# Search for H→μτ with the CMS experiment

Maria Cepeda

# Introduction

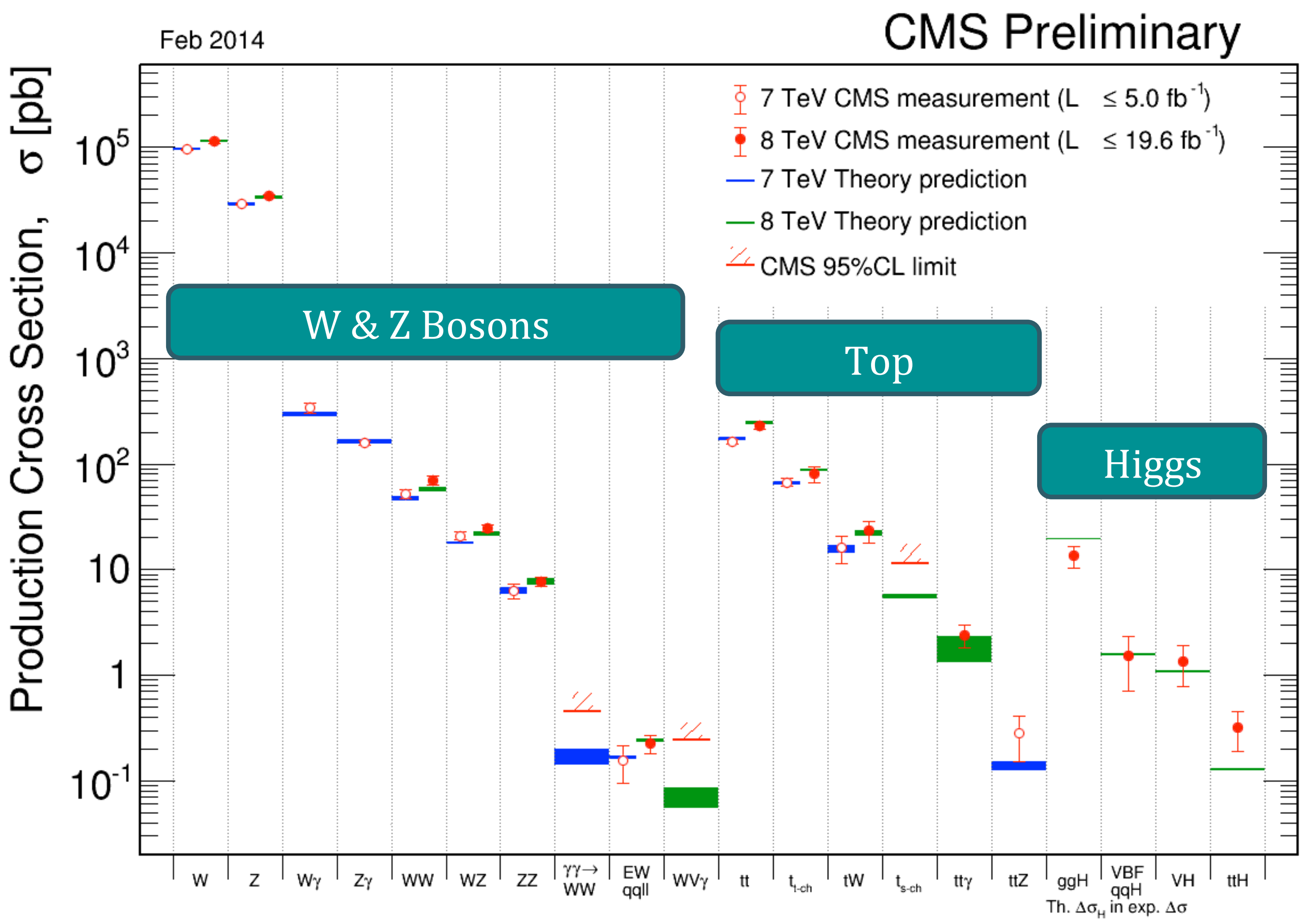
- With the discovery of the Higgs Boson by the ATLAS and CMS collaborations at the LHC, the quest for understanding its properties and decays started
- New physics could arise from unexpected corners

- Exploring the Higgs Flavor sector can hold surprises:
  - BSM models such as double Higgs models or extra dimensions allow LFV decays of the Higgs (for instance, to a μτ pair)
  - Experimentally, non-LHC bounds on such decays are weak, allowing Br(H→μτ, H→eτ) ~10%, well within the experimental reach of CMS

- This talks summarizes the first direct search for a LFV Higgs Decay, performed with a data sample of 20 $\text{fb}^{-1}$ @ 8 TeV collected by the CMS experiment

# CMS Run I: The SM

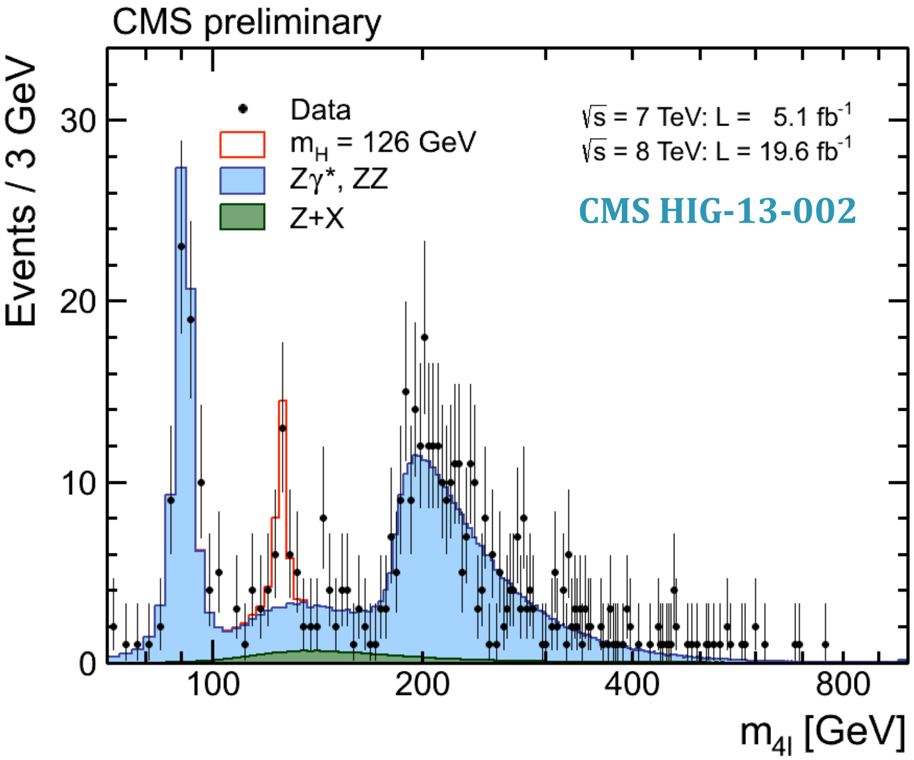
- 2 years of collisions → 5 $\text{fb}^{-1}$ @ 7 TeV + 20 $\text{fb}^{-1}$ @ 8 TeV



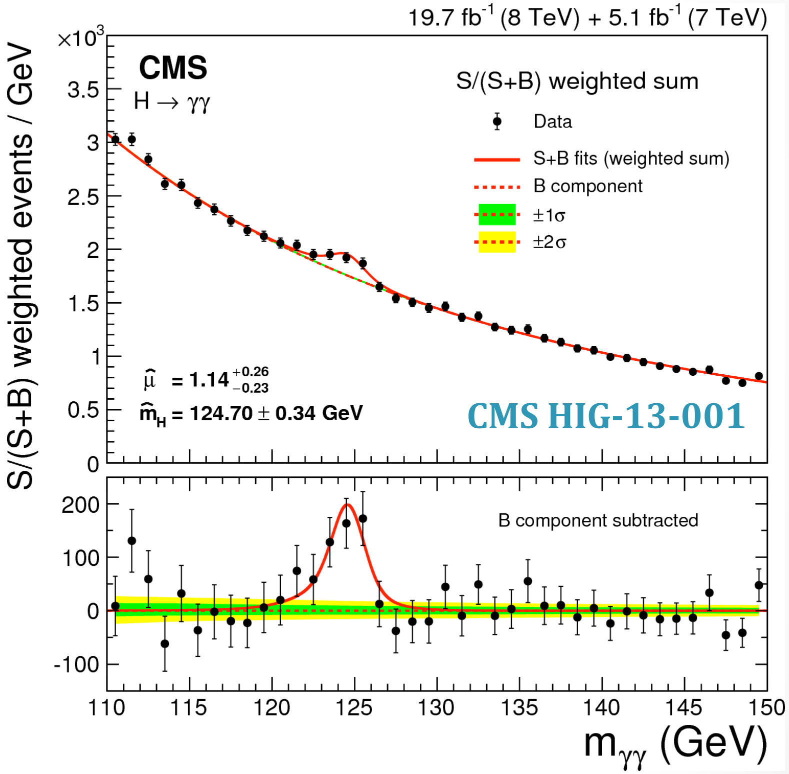
→ 6 orders of magnitude of SM precision physics measurements…

# CMS Run I: The SM

- .. and the discovery of a new particle



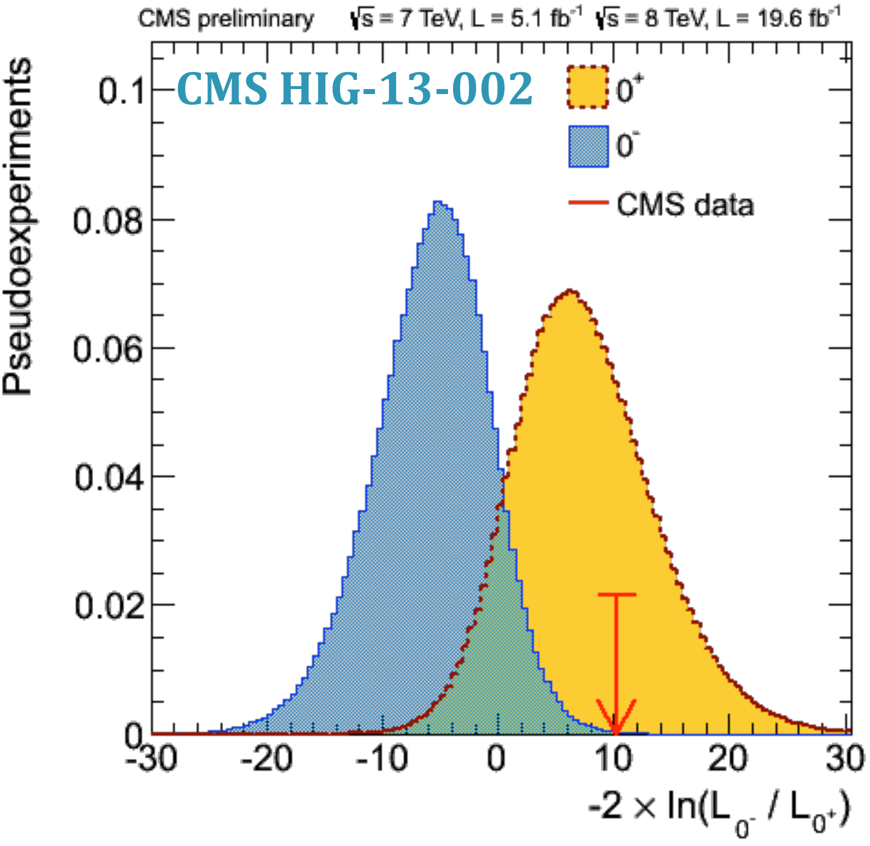
CMS HIG-13-002



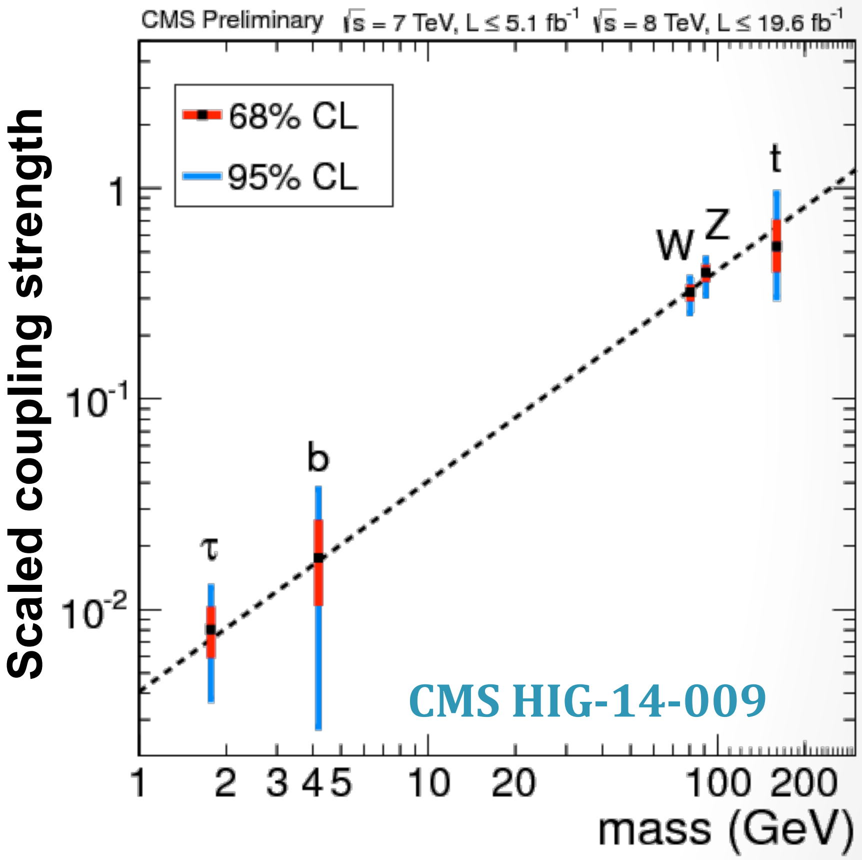
CMS HIG-13-001

$$\sigma/\sigma_{\mathrm{SM}} = 1.00 \pm 0.13 \left[\pm 0.09(\mathrm{stat.})^{+0.08}_{-0.07}(\mathrm{theo.}) \pm 0.07(\mathrm{syst.})\right]$$

# Measuring the Higgs from the SM point of view …



Its spin seems to be like that of SM Higgs ($0^+$)

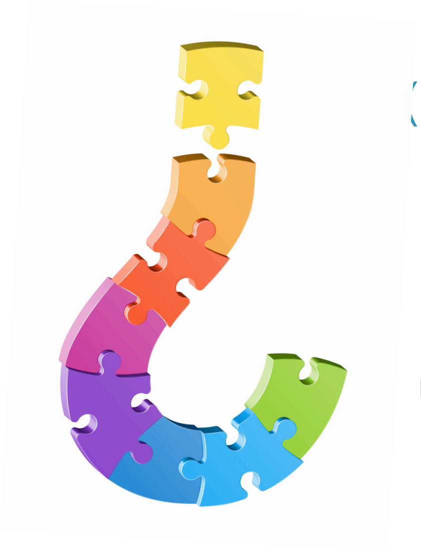


It appears to couple like the SM Higgs

# … so far yields no surprises

# Can this really be the full picture?

We already know it cannot be – the puzzle is incomplete



(No dark matter candidate, no explanation for three fermion generations, no explanation for hierarchy in fermion masses, inadequate amount of CP violation for baryon formation, no unification of forces, divergence of Higgs self energy corrections, missing connection to gravity…

**Probing further the newly discovered Higgs Sector can unfurl BSM clues ☺**

# Is the New Boson really the *minimal* SM Higgs?

- Is the ***signal strength***, where seen, at the correct SM level?
- Is this a ***scalar***, and not a pseudo-scalar or tensor?
- Does it ***couple*** to the SM particles at appropriate level? t,b,τ,μ
- Does it ***couple to itself*** ?
- Is this the ***only*** new non-vector boson, and not one of several?
- Does it ***couple*** unusually ?

- Thanks to its mass of about 125 GeV we will be able to answer many of these questions experimentally ☺
  - Early answers from 2011-12 (Run-1)
  - Preparation for 2015-2017 (Run-2)

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# WHY LFV?

# Higgs and Flavor

- In the SM, the Yukawa interactions are the only source of the fermion masses:

$$y_{ij}\bar{f}_{L_i}Hf_{R_j} = \underset{\substack{\uparrow\\ \text{mass}}}{\frac{y_{ij}v}{\sqrt{2}}\bar{f}_{L_i}f_{R_j}} + \underset{\substack{\uparrow\\ \text{higgs-fermion interactions}}}{\frac{y_{ij}}{\sqrt{2}}h\bar{f}_{L_i}f_{R_j}}$$

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mass

higgs-fermion interactions

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**This is not necessarily true anymore in BSM models:**

Misaligned flavor and/or phase (e.g., due to higher dimensional operators)

$$\mathcal{L}''_{Y_i} = Y_1^{ij} H f_L^i f_R^j + \hat{Y}_2^{ij} \frac{|H|^2}{\Lambda^2} H f_L^i f_R^j$$

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2-Higgs Doublets Model (e.g. in MSSM):

$$\mathcal{L}'_{Y_i} = Y_1^{ij} H_1 f_L^i f_R^j + Y_2^{ij} H_2 f_L^i f_R^j$$

# New Physics Higgs Couplings

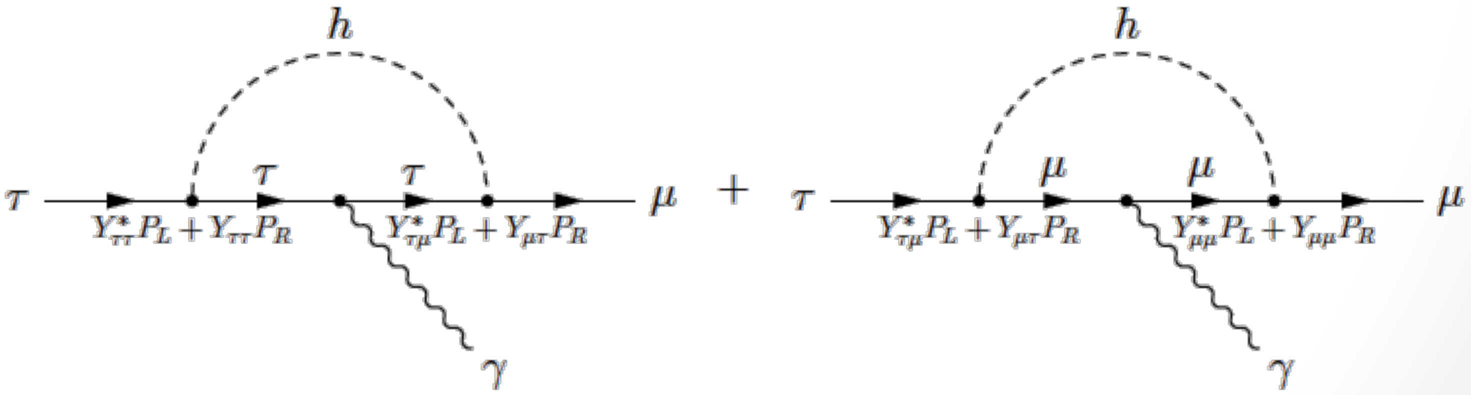
- With new physics Yukawa couplings can be
  - Flavor off-diagonal
  - Complex (CP violating)

$$\mathcal{L}'_{Y_i} = Y_{ij} h f^i_L f^j_R + h.c.$$

- To avoid tuning we expect, “natural” couplings

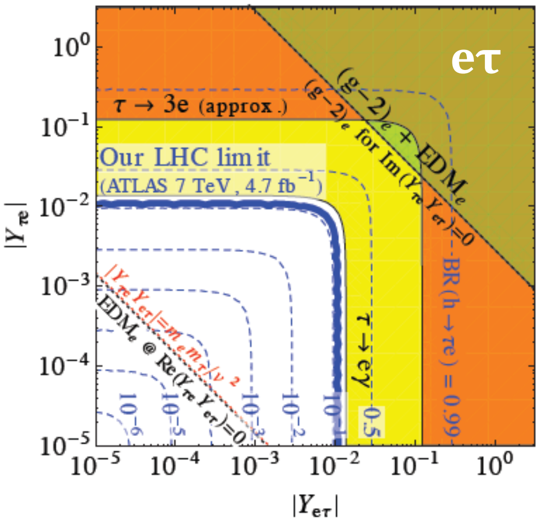
$$Y_{ij} \le \frac{\sqrt{m_i m_j}}{v} \text{ but phases unconstrained}$$

