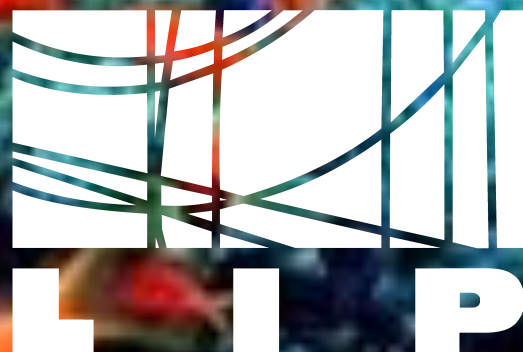


EXOTICS SEARCHES IN ATLAS

Rute Pedro, on behalf of the ATLAS Collaboration
BSM 2023: from Theory to Experiment, 6-9 November Urghada, Egypt



Acknowledgements: CERN/FIS-PAR/0010/2021 | 2021.01023.CEECIND



Exotics searches in ATLAS

Searches for New Physics is one of the **primary motivations of the LHC Physics** program

BSM physics needed to **address SM shortages** (eg. hierarchy problem, Dark Matter, matter/anti-matter asymmetry)

New physics **probed indirectly** (precise SM measurements) and directly by **searching for new particles**

This talk: overview of **direct searches for New Physics using full Run 2 LHC data collected by ATLAS**

- **Dark matter** in invisible or unconventional signatures
- **Vector-like quarks** and **leptoquarks**
- Generic **resonances**

Other ATLAS talks: **top physics, **SM** results, **Higgs** measurements and **SUSY** searches**

Dark Matter searches

Important ATLAS/LHC search program, complement direct/indirect detection

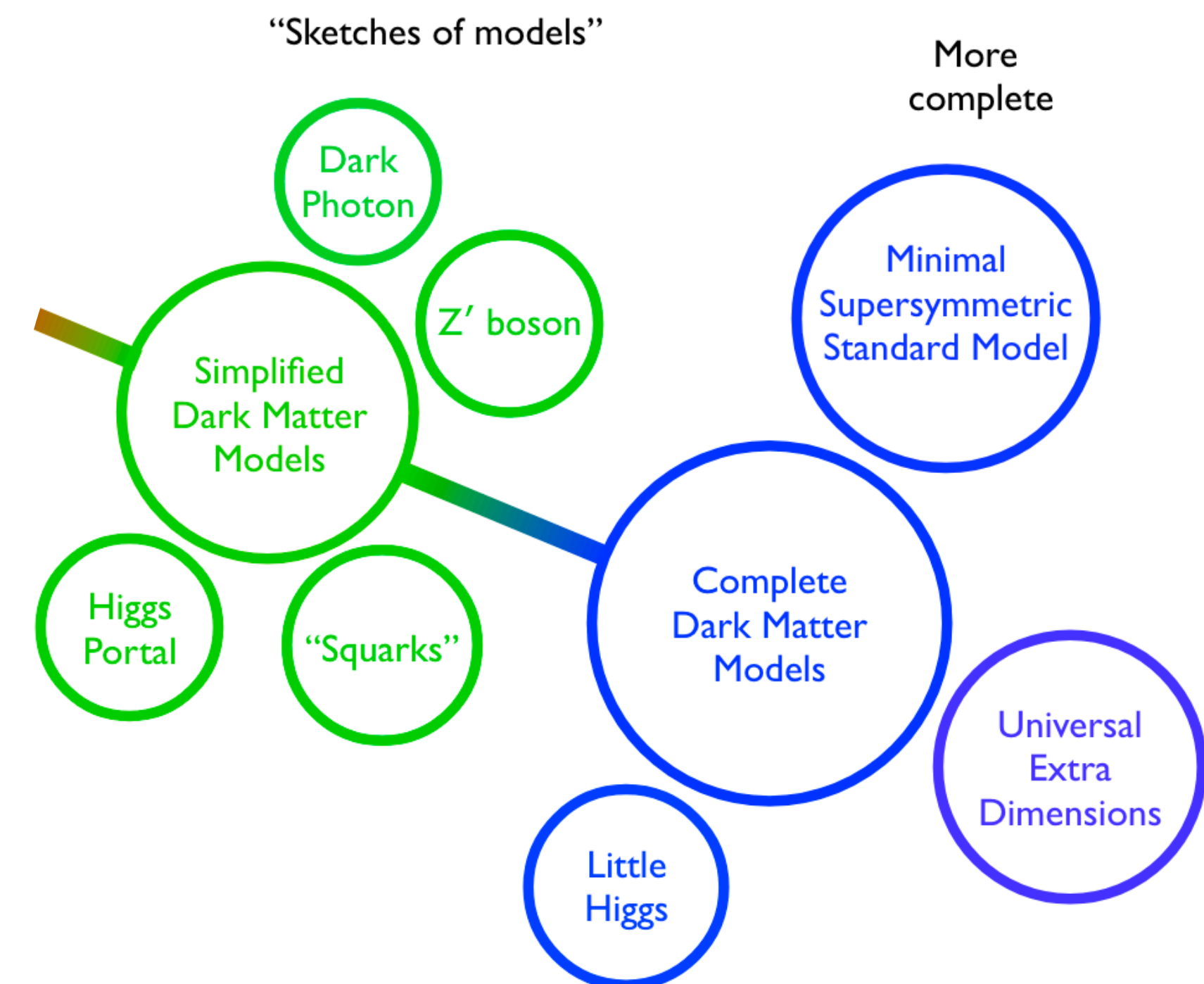
DM production at colliders yield final states with undetected particles: \cancel{E}_T

Simplified DM models searches: mediator coupling DM particle to SM matter

- **Mono- X (or $\cancel{E}_T + X$) topologies** or **mediator resonance**
- **Summary of a wealthy set of Run 2 results:** [ATL-PHYS-PUB-2023-018](#)
- Recent $Z' + \cancel{E}_T$ result: [ATLAS-CONF-2023-045](#)

Search for **unconventional DM signatures**

- New dark sectors, dark hadrons, long-lived particles,...



Combination of 2HDM+a DM searches

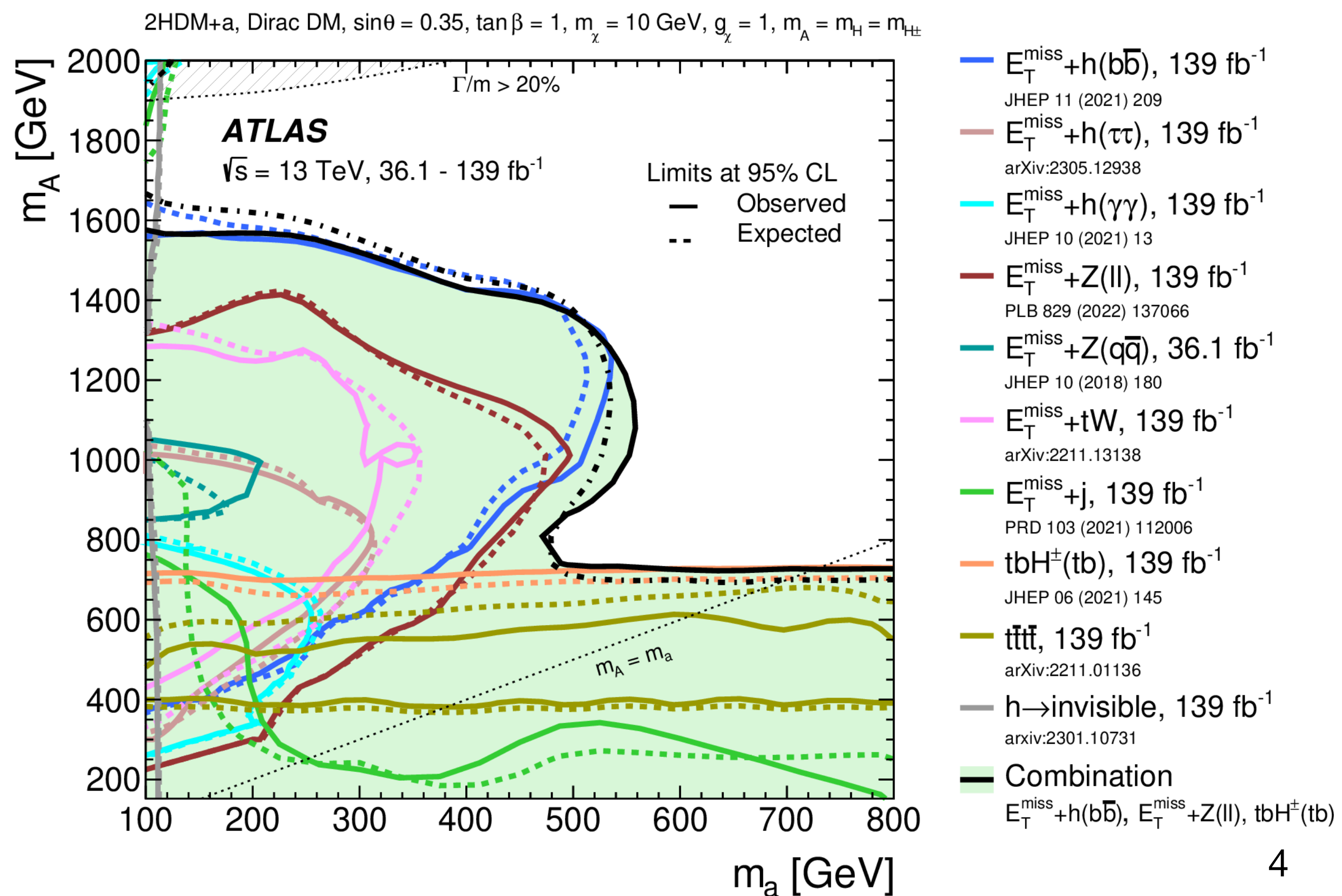
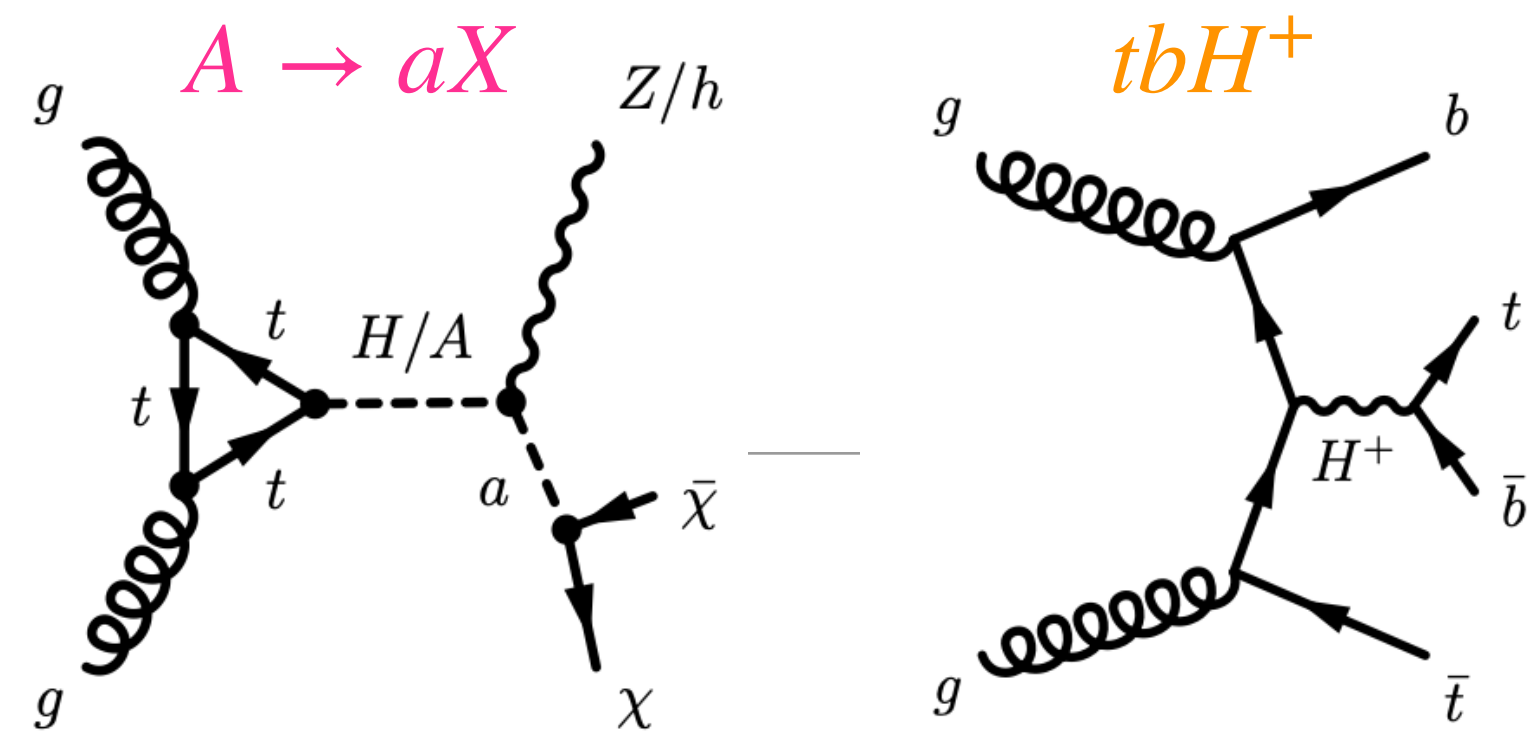
ATL-PHYS-PUB-2023-018, arxiv:2306.00641

Five new states: $\{H, H^\pm, A, a\}$, a mediates the interaction between the SM and a fermion DM candidate χ

Wide range of searches used to constrain 2HDM+a parameters, with $m_H = m_{H^\pm} = m_A$

Statistical combination of the three most sensitive analyses

- $A \rightarrow aX$ production: $E_T + X$ final states place strong limits in the (m_A, m_a) plane
- tbH^+ search sets a 700 GeV upper limit on m_A , quasi-independently on m_a



Dark quarks in di-jet final states

ATLAS-CONF-2023-047

Dark QCD sector hadronising to dark hadrons (DM candidates)

Dark hadron decay type lead to semi-visible jets, emerging jets,...

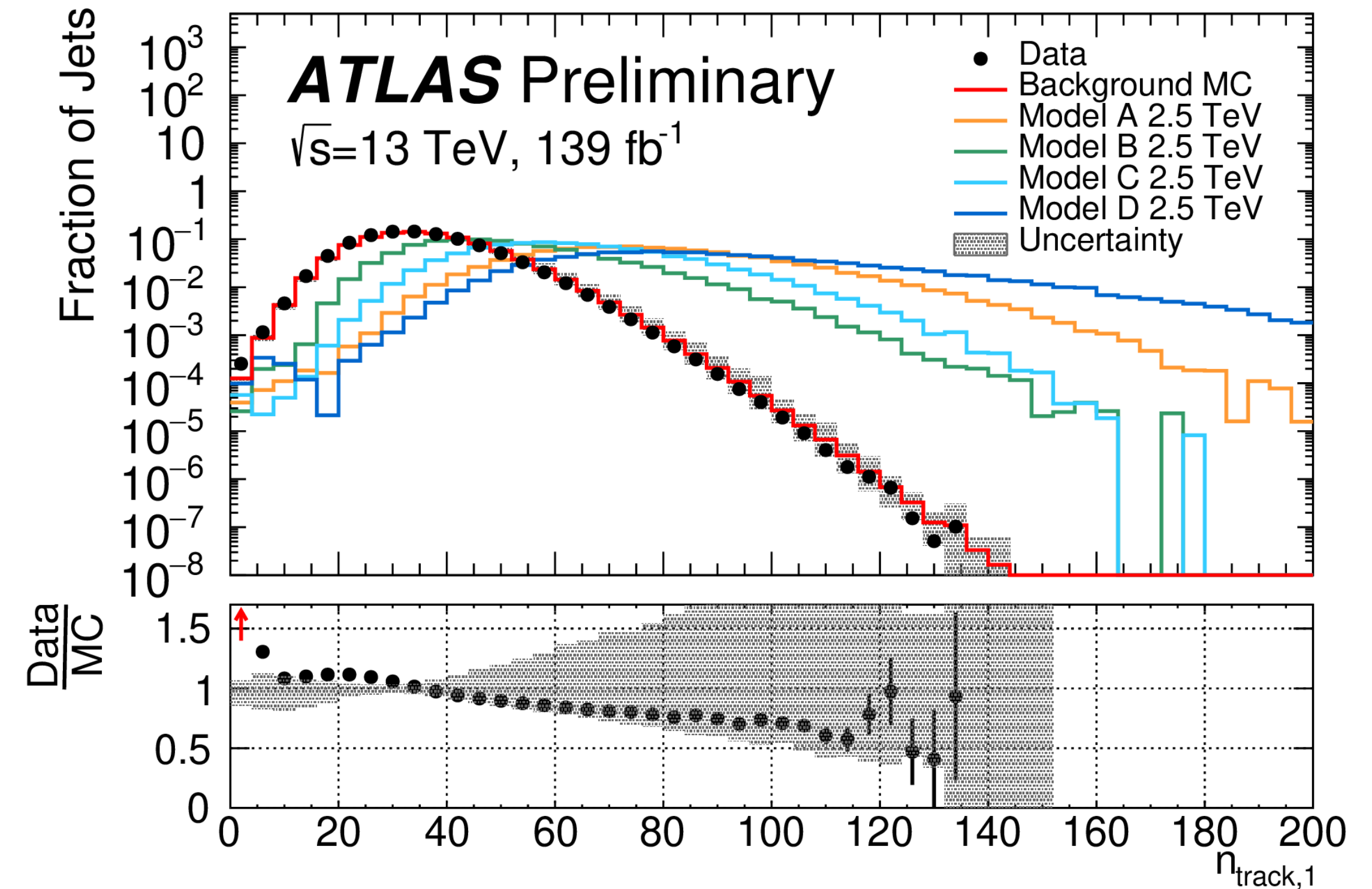
Number of tracks in leading jet

Search for di-jet final state of $Z' \rightarrow q_d \bar{q}_d$

- Wider jets due to SM and Dark hadronic components
- Jets with higher particle multiplicity

Four benchmark models (A,B,C,D) differing on dark quark/hadrons masses and dark confinement scale

