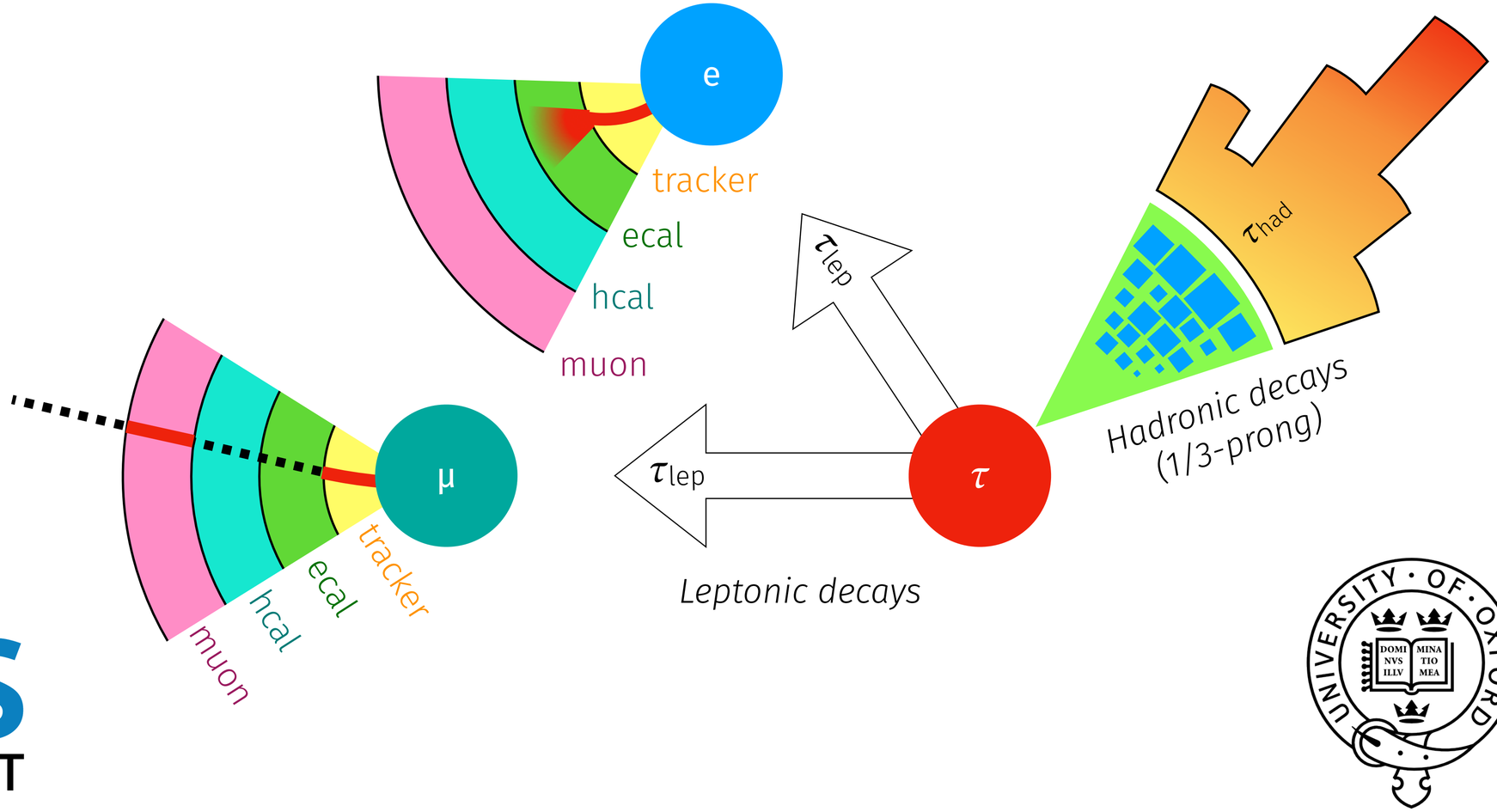
Searches for new physics with leptons using the ATLAS detector

Simon Koch

SUSY 2024, Madrid

10.06 - 14.06

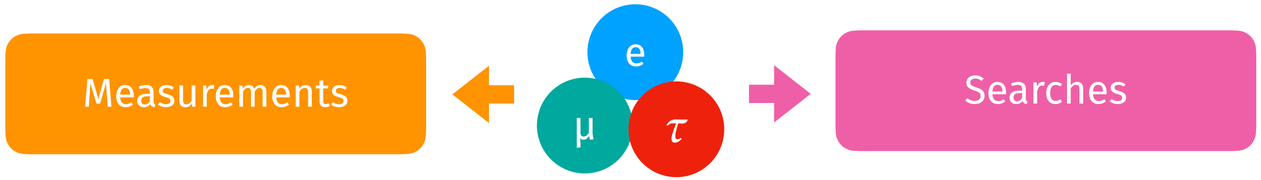


ATLAS EXPERIMENT

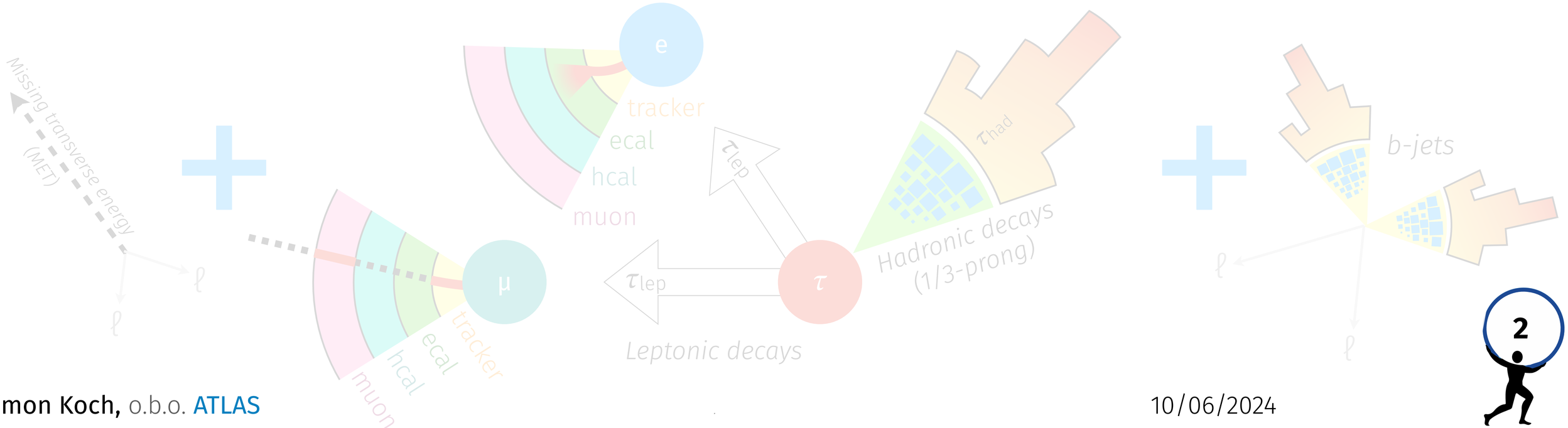
UNIVERSITY OF OXFORD

Motivation - Leptons in Final State

- Leptons provide a very clean signature → minimise detector resolution systematics



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



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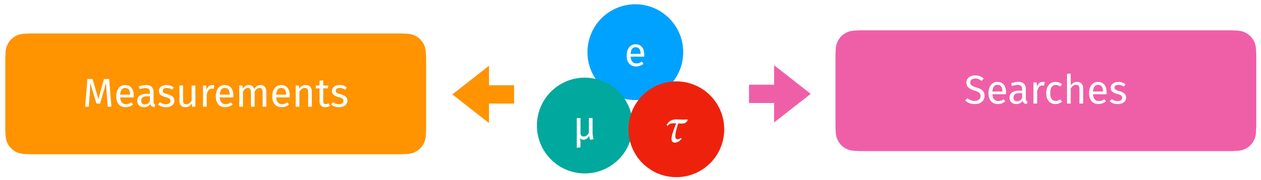

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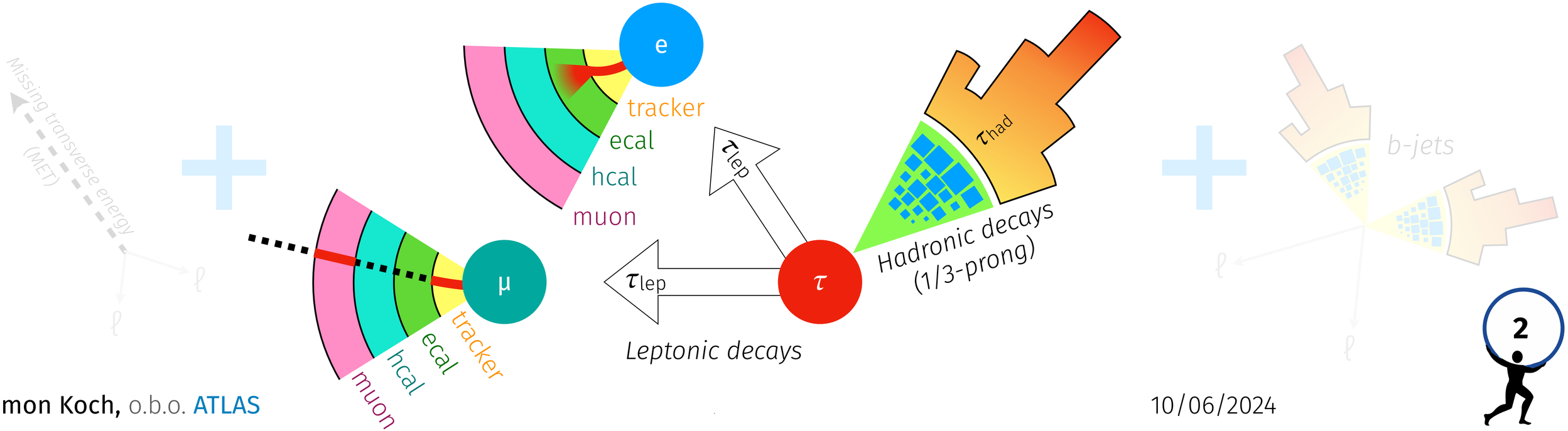

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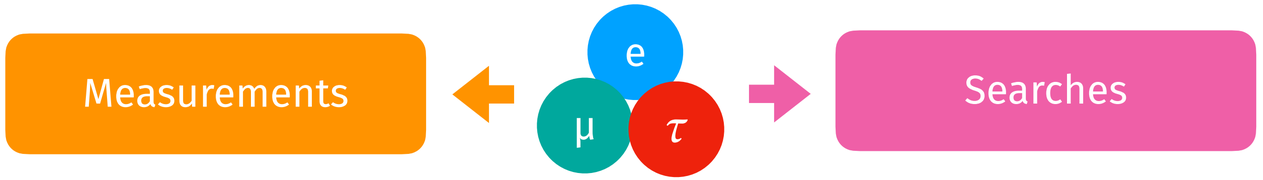

