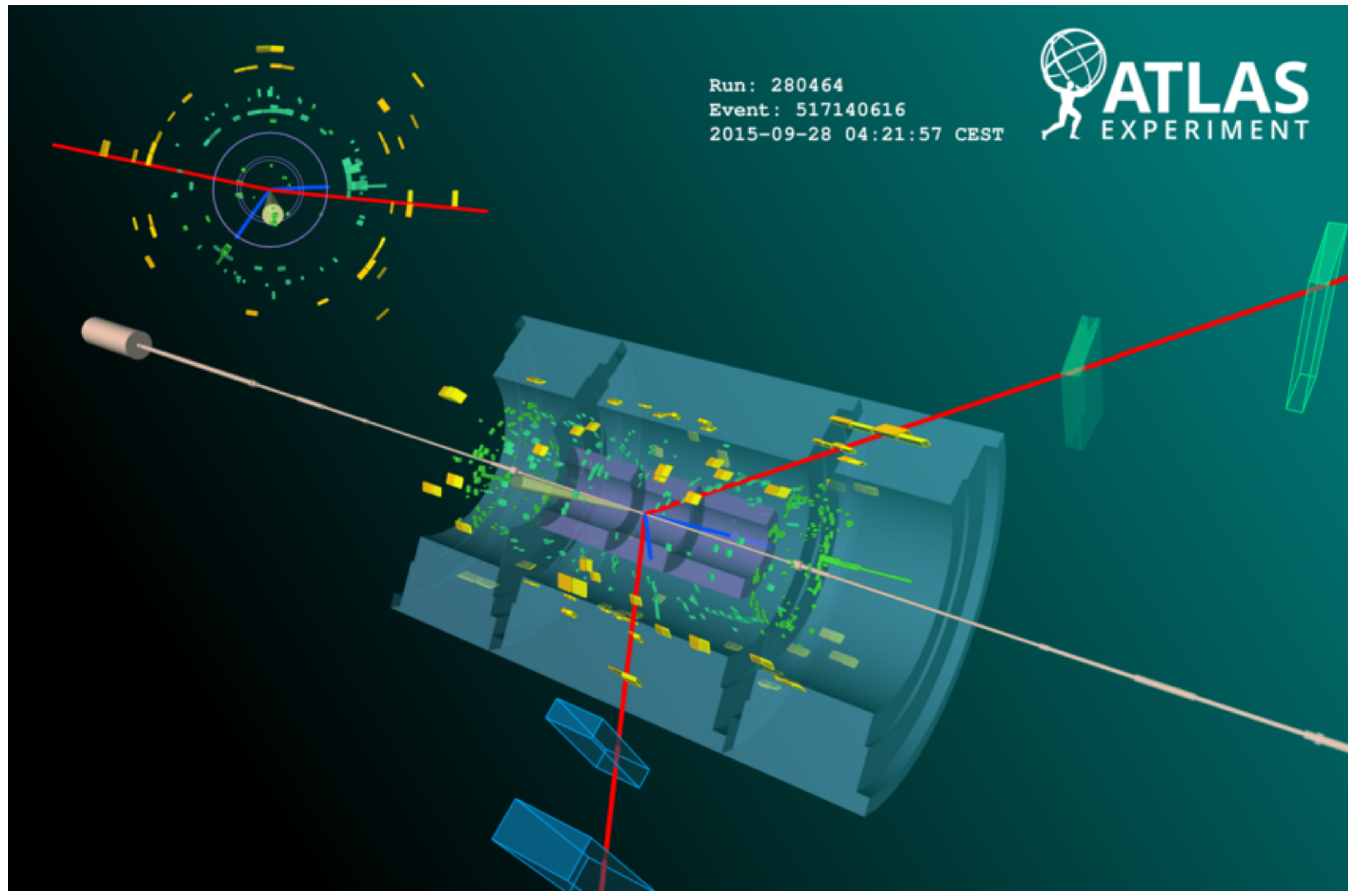
Searches for new physics with leptons using the ATLAS detector



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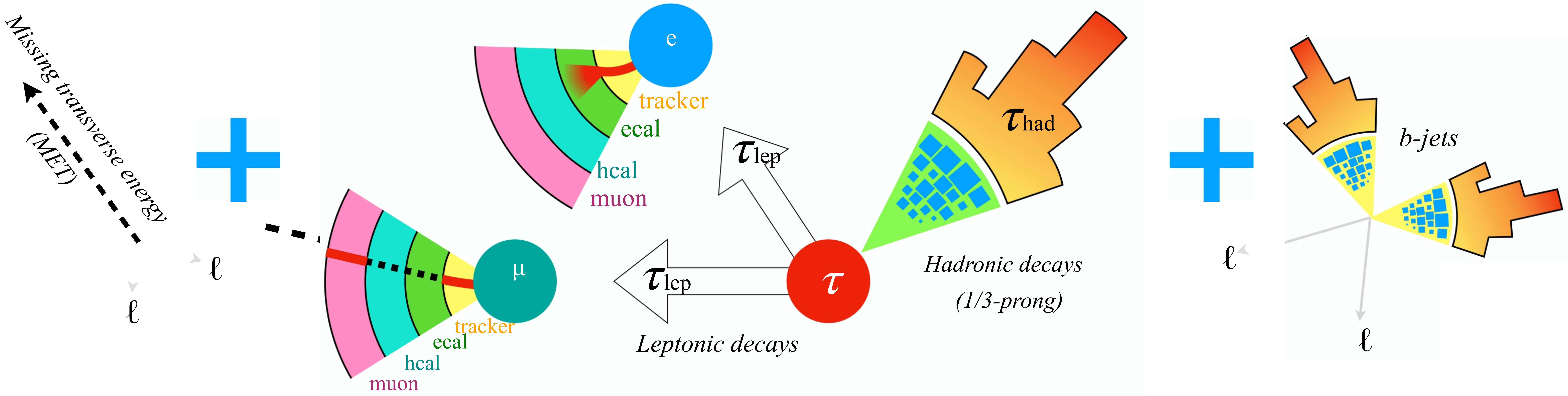
On behalf of ATLAS Collaboration of CERN

23rd October 2024
@43rd International Symposium on Physics in Collision (PIC), NCSR, Demokritos, Greece

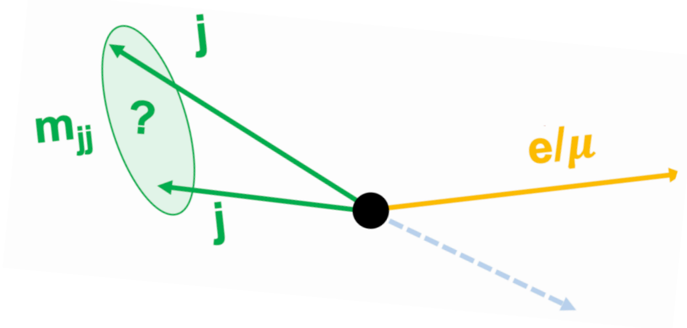
Motivation

- Leptons are crucial in performing both measurements and searches for new physics at the collider experiments, specially at ATLAS Experiment at CERN.
- Leptons provide a very clean signature → minimize detector resolution systematics
- Lepton, as a trigger reduces the QCD multi-jet background rate in many cases.

Wide range of different event topologies can make use of lepton triggers and physics



Resonance searches with lepton trigger



Dijet resonance searches with a single charged lepton of pT = 60 GeV:

- Single electron/muon triggers($pT\,(\,ET\,) > 24\,(\,26\,)$ GeV to trigger events:
- Exploit lower mass range(> 0.22 TeV)
- Requirement of lepton to suppresses QCD multi-jet background.

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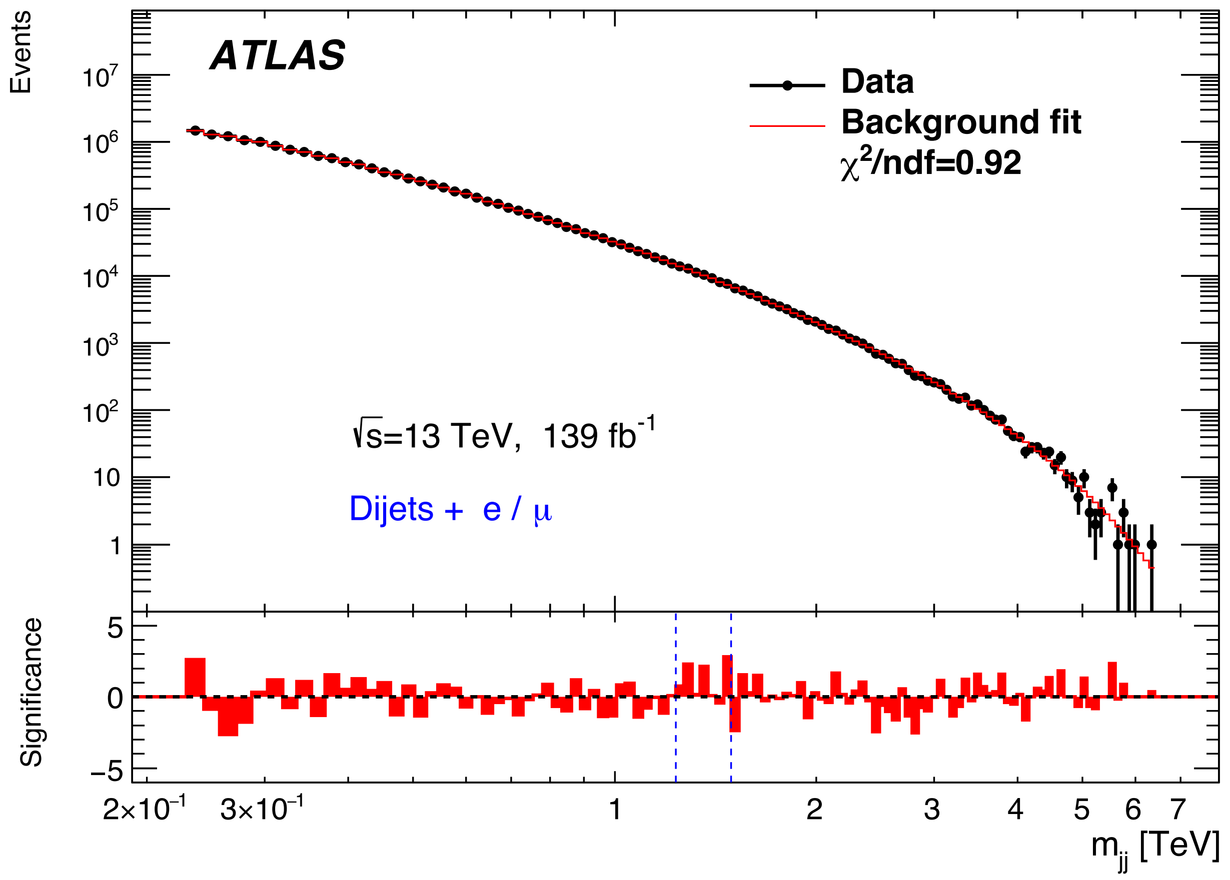
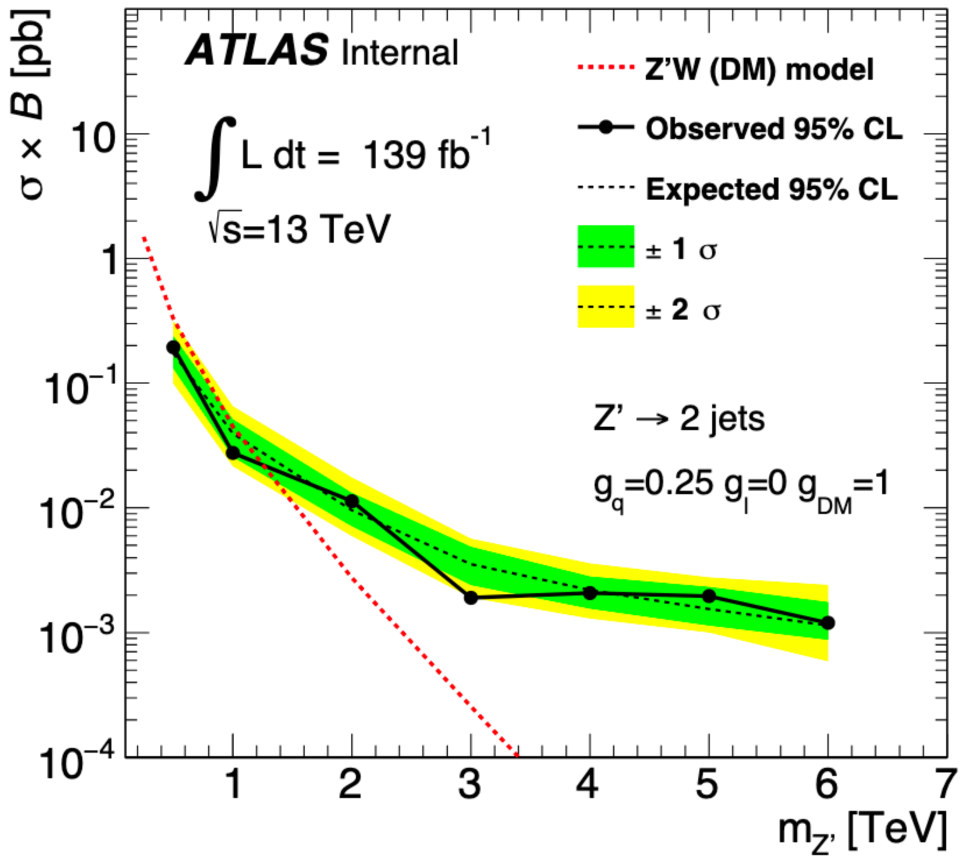
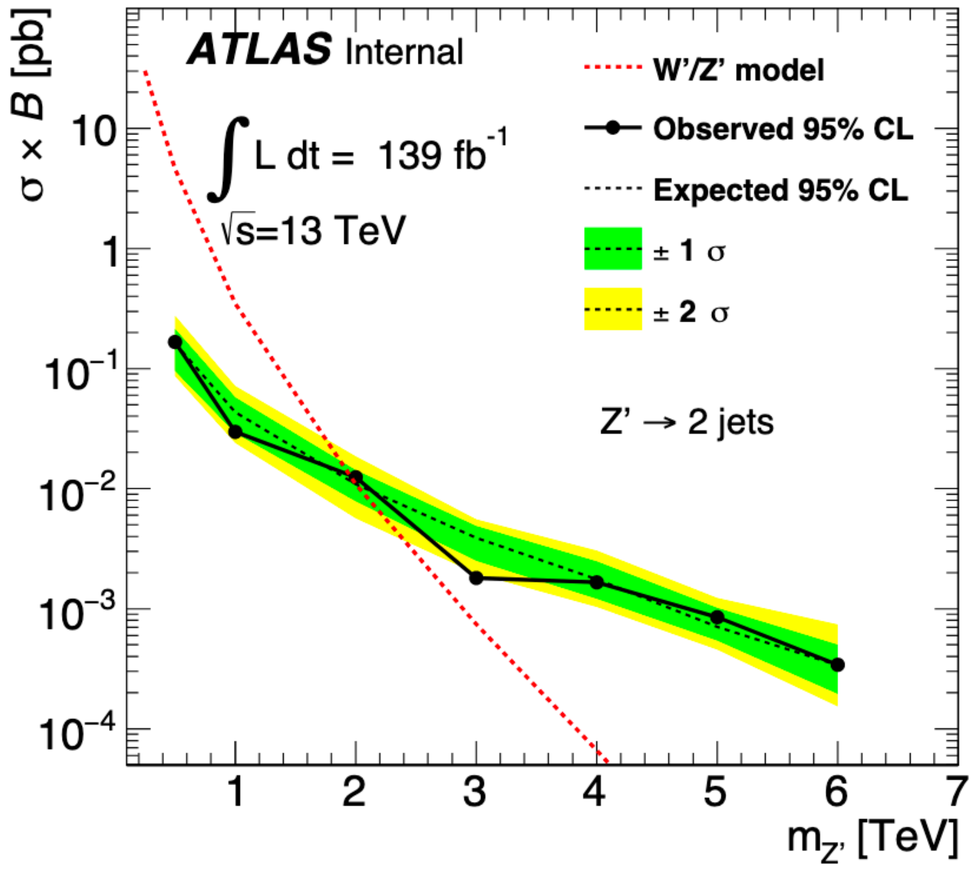


