Virtual Talk

Tau LFV at the LHC

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Outline

- Motivation for CLFV searches

- Search for charged-lepton-flavour violation in *Z*-boson decays with the ATLAS detector (Nature Physics volume 17, pages 819–825 (2021) [Run 2], arXiv:2105.12491v1 [Run 1, Run 2])

- Search for lepton-Flavour violating decays of the Higgs boson to $\mu\tau$ and $e\tau$ in proton-proton collisions at $\sqrt{s}$ = 13 TeV (Phys. Rev. D 104 (2021) 032013 [Run 2], JHEP06(2018)001[Run 2], Eur. Phys. J. C (2017) 77:70 [Run 2])

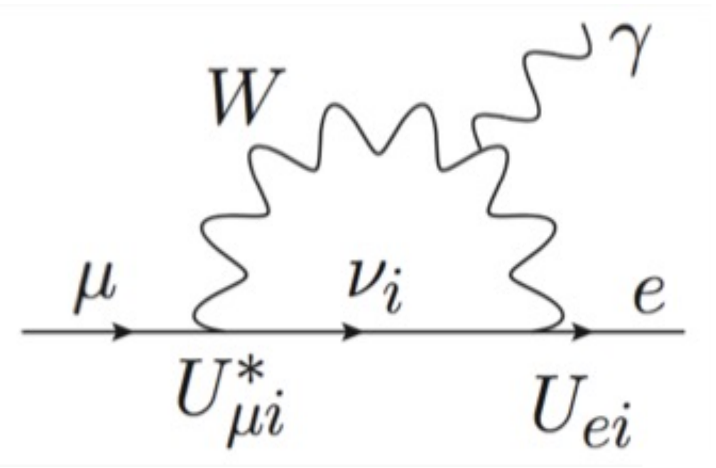
- Search for the lepton flavour violating decay $B^+ \rightarrow K^+\mu^-\tau^+$ using B^{*0}_{s2} decays (JHEP 06 (2020) 129 [Run 1, Run2])

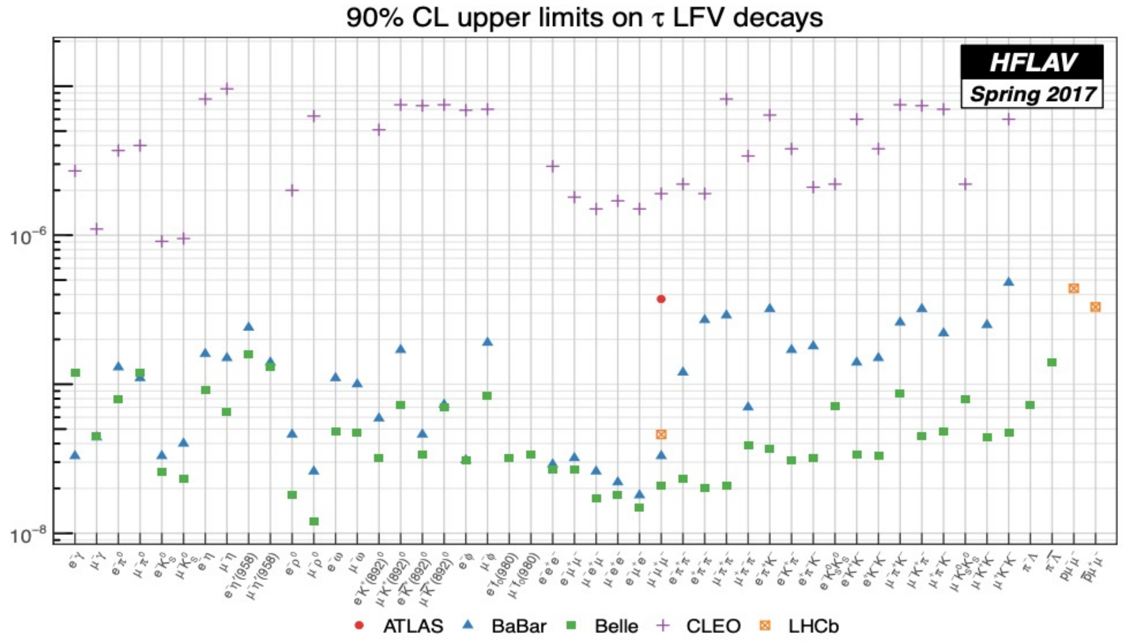
- Search for the lepton-flavour-violating decays $B_s^0 \rightarrow \tau^\pm\mu^\mp$ and $B^0 \rightarrow \tau^\pm\mu^\mp$ (Phys.Rev.Lett. 123 (2019) 211801 [Run 1])

- CLFV decay of $\tau \rightarrow \mu\mu\mu$ (JHEP 02 (2015) 121 [Run 1] , Eur. Phys. J. C 76 (2016) 232 [Run 1], JHEP 01 (2021) 163 [Run 2])

Motivation for CLFV Searches

- Charged Lepton Flavour Violation (CLFV) is a transition among e, μ and τ that doesn't conserve lepton family number
- In SM quarks and neutrinos can undergo Flavour change
- Flavour change in charged leptons is not necessarily forbidden by any fundamental symmetry of the SM; yet no such decay is observed
- Flavour change can occur through neutrino oscillations, but the branching ratios are heavily suppressed O(10^{-54})
- Several decades have been spent to improve the search sensitivity in many CLFV decay channels
- Many BSM theories predict the branching ratios much higher than what SM allows O(10^{-8})- currently, just in the reach of many detectors
- A discovery of CLFV would mean new physics!



