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SPECIAL TOPICS IN EXPERIMENTAL PARTICLE PHYSICS

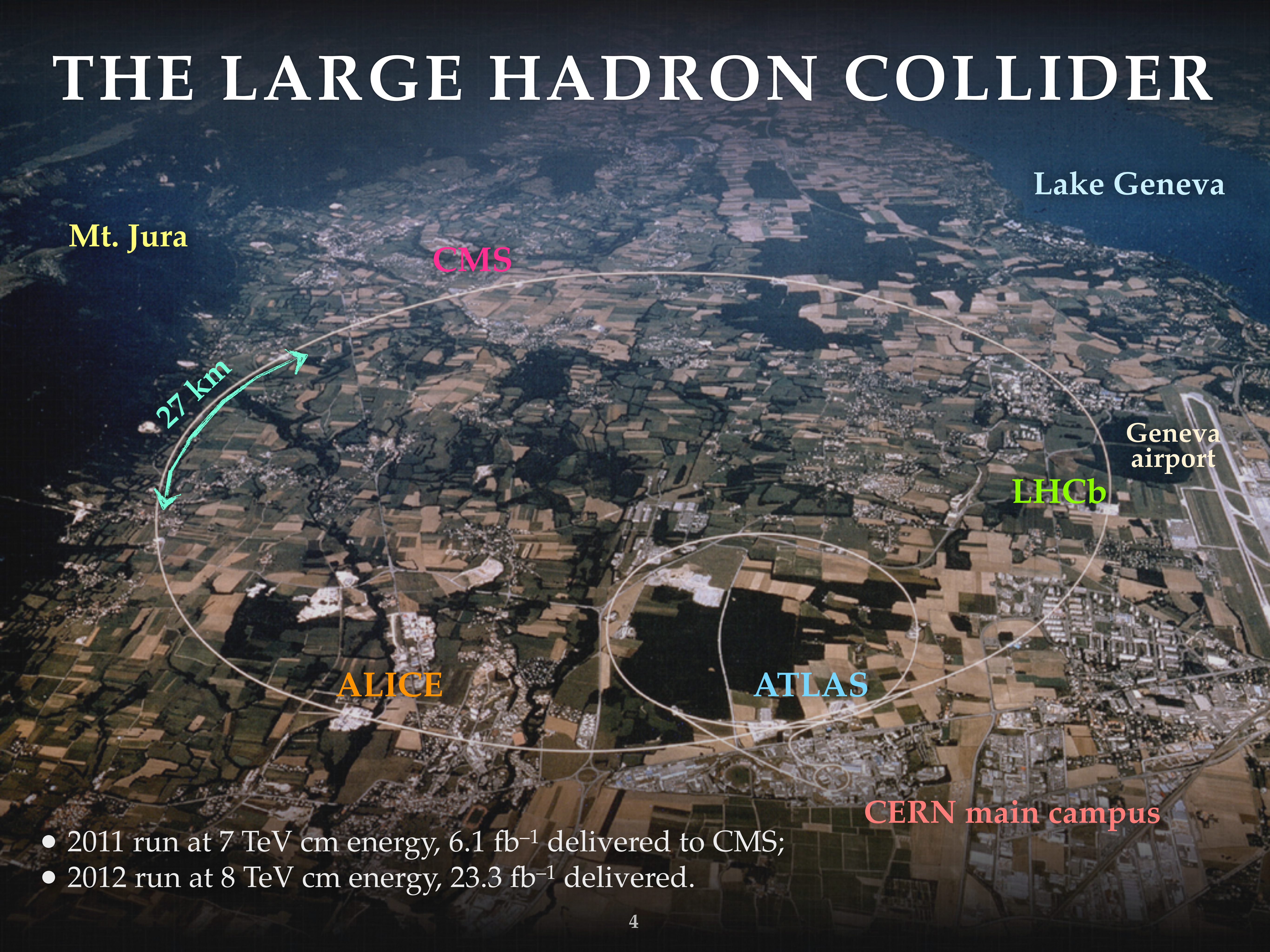
Lecture 2: A new boson named Higgs

SOME USEFUL PREAMBLES

EXPERIMENTAL JARGONS

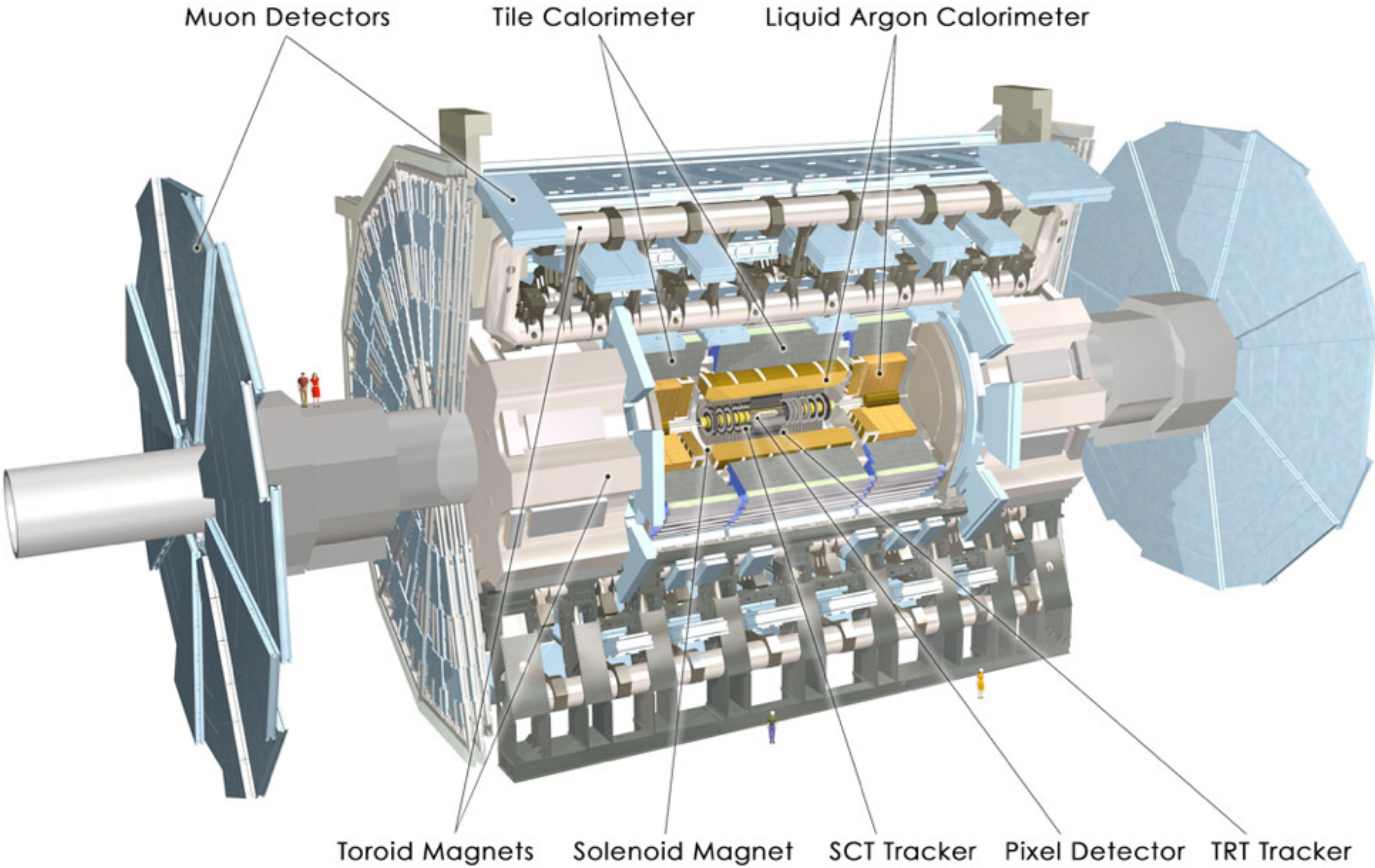
- Unfortunately there are plenty of "jargons" used in this slides and it is hard to avoid them.
- Here are just some of the examples:
  - ➡ Jet, MET (=missing energy)
  - ➡ Trigger
  - ➡ p-value, expected/observed limit
