Search for lepton flavor violation at ATLAS and CMS

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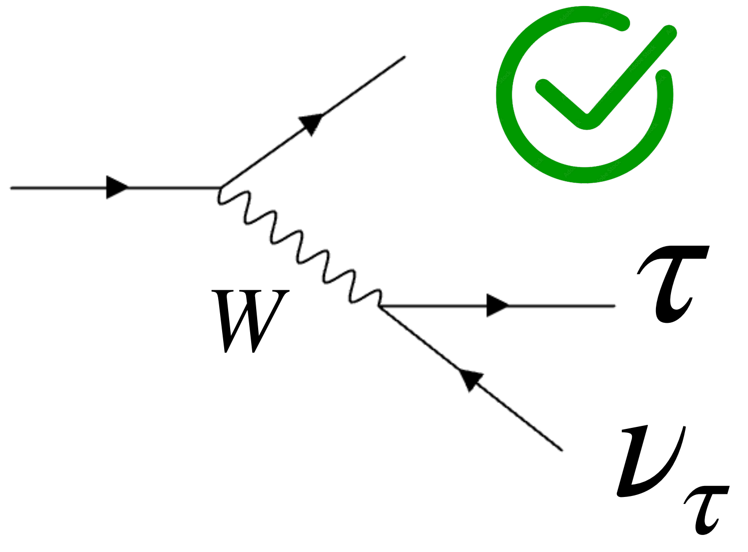
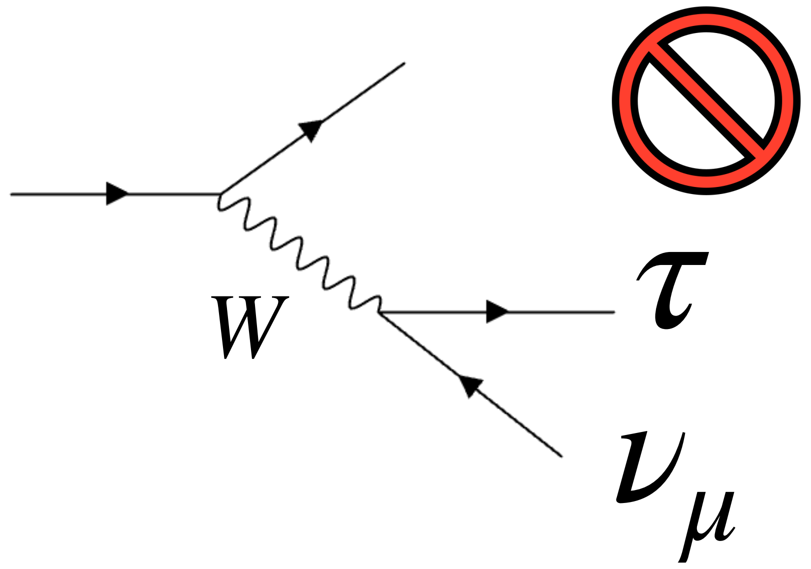
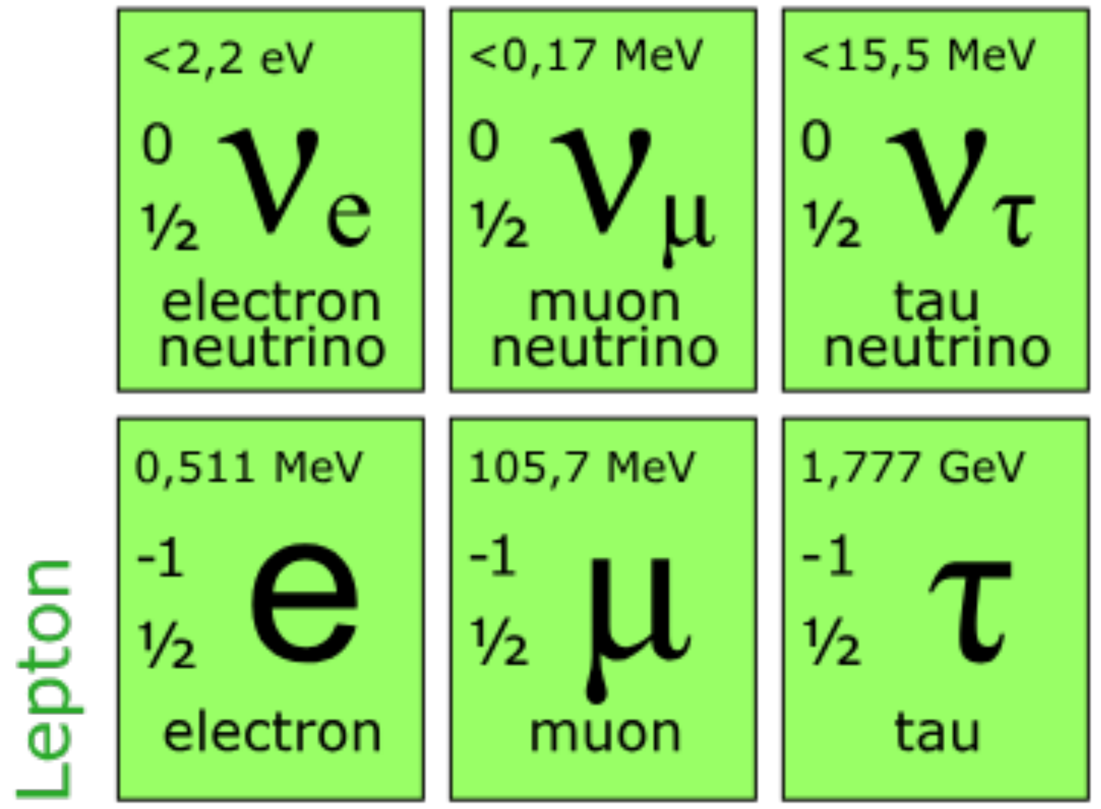
Lepton Flavor (accidental) Symmetry

- Standard Model (SM) has 3 families of leptons electron, muon and tau = ***lepton flavor (LF)***
- SM + massless left-handed neutrinos → ***LF*** quantum numbers **conserved**
  - interaction vertex between different flavors are forbidden
  - accidental symmetry not protected by any conservation law



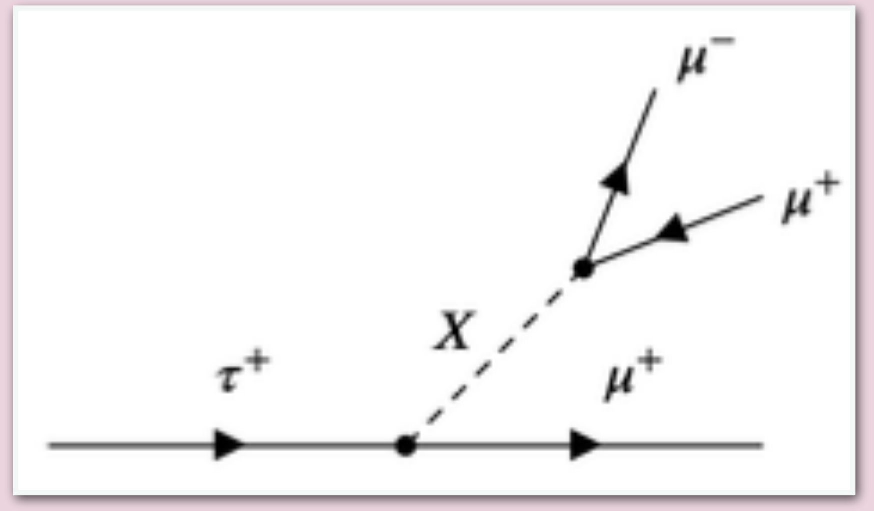




- Experimentally proved neutrinos are massive → they have mixing angles
  - neutrino oscillations prove **LF is not a fundamental symmetry**
- **Charged Lepton Flavor Violation** (cLFV) in charged lepton interactions is not yet observed
  - in SM frame strongly suppressed by power of (M_ν / M_W)
  - potential to probe physics scale much higher than TeV

Outline

LFV in lepton decay

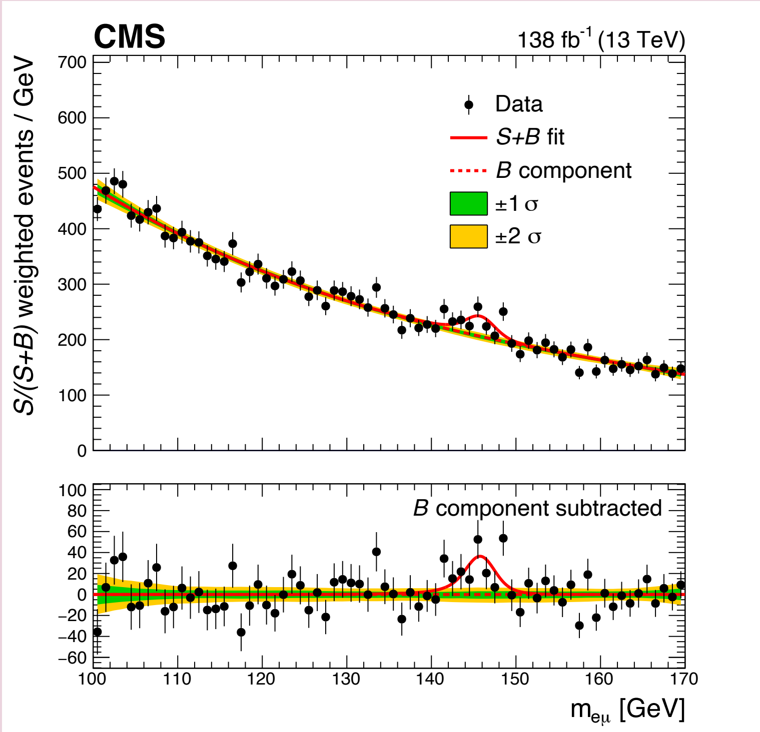


$\tau \to 3\mu$

LFV Yukawa couplings

H

$Y_{e\mu}$ $Y_{e\tau}$ $Y_{\mu\tau}$



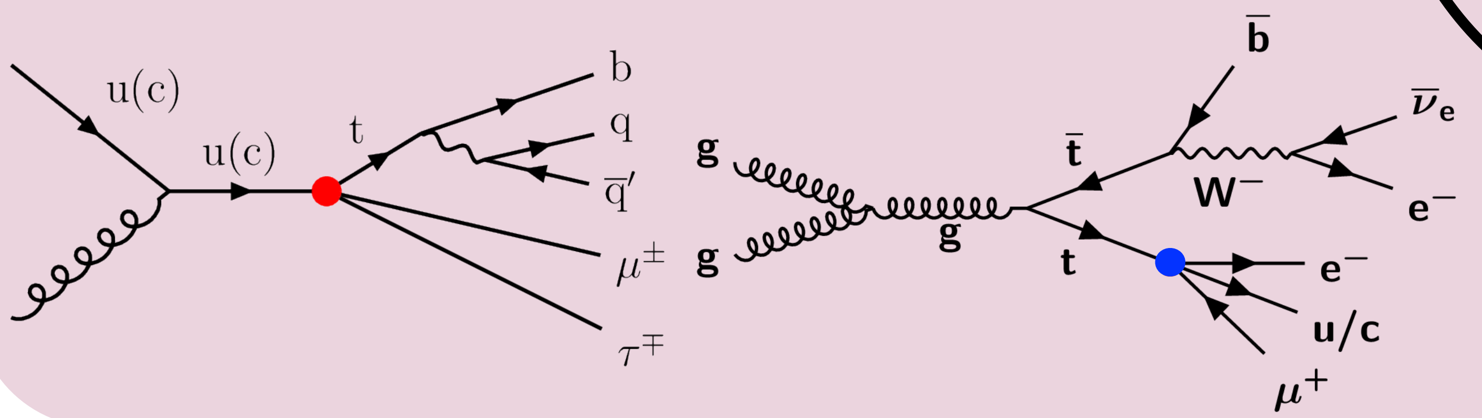
cLFV

ATLAS & CMS

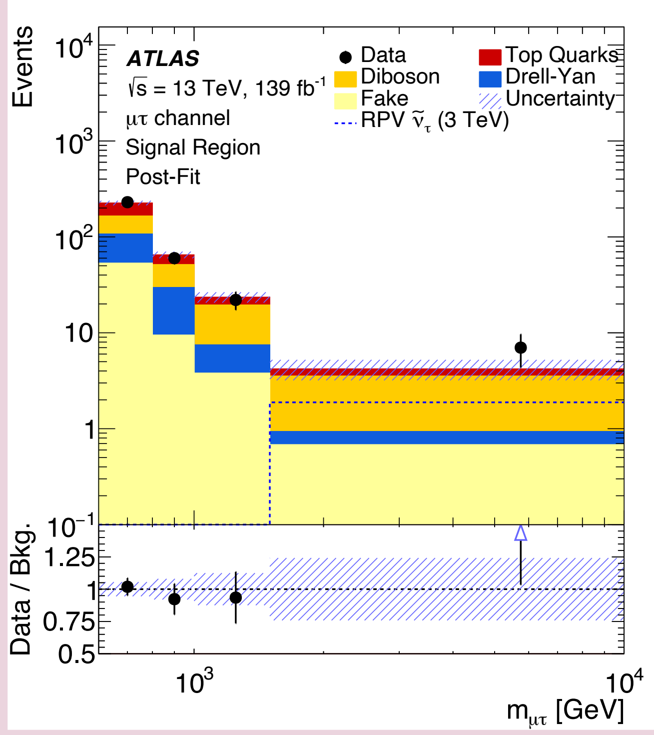
LFV in top

production and decay

t

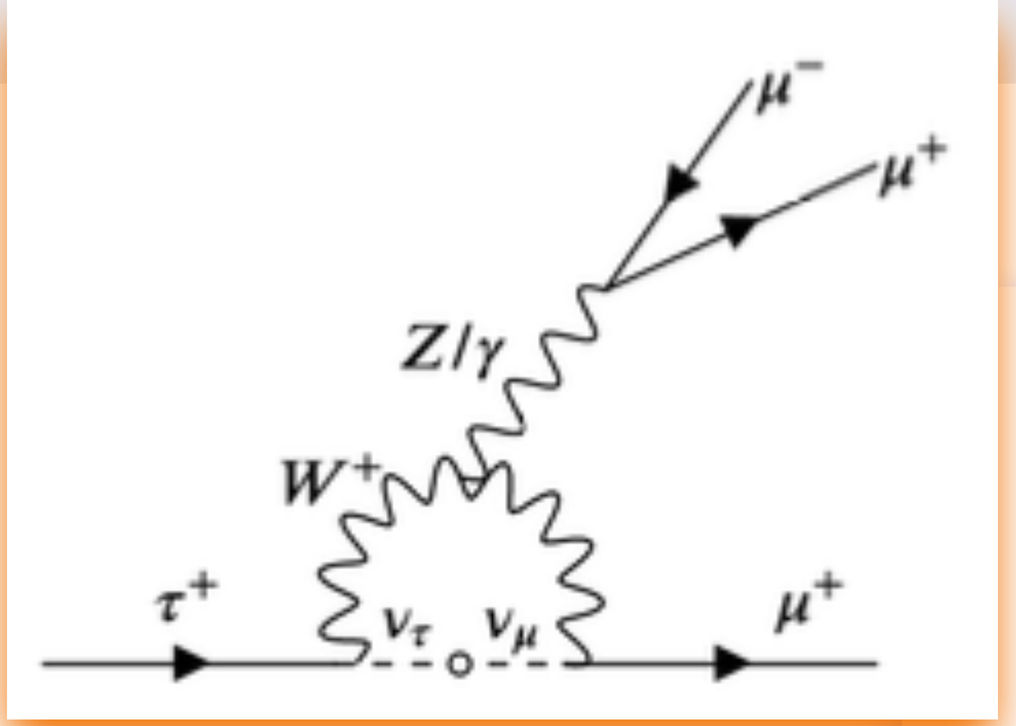


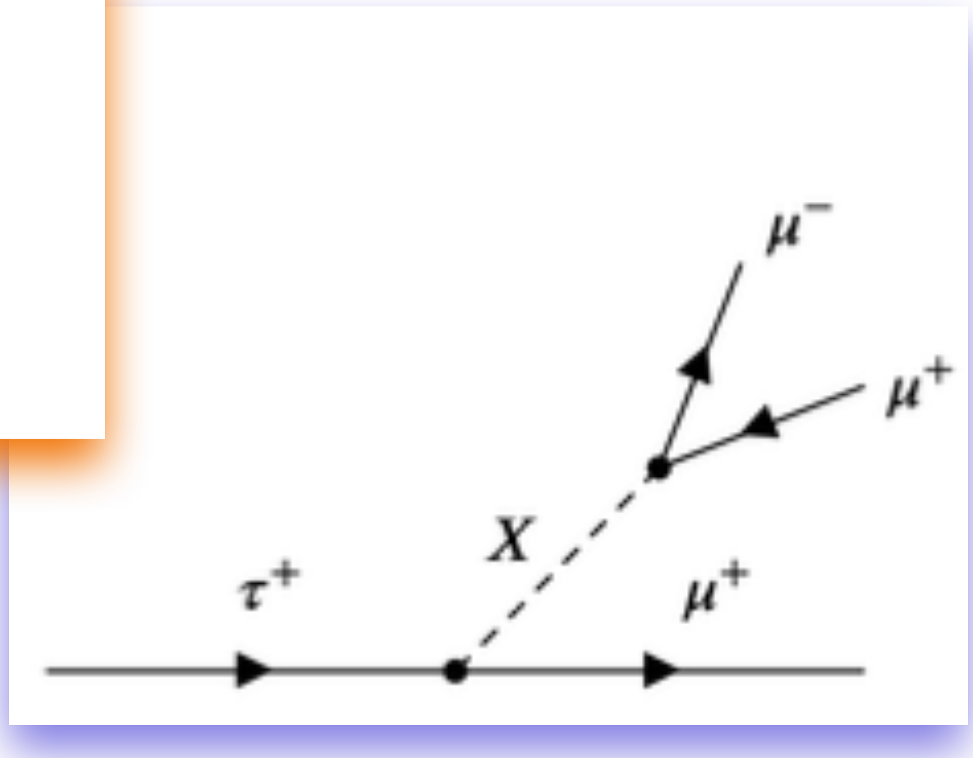
Z'



LFV in SM extensions

cLFV in $\tau \to 3\mu$ decay



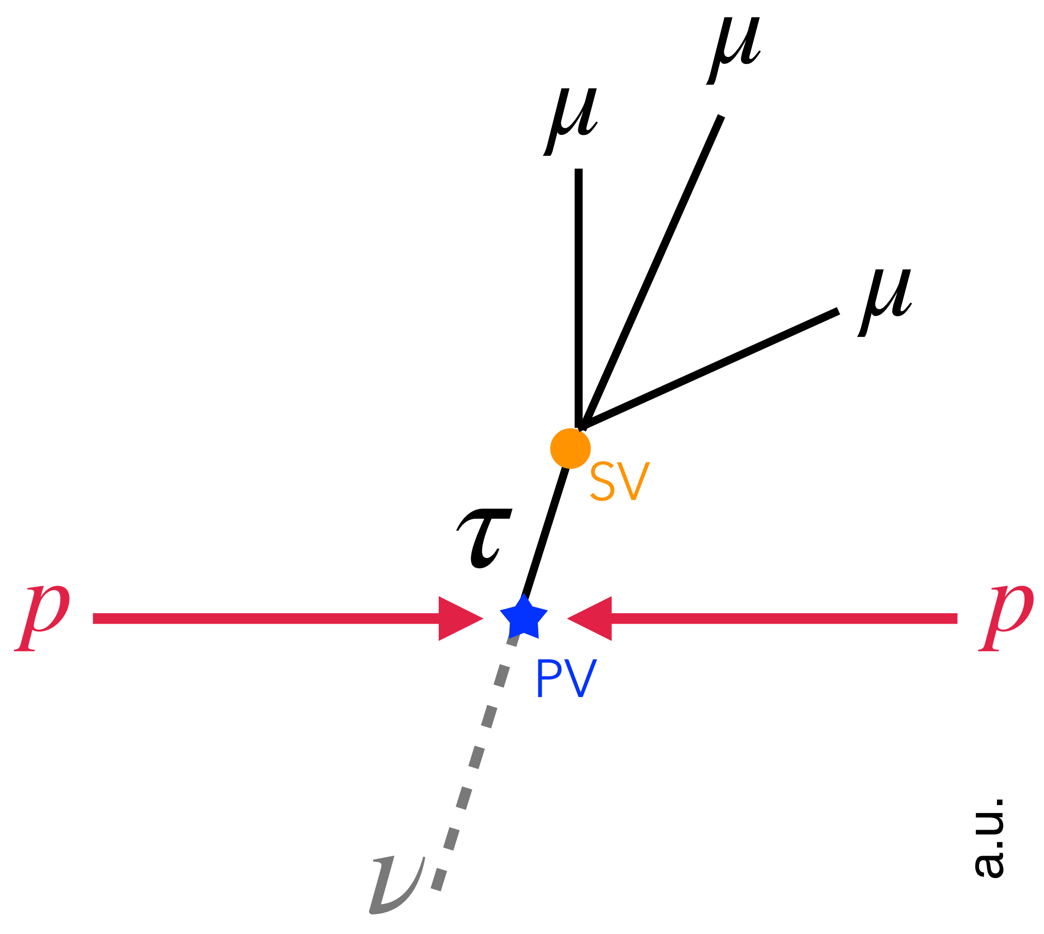


- Allowed in SM via neutrino oscillations
  - $Br(\tau \to 3\mu)$ ~ 10^{-55} = experimentally invisible
- Perfect playground to test presence of New Physics
  - some SM extensions predict $Br(\tau \to 3\mu)$ ~ o(10^{-9} -10^{-8}) = within ATLAS and CMS sensitivity
- **ATLAS** results [EPJC(2016)] based only on 20.3 fb^{-1} → focus on full-Run2 **CMS** results

cLFV in $\tau \to 3\mu$ decay

Introduction

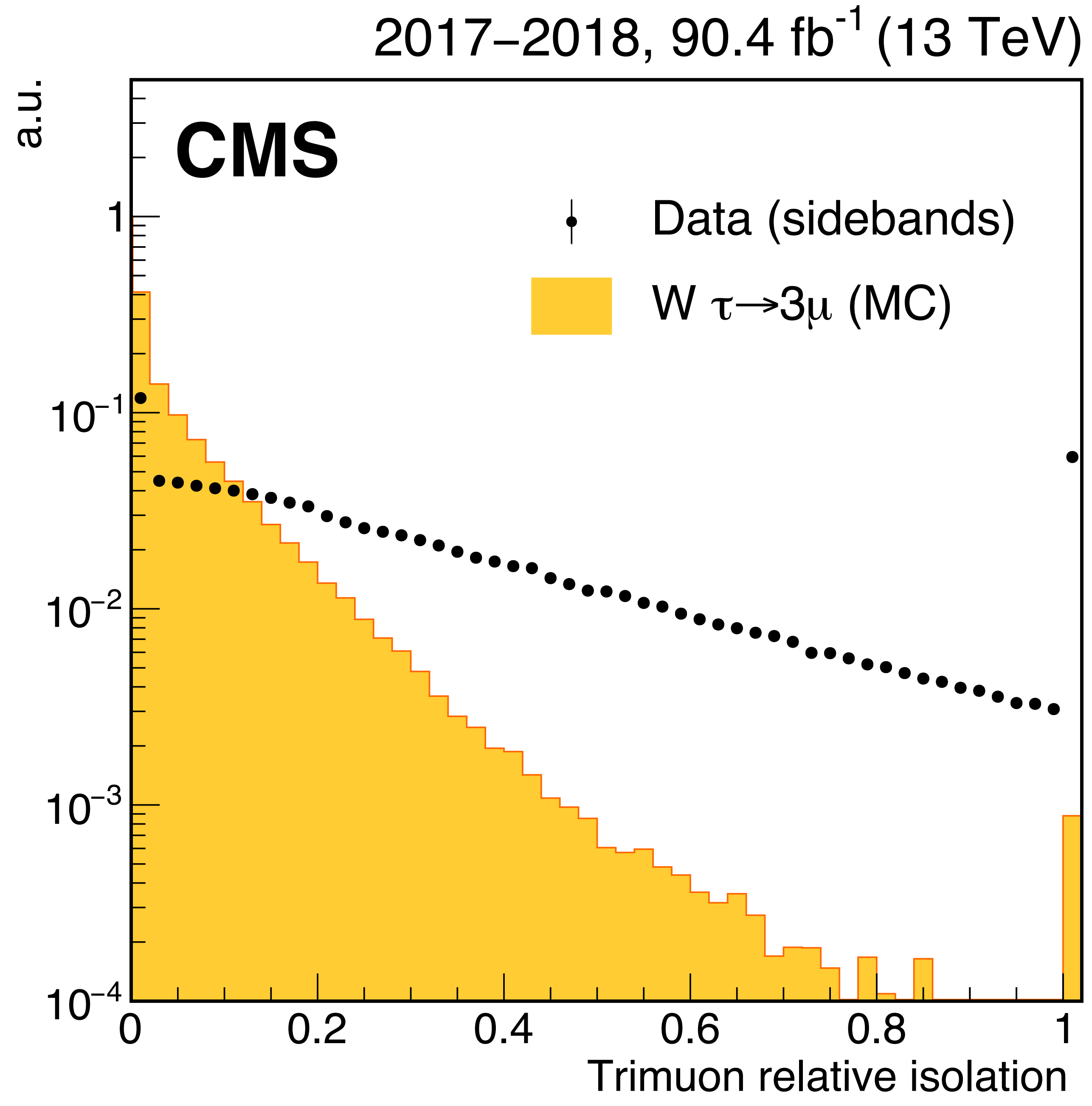
Phys. Lett. B 853 (2024) 138633



At LHC τ leptons abundantly produced mainly via:

