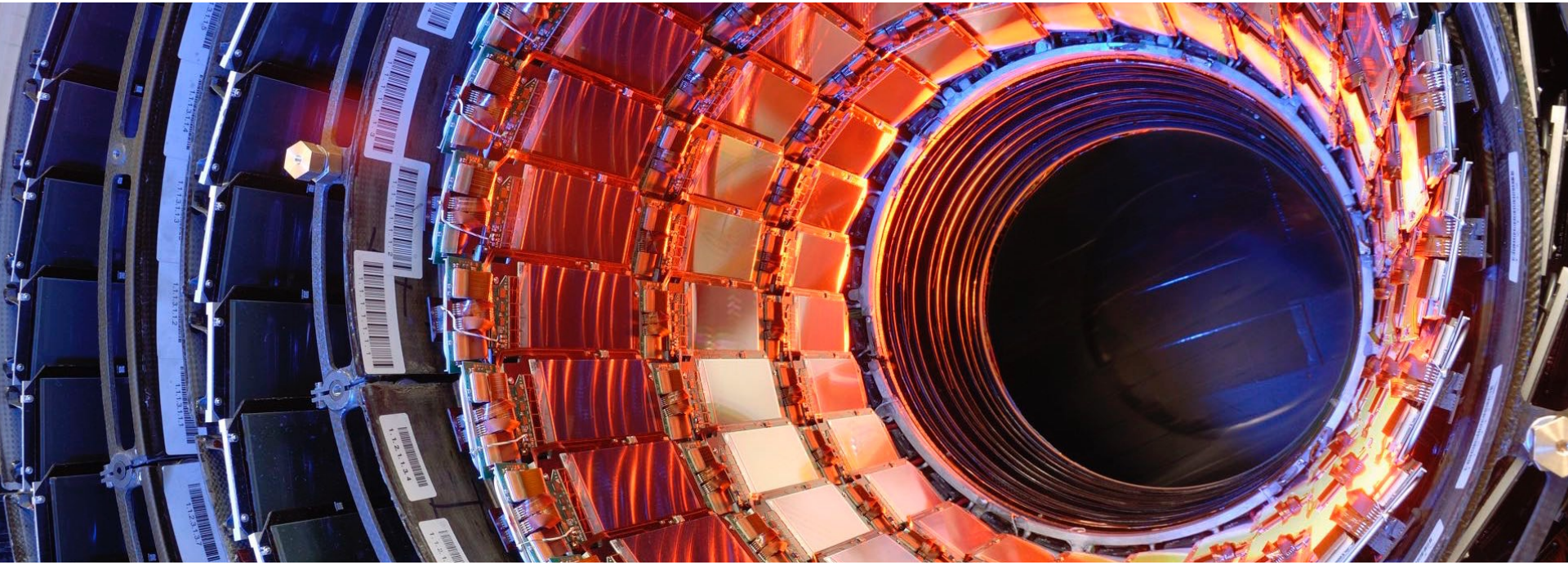
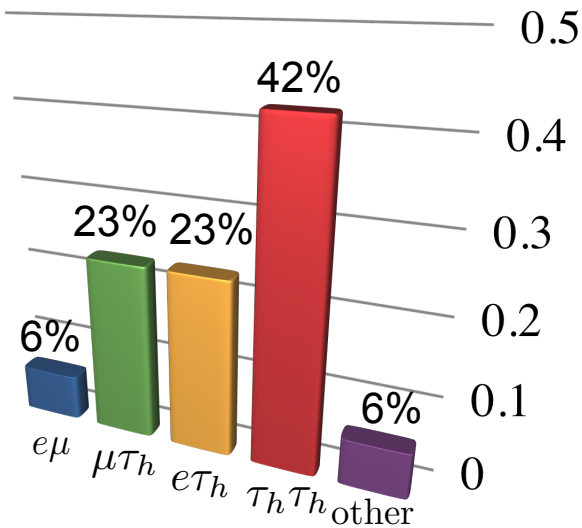
SM Higgs to a pair of tau leptons with LHC Run-2 data at CMS



Yiwen Wen
on behalf of the CMS Collaboration
Higgs Hunting 2017 Orsay-Paris
24th July 2017

SM Higgs -> tau tau: overview

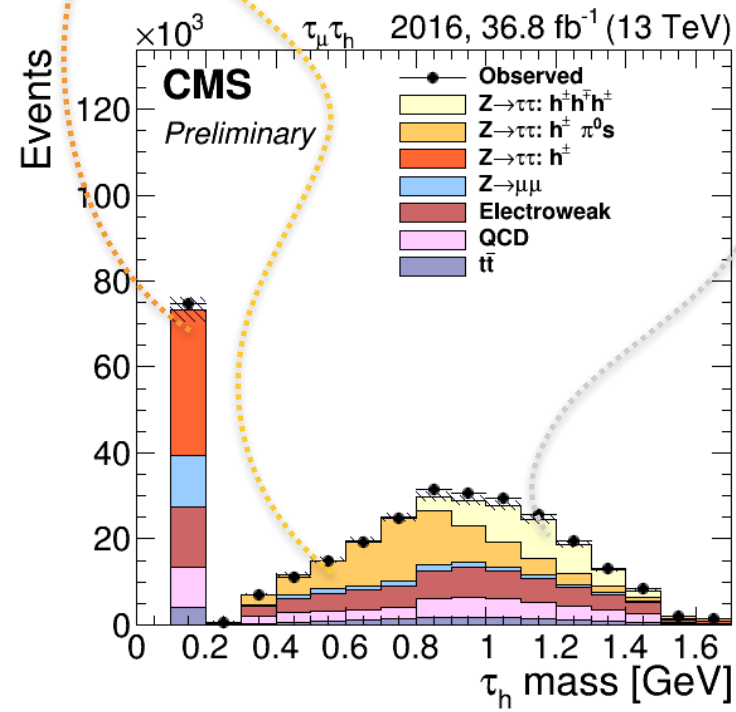
- Higgs to tau tau is very promising channel to study the **Yukawa couplings** to explore the mass generation mechanism for fermions
- **advantage**: higher event rate than other Higgs leptonic decays and less backgrounds than Higgs to bb
- in CMS Run-1 observed **3.2σ** [JHEP 05 (2014) 104], CMS+ATLAS observed **5.5σ** [JHEP 08 (2016) 045]
- **4 channels** ($e\mu$,$\mu\tau_h$,$e\tau_h$,$\tau_h\tau_h$) ~ **95% of di-tau** decay is covered
- 89% involving hadronic taus, **identify** and **trigger** hadronic taus in a high pile-up environment



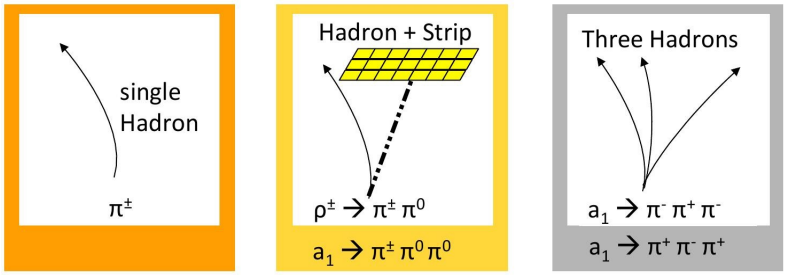
tau reconstruction in CMS

- leptonic decay -> 35%: standard electron ID or muon ID
- hadronic decay -> 65%: **hadron-plus-strip (HPS)** algorithm

	Decay Mode	Resonance	B [%]
leptonic decays	$\tau^- \to e^- \bar{\nu}_e \nu_\tau$		17.8
	$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$		17.4
1 - prong decays	$\tau^- \to \pi^- \nu_\tau$	$\pi(140)$	11.6
	$\tau^- \to \pi^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
	$\tau^- \to \pi^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	10.8
3 - prongs decays	$\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$	$a_1(1260)$	9.8
	$\tau^- \to \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$		4.8
	Other hadronic modes		1.7
	All hadronic modes		64.8



- hadronic taus reconstructed from a combination of charged hadrons and strips of cluster of e/γ candidates
- identify three main decay modes



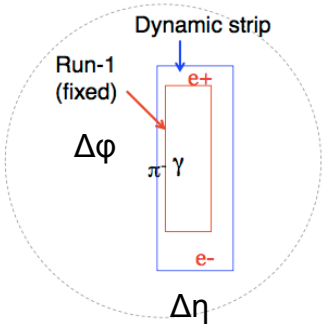
- tau mass reconstructed should be compatible with tau decay modes
- new feature: in run-2, strip size adjusted dynamically

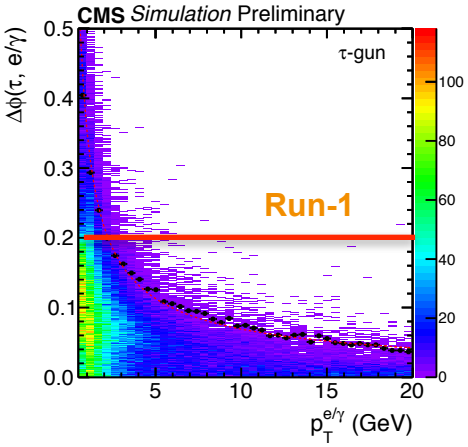
tau reconstruction in CMS

dynamic strip reconstruction

> in Run-2, strip size adjusted dynamically as a **function of the pT of e/γ**

- **better acceptance at low pT**
- **better jet rejection at high pT**

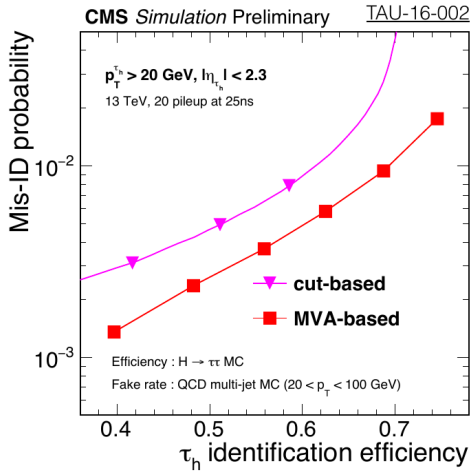




MVA-based discriminator rejecting jet faking tau

> using variables related to:

