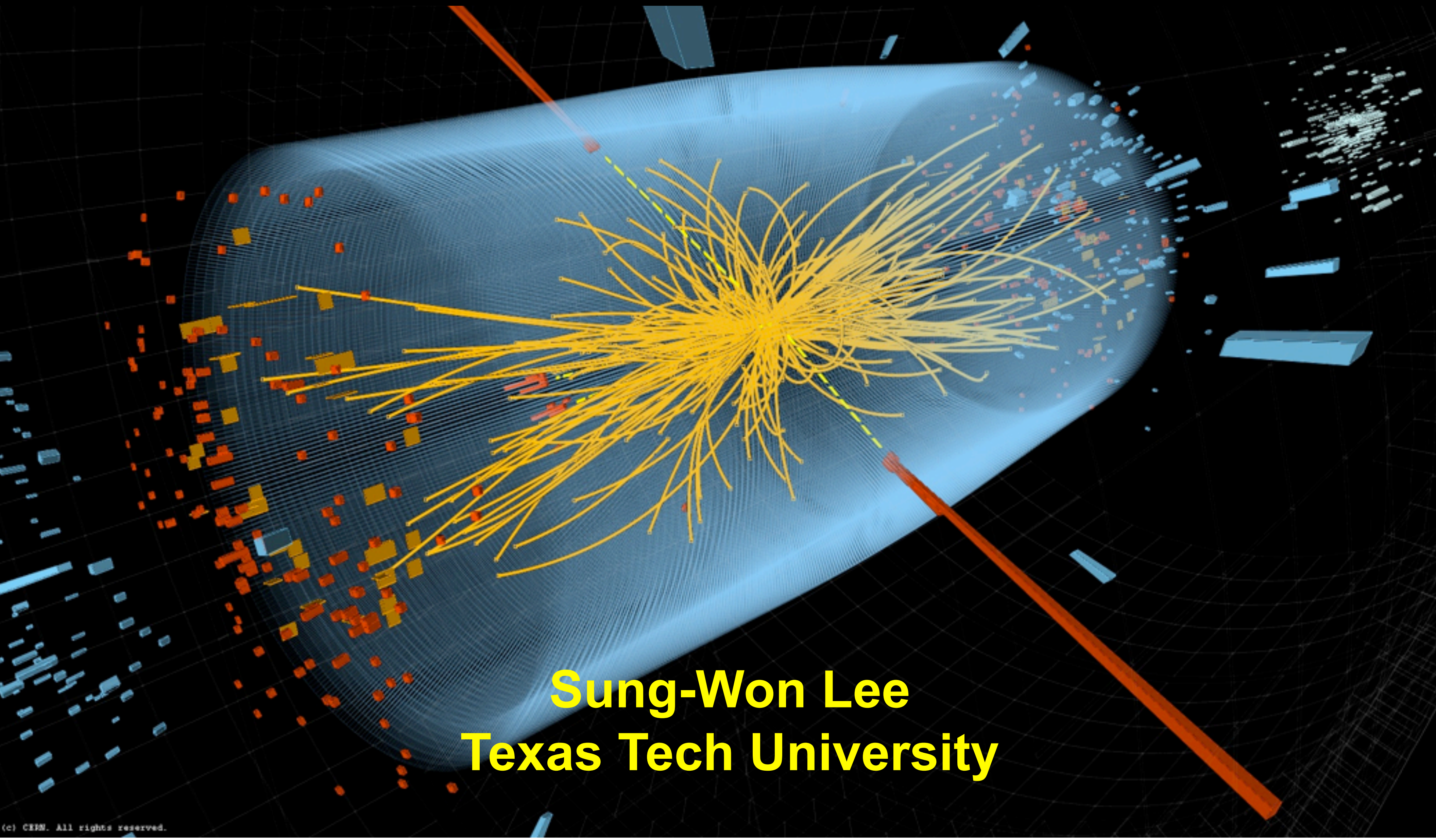
Recent Results on Higgs Search with CMS



Sung-Won Lee
Texas Tech University

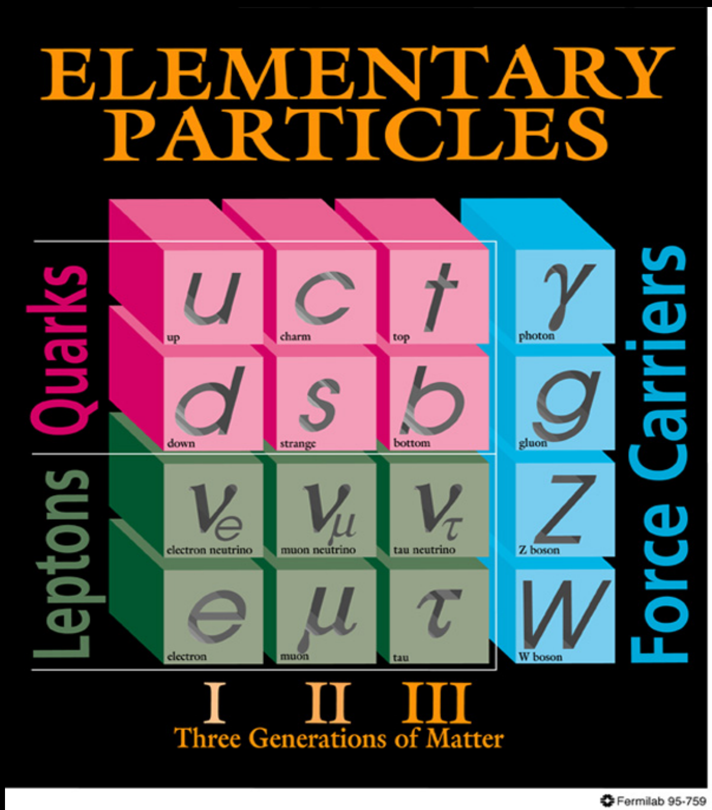
Outline

- Motivation & Experiment
- Searches for Heavy Higgs
- Searches for Light Higgs
- Combination of the searches: **putting it all together**
- Interpretation & Future Prospects
- Conclusion

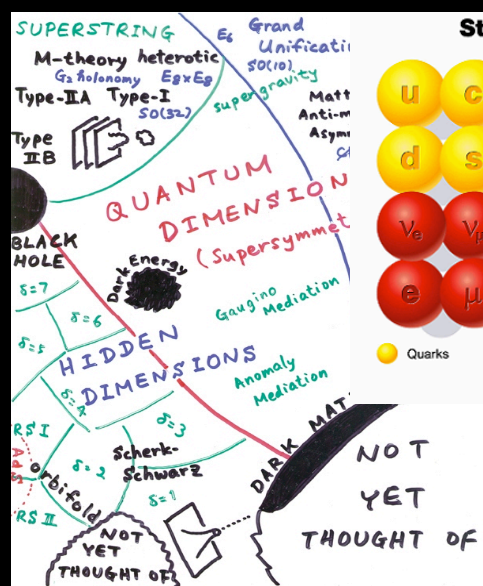
Particle Physics Today - Motivation

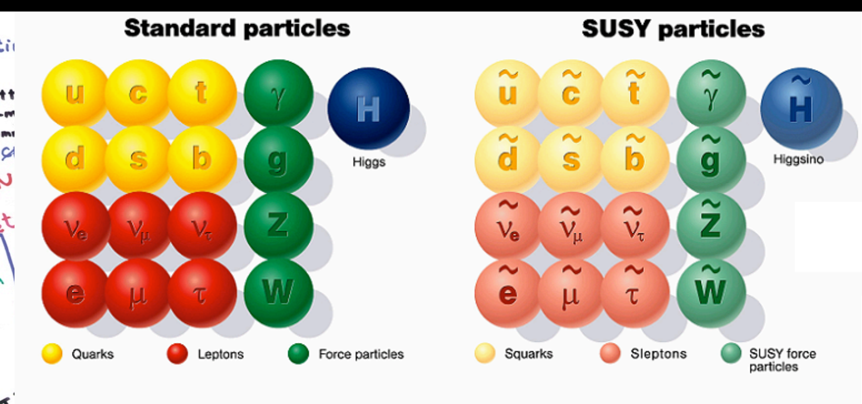
The Standard Model has been enormously successful, but it still haven't found why particles have mass! & leaves many important questions unanswered:

① Are quarks and leptons really fundamental ?
② Can we understand the source of their masses ?
③ Will we discover more types of particles and forces ?
④ Why does the universe consist almost entirely of matter ?
⑤ Are forces unified at large energy scale?
⑥ How can we incorporate gravity ?
⑦ Are fermions point-like or do they have substructure ?
⑧ Are there extra dimensions of space?
⑨ What is the nature of dark matter & dark energy ?, etc.



The Standard Model of particle physics is a description of the known particles and their interactions

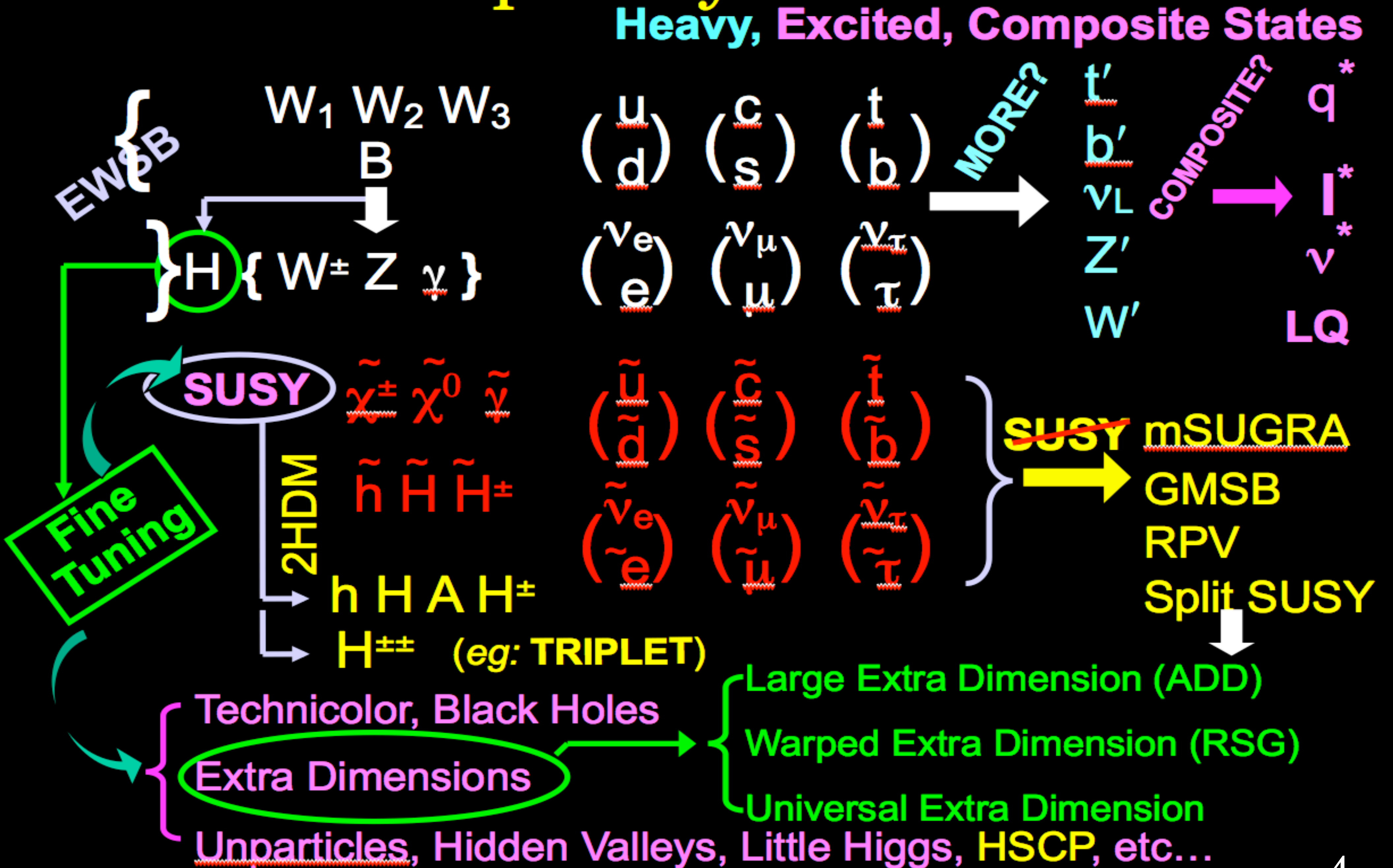


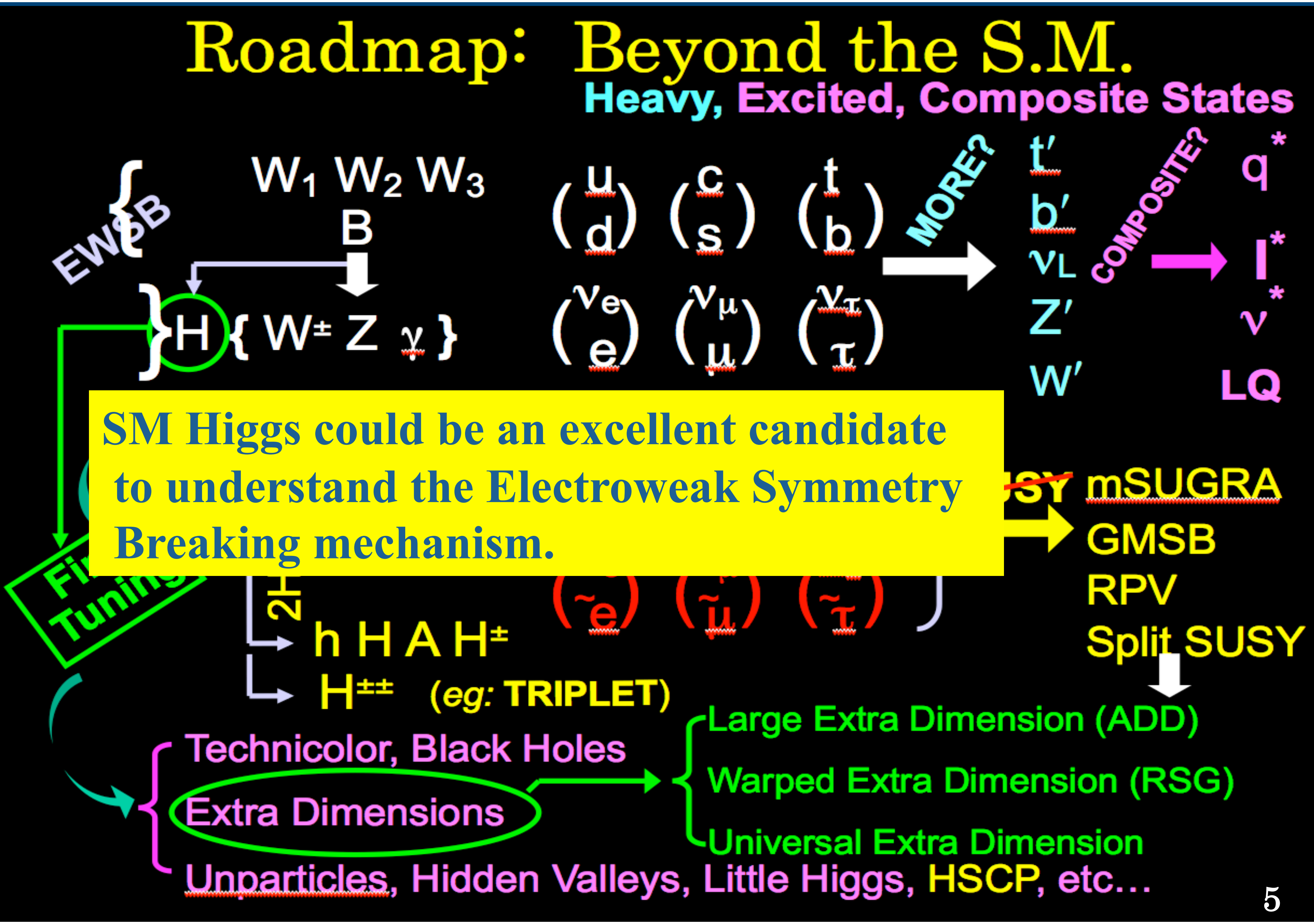


A huge challenge!
Big questions need big science!

Many theories attempt to address these issues (see next slide)

Roadmap: Beyond the S.M.

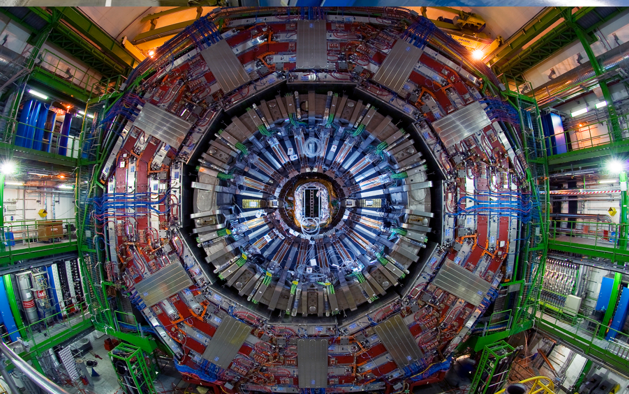




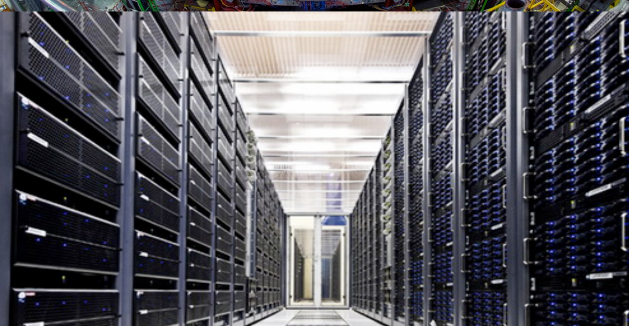
SM Higgs could be an excellent candidate to understand the Electroweak Symmetry Breaking mechanism.

Particle Physics Today

Machine



Detector



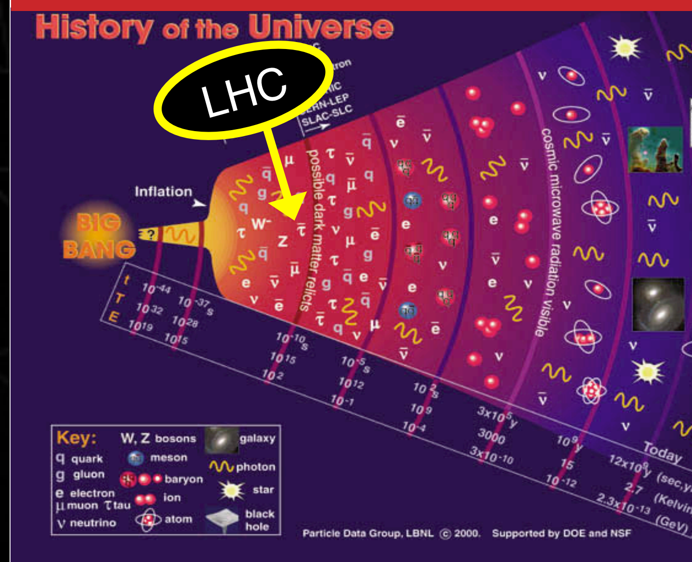
Computing

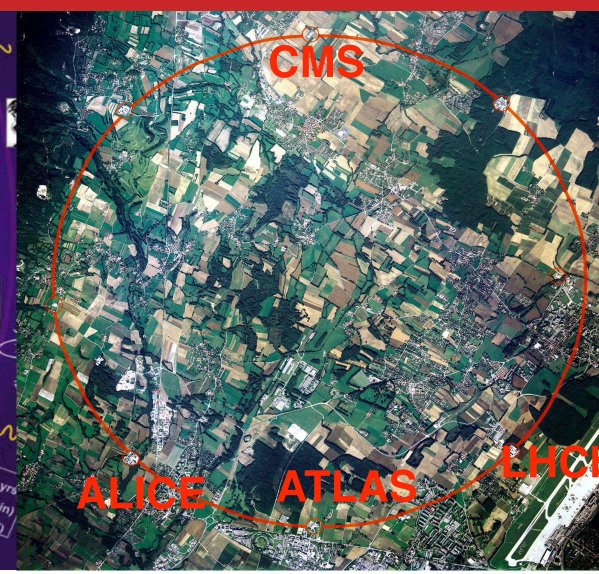
Collaboration

These goals lead particle physicists to do “start-of-art” experiments at new accelerators, seeking clues to their answers.

