The Problem of Mass: The Higgs and beyond

Dr. Laura Margaret Dodd

Standard model Higgs($\tau\tau$) and mono-Higgs dark matter search with CMS experiment

The problem of mass: today

old problem: adding mass terms for particles

$\lambda_f \bar{\psi}_f \psi_f \phi$

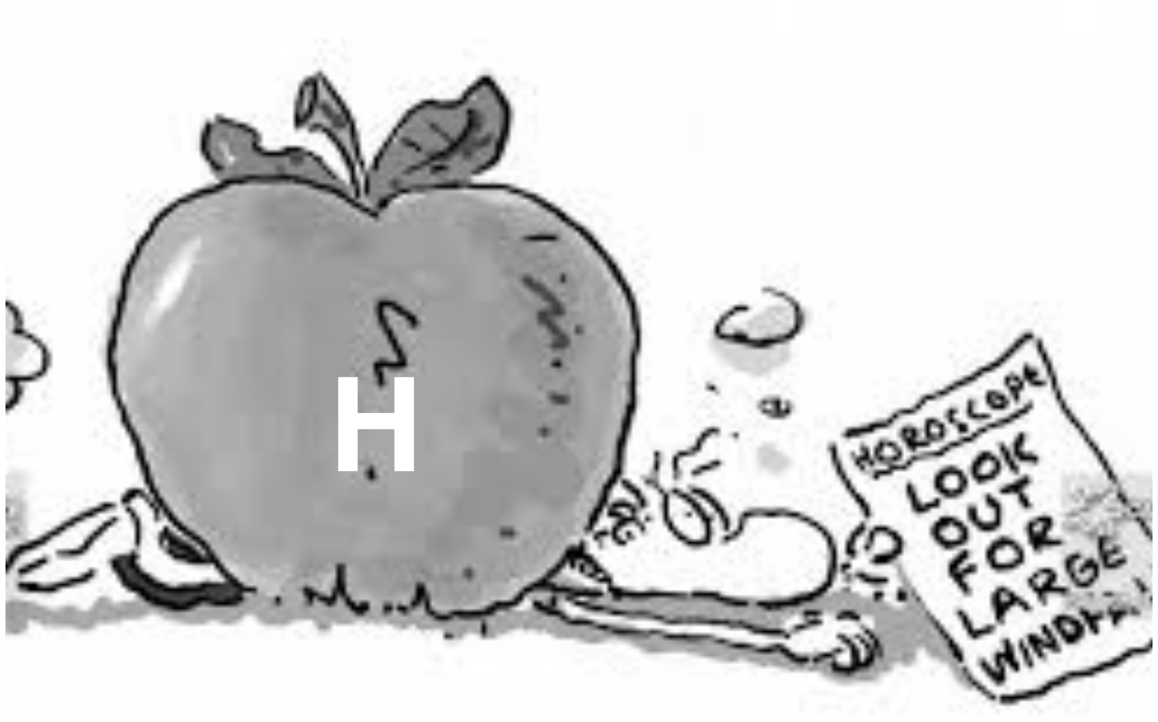
50 yr old solution: *Higgs mechanism* provides mass to W/Z, and also luckily provides mechanism for charged fermion masses as well

The problem of mass: today

old problem: adding mass terms for particles

50 yr old solution: *Higgs mechanism* provides mass to W/Z, and also provides mechanism for charged fermion masses as well

$\lambda_f \bar{\psi}_f \psi_f \phi$

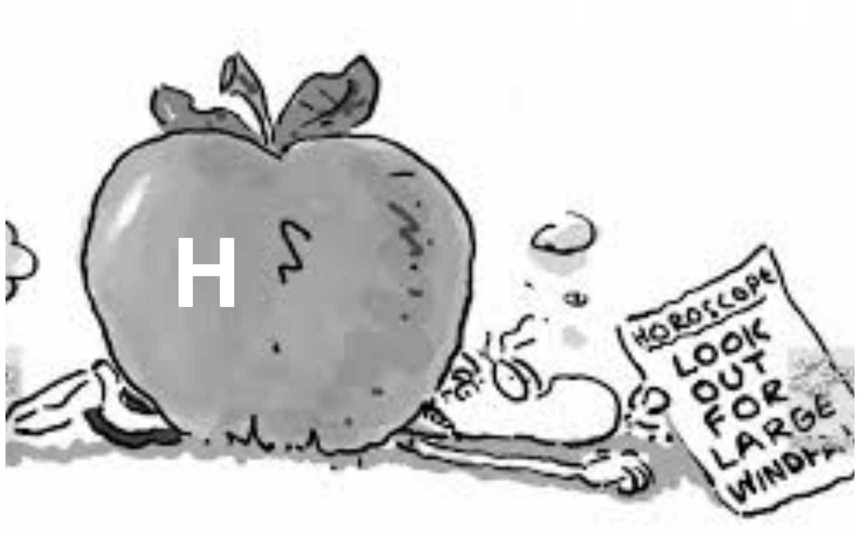


mass issue → coupling issue

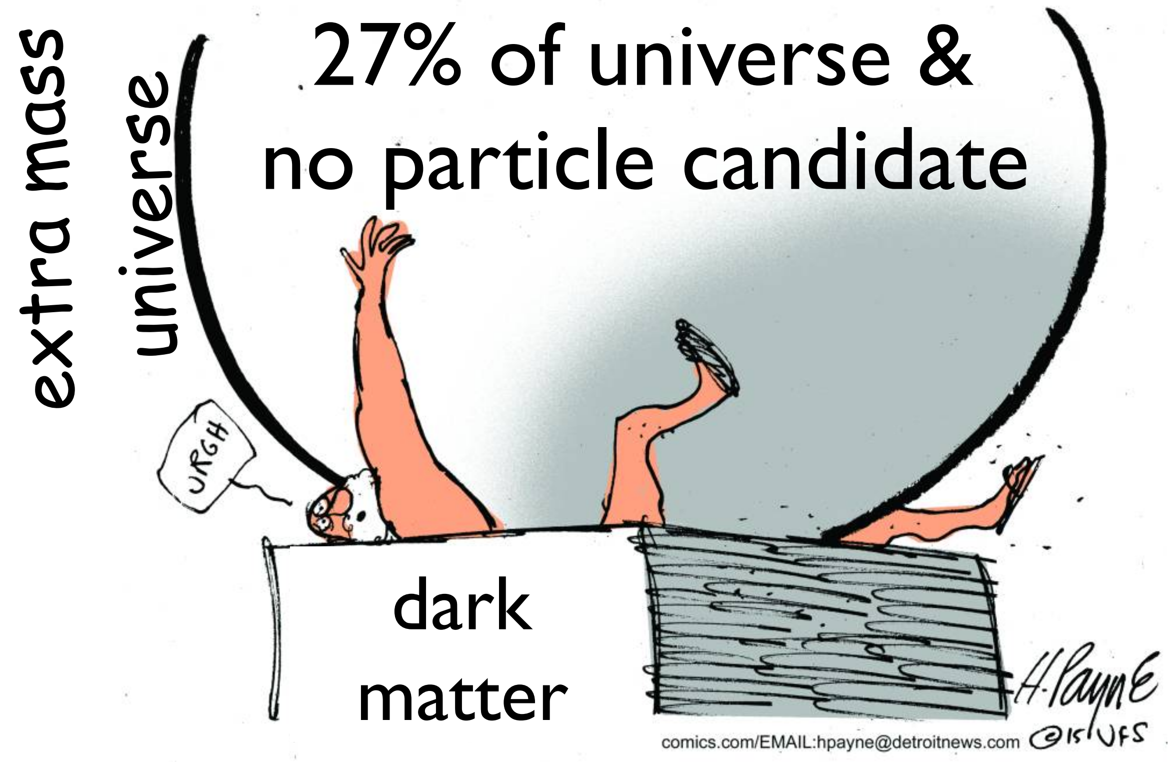
couplings widely vary—10^5. A Dirac neutrino mass coupling is even smaller!

The problem of mass: maybe

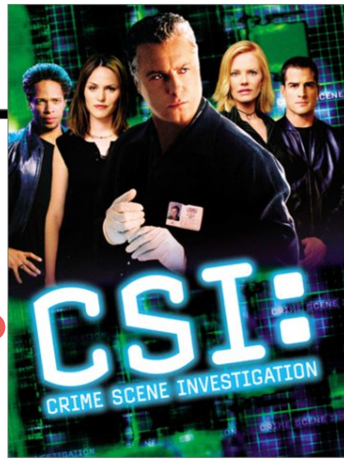
maybe the Higgs can answer another long standing *mass*ive problem: dark matter?



?



investigate
are they linked?



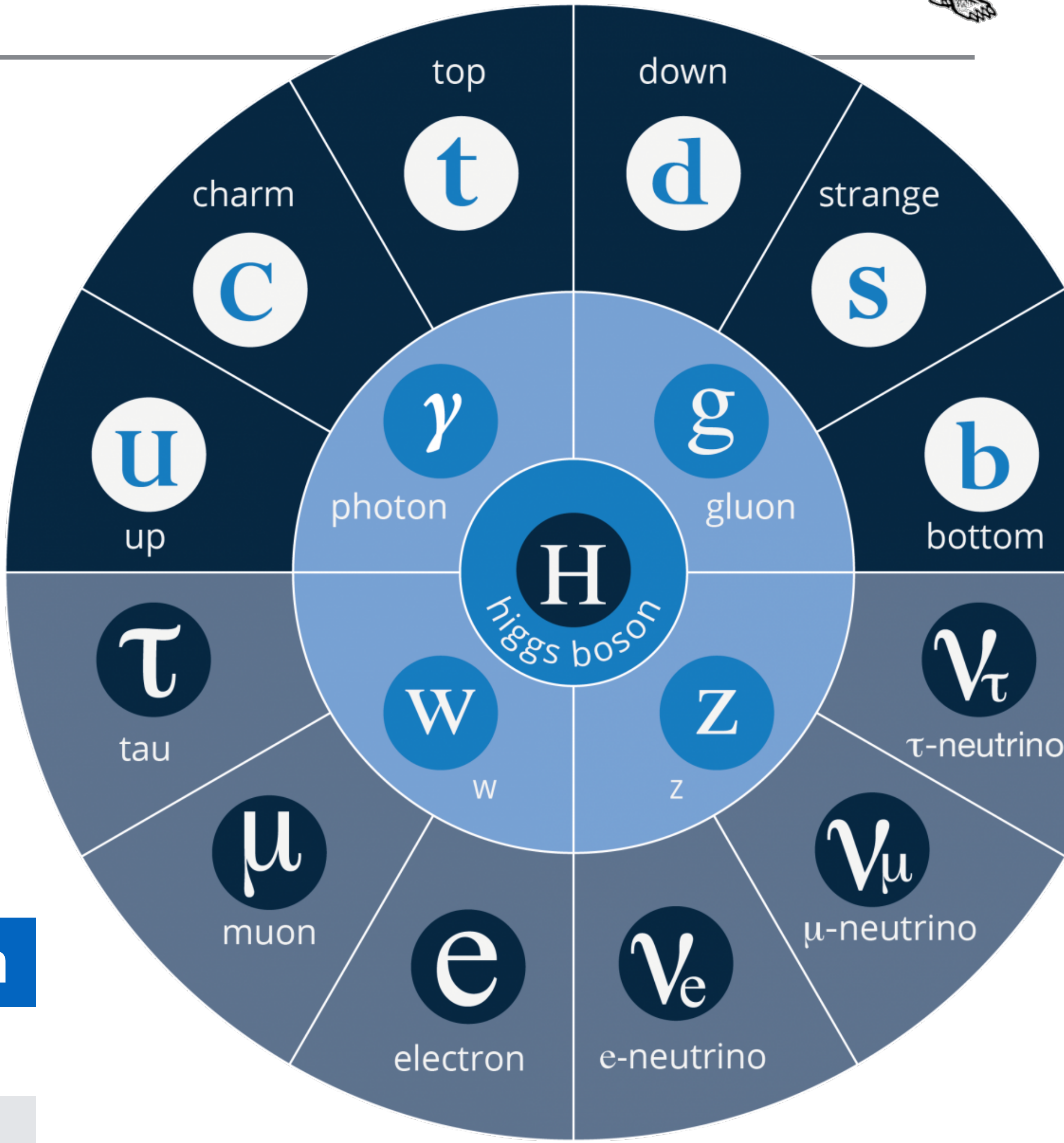
Mass and the Standard Model

why? how?

$$\lambda_f \bar{\psi}_f \psi_f \phi$$

$$m_f = \frac{\lambda_f v}{\sqrt{2}}$$

λ	1st gen	2nd gen	3rd gen
up-type q	2×10-5	9×10-3	~1
down-type q	4×10-5	8×10-4	3×10-2
charged lepton	3×10-6	6×10-4	1×10-2

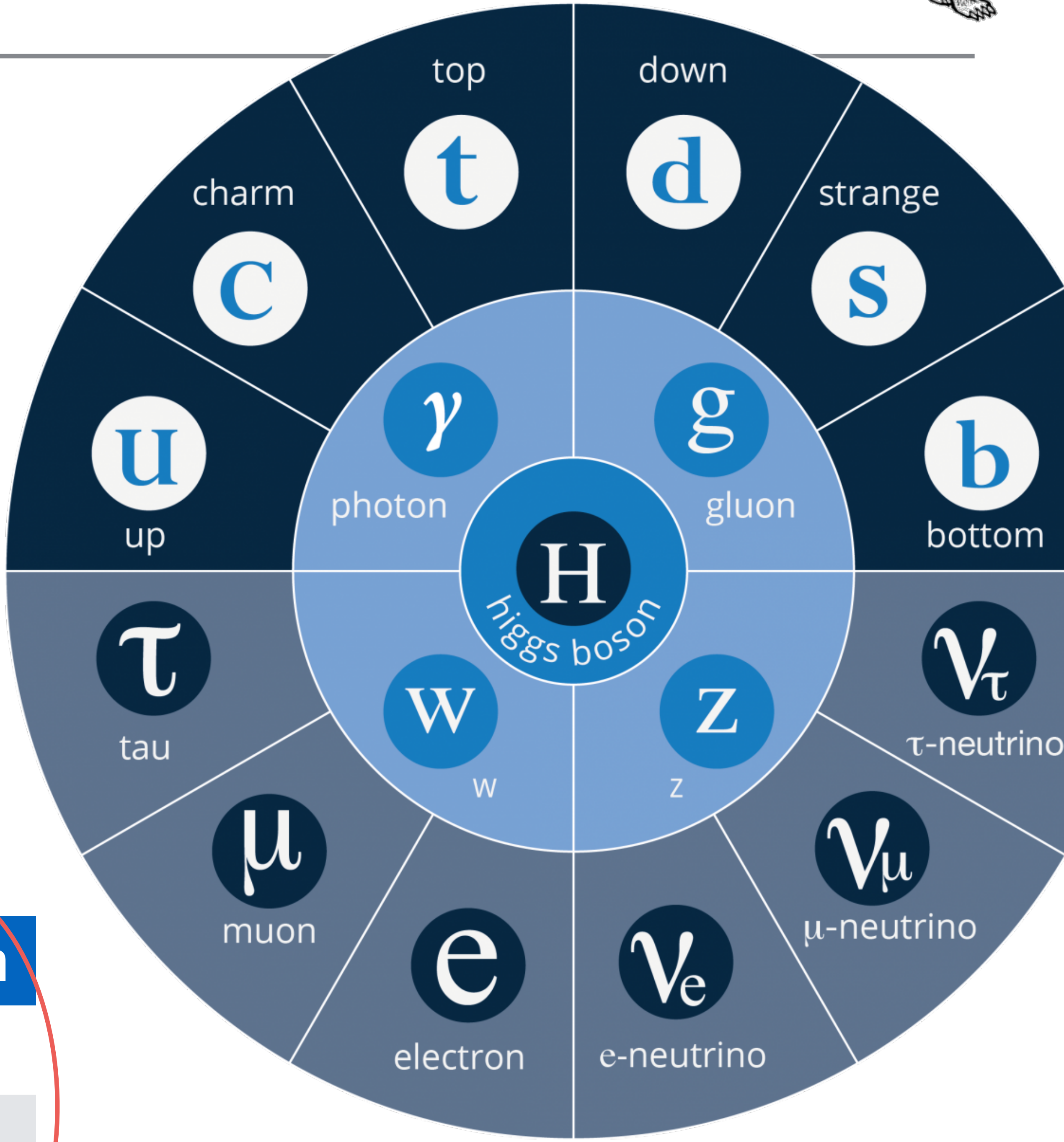


Mass and the Standard Model

why? how?

$$\lambda_f \bar{\psi}_f \psi_f \phi$$

$$m_f = \frac{\lambda_f v}{\sqrt{2}}$$



λ	1st gen	2nd gen	3rd gen
up-type q	2×10-5	9×10-3	~1
down-type q	4×10-5	8×10-4	3×10-2
charged lepton	3×10-6	6×10-4	1×10-2

large coupling

Outline for today

- Question: Is charged fermion mass proportional to Higgs boson λ_f coupling?
  - Answer: Higgs-Tau lepton coupling measurement at CMS
- Question: Is Higgs linked to dark matter?
  - Answer: Higgs boson measurements ($H\tau\tau$+combination) can indirectly constrain dark matter: "Higgs-portal models "
  - Answer: More direct Higgs+DM search

My PhD Thesis:

$H(\tau\tau)$
arXiv:1708.00373v2
CMS Collaboration

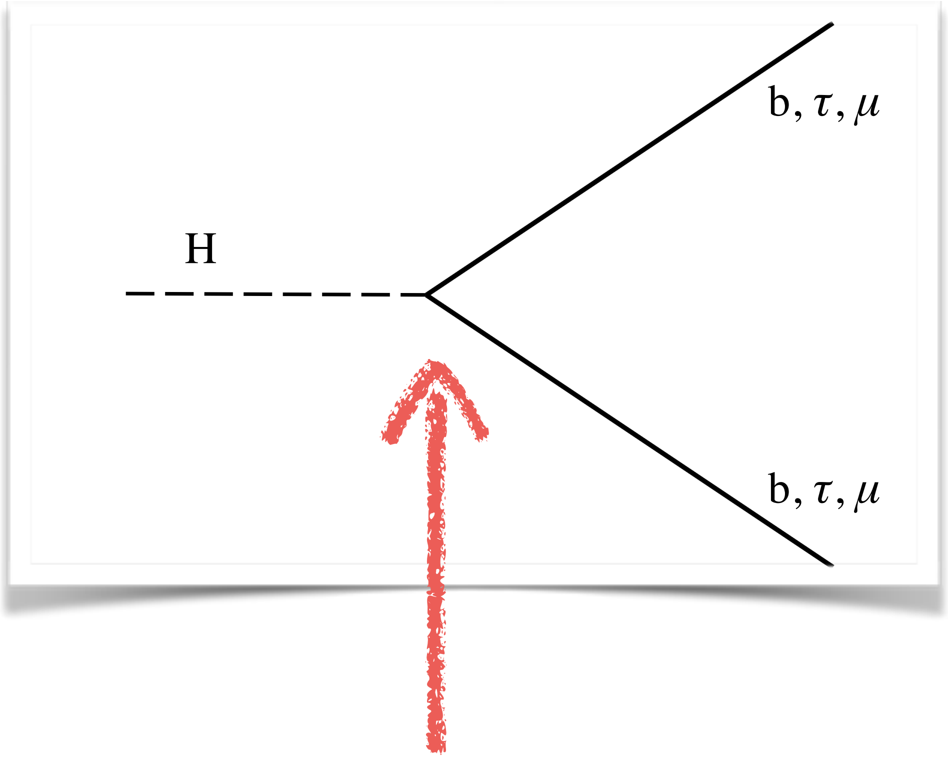
H+DM
https://cds.cern.ch/record/2308271
CMS Collaboration

CMS Higgs combination with 2016 data:
http://cds.cern.ch/record/2308127
CMS Collaboration

Yukawa coupling

Look at Higgs boson decays

$\lambda_f \bar{\psi}_f \psi_f \phi$

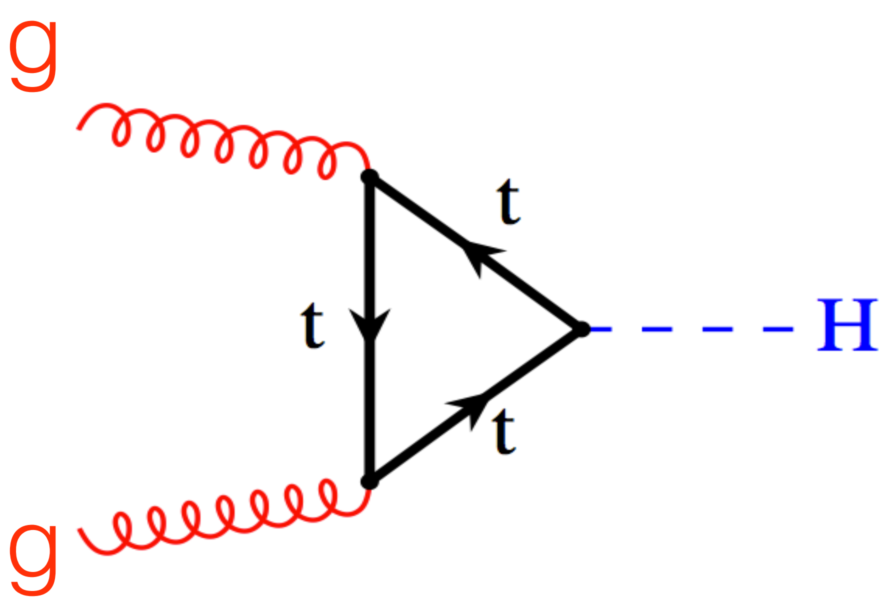


AIM: *Direct* measurement of charged fermionic coupling rather than indirect probing

LHC Higgs Production

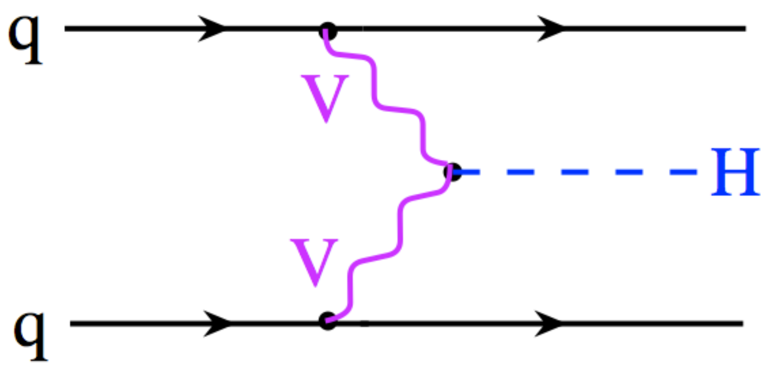
~45 pb

gluon fusion (ggH)



~5 pb

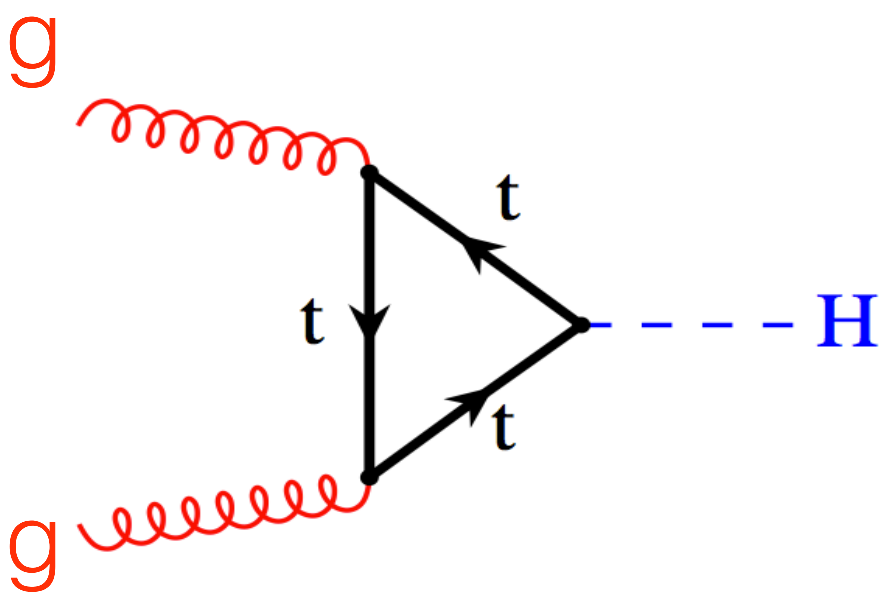
vector boson fusion (VBF)
rate is factor of ten
smaller than ggH at 13TeV



LHC Higgs Production

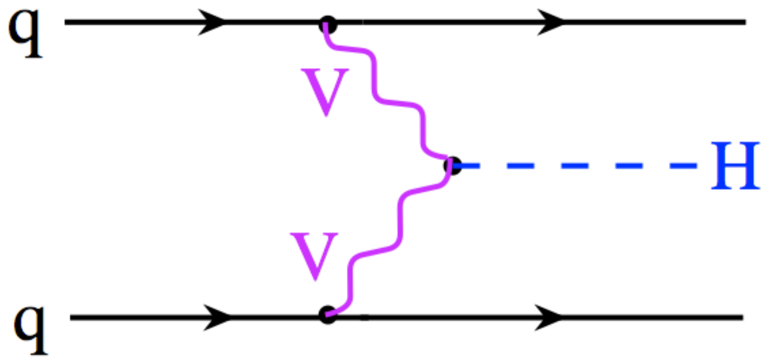
~45 pb

gluon fusion (ggH)



~5 pb

vector boson fusion (VBF)
rate is factor of ten
smaller than ggH at 13TeV

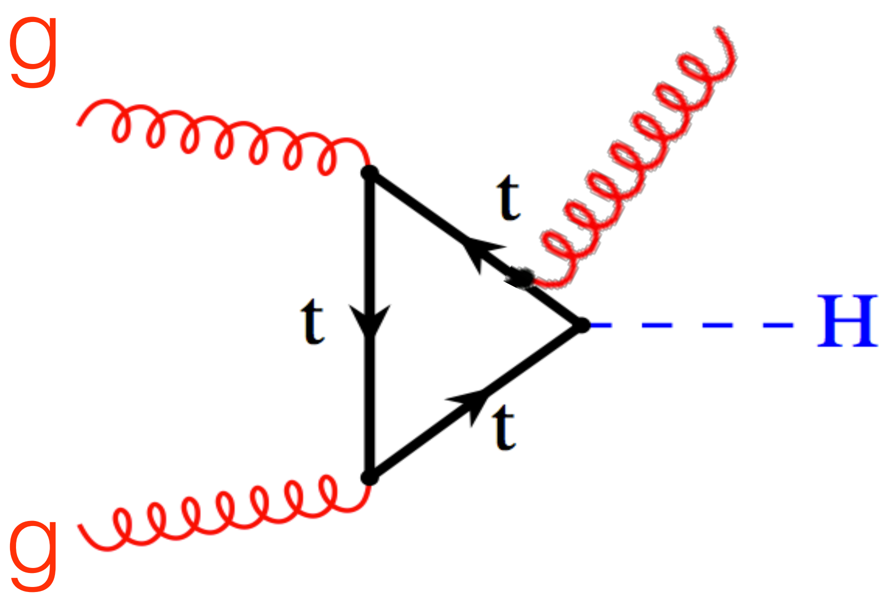


To measure the decay products: Useful to distinguish between production mechanism as well

LHC Higgs Production

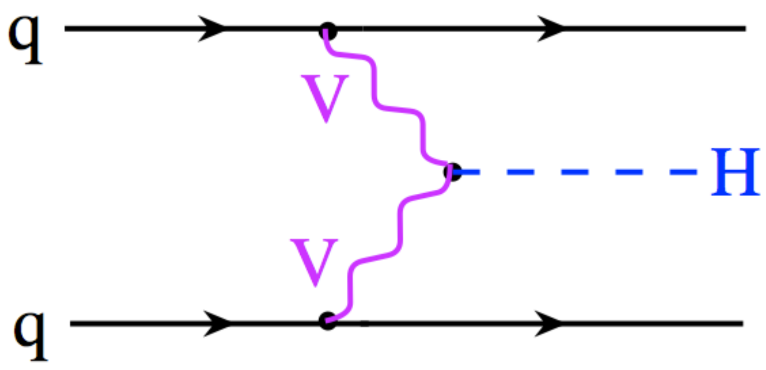
~45 pb

gluon fusion (ggH)



~5 pb

vector boson fusion (VBF) rate is factor of ten smaller than ggH at 13TeV



To measure the decay products: Useful to distinguish between production mechanism as well

boosted higgs from gluon fusion

Higgs Decays

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

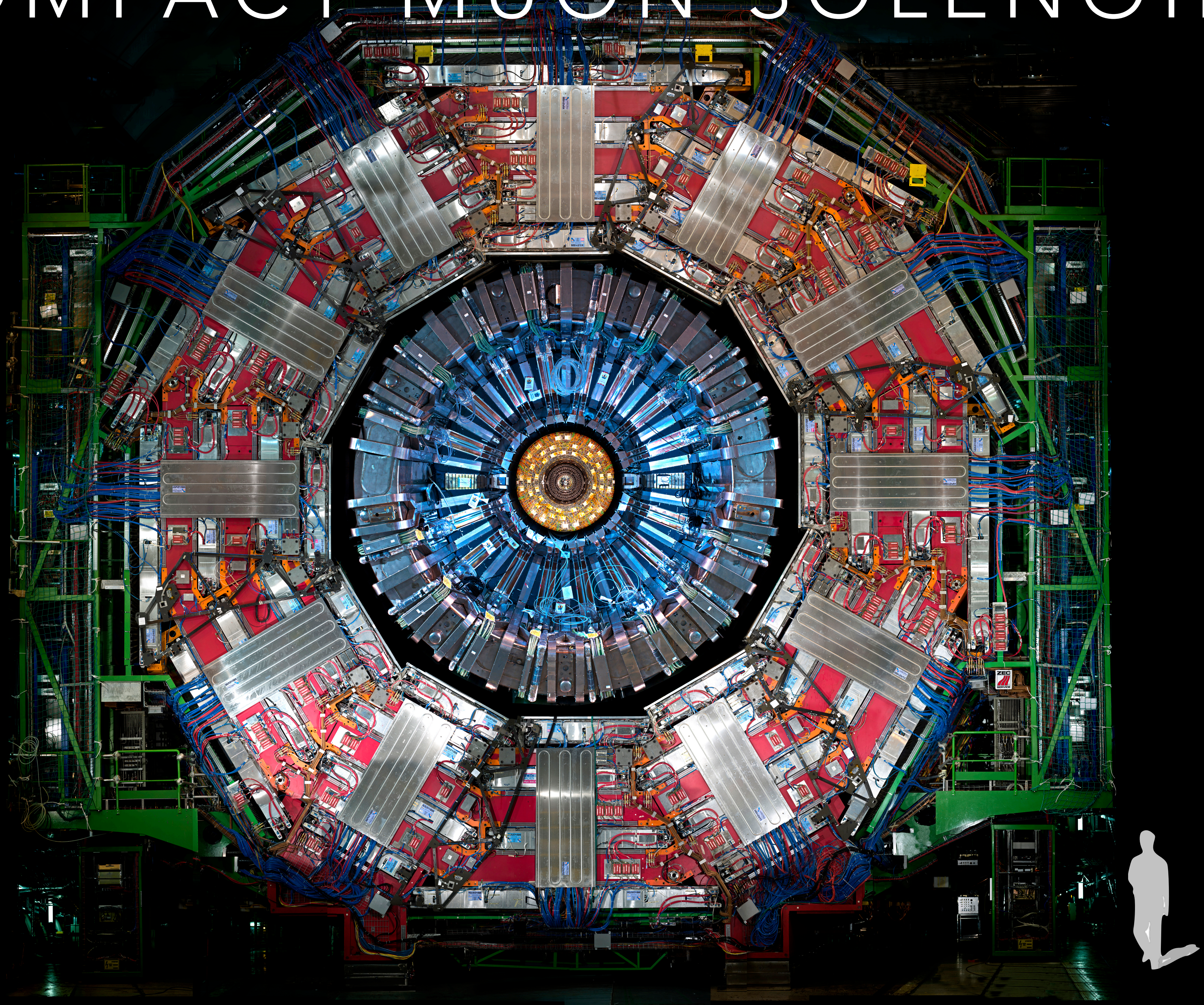
Now, use τ leptons
for Yukawa coupling
measurement!

measure H(ττ)
coupling strength and ask:
is it proportional to mass

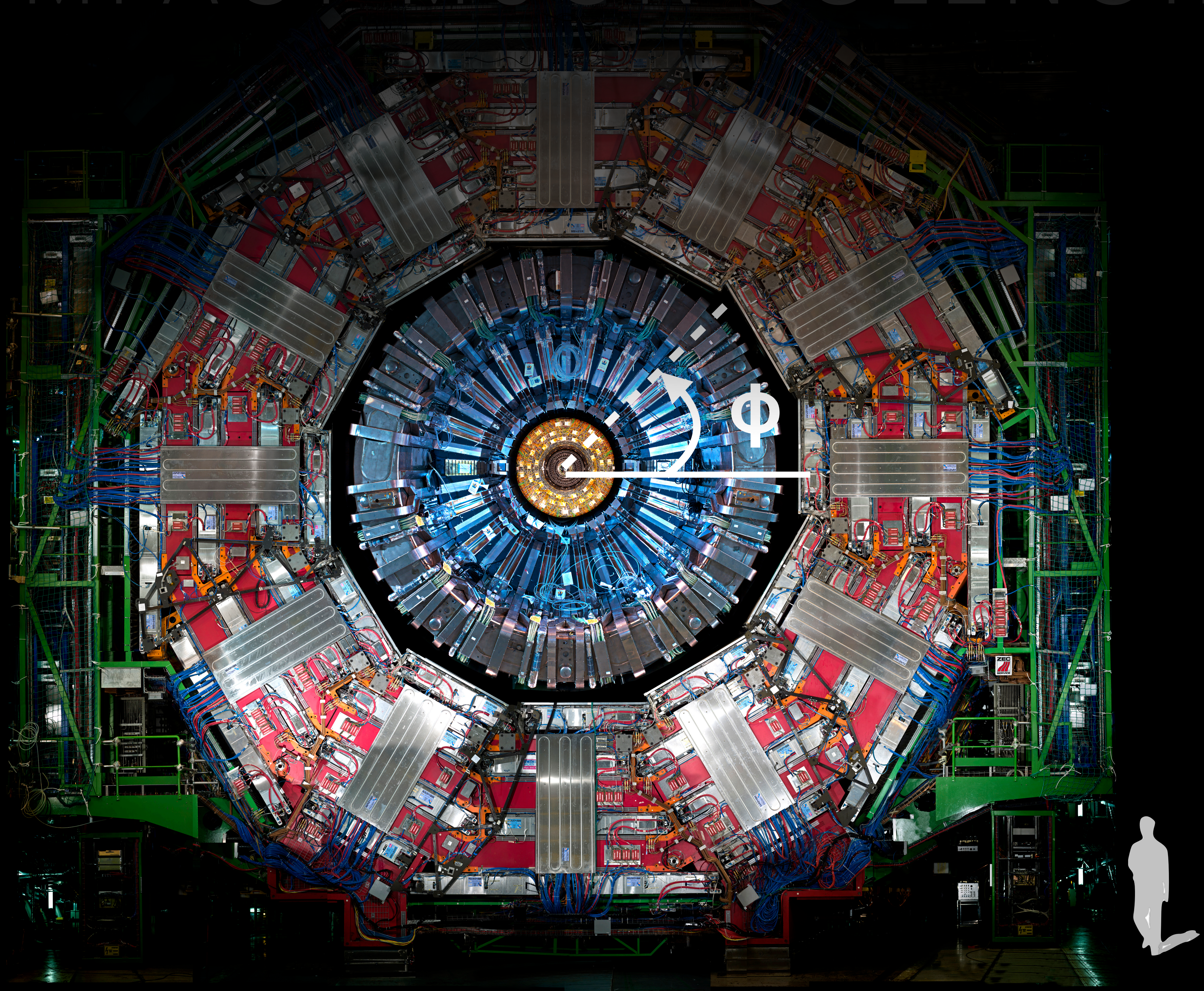
result "μ" is signal
strength modifier:
Obs. rate/ Exp. rate

