LFV searches at ATLAS and CMS

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Introduction

Theory:

- Lepton flavor violation exists in Nature (neutrino oscillations), but LFV in the charged sector (cLFV) is extremely suppressed in the SM: $BR(\mu \rightarrow e\gamma) < 10^{-48}$.
- Many models predict cLFV decays of leptons, Higgs and/or Z and/or other BSM particles.

ATLAS & CMS Experiments:

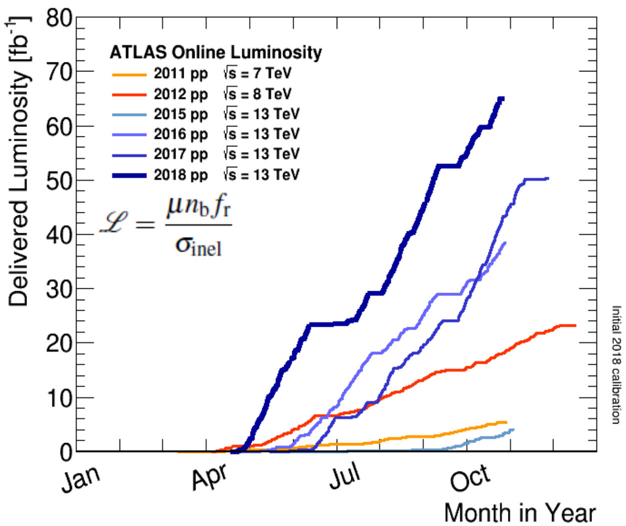
- Complementary efforts are made by both collaborations.
- Detector performance plays a leading role.

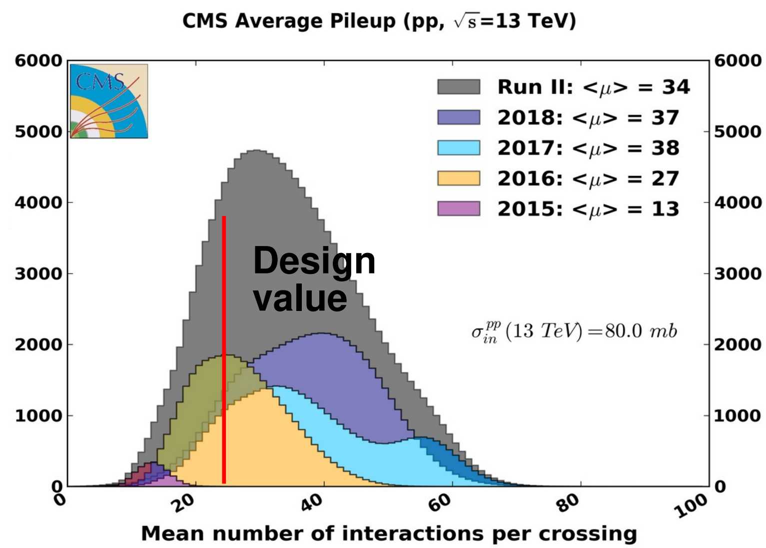
LFV searches in this talk:

- Search for $\tau \rightarrow \mu\mu\mu$
- Search for LFV Z decays

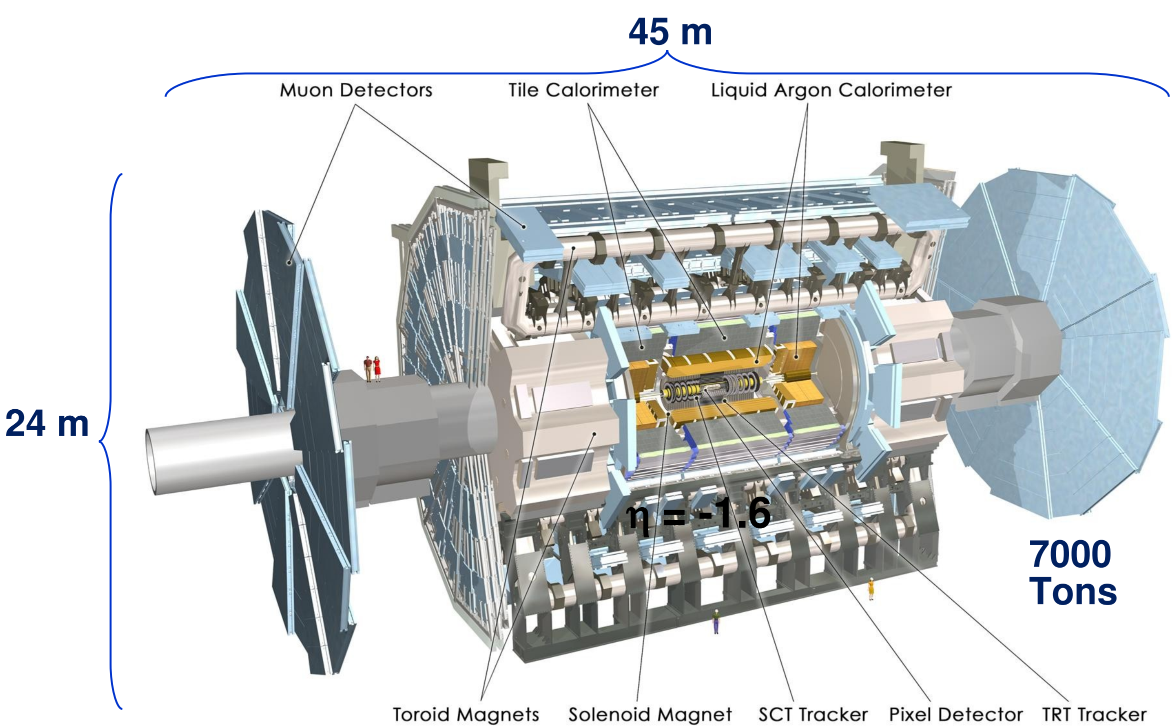
  (→ more in Matteo Franchini talk)
- Search for LFV Higgs decays
- Search for $t \rightarrow (u,c)\ell^{+}\ell'^{-}$
- Measurement of $B(W \rightarrow \tau\nu)/B(W \rightarrow \mu\nu)$
- Measurement of $\sigma(e^{+}\mu^{-})/\sigma(e^{-}\mu^{+})$

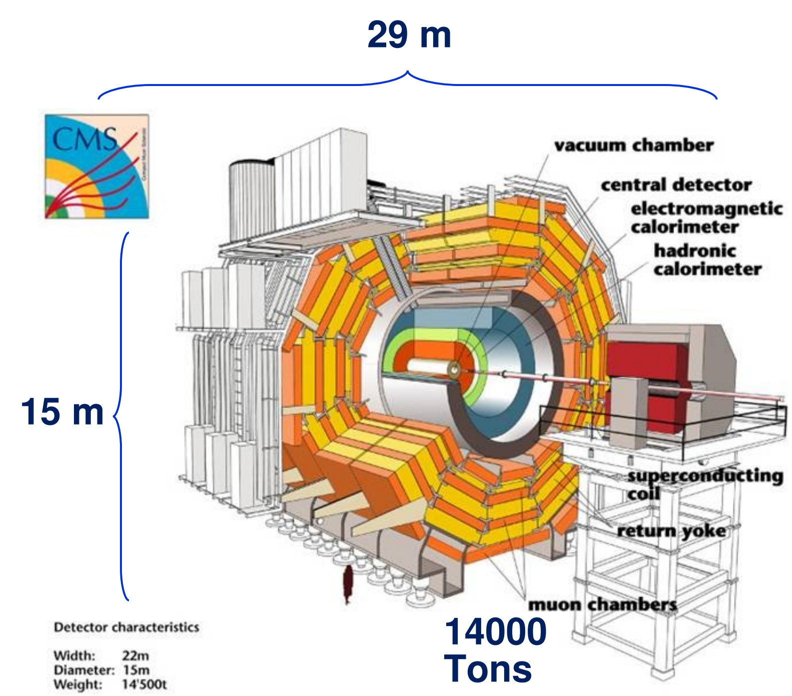
ATLAS & CMS Detectors





Luminosity is measured with forward/tracking detectors and calibrated with beam separation scans

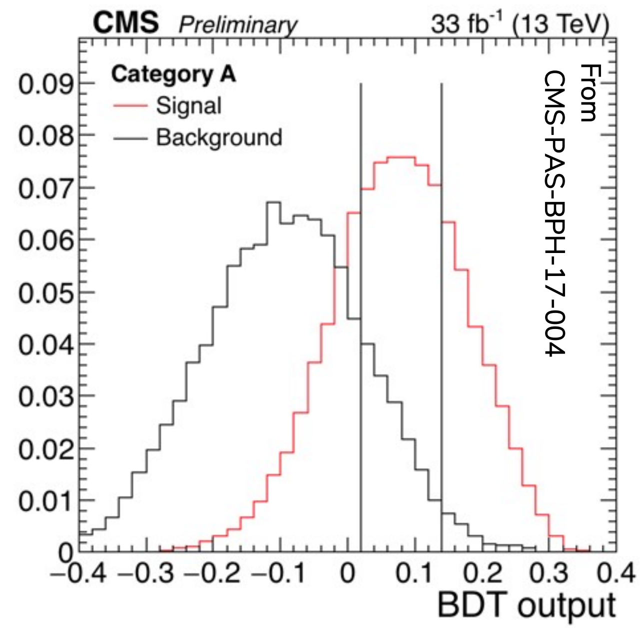


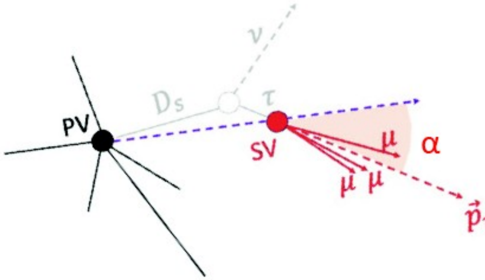


Search for $\tau \rightarrow \mu\mu\mu$ decay

- Compared to e^+e^- colliders, background for τ produced at LHC is significantly more challenging.
- Main source of τ–leptons at LHC are D mesons (>70%), B mesons (~25%) and W (~0.01%) decays.
- CMS employs dedicated channels for heavy flavour (HF) decays and W decays.
- A total of 33 fb^{-1} of Run 2 data has been analyzed.

- **Heavy Flavour channel:**
  - Low momentum muons boosted in the fwd region
  - High QCD background
- Dedicated online triggers for online event selection
- Mass resolution of the tau candidate varies with η.
- Multivariate Analysis (BDT) for background rejection:
  - 10 variables including 3μ vertex χ^2, vertex displacement significance, angle wrt PV direction, muon quality, …
- Event are divided in 6 categories based on mass resolution and BDT score.



