$H \rightarrow \mu\tau$, $H \rightarrow e\tau$, $H \rightarrow e\mu$ searches with the CMS experiment

Maria Cepeda (CERN)

12/October/2015

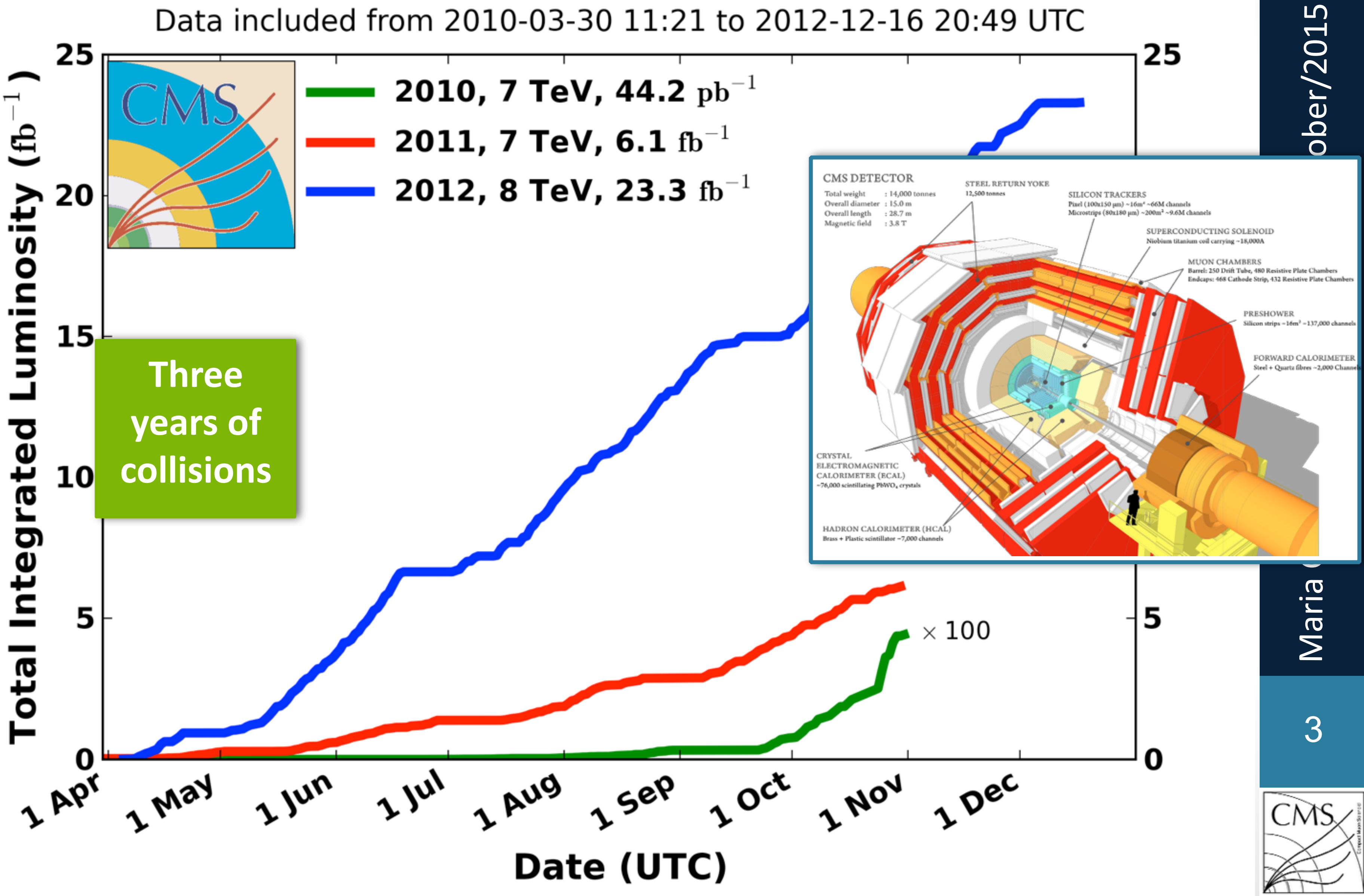
Introduction

- With the discovery of the Brout–Englert–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 Flavor sector can hold surprises:
  - BSM models such as double Higgs models or extra dimensions allow lepton flavour violating decays of the boson (for instance, to a $\mu\tau$ pair)
  - Experimentally, non-LHC bounds on such decays are weak, allowing Br($H \to \mu\tau$, $H \to e\tau$) ~10%, well within the experimental reach of CMS

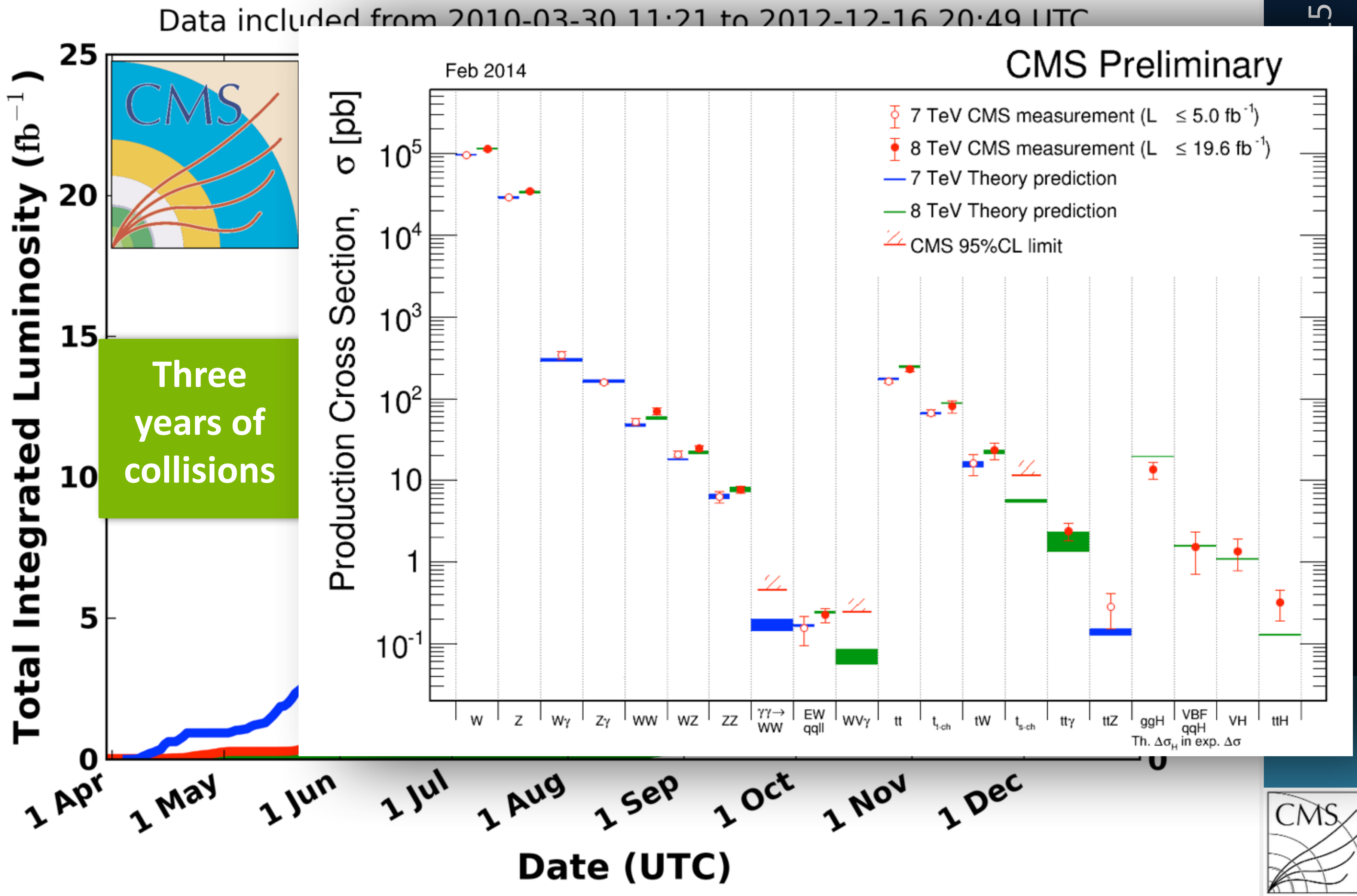
- This talks summarises the first direct search for a lepton flavour violating decay of the 125 GeV boson, performed with a data sample of 20 fb^{-1} @ 8 TeV collected by the CMS experiment

LHC Run I: The SM



Three years of collisions

LHC Run I: The SM



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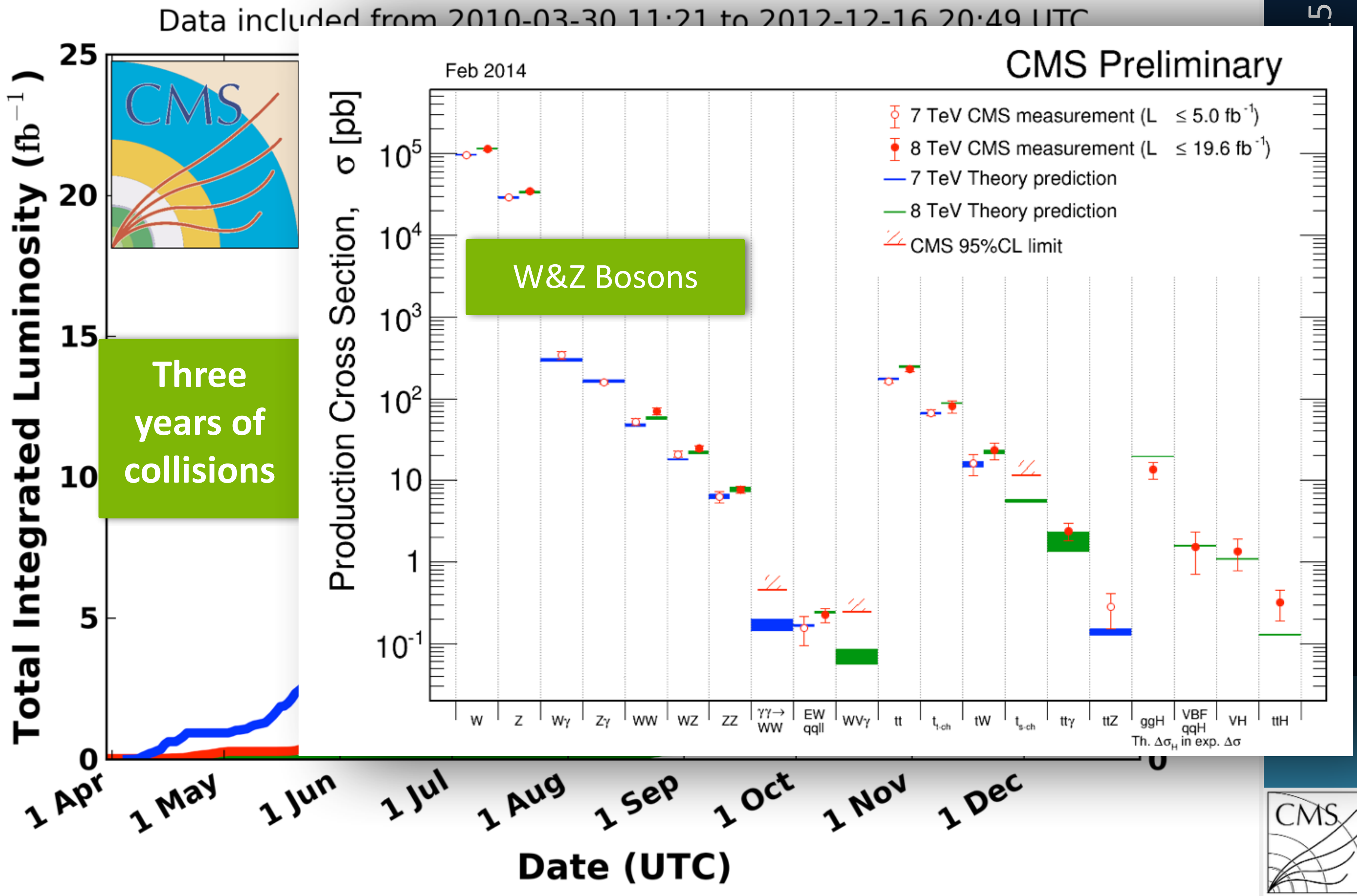
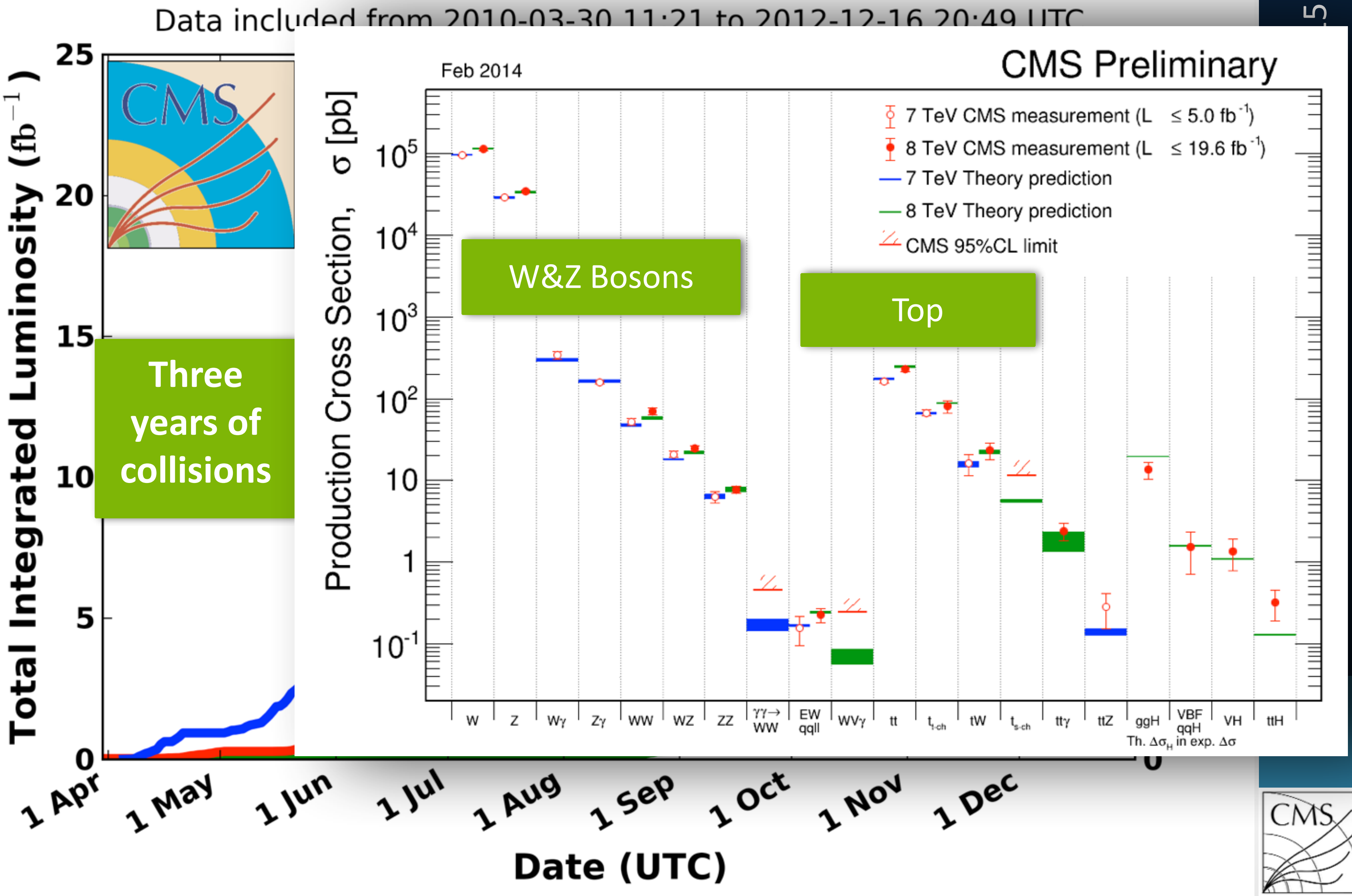


Three years of collisions

W&Z Bosons

LHC Run I: The SM

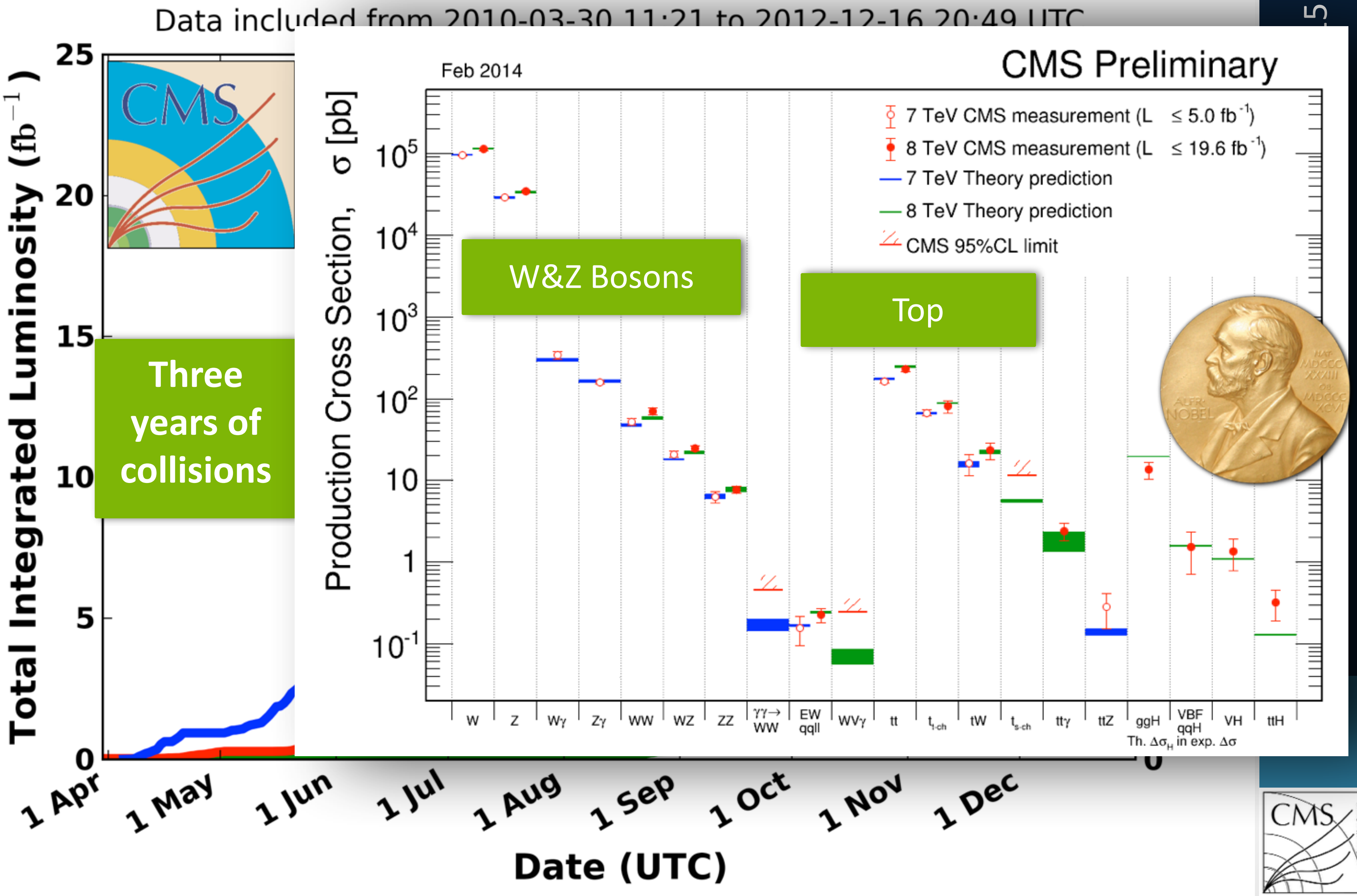


Three years of collisions

W&Z Bosons

Top

LHC Run I: The SM



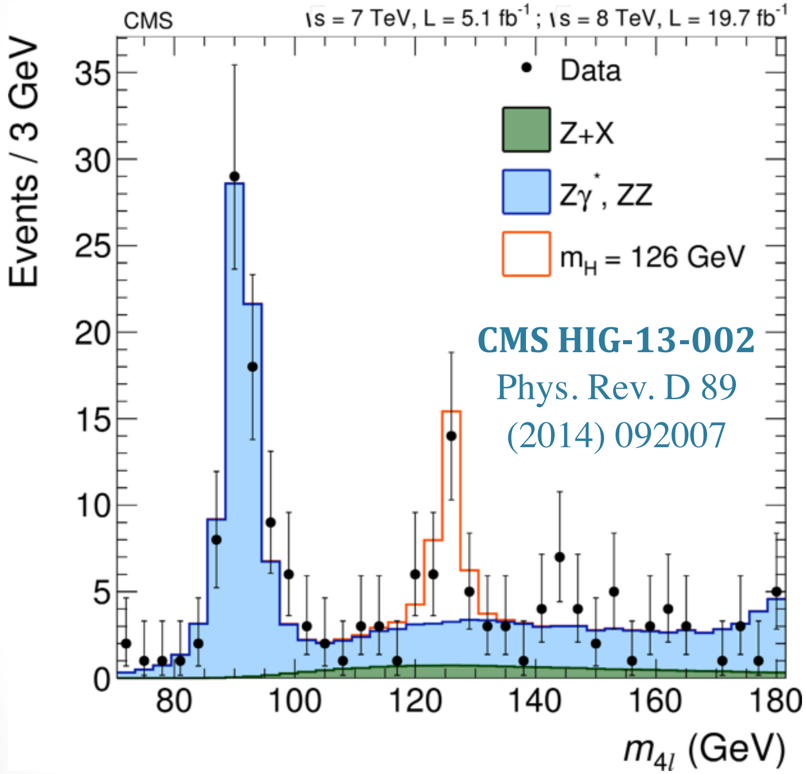
W&Z Bosons

Top

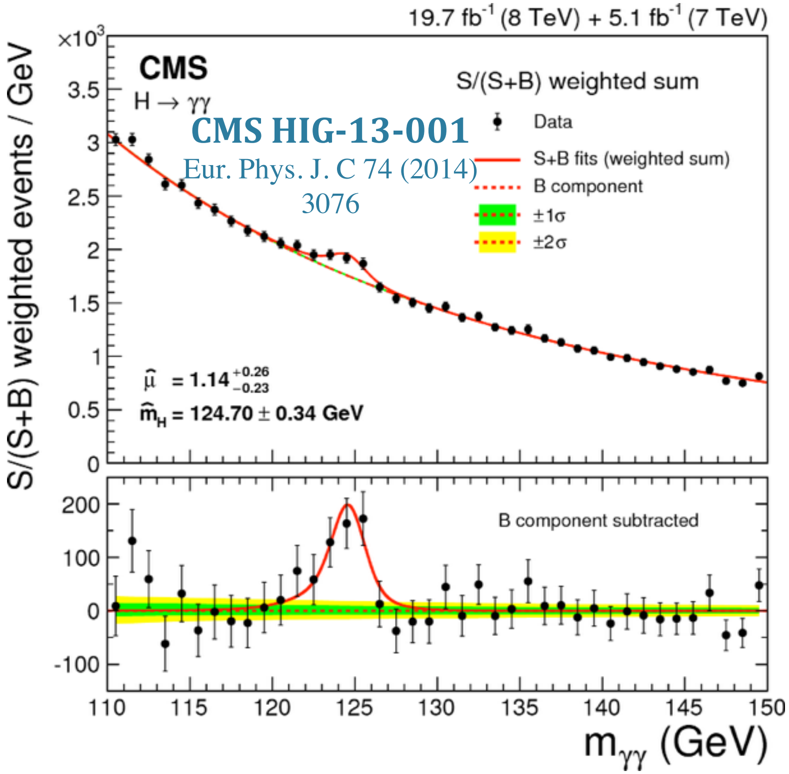
Three years of collisions

LHC Run I: The SM

- .. and the discovery of a new particle



CMS HIG-13-002
Phys. Rev. D 89 (2014) 092007



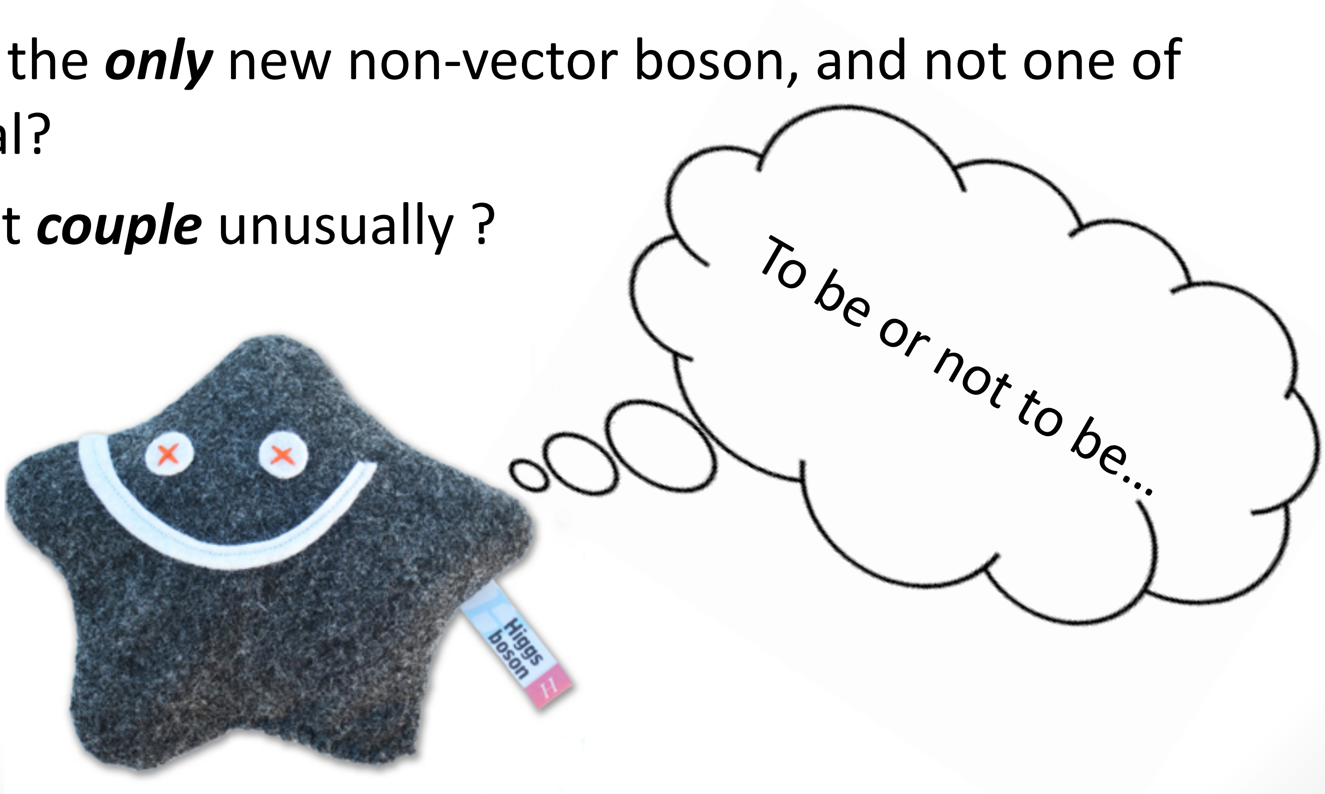
CMS HIG-13-001
Eur. Phys. J. C 74 (2014) 3076

$$m_H = 125.03 \pm 0.30 \left[{}^{+0.26}_{-0.27}(\text{stat.})\,{}^{+0.13}_{-0.15}(\text{syst.}) \right] \text{ GeV}$$

But what is it really?

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 ?



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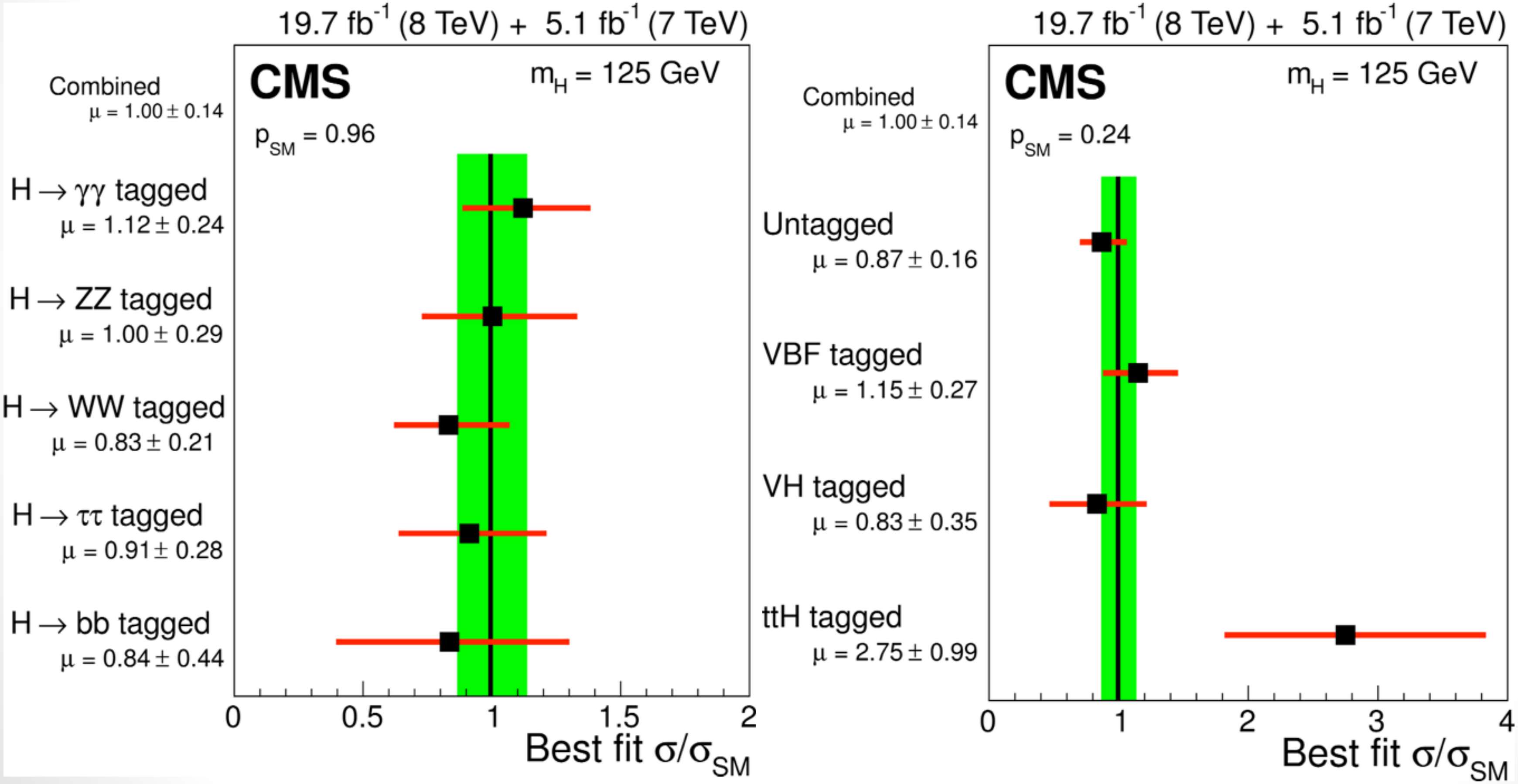
- Thanks to its mass of about 125 GeV we will be able to answer many of these questions experimentally ☺
  - Early answers from 2011-12 (Run-1)
  - Preparation for 2015-2017 (Run-2)

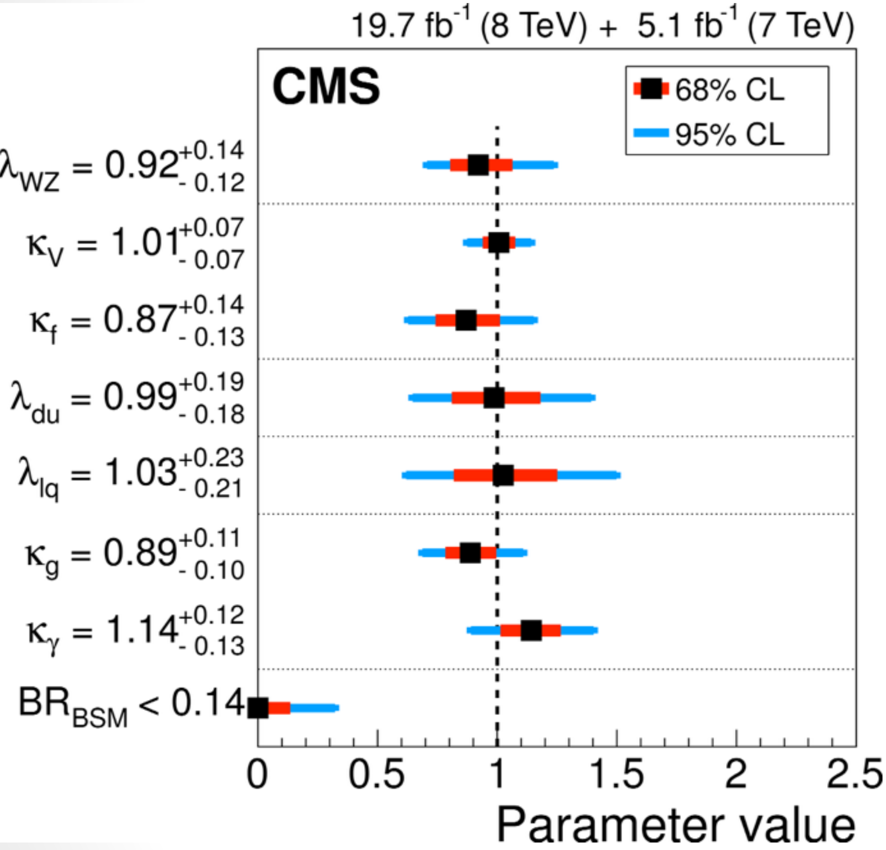
Its signal strength is like the SM predicts…

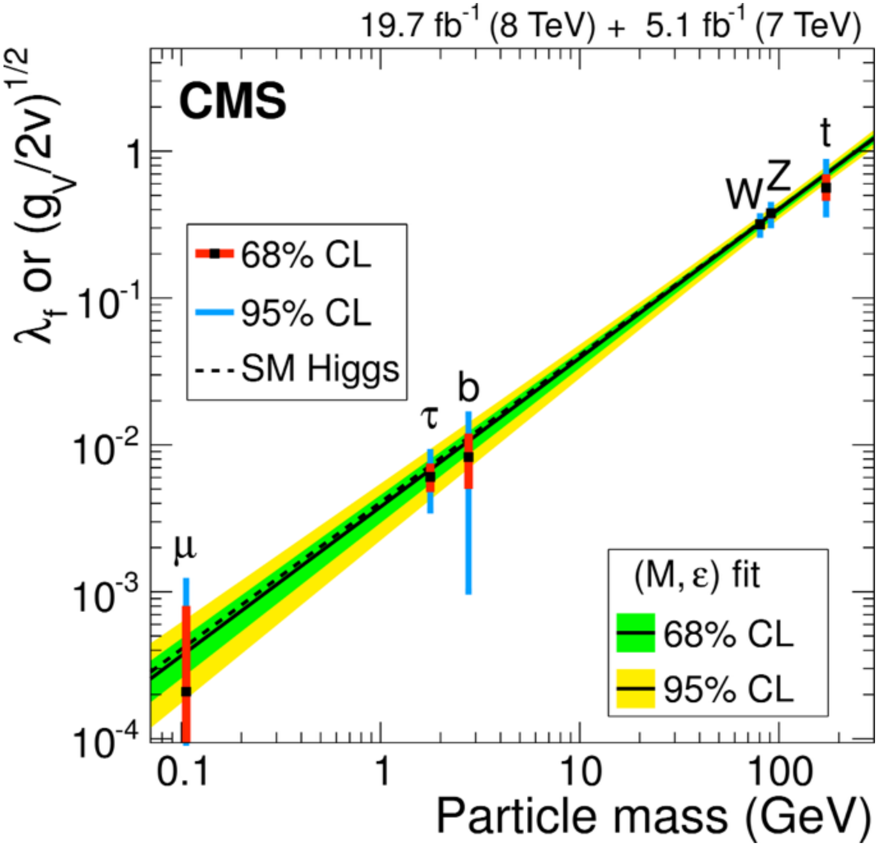
$$\sigma/\sigma_{\rm SM} = 1.00 \pm 0.13 \left[\pm 0.09({\rm stat.})^{+0.08}_{-0.07}({\rm theo.}) \pm 0.07({\rm syst.})\right]$$



CMS HIG-14-009
arXiv:1412.8662

It couples like the SM Higgs Boson…





- **No significant deviations from SM**

$\lambda_{xy} = \kappa_x/\kappa_y$, $\kappa_{xy} = \kappa_x\kappa_y/\kappa_H$

CMS HIG-14-009
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No surprises so far…..