2012: {
CMS H(ττ)
μ=0.88 ± ~0.30
ATLAS H(ττ)
μ=1.43 ± ~0.40

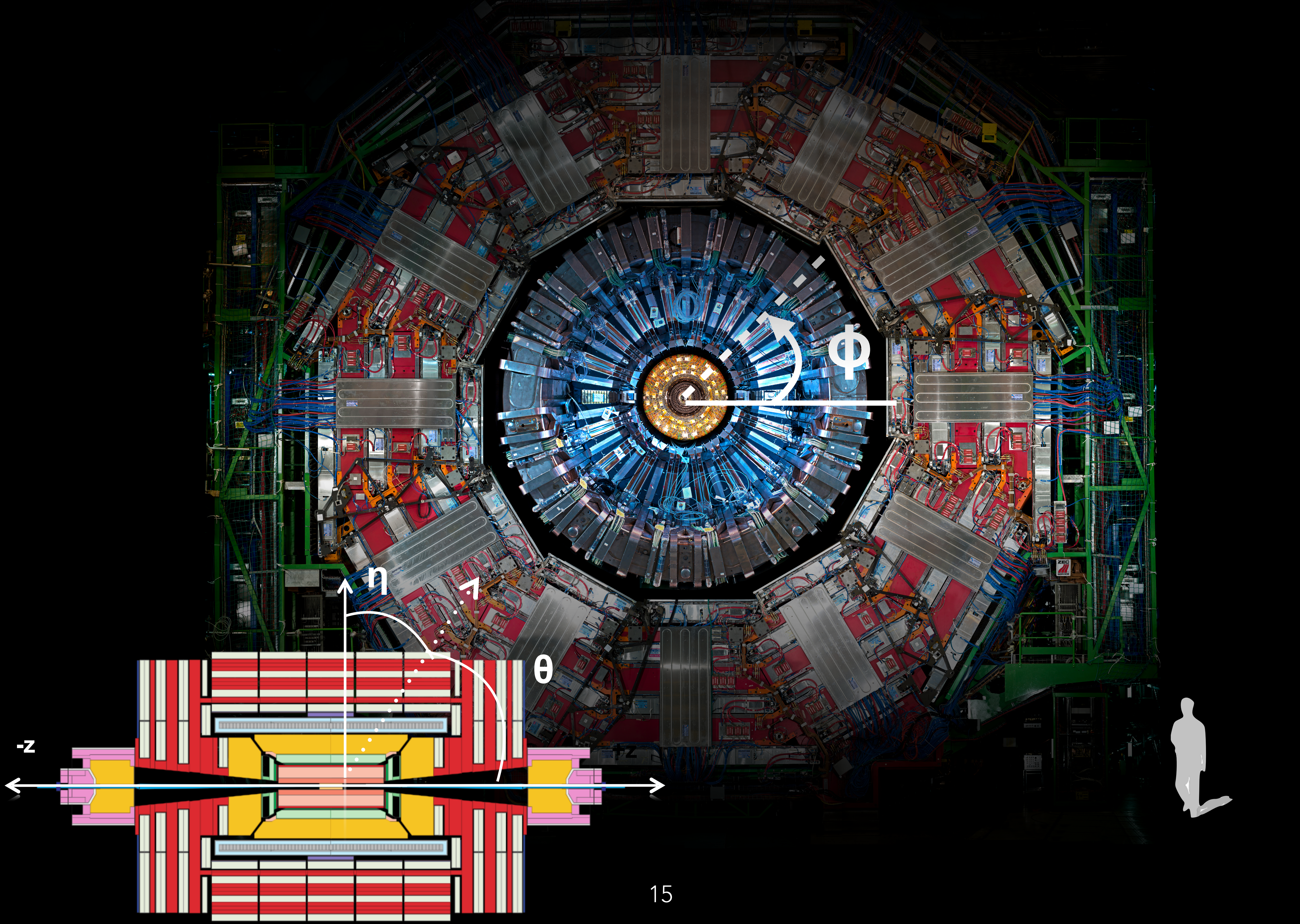
COMPACT MUON SOLENOID



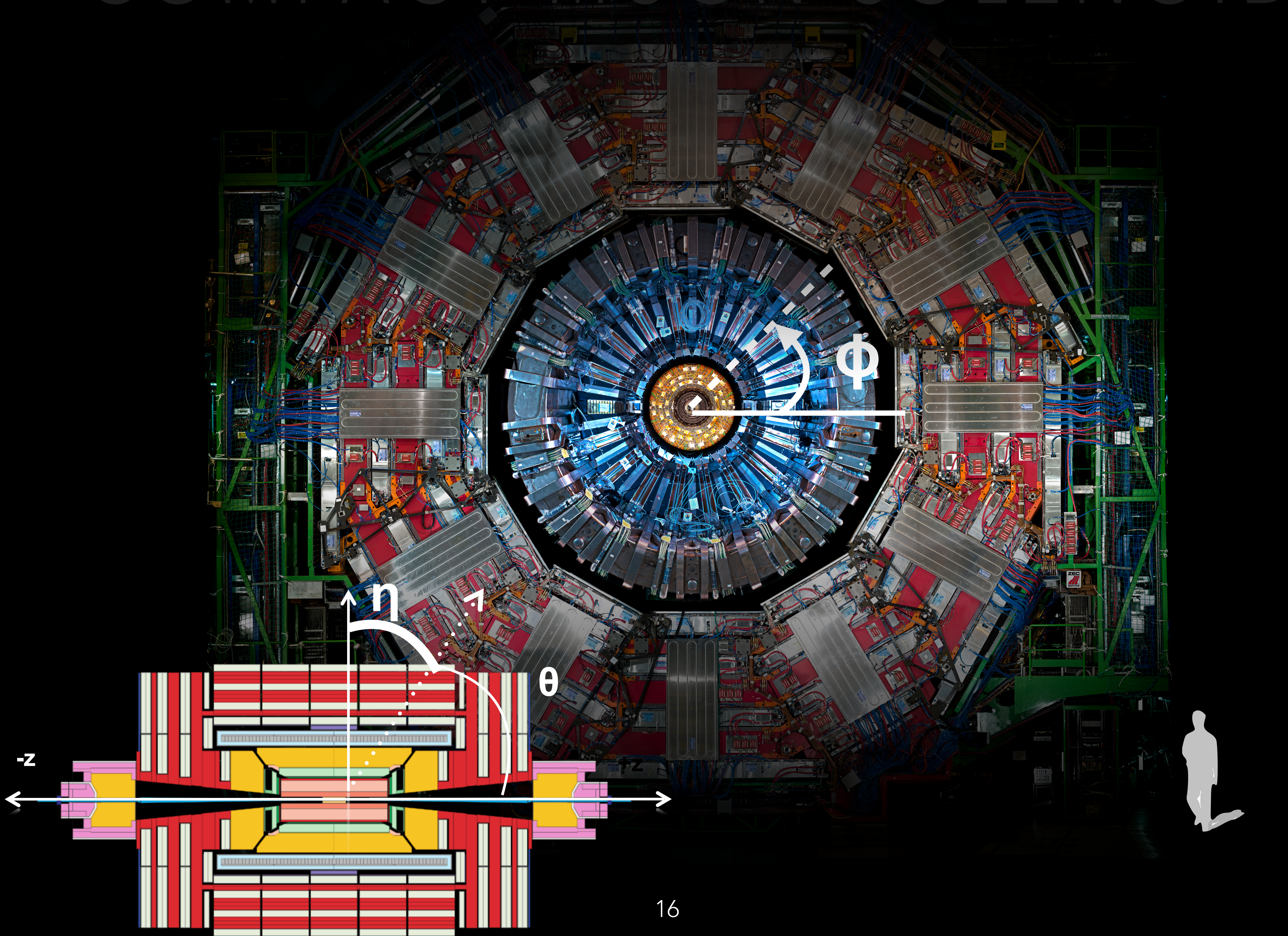
COMPACT MUON SOLENOID



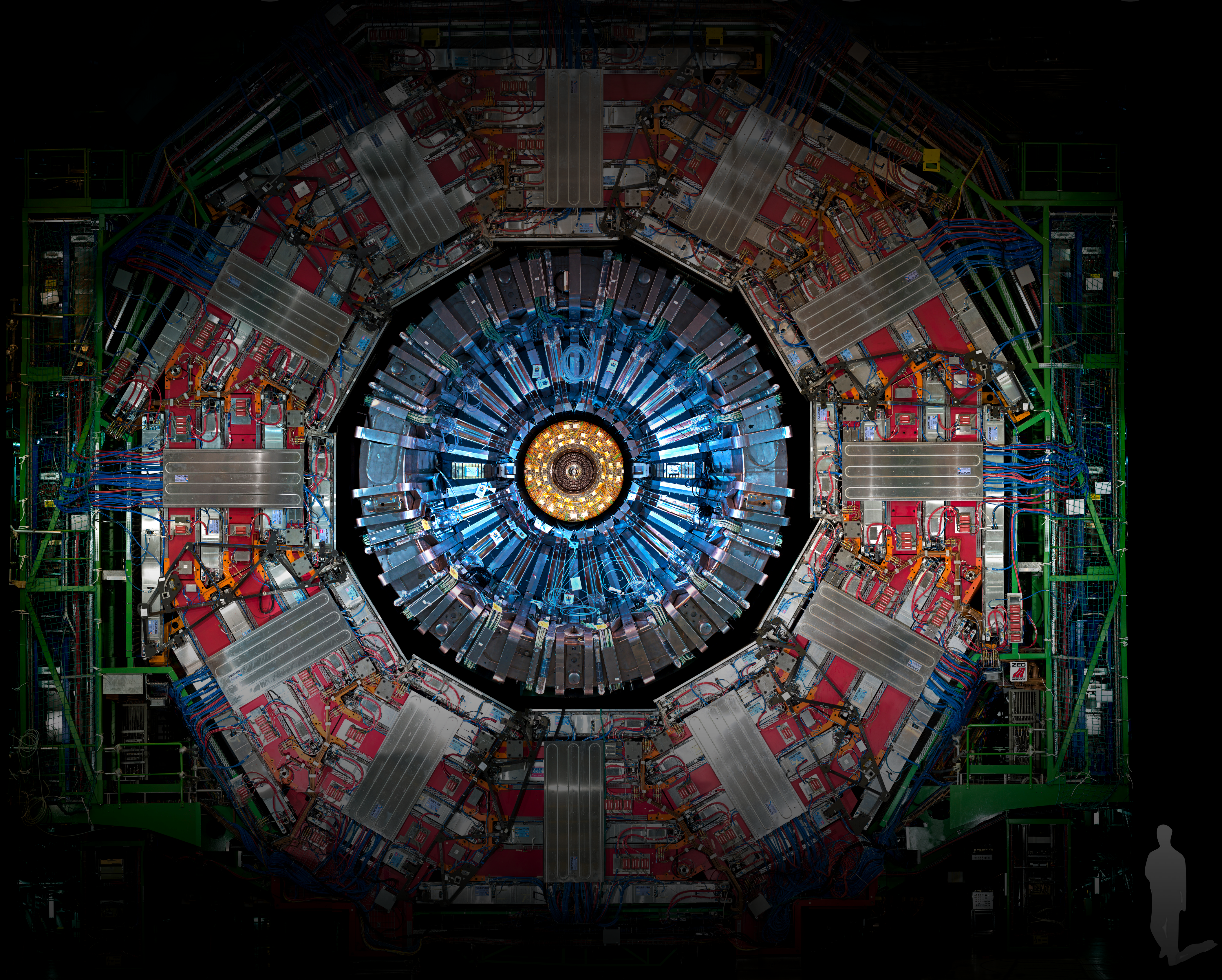
COMPACT MUON SOLENOID



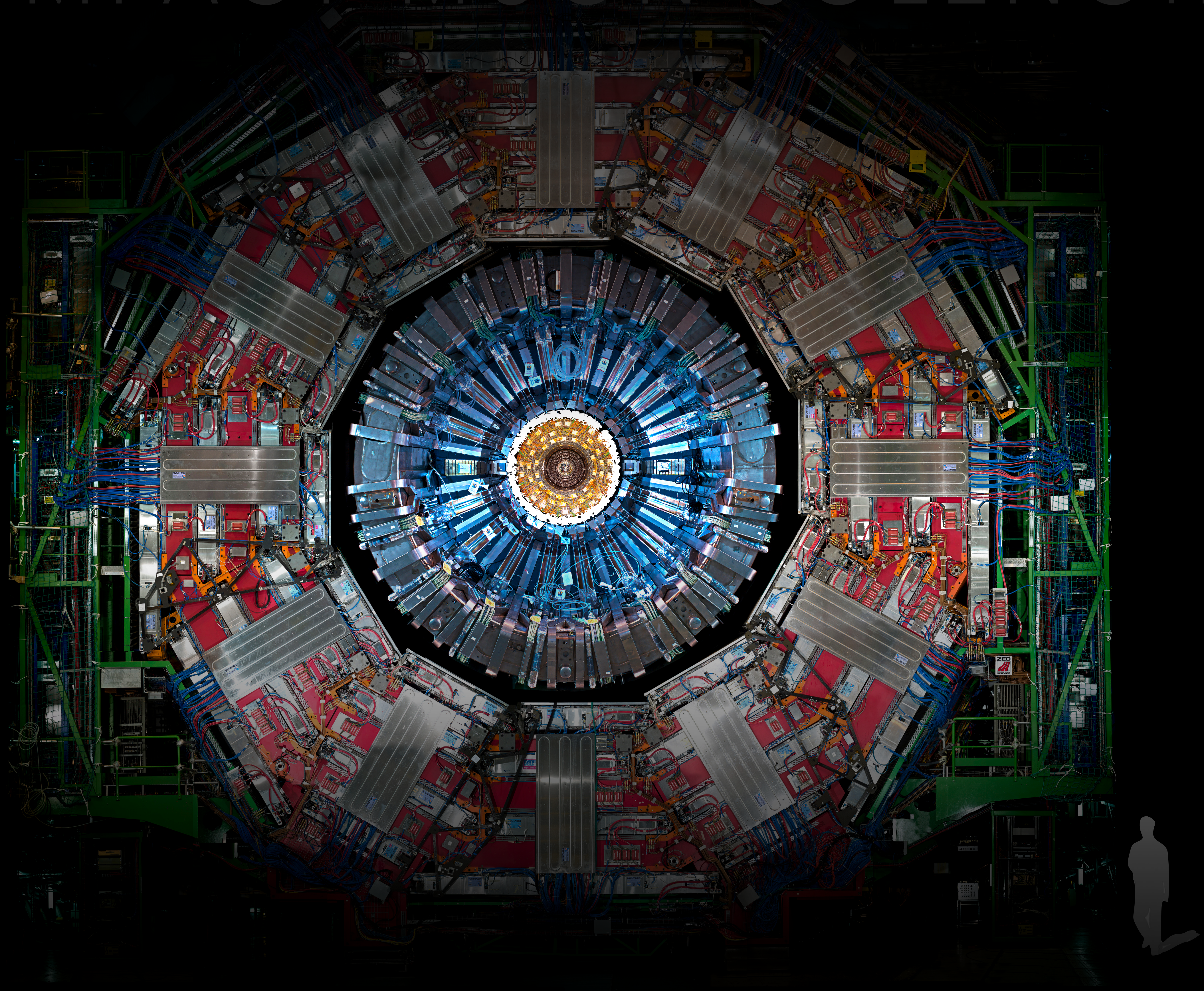
COMPACT MUON SOLENOID



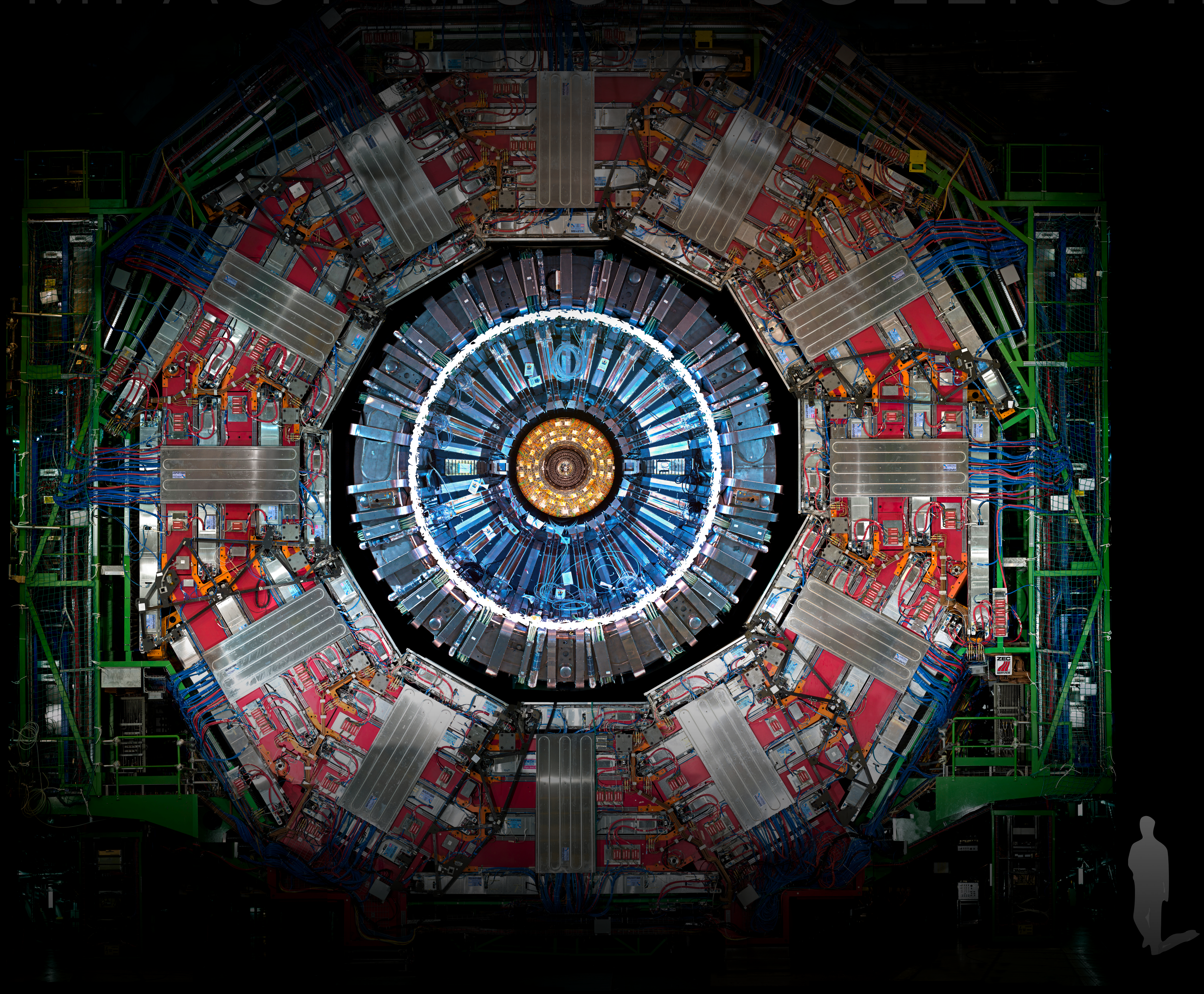
COMPACT MUON SOLENOID



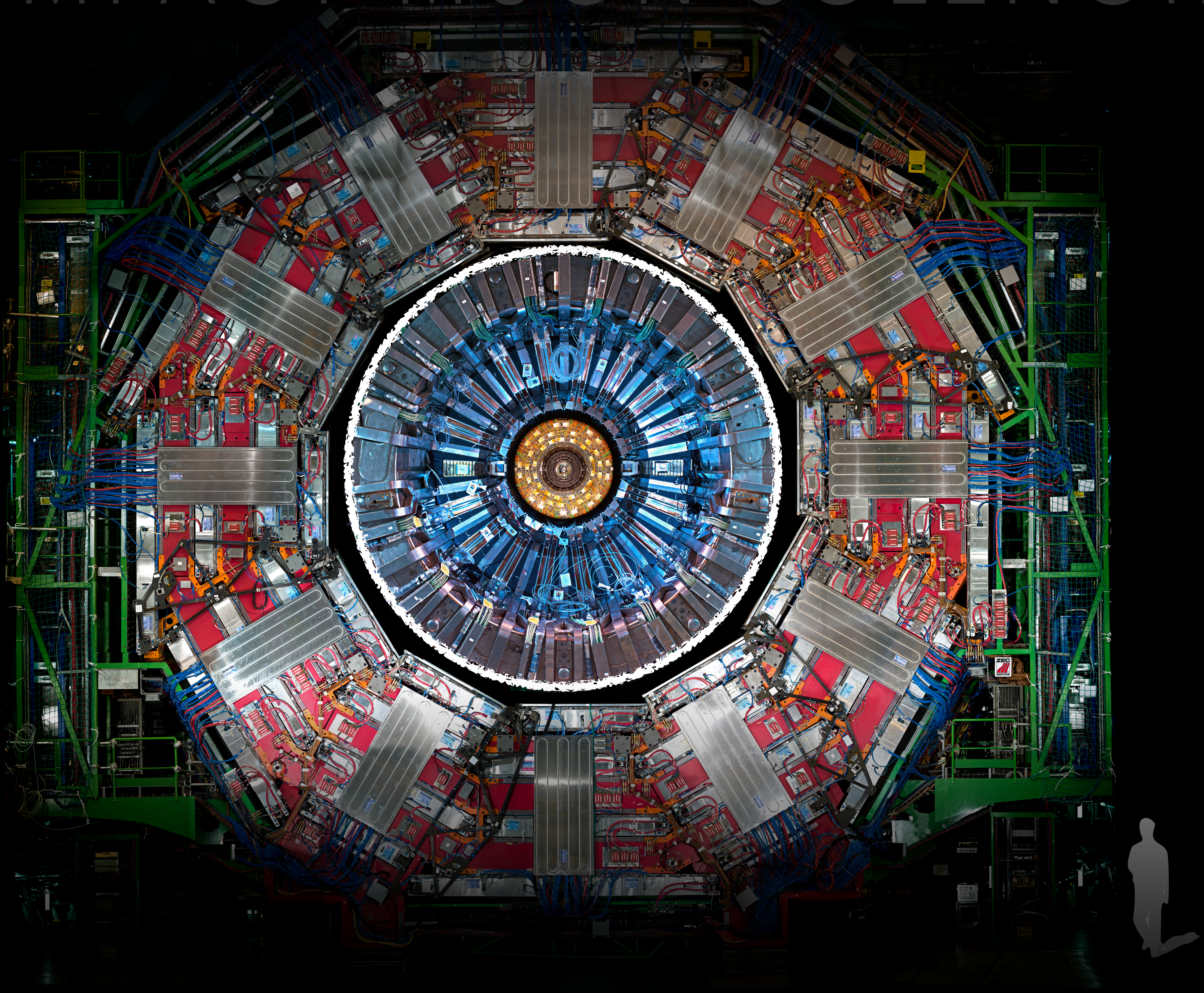
COMPACT MUON SOLENOID



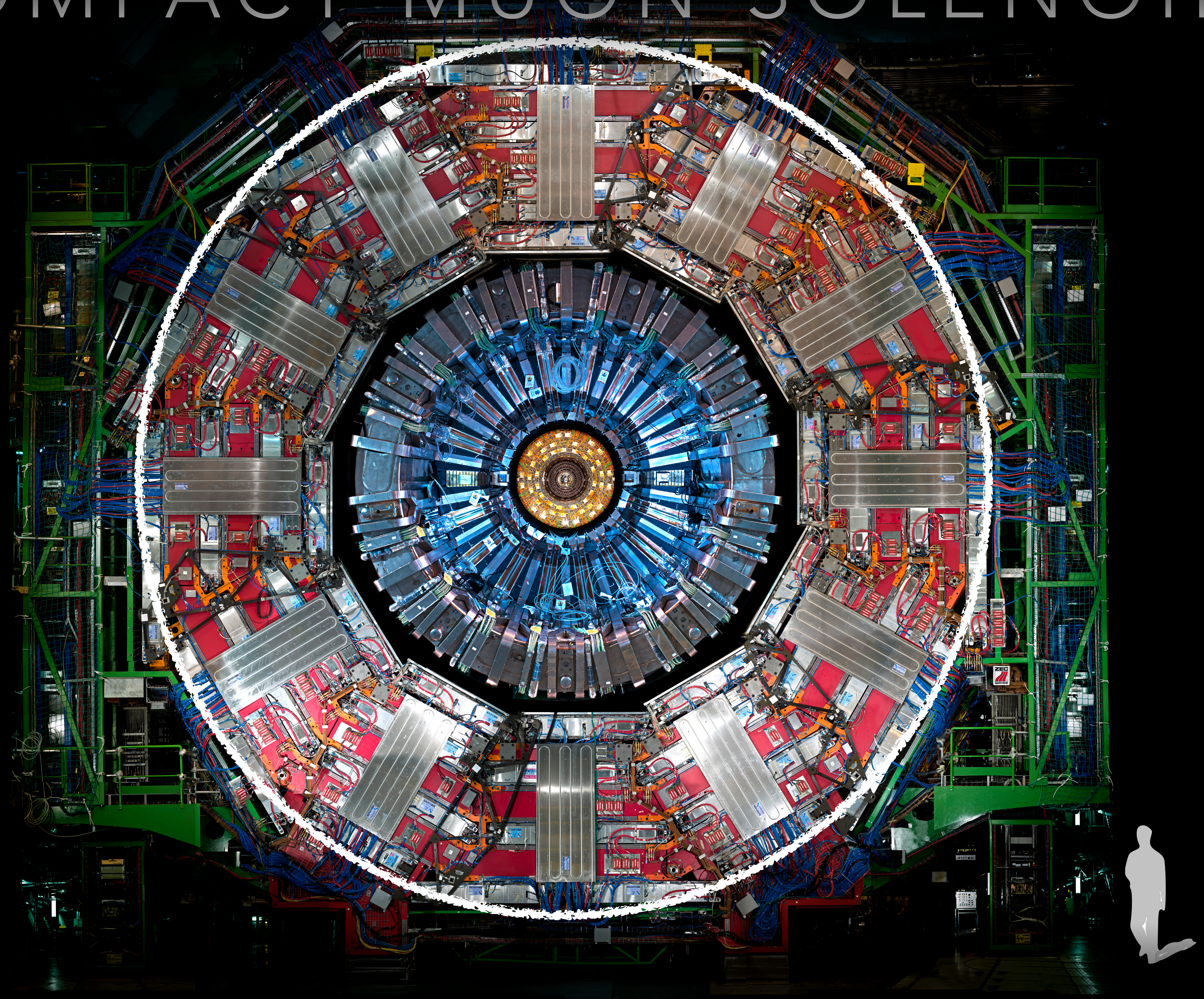
COMPACT MUON SOLENOID



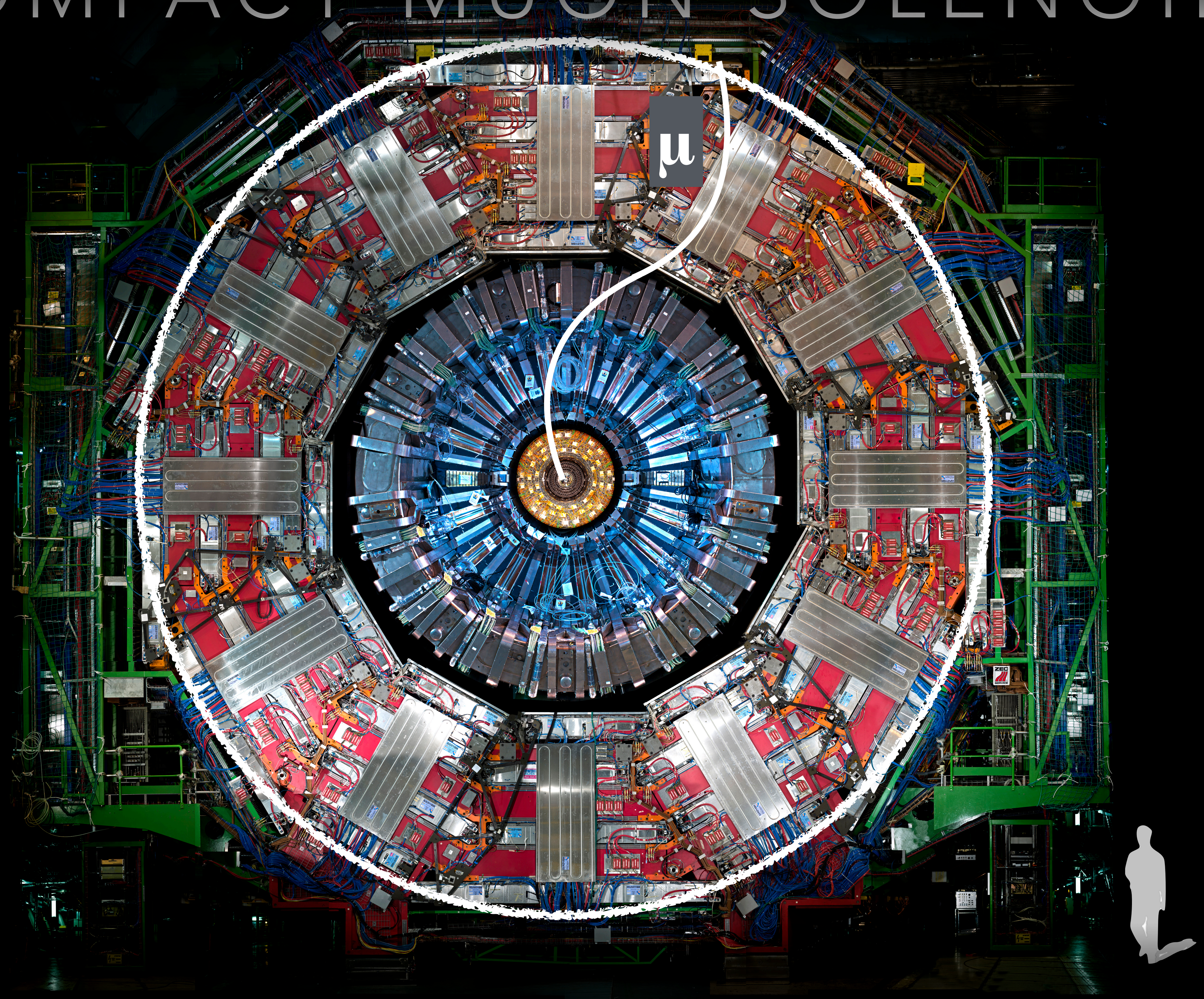
COMPACT MUON SOLENOID



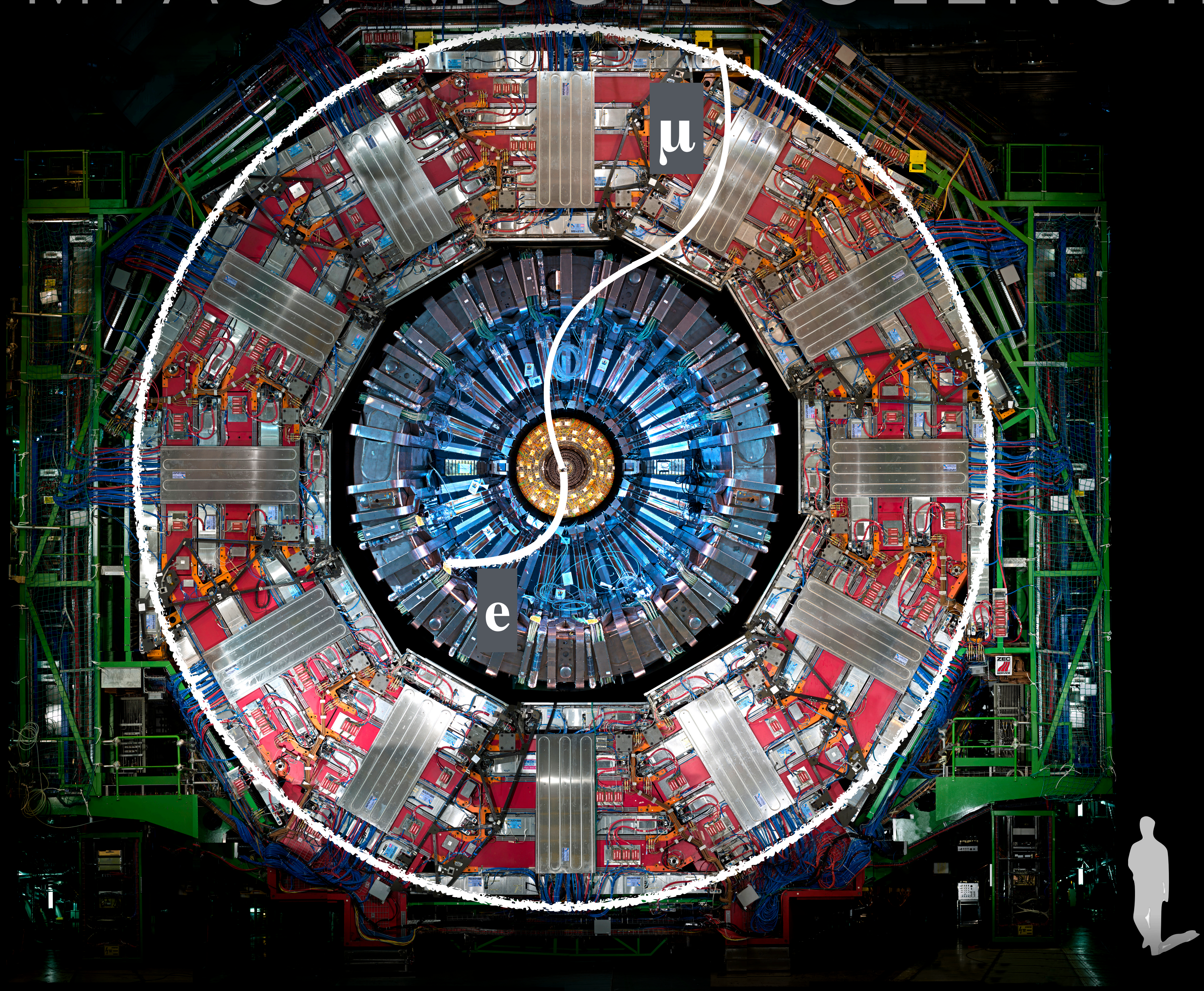
COMPACT MUON SOLENOID



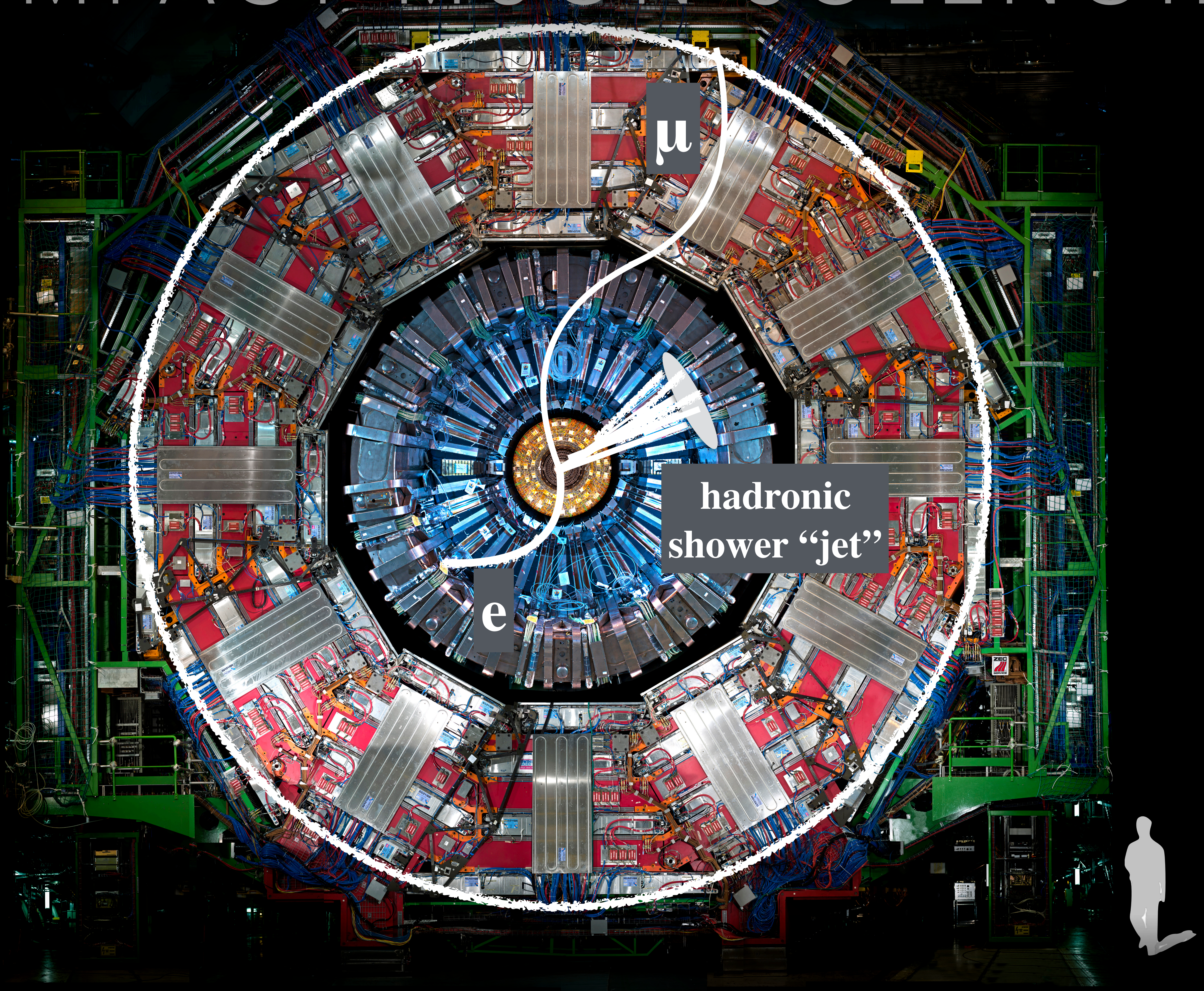
COMPACT MUON SOLENOID



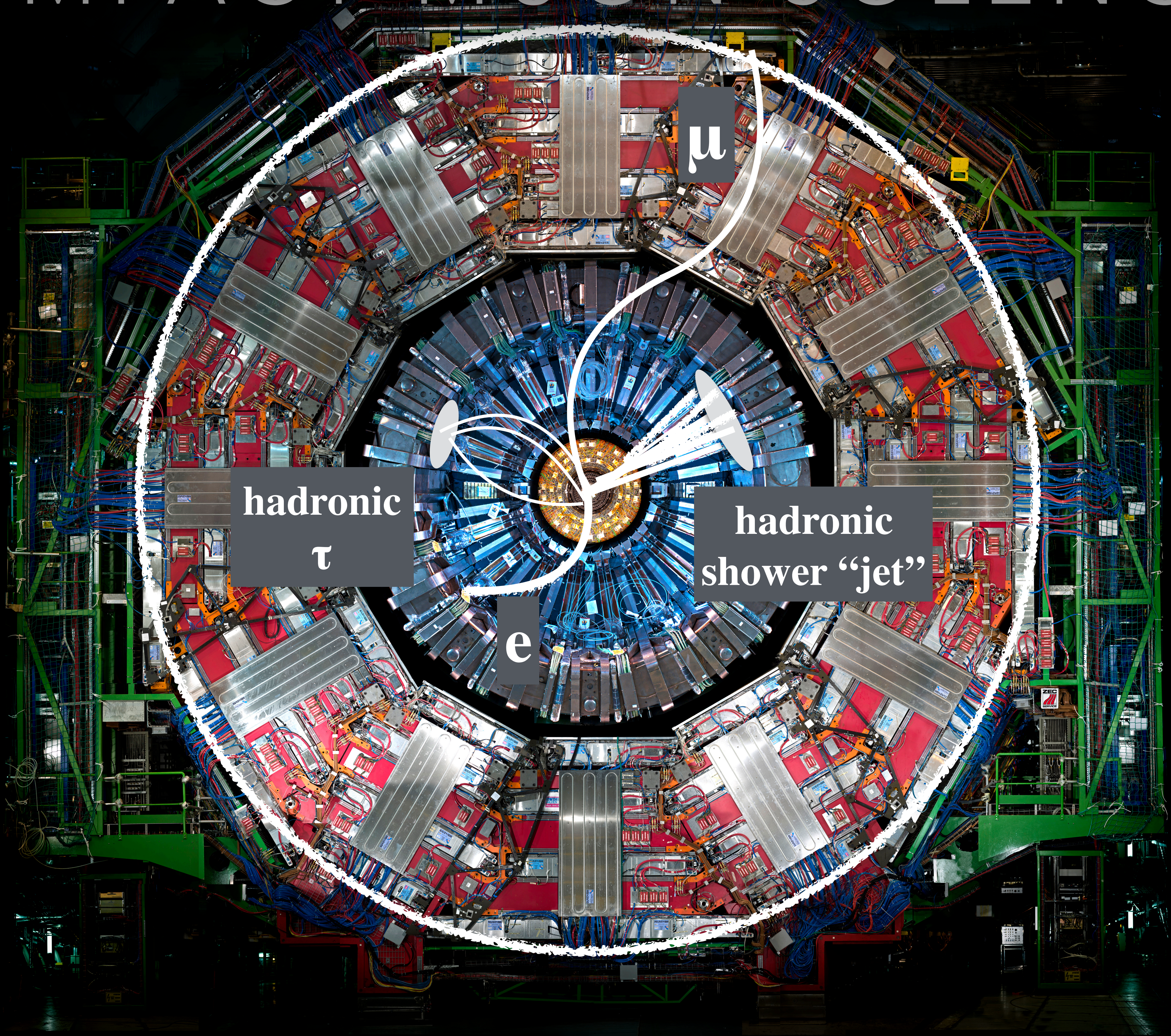
COMPACT MUON SOLENOID



COMPACT MUON SOLENOID

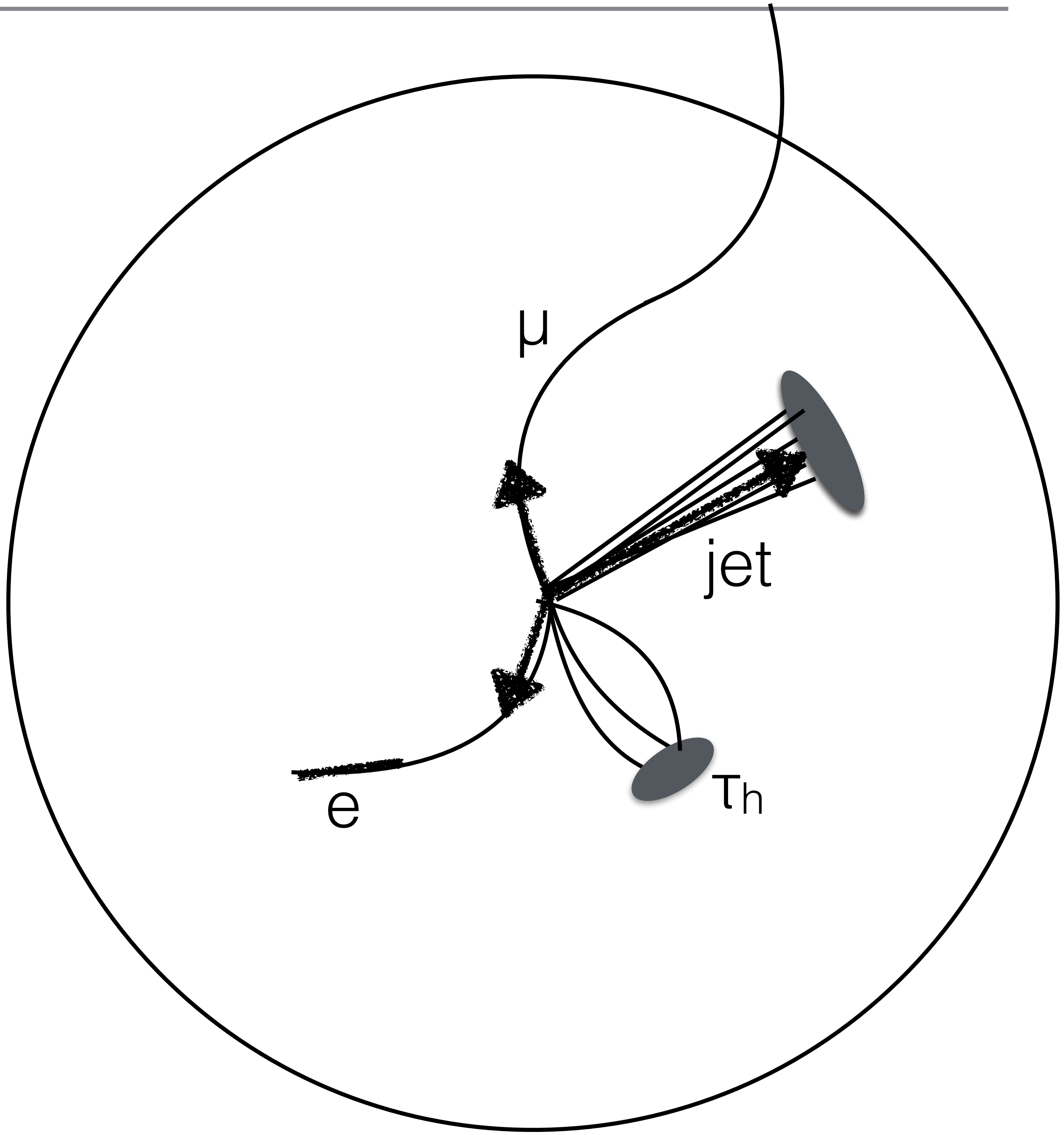


COMPACT MUON SOLENOID



Reconstruction: DM and Neutrinos

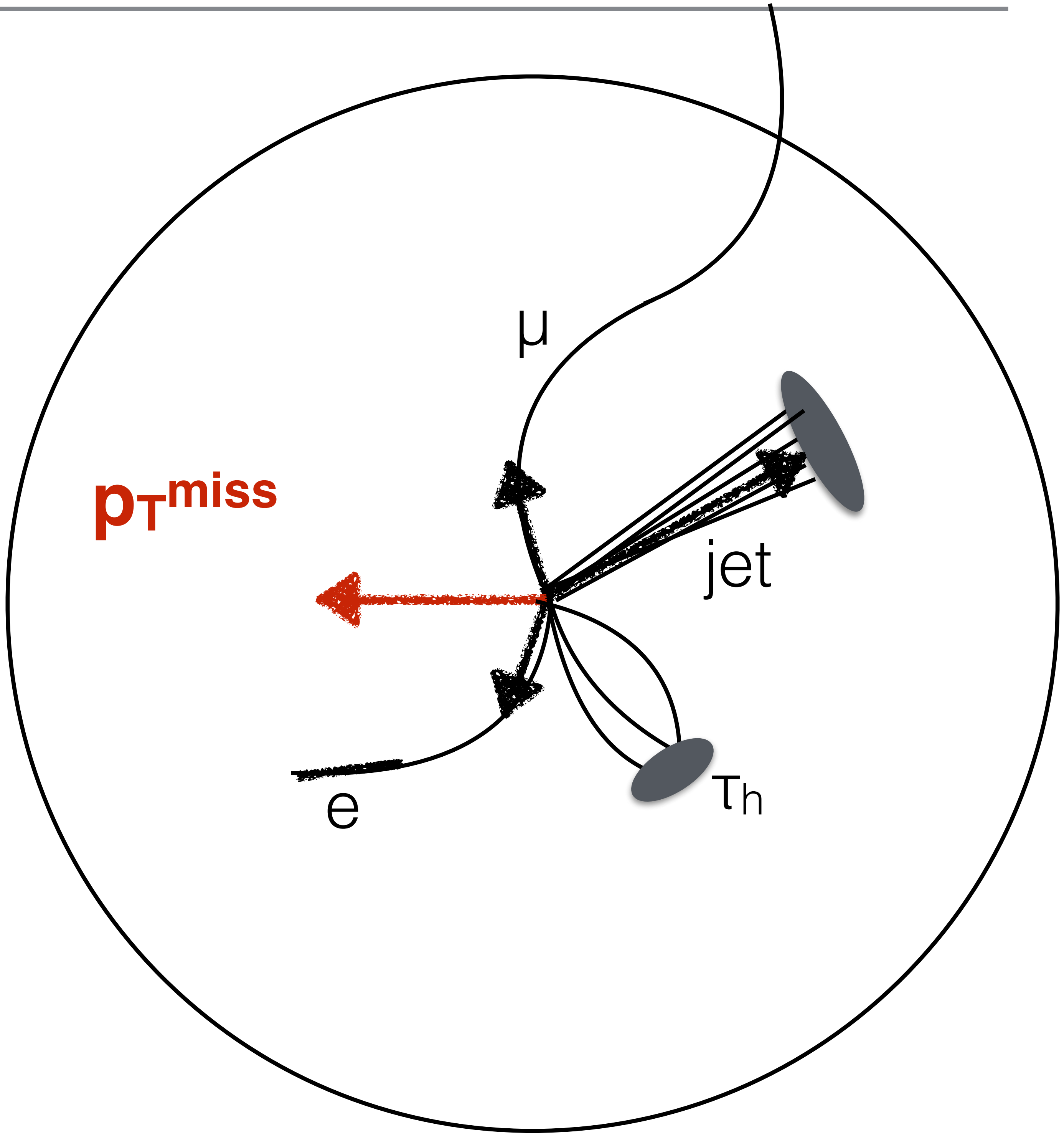
- Any particles that do not interact in detector, such as DM and neutrinos, show up as missing transverse momentum (**p_T^{miss}**)
- ∴ all other particle reconstruction uncertainties contribute to **p_T^{miss}** uncertainty!



negative vectorial sum of all reconstructed four-vectors

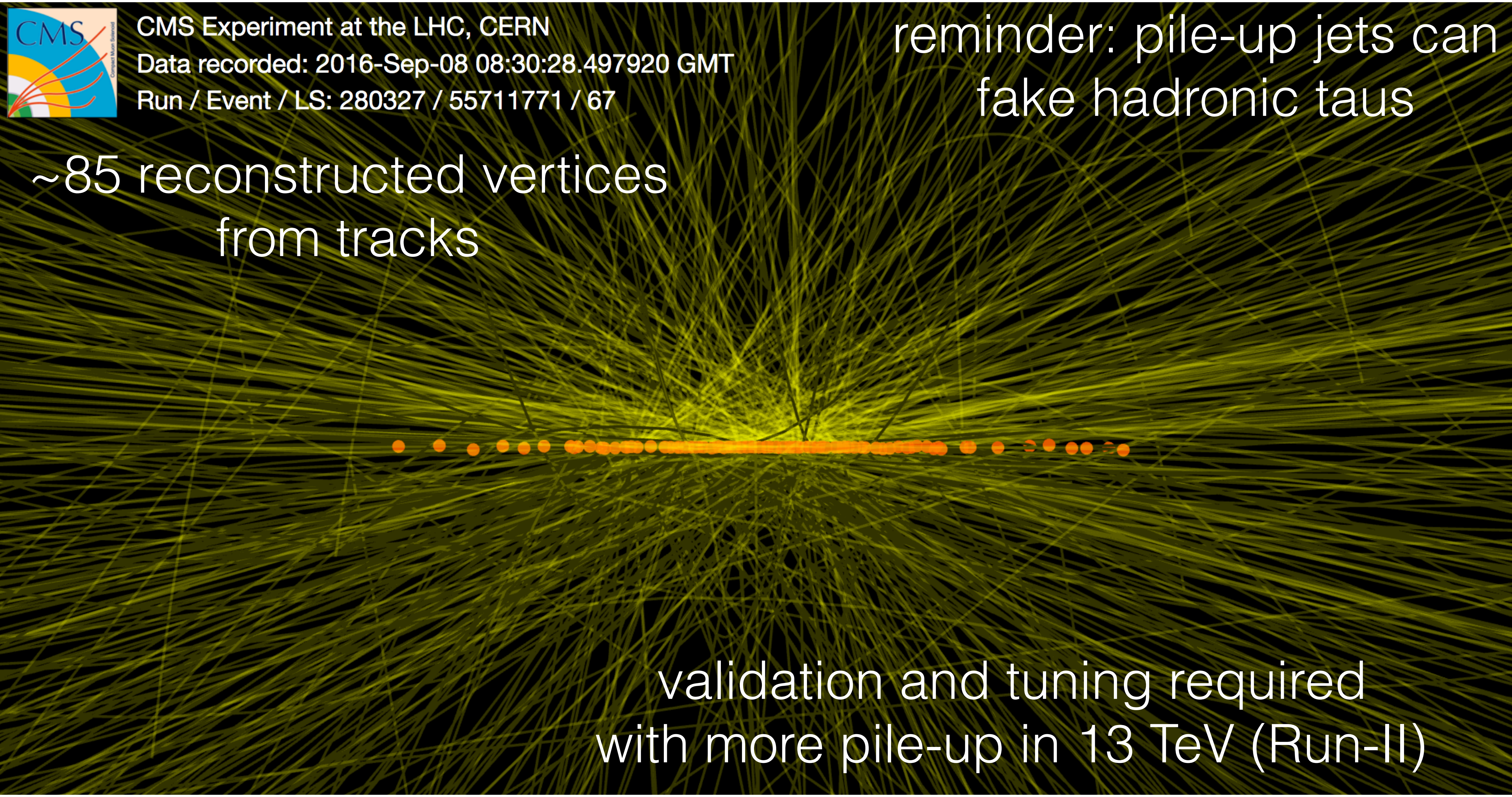
Reconstruction: DM and Neutrinos

- Any particles that do not interact in detector, such as DM and neutrinos, show up as missing transverse momentum (**p_T^{miss}**)
- ∴ all other particle reconstruction uncertainties contribute to **p_T^{miss}** uncertainty!



negative vectorial sum of all reconstructed four-vectors

Pile-up



reminder: pile-up jets can fake hadronic taus

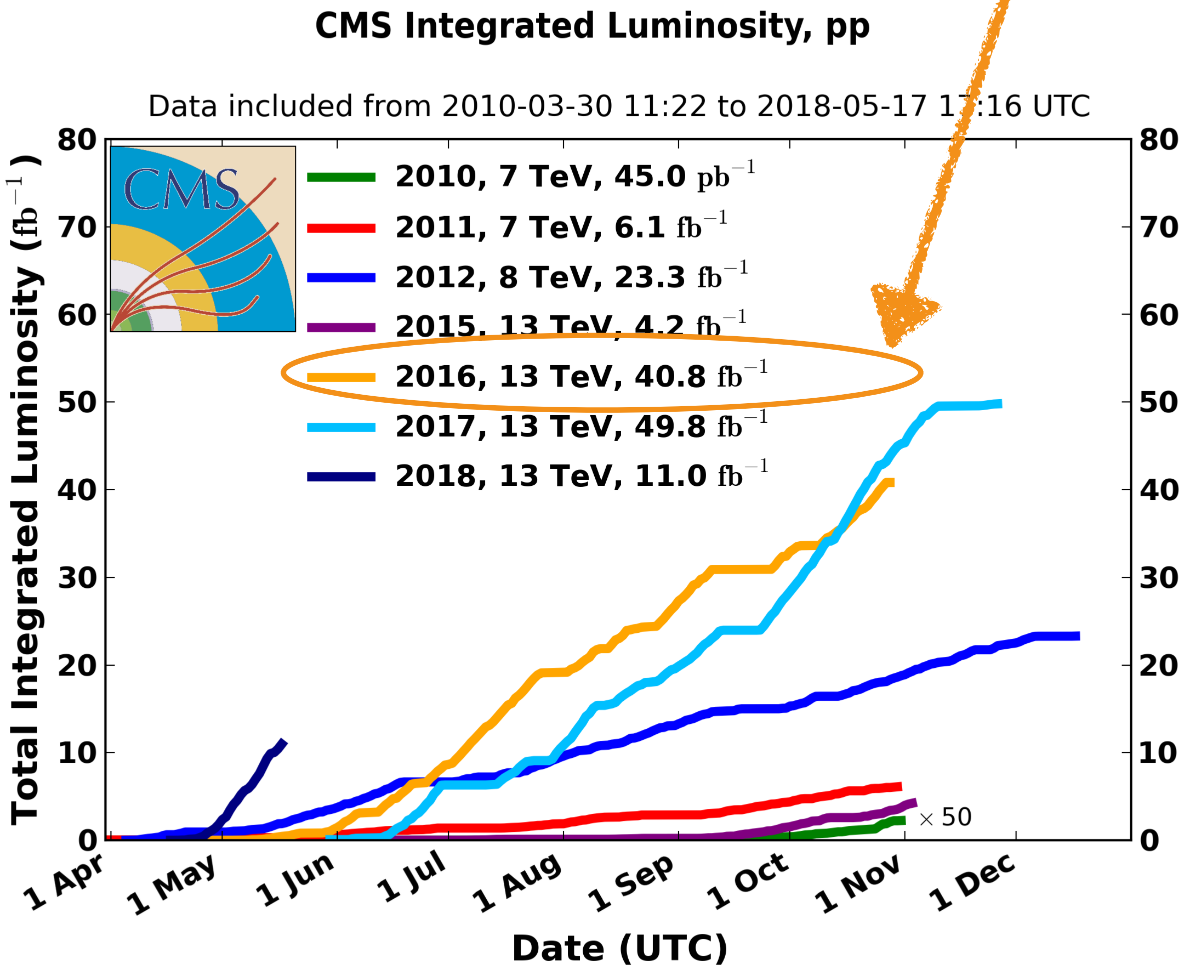
~85 reconstructed vertices from tracks

validation and tuning required with more pile-up in 13 TeV (Run-II)

LHC Operations

2016 pp: ~27 interactions/ bunch crossing

this talk


CMS Integrated Luminosity, pp

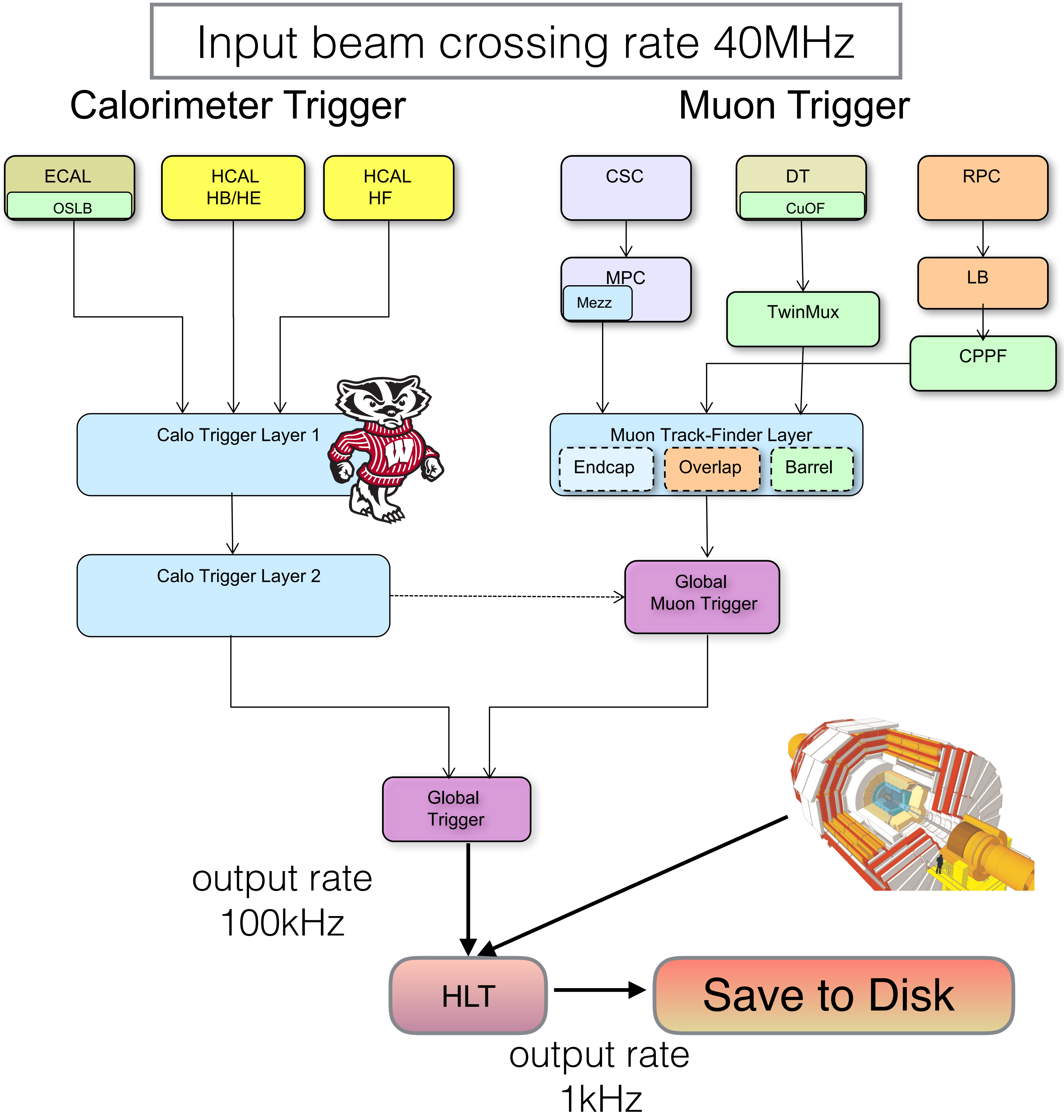
Data included from 2010-03-30 11:22 to 2018-05-17 17:16 UTC

10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$

LHC process	σ: xsec pb	2016 LHC Hz
inelastic total	10^{11}	10^{9} Hz
b	10^{9}	10^{7}
jets >100	10^{6}	10^{4}
W	10^{4}	10^{2}
Z	10^{3}	10
Diboson	10^{2}	1
Higgs	10	0.1
BSM	<1	<0.01

Tau Trigger and pile-up

- One of the largest difficulties for ττ analysis is triggering on taus!
    - Reduce misidentified jets at trigger level and pile-up subtraction at trigger level
- No tracker information, calibrate calorimeter energy deposits for charged hadrons!