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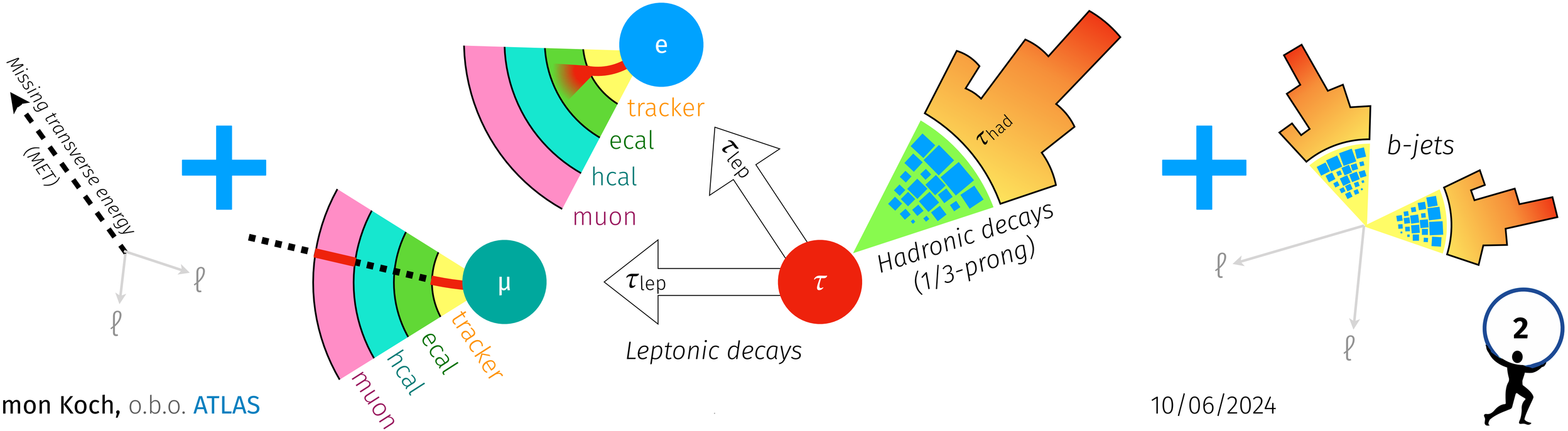


Motivation - Lepton Flavour Universality Violation (LFV)

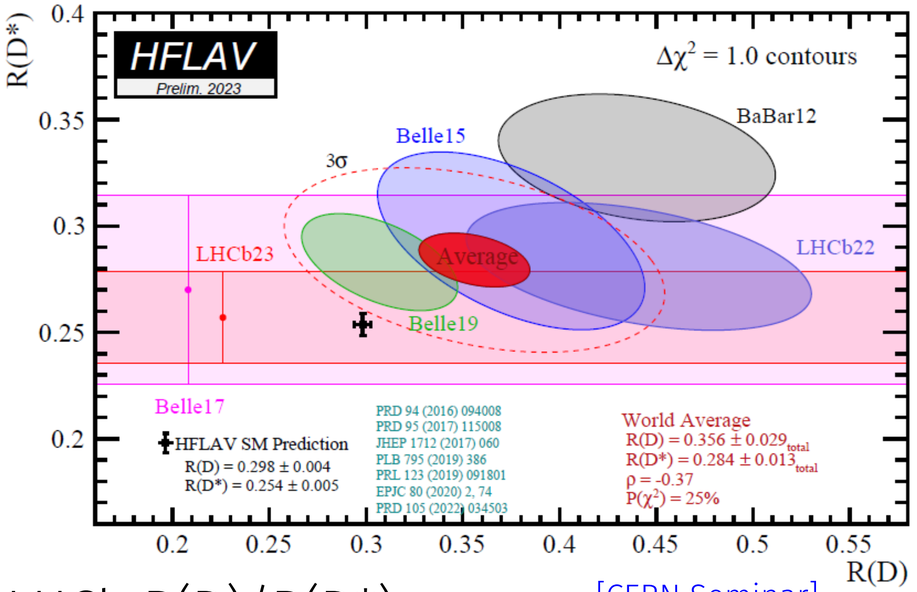
- Recent hints of multiple flavour anomalies
  - LHCb LFV in B meson decays
    - 3.2σ deviation in R_D/R_{D^*} [1]
    - ΔC_9, 3.4σ deviation [2]

$$R_D = \frac{\mathrm{Br}(B \to D\tau\bar{\nu}_\tau)}{\mathrm{Br}(B \to D\ell\bar{\nu}_\ell)}$$

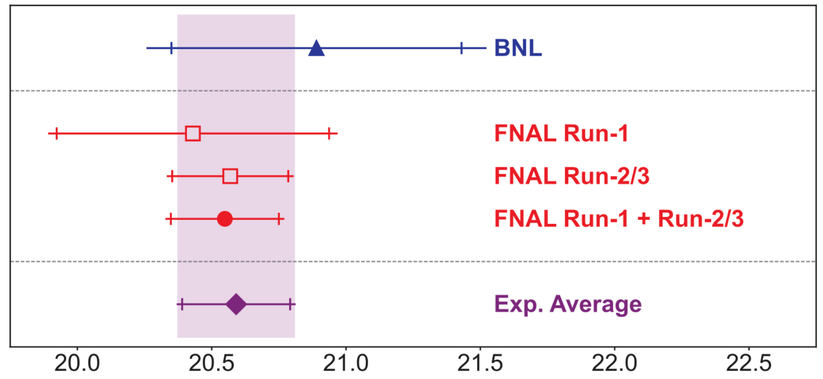
Wilson coefficient on $(\bar{s}\gamma_\mu P_L b)(\mu\gamma^\mu\mu)$

  - Muon anomalous magnetic moment $(g-2)_\mu$ at Fermilab

- Provide answers to some of the open questions on lepton properties:
  - *Neutrino mass generation mechanism*
  - *Flavour dependence of the Yukawa coupling strengths*



LHCb R(D)/R(D*) [CERN Seminar]



Fermilab $(g-2)_\mu$ $a_\mu \times 10^9 - 1165900$ [Phys. Rev. Lett. 131 (2023) 161802]

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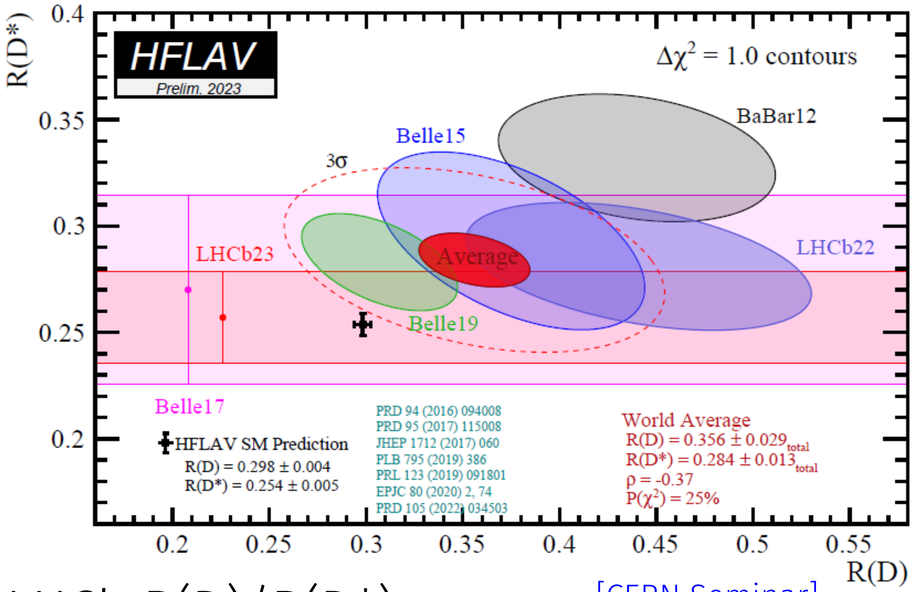

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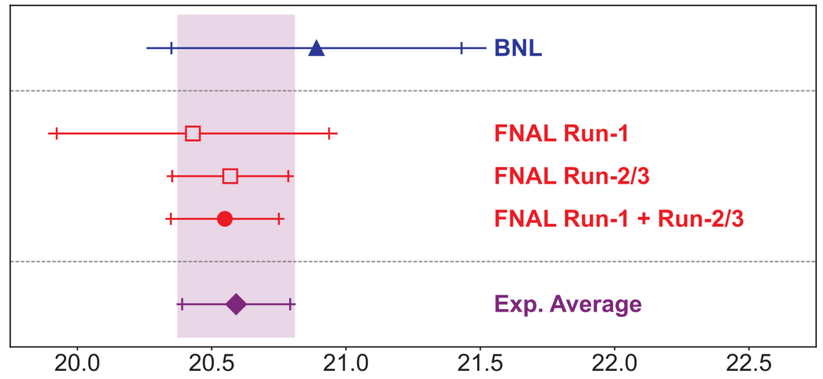

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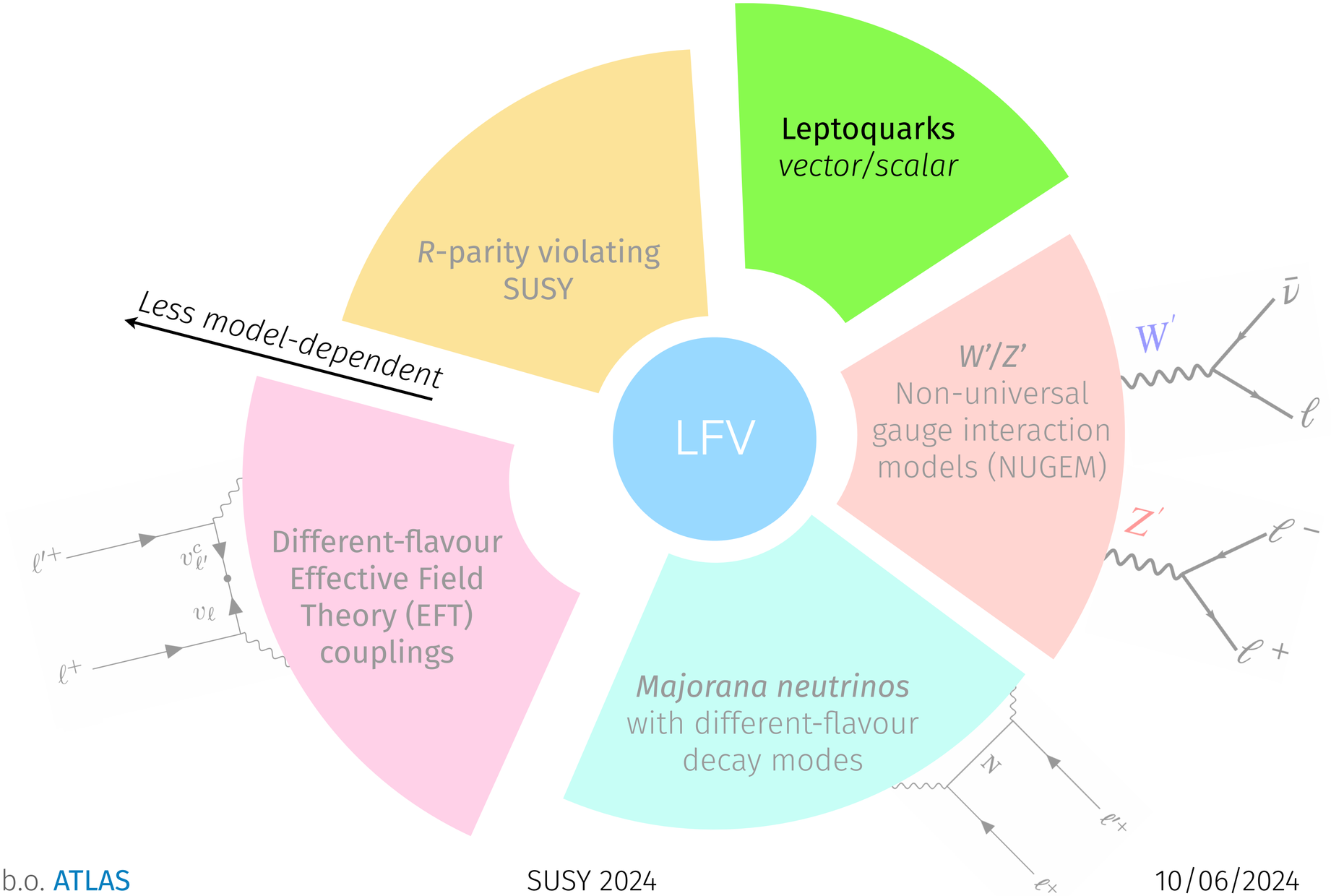

