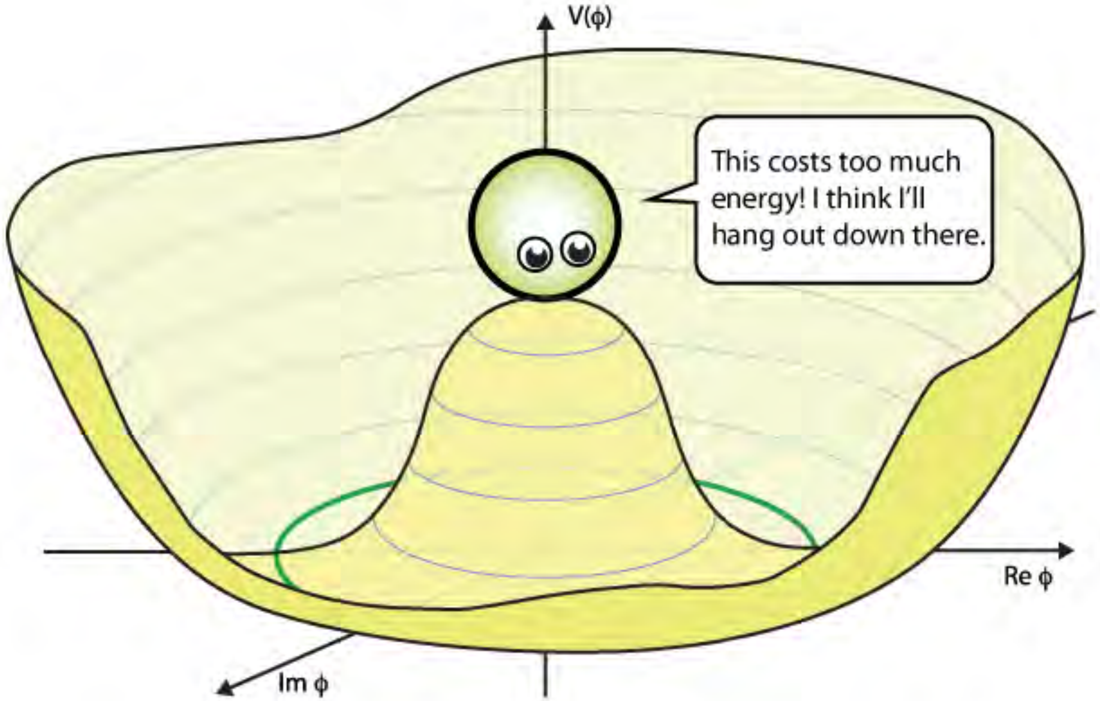
Search for Neutral Higgs Bosons which Decay to tau Pairs



$$\mathcal{L} = |D_\mu \Phi|^2 - \mu^2 \Phi^2 - \lambda \Phi^4$$

For $\mu^2 < 0$, minimum $v = \sqrt{-\frac{\mu^2}{2\lambda}}$

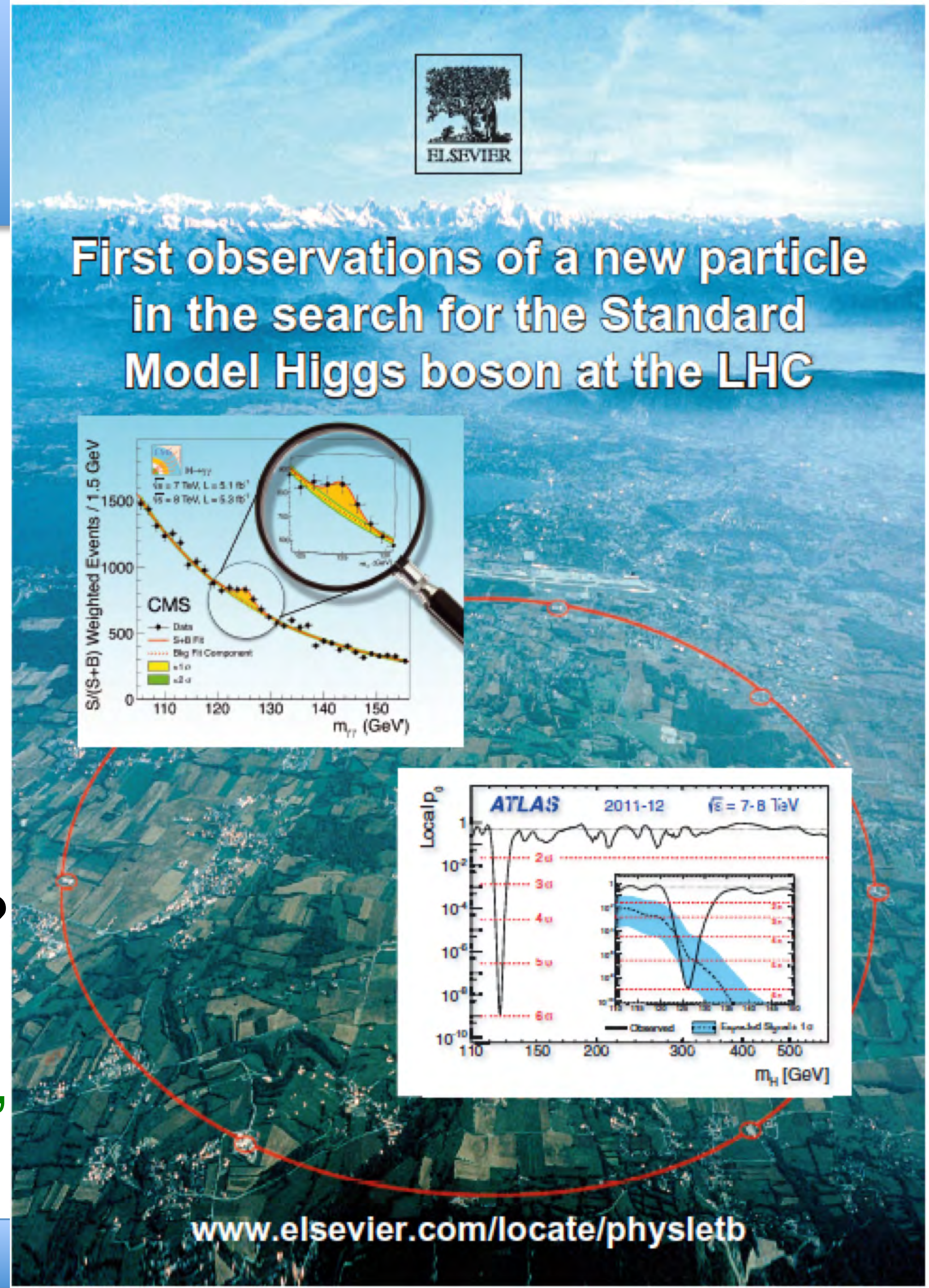
Higgsteria!

The Best of Times
for particle physics!

Is the new boson
the Higgs of SM?

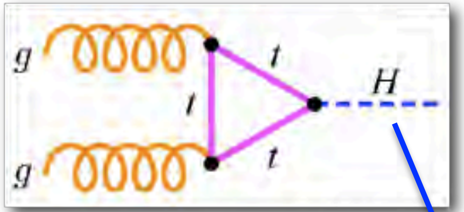
Does the new boson
couple to taus, as it
should if it is SM H?

We have x2 data now,
and good future ☺



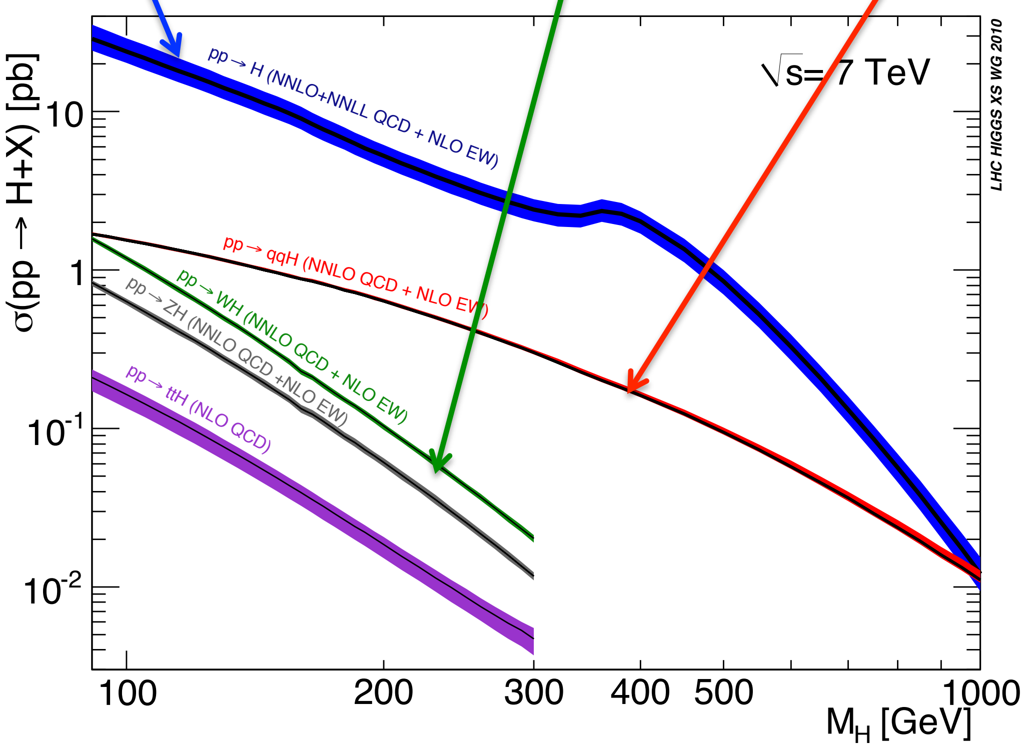
Standard Model Higgs Production

Gluon fusion



Associated Production

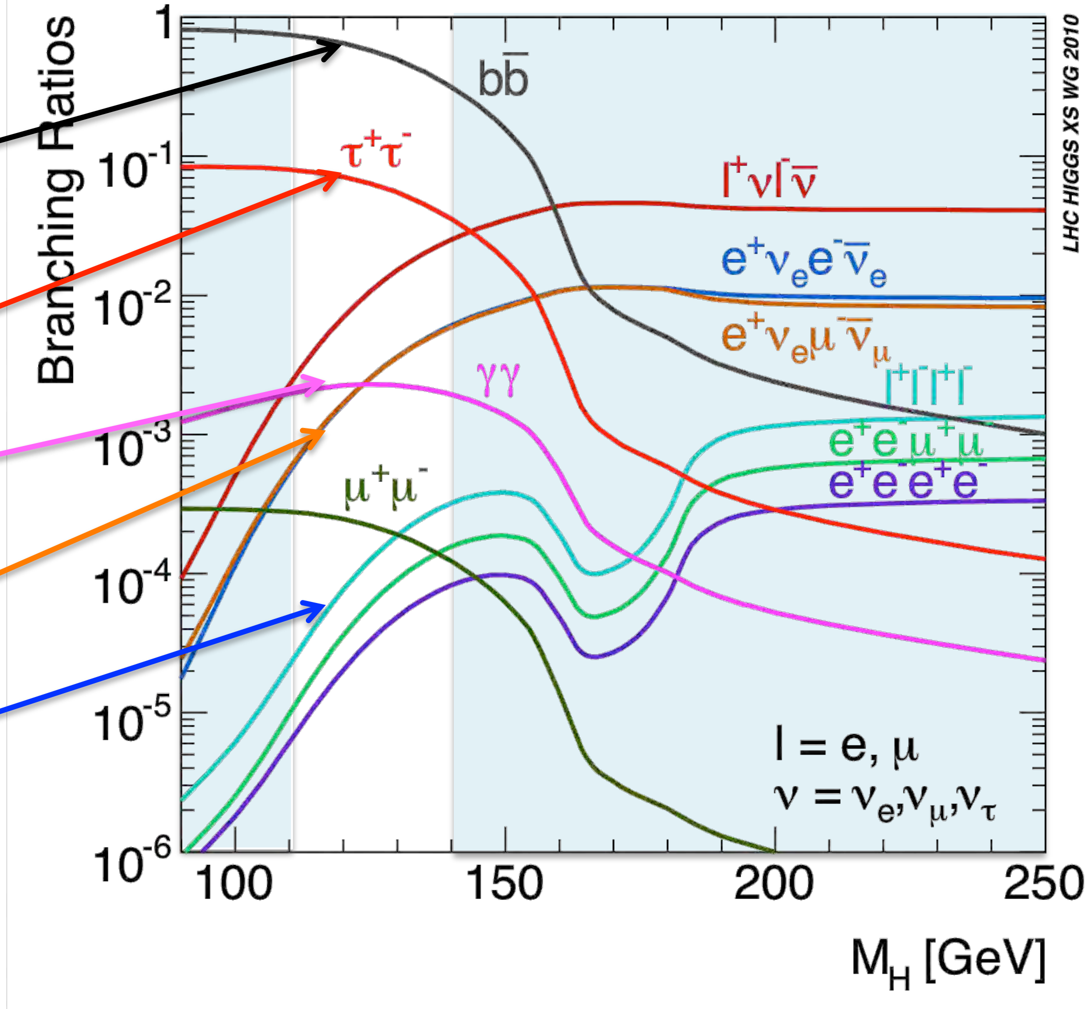
Vector boson fusion



Standard Model Higgs Decay

We search for several Higgs decay channels.

- H → bb
- H → ττ
- H → γγ
- H → WW
- H → ZZ



Cleaner Signal ↓

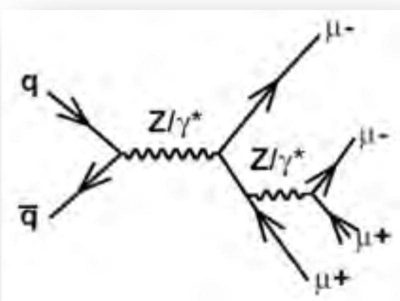
Better Mass Resolution ↓

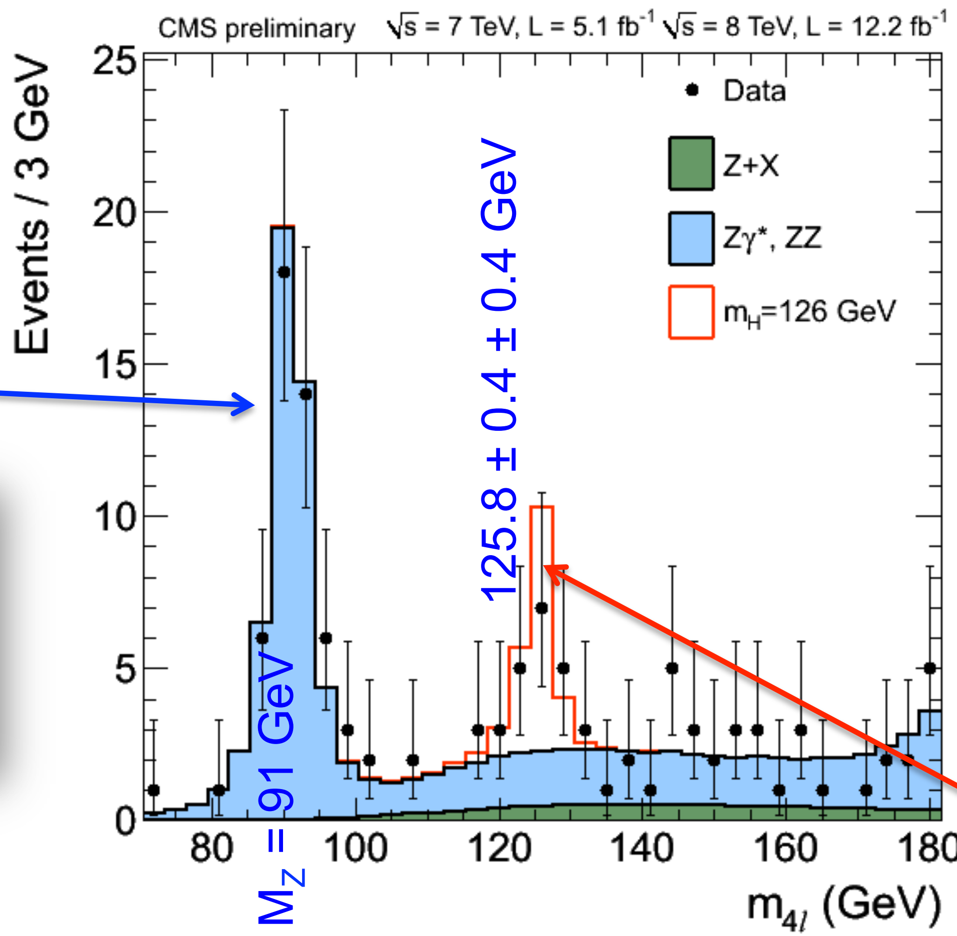
Decays to ZZ to 4-light leptons

CMS HIG-12-041

Golden mode – Zoom of loss 4L mass region

Clearly observe production of Z decay to 4 leptons





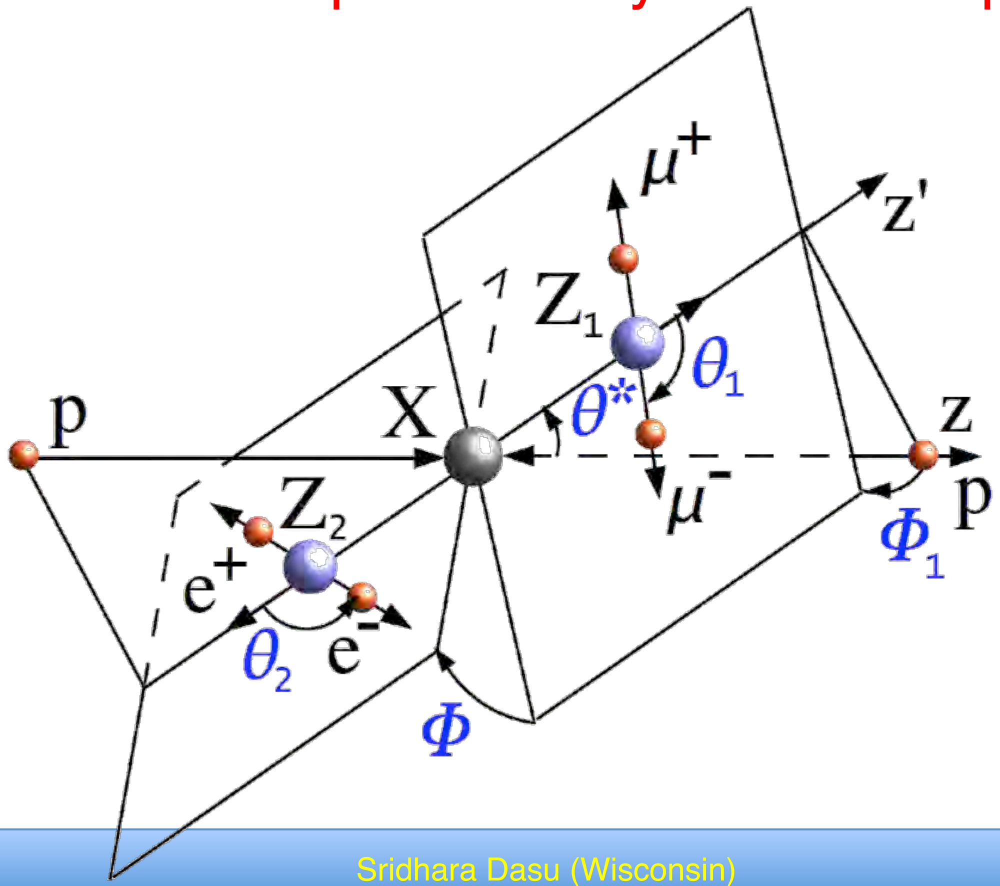
Cluster of events rising above the background consistent at 3-sigma level with SM Higgs signal

[1] Torino University
[2] John Hopkins University
[3] University of Florida
[4] CERN
[5] Laboratoire Leprince-Ringuet
[6] Purdue University
[7] FNAL
[8] Florida State University
[9] Bologna University
[10] Bari University
[11] University of Wisconsin
[12] Massachusetts Institute of Technology
[13] Saha Institute of Nuclear Physics and Visva-Bharati University
[14] University of California, San Diego
[15] California Institute of Technology
[16] Universit libre de Bruxelles
[17] University of California, Davis
[18] University of Split

Use Angular Information

Study additional properties of these events

- Angles shown carry information of scalar (SM H), pseudo-scalar vs spin-2 decay versus ZZ production