Dominant QCD background determined from data



Results

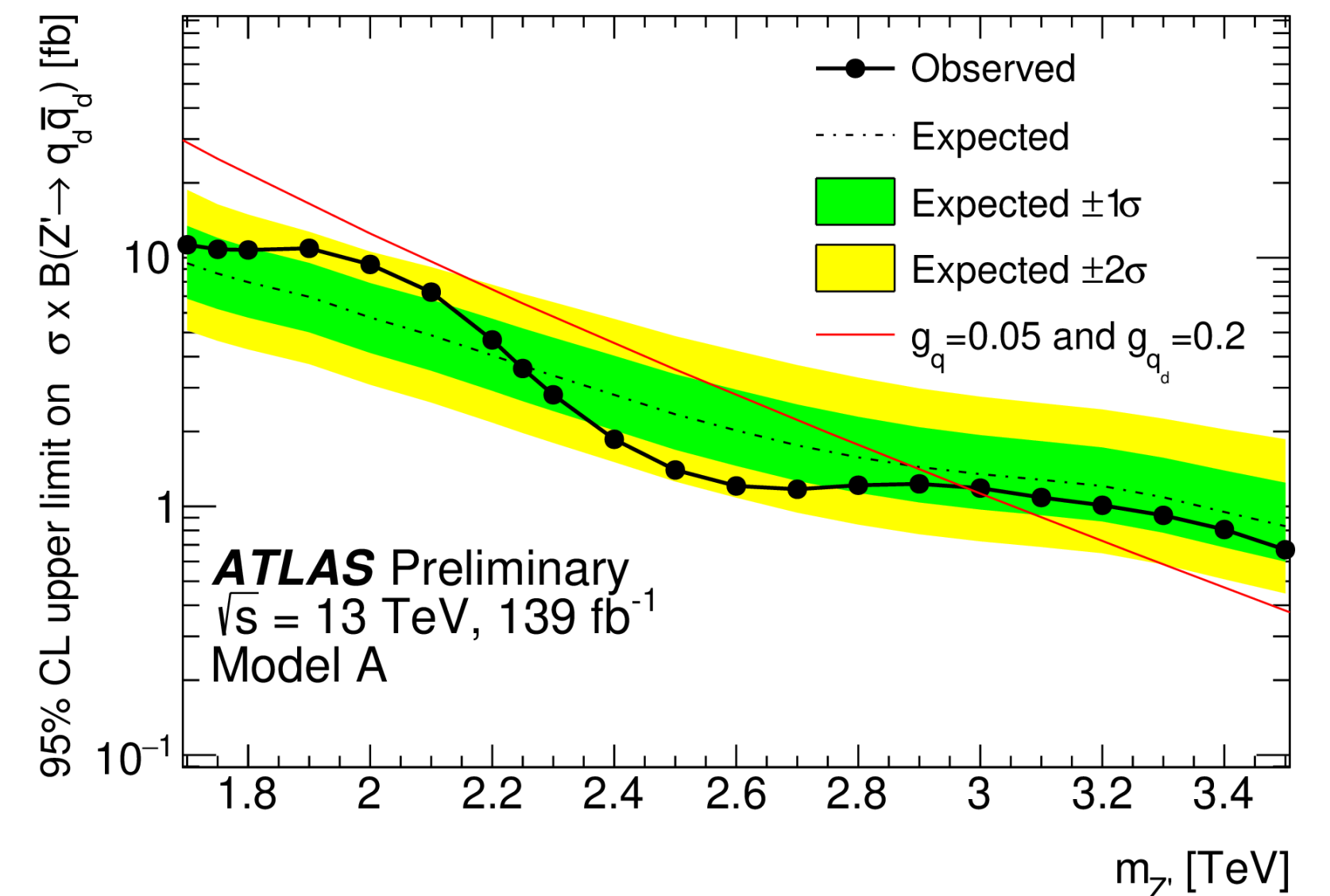
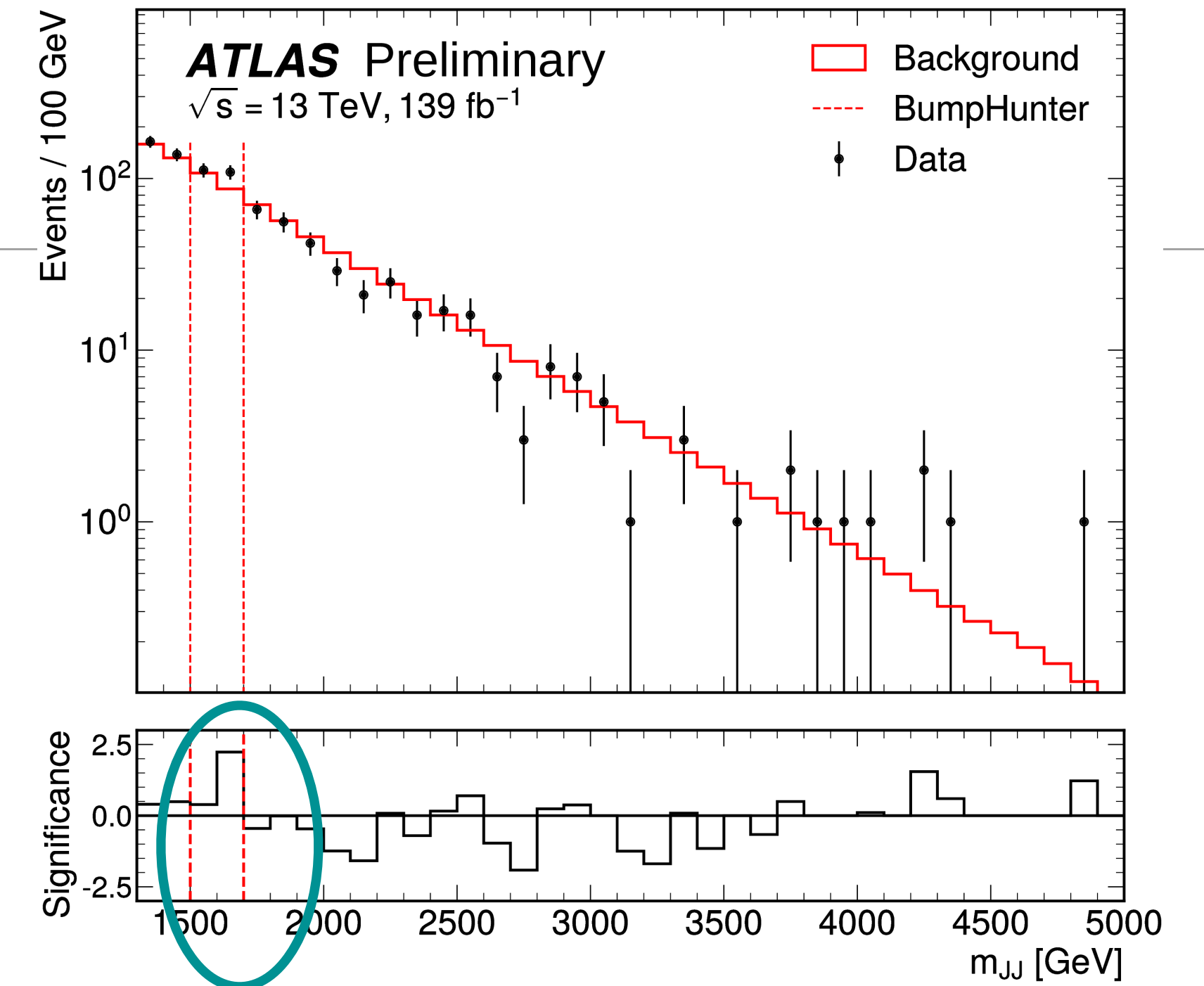
ATLAS-CONF-2023-047

Bump hunt in the invariant mass spectrum of the two large-R jet system

- Analysis probes $m_{JJ} \in [1300, 4800]$ GeV
- Larger data excess at ~ 1600 GeV (2σ)

Exclusion limits on $m_{Z'}$

- Dependent on the model type and coupling parameters
- Strongest limit: $m_{Z'} > 3$ TeV (model A)



Light long-lived photons from Higgs decays

ATLAS-CONF-2023-051

Dark sector accessible through Higgs portal

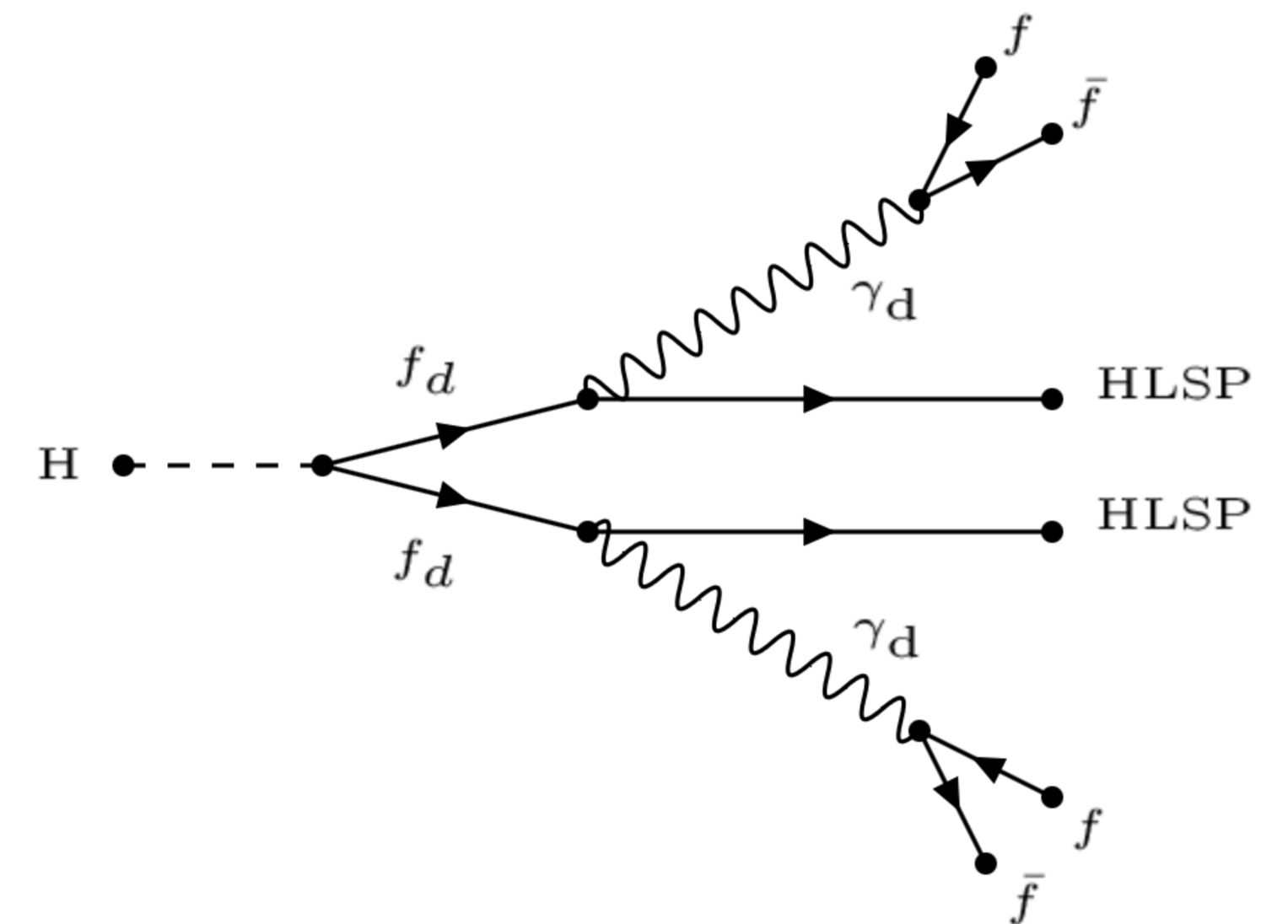
Search for Higgs decay to dark fermions originating dark photons

Dark photons with macroscopic decay length lead to displaced collimated group of fermions

Cosmic ray muons, beam induced backgrounds and prompt jets mitigated with dedicated neural network classifiers

Dark photon jets

Muon jets or calorimeter jets without inner tracks



Results

ATLAS-CONF-2023-051

Upper limits on the Higgs decay to dark photons BR as a function of the γ_d proper decay length

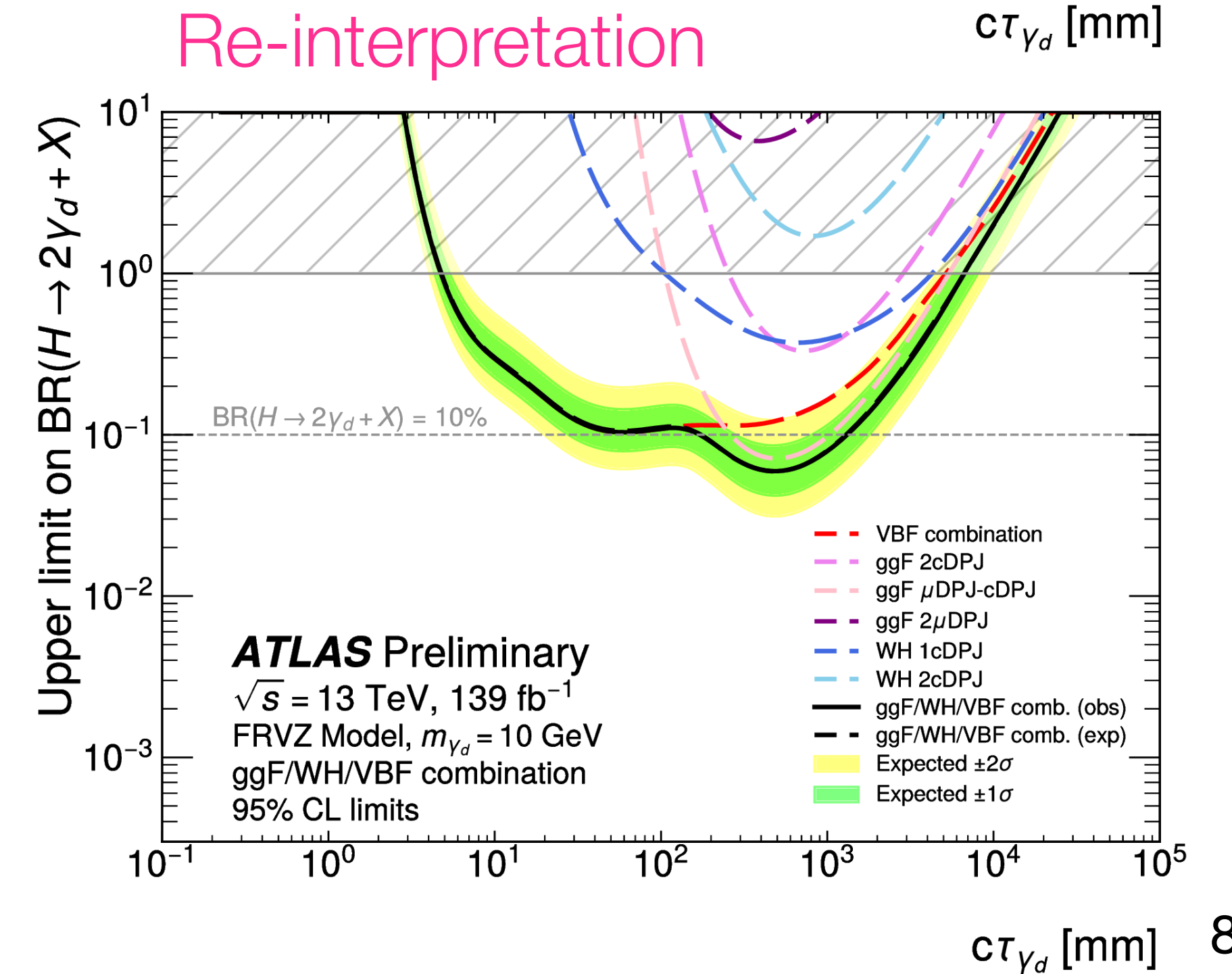
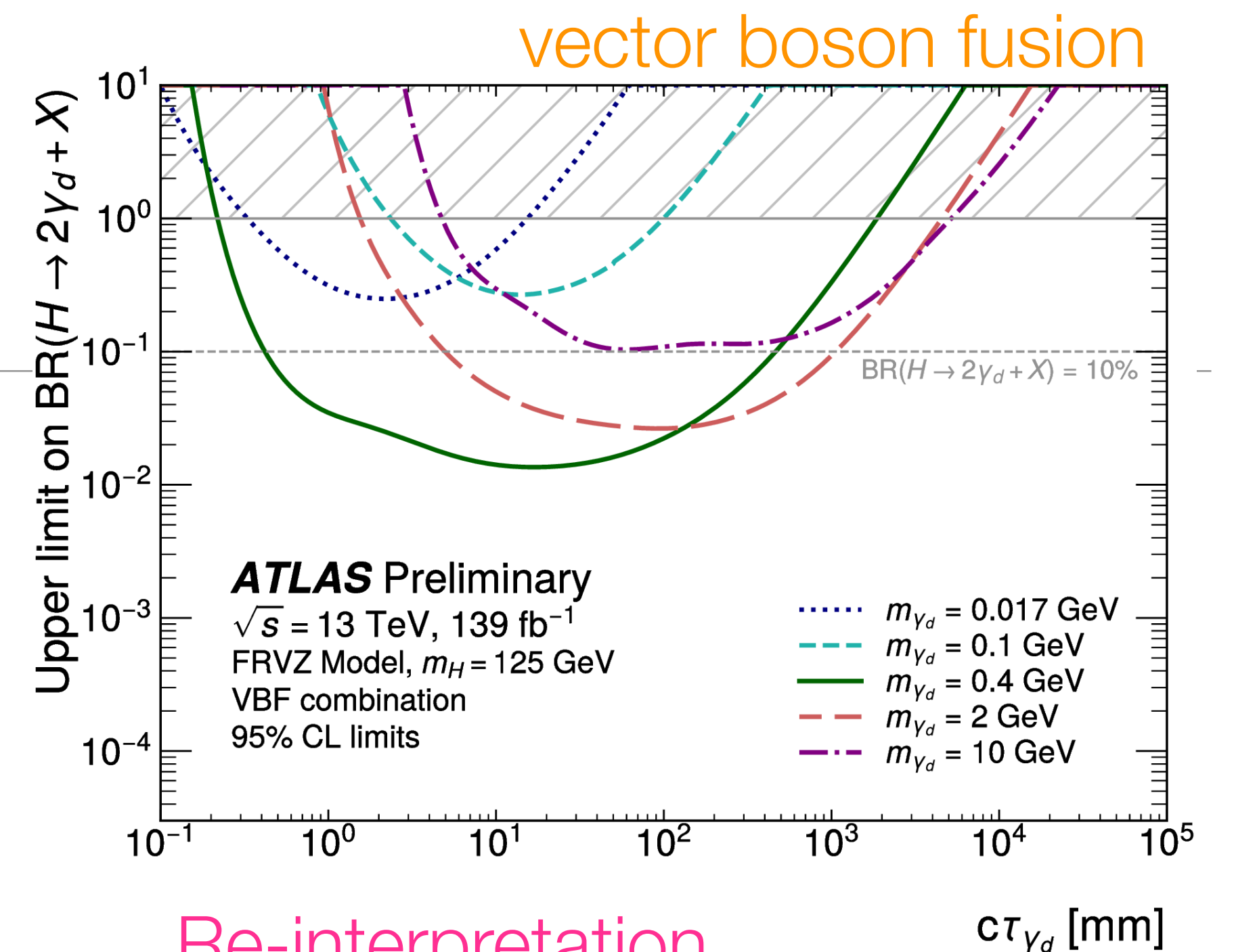
Search focus on Higgs vector boson fusion production