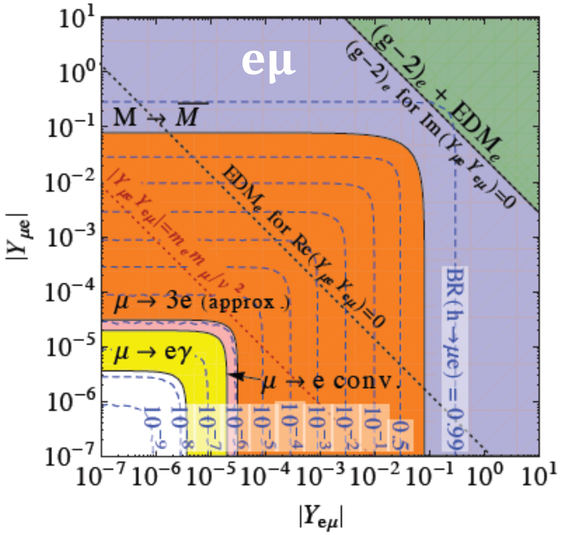
$$\boxed{\mathcal{L}_{Y_l} = Y_{e\mu}\bar{e}_L\mu_R h + Y_{\mu e}\bar{\mu}_L e_R h + Y_{e\tau}\bar{e}_L\tau_R h + Y_{\tau e}\bar{\tau}_L e_R h + Y_{\tau\mu}\bar{\tau}_L\mu_R h + Y_{\mu\tau}\bar{\mu}_L\tau_R h}$$

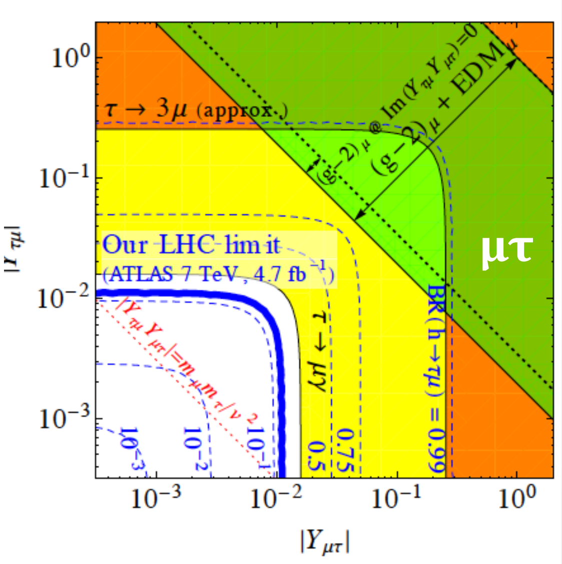


# What do we already know?

| Channel | Coupling | Bound |
|---|---|---|
| $\mu \to e\gamma$ | $\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$ | $< 3.6 \times 10^{-6}$ |
| $\tau \to e\gamma$ | $\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$ | $< 0.014$ |
| $\tau \to \mu\gamma$ | $\sqrt{\lvert Y_{\tau \mu}\rvert^2 + \lvert Y_{\mu\tau}\rvert^2}$ | 0.016 |







arXiv:1209.1397

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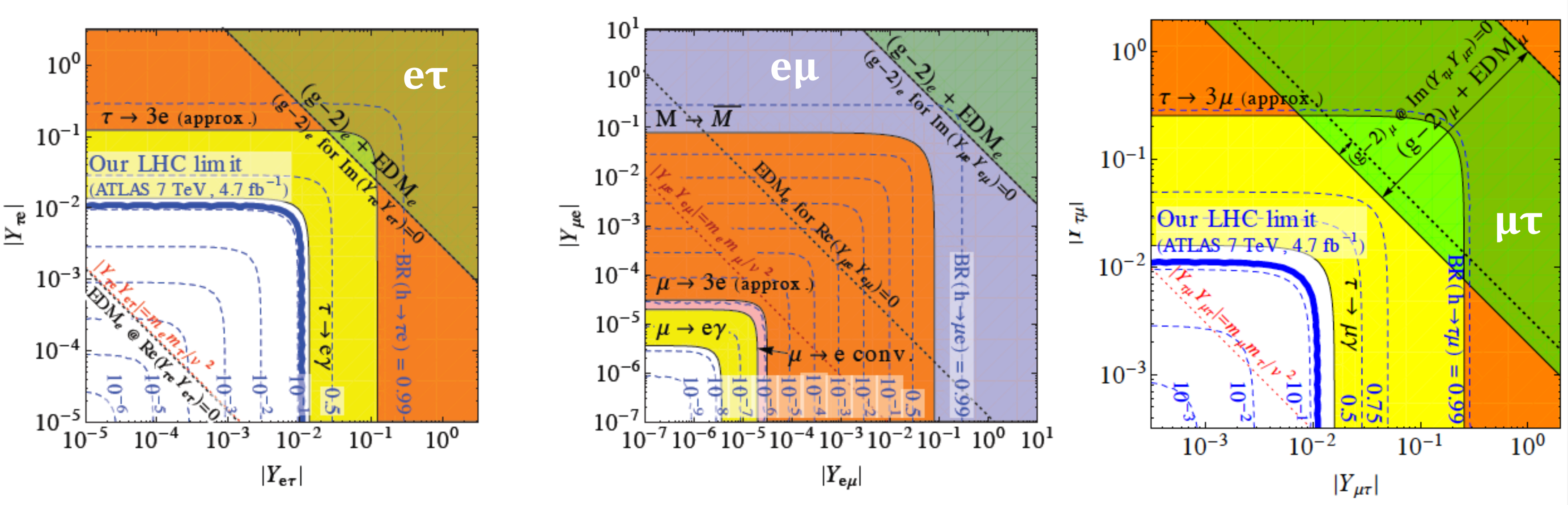
**Br≤10%**



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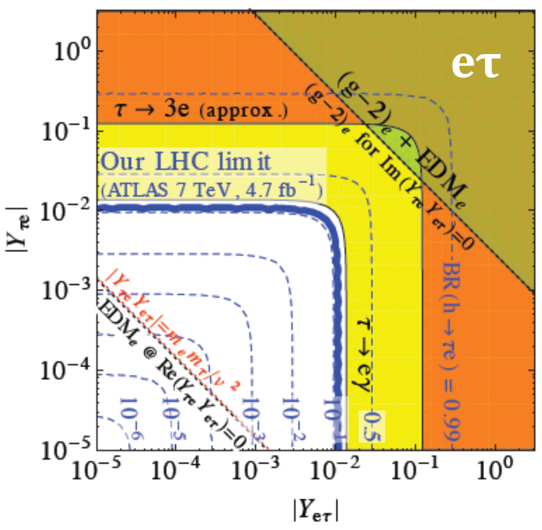

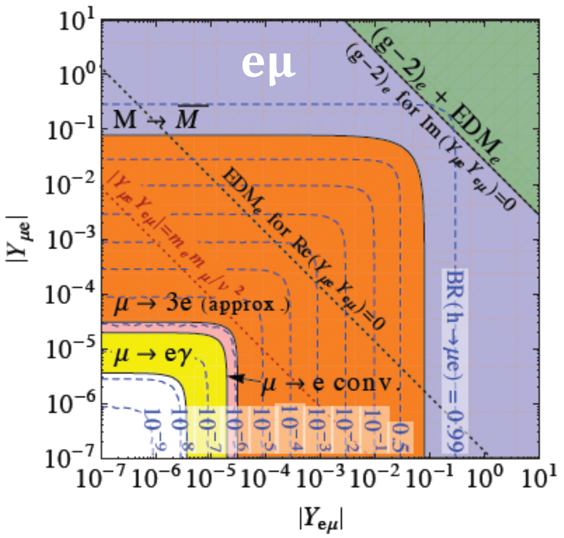

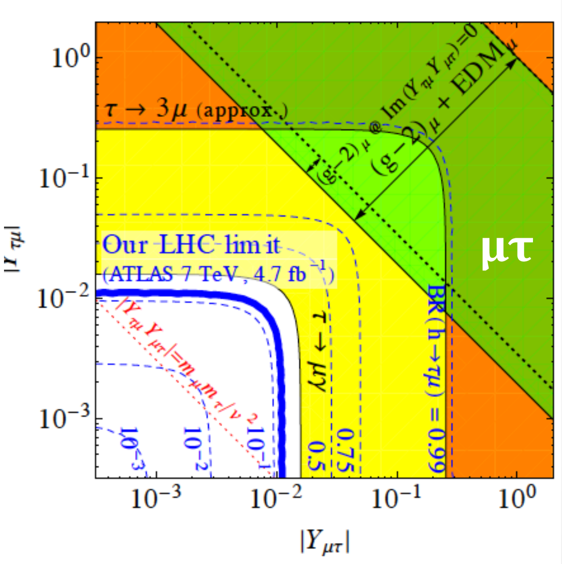

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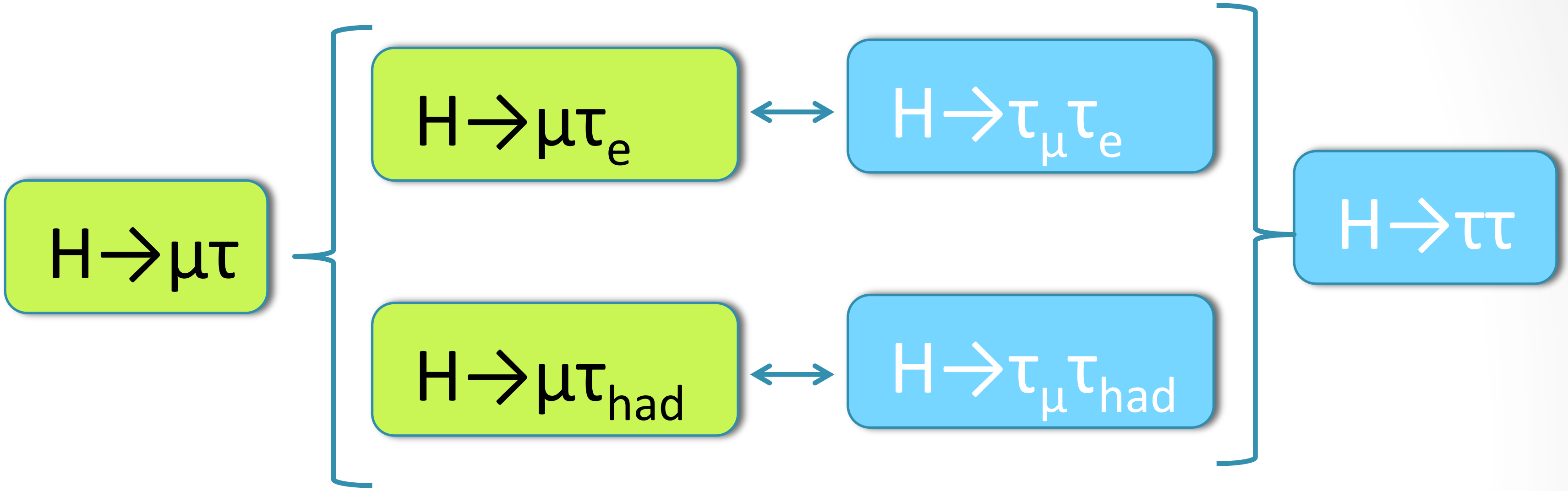
# And where can we start?



H→μτ

H→$\mu\tau_e$ ↔ H→$\tau_\mu\tau_e$

H→$\mu\tau_{had}$ ↔ H→$\tau_\mu\tau_{had}$

H→ττ

- Without any retuning, a reinterpretation of a LHC H→ττ search yields a Br<13% limit (arXiv:1209.1397)

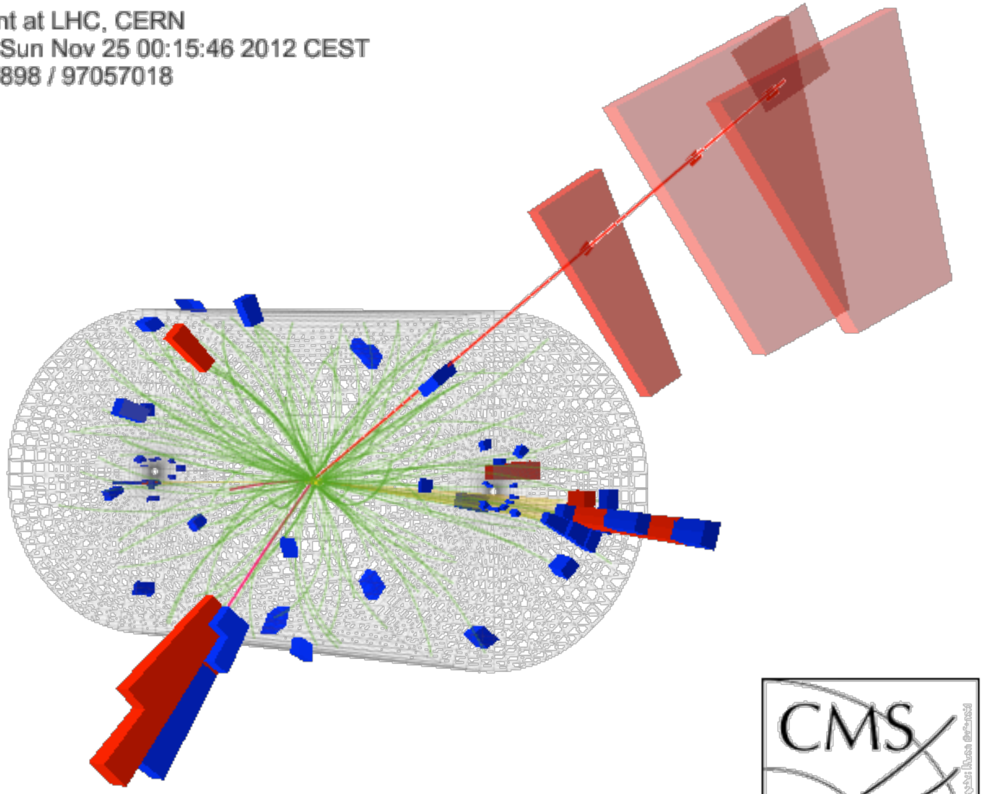
- With minimal tuning, the 8 TeV dataset will reach Br~1% (start of the natural regime)

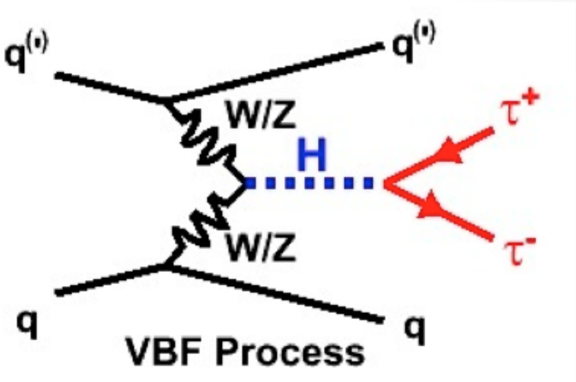
# HOW?: ANALYSIS DESCRIPTION

# Higgs Decay to Tau Pairs

Taus with high branching fraction can probe in all production modes:
W and Z boson fusion; Gluon fusion and W, Z, top associated production

CMS Experiment at LHC, CERN
Data recorded: Sun Nov 25 00:15:46 2012 CEST
Run/Event: 207898 / 97057018



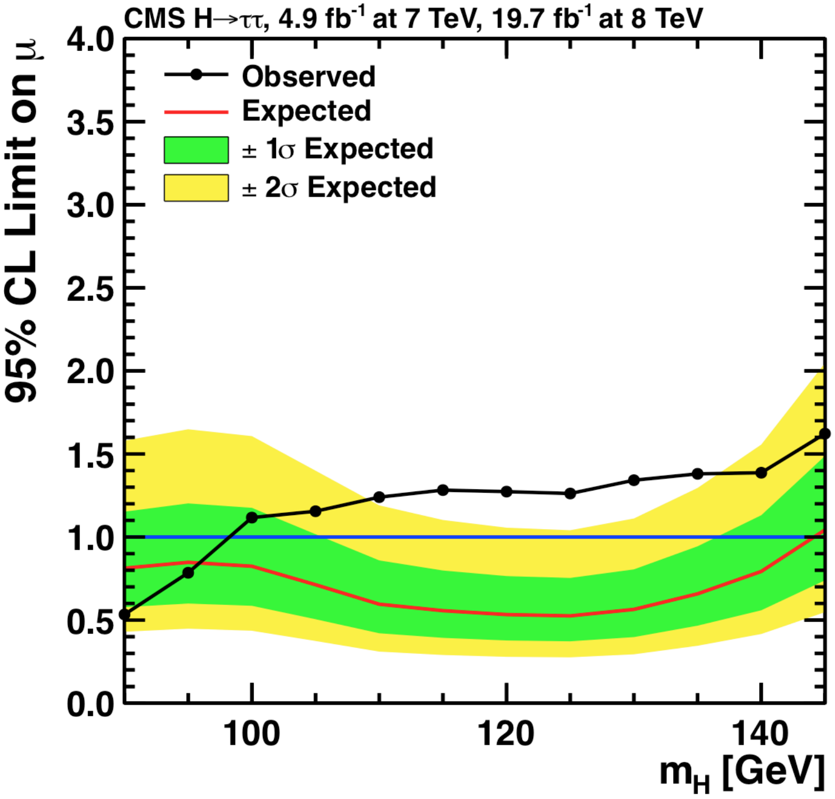


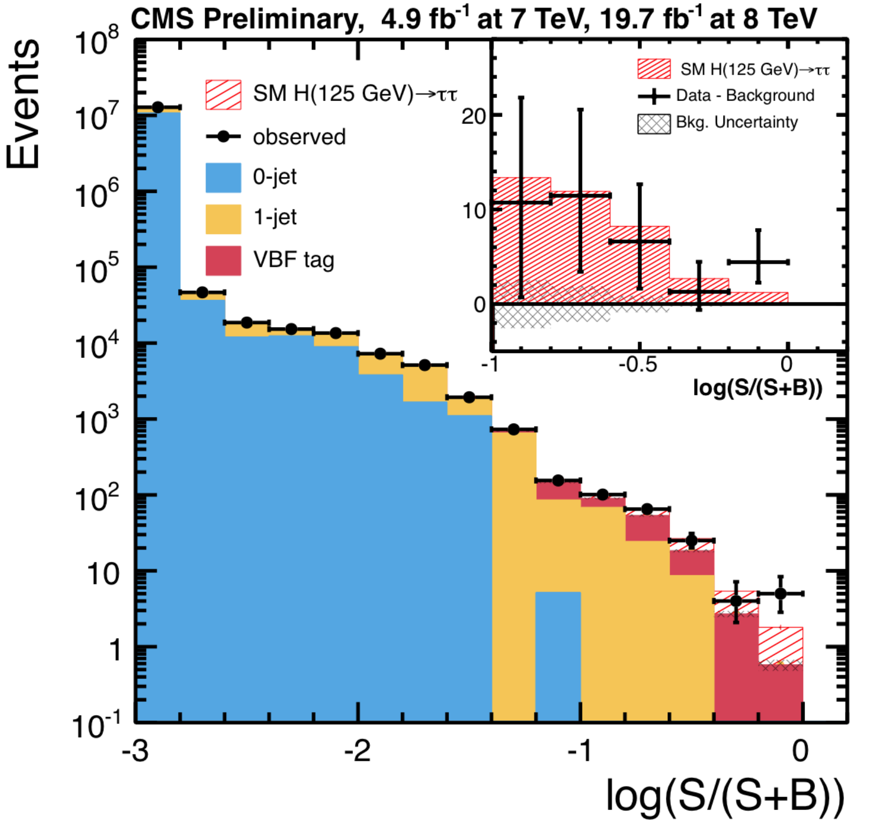
Final states VBF + GF:
$e\mu$, $\mu\mu$,
$e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$