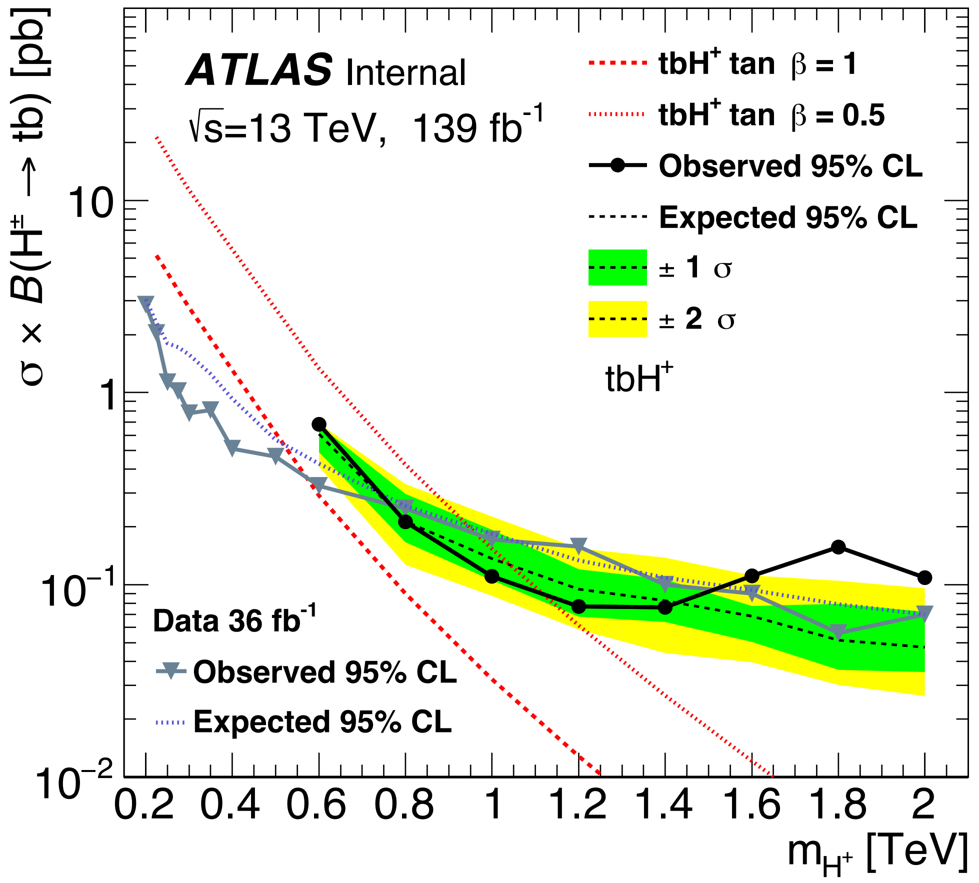
$m_{Z'_{DM}} < 1.2$ TeV



$m_{Z'_{SSM}} < 2.0$ TeV



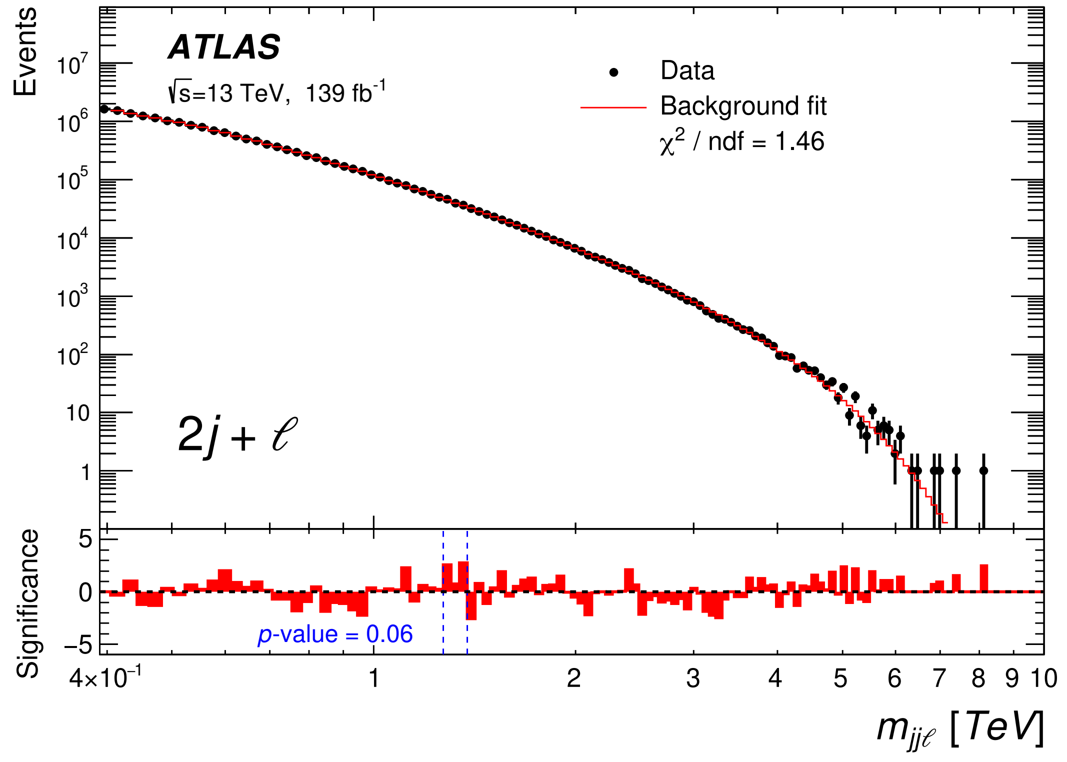
$m_{H^+} < 1.12$ TeV



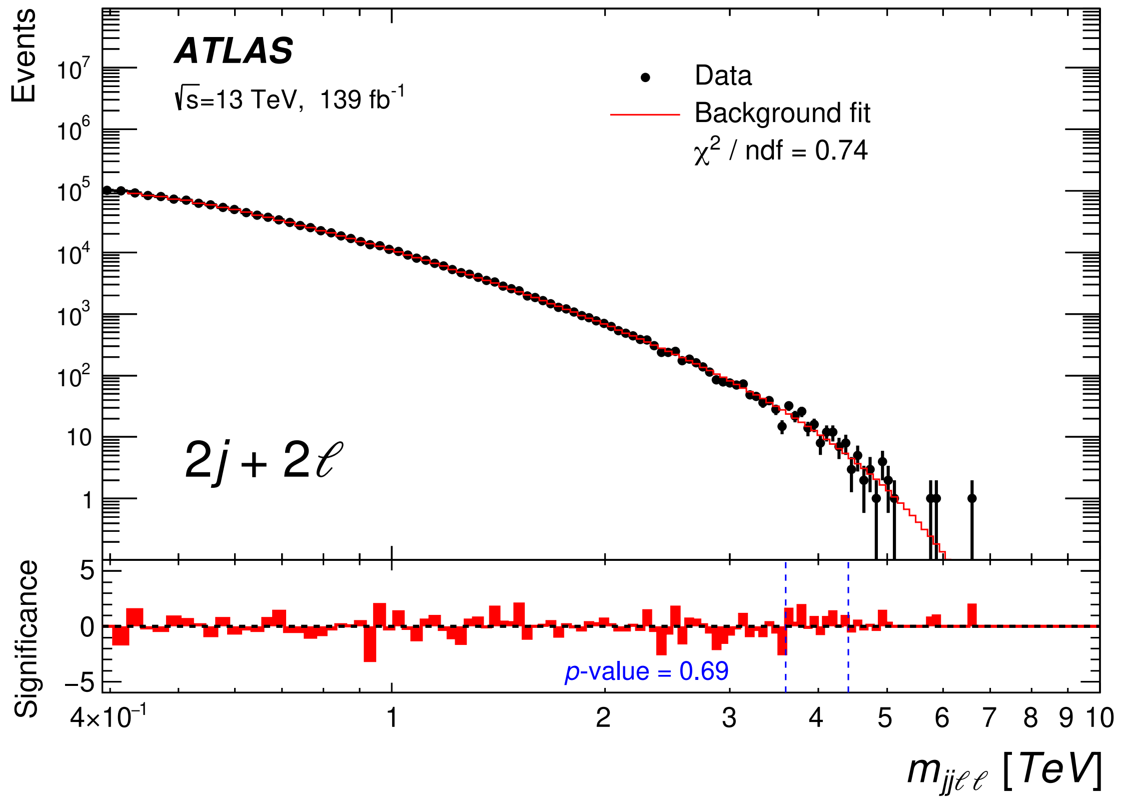
3/4 body resonance search with a charged lepton:

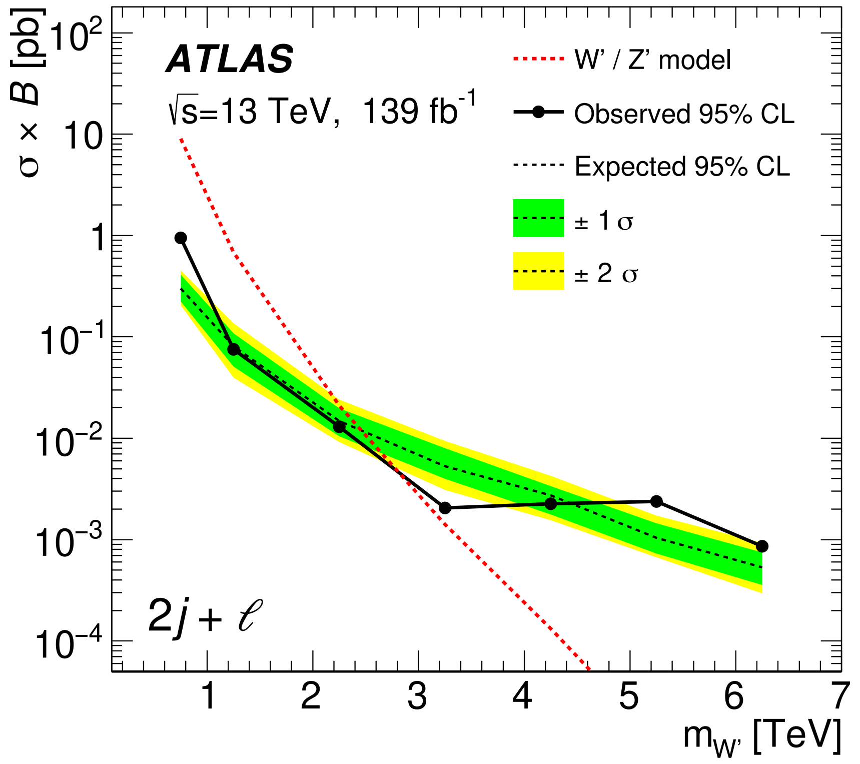
JHEP07(2023)202

m_{jjl}

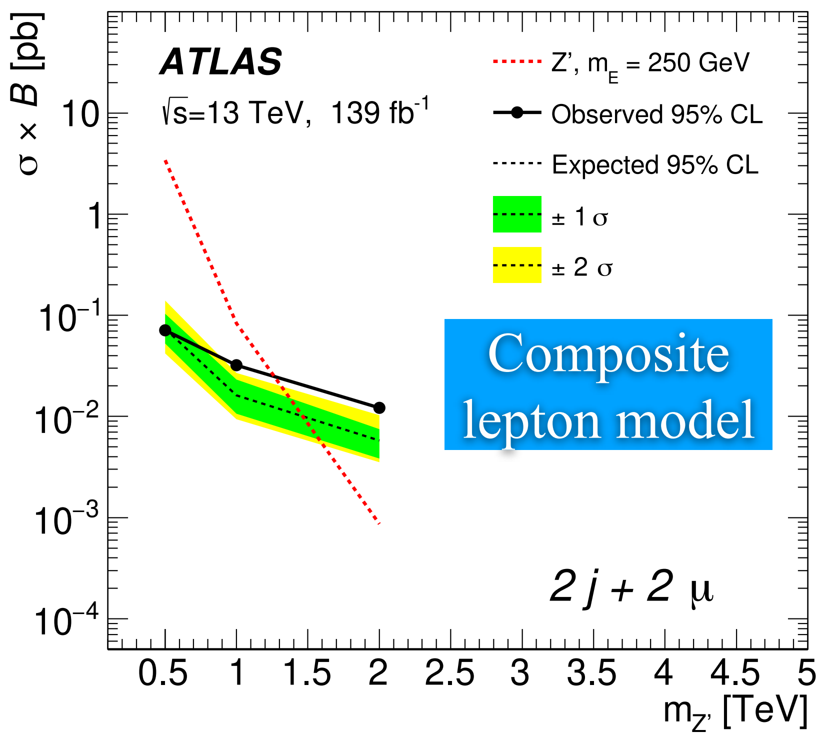


m_{jjll}

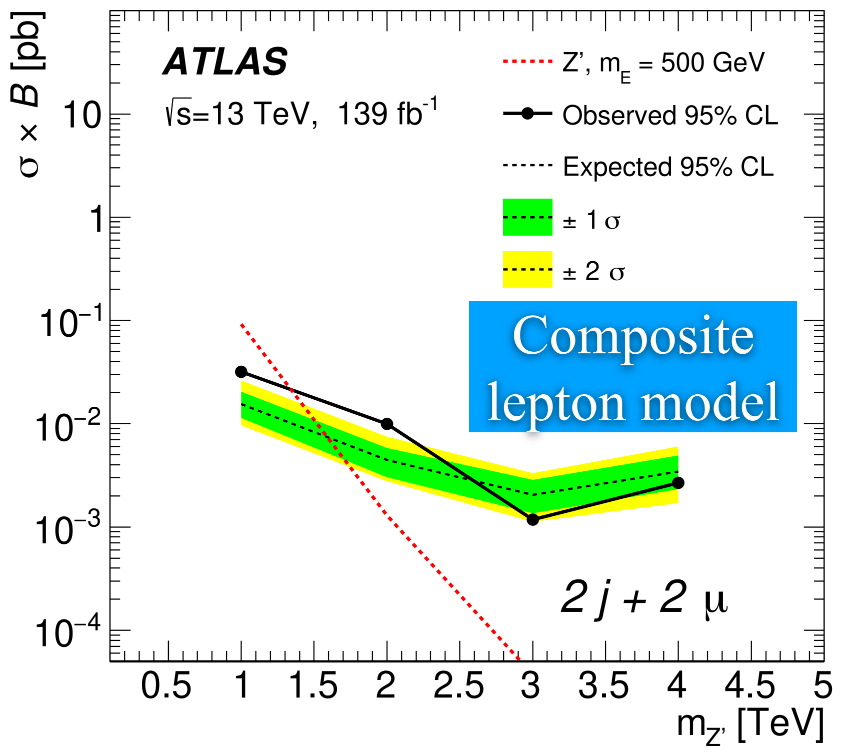




$m_{W'_{SSM}} < 2.5$ TeV



$m_{Z'} < 1.3$ TeV for $m_E = 250 GeV$



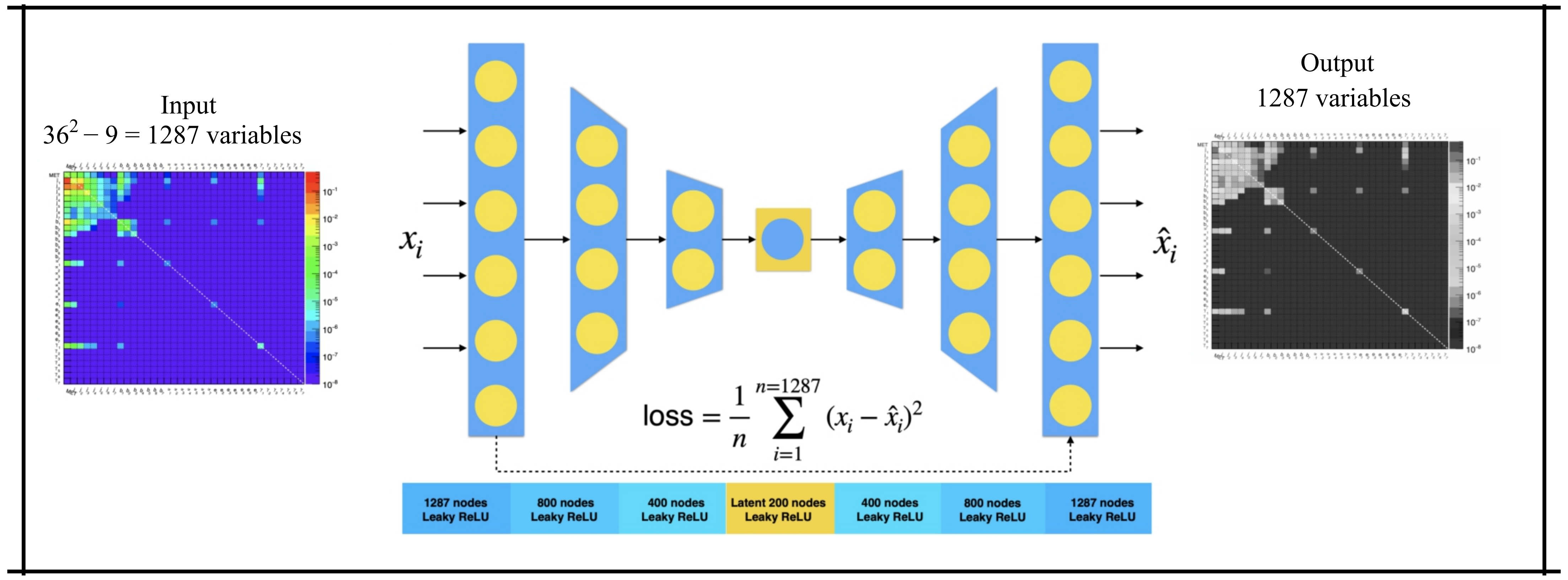
$m_{Z'} < 1.3$ TeV for $m_E = 500 GeV$

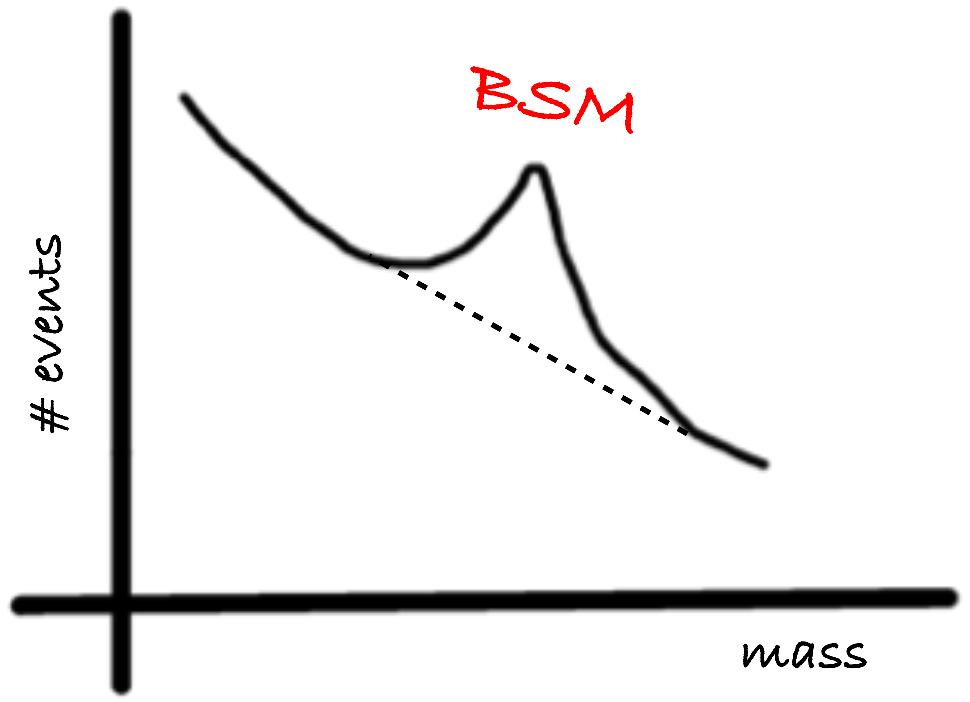
2-body resonance searches with lepton trigger

New Physics Searches with Anomaly Detection using unsupervised ML performed in 9 invariant masses in 3 Anomaly Regions in a mass range of 0.3 TeV - 8 TeV