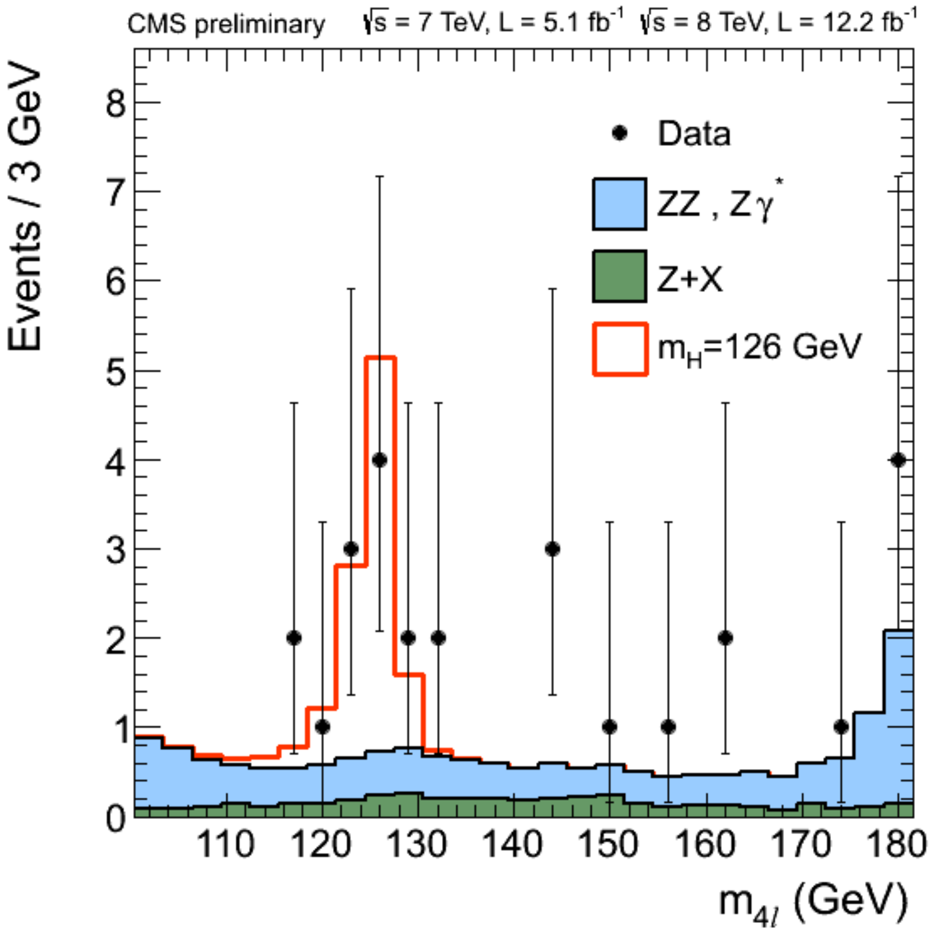


Strong Evidence in decays to ZZ

CMS HIG-12-041

Boost using angular information from 3 to 4.5 sigma

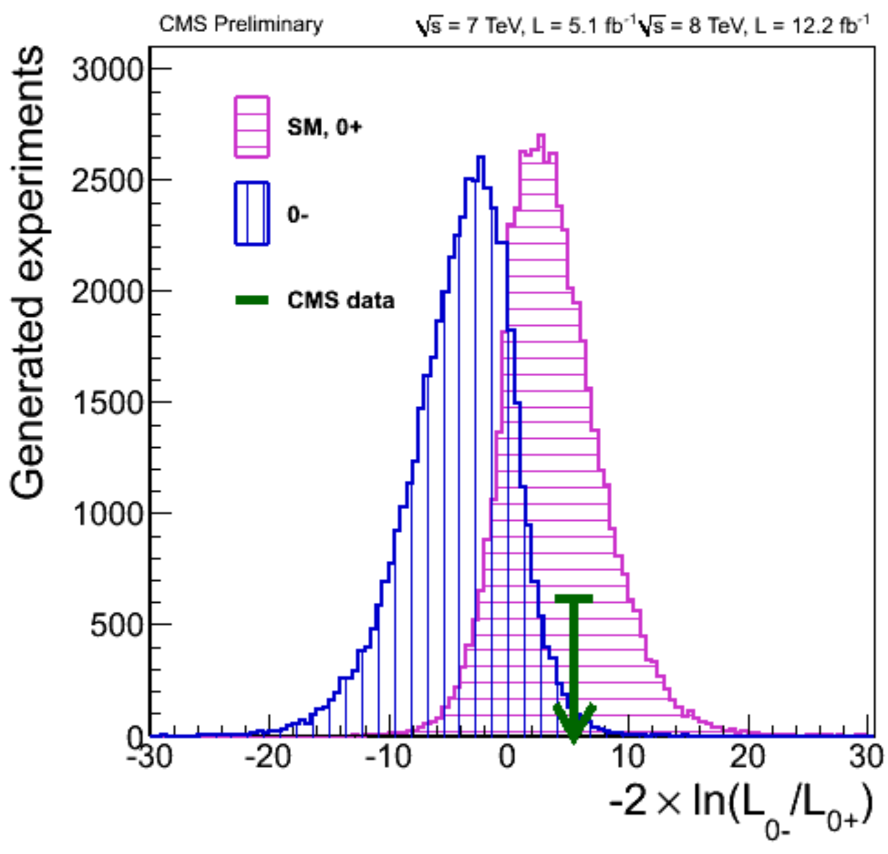
- Reduce background, while keeping signal-like events

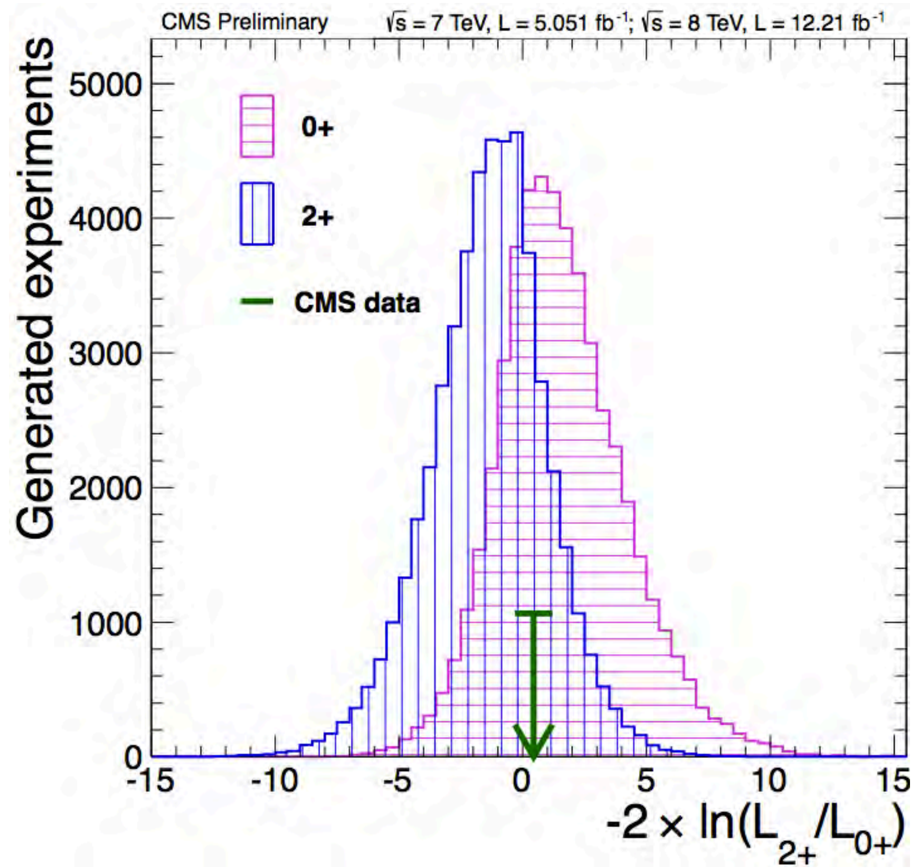


Is the new boson a scalar?

CMS HIG-12-041

Not yet significant, but favors 0^+ over 0^- by ~2sigma



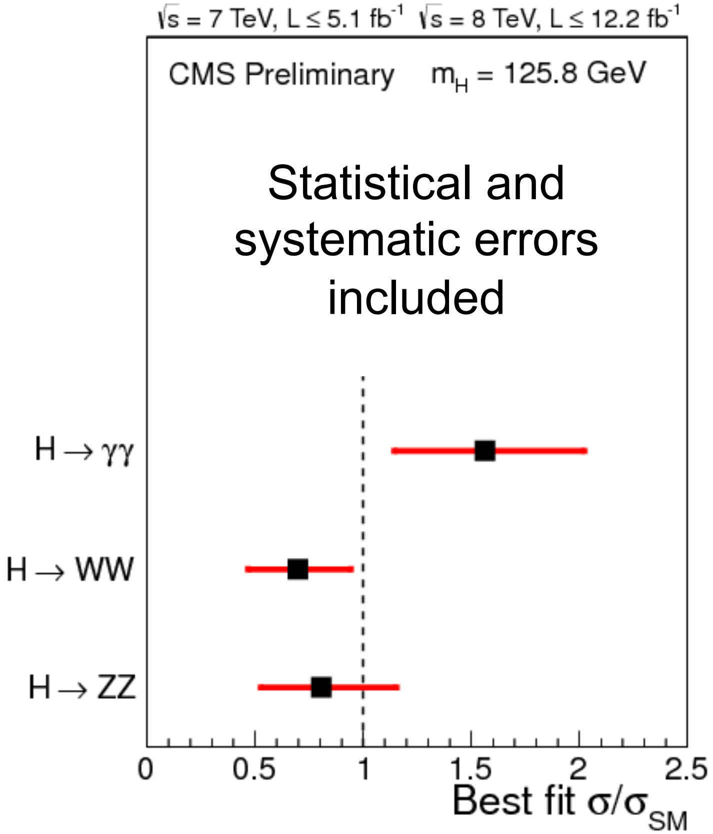


SM Higgs?

CMS HIG-12-045

Signal strength consistent with SM Higgs

Excesses seen in γγ, ZZ and WW in both experiments



Does it couple to fermions?

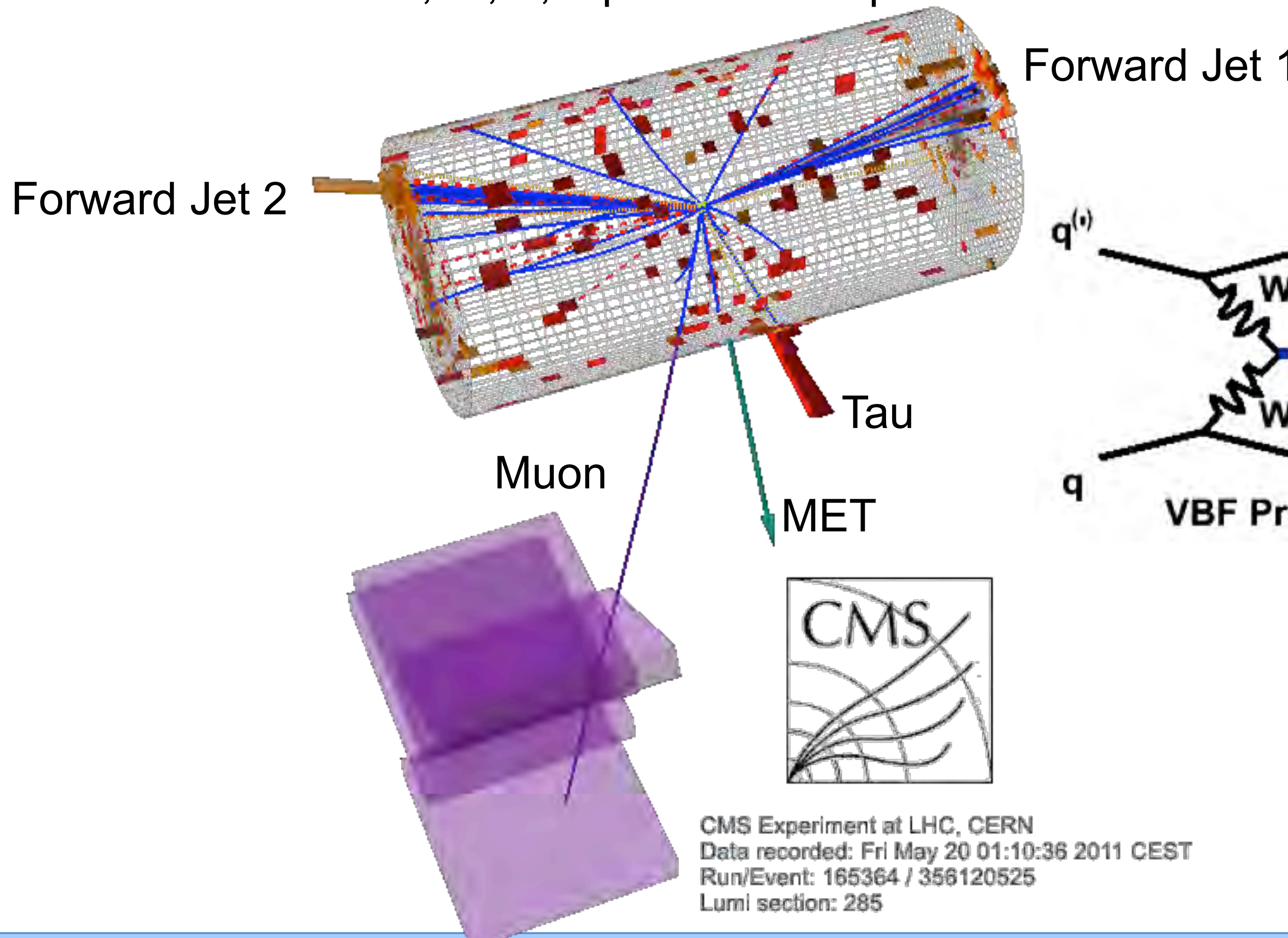
Answers, beginning to emerge

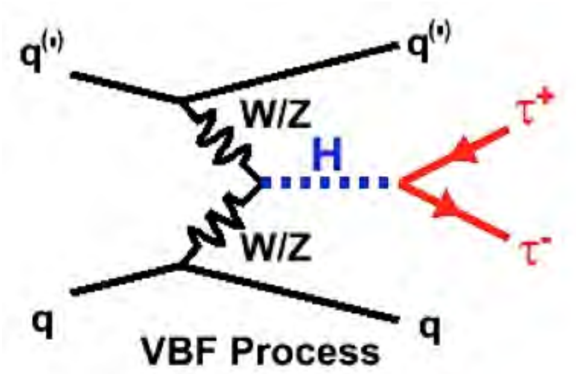
Self-coupling?

Must wait for several hundred fb^{-1}

Higgs Decay to tau Pairs

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

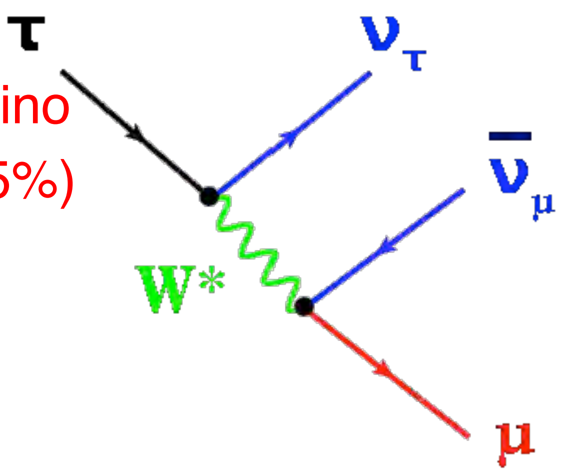




Tau Decays

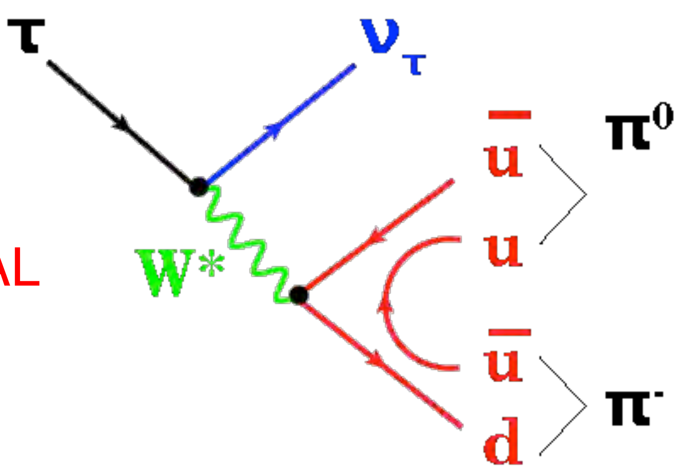
Weak decays

- Not fully reconstructed – MET from neutrino
- Leptonic electron/muon + 2 neutrinos (35%)
- Hadrons + 1 neutrino (65%)
  - Single charged hadron (~50%)
  - $\rho \rightarrow \pi^+\pi^0$
  - $a_1 \rightarrow \pi^+\pi^-\pi^+$, $\pi^+\pi^0\pi^0$



Hadronic tau identification is important

- Reconstruct intermediate light mesons
- Take advantage of good charged tracking
- Take advantage of highly segmented ECAL
- Suppress large background from jets



Decay Mode Reconstruction

Not "tau-jets"

HPS

The good

- Single prong: well measured isolated charged hadron
- Three prong: softer well measured and vertexed charged hadrons

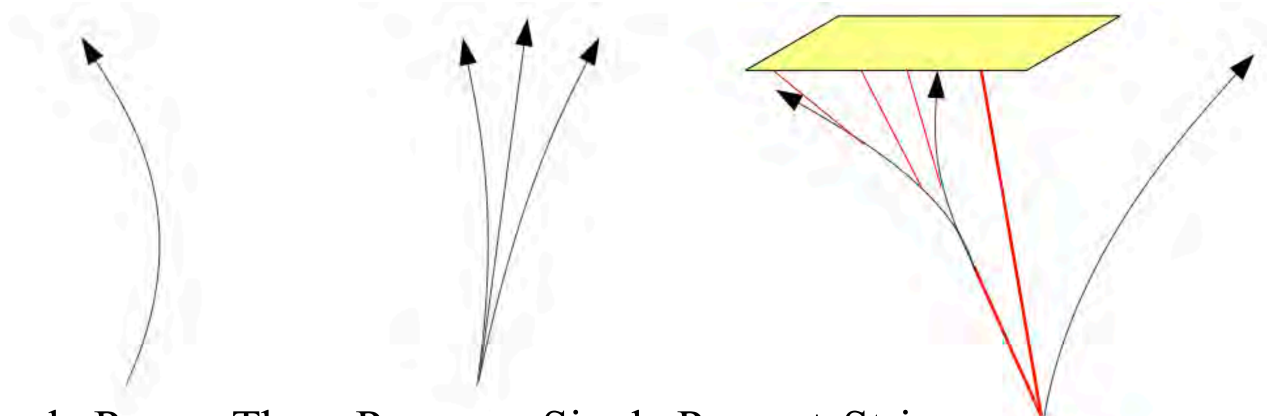
The bad

- n π^0s leading to 2n γs -- π^0 not always reconstructed fully
- EM energy clusters spread out in ϕ-strips

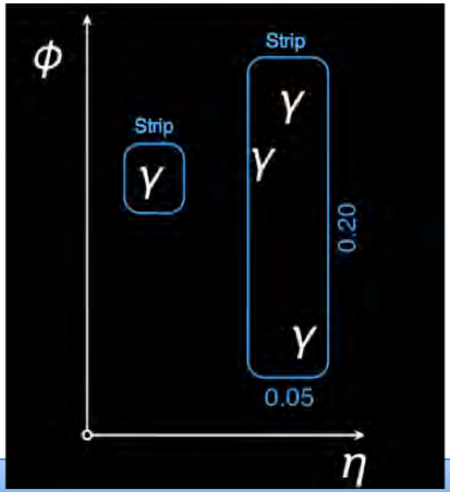
The ugly

- Missing neutrino: fit the missing momentum vector and secondary vertex of visible τ-pair components

