Flavor at High P_T Frontier: Higgs, Z, Top and FCNC

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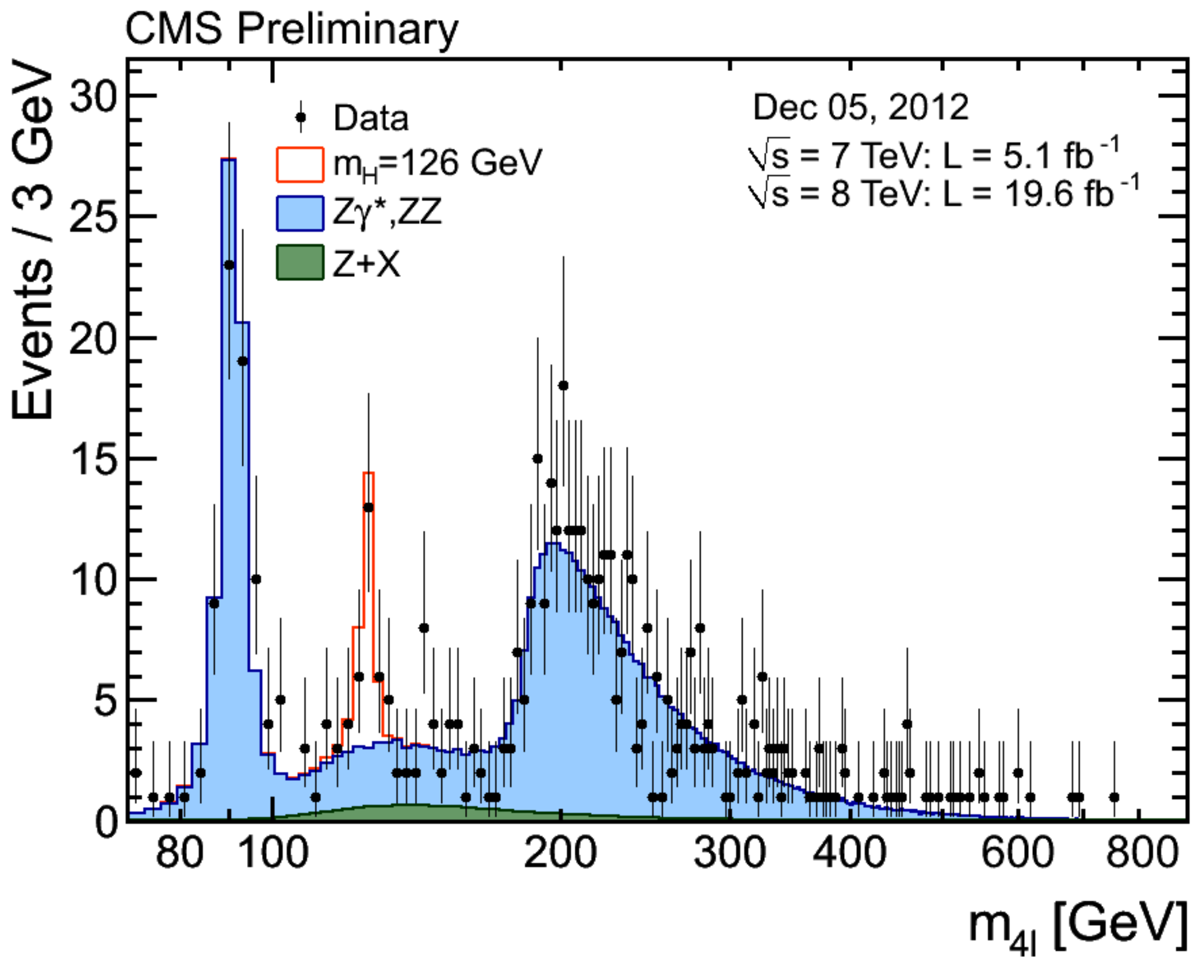
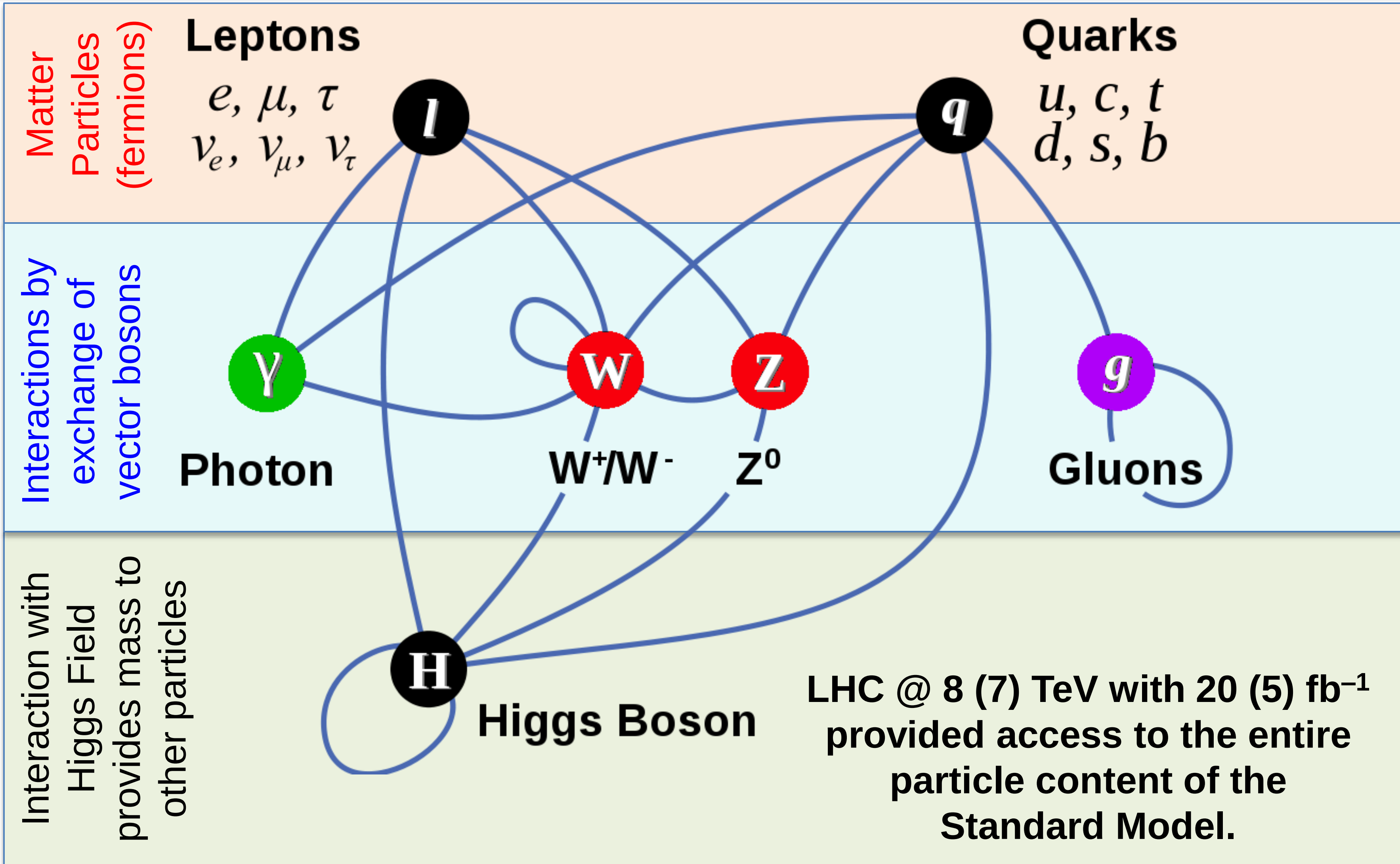
For CMS Collaboration



Completion of The Standard Model



Flavor Change in the SM

GIM mechanism used to suppress flavor changing neutral currents

Mixing matrices for quarks (CKM) and neutrinos (PMNS) result in complex phenomenology

Charged lepton flavor is conserved, although there is no known fundamental symmetry requiring it

Fertile ground for exploring new physics in rare processes due to LFV models (ex. R violating SUSY)

For example, neutrino mixing induced lepton flavor changing decay **BR($Z \rightarrow e\mu$) is 4x10^{-60}**, its ***observation immediately implies new physics!***

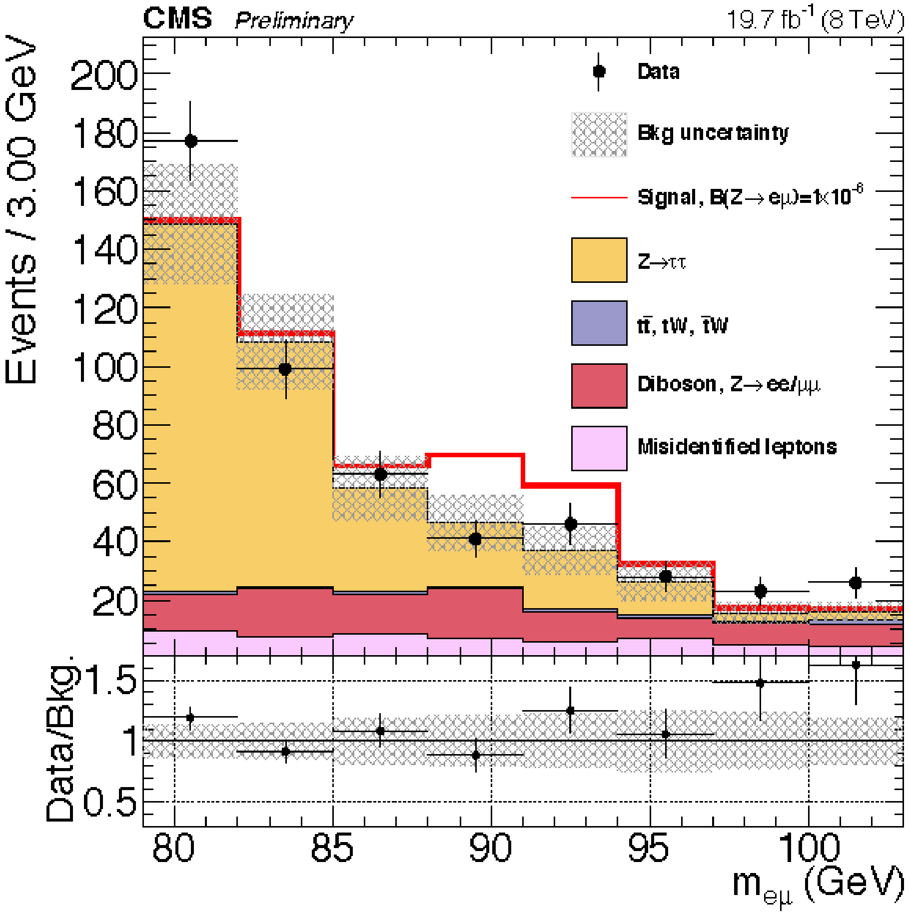
CMS Search for Z→eμ

CMS-PAS-EXO-13-005

Invariant mass of **eμ** consistent with smoothly falling BKG dominated by Z→ττ→eμνννν

