Observation of Standard Model Higgs boson decays to tau leptons and a search for dark matter with the CMS detector at the LHC

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About Me

- Laura Margaret Dodd
- B.S. in physics from Duke University
  - Worked in ATLAS group
- Entered UW-Madison physics Ph.D. program in 2012
  - Advisor: Wesley Smith
- Stationed at CERN between 2014 and 2017

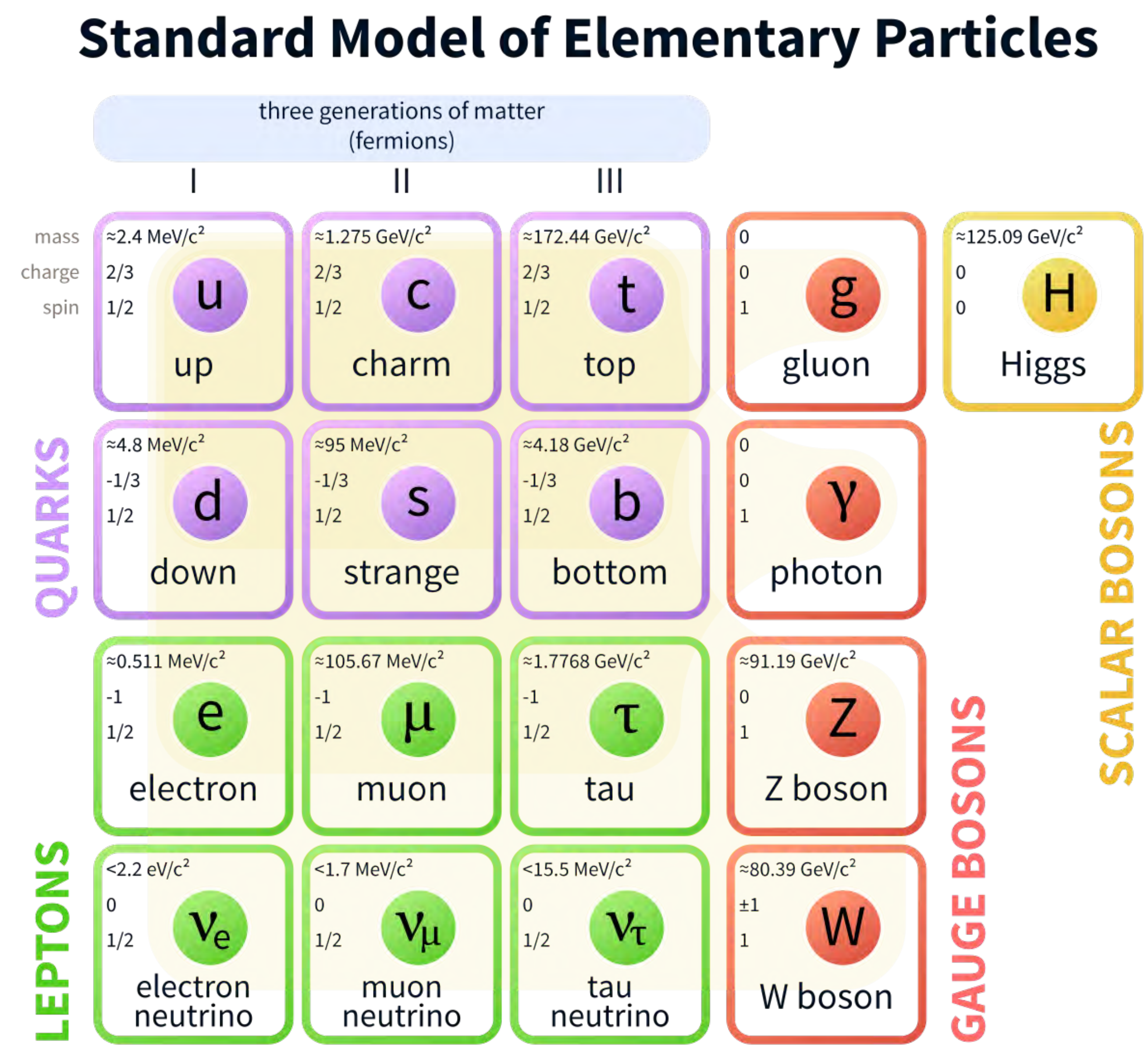
Roadmap

- Motivation and theory
- Experiment and background
- Observation of standard model (SM) Higgs boson to tau pairs
- Search for dark matter (DM) pairs in association with SM Higgs boson in tau pair final state.
- Summary

Standard Model (SM)

- Fermions (spin-1/2)
  - 3 generations of matter
    - 6 quarks, and 6 leptons
      - 3 charged and 3 neutral leptons
      - In SM, neutrinos are massless, unknown extension needed
- Bosons (integer spin) - force mediators
  - massless • gluons -> strong force
  - massless • γ -> EM force
  - massive • $W^{\pm}/Z^0$ -> Weak force

} unified electroweak force in SM

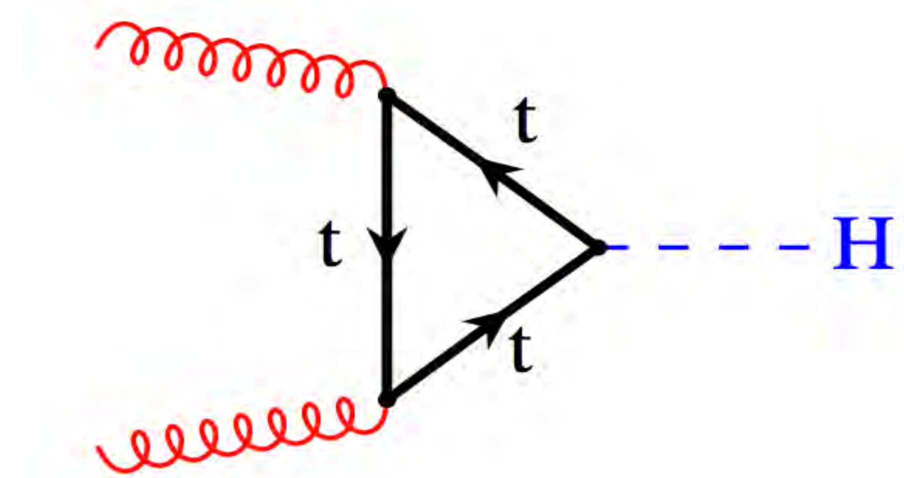


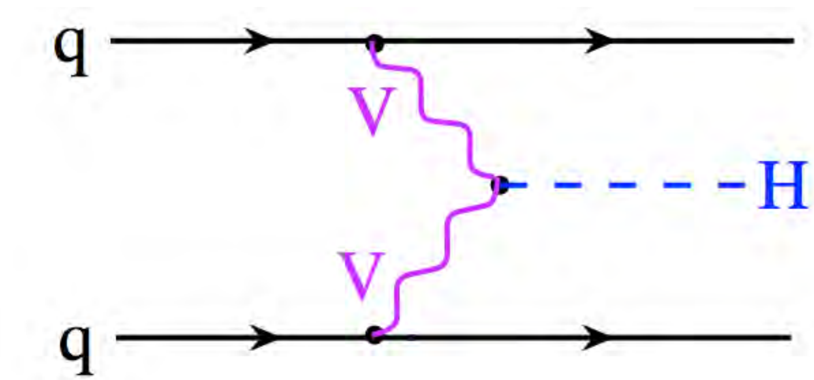
$W^{\pm}/Z^0$ sometimes denoted V

Standard Model (SM): Higgs I

- Higgs Mechanism
  - Scalar doublet is added
    - Gauge bosons $W^{\pm}/Z^{0}$ acquire mass through spontaneous symmetry breaking and nonzero vacuum expectation
    - Massive scalar boson predicted: Higgs boson
    - Higgs couples to fermions and therefore fermions gain mass
- 2 main production mechanisms considered:
  - gluon fusion (ggH/ggF) and vector boson fusion (VBF)

gluon fusion (ggH)





vector boson fusion (vbf) rate is factor of ten smaller than ggH

Standard Model (SM): Higgs III

arXiv:1401.6527 [hep-ex]

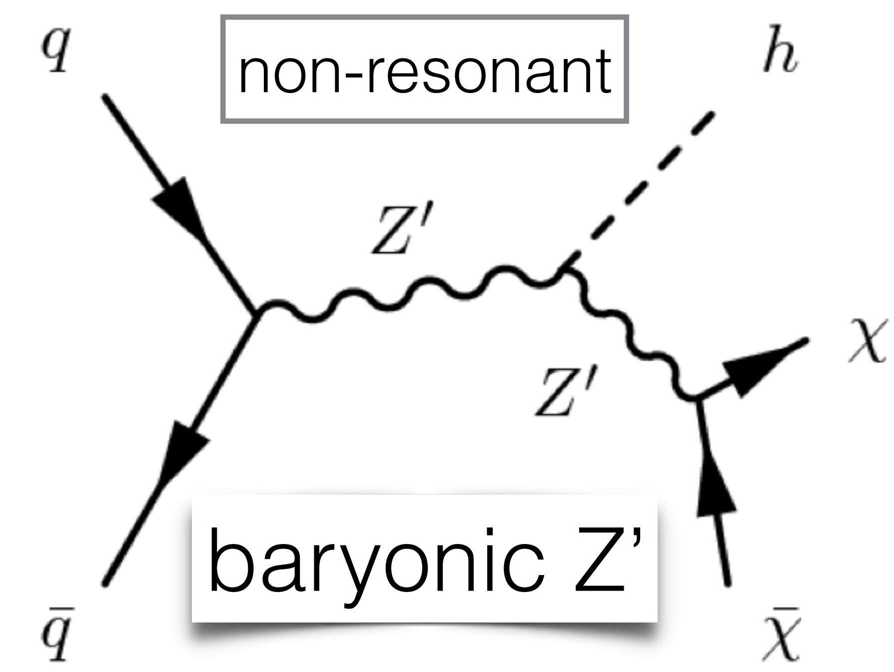
- In 2012 CMS and ATLAS measured the cross sectional rate of the Higgs coupling to tau leptons and the Higgs coupling to b quarks.
- **Signal strength** (μ) is **defined as *observed rate* / expected SM rate.**
- CMS measured the **rate** of H→ττ to be μ= **0.88±0.30 times the SM expectation**.
- ATLAS measured the **rate** of H→ττ to be μ=**1.41 ±0.40 times the SM expectation**

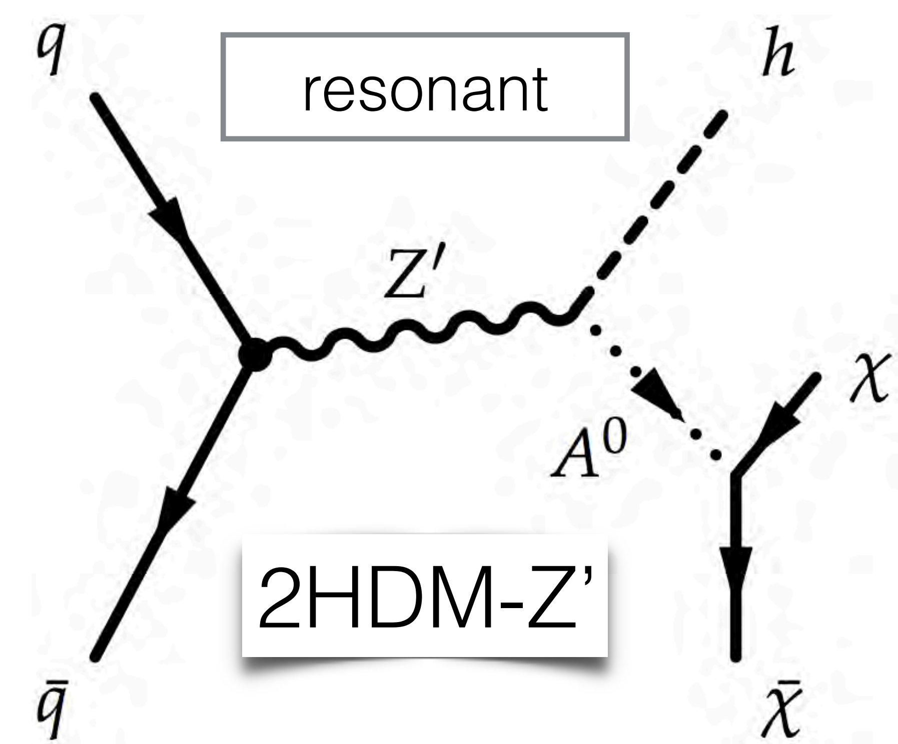
Decay mode	Branching fraction [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

ATLAS+CMS measure H(bb)
μ=0.70 ± 0.29

Dark Matter

- Dark matter (DM) exists; the majority of matter in the universe is DM.
- The fundamental nature of DM is not known
  - Weakly interacting massive particle (WIMP) may interact with SM through the Higgs sector, as in Higgs-portal models. WIMP DM is denoted χ.
  - I focus on a collider "**mono-Higgs**" signature e.g. **Higgs+ nothing detected**
  - Two models examined provide a non-resonant and a resonant handle

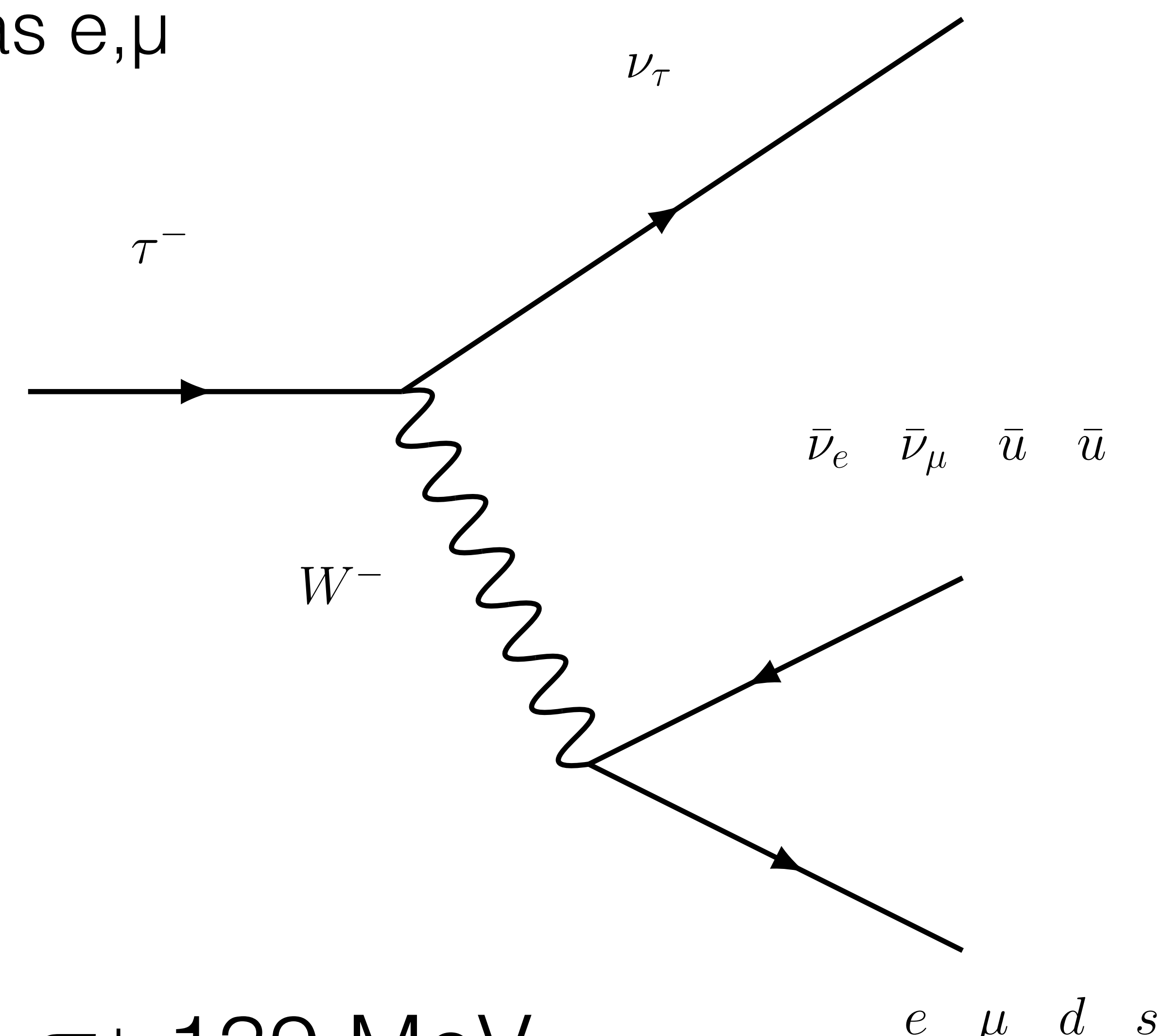




τ lepton decays

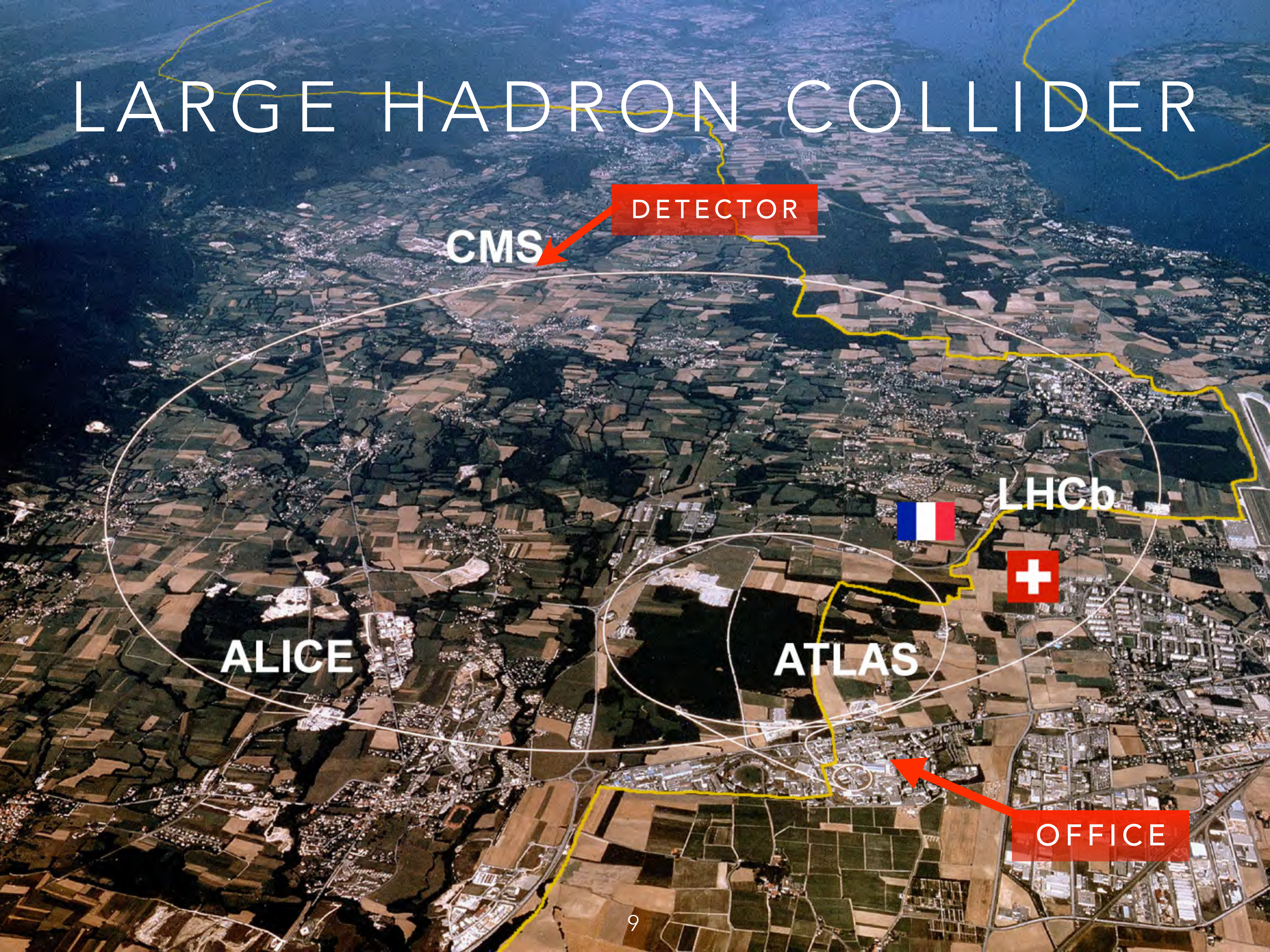
- Tau lepton heaviest lepton in the SM: 1.77 GeV
  - Most strongly coupled lepton to Higgs
- Tau lifetime is ~3×10^{-13} seconds
- Taus can decay to hadrons (τ_h) as well as e,μ

$\tau \to e\nu_e\ \nu_\tau$,	17.8 %
$\tau \to \mu\nu_\mu\ \nu_\tau$	17.4 %
$\tau \to \pi^\pm\nu_\tau$	11.1 %
$\tau \to \pi^0\pi^\pm\nu_\tau$	25.4 %
$\tau \to \pi^0\pi^0\pi^\pm\nu_\tau$	9.19 %
$\tau \to \pi^0\pi^0\pi^0\pi^\pm\nu_\tau$	1.08 %
$\tau \to \pi^\pm\pi^\pm\pi^\pm\nu_\tau$	8.98 %
$\tau \to \pi^0\pi^\pm\pi^\pm\pi^\pm\nu_\tau$	4.30 %
$\tau \to \pi^0\pi^0\pi^\pm\pi^\pm\pi^\pm\nu_\tau$	0.50 %
$\tau \to \pi^0\pi^0\pi^0\pi^\pm\pi^\pm\pi^\pm\nu_\tau$	0.11 %
$\tau \to K^\pm X\nu_\tau$	3.74 %
$\tau \to (\pi^0)\pi^\pm\pi^\pm\pi^\pm\pi^\pm\pi^\pm\nu_\tau$	0.10 %
others	0.03 %



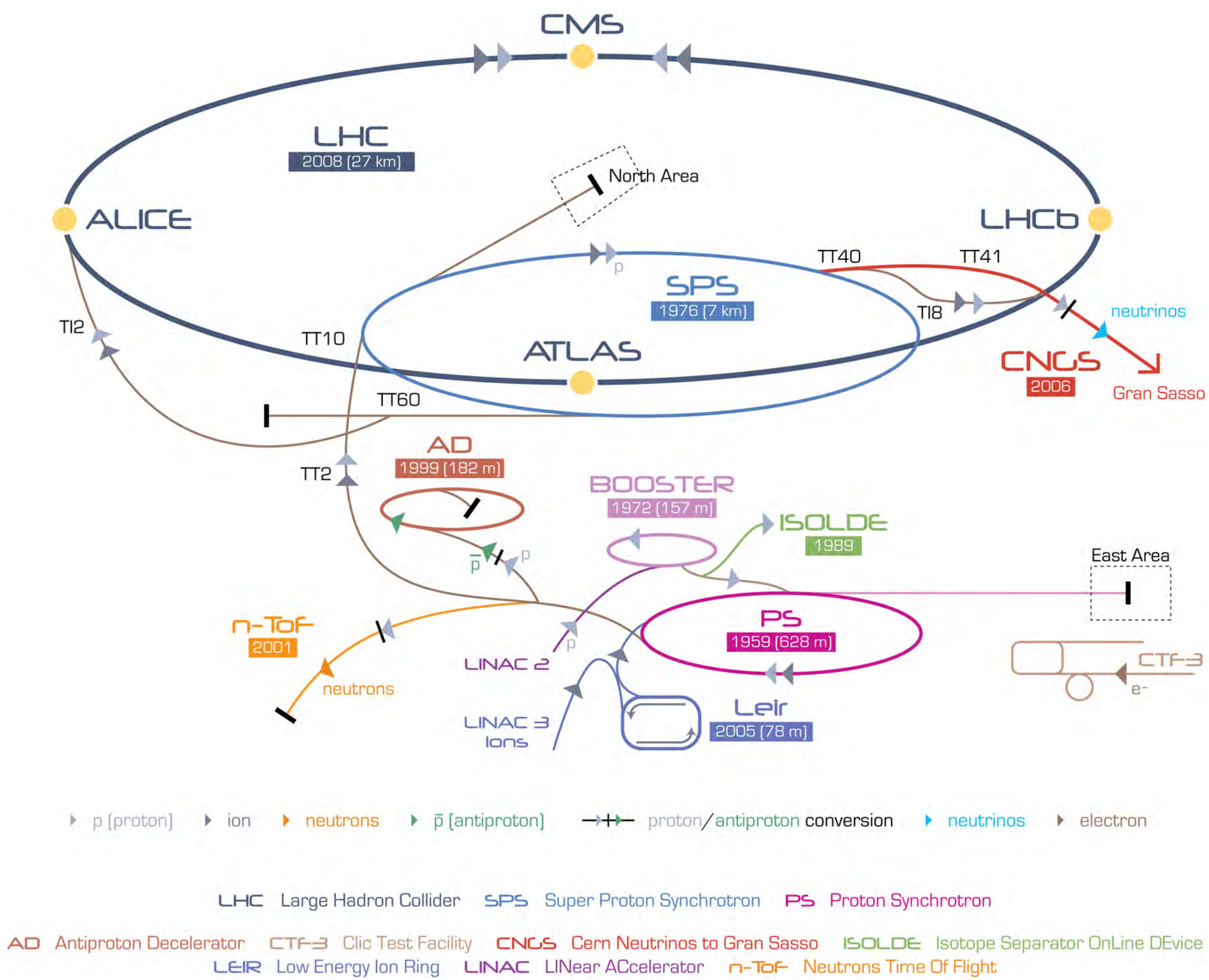
π^+ 139 MeV
π^0 135 MeV

LARGE HADRON COLLIDER



LHC

- 27 km proton-proton or heavy-ion collider
- In 2016, operated at 13 TeV center of mass energy
    - CMS and ATLAS, general purpose detectors
    - ALICE (heavy ion) and LHCb (b-physics)
- Protons accelerated in stages
    - Injected into LHC at 450 GeV and accelerated to 6.5 TeV by 400 MHz RF cavities



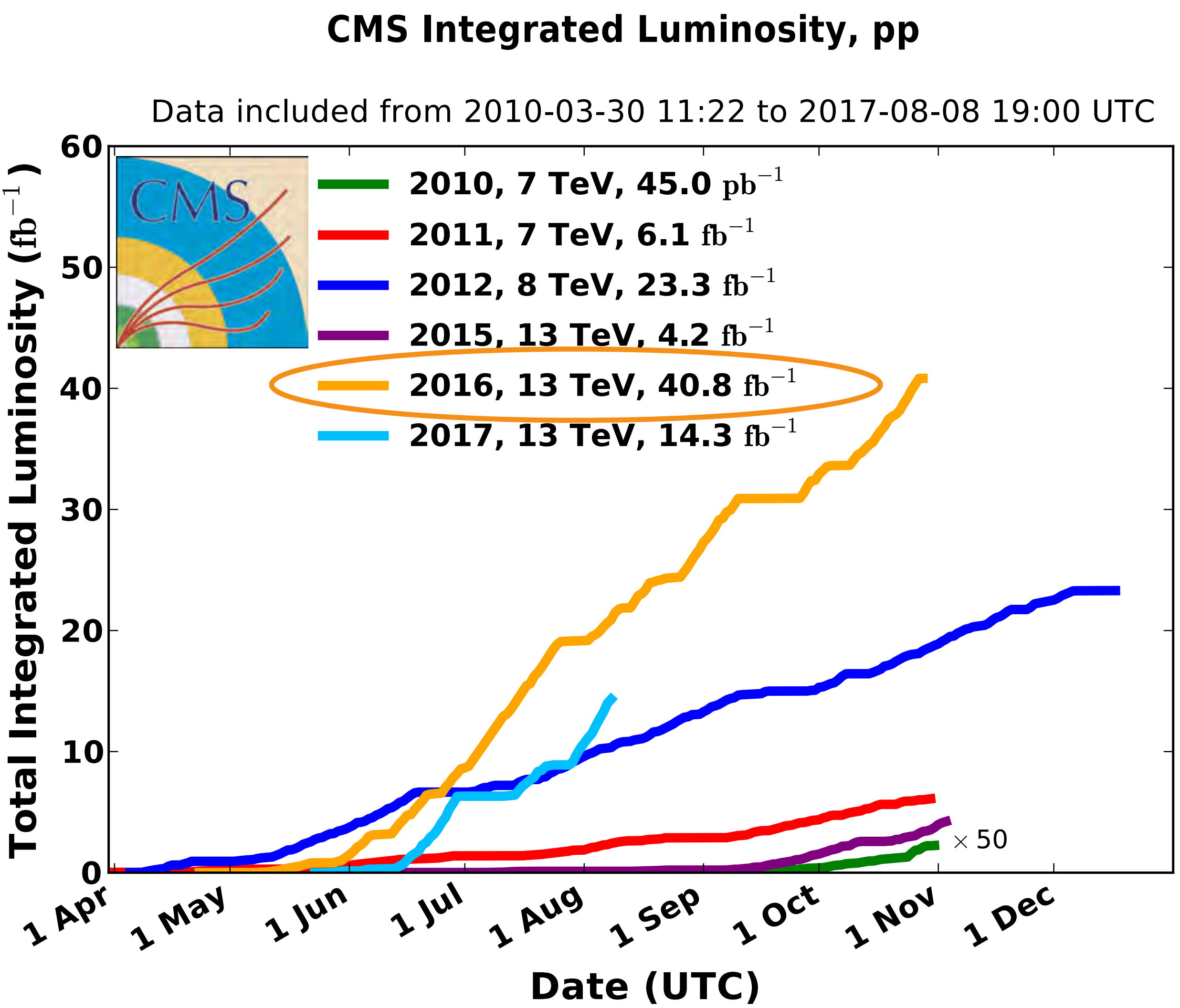
Cross section and Luminosity

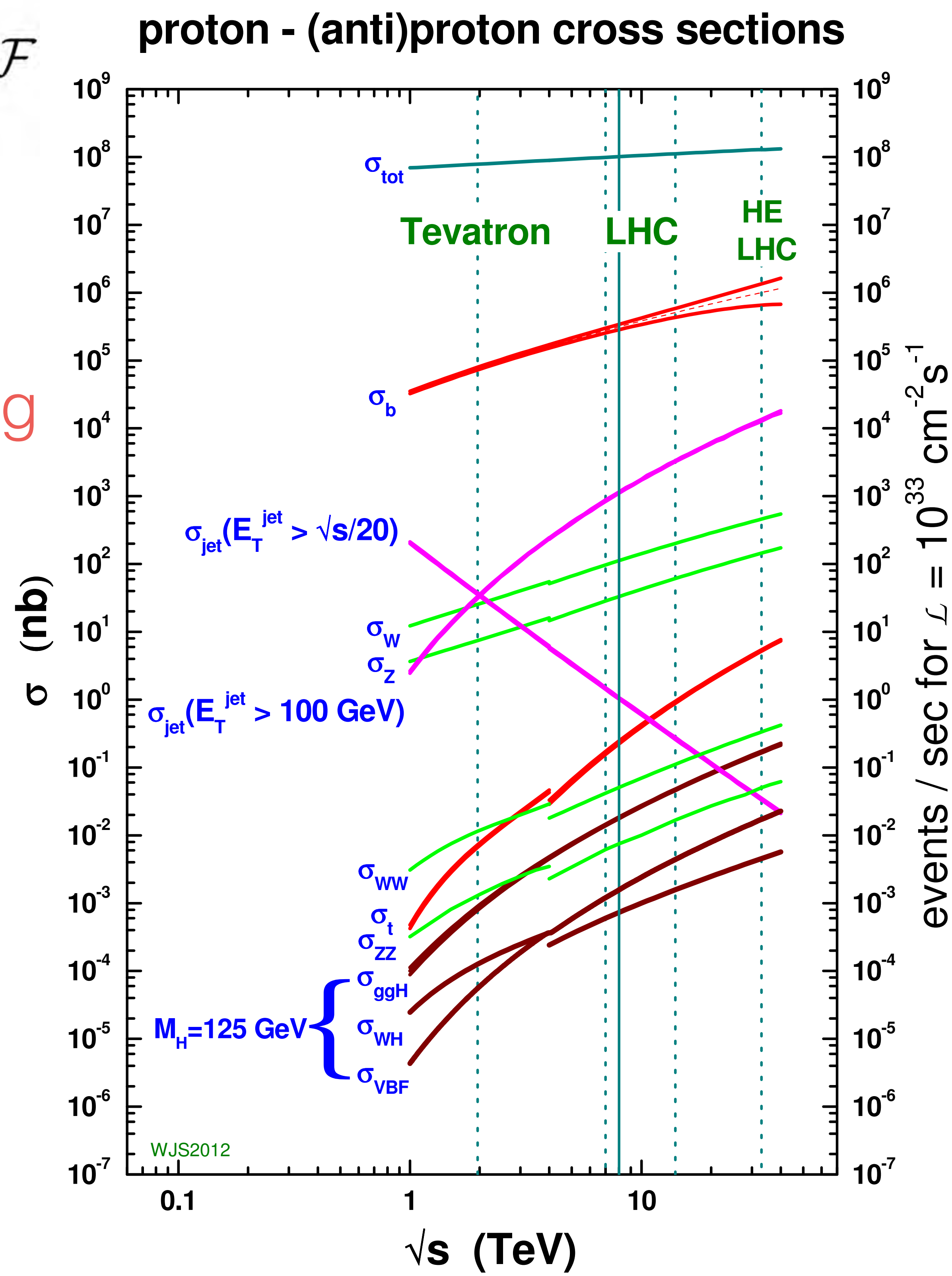
To increase luminosity: decrease the collision angle (β), maximize the number of particles per bunch (Nb), and squeeze each bunch (~ϵ)

$$\mathcal{L} \simeq \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi\epsilon_n \beta^*}\mathcal{F}$$

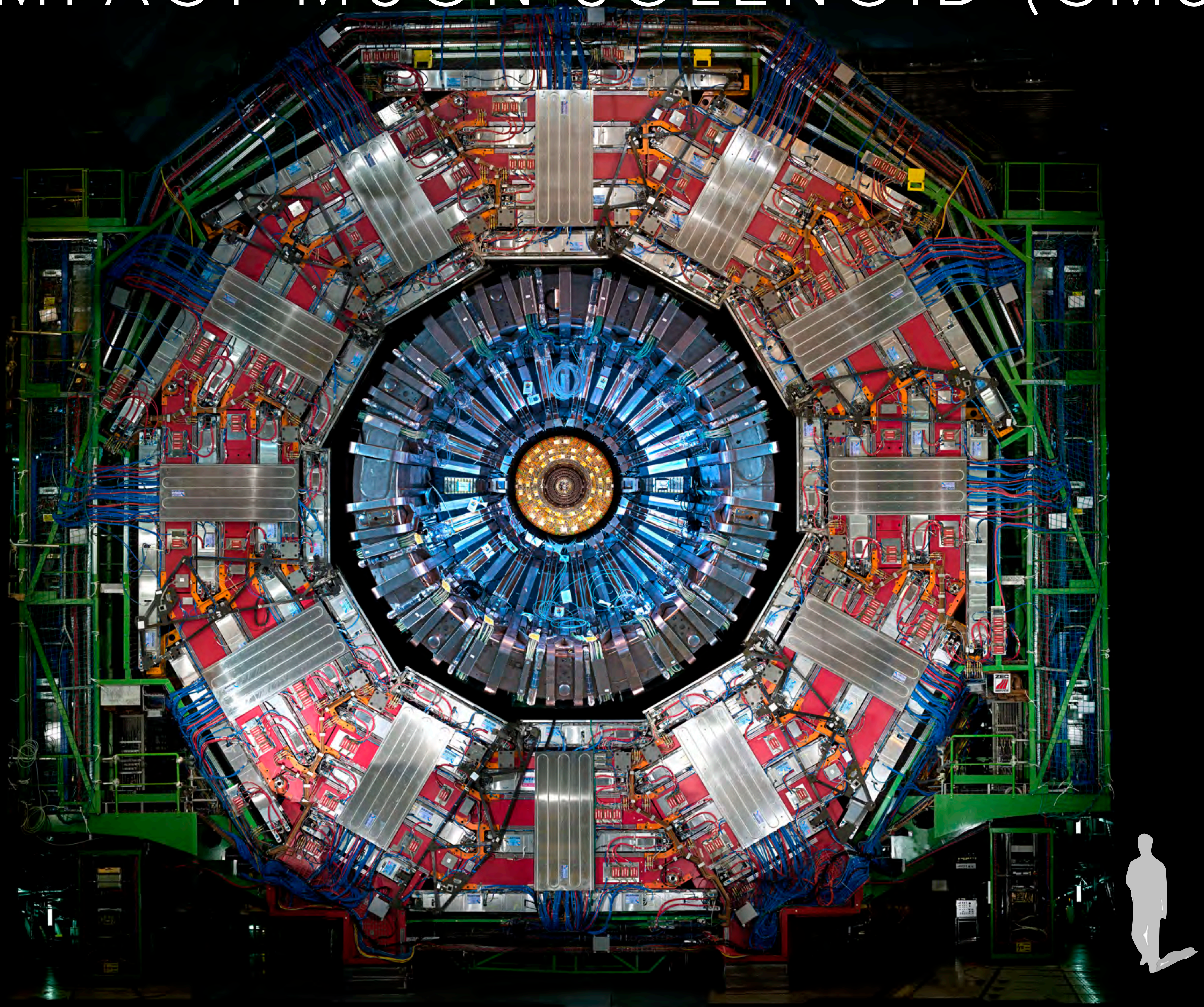
$$\mathcal{L} = \frac{R}{\sigma}$$

2016 pp: ~27 interactions/ bunch crossing



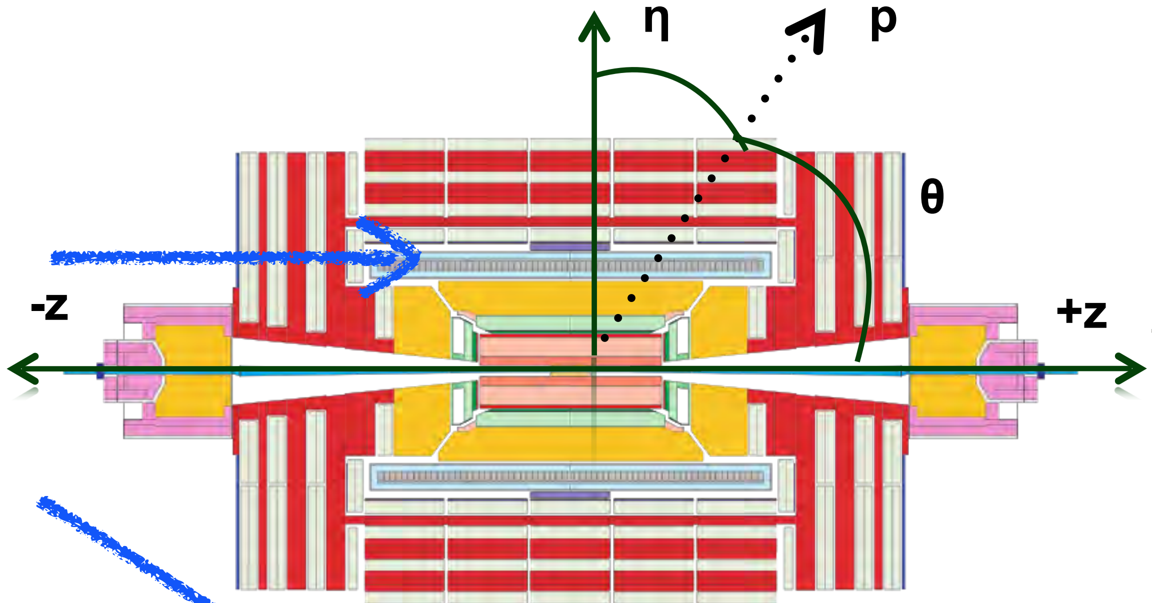


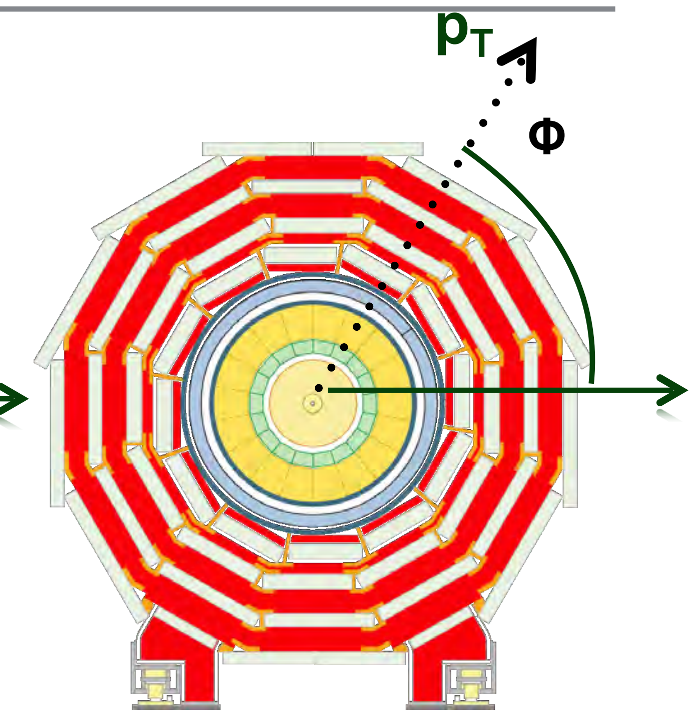
COMPACT MUON SOLENOID (CMS)

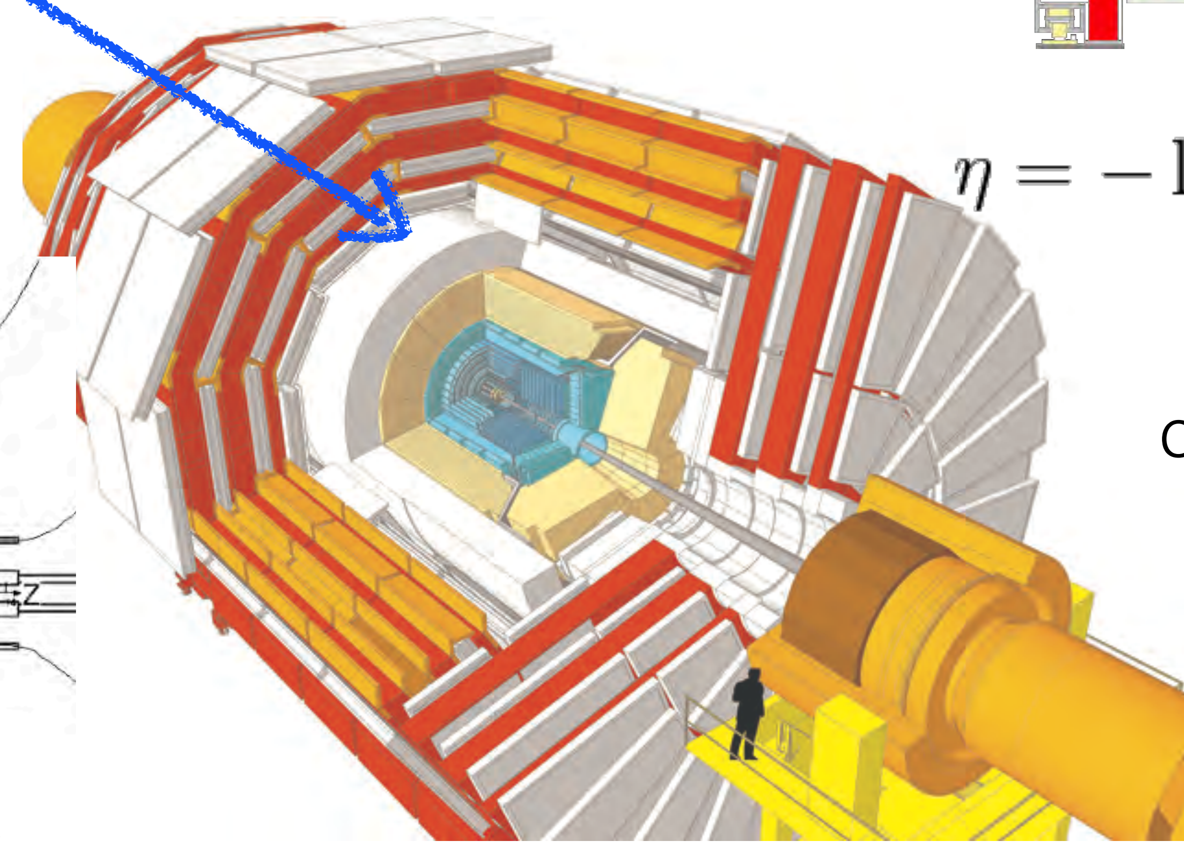


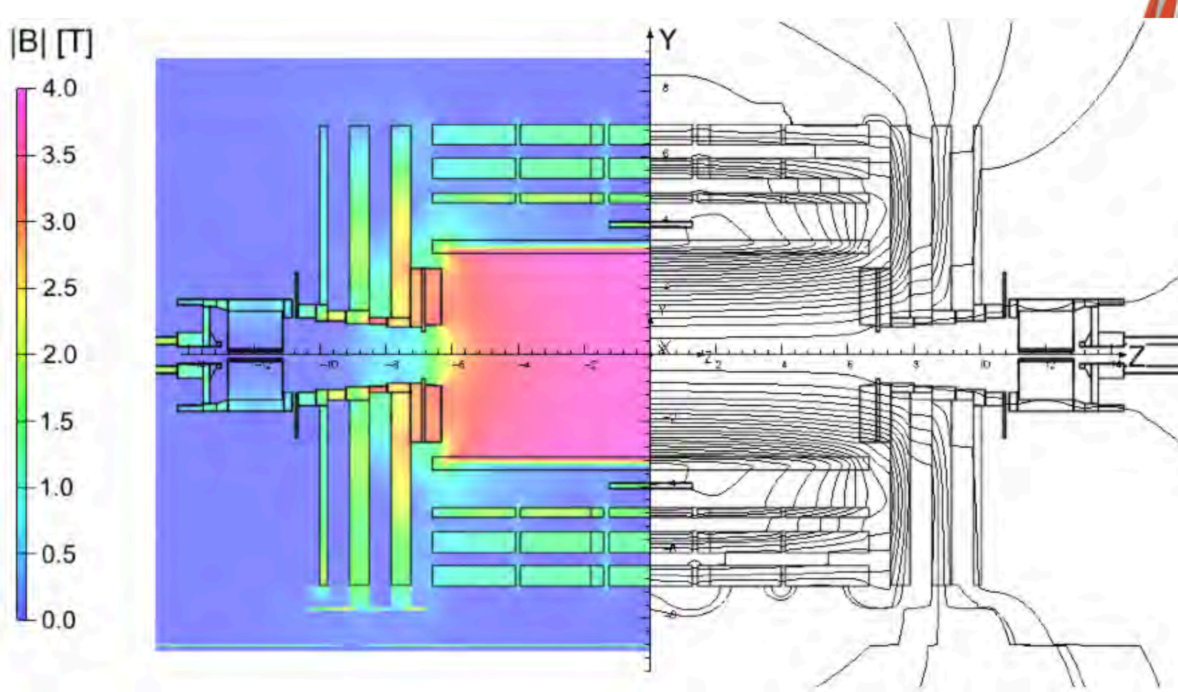
CMS Overview

3.8 T 19.5 kA superconducting solenoid cooled to 4.7K provides magnetic field to measure momenta of particles







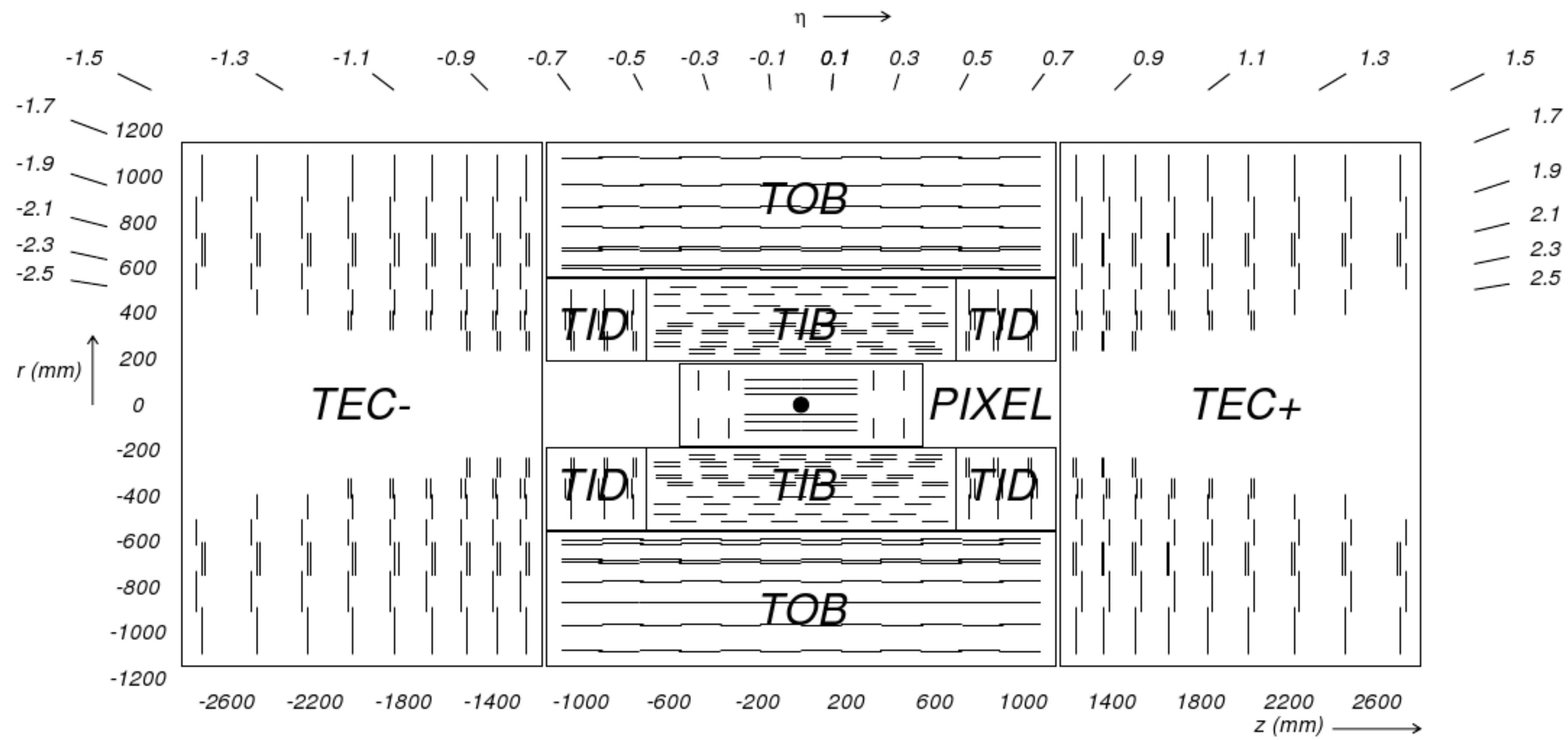


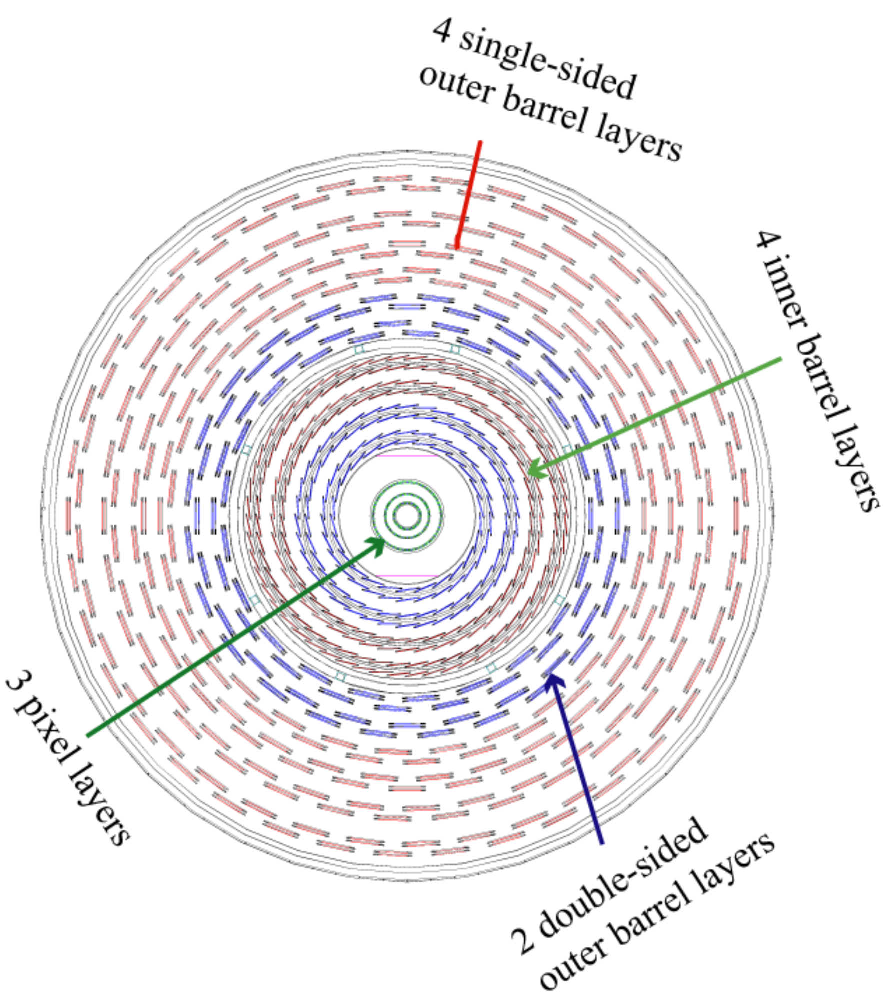
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

Hermetic, calorimeters inside solenoid

Tracker

$$\frac{\delta p_t}{p_t} = \left(\frac{p_t}{TeV} 15\%\right) \oplus 0.5\%$$



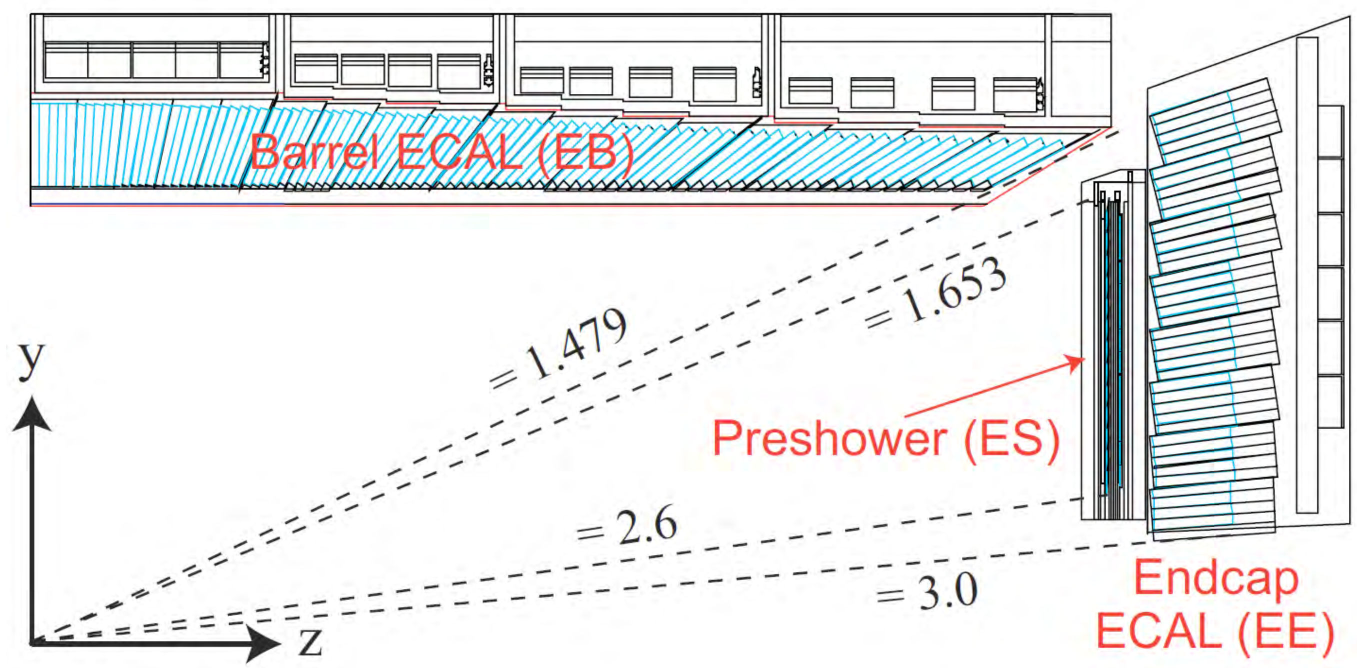


- Silicon tracking system is the first layer within CMS
  - Three pixel barrel layers at 4 cm, 7 cm and 10 cm, and two endcap layers extend to |η|<1.5.
  - The silicon strips outside the pixel extend coverage up to |η|<2.5

Electromagnetic Calorimeter

- Lead tungstate ($PbWO_4$) crystals
  - Measures scintillation light
- Extends up to |η| =3
- **26 radiation lengths**
- Overall resolution
  - Electrons: 0.4% (0.8%) in the barrel (endcaps)
  - Photons: roughly ~2%(~4%) in the barrel (endcaps)

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8}{\sqrt{E}}\right) + \frac{0.12^2}{E} + 0.003^2$$



density	8.28 g cm^{-3}
radiation length	0.89 cm
molière radius	2.2 cm
interaction length	20.27 cm
light yield	~100 γ /MeV