- D and B mesons decays (~10^{11} τs per fb^{-1})
  - low-pT and forward muons in the detector
- $W \to \tau\nu$ boson decays (~10^{7} τs per fb^{-1})
  - isolated τ topology and large missing transverse energy

← efficiency — statistic →



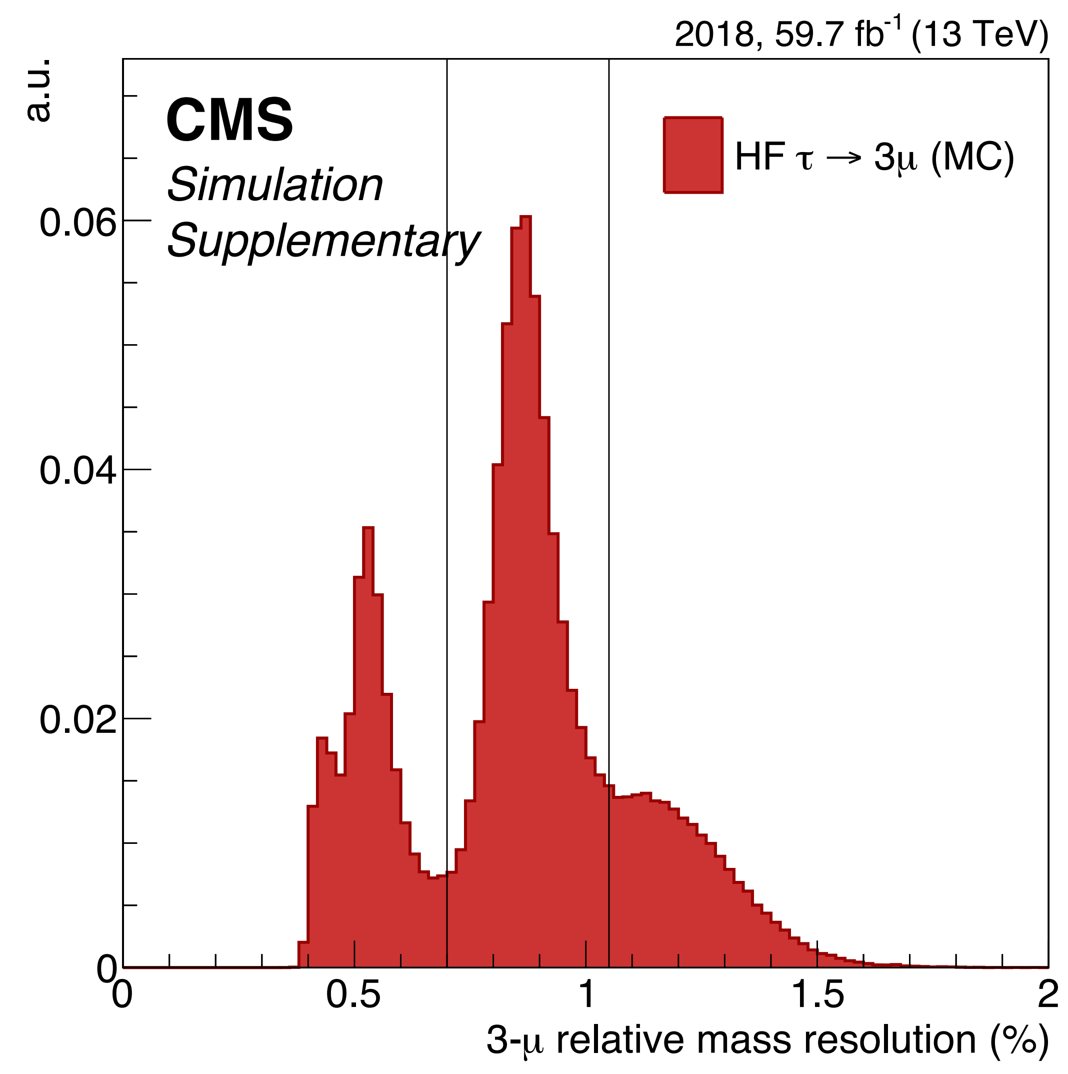
- Bump hunt in the reconstructed 3μ invariant mass around nominal $m(\tau)$ over a soothly falling background
  - measure/set UL on $Br(\tau \to 3\mu)$

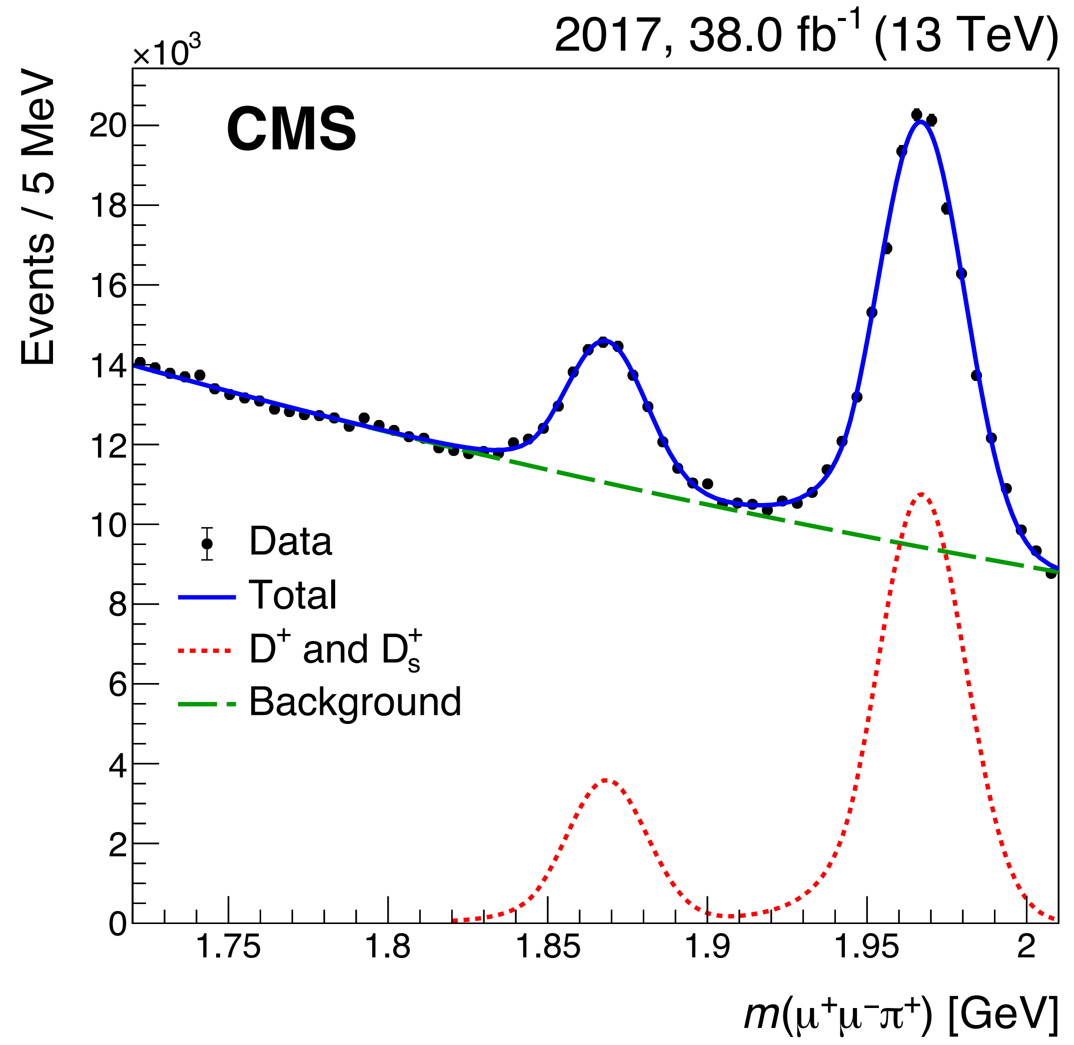
cLFV in $\tau \to 3\mu$ decay

Analysis strategy

Phys. Lett. B 853 (2024) 138633

- $\tau \to 3\mu$ candidates from muon tracks matching trigger object
  - common vertex fit to 3μ tracks → displaced SV
  - veto events compatible with di-muon hadronic resonances $\eta, \omega(783), \rho(770)$ ... Z
  - W ch. : combine with MET of the event
- Data-driven background modeling from 3μ mass sidebands
- Event categorization based on per-event 3μ mass resolution
- Signal candidate selection with **BDT**
- Control channel $D_s \to \phi(\mu\mu)\pi$ with misID π as muon
  - **control channel** to validate BDT inputs and score and signal modeling
  - normalization channel in HF ch.



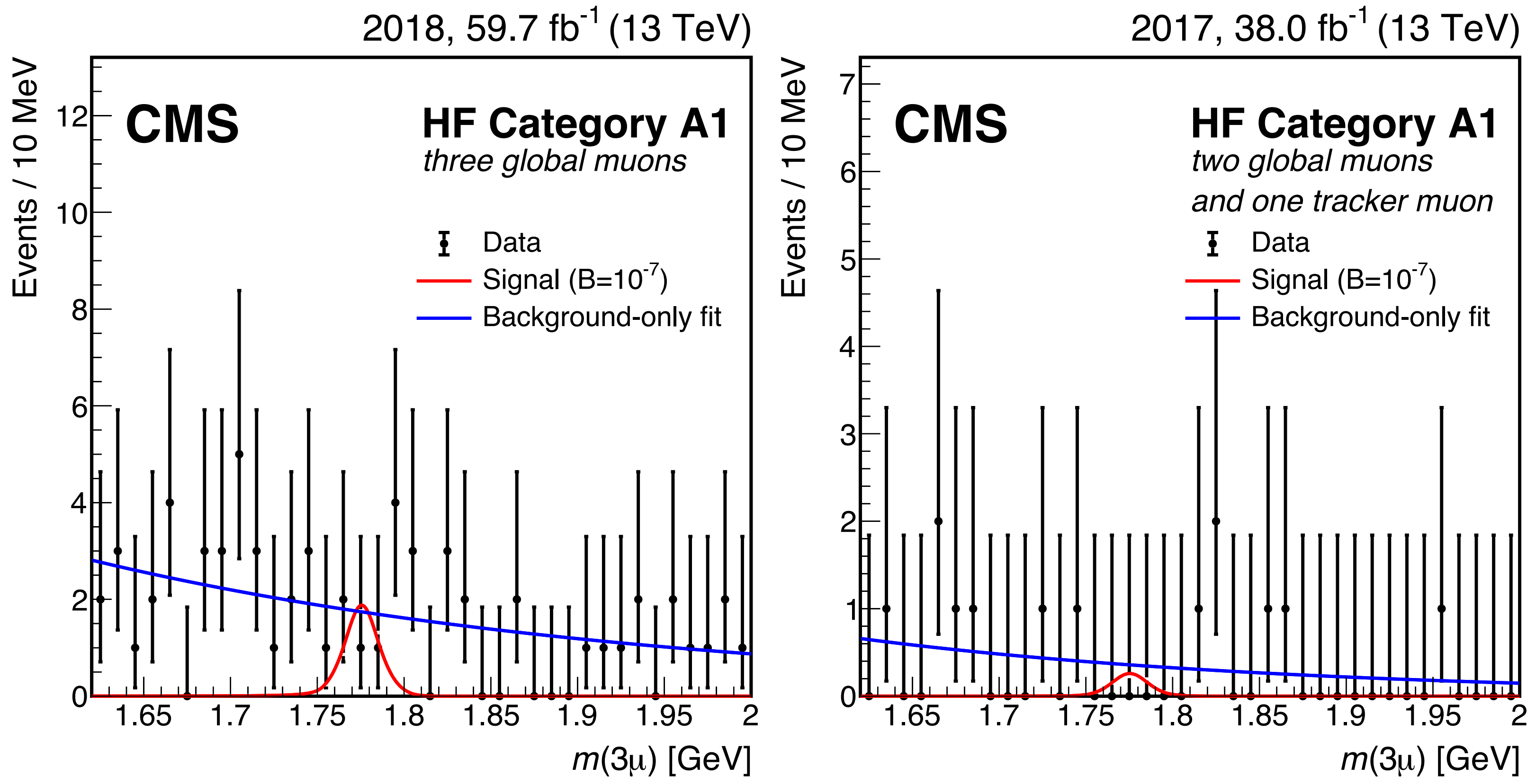


cLFV in $\tau \to 3\mu$ decay

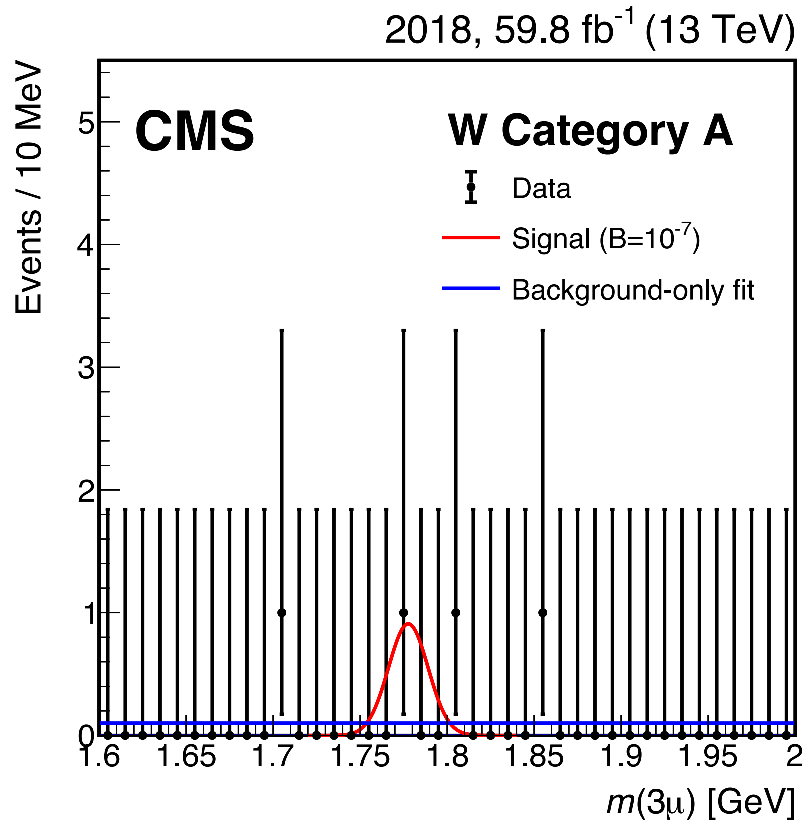
Results

- **POI** signal strength scaling $Br(\tau \to 3\mu)$
- Simultaneous unbinned maximum likelihood fit to $M(3\mu)$ in all the analysis categories
  - sensitivity dominated by statistics
- Current best limit by Belle II $Br(\tau \to 3\mu) < 1.9 \times 10^{-8}$ JHEP09(2024)062

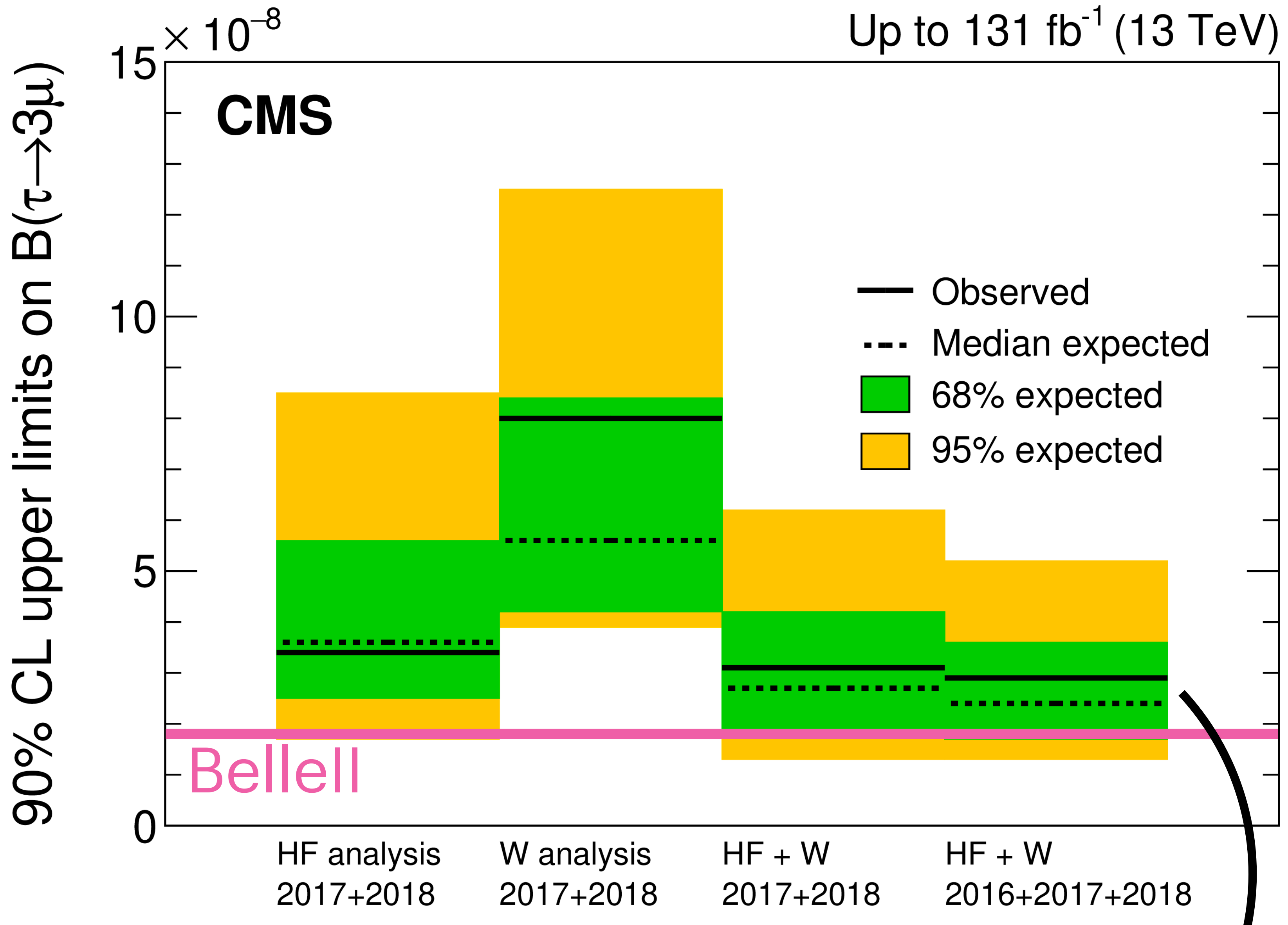
CMS sensitivity competitive to results obtained at B-factories



HF ch obs. (exp.) UL at 90% CL
$Br(\tau \to 3\mu) < 3.4\ (3.6) \times 10^{-8}$



W ch obs. (exp.) UL at 90% CL
$Br(\tau \to 3\mu) < 8.0\ (5.6) \times 10^{-8}$



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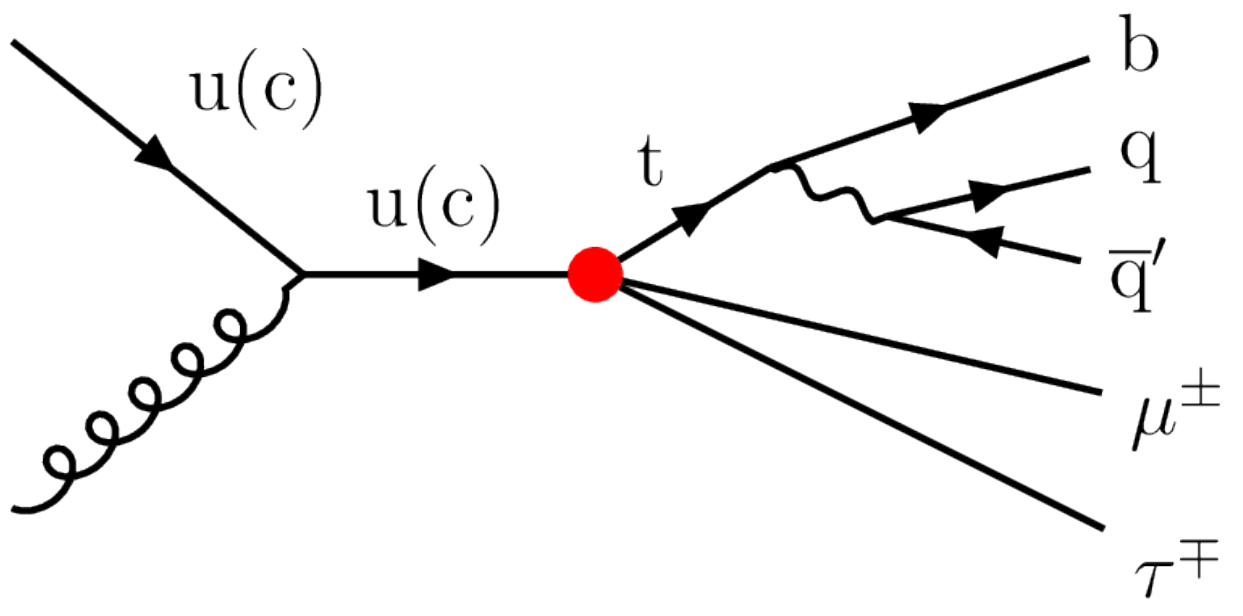
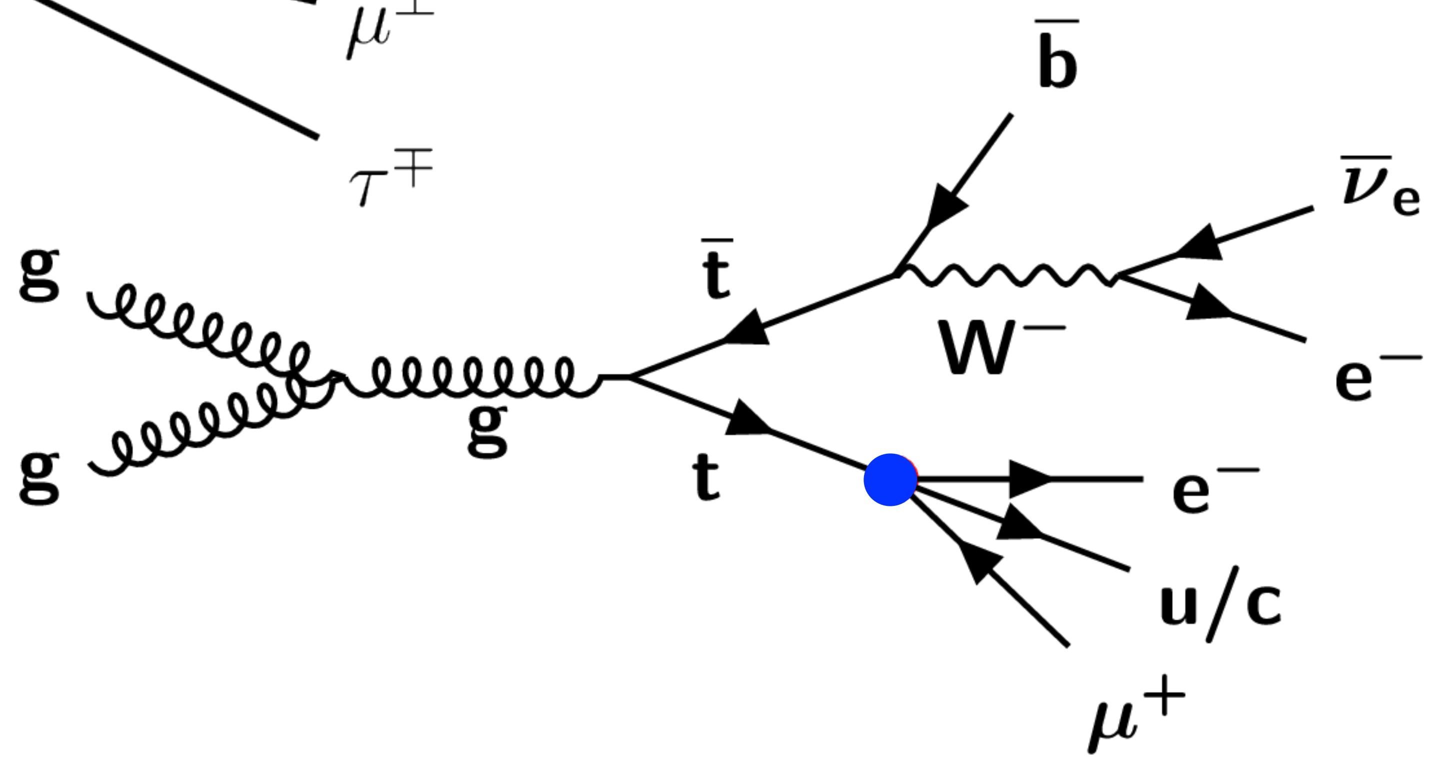
Full Run2 combination
obs. (exp.) UL at 90% CL
$Br(\tau \to 3\mu) < 2.9\ (2.4) \times 10^{-8}$