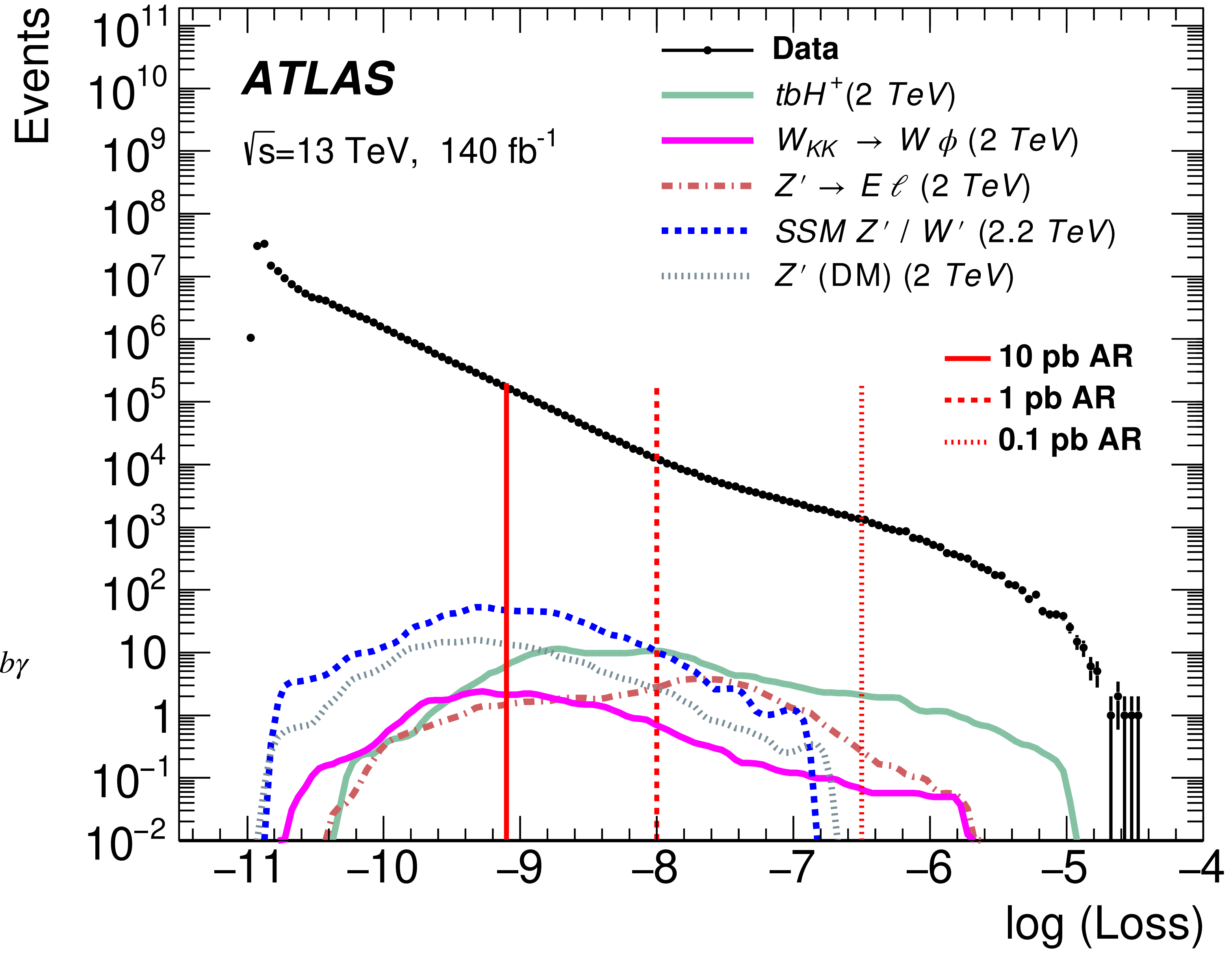
PhysRevLett.132.081801

using events with a single charged lepton of 60 GeV





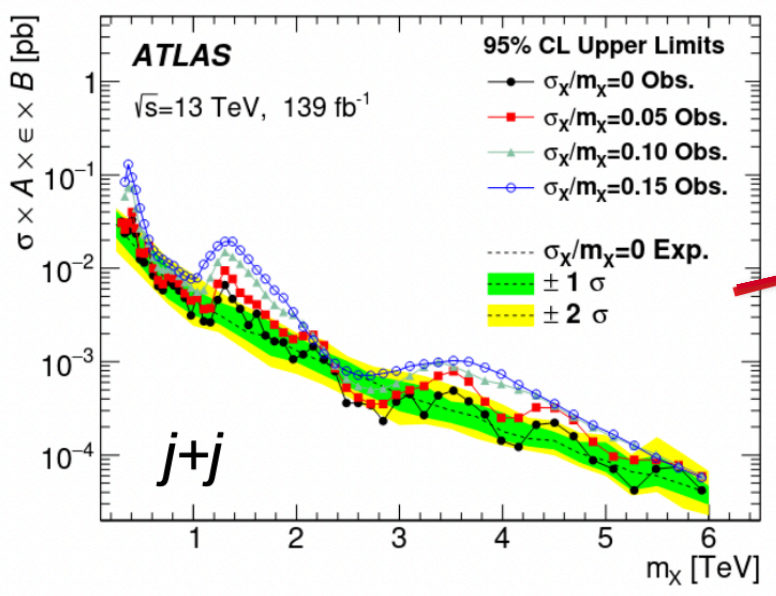
$m_{jj}, m_{jb}, m_{bb}, m_{je}, m_{j\mu}, m_{j\gamma}, m_{be}, m_{b\mu}, m_{b\gamma}$

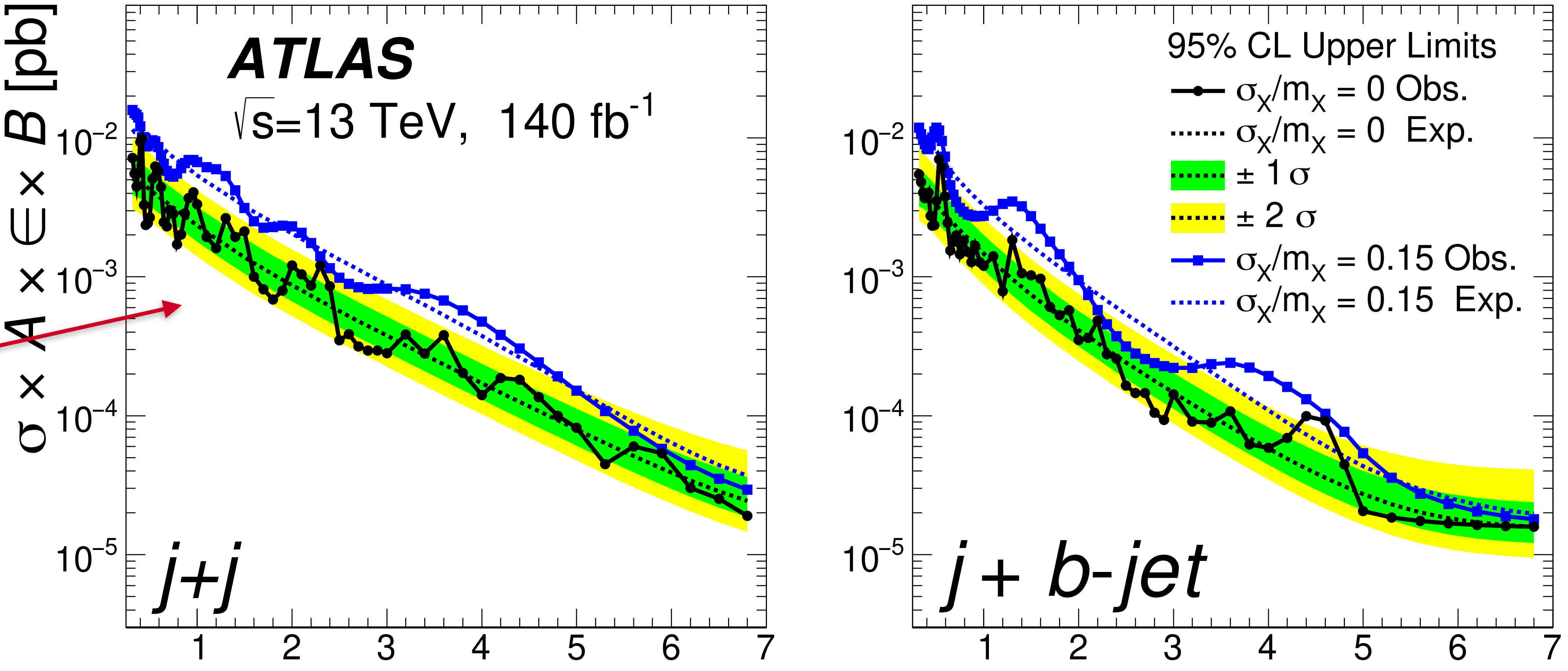


Loss distributions for BSM models

Background fit with p5 function : $f(x) = p_1(1-x)^{p_2}x^{p_3+p_4 \ln x + p_5 \ln^2 x}$, Where $x \equiv mass_{2-objects}/\sqrt{s} \in [0,1]$

Published: JHEP 06 (2020) 151



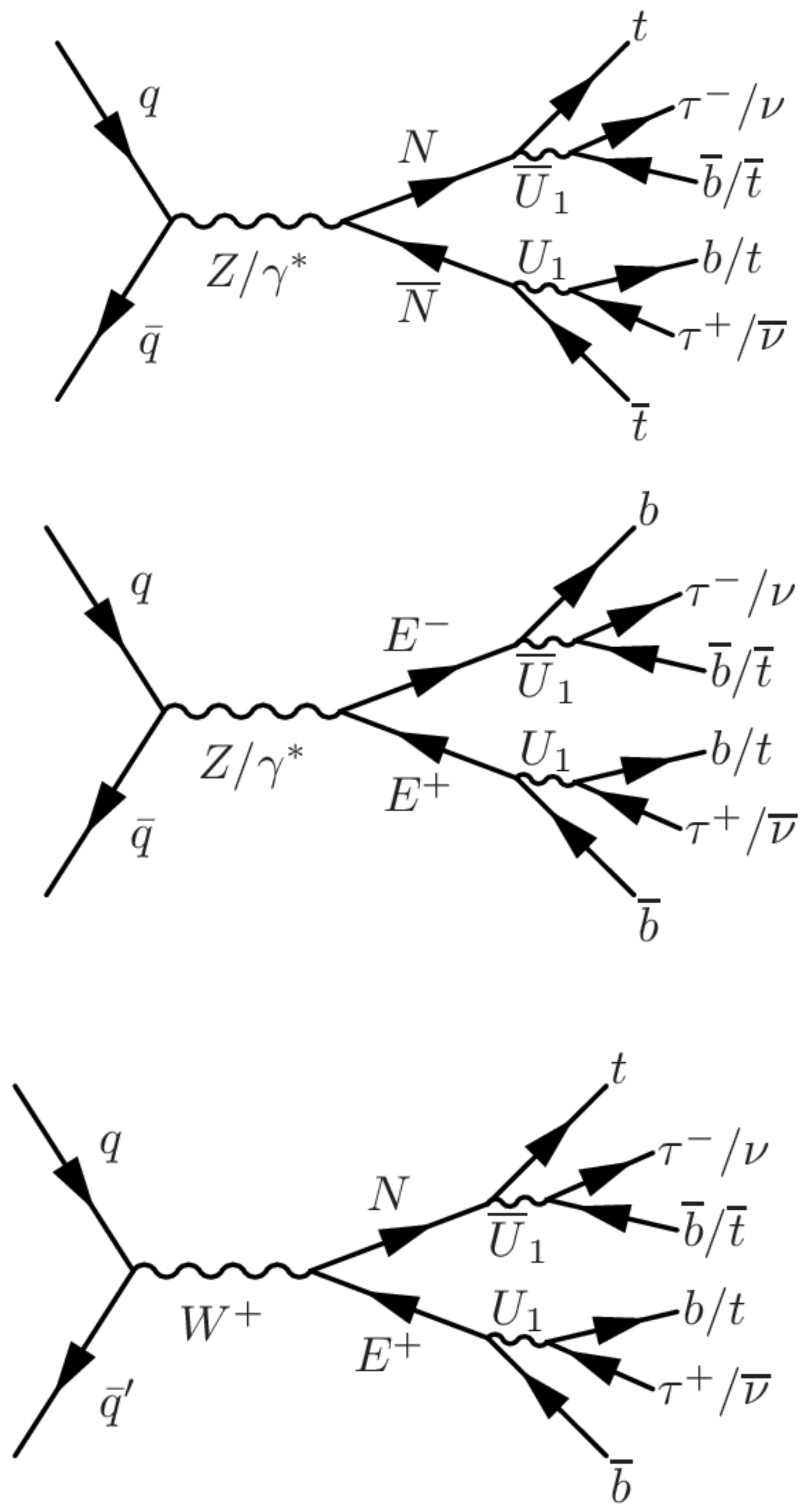


- At masses < 1 TeV the limits are factor 2-3 better than for similar selection without autoencoder (JHEP 06 (2020) 151).
- Discovery sensitivity improved significantly for various BSM models with this approach

Electroweak production of vector-like leptons (VLLs)

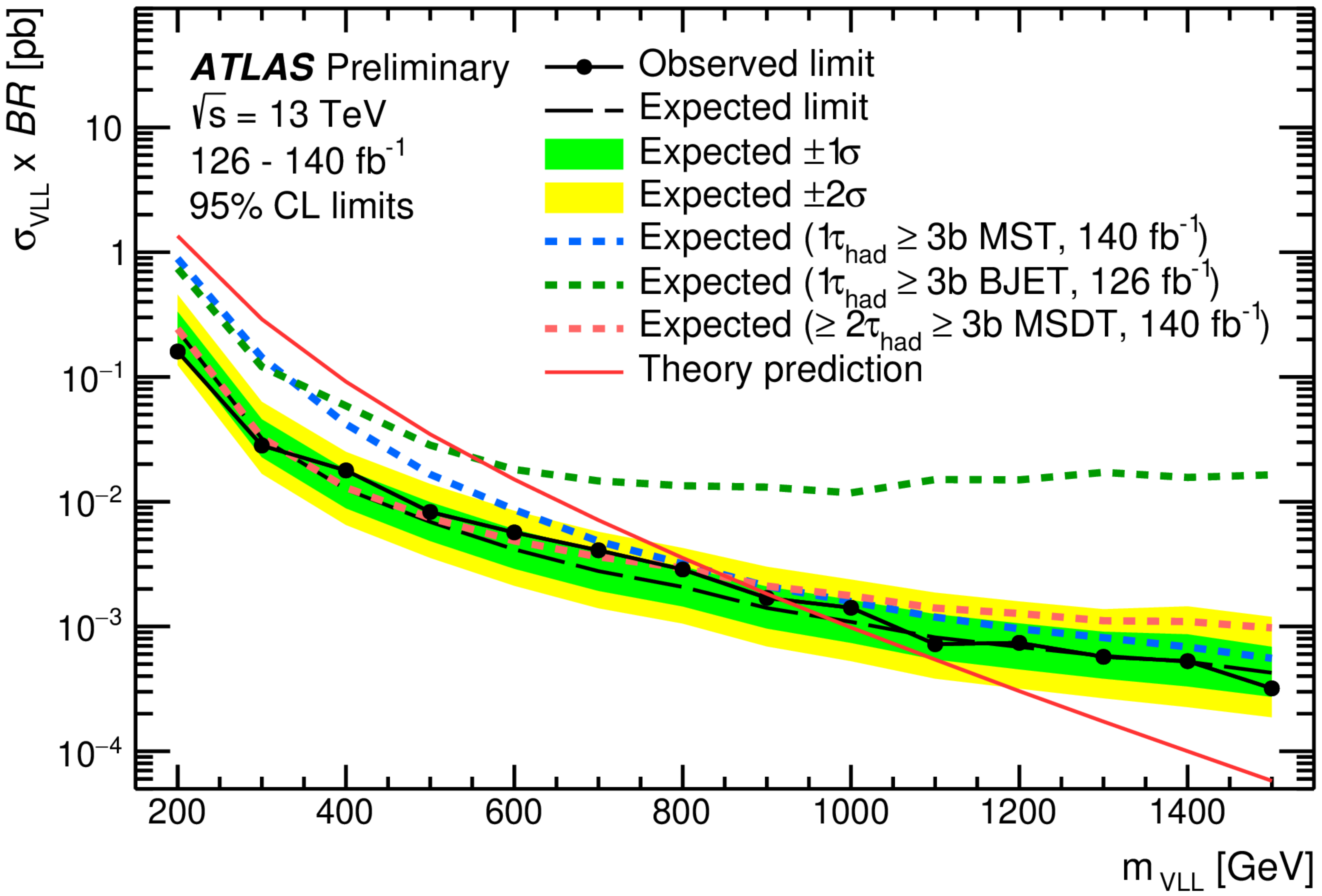
ATLAS-CONF-2024-008

VLLs : Hypothetical non-chiral, colour-singlet, spin-1/2 particles, predicted by many BSMs



Vector-like lepton pair production and decays

- EW production of a pair of VLLs **in multiple tau and b-jets final states** via decays of off-shell $W\pm$ or $Z/\gamma*$ bosons in the '4321' model.
- Events selected with at least one τ_{had} and at least two jets.
- Five Signal Regions with different τ_{had}, and b-jet multiplicities, 0 light leptons (electron or muon).
- Fit on Neural Network score distribution.

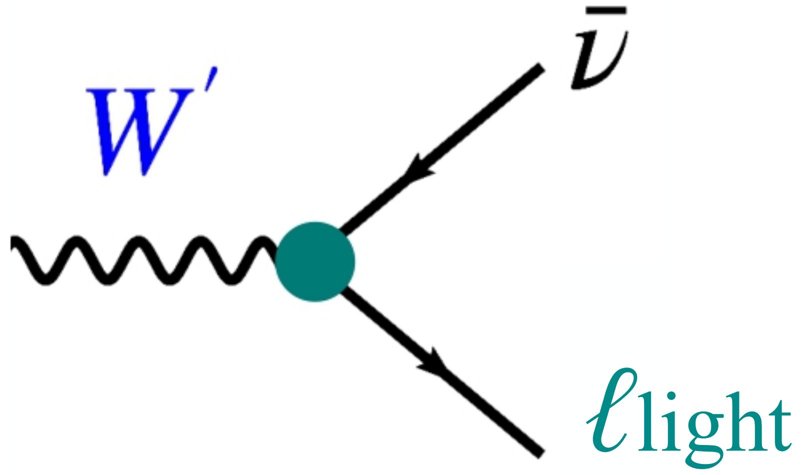


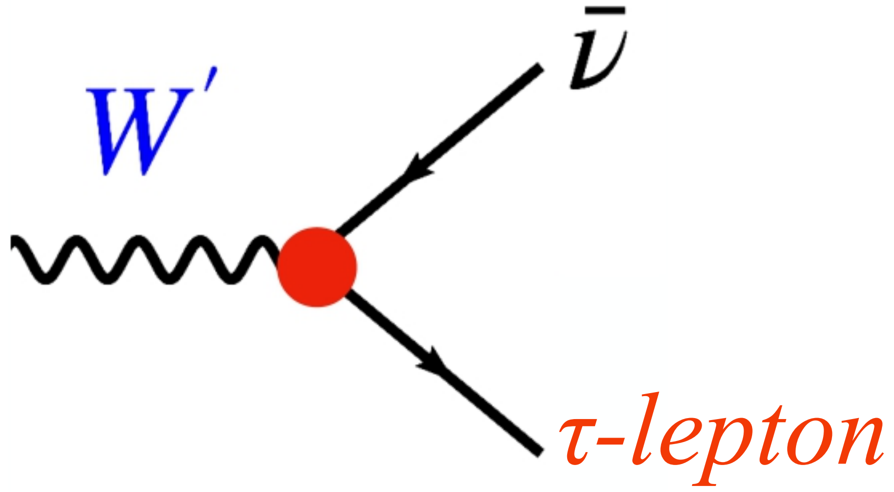
- ATLAS found the most stringent limits on this '4321' model to date.
- This first ATLAS result on the search for VLLs decaying through $U1$ to third generation SM fermions disfavours the 2.8σ excess at the 600 GeV VLL mass reported by the CMS Collaboration (Phys. Lett. B 846 (2023) 137713).
- Lower observed (expected) limit of 910 GeV (970 GeV) is set on the vector-like lepton mass.