Limit set at 95% CL for **BR(Z→eμ) < 7.3 x 10^{-7}** (expected 6.7 x 10^{-7})

Indirectly derived limit from μ→3e is 5 x 10^{-13}



FCNC & Top

Top quark is the most massive

- Top does not have time to form hadrons
- Provides most pristine of quark environments, with reduced QCD corrections, for FCNC search
- GIM suppressed t→Zq BR prediction: O(10^{-14})
- Again, observation → new physics
- Possible R-parity violating SUSY models …
  - Predictions of t→Zq BR range are of O(10^{-5})

Search for pp→tt→WbZq

PRL112,171802(2014)

Pre-selected events with leptonic Z and W decays:

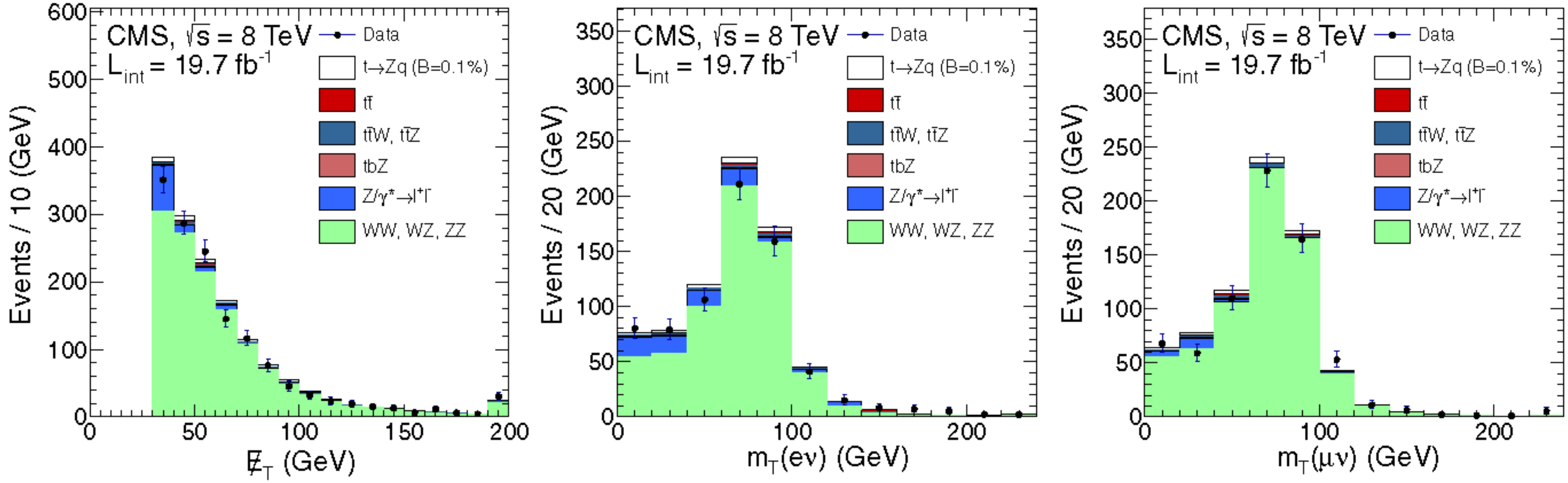


FIG. 1 (color online). Comparison between data and simulated events for an integrated luminosity of 19.7 fb^{-1}, after the basic event selection, for the $\not{E}_T$ distribution (left), the reconstructed $e\nu$ transverse mass (middle) of the W-boson candidate, and the reconstructed $\mu\nu$ transverse mass (right) of the W-boson candidate. The data are represented by the points with error bars, and the open histogram shows the expected signal assuming $\mathcal{B}(t \to Zq)$ is equal to 0.1%. Stacked solid histograms represent the dominant backgrounds, with statistical uncertainties on these backgrounds at the few percent level (not shown).

Search for pp→tt→WbZq

PRL112,171802(2014)

Pre-selected events with leptonic Z and W decays:

- Final selection requiring two jets (one b-tagged)

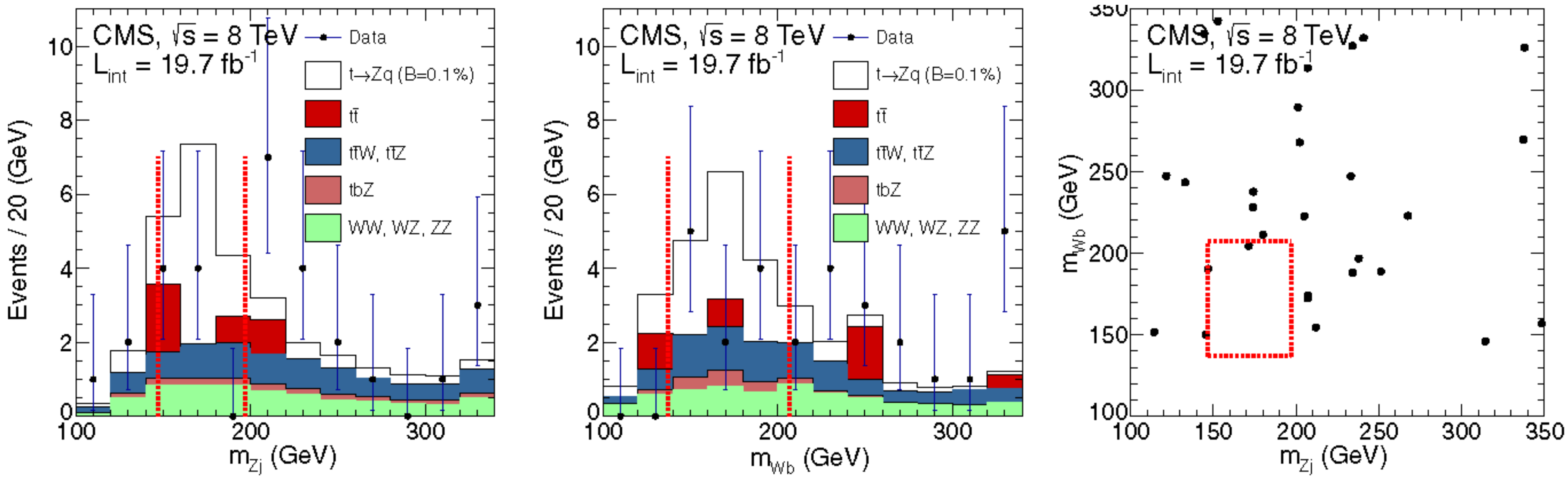


FIG. 2 (color online). Comparison between data and simulated events of the m_{Zj} (left), m_{Wb} (middle), and two-dimensional scatter (right) distributions after the event selection prior to the top-quark mass requirements, which are shown as the dotted vertical lines (left, middle) and box (right). The data, corresponding to an integrated luminosity of 19.7 fb^{-1}, are represented by the points with error bars and the open histogram is the expected signal. The stacked solid histograms represent the dominant backgrounds. The statistical uncertainties are not drawn. The last bin in each of the left two plots contains all the overflow events.

BR(t→Zq) Limit

PRL112,171802(2014)
PLB 718 (2013)

Beginning to probe the interesting range for some new physics models

- Awaiting 13 TeV data → large top cross section

TABLE IV. Upper limits at a 95% C.L. for $\mathcal{B}(t \to Zq)$, as obtained using the 8 TeV data with an integrated luminosity of 19.7 fb^{-1}, and from the combination with previous CMS 7 TeV (5.0 fb^{-1}) data.

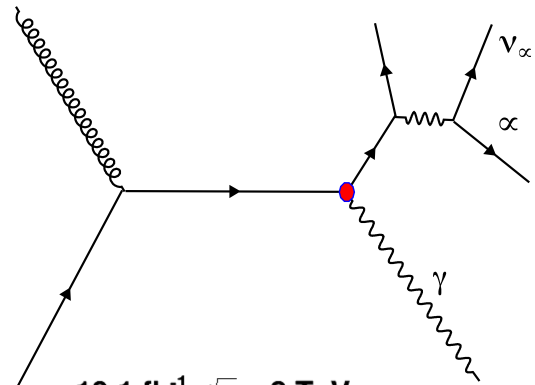
$\mathcal{B}(t \to Zq)$	8 TeV	7 + 8 TeV
Expected upper limit	$< 0.10\%$	$< 0.09\%$
Observed upper limit	$< 0.06\%$	$< 0.05\%$
1σ boundary	0.06–0.13%	0.06–0.13%
2σ boundary	0.05–0.20%	0.05–0.18%