cLFV in top quark production & decay

- **CMS** and **ATLAS** searches targeting $t\mu\tau q_u$ vertices

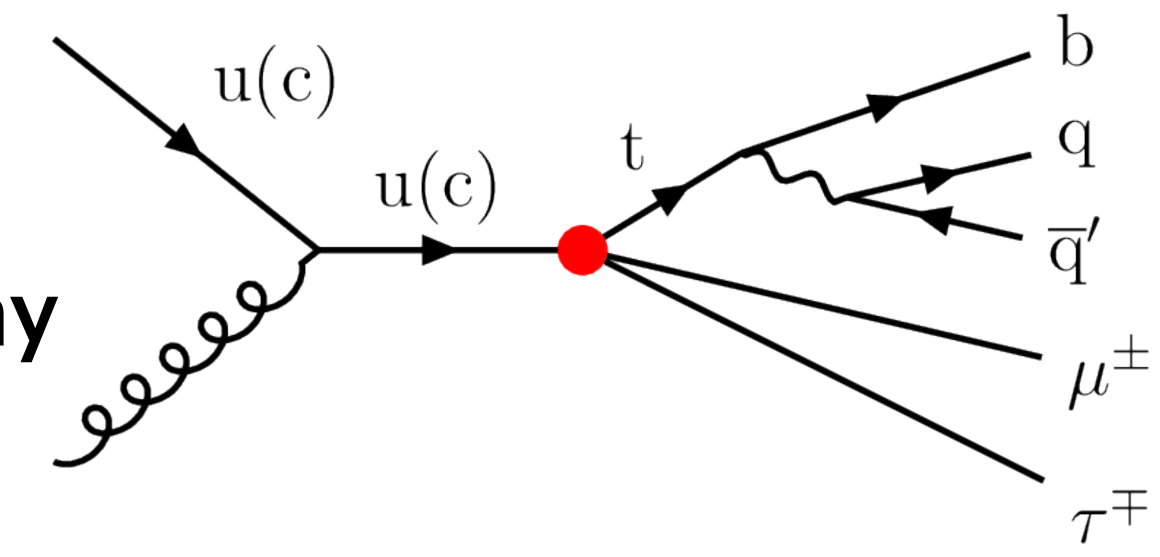


- **CMS** targets also $t\mu e q_u$ vertices in trilepton final state
  - details in backup

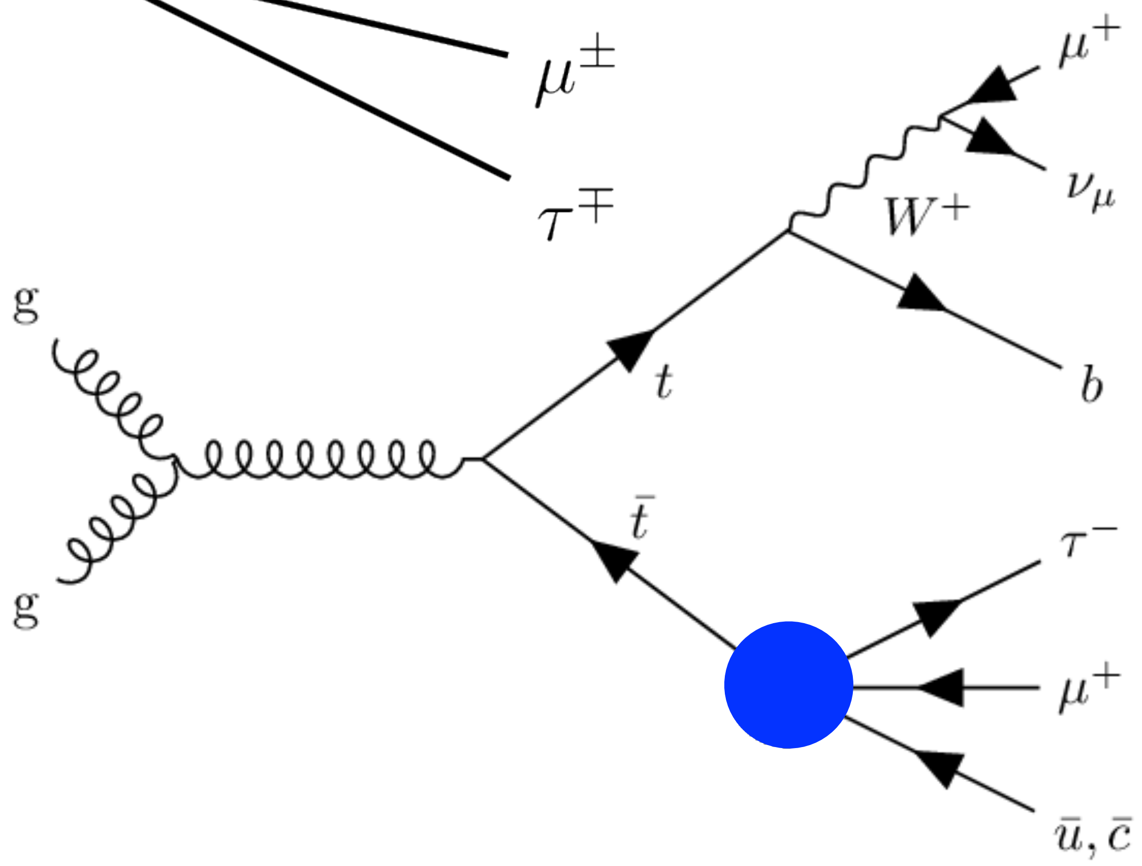


Search for $t\tau\mu q$ vertices ATLAS & CMS

Introduction



- SM extensions entail cLFV in top quark **production** and **decay**
  - **leptoquark model** predict $Br(t \to ll'c) \simeq 10^{-6}$
- Model independent approach **SMEFT** with 6-dim operator
  - pp-collision energy scale << new physics scale (Λ)
  - $t\ell\ell'q$ vertices with 6-dim EFT operator



- Target cLFV processes:
  - (ST) single top **production** via $gq_u \to t\mu\tau$
  - (TT) top **decay** in $t\bar{t}$ via $t \to \mu\tau q_u$
- MC separately for ST and TT and 6-dim operators **tensor structure**
  - scalar, vector or tensor Lorentz structure ($C/\Lambda^2 = 1TeV^{-2}$)

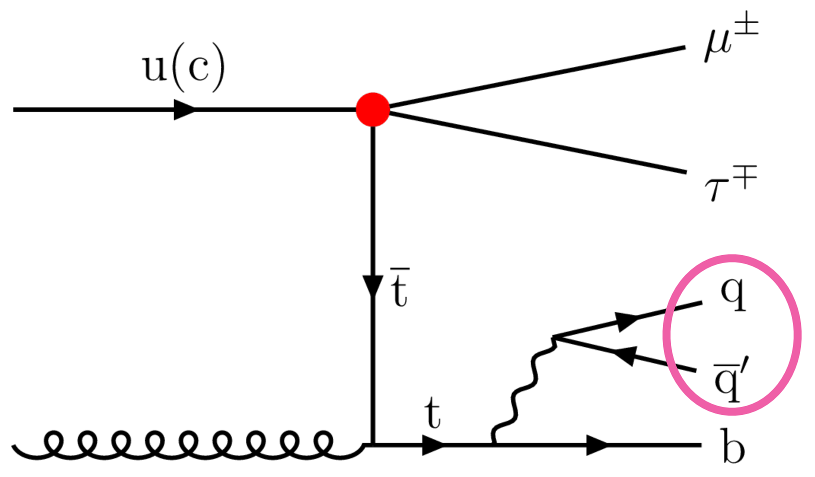
measurement target

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_a \frac{C^{(6)}}{\Lambda^2} O^{(6)} + O\left(\frac{1}{\Lambda^4}\right)$$

- Signature: opposite sign $\mu + \tau_h$ + 1 b-jet

Search for $t\tau\mu q$ vertices at CMS

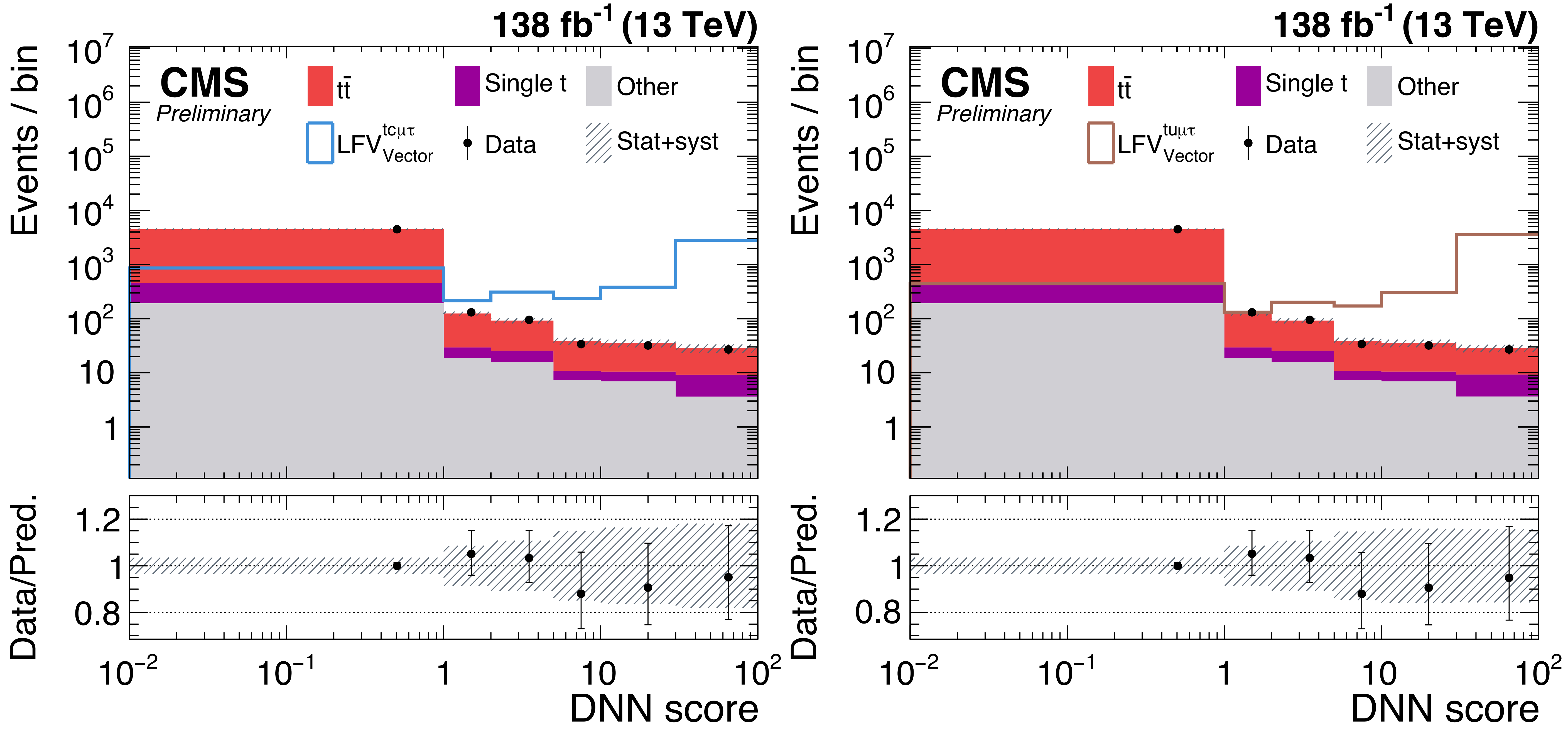
CMS analysis strategy



- SR signature $\mu + \tau_h + \geq 1$ b-jet & W fully hadronic

- Background mainly from $t\bar{t}$ SM in lepton+jet and di-leptonic final state
  - smaller contribution from single top tW mainly and fake τ_h

- Signal selection: 3 classes DNN signal ST, signal TT and background
  - single training combining
    - EFT operator Lorentz structure
    - interaction vertices $t\mu\tau u$ and $t\mu\tau c$



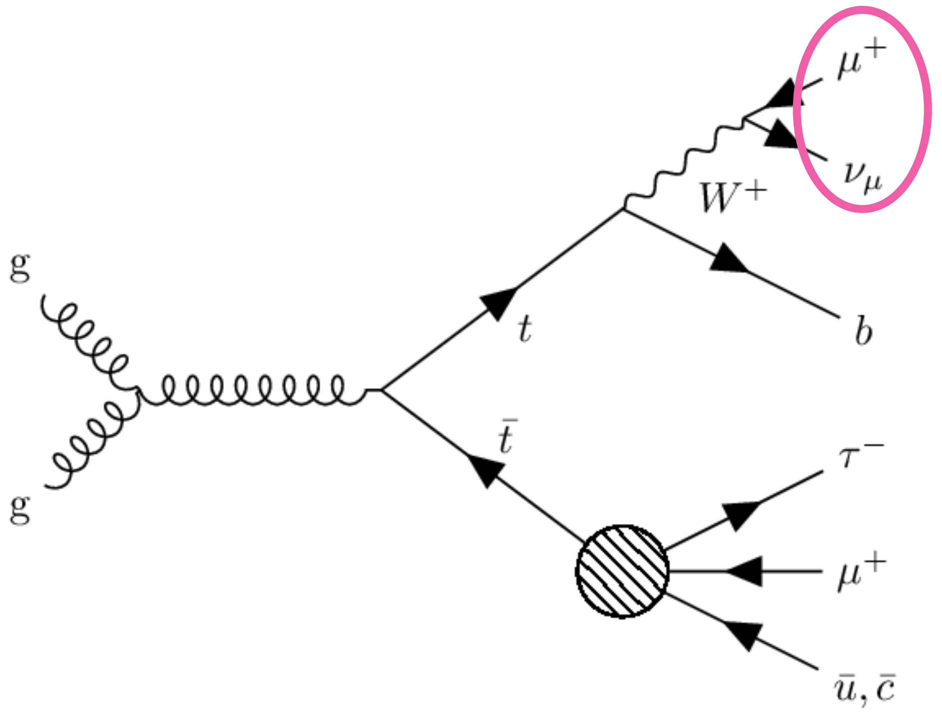
CMS-PAS-TOP-22-011

- Binned maximum likelihood fit to DNN score separately w.r.t. Lorentz structure

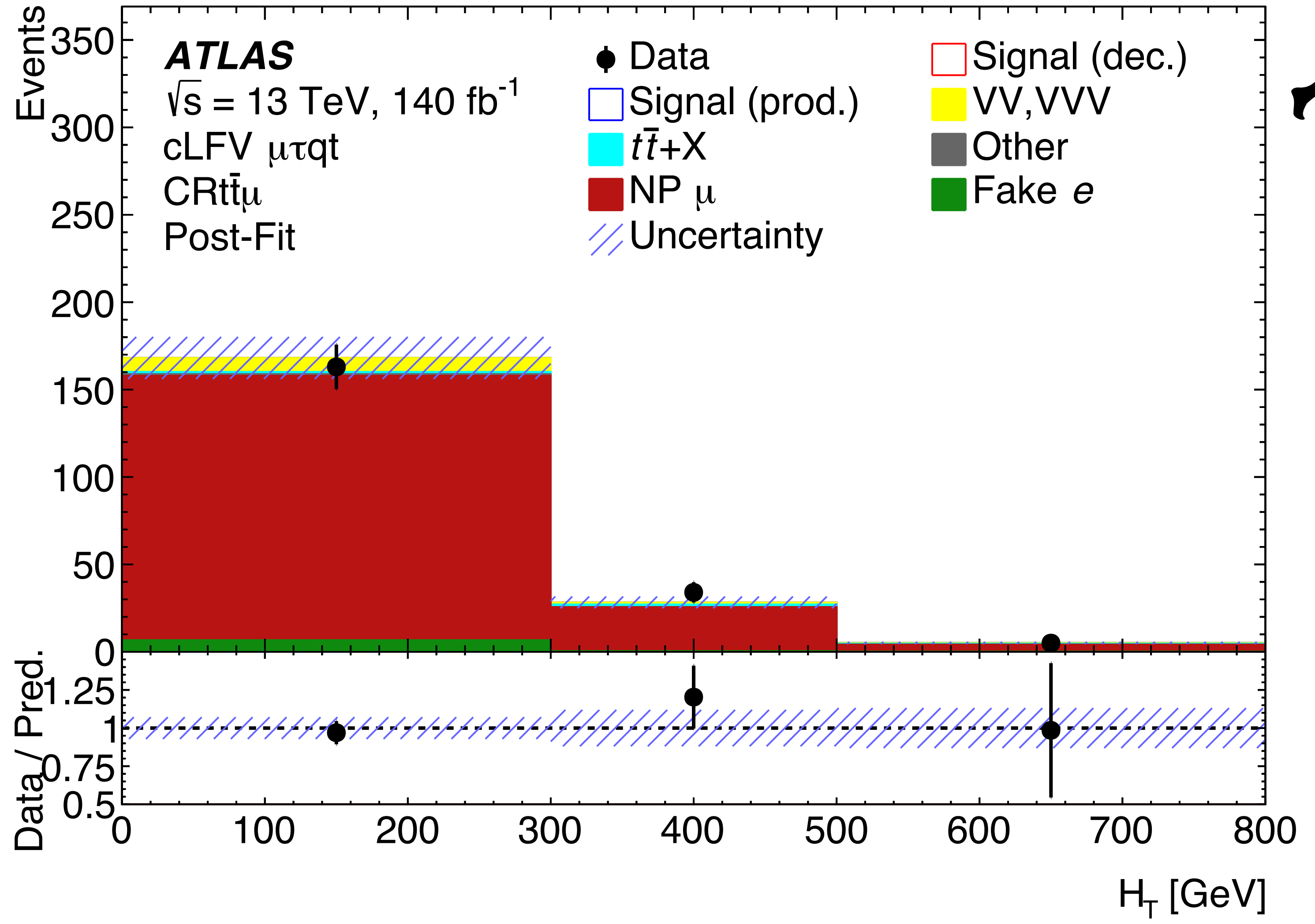
$$\text{DNN score} = \frac{0.1p(\text{TT}) + 0.9p(\text{ST})}{p(B)}$$

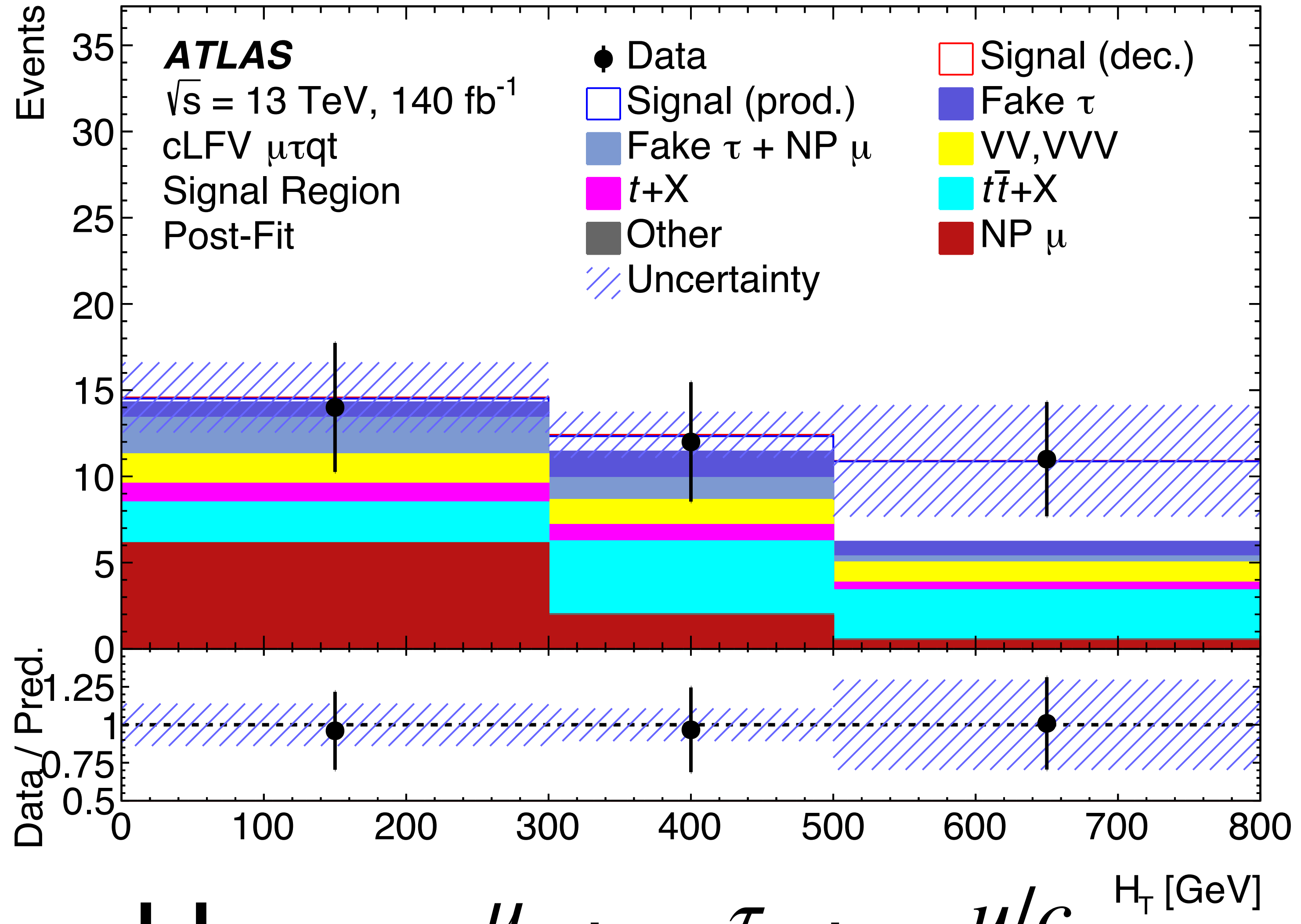
Search for $t\tau\mu q$ vertices at ATLAS

