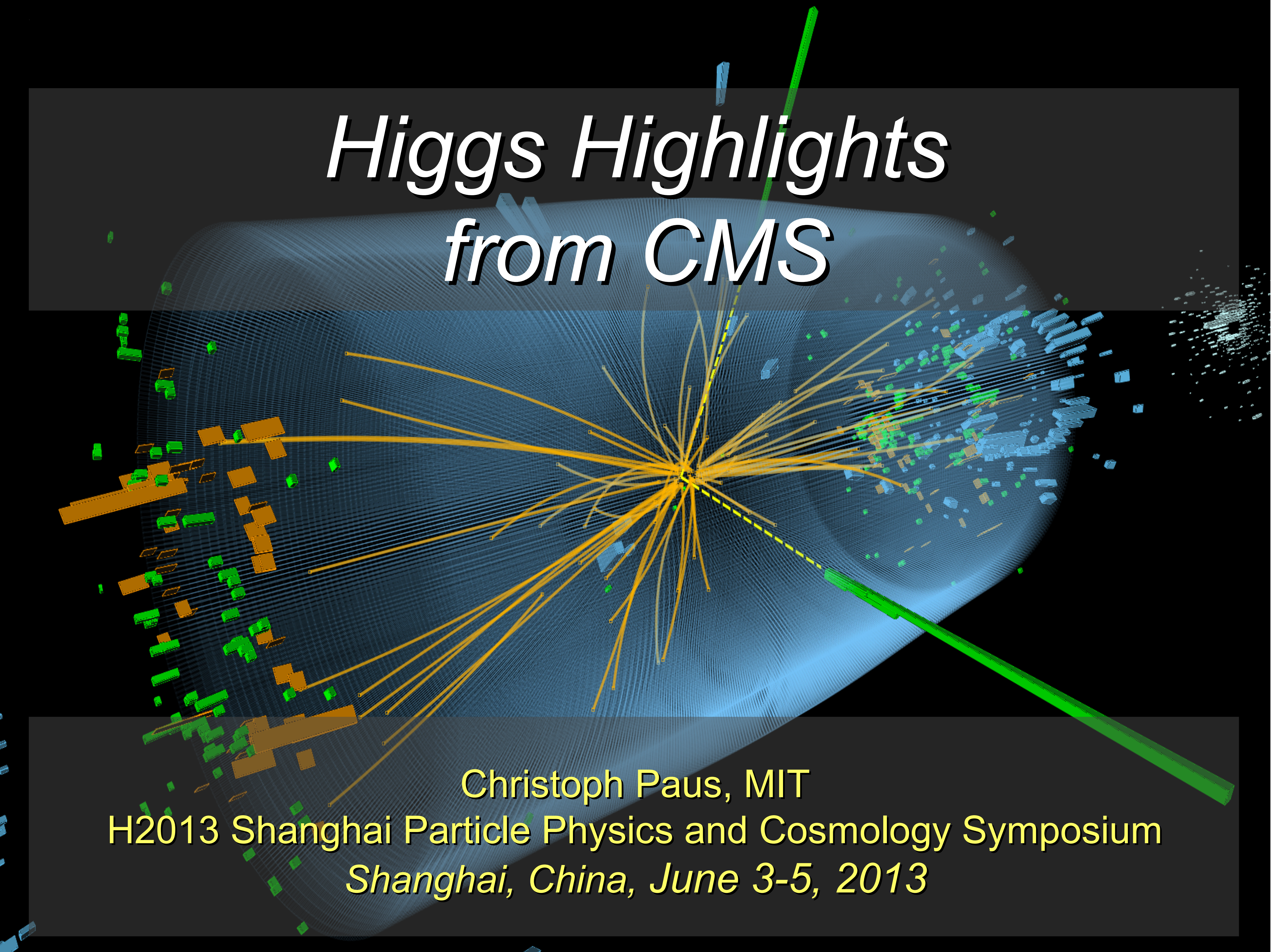


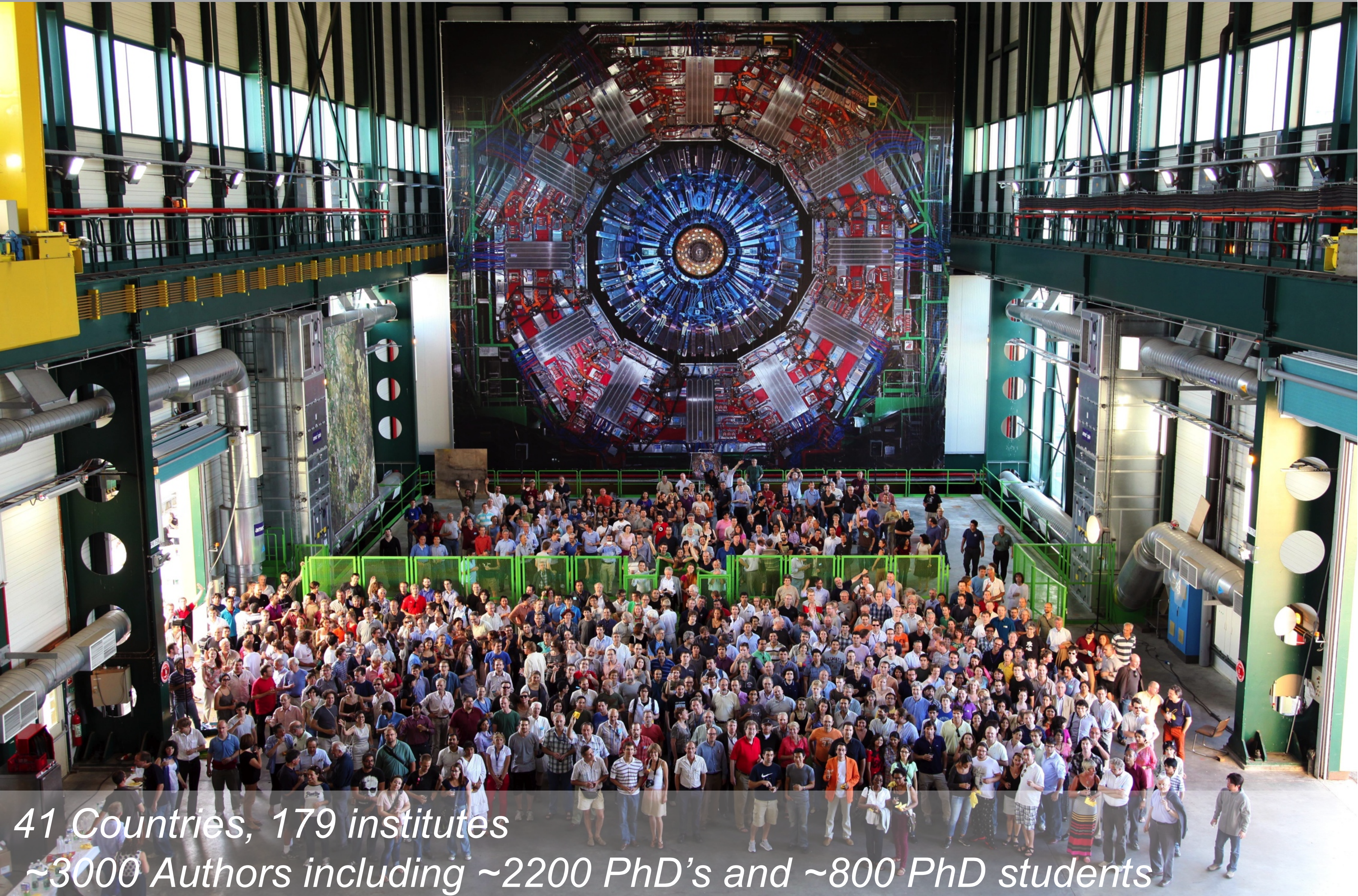
Higgs Highlights from CMS

Christoph Paus, MIT

H2013 Shanghai Particle Physics and Cosmology Symposium

Shanghai, China, June 3-5, 2013

Speaking on behalf of the CMS Collaboration



41 Countries, 179 institutes

~3000 Authors including ~2200 PhD's and ~800 PhD students

Historic Event: CERN–Melbourne

CERN

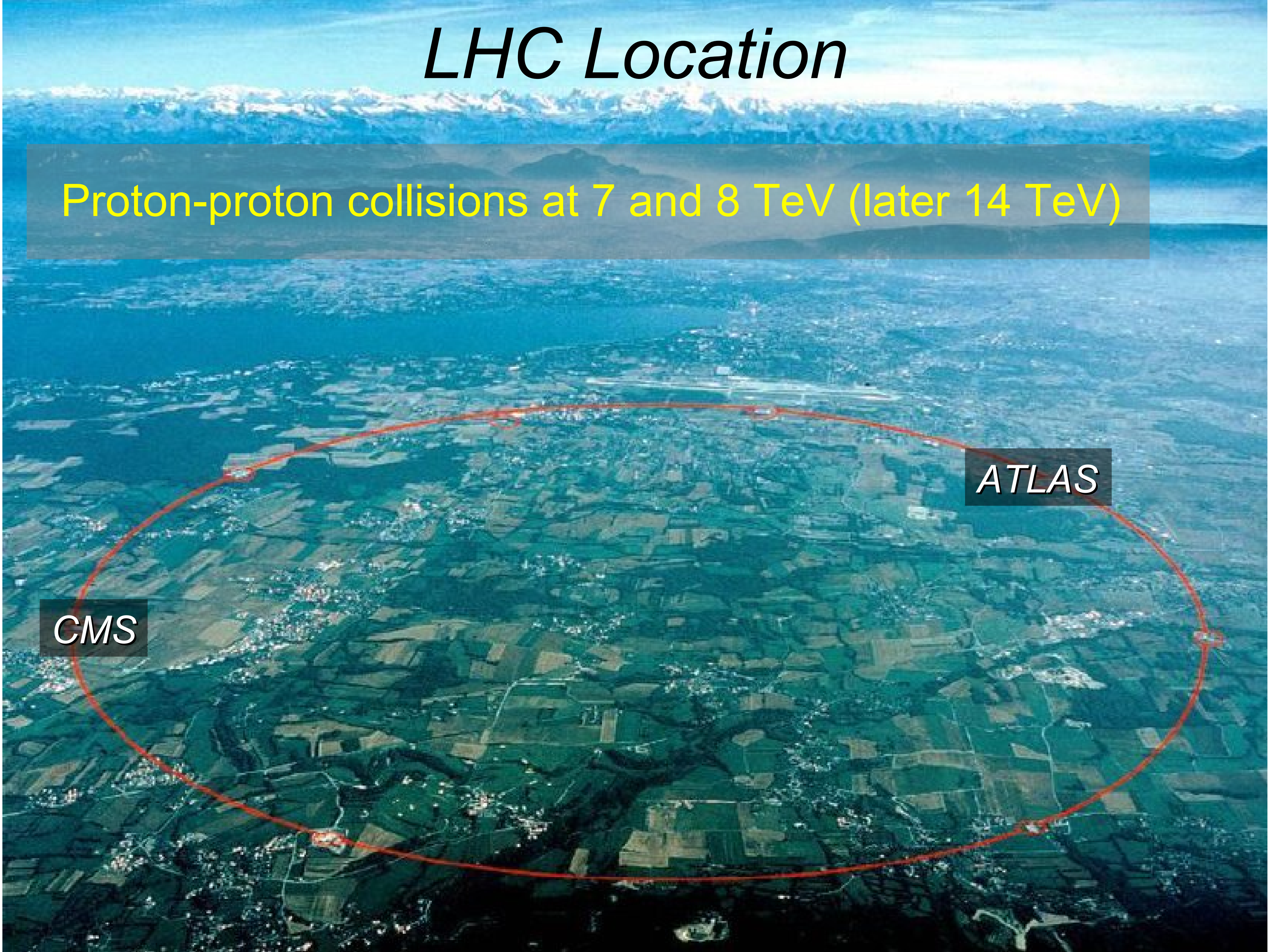
Melbourne

Rolf Heuer:

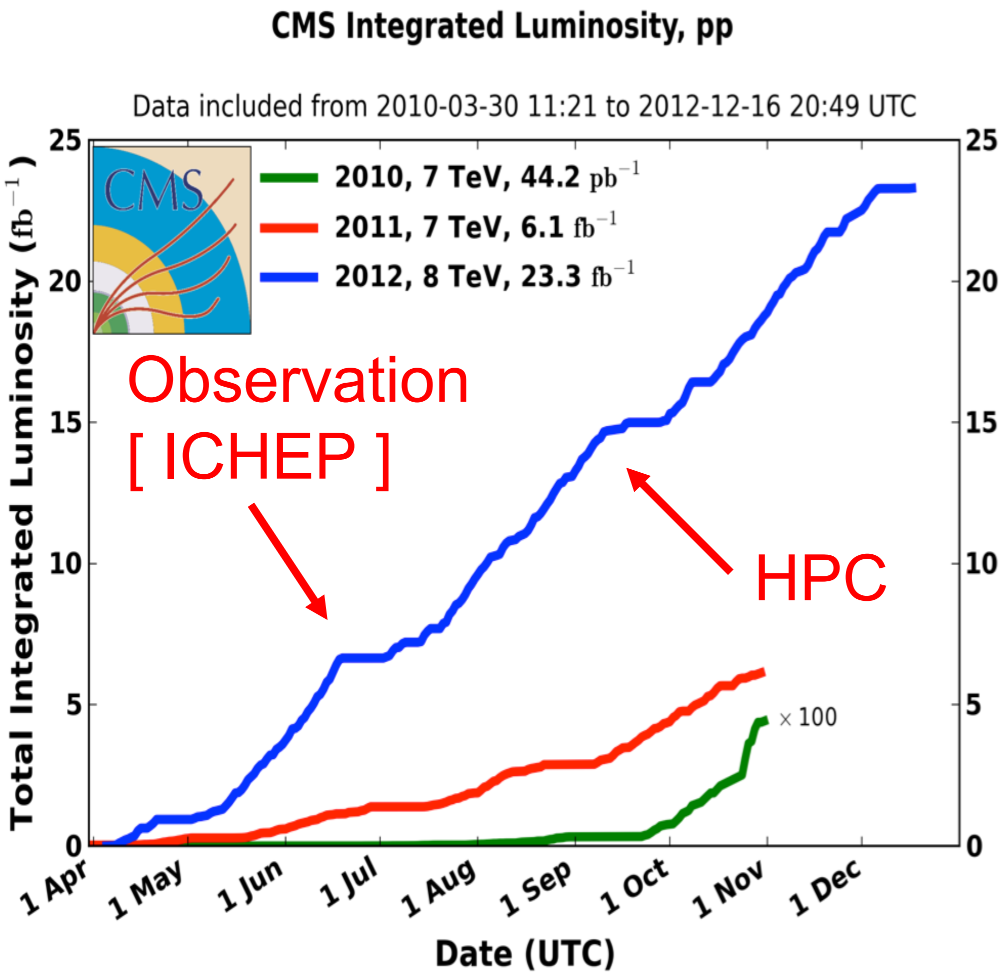
'We have it!'

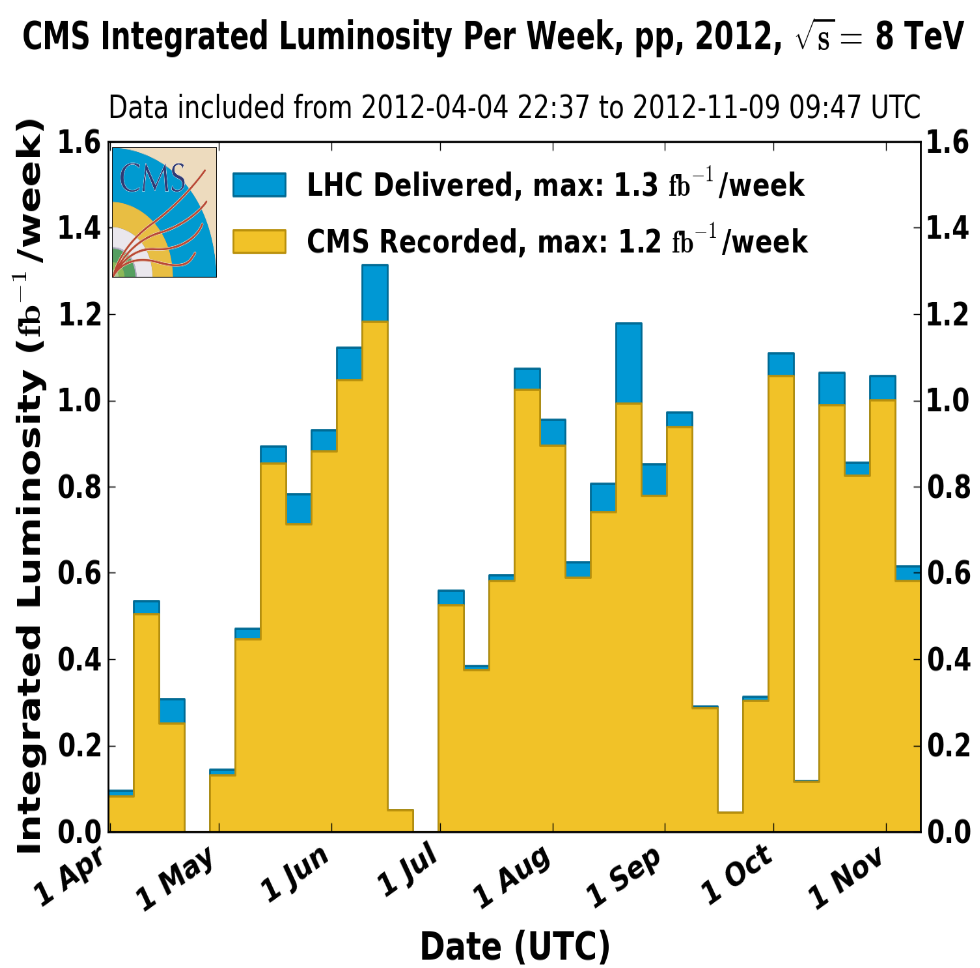
4th of July 2012 – new Higgs–like particle discovery

LHC Location



Delivered and Recorded Collisions

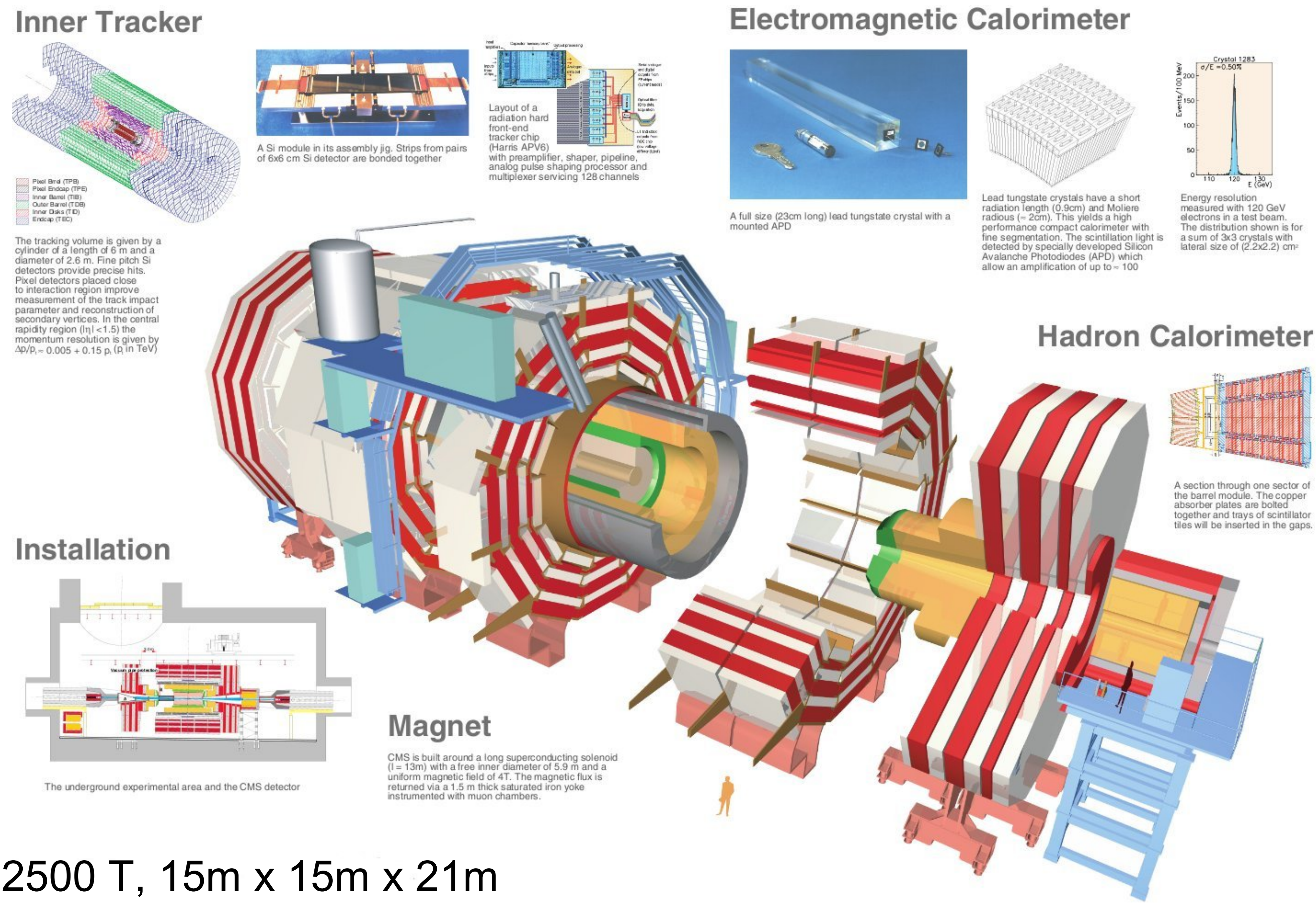




LHC performs better than expected – **thank you!!**

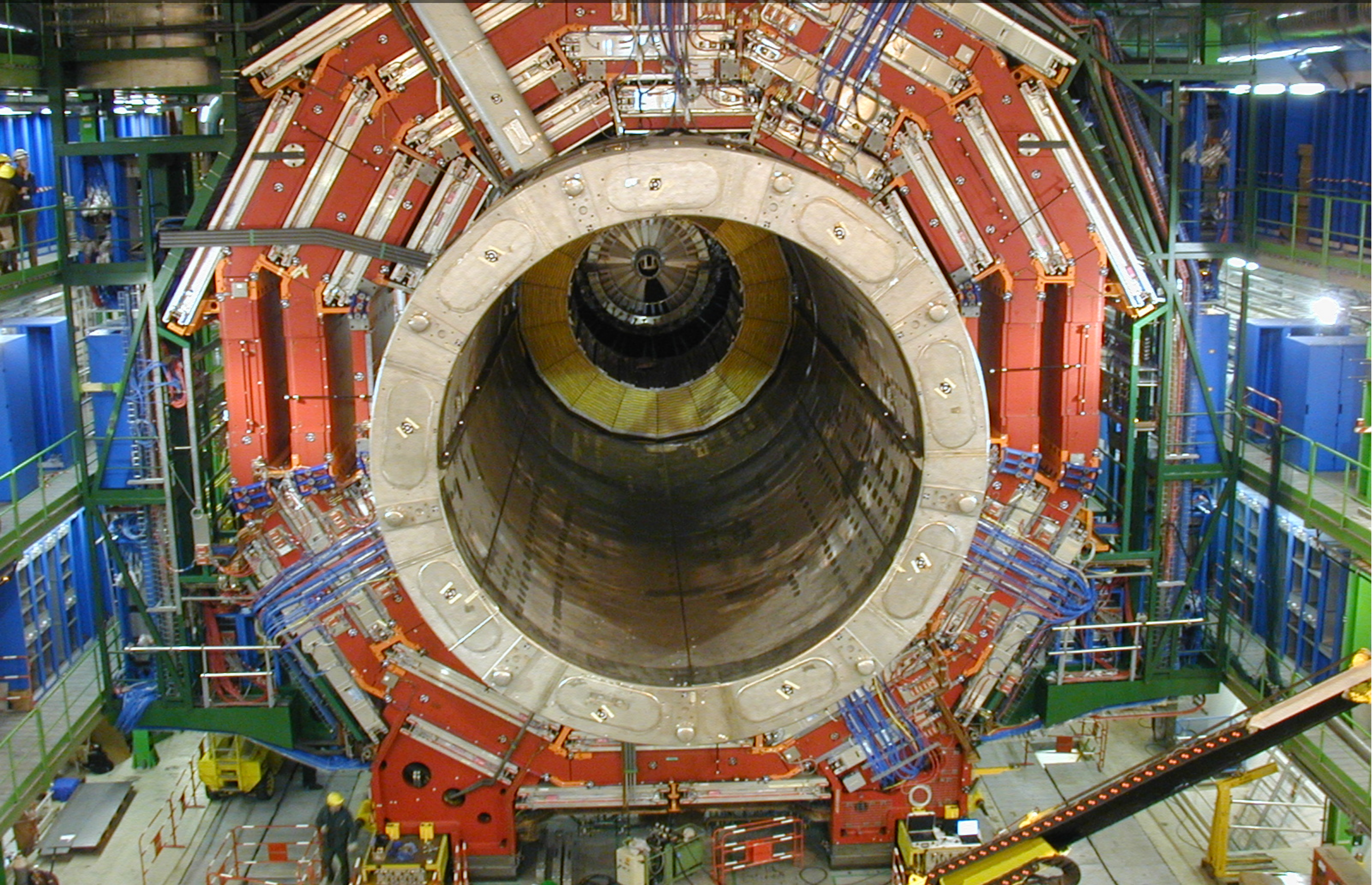
- all results based on ~ 20/fb at 8 TeV (2012)
- and ~ 5/fb used at 7 TeV (2011)