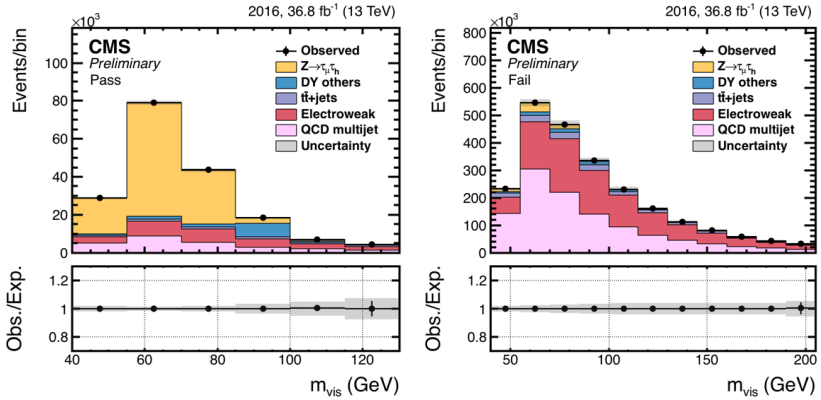
- **isolation variables (pT sums)**
- **τ decay length information (track impact parameters, SV decay length)**
- **etc..**



measurement of tau-id efficiency

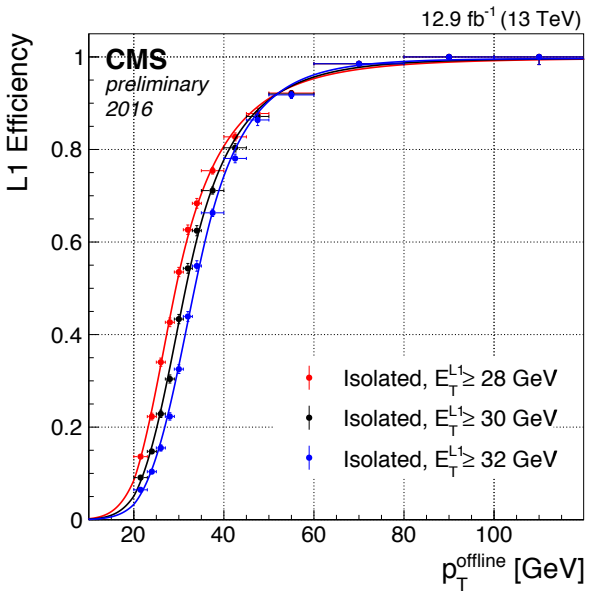
> using likelihood fit to visible mass in $\mu\tau_h$ channel

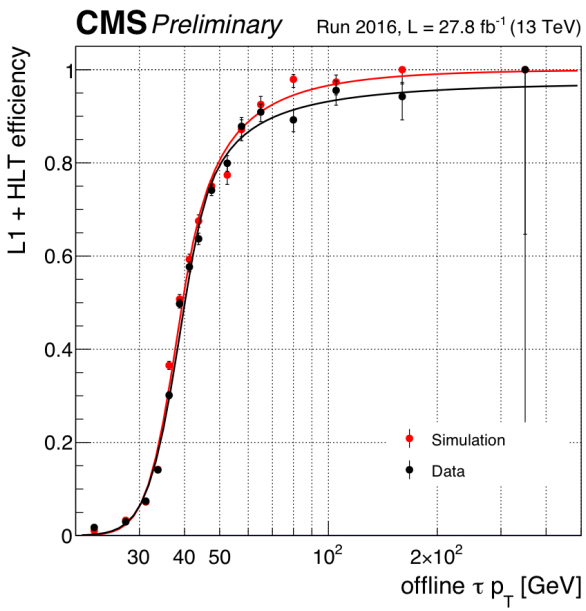
> data/MC scale factor of 0.95 ± 0.05



tau trigger in CMS Run-2

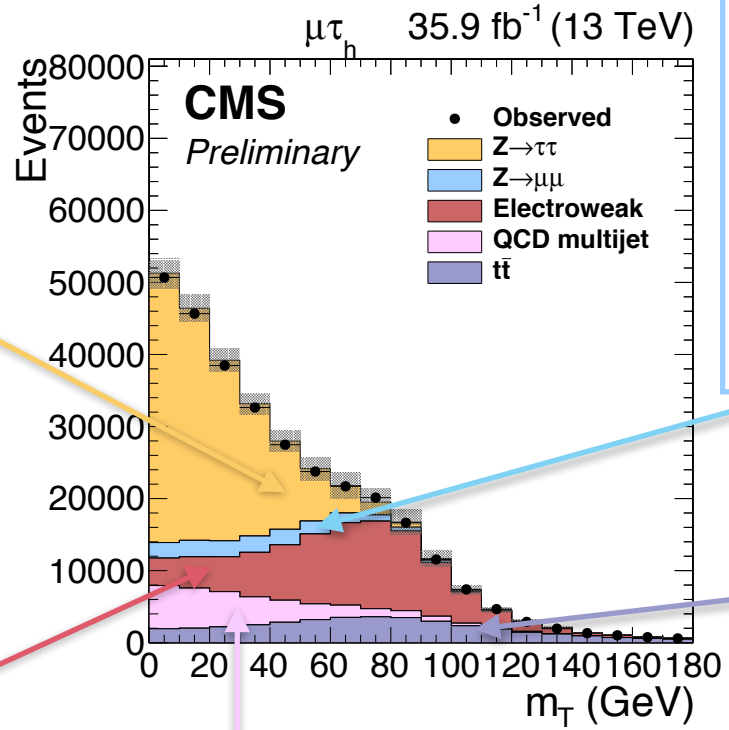
- with the more critical Run-2 pile-up condition, efficiency of Run-1 like L1 trigger would have reduced by more than a factor of 2
- in Run-2: **major upgrade of L1 trigger system**:
  - increases the algorithm complexity and the readout granularity
  - improving τ_h identification with dynamic clustering technique at the hardware level
- in high-level trigger:
  - despite the high pile-up, kept same nominal pT thresholds as Run-1(35 GeV) for di-τ_h trigger but improved turn-on and efficiency





background estimations

Z->ττ:
shapes from **Monte-Carlo (MC)**,
corrections (DY mass, p_T, m_{jj}) derived
from Z -> $\mu\mu$ sideband



leptons to τ fakes:
same as Z->ττ,with addition fake rate and energy scale data/MC corrections

W+Jets:shapes from **MC**, normalization constrained in high mT sideband region.
VV+SingleTop: **MC**

top pair:
shapes from **MC** normalization and shape is constrained in a $e\mu$+jets sideband region

QCD:
fully **data-driven** in sideband region of same-sign pair events

to further suppress background

- to reduce **W+Jets** in $e\tau_h$, $\mu\tau_h$ channel

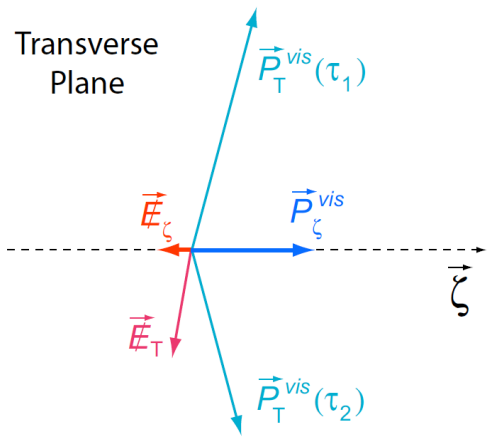
$$m_T = \sqrt{2 p_T^{e,\mu} E_T^{miss} (1 - \cos\Delta\phi)} < 50 GeV$$

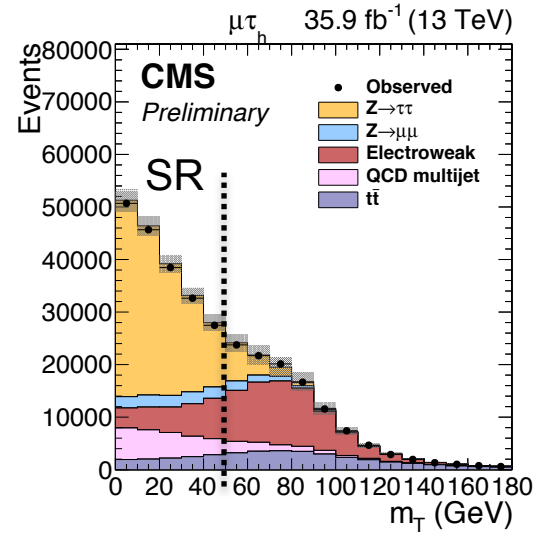
- to reduce **top pair production** in $e\mu$ channel

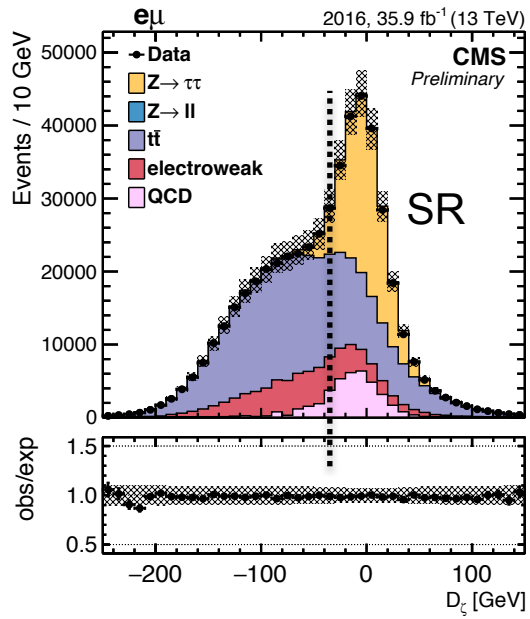
$$D_\zeta = P_\zeta - 1.85 \cdot P_\zeta^{vis} > -35 GeV$$

