WANTED: THE HIGGS BOSON DEAD OR ALIVE?

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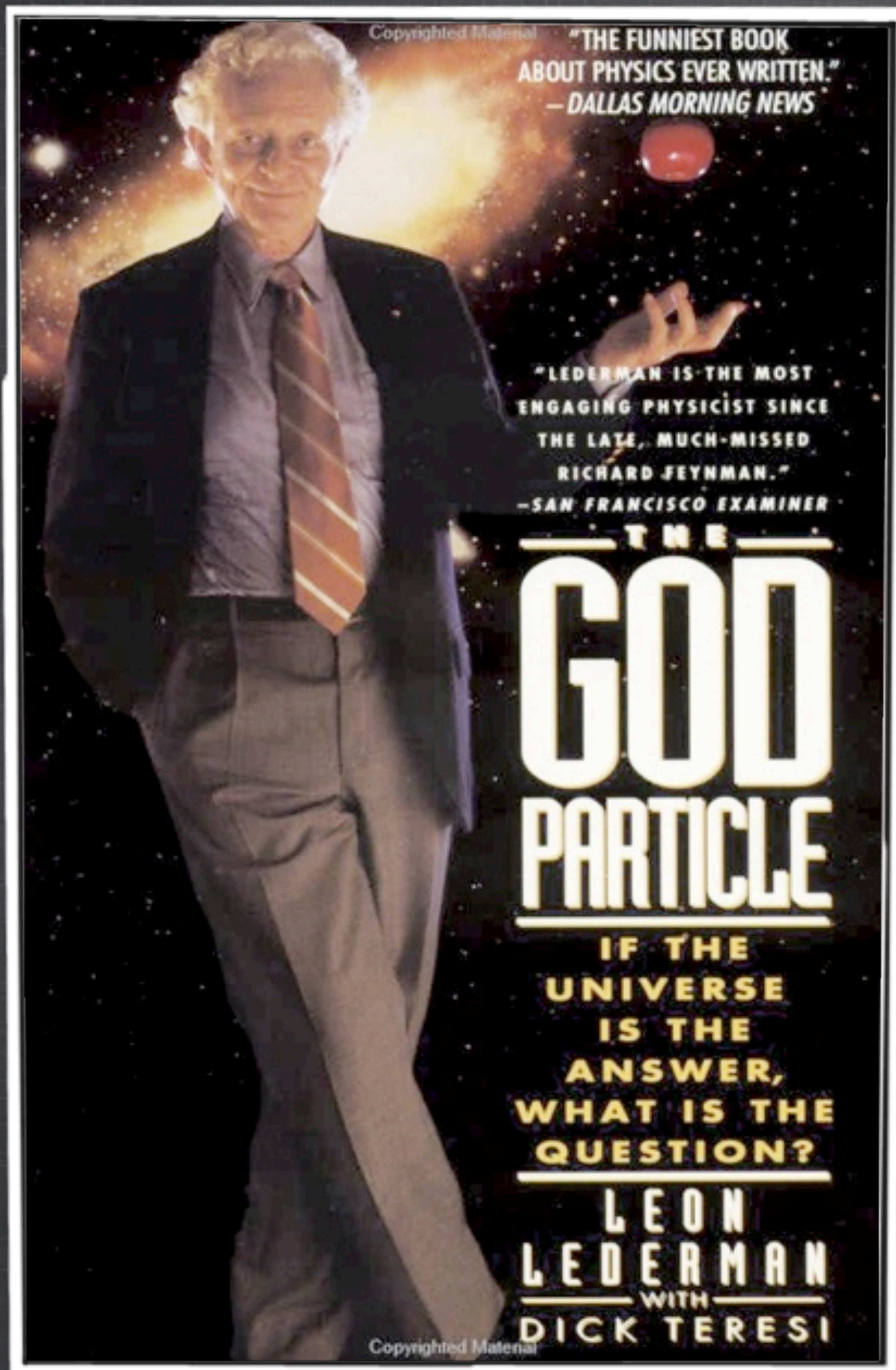
Joint Physics Colloquium on January 3rd, 2012

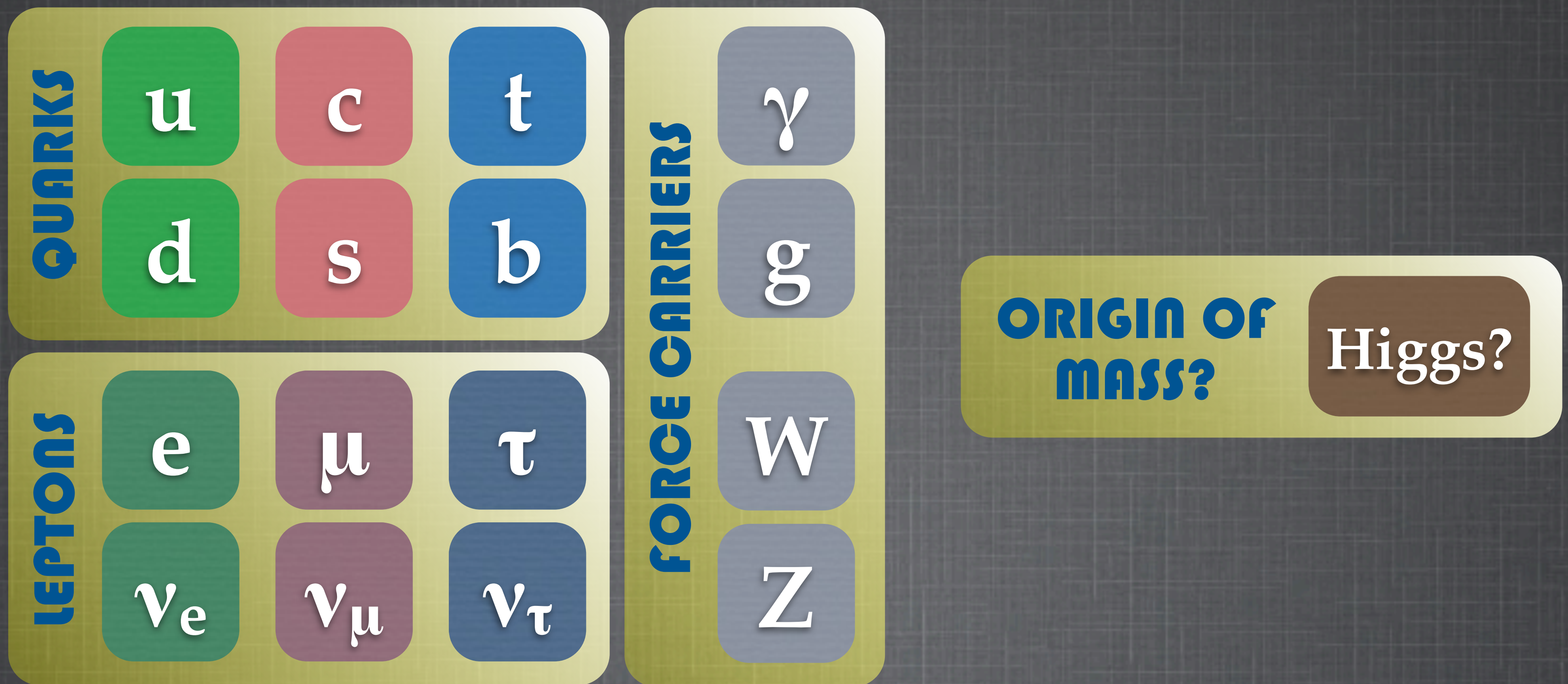


The God Particle?

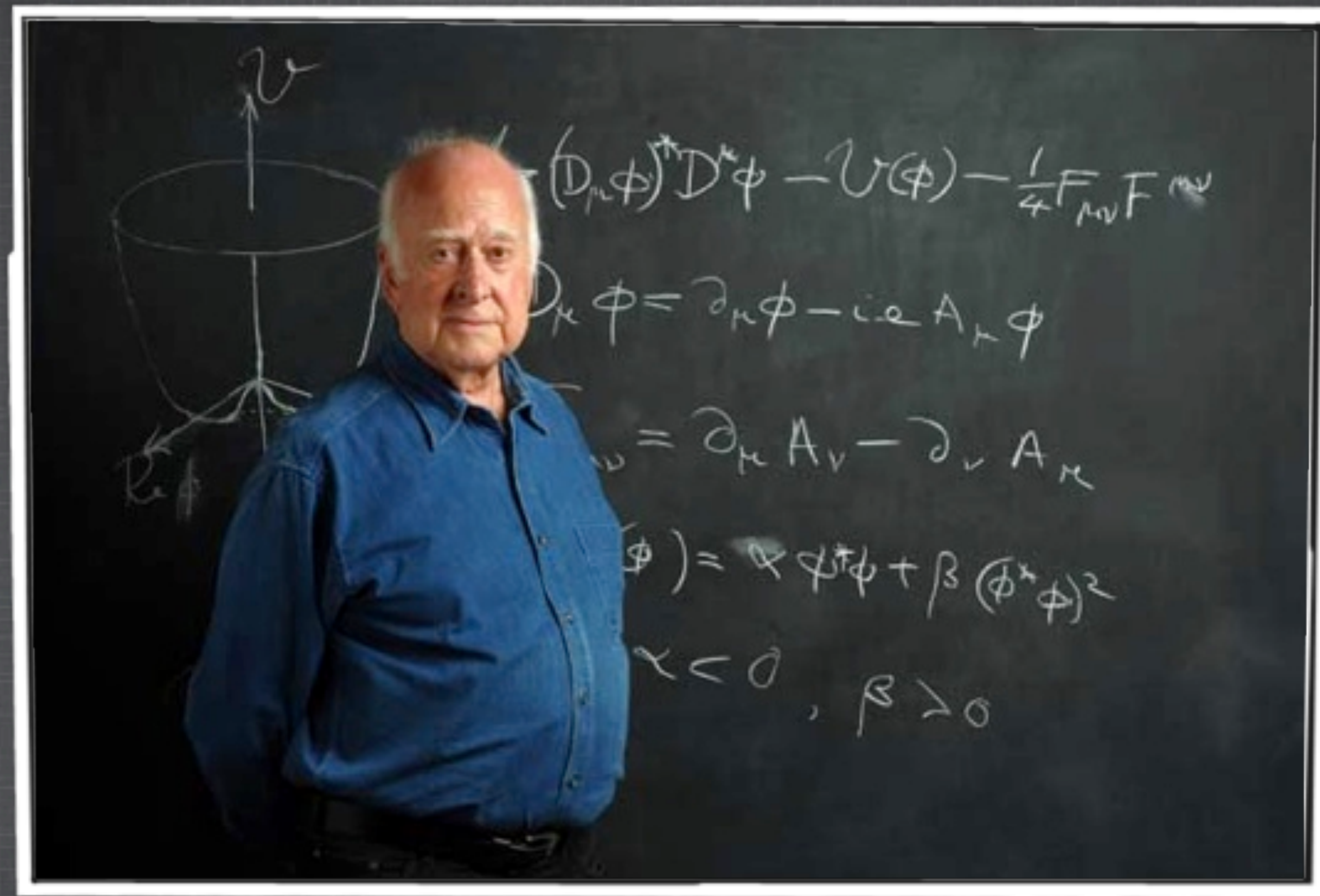
or

The Goddamn Particle?

The Higgs boson is often referred to as "the God particle" by the media, after the title of Leon Lederman's book. Lederman initially wanted to call it the "goddamn particle," but his editor would not let him...



- The **Higgs Boson** is an elementary particle predicted to exist by the **Standard Model** (SM). It is the last SM particle that has not yet been confirmed by the experiments.
- The Standard Model describes:
  - How the particles interact;
  - How different particles behave;
  - How the force between particles are manifested.
  - and, maybe explain the origin of mass?



- The **Higgs mechanism** was proposed in 1964 independently by three groups of physicists: by Peter Higgs; F. Englert and R. Brout; and by G. Guralnik, C. R. Hagen, and T. Kibble. They were awarded the 2010 J. J. Sakurai Prize for this work.
- The 1964 PRL papers by Higgs et al. displayed the field that would become the well known **Higgs boson** eventually.
- After 47 years, it is still the major objective at the Large Hadron Collider!

THE HIGGS MECHANISM
AN ANALOGY

Image a fairly crowed airport terminal, people are scattering around normally...

THE HIGGS MECHANISM
AN ANALOGY

If a super star just arrives the terminal...

THE HIGGS MECHANISM
AN ANALOGY

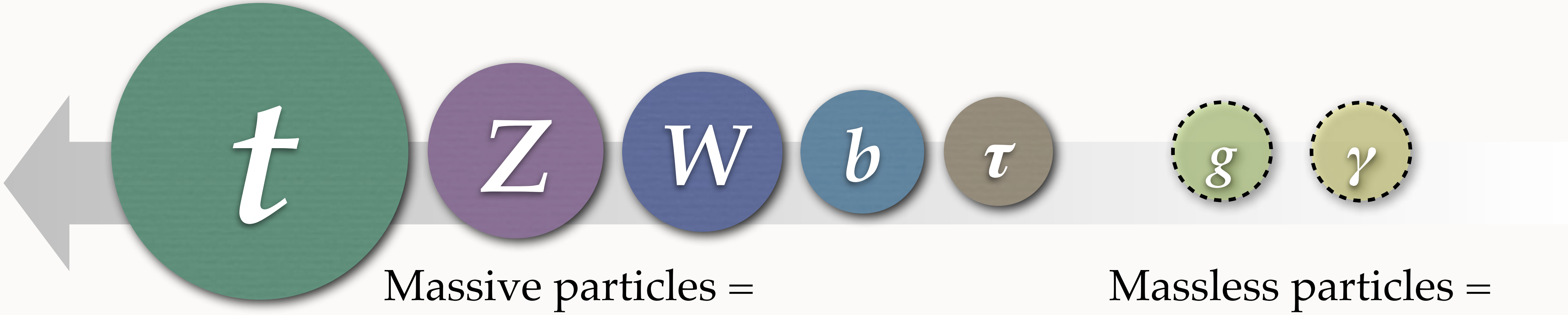
A “massive” particle

“Higgs bosons”

Now Faye Wang acts like a massive object,
due to the fact that followers are strongly interacting with her....

THE HIGGS MECHANISM

- The Higgs mechanism operates in a way similar to this analogy.
- Particles that have mass (e.g. weak force carriers and fermions) move through the Higgs field, interacting with the Higgs bosons.
- Heavier particles interact more with the Higgs field taking on more mass, while massless particles (e.g. photons) have no direct interactions with the Higgs boson.



Massive particles =
strong direct connections with Higgs

Massless particles =
connection with 2nd order loops

THE HIGGS MECHANISM

- The Standard Model, which is based on the Lagrangian, must be symmetric under gauge transformations.
- However, explicit mass terms for the gauge bosons are forbidden by gauge invariance. But the W/Z bosons are known to be massive!
- The way out is provided by Spontaneous Symmetry Breaking (SSB). The Lagrangian is still invariant but the gauge symmetry is broken by the vacuum.
- In the simplest way, the SSB can be achieved by introducing one complex scalar doublet. This gives 4 degrees of freedom:
  - ➡ 3 give the masses to W^+, W^-, Z^0 bosons.
  - ➡ 1 left for the Higgs boson.
- In some of SM extensions may contain more Higgs doublets. (= more Higgs bosons!)

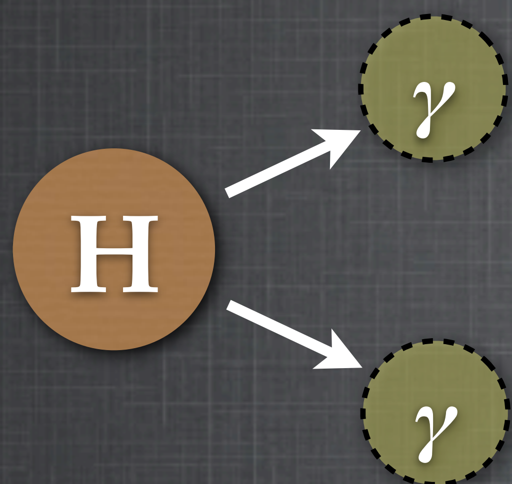
HOW TO FIND THE HIGGS BOSON?

- First, allocate 10 billion euros to build the Large Hadron Collider.
- Second – persuade thousands of physicists and engineers to live in Geneva and work day and night.
- Finally – be patient and wait for the conclusion.
- Since the Standard Model is so successful, most physicists believe the (SM-) Higgs boson can be found by the experiments at LHC. But don’t be too surprise if people cannot find it.
- If the Higgs is not found, it means that the current model (which is the simplest solution) is not working. But in this case, discovery of something else is almost guaranteed.

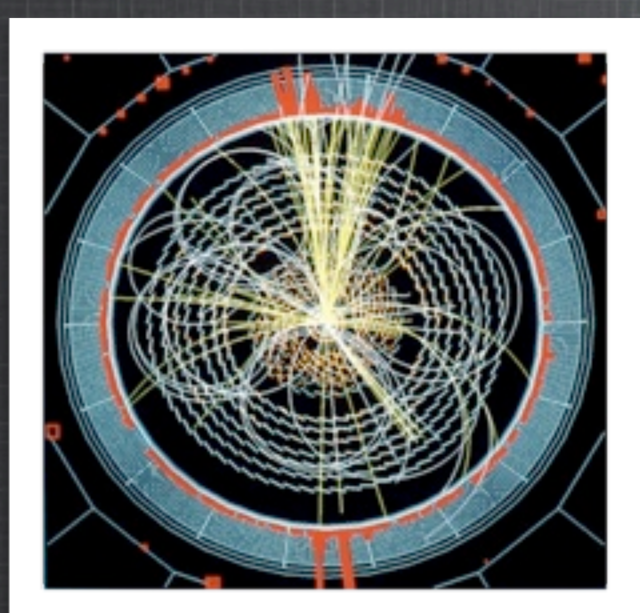
LET'S HUNT FOR HIGGS!

How to look for Higgs through its decays?
How the Higgs bosons are produced?
What are the predictions and experimental bounds?
How to tell its (non-)existence in terms of probability?
What are the newest results from the LHC?

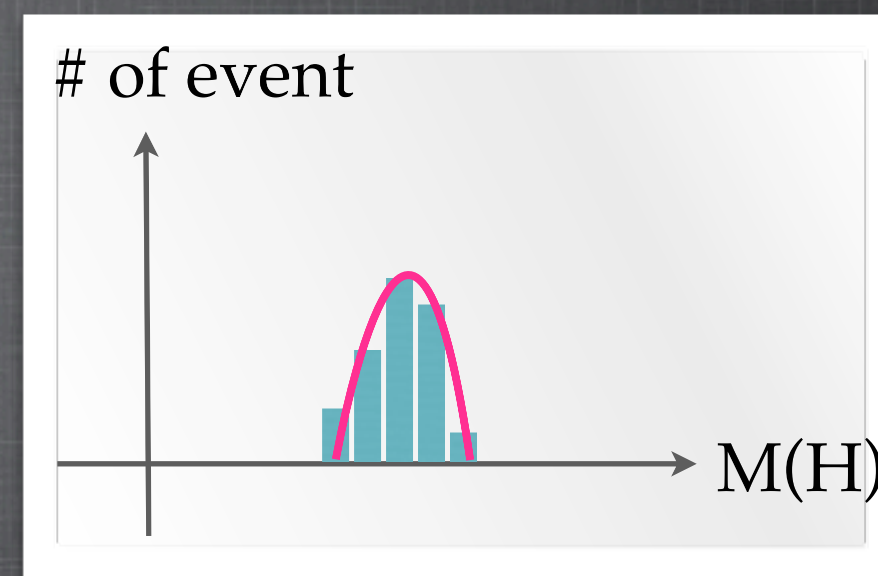
BUMP HUNTING IN A NUTSHELL



The Higgs boson should be short lived, quickly decay into some other particles. (e.g. photons)

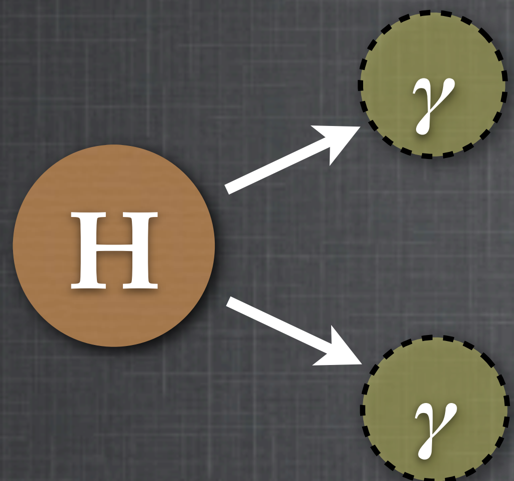


The detector can measure the decay products. The Higgs mass can be “reconstructed” using the measured energy and momentum of the particles.

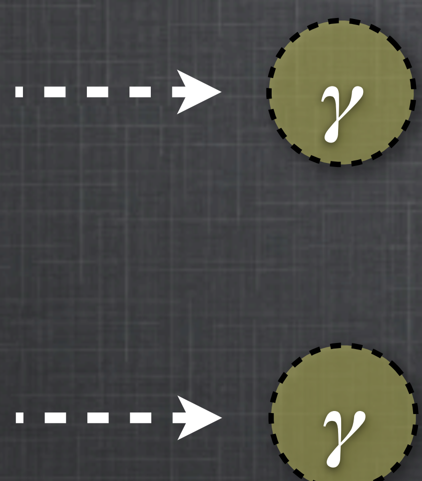


Collecting the measured mass from many events, the Higgs mass bump should be visible.

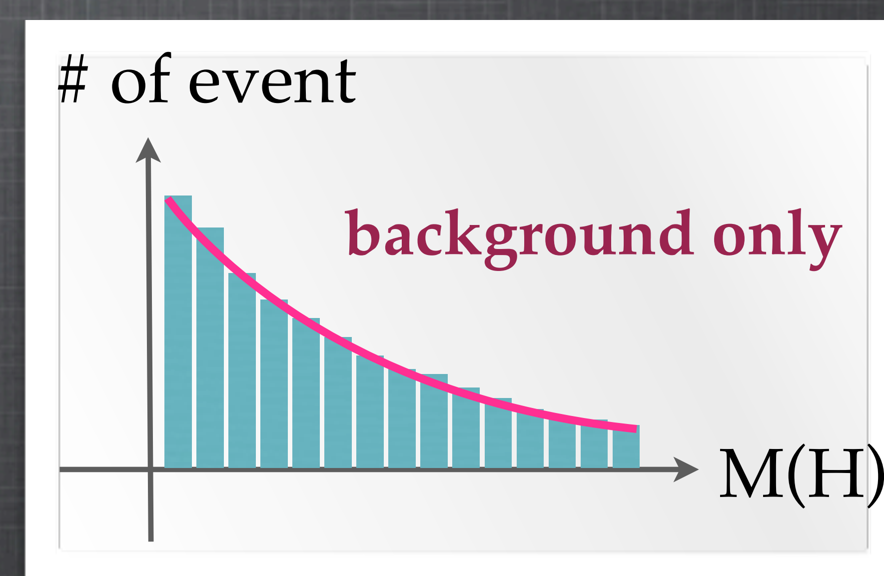
BUMP HUNTING IN A NUTSHELL



The Higgs boson should produce a peak on the mass spectrum

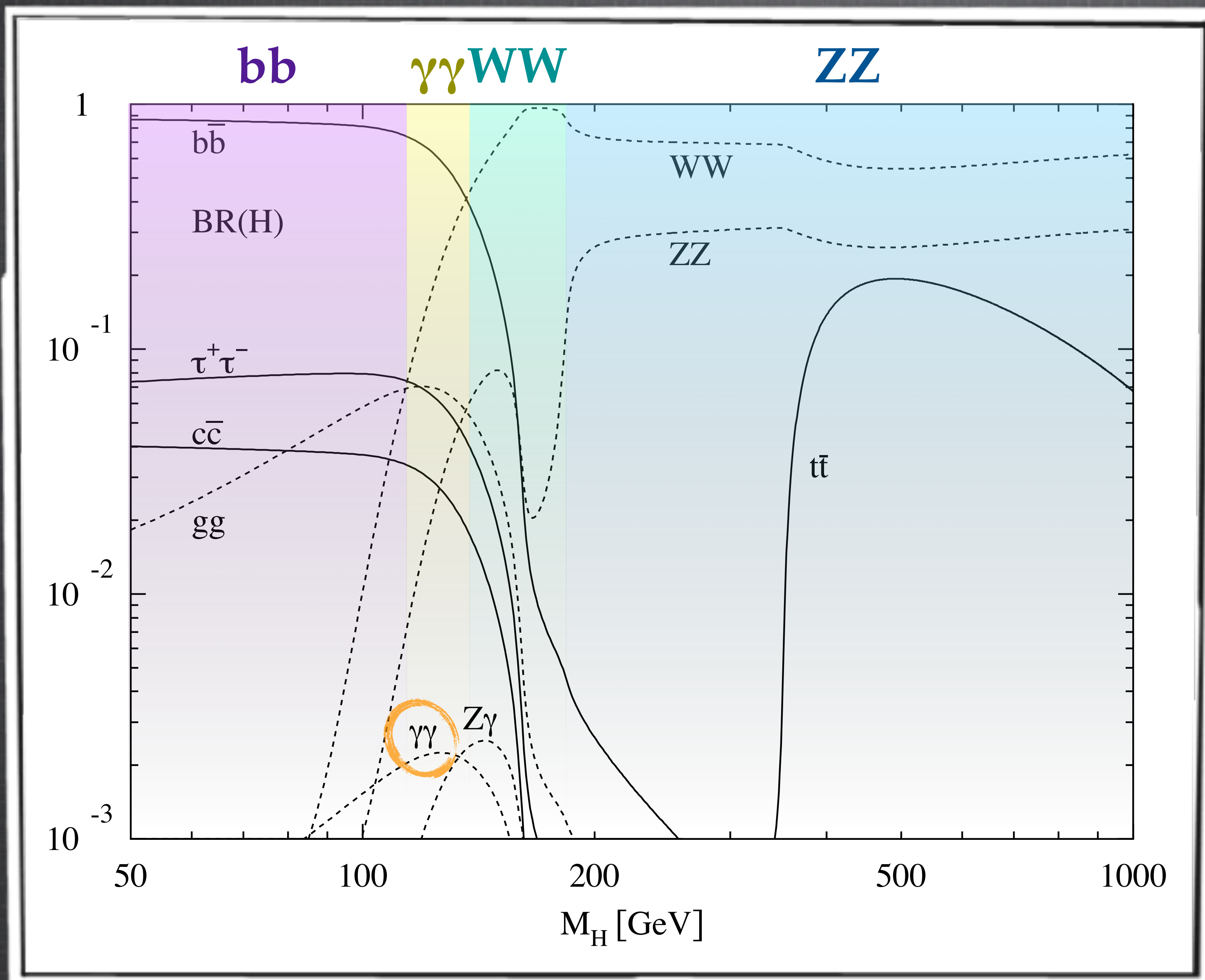


Background (e.g. two random photons) should generate a “flatter” distribution.



DECAY OF HIGGS

the “best channel”



Comment #1

Decay to heaviest particles, if they are kinematically allowed.

Comment #2

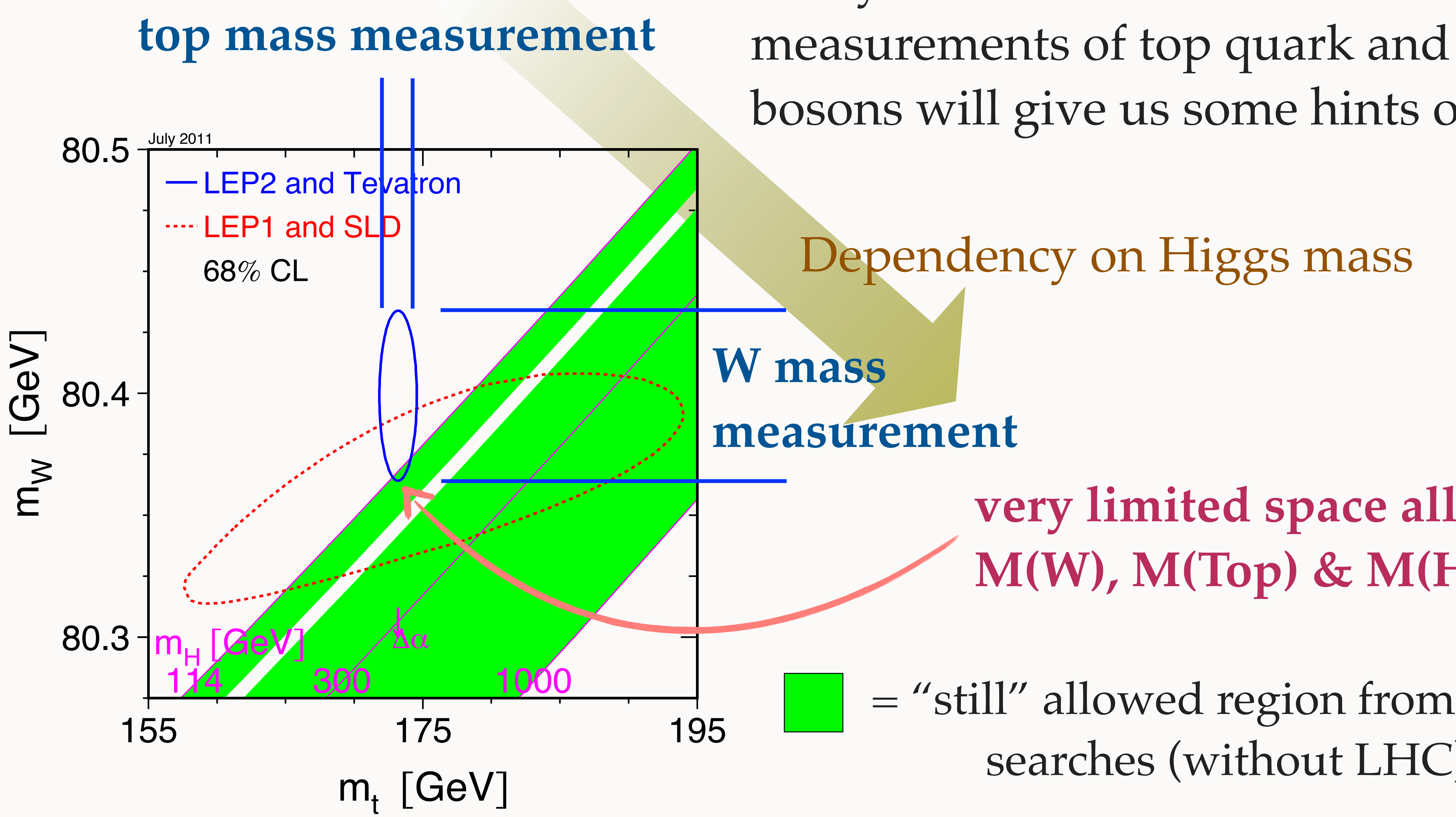
Decay to massless particles through loops.

Comment #3

“Best channel” is actually driven by background level.

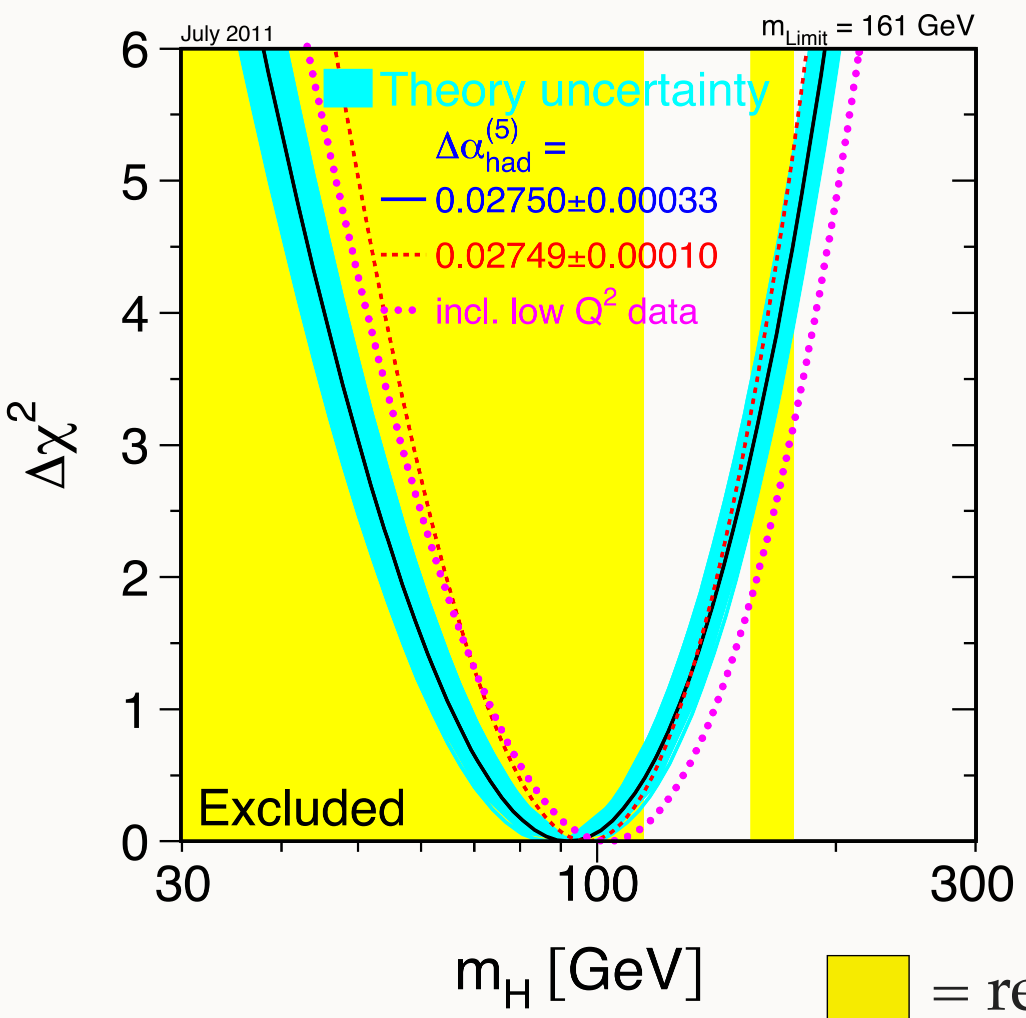
BEFORE THE ERA OF LHC

- Since Higgs tends to interact strongly with heavy stuff – it is obvious that the measurements of top quark and W/Z bosons will give us some hints of Higgs.



= "still" allowed region from direct searches (without LHC)

BEFORE THE ERA OF LHC



- Higgs mass is NOT predicted in the SM.
- But if we assume the SM is 100% correct and no other contributions, the Higgs mass can be constrained by existing precision measurements:

$$M(\text{Higgs}) = 92^{+34}_{-26}\ \text{GeV, or} < 161\ \text{GeV}$$

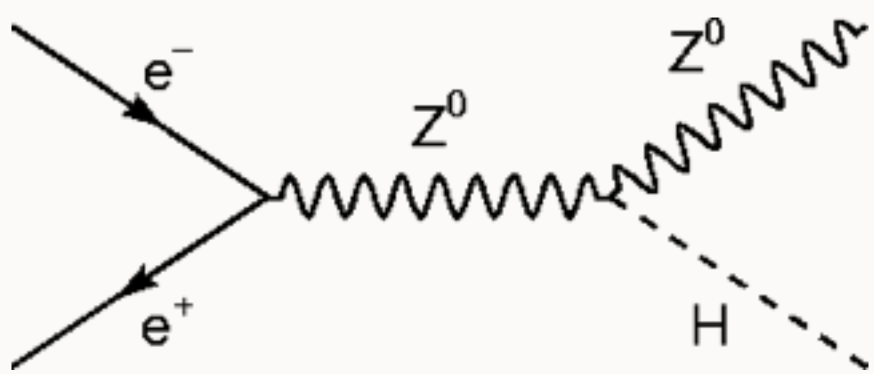
In any case, we still need to observe the Higgs boson directly...

= regions excluded by LEP and Tevatron

(to be discussed in next slides!)

LEP DIRECT SEARCHES

- LEP = Large Electron-Position Collider was the collider right before LHC at CERN.
- Four experiments on the ring (ALEPH, DELPHI, OPAL, L3).
- Search for Higgs using the so-called "Higgs-strahlung" process:

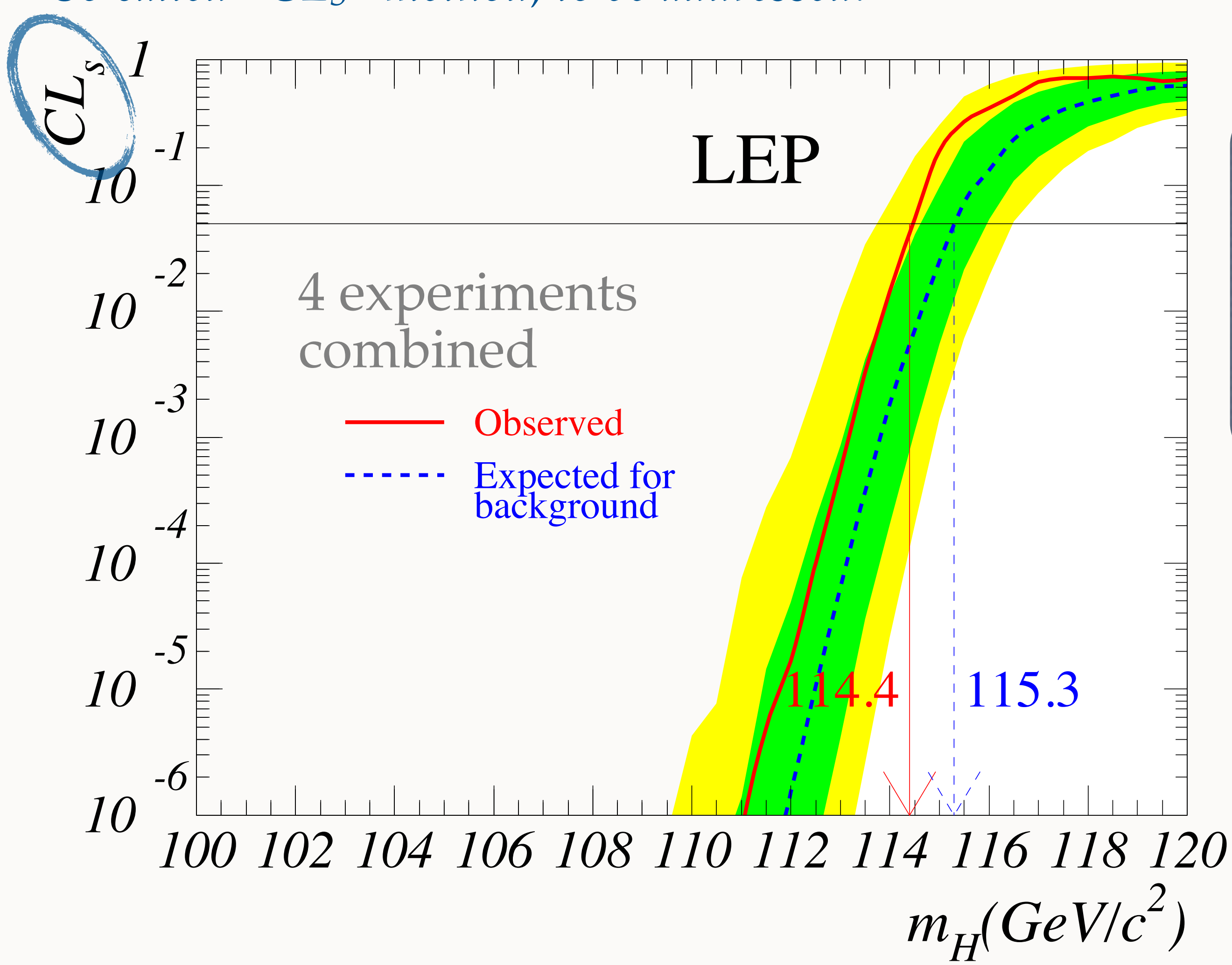


$$\sqrt{s} - M(Z) = 206.7 - 91.2 = 115.5 \text{ GeV}$$

(Maximum Higgs mass reach)

LEP DIRECT SEARCHES

So called "CL_S" method, to be addressed.

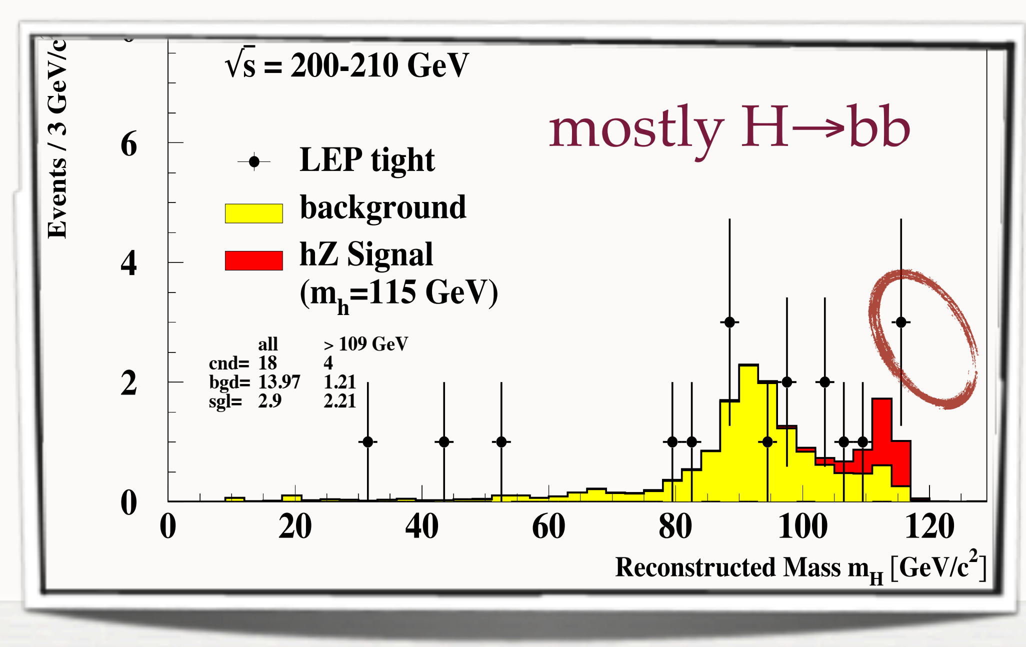


= ±1σ (~68%) from background hypothesis

= ±2σ (~95%) from background hypothesis

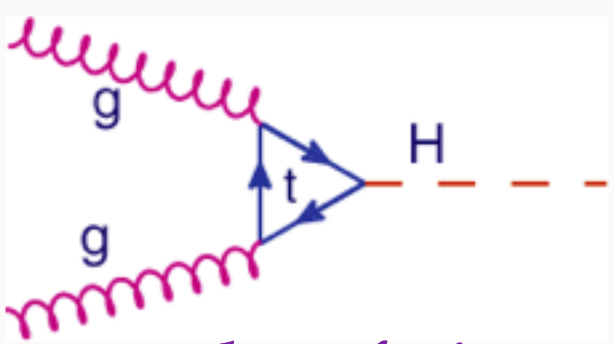
LEP combined
Observed limit >114.4 GeV
(Expected limit >115.3 GeV)
at 95% confidence level

A mild hint found ~118 GeV, but it is hard to concluded ⇓

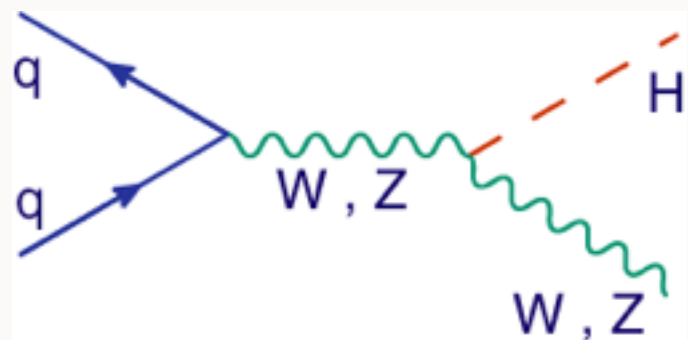


TEVATRON SEARCHES

- Tevatron is the hadron collider at Fermilab with a CM beam energy of 1.96 TeV (the highest CM energy before the LHC!).
- Two general purpose experiments: CDF and D∅.
- Higgs are mostly produced through:

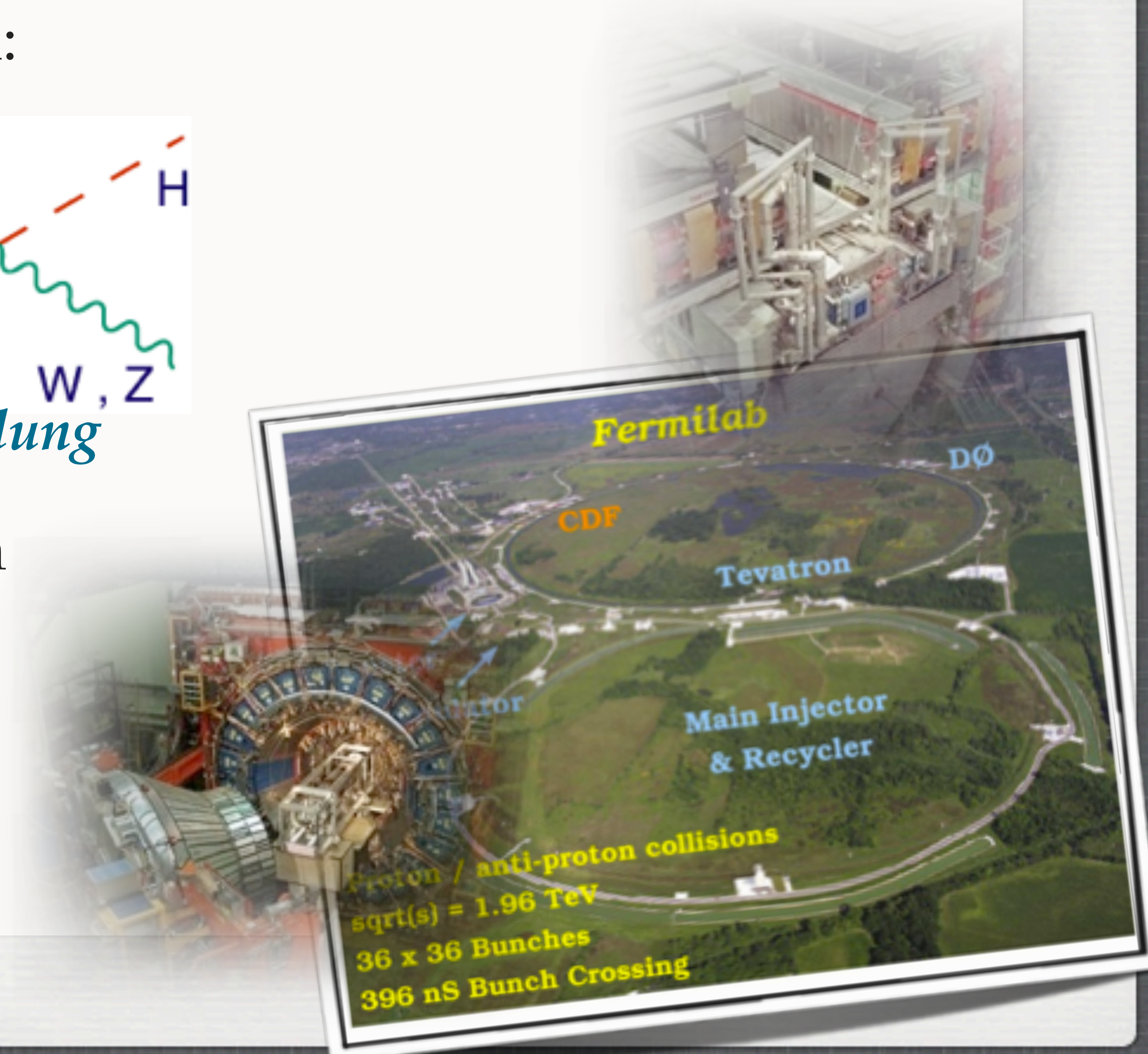


gluon fusion



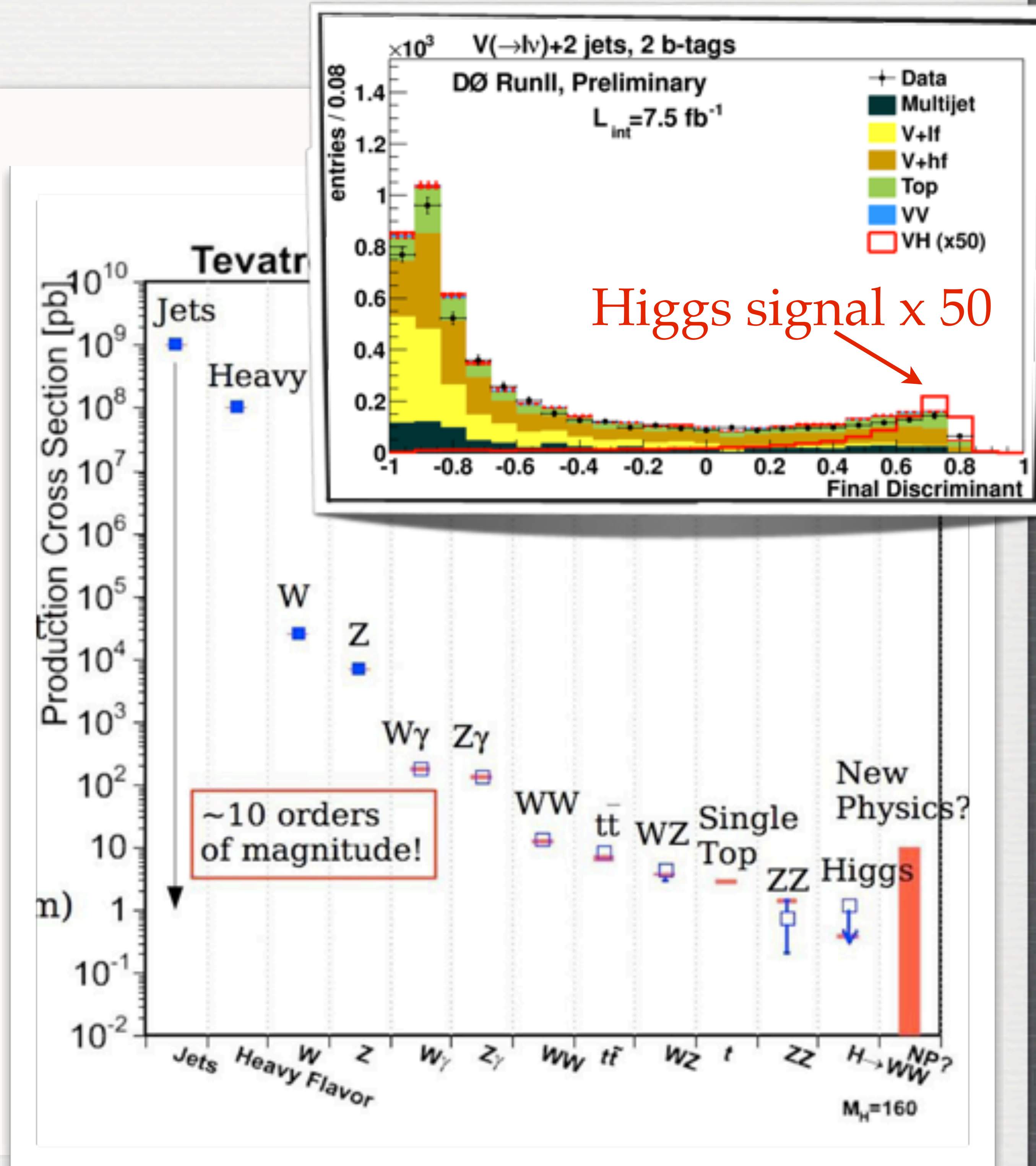
Higgs-strahlung

- Although the searching mass region can be much higher than LEP (which is totally limited by its CM energy), but the background level is also higher.



