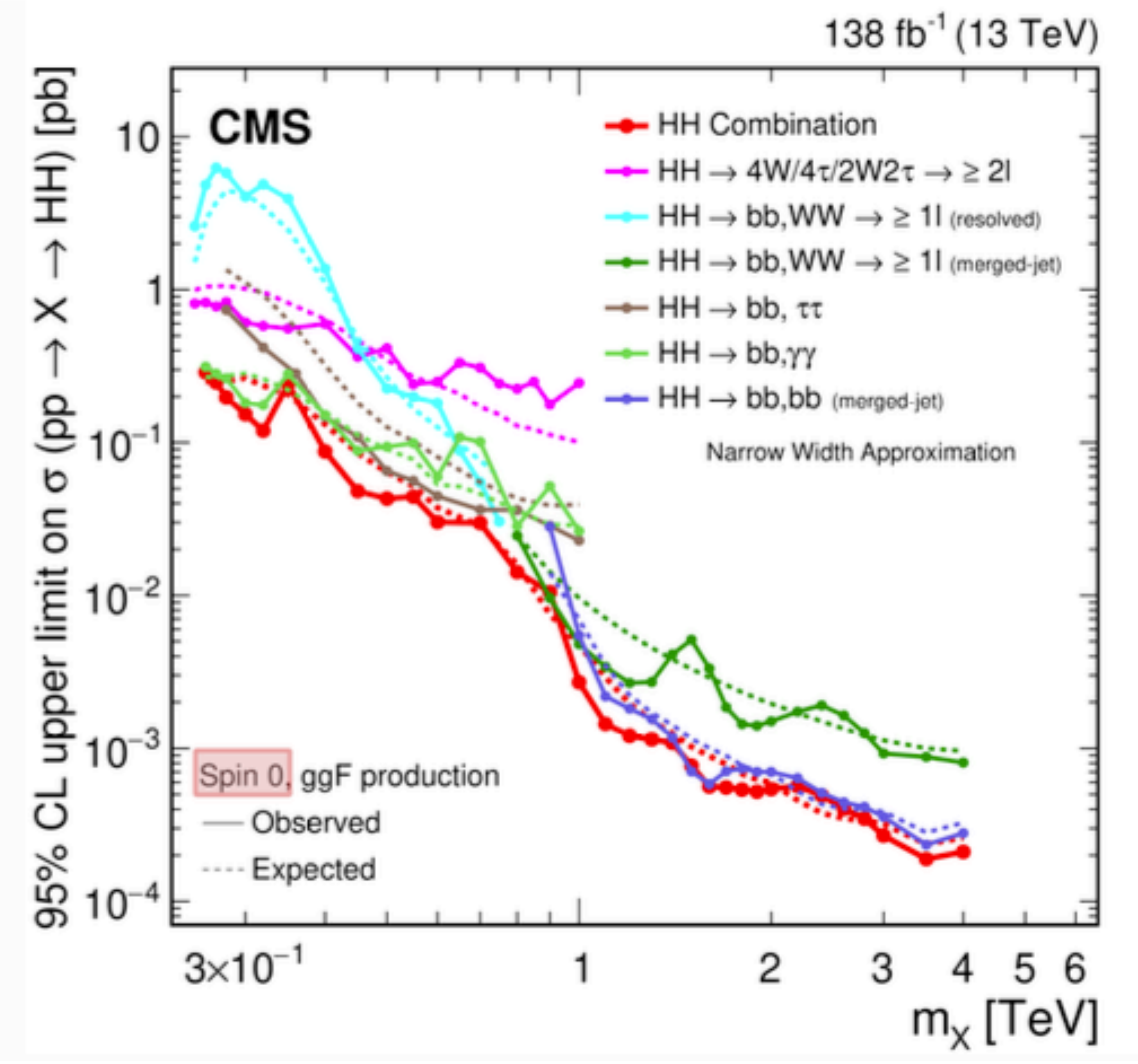
Local excess of 3.1σ in the hadronic analysis reduced to 2.5σ with the two channels combined

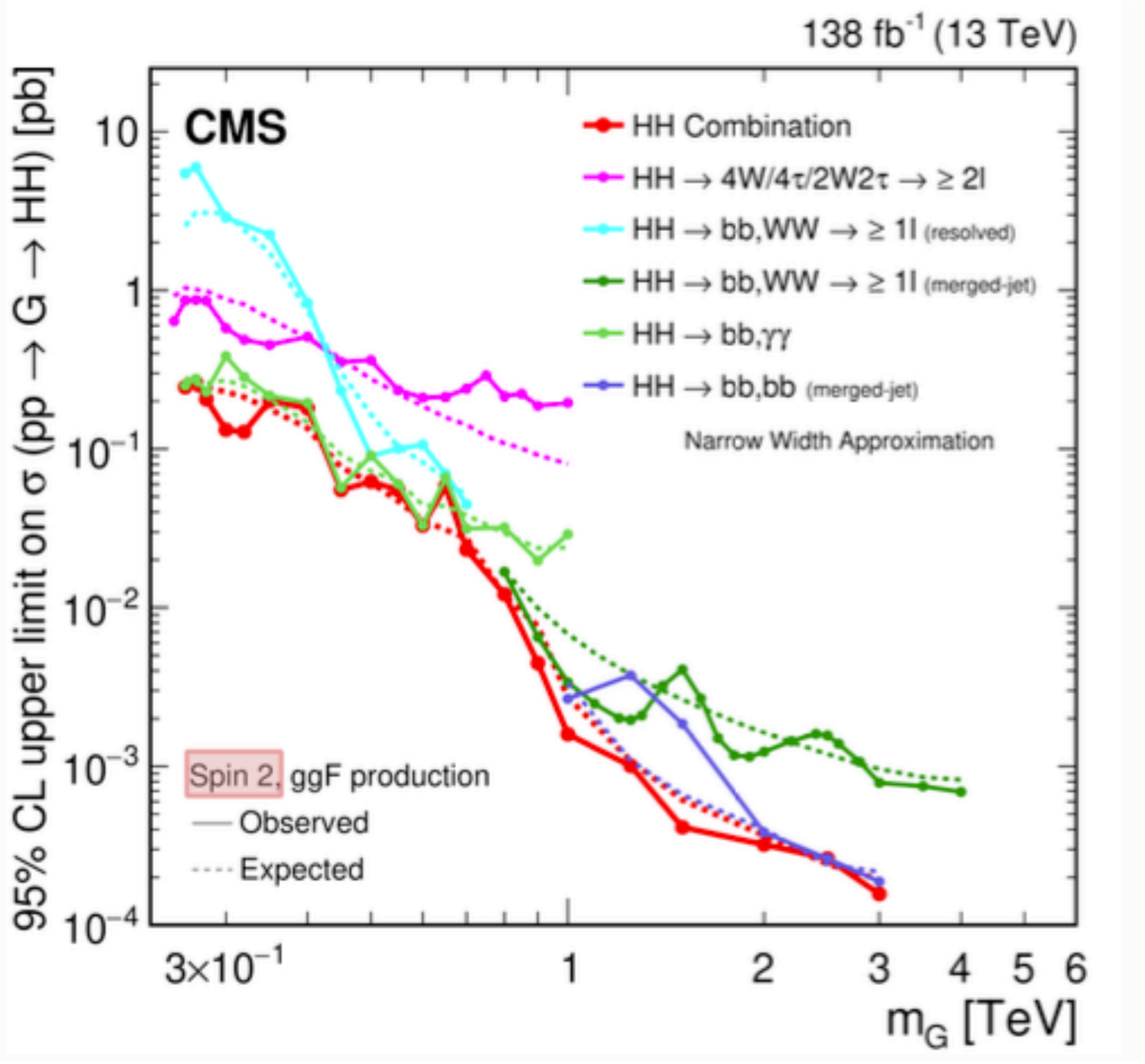
Search for resonances decaying to HH

- 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→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