$\vec{\zeta}$ is axis bisecting directions $\vec{p}_T^{\,e}$ and $\vec{p}_T^{\,\mu}$

$$P_\zeta = (\vec{p}_T^{\,e} + \vec{p}_T^{\,\mu} + \vec{p}_T^{\,miss}) \cdot \frac{\vec{\zeta}}{|\zeta|} \qquad P_\zeta^{vis} = (\vec{p}_T^{\,e} + \vec{p}_T^{\,\mu}) \cdot \frac{\vec{\zeta}}{|\zeta|}$$

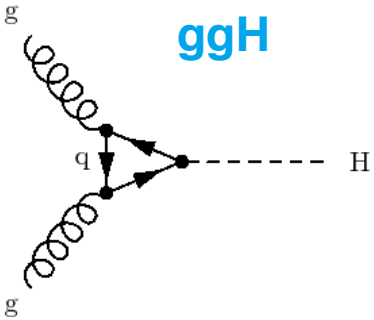


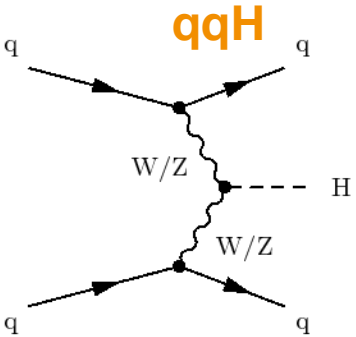




event categorization

- 3 categories focused on two most sensitive production mode **ggH** and **qqH**:
  - **0-jet:** targeting **ggH** and allowing for systematics to be constrained in other categories
  - **VBF**: targeting **qqH** events pass the di-jet cuts
  - **boosted:** targeting **ggH** events with a Higgs boson recoiling against a jet, and qqH events that fail the di-jet cut
- extracting the signal in 2D: one is **di-tau mass** (visible mass or SVFit mass) and the other is chosen targeting specific production modes



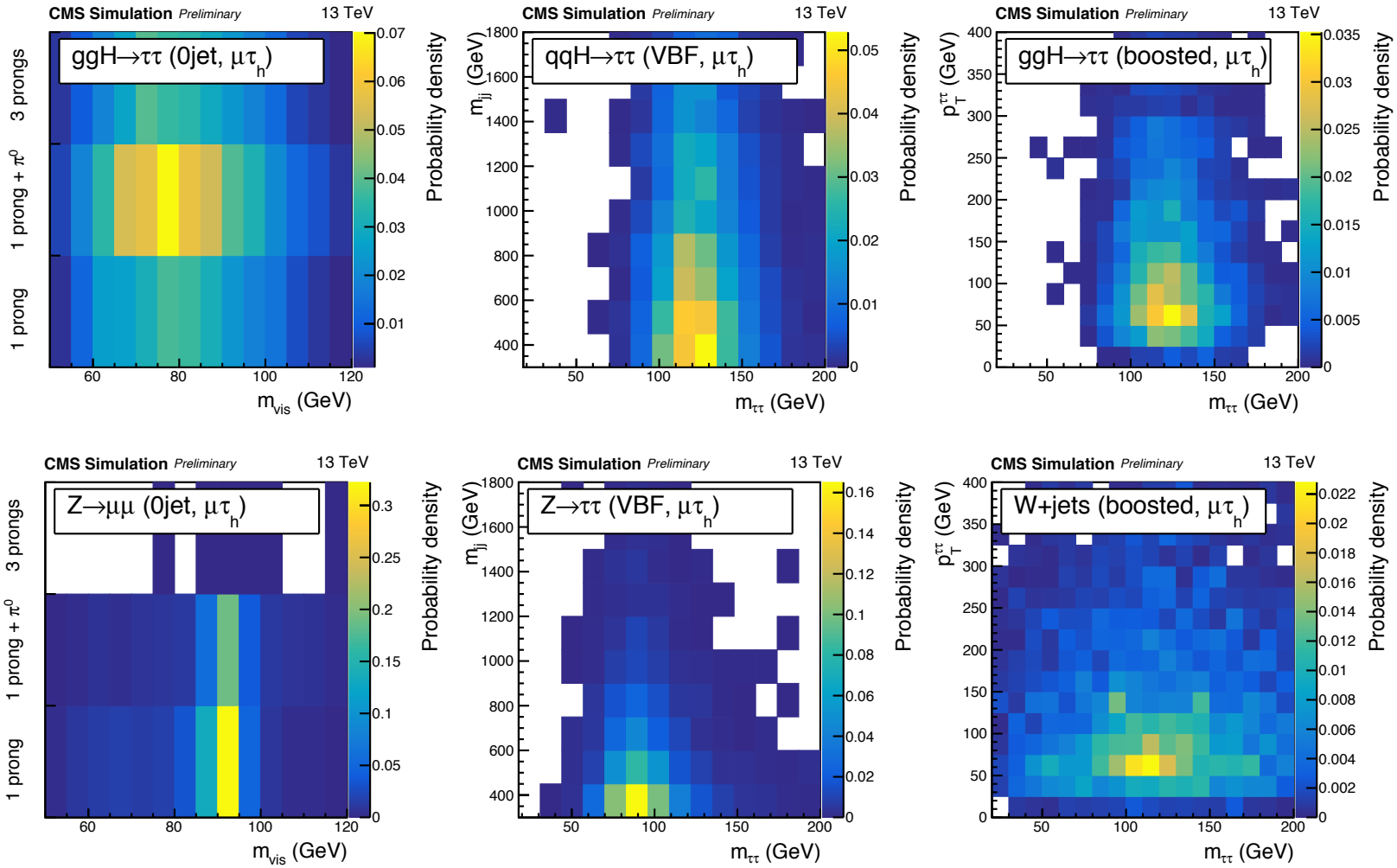


	Selection		
	0-jet	VBF	Boosted
$e\mu$	No jet	2 jets, $m_{jj} > 300\,\text{GeV}$	Others
$\mu\tau_h$	No jet	≥ 2 jets, $m_{jj} > 300\,\text{GeV}$, $p_T^{\tau\tau} > 50\,\text{GeV}$, $p_T^{\tau_h} > 40\,\text{GeV}$	Others
$e\tau_h$	No jet	≥ 2 jets, $m_{jj} > 300\,\text{GeV}$, $p_T^{\tau\tau} > 50\,\text{GeV}$	Others
$\tau_h\tau_h$	No jet	≥ 2 jets, $p_T^{\tau\tau} > 100\,\text{GeV}$, $\Delta\eta_{jj} > 2.5$	Others
	Variables		
$e\mu$	p_T^{μ}, m_{vis}	m_{jj}, $m_{\tau\tau}$	$p_T^{\tau\tau}$, $m_{\tau\tau}$
$\mu\tau_h$	τ_h decay mode, m_{vis}	m_{jj}, $m_{\tau\tau}$	$p_T^{\tau\tau}$, $m_{\tau\tau}$
$e\tau_h$	τ_h decay mode, m_{vis}	m_{jj}, $m_{\tau\tau}$	$p_T^{\tau\tau}$, $m_{\tau\tau}$
$\tau_h\tau_h$	$m_{\tau\tau}$	m_{jj}, $m_{\tau\tau}$	$p_T^{\tau\tau}$, $m_{\tau\tau}$

The signal/background increases as a function of **di-jet invariant mass**

The signal/background increases as a function of **di-tau pT**

example of 2D distributions



signals (top) and **backgrounds** (bottom) have different signatures

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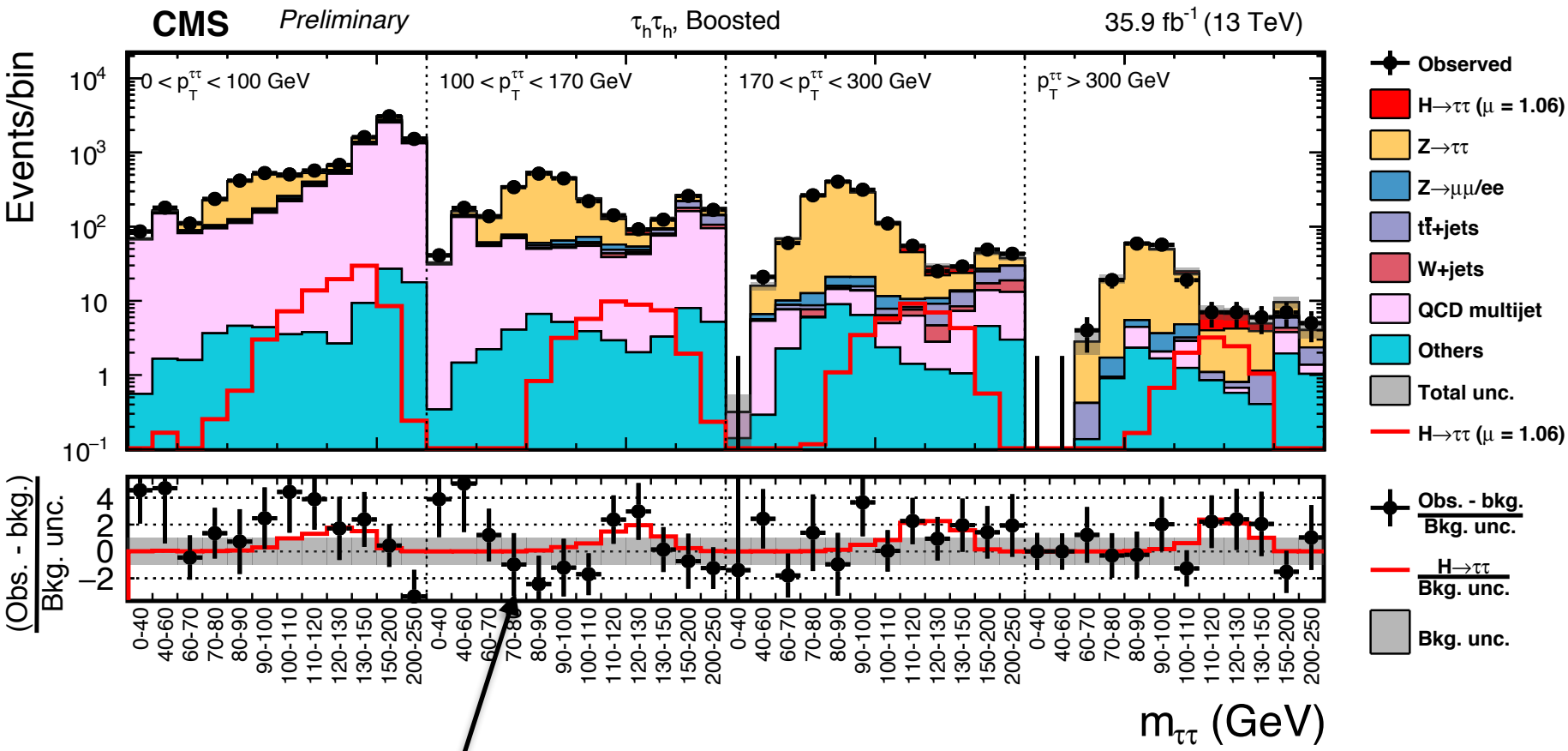
un-rolled 2D distribution