TEVATRON SEARCHES

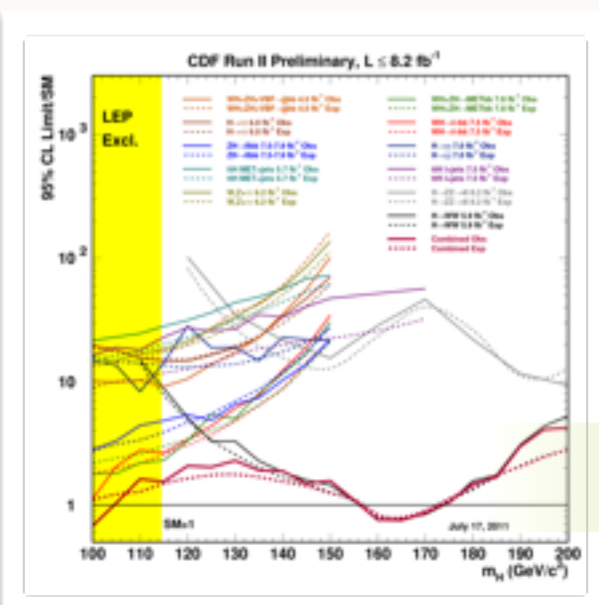
- The production rate for Higgs is almost 10 orders of magnitude lower than the QCD (=jets) processes.
- The search for Higgs is highly dependent on the background level. *(e.g. a direct search for H→bb will not work, but need to tag the associated W/Z boson.)*
- Adopt multivariate analysis tools, such as neural network, matrix element, boost decision tree, etc.
- Need to combine many analyses.



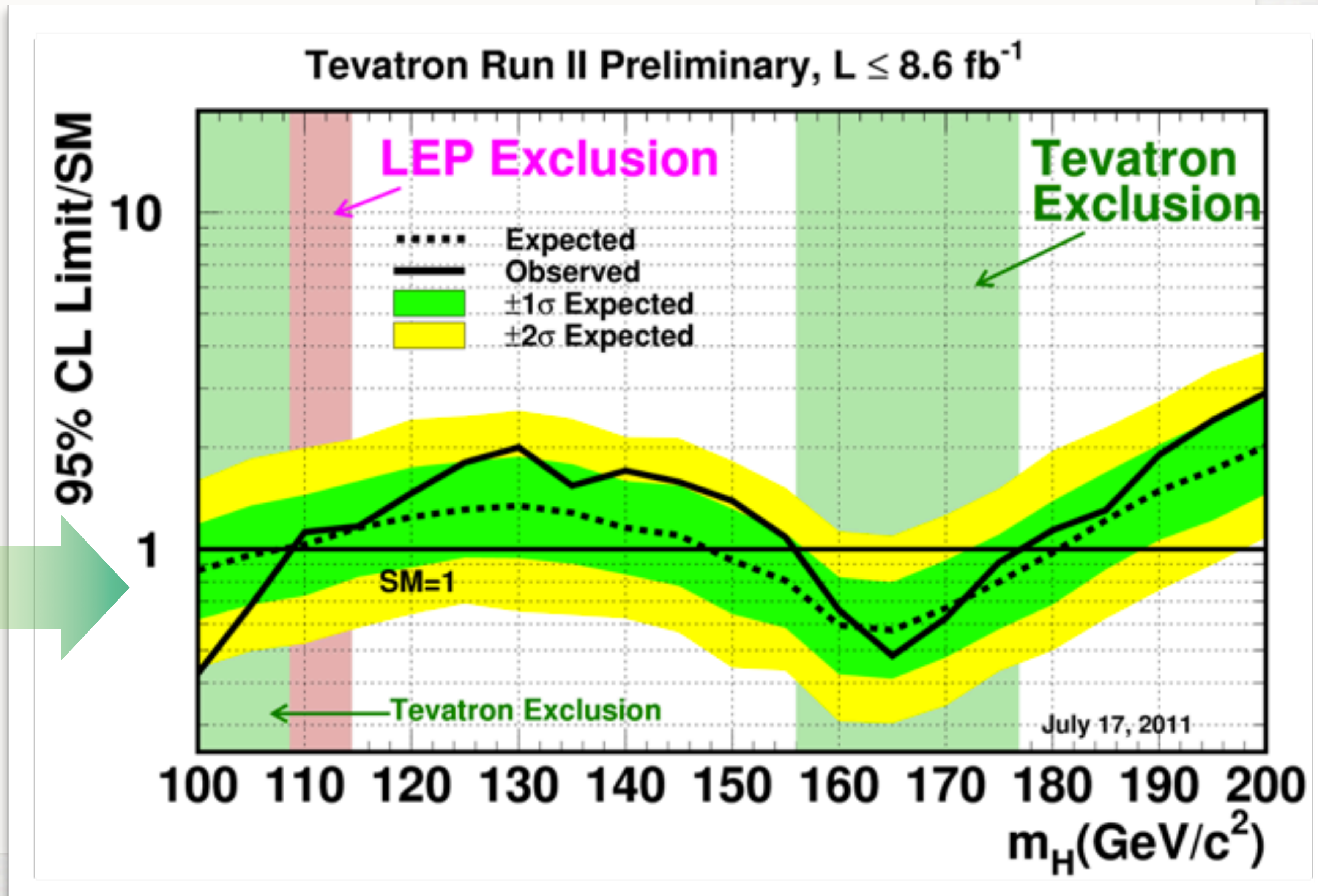
TEVATRON SEARCHES

- It's already very close to the best sensitivity of Tevatron (closed in 2011).

Tevatron combined exclusion
156 < M(H) < 177 GeV/c²
at 95% confidence level

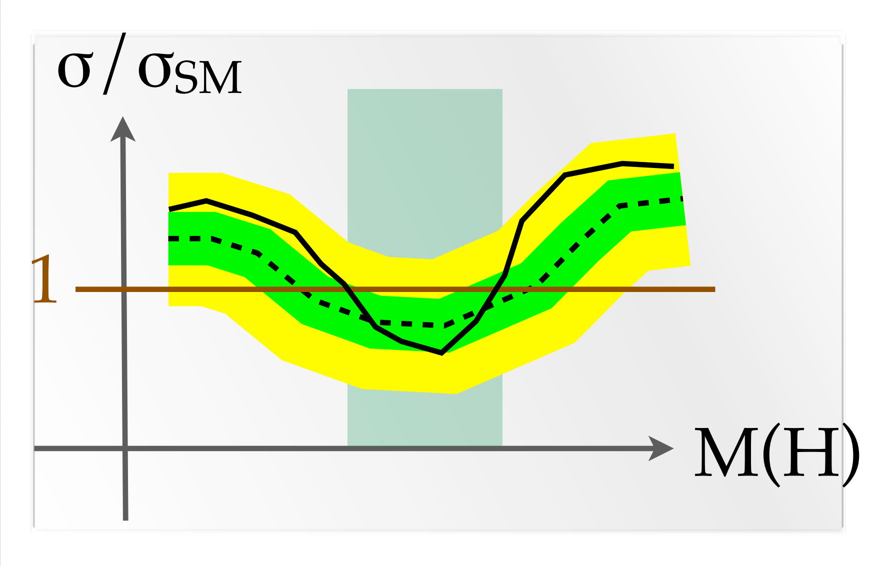


A global combination of 12 search channels



HOW TO READ THE LIMIT PLOT?

A typical limit plot



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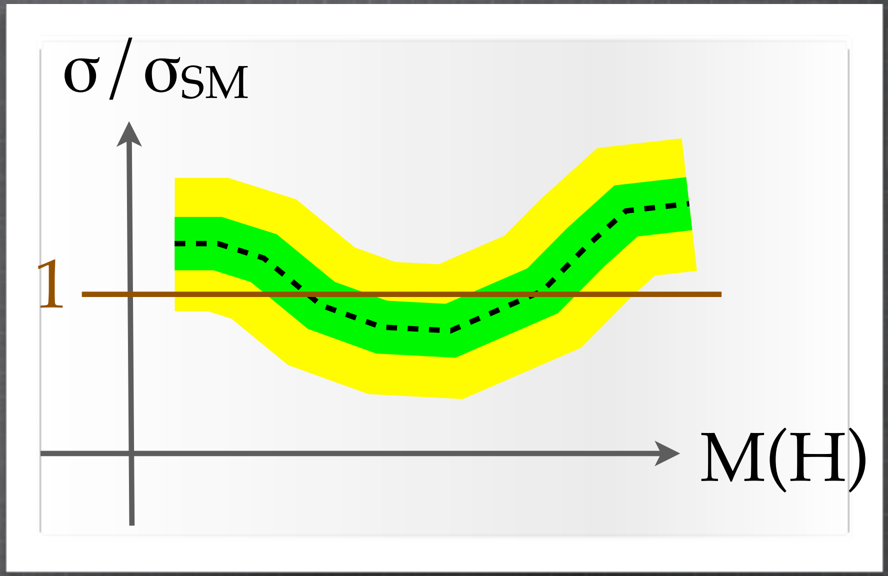
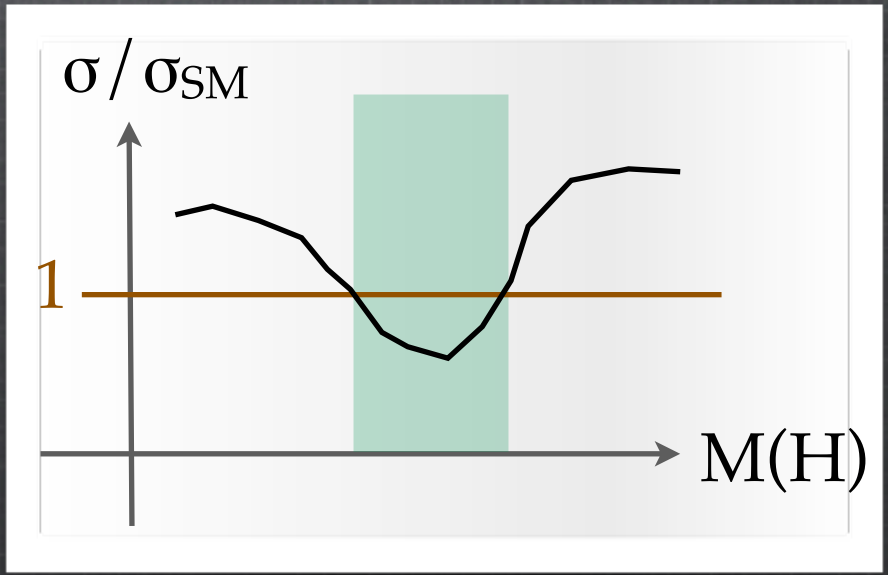


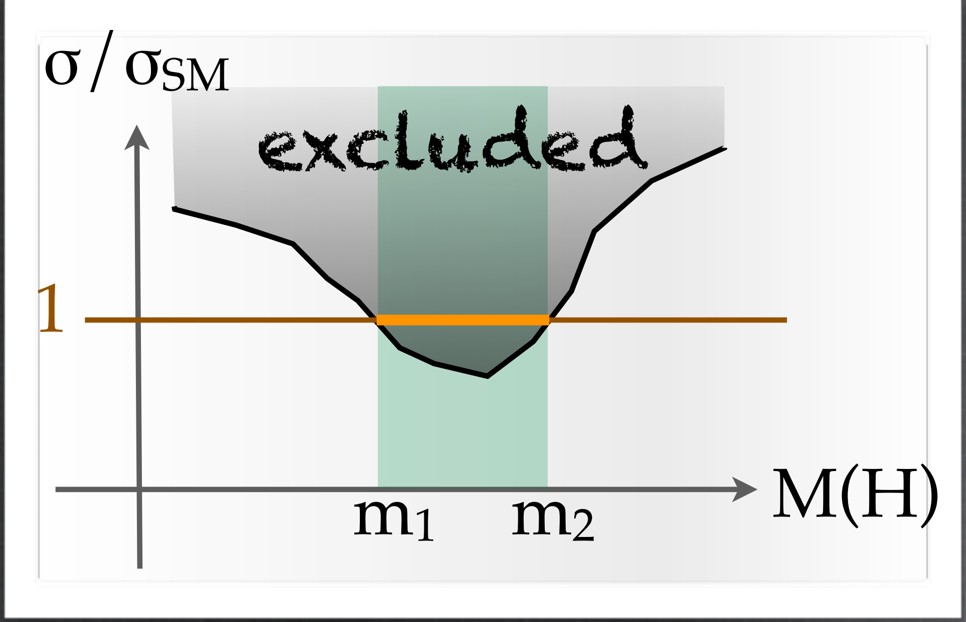
The "expected" limit curve and its uncertainties ($\pm1\sigma$,$\pm2\sigma$ bands)

+



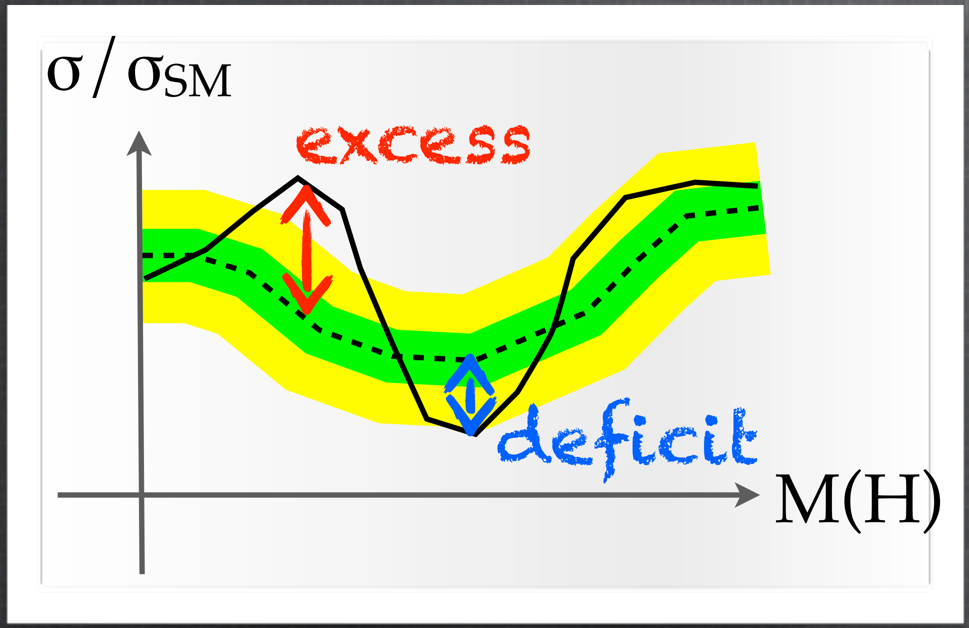
The "observed" limit curve

σ/σ_{SM} vs. M(H) = limit on relative cross sections to the SM versus the given Higgs mass



Comment #1

Any region above the "observed limit" curve is excluded. The **"$\sigma/\sigma_{SM} = 1$"** is excluded between m_1 and m_2, indicates SM Higgs with **M(H) ∈ [m1,m2] is excluded**.



Comment #2

If the "observed limit" is above the "expected limit", one can interpret such behavior as an "excess". But one cannot read the significance (# of σ) from such an exclusion plot.

However, there are still some difficult questions:

Q1: What's exactly the meaning of exclusion limit?

Q2: Why there are "expected" and "observed" curves?

Q3: How can we tell the strength of an excess?

CONSTRUCTION OF LIMIT

AN EXAMPLE

Suppose you have a magic Swiss-franc coin.

You want to toss it (do experiments!) to know if it has equal probabilities for head and tail.

However, since it's a **MAGIC** coin, it will cost you $100,000 per tossup *(ouch!)*...

So you prepared a proposal, explained the importance of this experiment, and fired it to the funding agency. Fortunately you received $1000,000 to do this experiment. Congratulations!

So you get the right to toss it for 10 time...

CONSTRUCTION OF LIMIT
AN EXAMPLE

- First, do a survey on arXiv and check several possible predictions:

			define the “UNFAIRNESS”
Fair Model	50%	50%	0
Cheat Model	40%	60%	0.2
Alien Model	20%	80%	0.6
You-Must-Be-Very-Lucky Model	1%	99%	0.98

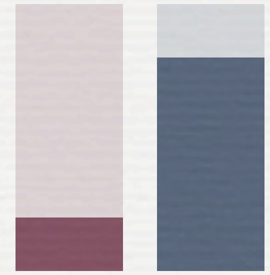
- Before doing the experiment, we shall use Monte Carlo (pseudo experiments) to examine what is the **EXPECTED** lowest “unfairness” can be excluded with only 10 tossups, at the 95% confidence level.
- Then we can just toss the coin 10 times and obtain the **OBSERVED** limit on the “unfairness”, also at the 95% confidence level.

- Generate Monte Carlo (10 tossups x 10000 trials x 2 hypothesis) according to

The Null Model

("unfairness" = 0)

(4,6) (1,9) (7,3) (5,5) (6,4) ...



The Alternative Model

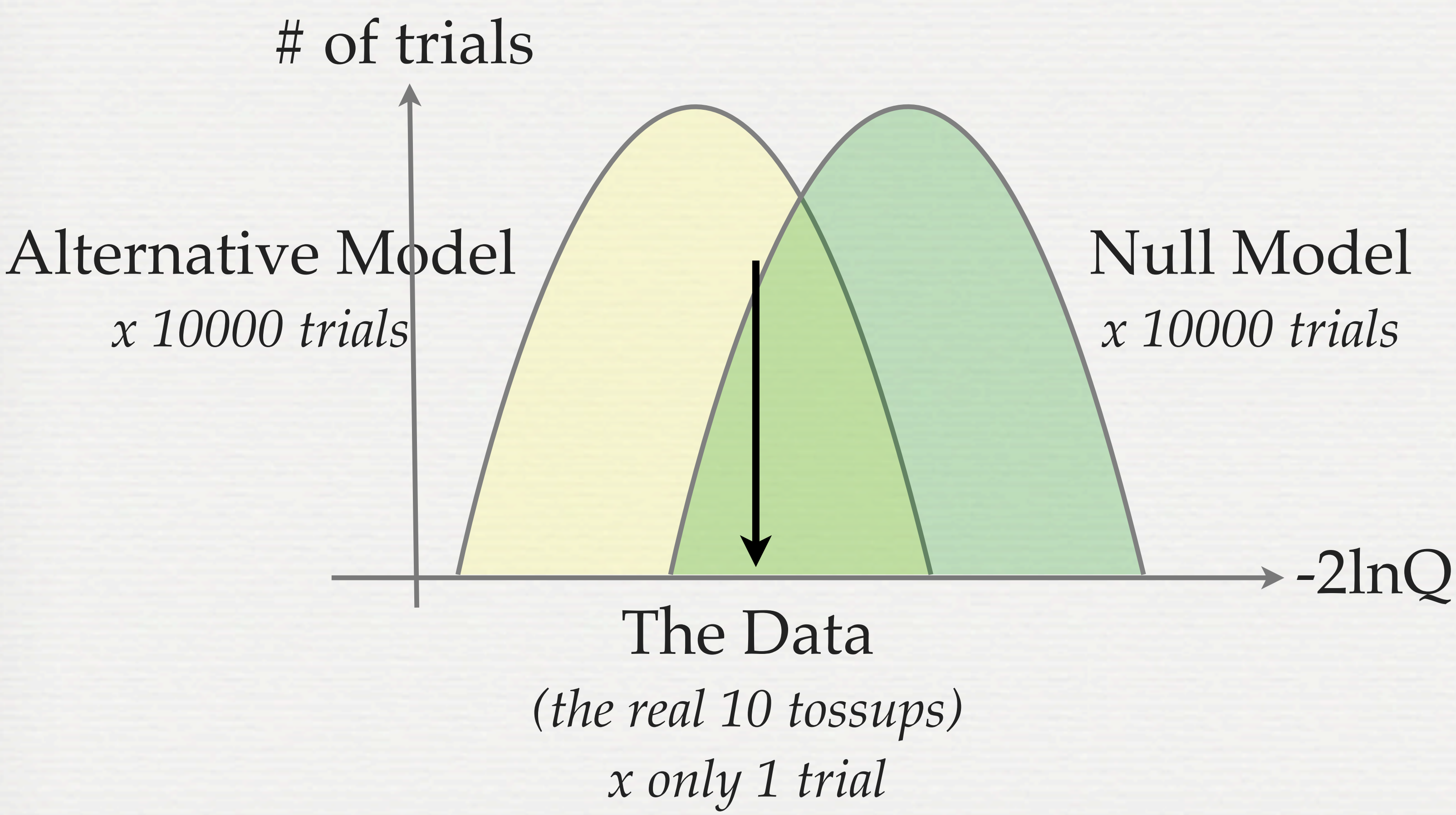
("unfairness" = 0.6, as an example)

(1,9) (0,10) (3,7) (6,4) (2,8) ...

- For each trial (=10 tossups), the relative likelihood (or $\Delta\chi^2$) can be calculated:

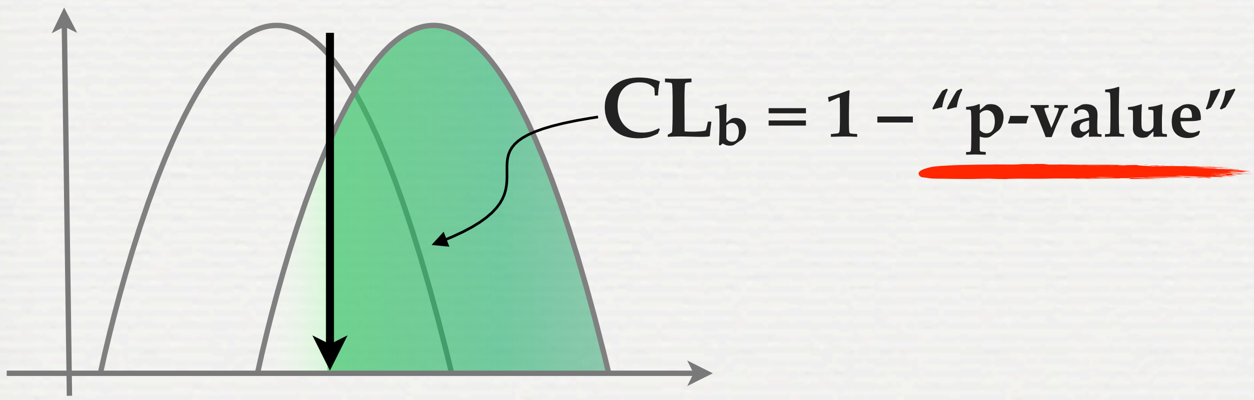
$$-2\ln Q = -2\ln(\mathcal{L}_{\text{alternative}}/\mathcal{L}_{\text{null}})$$

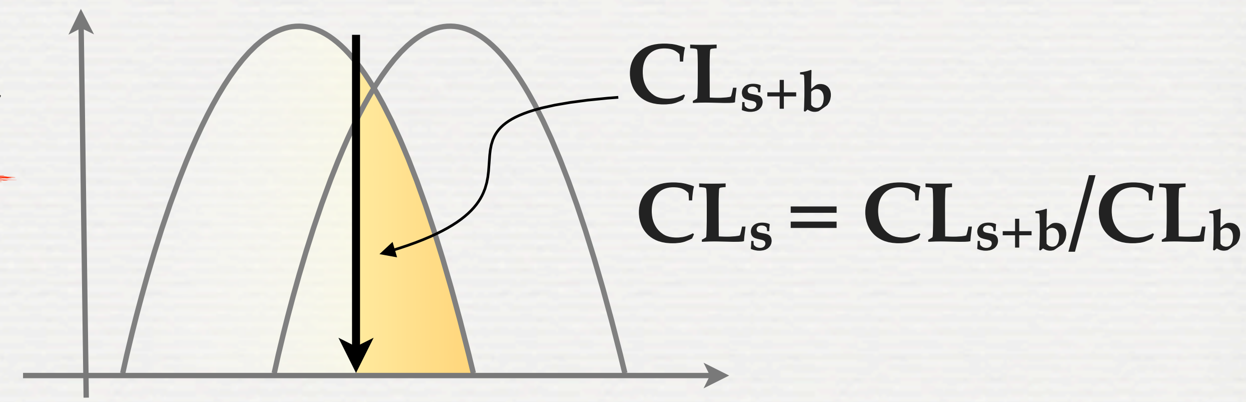
Then collect the trials and for each hypothesis and for data (the real 10 tossups):



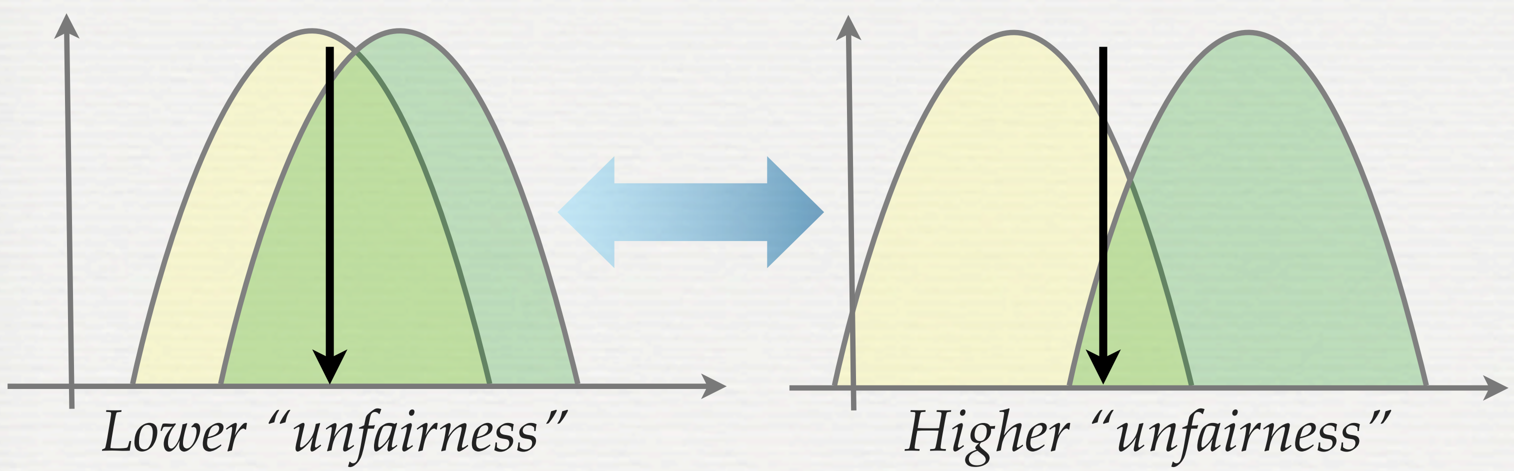
One can use these two distributions to calculate "CL_b" and "CL_s" for the statistics analysis.

- For a given “unfairness”, one can obtain a CLs value:



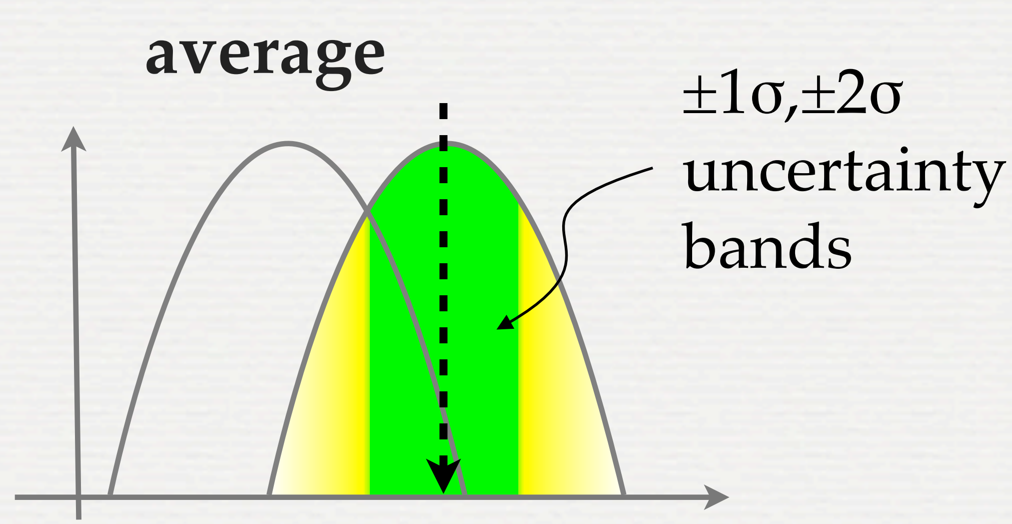


- Tuning the given “unfairness”, until the CL_s value is equal to 0.05 (=1 – 95%):



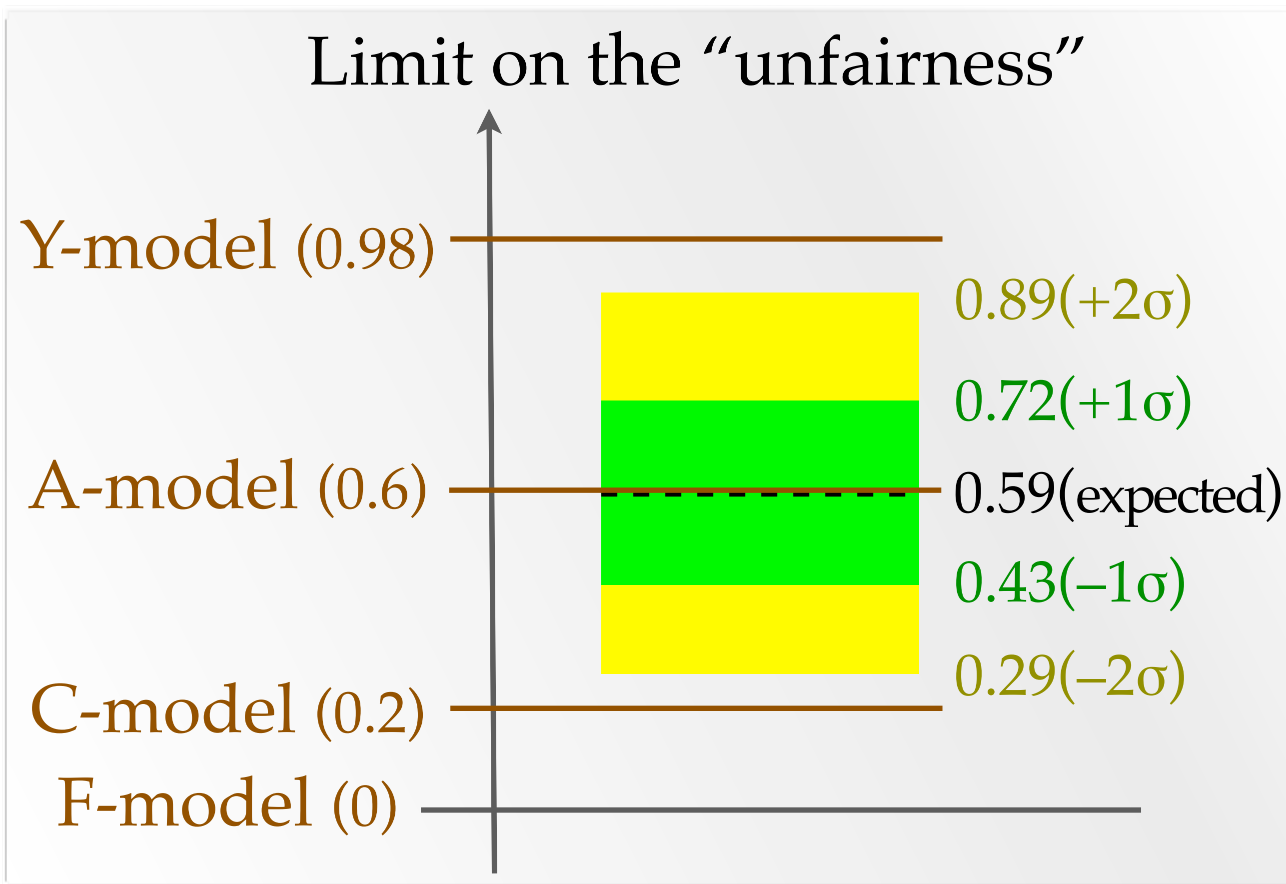
At this moment, the given “unfairness” is the **OBSERVED** limit at 95% CL_s confidence level.

- Replace the data point (↓) with the **average** (and its width) of the null model to determine the **EXPECTED** limit and the associated uncertainty band with the same “unfairness” tuning.



HERE WE GO...

The EXPECTED limit is 0.59 for 10 tossups =
We expected to exclude any model that gives an "unfairness" > 0.59 at 95% C.L.
For the OBSERVED limit, we have to do the experiment now!



Actually we need at least 100 tossups to exclude the C-model (40% / 60%)!

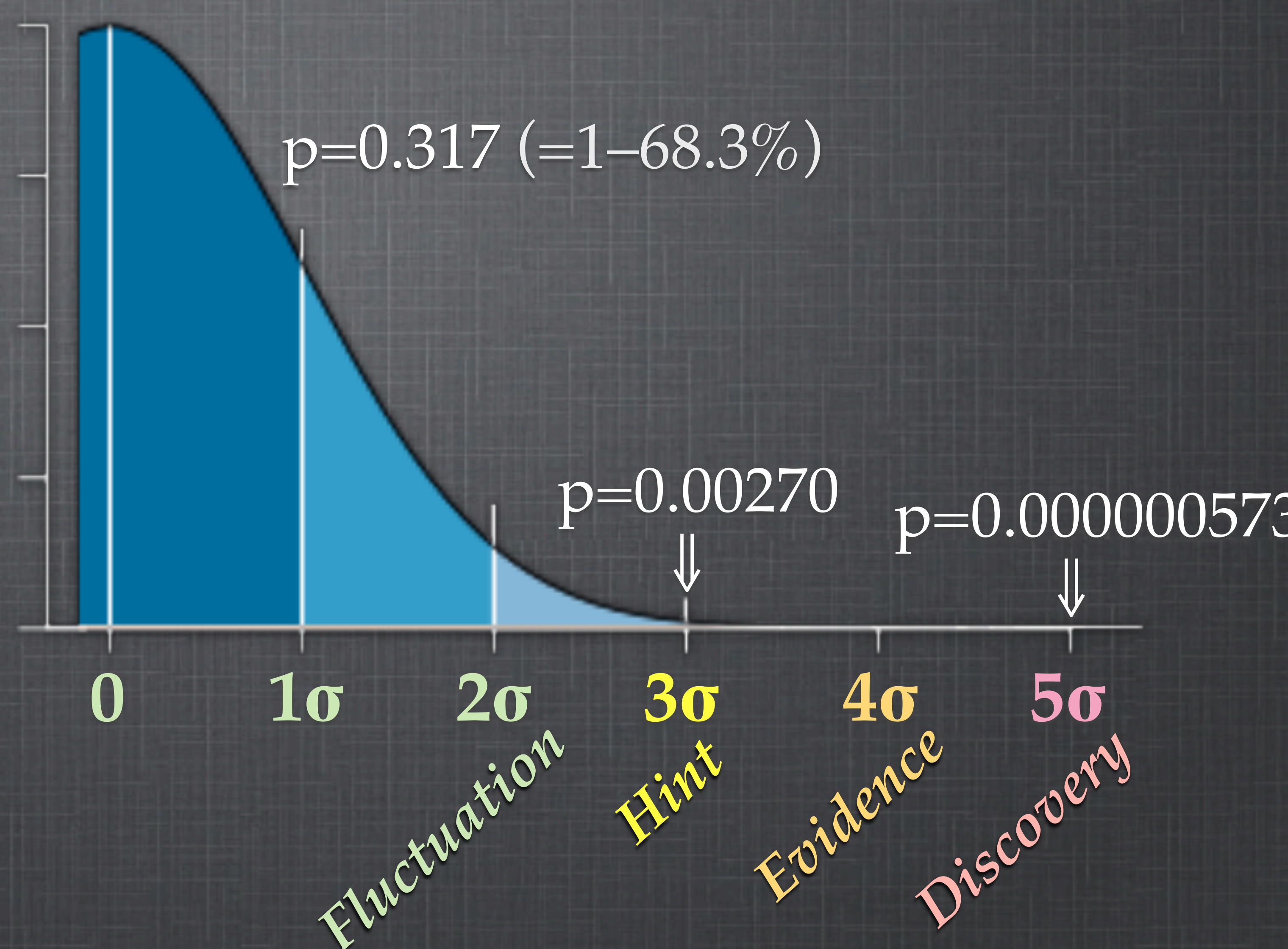
Tail	Head	Observed Limit
10	0	0.26
9	1	0.29
8	2	0.35
7	3	0.42
6	4	0.50
5	5	0.59
4	6	0.72
3	7	0.81
2	8	0.91
1	9	0.98
0	10	N/A

EXCESS?

The strength of an excess is given by the "p-value" (=1–CL_b), defined by the likelihood that the observed data is actually a fluctuation from null hypothesis.

(lower p-value = stronger excess; higher p-value = weaker excess.)

Tail	Head	Scanned p-value for A-model
10	0	1.0
9	1	0.999
8	2	0.99
7	3	0.95
6	4	0.83
5	5	0.62
4	6	0.38 (0.9σ)
3	7	0.17 (1.4σ)
2	8	0.055 (1.9σ)
1	9	0.011 (2.5σ)
0	10	0.00098 (3.3σ)



BEFORE MOVING FORWARD...

- The constraints from EWK precision data prefer a light Higgs boson:

$$M(H) = 92^{+34}_{-26}\ \mathrm{GeV}/c^2$$

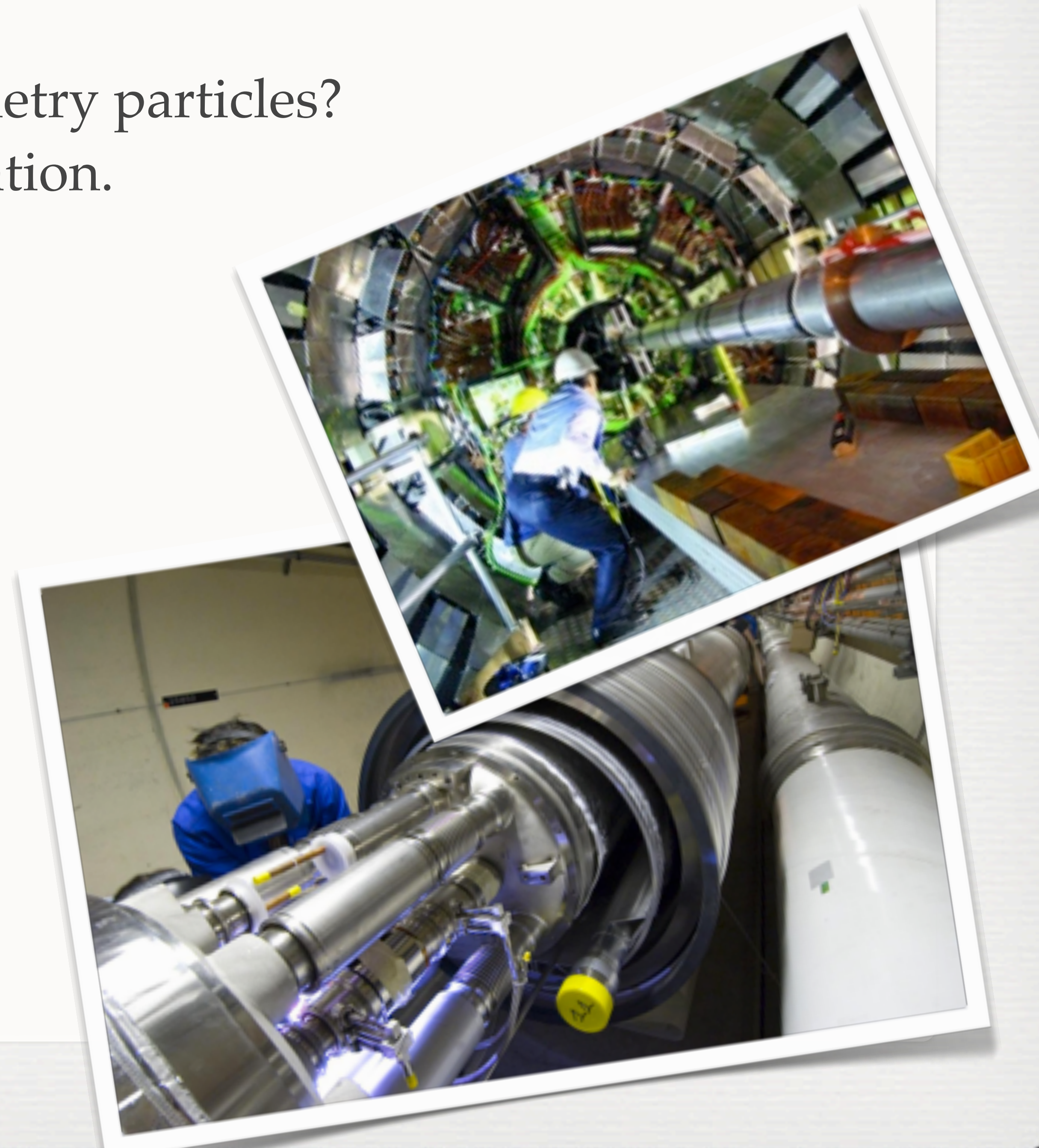
  if the Standard Model is correct.
- The direct searches from LEP exclude the SM Higgs boson below 114.4 GeV/c^2. The analyses at Tevatron exclude 156~177 GeV/c^2.
- Exclusion of Higgs should be calculated by the "**CLs**" statistics method introduced above.
- **LHC's major objectives – find or fully exclude the SM Higgs, and look for any possible new physics scenarios.**

It's Showtime!

THE LARGE HADRON COLLIDER

THE LHC AT CERN

- The LHC is the proton–proton collider at CERN, primary physics targets are:
  - The origin of mass, **the Higgs boson**.
  - What is the dark matter!? Supersymmetry particles?
  - Matter versus antimatter: the *CP* violation.
  - Understanding of the space and time.
  - and many others...
- 7 experiments:
  - General purpose: **ALTAS** and **CMS**.
  - *B*-physics: **LHCb**.
  - Heavy ion: **ALICE**.
  - Forward physics: **TOTEM** and **LHCf**.
  - Monopole search: **MoEDAL**.
- Start its 7 TeV (3.5 on 3.5) run since March 2010.



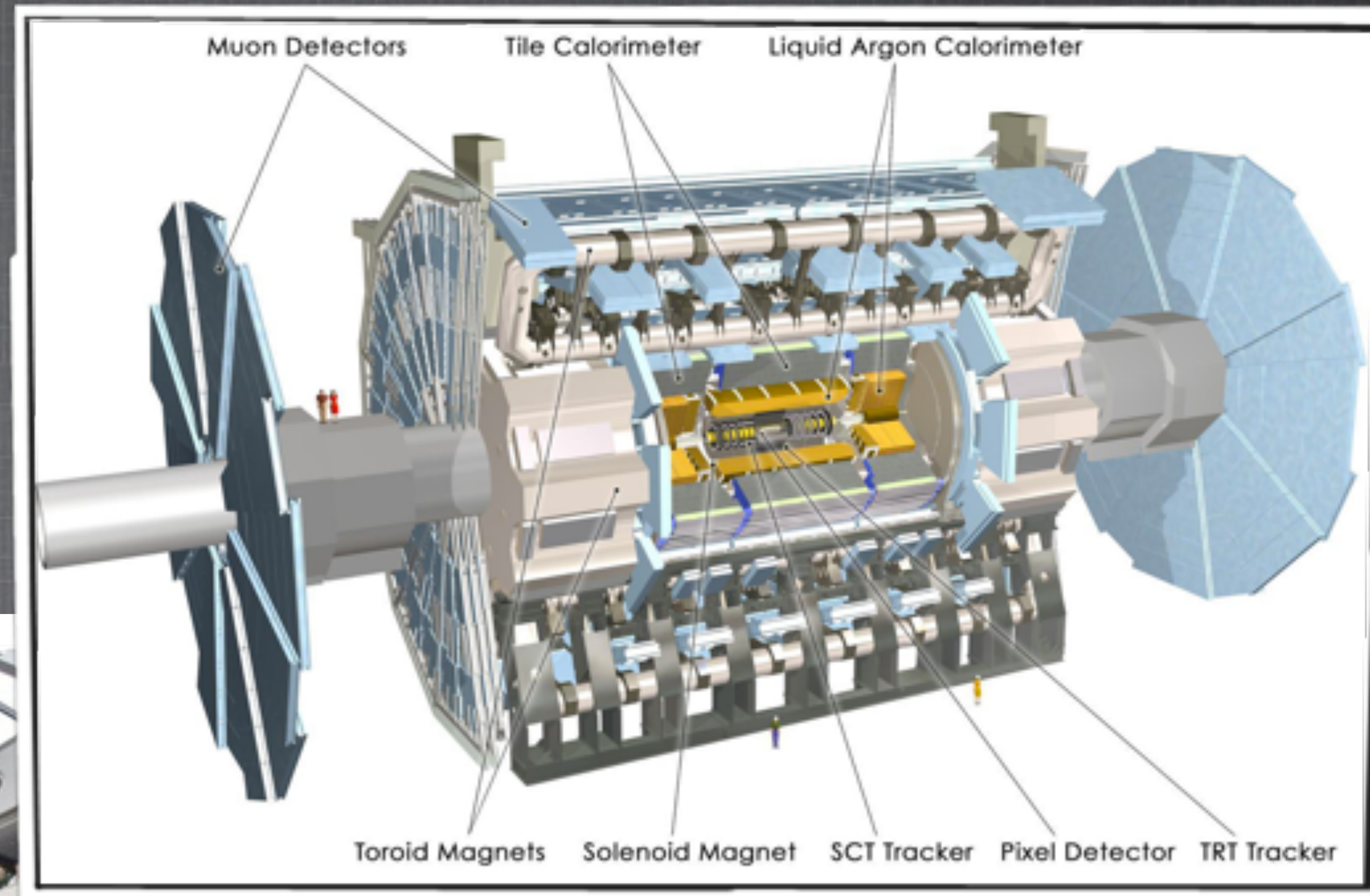
THE DECEMBER 13 EVENT

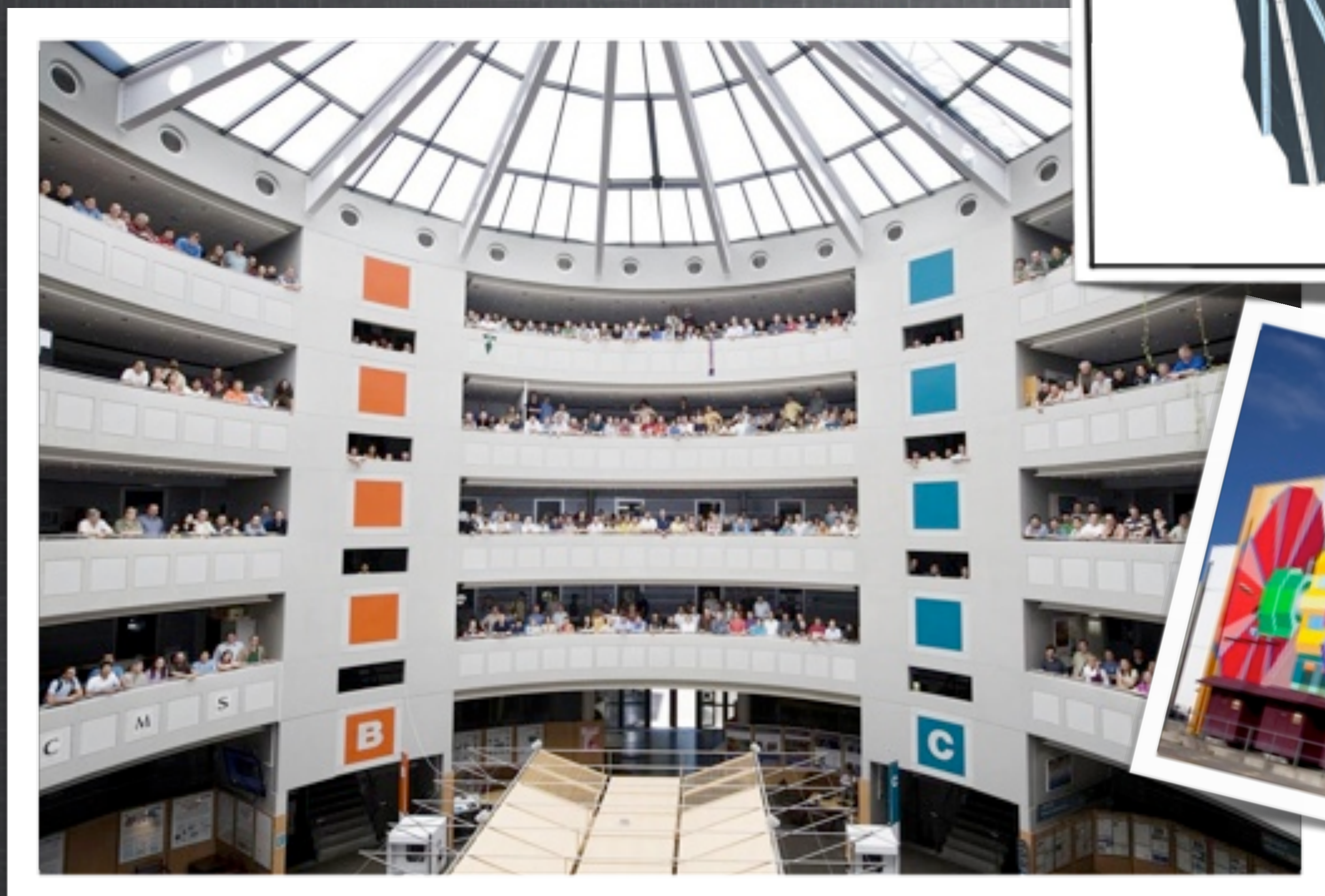
CERN prepared a nice X'mas gift for the particle physicists all over the world.
Atlas and CMS experiments reveal their newest results on Standard Model Higgs searches.