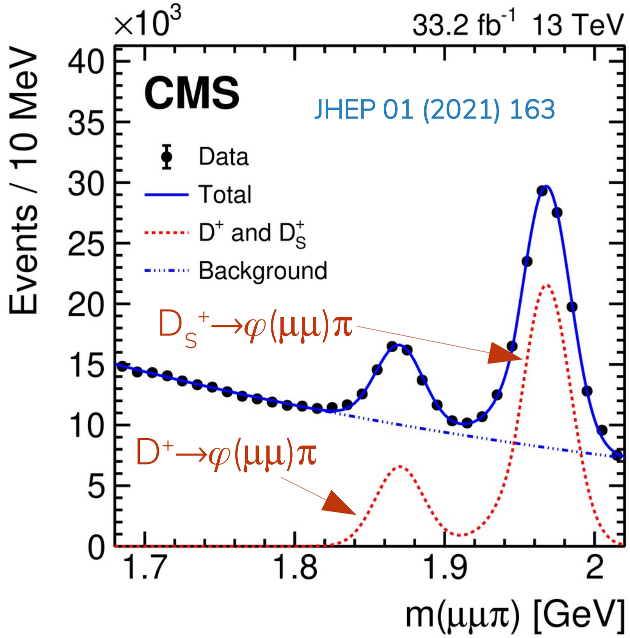


Search for $\tau \to \mu\mu\mu$ decay

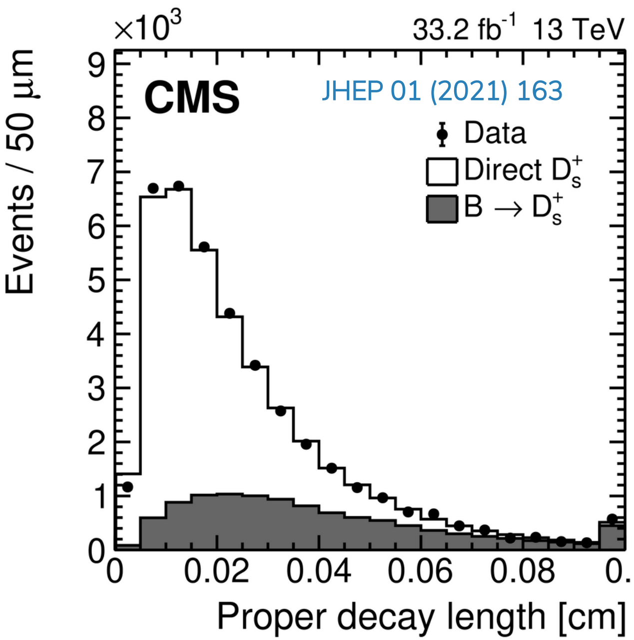
- **Heavy Flavour channel:**
  - Number of signal events:

$$N_{\mathrm{sig(D)}} = N_{\mathrm{norm}} \frac{\mathcal{B}(\mathrm{D_s^+} \to \tau^+ \nu)}{\mathcal{B}(\mathrm{D_s^+} \to \phi\pi^+ \to \mu^+\mu^-\pi^+)} \frac{\mathcal{A}_{3\mu(\mathrm{D})}}{\mathcal{A}_{\mu\mu\pi}} \frac{\epsilon^{\mathrm{reco}}_{3\mu(\mathrm{D})}}{\epsilon^{\mathrm{reco}}_{\mu\mu\pi}} \frac{\epsilon^{2\mu\mathrm{trig}}_{3\mu(\mathrm{D})}}{\epsilon^{2\mu\mathrm{trig}}_{\mu\mu\pi}} \mathcal{B}(\tau \to 3\mu)$$

- N_{norm} is the measured from $D_S^+ \to \varphi(\mu\mu)\pi$
- $\mathcal{A}$, ε^{reco} and ε^{trig} are the detector acceptance, selection efficiency, and trigger efficiency.
- Invariant mass peaks modelled using Crystal Ball functions.



- The B contribution to the signal is measured from the $D_S^+ \to \varphi(\mu\mu)\pi$ channel.
- Fit templates of D_s decay length corresponding to prompt and non-prompt decays.



Search for $\tau \to \mu\mu\mu$ decay

- $W \to \tau\nu$ channel:
  - Small fraction of τ production at LHC, but with several event selection advantages:
    - High trigger and reconstruction efficiency
    - Signature:
      - Isolated high-momentum muons
      - Large E_T^{miss} in the final state

      → Significantly less background than the heavy flavour channel.
  - Selection based on BDT with 18 variables.
  - Events are divided in 2 categories.

- Branching fraction extraction from the number of signal events:

$$\mathcal{B}(\tau \to 3\mu) = \frac{N_{\mathrm{sig(W)}}}{\mathcal{L}\,\sigma(\mathrm{pp} \to \mathrm{W} + X)\,\mathcal{B}(\mathrm{W} \to \tau\nu)\,\mathcal{A}_{3\mu(\mathrm{W})}\,\epsilon_{3\mu(\mathrm{W})}}$$

Main systematic sources:

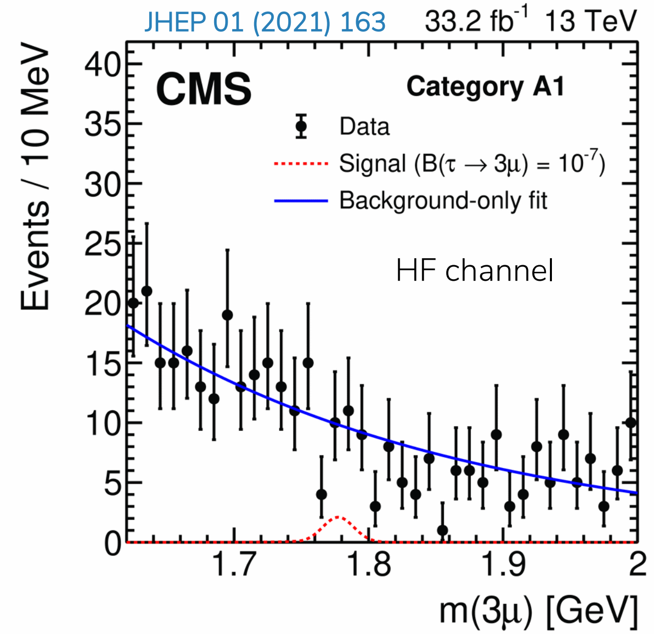
Source	Uncertainty (%) Barrel	Endcap
Signal efficiency	7.9	32
Limited size of simulated samples	4.3	6.2
Integrated luminosity	2.5	2.5
$\mathrm{pp} \to \mathrm{W}$ cross section	2.9	2.9
$\mathcal{B}(\mathrm{W} \to \mu\nu)$	0.2	0.2
$\mathcal{B}(\mathrm{W} \to \tau\nu)$	0.2	0.2

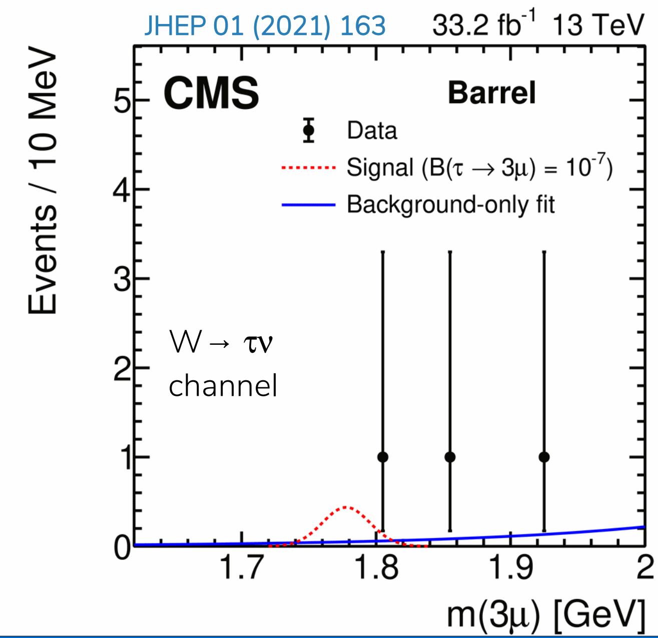
← (Endcap signal efficiency) dominated by the L1 trigger inefficiency correction

$\tau \rightarrow \mu\mu\mu$ search results

- **CMS Results:**
  - Observed (Expected) limit is **8.0 (6.9) x 10^{-8}** @ 90% C.L.
    - W boson channel: 20 (13) x 10^{-8} @ 90% C.L.
    - HF channel: 9.2 (10.0) x 10^{-8} @ 90% C.L.

Best mass resolution categories





Results comparison	$\tau \rightarrow 3\mu$ **90% CL Limits**
Belle Phys.Lett.B687:139-143 (2010)	2.1×10^{-8}
BaBar Phys.Rev.D81:111101 (2010)	3.3×10^{-8}
LHCb JHEP 02 (2015) 121	4.6×10^{-8} (8 TeV)
ATLAS Eur. Phys. J. C (2016) 76	3.76×10^{-7} (W → τν, 8 TeV)
CMS JHEP 01 (2021) 163	8.0×10^{-8} (W → τν and hadrons, 13 TeV)

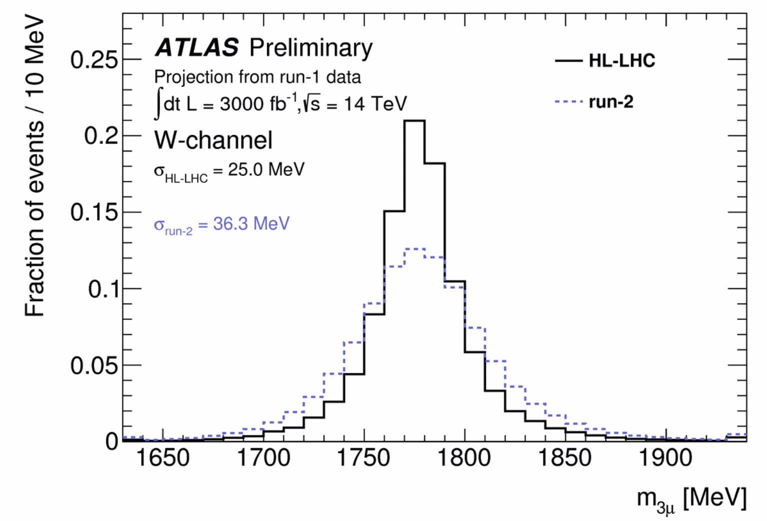
HL-LHC Projections $\tau \to \mu\mu\mu$

- ATLAS Projections for HL-LHC
- Ref: ATL-PHYS-PUB-2018-032

W → τν Channel

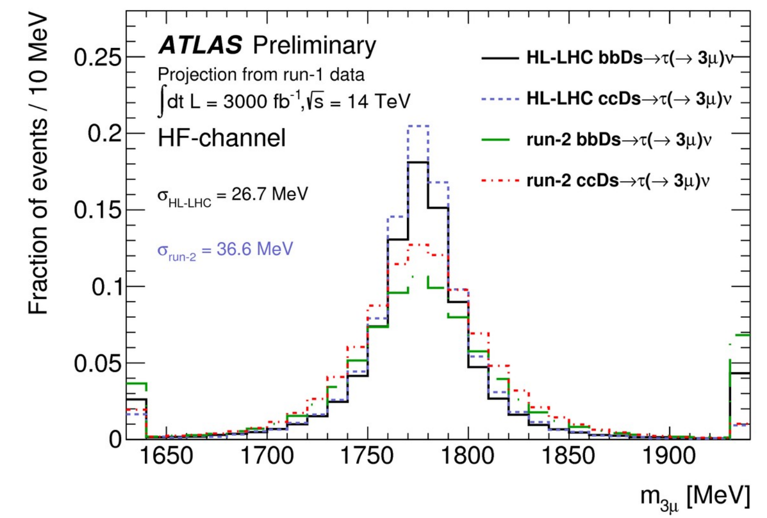
Scenario	$\mathcal{A} \times \epsilon$ [%]	N_{bkg}^{exp}	90% CL UL on BR($\tau \to 3\mu$) [10^{-9}]
Run 1 result	2.31	0.19	276
Non-improved	2.31	50.71	13.52
Intermediate	5.01	50.71	6.23
Improved	5.01	40.06	5.36

Increased acceptance (trigger, reco)
Better S/B separation



Heavy Flavour Channel

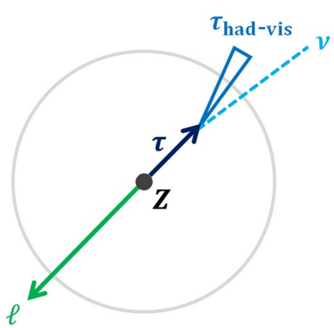
Scenario	$\mathcal{A} \times \epsilon$ [%]	N_{bkg}^{exp}	90% CL UL on BR($\tau \to 3\mu$) [10^{-9}]
High background	0.88	507.05	6.40
Medium background	0.88	152.12	2.31
Low background	0.88	50.71	1.03



Search for LFV Z decays

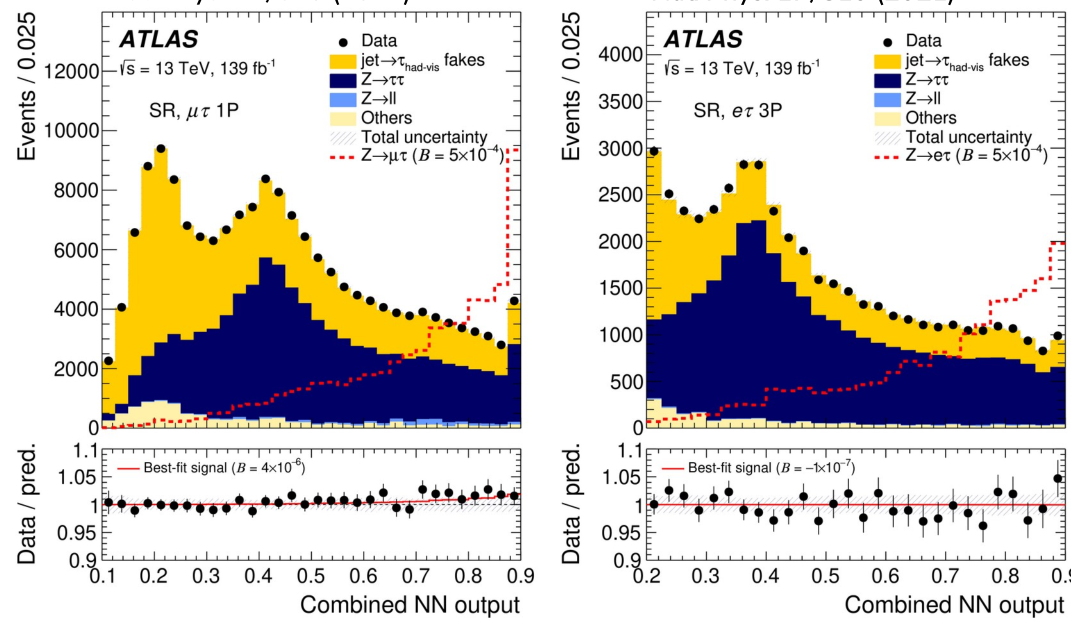
Conservation of Flavour is not inherent to gauge symmetry.