"boosted $\tau_h\tau_h$ di-tau mass unrolled in di-tau pT"



black dot shows **significance** per bin

red line shows **expected significance** of SM Higgs(125) per bin

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systematics

refined uncertainty model

- split jet energy scale into 27 different sources
- more detailed tau ID and scale uncertainties
- control regions in fit

Source of uncertainty	Magnitude	
	Prefit	Postfit
τ_h energy scale	1.2% on energy scale	0.2-0.3%
e energy scale	1-2.5% on energy scale	0.2-0.5%
e misidentified as τ_h energy scale	3% on energy scale	0.6-0.8%
μ misidentified as τ_h energy scale	1.5% on energy scale	0.3-1.0%
Jet energy scale	27 sources, event-by-event	-
E_T^{miss} energy scale	Event-by-event	-
τ_h ID & isolation	5% per τ_h	3.5%
τ_h trigger	5% per τ_h	3%
τ_h reconstruction per decay mode	3% migration between decay modes	2%
e ID & isolation & trigger	2%	-
μ ID & isolation & trigger	2%	-
e misidentified as τ_h rate	12% per τ_h decay mode	5%
μ misidentified as τ_h rate	25% per τ_h decay mode	3-8%
Jet misidentified as τ_h rate	20% per 100 GeV τ_h p_T	15%
$Z \to \tau\tau/\ell\ell$ estimation	Normalization: 7-15%	3-15%
	Uncertainty on $m_{\ell\ell/\tau\tau}$, $p_T(\ell\ell/\tau\tau)$, and $m_{\bar{\nu}}$ corrections	-
W + jets estimation	Normalization, eμ and $\tau_h\tau_h$: 4-20%	-
	Extrap. from high-m_T region, eτ_h and $\mu\tau_h$: 5-10%	-
	Unc. from CR, eτ_h and $\mu\tau_h$: $\simeq 5-15\%$	-
QCD multijet estimation	Normalization, eμ: 10-20%	5-20%
	Unc. from CR, eτ_h, $\tau_h\tau_h$, and $\mu\tau_h$: $\simeq 5-15\%$	-
	Extrap. from anti-iso. region, eτ_h and $\mu\tau_h$: 20%	7-10%
	Extrap. from anti-iso. region, $\tau_h\tau_h$: 3-15%	3-10%
Diboson normalization	5%	-
Single-top normalization	5%	-
$t\bar{t}$ estimation	Normalization from CR: $\simeq 5\%$	-
	Uncertainty on top quark p_T reweighting	-
Luminosity	2.5%	-
b-tagged jet veto (eμ)	3.5-5.0%	-
Limited number of events	Statistical uncertainty in every bin	-
Signal theoretical uncertainty	Up to 20%	-

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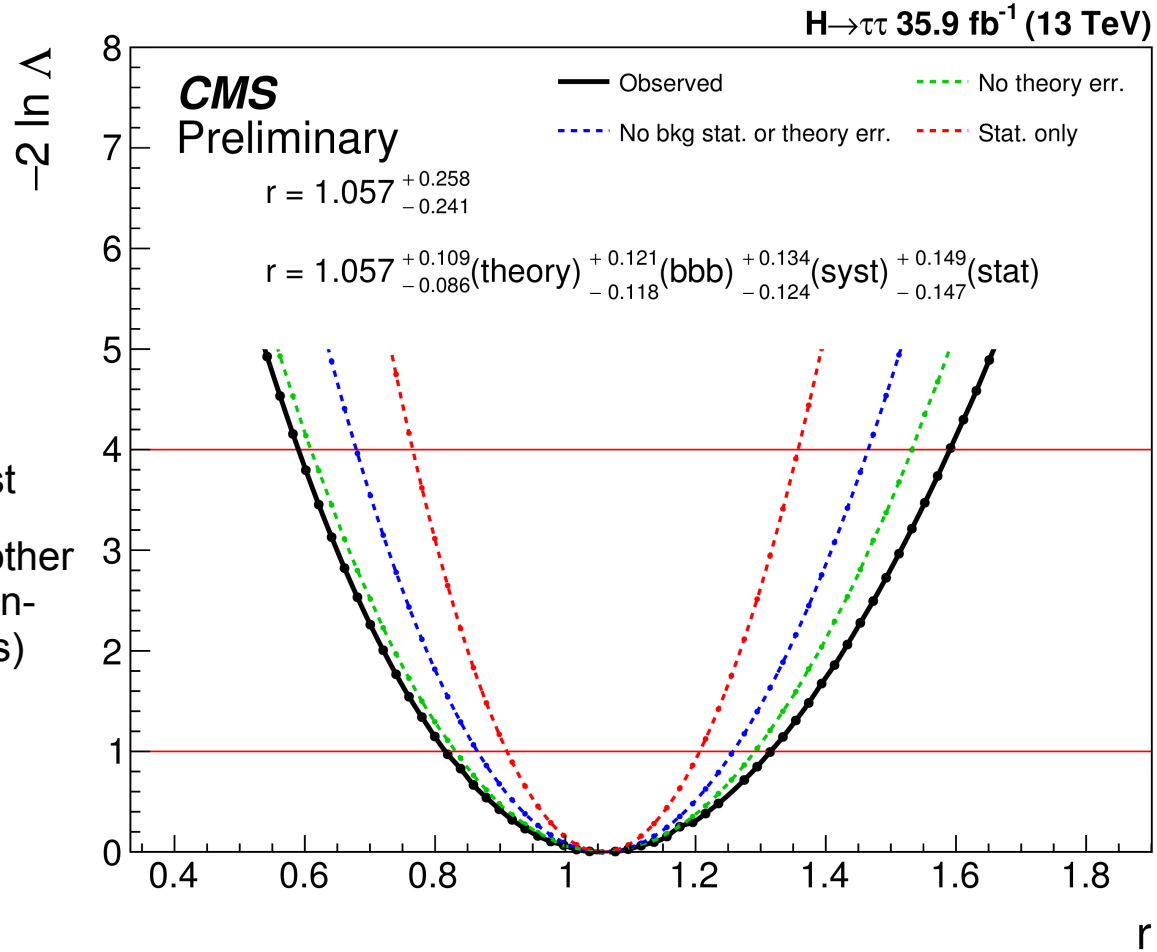
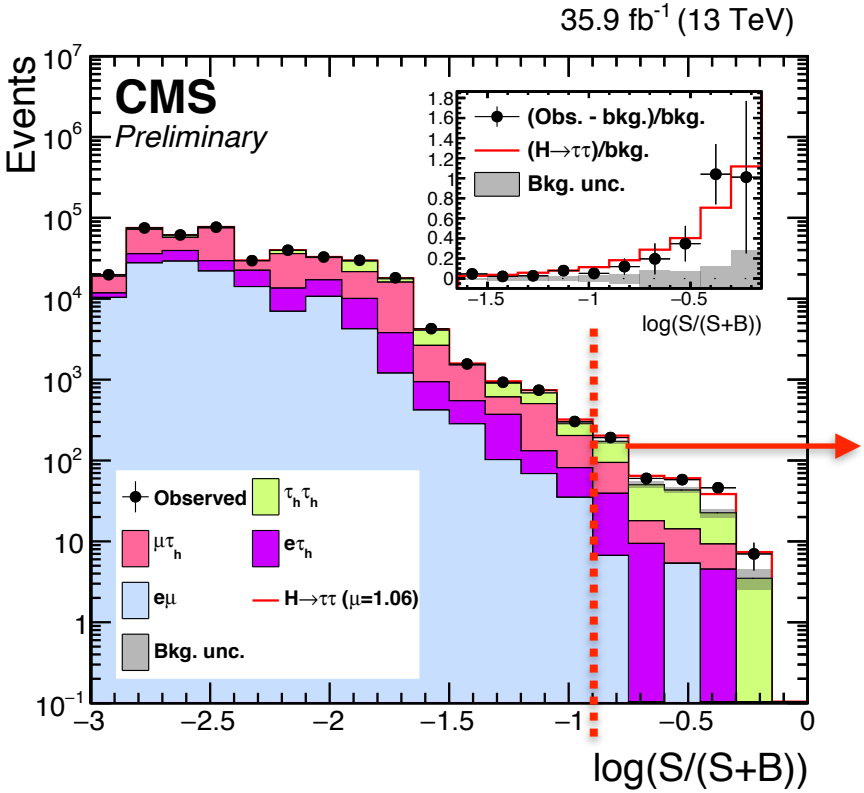
signal strength of SM Higgs mass = 125 GeV

only H -> tau tau decays treated as signal

- statistical uncertainties are largest
- significant contributions from all other sources, in particular also from bin-by-bin uncertainties (MC statistics)