Hadronic Calorimeter

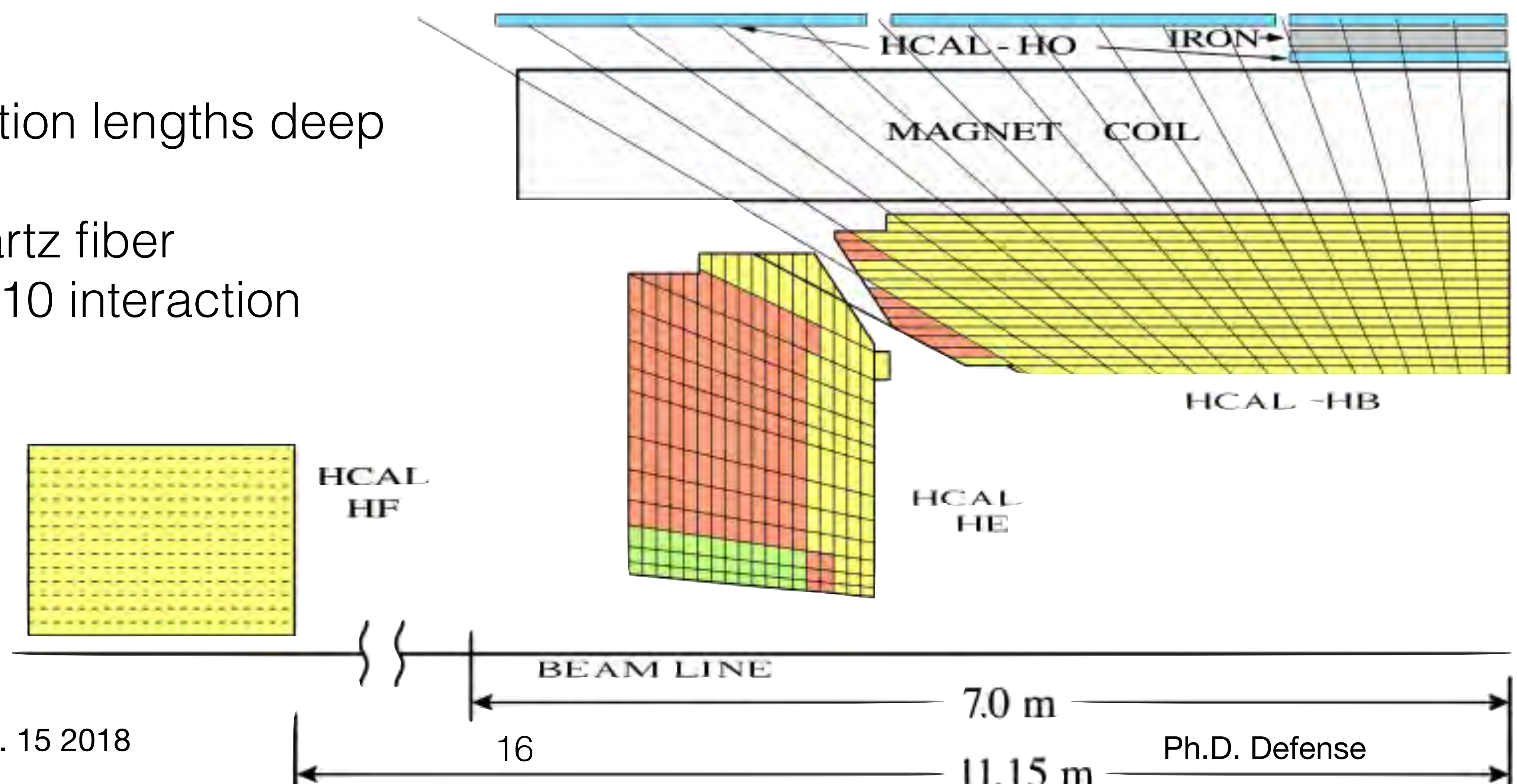
- Extends to |η|<5.2
- Non-ferromagnetic brass absorbers and plastic scintillators for HB/HE
  - 16.42 cm nuclear interaction length, and 1.49 cm radiation length
  - HB is 12 interaction lengths deep
- HF is steel and quartz fiber Cherenkov-based, 10 interaction lengths deep

HB/HE

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{115\%}{\sqrt{E}}\right)^2 + (5.5\%)^2$$

HF

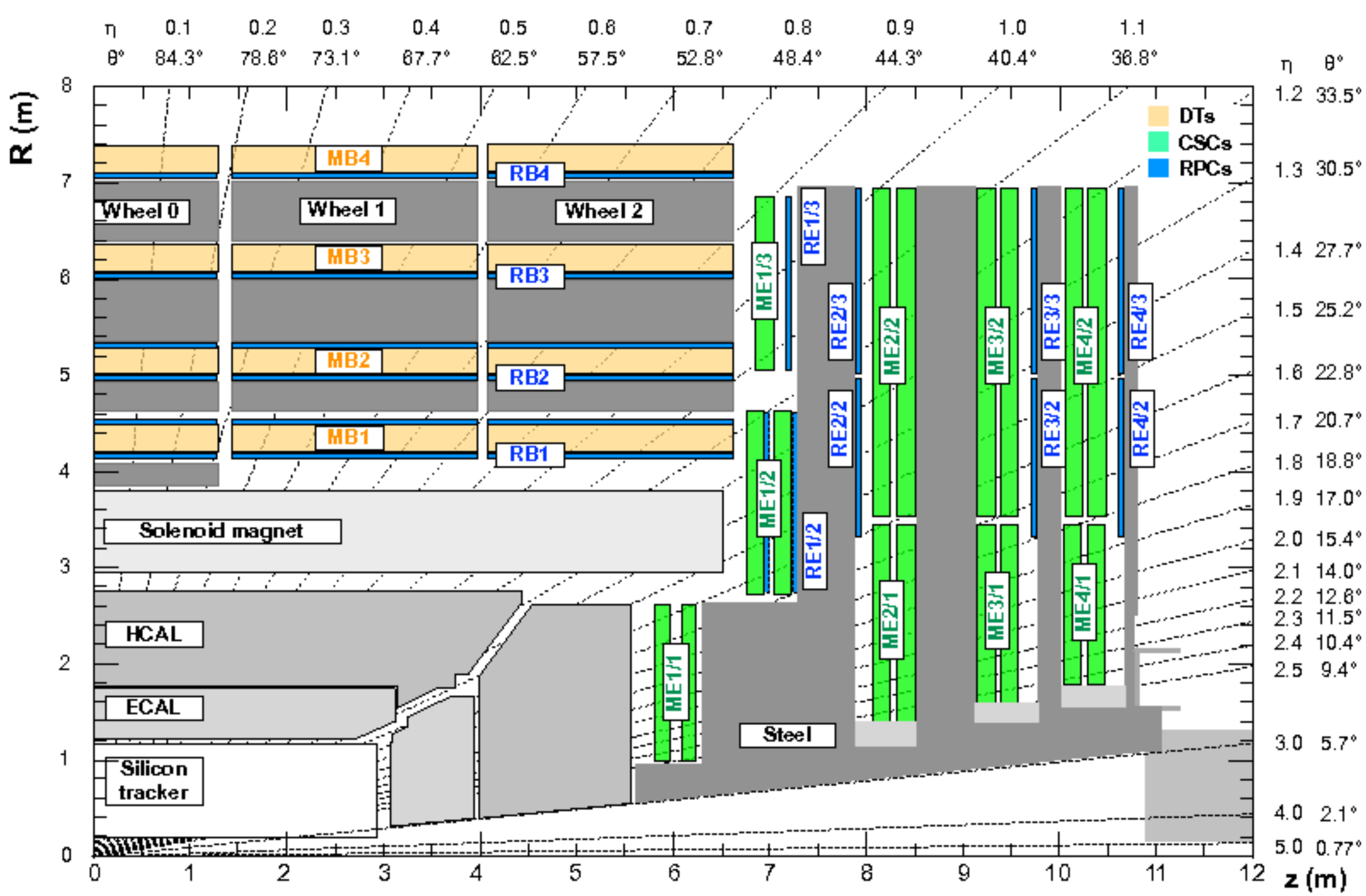
$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{280\%}{\sqrt{E}}\right)^2 + (11\%)^2$$



Muon System

- 1.9 T magnetic field
- Three gaseous chamber technologies until $|\eta|<2.4$
  - drift tubes (DTs), cathode strip chambers (CSCs), resistive plate chambers (RPCs).
- 10% resolution muons $|\eta|<2.4$ and $p_T<200$ GeV muon system only
  - Including the tracker measurement improves resolution to less than 2%

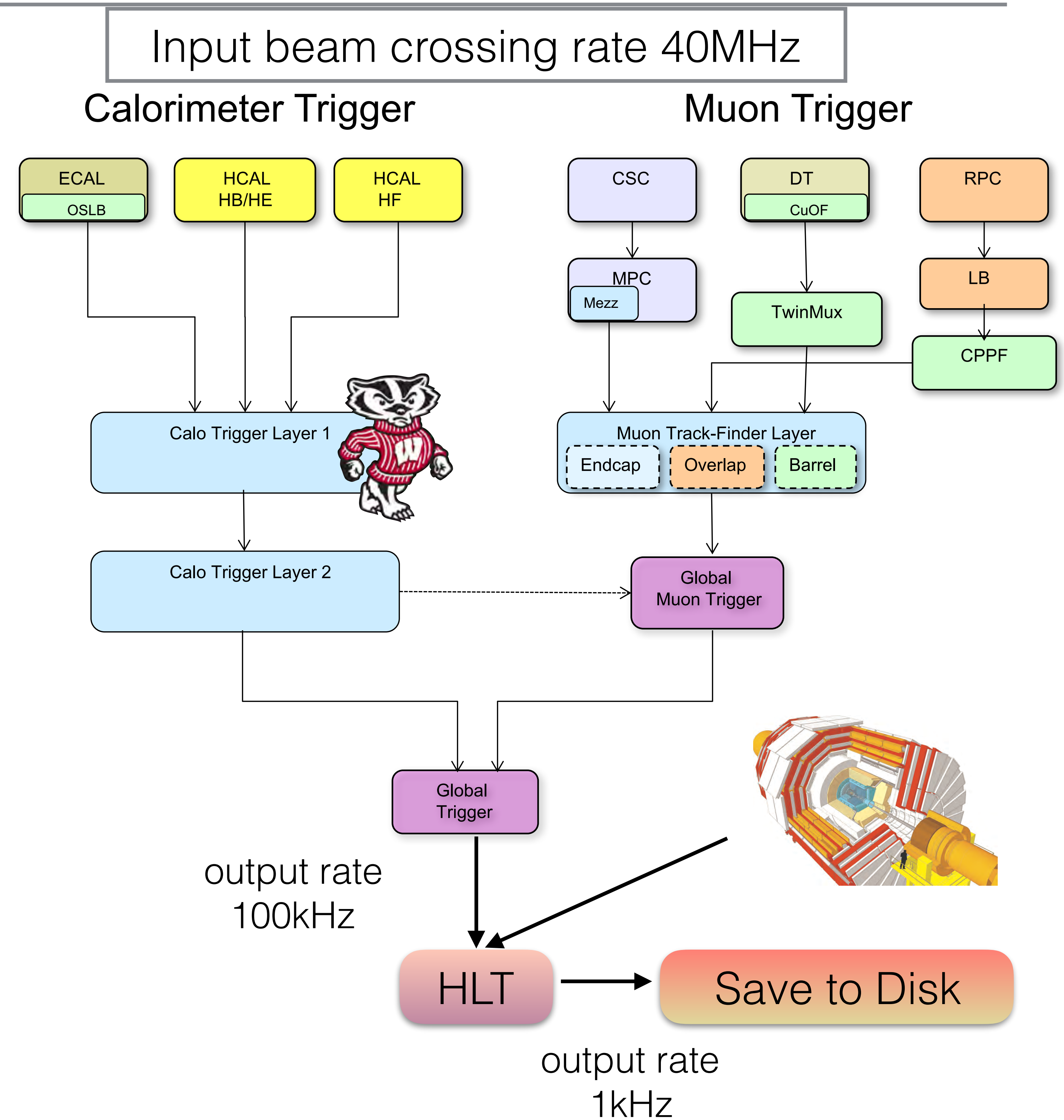
$|\eta|<2.4$ and $p_T>200$ GeV
muon system resolution still ~10%
global fit closer to 5%



CMS Trigger System

- Two level trigger system: hardware-based **Level-1** and software-based **High Level Trigger** (HLT)

single muon trigger	pt>22 or pt>24
single muon + tau	pt(mu) >18 and pt(tau)>20 (tau)>20
single electron	pt >25
double hadronic tau	both pt>35

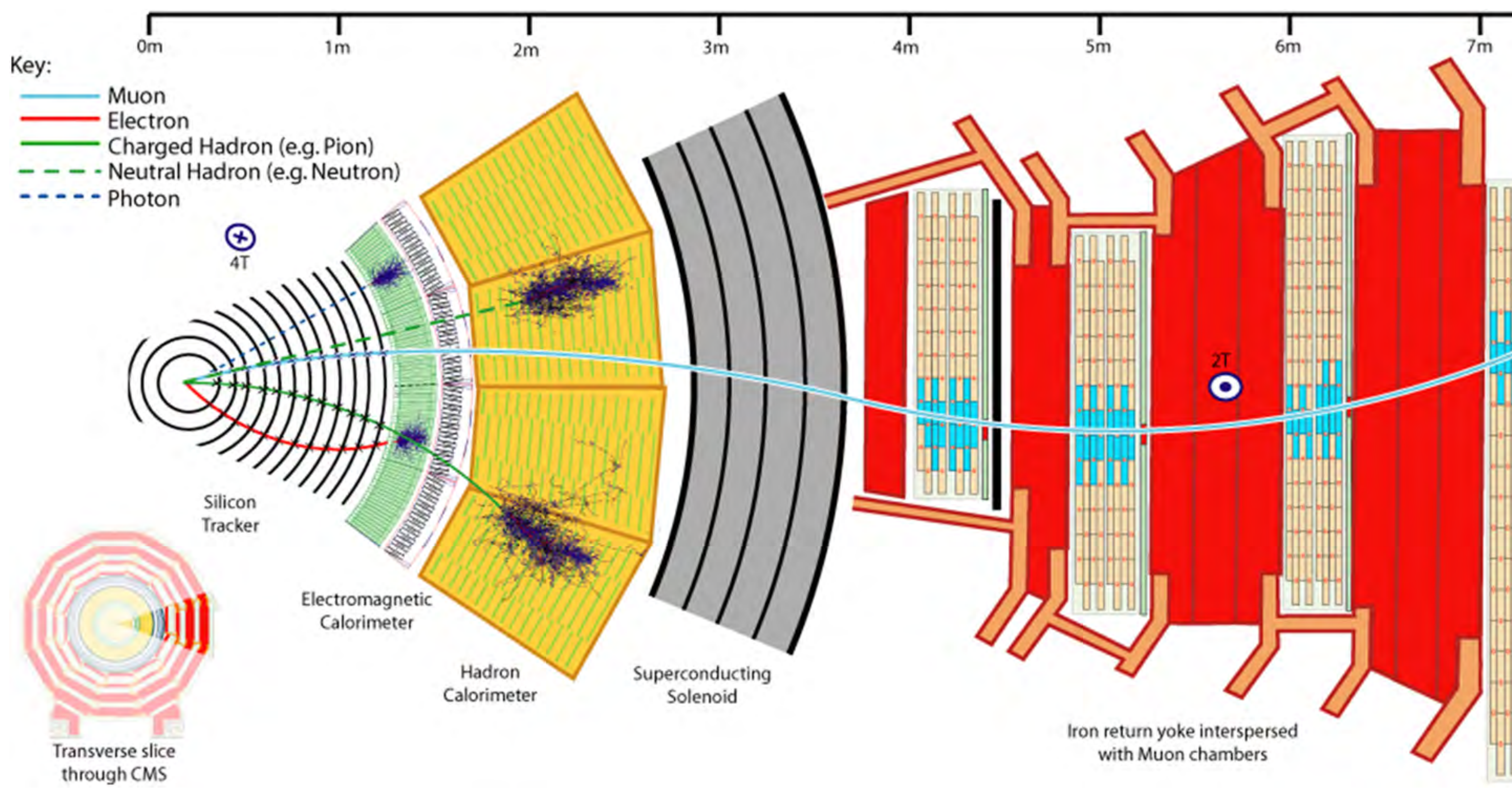


Particle Flow

- Particle Flow (PF) algorithm, used by CMS, links the subsystems together and creates four-vectors for reconstructed physics objects.
  - From tracker hits, muon hits, and calorimeter energy deposits, physics “object” four-vectors are created

PF jets: composed mostly of charged hadrons, photons, and neutral hadrons.

primary vertex: the collision(vertex) from which our objects are linked.



p_T Transverse Momentum

Electron/Muon Identification

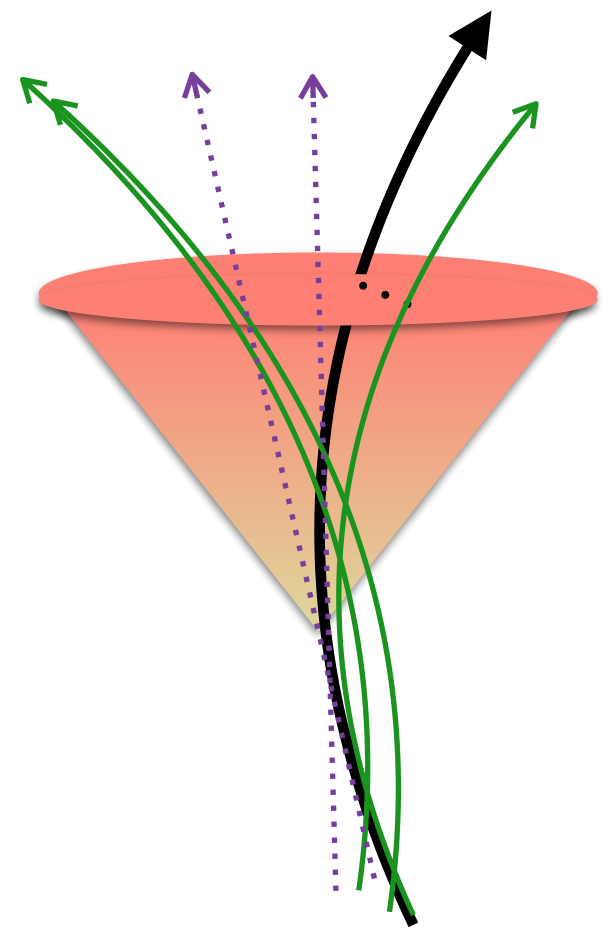
- Muons leave tracks in both the tracker and muon system, with no linked calorimeter deposit
- Muon is identified in both the tracker and the muon system
  - **Muons cut based identification >90% efficient**

- Electrons have a track+ ECAL deposit, with no HCAL/Muon deposits
- MVA based identification
  - **signal electrons: 80% efficiency**

signal isolation cone

charged, neutral

ΔR<0.3 (0.4) for electrons (muons)



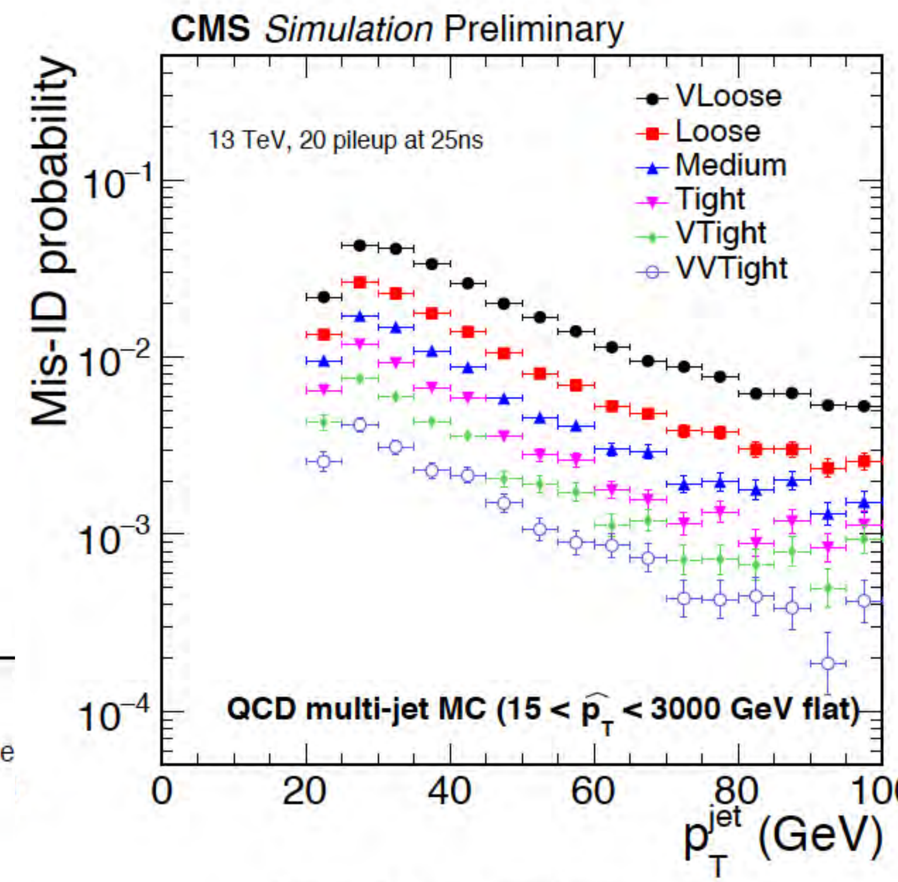
pileup subtraction term

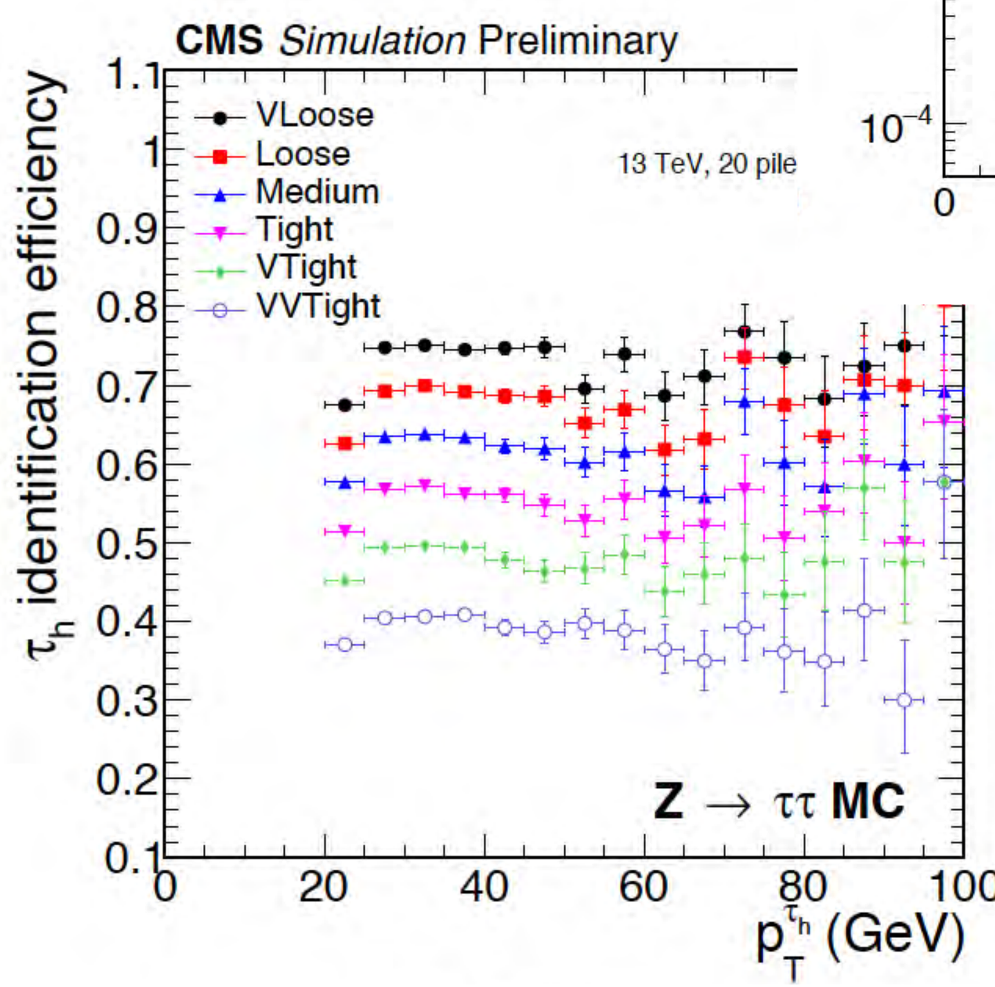
$$I = \left(\sum p_T{}^{\text{charged}} + \max[0, \sum p_T{}^{\text{neutral}} + \sum p_T{}^{\gamma} - 0.5 \times \sum p_T{}^{\text{PU}}]\right)/p_T{}^{l}$$

Hadronic Tau Identification

- 55% of tau lepton decays are hadronic τ_h
- Working point efficiencies and mis-identification probabilities (probability for a jet to fake a tau given loose jet identification requirements)

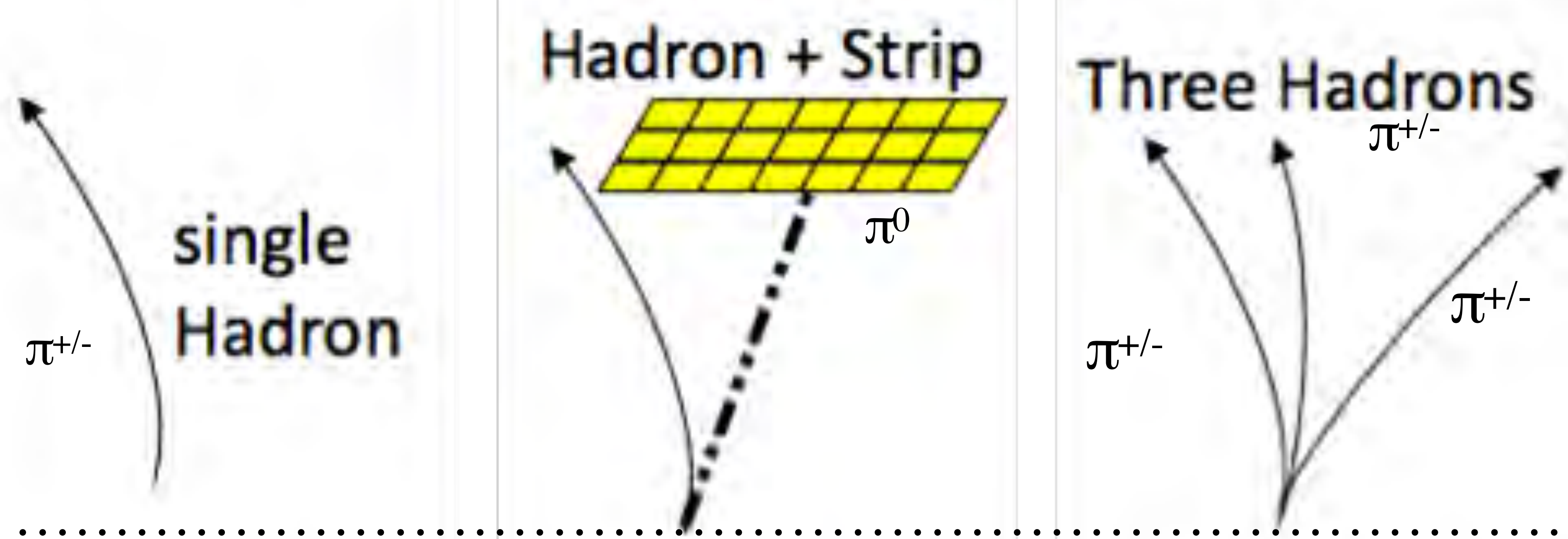
	Eff (%)	Mis-id prob (%)
tight	55	8x10-3
med	60	1x10-2
loose	65	2x10-2
anti-e	80	10-3
anti-mu	90	10-3





Hadronic Tau Reconstruction

- Hadronic taus are seeded from PF Jets with ΔR=0.4
- Hadron plus strips (HPS) algorithm used to reconstruct hadronic taus
- Dynamic strip reconstruction added in 2015, strip size varies



$$f_\eta(p_T) = 0.20 \cdot p_T^{-0.66}$$

$$g_\phi(p_T) = 0.35 \cdot p_T^{-0.71}$$

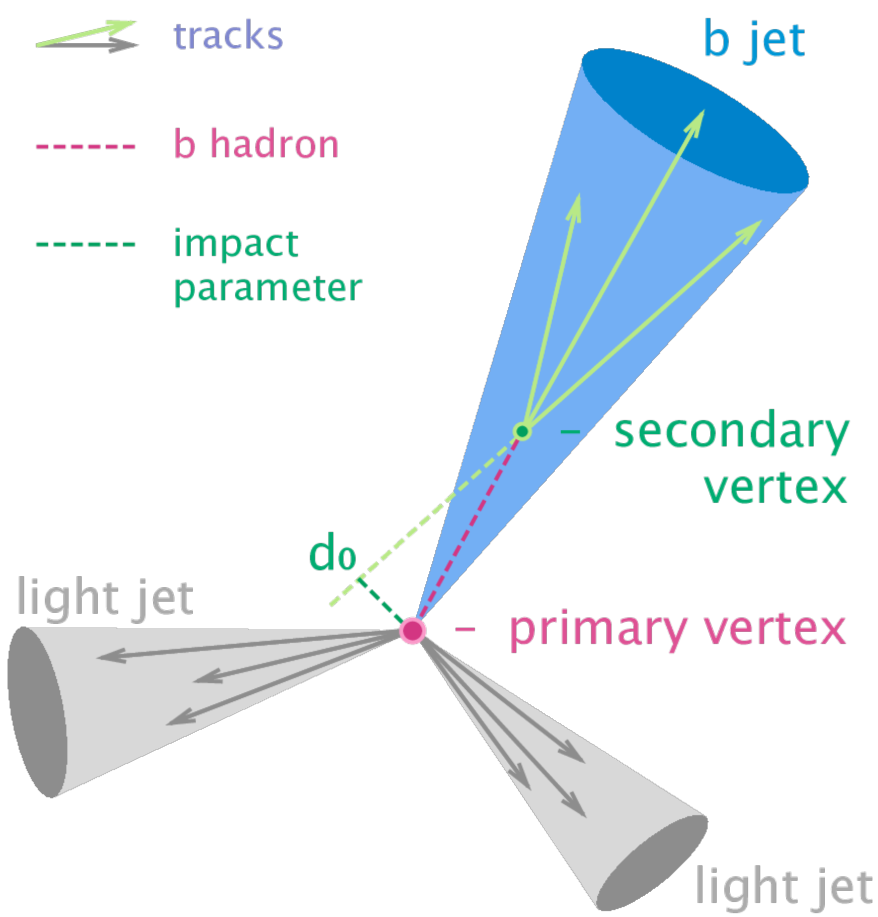
1-prong	1-prong 1-pi0	3-prong	DECAY MODE

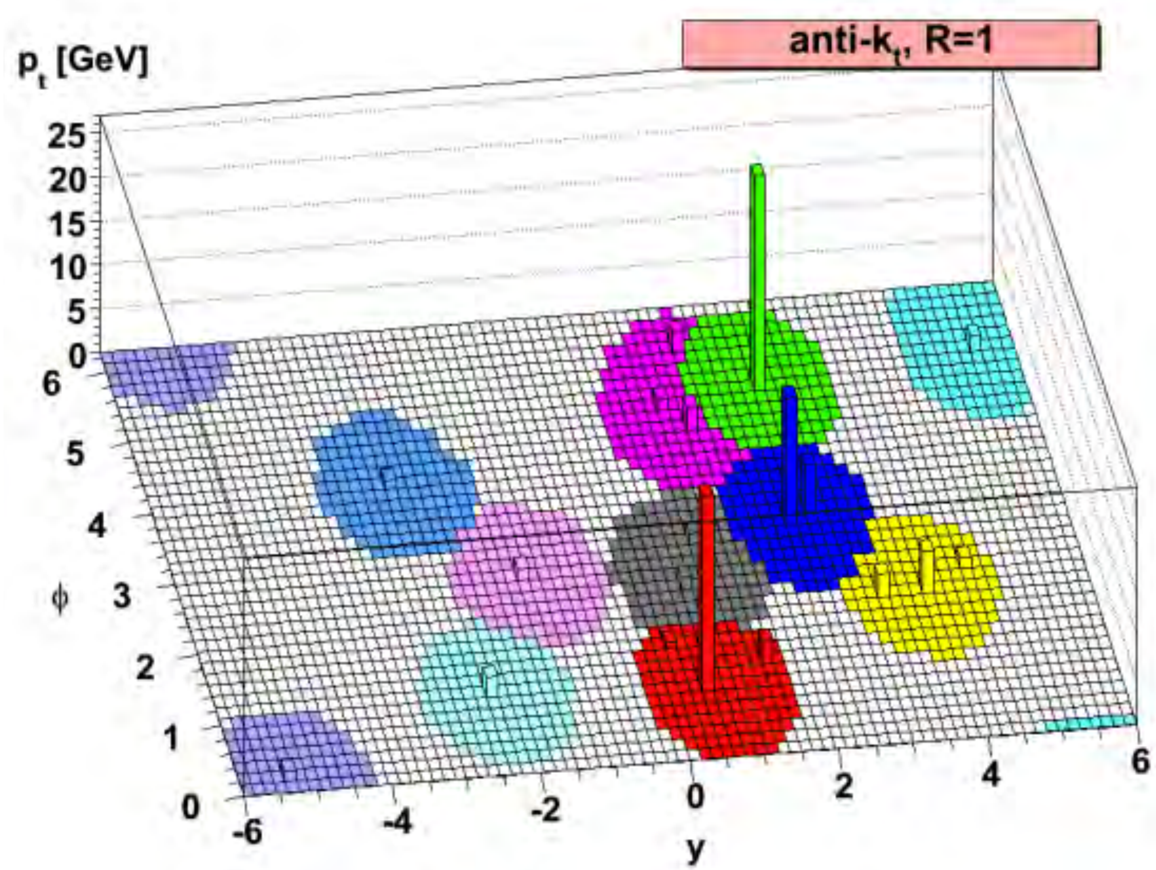
MET and Jet Identification

- PF Jets use the Anti-kt algorithm (AK) that clusters the harder particles first, resulting in more circular jets. Default cone size is ΔR=0.4 . They are further corrected with Jet Energy Corrections (JEC).

- Type-1 missing transverse energy (MET) is the negative sum of the transverse momenta of recalibrated jets, and PF objects (e.g. charged hadrons, electrons, and muons).

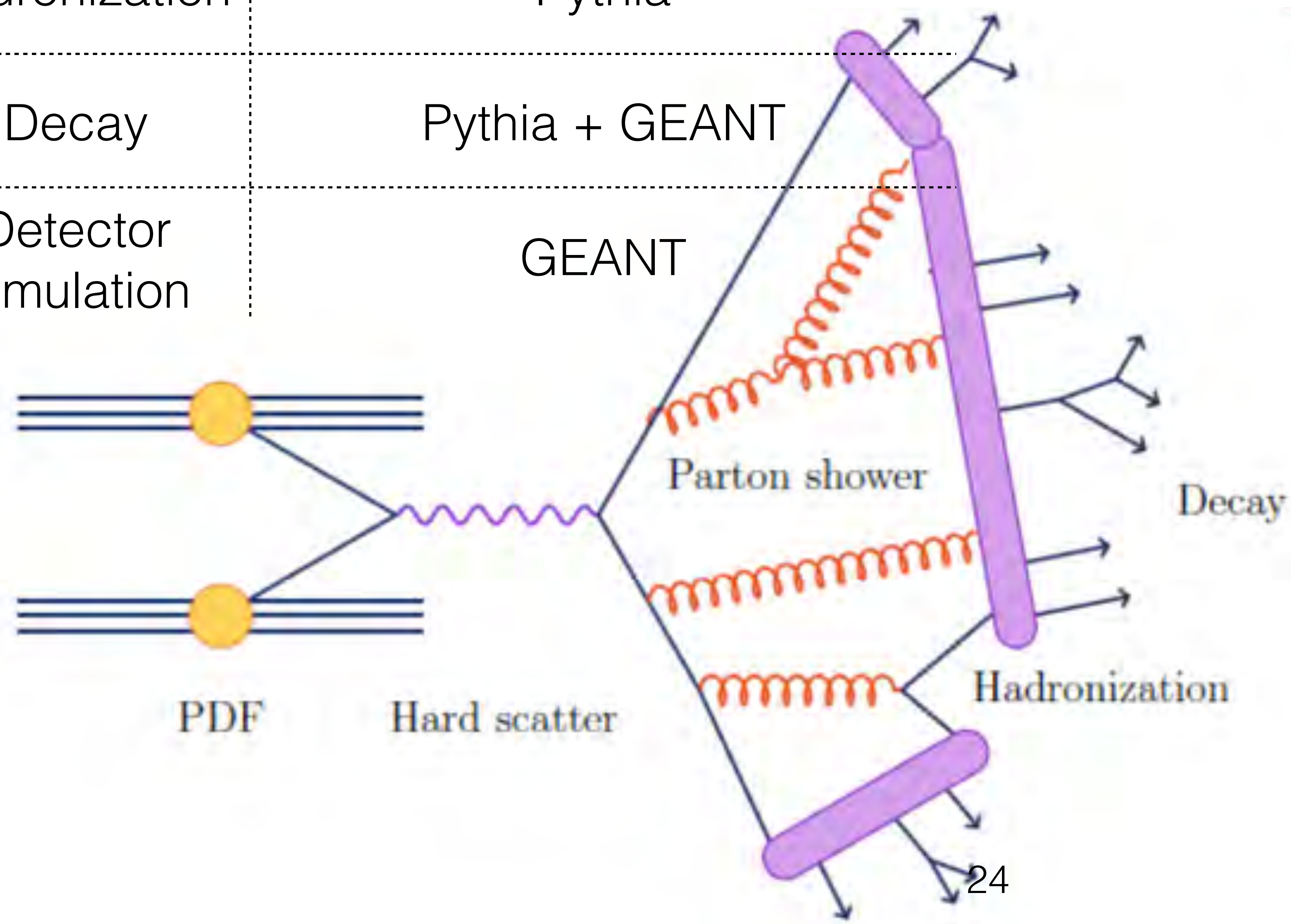
- Jets are tagged as a b quark jet by identifying possible secondary vertices





Simulation and Perturbation

PDF	NNPDF 3.0 and NNPDF3.1
Hard scatter	POWHEG, MadGraph5+aMC@NLO
Parton Shower	Pythia
Hadronization	Pythia
Decay	Pythia + GEANT
Detector Simulation	GEANT

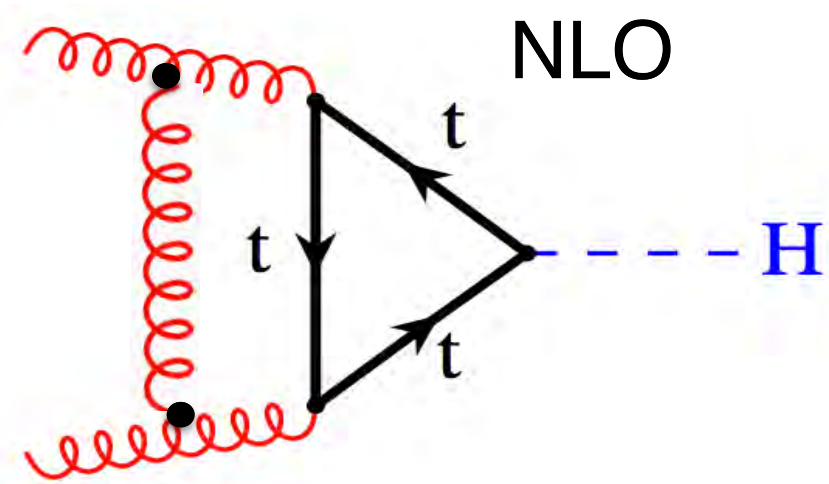


Perturbative expansion of a coupling constant: α<<1

$1 + \alpha + \alpha^2 + \alpha^3$

- Leading order (LO) → α
- Next to LO (NLO) → α^2
- Next to NLO (NNLO) → α^3

example: perturbative QCD NLO



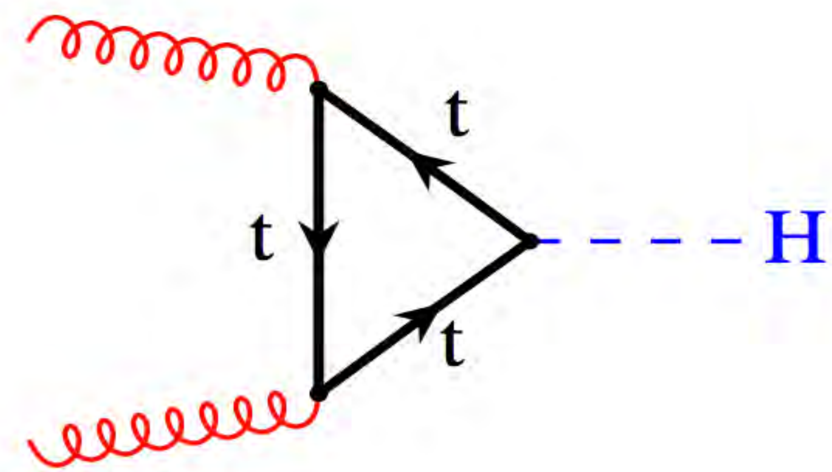
Standard Model
$H \rightarrow \tau\ \tau$

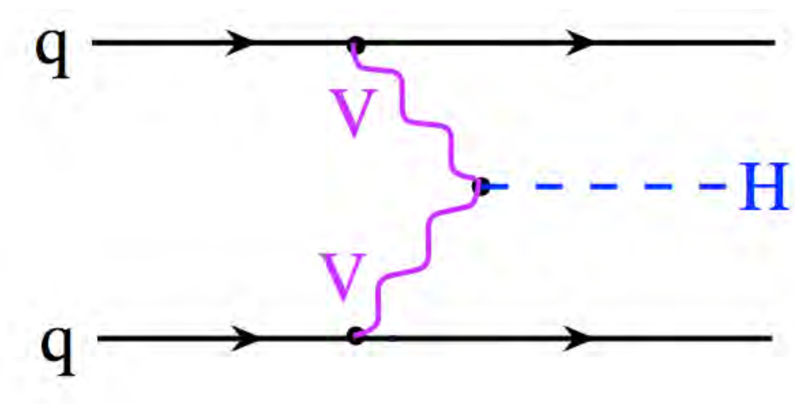
Analysis Overview

- **Goals: Measure coupling strength of Higgs boson to tau leptons.**
- Target **gluon fusion** and **vector boson fusion** productions to measure rate
- Four channels $\tau_e\tau_h$ (denoted $e\tau_h$) , $\tau_\mu\tau_h$ (denoted $\mu\tau_h$), $\tau_h\tau_h$, and $e\mu$
  - **I focus on $e\tau_h$, $\mu\tau_h$, together denoted as $\ell\tau_h$**
  - **Combined $\ell\tau_h$ make up over 50% of analysis sensitivity**
- **Two-dimensional** signal extraction is used:
  - One dimension: invariant **mass** distribution
  - Second dimension: **varies** on targeted production

gluon fusion (ggH)

13 TeV cross section: **48.58 pb**



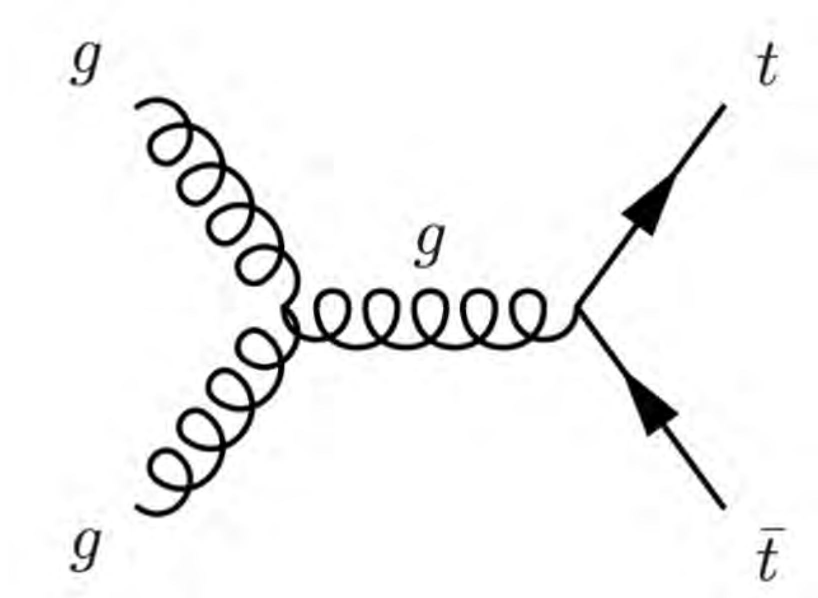


vector boson fusion (vbf)

13 TeV cross section: **3.78 pb**

ττ Backgrounds

and inclusive cross section



$t\bar{t} \rightarrow WbWb$

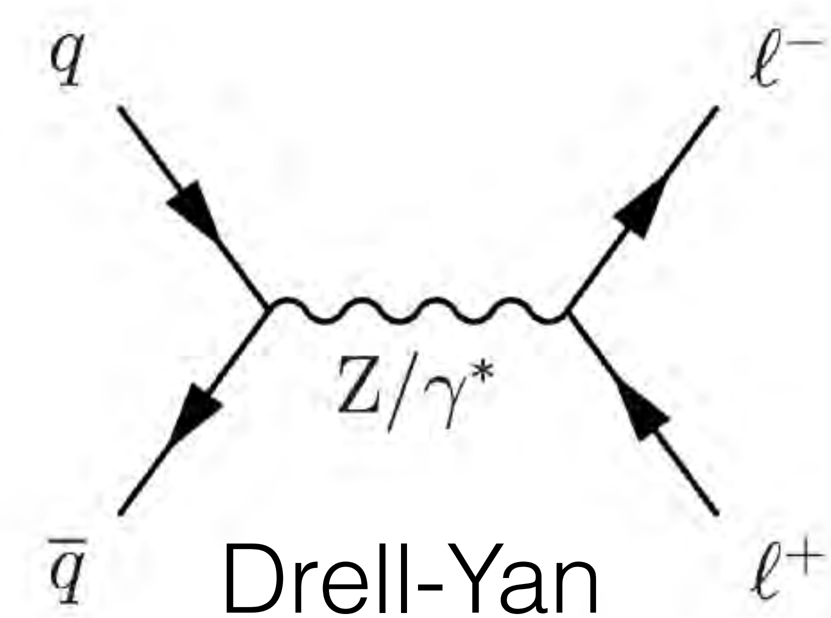
830 pb

ℓ=e,μ,τ

genuine tau background

non-resonant

resonant



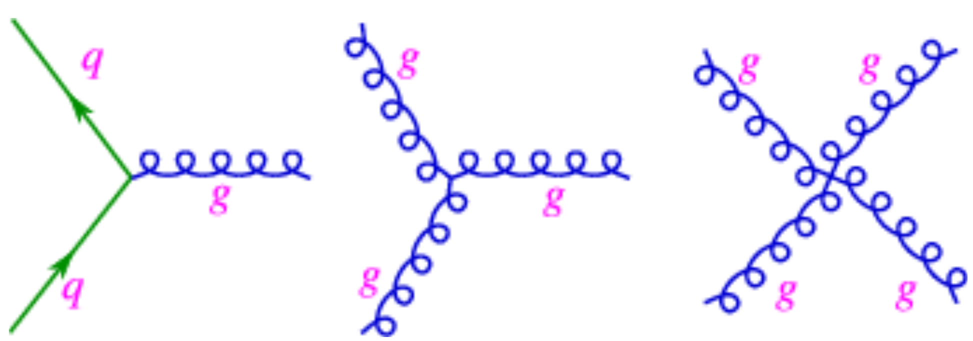
Drell-Yan

$Z \rightarrow \ell\ell$

5700 pb

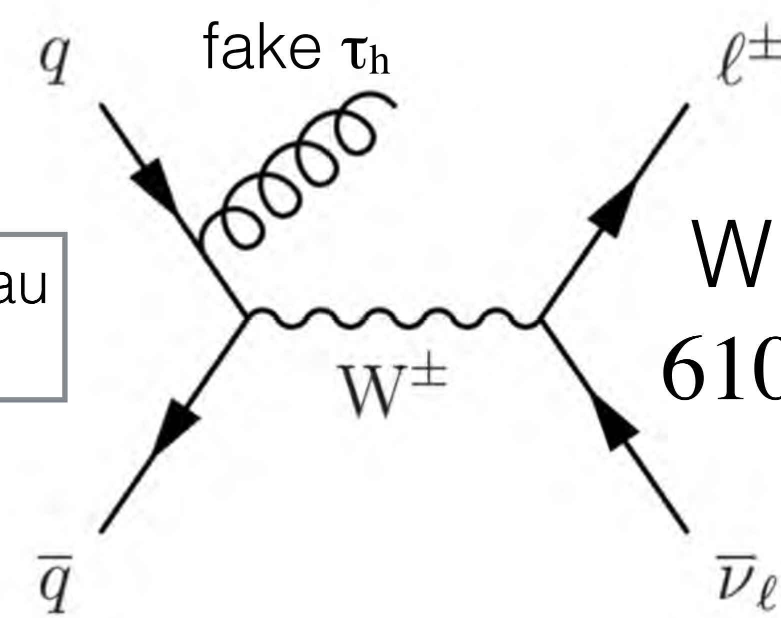
QCD/multijet

~1 mb



mis-reconstructed tau background

fake τ_h



$W \rightarrow \ell\nu$

61000 pb

Kinematic Selections

- Higgs (ττ) final decay products mostly low momentum
  - τ→μ and τ→e decay, majority of the τ momentum to go to neutrinos. Expect falling distribution from 15 GeV.
  - τ→τ_h expect falling distribution from 30 GeV.
  - Kinematic selections chosen to increase acceptance
    - However to reduce fake background, choose pT(τ_h)>30 in all channels

full selection table in thesis

this thesis (applies to the $e\tau_h$ and $\mu\tau_h$ rows)

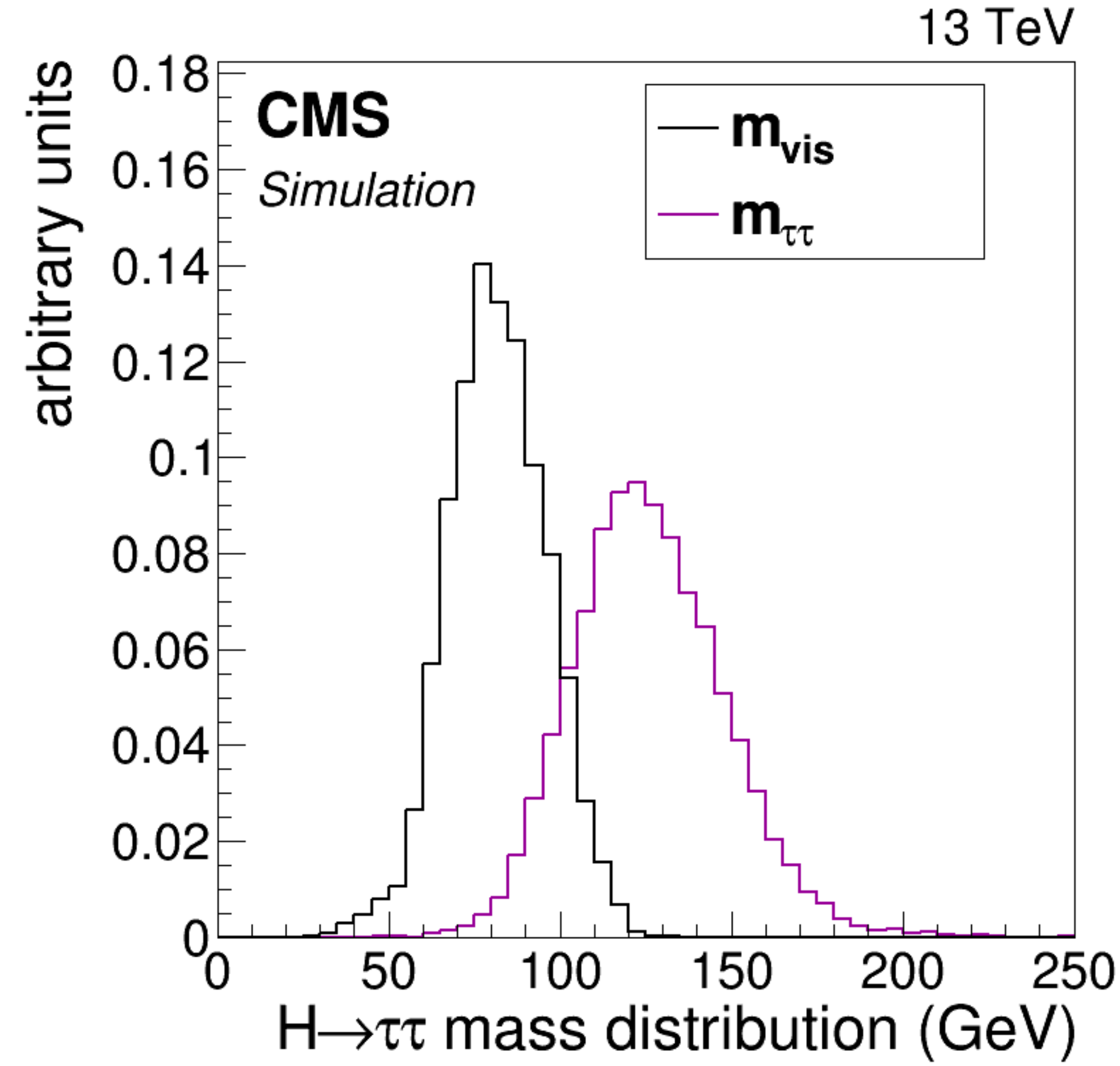
channel	pT
$e\tau_h$	e>26 τ_h>30
$\mu\tau_h$	μ>20 τ_h>30
$\tau_h\tau_h$	τ_h>50 τ_h>40
eμ	e>13(24) μ>24(15)

η within tracker range excluding eμ

Mass Reconstruction ($m_{\tau\tau}$)

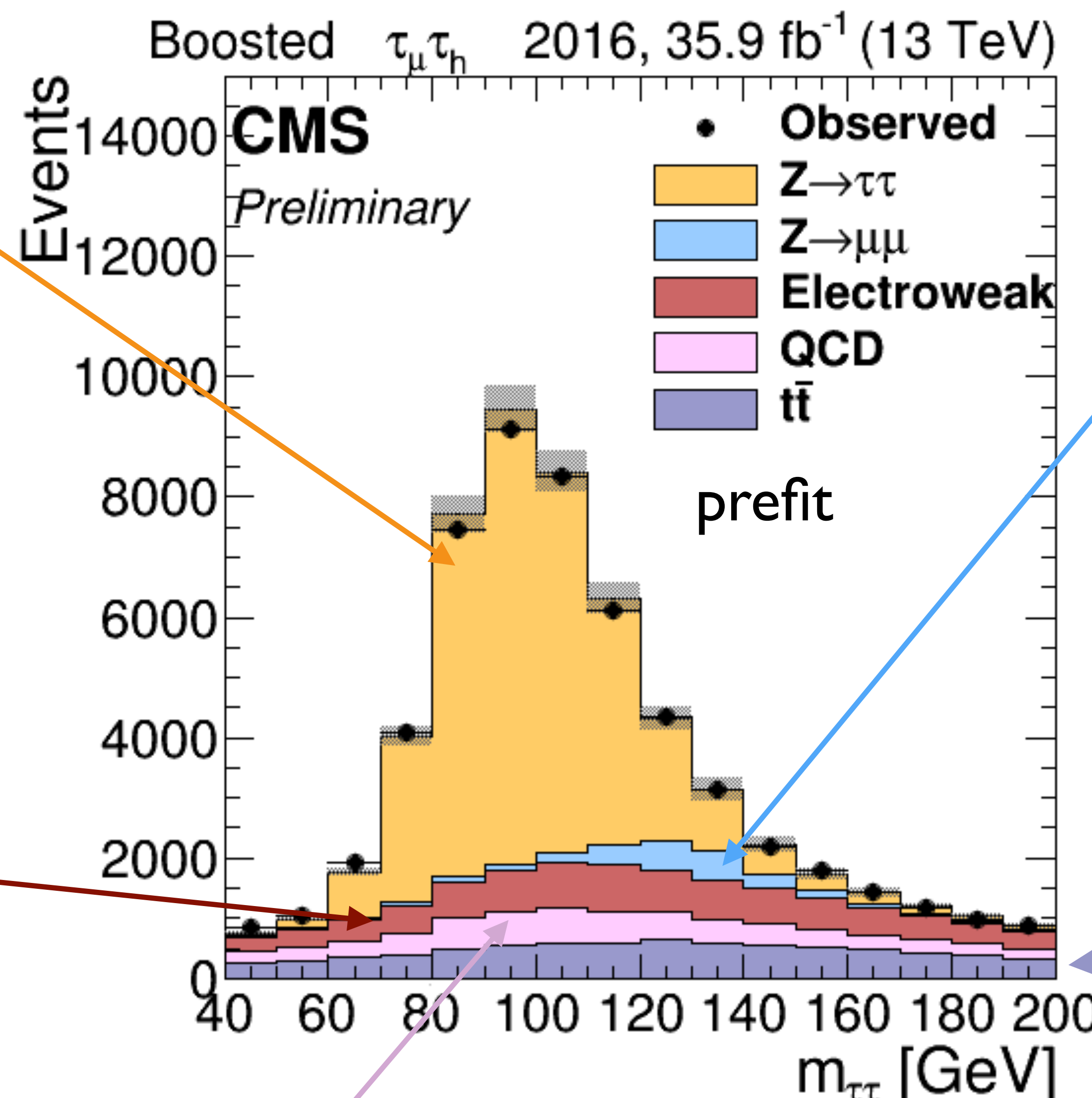
- **The di-tau mass ($m_{\tau\tau}$) is reconstructed using a kinematic fit in most categories**
  - Allows for some separation of $Z\rightarrow\tau\tau$ and $H\rightarrow\tau\tau$, and shifts the $H\rightarrow\tau\tau$ peak to 125 GeV.
- The kinematic fit takes as input: MET, MET uncertainty, each tau candidate's four vector. It assumes all MET in the event is from neutrinos in tau decay.

given all MET in event comes from tau decay, kinematic fit finds most likely original mass of di-tau system and is denoted $m_{\tau\tau}$. Visible mass is m_{vis}.



Background Methods I

Z->ττ simulation: Madgraph Drell-Yan Samples. Corrections derived from highly pure Z →μμ data sample.



DY ℓ->τ fakes simulation: Madgraph Drell-Yan Samples. Corrections derived from highly pure Z →μμ data sample. Additional ℓ->τ fake corrections applied.