- Search of the Z→eτ and Z→μτ decays.
- Performed in the τ_{had} (Nat. Phys. 17, 819 (2021)) and τ_{lep} (arxiv:2105.12491) channels.
- Event classification is based on Neural Networks (NN)



- Z→μ/e τ_{had} search:
  - Modelling:
    - Misidentified τ_{had} from q/g initiated jets are estimated from data.
    - Z→ττ estimation is based on MC, but uncertainties are reduced using data techniques.

Nat. Phys. 17, 819 (2021) Nat. Phys. 17, 819 (2021)

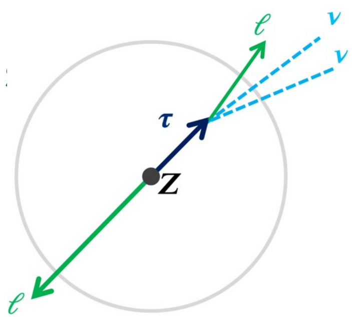


Source of uncertainty	Uncertainty on $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$] $e\tau$	$\mu\tau$
Statistical	±3.5	±2.8
Systematic	±2.3	±1.6
τ-leptons	±1.9	±1.5
Energy calibration	±1.3	±1.4
Jet rejection	±0.3	±0.3
Electron rejection	±1.3	
Light leptons	±0.4	±0.1
E_T^{miss}, jets and flavour tagging	±0.6	±0.5
Z-boson modelling	±0.7	±0.3
Luminosity and other minor backgrounds	±0.8	±0.3
Total	±4.1	±3.2

Search for LFV Z decays

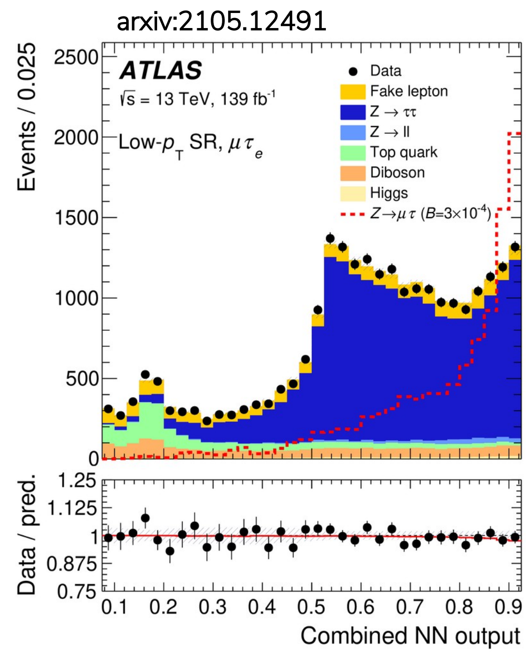
- Search of the $Z \to e\tau_{\mu}$ and $Z \to \mu\tau_{e}$ decays.

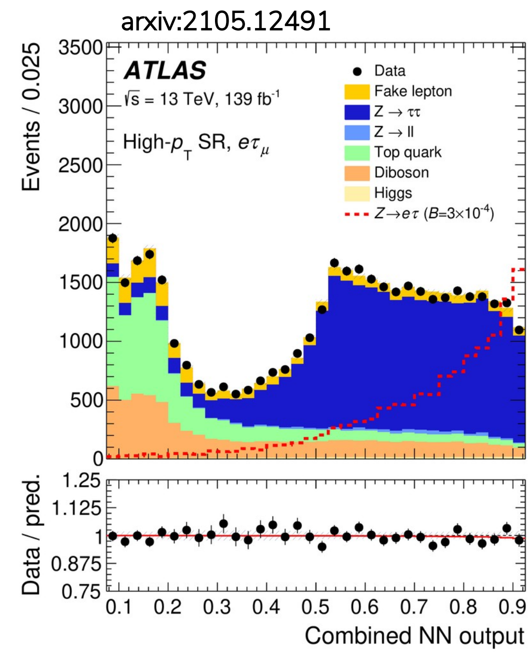
- Same flavour combination of light leptons is not considered due to high DY background.



- Deep neural networks with full kinematic information (4-momentum components) of particles. Similar for $Z \to \mu/e\ \tau_{had}$ search.

- Low- and High-p_T categorization based on sub-leading lepton:
  - $Z \to e\tau_{\mu}$ threshold: 20 GeV
  - $Z \to \mu\tau_{e}$ threshold: 25 GeV





Source of uncertainty	Uncertainty in $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$] $e\tau$	$\mu\tau$
Statistical	±3.5	±3.9
Fake leptons (statistical)	±0.1	±0.1
Systematic	±2.7	±3.4
Light leptons	±0.4	±0.4
E_T^{miss}, jets and flavor tagging	±2.1	±2.4
E_T^{miss}	±0.4	±0.8
Jets	±1.9	±2.2
Flavor tagging	±0.5	±0.9
Z-boson modeling	<0.1	±0.1
$Z \to \mu\mu$ yield	–	±0.8
Other backgrounds	±0.1	±0.6
Fake leptons (systematic)	±0.4	±0.9
Total	±4.4	±5.2

Results of LFV Z decays

- 95% C.L. limits on $B(Z\to e\tau)$ and $B(Z\to \mu\tau)$ for unpolarised and maximally polarised leptons.
- Due to spin correlations, the same polarisation has opposite effects on the energy fraction of the visible decay products in leptonic and hadronic decays.
- Combined results are almost independent of polarisation hypothesis.

Final state, polarization assumption	Observed (expected) upper limit on $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$] $e\tau$	$\mu\tau$
$\ell\tau_{\text{had}}$ Run 1 + Run 2, unpolarized τ	8.1 (8.1)	9.5 (6.1)
$\ell\tau_{\text{had}}$ Run 2, left-handed τ	8.2 (8.6)	9.5 (6.7)
$\ell\tau_{\text{had}}$ Run 2, right-handed τ	7.8 (7.6)	10 (5.8)
$\ell\tau_{\ell'}$ Run 2, unpolarized τ	7.0 (8.9)	7.2 (10)
$\ell\tau_{\ell'}$ Run 2, left-handed τ	5.9 (7.5)	5.7 (8.5)
$\ell\tau_{\ell'}$ Run 2, right-handed τ	8.4 (11)	9.2 (13)
Combined $\ell\tau$ Run 1 + Run 2, unpolarized τ	5.0 (6.0)	6.5 (5.3)
Combined $\ell\tau$ Run 2, left-handed τ	4.5 (5.7)	5.6 (5.3)
Combined $\ell\tau$ Run 2, right-handed τ	5.4 (6.2)	7.7 (5.3)

- ATLAS results improve previous 95% CL limits on $B(Z\to e\tau)$ and $B(Z\to \mu\tau)$ by LEP.
  - $B(Z\to e\tau) < 12 \times 10^{-6}$ [OPAL]
  - $B(Z\to \mu\tau) < 9.8 \times 10^{-6}$ [DELPHI]

Search for LFV Z decays

- Search for $Z \rightarrow e\mu$:
  - Fit of peak in the $m_{e\mu}$ invariant mass distribution
  - To reduce backgrounds, events with high-p_T jets and large E_T^{miss} are vetoed.
  - BDT is used to further improve background rejection
  - Normalization of Z decays determined from sample of $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ decays
  - Analysis limited by statistical uncertainties in data and in simulation
  - Upper limit set at 95% CL:
    - $B(Z \rightarrow e\mu) < 3.04 \times 10^{-7}$

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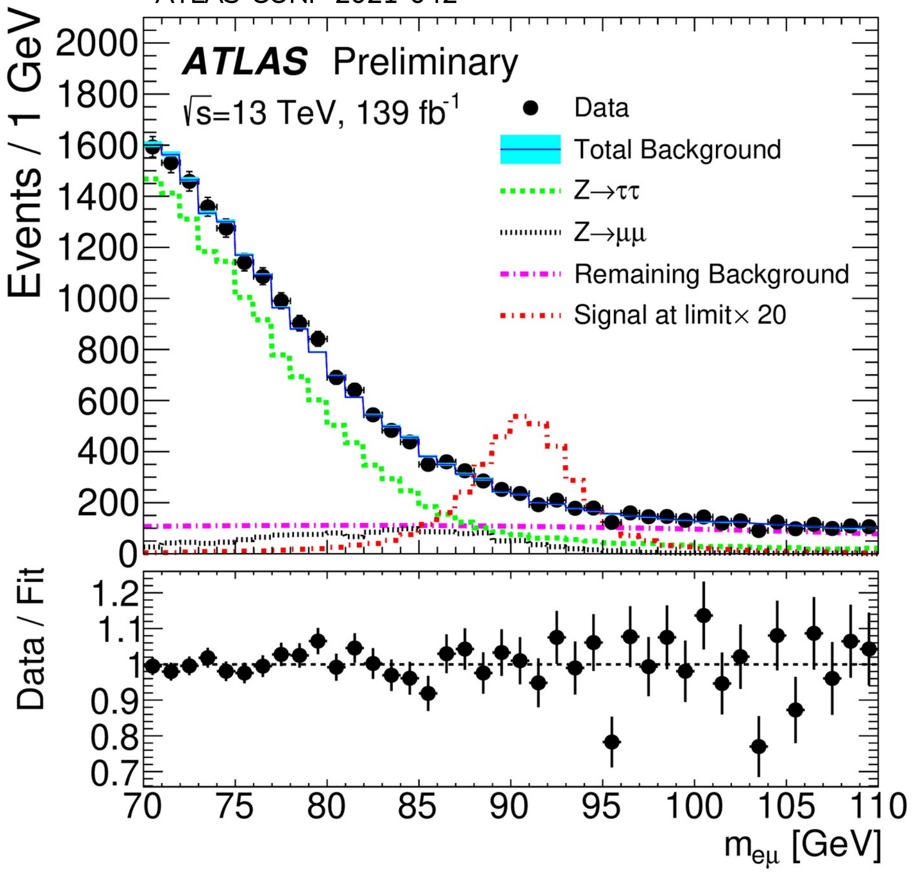
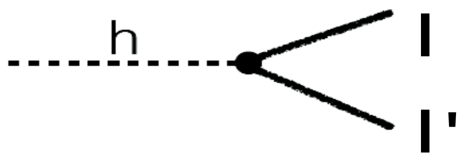