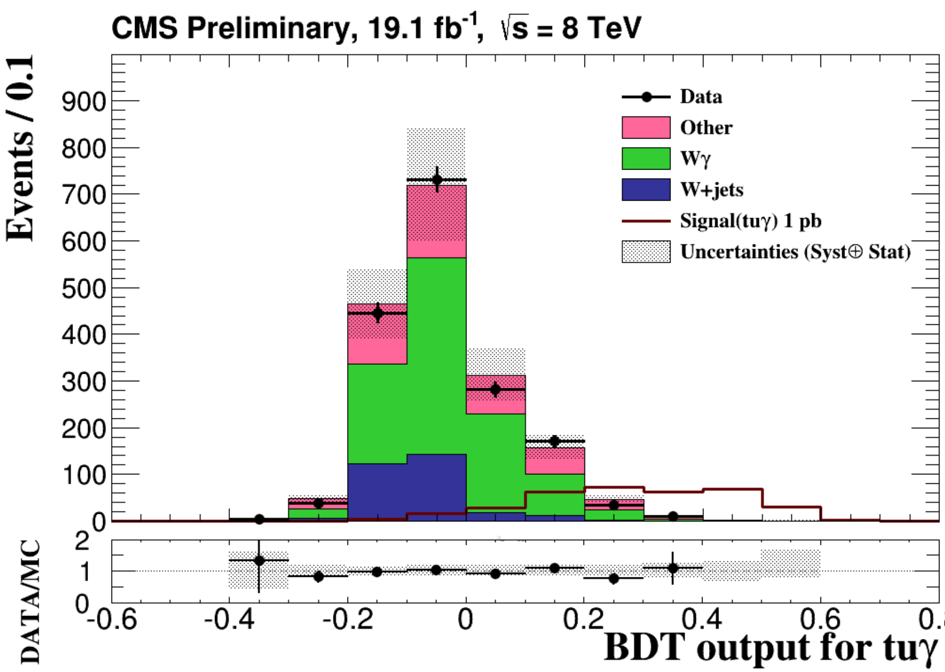
Top-Photon associated production

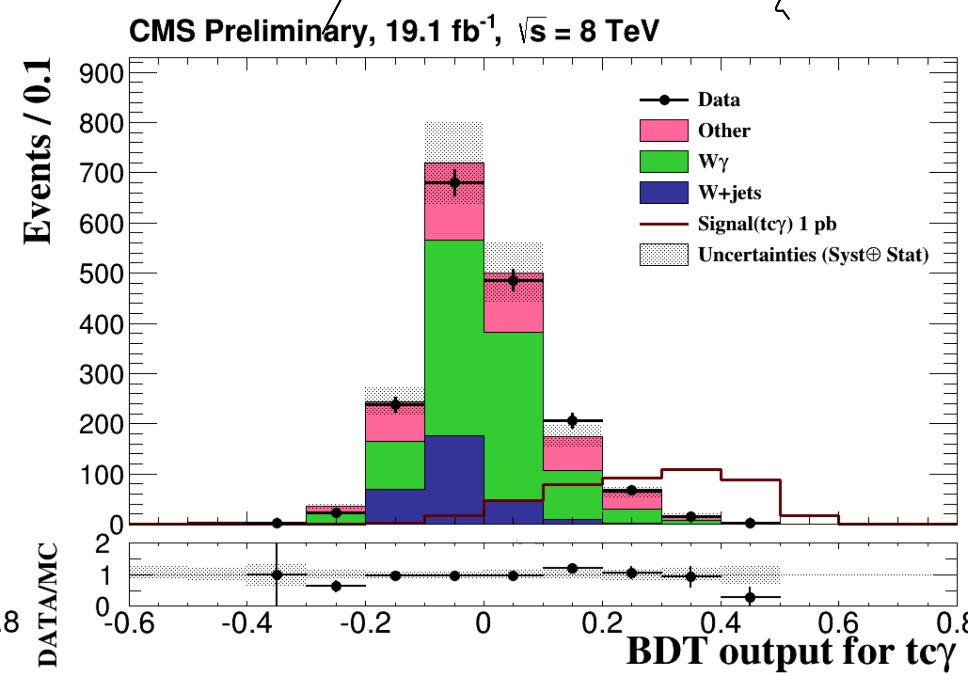
CMS PAS TOP-14-003

Flavor changing tuγ and tcγ coupling

- Select events with μ, b, γ
- BDT using kinematic variables

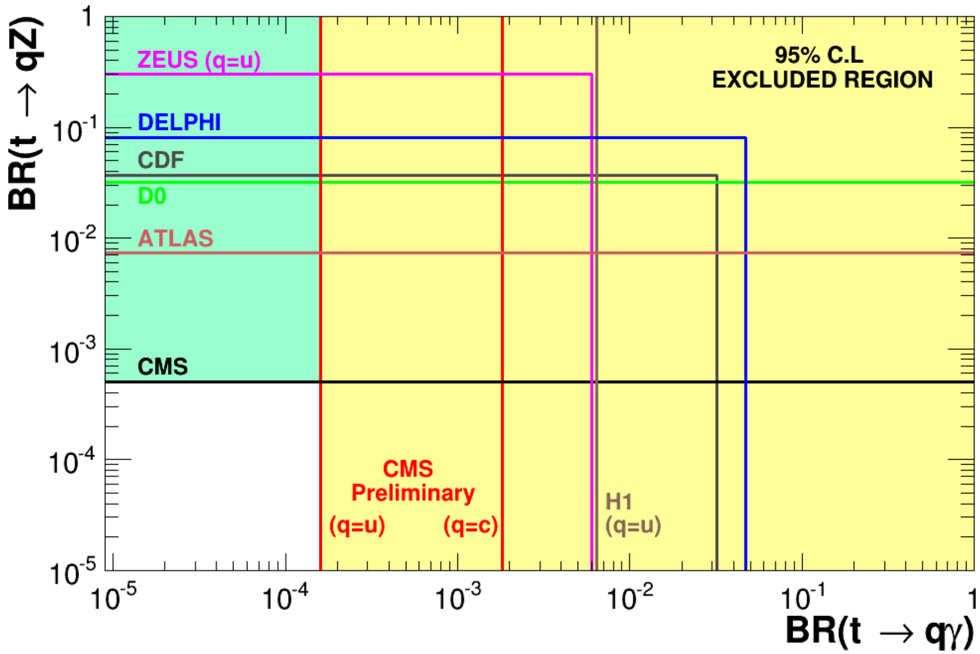






$t \rightarrow q\gamma$ Limits & FCNC in Top

	Exp. limit (LO)	Obs. limit (LO)	Exp. limit (NLO)	Obs. limit (NLO)
$\sigma_{tu\gamma} \times Br(W \rightarrow l\nu_l)$	0.0404 pb	0.0234 pb	0.0408 pb	0.0217 pb
$\sigma_{tc\gamma} \times Br(W \rightarrow l\nu_l)$	0.0411 pb	0.0281 pb	0.0410 pb	0.0279 pb
$\kappa_{tu\gamma}$	0.0367	0.0279	0.0315	0.0229
$\kappa_{tc\gamma}$	0.113	0.094	0.0790	0.0652
$Br(t \rightarrow u\gamma)$	0.0279%	0.0161%	0.0205%	0.0108%
$Br(t \rightarrow c\gamma)$	0.261%	0.182%	0.193%	0.132%



Approaching interesting territory at 10^{-5} and below

BSM Single Top Production Using tug & tcg couplings

CMS-PAS-TOP-14-007

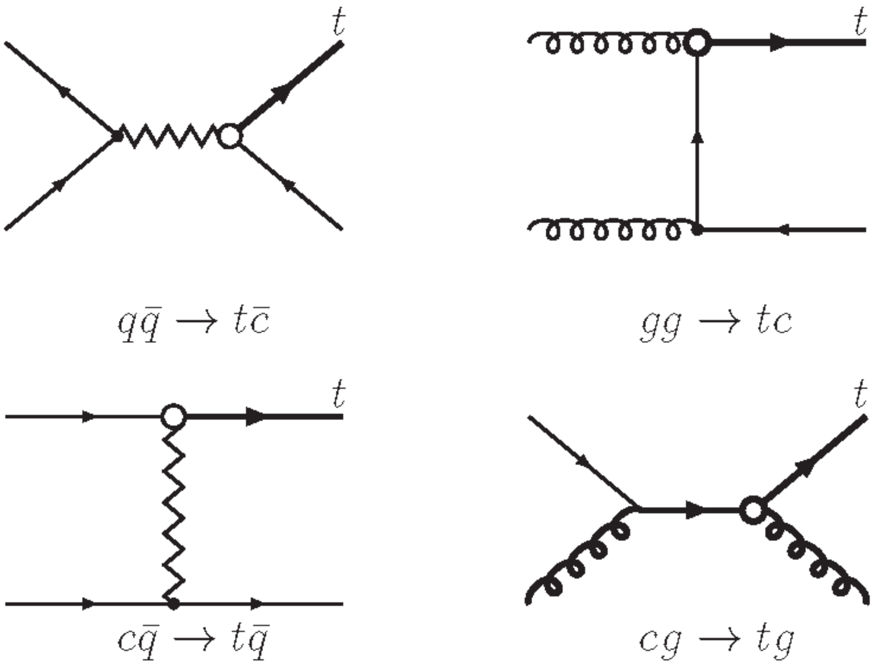
BSM flavor changing tug and tcg couplings

- Increased rate and distinct kinematics

$$\mathcal{L} = \frac{\kappa_{tqg}}{\Lambda} g_s \bar{f} \sigma^{\mu\nu} \frac{\lambda^a}{2} t G^a_{\mu\nu}$$

$$\Lambda \sim \mathcal{O}(TeV)$$

Strong production from tcg
Similarly, tug; 48 diagrams



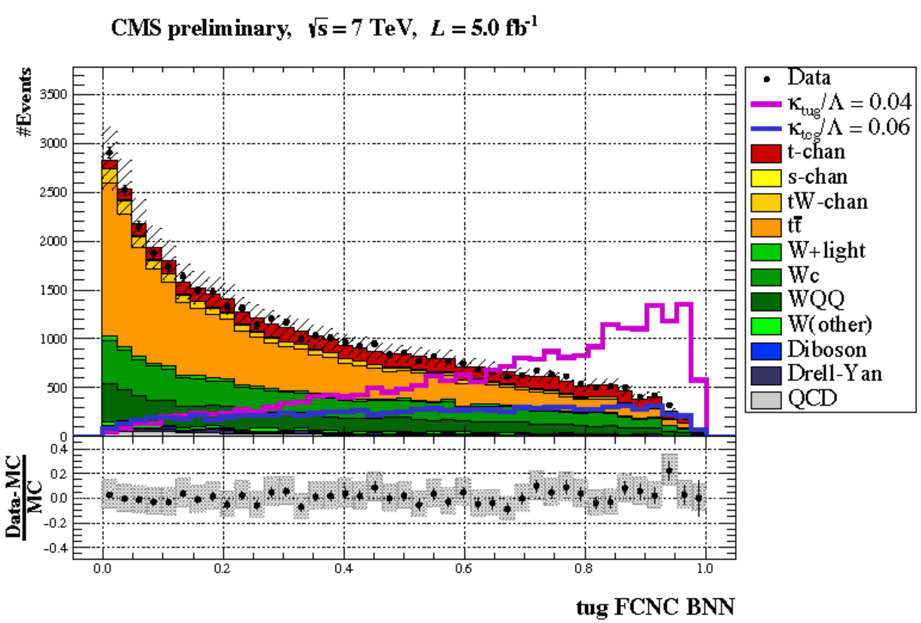
- Search for deviations from SM production
- Significant top-pair background

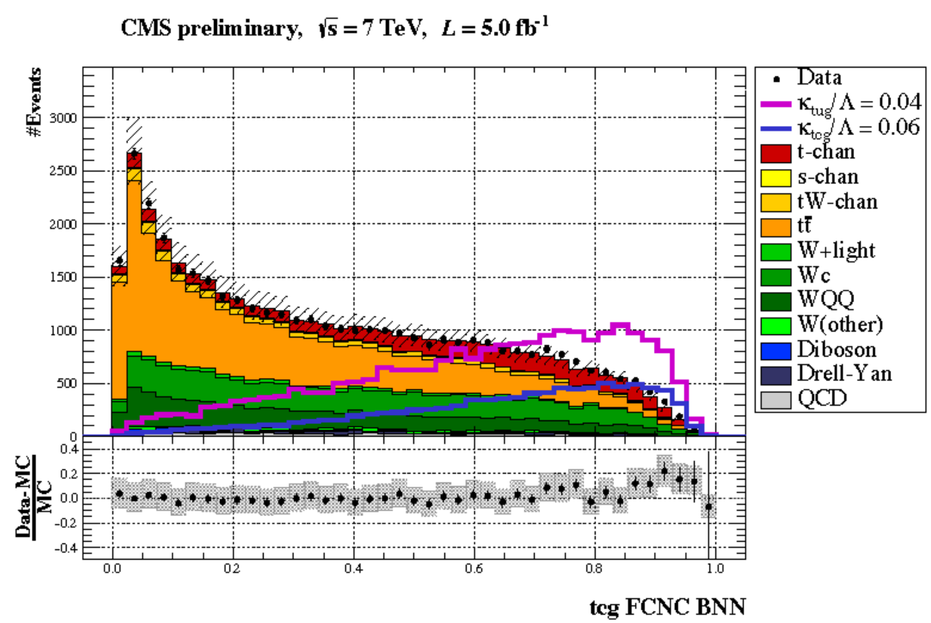
Neural Nets Trained For tug & tcg

CMS-PAS-TOP-14-007

Selected top decays in muon mode with a b-tag jet

- Several kinematic variables used to train neural nets separately for tug and tcg cases to discriminate against SM BG (top-pair dominant)