  - ➡ pile-up
  - ➡ b-tagging
  - ➡ MC-driven, data-driven
  - ➡ MVA (multivariate analysis), BDT (boosted decision tree)
- If you do not understand any of them when they show up in the lecture, please stop me and we can alway discuss them. Or they can be further discussion items as well!

THE LARGE HADRON COLLIDER

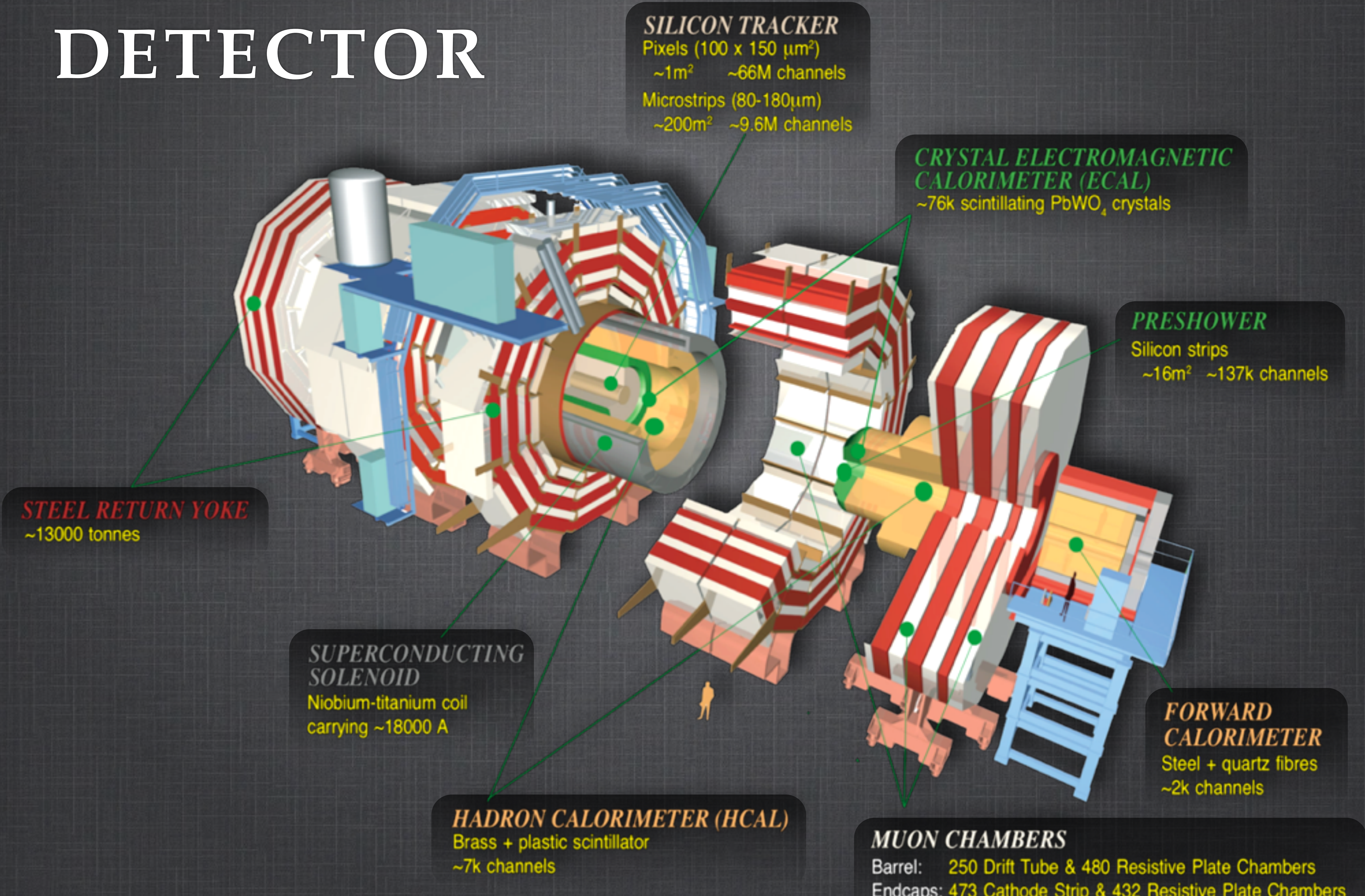


- 2011 run at 7 TeV cm energy, 6.1 fb^{-1} delivered to CMS;
- 2012 run at 8 TeV cm energy, 23.3 fb^{-1} delivered.