High-mass resonance search in final states with τ-lepton and MET

PhysRevD.109.112008

Searches were made for heavy gauge bosons W' bosons decaying into a light-lepton, W' → lν (l= e,μ) and τ-lepton, W' → τν channels.





Previous ATLAS $W' \rightarrow \ell\nu$ ($\ell = e, \mu$) limit: 6.0 TeV (95% CL) (139 fb −1 of the 2015-2018 13 TeV data sample) [Phys. Rev. D 100 (2019) 052013]

Generally better sensitivity to *universal couplings (SSM model)*

lower backgrounds, better lepton reconstruction

Previous ATLAS $W' \rightarrow \tau\nu$ limit: 3.7 TeV (95% CL)
(36.1 fb −1 of the 2015-2016 13 TeV data sample)
[Phys. Rev. Lett. 120 (2018) 161802]

Can be more sensitive for *NUGIM (LFV) models*

Signatures in LHC detectors are high-momentum plus large MET

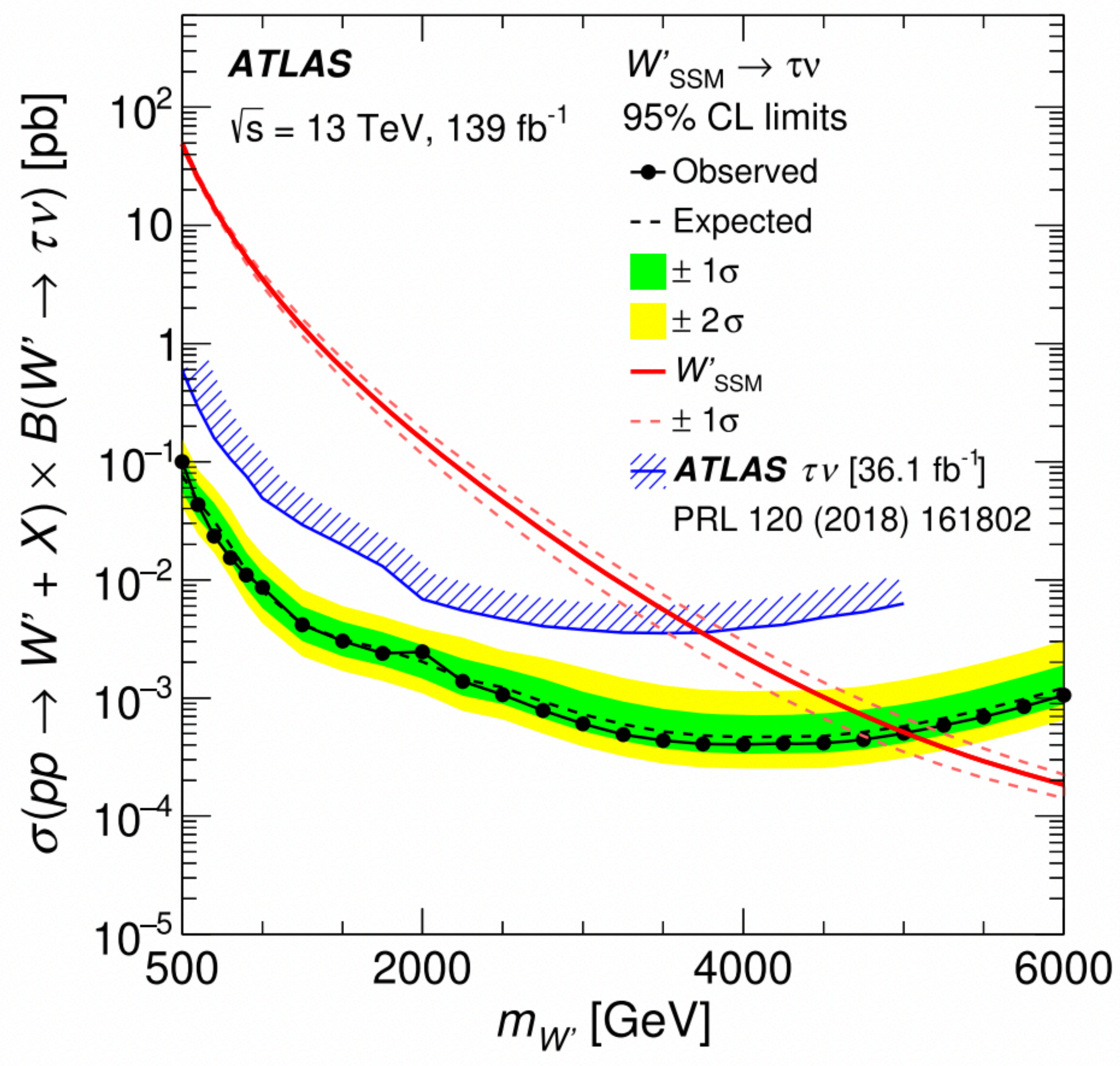
- Sequential Standard Model (SSM) : *assumes couplings of W', Z' to fermions are identical to W, Z in SM*
- Non-universal gauge interaction models (NUGIM) : *add non-universality via e.g. spontaneous symmetry breaking to 2* × SU(2) *with non-universality angle* θ_{NU}

High-mass resonance search in final states with τ-lepton and MET

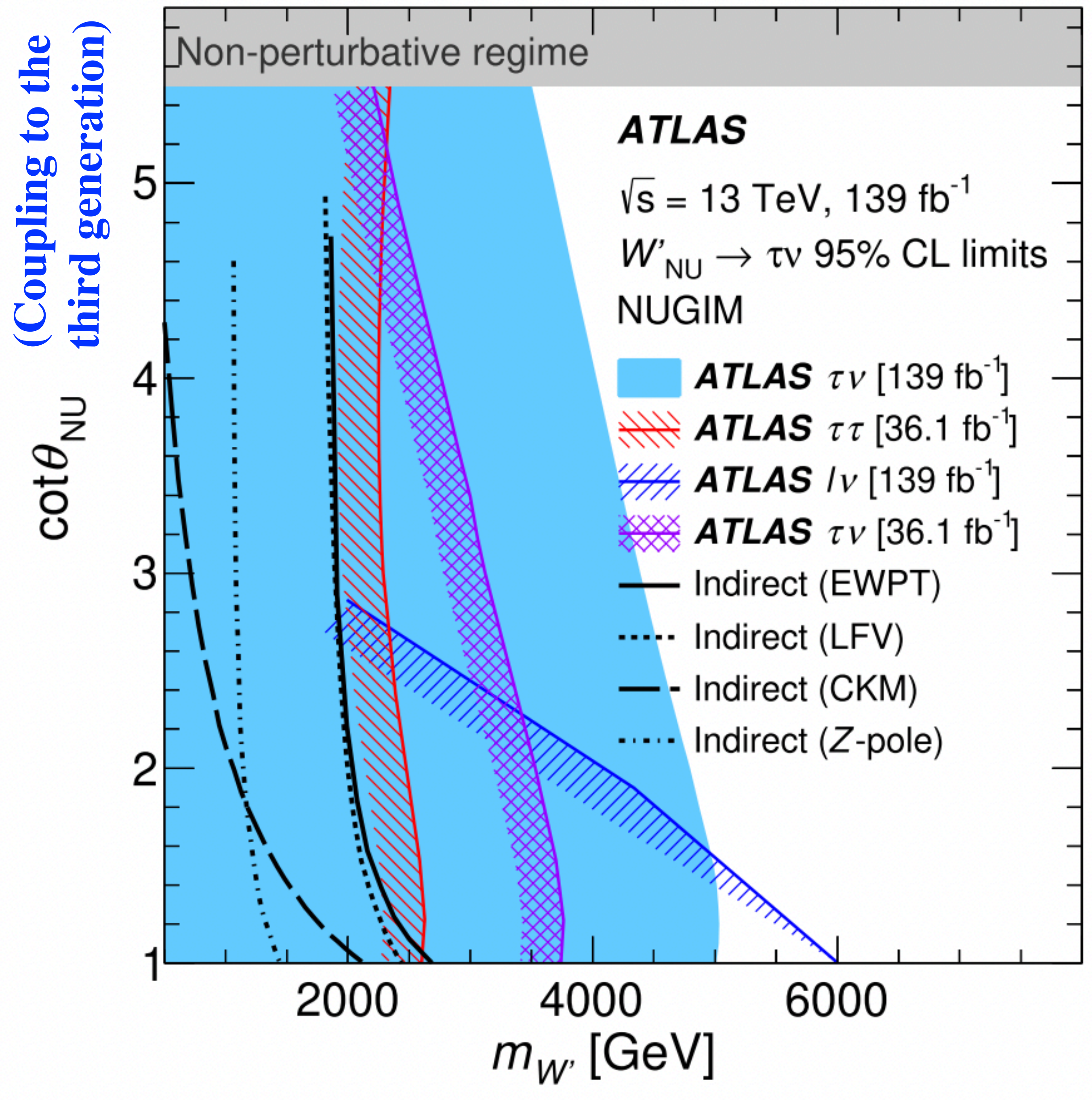
PhysRevD.109.112008

- Searched for resonance in the transverse mass spectrum
- Hadronic τ-lepton decays are identified with a recurrent neural network (RNN) algorithm
- A profile-likelihood fit to the m_T distributions of signal and background performed for statistical analysis

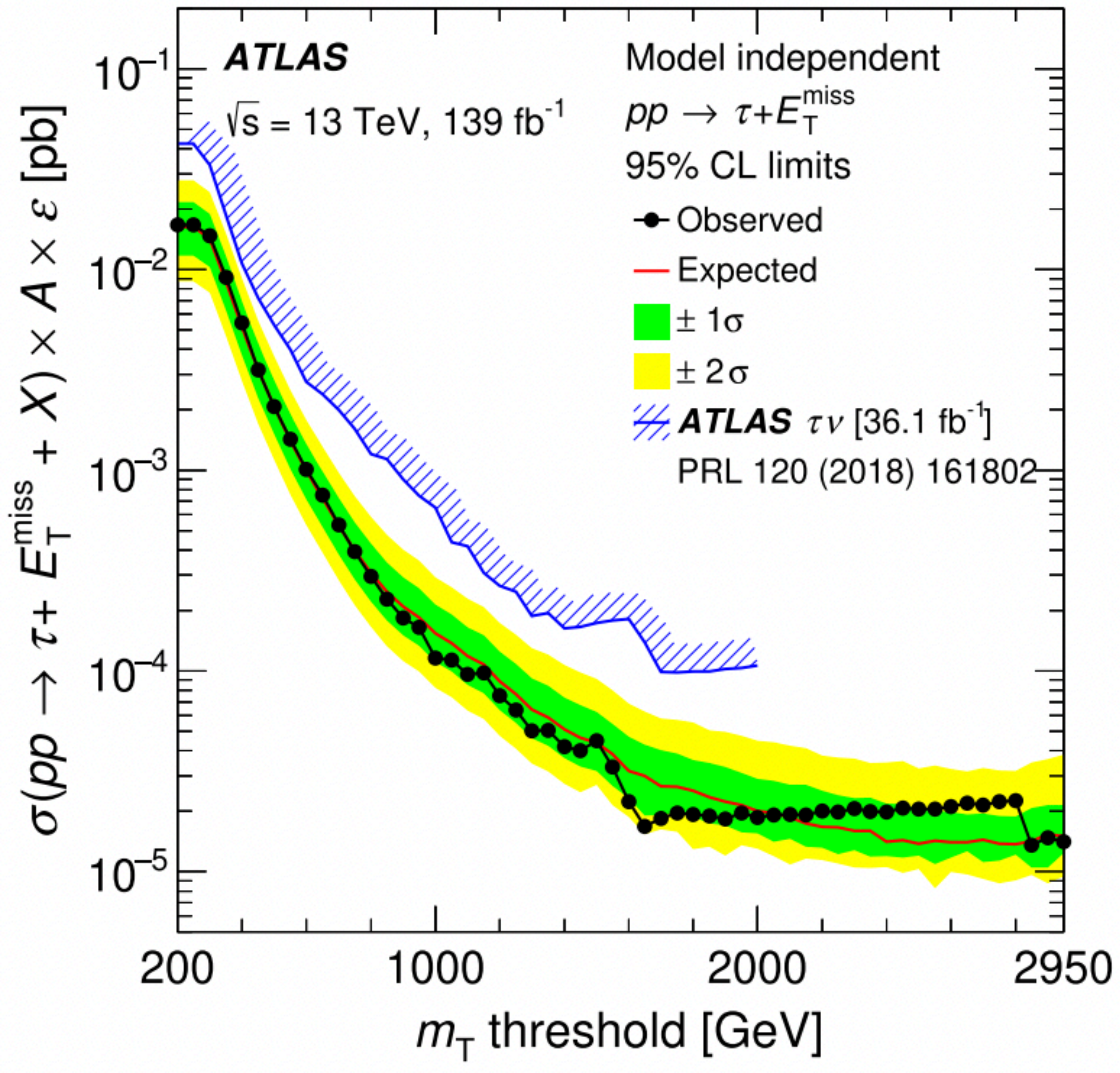
$W'_{SSM} \rightarrow \tau\nu < 5\ TeV$



Limit on NUGIM



Model-independent upper limits on production cross-section of $\tau + E_T^{miss}$:



- Exclusions at larger than 17 fb for $m_T^{thresh} = 0.2$ TeV and 0.014 fb for $m_T^{thresh} = 2.95$ TeV
- Improved upper limits on the visible cross section by a factor of 5 for for $m_T^{thresh} = 1.5$ TeV.

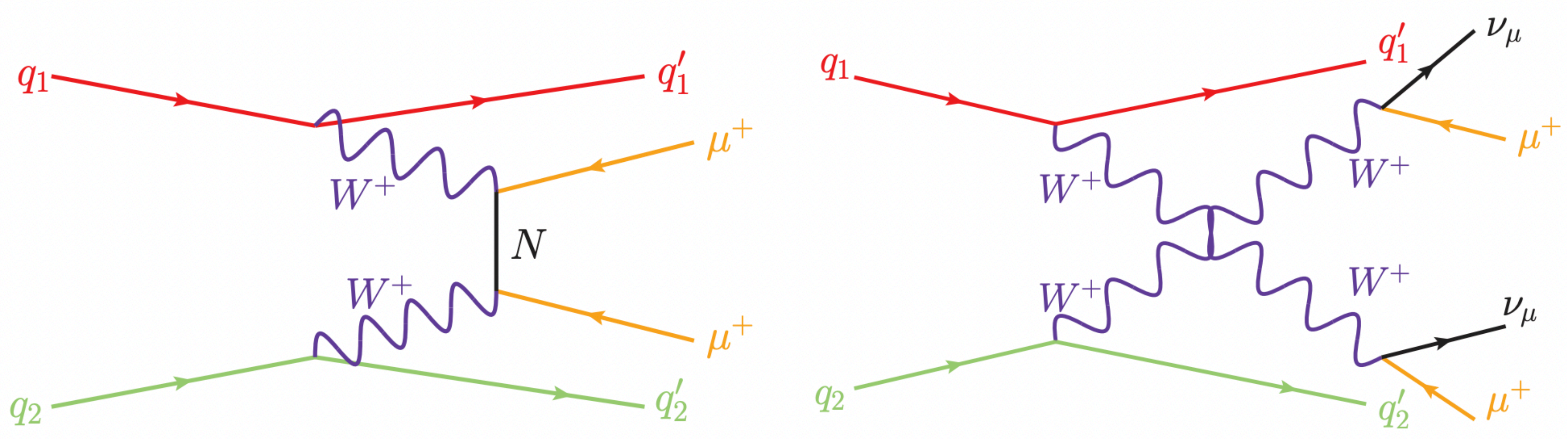
Transverse mass $m_T = \sqrt{2E_T^{miss}\, p_T^{\tau_{had\text{-}vis}}\,(1 - \cos\Delta\phi_{\tau_{had\text{-}vis},E_T^{miss}})}$

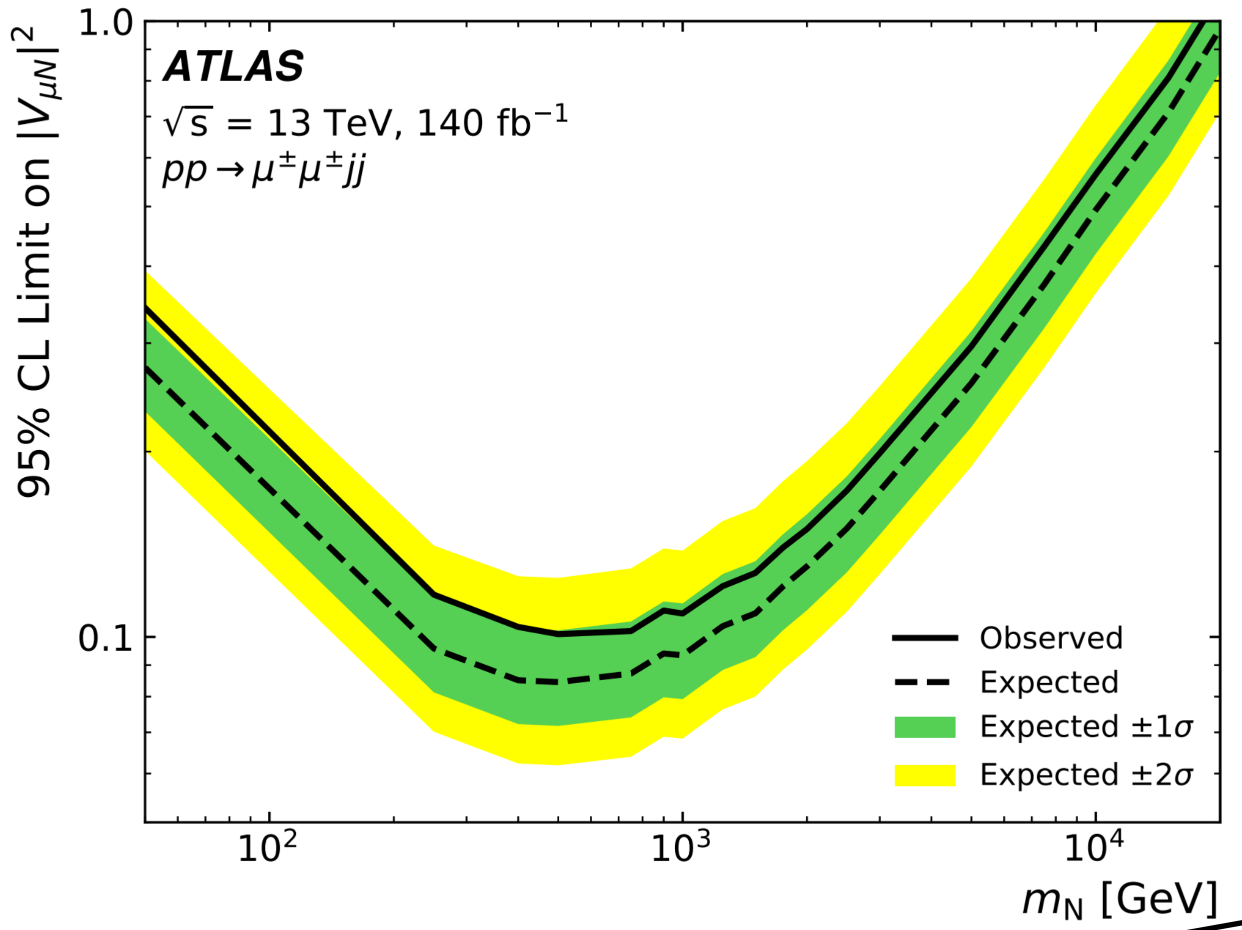
Heavy Majorana Neutrinos in same-sign *WW*