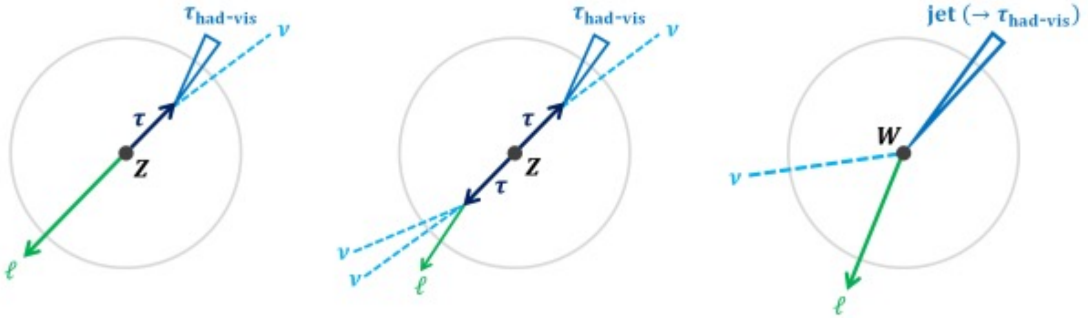


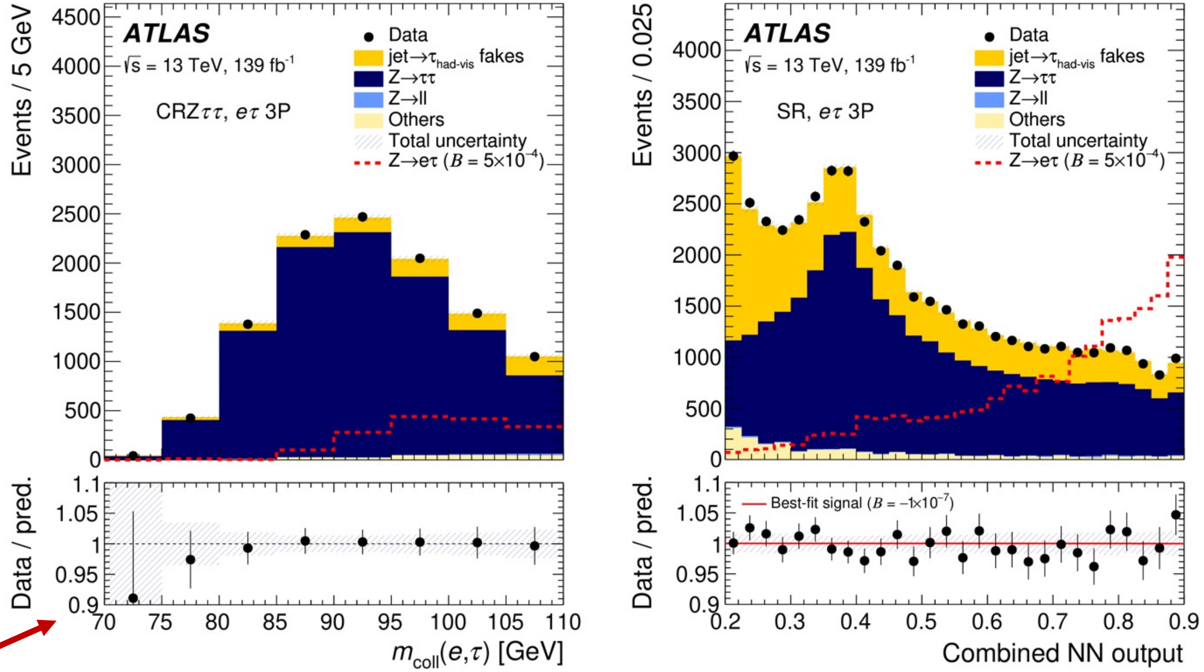
CLFV Higgs and Heavy Resonance Decays

$Z \rightarrow \mu\tau_h$ and $Z \rightarrow e\tau_h$ Searches at ATLAS

Hadronic

- Select isolated lepton and a τ candidate (1-prong or 3-prongs) to form a l-$\tau_{\text{had-vis}}$ pair
- $m(\tau, E_T^{\text{miss}}) < 35$GeV, $m_{\text{vis}}(l, \tau_{\text{had-vis}}) > 60$ GeV applied for background suppression
- b-tagged events are excluded to reject top events
- Neural Network is trained to identify signal from backgrounds (W+jets, $Z \rightarrow ll$ and $Z \rightarrow \tau\tau$)
- High-level variables such as collinear mass (m_{coll}) of τ are provided as an input along with momentum components of reconstructed l, $\tau_{\text{had-vis}}$ candidate and E_t^{miss}
- The overall signal yield is determined by binned maximum likelihood fit in the signal region (SR) and in the control region (CRZττ) enhanced in $Z \rightarrow \tau\tau$
- A simultaneous binned ML fit to the combined NN output in the and m_{coll} in the control region (CRZττ) to constrain the uncertainties





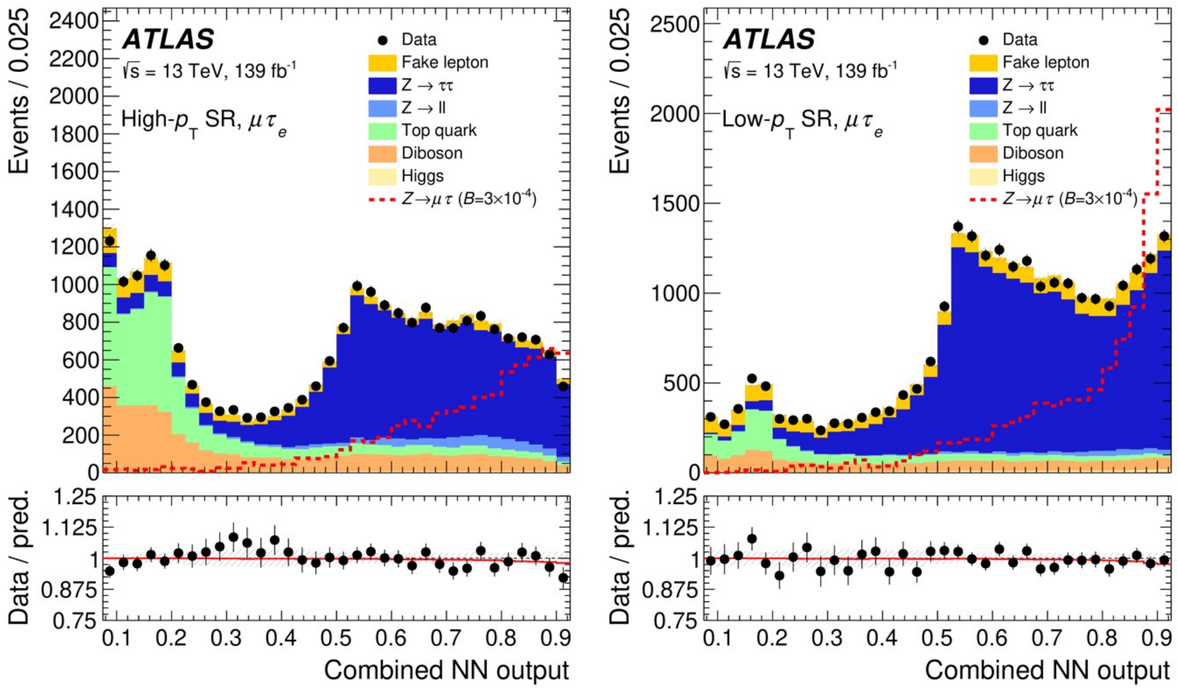
m_{coll} is the invariant mass of e-τ-ν system