THE ATLAS EXPERIMENT

3000+ scientists and engineers
(including ~1000 students)
from 174 institutes in 38 countries.

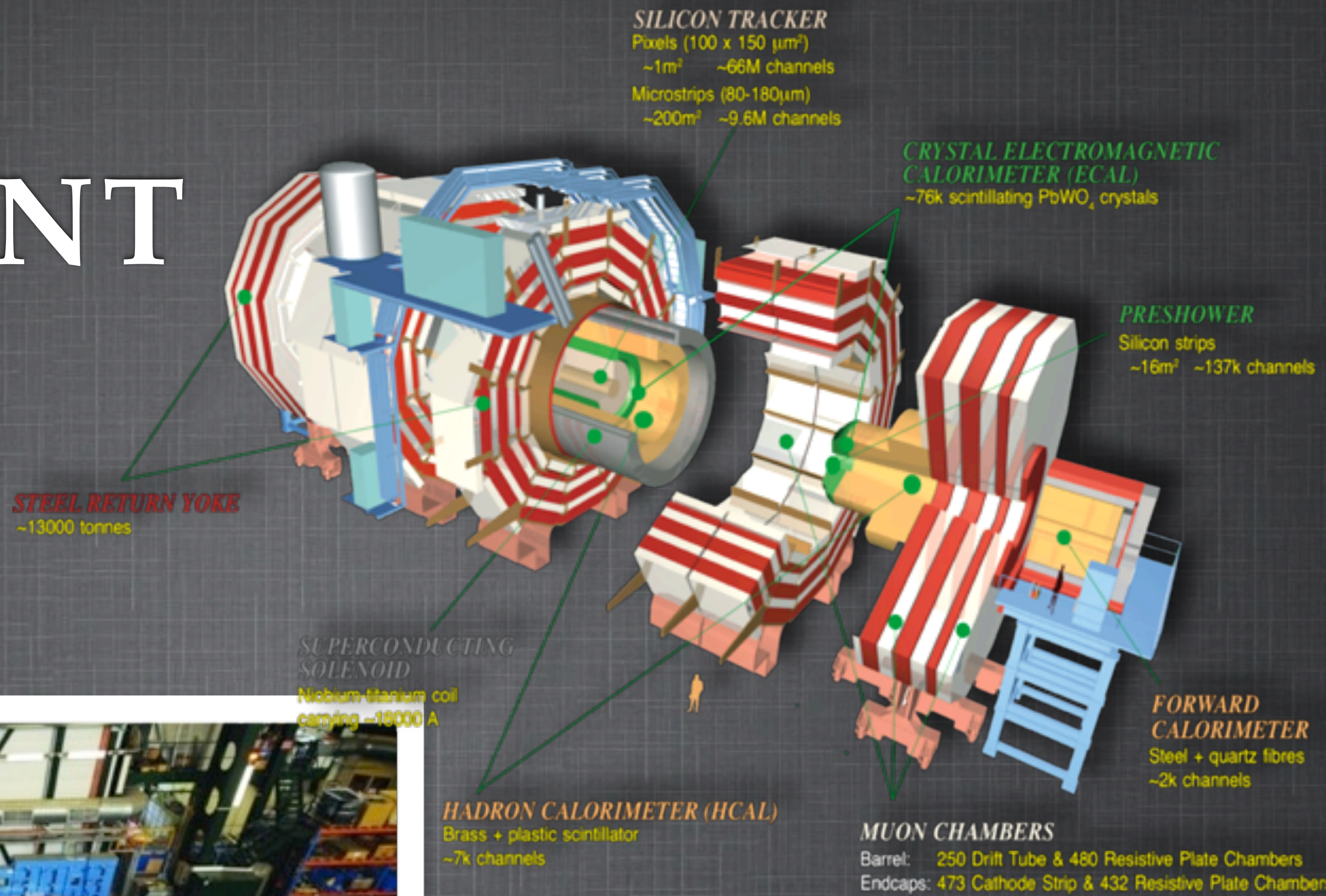
From Taiwan:
Academia Sinica

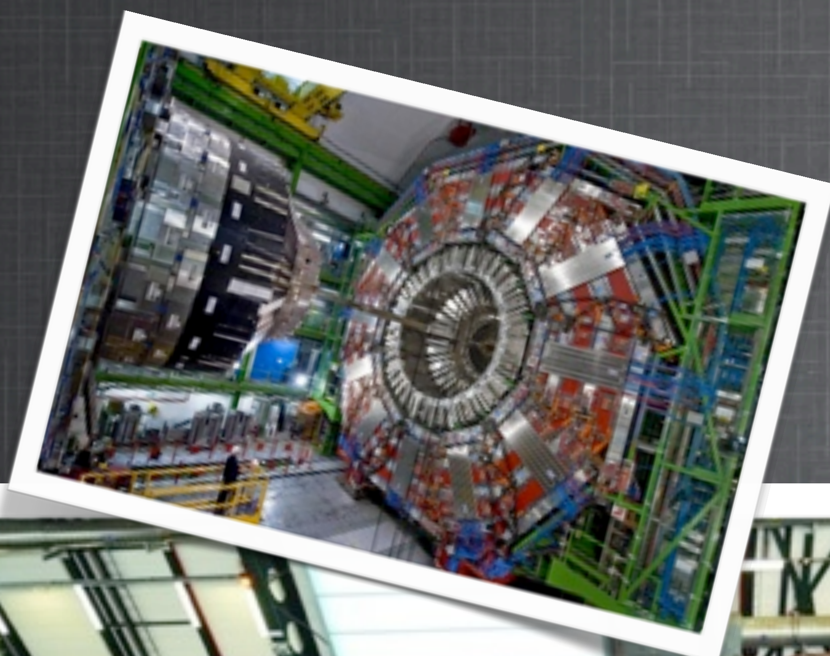




The colorful
Atlas control building

THE CMS EXPERIMENT

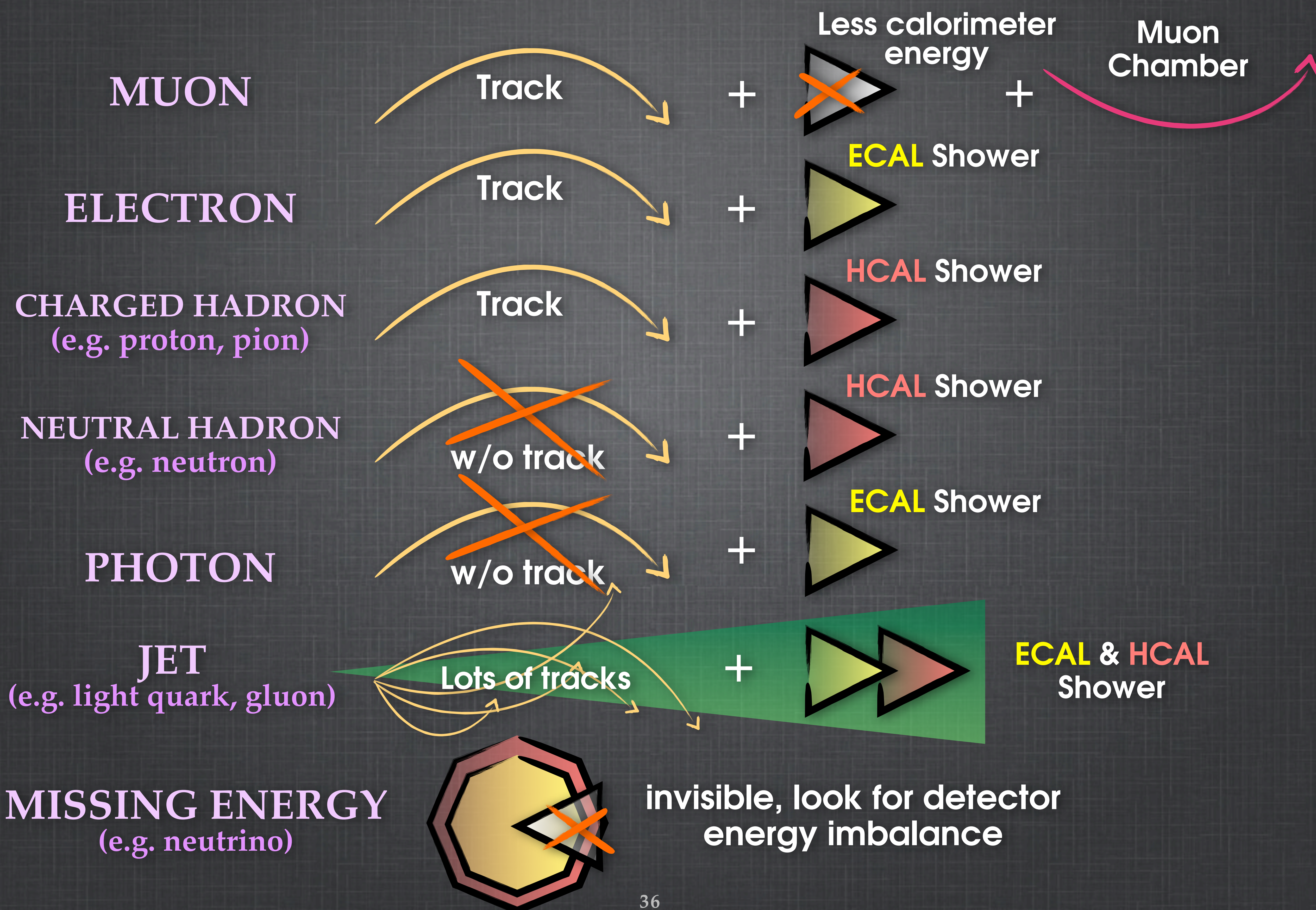


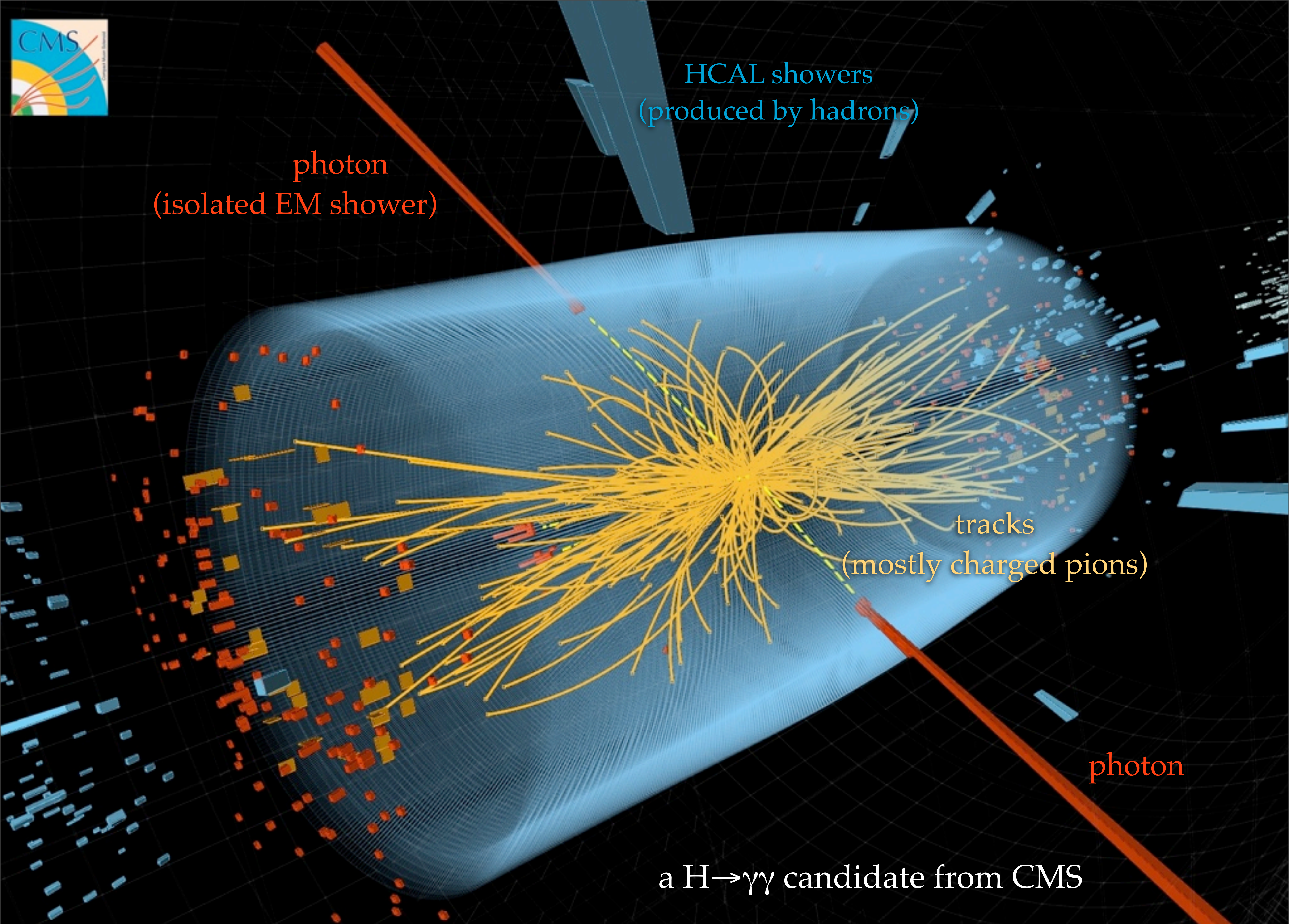


3000+ scientists and engineers
(including ~840 students)
from 173 institutes in 40 countries.

From Taiwan:
NTU and NCU

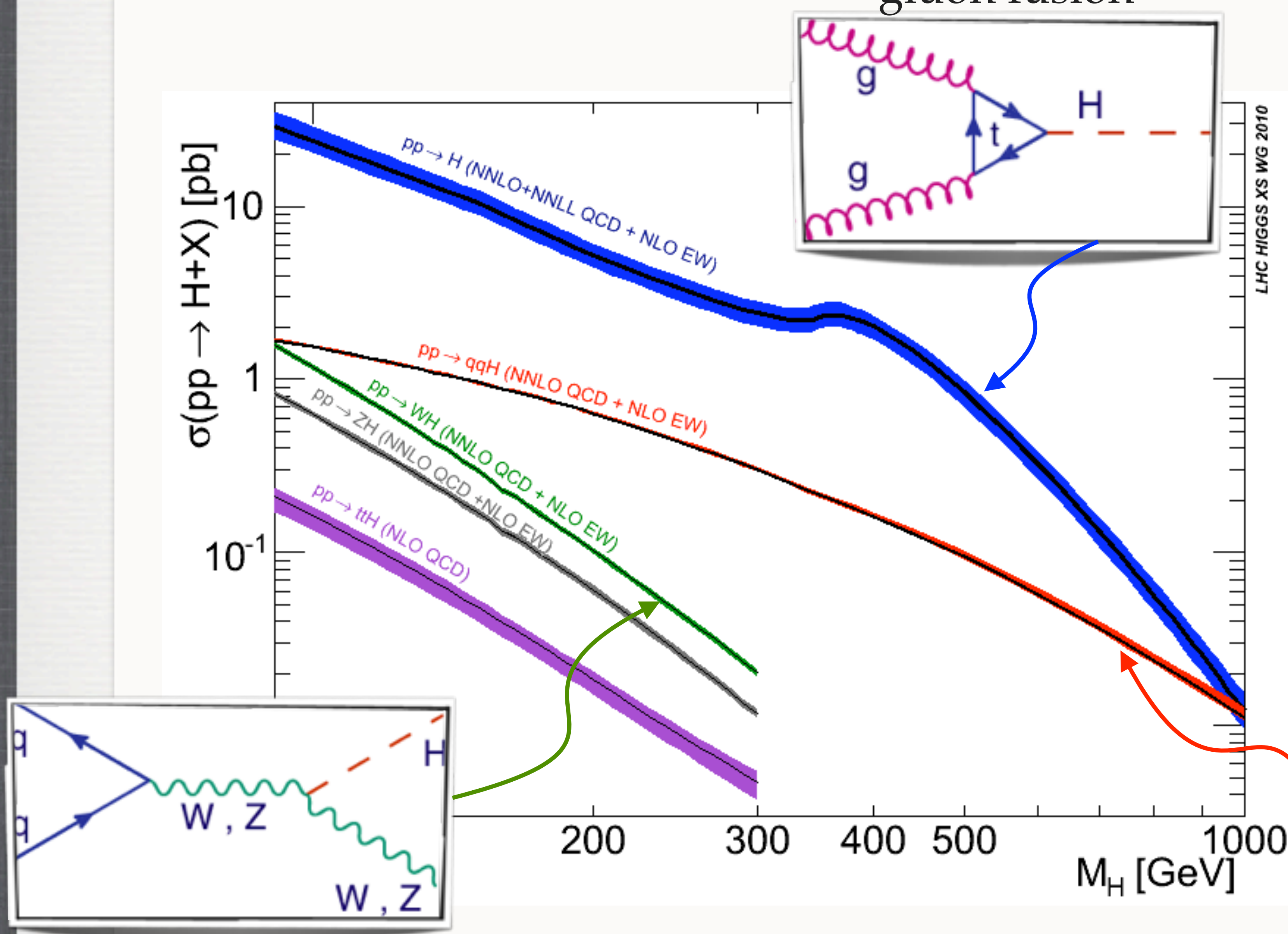
PARTICLE DETECTION



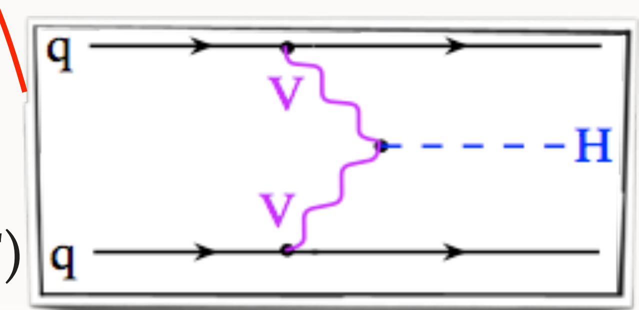

HCAL showers
(produced by hadrons)
photon
(isolated EM shower)
tracks
(mostly charged pions)
photon
a H→γγ candidate from CMS

HIGGS PRODUCTIONS AT LHC

gluon fusion



Higgs-strahlung (VH)



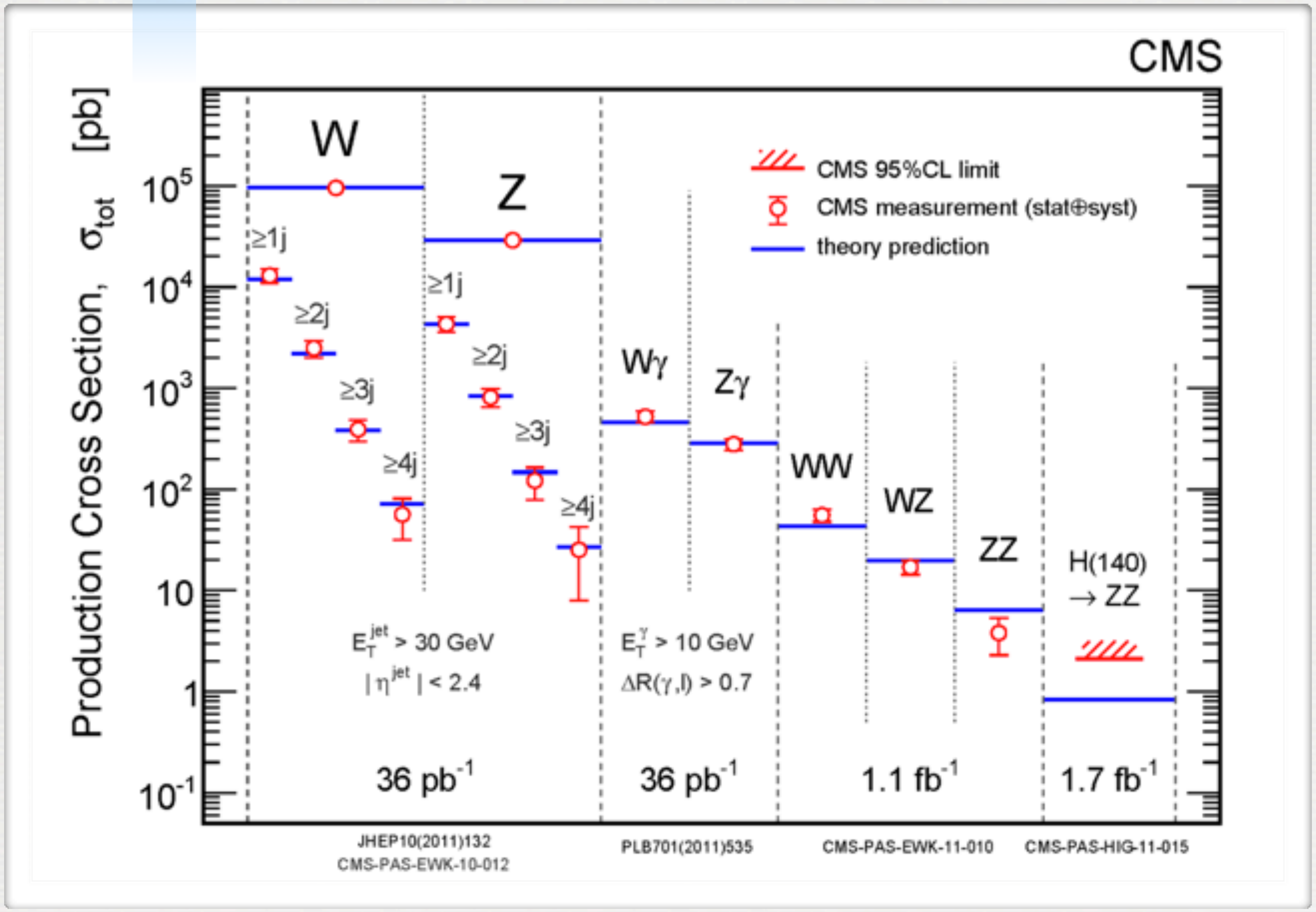
vector-boson fusion (VBF)

- Production rate of Higgs at LHC is roughly 10x to the Tevatron. Overall S/N is better in principle.
- Still dominated by gluon fusion, while the vector-boson fusion and Higgs-strahlung channels are also very useful.

THE CHALLENGE

dijet 10^8 pb

Huge background from non-Higgs processes



<u>*Events produced in 2011 per Experiment*</u>

dijet ~500,000,000,000

W ~500,000,000

Z ~150,000,000

WW ~200,000

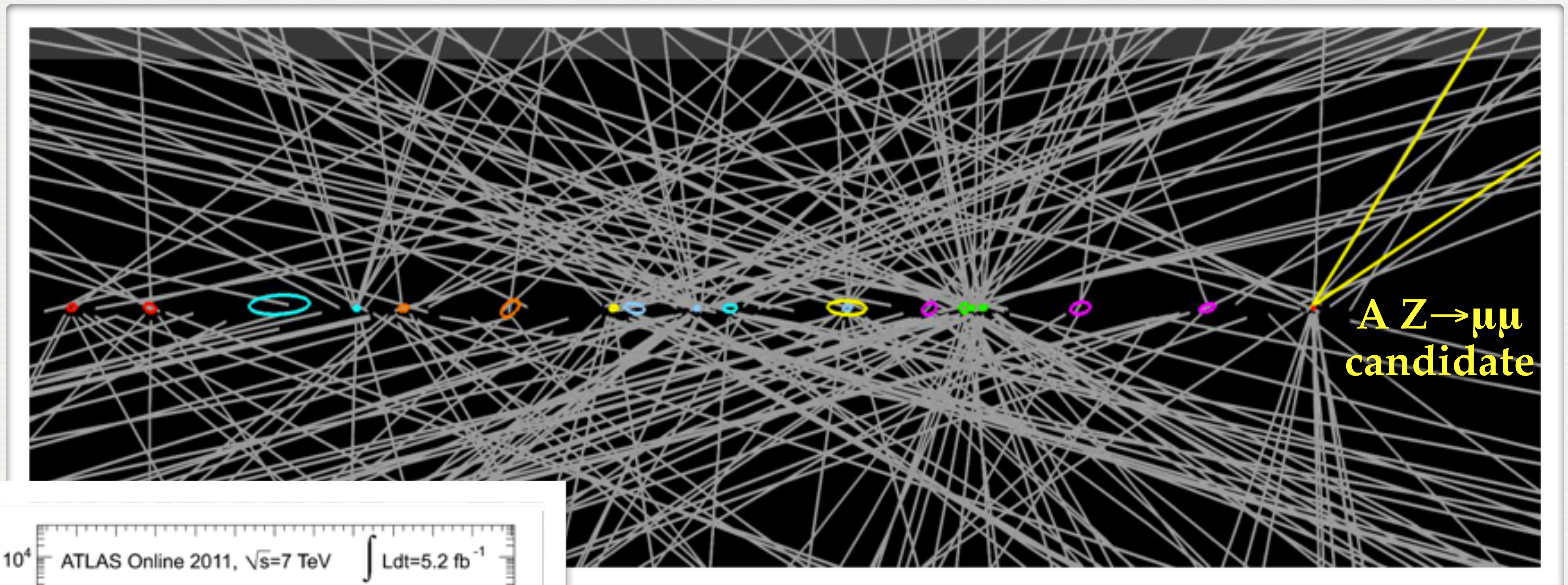
ZZ ~35,000

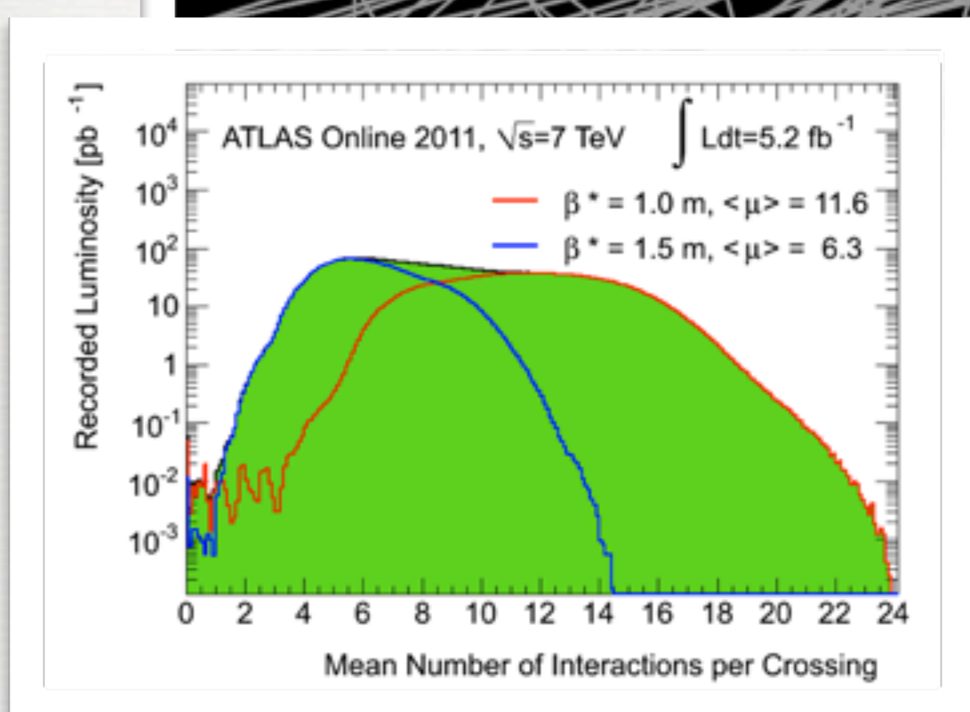
Higgs 5,000~50,000
(~100 visible)

The actual Higgs signal is highly dependent on its mass.

THE CHALLENGE

An Atlas event with 20 reconstructed vertices

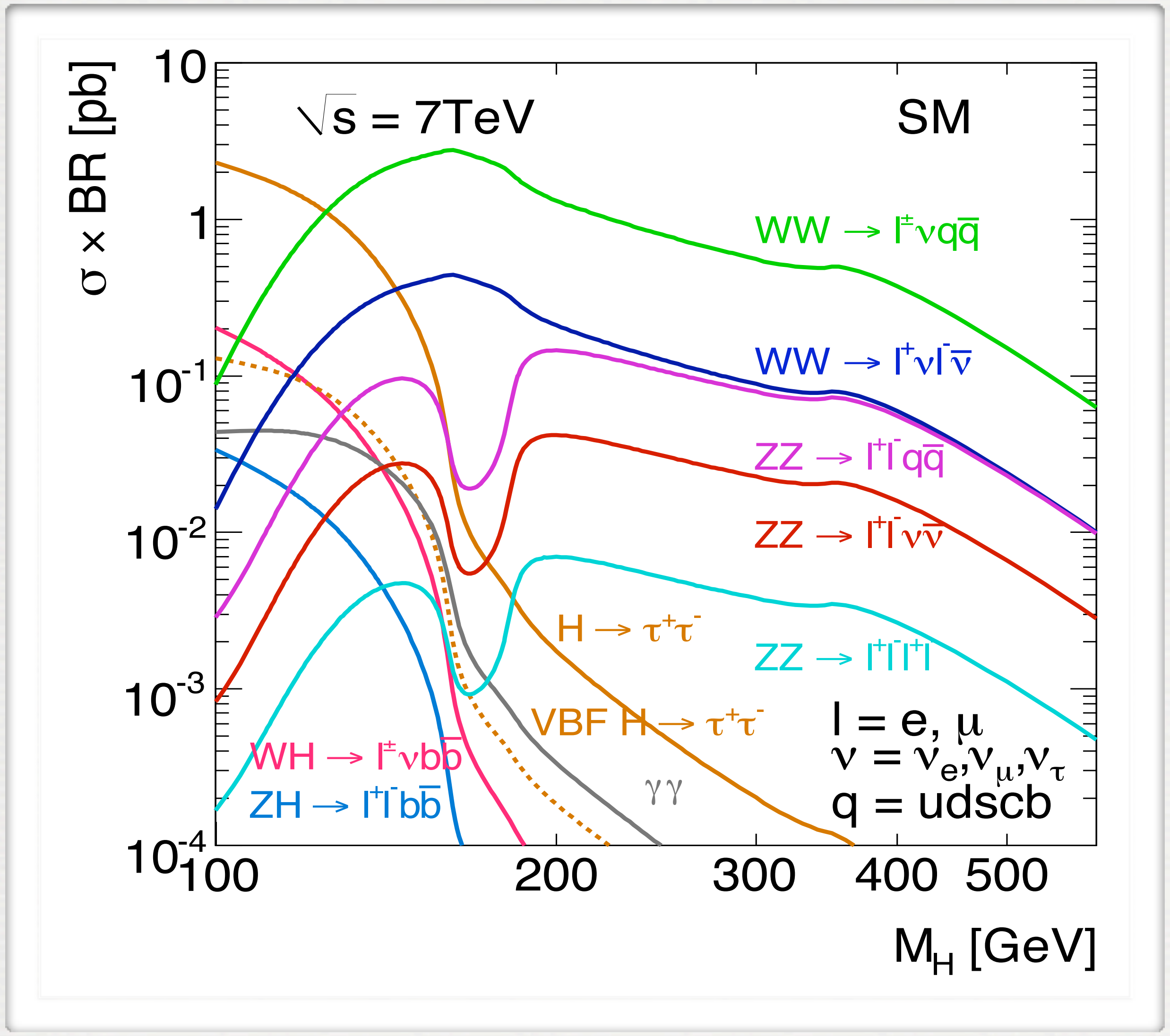




= 20x actual resolution (just for visibility)

The detectors record more than one interaction in a single snapshot. Number of interactions per crossing is high for higher luminosity. One has to pick up the right event from the right interaction. This is price to pay.

HIGGS DECAY CHANNELS



Channels with higher sensitivities

$H \rightarrow \gamma\gamma$ for M(H)<130 GeV/c²

- good mass resolution
- acceptable S/N (comparing to bb)

$H \rightarrow ZZ^{(*)} \rightarrow 4l$ for 125<M(H)<300 GeV/c²

- good mass resolution
- best S/N

$H \rightarrow WW^{(*)} \rightarrow 2l2\nu$ for 125<M(H)<180 GeV/c²

- larger production rate
- good S/N

$H \rightarrow ZZ \rightarrow 2l2\nu$ for M(H)>300 GeV/c²

- distinct signature (Z + missing energy)
- good S/N

ATLAS ANALYSES

channel	mass range (GeV/c^2)	Luminosity (fb^{-1})	Number of signals	S/N
$H \to \gamma\gamma$	110~150	4.9 NEW	~70	~0.02
$H \to \tau\tau \to 2l + \nu$	110~140	1.1	~0.8	~0.02
$H \to \tau\tau \to l + had.$	100~150	1.1	~10	~0.005
$HW/Z \to bbl(l)$	110~130	1.1	~6	~0.005
$H \to WW^{(*)} \to l\nu l\nu$	110~300	2.1 NEW	~20 (130 GeV)	~0.3
$H \to ZZ^{(*)} \to 4l$	110~600	4.8 NEW	~2.5 (130 GeV)	~1.5
$H \to ZZ \to 2l2\nu$	200~600	2.1	~20 (400 GeV)	~0.3
$H \to ZZ \to 2l2q$	200~600	2.1	2~20 (400 GeV)	0.05~0.5
$H \to WW \to l\nu 2q$	240~600	1.1	~45 (400 GeV)	0.001

Three channels (which have highest sensitivities in the low mass region) were updated on Dec/13, the rest analyses were shown at the summer conferences already.

NEW new results, shown today

CMS ANALYSES

ALL NEW

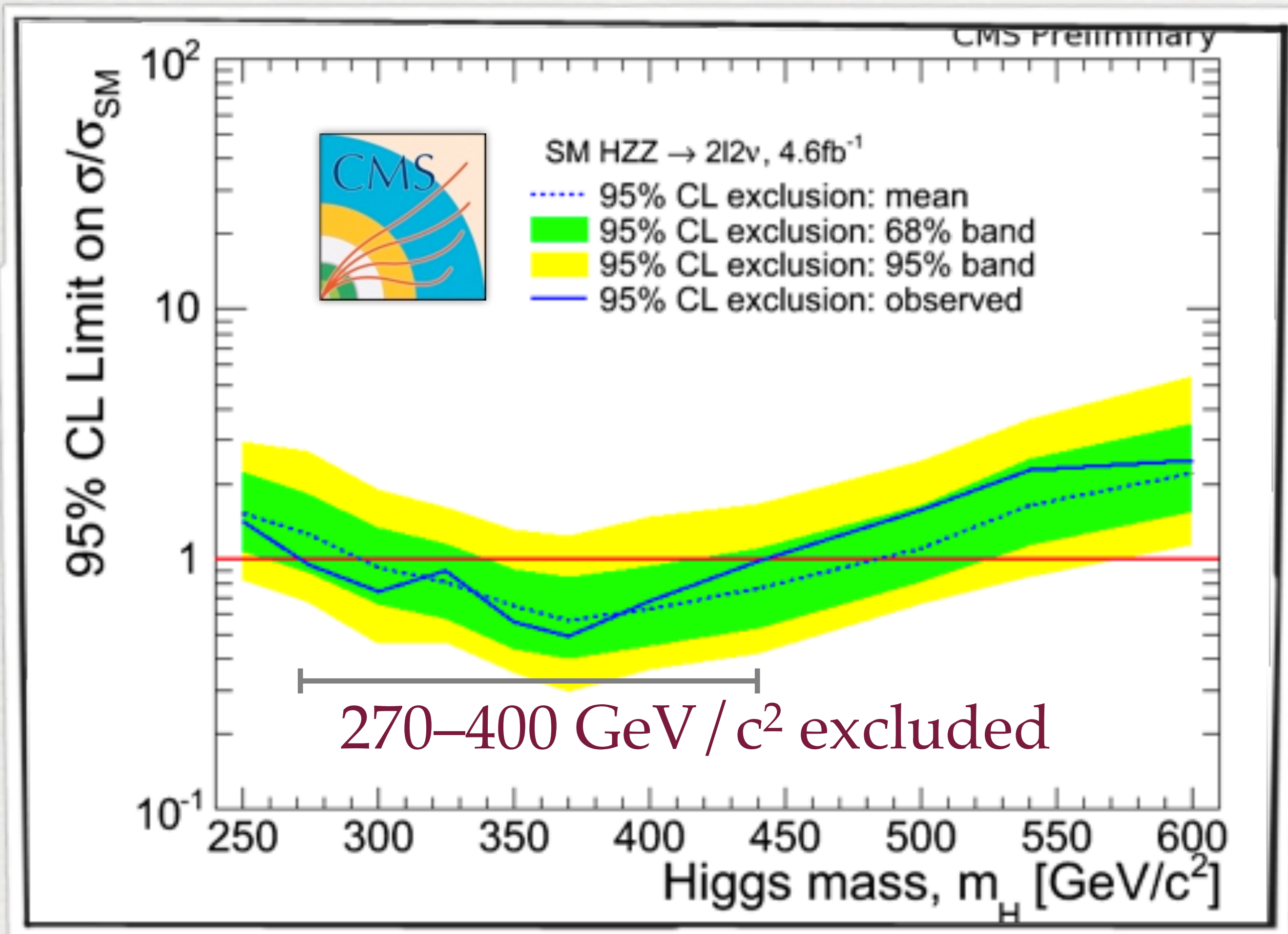
channel	mass range (GeV/c^2)	sub-channels	mass resolution	Luminosity (fb^{-1})	Document ID
$H\rightarrow\gamma\gamma$	110~150	4	1–3%	4.7	HIG-11-030
$H\rightarrow\tau\tau$	110~145	9	20%	4.6	HIG-11-031
$H\rightarrow bb$	110~135	5	10%	4.7	HIG-11-029
$H\rightarrow WW\rightarrow l\nu l\nu$	110~600	5	20%	4.6	HIG-11-024
$H\rightarrow ZZ\rightarrow 4l$	110~600	3	1–2%	4.7	HIG-11-025
$H\rightarrow ZZ\rightarrow 2l2\tau$	190~600	8	10–15%	4.7	HIG-11-028
$H\rightarrow ZZ\rightarrow 2l2\nu$	250~600	2	7%	4.6	HIG-11-027
$H\rightarrow ZZ\rightarrow 2l2q$	130~164/200~600	6	3%	4.6	HIG-11-026

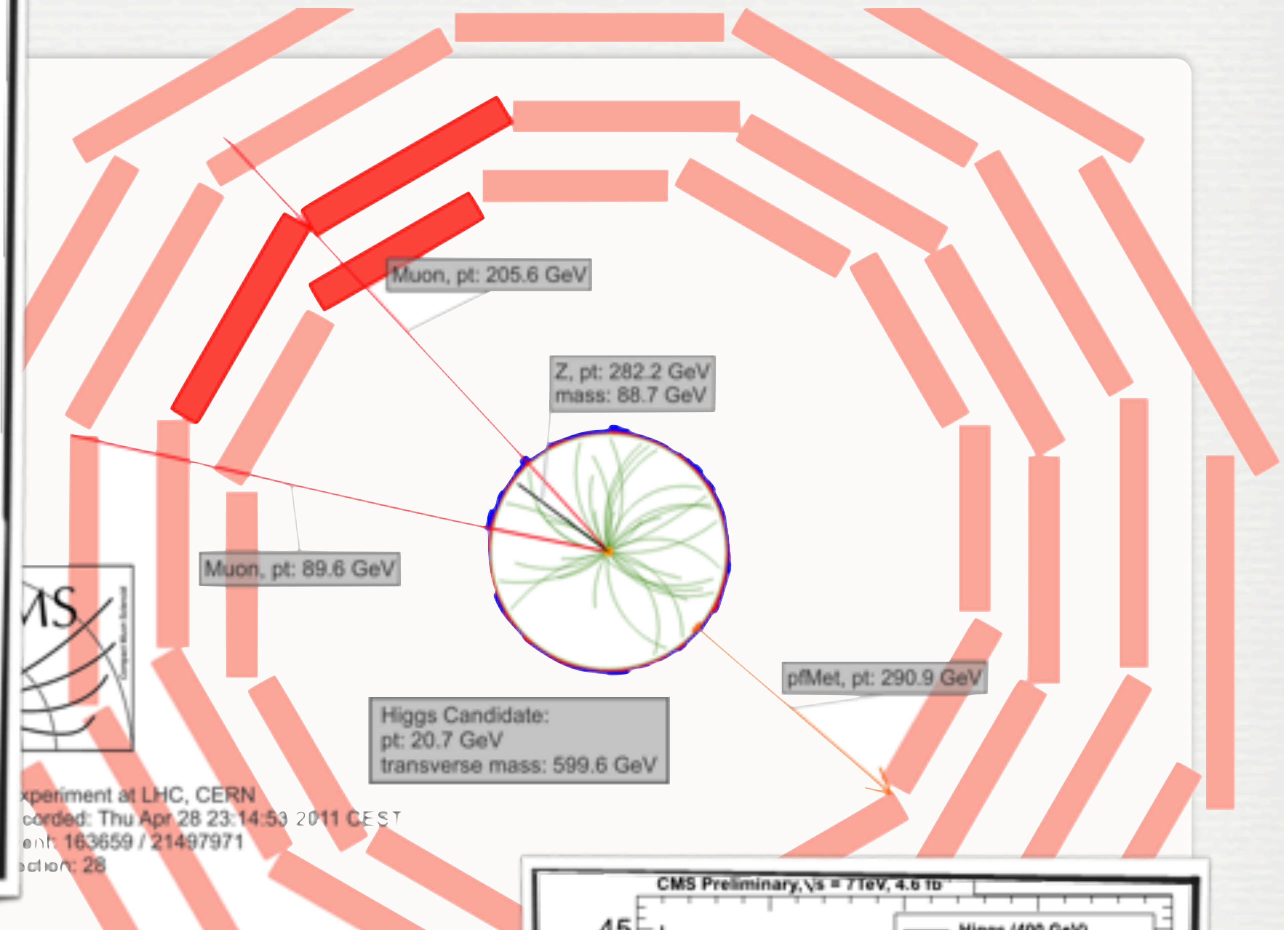
Channels with best mass resolution: $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ^{(*)}\rightarrow 4l$

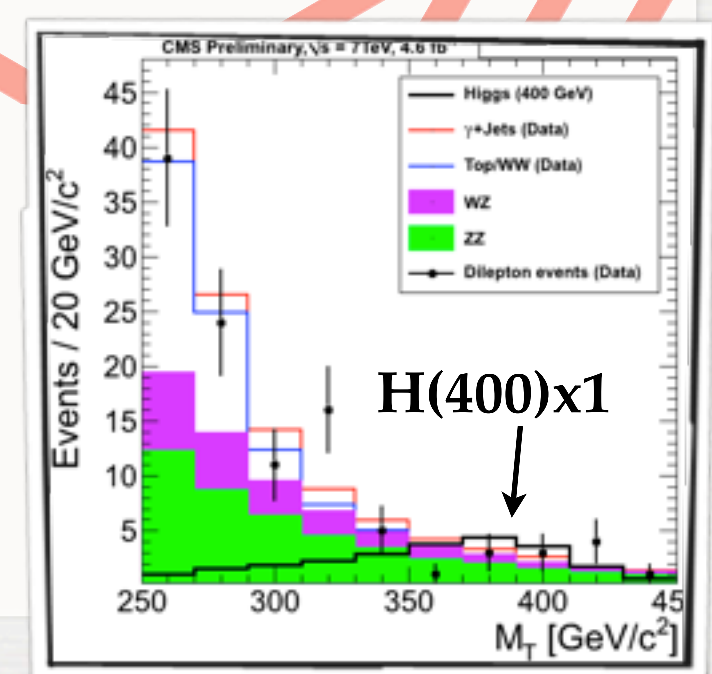
All eight analyses were shown on Dec/13; CMS combination documented in HIG-11-032.

Ready for tons of LHC results?

HIGH MASS: H→ZZ→2l2ν

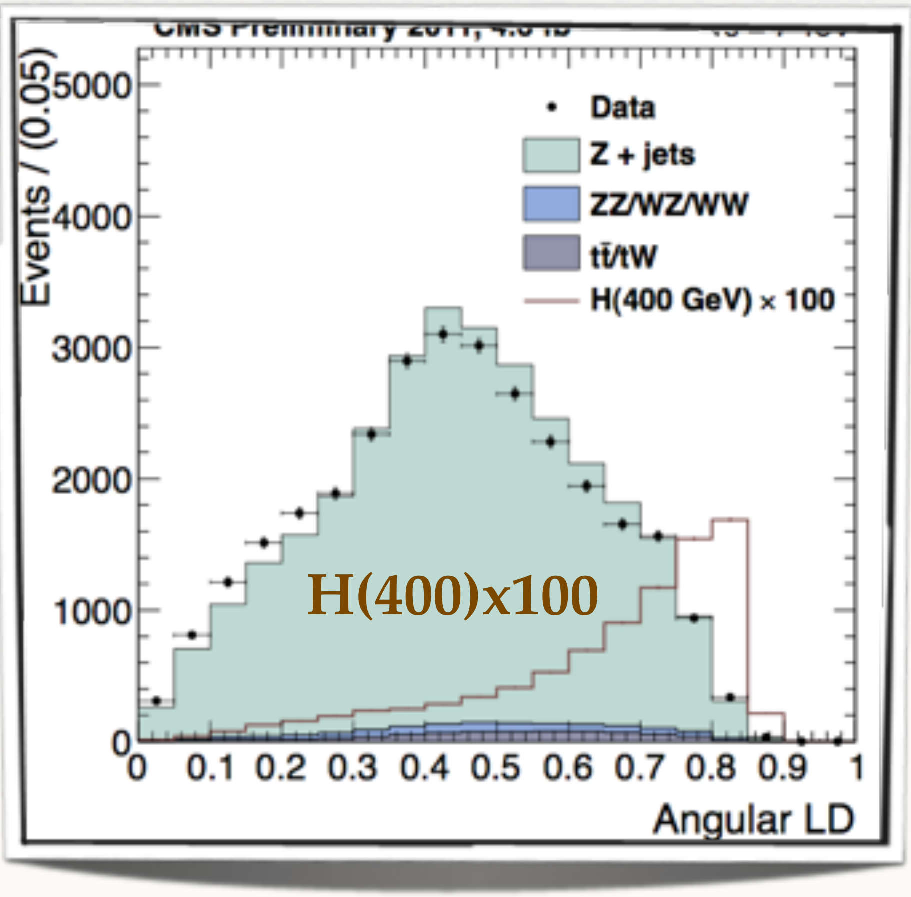


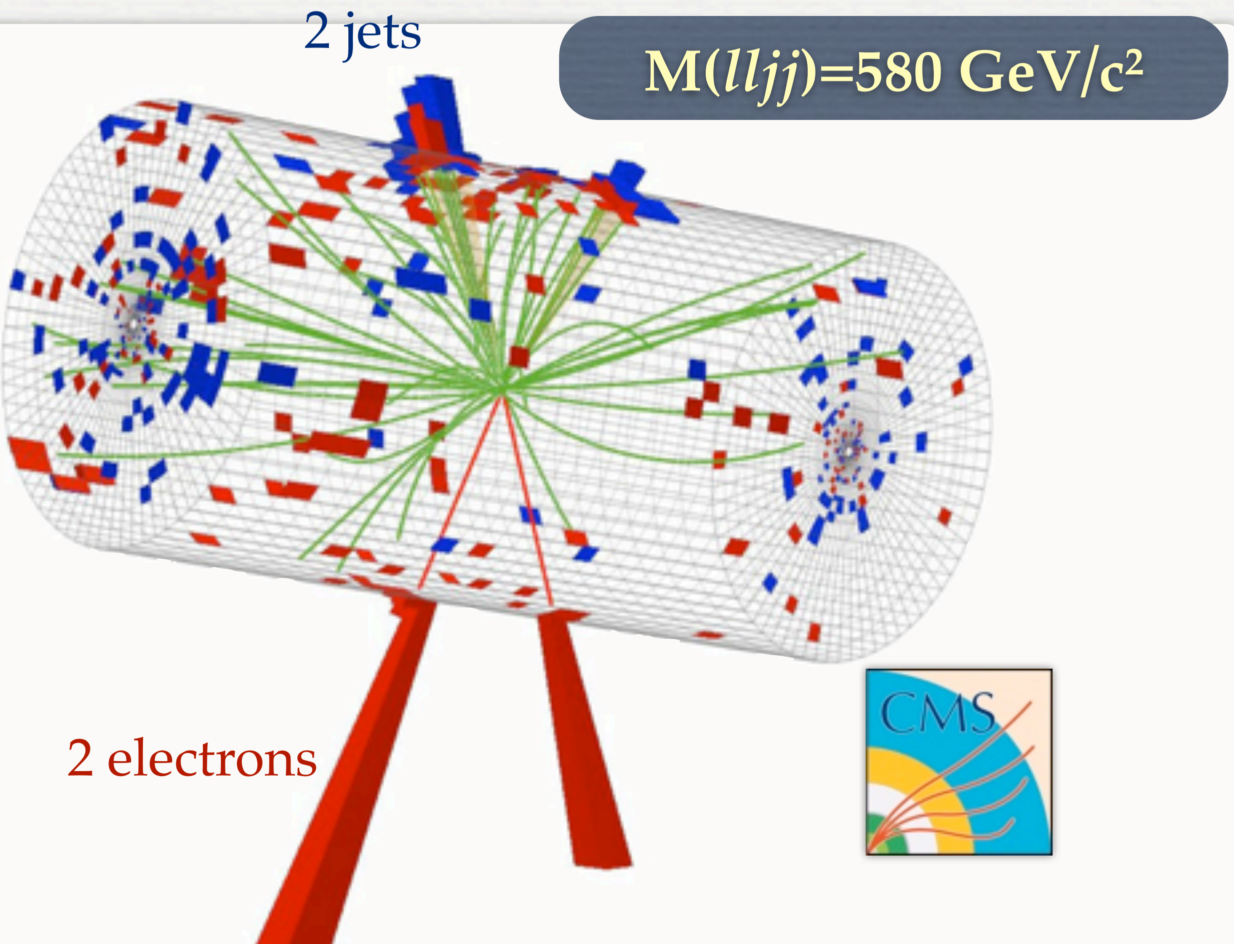




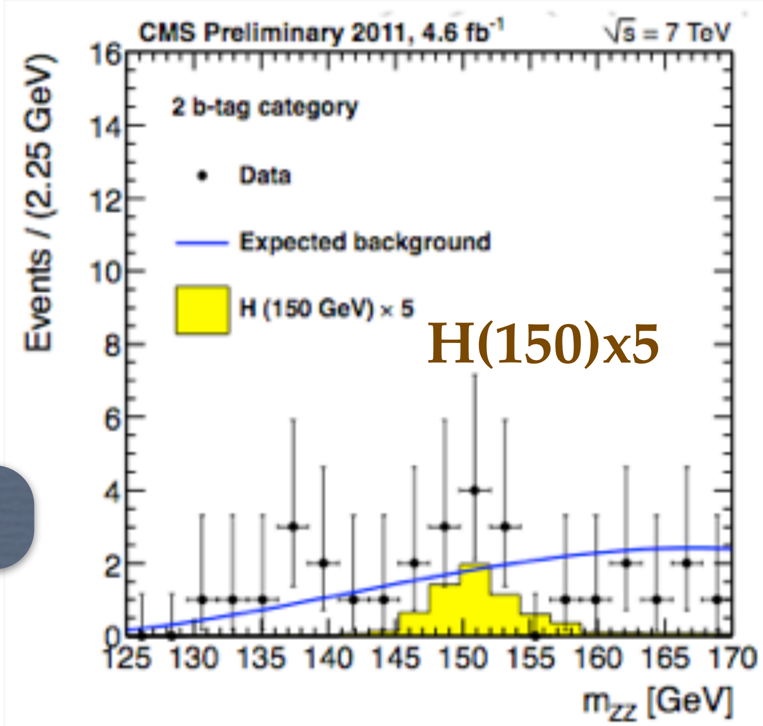
- Find a clean Z candidate + extra missing energy.
- Major background sources: Z+jets, top pair, WW.
- Reconstruct the transverse mass, M_T.
- M_T shape analysis improves the sensitivity by 10%.