ATLAS analysis strategy



- SR signature $2\mu + \tau_h + \geq 1$ jet & exactly 1 b-jet
  - targeting $W \to \mu\nu$ decay
  - same sign muons → reject $Z \to \mu^\pm\mu^\mp$ background
- Background enriched **CRs**
  - CRτ : opposite sign muons → enriched with fake τ_h (jet misID)
  - CR$t\bar{t}\mu$: mainly $t\bar{t}$ + non prompt(NP) μ
- Simultaneous profile likelihood fit to H_T in SR and CR$t\bar{t}\mu$ with 2 POIs
  - μ_{cLFV} : signal strength in EFT frame
  - $k(NP\mu)$: normalization of $NP\mu$ contribution





$$H_T = p_T^{\mu} + p_T^{\tau} + p_T^{u/c}$$

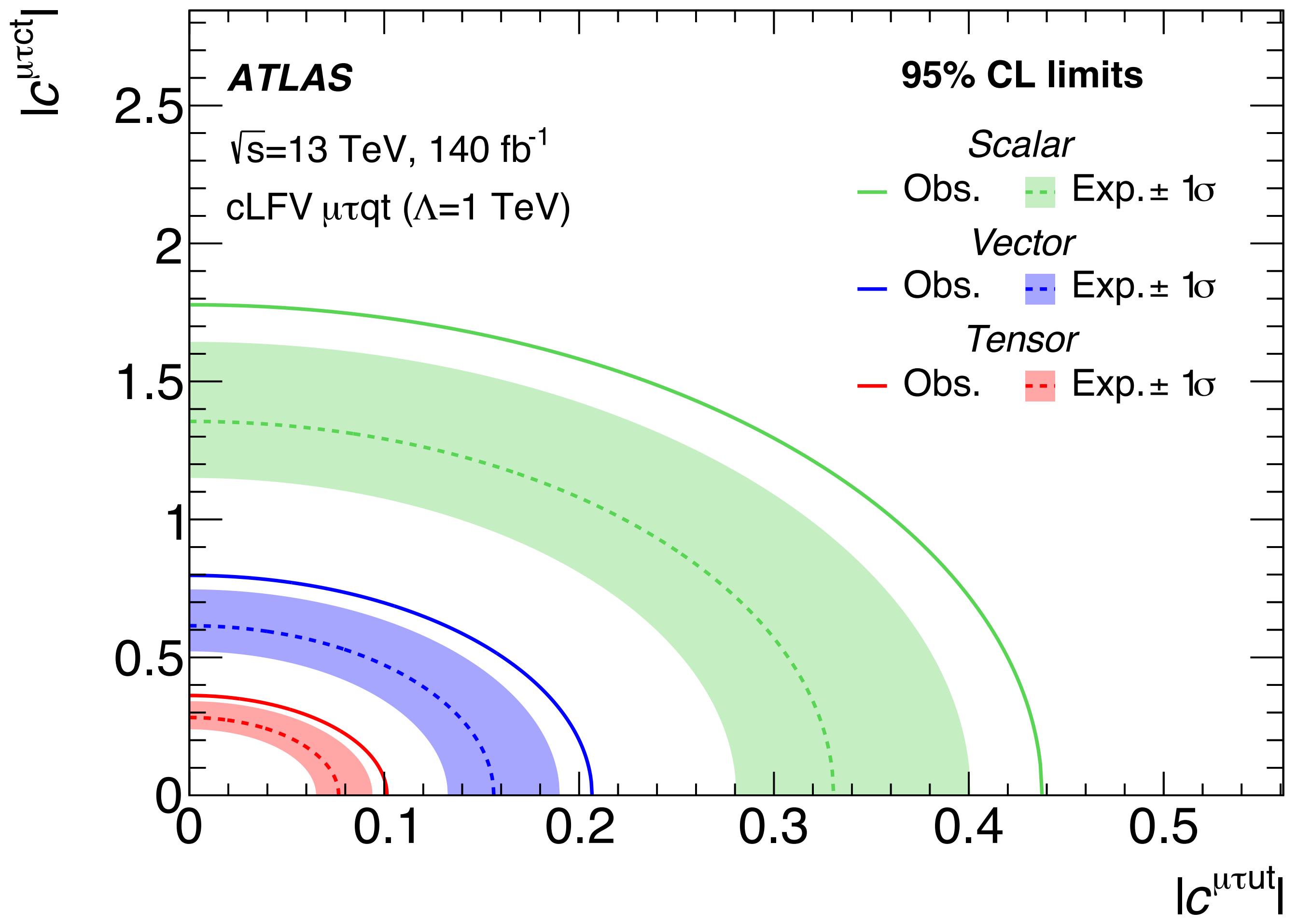
Phys.Rev.D 110 (2024) 012014

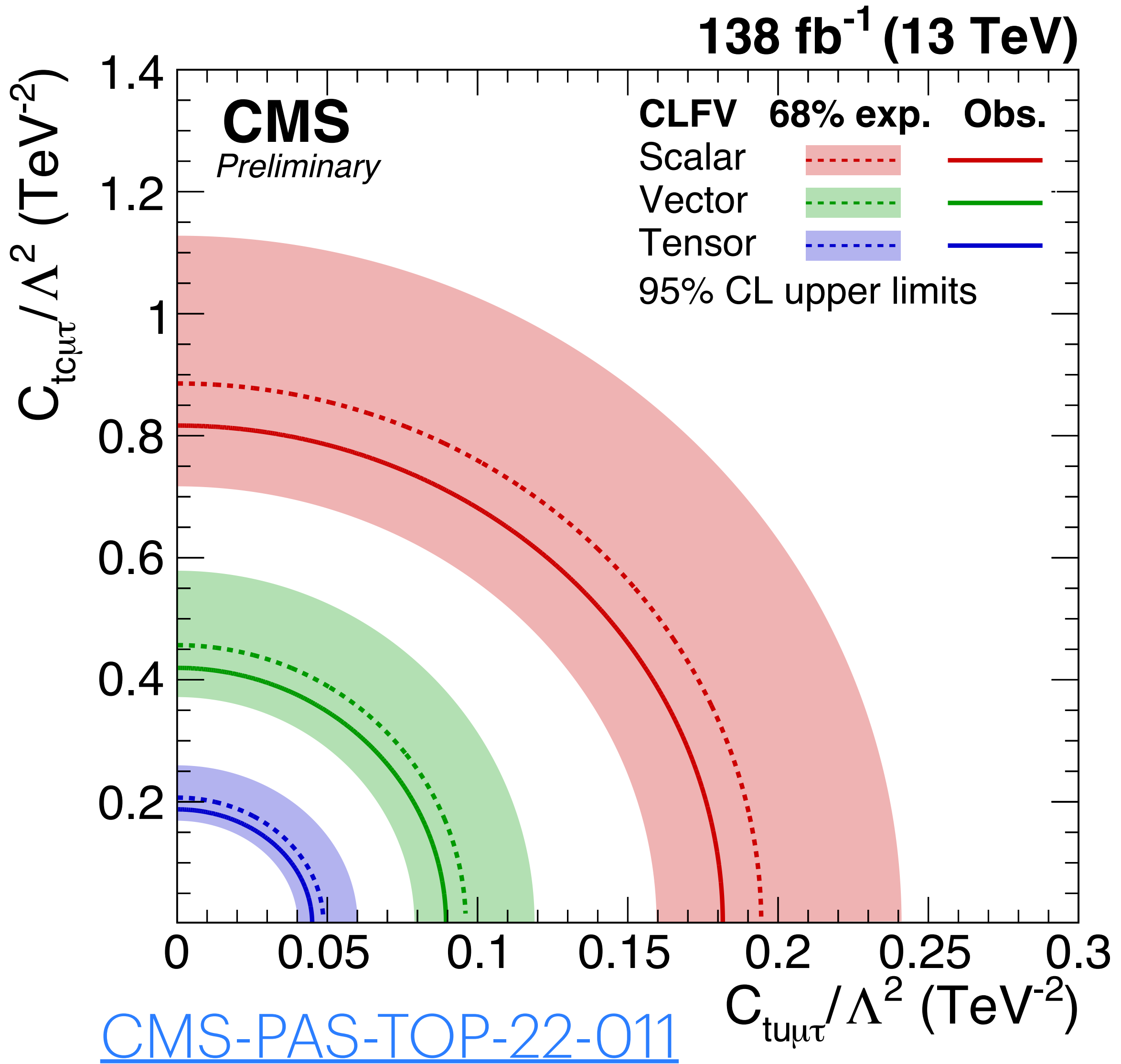
Search for $t\tau\mu q$ vertices

Results

- Probing EFT operator Lorentz structure separately → limits set Wilson coefficients ($c_{t\mu\tau u}$ & $c_{t\mu\tau c}$) and $Br(t \to \mu\tau q)$ branching ratios
  - assuming linear relation between $Br(t \to \mu\tau u)$ and $Br(t \to \mu\tau c)$
- σ_{cLFV} dominated by ST $gu \to tll'$ process and tensor operators
  - strongest limits on $t\mu\tau u$ than $t\mu\tau c$ and coupling to tensor operators

[Phys.Rev.D 110 (2024) 012014](#)





[CMS-PAS-TOP-22-011](#)

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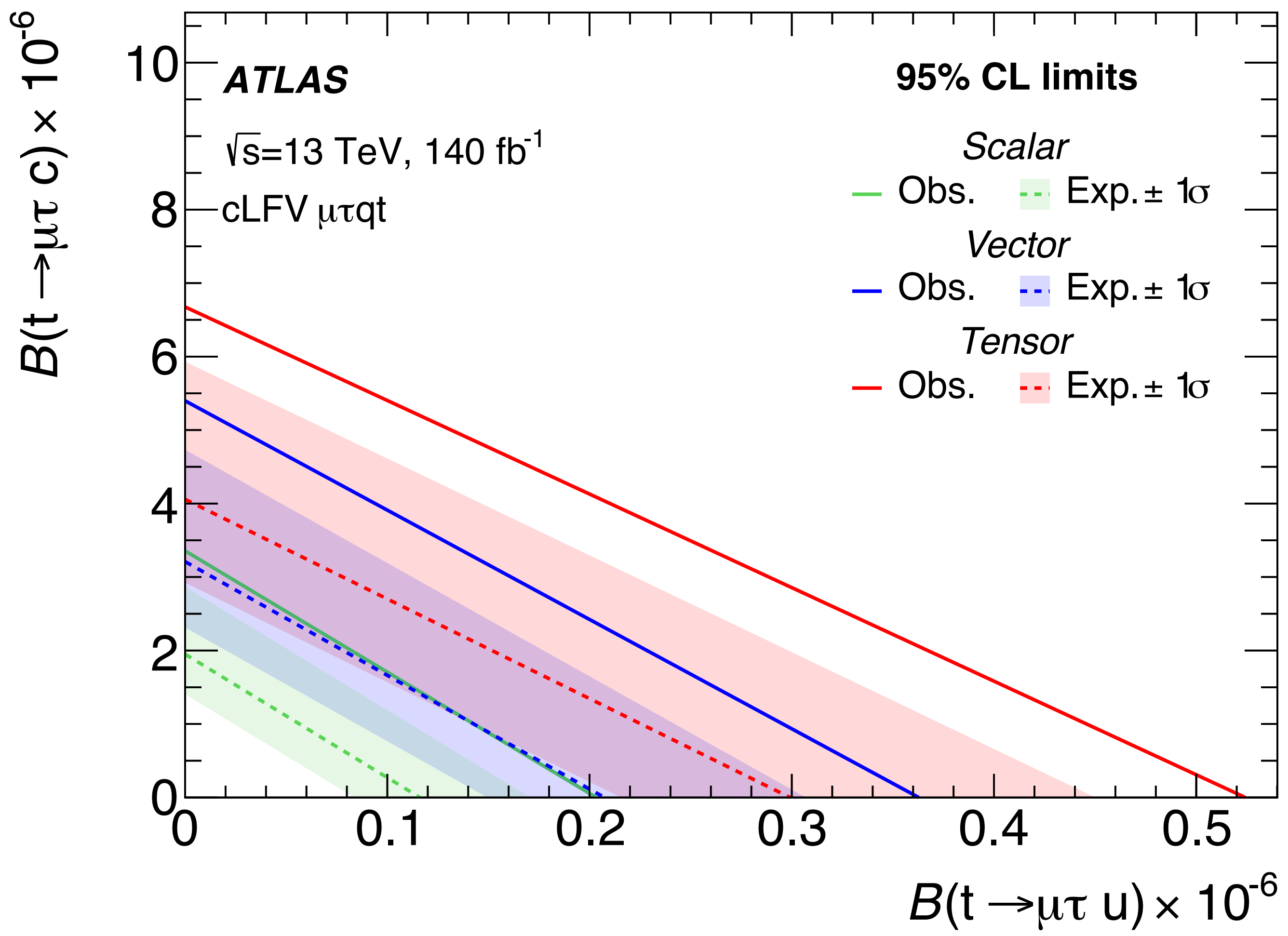
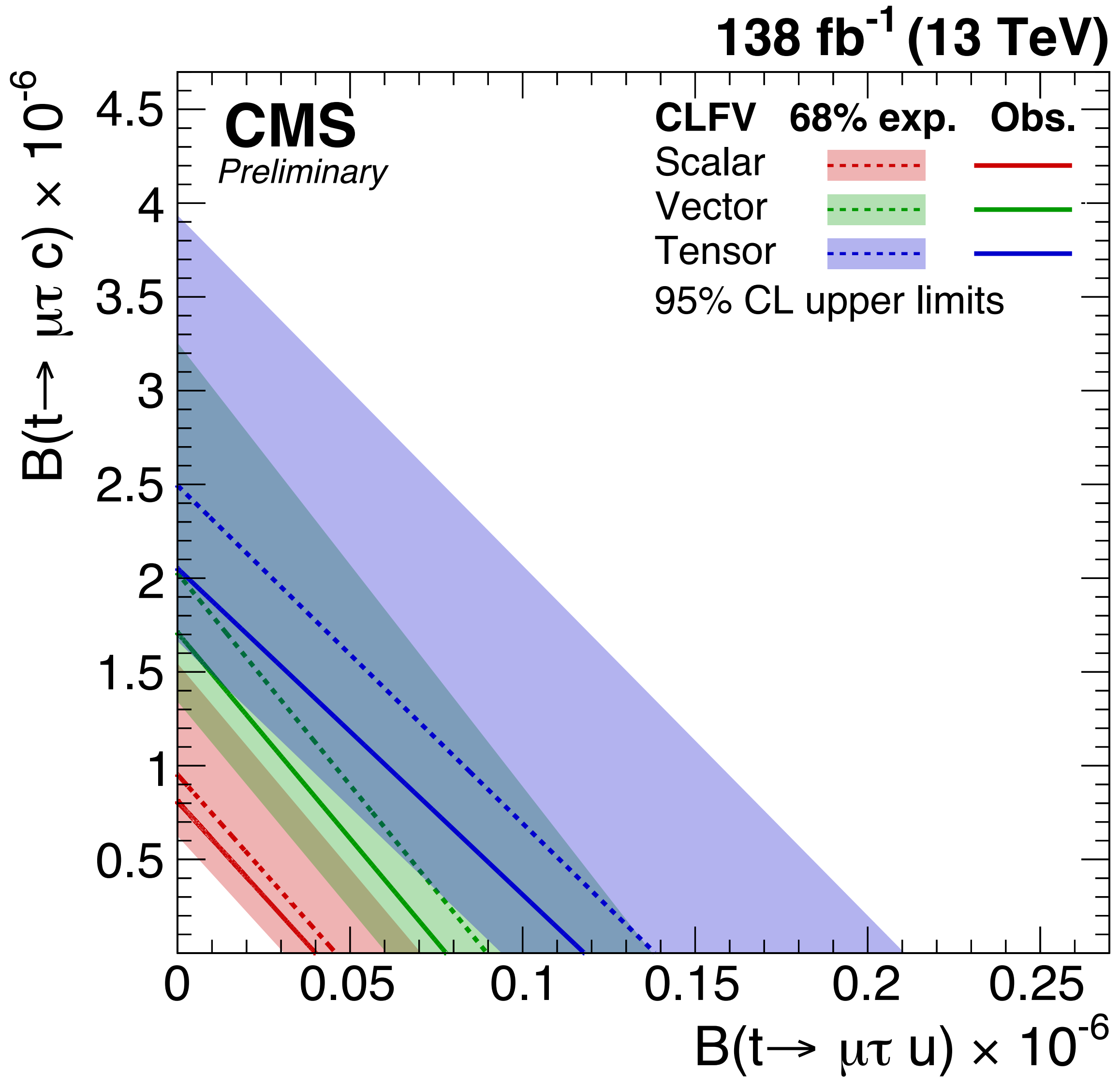
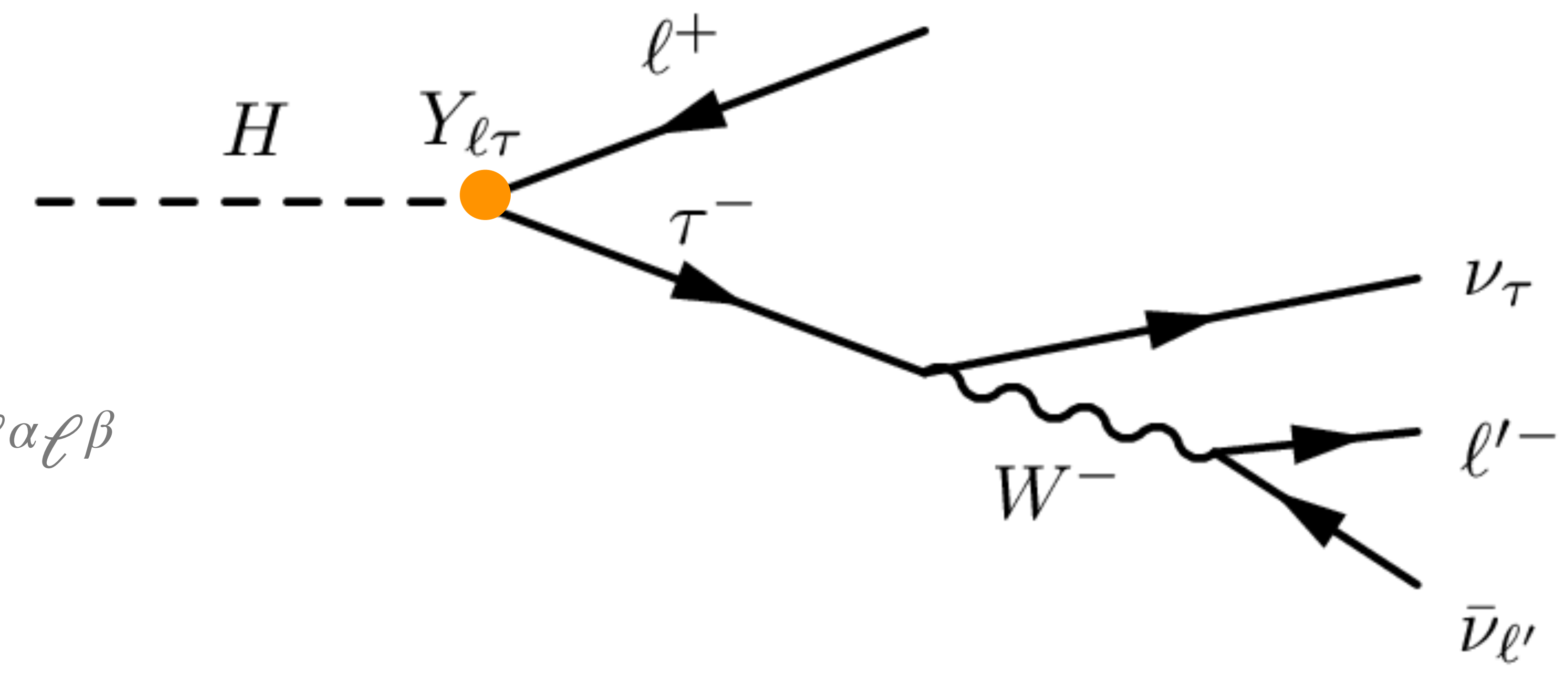




[CMS-PAS-TOP-22-011](#)

cLFV in Higgs sector

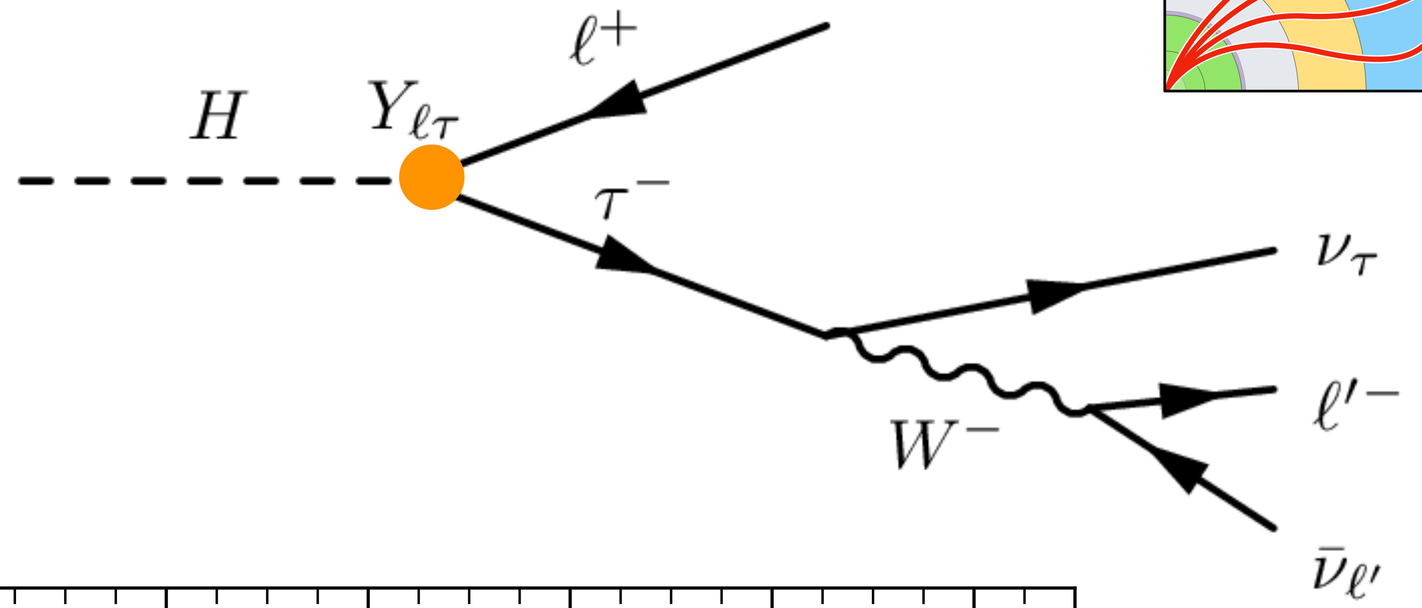
- Search for Higgs decays in $e\mu$, $e\tau$ and $\mu\tau$ final states
  - target measuring LFV **off diagonal Yukawa couplings** $Y_{\ell^\alpha \ell^\beta}$
- LFV arise in BSM models predicting
  - more than one Higgs doublet
  - SUSY models
  - composite Higgs model