Also, VH (WH & ZH)
$\ell\ell\tau_h$, $\ell\tau_h\tau_h$, $\ell\ell\tau_h\tau_h$

CMS HIG-13-004

# Higgs Decay to Tau Pairs

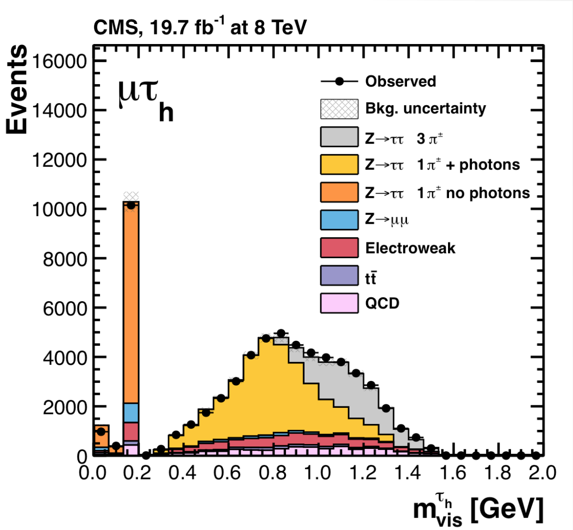


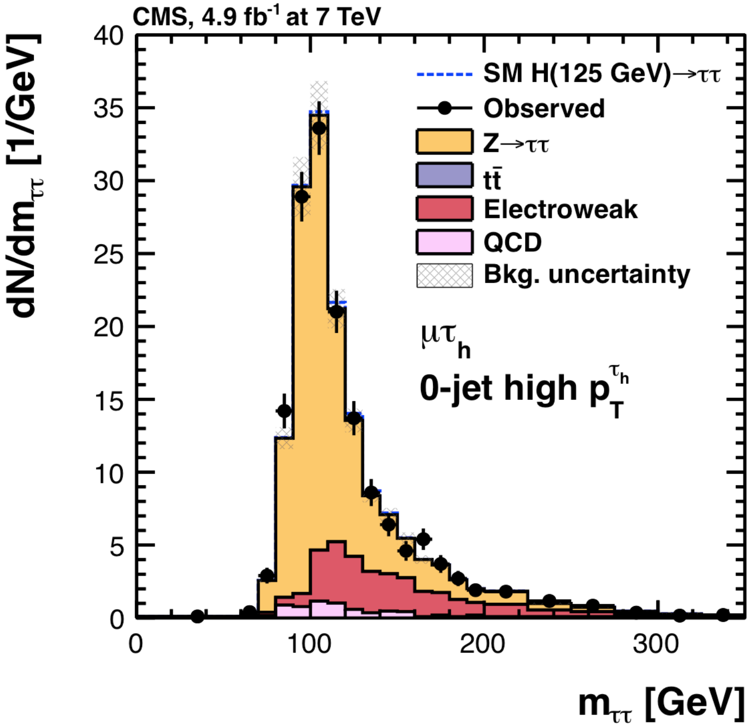


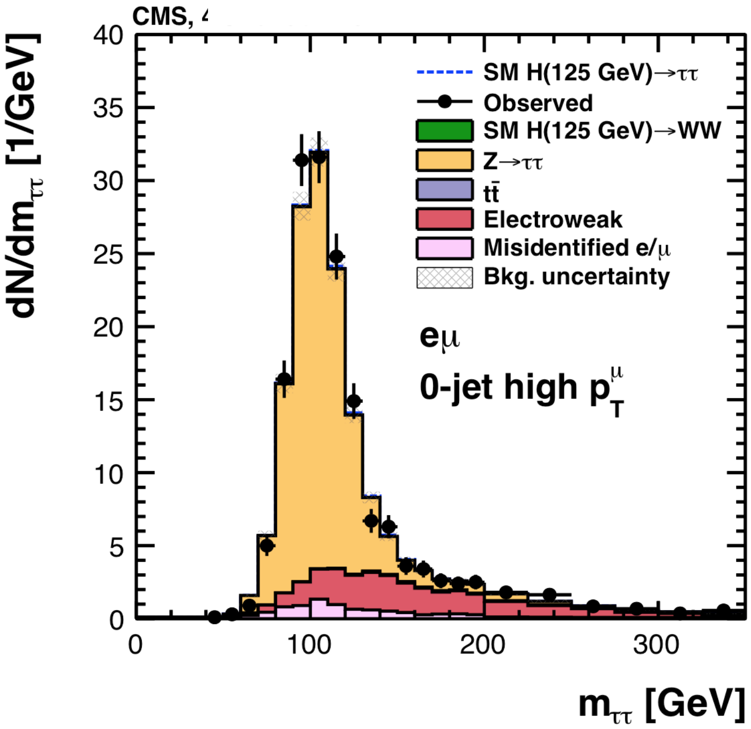
Approximately 4σ significance evidence for coupling to fermions

# Higgs Decay to Tau Pairs

- Following the baseline object definition by the CMS SM H→ττ analysis (common building blocks: taus, leptons, jets) allows us to profit from the modeling techniques and systematic studies developed in that context

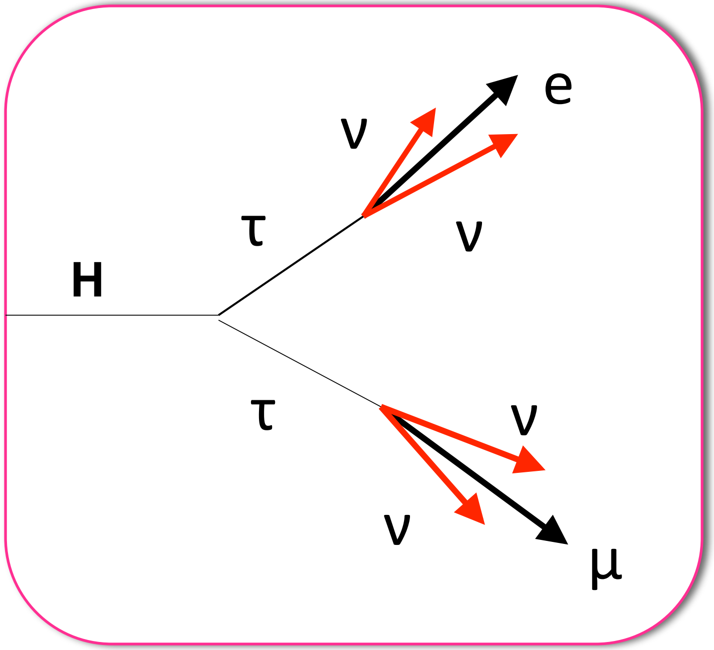


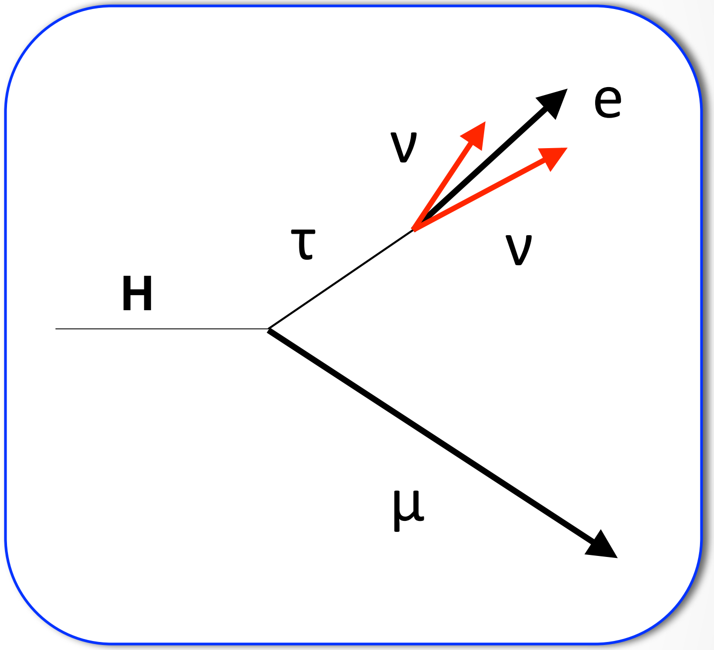




# Comparison of Kinematics

## $H \rightarrow \tau\tau$ vs. $H \rightarrow \mu\tau$



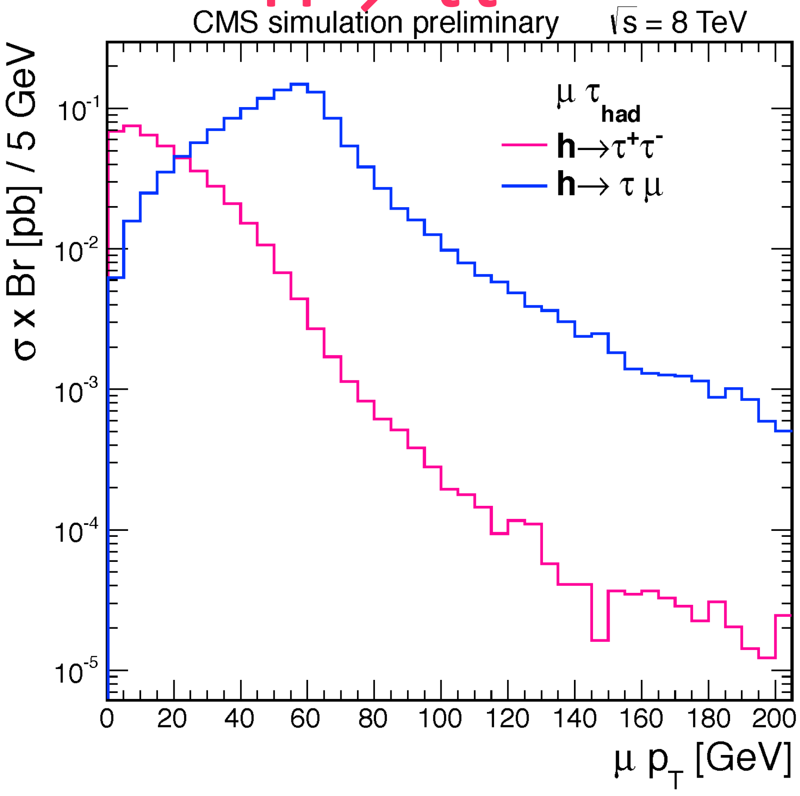


Exploit differences in event topology

- Harder $P_T$ spectrum of muons
- Different angular correlations:
  - Electron/Tau$_{had}$ – Neutrinos → ~ Collinear
  - Muon - Neutrinos → ~ back to back

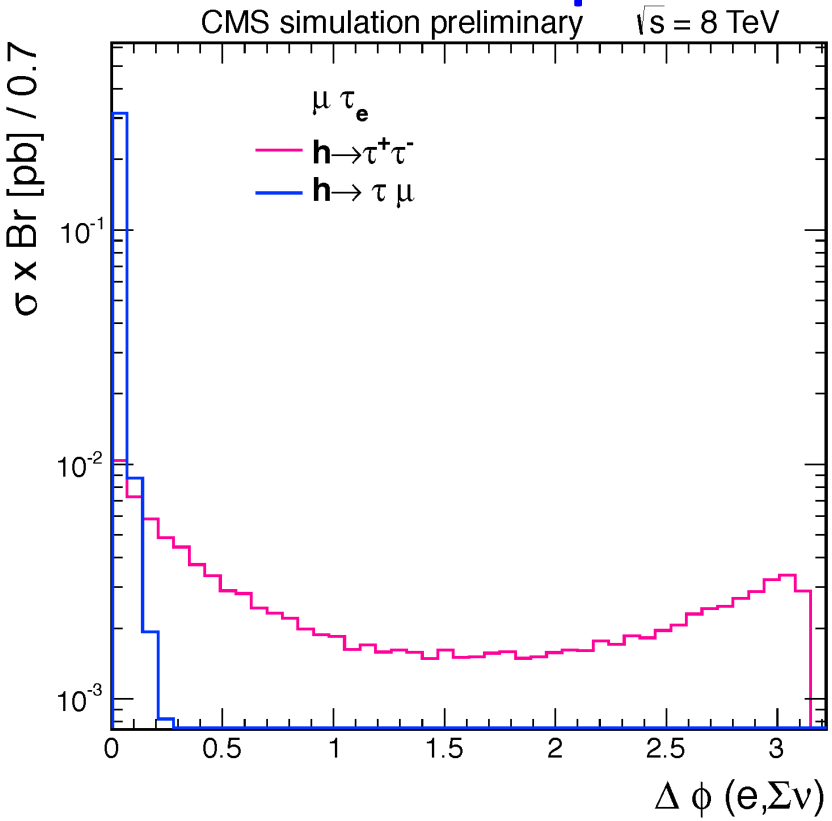
# Comparison of Kinematics

H→ ττ



vs.

H→μτ



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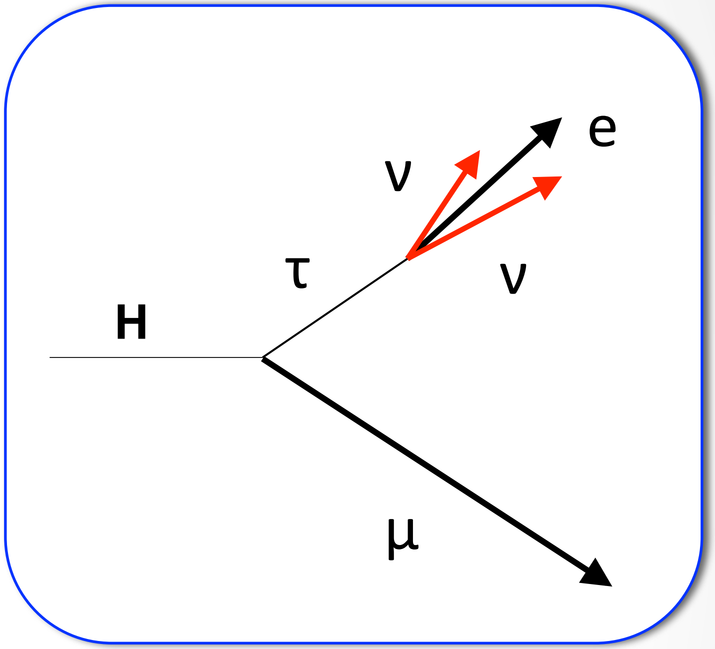
# Mass Reconstruction

- We cannot reconstruct the full Higgs mass from the visible objects
- Using a collinear mass approximation we can improve mass resolution

→ Assume neutrinos are collinear with the tau and define the visible fraction of tau momentum



$$\vec{p}_T^{\,\nu} = \vec{E}_T^{miss} \cdot \hat{p}_T^{\tau_{vis}}$$

$$x_{\tau_{vis}} = \frac{\left|\vec{p}_T^{\,\tau_{vis}}\right|}{\left|\vec{p}_T^{\,\tau_{vis}}\right| + \left|\vec{p}_T^{\,\nu}\right|}$$

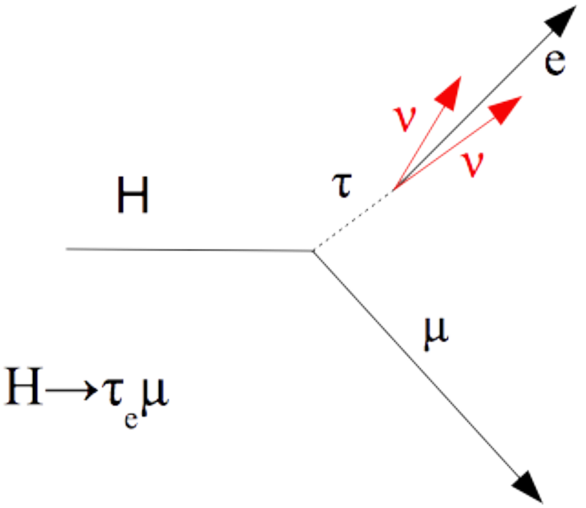
- Like this, the full system mass becomes:

$$\boxed{M_{collinear} = \frac{M_{vis}}{\sqrt{x_{\tau_{vis}}}}}$$

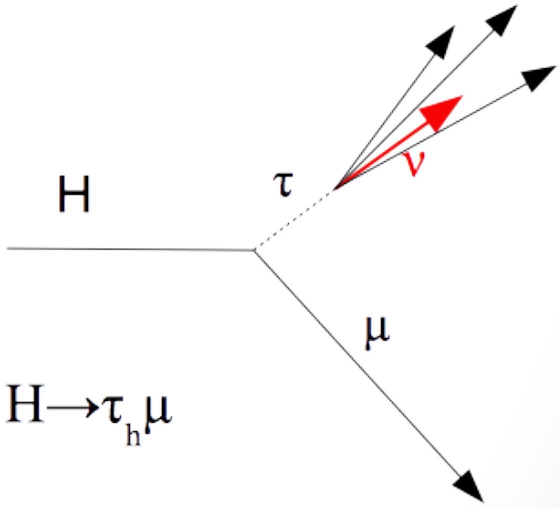
# Base selection in a snapshot

- Two channels:
  - $\boldsymbol{\mu\tau_{had}}$ (triggered by single muon)
  - $\boldsymbol{\mu\tau_{e}}$(triggered by muon-electron cross triggers)
- Three categories
  - 0 and 1 jet (dominated by GGF)
  - 2 jets (dominated by VBF)

- 1 Good, Isolated, High $p_T$ Muon
- 1 Good, isolated low $p_T$ Electron OR 1 Good, isolated high $p_T$ tau
- Opposite charge of the $\boldsymbol{\mu\tau_{had}}$ / $\boldsymbol{\mu e}$ Pair
- Veto on additional leptons