W+Jets/diboson: Normalization controlled by data agreement in sideband for ℓτ

QCD: derived from data in sideband region, for ℓτ, ττ, eμ

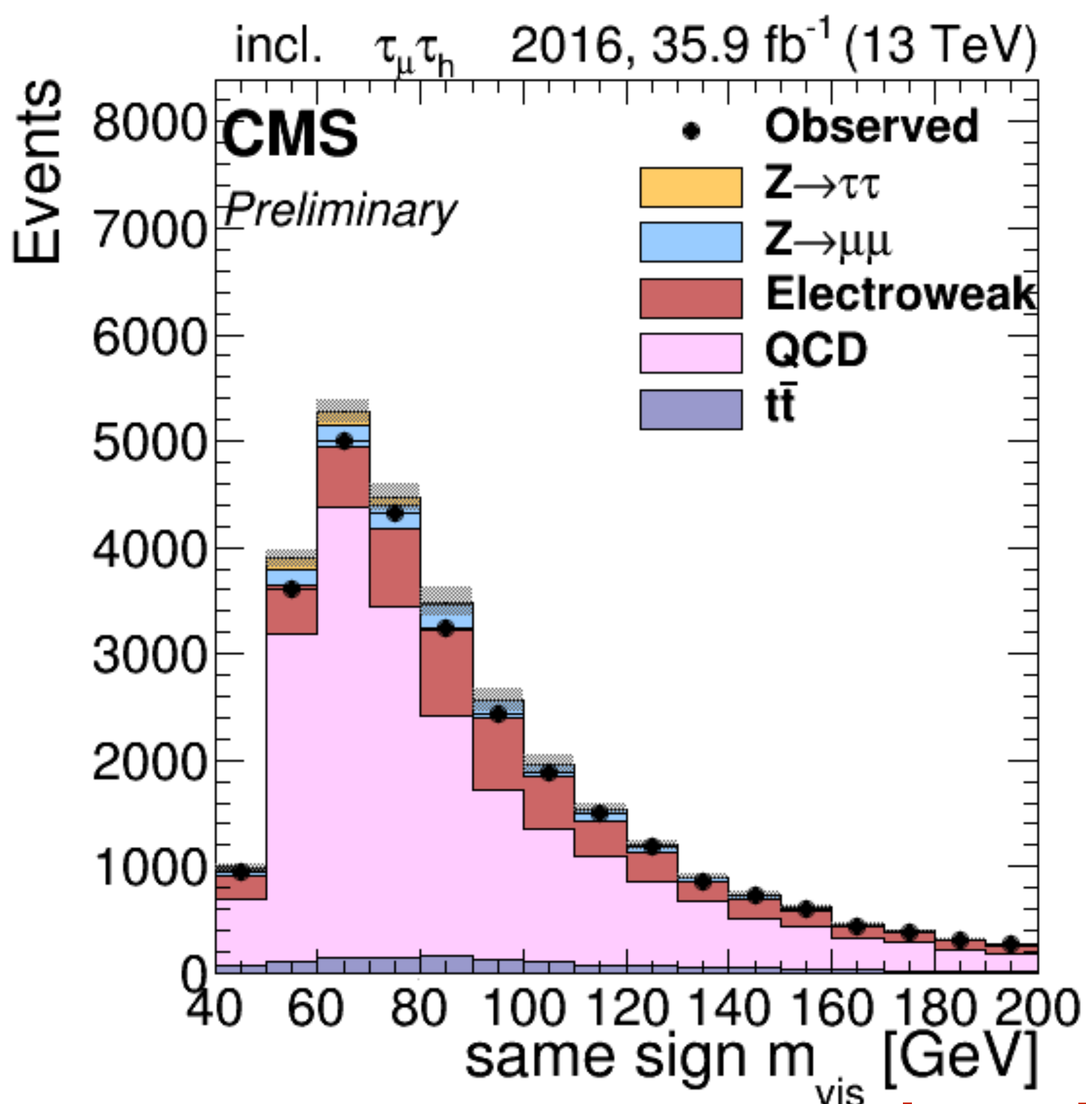
TTbar: NLO MC used. Normalization controlled by data agreement in sideband for all channels

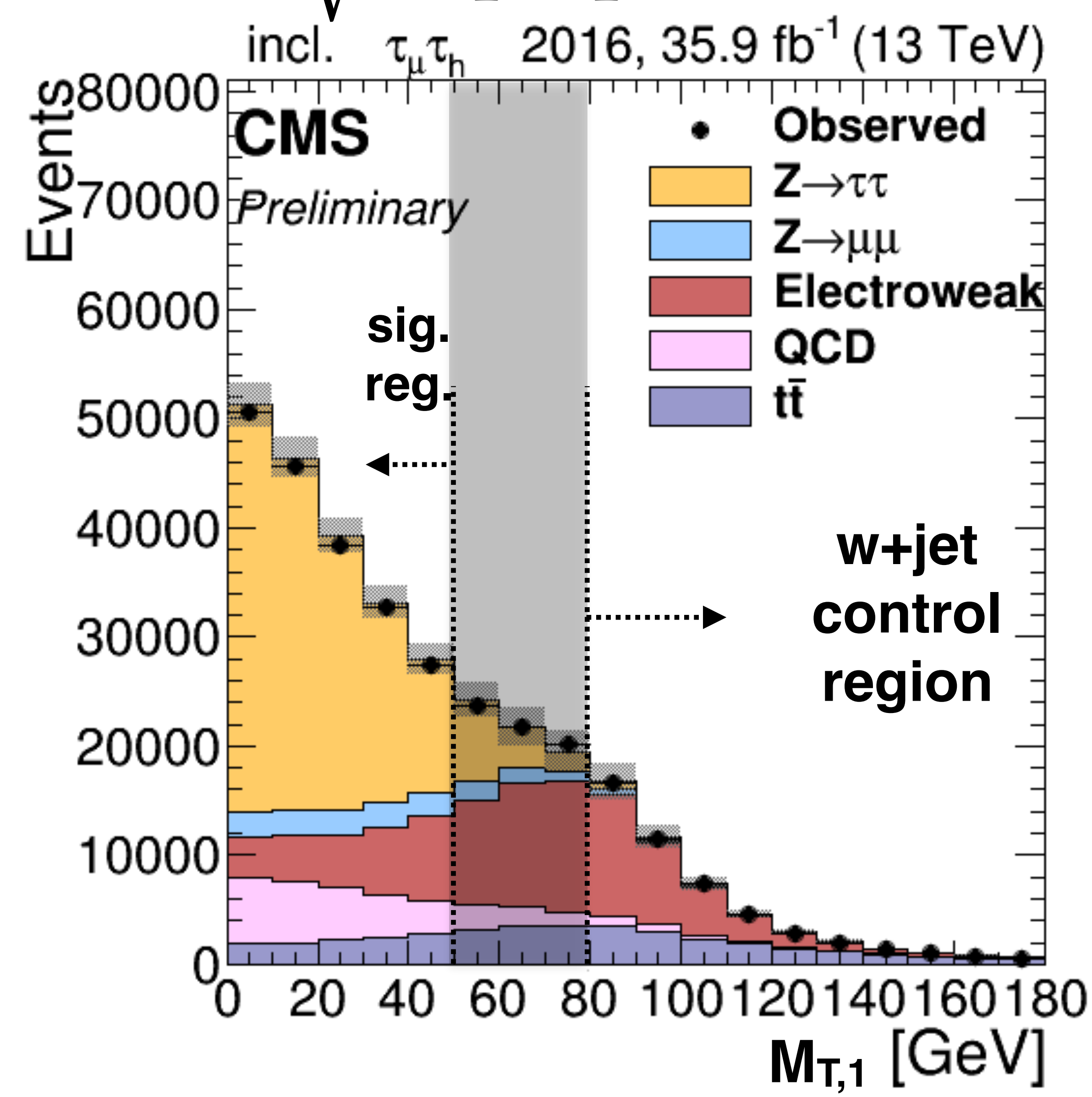
Background Methods II

ℓτ: QCD estimate is taken from same-sign region and scaled by factor to go to opposite-sign region

ℓτ: W+Jets estimate is taken from high $M_{T,1}$

$$M_{T,1} = \sqrt{2p_T^\ell E_T^{miss}(1 - cos(\phi))}$$





we expect no signal in the same-sign region

Event Selection I

- Vetoing extra leptons, and requiring well-isolated objects results in the largest decrease in events.

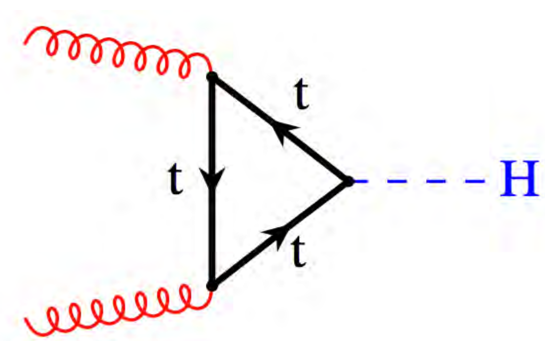
  - Next the $M_{T,1}$<50 GeV cut is applied

Looking for 109.9 events out of 492668 observed events

Process	$\mu\tau_h$ Events	$e\tau_h$ Events
Dataset/Trigger	786751488	942127424
Extra Lepton Veto and OS tau pair	9731414	6141090
Tight lepton identification	845627	343863
$M_{T,1} < 50$ GeV	492668	171301
Total expected VBF contribution	109.9	39.6
Total expected ggH contribution	1140.7	356.0

Event Selection II

- Expect **roughly 0.2% of collected events are from gluon fusion and vector boson fusion:** 1650 expected signal with 664000 expected background
- Need to increase sensitivity further, define 3 categories: **0jet (targets ggH), boosted (targets ggH), vbf (targets VBF).**

0jet	no jets with pT>30 GeV
vbf	≥2 jets with pT>30 GeV m_{jj}>300 GeV pT(ττ)>50 GeV pT(μ)>40 GeV ($\mu\tau_h$ only)
boosted	***>0 jets and not VBF*** 

Observed Events

Categorization helps separate ggH and VBF signal.
Look at $m_{\tau\tau}$ and m_{vis} distributions for shape discrimination

Process	$\mu\tau_h$ Events	$e\tau_h$ Events
Observed $M_T < 50$ GeV	492668	171301
Observed 0-jet	128571	41160
Observed boosted	60127	21250
Observed vbf	2927	2088
Total expected VBF events	109.9	39.6
exp. 0-jet	5.74	1.77
exp. boosted	58.3	18.5
exp. vbf	29.5	16.9
Total expected ggH events	1140.7	356.0
exp. 0-jet	569.1	187.2
exp. boosted	359.8	130.6
exp. vbf	31.2	18.1

Looking for
29.5 events out of
2927 observed events

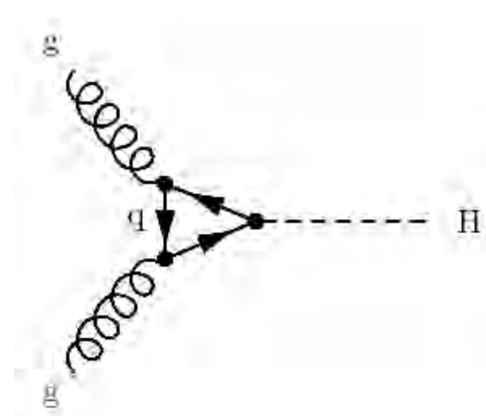
H$\tau\tau$ 2D Categories

	$\tau_h\tau_h$	$\mu\tau_h$	$e\tau_h$	$e\mu$
0jet	$m_{\tau\tau}$	m_{vis}:τ DM	m_{vis}:τ DM	m_{vis} : μ pT
boosted	$m_{\tau\tau}$: H pT	$m_{\tau\tau}$: H pT	$m_{\tau\tau}$: H pT	$m_{\tau\tau}$: H pT
vbf	$m_{\tau\tau}$: m_{jj}	$m_{\tau\tau}$: m_{jj}	$m_{\tau\tau}$: m_{jj}	$m_{\tau\tau}$: m_{jj}

and 12 addl' sidebands for norm. of bkgs.

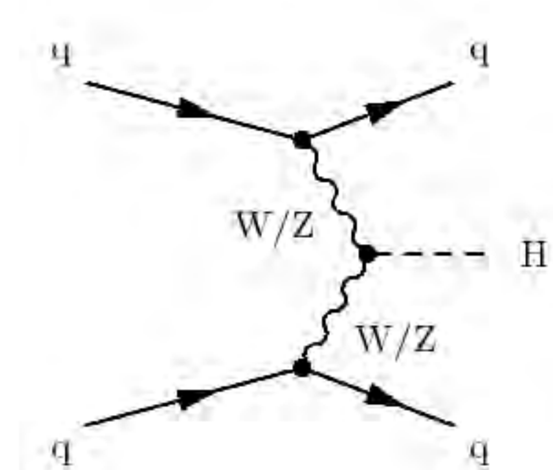
has better separation of fakes in visible mass (m_{vis}) and tau decay mode (τ DM): next slide

The signal/background increases as a function of total higgs pT (H pT)



$$p_T^{\tau\tau} = |\vec{p_T^L} + \vec{p_T^{L'}} + \vec{E}_T^{miss}|$$

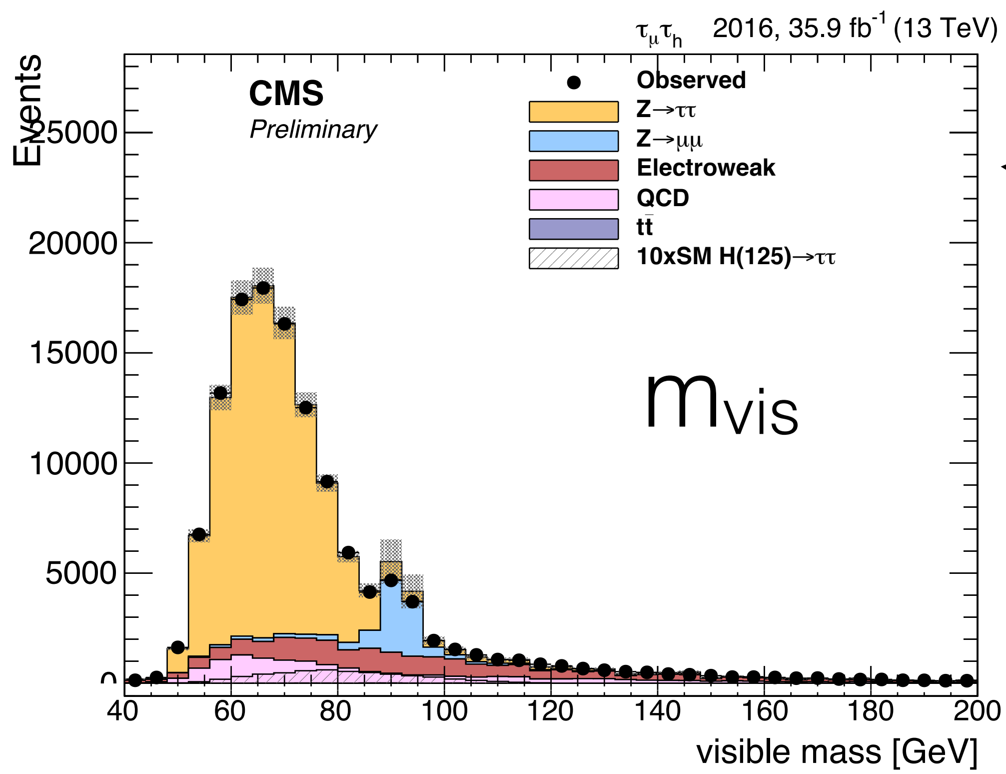
The signal/background increases as a function of leading di-jet invariant mass m_{jj}



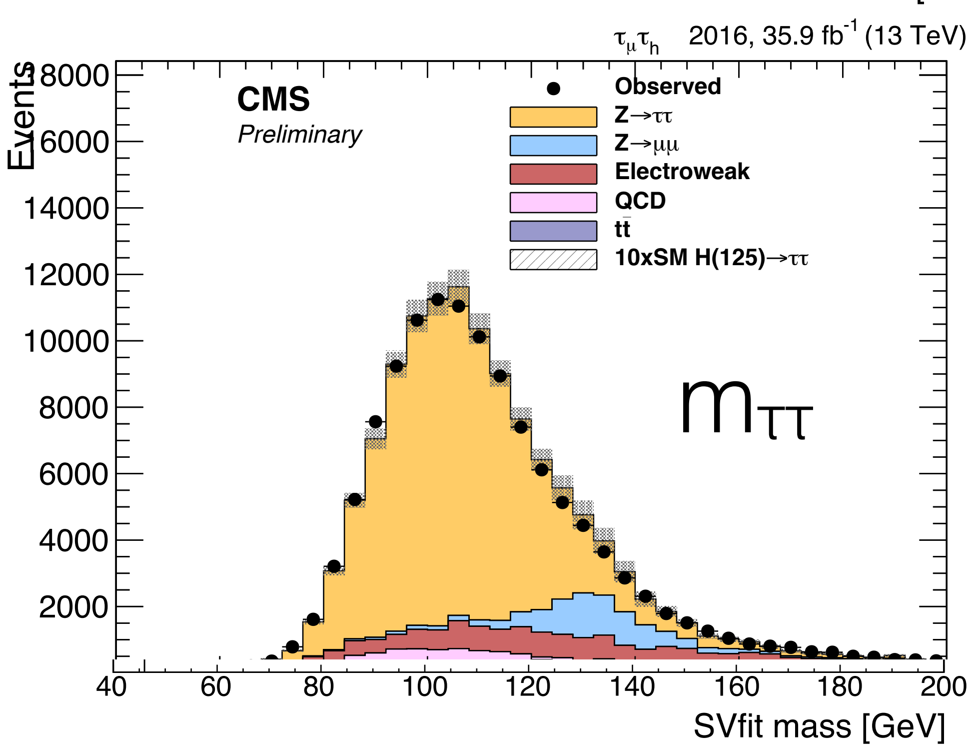
visible mass: tau decay mode

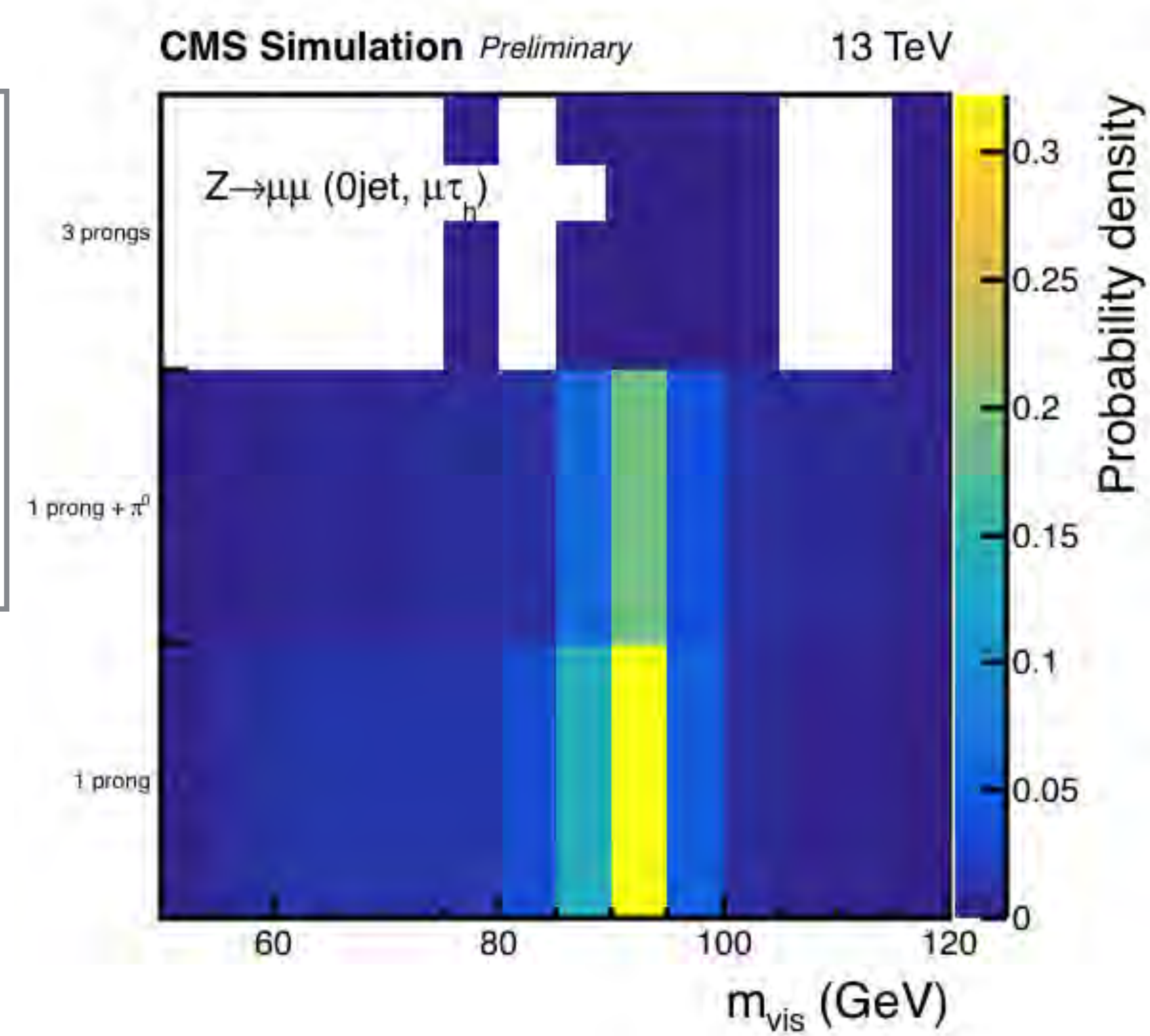
	ττ	μτ	eτ	eμ
0jet	$m_{\tau\tau}$	m_{vis}:τ DM	m_{vis}:τ DM	$m_{\tau\tau}$: μ pT

very few μ->τ fakes in 3 prong, higher S/B
use tau decay mode



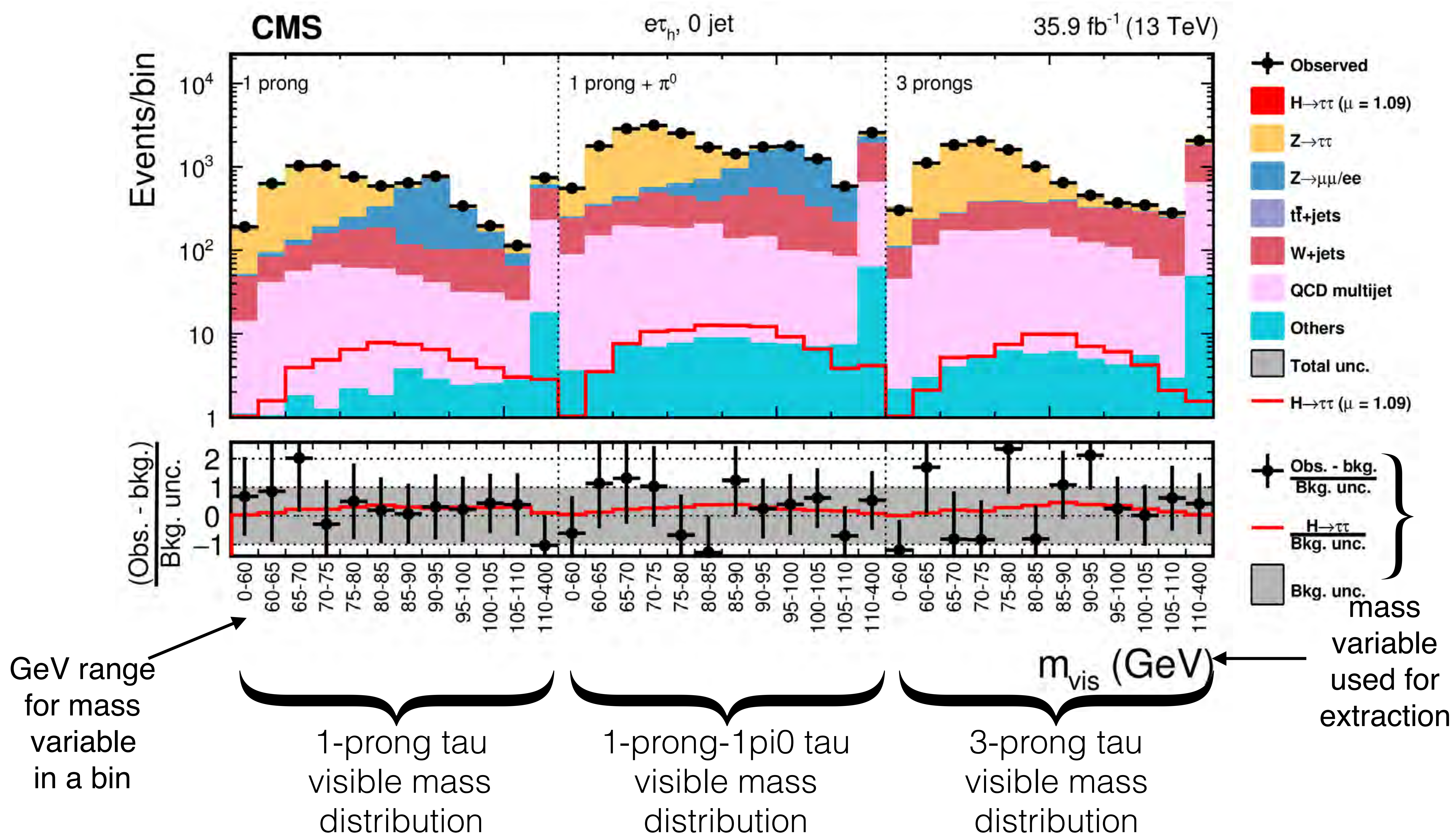
0jet:
better Z →μμ separation in **visible mass** than a kinematic fit





2D Distribution

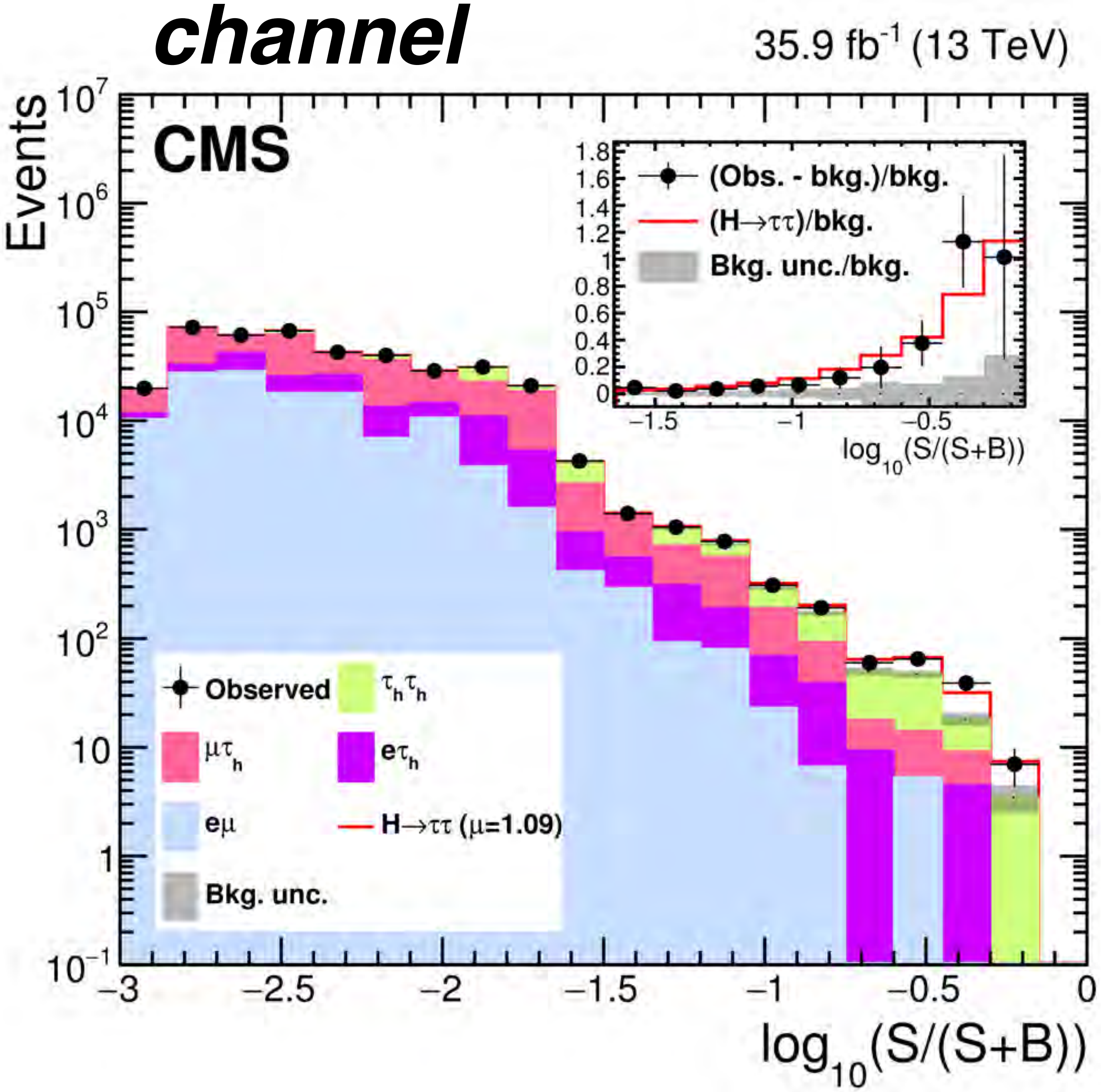
"0jet eτ visible mass versus tau decay mode"



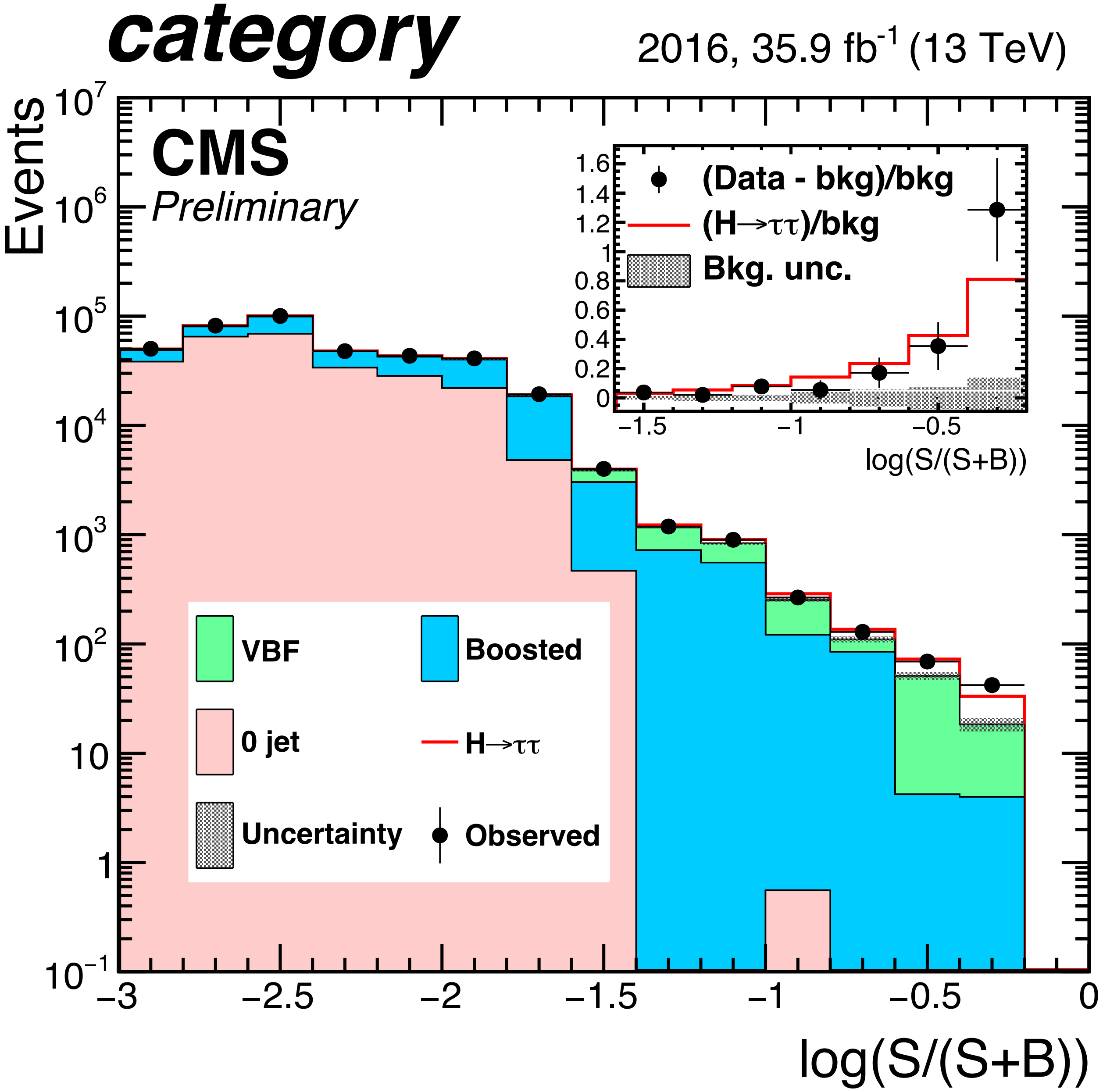
Channel and Category

- The SM Higgs excess is seen when sorted by significance of each bin
- VBF is the most sensitive category; $\mu\tau_h$ $e\tau_h$ are second and third significant channel.

channel

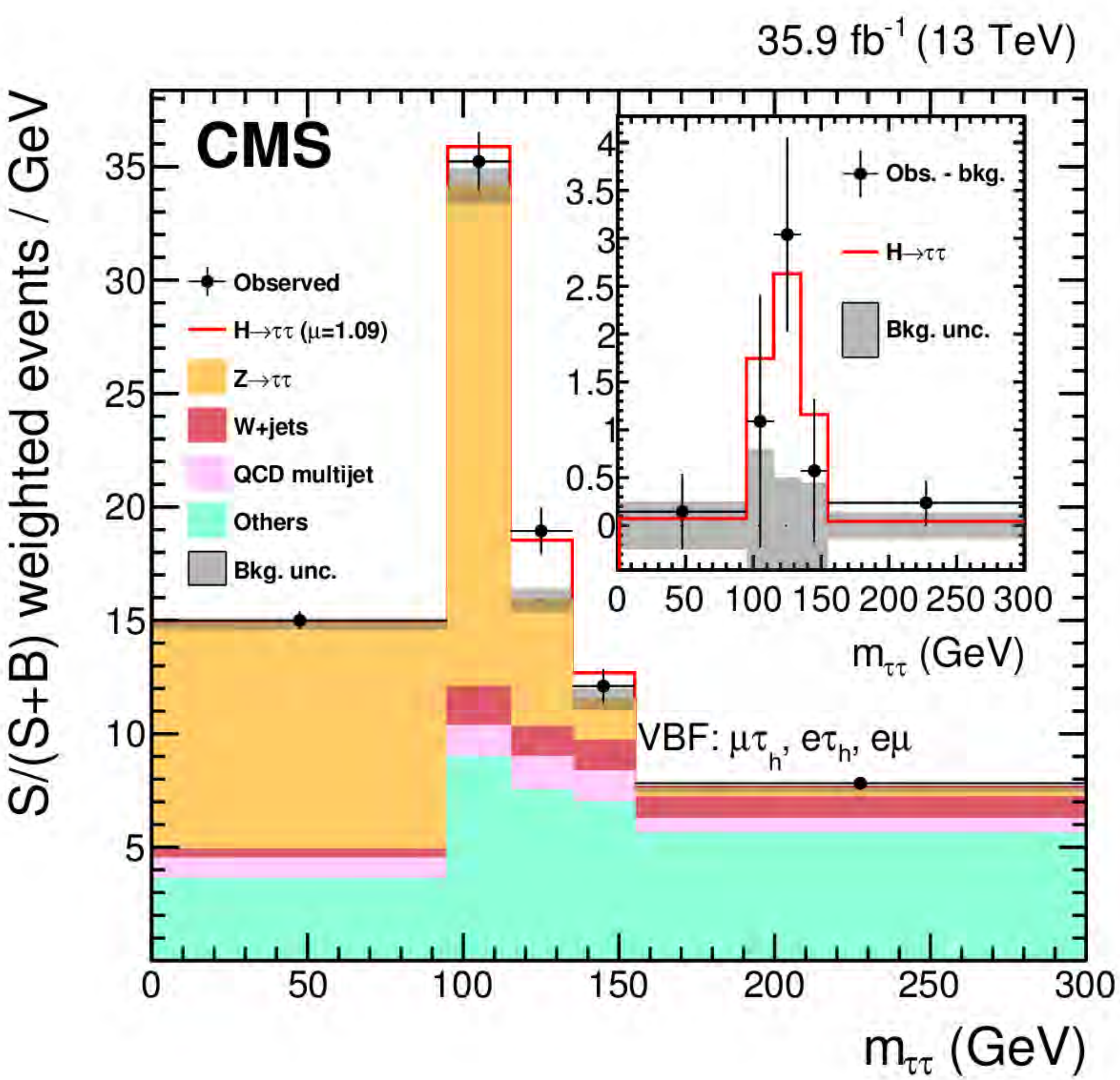


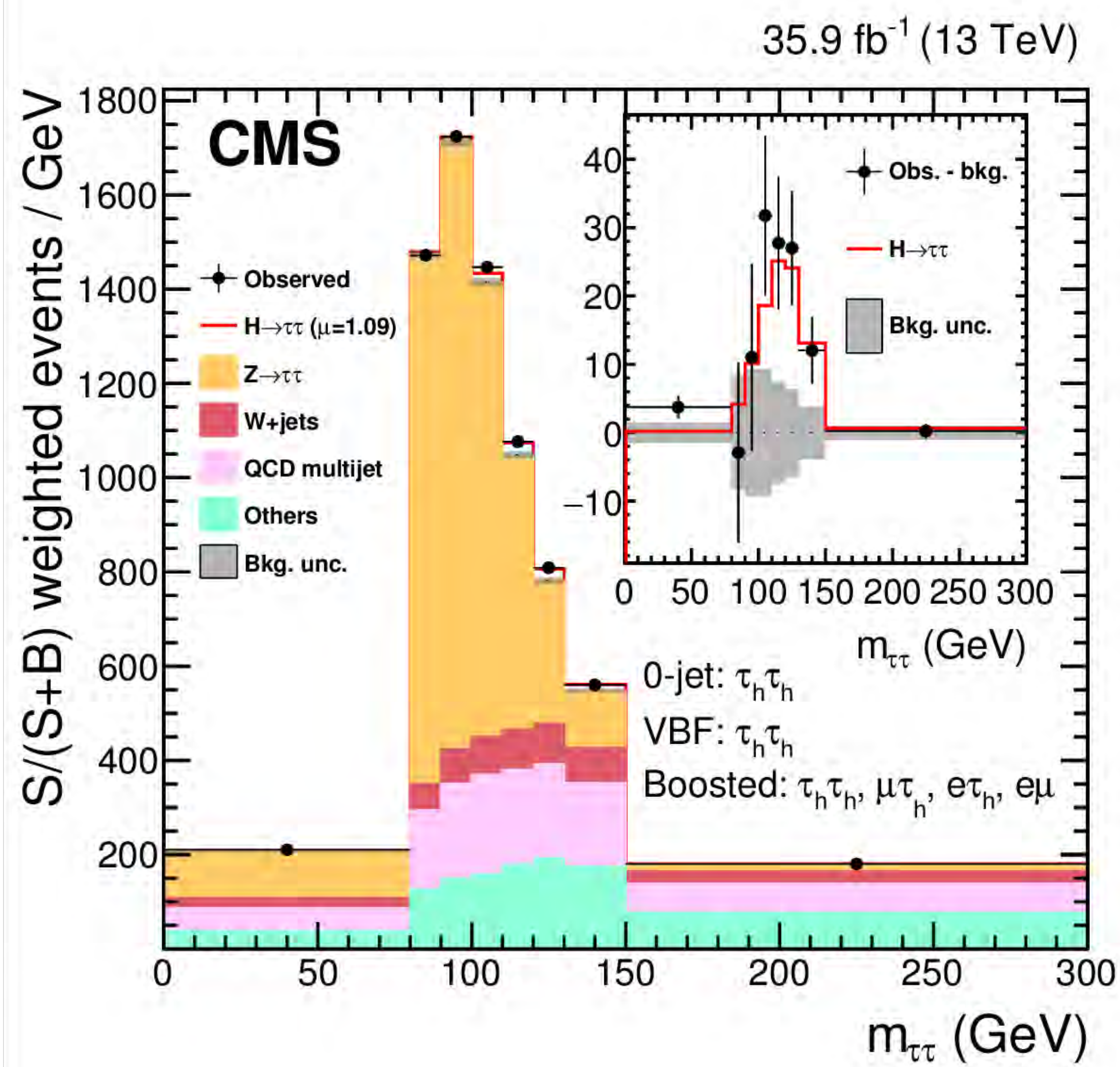
category



H(ττ) weighted mass plot

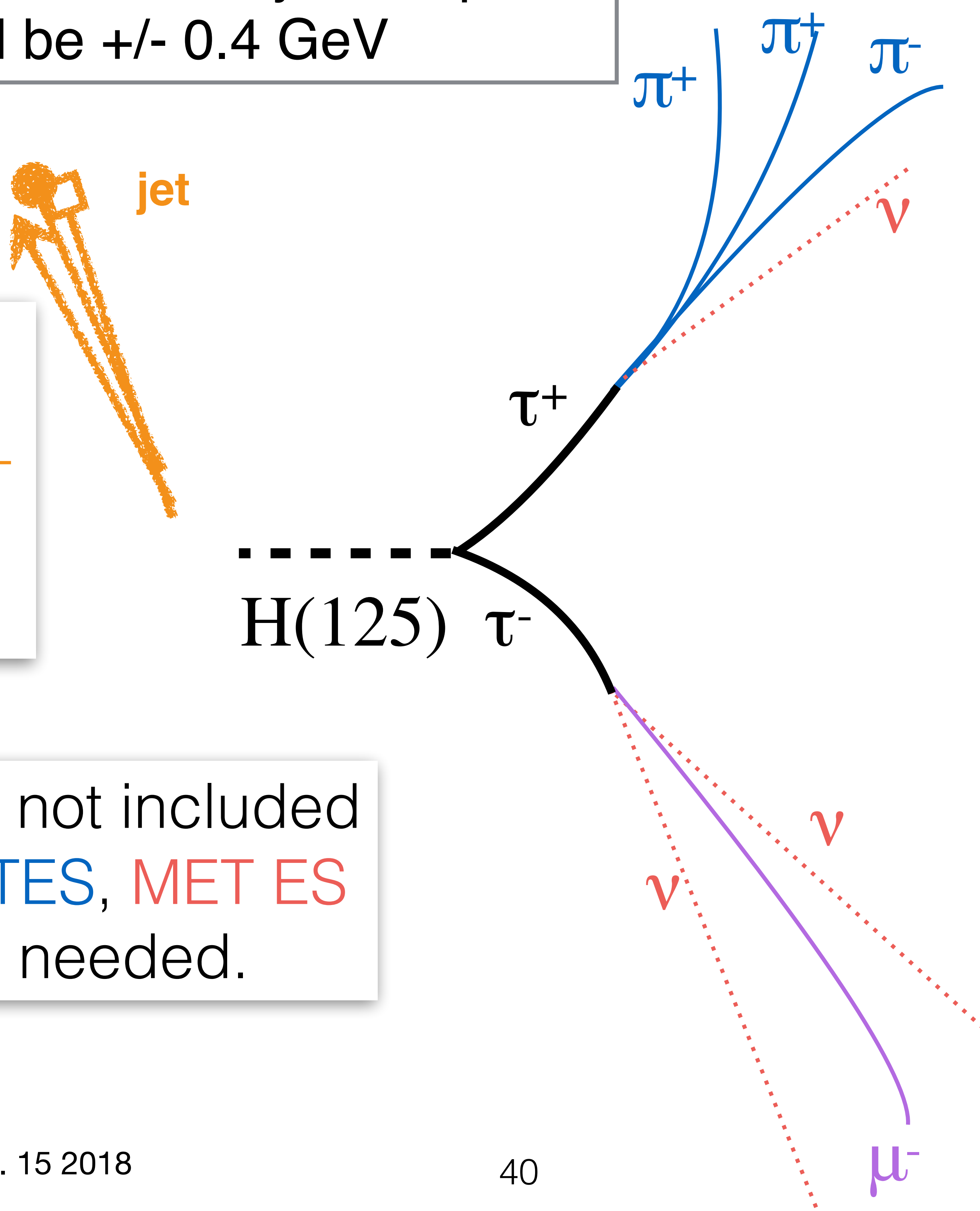
- The mass distributions weighted by S/(S+B) show a visible SM Higgs peak





Energy Scale Uncertainties

Energy Scales (ES) Uncertainty Example:
a 50 GeV tau could be +/- 0.4 GeV



π- are included in 1.2% Tau ES

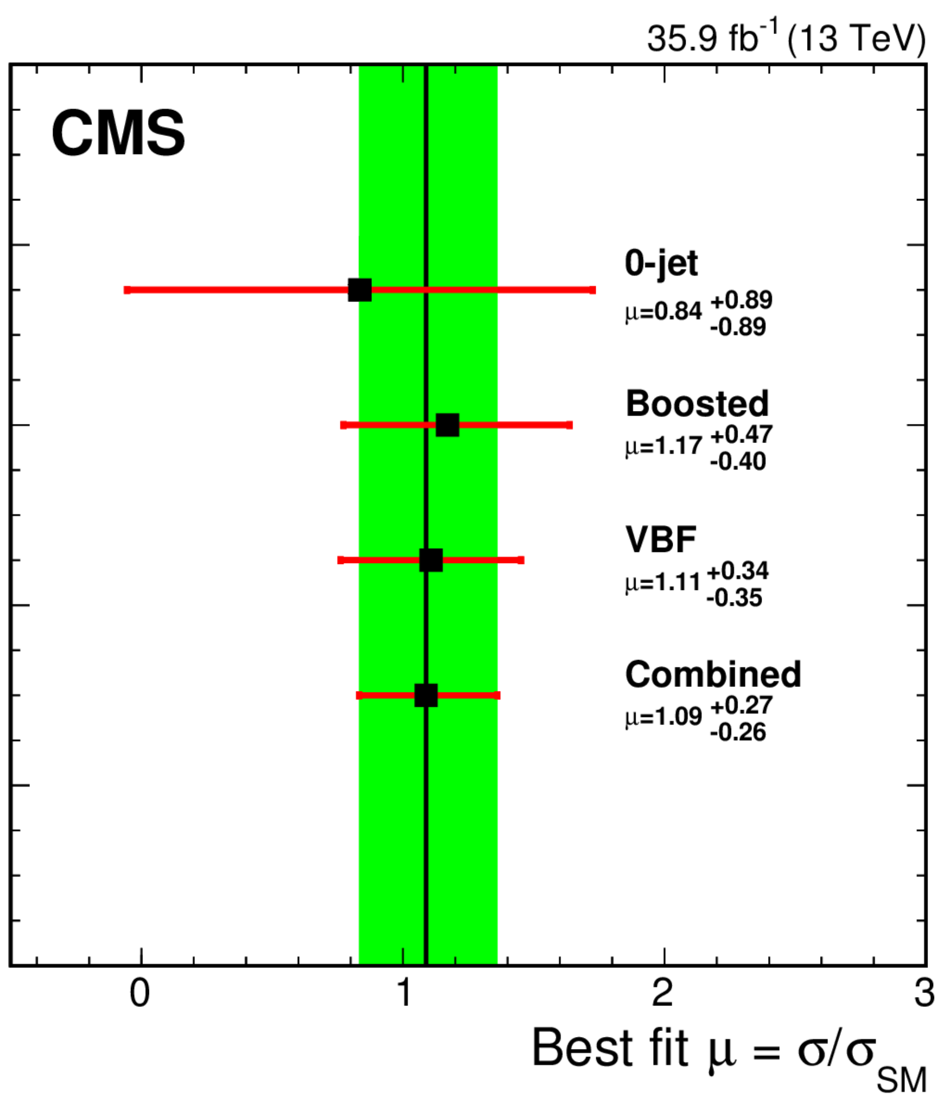
Jets in the event affect the MET measurement. JET ES added to MET calculation.

μ- have negligible ES compared with MET, Jet and Tau ES

ν is not included in TES, MET ES needed.

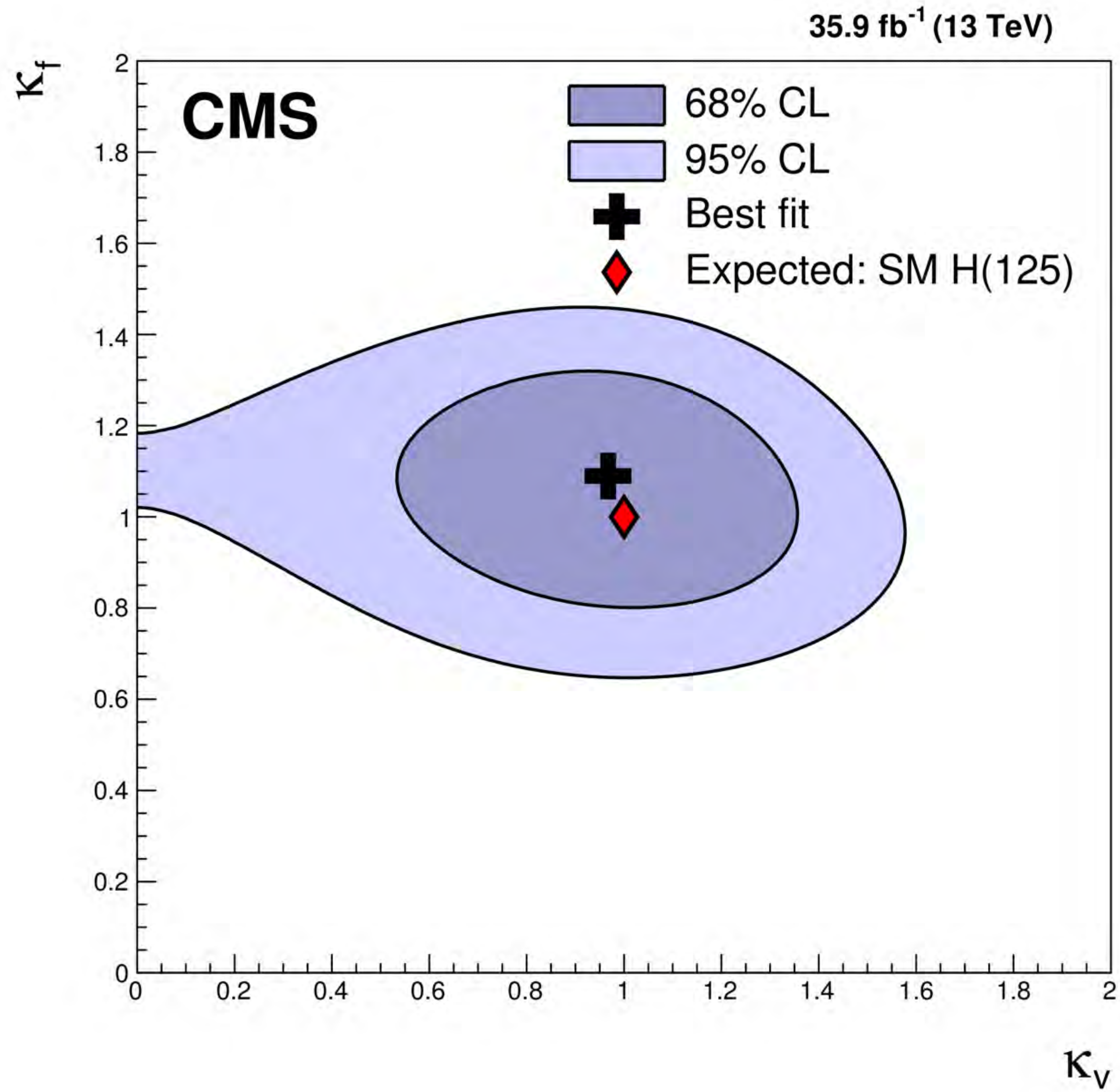
Rate measurement

- Measured versus expected rates are shown by category and channel
  - Measured SM Higgs(ττ) rate is **1.09 $^{+0.27}_{-0.26}$** of the expected SM rate.
  - When shapes are included in the statistic, the **observed (expected)** significance of the measured H(ττ) decay is **4.9 (4.7) sigma** compared to SM expectation without H(ττ) decay

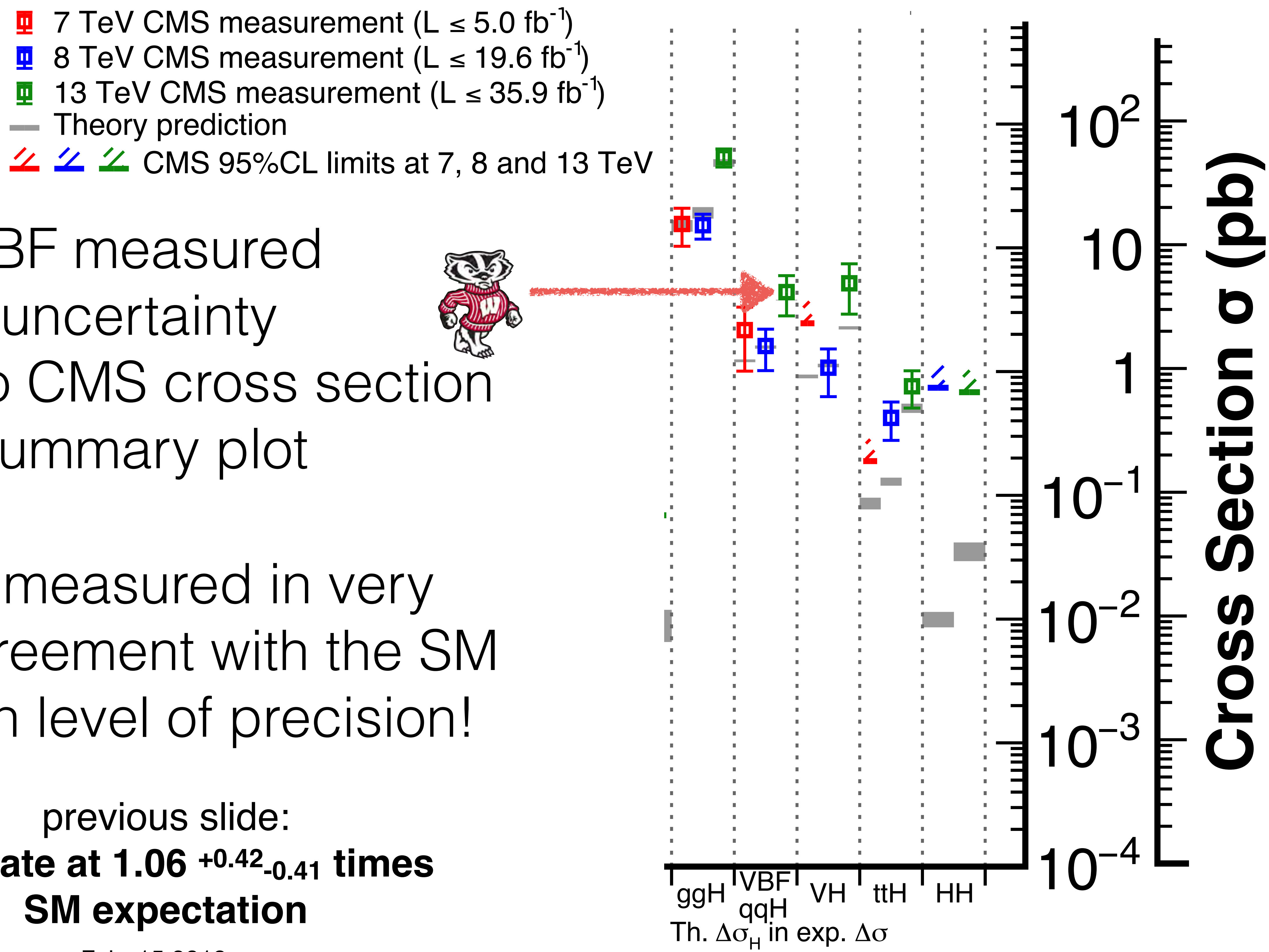


fermionic-vector coupling (ϰ)

- ϰ, is the ratio of the measured coupling to the SM expectation.
- The categories separate ggH and VBF for signal production measurements. The measured rate can be broken down as a function of the VBF and ggH process. The vector coupling rate, $\varkappa_V$, is compared to the fermionic coupling rate, $\varkappa_f$.
- Explicitly, we measure **ggH rate at** $\mathbf{1.07^{+0.45}_{-0.41}}$ times the SM expectation, and the **VBF rate at** $\mathbf{1.06^{+0.42}_{-0.41}}$ times the SM expectation.