Search for LFV H decays

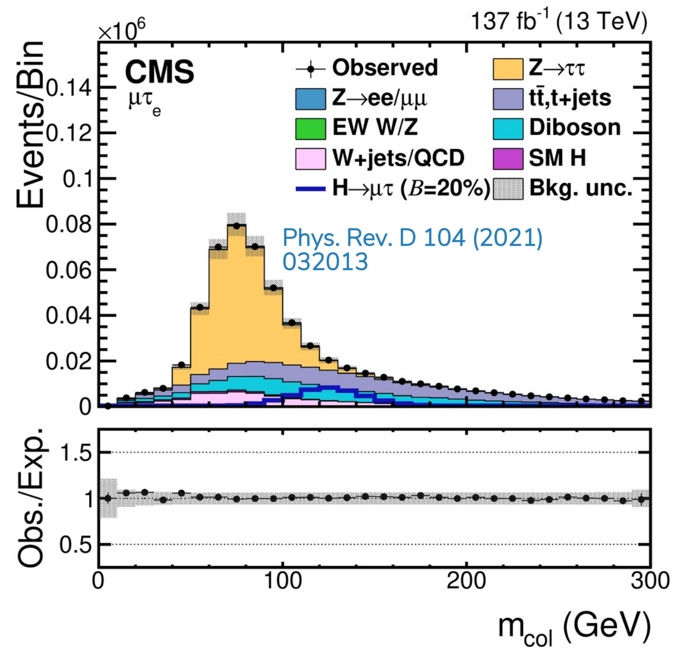


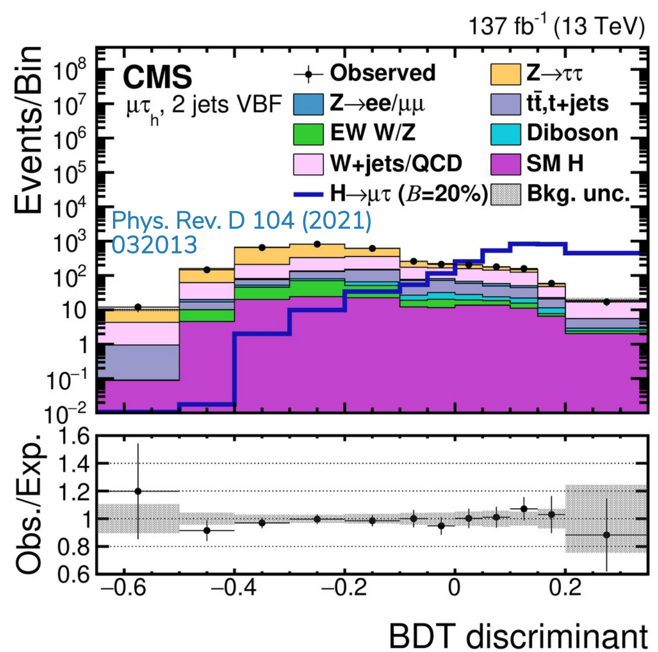
Yukawa off-diagonal terms

$$\mathcal{L}_Y = -m_i \bar{f}_L^i f_R^i - Y_{ij}(\bar{f}_L^i f_R^j)h + h.c. + \cdots ,$$

In the SM: $Y_{ij} = (m_i/v)\delta_{ij}$

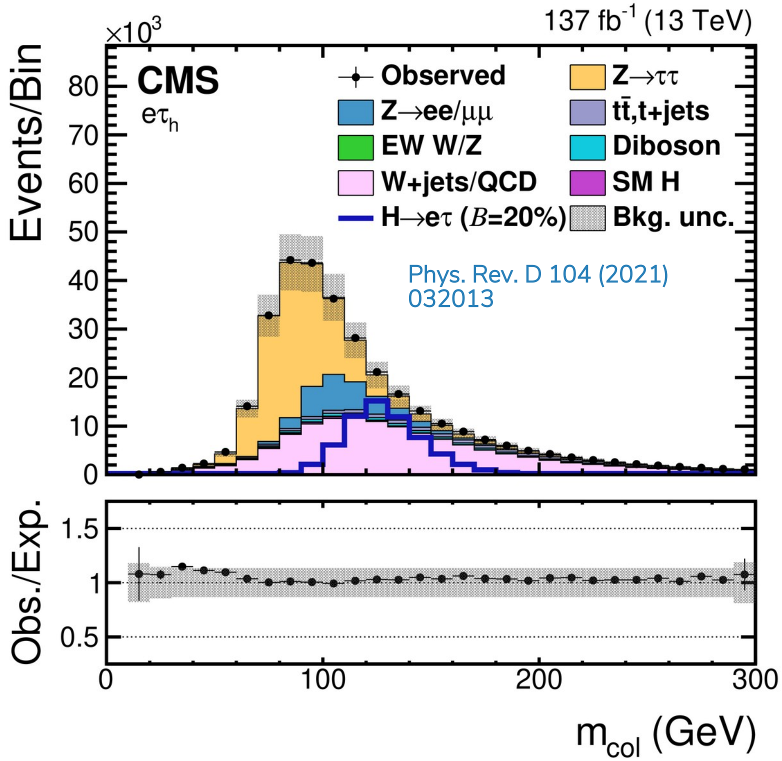
- Search for H→eτ and H→μτ decays.
  - Main backgrounds are the Z → ττ , W+jets and QCD production.
  - Embedding data-driven technique is used to model Z→ττ
  - Analysis employs four categories: 0-jet, 1-jet, 2-jet VBF and 2-jet noVBF.
  - Mass reconstruction based on collinear mass.
  - BDT discriminant is fit to achieve higher sensitivity.

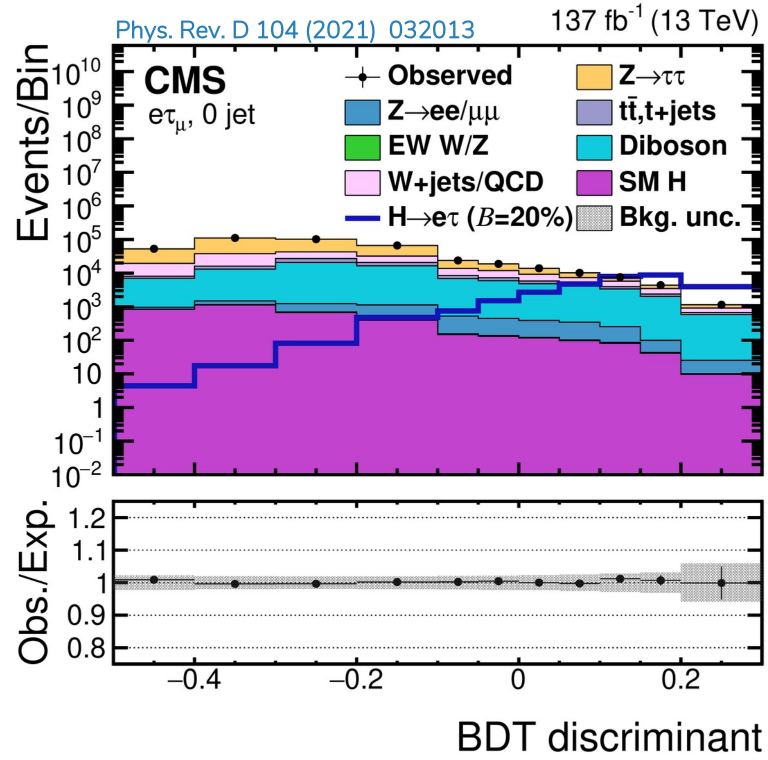




Search for LFV H decays

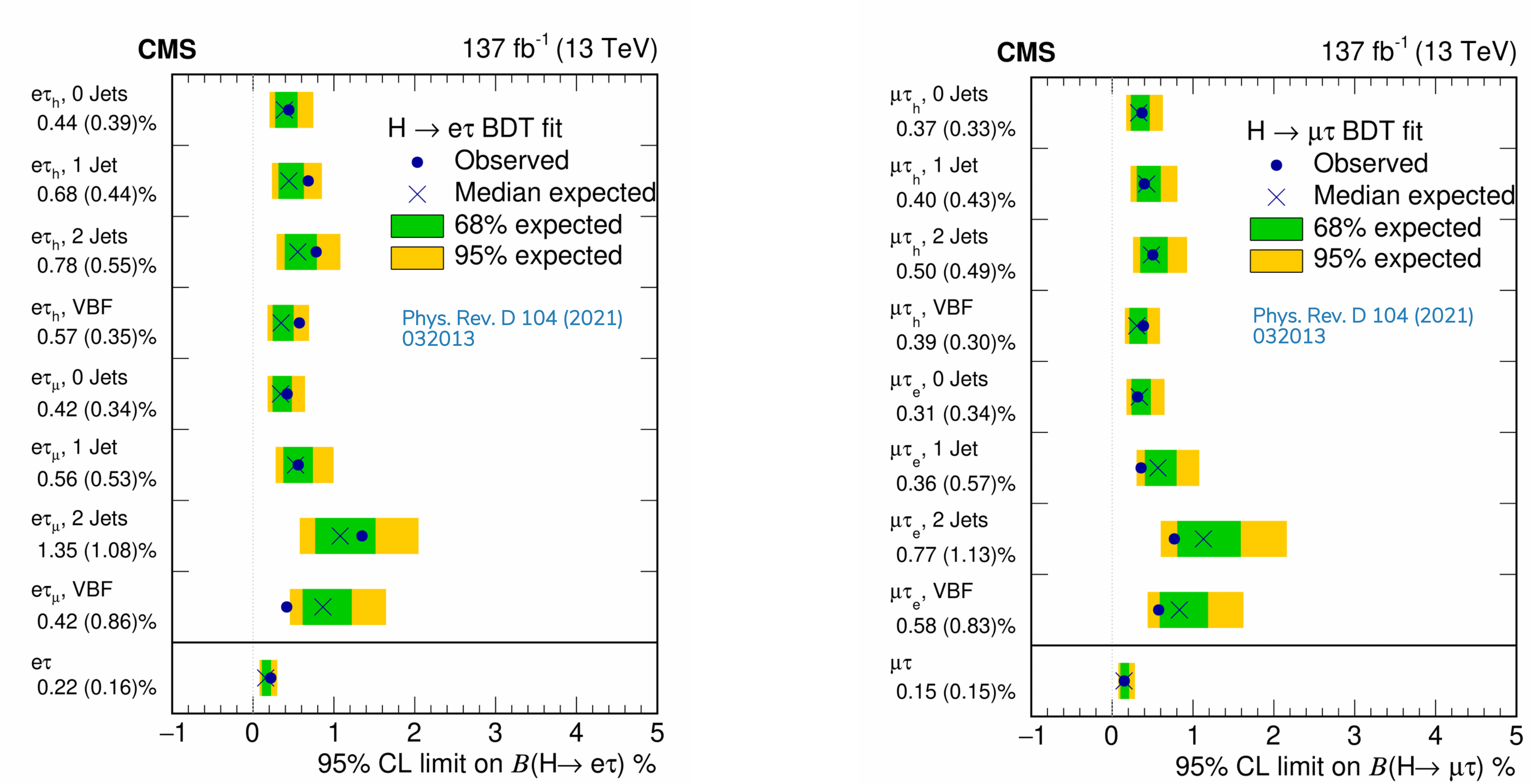
- For the $H \rightarrow e\tau$ decay search, additional $Z \rightarrow ee$ background with electron mis-identified as τ_{had}





Results of LFV H search

- 95% C.L. limits on $B(H \to e\tau)$ and $B(H \to \mu\tau)$ and on off-diagonal Yukawa coupling:

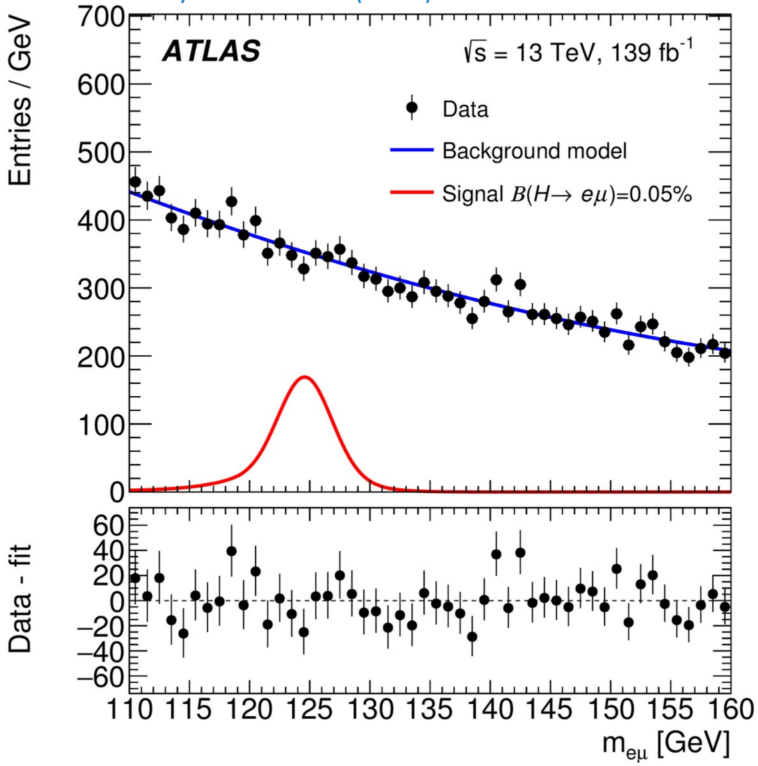


	Observed (expected) upper limits (%)	Best fit branching fractions (%)	Yukawa coupling constraints
$H \to \mu\tau$	$<0.15\ (0.15)$	0.00 ± 0.07	$< 1.11\,(1.10) \times 10^{-3}$
$H \to e\tau$	$<0.22\ (0.16)$	0.08 ± 0.08	$< 1.35\,(1.14) \times 10^{-3}$

Search for LFV $H \to e\mu$

- Unbinned fit of the $m_{e\mu}$ mass spectrum, similar to $H \to \mu\mu$ and $H \to \gamma\gamma$ analyses.
- Events are separated in 8 categories (Low p_T, VBF, 3 barrel and 3 endcap).
- Background modeled by a Bernstein polynomial of degree two with category-dependent parameters.
- Signal modeled by the sum of a Crystal Ball and a Gaussian distribution.