[Nature Physics volume 17, pages 819–825 (2021)]

$Z \to \mu\tau_e$ and $Z \to e\tau_\mu$ Searches at ATLAS

Leptonic

- Select a pair of opposite flavour isolated leptons
- Reject all $\tau_{\text{had-vis}}$ candidates
- $m(\tau, E_T^{miss})$ < 35GeV, $m(l_0, l_1)$ applied for background suppression
- b-tagged events are excluded to reject top events
- Neural Network is trained to identify signal from backgrounds ($Z \to ll, Z \to \tau\tau$, diboson and top)
- The high-level and low-level variables are similar to hadronic channel, except the $\tau_{\text{had-vis}}$ properties are replaced by those of the second lepton
- The signal is split into two categories depending on p_T of the subleading lepton ($p_T(l_1)$ < 20 (25) GeV for $e\tau_\mu$ ($\mu\tau_e$))
- A similar scheme of statistical analysis is applied as the hadronic channel



arXiv:2105.12491v1

$Z \to \mu\tau$ and $Z \to e\tau$ Searches at ATLAS

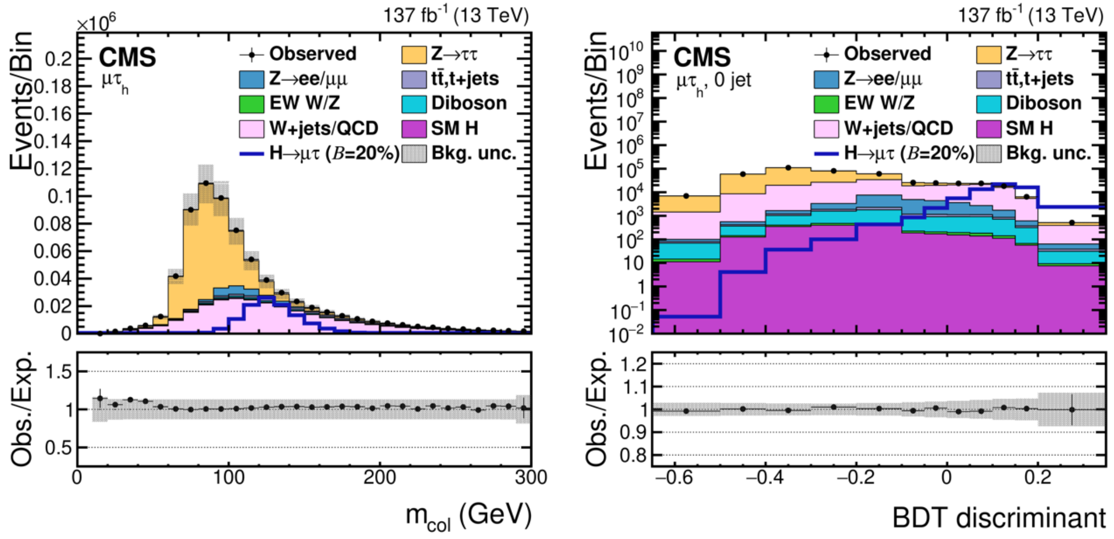
- No statistically significant deviation from the SM predictions is observed
- ATLAS has set the most stringent constraints on LFV Z-boson decays involving τ leptons- **B($e\tau$) < 5.0 × 10^{-6} and B($\mu\tau$) < 6.5 × 10^{-6}** at 95% C.L. assuming unpolarized τ using Run I and Run II datasets
- The limits vary a little depending on the τ polarization scenario
- The results supersede the limits set by LEP over two decades ago
- The precision of the search is mostly limited by the statistical uncertainties

	Observed (expected) upper limit on $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$]	
Final state, polarization assumption	$e\tau$	$\mu\tau$
$\ell\tau_{\text{had}}$ 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)

arXiv:2105.12491v1

$h \to \mu\tau$ and $h \to e\tau$ Searches at CMS

- Search is performed using both leptonic and hadronic decay modes τ_μ, τ_e and τ_h
- For leptonic decays, different flavoured leptons are selected in the $l'\tau_l$ system due to large DY background
- Hadronic tau decays are reconstructed using the Hardon-Plus-Strips (HPS) algorithm
- Events are divided into different categories depending on the number jets (upto 2 jets)
- Events with 2 jets are separated into two categories depending on the dijet invariant mass to improve sensitivity
- Mass of the higgs candidate estimated using collinear approximation
- BDTs are used to classify signal from background in each category
- A maximum likelihood is performed separately in each category and the best fit branching ratios are obtained