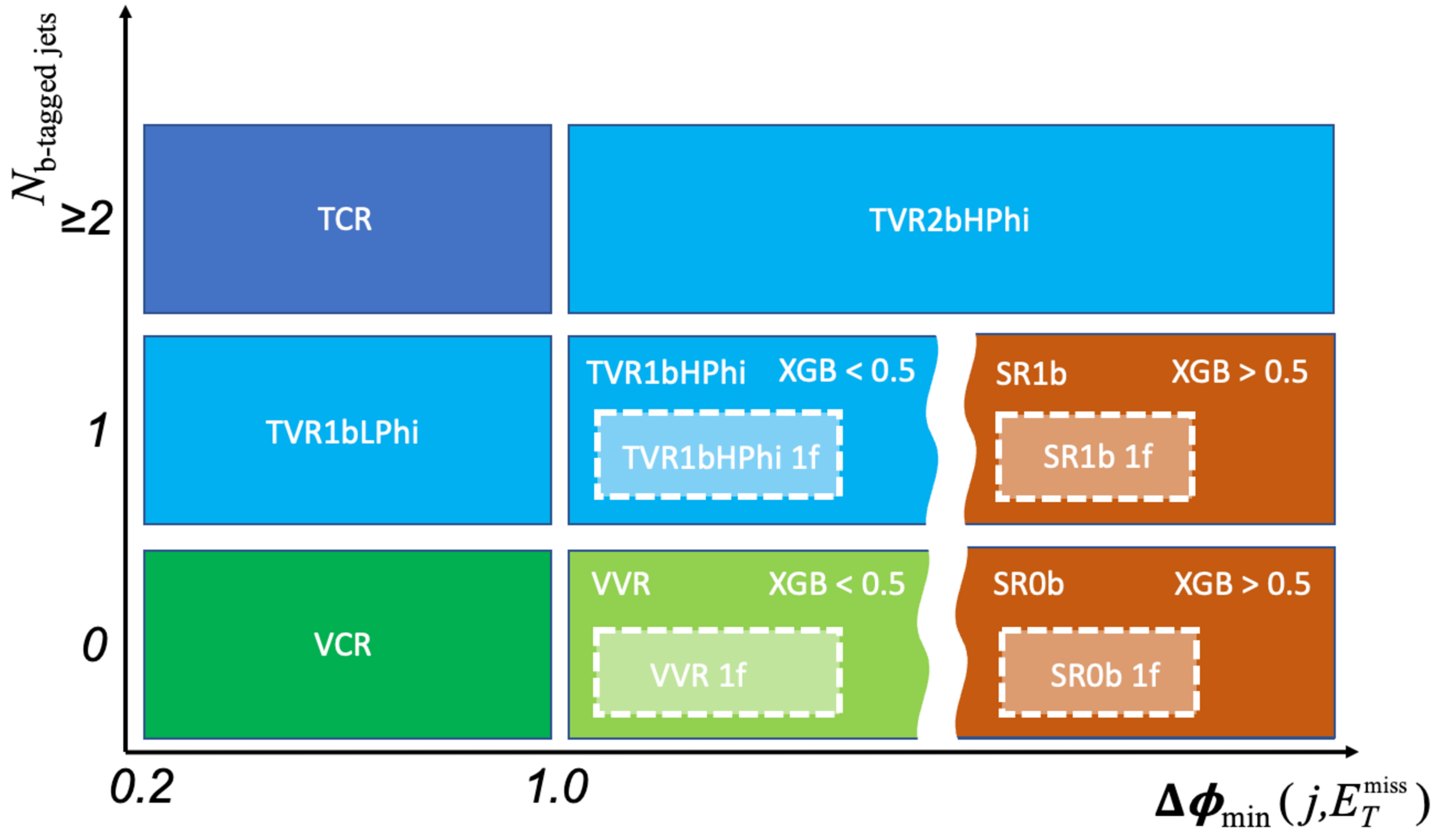
CERN-EP-2024-062

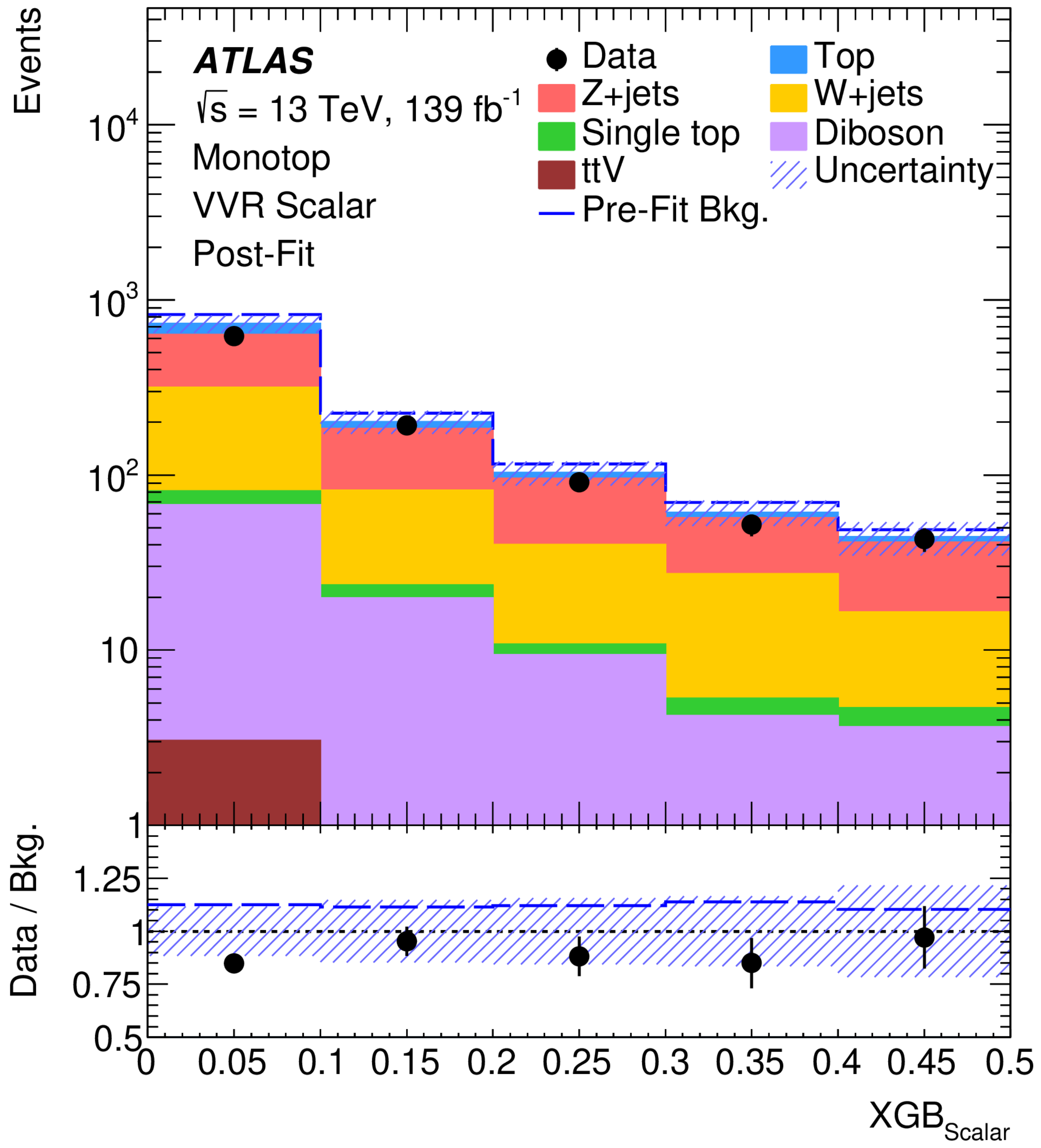
Outliers

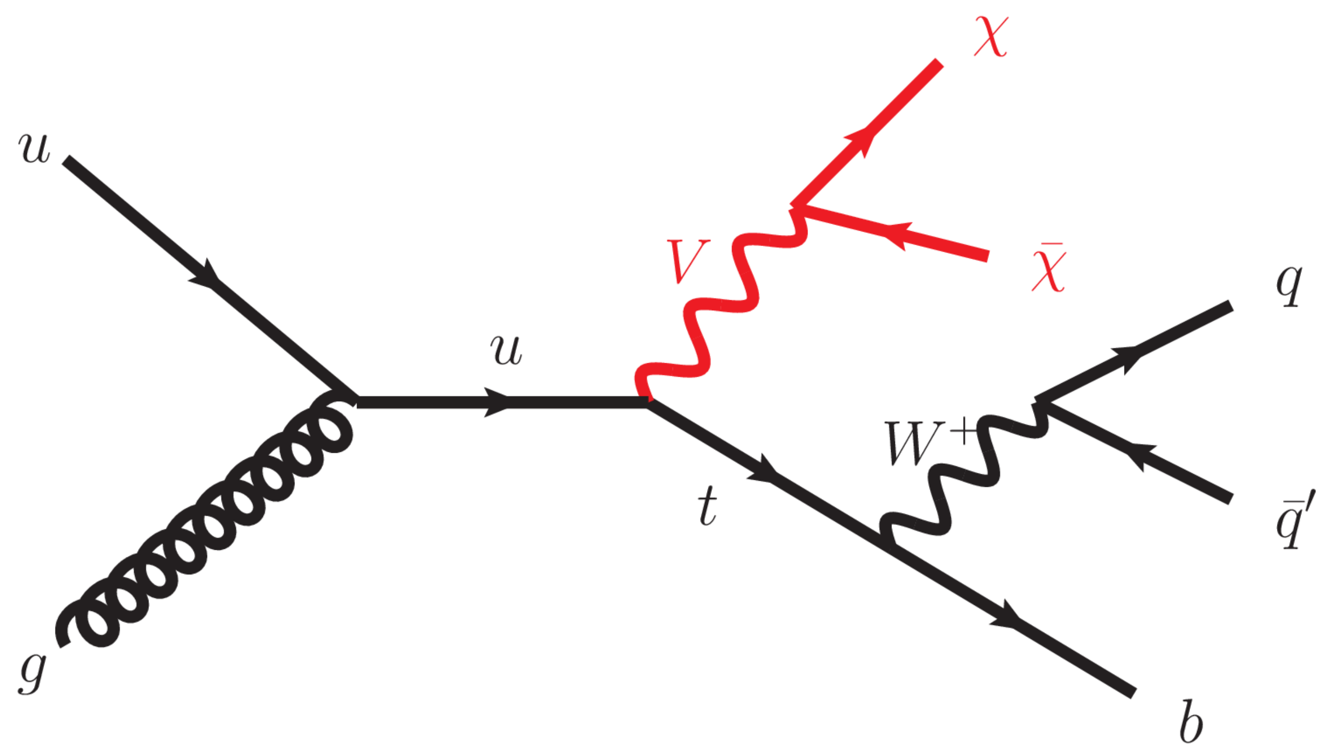
Mono-top

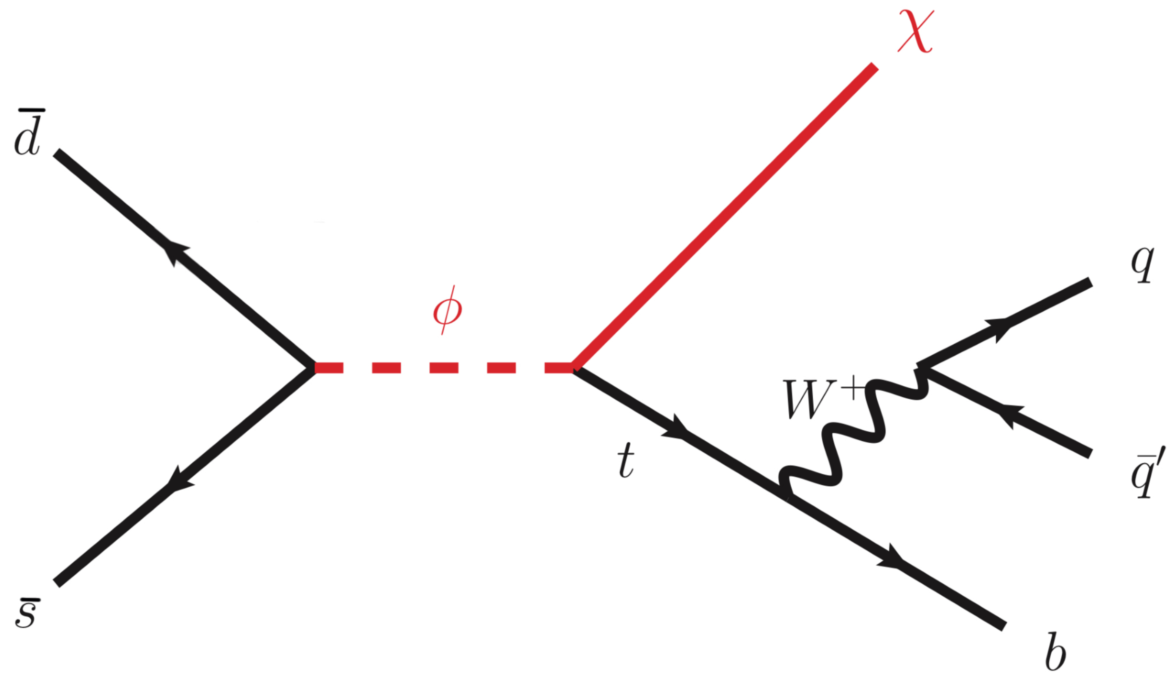
EXOT-2022-40

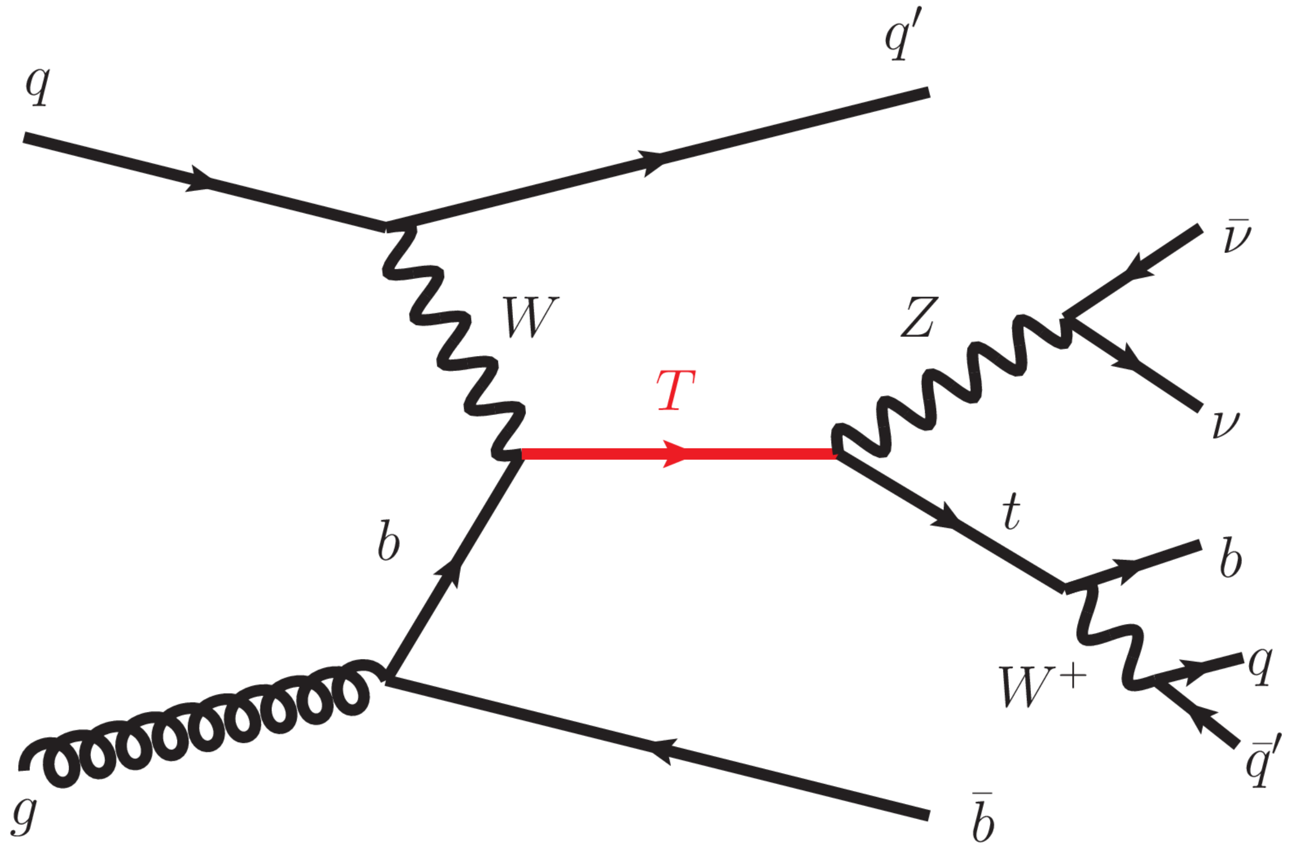
* New particles in final states with a boosted top+MET
* Results are interpreted in the context of simplified models for **Dark Matter particle** production and the single production of a **vector-like T quark**