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- Is this the ***only*** new non-vector boson, and not one of several?
- Does it ***couple*** unusually (e.g. changing Lepton Flavor?)

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WHY LFV?

Higgs and Flavor

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

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

- Both matrices are simultaneously diagonalizable → Lepton Flavor Violating Higgs decays are forbidden in the SM

$$Y = \begin{pmatrix} Y_{ee} & 0 & 0 \\ 0 & Y_{\mu\mu} & 0 \\ 0 & 0 & Y_{\tau\tau} \end{pmatrix}$$

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This is not necessarily true anymore in BSM models:

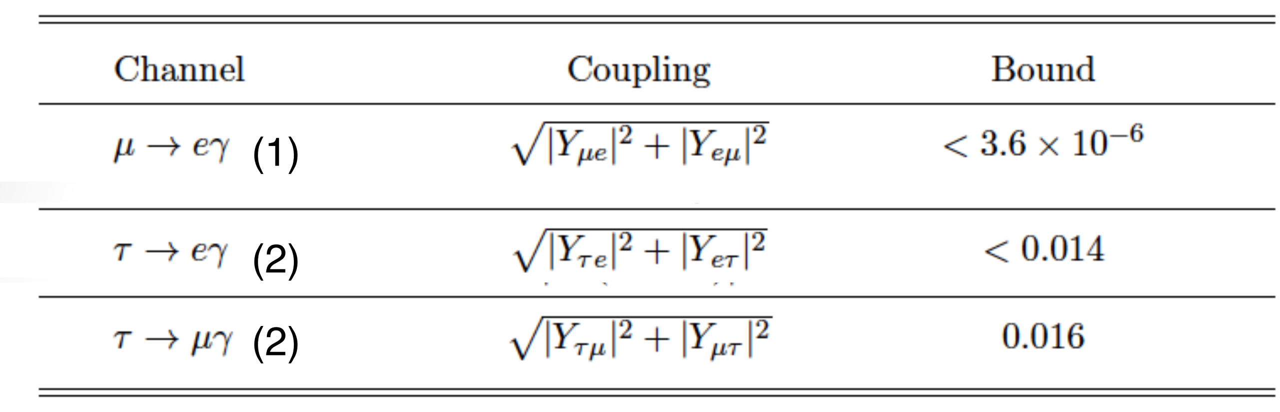
$$L'_{Y_i} = Y_{ij} h f^i_L f^j_R + h.c.$$

- Flavor off-diagonal
- Complex (CP violating)

SM values

$$Y = \begin{pmatrix} \boxed{Y_{ee}} & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & \boxed{Y_{\mu\mu}} & \boxed{Y_{\mu\tau}} \\ Y_{\tau e} & \boxed{Y_{\tau\mu}} & \boxed{Y_{\tau\tau}} \end{pmatrix}$$

Pre-LHC experimental bounds



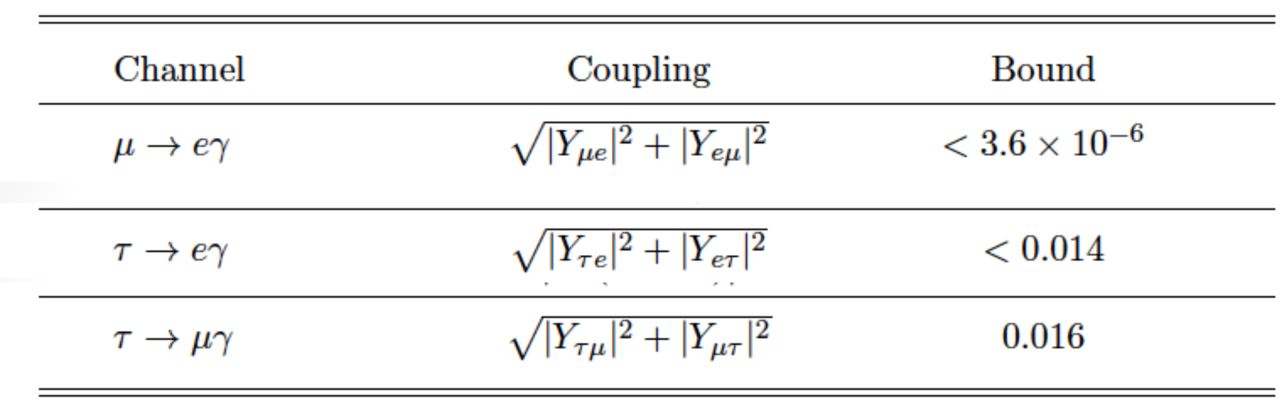
Channel	Coupling	Bound
$\mu \to e\gamma$ (1)	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 3.6 \times 10^{-6}$
$\tau \to e\gamma$ (2)	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	< 0.014
$\tau \to \mu\gamma$ (2)	$\sqrt{\lvert Y_{\tau\mu}\rvert^2 + \lvert Y_{\mu\tau}\rvert^2}$	0.016

R. Harnik, J. Kopp, J. Zupan, arXiv:1209.1397

(1) PRL 107 171801 J. Adam et al. (MEG Collab.)

(2) PRL 104 021802 B. Aubert et al. (BABAR Collab.)

Pre-LHC experimental bounds



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The limits on the yukawa couplings can be translated into a limit on the Higgs Br:

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

$$\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta) = \frac{m_{\mathrm{H}}}{8\pi}\left(\lvert \mathrm{Y}_{\ell^\beta \ell^\alpha}\rvert^2 + \lvert \mathrm{Y}_{\ell^\alpha \ell^\beta}\rvert^2\right)$$

Br≤10% for LFV decays with a tau lepton not excluded!

Pre-LHC experimental bounds

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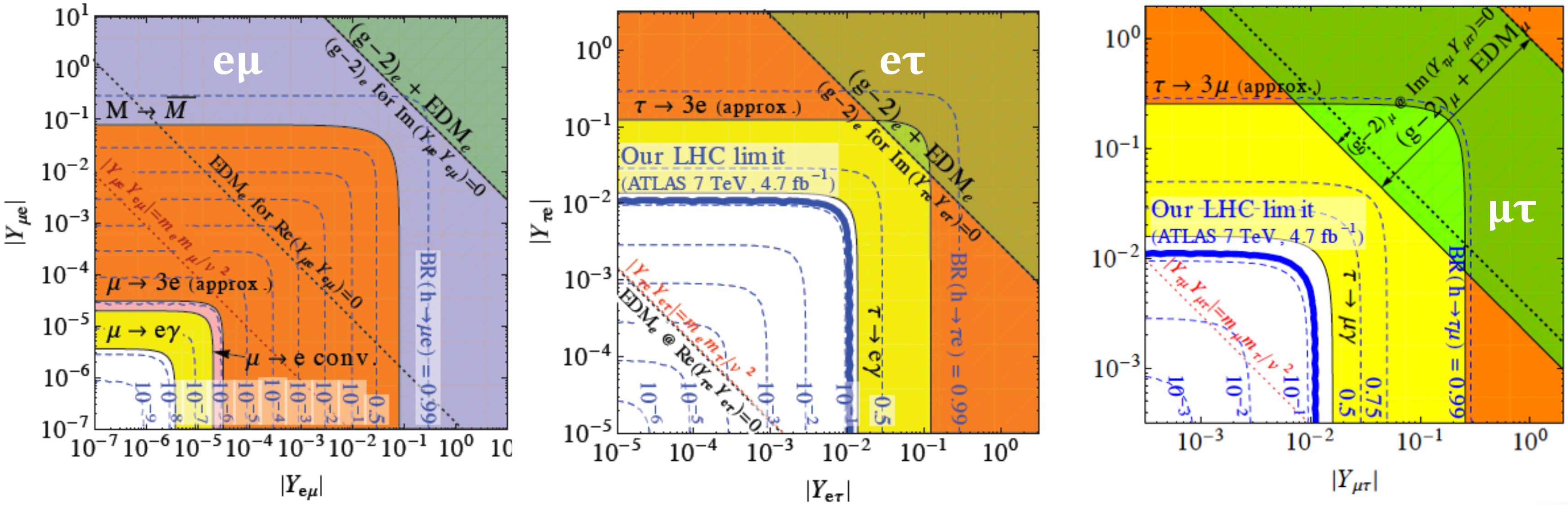
$Br \lesssim 10^{-8}$

$Br \lesssim 10\%$



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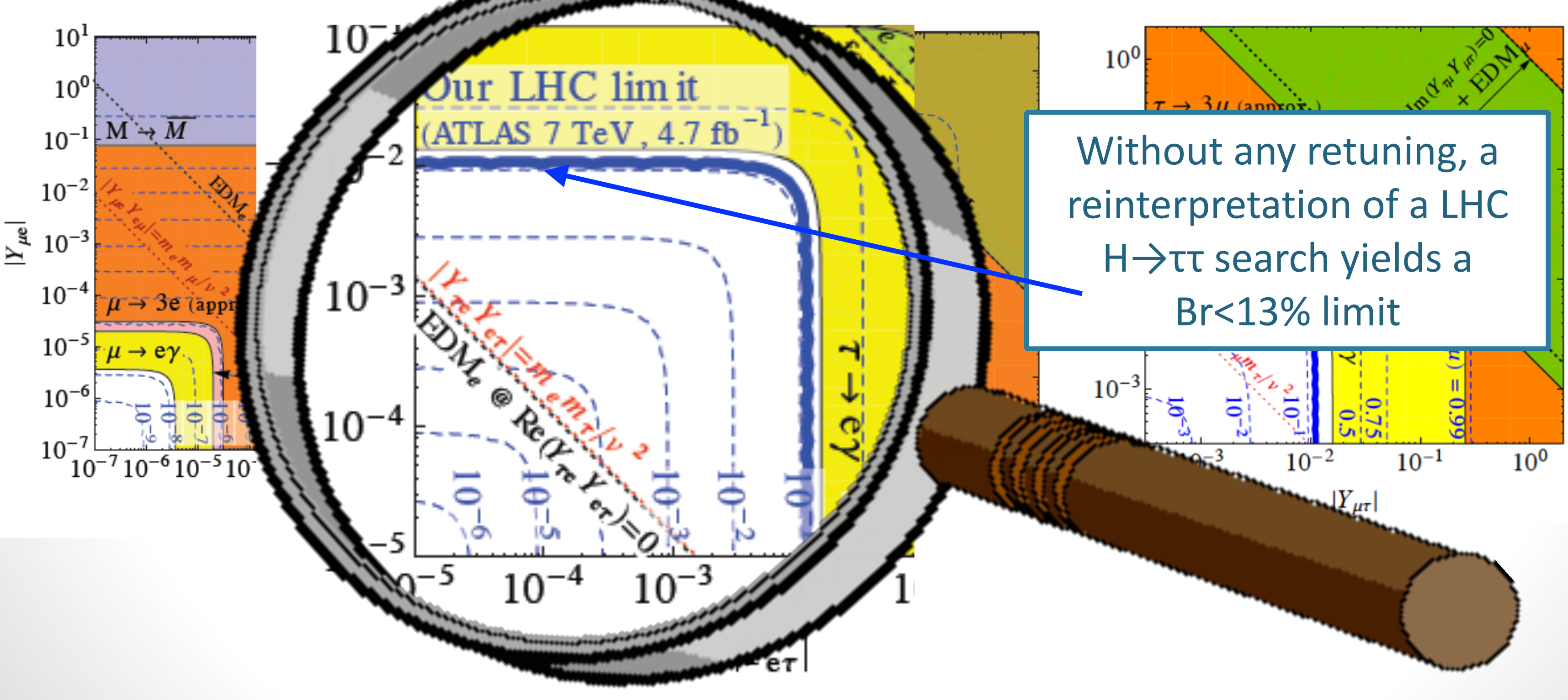

Without any retuning, a reinterpretation of a LHC H→ττ search yields a Br<13% limit

Pre-LHC experimental bounds

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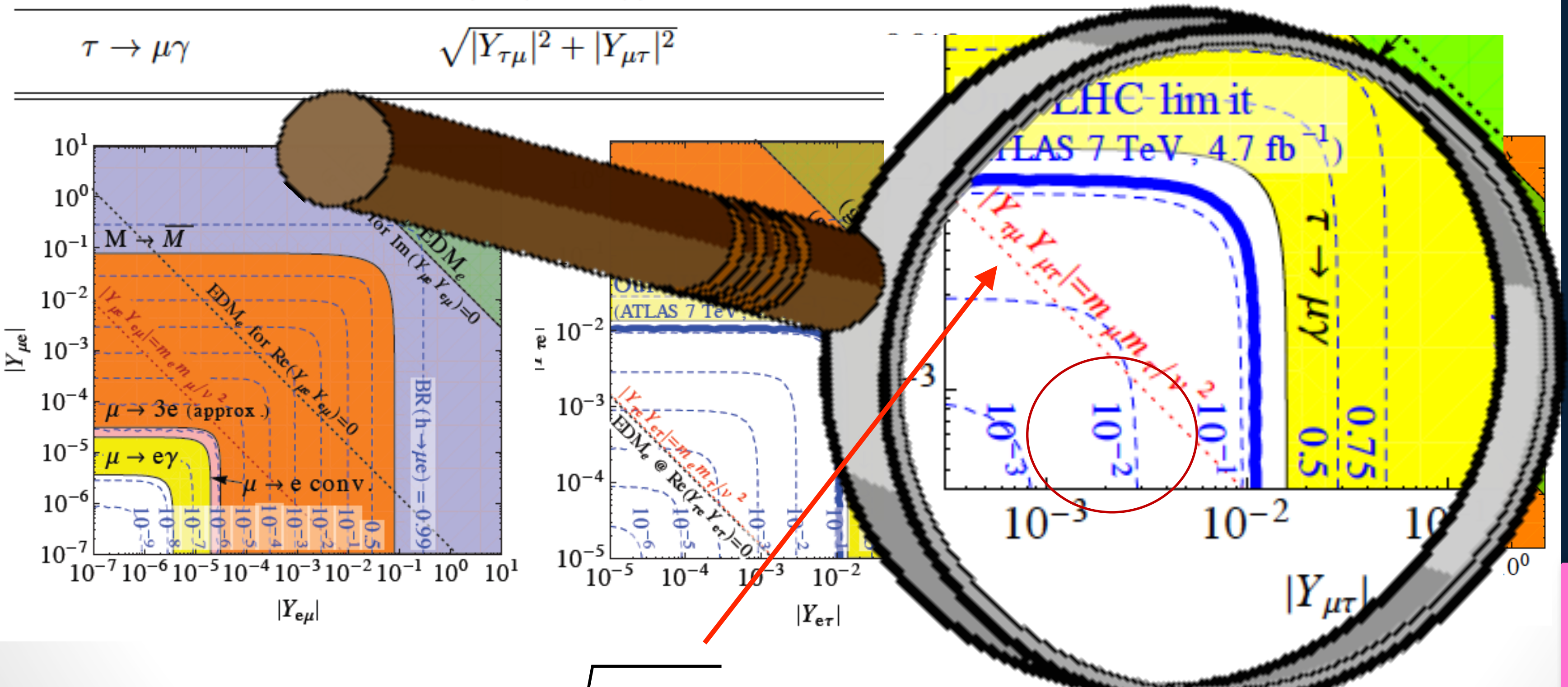


Naturalness: $Y_{ij} \le \frac{\sqrt{m_i m_j}}{v}$

CMS direct search for H→μτ , H→eτ , H→μe

3 decay modes probed by CMS

H→μτ

H→eτ

Experimental techniques close to H→ττ

Can we bridge the gap to reach the 1% Br limit?

H→μe

Experimental techniques close to H→μμ

$H\rightarrow\mu\tau$

$H\rightarrow e\tau$

Experimental techniques close to $H\rightarrow\tau\tau$

Can we bridge the gap to reach the 1% Br limit?

Lets start with the two decays involving a tau

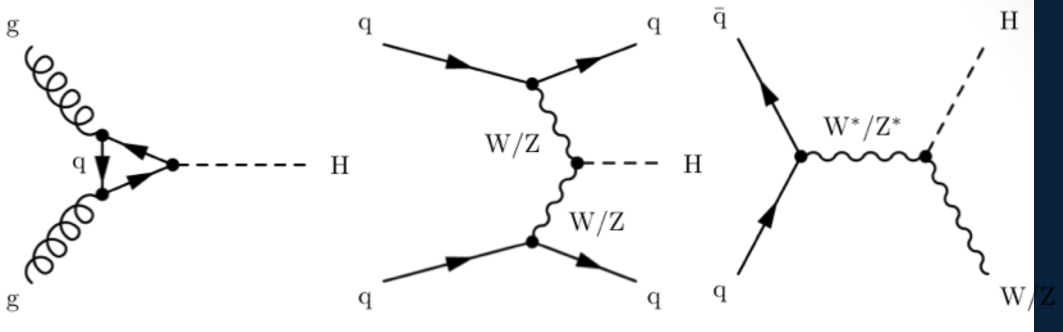
Higgs Decay to Tau Pairs in CMS…

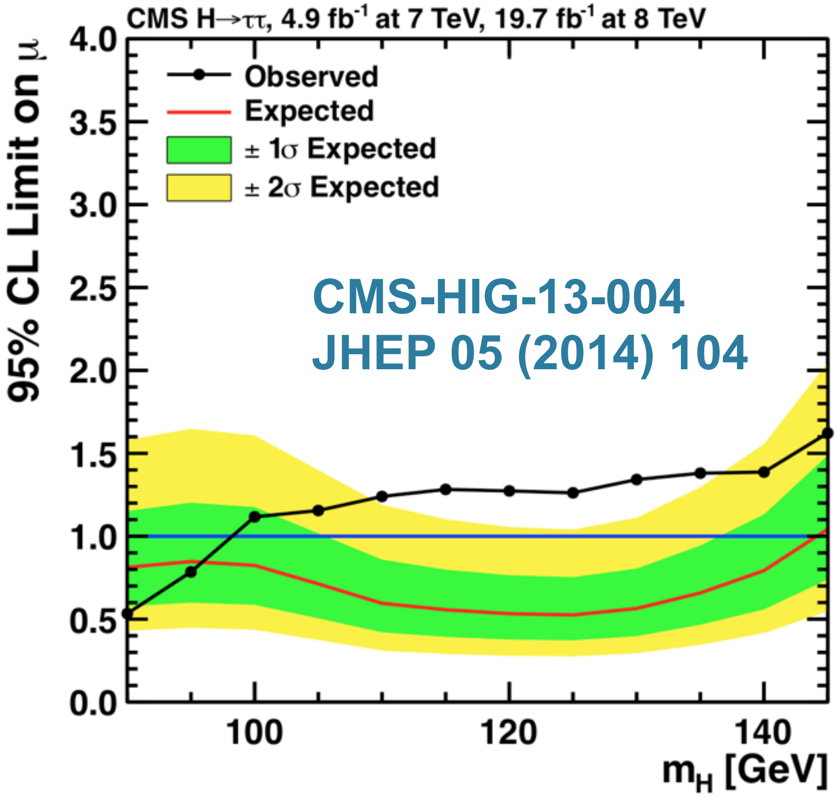
Final states VBF + GF:

$e\mu$, $\mu\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$

Also, VH (WH & ZH):

$\ell\ell\tau_h$, $\ell\tau_h\tau_h$, $\ell\ell\tau_h\tau_h$





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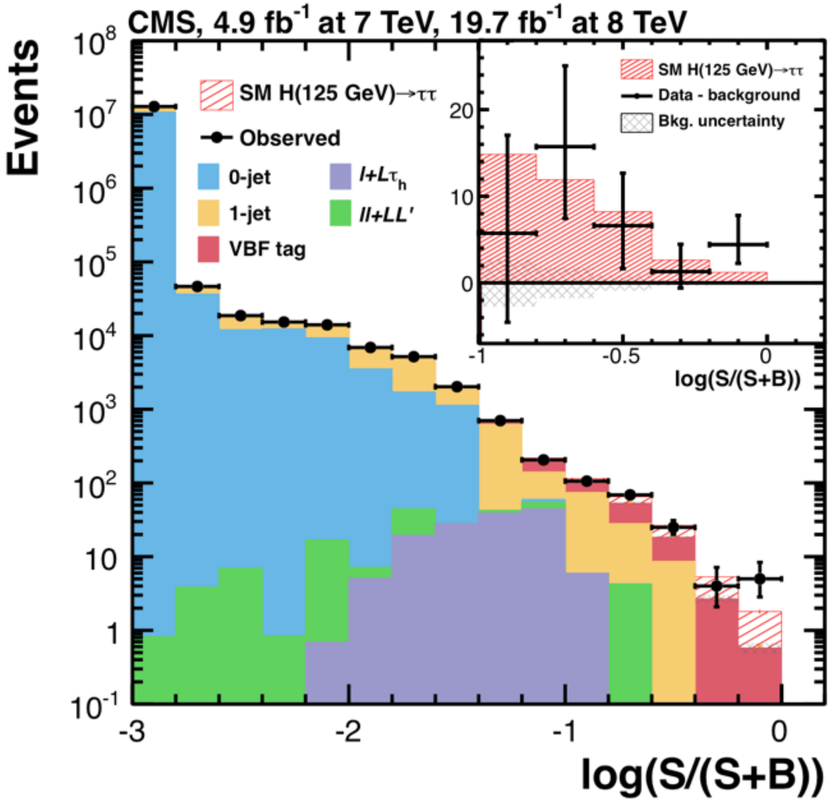
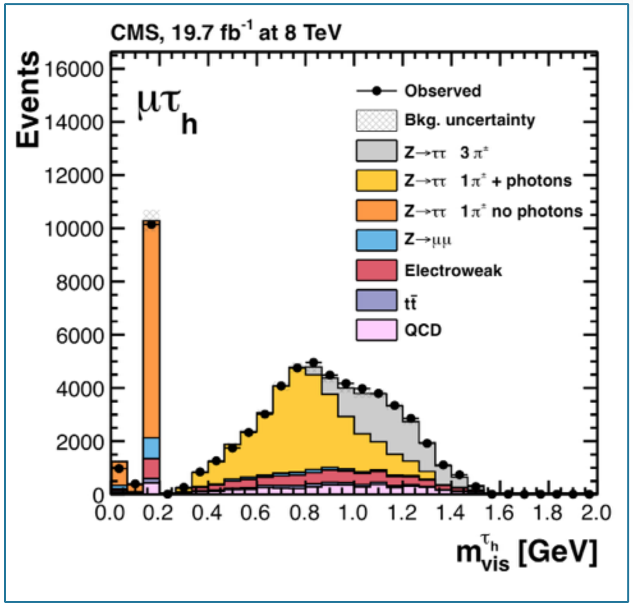


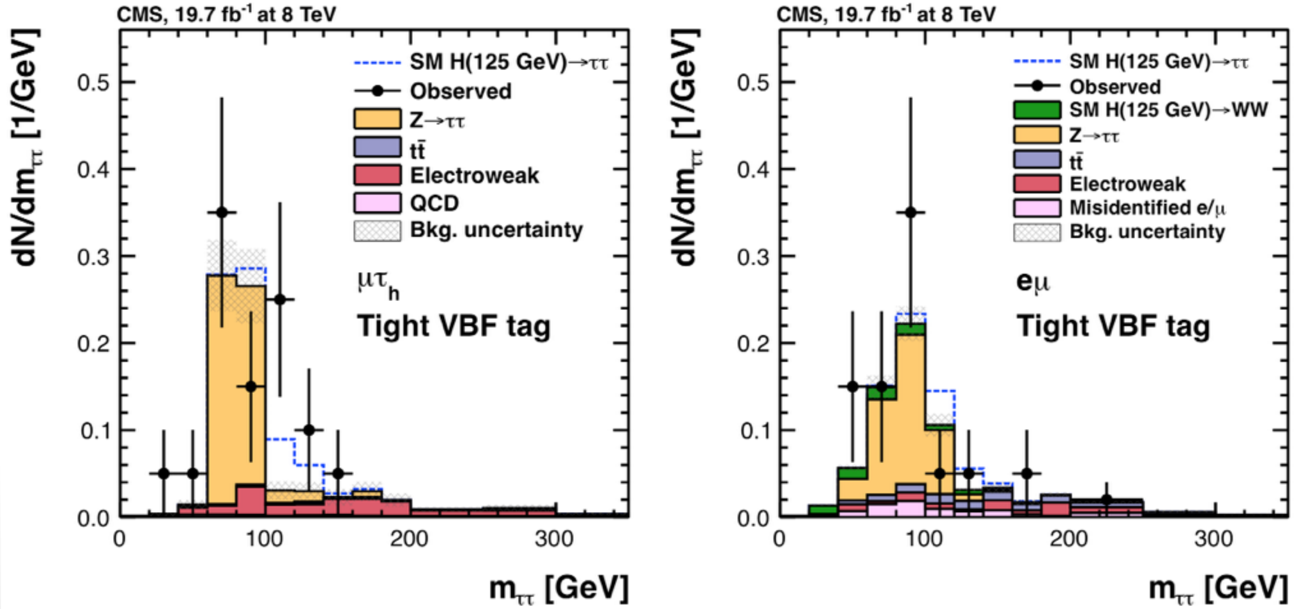
Local significance larger than 3σ for *m*H values between 115 and 130 GeV

Higgs Decay to Tau Pairs

- Excellent tau identification in CMS driven by the CMS SM H→ττ analysis
- Common building blocks: taus, leptons, jets allow us to profit from the modeling techniques and systematic studies developed in that context

→ VBF channels are the most sensitive





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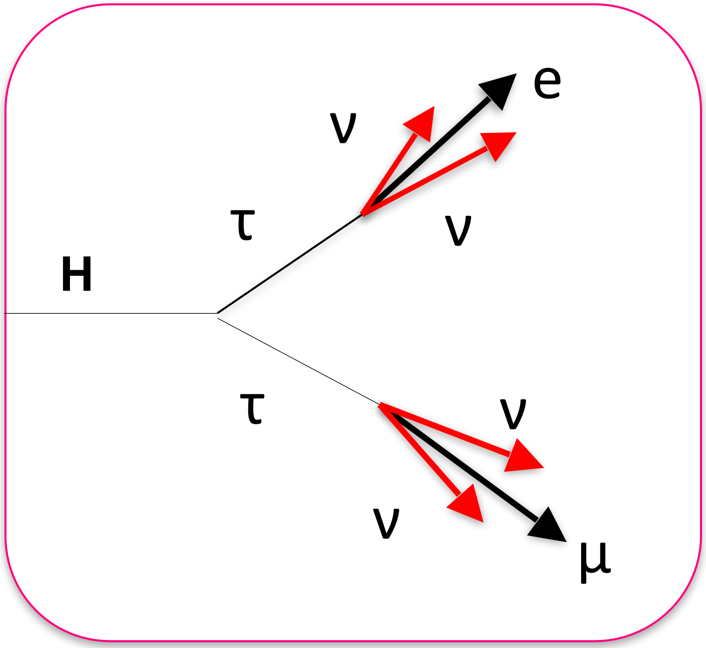
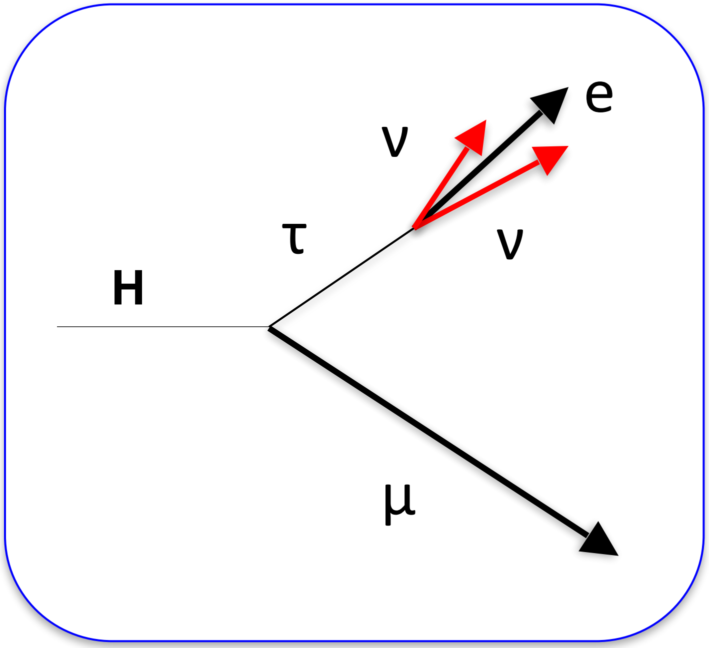
Comparison of Kinematics