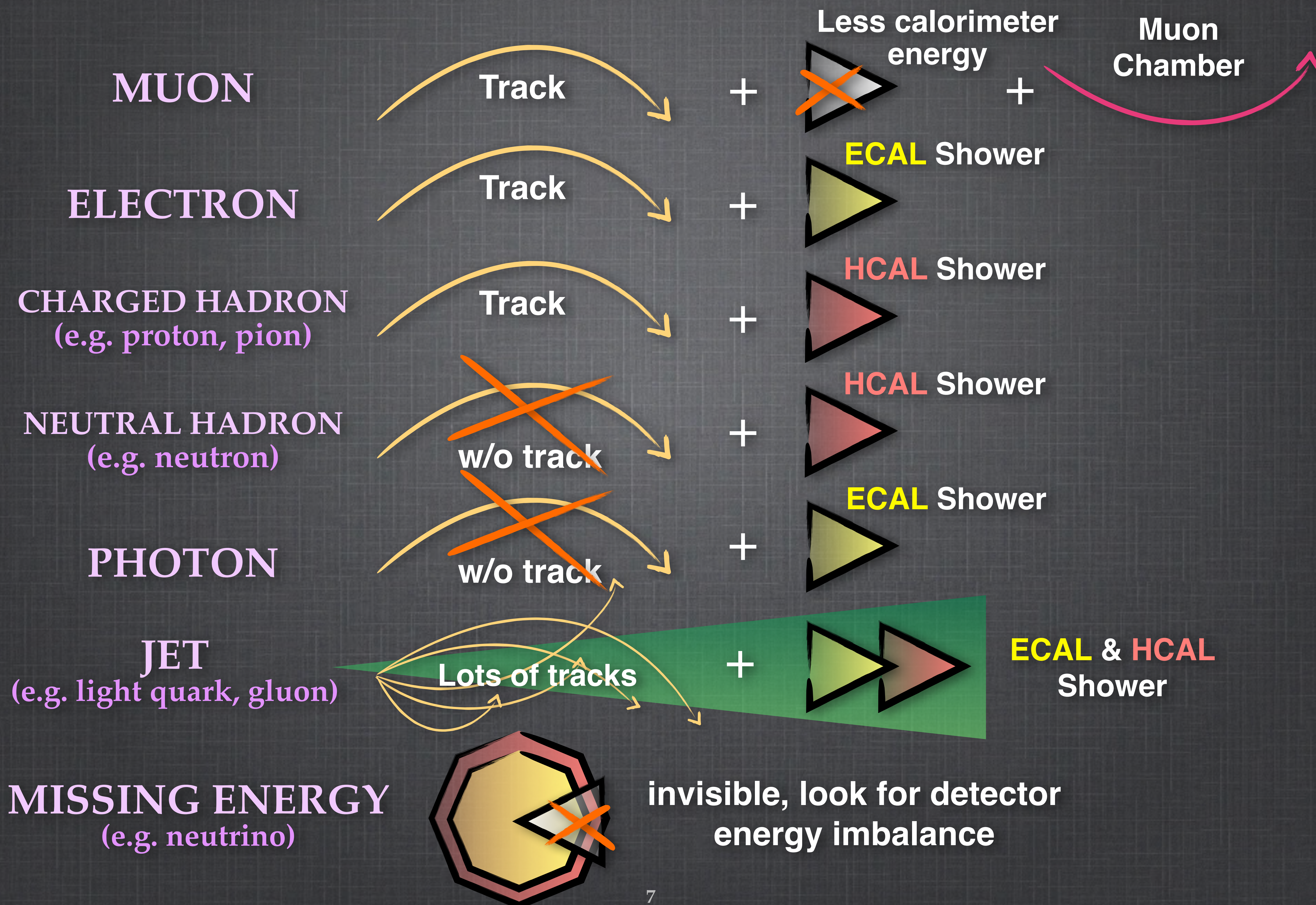
THE ATLAS DETECTOR



THE CMS DETECTOR



PARTICLE DETECTION



TRIGGER

Which photo you want to keep?

Trigger is an important piece toward the final physics analysis.
It is the first level of selection of events right after the data taking. At CMS:

- Fast hardware trigger (L1)
- Software trigger with full tracking & vertex reconstruction (HLT).

DATA PRODUCTION CHAIN

Collisions → Detector → Trigger/DAQ

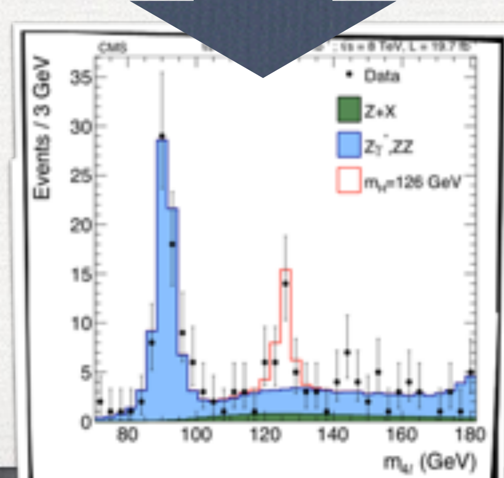
Theoretical model → Detector Simulation → Trigger Simulation