Large Hadron Collider & ATLAS/CMS experiment are the unique tools to address these questions today !!

Why LHC? - Big Bang Machine to prove early universe





The LHC will allow us to recreate particles since 10^{-12} sec after the Big Bang, & to search for a wide range of new phenomena, including the unexpected!!

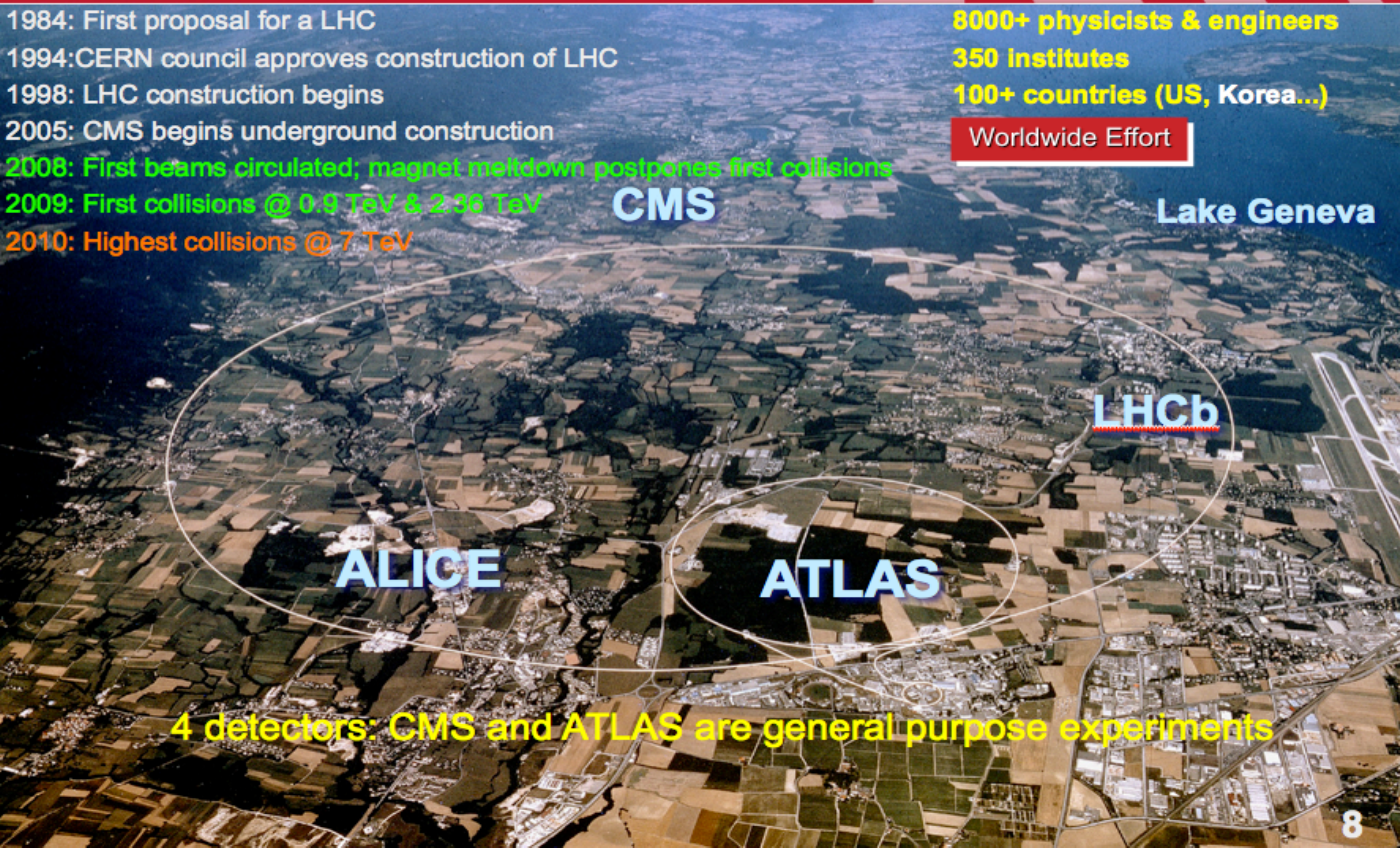
The Large Hadron Collider
At Discovery's Horizon

Large Hadron Collider (LHC) @ CERN
16.5 mi tunnel, 300 ft underground

1984: First proposal for a LHC
1994:CERN council approves construction of LHC
1998: LHC construction begins
2005: CMS begins underground construction
2008: First beams circulated; magnet meltdown postpones first collisions
2009: First collisions @ 0.9 TeV & 2.36 TeV
2010: Highest collisions @ 7 TeV

8000+ physicists & engineers
350 institutes
100+ countries (US, Korea...)

Worldwide Effort

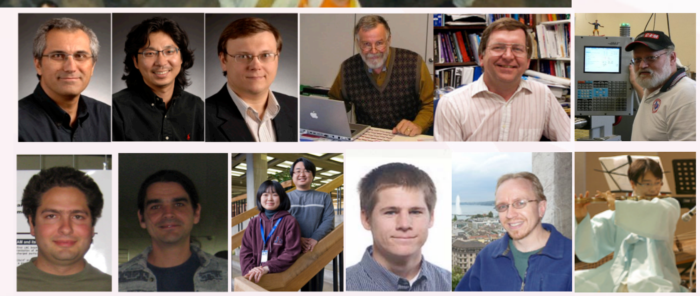


4 detectors: CMS and ATLAS are general purpose experiments

CMS Collaboration

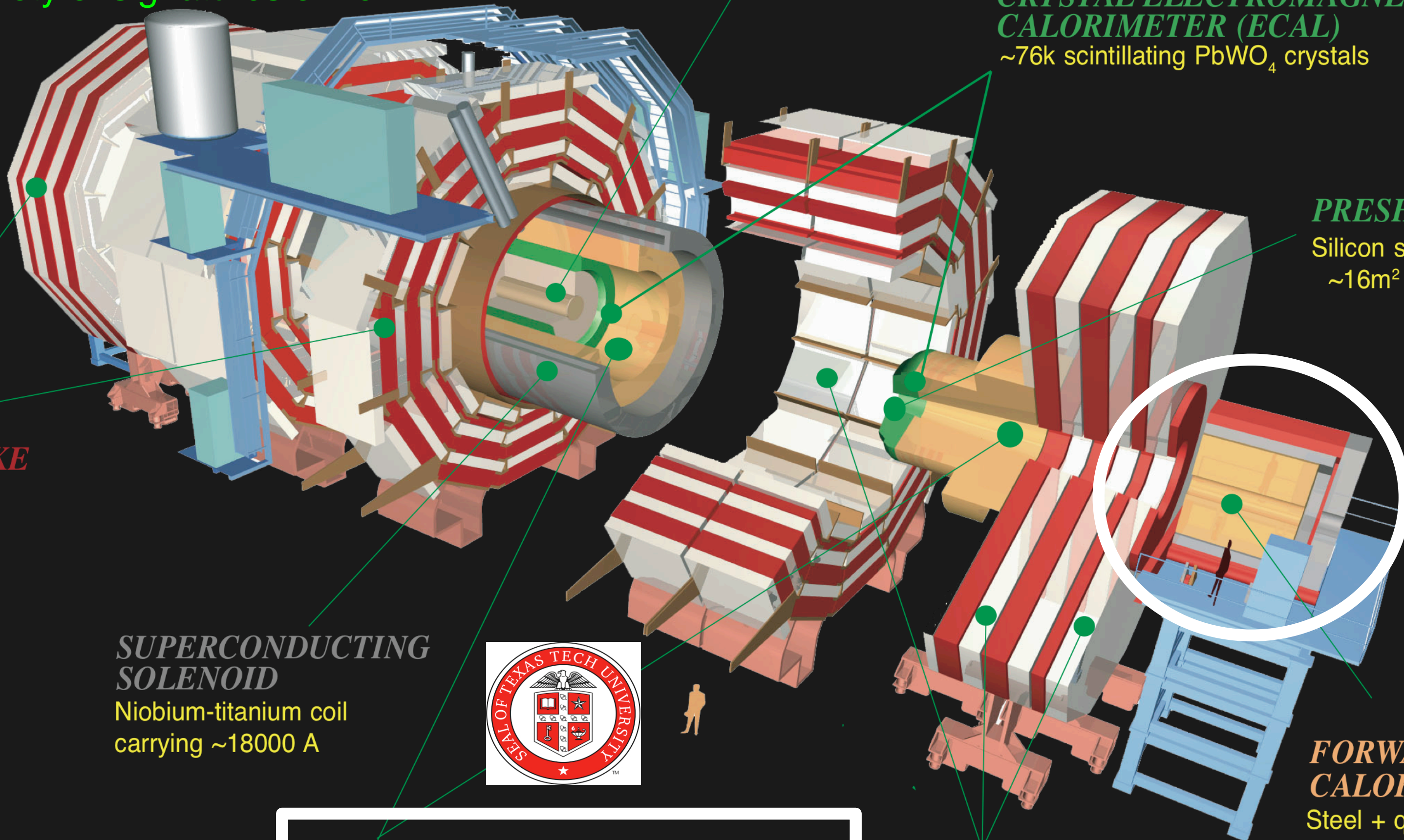
Texas Tech CMS Group

4 faculty, 1 research faculty, 5 postdocs, 6 grad.students, 2 tech & 4 physics teachers



CMS Detector

general-purpose 4π detector designed to look for a large variety of signatures of new physics.



Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

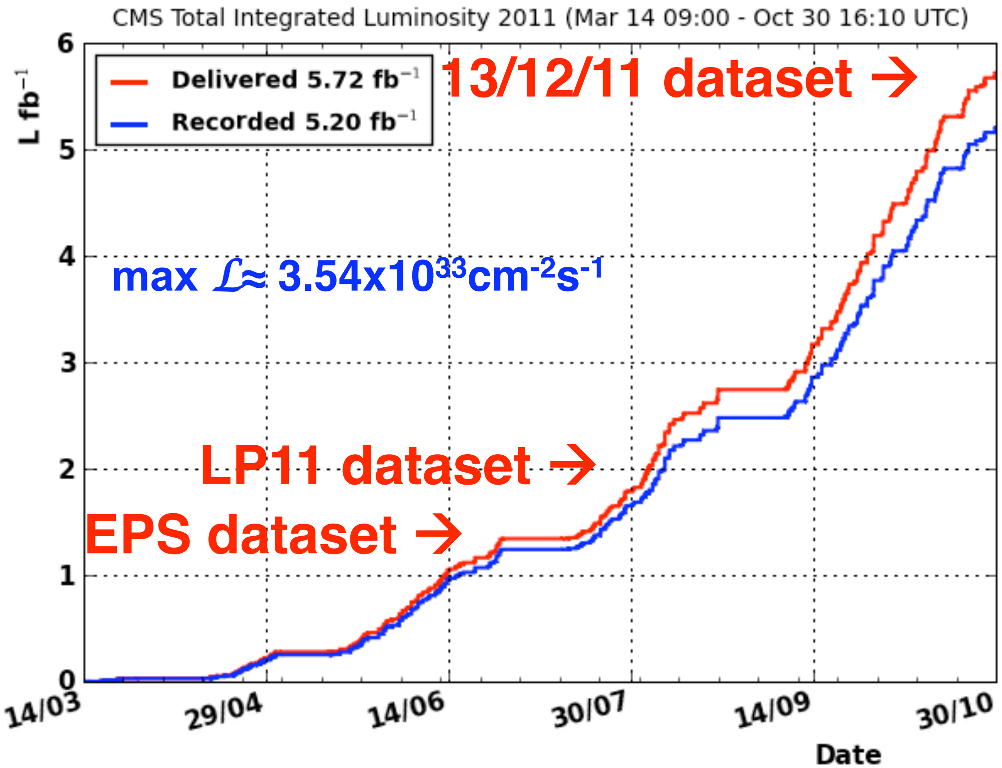
Highly modular concept, strong 3.8T solenoidal magnetic field, all-silicon tracker, high granularity crystal calorimetry, robust and redundant muon system, all software L2/L3 trigger (HLT)

2008: Finally, 15 Years in Development

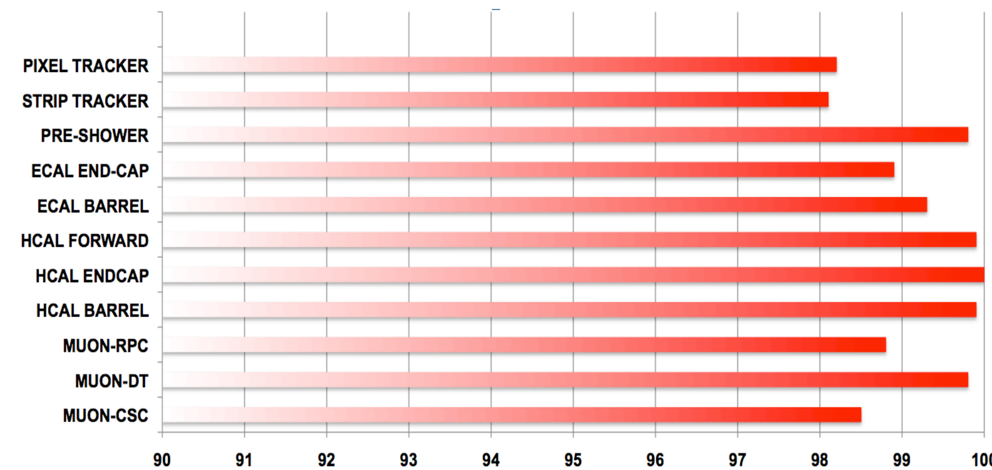
Readout Channels: 66M pixel, 10M silicon, 75k $PbWO_4$ crystals, 15k HCAL, 870k muon systems,10k CPU cores for DAQ, 50k cores for the GRID computing, 2M lines of off-line code. . .

Higgs Hunt: the Playground

5.72fb^{-1} delivered by LHC and **5.2fb^{-1}** recorded by CMS. Overall data taking efficiency **~91%. Average fraction of operational channels per subsystem >98.5%**



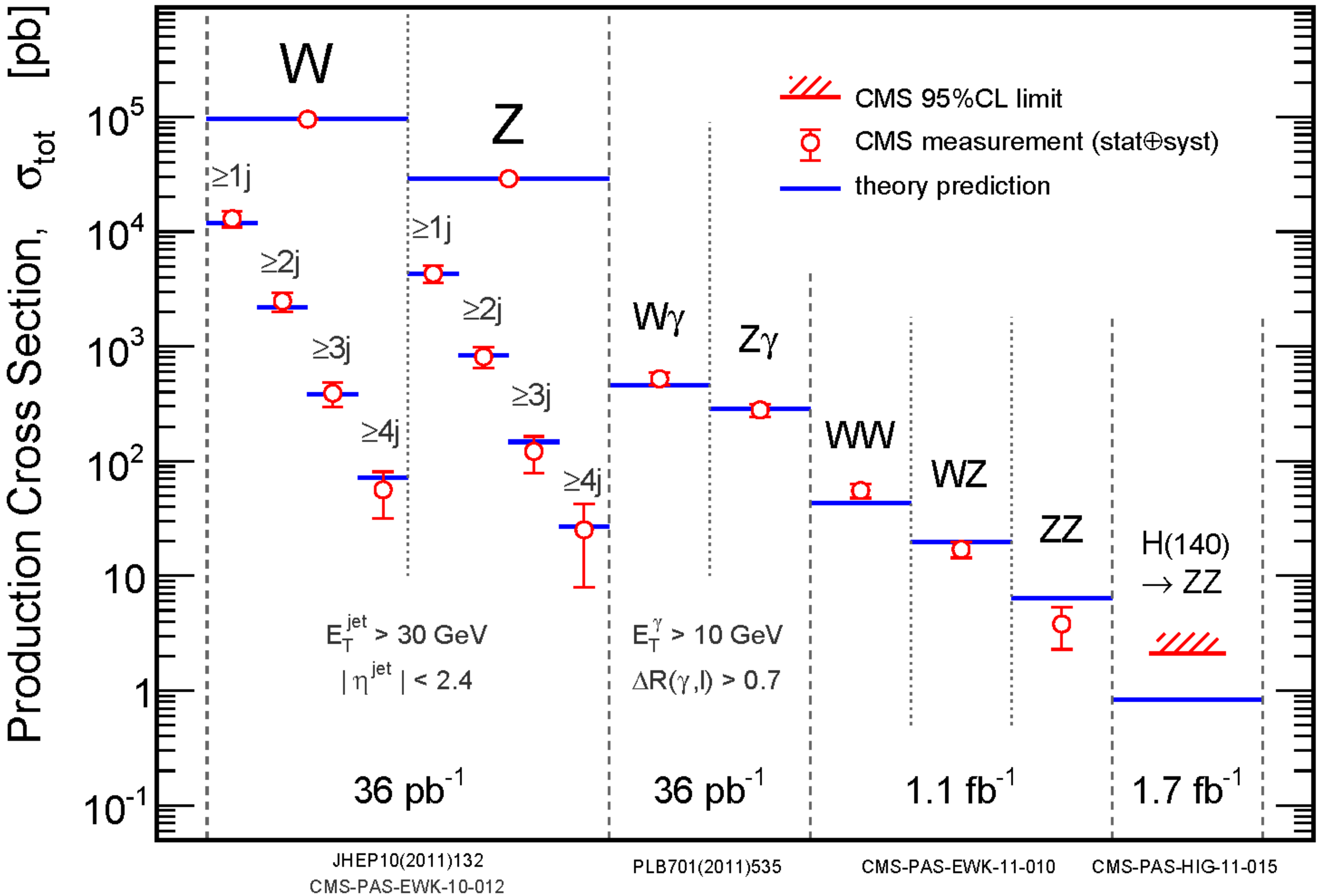
CMS Operations@ √s = 7 TeV in 2011



	MUON-CSC	MUON-DT	MUON-RPC	HCAL BARREL	HCAL ENDCAP	HCAL FORWARD	ECAL BARREL	ECAL END-CAP	PRE-SHOWER	STRIP TRACKER	PIXEL TRACKER
Series1	98.5	99.8	98.8	99.9	100	99.9	99.3	98.9	99.8	98.1	98.2

Average fraction of operational channels per CMS sub-system **> 99%.** Quality of the data for physics **~85%. Certified** data for physics: **Golden 4745pb^{-1} (~92%), Muon 4965pb^{-1} (~96%)**. Uncertainty on the luminosity determination **4.5%.**