Cross section summary



VBF measured uncertainty added to CMS cross section summary plot

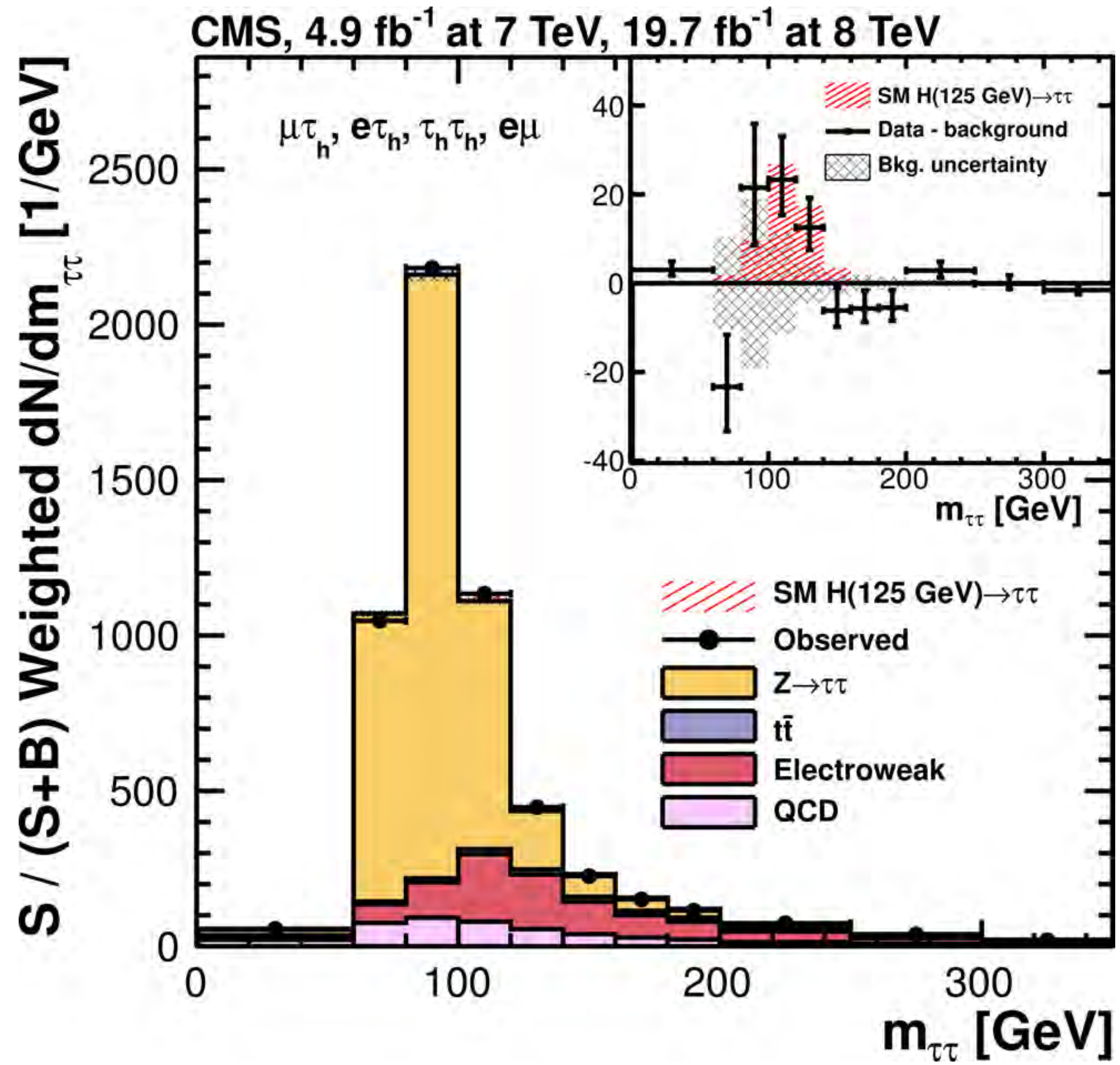
H→ττ measured in very good agreement with the SM at a high level of precision!

previous slide:

VBF rate at 1.06 $^{+0.42}_{-0.41}$ times SM expectation

Combination with 8 TeV

- Conservative combination with the 8 TeV CMS H(ττ) analysis is performed. The observed and expected significance of the H(ττ) decay increases to **5.9 (5.9) sigma** as compared with no SM H(ττ).



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Observation of the Higgs boson decay to a pair of τ leptons with the CMS detector

The CMS Collaboration *

Q1 Q2 CERN, Switzerland

A R T I C L E I N F O

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A B S T R A C T

A measurement of the $H \to \tau\tau$ signal strength is performed using events recorded in proton–proton collisions by the CMS experiment at the LHC in 2016 at a center-of-mass energy of 13 TeV. The data set corresponds to an integrated luminosity of 35.9 fb^{-1}. The $H \to \tau\tau$ signal is established with a significance of 4.9 standard deviations, to be compared to an expected significance of 4.7 standard deviations. The best fit of the product of the observed $H \to \tau\tau$ signal production cross section and branching fraction is $1.09^{+0.27}_{-0.26}$ times the standard model expectation. The combination with the corresponding measurement performed with data collected by the CMS experiment at center-of-mass energies of 7 and 8 TeV leads to an observed significance of 5.9 standard deviations, equal to the expected significance. This is the first observation of Higgs boson decays to τ leptons by a single experiment.

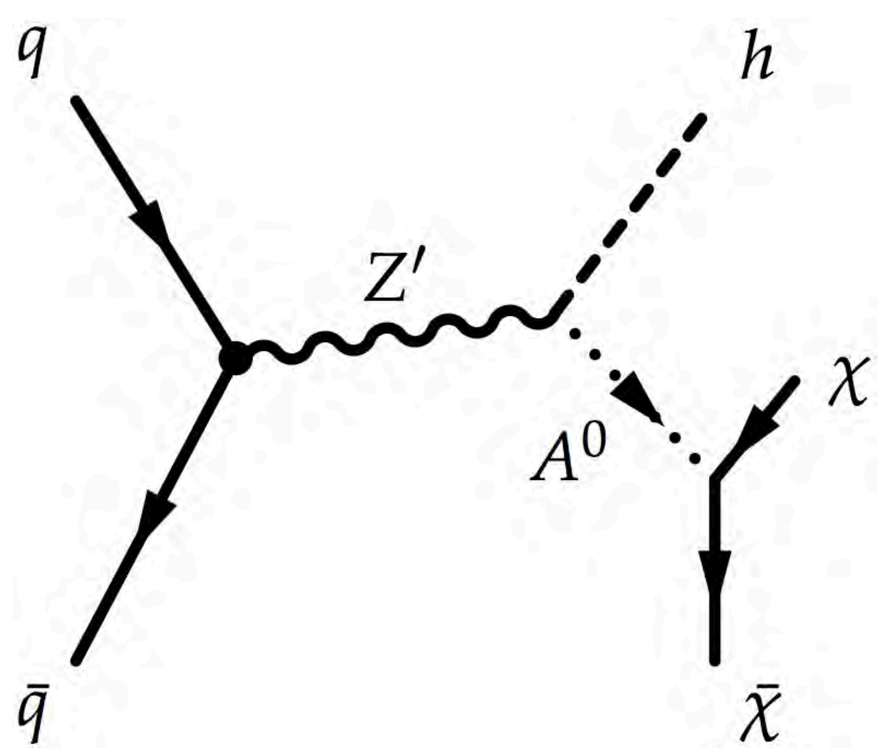
Mono-Higgs($\tau\tau$)

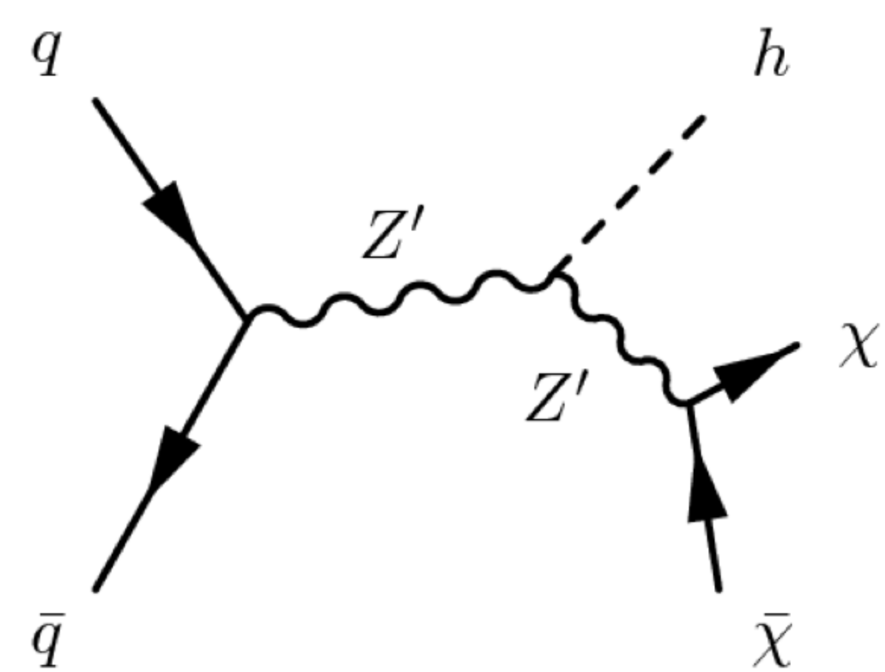
Mono-Higgs Overview

- **Produce a limit on the number of Higgs bosons (ττ) that decay in association with dark matter.**
  - **use $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$, final states only**
    similar background methods as SM Hττ
    3 signal regions ($e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$) and 5 control regions for background normalization
- Higgs and MET are roughly back to back, instead of roughly collinear in SM Higgs. The previously used kinematic fit is unusable. Di-boson backgrounds play larger role.

Final state	Trigger requirement	Lepton selection		
		p_T (GeV)	η	Isolation
$\mu\tau_h$	$\mu(24)$	$p_T^{\mu} > 26$ $p_T^{\tau_h} > 20$	$\|\eta^{\mu}\| < 2.4$ $\|\eta^{\tau_h}\| < 2.3$	$I^{\mu}_{rel} < 0.15$ Tight MVA τ_h ID Tight muon rejection Loose electron rejection
$e\tau_h$	$e(25)$	$p_T^{e} > 26$ $p_T^{\tau_h} > 20$	$\|\eta^{e}\| < 2.1$ $\|\eta^{\tau_h}\| < 2.3$	$I^{e} < 0.1$ Tight MVA τ_h ID Loose muon rejection Tight electron rejection
$\tau_h\tau_h$	$\tau_{h1,2}(35)$	$p_T^{\tau_{h1}} > 55$ $p_T^{\tau_{h2}} > 40$	$\|\eta^{\tau_{h1}}\| < 2.1$ $\|\eta^{\tau_{h2}}\| < 2.1$	Loose MVA τ_h ID Loose muon rejection Loose electron rejection

Mono-Higgs Overview





events with b-tagged jets (60% efficiency WP) are vetoed

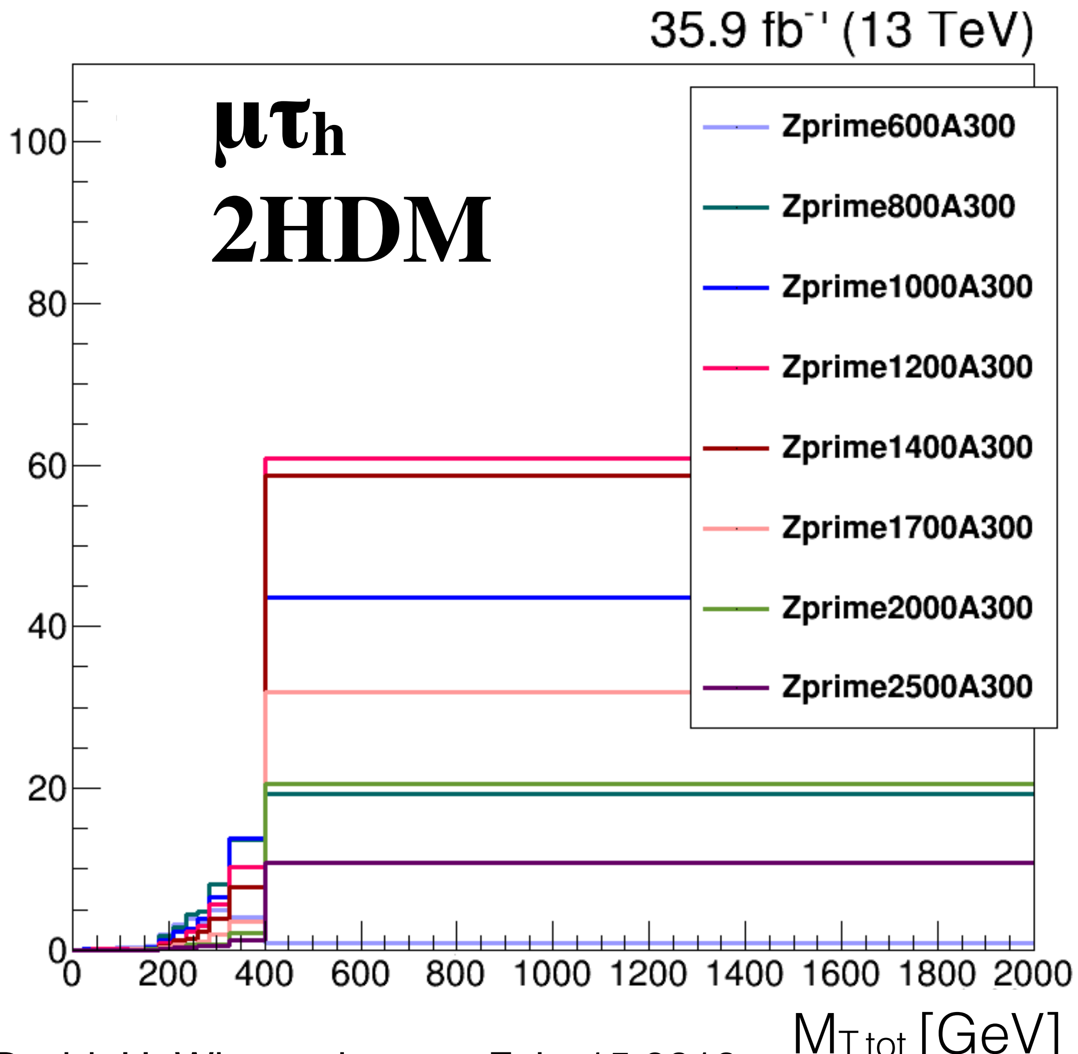
Process	$\mu\tau_h$ Events	$e\tau_h$ Events	$\tau_h\tau_h$ Events
Full identification criteria	535026	258505	175422
$E_T^{miss} > 105$ GeV	10127	4837	1244
$p_T(H) > 65$ GeV	4783	2559	958
$\Delta R_{\tau\tau} < 2.0$ GeV	2880	1577	655
$m_{vis} < 125$ GeV	2798	1533	629

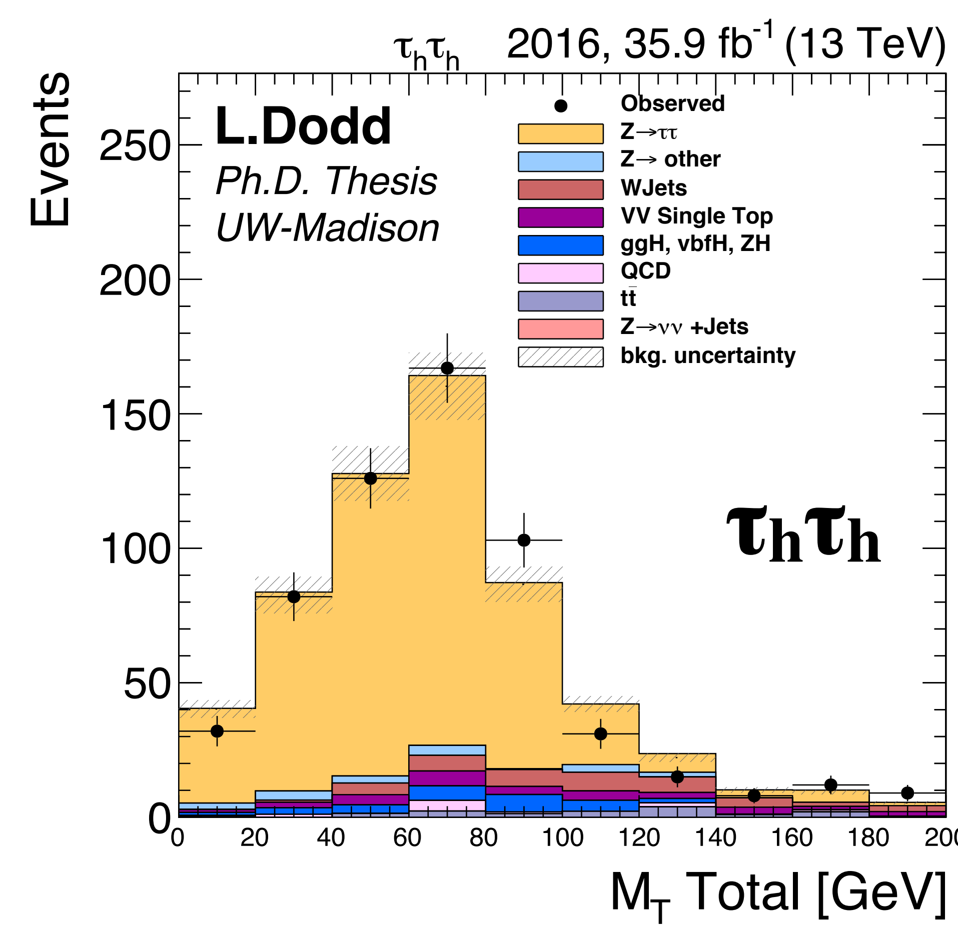
Table 9.6: Number of observed events in selection process.

Observable: $M_{T,tot}$

- Total transverse mass ($M_{T,tot}$) used for extraction, signal distributions beyond 260 GeV, background mostly below

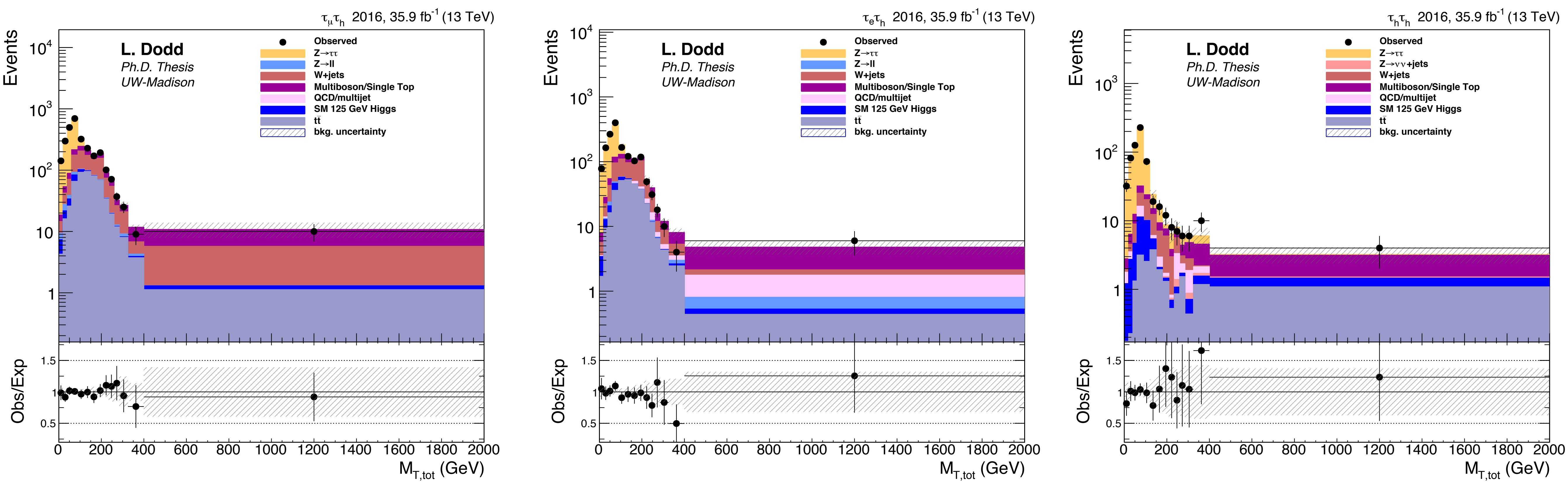
$$M_{T,tot} = \sqrt{(E_T^{\tau_1} + E_T^{\tau_2} + E_T^{miss})^2 - (p_x^{\tau_1} + p_x^{\tau_2} + p_x^{miss})^2 - (p_y^{\tau_1} + p_y^{\tau_2} + p_y^{miss})^2}$$





Limit Extraction

- Systematics roughly identical to SM Higgs to ττ
- Limited number of simulated events
  - Background precision decreases in tails of distribution
- W+jets, WW, and ZZ higher-order correction uncertainties applied, dependent on generated boson pT



Event Yield

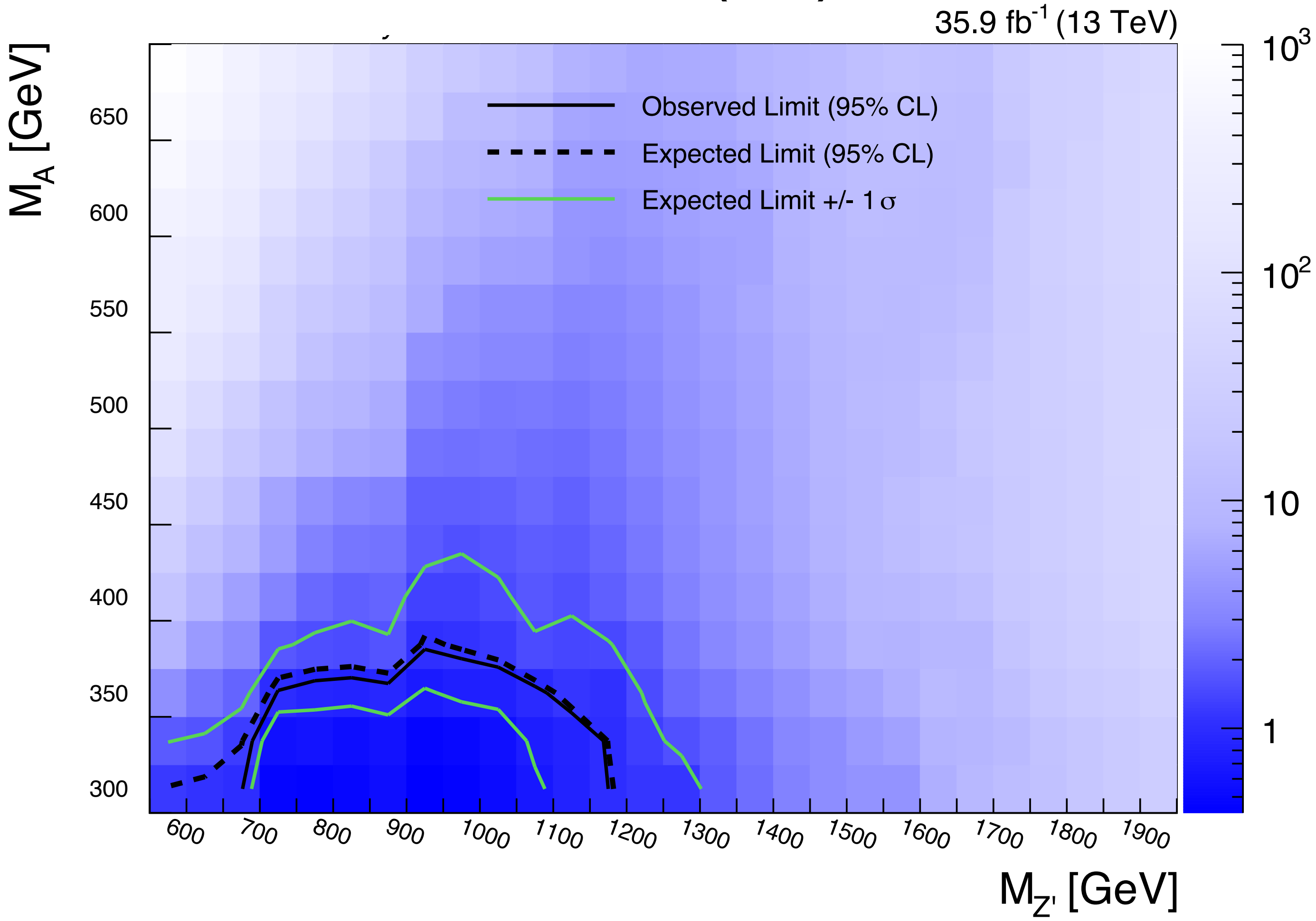
background yields in sensitive region dominated by statistical uncertainties

Process	$\mu\tau_h$	$e\tau_h$	$\tau_h\tau_h$
W + jets QCD	32.54 ± 6.18	13.11 ± 2.18	3.79 ± 2.59
$t\bar{t}$	24.83 ± 2.04	13.75 ± 1.60	4.24 ± 1.30
125 GeV H	0.72 ± 0.06	0.48 ± 0.08	1.21 ± 0.08
Multi-boson	21.53 ± 1.46	12.34 ± 0.99	7.30 ± 0.63
$Z \rightarrow \tau\tau$	0.14 ± 0.53	0.00 ± 0.01	3.57 ± 1.24
$Z \rightarrow \ell\ell$	2.00 ± 1.33	0.84 ± 1.87	-
$Z \rightarrow \nu\nu$	-	-	0.37 ± 0.25
Total expected	81.77 ± 6.31	40.50 ± 3.26	20.48 ± 2.97
Observed	81.00 ± 9.00	38.00 ± 6.16	26.00 ± 5.10

Can expect up to 5 events in each category for expected Mono-Higgs signal

Z'-2HDM Model Exclusion

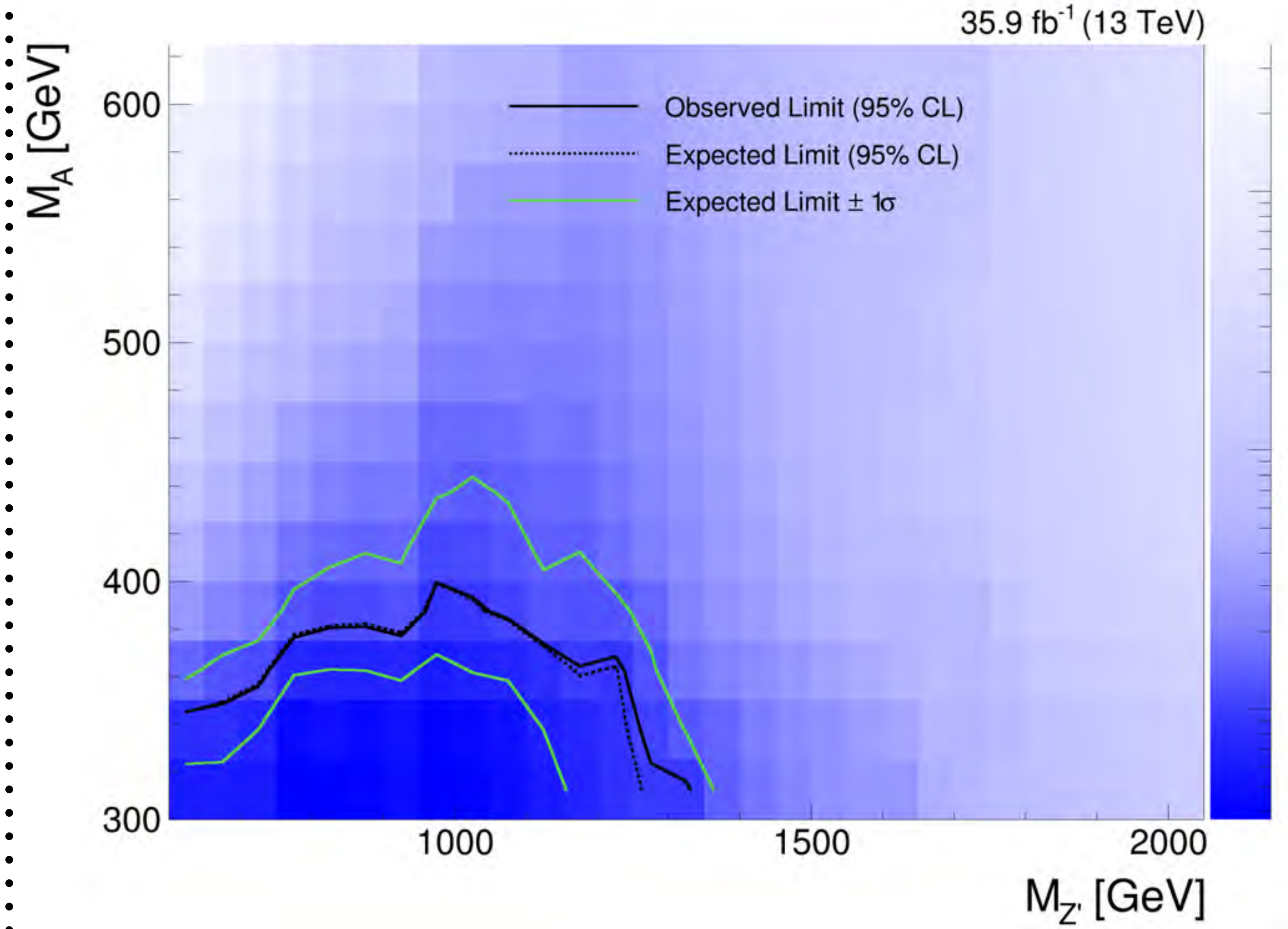
Mono(ττ)



exclude $M_{Z'}$ ={700 -1200 GeV} and M_A={300-375 GeV}

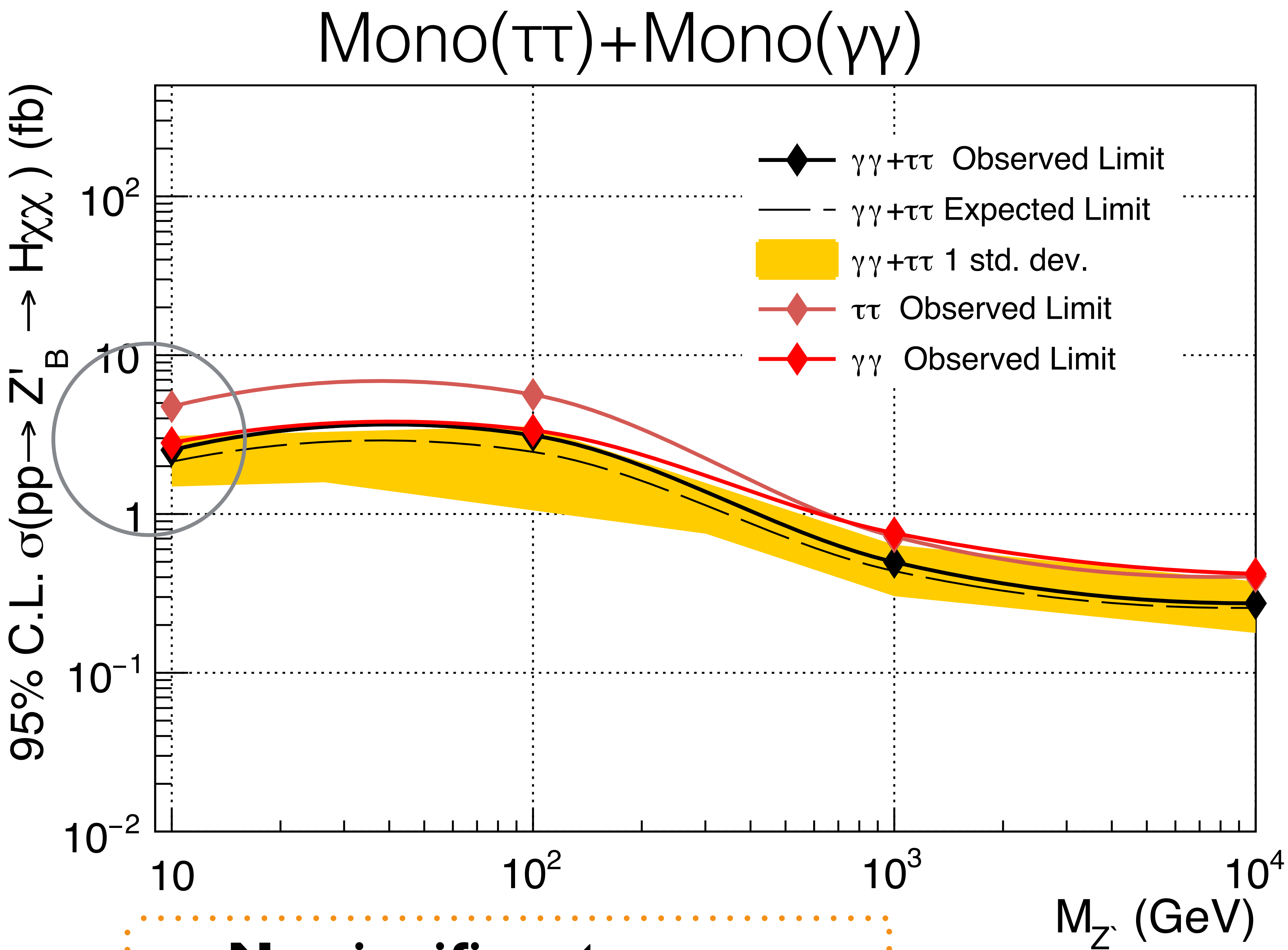
No significant excess compared to SM expectation

Mono(ττ)+Mono(γγ)



combination of γγ+ττ increases exclusion:
$M_{Z'}$ ={600 -1350 GeV}
and M_A={300-400 GeV}

Baryonic Z' Model Exclusion



currently preparing for publication

No significant excess compared to SM expectation

combination of γγ+ττ increases exclusion range

Summary

- SM H(ττ) measurement sees H(ττ) decay at high-level of precision consistent with prediction
- No significant excess compared to the standard model expectation in dark matter mono-Higgs search

END

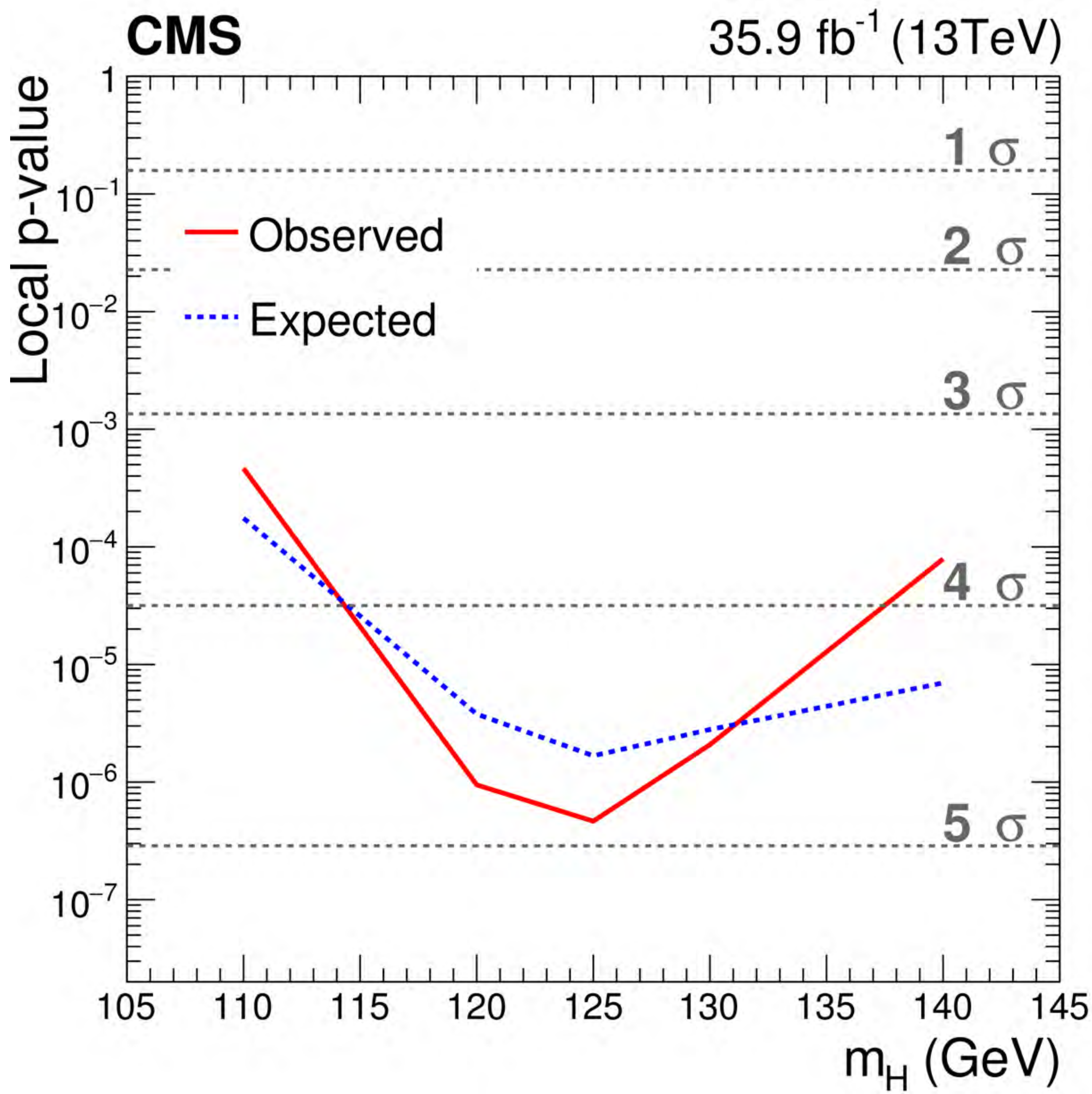
A thesis is never finished, only abandoned.
—Marià Cepeda,
quoting Juan Alcaraz,
quoting someone else

Backup

SMH backup

P-value and Significance

- 125 GeV SM Higgs
  - Expected (postfit) significance is 4.7 sigma
  - Observed significance is 4.9 sigma
  - Obs. p-value ~0.00000006



Visible Tau Energy Scale

- Visible Tau Energy Scale
  - Includes track and ECAL measurement
  - Assigned 1.2% Up/Down uncertainty
- TES constrained to small values (0.3%)
  - Correlate the taus whatever eta/pt/category
  - Core of Zττ has taus with pT$<$70 GeV highest boost still has mostly low pT taus
  - CMS measures tracks well, more final states included than 1.2% measurement.

tau decay mode	correction
1 prong	-1.8%
1 prong 1 pi0	+1%
3 prong	+0.4%

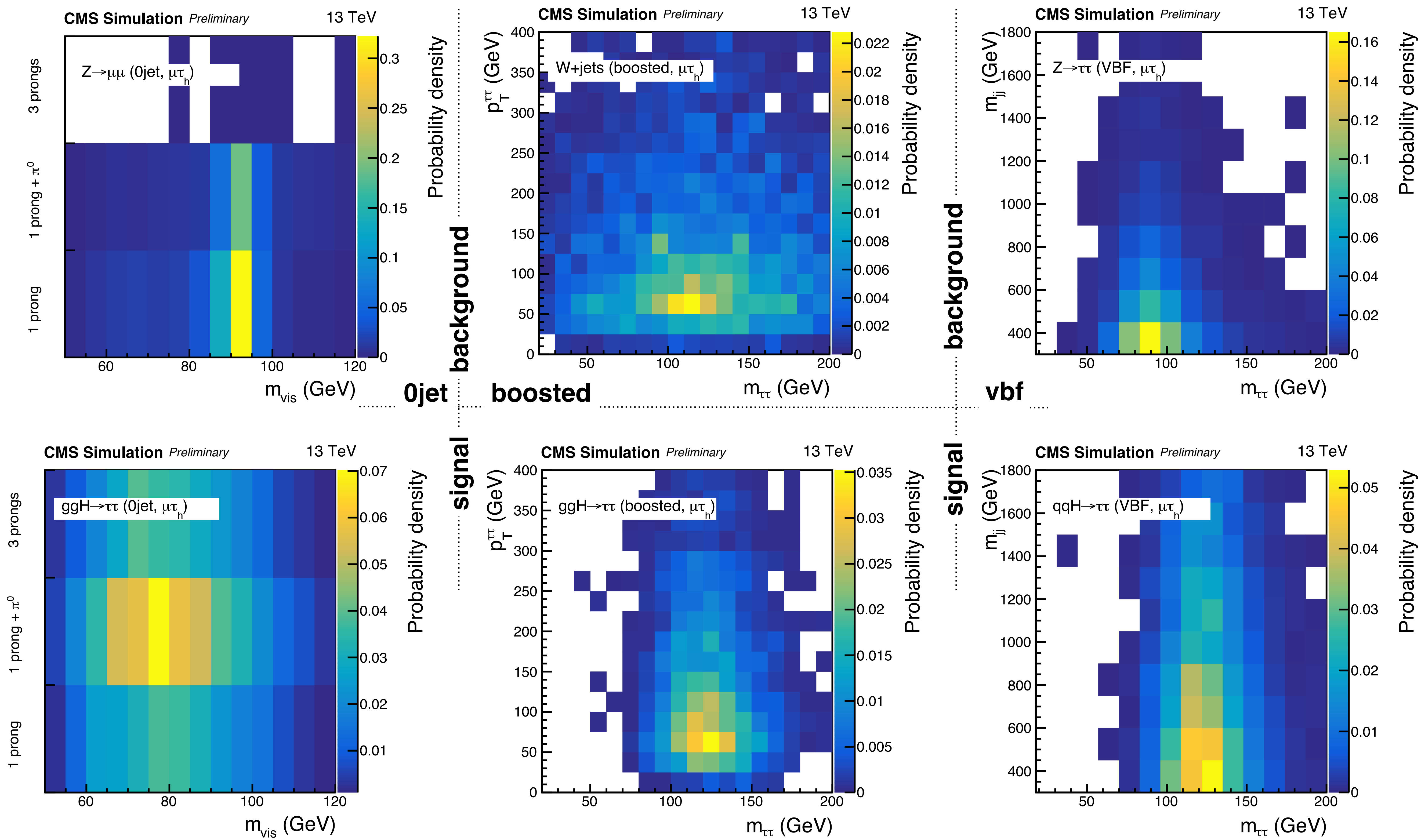
Systematic Uncertainties

- Full list included in thesis
- Systematics affecting normalization
  - Luminosity measurement
  - Trigger efficiencies
  - Hadronic tau reconstruction
- Systematics affecting shapes
  - Energy Scales (discussed next)
  - Drell Yan reweighting to match observed distributions
  - W+jet and QCD variation
  - Higgs momentum distributions (theory)
- Limited number of events (bin-by-bin)

Source of uncertainty	Prefit	Postfit (%)
τ_h energy scale	1.2% in energy scale	0.2–0.3
e energy scale	1–2.5% in energy scale	0.2–0.5
e misidentified as τ_h energy scale	3% in energy scale	0.6–0.8
μ misidentified as τ_h energy scale	1.5% in energy scale	0.3–1.0
Jet energy scale	Dependent upon p_T and η	—
$\vec{p}_T^{miss}$ energy scale	Dependent upon p_T and η	—
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%	5
μ misidentified as τ_h rate	25%	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 in $m_{\ell\ell/\tau\tau}$, $p_T(\ell\ell/\tau\tau)$, and m_{jj} corrections	—
W + jets estimation	Normalization (eμ, $\tau_h\tau_h$): 4–20%	—
	Unc. from CR (eτ_h, $\mu\tau_h$): ≃5–15	—
	Extrap. from high-m_T CR (eτ_h, $\mu\tau_h$): 5–10%	—
QCD multijet estimation	Normalization (eμ): 10–20%	5–20%
	Unc. from CR (eτ_h, $\tau_h\tau_h$, $\mu\tau_h$): ≃5–15%	—
	Extrap. from anti-iso. CR (eτ_h, $\mu\tau_h$): 20%	7–10
	Extrap. from anti-iso. CR ($\tau_h\tau_h$): 3–15%	3–10
Diboson normalization	5%	—
Single top quark normalization	5%	—
$t\bar{t}$ estimation	Normalization from CR: ≃5%	—
	Uncertainty on top quark p_T reweighting	—
Integrated luminosity	2.5%	—
b-tagged jet rejection (eμ)	3.5–5.0%	—
Limited number of events	Statistical uncertainty in individual bins	—
Signal theoretical uncertainty	Up to 20%	—

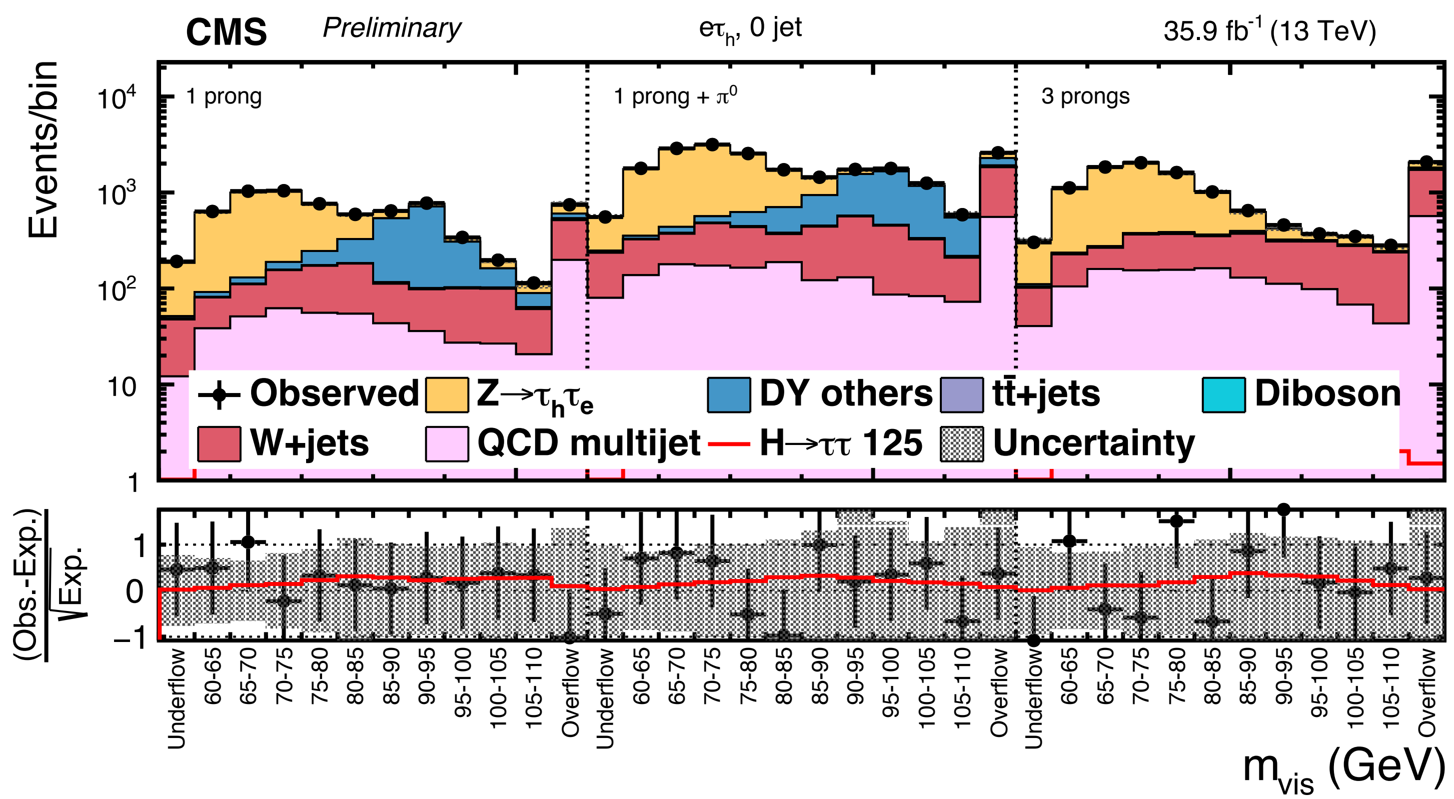
Figure 8.14: Summary of systematics, including postfit constraints