Search for $H \rightarrow e\tau$ and $H \rightarrow \mu\tau$ at ATLAS and CMS

General overview

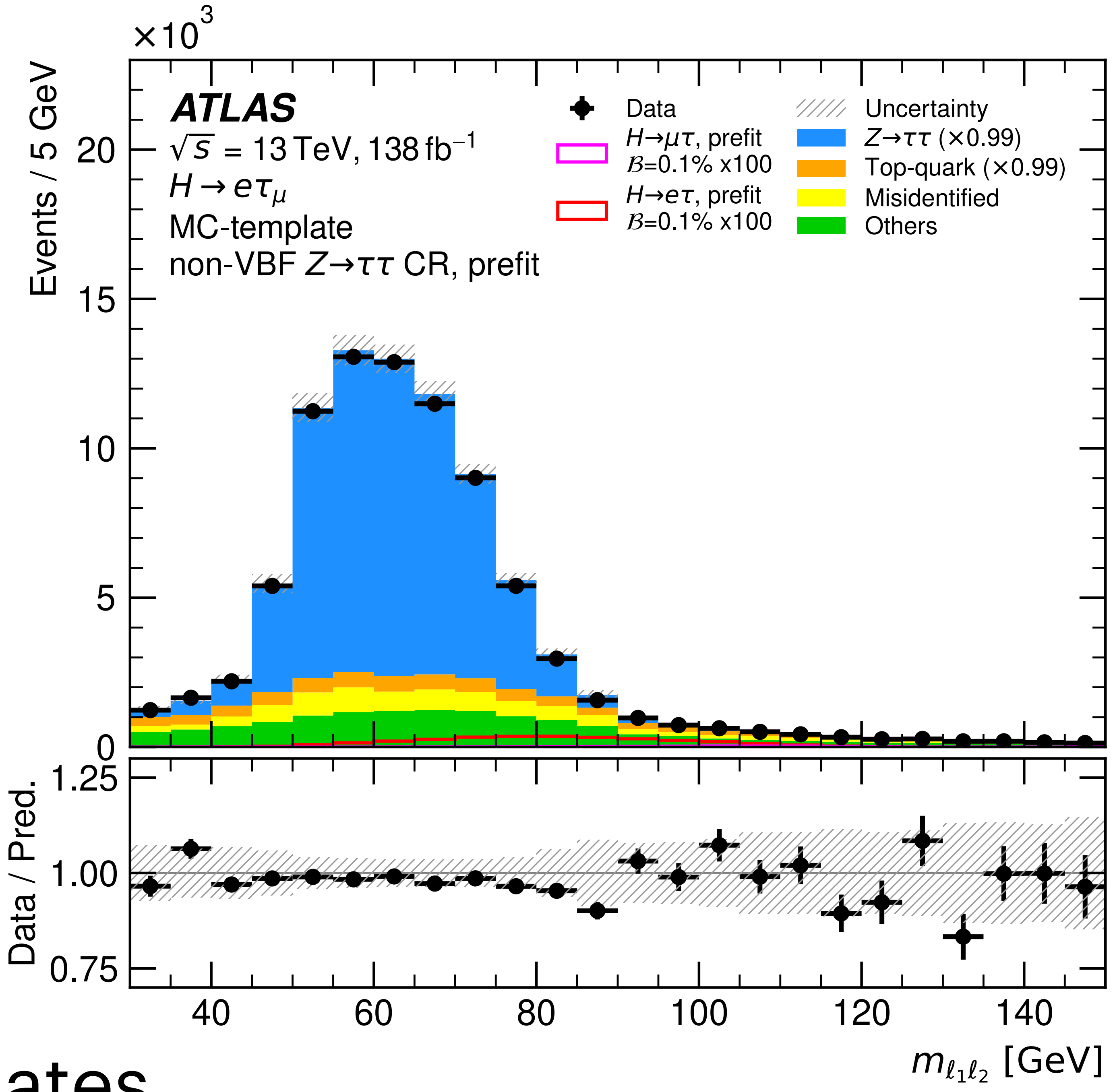
- Loose constraint $Br(H \rightarrow l\tau)_{LFV}$ < 10% from $\tau \rightarrow e\gamma$ and $\tau \rightarrow \mu\gamma$ searches
  - **direct searches** are much more powerful



- Final states considered $e\tau_h$, $e\tau_\mu$, $\mu\tau_h$ and $\mu\tau_e$
  - different flavor leptons in final state $\ell\tau_\ell$ → remove Z/γ* bkg

- Constraints set assuming contribution to Γ_H from
  - only one LFV vertex (CMS & ATLAS)
  - both $He\tau$ and $H\mu\tau$ (ATLAS)

- Higgs production mainly from ggF and VBF



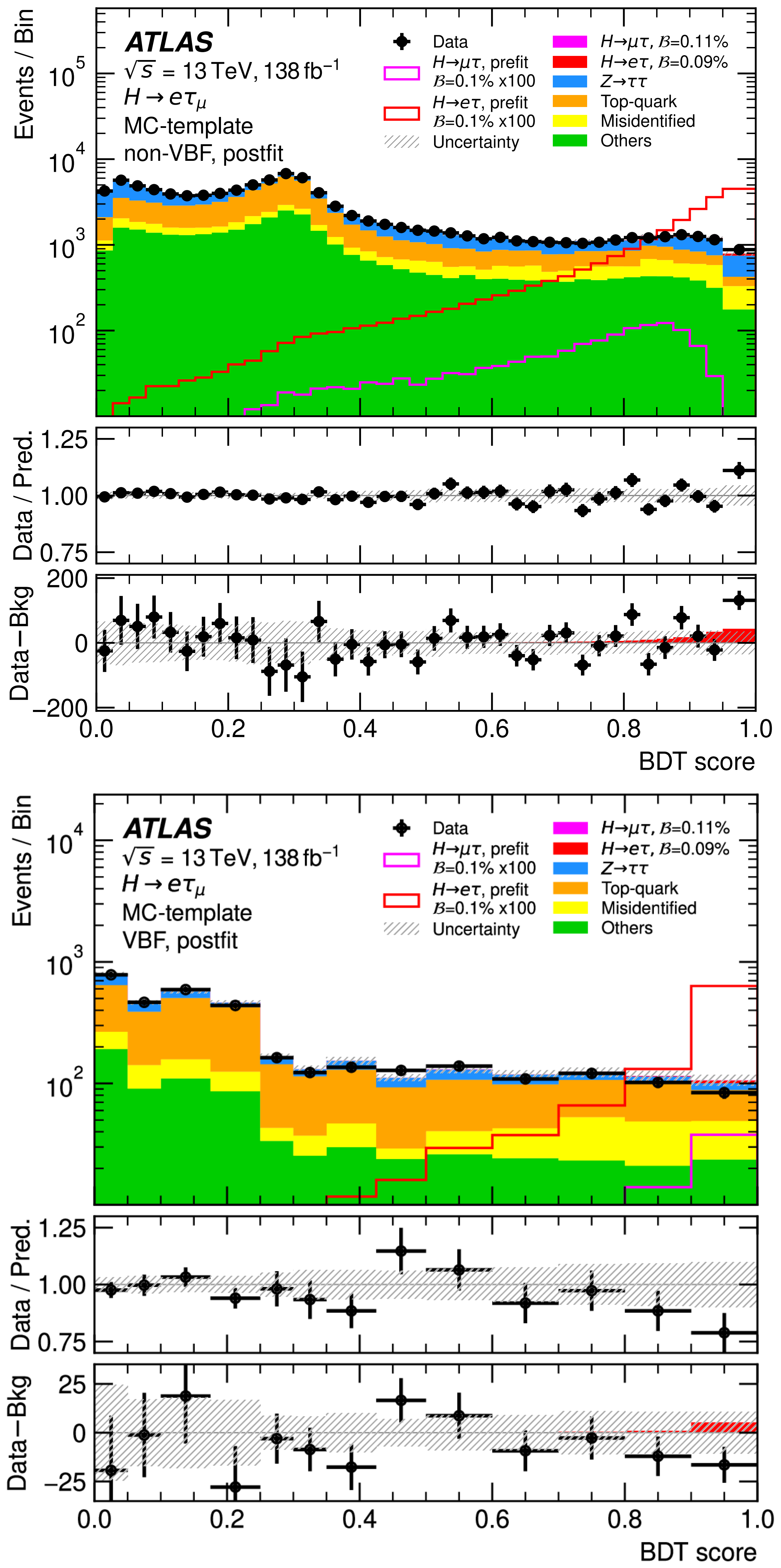
- Background from $Z\ell\ell$ with misID leptons and $t\bar{t}$ in di-leptons final states

Search for $H \to e\tau$ and $H \to \mu\tau$ at ATLAS

Analysis strategy

JHEP07(2023)166

- Signature oppositely charged $e + \tau$ or $\mu + \tau$
  - veto b-jet → suppress $t\bar{t}$ bkg
- Each channel $\ell\tau$ events split in **VBF** and **non-VBF** categories
- Multiple subsequent BDTs targeting different background
  - improve signal sensitivity
  - combination of the scores in a 1D variable
- Separate maximum likelihood fit targeting
  - **independent** search : $Br(H \to \ell\tau)$ combining $H\ell\tau_{\ell'}$ and $H\ell\tau_h$ setting $Br(H \to \ell'\tau) = 0$
  - **simultaneous** $H\mu\tau$ and $He\tau$ signal strength measurement

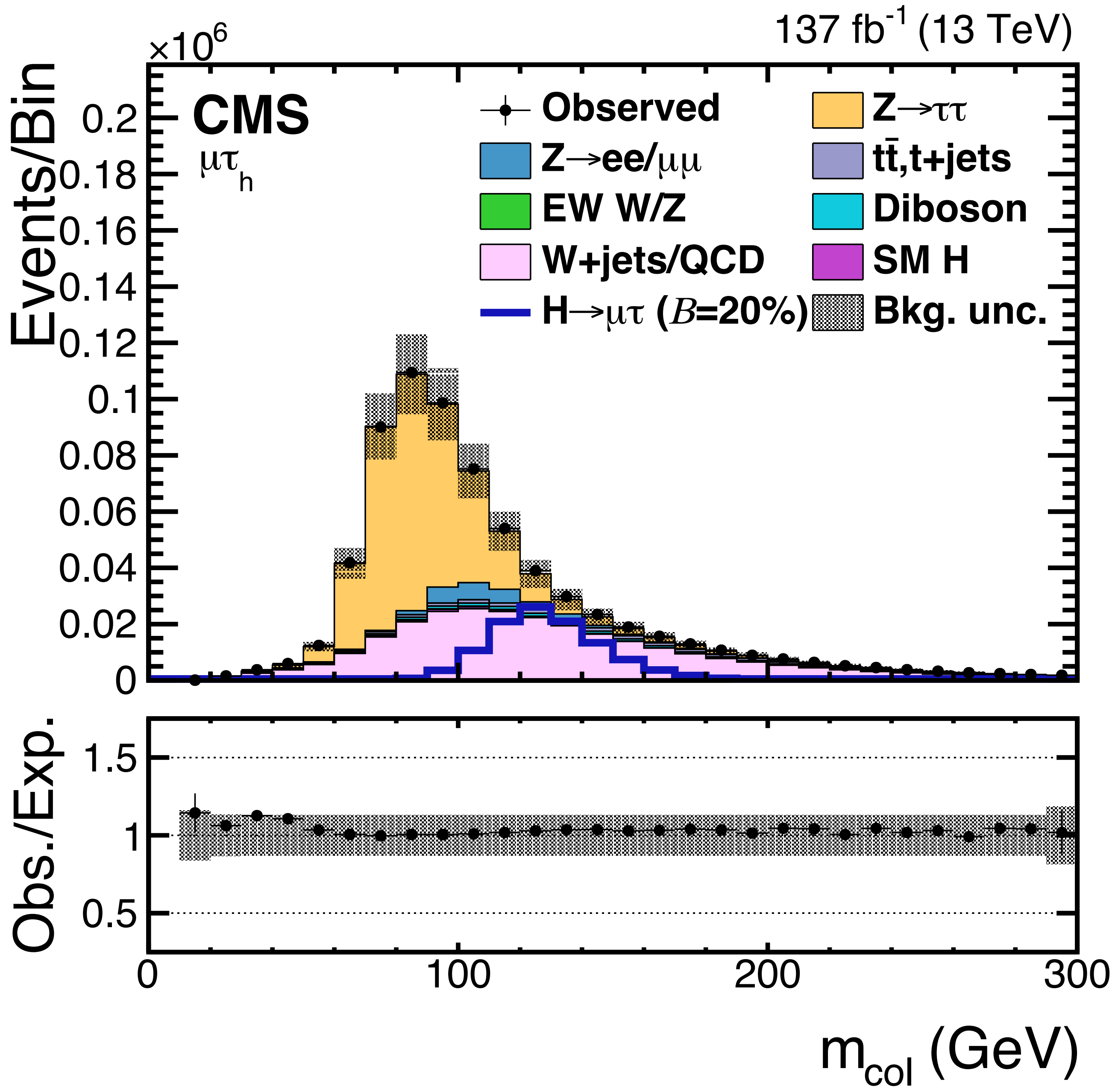


Search for $H \to e\tau$ and $H \to \mu\tau$ at CMS

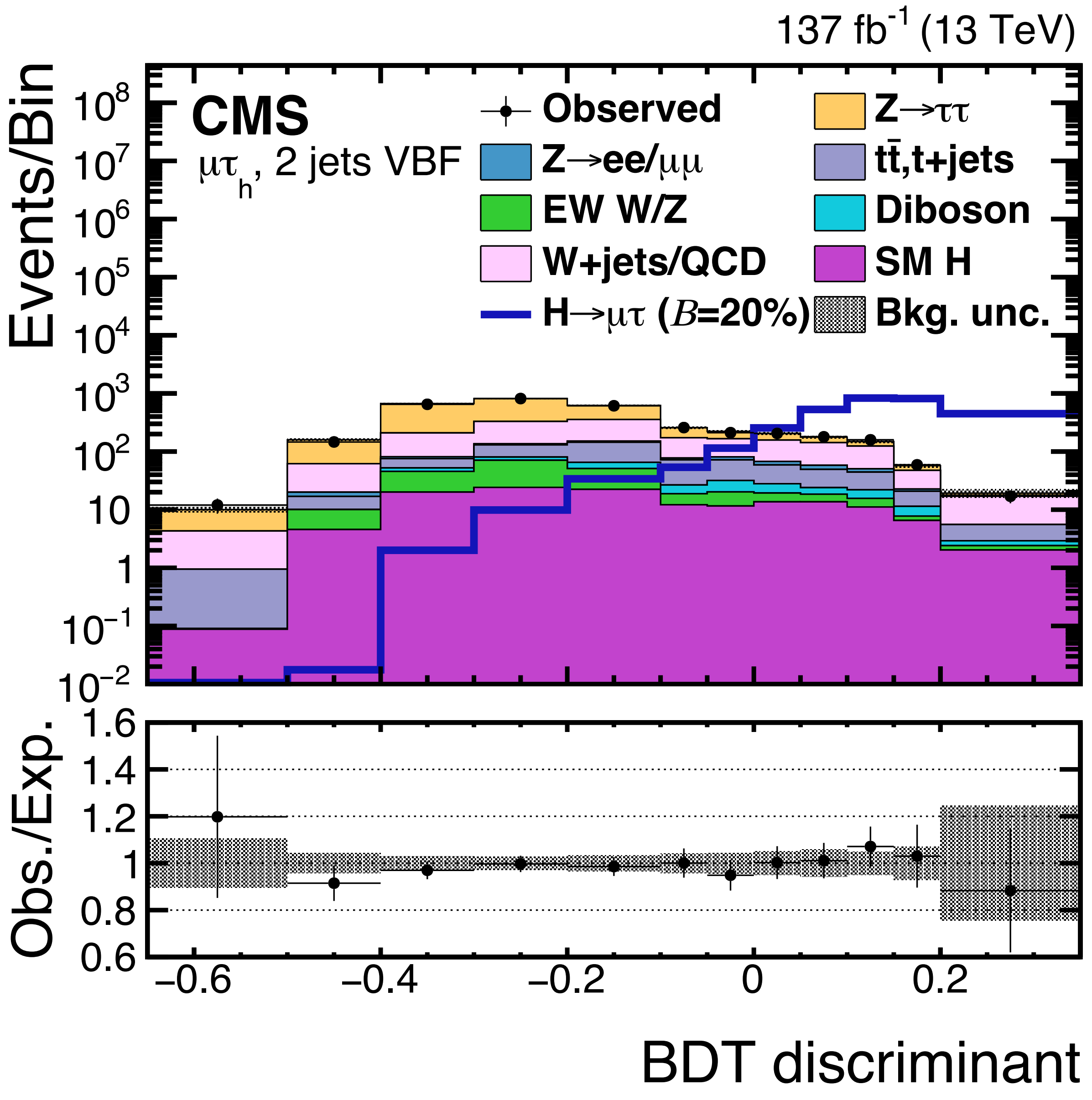
Analysis strategy

[Phys.Rev.D (2021) 104, 032013](#)

- Signature: opposite charged $e + \tau$ or $\mu + \tau$
  - isolated leptons and ≤ 2 jets no b-tagged jet
- Each channel $\ell\tau$ events split in 8 categories
  - 2 cat upon τ decay mode $\ell\tau_h$ and $\ell\tau_{\ell'}$
    - each one split in 4 : 0-jets, 1-jet, 2-jets ggH and 2-jets VBF
- Signal selection via BDT separately trained in $\ell\tau_h$ and $\ell\tau_{\ell'}$
  - collinear mass m_{col} as m_H proxy from visible energy
- Maximum likelihood fit to BDT in each channel separately



$$m_{col} = m_{vis}/\sqrt{x_\tau^{vis}}$$

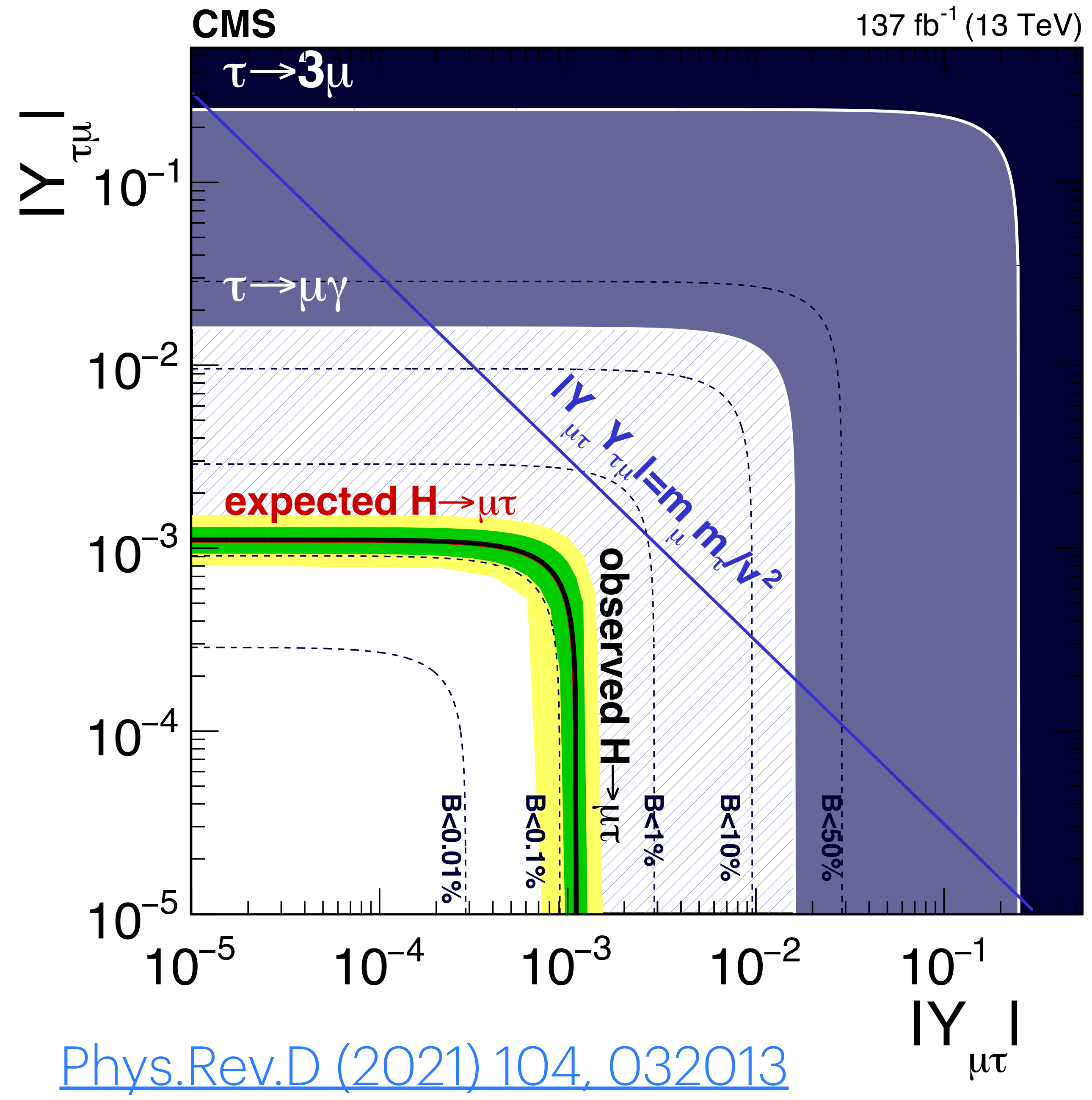


Yukawa couplings for $H \to e\tau$ and $H \to \mu\tau$

Results

- Independent searches upper limits @ 95% CL
  - ATLAS $Br(H \to \mu\tau)$ < 0.18% and $Br(H \to e\tau)$ < 0.20%
  - CMS $Br(H \to \mu\tau)$ < 0.15% and $Br(H \to e\tau)$ < 0.22%
- Off diagonal Yukawa couplings
  - direct $H \to \ell\tau$ searches → more stringent constraints than $\tau \to 3\ell$ and $\tau \to \ell\gamma$ searches

$$|Y_{\ell\tau}|^2 + |Y_{\tau\ell}|^2 = \frac{8\pi}{m_H} \frac{\mathcal{B}(H \to \ell\tau)}{1 - \mathcal{B}(H \to \ell\tau)} \Gamma_H(\mathrm{SM}),$$