→ Raw data or Monte Carlo

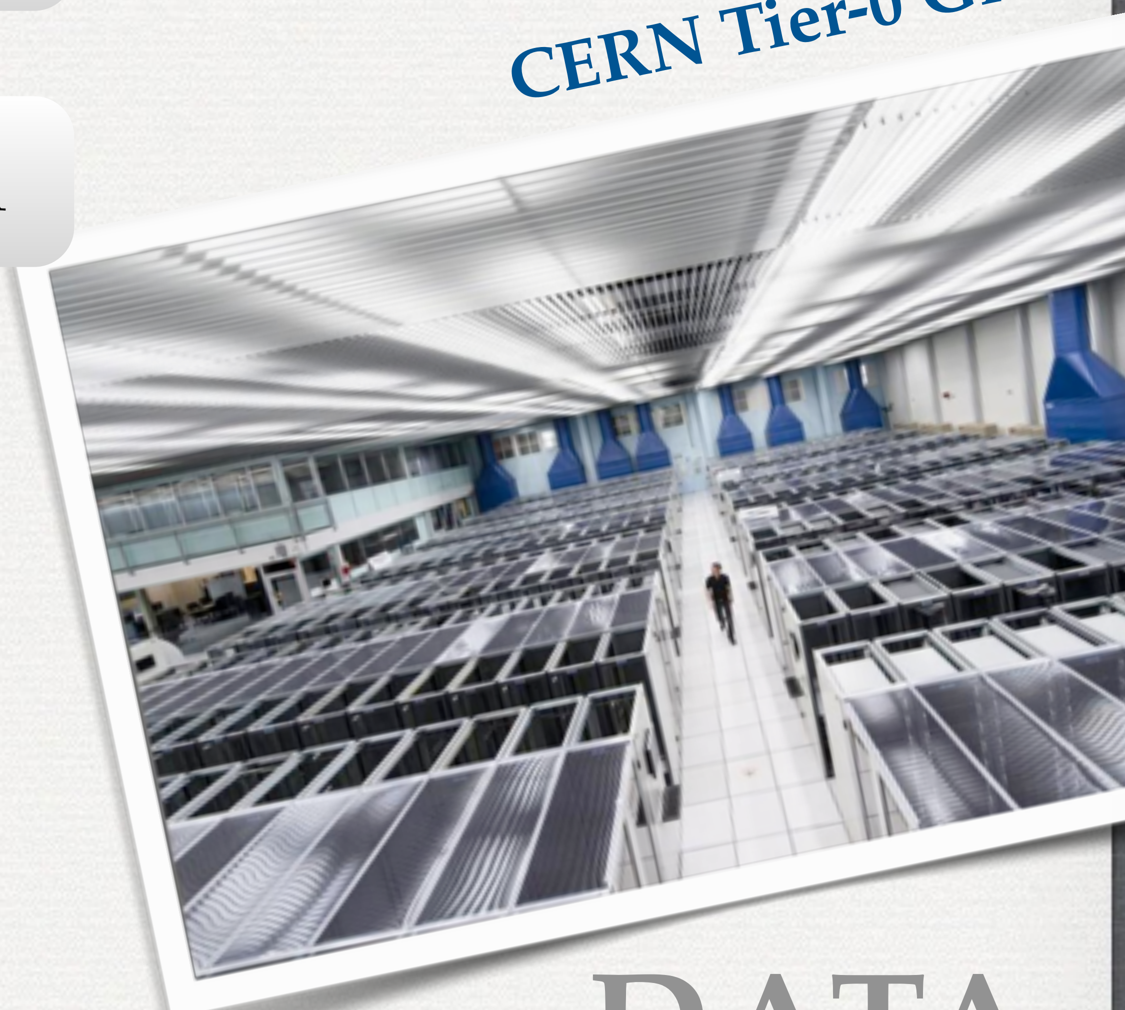
→ Processing @ T0/T1 Grid

→ User analysis @ T2/T3 Grid

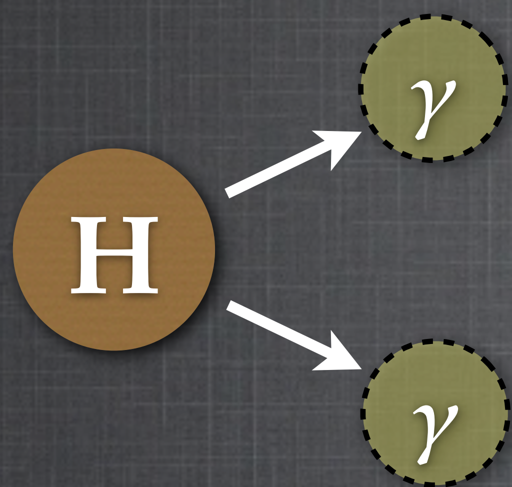
→ **FINAL PHYSICS RESULTS**



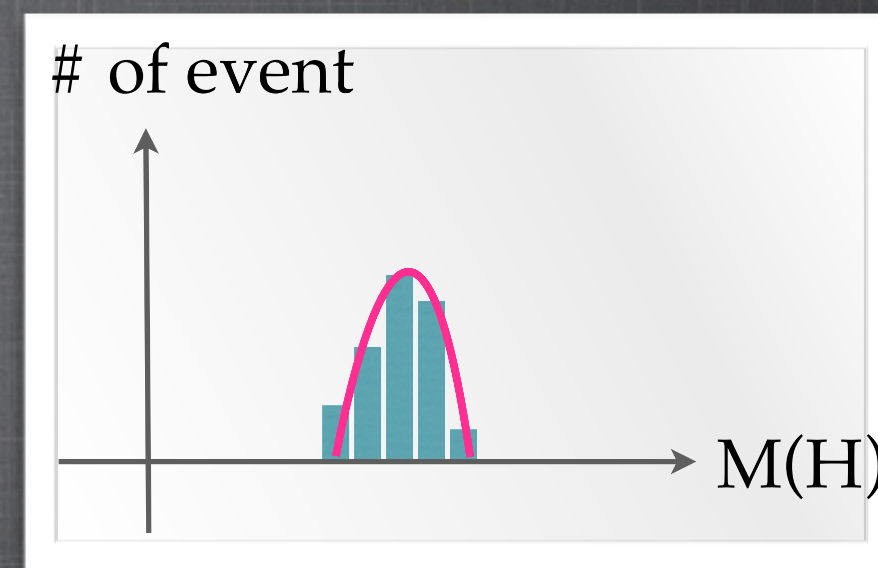
CERN Tier-0 Grid

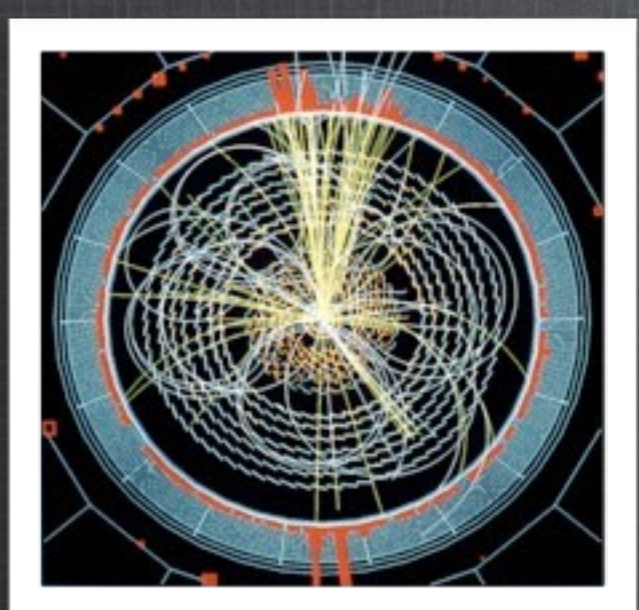


PARTICLE HUNTING IN A NUTSHELL



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

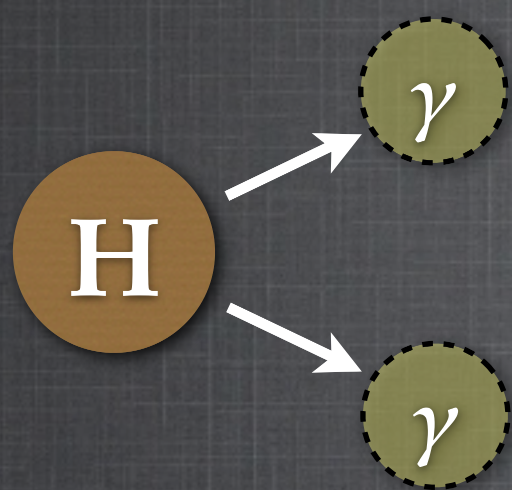




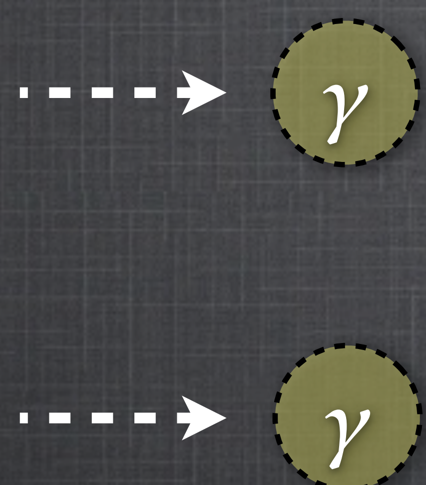