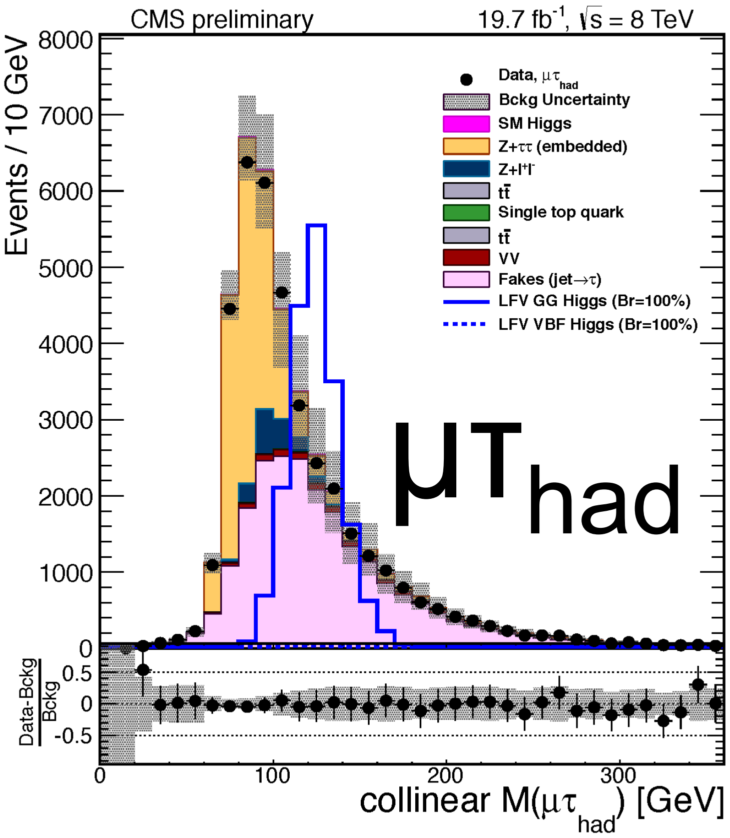


$H \rightarrow \tau_e \mu$

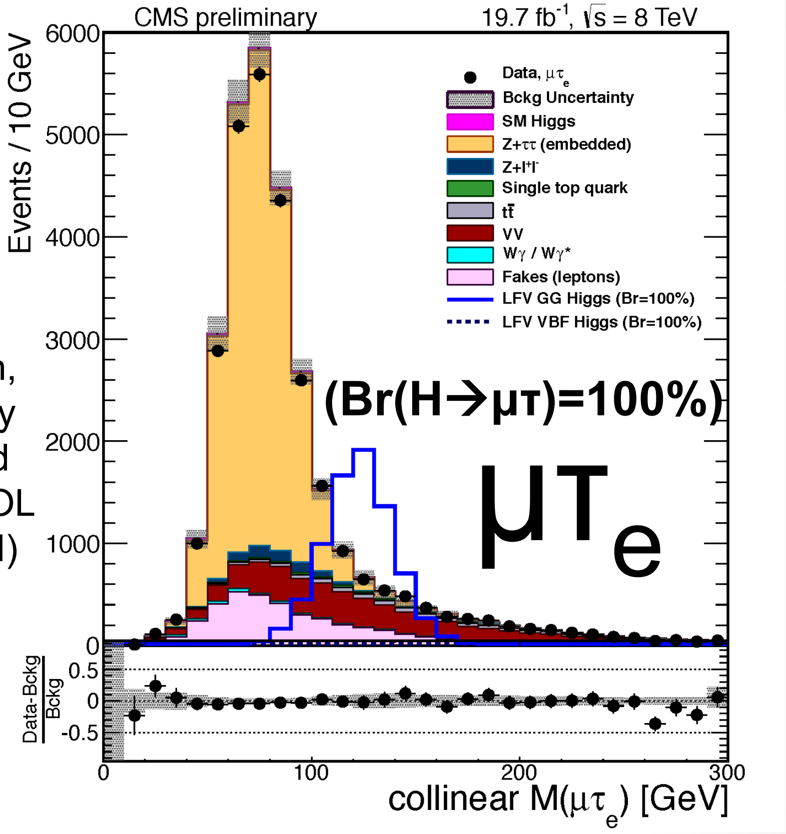


$H \rightarrow \tau_h \mu$

# Loosely selecting LFV Higgses…



Hττ-like selection, minimally changed (CONTROL REGION)



Lead backgrounds:

HTauTau

ZTauTau

SM backgrounds with real tau decays: top, VV

Fake Leptons (e, mu, tau)

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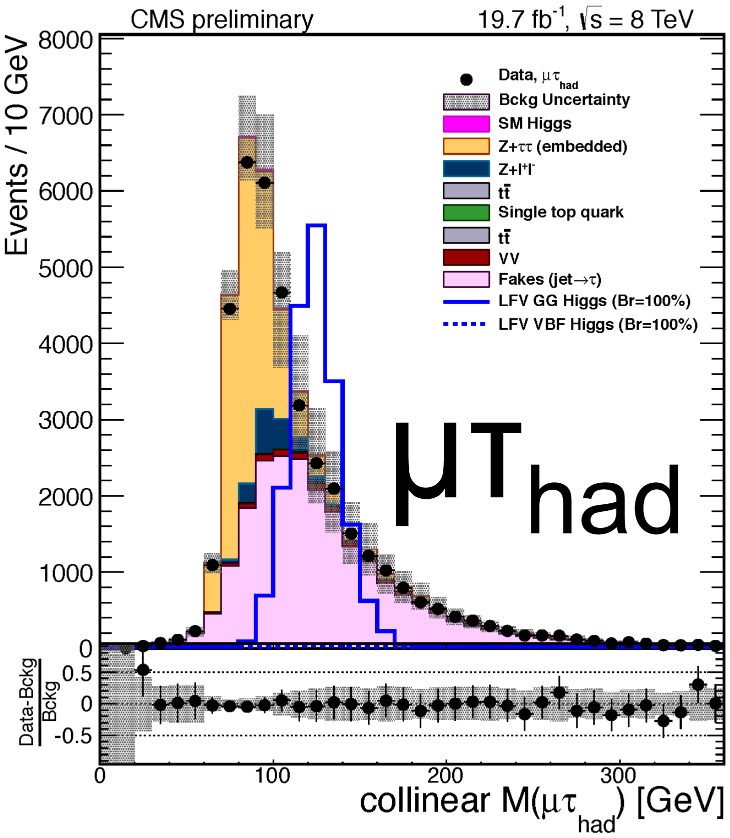
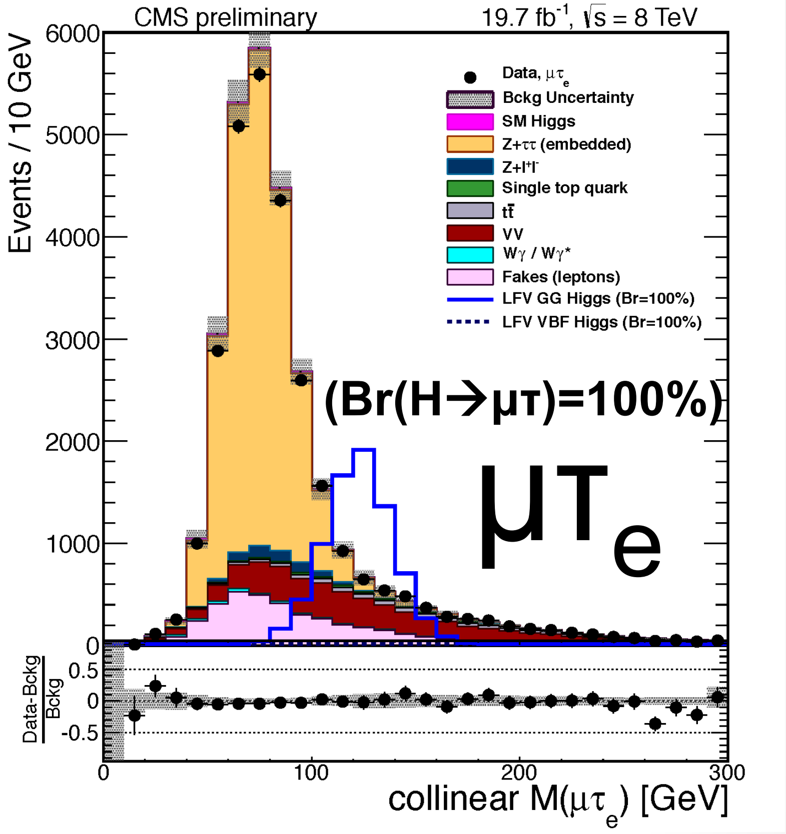




Lead backgrounds:

HTauTau

ZTauTau → Tau-Embedding technique

SM backgrounds with real tau decays: top, VV → from MC

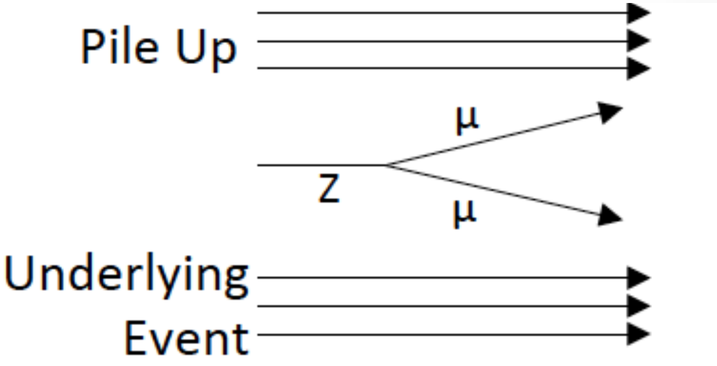
Fake Leptons (e, mu, tau) → from data

# Z→ττ Modeling

- Z→ττ is the dominant background in the $\mu\tau_e$ channel and significant in the $\mu\tau_{had}$ channel
- Very similar kinematics to the SM H→ττ & the signal

  - **Overall 3% yield systematic uncertainty → from Z→ττ cross-section**

  - **Shape modeling using the embedded technique developed by H→ττ →** exploits the 20 $fb^{-1}$ CMS Z→μμ dataset to model key issues like PU, MET → we rely on MC only for the tau decay



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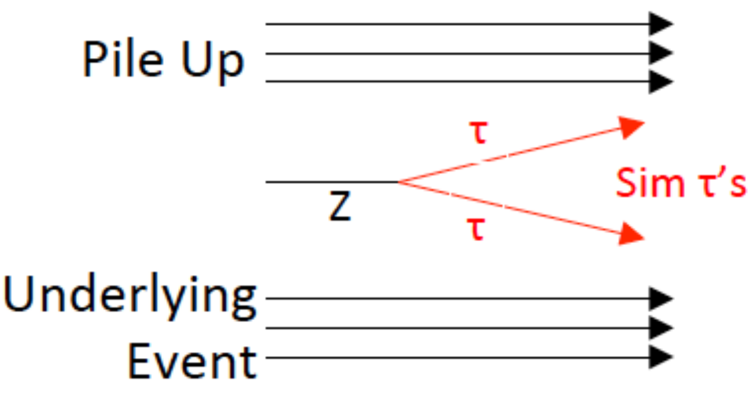

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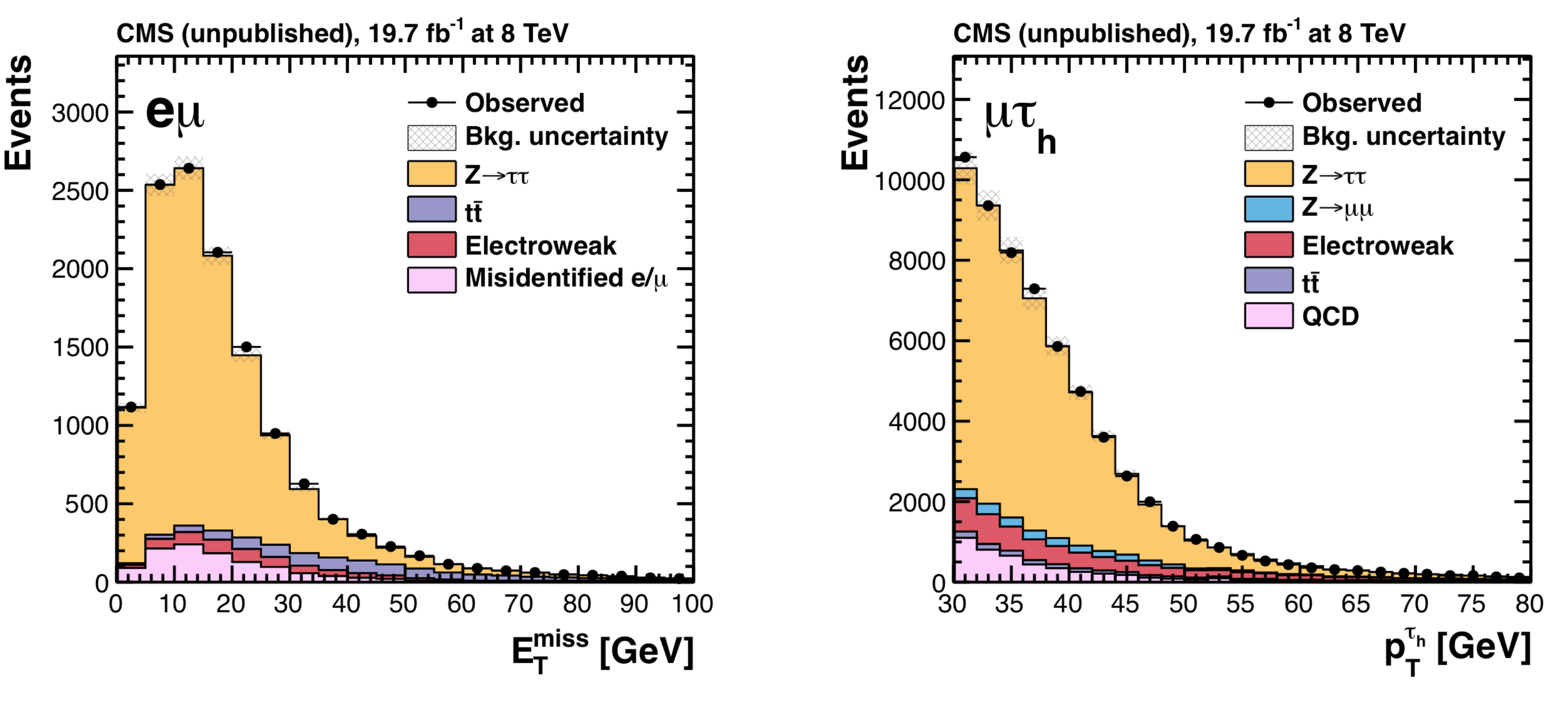


- Excellent data/MC agreement
- (Plots from SM Higgs Search, HIG-13-004)

# Jet→Lepton misidentification

- Leptons can arise from mis-id'ed jets in W+Jets and QCD multijet events → Difficult to model on MC → will be estimated directly on data

① **Measure the misidentification rate in an independent Zμμ sample**

$$f_\mu = \frac{N_{events}(Z(\mu\mu) + X = (\mu, isolated)}{N_{events}(Z(\mu\mu) + X = (\mu, not - isolated))}.$$

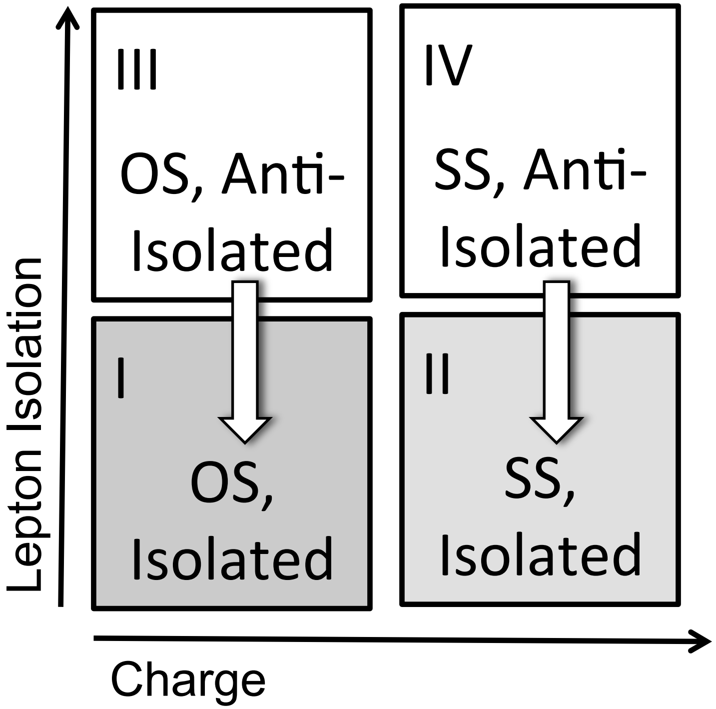
(similarly for fake electrons)

② **Apply** this ratio of non-isolated to isolated muons to **a data sample with anti-isolation required for one lepton that otherwise fulfills all selection criteria**

**Shape and yield prediction** for fake lepton backgrounds (mainly W+Jets)

# Jet→Lepton misidentification

- Validation based on SS control region



III

OS, Anti-Isolated

IV

SS, Anti-Isolated

I

OS, Isolated

II

SS, Isolated

Lepton Isolation

Charge

40% systematic uncertainty assigned to the rate
Shape uncertainty derived from the statistics of the Zμμ datasample

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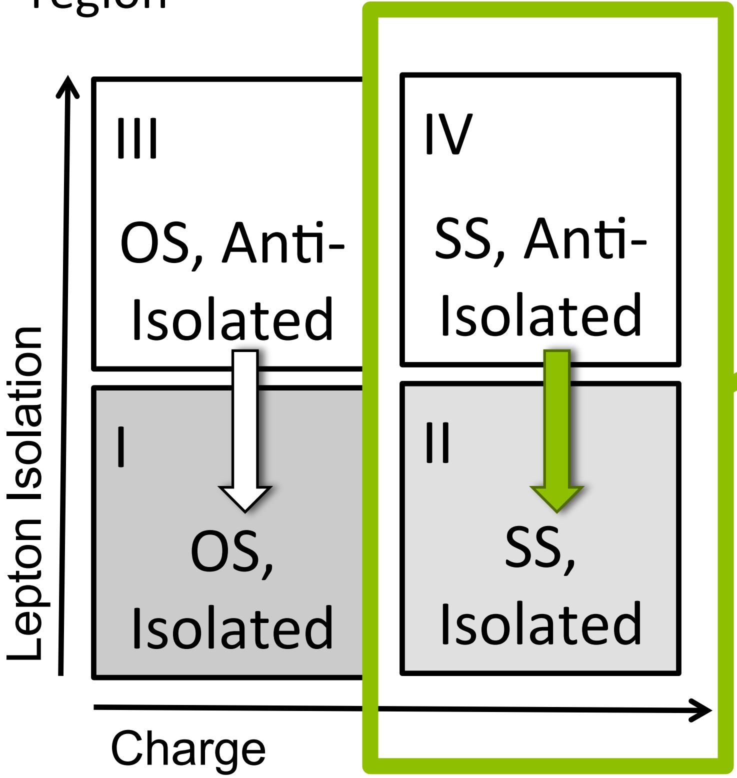
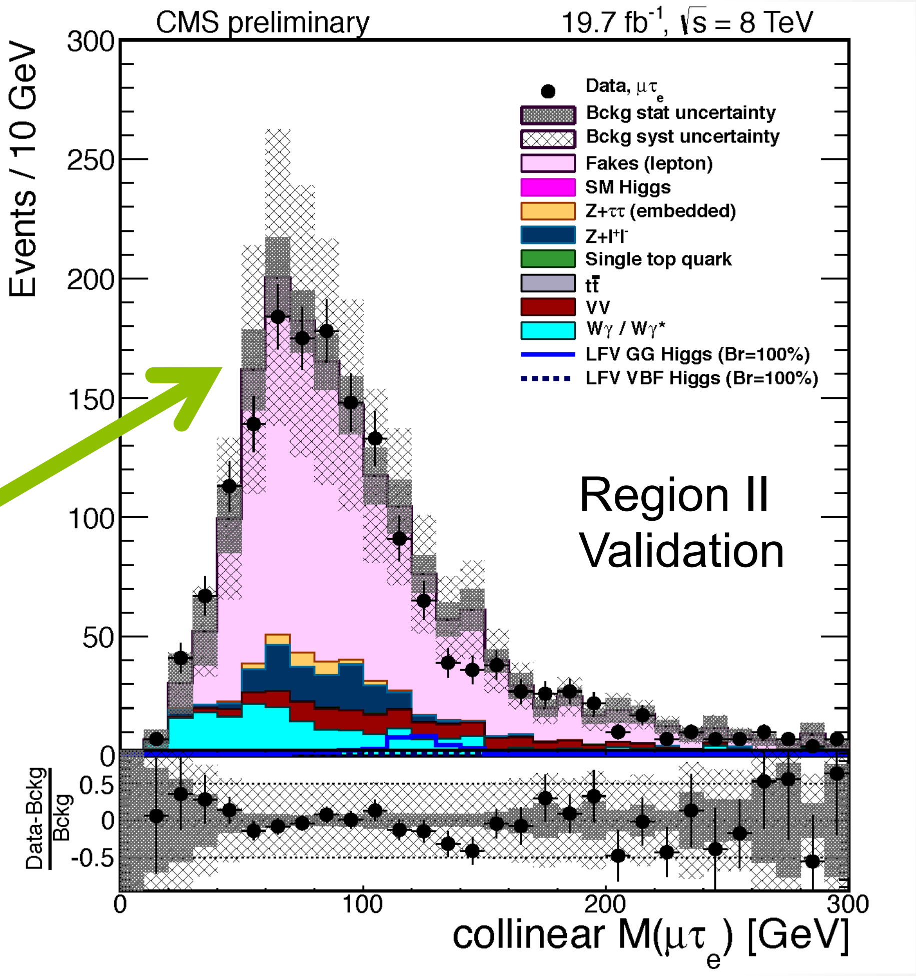
- Validation based on SS control region