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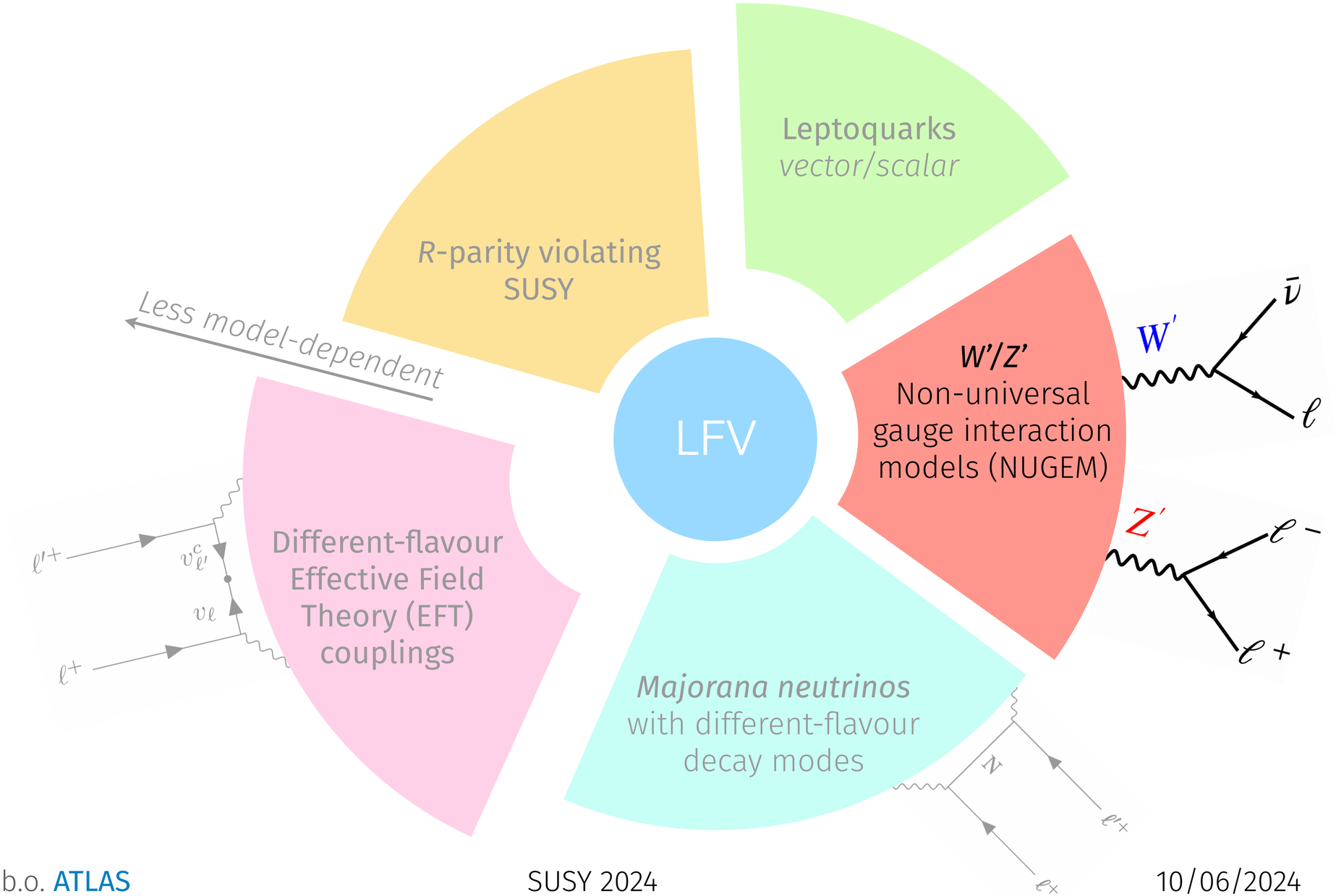

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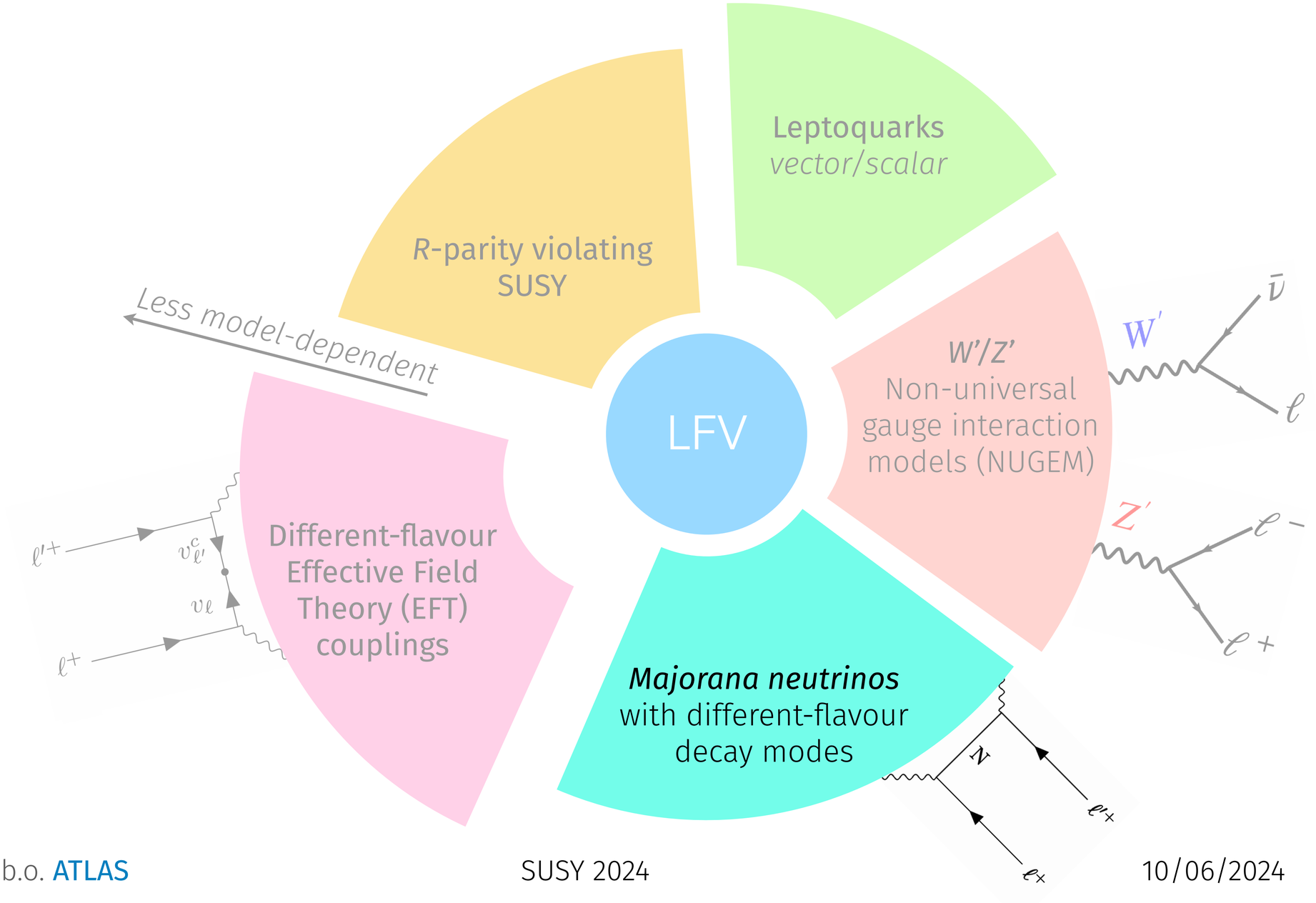

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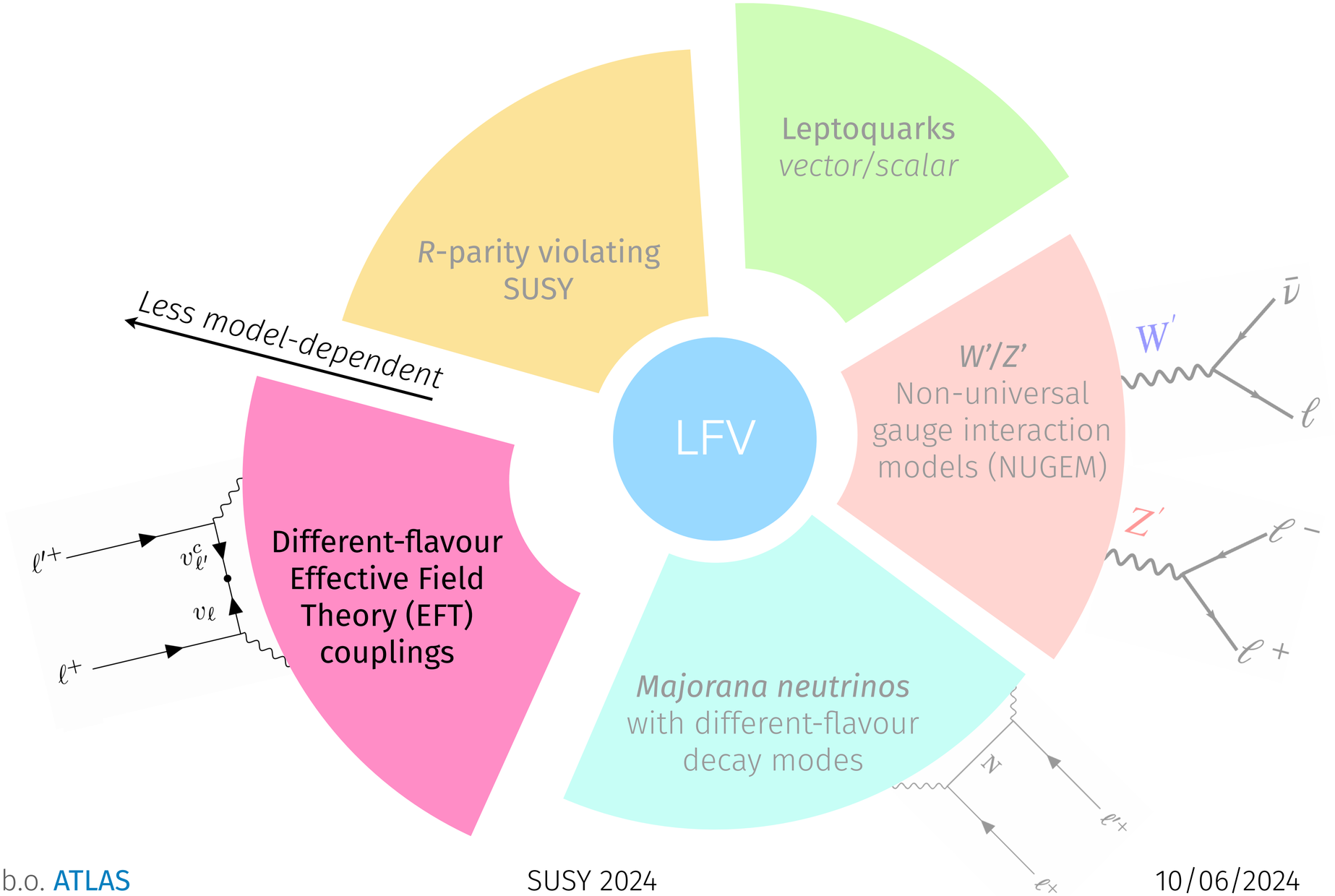