Input beam crossing rate 40MHz

Calorimeter Trigger

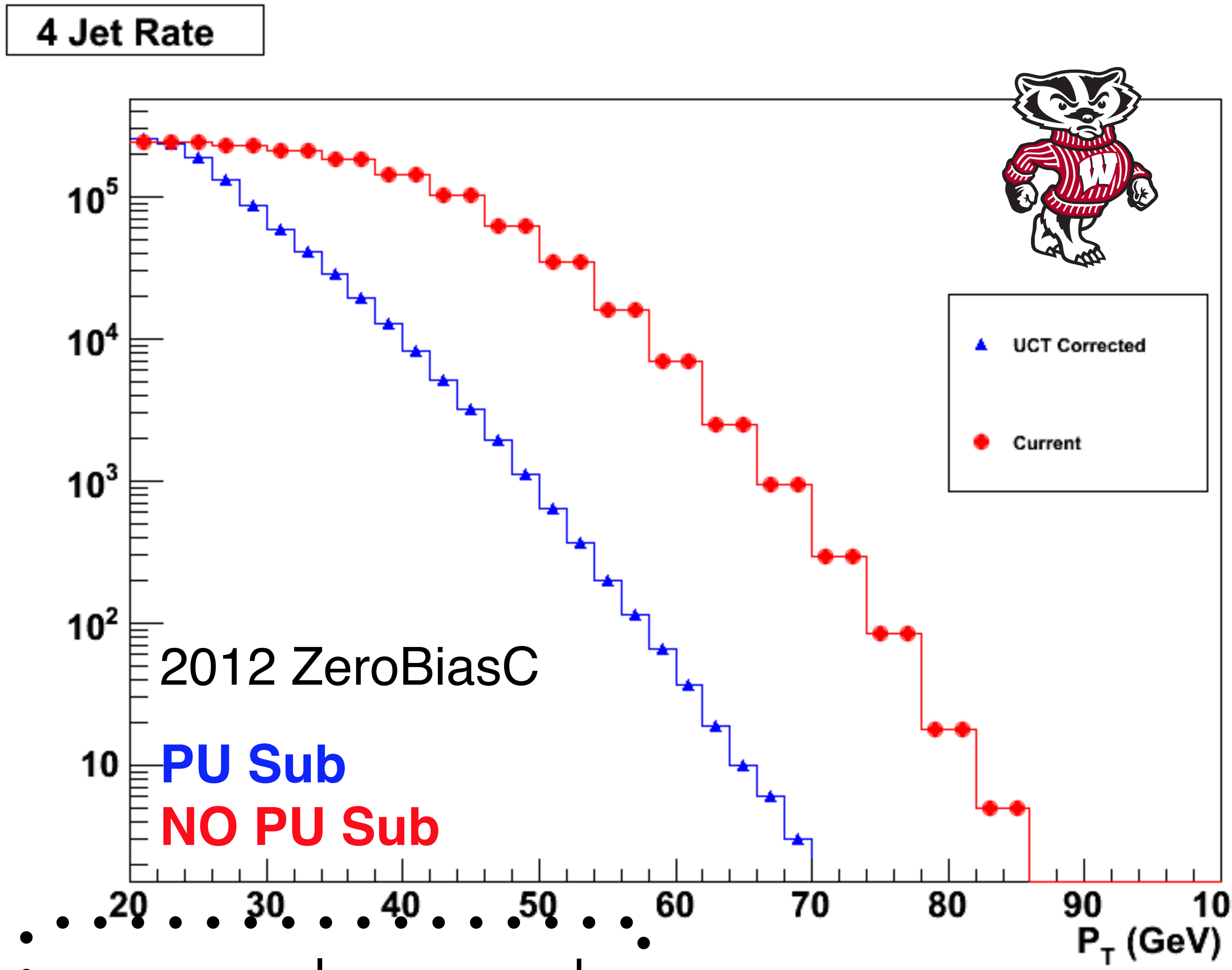
Muon Trigger

output rate 100kHz

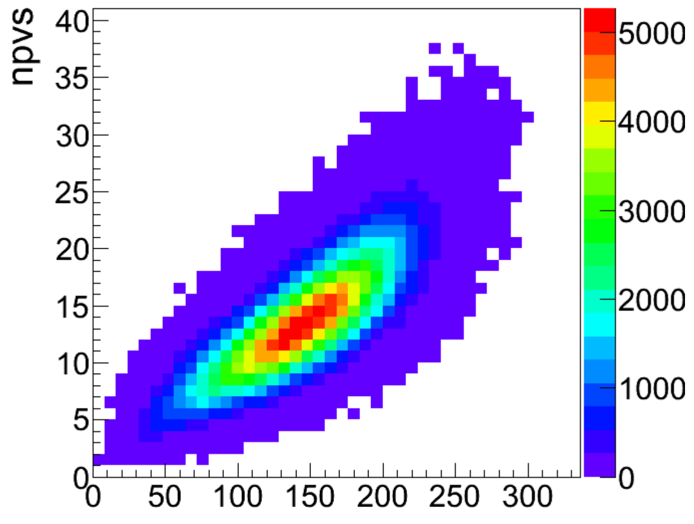
output rate 1kHz

Tau Trigger and pile-up

- One of the largest difficulties for ττ analysis is triggering on taus!
  - Reduce misidentified jets at trigger level and pile-up subtraction at trigger level
- No tracker information, calibrate calorimeter energy deposits for charged hadrons!



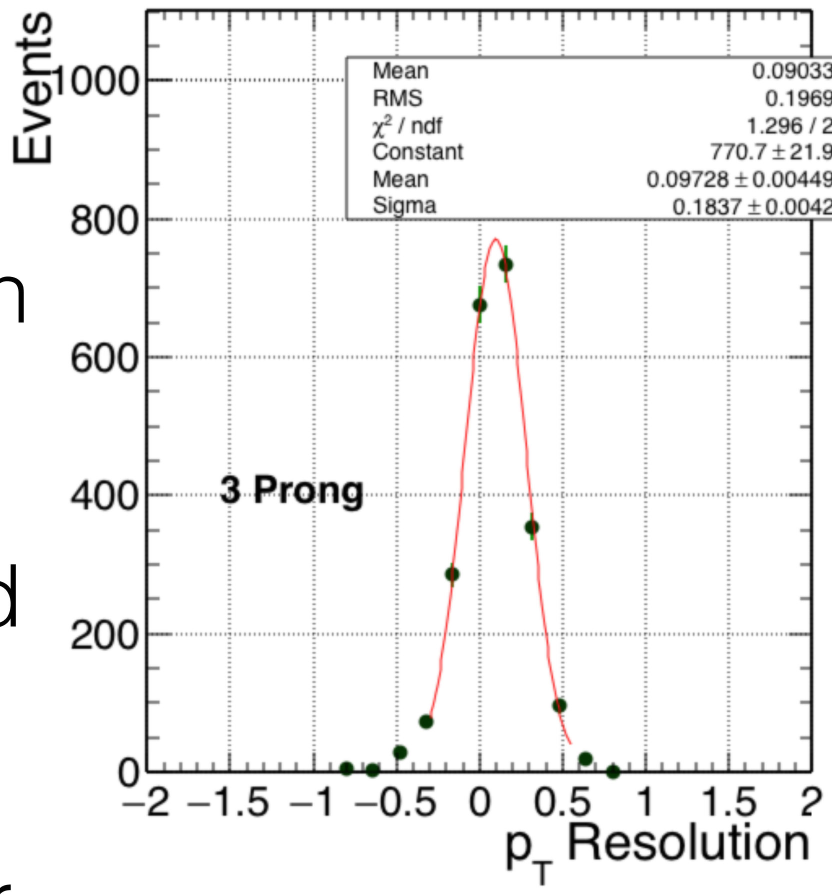
example: quad jet rate, before and after pile up subtraction 2012 studies



amount of calorimeter with energy deposits

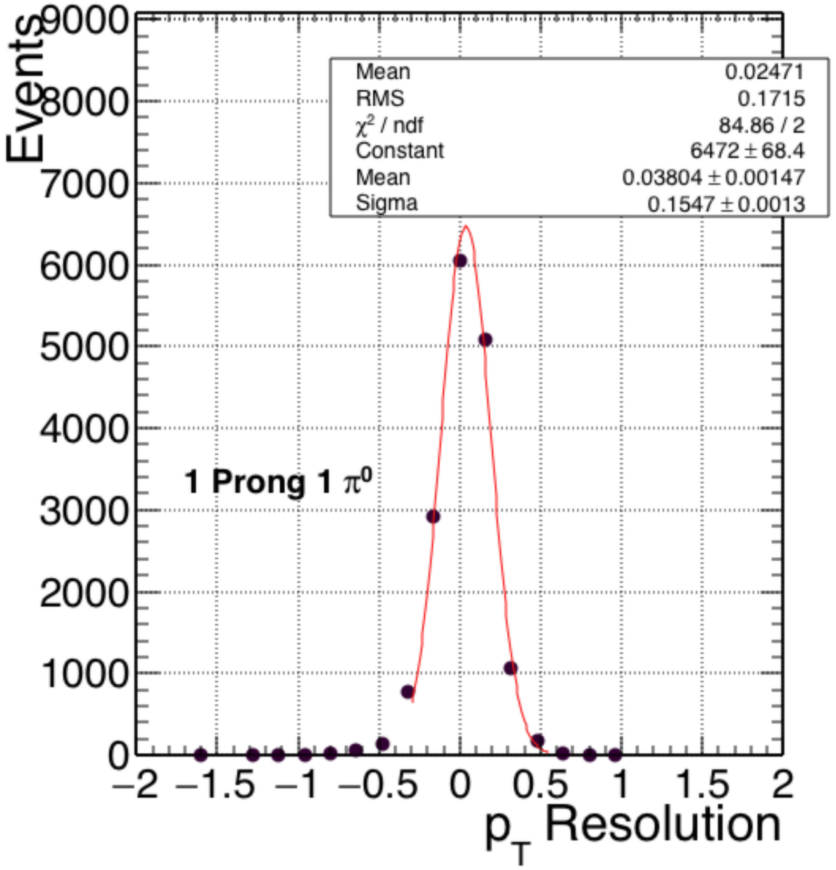
Tau Trigger and pile-up

- One of the largest difficulties for ττ analysis is triggering on taus!
    - Reduce misidentified jets at trigger level and pile-up subtraction at trigger level
- No tracker information, calibrate calorimeter energy deposits for charged hadrons!

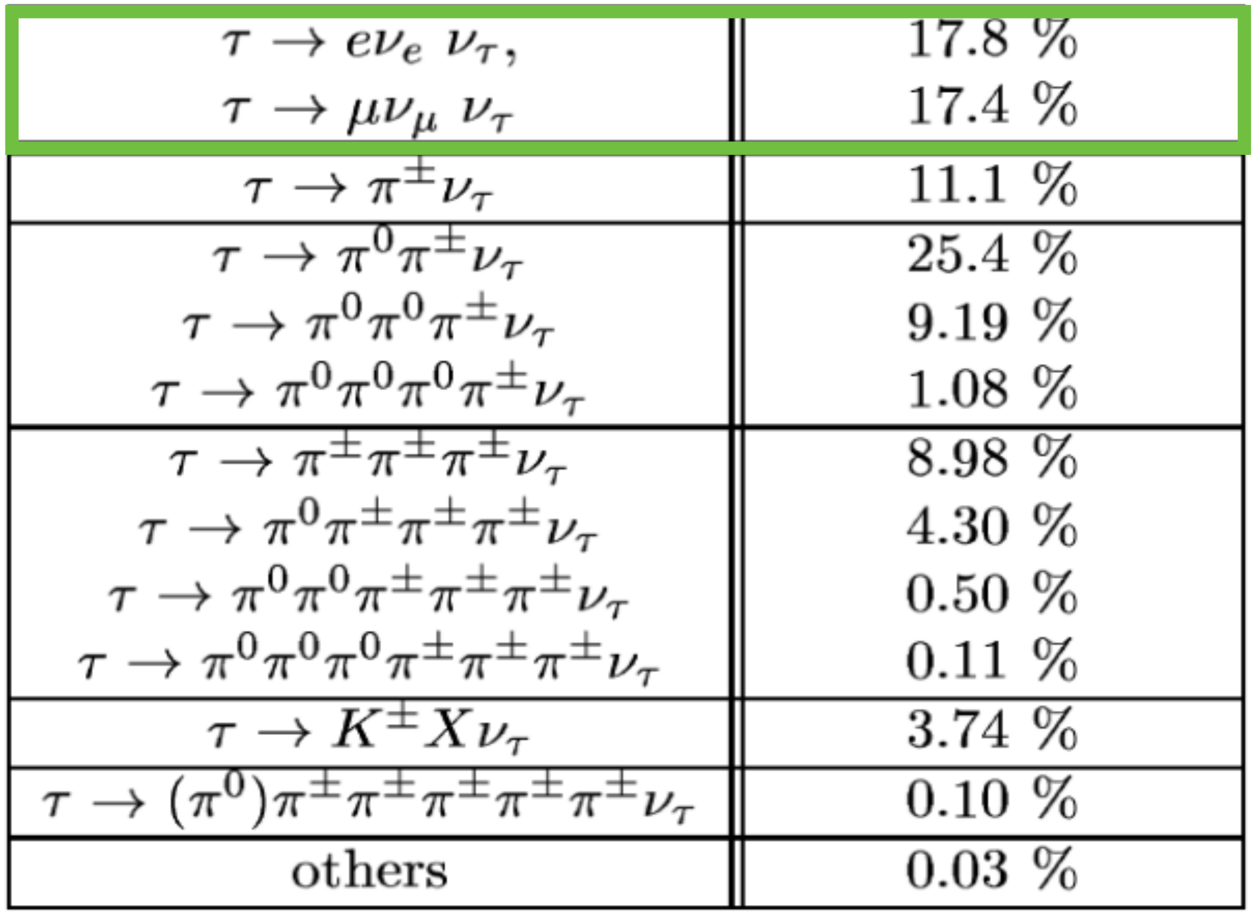


Account for annealing/ material budget. No tracker!

calibrations checked on data using hadronic tau decays



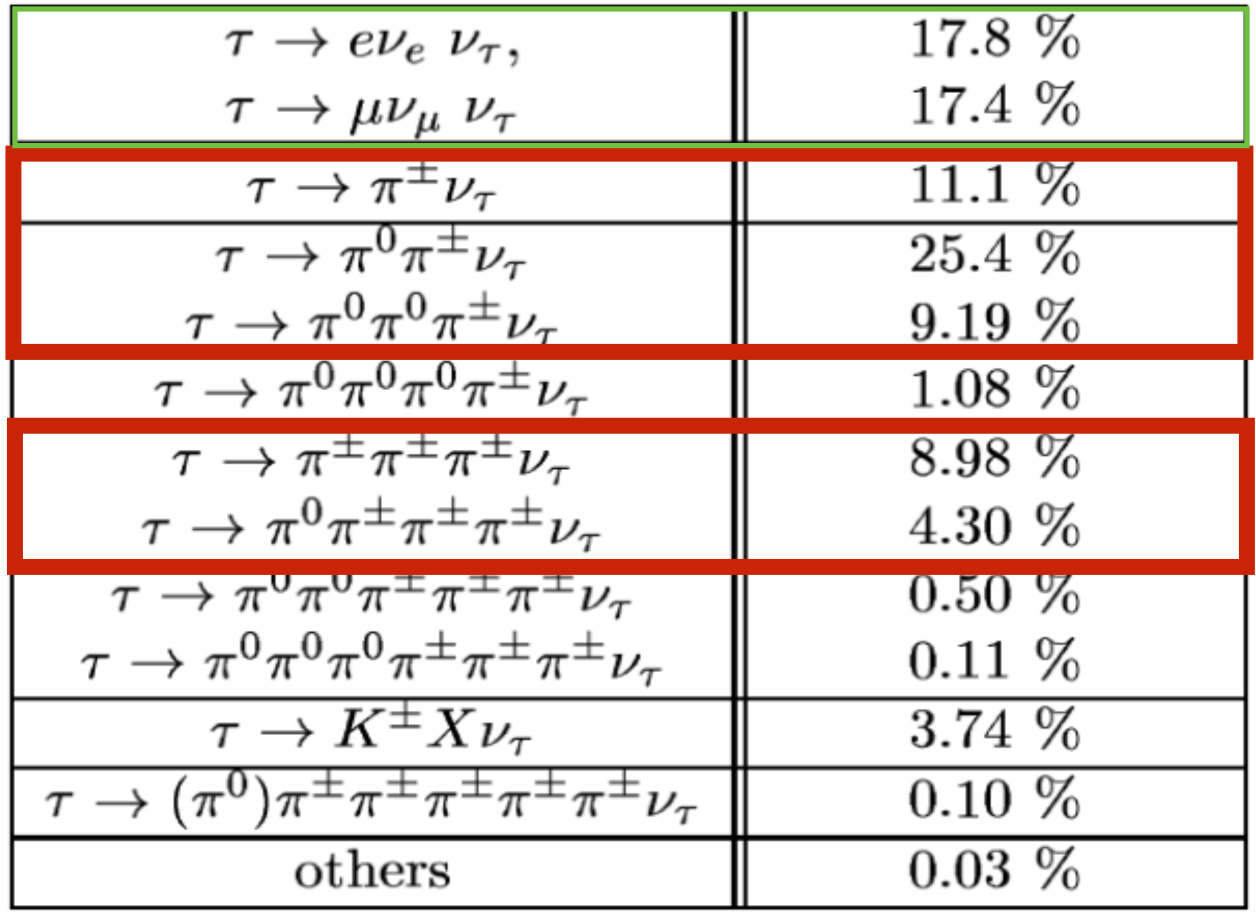
τ Reconstruction



$\tau \to e\nu_e\ \nu_\tau,$	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 %

τ_e and τ_μ reconstructed as electrons and muons

τ Reconstruction

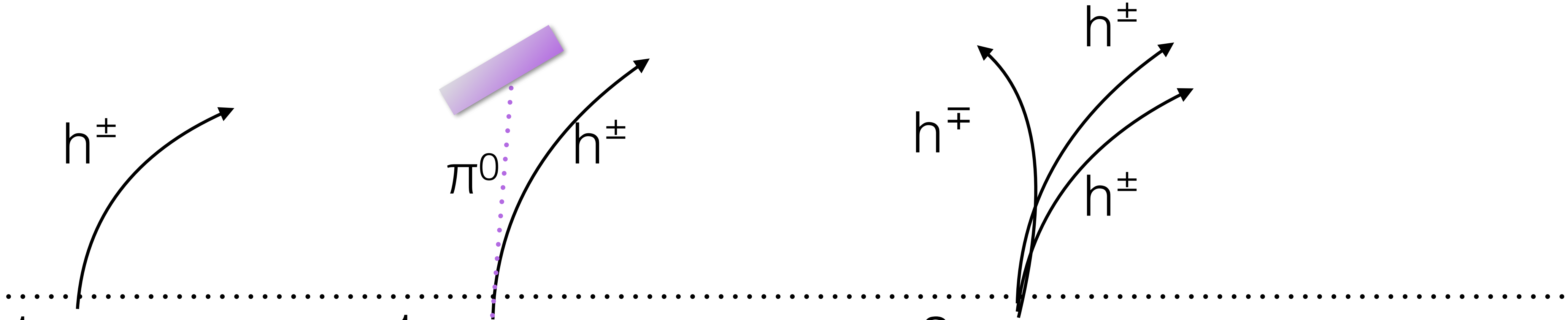


$\tau \rightarrow e\nu_e\ \nu_\tau,$	17.8 %
$\tau \rightarrow \mu\nu_\mu\ \nu_\tau$	17.4 %
$\tau \rightarrow \pi^\pm\nu_\tau$	11.1 %
$\tau \rightarrow \pi^0\pi^\pm\nu_\tau$	25.4 %
$\tau \rightarrow \pi^0\pi^0\pi^\pm\nu_\tau$	9.19 %
$\tau \rightarrow \pi^0\pi^0\pi^0\pi^\pm\nu_\tau$	1.08 %
$\tau \rightarrow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

τ_e and τ_μ reconstructed as electrons and muons

τ_h reconstructed by decay mode, classified by number of charged hadrons ($h^\pm$)

neutral pions recorded as nearby electromagnetic deposits



1-prong

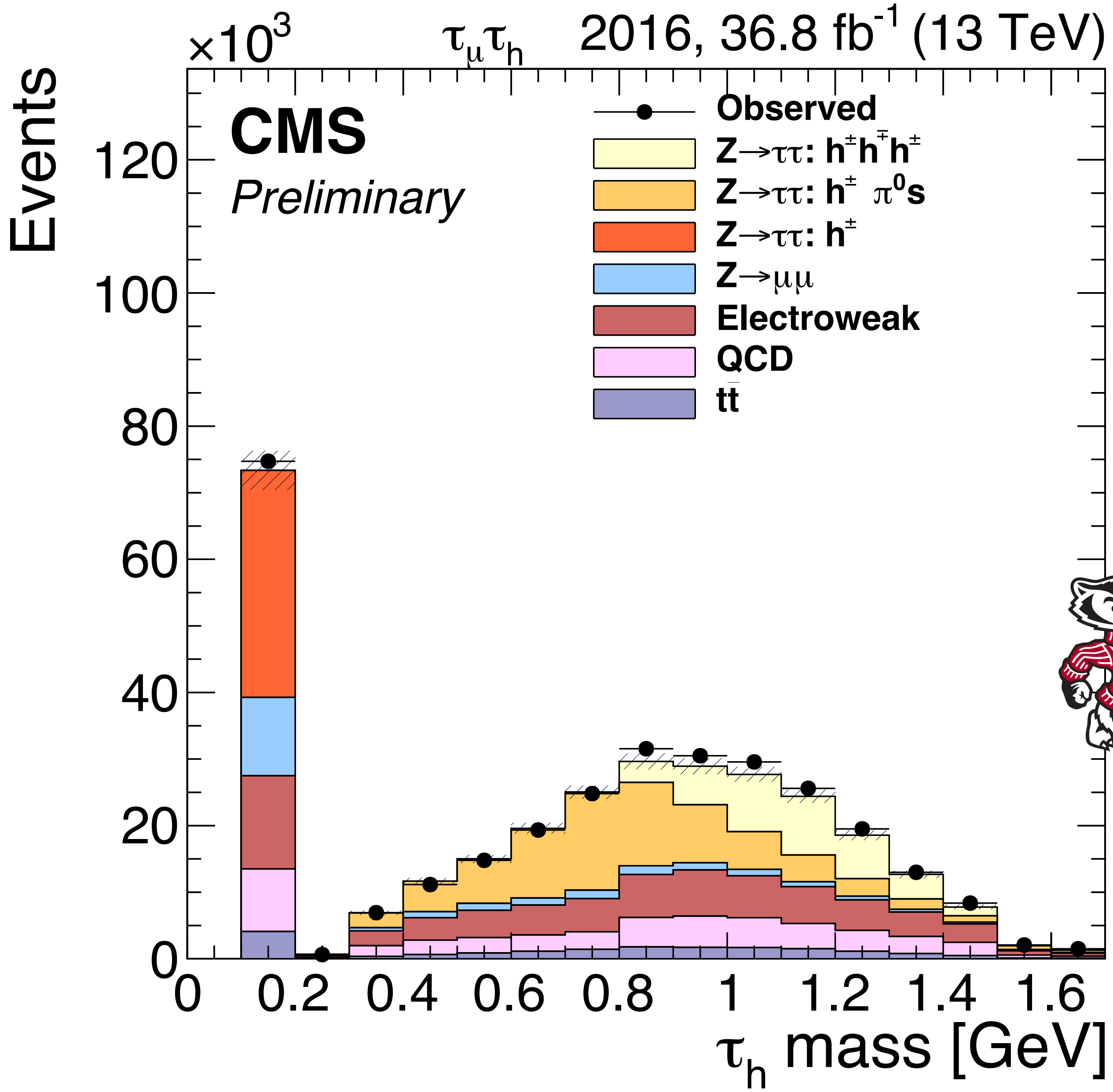
1-prong
1-π^0

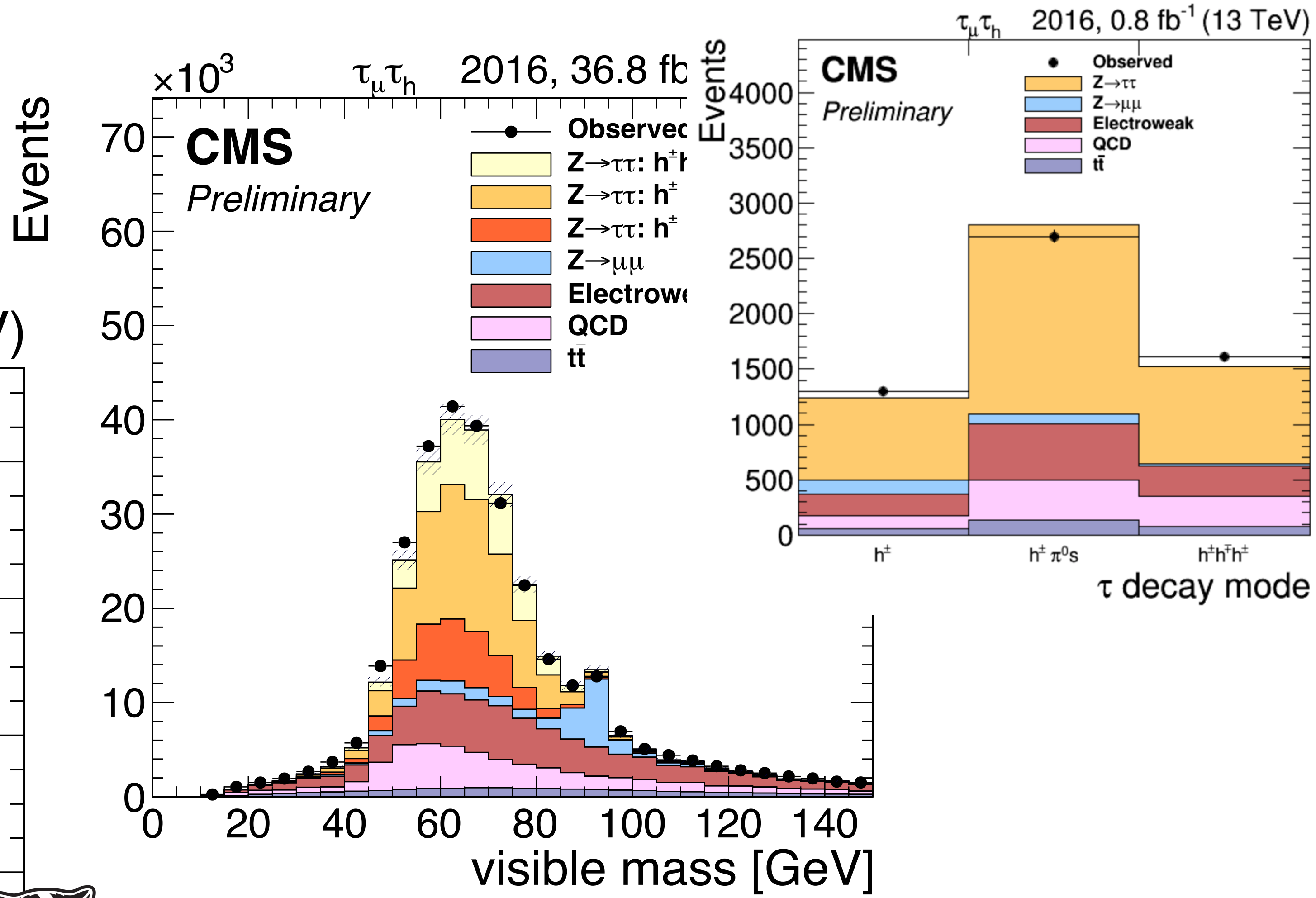
3-prong

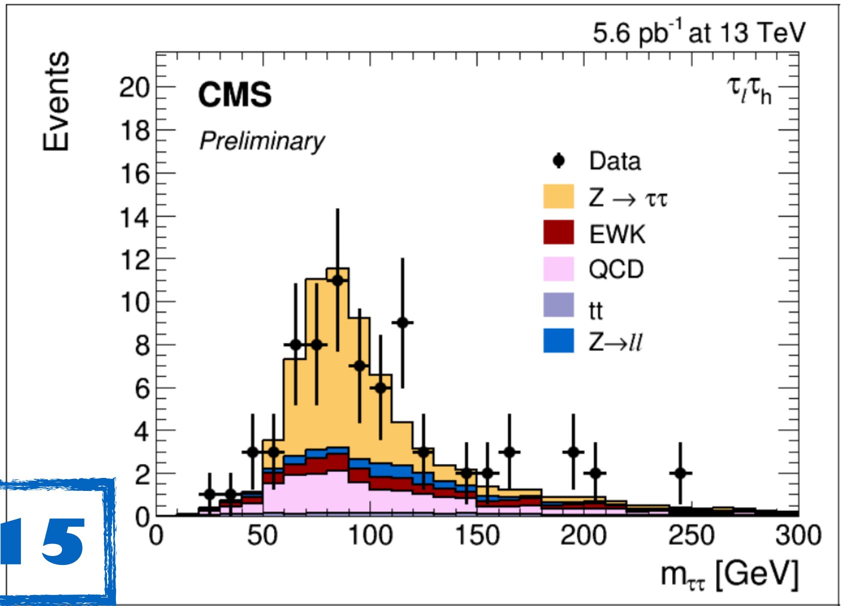
“DECAY MODE”

Hadronic Tau Identification: μτ

$\pi^{\pm}$: 139 MeV
$\rho^{\pm}$: 770 MeV
a_1: 1260 MeV

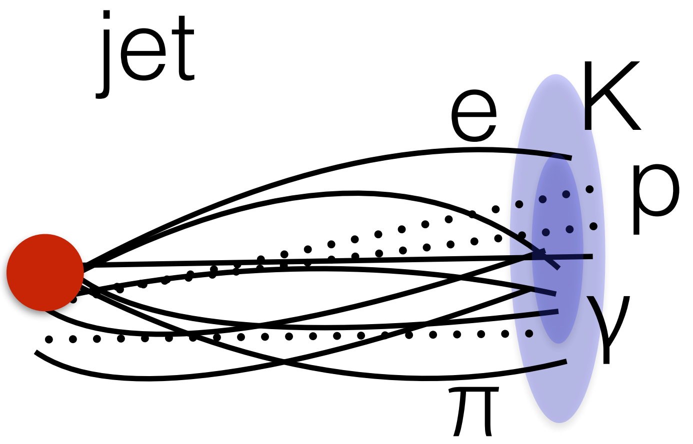


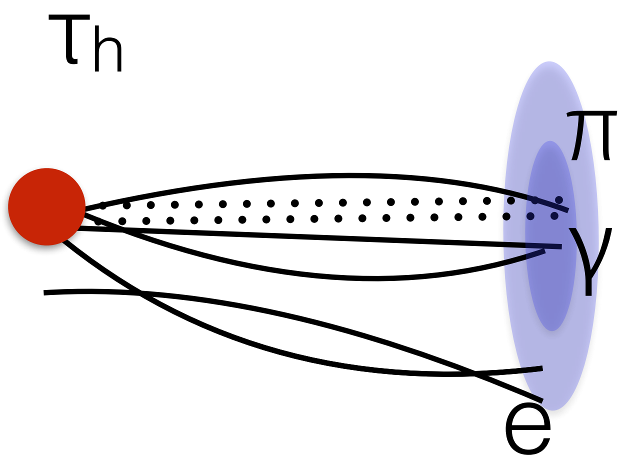


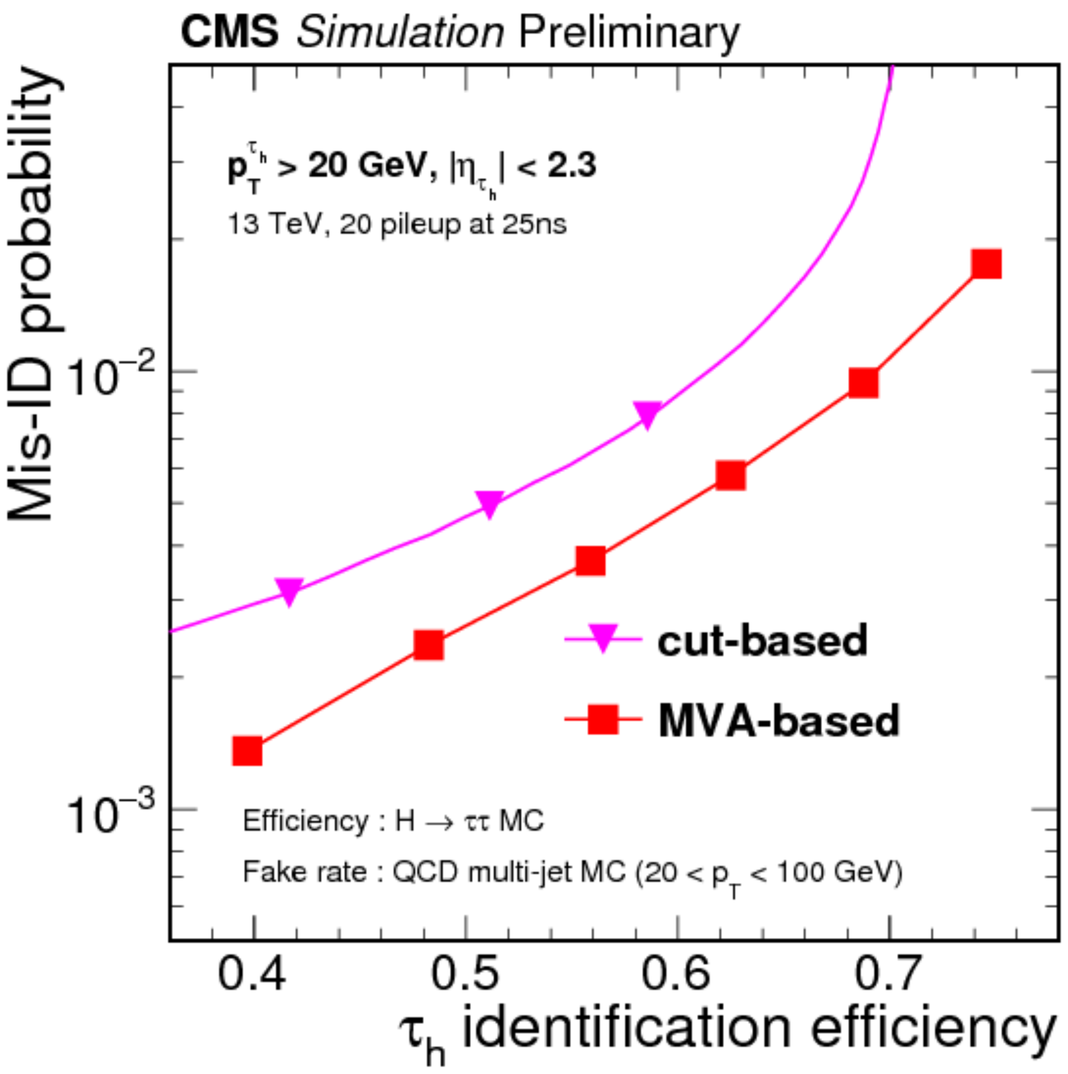


EPS2015

Hadronic Tau Identification



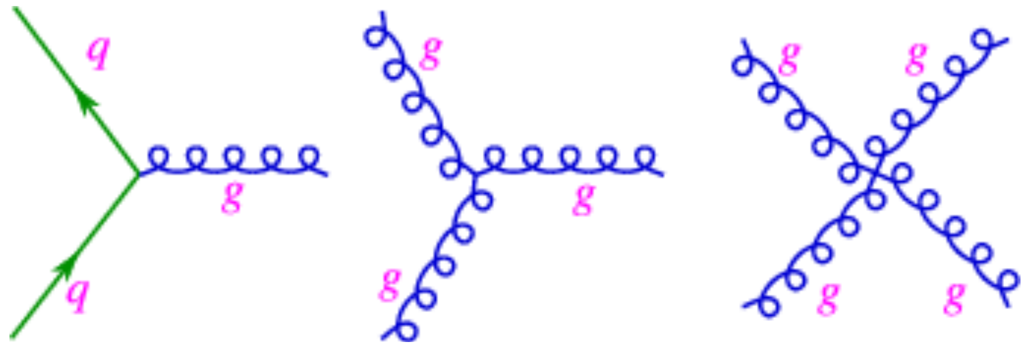




Jet, electrons, and muons can be mis-reconstructed as a τh. MVA with various inputs considered, including flight time information, to identify τh

QCD/multijet

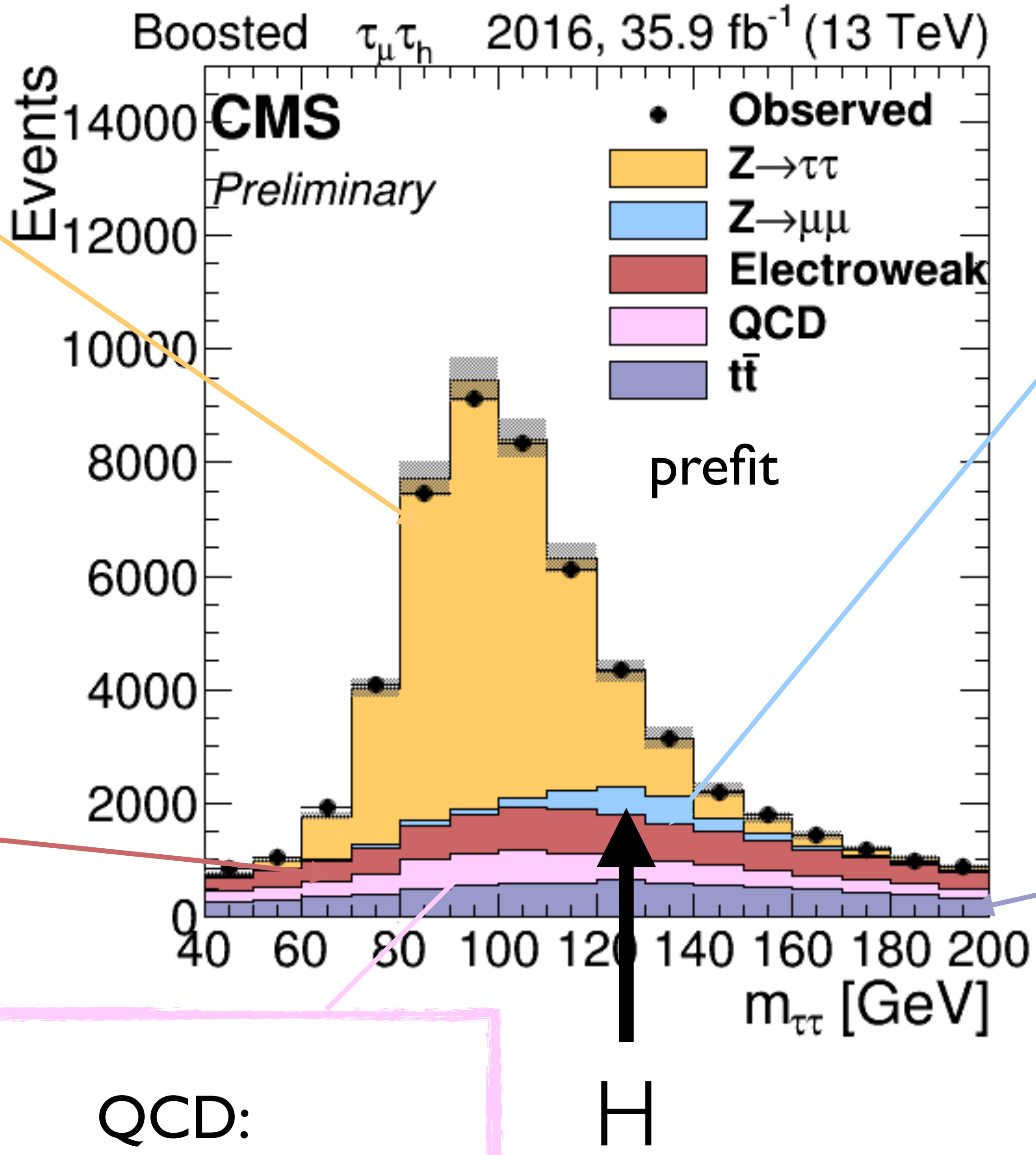
rate 1000000000x larger than signal



Backgrounds Overview

Z->ττ simulation: Madgraph (LO). Corrections derived from highly pure Z →μμ data sample.