2-Dimensional Distributions

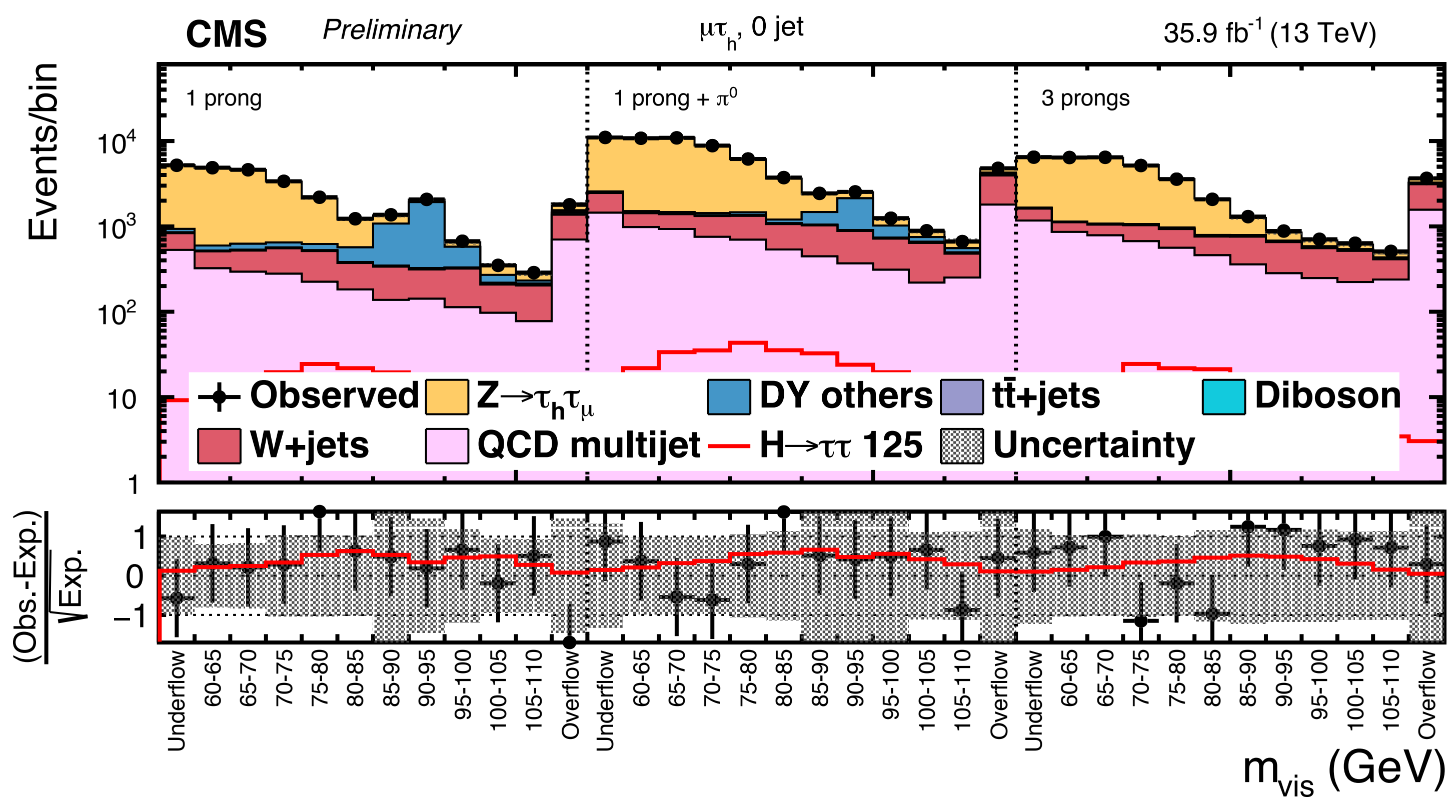


0jet distribution: eτ μτ

eτ 0jet:
m_{vis} : τ decay mode

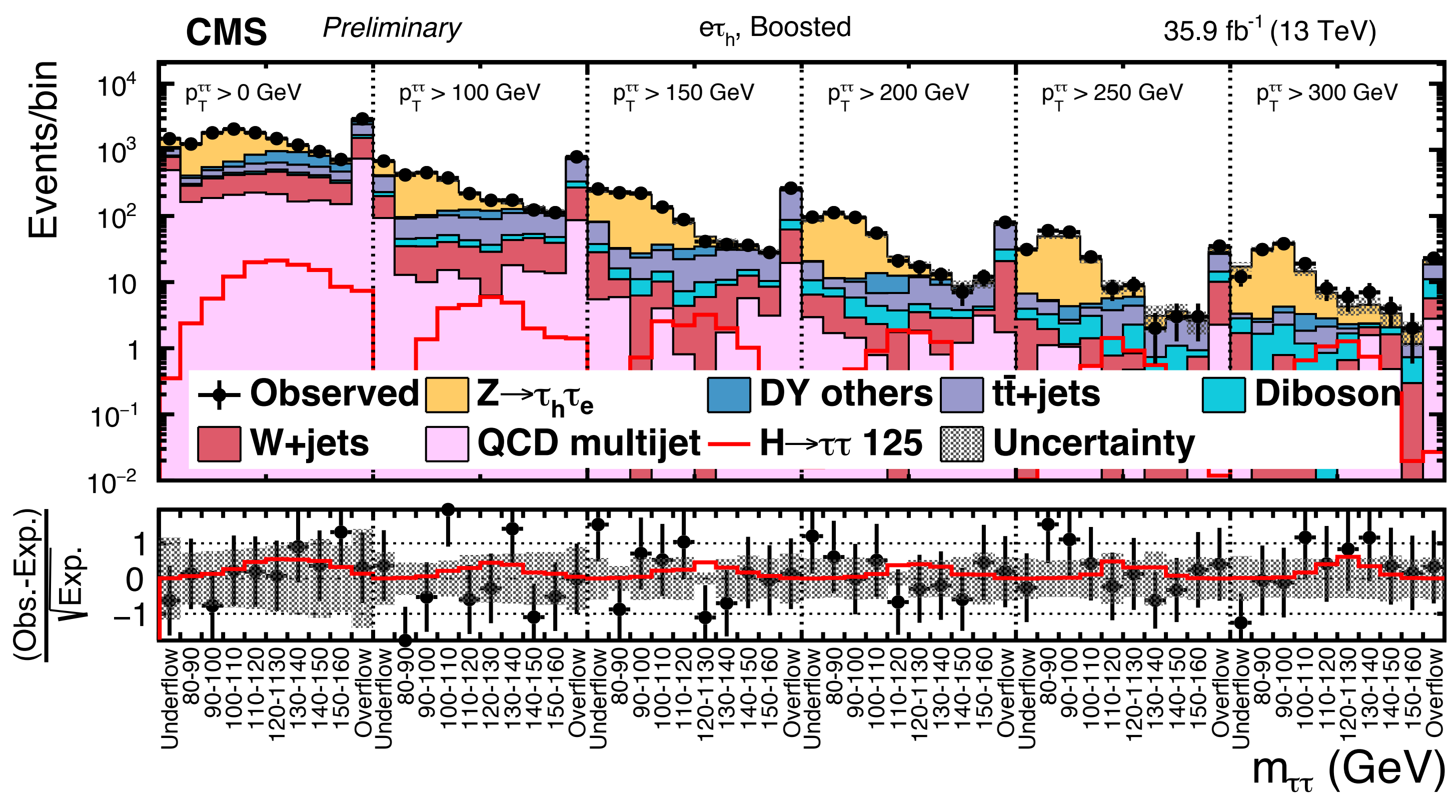


μτ 0jet:
m_{vis} : τ decay mode

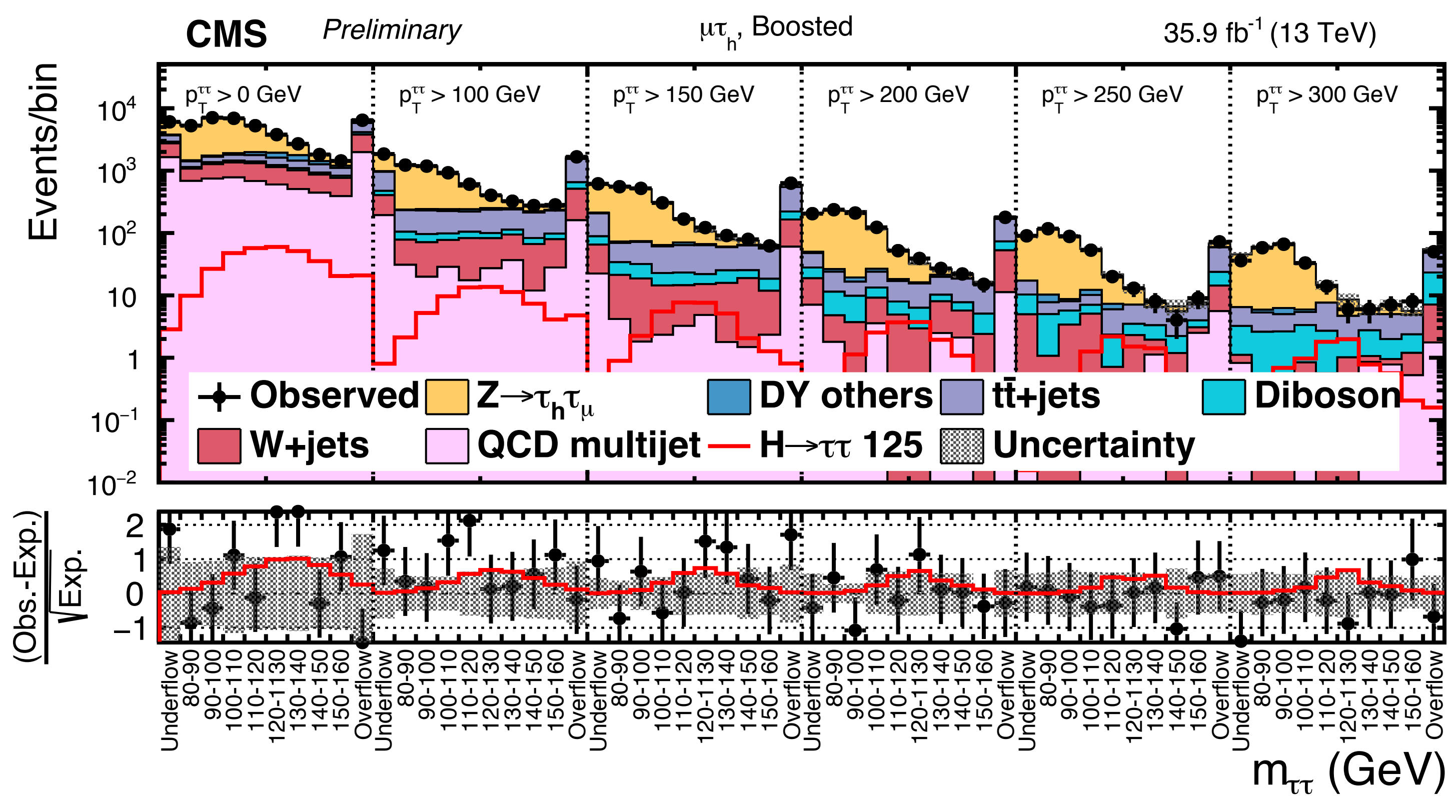


boosted distribution: eτ μτ

eτ boosted:
$m_{\tau\tau}$: H pt

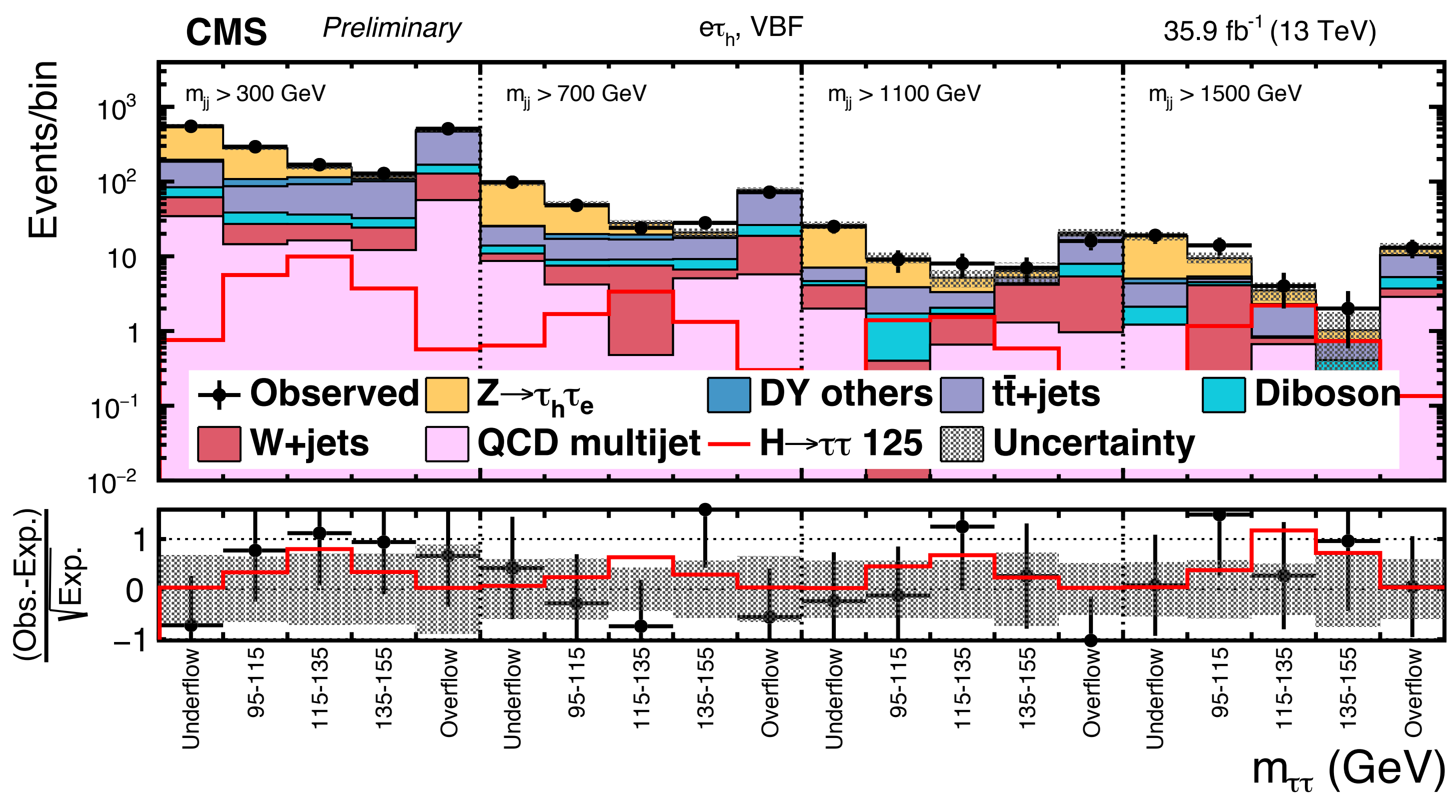


μτ boosted:
$m_{\tau\tau}$: H pT

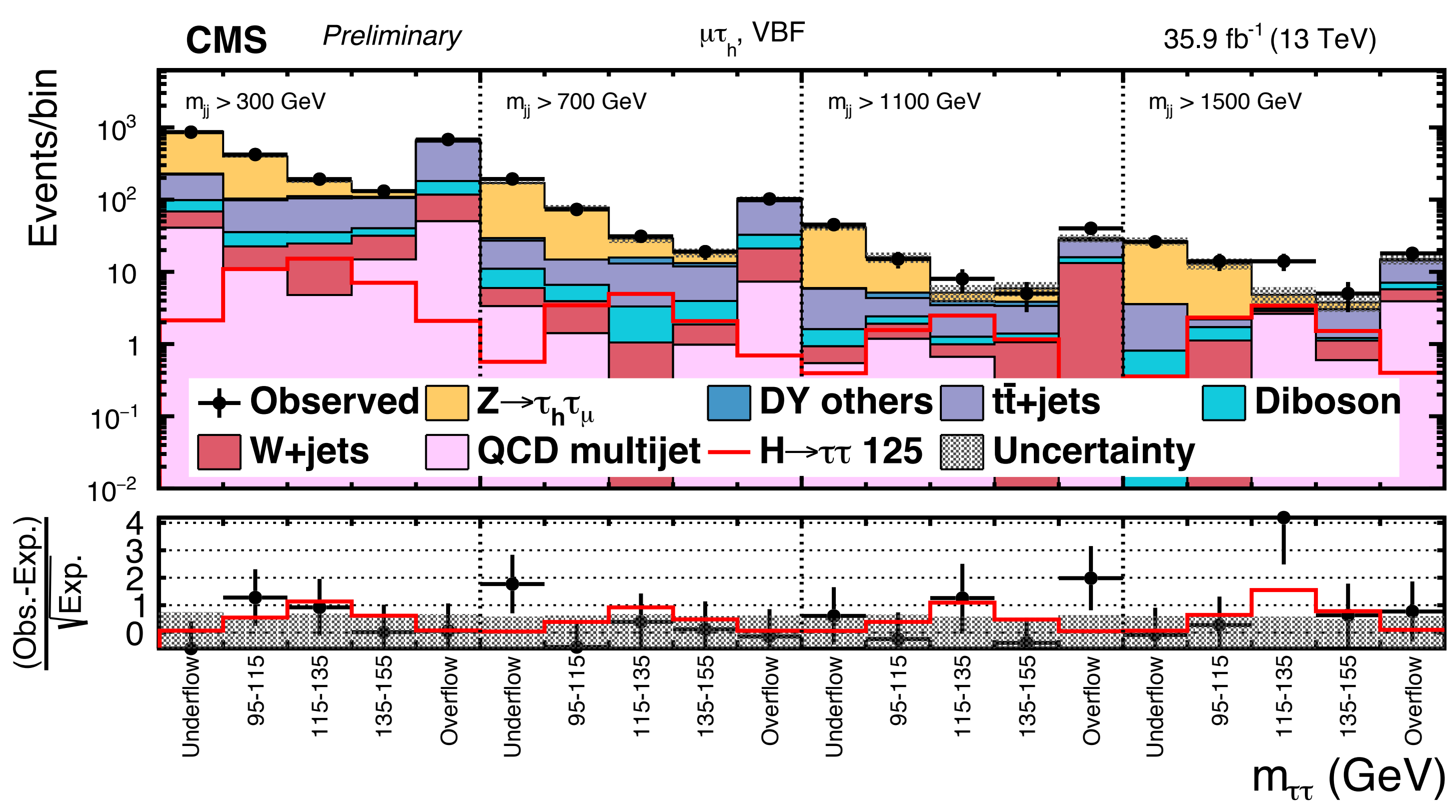


vbf distribution: eτ μτ

eτ vbf:
$m_{\tau\tau}$: di-jet mass

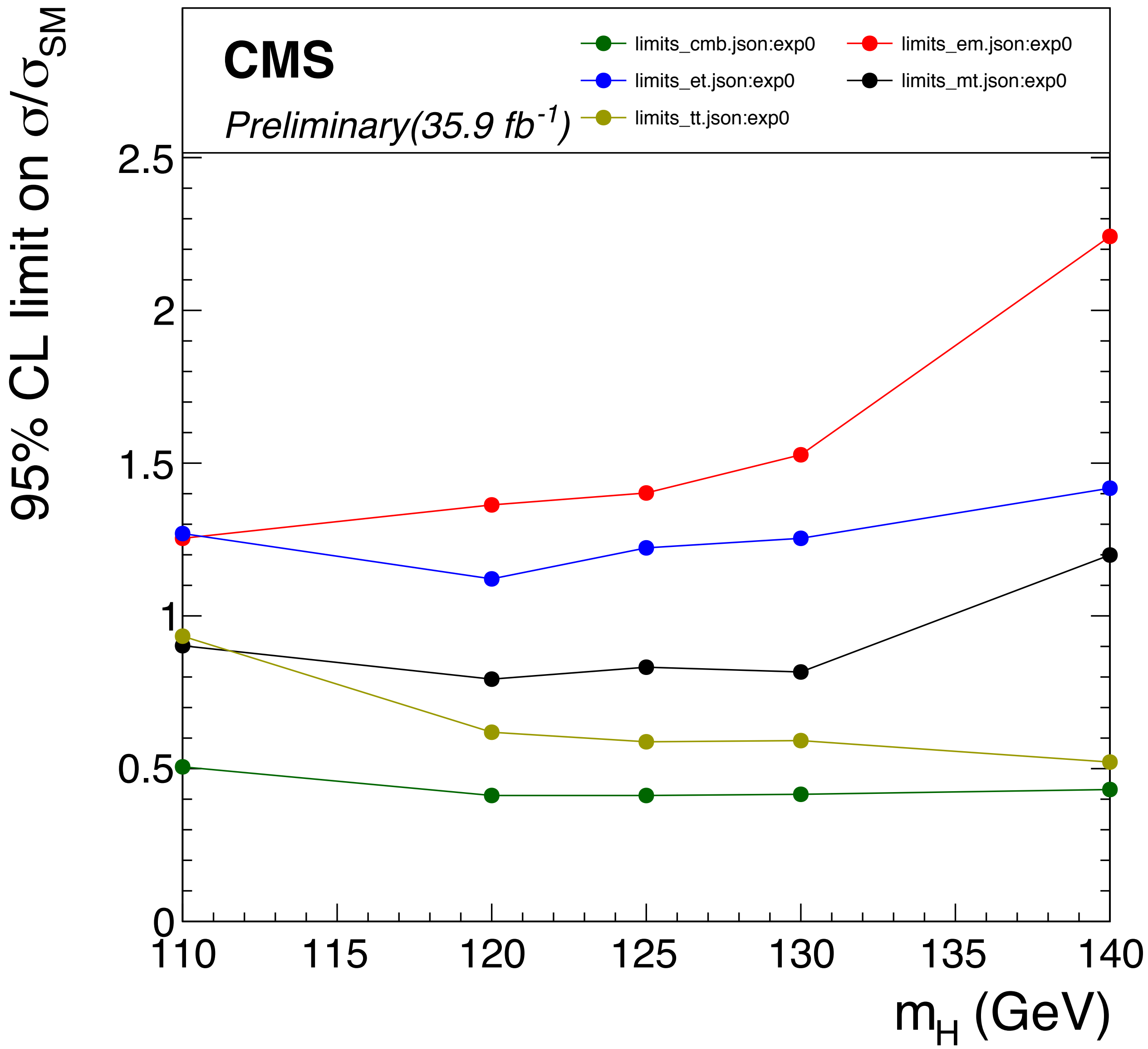


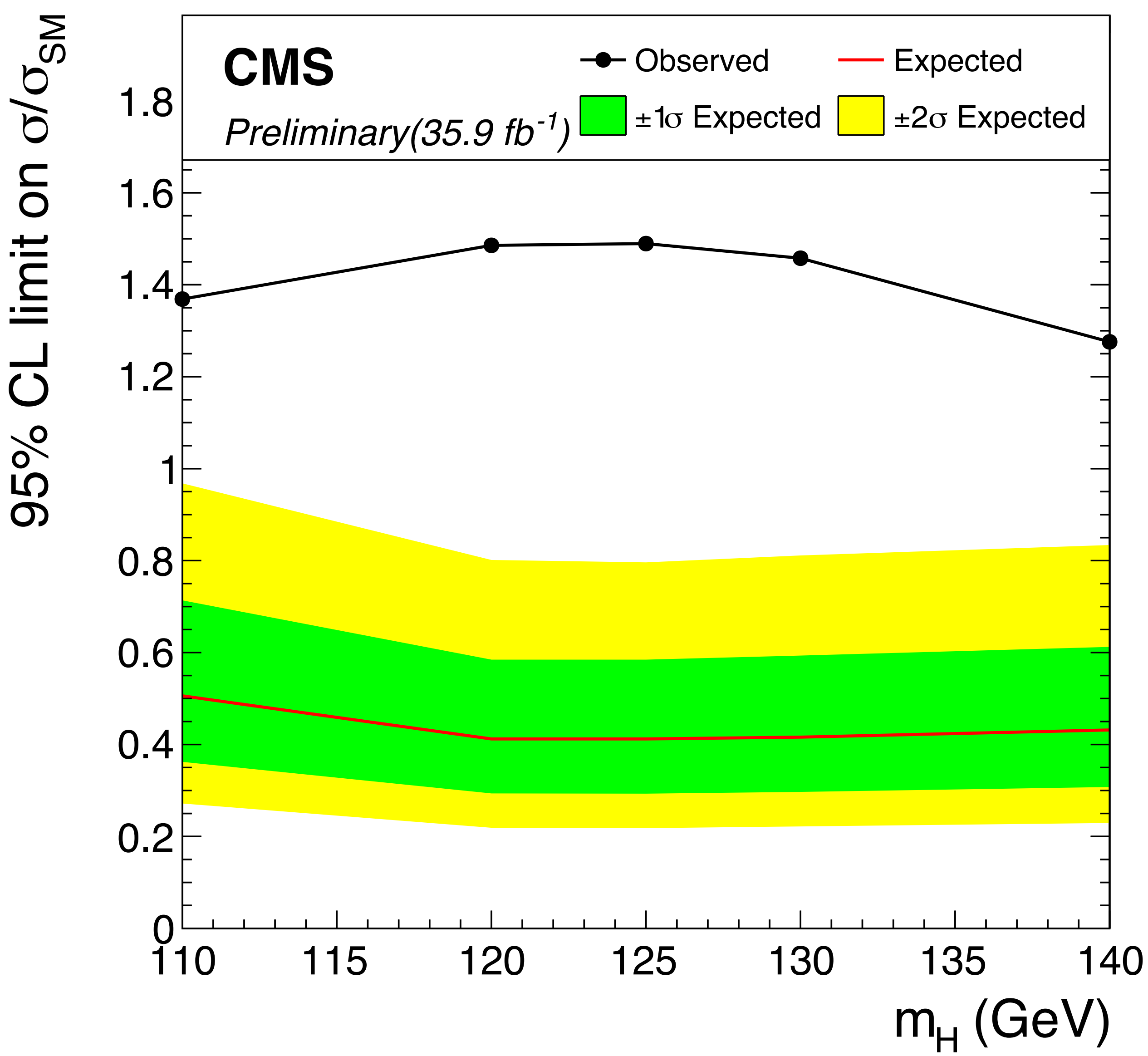
μτ vbf:
$m_{\tau\tau}$: di-jet mass



Combined Limit information

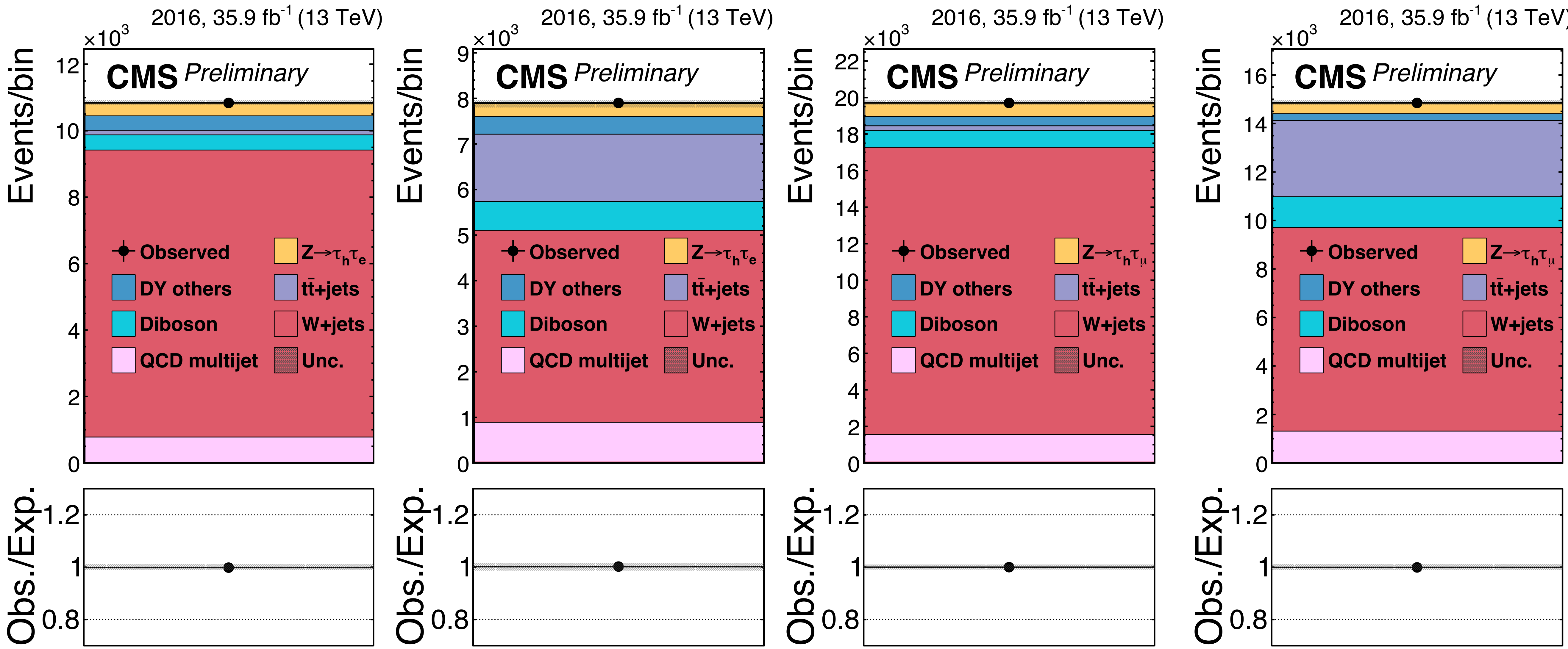
- ττ most sensitive channel, followed by μτ
- We see significant excess centered near 125 GeV combined asymptotic limits





W+Jets CR: ℓτ postfit

0jet | boosted | 0jet | boosted

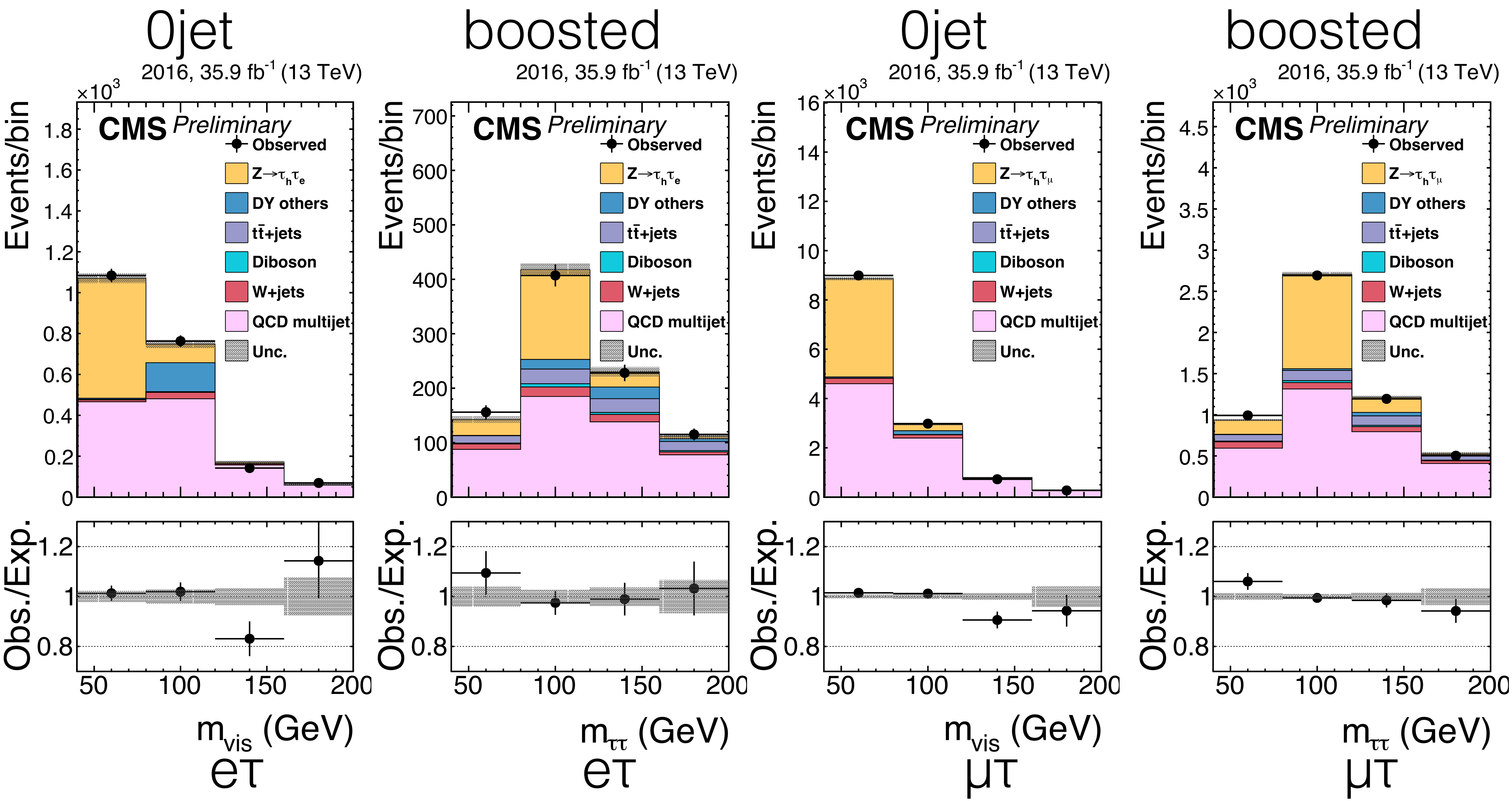


eτ | eτ | μτ | μτ

$$M_T = \sqrt{2p_T E_T^{miss}(1 - cos(\Delta\phi))}$$

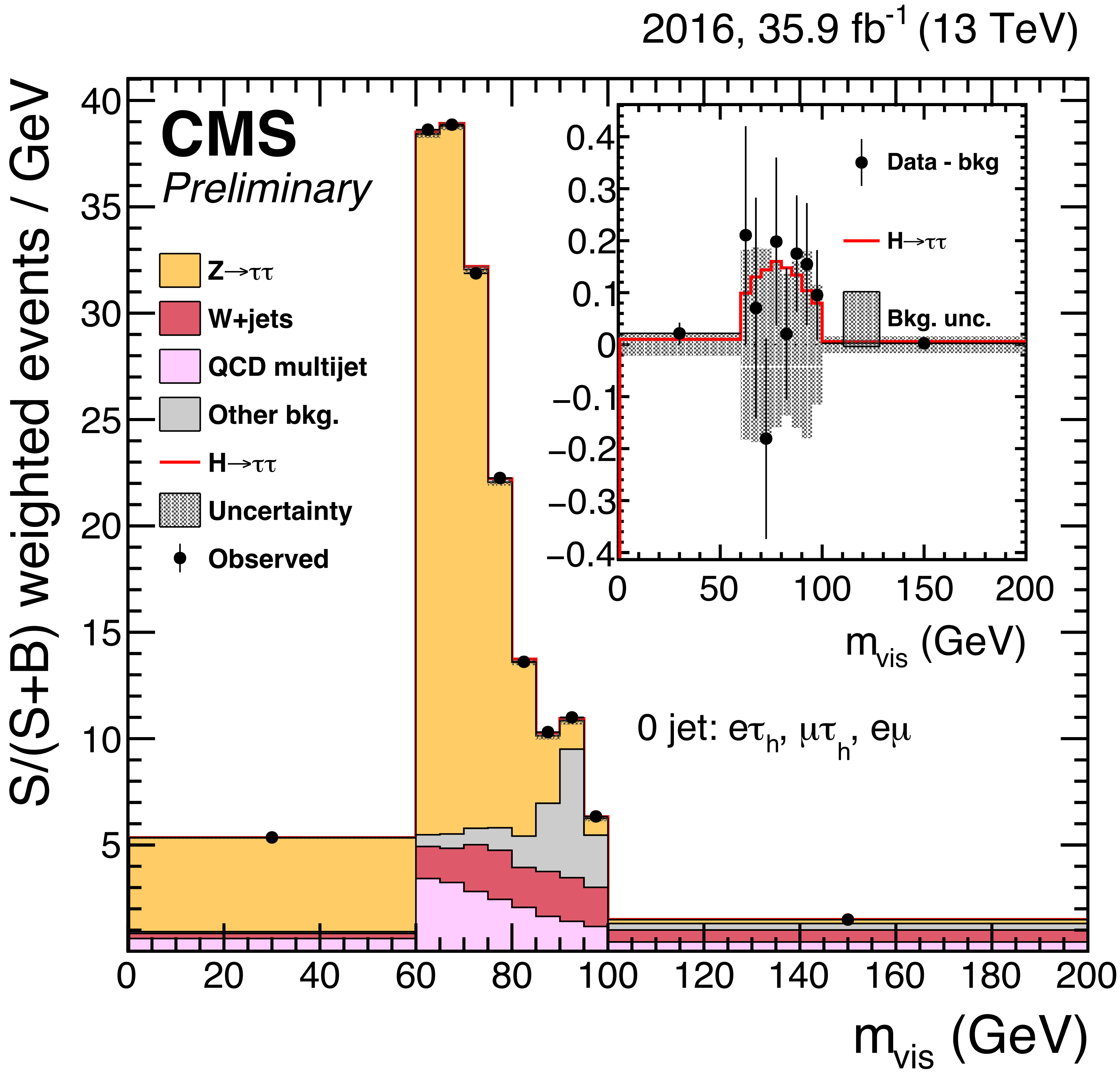
80 GeV <M_T < 200 GeV
signal region is M_T<50 GeV

QCD CR: $\ell\tau$ postfit



Anti-Isolated ℓ Region

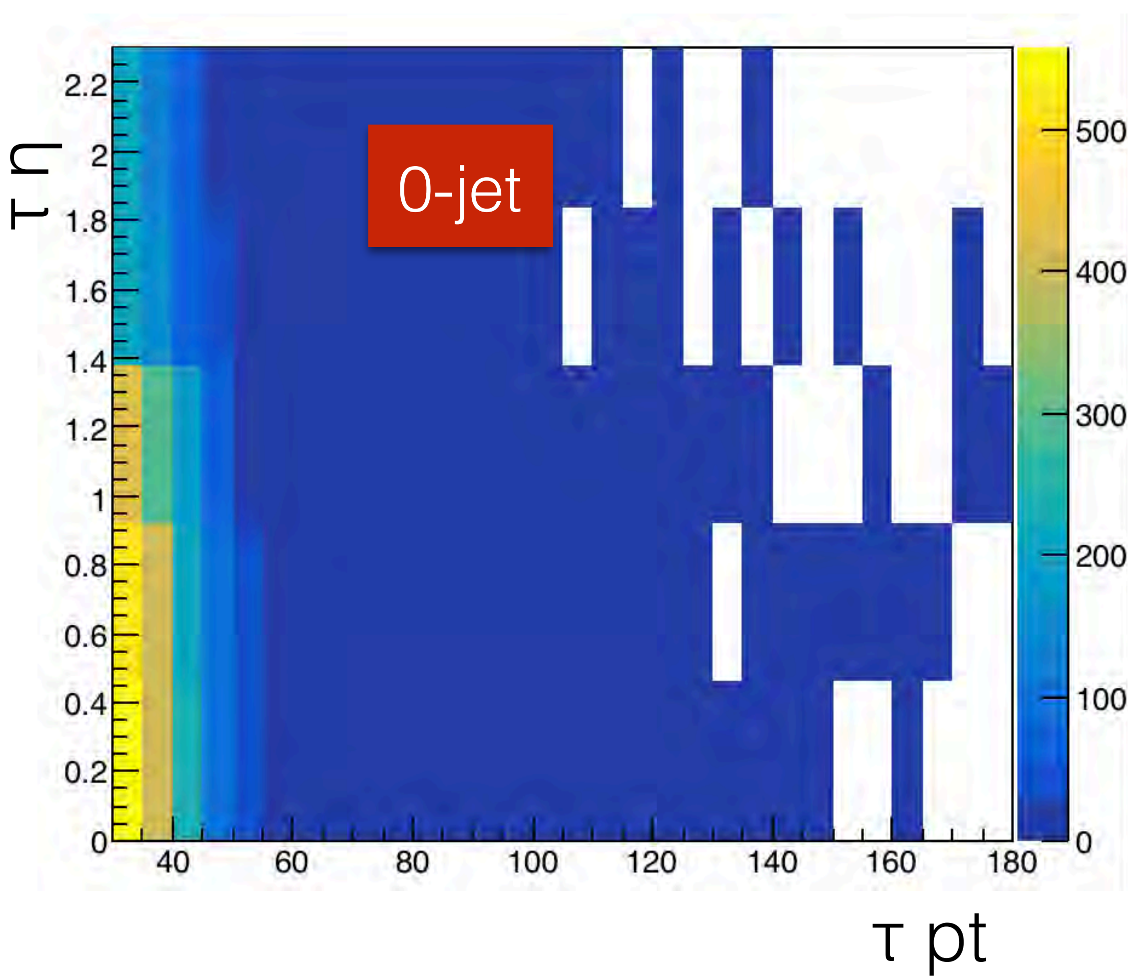
S/(S+B) Weighted M_VIS Plot

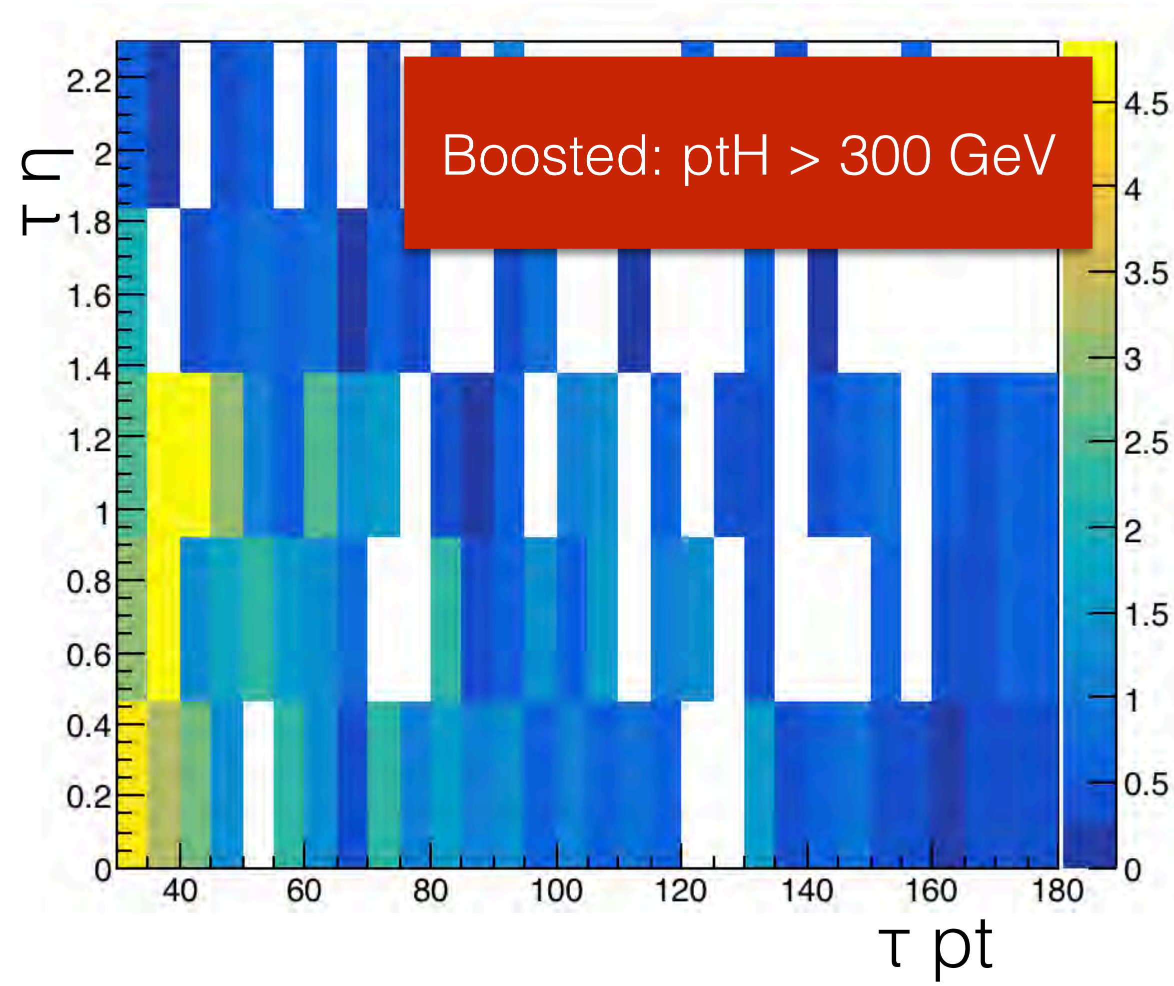


Visible TES treatment

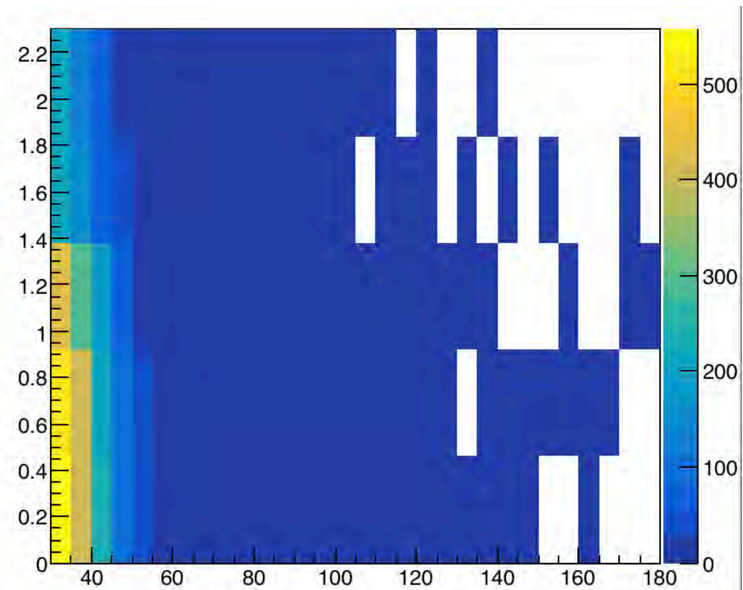
core of Zττ has taus with pT<70 GeV highest boost still has mostly low pT taus

tau decay mode	correction
1 prong	-1.8%
1 prong 1 pi0	+1%
3 prong	+0.4%

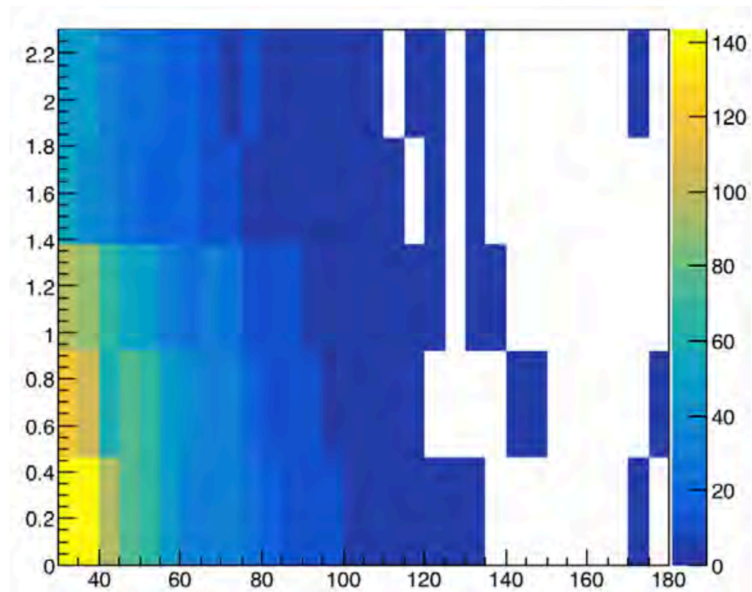




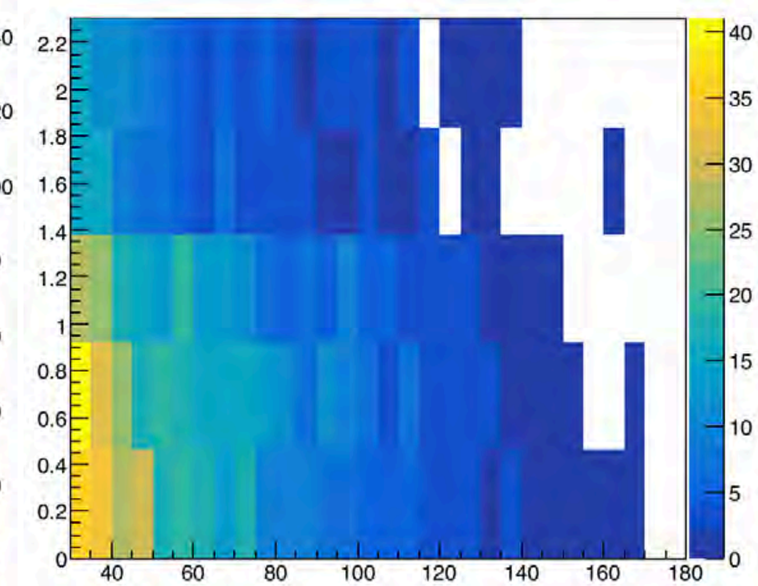
Tau eta vs Tau pt per category



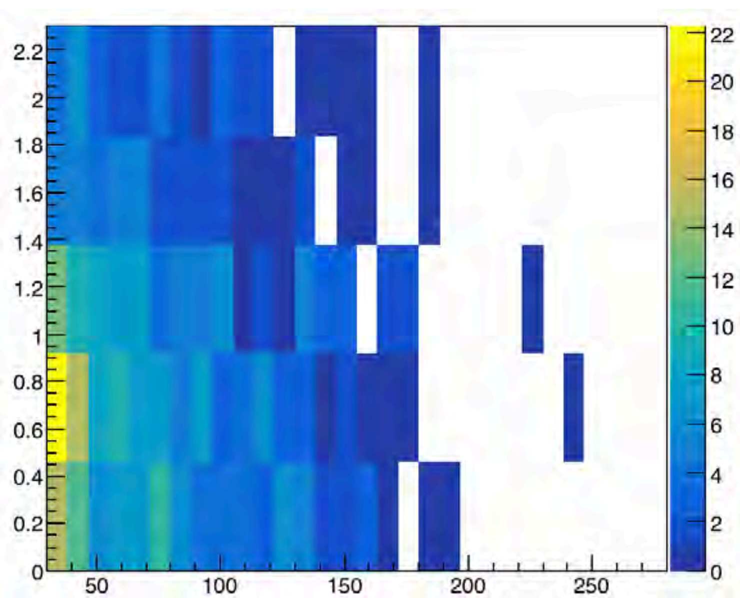
0 jet



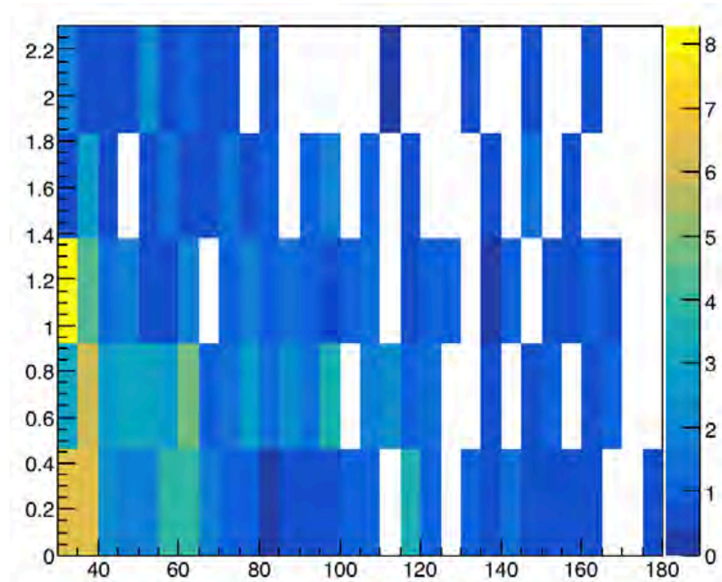
Boosted: 100 < ptH < 150 GeV



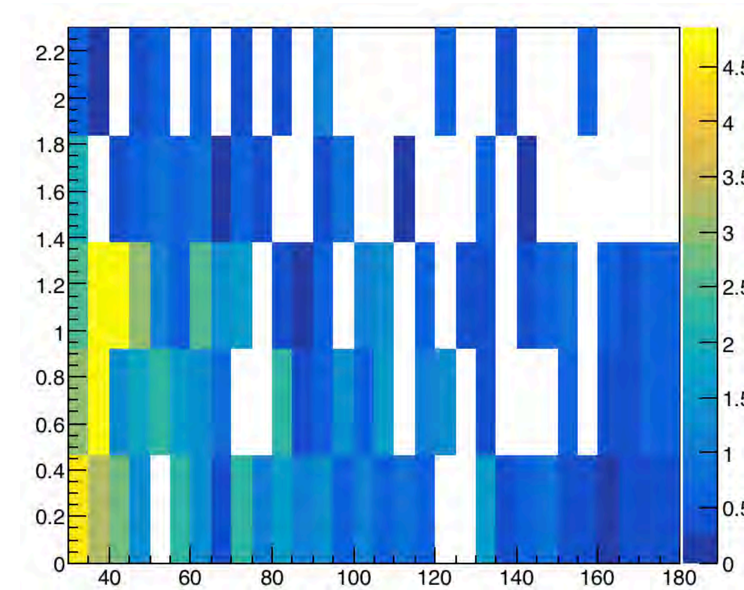
Boosted: 150 < ptH < 200 GeV



Boosted: 200 < ptH < 250 GeV



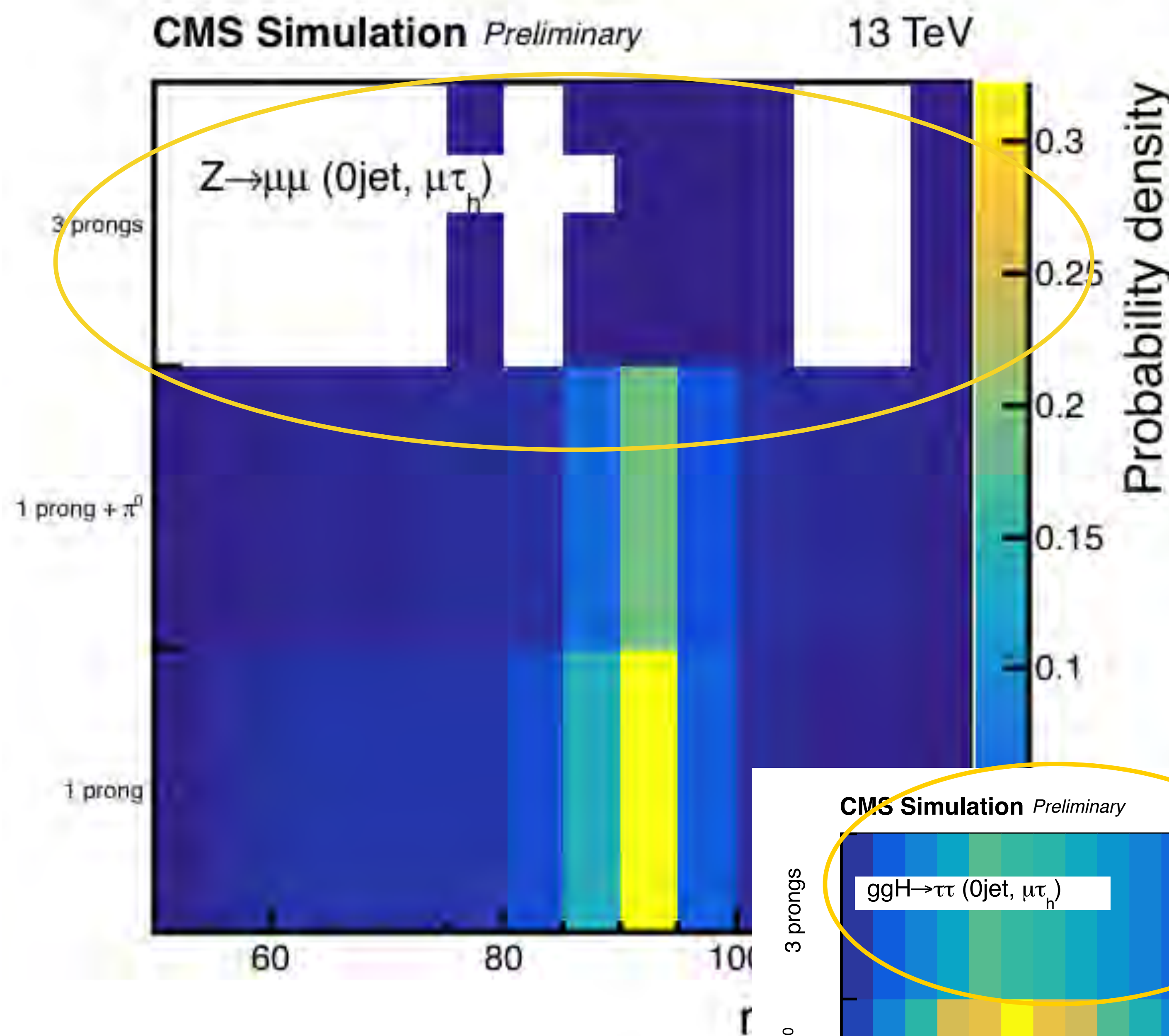
Boosted: 250 < ptH < 300 GeV

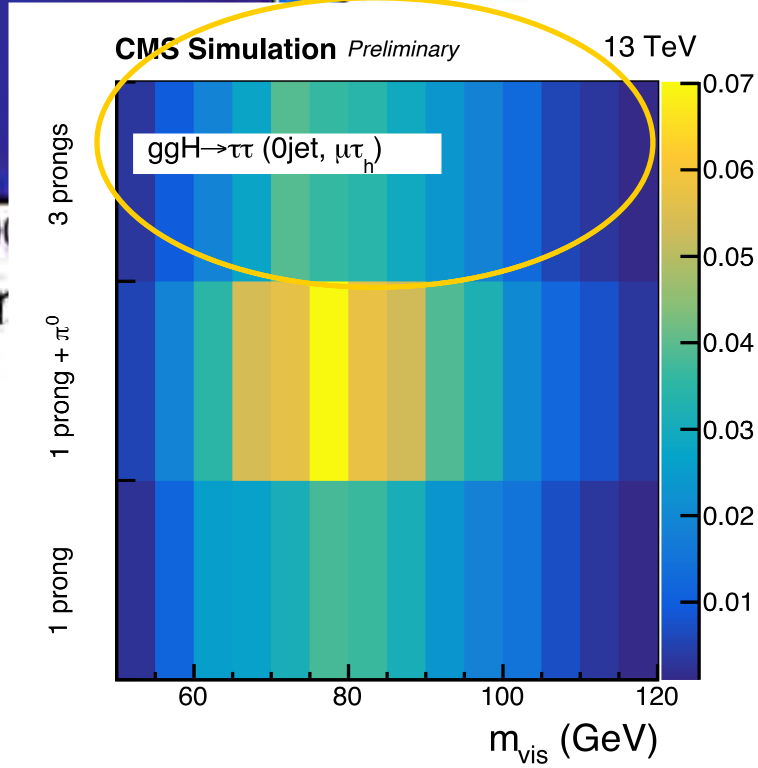


Boosted: ptH > 300 GeV

0-jet τ Decay Mode 2D

- In 0-jet category for ℓτ channels, ZL distribution is mostly confined to 1-prong decay mode and 1-prong 1-pi0. 3 prong is devoid of ZL background.
- Tau ℓ->τ fake scale factors were measured inclusively in pT and hard to extrapolate differentially
- Tau Energy Scale (TES) is better measured when versus by decay mode





Zee/Zμμ Treatment

- The e->τ, μ->τ fakes are further corrected in energy scale (ES) and yield in eτ and μτ. Versus by decay mode in 0-jet necessitated changes.

- The 1.2% τ_h ES is not applied to ℓ->τ fakes, the ES measured for ℓ->τ fakes is shown in the table below. Additionally τ_h anti-lepton discriminator scale factors were measured inclusively, not split by decay mode. Scale factors per decay mode are applied.

	1-Prong Decay Mode	1-Prong+pi0	3-Prong
μτ τ pt ES	-0.2% +/- 1.5%	1.5% +/- 1.5%	0 +/- 1.5%
μ->τ fake rate correction	0.75 (25%)	1.0 (25%)	-
eτ τ pt ES	0 +/- 3%	9.5% +/- 3%	0 +/- 3%
e->τ fake rate correction	0.98(12%)	1.2(12%)	-

Full Kinematic Selections

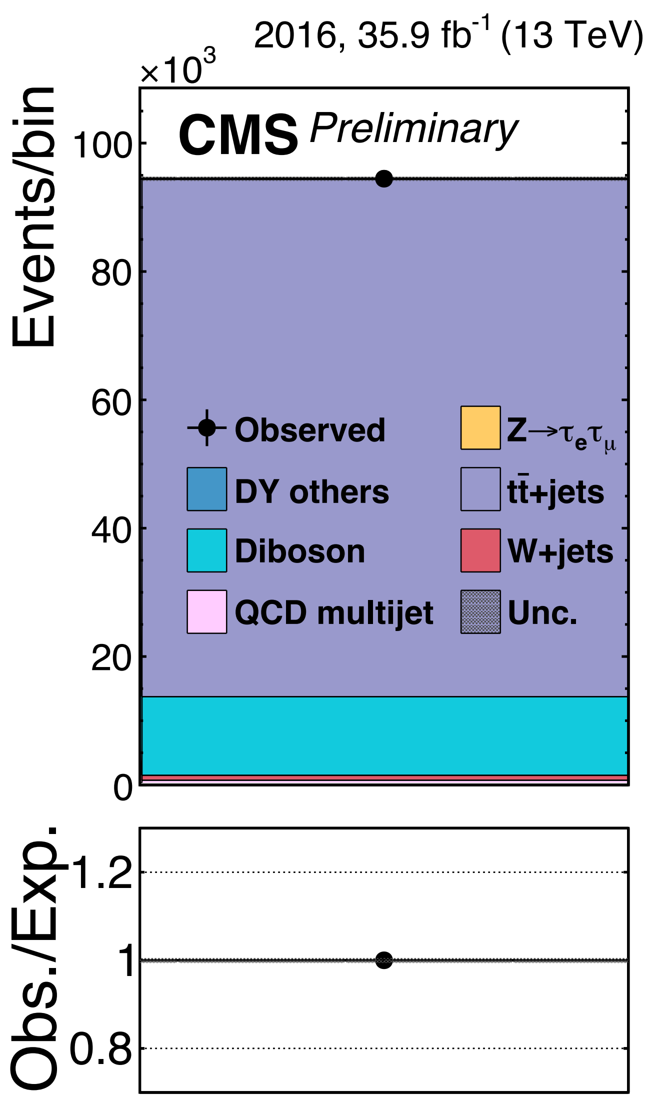
Table 8.1: Kinematic selection requirements for the four $\tau\tau$ decay channels.