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



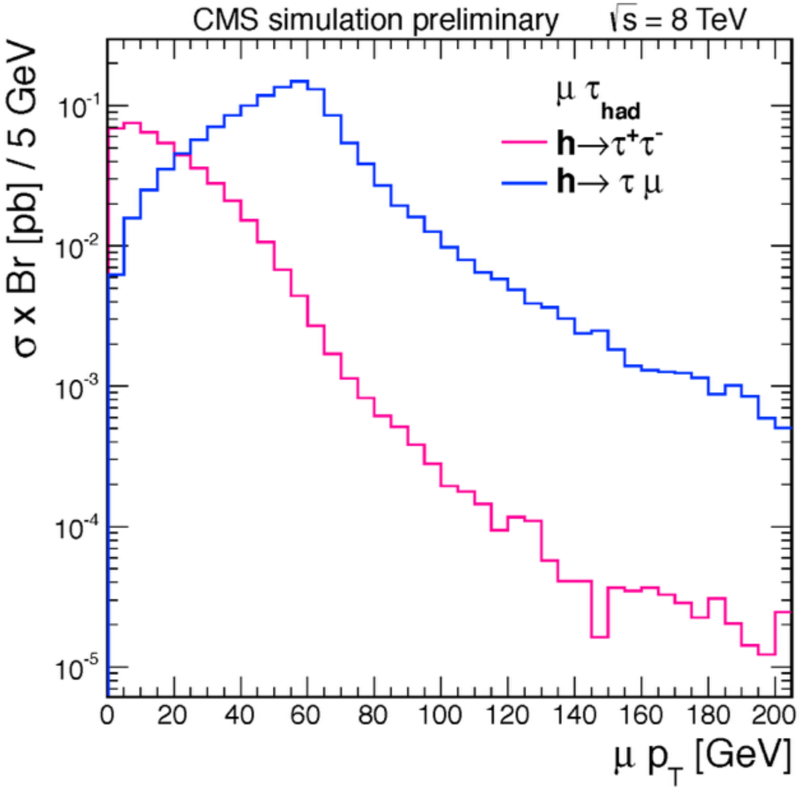


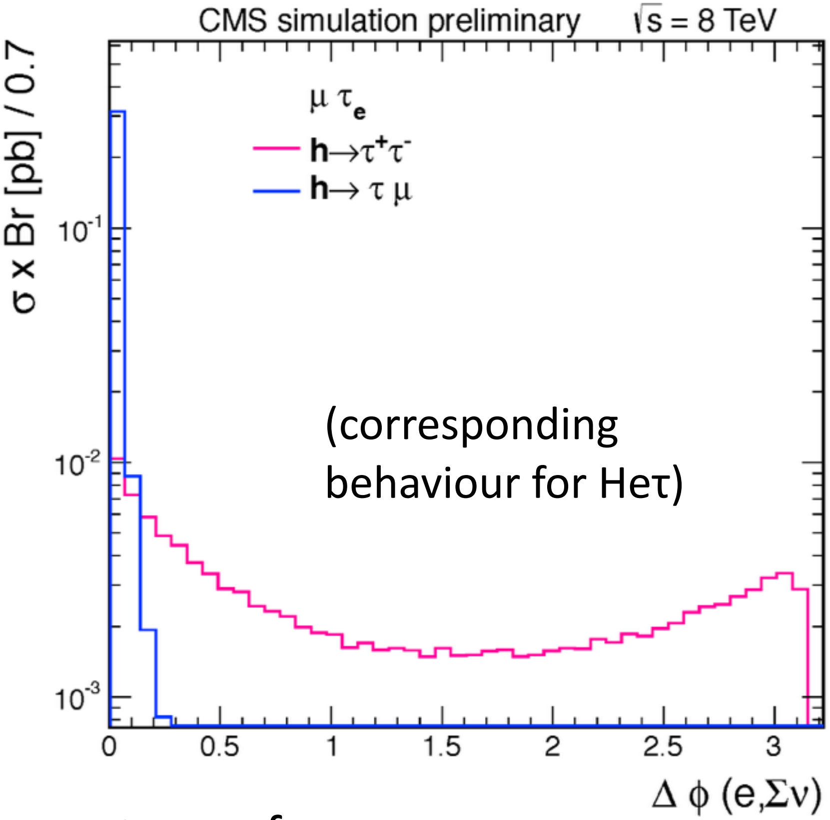
Exploit differences in event topology

- 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





(corresponding behaviour for Heτ)

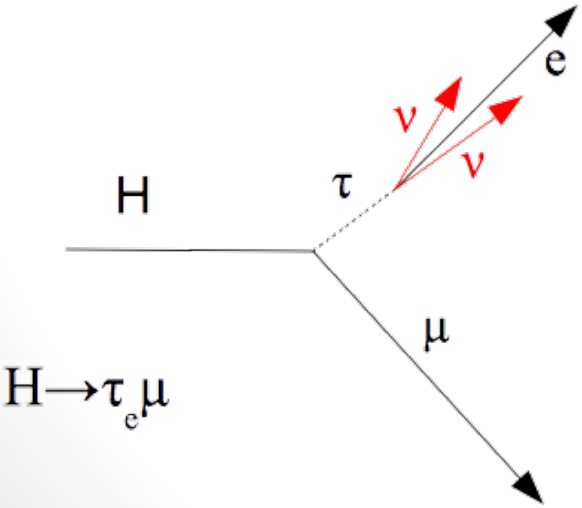
Exploit differences in event topology

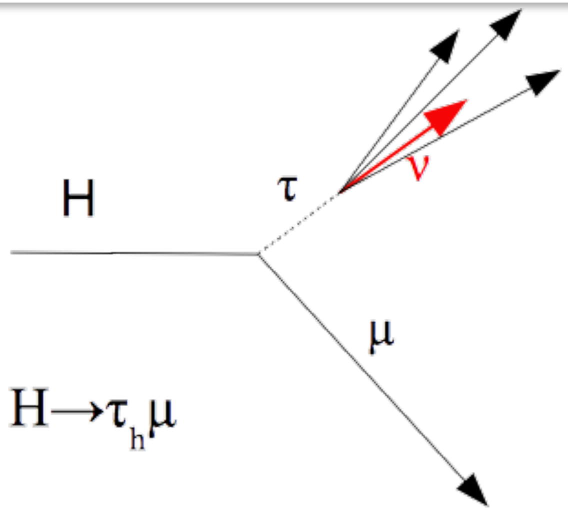
- Harder P_T spectrum of muons
- Different angular correlations:
  - Electron/Tau_{had} – Neutrinos → ~ Collinear
  - Muon - Neutrinos → ~ back to back

Base selection in a snapshot : I

- Two channels:
  - **$\mu\tau_{had}$** (triggered by single muon)
  - **$\mu\tau_{e}$**(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 **$\mu\tau_{had}$** / **μe** Pair
- Angular correlations used to enhance discrimination





Base selection in a snapshot : II

- Two channels:
  - **eτ$_{had}$** (triggered by single electron)
  - **eτ$_{\mu}$**(triggered by muon-electron cross triggers)
- Three categories
  - 0 and 1 jet (dominated by GGF)
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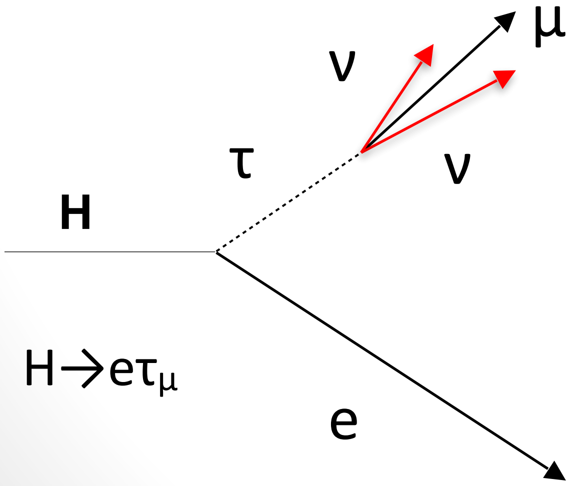
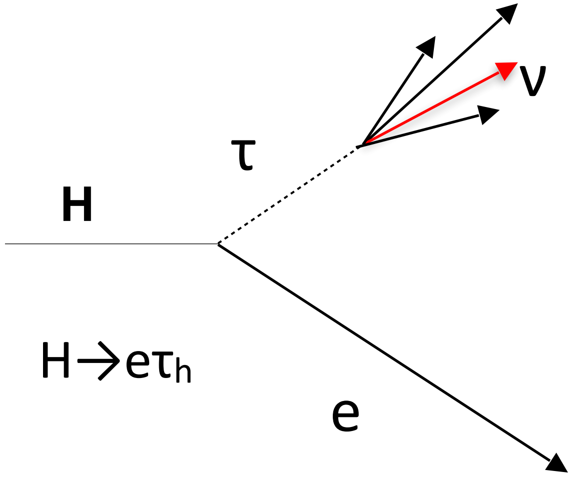




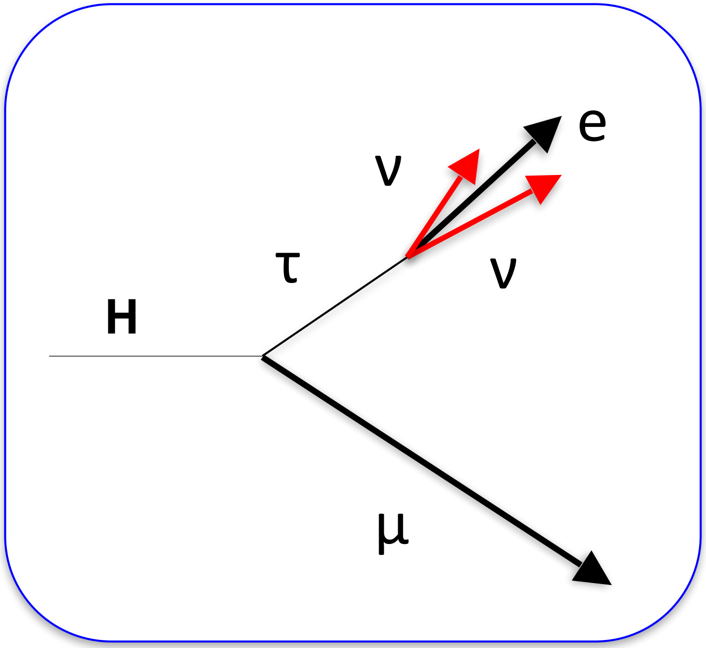
Mass Reconstruction

- 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:

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

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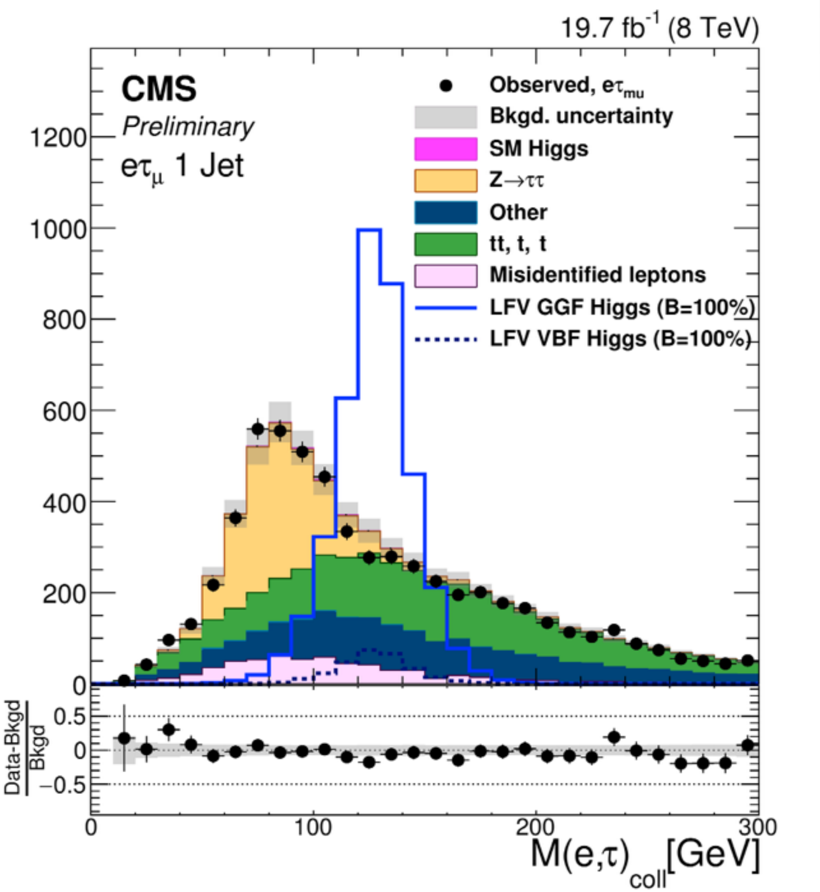

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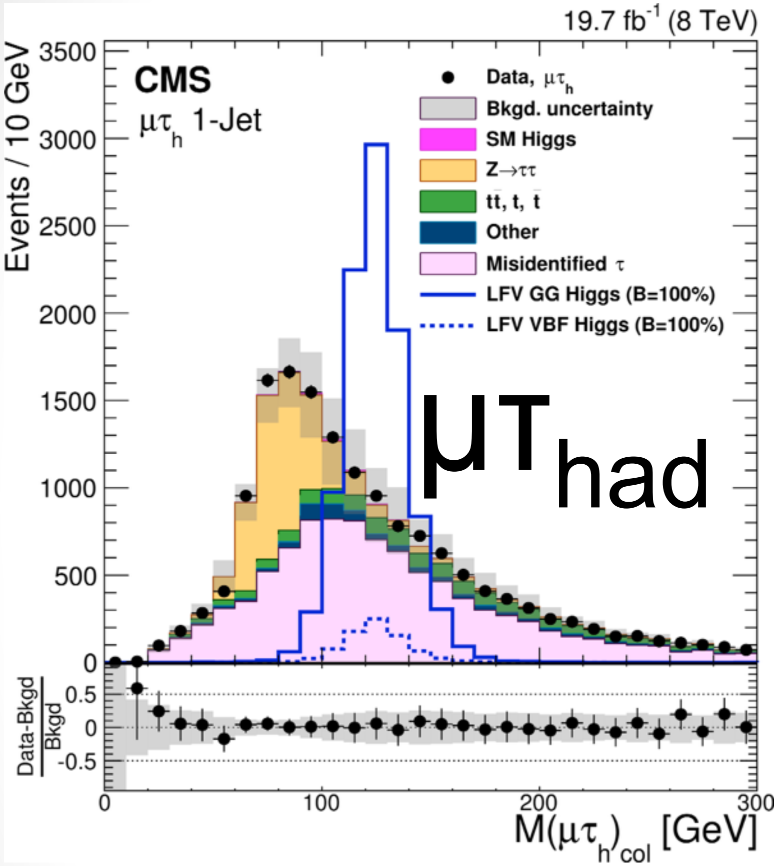
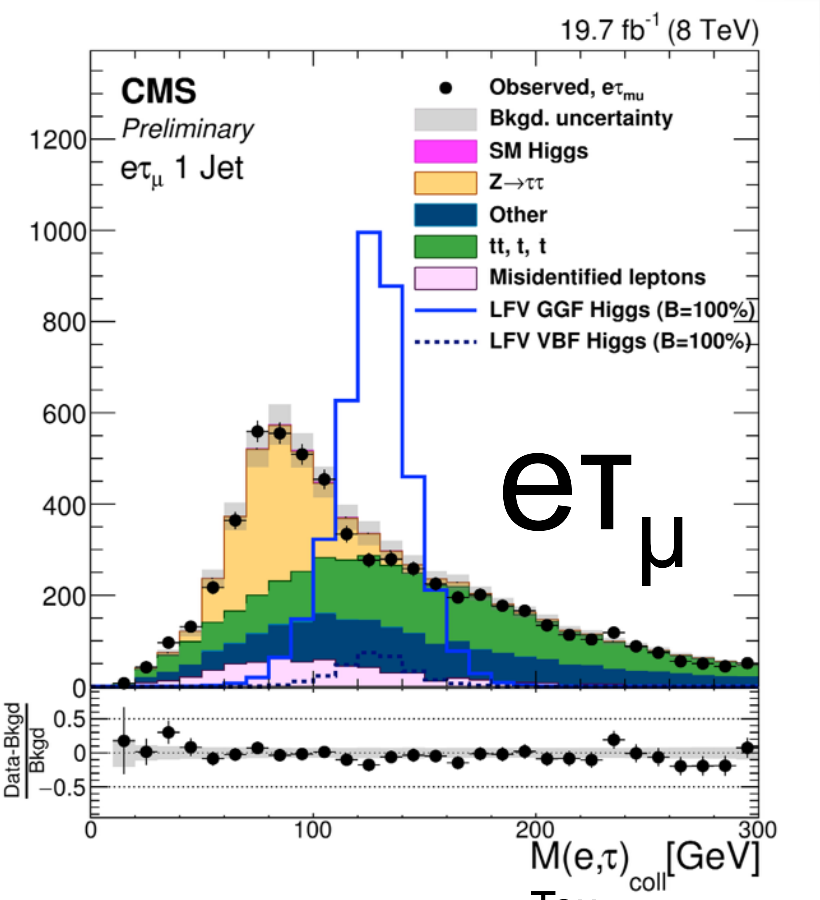
Loosely selecting LFV Higgses…



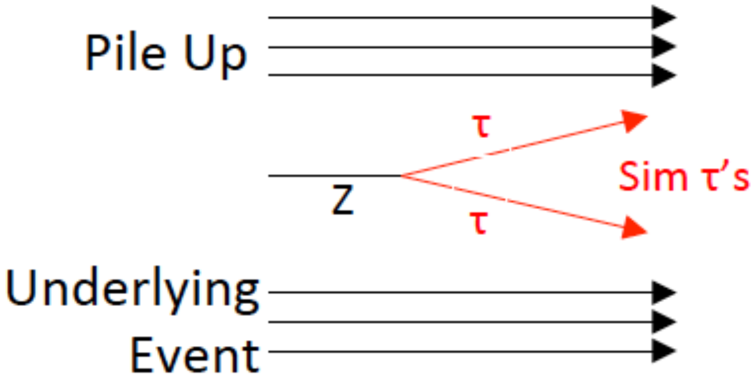


Lead backgrounds:

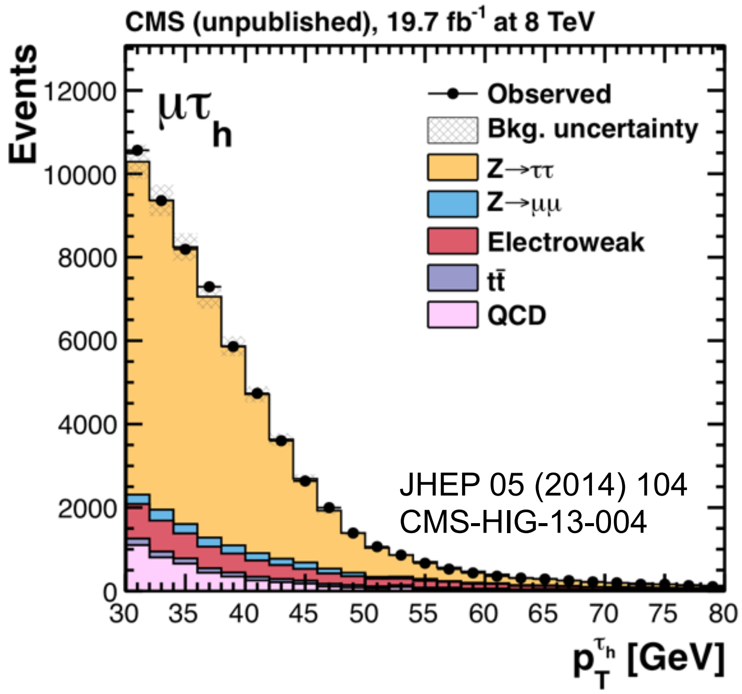
- HTauTau
- ZTauTau → Tau-Embedding technique
- SM backgrounds with real tau decays: top, VV → from MC
- Misidentifed Leptons (e, mu, tau) → from data

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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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 (fake rate) in an independent Zμμ sample:**

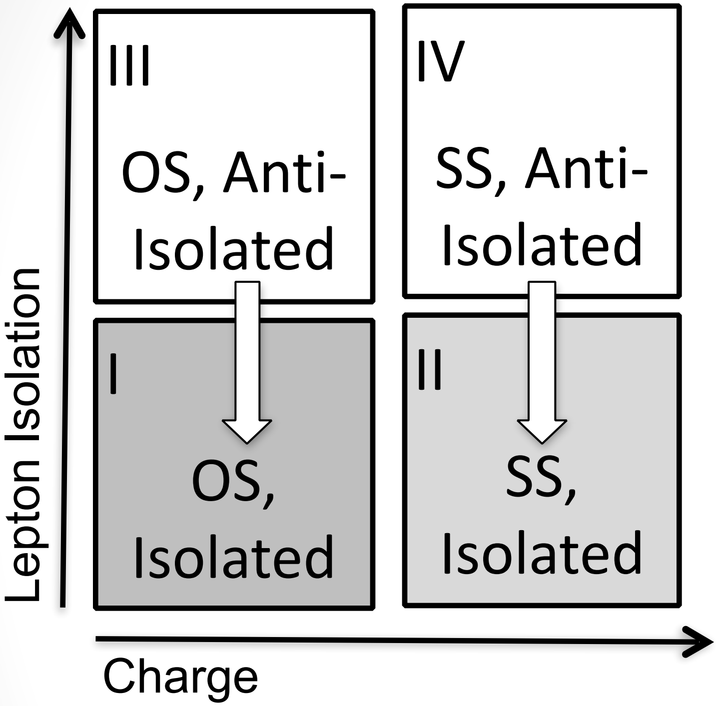
$$f_{\mu} = \frac{N[Z(\mu\mu)+\mu(\mathrm{tight})]}{N[Z(\mu\mu)+\mu(\mathrm{loose})]}$$

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**

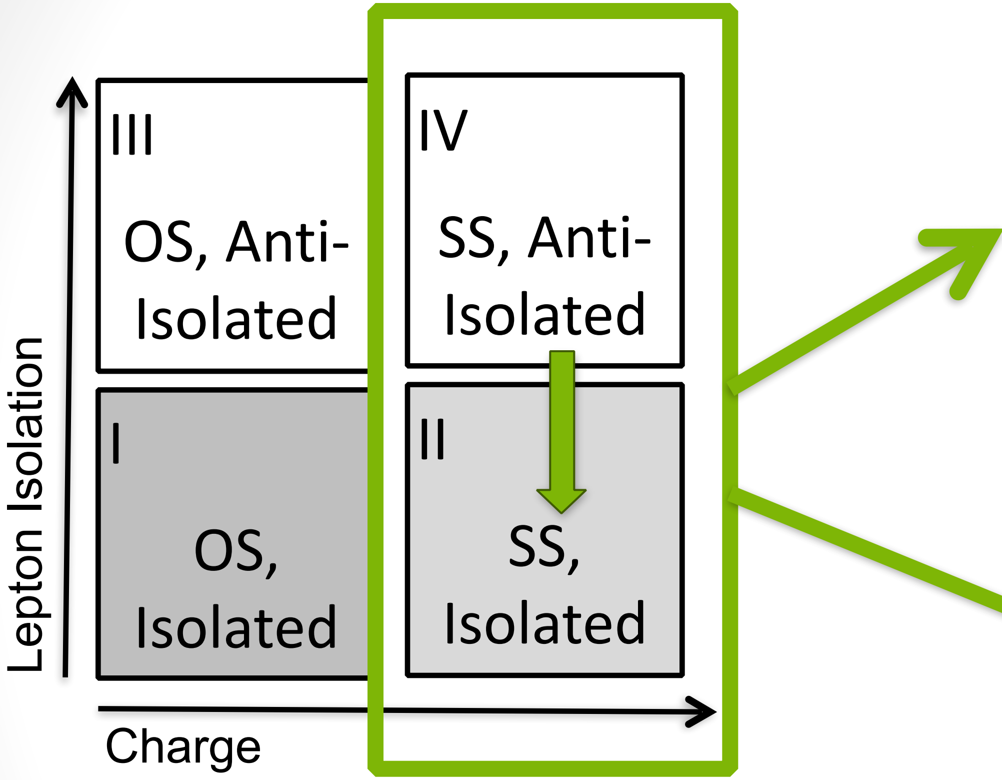
- This technique can be applied to obtain Jet→Tau, Jet→Electron, Jet→Muon misidentified lepton contributions

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

Jet→Lepton misidentification



1 - Validation



III

OS, Anti-Isolated

IV

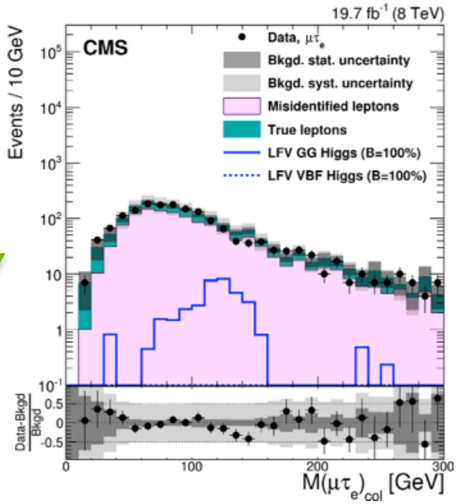
SS, Anti-Isolated

I

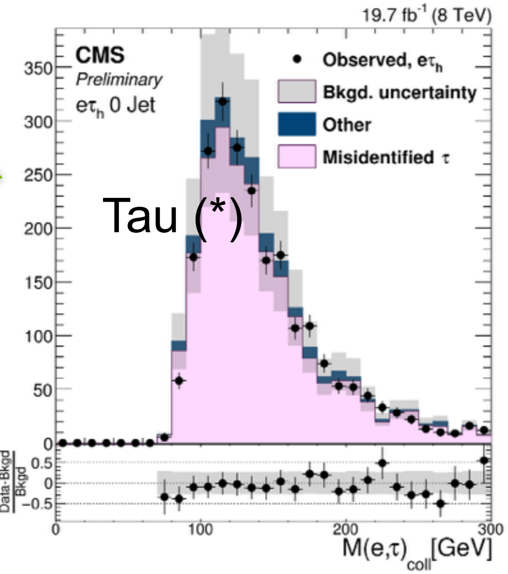
OS, Isolated

II

SS, Isolated



Muon, Electron

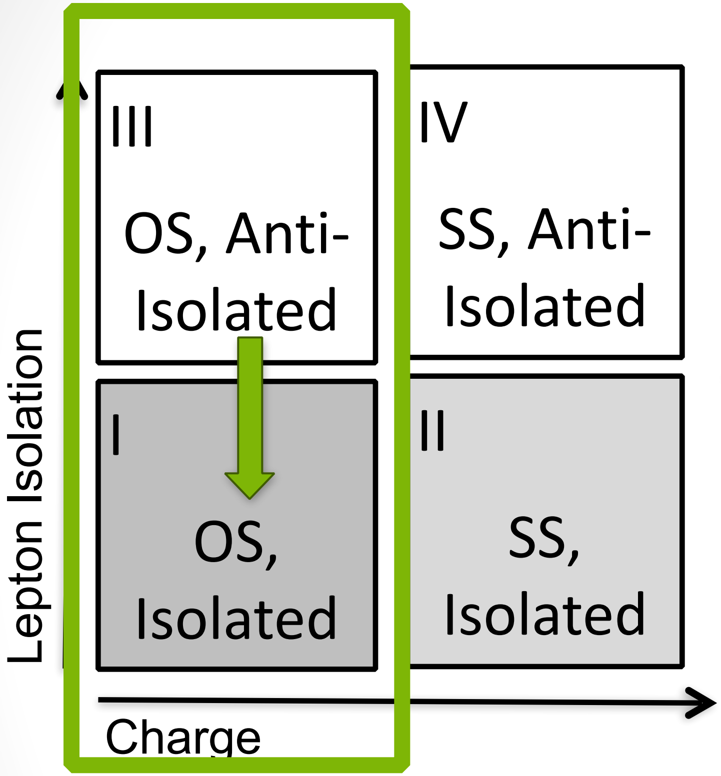


Tau (*)

Validation based on a SameSign Lepton control sample

(* for tau leptons, the anti isolated candidates of regions III and IV are substituted by loosely isolated candidates that fail to pass the strict criteria of regions I and II)

2 - Misidentified Lepton prediction



Lepton Isolation

III

OS, Anti-Isolated

IV

SS, Anti-Isolated

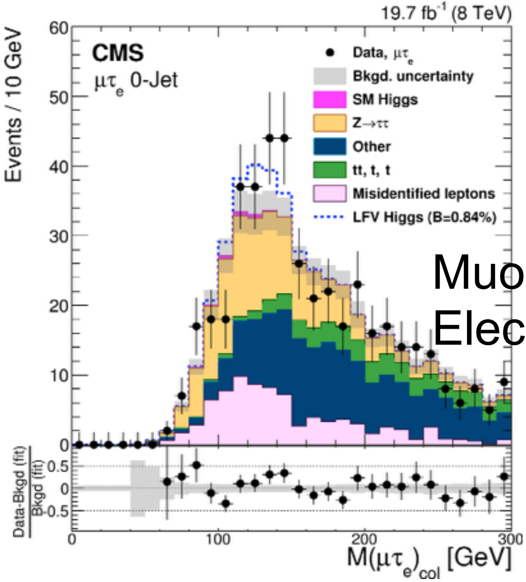
I

OS, Isolated

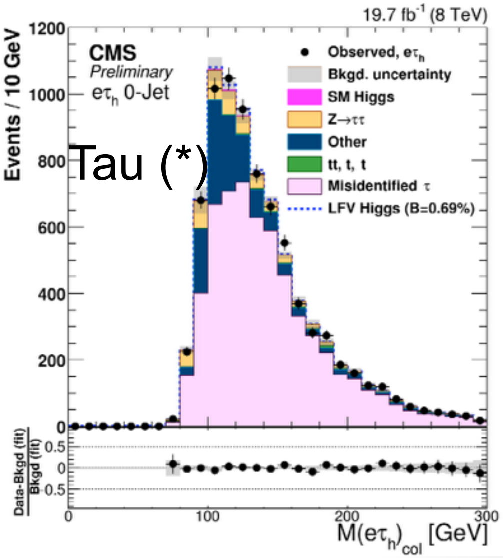
II

SS, Isolated

Charge



Muon, Electron



Tau (*)

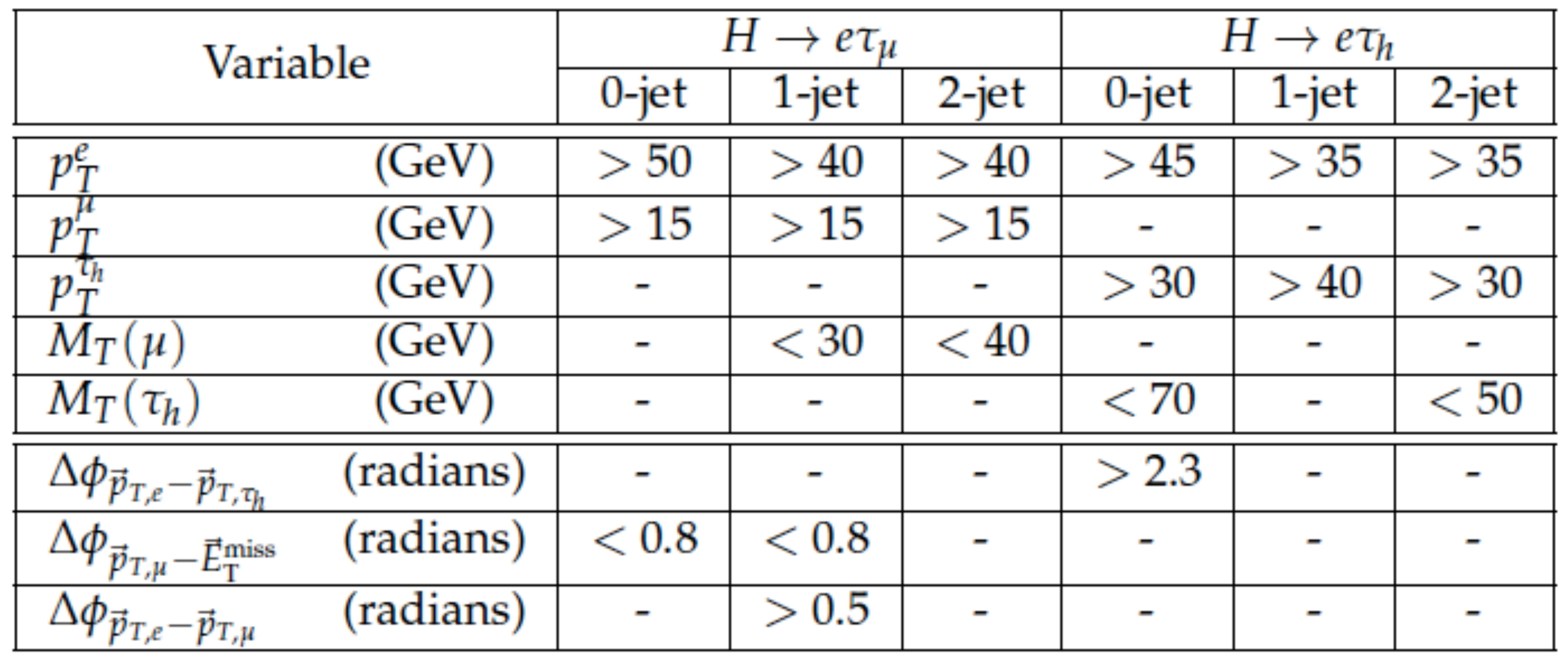
Conservative uncertainties (yield (30-40%) and shape)

Excellent description of the data

(* for tau leptons, the anti isolated candidates of regions III and IV are substituted by loosely isolated candidates that fail to pass the strict criteria of regions I and II)