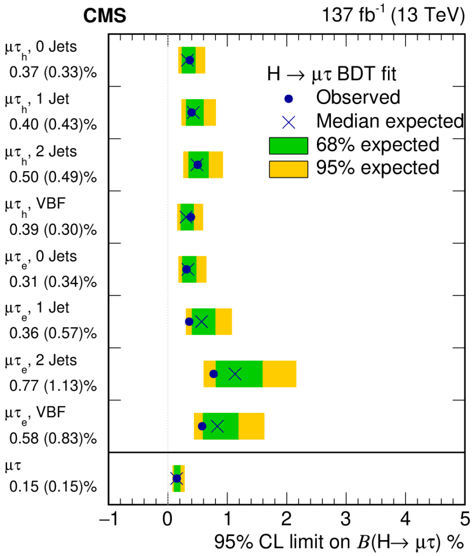


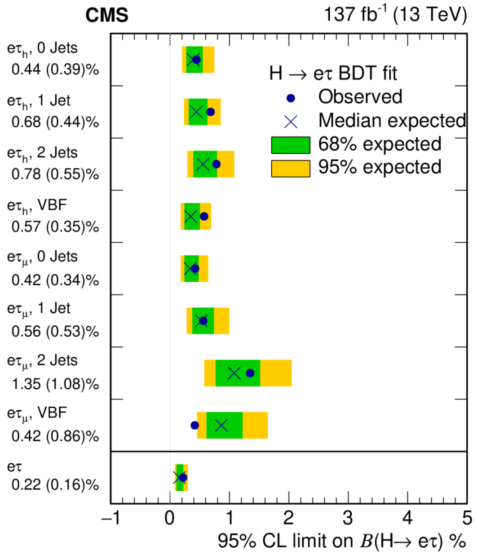
[Phys. Rev. D 104 (2021) 032013](https://doi.org/10.1103/PhysRevD.104.032013)

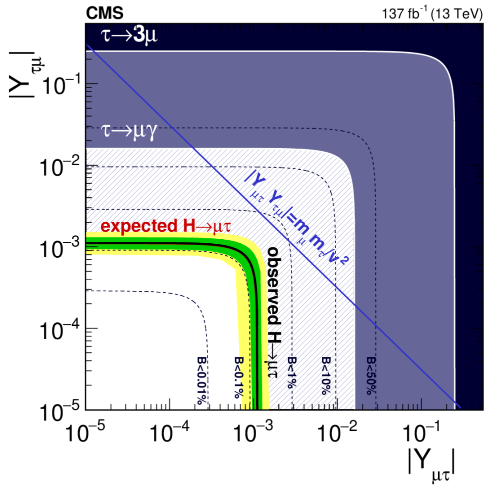
$h \to \mu\tau$ and $h \to e\tau$ Searches at CMS

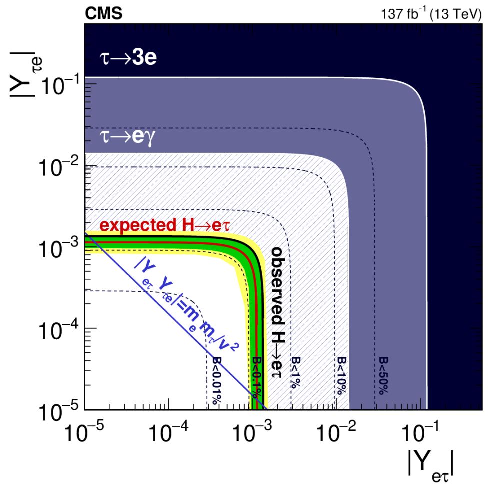
- No significant access has been found in both channels in CLFV higgs decays
- The observed (expected) limits on B($h \to \mu\tau$) = 0.15 (0.15) % and B($h \to e\tau$) = 0.22 (0.16) % at the 95% C.L.
- The results are dominated by the systematic uncertainties- bin-by-bin, mis-Id lepton background
- The off-diagonal Yukawa couplings are constrained using the branching ratios- $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|2} < 1.11 \times 10^{-3}$ and $\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 1.35 \times 10^{-3}$
- Improvement over previous CMS and ATLAS results

Limits	$h \to \mu\tau$ **(%)**	$h \to e\tau$ **(%)**
ATLAS JHEP06(2018)001	1.85 (1.24)	1.79 (1.73)
CMS Eur. Phys. J. C (2017) 77:70	0.25 (0.25)	0.61 (0.37)
CMS Phys. Rev. D 104 (2021) 032013	0.15 (0.15)	0.22 (0.16)