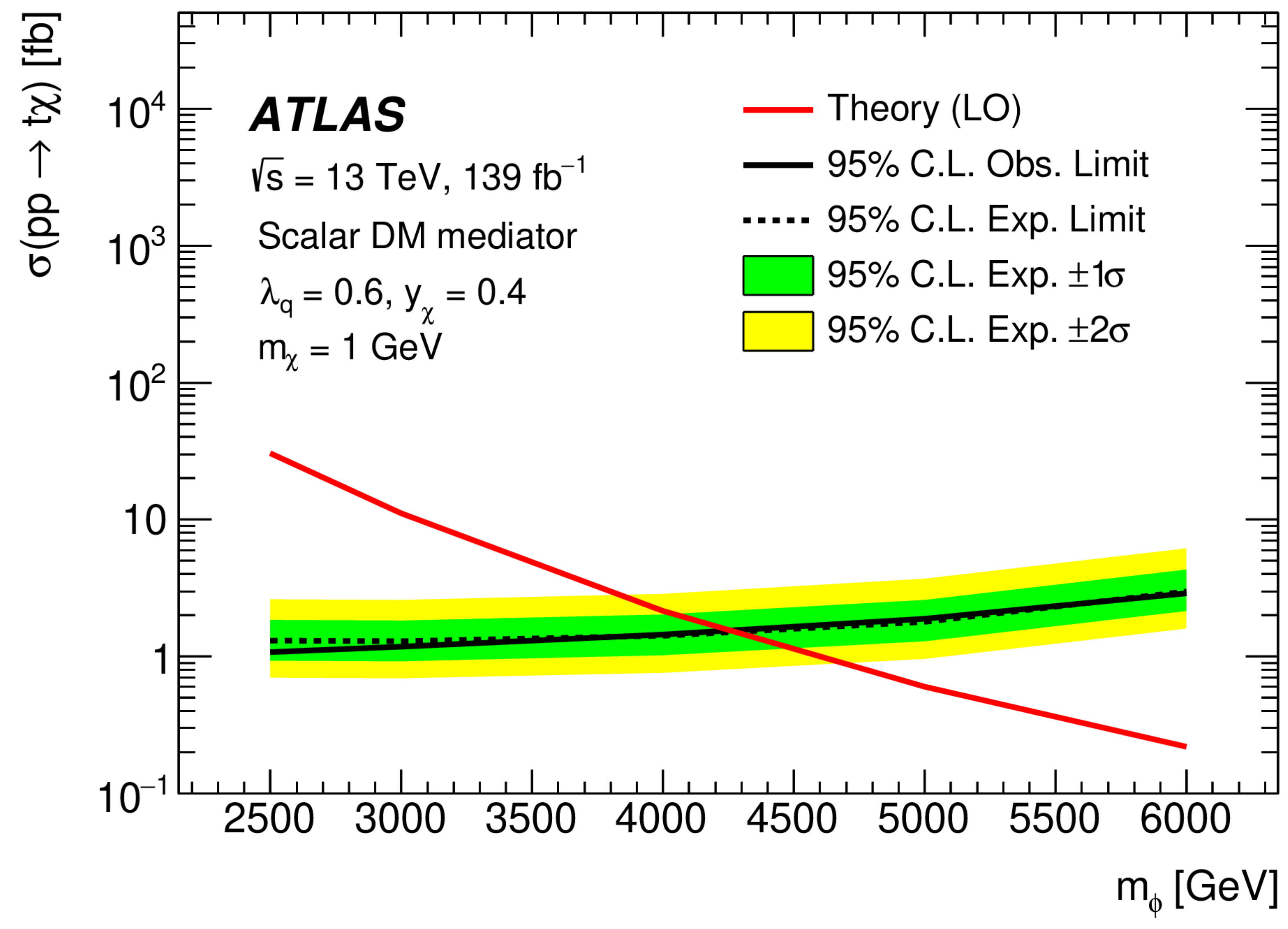


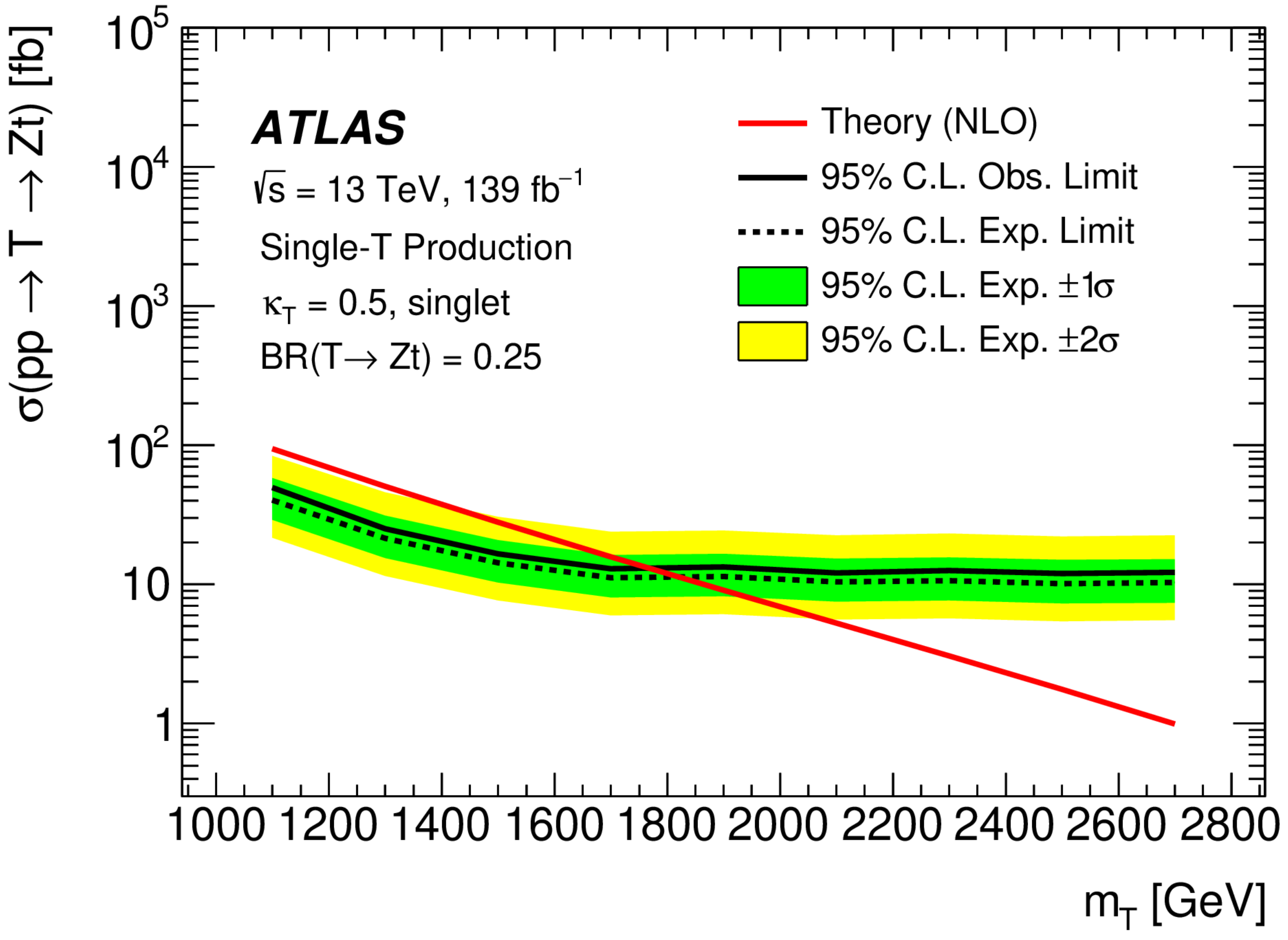


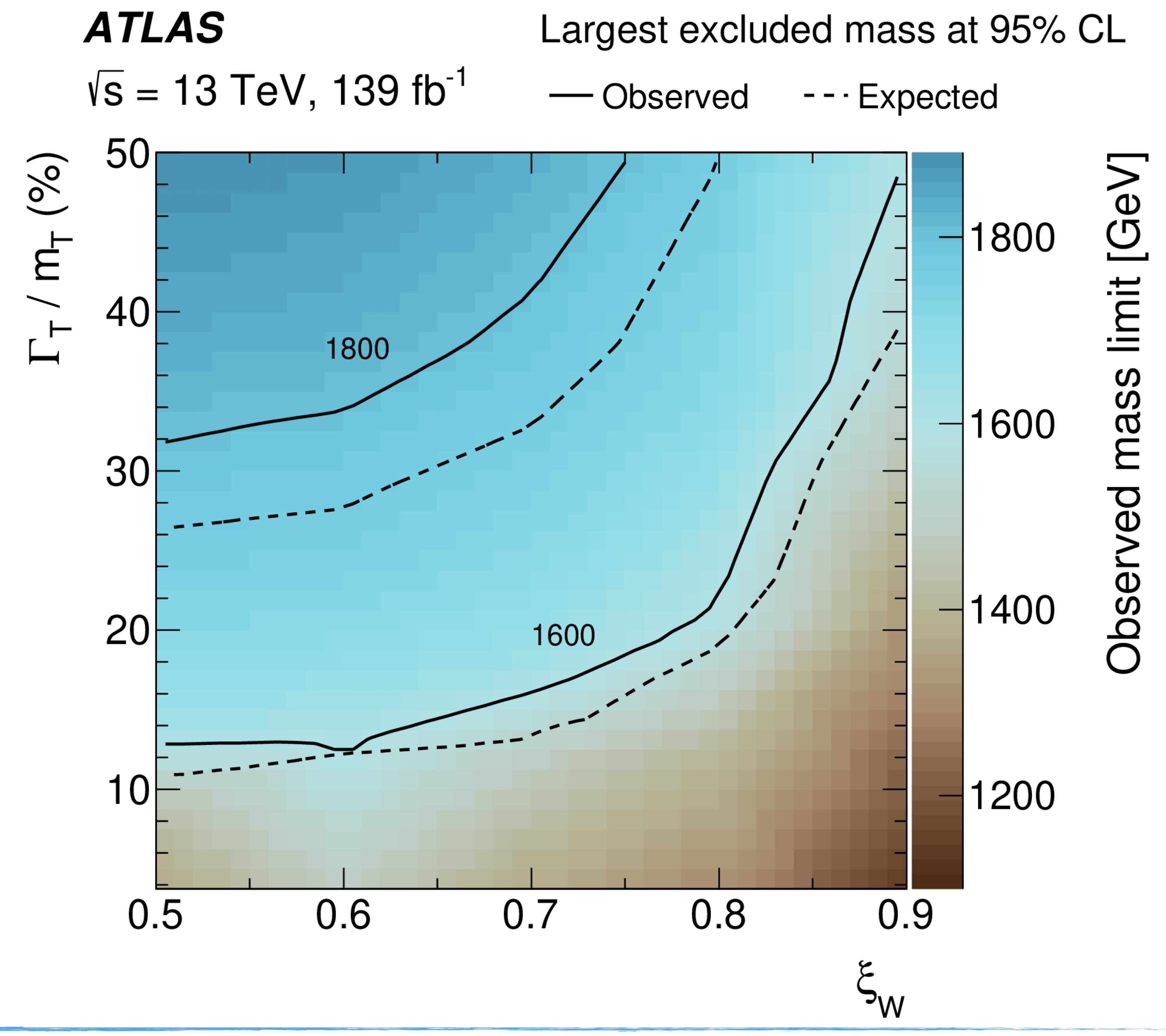
Mono-top

EXOT-2022-40

- 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

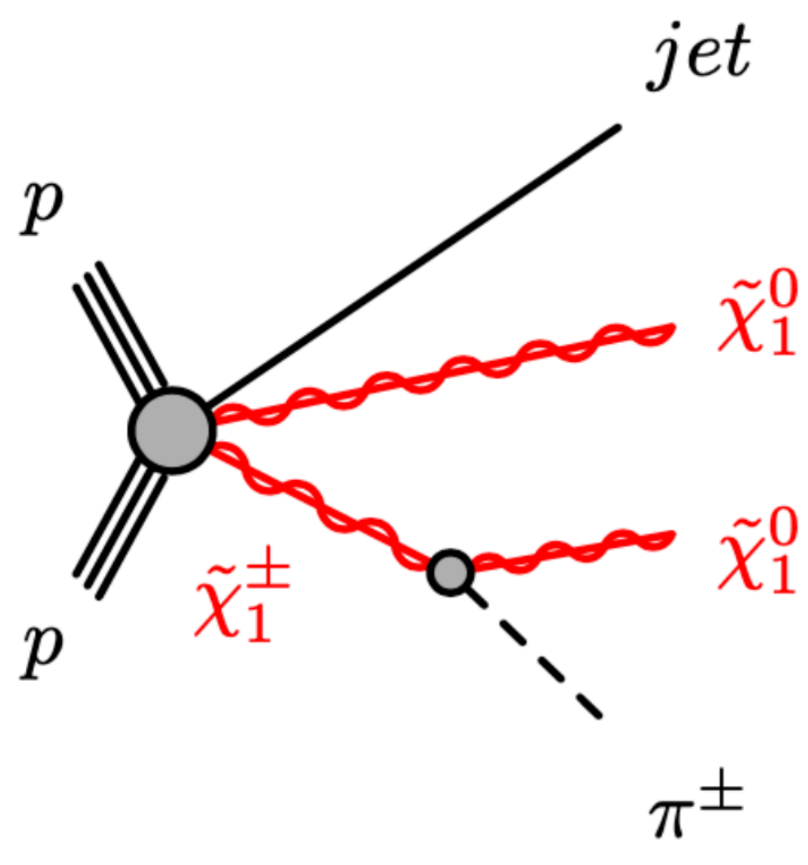


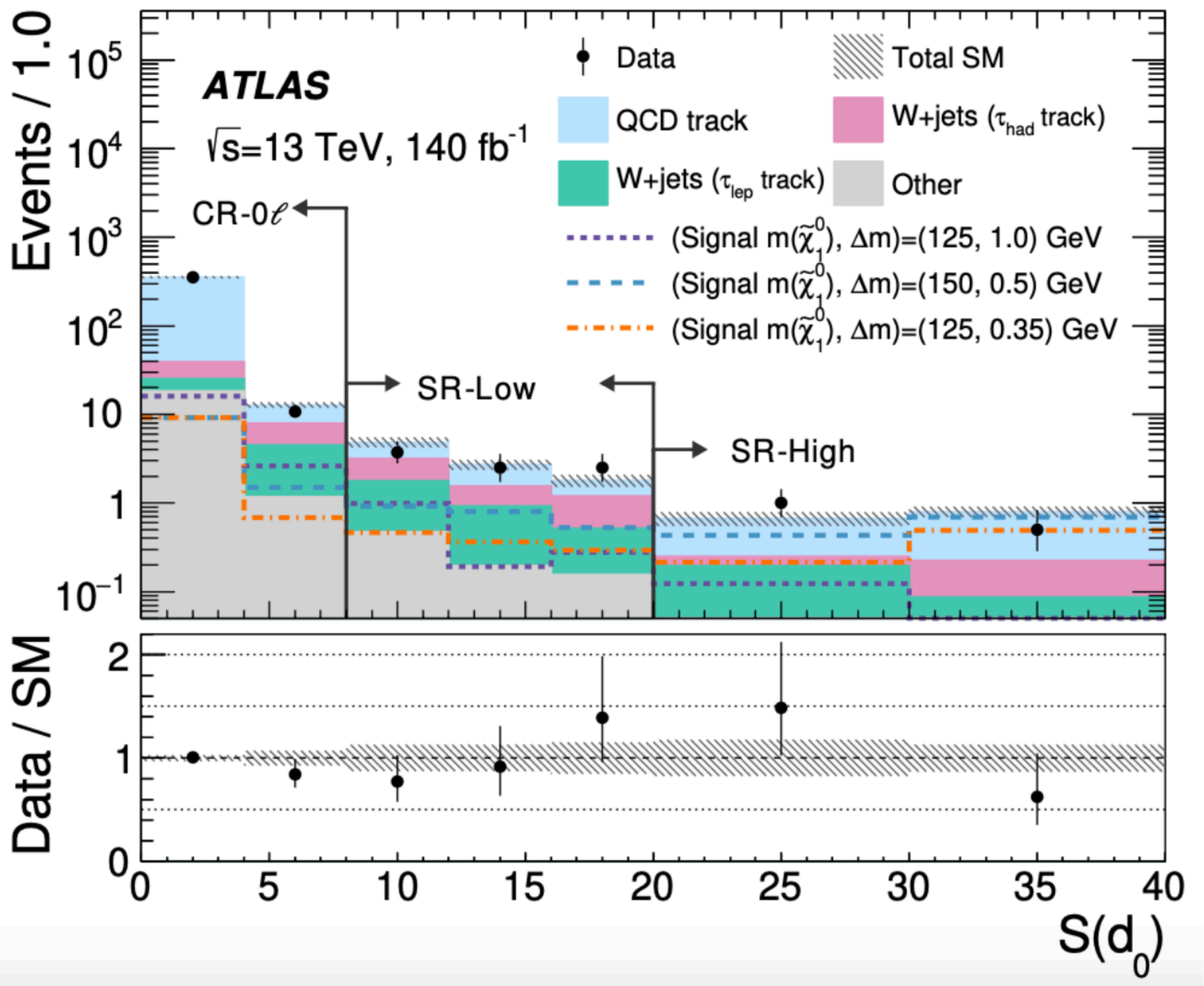


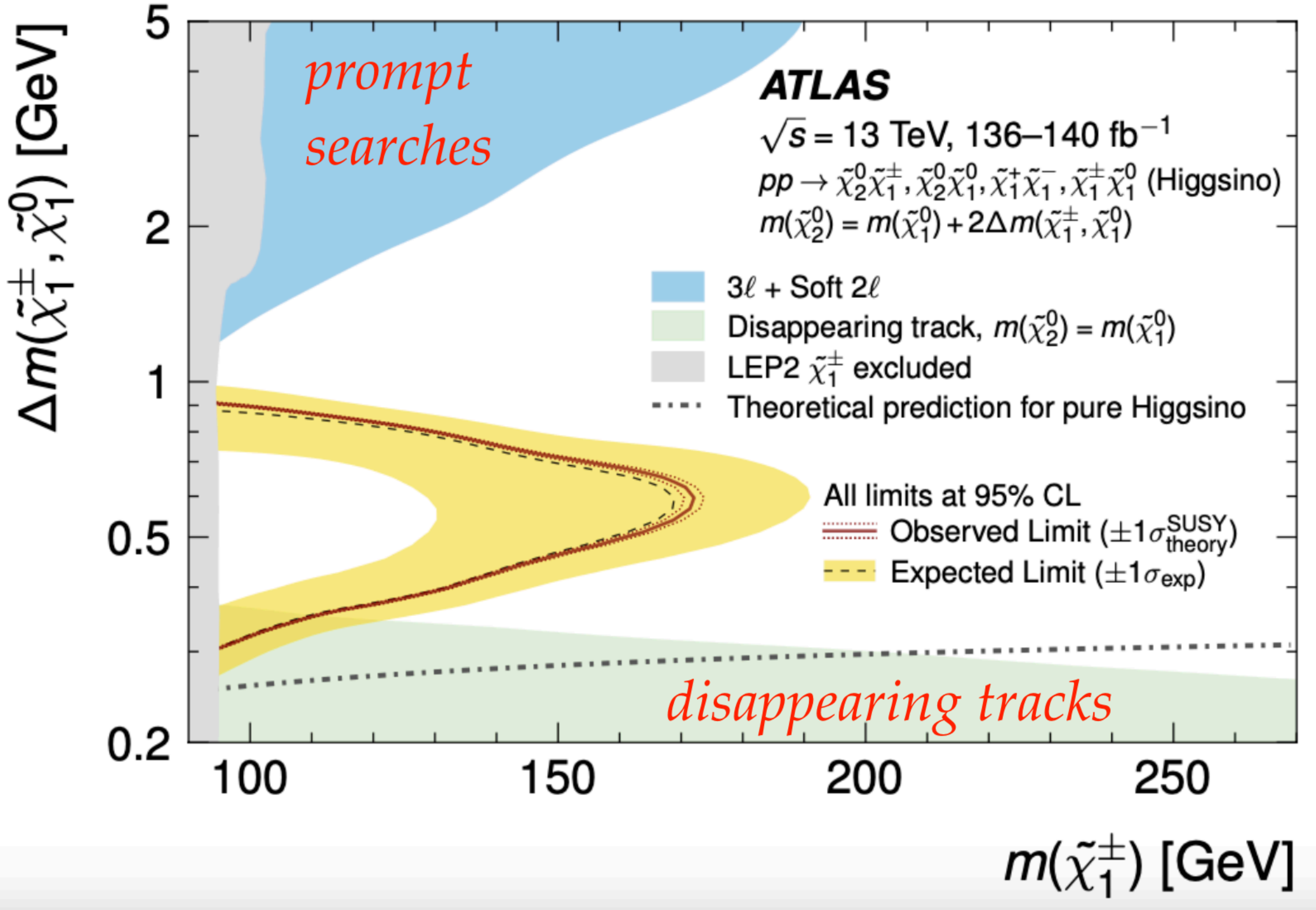


Search for mass-degenerate Higgsinos

- RPC SUSY: higgsino-like DM can be almost mass degenerate with charged NLSP ($\Delta(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0})$~ 250–400 MeV) → disappearing track signature
- For Δm of few GeV → 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 GeV < p_T < 5 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 → limits exceeding LEP results for first time