Phys. Lett. B 801 (2020) 135148



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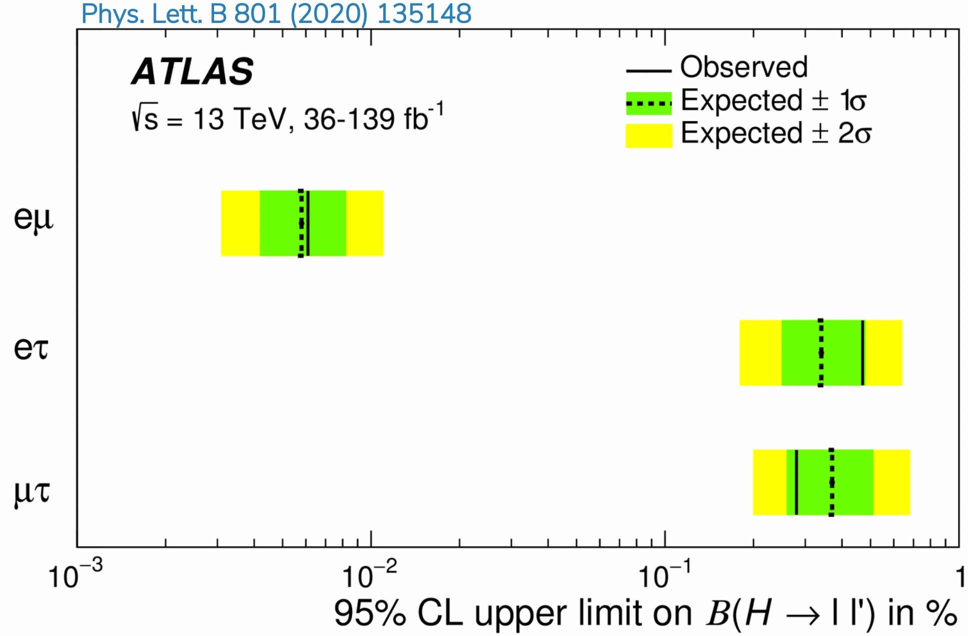

No excess observed, 95% CL limit is $B(H \to e\mu) < 6.1\times10^{-5}$ (5.8×10^{-5} expected)

Search for LFV in top quark decays

- Searching for $t \to (u,c)\ell^+\ell'^-$

- Probe of cLFV in top quark decays exploiting the large $pp \to t\bar{t}$ production at the LHC.

- Prior to this search, LFV branching ratios were only loosely constrained ($Br \lesssim 10^{-3}$).

- Event selection:
  - 3 isolated light leptons,
  - ≥ 2 jets, p_T > 25 GeV.

- 60% of the background is composed of $t\bar{t}$ and Z+jets events with an extra non-prompt lepton.

- A Boosted Decision Tree (BDT) is trained on simulated events.

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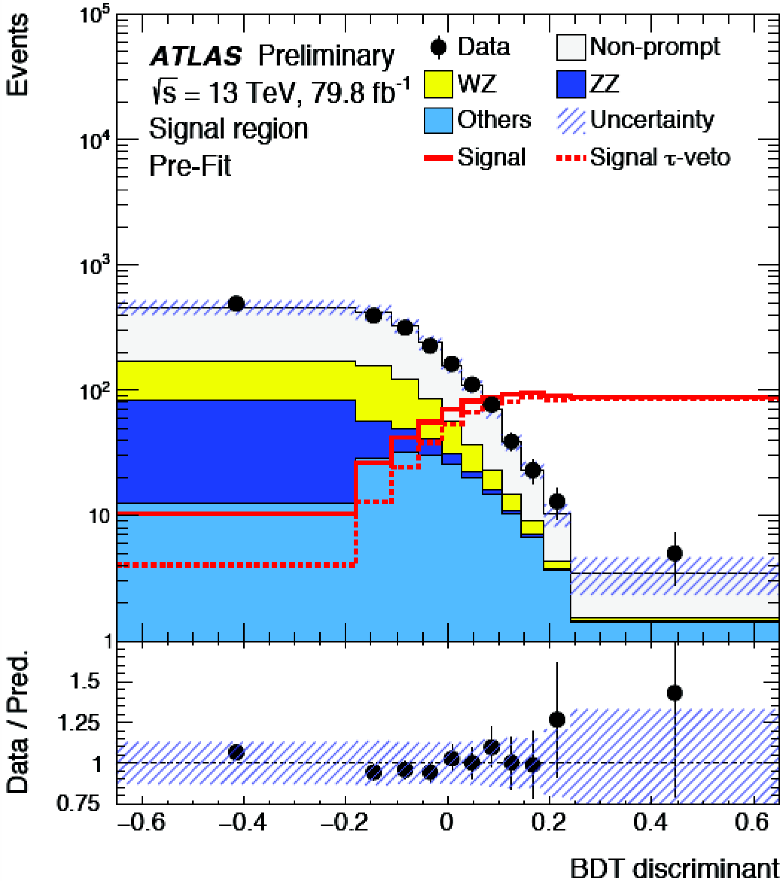


$$\mathcal{B}(t \to \ell\ell' q) < 1.86 \times 10^{-5} \quad \text{(observed)}.$$

$$\mathcal{B}(t \to \ell\ell' q) < 1.36^{+0.61}_{-0.37} \times 10^{-5} \quad \text{(expected)}.$$

$$\mathcal{B}(t \to e\mu q) < 4.8^{+2.1}_{-1.4} \times 10^{-6} \quad \text{(observed)}$$

$$\mathcal{B}(t \to e\mu q) < 6.6 \times 10^{-6} \quad \text{(expected)}$$

Search for LFV in top quark decays

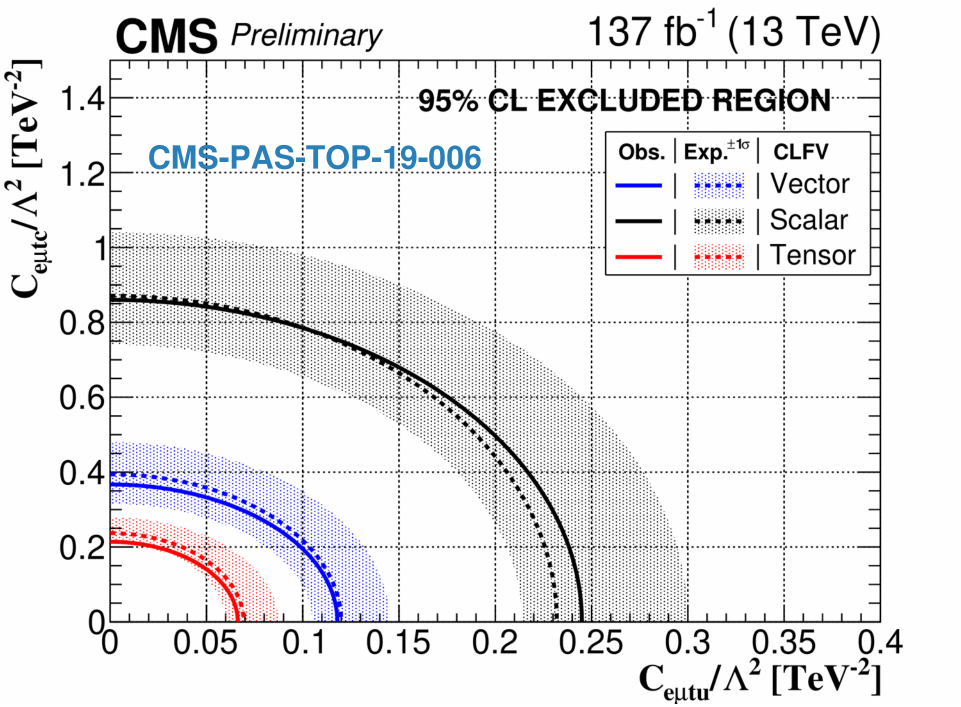
- Searching for $t \rightarrow (u,c)e\mu$

- CMS search uses full Run 2 statistics.

- SR events have $N_{b\text{-jets}}=1$.
- Events with $N_{b\text{-jets}}>1$ are assigned to the $t\bar{t}$ CR.

- C_{vector}, C_{scalar}, and C_{tensor} Wilson coefficients, related to the corresponding dimension-six operators, are probed in the context of EFT with NP scale chosen to be Λ = 1 TeV.

- A binned likelihood fit is performed on the full BDT discriminant distributions in the signal region and $t\bar{t}$ control region.



$$\mathcal{B}_{\text{tensor}}(t \rightarrow e\mu u(c)) < 0.25 \times 10^{-6}\ (2.59 \times 10^{-6})$$

$$\mathcal{B}_{\text{vector}}(t \rightarrow e\mu u(c)) < 0.135 \times 10^{-6}\ (1.3 \times 10^{-6})$$

$$\mathcal{B}_{\text{scalar}}(t \rightarrow e\mu u(c)) < 0.07 \times 10^{-6}\ (0.89 \times 10^{-6})$$

Search for LFU deviations

- **Measurement of R(τ/μ)= B(W→τν)/B(W→μν)**

- SM predicts R(τ/μ)~1.
- Previous most precise measurement LEP:
  - R(τ/μ)=1.070 ± 0.026, 2.7σ deviation from SM.

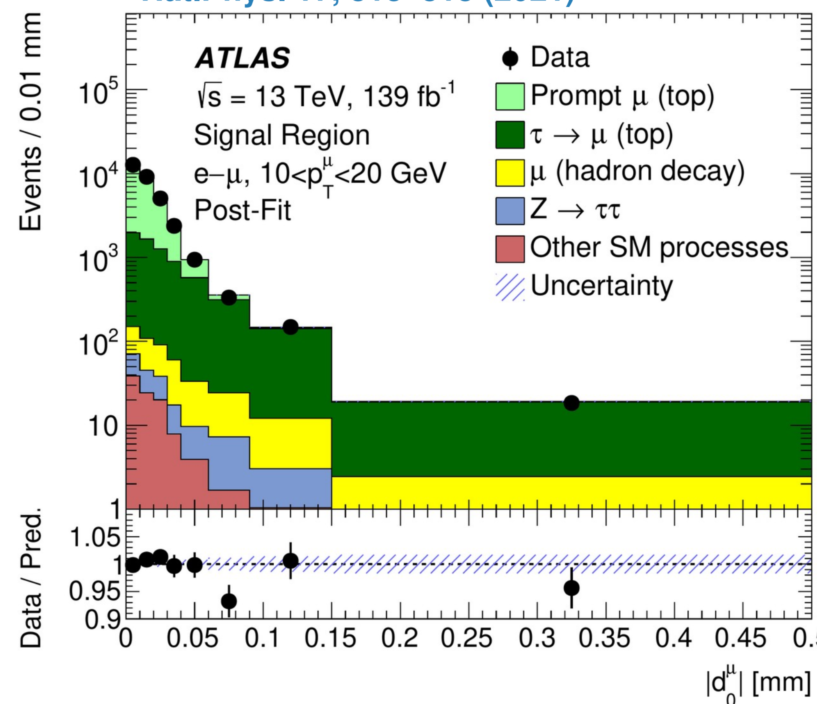
- Pure sample of W decays is obtained from $t\bar{t}$ decays.