The detector can measure the decay products.
The Higgs mass can be "reconstructed" using the measured energy and momentum of the particles.

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

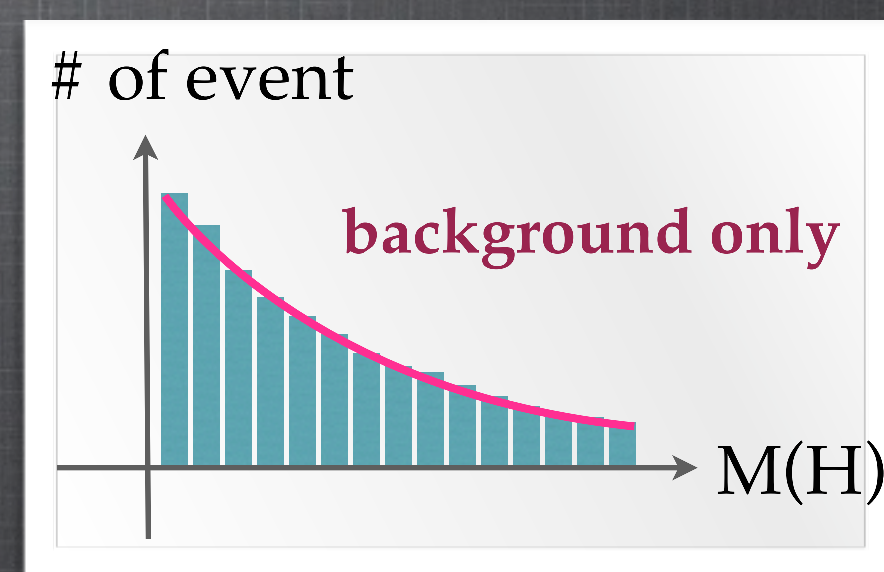
PARTICLE HUNTING IN A NUTSHELL



The Higgs boson should produce a peak on the mass spectrum



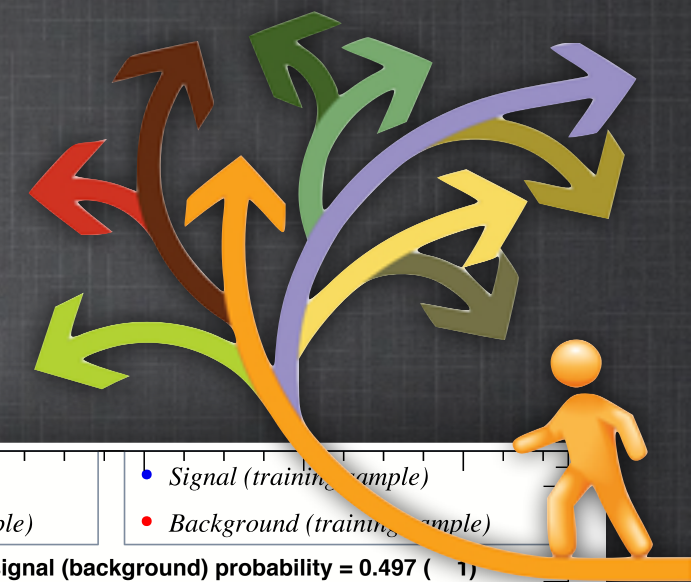
Background (e.g. two random photons) should generate a “flatter”distribution.