Full Selection

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



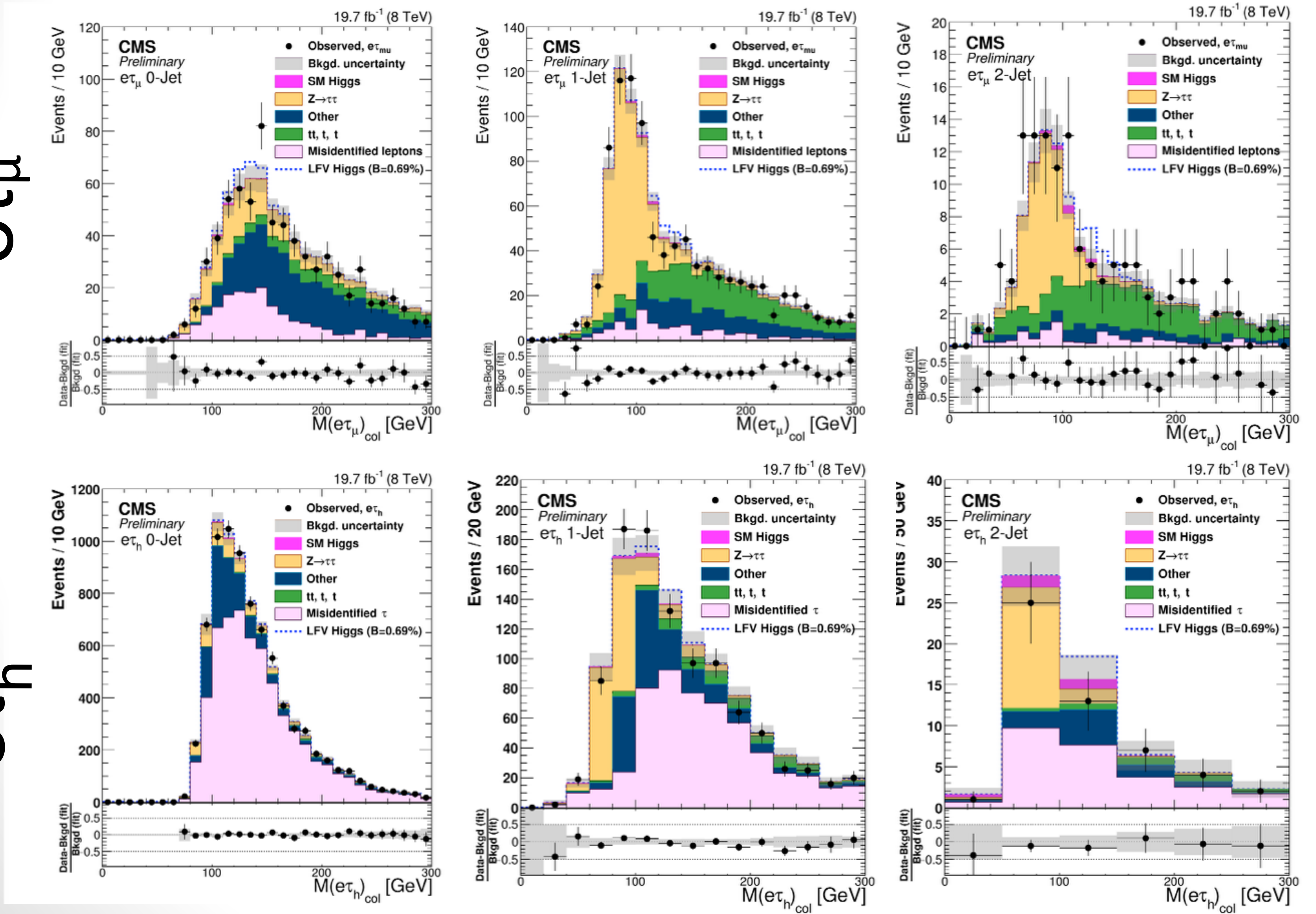
Variable	$H \rightarrow e\tau_\mu$			$H \rightarrow e\tau_h$		
	0-jet	1-jet	2-jet	0-jet	1-jet	2-jet
p_T^e (GeV)	> 50	> 40	> 40	> 45	> 35	> 35
p_T^μ (GeV)	> 15	> 15	> 15	-	-	-
$p_T^{\tau_h}$ (GeV)	-	-	-	> 30	> 40	> 30
$M_T(\mu)$ (GeV)	-	< 30	< 40	-	-	-
$M_T(\tau_h)$ (GeV)	-	-	-	< 70	-	< 50
$\Delta\phi_{\vec{p}_{T,e}-\vec{p}_{T,\tau_h}}$ (radians)	-	-	-	> 2.3	-	-
$\Delta\phi_{\vec{p}_{T,\mu}-\vec{E}_T^{\text{miss}}}$ (radians)	< 0.8	< 0.8	-	-	-	-
$\Delta\phi_{\vec{p}_{T,e}-\vec{p}_{T,\mu}}$ (radians)	-	> 0.5	-	-	-	-

$H\to e\tau$: Collinear Mass after selection

0 Jets **1 Jet** **2 Jets**

$e\tau_\mu$

$e\tau_h$

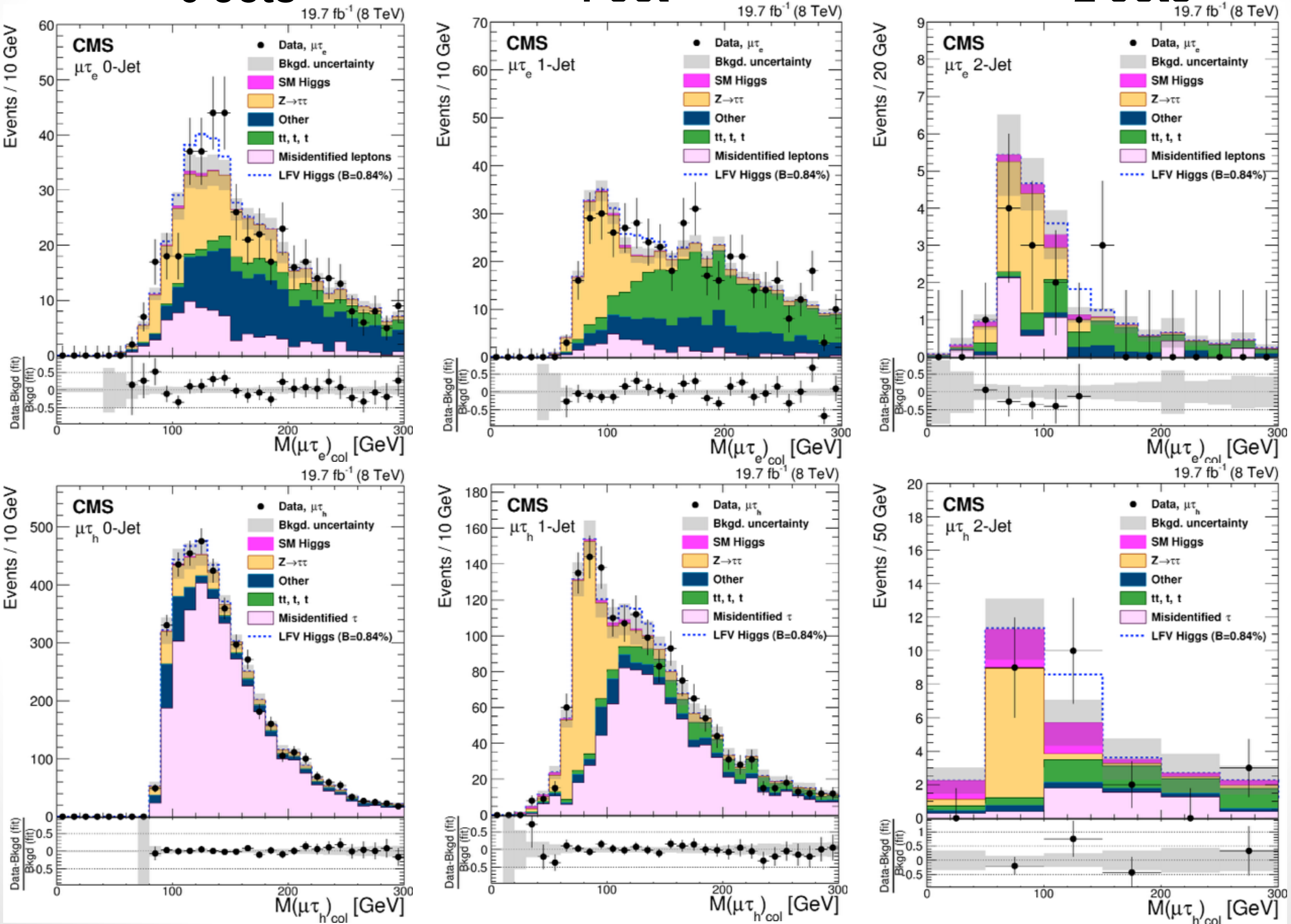


H→μτ: Collinear Mass after selection

0 Jets **1 Jet** **2 Jets**

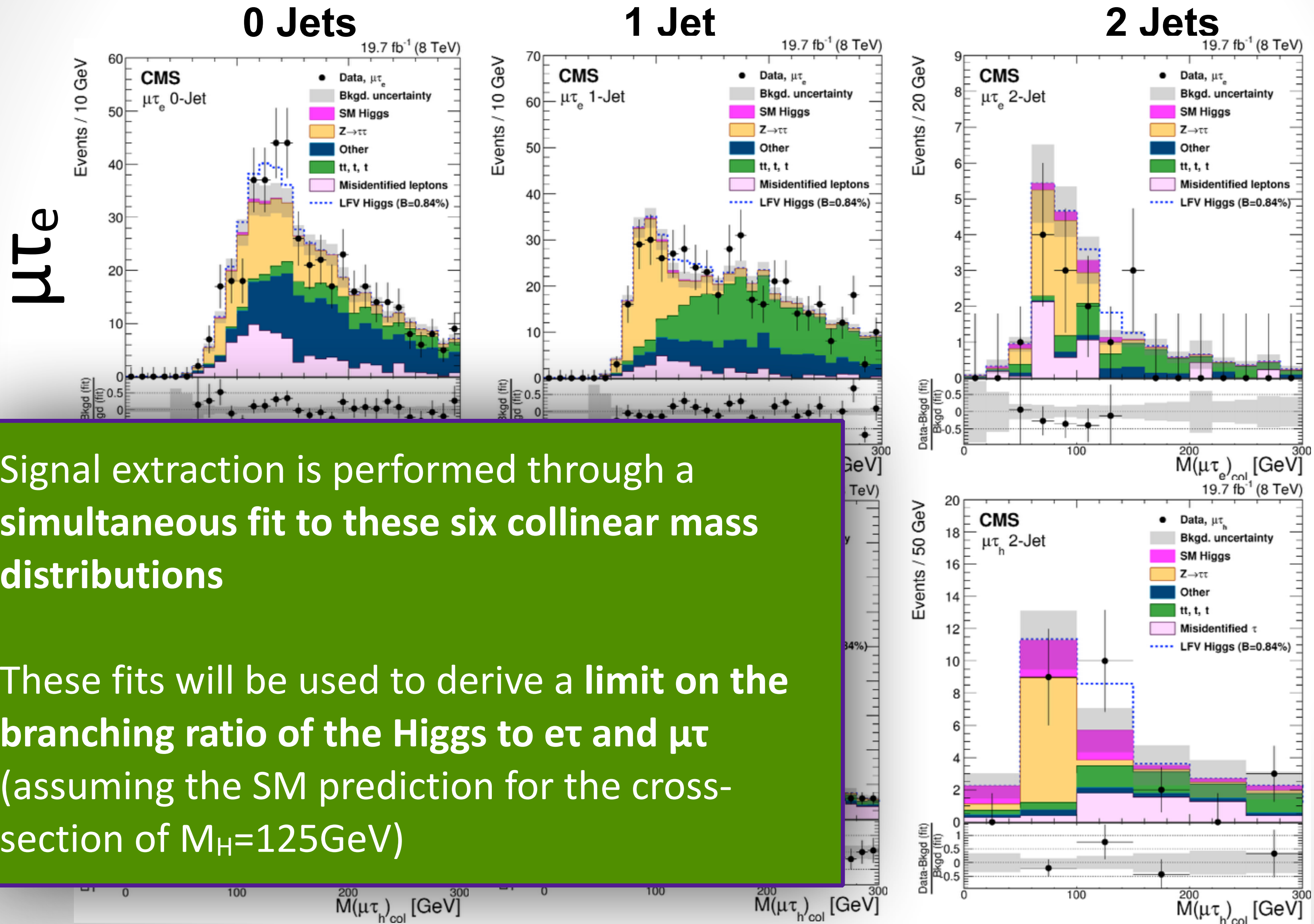
μτe

μτh



Maria Cepeda (CERN) - 12/October/2015

H→μτ: Collinear Mass after selection

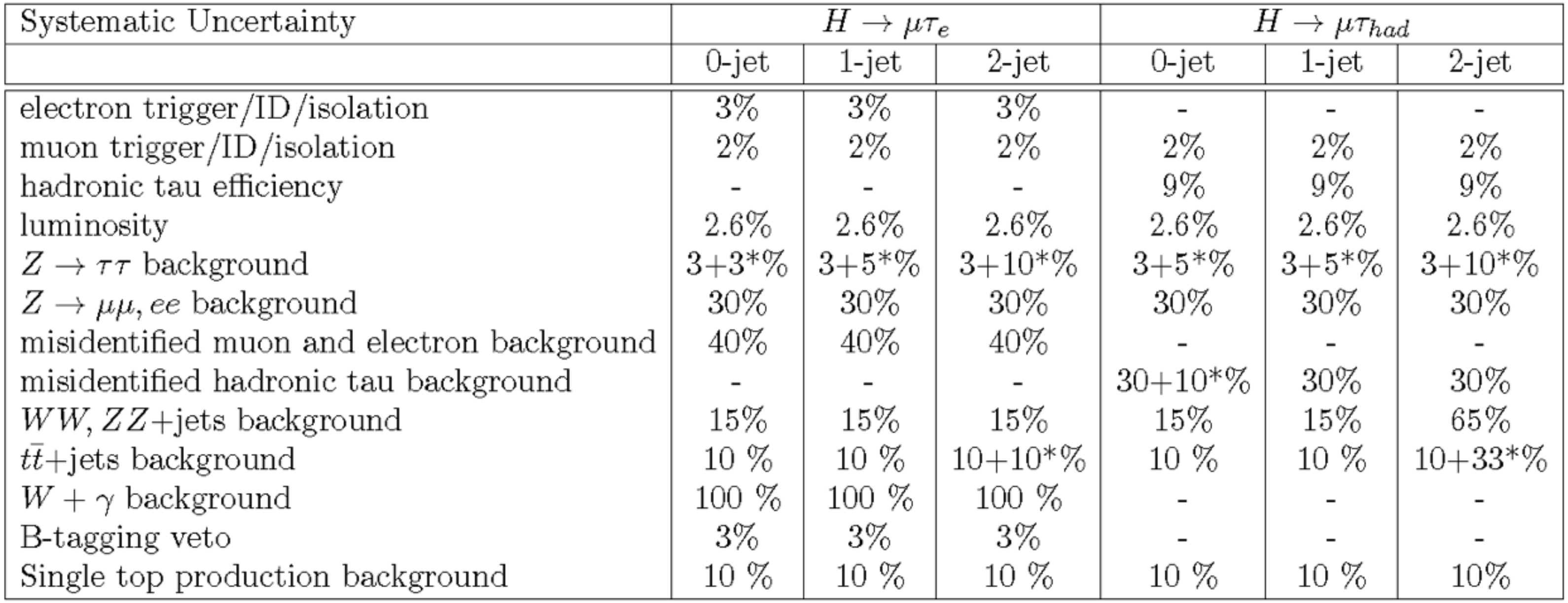


Signal extraction is performed through a **simultaneous fit to these six collinear mass distributions**

These fits will be used to derive a **limit on the branching ratio of the Higgs to eτ and μτ** (assuming the SM prediction for the cross-section of M_H=125GeV)

Systematic Uncertainties

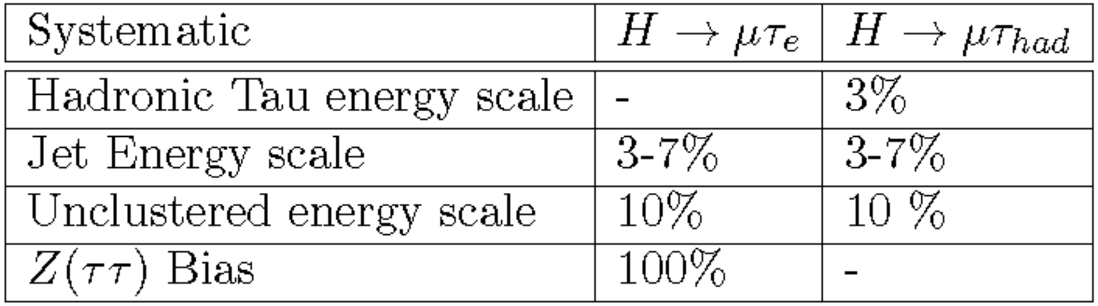
- **Background modeling (specially the fake background) is the lead experimental systematic uncertainty**
  - Normalization uncertainty taken either from our data driven estimates or from CMS measurements and correlated between bins
  - Additional uncorrelated uncertainty include to account for potential 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%

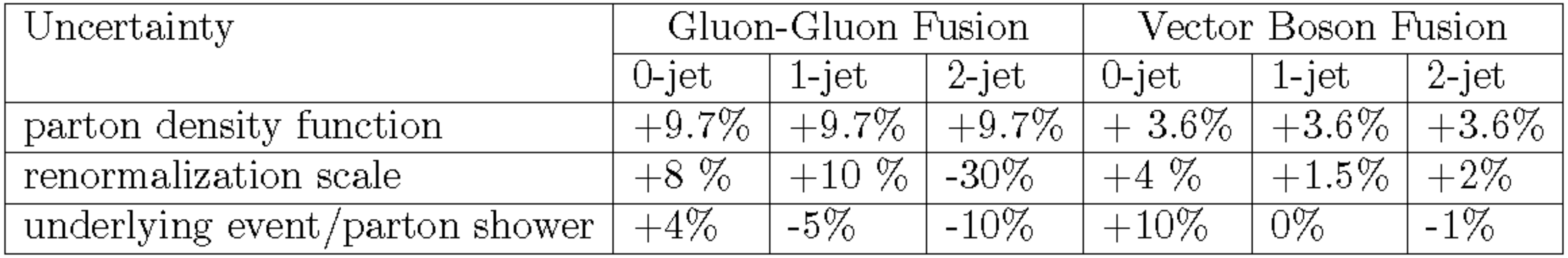
Systematic Uncertainties

- 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%

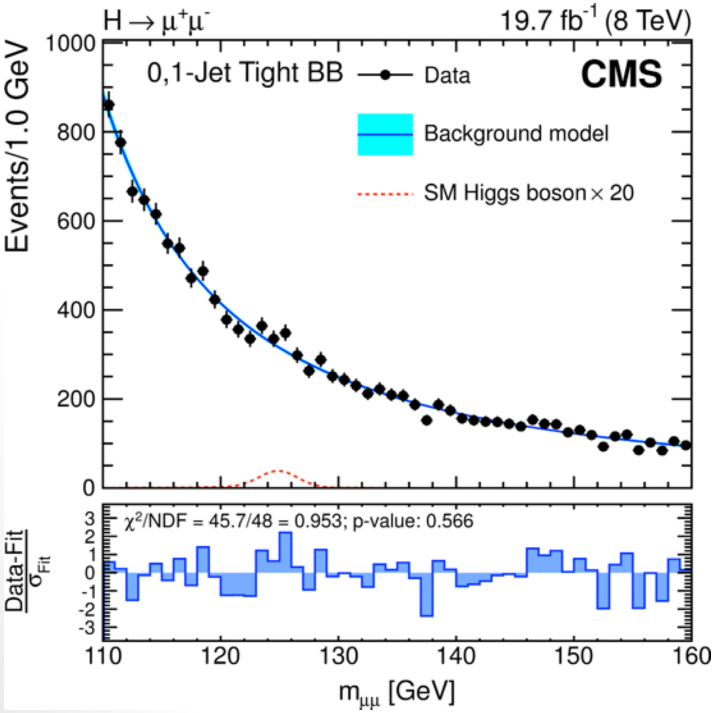
H→μe

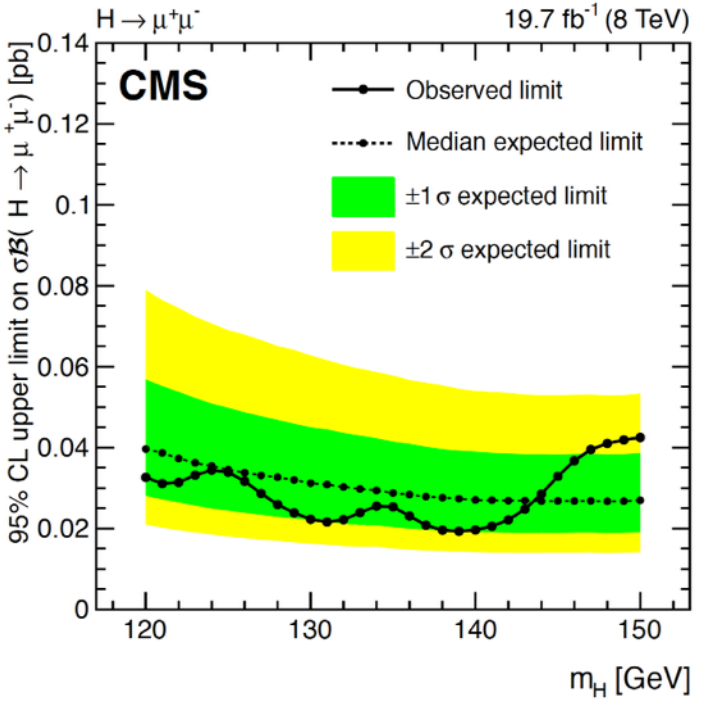
Experimental techniques close to H→μμ

What about Hμμ and Hee?

- For a Higgs of 125 GeV, the SM predicts:
  - BR(Hττ)=6.32%
  - BR(Hμμ)=0.0219%
  - BR(Hee)=5×10^{-9}

- CMS search:
  - Hμμ→ at 95% CL $\sigma/\sigma_{SM}< 7.4$ (expected $6.5^{+2.8}_{-1.9}$) → At 125 GeV, upper limit on the **Br(Hμμ)< 0.0016**
  - Hee→ **Br(Hee)< 0.0019** (3.7×10^5 times the SM!)





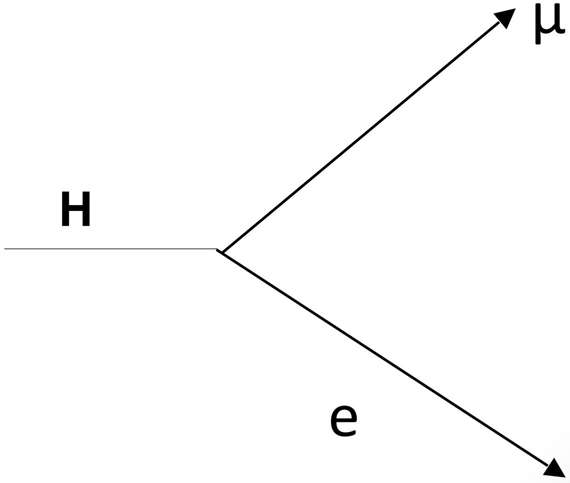
CMS-HIG-13-007
arXiv:1410.6679

Exclusion of universal coupling to leptons

Selection of Heμ events

- Very clean in comparison - but targeting a very small Br! (10^{-8} already excluded)
- Backgrounds: TTbar/Diboson/DY tails
- **10 Categories** based on:
  - GGF vs VBF discrimination:
    - inclusive categories: 0-1-2 jets
    - VBF categories (tight/loose) following Hγγ
  - Barrel/Endcap leptons

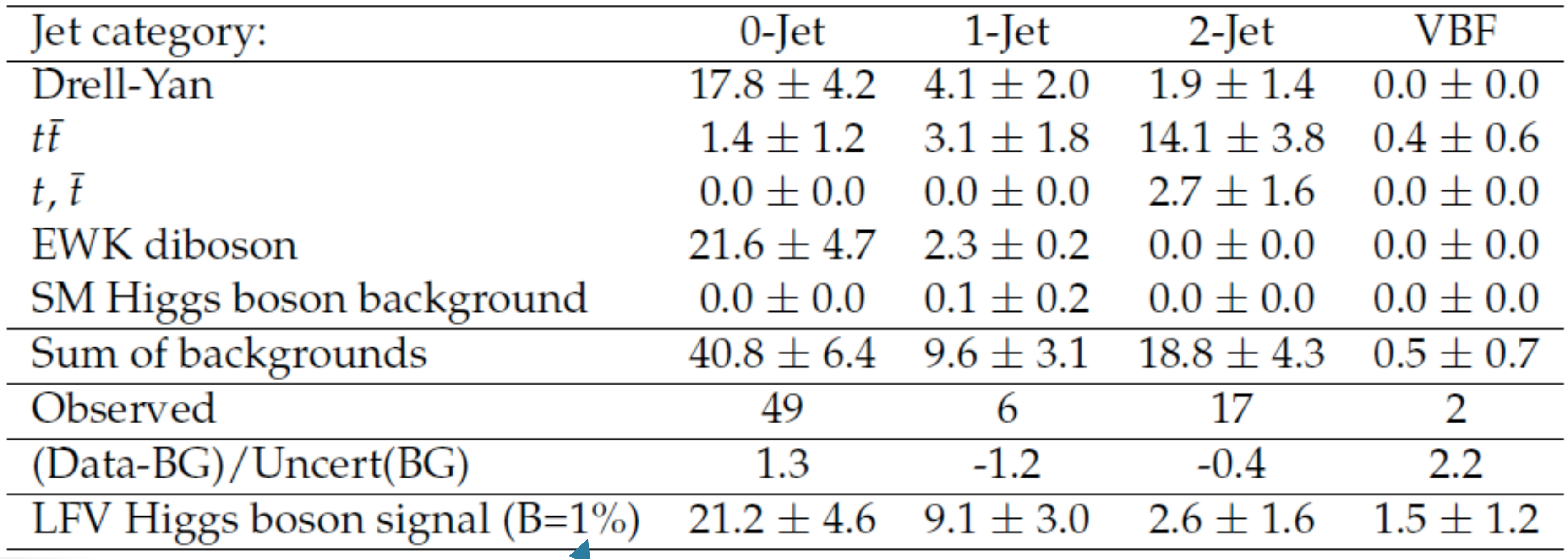
- 1 Good, Isolated, High p_T **Electron**
- 1 Good, isolated, High p_T **Muon**
- Opposite charge of the **μe** Pair
- Veto on additional leptons
- Btagged Jets veto



Background composition

- Very clean search comparison
- non-LHC limits already constrain the Br tightly

124 <Meμ< 126 GeV



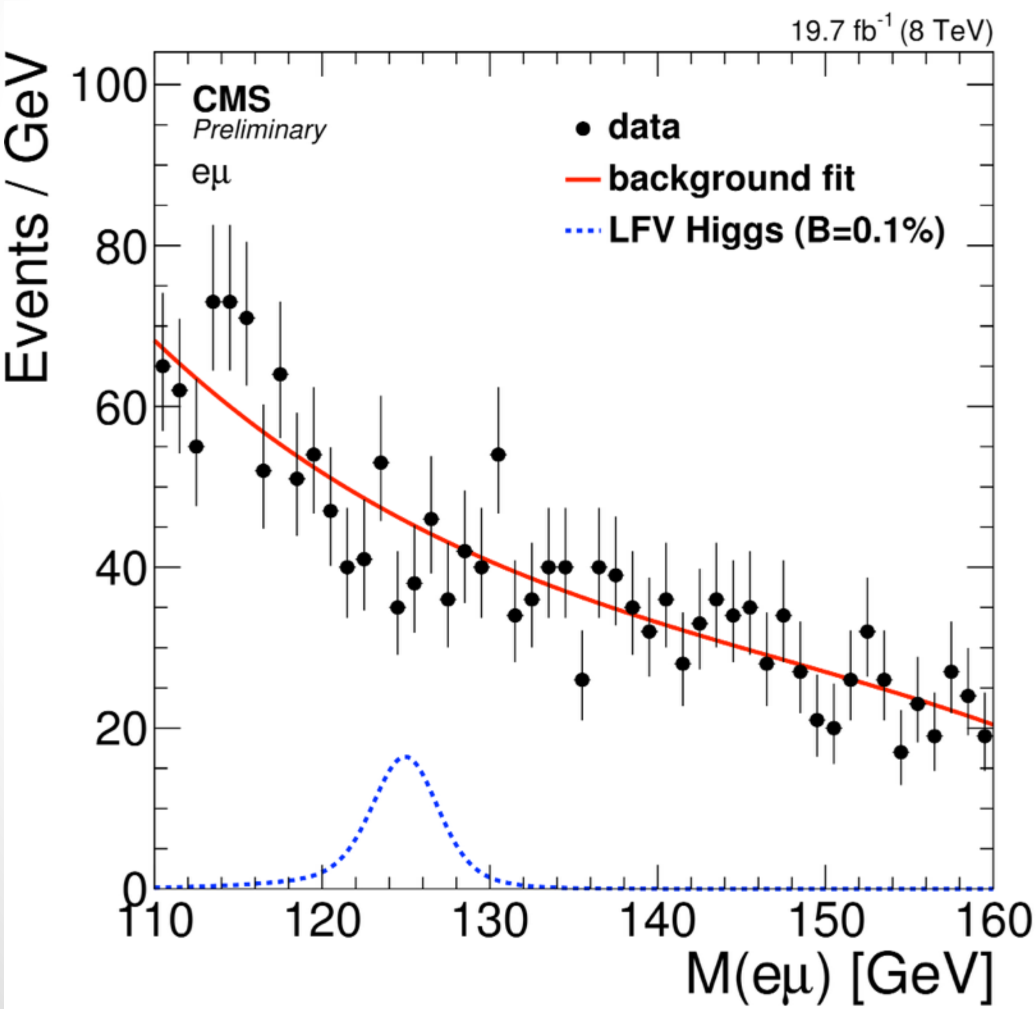
Jet category:	0-Jet	1-Jet	2-Jet	VBF
Drell-Yan	17.8 ± 4.2	4.1 ± 2.0	1.9 ± 1.4	0.0 ± 0.0
$t\bar{t}$	1.4 ± 1.2	3.1 ± 1.8	14.1 ± 3.8	0.4 ± 0.6
$t, \bar{t}$	0.0 ± 0.0	0.0 ± 0.0	2.7 ± 1.6	0.0 ± 0.0
EWK diboson	21.6 ± 4.7	2.3 ± 0.2	0.0 ± 0.0	0.0 ± 0.0
SM Higgs boson background	0.0 ± 0.0	0.1 ± 0.2	0.0 ± 0.0	0.0 ± 0.0
Sum of backgrounds	40.8 ± 6.4	9.6 ± 3.1	18.8 ± 4.3	0.5 ± 0.7
Observed	49	6	17	2
(Data-BG)/Uncert(BG)	1.3	-1.2	-0.4	2.2
LFV Higgs boson signal (B=1%)	21.2 ± 4.6	9.1 ± 3.0	2.6 ± 1.6	1.5 ± 1.2

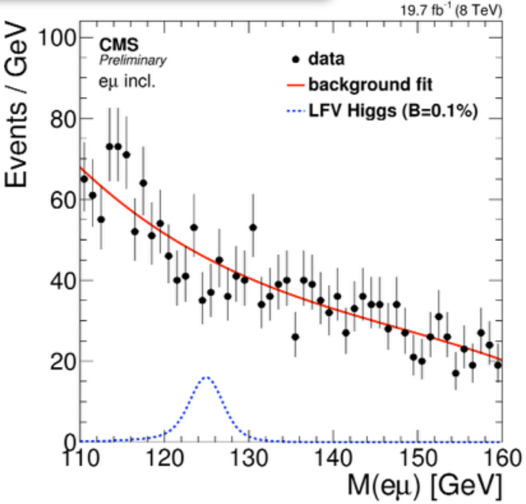
non-LHC limits at Br<10^{-8} …

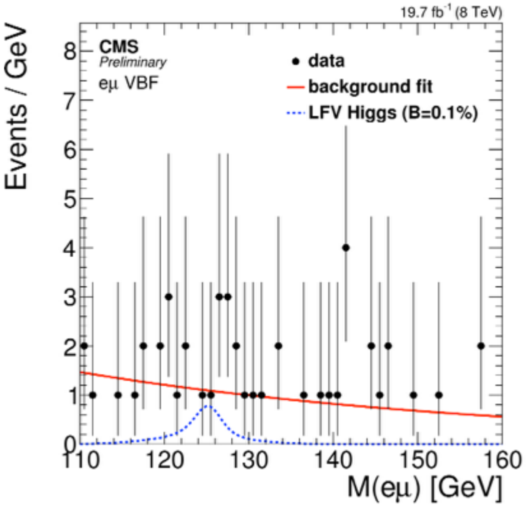
Signal Extraction

Signal Extraction through a fit to the invariant mass distribution:

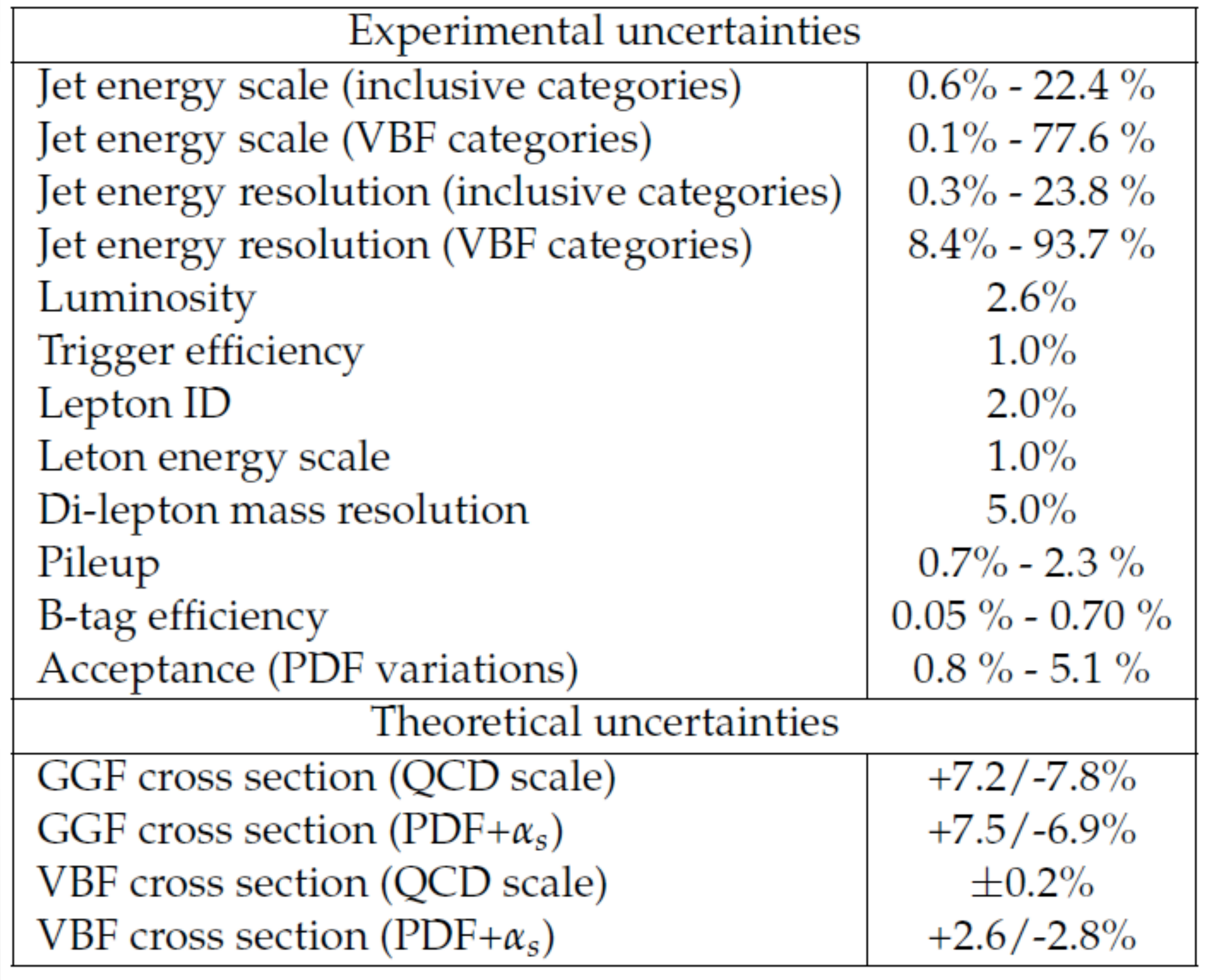
- **Background**: Modelled by a combination of polynomials
- **Signal**: Modelled using two gaussians







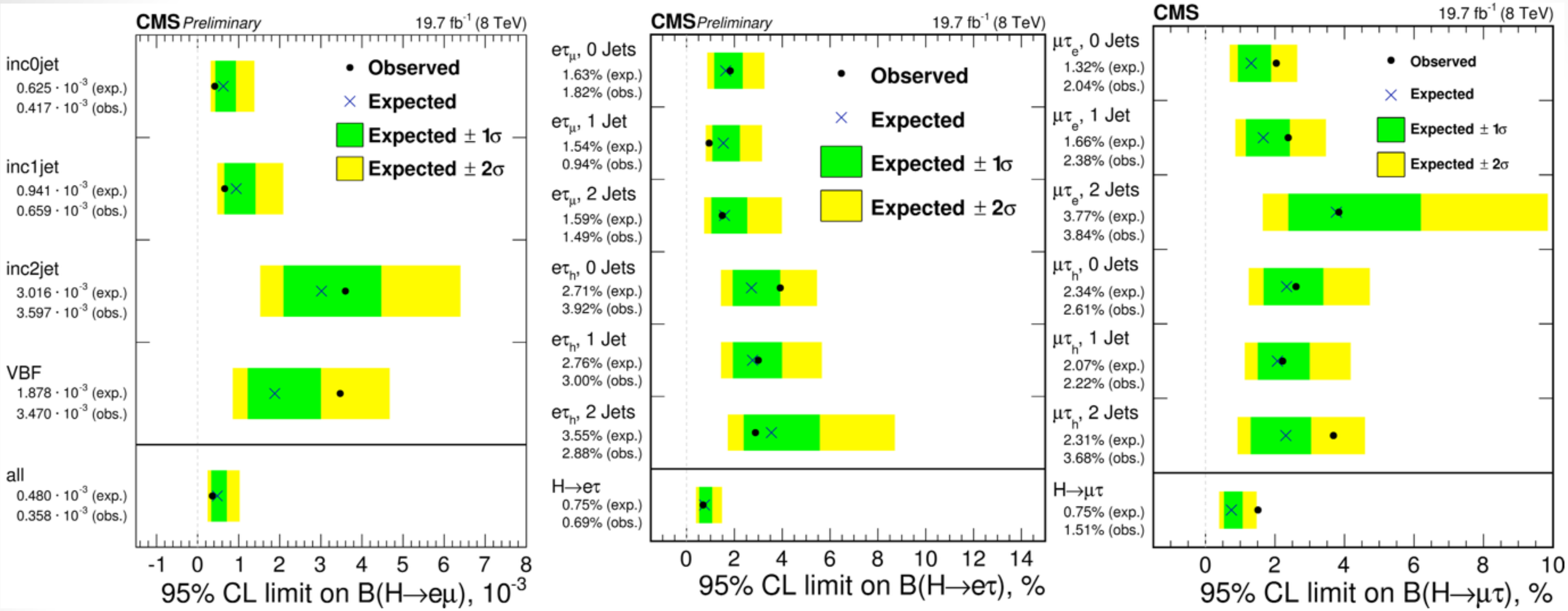
Systematic Uncertainties: Heμ



Experimental uncertainties	
Jet energy scale (inclusive categories)	0.6% - 22.4 %
Jet energy scale (VBF categories)	0.1% - 77.6 %
Jet energy resolution (inclusive categories)	0.3% - 23.8 %
Jet energy resolution (VBF categories)	8.4% - 93.7 %
Luminosity	2.6%
Trigger efficiency	1.0%
Lepton ID	2.0%
Leton energy scale	1.0%
Di-lepton mass resolution	5.0%
Pileup	0.7% - 2.3 %
B-tag efficiency	0.05 % - 0.70 %
Acceptance (PDF variations)	0.8 % - 5.1 %
Theoretical uncertainties	
GGF cross section (QCD scale)	+7.2/-7.8%
GGF cross section (PDF+α_s)	+7.5/-6.9%
VBF cross section (QCD scale)	±0.2%
VBF cross section (PDF+α_s)	+2.6/-2.8%

RESULTS

95% CL Limits on the Branching Ratio



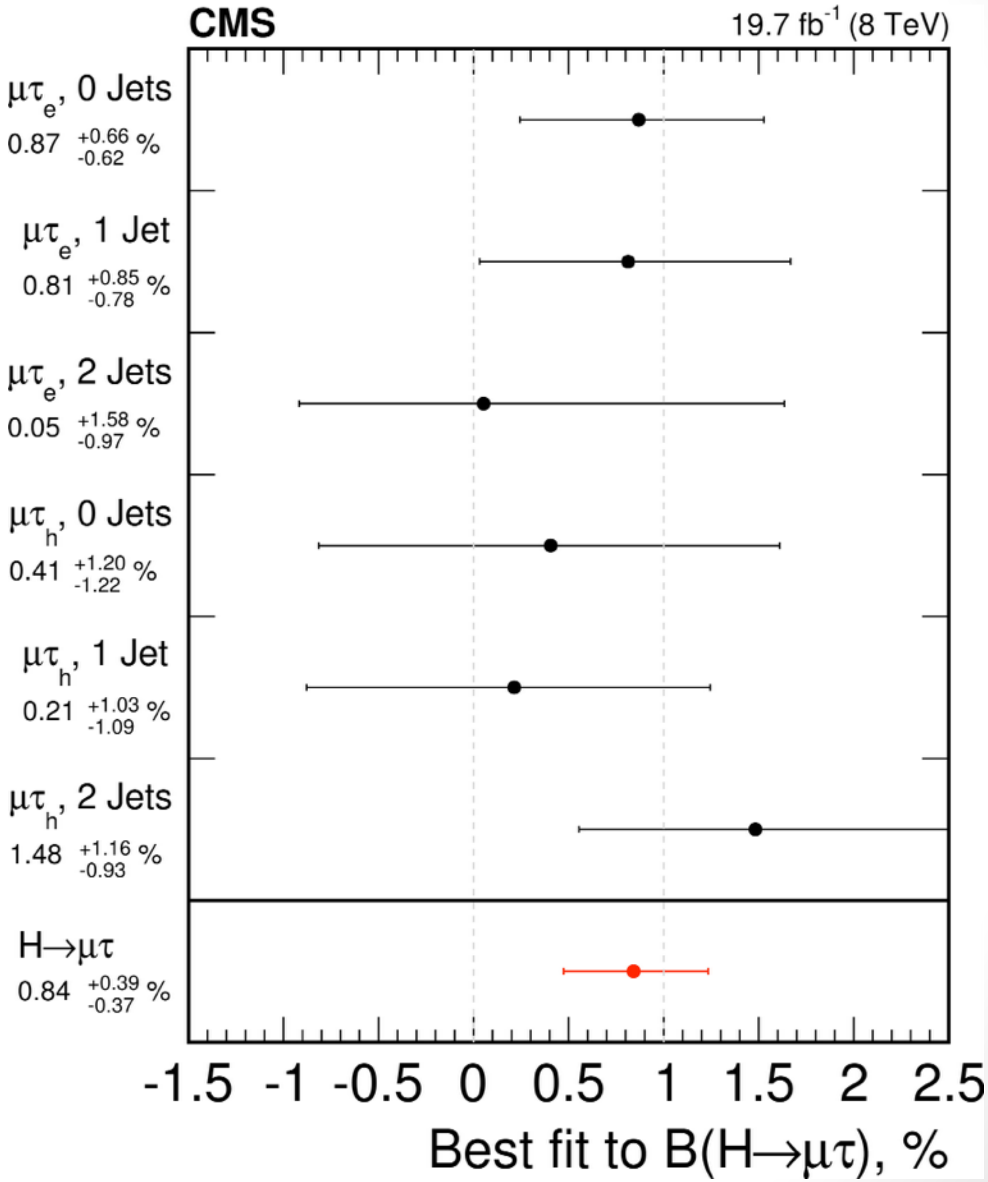
Br(H→eμ)<0.36e-3 (0.48e-3 expected)

Br(H→eτ)<0.69% (0.75% expected)

Br(H→μτ)<1.51% (0.75% expected)

Best Fit to the Branching Ratio

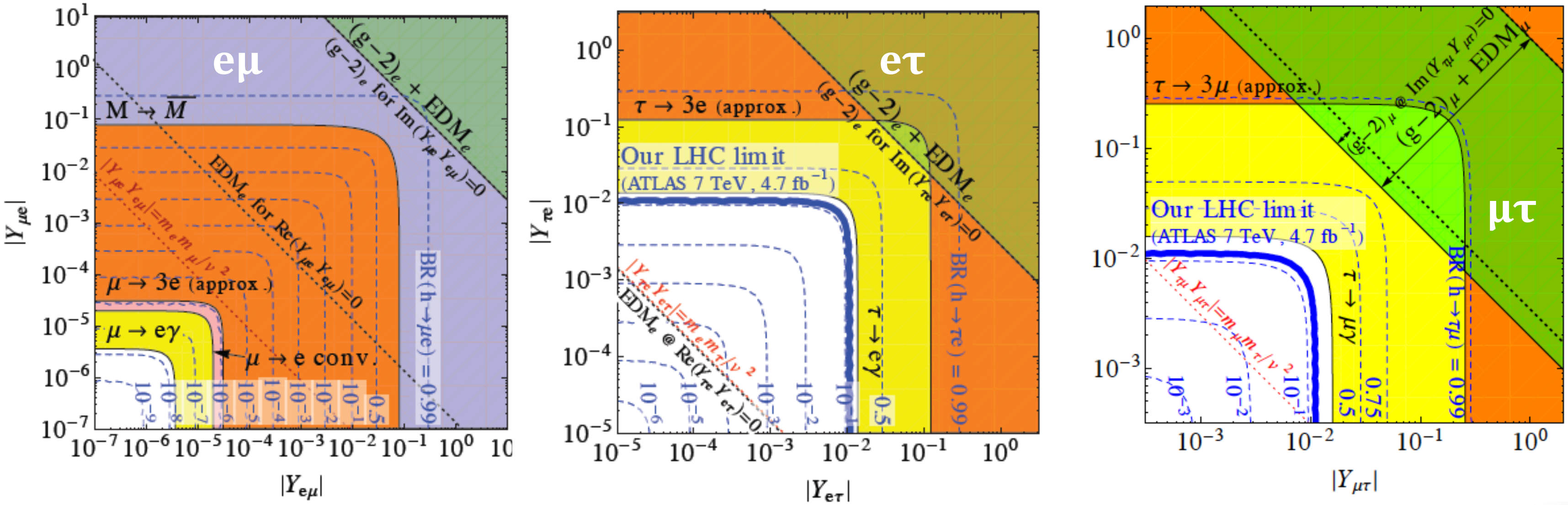
- Small deviations per category (at most ~1sigma)
- Hemu and Heτ fit compatible with 0.



Back to the couplings…

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

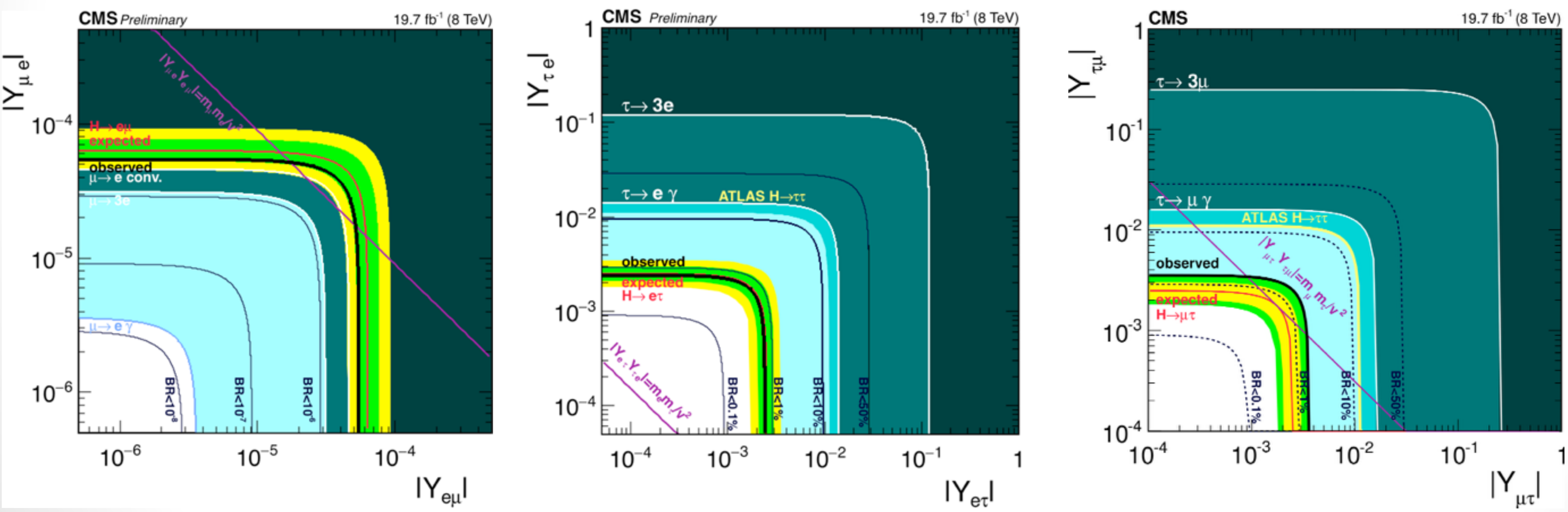
arXiv:1209.1397



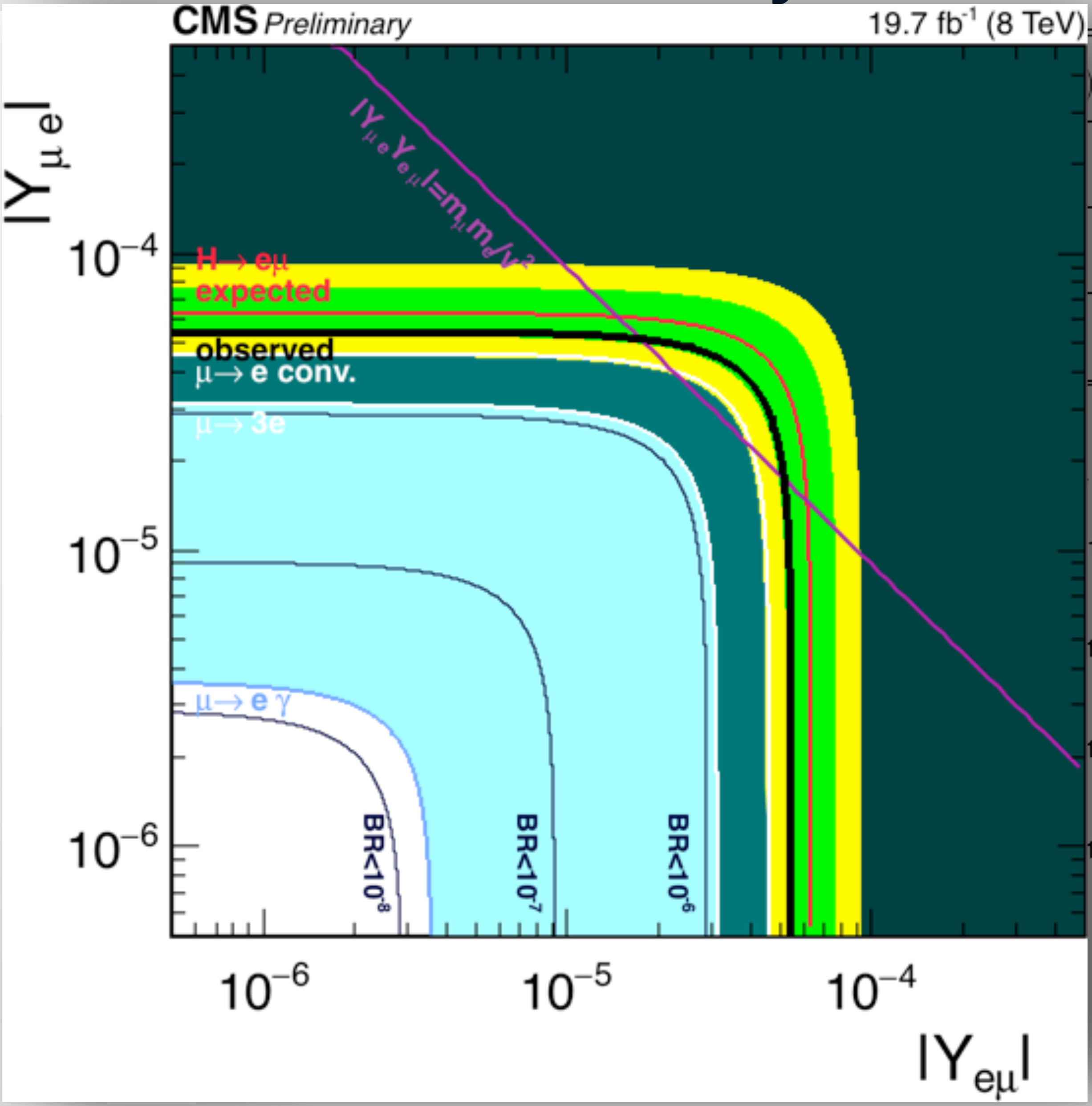
$$\mathrm{BR}(h \to \ell^\alpha \ell^\beta) = \frac{\Gamma(h \to \ell^\alpha \ell^\beta)}{\Gamma(h \to \ell^\alpha \ell^\beta) + \Gamma_{\mathrm{SM}}}$$

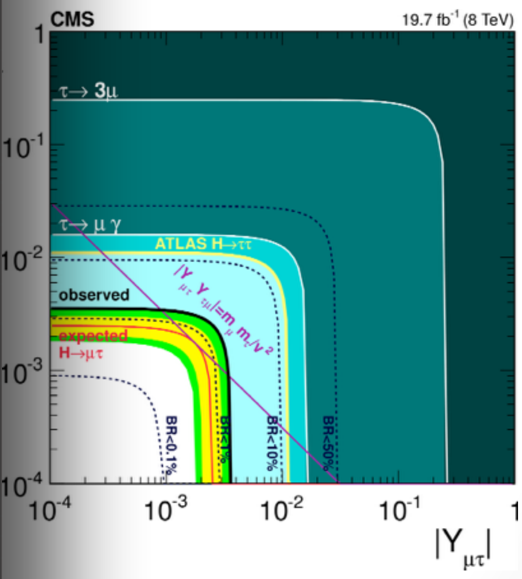
CMS limits on the yukawa couplings

Channel	Coupling	CMS Limit (95% CL)
$\mathrm{H} \to \mu e$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 5.4 \times 10^{-4}$
$\mathrm{H} \to e\tau$	$\sqrt{\lvert Y_{e\tau}\rvert^2 + \lvert Y_{\tau e}\rvert^2}$	$< 2.4 \times 10^{-3}$
$\mathrm{H} \to \mu\tau$	$\sqrt{\lvert Y_{\mu\tau}\rvert^2 + \lvert Y_{\tau\mu}\rvert^2}$	$< 3.6 \times 10^{-3}$



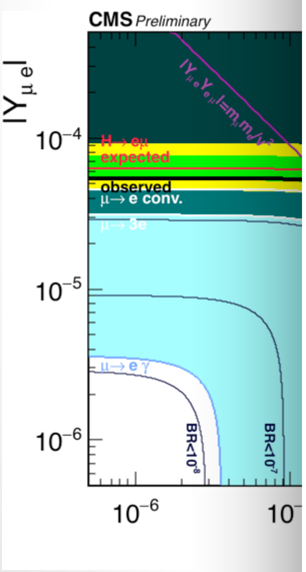
CMS limits on the yukawa couplings

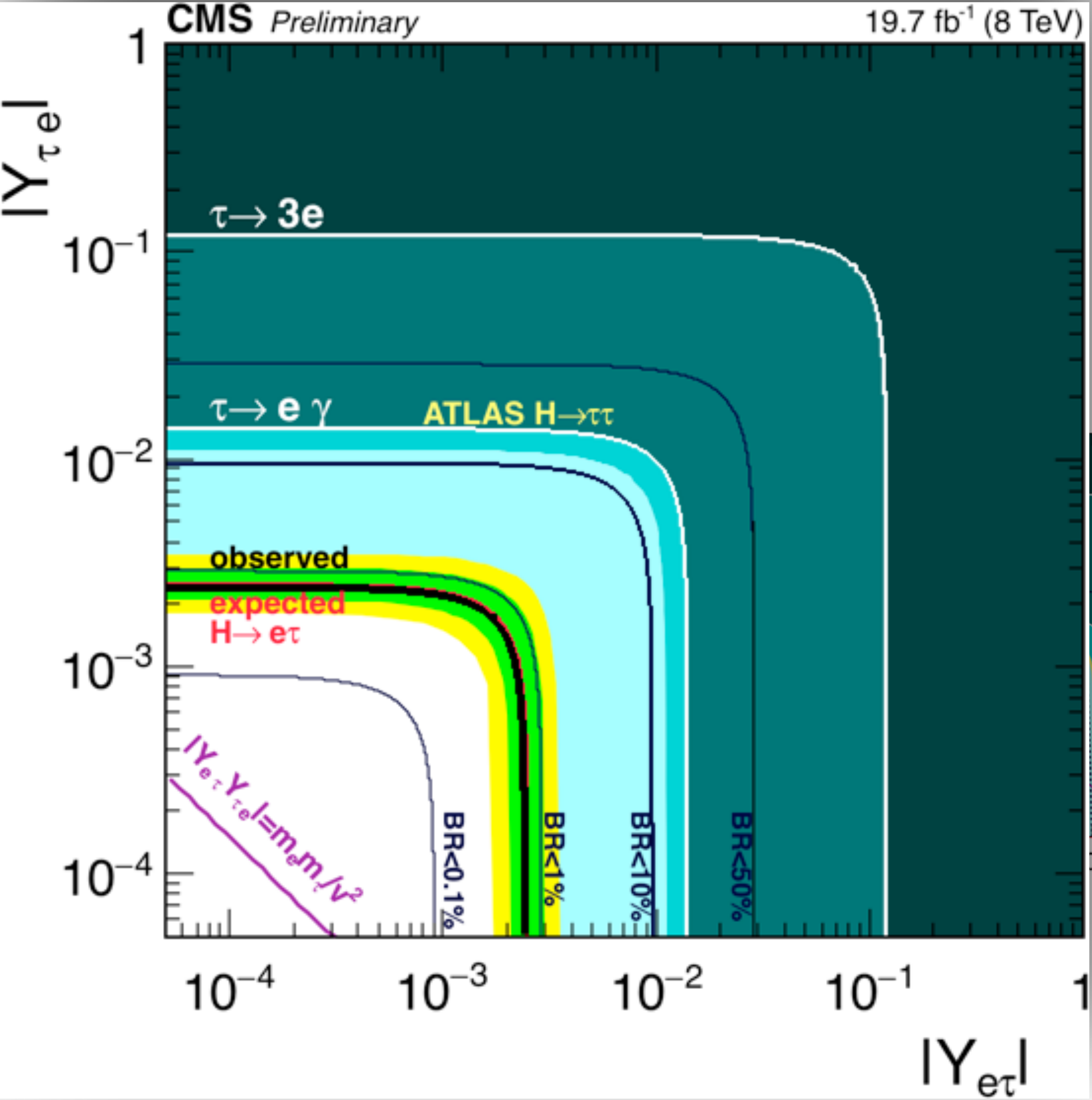


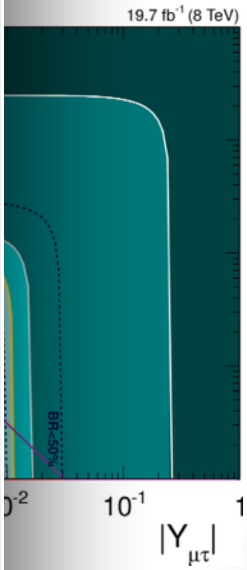


CMS limits on the yukawa couplings

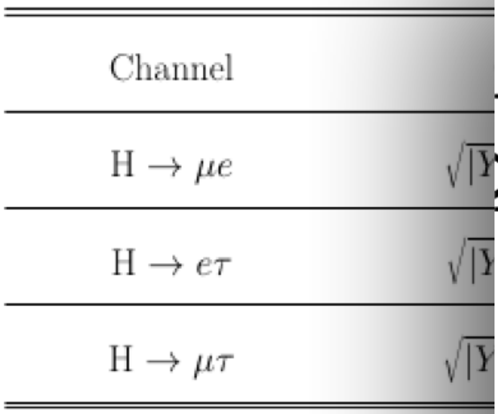
Channel
$H \to \mu e$
$H \to e\tau$
$H \to \mu\tau$



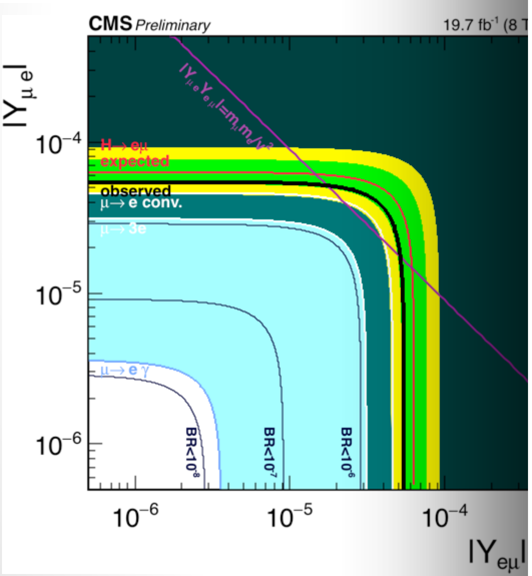


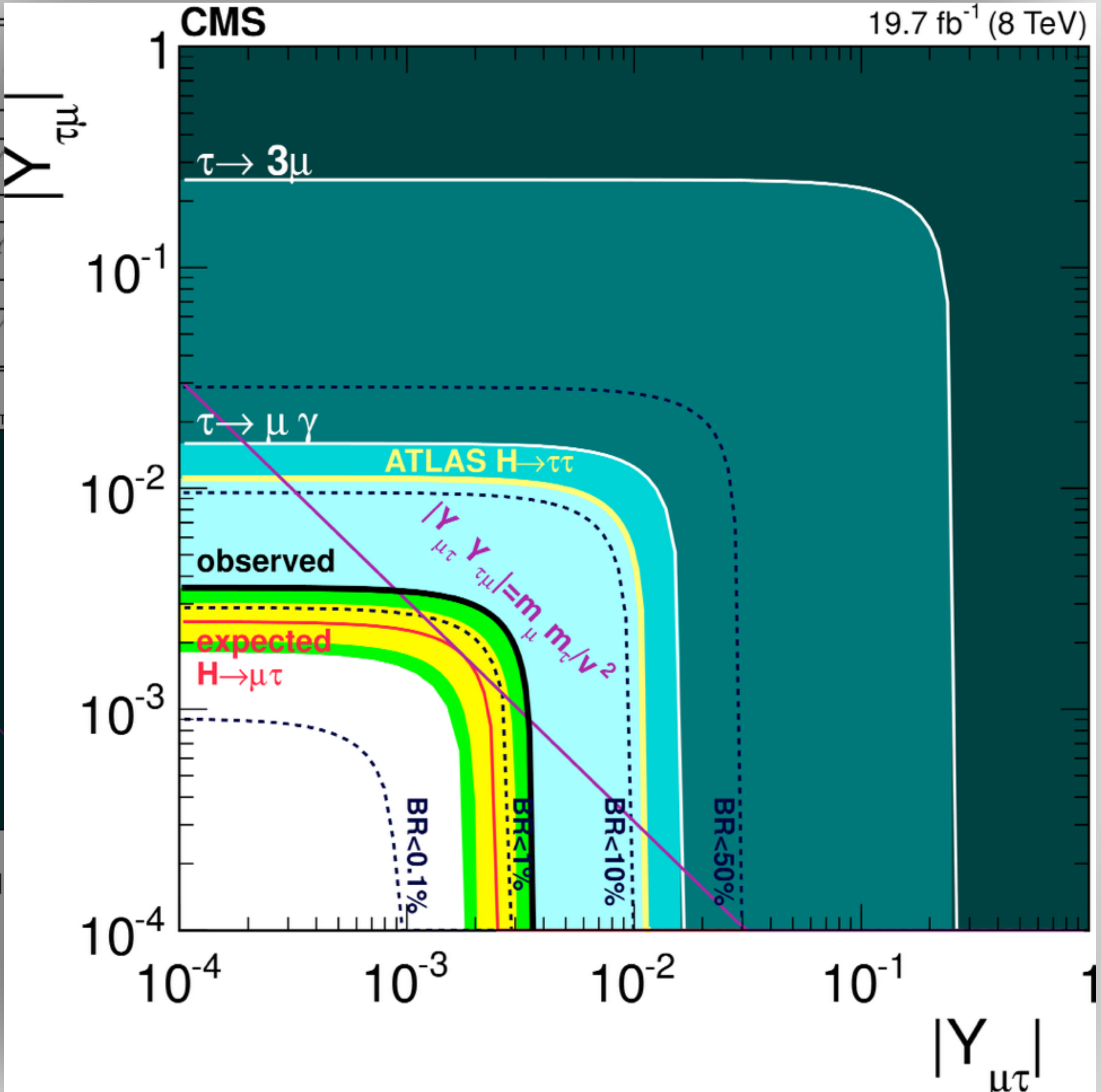


CMS limits on the yukawa couplings

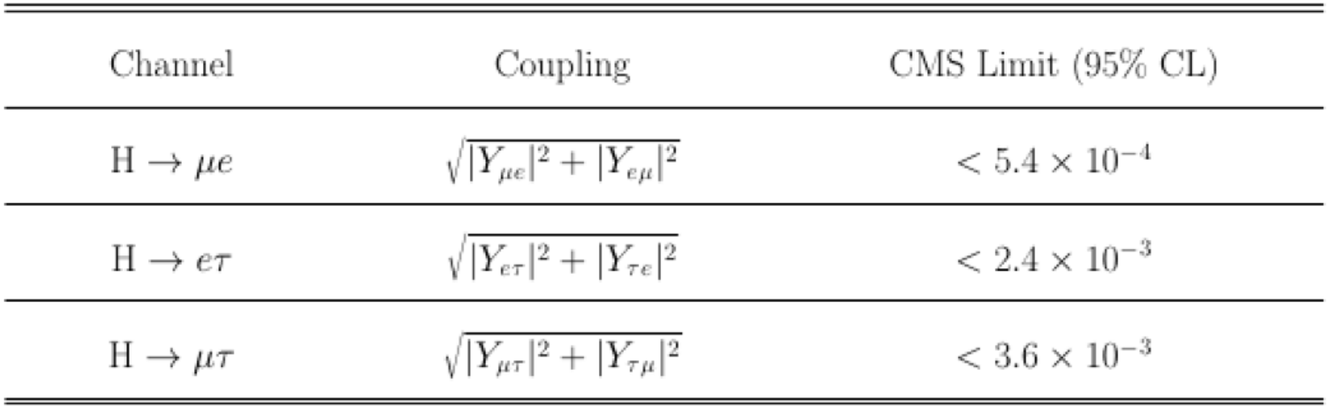


Channel	
H → μe	$\sqrt{\lvert Y$
H → $e\tau$	$\sqrt{\lvert Y$
H → $\mu\tau$	$\sqrt{\lvert Y$