Final state	Trigger requirement	Lepton selection		
		p_T (GeV)	η	Isolation
$\mu\tau_h$	$\mu(22)$	$p_T{}^{\mu} > 23$	$\lvert\eta^{\mu}\rvert < 2.1$	$I^{\mu}_{rel} < 0.15$
	–	$p_T{}^{\tau_h} > 30$	$\lvert\eta^{\tau_h}\rvert < 2.3$	MVA τ_h ID
	$\mu(19)$	$20 < p_T{}^{\mu} < 23$	$\lvert\eta^{\mu}\rvert < 2.1$	$I^{\mu}_{rel} < 0.15$
	$\tau_h(21)$	$p_T{}^{\tau_h} > 30$	$\lvert\eta^{\tau_h}\rvert < 2.3$	MVA τ_h ID
$e\tau_h$	e(25)	$p_T{}^{e} > 26$	$\lvert\eta^{e}\rvert < 2.1$	$I^{e}_{rel} < 0.1$
	–	$p_T{}^{\tau_h} > 30$	$\lvert\eta^{\tau_h}\rvert < 2.3$	MVA τ_h ID
$\tau_h\tau_h$	$\tau_h(35)$ (leading)	$p_T{}^{\tau_h} > 50$	$\lvert\eta^{\tau_h}\rvert < 2.1$	MVA τ_h ID
	$\tau_h(35)$ (sub-leading)	$p_T{}^{\tau_h} > 40$	$\lvert\eta^{\tau_h}\rvert < 2.1$	MVA τ_h ID
$e\mu$	e(12) (sub-leading)	$p_T{}^{e} > 13$	$\lvert\eta^{e}\rvert < 2.5$	$I^{e}_{rel} < 0.15$
	$\mu(23)$ (leading)	$p_T{}^{\mu} > 24$	$\lvert\eta^{\mu}\rvert < 2.4$	$I^{\mu}_{rel} < 0.2$
	e(23) (leading)	$p_T{}^{e} > 24$	$\lvert\eta^{e}\rvert < 2.5$	$I^{e}_{rel} < 0.15$
	$\mu(8)$ (sub-leading)	$p_T{}^{\mu} > 15$	$\lvert\eta^{\mu}\rvert < 2.4$	$I^{\mu}_{rel} < 0.2$

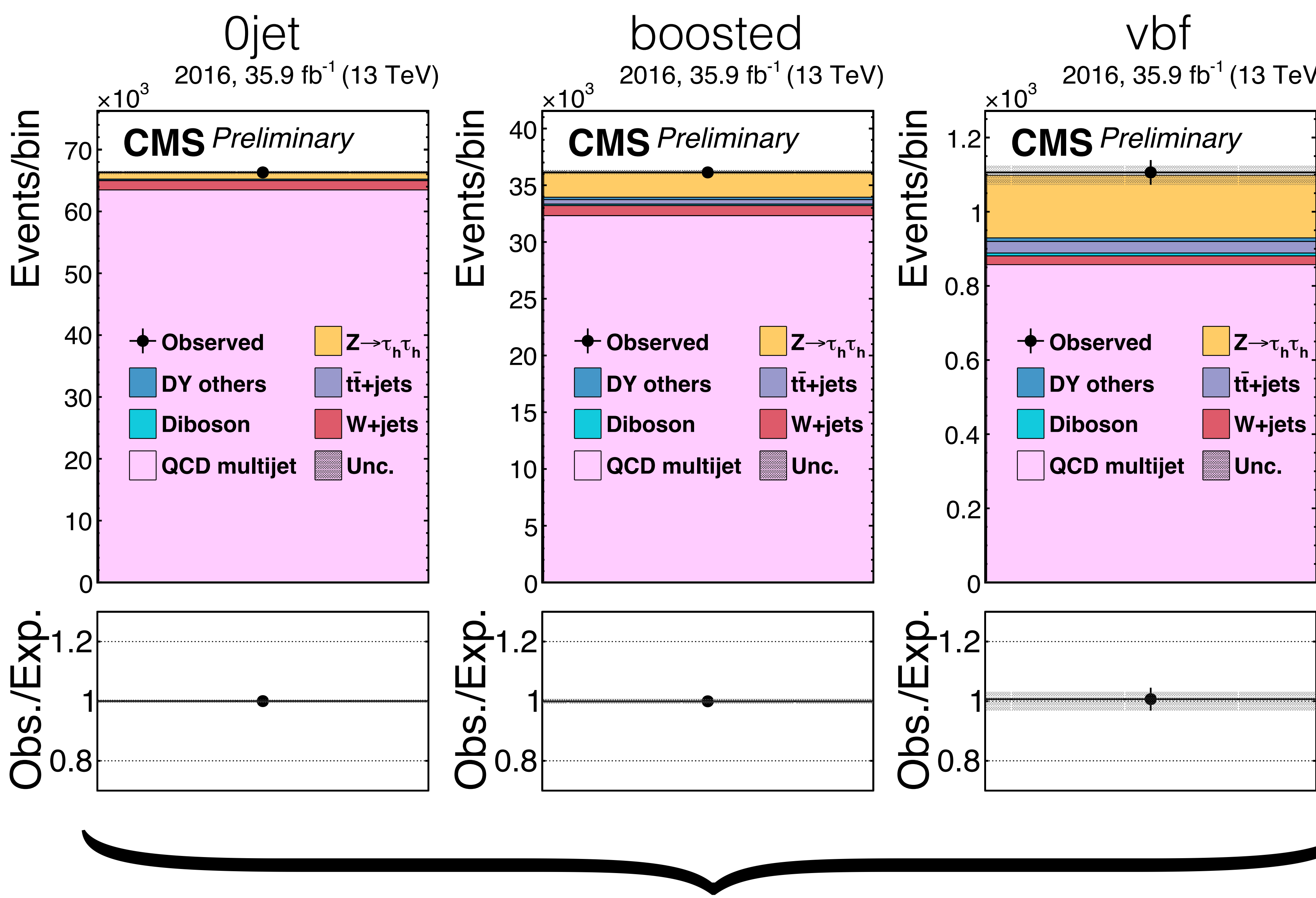
Other CR: ttbar, ττ QCD postfit

NOT MY THESIS

- ttbar control region produced from eμ channel
  - Affects rate in every channel/category in fit
  - Pζ <-35



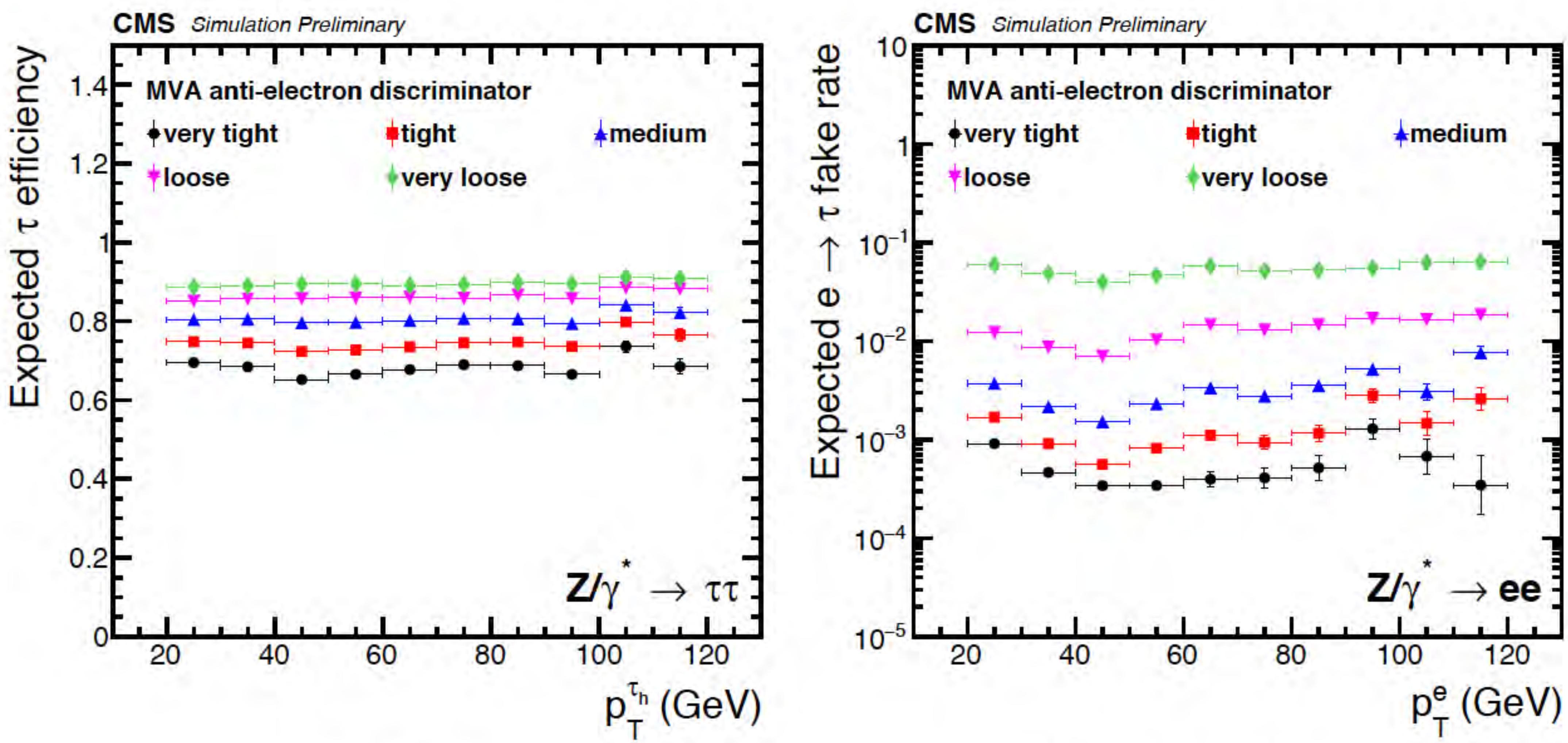
- OS, anti-isolated τ, svMass
- 0jet ($m_{\tau\tau}$: 0-300 GeV)
- boosted/vbf ($m_{\tau\tau}$: 0-250 GeV)



QCD ττ Control Regions

Hadronic Tau Identification

- Working point efficiencies and misidentification probabilities

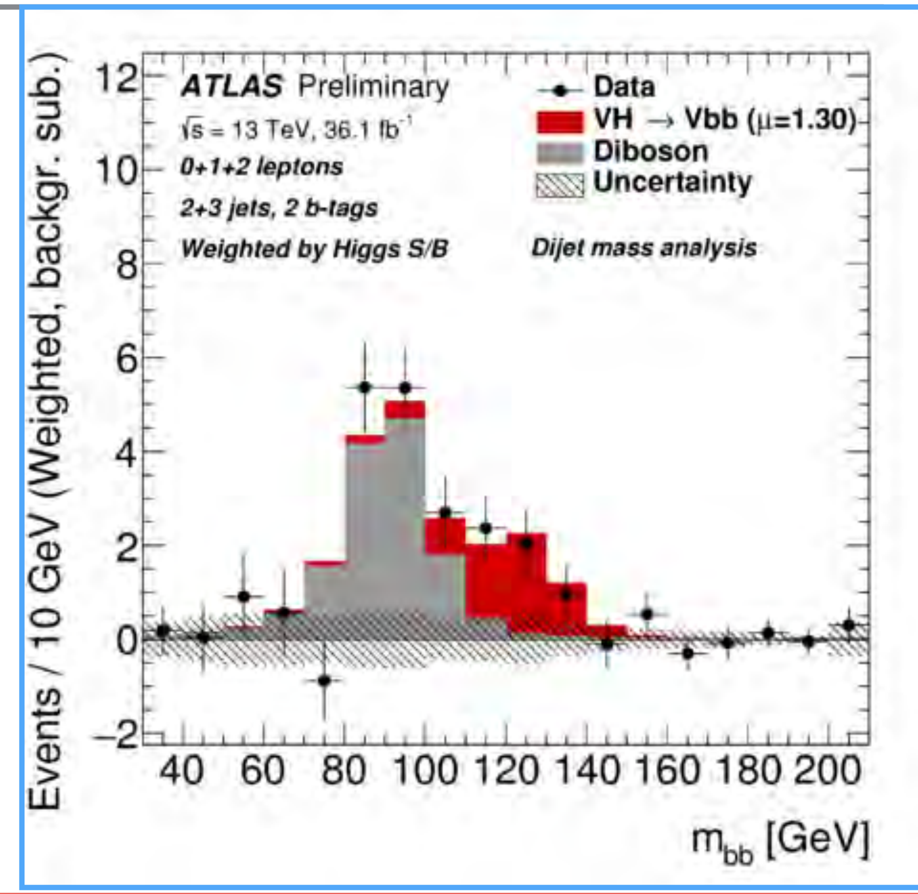


(a) τ_h efficiency

(b) electron-τ_h-fake rate

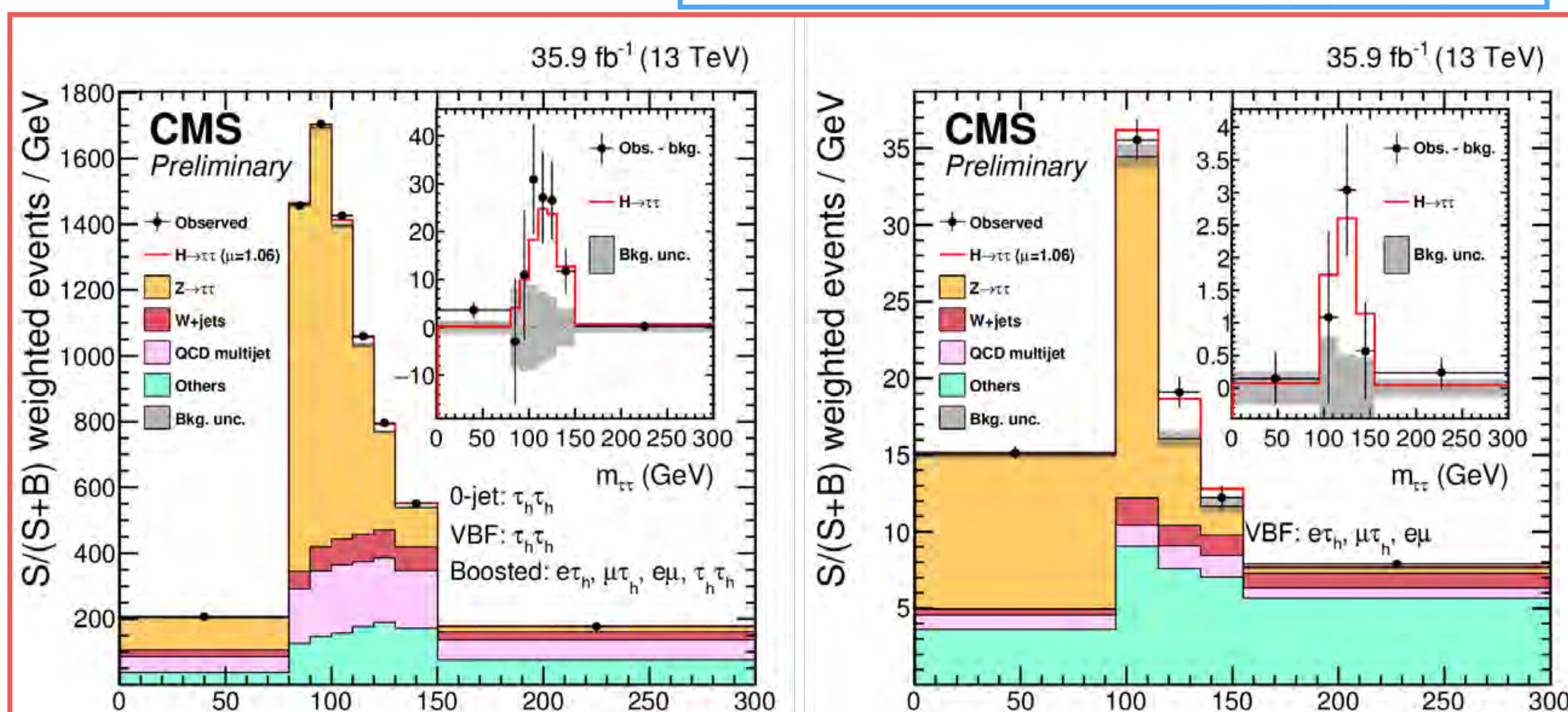
Status of 125 GeV Higgs

- Does the Higgs have a Yukawa coupling? Further confirmation of the yukawa-coupling arrives.
- VH(bb) Run-II evidence at ATLAS with 3.5(3.0) σ observed (expected) with a signal strength μ =1.20 +0.24 -0.23 (stat) +0.34 -0.28 (syst) in 13 TeV. Combination with Run-1: σ observed (expected) 3.6(4.0) with μ = 0.90 ± 0.18(stat.) +0.21 –0.19(syst.)
- H(ττ) Run-II at 4.9(4.7) σ observed (expected) at CMS in 2016 data. (μ=1.06 +0.25 -0.24).
- How can we use it to find dark matter?



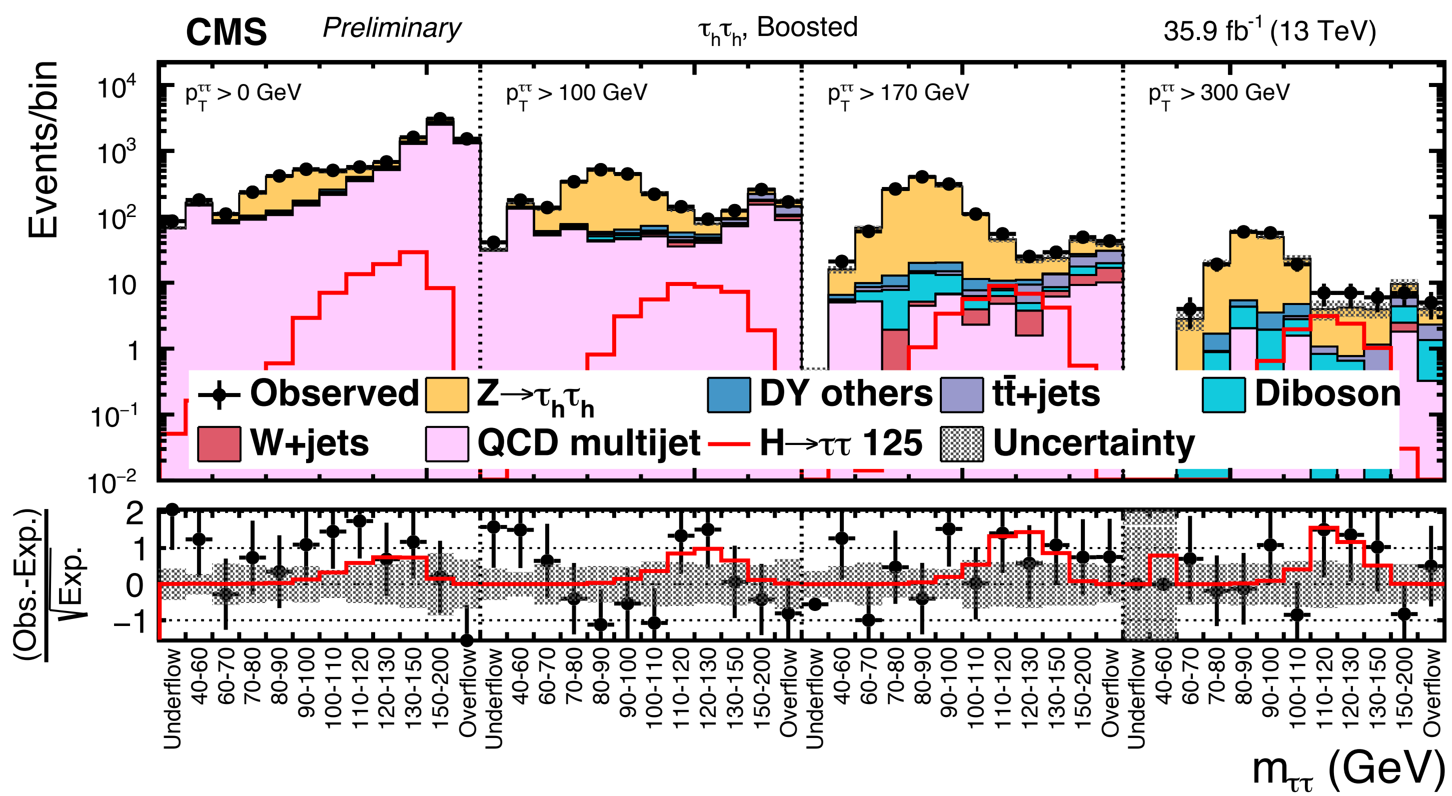
ATLAS and CMS continue Higgs measurements in Run-II at LHC.

ATLAS-CONF-2017-041
CMS-PAS-HIG-16-043



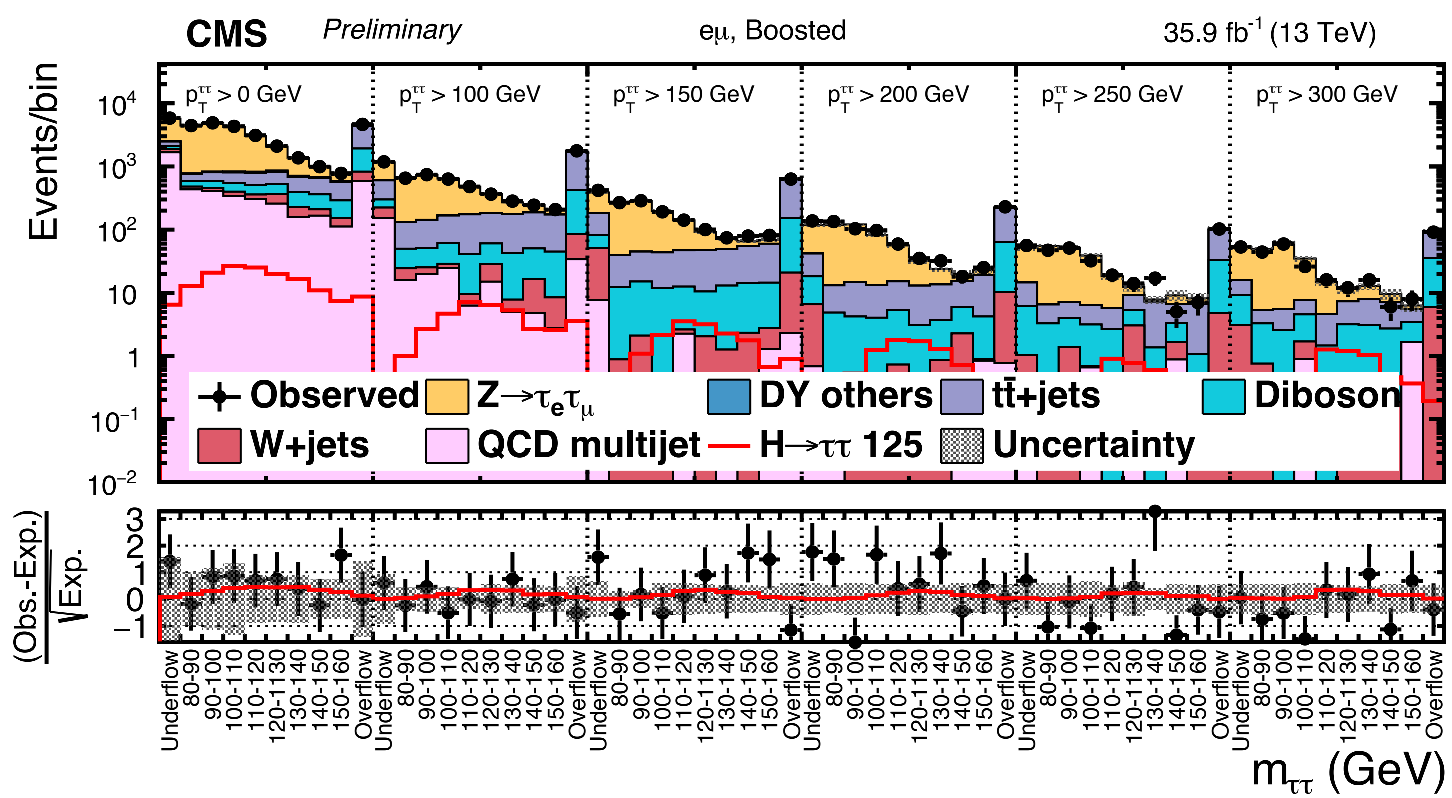
boosted postfit: eμ ττ

ττ boosted:
$m_{\tau\tau}$: H pT



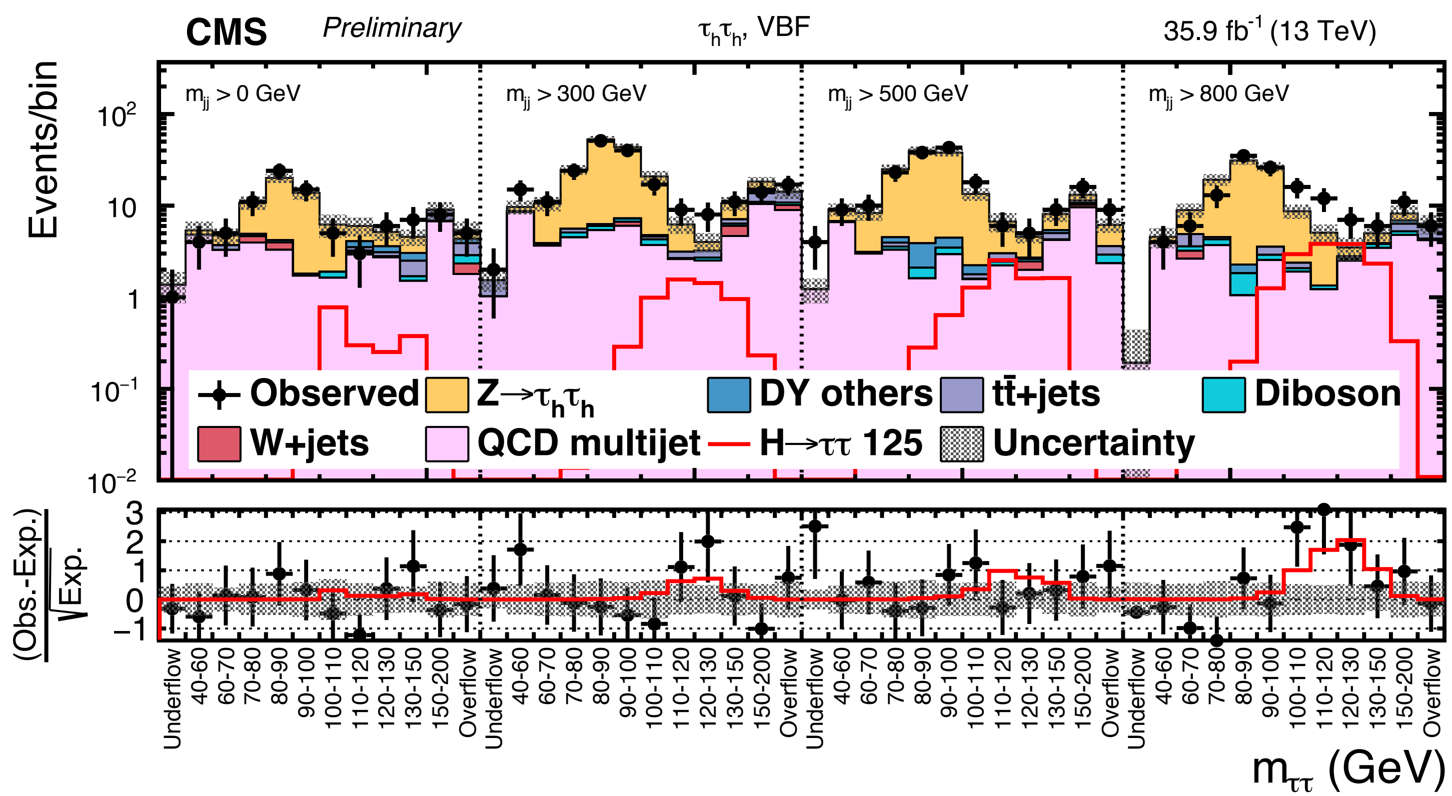
NOT MY THESIS

eμ boosted:
$m_{\tau\tau}$: H pT



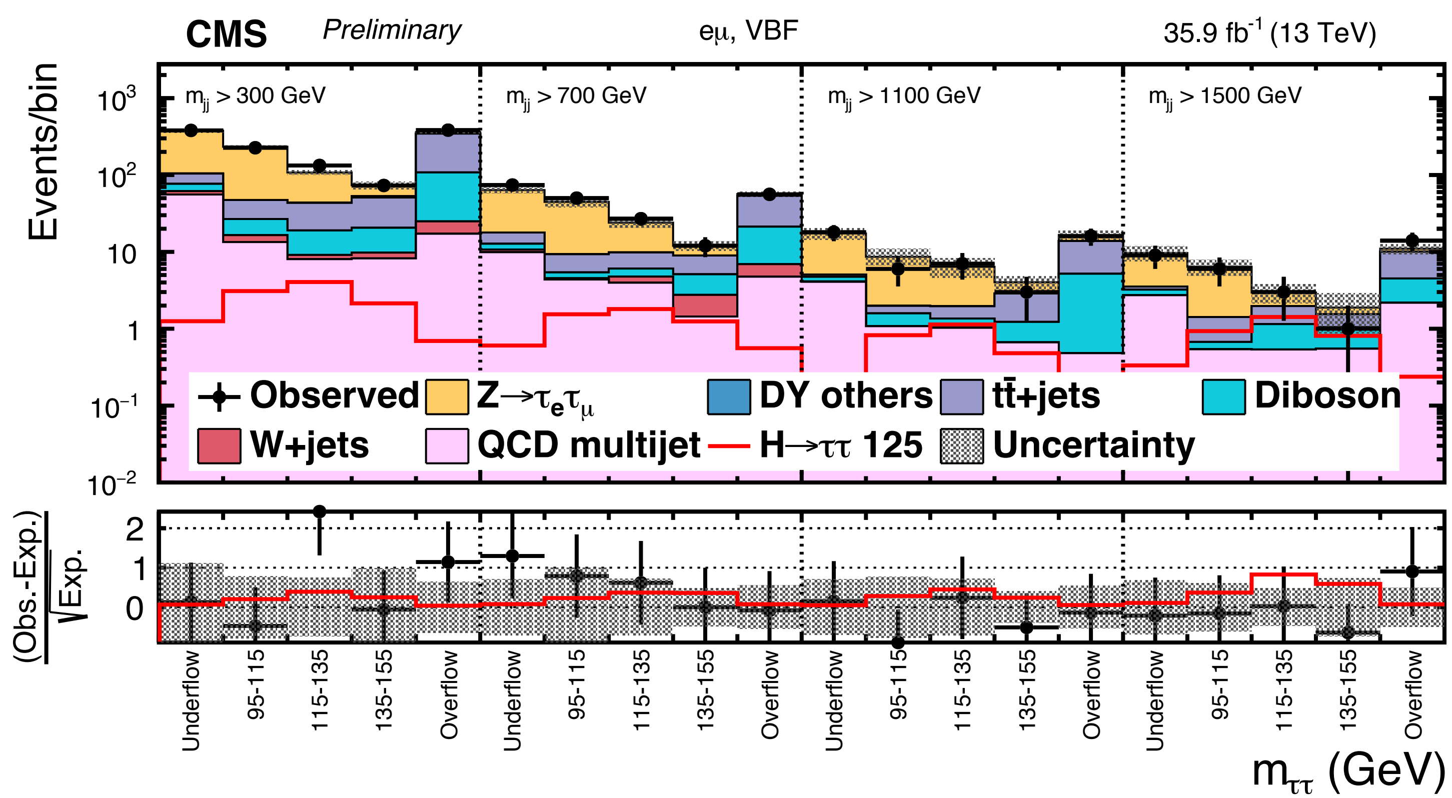
vbf postfit: eμ ττ

ττ vbf:
$m_{\tau\tau}$: di-jet mass



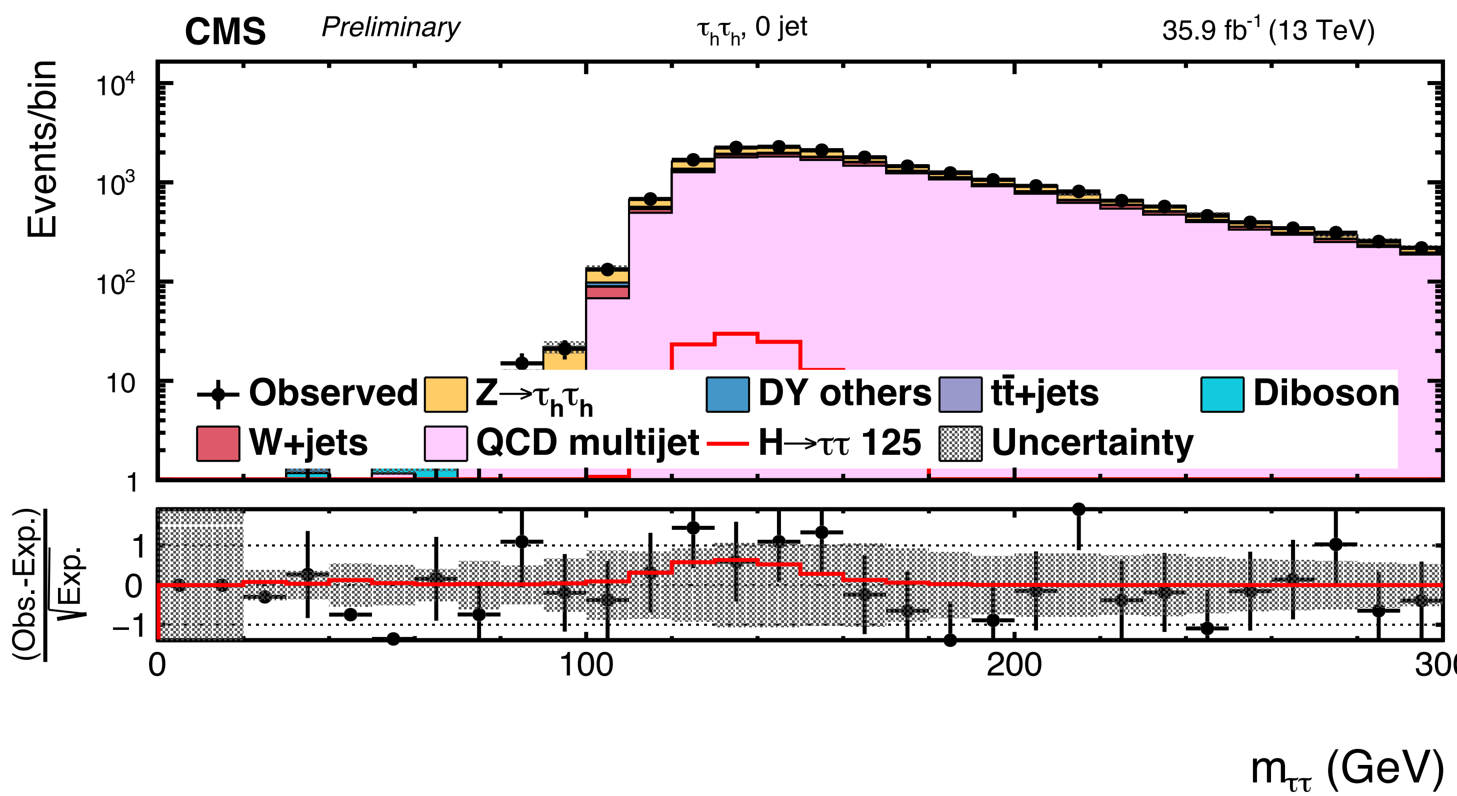
NOT MY THESIS

eμ vbf:
$m_{\tau\tau}$: di-jet mass



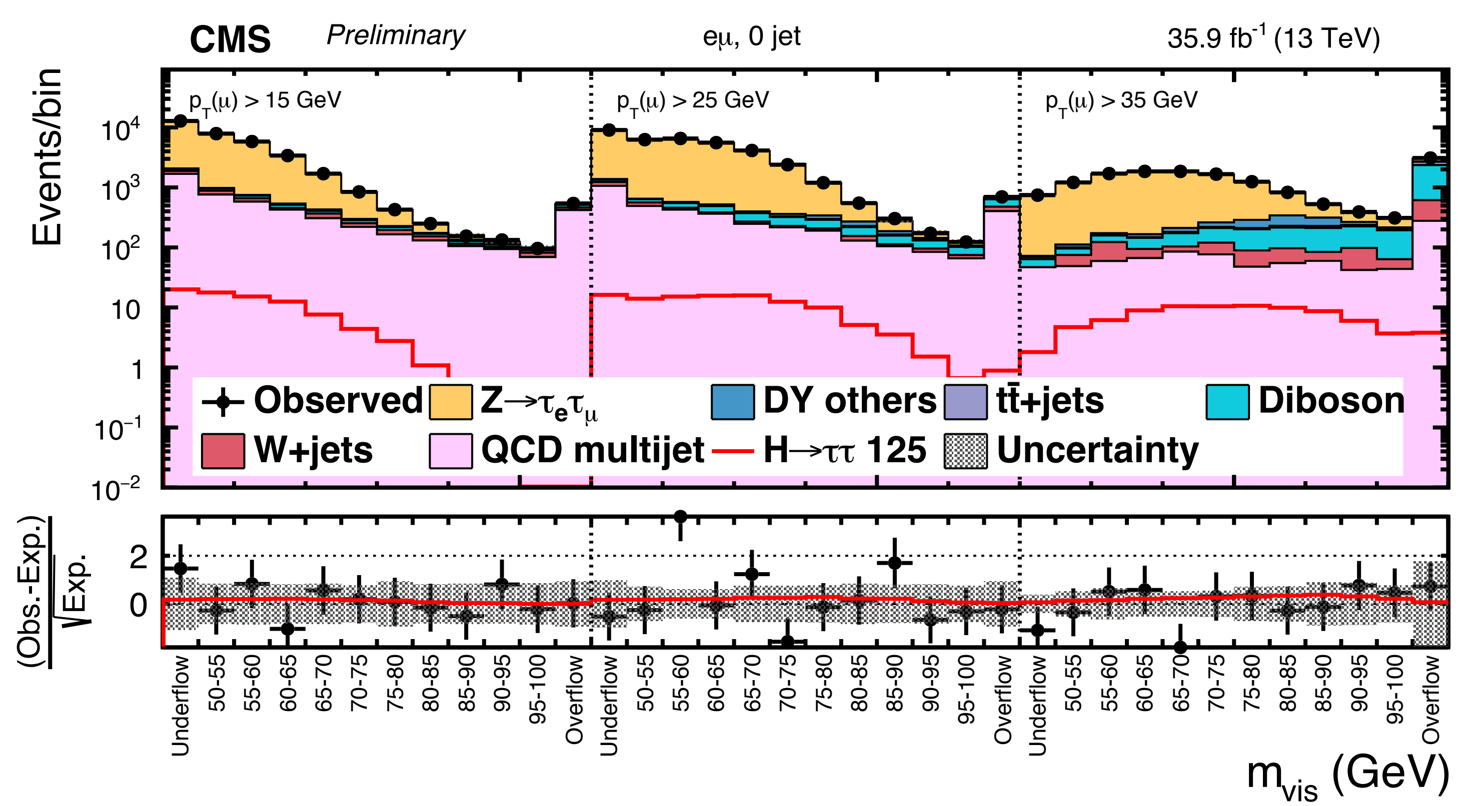
0jet postfit: eμ ττ

ττ 0jet:
1-D $m_{\tau\tau}$



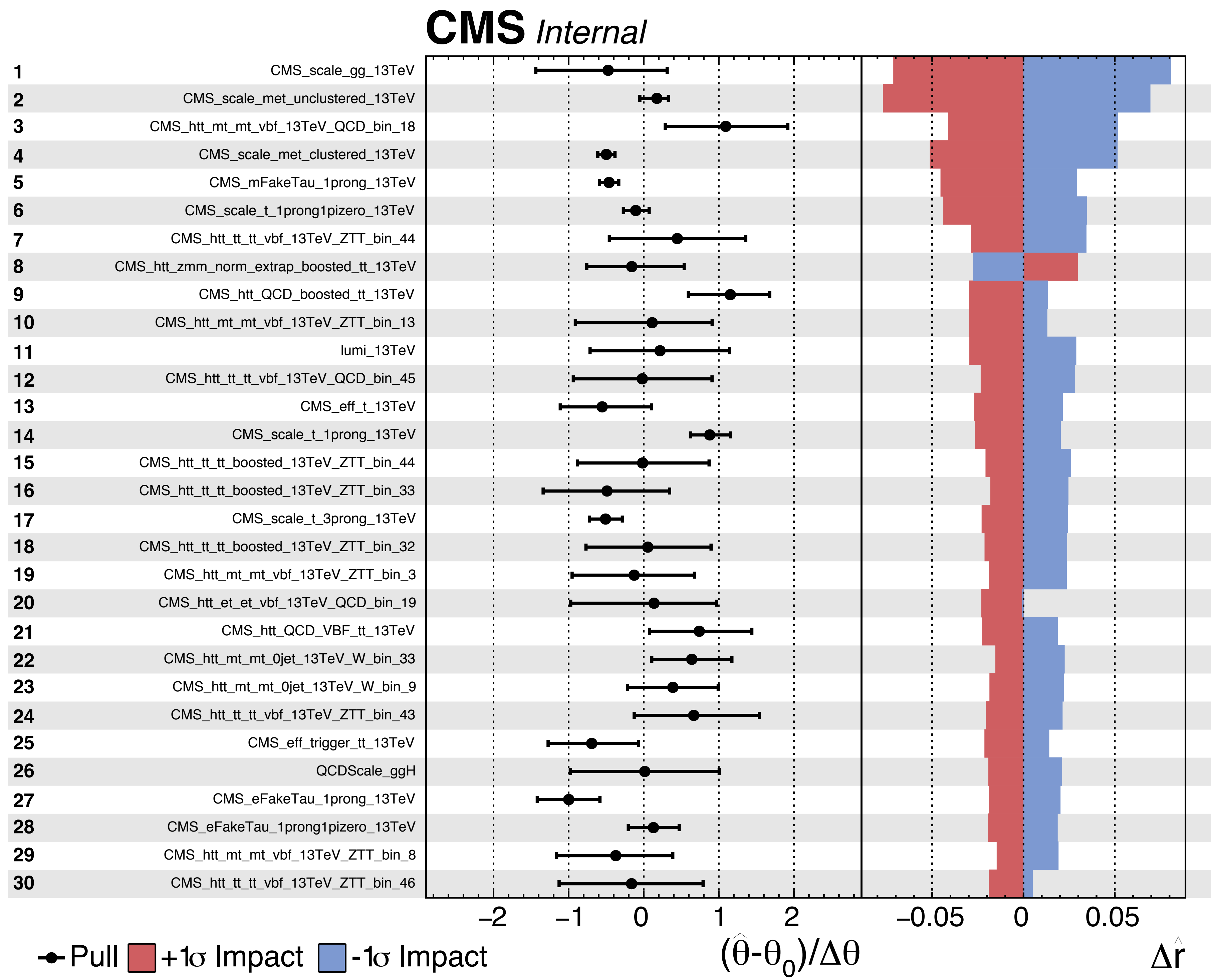
NOT MY THESIS

eμ 0jet:
m_{vis} : μ pT



Combined Impacts

- Highest impacts and respective pulls
- Combined all channels and all categories
- Theoretical uncertainty largest impact, unclustered energy scale second largest impact



Higgs Pt Uncertainty

Various sources of theoretical uncertainties are included in this analysis:

- Uncertainty on $H \to \tau\tau$ branching fraction, composed of three independent sources of uncertainties.
- Uncertainty on cross section based on YR4, composed of three independent sources of uncertainties.
- Uncertainty on acceptance due to renormalization and factorization scales: considered as a shape uncertainty as explained in the previous paragraph.
- Uncertainty on acceptance due to the parton shower tune.
- Uncertainty on acceptance by comparing Powheg (default) and aMC@NLO signal samples. Up to 20% for the ggH process, and up to 10% for the qqH process.
- Uncertainty on acceptance due to α_S: less than 1%.

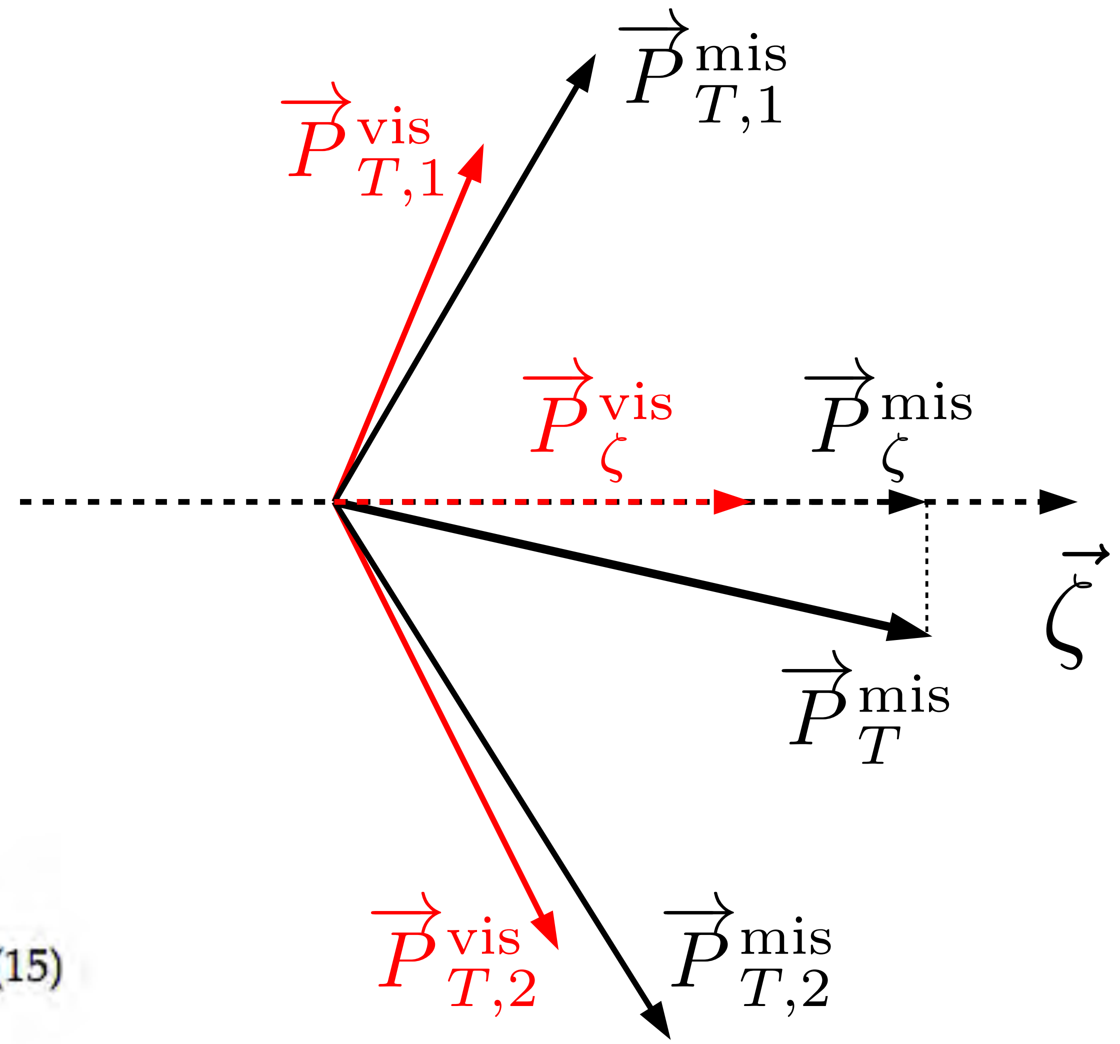
pzeta definition

- Variable used to cut for top control region
    - measure of MET collinearity with tau candidates

$$D_\zeta = P_\zeta - 1.85 P_\zeta^{vis}$$

$$\text{with } P_\zeta = (\vec{P}_{T,1}^{vis} + \vec{P}_{T,2}^{vis} + \vec{P}_T^{mis}) \frac{\vec{\zeta}}{|\vec{\zeta}|} \qquad (15)$$

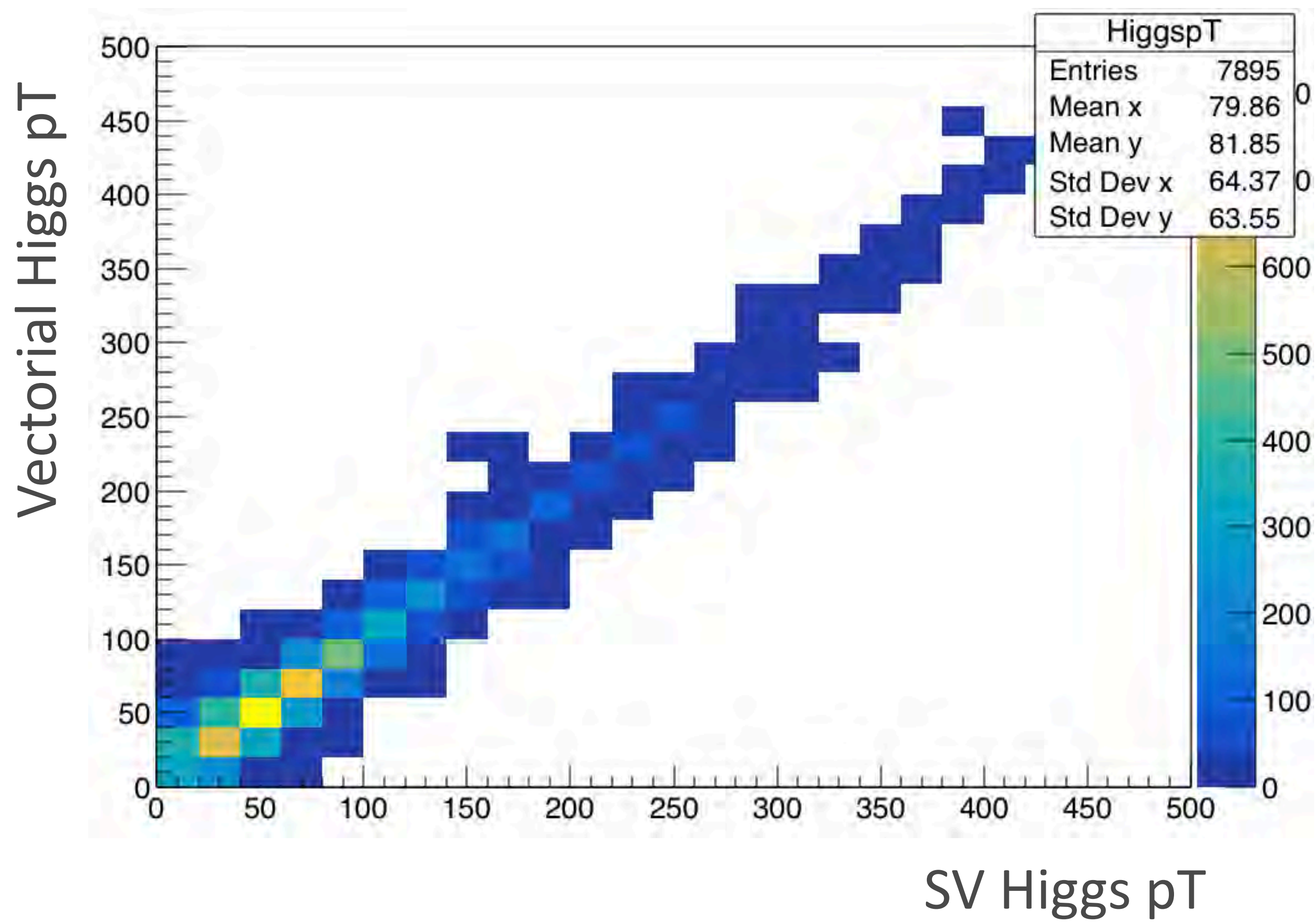
$$\text{and } P_\zeta^{vis} = (\vec{P}_{T,1}^{vis} + \vec{P}_{T,2}^{vis}) \frac{\vec{\zeta}}{|\vec{\zeta}|}$$



2D Boosted Category

- Moved from svFit total pT to vectorial higgs pT
  - Vectorial higgs pT distribution more smooth
  - Small impact on expected limit: <2%.

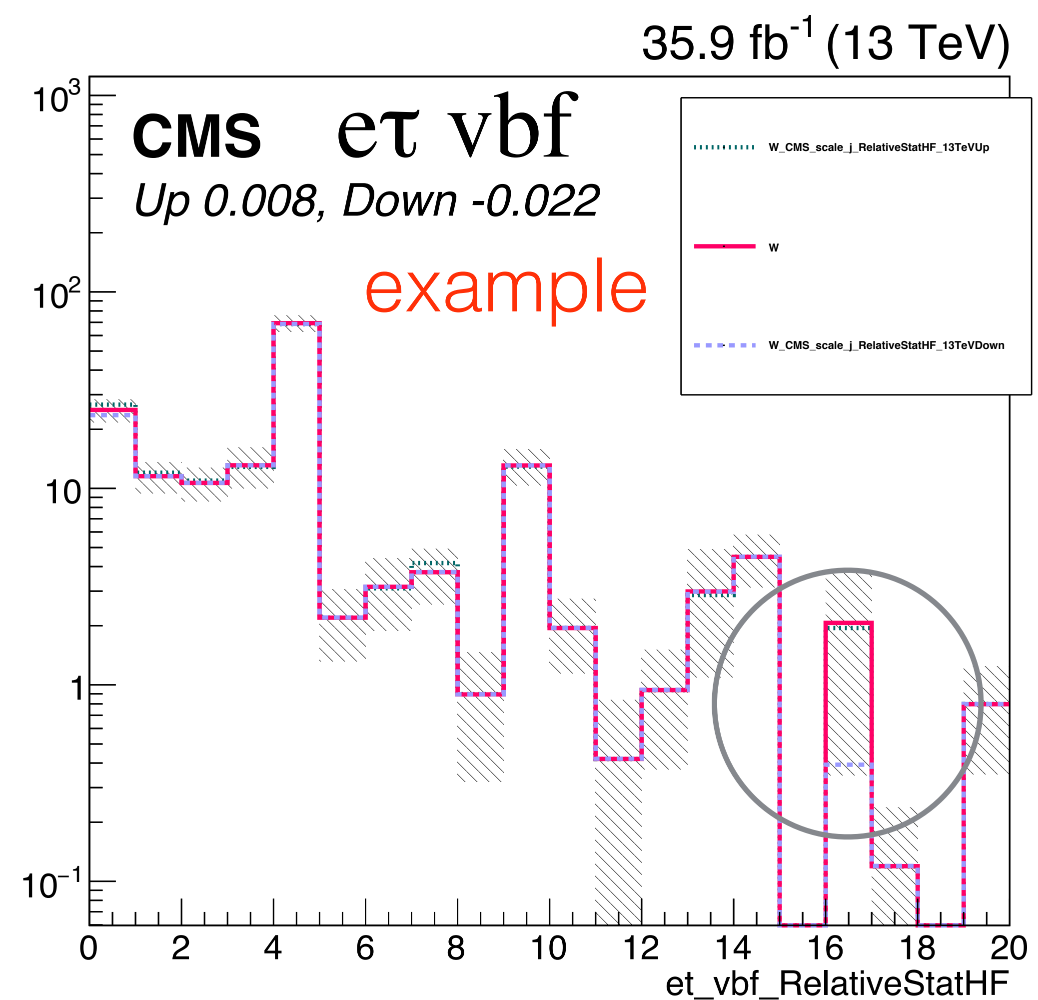
$$p_T^{\tau\tau} = |\vec{p}_T^{L} + \vec{p}_T^{L'} + \vec{E}_T^{miss}|$$



Factorized JES Treatment

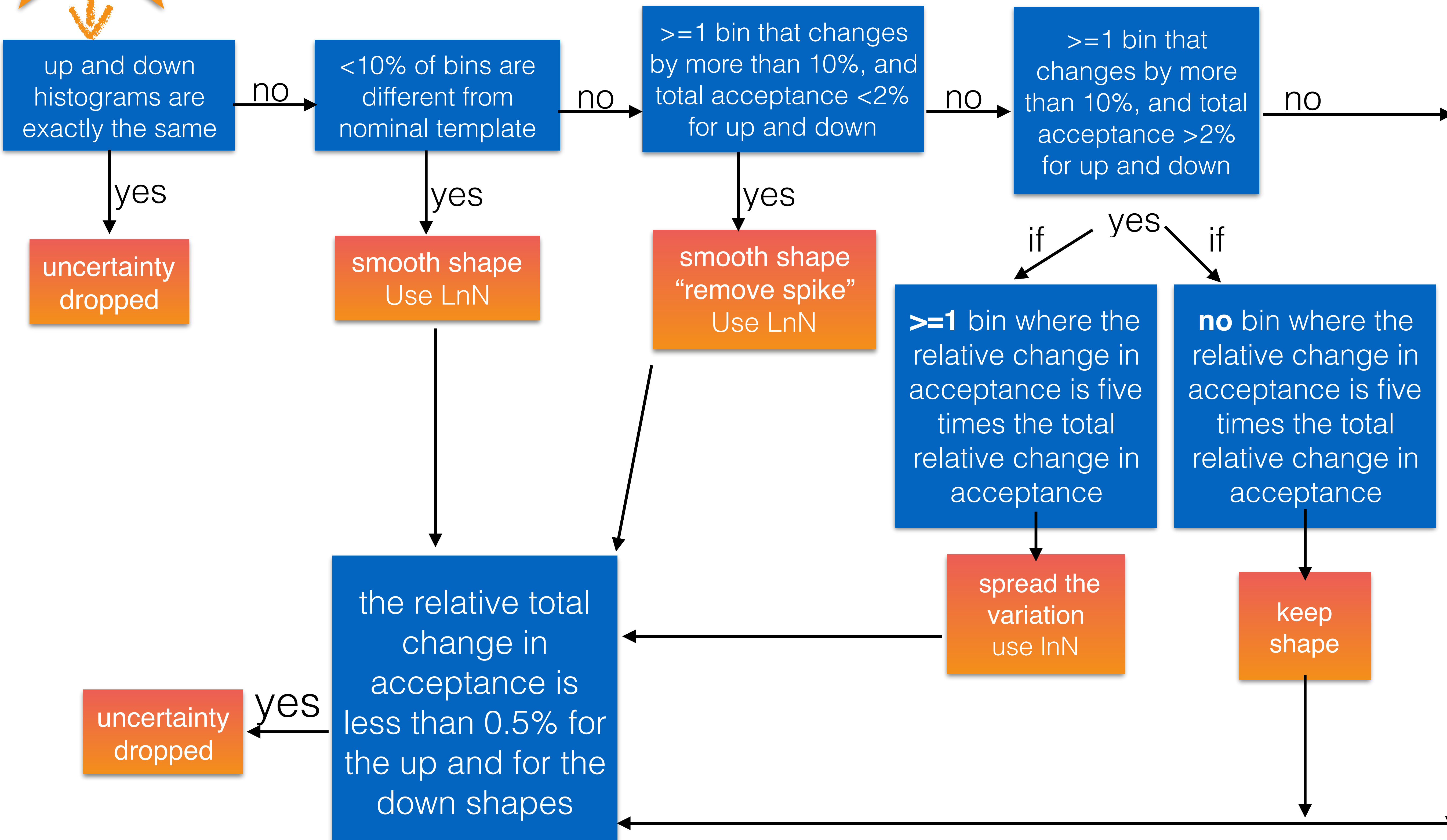
- 27 sources of JES in all categories and channels
- Poorly populated templates in sensitive regions caused impacts to behave poorly.
- JES shape treatment:
  - Shapes either kept if variation is smooth, demoted to lnN if “spiky” template, or dropped from the channel and category if negligible.

W Template Up and Down “RelativeStatHF”



example of poorly behaved template with “spike”

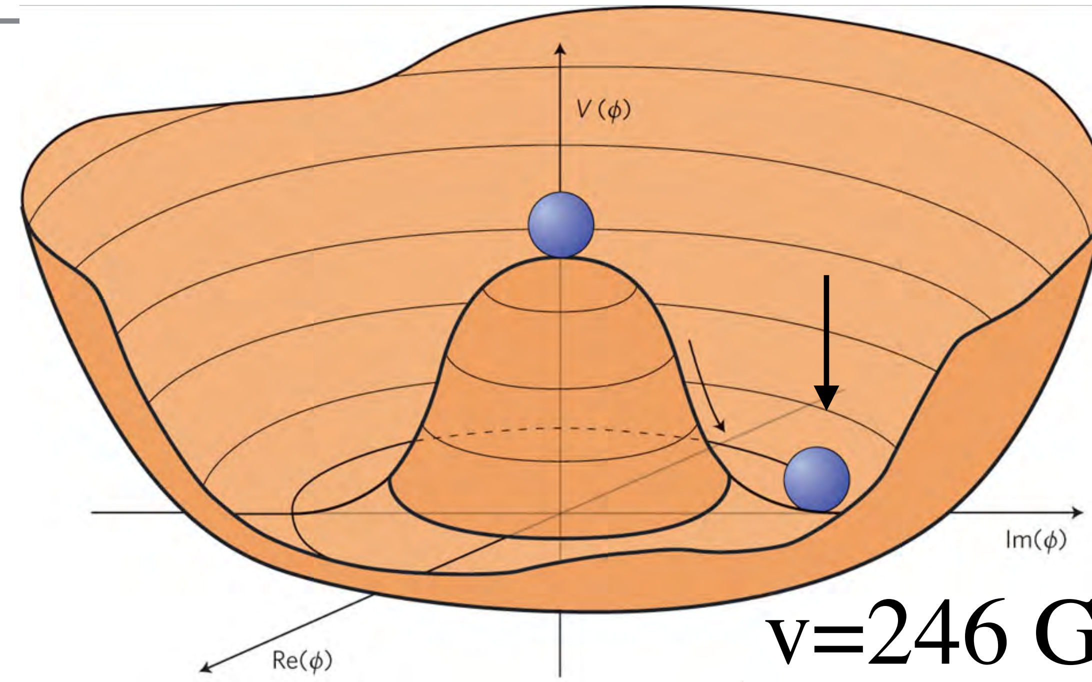
JES Treatment: Chart



Standard Model (SM): Higgs I

scalar doublet

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$



v=246 GeV

$\phi_1^2+\phi_2^2=v$

is put into the following Lagrangian,

$$\mathcal{L} = (D_\mu \phi)^\dagger (D^\mu \phi) + V(\phi) \tag{2.2}$$

where D_μ is a covariant derivative and the potential $V(\phi)$ is

$$V(\phi) = \mu^2 \phi^\dagger \phi + \frac{\lambda}{4}(\phi^\dagger \phi)^2. \tag{2.3}$$

$M_H^2=2\lambda v$

when $\mu^2 < 0$ and $\lambda > 0$

$$M_W = \frac{1}{2} g v, \quad M_Z = \frac{g^2 + g'^2}{2}$$

$$v^2 = -\frac{\mu^2}{\lambda} \equiv 246 \quad \text{GeV}.$$

MonoHbackup

Mono-Higgs Outlook

A thesis is never finished, only abandoned.
—Marià Cepeda,
quoting Juan Alcaraz,
quoting someone else

- Near future
  - Produce more baryonic simulation samples
  - Combine with other mono-Higgs decay channels
  - Interpret results for DM-nucleon cross section exclusion
- Full Run-II
  - Expand analysis to boosted regime where hadronic taus overlap with muon/electron to allow for overlapping tau topology
  - Search for heavy scalar ($\tau\tau$) + DM model

CMS Summary Invisible

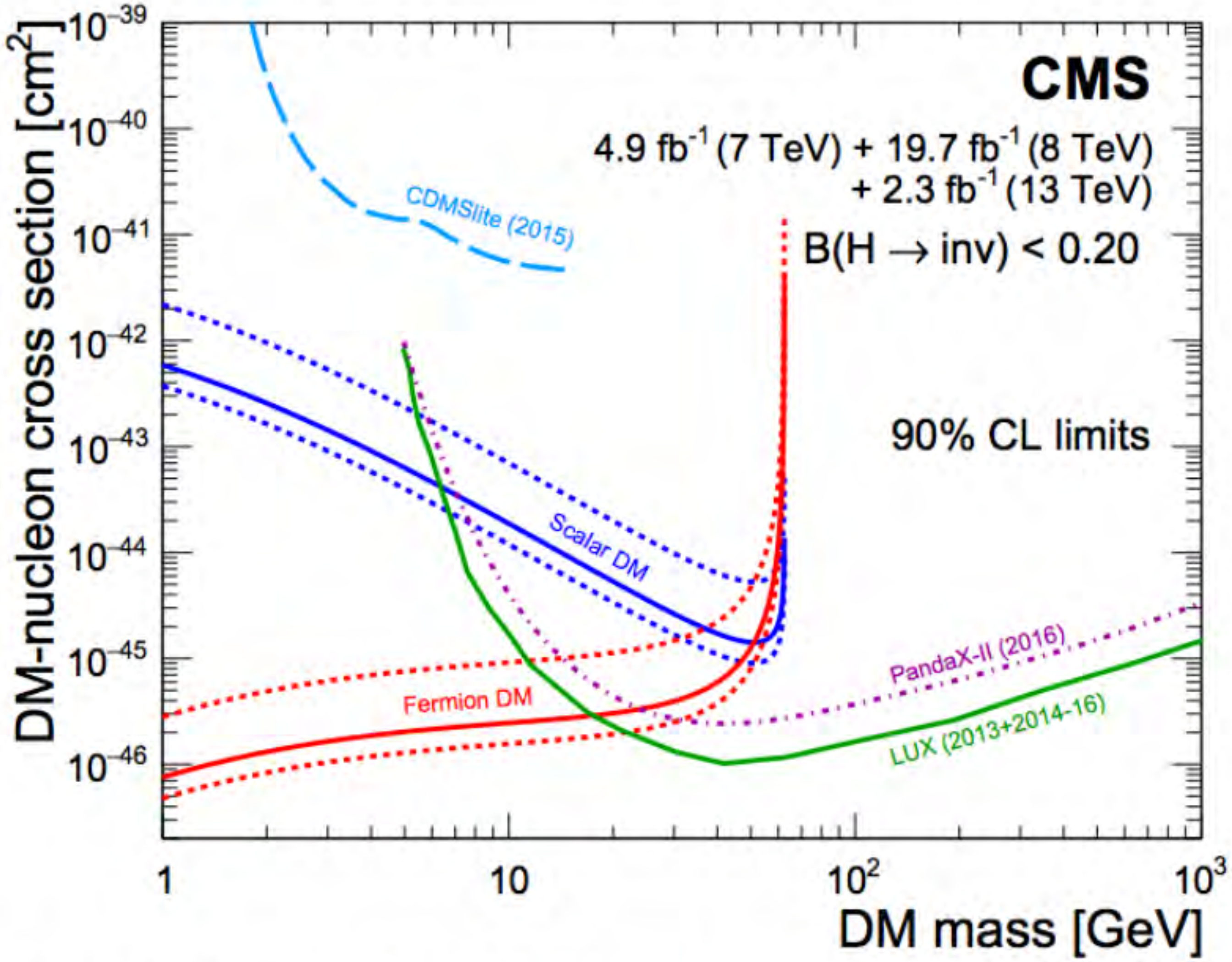
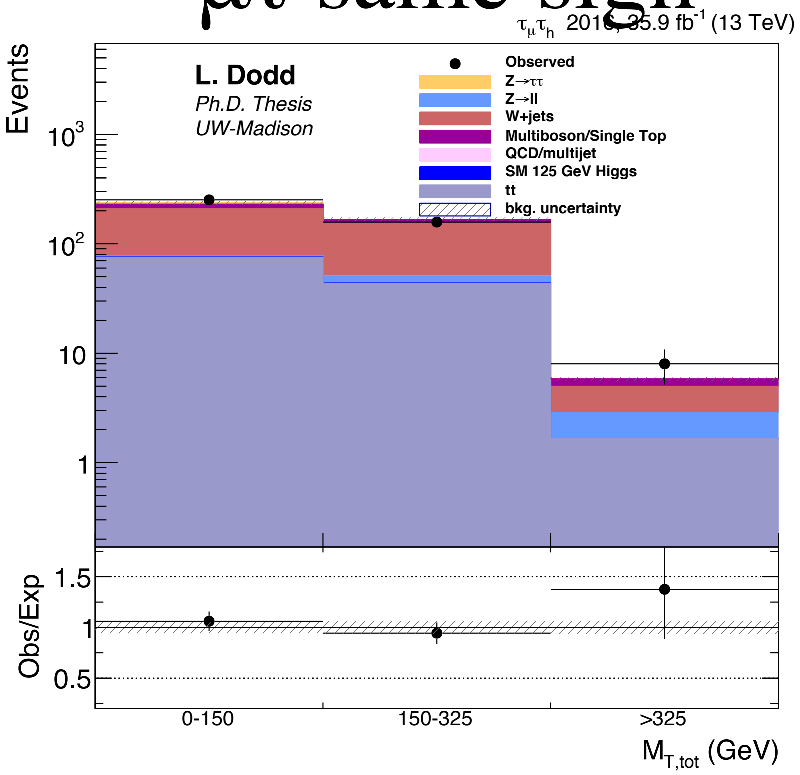


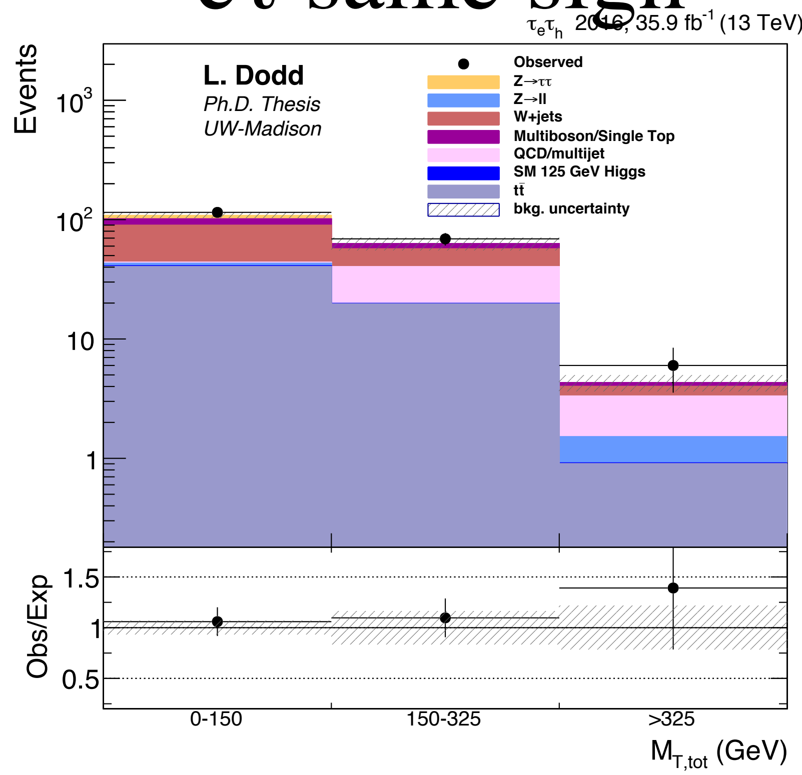
Figure 9: Limits on the spin-independent DM-nucleon scattering cross section in Higgs-portal models assuming a scalar or fermion DM particle. The dashed lines show the variation in the exclusion limit using alternative values for f_N as described in the text. The limits are given at the 90% CL to allow for comparison to direct detection constraints from the LUX [95], PandaX-II [96], and CDMSlite [97] experiments.