Limits on FCNC tug & tcg Couplings

CMS-PAS-TOP-14-007

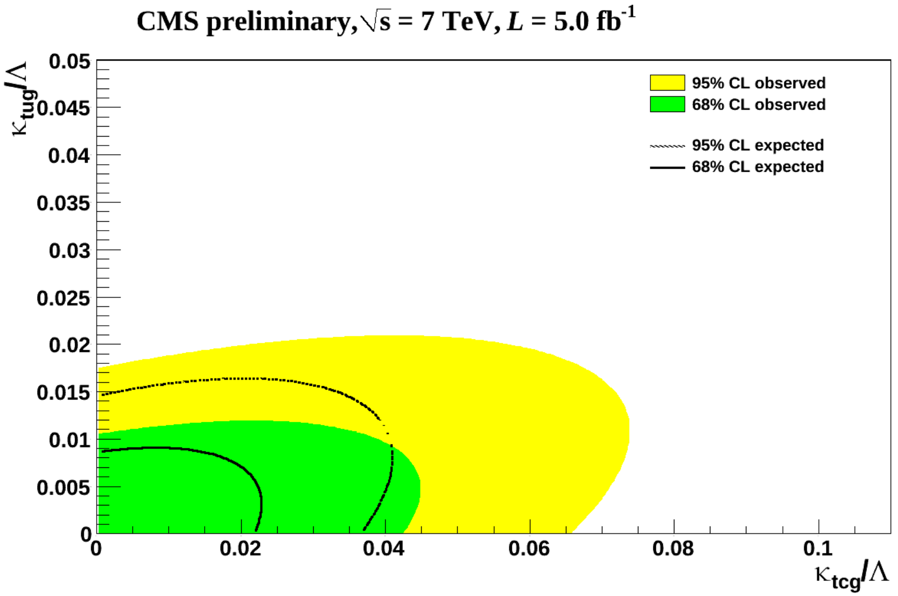
Observed (expected) exclusion limits @ 95% CL are:

- $\kappa_{tug}/\Lambda < 1.8\times 10^{-2}$ (1.2×10^{-2}) TeV^{-1}
- $\kappa_{tcg}/\Lambda < 5.6 \times 10^{-2}$ (3.1×10^{-2}) TeV^{-1}

Branching fraction limits:

- BR(t → u+g) < 3.55×10^{-4} (1.58×10^{-4})
- BR(t → c+g) < 3.44×10^{-3} (1.05×10^{-3})

Individual exclusion limits on κ_{tug}/Λ are obtained by fixing κ_{tcg}/Λ to zero and vice versa.



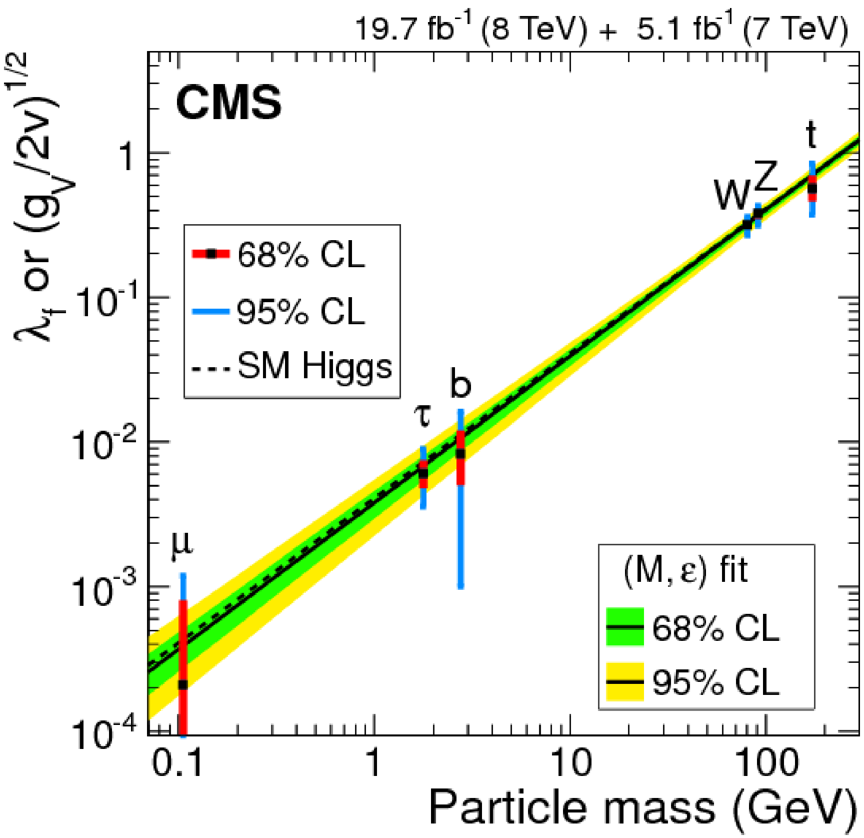
The Minimal Higgs Sector of SM

The single complex scalar doublet

- A scalar boson discovered (m_H ~ 125 GeV)!
- Fermion masses through couplings to Higgs field

$$\mathcal{L}_{Y_i} = y_i h f_L^i f_R^i + h.c. \text{ with } y_i = \frac{m_i}{v}$$

  - Coupling strength proportional to mass
  - Flavor diagonal
- Percent level LFV & FCNC could be looked for



It appears to couple like the SM Higgs

Flavor Changing Higgs Coupling Search for t→qH(→γγ)

New CMS PAS TOP-14-019

Hadronic

	$t \to cH$	$t \to uH$	Data [events]
two photons	34.2 %	34.2 %	505408
≥ 4 jets and = 1 b-tagged jet	7.6 %	8.0 %	862
$158 \leq M_1 \leq 202$ GeV, $142 \leq M_2 \leq 222$ GeV	3.0 %	3.4 %	112
$44 \leq M_w \leq 140$ GeV	2.7 %	3.1 %	83
$100 \leq M_{\gamma\gamma} \leq 180$ GeV	2.7 %	3.1 %	29
expected yields for $\mathcal{B}$ (t → c(u)H) = 1%	6.26 ± 0.07 (stat.)	7.09 ± 0.08 (stat.)	-

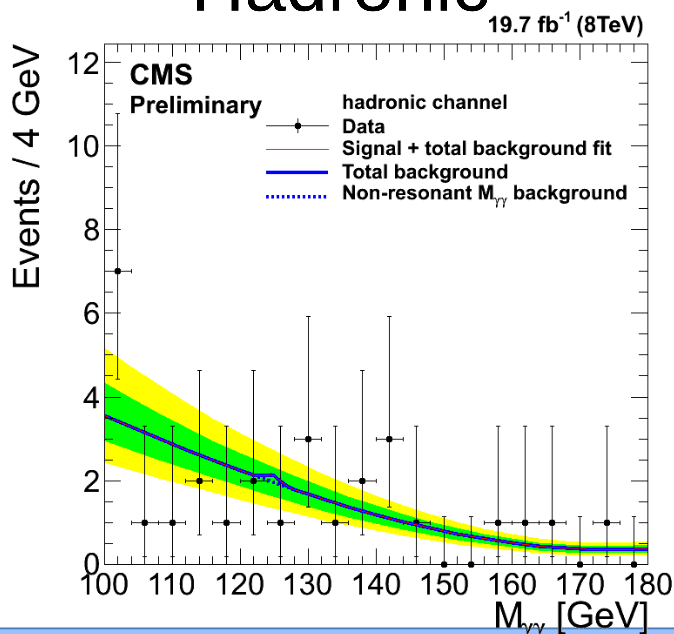
Leptonic

	$t \to cH$	$t \to uH$	Data [events]
two photons	34.2 %	34.2 %	505408
≥ 2 jets and = 1 b-tagged jet	16.0 %	16.1 %	6644
≥ 1 lepton	2.8 %	2.8 %	402
$158 \leq M_1 \leq 202$ GeV, $142 \leq M_2 \leq 222$ GeV	0.8 %	0.9 %	41
$100 \leq M_{\gamma\gamma} \leq 180$ GeV	0.8 %	0.9 %	8
expected yields for $\mathcal{B}$ (t → c(u)H) = 1%	1.91 ± 0.04 (stat.)	2.02 ± 0.04 (stat.)	-

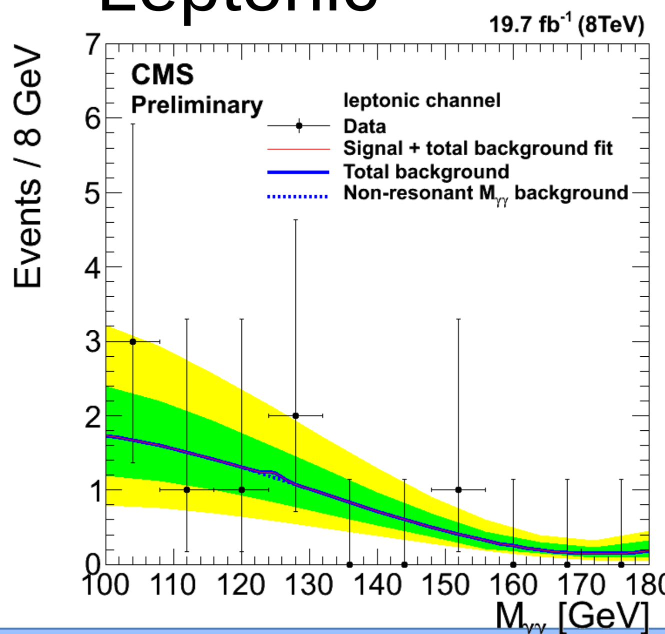
Flavor Changing Higgs Coupling Search for t→qH(→γγ)

	Hadronic channel	Leptonic channel
Data	29	8
Resonant diphoton background	0.152 ± 0.021 (stat.)	0.038 ± 0.008 (stat.)
Non-resonant diphoton background	28.9 ± 5.4 (stat.)	8.0 ± 2.8 (stat.)
expected signal yields for $\mathcal{B}$ (t → cH) = 1%	6.26 ± 0.07 (stat.)	1.91 ± 0.04 (stat.)
expected signal yields for $\mathcal{B}$ (t → uH) = 1%	7.09 ± 0.08 (stat.)	2.02 ± 0.04 (stat.)