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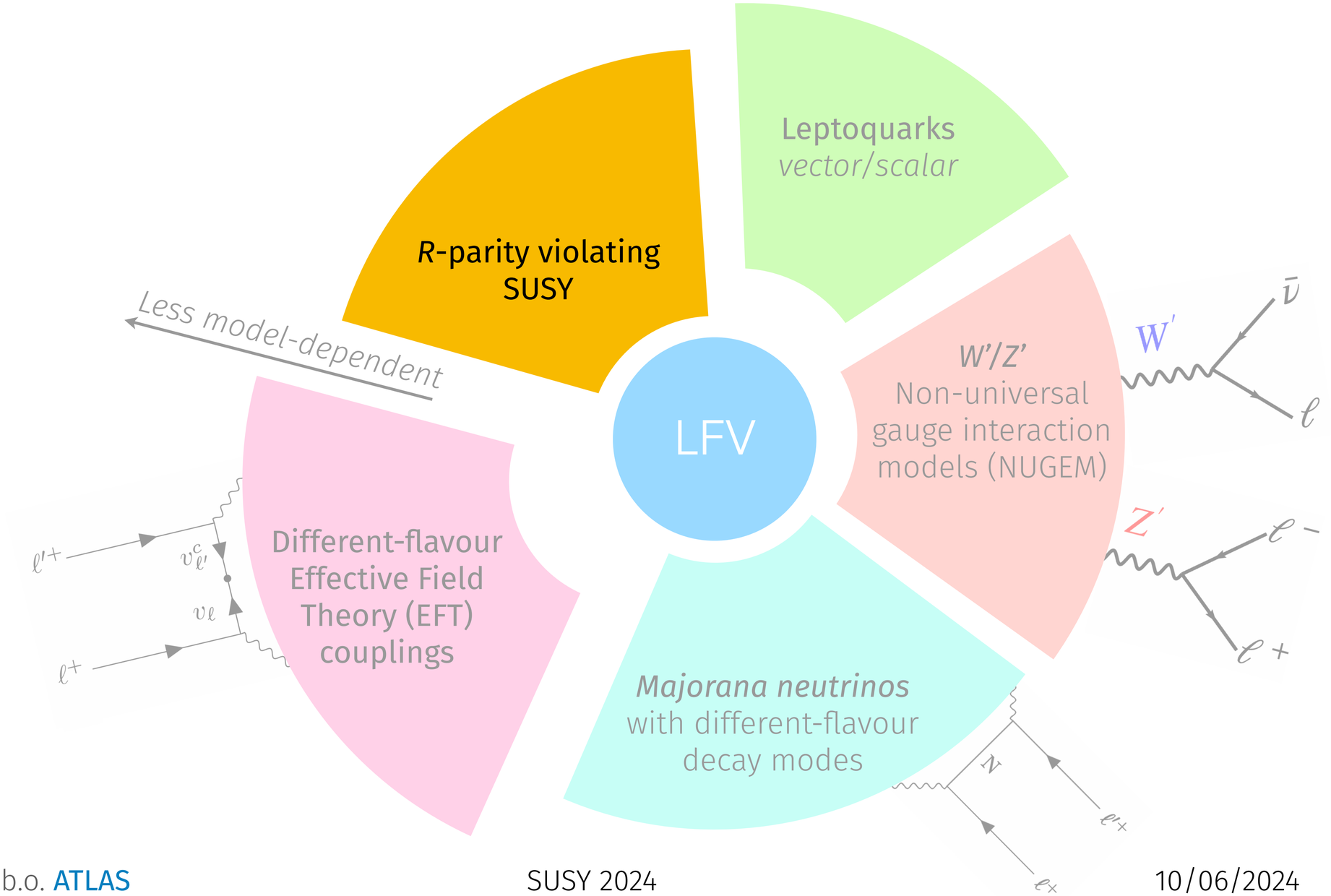
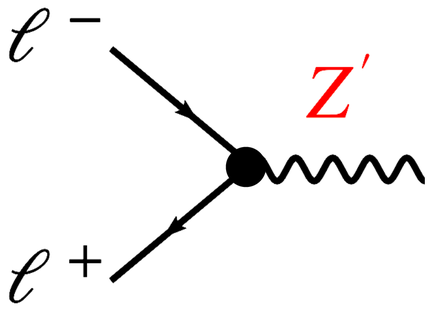


Overview

- New results in leptonic final states:
  - Heavy Neutral Gauge bosons in τ + E_T^{miss} [EXOT-2018-37]
  - Various interpretations of high-mass di-lepton final states ($e\mu$, $e\tau_{\text{had}}$, $\mu\tau_{\text{had}}$ pairs) [EXOT-2023-16]
  - Heavy Majorana neutrinos in same-sign WW decays [EXOT-2023-16]
- All using full run-2 ATLAS data:
  2015-2018, 13 TeV - 139 fb^{-1} with an uncertainty of 1.7%

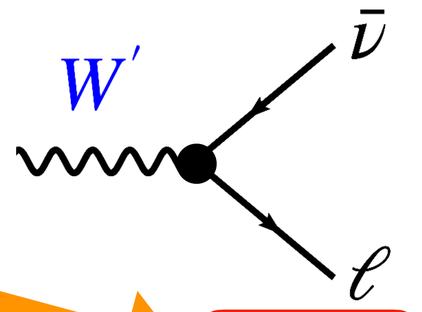
Heavy Neutral Gauge Bosons in τ+MET

[EXOT-2018-37]



Sequential Standard Model (SSM)

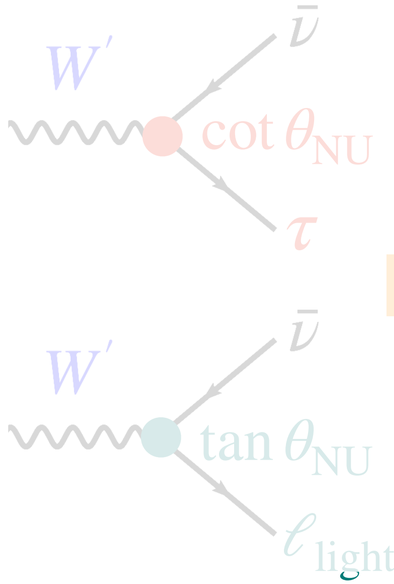
→ *assumes couplings of* ***W'***, ***Z'*** *to fermions are identical to W, Z in SM*



No LFV

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}



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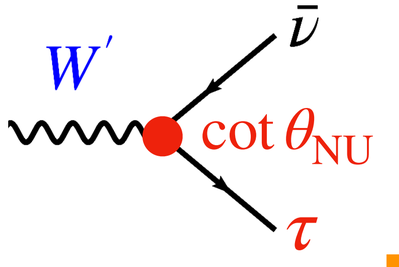

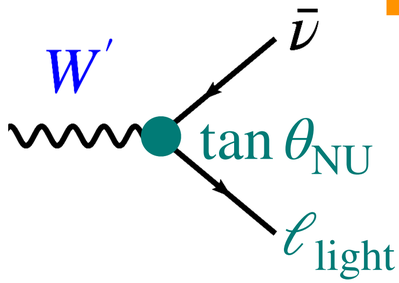

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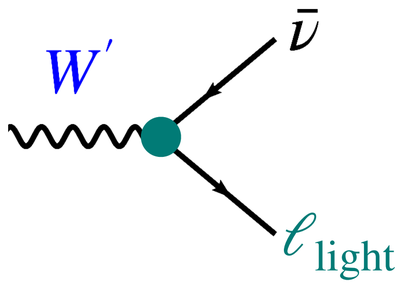

Light-lepton channel

- Generally better sensitivity to *universal couplings (SSM)*
  - lower backgrounds, better lepton reconstruction

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

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CMS $W' \to \tau\nu$ limit: **4.8** TeV (95% CL)
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[JHEP 09 (2023) 051]

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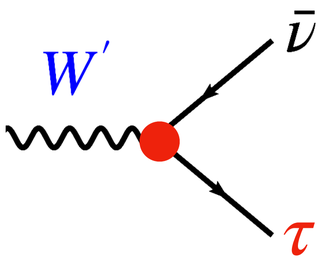

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Heavy Neutral Gauge Bosons in τ+MET

[EXOT-2018-37]

Selection

$$E_T^{\text{miss}} = -\sum_{\text{event}} p_T$$

Use MET triggers with 70/90/110 GeV threshold, depending on data period

τ_{had}

visible p_T > 30GeV, $|\eta|$ < 2.4

1/3-prongs within ΔR < 0.2

Efficiencies

	Trigger efficiency
overall	80%
$E_T^{miss} > 200$ **GeV**	>99%

	Efficiency	Background rejection
1-prong τ	85%	21
3-prong τ	75%	90

"loose" Recurrent NN ID

Kinematic Selection

Since $W' \to \tau\nu$ produced back-to-back in transverse frame:

$\Delta\phi_{\tau_{\text{had-vis}}, E_T^{\text{miss}}} < 2.4$,

$0.7 < p_T^{\tau_{\text{had-vis}}}/E_T^{\text{miss}} < 1.3$

Heavy Neutral Gauge Bosons in τ+MET

[EXOT-2018-37]

Backgrounds

MC simulation

W/Z + jets

$t\bar{t}$

Single top

Diboson

$Z(\rightarrow \nu\nu) + \text{jets}$

Data-driven

multijet (τ_{had} fakes)

Transfer factors from CRs

CR1: fail *loose* τ *ID*, satisfy *very loose* τ *ID*

CR2: E_T^{miss} < 100 GeV; *loose* τ *ID*

CR3: E_T^{miss} < 100 GeV; *very loose* τ *ID*

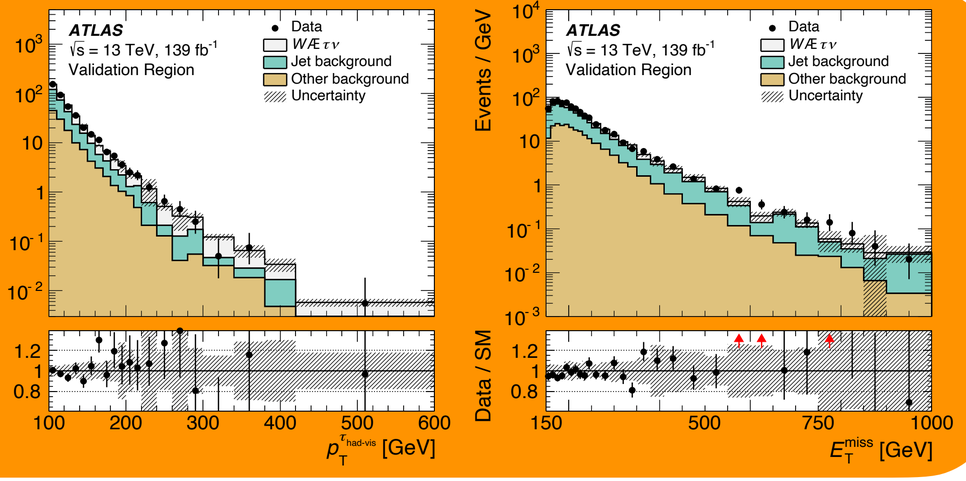
Validation Region

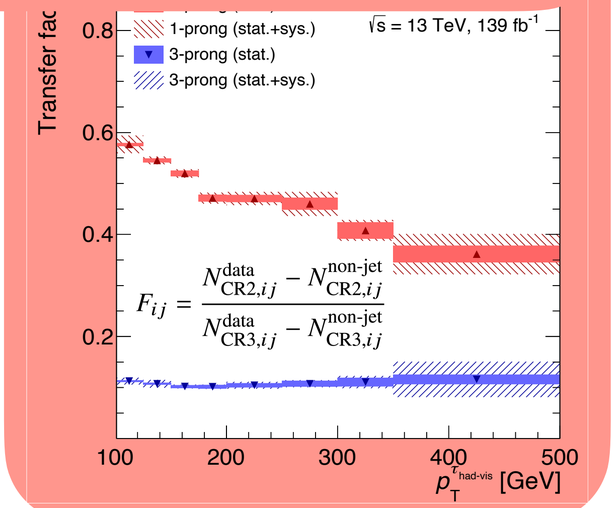
loose τ *ID*

E_T^{miss} > 150 GeV

$p_T^{\tau_{\text{had-vis}}}/E_T^{\text{miss}}$ < 0.7

m_T > 240 GeV





Signal

Binned $m_T(\tau)$ distributions for *W'* masses: **500 GeV < $m_{W'}$ < 6 TeV**

Heavy Neutral Gauge Bosons in τ+MET

[EXOT-2018-37]