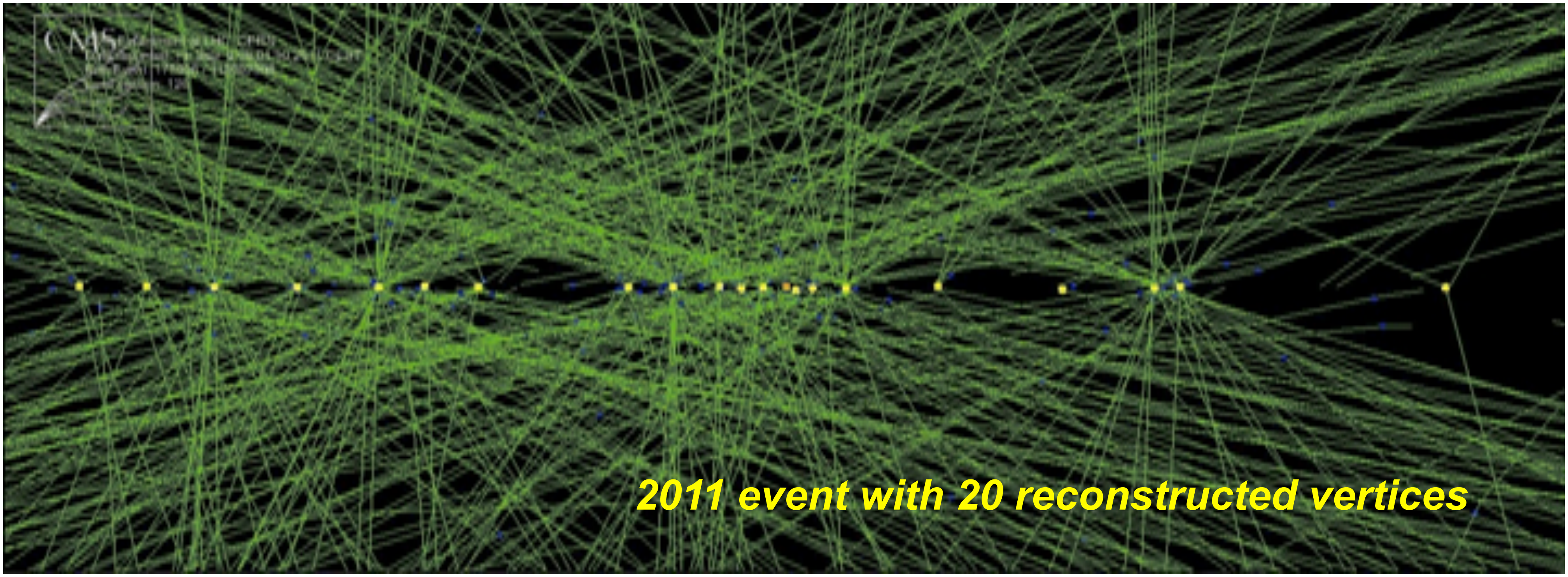
The Challenge: SM backgrounds



The Challenge: Pile-Up

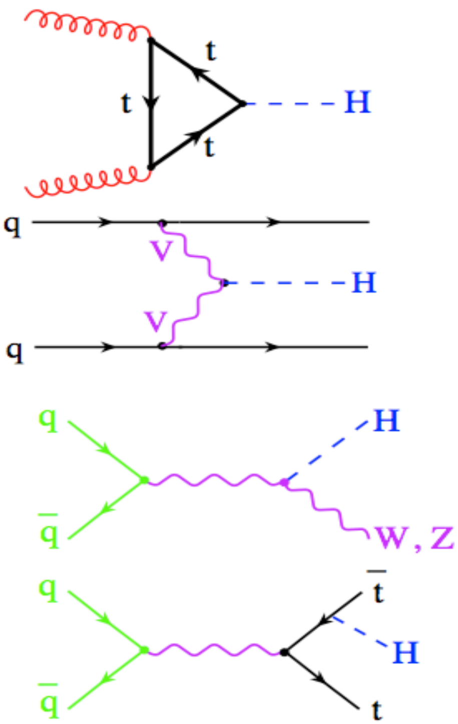
Fall 2011 data corresponds to a large pile-up

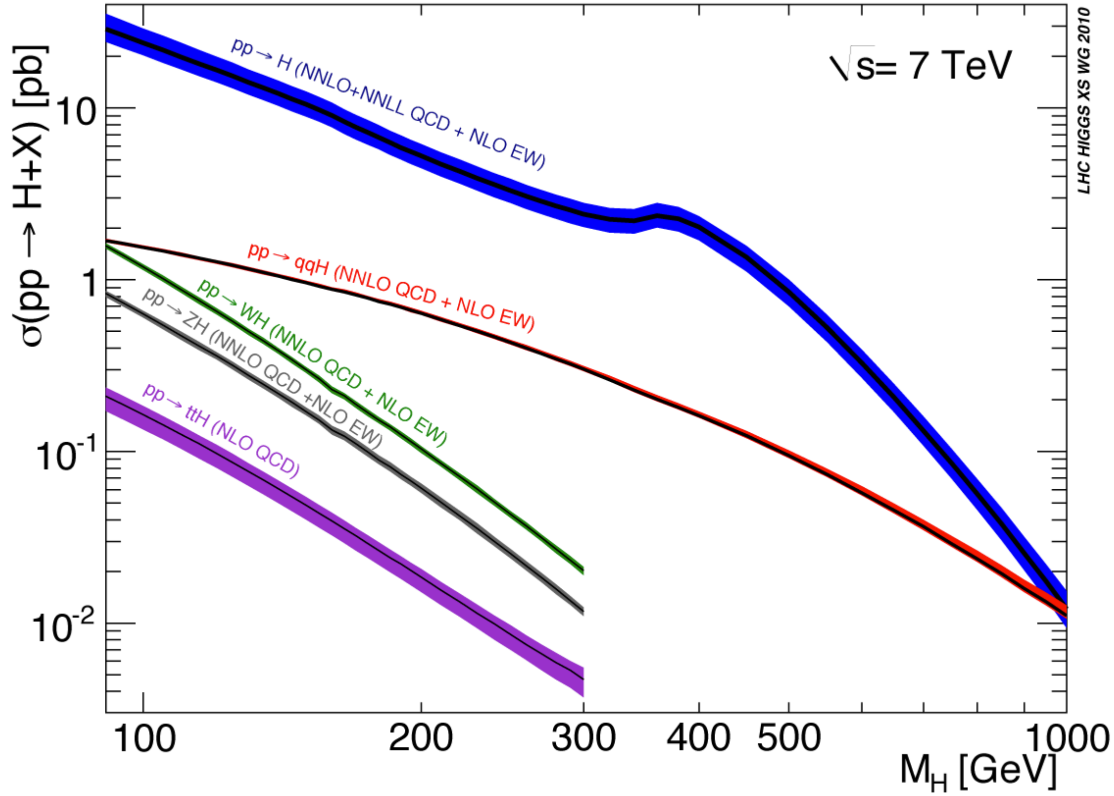
- Additional challenge for h $\rightarrow \gamma\gamma$ channel, where the hard-scattering vertex is often not known well
- Picking a wrong vertex deteriorates the mass resolution by roughly a factor of two



Higgs Production @ LHC

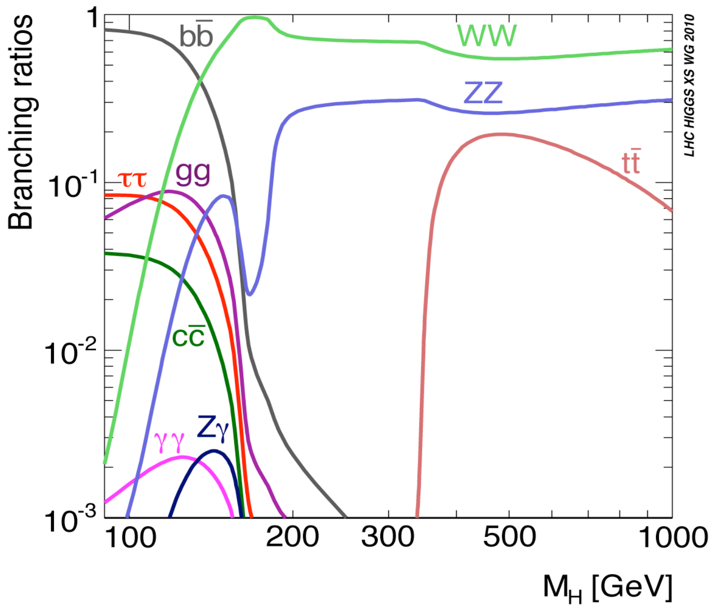
- ☐ **Gluon fusion**
- ☐ **VBF**
- ☐ **VH**
- ☐ **ttH**

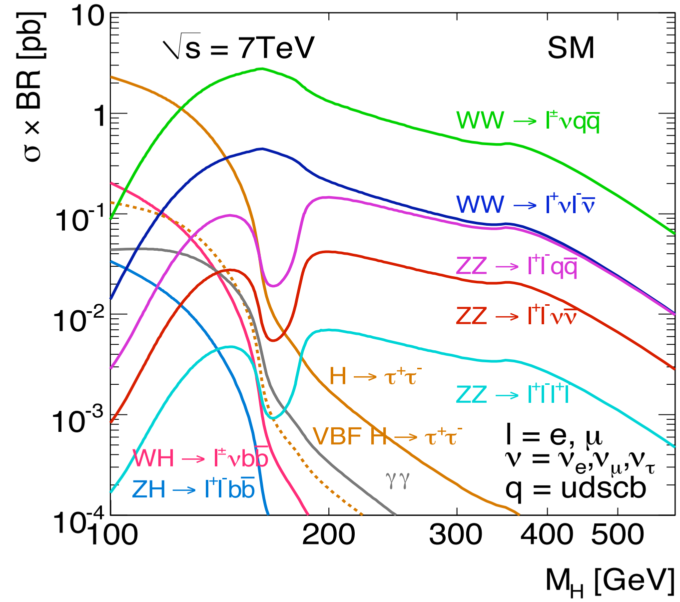




- Gluon fusion (gg→ H) is the dominant production mechanism at LHC.
- gg production is ~x20 that of the Tevatron, whereas qqbar production is ~x4.
- Irreducible backgrounds in H → WW, ZZ, γγ are from qq annihilation.
- Signal to Noise better than at Tevatron except in VH.

Higgs Decay Modes & CMS Analyses





- 8 channels have been processed with full statistics
- 5 of them are important for low-mass Higgs
- Each analysis consists of several sub-channels
- Altogether, 42 sub-channels have been analyzed!

Channel	m_H range (GeV/c^2)	Lumi (fb^{-1})	sub-channels	m_H resolution
$H \to \gamma\gamma$	110–150	4.7	4	1.2–2.7%
$H \to \tau\tau$	110–145	4.6	9	20%
$H \to bb$	110–135	4.7	5	10%
$H \to WW \to \ell\nu\ell\nu$	110–600	4.6	5	20%
$H \to ZZ \to 4\ell$	110–600	4.7	3	1–2%
$H \to ZZ \to 2\ell 2\tau$	180–600	4.7	8	10–15%
$H \to ZZ \to 2\ell 2\nu$	250–600	4.6	2	7%
$H \to ZZ \to 2\ell 2q$	200–600 130–165	4.6	6	3%

Searches for Higgs in CMS

so far CMS does not see the Higgs but…
we could have seen it in some mass interval and
thus we exclude those regions.
Let's see what we have so far.

By the way, I found a Higgs in Y2K

The Large Hadron Collider

At Discovery's Horizon

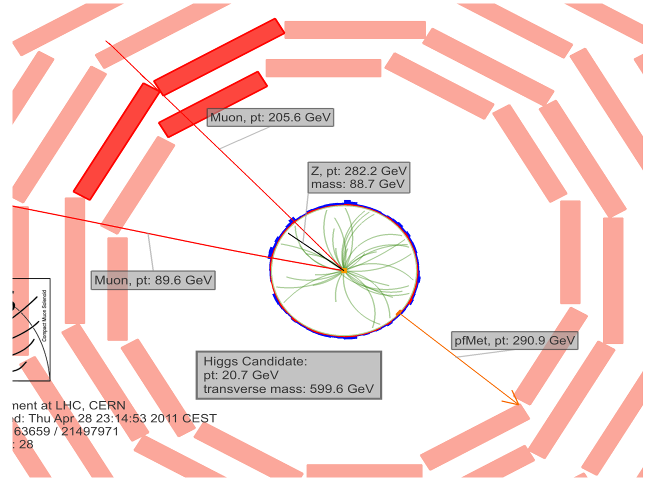
The Large Hadron Collider
At Discovery's Horizon

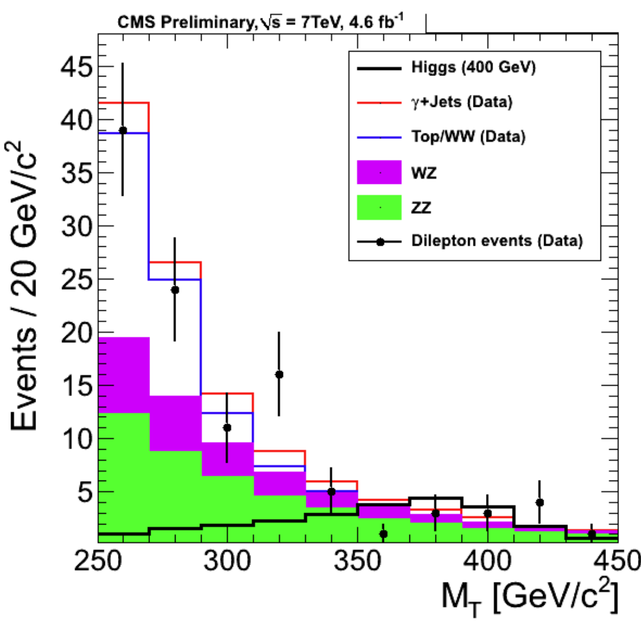
Searches for a Heavy Higgs

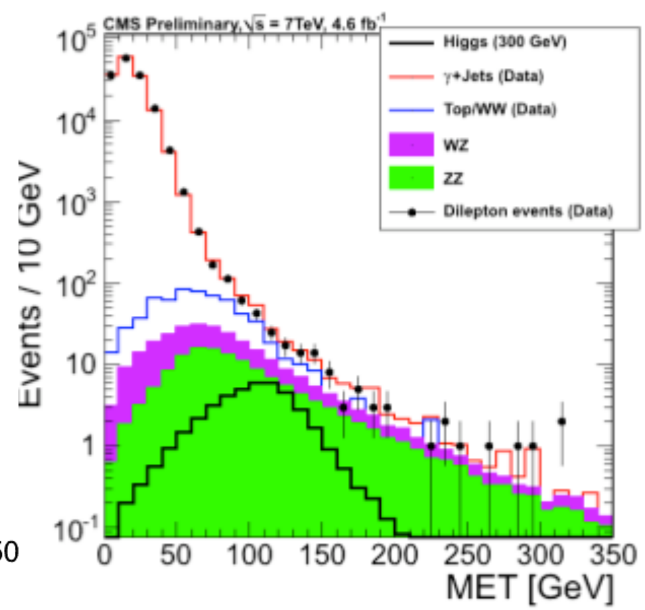
Fermilab CERN U.S. DEPARTMENT OF ENERGY National Science Foundation

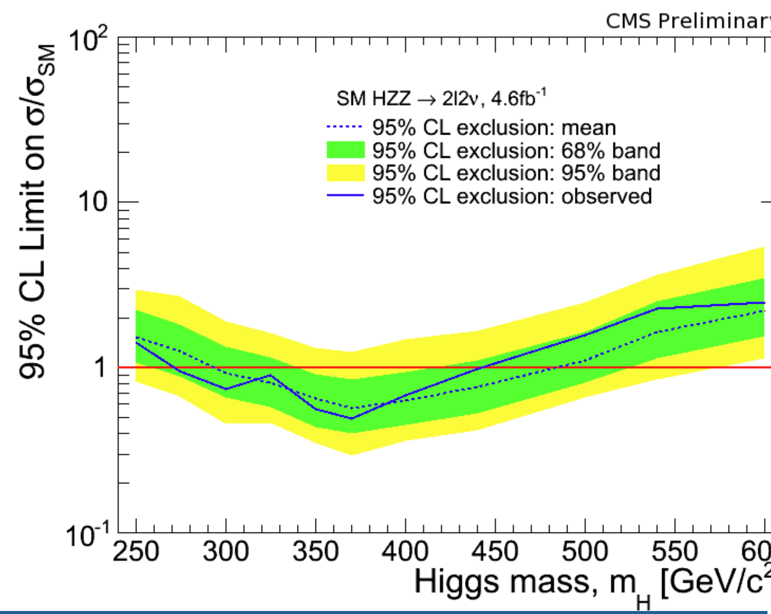
High Mass Higgs: H → ZZ → 2l 2ν

- High sensitivity analysis for the high mass
- Explore both cut-based and shape-based (10% better!) approaches in both e and μ channels
- Backgrounds: ZZ (irreducible), Z+jets, WW, tt
- Require dileptons mass ~ MZ ± 15 GeV
- Use M_T as the discriminating variable.





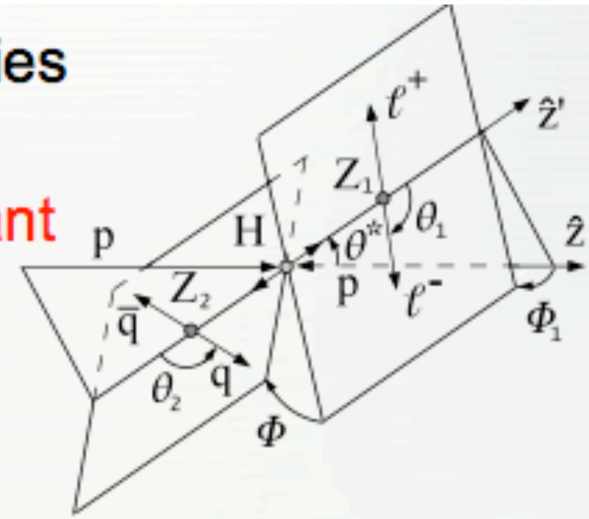


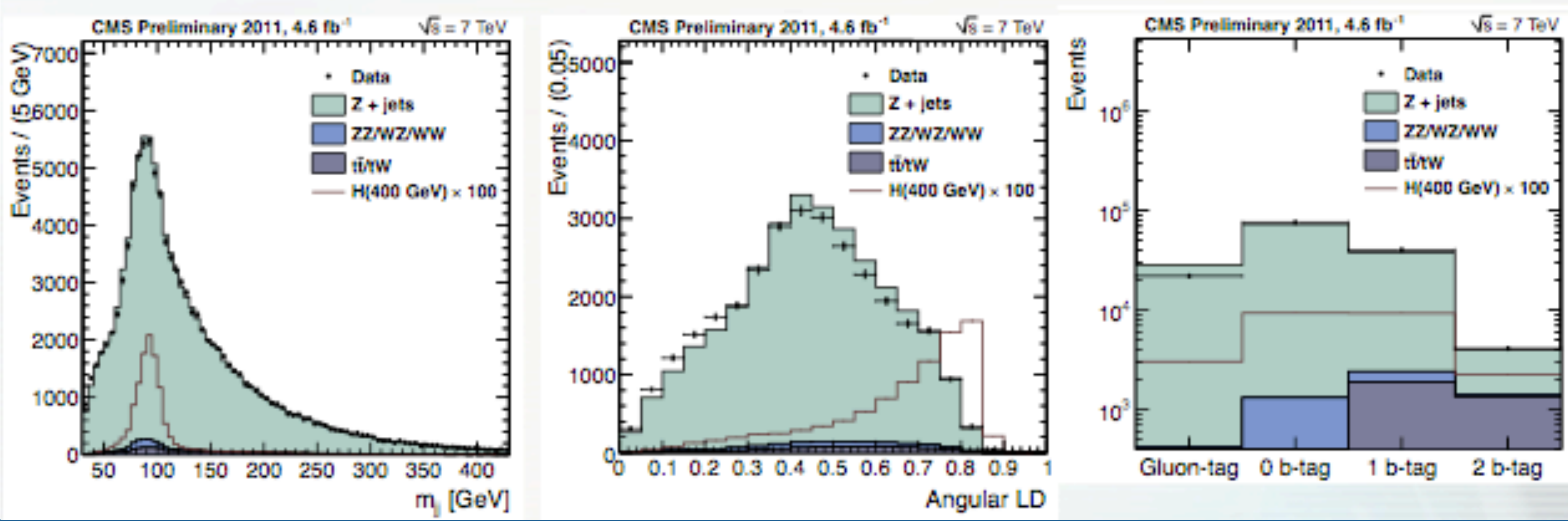


95% CL exclusion limits for a SM Higgs boson in the range 270-440 GeV (M_T shape based analysis)