Hadronic



Leptonic



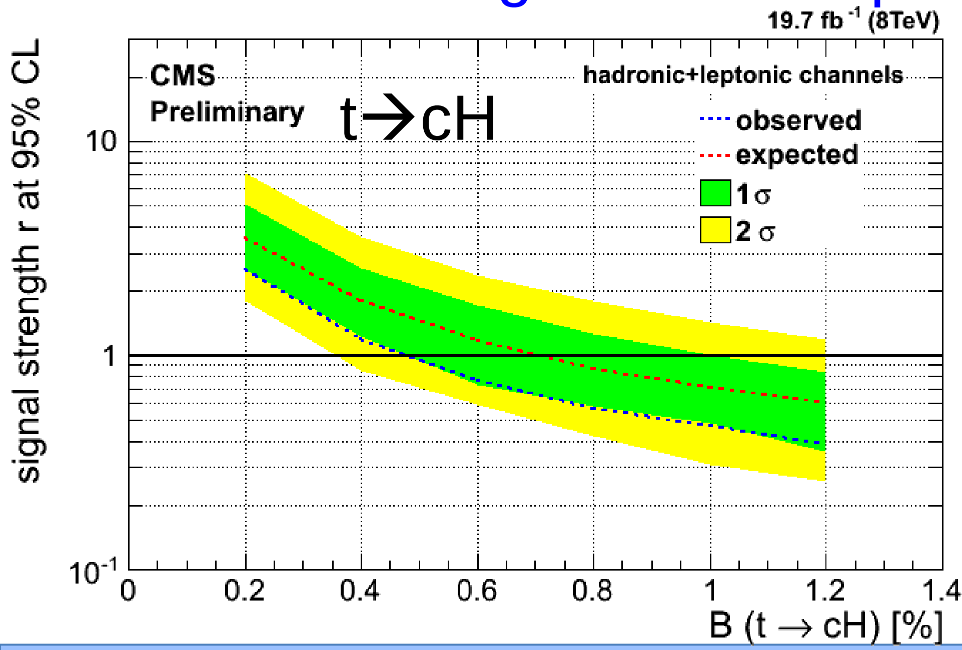
New CMS PAS TOP-14-019

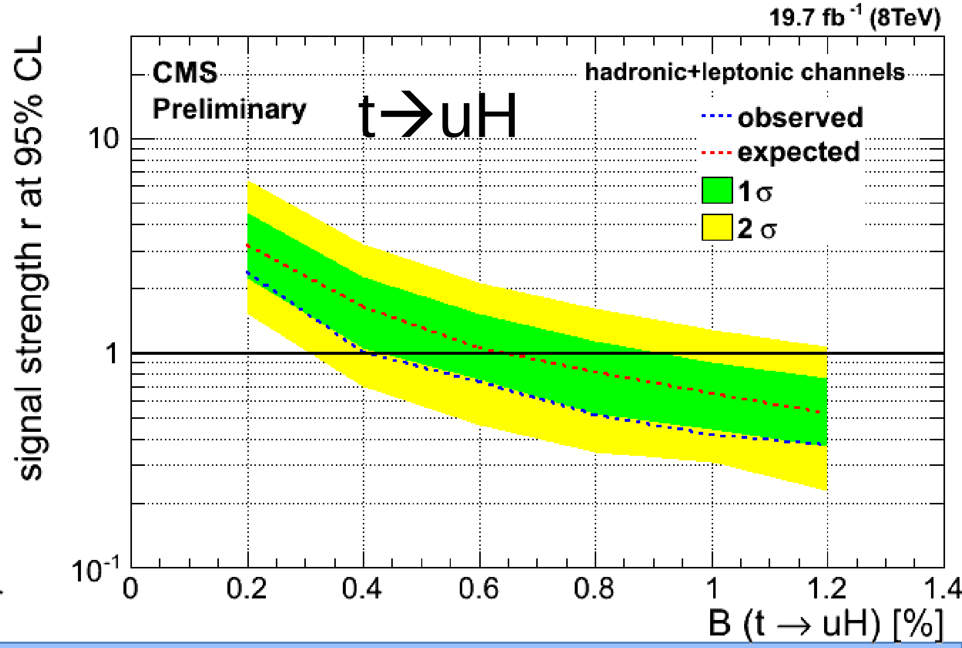
Flavor Changing Higgs Coupling Search for t→qH(→γγ)

New CMS PAS TOP-14-019

Combined hadronic and leptonic channels

- Upper limit for BR(t→cH) is 0.47% @ 95% CL
- Upper limit for BR(t→uH) is 0.42% @ 95% CL
  - Both tighter than expected

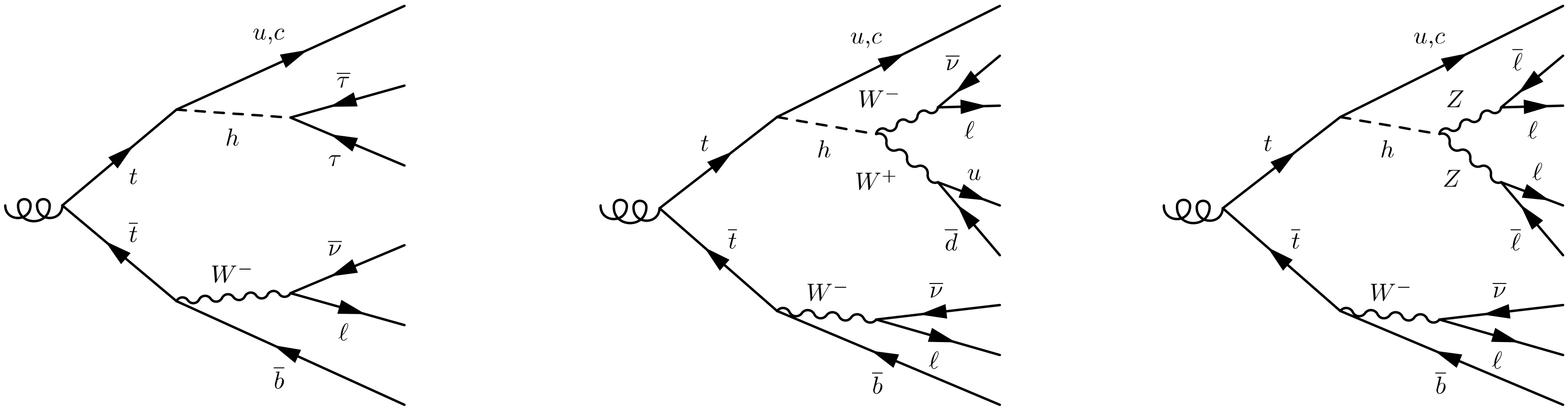




Flavor Changing Higgs Coupling Contribution to Multilepton Events

New CMS PAS TOP-13-017

Higgs mediated decay to ττ, WW, ZZ in leptonic states

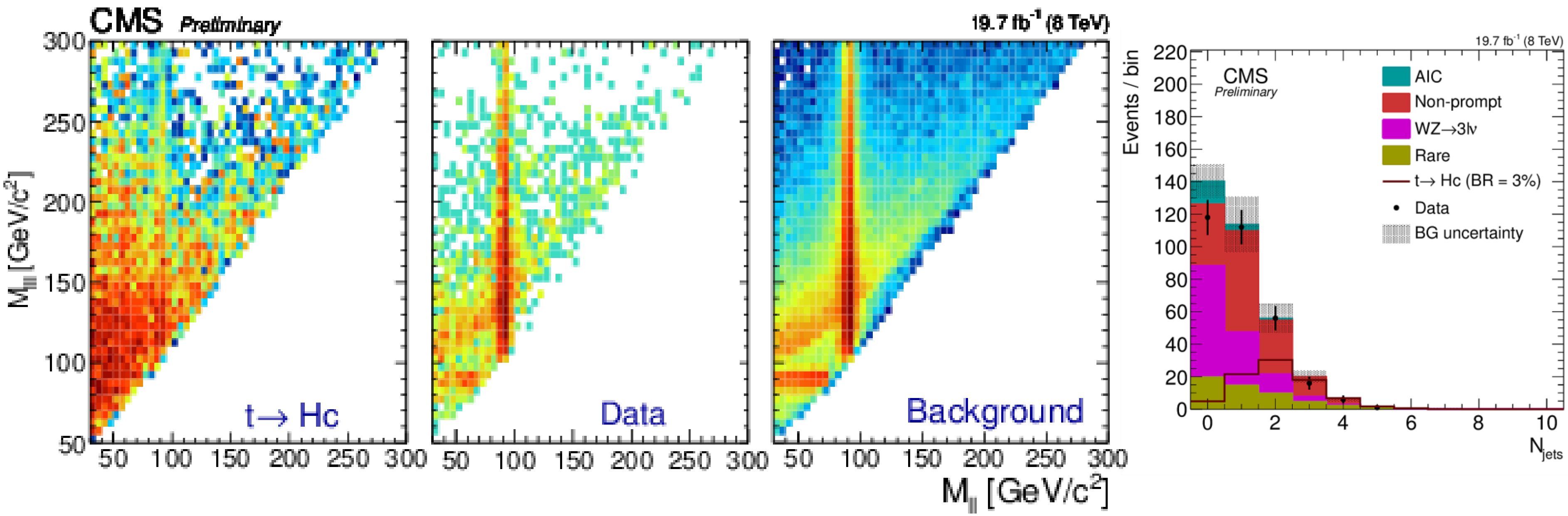


Flavor Changing Higgs Coupling Trilepton Analysis

New CMS PAS TOP-13-017

Higgs mediated decay to $\tau\tau$, WW, ZZ in leptonic states

- Three or more leptons & same sign leptons
- Z-removal important
- Further improve with 2-jet requirement



Flavor Changing Higgs Coupling Results : t→Hc < 1% @ 95% CL

New CMS PAS TOP-13-017

Observed yields consistent with SM

Three lepton case →

process	trilepton	Z removal	$\geq$ 2 jets
Rare	380.4 ± 11.9	54.3 ± 2.1	19.6 ± 1.4
$WZ \to 3l\nu$	1451.9 ± 93.4	117.0 ± 7.6	15.8 ± 1.1
Non-prompt	613.4 ± 97.3	148.8 ± 25.7	49.4 ± 9.0
BG	2598.3 ± 135.5	339.4 ± 27.0	86.2 ± 9.3
Observed	2555	309	79
$FCNH \to WW$	27.9 ± 1.9	21.0 ± 1.5	14.4 ± 1.1
$FCNH \to \tau\tau$	9.1 ± 0.6	6.4 ± 0.4	4.4 ± 0.3
$FCNH \to ZZ$	2.9 ± 0.2	0.5 ± 0.0	0.4 ± 0.0

Same-sign di-lepton case ↓

process	same-sign dilepton	Z removal	$\geq$ 2 jets	MET-dependendent HT
Rare	512.3 ± 12.9	495.6 ± 12.5	225.5 ± 9.7	128.1 ± 6.4
$WZ \to 3l\nu$	1080.1 ± 68.4	1041.9 ± 66.0	242.2 ± 15.4	83.9 ± 5.4
Charge MisID	4407.3 ± 881.7	521.1 ± 104.3	101.6 ± 20.3	32.1 ± 6.4
Non-prompt	10644.2 ± 1574.7	10493.7 ± 1568.4	1561.4 ± 248.9	409.8 ± 72.3
BG	16643.9 ± 1806.3	12552.3 ± 1573.5	2130.7 ± 250.6	654.3 ± 73.1
Observed	16790	12686	2032	631
$FCNH \to WW$	307.8 ± 19.2	295.4 ± 18.4	246.2 ± 15.4	112.2 ± 7.1
$FCNH \to \tau\tau$	82.0 ± 5.1	79.4 ± 4.9	65.0 ± 4.0	30.8 ± 1.9
$FCNH \to ZZ$	3.4 ± 0.2	3.2 ± 0.2	2.9 ± 0.2	1.1 ± 0.1