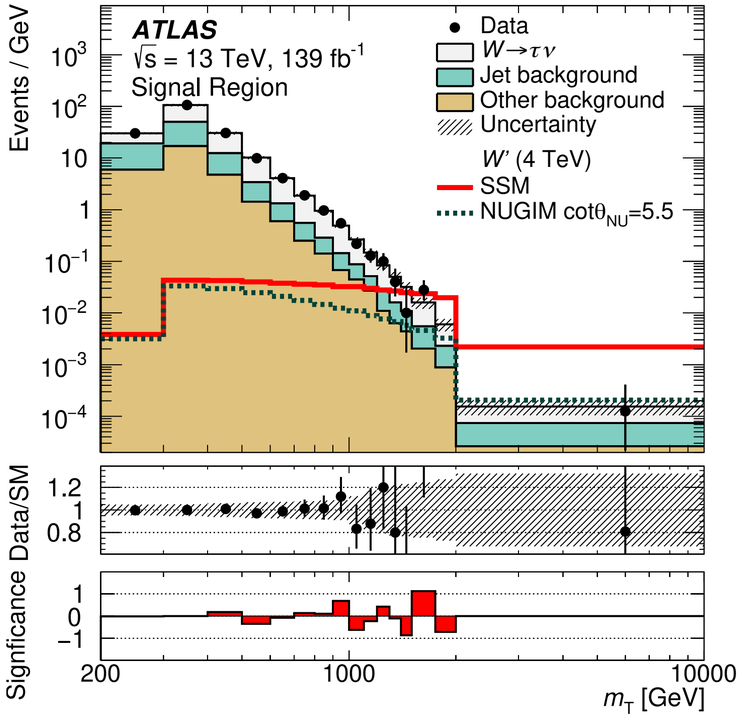
- Excludes W' masses up to 5.0 TeV at 95% CL

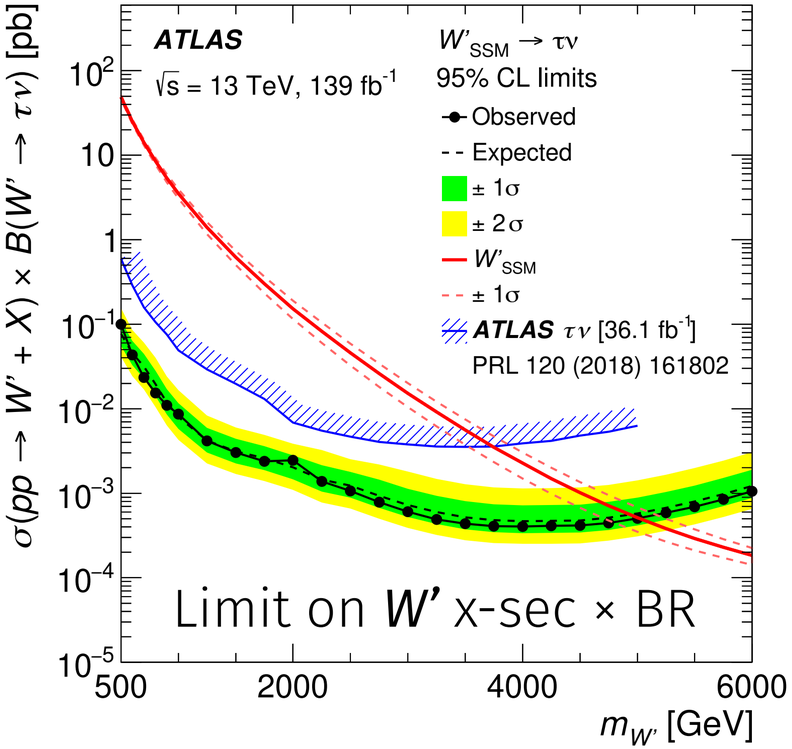
  ...improves on previous result by 1.3 TeV

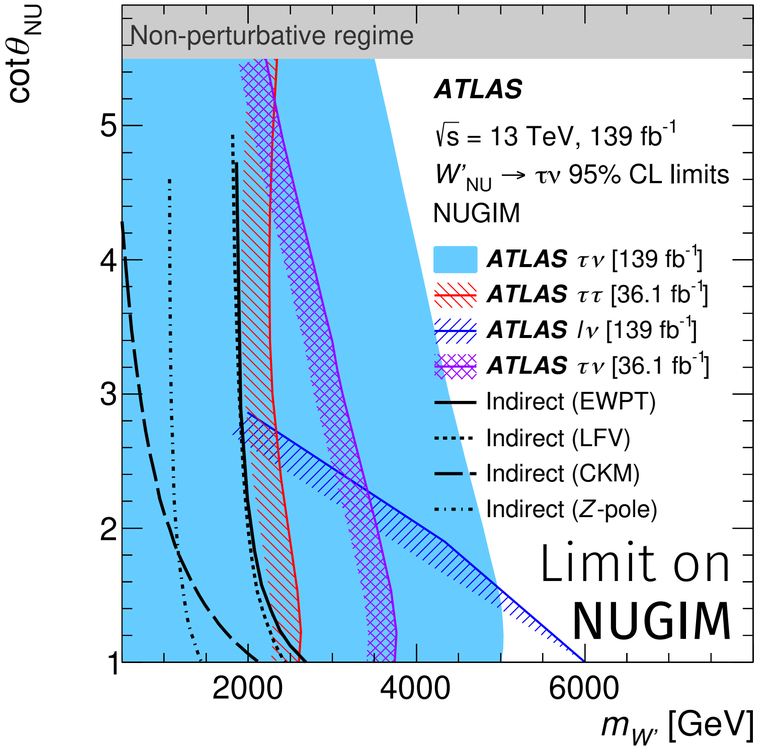
- Upper exclusion limits for $1 \leq \cot\theta_{NU} \leq 5.5$
  → *W'* bosons in range 3.5-5 TeV excluded

- Model-independent upper limits on production cross-section of τ+E_T^{miss}:
  17 fb @ m_T^{thresh} = 200GeV to 0.014fb @ m_T^{thresh} = 2.95 TeV

→backup







LFV in High-Mass Dilepton Final States

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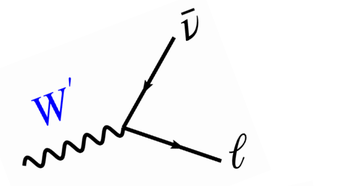

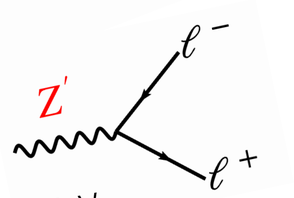

Arkani-Hamed–Dimopoulos–Dvali (ADD) model [3]
Randall–Sundrum (RS) model [4]

Quantum black holes in quantum-gravity theories with extra spatial dimensions

Previous ATLAS QBH m_{th} limit: **5.5/3.4**, **4.9/2.9**, and **4.5/2.6** TeV with **ADD/RS** model for $e\mu$, $e\tau$, $\mu\tau$ pairs, (36.1 fb^{-1} of the 13 TeV data sample)
[Phys. Rev. D 98 (2018) 092008]

Interpretations

Sequential Standard Model (SSM) W' and Z' heavy gauge bosons

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CMS $\tilde{\nu}_\tau$ limit: **2.2** TeV
[JHEP 05 (2022) 227]

$\frac{1}{2}\lambda_{ijk}L_iL_j\bar{e}_k + \lambda'_{ijk}L_iQ_j\bar{d}_k$

Assumption on Yukawa coupling λ_{ijk}

$\lambda_{312} = \lambda_{321} = 0.07$

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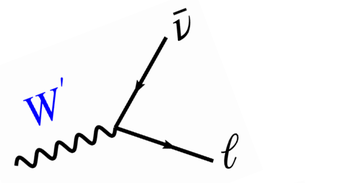

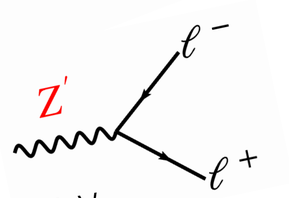

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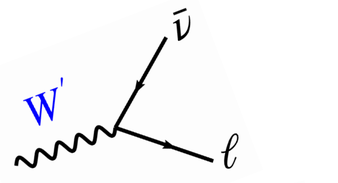

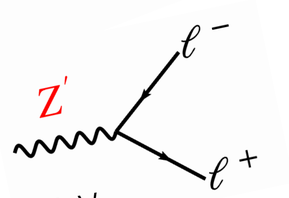

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W' and Z' heavy gauge bosons

Previous ATLAS Z' limit: **4.5**, **3.7**, and **3.5** TeV for $e\mu$, $e\tau$, $\mu\tau$ pairs,
(36.1 fb^{-1} of the 13 TeV data sample)
[Phys. Rev. D 98 (2018) 092008]

R-parity violating SUSY
τ-sneutrino ($\tilde{\nu}_\tau$) interpretation

Previous ATLAS $\tilde{\nu}_\tau$ limit: **3.4**, **2.6**, and **2.3** TeV for $e\mu$, $e\tau$, $\mu\tau$ pairs,
(36.1 fb^{-1} of the 13 TeV data sample)
[Phys. Rev. D 98 (2018) 092008]

CMS $\tilde{\nu}_\tau$ limit: **2.2** TeV
[JHEP 05 (2022) 227]

$\frac{1}{2}\lambda_{ijk}L_iL_j\bar{e}_k + \lambda'_{ijk}L_iQ_j\bar{d}_k$

Assumption on Yukawa coupling λ_{ijk}

$\lambda_{312} = \lambda_{321} = 0.07$

$\lambda_{312} = \lambda_{321} = \lambda'_{311} = 0.01$

[EXOT-2018-37]

LFV in High-Mass Dilepton Final States

[EXOT-2018-37]

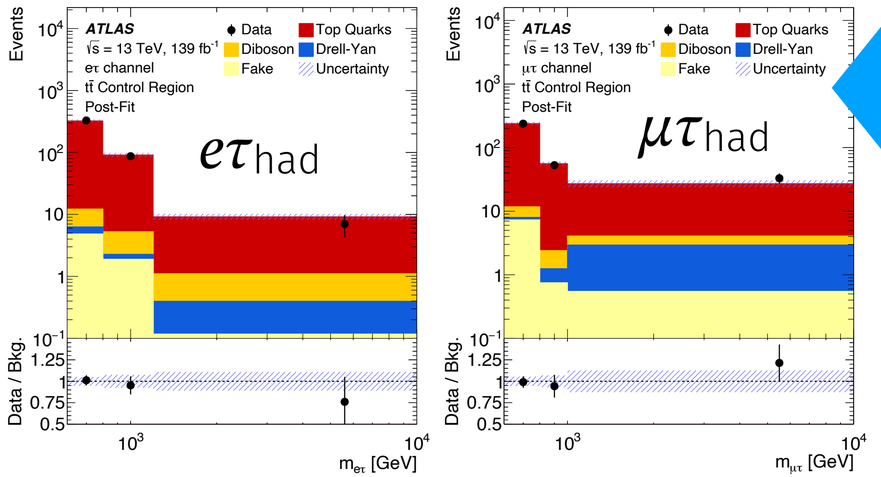
- Backgrounds:
  - *Irreducible:* $t\bar{t}$ and WW are dominant
    → MC simulation
  - Reducible: W+jets and multijet
    → data-driven fakes estimate

    $e\mu$: matrix method **largest systematic uncertainty contribution*

    $e\tau_{\text{had}}$, $\mu\tau_{\text{had}}$: extrapolation from dedicated CRs to SR:

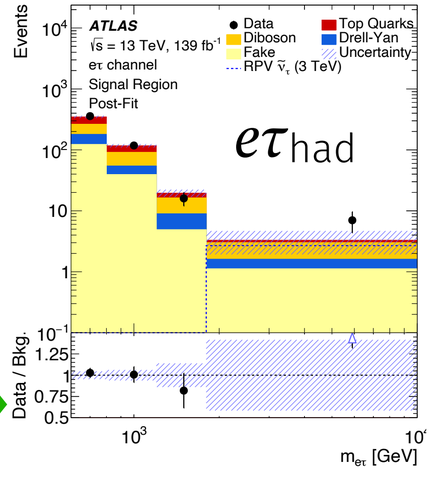
Region	Channels	Requirements
	Nominal $\Delta\phi_{\ell\ell'}$	
SR	$e\mu$, $e\tau$ and $\mu\tau$	$\Delta\phi_{\ell\ell'} > 2.7$, no b-jet, $m_{\ell\ell'} > 600$ GeV
$t\bar{t}$ CR	$e\mu$, $e\tau$ and $\mu\tau$	$\Delta\phi_{\ell\ell'} > 2.7$, at least one b-jet, $m_{\ell\ell'} > 600$ GeV
	Reversed $\Delta\phi_{\ell\ell'}$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

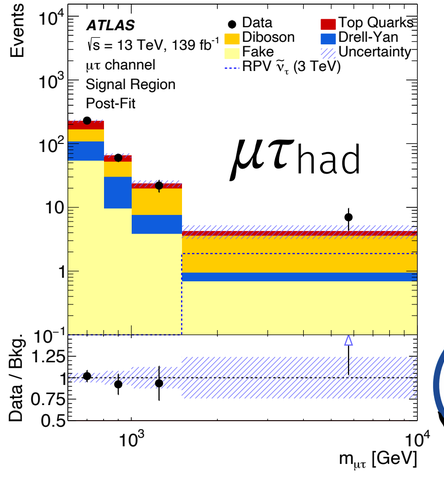
CRs $\Delta\phi_{ll'} < 2.7$ → extrapolation → SRs $\Delta\phi_{ll'} > 2.7$



$t\bar{t}$ CR ≥1 b-jets

SRs no b-jets





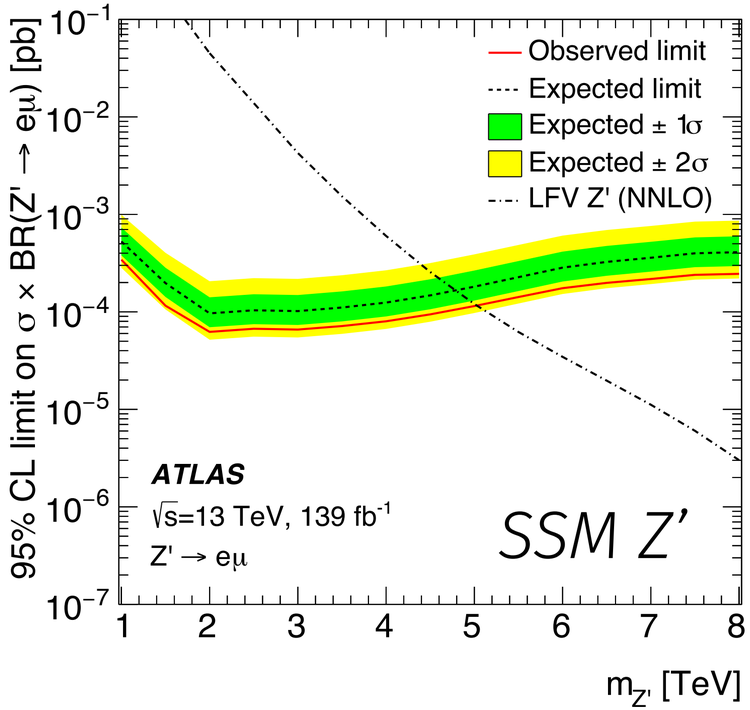
LFV in High-Mass Dilepton Final States

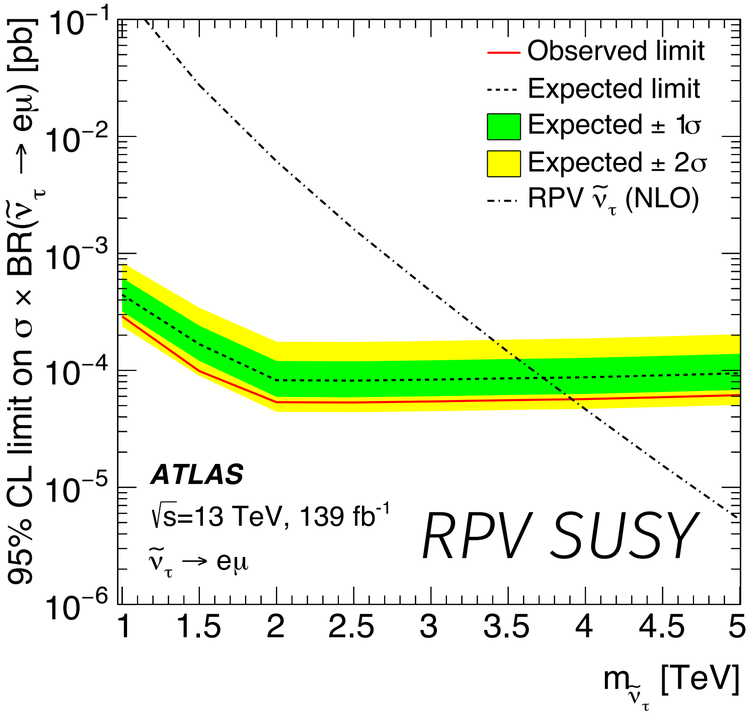
- Data consistent with SM
- In $\ell\tau$ channels, mild excess above background at 2.0-2.3 TeV
- Profile-likelihood fits on $m_{\ell\ell}$ set 95% CLs:

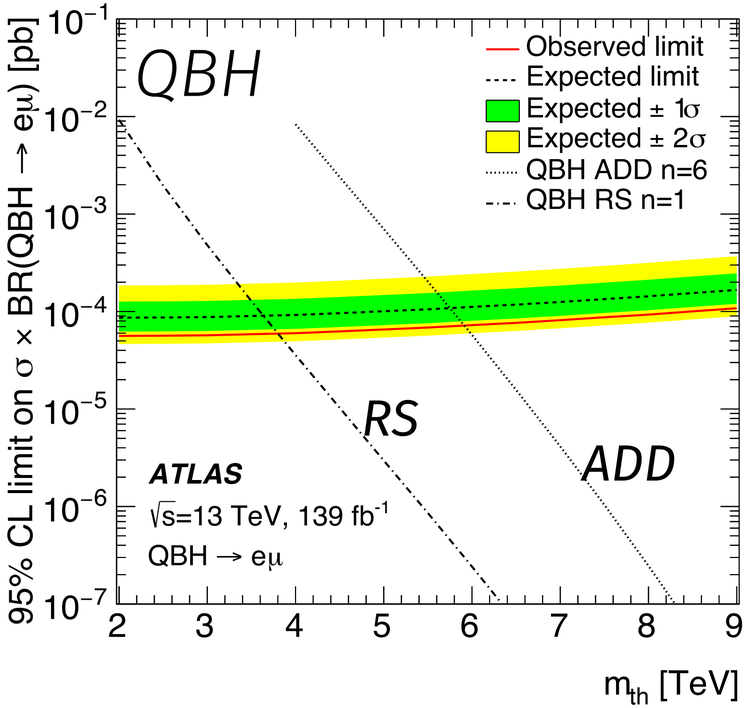
[EXOT-2018-37]

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

Previous ATLAS limits (Run 2, 2015-2016) ←







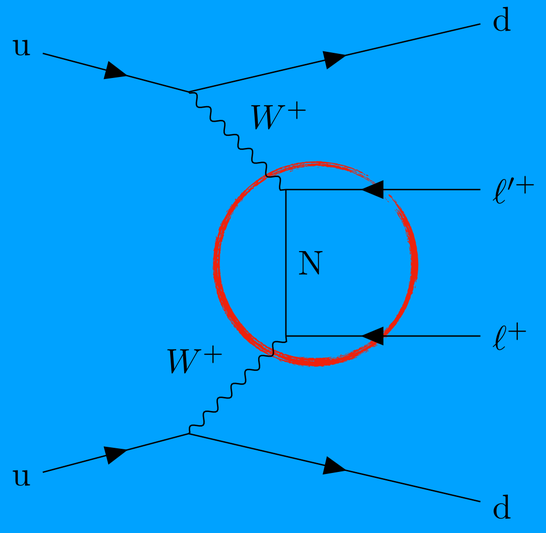
eμ channel

Heavy Majorana Neutrinos in same-sign *WW*

[EXOT-2023-16]

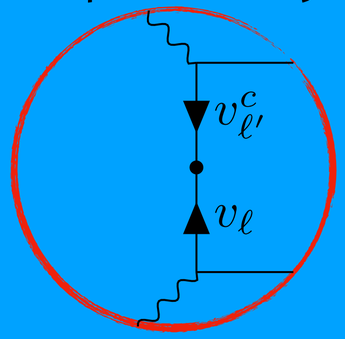
- Heavy Majorana neutrinos - *couple to SM through mixing with SM neutrinos*
  - *Type-1 Seesaw mechanism:* $m_\nu \approx \mathcal{O}(v^2/m_N)$ *where* v *= 246 GeV (Higgs v.e.v.)*
  - *Help explain leptonic mass hierarchy, or part of Grand Unified Theories*

Signal



$$\sigma \sim \left| V_{\ell N} V^*_{\ell' N} \right|^2$$

- Same-sign leptons from *WW*
  - Di-electron channel ee
  - LFV channel $e\mu$
- EFT interpretation - replace by dim-5 Weinberg operator



$$\sigma \sim \left| C_5^{ll'} \right|^2 / \Lambda^2$$

Heavy Majorana Neutrinos

[EXOT-2023-16]

Triggers

ee — **Di-electron triggers**
p_T thresholds: 12, 17, 24 GeV*

$e\mu$ — **Single-e/μ triggers**
p_T threshold in range 20-26 GeV

Selection

e
baseline: loose signal: tight

μ
baseline: loose signal: medium

Backgrounds

MC simulation

WZ

electroweak WW

(minor) $\ell\gamma jj$, ZZ, tZq

Data-driven

Non-prompt ℓ (e/μ fakes)

e-charge mis-ID

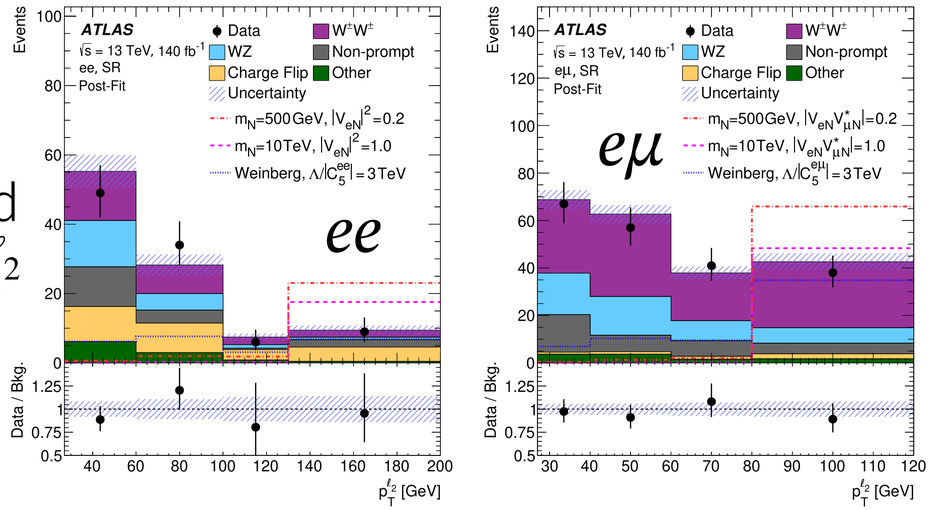
Fake-factor method
as function of e/μ p_T/η
$j-\ell$ *back-to-back topology:* $|\Delta\phi_{\ell j}| > 2.8$
MC fakes subtracted