- To reduce systematics, W → τ (→ μνν)ν decays are used for the R(τ/μ) measurement.

- The difference in transverse impact parameter d_0 is exploited to differentiate between μ and τ_μ decays of the W.
- A 2D profile likelihood in p_T-d_0 (3x8 bins) is performed.

- Results are in agreement with the SM expectations: R(τ/μ)=0.992±0.013

Nat.Phys. 17, 813–818 (2021)



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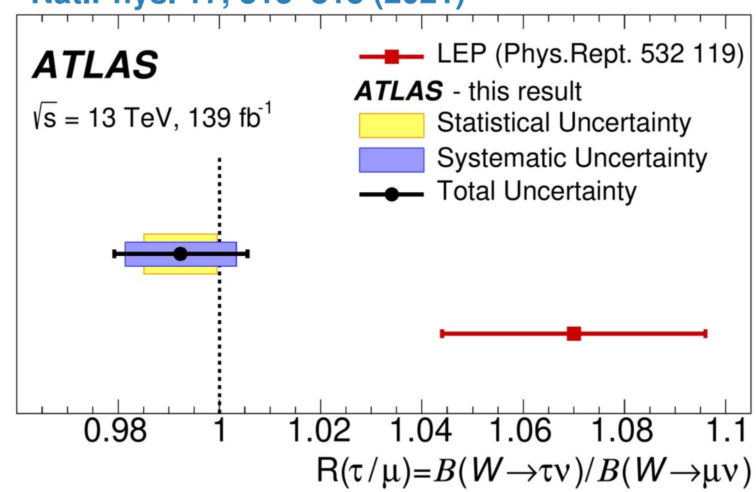


ATLAS $e^+\mu^-/\mu^+e^-$ asymmetry

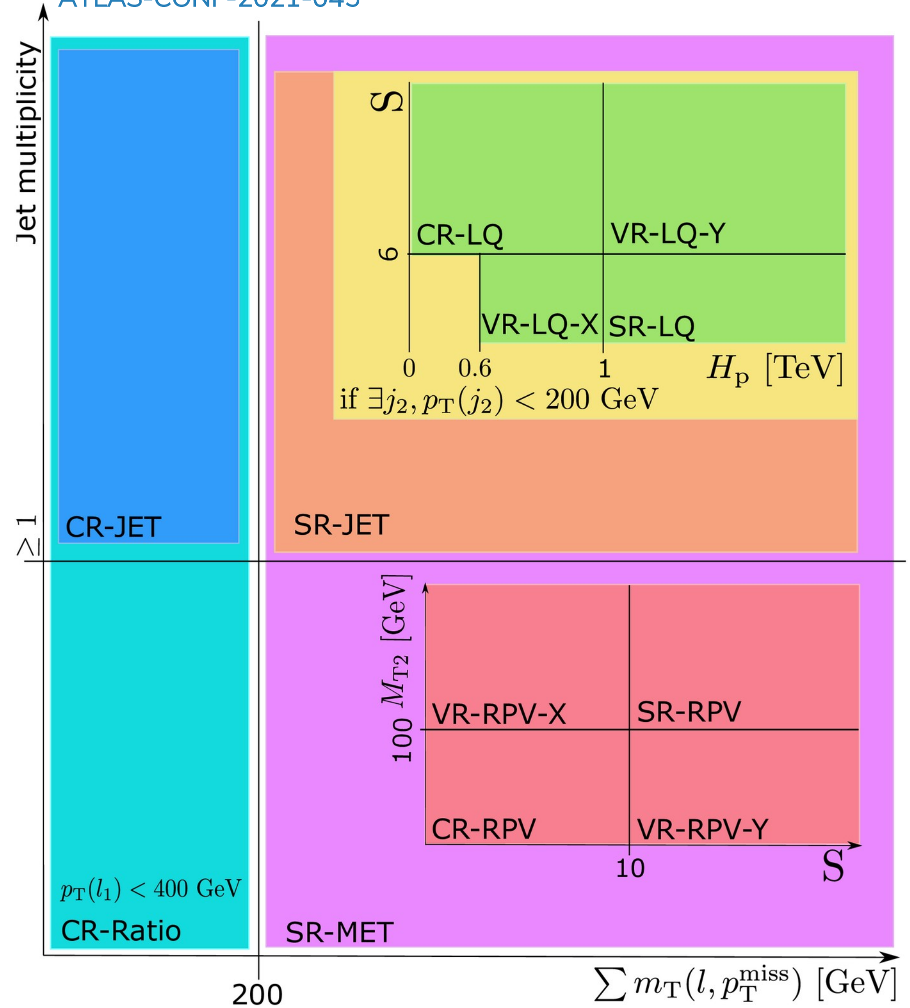
- In the SM: $\rho_{SM}=1$. $\rho \equiv \frac{\sigma(pp \to e^+\mu^- + X)}{\sigma(pp \to e^-\mu^+ + X)}$

- Searches for $\rho \neq 1$ motivated by BSM models:
  - RPV SUSY smuons.
  - Leptoquarks.
  - LFU violation related to B-anomalies.

- ATLAS search for $\rho>1$, because $\rho<1$ is more challenging due to experimental biases:
  - mis-id $P(j\to e)>P(j\to\mu)$
  - $\sigma(W^+j)>\sigma(W^-j)$

- Events separated in categories with E_T^{miss} (SR-MET and SR-RPV) and with jets (SR-JET and SR-LQ)

ATLAS-CONF-2021-045



ATLAS $e^+\mu^-/\mu^+e^-$ asymmetry

- Sources of bias corrected for:
  - Difference in fakes contribution, $e^-_{fake}\mu^+_{real} > e^+_{fake}\mu^-_{real}$
  - Difference in μ^+/μ^- efficiency due to toroid field
  - Muon sagitta bias, charge asymmetry dependent on the muon p_T caused by detector misalignment.

$m_T(\ell, \vec{p}_T^{miss}) \equiv \sqrt{2|\vec{p}_T^{\ell}||\vec{p}_T^{miss}| - 2\vec{p}_T^{\ell} \cdot \vec{p}_T^{miss}}$ $M_{T2} \equiv \min_{\vec{a}+\vec{b}=\vec{p}_T^{miss}} \max\left[m_T(e,\vec{a}), m_T(\mu,\vec{b})\right]$

$H_P \equiv |\vec{p}_T^{e}| + |\vec{p}_T^{\mu}| + |\vec{p}_T^{j_1}|$

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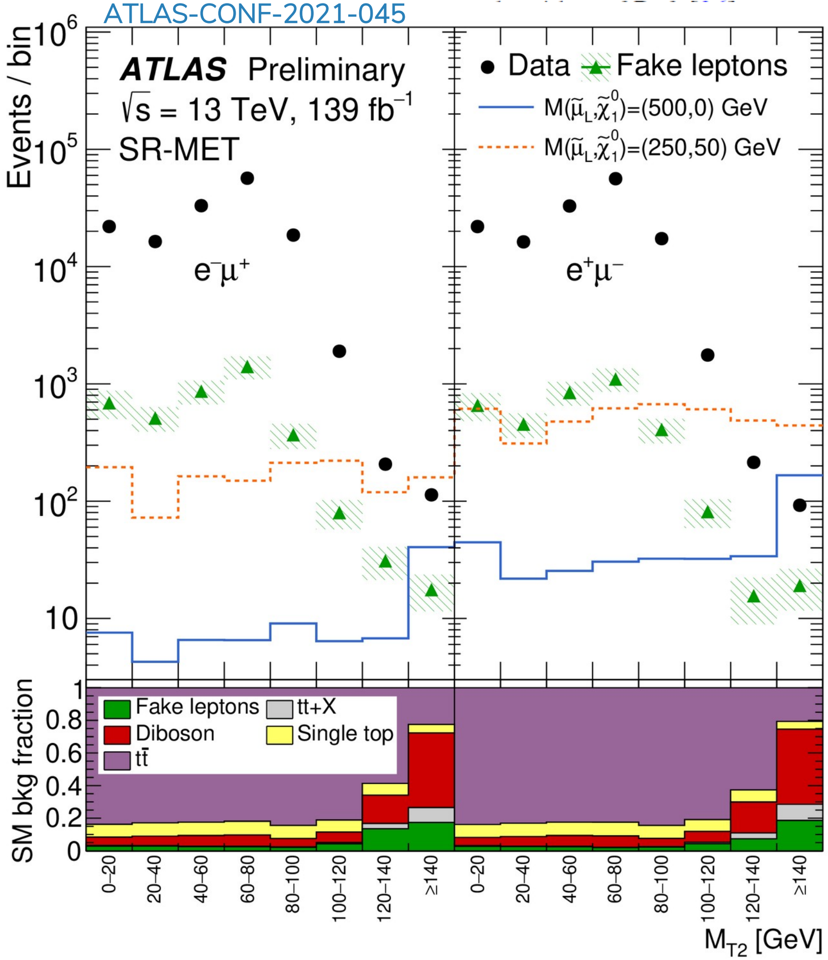
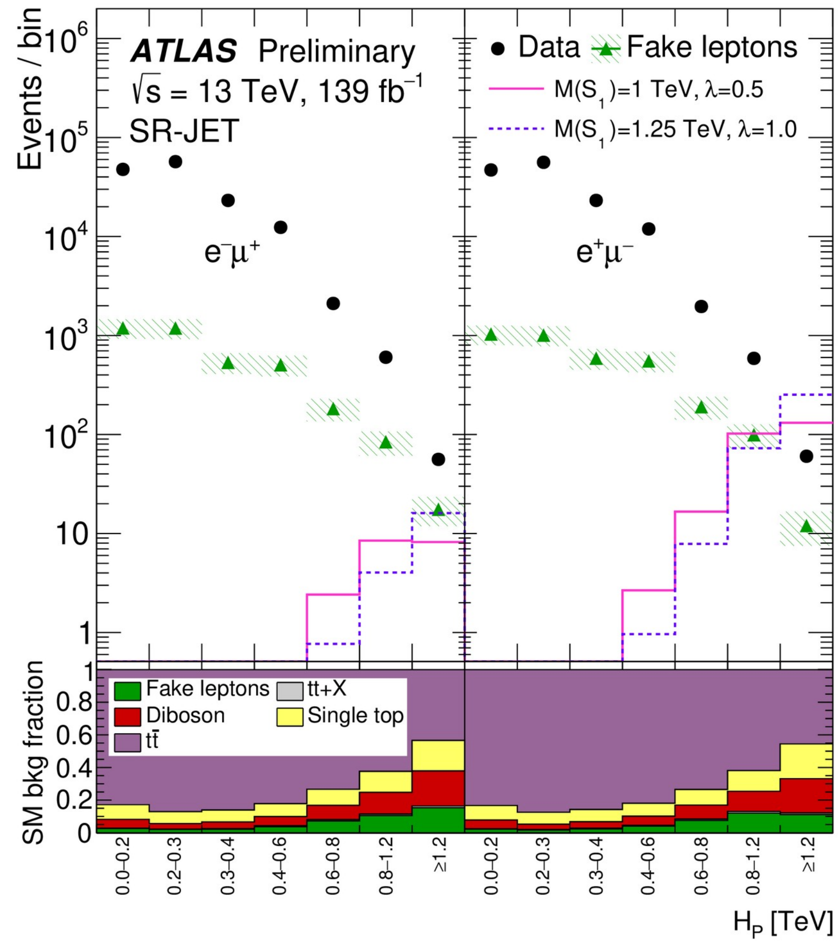
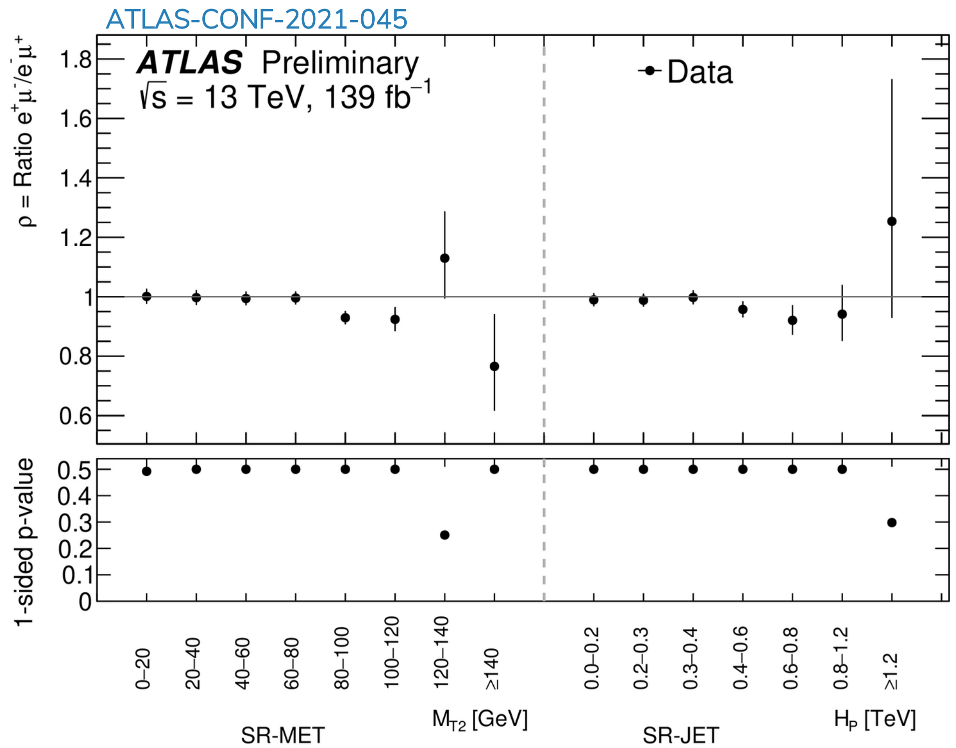