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



QCD: Derived from data in sideband region

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

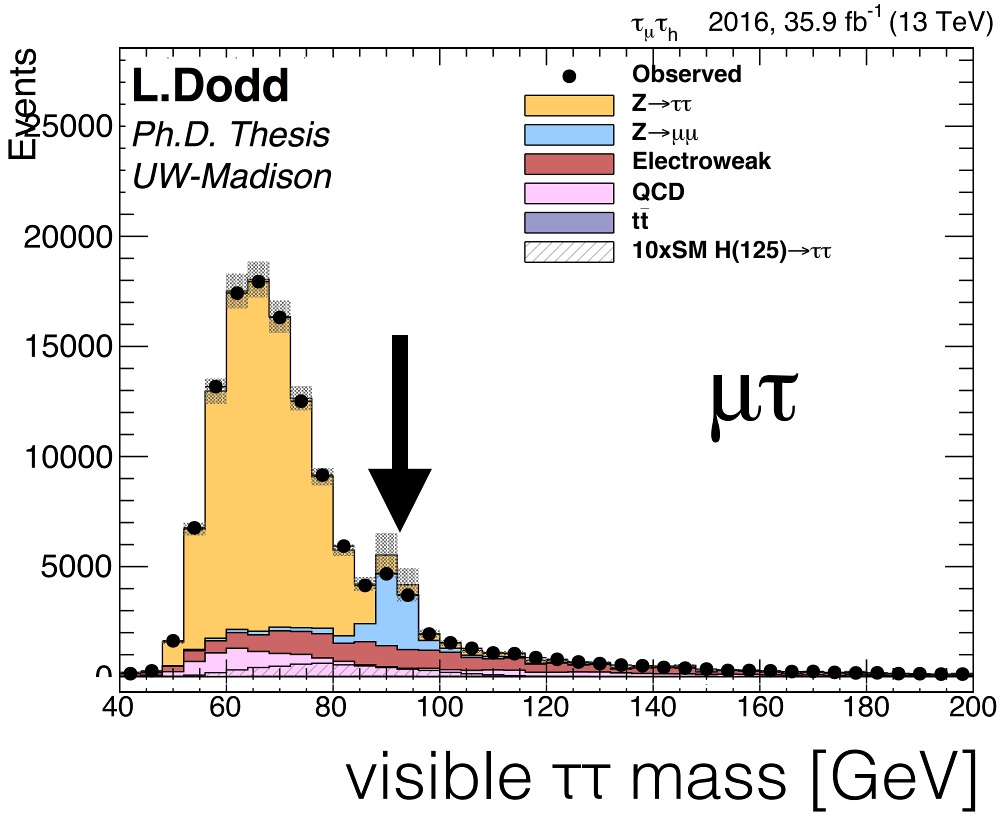
TTbar: Powheg (NLO) Normalization controlled by data agreement in sideband

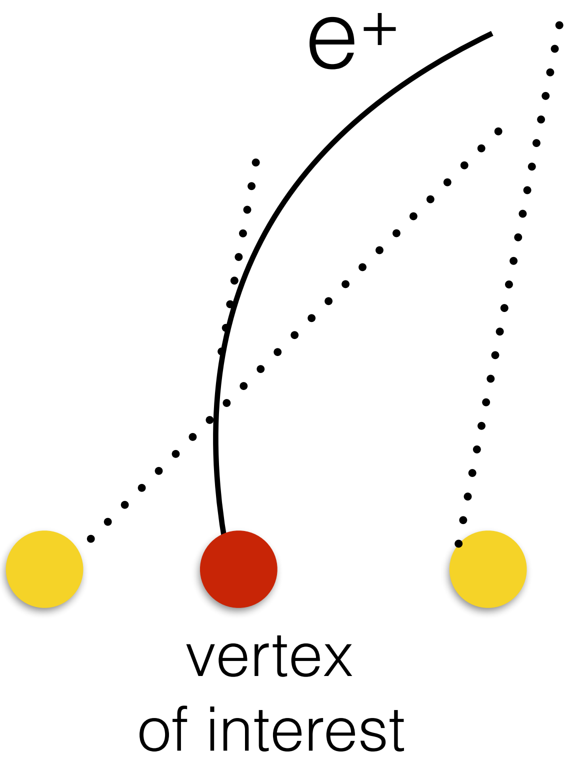
also include 9 data sidebands for control of backgrounds

ℓ->τ_h misidentification

- Visible ττ invariant mass used to measure simulation corrections for ℓ->τ_h fakes

μ/e→τ_h misidentification is pile-up dependent



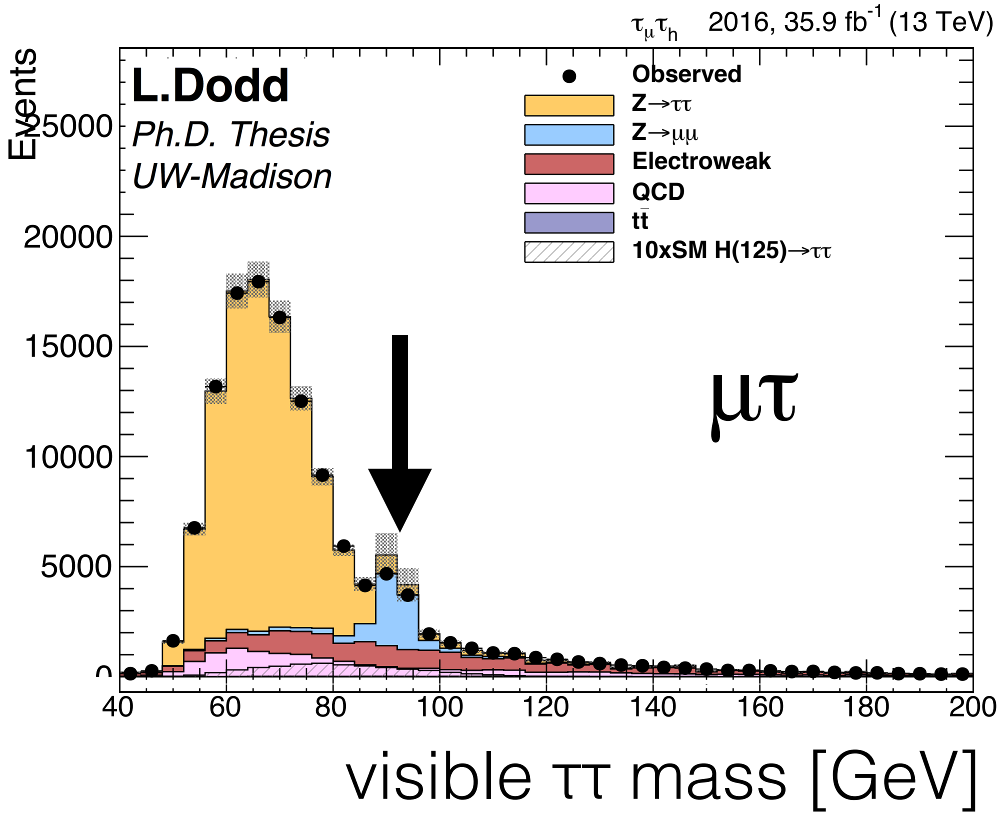


$\ell \to \tau_h$ misidentification

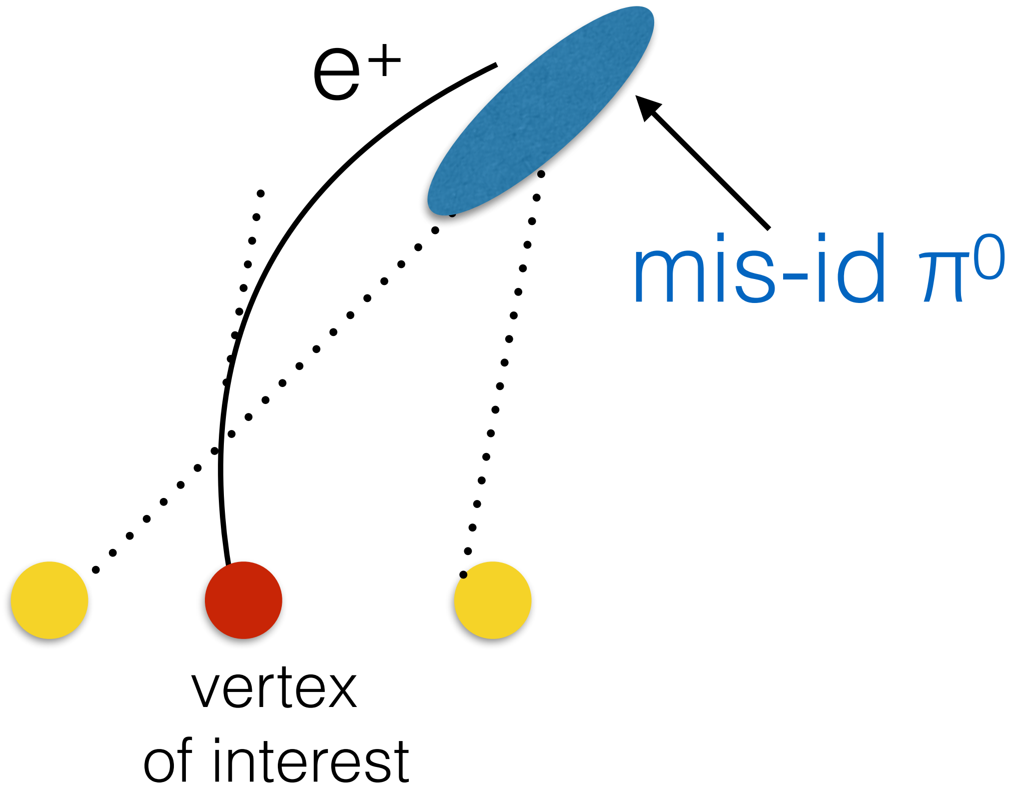
- Visible ττ invariant mass used to measure simulation corrections for $\ell \to \tau_h$ fakes

$\mu/e \rightarrow \tau_h$ misidentification is pile-up dependent

electrons/photons from adjacent vertices- can form ϕ-strips! misidentified $h^{\pm}\pi^0$ decay mode



visible ττ mass [GeV]

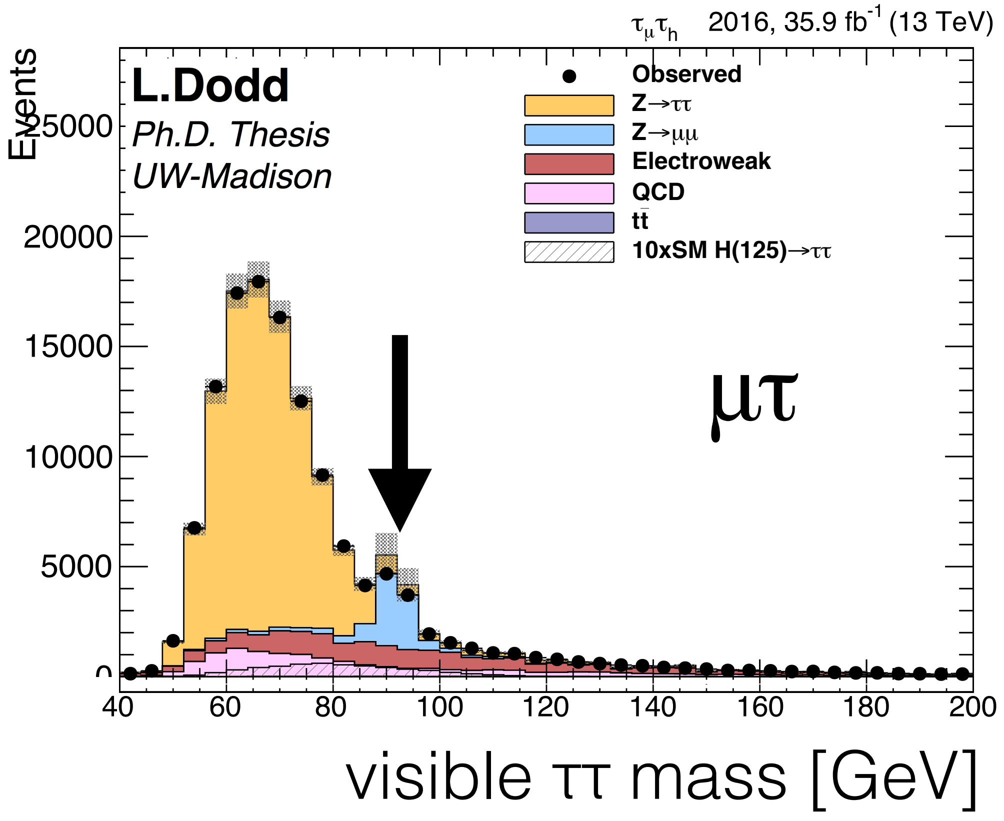


ℓ->τ_h misidentification

- Visible ττ invariant mass used to measure simulation corrections for ℓ->τ_h fakes

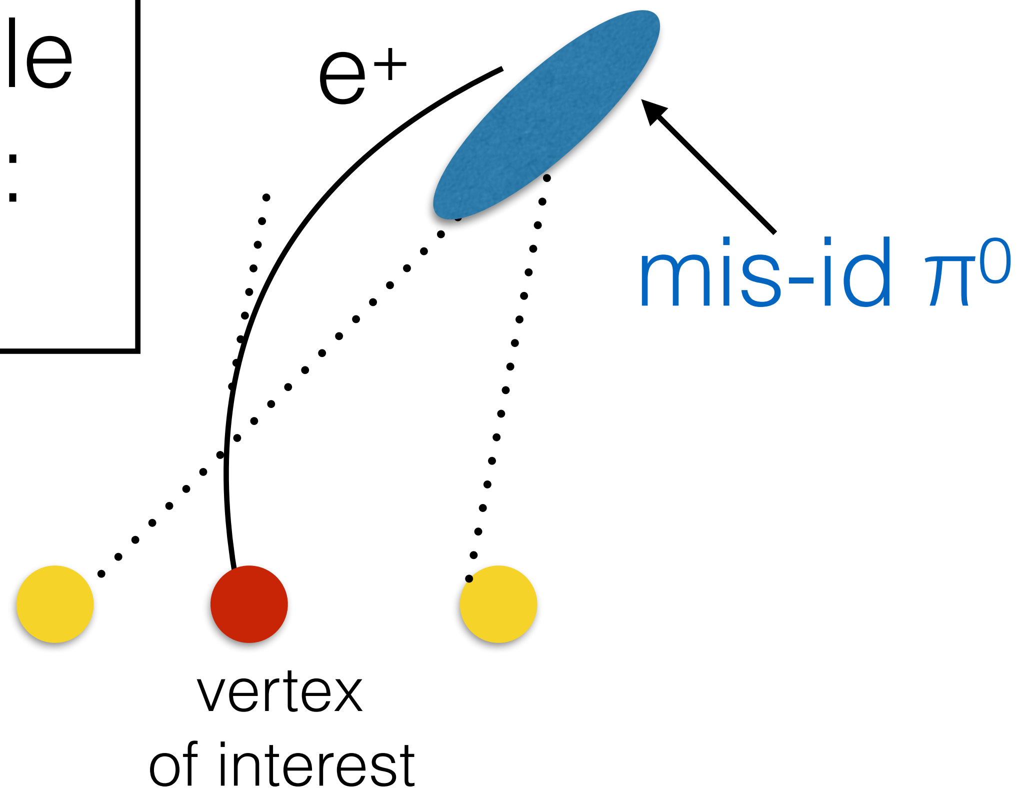
μ/e→τ_h misidentification is pile-up dependent

electrons/photons from adjacent vertices- can form ϕ-strips! misidentified $h^{\pm}\pi^0$ decay mode

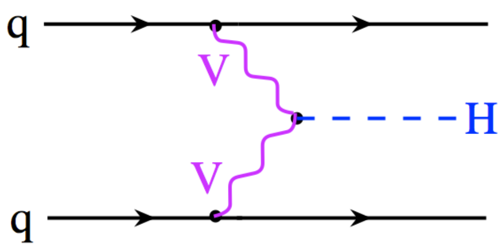
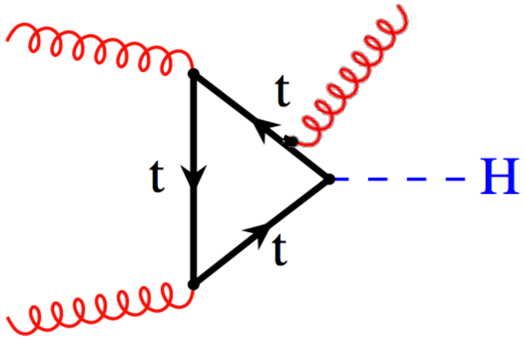


measure e→τ_h energy scale correction:

+9.5%

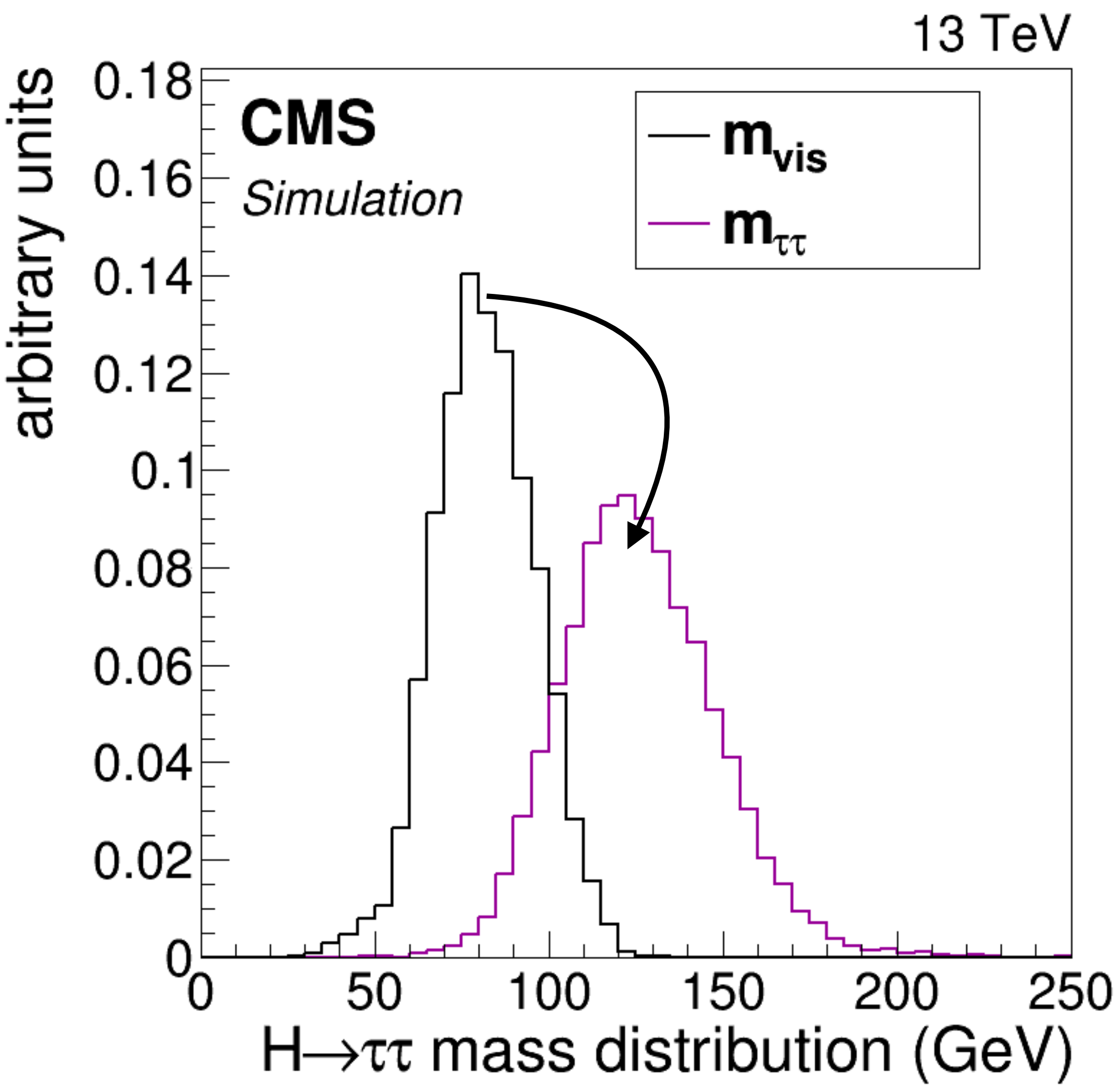


Categorization and $m_{\tau\tau}$

0-jet	no jets: used to control backgrounds	
vbf	≥2 jets	
boosted	1 jet	

VBF process 1% expected contribution in vbf category

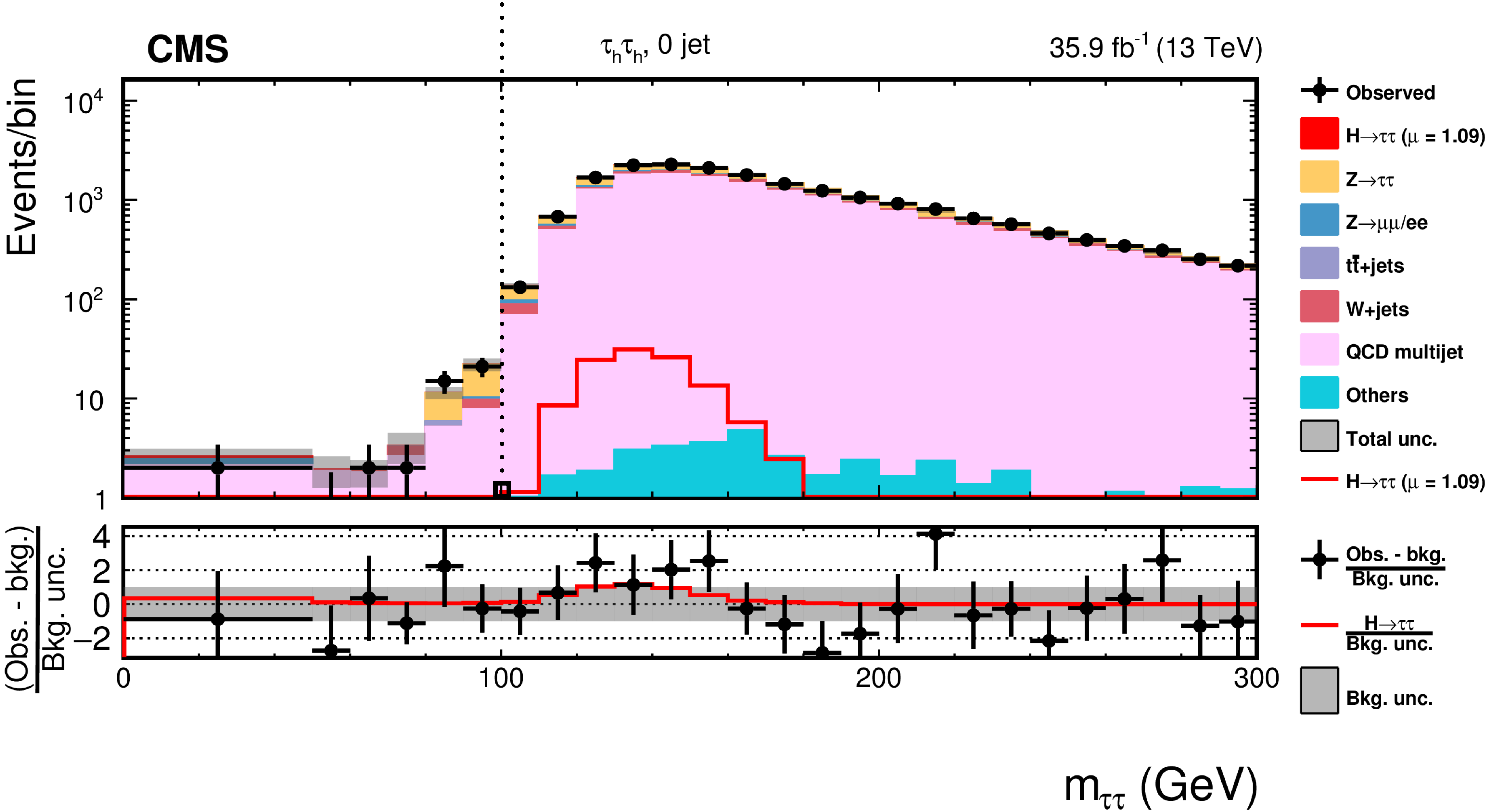
Given all p_T^{miss} in event comes from tau decay, kinematic fit finds most likely original mass of $\tau\tau$ system and is denoted $m_{\tau\tau}$. Visible mass is m_{vis}.



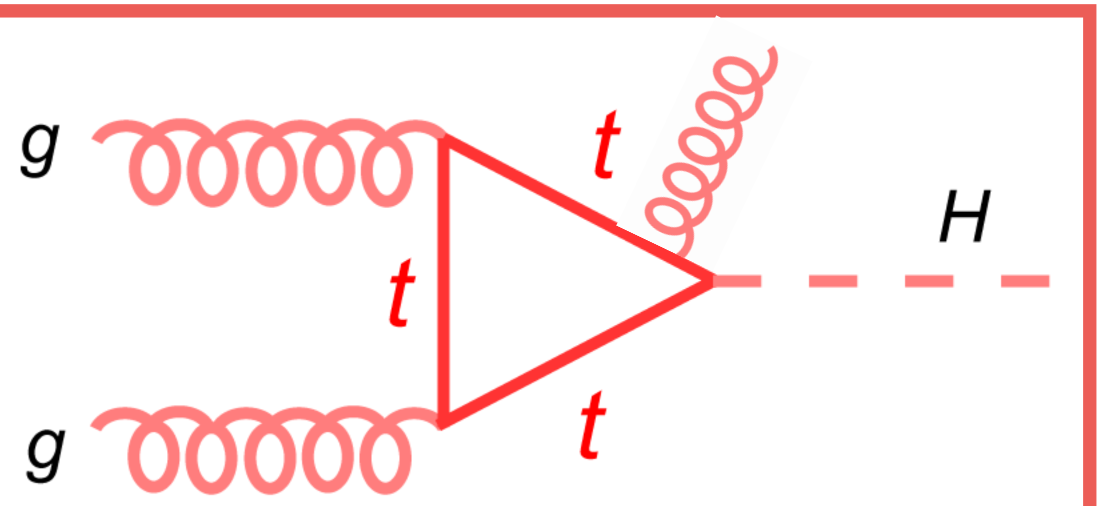
$m_{\tau\tau}$ 0-jet: multijet

kinematic “turn-on” region for online data collection

large multijet background



Signal Extraction



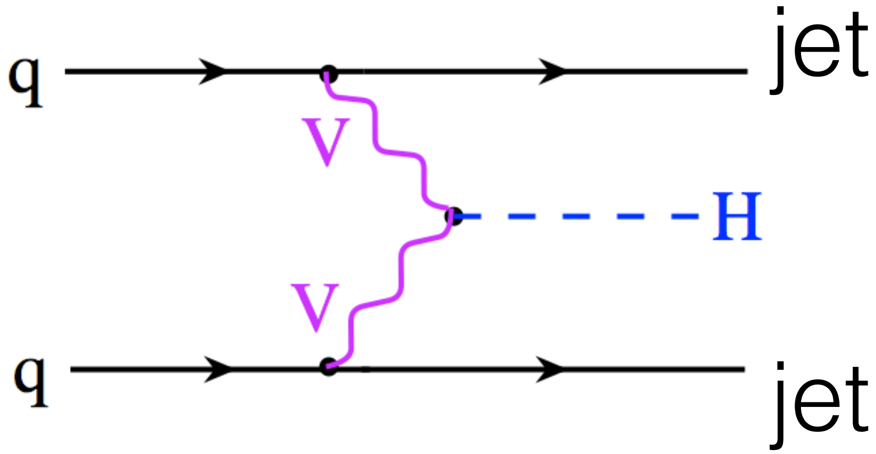
gluon fusion signal/ background increases as function of Higgs pt

H pT: m(ττ)

0-jet category controls backgrounds

τ decay mode: m(vis)

extract signal in two dimensions!

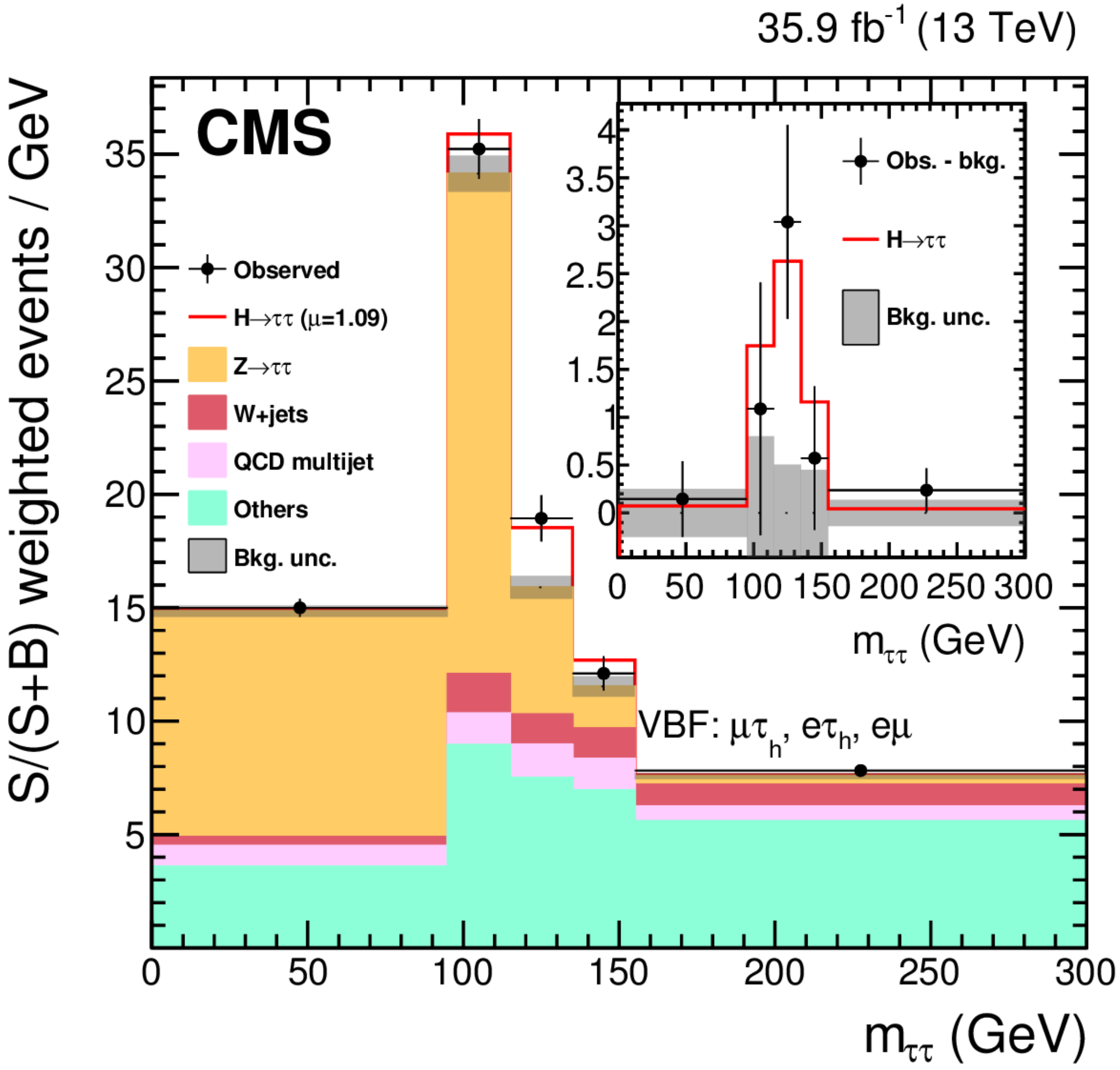


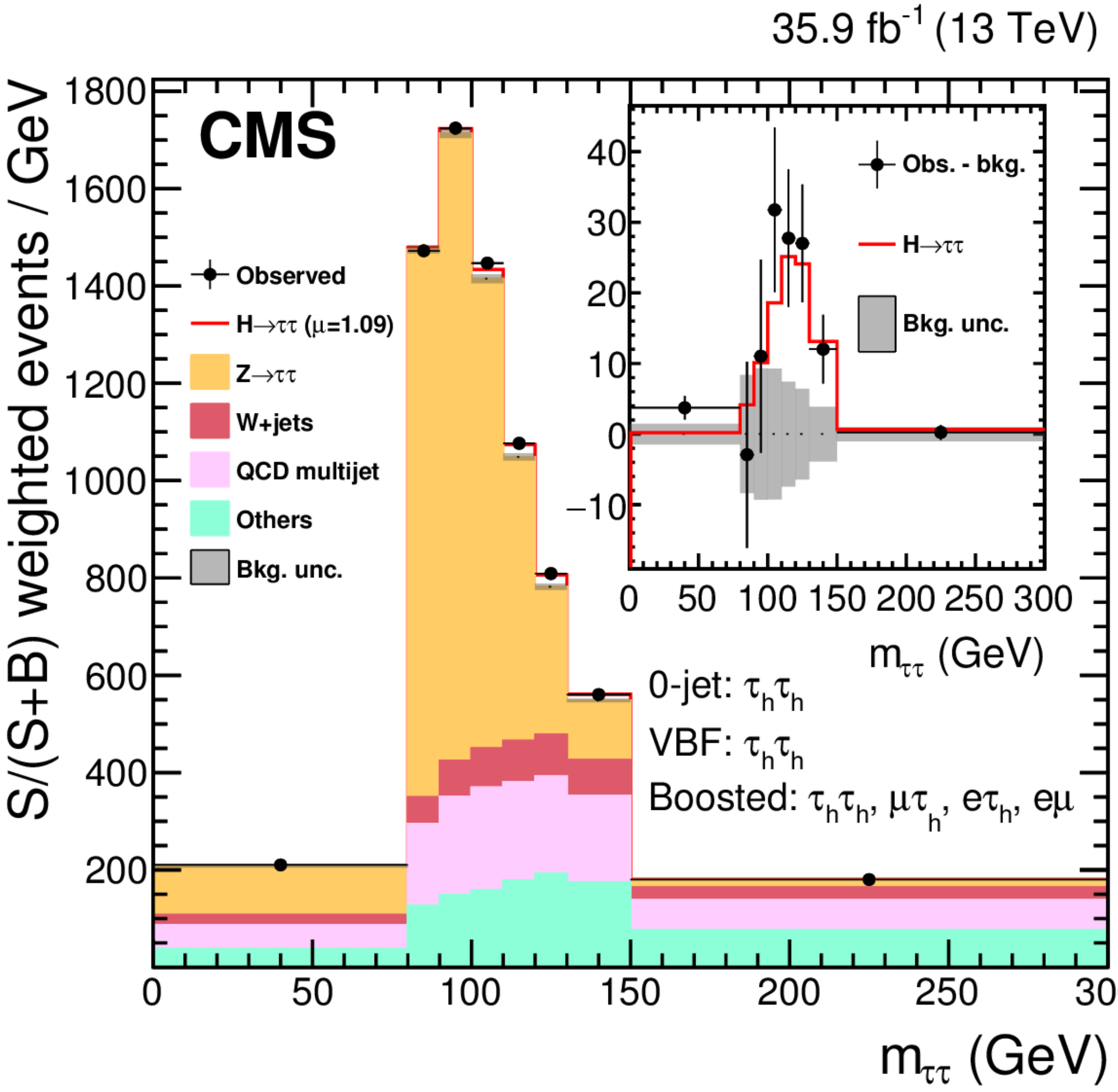
vector-boson fusion signal/ background increases as function of jet-jet invariant mass.

di-jet mass: m(ττ)

H(ττ) weighted mass plot

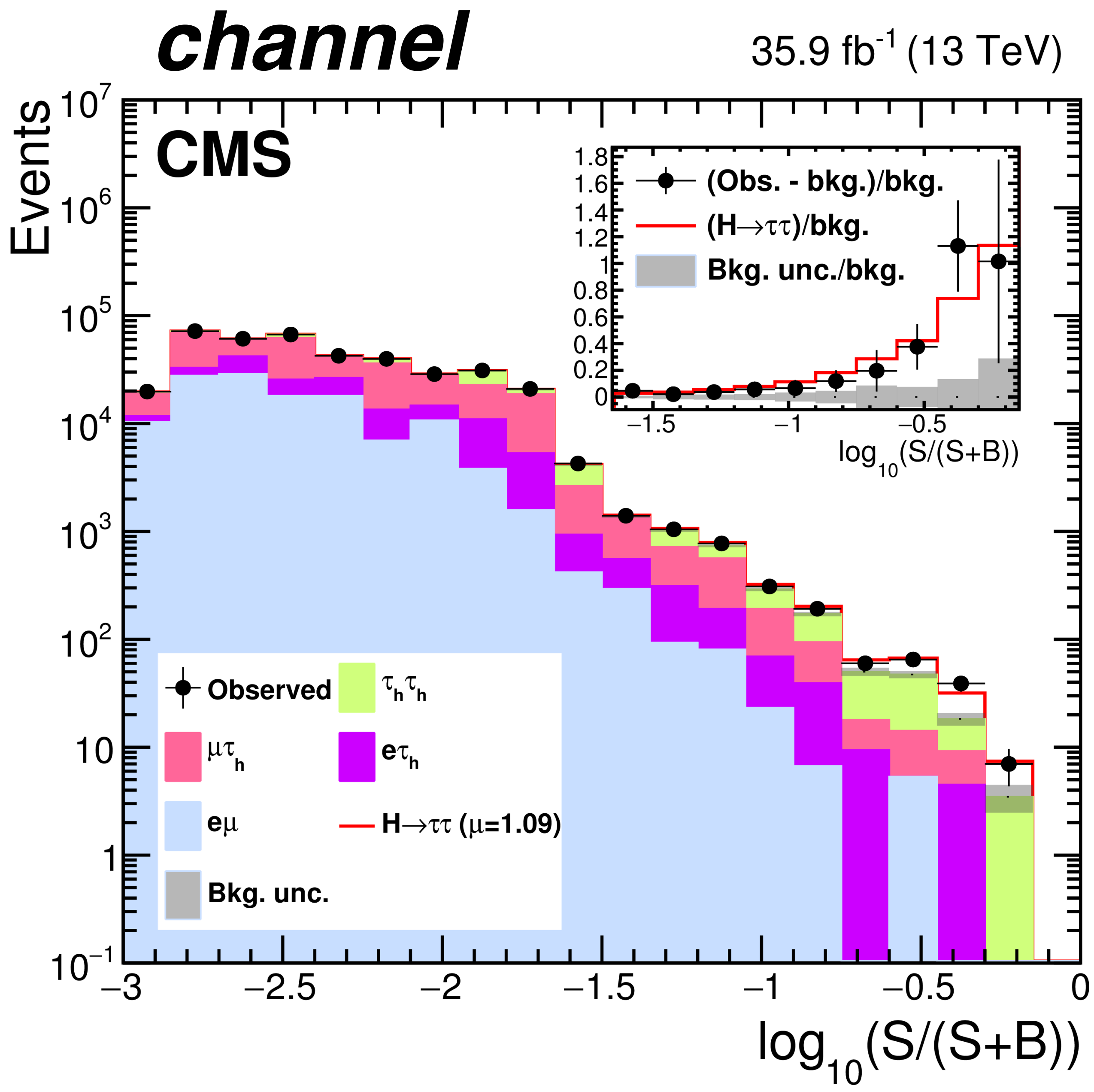
- The mass distributions weighted by expected S/(S+B) show a visible SM Higgs peak



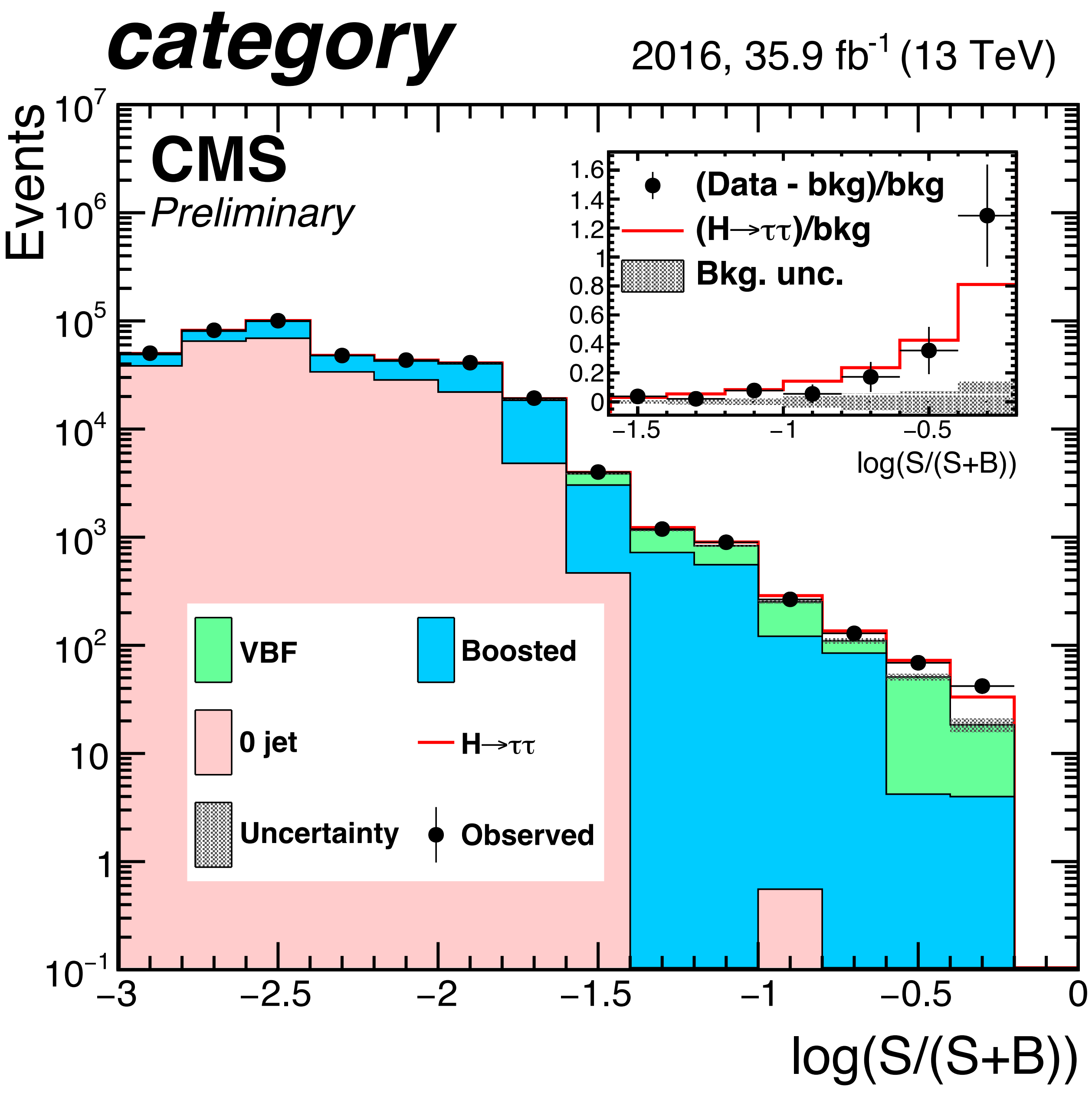


Channel and Category

- The SM Higgs excess is seen when sorted by significance of each bin of input 2D distributions. VBF is the most sensitive category.



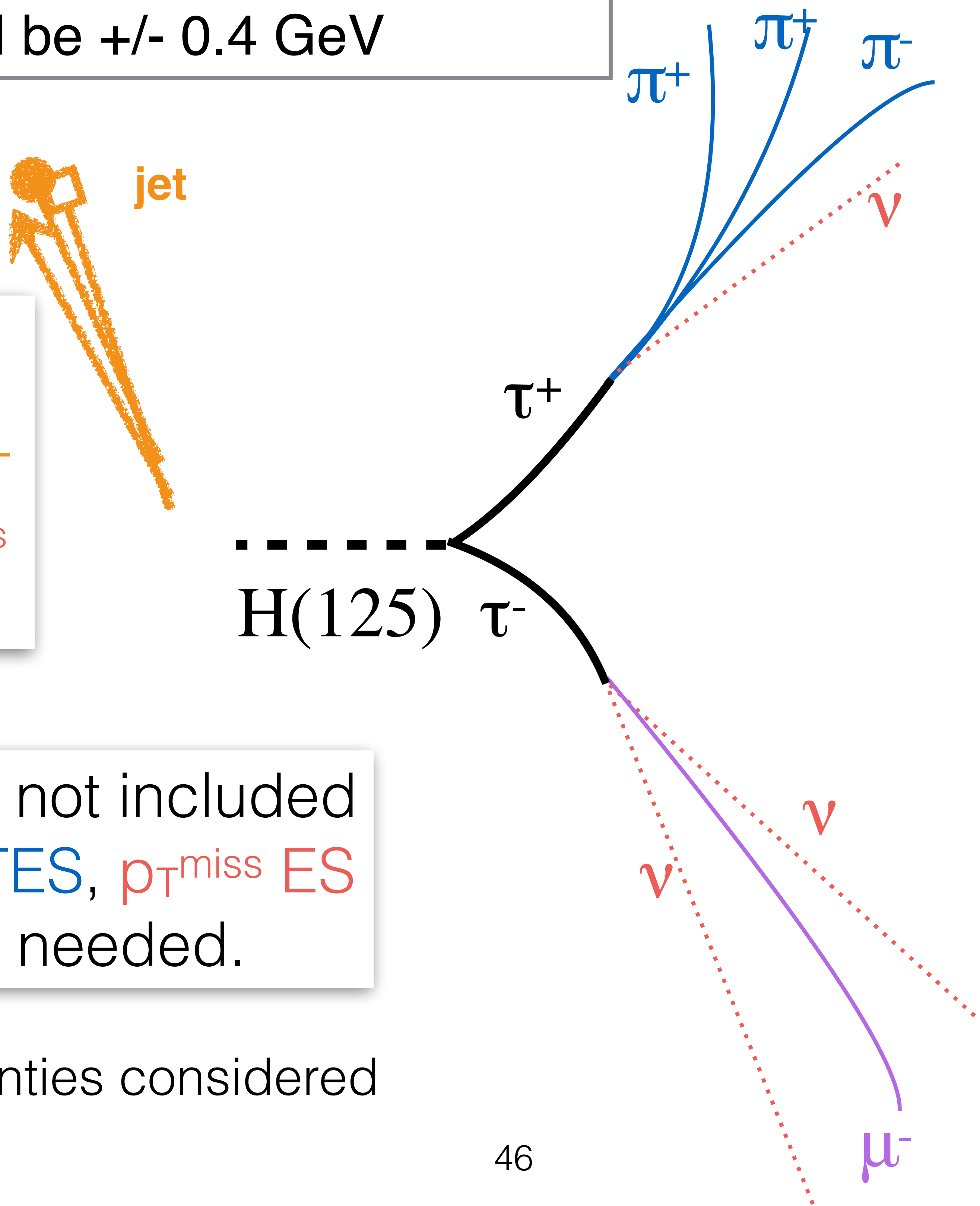
channel



category

$\tau\tau$ 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 p_T^{miss} measurement. JET ES added to p_T^{miss} calculation.

μ^- have negligible ES compared with p_T^{miss}, Jet and Tau ES

ν is not included in TES, p_T^{miss} ES needed.

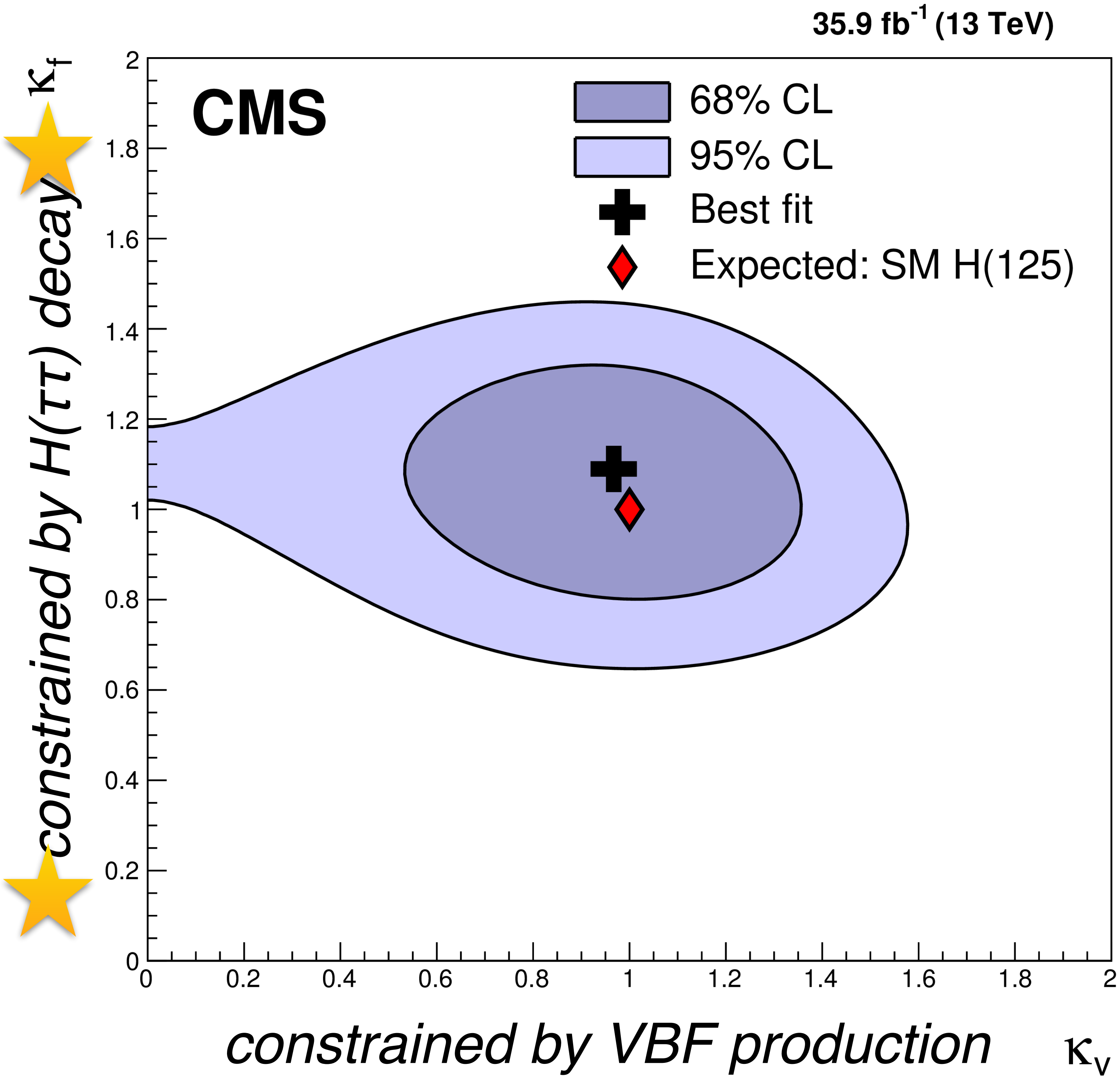
Many more uncertainties considered

Fermionic-vector coupling

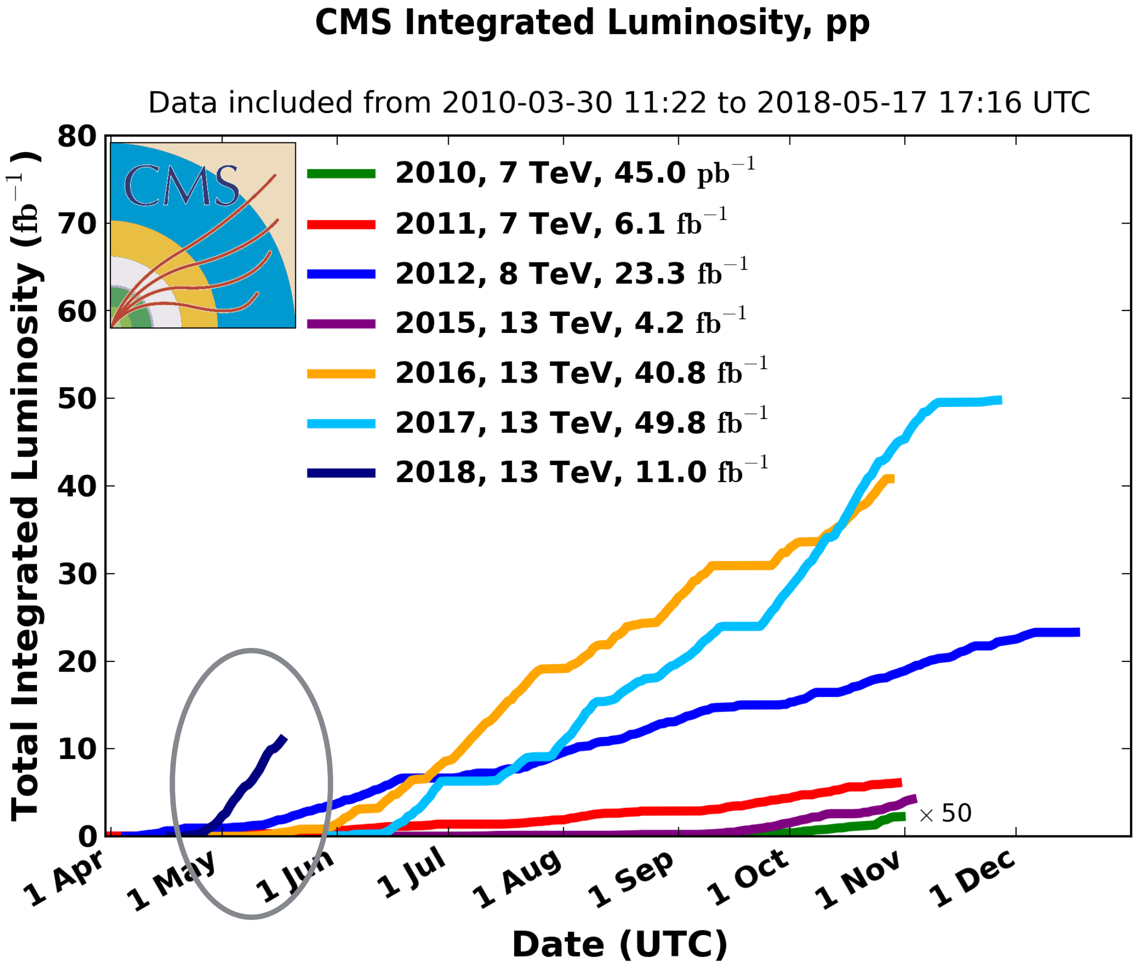
- Coupling modifier, ϰ, is ~the ratio of the measured coupling to the SM expectation.

- Measured SM Higgs(ττ): **1.09** $^{+0.27}_{-0.26}$ of the expected SM rate.