Re-interprets results from other Higgs production modes

- BR > 10% excluded for γ_d with decay length between 173 and 1296 mm

Other recent results on Higgs portal:

- $H \rightarrow inv$ combination, probes small DM masses
[arxiv:2301.10731](https://arxiv.org/abs/2301.10731)



Vector-like Quarks

Postulated as $(T^{2/3}, B^{-1/3}, X^{5/3}, Y^{-4/3})$ isospin singlets, doublets or triplets

- **Pair production** by strong interaction dominates for $m_Q \lesssim 1$ TeV: $\sigma_{Q\bar{Q}} = f(m_Q)$
- **Single production** via electroweak vertex, significant at high mass, **scales with couplings to SM** and multiplet model

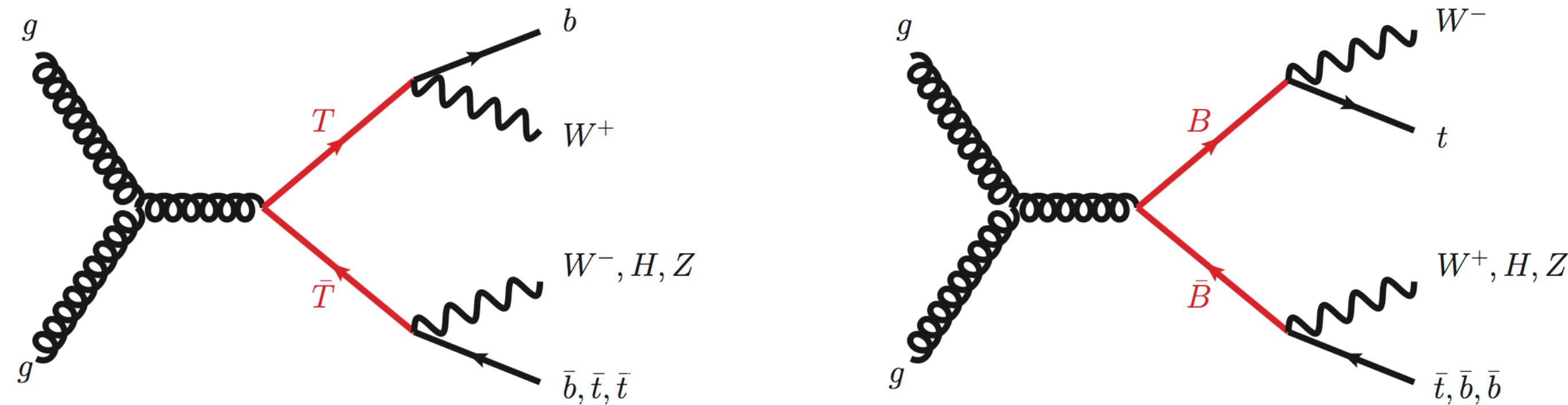
VLQs assumed to **decay to 3rd generation SM quarks** via charged and neutral currents

- $T \rightarrow Zt/Ht/Wb, B \rightarrow Zb/Hb/Wt$
- **BR not fixed** by theory: regulated by (ξ_Z, ξ_W, ξ_H) parameters dependent on multiplet model

All possible VLQ decays searched in many final states

VLQ Pair production in lepton+jets final states with at least 1 b -jet

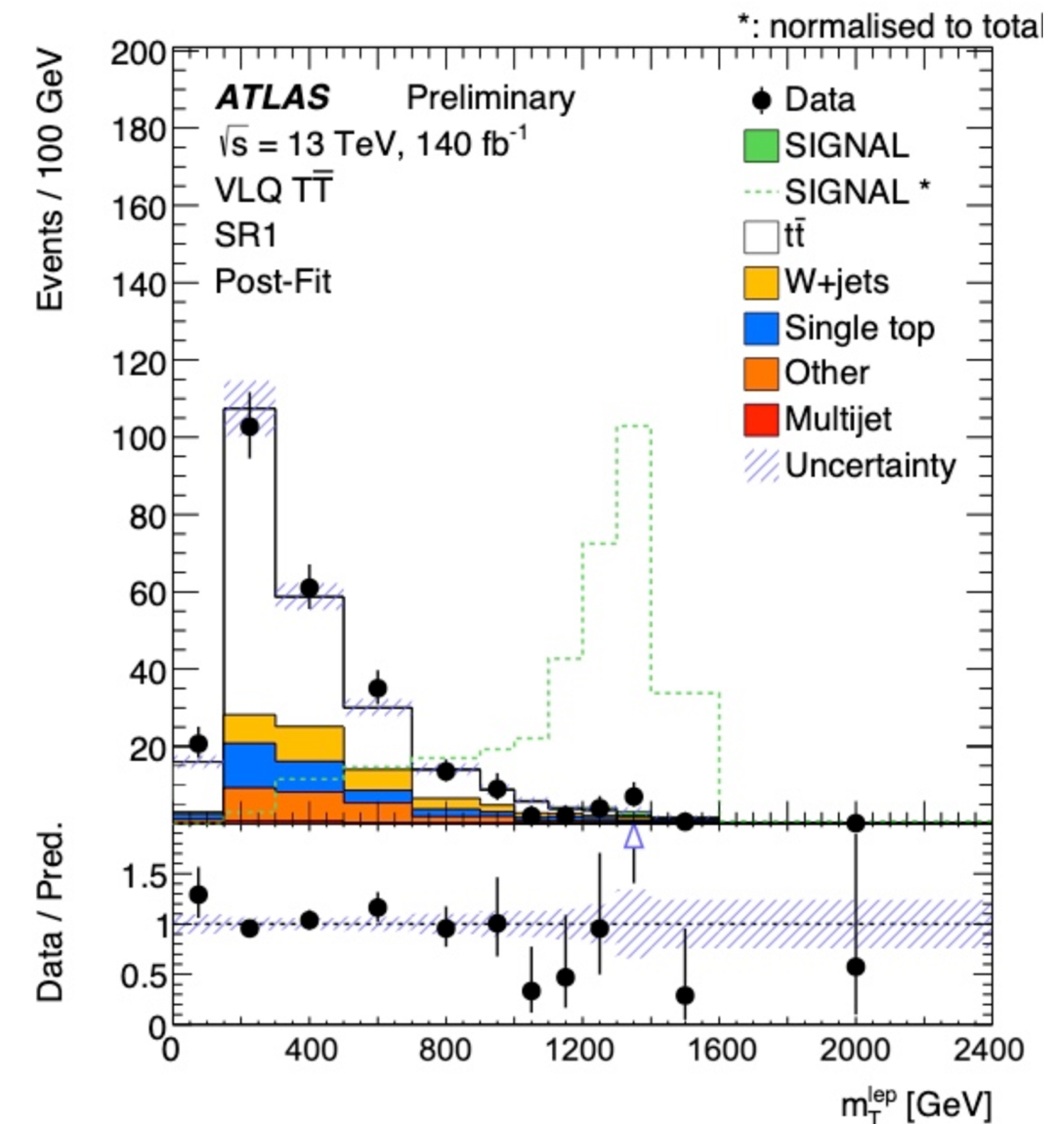
ATLAS-CONF-2023-070



Optimised to $T \rightarrow Wb$ decay

Focus large m_Q not yet excluded, leads to collimated products

- One large-radius W -tagged jet (W hadronic decay)
- Other W decaying leptonically: m_T^{lep} used as discriminant



Results

ATLAS-CONF-2023-070

No significant excesses

$m_T > 1.70$ TeV with $\text{BR}(T \rightarrow Wb) = 1$

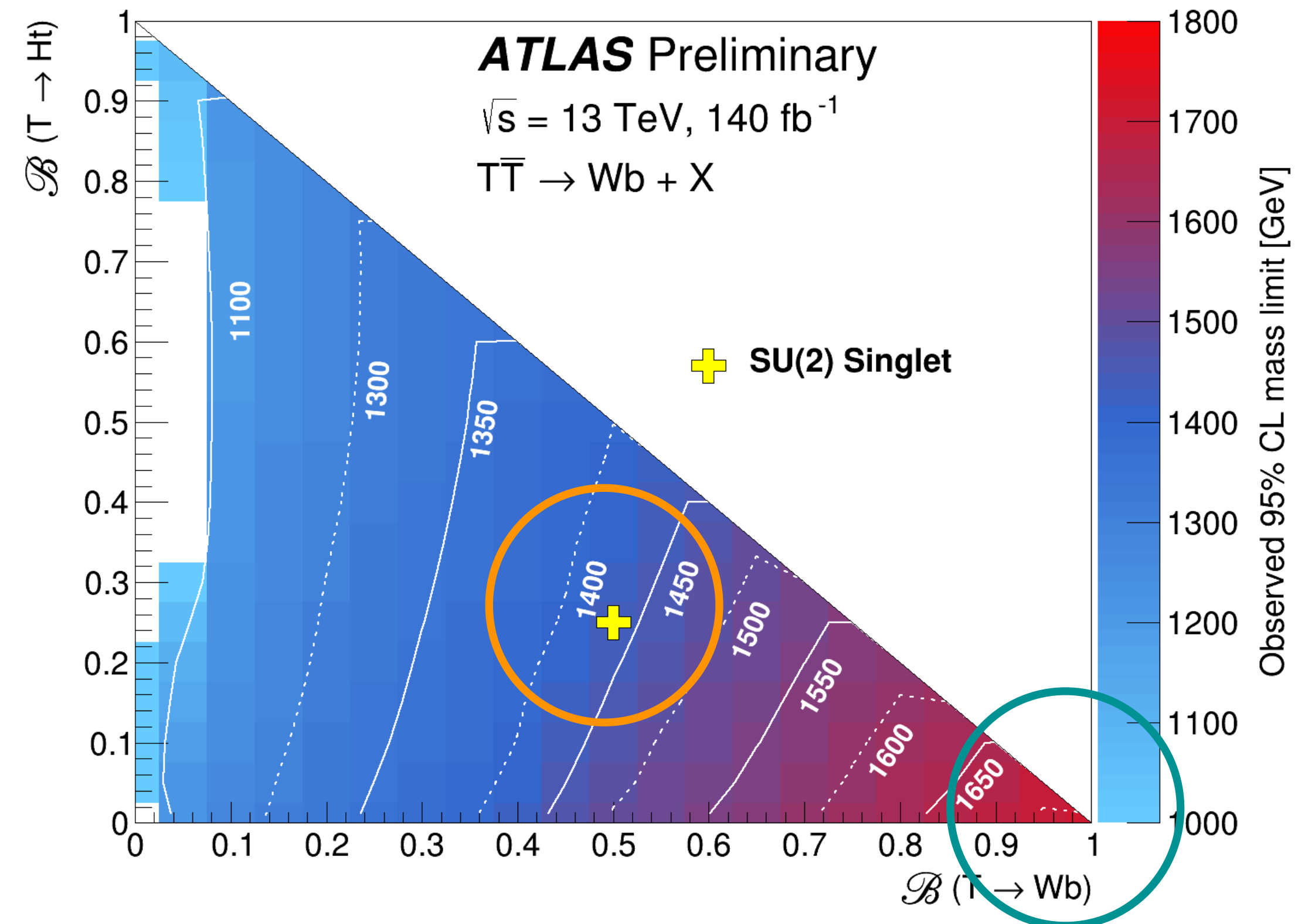
$m_T > 1.42$ TeV for SU(2) singlet BRs

Sensitivity limited by data statistics

- 250-350 GeV mass limit improvement wrt 36 fb⁻¹

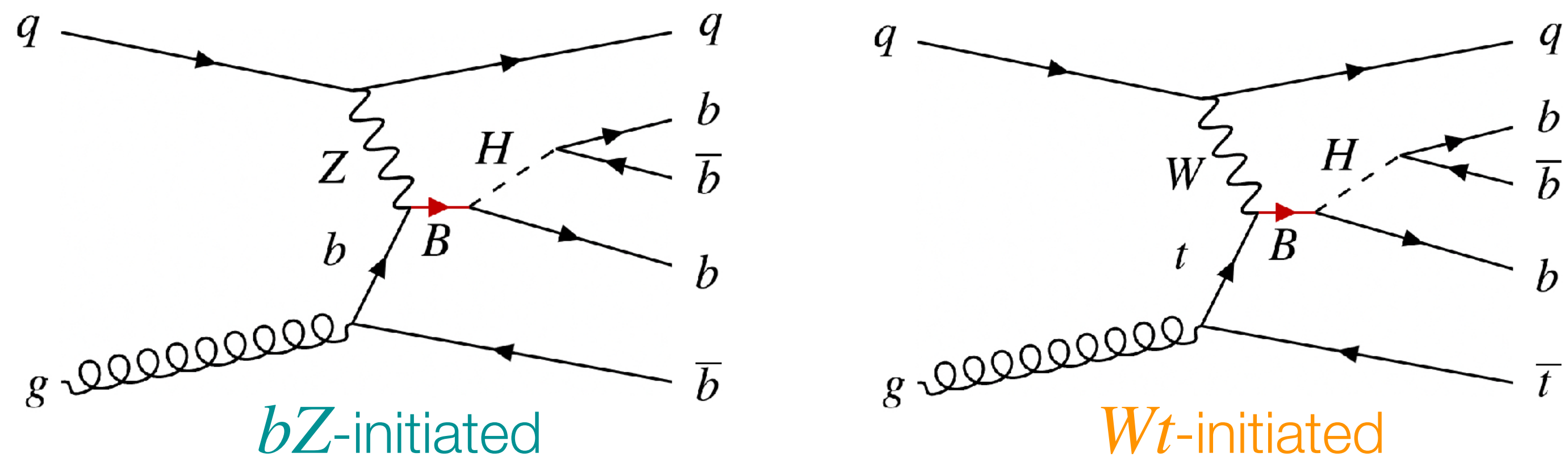
Other VLQ pair production results

- $Q \rightarrow Z(\ell\ell) + t/b$, [Phys. Lett. B 843 \(2023\) 138019](#)
- Large E_T , [Eur. Phys. J. C 83 \(2023\) 719](#)



Single VLB production with $B \rightarrow bH(b\bar{b})$

arxiv:2308.02595



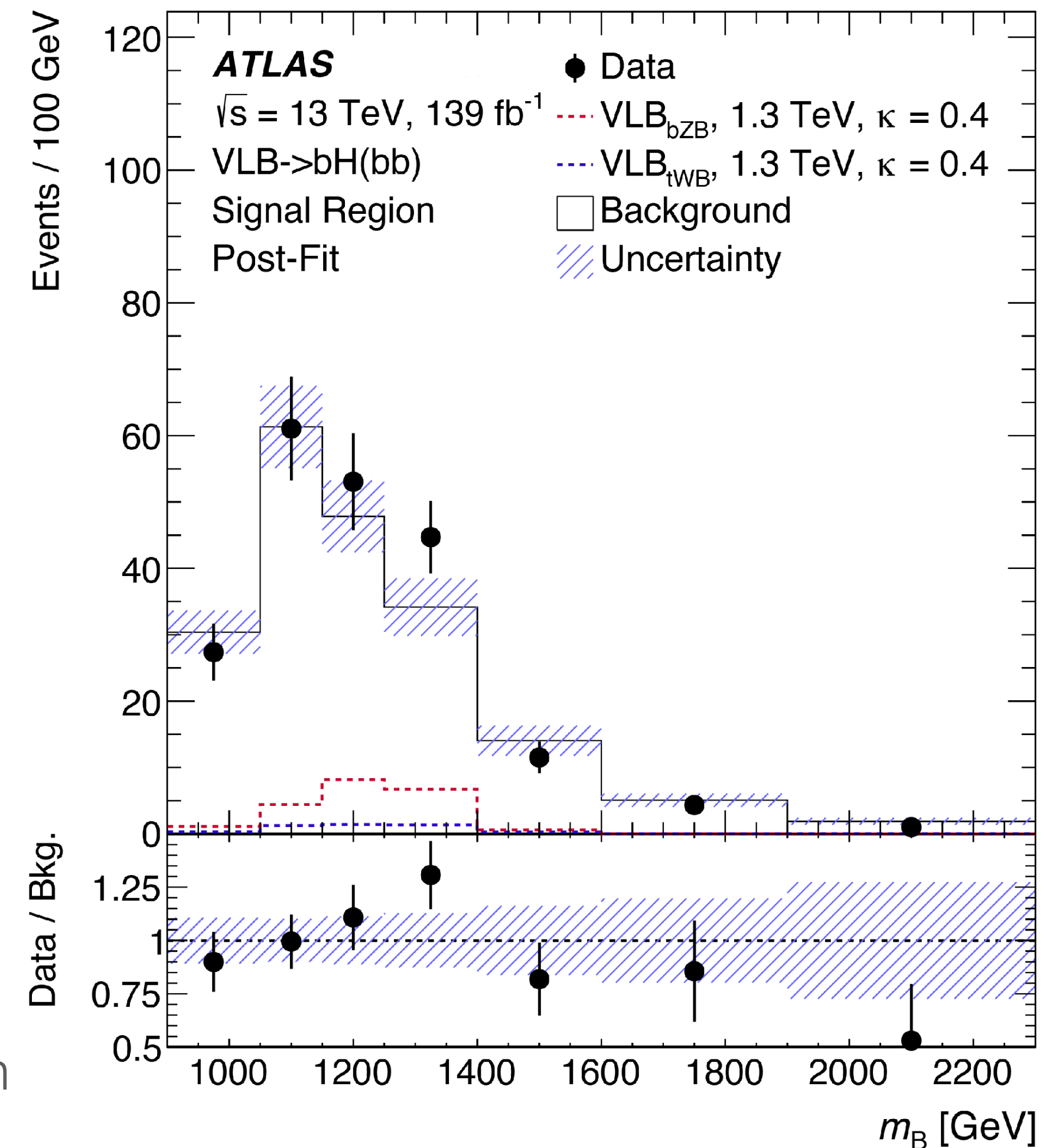
bZ initiated production dominant for B singlet model