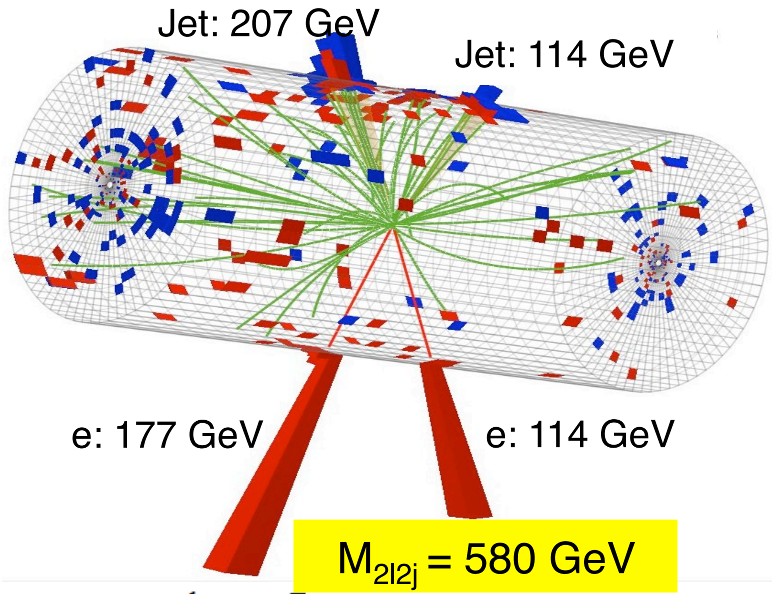
High Mass Higgs: H→ZZ→2l 2q

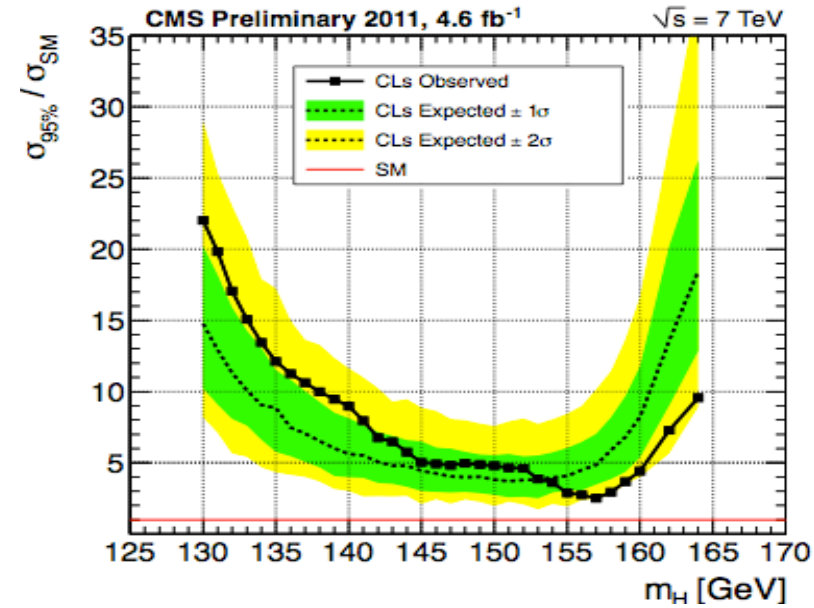
- Two channels (e and μ) and 3 categories (0-2 b-tags)
  - 0 b-tag uses additional q/g discriminant
- Major backgrounds: Z+jets, tt
- Use angular discriminant based on 5 production and decay angles
- Extended the analysis to lower masses [125,170] GeV

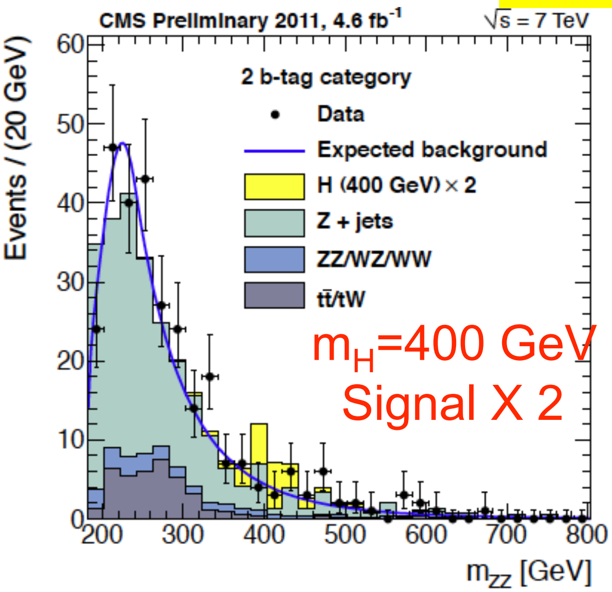


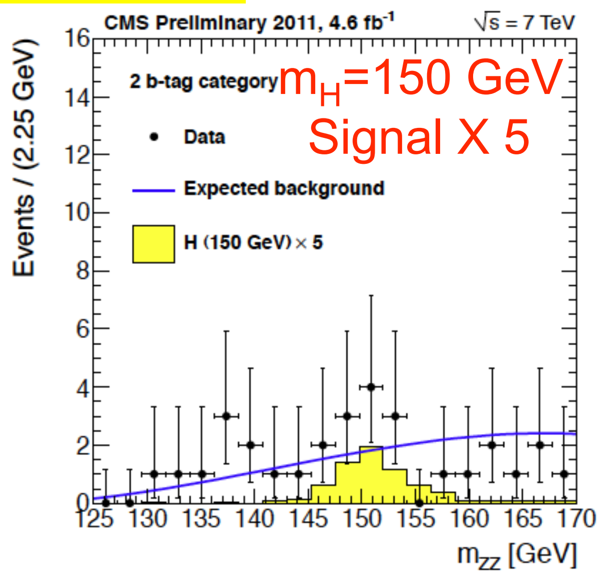


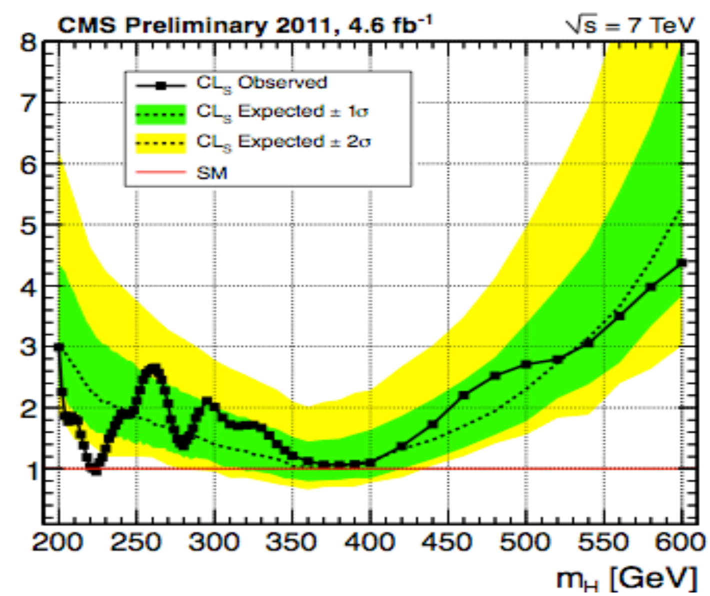
H →ZZ→2l 2q: data and limits





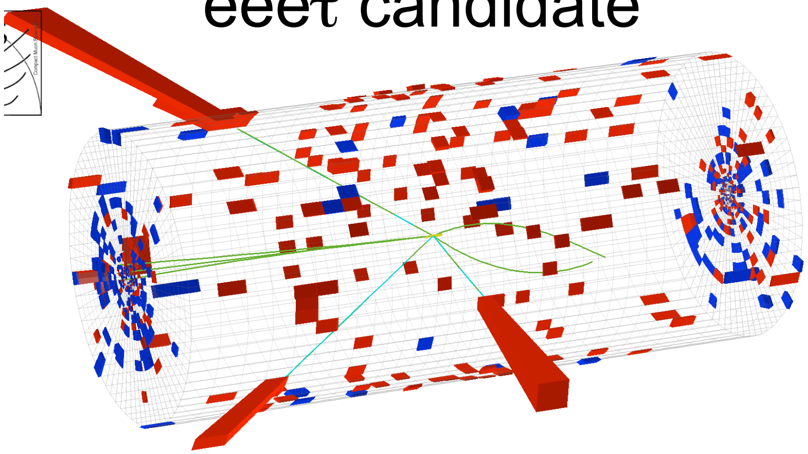




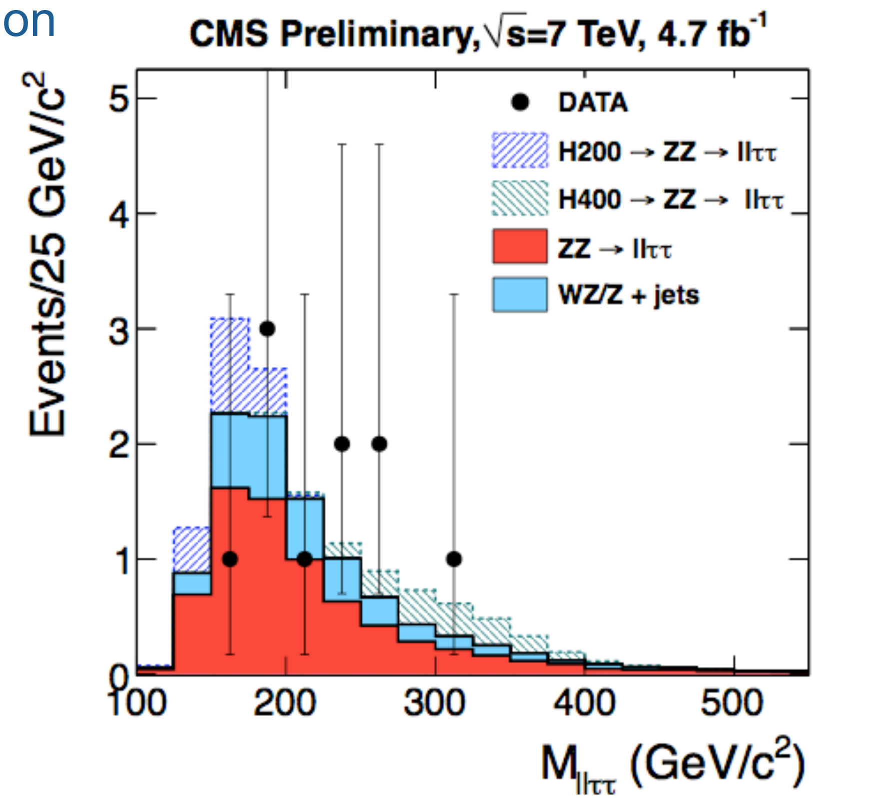


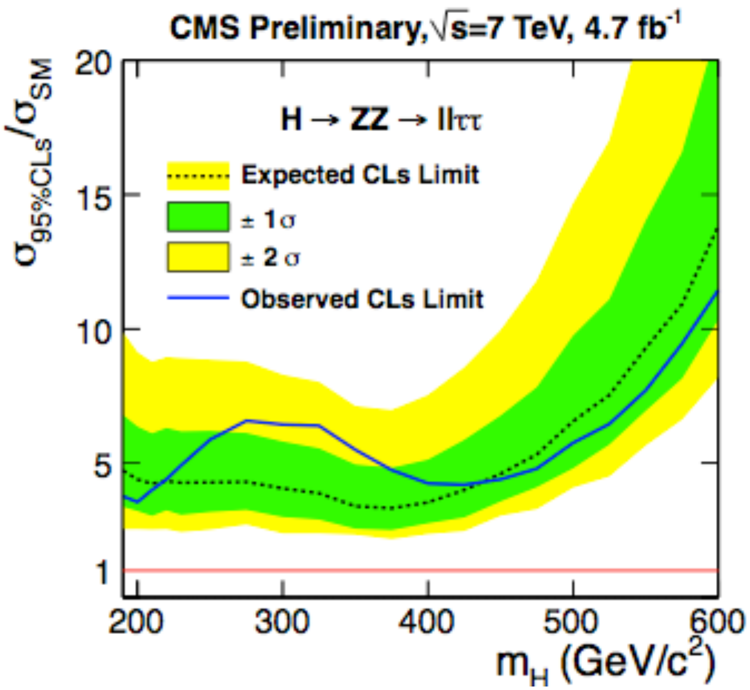
High Mass Higgs: H →ZZ→2l 2τ

eeeτ candidate



- 8 categories: Z(ee), Z(μμ) and ($\tau_h\tau_e$, $\tau_h\tau_\mu$, $\tau_\mu\tau_e$, $\tau_h\tau_h$)
- Look for a broad excess peak in visible mass distribution



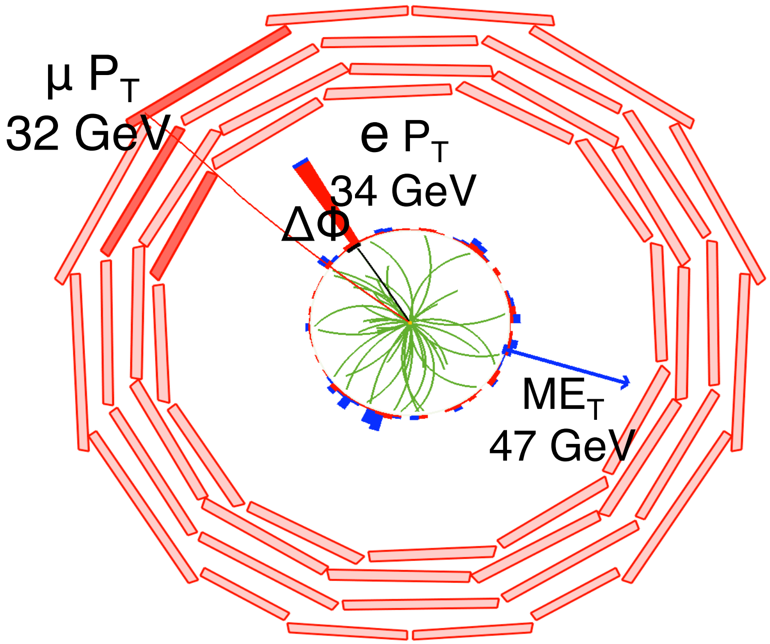


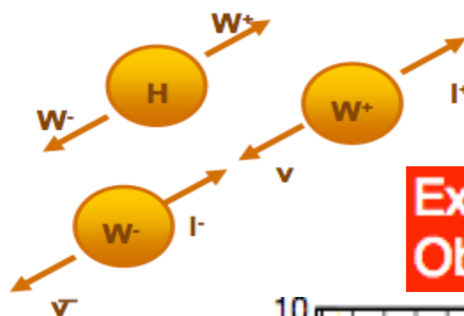
10 observed events, 10.3 expected background

Background shapes are taken from MC simulation and normalized to the values obtained using data-driven techniques.

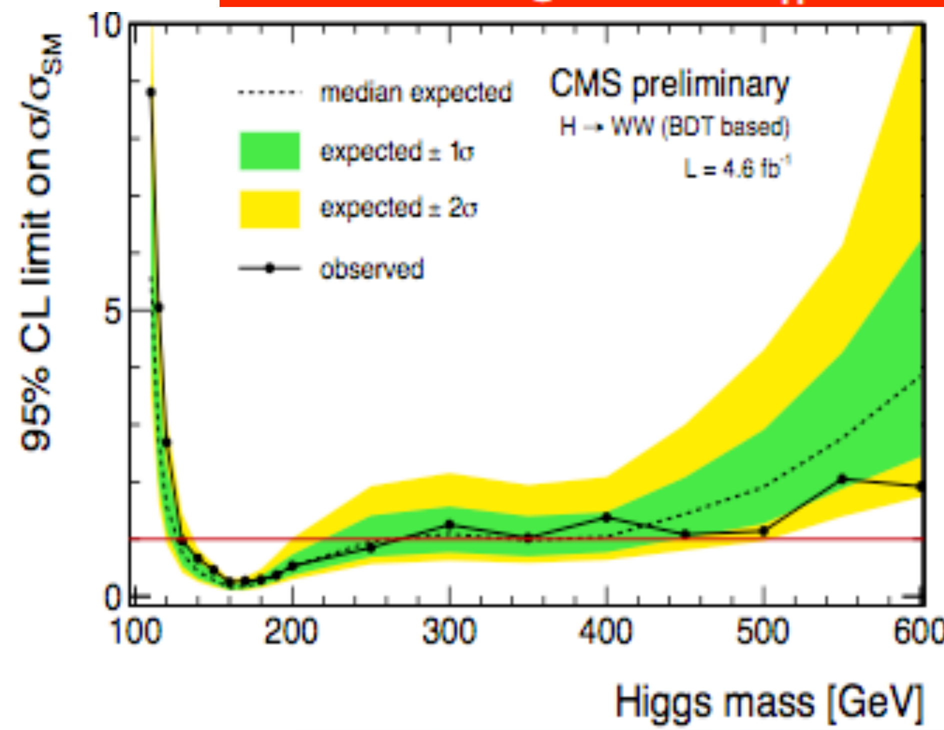
H→ WW → 2l 2ν

- No signal mass peak (missing νν) ➔ Counting expt.
- Challenge is to remove & control large backgrounds