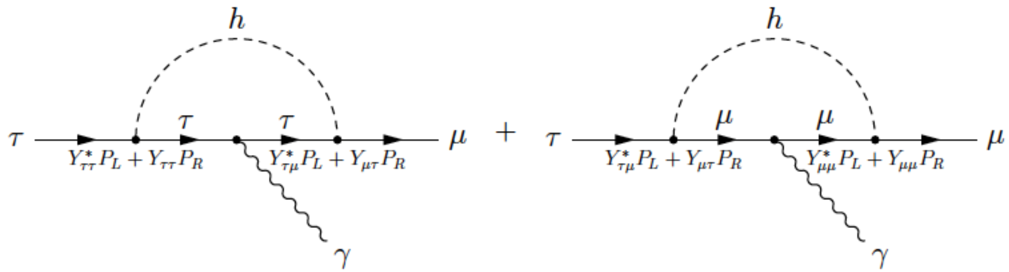
	$-\sigma$	$\mathrm{BR}_{exp}(\mathrm{t} \to \mathrm{Hc})$	$+\sigma$	$\mathrm{BR}_{obs}(\mathrm{t} \to \mathrm{Hc})$
trilepton	0.95	1.33	1.87	1.26
same-sign dilepton	0.68	0.93	1.26	0.99
combined	0.65	0.89	1.22	0.93

Lepton Flavor Violation

Lepton Yukawa Couplings are:

$$\mathcal{L}_{Y_l} = Y_{e\mu}\bar{e}_L \mu_R h + Y_{\mu e}\bar{\mu}_L e_R h + Y_{e\tau}\bar{e}_L \tau_R h + Y_{\tau e}\bar{\tau}_L e_R h + Y_{\tau\mu}\bar{\tau}_L \mu_R h + Y_{\mu\tau}\bar{\mu}_L \tau_R h$$

- Coupling to μe constrained by LFV μ→eγ search
  - Not in LHC domain, but one can double check
- Coupling to μτ not well constrained by τ decay BR ~ 10%



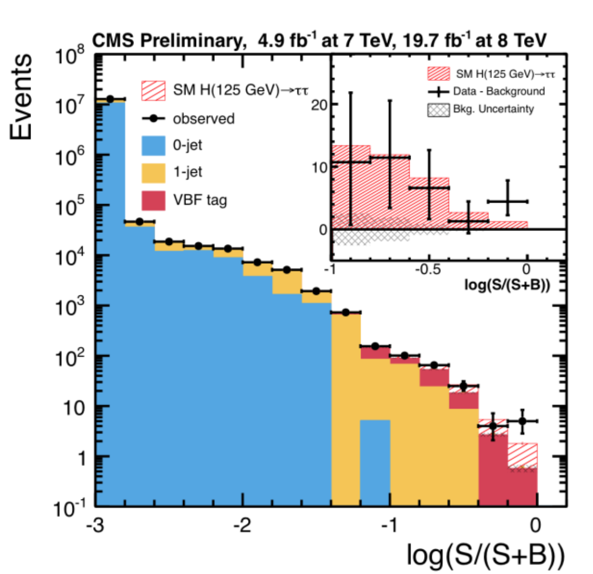
  - Direct search at LHC possible and interesting
    - H → μτ and H → eτ
  - Basis of search is H → ττ → μτ MET analysis

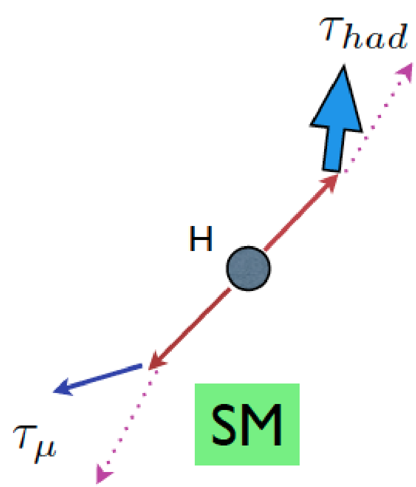
SM H→ | | vs H→μ |

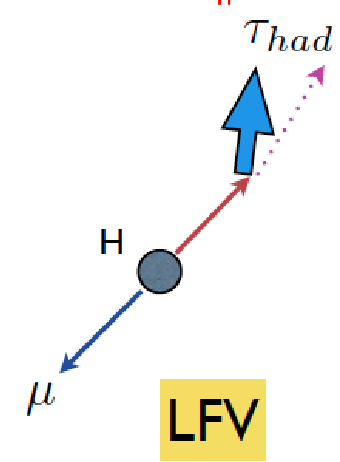
- $H\to\tau_\mu\tau_h$ and $H\to\tau_\mu\tau_e$ have a very similar signature to $H\to\mu\tau$
- Allows use identical methods as in CMS SM $H\to\tau\tau$ analysis
- Exploit differences in event topology
  - Harder P_T spectrum of muons
  - Different $\Delta\phi_{\mu\text{-MET}}$ $\Delta\phi_{\tau\text{-MET}}$

Three categories
- 0 and 1 jet (dominated by GGF)
- 2 jets (dominated by VBF)

Two channels per category
- $H\to\mu\tau_e$ and $H\to\mu\tau_h$



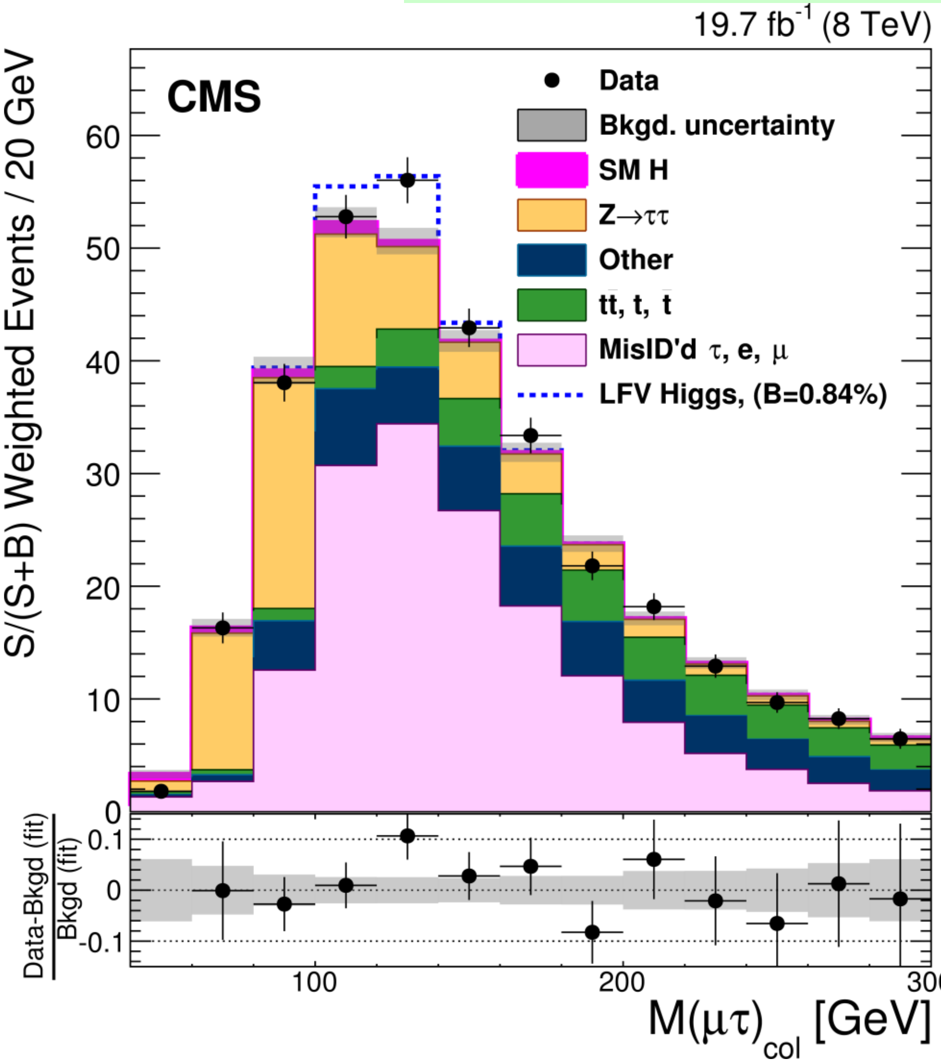




Collinear Mass Spectrum Fit

PLB 749 (2015) 337

- Fit to collinear mass using
  - BG & signal shapes
  - Categories & Channels
- Extracted 95% CL limits on BR(H → $\mu\tau$)
- Systematics included in fit
  - Nuisance parameters
    - Dominated by tau
  - Normalization & shape
- Small excess seen



Observed vs Expected Limits

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	0-Jet (%)	1-Jet (%)	2-Jets (%)
Expected Limits			
$\mu\tau_e$	$<1.32\ (\pm 0.67)$	$<1.66\ (\pm 0.85)$	$<3.77\ (\pm 1.92)$
$\mu\tau_h$	$<2.34\ (\pm 1.19)$	$<2.07\ (\pm 1.06)$	$<2.31\ (\pm 1.18)$
$\mu\tau$		$<0.75\ (\pm 0.38)$	
Observed Limits			
$\mu\tau_e$	<2.04	<2.38	<3.84
$\mu\tau_h$	<2.61	<2.22	<3.68
$\mu\tau$		<1.51	Small Excess
Best Fit Branching Fractions			
$\mu\tau_e$	$0.87^{+0.66}_{-0.62}$	$0.81^{+0.85}_{-0.78}$	$0.05^{+1.58}_{-0.97}$
$\mu\tau_h$	$0.41^{+1.20}_{-1.22}$	$0.21^{+1.03}_{-1.09}$	$1.48^{+1.16}_{-0.93}$
$\mu\tau$		$0.84^{+0.39}_{-0.37}$	