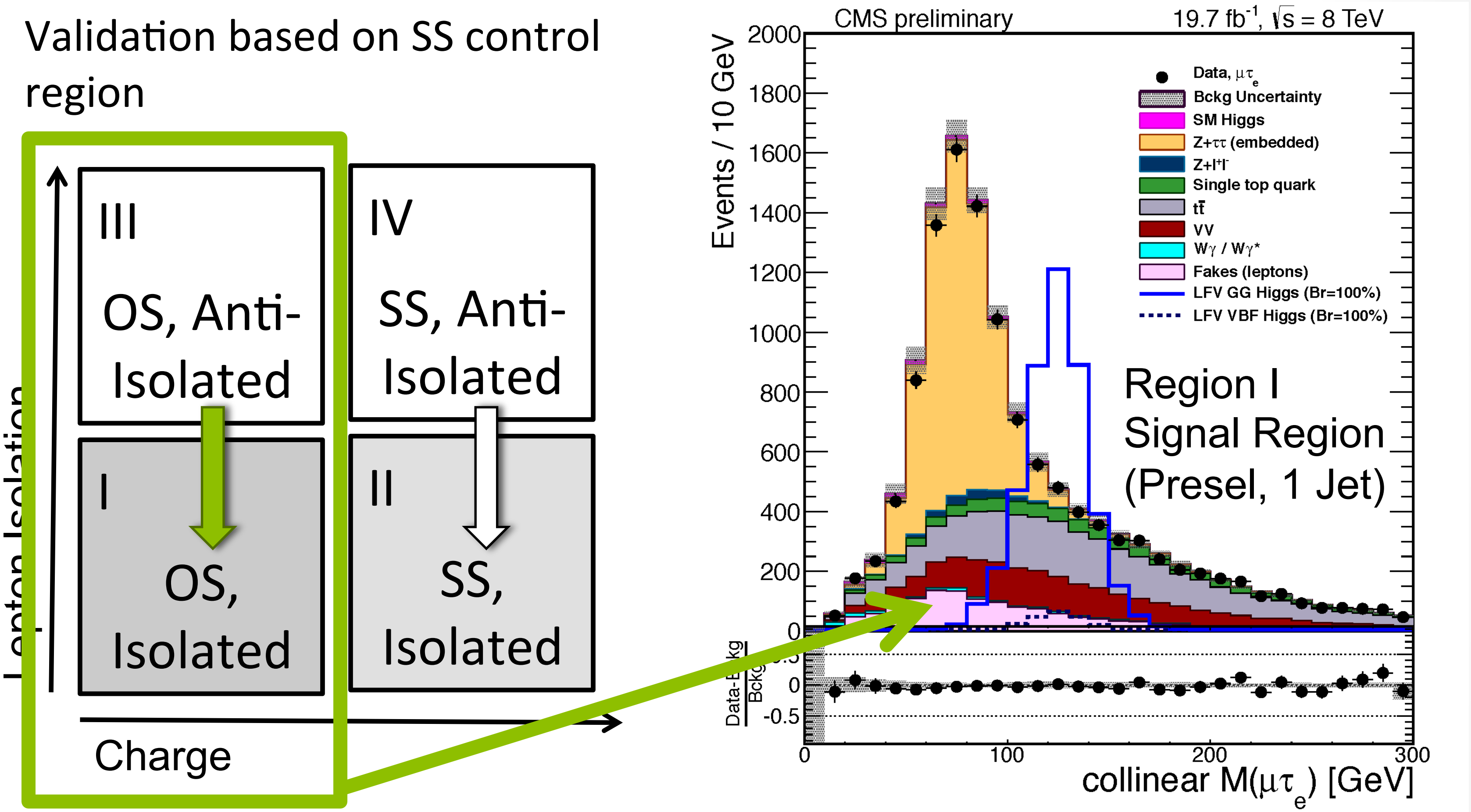


40% systematic uncertainty assigned to the rate

Shape uncertainty derived from the statistics of the Zμμ datasample

# Jet→Lepton misidentification

- Validation based on SS control region



40% systematic uncertainty assigned to the rate
Shape uncertainty derived from the statistics of the Zμμ datasample

# Jet→Tau misidentification

- Similarly, hadronic taus can arise from misid'ed jets that pass our tau selection criteria → Very difficult to model in MC!

① **Measure the rate of jets faking our tau selection in a Z sample and parameterize as a function of jet/tau kinematics**

$$f_\tau = \frac{N_{events}(Z(\mu\mu) + X = (\tau, ID + tight - isolated))}{N_{events}(Z(\mu\mu) + X = (\tau, ID + loose - isolated))}$$

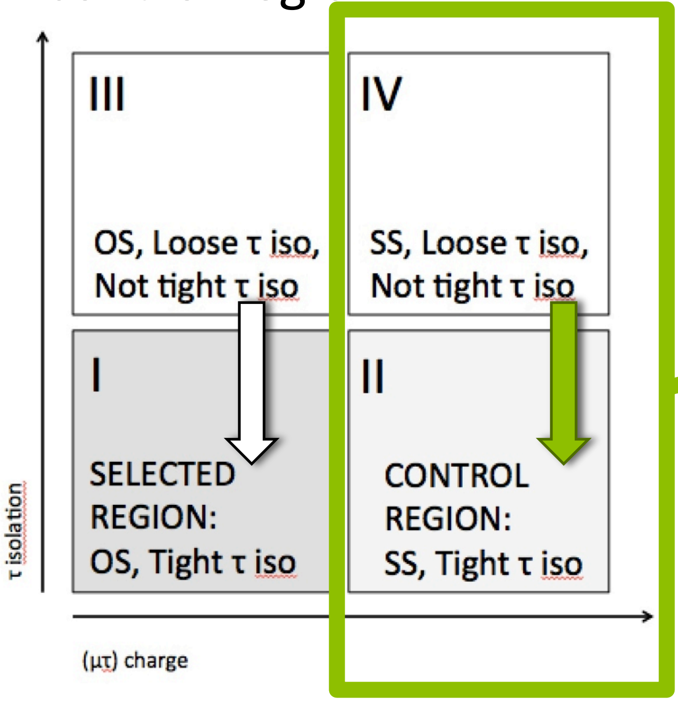
② Extrapolate to **a single-muon data sample** to obtain both shape and yield of WJets/QCD fake tau contribution in data:

$$N_{events}(\tau_{tight-isolated}) = \frac{f_\tau}{(1 - f_\tau)} N_{events}(\tau_{loose-isolated.\&.not-tight-isolated})$$

**Shape and yield prediction** for fake tau backgrounds (mainly W +Jets, small contributions of QCD, TT, ZMuMu…)

# Jet→Tau misidentification

- Validation based on SS control region



III

OS, Loose τ iso,
Not tight τ iso

IV

SS, Loose τ iso,
Not tight τ iso

I

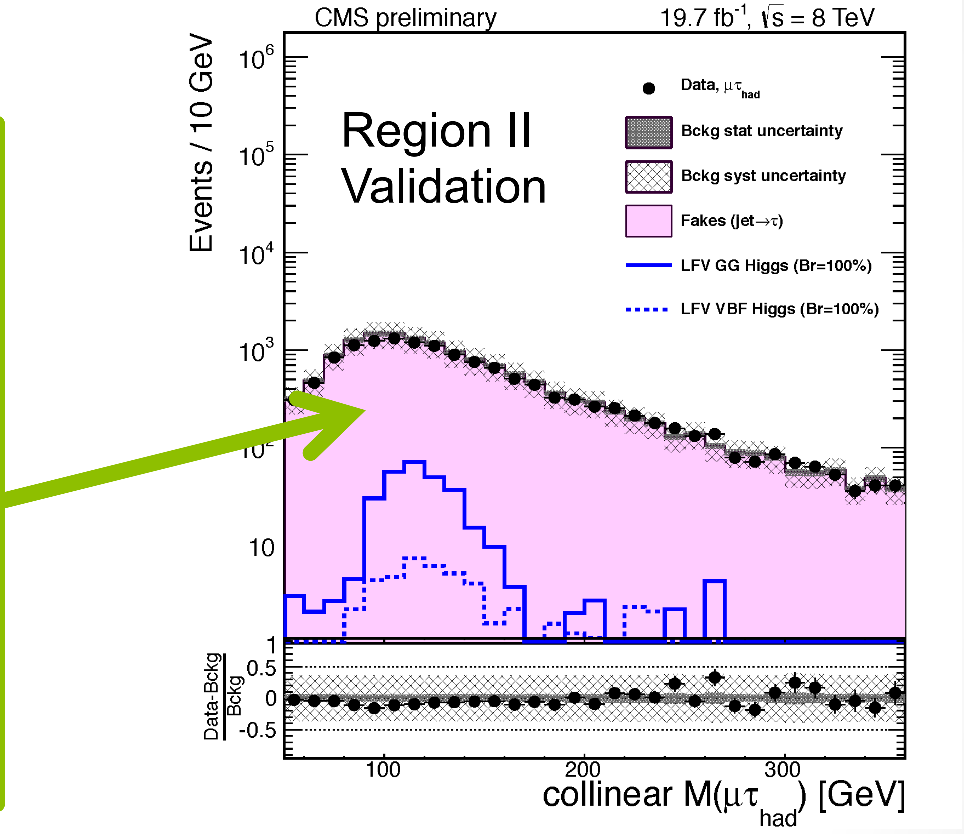
SELECTED
REGION:
OS, Tight τ iso

II

CONTROL
REGION:
SS, Tight τ iso

τ isolation

(μτ) charge



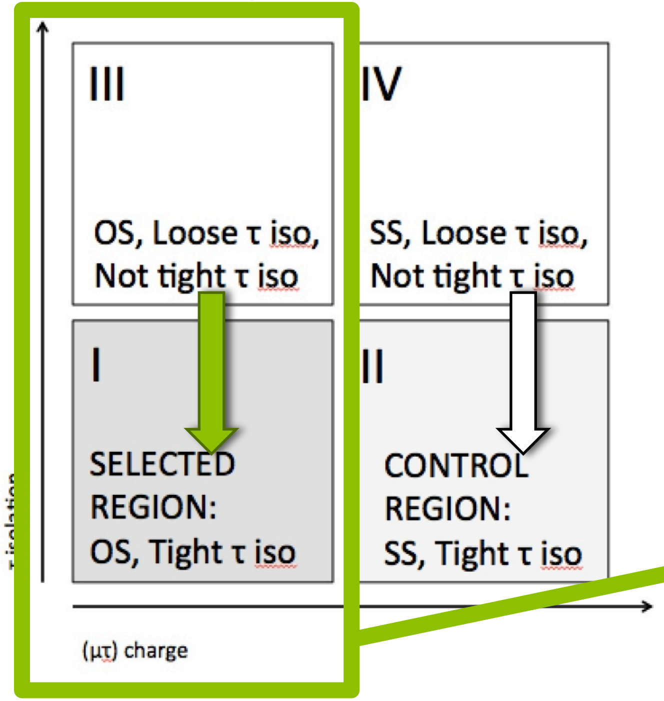
30% systematic uncertainty assigned to the rate

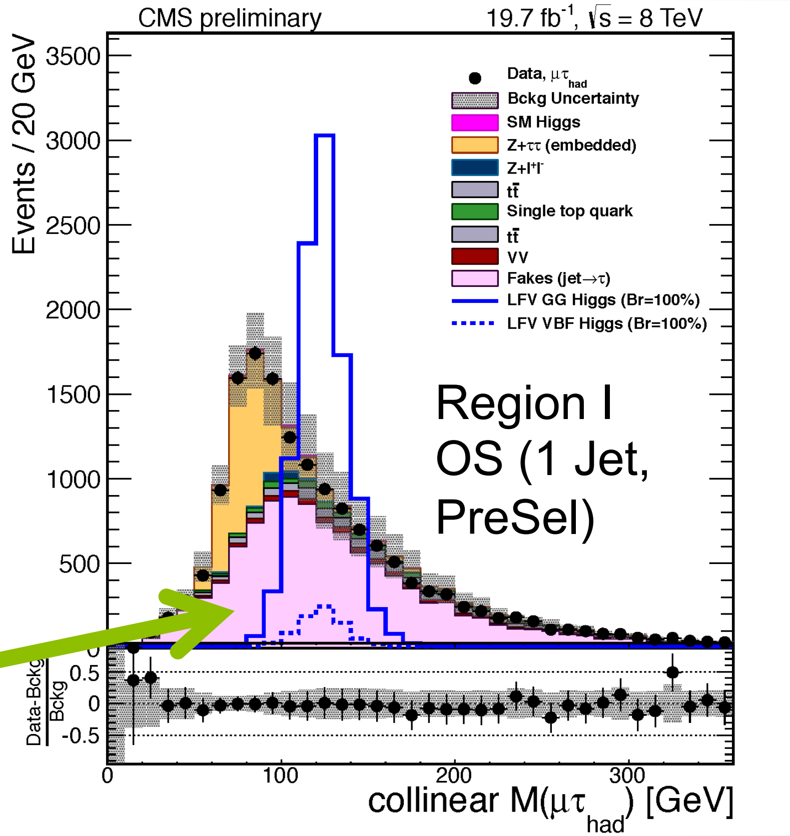
Covers (conservatively) differences between the W&Z+Jets production, and differences between EWK-like and QCD-like tau fake production

Additional shape uncertainty based on the stability of the parametrization

# Jet→Tau misidentification

- Validation based on SS control region





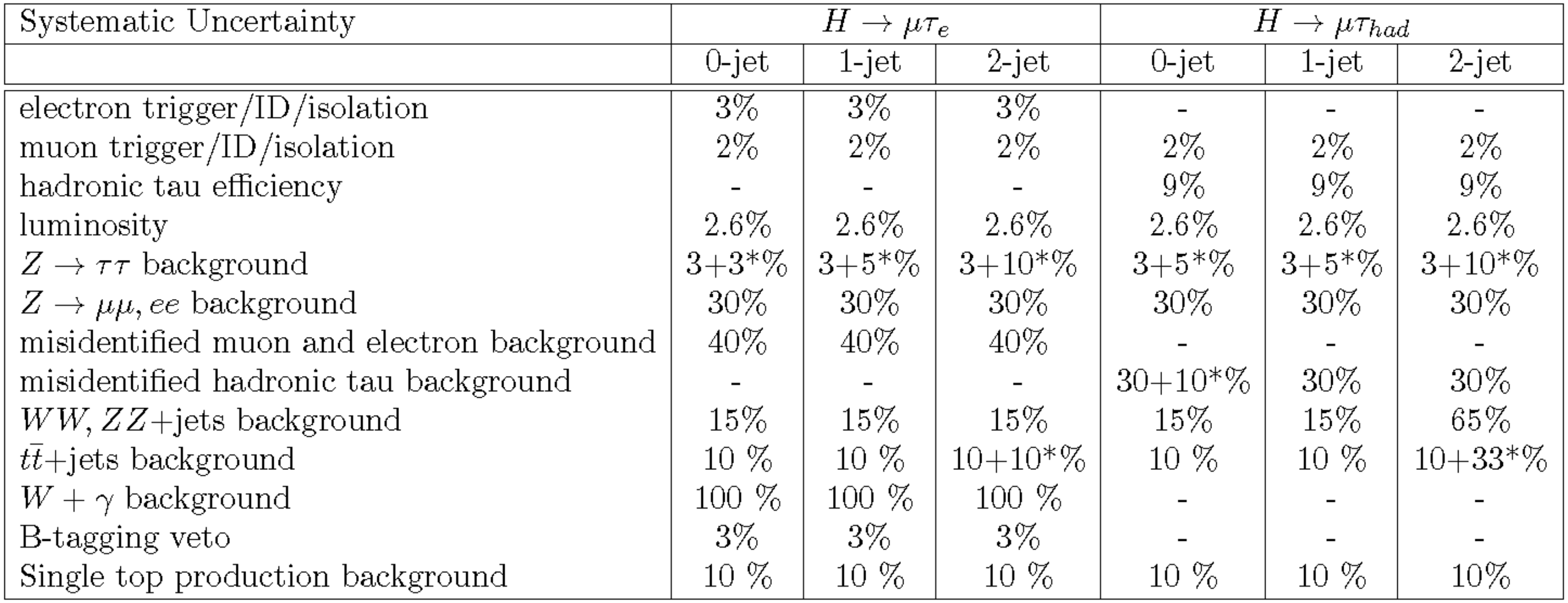
30% systematic uncertainty assigned to the rate

Covers (conservatively) differences between the W&Z+Jets production, and differences between EWK-like and QCD-like tau fake production

Additional shape uncertainty based on the stability of the parametrization

# Systematic Uncertainties

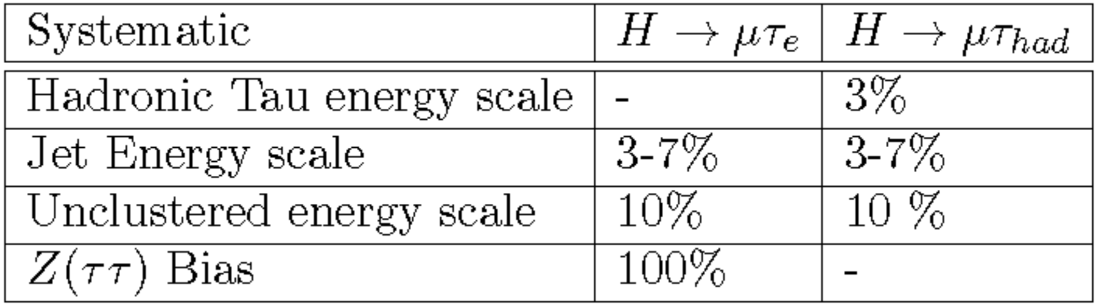
- Background modeling (specially the fake background) is the lead experimental systematic uncertainty
  - Normalization uncertainty taken either from our data driven estimates or from CMS measurements and correlated between bins
  - Additional uncorrelated uncertainty include to account for potential control region biases
- **The remaining experimental uncertainties (eg: lepton efficiencies) come from dedicated data studies performed centrally in CMS**



| Systematic Uncertainty | $H \to \mu\tau_e$ | | | $H \to \mu\tau_{had}$ | | |
|---|---|---|---|---|---|---|
| | 0-jet | 1-jet | 2-jet | 0-jet | 1-jet | 2-jet |
| electron trigger/ID/isolation | 3% | 3% | 3% | - | - | - |
| muon trigger/ID/isolation | 2% | 2% | 2% | 2% | 2% | 2% |
| hadronic tau efficiency | - | - | - | 9% | 9% | 9% |
| luminosity | 2.6% | 2.6% | 2.6% | 2.6% | 2.6% | 2.6% |
| $Z \to \tau\tau$ background | 3+3*% | 3+5*% | 3+10*% | 3+5*% | 3+5*% | 3+10*% |
| $Z \to \mu\mu, ee$ background | 30% | 30% | 30% | 30% | 30% | 30% |
| misidentified muon and electron background | 40% | 40% | 40% | - | - | - |
| misidentified hadronic tau background | - | - | - | 30+10*% | 30% | 30% |
| $WW, ZZ$+jets background | 15% | 15% | 15% | 15% | 15% | 65% |
| $t\bar{t}$+jets background | 10 % | 10 % | 10+10*% | 10 % | 10 % | 10+33*% |
| $W + \gamma$ background | 100 % | 100 % | 100 % | - | - | - |
| B-tagging veto | 3% | 3% | 3% | - | - | - |
| Single top production background | 10 % | 10 % | 10 % | 10 % | 10 % | 10% |