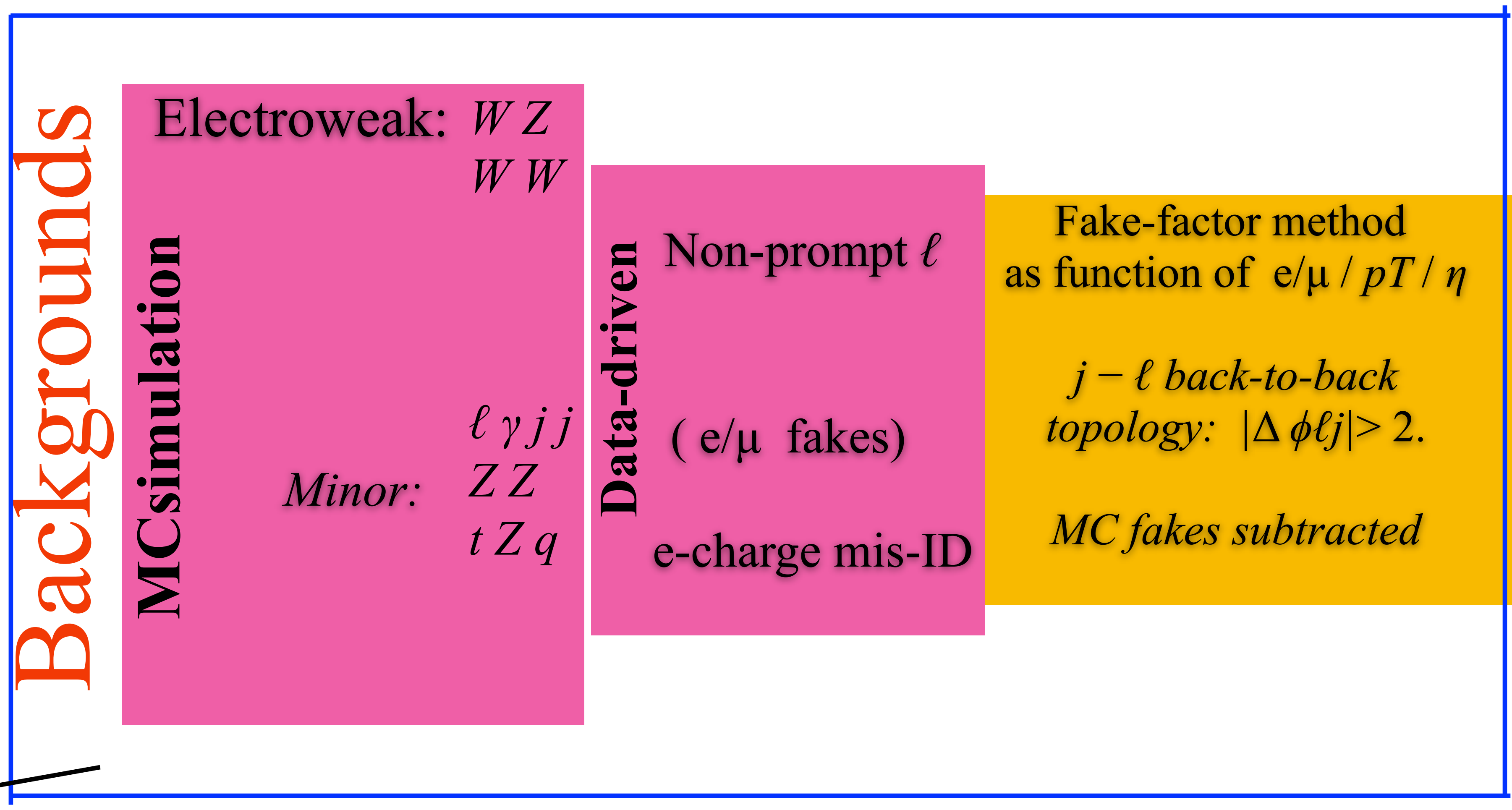
- Heavy Majorana neutrinos - couple to SM through mixing with SM neutrinos
- Type-1 Seesaw mechanism: $m_\nu \approx$ order of (v^2/m_N) where v = 246 GeV (Higgs v.e.v.) [Benchmark model]

V_{lN} : *Majorana neutrino mixing elements*

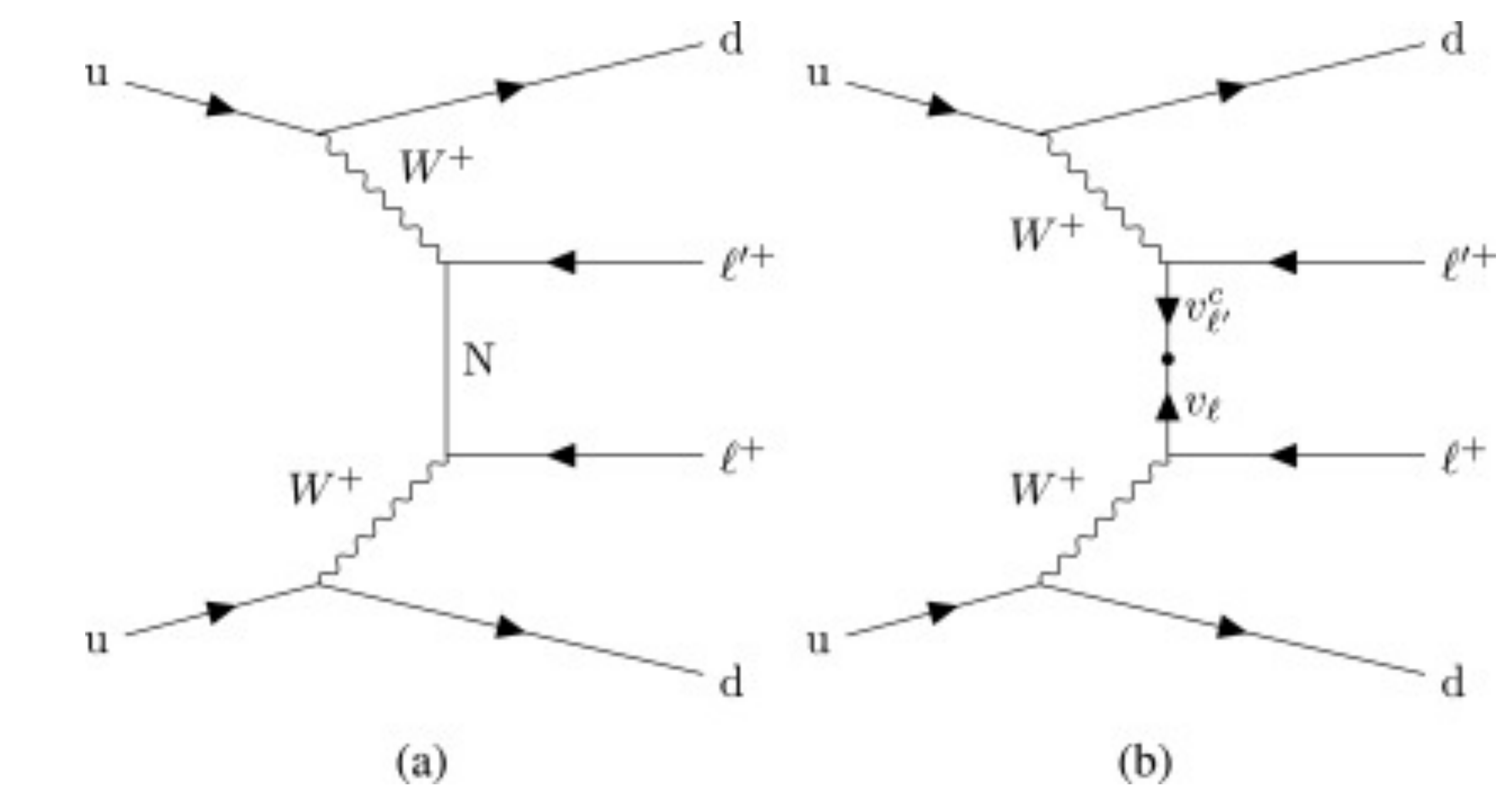
$\mu\mu$ channel : Eur. Phys. J. C 83 (2023) 824 :

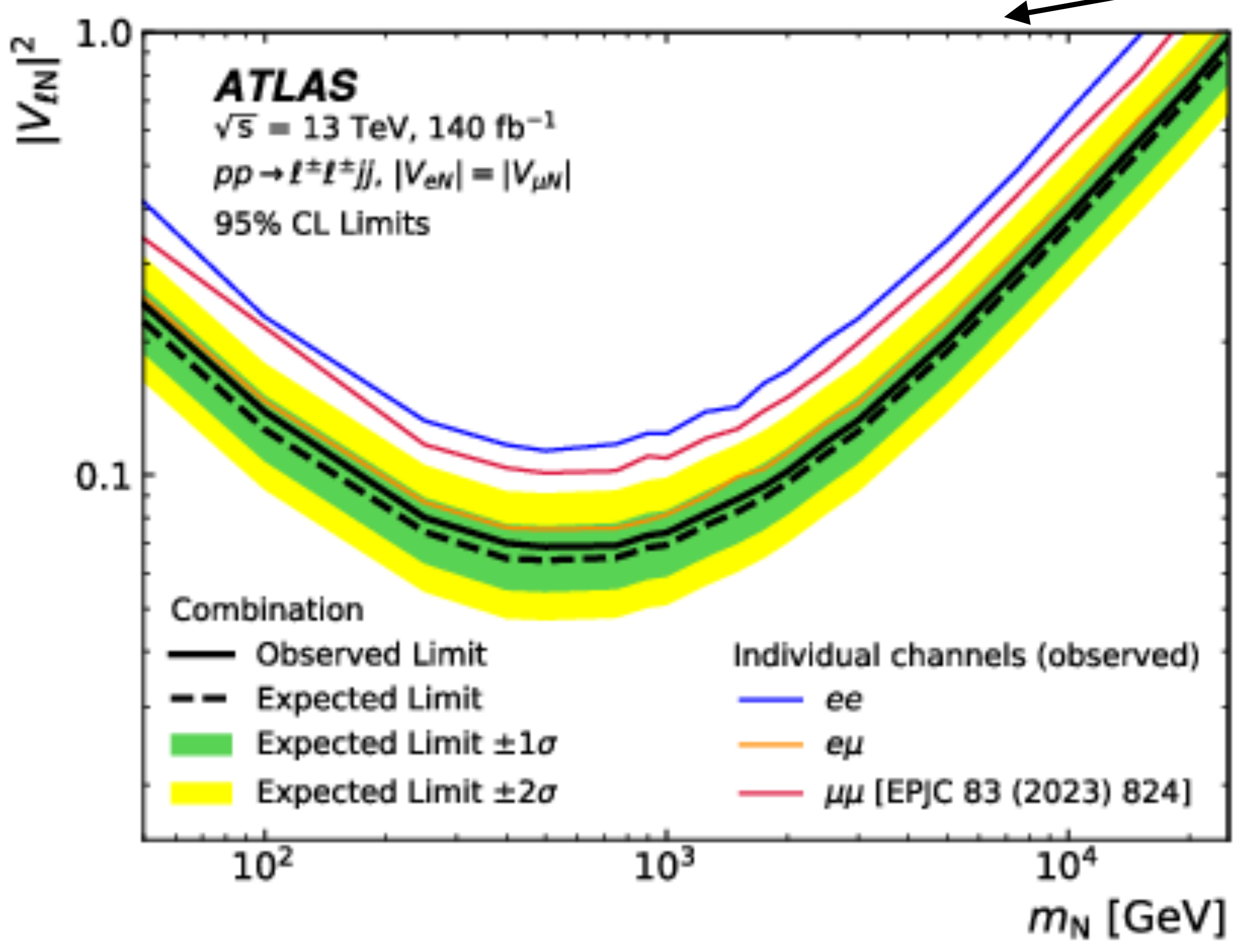


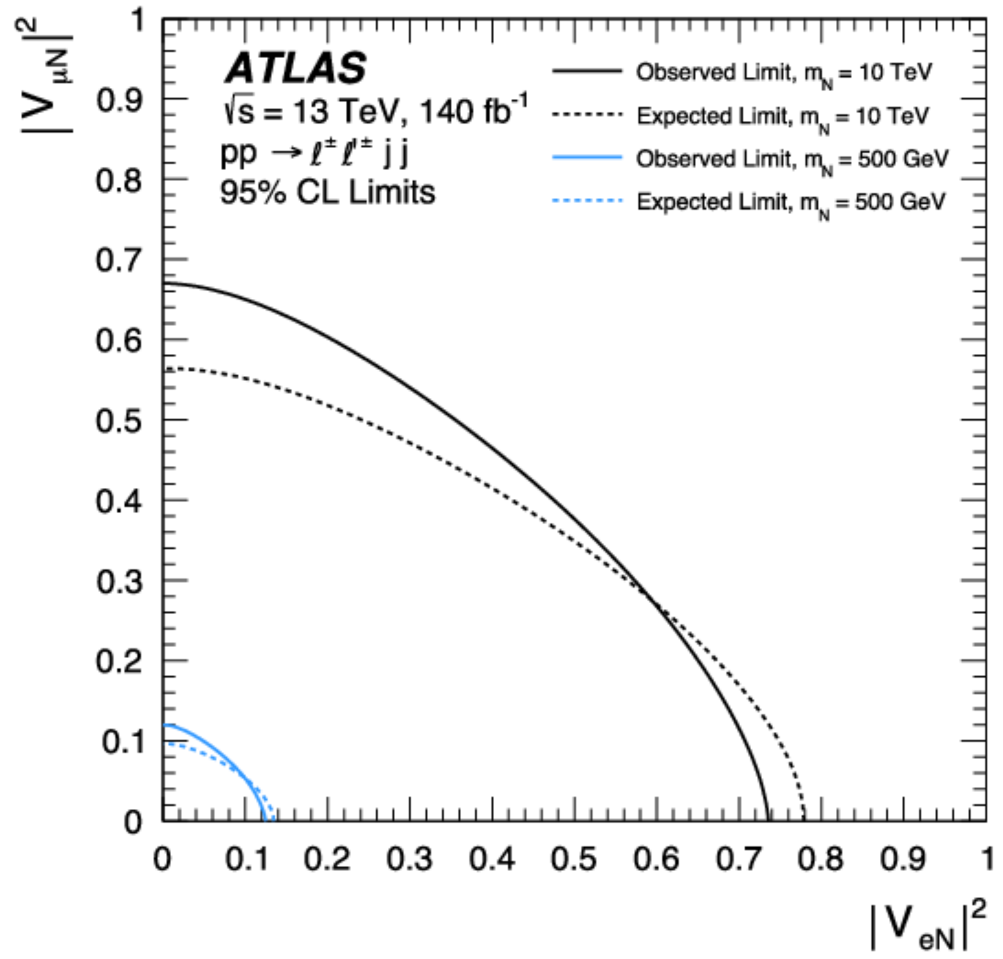




eμ/ee channel : Phys. Lett. B 856 (2024) 138865 :







- Statistical combination with $\mu\mu$ performed
- Combined limits 27% (16%) more stringent than $\mu\mu$ alone
- Observed. (Expected) limits are found as :
  m_{ee} : 24 GeV (24 GeV)
  $m_{e\mu}$: 13 GeV (15 GeV)
- At m_N = 500 GeV, strongest exclusion found

LFV in High-Mass Dilepton Final States

JHEP10(2023)082

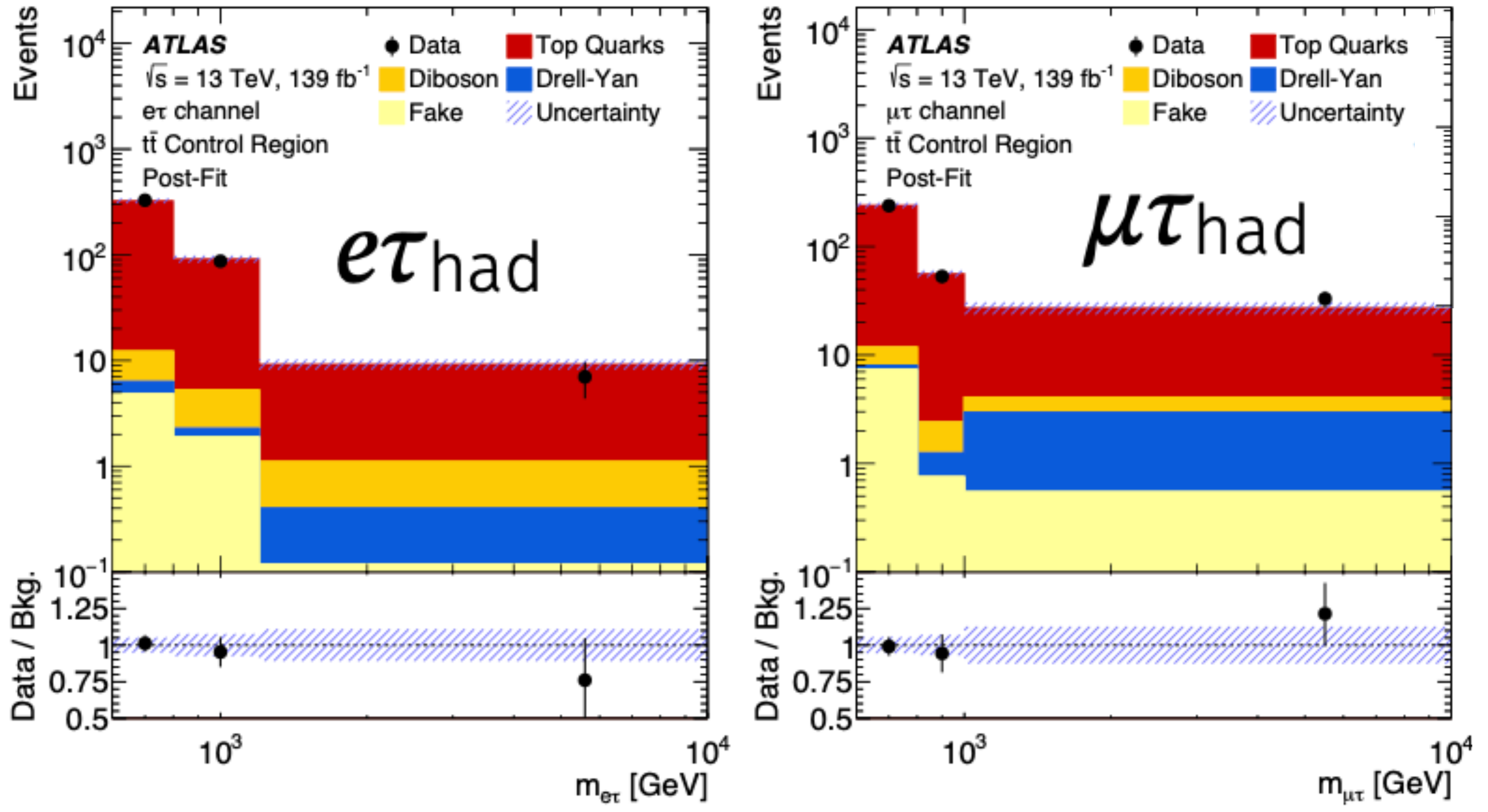
Search for new physics in final states with $e\mu$, $e\tau_{\text{had}}$, or $\mu\tau_{\text{had}}$ pairs are relevant for theories such as :