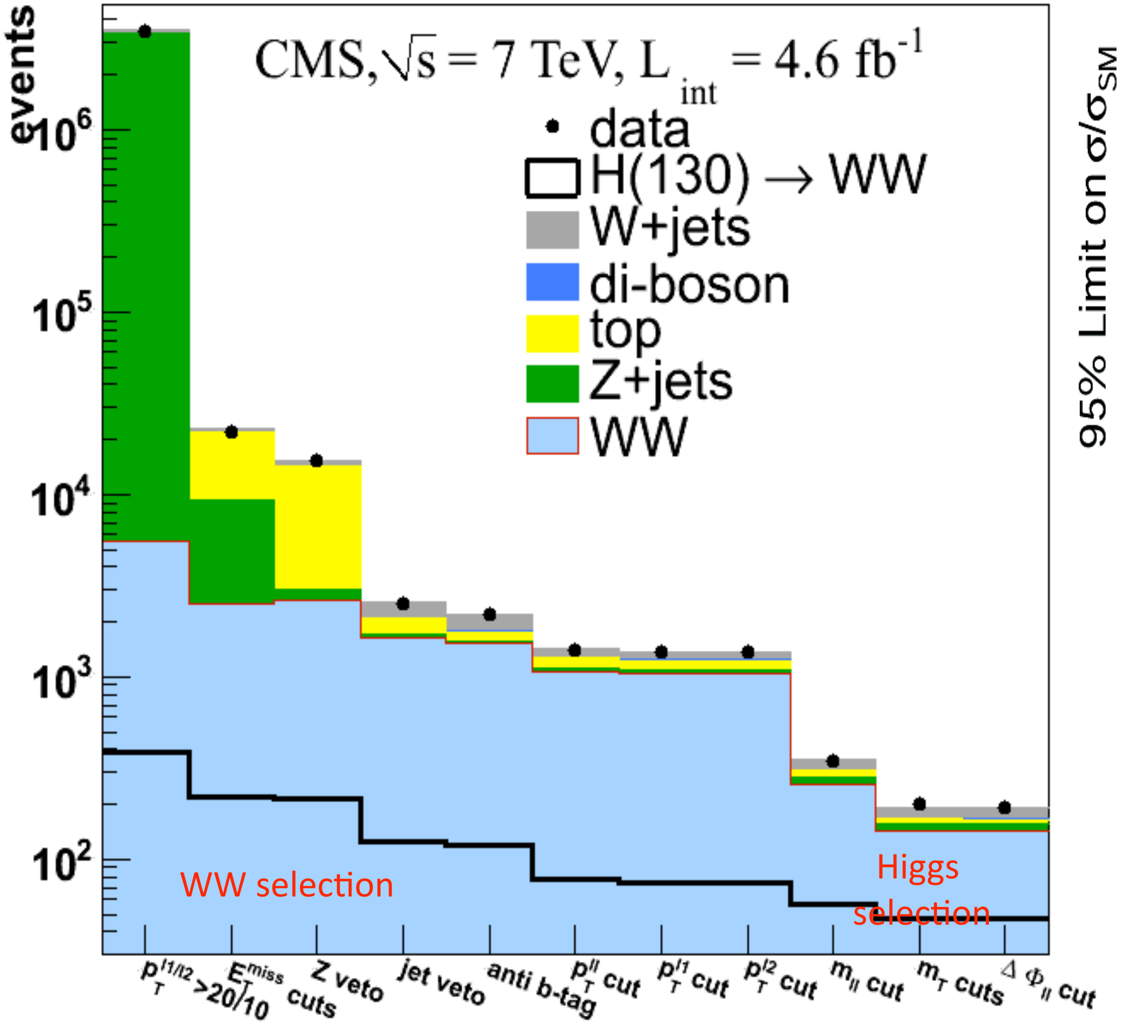


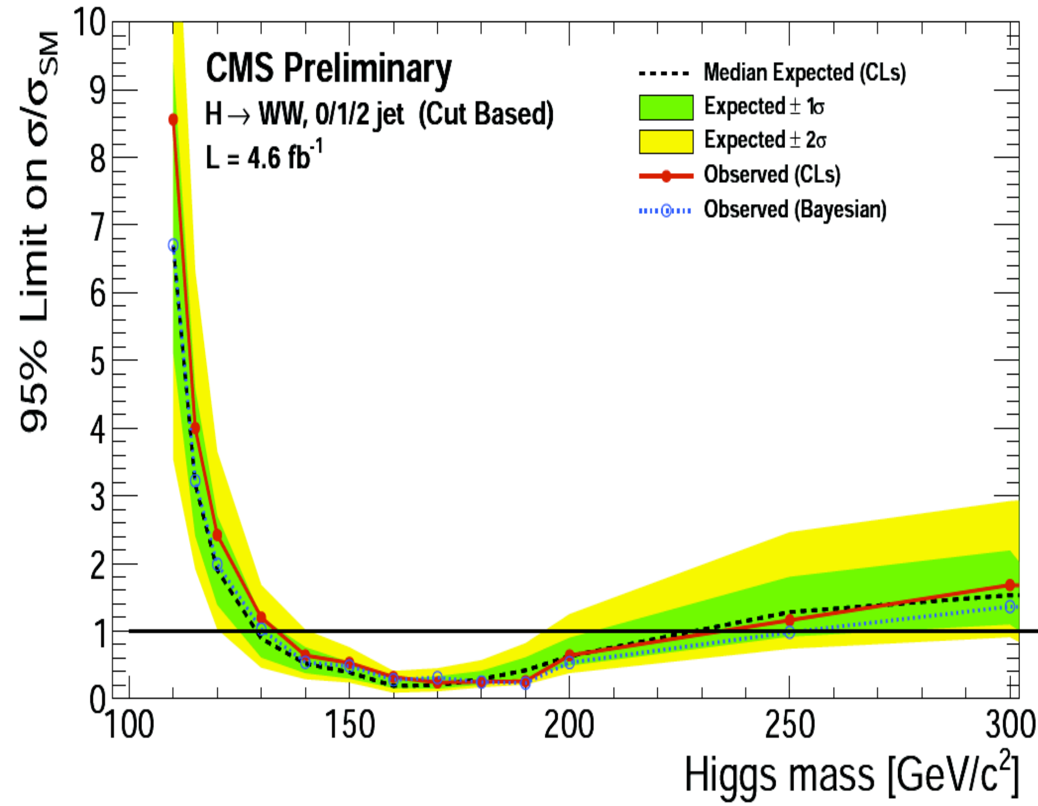
Expected range: 127 < M_H < 270 GeV
Observed range: 129< M_H < 270 GeV



- Signal characteristics:
  - Only 2 opposite sign, isolated leptons
  - significant ME_T➔ No mass peak
  - No b-jets, no additional low p_T μ
  - With additional 0, 1 or 2 jets (VBF)
  - Small ΔΦ (l^+l^-) ← Higgs scalarity

Data and limits in cut and count analysis



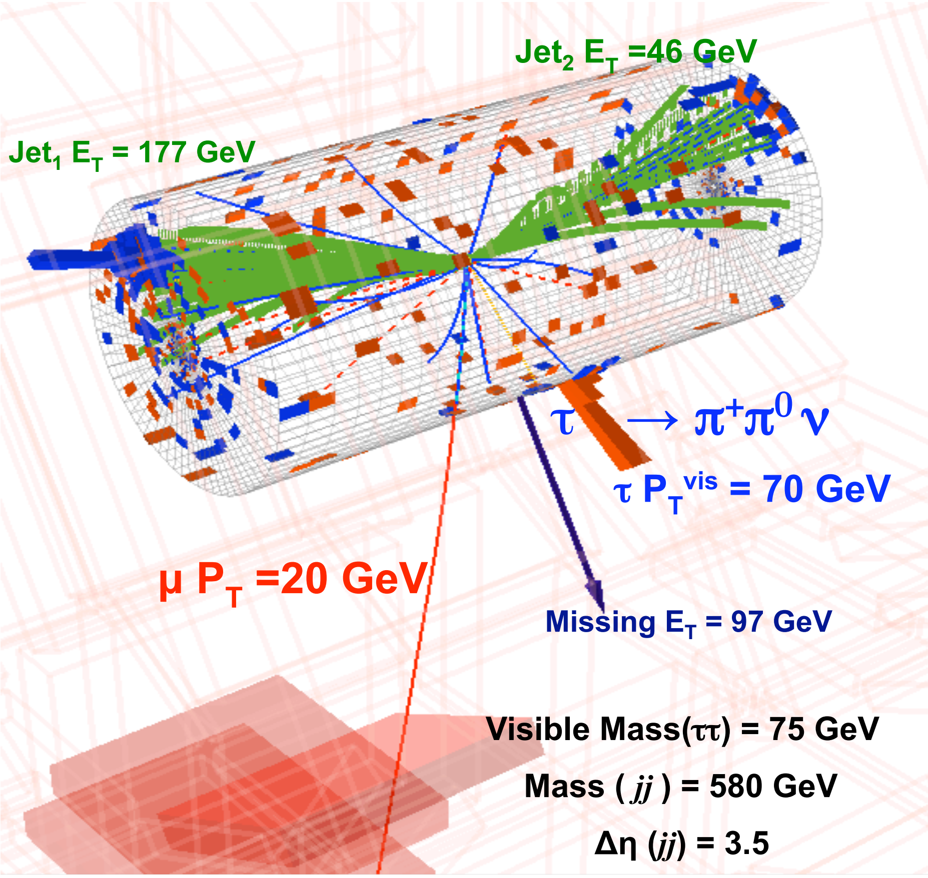


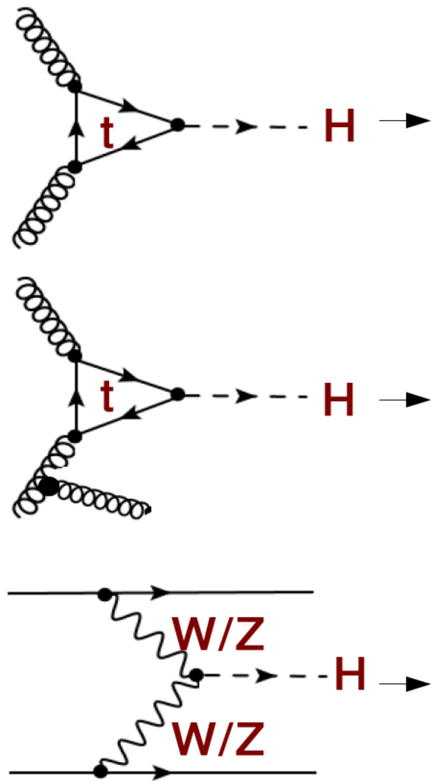
Expected range: 128 < M_H < 236 GeV
Observed range: 132< M_H < 238 GeV

Data describes predicted background well.

Searches for a Light Higgs

Low Mass Higgs Search : H→ ττ





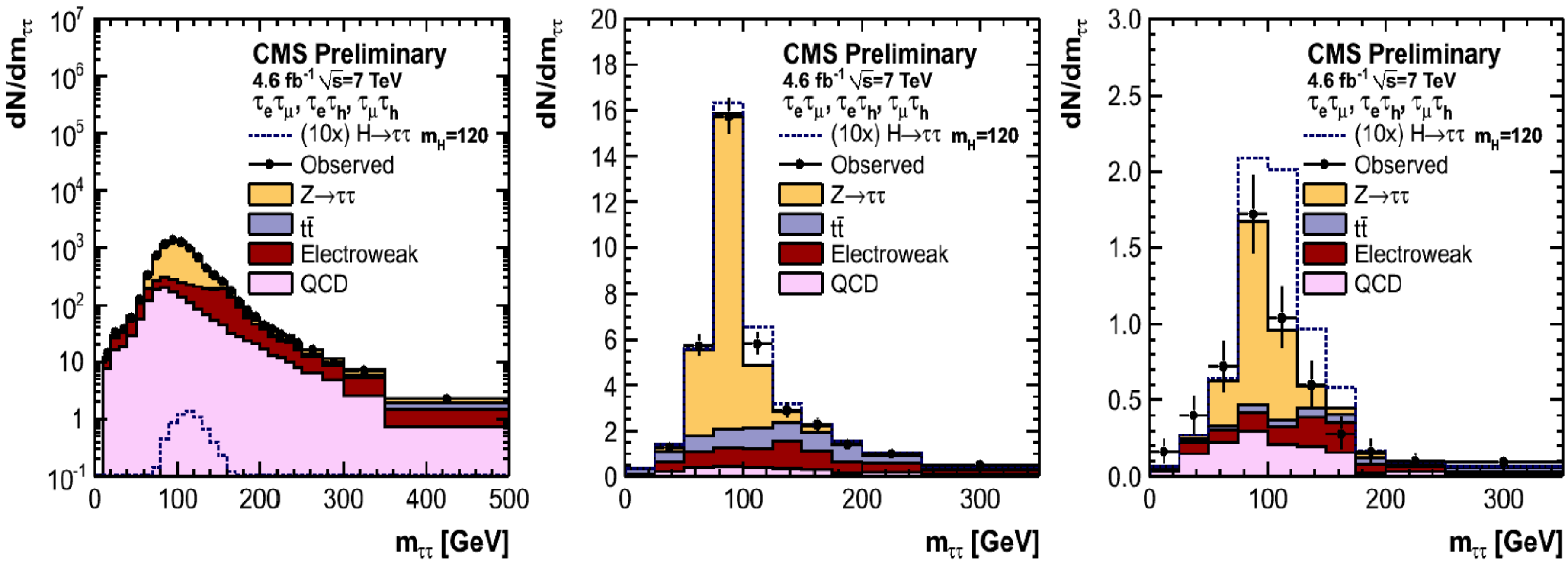
SM-0/1 jet
0 jets >30 GeV or 1 jet<150 GeV

SM-Boosted
One jet Pt>150 GeV
No other jets>30 GeV

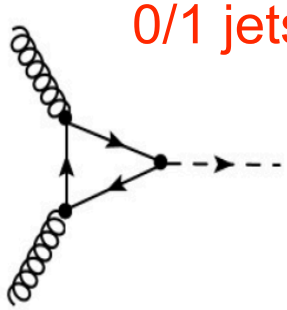
SM-VBF
>=2 Jets >30 GeV
Δη>4 , Mjj>400 GeV
No additional jets with Pt>30 in the rapidity gap

Analyzed 9 channels: $\tau_h\tau_e$, $\tau_h\tau_\mu$, $\tau_\mu\tau_e$ in 3 categories; 0/1 jets, boosted, and VBF
VBF mode is the cleanest and the most sensitive
Mass resolution is 20%

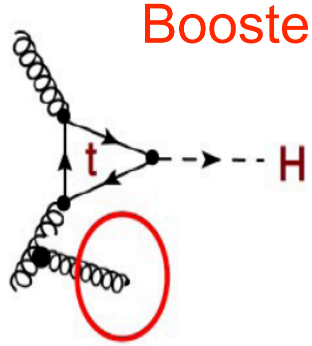
H→ ττ : Mass Spectrum By Categories



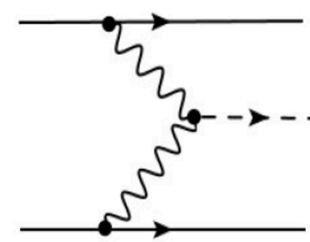
0/1 jets



Boosted

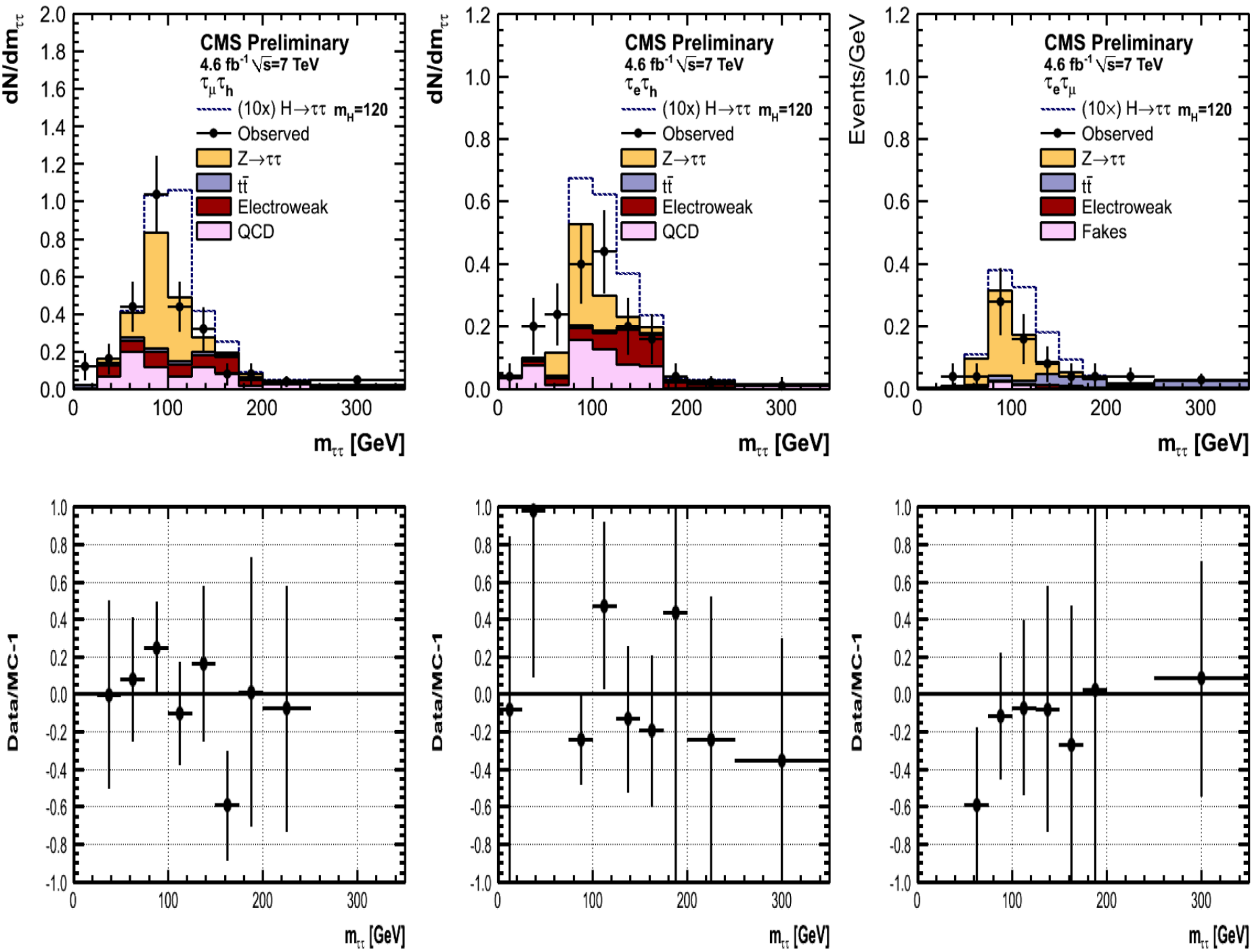


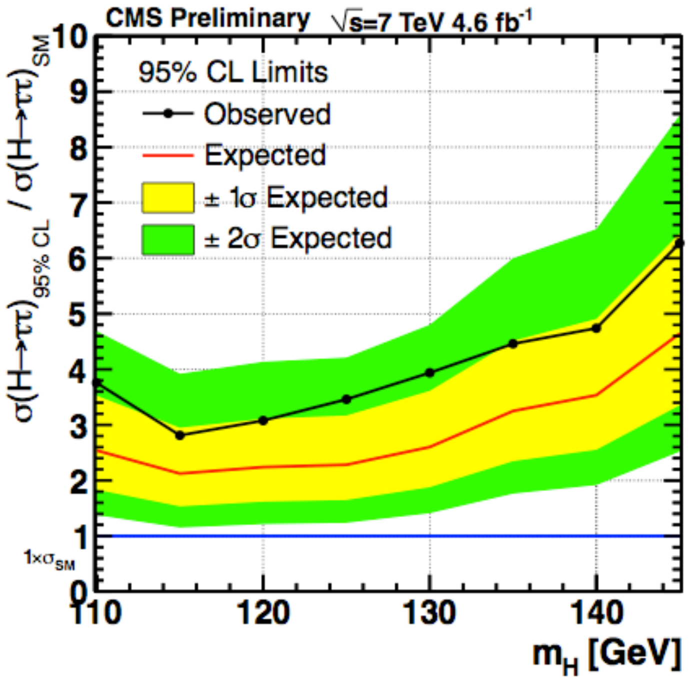
VBF



H→ ττ : data and limits

Data in VBF Channels





@ 120 GeV

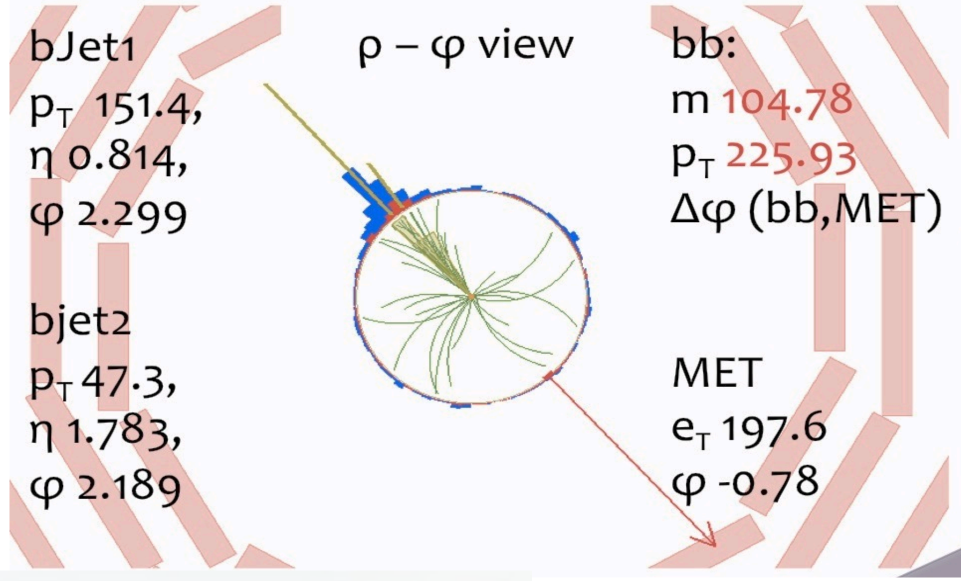
Sensitivity = 2.3

Observed = 3.2

VBF channel is further divided into $\tau_\mu\tau_h$, $\tau_e\tau_h$, and $\tau_\mu\tau_e$.