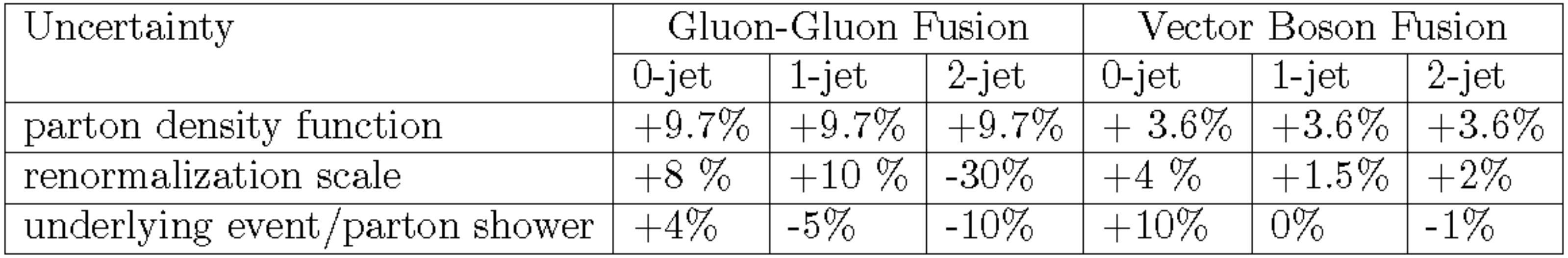
# Systematic Uncertainties

- Additional experimental systematic uncertainties (effects on the mass resolution and shape):



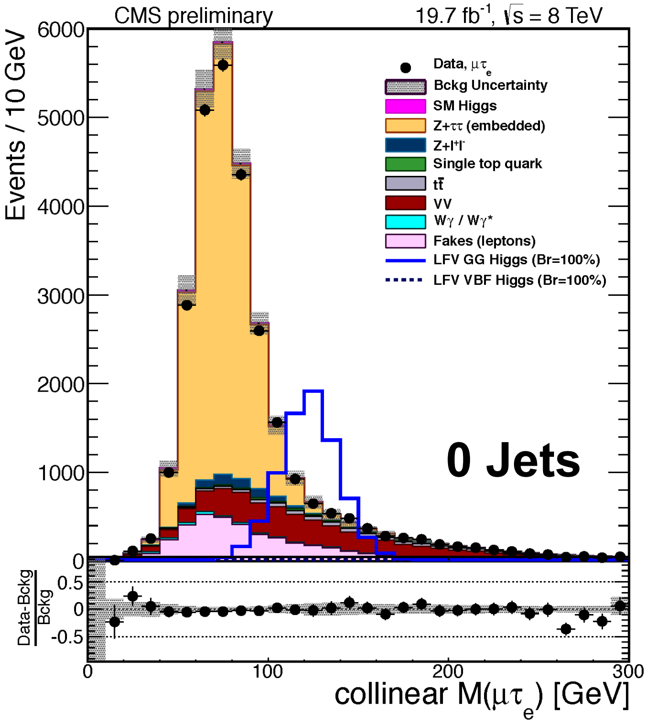
| Systematic | $H \to \mu\tau_e$ | $H \to \mu\tau_{had}$ |
|---|---|---|
| Hadronic Tau energy scale | - | 3% |
| Jet Energy scale | 3-7% | 3-7% |
| Unclustered energy scale | 10% | 10 % |
| $Z(\tau\tau)$ Bias | 100% | - |

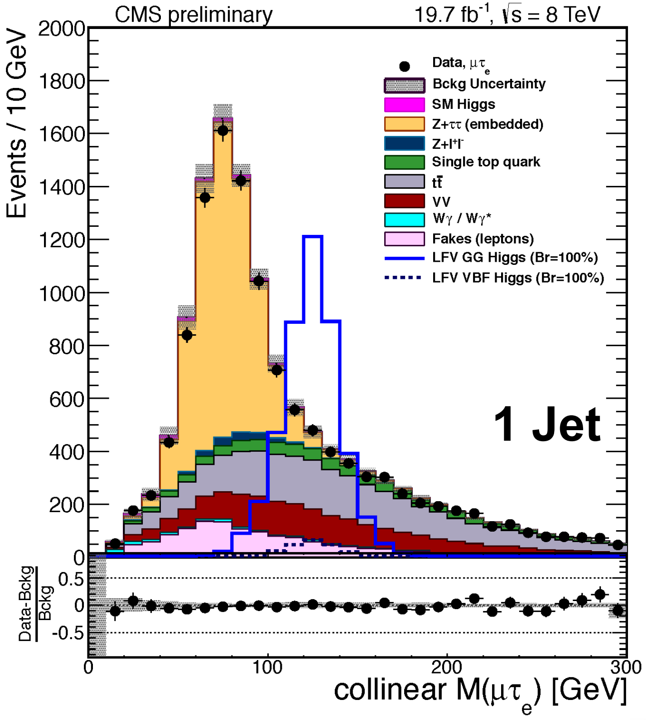
- Theoretical uncertainties:



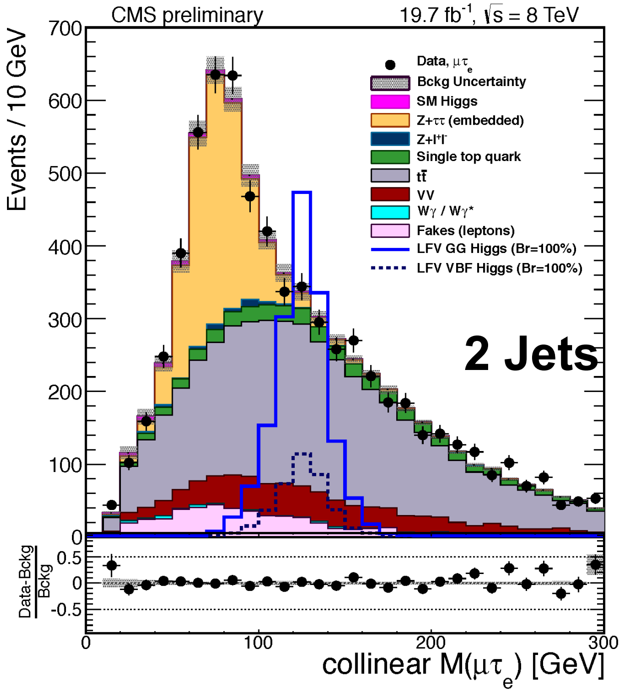
| Uncertainty | Gluon-Gluon Fusion | | | Vector Boson Fusion | | |
|---|---|---|---|---|---|---|
| | 0-jet | 1-jet | 2-jet | 0-jet | 1-jet | 2-jet |
| parton density function | +9.7% | +9.7% | +9.7% | + 3.6% | +3.6% | +3.6% |
| renormalization scale | +8 % | +10 % | -30% | +4 % | +1.5% | +2% |
| underlying event/parton shower | +4% | -5% | -10% | +10% | 0% | -1% |

# PUTTING ALL THE PIECES TOGETHER …





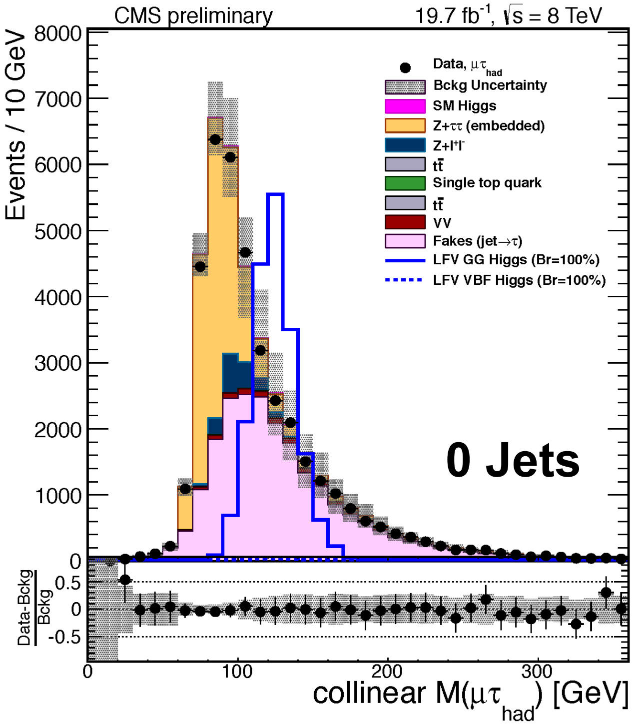
# $\mu\tau_e$

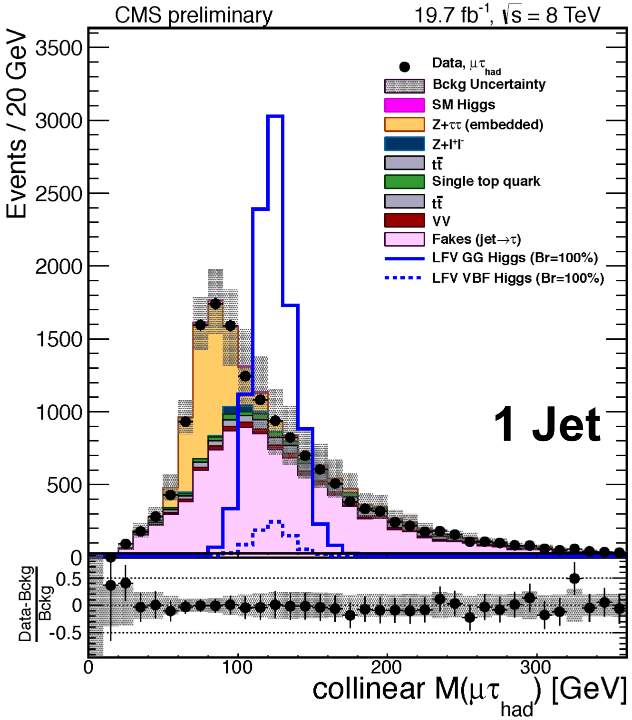


Br(H→μτ)=100%

# Preselection / Control Region

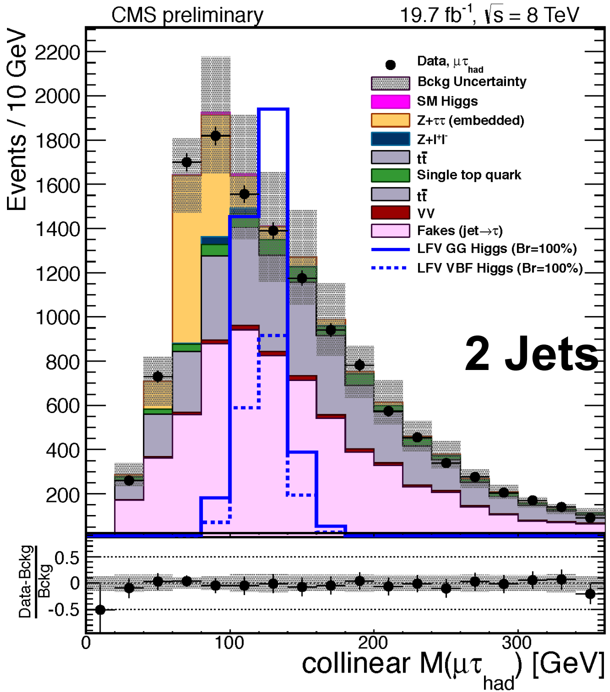
Excellent data/ mc agreement





# $\mu\tau_{had}$

## Preselection / Control Region



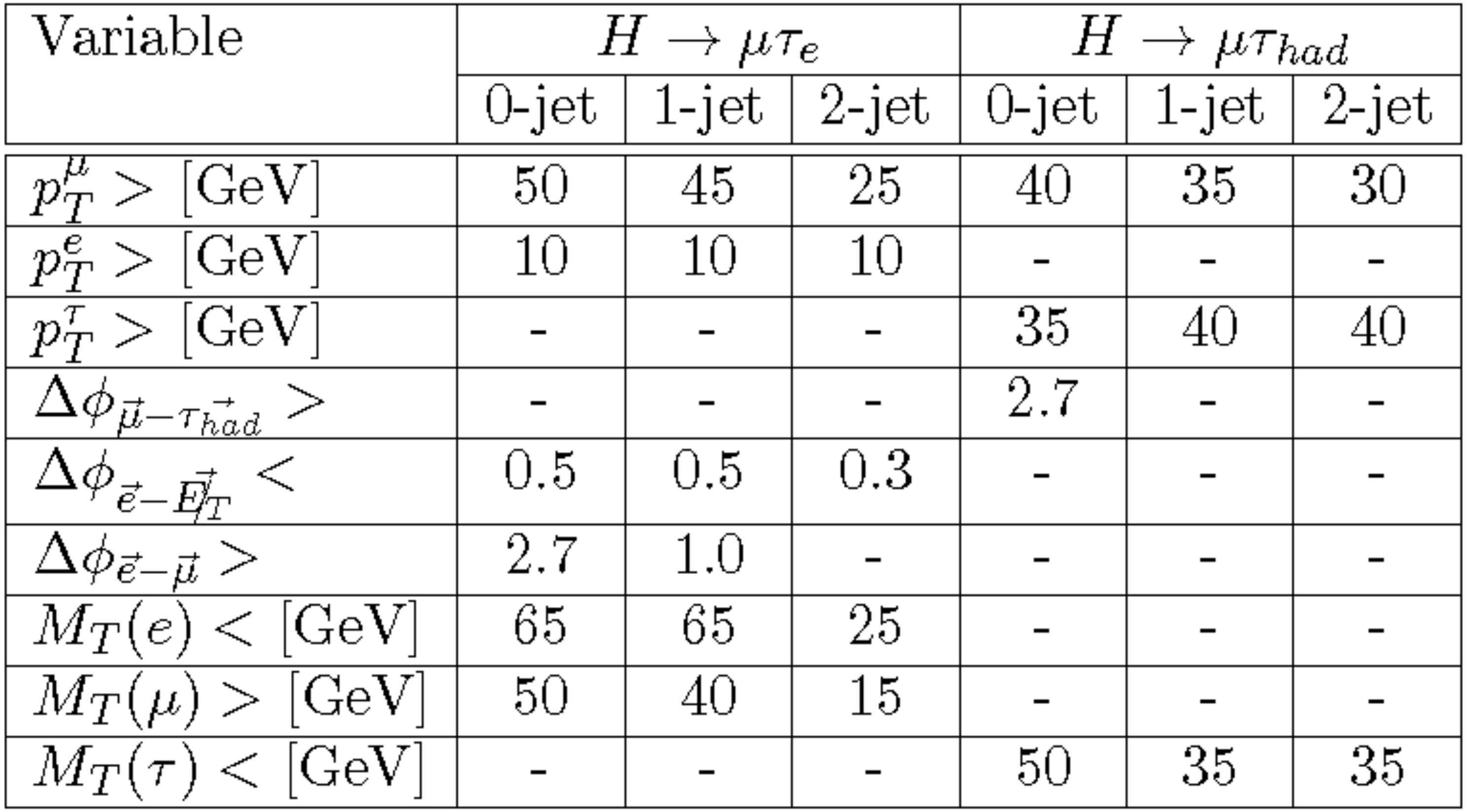
Br(H→μτ)=100%

Excellent data/ mc agreement

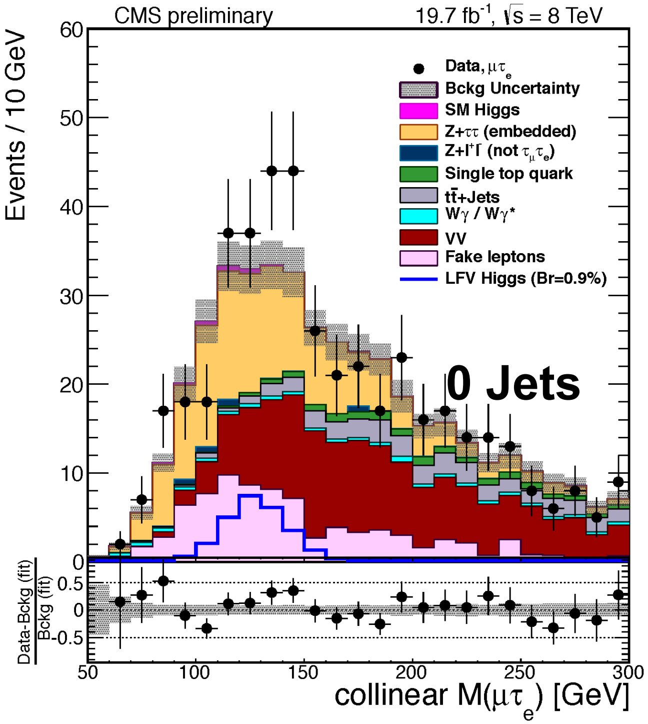
# FINALLY: FULL SELECTION & RESULTS

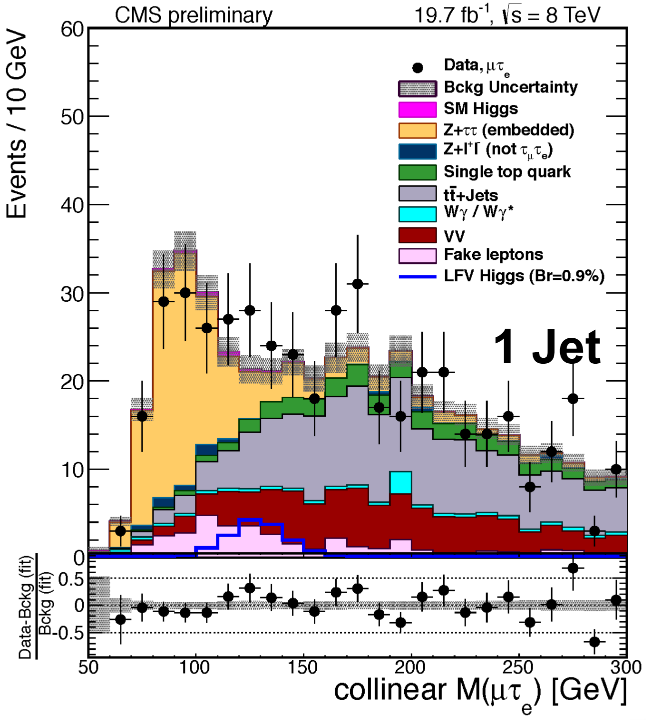
# Full Selection

- →Greatly improve S/B by applying what we have learned about kinematics → higher muon $p_T$, smart angular requirements
- →Differentiated by category to account for differences in sample composition in the 0-1-2 Jet bins