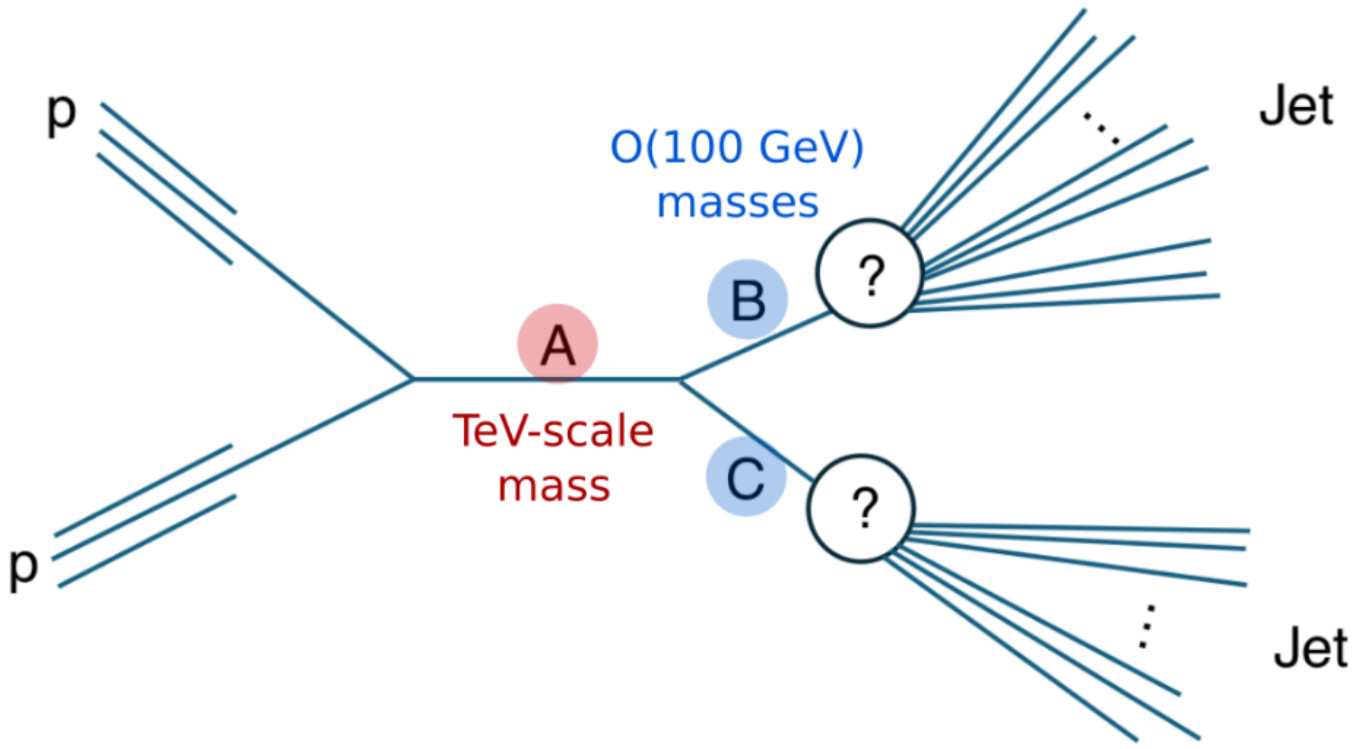




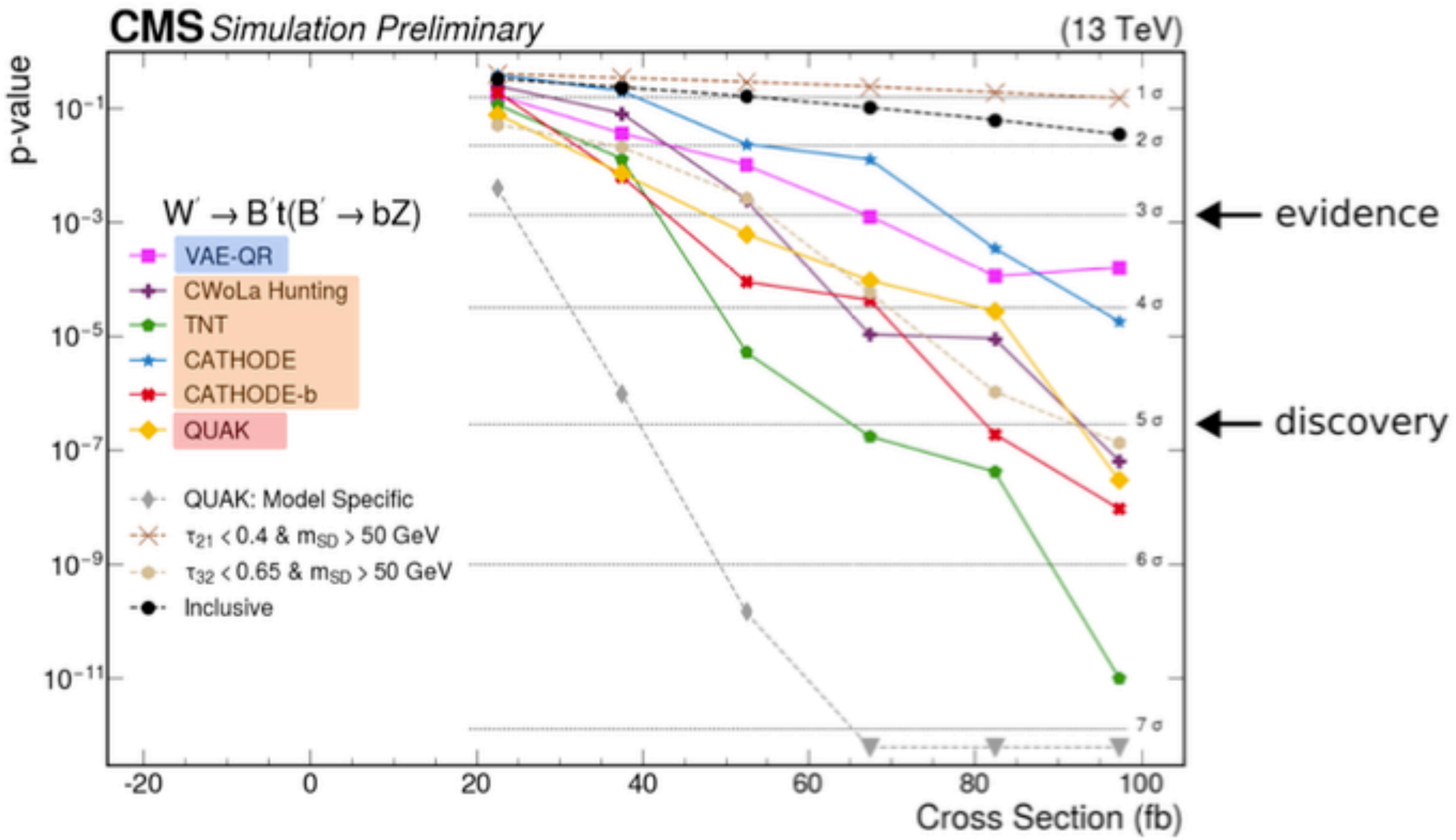
2401.14046 [hep-ex]

Model-agnostic search with dijet resonances

CMS-PAS-EXO-22-026



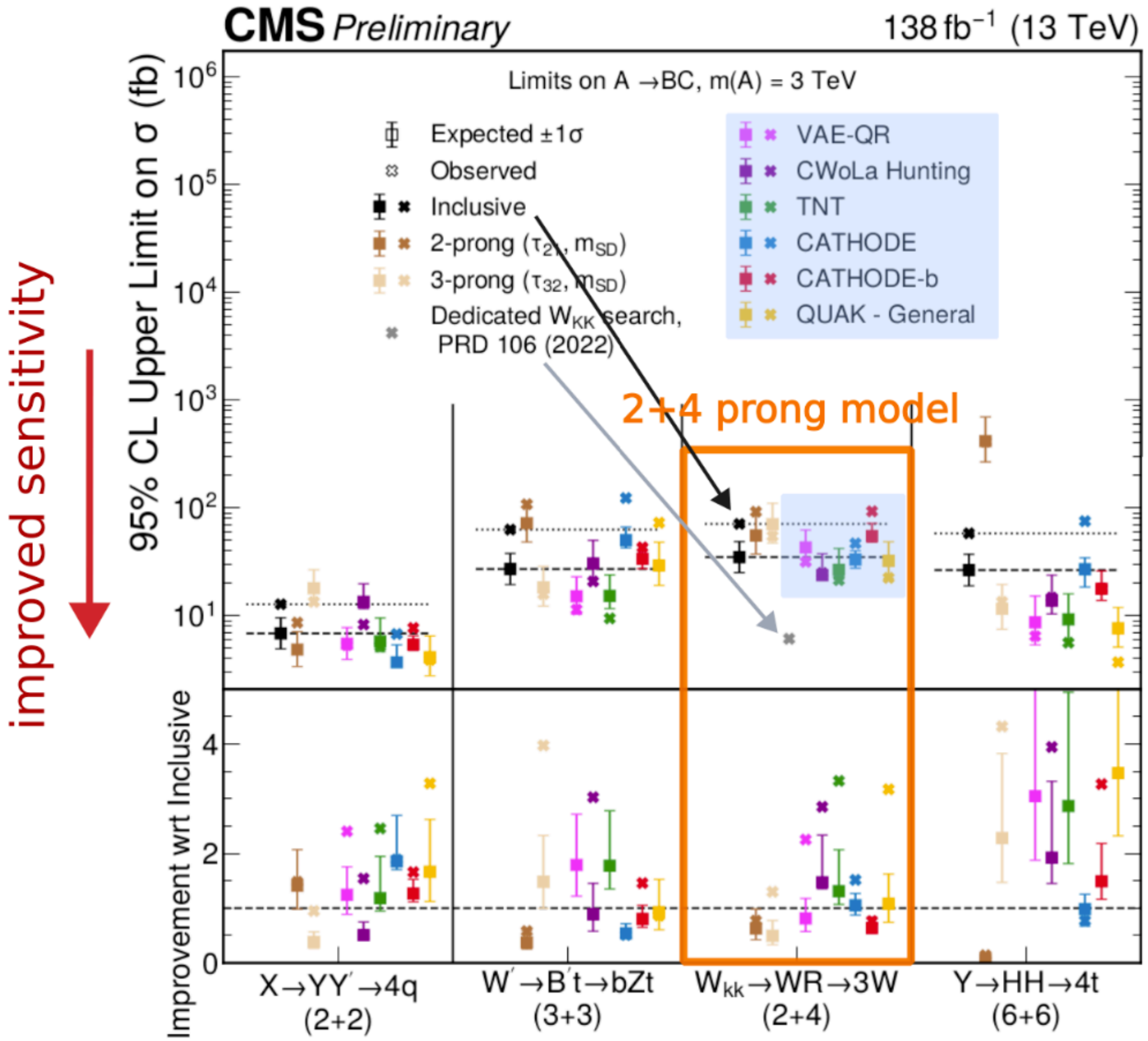
- Search for new physics in di-jet final states in a model-agnostic manner
- Based on anomaly detection
  - ☆ Identify jets with non-QCD-like substructure
  - ☆ Maximisation of the sensitivity to unknown new physics signatures
- First results derived with anomaly detection at CMS!
- Five machine learning 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

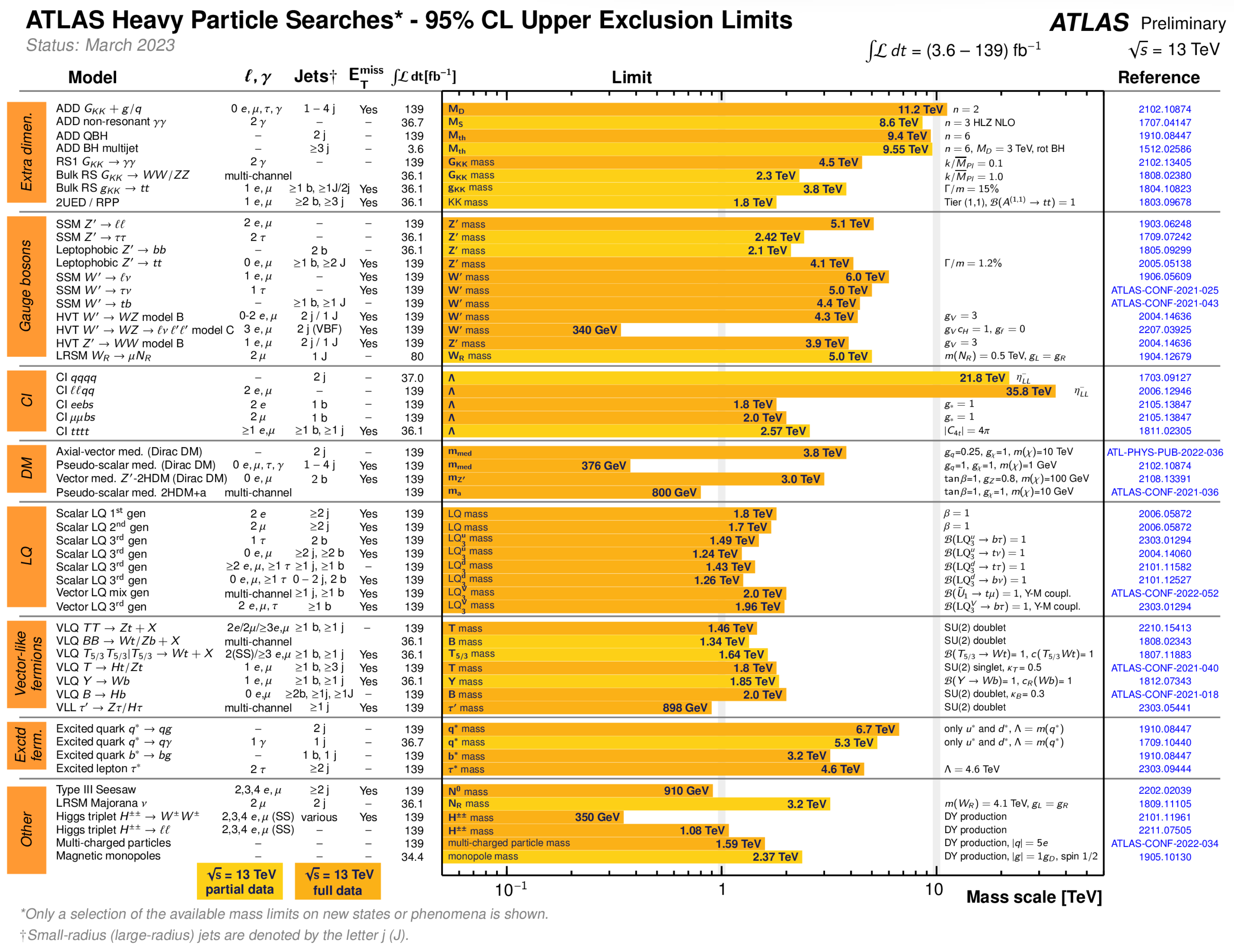
- Events selected based on the anomaly score
- Bump hunt in the di-jet mass spectrum
- Sensitivity evaluated on benchmark models
  - For most of the models, these are the first limits ever presented
- Sensitivity improved up to a factor 4 compared to "inclusive" case (no cut on anomaly score)
- Sensitivity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