- ggH: **1.07** $^{+0.45}_{-0.41}$ x SM
  VBF: **1.06** $^{+0.42}_{-0.41}$ x SM



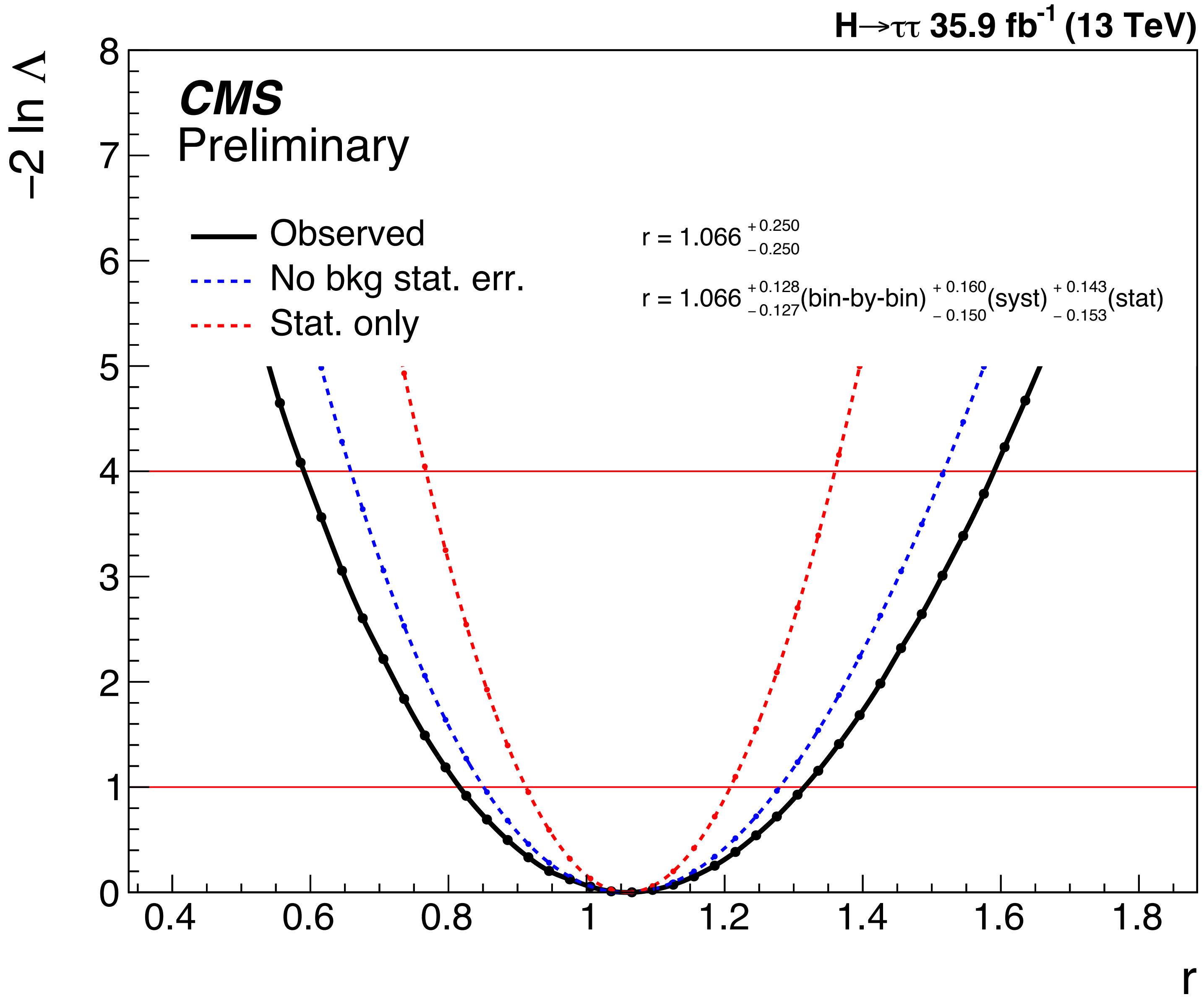
H(ττ) Looking Forward



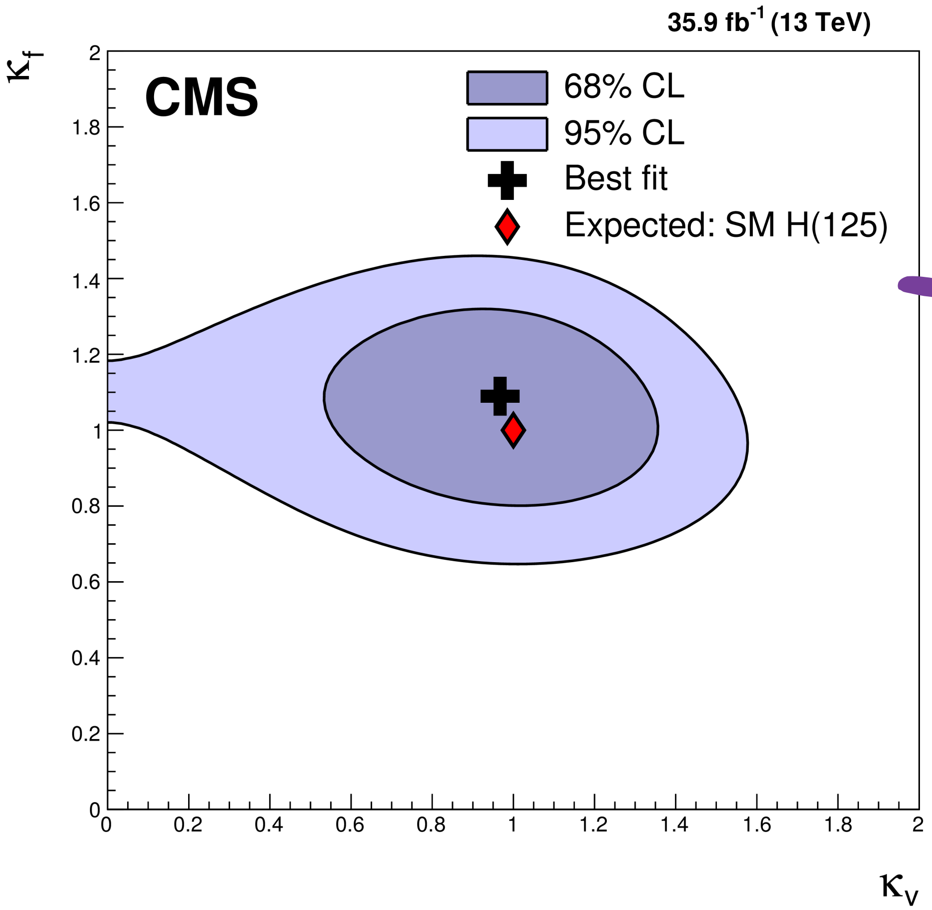
~25% uncertainty on obs value

12% uncert. from MC stat. precision

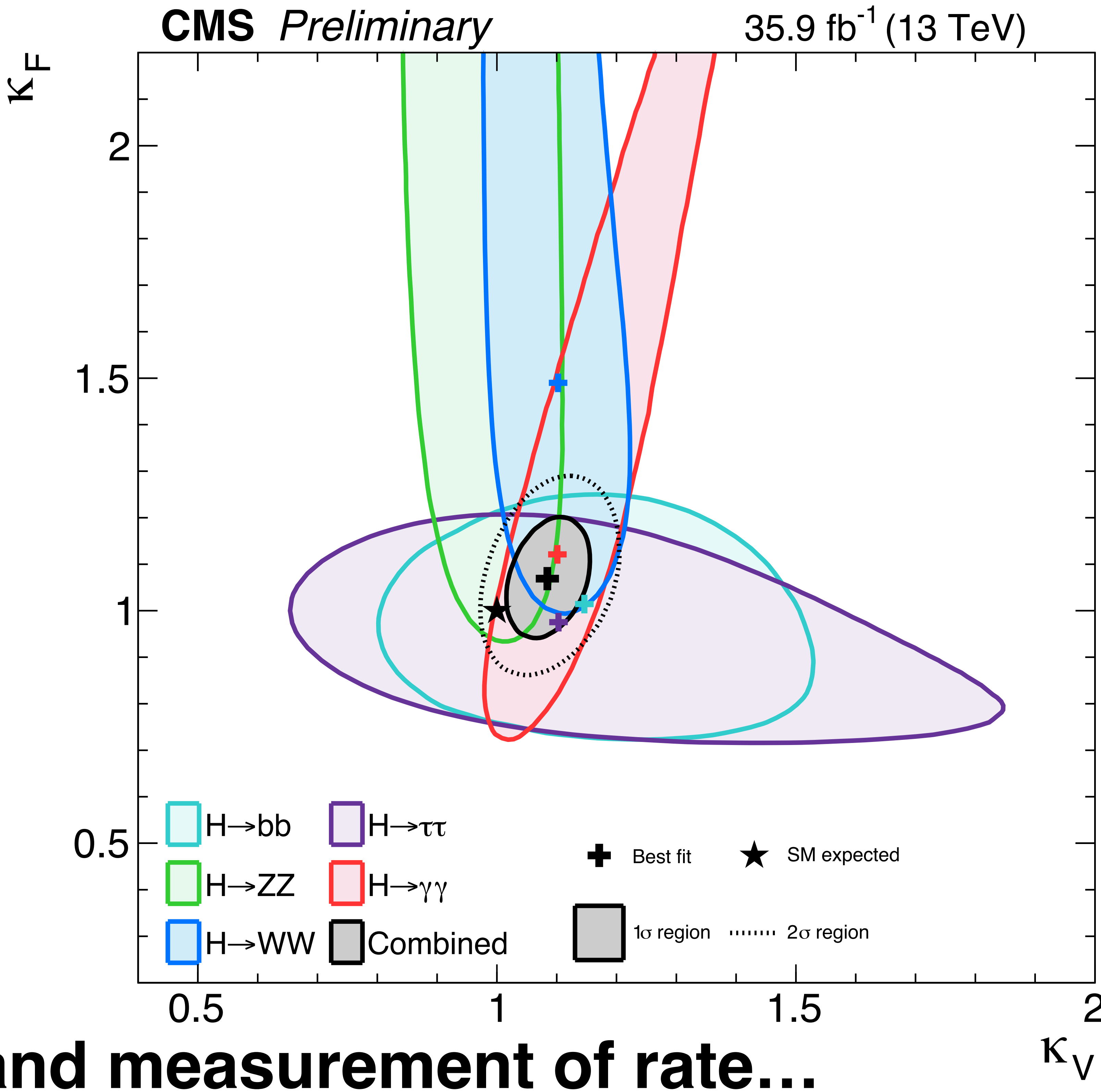
14% uncert. from Data stat. precision



Higgs Combination



Hττ sets most stringent upper limit on κ_F

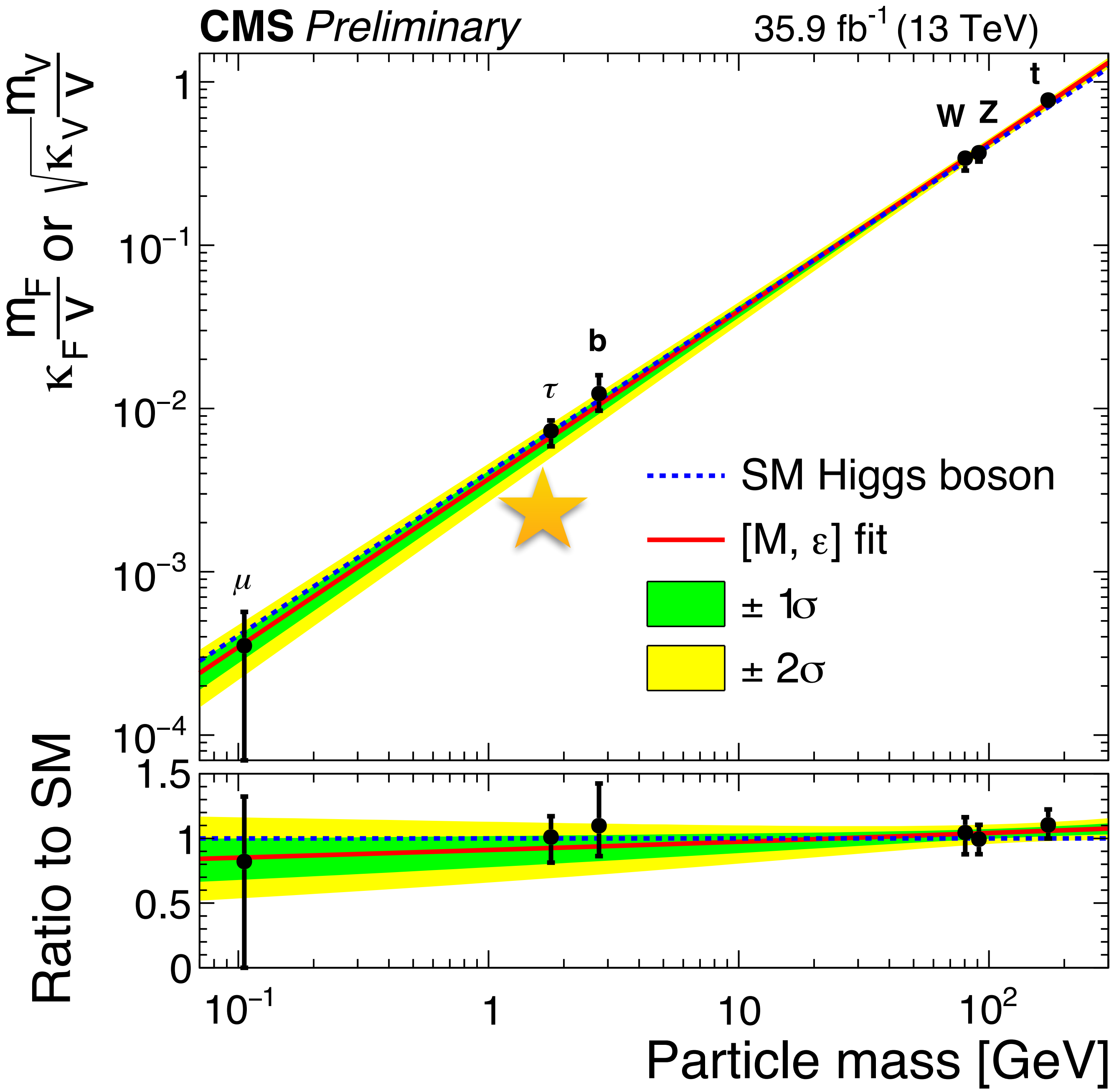


Good test of SM and measurement of rate…

Higgs Combination

Good test of SM and measurement of rate…

τ coupling is proportional to mass!



How can Higgs measurements help with the dark matter question?

Higgs → Dark Matter

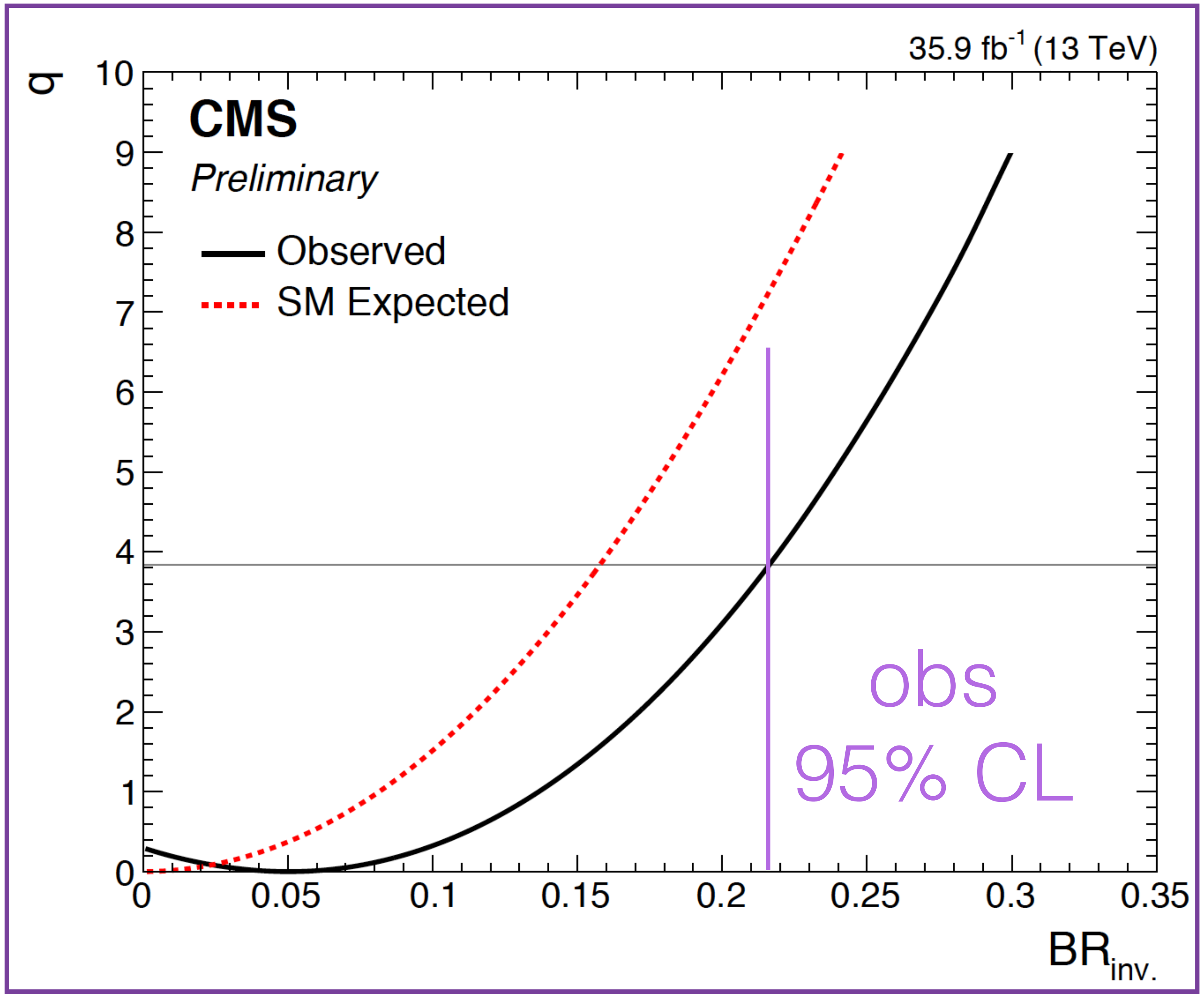
Measuring Higgs couplings
in H(ττ)+H(ZZ)+H(γγ)+…
helps place indirect limits on invisible (DM) decays of the Higgs.

Only valid for m_{DM}<62 GeV.

$$\mathcal{B}_{inv} = \frac{\Gamma_{h\to\chi\bar{\chi}}}{\Gamma_{\mathrm{SM}}+\Gamma_{h\to\chi\bar{\chi}}}$$

$$\frac{\Gamma_{\mathrm{H}}}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}} = \frac{\kappa_{\mathrm{H}}^2}{1-(\mathrm{BR}_{\mathrm{undet.}}-\mathrm{BR}_{\mathrm{inv.}})}$$

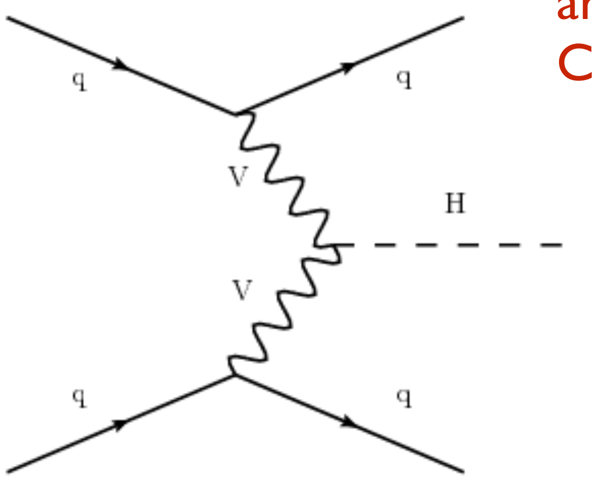
22% Indirect upper limit on the branching fraction to invisible BSM/DM decays



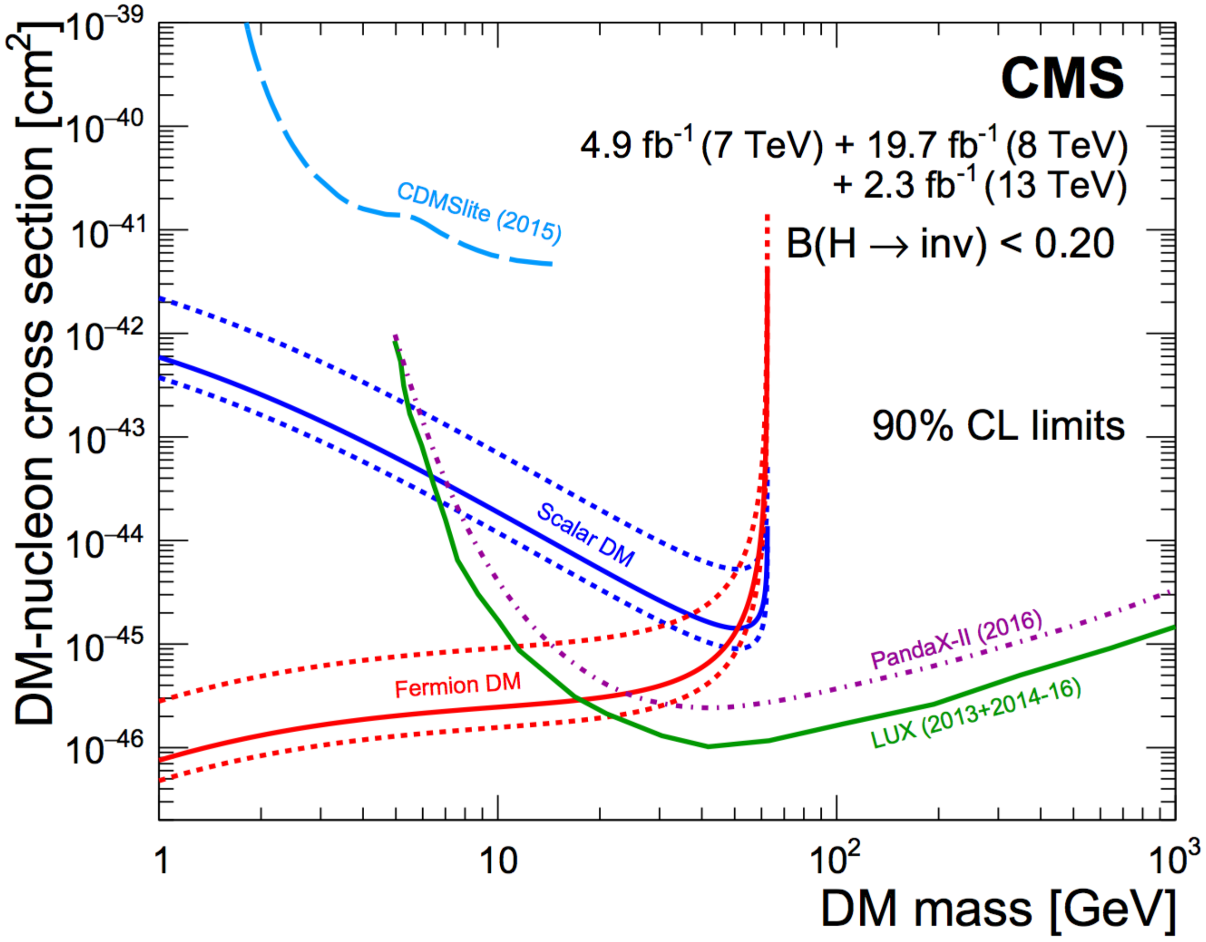
Invisible Higgs: a portal to DM

- “Higgs portal” models connect the Higgs sector to a hidden DM sector
- Simplest search is direct coupling: H→invisible
  - Valid for about $m_{DM} \leq 62$ GeV
- Limits from Higgs decay and H→invisible place a limit on DM mass roughy $m_\chi > 54$ GeV

arXiv:1512.06458
Beniwal et al.
BR(inv)<19%



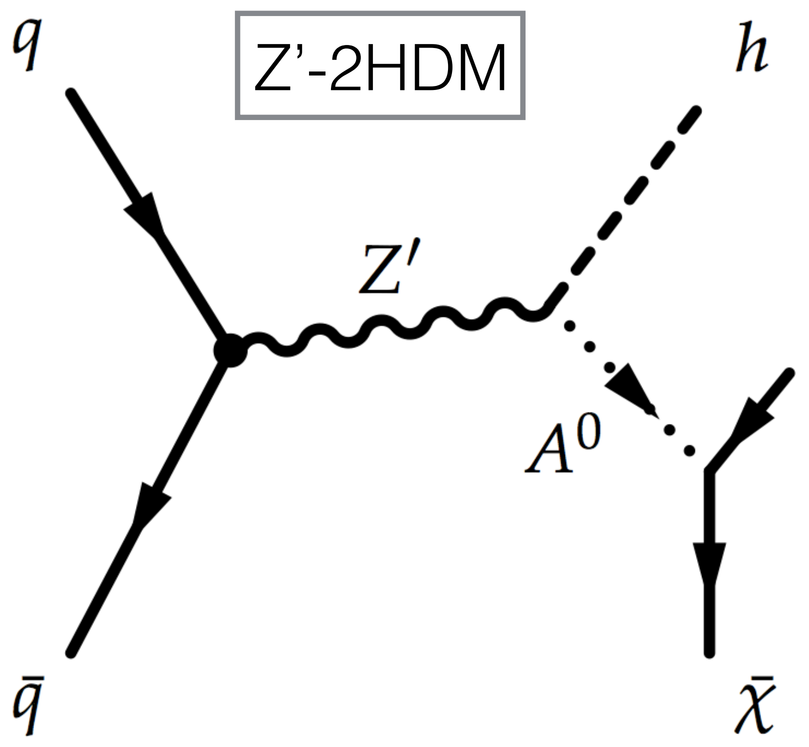
arXiv:1610.09218
CMS BR(inv)<20%



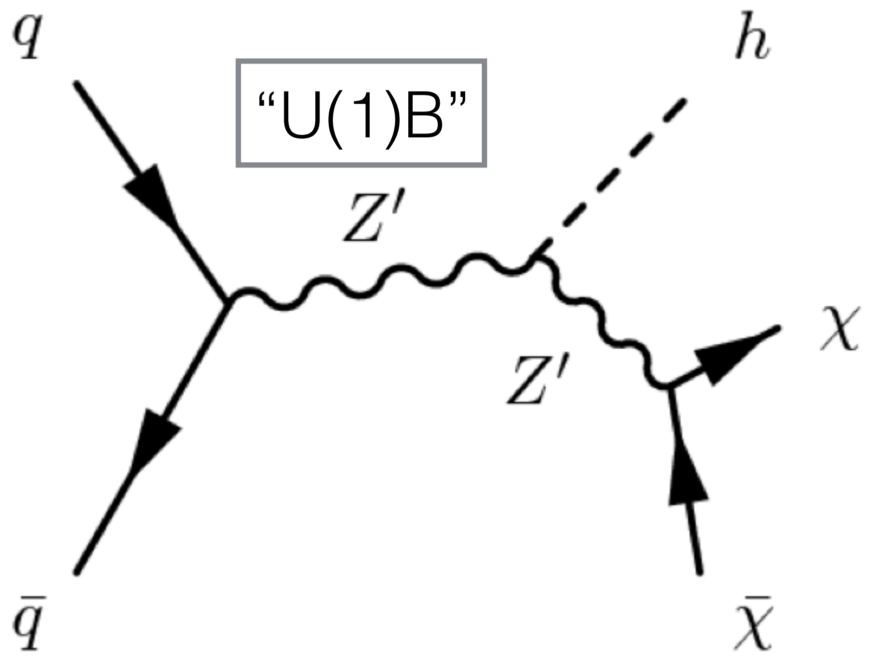
not my work

Mono-Higgs: H(ττ)+DM

- Above 62 GeV, how can we search?
- Already found Hττ so can Hττ help us find DM? Use τ trigger to look for H(ττ)+DM!
- Two **DM simplified** benchmark models are considered: 1) one resonant final state with multiple new particles, 2) one non-resonant final state



$\sigma \lesssim 1$ pb



“U(1)B” gauge symmetry
“baryonic”-model

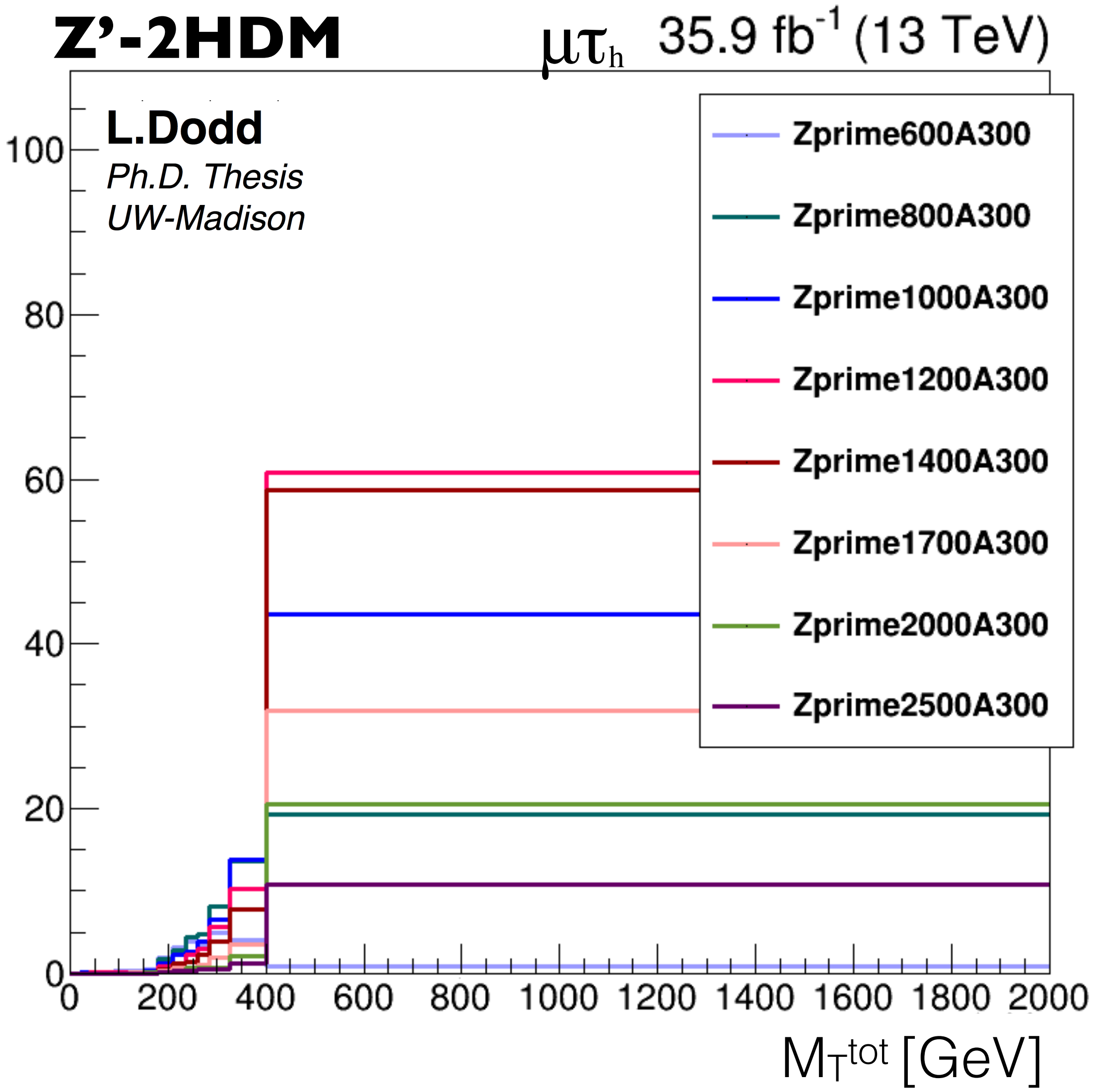
benchmark models
arXiv:1507.00966
Abercrombie et al.

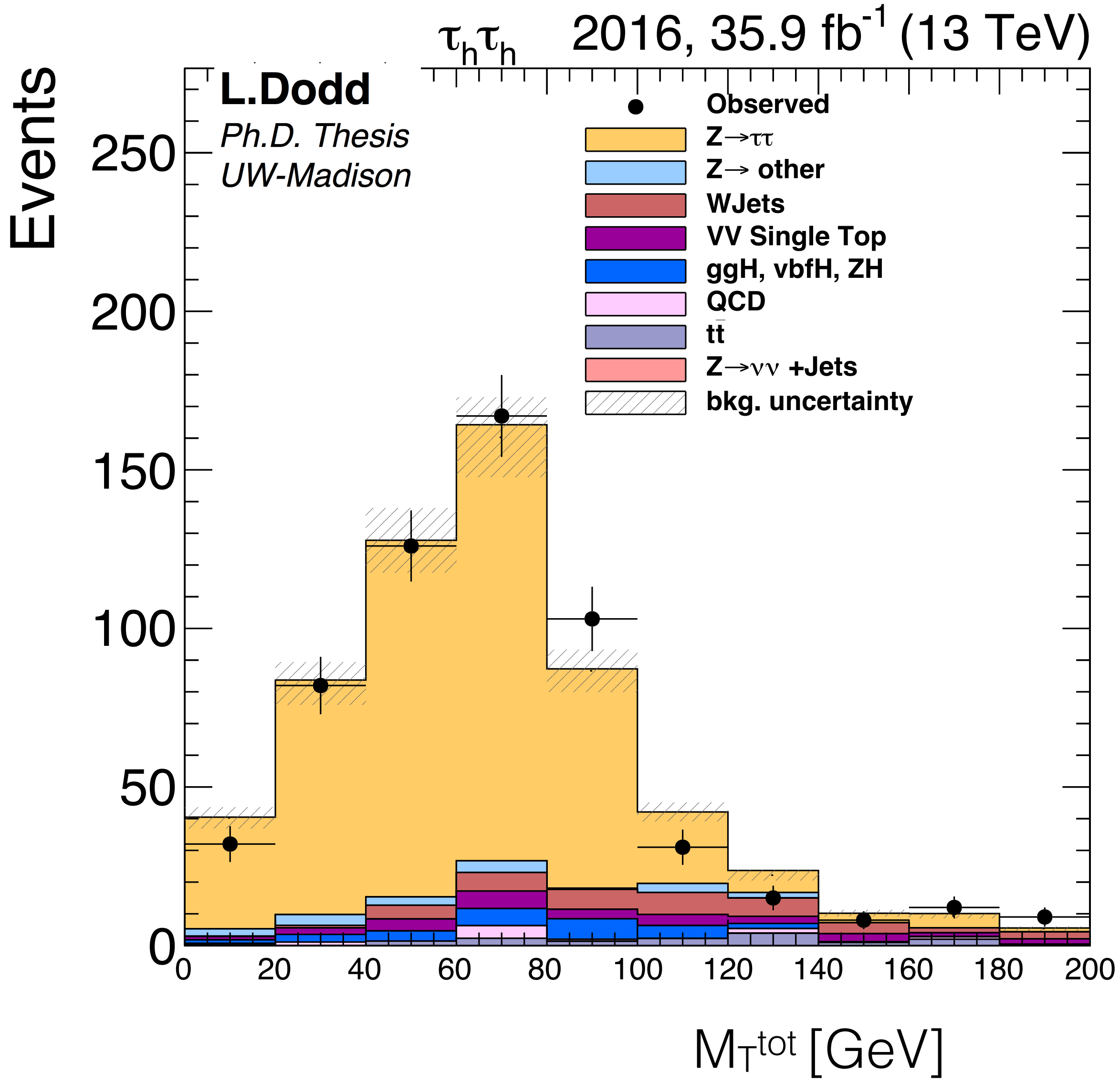
New Observable: M_T^{tot}

M_T^{tot} Total invariant mass of (p_T^{miss} +τ_1+τ_2) used for discrimination.

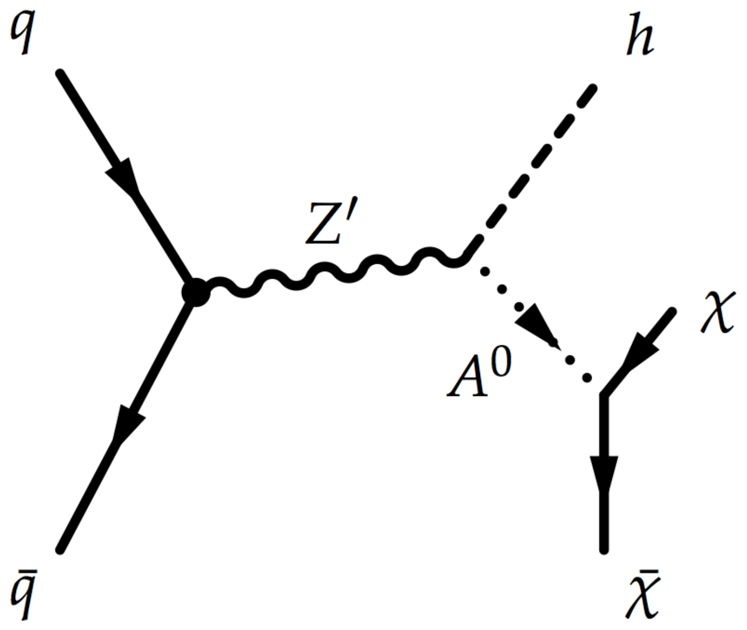
$$M_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{(E_{\mathrm{T}}^{\tau_1} + E_{\mathrm{T}}^{\tau_2} + p_{\mathrm{T}}^{\mathrm{miss}})^2 - (p_x^{\tau_1} + p_x^{\tau_2} + p_x^{\mathrm{miss}})^2 - (p_y^{\tau_1} + p_y^{\tau_2} + p_y^{\mathrm{miss}})^2}$$

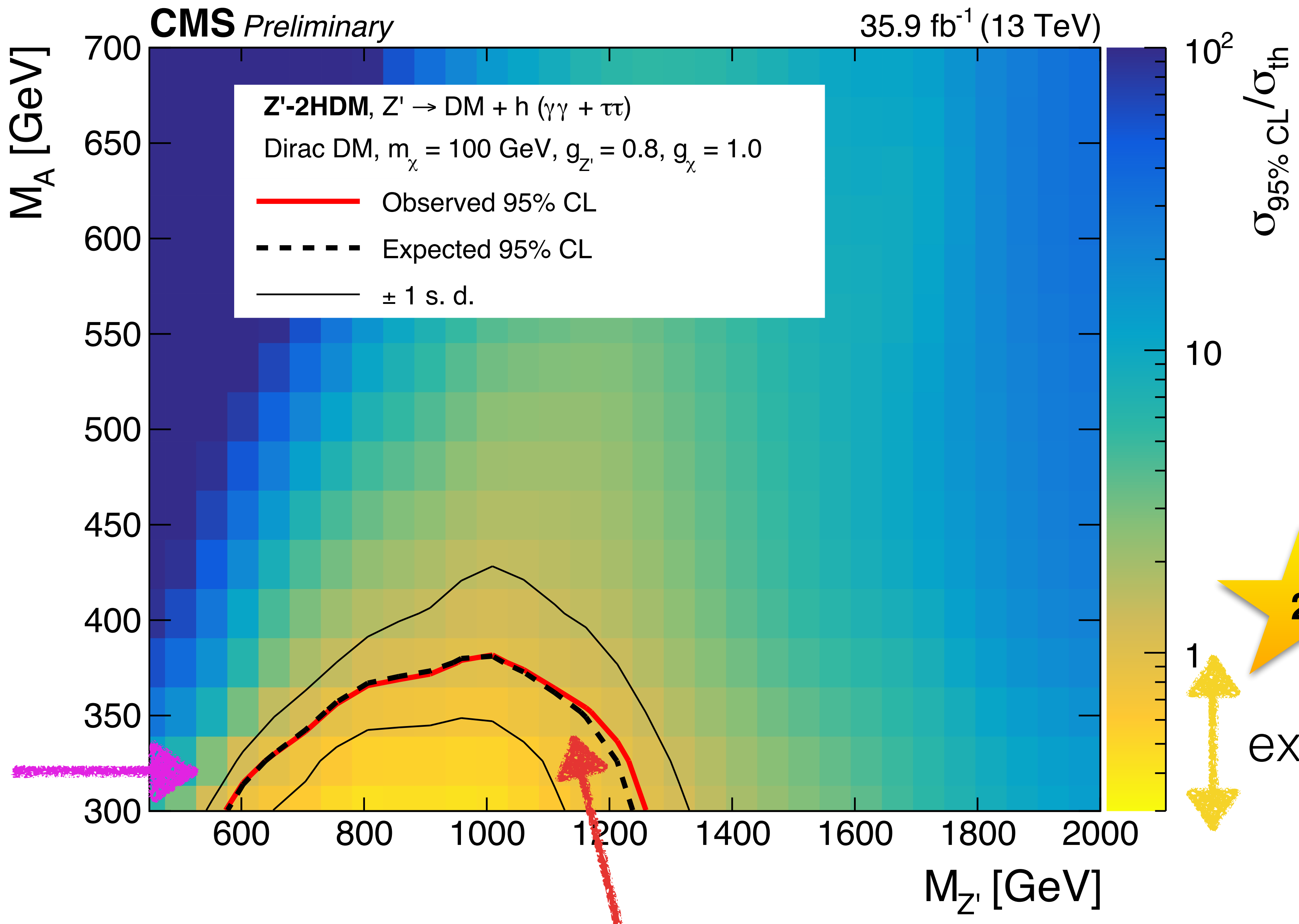
Require at least 100 GeV of p_T^{miss} and <u>combine with H(γγ)+DM analysis</u>!





Z'-2HDM Interpretation





2

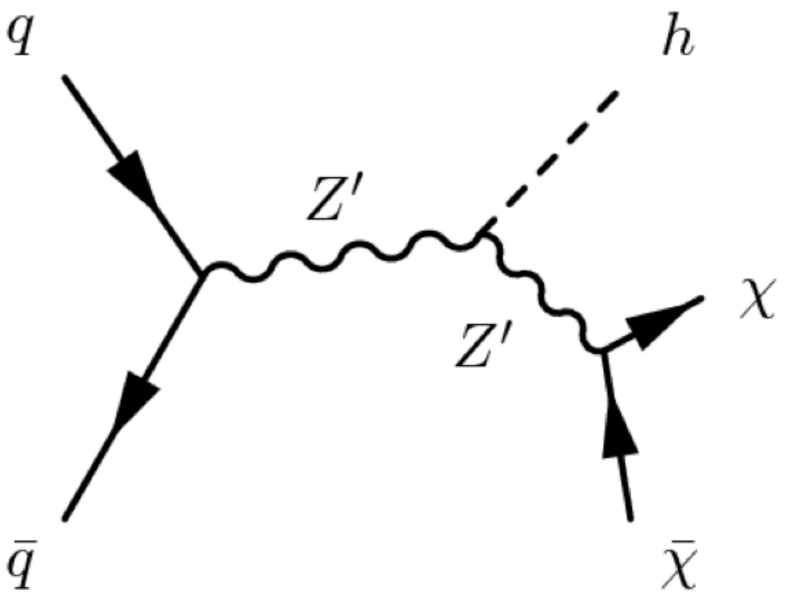
excl.