- Quantum black holes in quantum gravity with extra-spatial dimensions
- Sequential Standard Model with W', Z' heavy gauge bosons
- R-parity violating SUSY : *τ-sneutrino* ($\tilde{\nu}_\tau$) interpretations

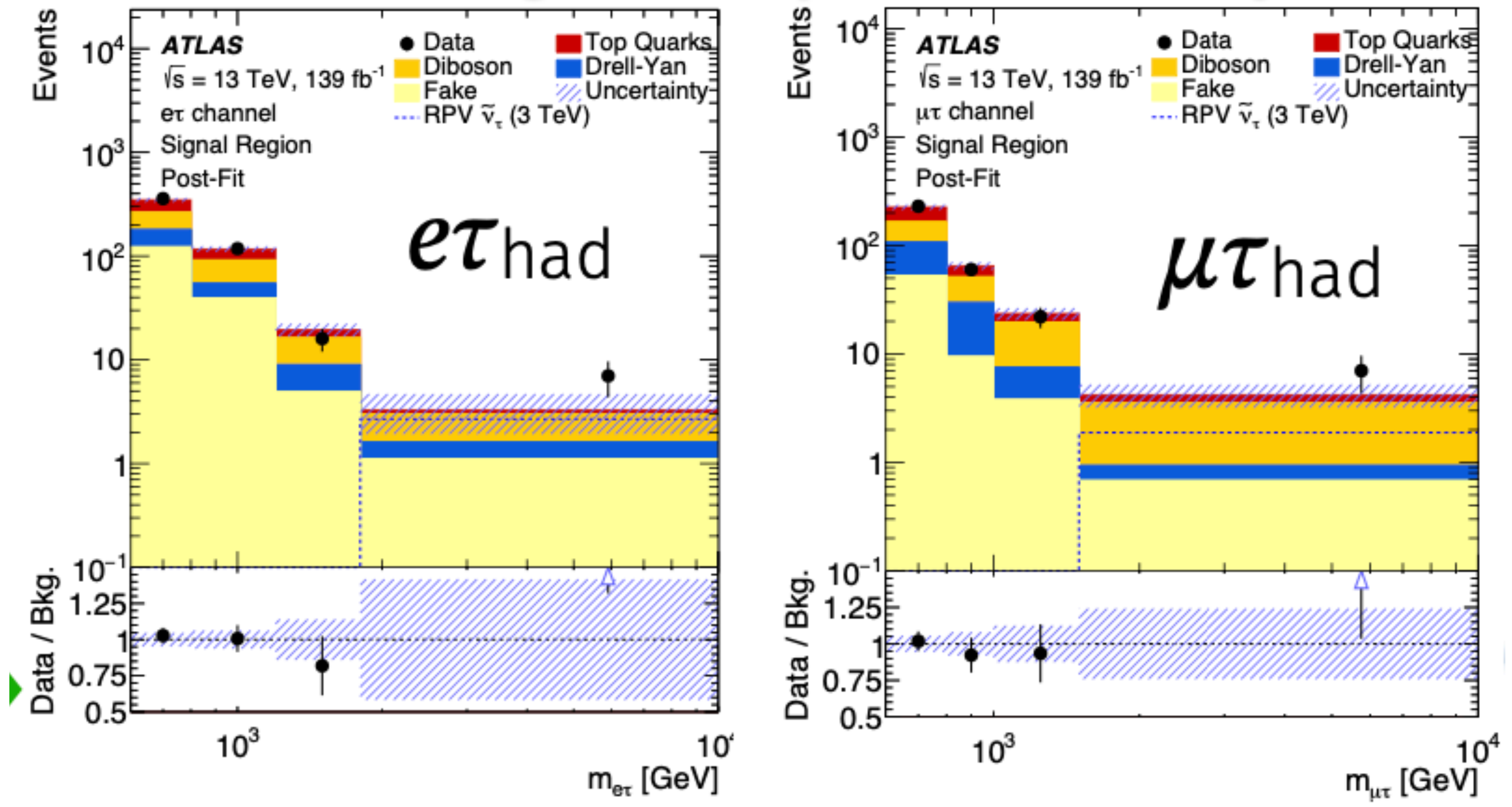
- Backgrounds: *Irreducible:* $t\bar{t}$ and WW are dominant (MC Simulation), Reducible: W+jets and multijet

Region	Channels	Requirements
		Nominal $\Delta\phi_{\ell\ell'}$
SR	$e\mu$, $e\tau$ and $\mu\tau$	$\Delta\phi_{\ell\ell'} > 2.7$, no b-jet, $m_{\ell\ell'} > 600$ GeV
$t\bar{t}$ CR	$e\mu$, $e\tau$ and $\mu\tau$	$\Delta\phi_{\ell\ell'} > 2.7$, at least one b-jet, $m_{\ell\ell'} > 600$ GeV
		Reversed $\Delta\phi_{\ell\ell'}$
Low $\Delta\phi_{\ell\ell'}$ $t\bar{t}$ CR	$e\mu$	$\Delta\phi_{\ell\ell'} < 2.7$, at least one b-jet, $m_{\ell\ell'} > 600$ GeV
WW CR	$e\mu$	$\Delta\phi_{\ell\ell'} < 2.7$, no b-jet, $m_{\ell\ell'} > 600$ GeV

Background-only fit in $t\bar{t}$ CR ≥ 1 b-jets



Background-only fit in SRs : no b-jets



LFV in High-Mass Dilepton Final States

JHEP10(2023)082

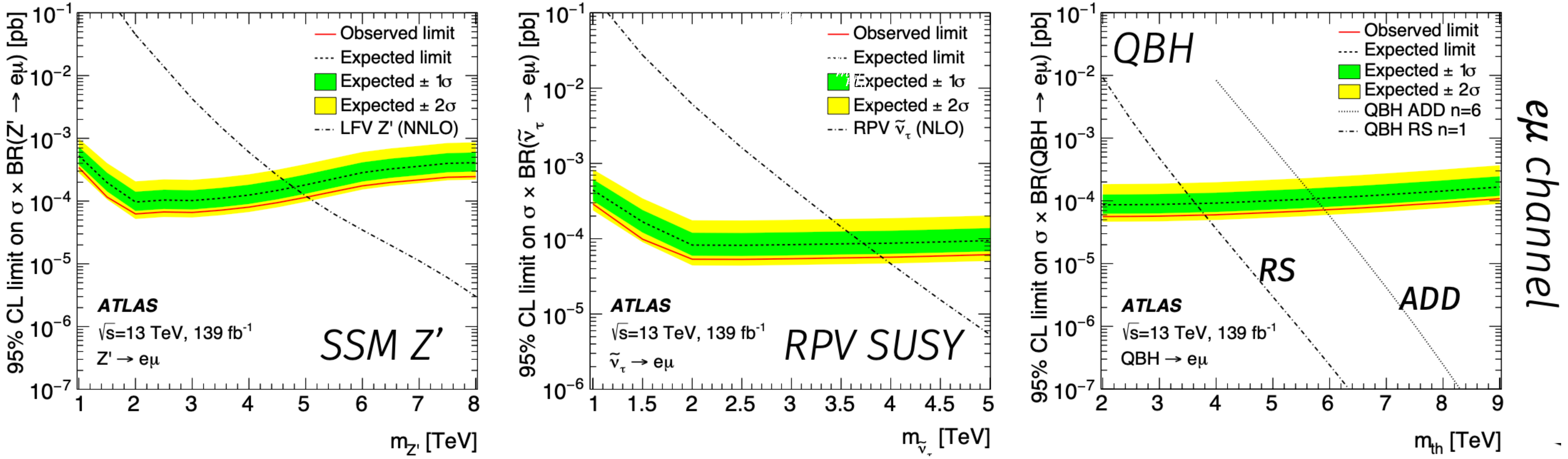
Search for new physics in final states with $e\mu$, $e\tau_{\text{had}}$, or $\mu\tau_{\text{had}}$ pairs are relevant for theories such as :

- Quantum black holes in quantum gravity with extra-spatial dimensions
- Sequential Standard Model with W', Z' heavy gauge bosons
- R-parity violating SUSY : τ-*sneutrino* ($\tilde{\nu}\tau$) interpretations

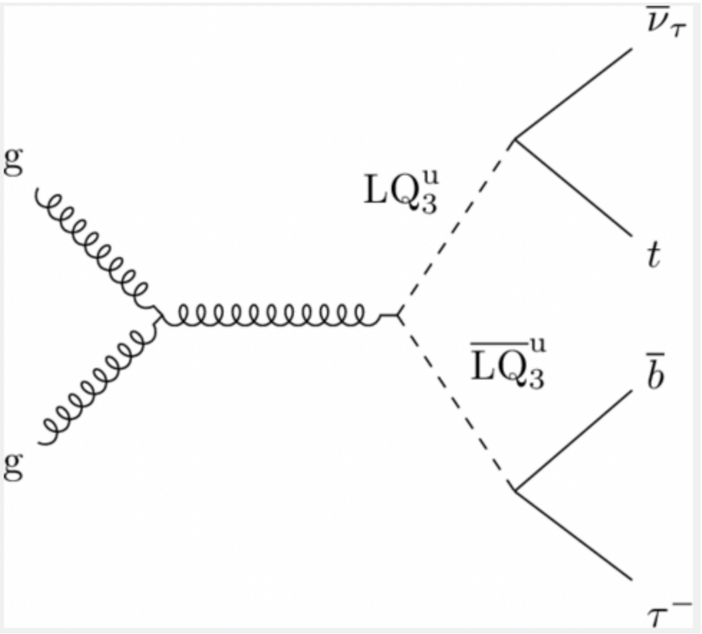
- Data consistent with SM
- In $\ell\tau$ channels, mild excess above background at 2.0-2.3 TeV
- Profile-likelihood fits on $m_{\ell\ell}$ set 95% CLs:

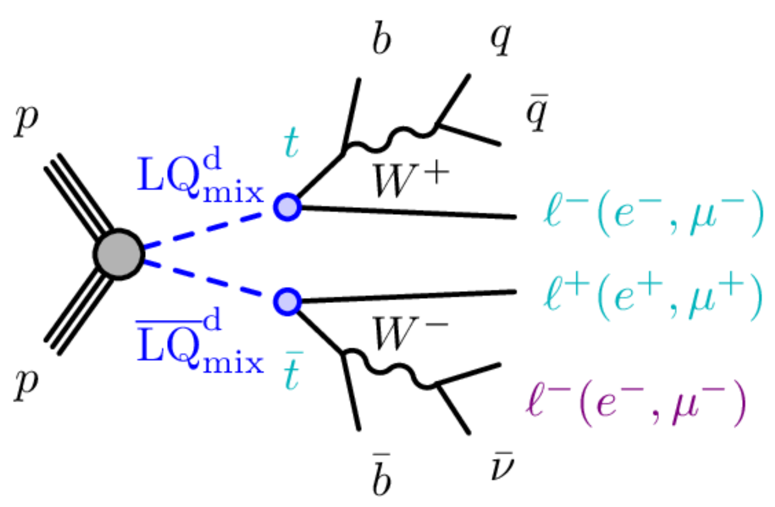
Limit	$e\mu$	$e\tau$	$\mu\tau$
LPV Z'	5.0	4.0	3.9
	4.5	*3.7*	*3.5*
RPV SUSY $\tilde{\nu}_\tau$	3.9	2.8	2.7
	3.4	*2.6*	*2.3*
QBH m_{th} (ADD)	5.9	5.2	5.1
	5.5	*4.9*	*4.5*
QBH m_{th} (RS)	3.8	3.0	3.0
	3.4	*2.9*	*2.6*

Previous ATLAS limits (Run 2, 2015-2016)



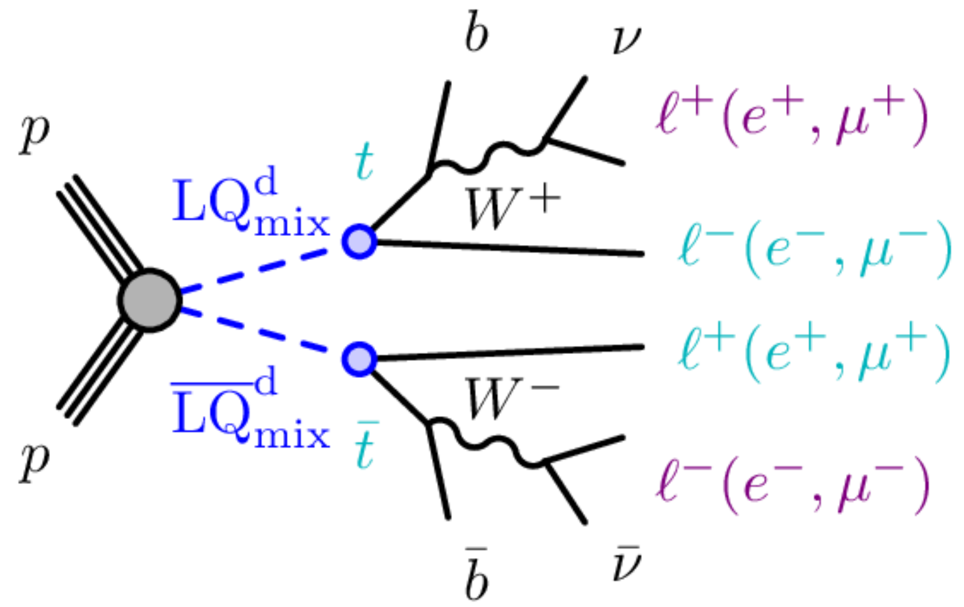
Searching for Leptoquarks





[JHEP 10 (2023) 001]

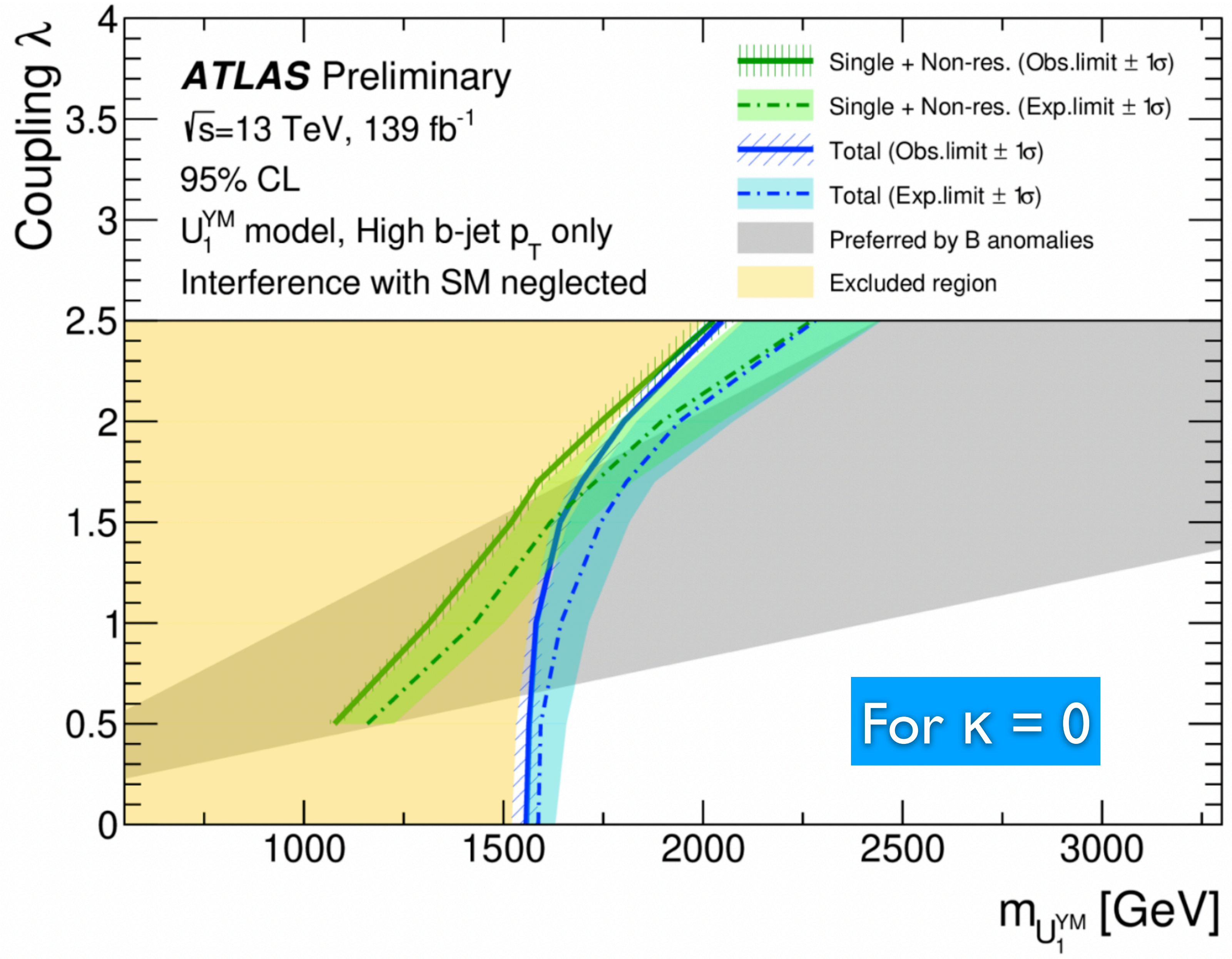
- Searched for **singly-produced** and **pair-produced leptoquarks** - Using full LHC Run-2 dataset ($139 fb^{-1}$)