** data-taking conditions from 2015, 16, 17-18, respectively*

Heavy Majorana Neutrinos

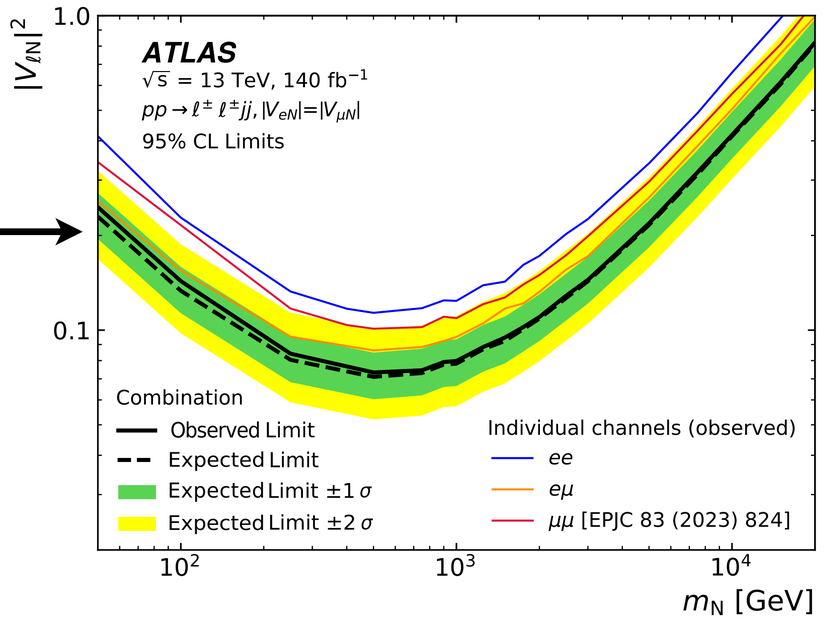
- No significant deviation from SM observed
- Obs. (exp.) limits using dim-5 Weinberg operator:
  - m_{ee}: 24 GeV (24 GeV)
  - $m_{e\mu}$: 13 GeV (15 GeV)
- Statistical combination with $\mu\mu$ performed
  - Combined limits 27% (16%) more stringent than $\mu\mu$ alone

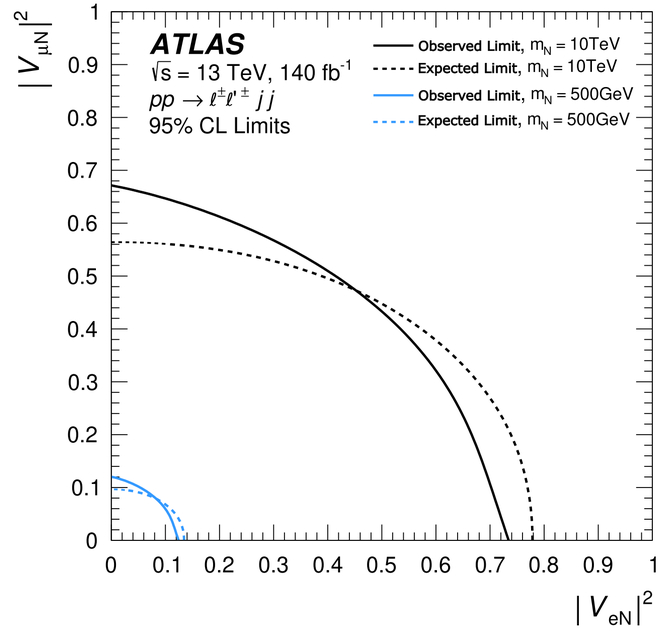
Fits performed on $p_T^{\ell_2}$



[EXOT-2023-16]

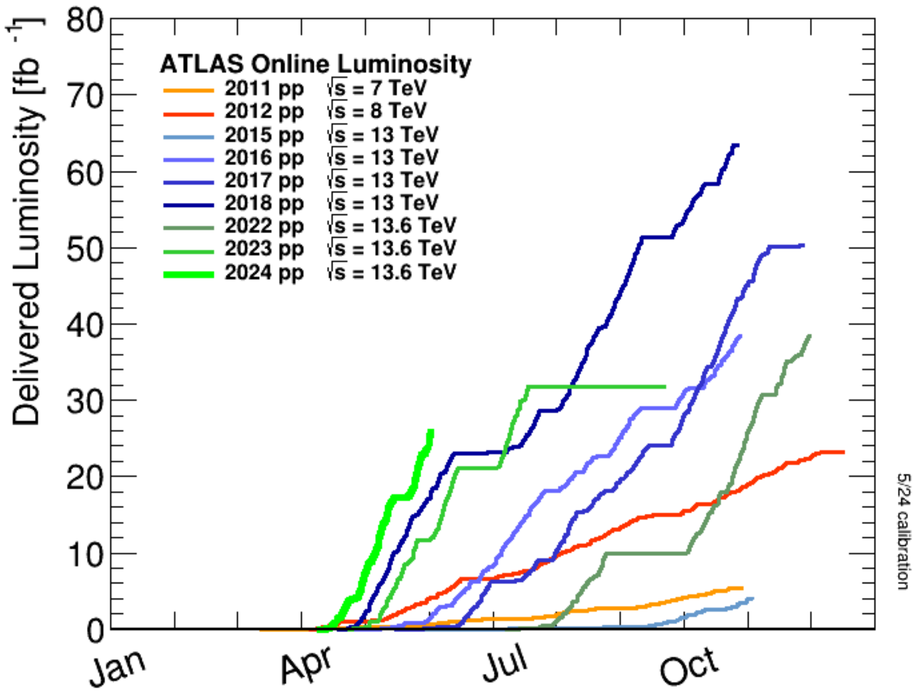
Majorana neutrino mixing elements: $V_{\ell N}$





Summary and Outlook

- Across multiple searches for new physics following LFV hints, no substantial deviations from SM found yet
- Run 3 is well underway, with almost 100 fb^{-1} recorded so far and greater reach for searches:
  - Higher centre-of-mass energy
  - Improved hardware trigger
  - Many lepton performance improvements (e.g. electron ID CNN [ATL-PHYS-PUB-2023-001], new/improved software triggers for Run 3)
- *Toward HL-LHC:*
  - large luminosity benefit for searches
  - tracking improvements from new Inner Tracker (ITk)



[ATLAS Luminosity Public Results]

References

[1] A. Mathad, *Lepton flavour universality tests in $b \to c l \nu$ decays at LHCb*, 57th Recontres de Moriond EW (2023)

[2] Aguillard, D. P. et. al. *Measurement of the Positive Muon Anomalous Magnetic Moment to 0.20 ppm*, Phys. Rev. Lett. 131 (2023) 161802

[3] N. Arkani-Hamed, S. Dimopoulos and G. Dvali, *The hierarchy problem and new dimensions at a millimeter*, Phys. Lett. B 429 (1998) 263, **arXiv: hep-ph/9803315**.

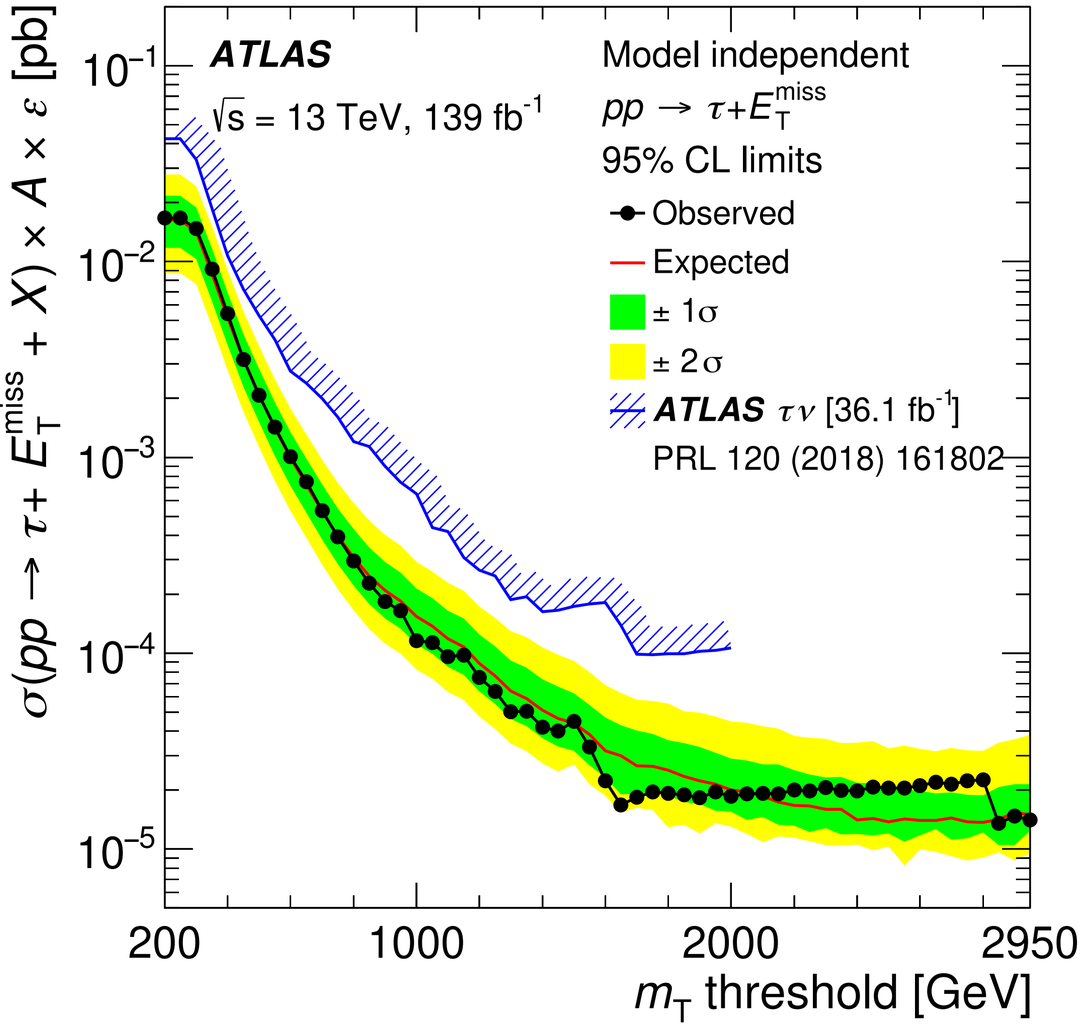
[4] L. Randall and R. Sundrum, *A Large Mass Hierarchy from a Small Extra Dimension*, Phys. Rev. Lett. 83 (1999) 3370, **arXiv: hep-ph/9905221**.