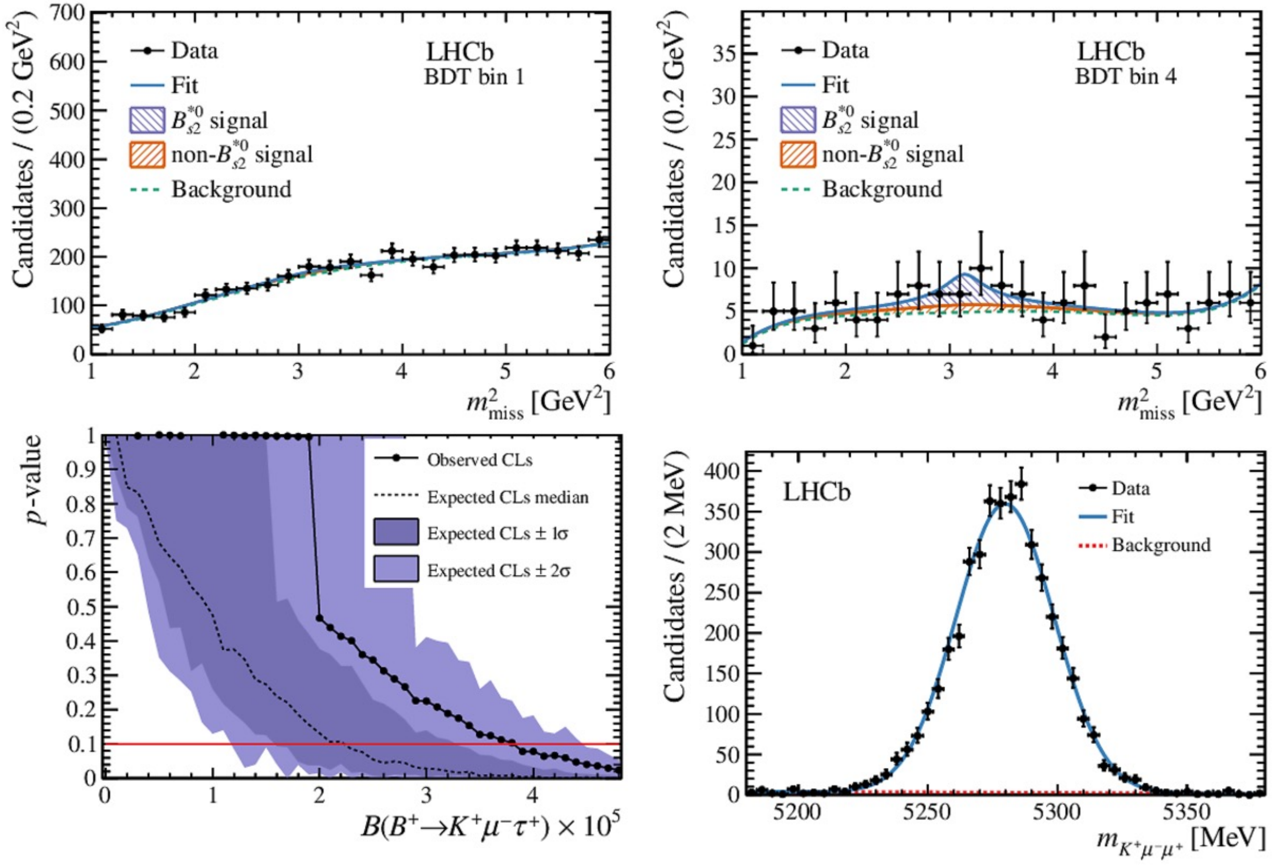


Phys. Rev. D 104 (2021) 032013

τ CLFV in B Meson Decays

CLFV in $B \to K^+\mu^-\tau^+$ Decays at LHCb

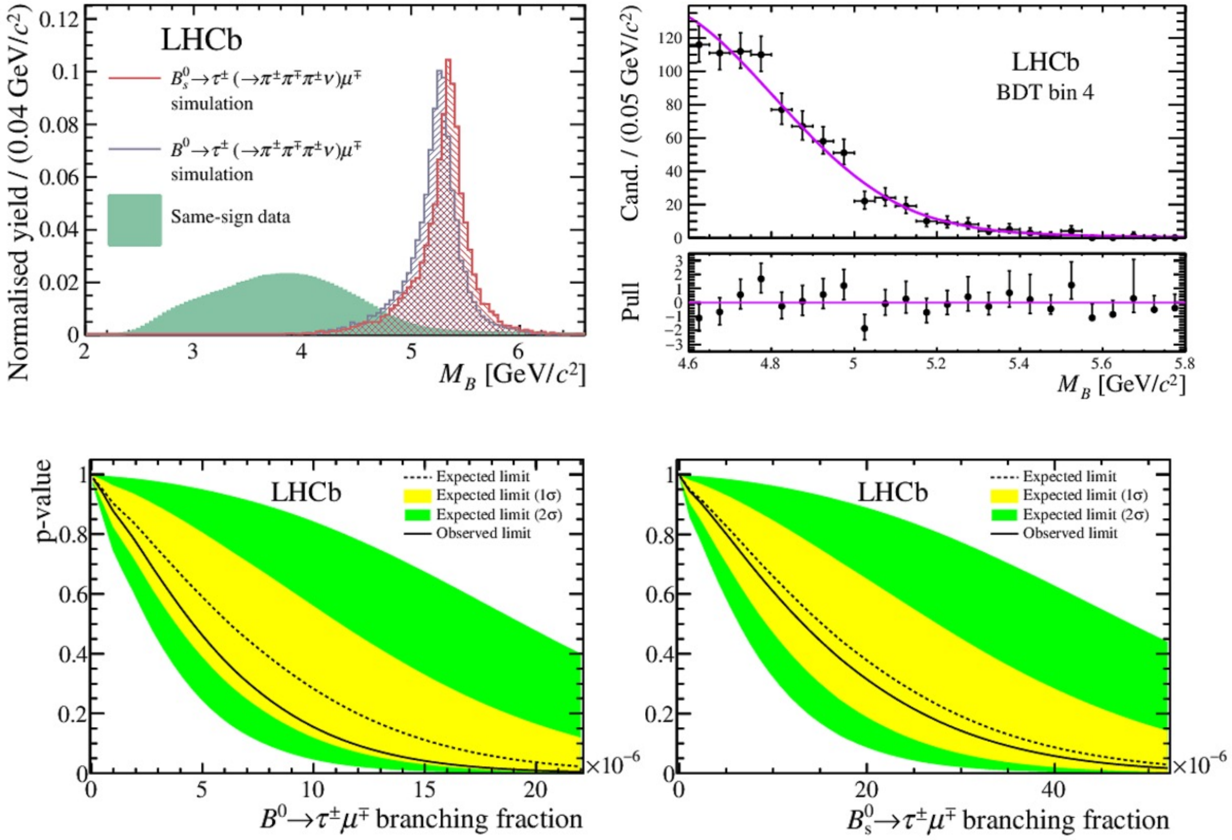
- CLFV decay of $B \to K\mu^{\pm}\tau^{\mp}$ can occur through many models such as leptoquarks with large branching ratio
- B+ candidates selected using $K^+\mu^-$ pairs with $m(K^+\mu^-) > 4.8$ GeV with a common vertex displaced from PV
- Four momenta of τ constructed using $B^{*0}_{s2} \to B^+K^-$ decays
- Signal normalized using $B^+ \to J/\psi K^+$ decays
- BDT classifiers are used to separate signal from background
- The fit to the signal is performed in 4 bins of the BDT output
- No significant excess is observed, the upper limit for $\mathcal{B}(B^+ \to K^+\mu^-\tau^+) <$ **3.9×10^{-5} at 90% C.L., 4.5×10^{-5} at 95% C.L.**
- Competitive with the limit set by BaBar: **$\mathcal{B}(B^+ \to K^+\mu^-\tau^+) <$ 2.8×10^{-5}** at 90% C.L.