CMS Overview



12500 T, 15m x 15m x 21m

CMS Detector in the Cavern



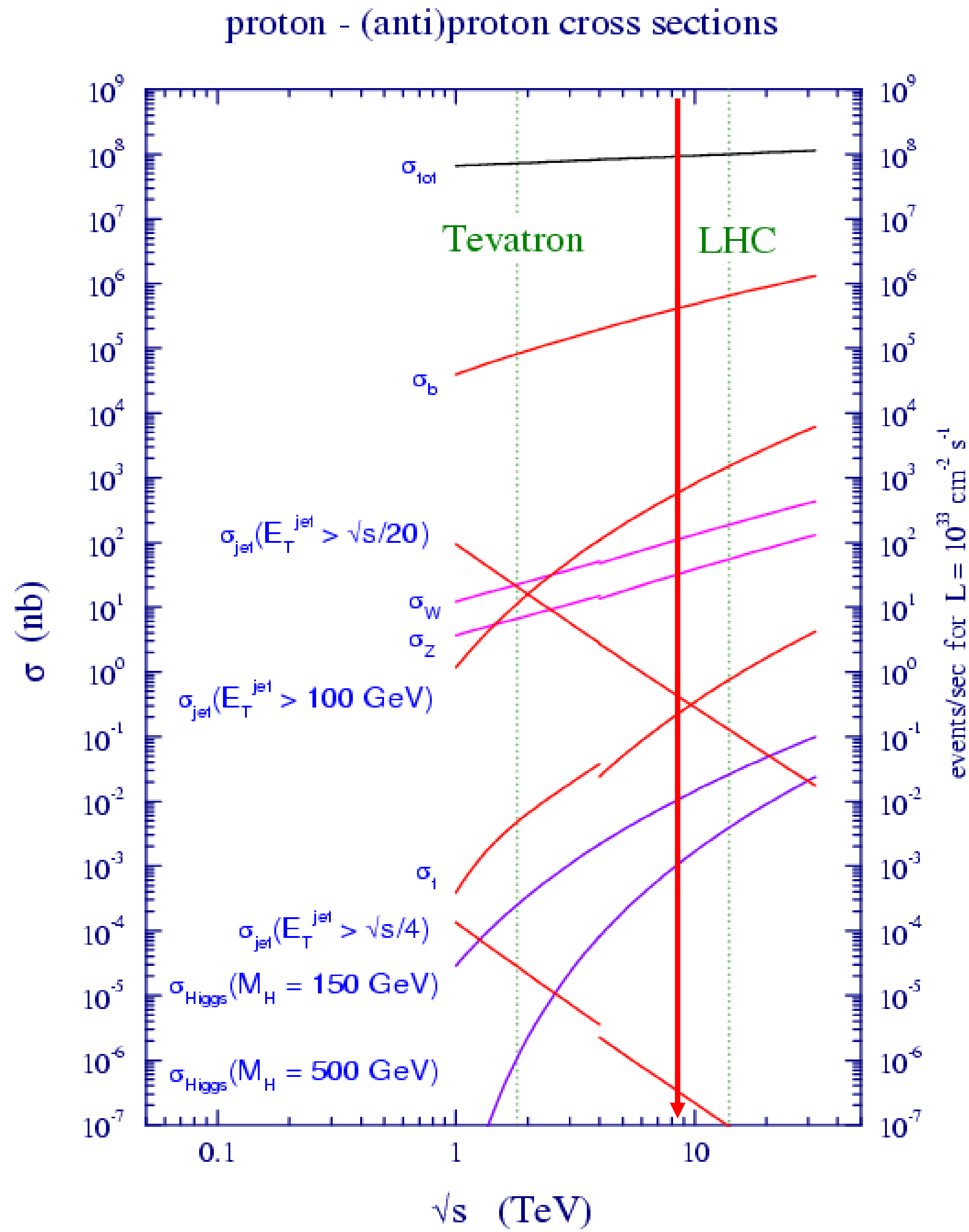
Higgs Hunting Basics

Physics processes

- production relative to σ_{tot}:
  - *bb* at 10^{-3},
  - $W \rightarrow \ell\nu$ at 10^{-6} and
  - *Higgs* (*m*=110 GeV) at ~10^{-11}
- 32 MHz beam crossing, only about 300 Hz tape writing: $1/10^5$
- fast and sophisticated selection process essential: trigger

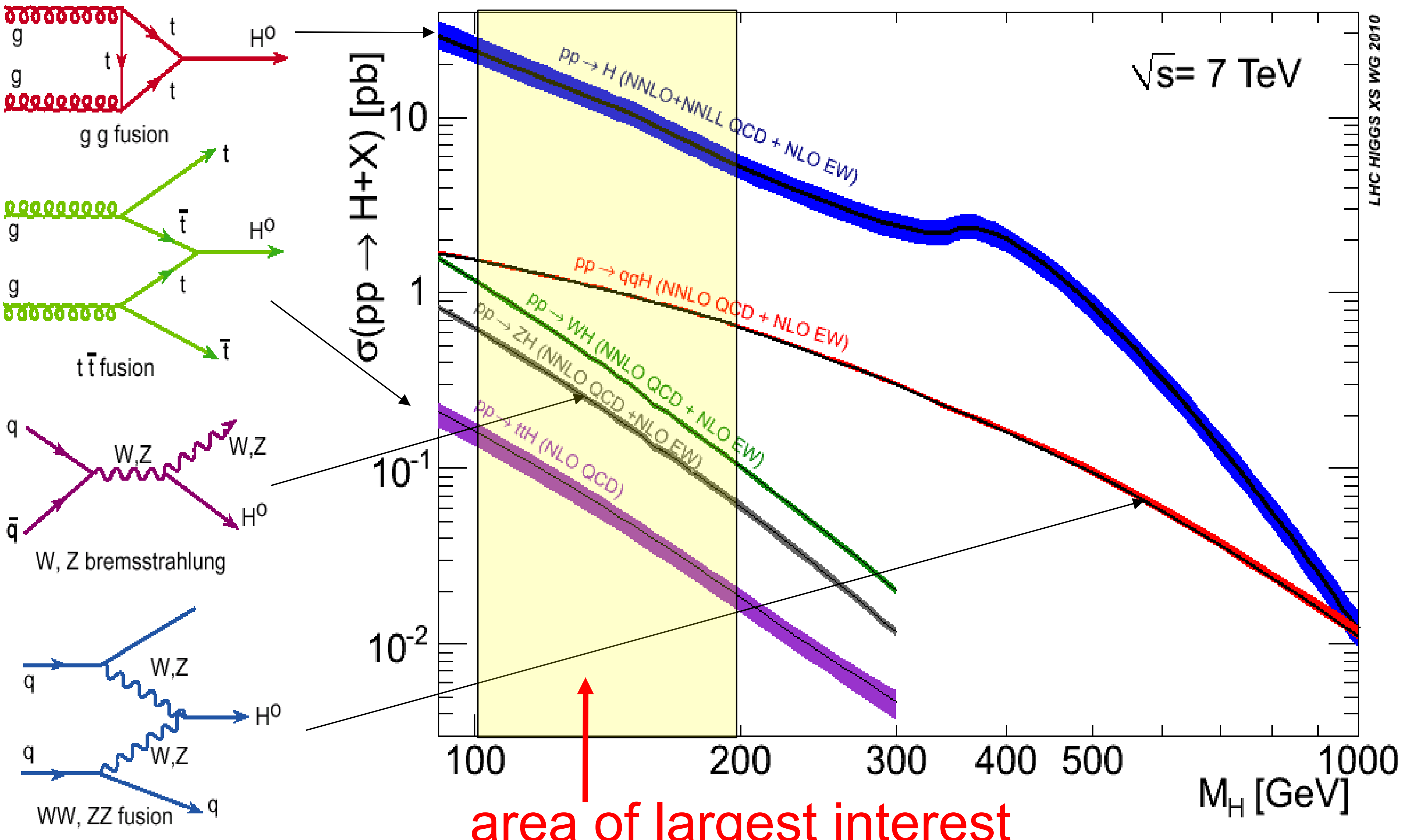
Trigger

- trigger has to work: otherwise no useful data registered
- already in first data taking: rate enormous and trigger important
- core trigger organization: use electron, muon, jet and energy signatures

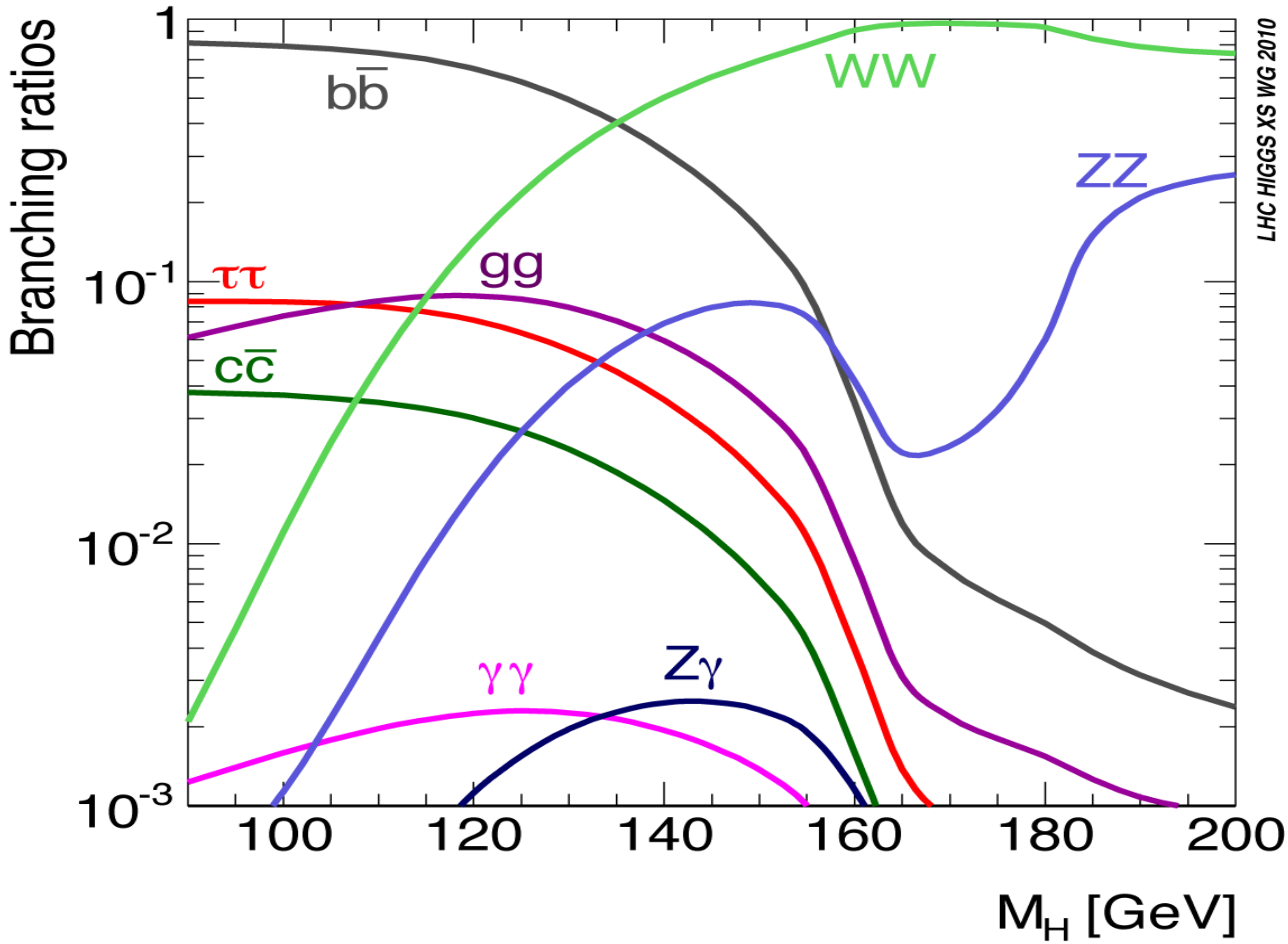


Higgs Production at the LHC

Higgs production in proton-proton collisions



Higgs Decays



Higgs boson couples to mass

Messy: many channels, many subsequent decays *etc. etc.*

- common: leptons/photons essential for any search
- 5 channels are most promising

Higgs Hunting – The big five

Overview – The big five

Channel	m_H range [GeV/c^2]	data set [fb^{-1}]	Data used CMS [fb^{-1}]	m_H resolution
1) $H \rightarrow \gamma\gamma$	110-150	5+20/fb	2011+12	1-2%
2) $H \rightarrow$ tau tau	110-145	5+20/fb	2011+12	15%
3) $H \rightarrow$ bb	110-135	5+20/fb	2011+12	10%
4) $H \rightarrow WW \rightarrow l\nu l\nu$	110-600	5+20/fb	2011+12	20%
5) $H \rightarrow ZZ \rightarrow 4l$	110-1000	5+20/fb	2011+12	1-2%

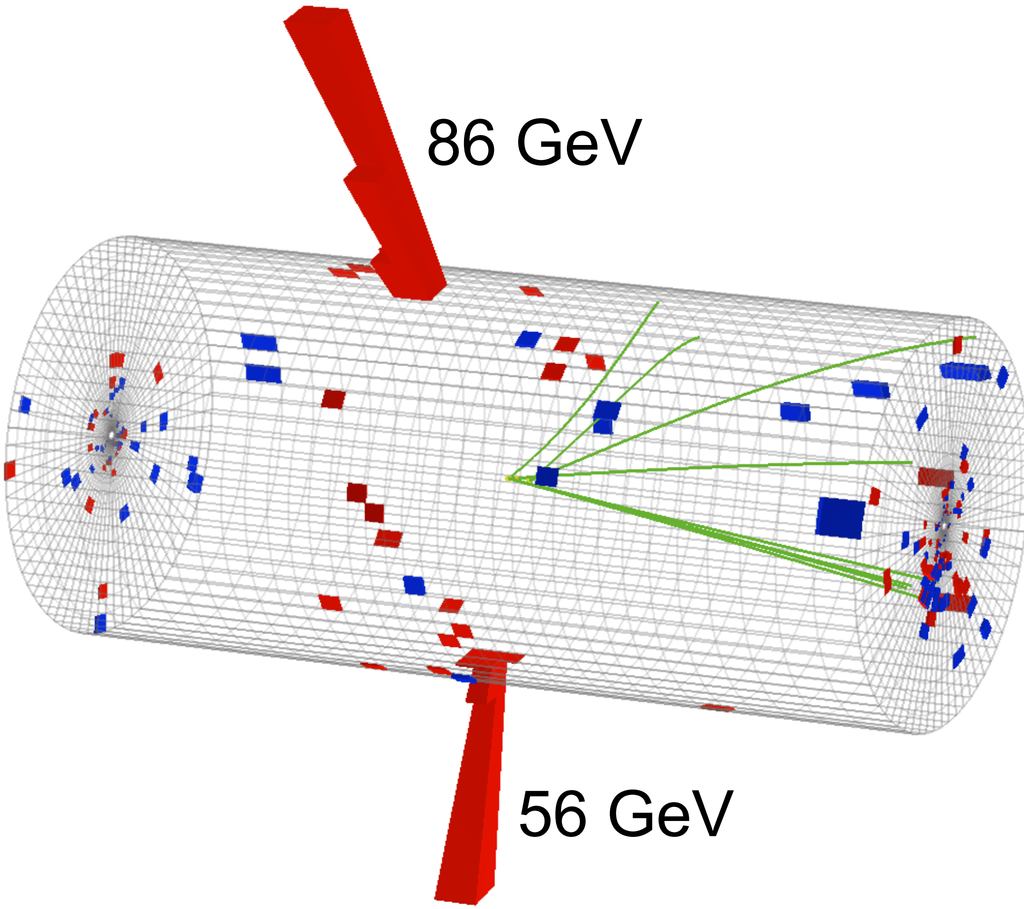
Performance – The big five

	Significance (m_H = 125.7 GeV)		
Combination	Expected (pre-fit)	Expected (post-fit)	Observed
$H \rightarrow ZZ$	7.1 σ	7.1 σ	6.7 σ
$H \rightarrow \gamma\gamma$	4.2 σ	3.9 σ	3.2 σ
$H \rightarrow WW$	5.6 σ	5.3 σ	3.9 σ
$H \rightarrow bb$	2.1 σ	2.2 σ	2.0 σ
$H \rightarrow \tau\tau$	2.7 σ	2.6 σ	2.8 σ
$H \rightarrow \tau\tau$ and $H \rightarrow bb$	3.5 σ	3.4 σ	3.4 σ

The new particle is of course still there

- analyses sensitivities have steadily increased (large part due to improved techniques)
- some fluctuations in the observed signal significance

Low Mass Specialist: $H \rightarrow \gamma\gamma$



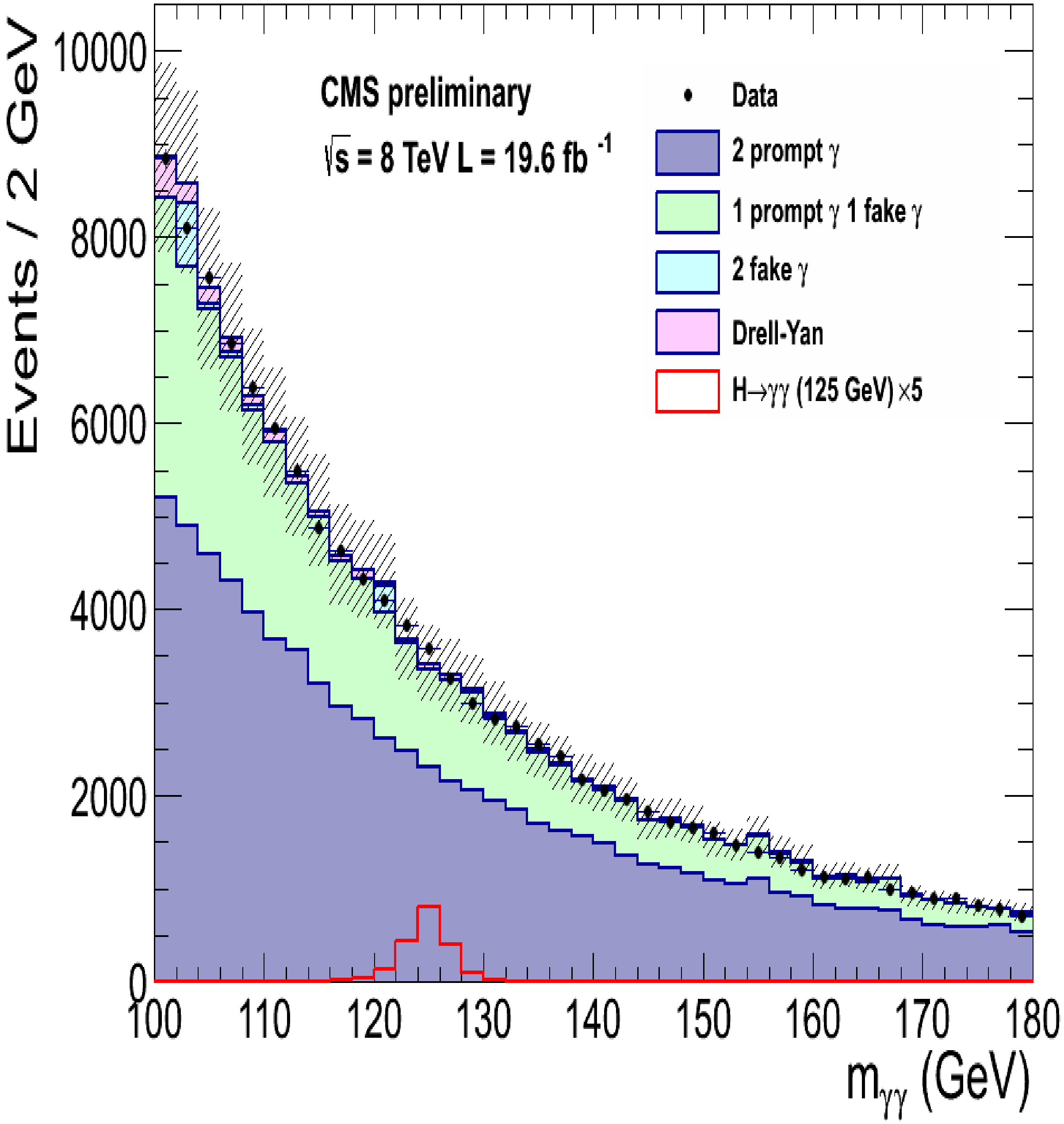
Signature and background

- two high momentum photons
- low mass Higgs narrow
- two photon resolution excellent
- looking for narrow peak
- large irreducible background from direct two photons
- smaller fake photon background

Key analysis features

- energy resolution is almost everything: calibrate and optimize
- rejection of fake photons and optimized use of kinematics

Low Mass Specialist: $H \rightarrow \gamma\gamma$

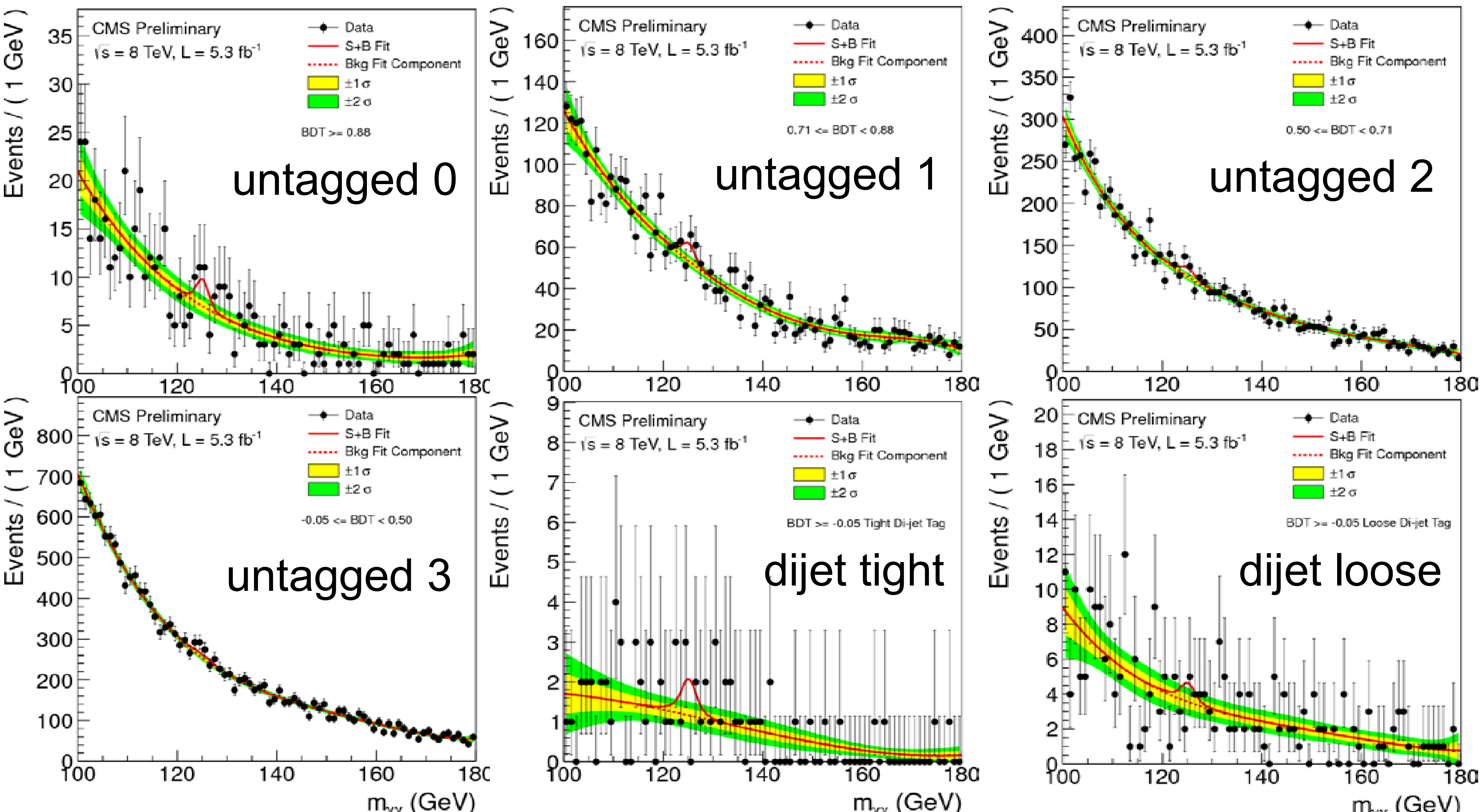


Data MC comparison

- only used for illustration
- general agreement
- fake/real photons about: 30%/70%
- perform analysis in optimized 4 categories
- idea: separate well measured from less well measured photons
- assume smooth background shape: no MC needed for mass fit

Low Mass Specialist: $H \rightarrow \gamma\gamma$

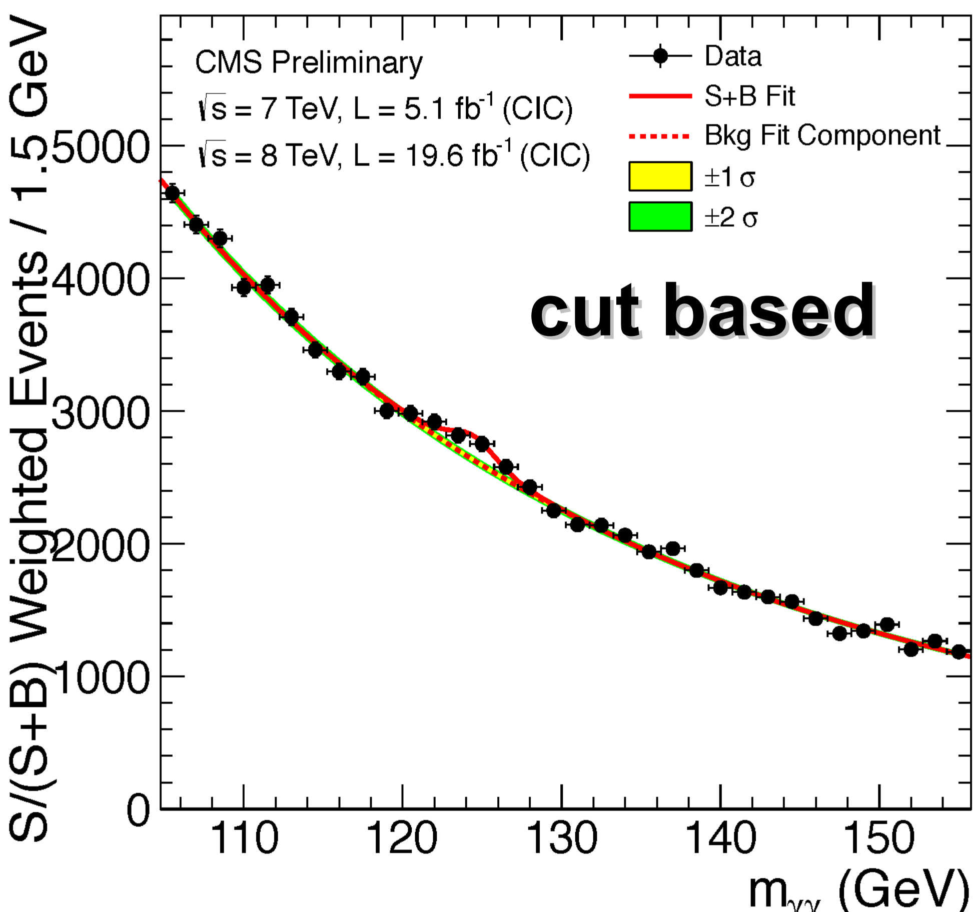
Key idea: use categories to separate events in good resolution and good B/S