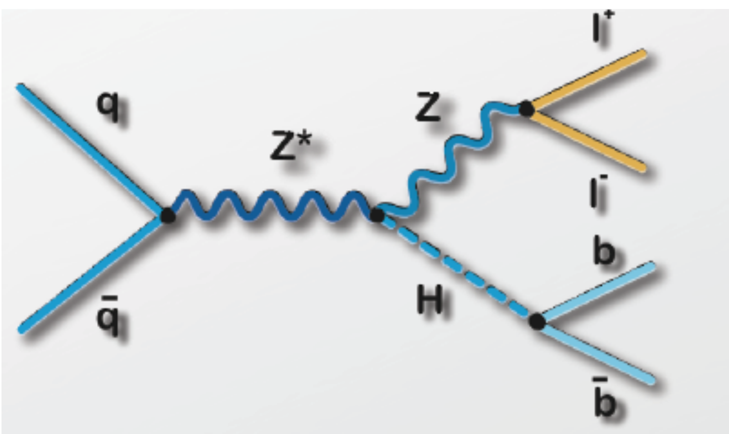
Low Mass Higgs Search : H→ bb

- gg→ H→ bb and VBF are dominant production modes but overwhelmed by enormous QCD di-jet background
- Use associated production with a vector boson (W, Z) to maximize sensitivity
- Best option: qq→ VH; H → bb
  - Major backgrounds are V+jets, VV, ttbar



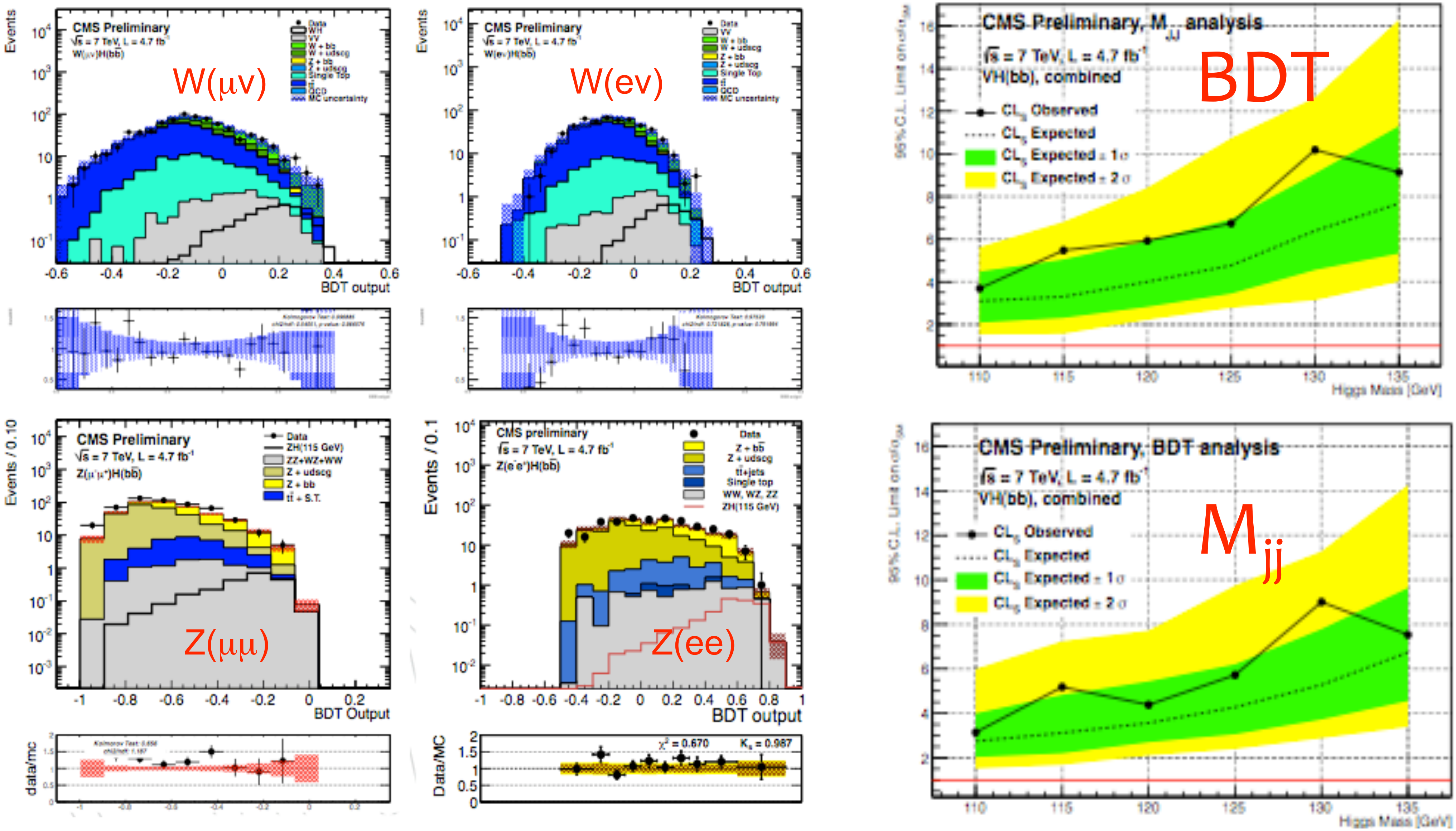
Five channels studied:

- W(eν)h(bb), W(μν)h(bb)
- Z(ee)h(bb), Z(μμ)h(bb)
- Z(νν)h(bb)



- Used tight b-tagging and MET selection to reduce backgrounds
- Estimate backgrounds from control data samples

H→ bb: data and limits



- MVA analysis based on BDTs offer 10% improvements over the cut-based analysis
- Limits as low as 3-4 SM cross sections have been obtained at low masses.

H → ZZ →4e, 4μ, 2e2μ: The Golden Channel

3 categories

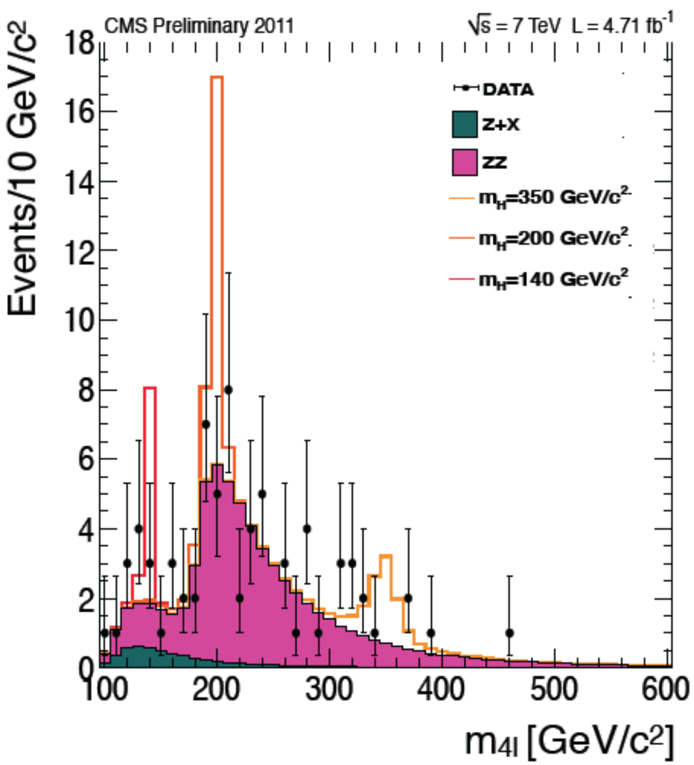
Look for a mass peak over a continuum

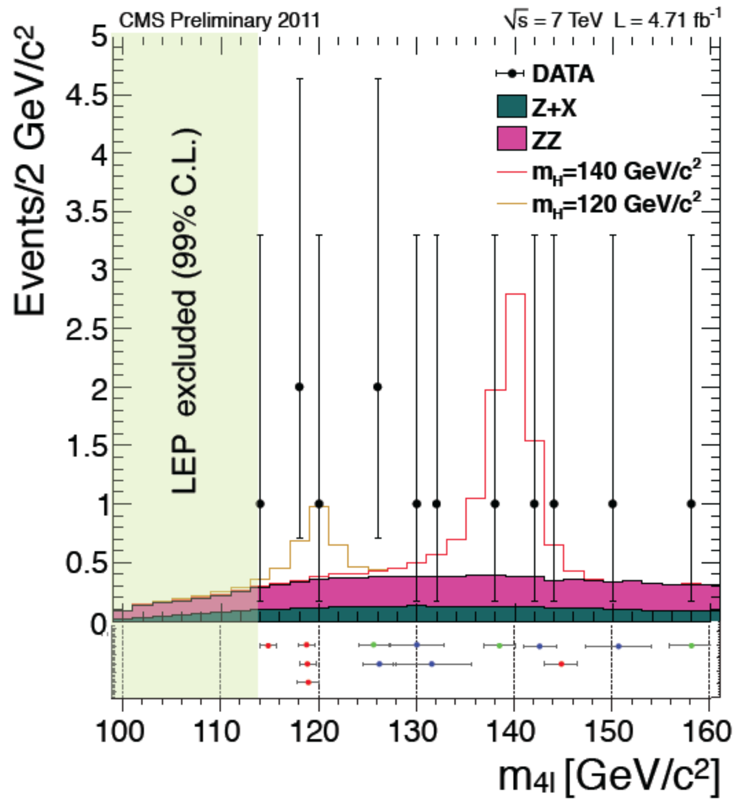
m_{4l} >100 GeV/c^2

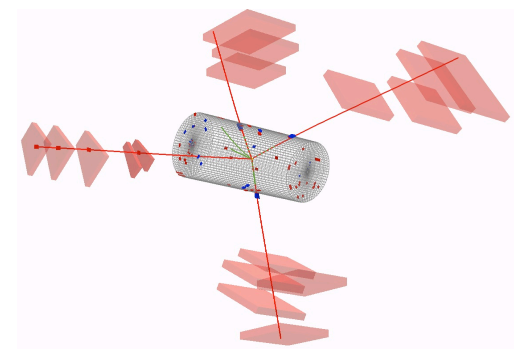
Observed events = 72

Expected events = 67.1 ± 6.0

Baseline	$4e$	4μ	$2e2\mu$
ZZ	12.27 ± 1.16	19.11 ± 1.75	30.25 ± 2.78
Z+X	1.67 ± 0.55	1.13 ± 0.55	2.71 ± 0.96
All background	13.94 ± 1.28	20.24 ± 1.83	32.96 ± 2.94
$m_H = 120$ GeV/c^2	0.25	0.62	0.68
$m_H = 140$ GeV/c^2	1.32	2.48	3.37
$m_H = 350$ GeV/c^2	1.95	2.61	4.64
Observed	12	23	37







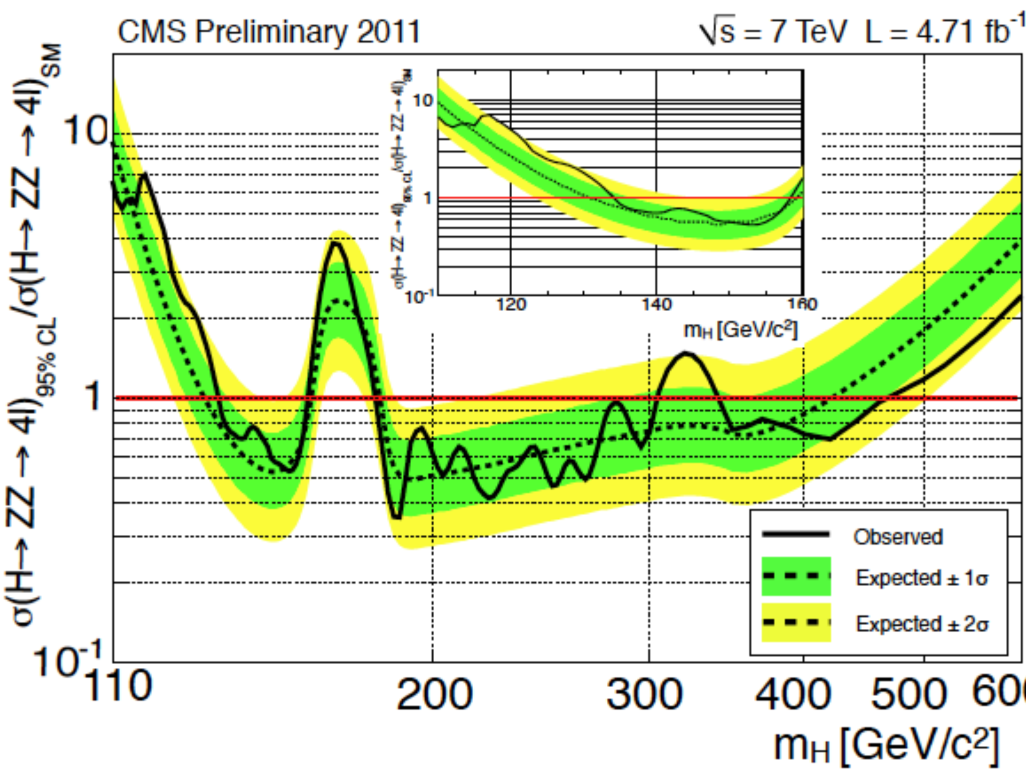
100 < m_{4l} < 160 GeV

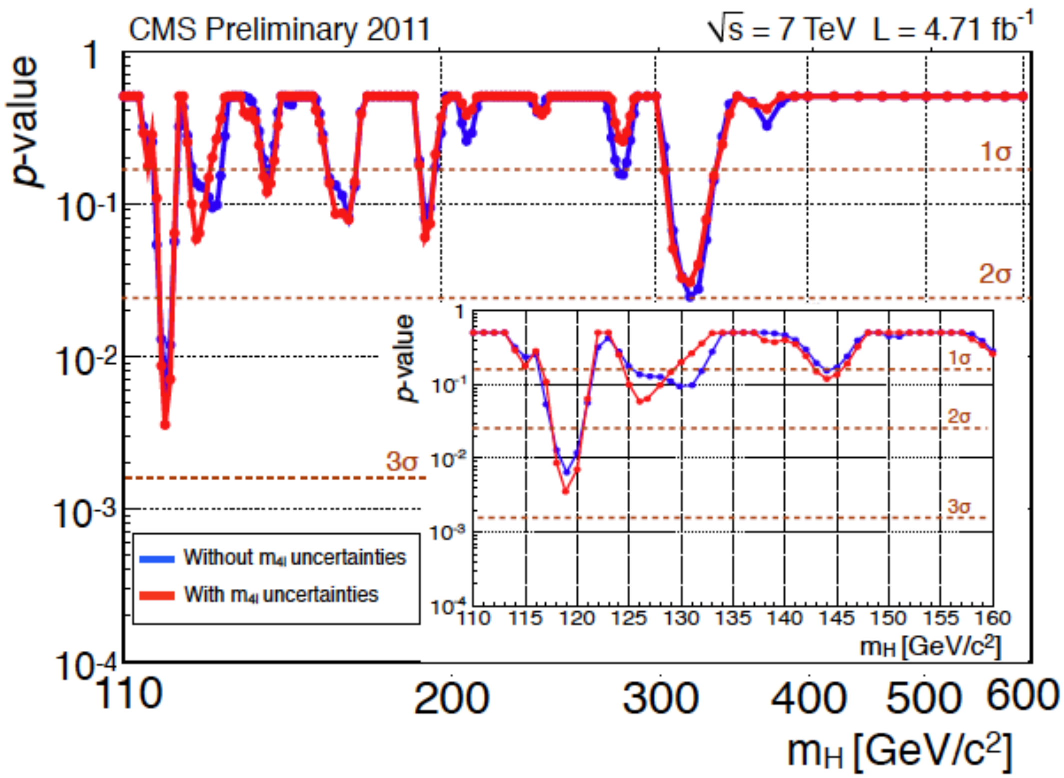
Observed events = 13

Expected events = 9.5±1.3

Final state:	4e	4μ	2e2μ
obs. events:	3	5	5
exp. events:	1.7	3.3	4.5

H→ZZ→4l: 95%CL Excl. Limits



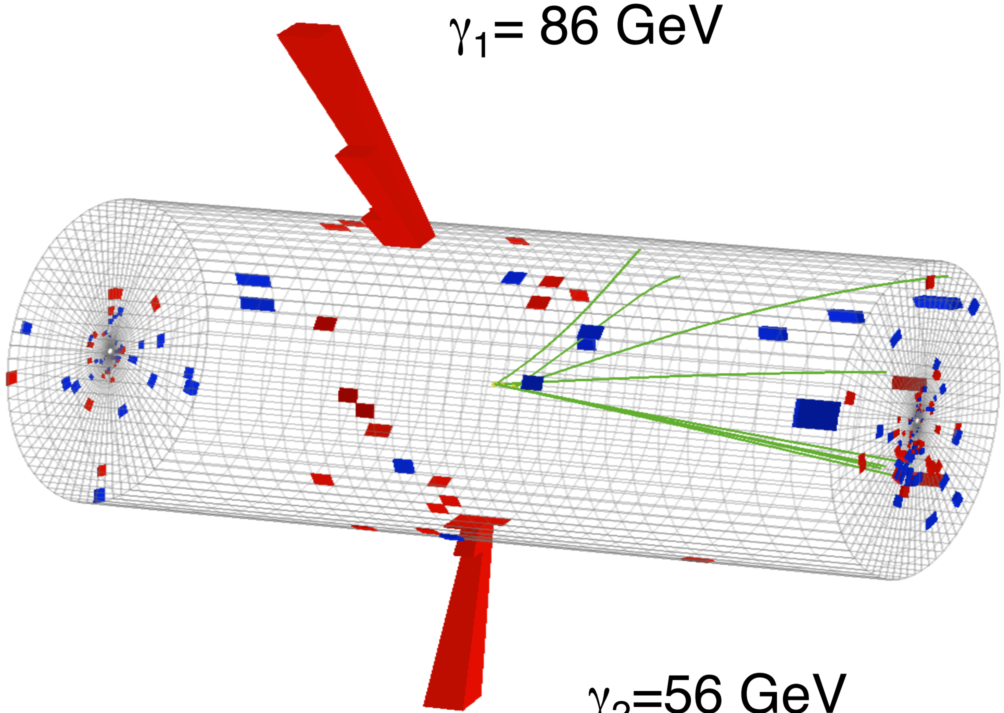


Expected range: $130 < M_H < 160$ GeV; $182 < M_H < 420$ GeV
Observed range: $134 < M_H < 158$ GeV; $180 < M_H < 305$ GeV; $340 < M_H < 460$ GeV

Note: LEE trials factor is ~40 for the full mass range,
therefore 2σ deviations are not significant

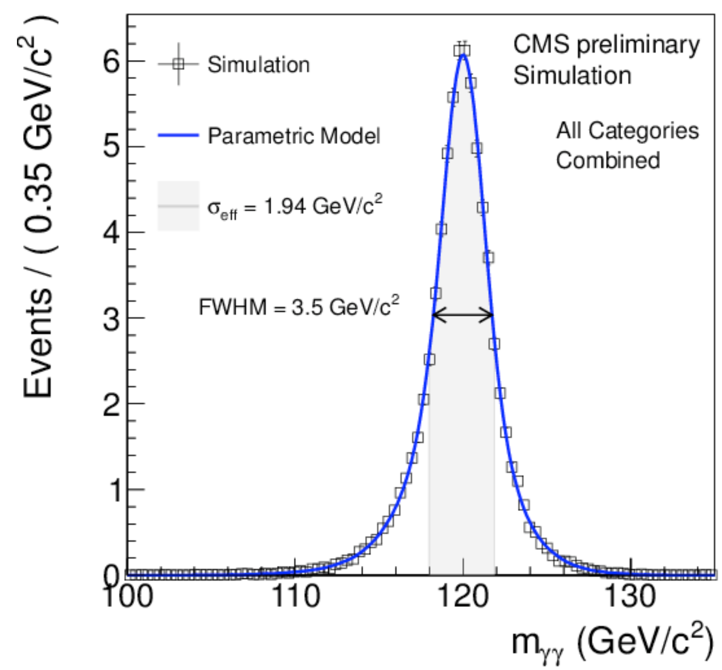
Low Mass Higgs Search : H→ γγ

Signal: 2 energetic, isolated γ.
Search for a narrow mass peak.