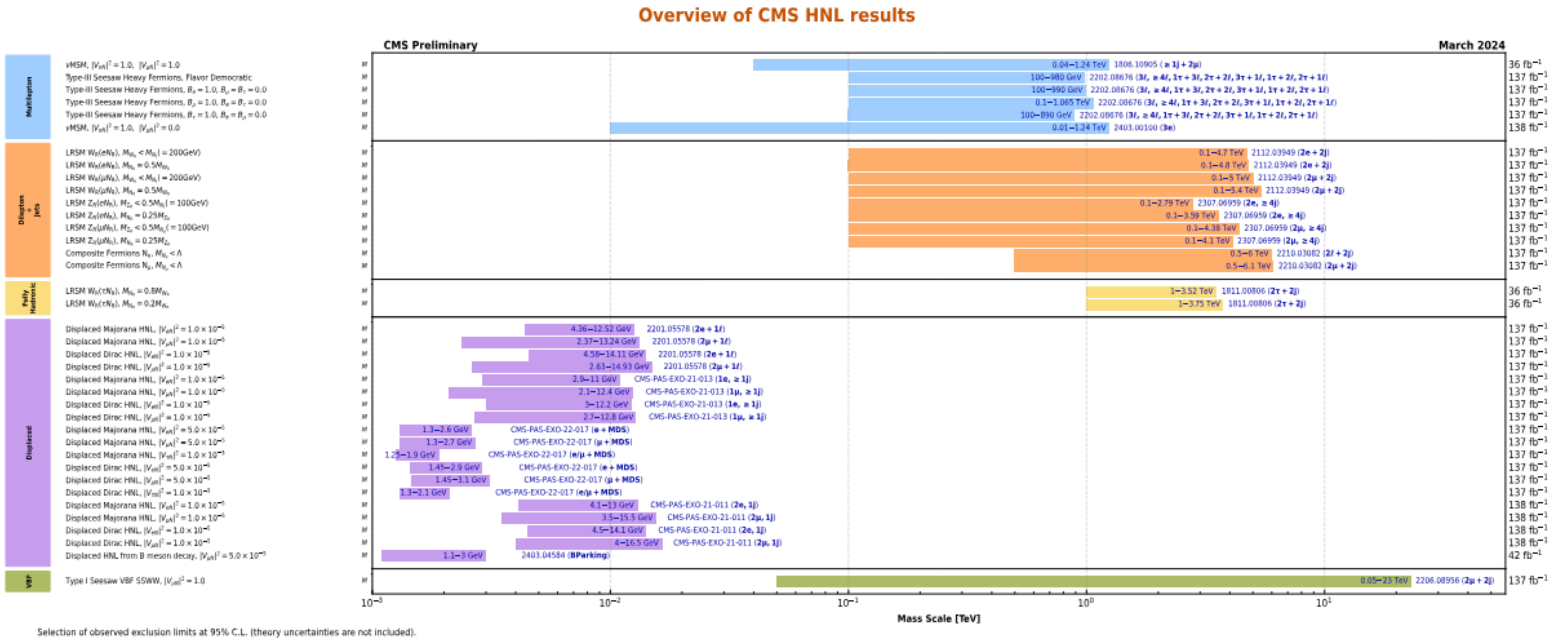
Summary

* 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

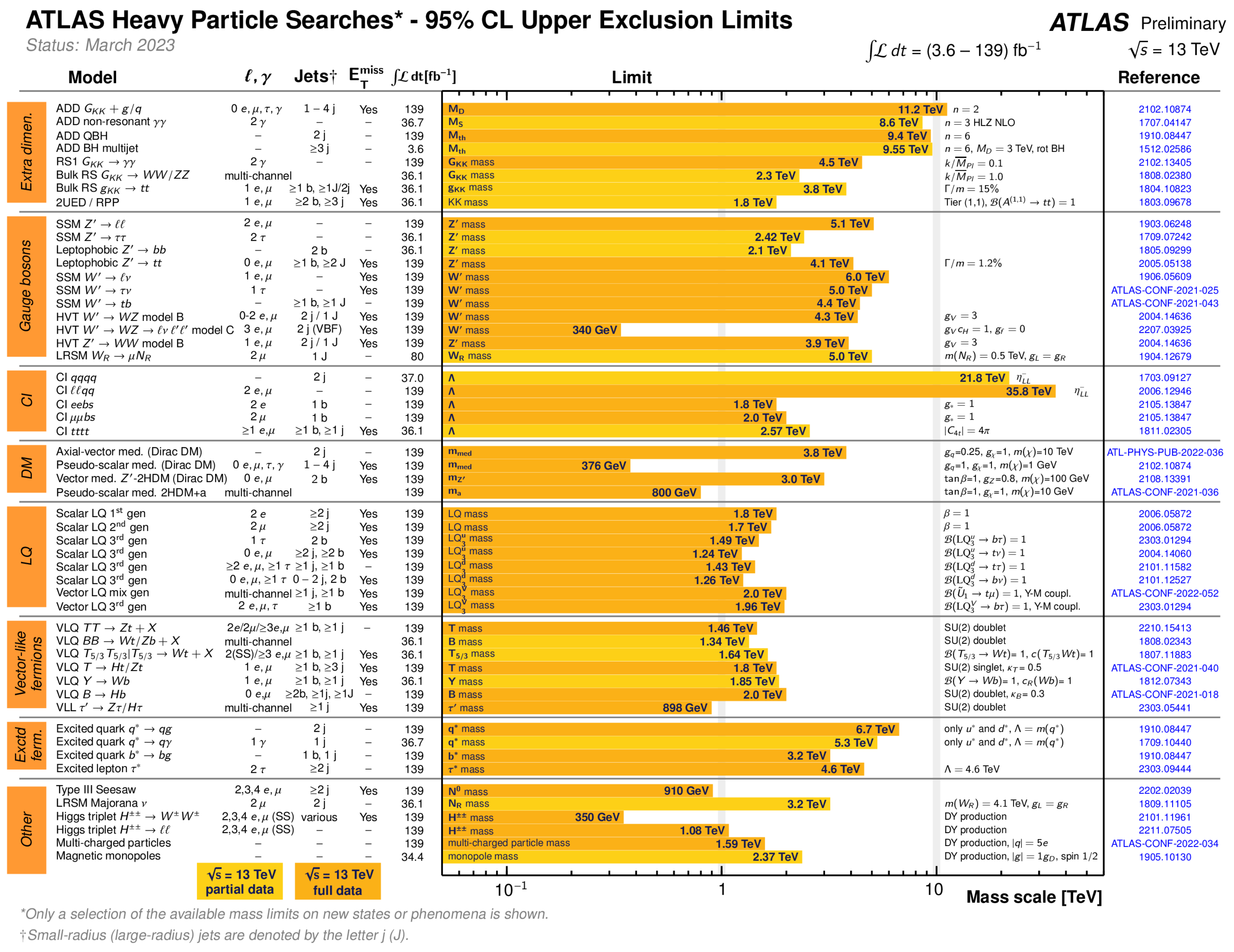


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2023-008/



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

Backup



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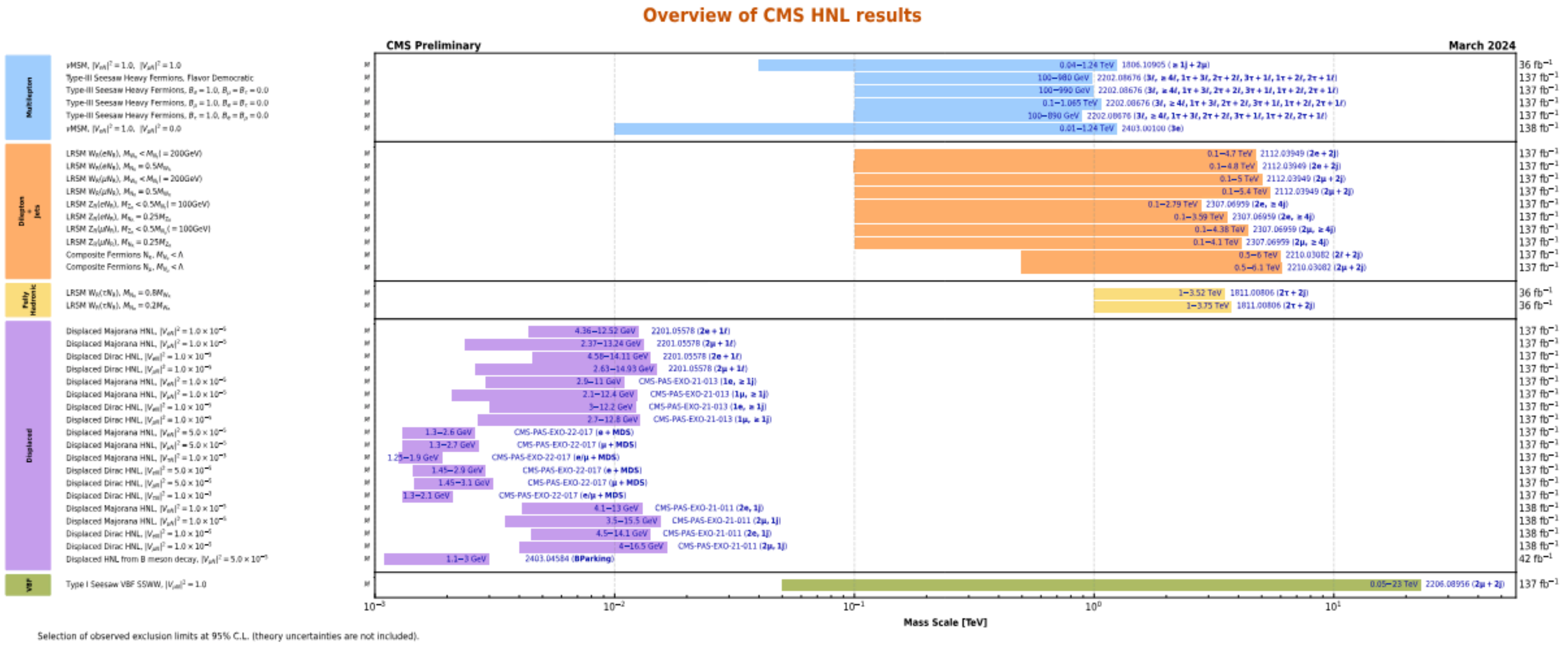
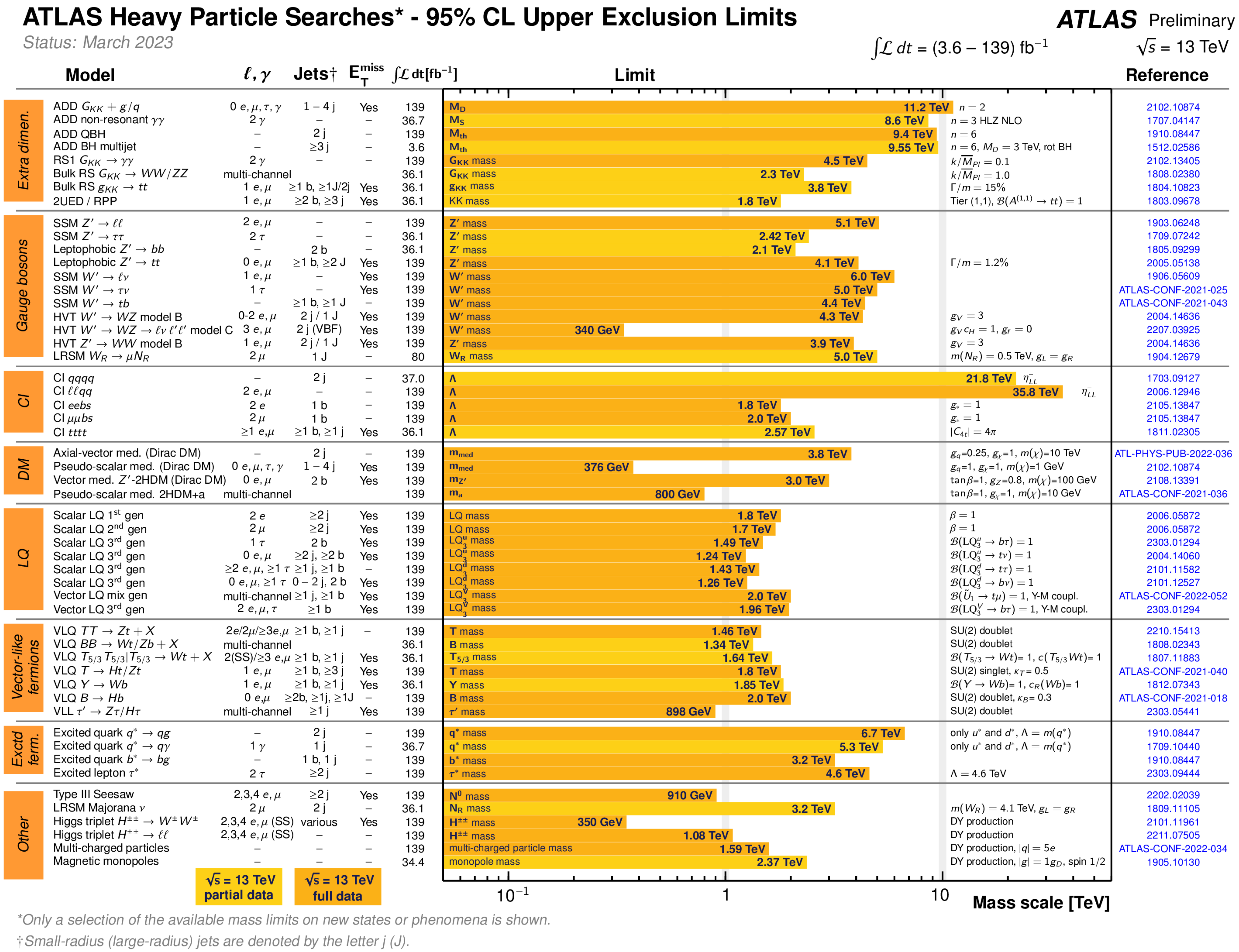