Observed Limit Bands

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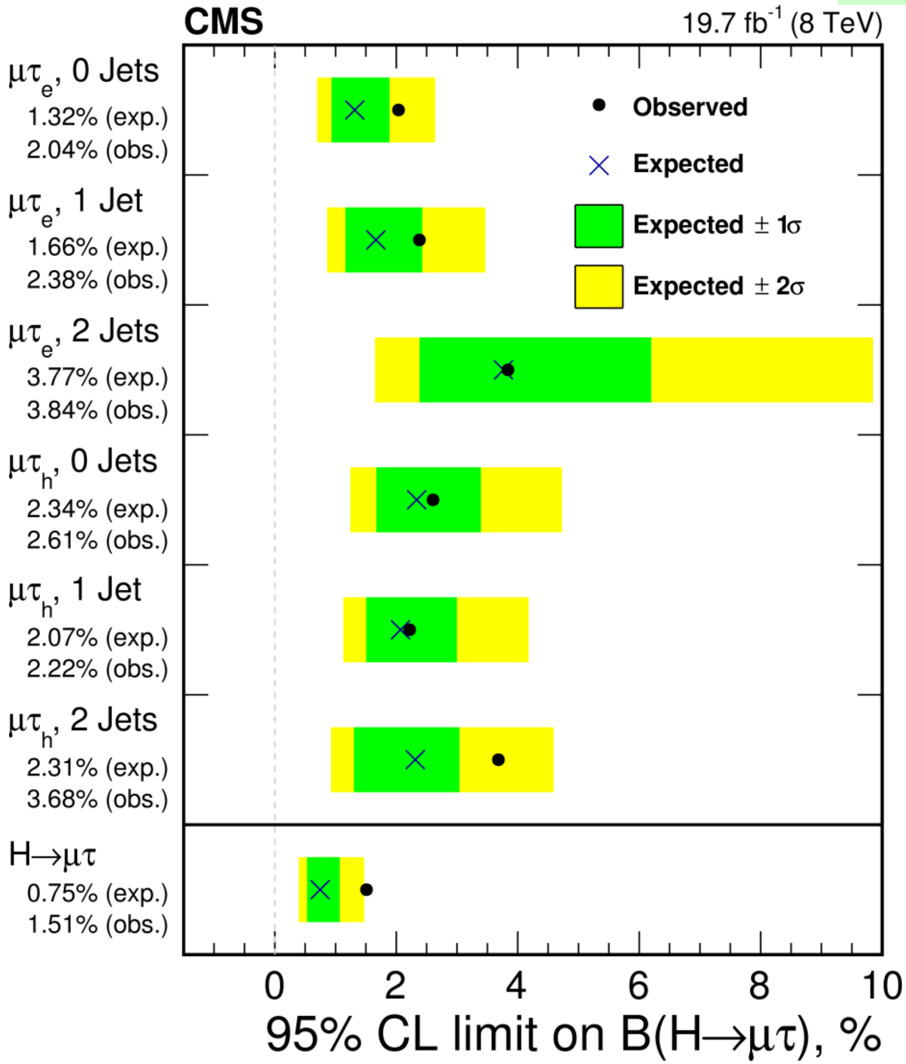
A small excess at 2.4σ level with p-value of 0.01 is intriguing



Fitted BR (H → μτ)

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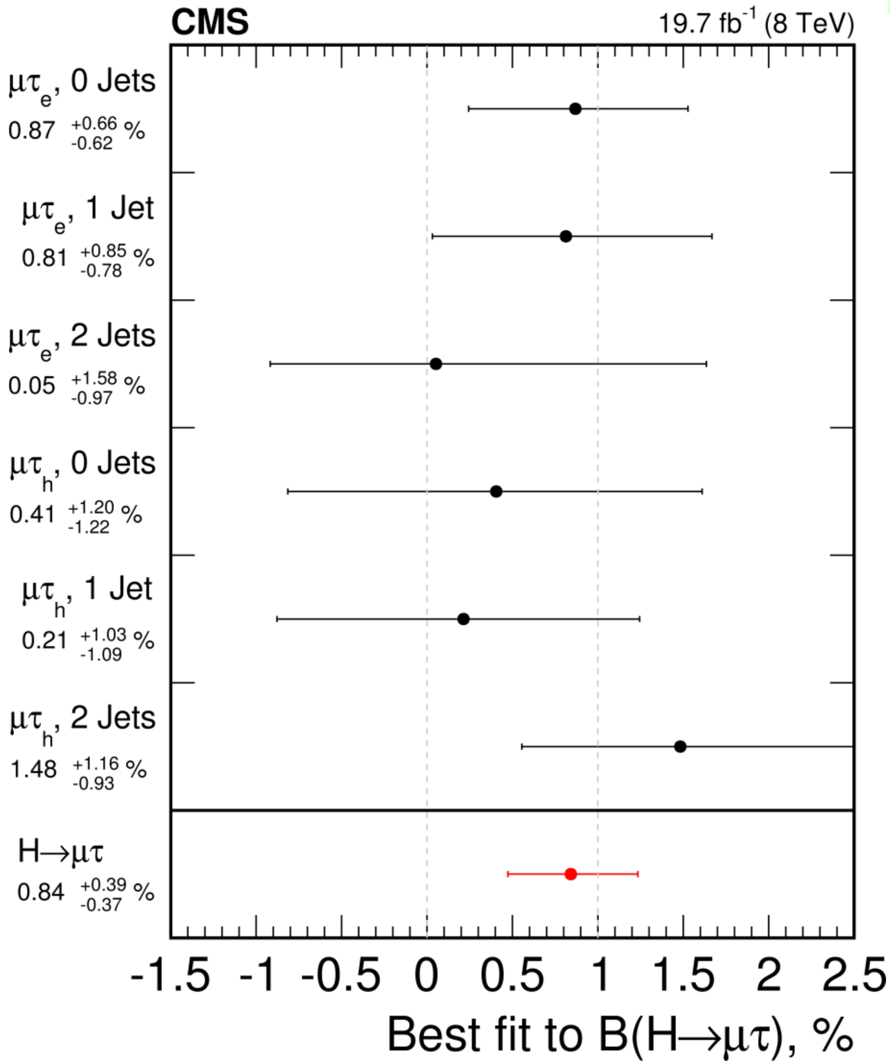
A small excess at 2.4σ level with p-value of 0.01 is intriguing



If interpreted as BR measurement, the best fit value is 0.84 ± 0.39

BR → Yukawa Couplings

- Width of LFV Higgs decay can be determined from LFV Yukawa couplings in Lagrangian

$$L_V \equiv -Y_{\tau\mu}\bar{\tau}_L\mu_R h - \ldots \quad \Longrightarrow \quad \Gamma\left(h \to \ell^\alpha \ell^\beta\right) = \frac{m_h}{8\pi}\left(\left|Y\ell^\alpha\ell^\beta\right|^2 + \left|Y\ell^\beta\ell^\alpha\right|^2\right)$$

- Dependence of width on LFV couplings gives dependence of BR on LFV couplings

$$BR\left(h \to \ell^\alpha \ell^\beta\right) = \frac{\Gamma\left(h \to \ell^\alpha \ell^\beta\right)}{\Gamma\left(h \to \ell^\alpha \ell^\beta\right) + \Gamma_{SM}} \quad \Longrightarrow \quad \boxed{\sqrt{\left|Y\ell^\alpha\ell^\beta\right|^2 + \left|Y\ell^\beta\ell^\alpha\right|^2} = \sqrt{\frac{8\pi \cdot BR}{m_h\left(1 - BR\right)}}}$$

Limits on Yukawa Couplings

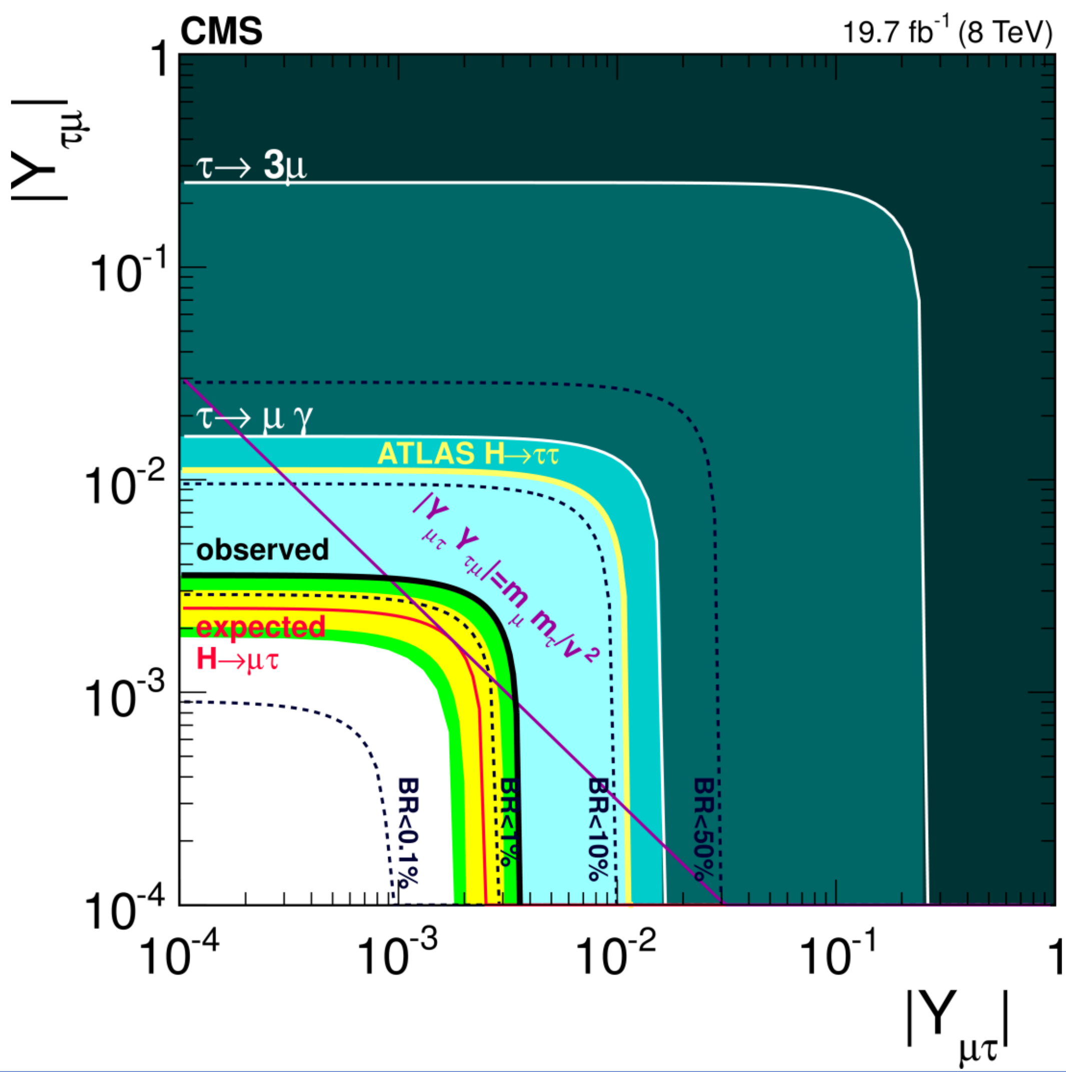
PLB 749 (2015) 337

- Best prior limit on Yukawa couplings:

$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 0.016$$

- Current observed limit:

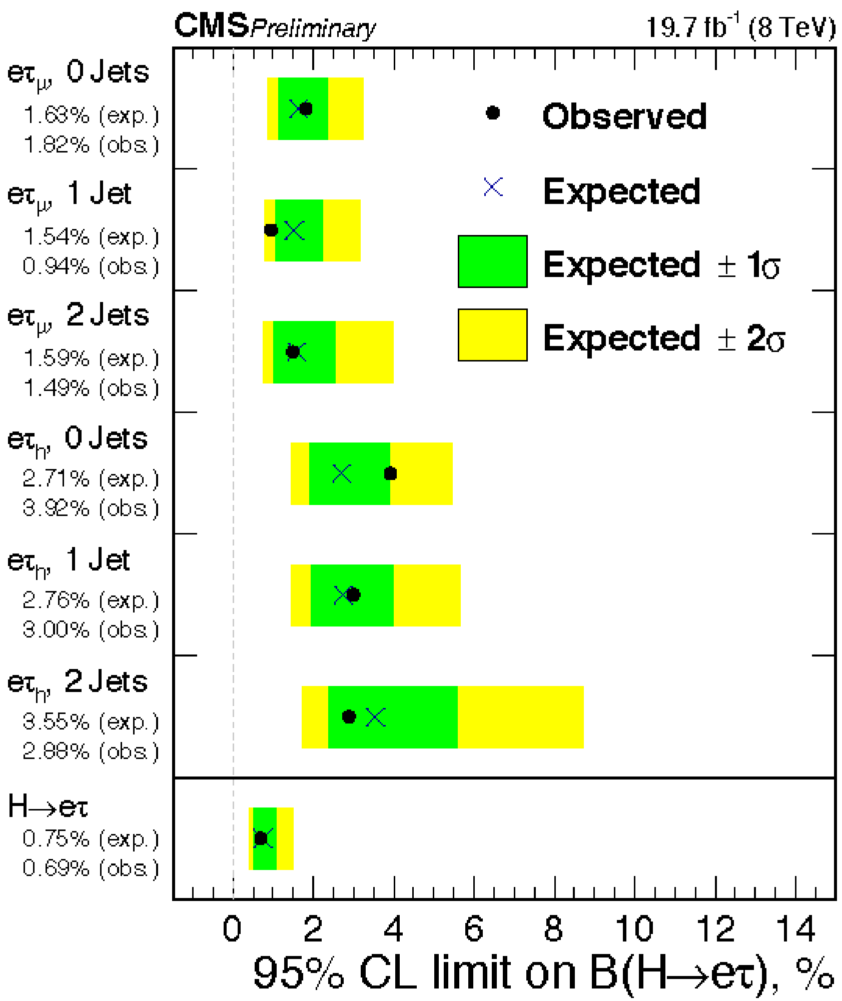
$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 0.0036$$

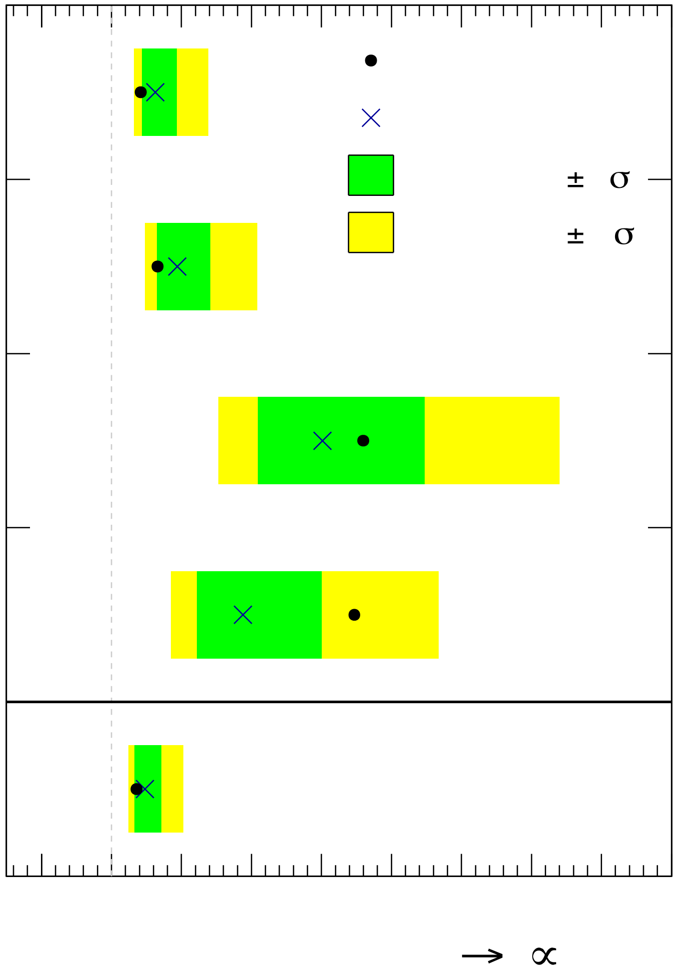


Search for LFV H→eτ and H→eμ

New CMS-PAS-HIG-14-040

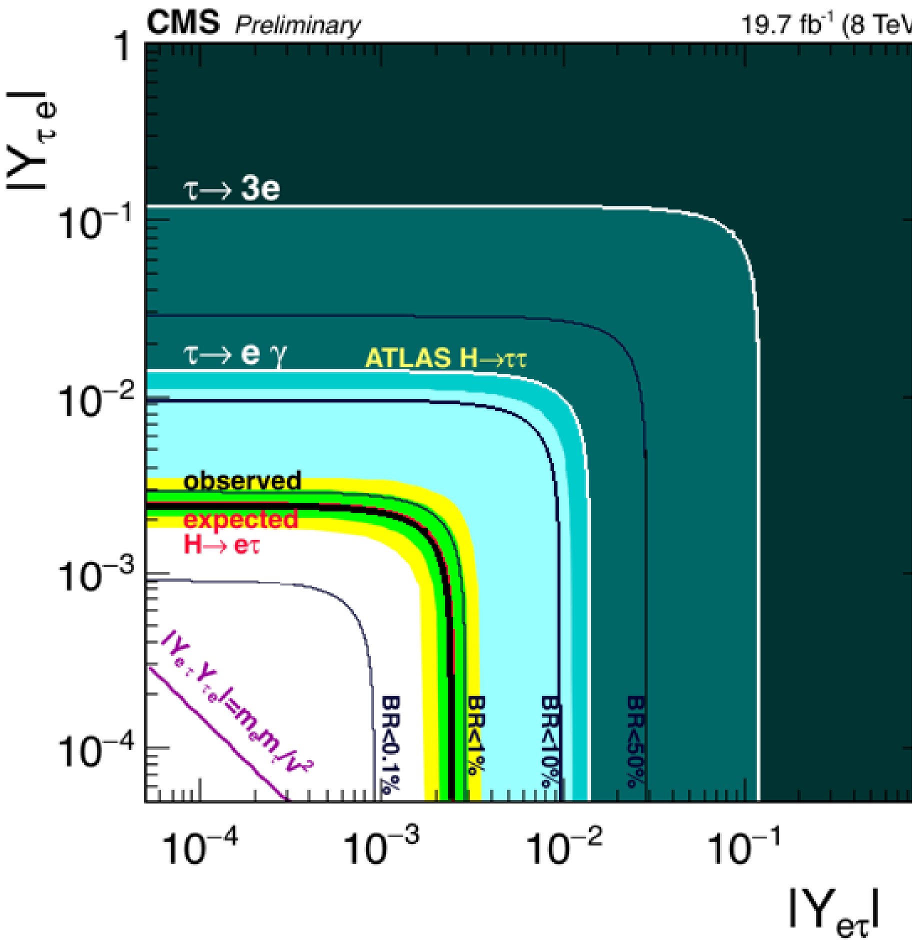
No excess seen unlike in μτ mode

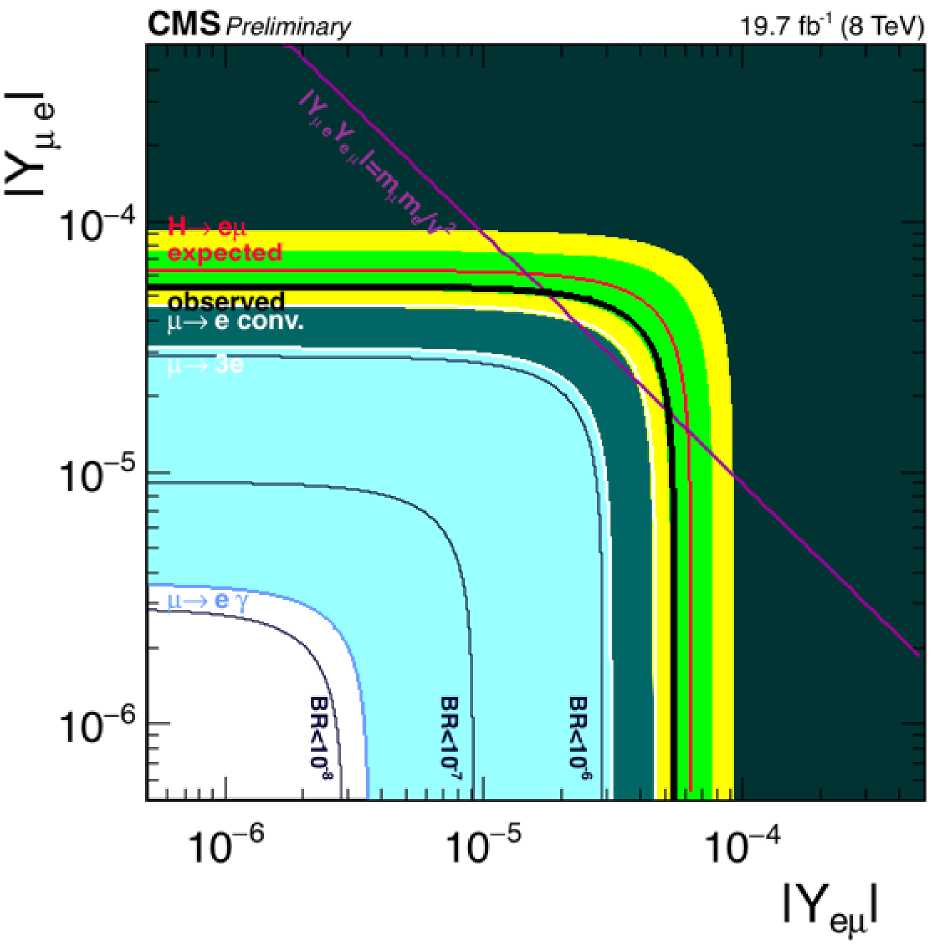




Limits on Yukawa Couplings

New CMS-PAS-HIG-14-040





Summary

Search for LFV Z decay was made to set limit BR($Z \rightarrow e\mu$) < 7 x 10^{-7}

- Not as strong as $\mu \rightarrow e\gamma$ but still important to probe at LHC

Flavor changing neutral currents in top are unique LHC territory now

- Searches yielded null results for $t \rightarrow Zq$ (< 0.05%)
- Searches for tug & tcg couplings also yielded null results
- No new flavor change due to top-higgs either

Search for LFV Higgs was made in $\mu\tau$, $e\tau$ and $e\mu$

- BR for LFV decay to $\mu\tau$ is constrained to be less than 1.57 %
- A small excess at 2.4σ level with p-value of 0.01 is intriguing
  - More data is needed to conclusions
- Null result for $e\tau$ and $e\mu$ seen

What next?

- The LHC Run 2015-17 @ 13 TeV ➔ 100 fb^{-1} is underway
- Stay tuned !!