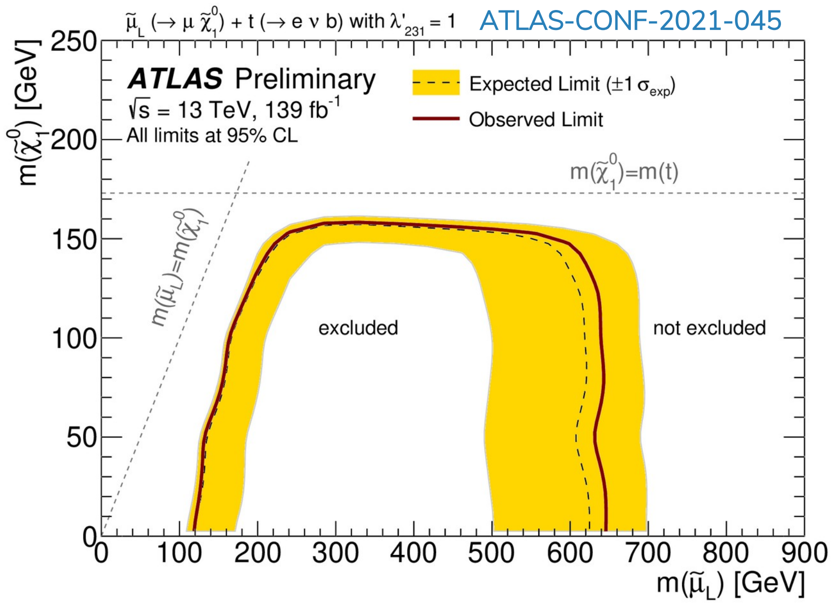
ATLAS-CONF-2021-045

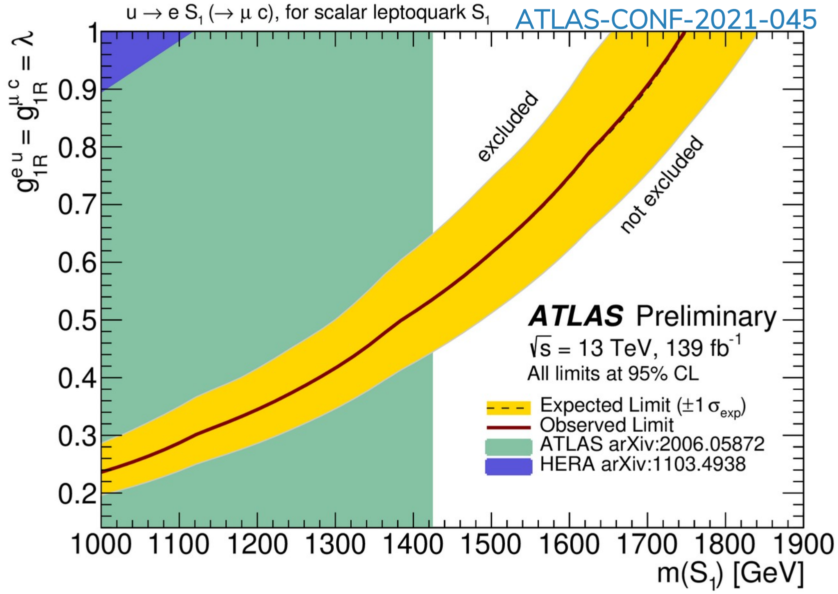


ATLAS $e^+\mu^-/\mu^+e^-$ results

- No excess observed for ρ>1
- 95% CL upper limits are set for RPV SUSY and scalar LQ models.







Conclusions

- Search for $\tau \rightarrow \mu\mu\mu$ was performed by CMS using both Heavy Flavor (HF) and W channels. The limit on the branching ratio is 8.0×10^{-8} at 90% CL.
- ATLAS projections for HL-LHC indicate sensitivity to the 10^{-9} level.

- Limits set at LHC in the search for LFV decays of the Z and Higgs bosons constantly improve.

- ATLAS and CMS exploit top-quark decays to searches for LFV and deviation of LFU.

- Limits of the ATLAS search for $\sigma(e^-\mu^+ + X)/\sigma(e^+\mu^- + X)$ excess interpreted in terms of RPV SUSY and Scalar LQ models.

- Growing evidence for anomalies in lepton interactions, but no direct evidence of LFV processes so far.

Bonus Slides

Neutrinoless $\tau \rightarrow 3\mu$ decay

- **Searching for $\tau \rightarrow 3\mu$**

- Searching $\tau \rightarrow 3\mu$ at a hadron collider is difficult:
  - Low energy muons have lower reconstruction efficiency.
  - Need multiobject triggers.
- Uses $W \rightarrow \tau\nu$ channel to select events with 3 boosted muons and E_T^{miss}.

- Result based on 20.3 fb1 at $\sqrt{s}$ = 8 TeV

- Signal Region: $|M(3\mu) - M_\tau| < 1$ GeV
- Concept: extrapolation of backgrounds from sidebands.

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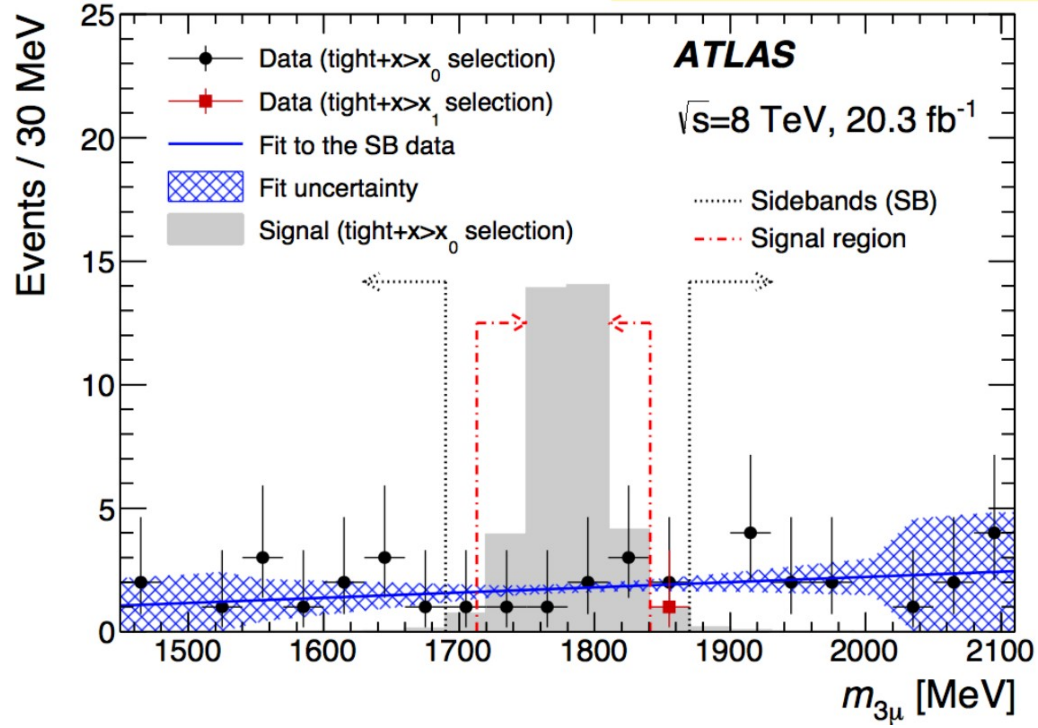

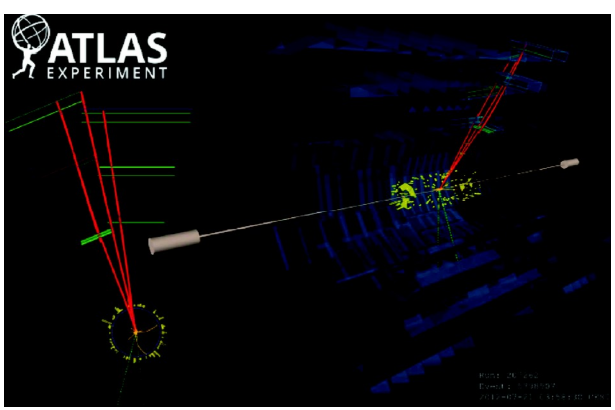

- Limits only from W decays less stringent than Bell/BaBar/LHCb results.

$BR(\tau \rightarrow \mu\mu\mu) < 3.8\ 10^{-7}$ @ 90% CL
Belle: $BR(\tau \rightarrow \mu\mu\mu) < 2.1\ 10^{-8}$ @ 90% CL

CMS $\tau \rightarrow 3\mu$ decay projections

- Projection for HL-LHC (3000 fb^{-1})

- Forward muon detectors will be enhanced.
- The new ME0 detector extends coverage from η = 2.4 to 2.8

- The major source of τ at LHC is D,B meson decays

Signal and background yields in (1.55, 2.00) GeV, assuming BR(τ->3μ)=2x10^{-8}

	Category 1	Category 2
Number of background events	2.4×10^6	2.6×10^6
Number of signal events	4 580	3 640
Trimuon mass resolution	18 MeV	31 MeV
$B(\tau \to 3\mu)$ limit per event category	4.3×10^{-9}	7.0×10^{-9}
$B(\tau \to 3\mu)$ 90%C.L. limit	3.7×10^{-9}	