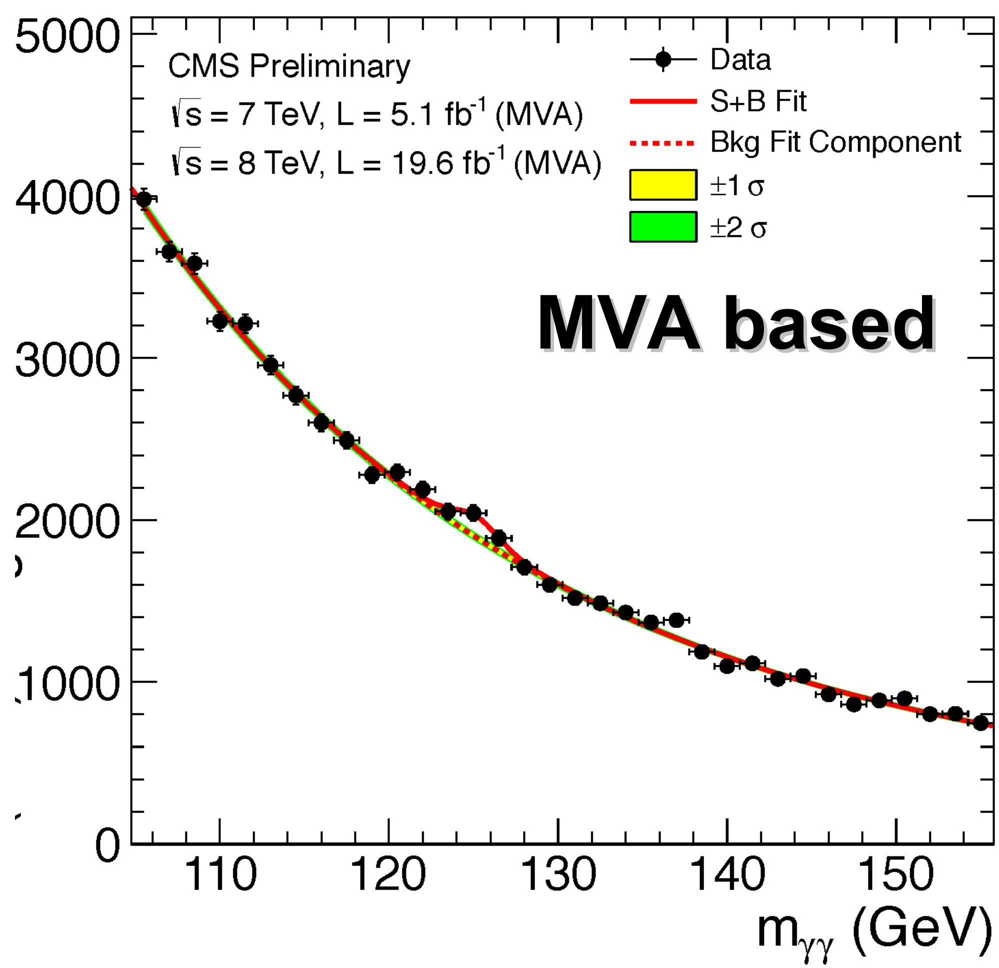


Low Mass Specialist: $H \rightarrow \gamma\gamma$

Combined plots.... illustrating effective peaks

- nice peak appeared over continuous background
- MVA and cut based analysis show an excess

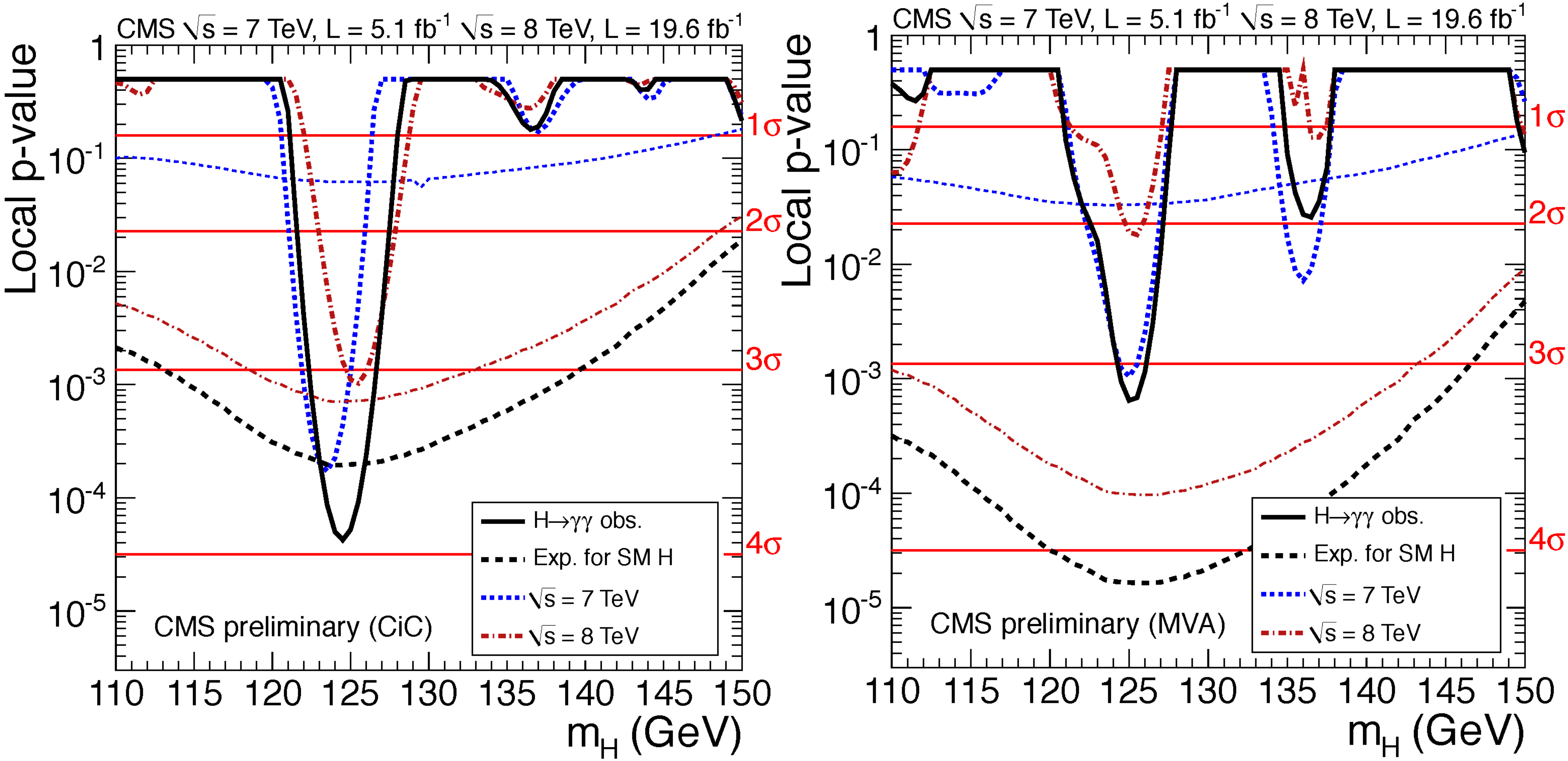




Low Mass Specialist: $H \rightarrow \gamma\gamma$

Significance of the observed signal

- consistent result between the two analysis
- mild surprise: observed significance better for cut-based analysis
- perfect example: selection of analysis must be *a priori*



Low Mass Specialist: $H \rightarrow \gamma\gamma$

How consistent are the various categories?

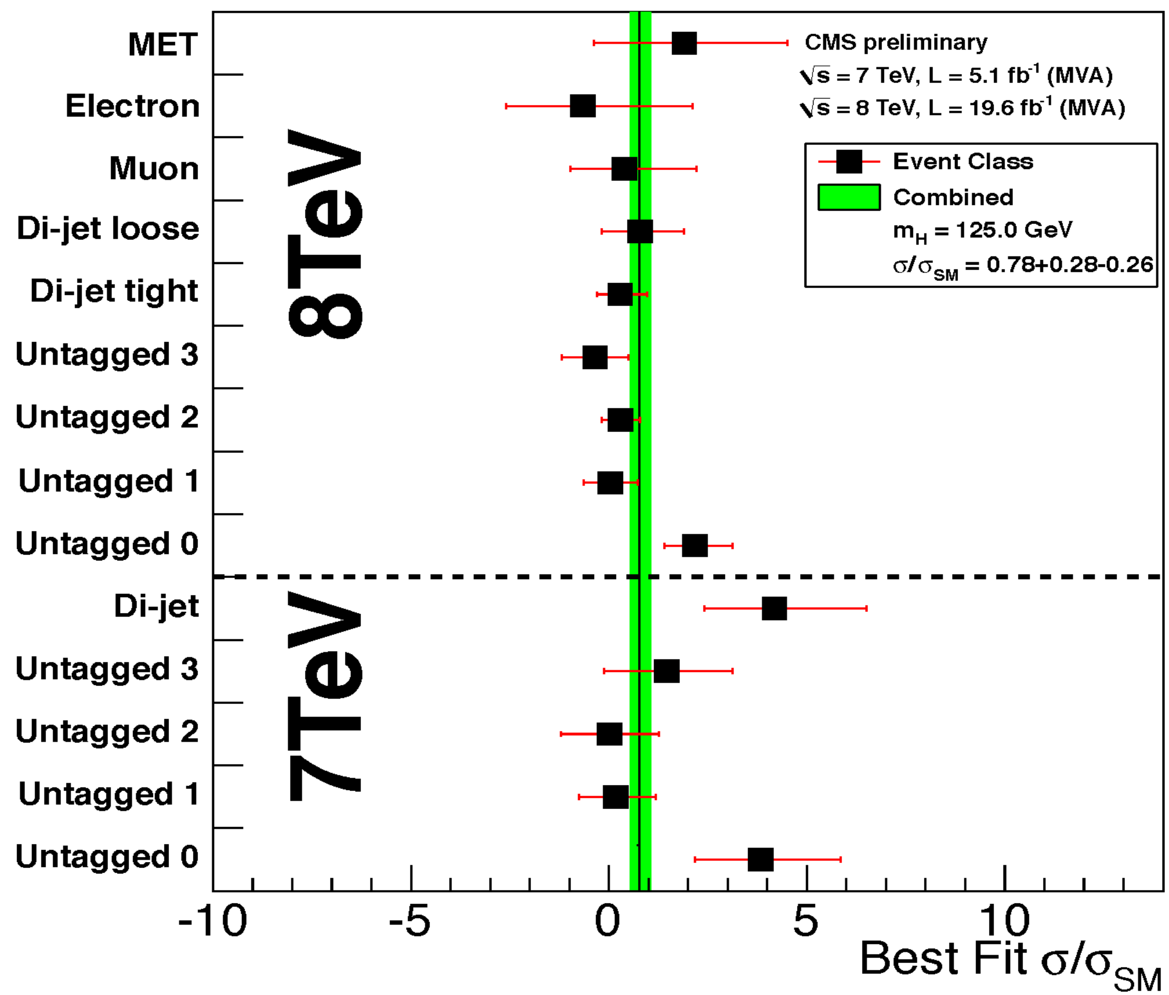
$$\sigma/\sigma_{SM} = 0.78\,^{+0.28}_{-0.26}$$

Categories

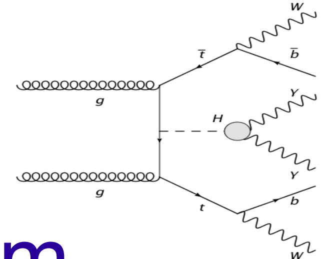
- defined taking into account S/B and resolution (untagged)
- separate 2 VBF type categories (di-jet)

Plans

- finalize the calibration for 7 TeV and 8 TeV



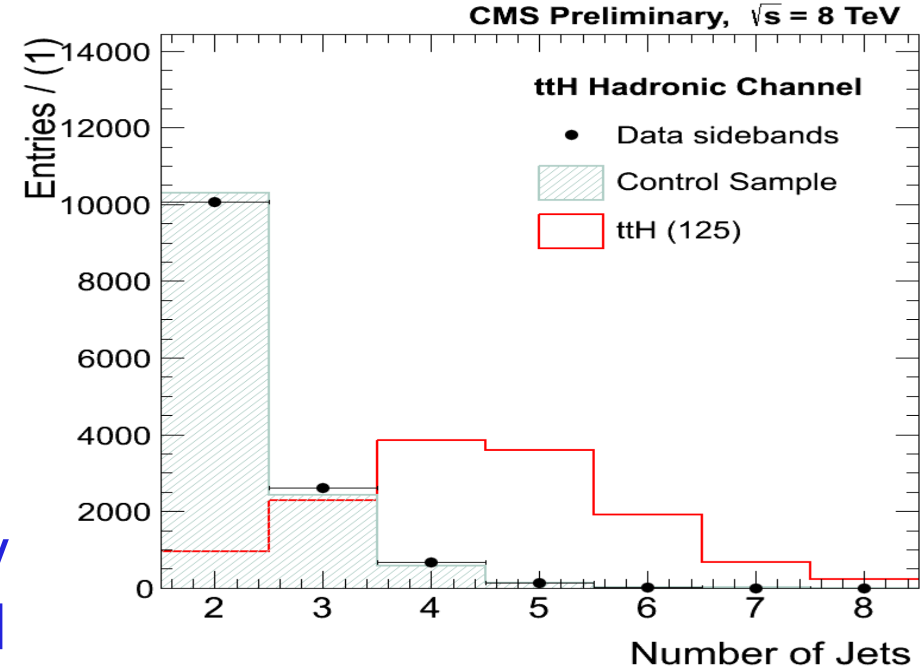
NEW

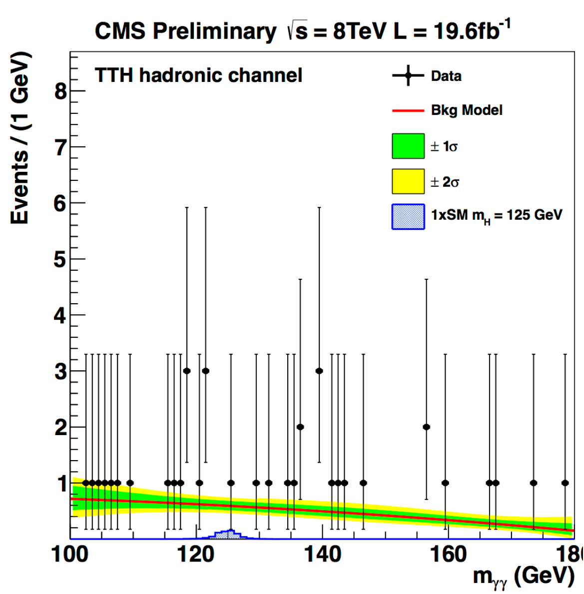


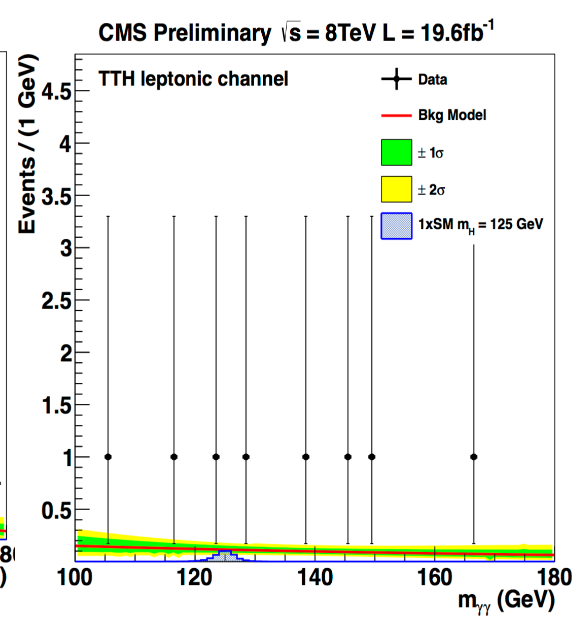
Still $H \rightarrow \gamma\gamma$ *but ttH*

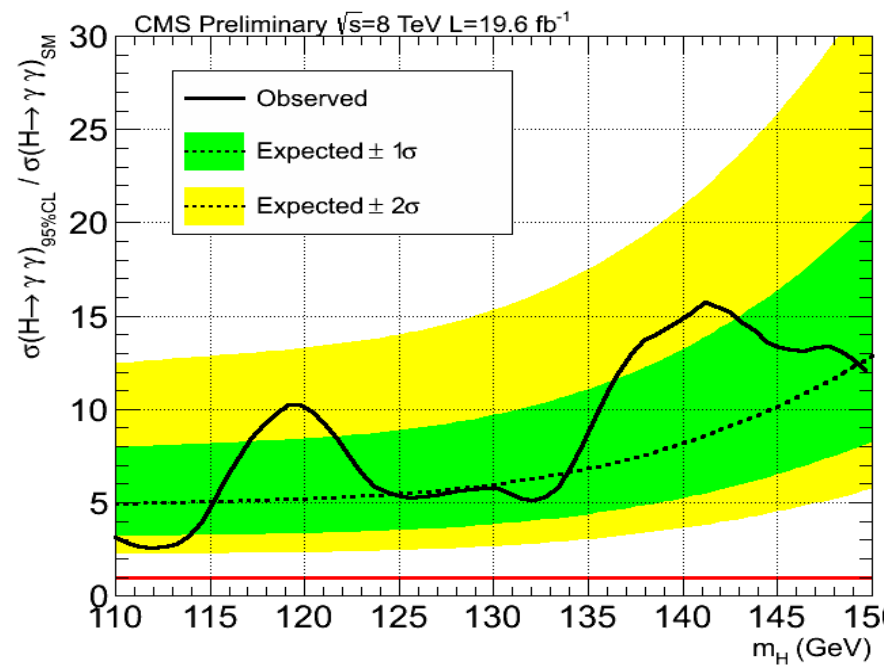
Telegram

– background almost completely disappears: tops are great handle
– but small signal
– optimize for hadronic and leptonic top decays separately
– no significant excess, but sensitivity only at 5.4 (5.3 expected) times SM

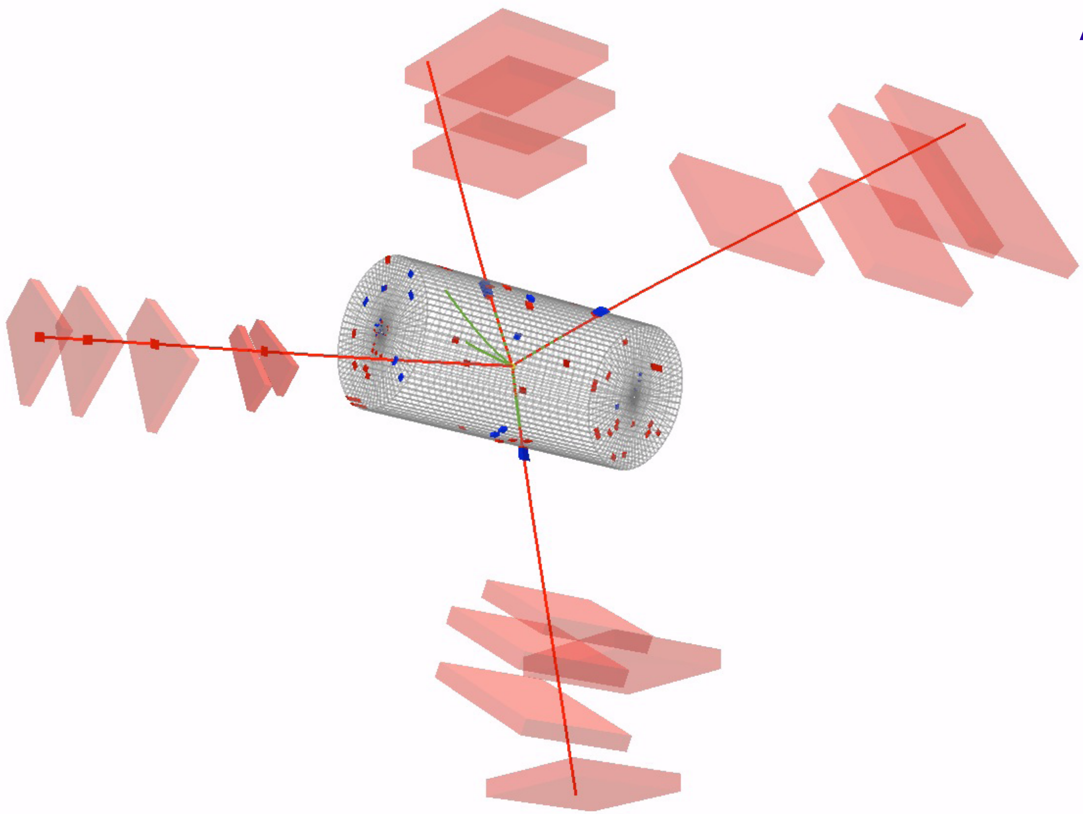








The Golden Mode: $H \rightarrow ZZ \rightarrow 4l$



Analysis telegram

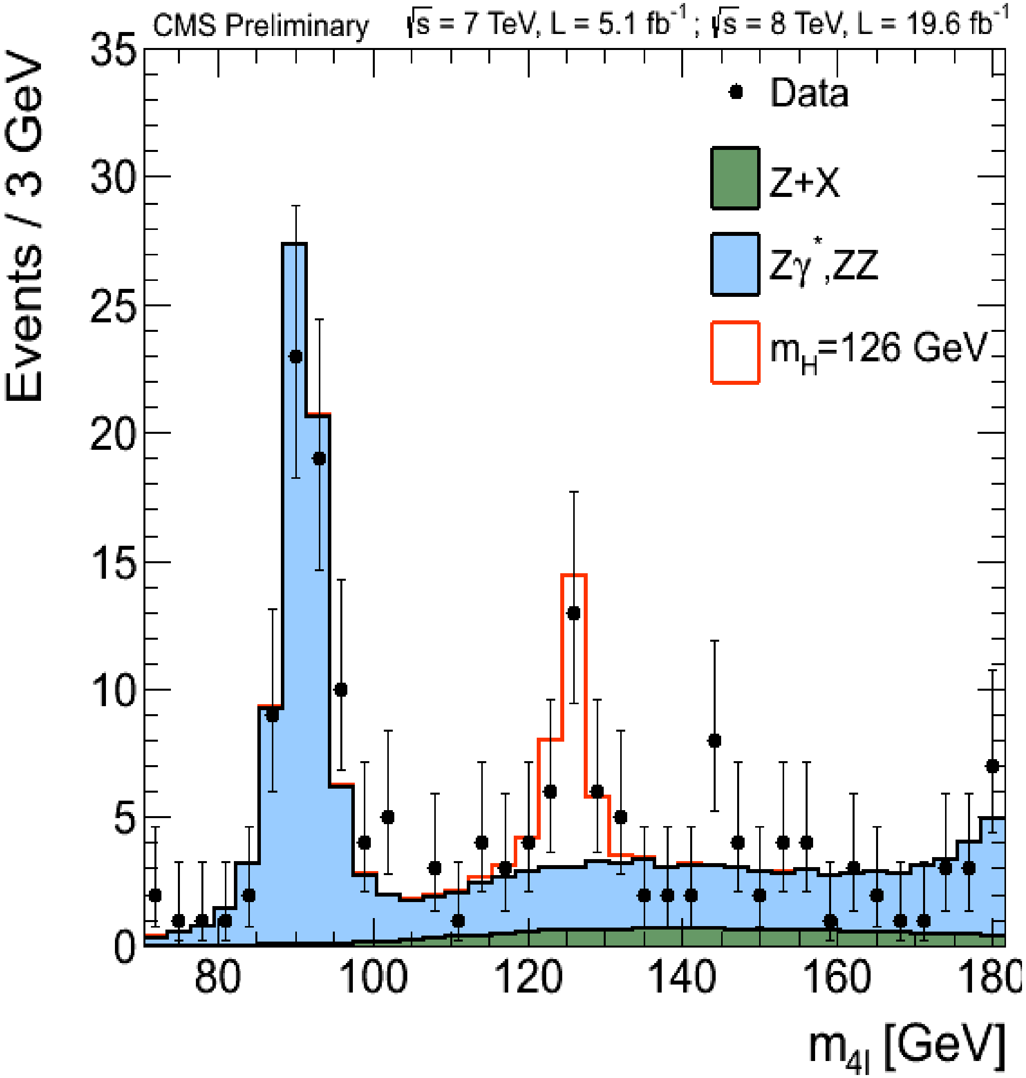
- 4 isolated high p_T leptons
- consistent with *Z* decays
- from same vertex
- fit mass peak with resolution: 2-4 GeV
- little background, non-resonant *ZZ* production
- also *Zbb* and top (*2l2nu2b*)