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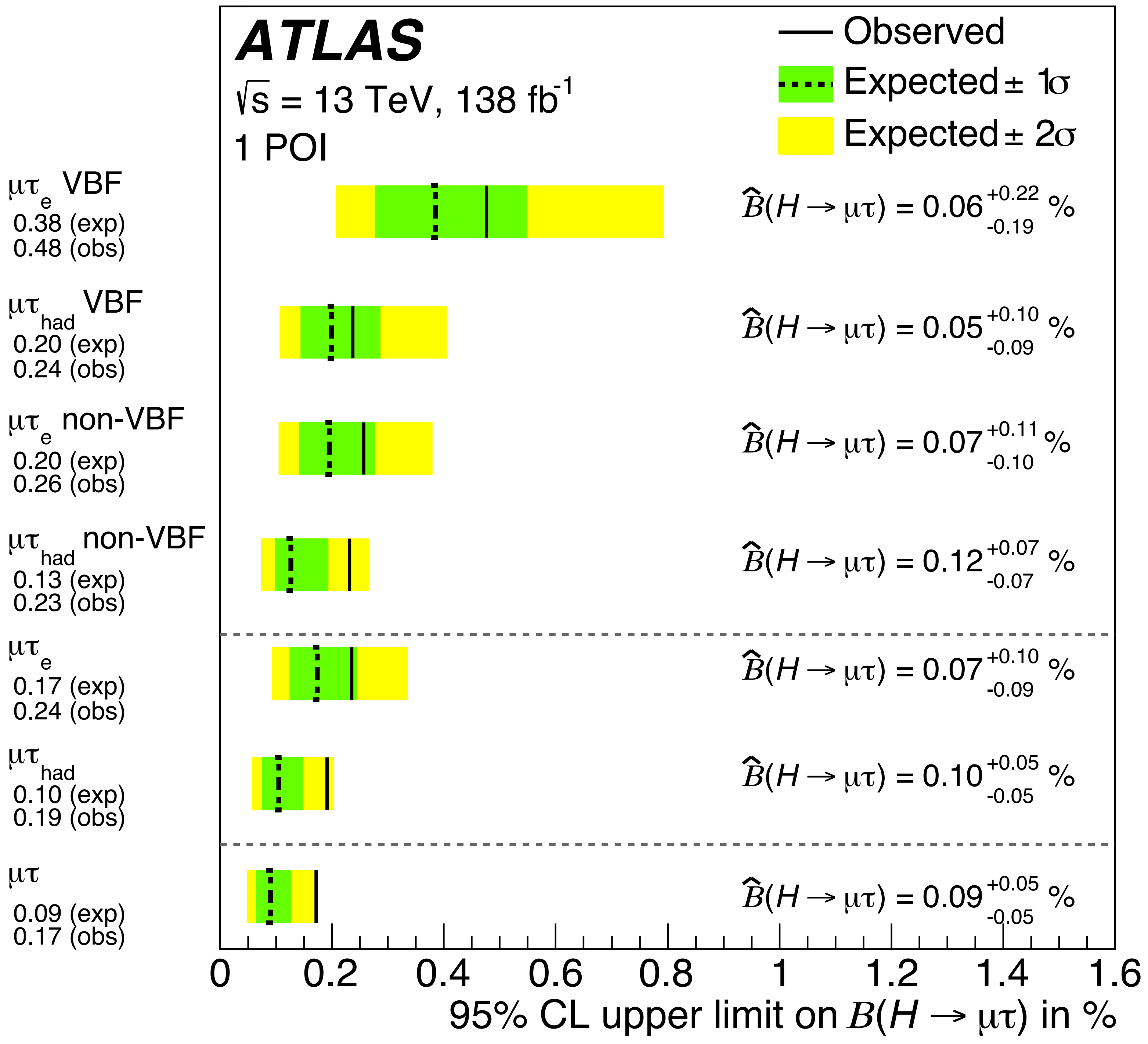
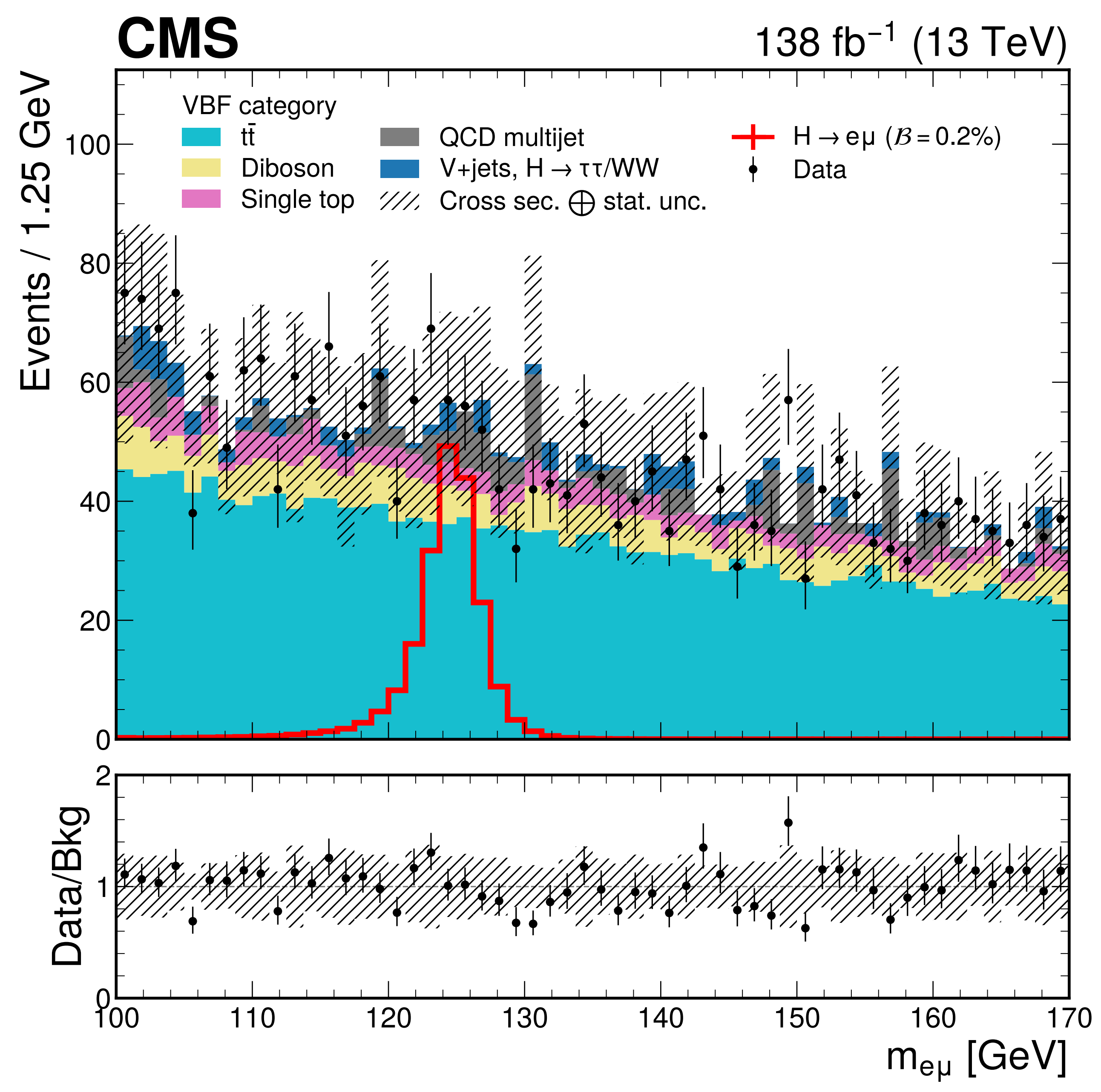
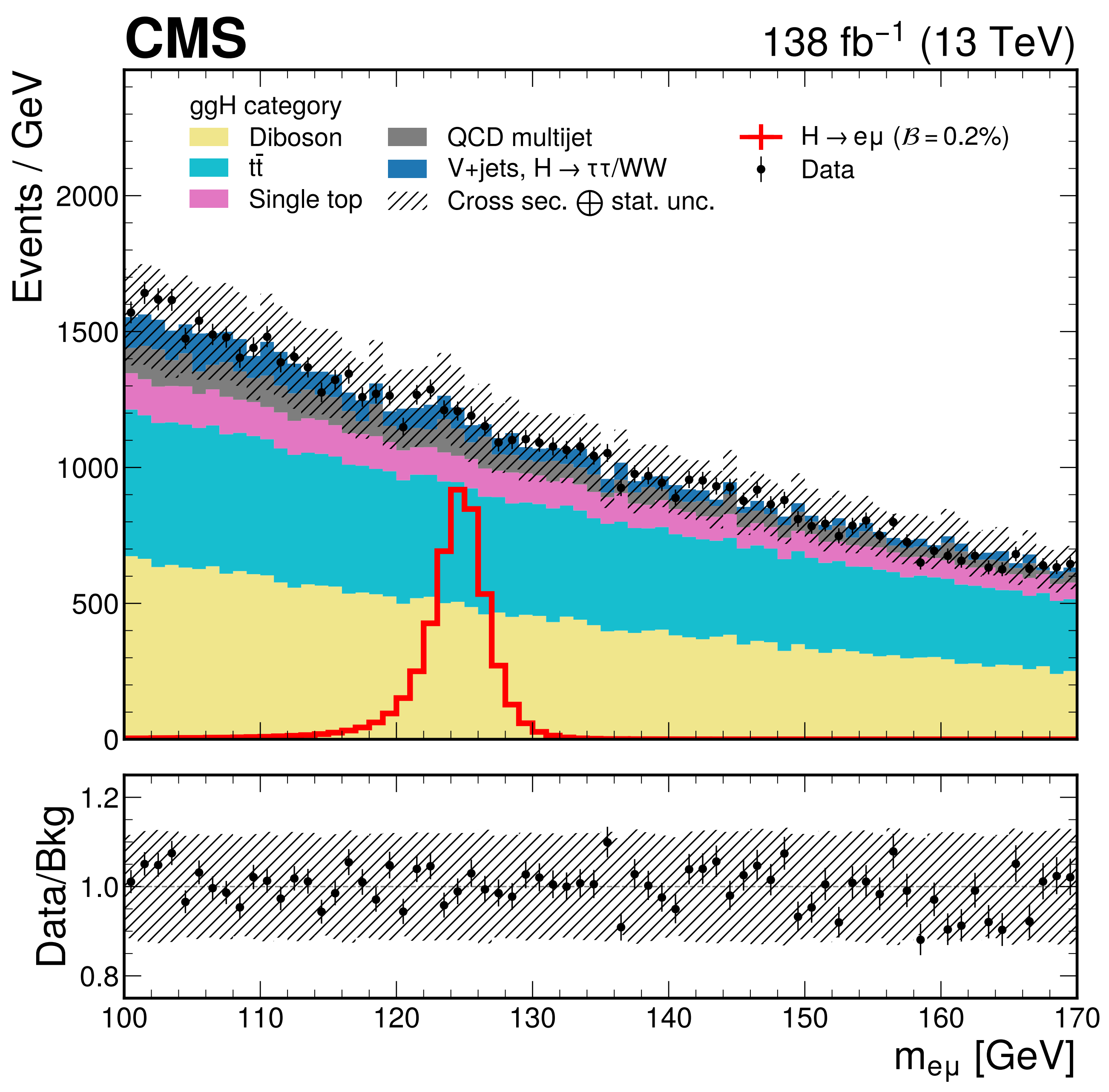


Search for $H \to e\mu$

Overview

- LFV in **SM** and **BSM** Higgs decay
- LFV can arise in additional Higgs bosons decays → Type-III 2 Higgs Doublet Model (2HDM)
    - strong constraint from searches of H′ in below $2m_W$
- Signature $e^{\pm}\mu^{\mp}$ mass within 100 and 160 GeV





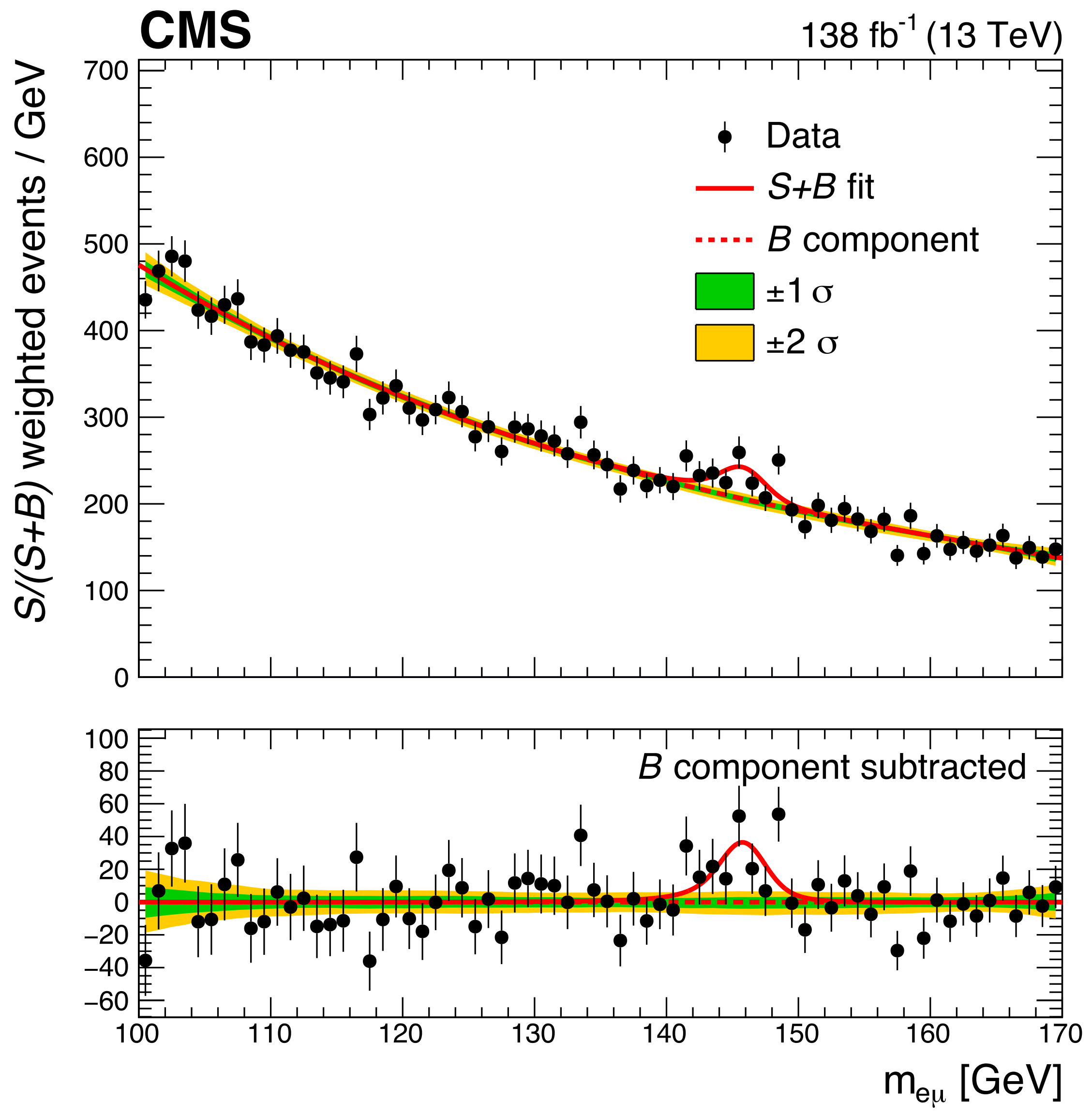
Phys.Rev.D.(2023)108.072004

- Categorization upon
    - ggH and VBF Higgs production
        - BDT score sensitivity
- Fit to $M(e\mu)$ spectrum simultaneously in all categories targeting
    - $Br(H \to e\mu)$ and $Y_{e\mu}$ for 125 GeV Higgs
    - $\sigma_{\rm BSM}(pp \to X \to e\mu)$

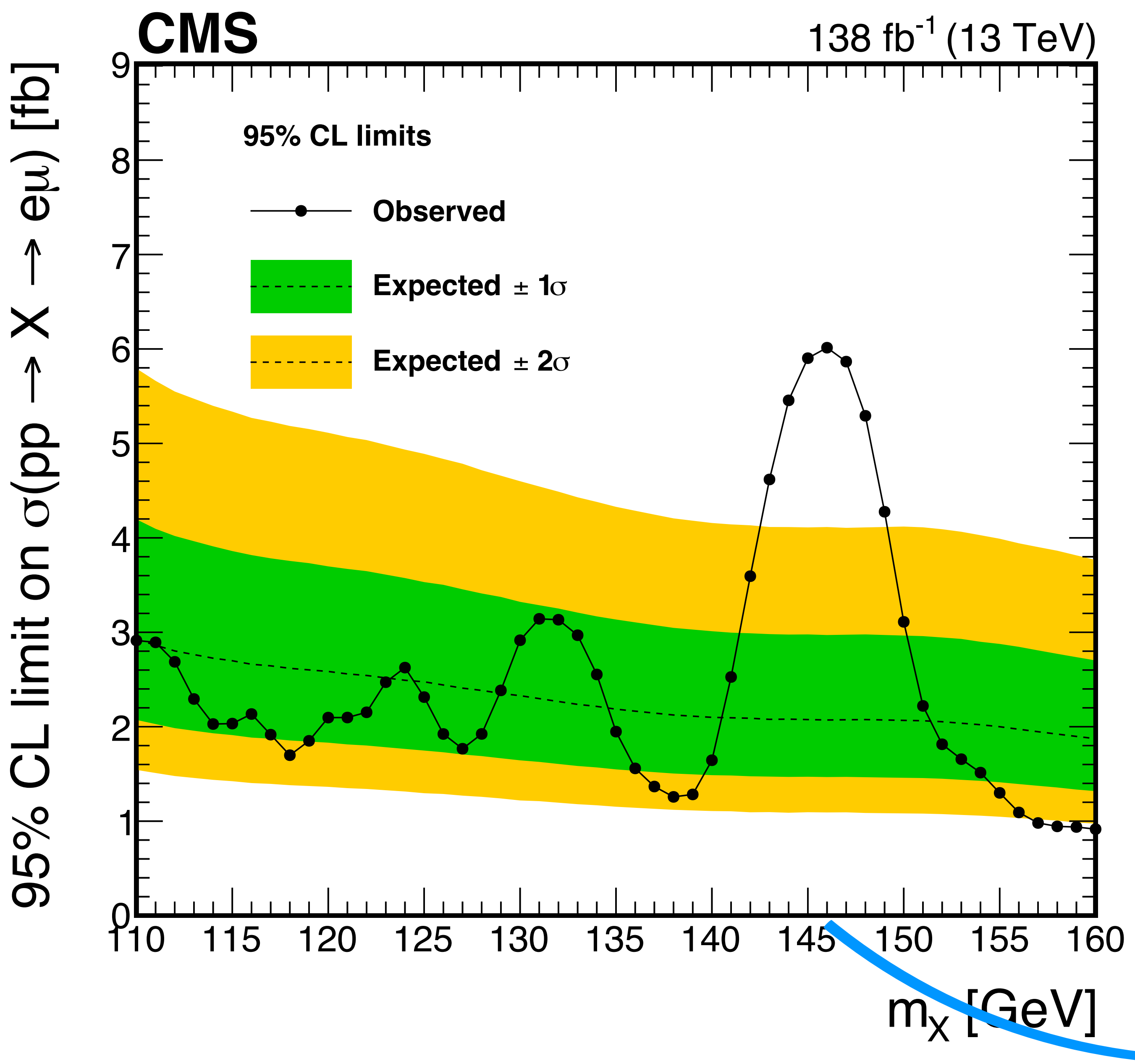
Search for $H \to e\mu$

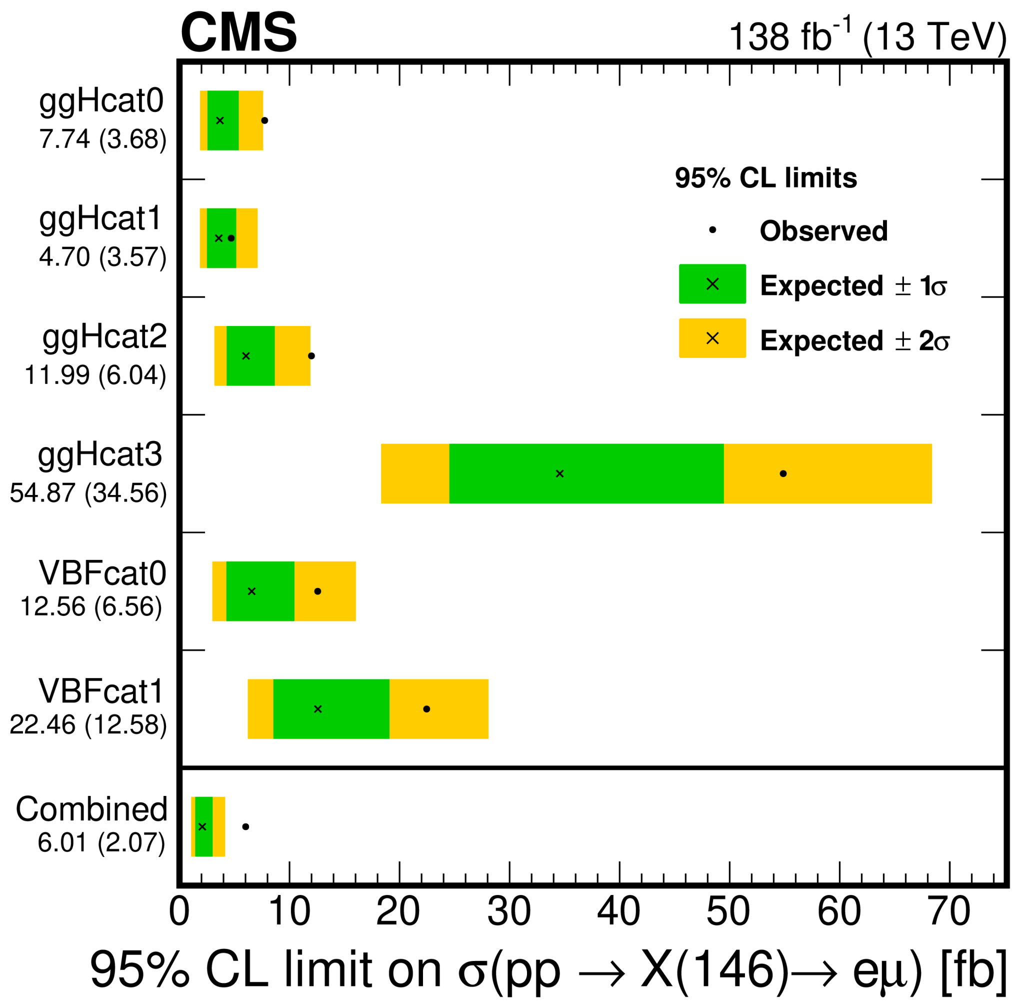
Results

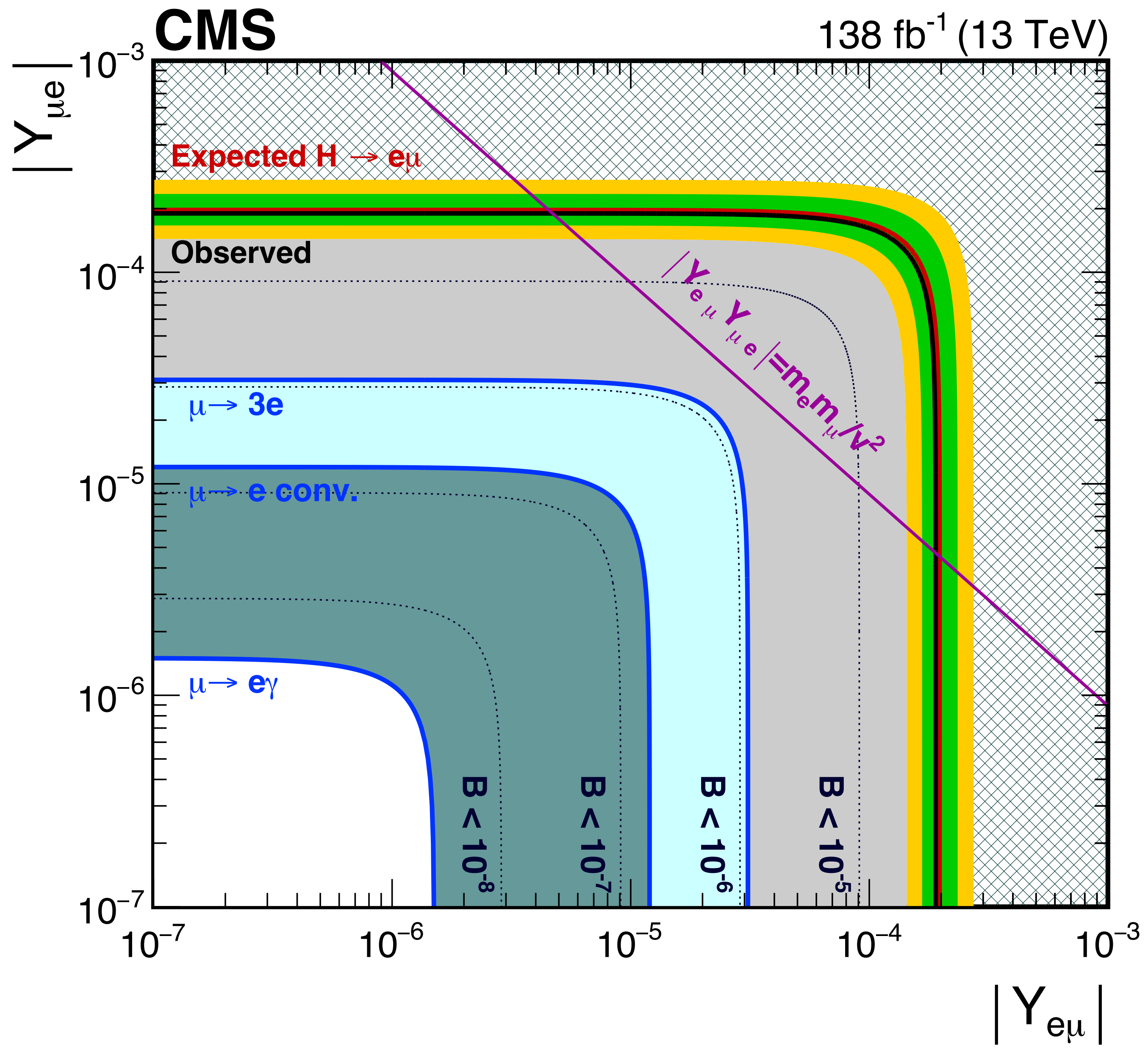
Phys.Rev.D.(2023)108.072004



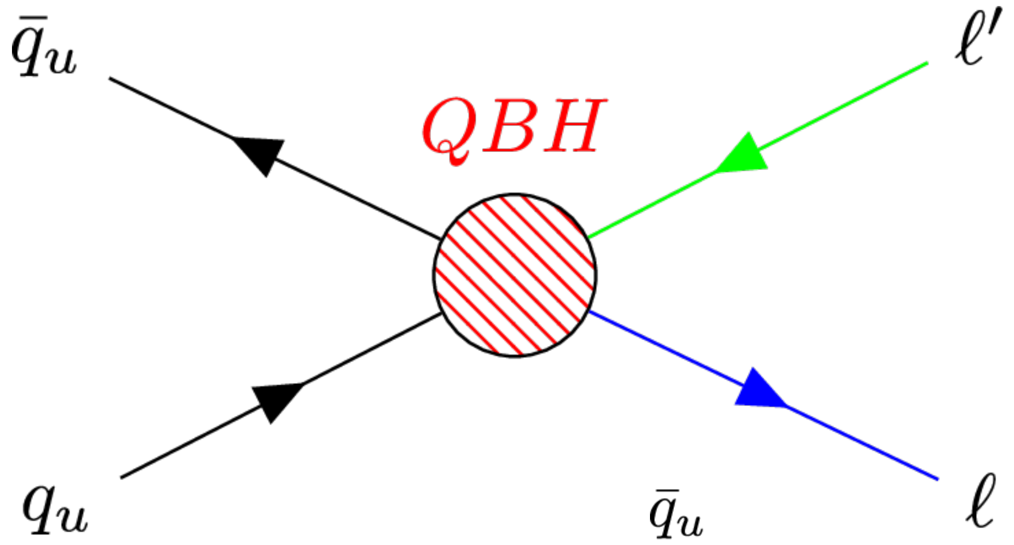
- No significant excess for SM Higgs
  - CMS obs. (exp.) UL $Br(H \to e\mu) < 4.4(4.7) \times 10^{-5}$ @ 95% CL
    - ATLAS $Br(H \to e\mu) < 6.2(5.9) \times 10^{-5}$ @ 95% CL PhysLetterB(2019)135143
- Excess of global (local) 2.8σ (3.8σ) for M_X ~ 146 GeV
  - not sufficient to claim any observations