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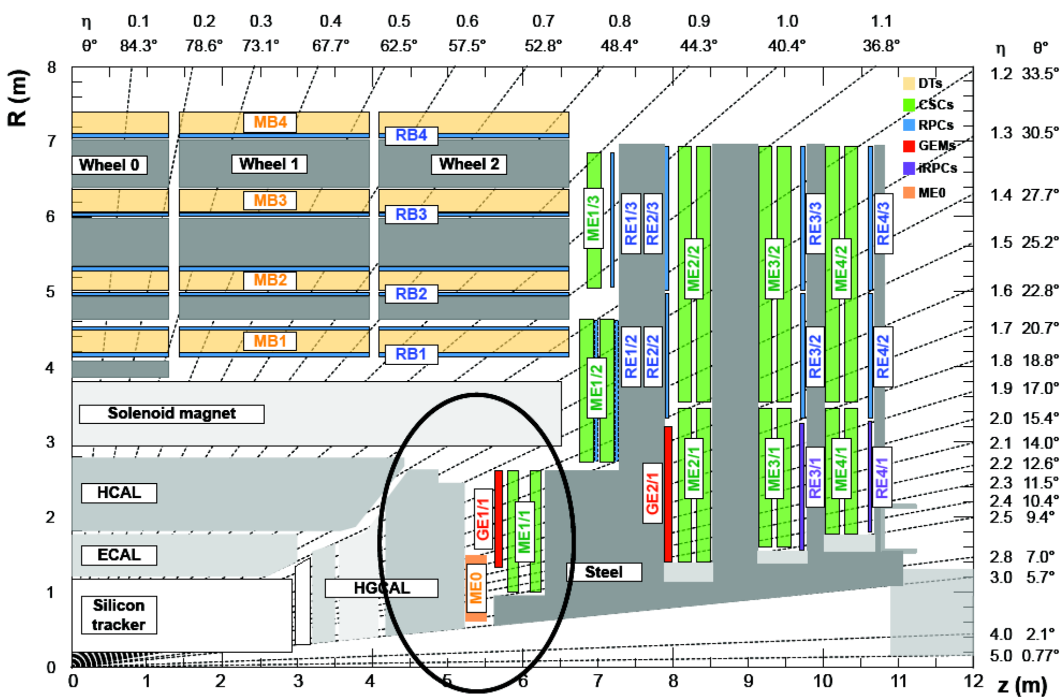
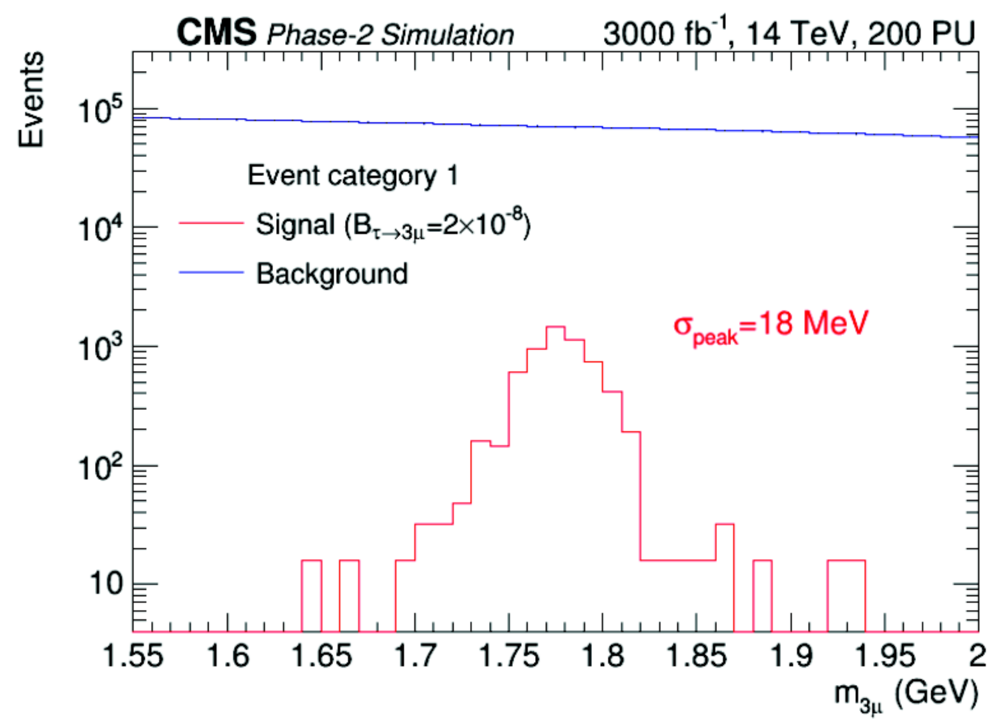
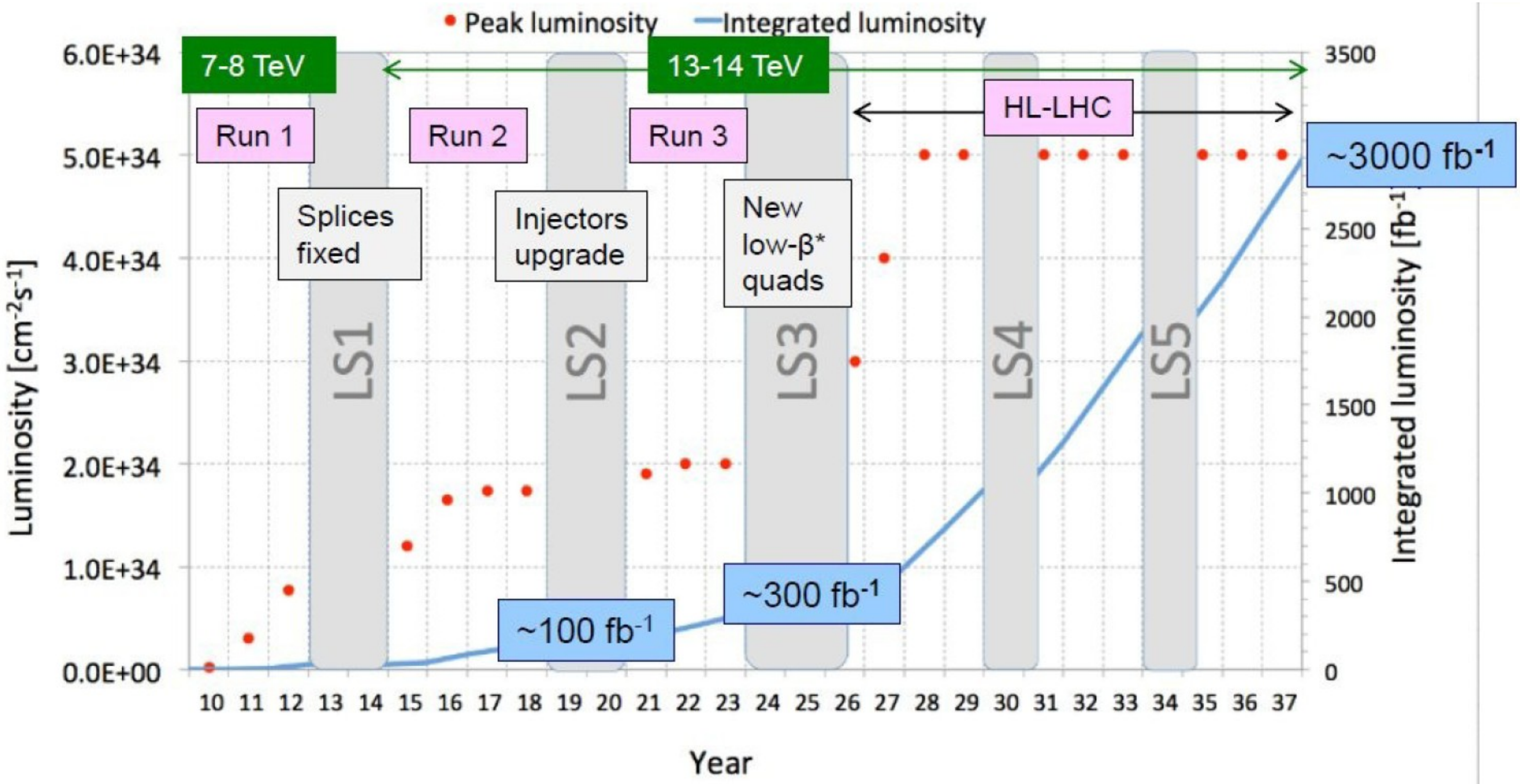


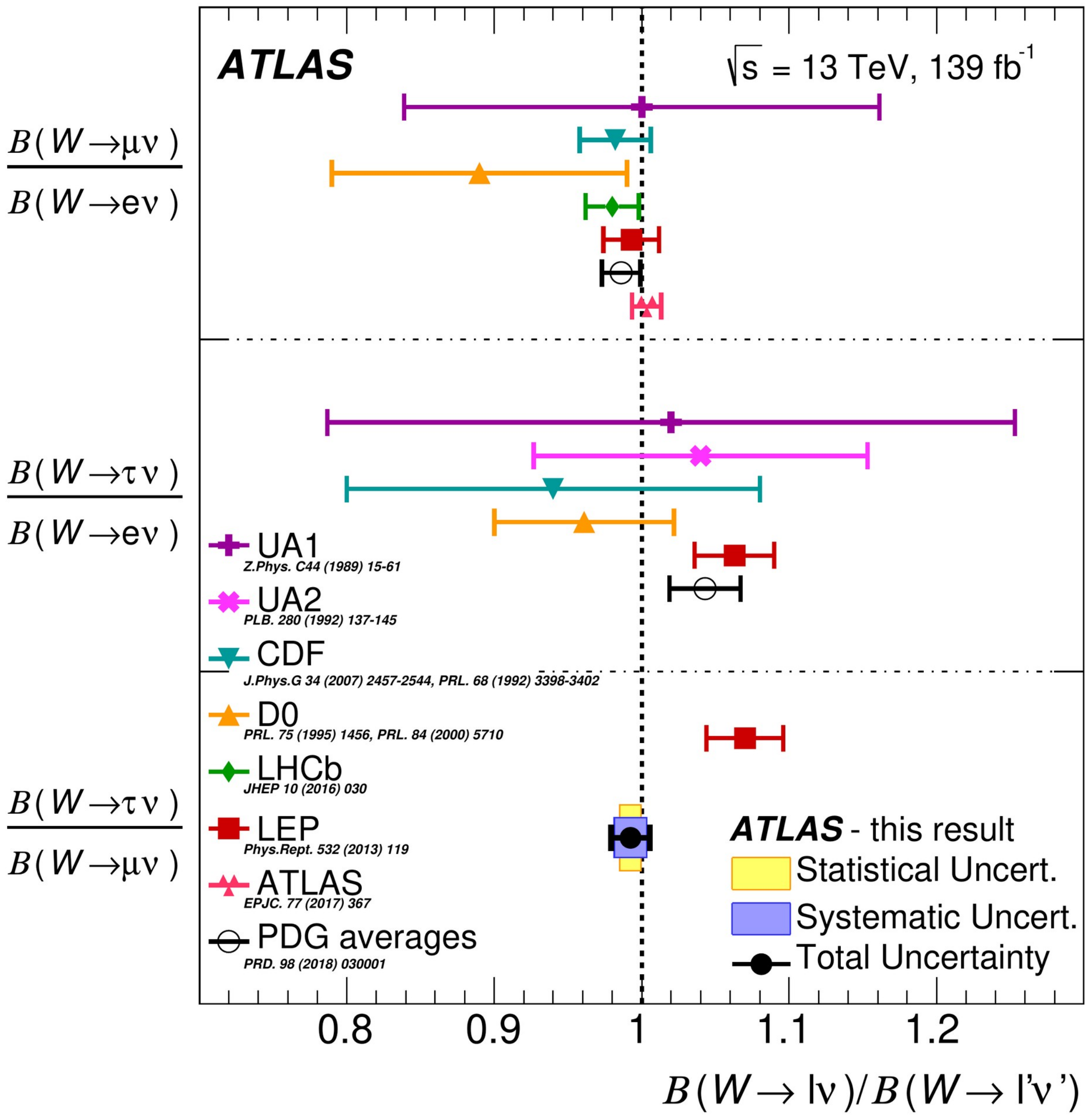


LHC Upgrade



- In parallel design of electron-positron linear colliders ILC, CLIC
- At CERN for >2035: HE-LHC, VHE-LHC, TLEP,...

LFU Summary



ATLAS
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
$B(W\to\mu\nu)/B(W\to e\nu)$
$B(W\to\tau\nu)/B(W\to e\nu)$
$B(W\to\tau\nu)/B(W\to\mu\nu)$
UA1
Z.Phys. C44 (1989) 15-61
UA2
PLB. 280 (1992) 137-145
CDF
J.Phys.G 34 (2007) 2457-2544, PRL. 68 (1992) 3398-3402
D0
PRL. 75 (1995) 1456, PRL. 84 (2000) 5710
LHCb
JHEP 10 (2016) 030
LEP
Phys.Rept. 532 (2013) 119
ATLAS
EPJC. 77 (2017) 367
PDG averages
PRD. 98 (2018) 030001
ATLAS - this result
Statistical Uncert.
Systematic Uncert.
Total Uncertainty
0.8
0.9
1
1.1
1.2
$B(W\to l\nu)/B(W\to l'\nu')$