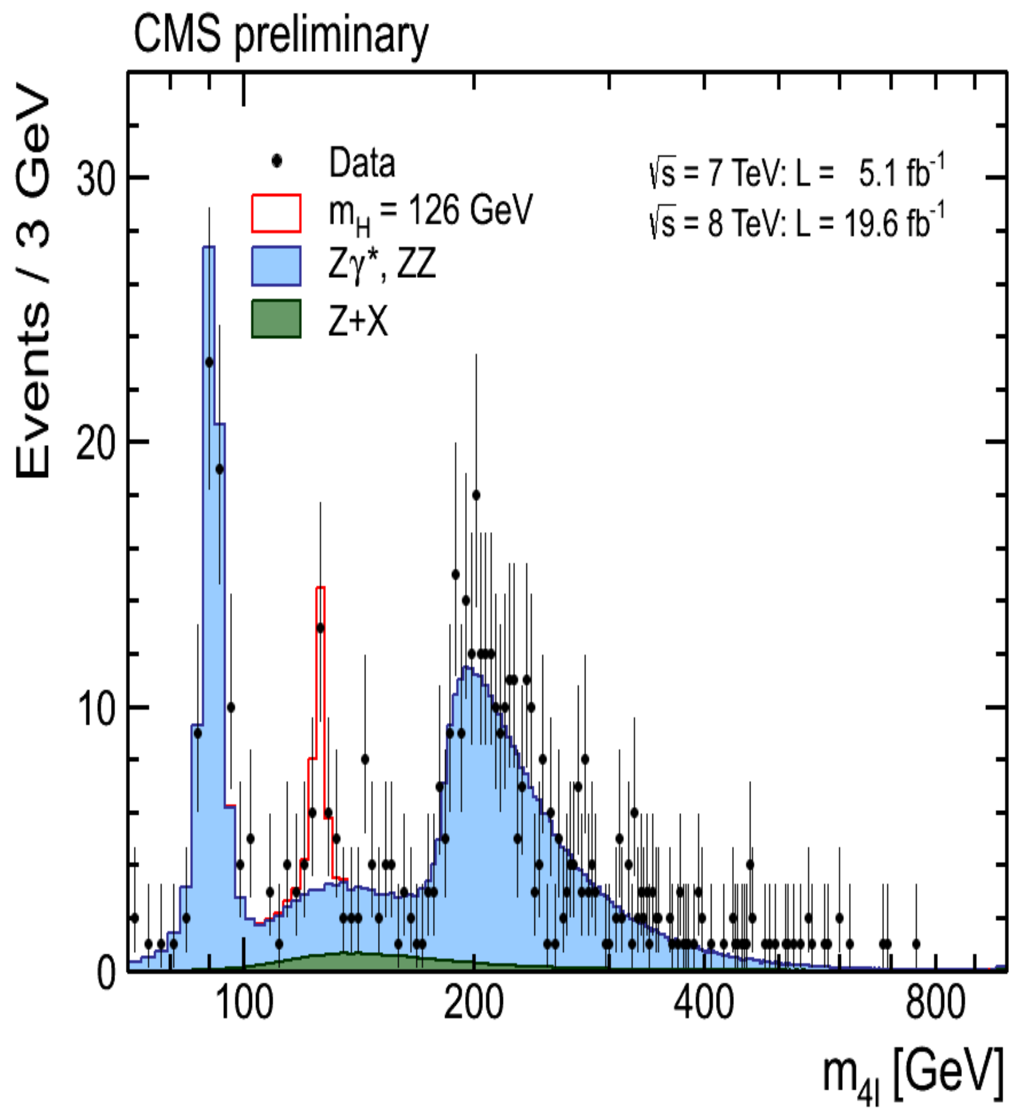
Background removal

- leptons from *b*-decays are non-isolated and displaced

Analysis with only minor modifications since ICHEP

The Signal – H → ZZ → 4l

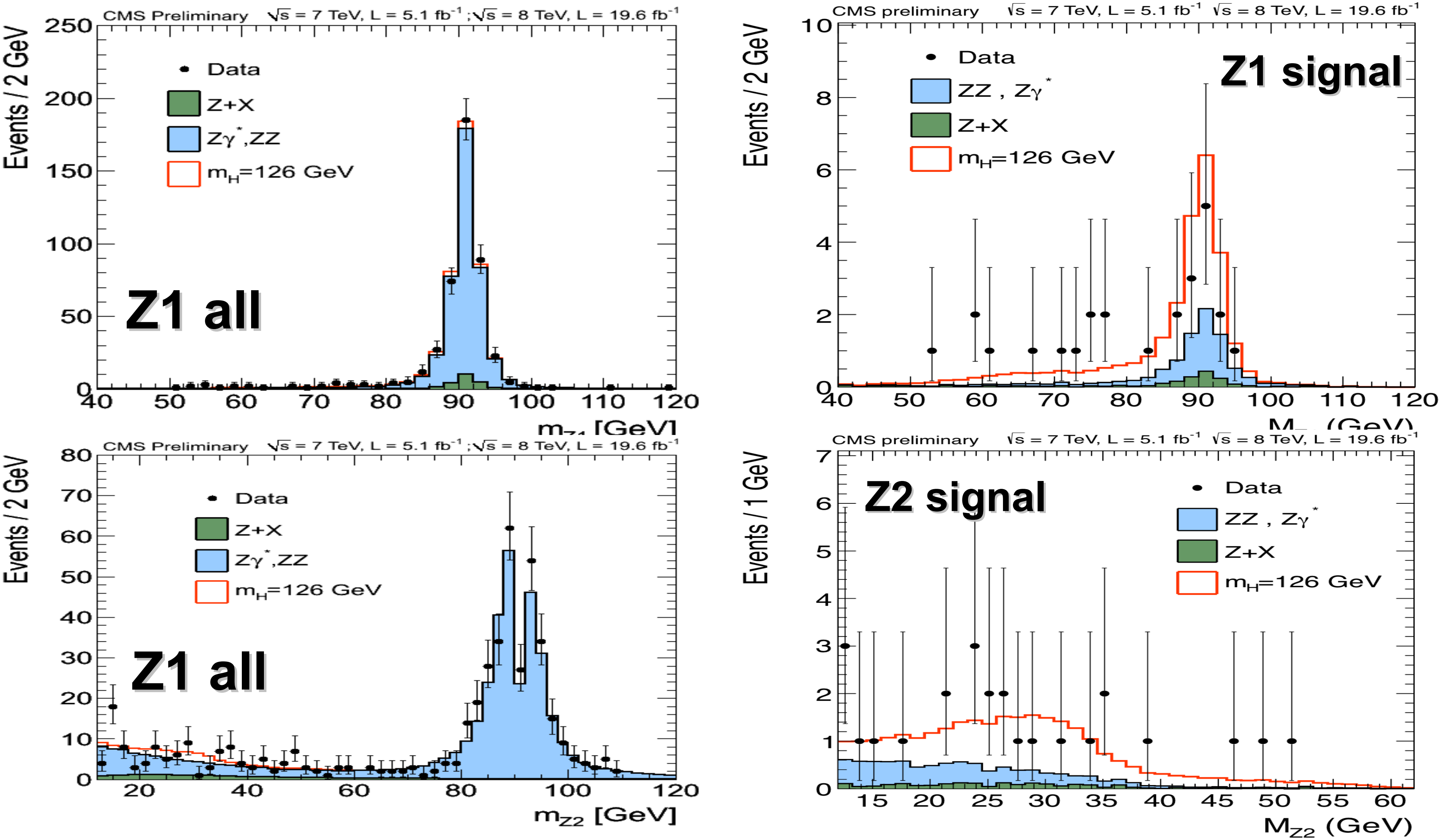




Peak around 125 GeV is very obvious and significant

- no other excess up to m_{4l} ~ 800 GeV

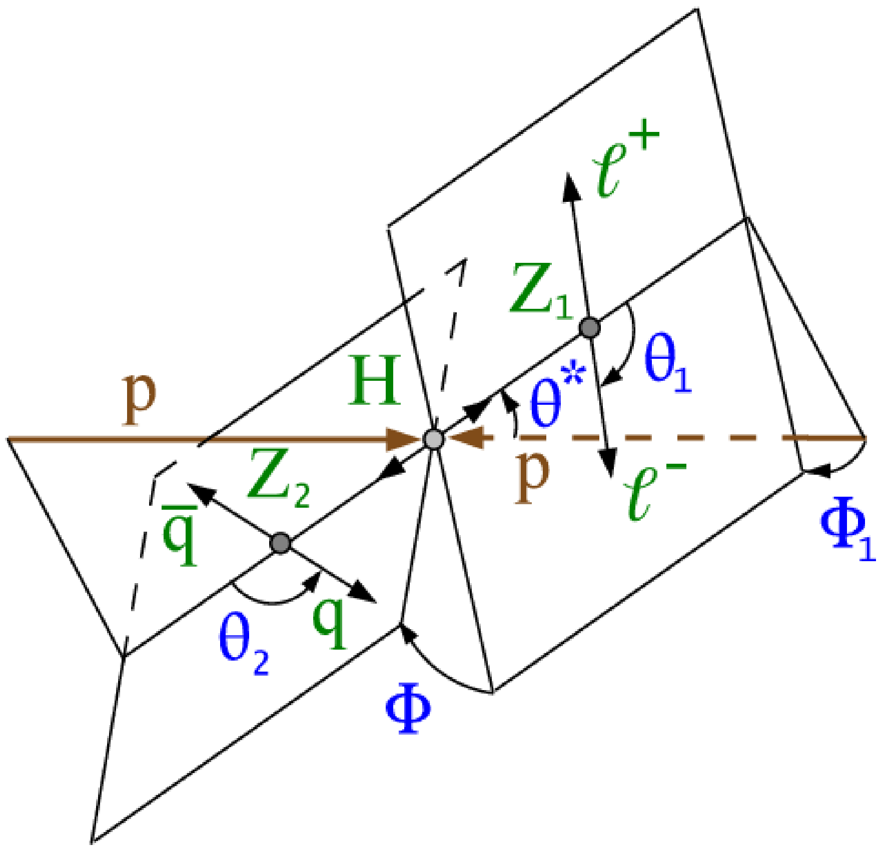
The Component Zs in H → ZZ → 4l

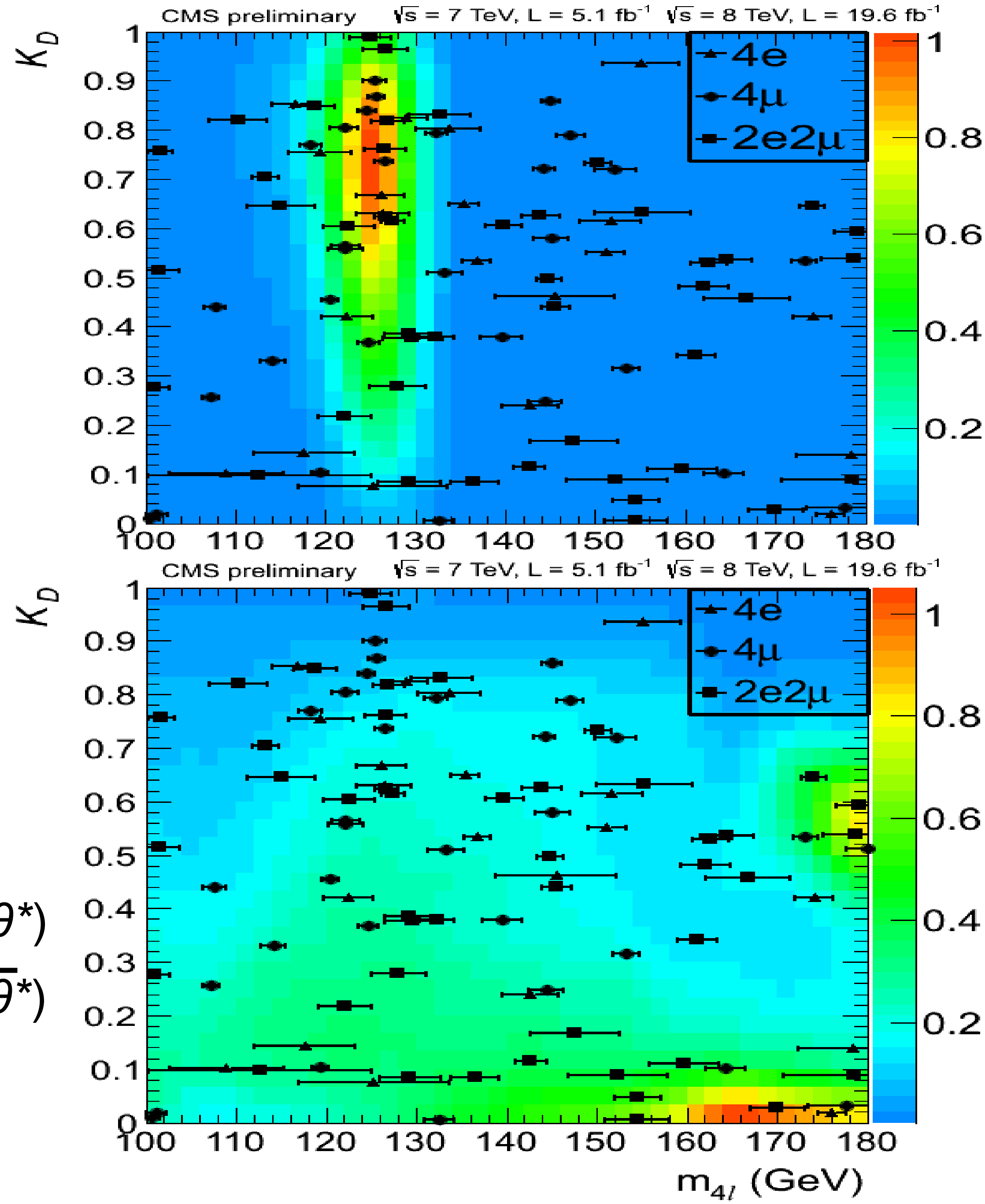


Mass distributions of the two Z candidates

- overall and in signal region data and MC show consistent behavior

Kinematic Discriminant: H → ZZ → 4l



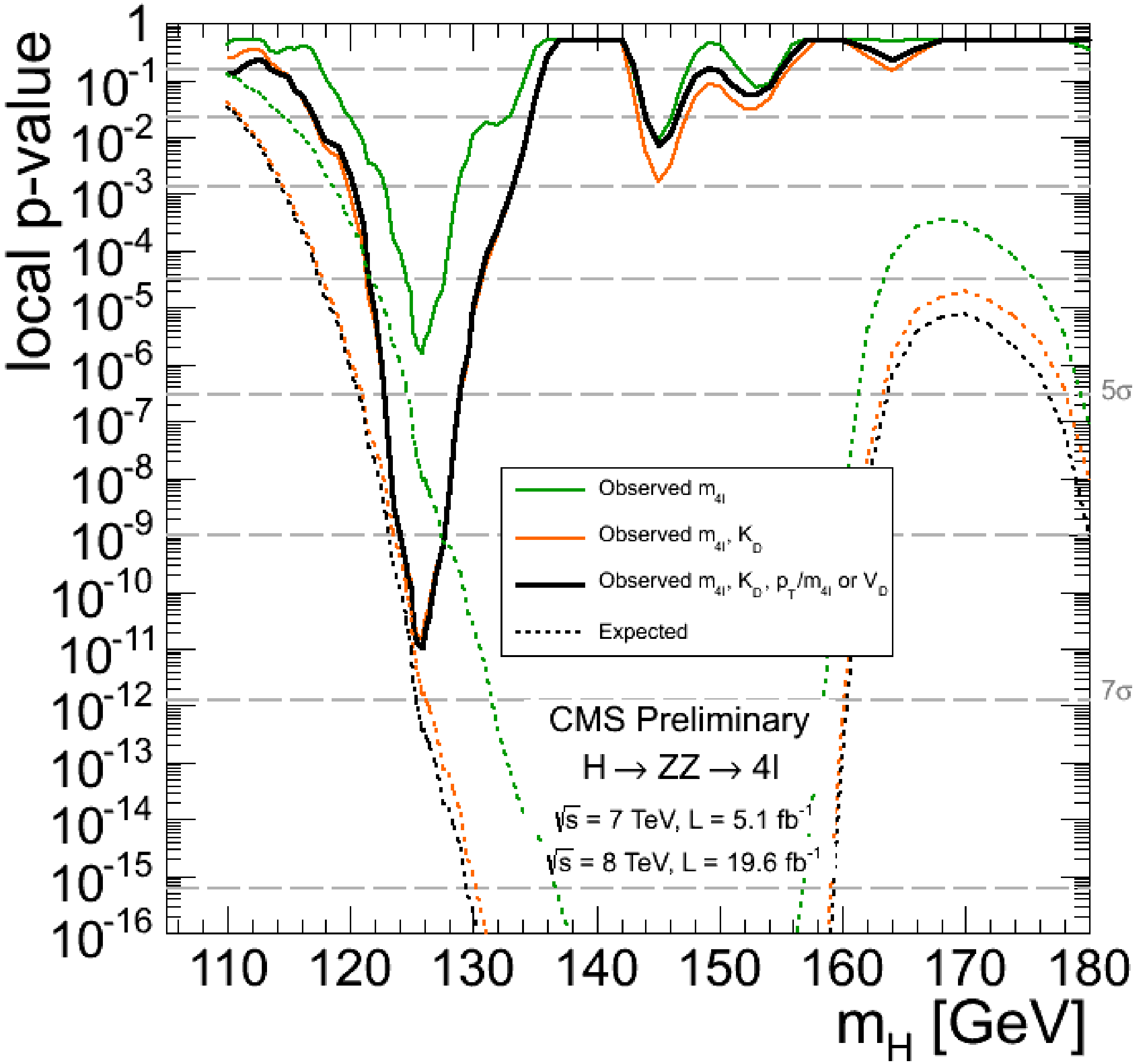


Angular analysis in CMS

$$1/K_D = 1 + \frac{P_{background}(m_1,m_2,\theta_1,\theta_2,\Phi_1,\Phi,\theta^*)}{P_{signal}(m_1,m_2,\theta_1,\theta_2,\Phi_1,\Phi,\theta^*)}$$

enhances analysis sensitivity

Results Summary: $H \to ZZ \to 4l$



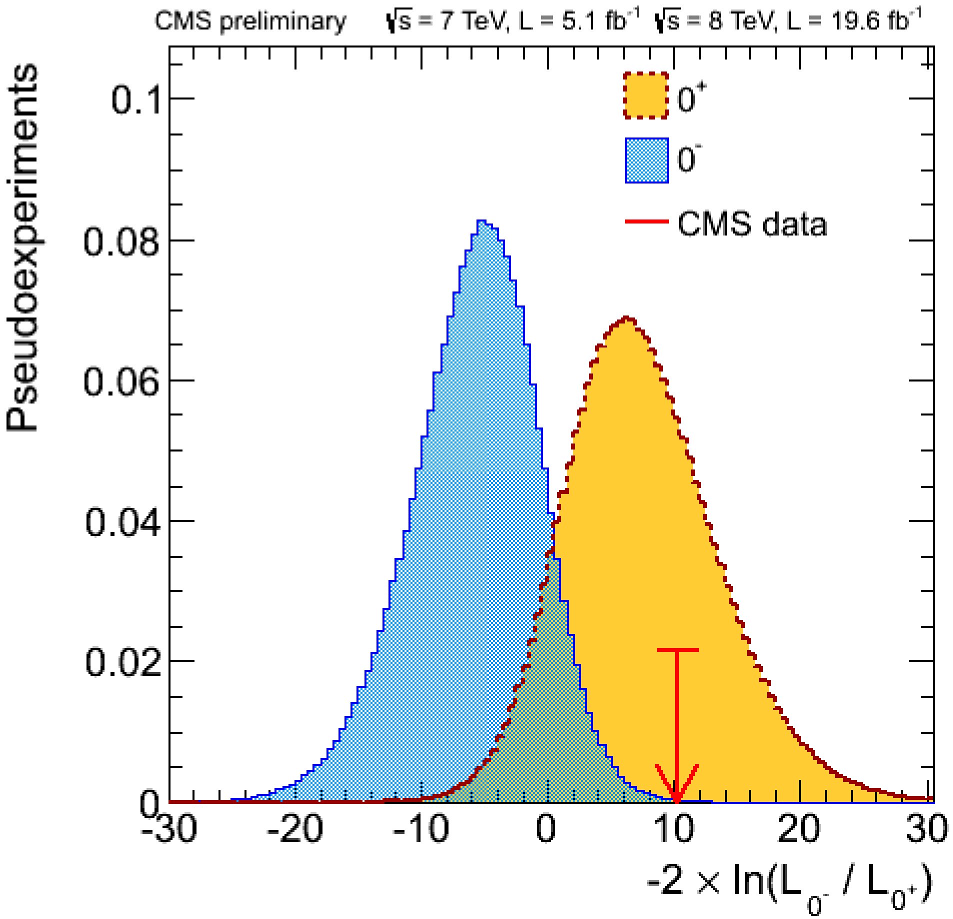
Summary

- use 3d fit to m_H, K_D and $p_T(4l)/m_{4l}$ (or linear discriminant - VBF)
- observe: 6.7 std dev. (expecting: 7.2)

$$\sigma/\sigma_{SM} = 0.91^{+0.30}_{-0.24}$$

$$m_H = 125.8 \pm 0.5(stat) \pm 0.2(syst) \text{ GeV}$$

Scalar or Pseudoscalar: $H \rightarrow ZZ \rightarrow 4l$

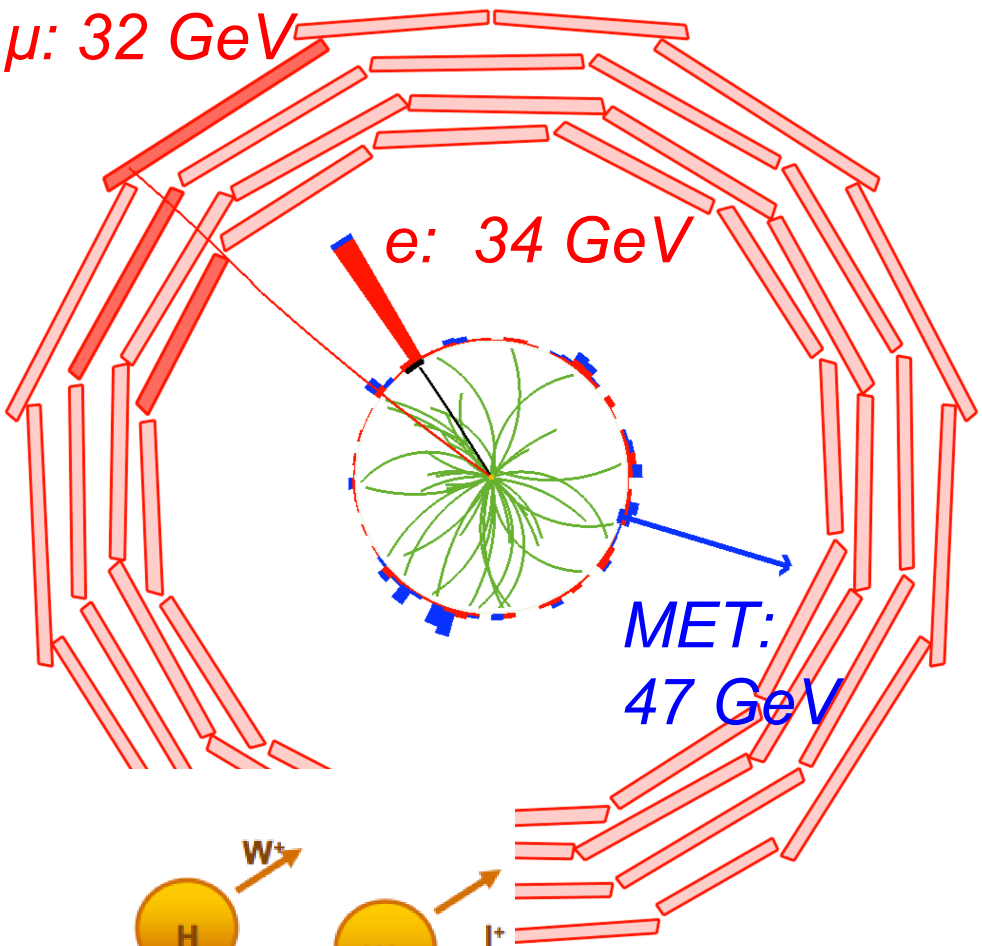


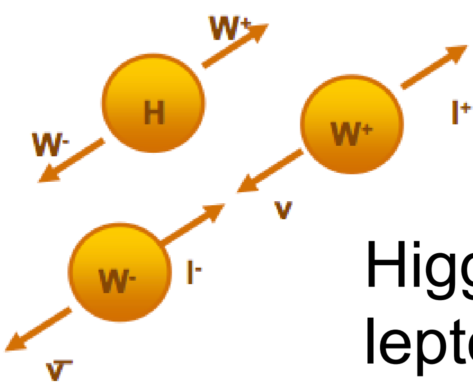
Testing decay kinematics

- particle properties define decay kinematics
- find consistency and inconsistency of various models with our data
- $J^P = 0^+$ (scalar) is consistent, many other models are more or less inconsistent with the data

J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \rightarrow X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \rightarrow X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2_{mgg}^+	$gg \rightarrow X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2_{mq\bar{q}}^+$	$q\bar{q} \rightarrow X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \rightarrow X$	exotic vector	2.8σ (3.1σ)	1.4σ	>4.0σ	<0.1%
1^+	$q\bar{q} \rightarrow X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	>4.0σ	<0.1%

$H \rightarrow WW \rightarrow 2l\ 2nu$





Higgs is scalar
leptons are close

Signature

- 2 opposite charged leptons (leptons only *e*, *μ*)
- 2 neutrinos == missing transverse energy (MET)
- no Higgs mass peak
- basically a counting analysis

Analysis challenges

- understand backgrounds
- normalize to control regions
- backgrounds: WW, W+jets, top, DY

Analysis strategy – H → WW → 2l2nu

		VBF not yet updated	
0-jets, shape	1-jet, shape	2-jets, VBF	different flavor, DF
0-jets	1-jets	2-jets, VBF	same flavor, SF substantial DY background

jets with p_T > 30 GeV

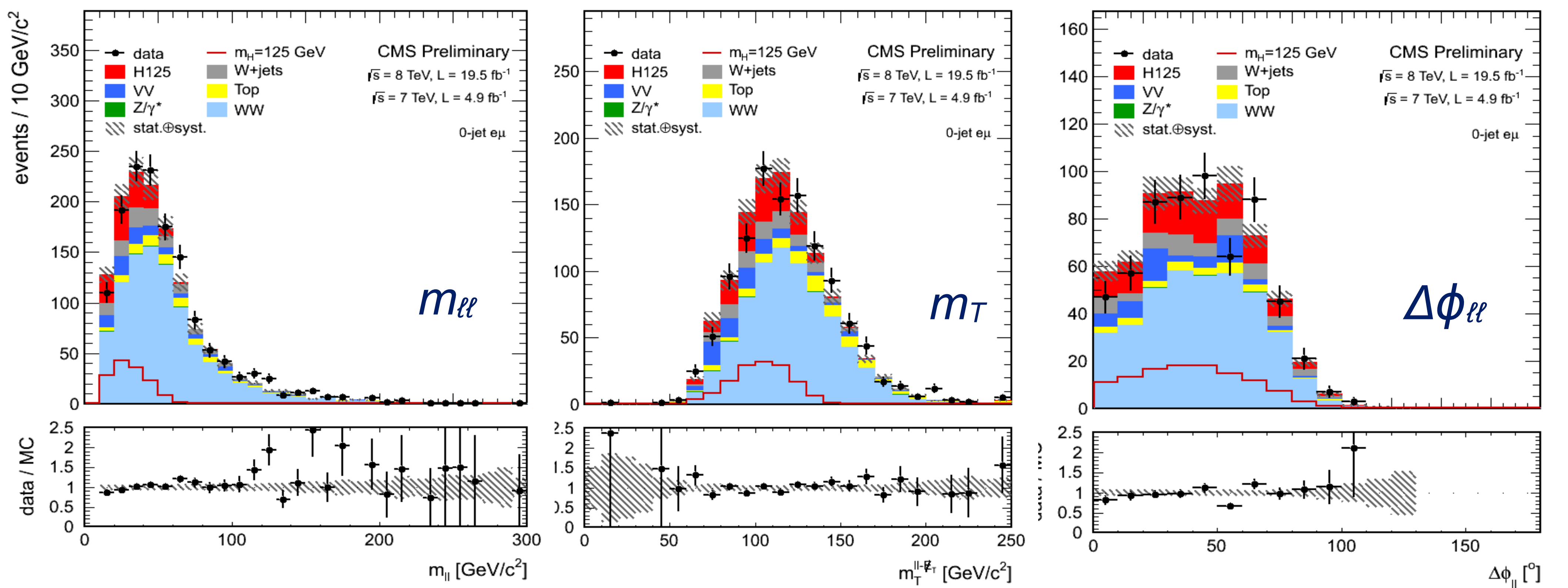
- different flavor (DF) most sensitive (0 and 1 jet categories)
- shape analysis for those two DF categories only
- other categories use easier to control cut-and-count strategy

New for HCP

- shape analysis uses (m_{ll}-m_T) plane
- mass independent DY rejection, VBF selection optimized