JHEP 06 (2020) 129

CLFV in $B \to \mu\tau$ Decays at LHCb

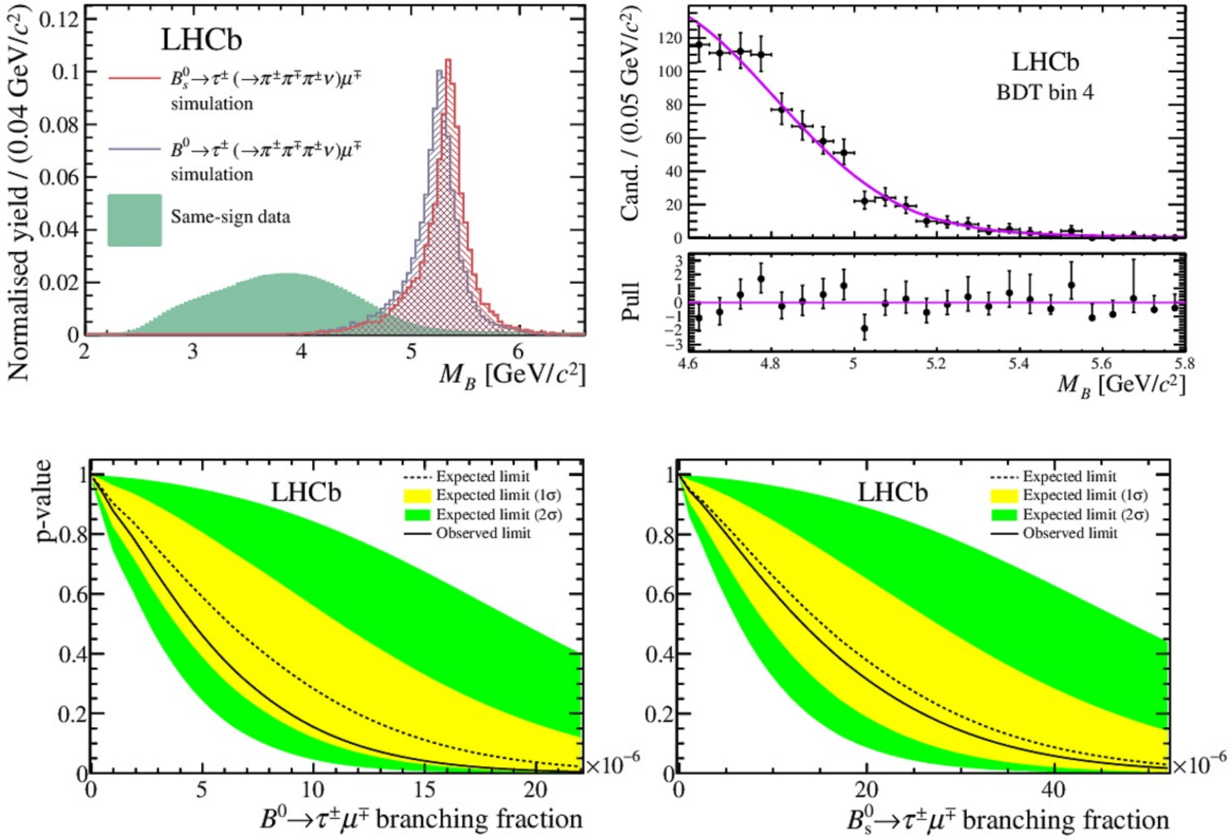
- τ candidates ($\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$) are selected using three tracks forming a common vertex
- The neutrino momentum is constrained using the measured position of PV and τ decay vertices, muon trajectory and the momenta of decay products
- A set of BDTs is used to discriminate signal from background
- Signal normalization performed by a maximum likelihood fit using $B^0 \to D^+(K^+\pi\pi)\pi^-$ channel



Phys.Rev.Lett. 123 (2019) 211801

CLFV in $B \to \mu\tau$ Decays at LHCb

- τ candidates ($\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$) are selected using three tracks forming a common vertex
- The neutrino momentum is constrained using the measured position of PV and τ decay vertices, muon trajectory and the momenta of decay products
- A set of BDTs is used to discriminate signal from background
- Signal normalization performed by a maximum likelihood fit using $B^0 \to D^+(K^+\pi\pi)\pi^-$ channel
- Assuming no contribution from $B^0 \to \mu^\mp\tau^\mp$, $\mathcal{B}(B^0_s \to \mu^\mp\tau^\mp) <$ 4.2×10^{-5} at 95% C.L.
- Assuming no contribution from $B^0_s \to \mu^\mp\tau^\mp$, $\mathcal{B}(B^0 \to \mu^\mp\tau^\mp) <$ 1.4×10^{-5} at 95% C.L.
- The first limits on $B^0_s \to \mu^\mp\tau^\mp$ search and the most stringent limits on $B^0 \to \mu^\mp\tau^\mp$