3 small cross section: $M_{Z'}<2^*M_A$

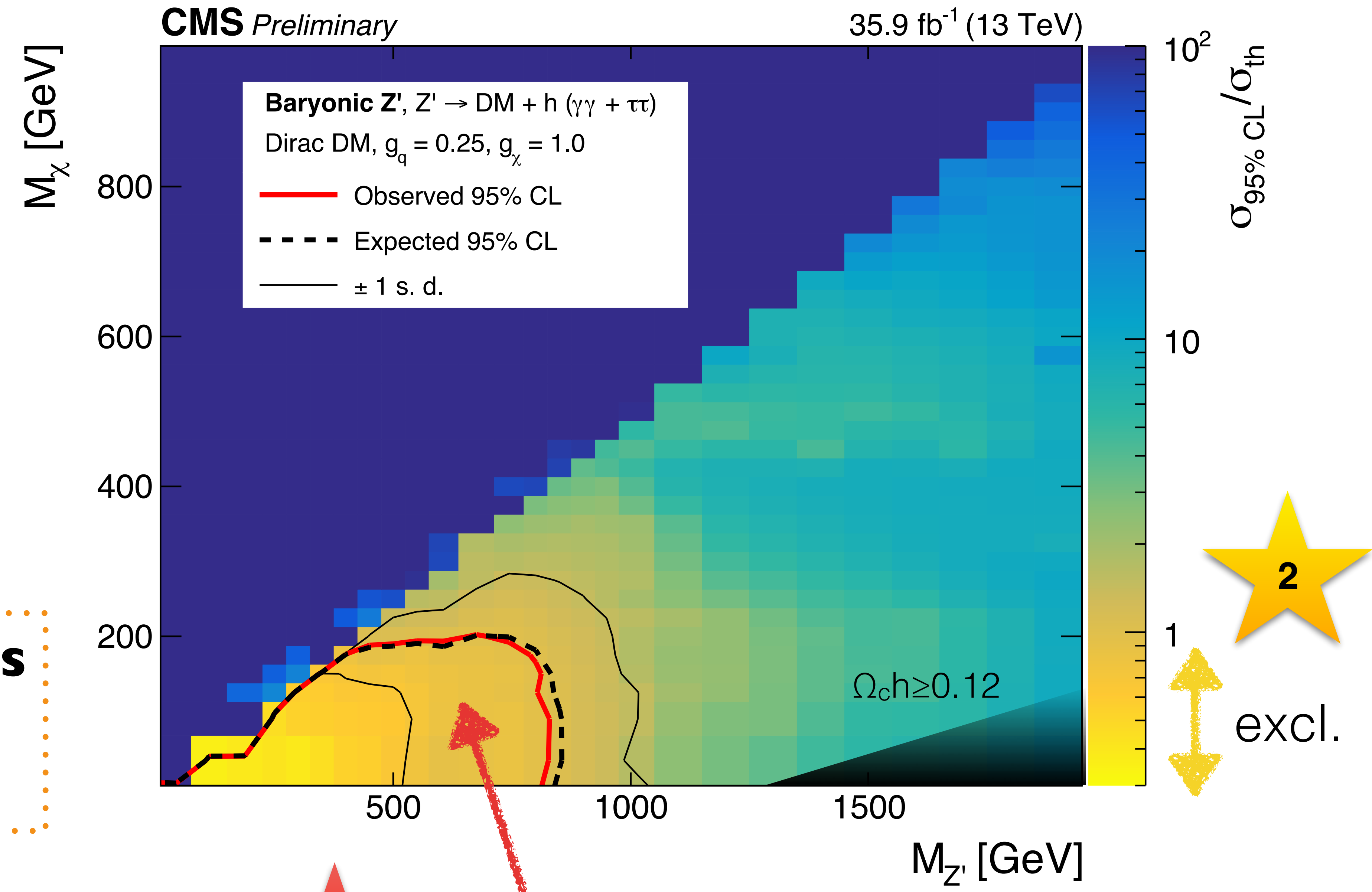
No significant excess compared to SM expectation

1 region below red-line excluded and driven by ττ result

“U(1)B” Interpretation



No significant excess compared to SM expectation



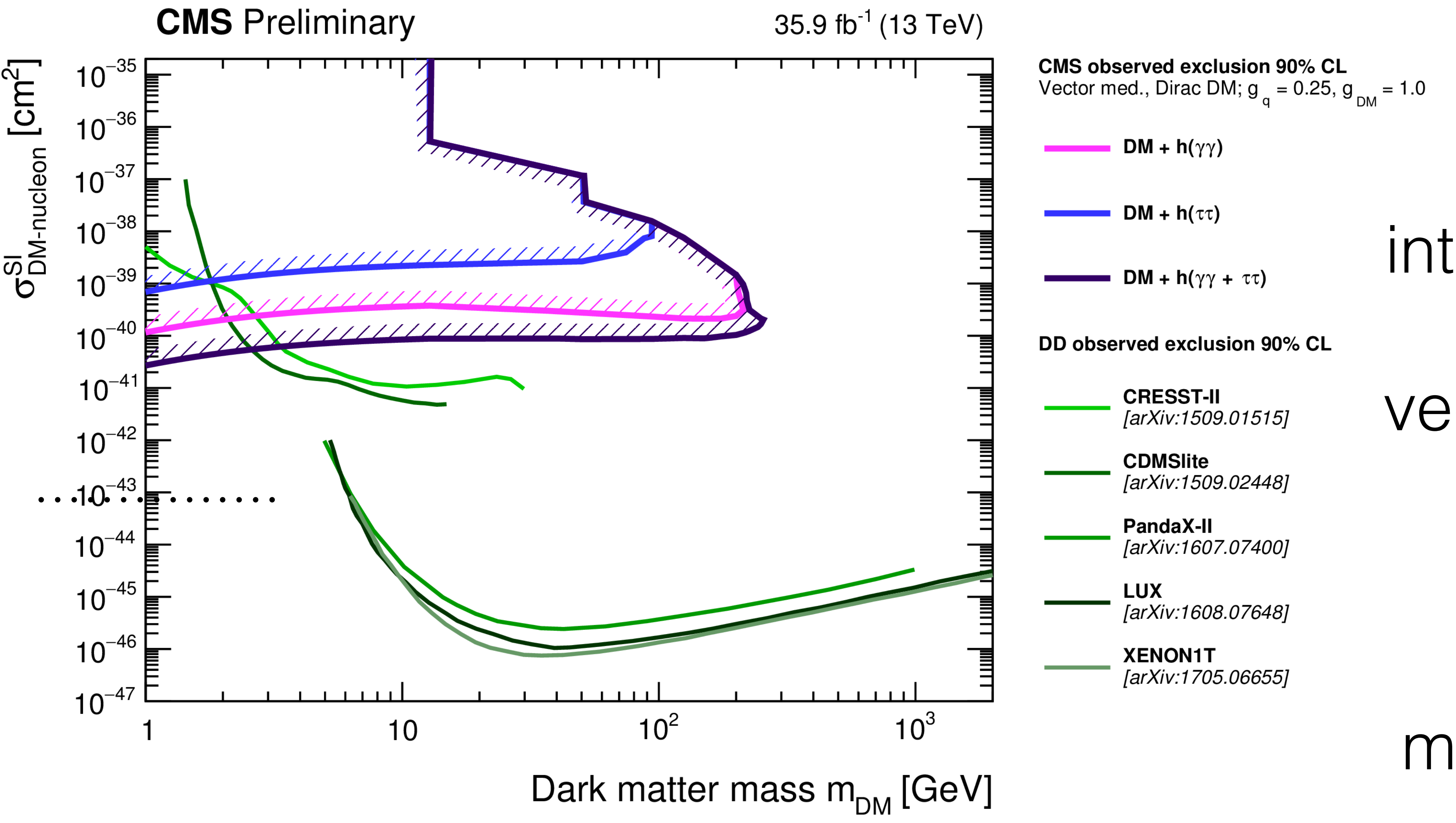
1 region below red-line excluded and driven by both ττ+γγ

mDM = 1 GeV, mediator masses up to ~800 GeV are excluded

“U(1)B” SI Interpretation

Summary: “Higgs portal” models increasingly constrained by direct detection.

$$\sigma^{\rm SI} = \frac{f^2(g_q)g_{DM}^2\mu_{n\chi}^2}{\pi m_{\rm med}^4}$$



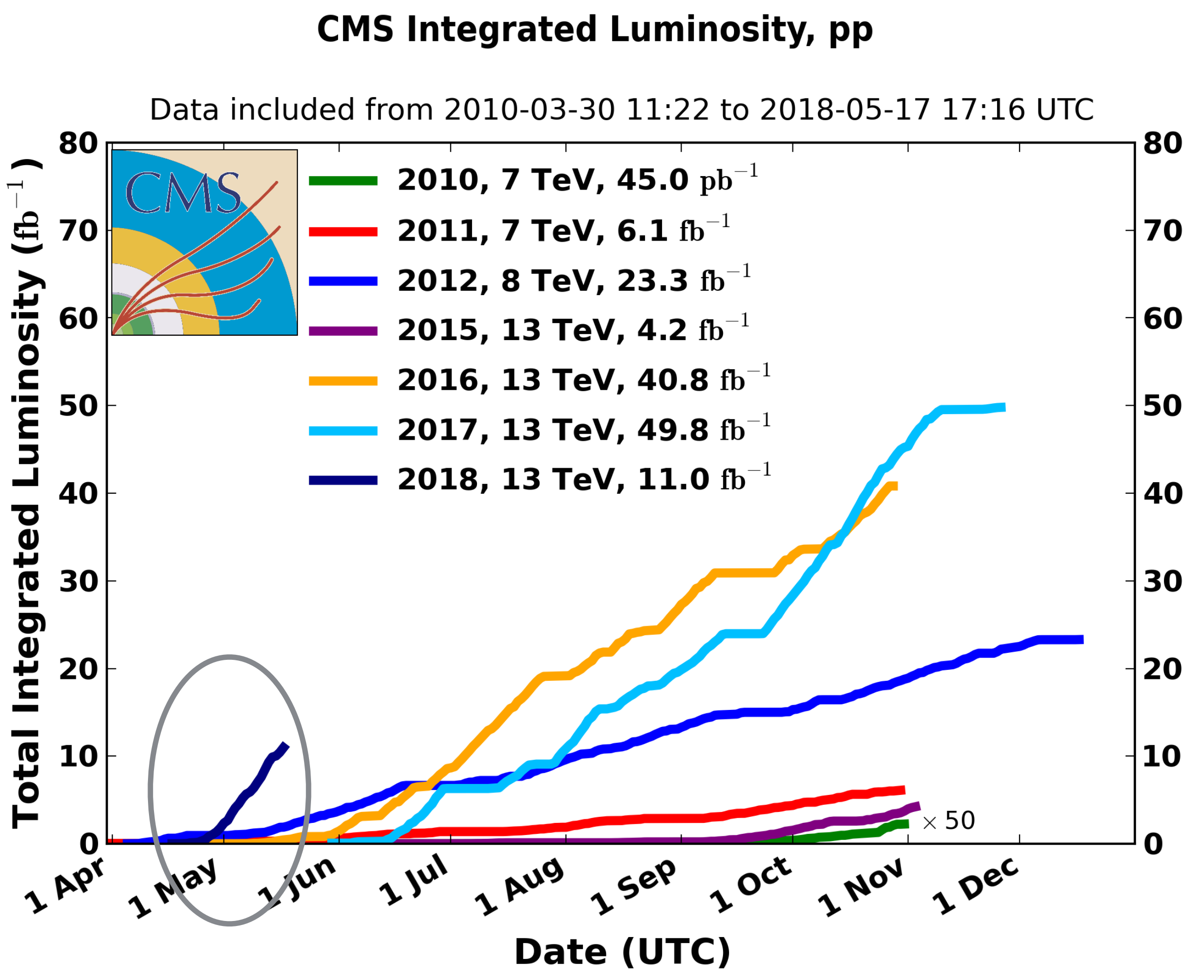
U(1)B interpreted with s-channel vector mediator

Other DM searches more sensitive

H+DM Looking forward

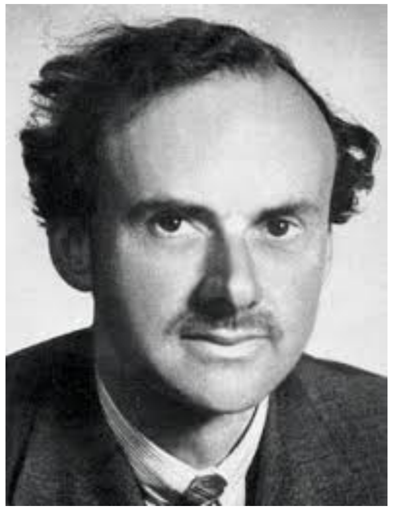
- Question: Is Higgs linked to dark matter?
  - **Answer: Do not know** H(ττ)+ DM did not answer with 2016 CMS data.
  - Solution: Keep looking.

Low expected yield from signal.
Stat. precision of data will improve result.
Run-II may exclude Z’-2HDM. Other models will require advancement of techniques



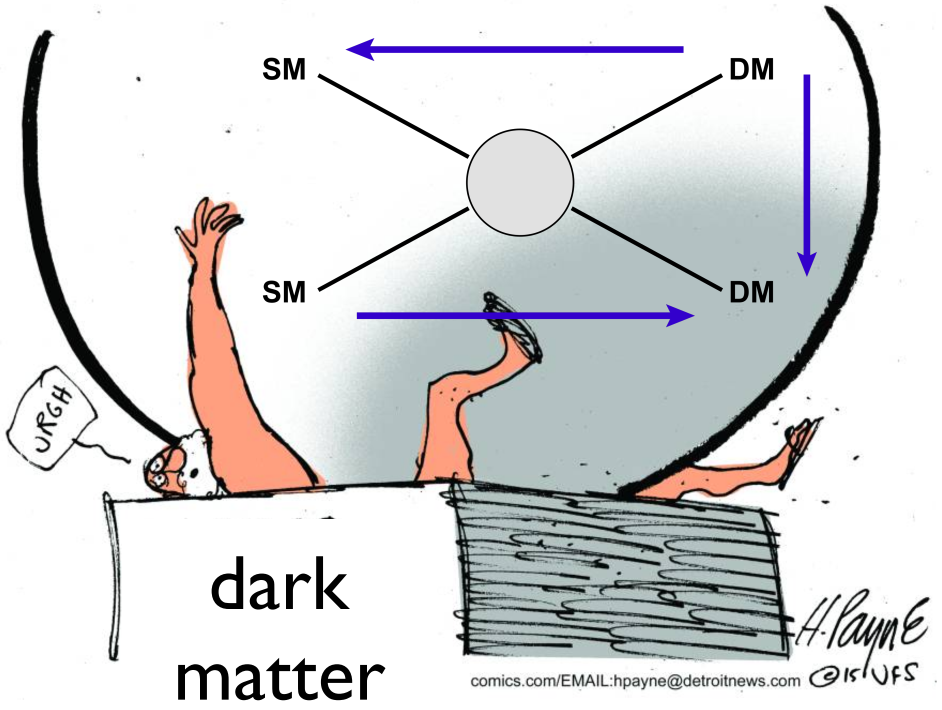
The Mass Problem: Current status

- Fermion mass: The tau lepton couples to H proportional to τ mass!
  - Is there CP violation in the Yukawa coupling? Check other fermions with Higgs measurements?
  - How do neutral leptons get mass? Currently unknown. Is neutrino: Dirac or Majorana?
- Dark matter mass:
  - Particle nature of dark matter and mass generation? Direct, indirect, and collider searches play vital roles



neutrino

or ?

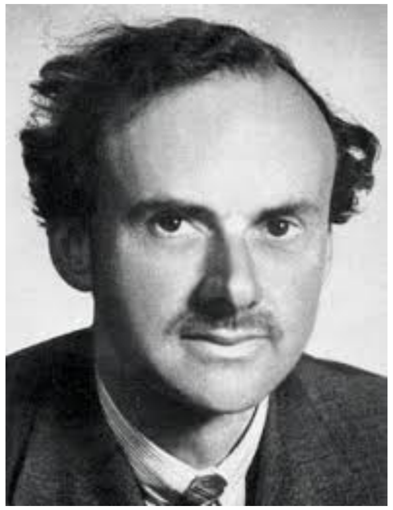


The Mass Problem: Current status

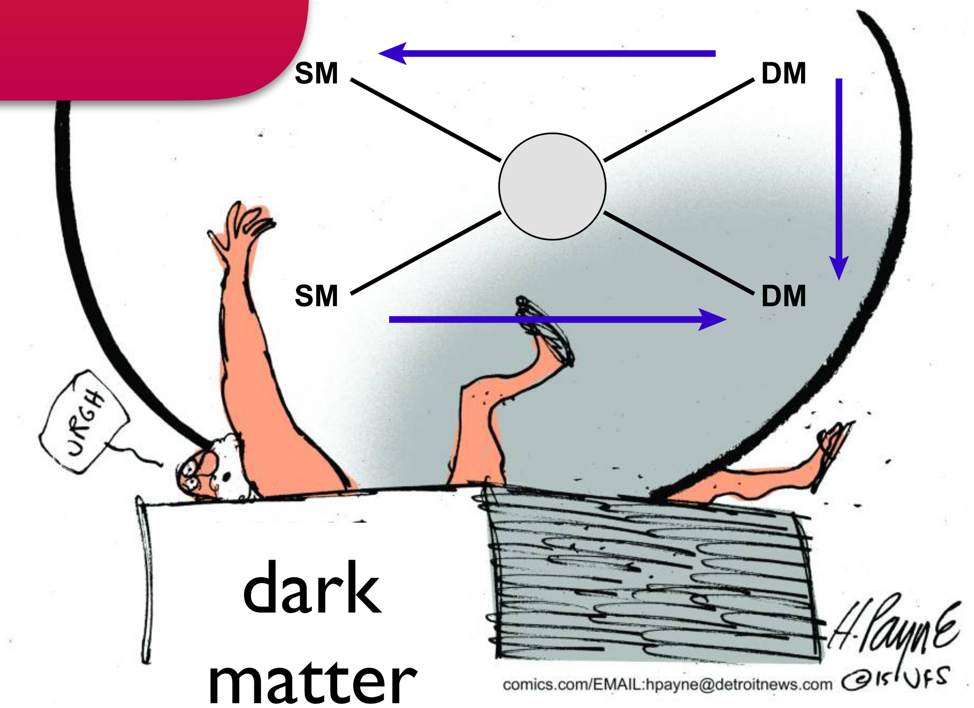
- Fermion mass: The tau lepton couples to H proportional to τ mass!
    - Is there CP violation in the Yukawa coupling? Check other fermions with Higgs measurements?
    - How do neutral leptons get mass? Currently unknown. Is neutrino: Dirac
- Dark matter mass:
    - Particle nature ct, indirect, and co

Stay tuned!

neutri



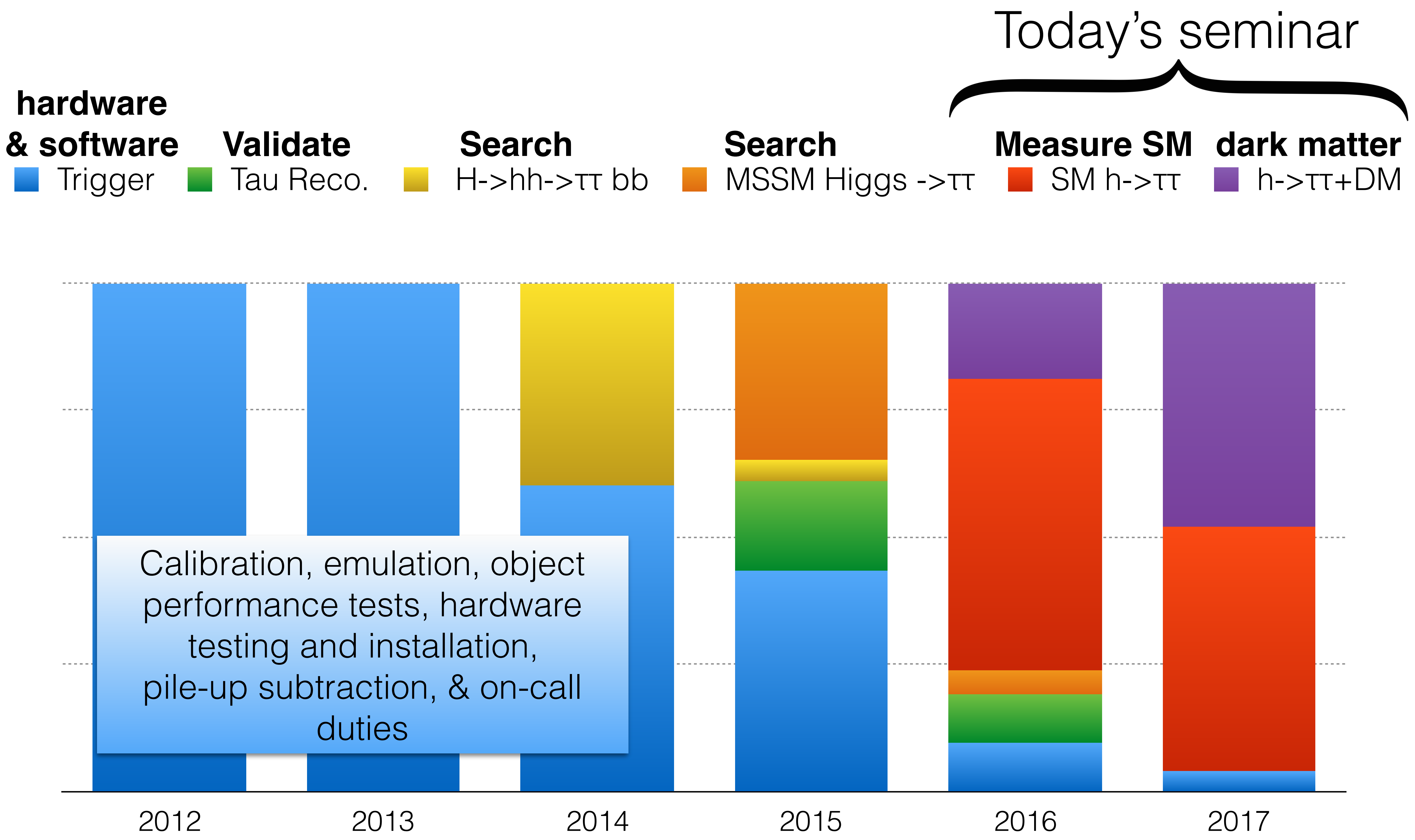
or ?



comics.com/EMAIL:hpayne@detroitnews.com

backup

My HEP Timeline



Today's seminar

hardware & software 🟦 Trigger

Validate 🟩 Tau Reco.

Search 🟨 H->hh->ττ bb

Search 🟧 MSSM Higgs ->ττ

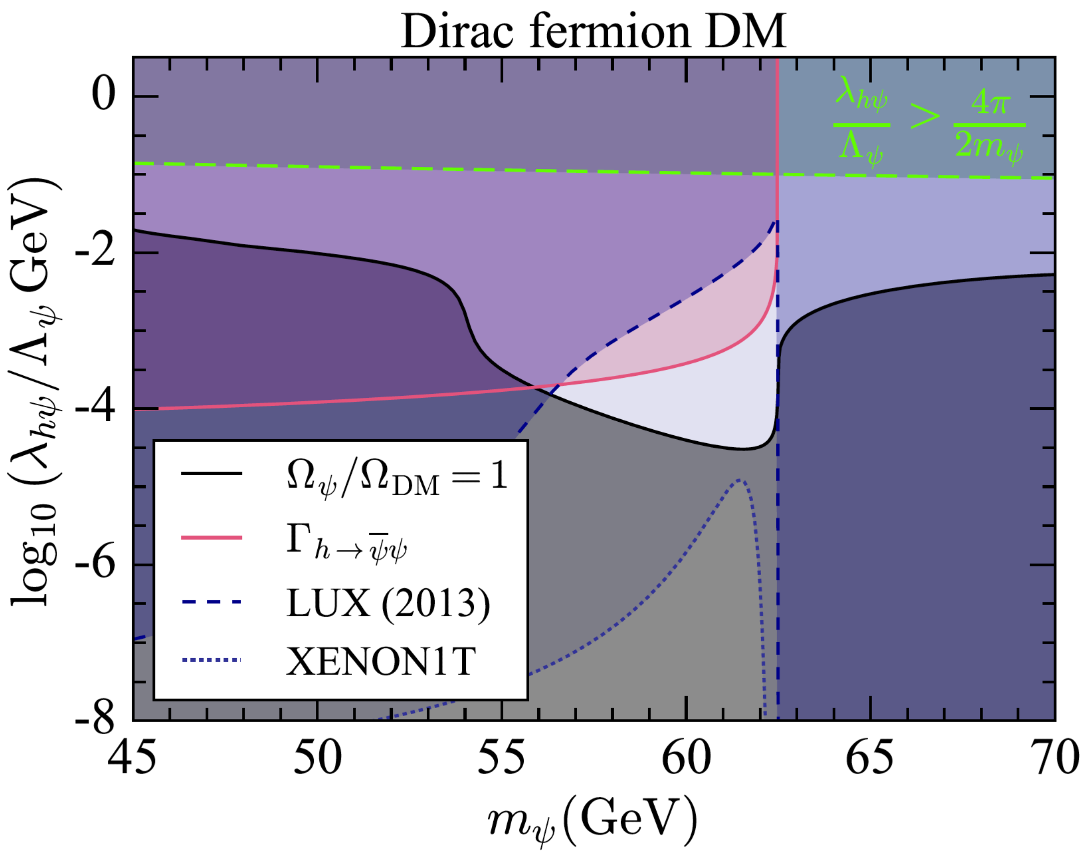
Measure SM 🟥 SM h->ττ

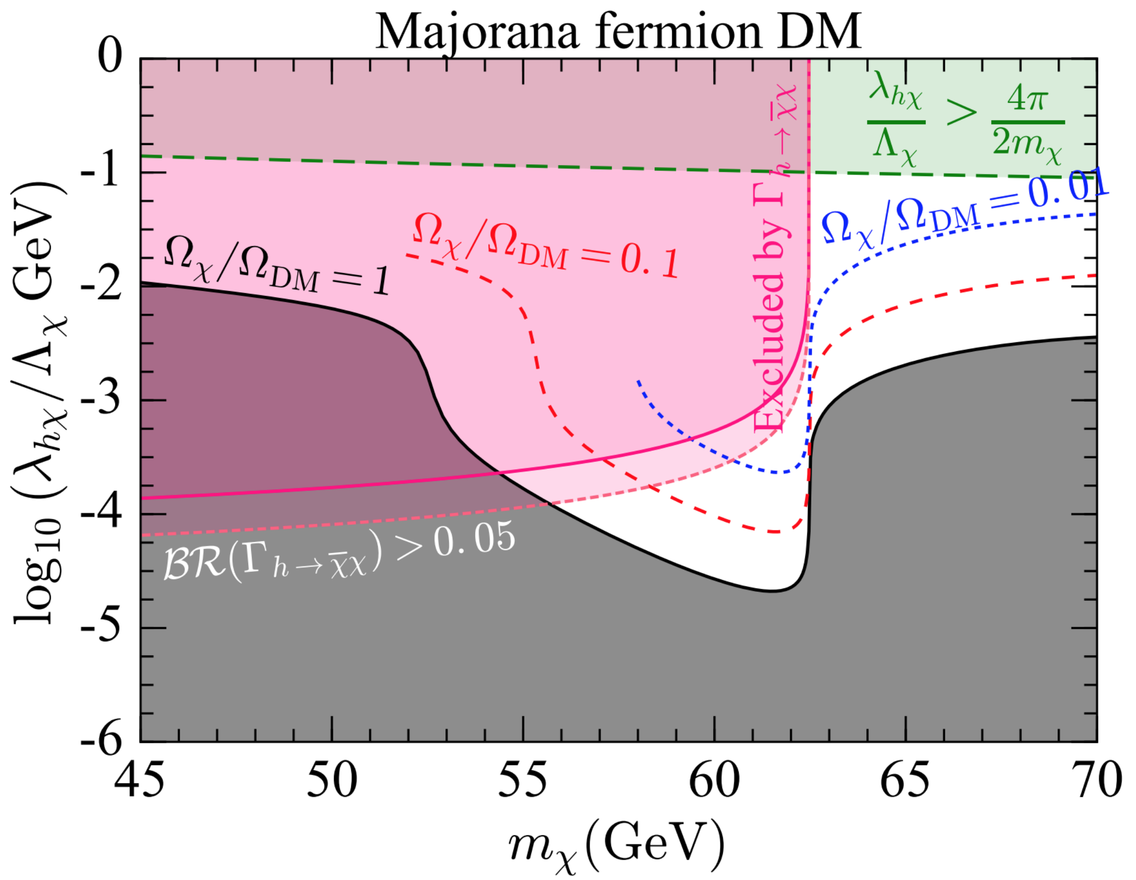
dark matter 🟪 h->ττ+DM

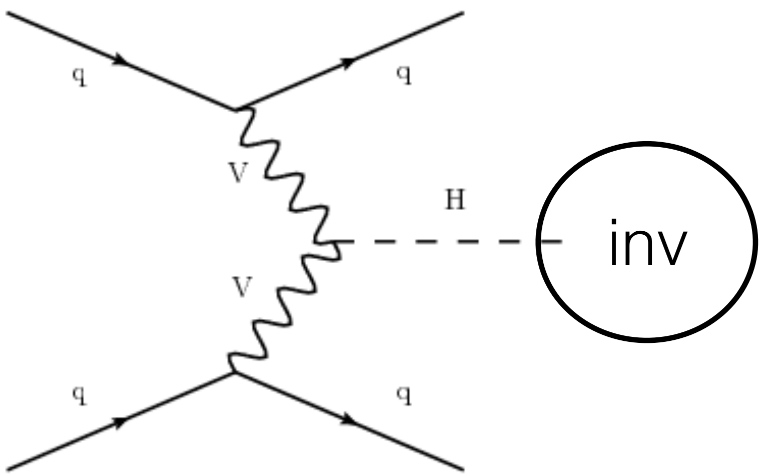
Calibration, emulation, object performance tests, hardware testing and installation, pile-up subtraction, & on-call duties

Invisible Higgs: a portal to DM

- "Higgs portal" models connect the Higgs sector to a hidden DM sector
- Simplest search is direct coupling: H→invisible
  - Valid for about $m_{DM} \leq 62$ GeV
- Limits from Higgs decay and H→invisible place a limit on DM mass roughy m_χ >54 GeV

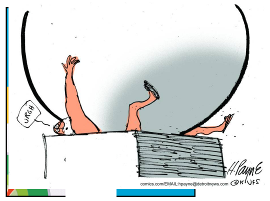






arXiv:1512.06458
Beniwal et al.
BR(inv)<20%

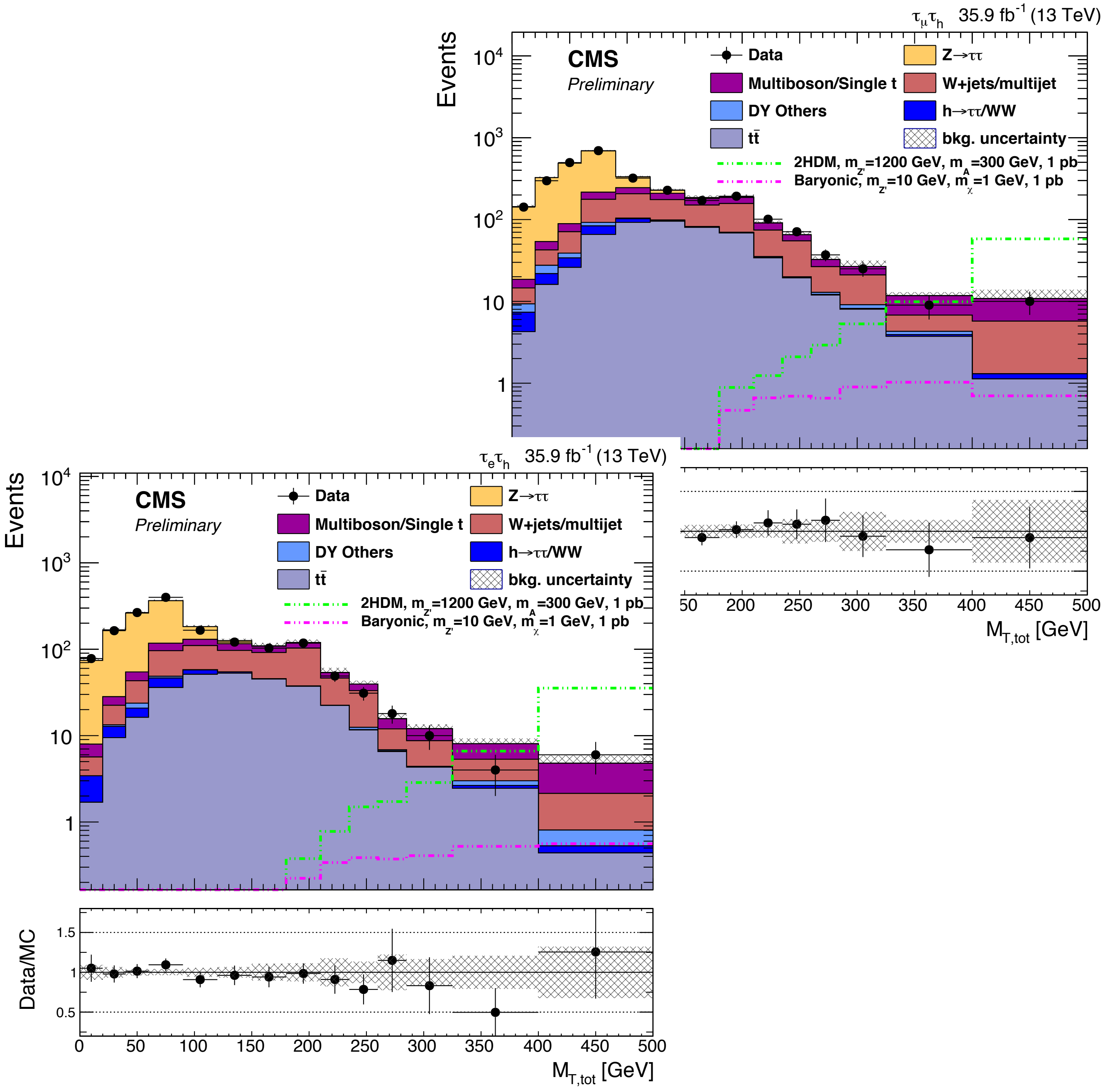
not my work

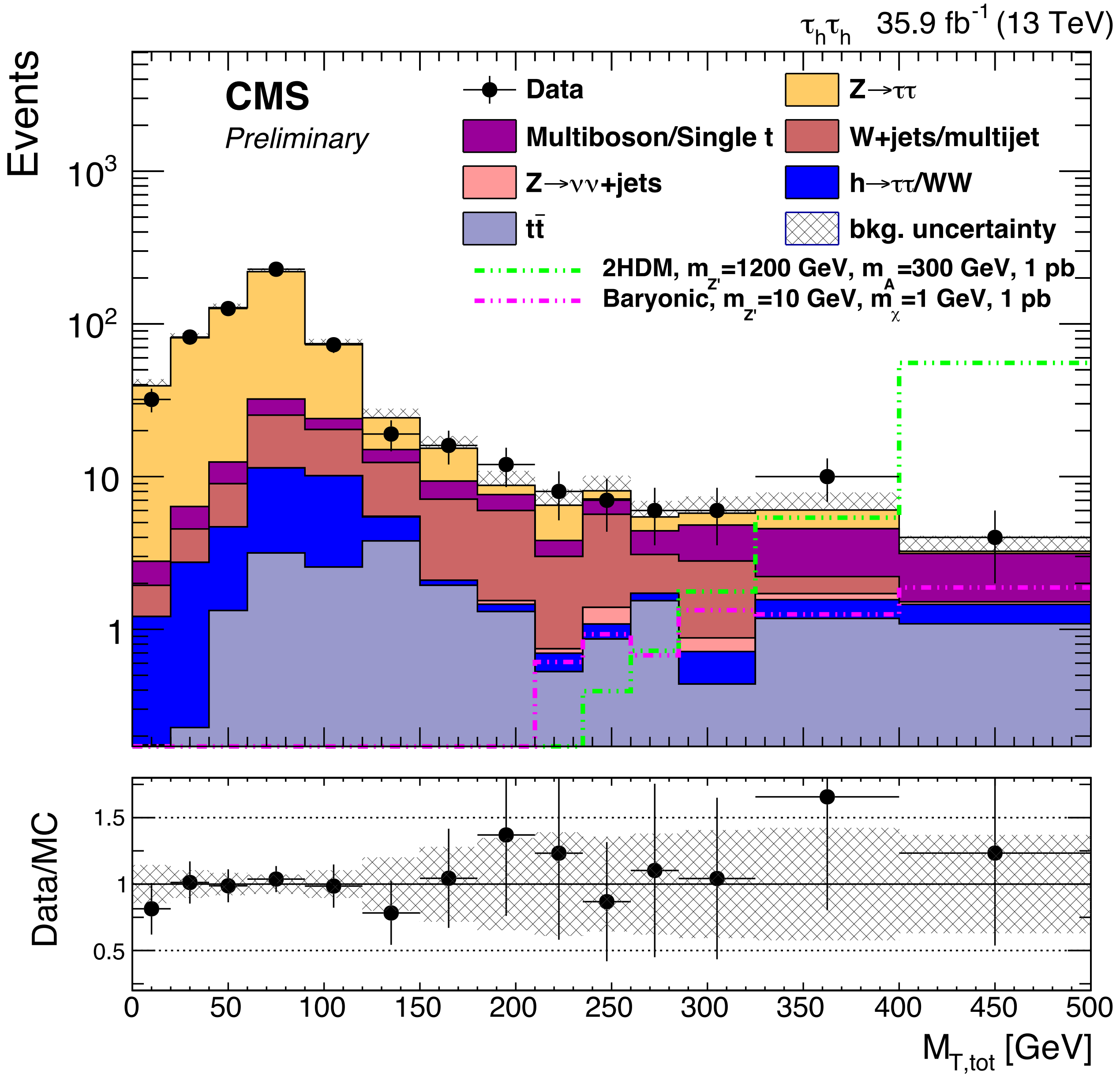


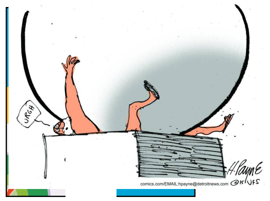
Observable Distributions

include 5 data sidebands for control of backgrounds

and then combine result with H(γγ)+DM result



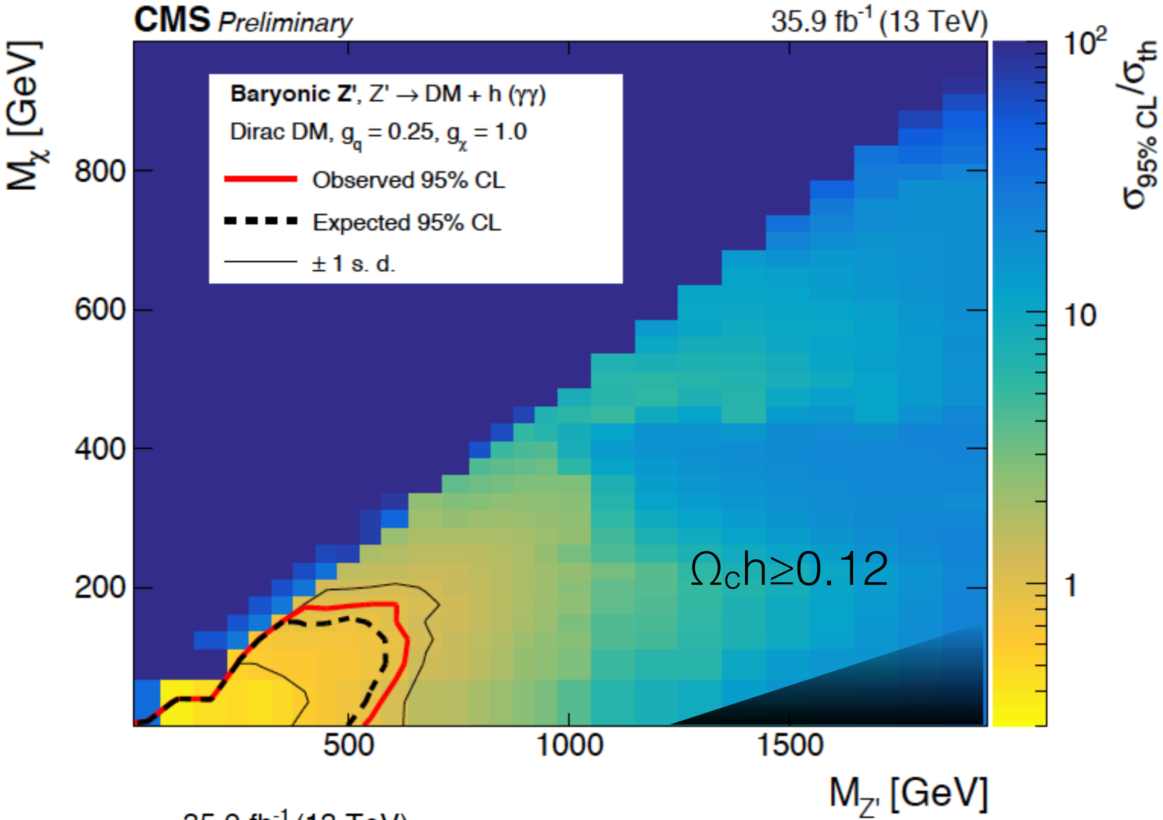


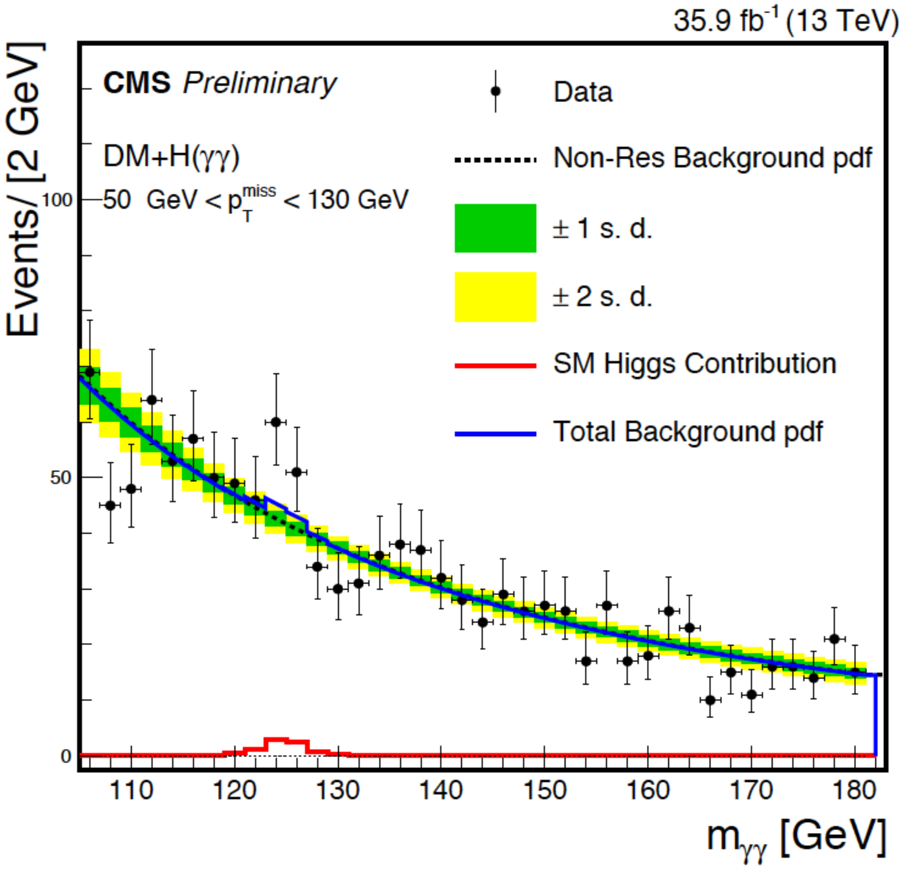


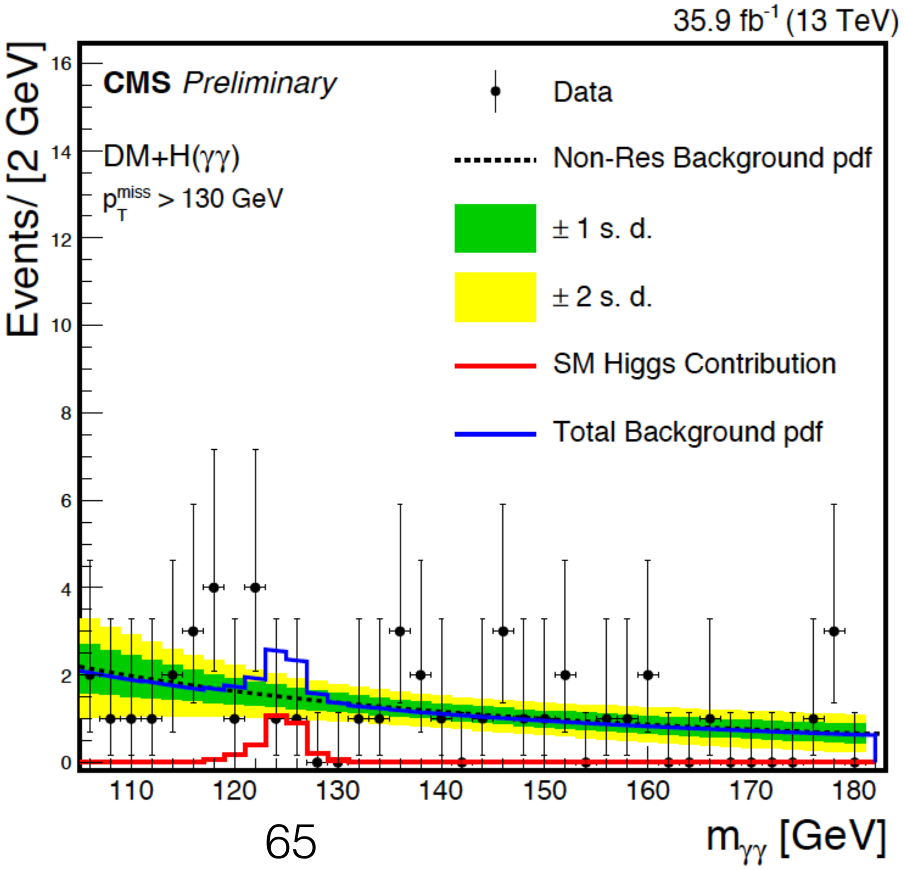
Combination with h→γγ

- Luminosity, SM Higgs background production, theoretical uncertainties are correlated

- No significant deviation in observed limits, limits are driven by the higher p_T^{miss} regions.