Wt initiated diagram forbidden for (B, Y) doublet ($\xi_W = 0$)

Fully hadronic final state, $H \rightarrow b\bar{b}$ reconstructed as a large-radius jet

- m_B used as discriminant
- Overwhelming multijet background estimated with data-driven approach

Largest data/bkg discrepancy $m_B \sim 1.3$ TeV (local $p_0 = 0.06$)



Results

[arxiv:2308.02595](https://arxiv.org/abs/2308.02595)

Mass-dependent 95% CL upper limits for the B singlet and (B, Y) doublet production cross-section for various coupling values

B singlet

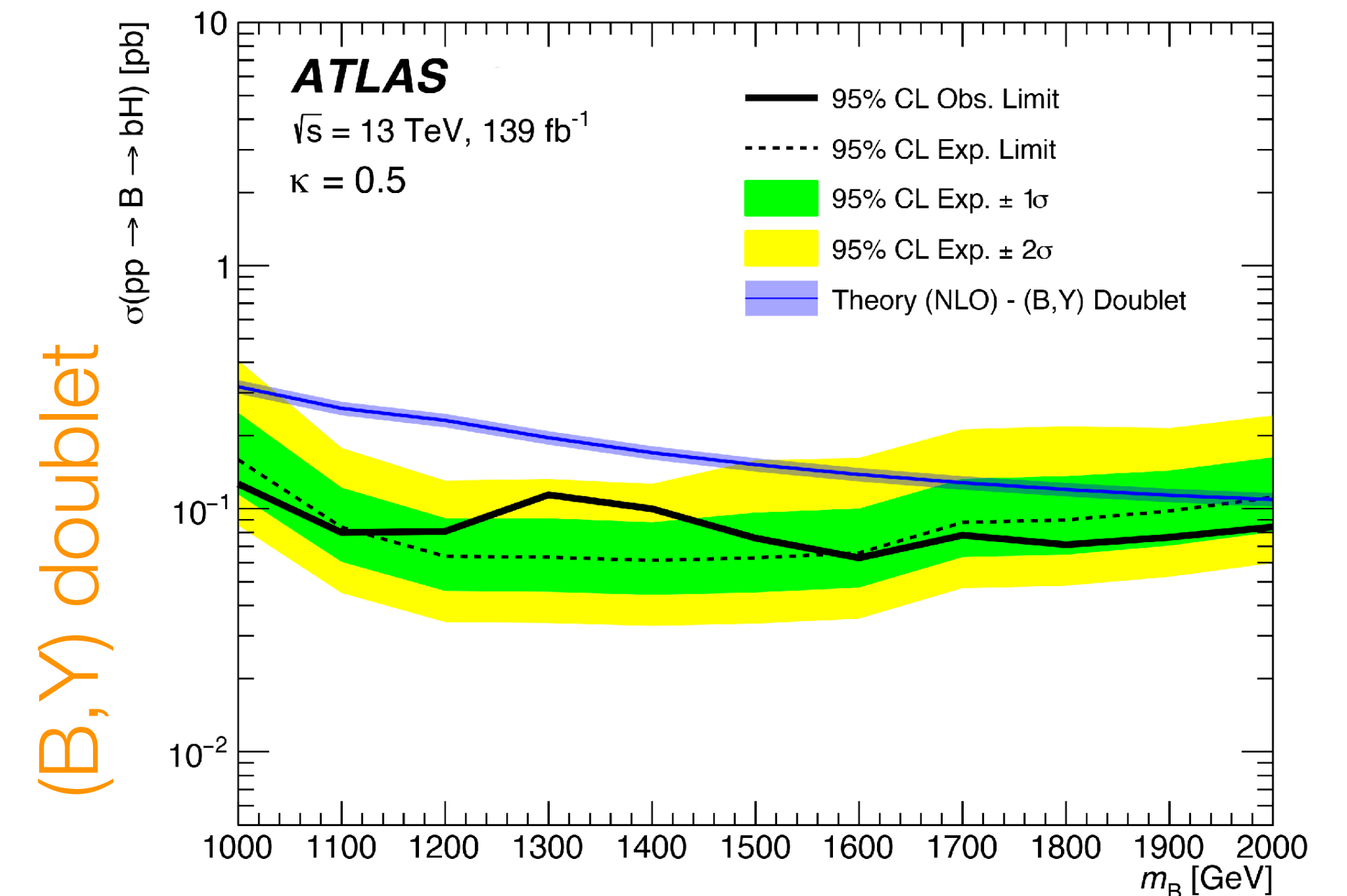
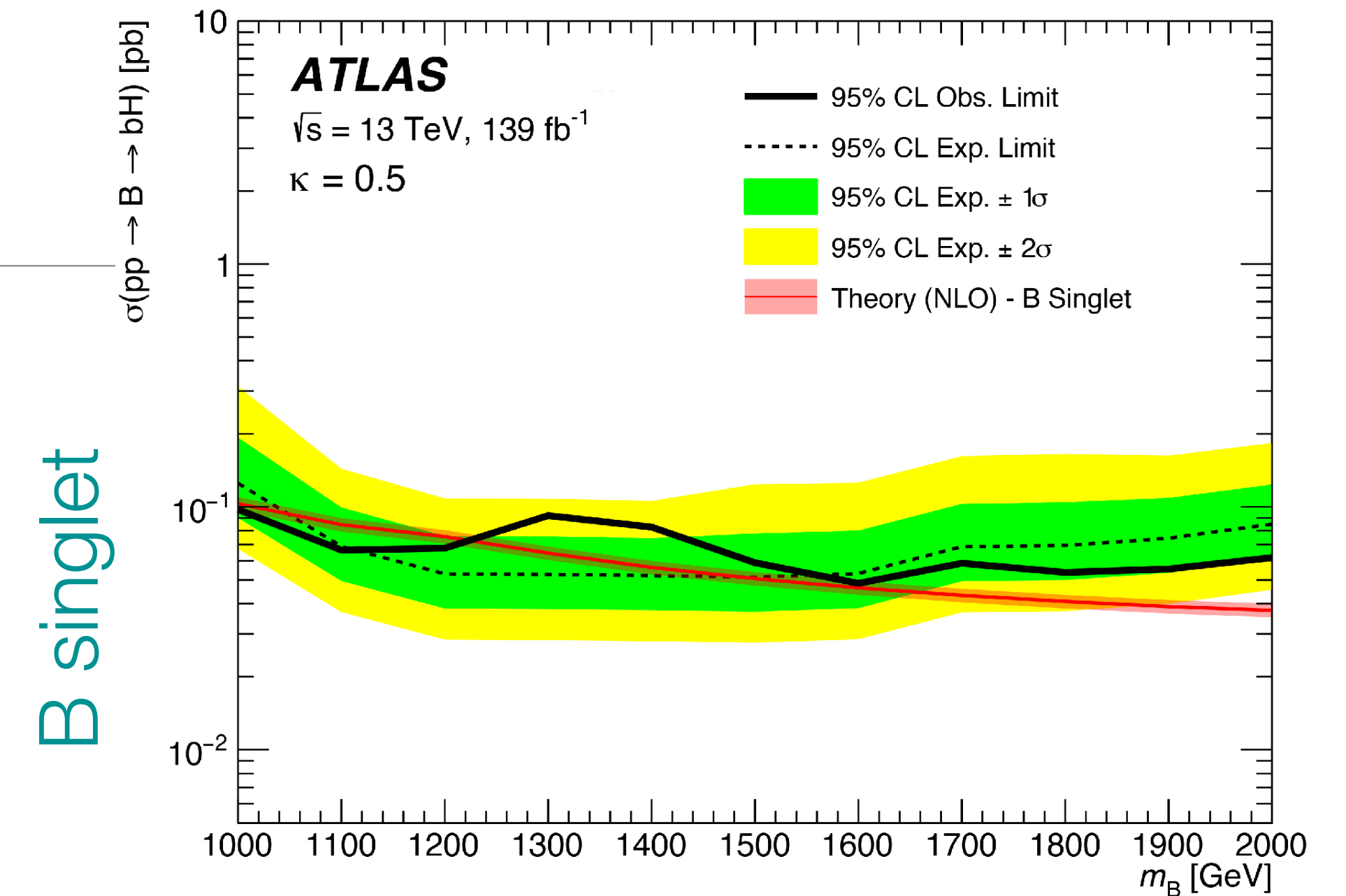
- $c_W < 0.45$ excluded for $1.0 < m_B < 1.3$ TeV
- $c_W < 0.50-0.65$ excluded for $1.2 < m_B < 2.0$ TeV

(B, Y) doublet

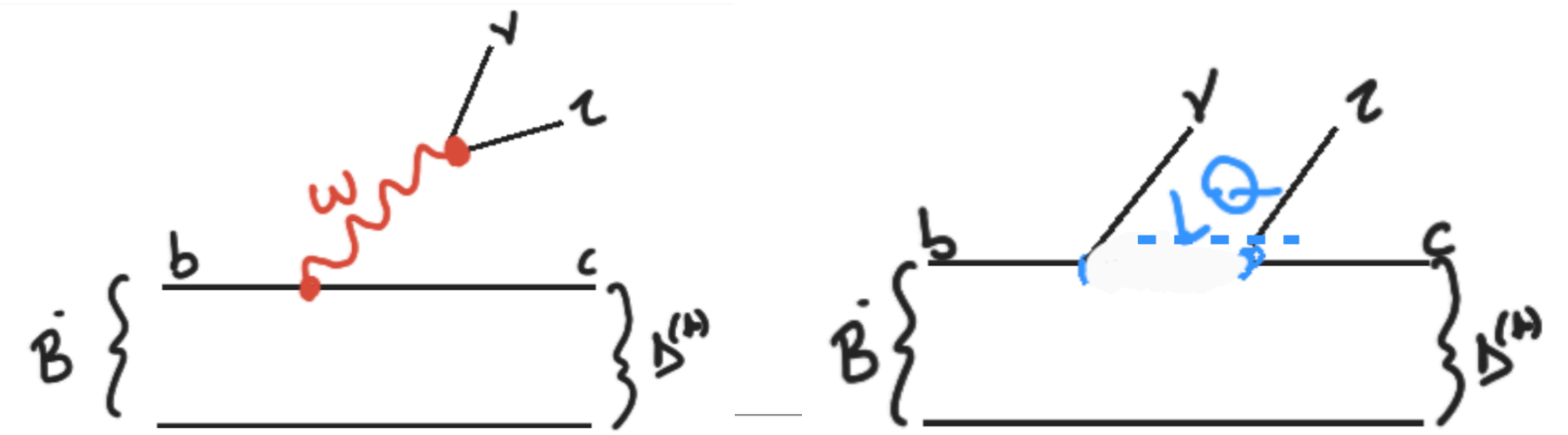
- $c_W < 0.3-0.5$ excluded for $1.0 < m_B < 2.0$ TeV

Recent results on single vector-like T production

- $T \rightarrow Ht/Zt$ [JHEP 08 \(2023\) 153](https://arxiv.org/abs/2308.02595)
- Final states with **opposite sign leptons** (targeting $T \rightarrow Zt$)
[arxiv:2307.07584](https://arxiv.org/abs/2307.07584)



Leptoquarks



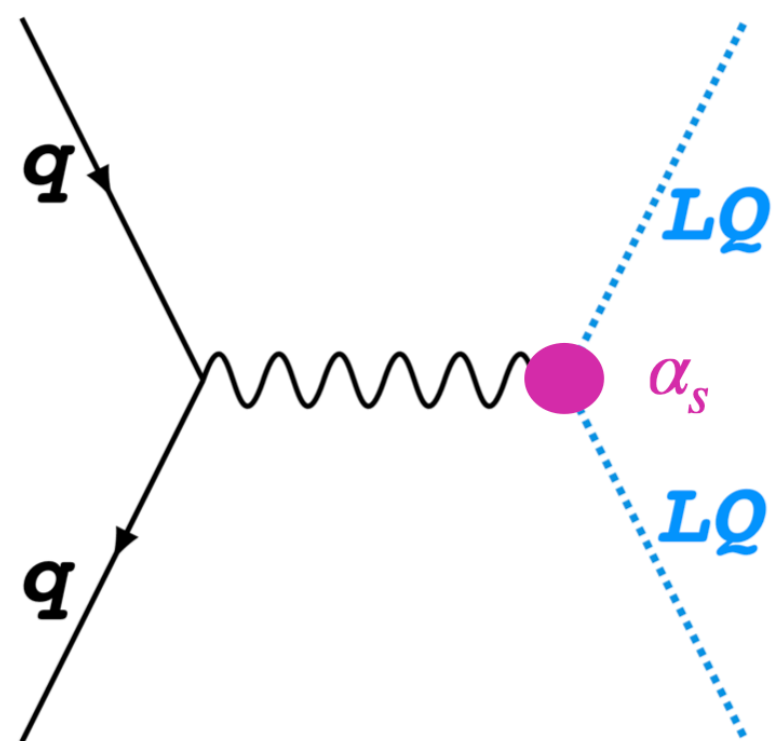
Color-triplet scalar or vector bosons with lepton and baryon number

Couple SM quarks and leptons directly through Yukawa λ interaction and can mediate lepton-flavour violation

Can explain B-anomalies and anomalous muon dipole moment $g_\mu - 2$, present in GUTs

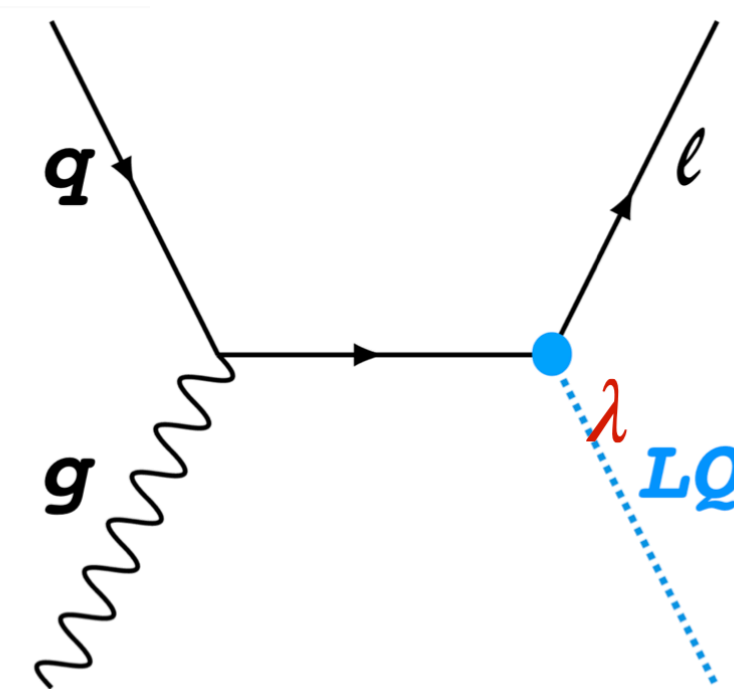
Rich phenomenology and many searches depending on decay combinatorial

Broad program of searches for pair production, single production starting to be searched too



Pair Production

Governed by QCD
 σ depends on m_{LQ}



Single production

σ proportional to λ^2

Summary of searches for Leptoquark pairs

ATL-PHYS-PUB-2023-006

Overlaid results on scalar LQ pair searches, [towards combination](#)