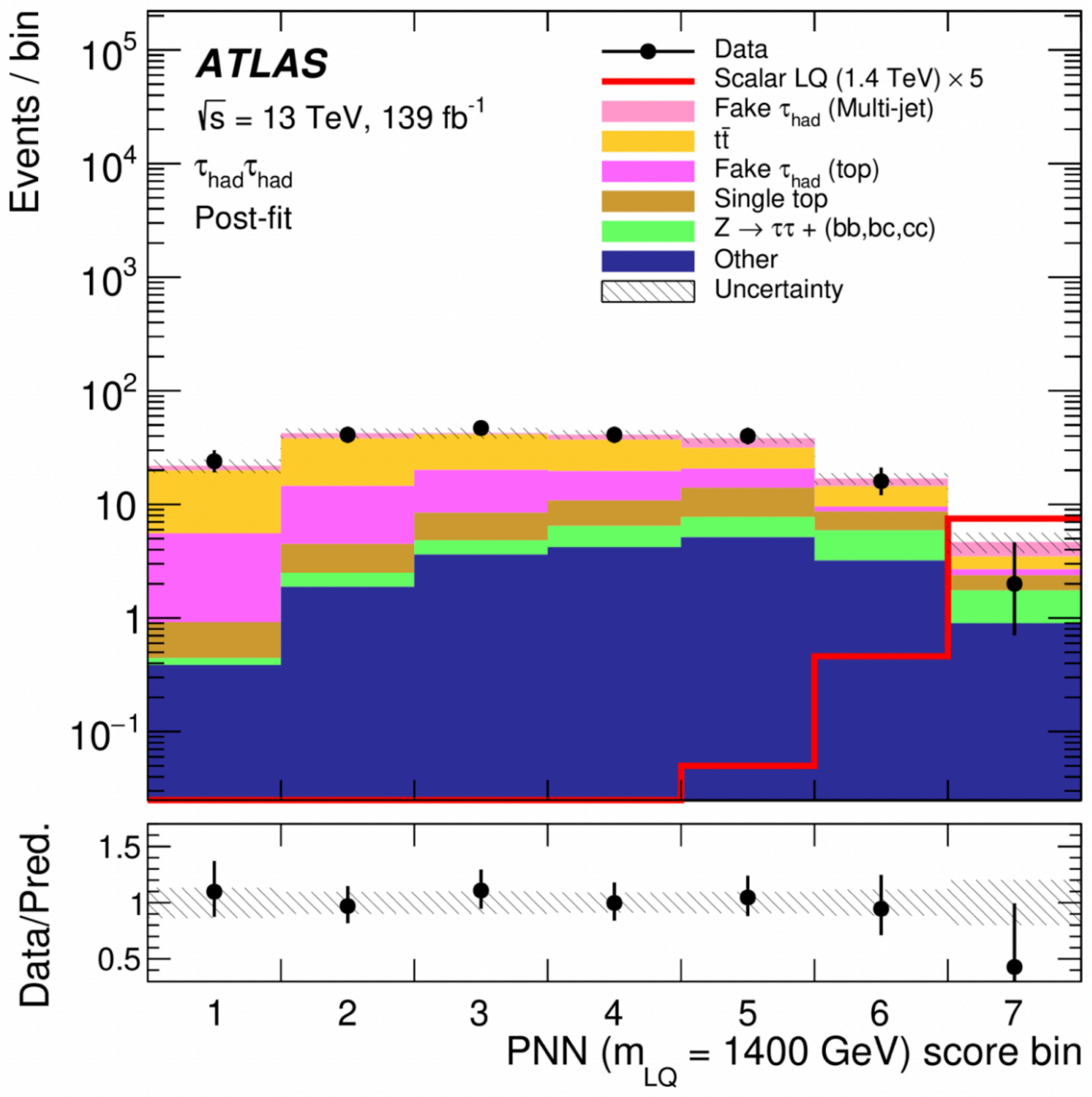
- Focused on interactions with third-generation quarks and leptons
  Such as : b-quark and τ lepton or top quark and light lepton (e / μ)

- Considered background processes (top-quark pairs with 'jets' of particles, W/Z bosons)

Singly+Non-res.+pair vector LQs



Pair-produced leptoquarks

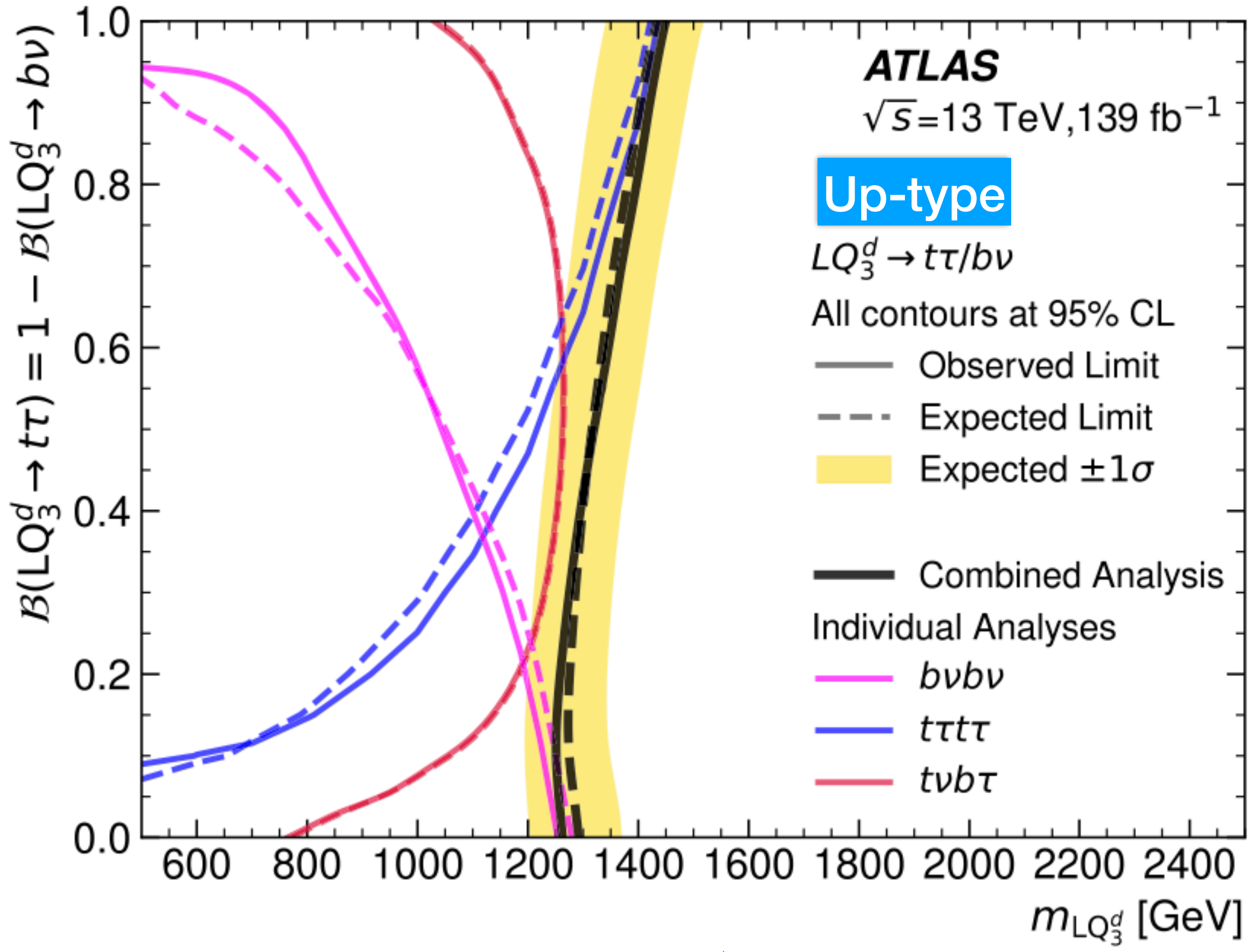


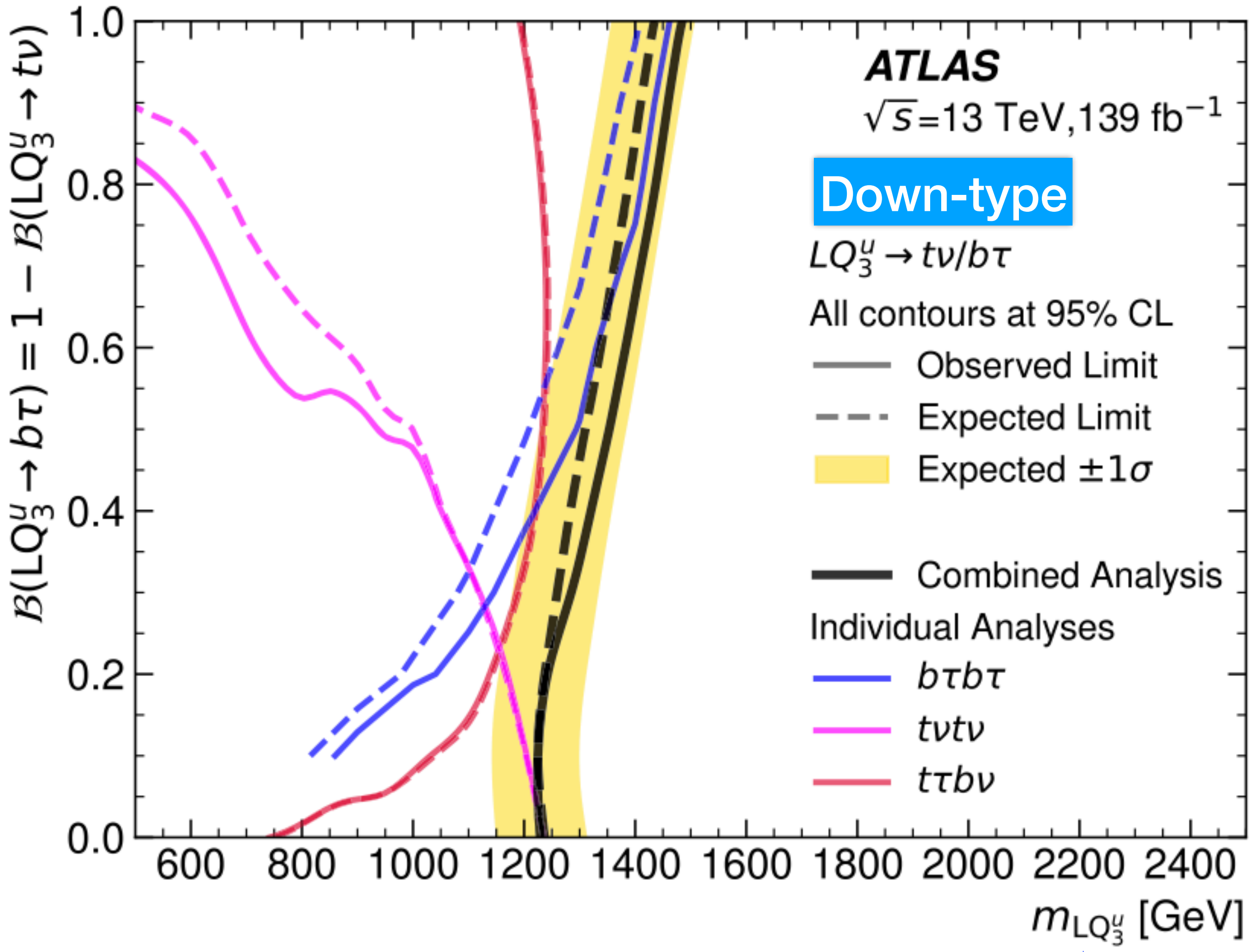
- **Singly-produced leptoquarks:**
  - For lower couplings (up to 1) : Lower mass limit of 1.58 TeV [Yang-Mills couplings].
  - For higher couplings (up to 2.5): Lower mass limit of 2 TeV
- **Pair-produced leptoquarks:**
  - Used a parameterised neural network (PNN) to improve mass bounds
  - Lower mass limit of 1.75 TeV for b-quark and tau-lepton decays
  - Scalar leptoquark mass below 1.64 TeV excluded for top quark and muon decays

Combination of pair-produced leptoquarks searches

Phys. Lett. B 854 (2024) 138736

Search		Scalar				Vector		Signal Region		
Final State	Citation	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}
$t\nu b\tau$	[54]	✓	✓	–	–	✓	–	0	1	≥ 2
$b\tau b\tau$	[55]	✓	–	–	–	✓	–	$\{0,1\}$	$\{1,2\}$	$\{1,2\}$
$t\tau t\tau$	[57]	–	✓	–	–	–	✓	$\{1,2,3\}$	≥ 1	≥ 1
$t\nu b\ell$	[40]	–	–	✓	✓	✓	–	1	–	≥ 1
$b\ell b\ell$	[58]	–	–	✓	–	–	–	2	–	$\{0,1,2\}$
$t\ell t\ell$ (2ℓ)	[59]	–	–	–	✓	–	–	2	–	–
$t\ell t\ell$ ($\geq 3\ell$)	[61]	–	–	–	✓	–	–	$\{3,4\}$	–	≥ 2
$t\nu t\nu$	[62]	✓	–	✓	–	✓	–	0	0	≥ 2
$b\nu b\nu$	[64]	–	✓	–	✓	–	–	0	–	≥ 2





Improvements in limits

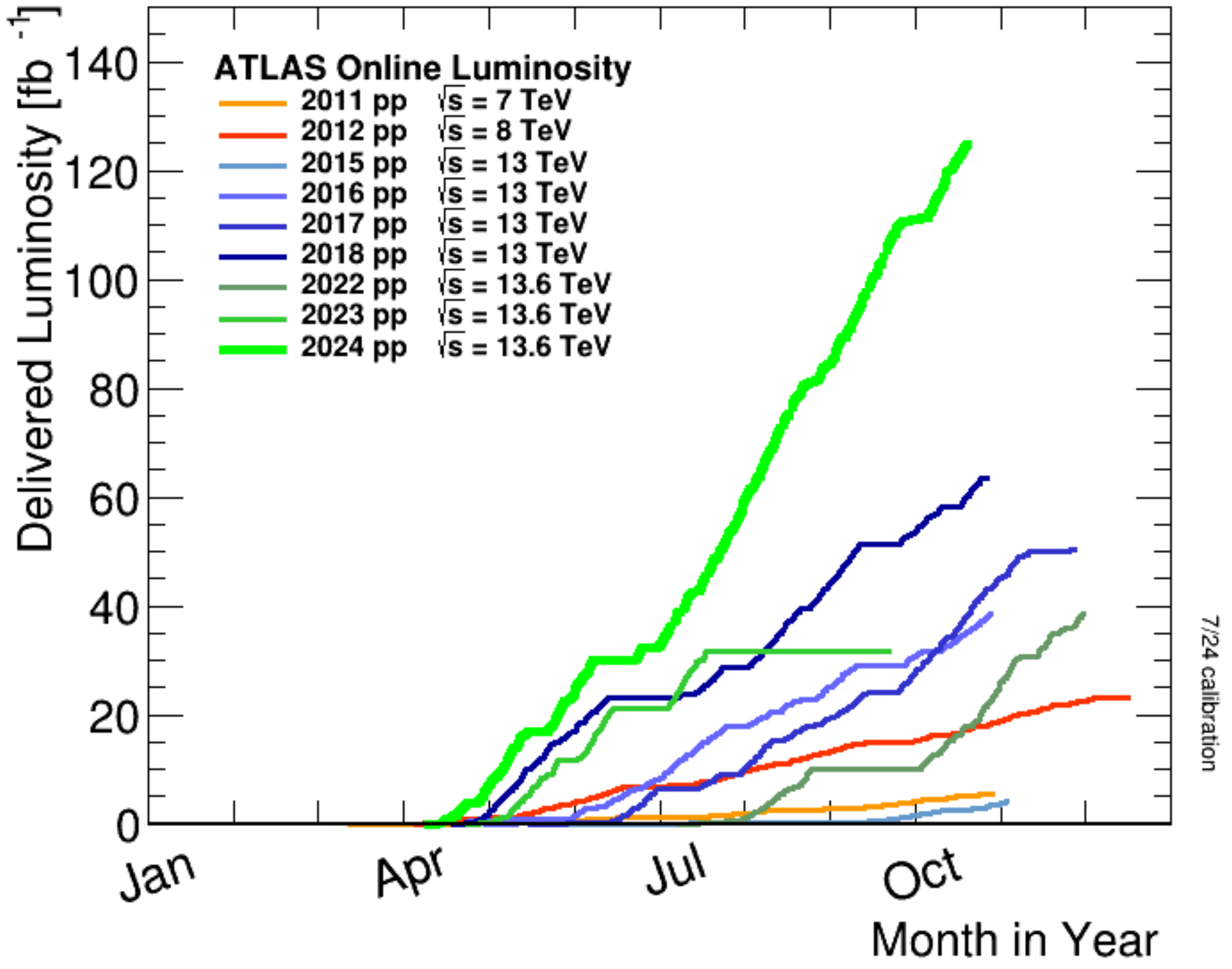
Leptoquark Type	Decay Channel / Conditions	Exclusion Limit Improvement
Scalar Third-Generation Up-type	For intermediate values of β	Up to 100 GeV
Scalar Third-Generation Down-type	-	Up to 70 GeV
Scalar Up-type	Third-generation quark + first- or second-generation lepton	Up to 80 GeV (muon), 90 GeV (electron)
Scalar Down-type	Third-generation quark + first- or second-generation lepton	Up to 60 GeV (muon), 80 GeV (electron)
Pair Produced Scalar LQs	All decay channels	Better than CMS limits at Beta = 0.0, 0.5, 1.0

Branching ratio	$\mathcal{B}=0.0$		$\mathcal{B}=0.5$		$\mathcal{B}=1.0$	
	95 % CL Limit [GeV]		95 % CL Limit [GeV]		95 % CL Limit [GeV]	
	Observed	Expected	Observed	Expected	Observed	Expected
$LQ_3^u \rightarrow t\nu/b\tau$	1240	1240^{+70}_{-90}	1340	1300^{+70}_{-80}	1480	1440^{+70}_{-80}
$LQ_3^d \rightarrow t\tau/b\nu$	1260	1260^{+80}_{-80}	1360	1340^{+60}_{-70}	1520	1470^{+70}_{-70}
$LQ_{mix}^u \rightarrow t\nu/b\mu$	1230	1310^{+70}_{-70}	1570	1510^{+70}_{-70}	1710	1650^{+90}_{-90}
$LQ_{mix}^u \rightarrow t\nu/be$	1230	1310^{+70}_{-70}	1510	1550^{+80}_{-80}	1730	1740^{+90}_{-100}
$LQ_{mix}^d \rightarrow t\mu/b\nu$	1240	1260^{+70}_{-80}	1430	1470^{+70}_{-70}	1600	1650^{+80}_{-80}
$LQ_{mix}^d \rightarrow te/b\nu$	1230	1250^{+70}_{-70}	1450	1500^{+70}_{-70}	1650	1660^{+90}_{-90}
$U_1^{YM} \rightarrow t\nu/b\tau$	-	-	1840	1810^{+80}_{-90}	-	-
$U_1^{MC} \rightarrow t\nu/b\tau$	-	-	1580	1560^{+70}_{-70}	-	-
$U_1^{YM} \rightarrow t\nu/b\mu$	-	-	1980	1930^{+50}_{-60}	-	-
$U_1^{MC} \rightarrow t\nu/b\mu$	-	-	1710	1660^{+50}_{-50}	-	-
$U_1^{YM} \rightarrow t\nu/be$	-	-	1900	1930^{+50}_{-70}	-	-
$U_1^{MC} \rightarrow t\nu/be$	-	-	1620	1650^{+50}_{-60}	-	-
$\tilde{U}_1^{YM} \rightarrow t\tau$	-	-	-	-	1810	1810^{+80}_{-70}

Summary and Future Prospects

- Various ongoing efforts underway in ATLAS to search for new physics signals using leptons.
- Innovative data-driven and Machine learning techniques are being used.
- No significant deviations from the predictions of the Standard Model (SM) have been observed.