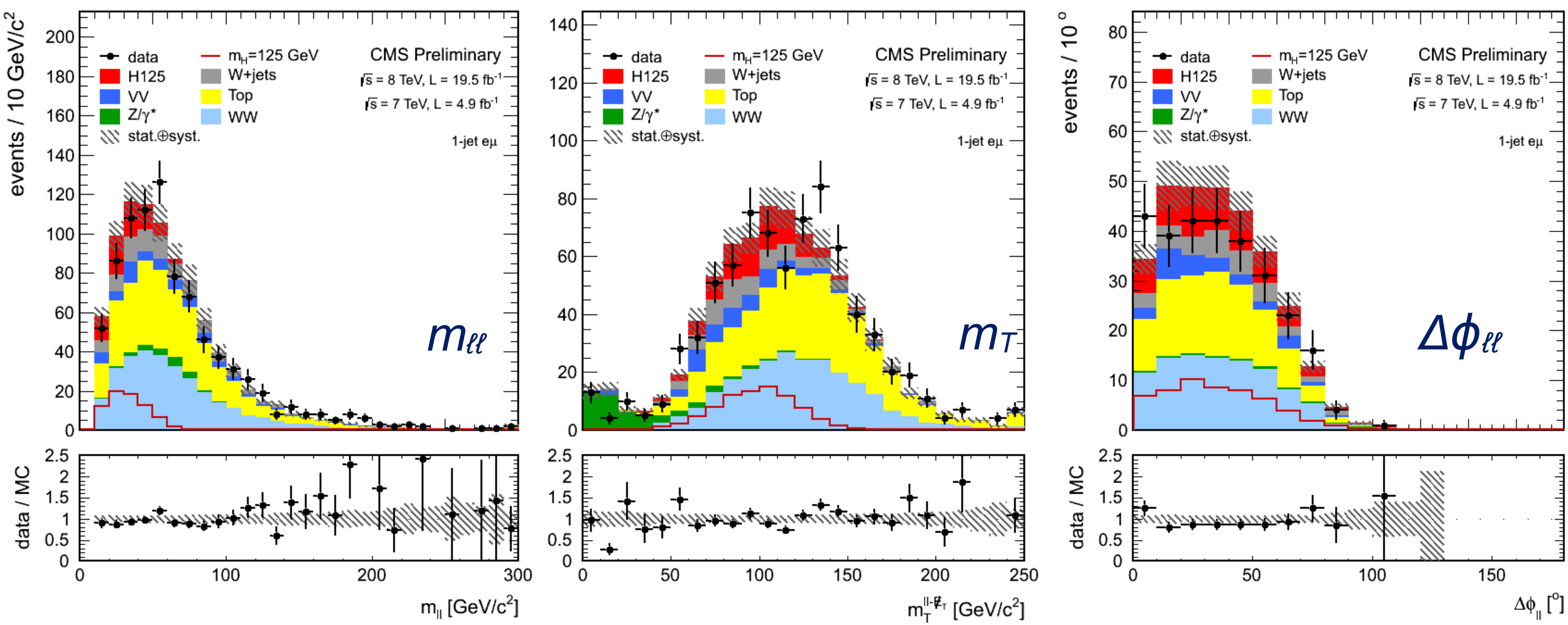
Cut and Count – DF 0-jet

m_H	H→WW	pp→WW	WZ+ZZ+Drell-Yan	Top	W+jets	W+gamma(*)	All bkg.	Data
0-jet category eμ final state								
120	12.2±2.6	62.2±6.5	1.8±0.4	3.4±0.8	9.7±2.8	6.0±2.9	83.1±7.7	85
125	20.3±4.3	75.5±7.8	2.1±0.4	4.2±1.0	10.8±3.1	6.5±3.0	99.1±9.0	115
130	32.4±6.9	84.4±8.7	2.2±0.4	5.0±1.2	11.8±3.4	6.4±3.0	109.8±9.9	122
160	74±16	44.8±4.6	0.7±0.1	4.1±1.0	2.6±1.1	1.2±1.0	53.4±5.0	59
200	28.7±6.4	71.4±7.4	1.1±0.1	11.1±2.5	2.9±1.2	0.1±0.2	86.7±7.9	85
400	11.2±3.0	40.1±4.3	0.9±0.1	17.4±3.9	3.3±1.3	1.4±0.7	63.1±6.0	58
600	2.3±1.0	11.7±1.3	0.3±0.0	5.3±1.2	0.9±0.5	0.3±0.2	18.5±1.9	16



Cut and Count – DF 1-jet

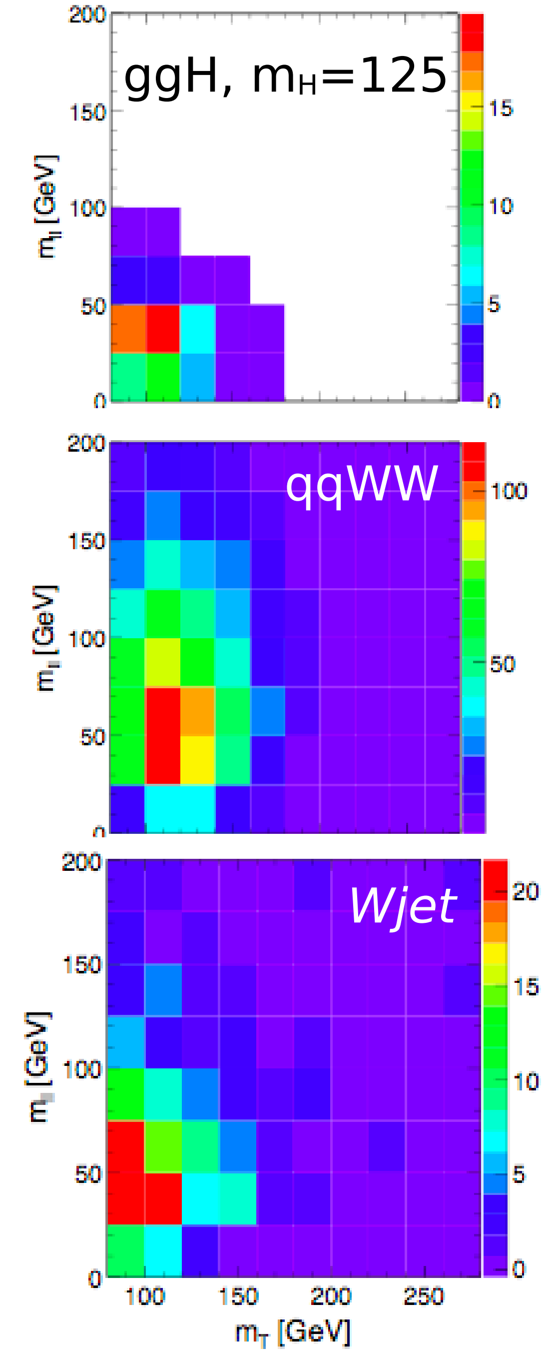
1-jet category eμ final state								
120	5.1±1.5	16.5±2.8	2.1±0.4	11.1±0.9	6.2±1.9	1.0±0.6	37.0±3.6	44
125	7.9±2.3	20.4±3.4	2.4±0.4	14.0±1.1	6.3±2.0	2.0±1.2	45.0±4.3	53
130	12.6±3.8	22.9±3.8	2.6±0.4	15.9±1.2	6.8±2.1	2.2±1.2	50.3±4.7	64
160	37±11	18.2±3.0	1.1±0.1	14.1±1.1	1.6±0.8	0.3±0.2	35.3±3.3	32
200	16.0±4.2	31.4±5.3	1.3±0.1	31.1±2.2	2.2±1.0	0.0±0.0	66.0±5.8	49
400	8.3±2.3	31.3±4.8	2.1±0.7	34.2±2.4	4.3±1.6	0.3±0.3	72.1±5.6	60
600	2.3±0.8	10.9±1.7	1.4±0.7	9.8±0.8	2.2±0.9	0.2±0.2	24.4±2.2	19



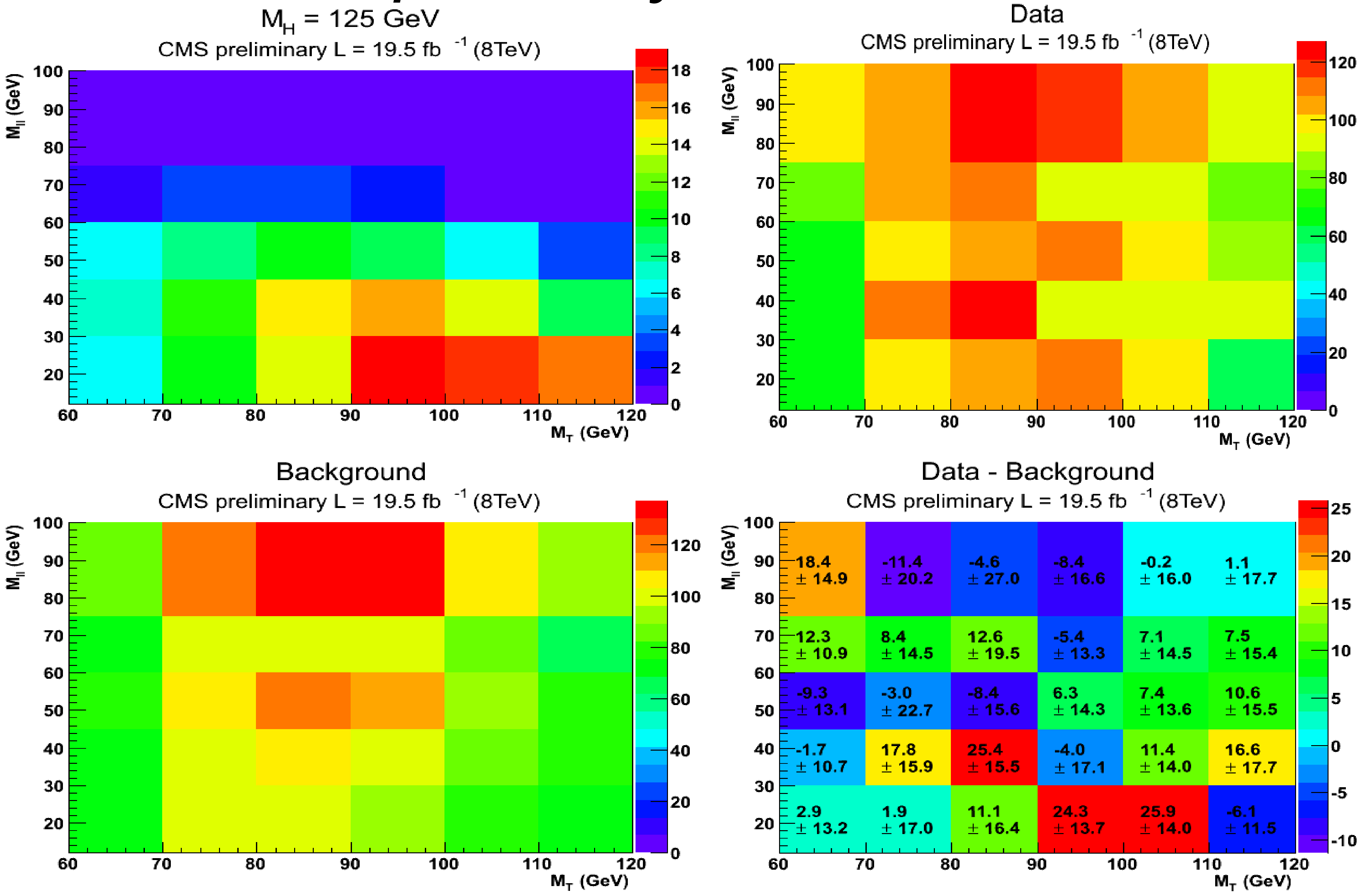
Shape – 2 Dimensions (m_{ll} - m_T)

Optimization for specific backgrounds

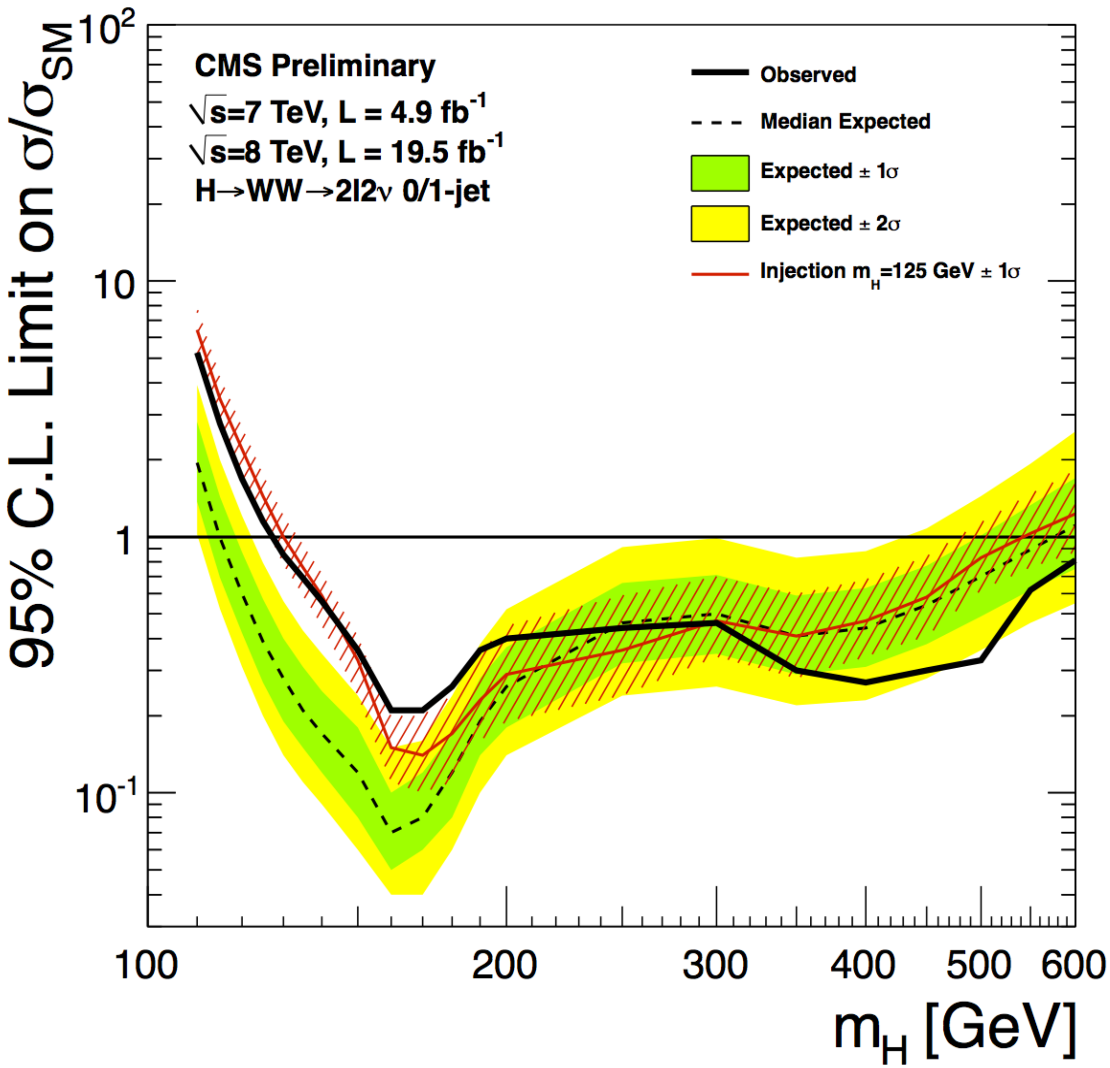
- 2*D* shape analysis allows to separate background in two dimensions
- improve analysis sensitivity if background behaves different in 2 dimensions
- main backgrounds do behave differently
- expect improvement
- evaluating systematic uncertainties adjusted (in 2*D* now)

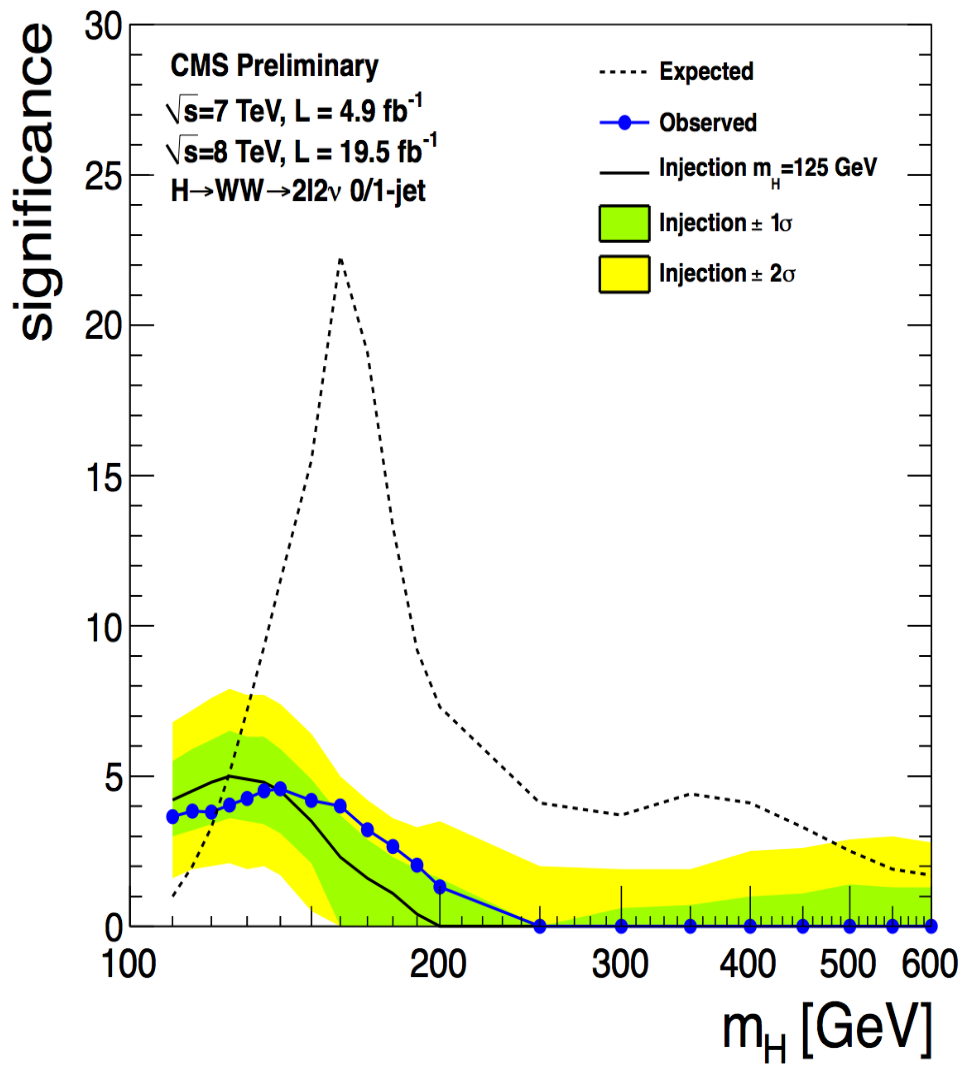


New Shape Analysis – Ex. DF 0-jet



Significance of Excess

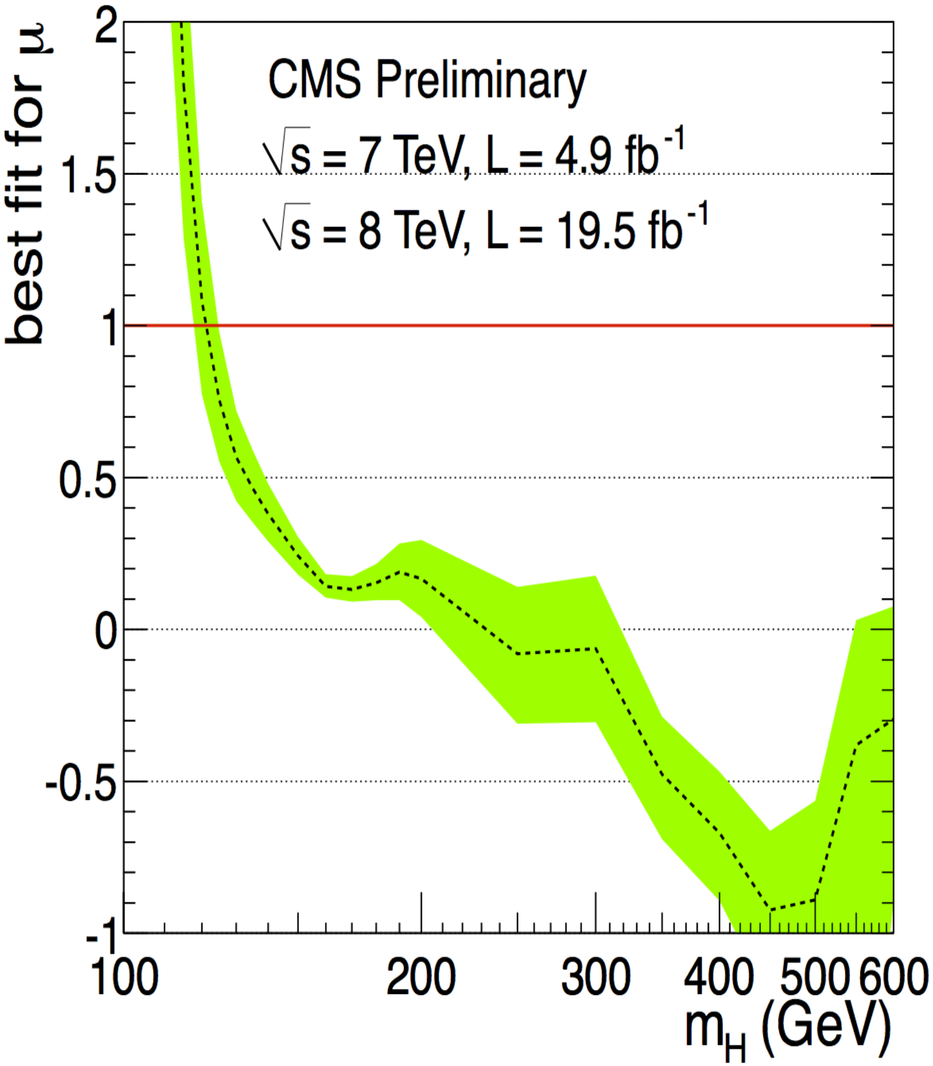


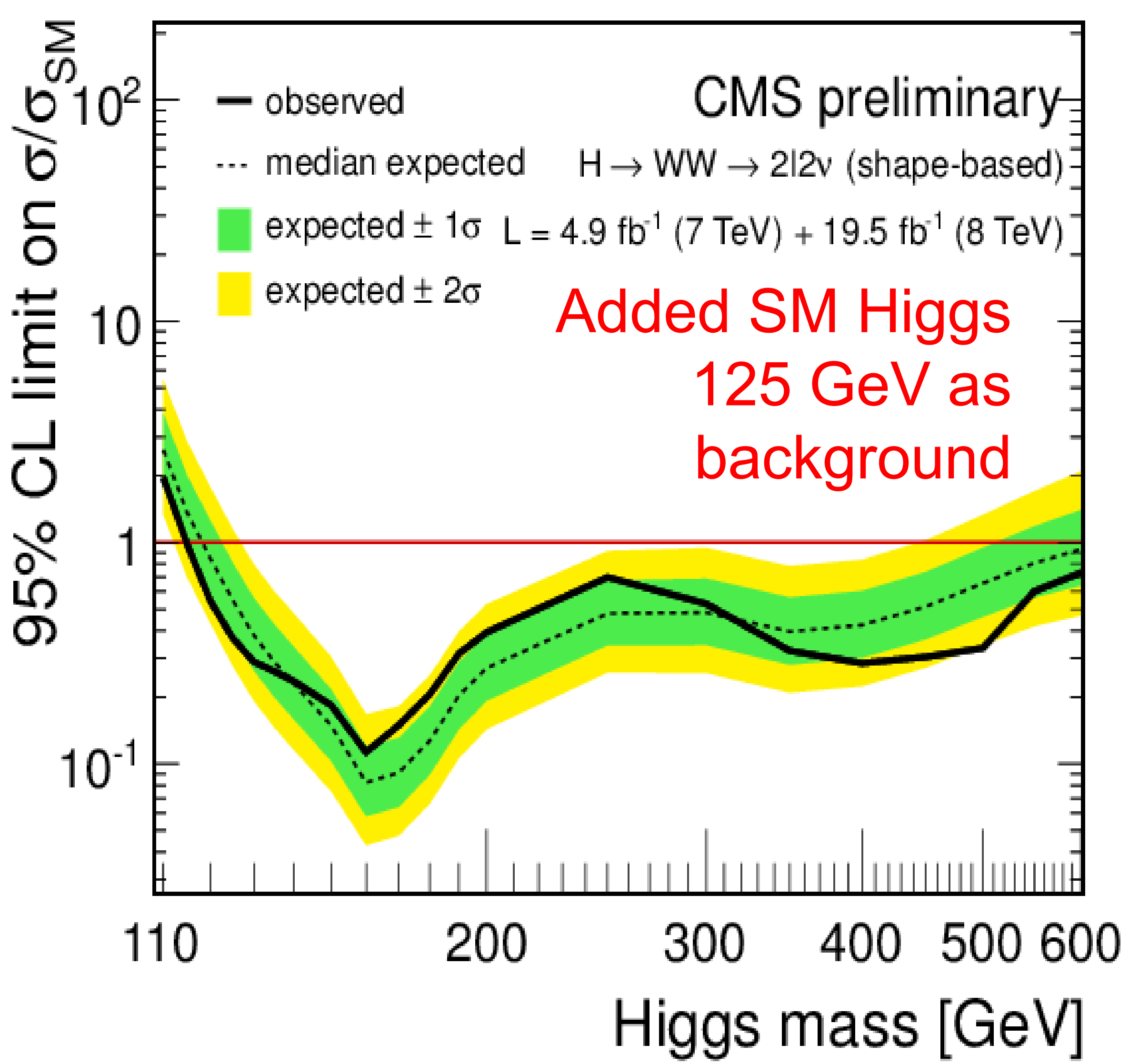


CMS experiment sees significant excess

- observed: 4.0 std and expected: 5.1 std

Signal Strength

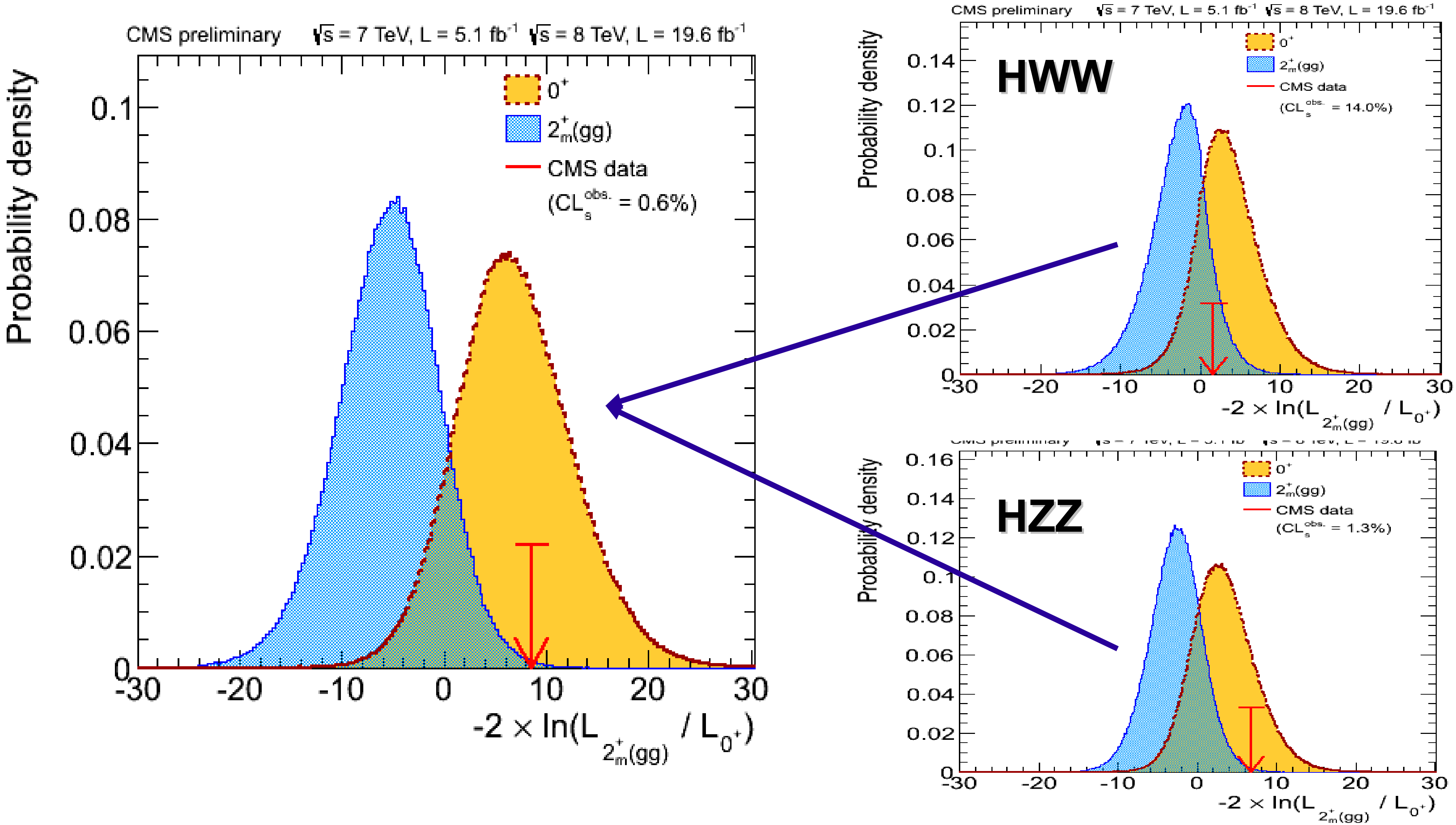




Steeply falling signal strength versus mass

– measure signal strength: 0.76 ± 0.21 (at m_H = 125 GeV)

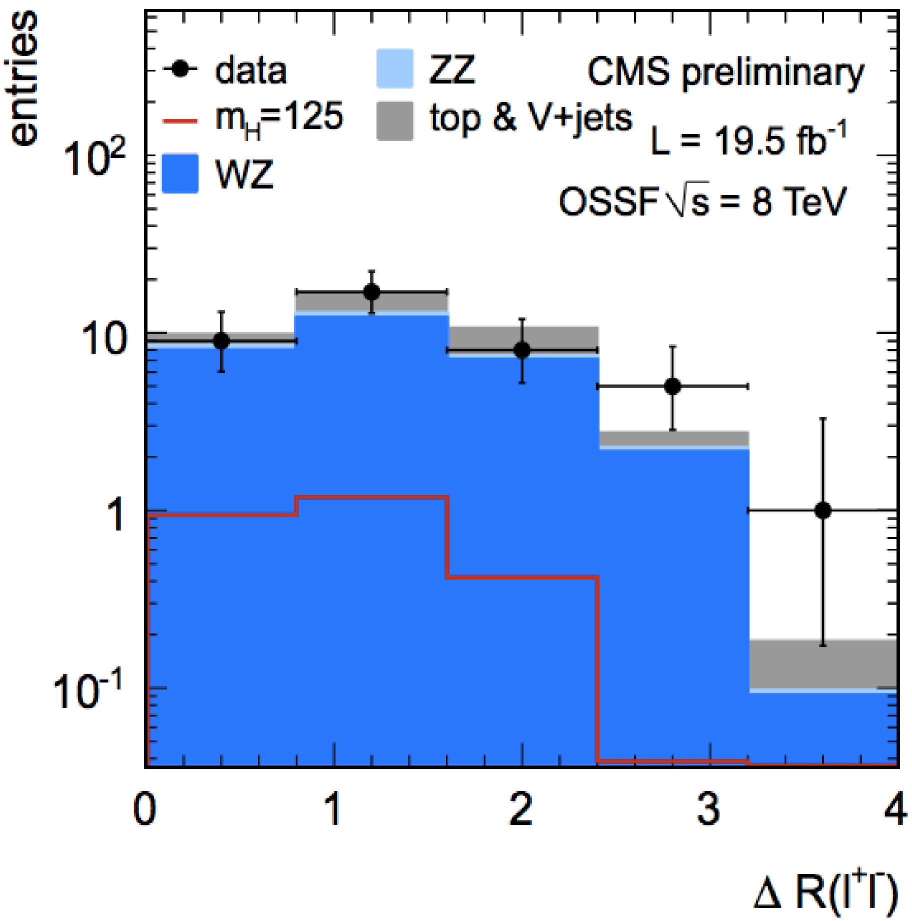
HWW/HZZ Compatible with Spin 2 ?