https://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/

More ATLAS results overview



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

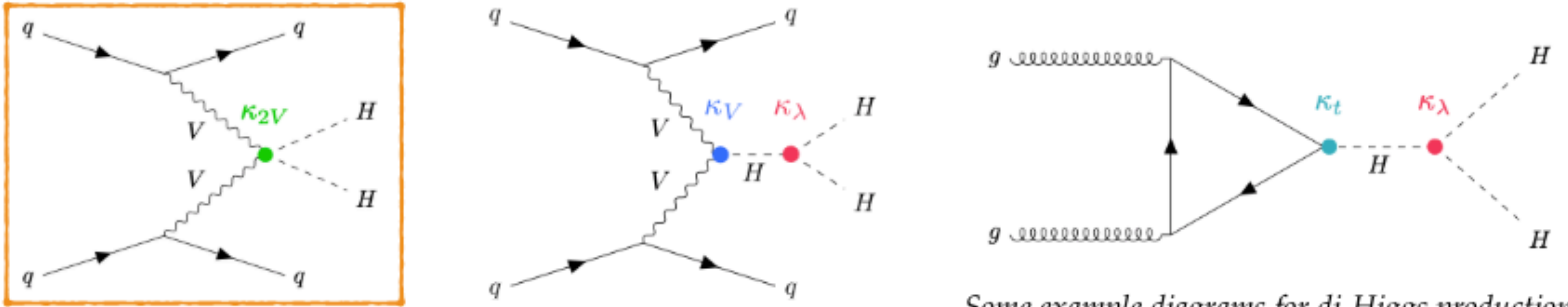
More CMS results overview

Overview of CMS HNL results

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

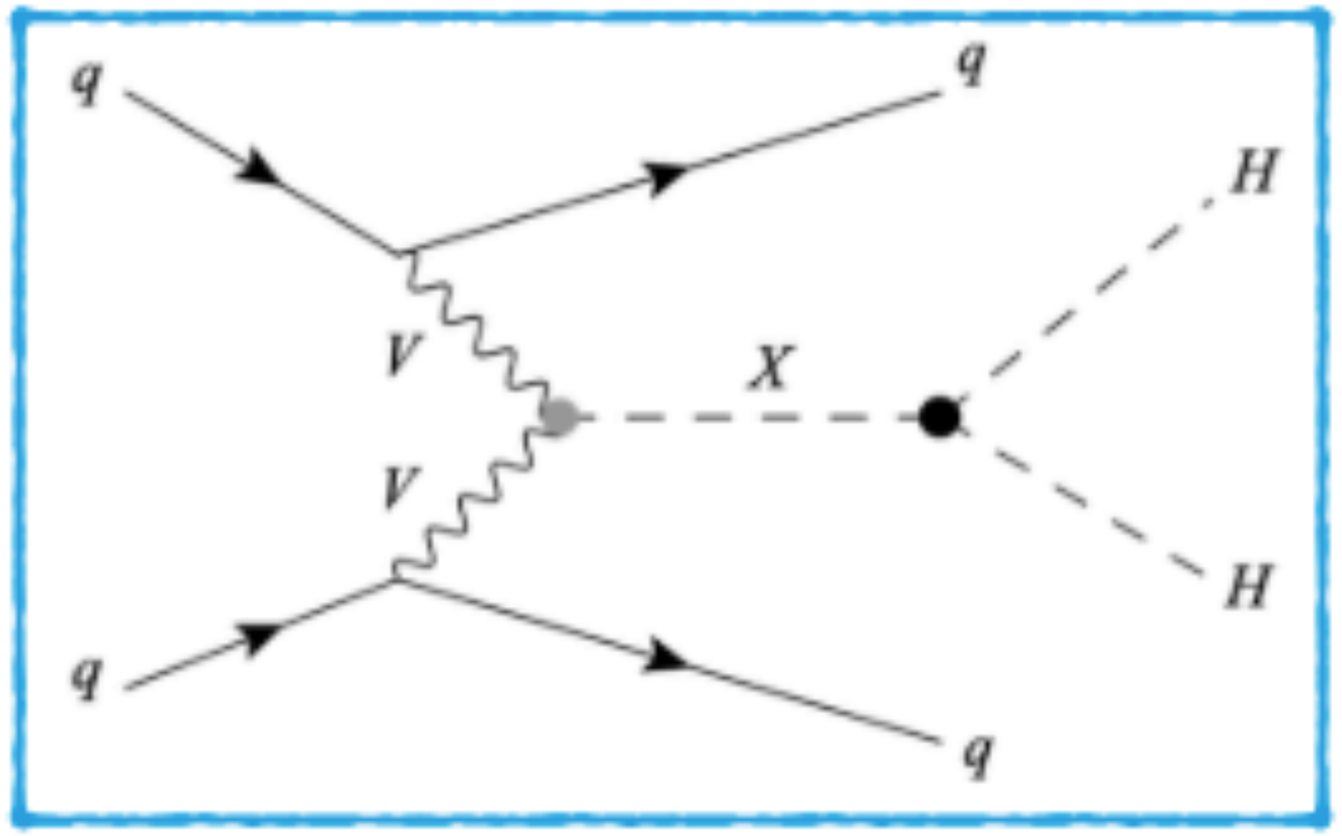
https://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/

Di-Higgs -> bbbb



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 $H \to b\bar{b}b\bar{b}$ 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

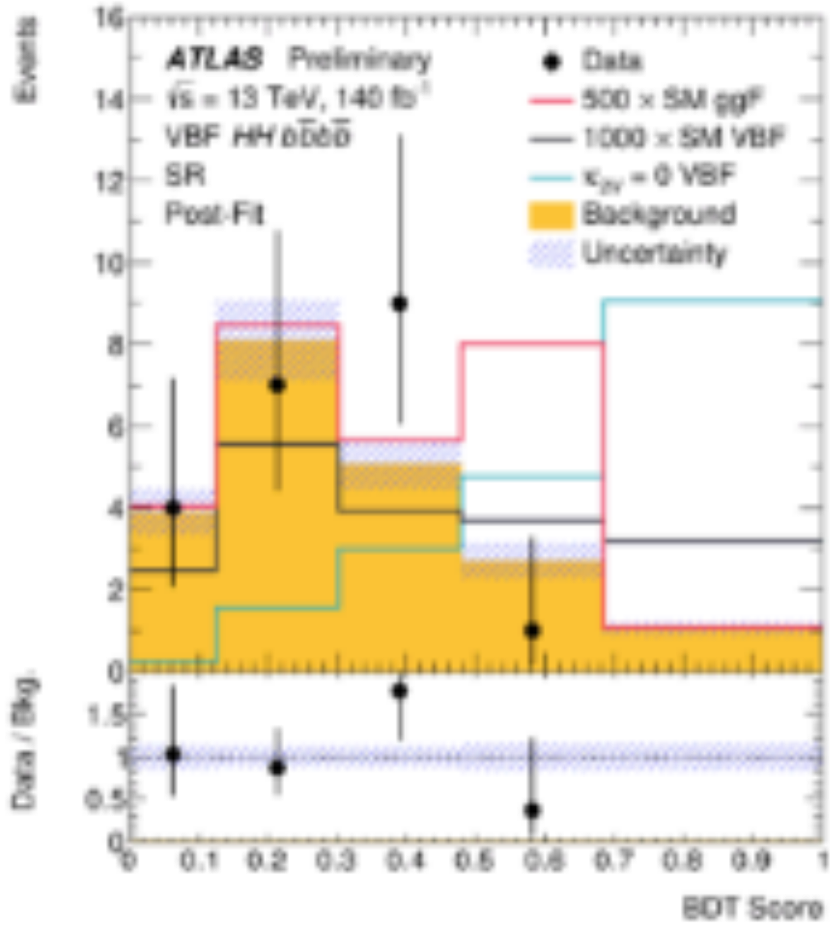
Di-Higgs -> bbbb

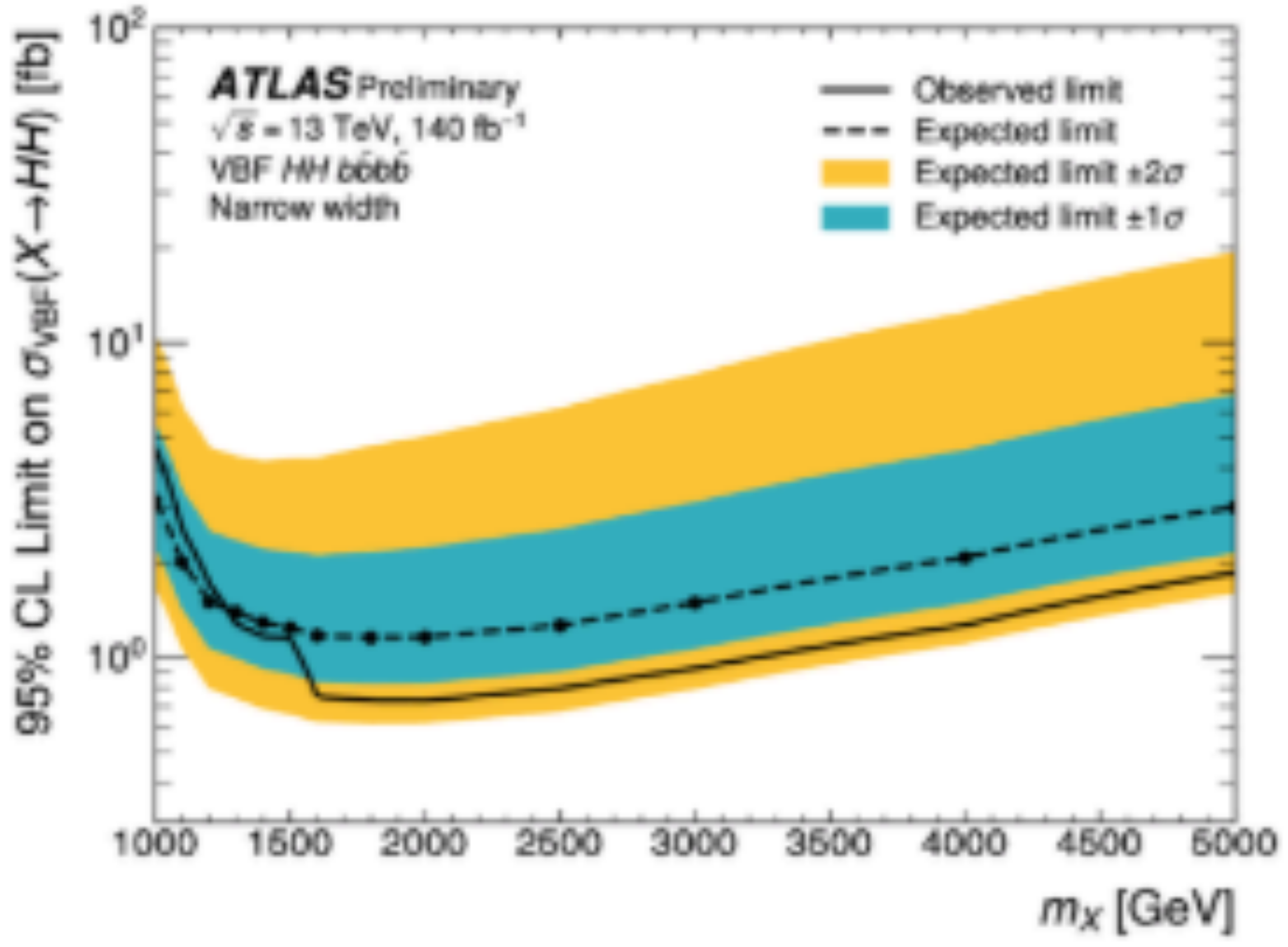
- Bkg. from events with 1 double-b tag normalised in CR with 2 double-b tags
- BDT trained to separate sig. ($\kappa_{2V} = 0$) from bkg.
- No, excess → combination with resolved result [PRD 108 (052003)]:

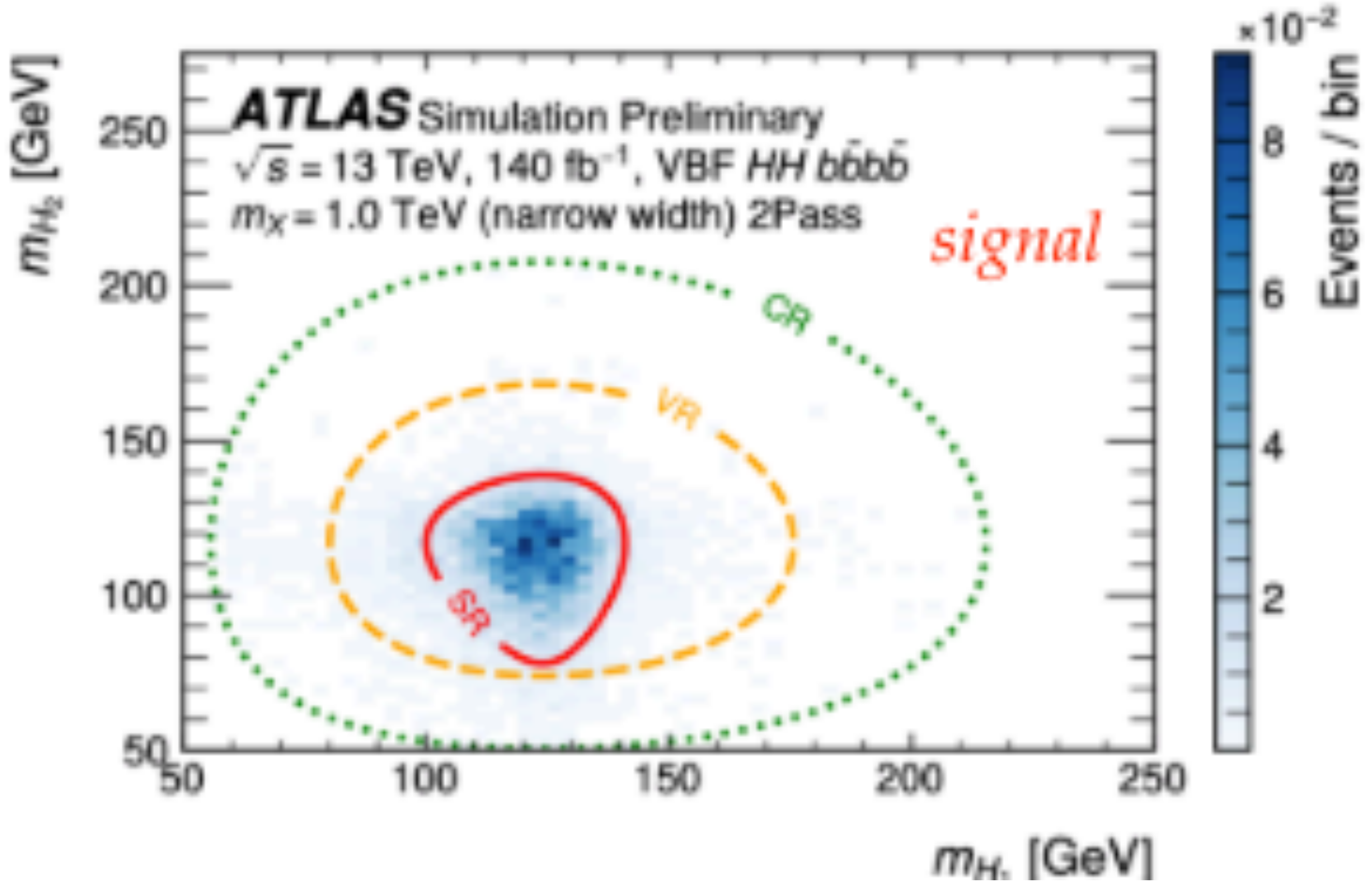
  $\kappa_{2V} = 0$ excluded with 3.8 σ (3.3 σ)