Control Regions

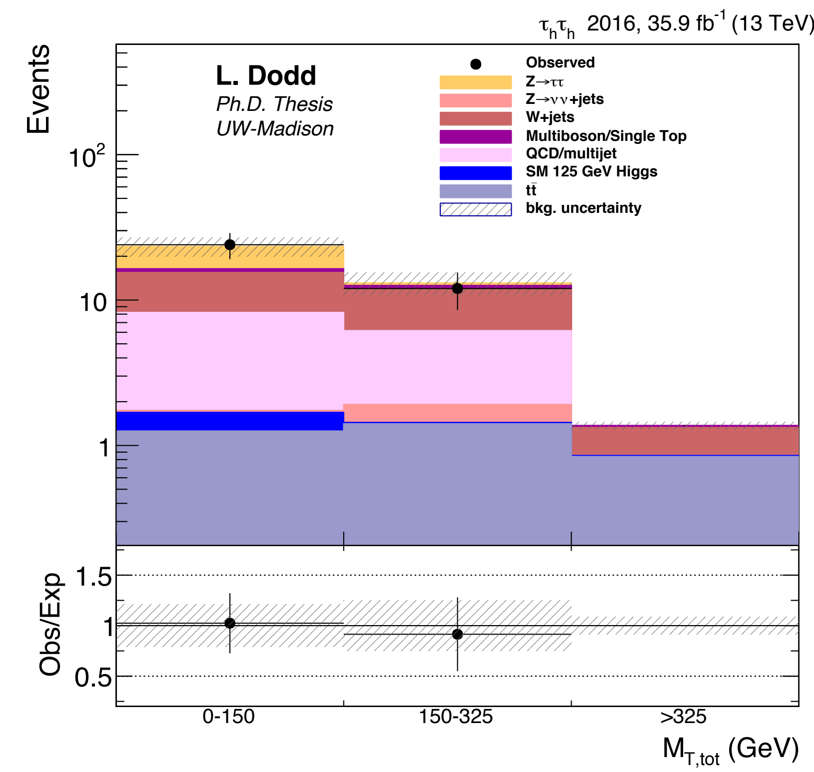
μτ same sign

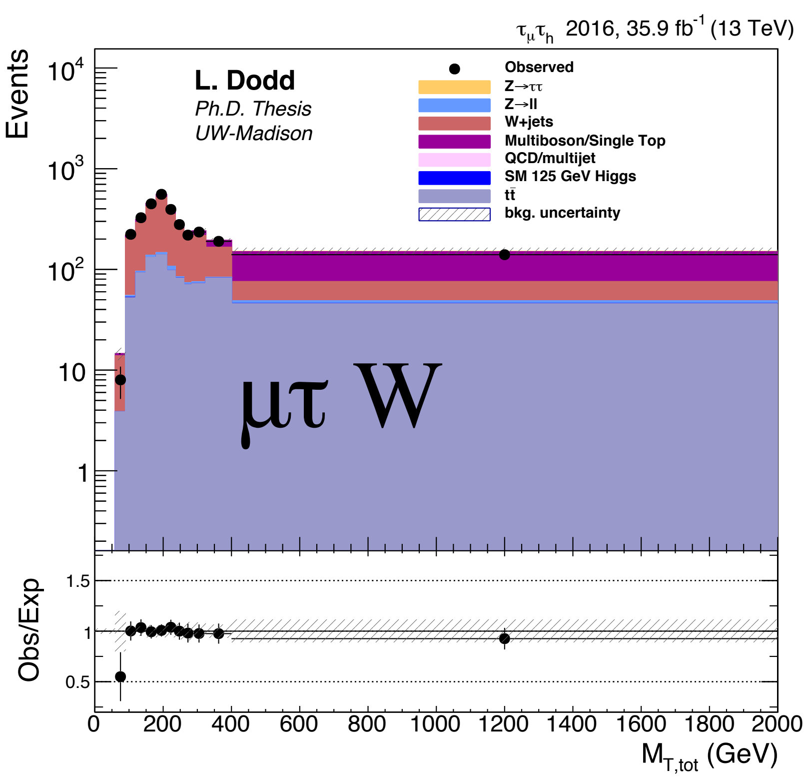


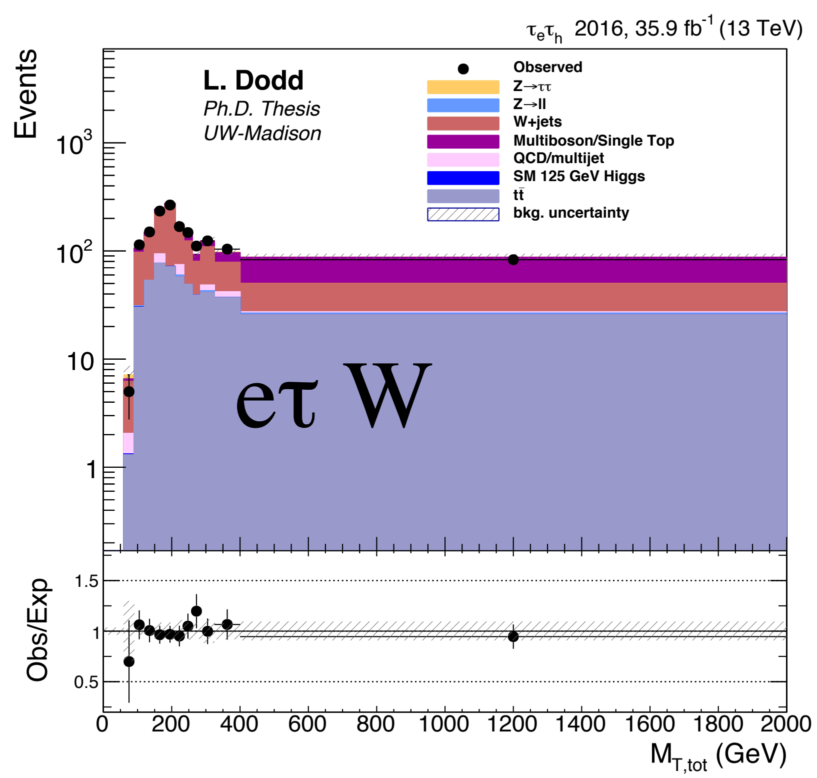
eτ same sign



ττ same-sign







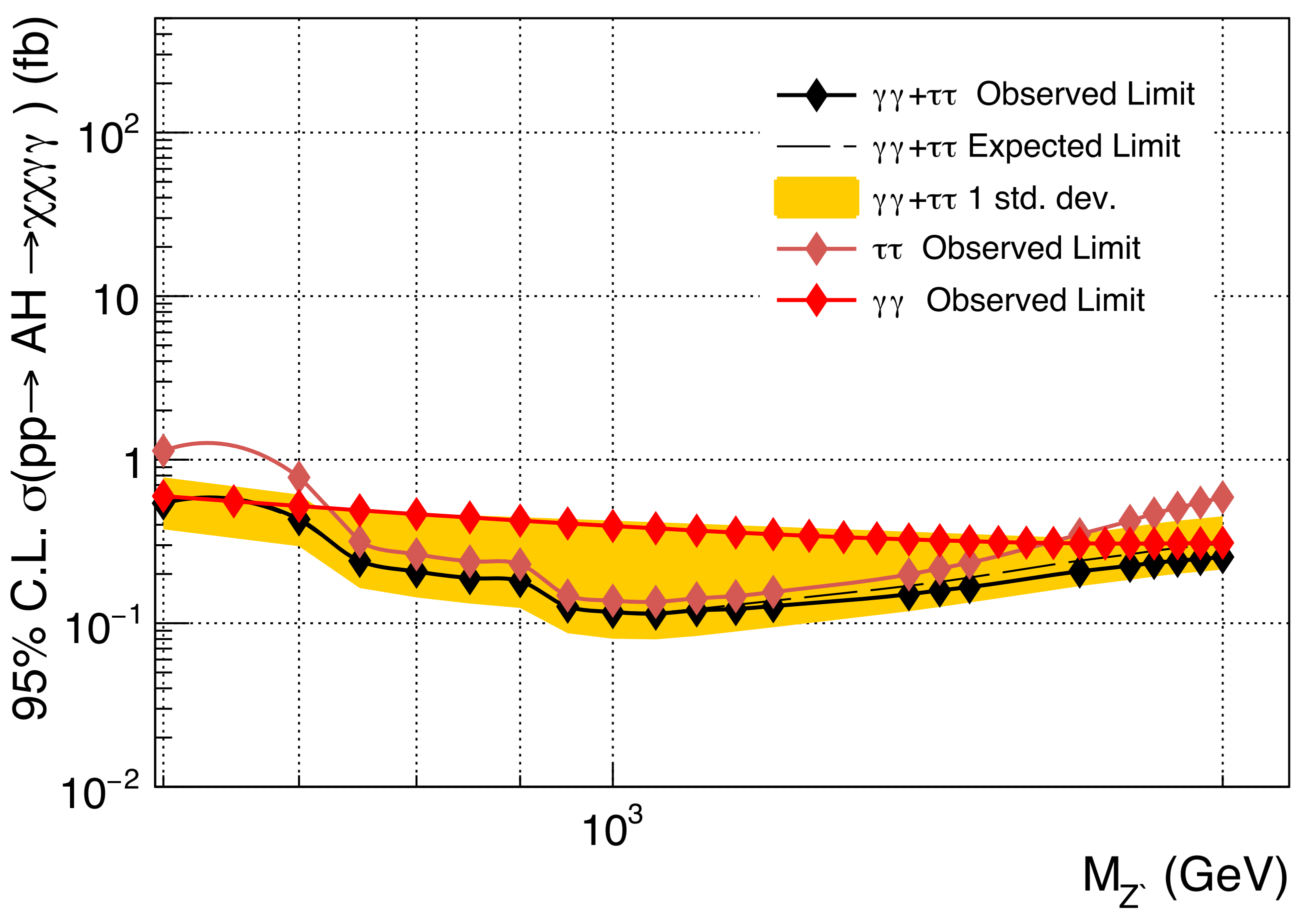
Mono-Higgs Cutflow

Table 9.2: Number of observed events in selection process.

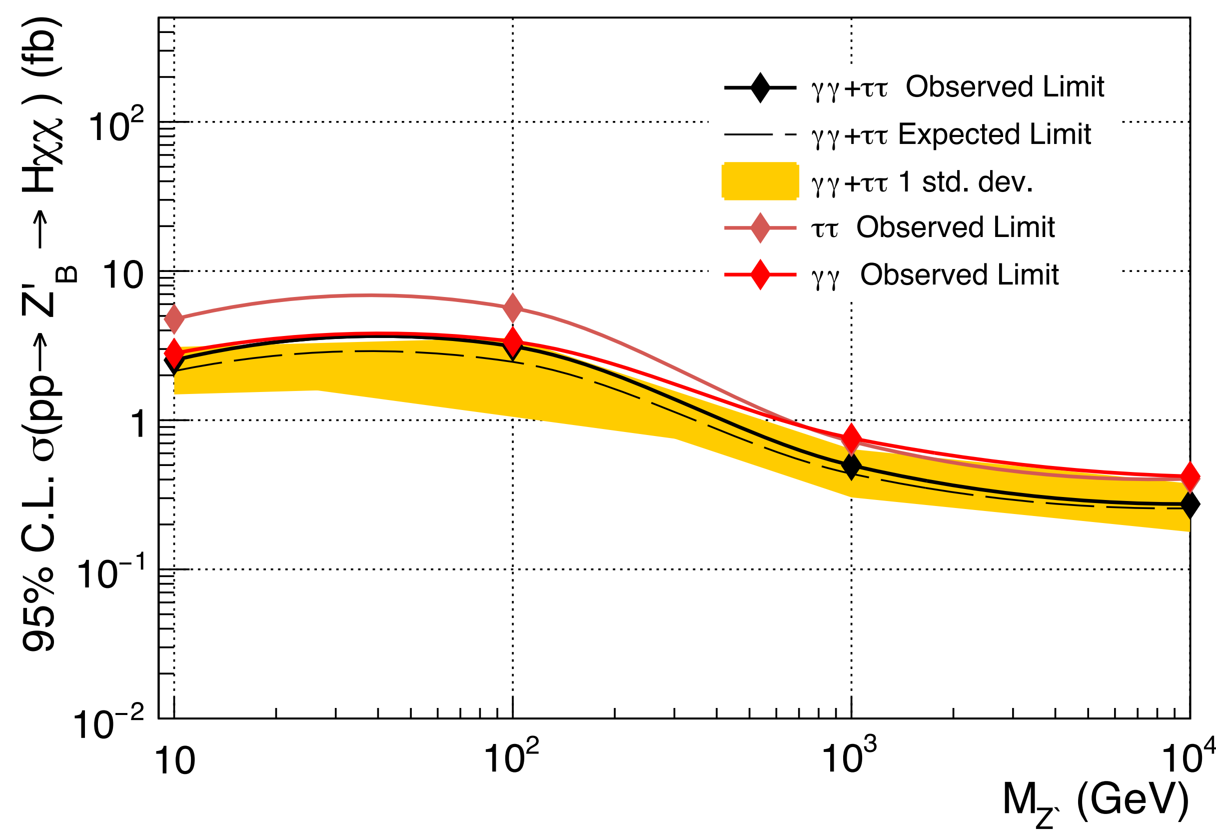
Process	$\mu\tau_h$ Events	$e\tau_h$ Events	$\tau_h\tau_h$ Events
Dataset/Trigger	564814720	942127424	379366752
Extra lepton veto and OS tau pair	6600148	5751308	4246205
B-tagged jet veto	5901391	5474527	4037097
Full identification criteria	535026	258505	175422

Results II: Combination ττ+γγ

Z'-2HDM



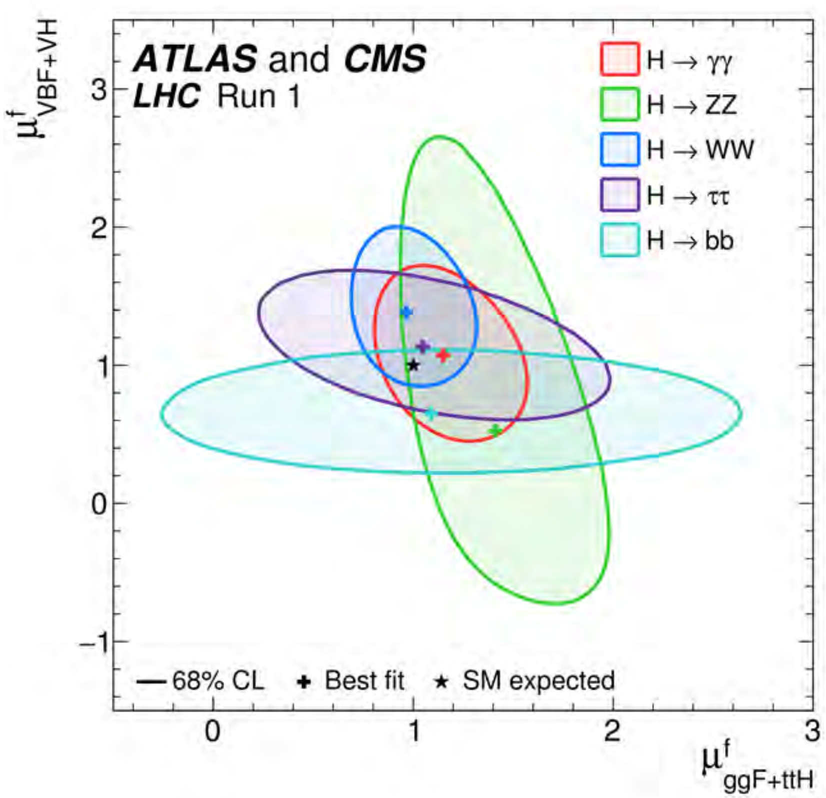
Baryonic-Z'

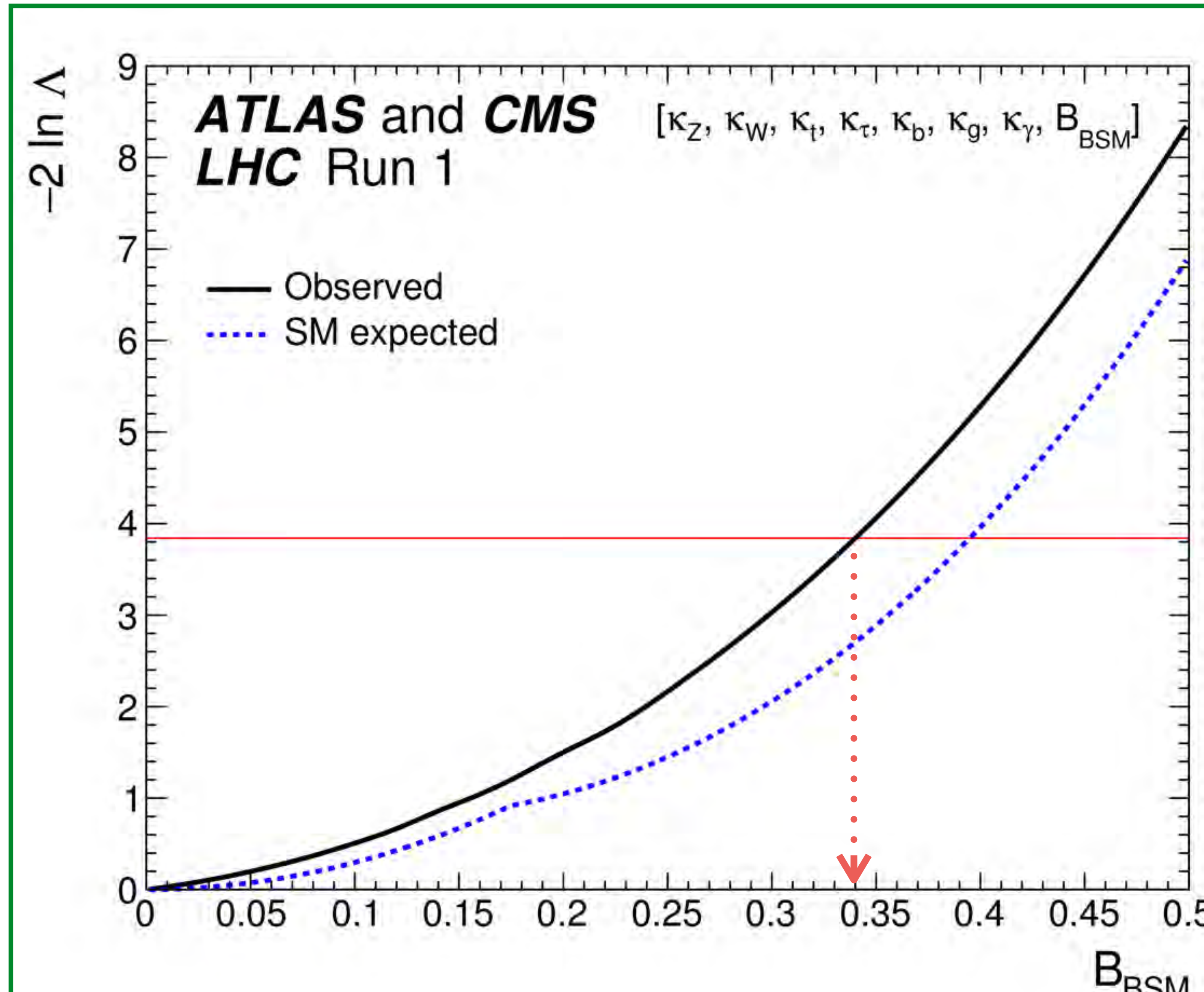


Status of 125 GeV Higgs

- How does SM Higgs boson help with finding dark matter?
- With Run-I combination results, the **indirect** searches limit the beyond the standard model branching ratio of Higgs to 34%.
- Better **H(ττ)** and other measurements will help to constrain further.
- We can improve with direct searches.

Indirect limit on the branching fraction to Beyond the Standard Model (BSM) decays, including dark matter (invisible decays)





Event Yield

background yields in sensitive region dominated by statistical uncertainties

Process	$\mu\tau_h$	$e\tau_h$	$\tau_h\tau_h$
W + jets QCD	32.54 ± 6.18	13.11 ± 2.18	3.79 ± 2.59
$t\bar{t}$	24.83 ± 2.04	13.75 ± 1.60	4.24 ± 1.30
125 GeV H	0.72 ± 0.06	0.48 ± 0.08	1.21 ± 0.08
Multi-boson	21.53 ± 1.46	12.34 ± 0.99	7.30 ± 0.63
$Z \rightarrow \tau\tau$	0.14 ± 0.53	0.00 ± 0.01	3.57 ± 1.24
$Z \rightarrow \ell\ell$	2.00 ± 1.33	0.84 ± 1.87	-
$Z \rightarrow \nu\nu$	-	-	0.37 ± 0.25
Total expected	81.77 ± 6.31	40.50 ± 3.26	20.48 ± 2.97
Observed	81.00 ± 9.00	38.00 ± 6.16	26.00 ± 5.10
Expected Zprime1200A300 events	5.75 ± 0.27	3.52 ± 0.16	4.78 ± 0.33

Experiment backup

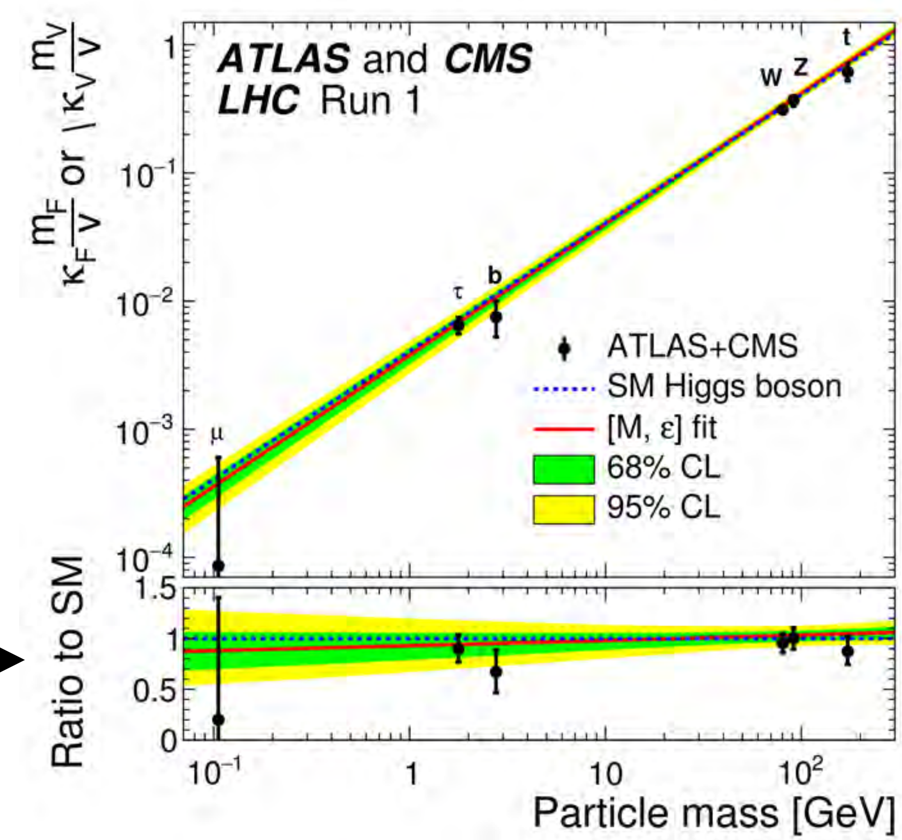
Standard Model (SM): Higgs II

arXiv:1606.02266 [hep-ex]

- Scalar boson discovered by CMS and ATLAS in 2012
- Significance of results driven by ZZ and γγ channels.
- Mass: 125 GeV measured spin-0 scalar

Table 2.2: Branching fractions for 125 GeV SM Higgs boson

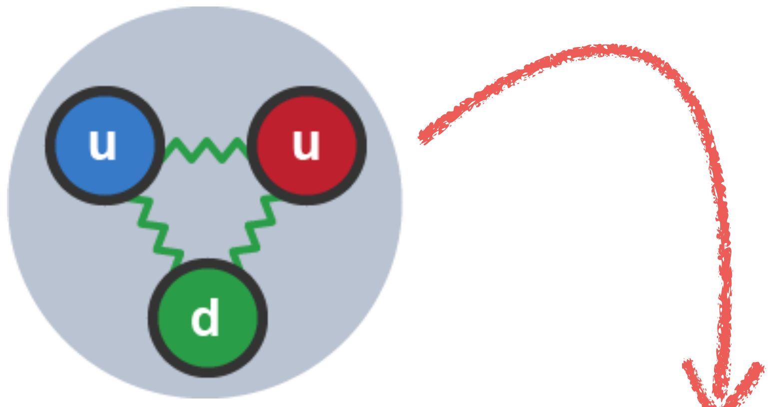
Higgs boson decay channel	Branching Fraction [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

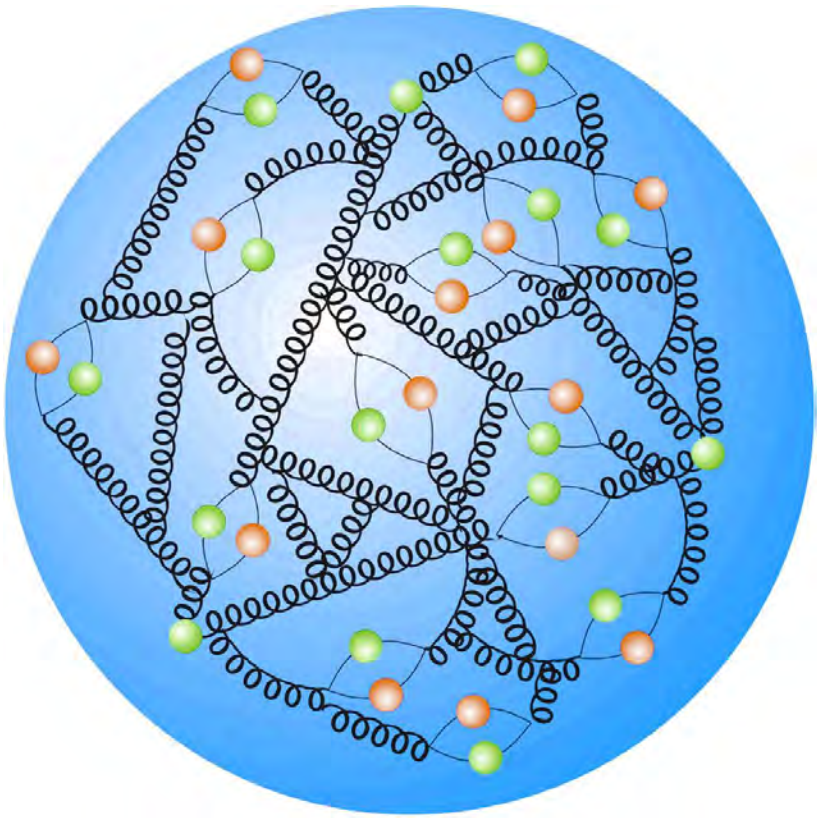


run-II goal:
reduce uncertainties!

Proton Structure

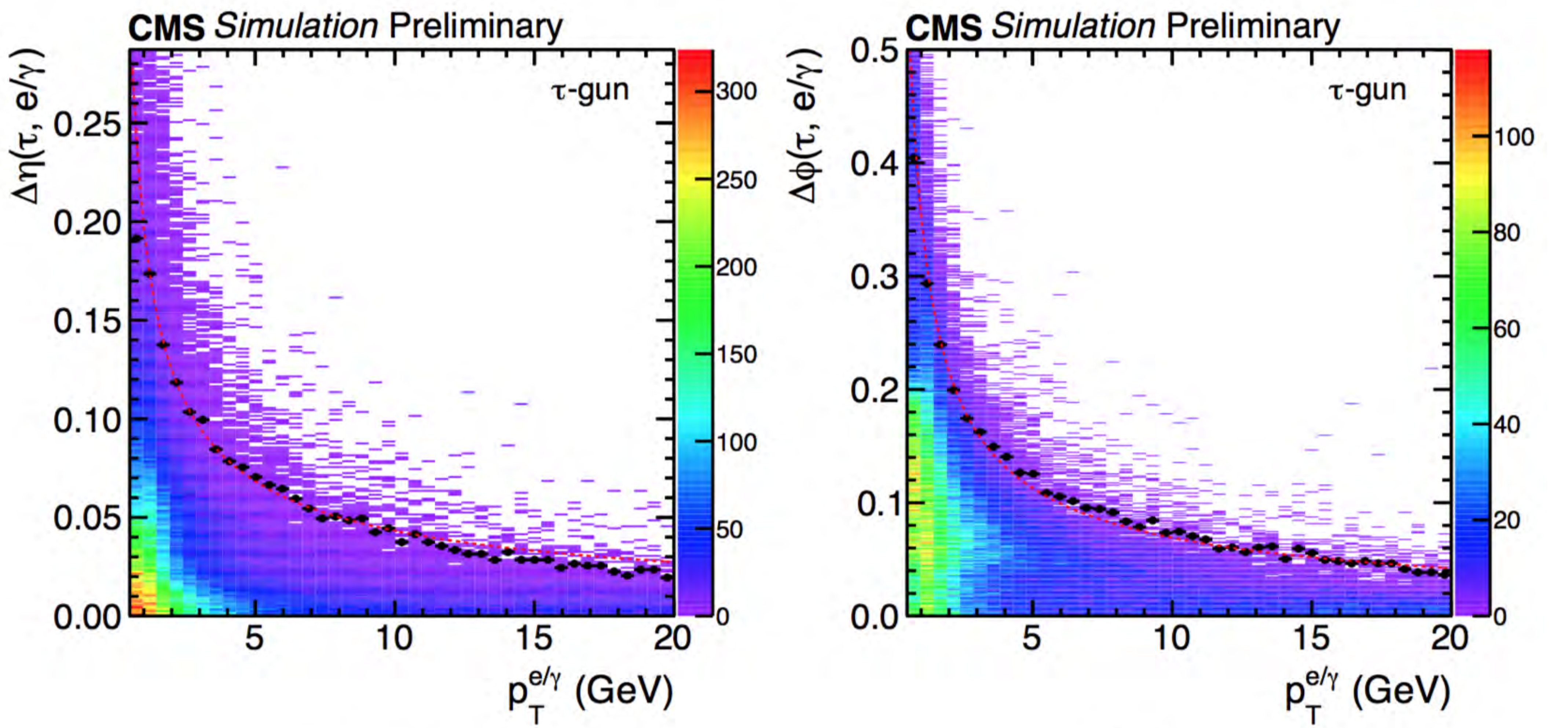
- The LHC collides protons
  - Partons (gluons and quarks) interact in collisions
  - Gluons, valence quarks (u and d) and sea quarks (virtual q anti-q pairs)
- Parton distribution functions
  - Deep inelastic scattering experiments (such as at HERA) provide the probability $f(x)$ for a quark or gluon to have fraction of the protons momentum x
  - Without accurate pdfs, no cross section normalization





gluons carry ~50% of proton momenta

Dynamic strip envelope

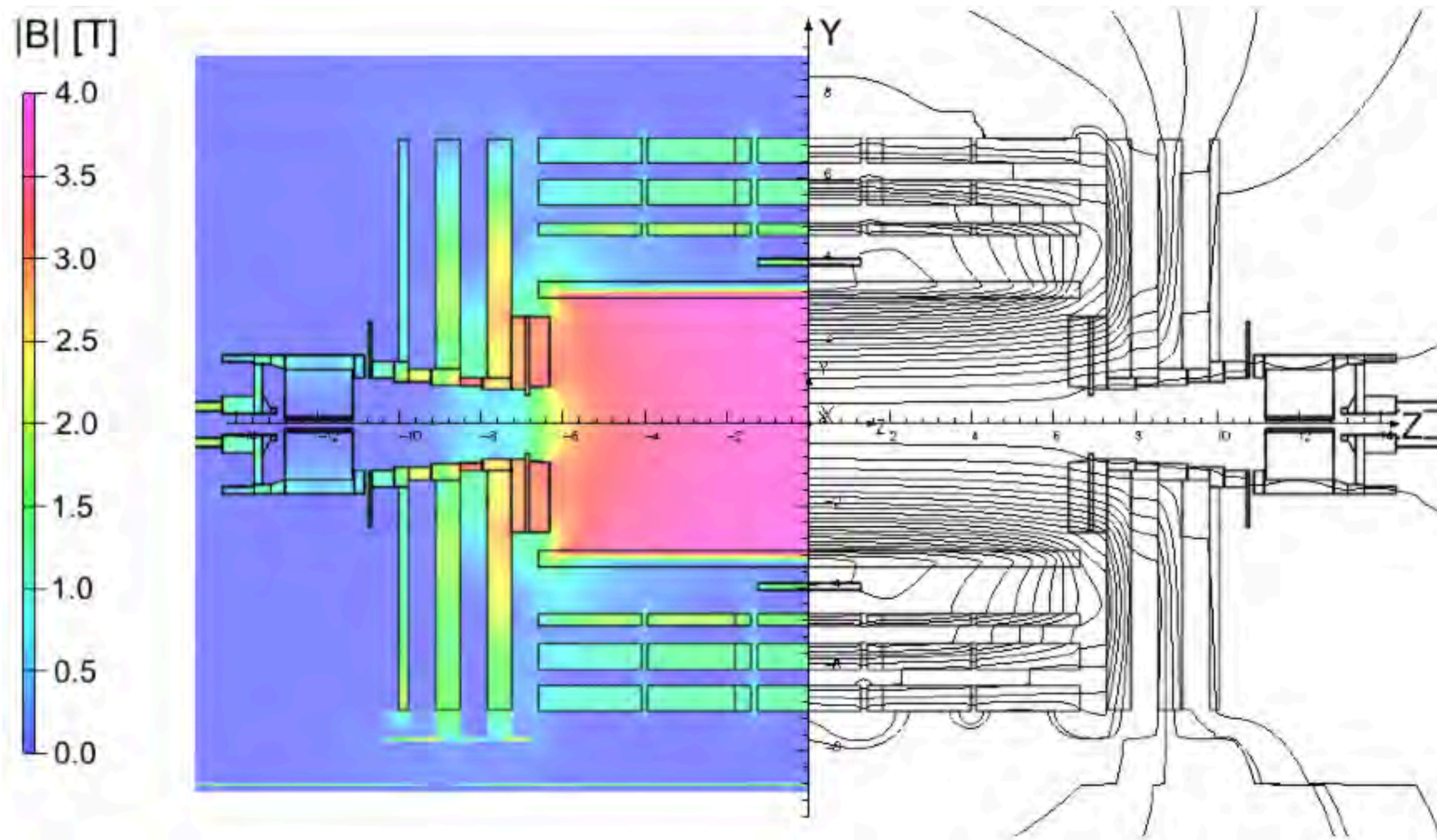


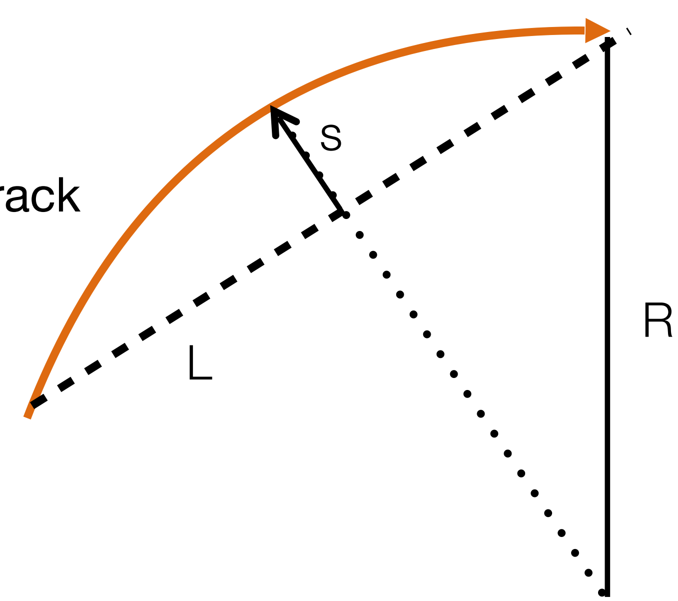
(a) η-size (b) ϕ-size

Figure 6.4: Dynamic strip sizing 95% envelope shown in η and ϕ.

Solenoid

3.8 T superconducting solenoid cooled to 4.7K provides critical magnetic field to measure momenta of particles





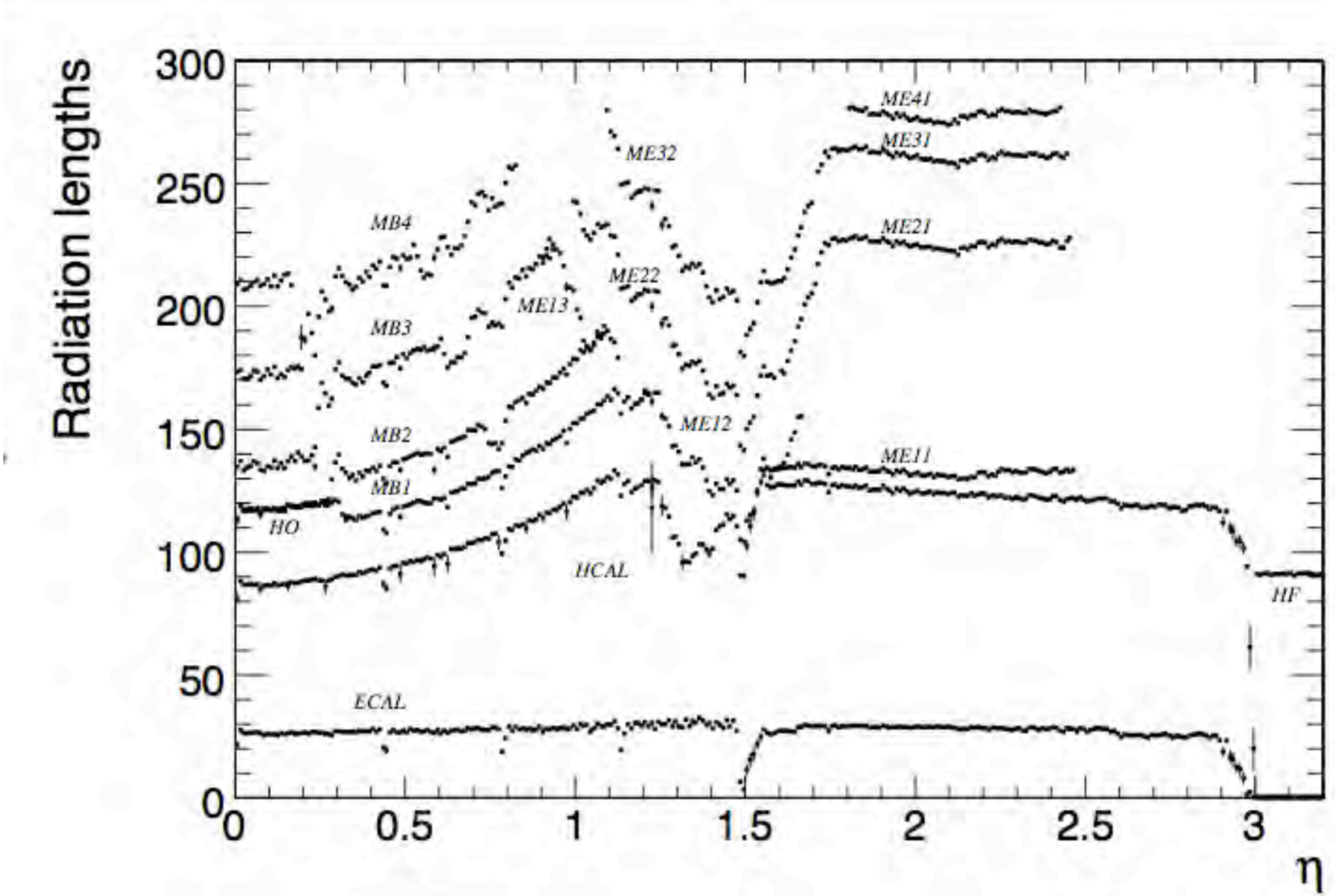
$$p_T \approx \frac{0.3 L^2 B}{8s}$$

LHC Parameters

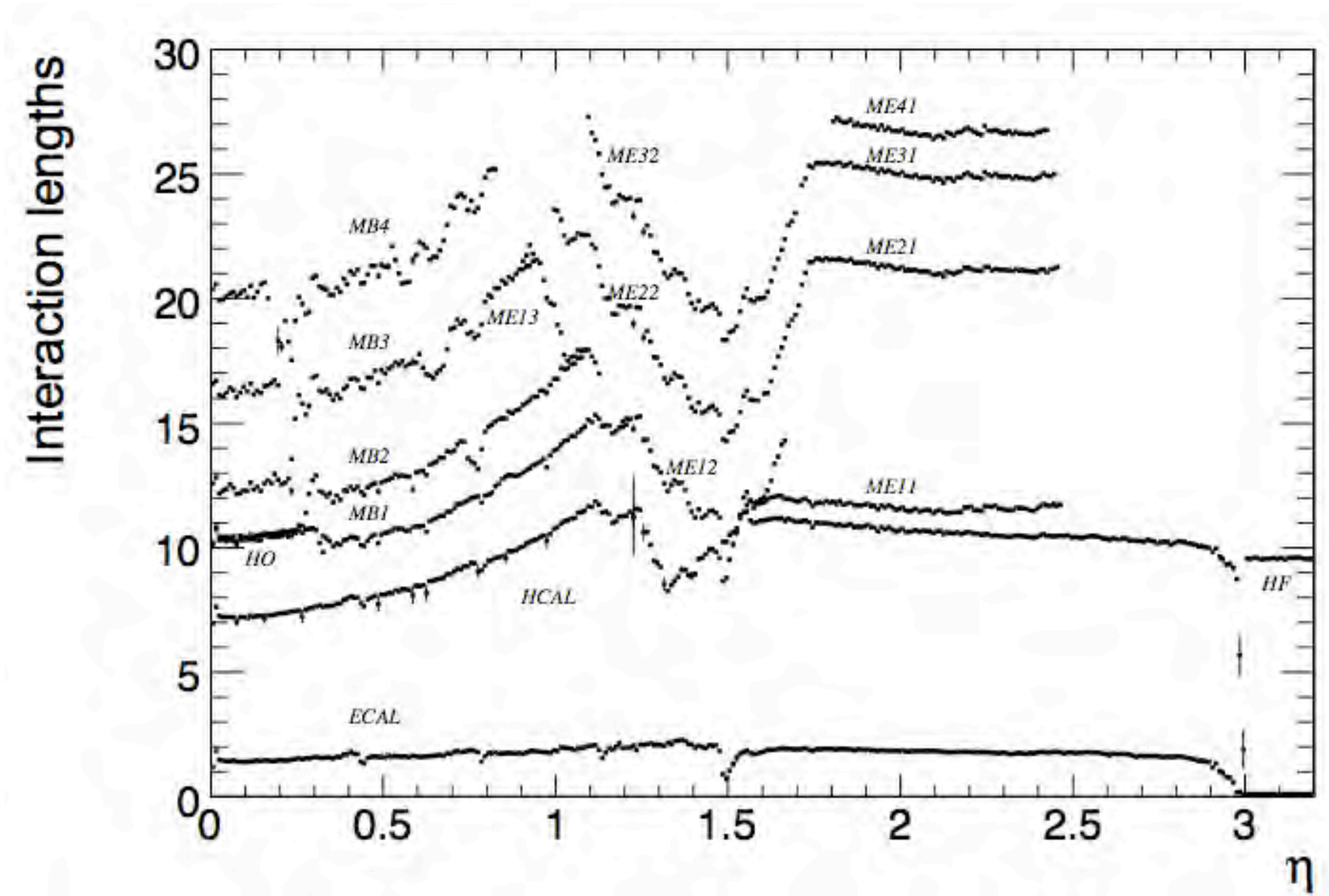
Table 4.1: LHC design beam and operation conditions between 2010 and 2016.

Year	2010	2011	2012	2015	2016	Design
Center of Mass Energy (TeV)	7	7	8	13	13	14
Energy per Beam (TeV)	3.5	3.5	4	6.5	6.5	7
Proton bunch spacing (ns)	150	50	50	50/25	25	25
N_b ($\times 10^{11}$)	1.2	1.5	1.7	1.15	1.25	1.15
n_b	348	1331	1368	2232	2208	2808
β^*	3.5	1.0	0.6	0.8	0.4	0.55
ϵ_n	2.2	2.3	2.5	3.5	3.0	3.75
Peak Instantaneous $\mathcal{L}$ 10^{34}	0.02	0.35	0.77	0.52	1.53 (above design)	1
Total Integrated $\mathcal{L}$ (fb^{-1})	0.04	6.1	23.3	4.2	40.8	-

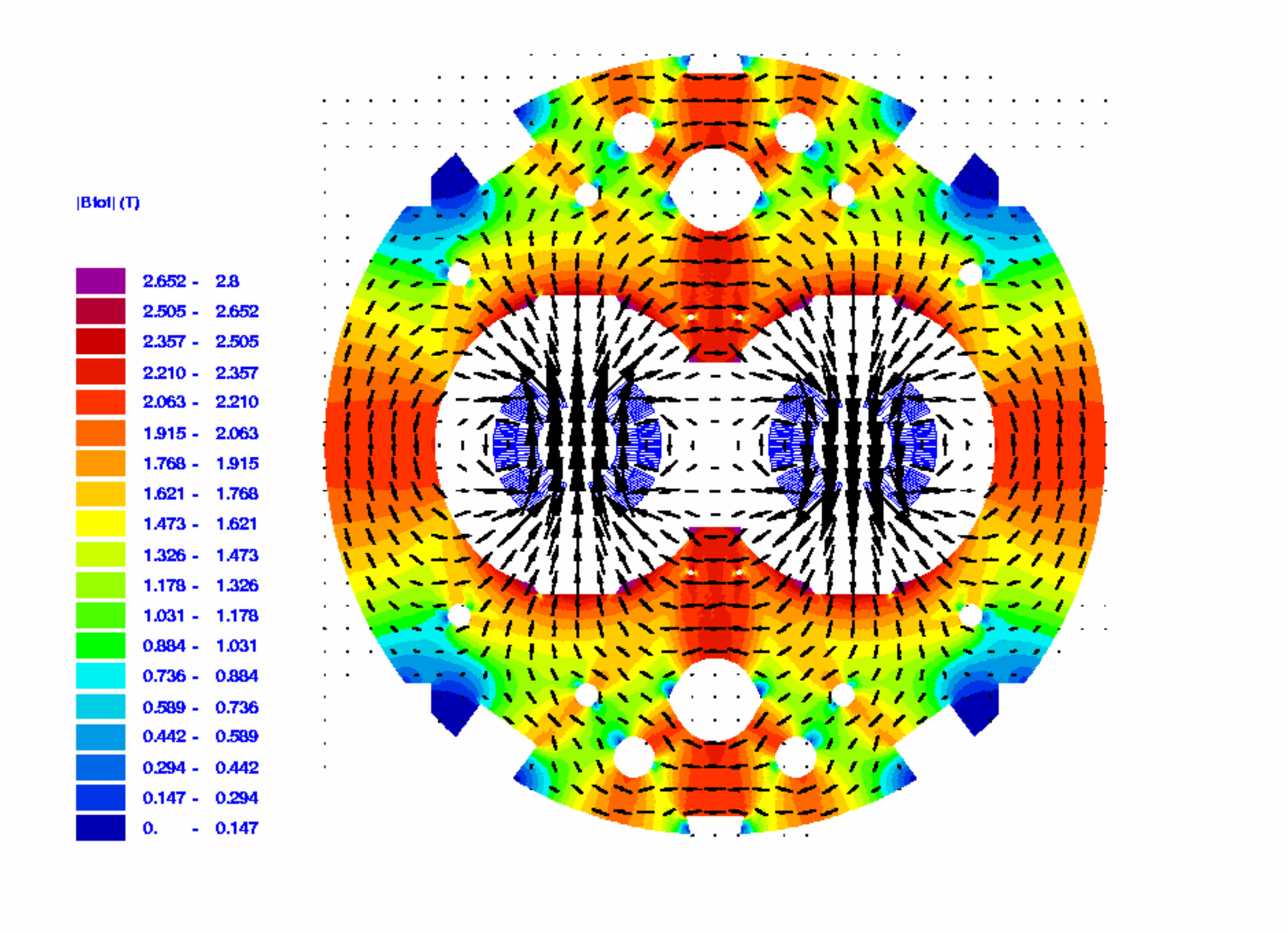
Radiation lengths



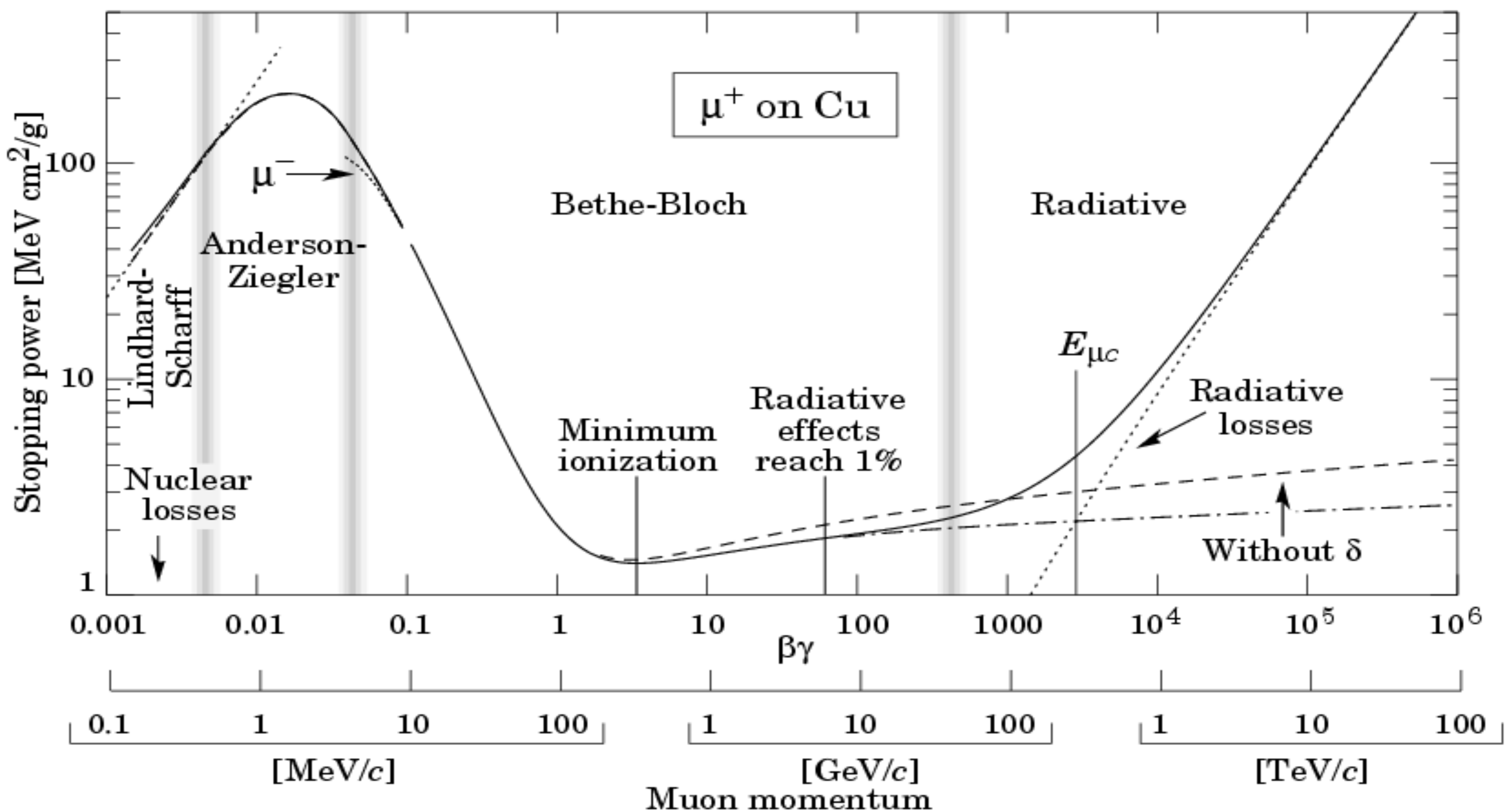
Interaction lengths



Dipole magnetic fields

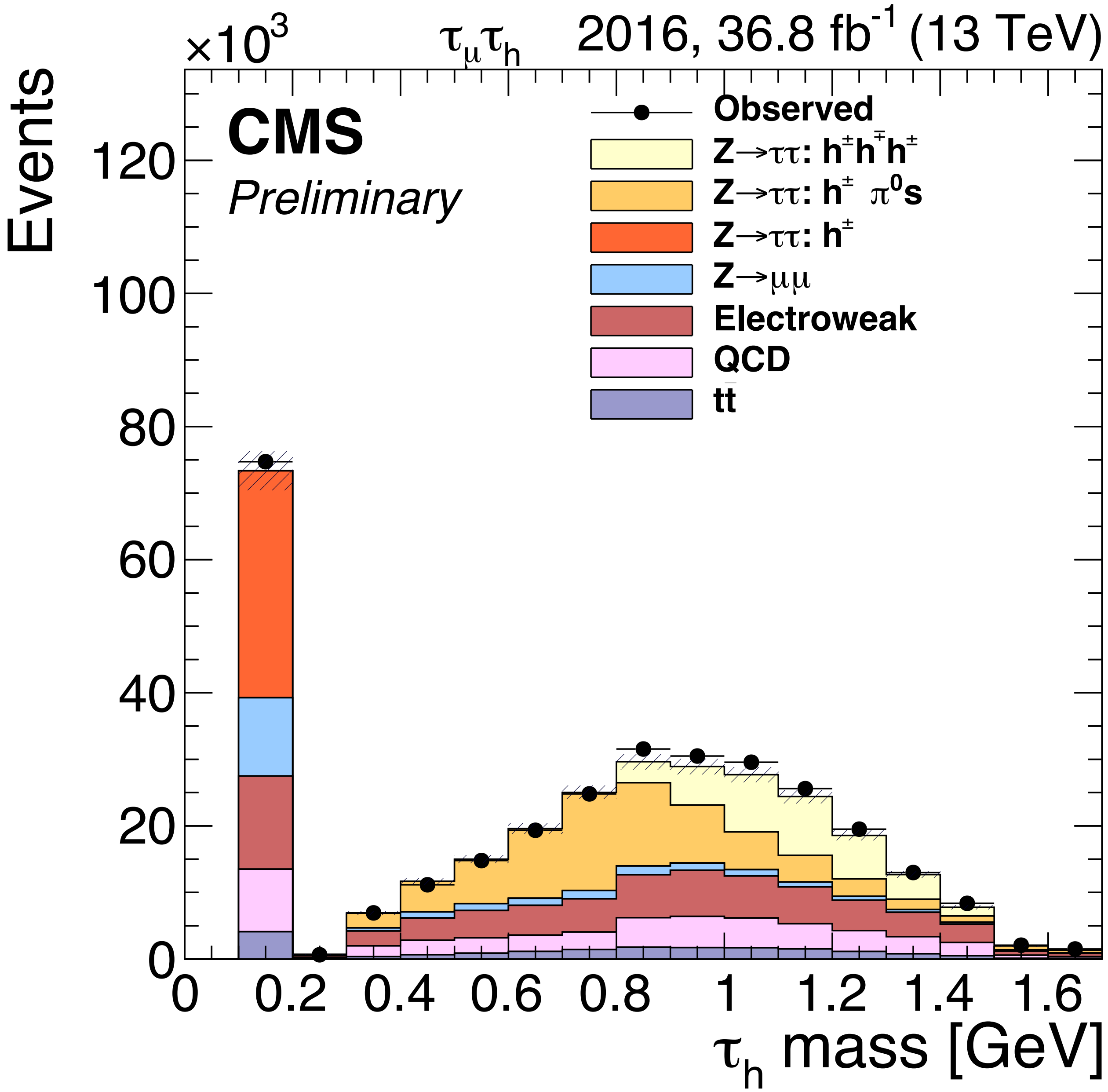


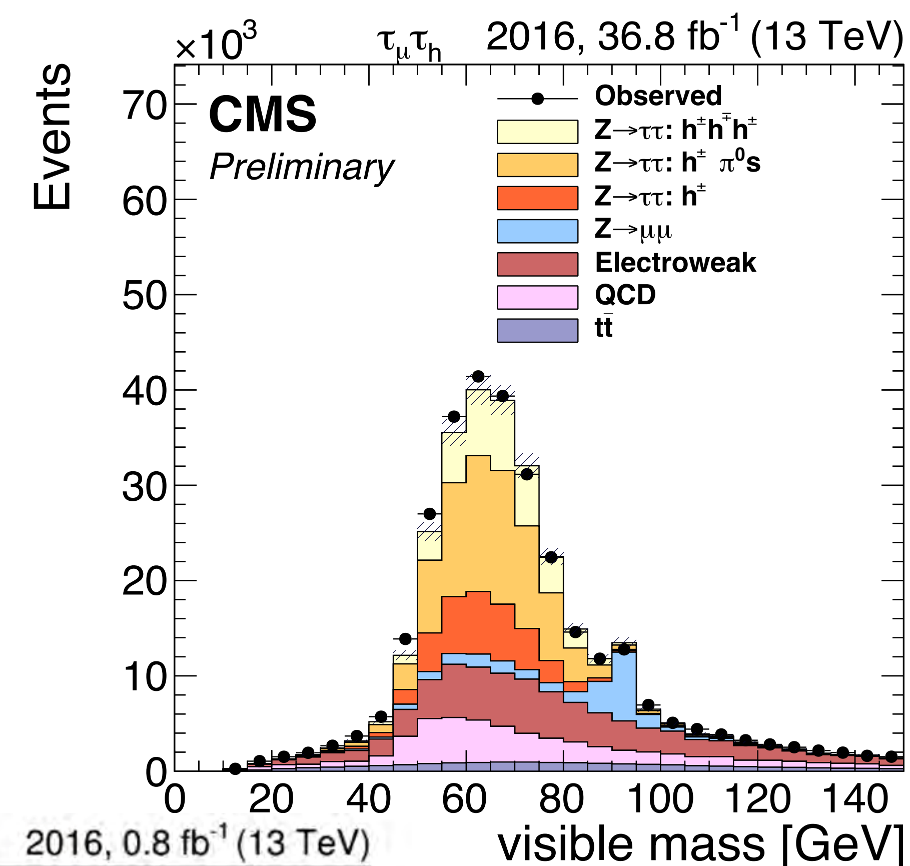
Bethe-Bloch

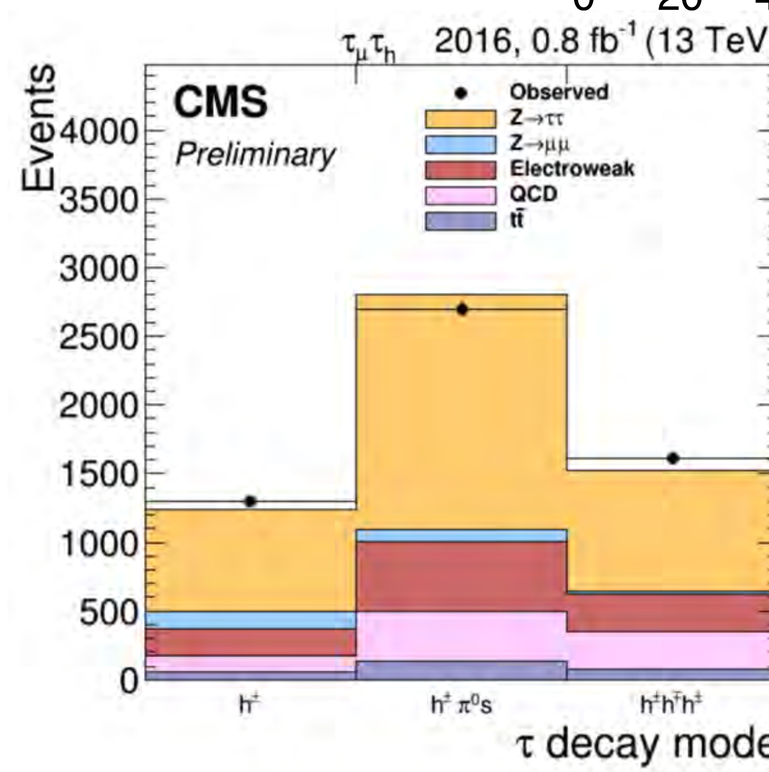


μ⁺ on Cu
μ⁻
Bethe-Bloch
Radiative
Anderson-
Ziegler
Lindhard-
Scharff
Stopping power [MeV cm²/g]
100
10
1
$E_{\mu c}$
Radiative
losses
Minimum
ionization
Radiative
effects
reach 1%
Nuclear
losses
Without δ
0.001
0.01
0.1
1
10
100
1000
10⁴
10⁵
10⁶
βγ
0.1
1
10
100
1
10
100
1
10
100
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum

Hadronic Tau Reconstruction



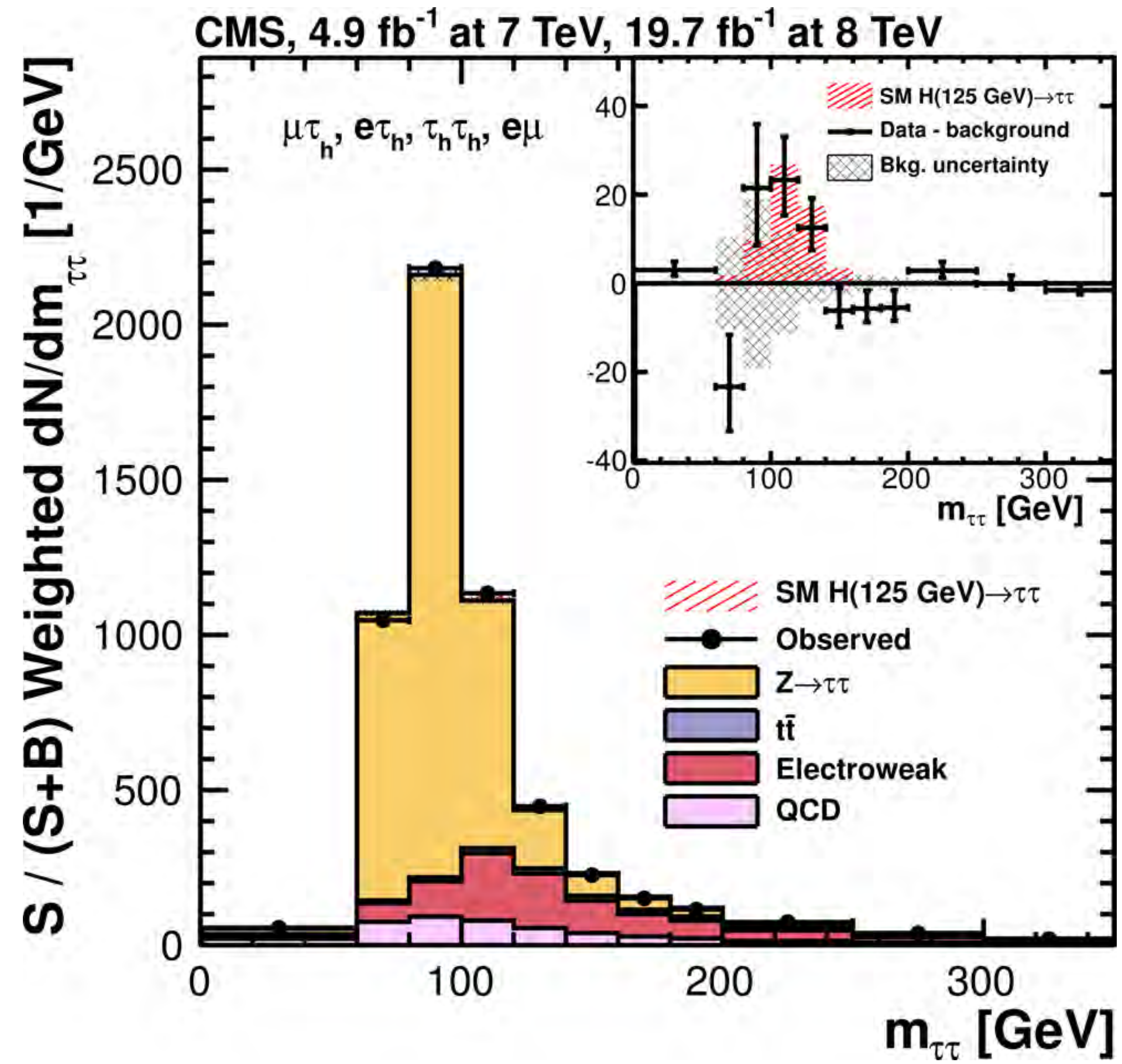




SM Hττ 8TeV

SM Higgs TauTau 8 TeV Analysis

- Straightforward mass-based analysis
- Used reconstructed invariant di-Tau mass for signal extraction.
  - Multi-Variate Analysis(MVA) correction for MET based of the decay modes of each tau.
  - SVFit
    - Mass reconstructed using likelihood fit to determine most probable 4 vectors of taus, and met.
    - Assume all met in event is from taus and need to specify what decay mode of each tau for accurate neutrino estimates
    - tau decay modes $\tau_e\tau_h$, $\tau_\mu\tau_h$, $\tau_h\tau_h$, $\tau_e\tau_\mu$, $\tau_e\tau_e$ $\tau_\mu\tau_\mu$ examined
  - WH/ZH addition



CMS-HIG-13-004

arXiv:1401.5041 [hep-ex]

SM H->ττ at 8TeV

SM Higgs TauTau 8 TeV Analysis

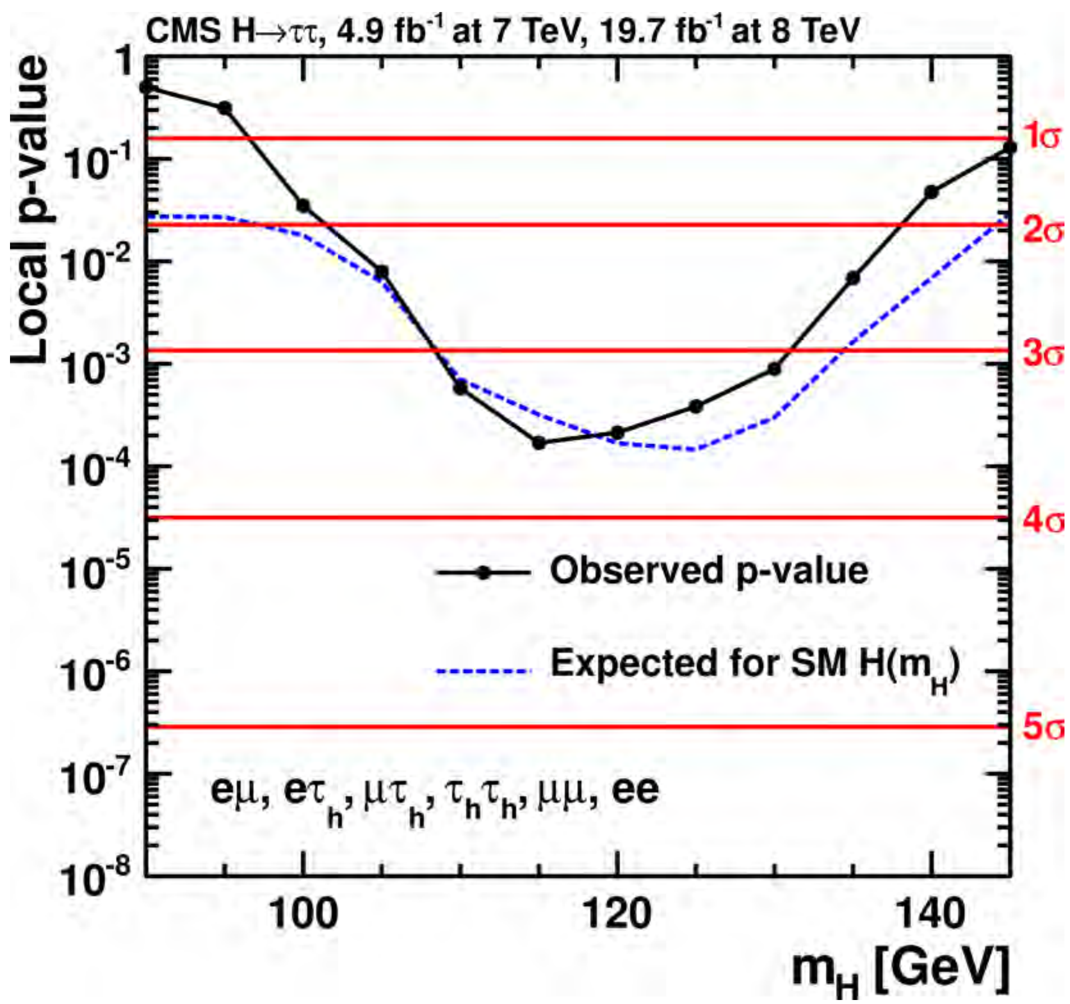
- 95% CL limits on SM H→ττ signal strength
  - excess on mass spectrum from 115 GeV–135 Gev

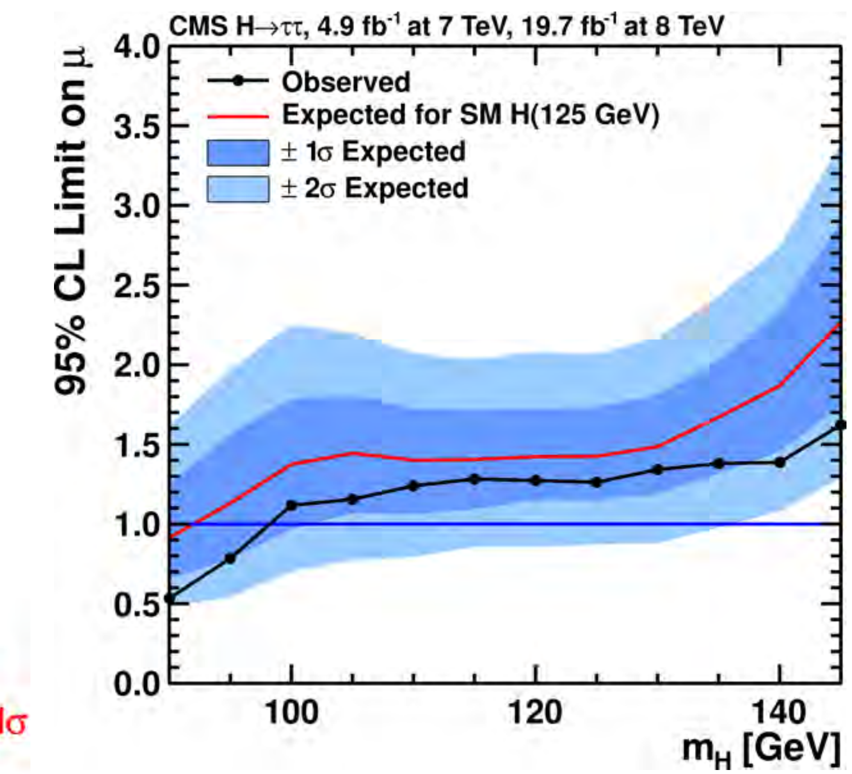
discriminating variables used

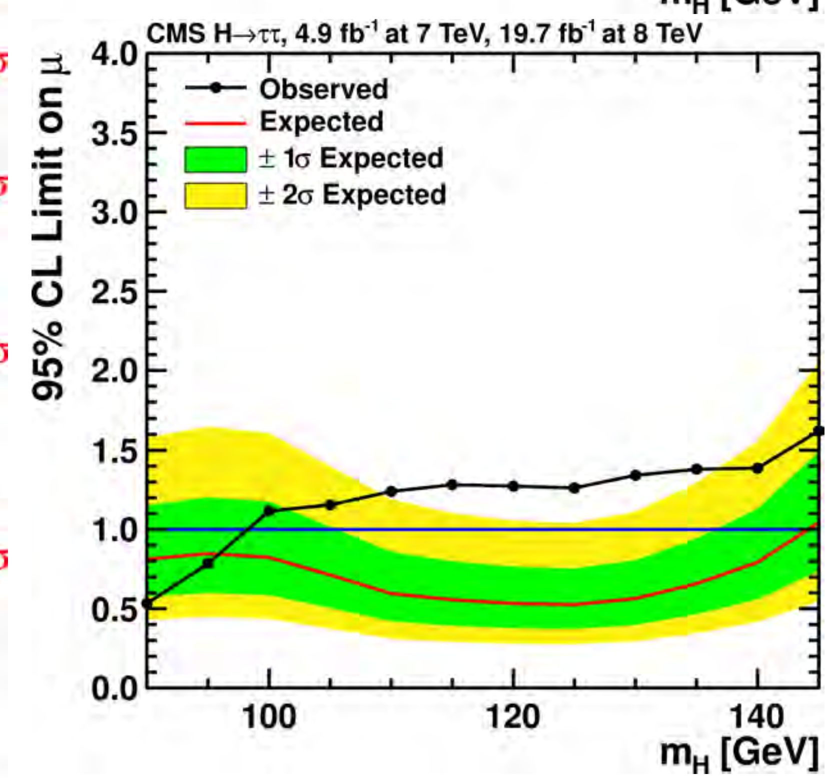
$$M_T = \sqrt{2 p_T E_T^{miss} (1 - cos(\Delta\phi))}$$

$$p_T^{\tau\tau} = |\vec{p}_T^L + \vec{p}_T^{L'} + \vec{E}_T^{miss}|$$

and SVfit mass



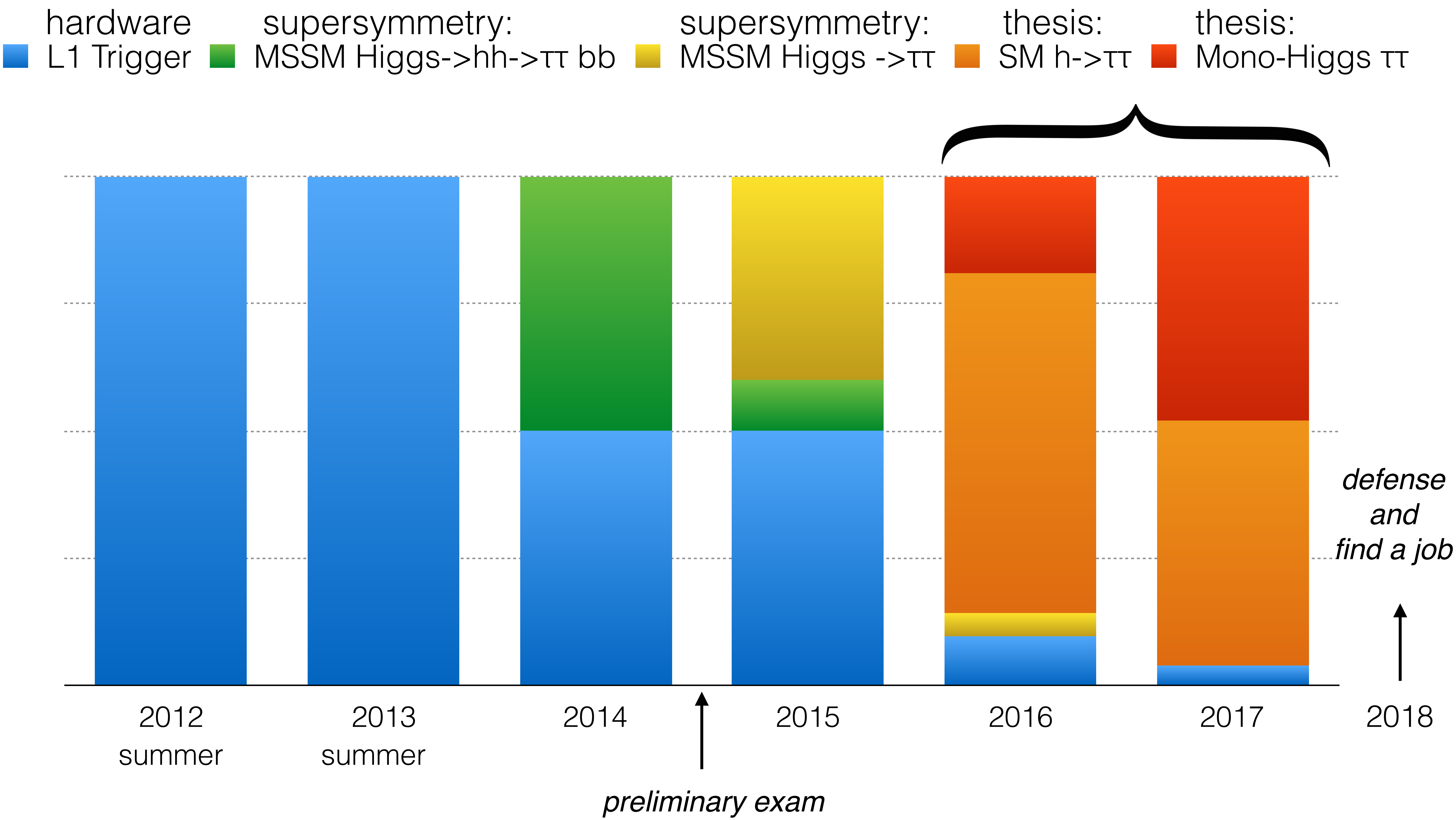




CMS-HIG-13-004
SM H->ττ at 8TeV

arXiv:1401.5041 [hep-ex]

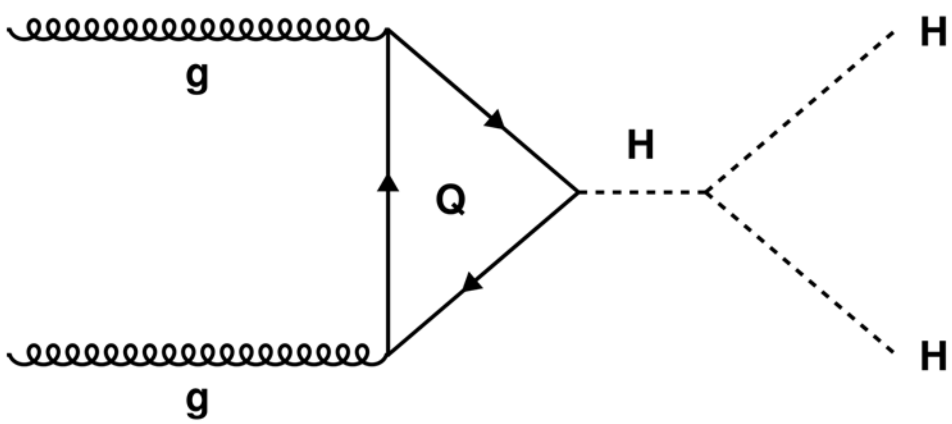
Laura in HEP: summary

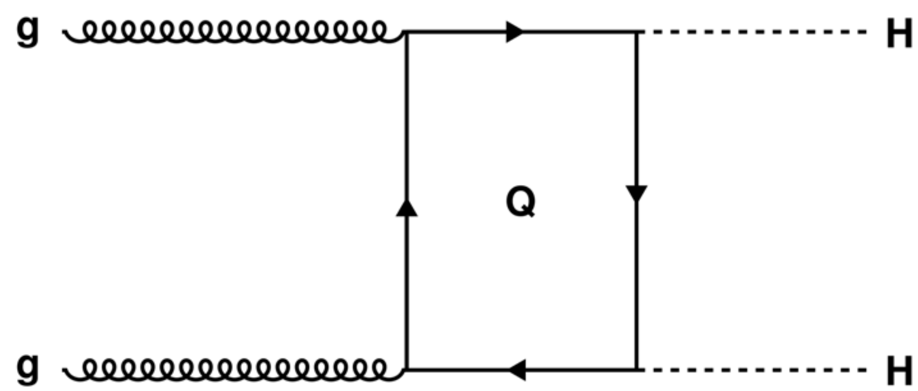


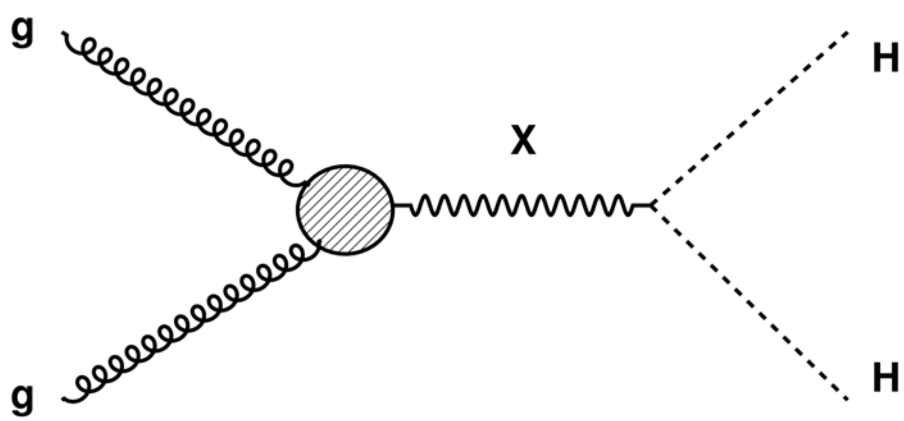
MSSM Hhh

SM Higgs as a tool for discovery

- Di-Higgs 2 main flavors
    - Measure: SM Trilinear Higgs coupling
    - Search: New heavy resonance X
- Several di-Higgs bbττ analyses done at CMS
    - Non-resonant
        - Aims to measure trilinear Higgs coupling
    - Resonant analysis
        - Aims to reconstruct mass peak of “X”
- VH Analysis
    - Search for resonant MSSM A->Zh(125)





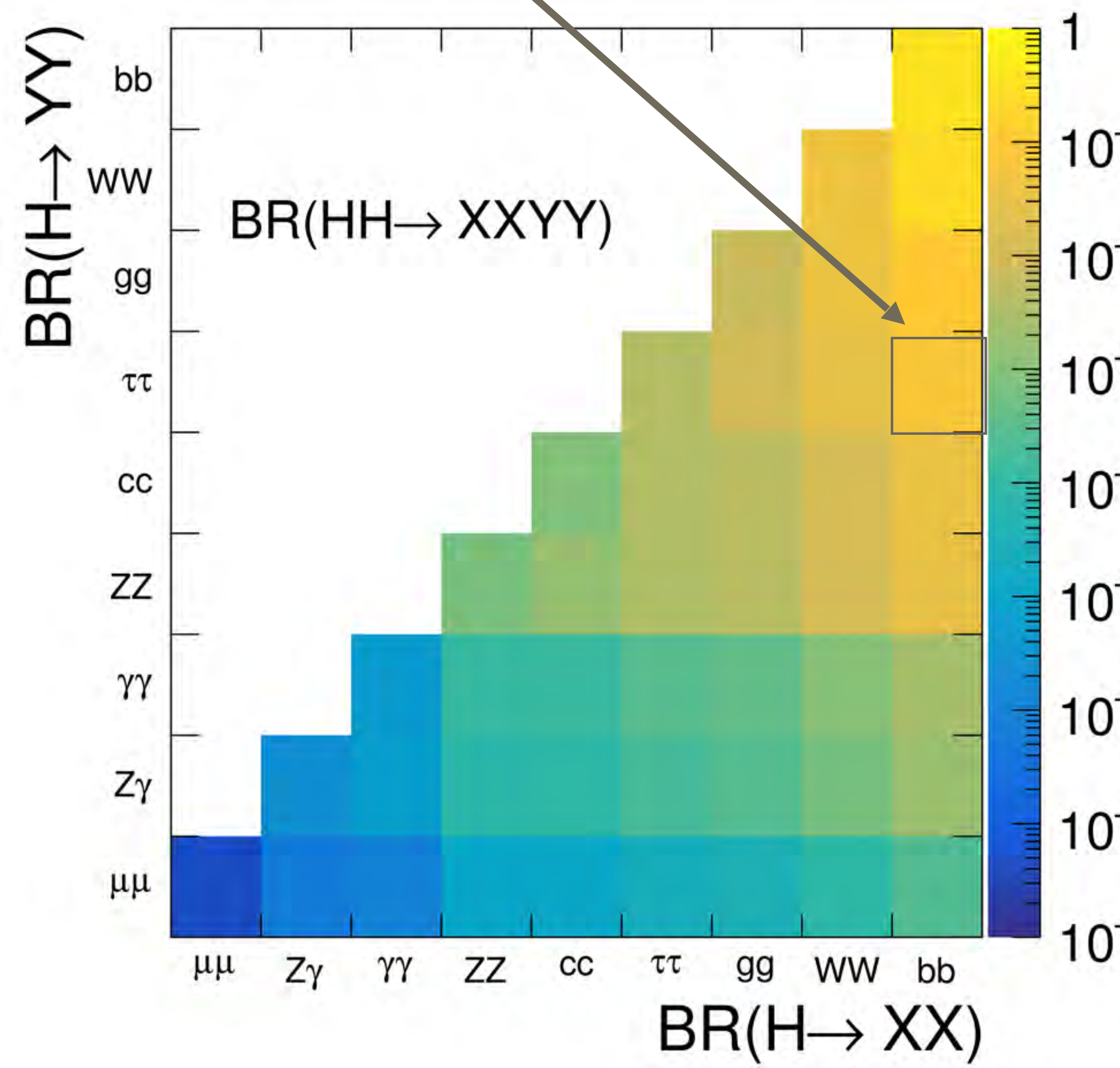


125 GeV H->ττ used as a tool for searches

bbττ

BR h(bb) h(ττ)= 3.6%

- Performed at 8 TeV
  - 8 TeV Run1 in two different results
    - MSSM-driven analysis and Mode
- Performed at 13TeV in 2015 and 201
  - 2016 Analysis has 12.9 /fb
    - Resonant and non-resonant proc



plot: CMS-PAS-HIG-16-011
125 GeV H->ττ used as a tool for searches

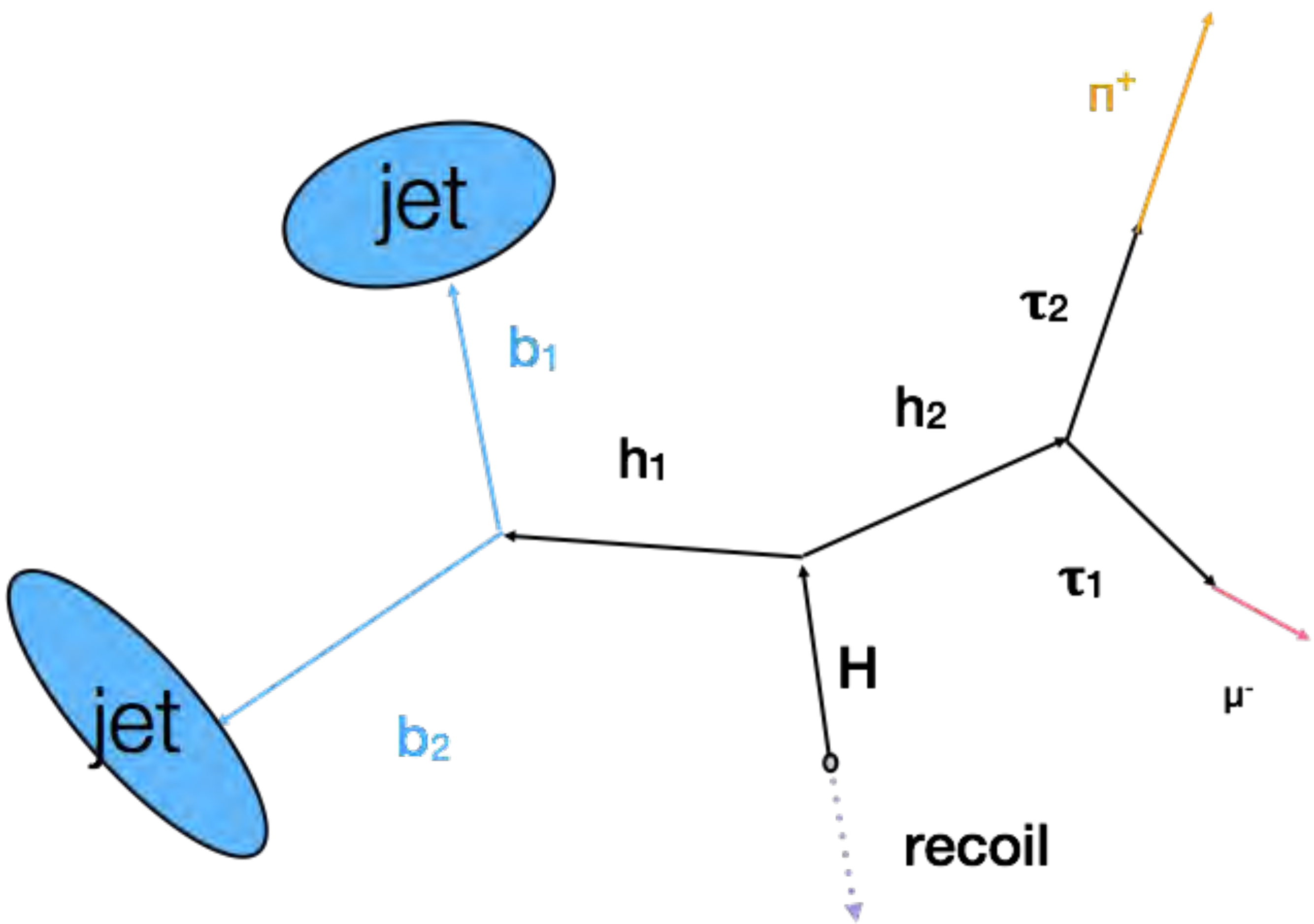
8 TeV bbττ

CMS-HIG-14-034
CMS-PAS-HIG-15-013

125 GeV H->ττ used as a tool for searches

- MSSM Analysis search for Heavy H decays to two 125 GeV h
  - Probe low tanβ MSSM
- Model Independent analysis used same techniques and extended the mass range of the search
  - Resonant and non-resonant

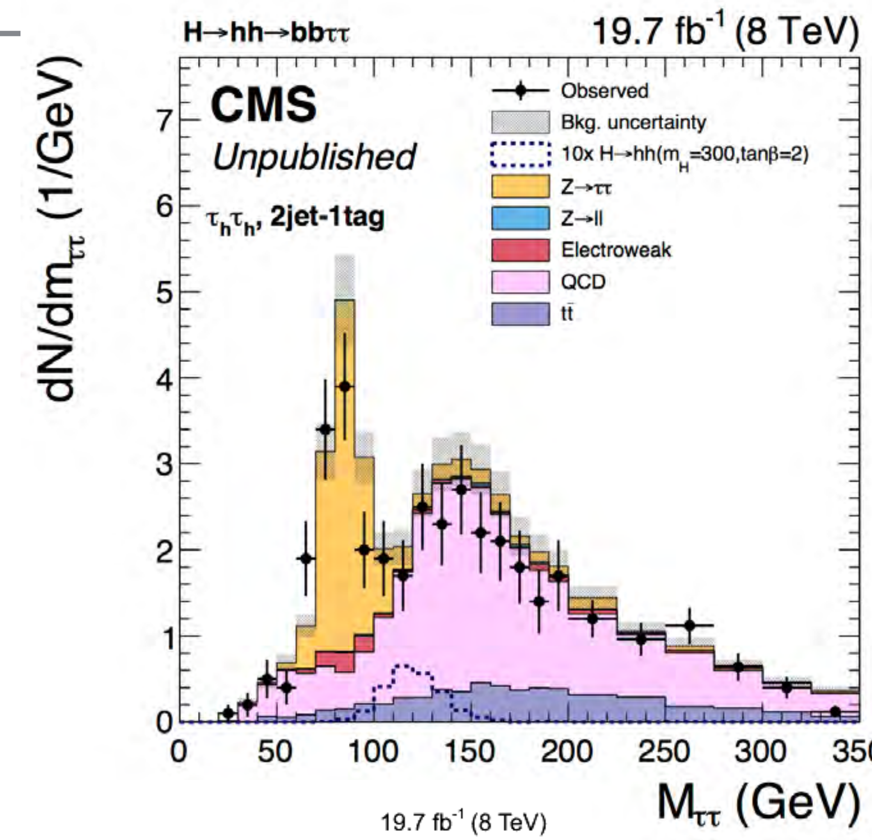
- HHKinFit
  - Maximum likelihood fit for mass Heavy Higgs, H, using the topology below.
    - Input: (1) SVfit rebuilds H->ττ first (2) 2 Reconstructed Jets
    - Di-jet invariant mass constrained to be 125 GeV

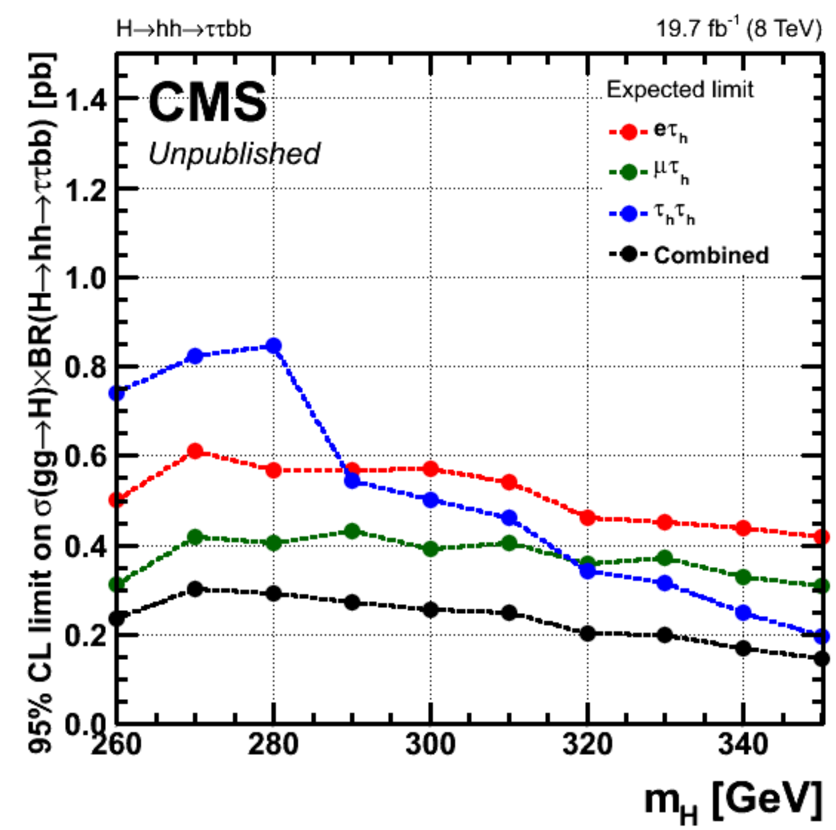


HhhττbbA

8 TeV MSSM H->hh->bbττ

- MSSM Analysis search for Heavy H decays to two 125 GeV h
  - Kinematic fits assume no other MET in event
    - Tau decay Modes: $\tau_e\tau_h$ $\tau_\mu\tau_h$ $\tau_h\tau_h$ $\tau_e\tau_\mu$
      - $\tau_\mu\tau_h$ most sensitive at low M_H- similar to Legacy SM Higgs result.
      - $\tau_h\tau_h$ drives limit at high mass.
- Performed in tandem with A->Zh to probe low tanβ MSSM



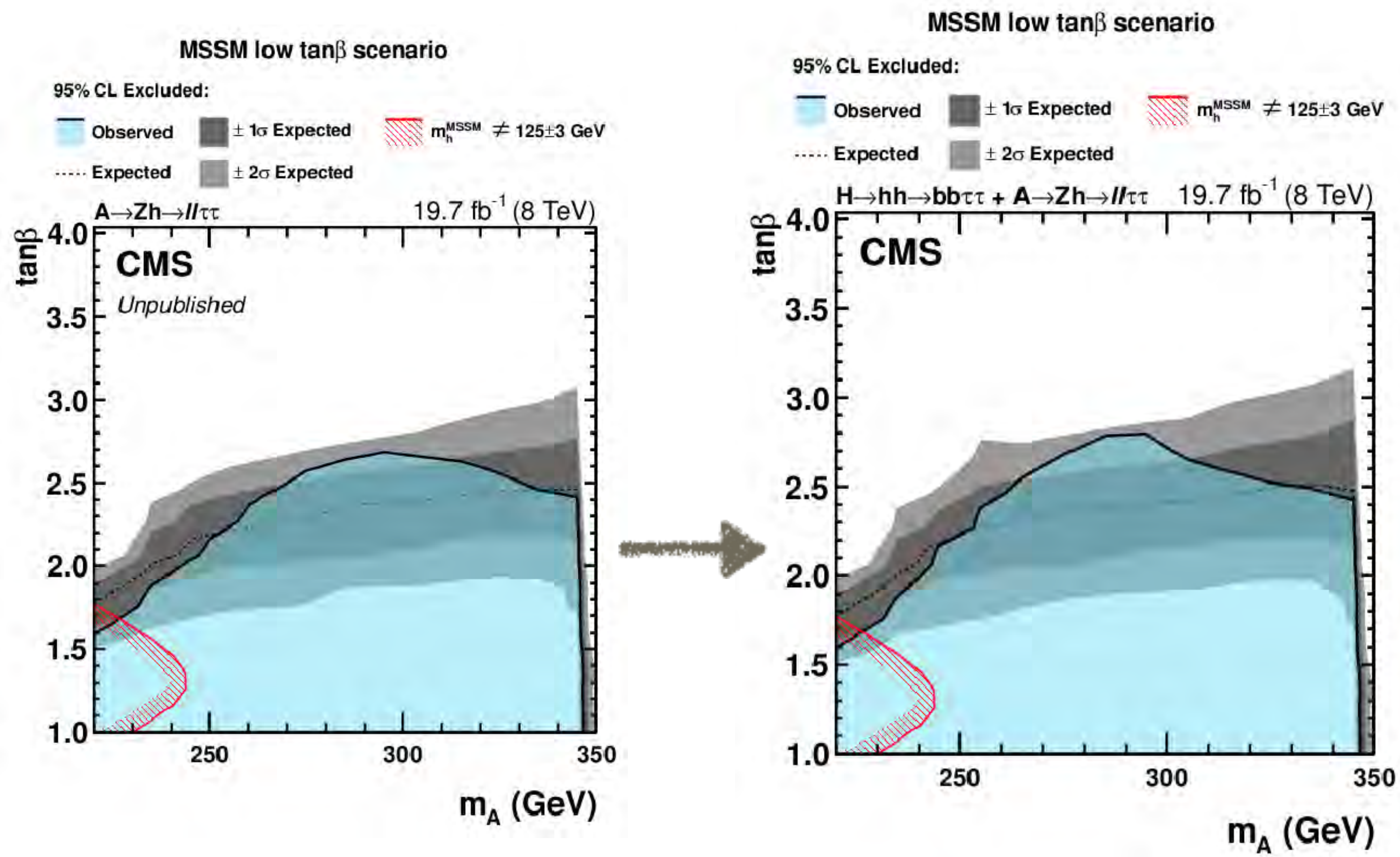


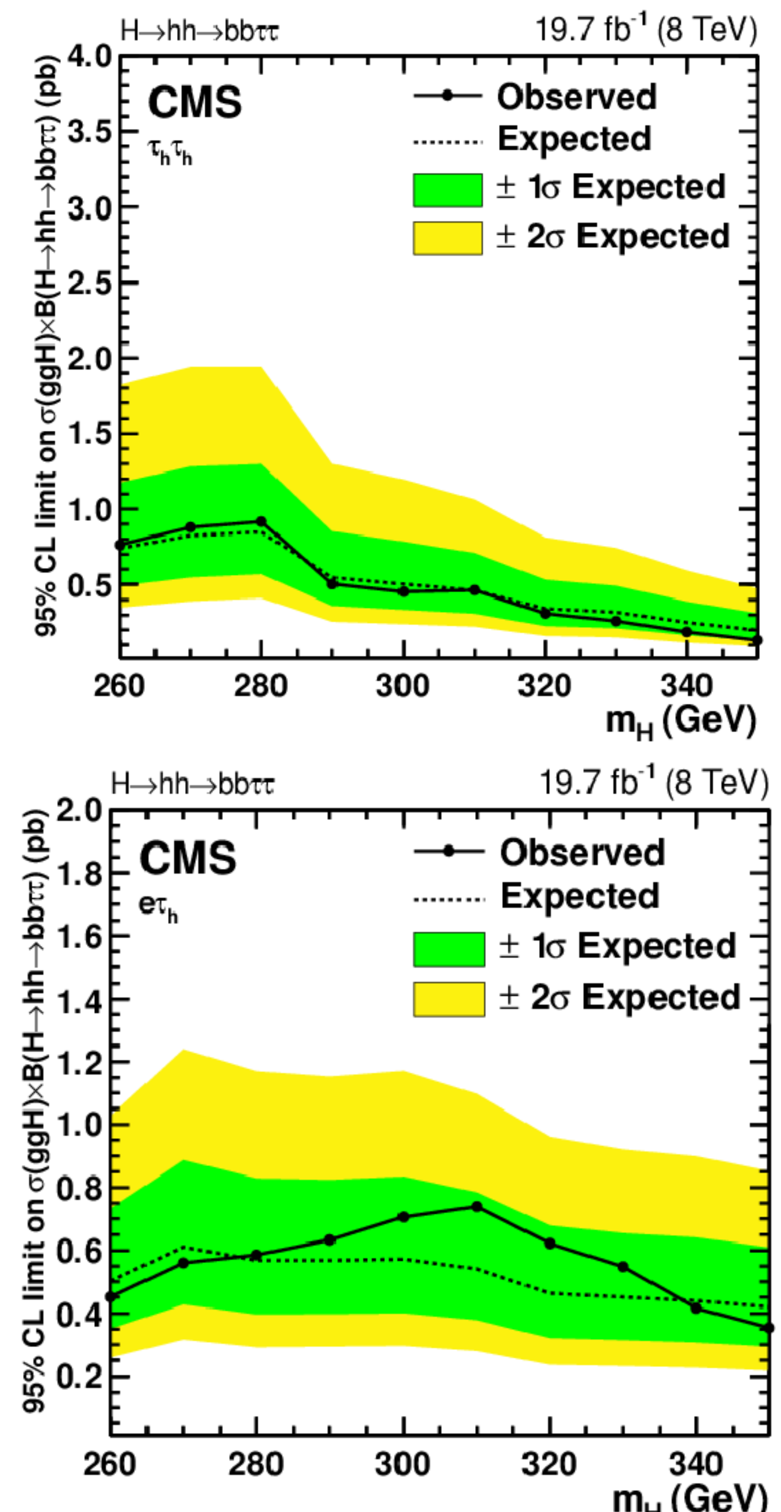
ME: LTAU

CMS-HIG-14-034

8 TeV MSSM H->hh->bbττ

- A->Zh set stronger limits in M_A-tanβ plane

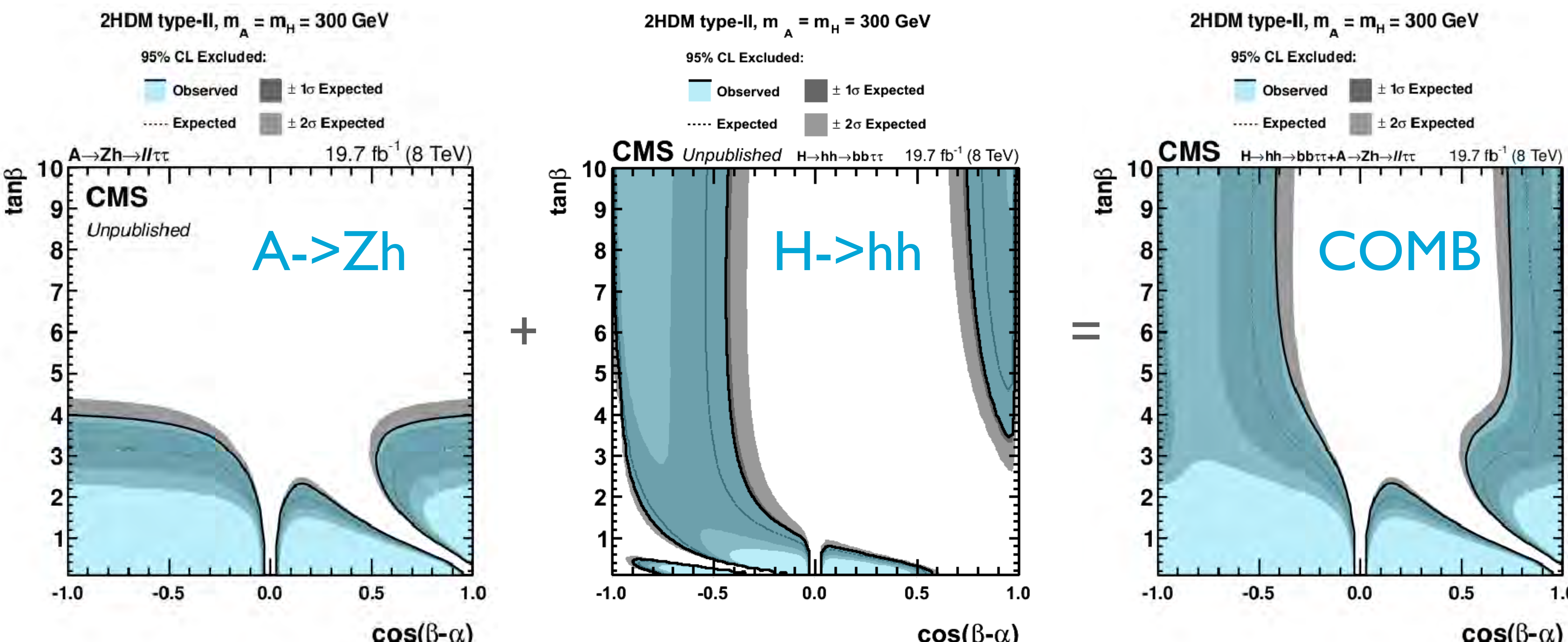




CMS-HIG-14-034

Hhhττbb

8 TeV MSSM bbττ+llττ



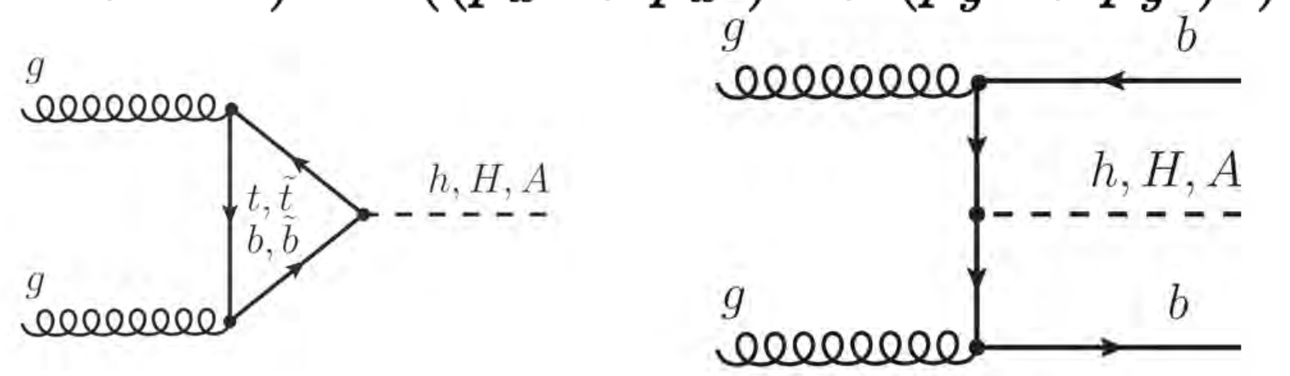
CMS-HIG-14-034

MSSM $H\tau\tau$

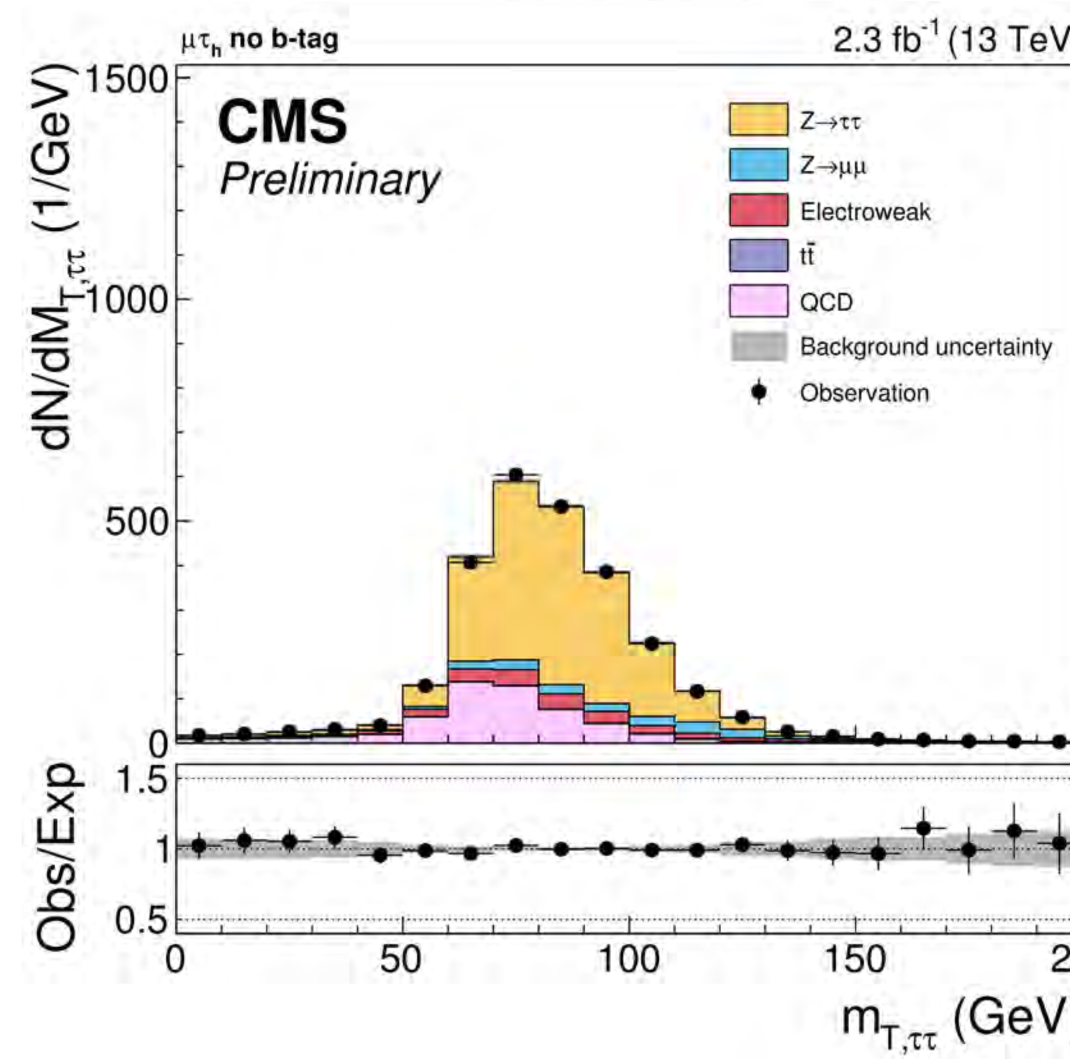
MSSM Higgs TauTau

CMS-PAS-HIG-16-006

$$m_{T,\tau\tau} = \sqrt{(E^{\tau_1} + E^{\tau_2})^2 - ((p_x^{\tau_1} + p_x^{\tau_2})^2 + (p_y^{\tau_1} + p_y^{\tau_2})^2)}$$



- MSSM Higgs ττ search with 2.3 /fb in 2015 at 13 TeV
  - Gluon-gluon fusion and associated-b production
    - 2 categories: one b-tagged jet, no b-tagged jets using medium working point.
  - Very similar analysis strategy and event selection to SM Higgs->ττ
    - However, single lepton triggers used. No trigger requirement for the tau was applied.
  - SVFit is used. The $M_{T,tot}$ variable rebuilt from svFit output performed better than $M_{\tau\tau}$ variable



MSSM Higgs TauTau

CMS-PAS-HIG-16-006

- Event selection optimized for high mass
- $M_{T,tot}$ used to set limits
- Compared to 8 TeV better high mass limits, but not as sensitive to the low mass as 8 TeV, primarily due to better separation of ttbar backgrounds.