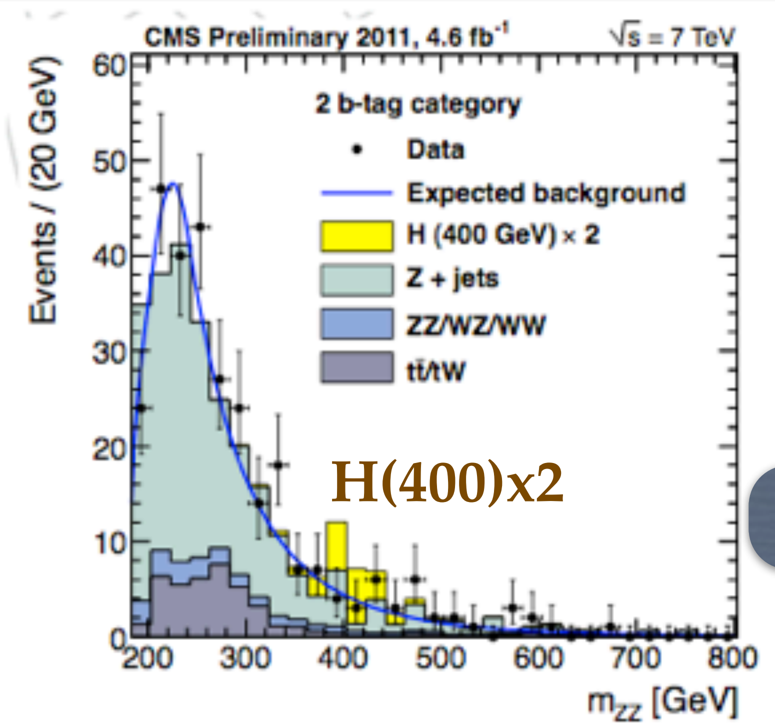
HIGH+LOW MASS: H→ZZ→2l2q





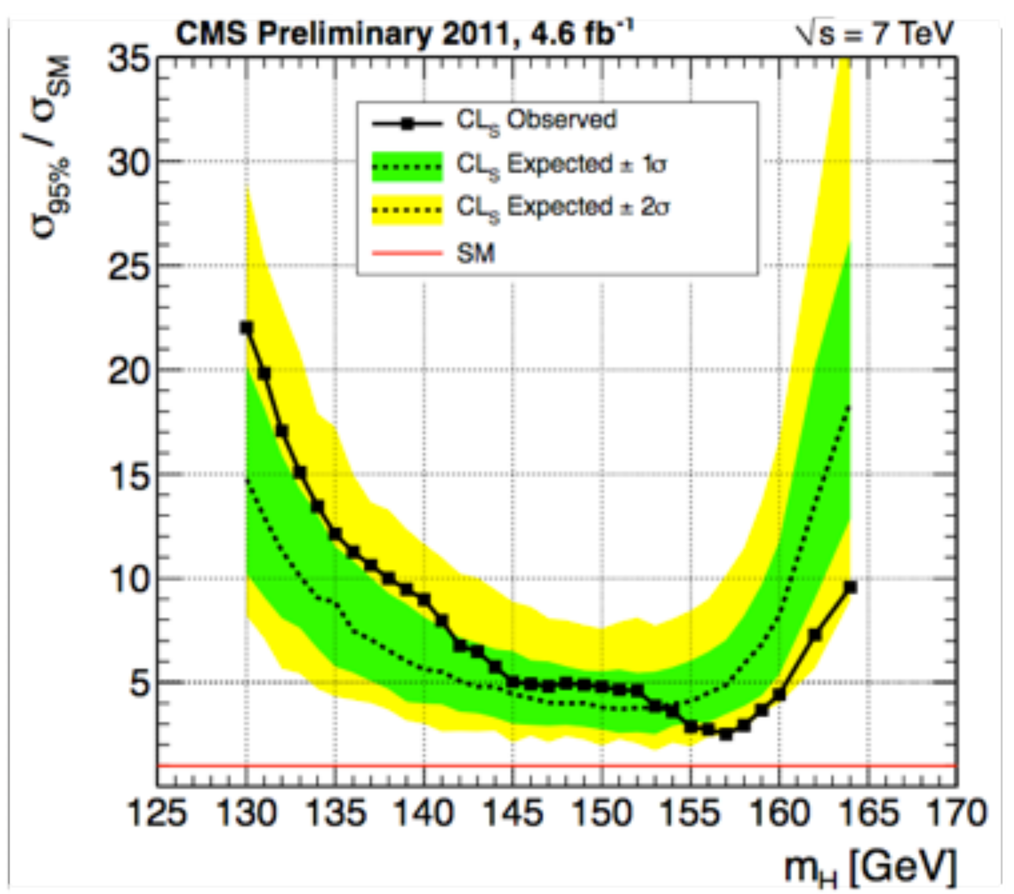
- Find a clean Z→ll candidate + Z→2jets candidate, no missing energy.
- Categorized by presence of 0,1,2 b-jets
- Major background sources: Z+jets.
- Use scaler Higgs assumption in an angular likelihood discriminant.
- Background normalized to data sideband.

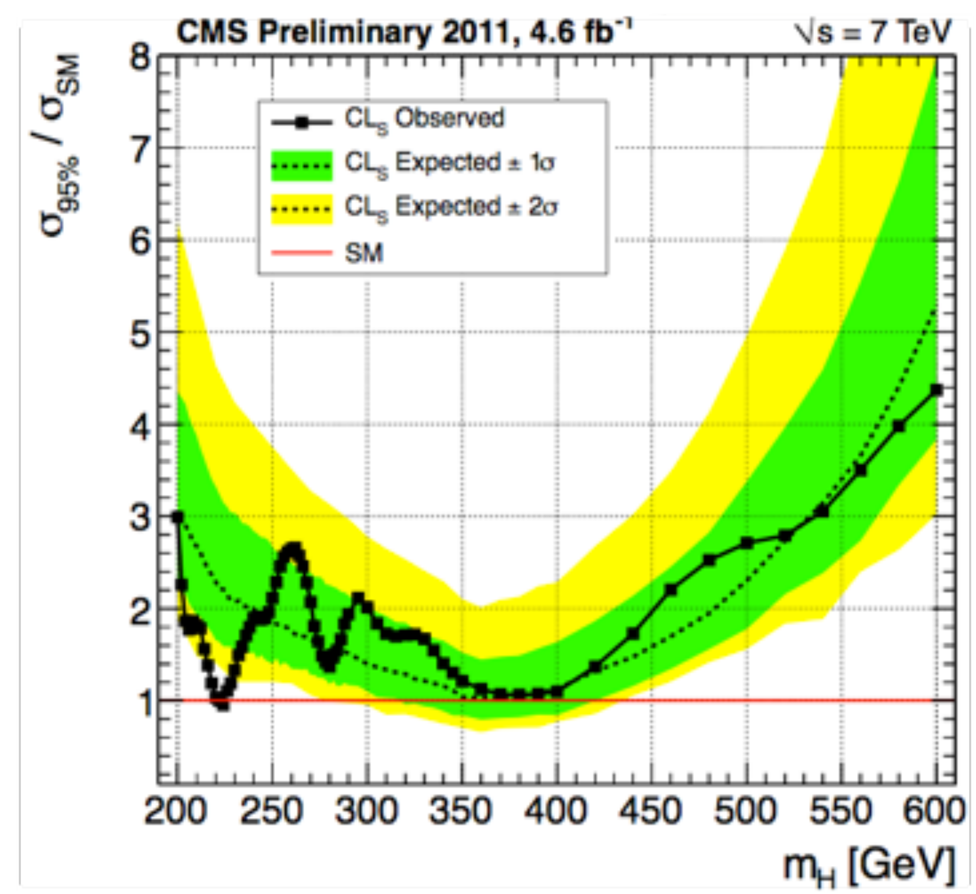




Low Mass

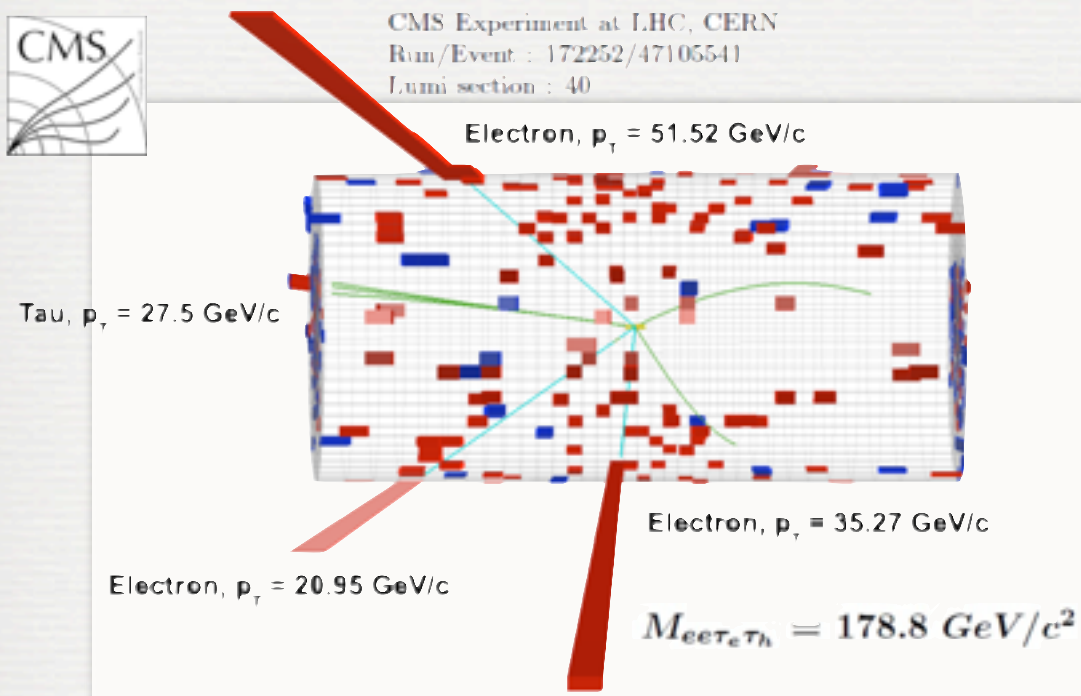
High Mass

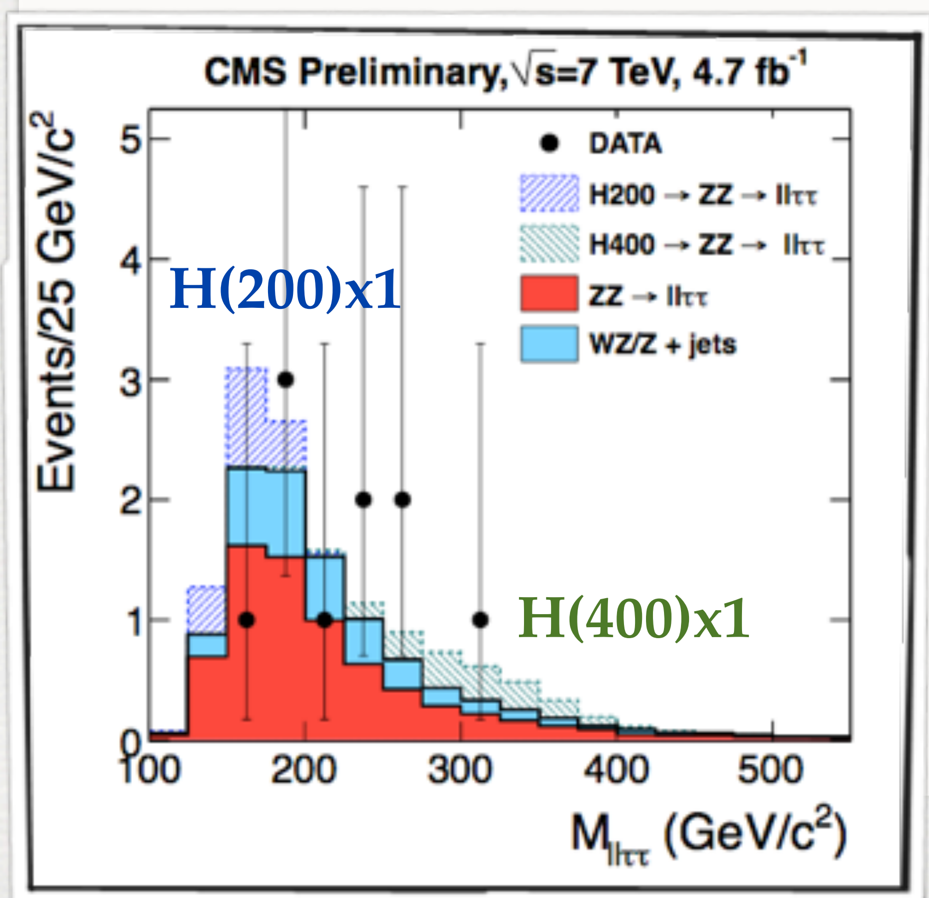


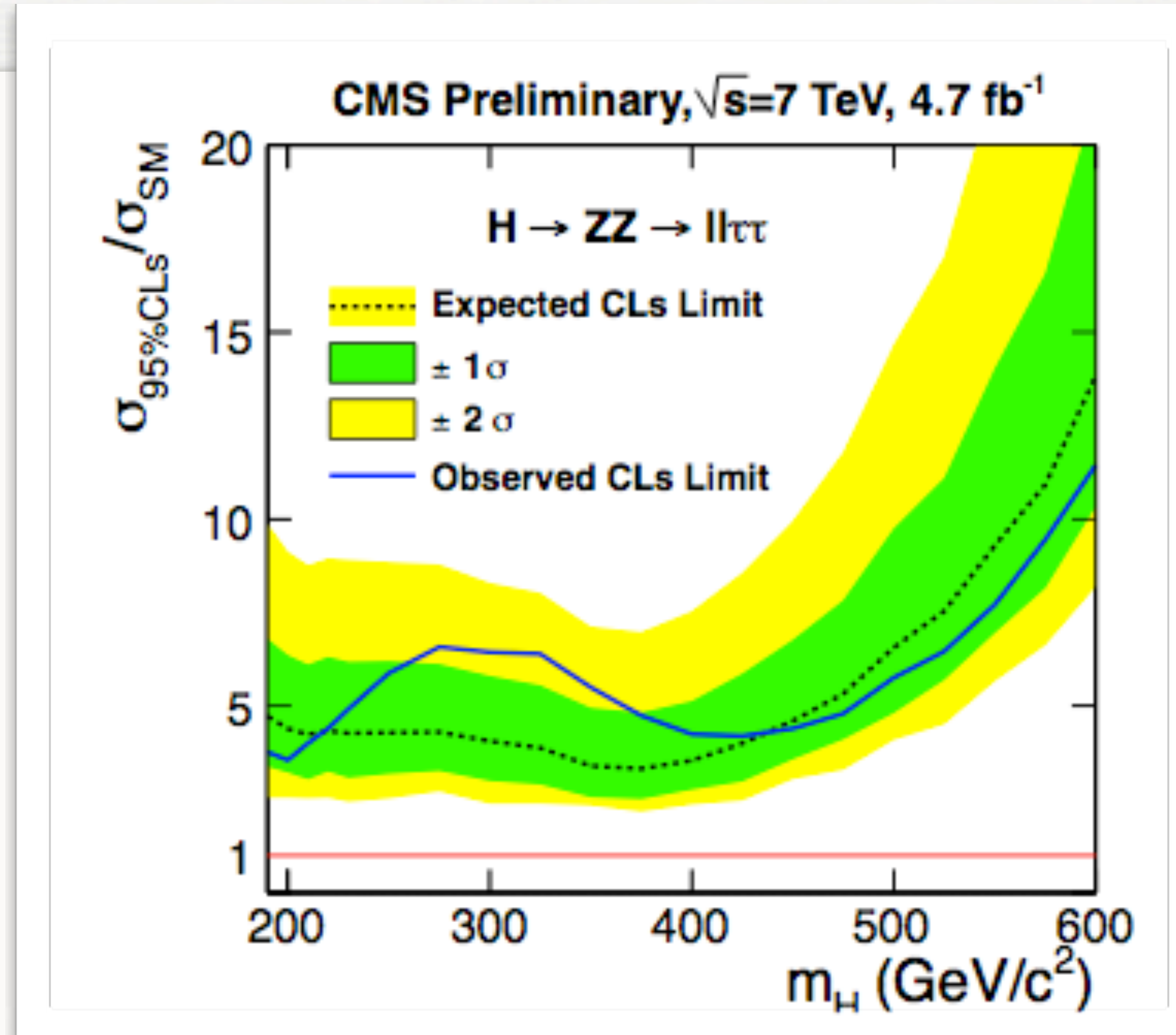


Exclude nothing yet, to be combined with other channels.

HIGH MASS: $H \to ZZ \to 2l2\tau$

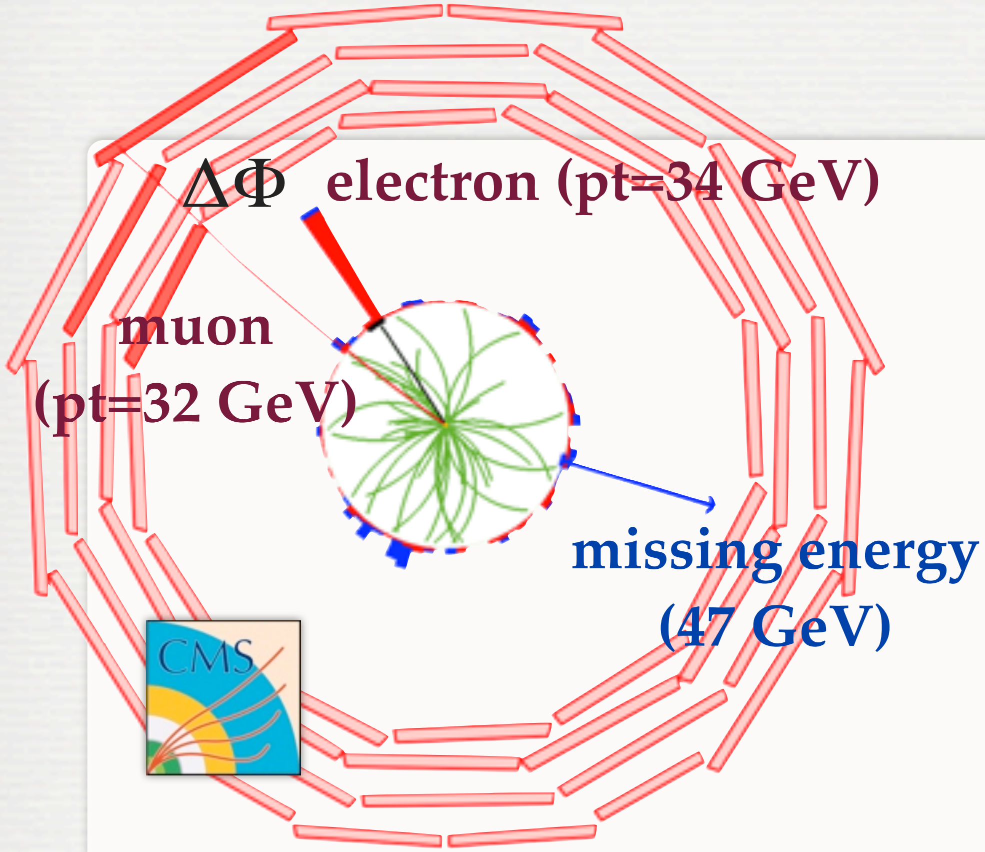


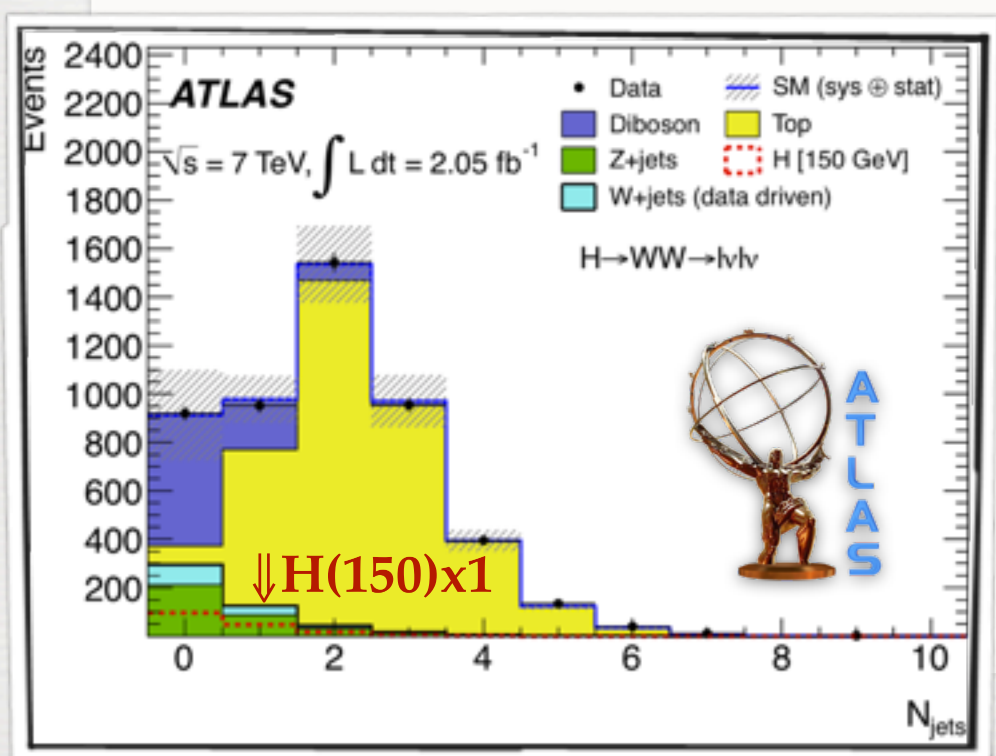




10 observed events, 10.2 expected background. Background shapes are taken from MC simulation and normalized to the values obtained using data-driven techniques.

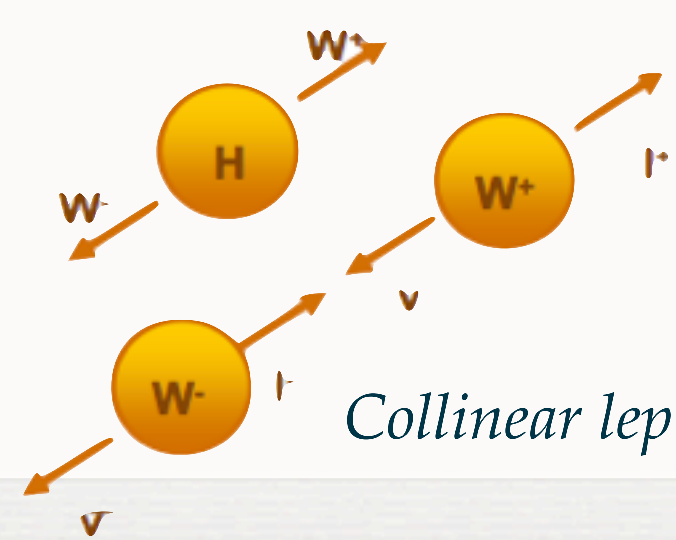
H→WW→2l2ν





- Only two oppositely charged, isolated leptons and some missing energy.
- With additional 0,1,2 jets from vector-boson-fusion process.
- Scalar Higgs ⇒ small opening angle (ΔΦ) between two charged leptons.
- Two neutrinos in the event, cannot form a mass peak ⇒ a counting experiment.
- Challenge to remove the large backgrounds.

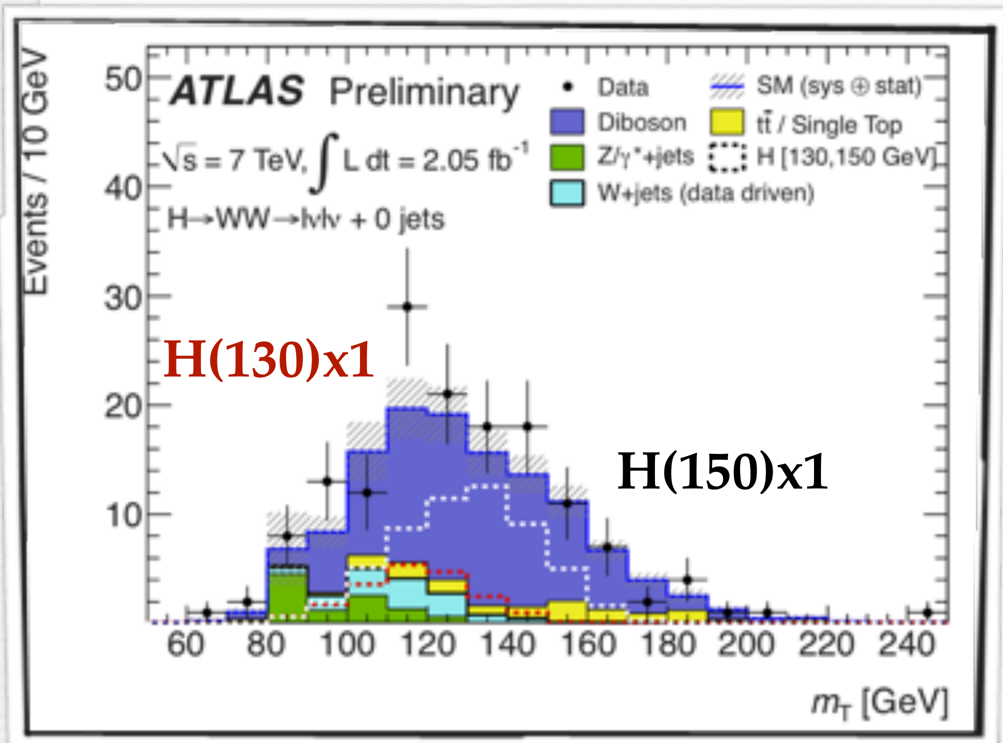
Large background from ttbar/WW/Z+jets.

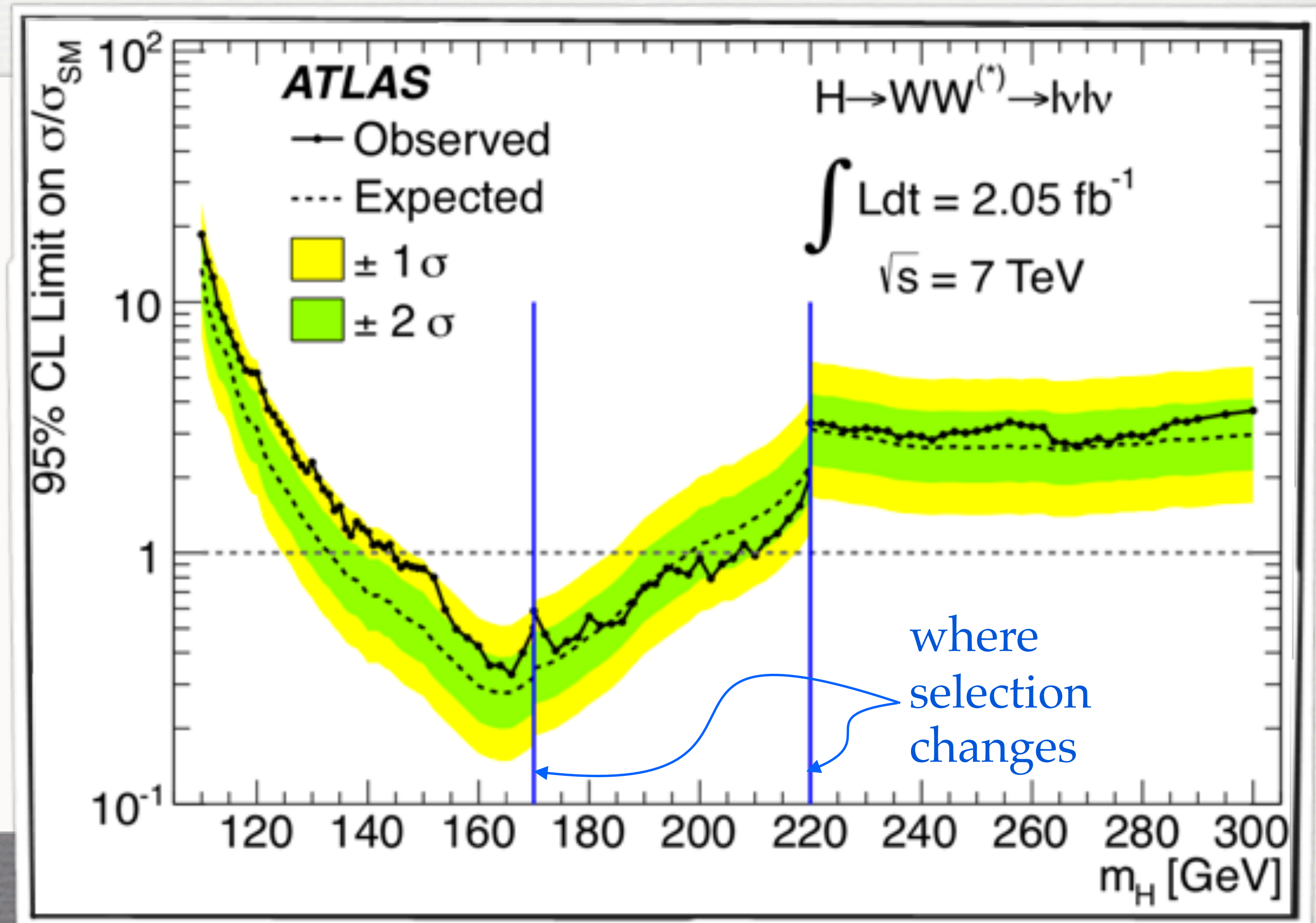


Collinear leptons

ATLAS H→WW→2*l*2ν

transverse mass after full selection



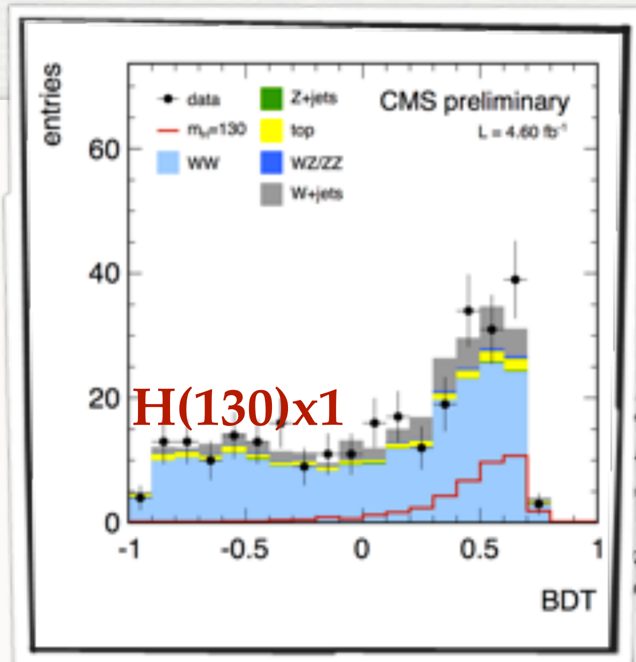


Events with full selection criteria	
Observed data	94 events (10 ee / 42 eμ / 42 μμ)
Expected background	76 ± 11
Expected signal, M(H)=130	19 ± 4

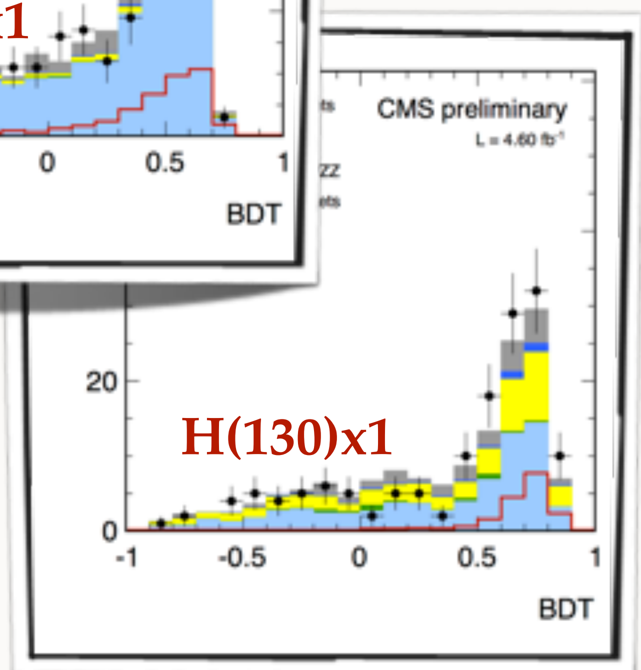
145 < M(H) < 206 GeV / c^2 excluded at 95% C.L.

~1.9σ for M(H)=130 GeV / c^2

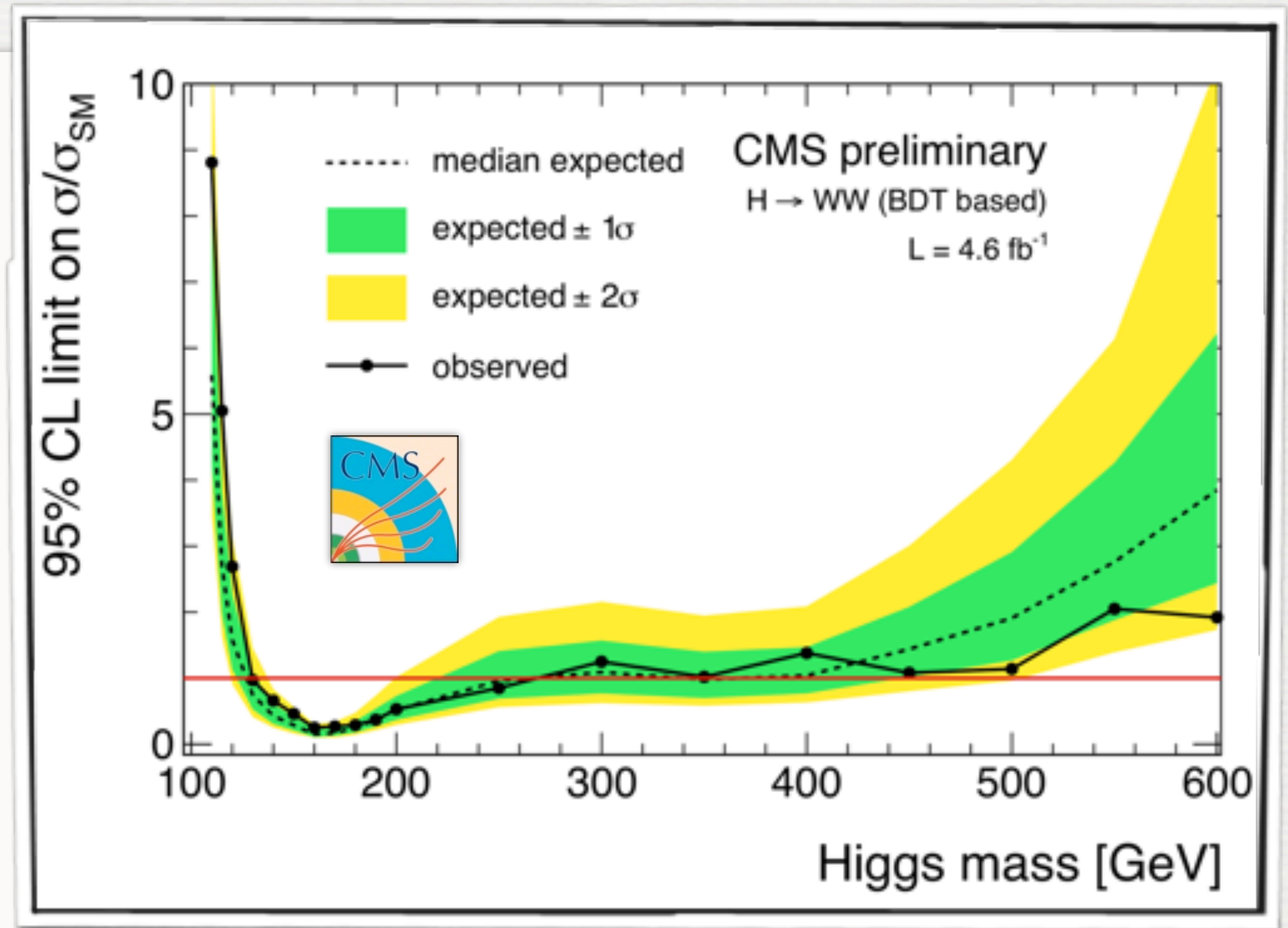
CMS H→WW→$2l2\nu$



opposite favor, 0 jet



opposite favor, 1 jet

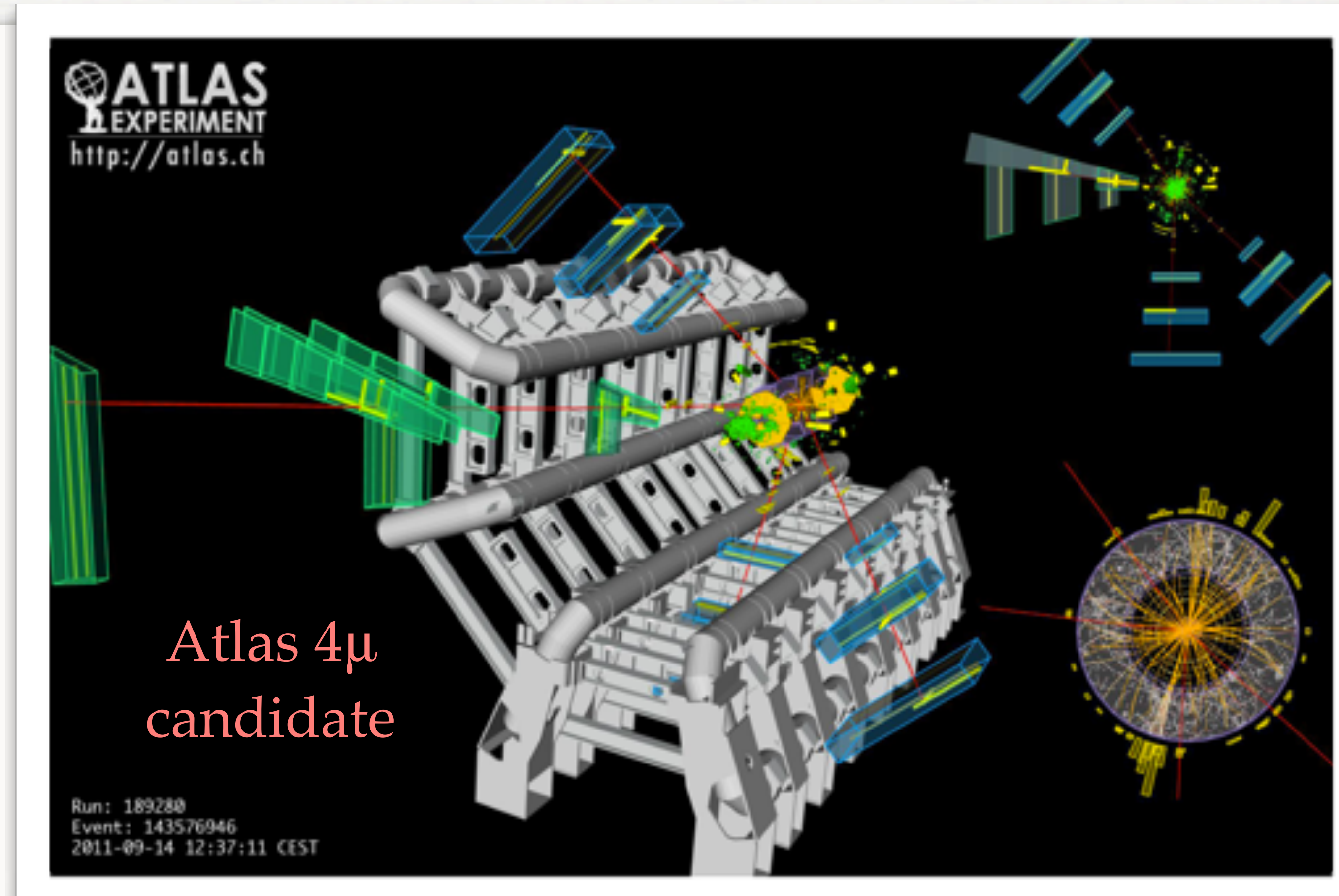


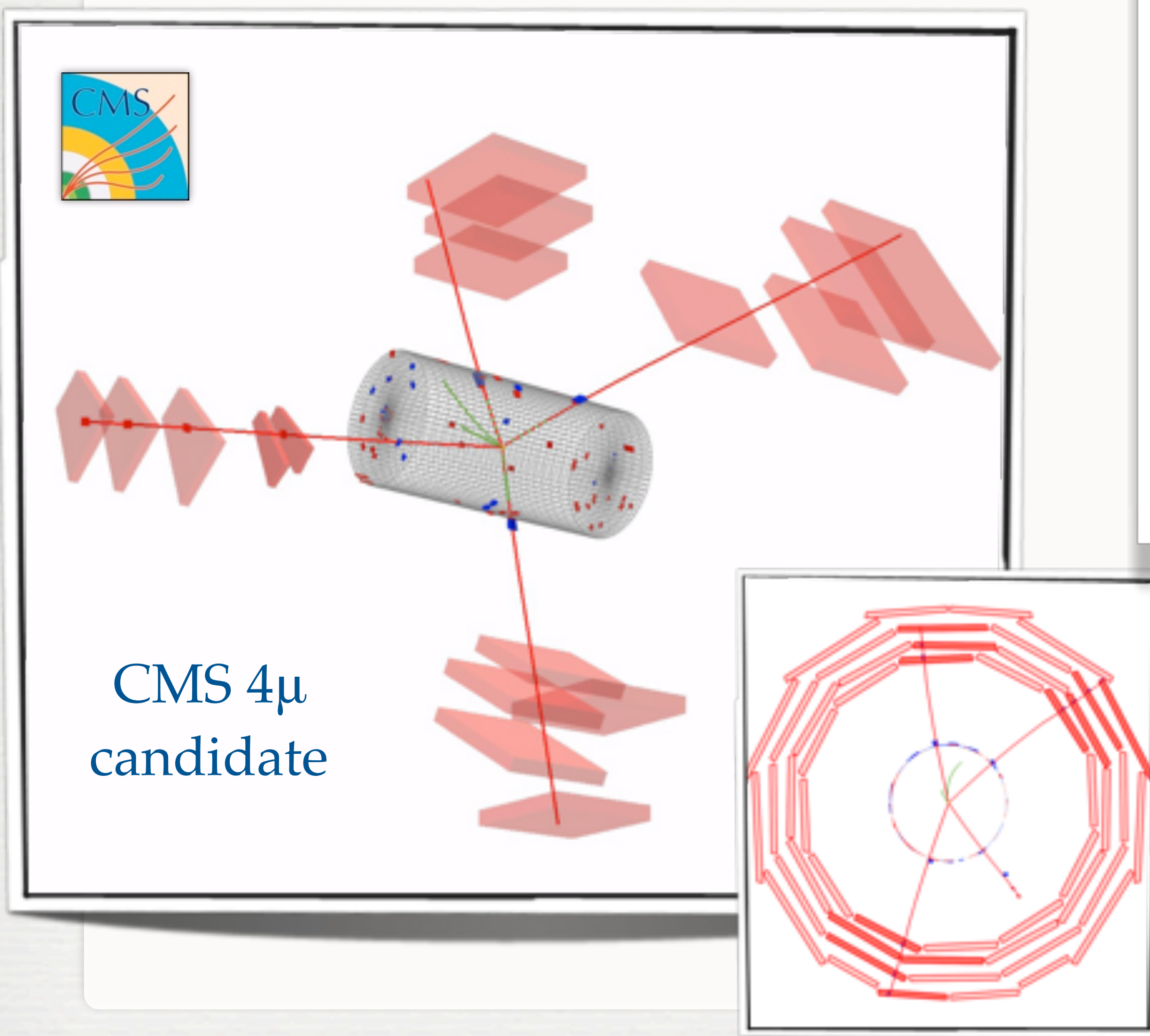
- Two independent studies: cut-based versus BDT(boost decision tree, shown here).
- Categorizing the events with same flavor/opposite flavor/0,1 jet.

$129 < M(H) < 270$ GeV/c^2 excluded at 95% C.L.

THEGOLDEN CHANNEL
$H \to ZZ \to 4l$

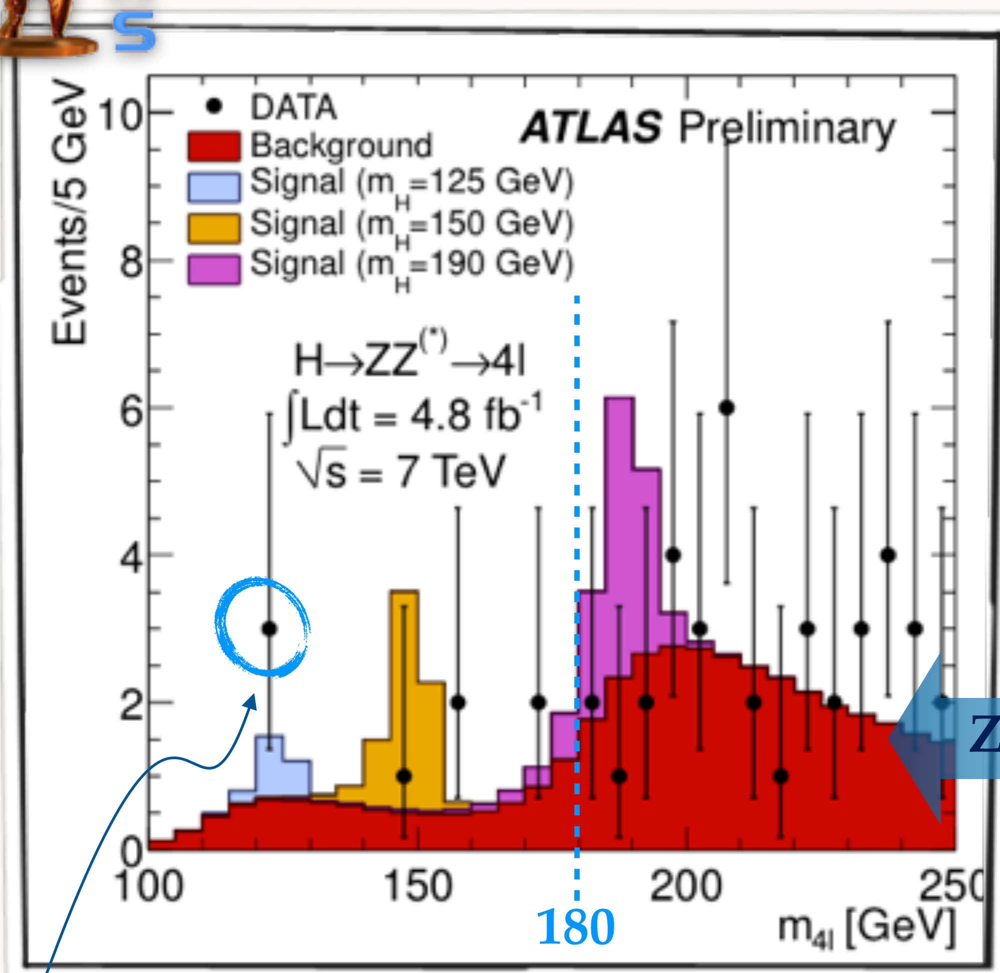
The best single channel for Higgs discovery!