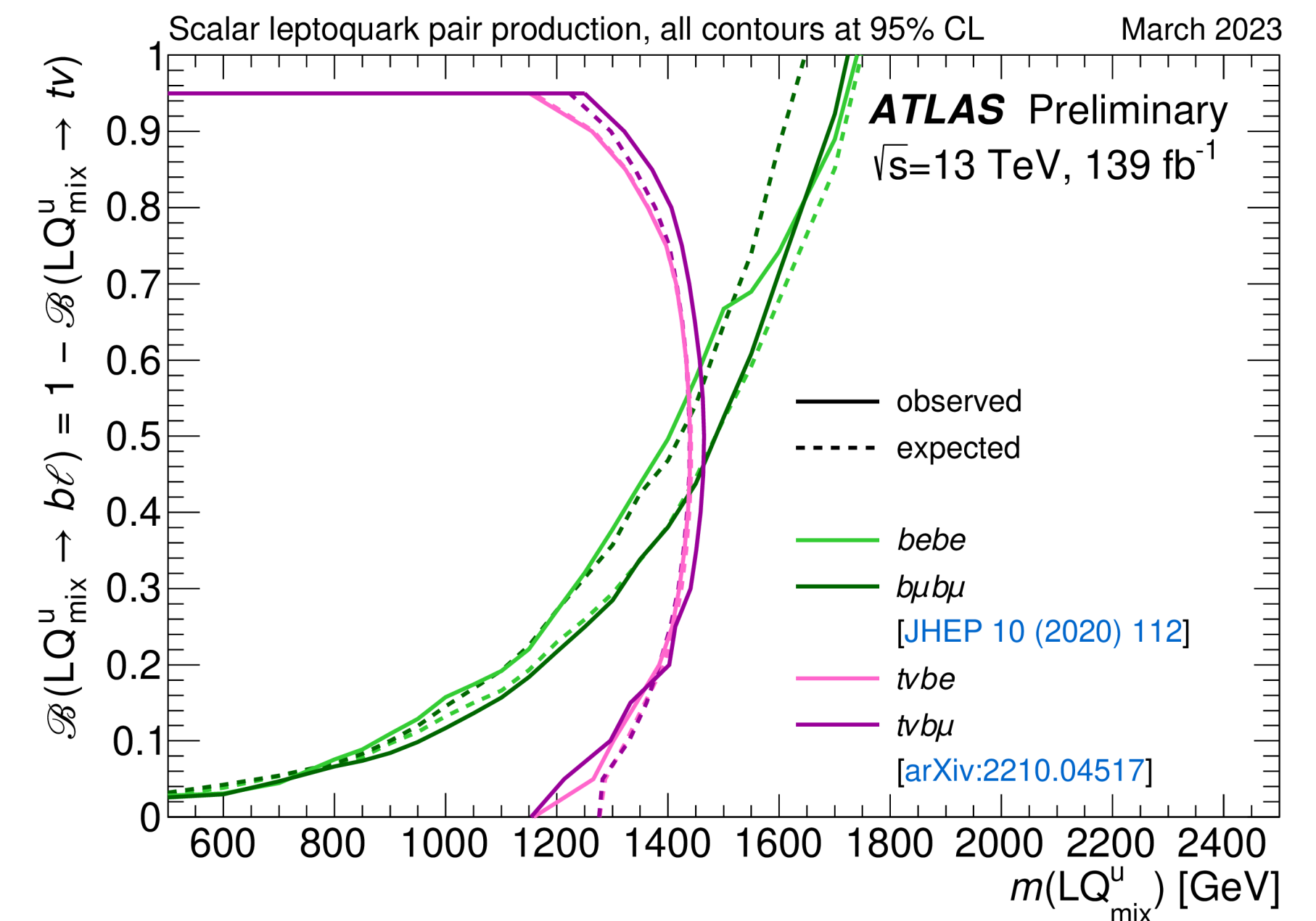
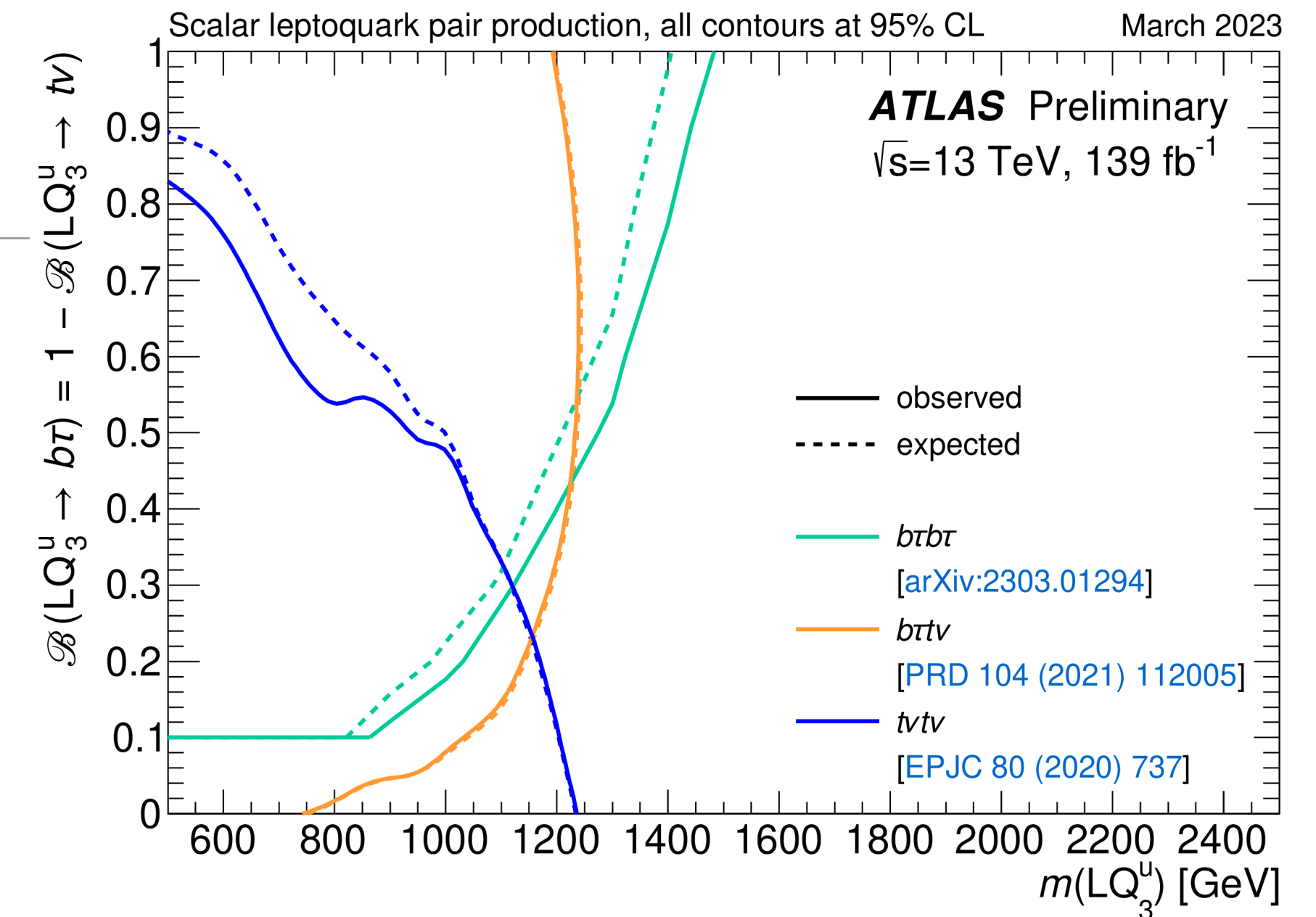
- From [dedicated LQ pair searches](#)
- [Re-interpretations](#) from searches for [pair produced SUSY particles](#)

[Up/down](#) type scalars, with two general [coupling scenarios](#)

- [3rd generation](#): couples quarks and leptons of the 3rd family
 - $LQ_3^u \rightarrow t\nu/b\tau$, $LQ_3^d \rightarrow b\nu/t\tau$
- [Mixed-generation](#): couples t, b - quarks with 2nd family leptons
 - $LQ_3^u \rightarrow t\nu/b\ell$, $LQ_3^d \rightarrow b\nu/t\ell$, with $\ell = e, \mu$

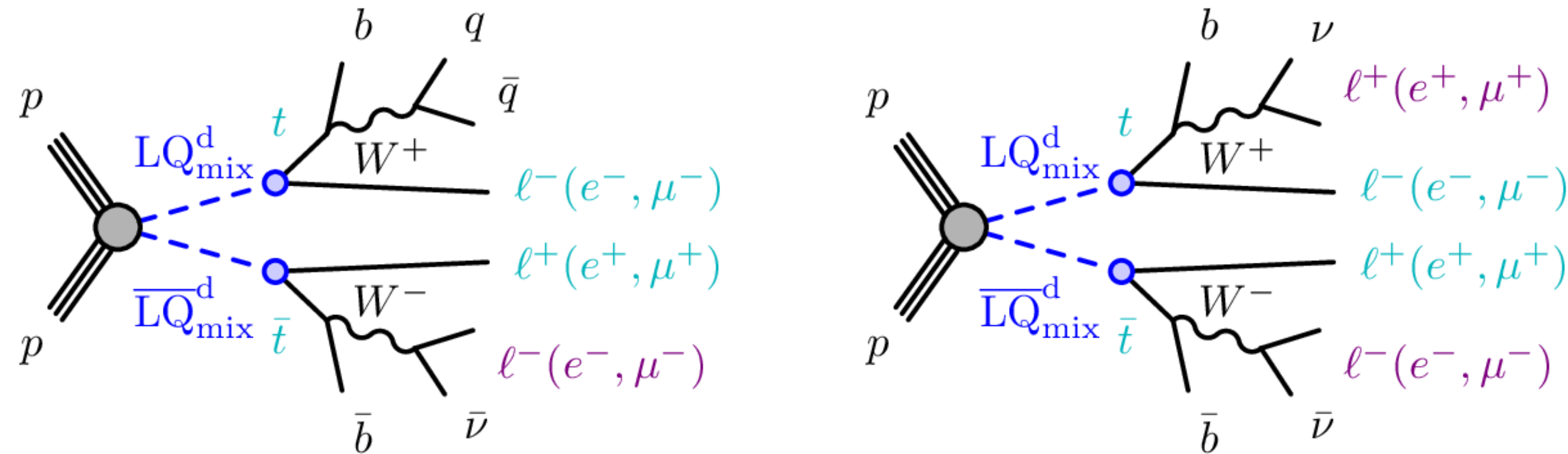
95% CL exclusion limits on BR as a function of the LQ mass

[Different final states](#) have [complementary sensitivity](#)



Leptoquark pairs decaying into $tete/t\mu t\mu$ in multi lepton final states

arxiv:2306.17642



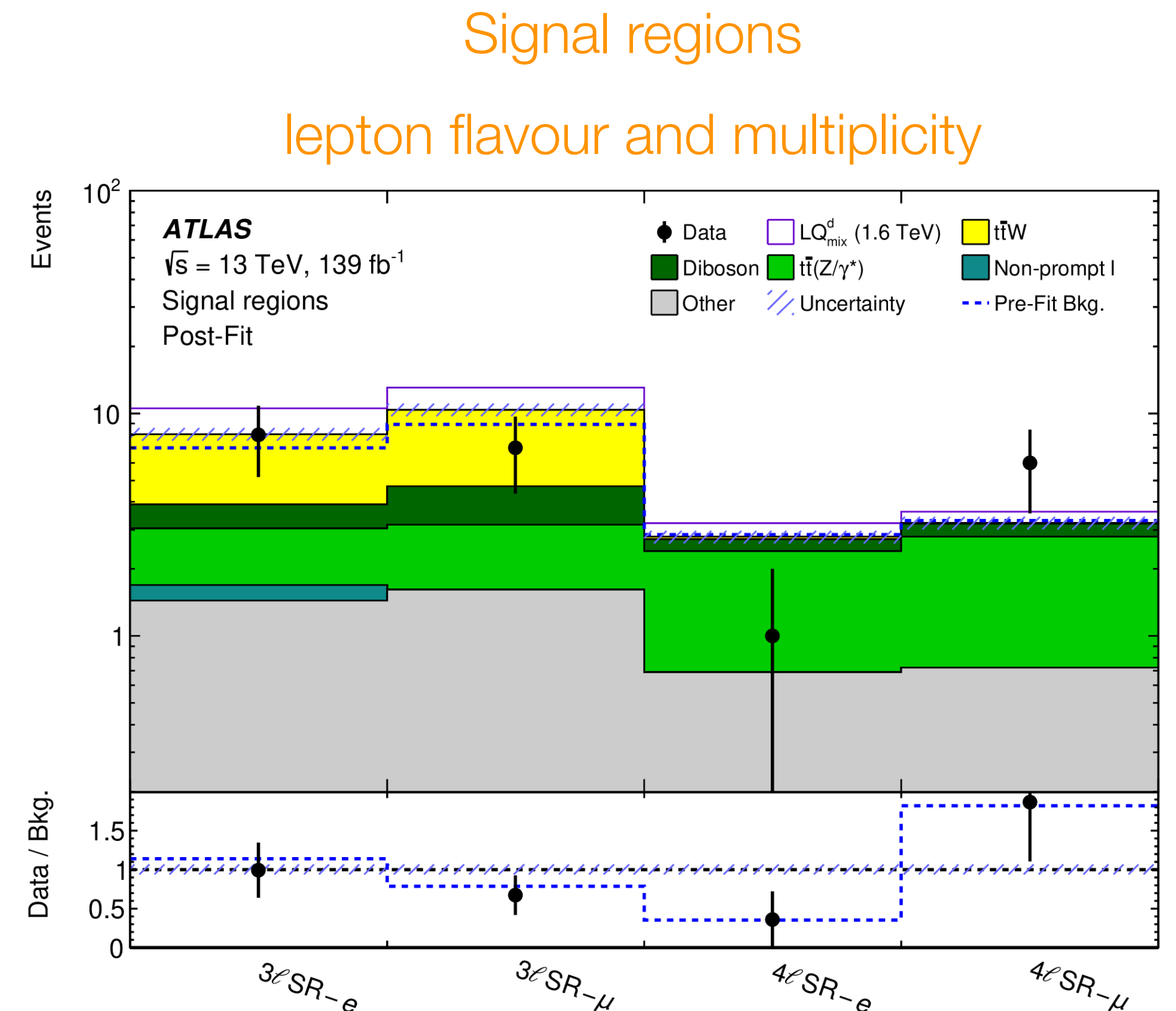
Search for d -type scalar LQs in the mixed scenario, mass range: 1.0 to 1.9 TeV

At least one leptonic top decay

- Multilepton final state: 3 or 4 same flavour leptons
- Additional sensitivity wrt searches with hadronic tops

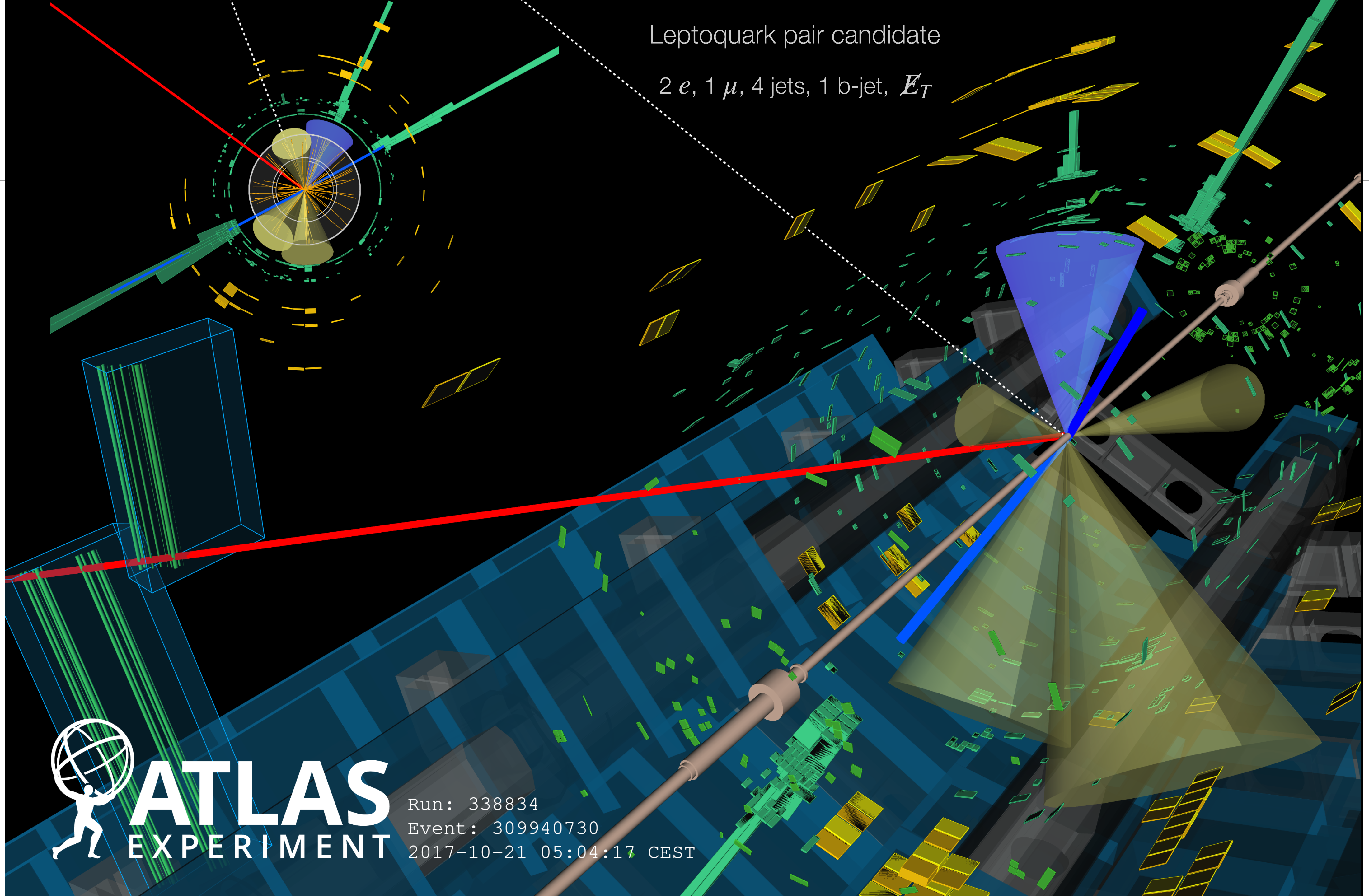
Main backgrounds: diboson and $t\bar{t}V$

- Scalar sum of final state lepton and jets p_T is large for LQ signal -> provides a good discriminant