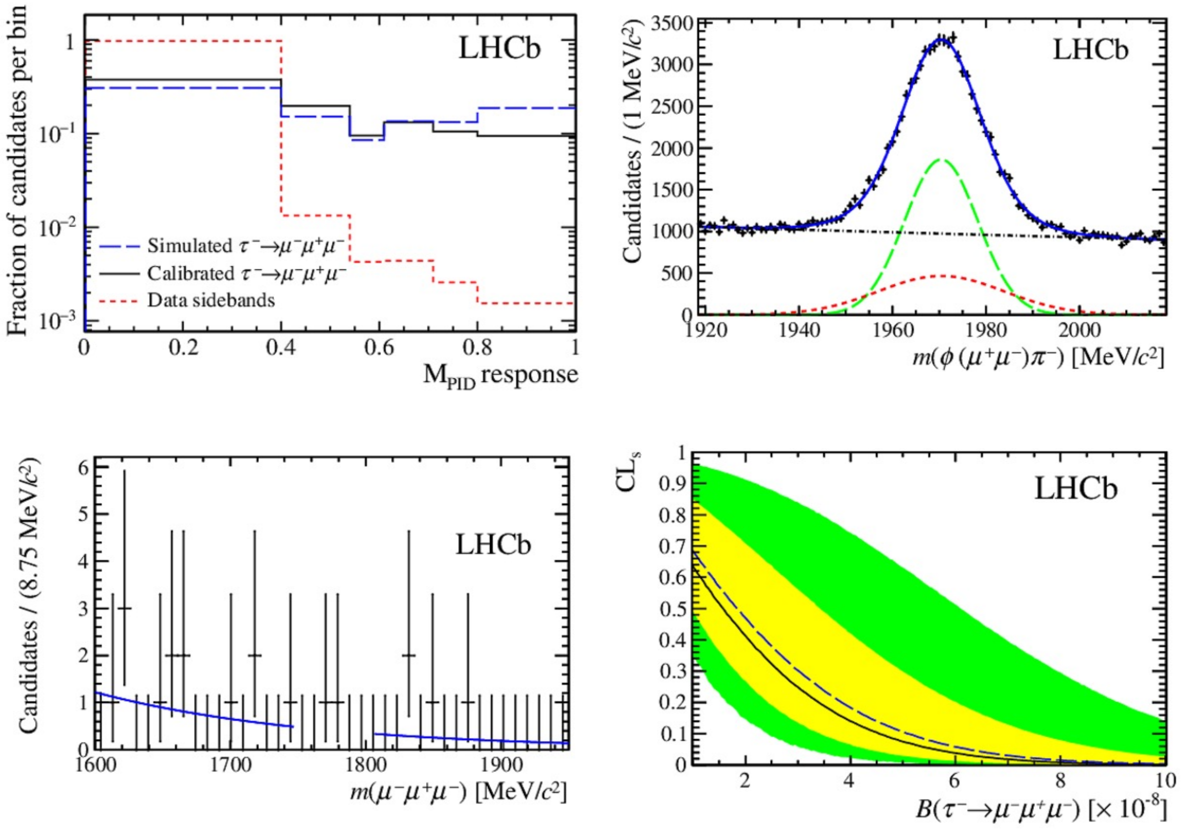


[Phys.Rev.Lett. 123 (2019) 211801]

CLFV $\tau \rightarrow \mu\mu\mu$ decay

$\tau \to \mu\mu\mu$ at LHCb

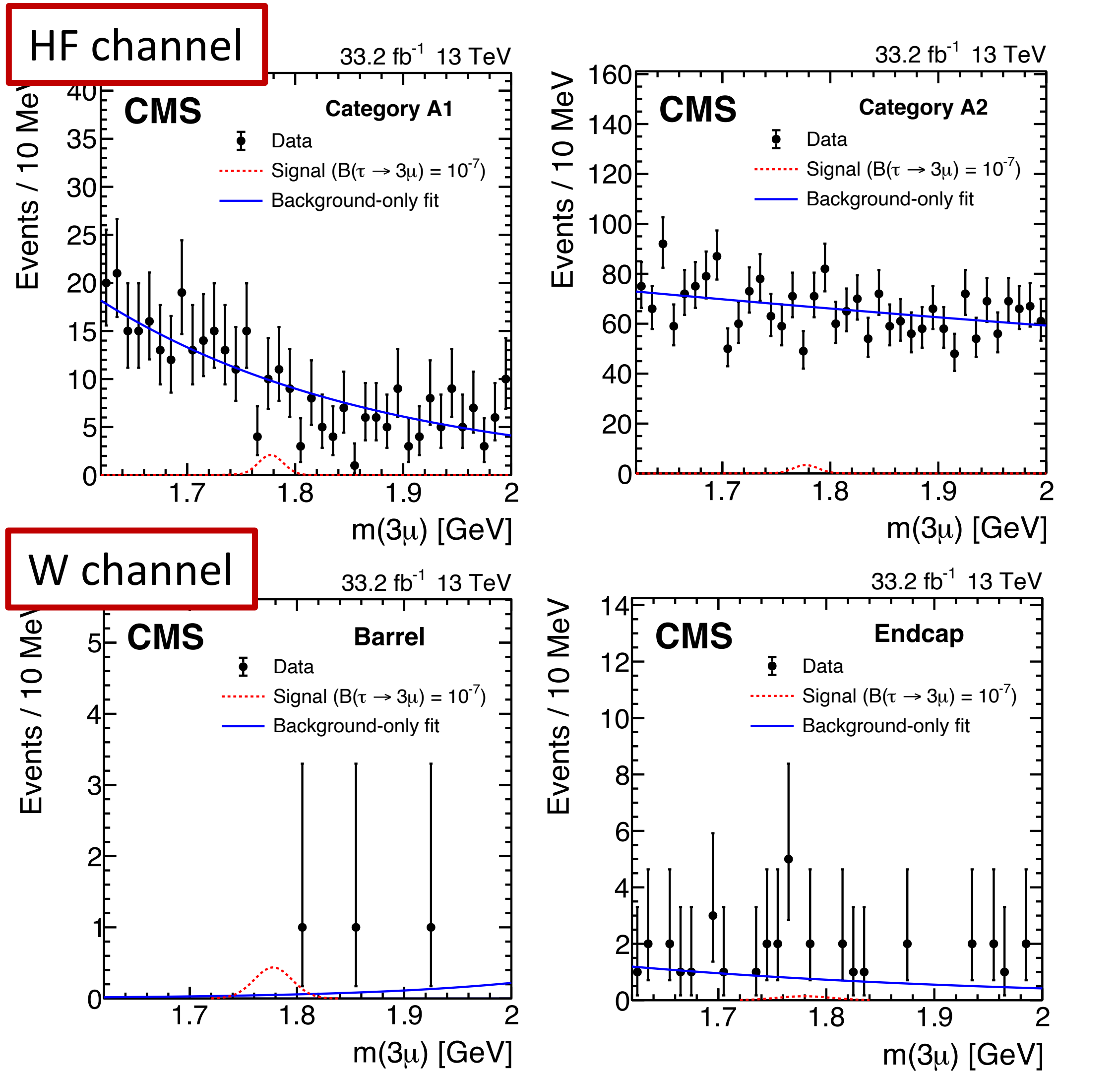
- τ candidates are formed by selecting three muons forming a displaced secondary vertex w.r.t. the primary vertex
- Signal normalization is performed using $D_s \to \Phi(\mu\mu)\pi$ channel
- MVA classifier used to perform signal background discrimination
  - M_{3body} : BDT classifier to reject background based on geometric and kinematic properties of the 3 body system
  - M_{PID} : NN based classifier to check the compatibility of tracks with the muon hypothesis
- Fits performed in different categories- events classified in different bins of MVA outputs (M_{3body}, M_{PID})
- Model independent upper limit for the branching ratio is set to B($\tau \to \mu\mu\mu$) < 4.6 x 10^{-8} at 90% C.L.
- Upper limit varies from B($\tau \to \mu\mu\mu$) < (4.1-6.8) x 10^{-8} depending on the choice of BSM operator