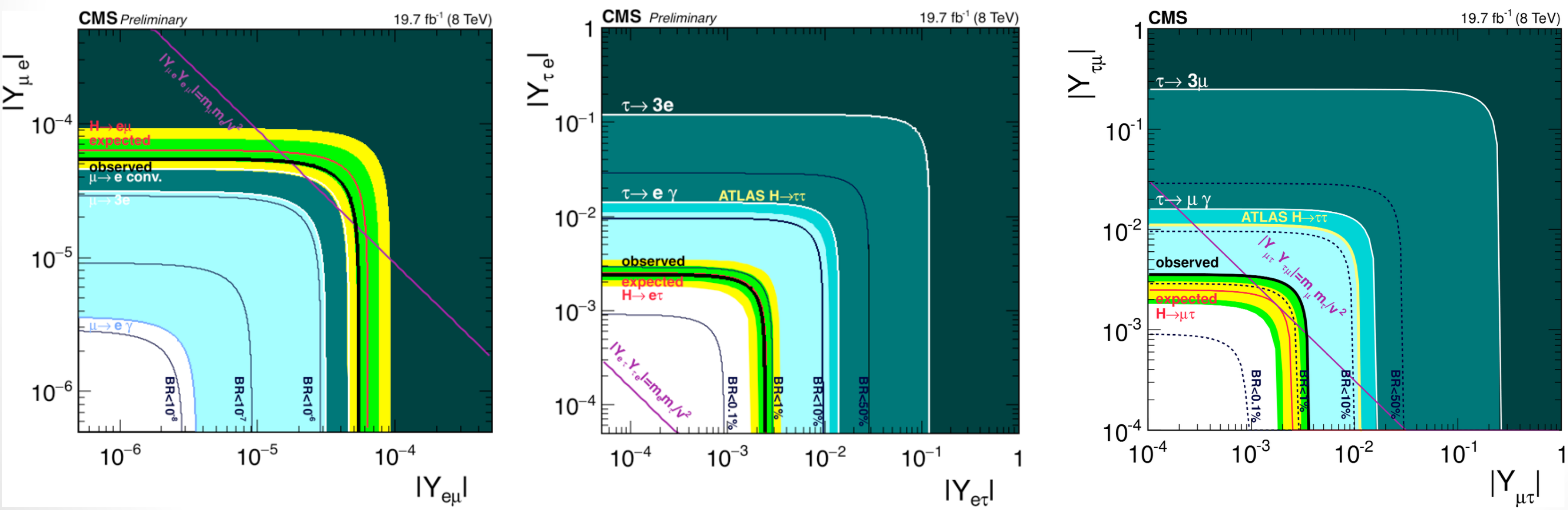


CMS limits on the yukawa couplings



Channel	Coupling	CMS Limit (95% CL)
$\mathrm{H} \to \mu e$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 5.4 \times 10^{-4}$
$\mathrm{H} \to e\tau$	$\sqrt{\lvert Y_{e\tau}\rvert^2 + \lvert Y_{\tau e}\rvert^2}$	$< 2.4 \times 10^{-3}$
$\mathrm{H} \to \mu\tau$	$\sqrt{\lvert Y_{\mu\tau}\rvert^2 + \lvert Y_{\tau\mu}\rvert^2}$	$< 3.6 \times 10^{-3}$

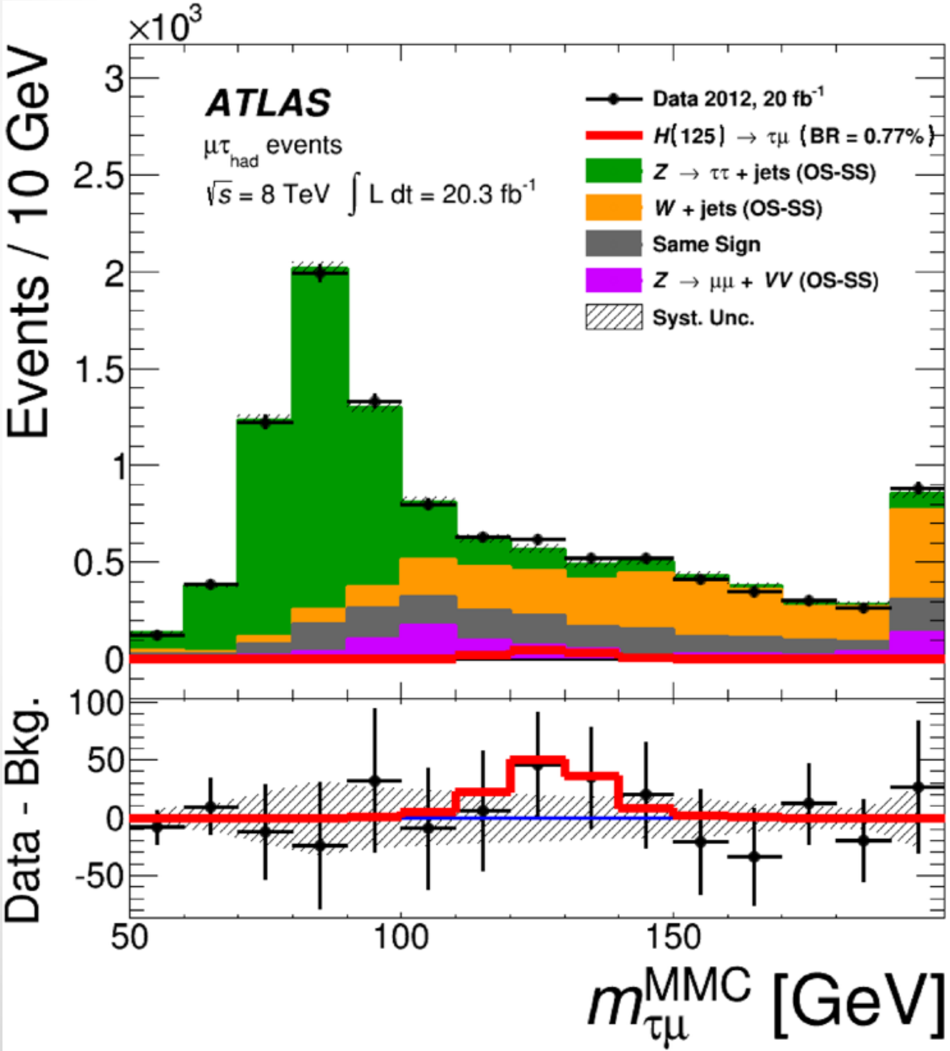
One order of magnitude improvement for μτ/eτ



- Already digging into the “natural” regime for μτ

ATLAS LFV Higgs search

- So far, only made public for the $\mu\tau_h$ channel



Upper limit for background hypothesis: BR(H→$\mu\tau$) <1.85% (1.24% exp)

1.3σ excess corresponding to BR(H→$\mu\tau$) = (0.77±0.62)%

2 categories: excess only observed in one of them

arXiv:1508.03372

Maria Cepeda (CERN) 7-Jan-15

SUMMARY

Summary

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

  → **Comprehensive set of production and decay measurements performed using the 7 and 8 TeV CMS data**

  → **Searches in rarer modes become sensitive enough for discovery**

- **CMS performed the first ever direct search for LFV Higgs decays, in the three decay channels: μτ, μe, eτ**
  - **The CMS limits on the Br(H->lτ) are one order of magnitude tighter than the preexisting non-LHC ones**
  - **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 %.
  - No deviation from the background-only hypothesis is observed for the **eτ channel or μe channels**

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Run II has arrived!—> 13TeV searches for LFV decays of the Higgs have already started —> one of the key BSM Higgs Searches

Could new physics be hidden in the Higgs Flavor sector?

Thanks! ☺

CMS Results on LFV

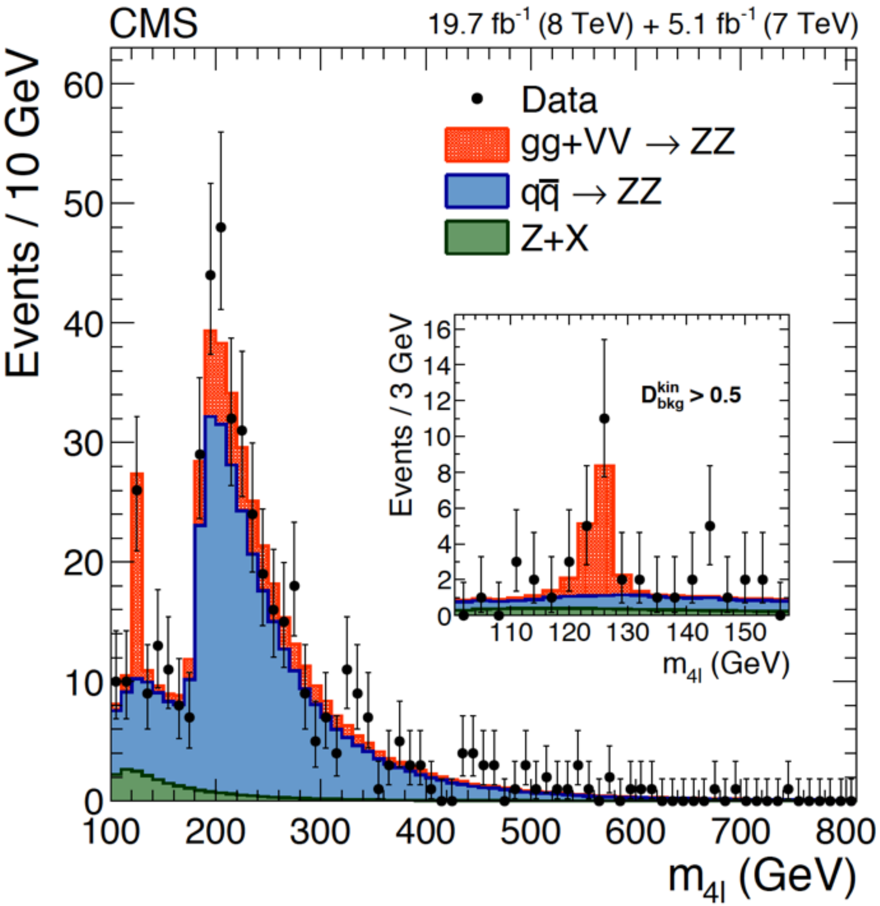
- Search for lepton-flavour-violating decays of the Higgs boson (μτ): http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-14-005/

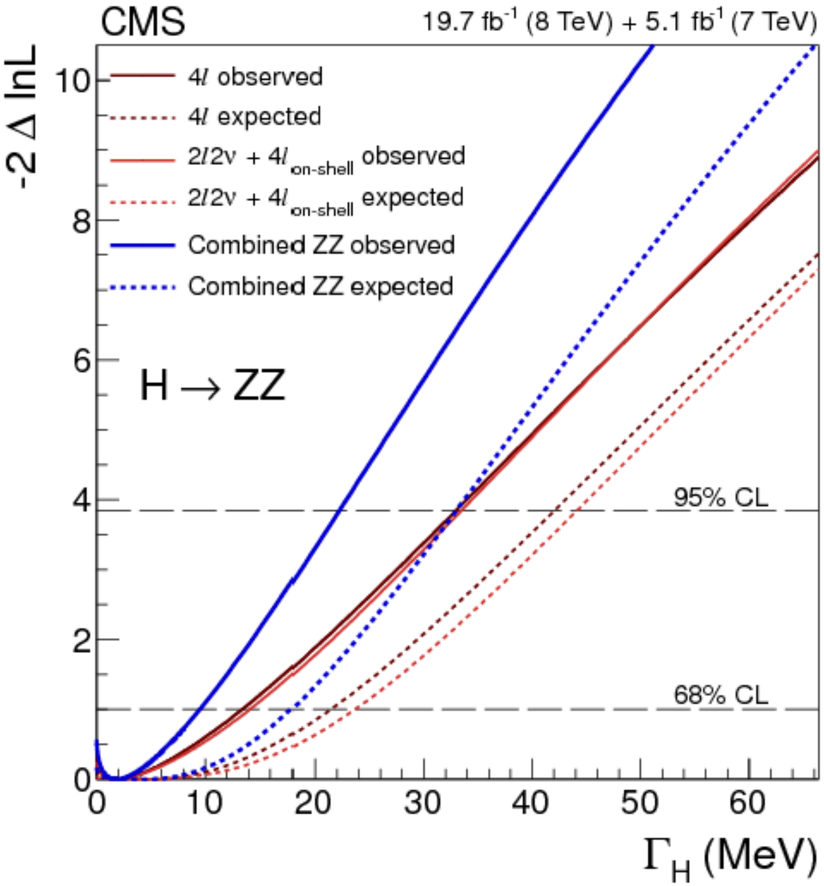
- Search for lepton-flavour-violating decays of the Higgs boson to eτ and eμ at 8 TeV : http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-14-040/

Its width is as the SM predicts…

- Γ_H SM = 4.7 MeV
- Γ_H<22 MeV (expected 33 MeV)
- Best Fit: $\Gamma_H = 1.8^{+7.7}_{-1.8}$ MeV

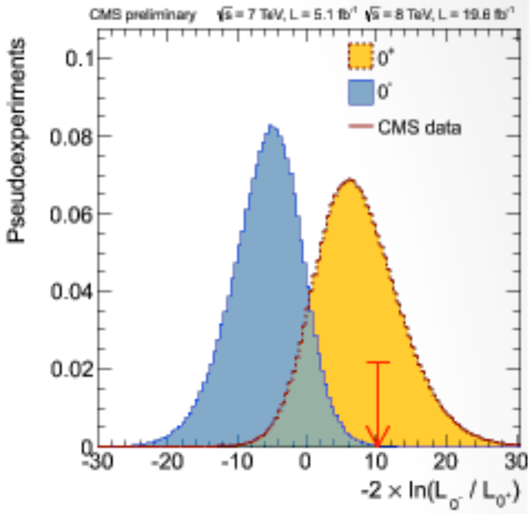
CMS-HIG-14-002
Phys. Lett. B 736 (2014) 64

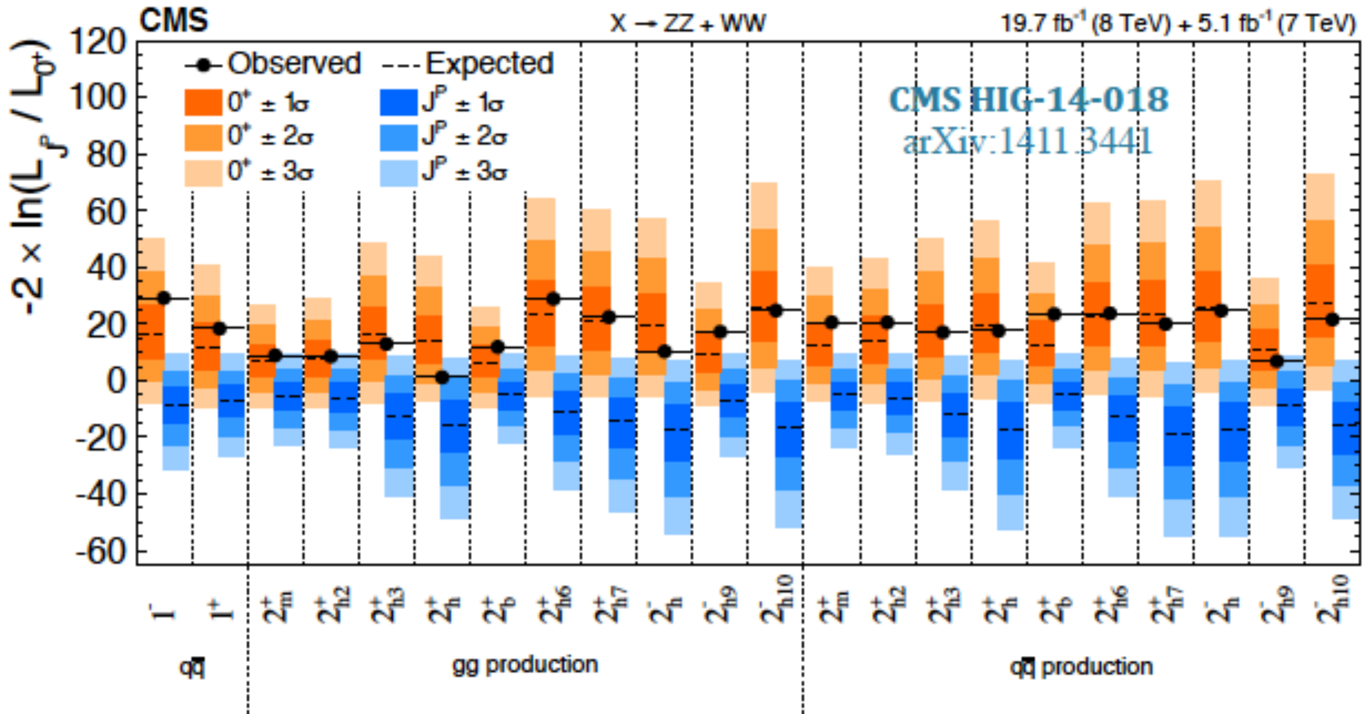




Its spin is like the SM Higgs Boson's one…

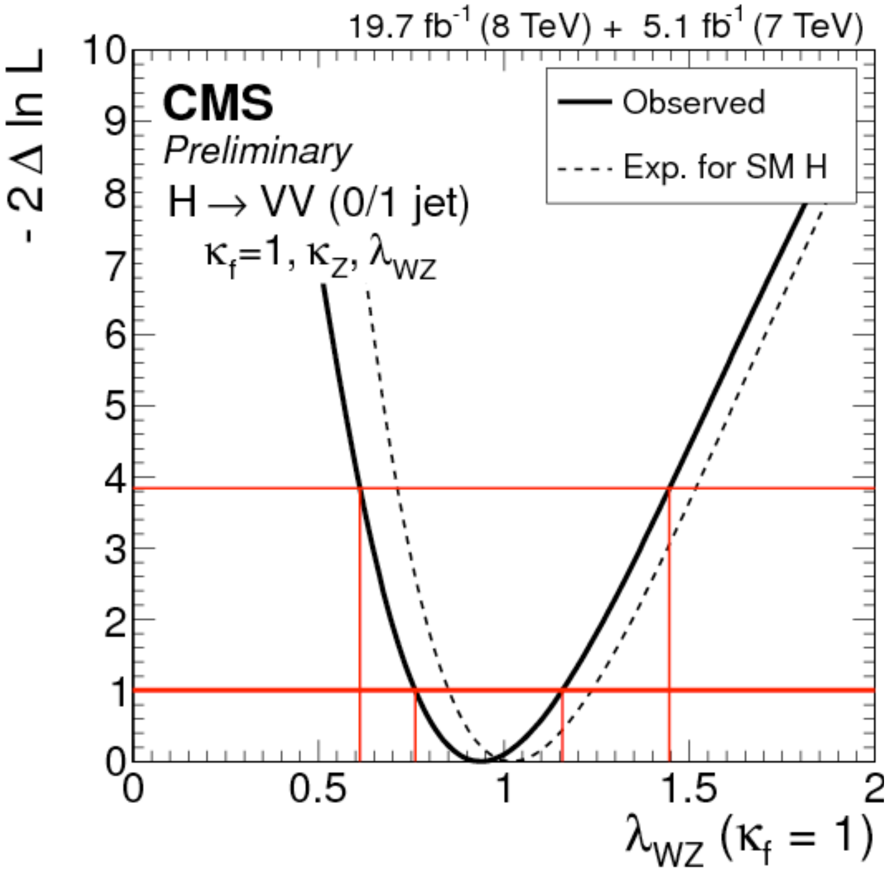
- Spin 1 excluded by observation of Hγγ
- All tested hypotheses excluded at more than 99.9% CLS (HZZ/Hγγ/HWW)
- **$J^{PC} = 0^{++}$**



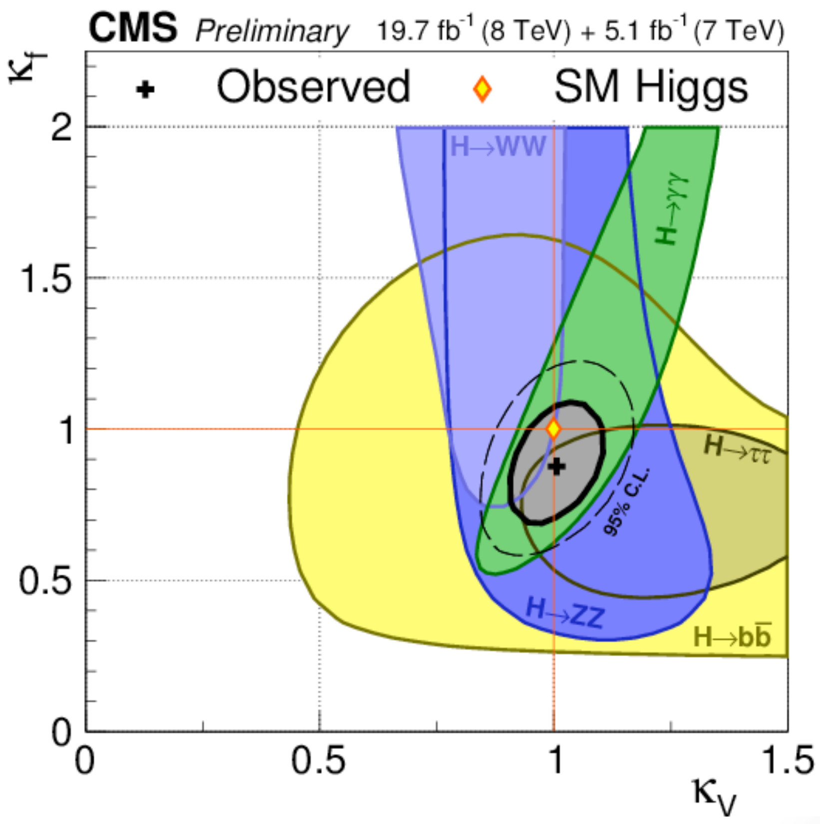


It couples like the SM Higgs

- Symmetry between W and Z couplings



- All decay channels converge around SM expectation

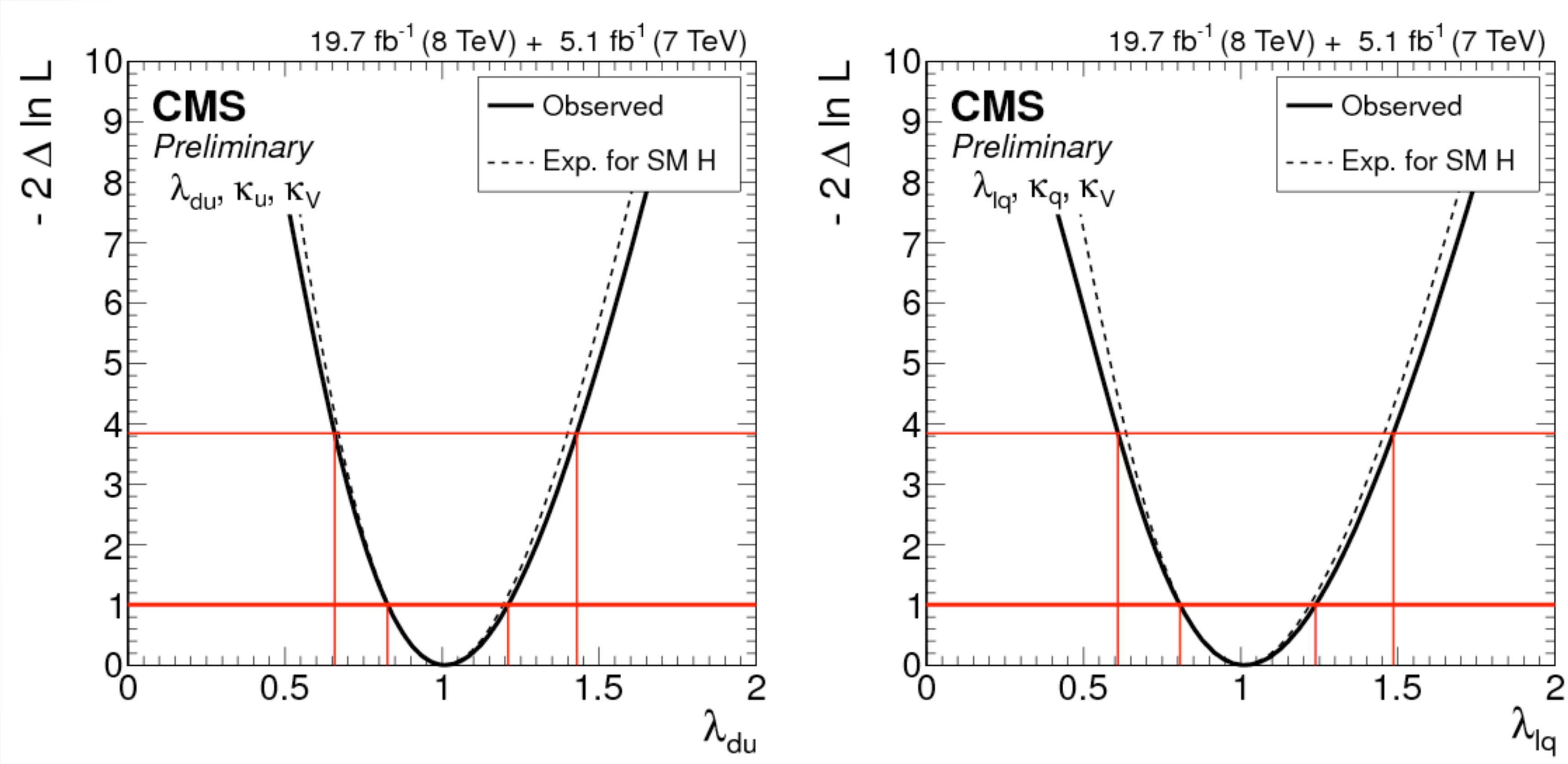


$\lambda_{xy} = \kappa_x/\kappa_y$

CMS HIG-14-009
arXiv:1412.8662

It couples like the SM Higgs

- Similar coupling to up-type vs down-type fermions



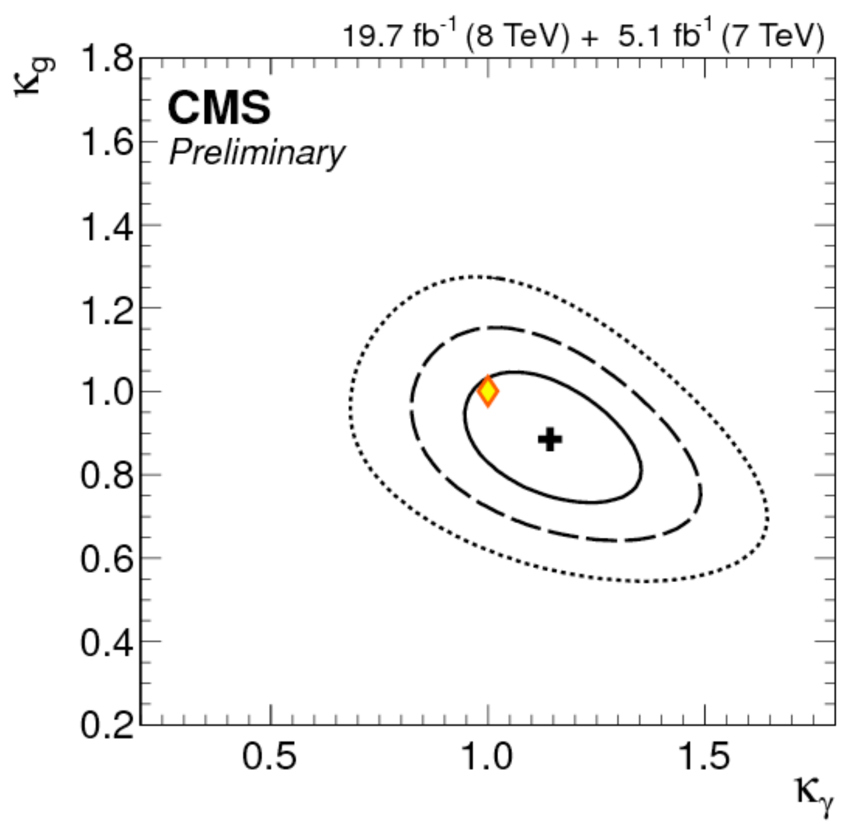
- Similar coupling to quarks and leptons