Leptoquark pair candidate

$2 e, 1 \mu, 4 \text{ jets}, 1 \text{ b-jet}, \cancel{E}_T$



ATLAS
EXPERIMENT

Run: 338834
Event: 309940730
2017-10-21 05:04:17 CEST

Results

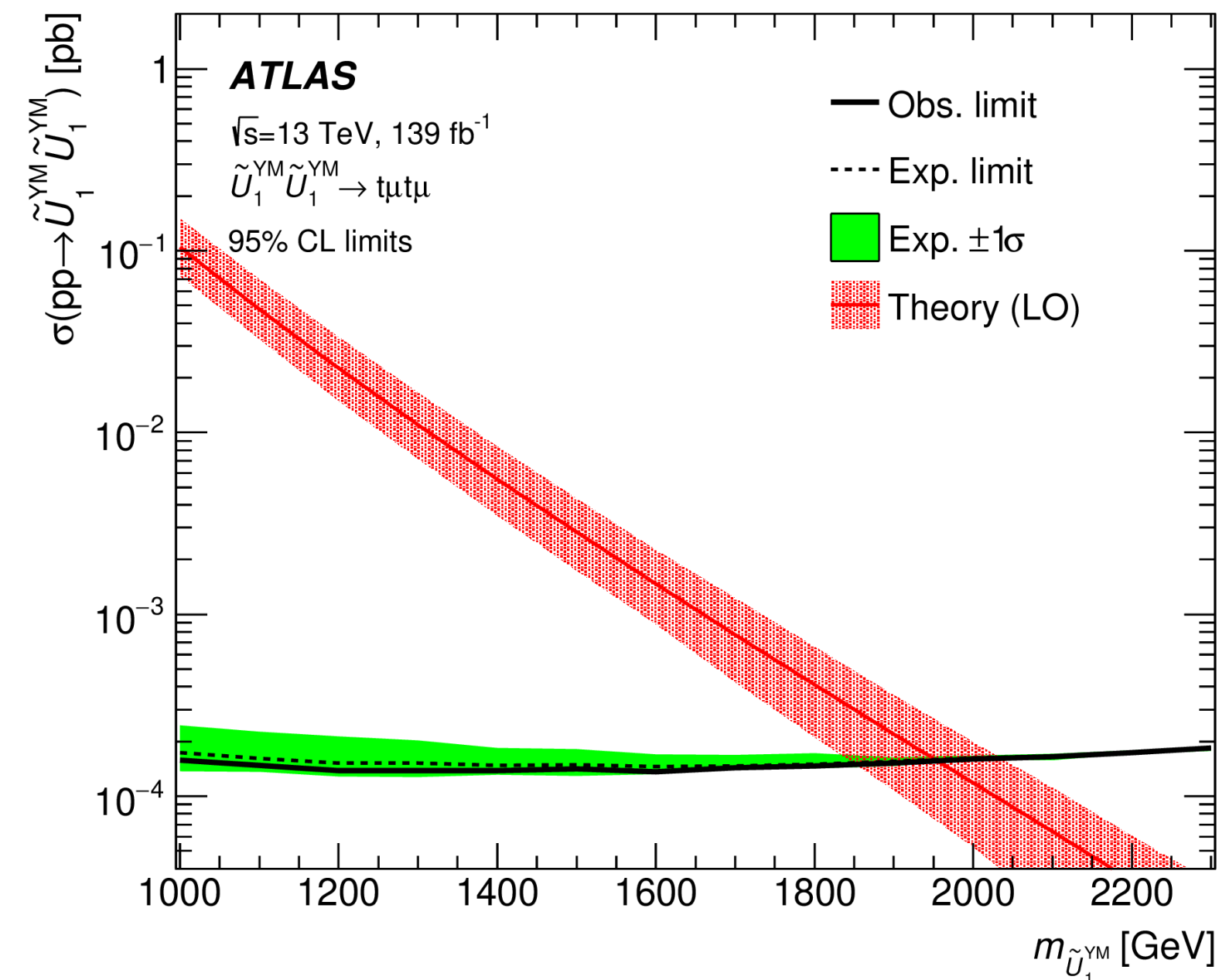
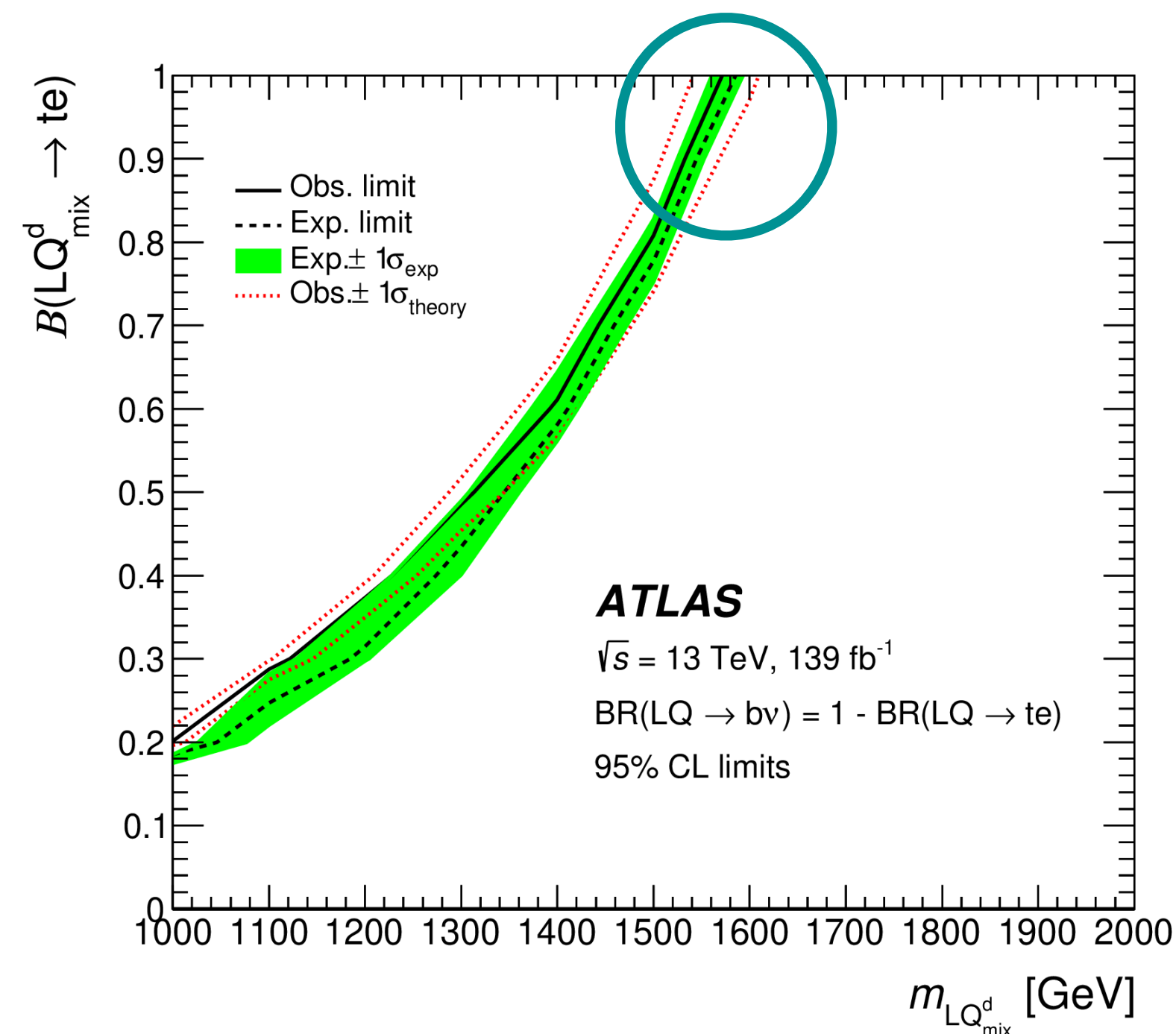
arxiv:2306.17642

BR limits as a function of mass, compatible with 2-lepton final state result

- Assuming exclusive $LQ_{mix}^d \rightarrow te(t\mu)$ decay, mass lower limit is 1.58 (1.59) TeV

Also interpreted as a vector LQ, charge +2/3 model

- Minimal (U_1^{min}) or Yang-Mills (U_1^{YM}) SM gauge boson couplings, U_1^{min} mass > 1.67 TeV and $U_1^{YM} > 1.95$ TeV



Yang-Mills
scenario

Resonance searches

Direct way of searching for BSM physics predicting **new heavy particles**

- Heavy resonances decaying to SM particles lead to **boosted products** in the detector
- Need powerful **tools to reconstruct/identify boosted objects** (hadronic top/boson decays)
- **Hunt for bumps** in the **invariant mass** spectra of the decay products

Signature of many BSM models

- **Model-dedicated searches**: Heavy vector triplets, SUSY, DM models, VLQs, LQs, ...
 - Recent result on $W' \rightarrow tb$: [arxiv:2308.08521](https://arxiv.org/abs/2308.08521)
- **Generic** searches including **anomaly detection**

Di-jet resonances in tetra-jet events

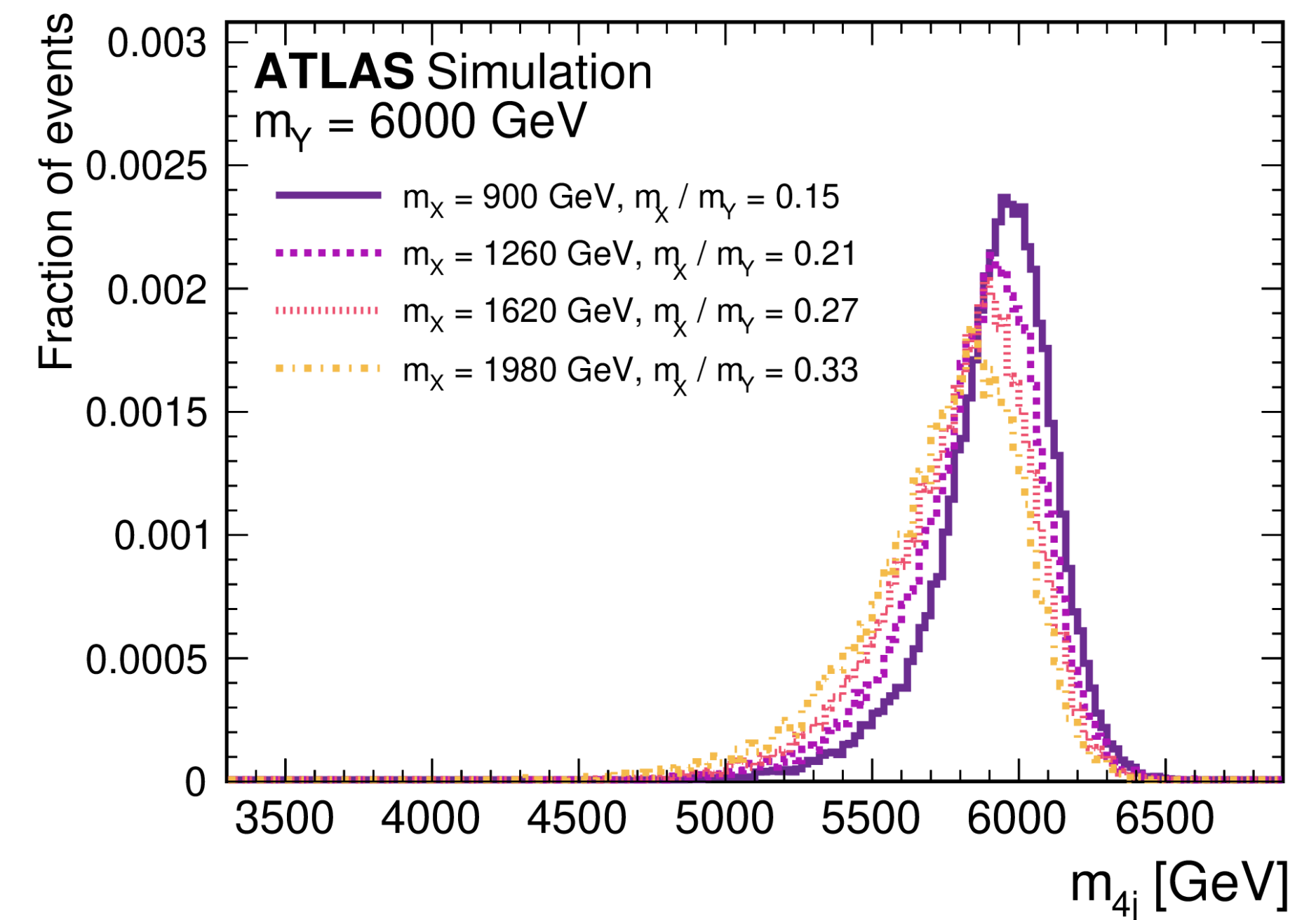
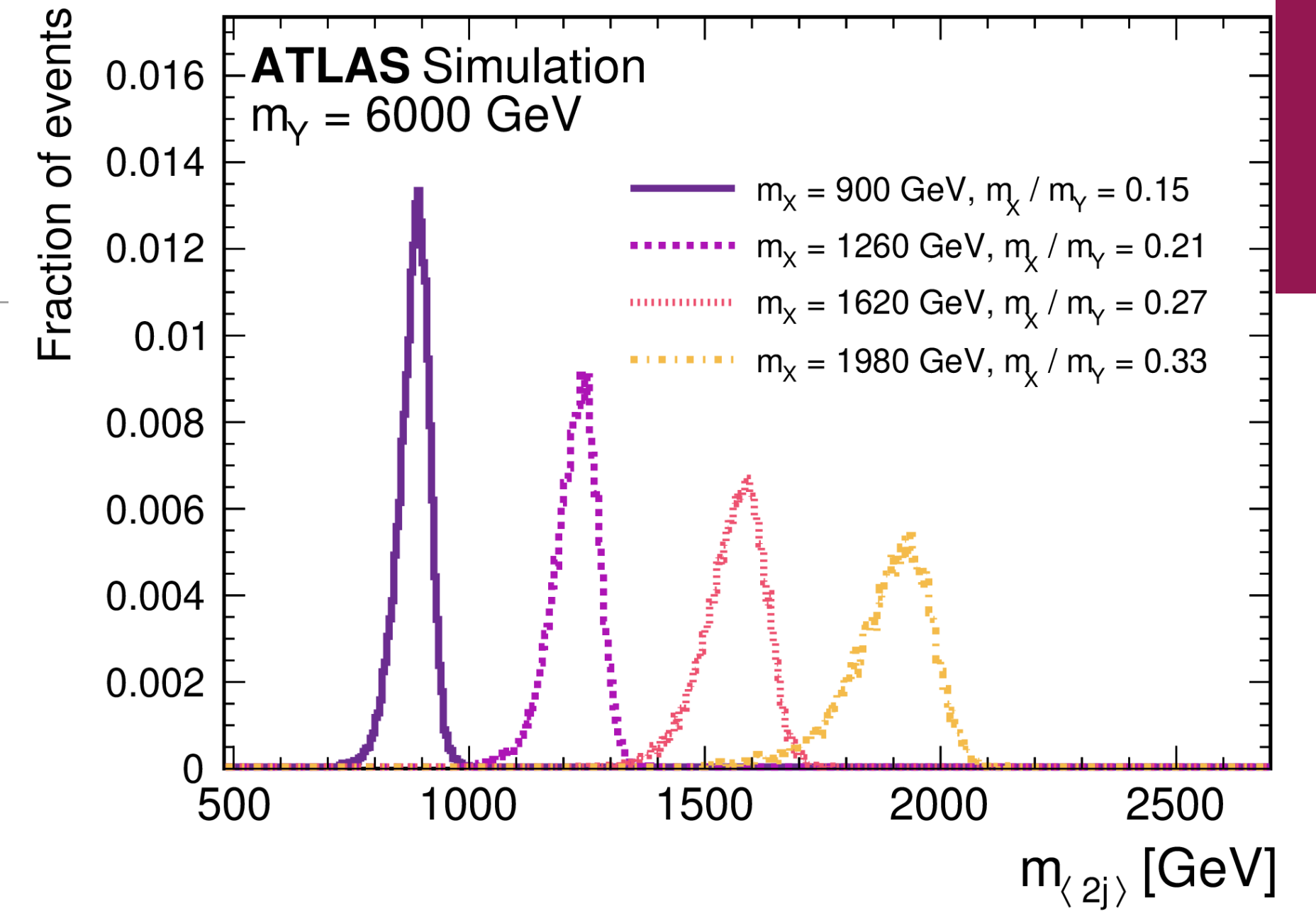
[arxiv:2307.14944](https://arxiv.org/abs/2307.14944)

Search for $Y \rightarrow XX \rightarrow jjjj$ generic signal following up 3.9σ local excess reported by CMS [arxiv:2206.09997](https://arxiv.org/abs/2206.09997)

Events with 4 small-radius jets

- Two di-jet pair combination obtained by minimising the distance between jet pairs
- $\langle m_{2j} \rangle$ and m_{4j} used to reconstruct the X and Y masses

Background dominated by QCD processes, obtained from modelling the m_{2j} and m_{4j} spectra in data