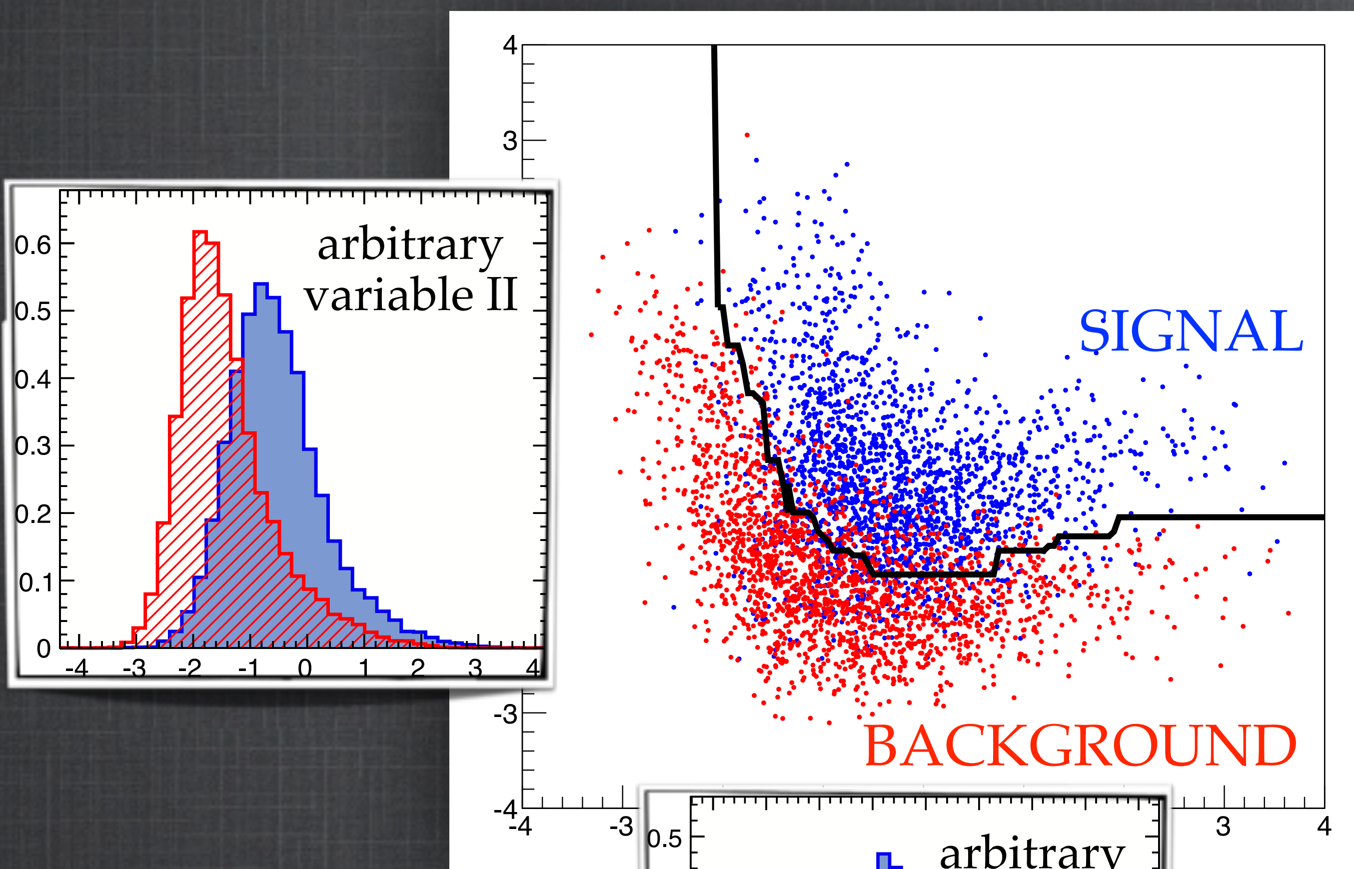


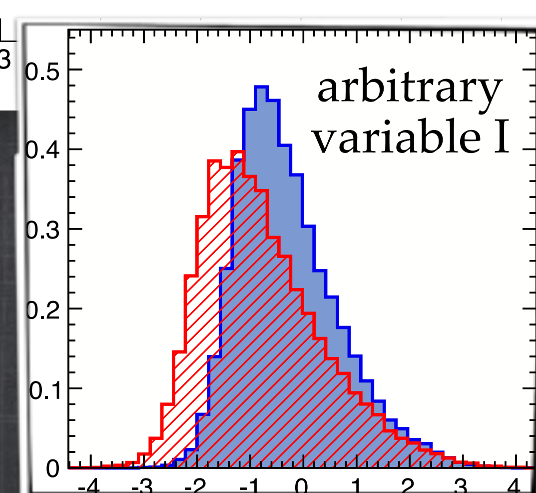
One always need to work hard for reducing the background events.