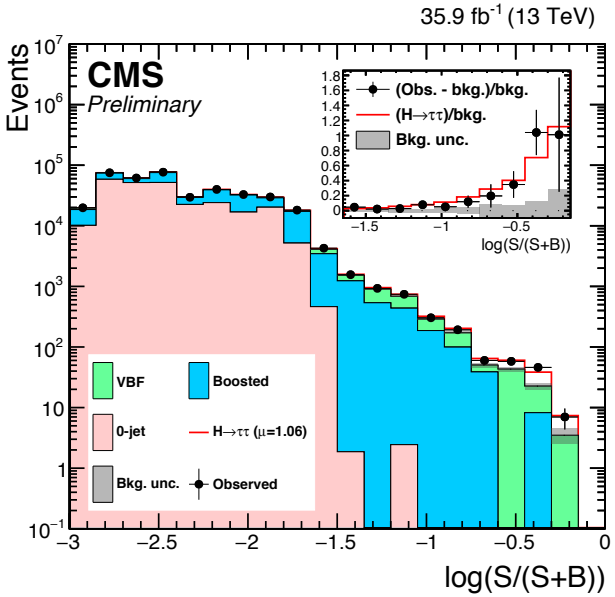


visualizing the excess



Process	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
$Z \to \tau\tau$	5.77± 2.22	21.16± 3.28	34.57± 4.87	89.05± 6.91
$Z \to ee/\mu\mu$	0.00± 0.00	2.94± 0.18	3.66± 0.22	4.96± 0.24
$t\bar{t}$+jets	1.93± 0.09	10.38± 0.29	22.22± 1.79	13.91± 0.51
W+jets	0.81± 0.02	4.03± 0.30	6.59± 1.28	7.56± 0.81
QCD multijet	2.12± 0.25	3.33± 2.50	5.00± 1.27	35.50± 2.08
Other bkg.	1.44± 0.04	5.19± 0.20	6.05± 0.21	7.25± 0.20
$gg \to H, H \to \tau\tau$	0.58± 0.09	5.00± 0.55	6.01± 0.58	27.38± 2.09
$qq \to H, H \to \tau\tau$	2.78± 0.30	5.14± 0.47	12.55± 1.02	17.50± 1.04
$VH, H \to \tau\tau$	0.00± 0.00	0.29± 0.03	0.24± 0.03	1.34± 0.10
Total bkg.	12.05± 2.16	46.53± 4.10	77.66± 5.50	156.16± 7.34
Total signal	3.37± 0.36	10.92± 0.79	19.24± 1.39	48.29± 2.63
Observed	11	54	91	207

yields in the region log(S/(S+B)) > -0.9



- rearranged in a histogram based on the the decimal logarithm of the ratio of the signal (S) to signal-plus-background (S+B) in each bin
- signal is clearly visible

summaries

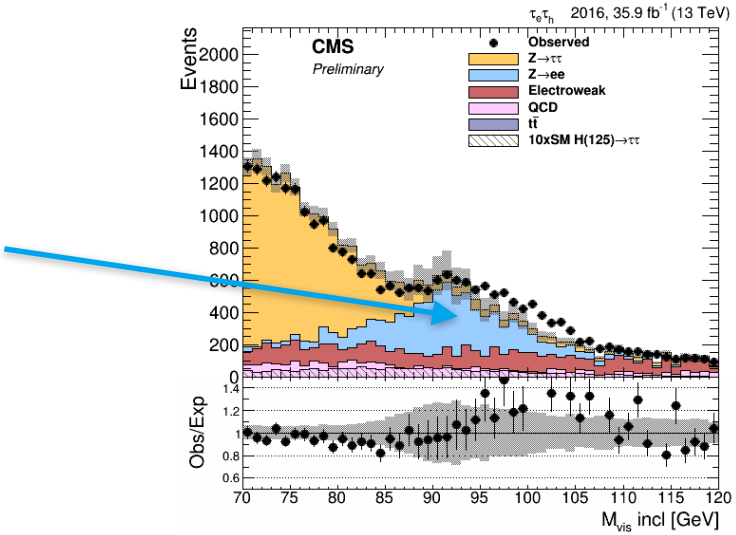
- we have observation for Higgs -> tau tau in CMS experiment (CMS-PAS-HIG-16-043):
  - **4.9 σ** at Run-2 13 TeV
  - **5.9 σ** in the combination with the CMS Run-1 analysis (7+8+13 TeV)
- results are compatible with SM predictions

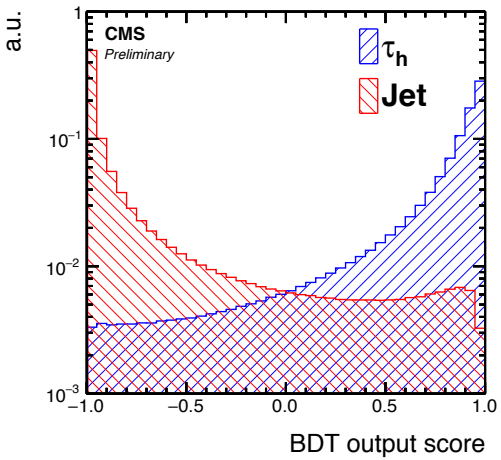
👍 first direct observation of the tau Yukawa coupling in a single experiment!

Back-up

challenges in the analysis

- $\mu\tau_h/e\tau_h$
  - electron faking tau looks just like H -> tau tau signal
  - require anti-electron(muon) discriminator works well
- $\tau_h\tau_h$
  - With two hadronic tau, challenge of jet background in both the trigger and the tau ID
  - new L1 trigger (run 2 trigger upgrade) helped keeping low rates and Pt threshold
  - well working discriminator against jet, any improvement of it will be twice better
  - the most sensitive channel





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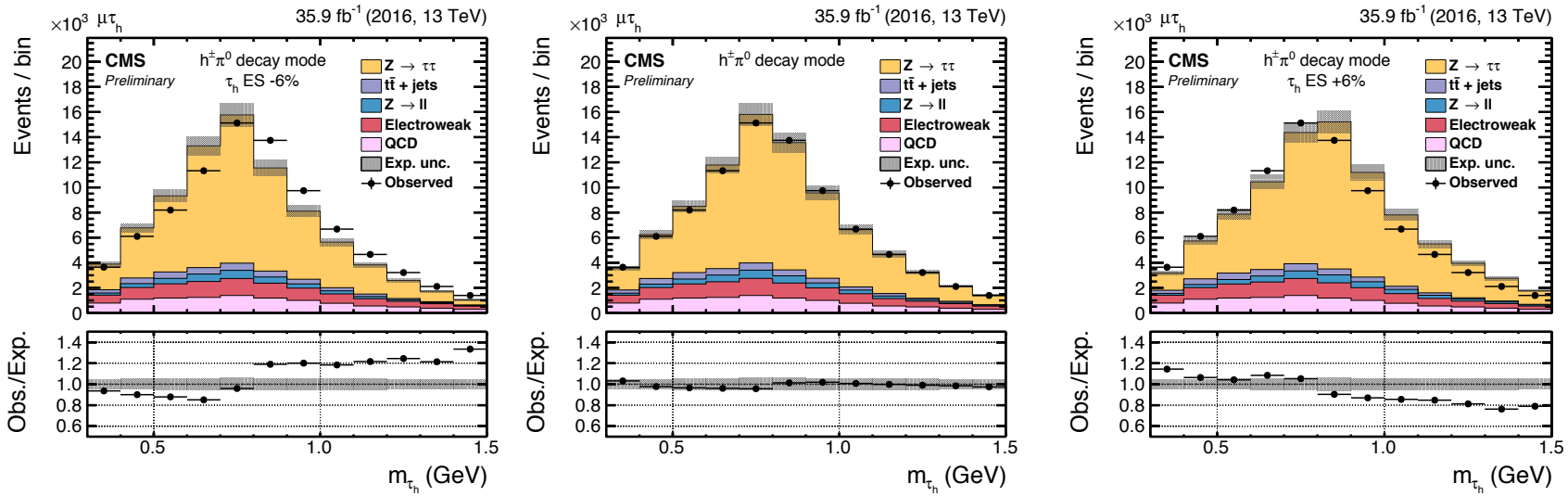
tau energy scale correction

- Tau energy scale (TES) correction is determined by fitting visible mass and tau mass distribution, using $Z/\gamma^{\star} \rightarrow \mu\tau$ events
- TES is measured per decay mode: 1prong, 1prong+1π_0 and 3 prongs



decay mode	shift
1prong	-1.8%
1prong + π_0	+1.0%
3 prongs	+0.4%

uncertainty for all 3 decay modes: +/- 1.2%

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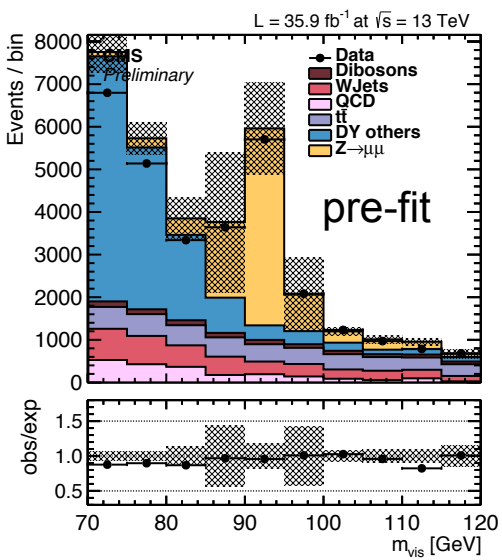
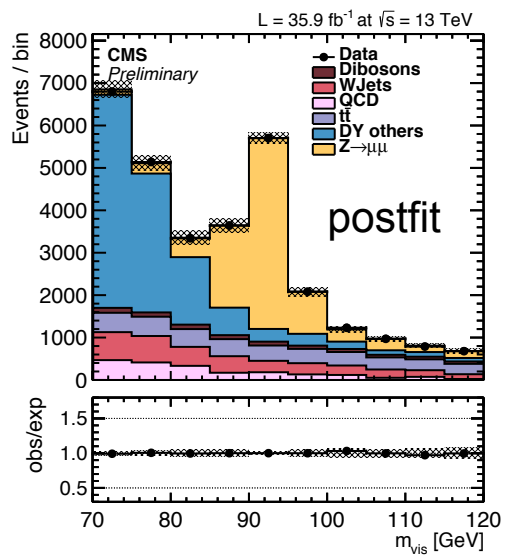
data/MC corrections: e/μ -> tau fake rate scale factor