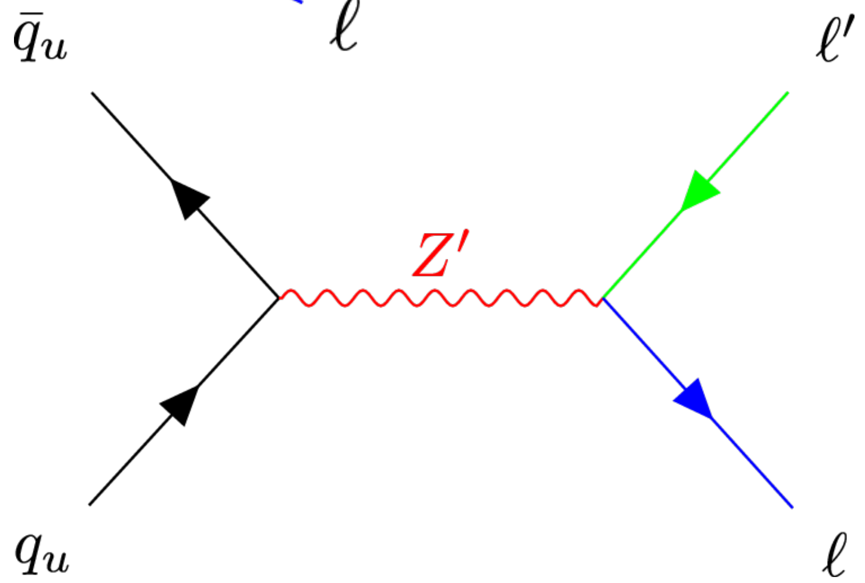




cLFV in Z′ decays



- SM extension predicting LFV interactions at TeV energy scale
  - SM+ $U(1)$ gauge symmetry → Z′ boson → this talk focus
  - scalar ν in R-aprity violating SUSY
  - quantum black holes (QBH) in low-scale gravity
- Clear experimental signature: 2 prompt opposite sign different flavor (**OSDF**) leptons



LFV in heavy resonance BSM

LFV Z′ benchmark model

- Benchmark model : Z' boson with SM quark coupling and chiral structure + LFV couplings

- Signature from prompt **OSDF** leptons $e\mu$, $e\tau$ and $\mu\tau$
  - bump search in $M(\ell\ell')$ in TeV range

- Irreducible background from SM $t\bar{t}$, tW , $Z\tau\tau$ and VV decays producing **OSDF** leptons in final state

- Simultaneous fit to SR and CRs in $M(\ell\ell')$ separately for the different flavors
  - less than 2σ tension with SM in $\ell\tau$ channels at 2.0 and 2.3 TeV

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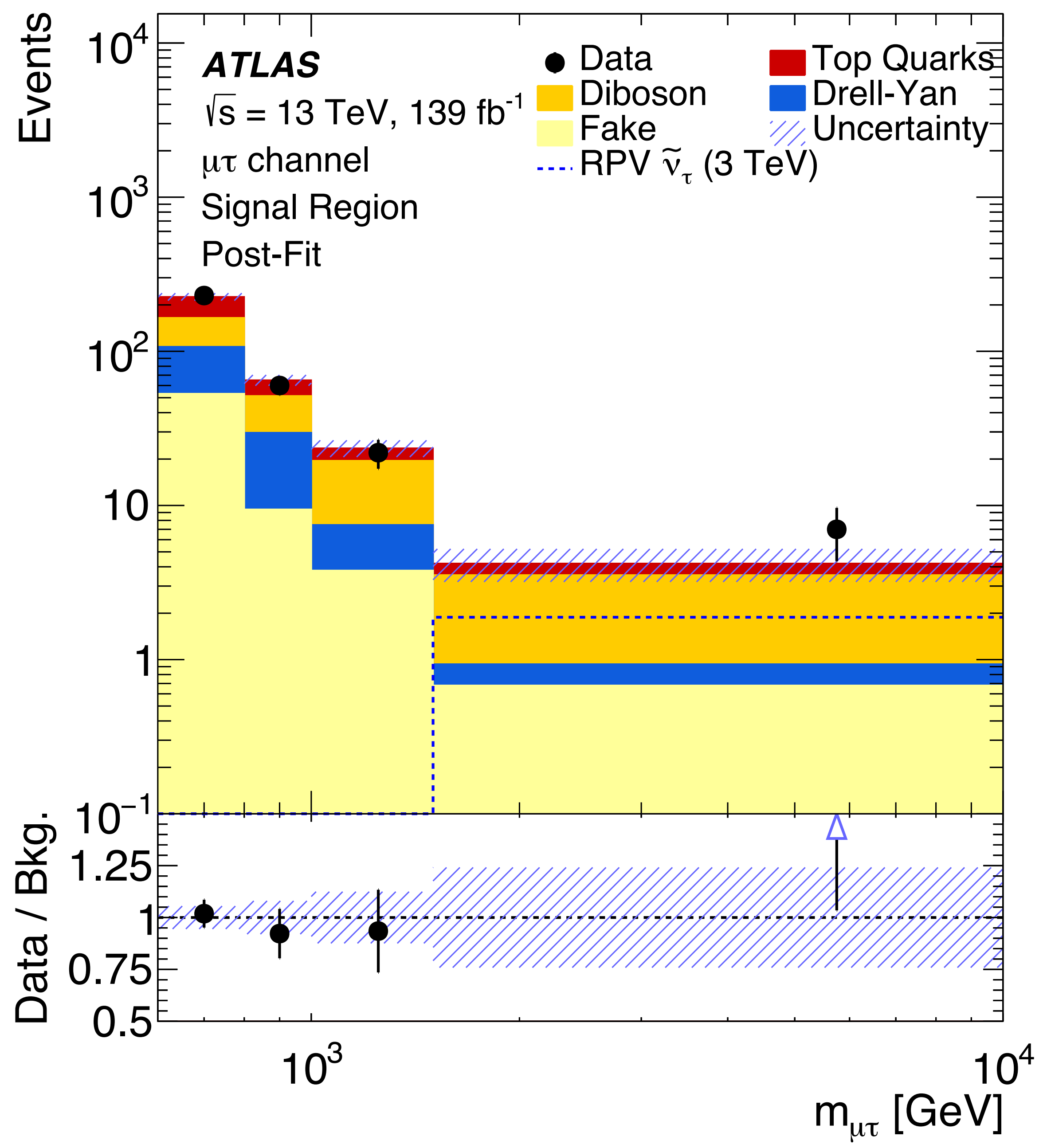

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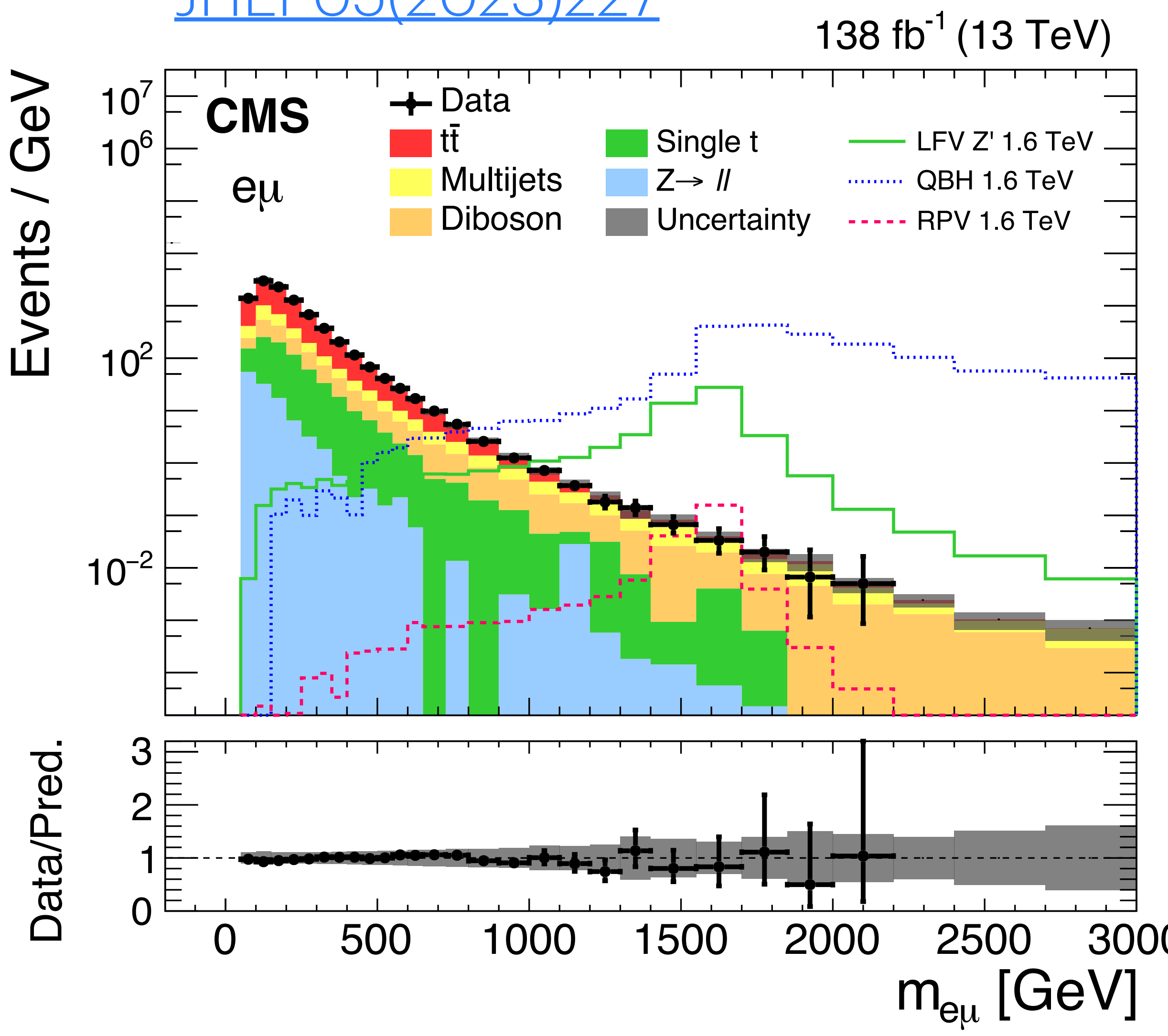
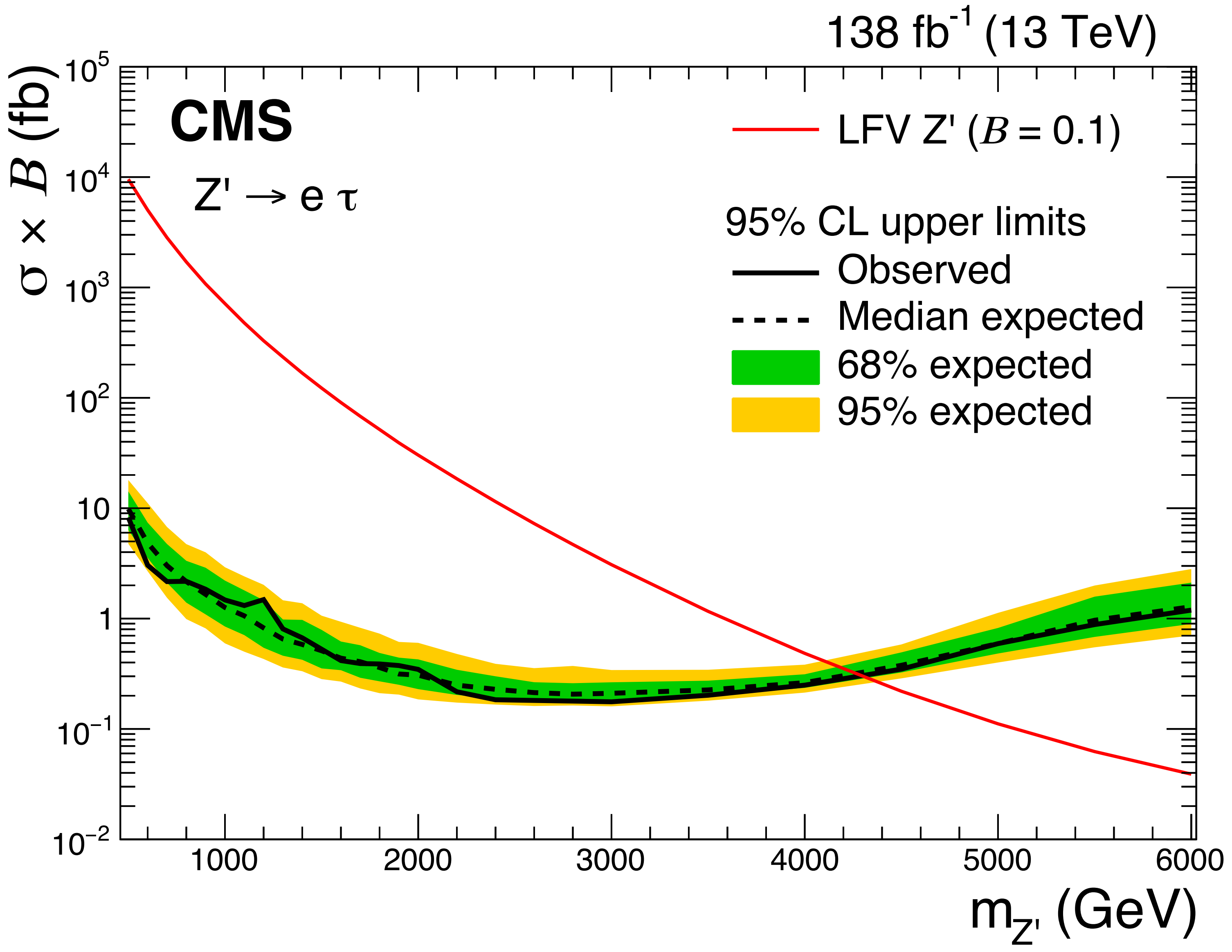


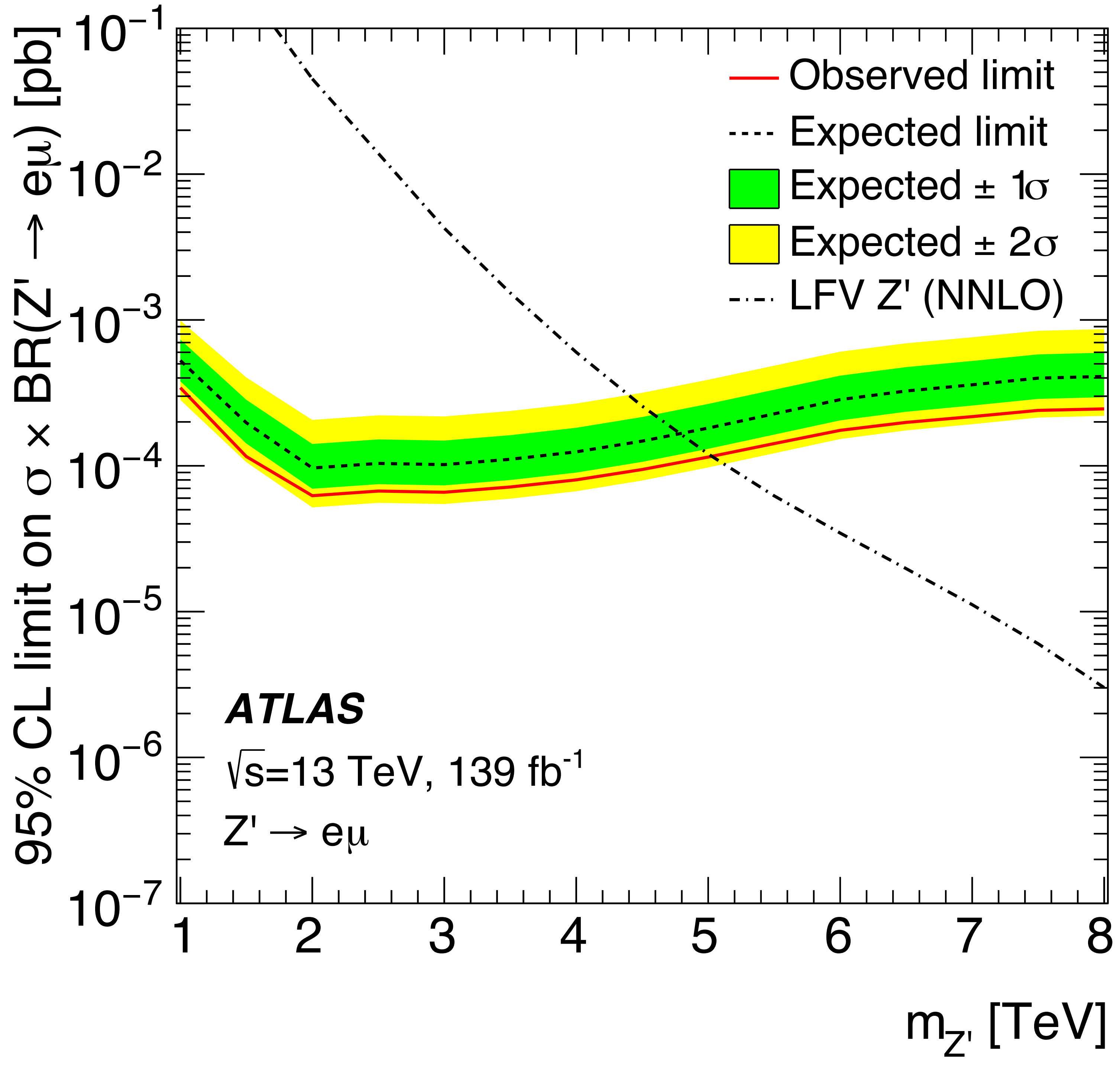
LFV in heavy resonance BSM

Results

- **CMS** and **ATLAS** have the same sensitivity in all channels
  - more stringent constraint on Z′ mass from $e\mu$ final state
- Constrains are consistent with LF conserving $Z' \to \ell^+\ell^-$ searches

Channel	LFV Z′ (TeV) $\mathcal{B} = 0.1$
$e\mu$	5.0 (4.9)
$e\tau$	4.3 (4.3)
$\mu\tau$	4.1 (4.2)

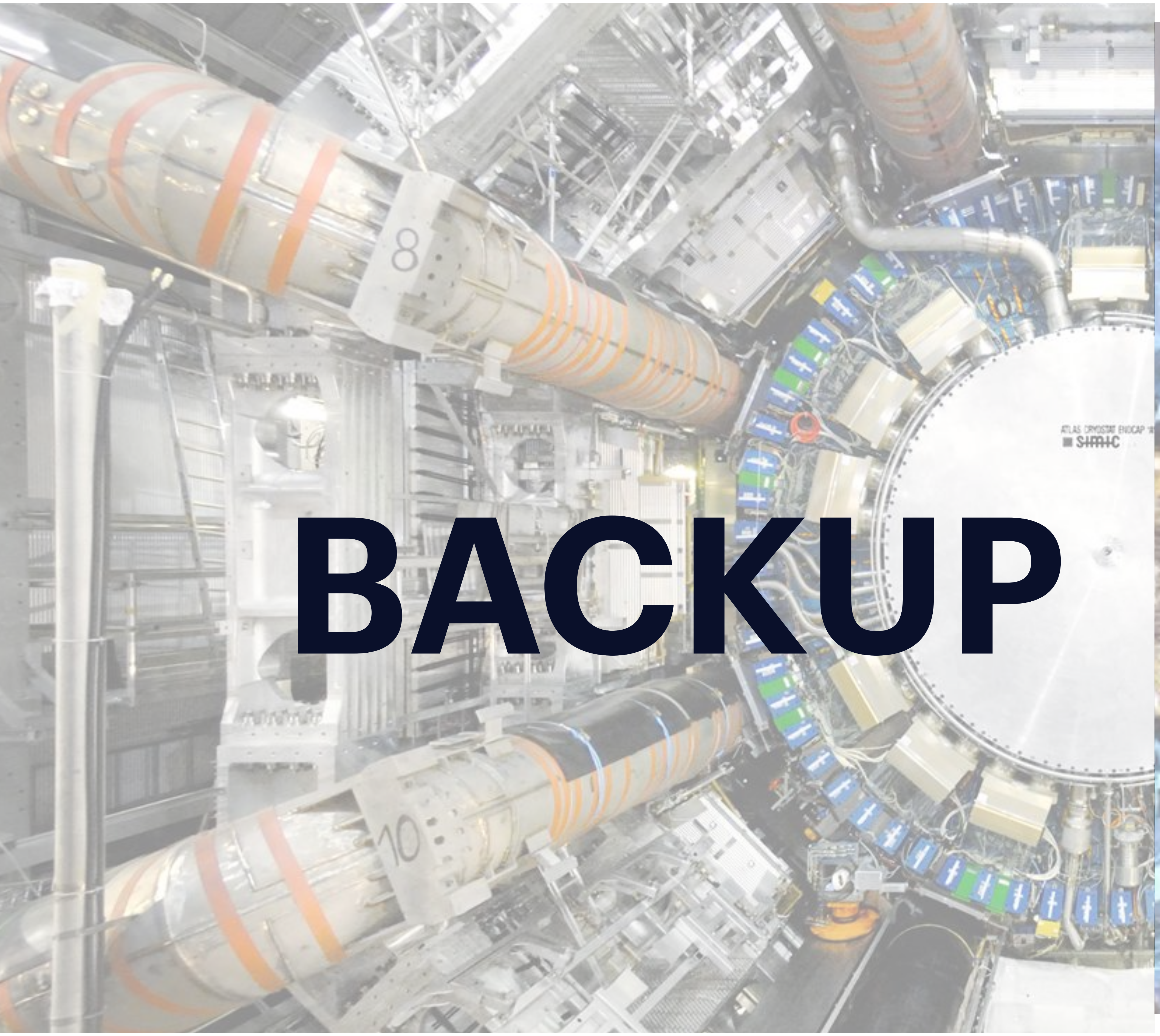




Conclusions

- An overview of the latest cLFV searches conducted by ATLAS and CMS
- cLFV searches are an ideal playground to look for new physics
  - possibility to probe physics scales much larger than the TeV → **SMEFT** frame
  - observation of SM suppressed decays → evidence of **new particles/interaction** vertices !
- CMS and ATLAS are able to exclude rare decays branching ratios up to 10^{-8}
  - there is still room to accommodate BSM theories predictions!
- Sensitivity for rare process will benefit form the new data coming from ongoing Run3
  - CMS and ATLAS already collected almost 184 /fb !
    - > 120 /fb only during 2024!
- Sensitivity increase from new strategies for trigger design and reconstruction algorithms
  - targeting higher acceptance and efficiency
    - in particular for low-pT rare decays signatures such as $\tau \to 3\mu$