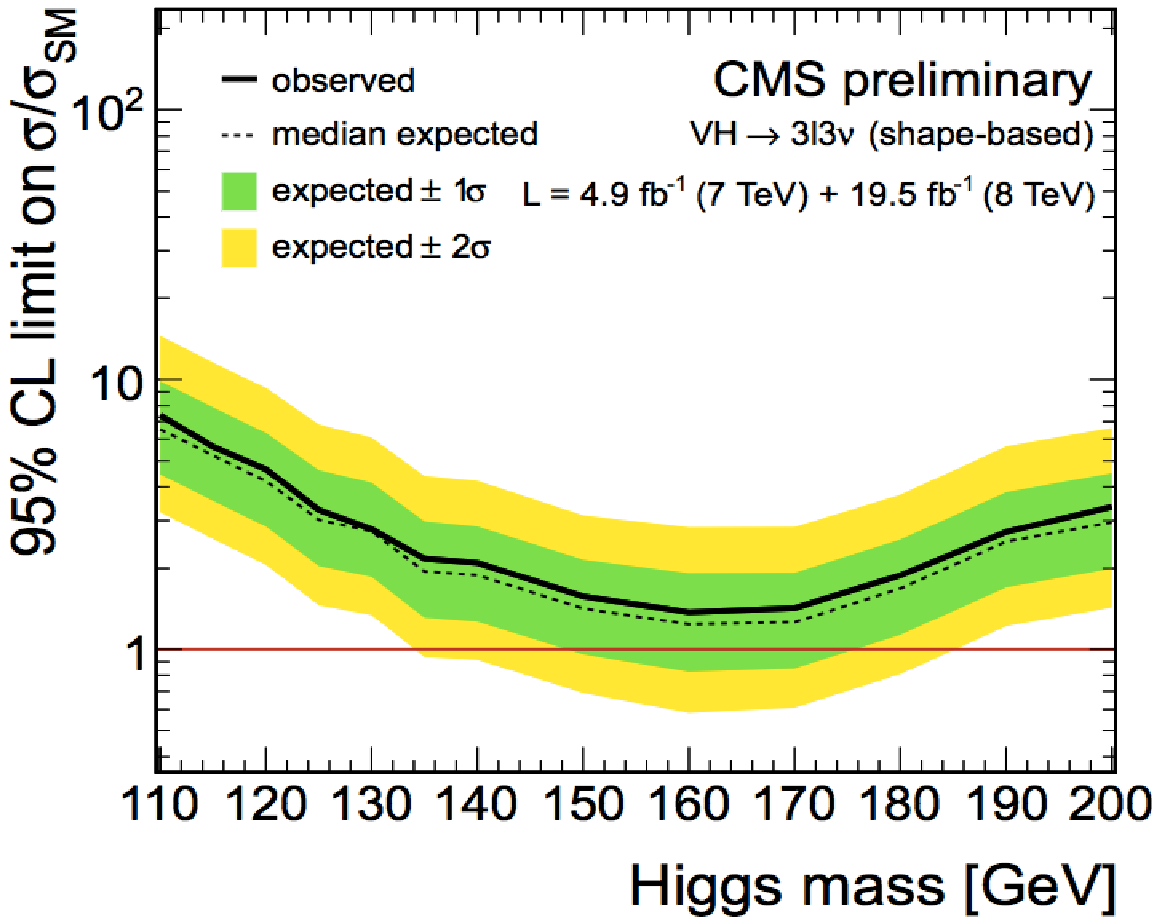


Steeply falling signal strength versus mass

– *0^+* consistent at 0.44 std while *2^+_m(gg)* inconsistent at 2.84 std

More recent result: $H \rightarrow 3l\ 3nu$

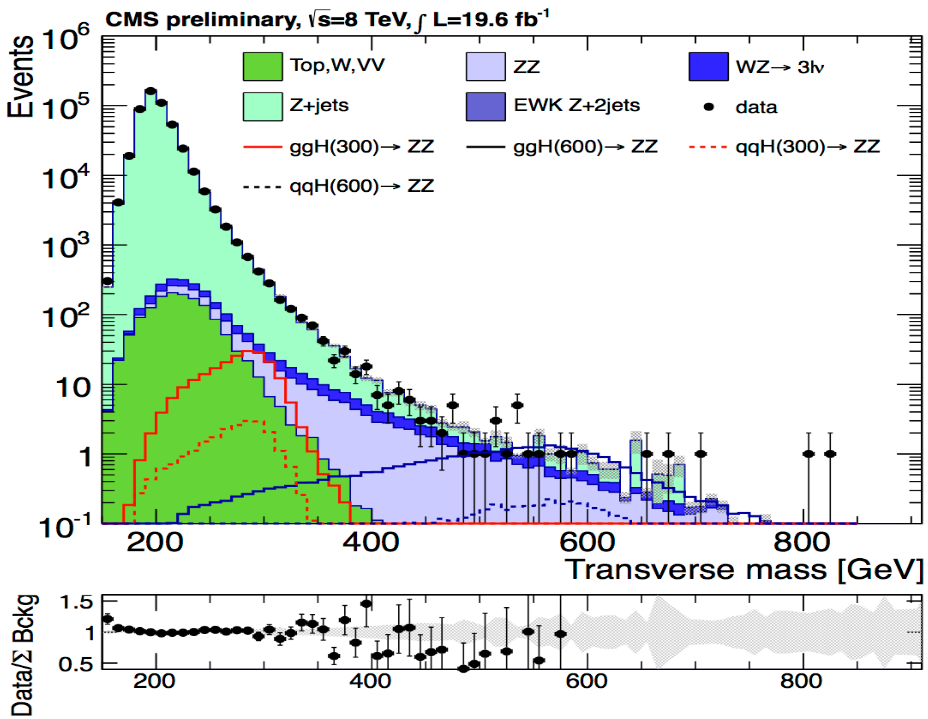


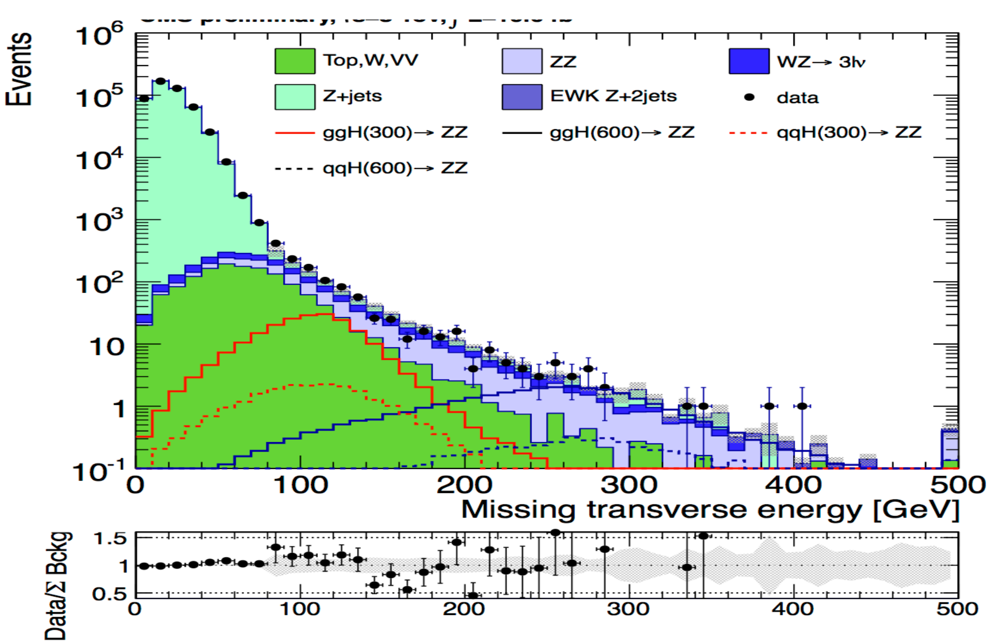


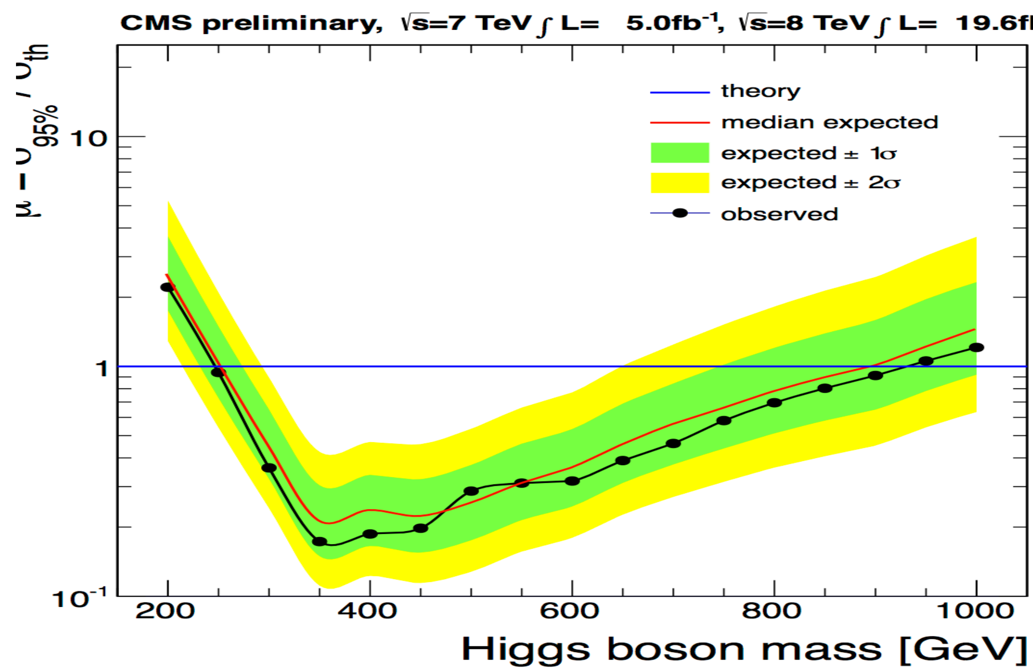
Analysis telegram (cut and shape based analysis)

- 3 high p_T leptons (leptons only e, μ) and MET
- reduce background from WZ with Z veto and anti b-tag
- no excess observed but sensitivity around 3xSM cross section

$H \rightarrow ZZ \rightarrow 2l\ 2nu$







Signature

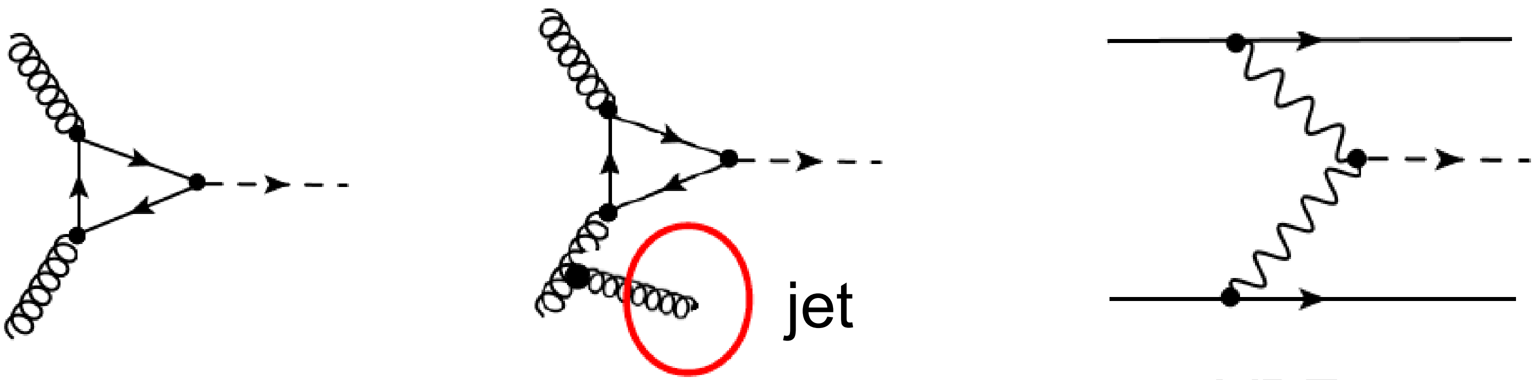
NEW

- 2 opposite charged same flavor leptons (leptons only *e, μ*)
- 2 neutrinos == missing transverse energy (MET)
- no Higgs mass peak
- optimized in categories, high mass
- interpretation: another SM like scalar

And the fermions ?

Search for $H \rightarrow \tau\tau$ in Pictures

Standard model



Inclusive — Boosted — VBF

jets with p_T > 30 GeV

p_T

0-jets, low p_T	1-jets, low p_T
0-jets, high p_T	1-jets, high p_T

Just used to fit background

e, μ, τ_{had} used to reconstruct a tau

VBF

VH

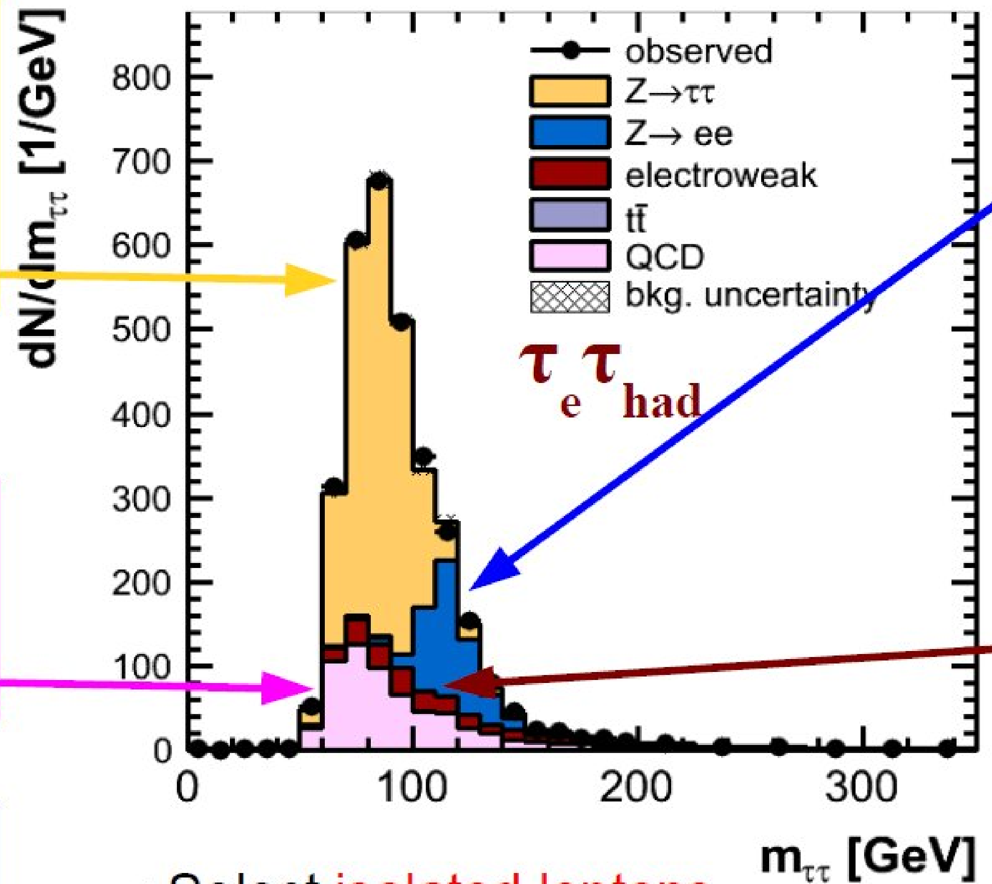
categories enhance sensitivity

Anatomy of the $H \rightarrow \tau\tau$ in Analysis

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

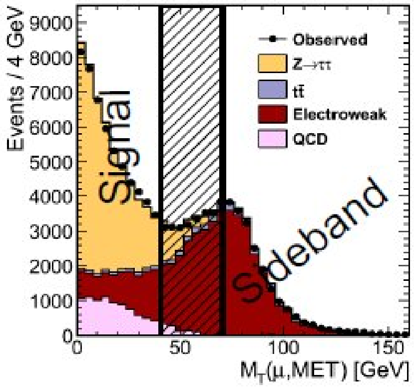
QCD:
- Normalization & shape taken from LS/OS or fakerate.

ttbar:
- From madgraph.
- Normalization from sideband.



$Z \rightarrow ee(/\mu\mu)$:
- From powheg.
- Corrected for jet→τ, e/μ→τ fakerate.

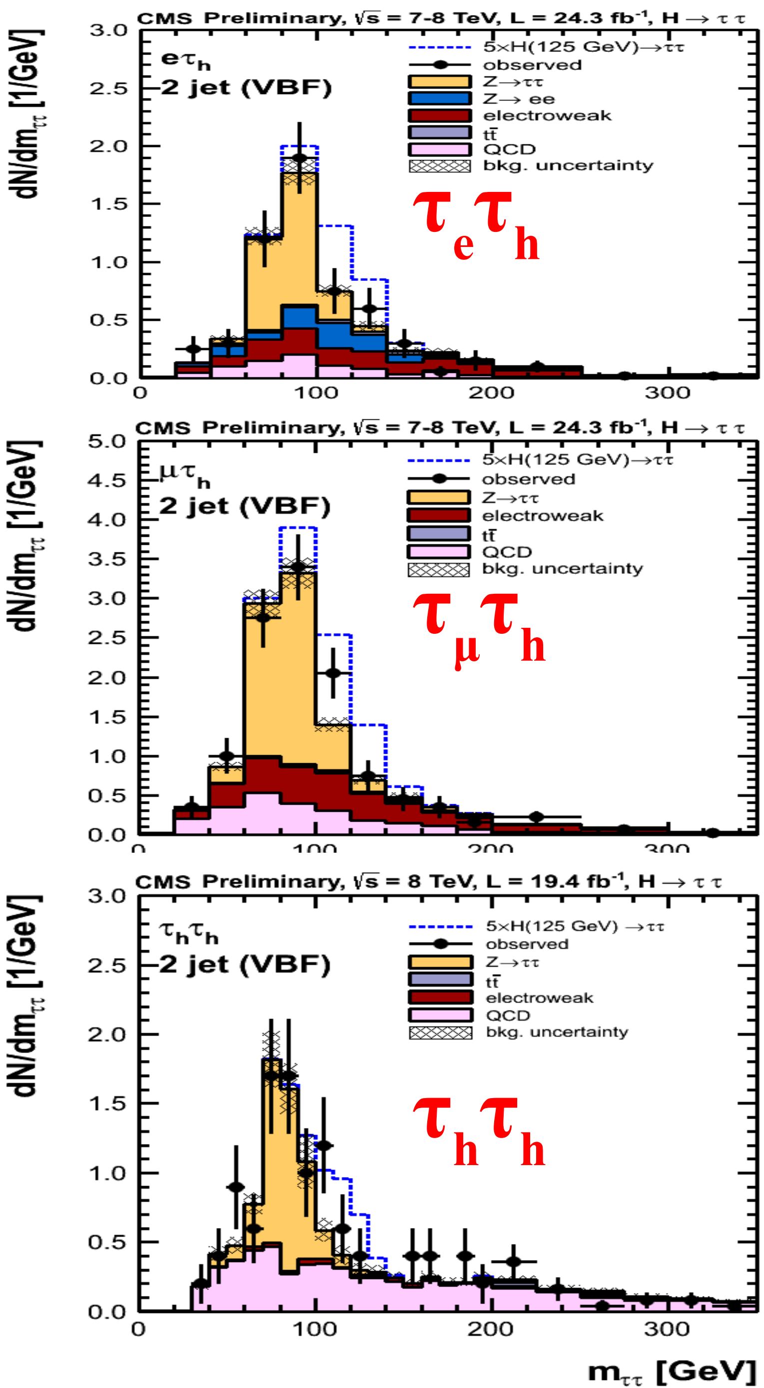
Diboson/W+jets:
- From madgraph.
- Normalization from sideband.

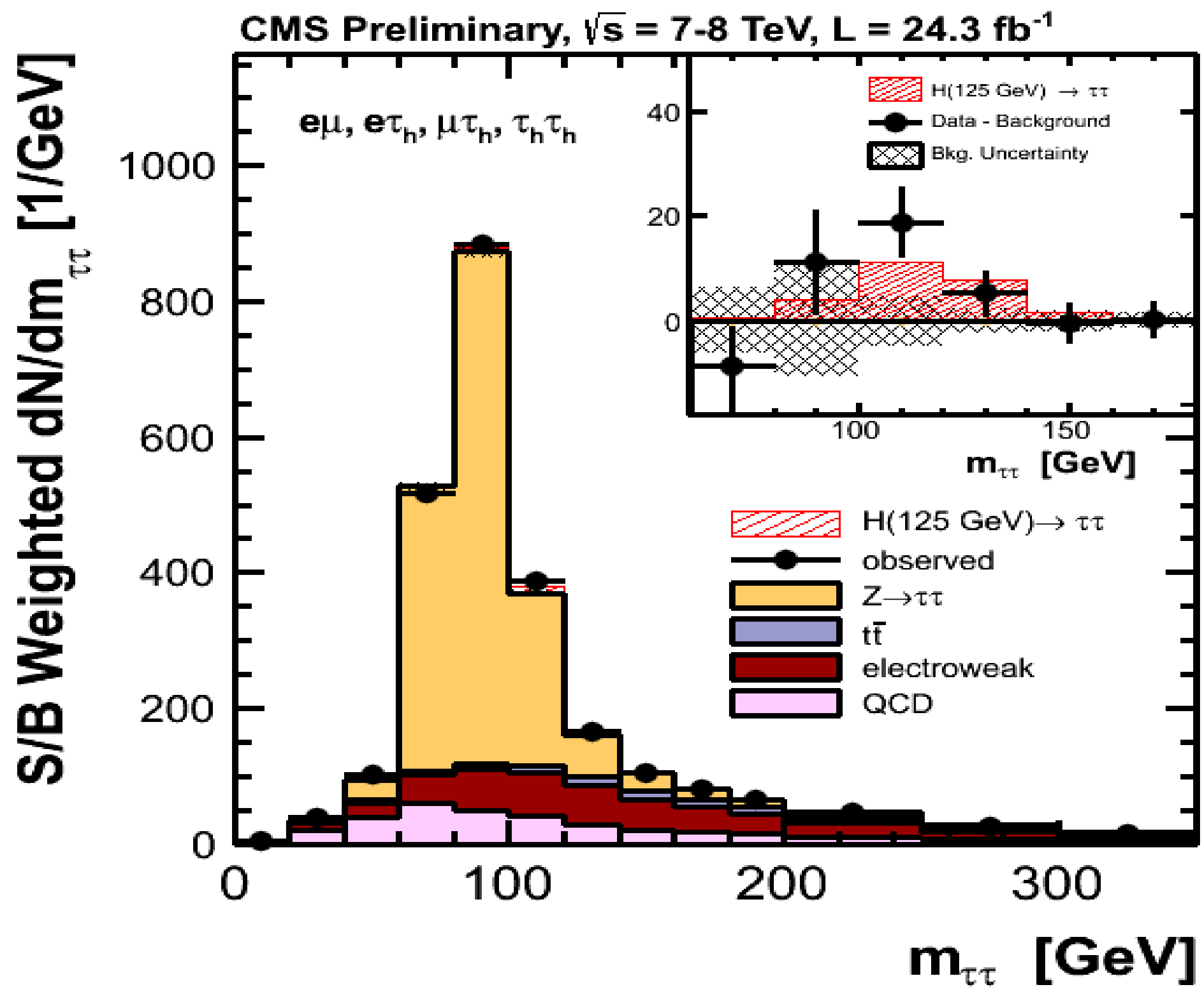


- Select isolated leptons.
- Restrict $\not{E}_T$ (supp. W+jets, ttbar).
- Discriminate signal from background based on $m_{\tau\tau}$.