SVFit



Single Prong Three Prong Single Prong + Strip

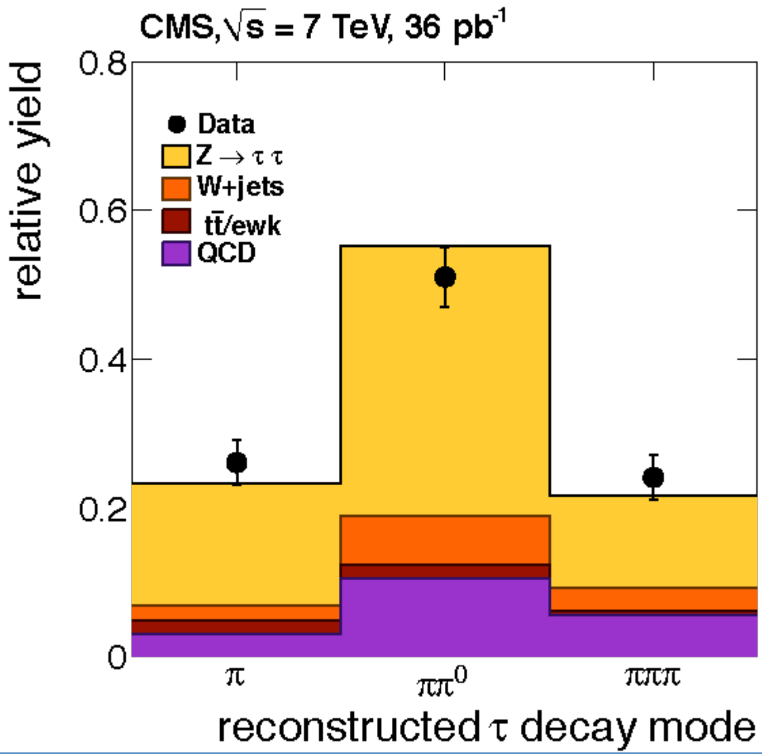


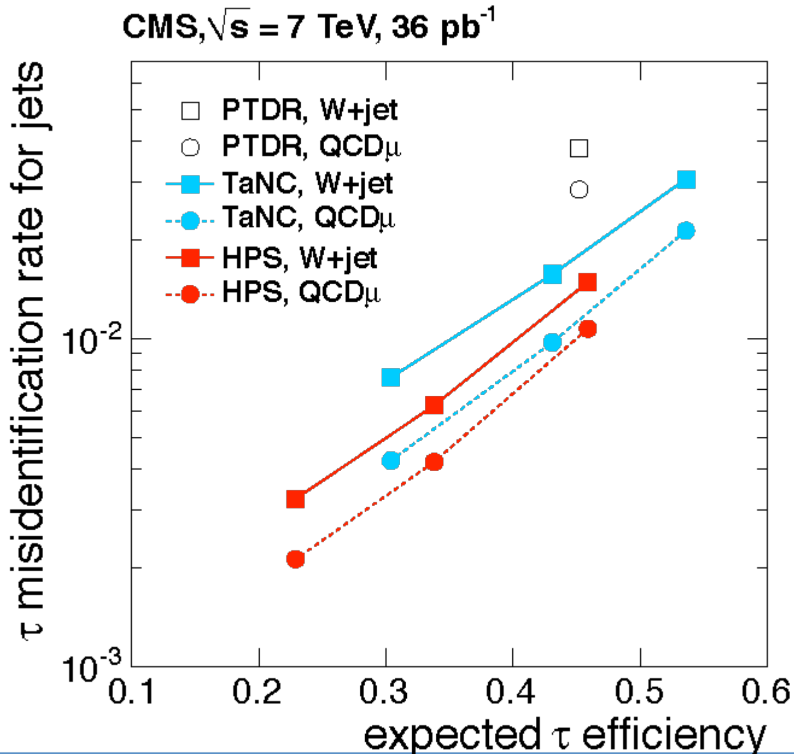
τ lepton reconstruction

JINST 7 (2012) P01001

Bachtis (Wisconsin), Friis (Davis)

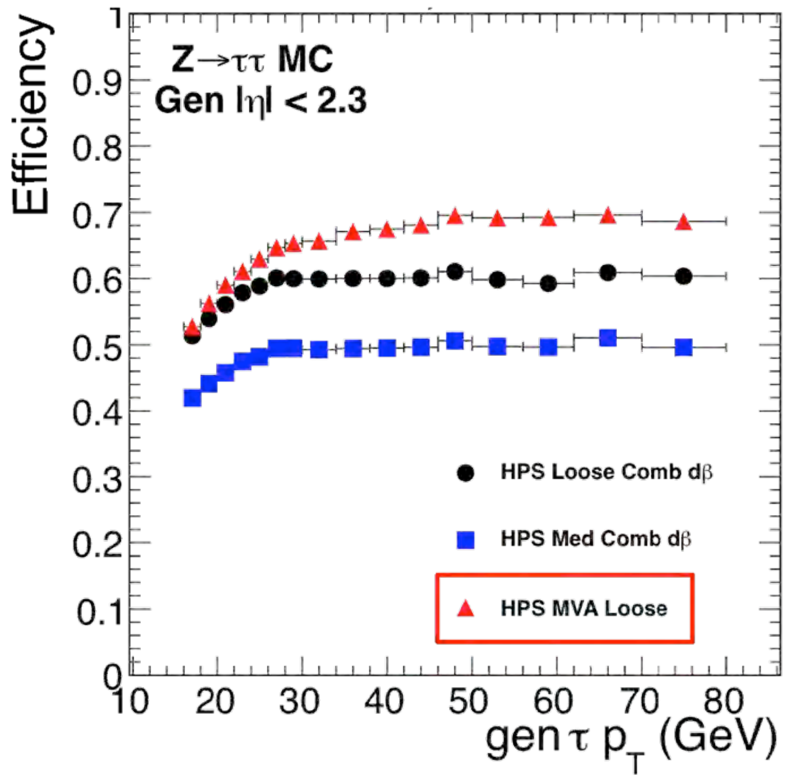
- Instead of jets of narrow cone, shrinking cone … we truly reconstruct taus
  - In single and three prong modes, adding neutral pizeros
- Decay mode algorithms HPS and TaNC
- Established HPS algorithm and analysis techniques for τ physics



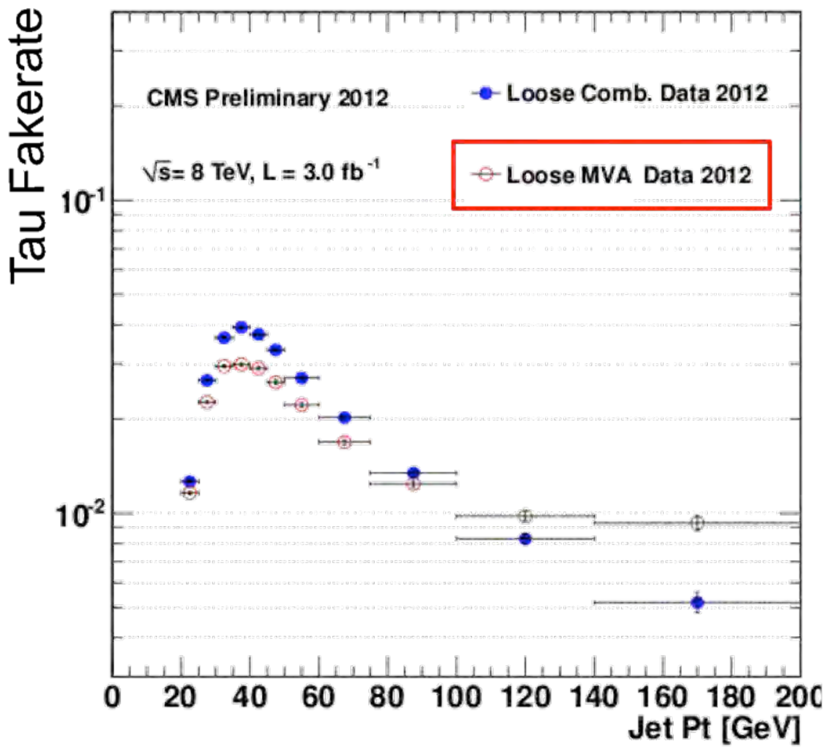


τ reconstruction performance

Efficiency for tau reco:



Fakerate from jets:



- Reconstruction efficiency >60% (flat for p_T(tau)>30GeV).
- Fakerate 1–3%.

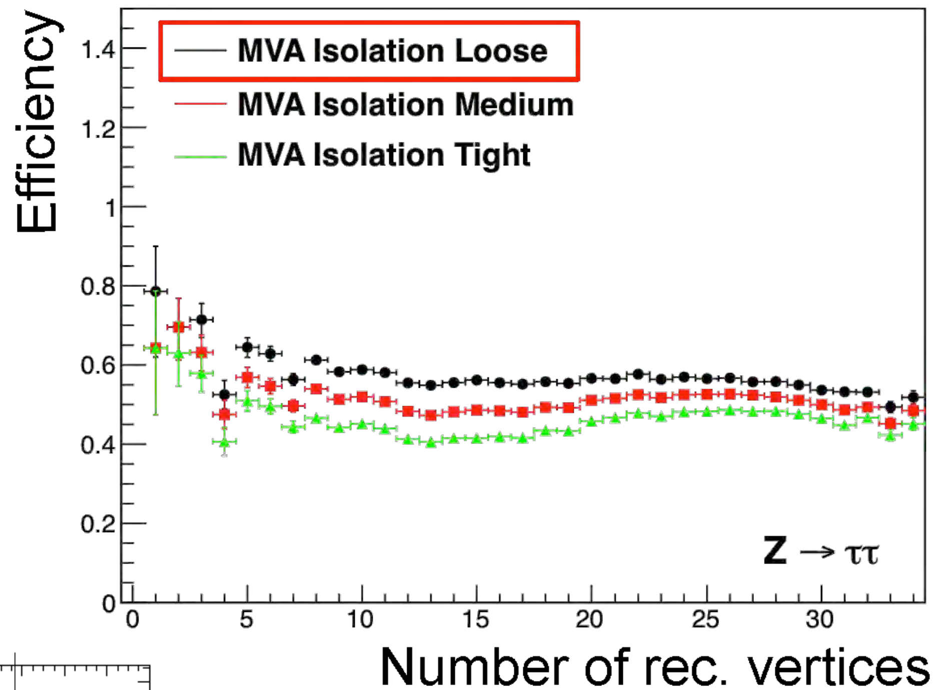
Swanson (Wisconsin), Rebecca (Imperial)

τ reco pileup dependence

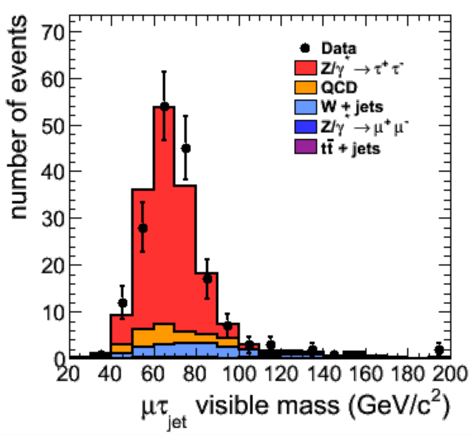
Efficiency is ~flat at > 60% independent of pileup level

Fake rate 1-3%

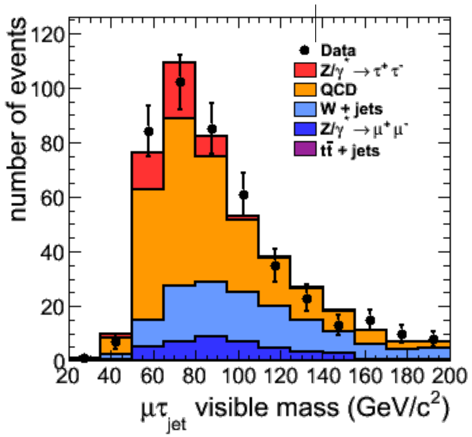
Measured using real data with tag and probe technique to 7%



Passed

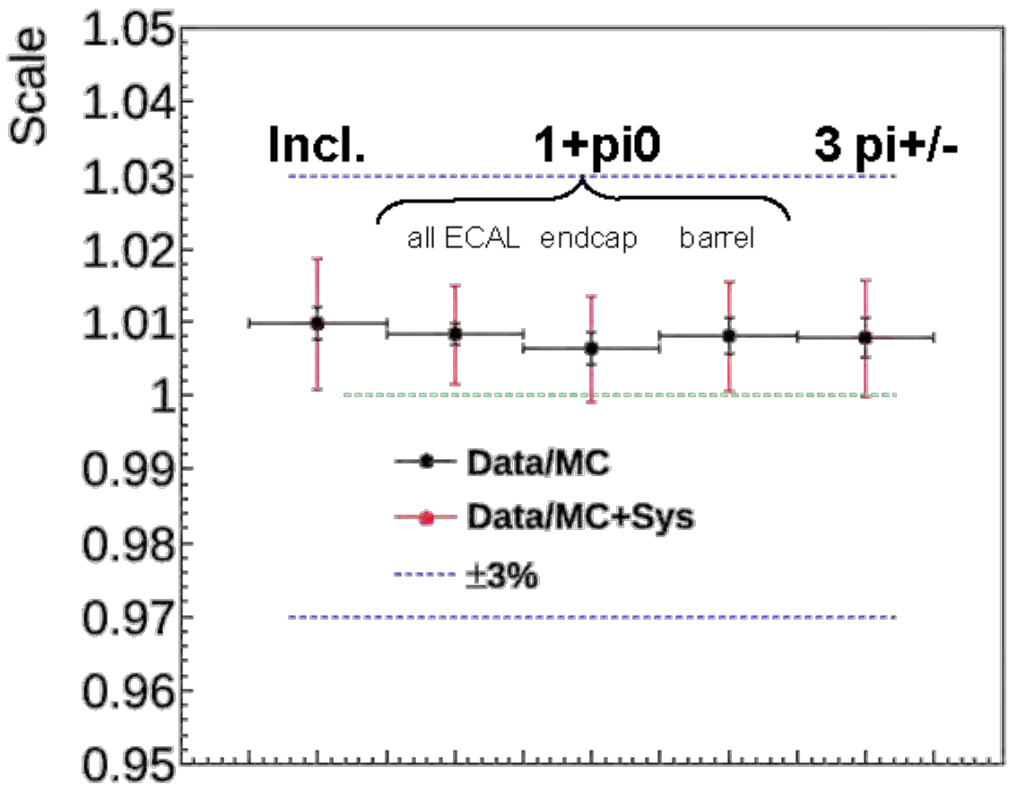


Fail



Chan (MIT)
Swanson (Wisconsin),
Veelken (LLR)

τ energy scale



- Determined from fit to reconstructed tau-mass from decay products.
- Agreement of simulation and data within 1%.
- Assign 3% uncertainty (conservative).
- Further constraint in ML fit for limit calculation.

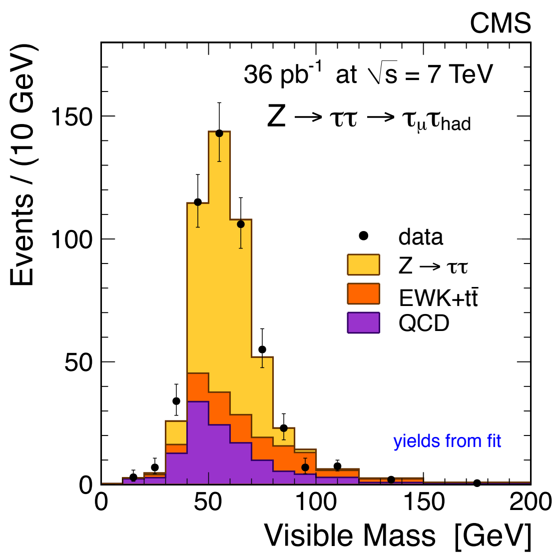
Bachtis (Wisconsin), Veelken (LLR)

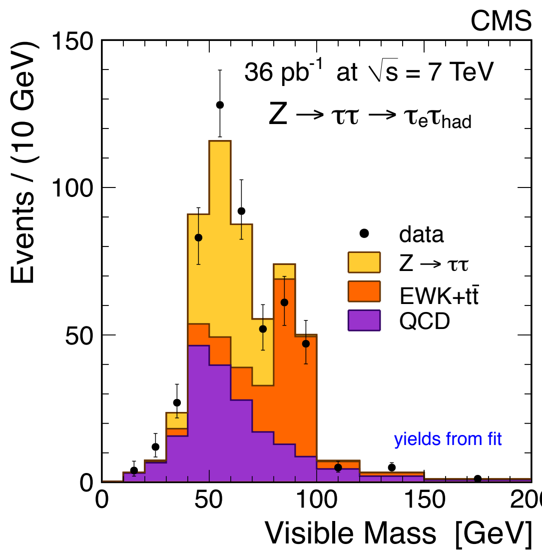
Z to ττ : 2010 Data

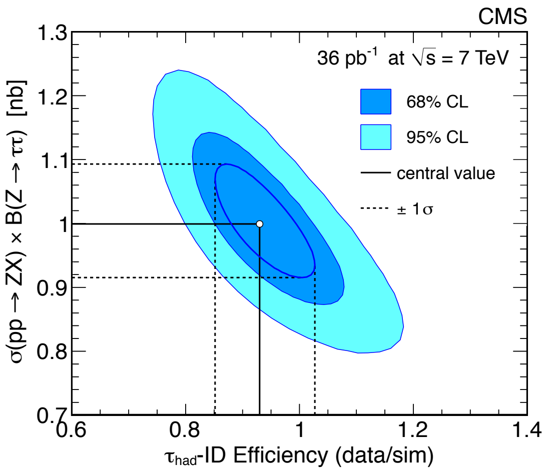
J. High Energy Phys. 08 (2011) 117

Bachtis (Wisconsin), Friis (Davis), Swanson (Wisconsin), Cutajar (Imperial)

- Measure Z to τ τ cross section and τ identification efficiency
- Necessary precursor to searches for higgs decays in τ modes



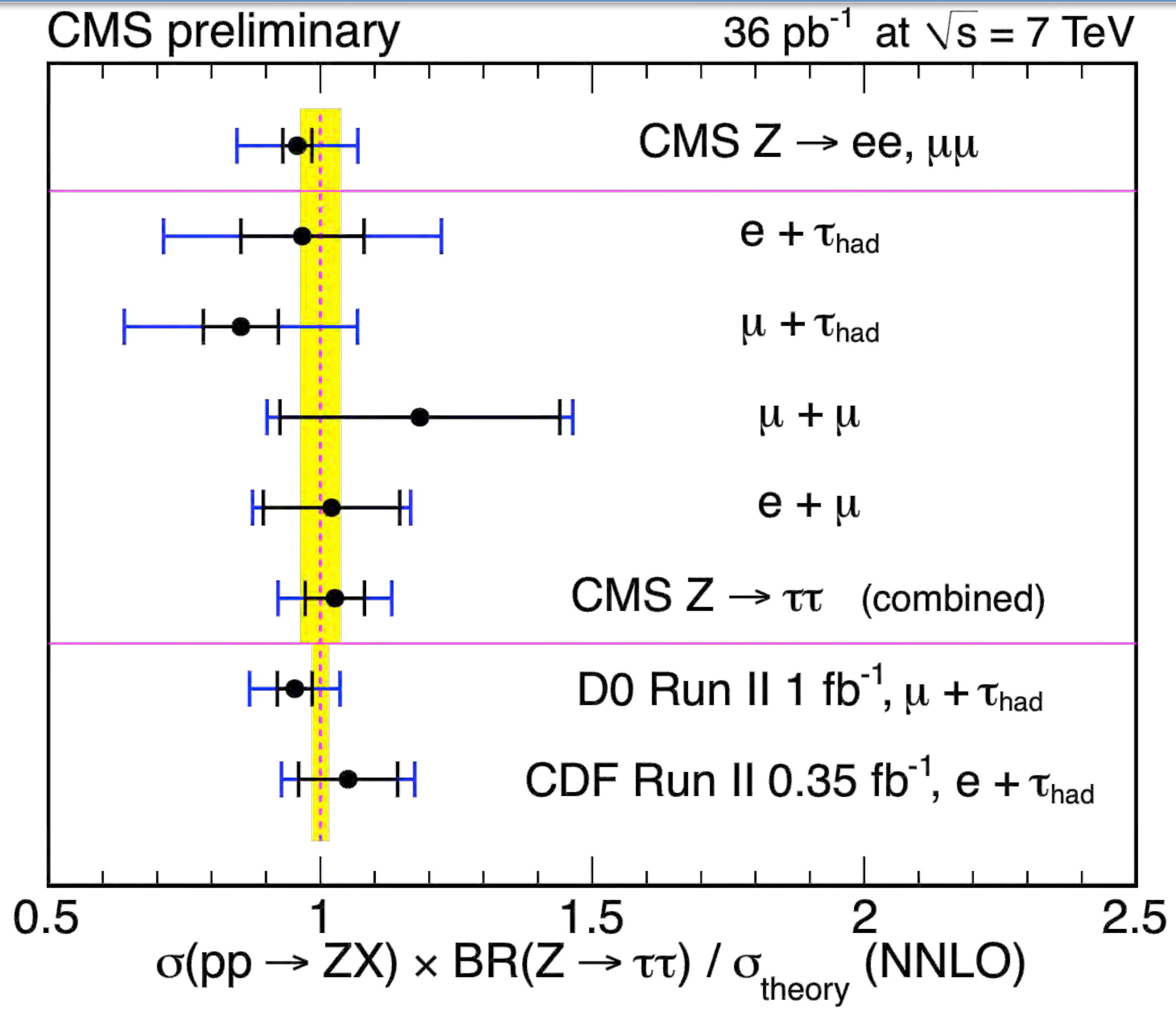




Clean Z signals in τ modes enabled cross section measurement + simultaneously extract τ ID efficiency.