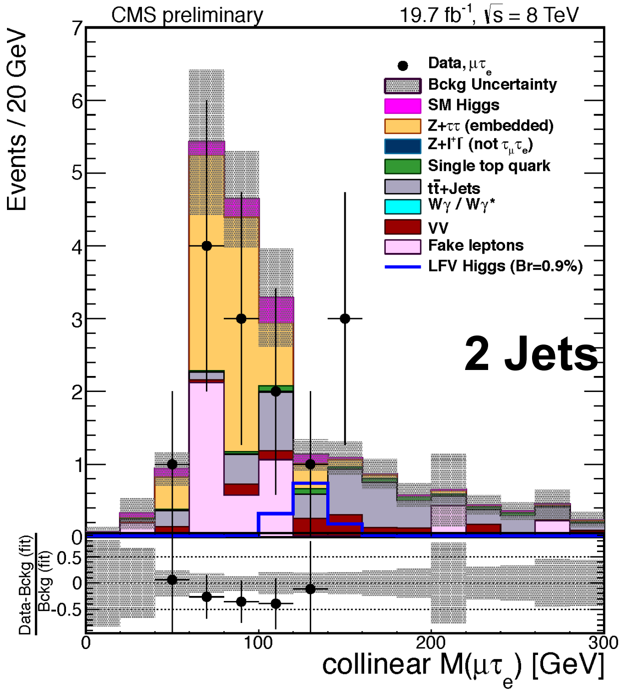
| Variable | $H \rightarrow \mu\tau_e$ | | | $H \rightarrow \mu\tau_{had}$ | | |
|---|---|---|---|---|---|---|
| | 0-jet | 1-jet | 2-jet | 0-jet | 1-jet | 2-jet |
| $p_T^\mu >$ [GeV] | 50 | 45 | 25 | 40 | 35 | 30 |
| $p_T^e >$ [GeV] | 10 | 10 | 10 | - | - | - |
| $p_T^\tau >$ [GeV] | - | - | - | 35 | 40 | 40 |
| $\Delta\phi_{\vec{\mu}-\vec{\tau}_{had}} >$ | - | - | - | 2.7 | - | - |
| $\Delta\phi_{\vec{e}-\vec{E\!\!\!/}_T} <$ | 0.5 | 0.5 | 0.3 | - | - | - |
| $\Delta\phi_{\vec{e}-\vec{\mu}} >$ | 2.7 | 1.0 | - | - | - | - |
| $M_T(e) <$ [GeV] | 65 | 65 | 25 | - | - | - |
| $M_T(\mu) >$ [GeV] | 50 | 40 | 15 | - | - | - |
| $M_T(\tau) <$ [GeV] | - | - | - | 50 | 35 | 35 |

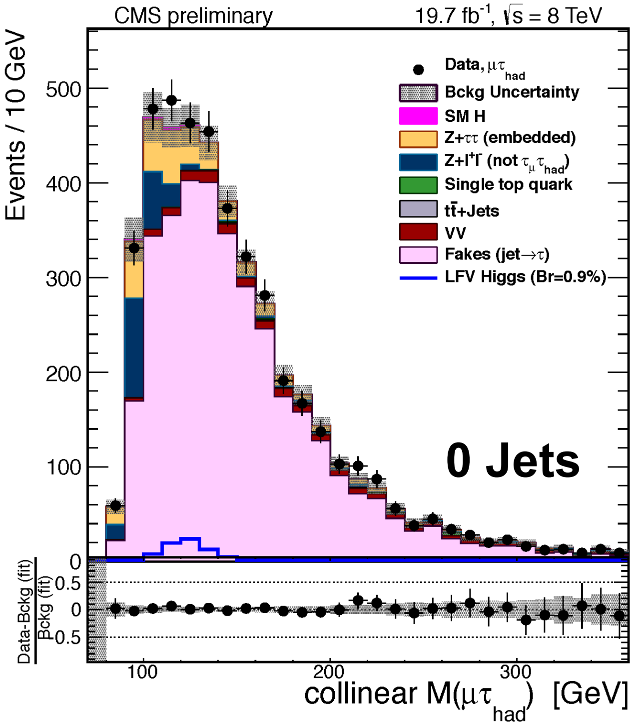


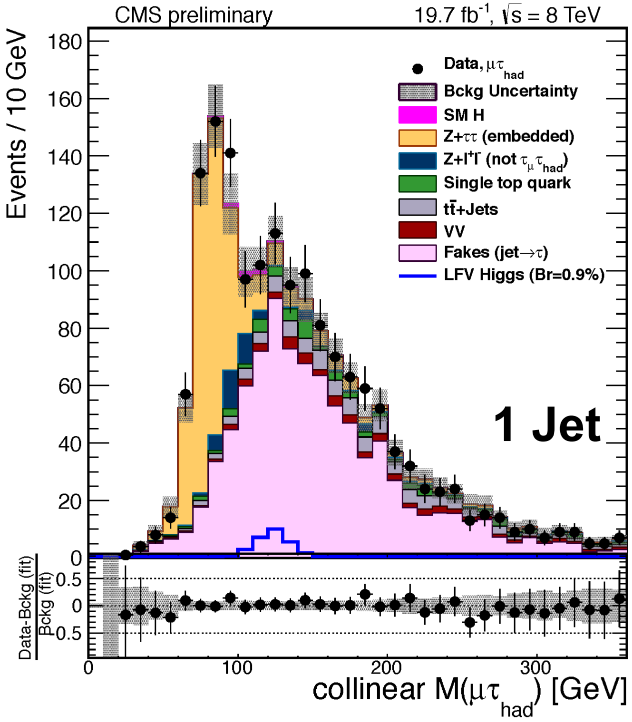


# $\mu\tau_e$

(Br(H→μτ)=0.9%)

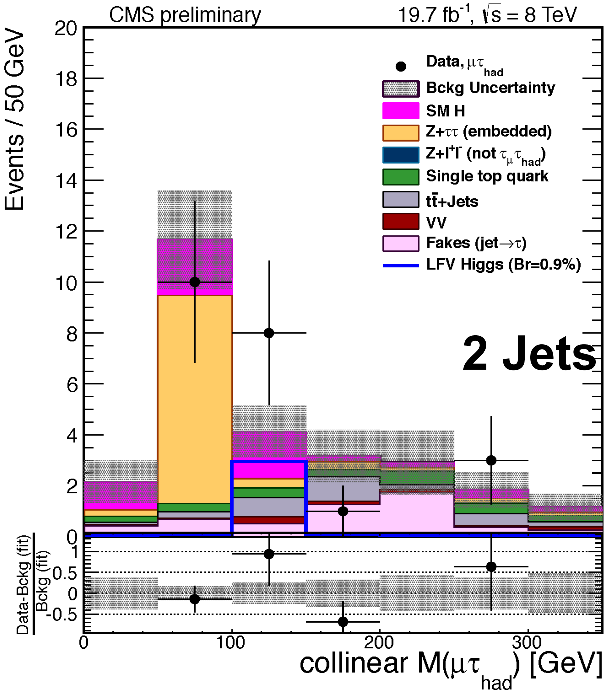




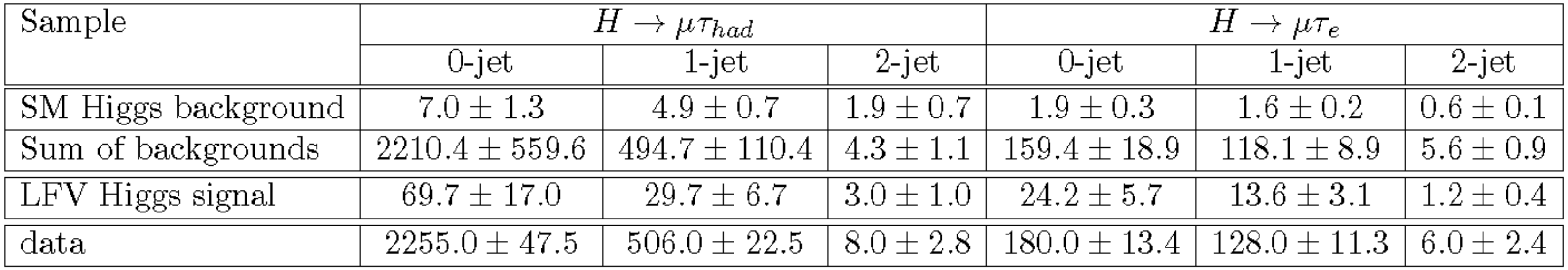


# $\mu\tau_{had}$

(Br(H→μτ)=0.9%)

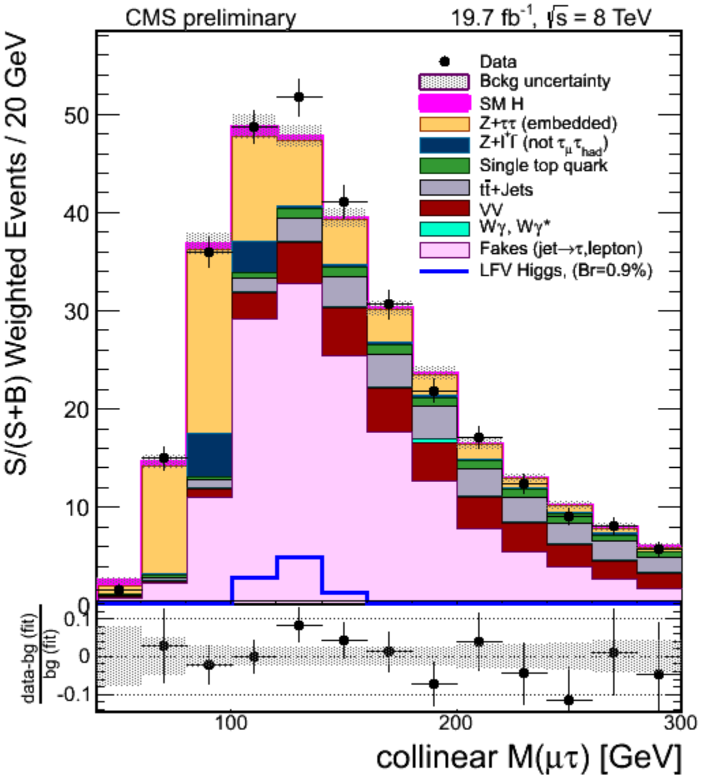


# Analysis of the data

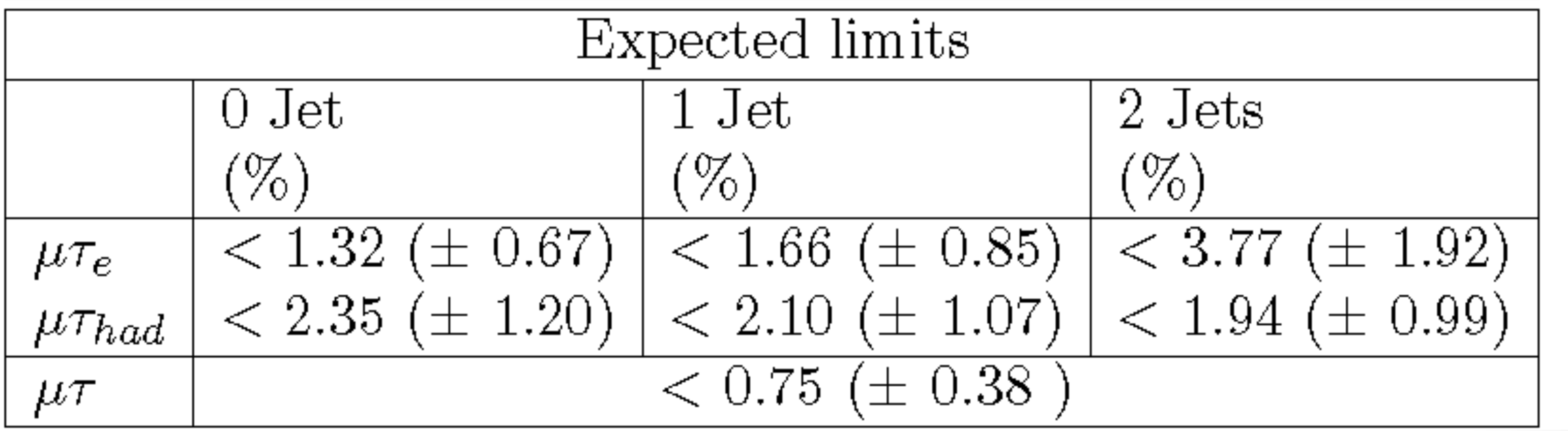


<table>
<tr><th rowspan="2">Sample</th><th colspan="3">$H \to \mu\tau_{had}$</th><th colspan="3">$H \to \mu\tau_e$</th></tr>
<tr><th>0-jet</th><th>1-jet</th><th>2-jet</th><th>0-jet</th><th>1-jet</th><th>2-jet</th></tr>
<tr><td>SM Higgs background</td><td>$7.0 \pm 1.3$</td><td>$4.9 \pm 0.7$</td><td>$1.9 \pm 0.7$</td><td>$1.9 \pm 0.3$</td><td>$1.6 \pm 0.2$</td><td>$0.6 \pm 0.1$</td></tr>
<tr><td>Sum of backgrounds</td><td>$2210.4 \pm 559.6$</td><td>$494.7 \pm 110.4$</td><td>$4.3 \pm 1.1$</td><td>$159.4 \pm 18.9$</td><td>$118.1 \pm 8.9$</td><td>$5.6 \pm 0.9$</td></tr>
<tr><td>LFV Higgs signal</td><td>$69.7 \pm 17.0$</td><td>$29.7 \pm 6.7$</td><td>$3.0 \pm 1.0$</td><td>$24.2 \pm 5.7$</td><td>$13.6 \pm 3.1$</td><td>$1.2 \pm 0.4$</td></tr>
<tr><td>data</td><td>$2255.0 \pm 47.5$</td><td>$506.0 \pm 22.5$</td><td>$8.0 \pm 2.8$</td><td>$180.0 \pm 13.4$</td><td>$128.0 \pm 11.3$</td><td>$6.0 \pm 2.4$</td></tr>
</table>

- Fit to the collinear mass distribution using templates of background and signal shapes
  - Systematic uncertainties treated as nuisance parameters in the fit
- Extract 95% CL limits on branching ratio of H → μτ
  - Set using $CL_s$ method

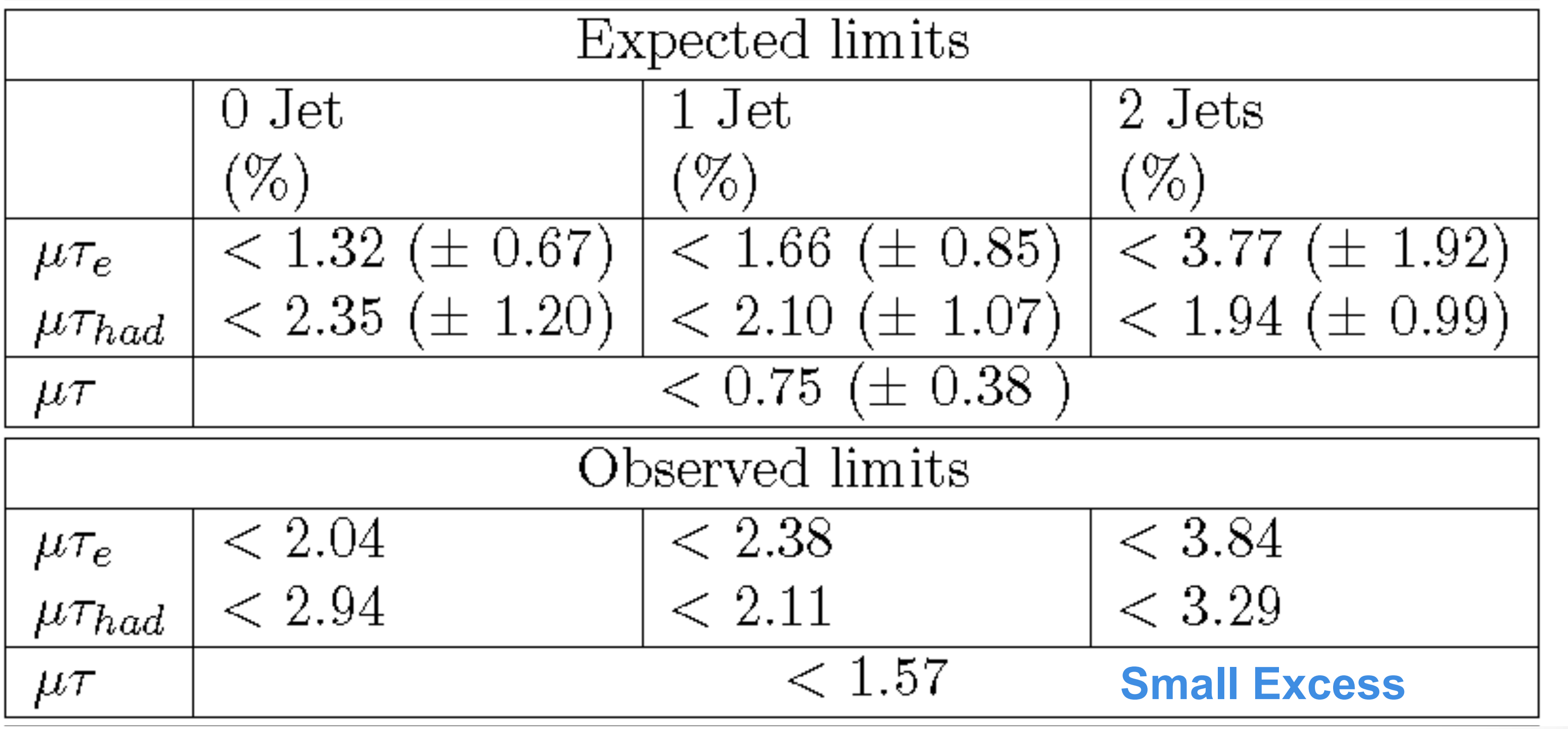


# Observed vs Expected Limits



| Expected limits | | | |
|---|---|---|---|
| | 0 Jet (%) | 1 Jet (%) | 2 Jets (%) |
| $\mu\tau_e$ | $< 1.32\ (\pm\ 0.67)$ | $< 1.66\ (\pm\ 0.85)$ | $< 3.77\ (\pm\ 1.92)$ |
| $\mu\tau_{had}$ | $< 2.35\ (\pm\ 1.20)$ | $< 2.10\ (\pm\ 1.07)$ | $< 1.94\ (\pm\ 0.99)$ |
| $\mu\tau$ | $< 0.75\ (\pm\ 0.38\ )$ | | |

# Observed vs Expected Limits



Expected limits

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|---|---|---|---|
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| $\mu\tau$ | $< 0.75$ ($\pm$ 0.38 ) | | |