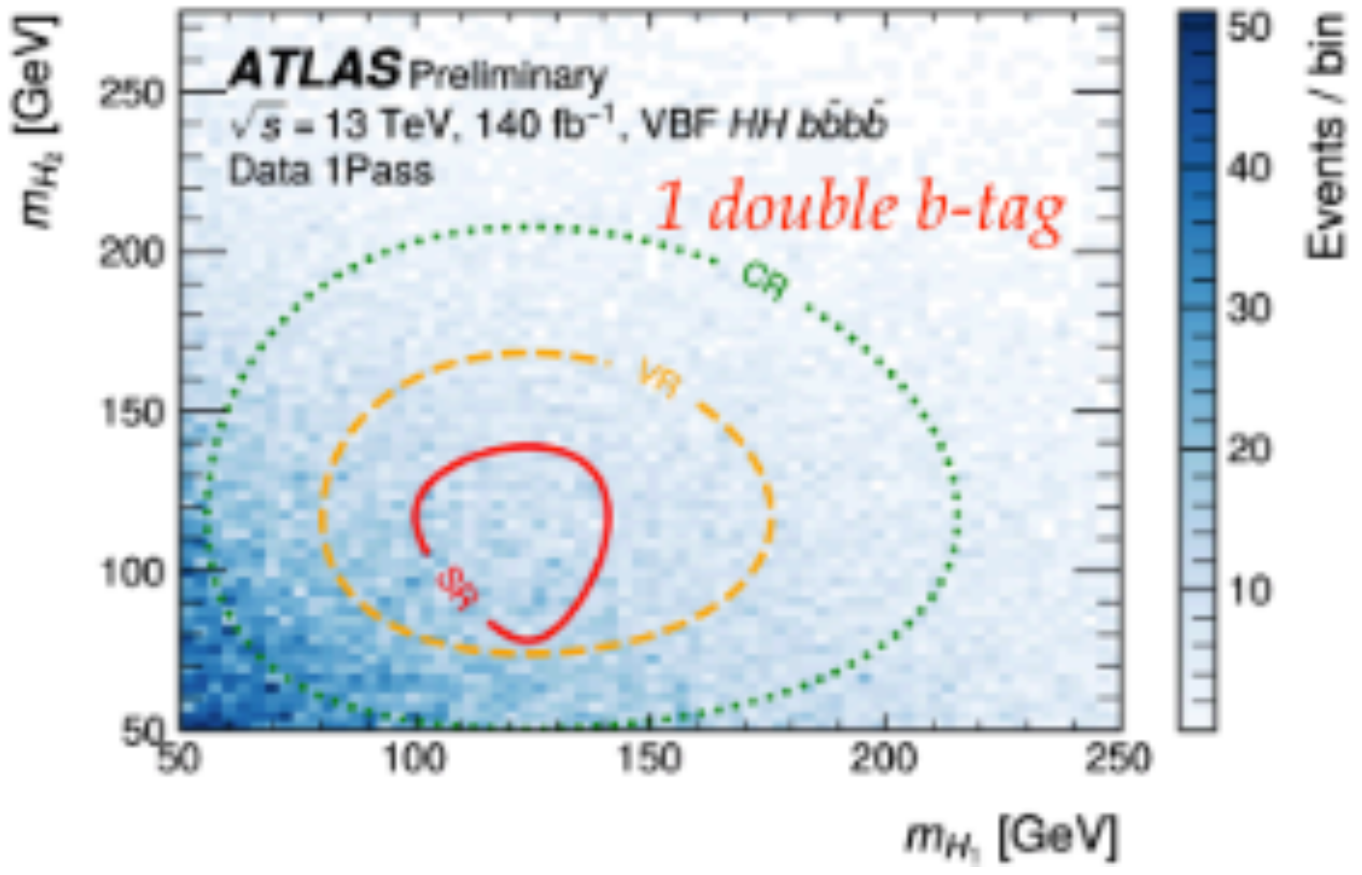
  $0.6 < \kappa_{2V} < 1.5$ ($0.4 < \kappa_{2V} < 1.7$) at 95% CL

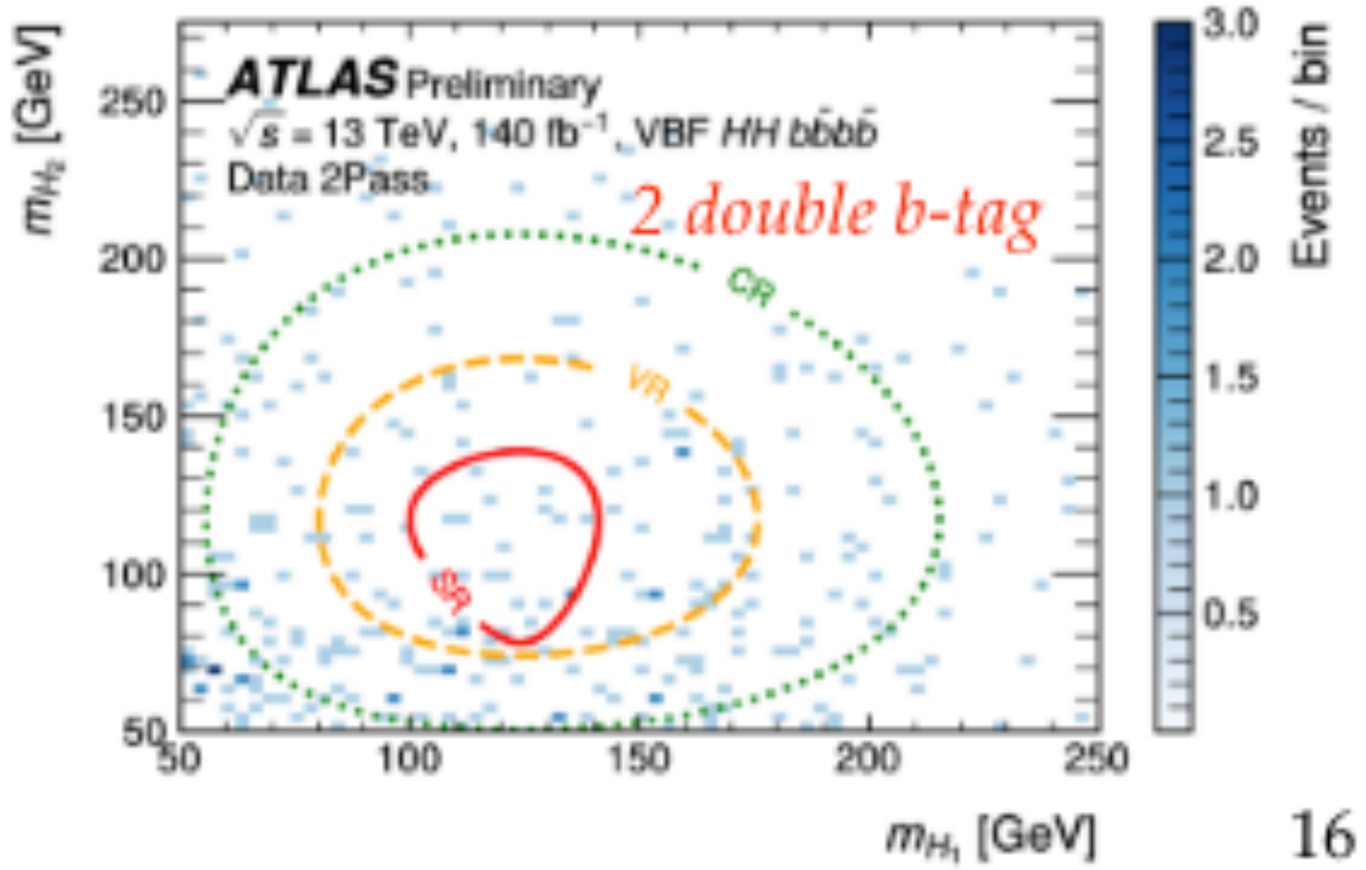
- Cross section limits on heavy scalar mediator











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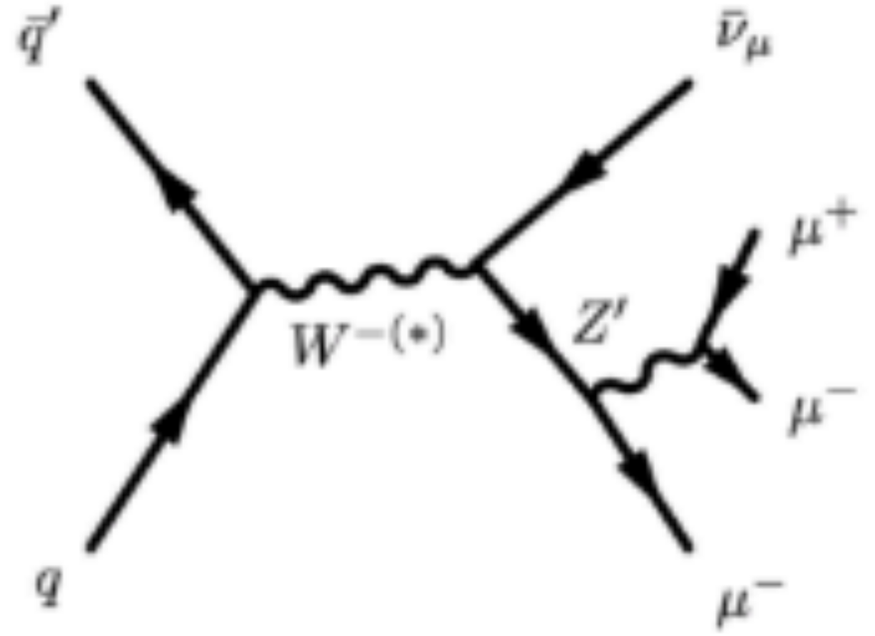
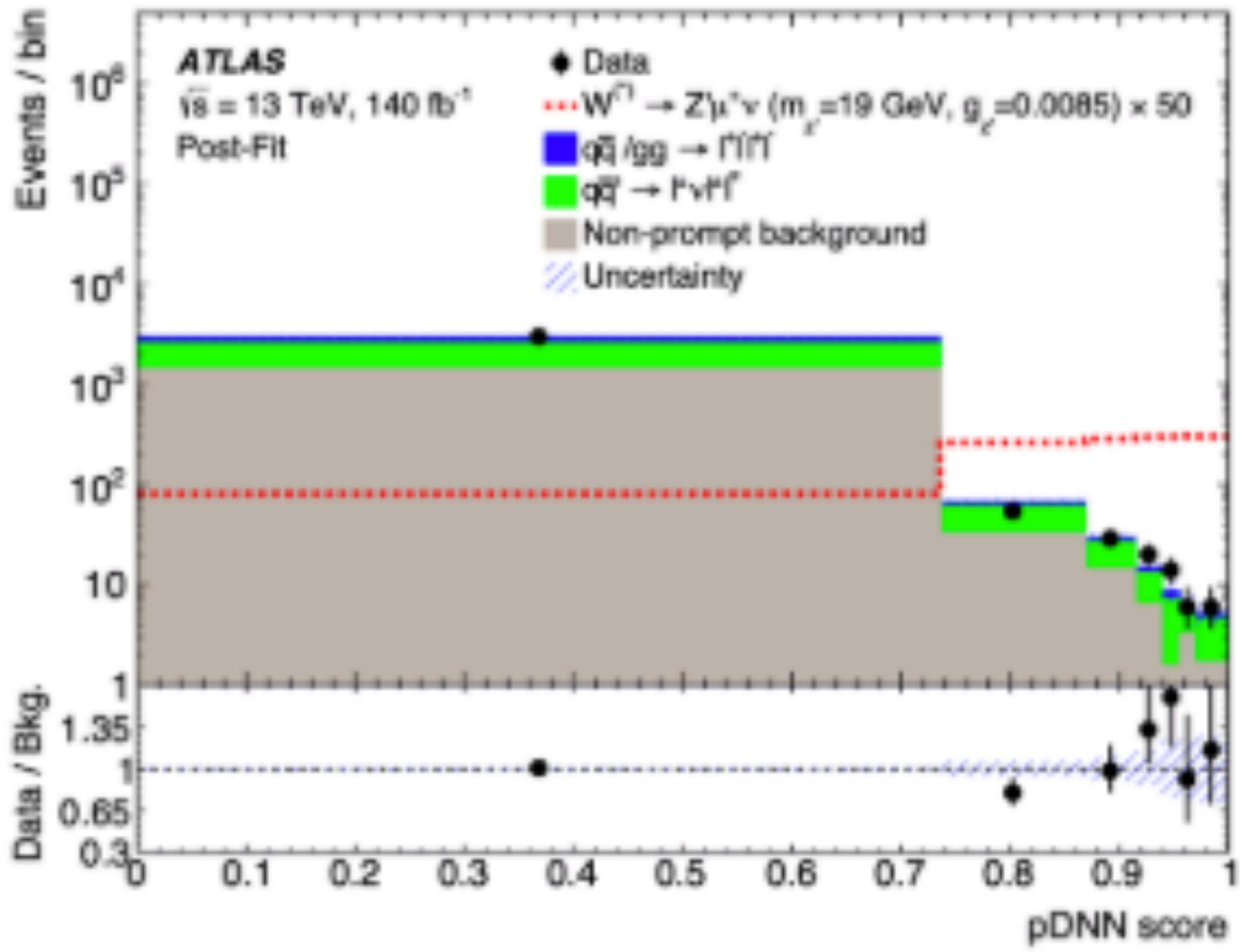
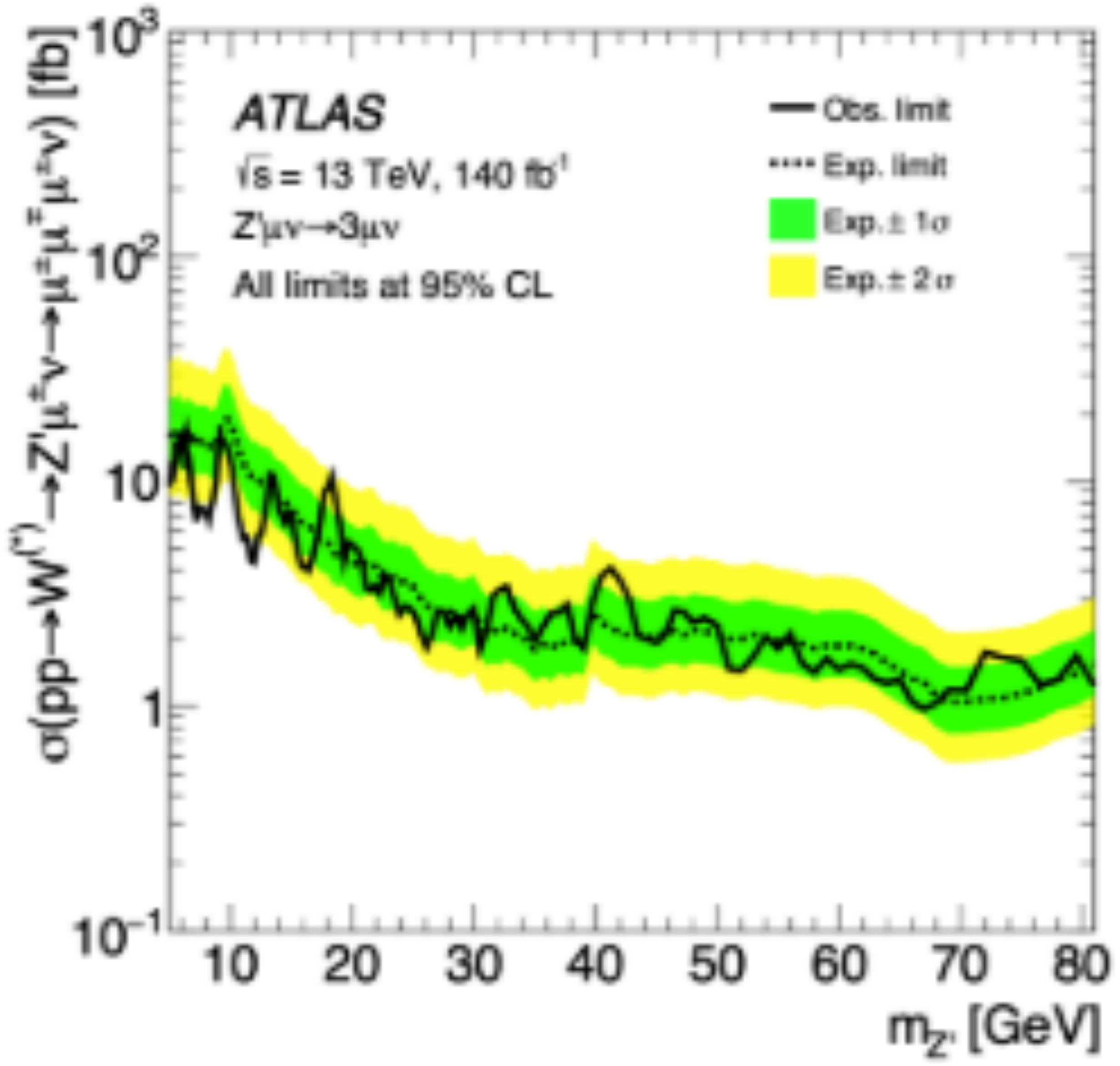
Z′ -> 3mu