Z to ττ Cross Section

Taus are legit !

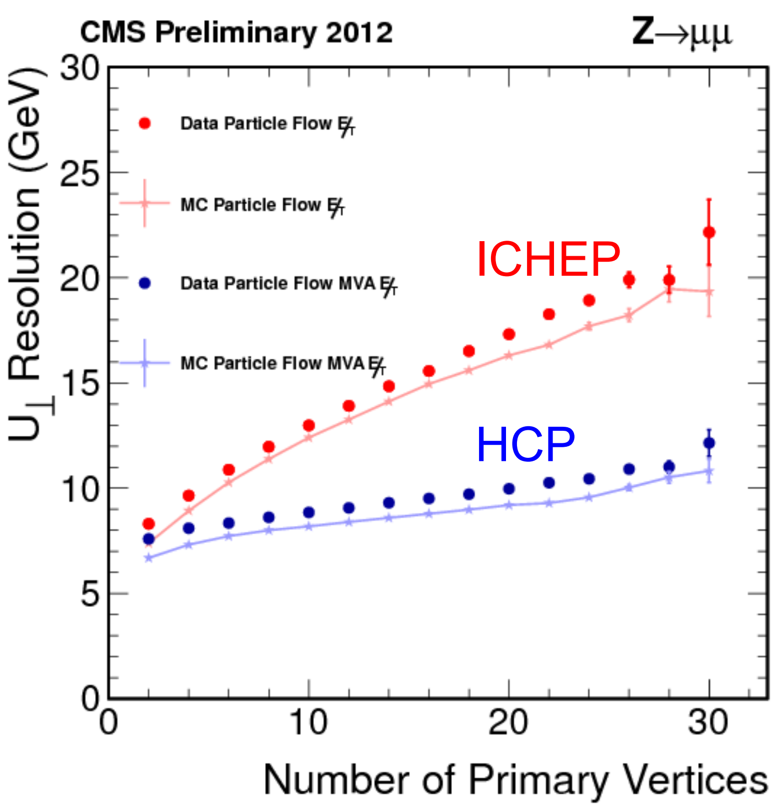


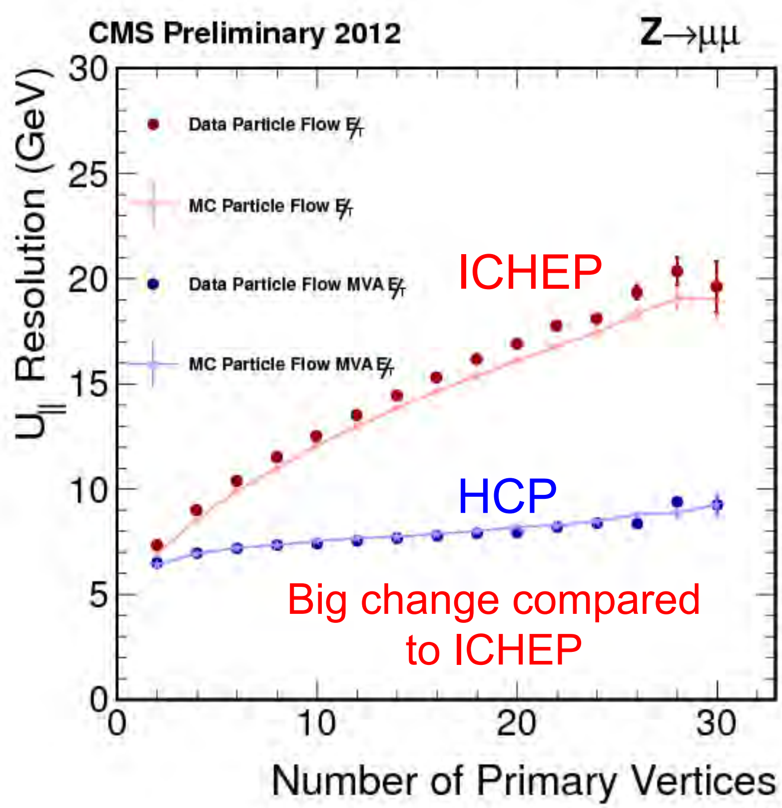
MET Improvement

Harris (CERN)

Particle flow MET corrected using Z recoil in μμ data events

Further improved using multi-variate analysis

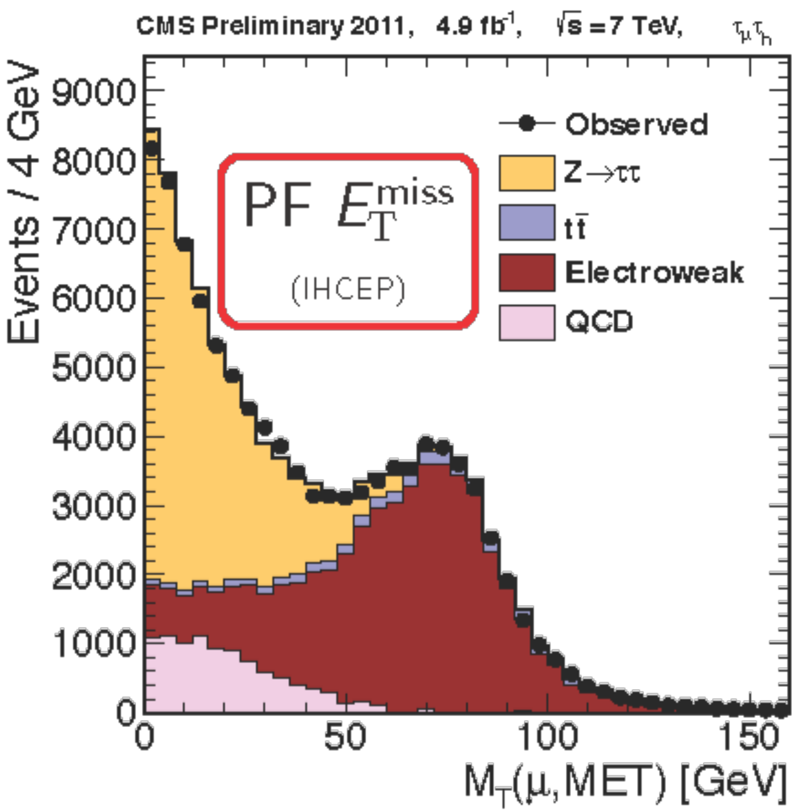


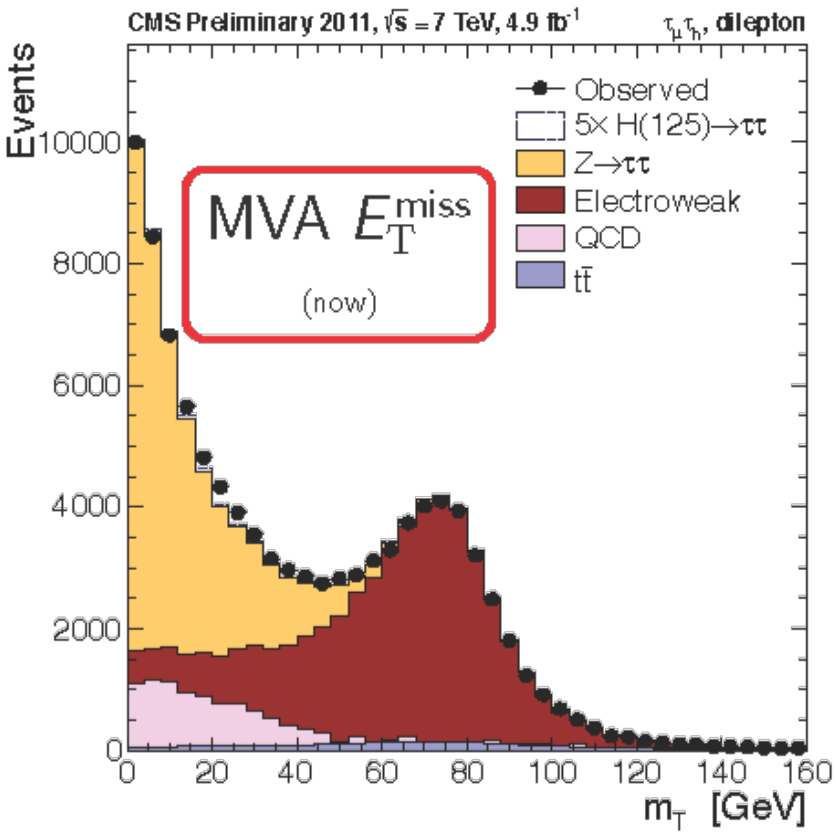


M_T Improvement

Harris (CERN)

MVA MET significantly improves performance of m_T and p_ζ cuts



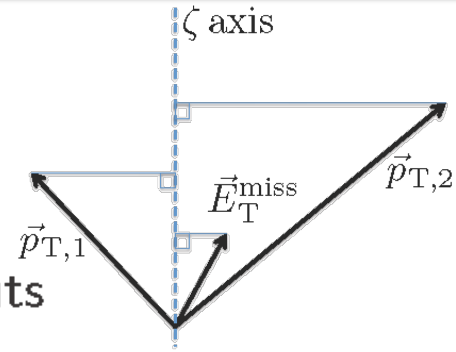


tightened m_T from < 40 GeV to < 20 GeV

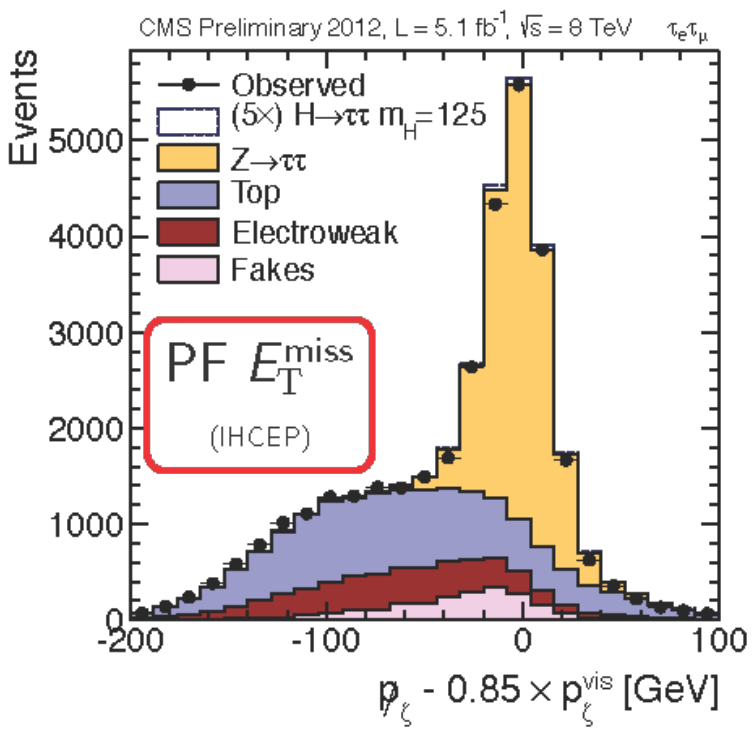
pZeta Improvement

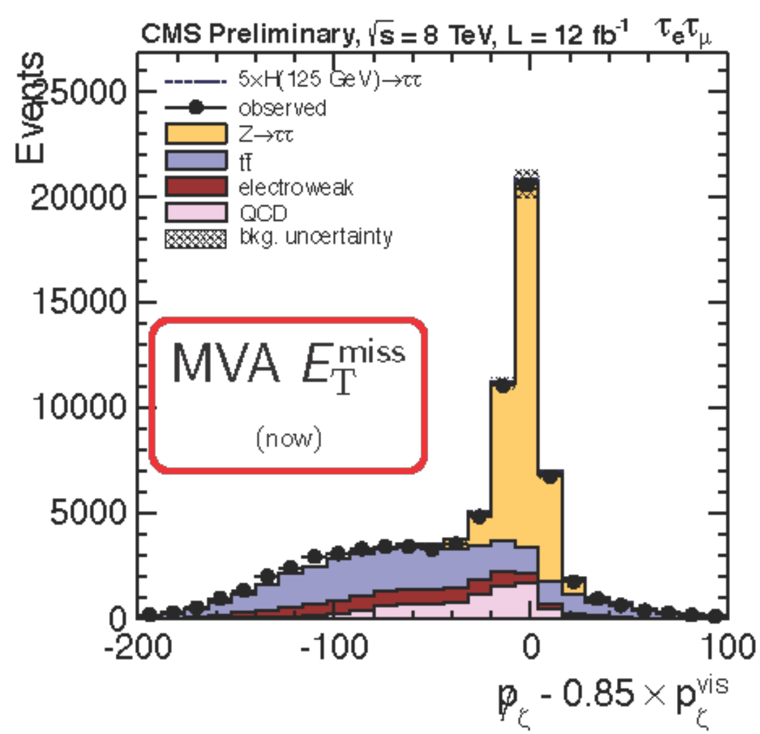
Harris (CERN), Dutta (MIT)

Kinematic variable in eμ channel with larger MET



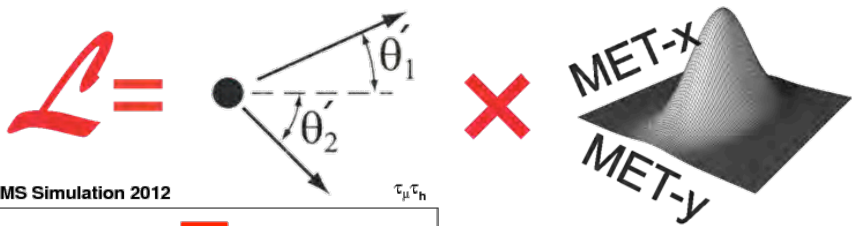
MVA MET significantly improves performance of m_T and p_ζ cuts

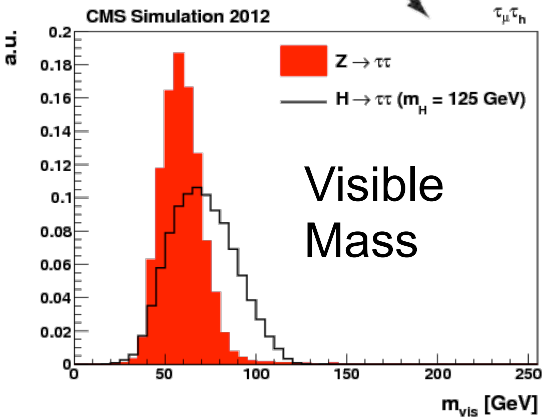


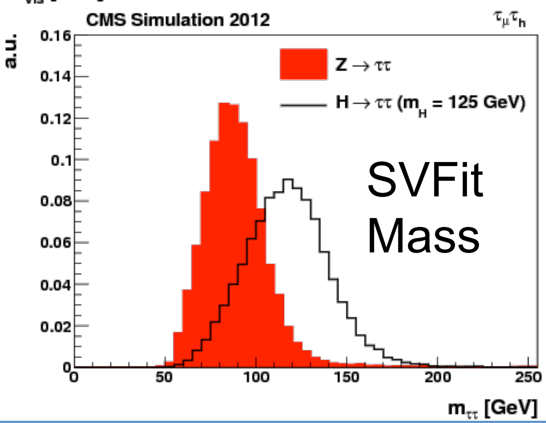


Di-tau Mass Reconstruction

Veelken (LLR), Lorenzo (LLR), Friis (Wisconsin)







- **SVFit**
  - Event by Event estimator of true di-τ mass likelihood
  - Exact Matrix Element used for τ→lνν
  - Phase-Space is used for τ→π
  - Nuisance parameters are integrated out

Mass peaks at true value

Mass resolution improved by 20%

Better separation between H/Z

Decay Channels Covered

Inclusive $H \to \tau\tau$ Decay Channels		Luminosity(fb^{-1})	
Label	Decay Channel	Data in 2011	Data in 2012
$\mu\mu$	both τ-leptons into μ	4.8	12.0
$e\mu$	τ-leptons into a e and μ	4.9	12.1
$\mu\tau_h$	τ-leptons into a μ and hadrons (τ_h)	4.9	12.1
$e\tau_h$	τ-leptons into a e and hadrons (τ_h)	4.9	12.1
$\tau_h\tau_h$	both τ-leptons into hadrons (τ_h)	-	12.1

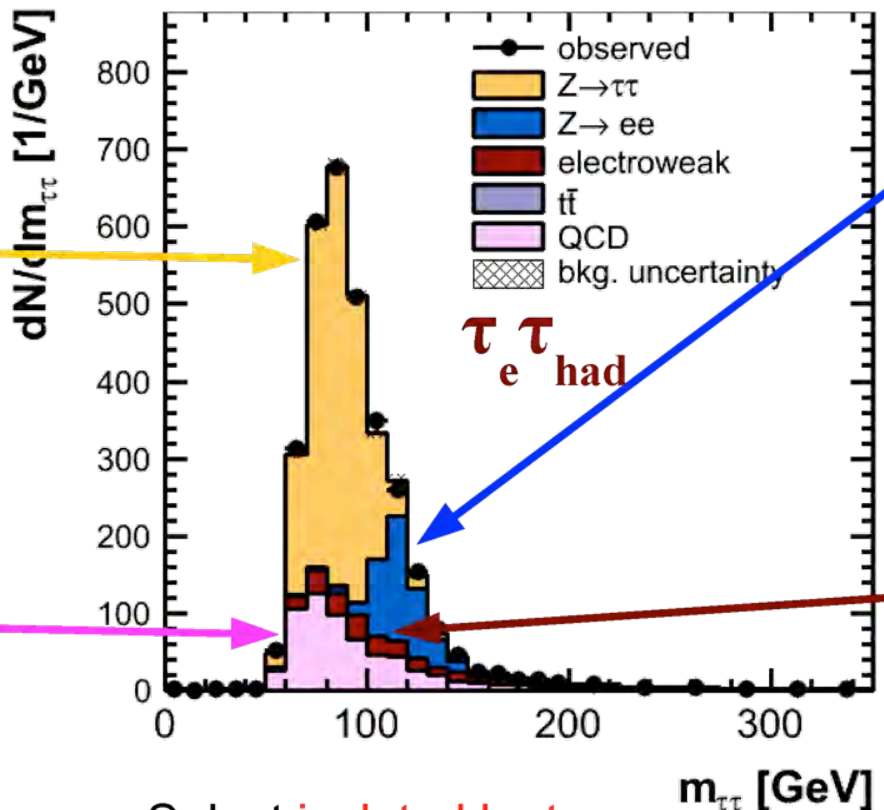
$WH \to l\tau\tau$ or $ZH \to ll\tau\tau$ Decay Channels		Luminosity(fb^{-1})	
Label	Decay Channel	Data in 2011	Data in 2012
VH(lep.)	both τ-leptons into μ	4.9	12.1
	τ-leptons into e and μ	4.9	12.1
	τ-leptons into μ and hadrons (τ_h)	4.9	12.1
	τ-leptons into e and hadrons (τ_h)	4.9	12.1

Backgrounds in Inclusive Analysis

$Z \to \tau\tau$:
- Embedding: in $Z \to \mu\mu$, replace μ by sim. τ decay.
- Normalized from $Z \to \mu\mu$ events.

QCD:
- Normalization & shape taken from LS/OS or fakerate.

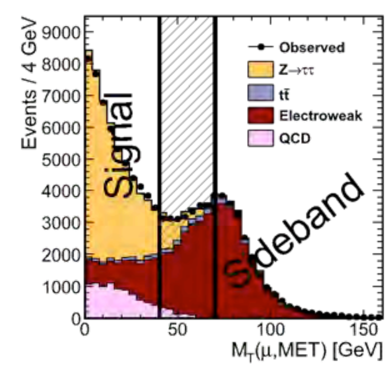
ttbar:
- From madgraph.
- Normalization from sideband.



- Select isolated leptons.
- Restrict $\not{E}_T$ (supp. W+jets, ttbar).
- Discriminate signal from background based on $m_{\tau\tau}$.

$Z \to ee(/\mu\mu)$:
- From powheg.
- Corrected for jet$\to\tau$, $e/\mu\to\tau$ fakerate.

Diboson/W+jets:
- From madgraph.
- Normalization from sideband.