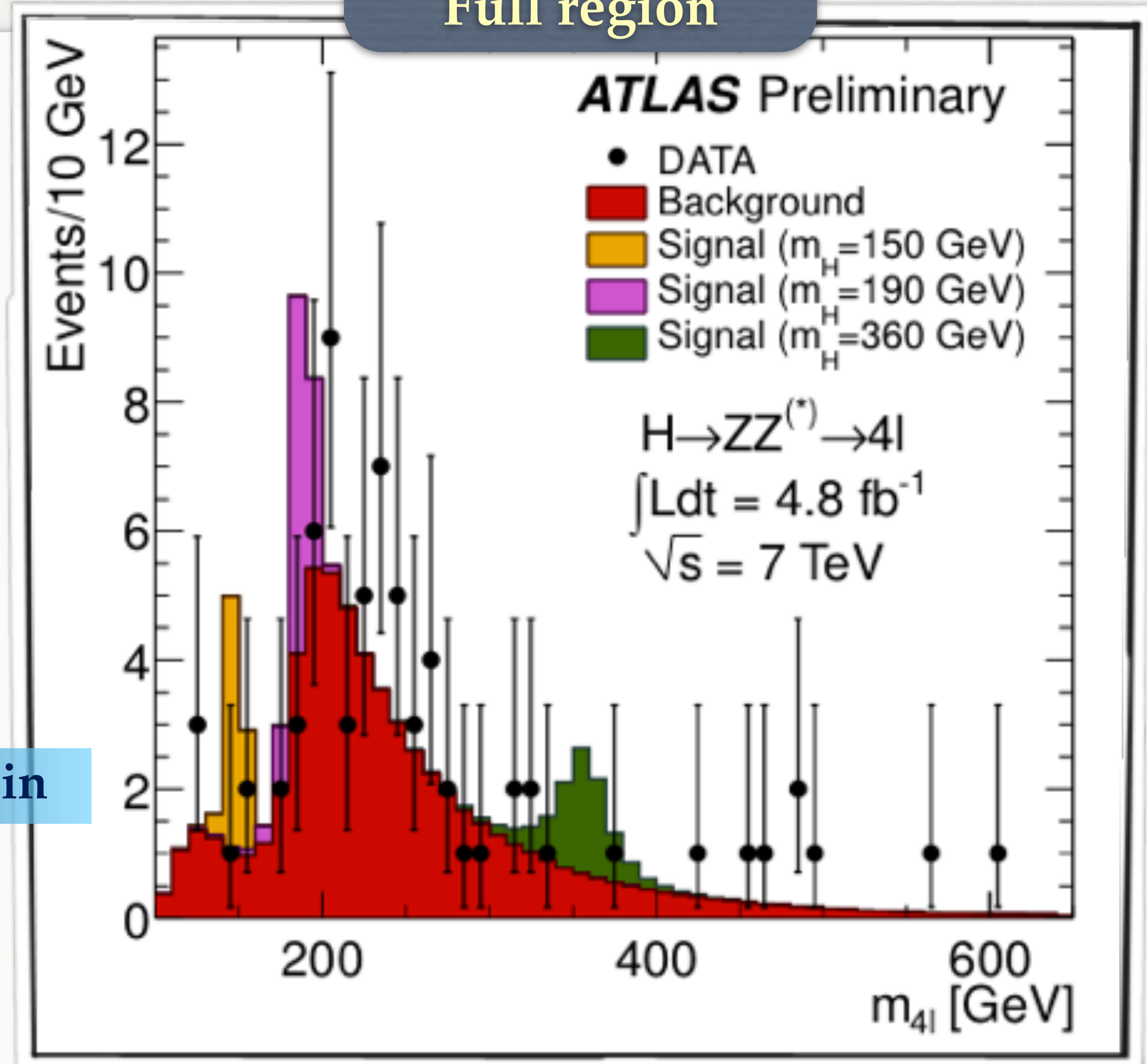


- Mass can be fully reconstructed; no missing particles.
- Best width and mass resolution.
- Extremely clean: **S/N ~ 1**

ATLAS $H \to ZZ \to 4l$



Full region



Counting in $M(4l)<180$ GeV/c^2

Expected background: 9.3 ± 1.5

Observed events: 8

3 events in a single bin $M \sim 125$ GeV/c^2

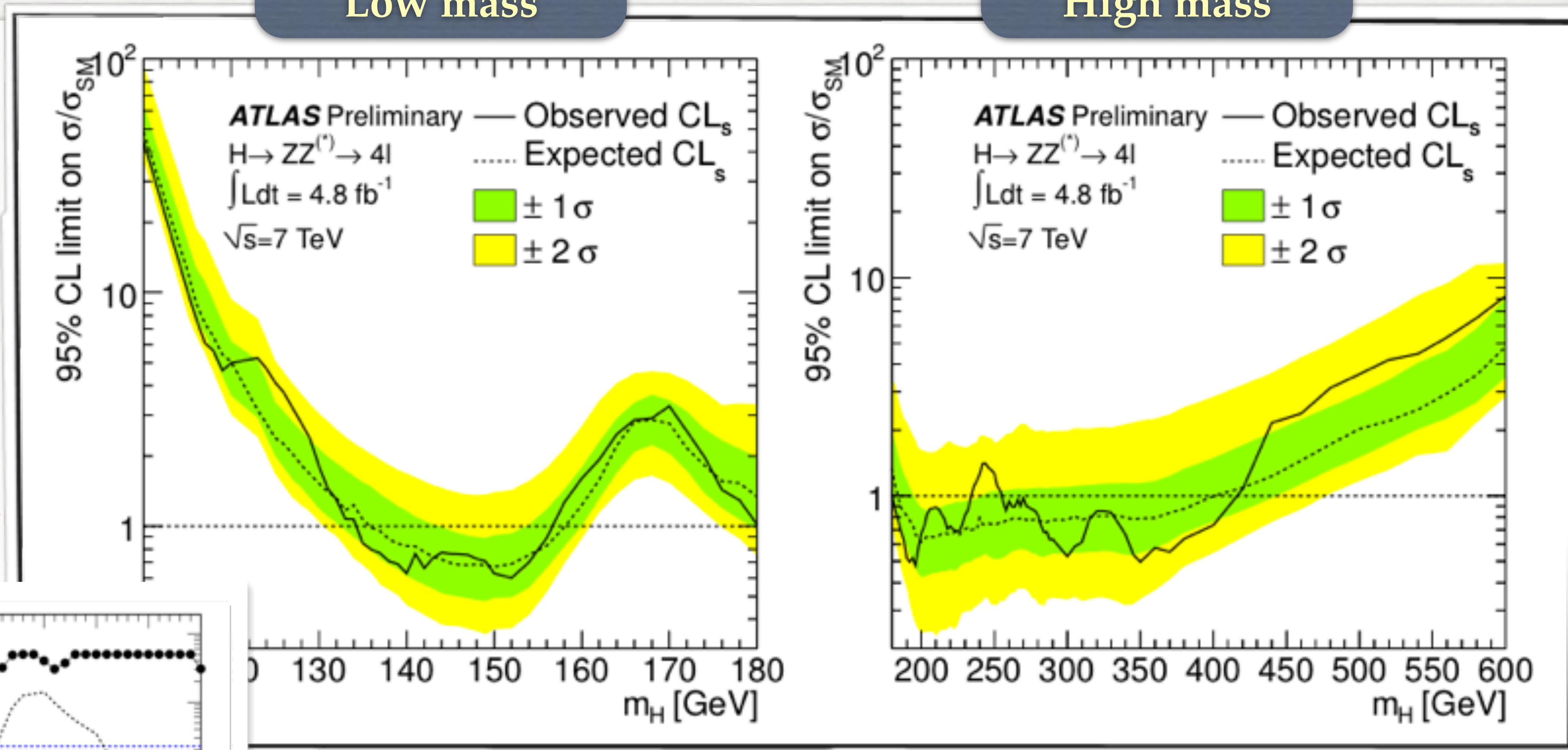
Expected background: 62 ± 9

Observed events: 71

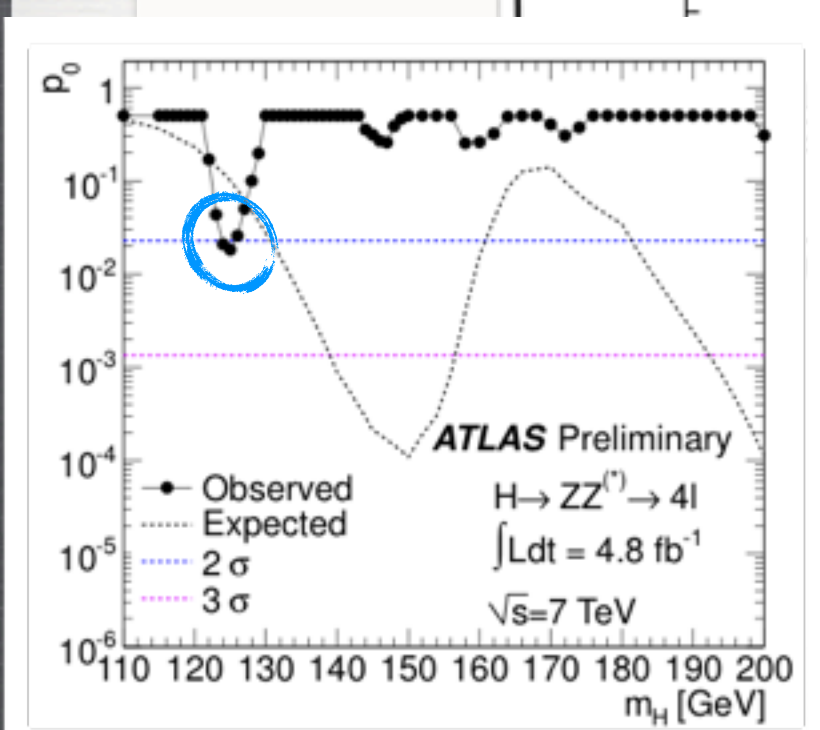
ATLAS H→ZZ→4*l*

Low mass

High mass



The 3 events produce a local p-value ~2.1σ



Excluded at 95% C.L.

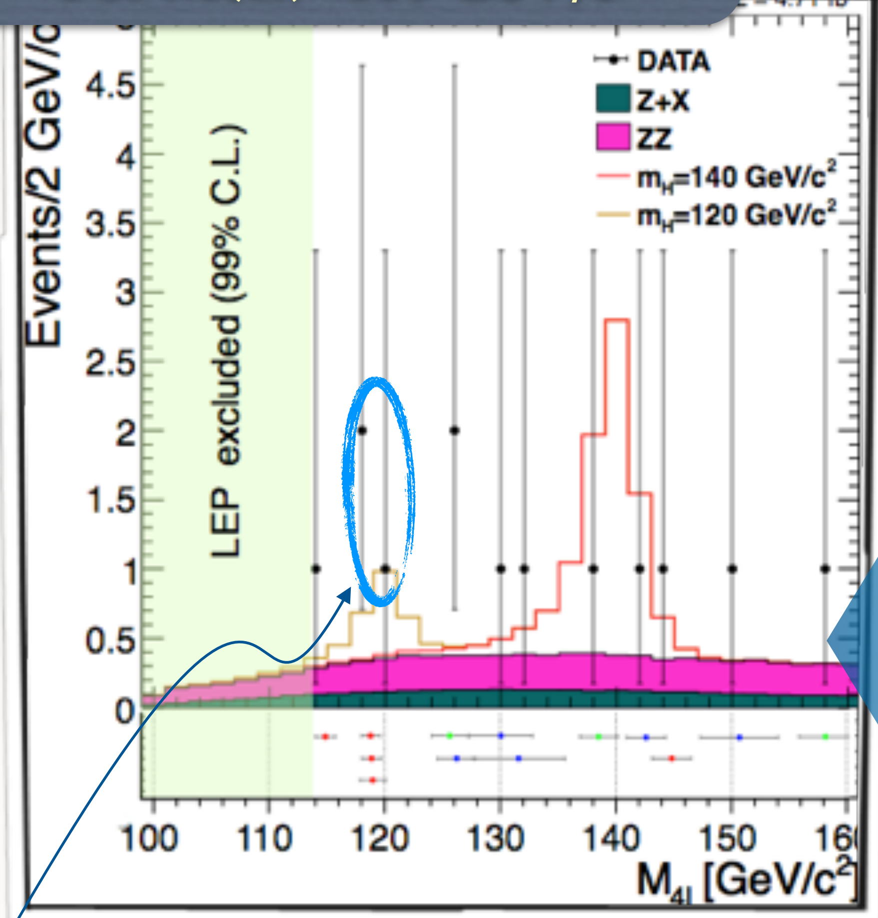
$135 < M(H) < 156\ GeV/c^2$

$181 < M(H) < 234\ GeV/c^2$

$255 < M(H) < 415\ GeV/c^2$

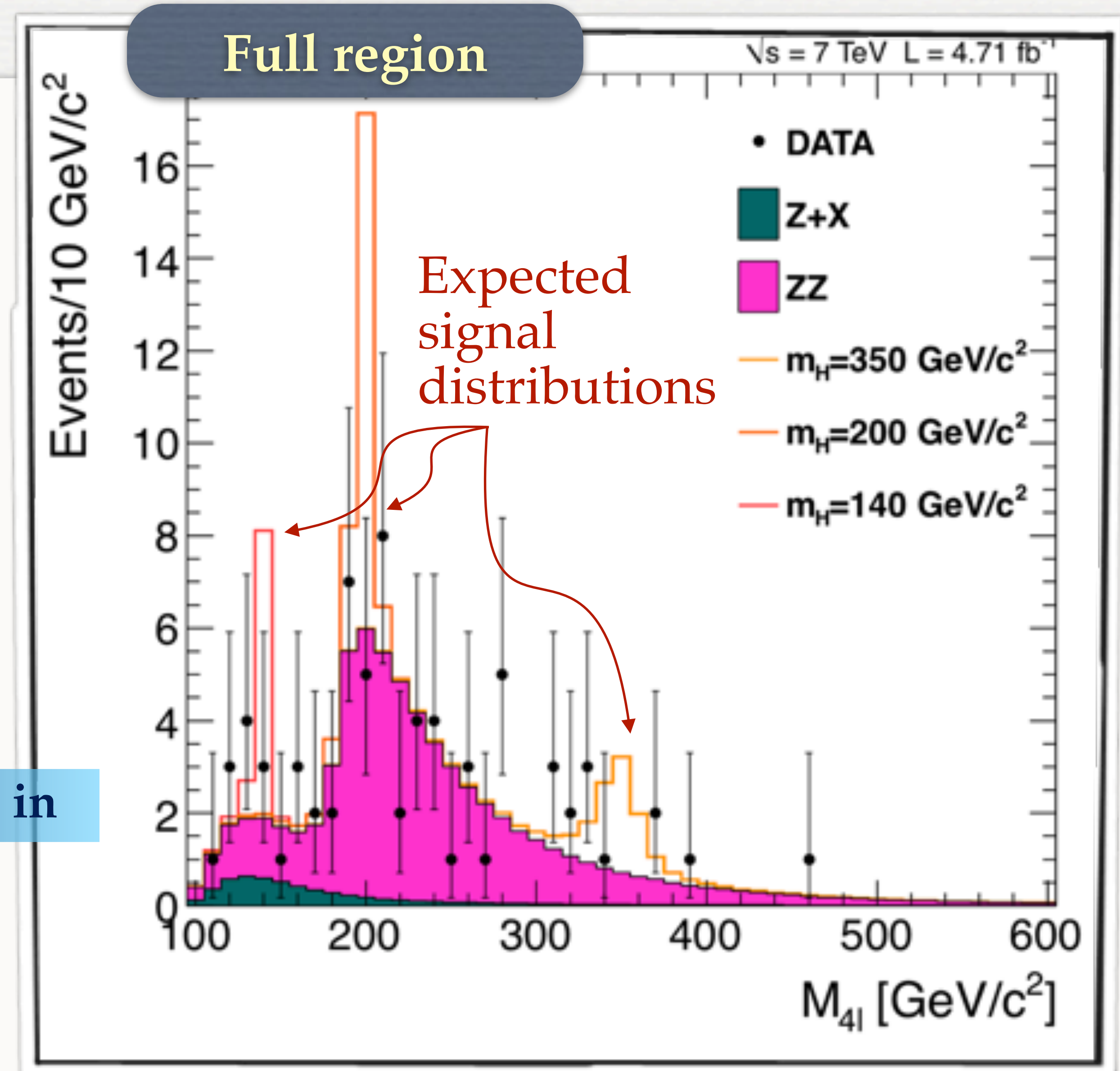
CMS $H \rightarrow ZZ \rightarrow 4l$

For $M(4l)<160\ GeV/c^2$



Zoom in

Full region



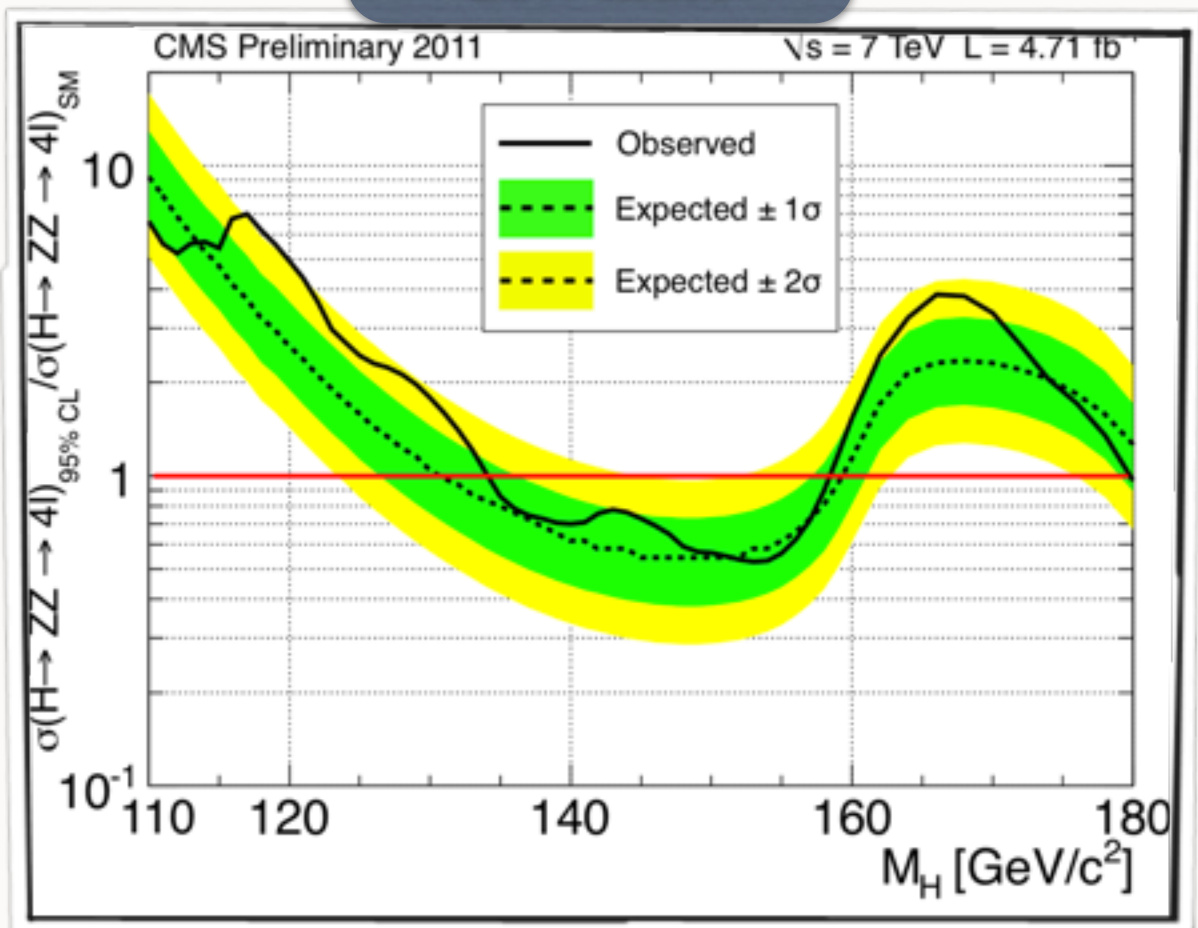
Expected background: 9.5 ± 1.3
Observed events: 13

Expected background: 67.1 ± 6.0
Observed events: 72

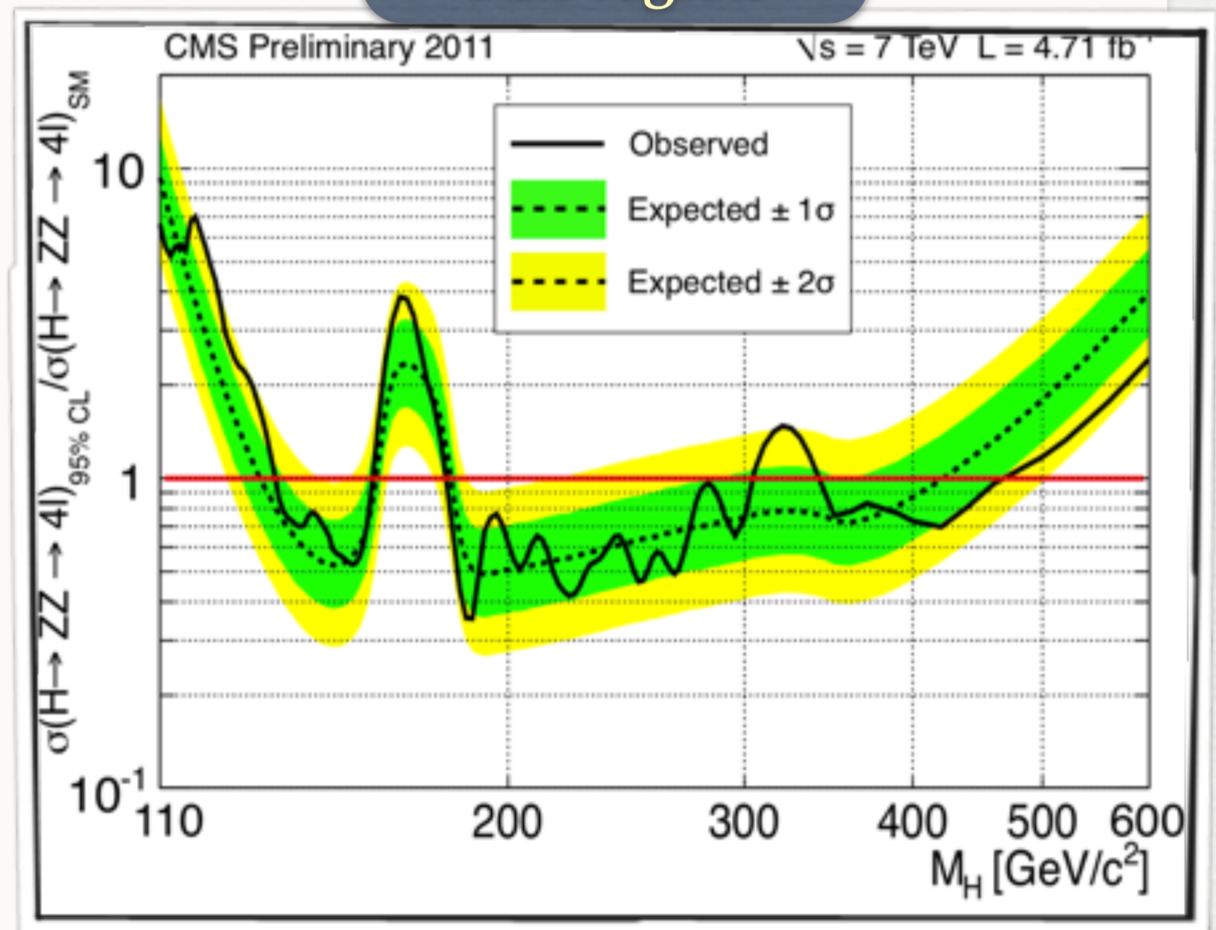
3 events in 2 bins
M ~ 119 GeV/c²

CMS H→ZZ→4*l*

Low mass



Full region



The 3 events also produce a local p-value ~2.5σ around 119 GeV, but the atlas excess is around 125 GeV...

Excluded at 95% C.L.

$134 < M(H) < 158$ GeV/c²
$180 < M(H) < 305$ GeV/c²
$340 < M(H) < 460$ GeV/c²

High mass regions were more or less excluded:

With $H \rightarrow WW \rightarrow 2l2\nu$ along, no Higgs in 129~270 GeV/c^2

With $H \rightarrow ZZ \rightarrow 2l2\nu$ along, no Higgs in 270~400 GeV/c^2

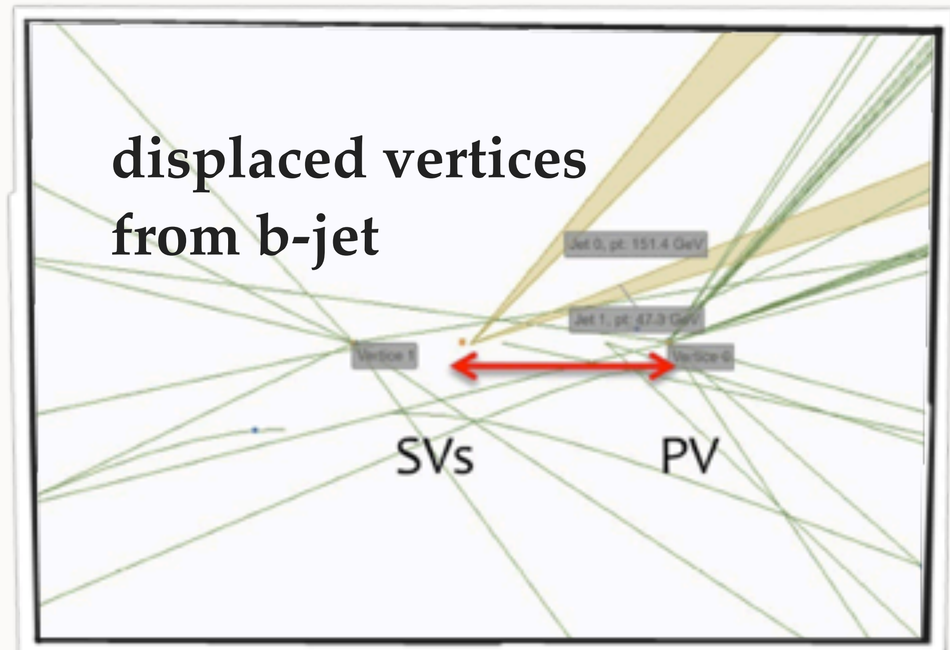
With $H \rightarrow ZZ \rightarrow 4l$ along, pushes to limit to 460 GeV/c^2

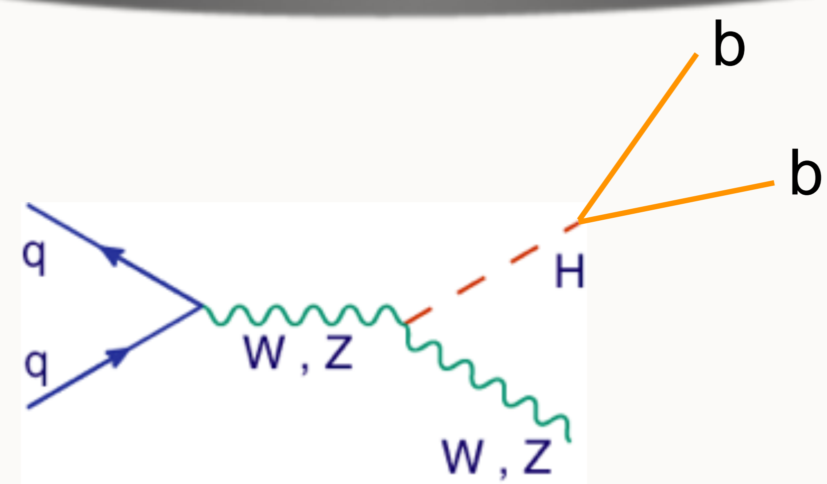
Have to go to low mass, which is very difficult for hadron colliders...

Remark: the indirect fit prefers a lighter Higgs!

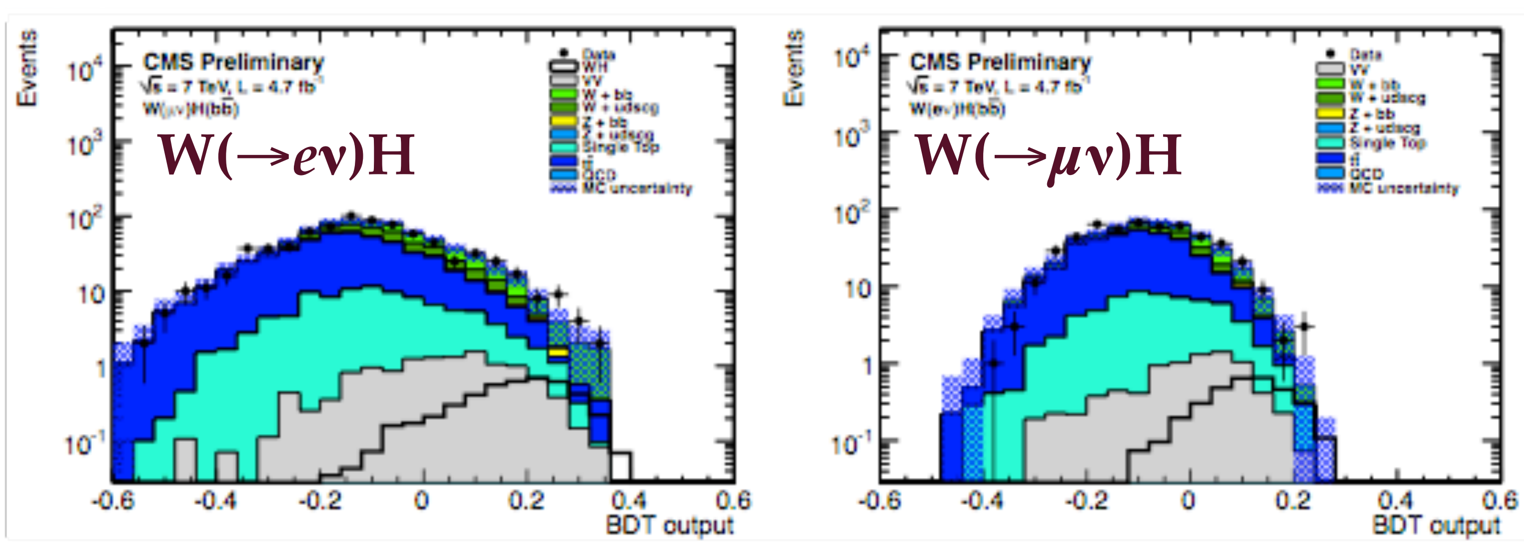
LOW MASS SEARCHES: H→bb

- At low mass, H→bb is the dominant channel, but overwhelmed by enormous QCD dijet background (S/N<1/1M..).
- The best option: qq→VH→Vbb.
  Tag another vector boson + strong b-tagging + BDT analysis.
- Reconstruct Z(→*ll*,νν)H and W(→*l*ν)H.

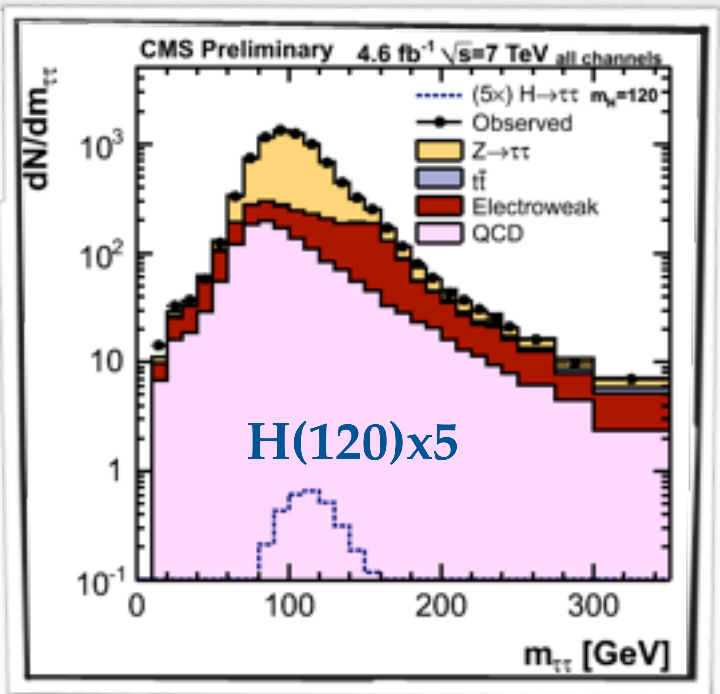


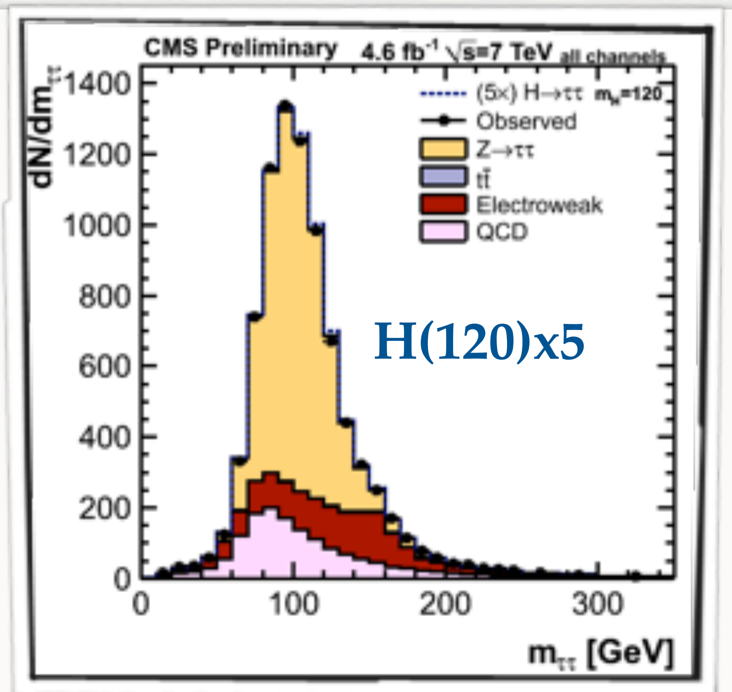


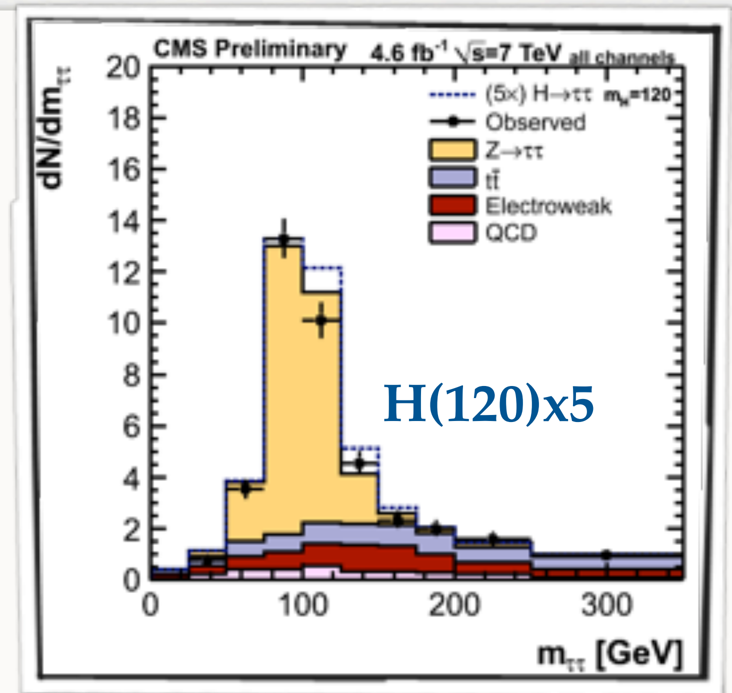
Tag a clean/boosted W/Z
from Higgs-strahlung production

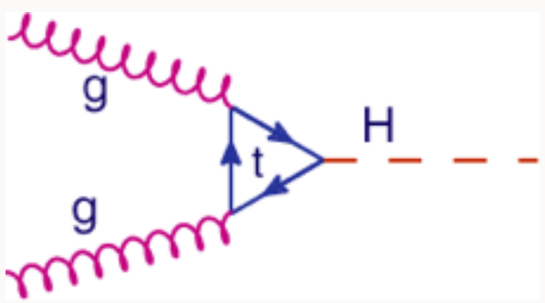


LOW MASS SEARCHES: $H \rightarrow \tau\tau$

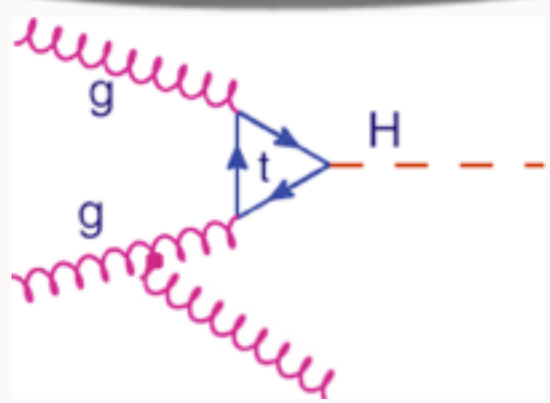




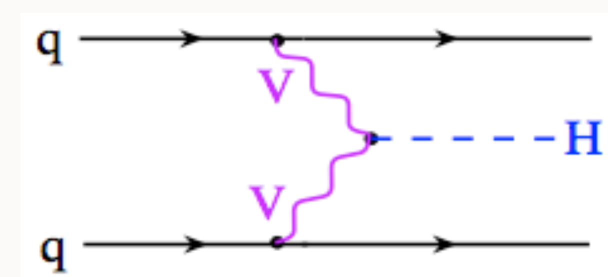




Gluon fusion,
with 0 or 1 jet in addition



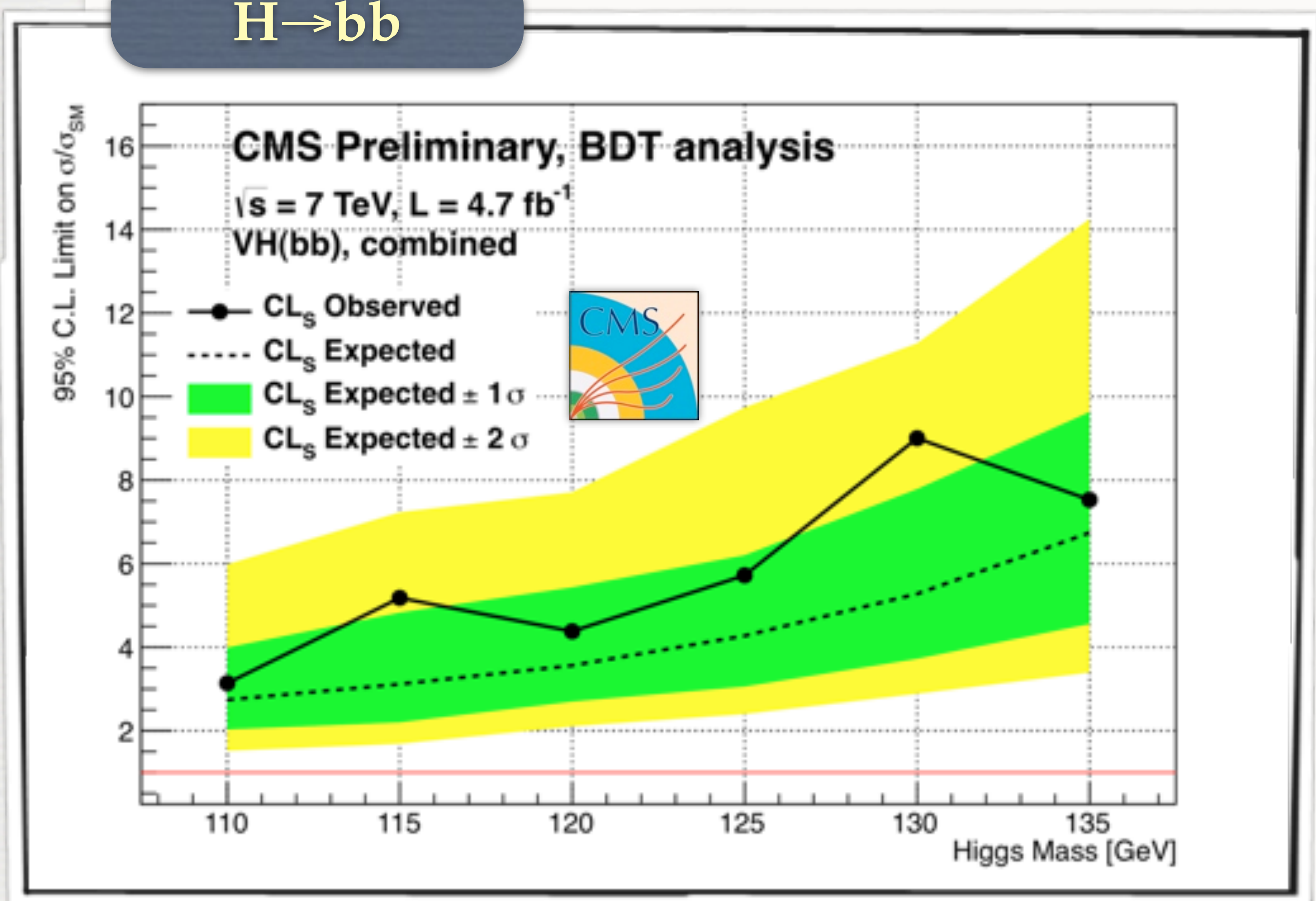
Boosted mode,
with 1 high p_T (>150 GeV/c) jet



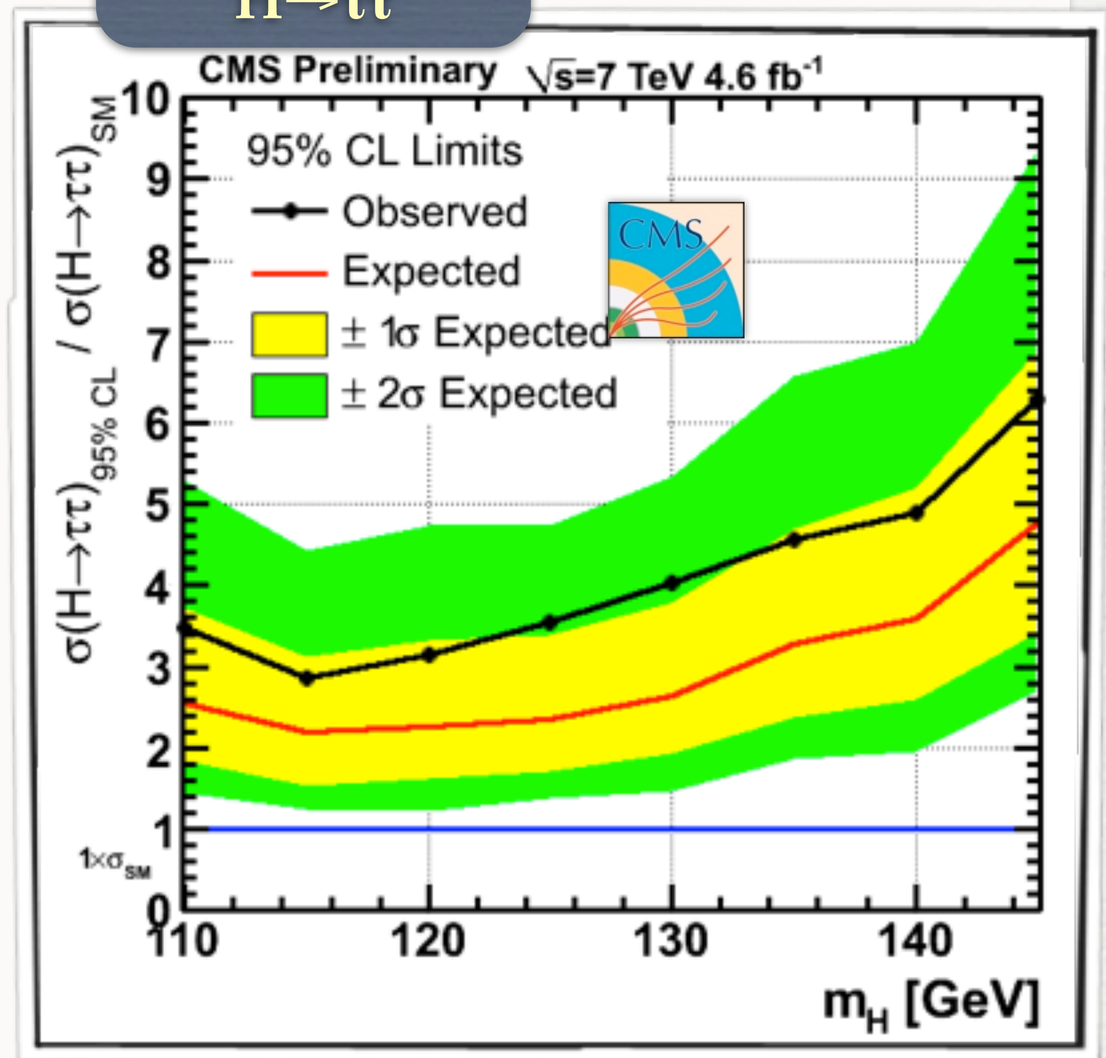
Vector-boson fusion
with 2 additional jets
(best channel)

LOW MASS SEARCHES: H→bb & H→ττ

H→bb

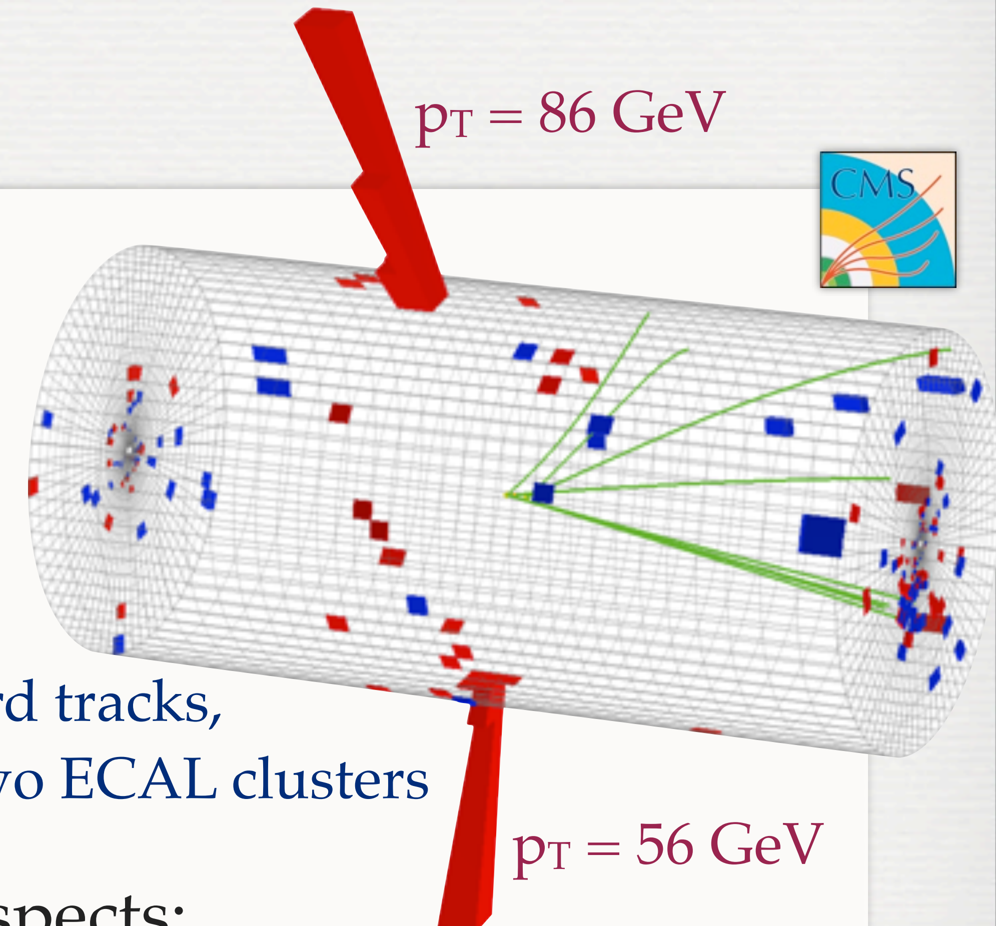


H→ττ



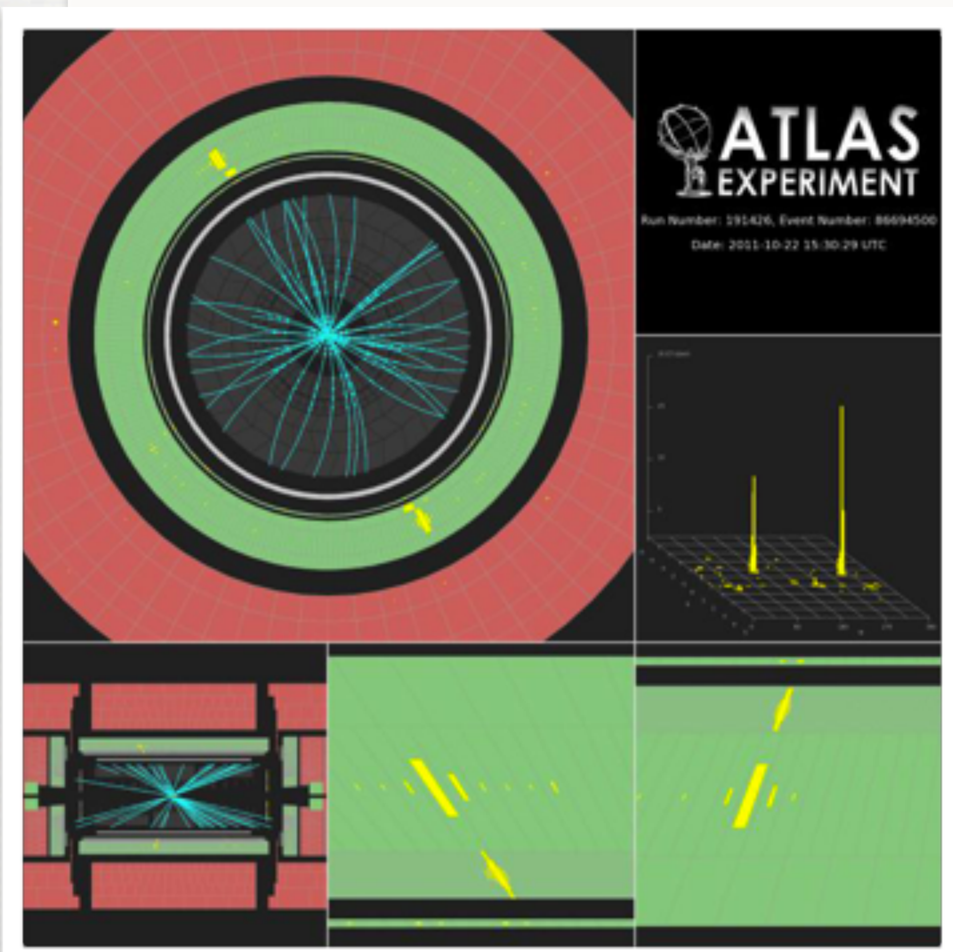
- Search for Higgs in low mass region is very difficult (background level is very high).
- The best channel is still H→γγ (low branching fraction, but cleaner).