- **anti-electron(muon) discriminator** is used to reject e(μ) faking tau events
- tau POG provides SF to correct data/MC difference
- applied on background when reco tau is matched at GEN-level to a prompt electron(muon)
- fake rates measured using tag-and-probe on Z->eτ_h (Z->μτ_h) events when τ_h matched to GEN-level e(μ)
- **tag**: identified electron(muon)
  probe: τ candidate which either passes or fails anti-e(μ) discriminant

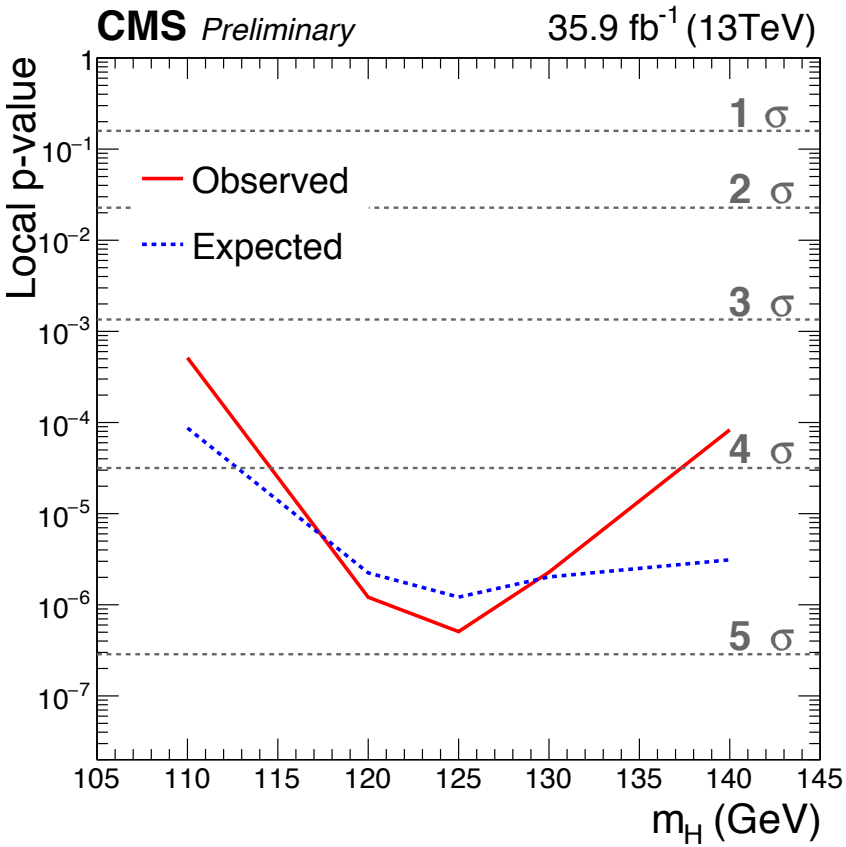




Tau discriminator	η range	Scale factor
againstElectronMVAVLoose	$\lvert\eta\rvert < 1.460$	1.21 ± 0.07
againstElectronMVALoose	$\lvert\eta\rvert < 1.460$	1.32 ± 0.04
againstElectronMVAMedium	$\lvert\eta\rvert < 1.460$	1.32 ± 0.07
againstElectronMVATight	$\lvert\eta\rvert < 1.460$	1.40 ± 0.11
againstElectronMVAVTight	$\lvert\eta\rvert < 1.460$	1.20 ± 0.18
againstElectronMVAVLoose	$\lvert\eta\rvert > 1.558$	1.37 ± 0.05
againstElectronMVALoose	$\lvert\eta\rvert > 1.558$	1.38 ± 0.04
againstElectronMVAMedium	$\lvert\eta\rvert > 1.558$	1.52 ± 0.13
againstElectronMVATight	$\lvert\eta\rvert > 1.558$	1.90 ± 0.30
againstElectronMVAVTight	$\lvert\eta\rvert > 1.558$	1.96 ± 0.46
againstMuonLoose3	$\lvert\eta\rvert < 0.4$	1.01 ± 0.02
againstMuonTight3	$\lvert\eta\rvert < 0.4$	1.26 ± 0.07
againstMuonLoose3	$0.4 < \lvert\eta\rvert < 0.8$	1.00 ± 0.03
againstMuonTight3	$0.4 < \lvert\eta\rvert < 0.8$	1.36 ± 0.28
againstMuonLoose3	$0.8 < \lvert\eta\rvert < 1.2$	0.87 ± 0.03
againstMuonTight3	$0.8 < \lvert\eta\rvert < 1.2$	0.85 ± 0.04
againstMuonLoose3	$1.2 < \lvert\eta\rvert < 1.7$	1.15 ± 0.13
againstMuonTight3	$1.2 < \lvert\eta\rvert < 1.7$	1.71 ± 0.5
againstMuonLoose3	$1.7 < \lvert\eta\rvert < 2.3$	2.28 ± 0.26
againstMuonTight3	$1.7 < \lvert\eta\rvert < 2.3$	2.32 ± 0.5

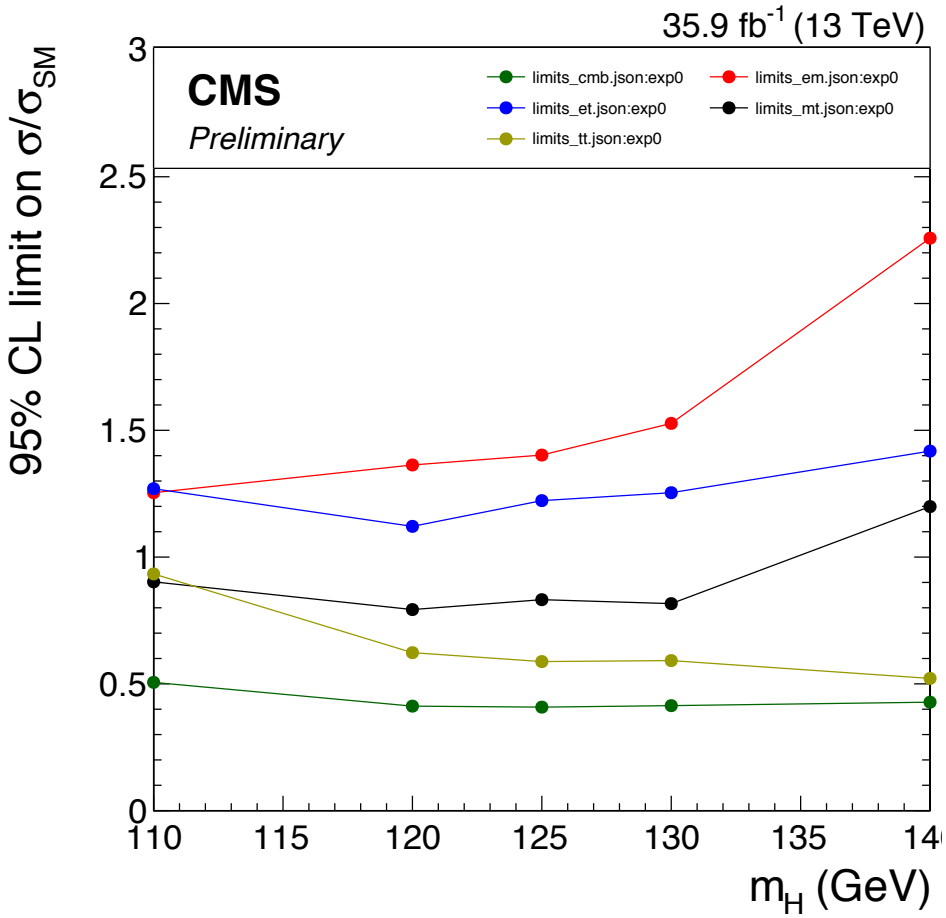
observation of SM Higgs decays to tau tau

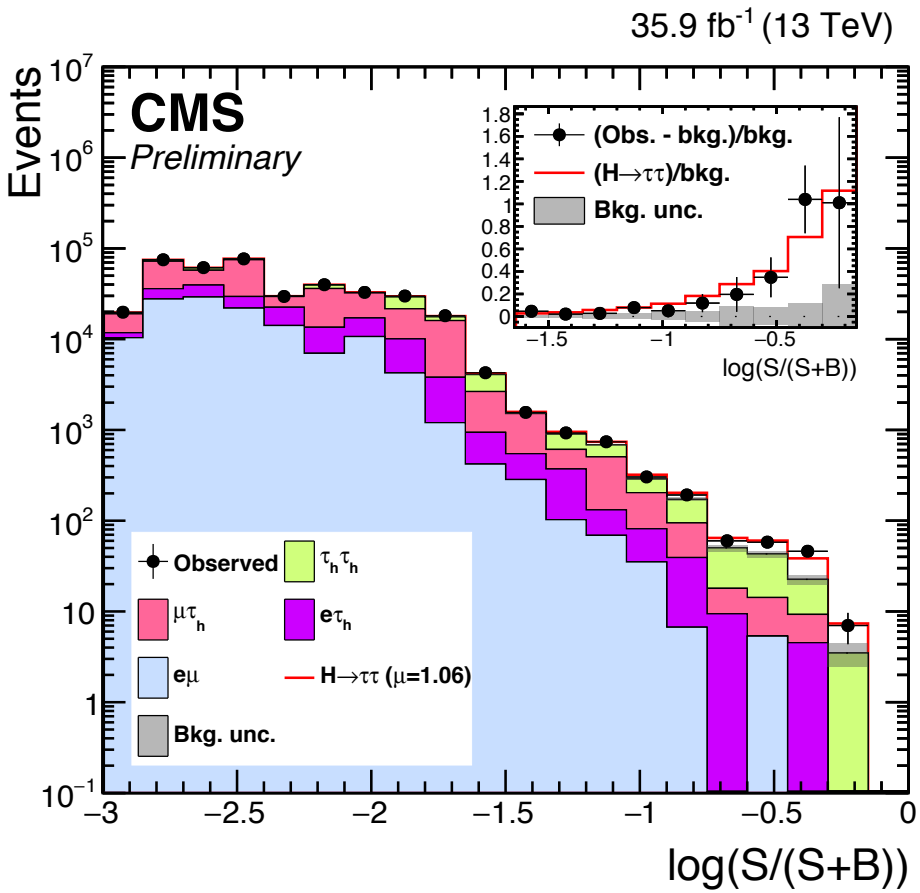
- local p-value using a profile likelihood ratio test statistic
- for 125 GeV SM Higgs
- expected significance is **4.7 σ**
- observed significance is **4.9 σ**
- first observation in a single experiment!