Event Characterization

Jets $p_T > 30$ GeV

All categories are fit simultaneously

$p_T\ \tau_h\ (\tau_\mu)$

0 Jet

High Background Constrains fit

Used to fix normalization & tau efficiency

1 Jet, Low p_T

Enhancement from Jet Requirement

1 Jet, High p_T

Enhancement from p_T and Jet requirement

VBF

2 Jets

Rapidity Gap Veto

$\Delta\eta > 3.5$

$M_{JJ} > 500$ GeV

Simplified compared to ICHEP

Signal is negligible

Gluon Fusion Enhanced

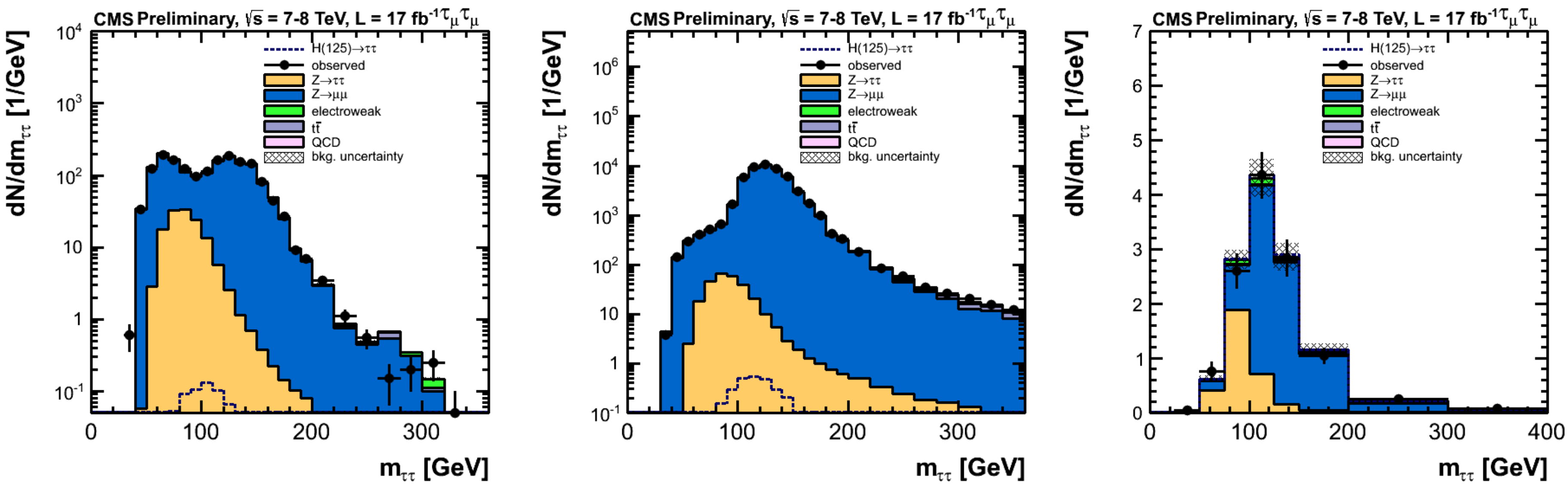
VBF Enhanced

μμ Channel

CMS HIG-12-043

Overwhelming Z to μμ background results in poor sensitivity

MET and $M_{\tau\tau}$ are used in 2D fit to extract signal for this channel



Bethani (DESY), Raspareza (DESY)

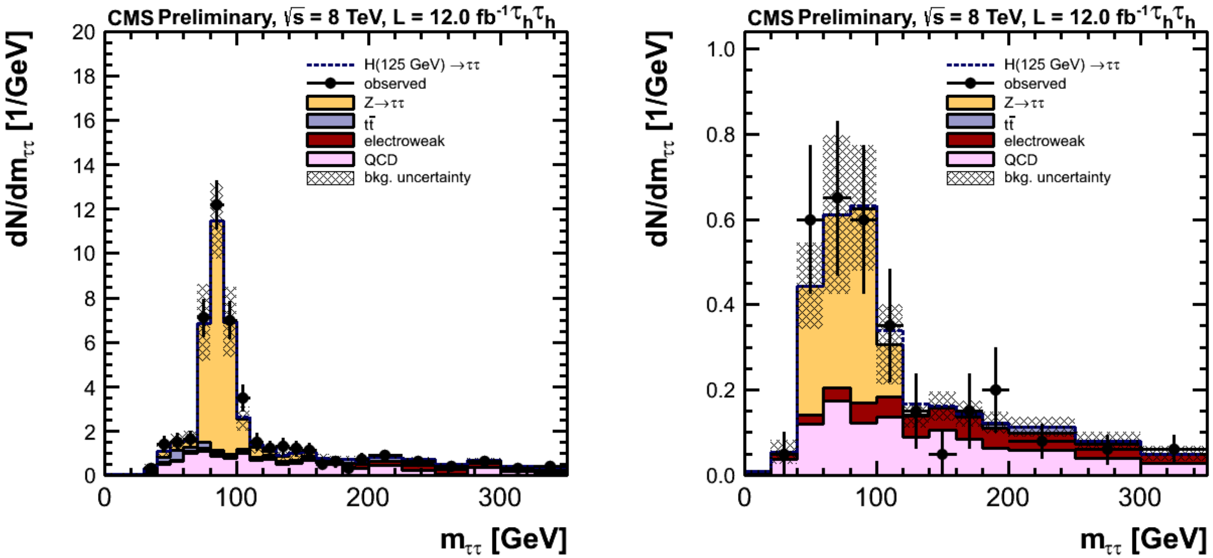
ττ Channel

CMS HIG-12-043

Trigger required additional jet, so only high boost and VBF

Data driven background estimates

Larger than desired thresholds and QCD BG make this less sensitive



$M_{\tau\tau}$ shape fit is used to extract signal

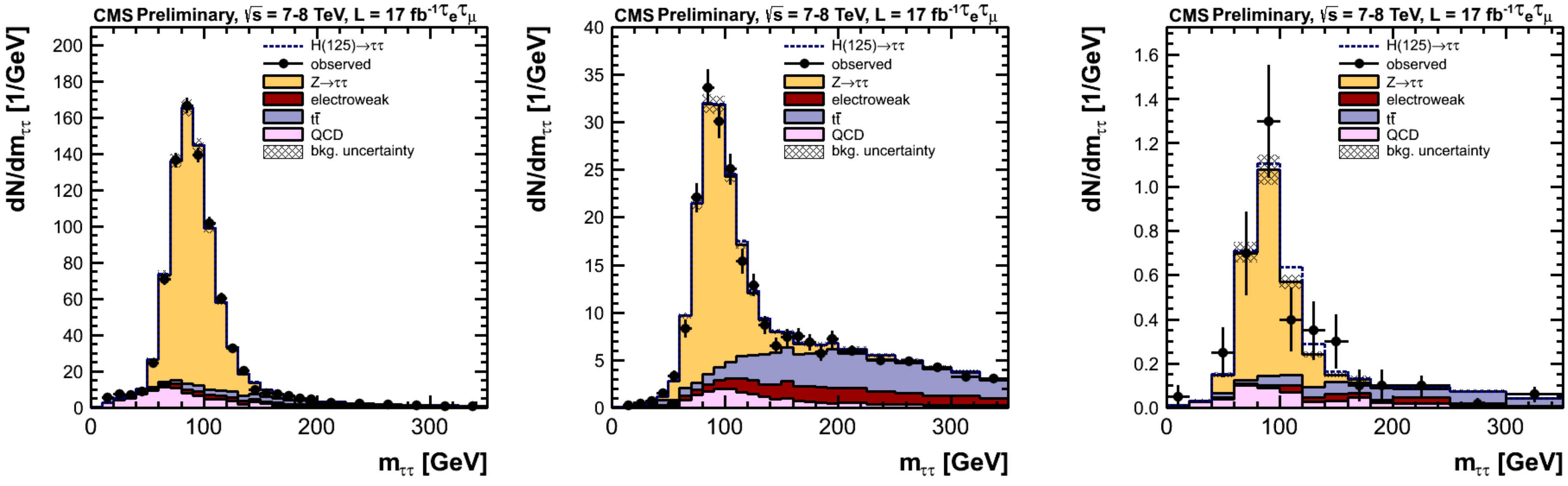
Hinzmann (CERN)

eμ Channel

CMS HIG-12-043

Channel with least background, but also small signal

$M_{\tau\tau}$ shape fit is used to extract signal



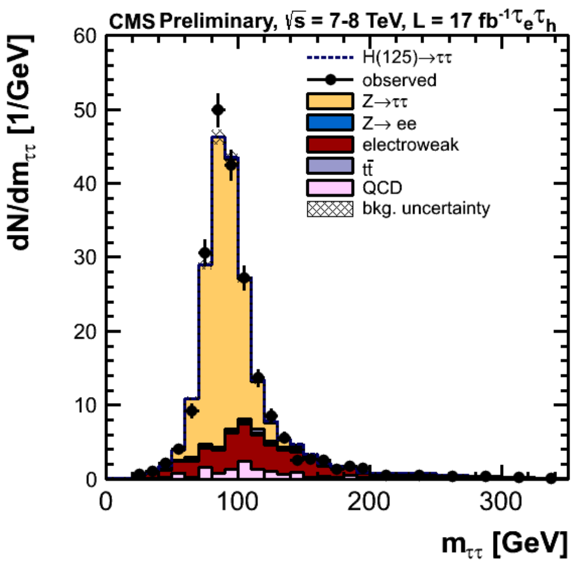
Dutta (MIT)

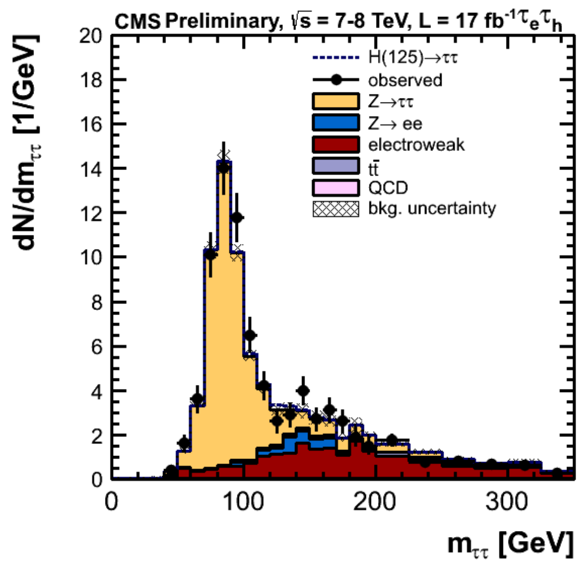
$e\tau$ Channel

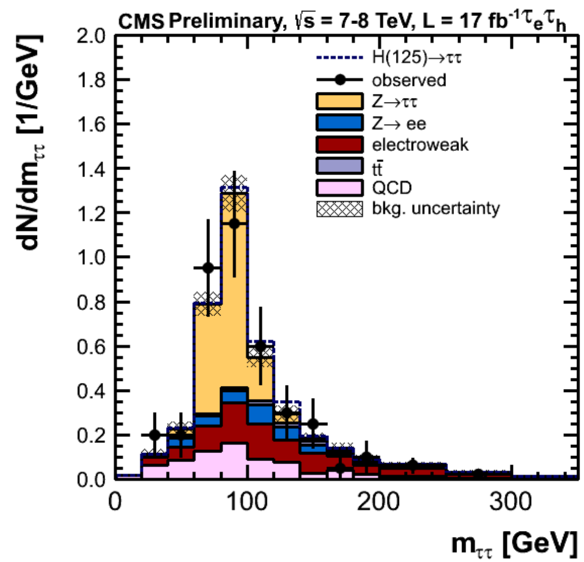
CMS HIG-12-043

Second most sensitive channel

$M_{\tau\tau}$ shape fit is used to extract signal







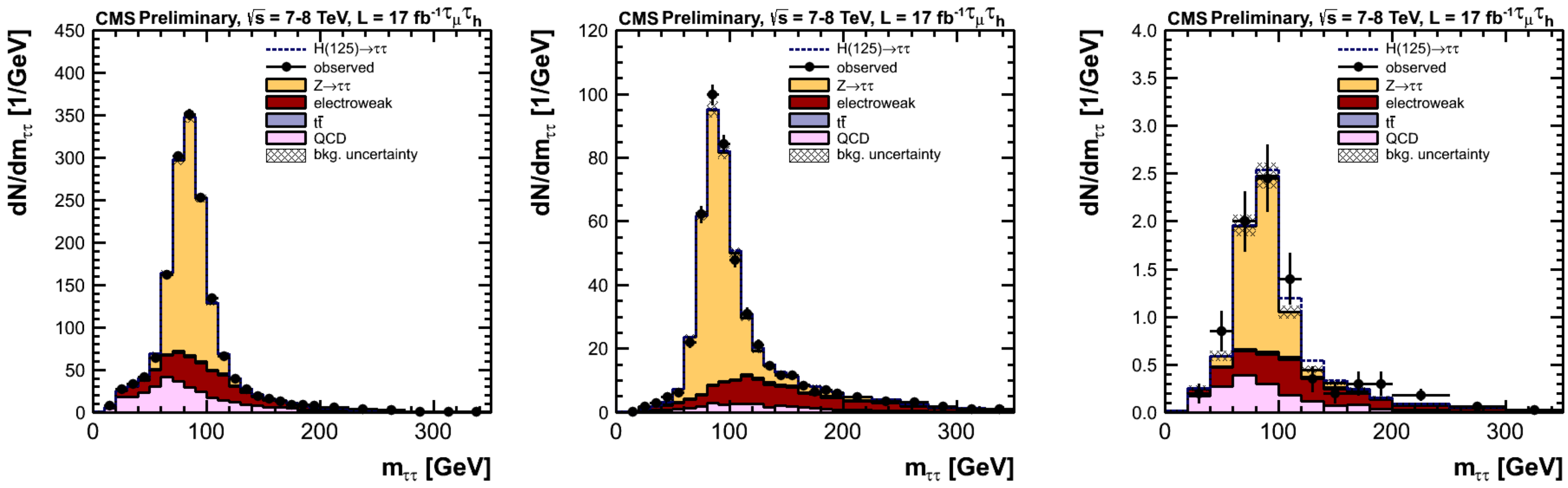
Swanson (Wisconsin), Gilbert (Imperial)

μτ Channel

CMS HIG-12-043

Most sensitive channel

$M_{\tau\tau}$ shape fit is used to extract signal

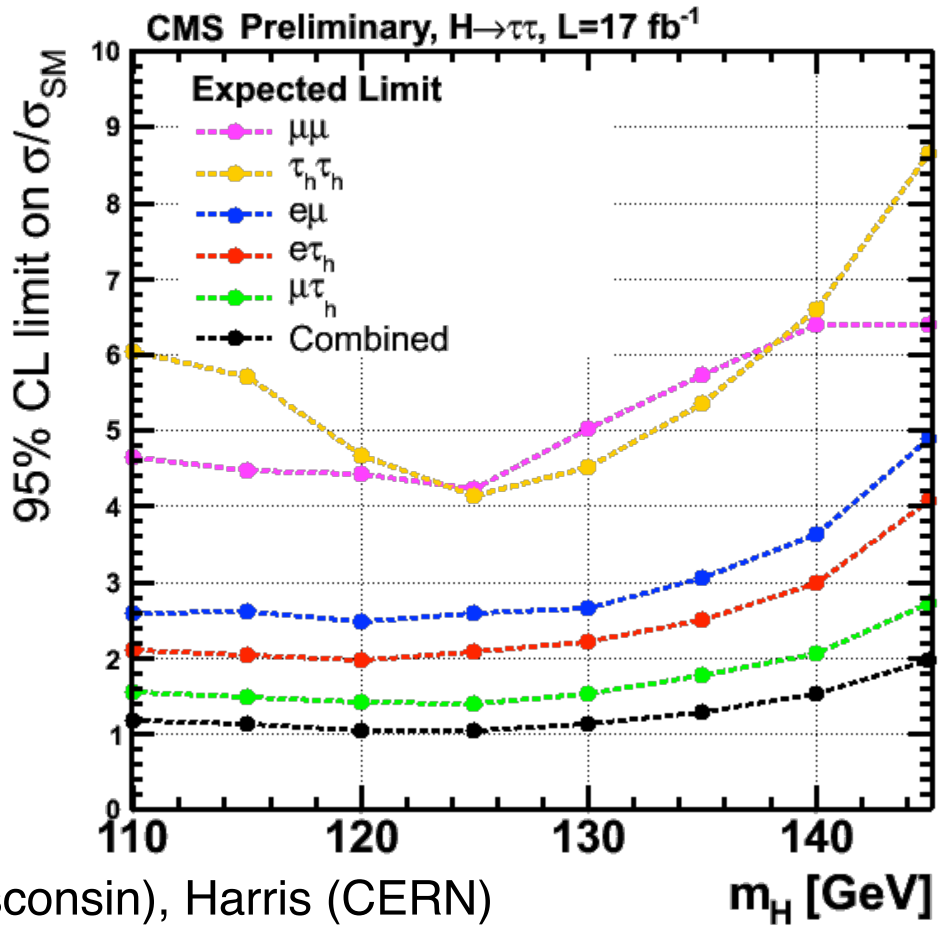


Bianchini (LLR), Swanson (Wisconsin), Gilbert (Imperial)

By Channel Expected Significance

CMS HIG-12-043

Combined significance approaches SM sensitivity

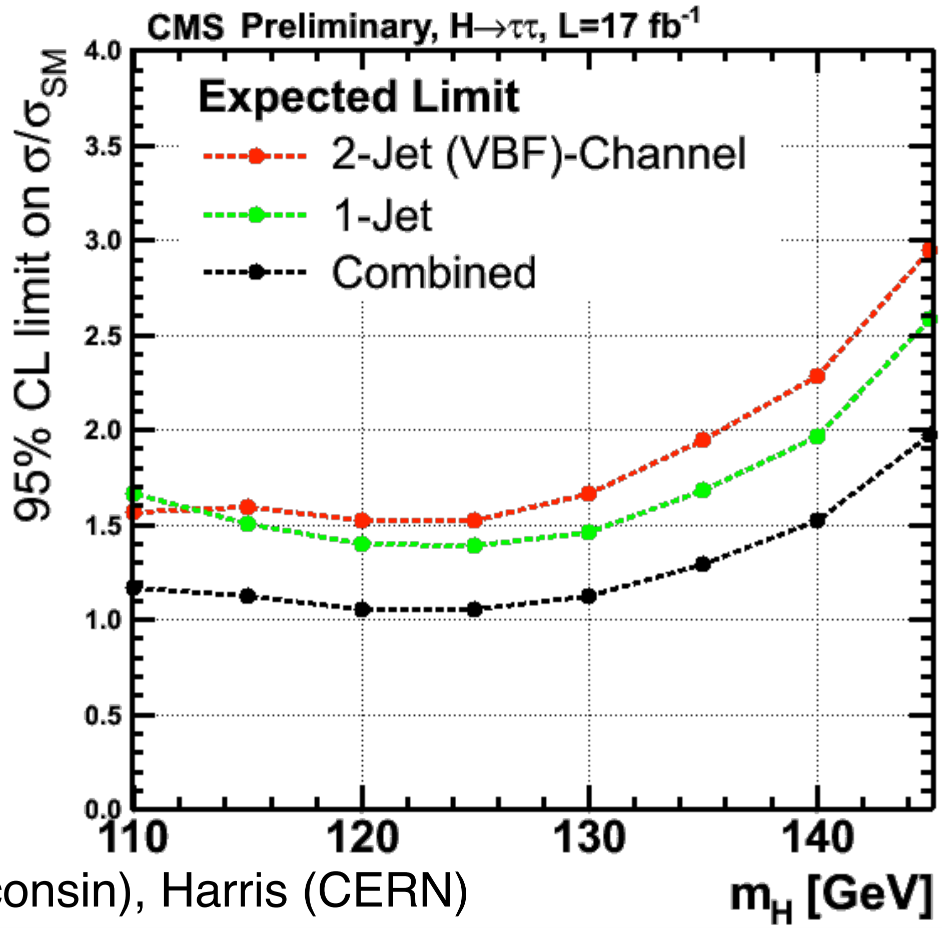


Wolf (MIT), Friis (Wisconsin), Harris (CERN)

Expected Significance By Category

CMS HIG-12-043

Boosted 1-jet (gluon fusion) and 2-jet (VBF) are ~equal



Wolf (MIT), Friis (Wisconsin), Harris (CERN)