LOW MASS SEARCHES: $H \to \gamma\gamma$



- Very simple final state: two isolated photons.
- Smaller effective cross-section: σ~40 fb
- Smooth irreducible background (S/N~0.02)

no hard tracks,
just two ECAL clusters

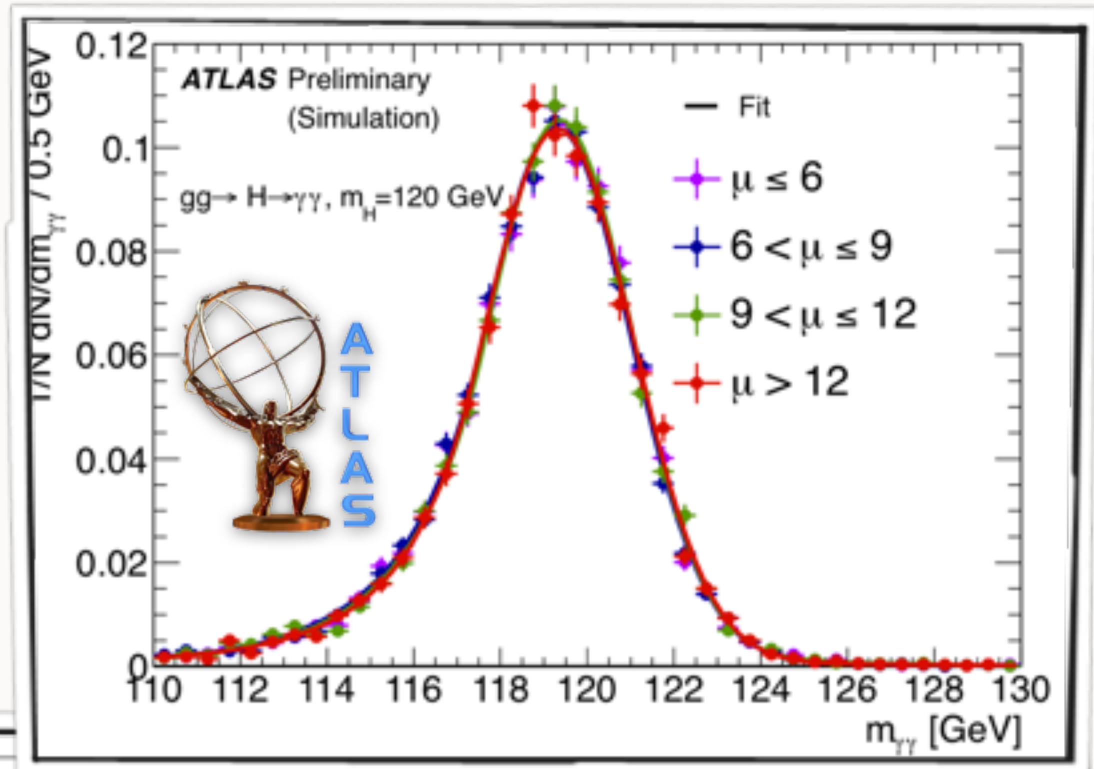


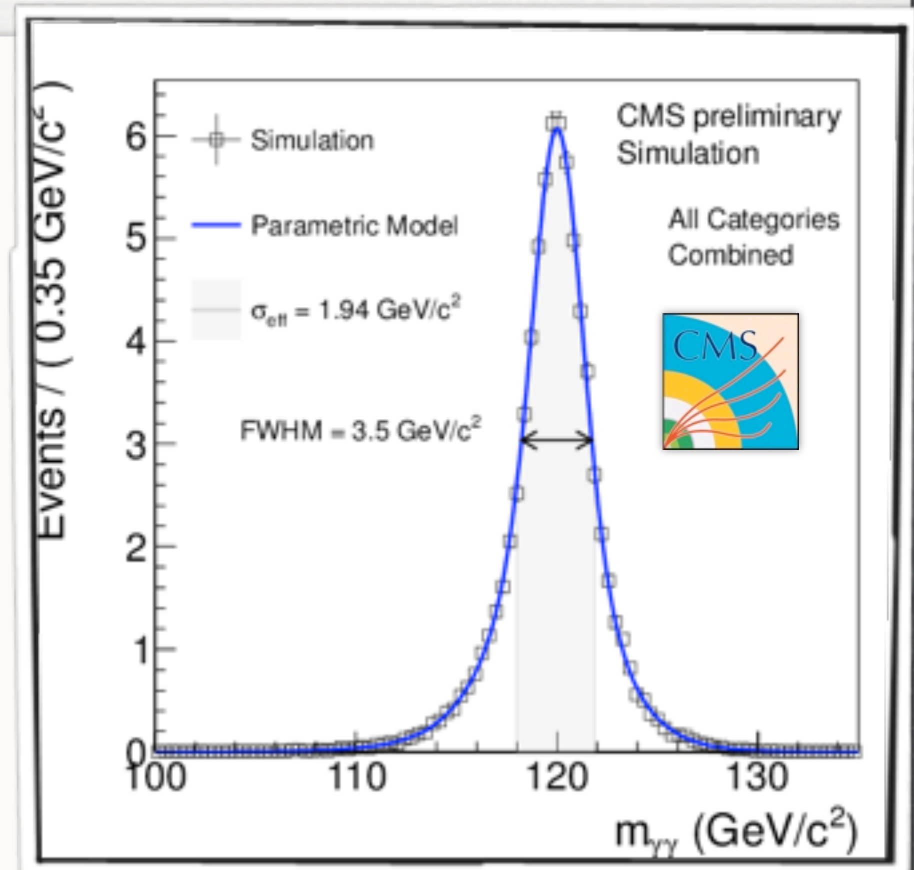
- Experimental aspects:
  - Reject non-photon background (fakes from jets, π^0, etc.)
  - $M(\gamma\gamma)$ mass resolution and calibration
  - Vertex finding
  - Optimizing the sensitivities in different event categories.

LOW MASS SEARCHES: $H\to\gamma\gamma$

Simulated $H\to\gamma\gamma$ peak $\Rightarrow$

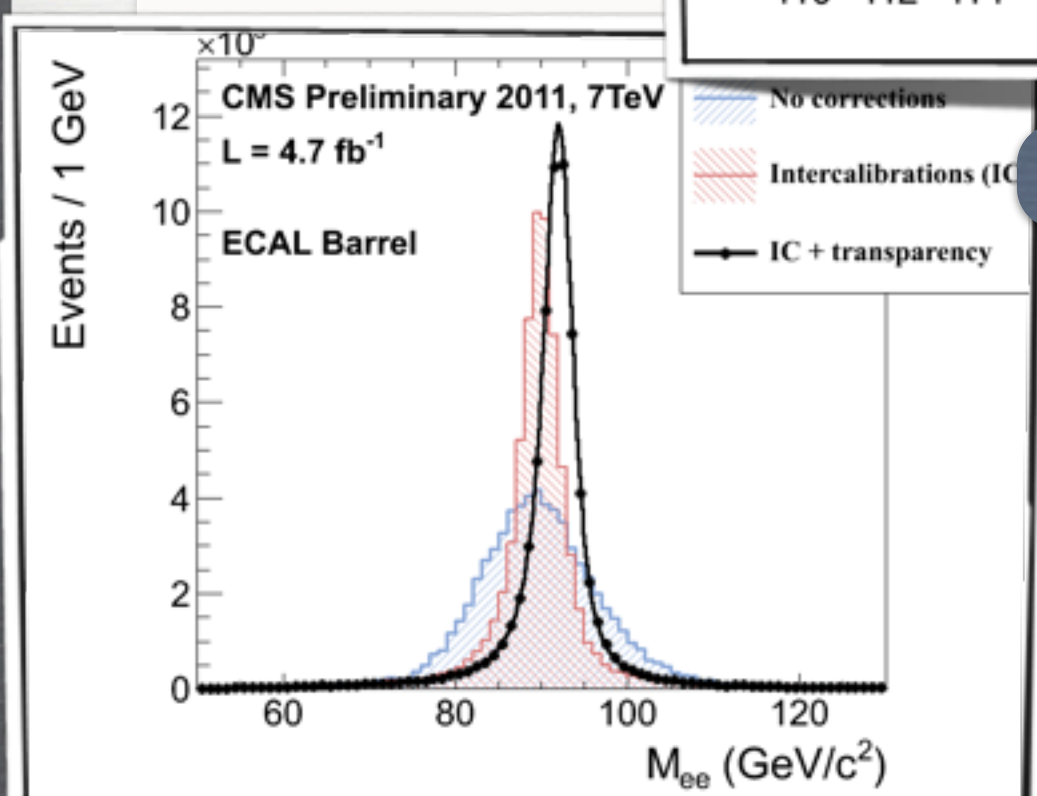
Width of the peak is around **2 GeV**.





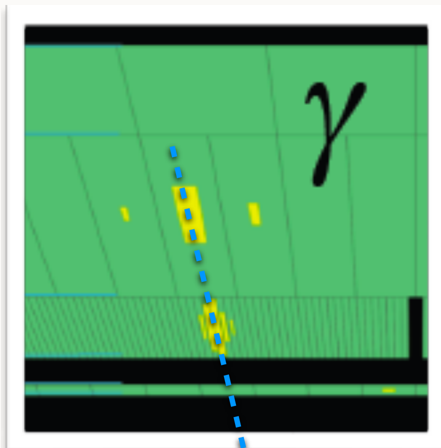
$\sigma \sim 1.4 \sim 2.3$ GeV/c^2

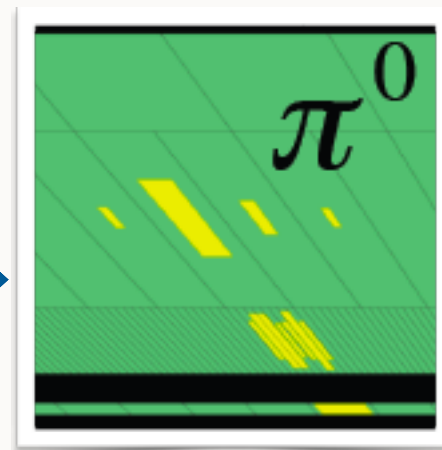
$\sigma \sim 1.9$ GeV/c^2



$\Leftarrow$ The calibration of calorimeter has been confirmed by the $Z\to ee$ data.
The resolution of peak position is much better then the width.

LOW MASS SEARCHES: $H \rightarrow \gamma\gamma$



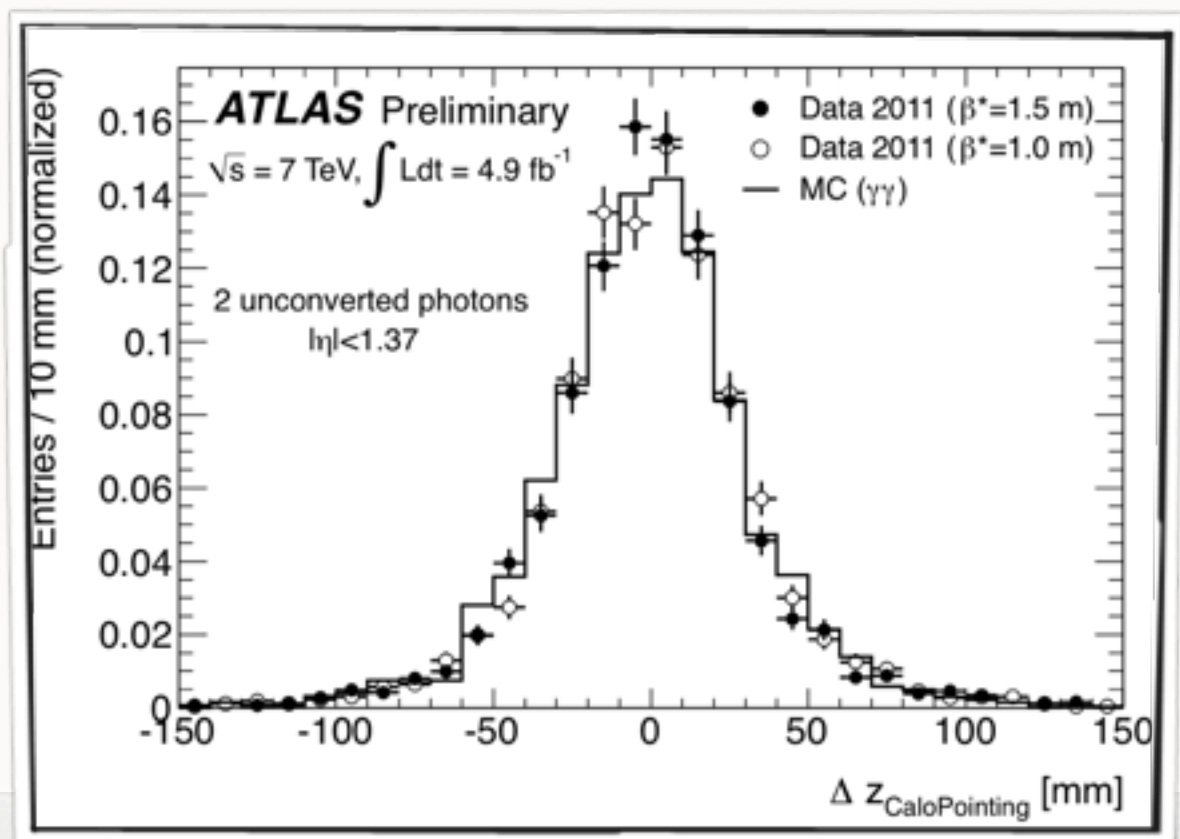


⇐ The Atlas calorimeter has fine η segmentations (4mm strips) can well separate π^0 and photon.

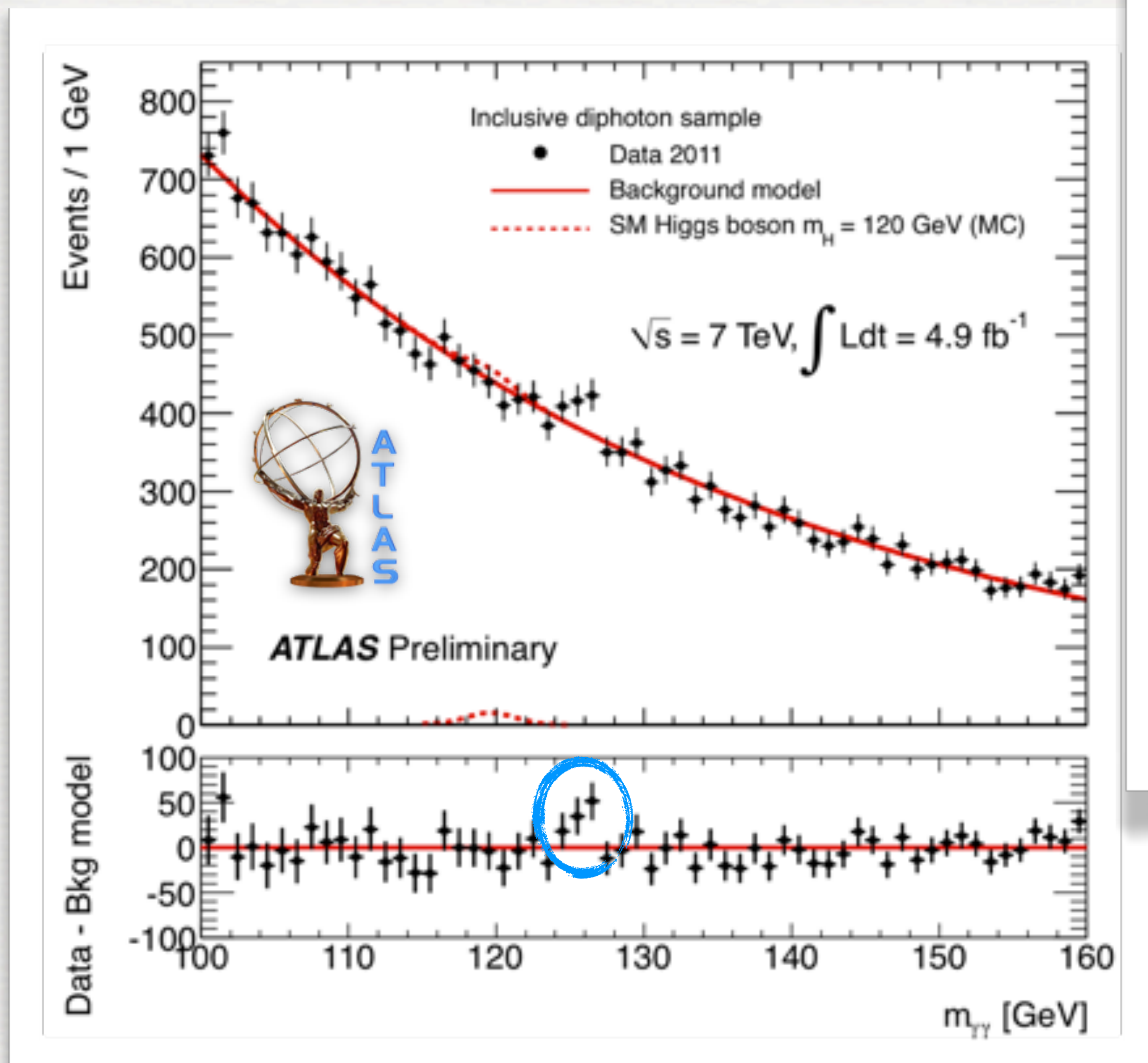
Deduce Z of primary vertex

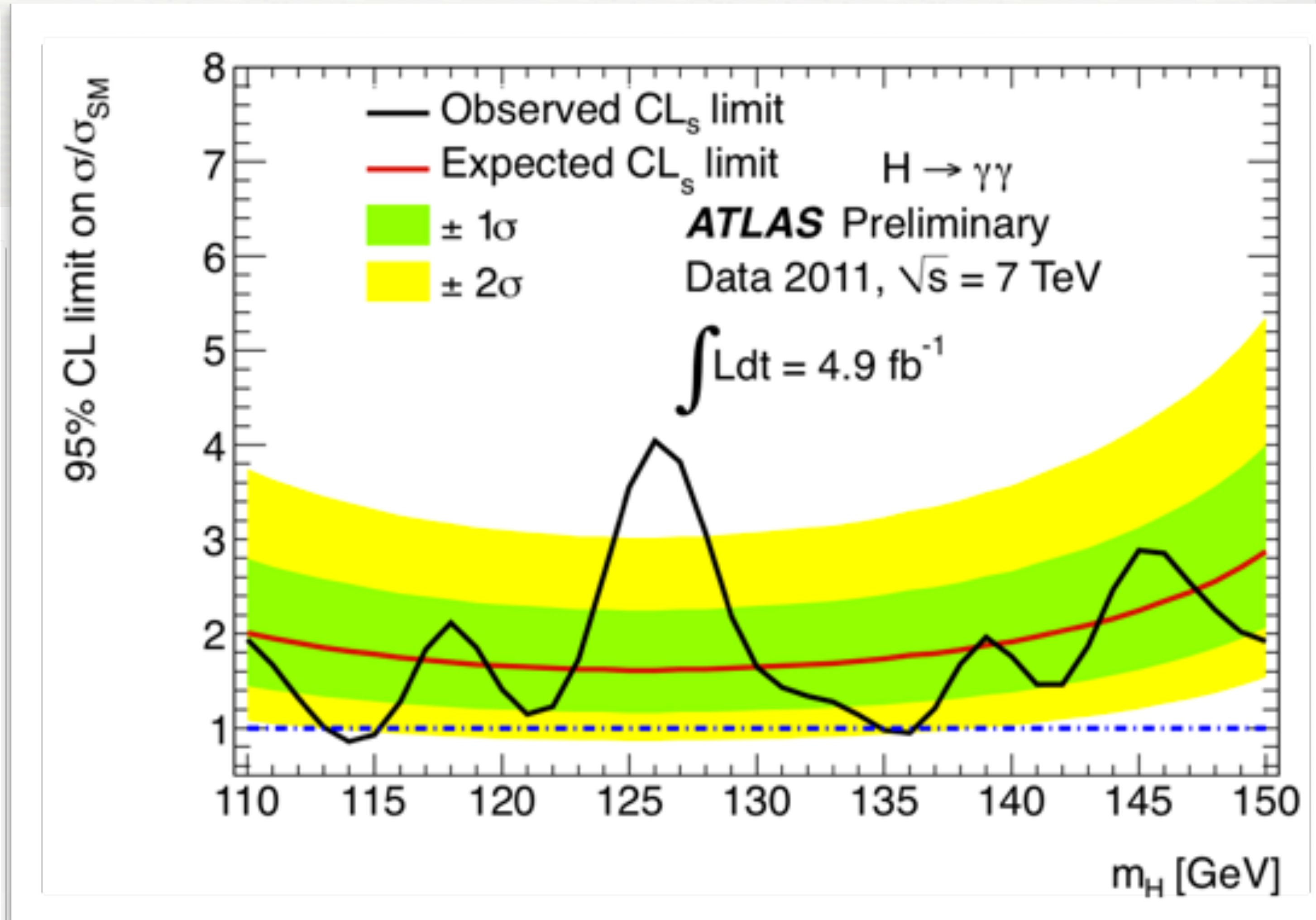
beam axis

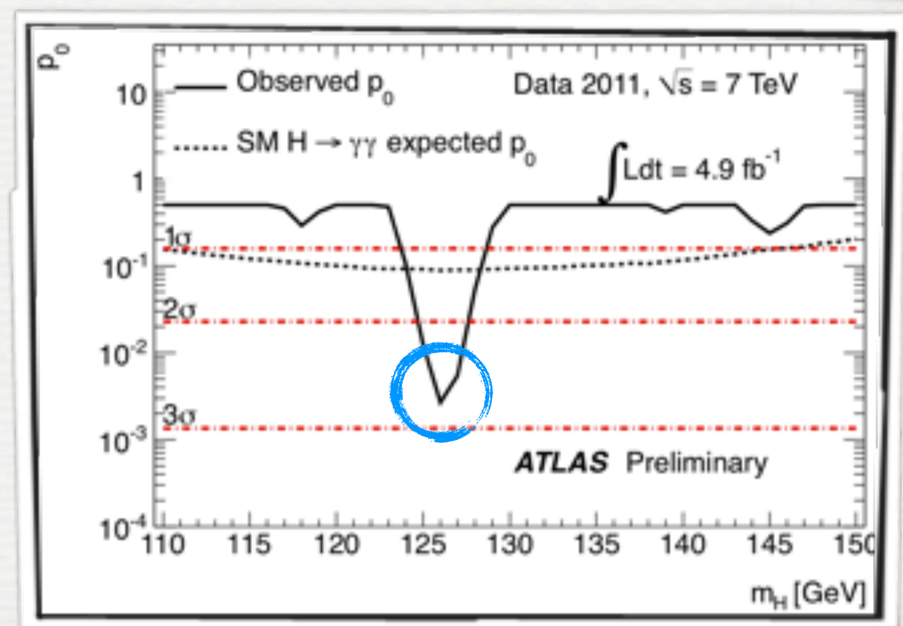
$Z(\gamma_1) - Z(\gamma_2) \Rightarrow$ Calorimeter pointing capability reduces vertex uncertainty to 1.5 cm



ATLAS H→γγ

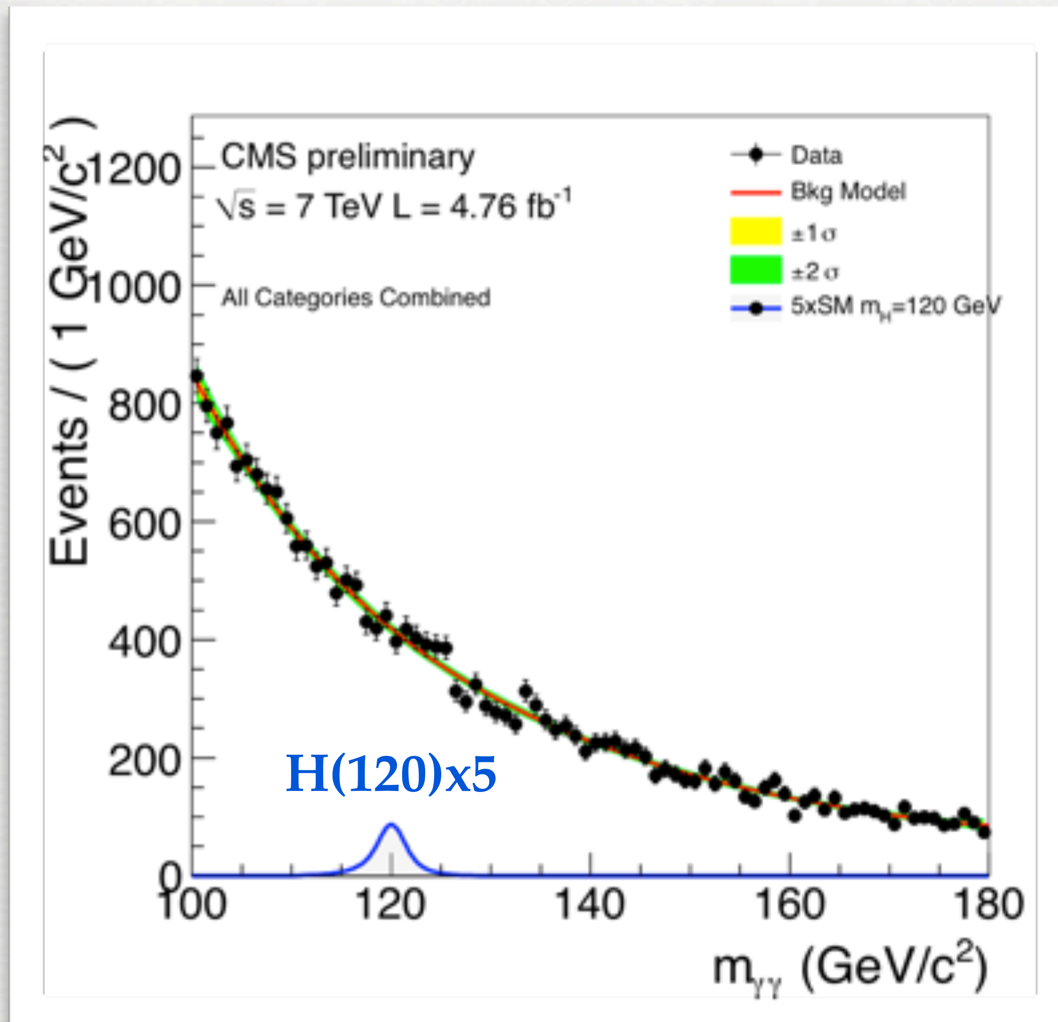




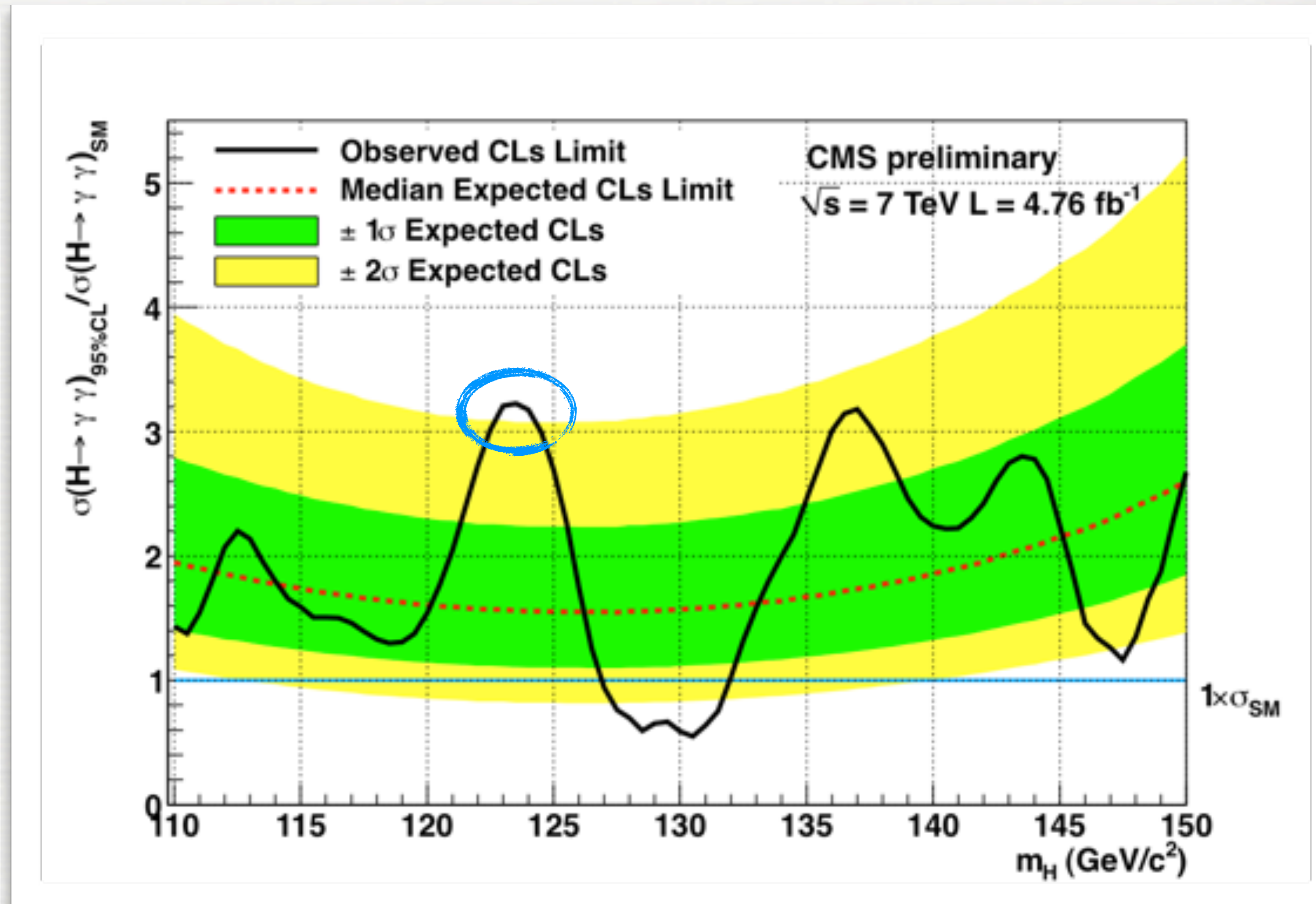


The events around 126 GeV has a local p-value ~2.8σ
Global p-value is around 1.5σ only.
(to be discussed later)

CMS H→γγ



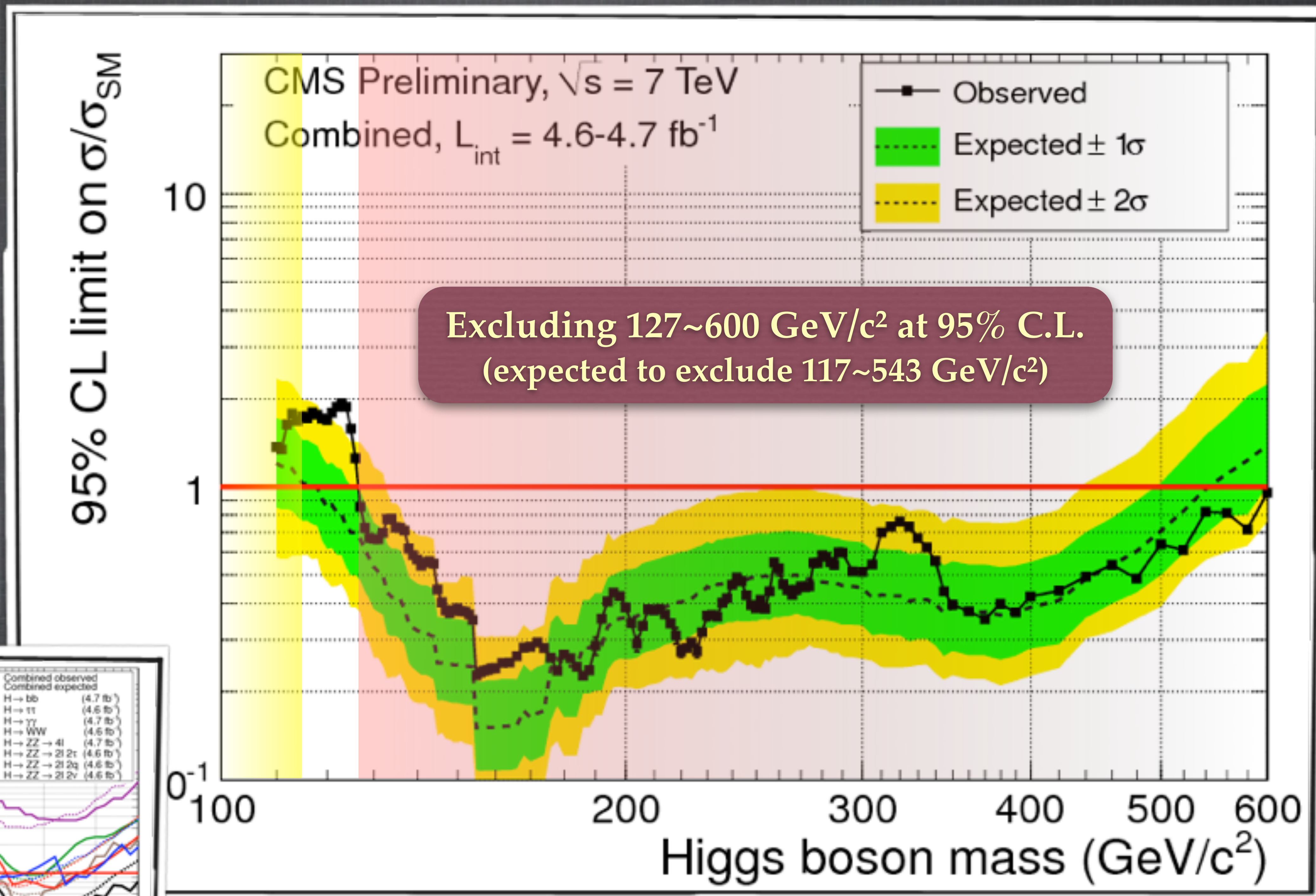
Background is normalized to data.
(conservation of excess & deficit...)

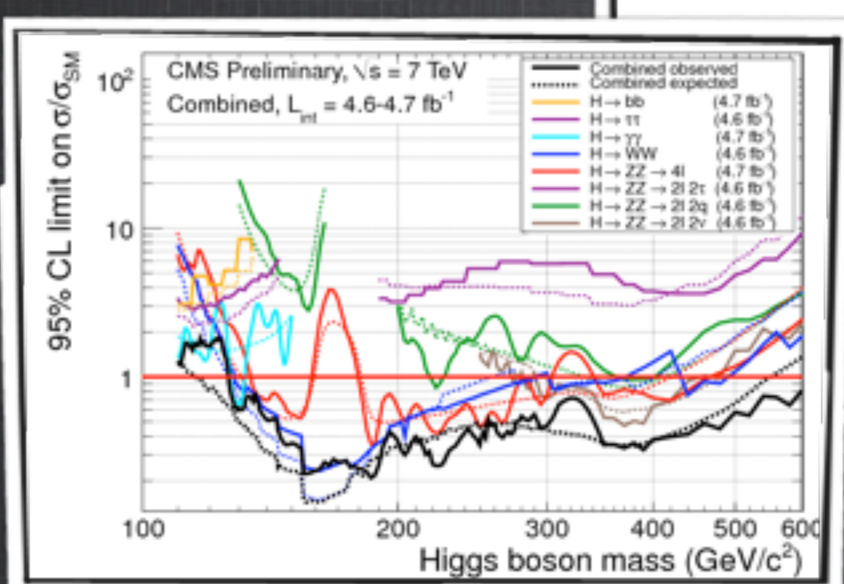


The events around 124 GeV has a local p-value ~2.5σ away from Atlas excess by 2 GeV
(already differ by a full width ~ unlikely to be a fluctuation...)

If we can combine everything together, shall we become stronger?

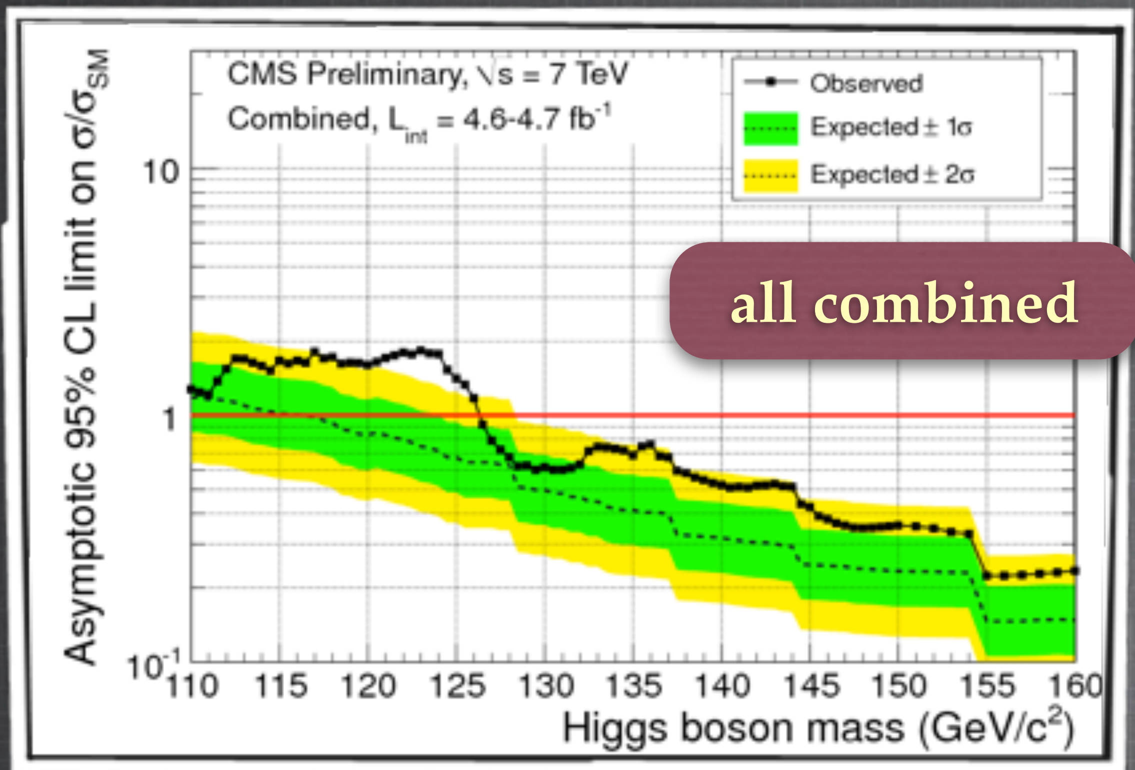
CMS COMBINED

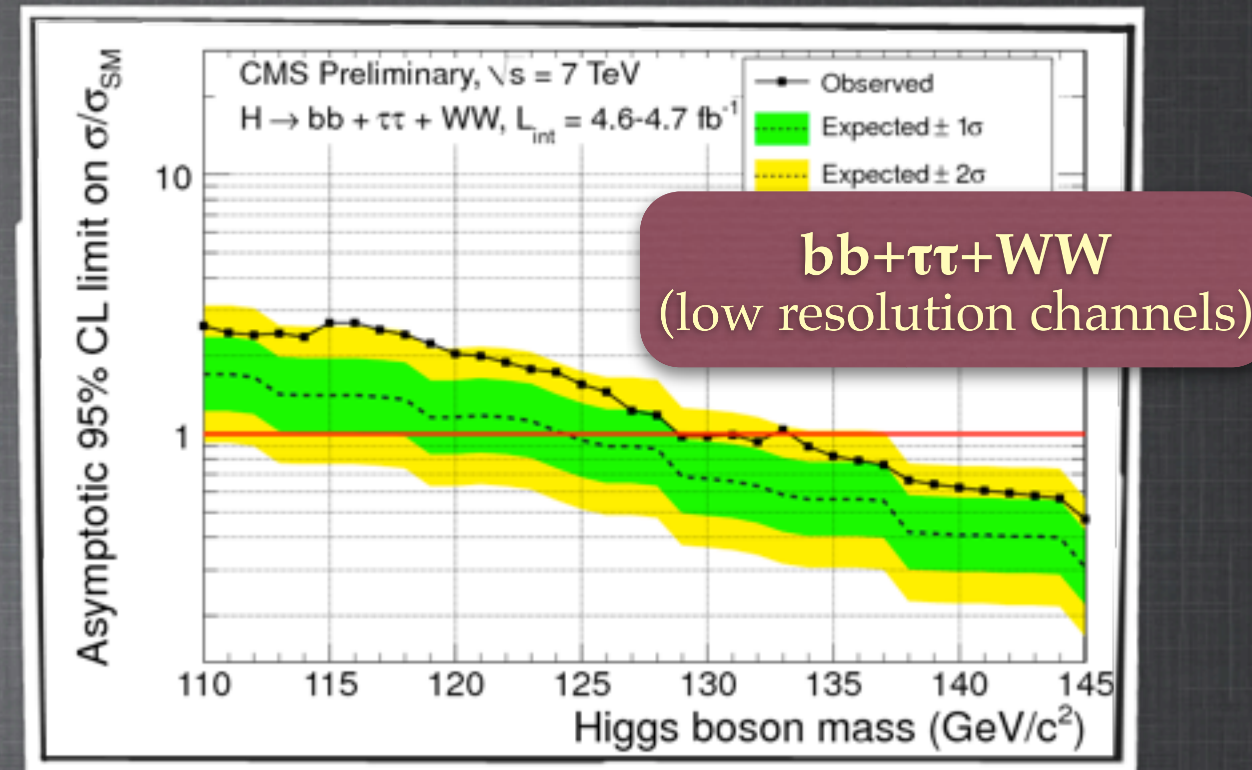


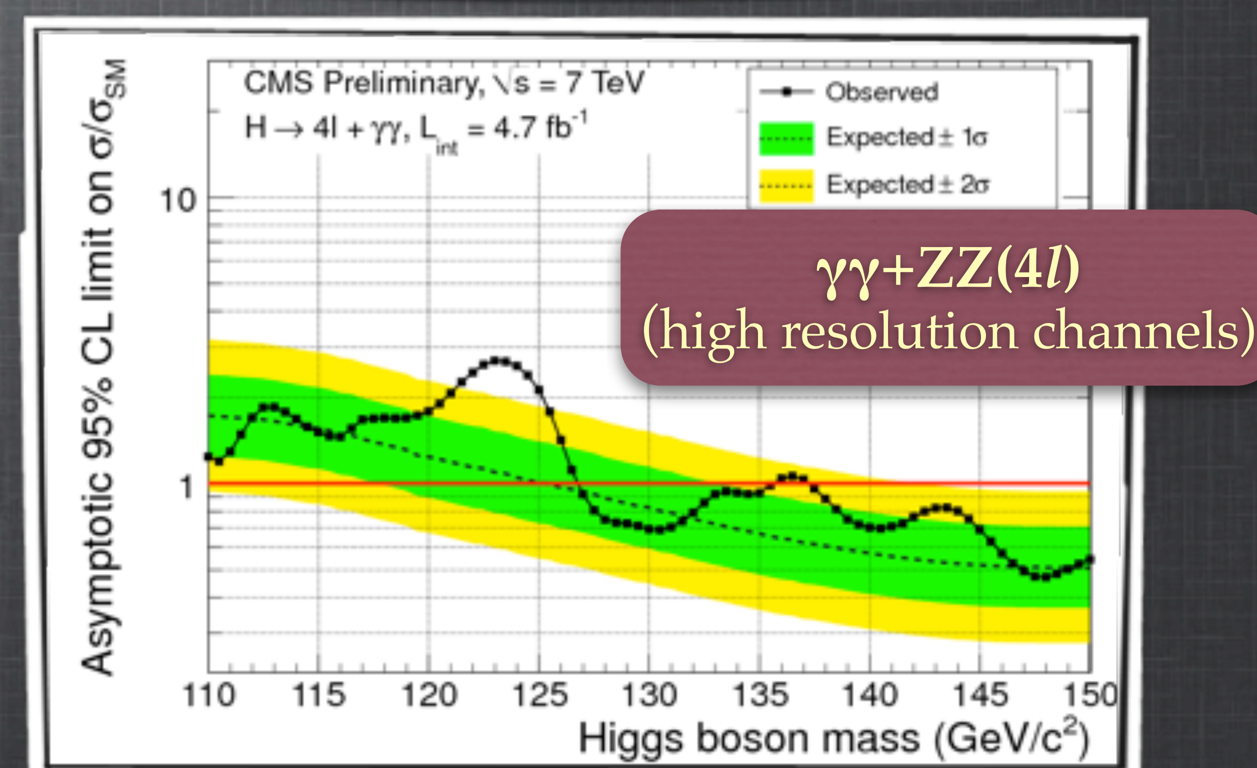


Combining all analyses into single limit plot

ZOOM IN THE LOW MASS



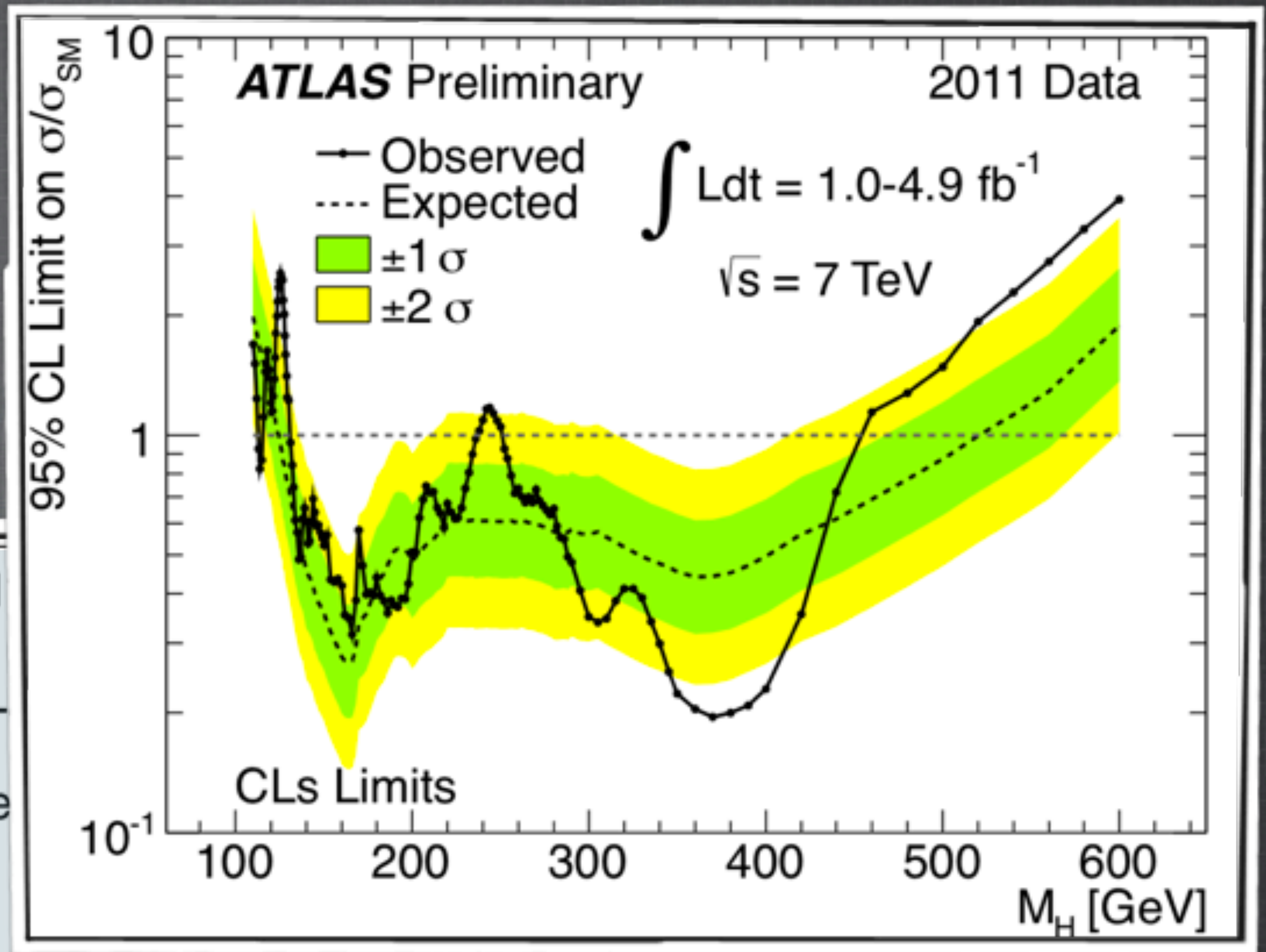


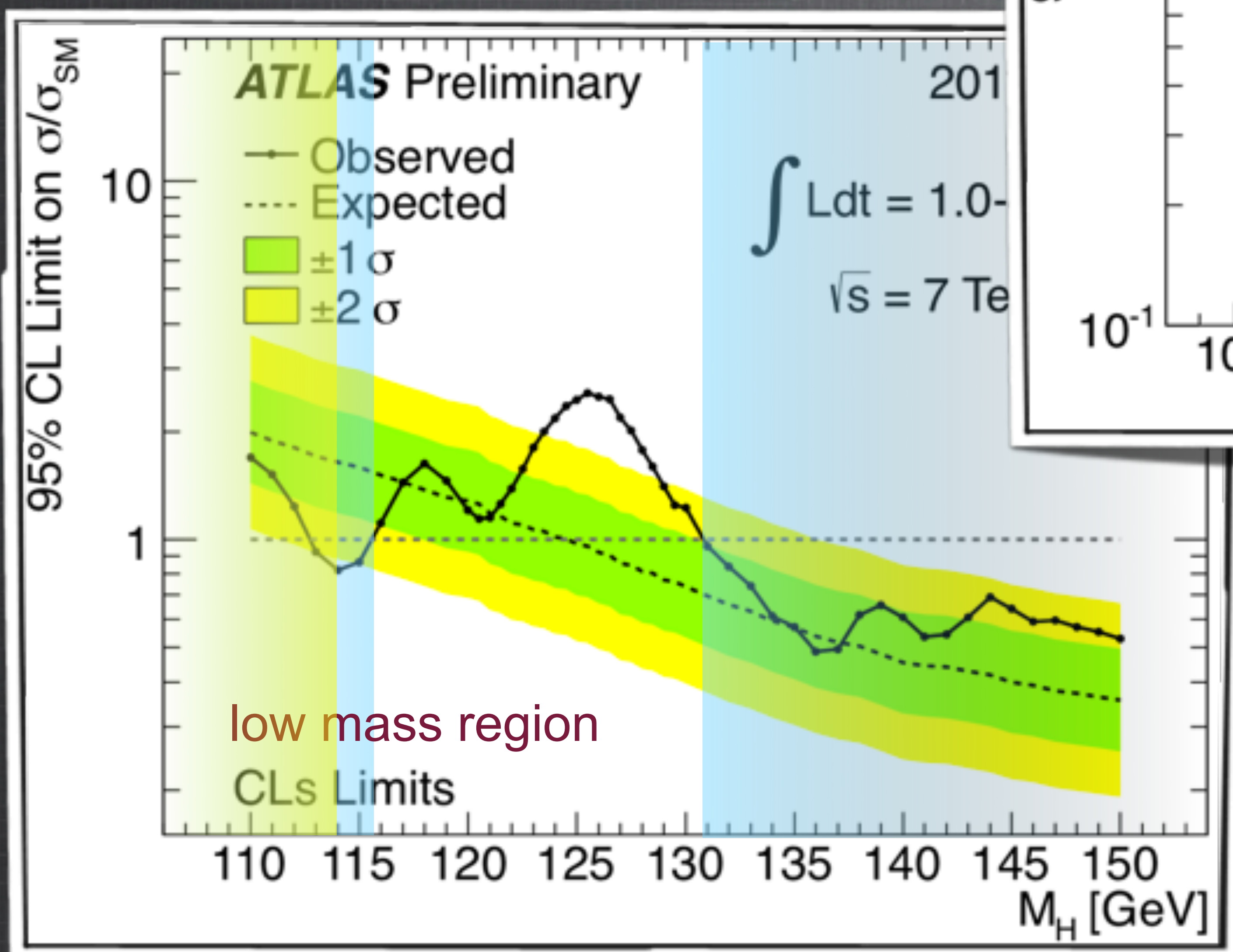


We cannot exclude the presence of the SM Higgs boson below 127 GeV / c^2 because of a modest excess of events in the region between 115 and 127 GeV / c^2.