- combined with 7, 8 TeV and 13 TeV data
- the combination give observed and expected significance of **5.9 σ**!

expected limits and log(S/(S+B)) distribution





- expected limit comparison
  ττ channel is the most sensitive

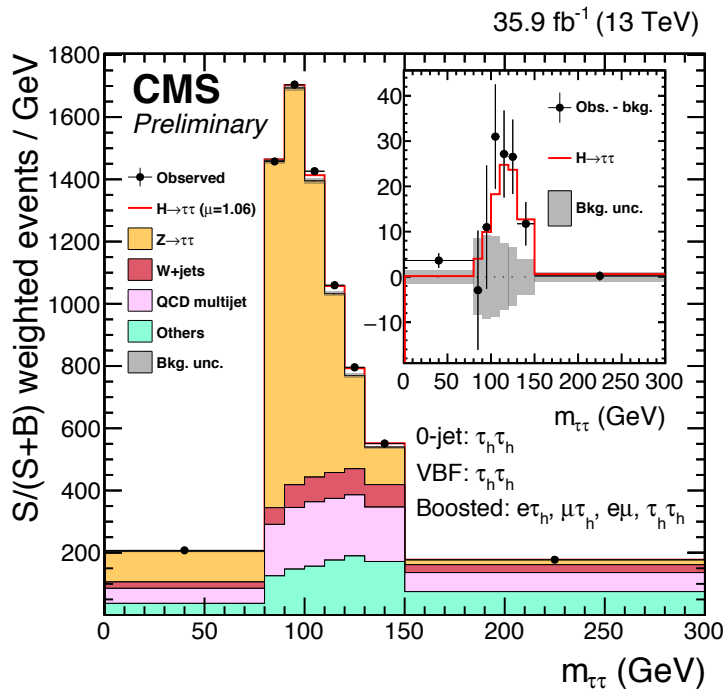
- rearranged in a histogram based on the the decimal logarithm of the ratio of the signal (S) to signal-plus-background (S + B) in each bin
- signal is clearly visible

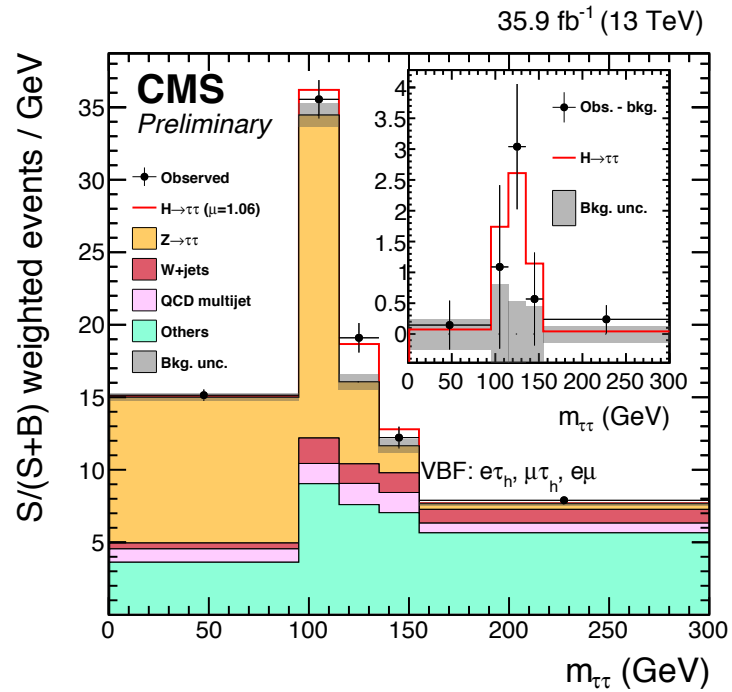
$$\mu = 1.06^{+0.11}_{-0.09}(th.)^{+0.12}_{-0.12}(bbb.)^{+0.13}_{-0.12}(syst.)^{+0.15}_{-0.15}(stat.)$$

The combined best-fit signal strength is μ = 1.06 ± 0.25

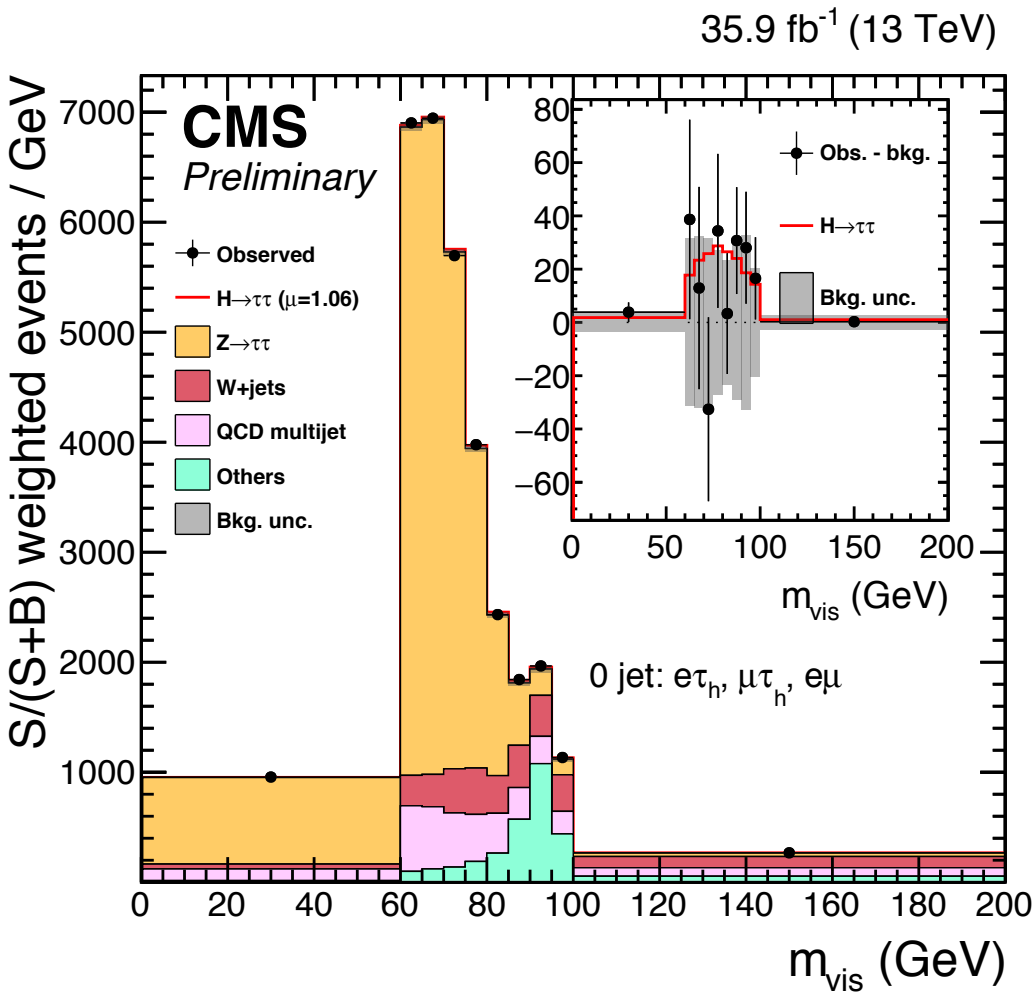
combined observed and predicted mττ distributions

- to visualize the excess
- mττ mass distribution weighted S/(S + B)
- the signal is normalized to its best-fit signal strength
- data in **good agreement with** 125 GeV Higgs **signal**