Observed event with highest m_{4j}

$$m_{4j} = 6.6 \text{ TeV}, \quad \langle m_{2j} \rangle = 2.2 \text{ TeV}$$



Run: 336678

Event: 1202524014

2017-09-26 18:00:56 CEST

Results

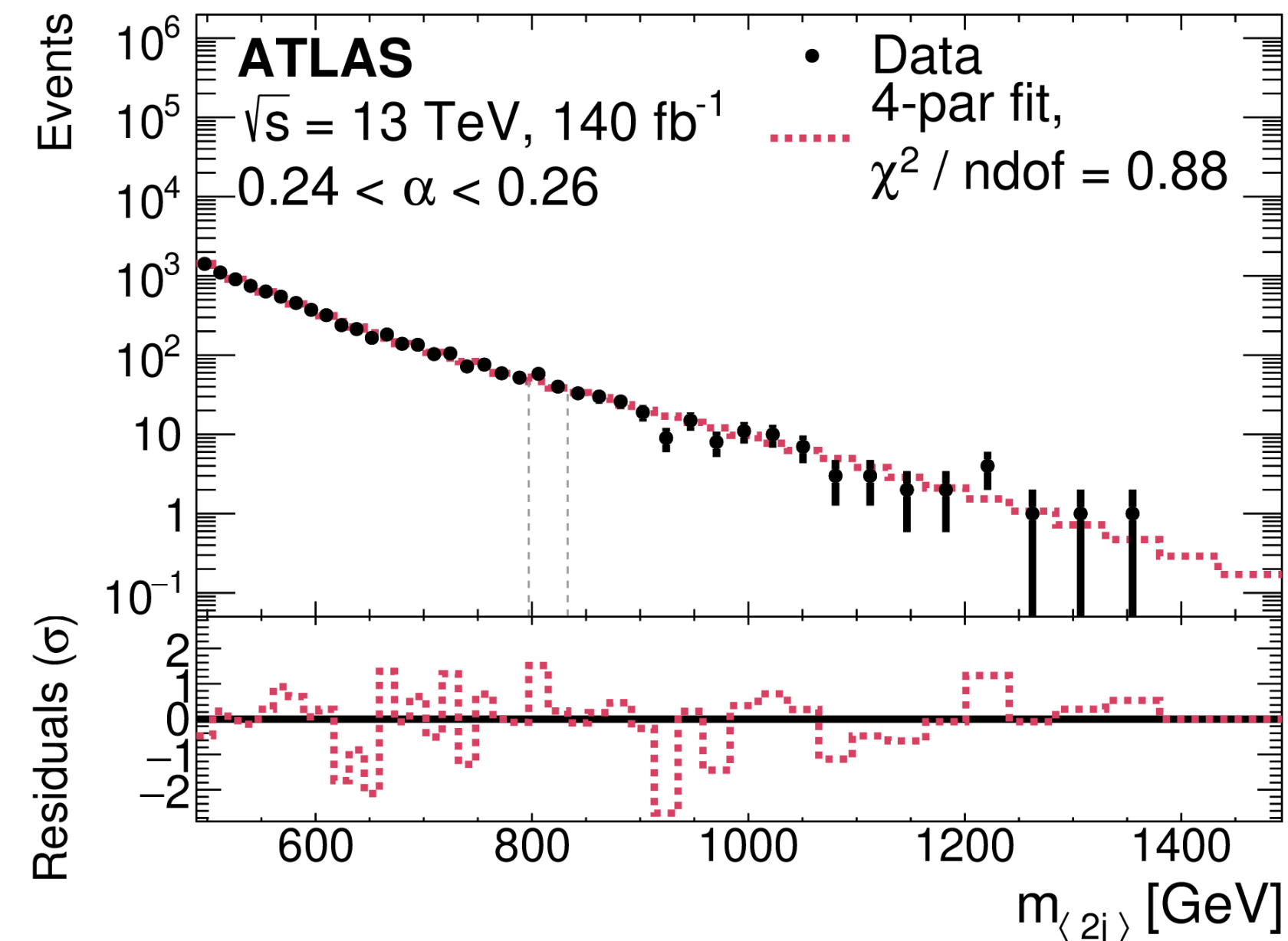
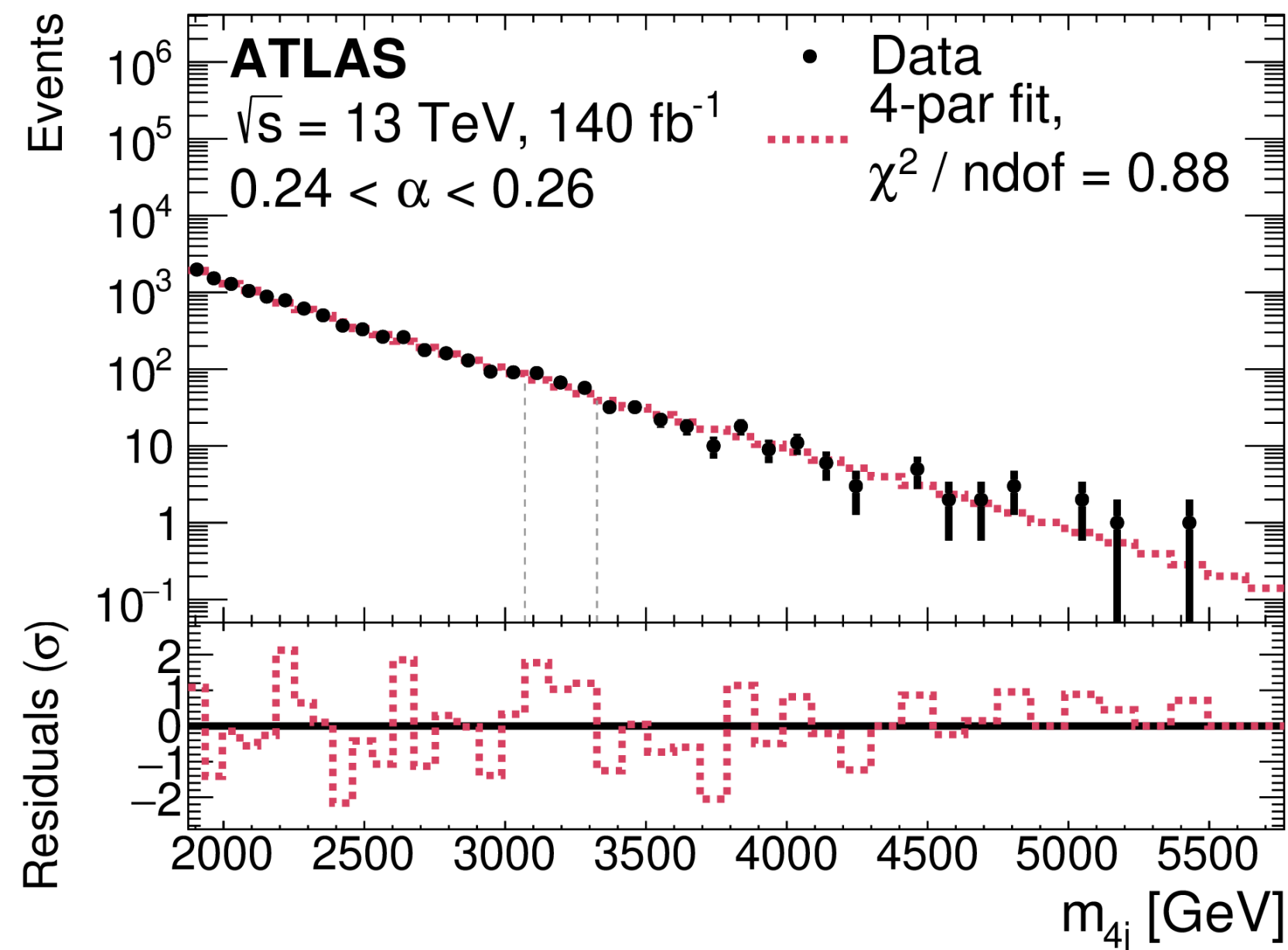
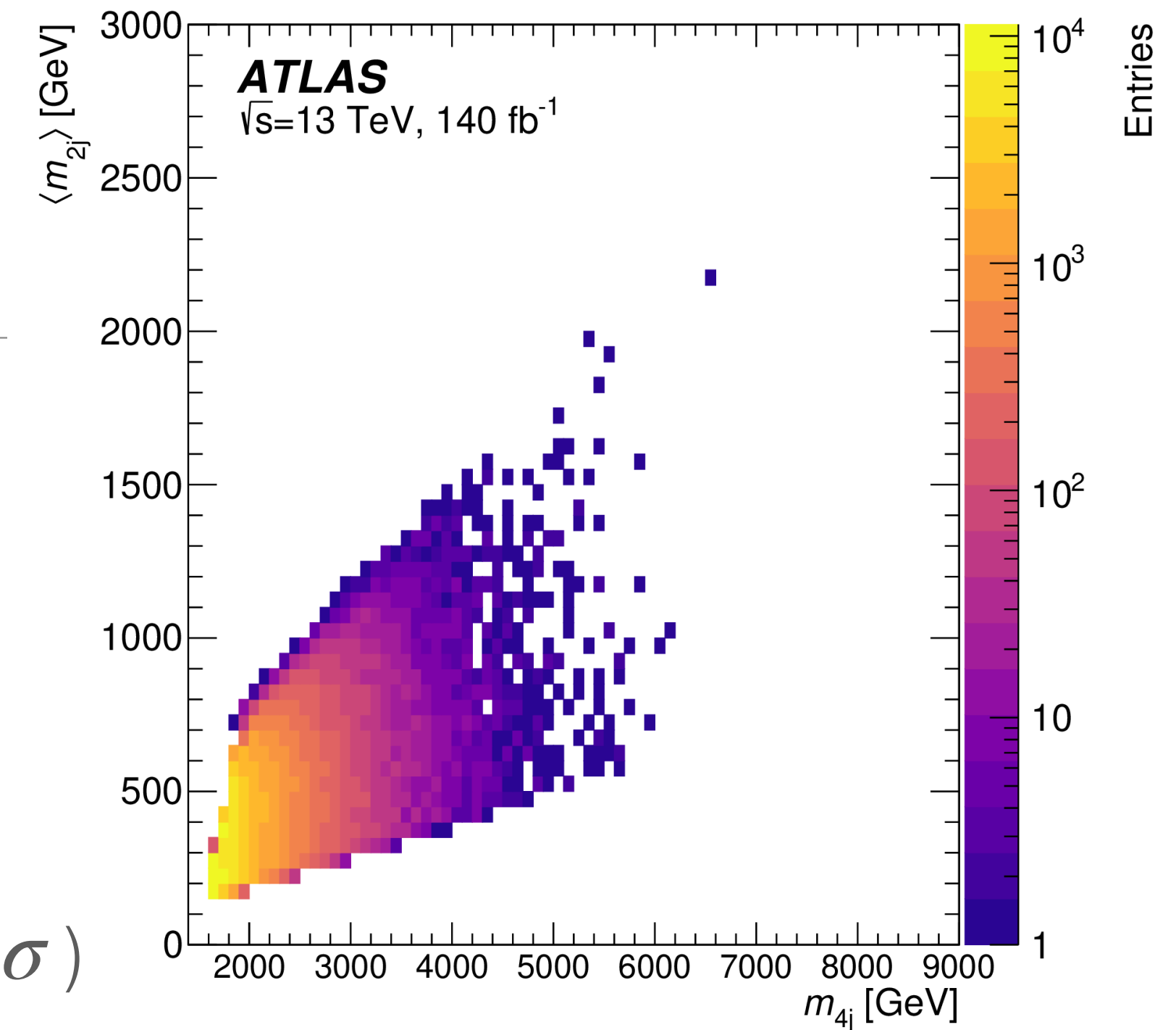
[arxiv:2307.14944](https://arxiv.org/abs/2307.14944)

Data probes a wide range of $\langle m_{2j} \rangle$ and m_{4j}

Bump hunt in the invariant mass spectra

No data excess over modelled background, most significant deviations:

- $m_{4j} = 3.2$ TeV (global 0.53σ) and $\langle m_{2j} \rangle = 800$ GeV (global 1.98σ)



Two-body invariant mass bumps enhanced with anomaly detection [arxiv:2307.01612](https://arxiv.org/abs/2307.01612)

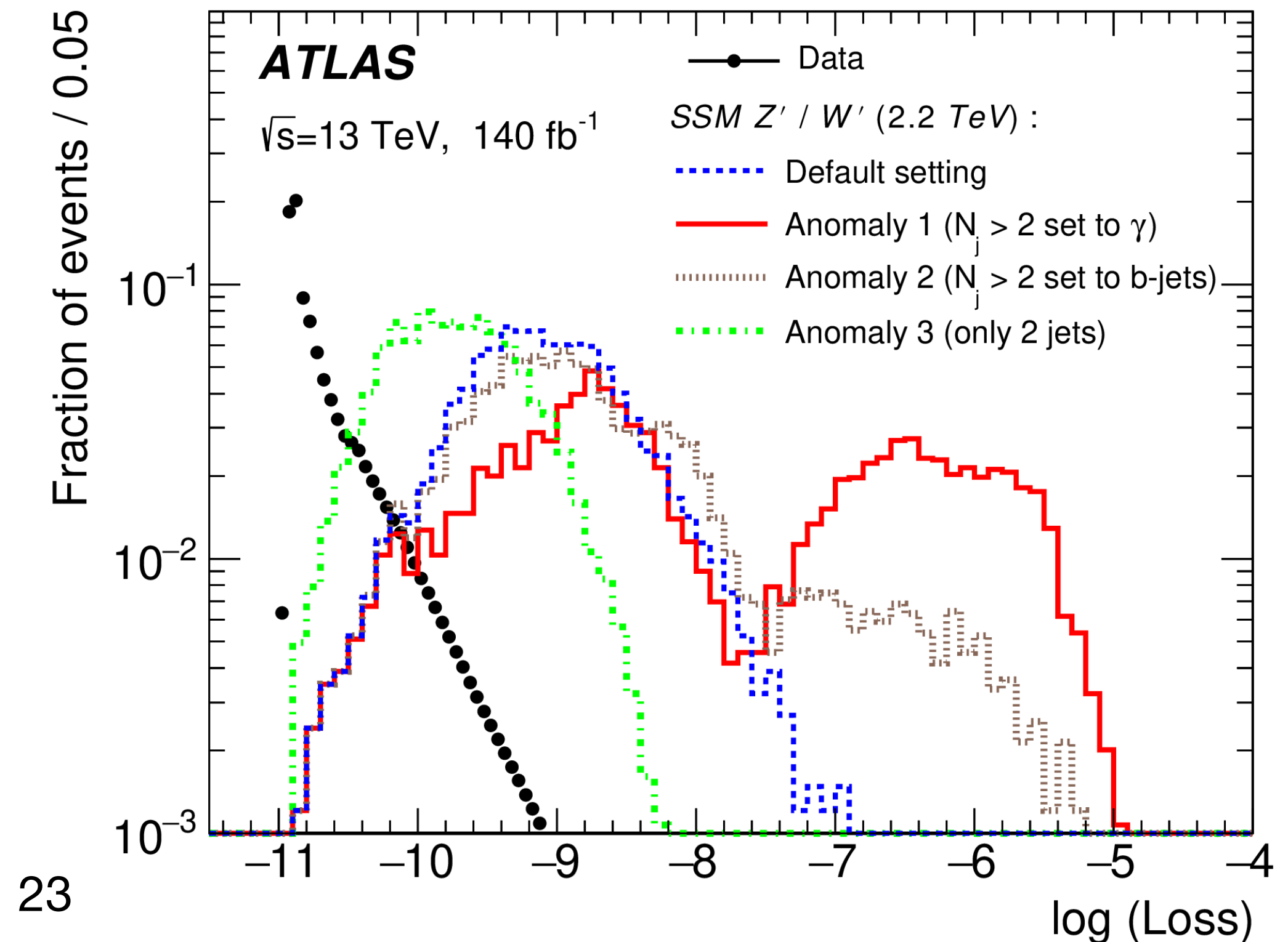
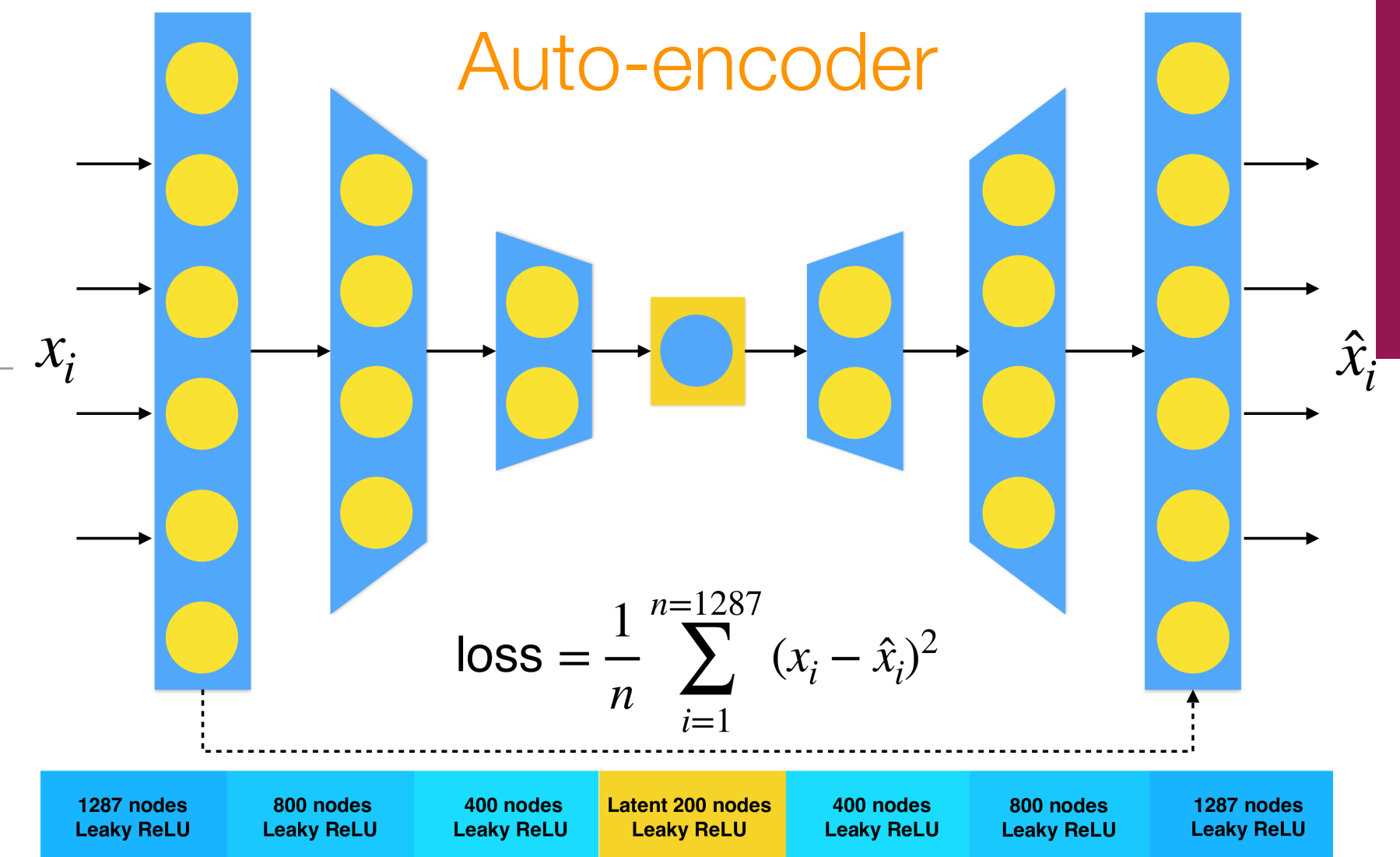
New

Search topologies with at least an electron or a muon

Auto-encoder trained on 1% of real data (dominated by SM background) triggered by isolated lepton

- Reconstruction loss larger for signal is used as anomaly discriminant to select possibly enriched signal samples

Few BSM models and anomaly scenarios used as benchmarks



Results

[arxiv:2307.01612](https://arxiv.org/abs/2307.01612)