Improvement highlights since ICHEP: new MVA MET, fully hadronic

VBF Category ($H \rightarrow \tau\tau$) and Summary

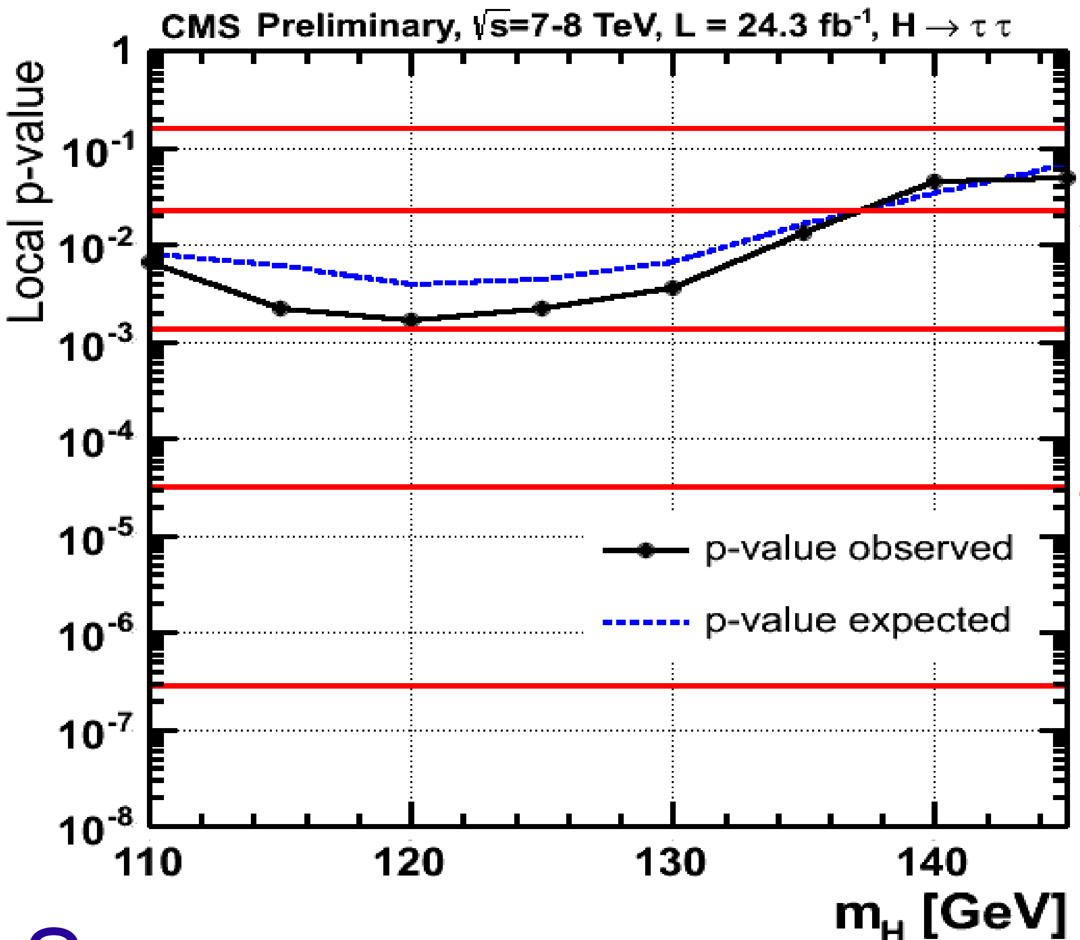


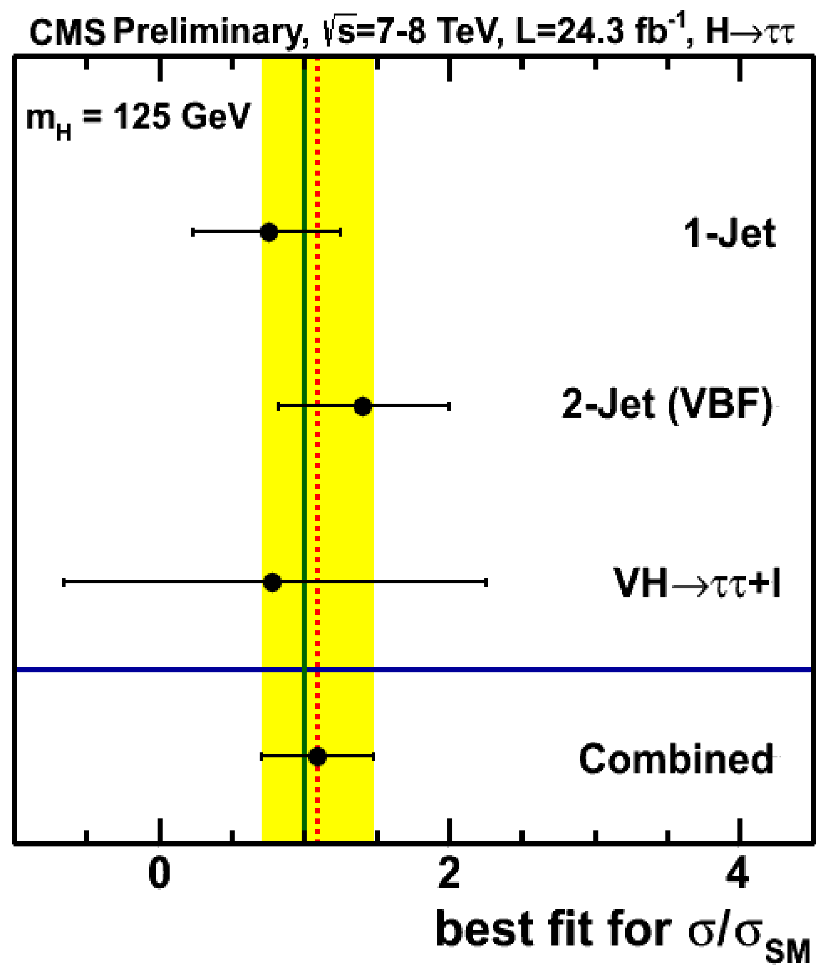


Summary plot

– all channels weighted to represent proper overlay in one plot

Taus Zooming in on the Higgs

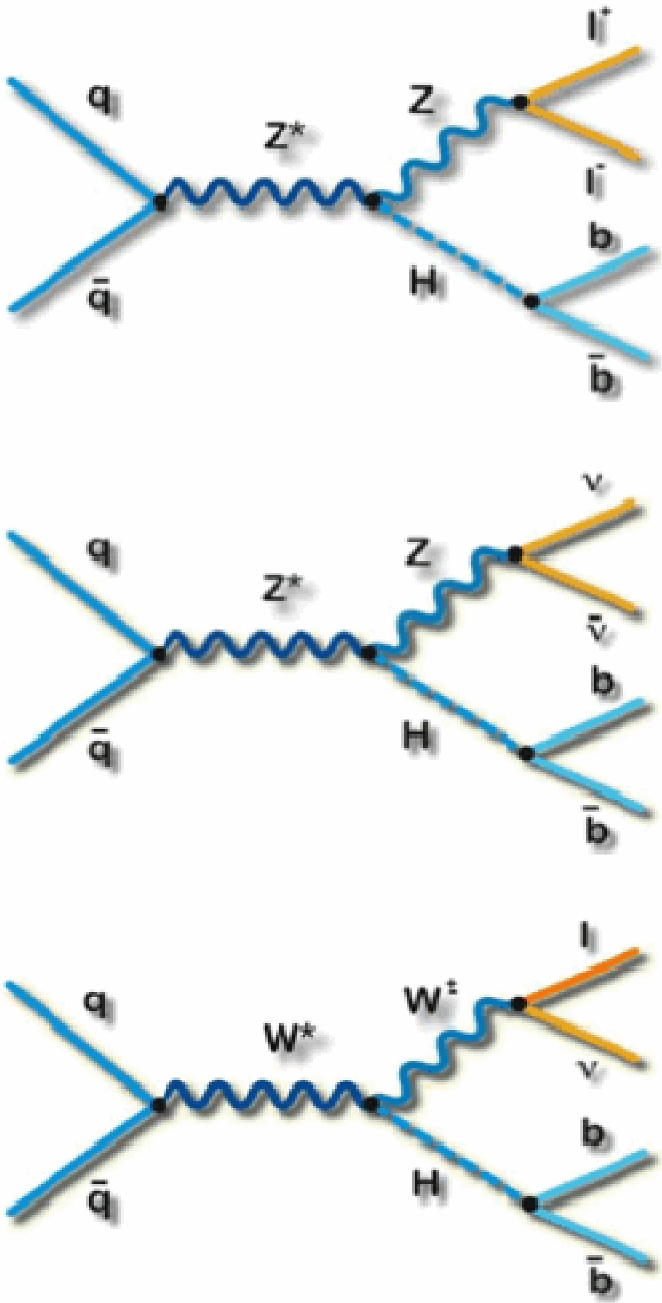




Summary

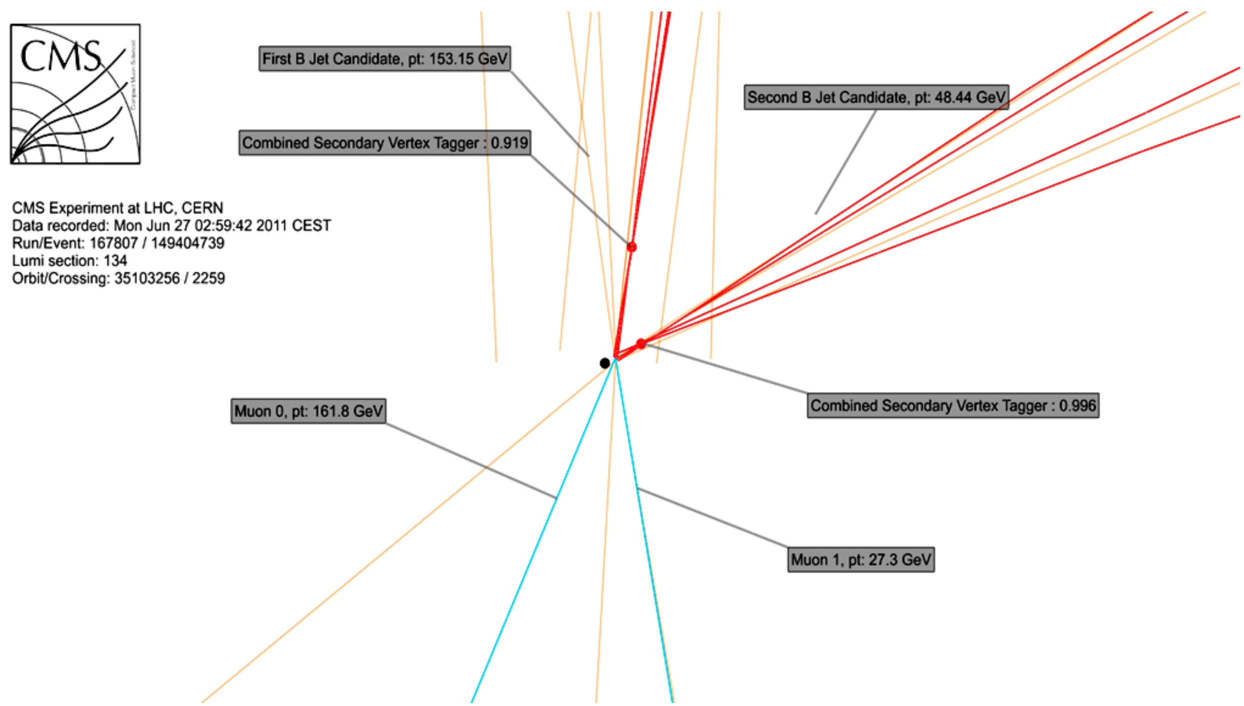
- analysis made dramatic improvement – not just added data
- sensitivity below 1xSM... excess observed at 2.9 std (exp: 2.6)
- consistent picture between categories: $\sigma/\sigma_{SM} = 1.1 \pm 0.4$

Analysis Telegram: VH → Vbb

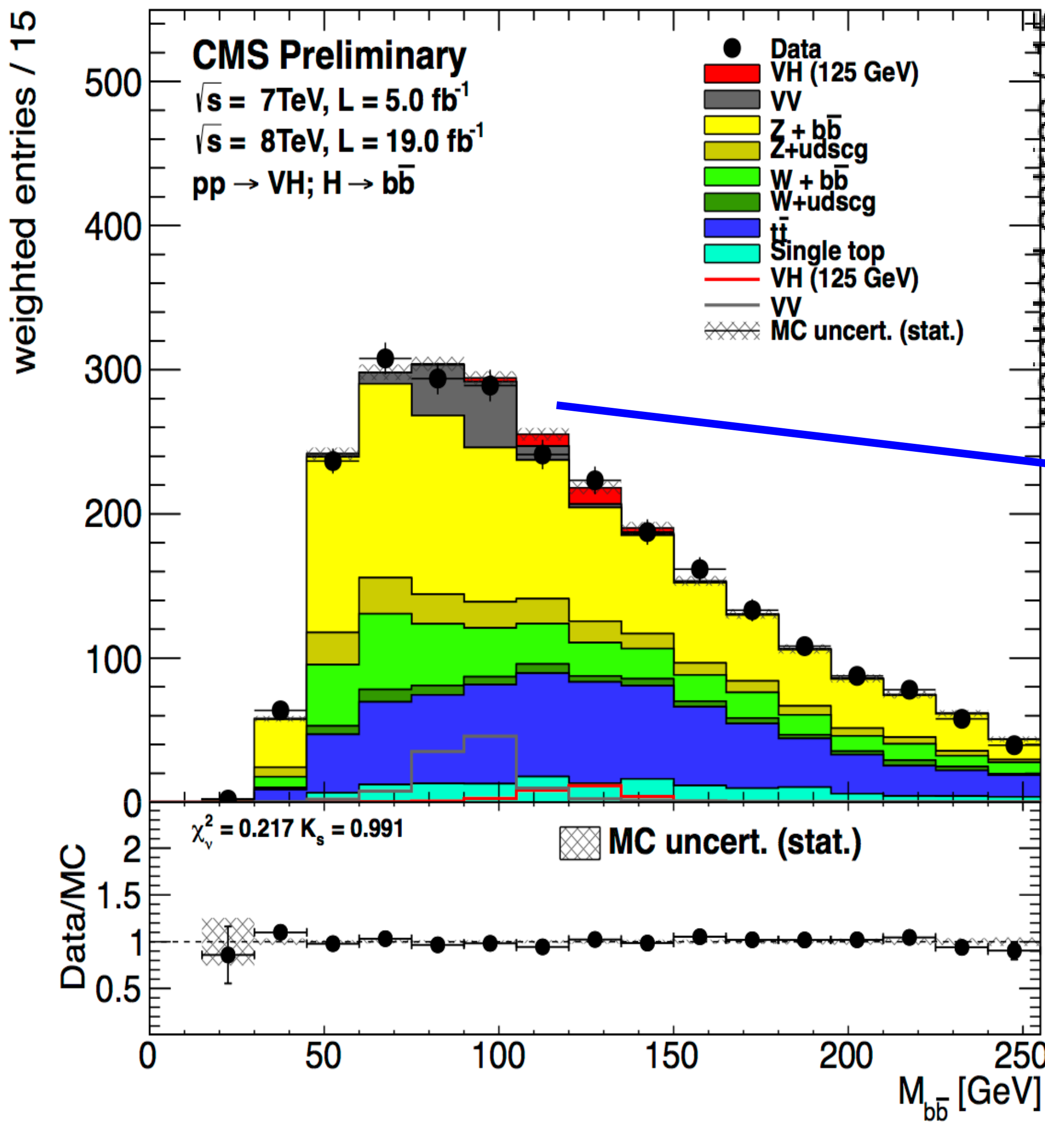


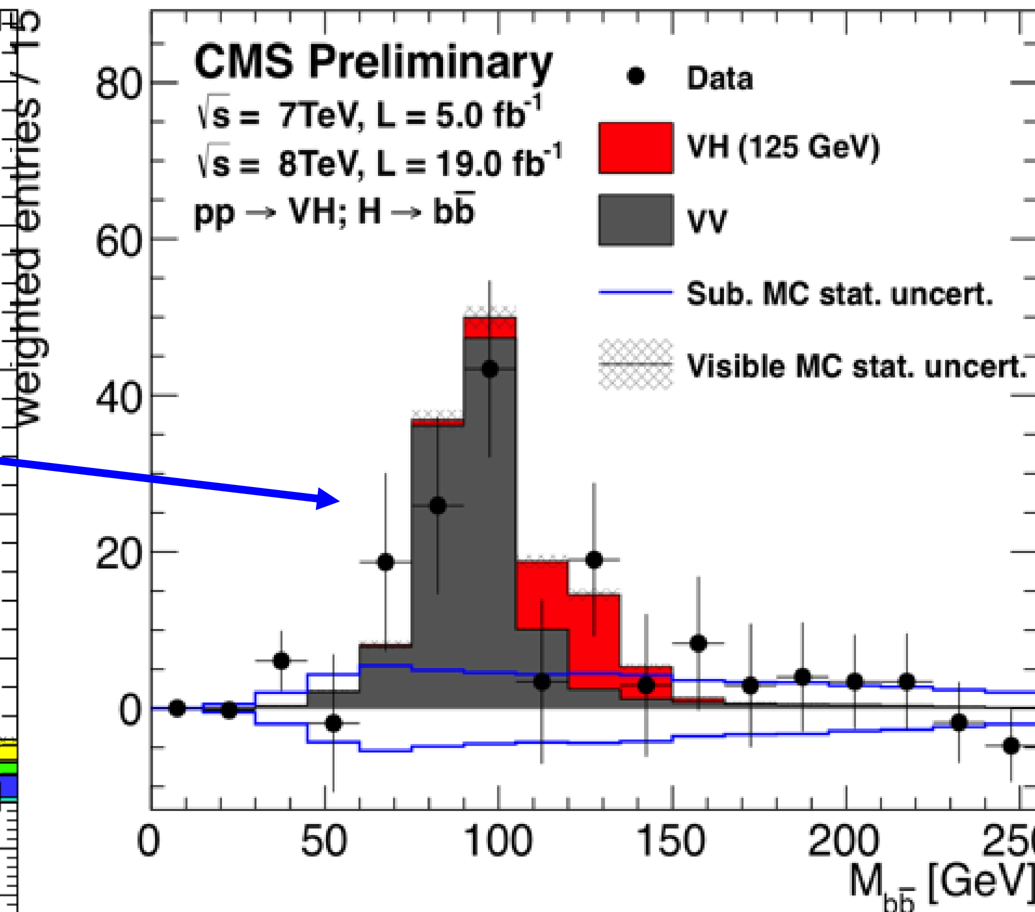
Basic analysis idea

- by far largest number of Higgs decays
- but lots of background (jets)
- trigger based on leptons and missing E_T
- *b*-jets identified through displaced tracks
- go to high p_T where Higgs is enhanced
- main background W/Z+jets and top