JHEP 02 (2015) 121

$\tau \rightarrow \mu\mu\mu$ at CMS

- Search performed in two channels – Heavy flavour (HF) and W channel
- Event preselection to reconstruct displaced $\tau \rightarrow \mu\mu\mu$ vertex
- Event categorized into different categories depending on the mass resolution of the tau candidate
- Further MVA based sub-categorization to improve the sensitivity
- Full Run 2 analysis is currently ongoing and the results are going to be released soon
  - 4 times more integrated luminosity
  - new pixel detector since 2017



[JHEP 01 (2021) 163](#)

Experiment	Observed (Expected) upper limit on B($\tau \rightarrow 3\mu$) (x 10^8 at 90% C.L.)
Belle	2.1 (-)
BaBar	3.3 (4.0)
LHCb (Run I data)	4.6 (5.0)
ATLAS (Run I data)	38 (39) Eur. Phys. J. C 76 (2016) 232
CMS	8.0(6.9)

Summary

- ATLAS, CMS and LHCb have published good results, setting the most stringent limits on some of the channels of CLFV tau decays.
- While the others are very competitive the best limits.
- Run 3 and beyond is going to be an exiting era for CLFV searches at LHC. Stay tuned for more interesting results!

Summary

- ATLAS, CMS and LHCb have published good results, setting the most stringent limits on some of the channels of CLFV tau decays.
- While the others are very competitive the best limits.
- Run 3 and beyond is going to be an exiting era for CLFV searches at LHC. Stay tuned for more interesting results!

Thank you!

Backup

$Z \to \mu\tau$ and $Z \to e\tau$ Searches at ATLAS

Selection criterion	Purpose
Exactly two isolated light leptons (ℓ_0, ℓ_1) with opposite electric charge and different flavor (e or μ); $p_T(\ell_0) > p_T(\ell_1)$	Select events consistent with signal decays.
No $\tau_{\text{had-vis}}$ candidate	Orthogonality with $\ell\tau_{\text{had}}$ channel.
Transverse mass[1] $m_T(\ell_1, E_T^{\text{miss}}) < 35$ GeV $\lvert\Delta\phi(\ell_0, E_T^{\text{miss}})\rvert > 1$ rad No b-tagged jets (using the 77% efficiency working point)	Reject top-quark and diboson events.
Invariant mass of the ℓ_0–ℓ_1 pair $m(\ell_0, \ell_1) > 40$ GeV	Reject events incompatible with Z-boson decays.
Neural network (optimized for signal vs. $Z \to \tau\tau$) output > 0.2	Ensure selection is orthogonal to the CRZ$\tau\tau$ region.
In $\mu\tau_e$ channel: $p_T^{\text{track}}(e)/p_T^{\text{cluster}}(e) < 1.1$	Reject $Z \to \mu\mu$ events.

Source of uncertainty	Uncertainty in $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$] $e\tau$	$\mu\tau$
Statistical	±2.5	±2.3
Systematic	±1.8	±1.2
$\tau_{\text{had-vis}}$ candidates	±1.1	±1.1
Light leptons	±0.4	±0.2
E_T^{miss}, jets and flavor tagging	±1.1	±0.7
E_T^{miss}	±0.2	±0.2
Jets	±1.0	±0.7
Flavor tagging	±0.3	±0.3
Z-boson modeling	±0.6	±0.1
$Z \to \ell\ell$	±0.1	±0.2
Luminosity	±0.2	<0.1
Other minor backgrounds	±0.4	±0.3
Fake leptons	±0.2	±0.3
Total	±3.0	±2.8

Variable	Description
$p_z(\ell_1)$	z-component of the leading-p_T lepton's momentum.
$E(\ell_1)$	Energy of the leading-p_T lepton.
$p_x(\ell_2)$	x-component of the subleading-p_T lepton's momentum.
$p_z(\ell_2)$	z-component of the subleading-p_T lepton's momentum.
$E(\ell_2)$	Energy of the subleading-p_T lepton.
E_T^{miss}	The missing transverse momentum.
$m(e, \mu)$	The invariant mass of the e–μ system.
$m_{\text{coll}}(e, \mu)$	The collinear mass: the invariant mass of the e–μ–ν system, where the ν is assumed to have a momentum that is equal in the transverse plane to the measured E_T^{miss} and collinear in η with the subleading-p_T lepton.
$\Delta\alpha$	A kinematic discriminant sensitive to the different fractions of τ-lepton four-momentum carried by neutrinos in signal and background .