MULTIVARIATE ANALYSIS

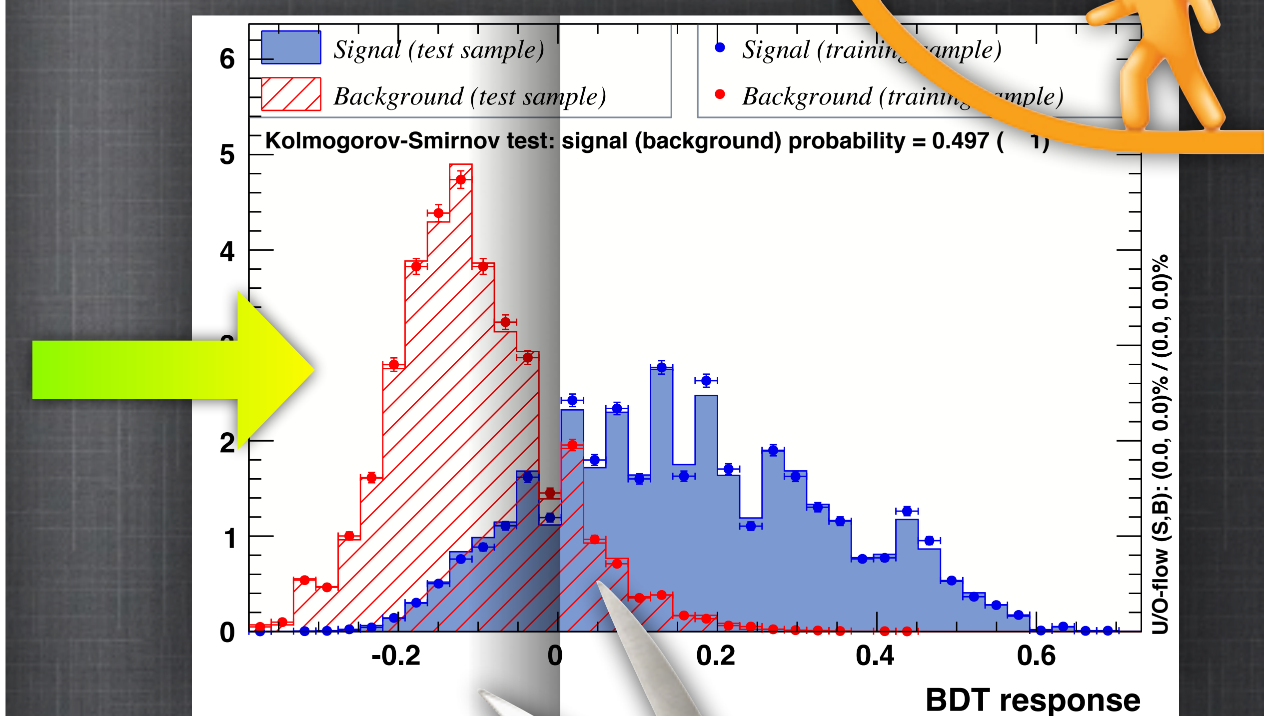
The **multivariate analysis** studies the correlations between variables and find the optimal way to classification of the events.







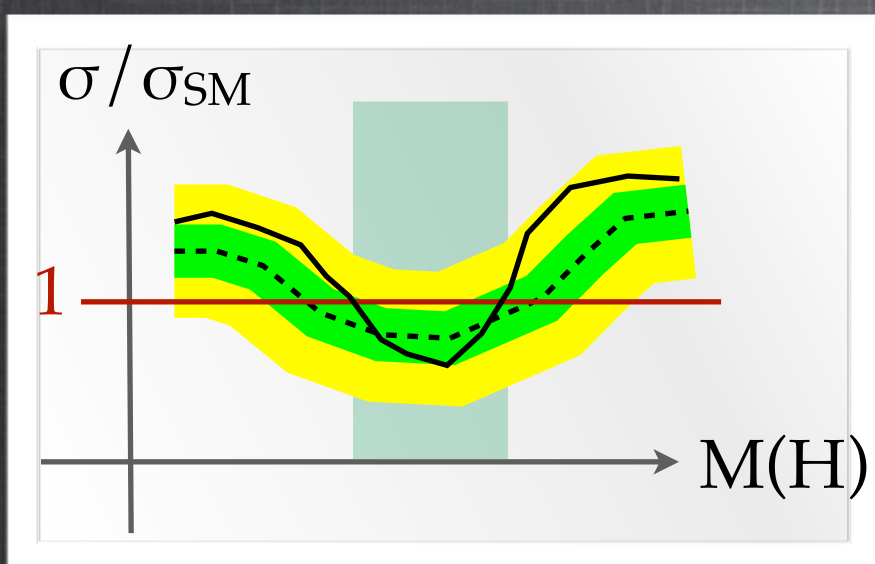
Reach the best background reduction!



MAKE A CUT!

HOW TO READ THE LIMIT PLOT?