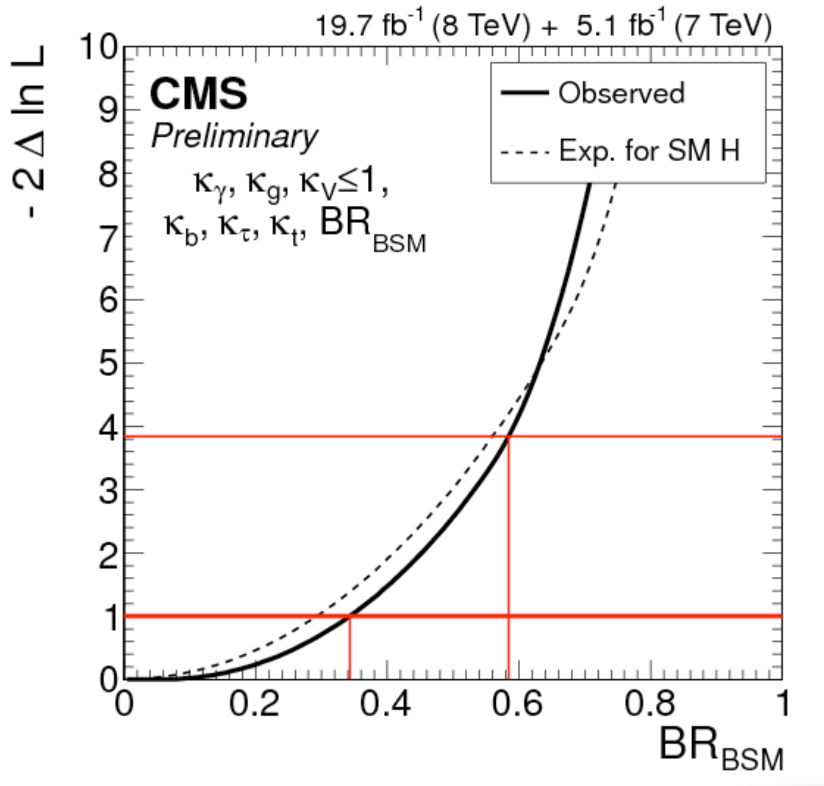
$\lambda_{xy} = \kappa_x/\kappa_y$

CMS HIG-14-009
arXiv:1412.8662

It couples like the SM Higgs

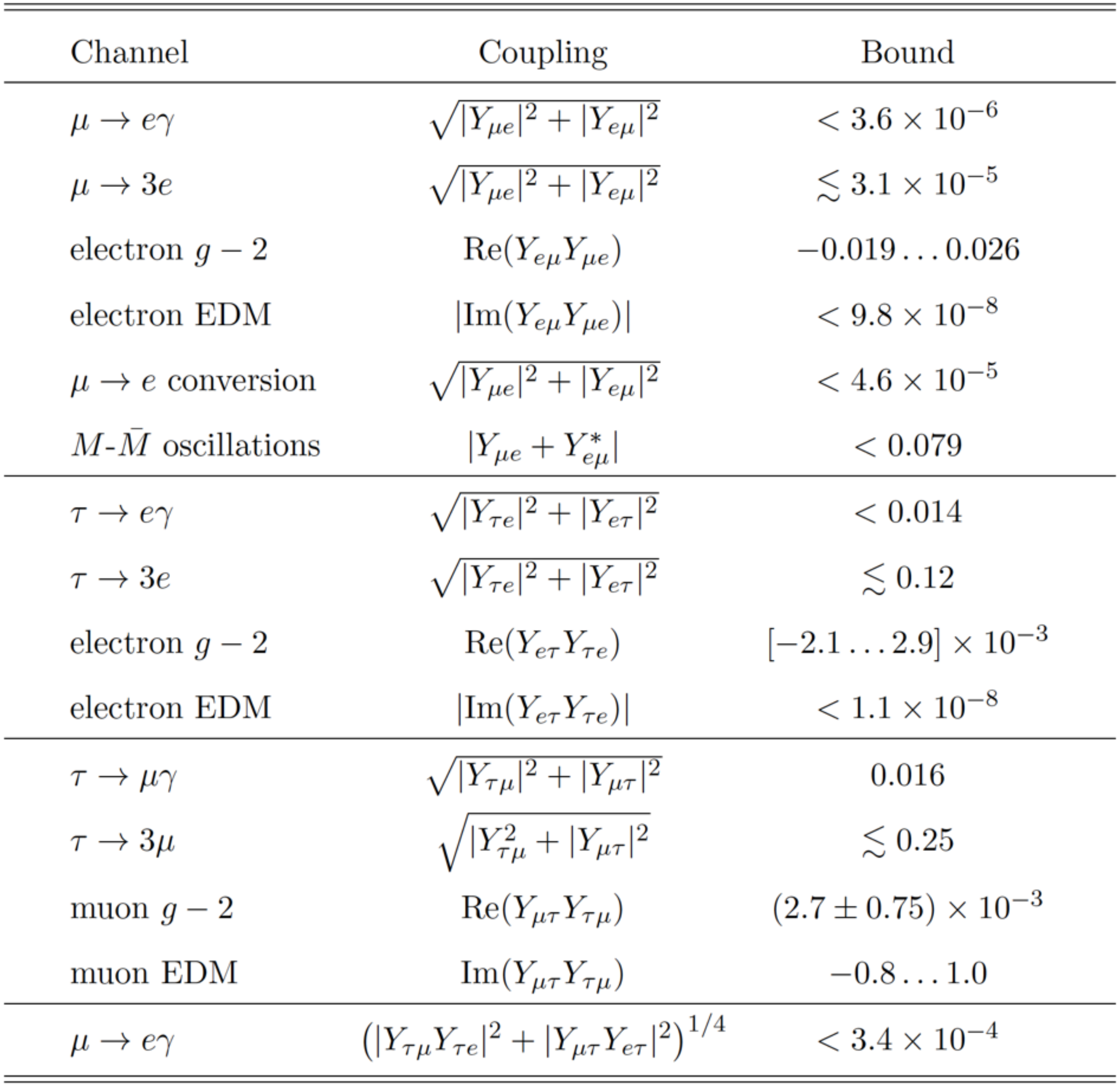
- New physics can show up in loop mediated processes
- BR(BSM)<0.32 if we fix all tree level couplings to the SM values
- BR(BSM)<0.58 for k_V<=1





CMS HIG-14-009
arXiv:1412.8662

Previous limits on $|Y_{ij}|$



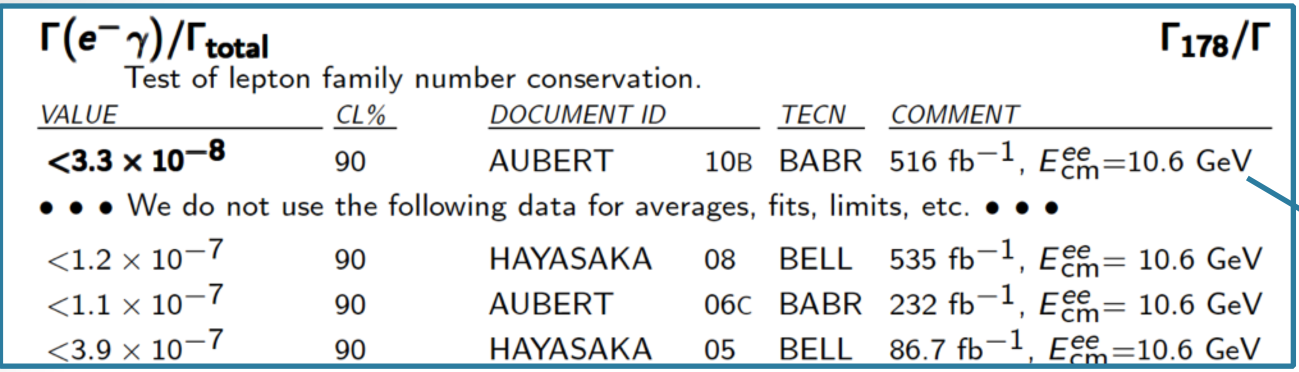
Channel	Coupling	Bound
$\mu \to e\gamma$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 3.6 \times 10^{-6}$
$\mu \to 3e$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$\lesssim 3.1 \times 10^{-5}$
electron $g-2$	$\mathrm{Re}(Y_{e\mu}Y_{\mu e})$	$-0.019 \ldots 0.026$
electron 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	$\mathrm{Im}(Y_{\mu\tau}Y_{\tau\mu})$	$-0.8 \ldots 1.0$
$\mu \to e\gamma$	$\left(\lvert Y_{\tau\mu}Y_{\tau e}\rvert^2 + \lvert Y_{\mu\tau}Y_{e\tau}\rvert^2\right)^{1/4}$	$< 3.4 \times 10^{-4}$

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

arXiv:1209.1397

(and references therein)

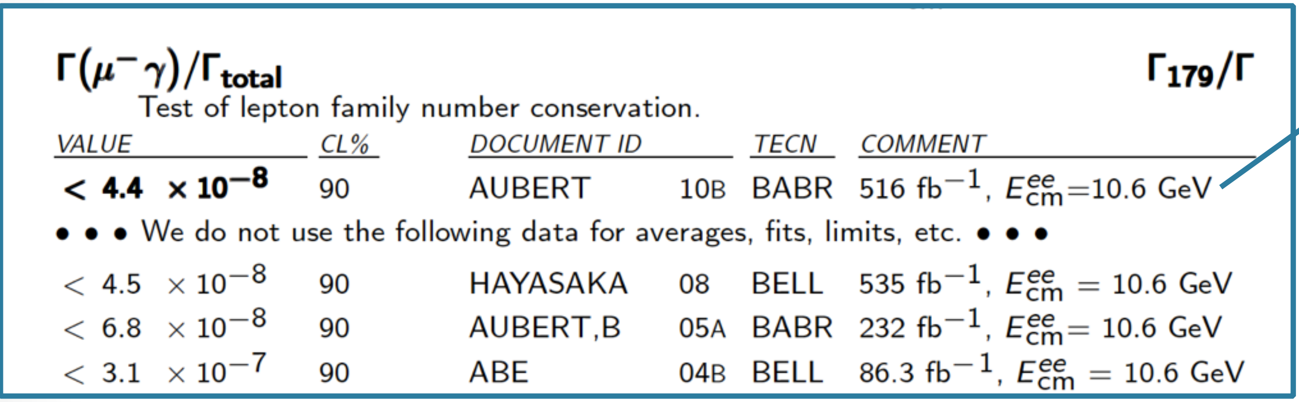
From the PDG



$\Gamma(e^-\gamma)/\Gamma_{\text{total}}$ Γ_{178}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.3\times10^{-8}$	90	AUBERT	10B	BABR	516 fb^{-1}, E^{ee}_{cm}=10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.2\times10^{-7}$	90	HAYASAKA	08	BELL	535 fb^{-1}, E^{ee}_{cm}= 10.6 GeV
$<1.1\times10^{-7}$	90	AUBERT	06C	BABR	232 fb^{-1}, E^{ee}_{cm}= 10.6 GeV
$<3.9\times10^{-7}$	90	HAYASAKA	05	BELL	86.7 fb^{-1}, E^{ee}_{cm}=10.6 GeV

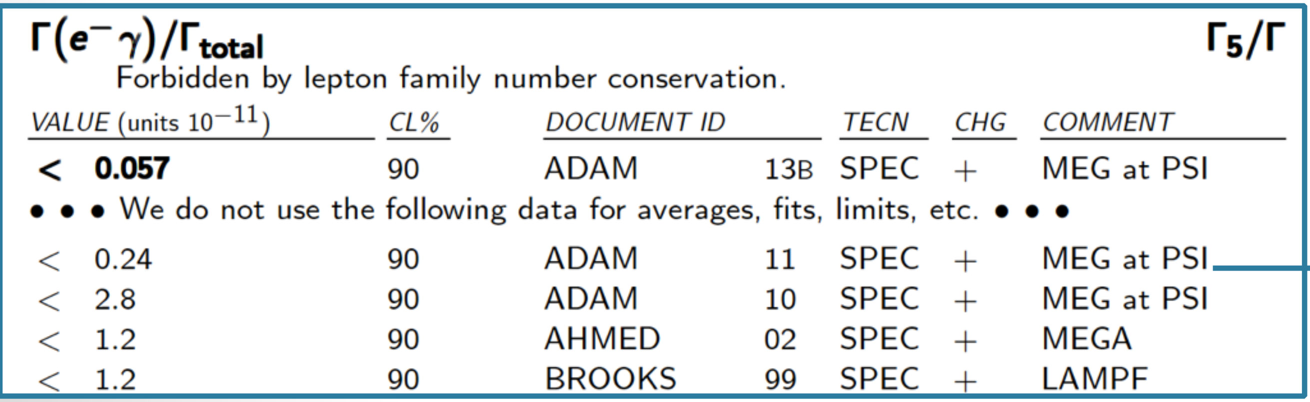


$\Gamma(\mu^-\gamma)/\Gamma_{\text{total}}$ Γ_{179}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.4\times10^{-8}$	90	AUBERT	10B	BABR	516 fb^{-1}, E^{ee}_{cm}=10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.5\times10^{-8}$	90	HAYASAKA	08	BELL	535 fb^{-1}, E^{ee}_{cm} = 10.6 GeV
$<6.8\times10^{-8}$	90	AUBERT,B	05A	BABR	232 fb^{-1}, E^{ee}_{cm}= 10.6 GeV
$<3.1\times10^{-7}$	90	ABE	04B	BELL	86.3 fb^{-1}, E^{ee}_{cm} = 10.6 GeV

PRL 104 021802
B. Aubert et al.
(BABAR)



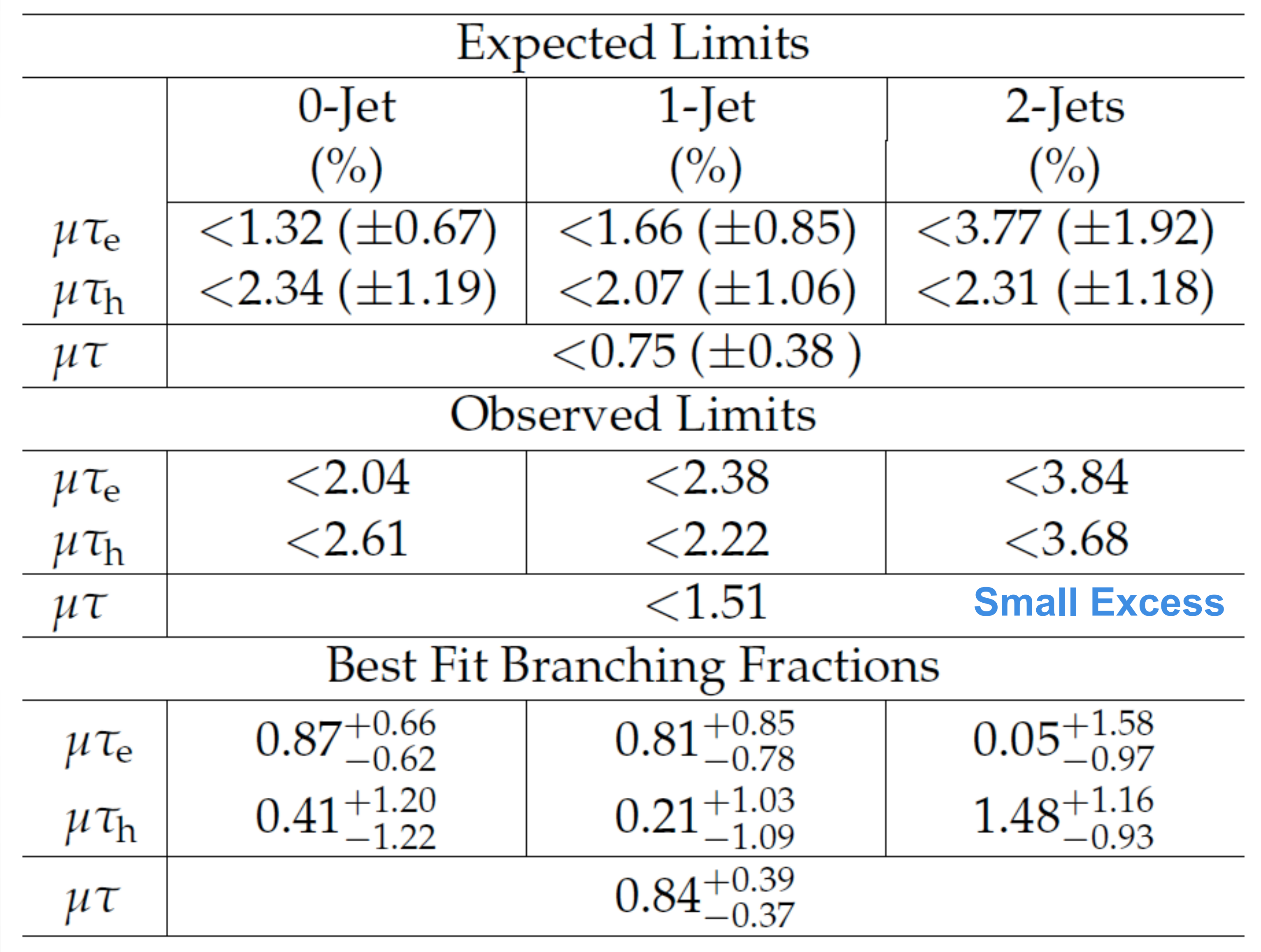
$\Gamma(e^-\gamma)/\Gamma_{\text{total}}$ Γ_5/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-11})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
$<$ 0.057	90	ADAM	13B	SPEC	+	MEG at PSI
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<$ 0.24	90	ADAM	11	SPEC	+	MEG at PSI
$<$ 2.8	90	ADAM	10	SPEC	+	MEG at PSI
$<$ 1.2	90	AHMED	02	SPEC	+	MEGA
$<$ 1.2	90	BROOKS	99	SPEC	+	LAMPF

PRL 107 171801
J. Adam et al.
(MEG Collab.)

Observed vs Expected Limits: μτ

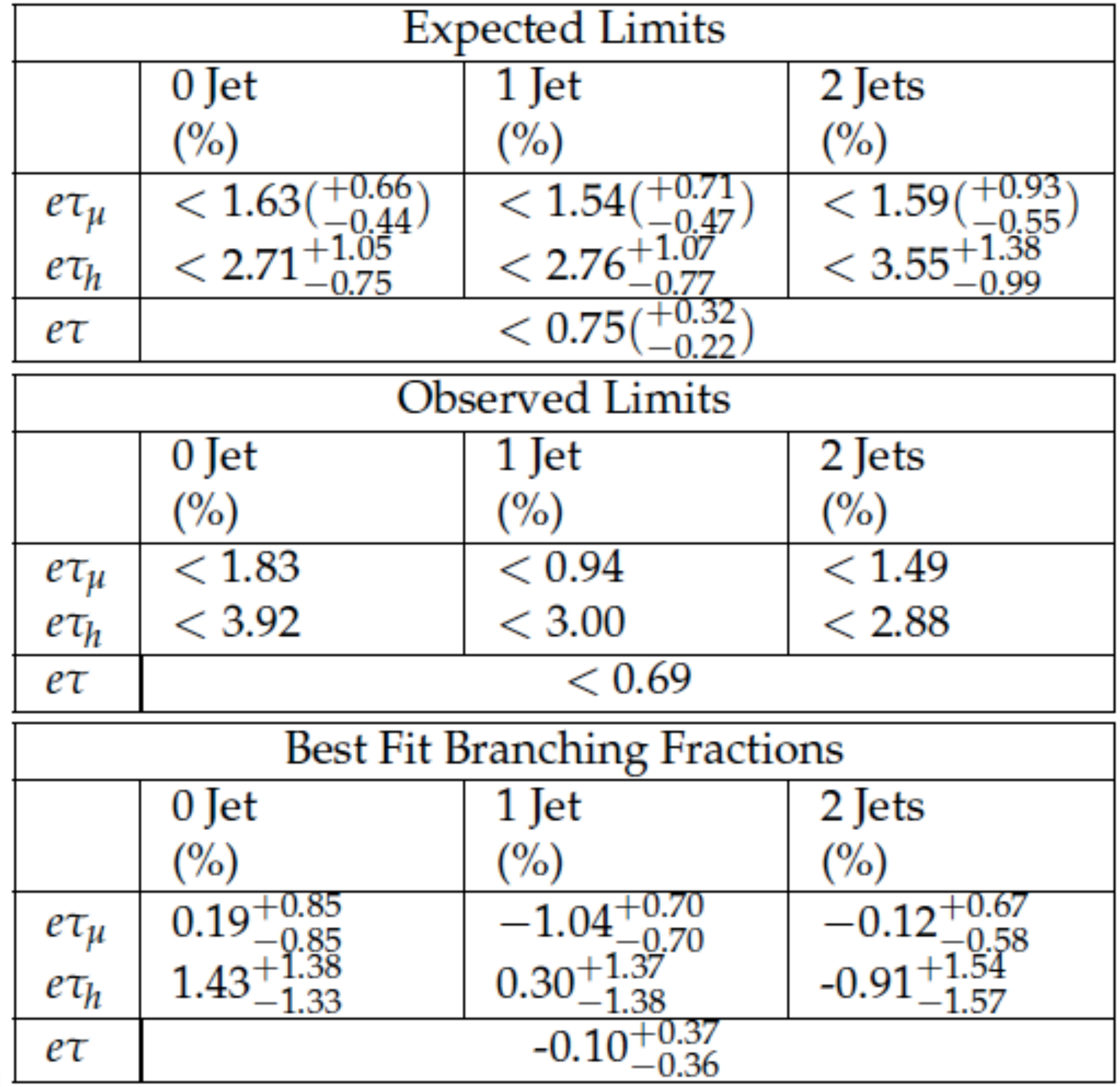


Expected Limits

	0-Jet (%)	1-Jet (%)	2-Jets (%)
$\mu\tau_e$	<1.32 (±0.67)	<1.66 (±0.85)	<3.77 (±1.92)
$\mu\tau_h$	<2.34 (±1.19)	<2.07 (±1.06)	<2.31 (±1.18)
$\mu\tau$	<0.75 (±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		
Best Fit Branching Fractions			
$\mu\tau_e$	$0.87^{+0.66}_{-0.62}$	$0.81^{+0.85}_{-0.78}$	$0.05^{+1.58}_{-0.97}$
$\mu\tau_h$	$0.41^{+1.20}_{-1.22}$	$0.21^{+1.03}_{-1.09}$	$1.48^{+1.16}_{-0.93}$
$\mu\tau$	$0.84^{+0.39}_{-0.37}$		

Small Excess

Observed vs Expected Limits: eτ

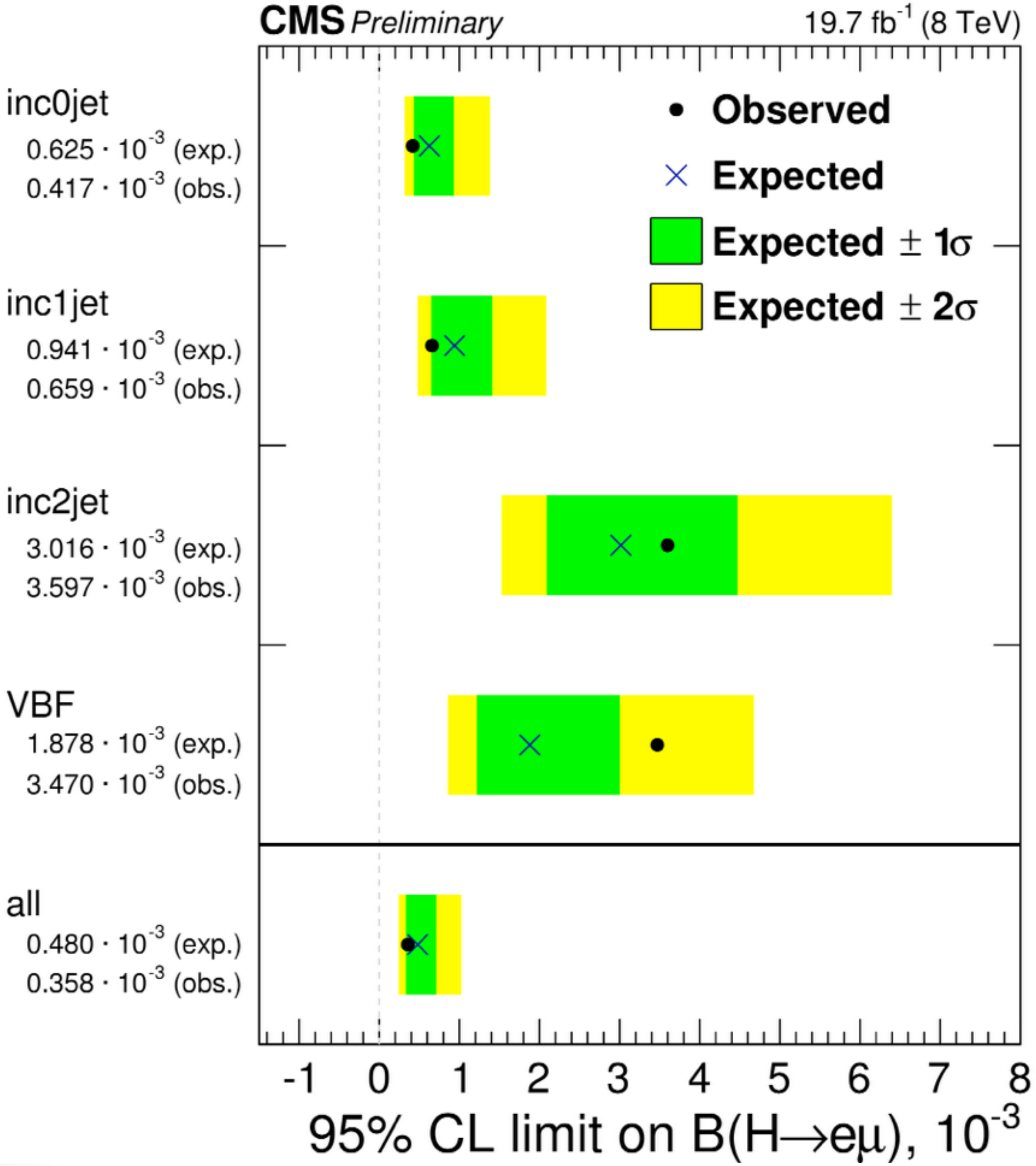


Expected Limits			
	0 Jet (%)	1 Jet (%)	2 Jets (%)
$e\tau_\mu$	$< 1.63(^{+0.66}_{-0.44})$	$< 1.54(^{+0.71}_{-0.47})$	$< 1.59(^{+0.93}_{-0.55})$
$e\tau_h$	$< 2.71^{+1.05}_{-0.75}$	$< 2.76^{+1.07}_{-0.77}$	$< 3.55^{+1.38}_{-0.99}$
$e\tau$	$< 0.75(^{+0.32}_{-0.22})$		

Observed Limits			
	0 Jet (%)	1 Jet (%)	2 Jets (%)
$e\tau_\mu$	< 1.83	< 0.94	< 1.49
$e\tau_h$	< 3.92	< 3.00	< 2.88
$e\tau$	< 0.69		

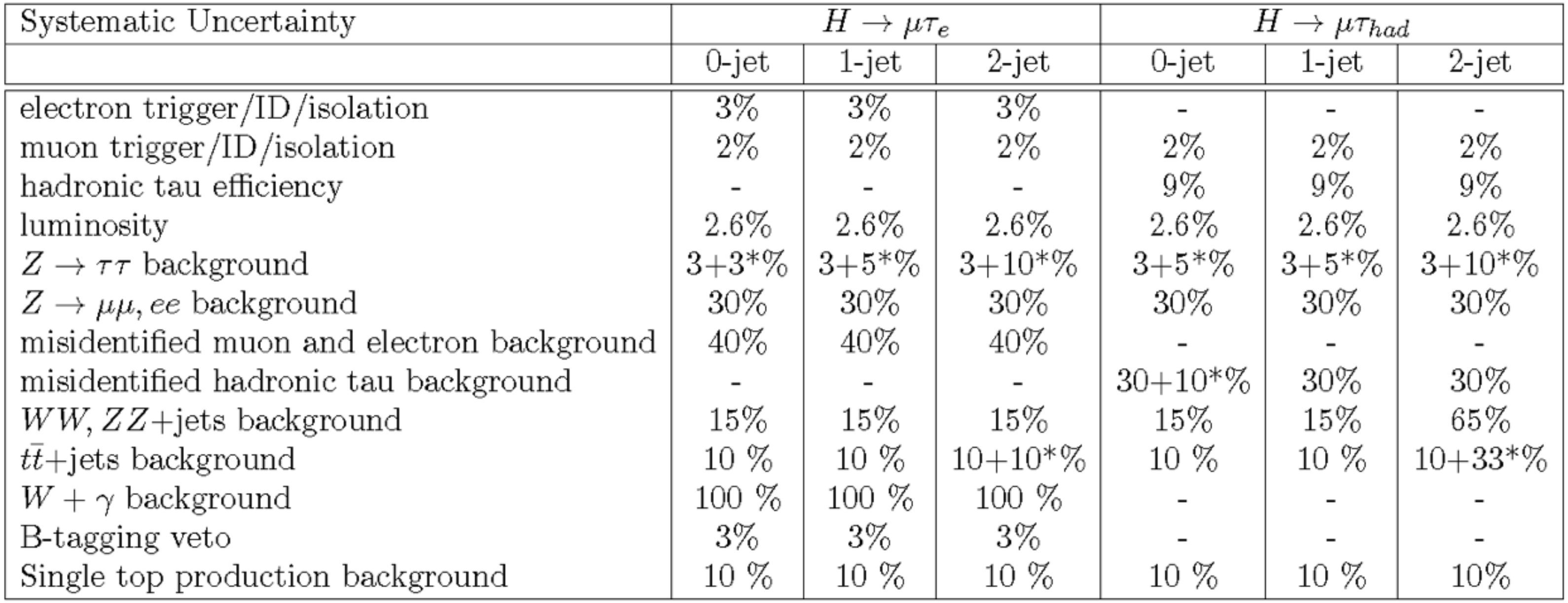
Best Fit Branching Fractions			
	0 Jet (%)	1 Jet (%)	2 Jets (%)
$e\tau_\mu$	$0.19^{+0.85}_{-0.85}$	$-1.04^{+0.70}_{-0.70}$	$-0.12^{+0.67}_{-0.58}$
$e\tau_h$	$1.43^{+1.38}_{-1.33}$	$0.30^{+1.37}_{-1.38}$	$-0.91^{+1.54}_{-1.57}$
$e\tau$	$-0.10^{+0.37}_{-0.36}$		

Observed vs Expected Limits: eμ



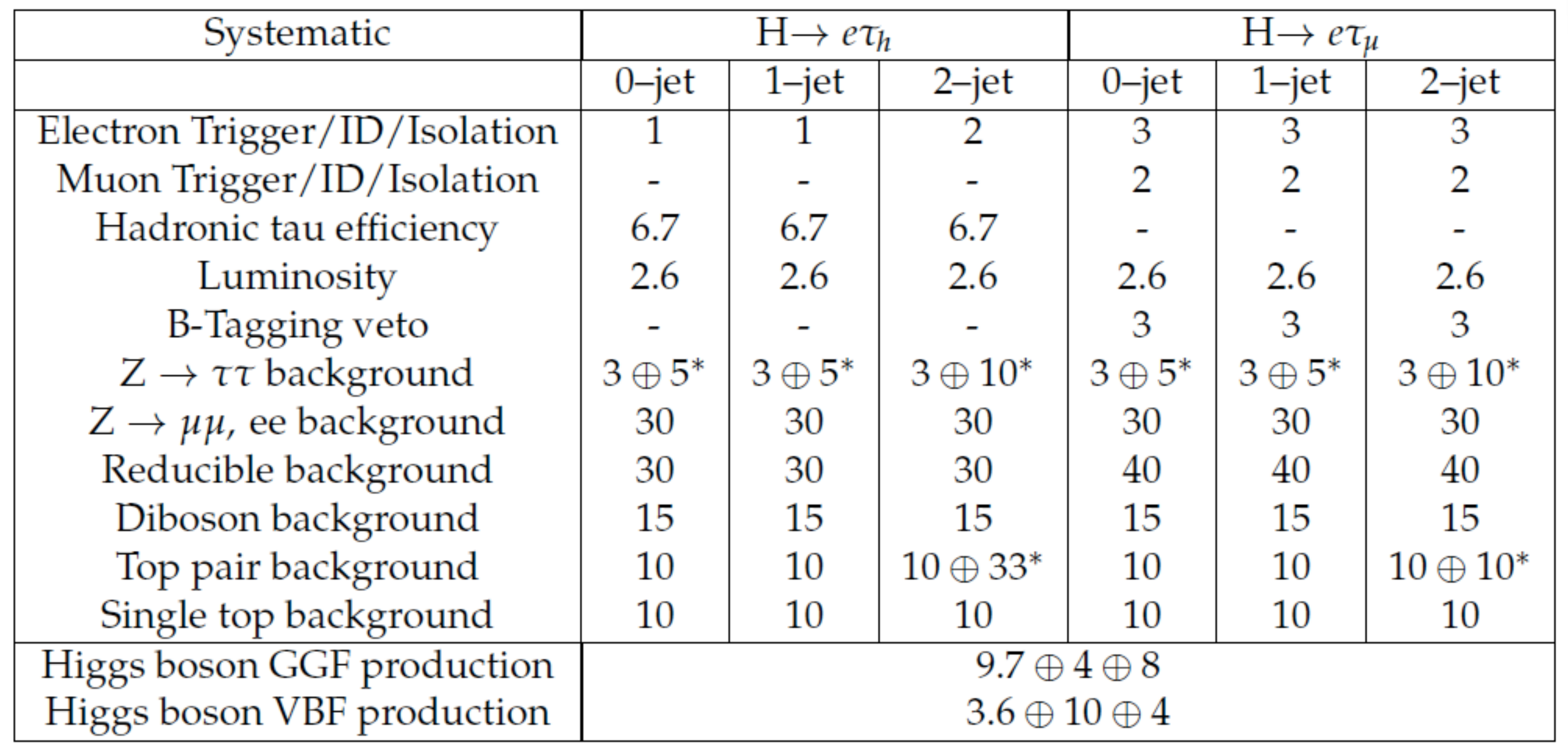
Systematic Uncertainties: Hμτ

- **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%

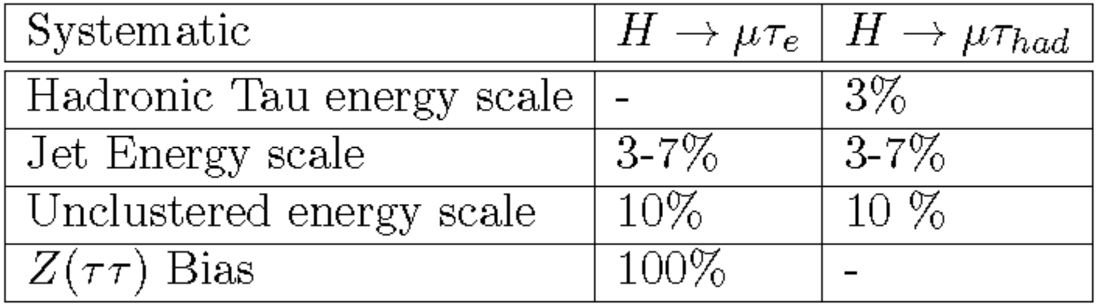
Systematic Uncertainties: Heτ



Systematic	H→ $e\tau_h$			H→ $e\tau_\mu$		
	0–jet	1–jet	2–jet	0–jet	1–jet	2–jet
Electron Trigger/ID/Isolation	1	1	2	3	3	3
Muon Trigger/ID/Isolation	-	-	-	2	2	2
Hadronic tau efficiency	6.7	6.7	6.7	-	-	-
Luminosity	2.6	2.6	2.6	2.6	2.6	2.6
B-Tagging veto	-	-	-	3	3	3
$Z \to \tau\tau$ background	$3 \oplus 5^*$	$3 \oplus 5^*$	$3 \oplus 10^*$	$3 \oplus 5^*$	$3 \oplus 5^*$	$3 \oplus 10^*$
$Z \to \mu\mu$, ee background	30	30	30	30	30	30
Reducible background	30	30	30	40	40	40
Diboson background	15	15	15	15	15	15
Top pair background	10	10	$10 \oplus 33^*$	10	10	$10 \oplus 10^*$
Single top background	10	10	10	10	10	10
Higgs boson GGF production	$9.7 \oplus 4 \oplus 8$					
Higgs boson VBF production	$3.6 \oplus 10 \oplus 4$					