9 invariant masses constructed from the possible final state objects

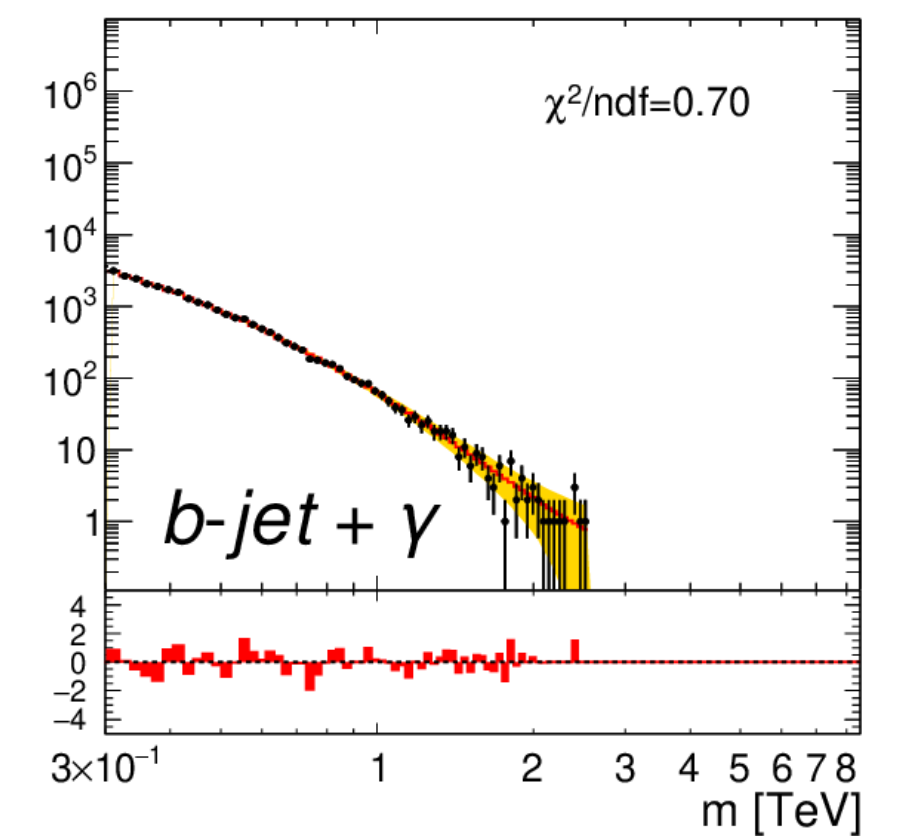
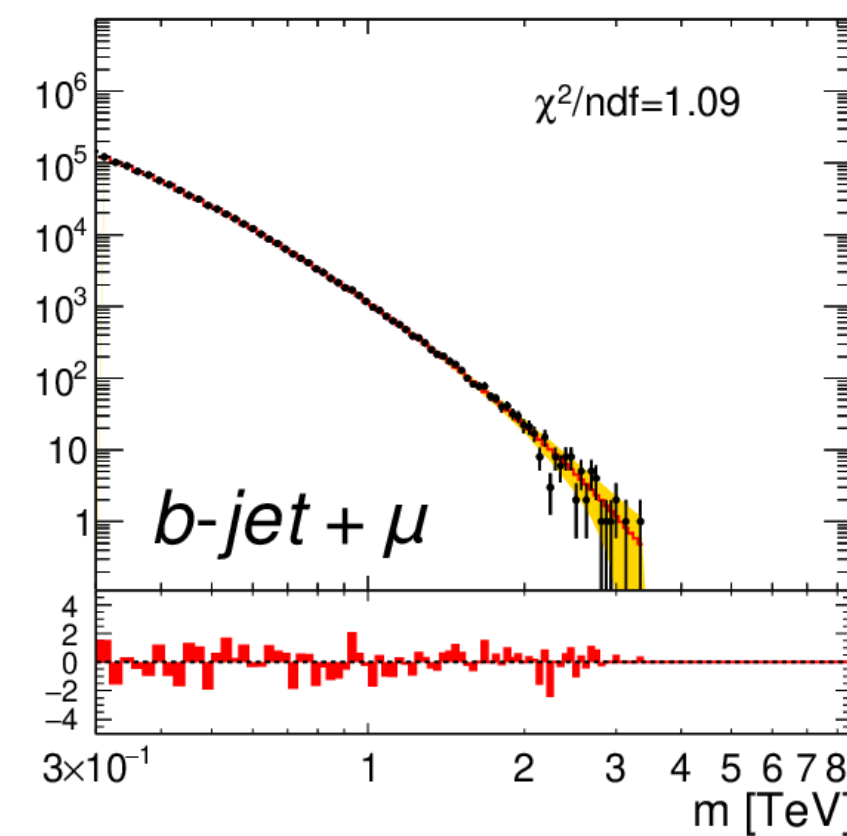
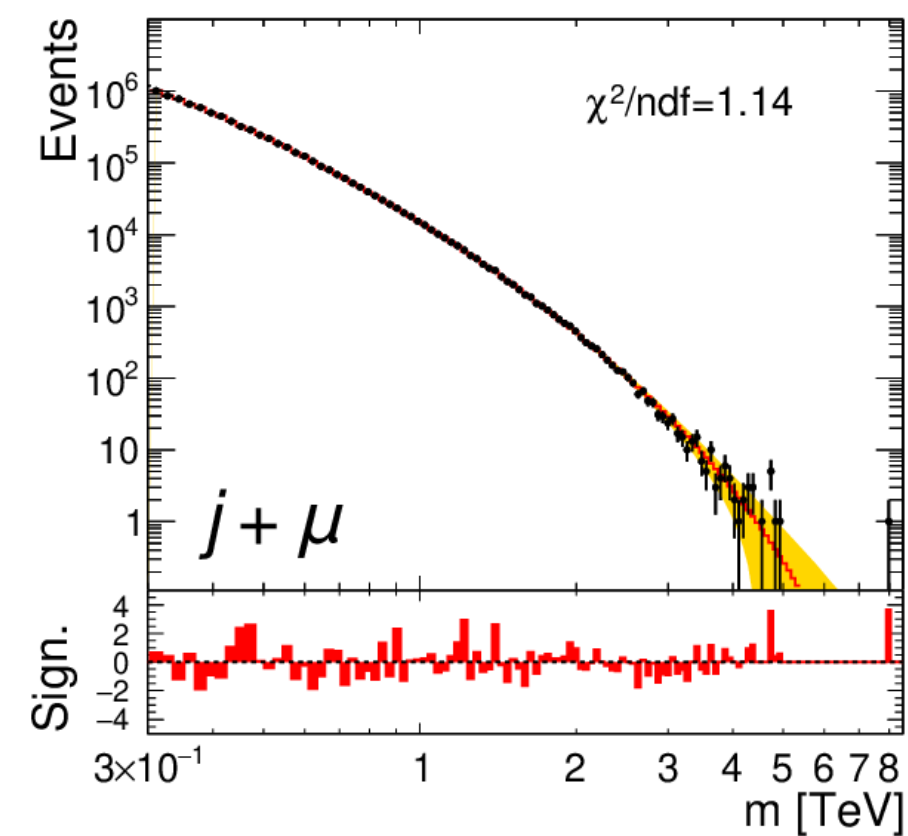
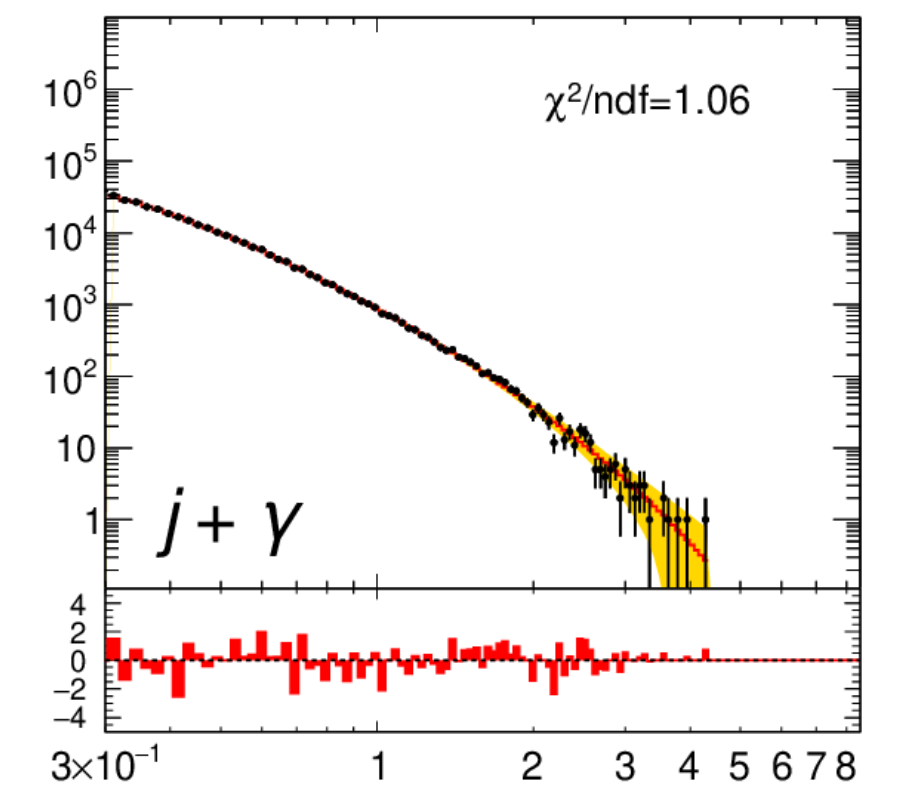
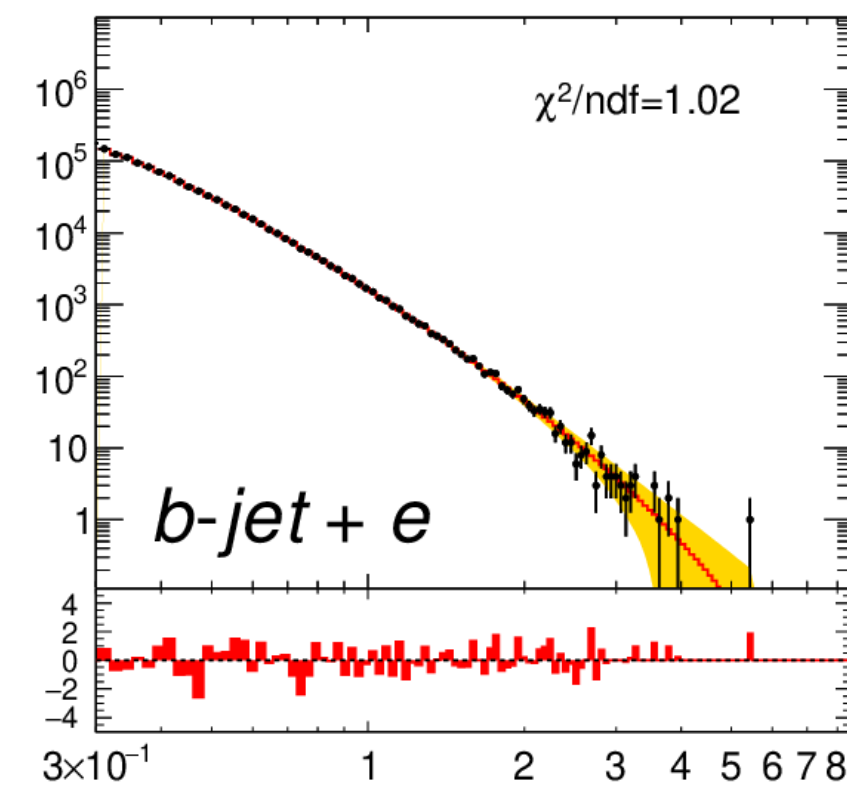
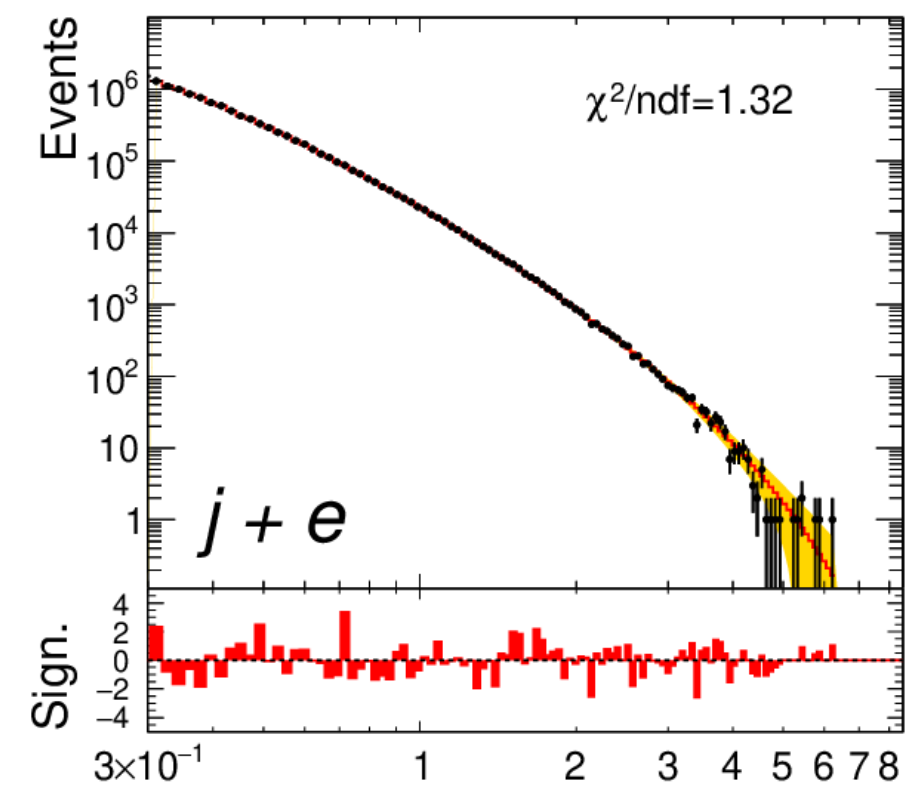
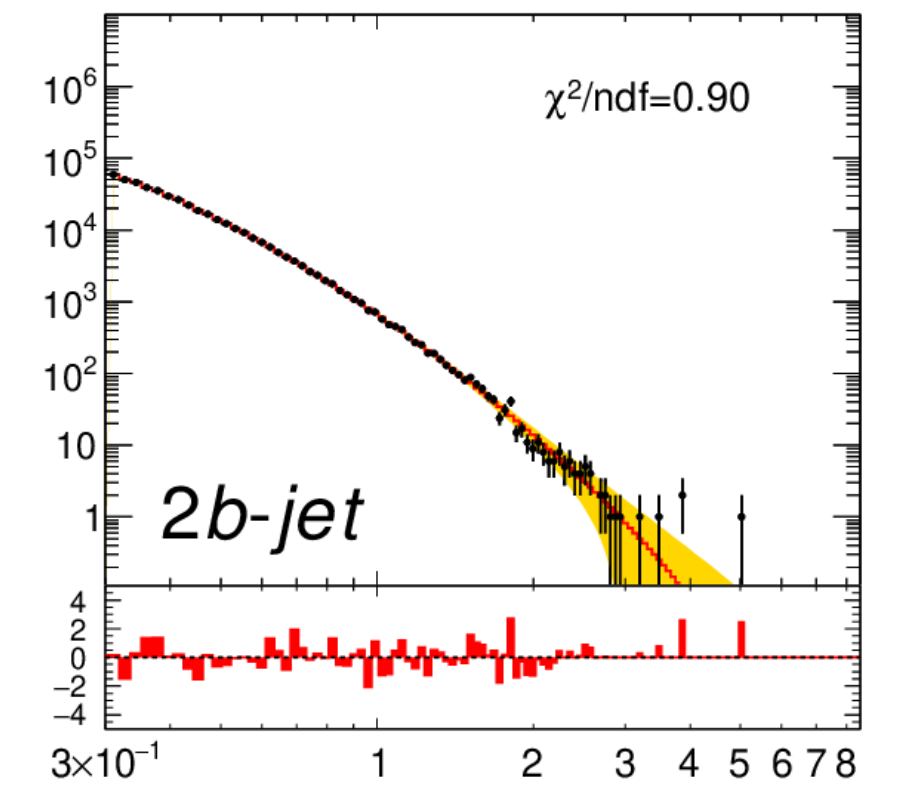
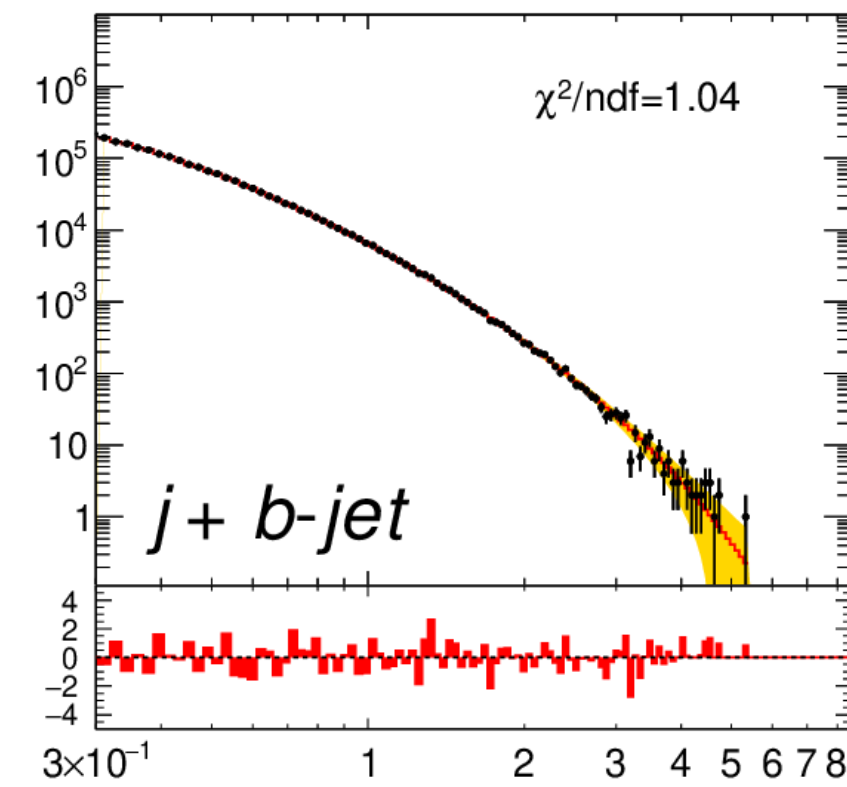
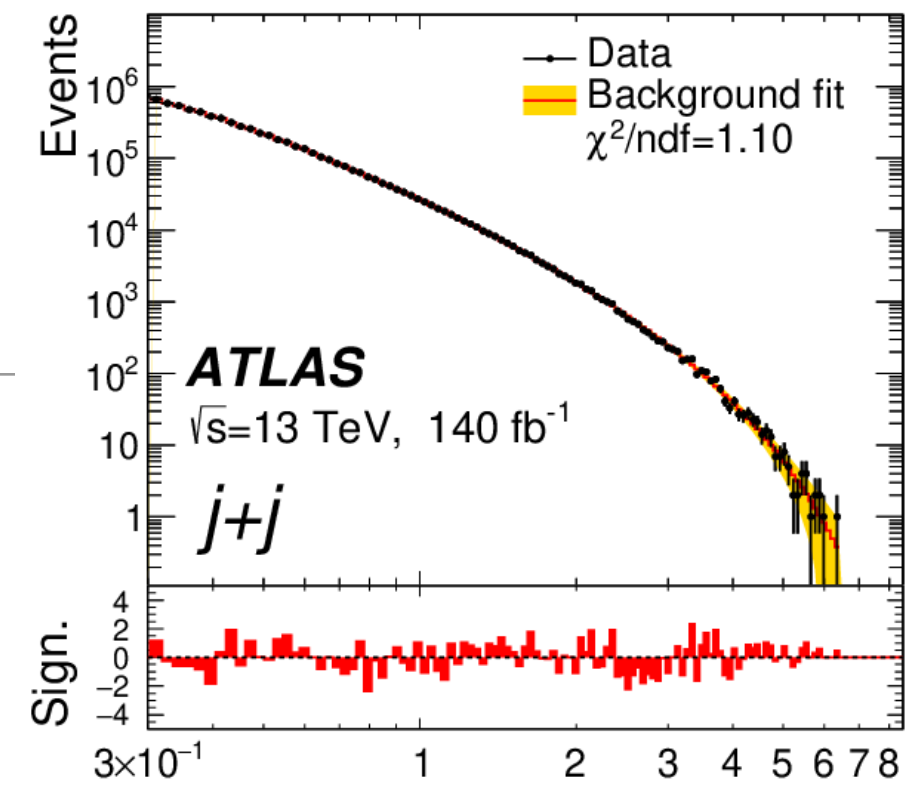
- jets, b-jets, electrons, muons, photons

Mass distributions analysed with **Bump Hunter** to find data excesses

- Largest excess in $m_{j\mu} = 4.8$ TeV (local 2.9σ , assuming 0 width)

Another search using anomaly detection:

- $Y \rightarrow XH$ heavy resonance [arxiv:2306.03637](https://arxiv.org/abs/2306.03637)



Summary and Conclusions

A rich program to search for exotics physics and new resonances in ATLAS

- Many models exploited, from simplified to most complete
- Complemented with model-independent searches

Presented latest results from exotics searches with full ATLAS/LHC Run 2 data

- Summary of ATLAS [ExoticsPublicResults](#)
- No evidence for New Physics yet: stronger limits on the models parameters

Run 3 data collection ongoing and first results will start to come