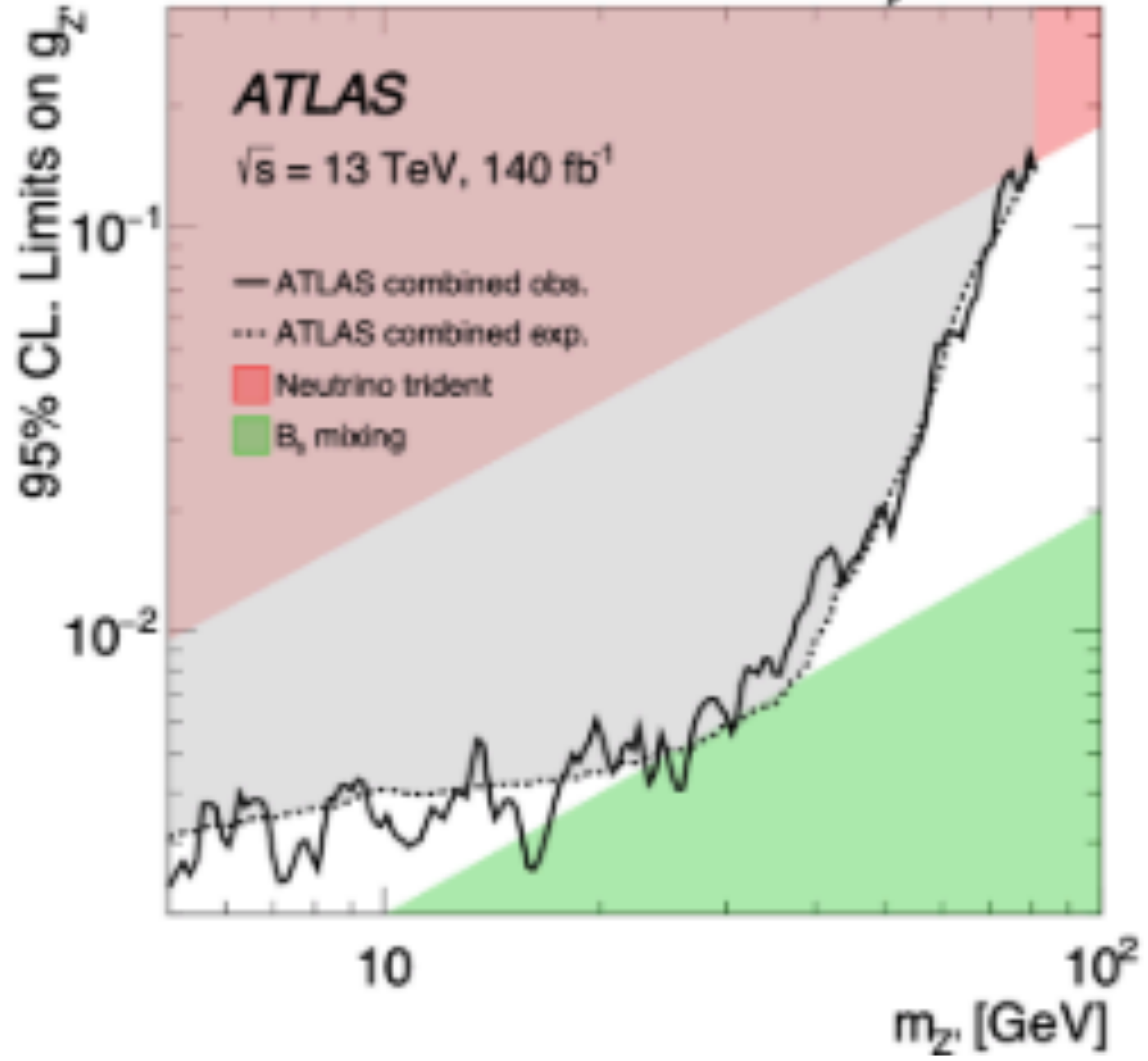
- Target: Z′ from $U(1)_{L\mu-L\tau}$ only coupling to 2nd and 3rd gen. leptons
- Dominant bkg: $q\bar{q}' \rightarrow W(Z/\gamma^*) \rightarrow \ell^\pm \nu \ell^\mp \ell^\pm$
- Single parameterised Deep NN trained for various mass hypotheses
- Combination with ATLAS result from 4-lep (slightly better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







Combination of 3l+4l



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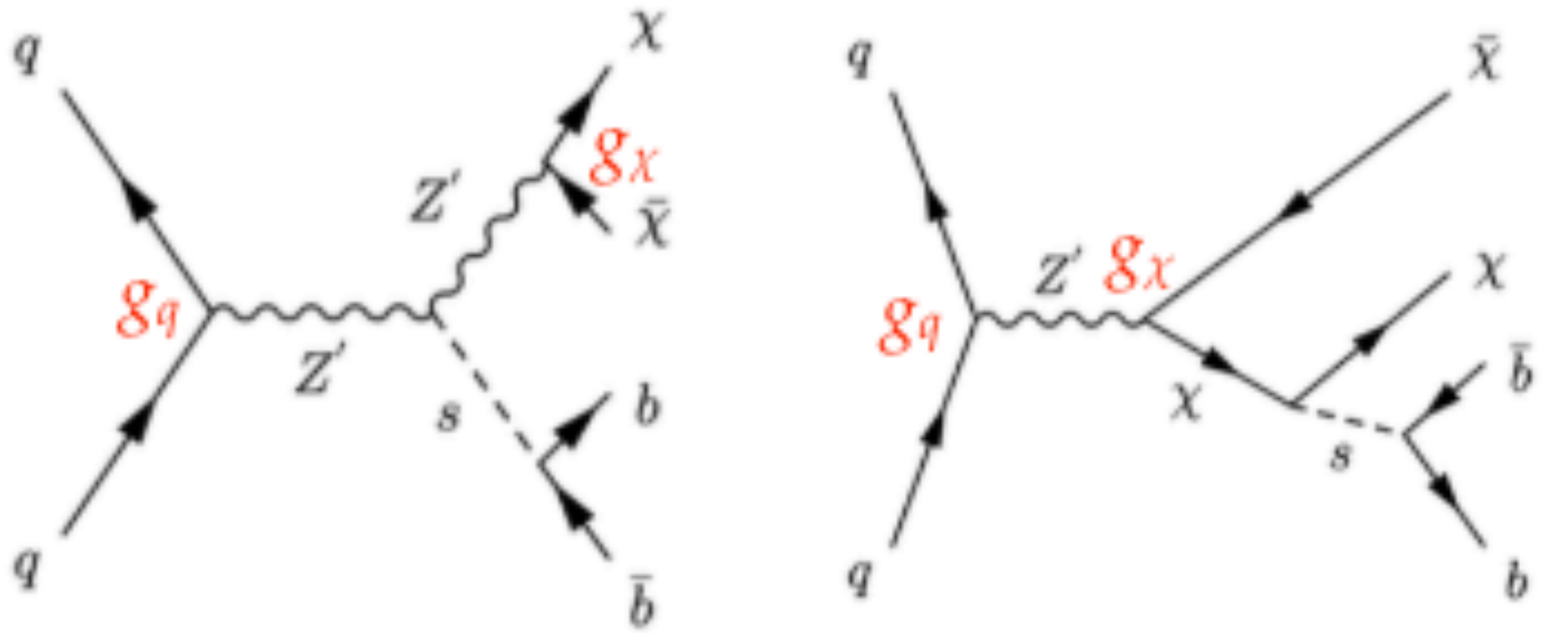
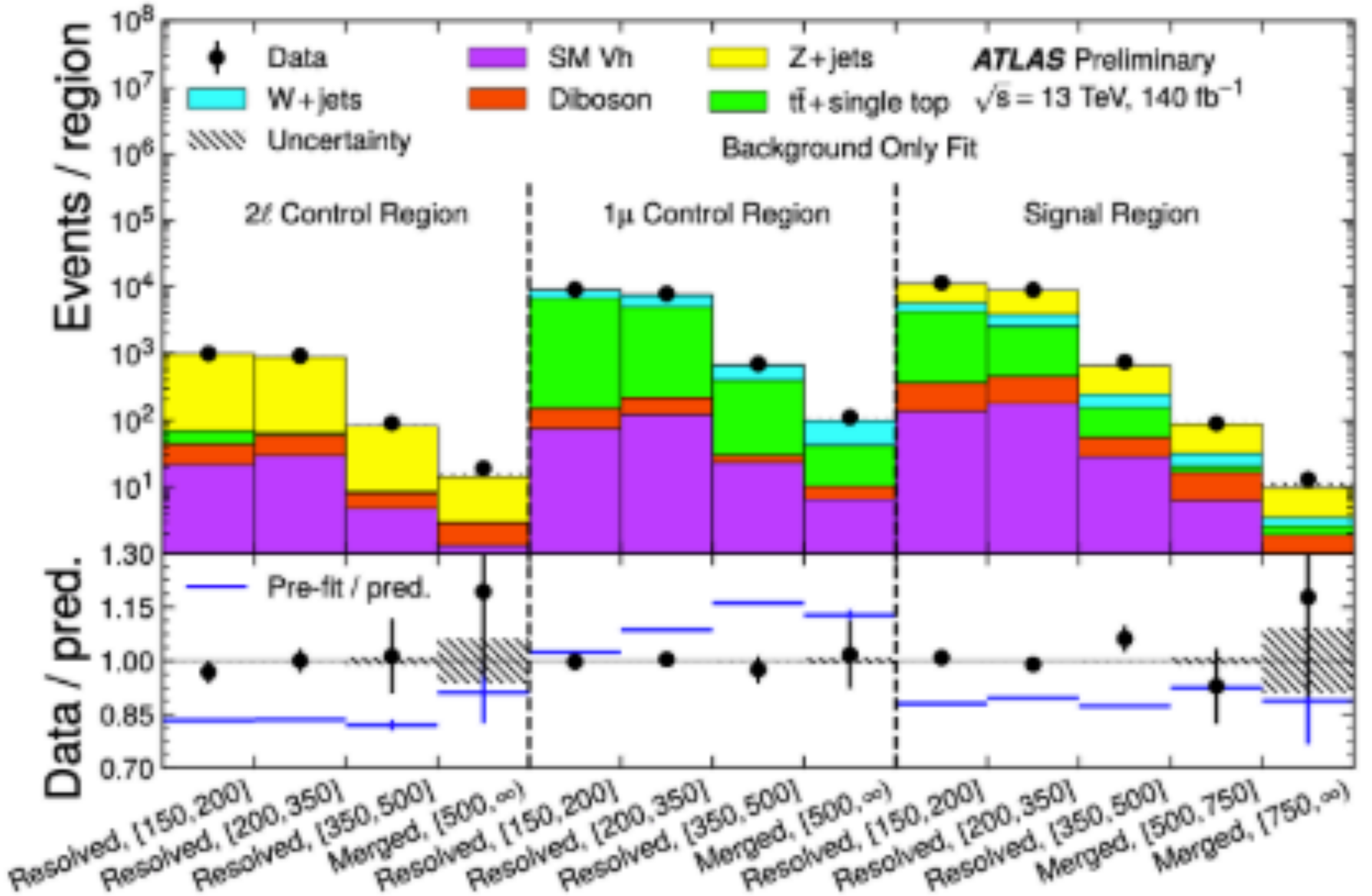
Mono S(bb)

- 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 < MET < 500 GeV) and merged (MET > 500 GeV) SRs
- Using **optimised X → bb tagging** [ATL-PHYS-PUB-2020-019] in boosted SR (for m_{bb} > 50 GeV) … and DL1r for resolved and boosted SR (m_{bb} < 50 GeV)
- Control bkgs in 1- and 2-lepton CRs
- No excess: Limits in three different scenarios …



MET bins →



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Mono S(bb)

Scenario 1 ("conventional")

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

Scenario 2

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

Scenario 3

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

Tune g_χ to get $\Omega h^2 = 0.12$