Z Associated Production

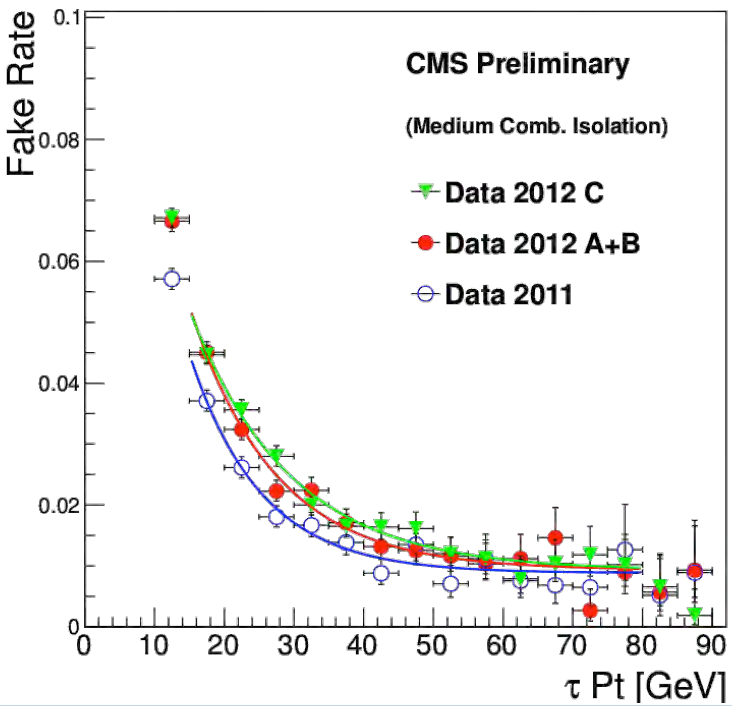
CMS HIG-12-050

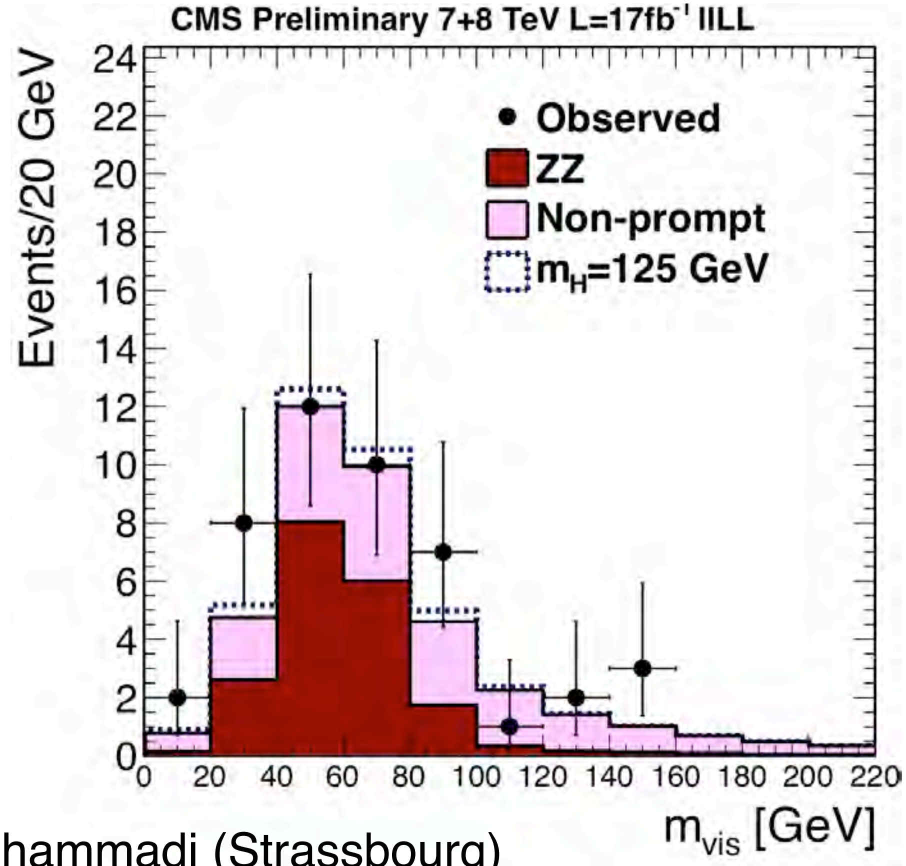
Reconstructed eight final states with $ll\tau_h\tau_h$, $lll\tau_h$

Z_1 in light leptons with $60 < M_{ll} < 120$ GeV

ZZ BG from simulation

Non-prompt BG using data





Mohammadi (Strassbourg)

W Associated Production

CMS HIG-12-050

Reconstructed $e\mu\tau_h$ and $\mu\mu\tau_h$ ($ee\tau_h$, $e\tau_h\tau_h$ and $\mu\tau_h\tau_h$ in to do list)

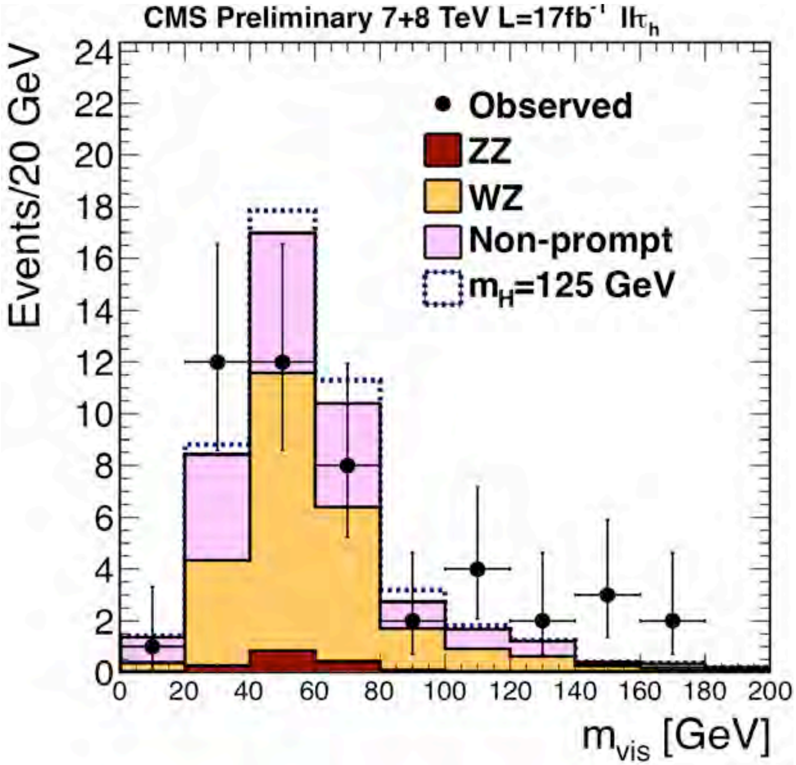
Same charge light leptons to reject Z+jet background

Kill fakes with cut on scalar sum of leptons, $L_T > 80$ GeV

Extra lepton and b-jet veto

WZ and ZZ from simulation

Non-prompt BG (Z+jet, top, etc) estimated from data (fake rate)



Higgs visible mass shape used for limit setting

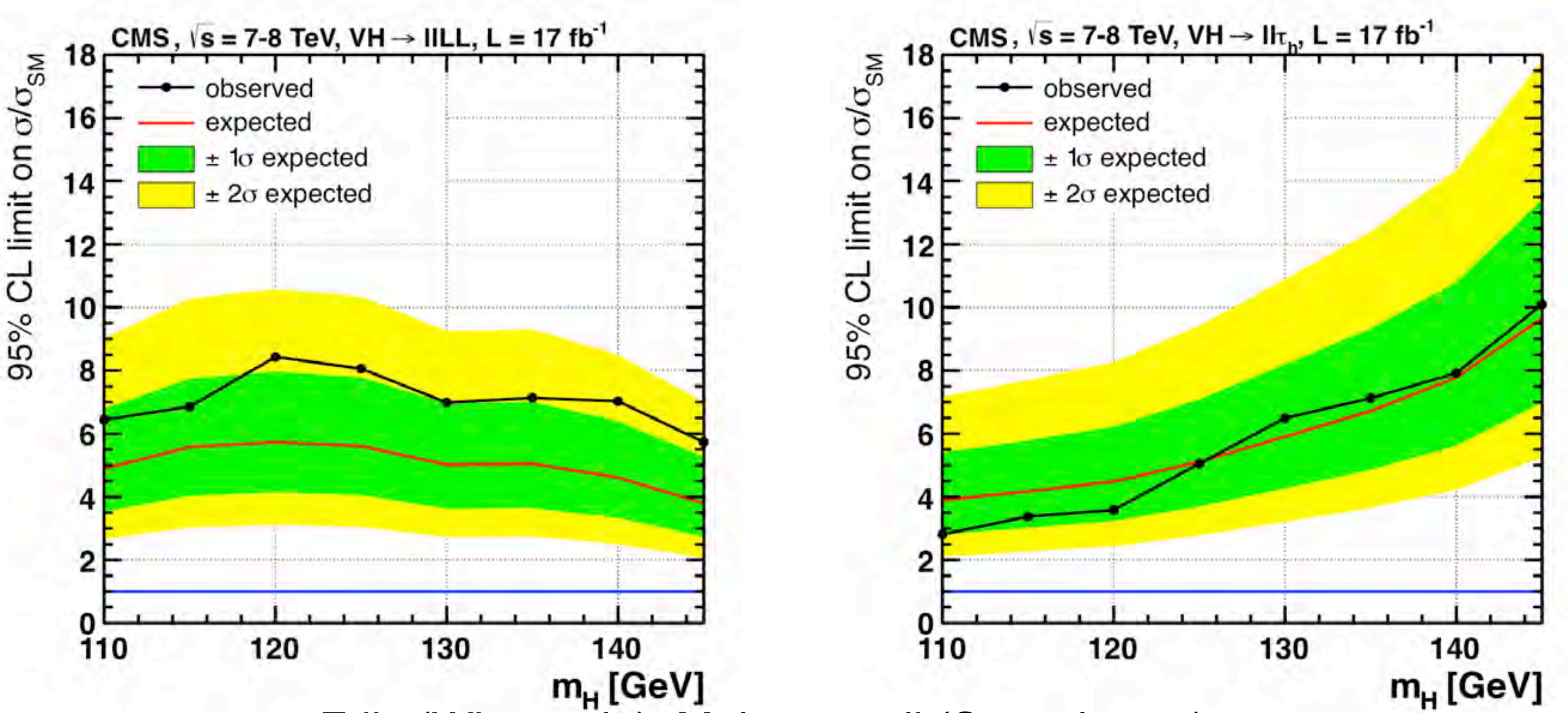
Friis (Wisconsin)

VH Limits

CMS HIG-12-050

By themselves neither are sensitive at SM level

However, they provide important VH sensitivity



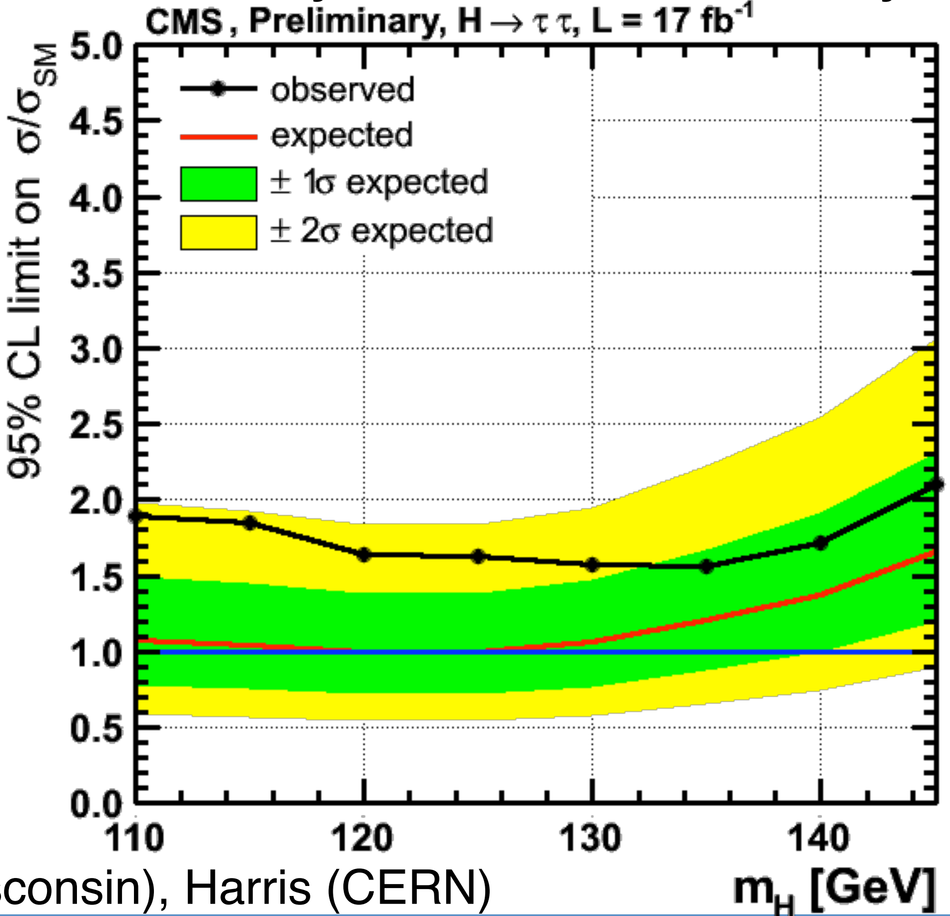
Friis (Wisconsin), Mohammadi (Strassbourg)

Limit on SM Higgs

CMS HIG-12-043

Everything combined (5 channels x 3 categories) + VH

Small excess, but within systematic uncertainty bands



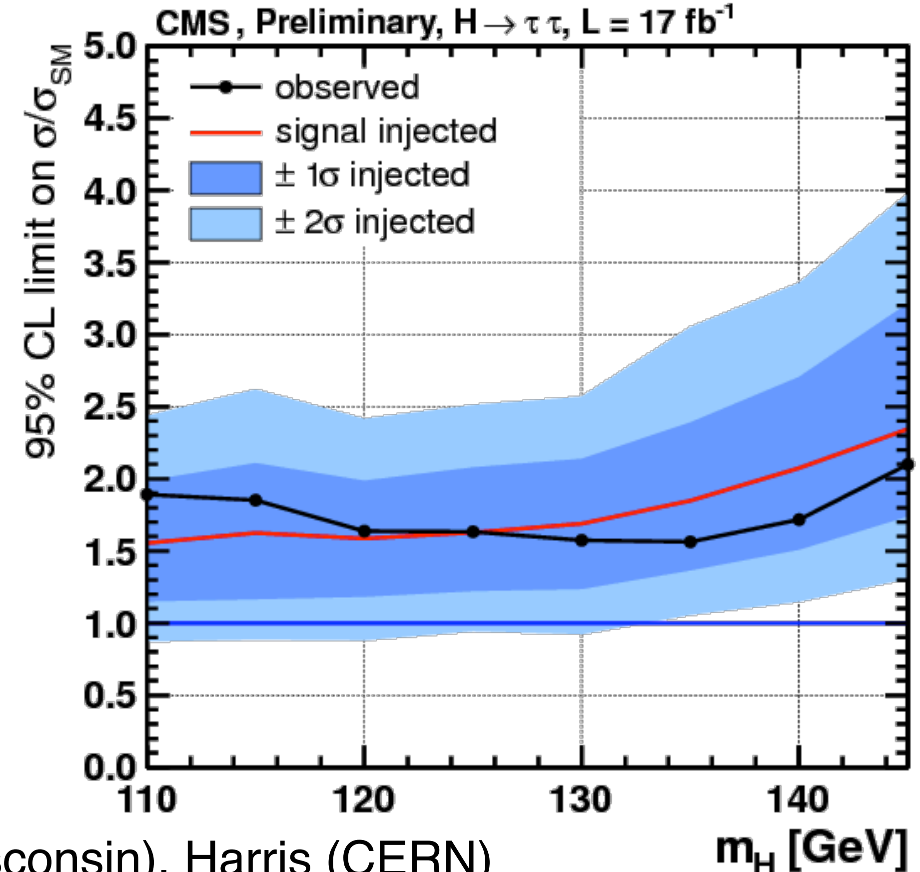
Wolf (MIT), Friis (Wisconsin), Harris (CERN)

Observed vs SM H(125 GeV) Injected

CMS HIG-12-043

Everything combined (5 channels x 3 categories) + VH

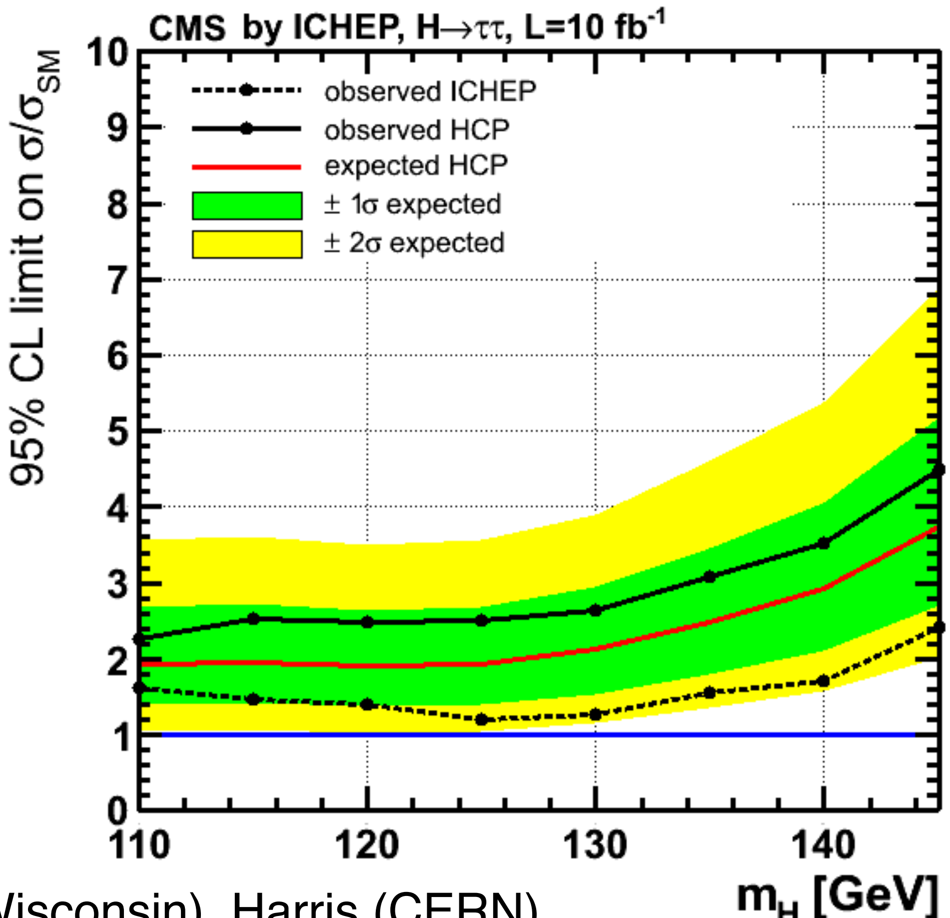
Consistent with SM H signal – large systematic band



Wolf (MIT), Friis (Wisconsin), Harris (CERN)

Change from ICHEP?