Observed limits

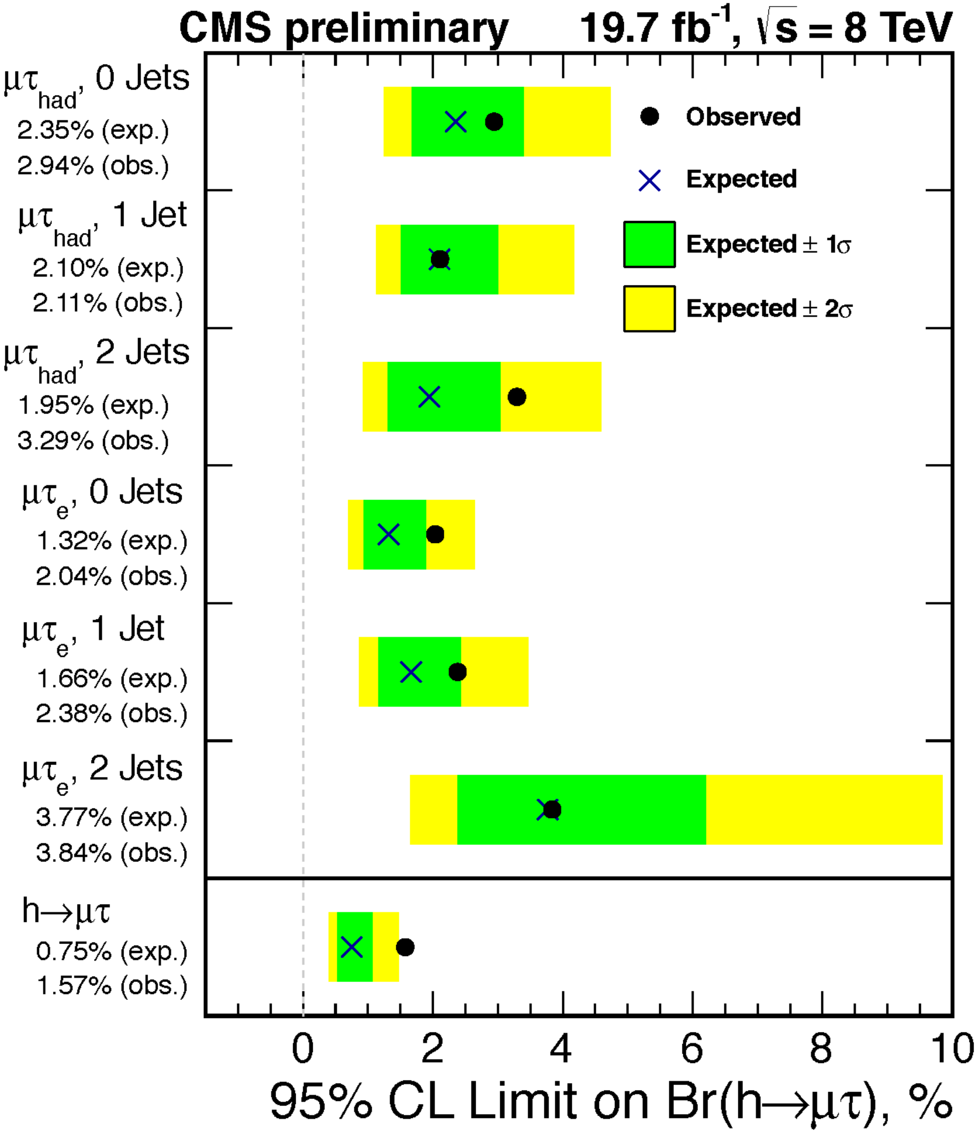
| | | | |
|---|---|---|---|
| $\mu\tau_e$ | $< 2.04$ | $< 2.38$ | $< 3.84$ |
| $\mu\tau_{had}$ | $< 2.94$ | $< 2.11$ | $< 3.29$ |
| $\mu\tau$ | $< 1.57$ | | |

**Small Excess**

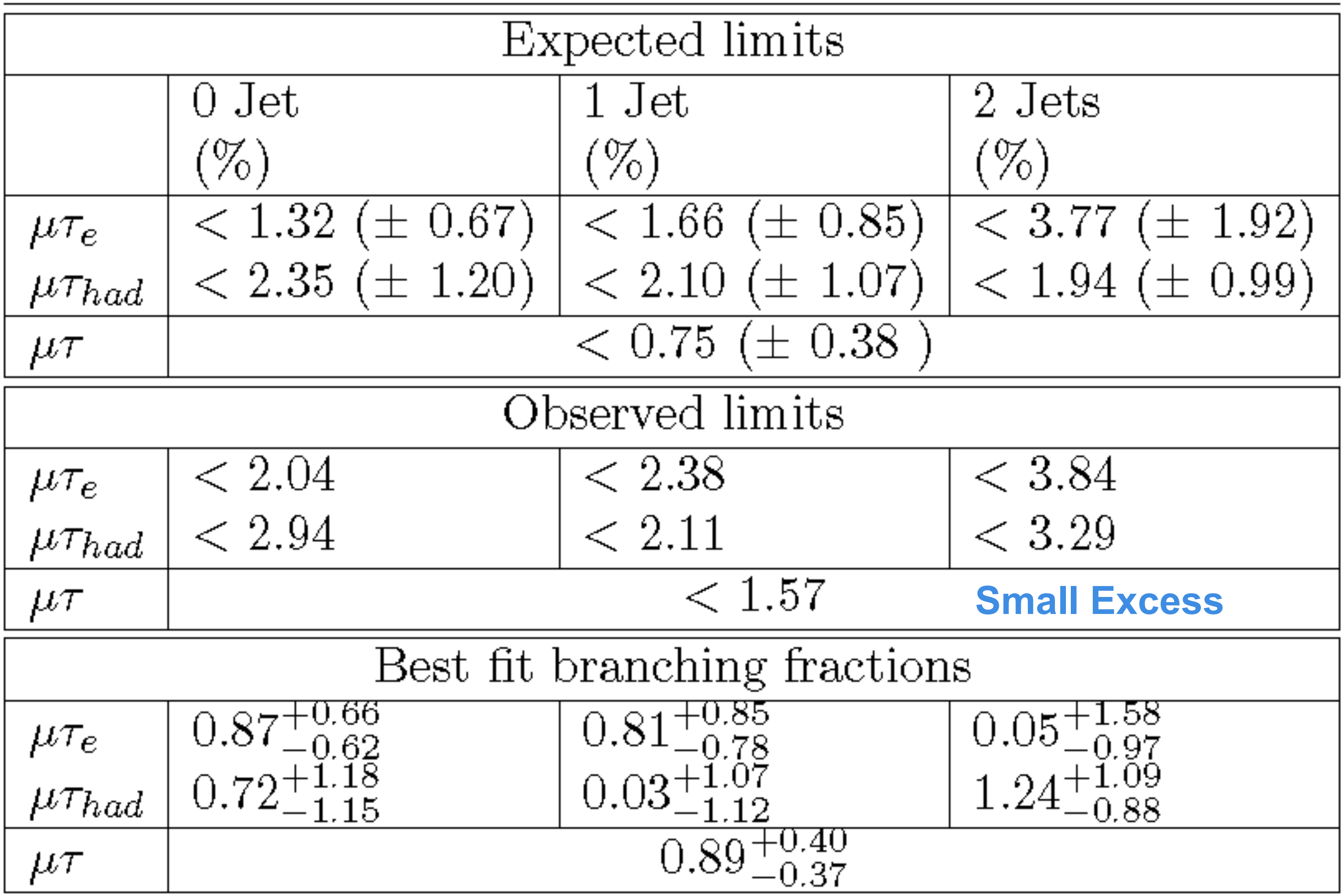
# Observed vs Expected Limits

- Small deviations per category (~1sigma)

- Combined they yield a 2.5 sigma deviation from the expected Br Limit



# Observed vs Expected Limits



| Expected limits | | | |
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| **Observed limits** | | | |
| $\mu\tau_e$ | $< 2.04$ | $< 2.38$ | $< 3.84$ |
| $\mu\tau_{had}$ | $< 2.94$ | $< 2.11$ | $< 3.29$ |
| $\mu\tau$ | $< 1.57$ | | |
| **Best fit branching fractions** | | | |
| $\mu\tau_e$ | $0.87^{+0.66}_{-0.62}$ | $0.81^{+0.85}_{-0.78}$ | $0.05^{+1.58}_{-0.97}$ |
| $\mu\tau_{had}$ | $0.72^{+1.18}_{-1.15}$ | $0.03^{+1.07}_{-1.12}$ | $1.24^{+1.09}_{-0.88}$ |
| $\mu\tau$ | $0.89^{+0.40}_{-0.37}$ | | |

**Small Excess**

# Interpretation: Off-Diagonal Yukawa couplings

- The width of the LFV Higgs decay can be determined from the LFV Yukawa couplings in the Lagrangian

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

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

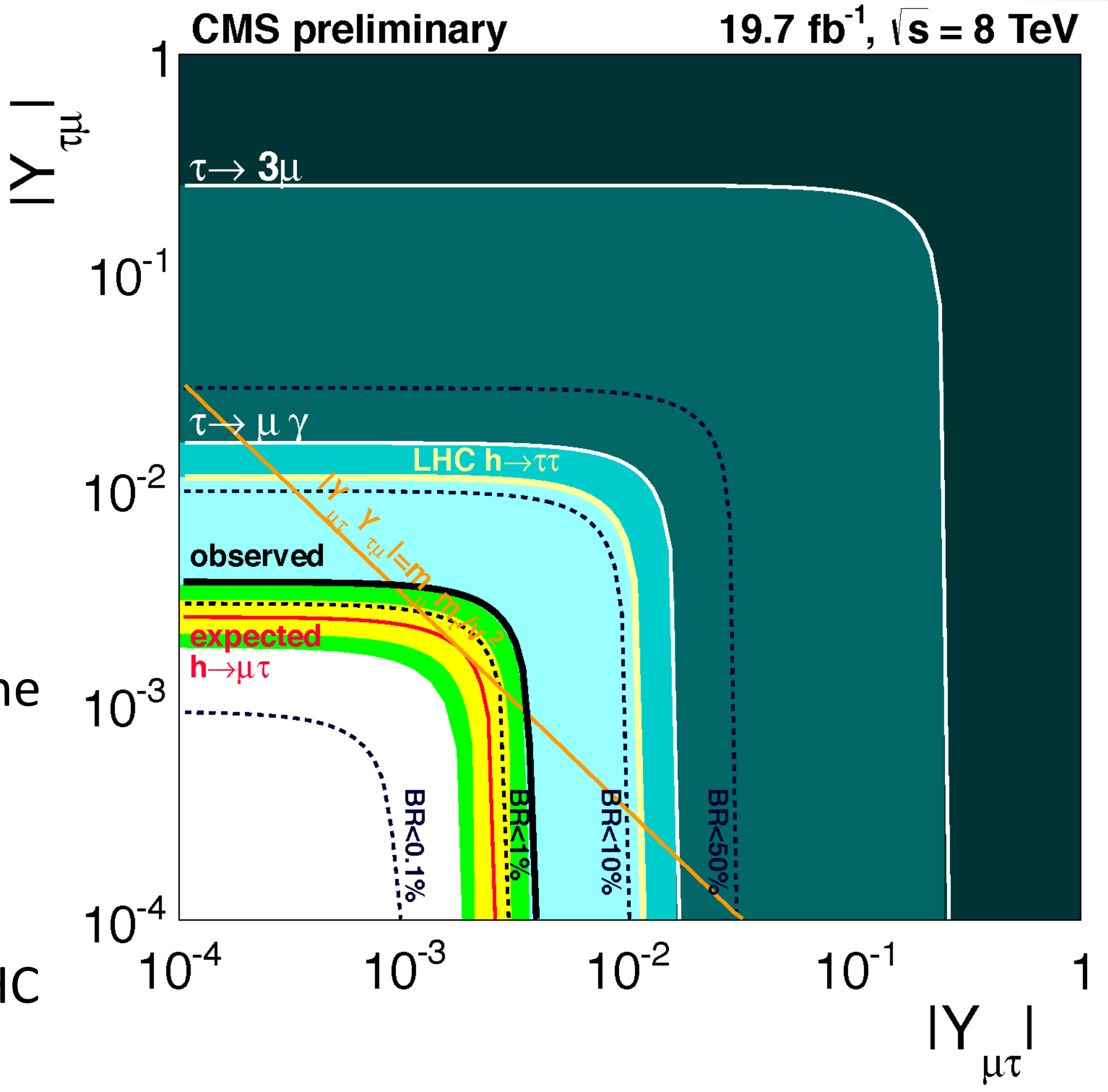
$$\mathrm{BR}(h \to \ell^\alpha\ell^\beta) = \frac{\Gamma(h \to \ell^\alpha\ell^\beta)}{\Gamma(h \to \ell^\alpha\ell^\beta) + \Gamma_{\mathrm{SM}}}$$

$$\boxed{\left(\left|Y_{\mu\tau}\right|^2 + \left|Y_{\tau\mu}\right|^2\right) = \frac{8\pi}{m_h}\frac{BR(h \to \mu\tau)\Gamma_{SM}}{1 - BR(h \to \mu\tau)}}$$

# New limit on $|Y_{\mu\tau}|$

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

(at 95% CL)



- Already digging into the “natural” regime
- 1 order of magnitude better than the pre-LHC limits

# SUMMARY

# Summary

- The SM-like Higgs boson discovery opens a era of Higgs precision physics

  → Searches in rarer modes become sensitive enough for discovery
- **CMS performed the first ever direct search for LFV Higgs decays**
  - **The branching ratio for LFV decay to μτ is constrained to be less than 1.57 %** (one order of magnitude better than previous experimental constraints)
  - The expected BR limit was 0.75 %
  - **A small excess at 2.5σ level with p-value of 0.007 is intriguing**
    - More data is needed to extract conclusions

# Summary

- The SM-like Higgs boson discovery opens a era of Higgs precision physics

  →Searches in rarer modes become sensitive enough for discovery
- CMS performed the first ever direct search for LFV Higgs decays
  - The branching ratio for LFV decay to μτ is constrained to be less than 1.57 % (one order of magnitude better than previous experimental constraints)
  - The expected BR limit was 0.75 %
  - A small excess at 2.5σ level with p-value of 0.007 is intriguing

- What next?
  - The LHC Run II @ 13 TeV ➔ 100 $\mathrm{fb}^{-1}$ is critical
  - Upgrades to accelerator and detector are underway
  - Promising exploration of new physics just around the corner

**Stay Tuned for 2015 surprises !!!**

# Further reading

- **CMS HIG-14-005: LFV Higgs Decays**

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig14005TWiki

- **CMS HIG-13-004: SM Hττ Search**

https://cds.cern.ch/record/1643937?ln=en

- R. Harnik, J. Kopp, J. Zupan, “Flavor Violating Higgs Decays”, arXiv: 1209.1397

# (Recent) theoretical references on LFV Higgs Decays

- G. Blankenburg, J. Ellis, G. Isidori, “Flavour-Changing Decays of a 125 GeV Higgs-like Particle”, arXiv:1202.5704
- A. Goudelis, O. Lebedev, J. H. Park, “Higgs-induced lepton flavor violation », arXiv:1111.1715
- D. McKeen, M. Pospelov, A. Ritz, “Modified Higgs branching ratios versus CP and lepton flavor violation“, arXiv:1208.4597
- A. Arhrib, Y. Cheng, O. C. Kong, “A Comprehensive Analysis on Lepton Flavor Violating Higgs to taumu Decay in Supersymmetry without R Parity”, arXiv:1210.8241
- K. Agashe, R. Contino, , “Composite Higgs-Mediated FCNC“, arXiv:0906.1542.
- A. Azatov, M. Toharia, L. Zhu,, “Higgs Mediated FCNC’s in Warped Extra Dimensions“, arXiv:0906.1990.
- G. Perez, L. Randall, “Natural Neutrino Masses and Mixings From Warped Geometry“, arXiv:0805.4652
- S. Casagrande, F. Goertz, U. Haisch, M. Neubert, T. Pfoh, “Flavor Physics in the Randall-Sundrum Model: I. Theoretical Setup and Electroweak Precision Tests“, arXiv:0807.4937

This is not a comprehensive list: See references in CMS-HIG-14-005 for further details.

- M. D. Campos, A. E. Carcamo Hernandez, H. Pas, E. Schumacher, “HiggsToMuTau as an indication for S4 flavor symmetry“, arXiv:1408.1652v1
- A. Dery , A. Efrati , Y. Nir , Y. Soreq , V. Susi, “Model building for flavor changing Higgs couplings”, arXiv:1408.1371v1

→ Motivated by the CMS search!

# Previous limits on $|Y_{ij}|$

| Channel | Coupling | Bound |
|---|---|---|
| $\mu \to e\gamma$ | $\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$ | $< 3.6 \times 10^{-6}$ |
| $\mu \to 3e$ | $\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$ | $\lesssim 3.1 \times 10^{-5}$ |
| electron $g-2$ | $\mathrm{Re}(Y_{e\mu}Y_{\mu e})$ | $-0.019 \ldots 0.026$ |
| electron EDM | $\lvert\mathrm{Im}(Y_{e\mu}Y_{\mu e})\rvert$ | $< 9.8 \times 10^{-8}$ |
| $\mu \to e$ conversion | $\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$ | $< 4.6 \times 10^{-5}$ |
| $M$-$\bar{M}$ oscillations | $\lvert Y_{\mu e} + Y^*_{e\mu}\rvert$ | $< 0.079$ |
| $\tau \to e\gamma$ | $\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$ | $< 0.014$ |
| $\tau \to 3e$ | $\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$ | $\lesssim 0.12$ |
| electron $g-2$ | $\mathrm{Re}(Y_{e\tau}Y_{\tau e})$ | $[-2.1 \ldots 2.9] \times 10^{-3}$ |
| electron EDM | $\lvert\mathrm{Im}(Y_{e\tau}Y_{\tau e})\rvert$ | $< 1.1 \times 10^{-8}$ |
| $\tau \to \mu\gamma$ | $\sqrt{\lvert Y_{\tau\mu}\rvert^2 + \lvert Y_{\mu\tau}\rvert^2}$ | $0.016$ |
| $\tau \to 3\mu$ | $\sqrt{\lvert Y^2_{\tau\mu} + \lvert Y_{\mu\tau}\rvert^2}$ | $\lesssim 0.25$ |
| muon $g-2$ | $\mathrm{Re}(Y_{\mu\tau}Y_{\tau\mu})$ | $(2.7 \pm 0.75) \times 10^{-3}$ |
| muon EDM | $\mathrm{Im}(Y_{\mu\tau}Y_{\tau\mu})$ | $-0.8 \ldots 1.0$ |
| $\mu \to e\gamma$ | $(\lvert Y_{\tau\mu}Y_{\tau e}\rvert^2 + \lvert Y_{\mu\tau}Y_{e\tau}\rvert^2)^{1/4}$ | $< 3.4 \times 10^{-4}$ |

R. Harnik, J. Kopp, J. Zupan,

arXiv:1209.1397

(and references therein)

# Some details… ($\mu\tau_{had}$)

Tau Reco by DecayFinding (HPS)

- $P_T > 30$ GeV
- $|\eta| < 2.3$, $\Delta z < 0.2$
- Tight isolation criterion
- Discriminate against electron fakes
- Discriminate against muon fakes

Muon

- High Reco Quality
- $P_T > 25$ GeV
- $|\eta| < 2.1$, $\Delta z < 0.2$
- Relative Isolation < 0.12

Jets Reco using Particle Flow

- $P_T > 30$ GeV
- $|\eta| < 4.7$
- Discriminate noise & PU

Event level cuts

- Muon and tau charge opposite
- Veto if extra isolated muons with $P_T > 5$ GeV
- Veto if isolated electrons with $P_T > 10$ GeV
- Veto if extra taus with $P_T > 20$ GeV
- $\Delta R\tau$-jet > 0.4, $\Delta R\mu$-jet > 0.4 for jet $P_T > 30$

# Some details… ($\mu\tau_e$)

## Electron

- Loose ID
- $P_T > 10$ GeV
- $|\eta| < 2.3$, $\Delta z < 0.2$
- Relative Isolation < 0.12

## Muon

- Tight ID
- $P_T > 25$ GeV
- $|\eta| < 2.1$, $\Delta z < 0.2$
- Relative Isolation < 0.12

Particle Flow Jets

- $P_T > 30$ GeV
- $|\eta| < 4.7$
- Discriminate noise & PU
- b-tag veto

## Event

- Muon and electron charge opposite
- Veto b-tagged jet $P_T > 30$ GeV
- Veto extra tight muons with $P_T > 7$ GeV
- Veto extra loose electrons with $P_T > 7$ GeV
- $\Delta R_{e\text{-}\mu} > 0.1$, $\Delta R_{e\text{-jet}} > 0.4$, $\Delta R_{\mu\text{-jet}} > 0.4$ for jet $P_T > 30$