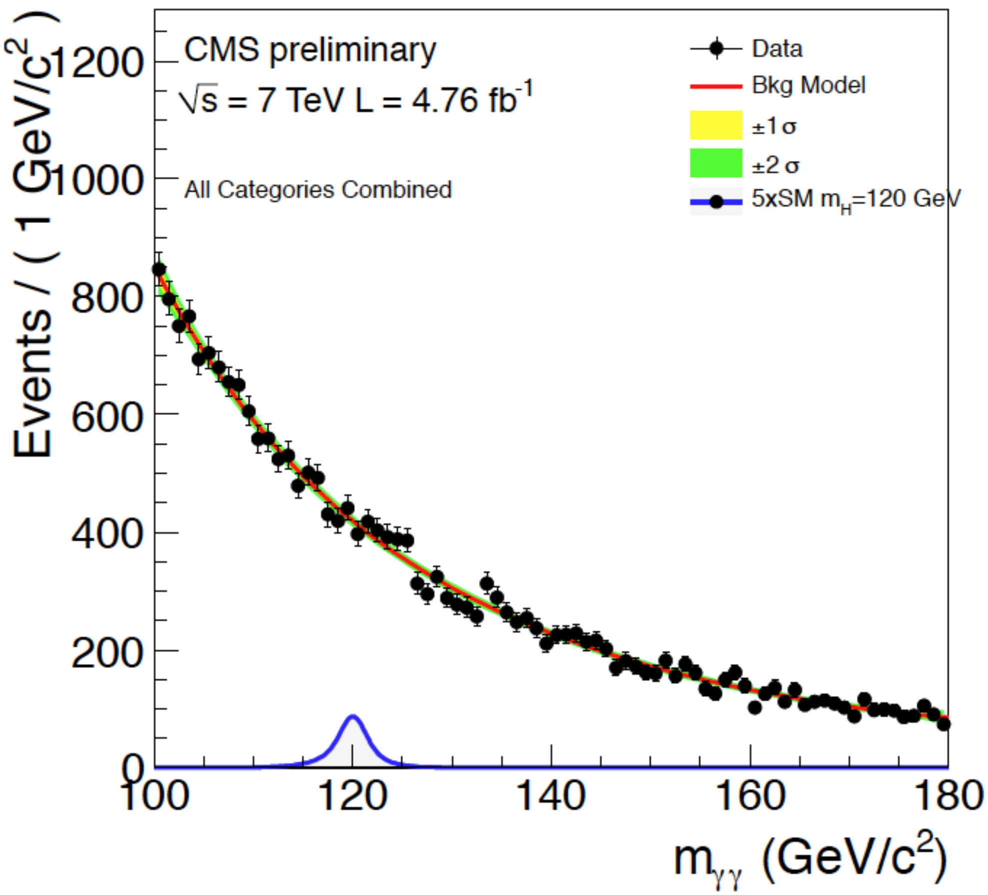
Challenges: vertexing with PU, calibrations and transparency corrections for the crystals.

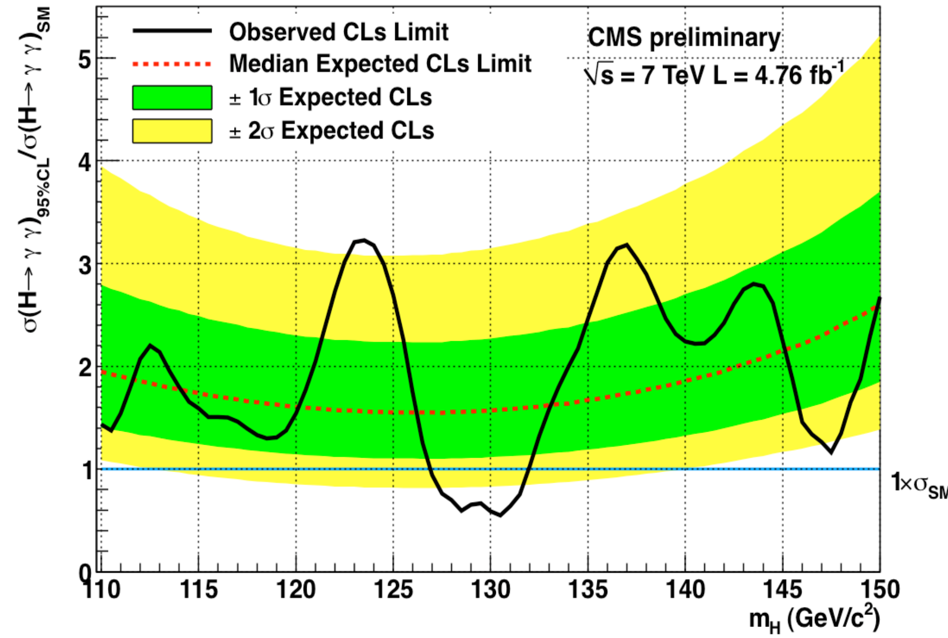
Calibration constants derived from Z→ee data

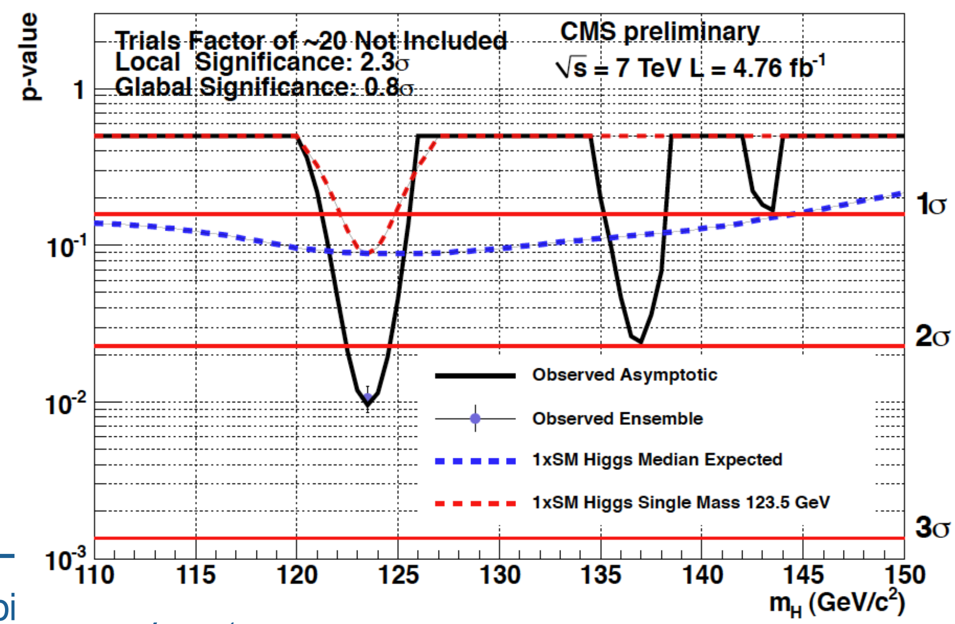


Background: Large and partly irreducible QCD. Measured from $M_{\gamma\gamma}$ sidebands in data

H→ γγ: data and exclusion limits







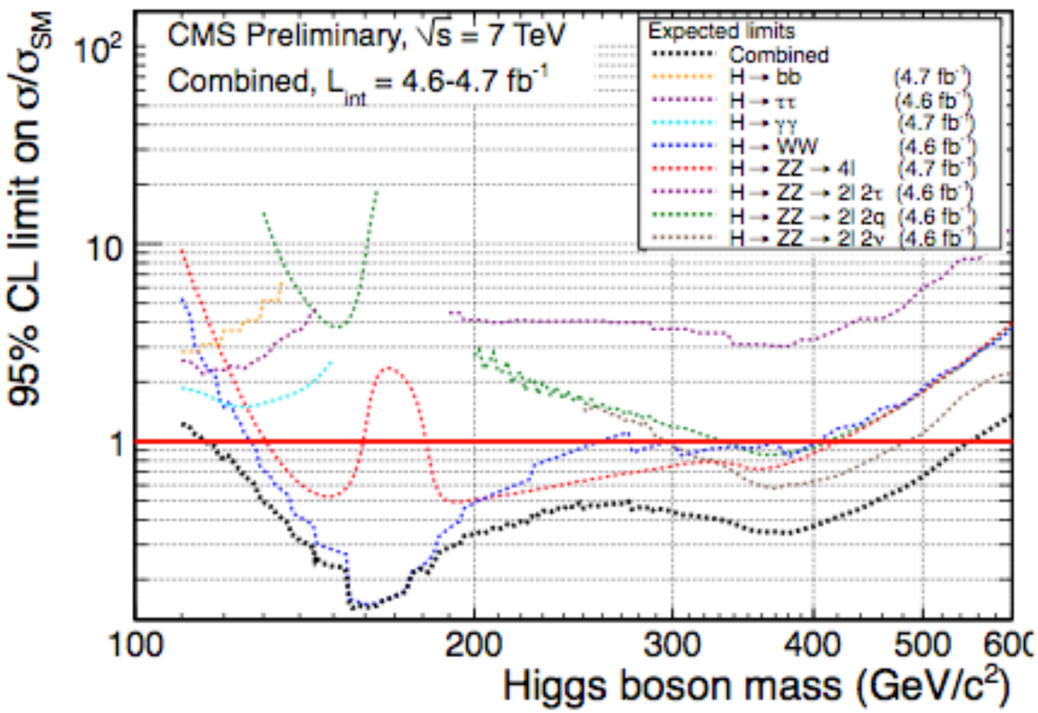
Using 5th order polynomial fit to background: some loss in sensitivity but negligible bias.

The Large Hadron Collider
At Discovery's Horizon

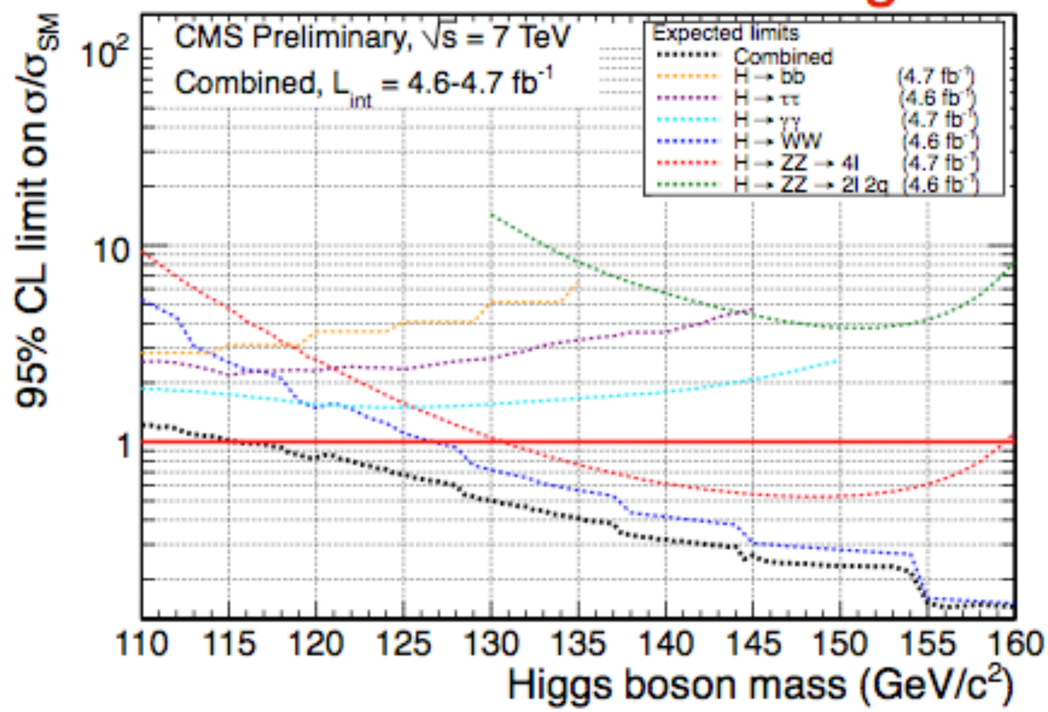
Combination & Interpretation

Fermilab CERN U.S. DEPARTMENT OF ENERGY National Science Foundation

CMS combination and sensitivity @4.7fb^{-1}



Zoom on the low-mass region

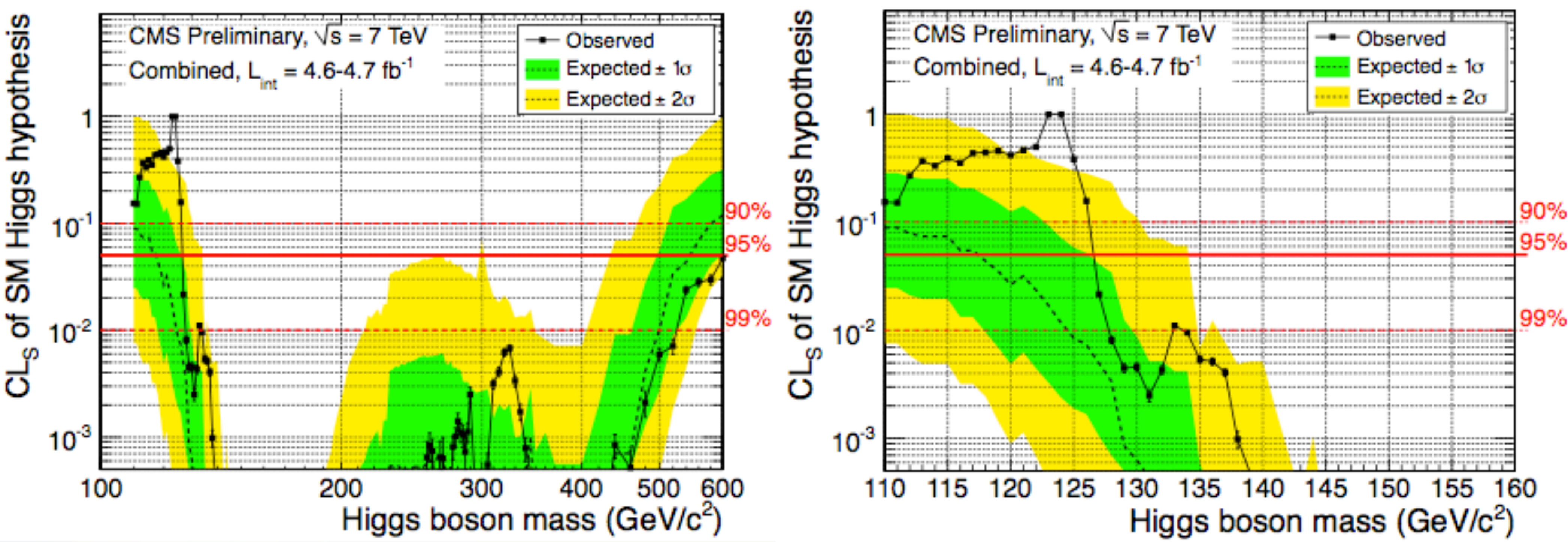


Very close or better than 1xSM in the full mass range.
Optimization of some analyses still ongoing.
A few more channels are still being analyzed

SM Higgs Exclusion

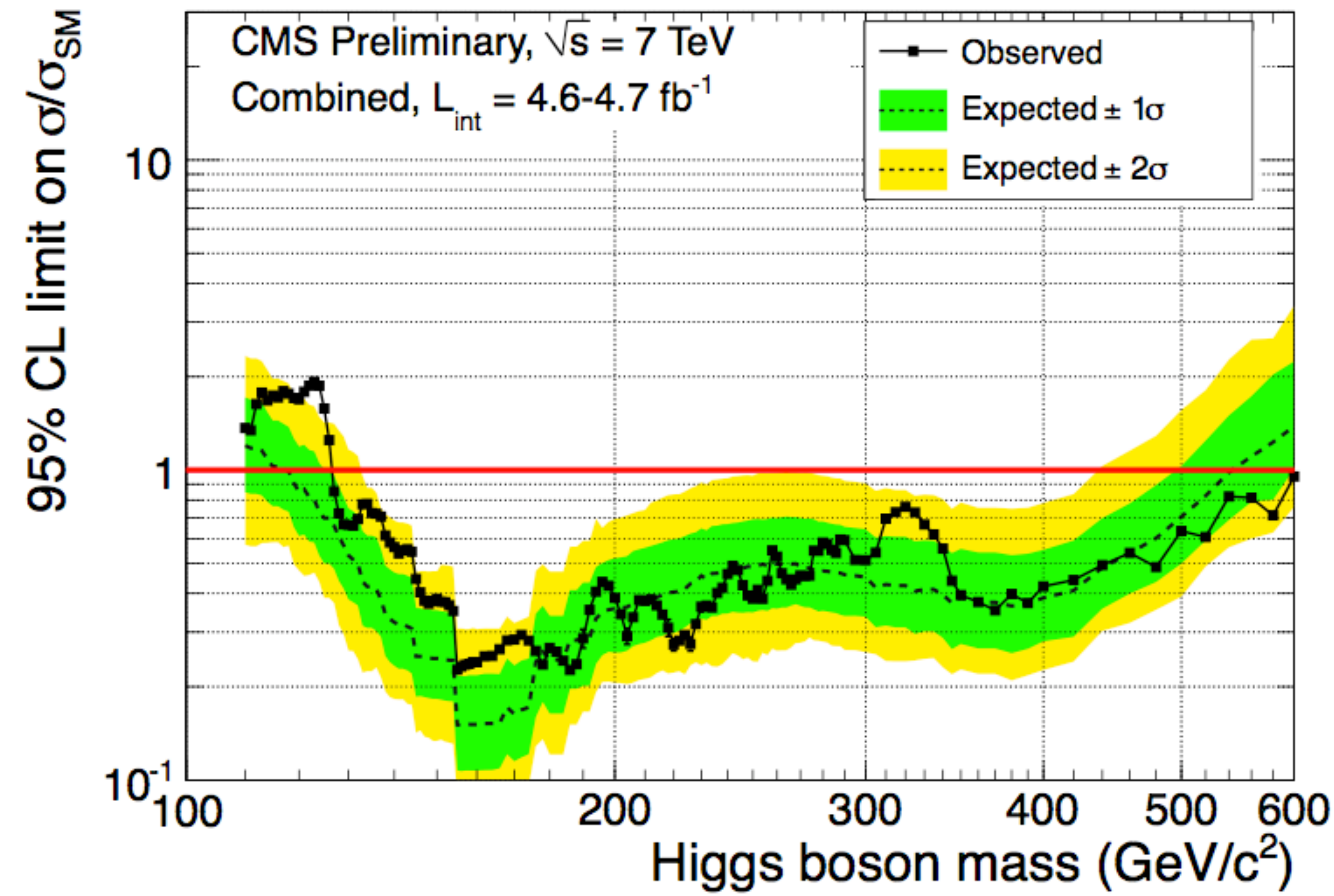
Preliminary 95 and 99%CL exclusion limits