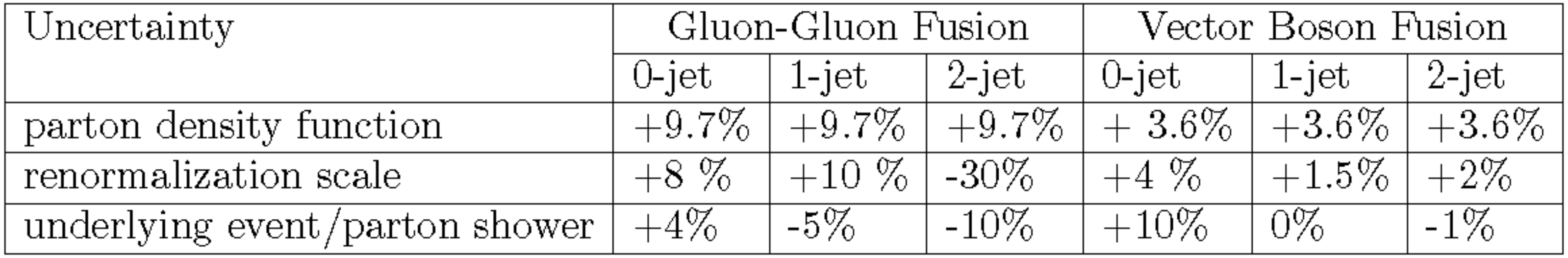
Systematic Uncertainties: Hμτ/Heτ

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



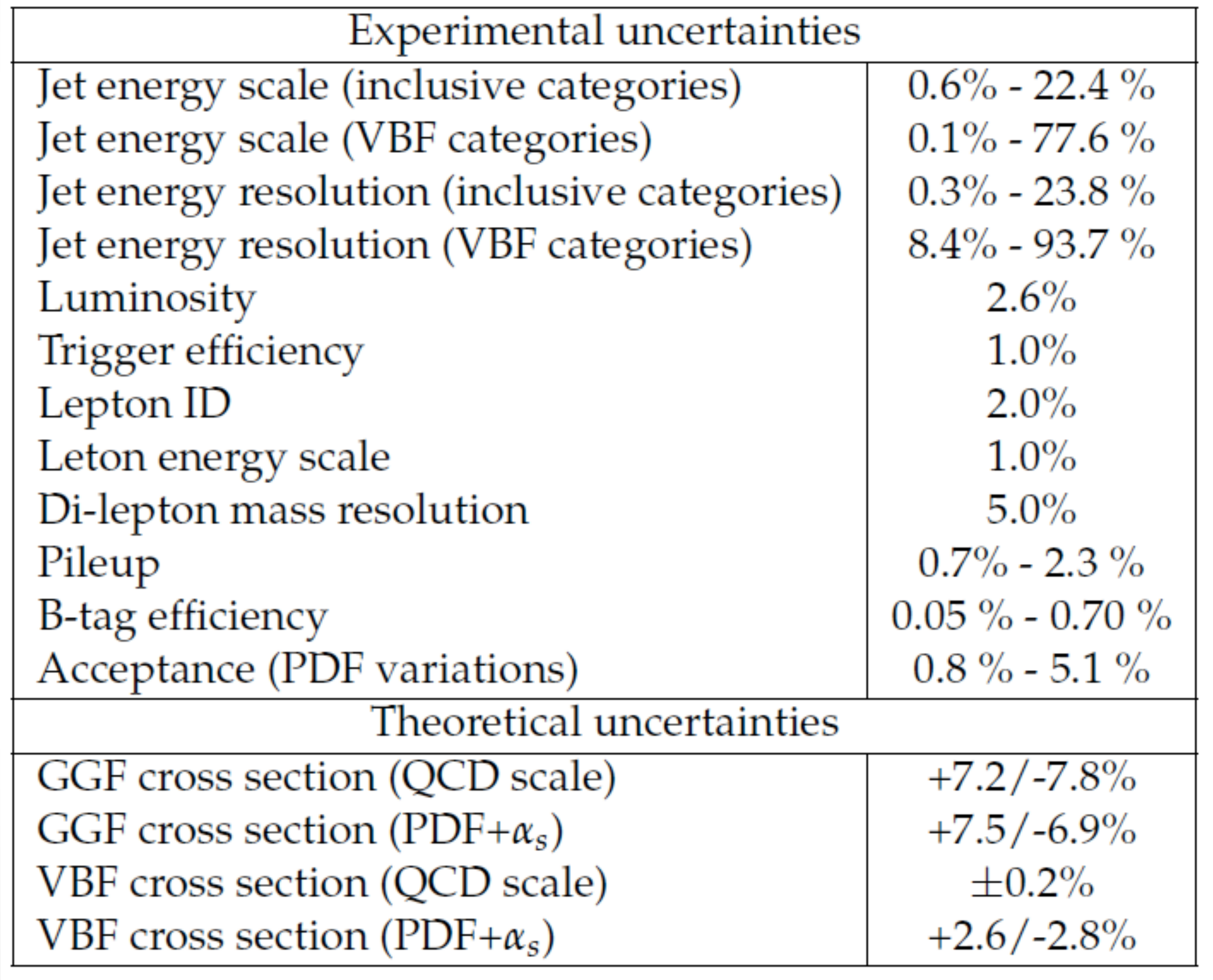
Systematic	$H \to \mu\tau_e$	$H \to \mu\tau_{had}$
Hadronic Tau energy scale	-	3%
Jet Energy scale	3-7%	3-7%
Unclustered energy scale	10%	10 %
$Z(\tau\tau)$ Bias	100%	-

- Theoretical uncertainties:



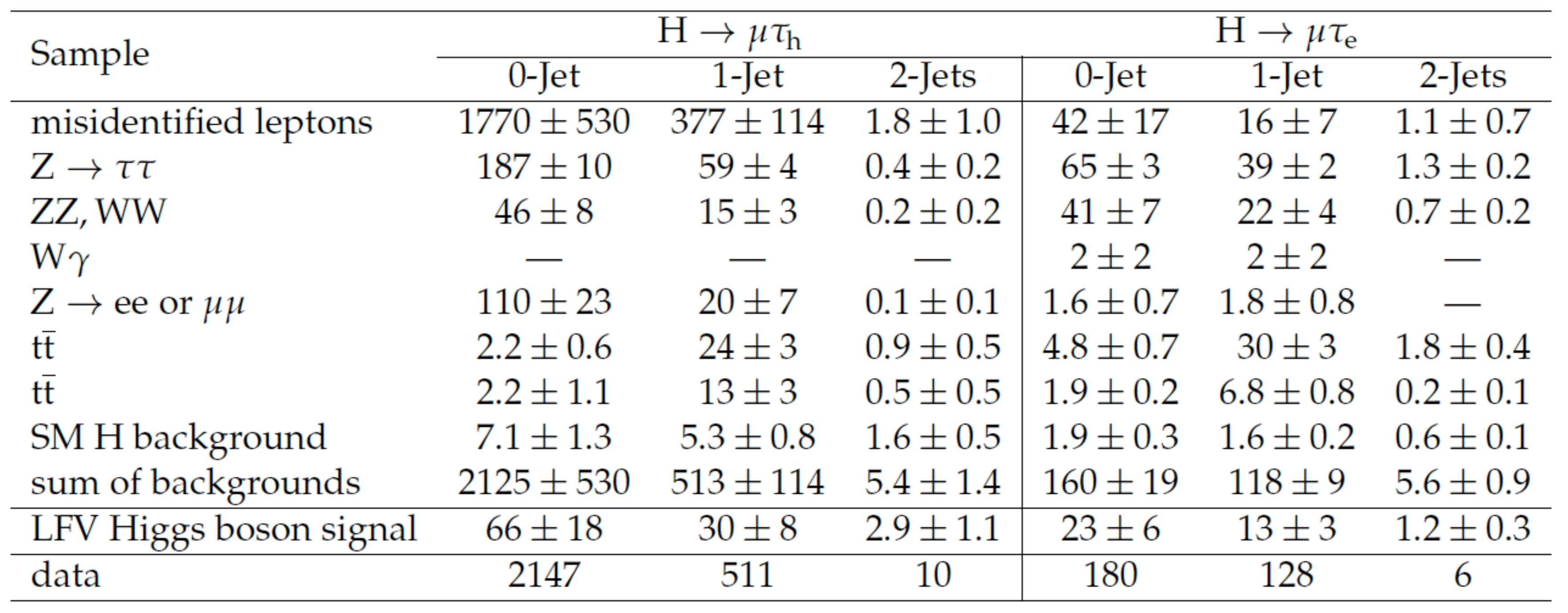
Uncertainty	Gluon-Gluon Fusion			Vector Boson Fusion		
	0-jet	1-jet	2-jet	0-jet	1-jet	2-jet
parton density function	+9.7%	+9.7%	+9.7%	+ 3.6%	+3.6%	+3.6%
renormalization scale	+8 %	+10 %	-30%	+4 %	+1.5%	+2%
underlying event/parton shower	+4%	-5%	-10%	+10%	0%	-1%

Systematic Uncertainties: Heμ



Experimental uncertainties	
Jet energy scale (inclusive categories)	0.6% - 22.4 %
Jet energy scale (VBF categories)	0.1% - 77.6 %
Jet energy resolution (inclusive categories)	0.3% - 23.8 %
Jet energy resolution (VBF categories)	8.4% - 93.7 %
Luminosity	2.6%
Trigger efficiency	1.0%
Lepton ID	2.0%
Leton energy scale	1.0%
Di-lepton mass resolution	5.0%
Pileup	0.7% - 2.3 %
B-tag efficiency	0.05 % - 0.70 %
Acceptance (PDF variations)	0.8 % - 5.1 %
Theoretical uncertainties	
GGF cross section (QCD scale)	+7.2/-7.8%
GGF cross section (PDF+α_s)	+7.5/-6.9%
VBF cross section (QCD scale)	±0.2%
VBF cross section (PDF+α_s)	+2.6/-2.8%

Yields H→μτ



Sample	$H \to \mu\tau_h$			$H \to \mu\tau_e$		
	0-Jet	1-Jet	2-Jets	0-Jet	1-Jet	2-Jets
misidentified leptons	1770 ± 530	377 ± 114	1.8 ± 1.0	42 ± 17	16 ± 7	1.1 ± 0.7
$Z \to \tau\tau$	187 ± 10	59 ± 4	0.4 ± 0.2	65 ± 3	39 ± 2	1.3 ± 0.2
ZZ, WW	46 ± 8	15 ± 3	0.2 ± 0.2	41 ± 7	22 ± 4	0.7 ± 0.2
$W\gamma$	—	—	—	2 ± 2	2 ± 2	—
$Z \to ee$ or $\mu\mu$	110 ± 23	20 ± 7	0.1 ± 0.1	1.6 ± 0.7	1.8 ± 0.8	—
$t\bar{t}$	2.2 ± 0.6	24 ± 3	0.9 ± 0.5	4.8 ± 0.7	30 ± 3	1.8 ± 0.4
$t\bar{t}$	2.2 ± 1.1	13 ± 3	0.5 ± 0.5	1.9 ± 0.2	6.8 ± 0.8	0.2 ± 0.1
SM H background	7.1 ± 1.3	5.3 ± 0.8	1.6 ± 0.5	1.9 ± 0.3	1.6 ± 0.2	0.6 ± 0.1
sum of backgrounds	2125 ± 530	513 ± 114	5.4 ± 1.4	160 ± 19	118 ± 9	5.6 ± 0.9
LFV Higgs boson signal	66 ± 18	30 ± 8	2.9 ± 1.1	23 ± 6	13 ± 3	1.2 ± 0.3
data	2147	511	10	180	128	6

Yields H→eτ

$e\tau_\mu$

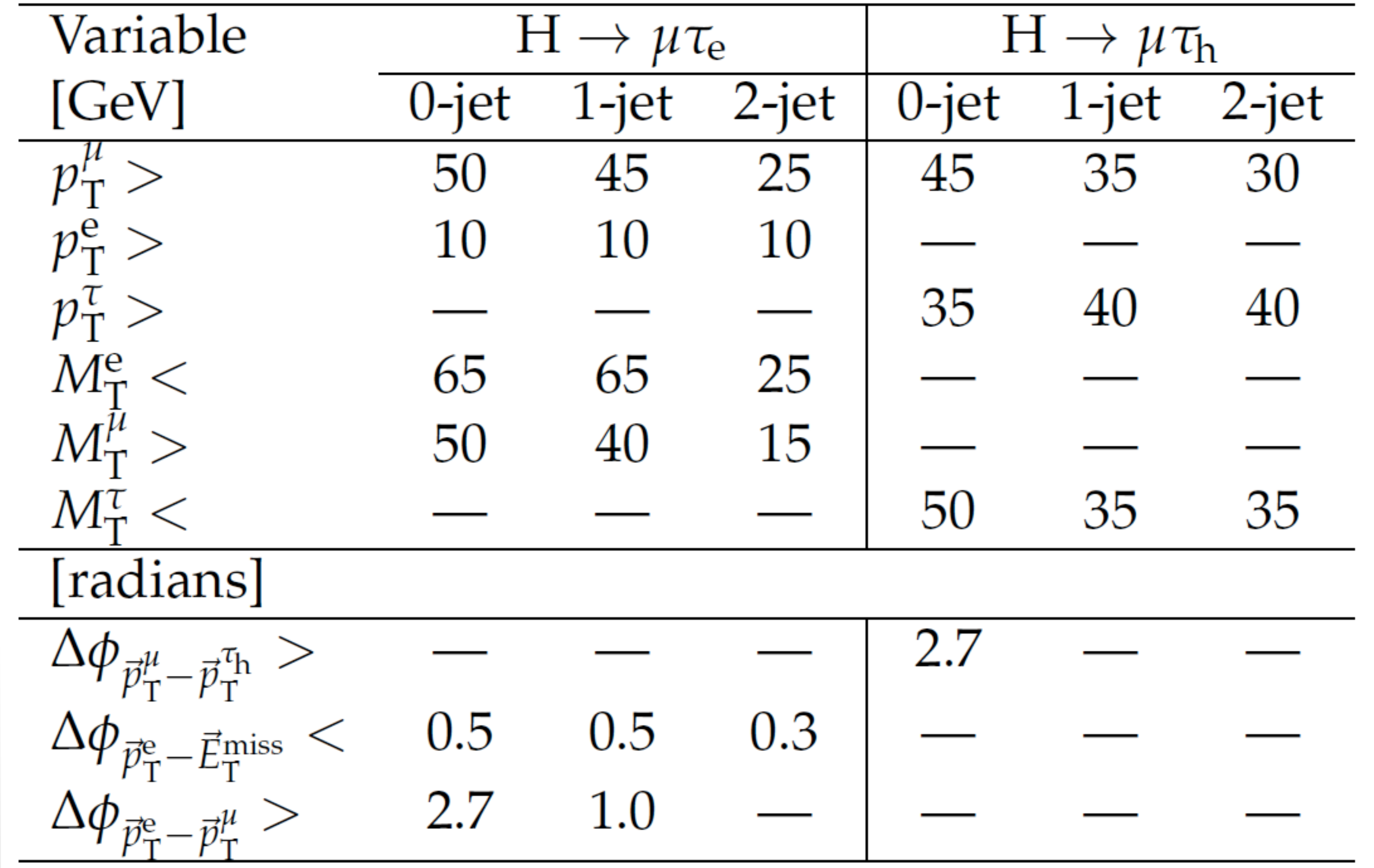
Jet category:	0-Jet	1-Jet	2-Jet
Misidentified leptons	85.2±5.9	38.1±3.9	2.1±0.7
$Z \to ee, \mu\mu$	2.3±0.6	5.4±0.5	-
$Z \to \tau\tau$	84.7±2.1	113.3±4.2	8.5±0.6
$t\bar{t}, t, \bar{t}$	13.8±0.3	69.4±2.3	12.7±0.8
EWK diboson	83.0±2.7	51.7±2.0	3.6±0.4
$W\gamma, W\gamma*$	2.2±1.0	1.2±0.6	-
SM Higgs boson background	2.3±0.3	3.6±0.4	1.1±0.2
Sum of background	273.5±6.1	282.0±6.0	28.1±1.3
LFV Higgs boson signal (BR=1%)	33.4±2.3	23.2±1.7	8.6±1.4
Observed	286	268	33

$e\tau_h$

Jet category:	0-Jet	1-Jet	2-Jet
Misidentified leptons	3366±25	223±11	8.7± 2.23
$Z \to ee, \mu\mu$	714±30	85±4	3.2± 0.25
$Z \to \tau\tau$	270±10	32±3	1.6± 0.30
$t\bar{t}, t, \bar{t}$	10±2	13±2	0.5± 0.2
EWK diboson	53±2	6±1	0.3± 0.1
SM Higgs boson background	12±1	3±1	1.0± 0.1
Sum of background	4425±28	363±11	15.3±2.3
LFV Higgs boson signal (BR=1%)	88±6	22±2	4.1±0.7
Observed	4438	375	13

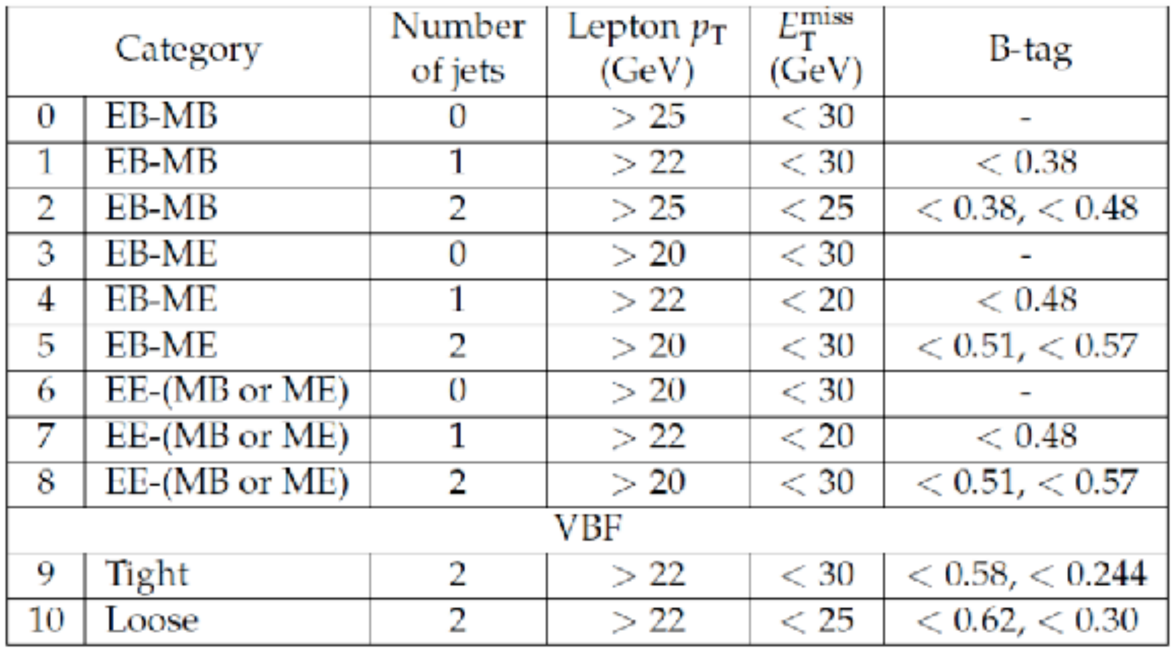
Full Selection

- →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

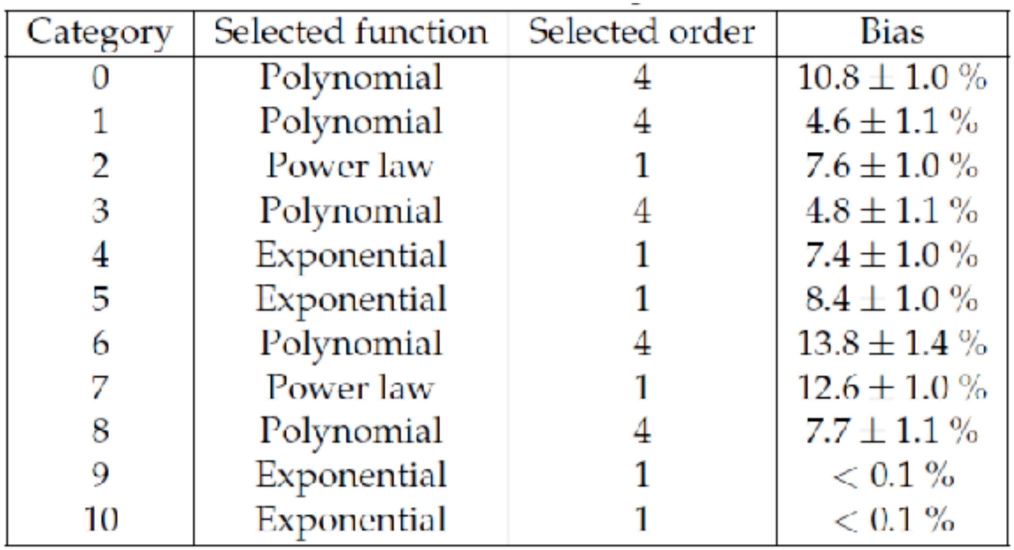


Variable	$H \to \mu\tau_e$			$H \to \mu\tau_h$		
[GeV]	0-jet	1-jet	2-jet	0-jet	1-jet	2-jet
$p_T^{\mu} >$	50	45	25	45	35	30
$p_T^{e} >$	10	10	10	—	—	—
$p_T^{\tau} >$	—	—	—	35	40	40
$M_T^{e} <$	65	65	25	—	—	—
$M_T^{\mu} >$	50	40	15	—	—	—
$M_T^{\tau} <$	—	—	—	50	35	35
[radians]						
$\Delta\phi_{\vec{p}_T^{\mu}-\vec{p}_T^{\tau_h}} >$	—	—	—	2.7	—	—
$\Delta\phi_{\vec{p}_T^{e}-\vec{E}_T^{miss}} <$	0.5	0.5	0.3	—	—	—
$\Delta\phi_{\vec{p}_T^{e}-\vec{p}_T^{\mu}} >$	2.7	1.0	—	—	—	—

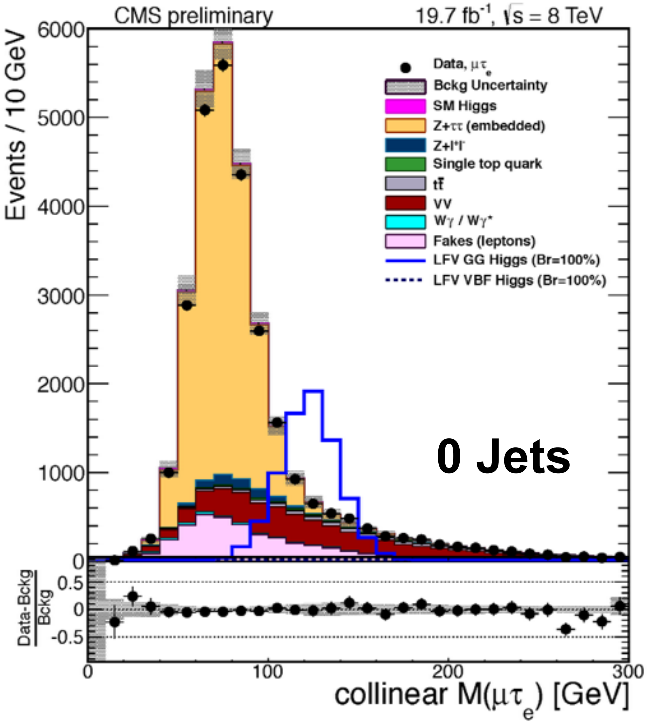
Hμe: categories and background

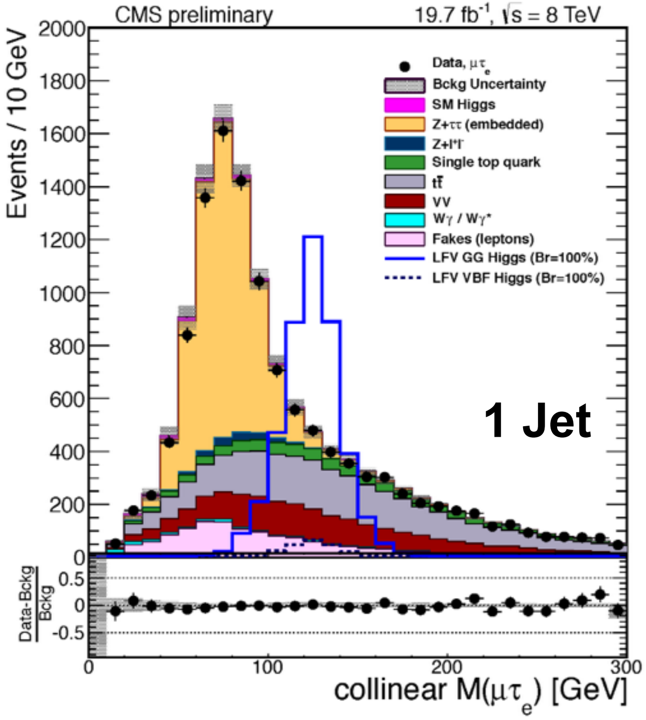


Category		Number of jets	Lepton p_T (GeV)	E_T^{miss} (GeV)	B-tag
0	EB-MB	0	> 25	< 30	-
1	EB-MB	1	> 22	< 30	< 0.38
2	EB-MB	2	> 25	< 25	$< 0.38, < 0.48$
3	EB-ME	0	> 20	< 30	-
4	EB-ME	1	> 22	< 20	< 0.48
5	EB-ME	2	> 20	< 30	$< 0.51, < 0.57$
6	EE-(MB or ME)	0	> 20	< 30	-
7	EE-(MB or ME)	1	> 22	< 20	< 0.48
8	EE-(MB or ME)	2	> 20	< 30	$< 0.51, < 0.57$
		VBF			
9	Tight	2	> 22	< 30	$< 0.58, < 0.244$
10	Loose	2	> 22	< 25	$< 0.62, < 0.30$



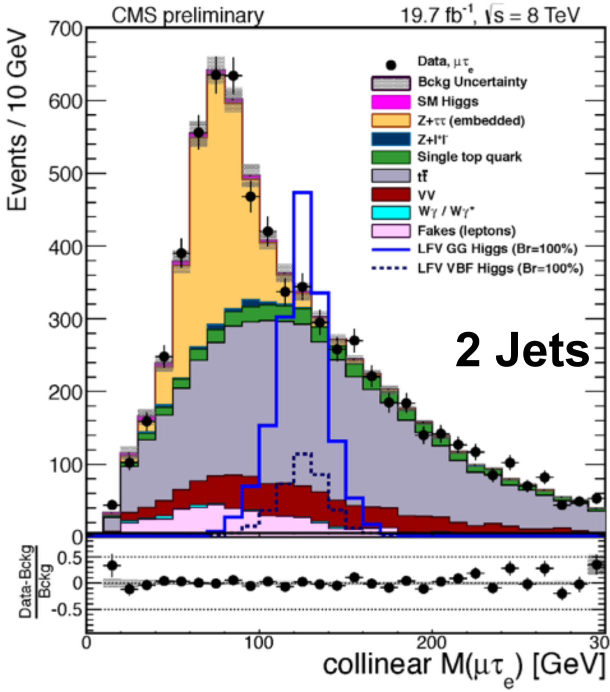
Category	Selected function	Selected order	Bias
0	Polynomial	4	10.8 ± 1.0 %
1	Polynomial	4	4.6 ± 1.1 %
2	Power law	1	7.6 ± 1.0 %
3	Polynomial	4	4.8 ± 1.1 %
4	Exponential	1	7.4 ± 1.0 %
5	Exponential	1	8.4 ± 1.0 %
6	Polynomial	4	13.8 ± 1.4 %
7	Power law	1	12.6 ± 1.0 %
8	Polynomial	4	7.7 ± 1.1 %
9	Exponential	1	< 0.1 %
10	Exponential	1	< 0.1 %





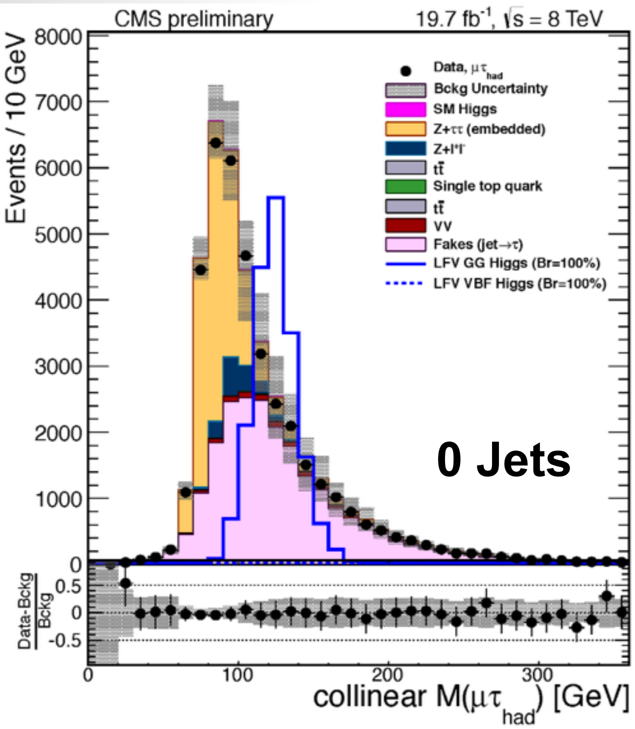
$\mu\tau_e$

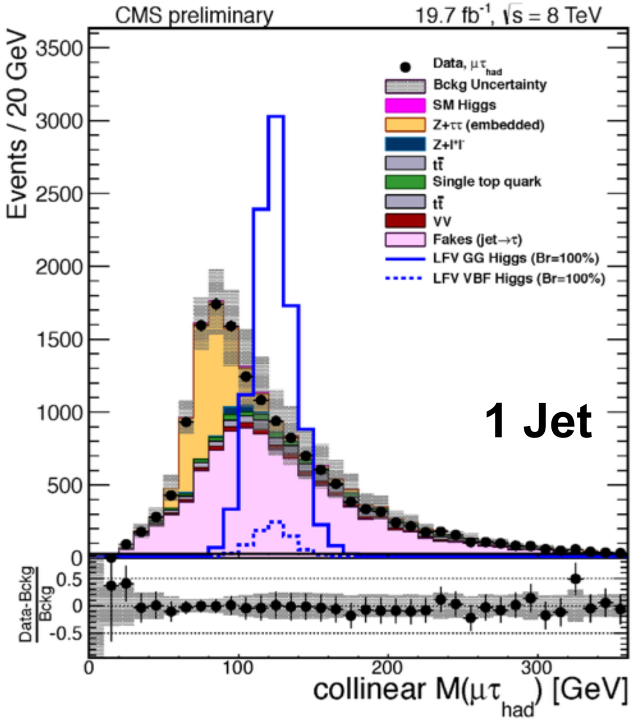
Preselection / Control Region



Br(H→μτ)=100%

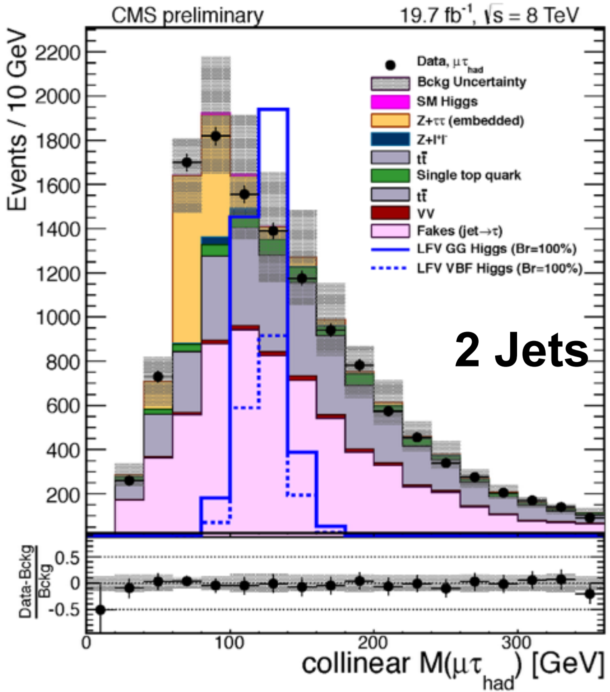
Excellent data/ mc agreement





$\mu\tau_{had}$

Preselection / Control Region



Br(H→μτ)=100%

Excellent data/ mc agreement

The Compact Muon Solenoid