ATLAS luminosity graph



Run 3 Improvements :

- Increased data collection (100 fb-1)
- Higher center-of-mass energy
- Enhanced hardware and software triggers
- Improved lepton performance

HL-LHC Potential :

- Massive increase in luminosity
- Improved tracking performance with ITk
- Enhanced discovery potential for new lepton physics

Stay tuned for new results from ATLAS experiment at CERN !


Thank You!

Back up slides

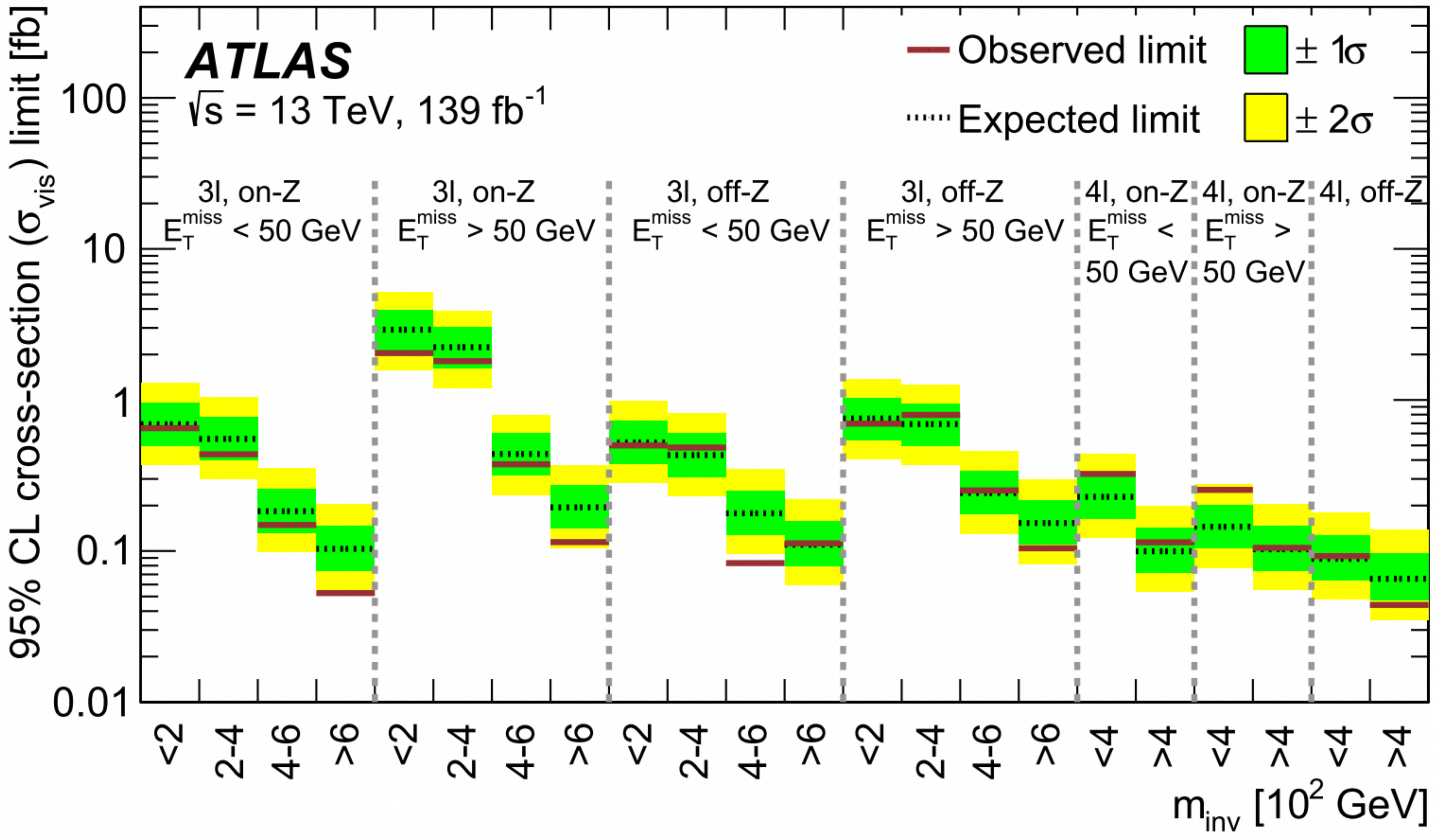
m_{jjl}

Search for new phenomena in three- or four-lepton events

Phys. Lett. B 824 (2022) 136832

ATLAS analysis at $\sqrt{s}$ = 13 TeV with full Run 2 data used Dilepton triggers and lepton flavour combinations while looking for 3-leptons and 4-leptons in final states.

A total of 22 signal regions were defined according to the number of leptons, the missing transverse momentum, the presence of a lepton pair originating from a Z-boson decay, and the invariant mass of the leptons etc.

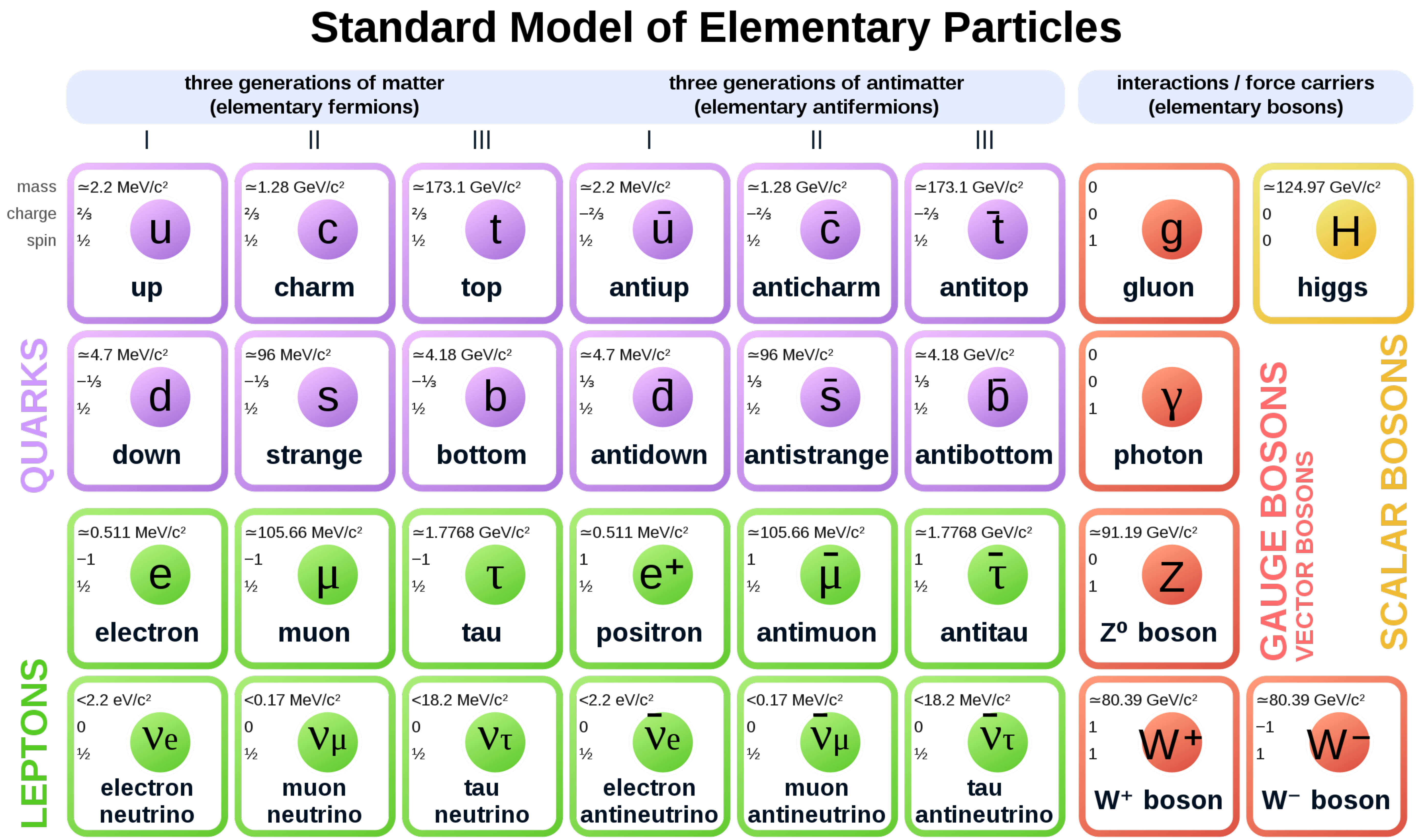


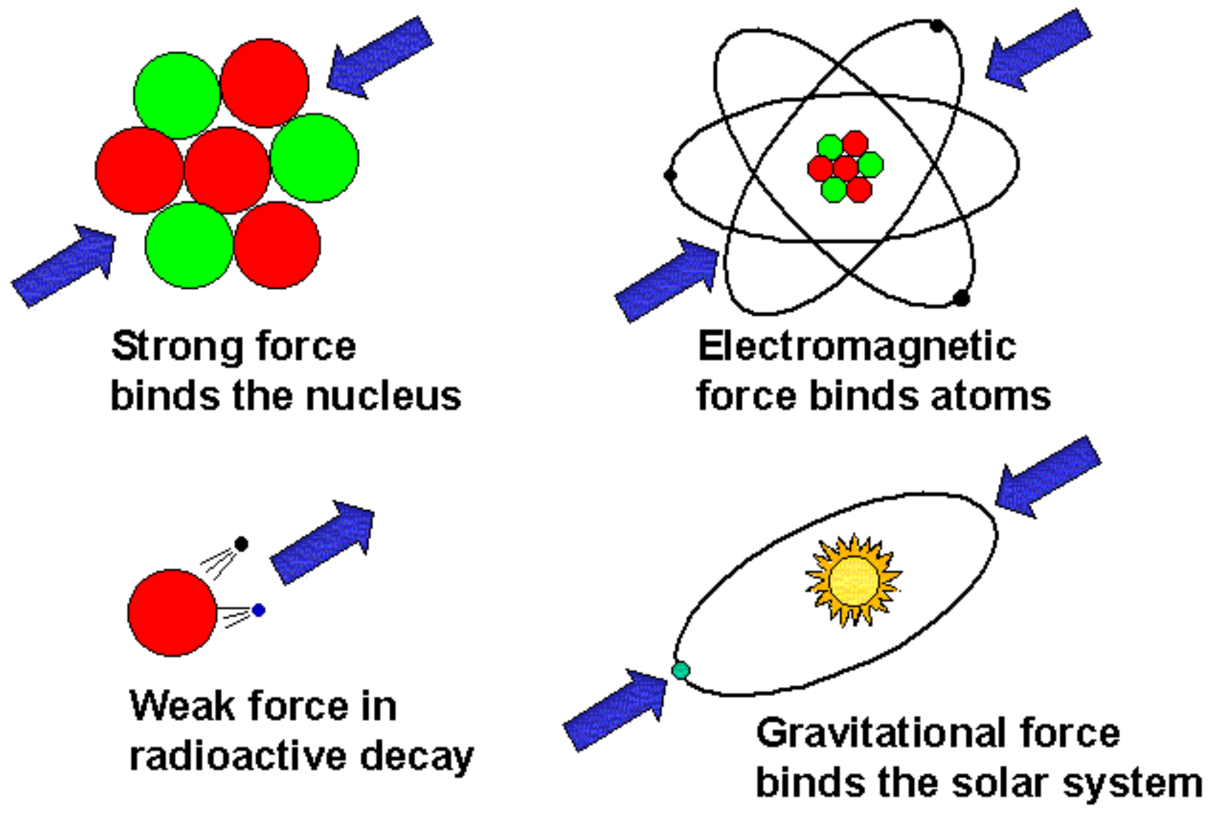
Model-specific limits

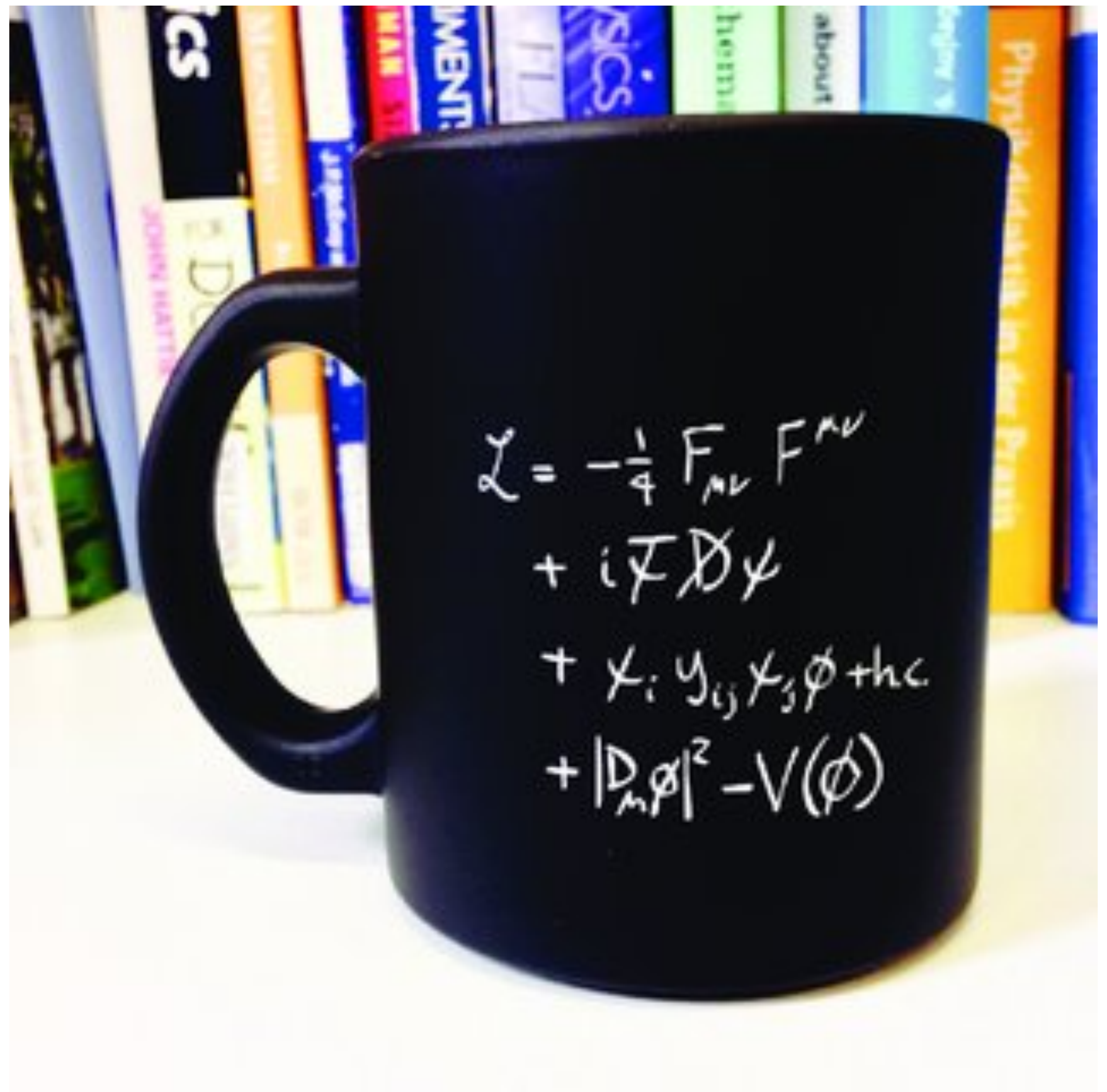
Expected and observed cross-section exclusion limits at 95% CL for representative mass values of the two selected models. Also the most sensitive bin, which was used to obtain these limits for each case, is listed, along with the signal acceptance times efficiency in this region (denoted by $A \times \epsilon$).

Model	Mass [GeV]	Best single SR	m_{inv}	$A \times \epsilon$	$\sigma^{95}_{\mathrm{exp}}$ [fb]	$\sigma^{95}_{\mathrm{obs}}$ [fb]
Type-III Seesaw	400	3ℓ, Off-Z, $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV	> 600 GeV	0.0036	41^{+17}_{-11}	27
	700	3ℓ, Off-Z, $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV	> 600 GeV	0.012	12^{+5}_{-3}	8.8
$H^{\pm\pm}$	300	4ℓ, Off-Z	> 400 GeV	0.37	$0.18^{+0.08}_{-0.05}$	0.12
	500	4ℓ, Off-Z	> 400 GeV	0.40	$0.16^{+0.07}_{-0.05}$	0.11

The Standard Model of Particle Physics







ATLAS detector of CERN

ATLAS (A Toroidal LHC ApparatuS) is one of the two general purpose detectors placed at one of the collision points of LHC ring at CERN.

At 46 m long, 25 m high and 25 m wide, the 7000-tonne ATLAS detector is the largest volume particle detector at CERN.

It sits in a cavern 100 meter below ground near the main CERN site, close to the village of Meyrin in Switzerland.