95% CL:	obs 127-600,	exp:117-543
99% CL:	obs 128-525,	exp:125-500

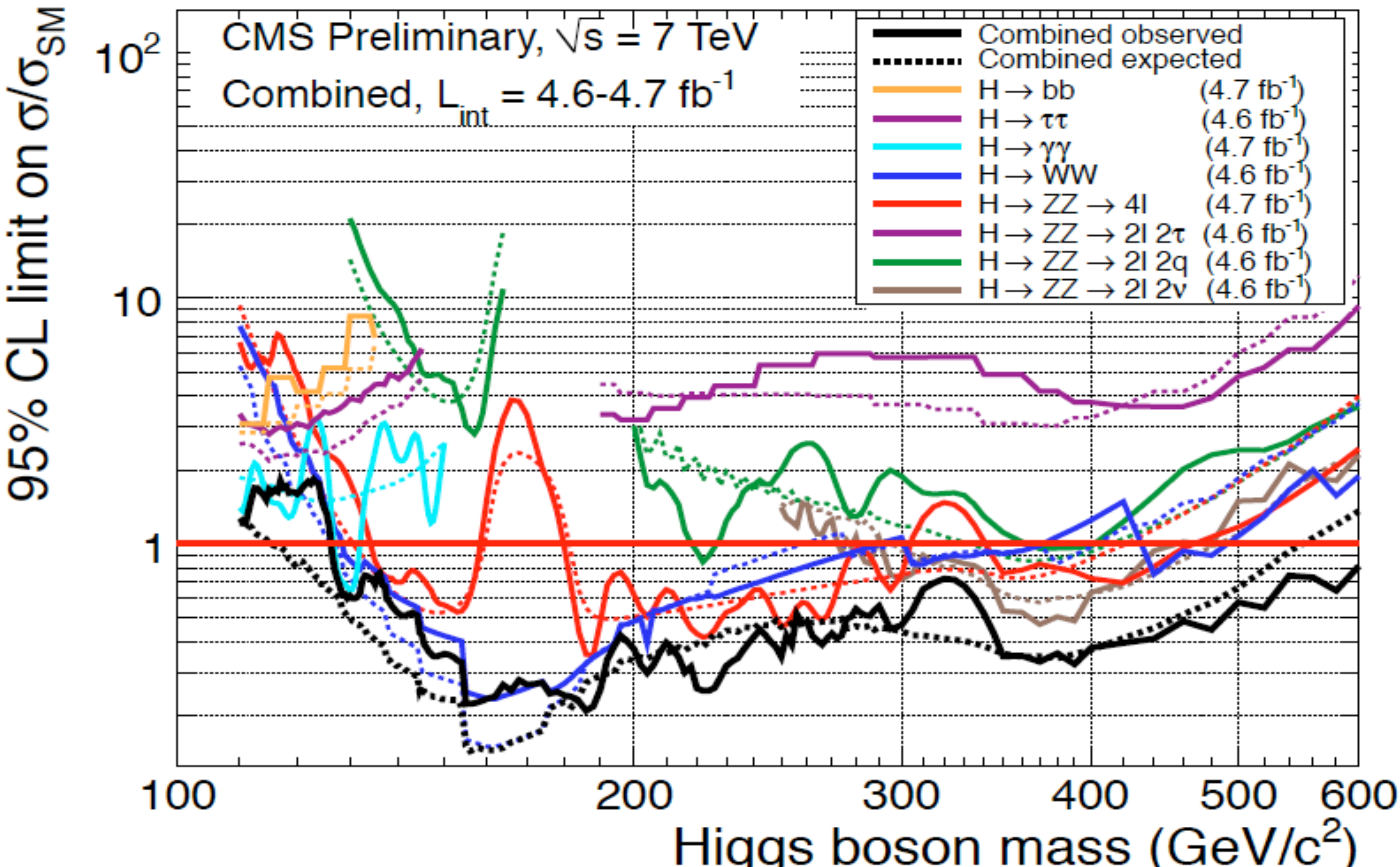


Limits on σ/σ_{SM} (CLs method)

Excluded SM Higgs in the 127-600 GeV range

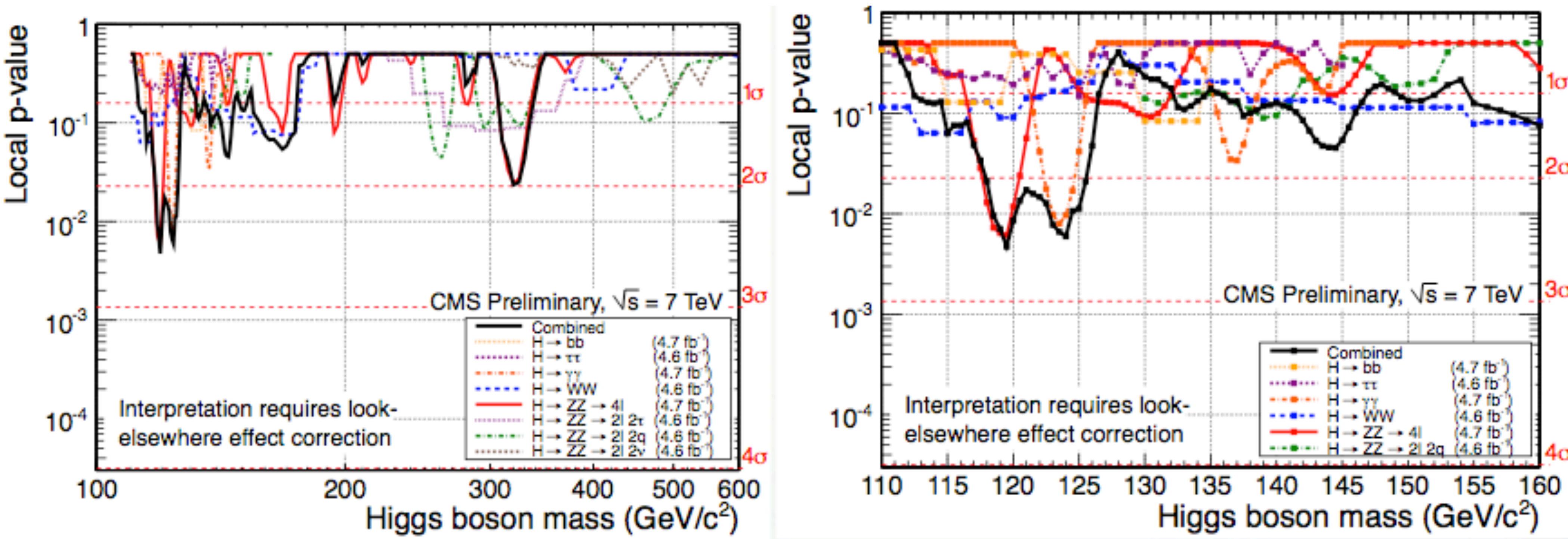


Limits by Channel



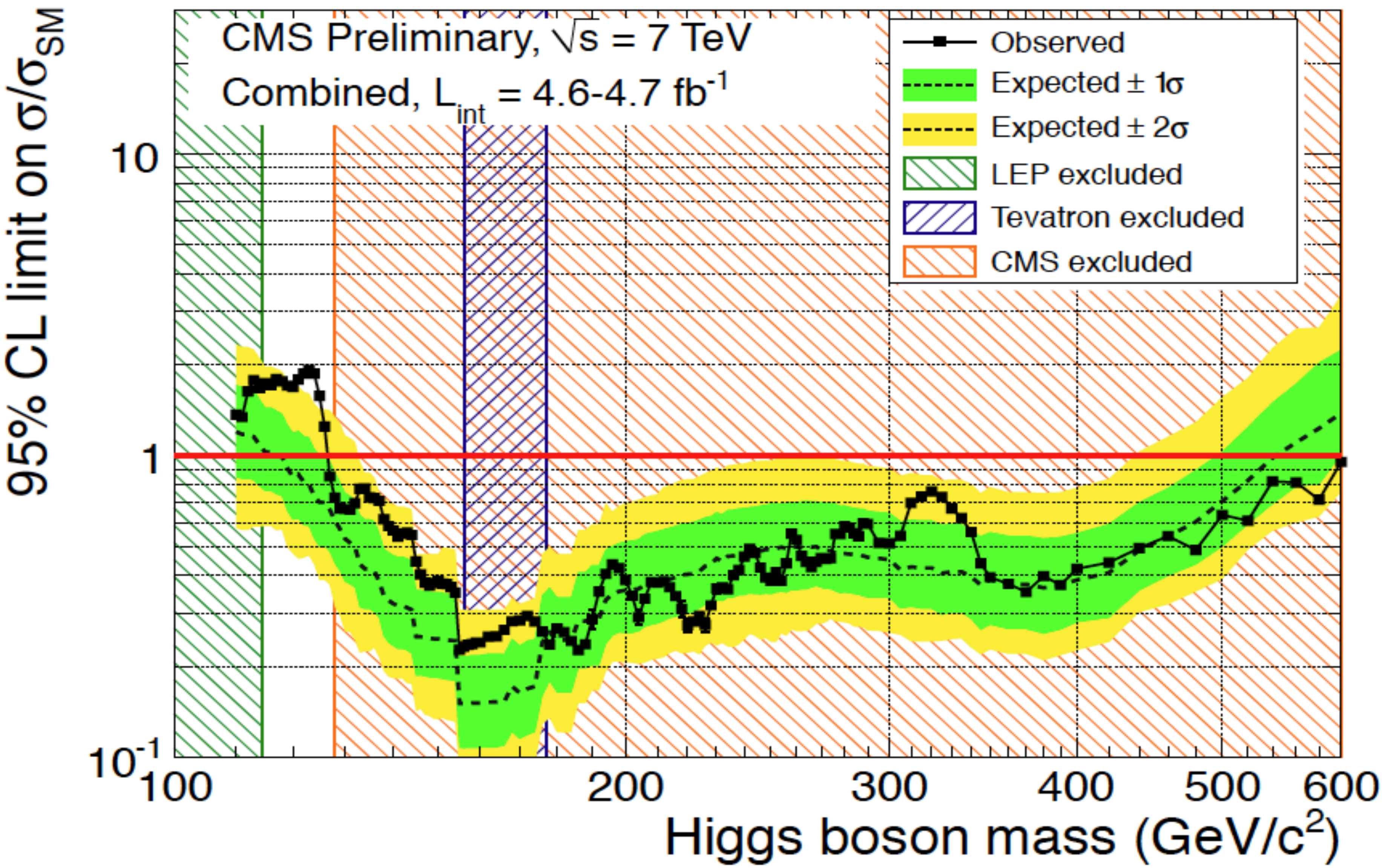
Anatomy of the Excess: p-values

Minimum local p-value corresponds to 2.6 σ
LEE corrected significance is 1.9 s in the 110-145 GeV mass range amd 0.6 σ in the 110-600 GeV mass range

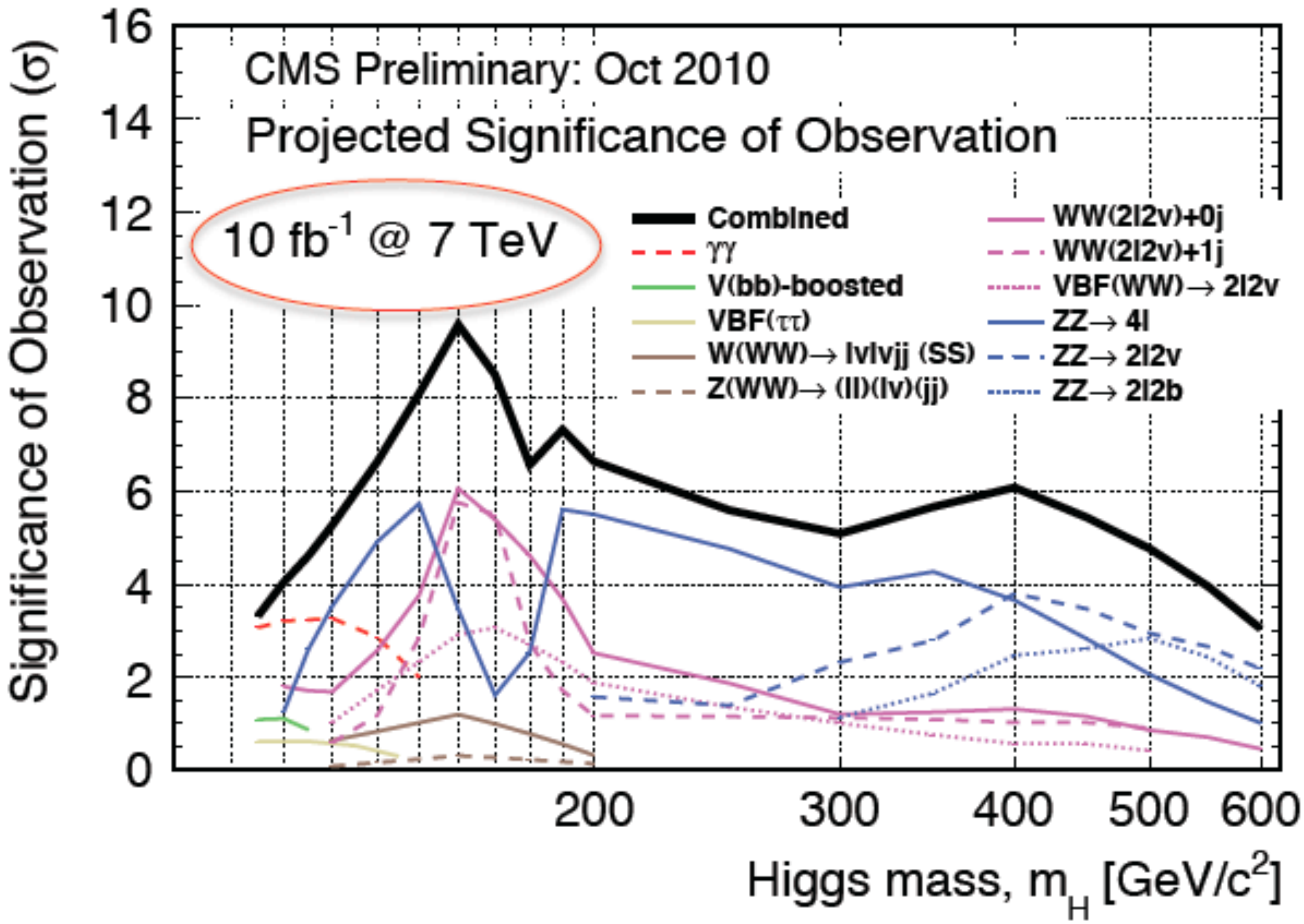


We cannot exclude the presence of the SM Higgs boson below 127GeV because of a modest excess of events in the region between 115 and 127GeV. **But the excess we see could be a fluctuation of background.**

One Plot Summary on CMS Higgs



What to expect in 2012?



In 2012, the integrated luminosity is likely to be 20-30 fb^{-1}. If SM Higgs exists, its discovery is likely with that dataset.

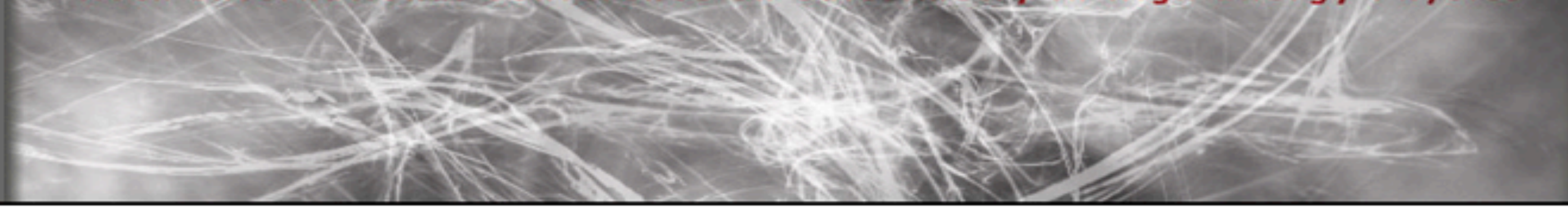
Conclusion

- CMS reached the SM Higgs boson exclusion sensitivity in mass range 127-600 GeV at 95% CL and 128-525 GeV at 99%.
- We are not able to exclude the presence of the SM Higgs below 127GeV since we observe in our data a modest excess of events between 115 and 127GeV.
- The excess is most compatible with a SM Higgs hypothesis in the vicinity of 124 GeV and below, but the statistical significance (2.6σ local and 1.9σ global after correcting for the LEE in the low mass region) is not large enough to say anything conclusive.
- As of today what we see is consistent either with a background fluctuation or with the presence of the SM Higgs boson.
- Additional data in 2012 will definitely give an answer.

CALOR 2012

June 4 - 8, 2012

"XVth International Conference on Calorimetry in High Energy Physics"



WELCOME TO CALOR 2012

Santa Fe Convention Center, 201 W. Marcy Street, Santa Fe, NM

The XVth International Conference on Calorimetry in High Energy Physics (Calor 2012) will be held in Santa Fe, New Mexico from June 4 to 8, 2012. This conference brings together all interested parties in high energy physics and related fields for in-depth discussions of the latest developments and innovations of calorimetry.

The conference venue is at the Santa Fe Convention Center, 201 W. Marcy Street.

A few facts about Santa Fe:

- Santa Fe has more than 225 restaurants, 250 art galleries, 70 jewelry shops, 13 museums and one world-famous opera.
- Santa Fe is the second oldest town in the U.S., founded in 1607 by the Spanish, 13 years before the Pilgrims landed at Plymouth Rock.
- Santa Fe, the capital of New Mexico, is the oldest capital city in the U.S.
- Indians lived there long before Santa Fe was a town, more than 1,000 years ago.
- Santa Fe is one of the largest art markets in the world.
- Santa Fe is easy to get to. Albuquerque is served by nine major commercial carriers: American, America West, Continental, Delta, Frontier, Northwest, Southwest, and United. Several shuttle services provide transportation 7 to 10 times daily between the Albuquerque International Airport and downtown Santa Fe.

We are looking forward to seeing you!

TEXAS TECH
UNIVERSITY
From here, it's possible.

Comments on Excesses - 1

p-value : chance of background fluctuating as high or higher than what has been observed in data

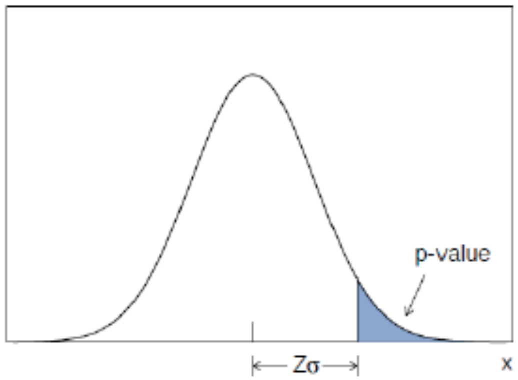
$p = P(\, n \geq n_{obs} \mid b)$

(Local *p*-value: What is the chance that the top card in a deck is Queen of Hearts?)

(Global *p*-value: What is the chance that the top card in at least one of N decks is Queen of Hearts?)

Comments on Excesses - 2

Significance Z is related to p-value via the tail probability of the normal distribution



Local and global p-values are not the same due Look-elsewhere Effect (LEE)

Trials Factor: K = (global p-value for Z_{max})/ (local p-value of Z_{max})

Ways to estimate LEE

- If background model for a search in the full mass range is available, one can toss toys
- If MC sample is much larger that data, one can use MC fragments as pseudo-data
- One can assess trials factor from a number of observed low-Z up-crossings
- Use a plain bound: K cannot be larger than the number of tested mass points