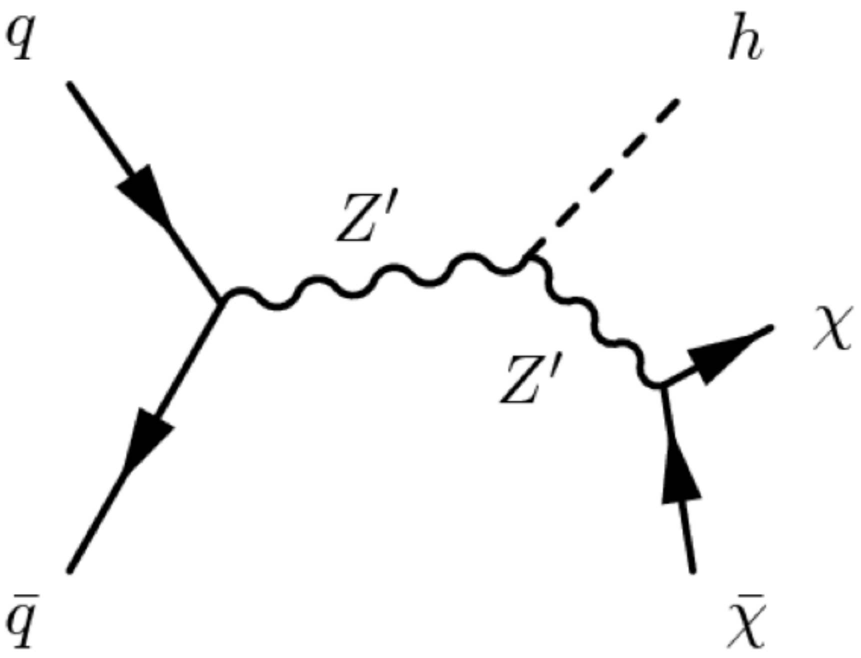




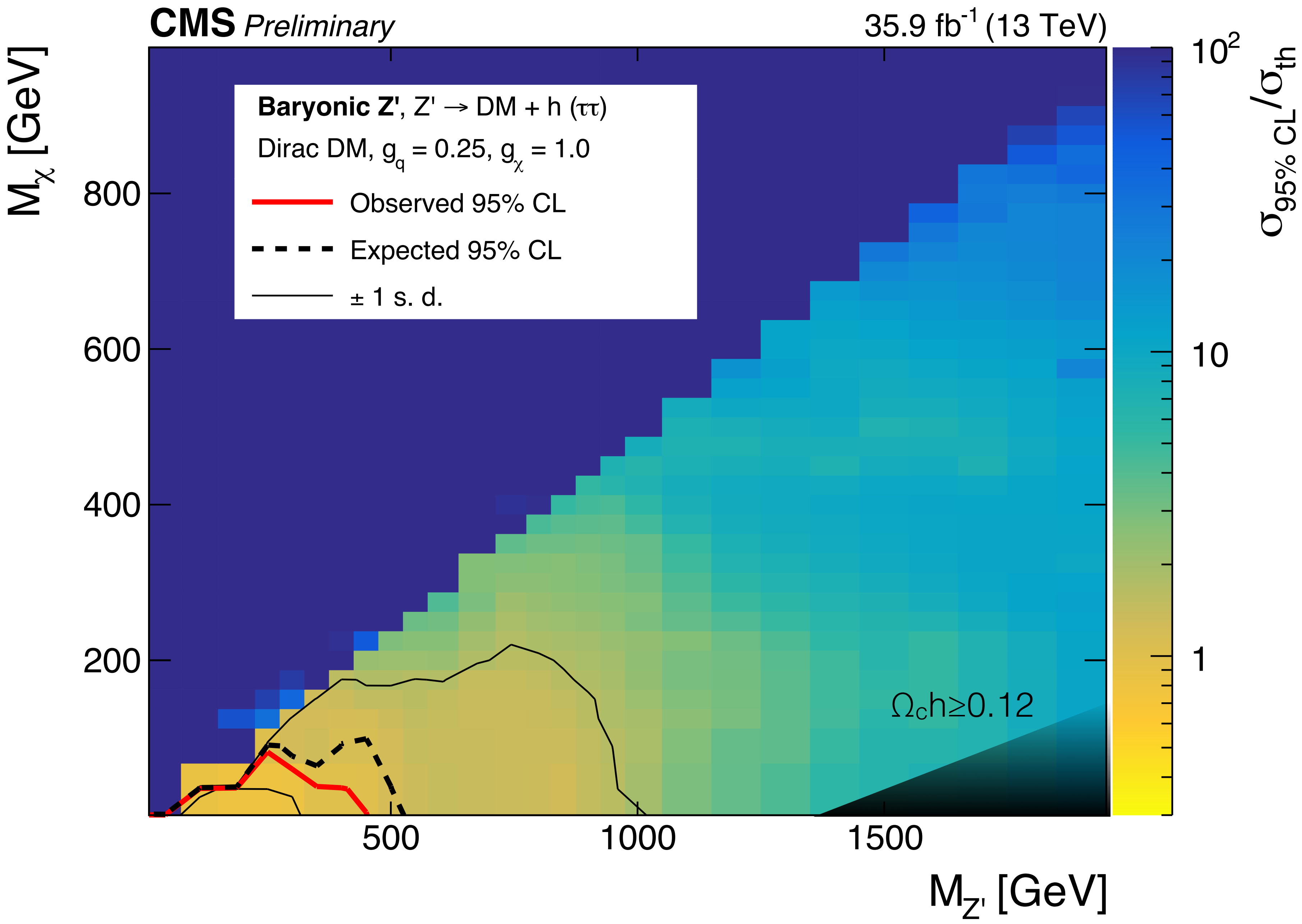


γγ 2σ deviation wrt to standard model in low pt miss

U(1)B Model Exclusion



No significant excess compared to SM expectation

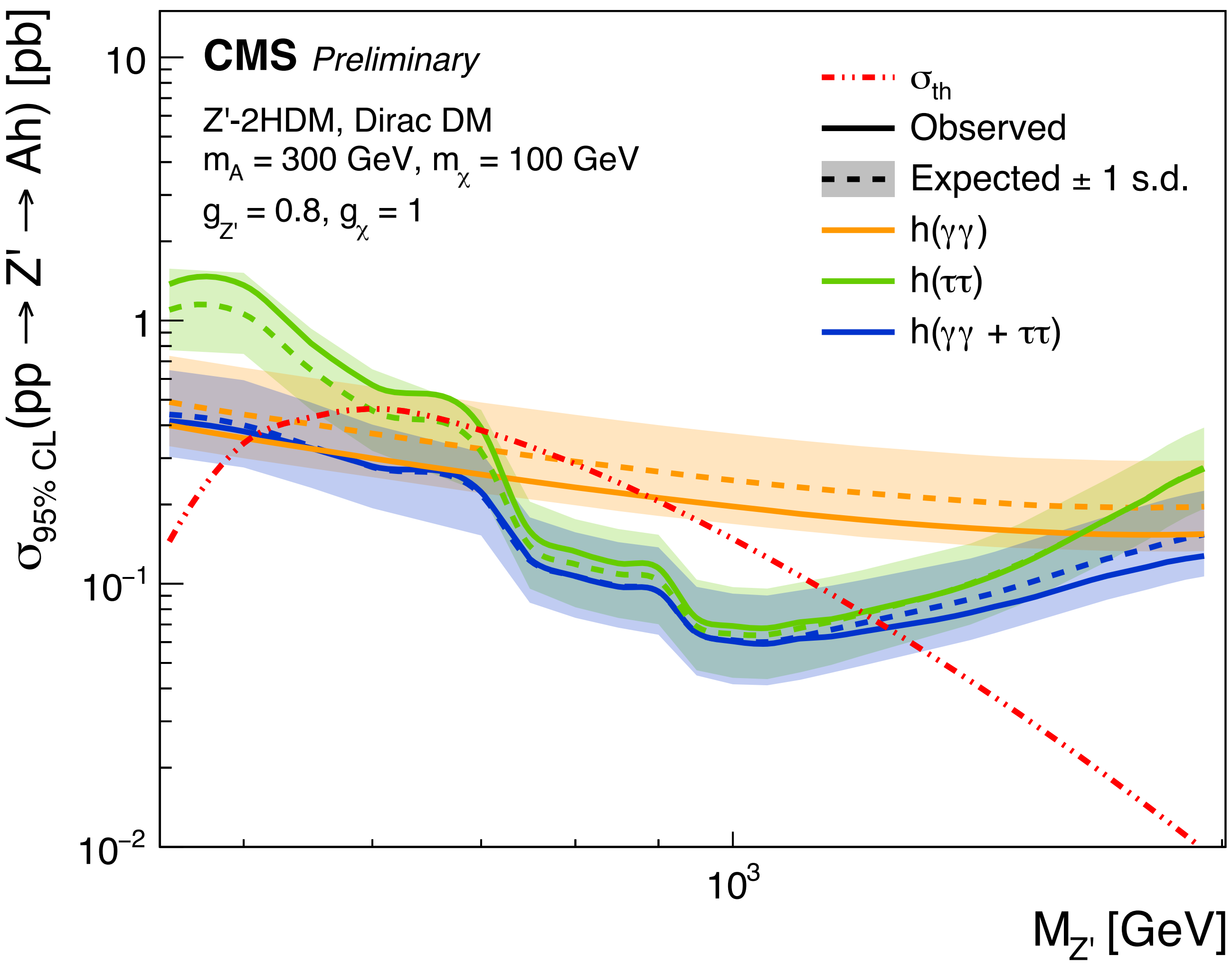


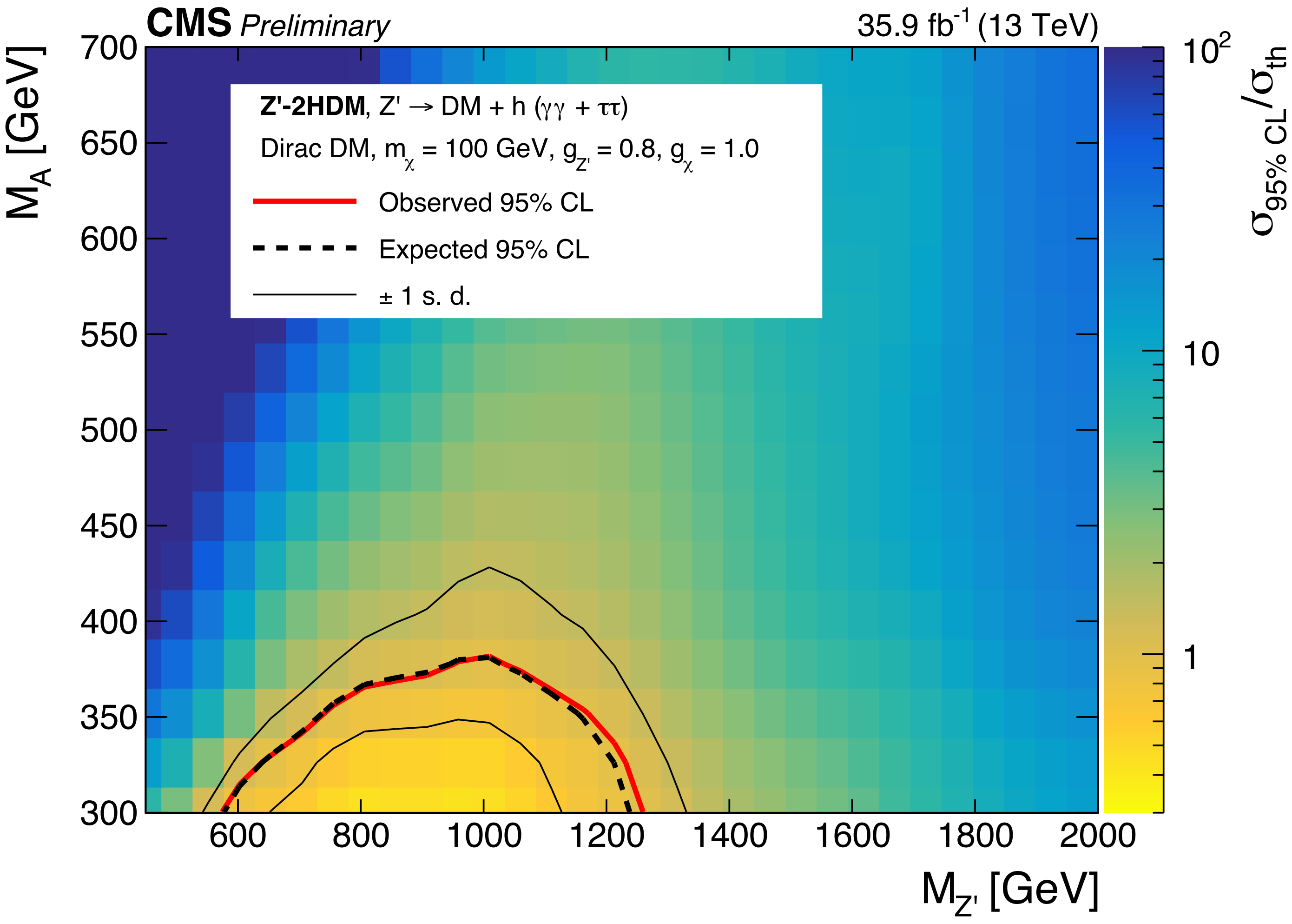
mDM = 1 GeV, Z' masses up to ~475 GeV are excluded

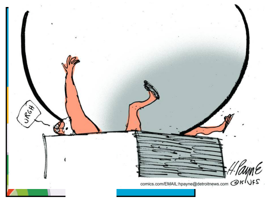
ττ+γγ Combination: Z’-2HDM

ττ+γγ are combined. The similar/complementary sensitivity
∴ there are gains when combined

combination of γγ+ττ increases exclusion:
$M_{Z'}$ ={600 -1265 GeV}
and M_A={300-400 GeV}



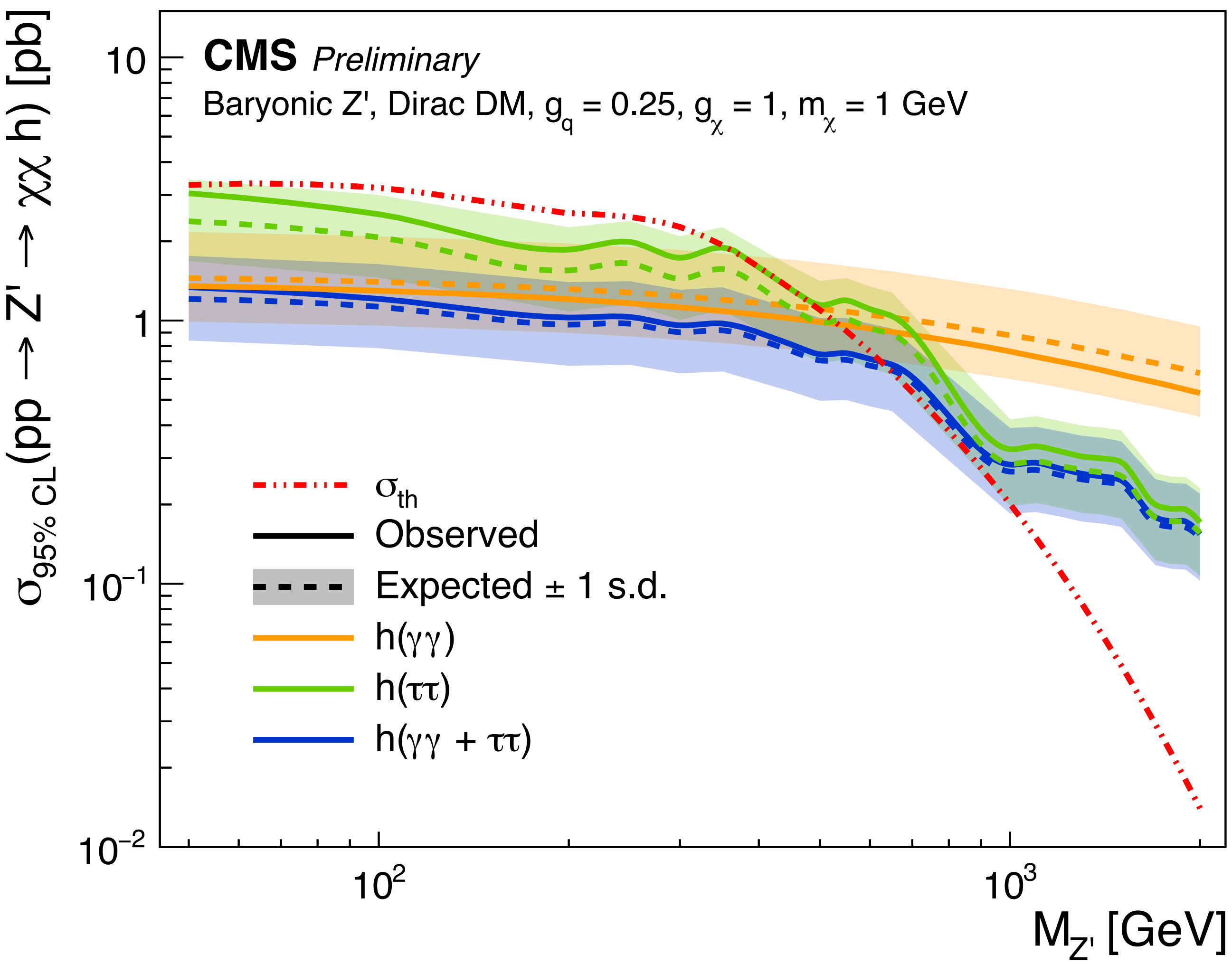


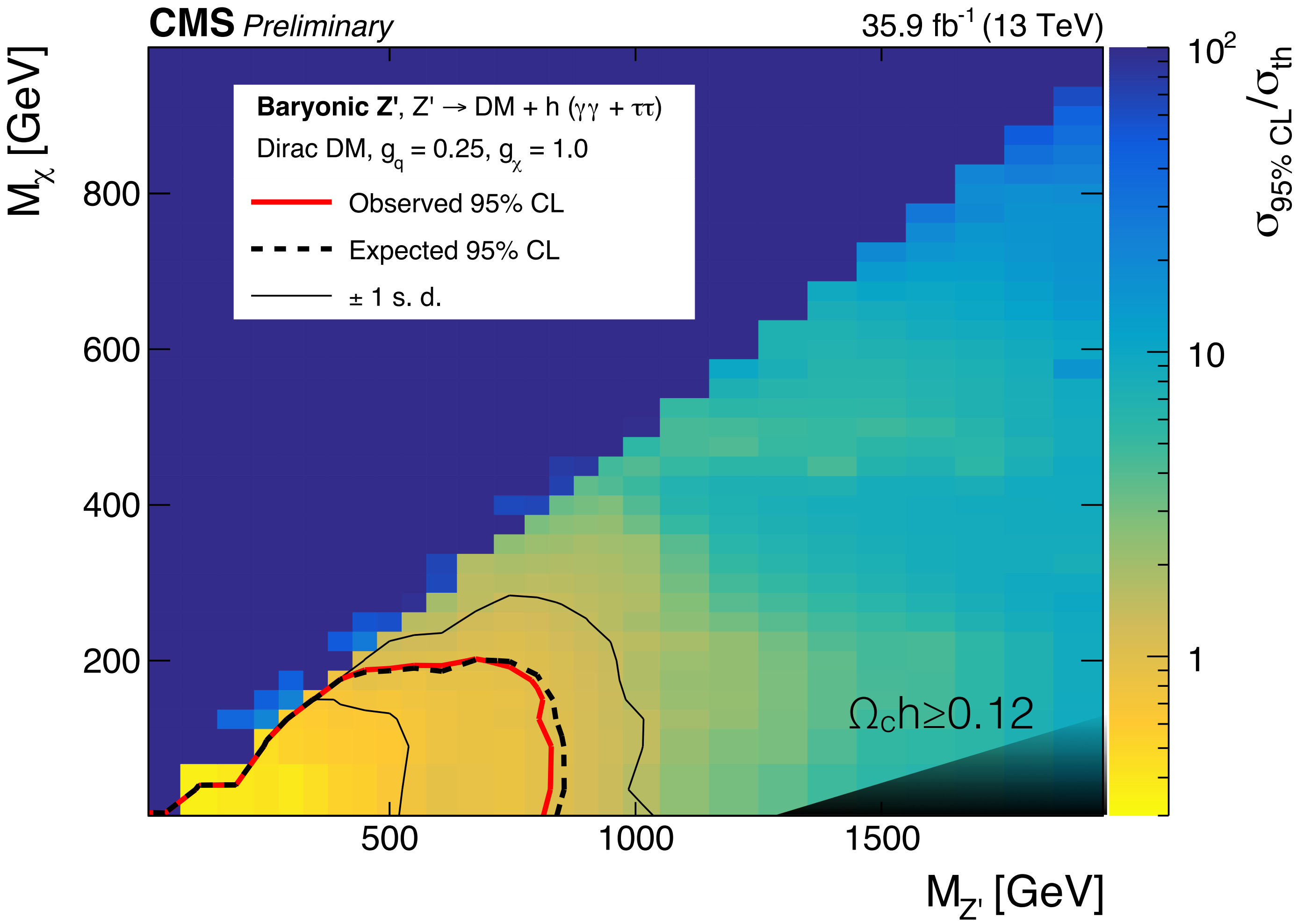


ττ+γγ Combination: U(1)B

ττ+γγ are combined. The similar/complementary sensitivity ∴ there are gains when combined

combination of γγ+ττ increases exclusion: mDM = 1 GeV, Z' masses up to 815 GeV are excluded





Higgs Combination ϰ framework

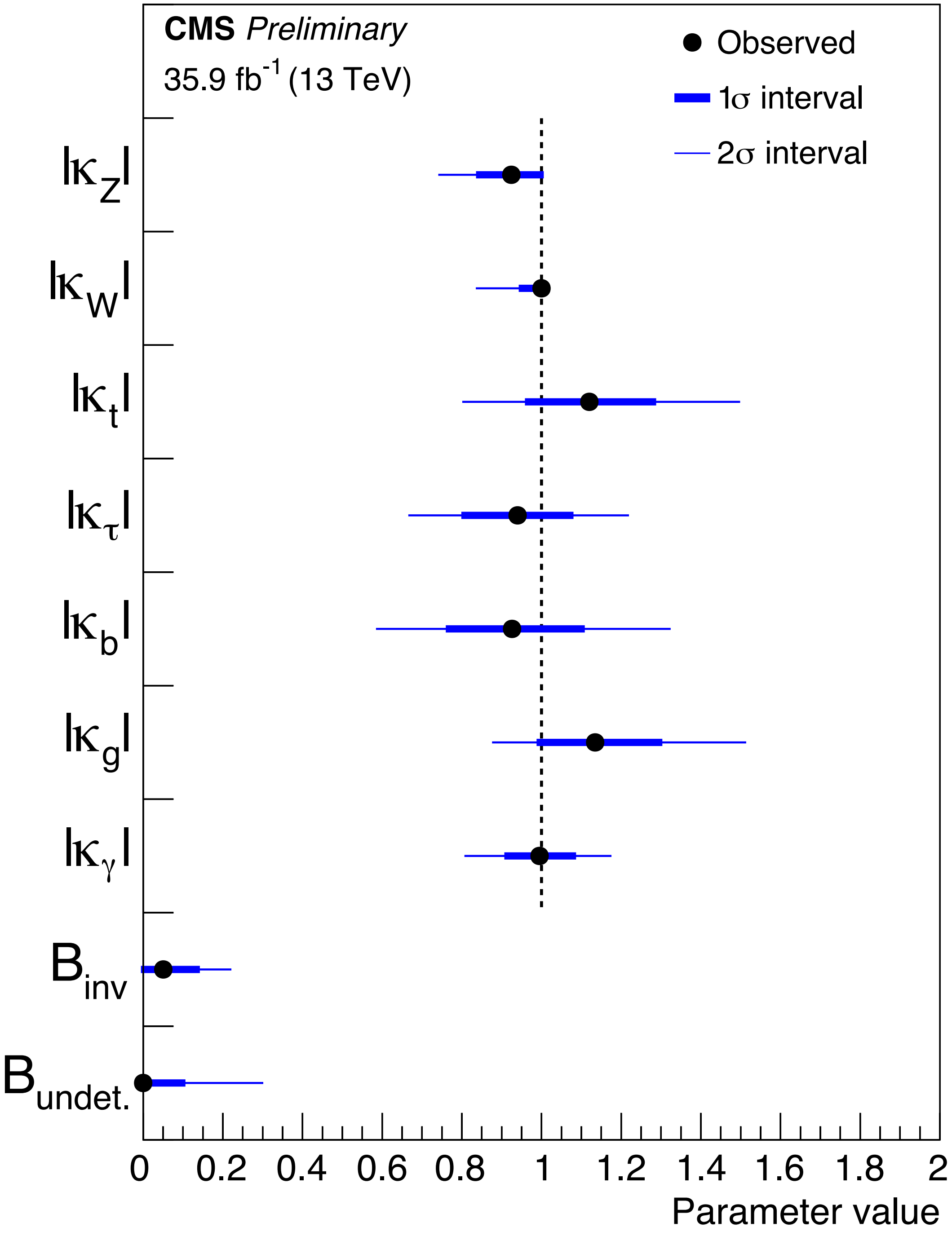
assume

no new particles in ggH production loop or in H→γγ decay loop

↓

add

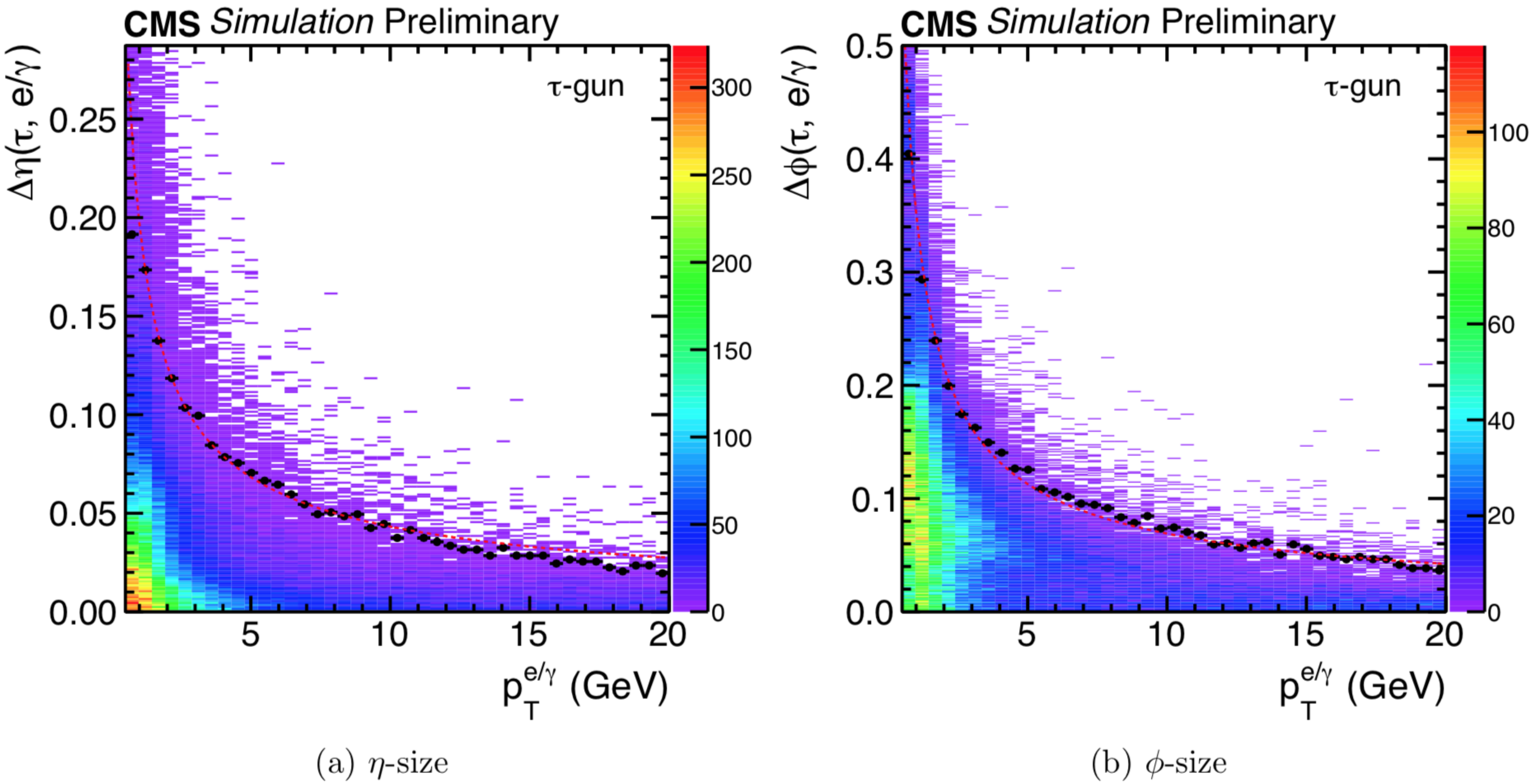
coupling modifiers ϰ



Hadronic Tau Identification: Envelope

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

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



(a) η-size

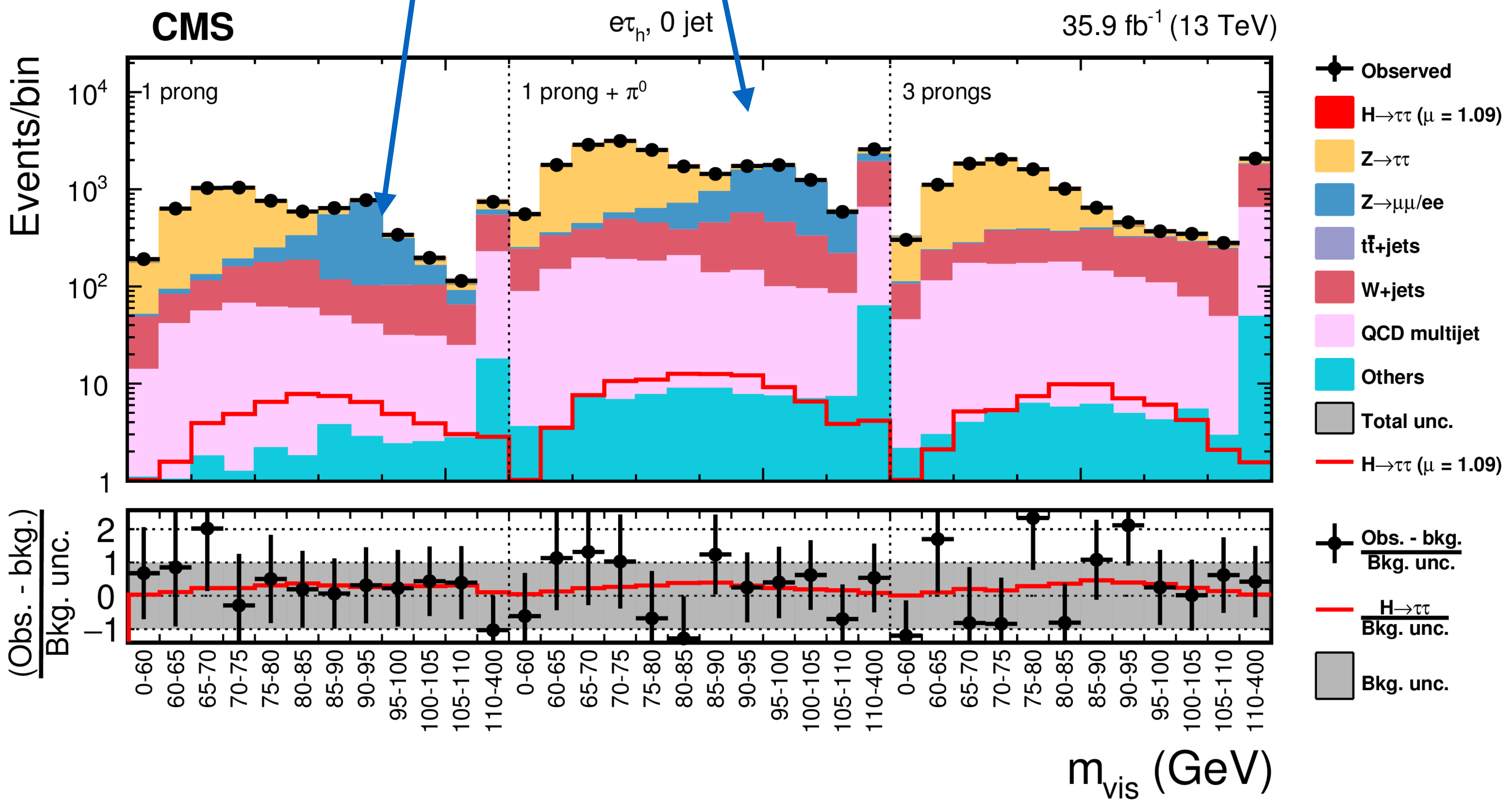
(b) ϕ-size

Visible Mass versus τ Decay Mode

“0 jet eτ visible mass versus τ decay mode”

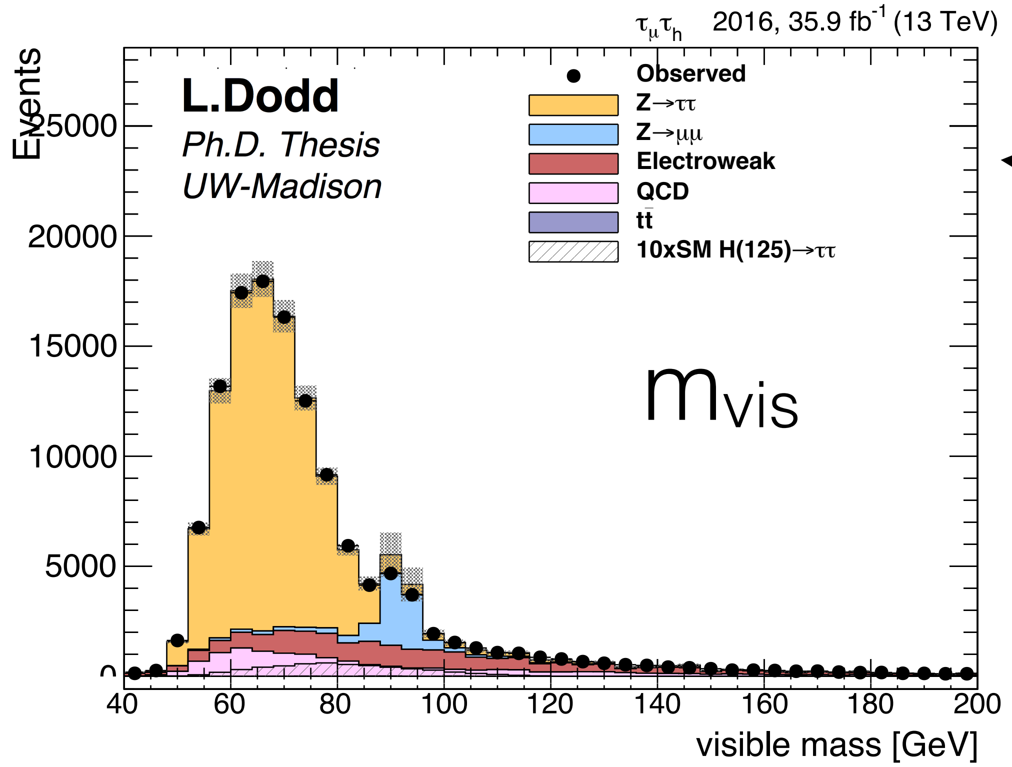
misidentified e
large DY contribution

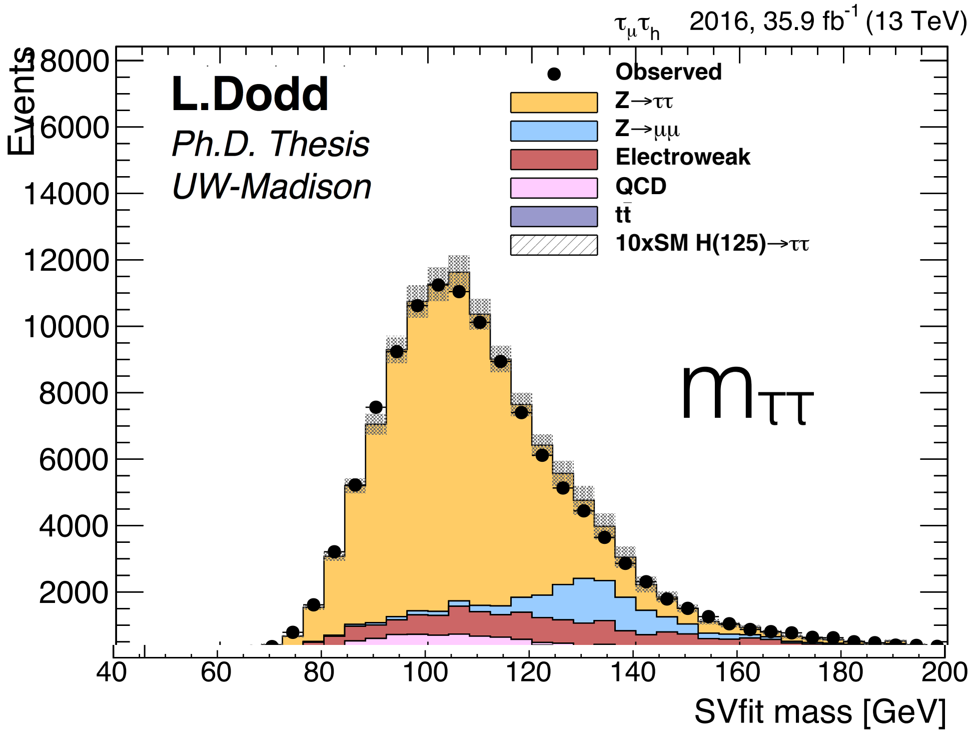
decay mode separation allows for constraint on fake backgrounds



visible mass: tau decay mode

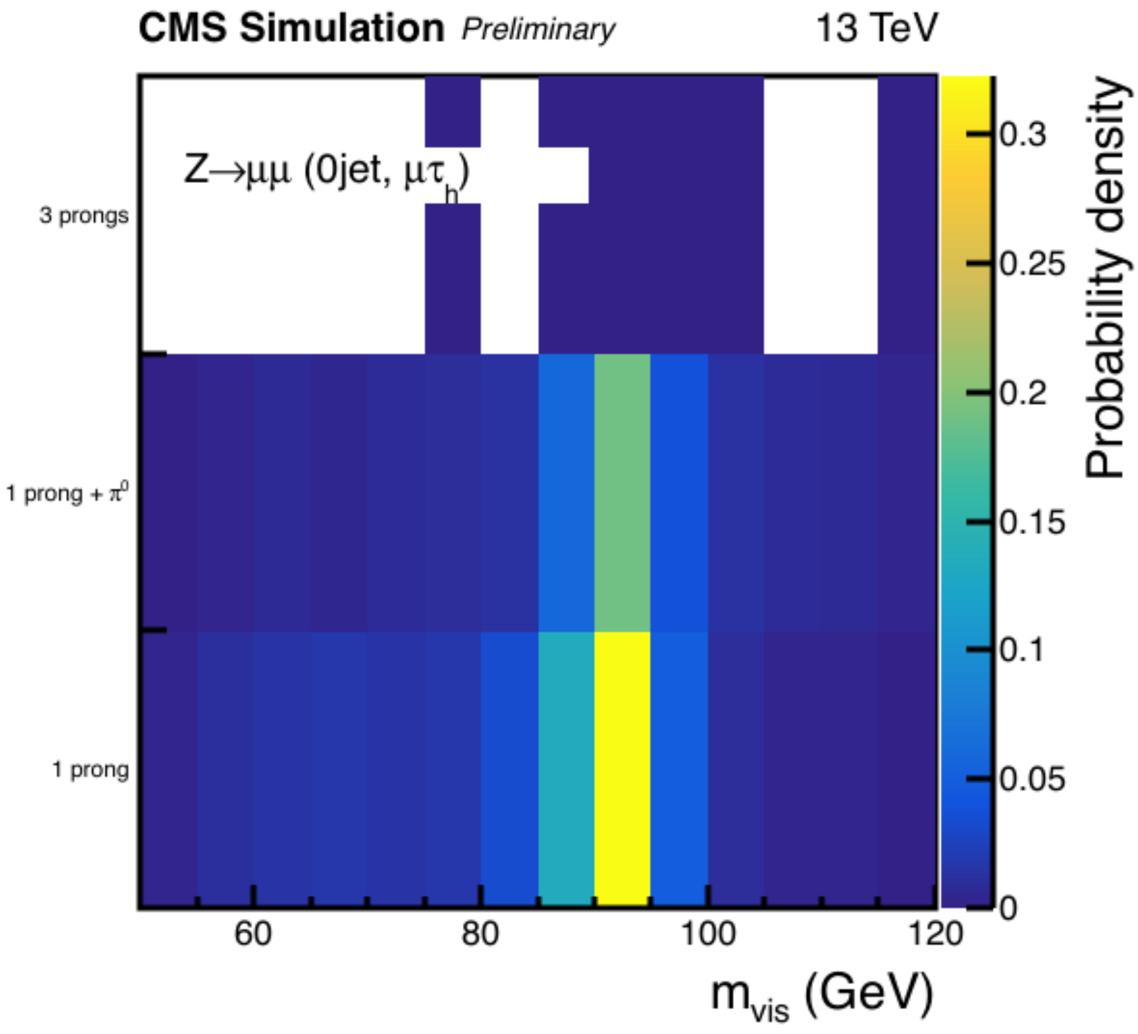
	μτ	eτ
0jet	m_{vis}:τ DM	m_{vis}:τ DM





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

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

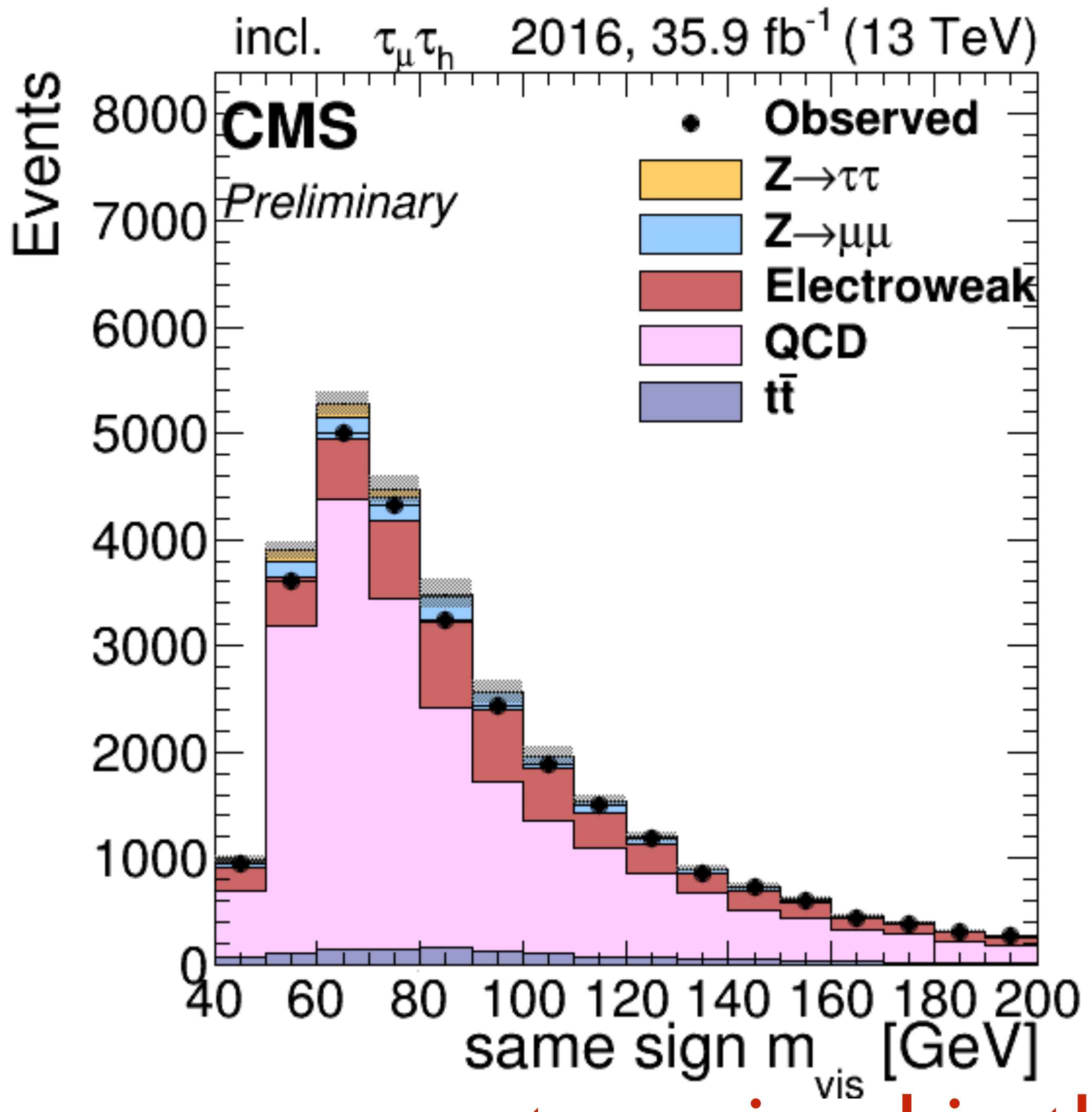


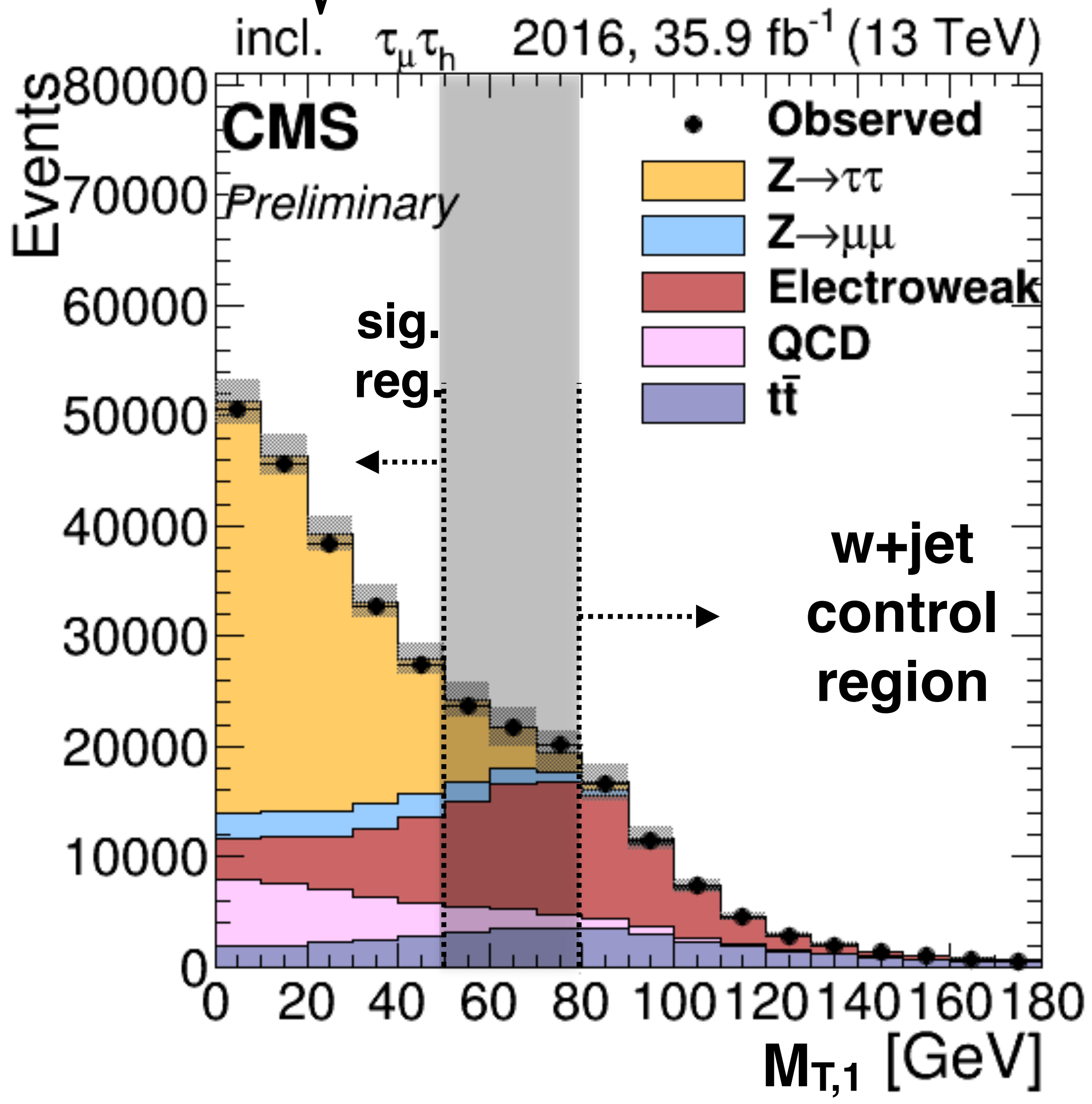
Background Methods II

$\ell\tau$: QCD estimate is taken from same-sign region and scaled by factor to go to opposite-sign region

$\ell\tau$: 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

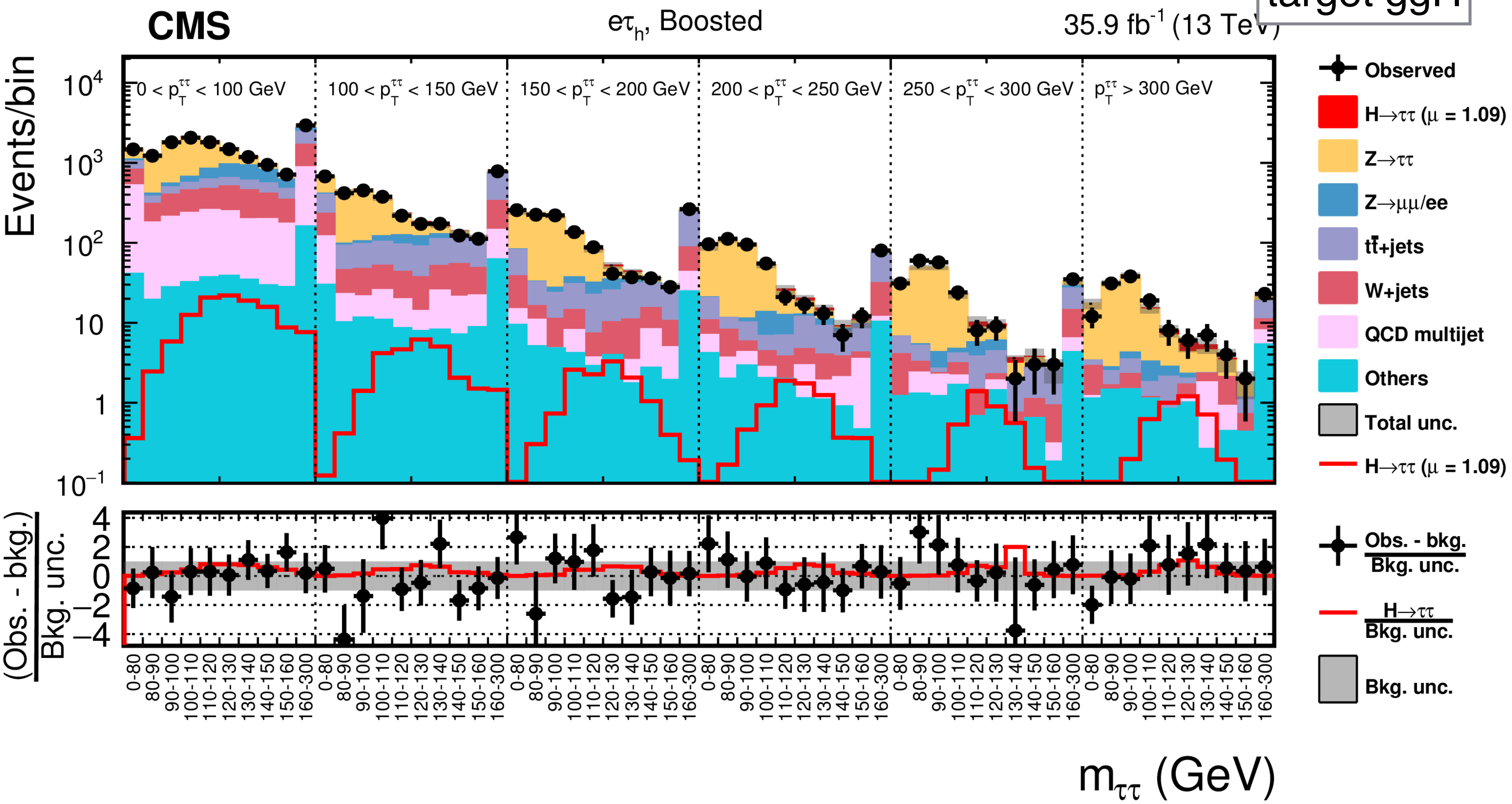
- Vetoing extra leptons, and requiring well-isolated objects results in the largest increase in purity and decrease of overall rate.
- Expect signal to make up **0.2% of observed collisions passing criteria**
- **Next increase sensitivity of analysis using $m_{\tau\tau}$ reconstruction techniques and categorization**

Channel	$\tau_\mu\tau_h$	$\tau_e\tau_h$
collected $\tau\tau$ events	**492668**	**171301**
vector boson fusion	109.9	39.6
gluon gluon fusion	1140.7	356.0