ATLAS COMBINED

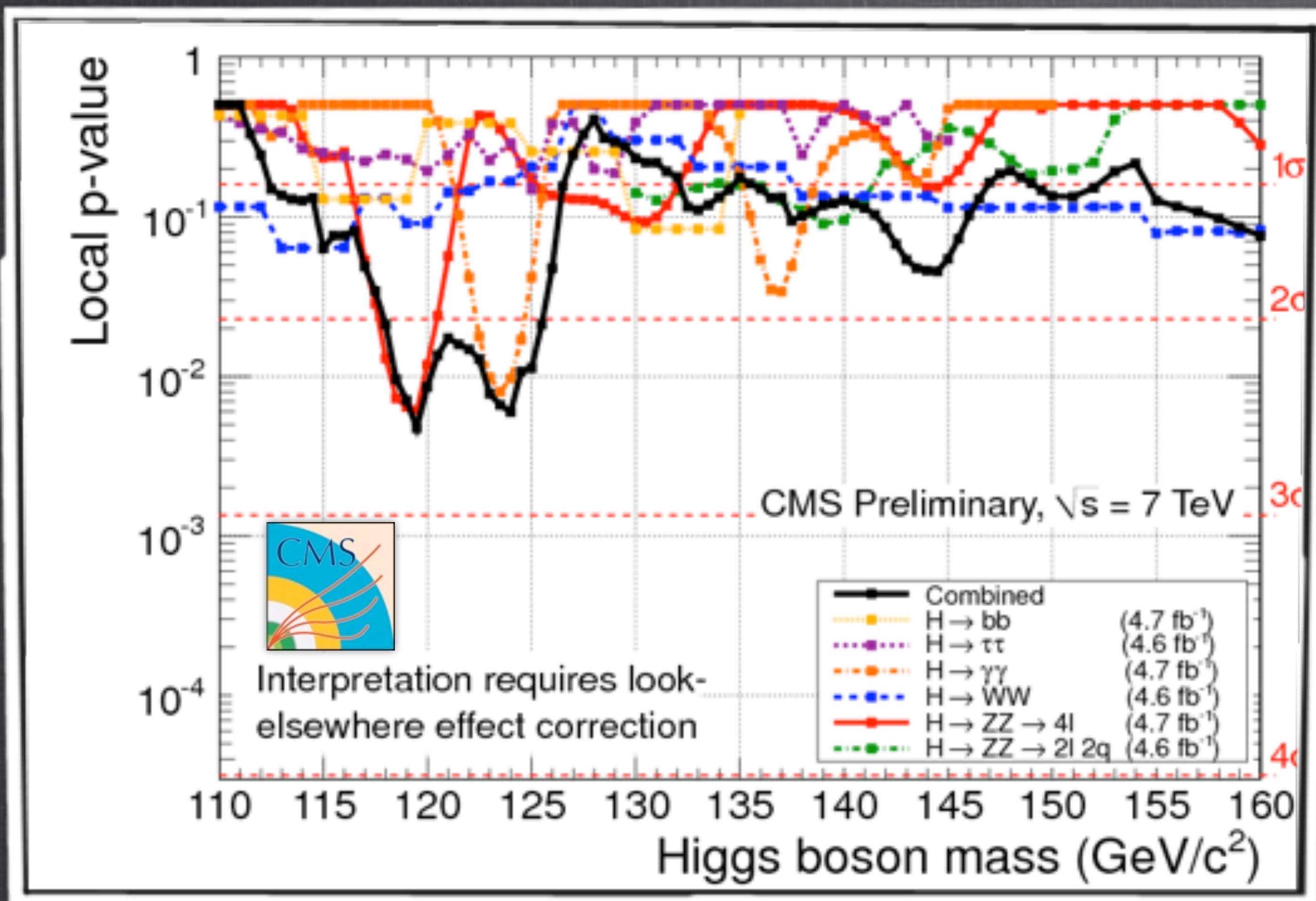
Remark: some of the channels were not yet updated from the summer analysis (1 fb^{-1}).

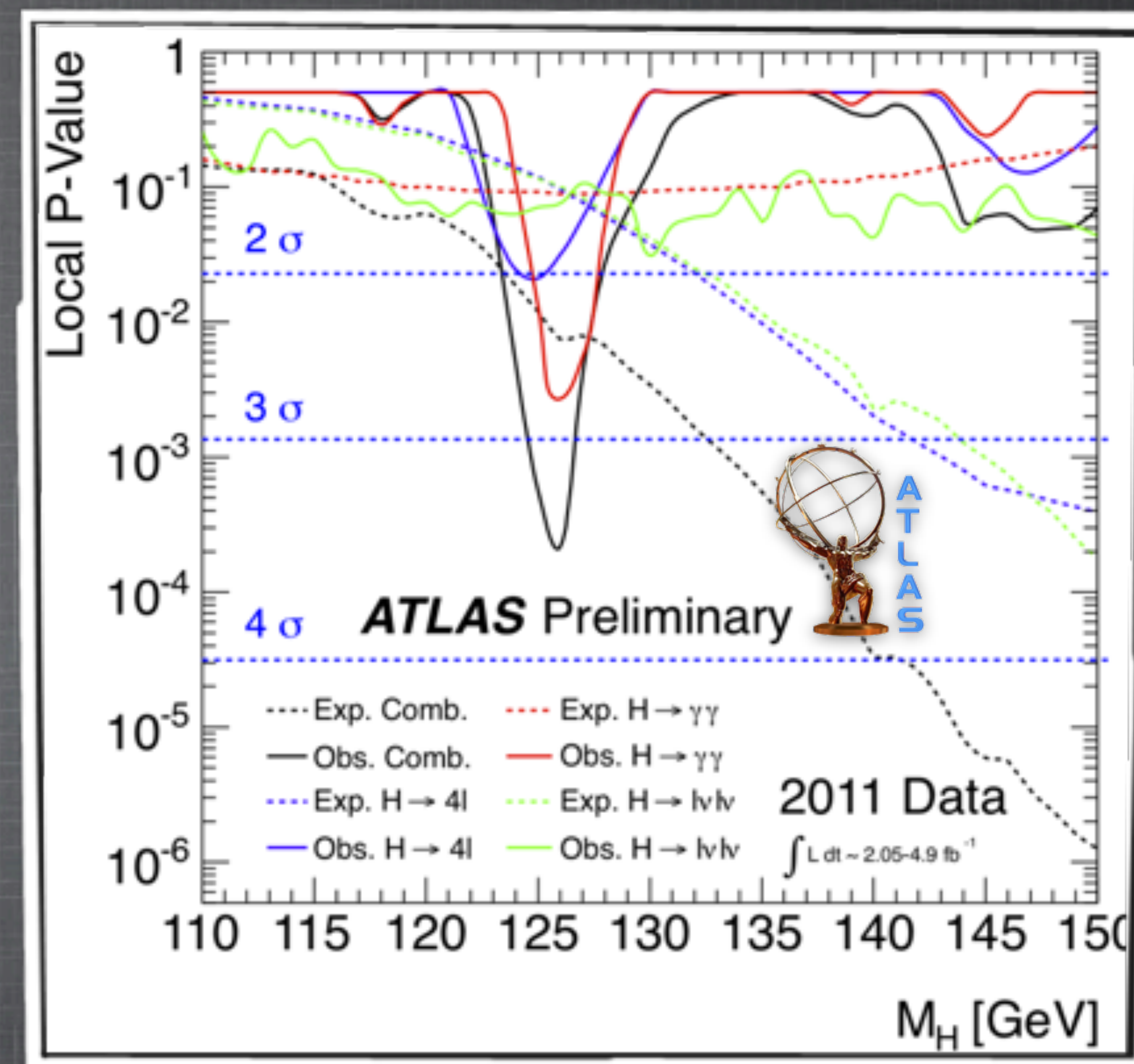




Excluding 112.7~115.5 GeV/c^2
131~237 GeV/c^2
251~453 GeV/c^2 at 95% C.L.
(expected to exclude 124.6~520 GeV/c^2)

THE EXCESS(ES) IN LOW MASS

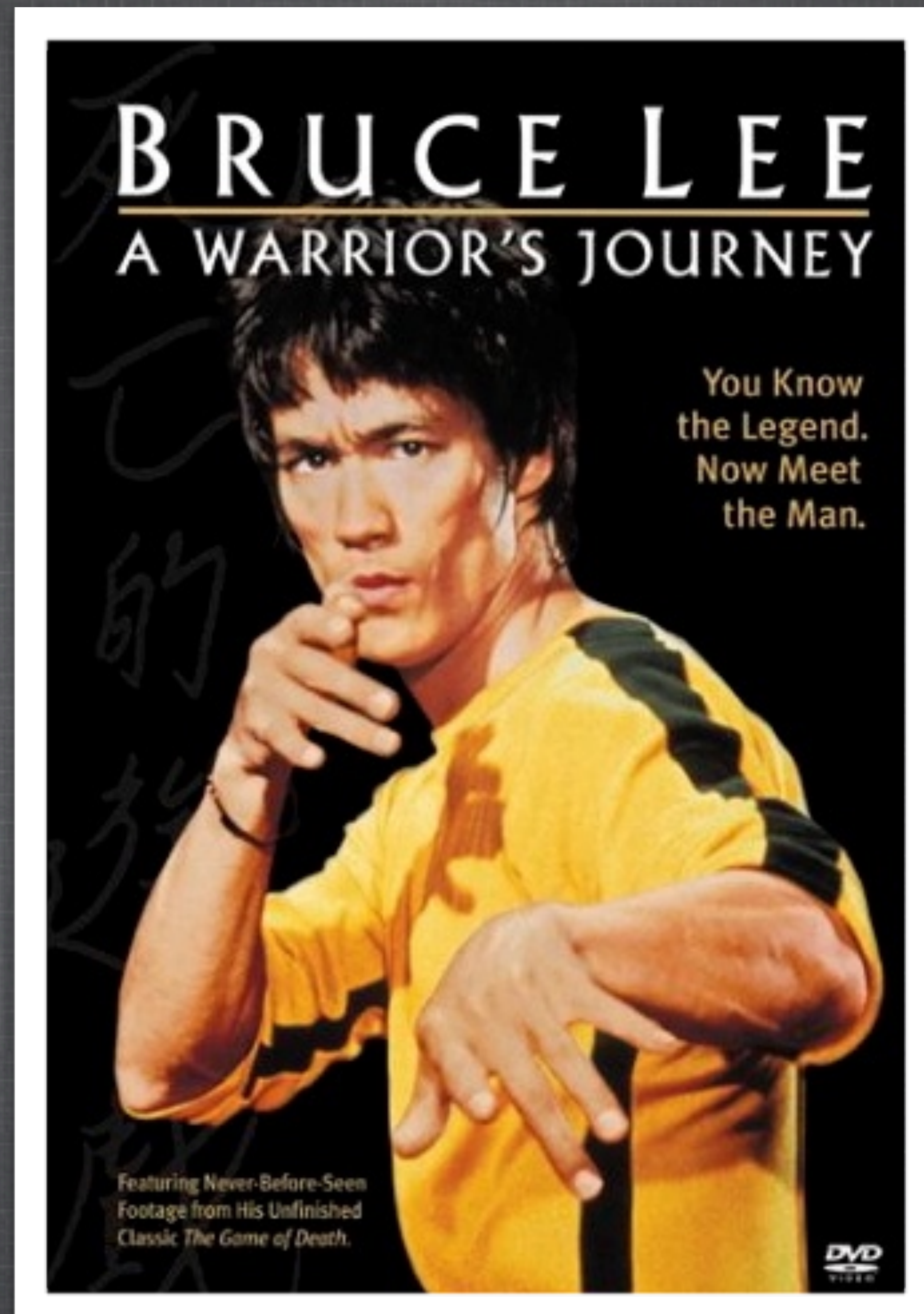




Maximum local significance ~2.6σ
at 119 GeV /c² and 124 GeV/c²
(H→4l) (H→γγ)

Maximum local significance ~3.6σ
(2.8σ H→γγ + 2.1σ H→4l + 1.4σ H→2l2ν)
at 126 GeV /c²

Getting excited about the high significance? Wait a minute!

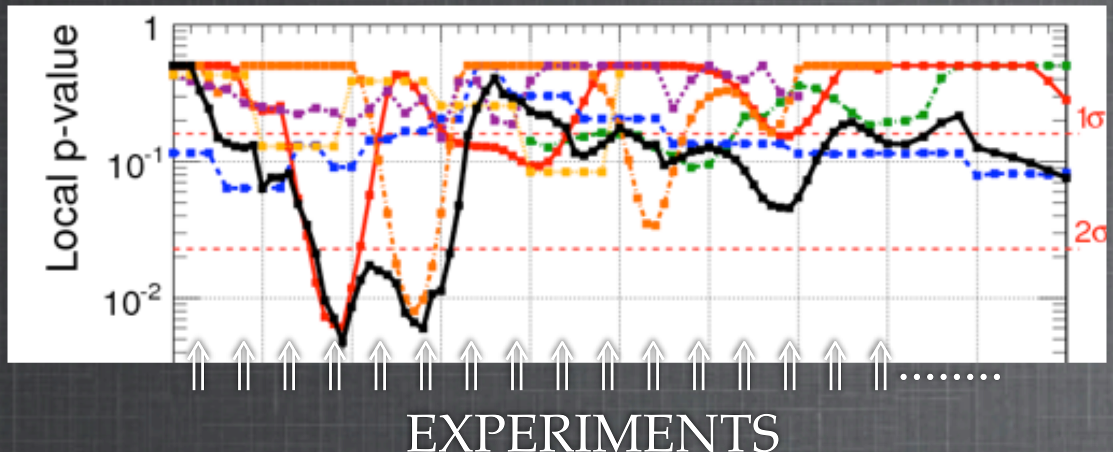


We still have to consider the LEE (*Look-Elsewhere Effect*)...

THE LOOK-ELSEWHERE EFFECT

The look-elsewhere effect is a phenomenon, where an apparently statistically significant observation may have actually arisen by chance because of the size of the parameter space to be searched.

– from Wikipedia



Actually, this is not a single experiment. When we look for different Higgs masses, these are equivalently **MANY** experiments.

The significance is overestimated if we take the maximum local value.

CMS

Maximum local significance: **2.6σ**
LEE corrected in full range (110~600): **0.6σ**
LEE corrected in low mass (110~145): **1.9σ**

ATLAS

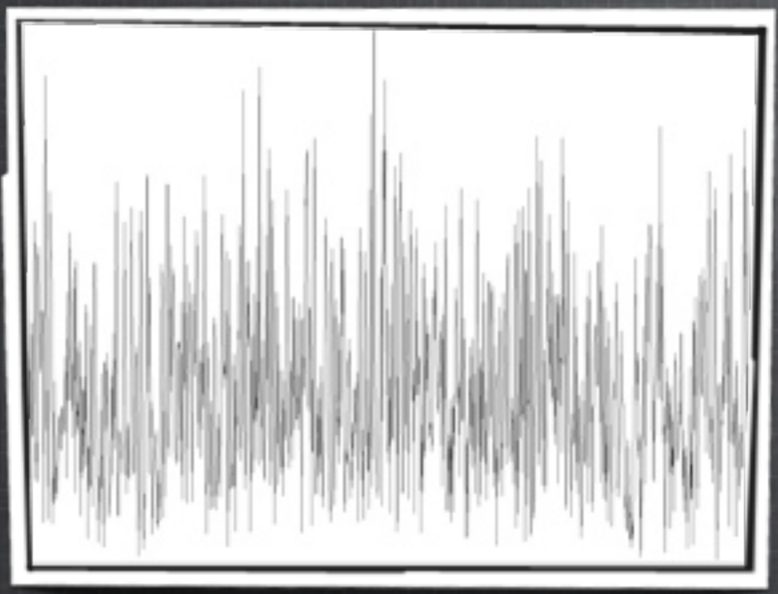
Maximum local significance: **3.6σ**
LEE corrected in full range (110~600): **2.2σ**
LEE corrected in low mass (110~146): **2.5σ**

The excess observed in the low mass region has a modest statistical significance and could be still reasonably a fluctuation of the background.

THE LOOK-ELSEWHERE EFFECT

Analogy #1

In our magic coin example, if you have examined a bag of coins, the chance to find an unfair coin is definitely higher than just one coin.



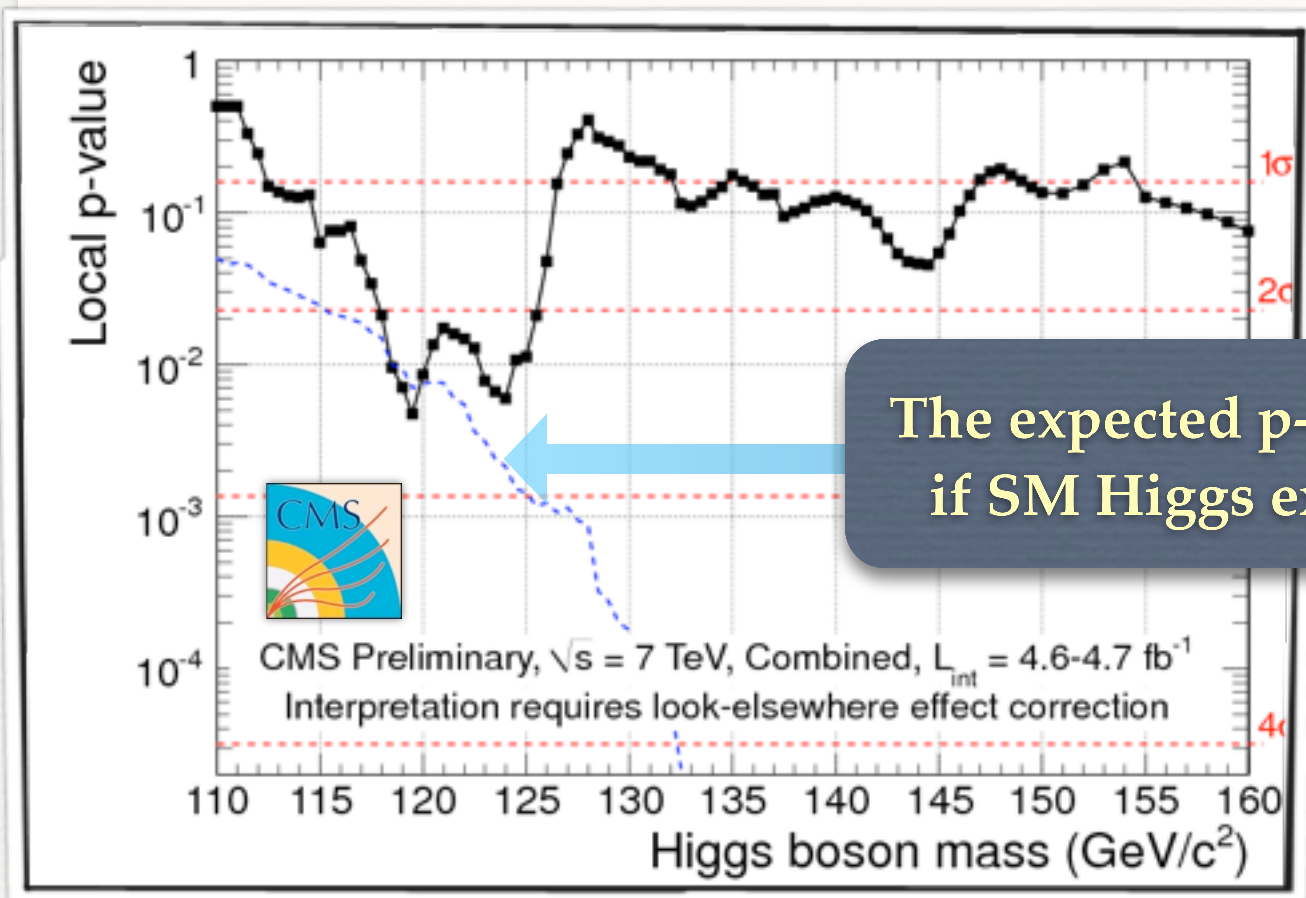
Analogy #2

Surely you can find many peaks on a random noise distribution. It is not too difficult to find a single peak with 3σ as well.

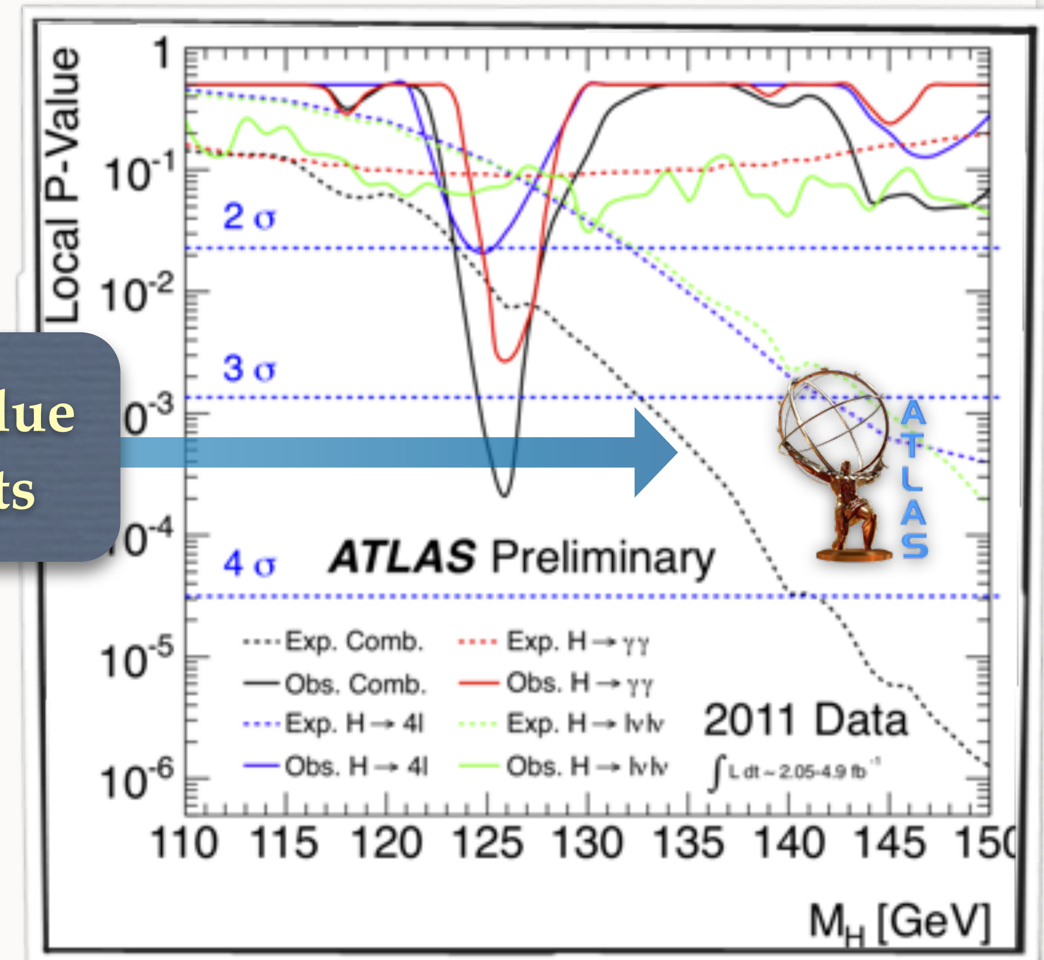
This is the same as the Higgs hunting, scanning over a large mass region.

THIS IS EXPECTED...

- Don't be too disappointed: actually both experiments do not expect to see a >3σ effect in low mass region with the current data sets:

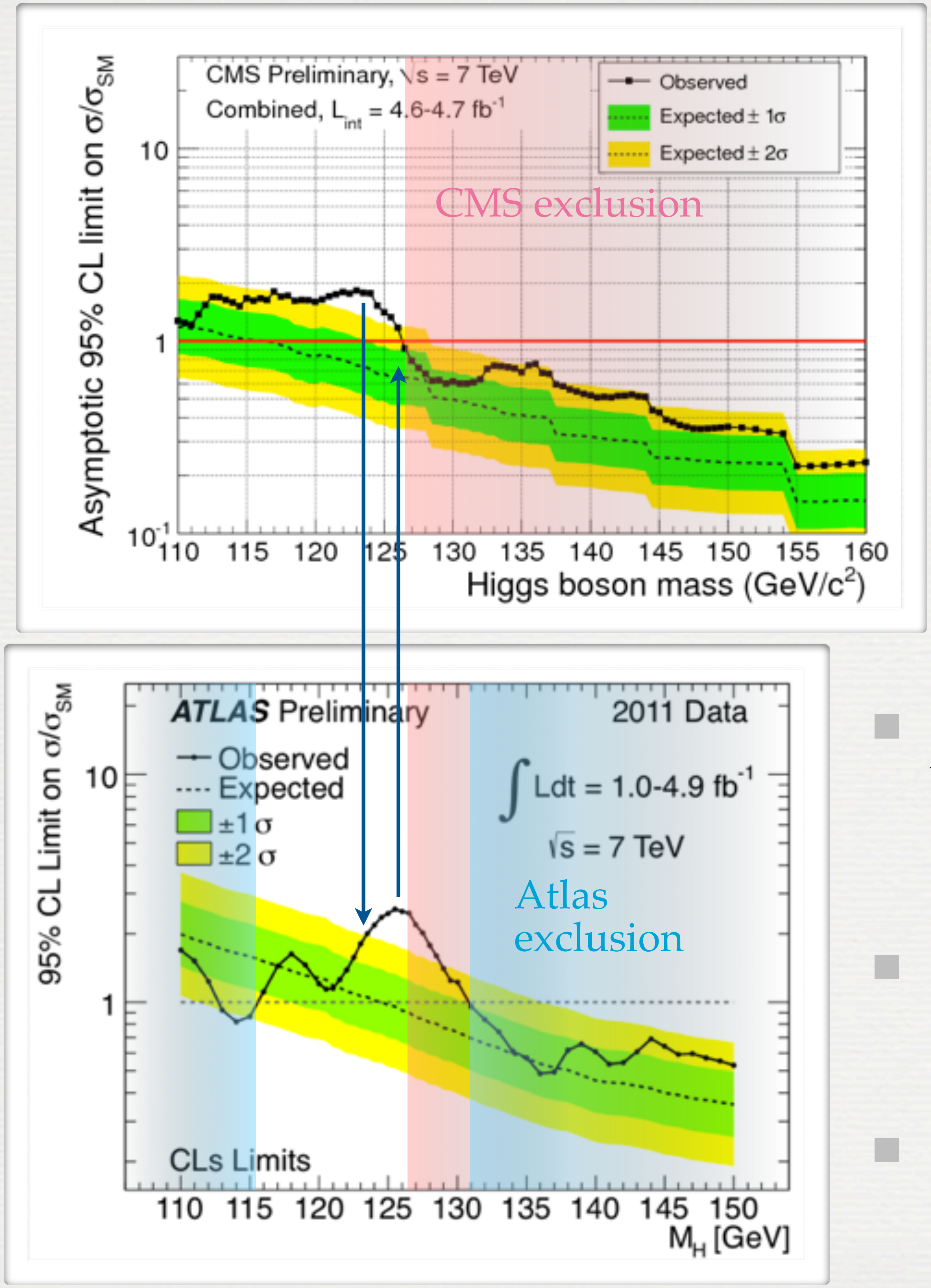


The expected p-value if SM Higgs exists



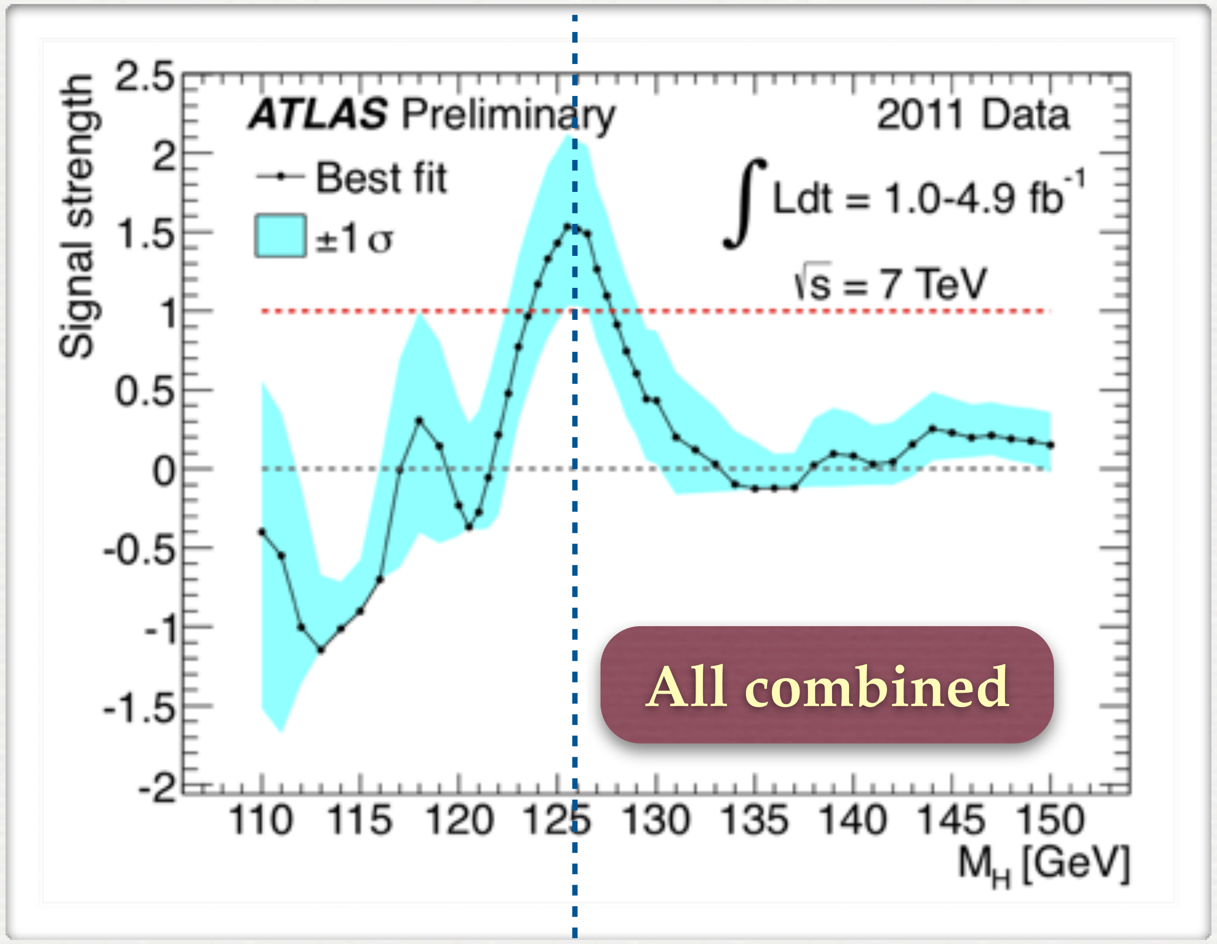
Both experiments only expect to see a 2~3σ excess in 115~127 GeV/c² even if SM Higgs is there....

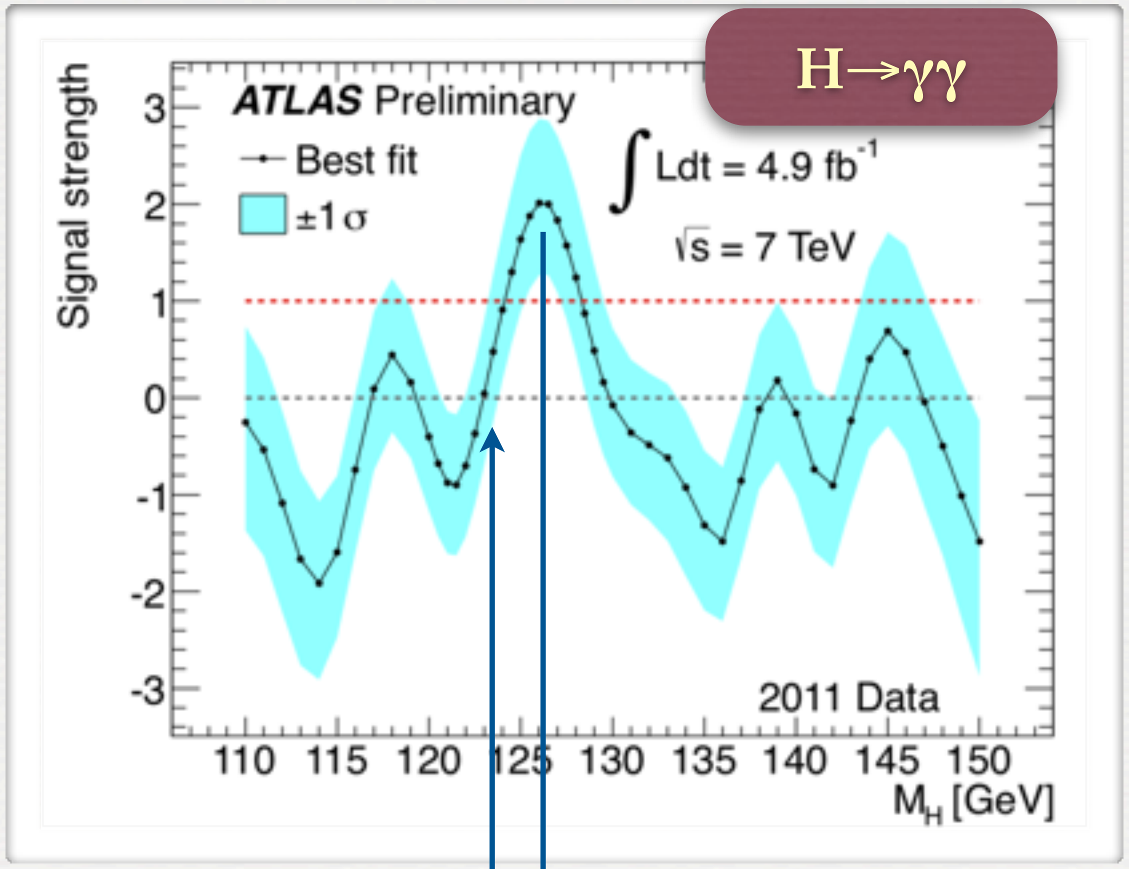
CMS VERSUS ATLAS

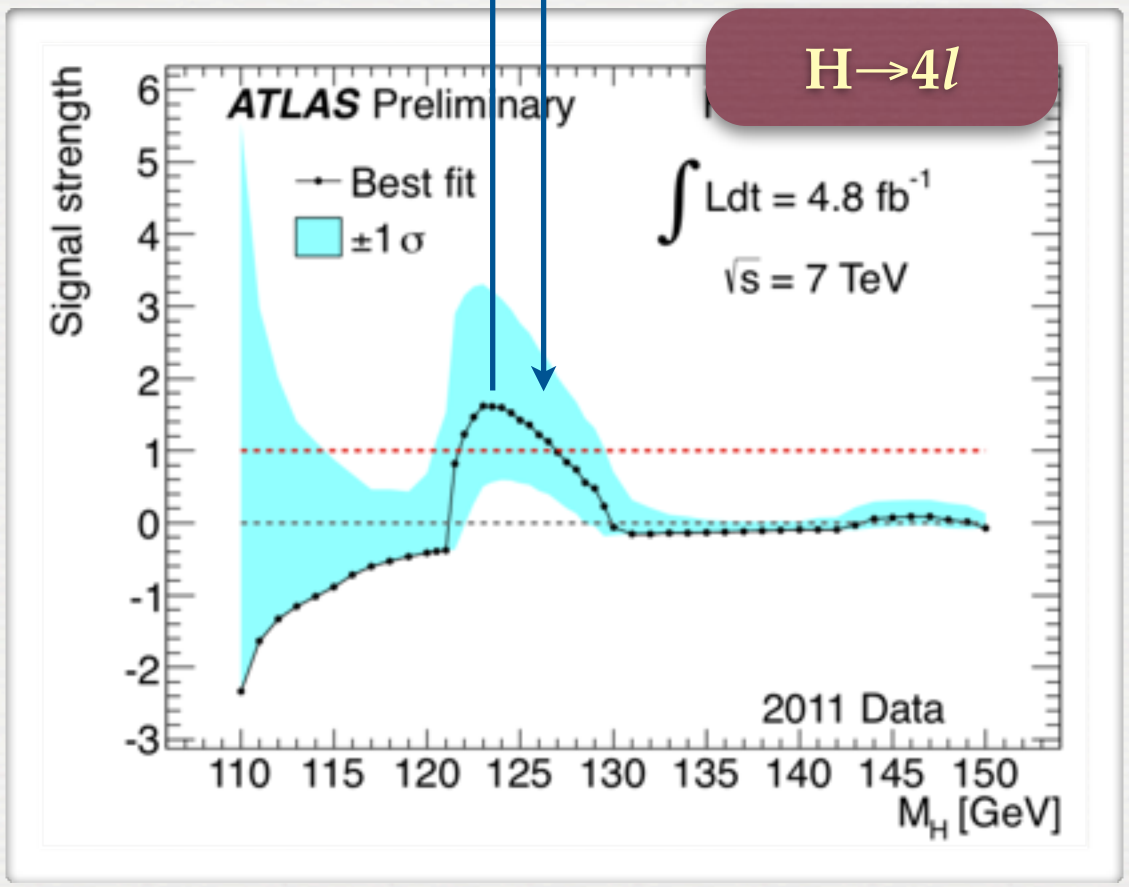


- The excesses from two experiments differ by 2 GeV. This is hard to be explained by the peak resolution (since the Z mass peak is already well calibrated).
- The Atlas excess at 126 GeV / c^2 is supported by both $H\rightarrow\gamma\gamma$ and $H\rightarrow\gamma\gamma$, but it's too close to CMS lower bound.
- The CMS excesses are at different places *($H\rightarrow\gamma\gamma$ is at 124 GeV/c^2, $H\rightarrow\gamma\gamma$ is at 119 GeV/c^2)*

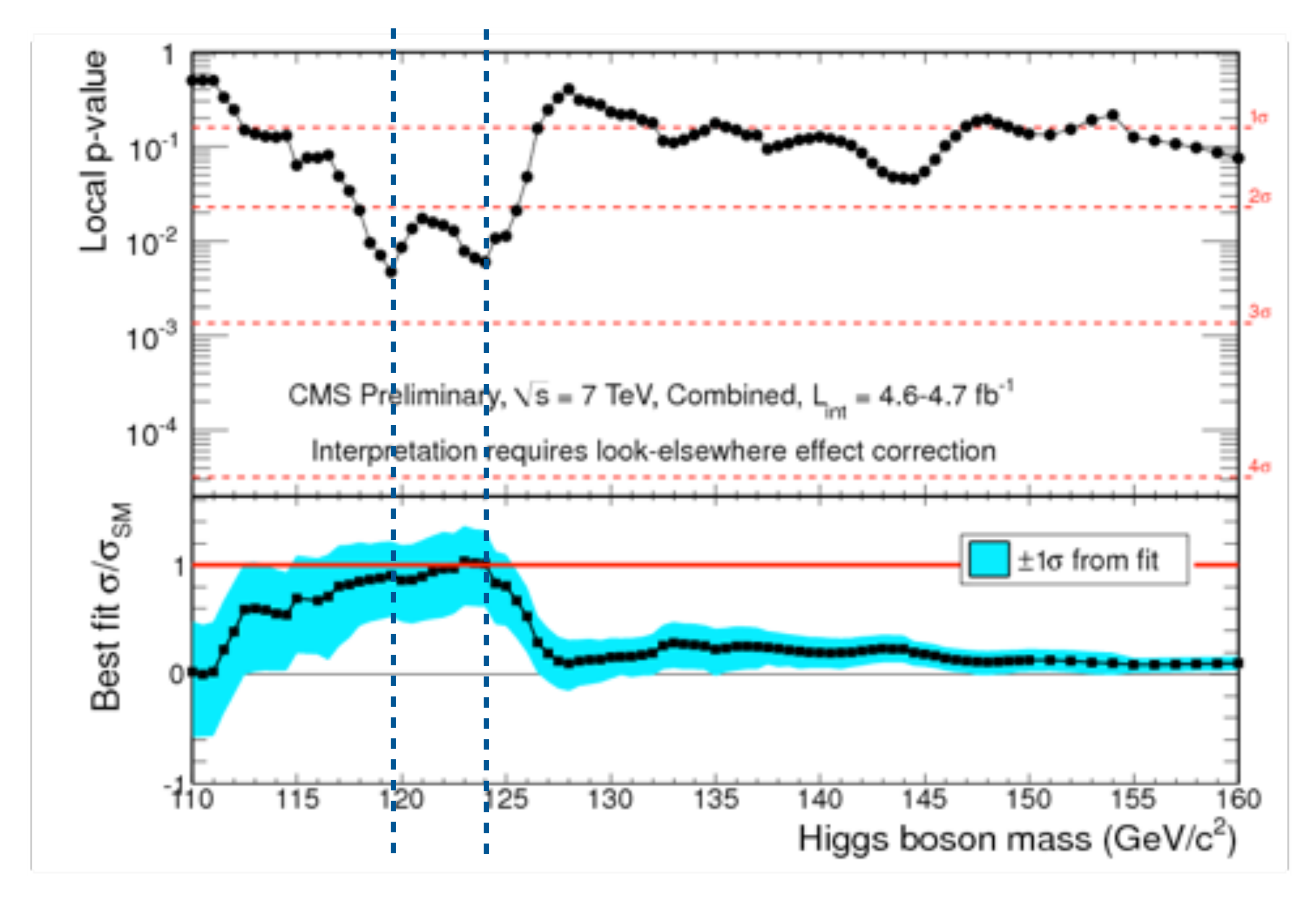
BEST FITTED CROSS SECTIONS



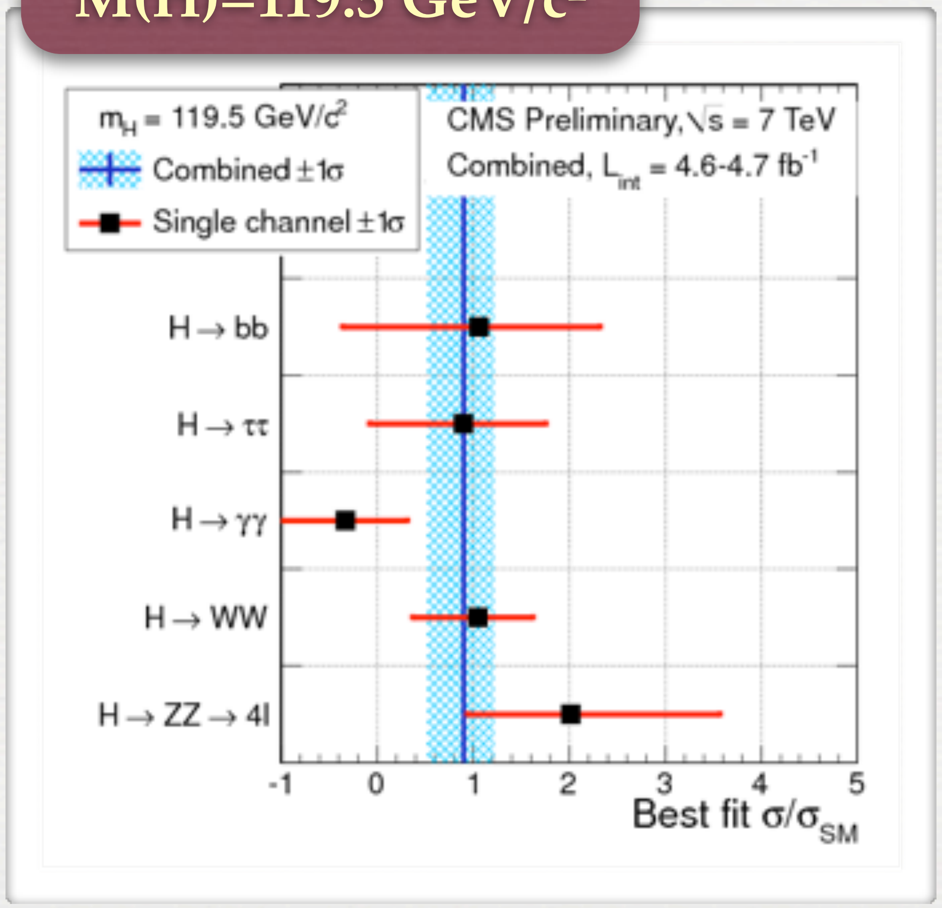




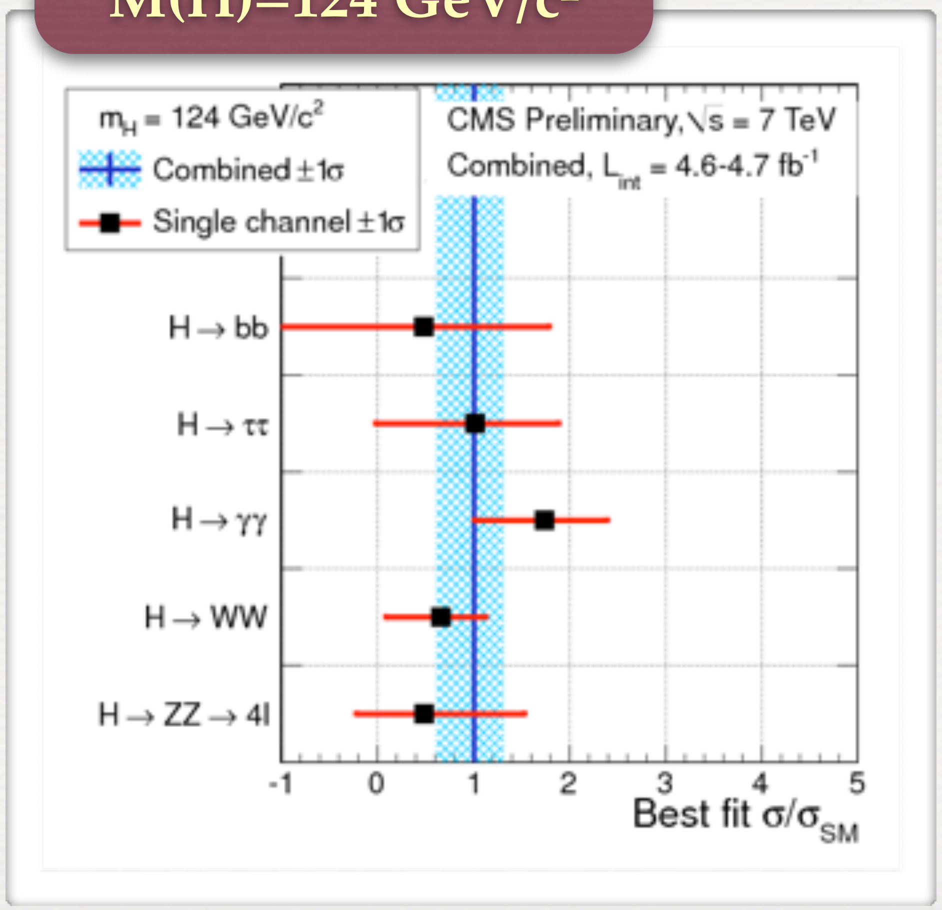
BEST FITTED CROSS SECTIONS



M(H)=119.5 GeV/c²



M(H)=124 GeV/c²

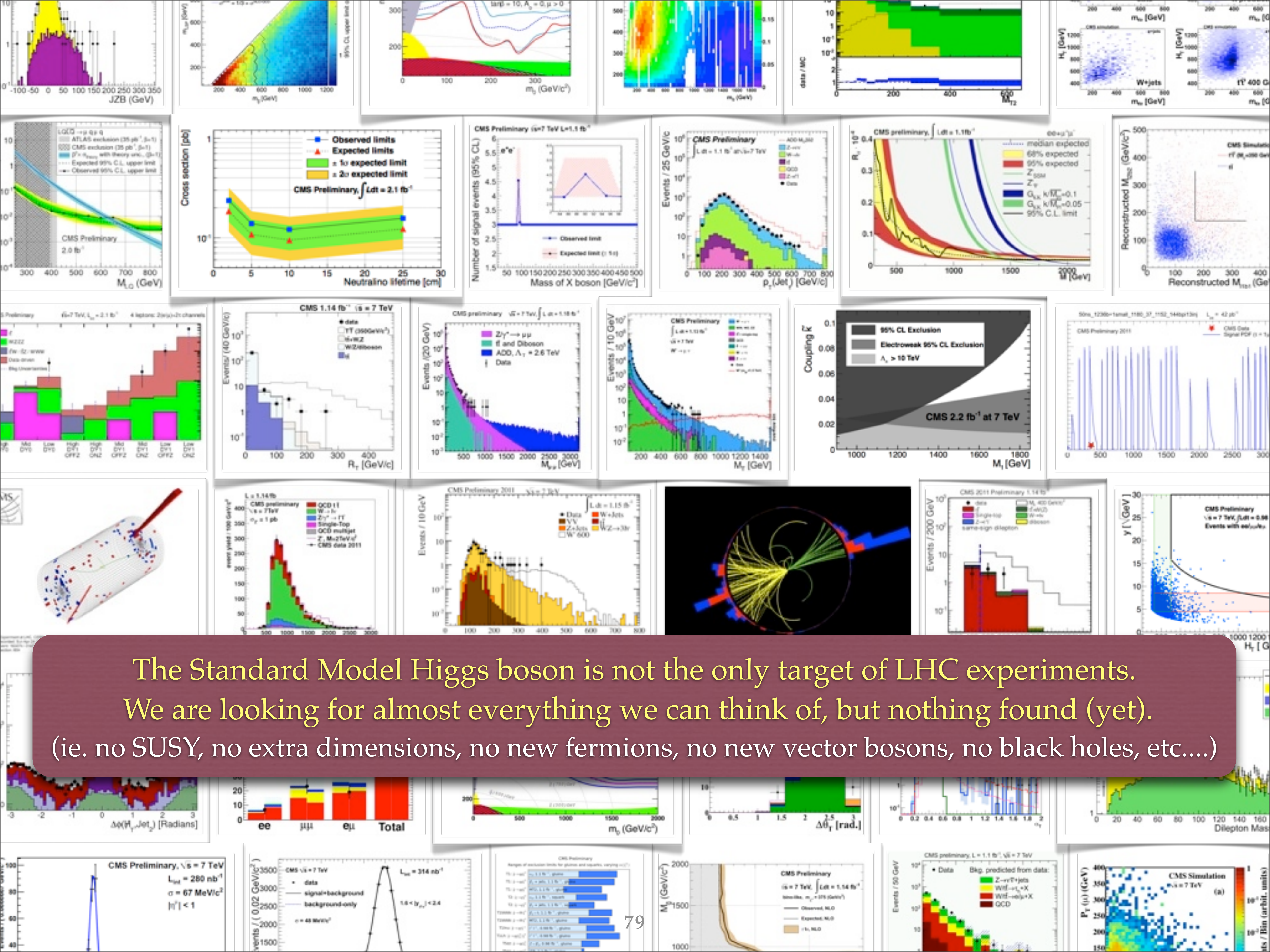


CLOSING REMARKS

OFFICIAL CERN STATEMENT

"The main conclusion is that the Standard Model Higgs boson, if it exists, is most likely to have a mass constrained to the range 116-130 GeV by the ATLAS experiment, and 115-127 GeV by CMS. Tantalising hints have been seen by both experiments in this mass region, but these are not yet strong enough to claim a discovery."