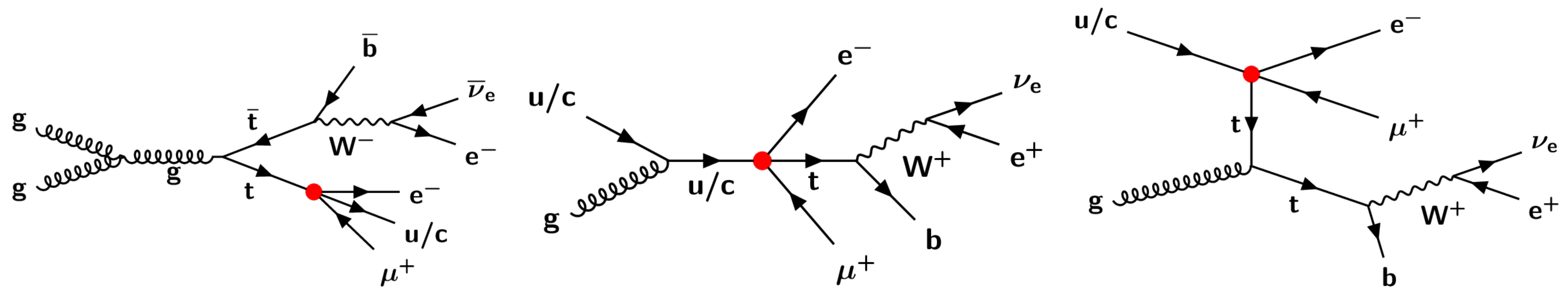
BACKUP



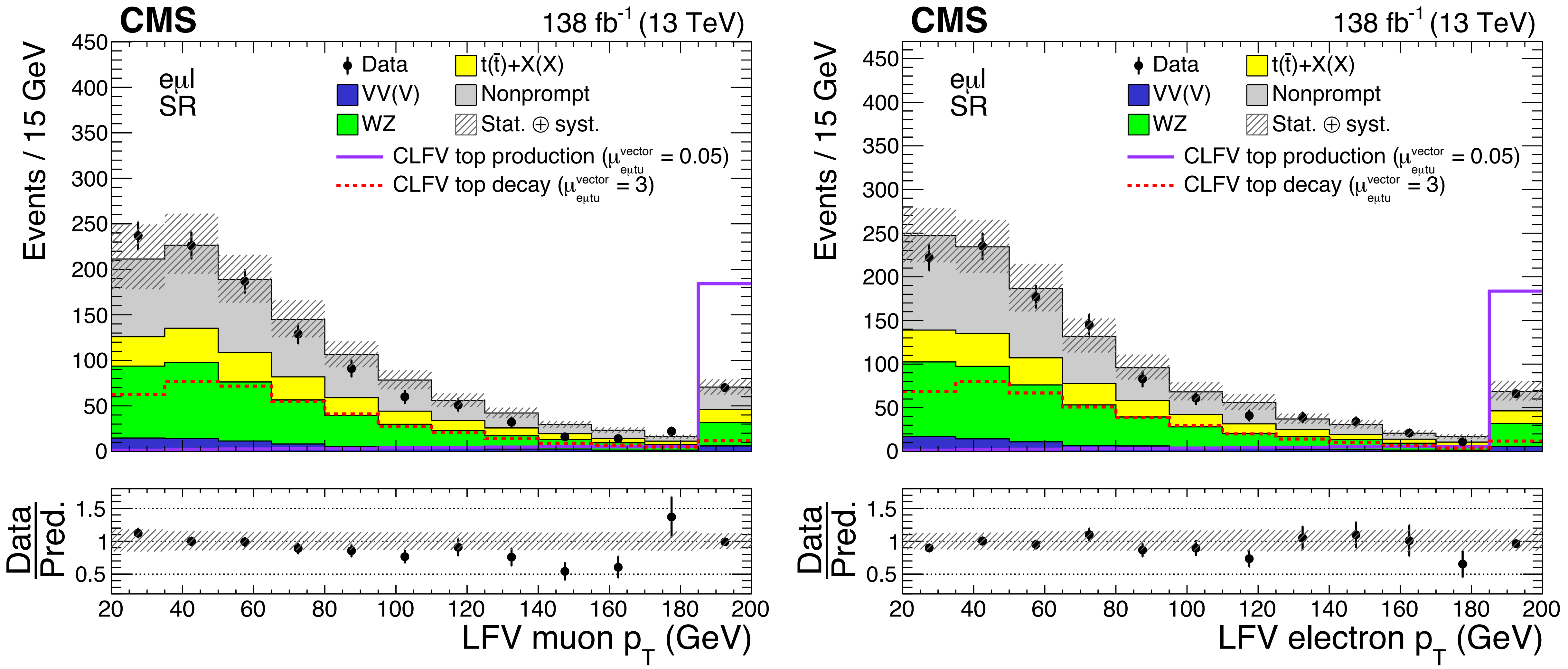
cLFV in top quark sector with 3 lepton final state

Overview

- Experimental signature :3 lepton in the final state
  - $\mu^{\pm}e^{\mp}$ from cLFV vertex
  - 1ℓ from SM W $\rightarrow \ell\nu$
  - ≥ 1 b-tagged jet



- Target $te\mu q_u$ cLFV vertices both in top production and decay → 2 SRs
  - $M(e\mu) > 150$GeV - production
  - $M(e\mu) < 150$GeV - decay



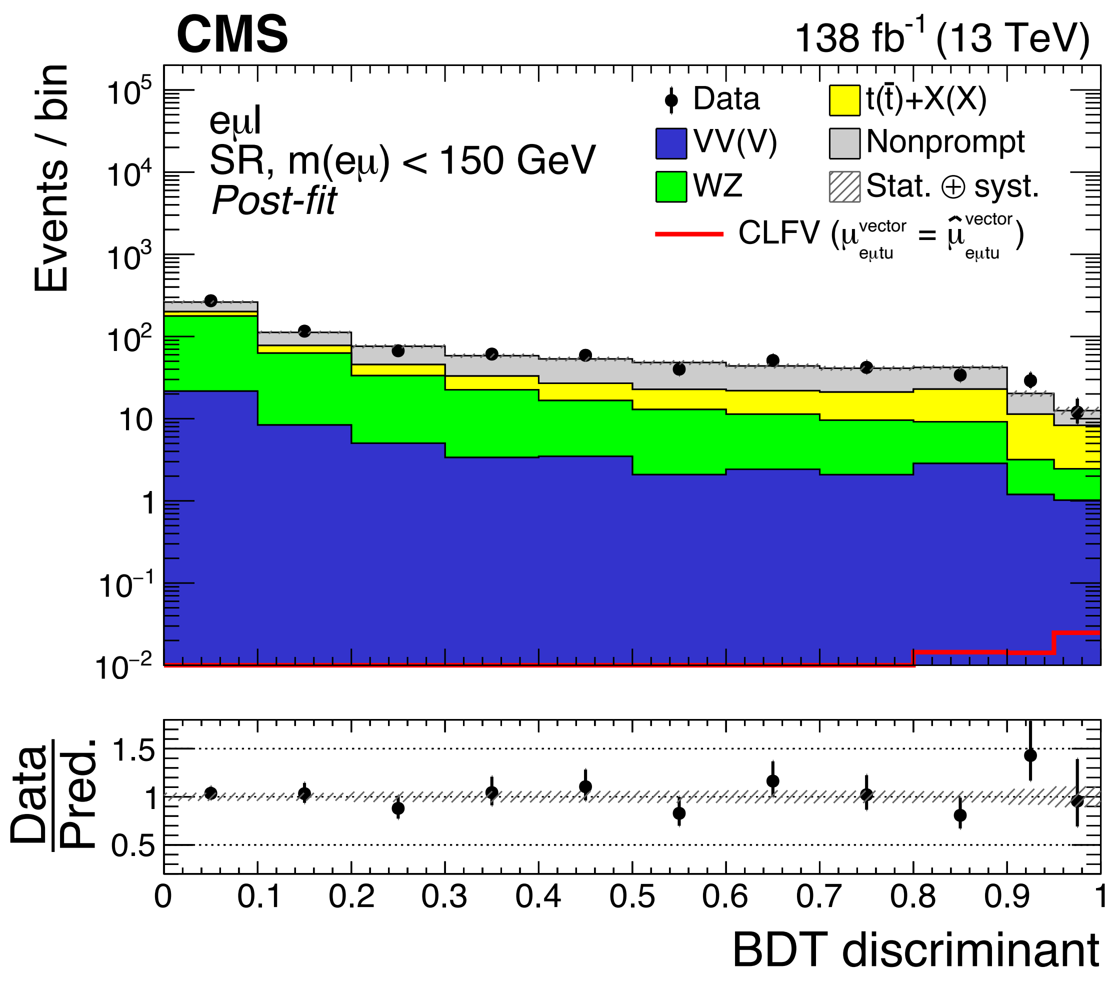
- 3 events categories:
  - $eee/\mu\mu\mu$: LFC → background modeling
  - $e\mu\ell$: LFV signal category

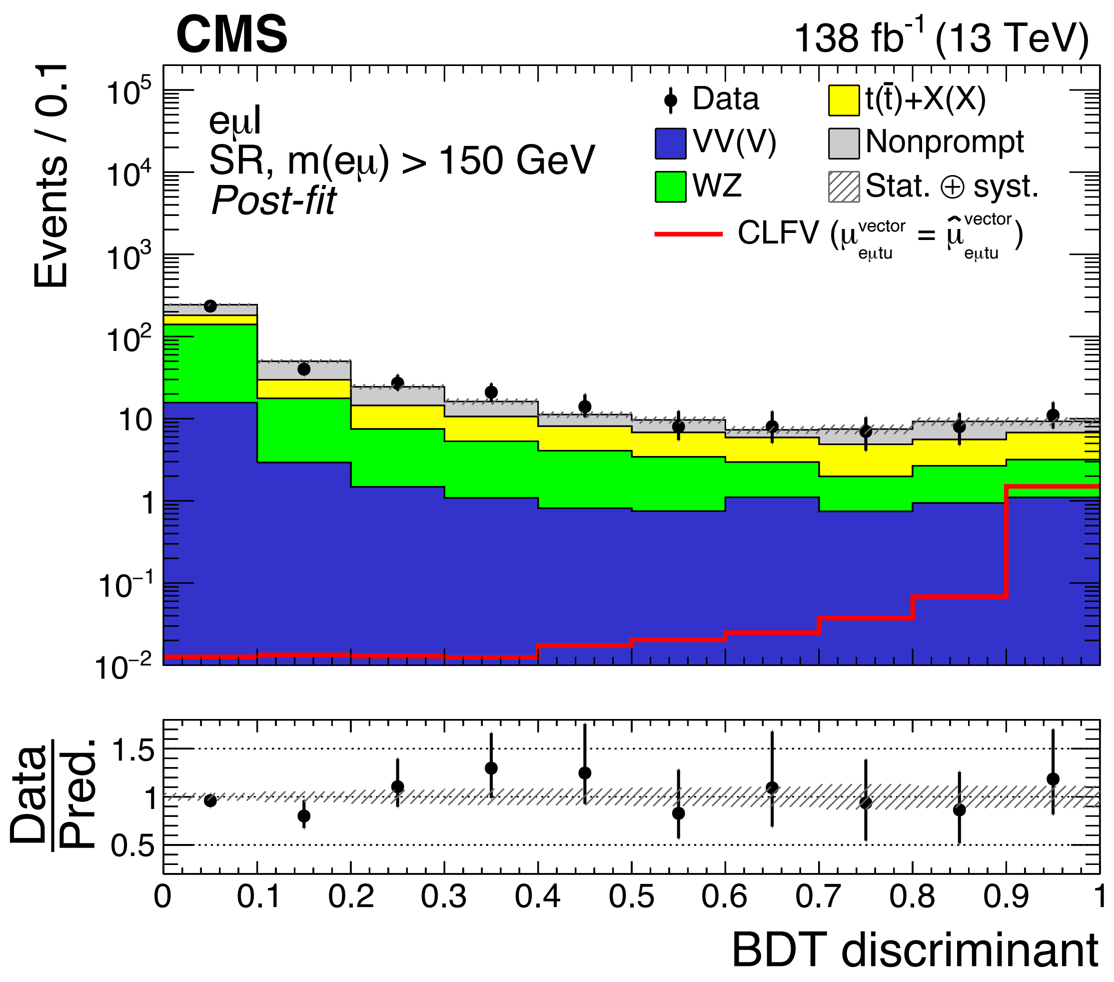
arXiv:2312.03199v1

cLFV in top quark sector with 3 lepton final state

Analysis strategy and results

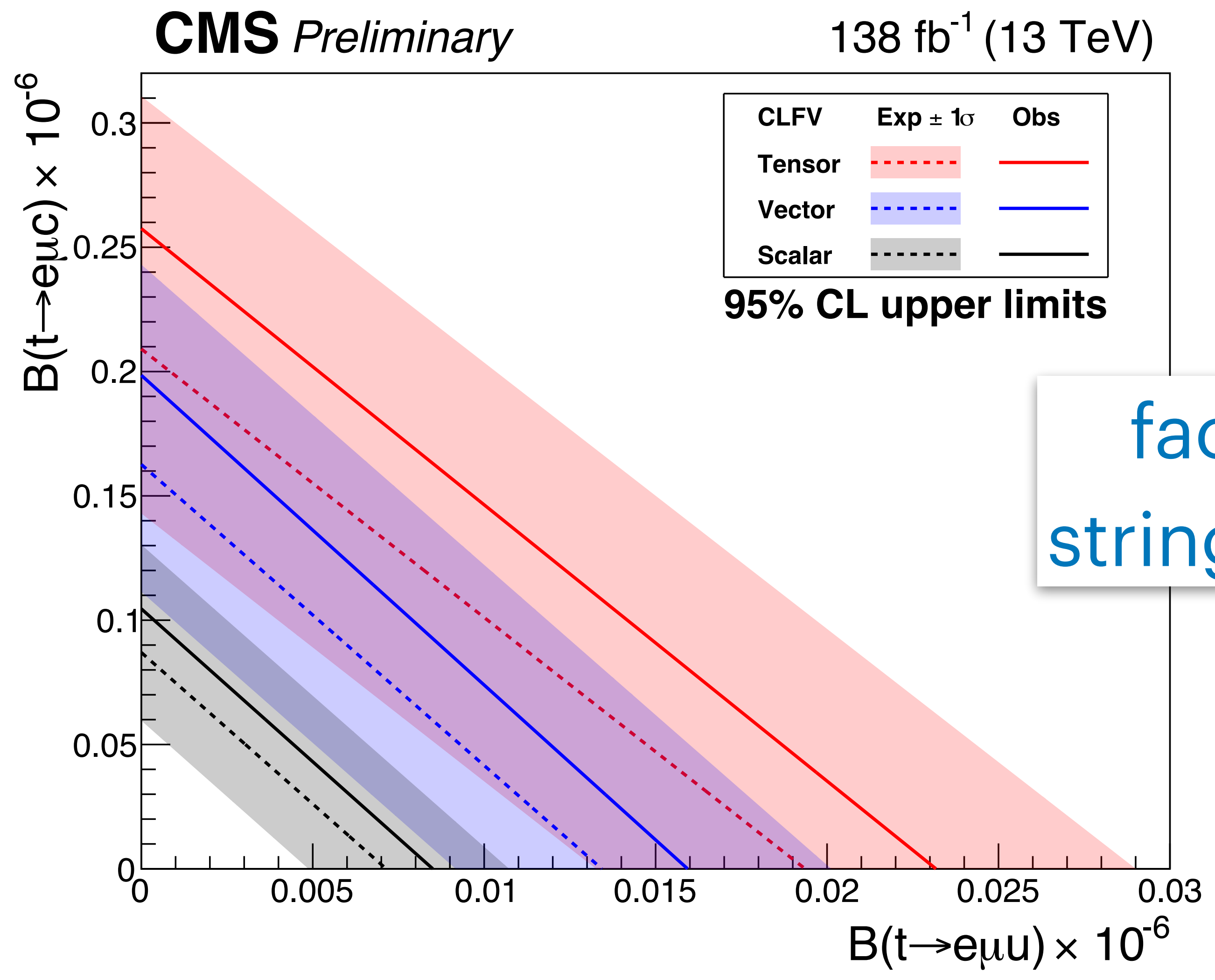
arXiv:2312.03199v1





- SM background sources divided in
  - prompt mainly from WZ → MC modeled
  - non-prompt from other process (DY..) → data-driven
- MVA with 2 BDTs for the top production and decay SRs
  - training inclusively w.r.t. $te\mu u$ and $te\mu c$ and the EFT Lorentz structure
- Binned likelihood fit to BDT distribution simultaneously to decay and production SRs and separately w.r.t. EFT operator Lorentz structure
- POI : signal strength scaling of σ_{cLFV} in SMEFT dim-6 frame
  - with only 1 non-vanishing Lorentz structure coefficient

$$\mu(C/\Lambda^2) = \frac{\sigma_{\text{cLFV}}(C/\Lambda^2)}{\sigma_{\text{cLFV}}(1\text{TeV}^{-2})}$$

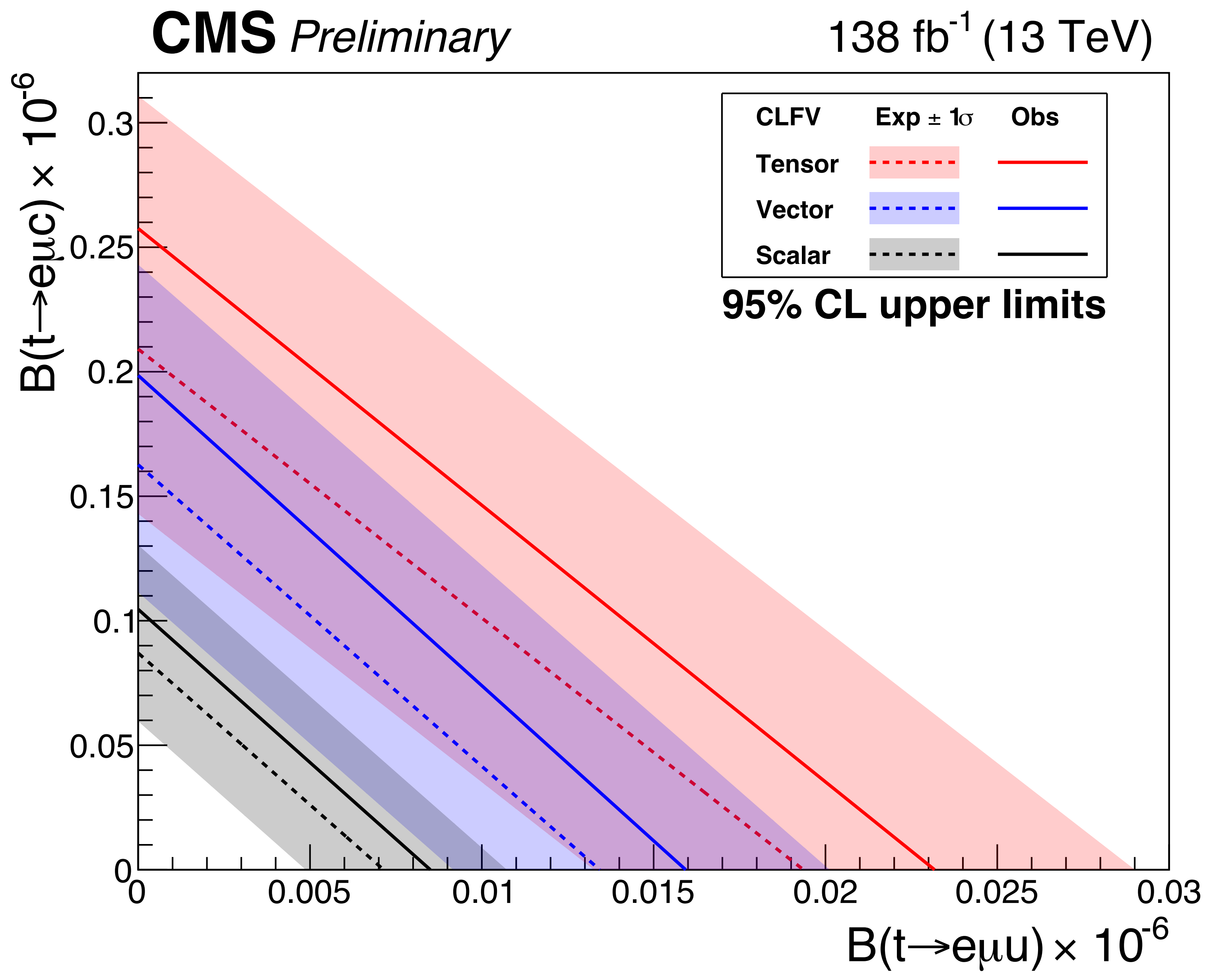


factor 10 more stringent w.r.t. $t\mu\tau q$

SMEFT coupling and branching ratio relation

$$Br(t \to e\mu c) + Br(t \to e\mu u) = \frac{m_t}{f \cdot \pi^3 \Gamma_t^{SM}} \cdot (|C_{te\mu c}|^2 + |C_{te\mu u}|^2)$$

$$\mathcal{B}(\mathrm{t} \to \mathrm{e}\mu\mathrm{q}) = \begin{cases} \frac{|C^{\mathrm{tensor}}_{\mathrm{e}\mu\mathrm{tq}}|^2}{\Lambda^4} \frac{m_\mathrm{t}^5}{64\pi^3\Gamma_\mathrm{t}^{\mathrm{SM}}} \\ \frac{|C^{\mathrm{vector}}_{\mathrm{e}\mu\mathrm{tq}}|^2}{\Lambda^4} \frac{m_\mathrm{t}^5}{384\pi^3\Gamma_\mathrm{t}^{\mathrm{SM}}} \\ \frac{|C^{\mathrm{scalar}}_{\mathrm{e}\mu\mathrm{tq}}|^2}{\Lambda^4} \frac{m_\mathrm{t}^5}{3072\pi^3\Gamma_\mathrm{t}^{\mathrm{SM}}} \end{cases}$$



Simultaneous $He\tau$ $H\mu\tau$ measurement

Results

- 2.4 σ for $Br(H \to \mu\tau)$ and 1.6 σ for $Br(H \to e\tau)$ excess w.r.t. SM
  - overall 2.1 σ compatibility with SM