Data Summary: VH → Vbb



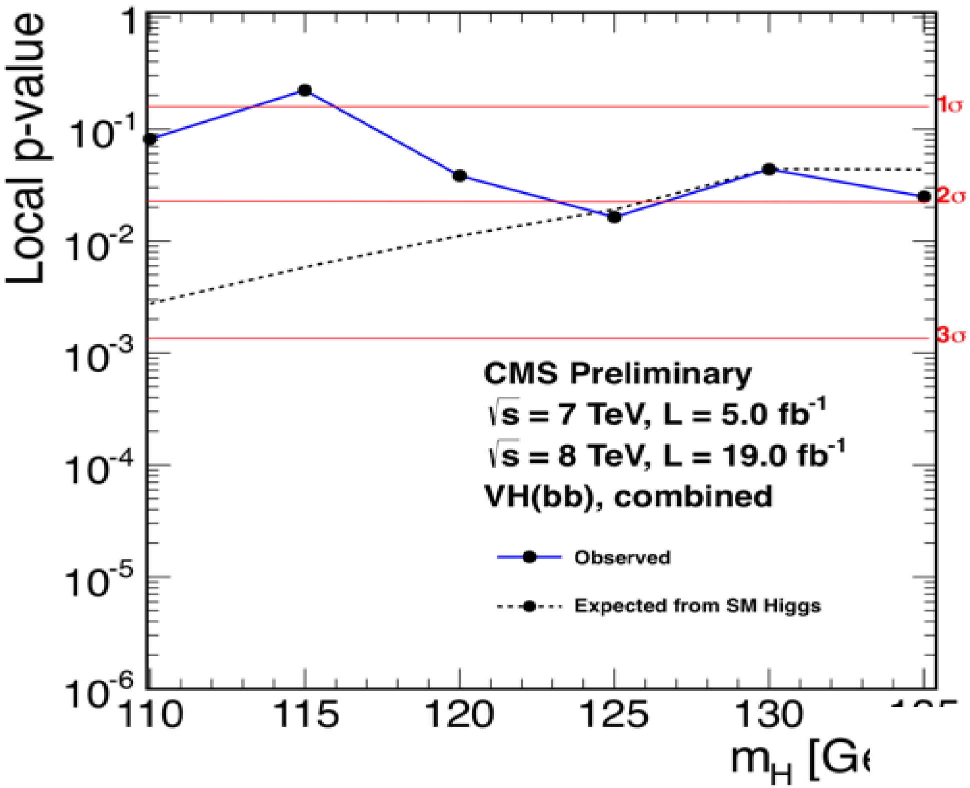


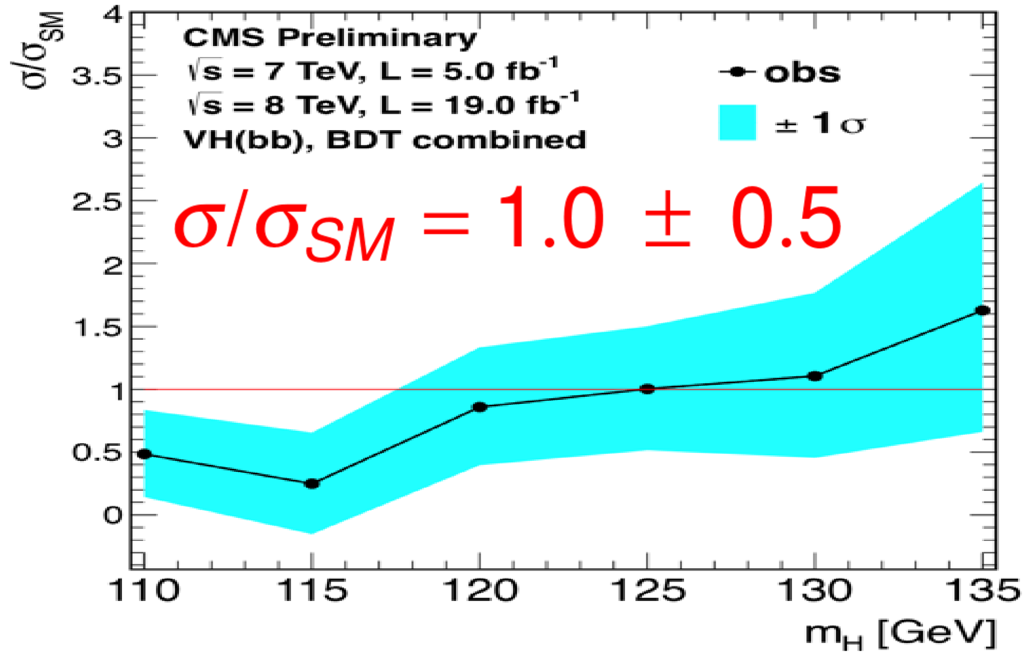
Full 2011+2012 dataset

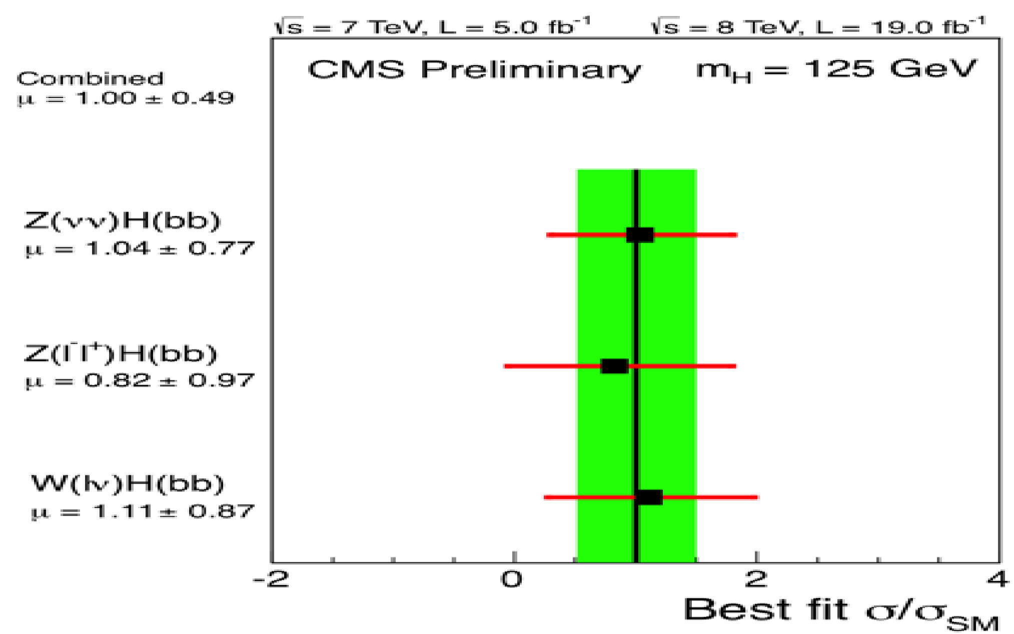
Summary

– seeing diboson production (VV), Higgs excess starting to build up

Results Summary: $H \rightarrow bb$



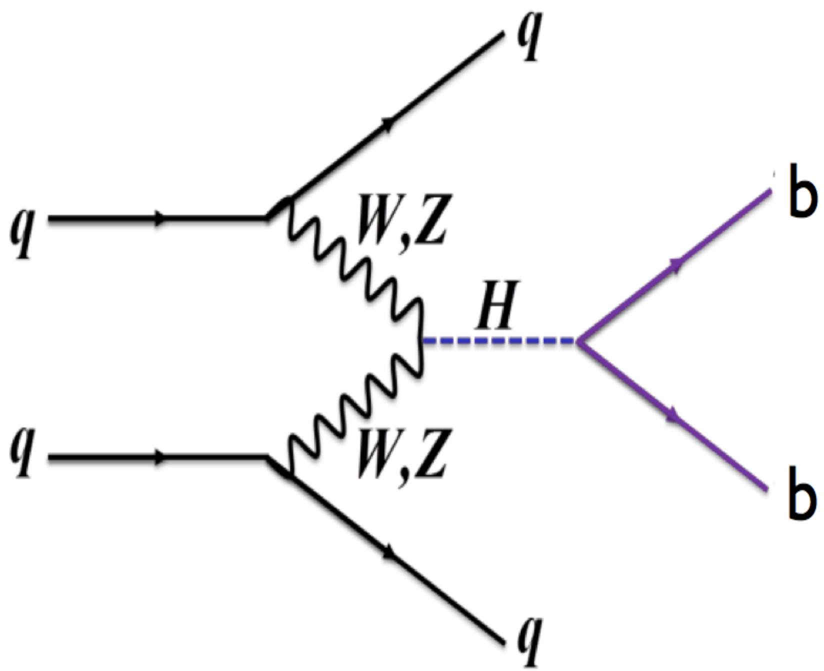


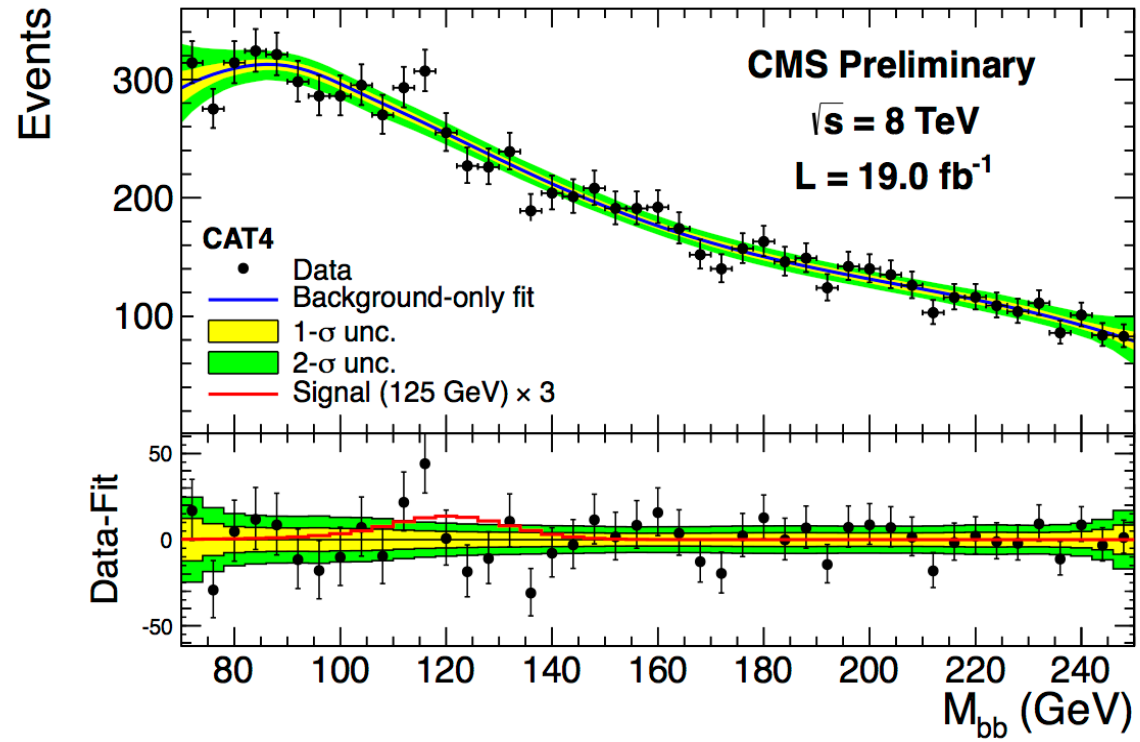


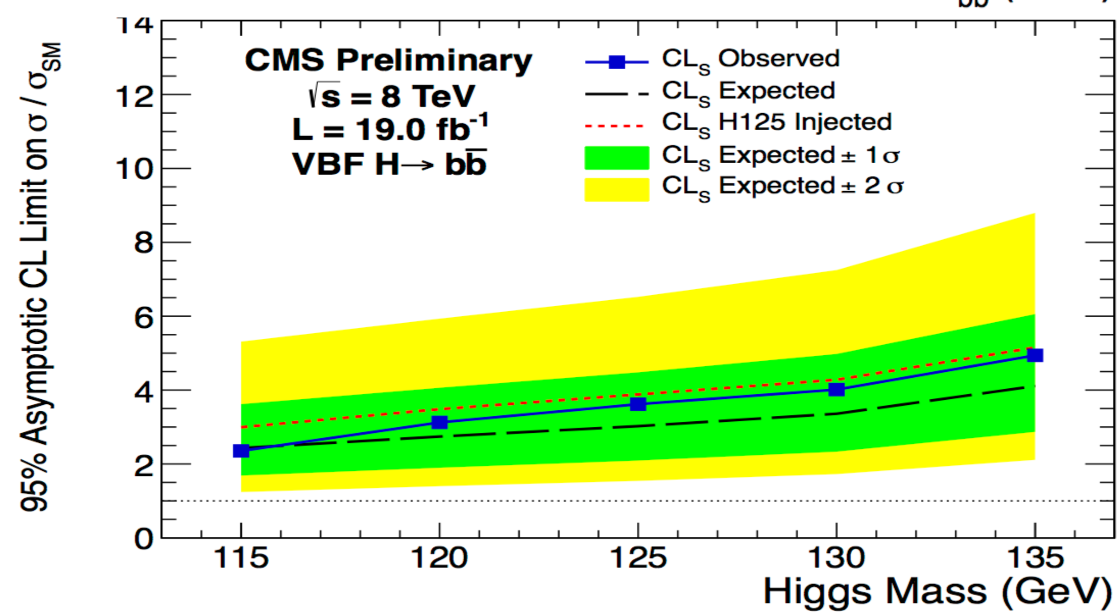
CMS result

- SM sensitivity reached
- mild excess is observed, channels consistent
- need more data

VBF Channel with H → bb







Telegram

- VBF: full hadronic final state
- 4 categories (NN) are used
- mass of di-bjets used as discriminant

Higgs Result Combination

H -> WW -> 2l2ν

H -> $\gamma\gamma$

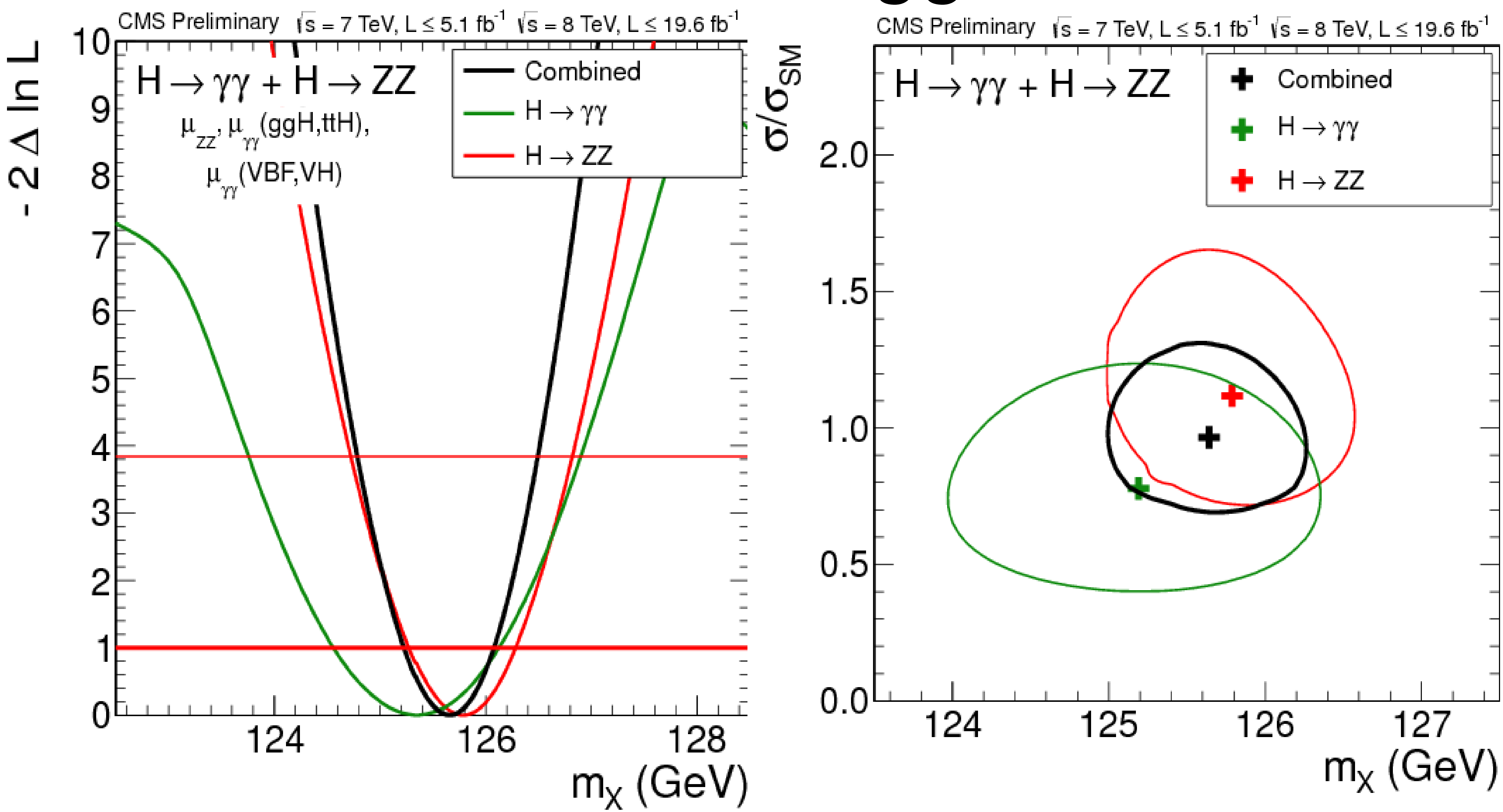
H -> $\tau\tau$

H -> bb

H -> ZZ -> 4l

ATLAS and CMS use consistent,
statistical tools.

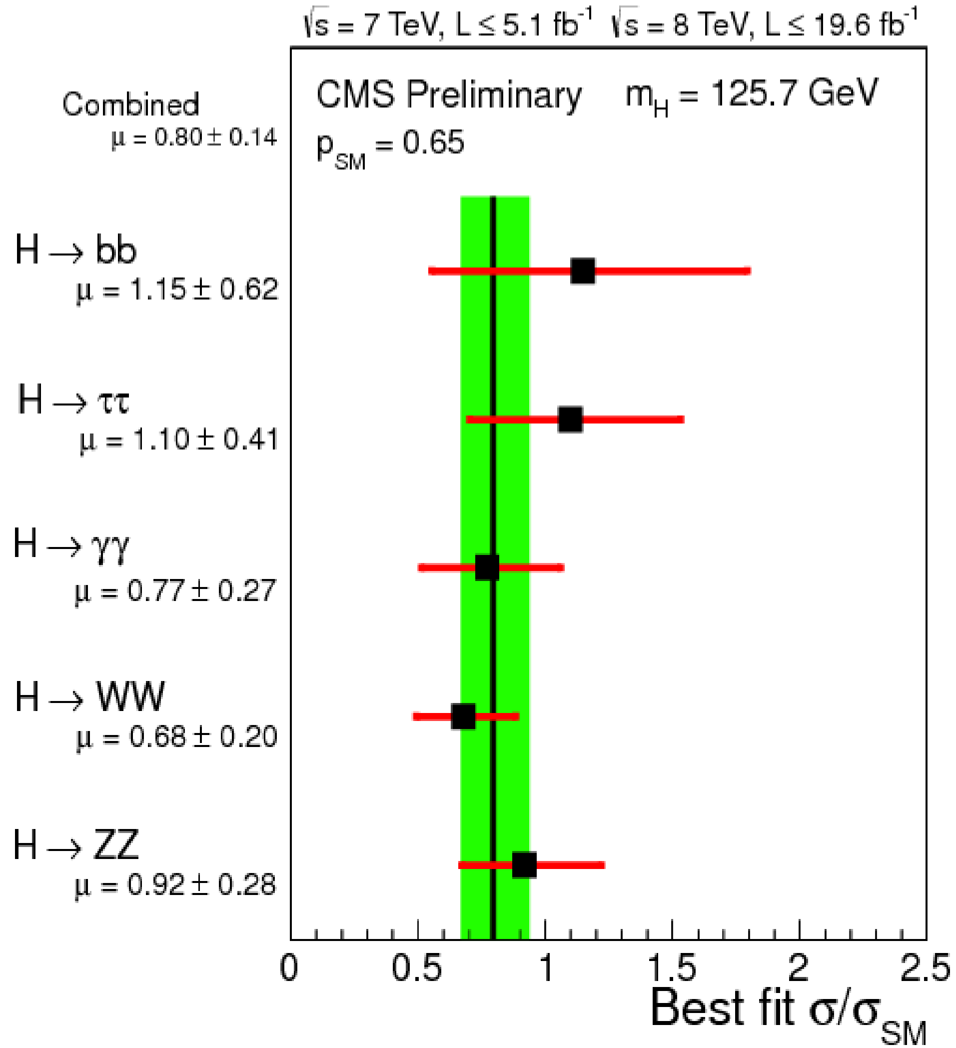
Combination of Higgs Results

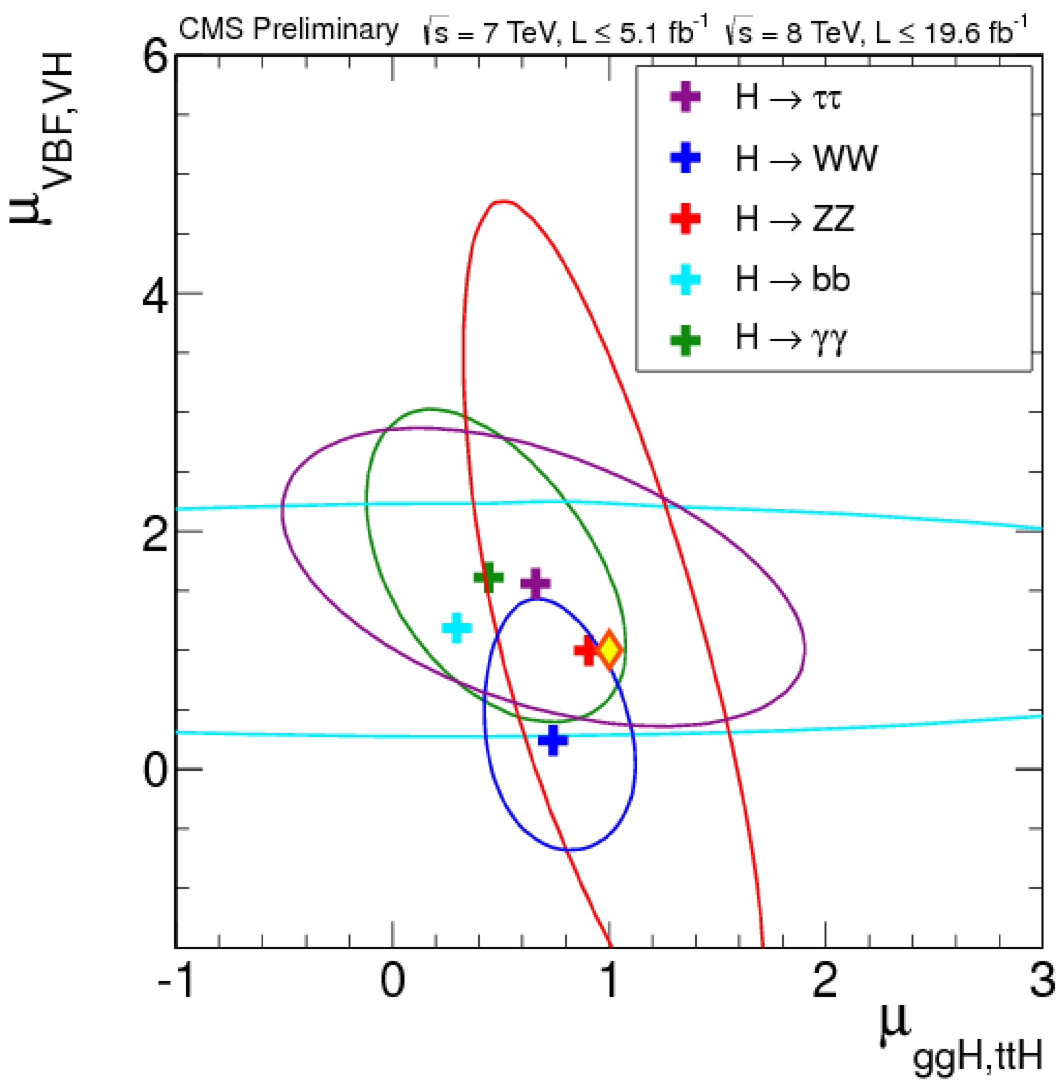


Mass measurement and signal strength

- m_X = **125.7 ± 0.3(stat) ± 0.3(syst) GeV**
- Signal strengths consistent with each other and with SM

Combination of Higgs Results

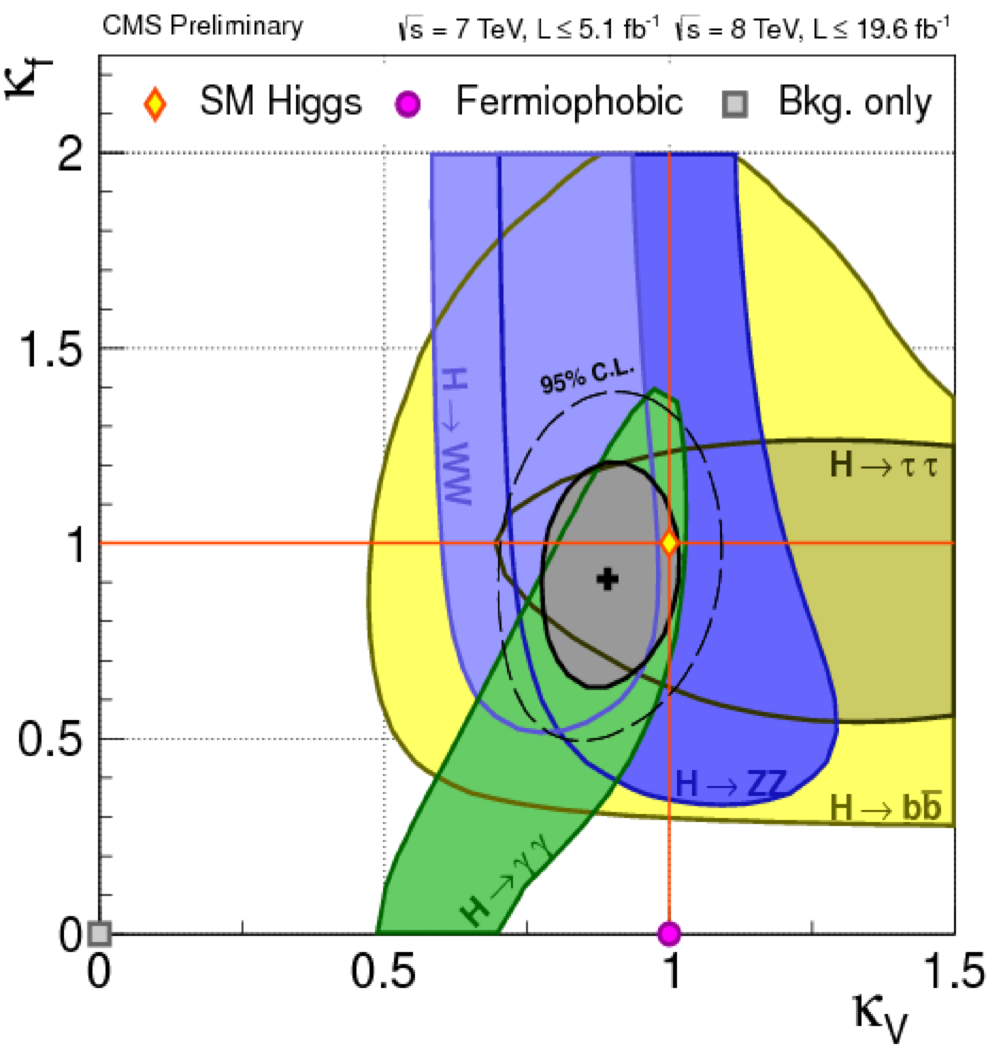


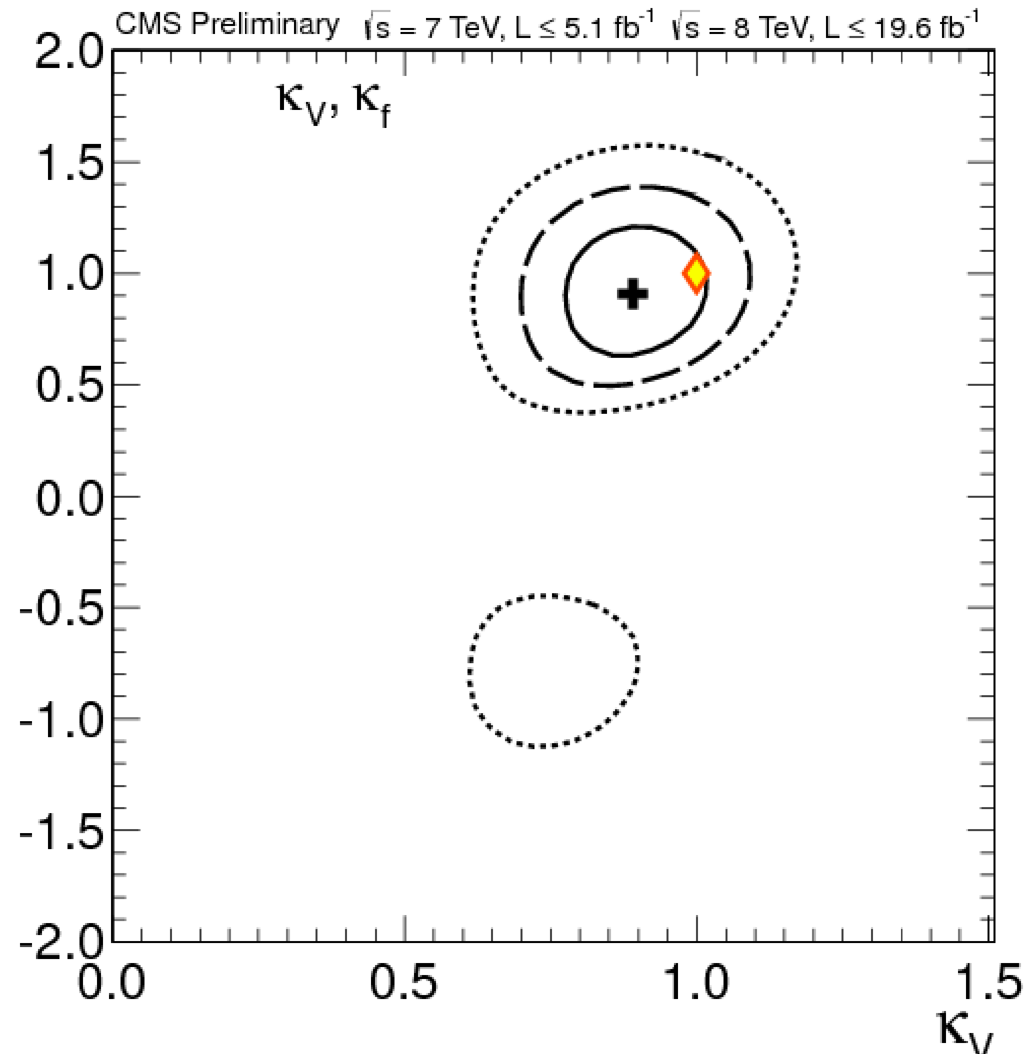


Compatibility per analysis channel and production

– combined signal strength: **0.80 ± 0.14**

Combination of Higgs Results





Couplings consistent with each other and standard model

- Fermions versus vector bosons
- effective gluon versus photon couplings (loops)

Conclusion

New results consistent with publications

- Significance of the signal well beyond 7 standard deviations
- Mass of the particle: m_χ = 125.7 ± 0.3(stat) ± 0.3(syst) GeV

Particle behaves just like the Higgs but ....

- fermionic final states steadily building up excess
- 3.3 standard deviations disfavoring particle to be pseudo scalar
- couplings are well within 2 standard deviations of SM
- more data might still expose the particle as SM Higgs imposter

Stay tuned the LHC will switch back on in 2015.

Future Higgs Program Overview

Higgs Properties

- mass, natural width (will be known very precisely)
- relative branching ratios
- coupling parameters

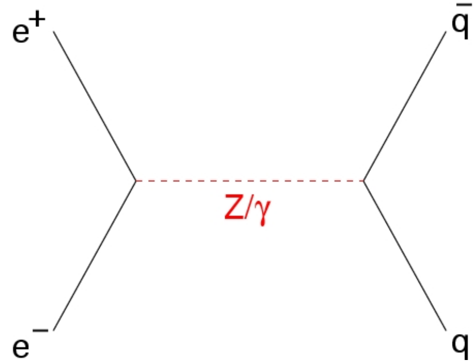
Diboson Scattering

- Higgs was invented to keep process finite
- good place to check for irregularities
- needs lots of data

Unexpected Higgs

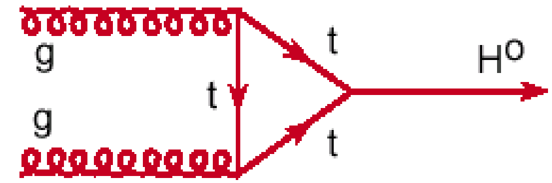
- Higgs could have other decay modes

Remember the Z/W Bosons

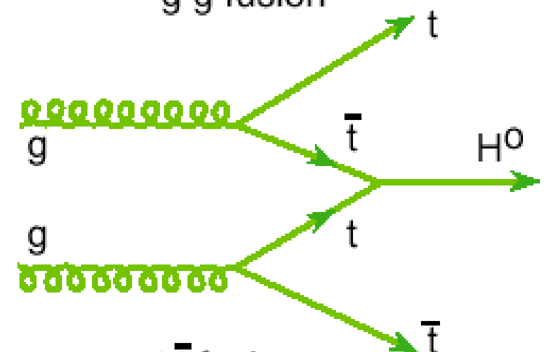


LEP program measured

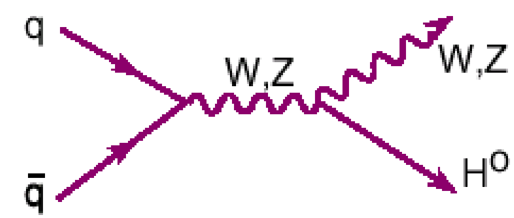
- mass, natural width
- relative branching ratios
- coupling parameters



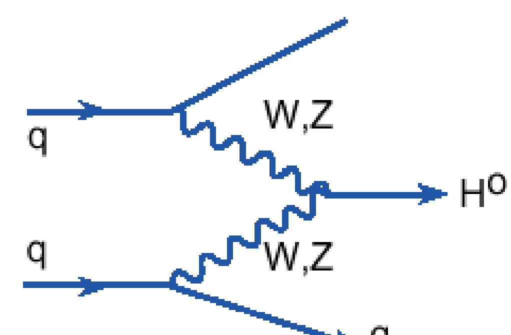
g g fusion



t t̄ fusion



W, Z bremsstrahlung



WW, ZZ fusion

Differences

- Higgs mass and width precisions do not constrain SM
- branching ratios test consistency of SM
- production and decay more complex due to mass dependent coupling strength

Plan for LHC and beyond

Year	Phase	Plan	Integrated luminosity
2009		✧ LHC startup, □s = 900 GeV	
2010–2012		□s=7~8 TeV, L=6x10^{33} cm^{-2} s^{-1}, bunch spacing 50 ns	~20-25 fb^{-1}
2013–2014	LS1	Go to design energy, nominal luminosity	
2015–2017		□s=13~14 TeV, L~1x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns	~75-100 fb^{-1}
2018	LS2	Injector and LHC Phase-1 upgrade to full design luminosity	
2019–2021		□s=14 TeV, L~2x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns	~350 fb^{-1}
2022	LS3	HL-LHC Phase-2 upgrade, IR, crab cavities?	
2023 … 2030?		□s=14 TeV, L=5x10^{34} cm^{-2} s^{-1}, luminosity levelling	~3000 fb^{-1}

discovery

↓

O(%) couplings

Particle Reconstruction in CMS