Backup

Heavy Neutral Gauge Bosons in tau+MET

[EXOT-2018-37]

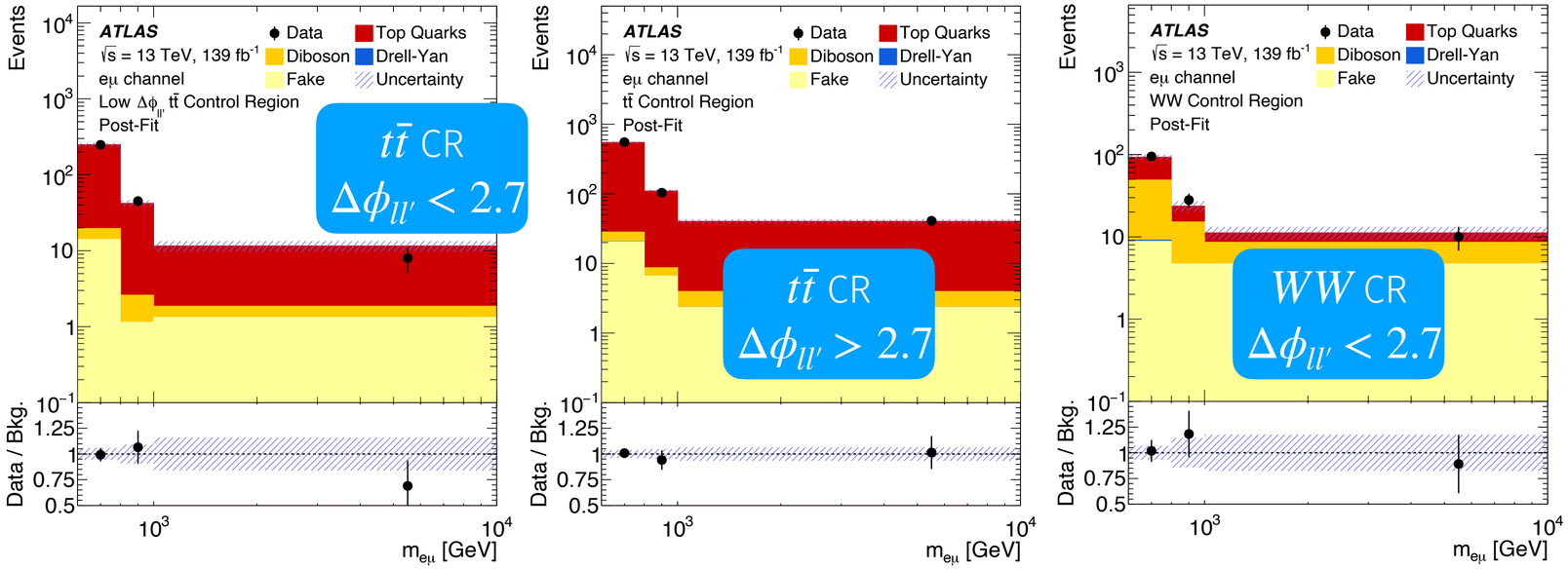
Model-independent
upper limits on production
cross-section of τ+E_T^{miss}:

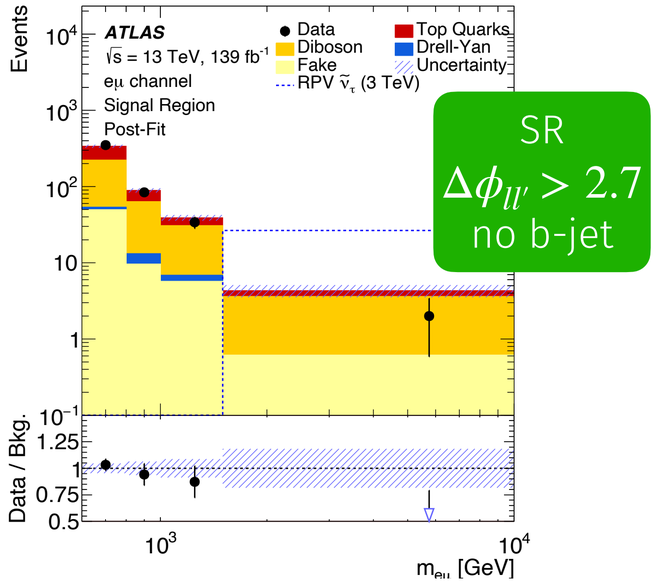


LFV in High-Mass Dilepton Final States

[EXOT-2018-37]

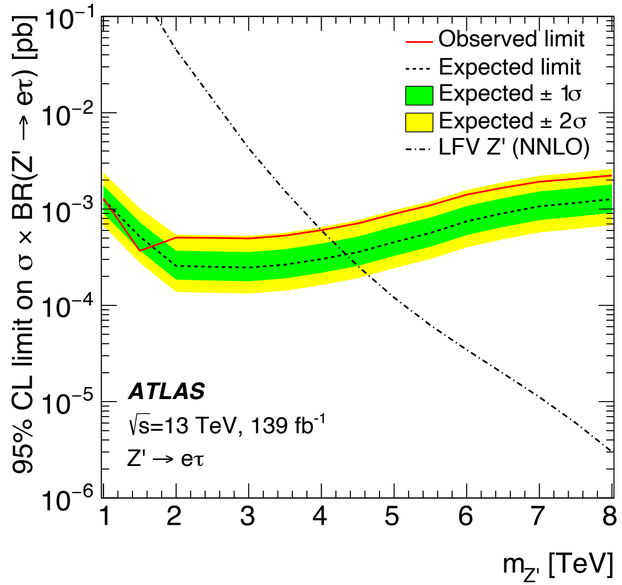
$e\mu$

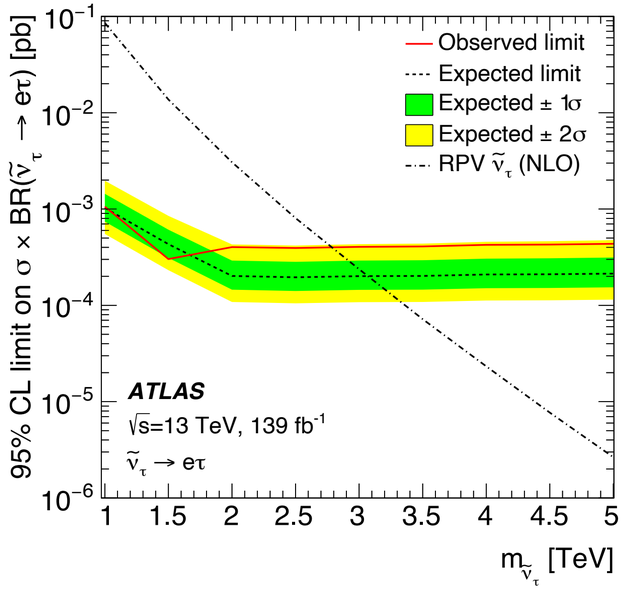


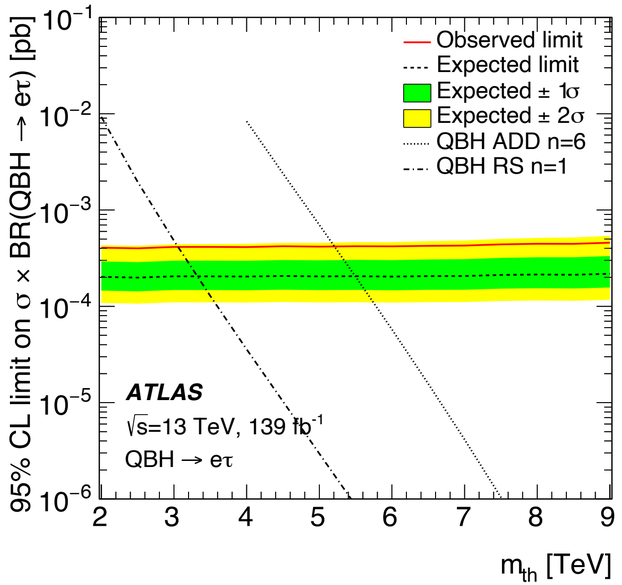


LFV in High-Mass Dilepton Final States

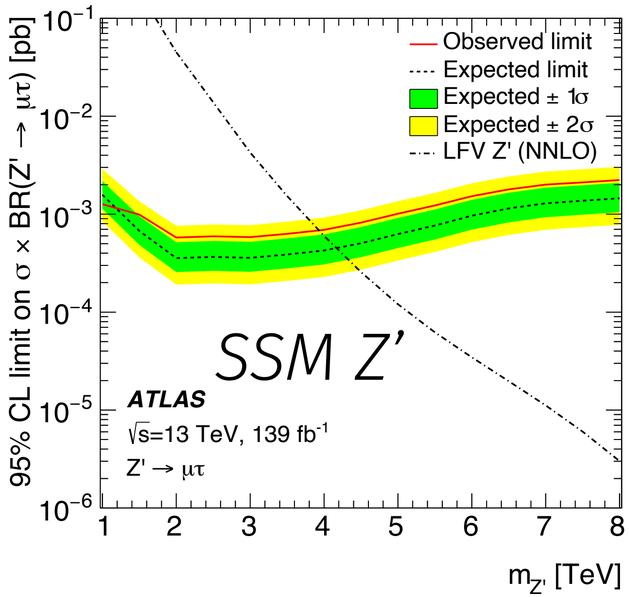
[EXOT-2018-37]

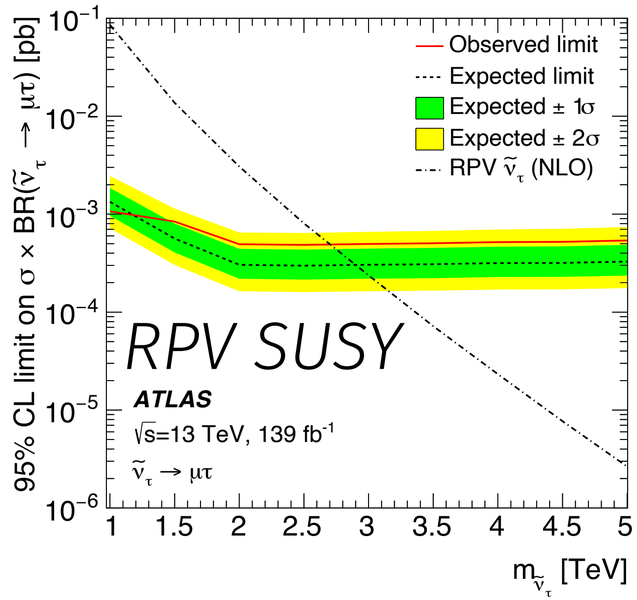


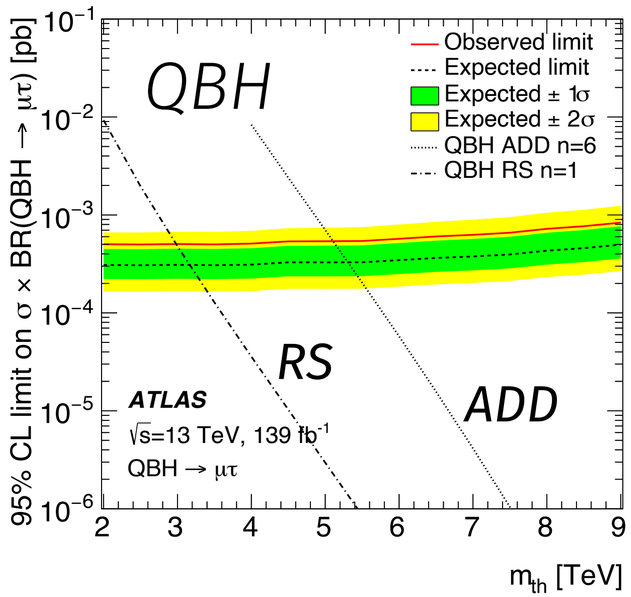




$e\tau_{had}$







$\mu\tau_{had}$

Heavy Majorana Neutrinos

Selection

Channel	Variable	SR	$W^{\pm}W^{\pm}$ CR	WZ CR
$ee/e\mu$	N_ℓ	=2		=3
	$\lvert\Delta y_{jj}\rvert$	> 2		
	m_{jj}	> 500 GeV		
	$m_{\ell\ell\ell}$	–	–	> 106 GeV
ee	$\lvert m_{\ell\ell} - m_Z\rvert$	> 15 GeV		–
	$\lvert\eta_\ell\rvert$	<2		
	$m_{\ell\ell}$	> 20 GeV		
	$p_{\mathrm{T}}^{\ell_1}$	–	< 250	–
	$p_{\mathrm{T}}^{j_1}$	> 30 GeV	> 45 GeV	> 30 GeV
	$p_{\mathrm{T}}^{j_2}$	> 25 GeV	> 30 GeV	> 25 GeV
	$\mathcal{S}$	< 4.5	> 4.5	–
$e\mu$	$p_{\mathrm{T}}^{j_1}$	> 30 GeV	> 45 GeV	> 45 GeV
	$p_{\mathrm{T}}^{j_2}$	> 25 GeV	> 30 GeV	> 30 GeV
	$\lvert\Delta\phi_{e\mu}\rvert$	> 2.0	< 2.0	–

Heavy Majorana Neutrinos

Majorana neutrino mixing elements: $V_{\ell N}$