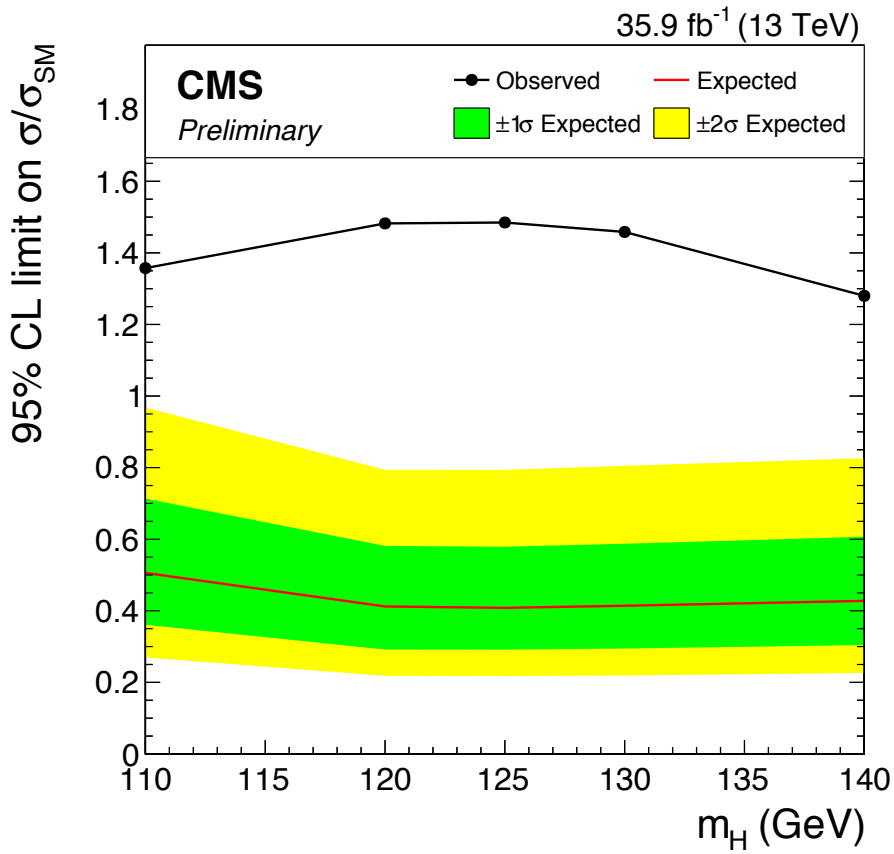




Yiwen Wen, DESY

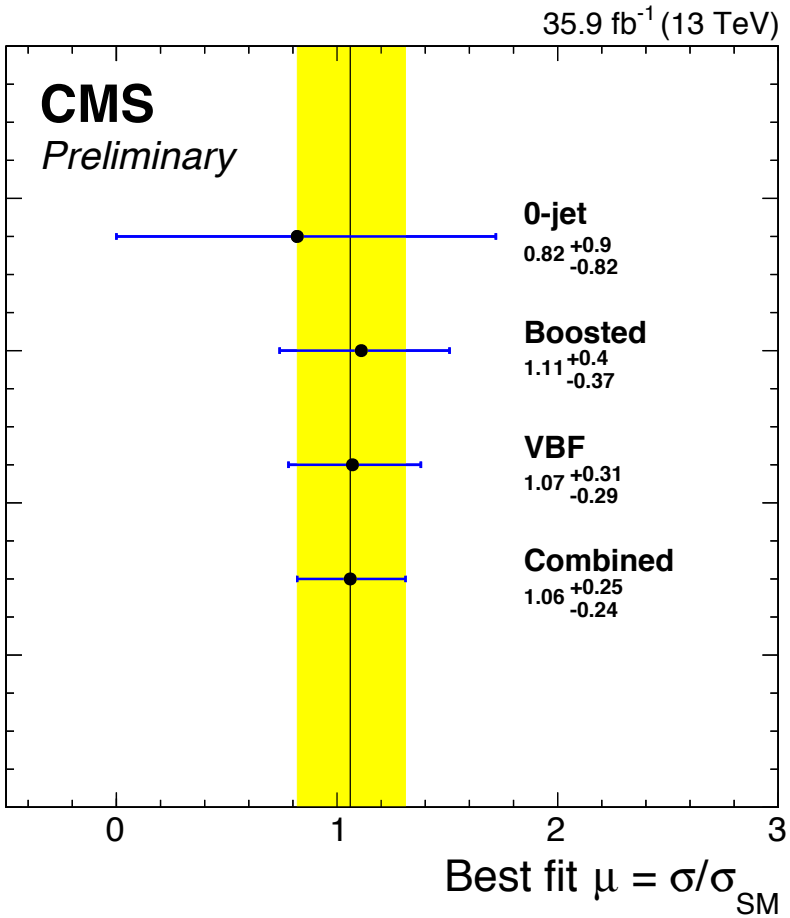

35.9 fb-1 (13 TeV)
CMS
Preliminary
Observed
H→ττ (μ=1.06)
Z→ττ
W+jets
QCD multijet
Others
Bkg. unc.
Obs. - bkg.
H→ττ
Bkg. unc.
0 jet: eτh, μτh, eμ
S/(S+B) weighted events / GeV
mvis (GeV)
mvis (GeV)

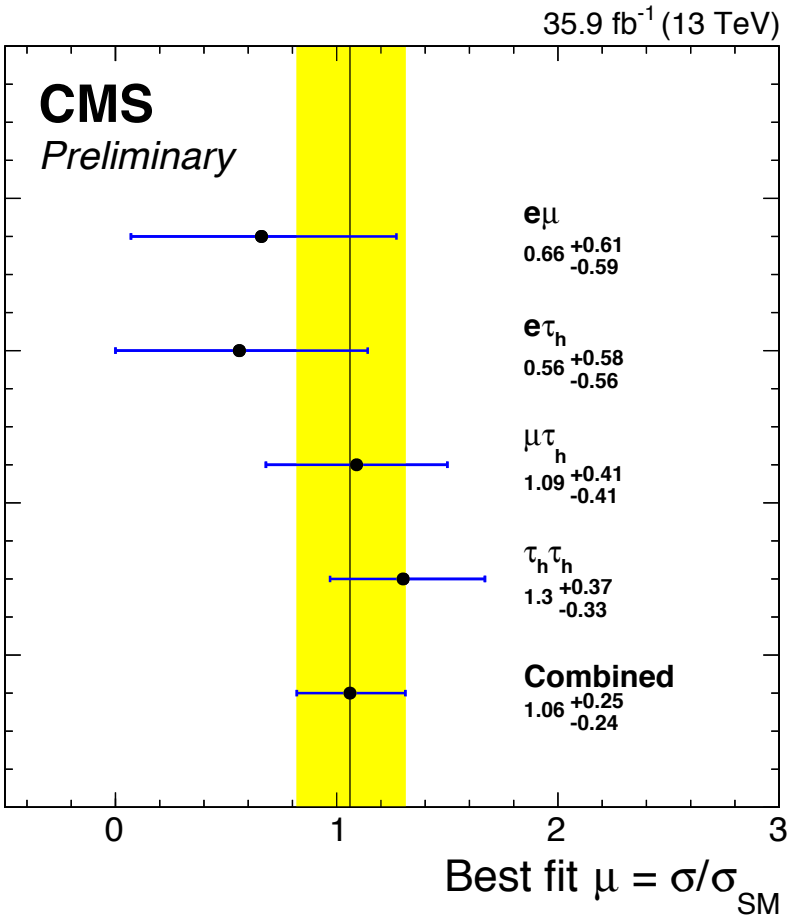
observation of SM Higgs decays to tau tau (HIG-16-043)



> significant excess centered near 125 GeV

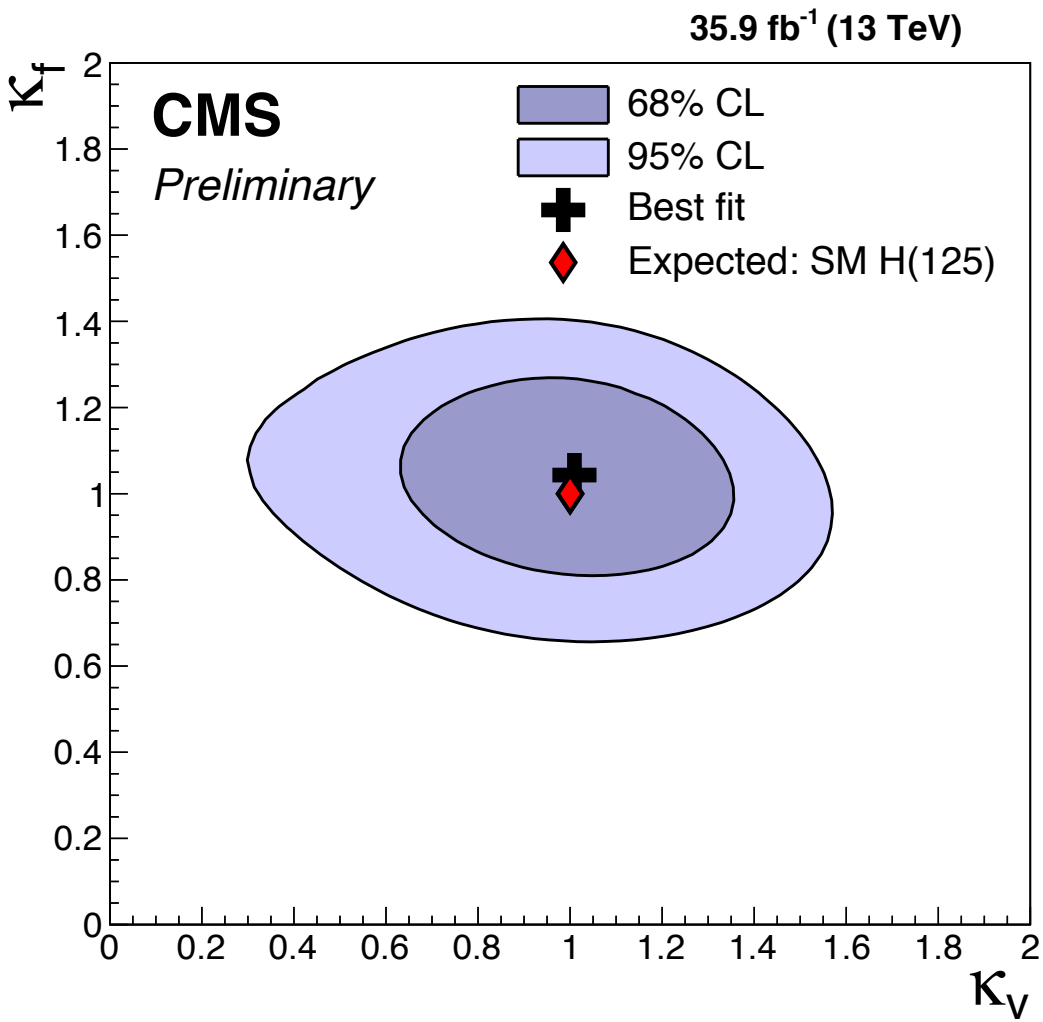
best fit signal strength value





The combined best-fit signal strength is $\mu = 1.06 \pm 0.25$

likelihood scan for 125 GeV Higgs in (κ_v,κ_f) parameter space



the observed likelihood contour is consistent with the SM expectation of κ_v and κ_f equal to unity.