MVA MET vs PF MET; Simplified VBF; Updated Reco



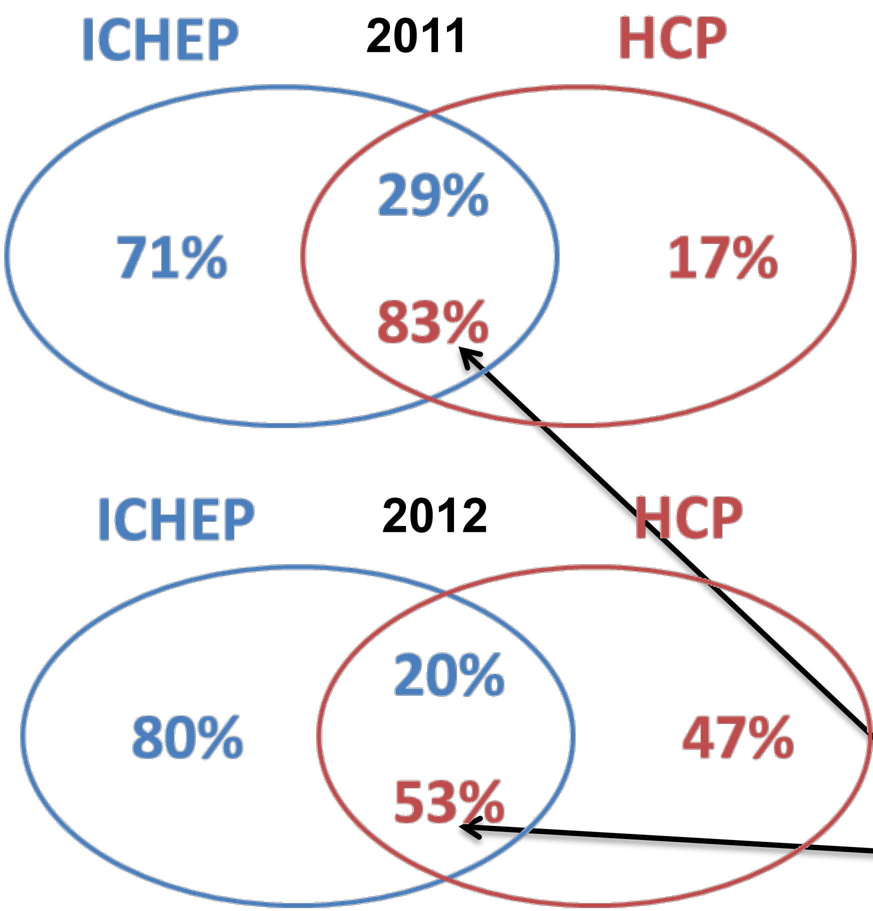
Results obtained from the same data set have changed ☹

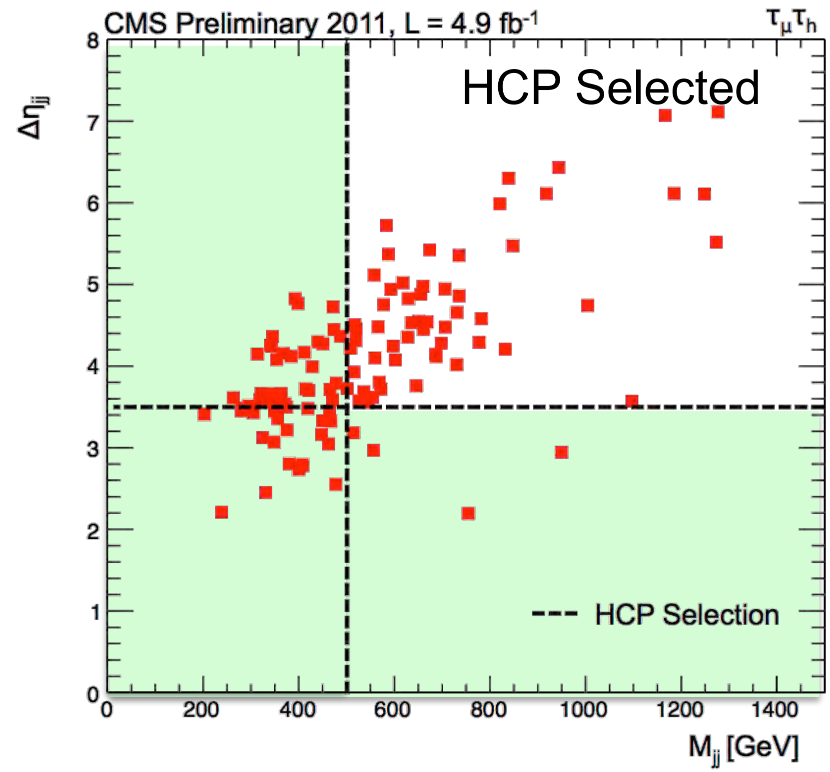
Wolf (MIT), Friis (Wisconsin), Harris (CERN)

Overlap of Events

Swanson (Wisconsin), Harris (CERN)

Small overlap ☹ -- however, reduced BGs in HCP





Worry: Re-reconstruction seems to have affected the results

SM Higgs Signal Strength

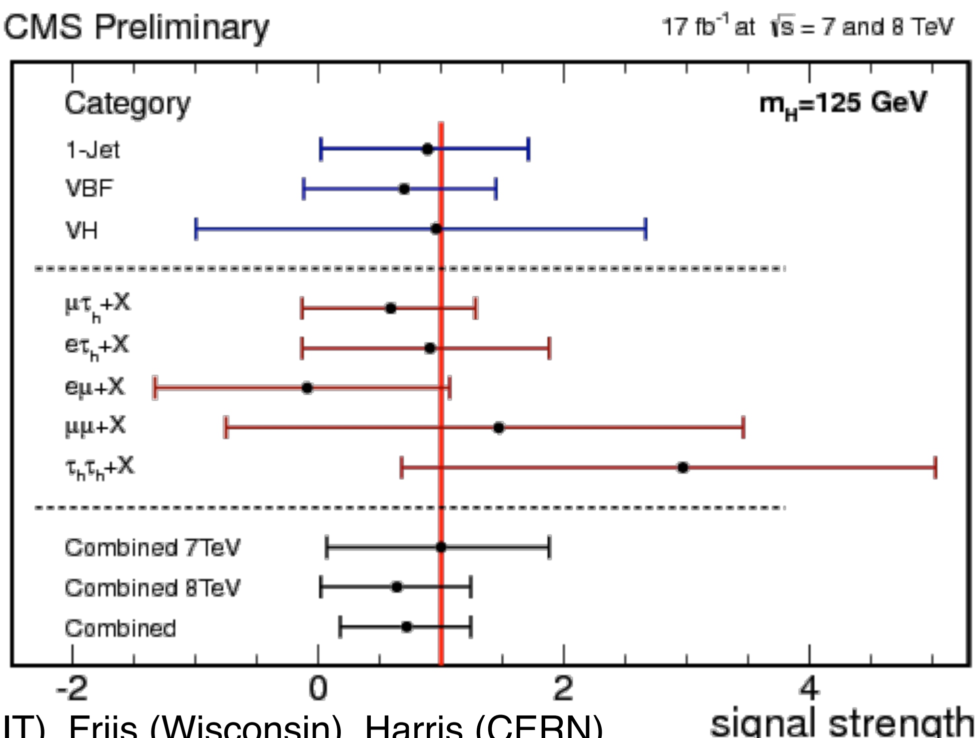
CMS HIG-12-043

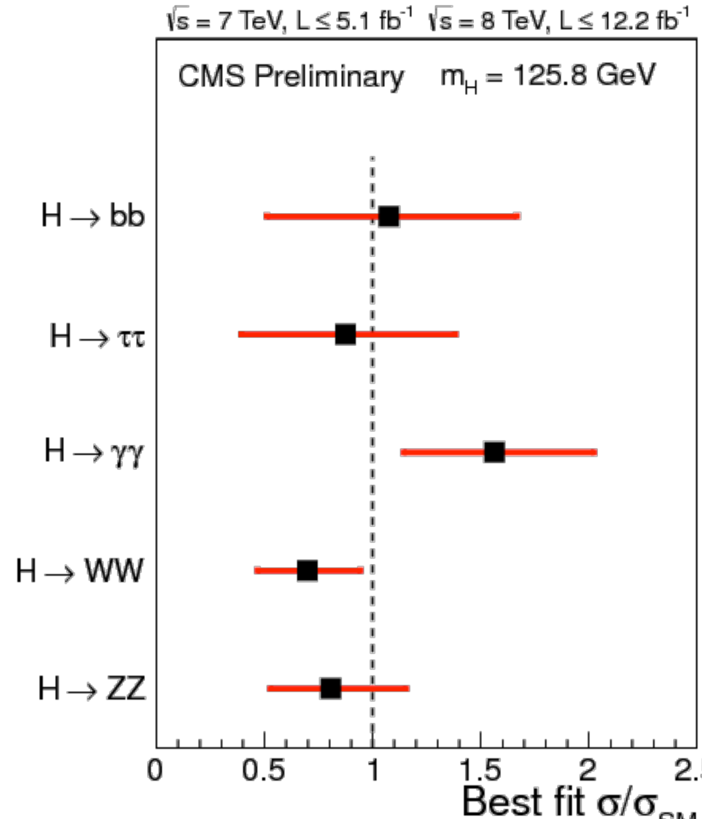
CMS HIG-12-045

Consistent with SM H and also zero ☹

~50% more statistics for final result from 2012

Need ~50 fb^{-1} at 14 TeV for 3-sigma observation





Wolf (MIT), Friis (Wisconsin), Harris (CERN)

Beyond the Standard Model

There are many possibilities that change the precise predictions of the minimal higgs sector of the Standard Model

- Fourth (heavy) generation of fermions modify H couplings
  - Enhances SM4 higgs cross section over SM
  - Already ruled out in entire parameter space with 2011 data
- Fermiophobic – fermion mass of different origin than higgs
  - Changes low mass higgs production & decays dramatically
  - Also ruled out for 126 GeV object
- Beyond minimal higgs doublet field
  - Two higgs doublet model (2HDM)
    - Multiple higgs bosons: 3 neutral and 2 charged
    - Minimal Supersymmetric Model (MSSM) requires 2HDM
  - NMSSM, triplets … have even more higgses
    - Very light pseudoscalar higgs, Doubly charged …
- This talk focuses on these non-standard higgs bosons

MSSM Higgs

Higgs sector in SUSY theory is more complicated

- Need 2 higgs doublets each with 4 degrees of freedom
  - Results in the Standard Model like Higgs (h^0)
  - Plus, two neutral higgs (A^0, H^0) and charged ($H^\pm$)
  - However, only 2 parameters (M_A, tanβ – ratio of the two doublets)
  - Masses of higgs and Z related
  - Search in (M_A, tanβ) plane

Neutral Higgs

– Look for ϕ=($h^{0,}$ A^0, H^0) in decays to tau-leptons

Charged Higgs

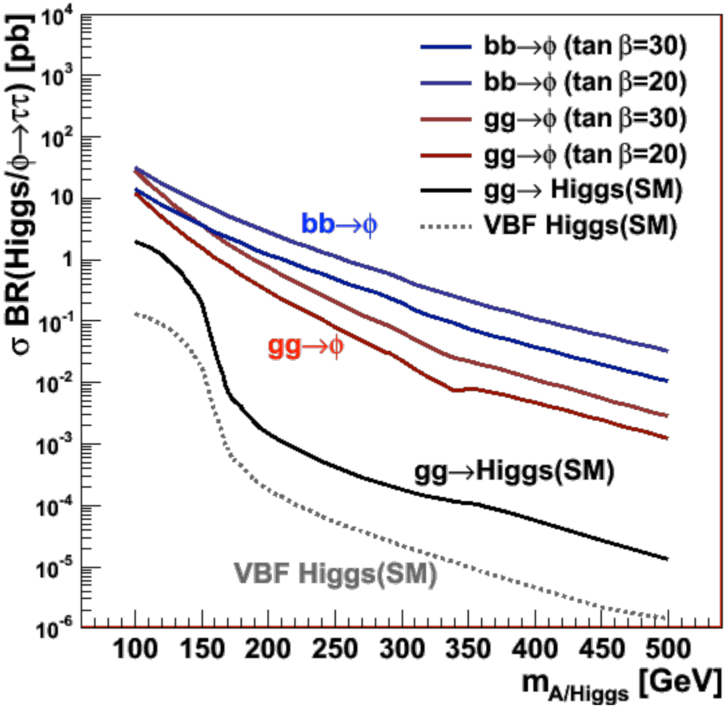
– Look for $H^\pm$ in top decays

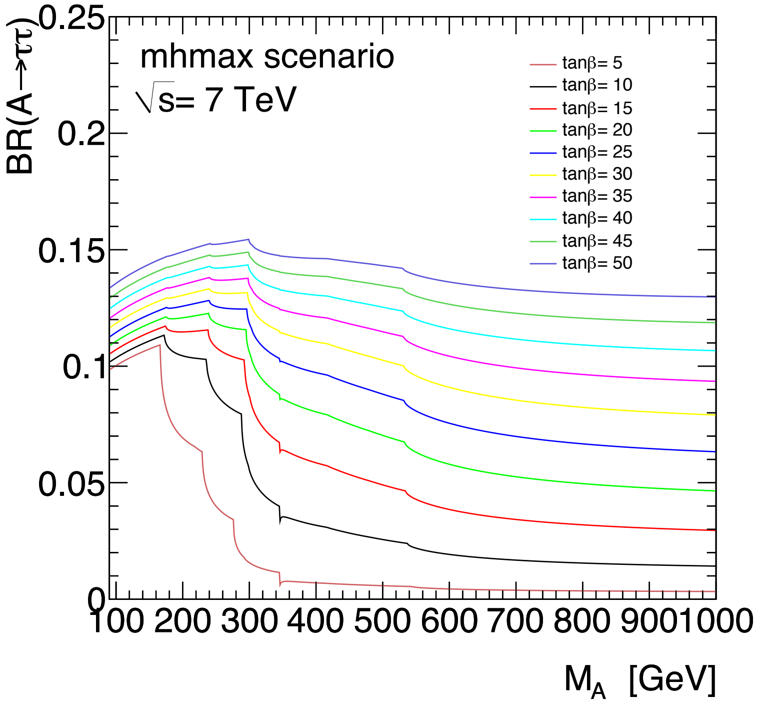
MSSM ϕ(h, H, A)

Use MHMAX Scenario

Enhanced coupling to b-quarks and τ-leptons

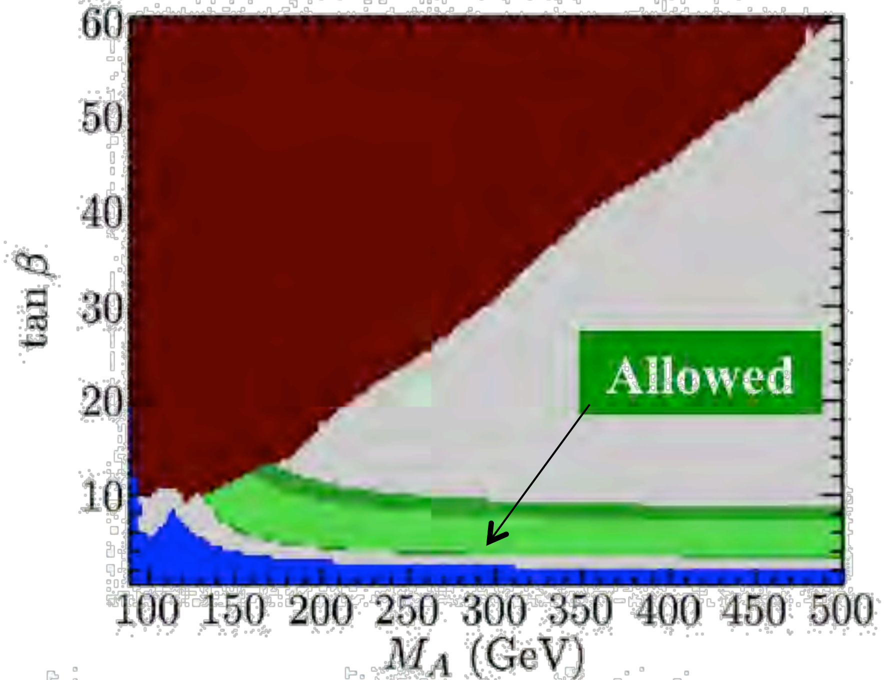
- Production rate enhanced × $\tan^2\beta$
  - Gluon fusion with b,t loops + associated b quark production
- Decays to b-quark and τ-lepton pairs enhanced at all masses





Implications of SM Like H126 on MHMAX scenario

Phys. Lett. B 710 (2012) 201



Interpret as CP-even light h with
$123 < M_h < 127$ GeV
(theoretical uncertainty on $M_h + m_{top}$)

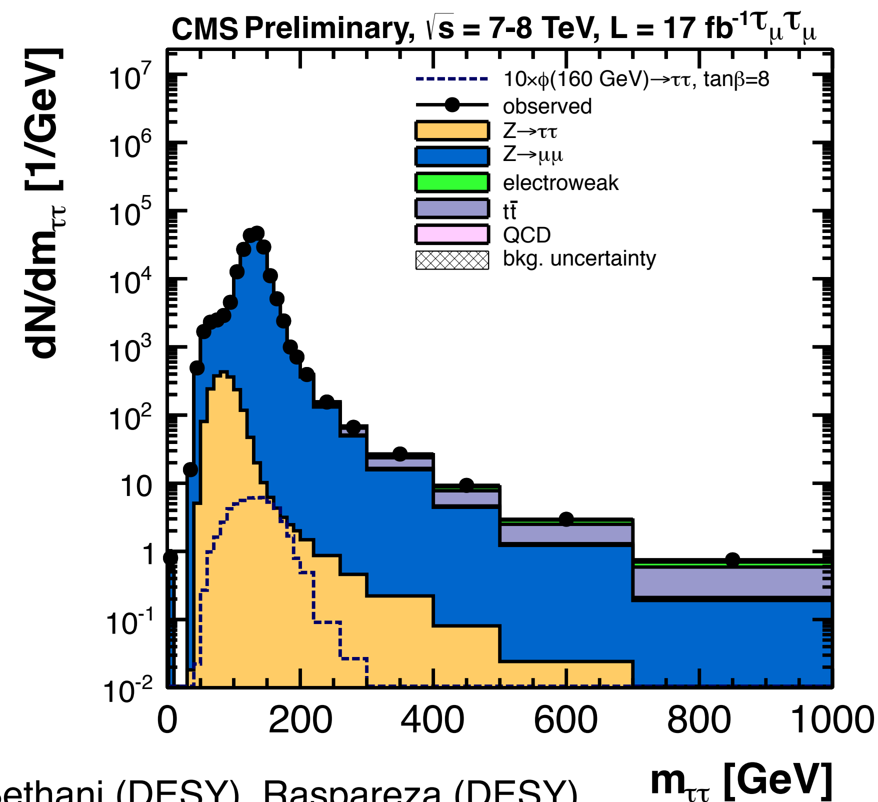
Allowed region strip in M_A-tanβ

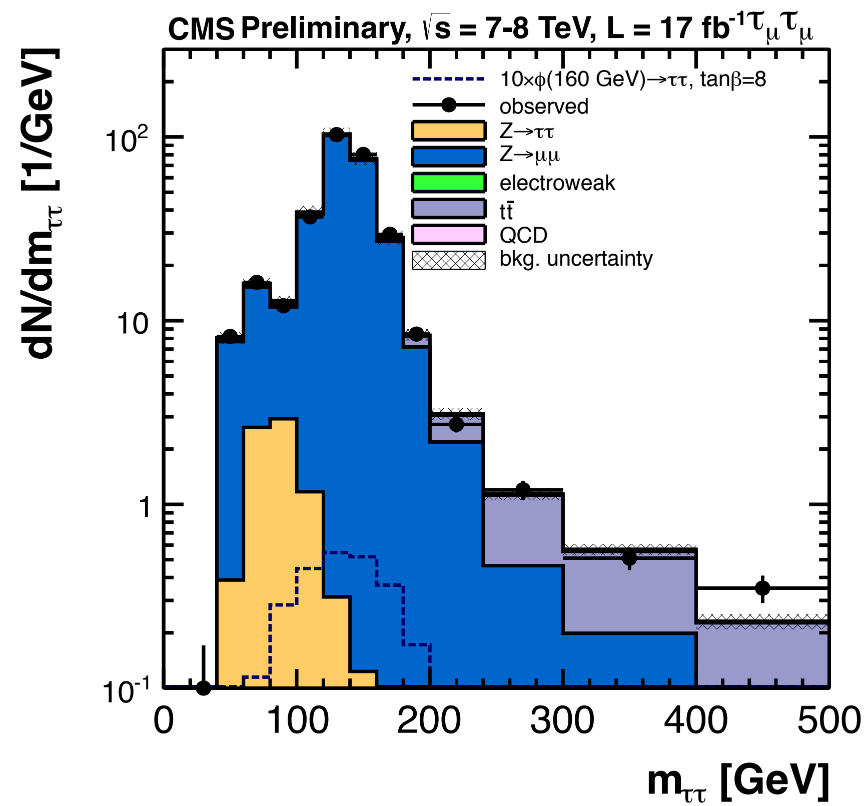
mhmax scenario

Mass of ττ : 17 fb^{-1} Data

CMS HIG-12-051

Tau pairs reconstructed in decays to leptons (e or μ) + hadrons (1 or 3 prong) or two leptons (eμ)
Kinematic fit to obtain tau pair mass – used to search for H to ττ contribution
Two categories: non-b-tagged and b-tagged to enhance bbϕ





Bethani (DESY), Raspareza (DESY)