$m_{\tau\tau}$ versus higgs pt

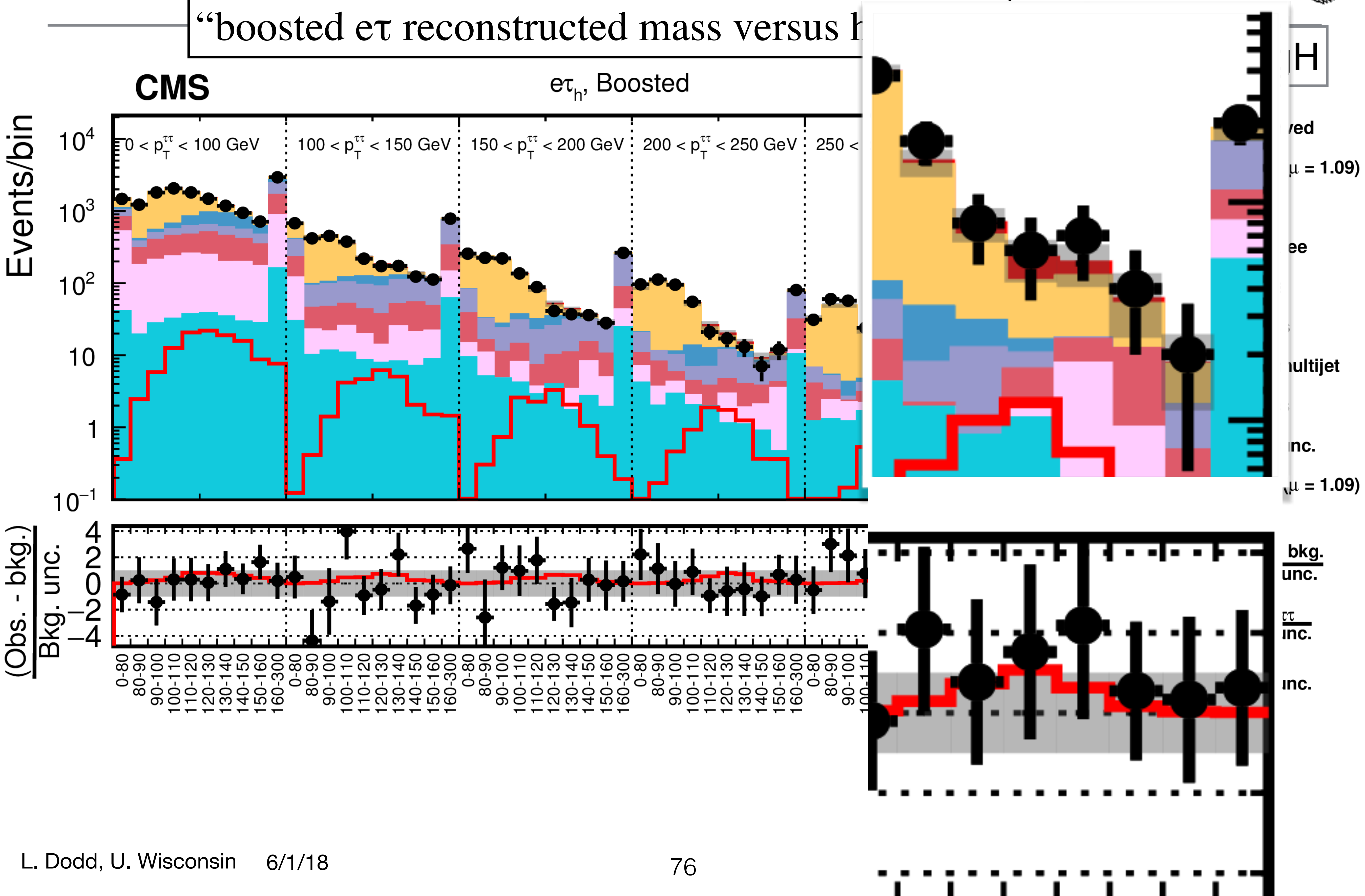
“boosted eτ reconstructed mass versus higgs pt”

target ggH



$m_{\tau\tau}$ versus higgs pt

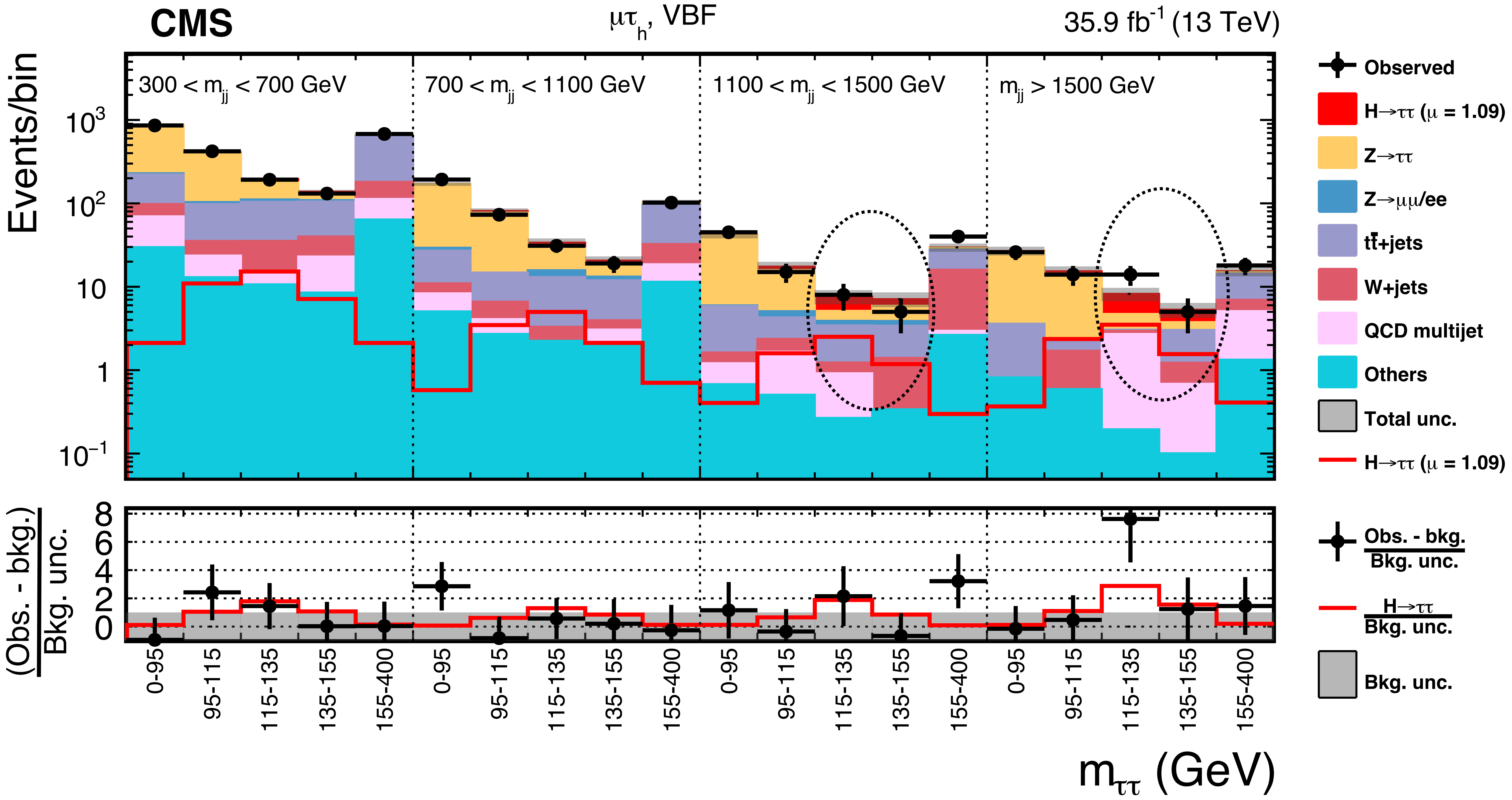
“boosted eτ reconstructed mass versus h



$m_{\tau\tau}$ versus 2-jet mass

“vbf μτ mττ versus dijet mass”

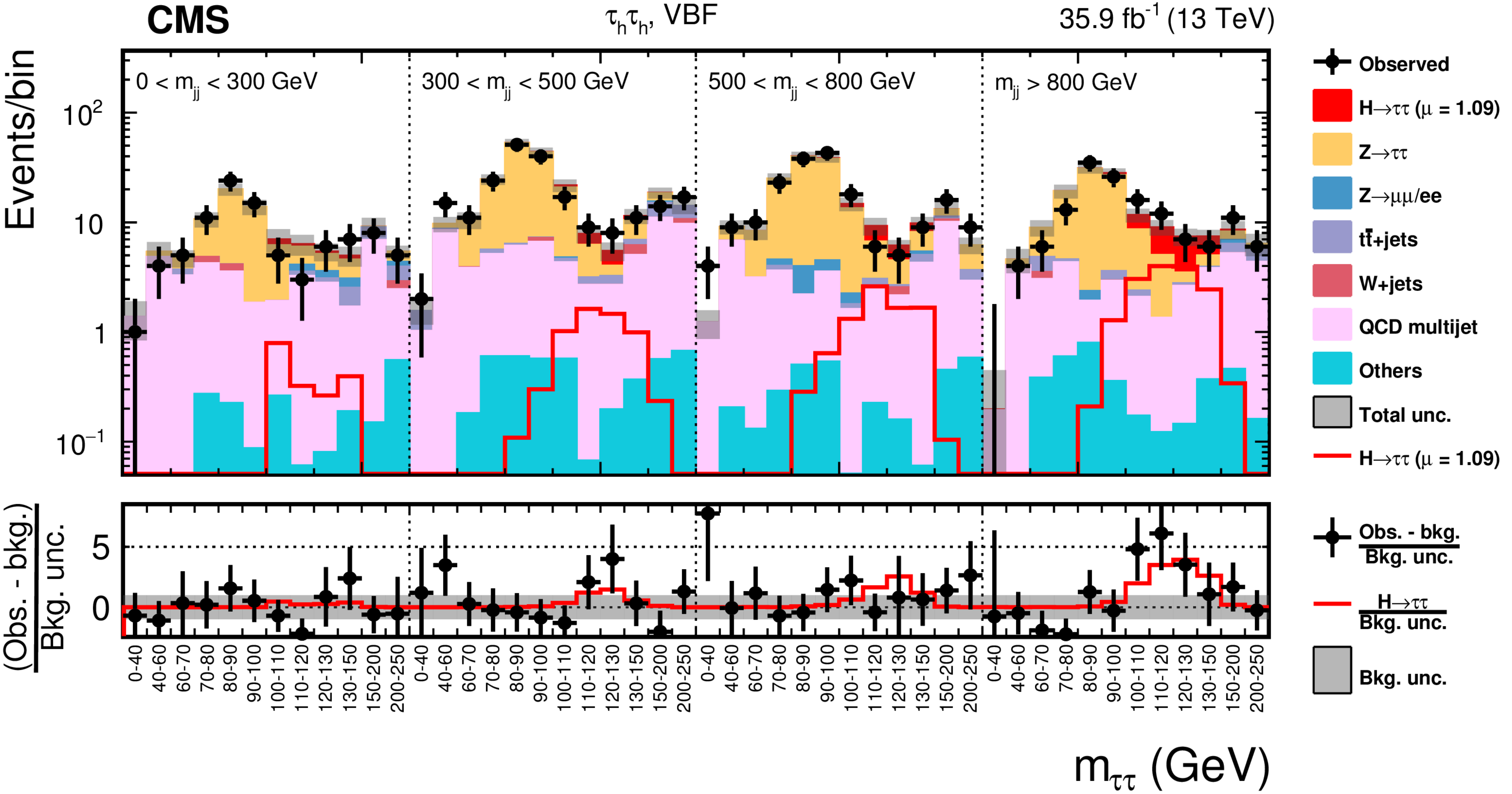
vbf category
rich in SM Higgs



$m_{\tau\tau}$ versus 2-jet mass

"vbf ττ mττ versus dijet mass"

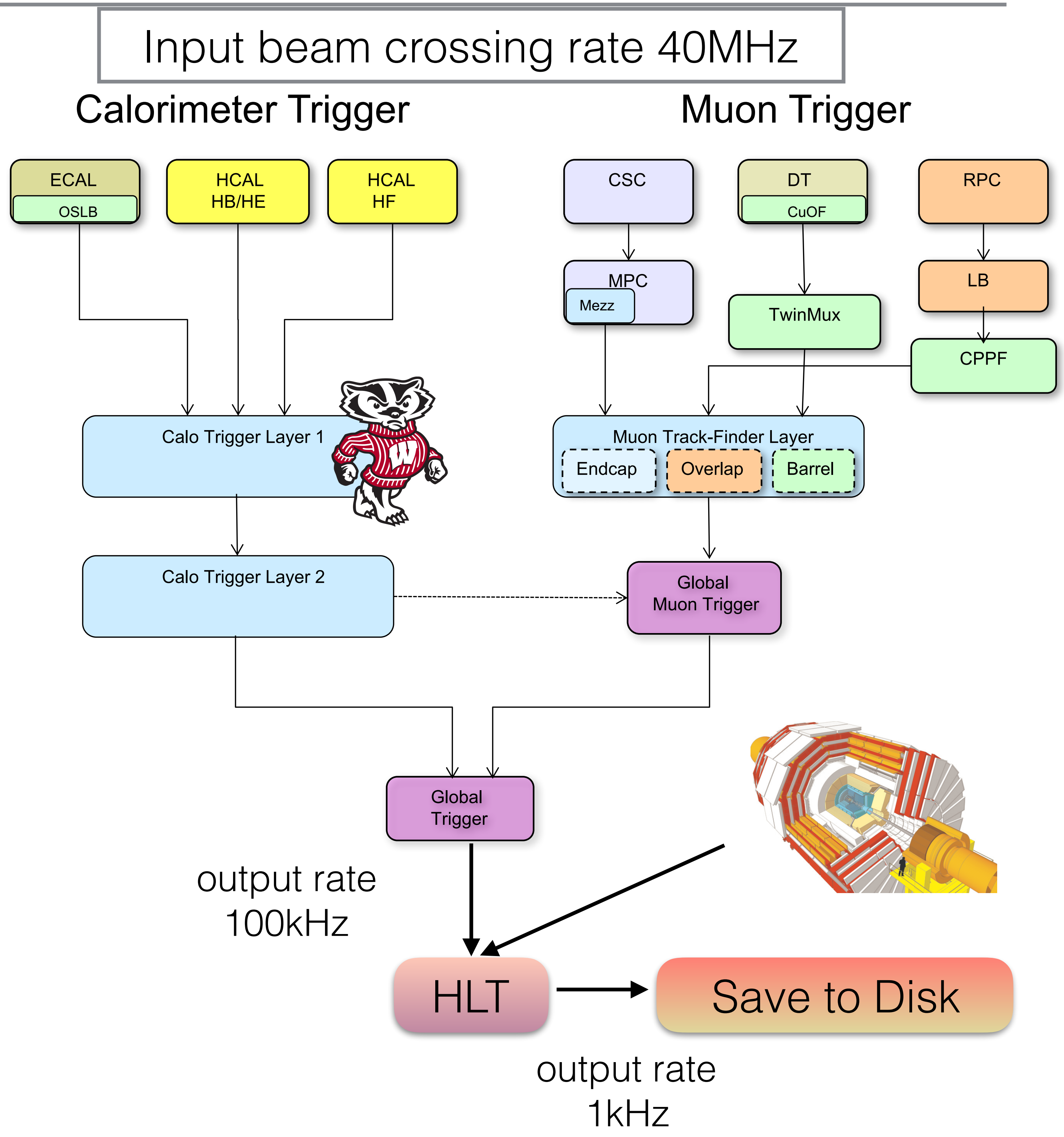
vbf category
rich in SM Higgs



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



Input beam crossing rate 40MHz

Calorimeter Trigger

Muon Trigger

ECAL
OSLB

HCAL HB/HE

HCAL HF

CSC

MPC
Mezz

DT
CuOF

TwinMux

RPC

LB

CPPF

Calo Trigger Layer 1

Muon Track-Finder Layer
Endcap
Overlap
Barrel

Calo Trigger Layer 2

Global Muon Trigger

Global Trigger

output rate 100kHz

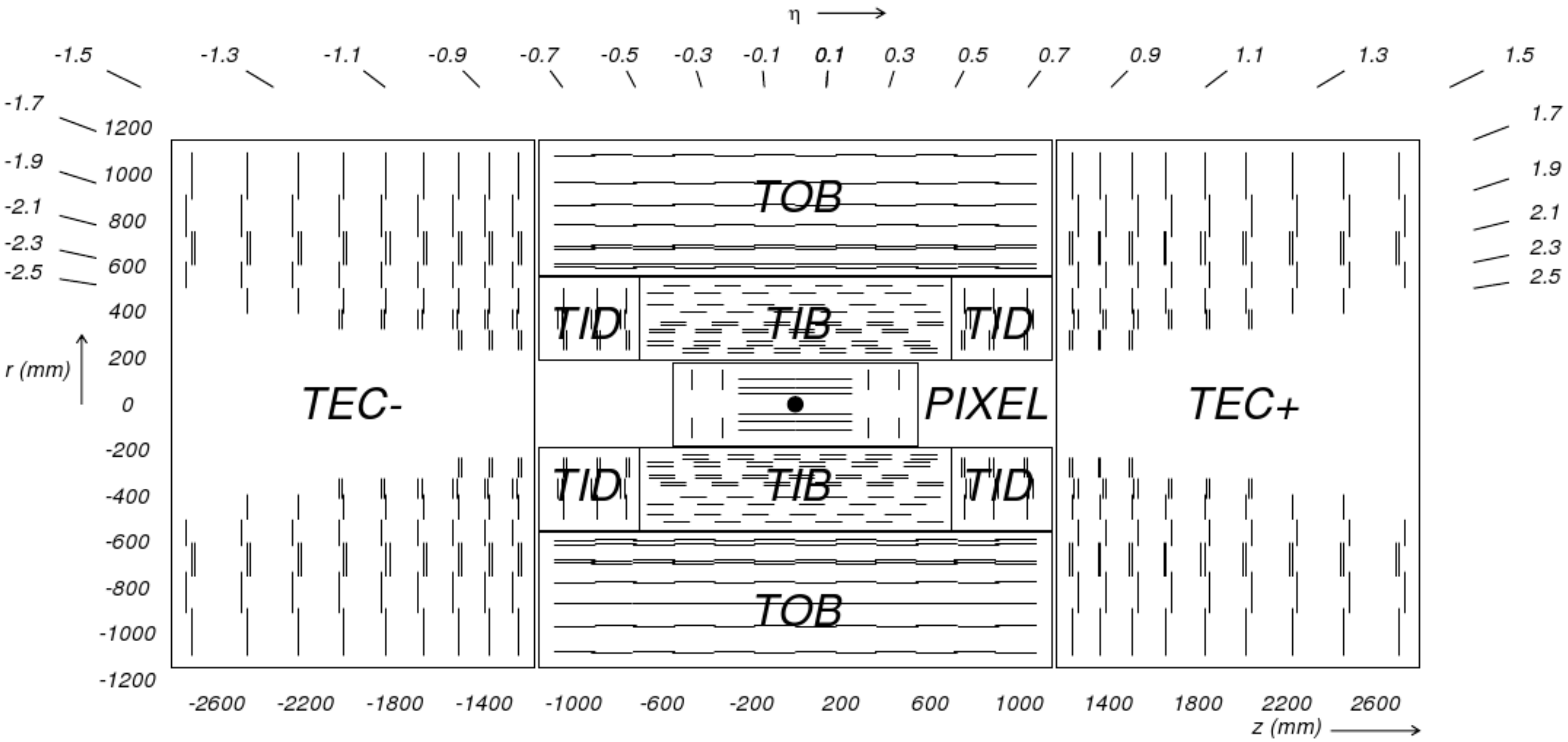
HLT

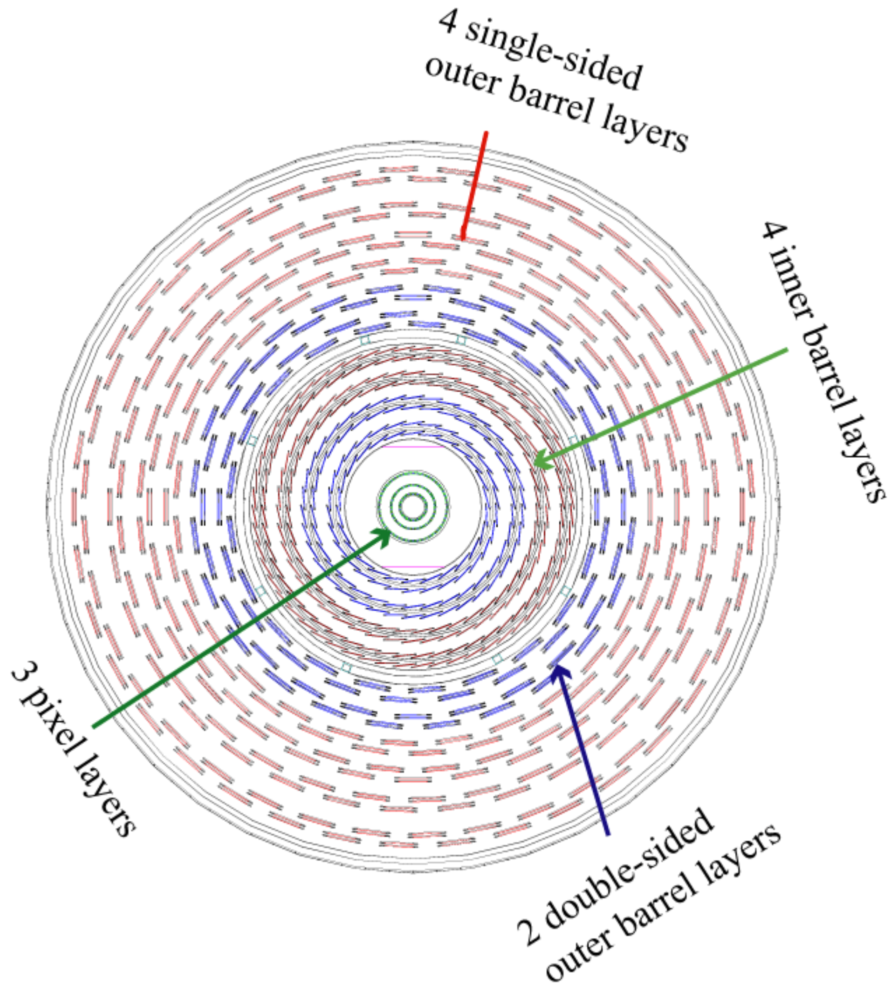
Save to Disk

output rate 1kHz

Tracker

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

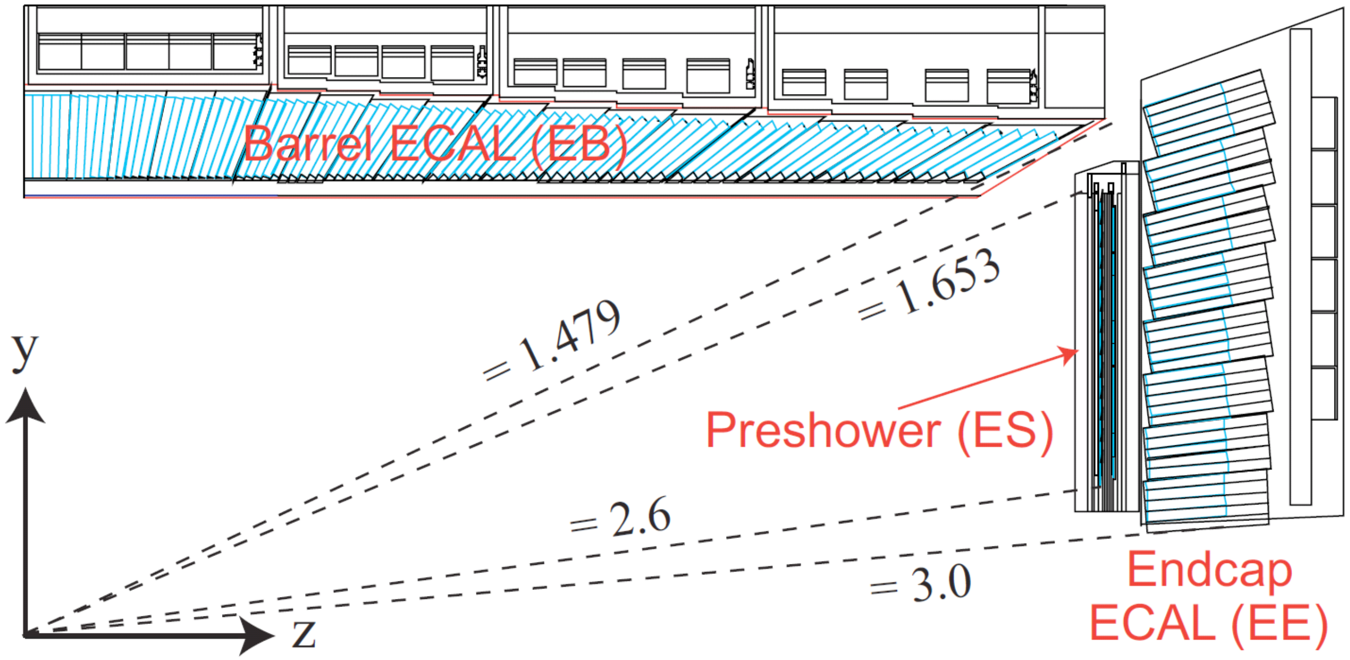




- Silicon tracking system is the first layer within CMS
  - Three pixel barrel layers at 4 cm, 7 cm and 10 cm, and two endcap layers extend to |η|<1.5.
  - The silicon strips outside the pixel extend coverage up to |η|<2.5

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)



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

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

Hadronic Calorimeter

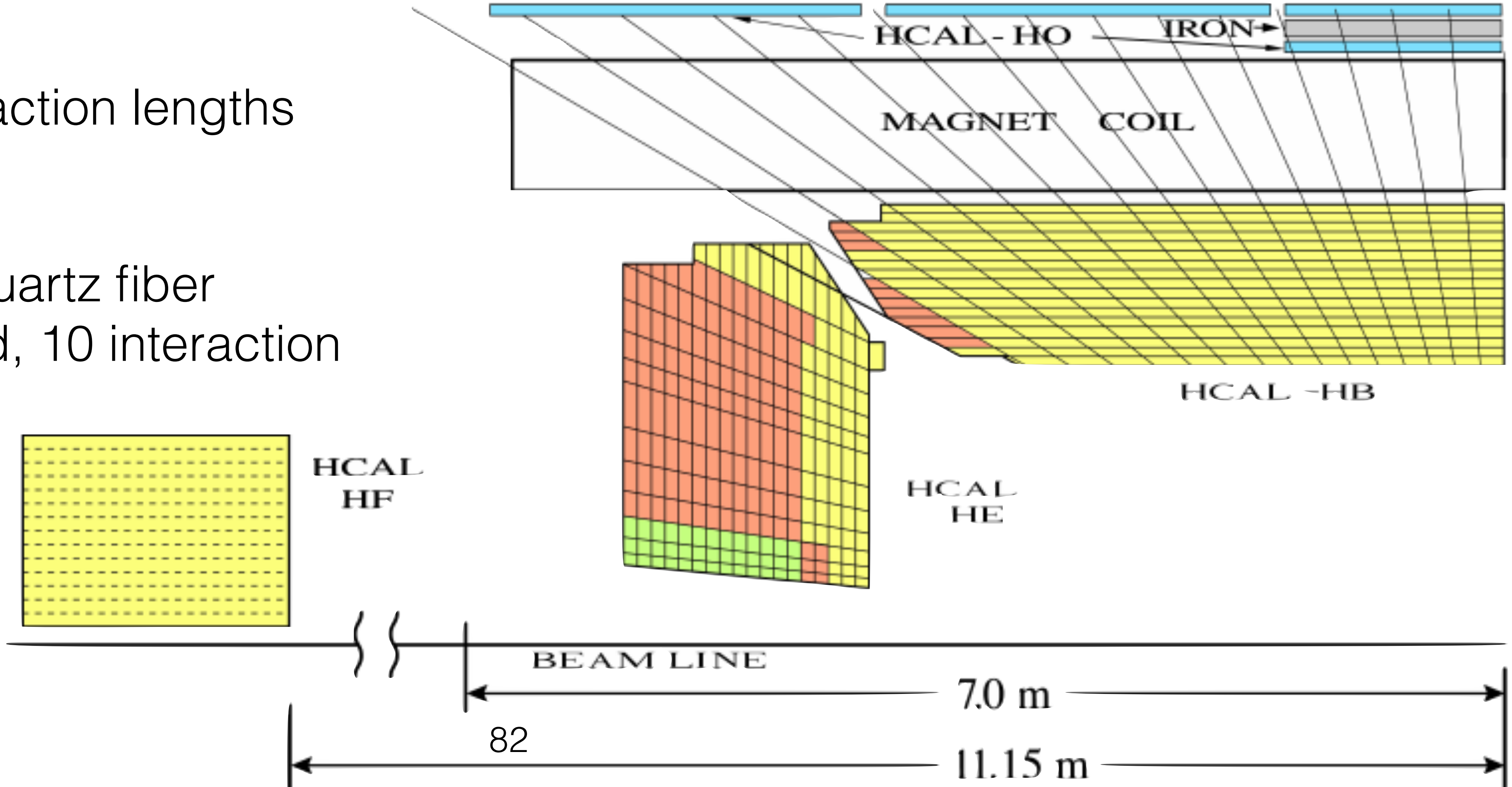
- Extends to |η|<5.2
- Non-ferromagnetic brass absorbers and plastic scintillators for HB/HE
  - 16.42 cm nuclear interaction length, and 1.49 cm radiation length
  - HB is 12 interaction lengths deep
- HF is steel and quartz fiber Cherenkov-based, 10 interaction lengths deep

HB/HE

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

HF

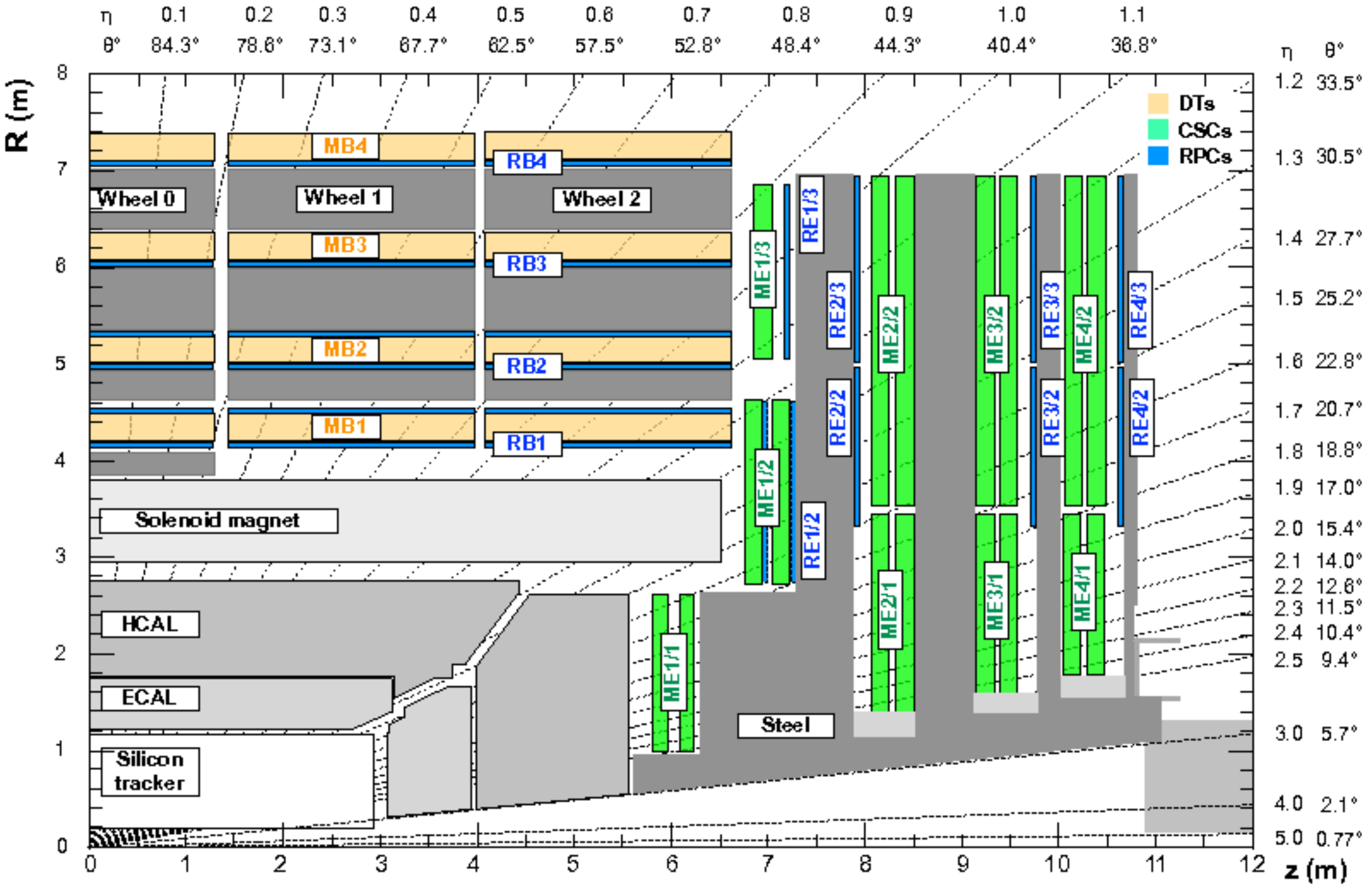
$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{280\%}{\sqrt{E}}\right)^2 + (11\%)^2$$



Muon System

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

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

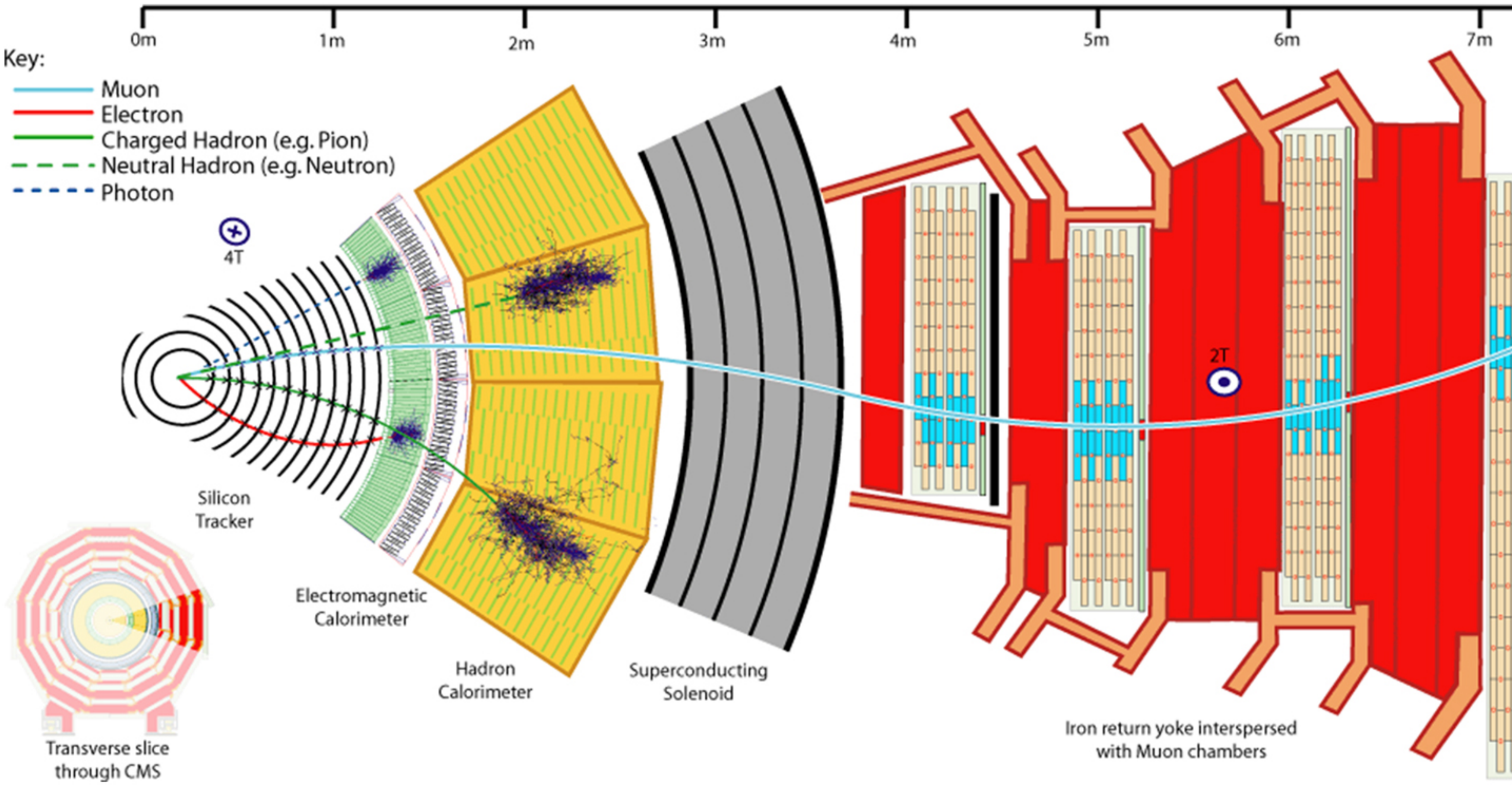


Particle Flow

- 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

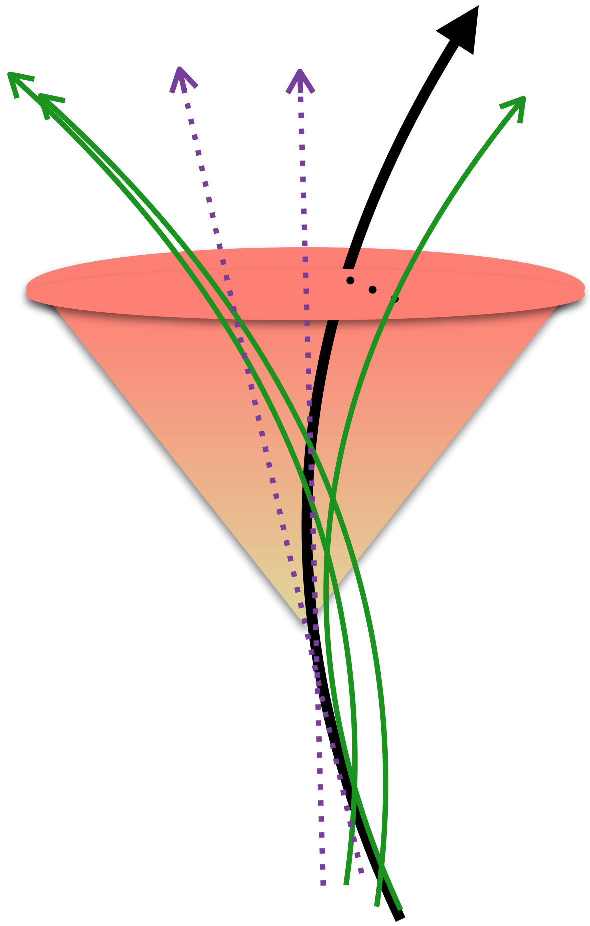
- Muons leave tracks in both the tracker and muon system, with no linked calorimeter deposit
- Muon is identified in both the tracker and the muon system
- **Muons cut based identification >90% efficient**

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

signal isolation cone

charged, neutral

$\Delta R<0.3$ (0.4) for electrons (muons)



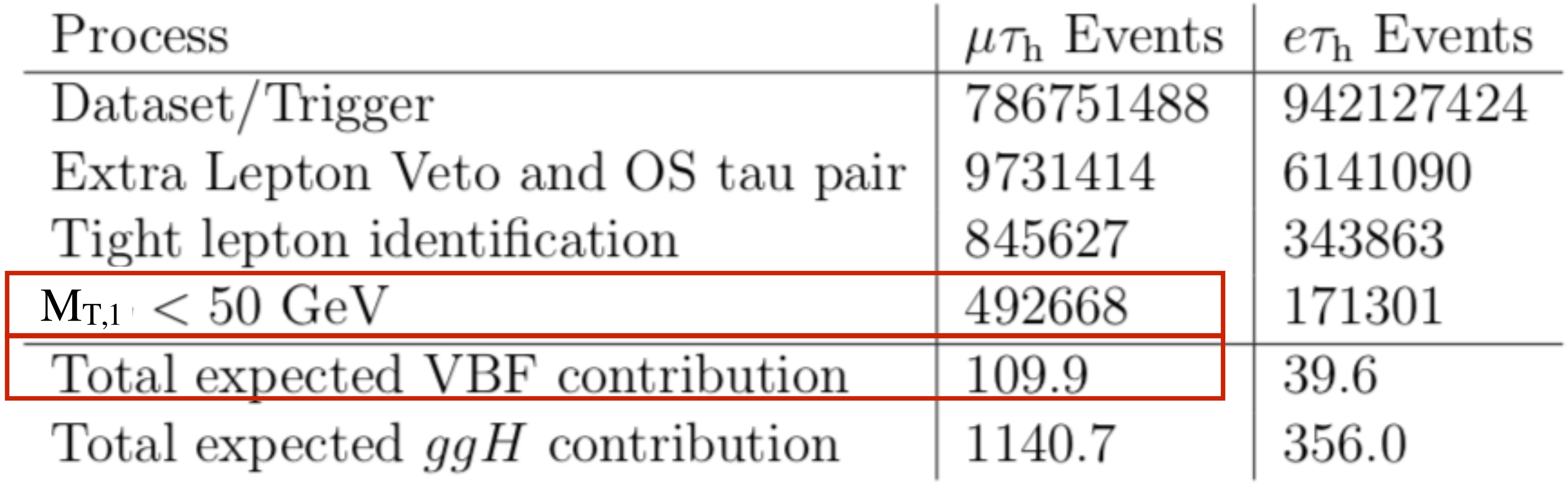
pileup subtraction term

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

Event Selection I

- Vetoing extra leptons, and requiring well-isolated objects results in the largest decrease in events.
- Expect signal to make up 0.2% of collected events

Looking for 109.9 events out of 492668 observed events

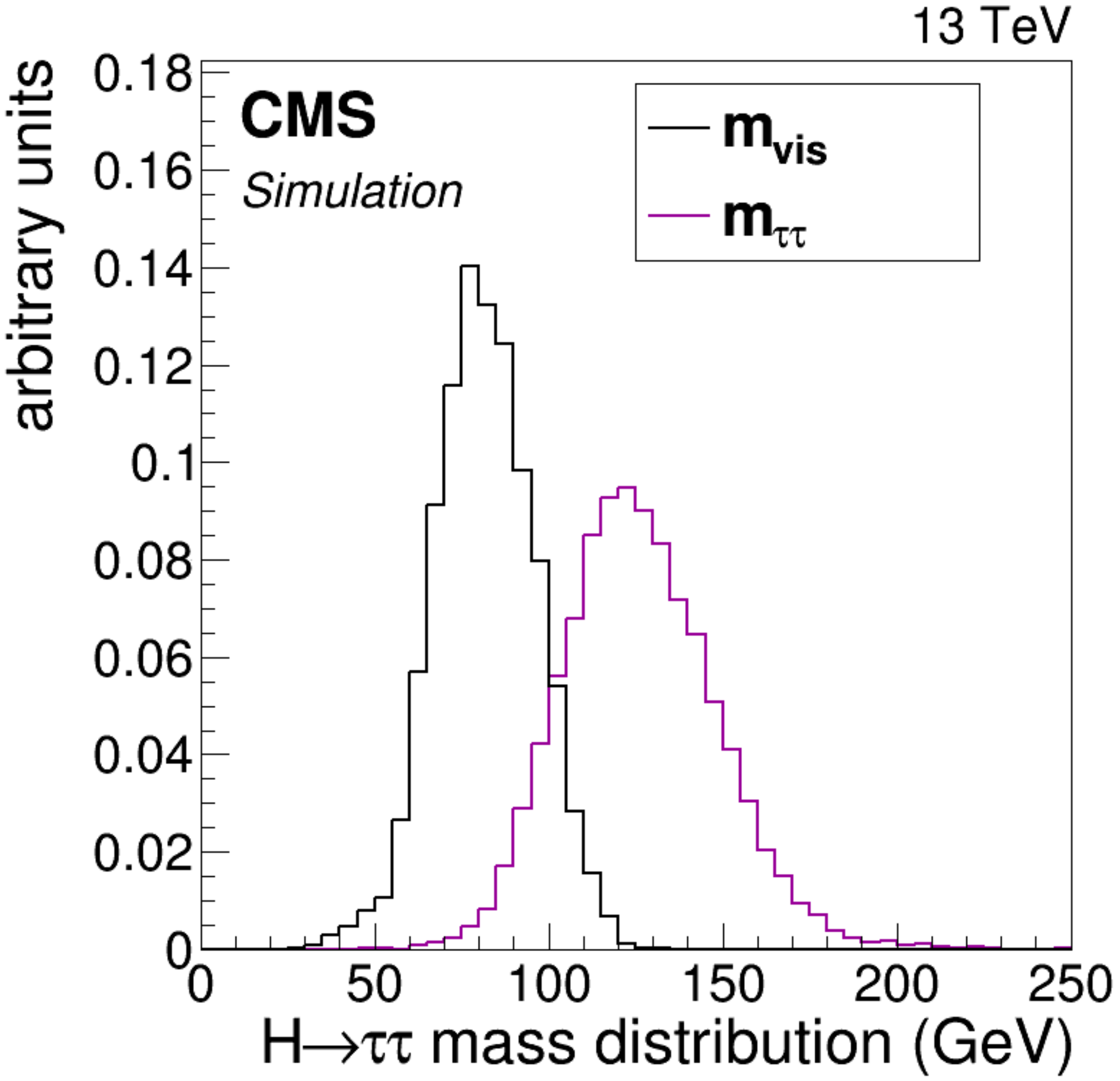


Process	$\mu\tau_h$ Events	$e\tau_h$ Events
Dataset/Trigger	786751488	942127424
Extra Lepton Veto and OS tau pair	9731414	6141090
Tight lepton identification	845627	343863
$M_{T,1} < 50$ GeV	492668	171301
Total expected VBF contribution	109.9	39.6
Total expected ggH contribution	1140.7	356.0

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

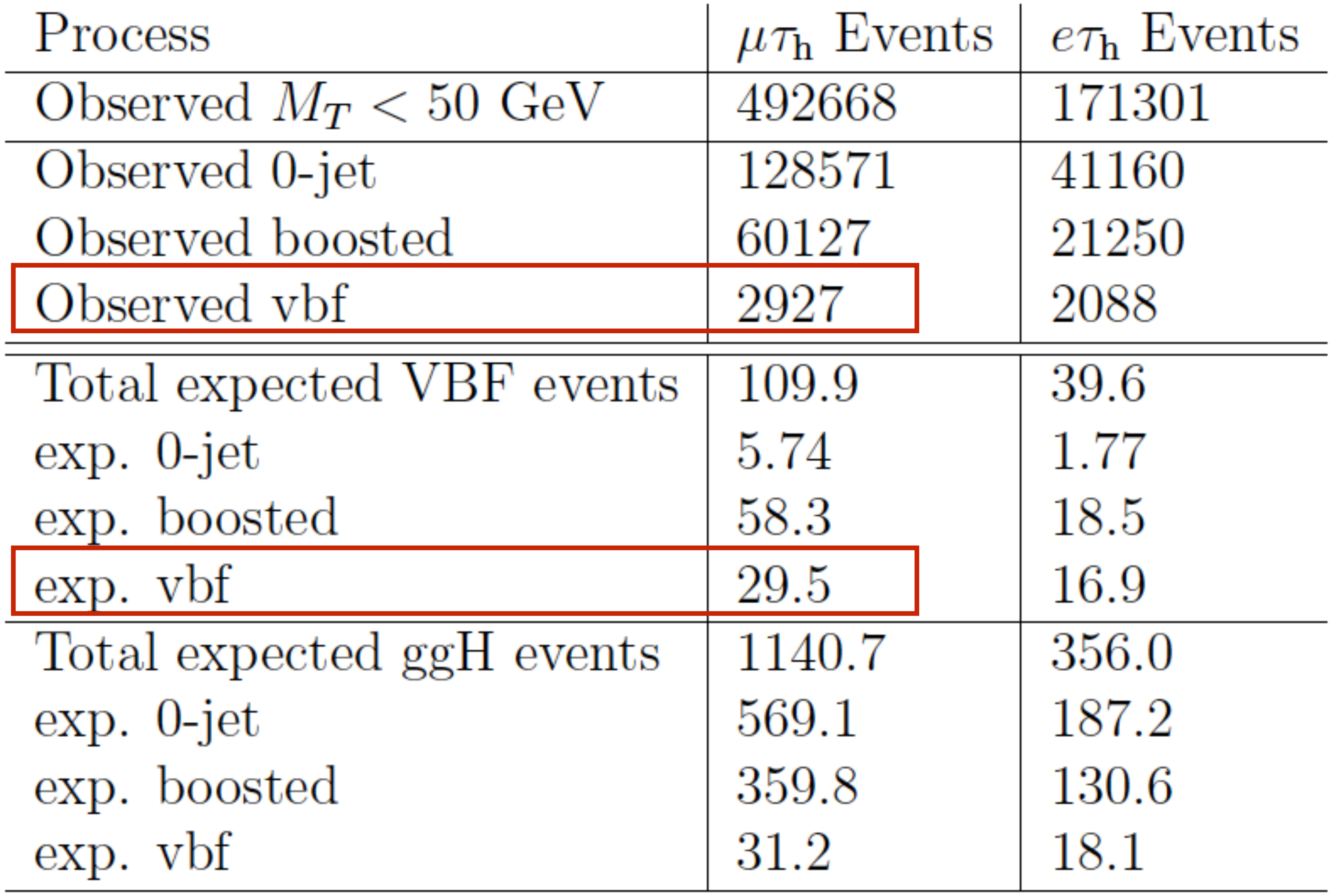
- **The di-tau mass ($m_{\tau\tau}$) is reconstructed using a kinematic fit in most categories**
  - Allows for some separation of Z→ττ and H→ττ, and shifts the H→ττ peak to 125 GeV.
- The kinematic fit takes as input: p_T^{miss}, p_T^{miss} uncertainty, both tau candidate's four vector.
- *It assumes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

given all $\boldsymbol{p_T^{miss}}$ *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}.*



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