This is a true, accurate statement.



The Standard Model Higgs boson is not the only target of LHC experiments.
We are looking for almost everything we can think of, but nothing found (yet).
(ie. no SUSY, no extra dimensions, no new fermions, no new vector bosons, no black holes, etc....)

CLOSING REMARKS

CMS and Atlas have published 200 papers
(with another 200 papers in the pipeline), but none of them
shown a significant deviation from the Standard Model.

We already know that the Standard Model is imperfect,
even with a not-yet-concluded light Higgs boson.
(e.g. non-zero neutrino mass, hierarchy problem, etc.)

It is very strange that we observed nothing other than the Standard Model particles.
Maybe we just need to wait a little bit more time.

In year 2012, LHC will deliver 20 fb^{-1} integrated luminosity, probably at 8 TeV.
We shall be able to draw a final conclusion for the Higgs boson,
and maybe, even better, we start to see some other new physics signals.

CLOSING REMARKS

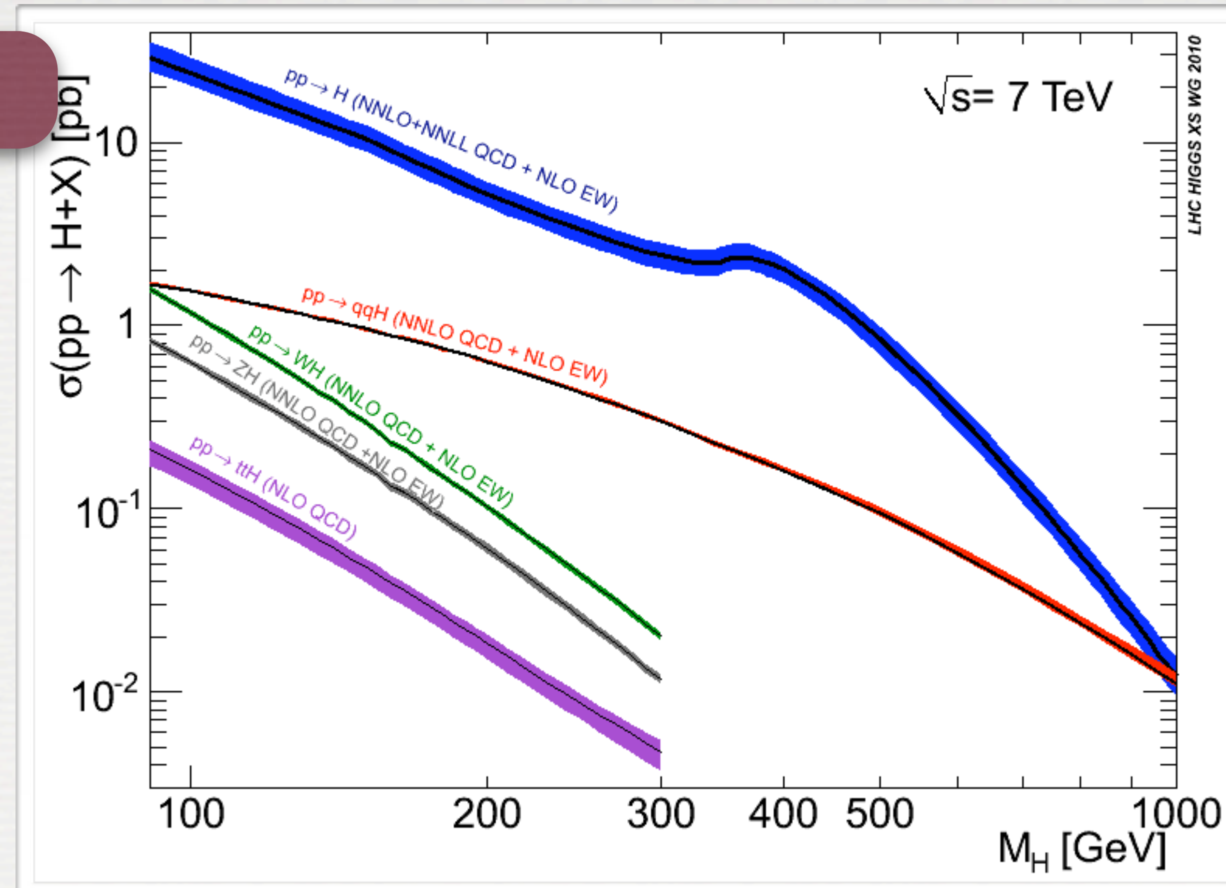
If you believe in Higgs, you may safely interpret the excess as the Higgs boson, and continue your reach life.

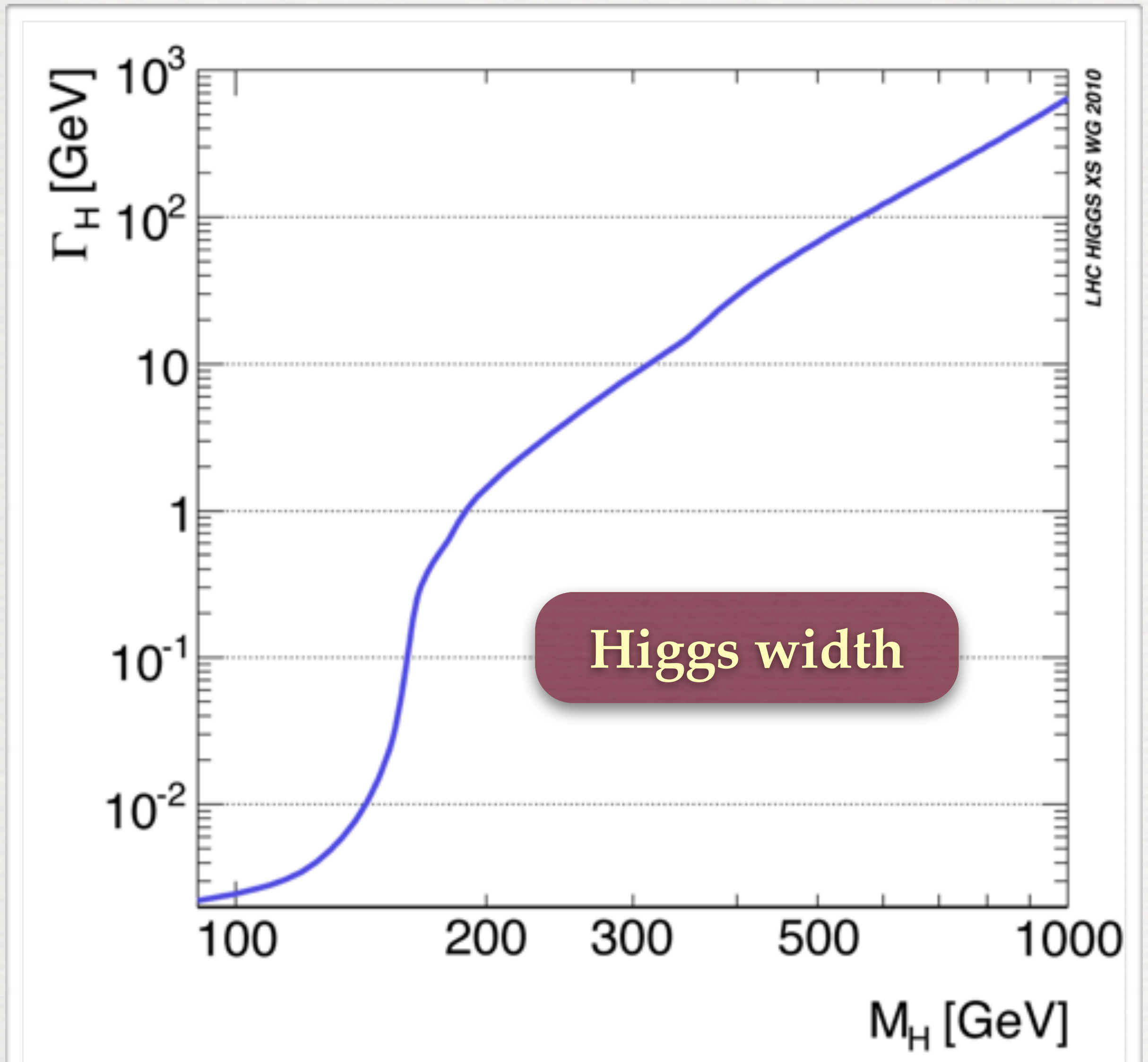
If you don't believe in Higgs, you can still claim this is just a statistical fluctuation of background.

Then just wait for one more year for the final judgement.

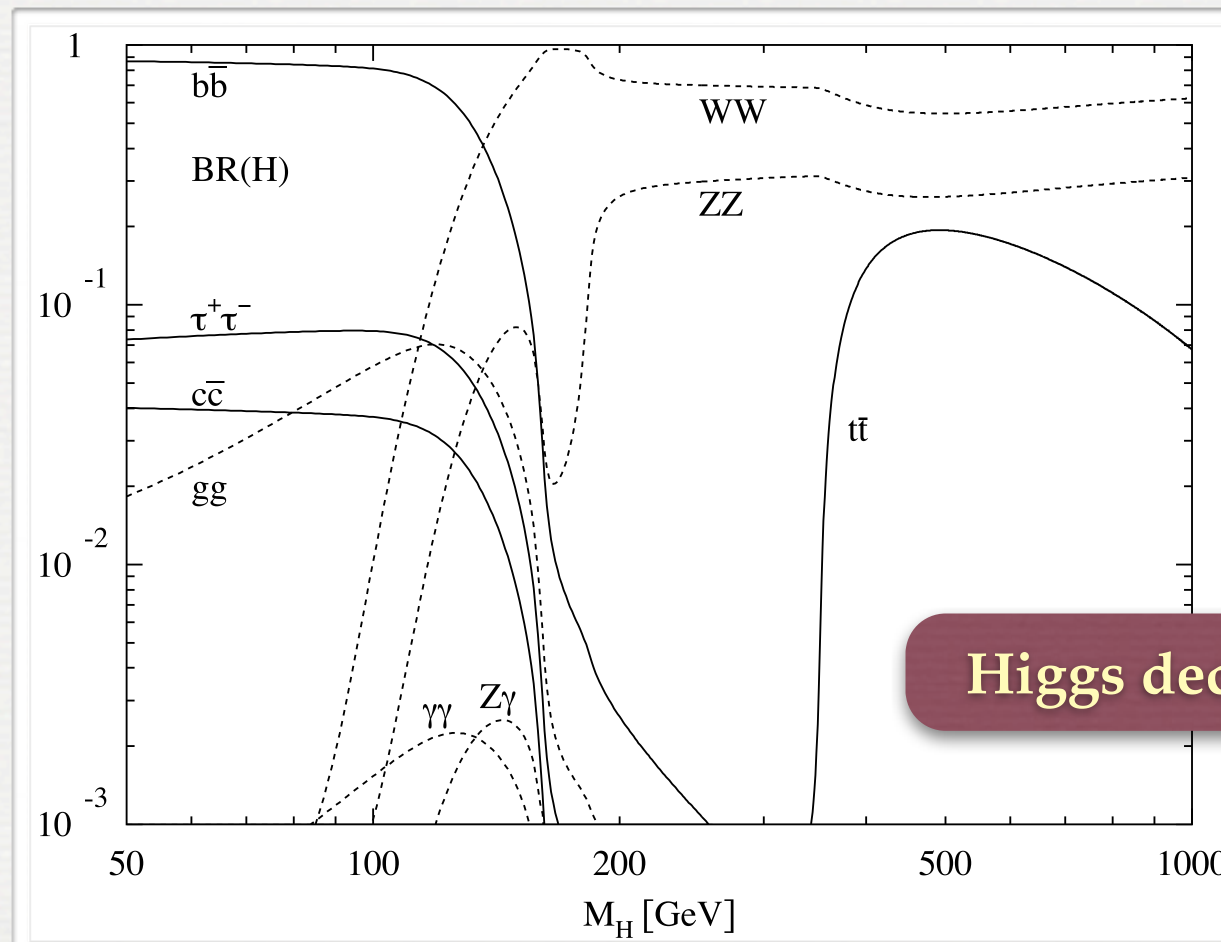
BACKUP SLIDES

Higgs production at LHC

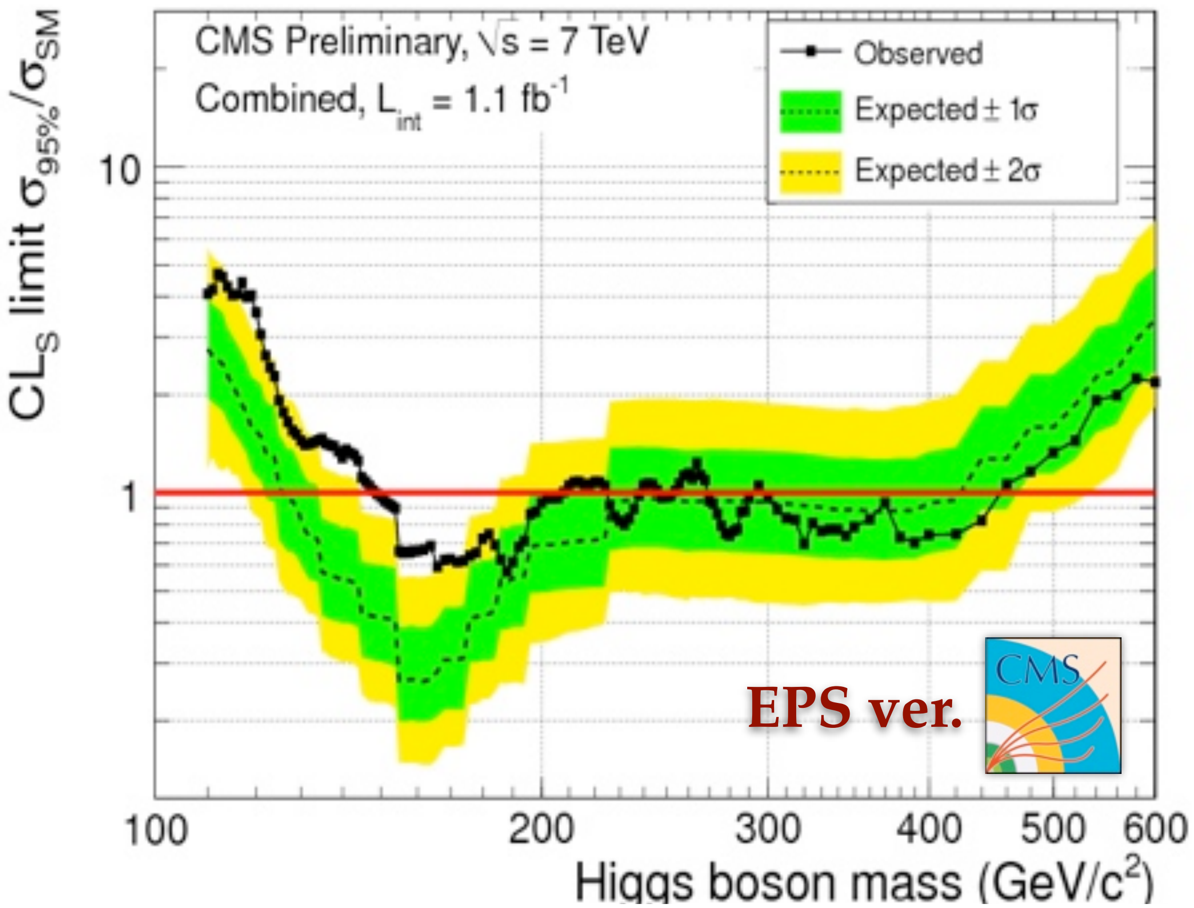


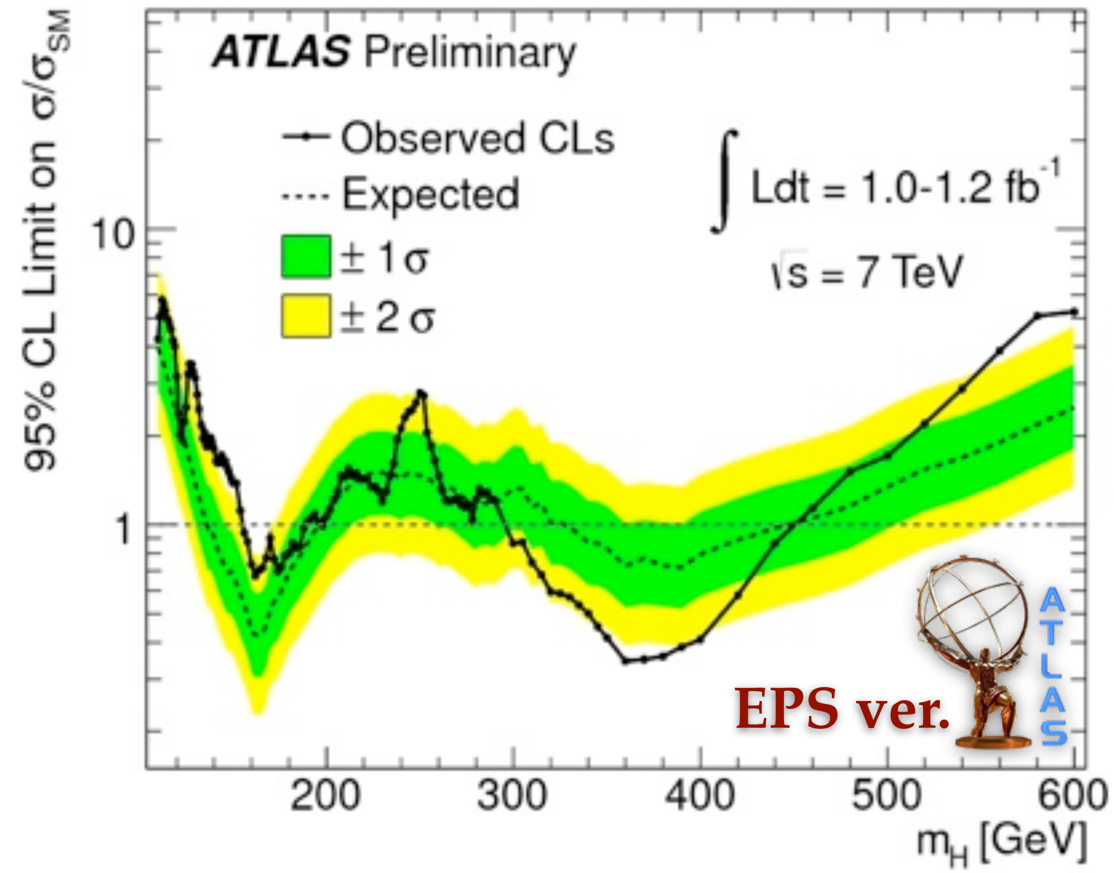


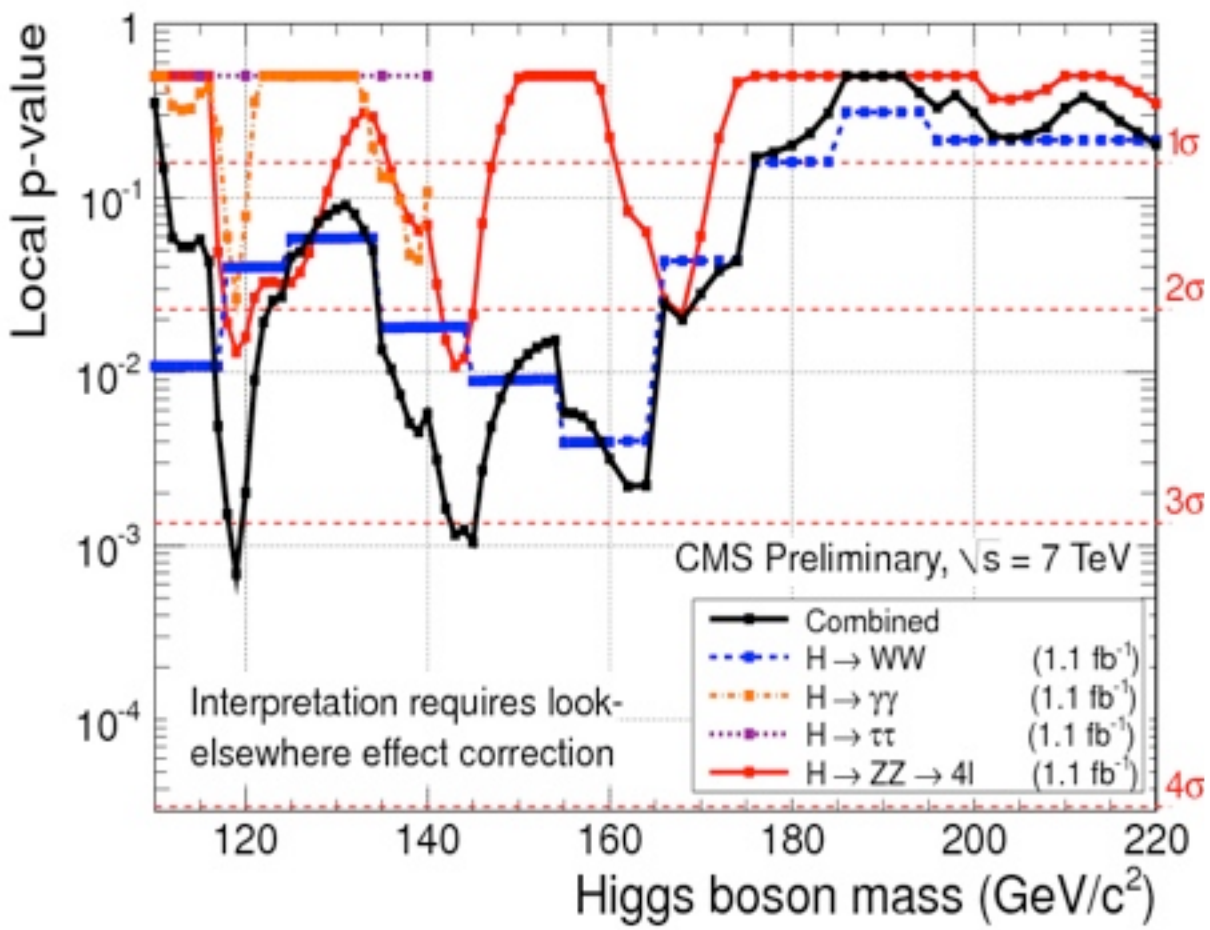
Higgs width

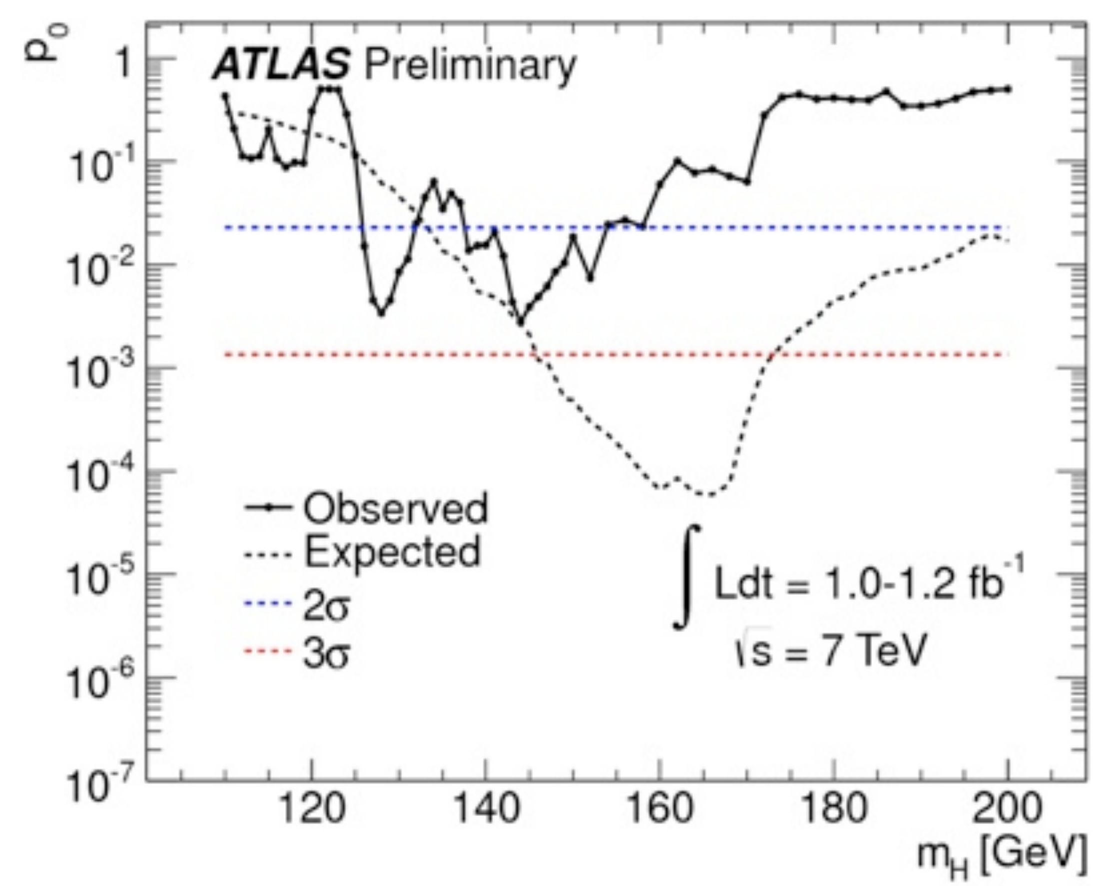


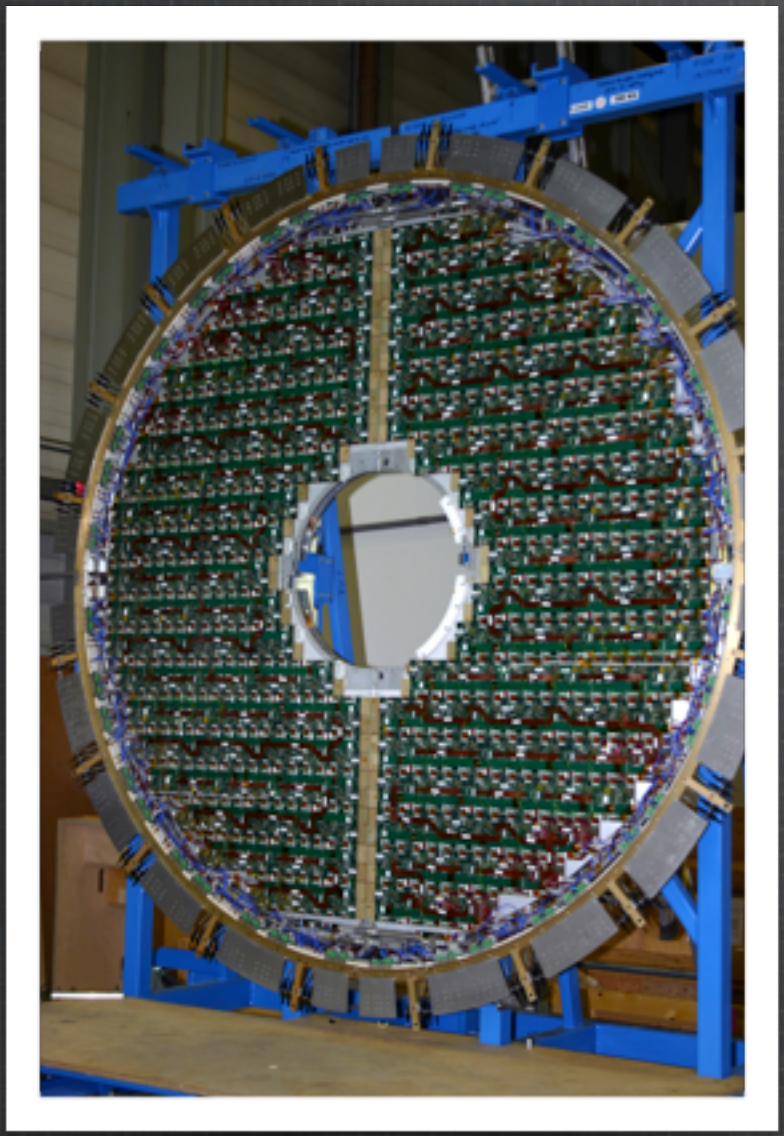
Higgs decay


CMS Preliminary, √s = 7 TeV
Combined, L_int = 1.1 fb^-1
Observed
Expected ± 1σ
Expected ± 2σ
CLs limit σ95%/σSM
10
1
100
200
300
400
500
600
Higgs boson mass (GeV/c²)
EPS ver.
CMS

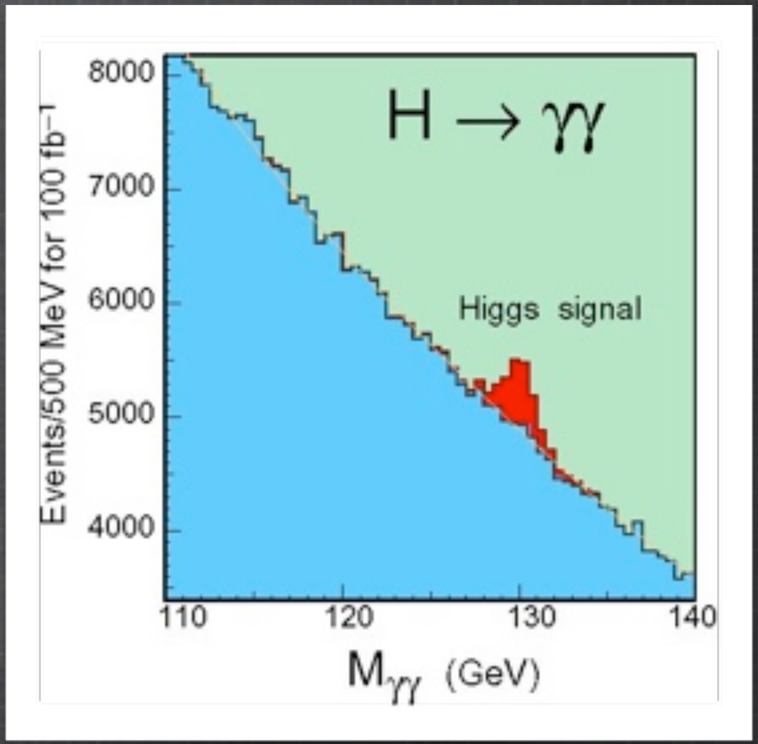

ATLAS Preliminary
Observed CLs
Expected
± 1σ
± 2σ
∫ Ldt = 1.0-1.2 fb^-1
√s = 7 TeV
95% CL Limit on σ/σSM
10
1
200
300
400
500
600
m_H [GeV]
EPS ver.
ATLAS


Local p-value
1
10^-1
10^-2
10^-3
10^-4
1σ
2σ
3σ
4σ
CMS Preliminary, √s = 7 TeV
Combined
H → WW (1.1 fb^-1)
H → γγ (1.1 fb^-1)
H → ττ (1.1 fb^-1)
H → ZZ → 4l (1.1 fb^-1)
Interpretation requires look-elsewhere effect correction
120
140
160
180
200
220
Higgs boson mass (GeV/c²)


ATLAS Preliminary
p0
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
Observed
Expected
2σ
3σ
∫ Ldt = 1.0-1.2 fb^-1
√s = 7 TeV
120
140
160
180
200
m_H [GeV]



FROM PRESHOWER TO HIGGS

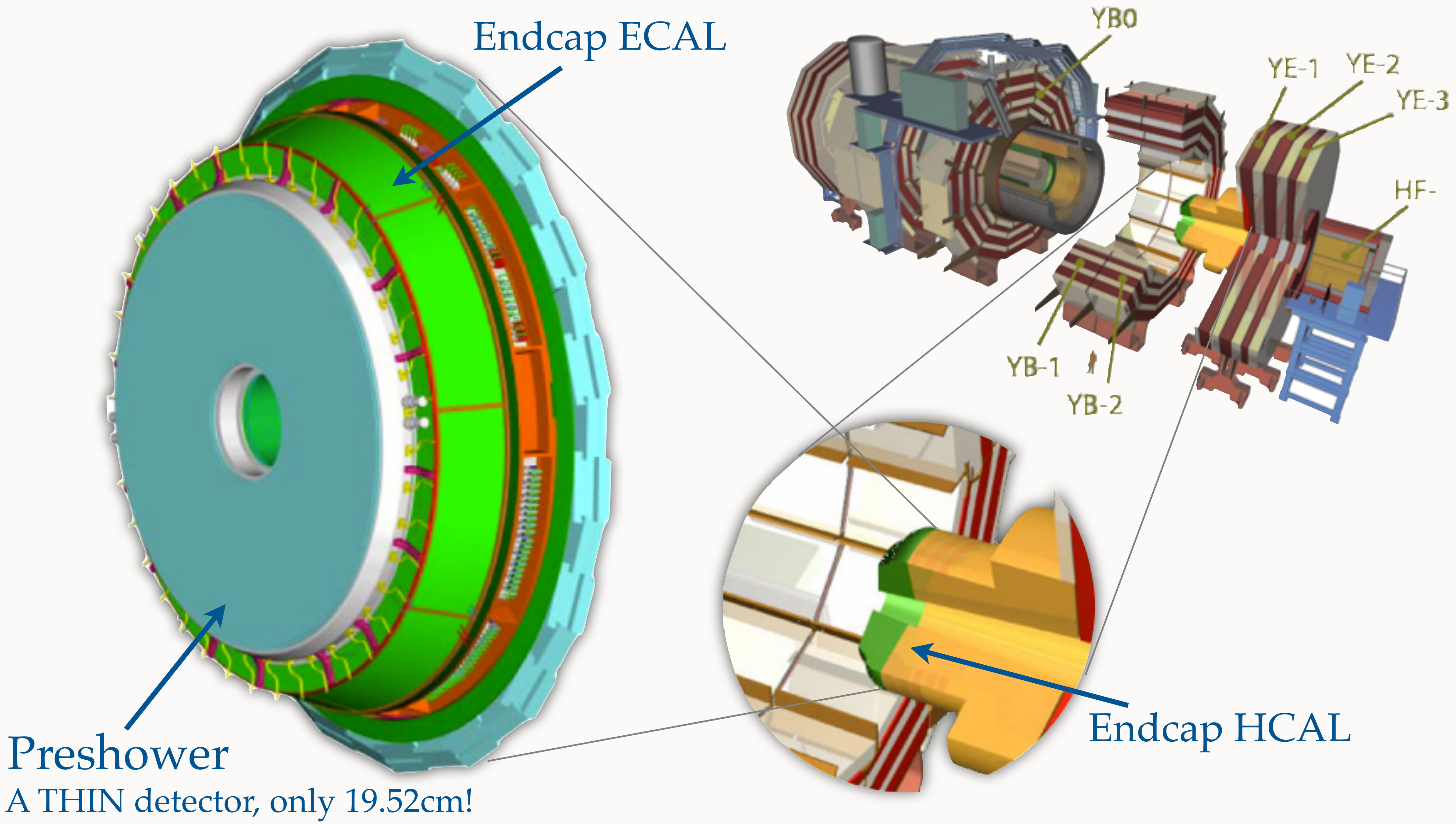


Higgs searches are very difficult, but it is not due to the rarity...

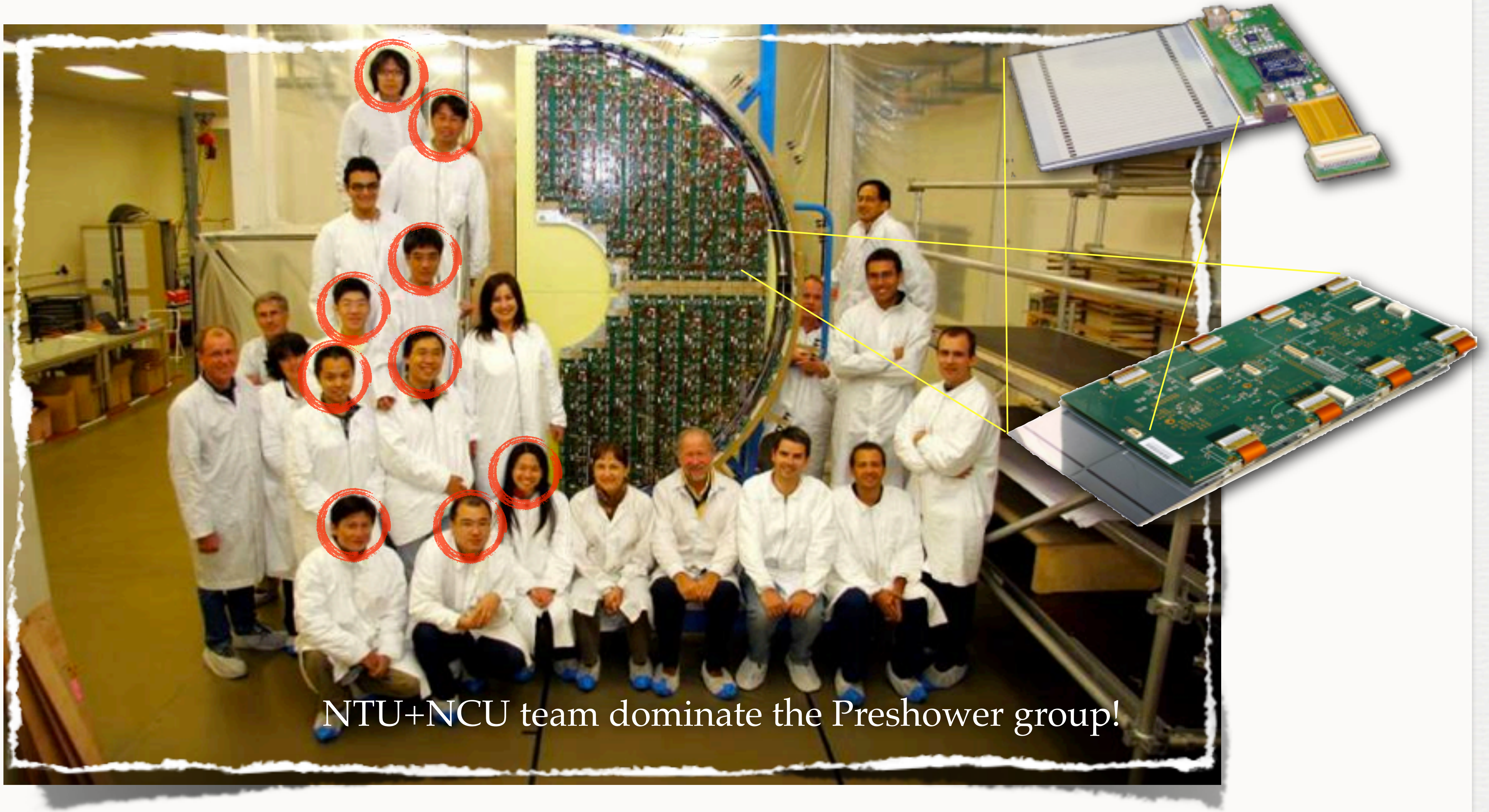
We all want to work on Higgs!

Unless we are well prepared, it's better not to join the battle too early...

OUR COMMITMENT:
THE PRESHOWER DETECTOR

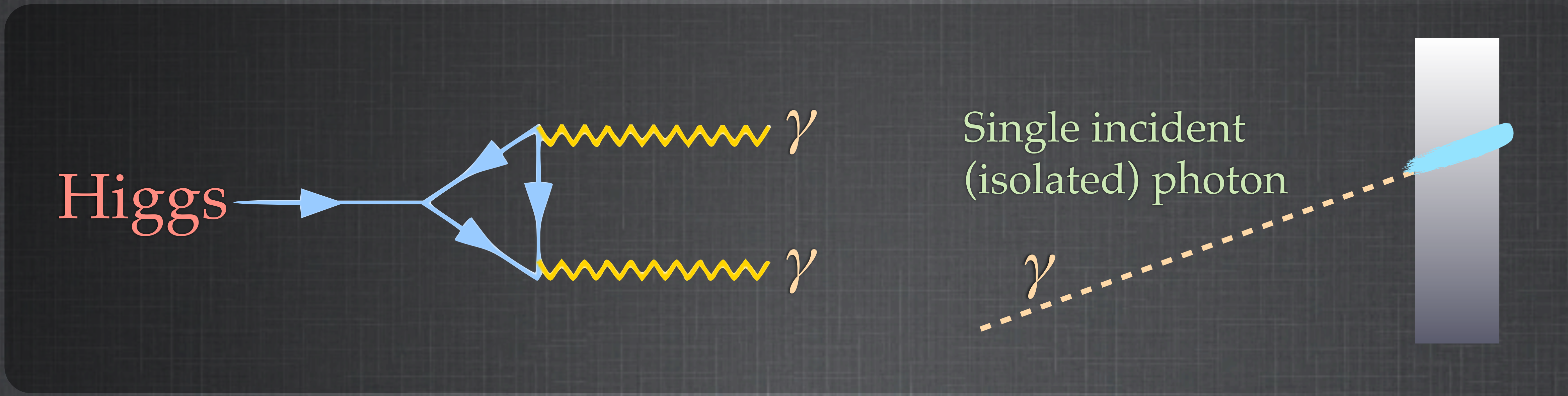


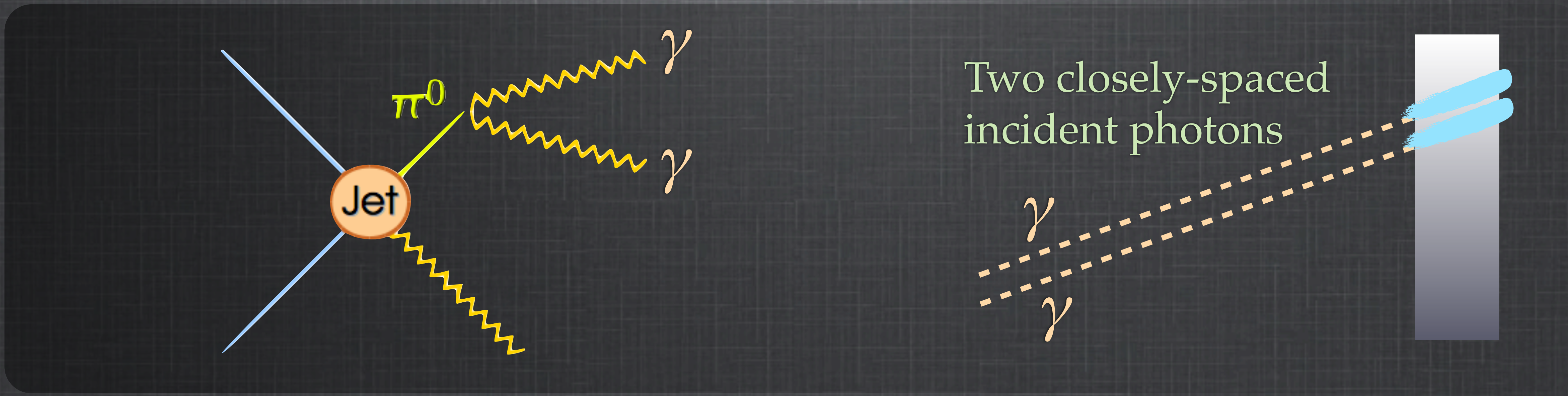
OUR COMMITMENT:
THE PRESHOWER DETECTOR



NTU+NCU team dominate the Preshower group!

WHY PRESHOWER?





Silicon sensors had chosen for improving spatial resolution for endcap ECAL.

WHY PRESHOWER?

We built the Preshower detector

We maintain the detector

We provide the calibration and alignment constants.

We develop the algorithm to suppress π^0 background

Then, we can finally join the work on $H \rightarrow \gamma\gamma$!

It's a long track, but if we can maintain all the required work very well, we can eventually be part of the Higgs analysis!

Q&A

Q: Why does the current search stop at 600 GeV?
A: The SM Higgs boson of high mass becomes very wide, which leads to large theoretical uncertainties in predictions of its production and mass line shape m(H*). For a SM Higgs boson with mass of 600 GeV, the production uncertainties are about 30% and rapidly grow for higher masses. Advanced theoretical calculations for the SM Higgs boson with a mass greater than 600 GeV are expected next year, according to the LHC Higgs cross section group.

Q: You say the mass range [127, 600] GeV is excluded at 95% CL. Is it sufficient level of confidence? Is the presence of a SM Higgs boson there now truly excluded or…?
A: No, it is never excluded at 100%. A 95% exclusion is a common practice in HEP. One can read exclusion limits at any desired confidence level form the CLs plot we provide as a part of our results. For example, at 99% CL, today's results exclude the mass range of [128,525] GeV.

Q: Last summer you had an excess at ~140GeV, which was similar in shape and significance to the one you have now at ~124GeV. Did the 140 move down to 124? Or is the 140 excess still there? If it's the latter, can the 140GeV excess be an indication for a BSM Higgs with a x-section significantly lower than the SM one for that mass?
A: No, the modest excess we had at 140GeV did not move down to 124GeV. Due to the excellent momentum resolution of our detector, these two modest excesses are seen in the data independently. In fact, the modest excess around 140GeV is still there, but its significance is now considerably smaller as the new data we collected since the EPS conference did not bring as many new events in that mass range. This is why we make it very clear that one needs be prudent and not get overexcited about modest excesses of events. Statistical fluctuations are not unlikely and do happen.

Q&A

Q: Is the observed excess an indication for the Higgs boson ?
A: With the current amount of data, the excess is not unlikely to be a plain statistical fluctuation. On the other hand, it is not inconsistent with the Standard Model Higgs boson either. It also may turn out to be due to some other unaccounted backgrounds. Much more data coming in 2012 will allow us to pin down the true nature of the observed excess.

Q: At the low end you had some excess at 140GeV in the summer, which went away and now there is a new excess at 124? Why did this excess move? How likely are these bumps to move around? How stable (reliable?) is this analysis?
A: No, the modest excess we had last summer at 140GeV did not move down to 124GeV. Due to the excellent momentum resolution of our detector, these two modest excesses are seen in the data independently. They do not move around. In fact, the modest excess at 140GeV is still there, but the number of events observed is already below that expected from SM backgrounds, hence we can exclude that this excess is due to SM Higgs. Should we mention potential BSM Higgs with production x-section significantly smaller than SM Higgs?

Q: What happens to the two dips in the p-value distribution if one were to eliminate one event from each one of them? Is any one of them become significantly more likely to be consistent with background-only interpretation and hence less signal-like?
A: If one were to eliminate one event from the 119GeV excess, its significance would have been reduced from 2.8 sigma down to 1.9 sigma, which makes it a lot less impressive. Eliminating one event from the 124GeV excess, its significance would have been reduced from 2.5 sigma down to 2.4 sigma, basically remaining intact.

Q&A

Q: Could the two bumps (119 & 124GeV) come from one source? If it's probable, that is an interesting piece of information. If on the other hand it's not, then we know that one has to deal with each one separately and maybe one of them is "worth" more than the other (e.g. see one candidate test for that in the previous question).
A: In principal no, due to the excellent momentum resolution of our detector. However, other physics effect, which are yet to be studied carefully may move a few events around.

Q: What's the right/relevant LEE for today's analysis? Is it the full available mass range of (115,1000) or the not-yet-excluded range (<130 today or <140 last summer) or (take a deep breath!) since ATLAS has already showed its excess at 125GeV there is no need for the LEE here at all.
A: We are quoting two LEEs, one for the full mass range of (100,600) and one for the allowed mass range from the LEP direct searches and precision EWK fits of (110,145). They give you an idea for the sensitivity of this search and the significance of the current result.

Q: What's the likelihood of the composition of excess of events that CMS has in the different channels when comparing with SM expectations? This may sound trivial, yet it carried non-negligible weight since this excess may represent something (or nothing) very different (unlikely) from SM Higgs. The quantitative answer to this question may go a long way to substantiate a statement that if it looks like a duck and it walks like a duck, it is more likely to be (though we certainly cannot say it yet) a duck.
A: As we have shown in the X plot, we have excess of events in all decay channels that we studied so far. They are compatible with the SM Higgs, but also with statistical fluctuations. The likelihood of the data from those channels to come from SM Higgs based on this plot, namely the Chi2 is ...

Q&A

Q: What is sensitivity of CMS for discovering a Higgs Boson of 125GeV compared to ATLAS?
A: This is an excellent question! In fact, to compare the two experiments one should look at their corresponding sensitivities, or in our language "expectations", rather than the observed number of events, where both experiments may have statistical fluctuations up or down. CMS has a larger sensitivity for Higgs at the vicinity of this mass. The expected local P-value of CMS is about 0.001 whereas for ATLAS it is ???

Q: Does the combined CMS/ATLAS result, yet to be done systematically/correctly, constitute a scientific claim of "Evidence for..."? One may argue that two independent experiments seeing about 3 sigma effects in very similar masses is a stronger evidence than a single one seeing ~4 sigma deviation from background-only interpretation.
A: We believe that at this time we should look at each experimental result independently and not draw any conclusions from the two of them combined. As we know from combining the different channels in CMS data, there are subtle issues to be addressed before carefully combining results from the two experiments, and we caution others against a premature combination.

Q: When should one expect the definitive answer on the existence or absence of the Standard Model Higgs boson in the remaining low mass gap?"
A: In 2012, provided that LHC continues to maintain its performance level reached in the fall of 2011.

Q&A

Q: When will you combine the results of CMS and ATLAS? Will you be willing to claim Evidence, or maybe even Discovery, if the corresponding scientific criterion, 3 sigma or 5 sigma, is met?
A: The decision on the combination is the hands of the two collaborations and has not been yet made. Just counting sigma's does not constitute the evidence or discovery. It is an indicator of how the observation is consistent with the background-only **expectation**. A substantial number of self-consistency crosschecks and validation tests will be needed to make such a high-impact claim as a discovery of a Higgs boson.

Q: What happens if the Higgs boson is not found in 2012?
A: The search will go on. There are models where the observable yield of Higgs boson events is reduced with respect to the SM Higgs (e.g. in the fermiophobic Higgs models). With more data and higher center-of-mass energy, we will be able to explore vector boson fusion process. If the light Higgs boson is indeed absent, we should start seeing deviations in the di-boson scattering at 1-TeV scattering energies with an onset of strong electroweak interactions above 1 TeV scale. There are models proposing new physics that will regularize electroweak interactions at the same energy scale---they typically result in 1-TeV scale resonances.

Q: You have excluded at 95% CL up to ~600GeV. How high can you go up with the data to be taken next year? When will you exclude up to 1 TeV?
A: Uncertainties in theoretical predictions for the Standard Model Higgs boson at so high masses are still very high for making quantitative projections on high mass exclusion sensitivities. Advanced theoretical calculations for the SM Higgs boson with a mass greater than 600 GeV are expected early next year, according to the LHC Higgs cross section group. Once these calculations are available, we will be able to project how much data we need to extend the exclusion range to 1 TeV.