Mass of ττ : 17 fb^{-1} Data

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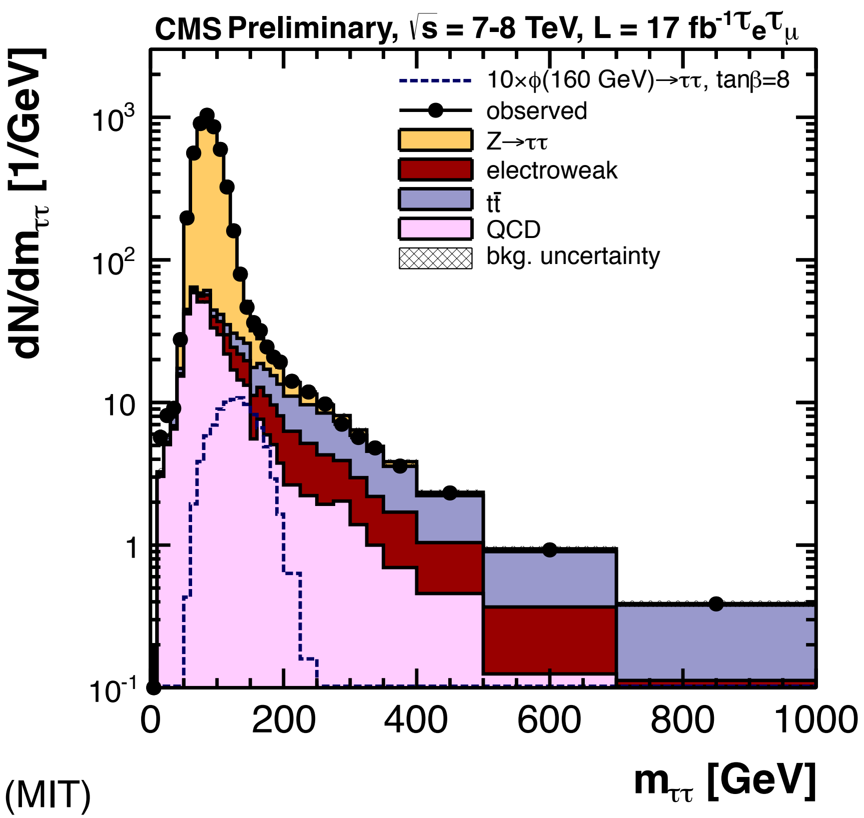

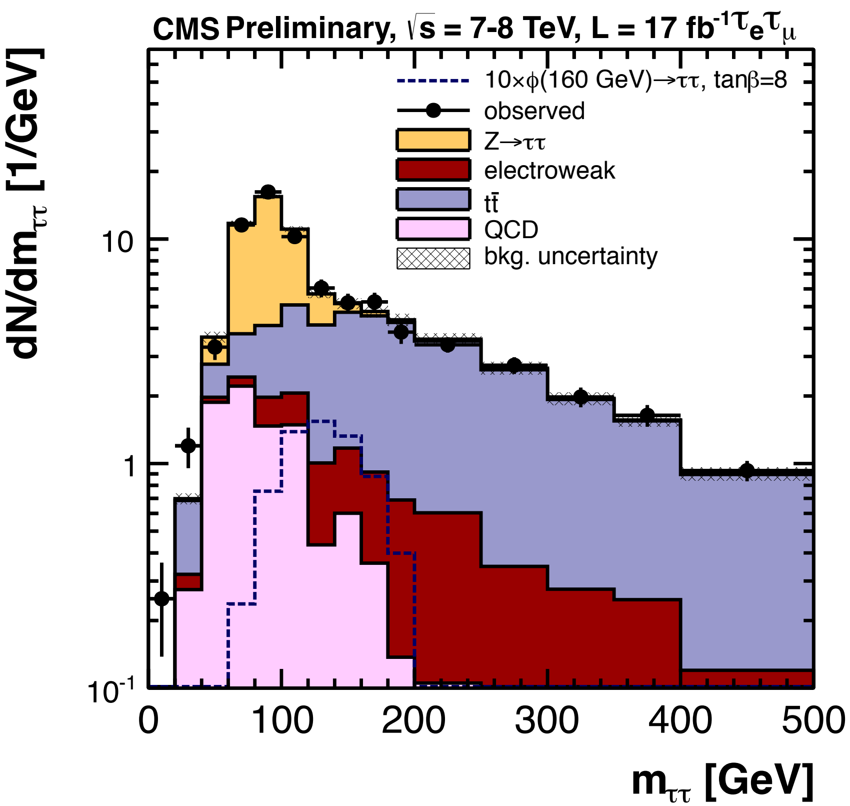

Dutta (MIT)

Mass of ττ : 17 fb^{-1} Data

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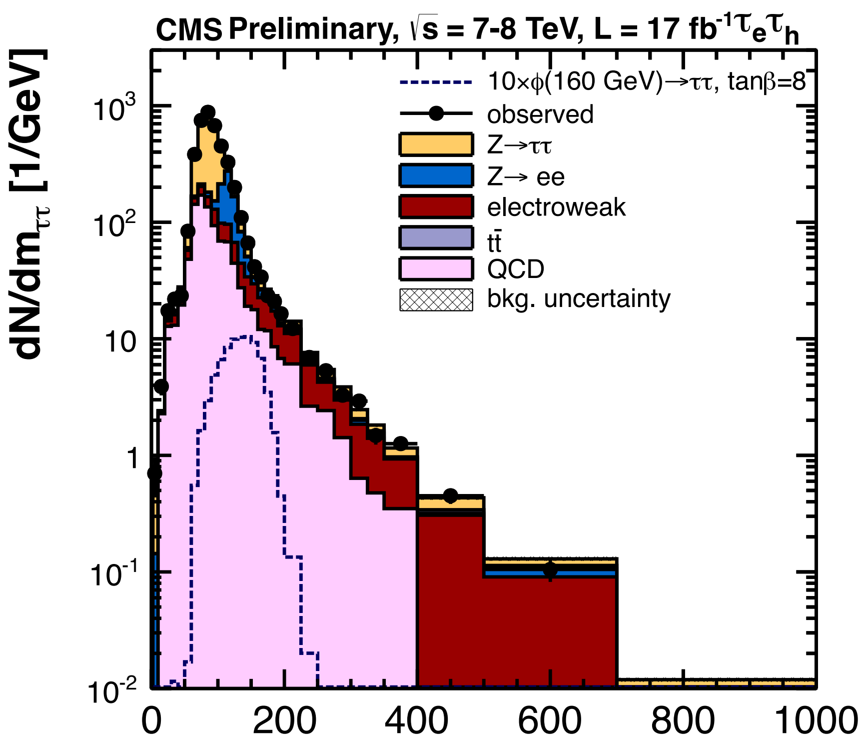

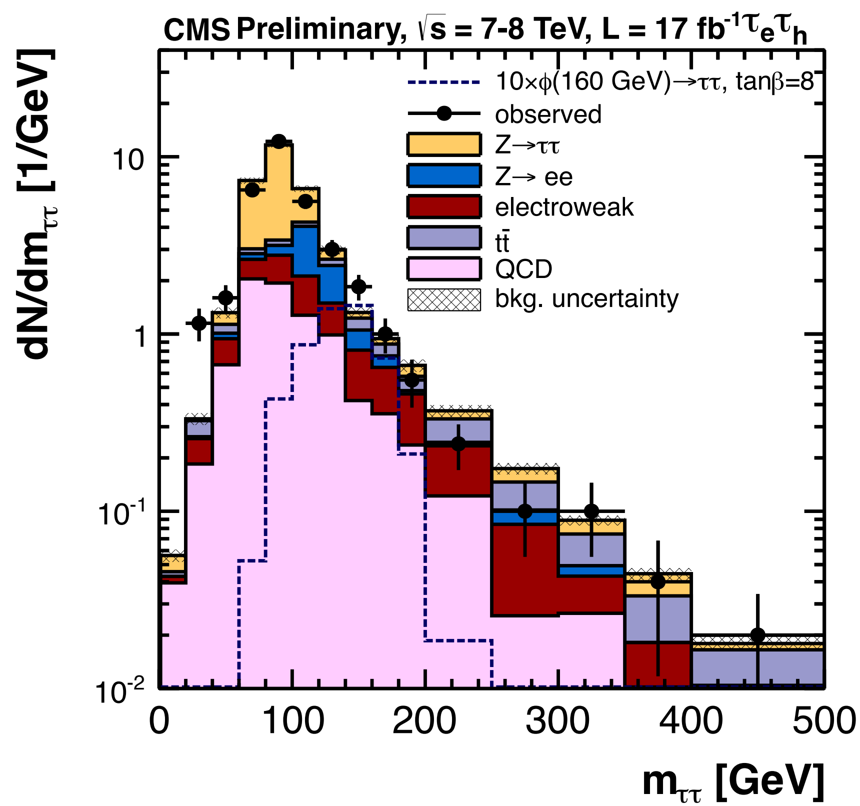

Swanson (Wisconsin), Gilbert (Imperial)

Mass of ττ : 17 fb^{-1} Data

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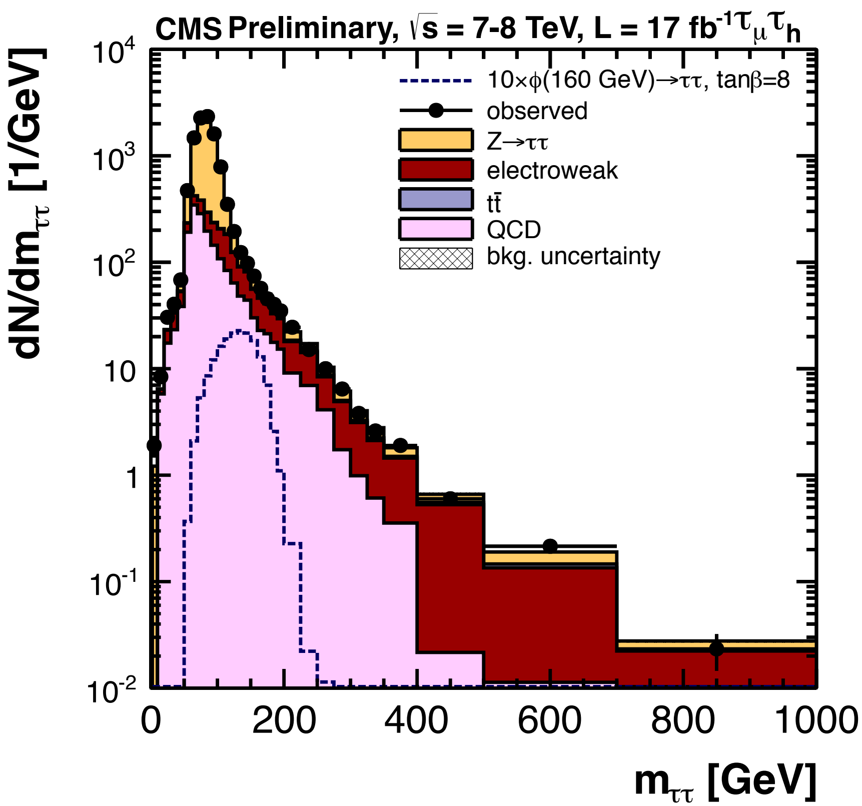
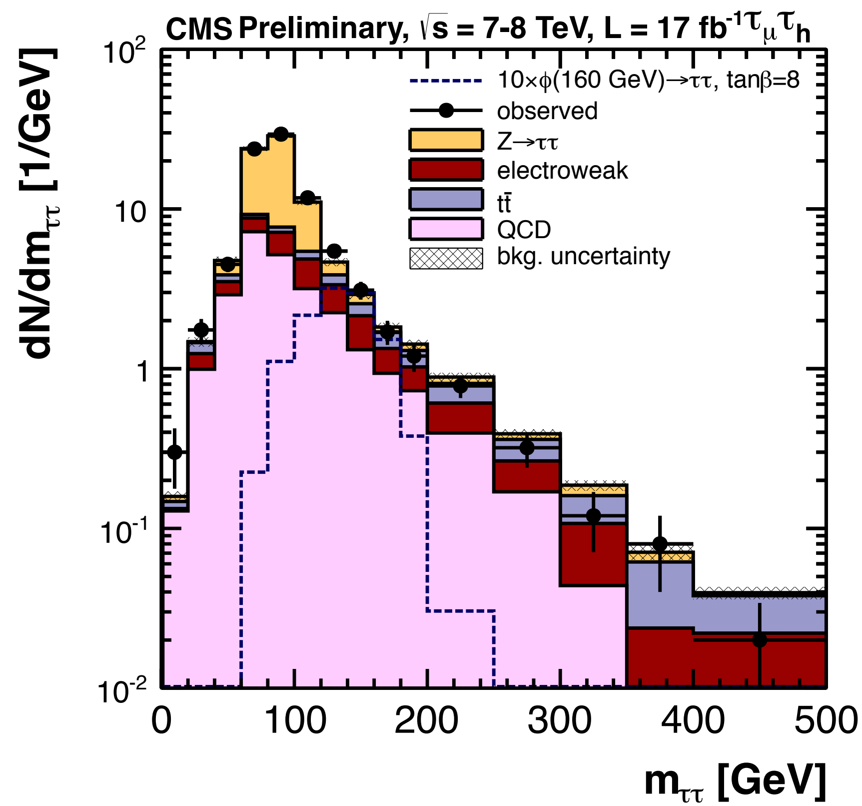
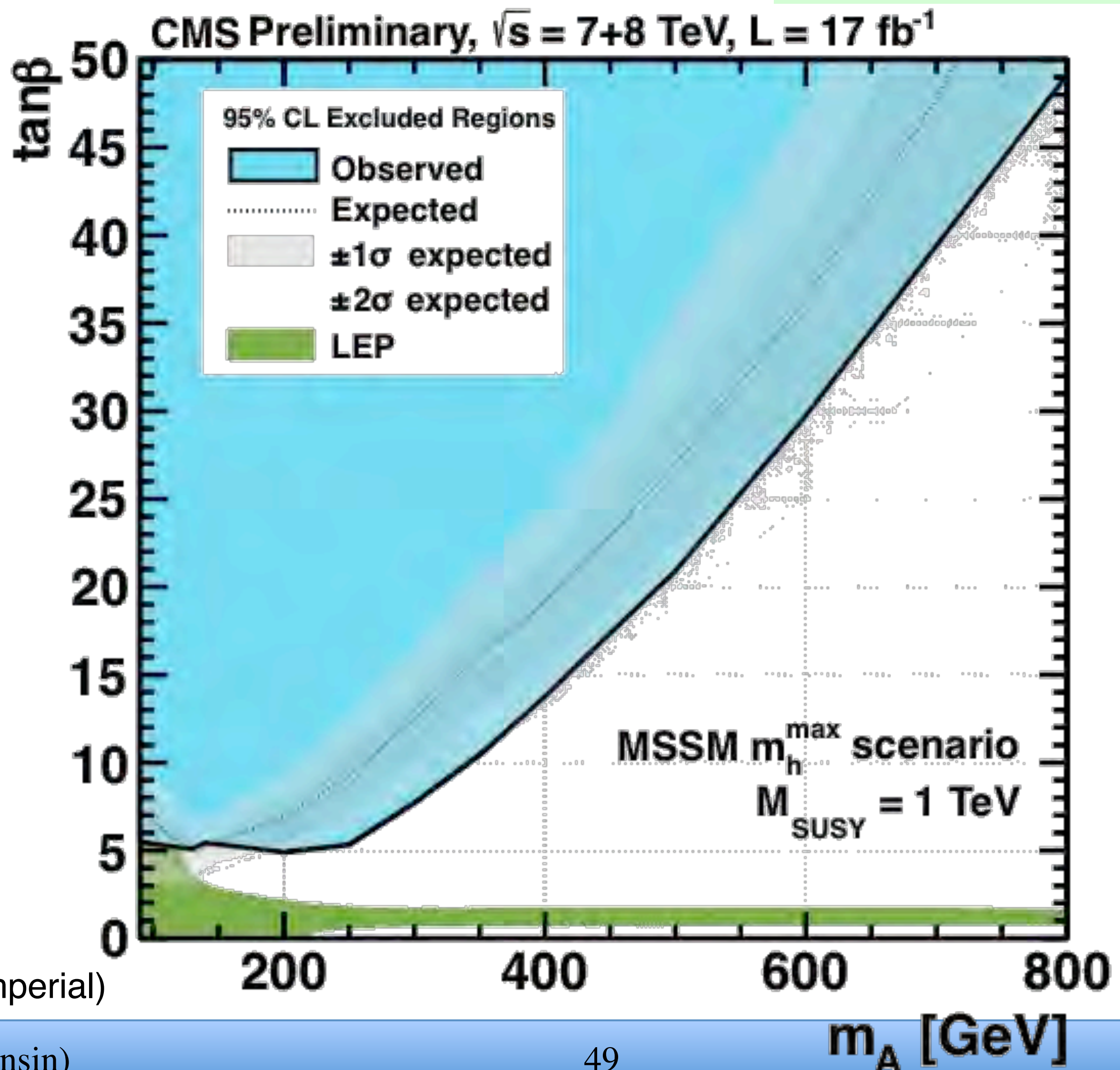




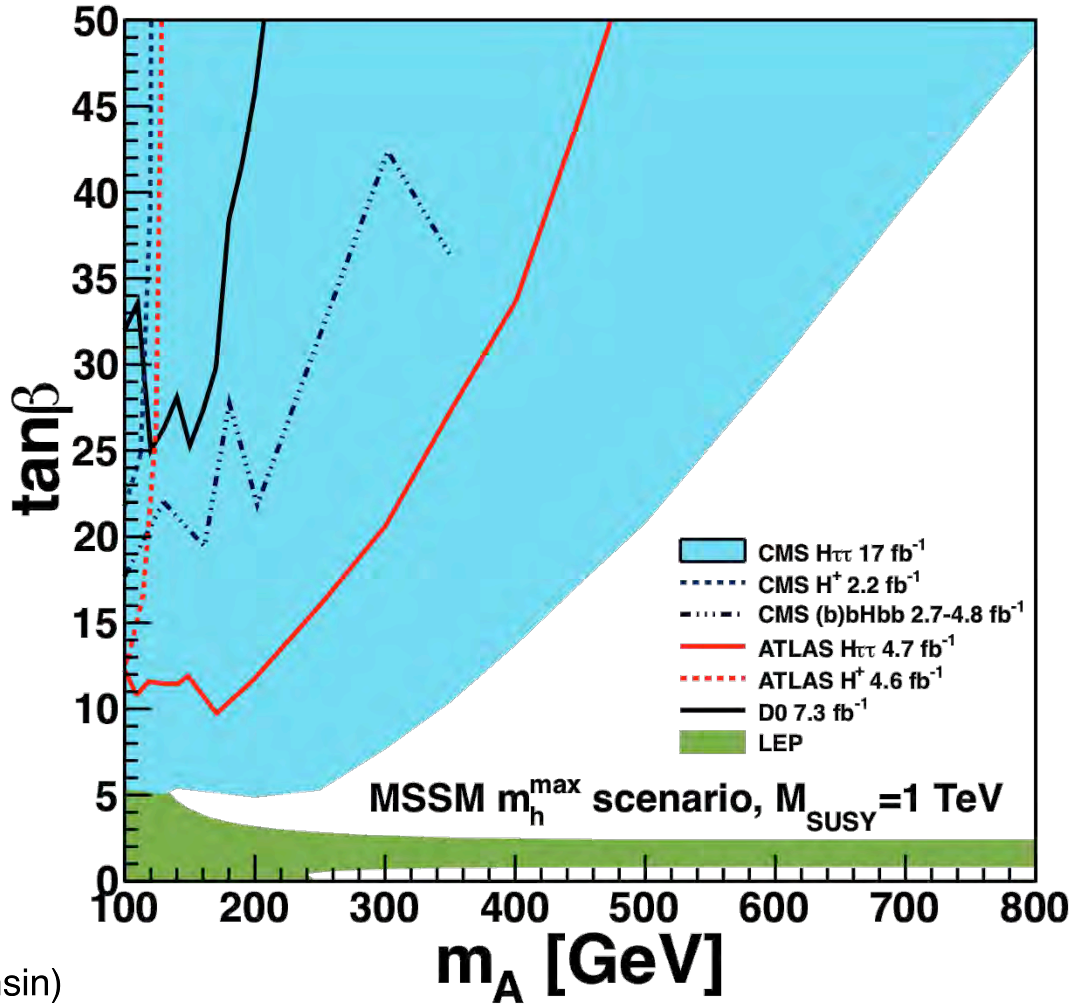
Limit in m_A-tanβ Plane

CMS HIG-12-051



Wolf (MIT),
Friis (Wisconsin),
Vazquez Acosta (Imperial)

MSSM Higgs Summary



Friis (Wisconsin)

CMS PAS HIG-11-019

ATLAS CONF 2012-11

CMS PAS HIG-12-026
CMS PAS HIG-12-027

CMS PAS HIG-12-050

Summary

LHC discovered a new particle
- Both ATLAS & CMS see the same thing at the same mass
- Updated evidence in Z-pair decay mode is excellent

Is it the Standard Model Higgs Boson?
- It is a boson – because it decays to bosons
- Its mass is in the right window – consistency with SM
- However, its properties are yet to be determined to confirm that it is the SM Higgs Boson, 0^+ slightly favored
- Not confirmed yet if the new boson couples to taus ☹
- Fermion channels are consistent with it being SM Higgs

LHC has performed well in 2012 but will be down 2013-2014
- Both experiments collected > 20 fb^{-1} in 2012
- Should be able to update with 50% more data in Spring 2013
- It will take ~50 fb^{-1} 14 TeV to confirm SM Higgs to taus, 2015-2016?
- If it is not SM like Higgs, it will be even more exciting!