A typical limit plot



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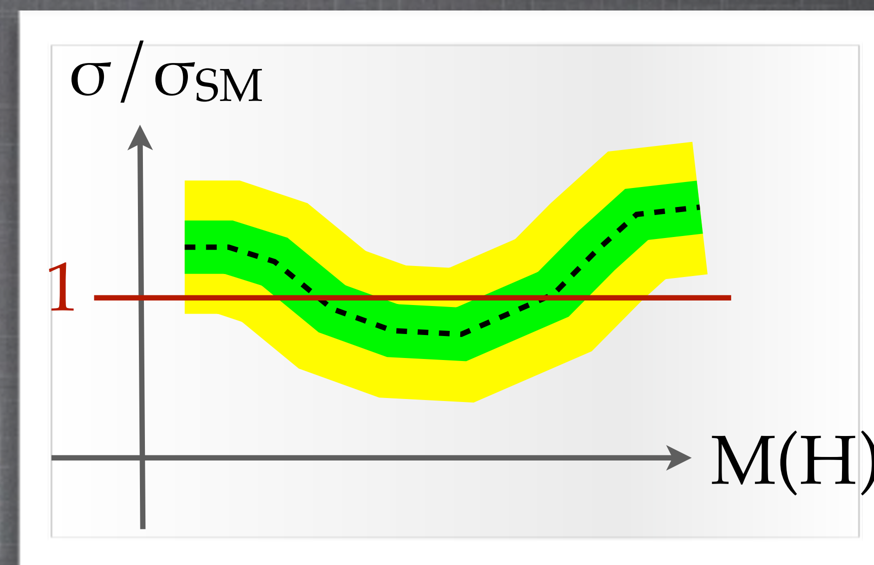
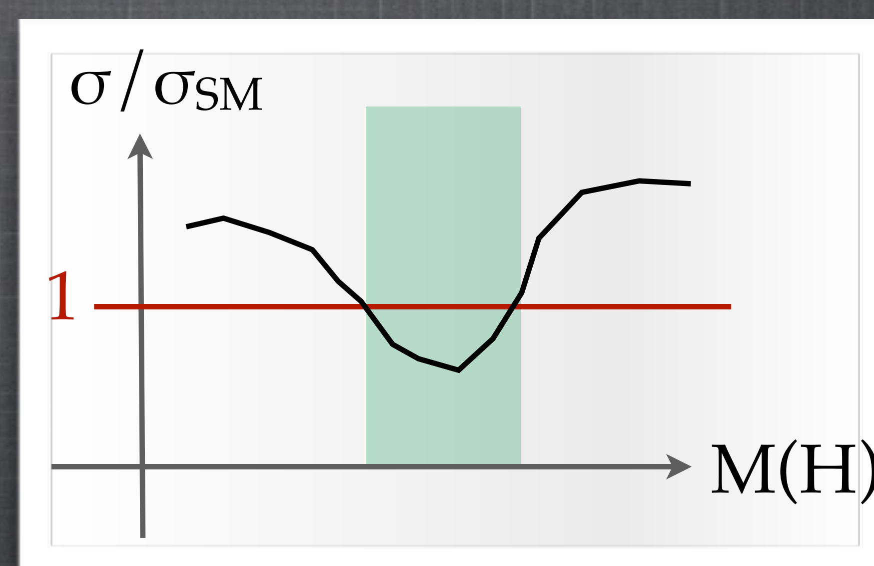


The “expected” limit curve and its uncertainties (±1σ,±2σ bands)

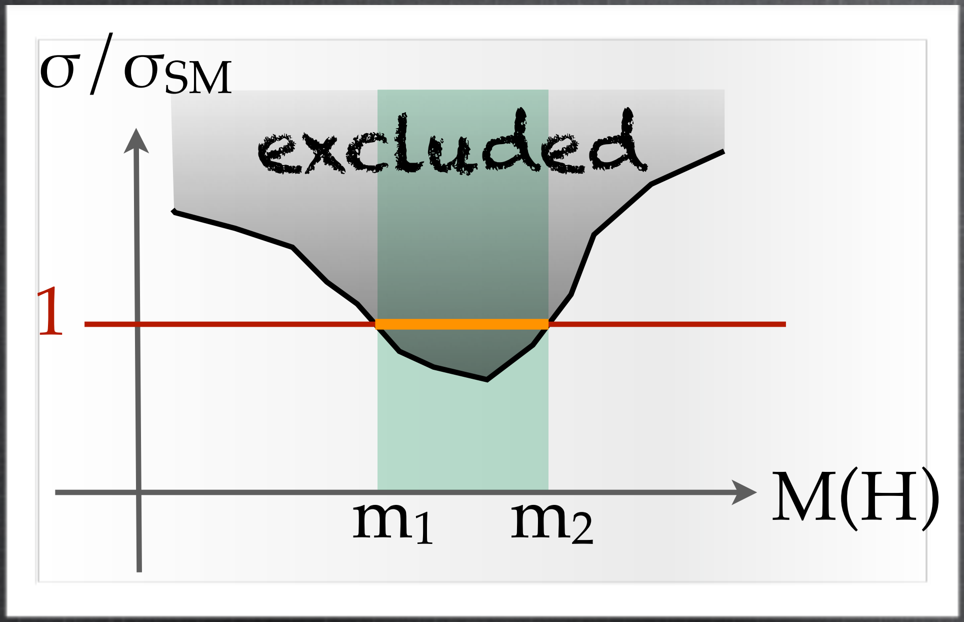
+



The “observed” limit curve

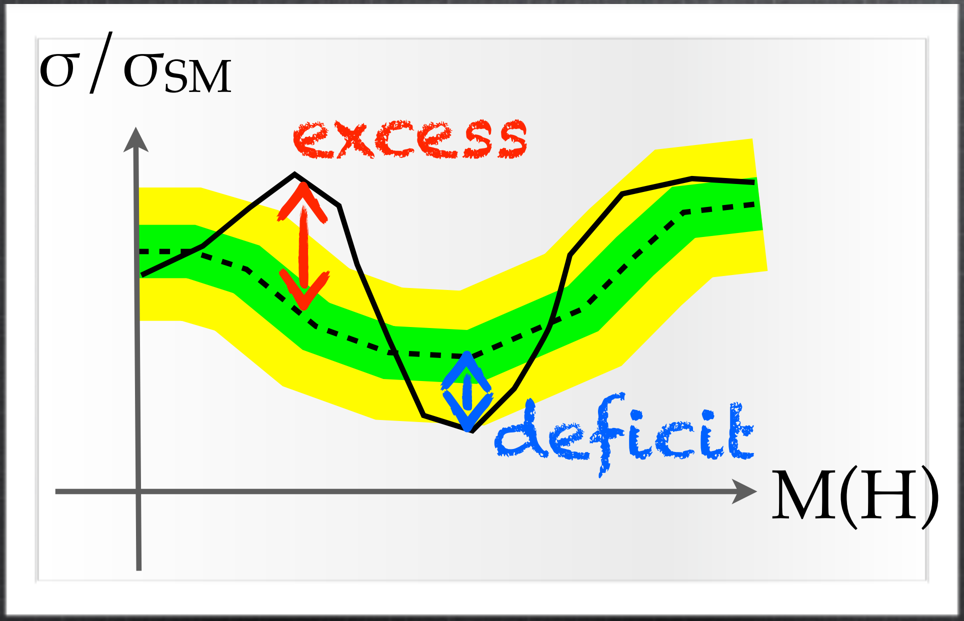
σ/σ_{SM} vs. M(H) = limit on relative cross sections to the SM versus the given Higgs mass

HOW TO READ THE LIMIT PLOT?



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**.



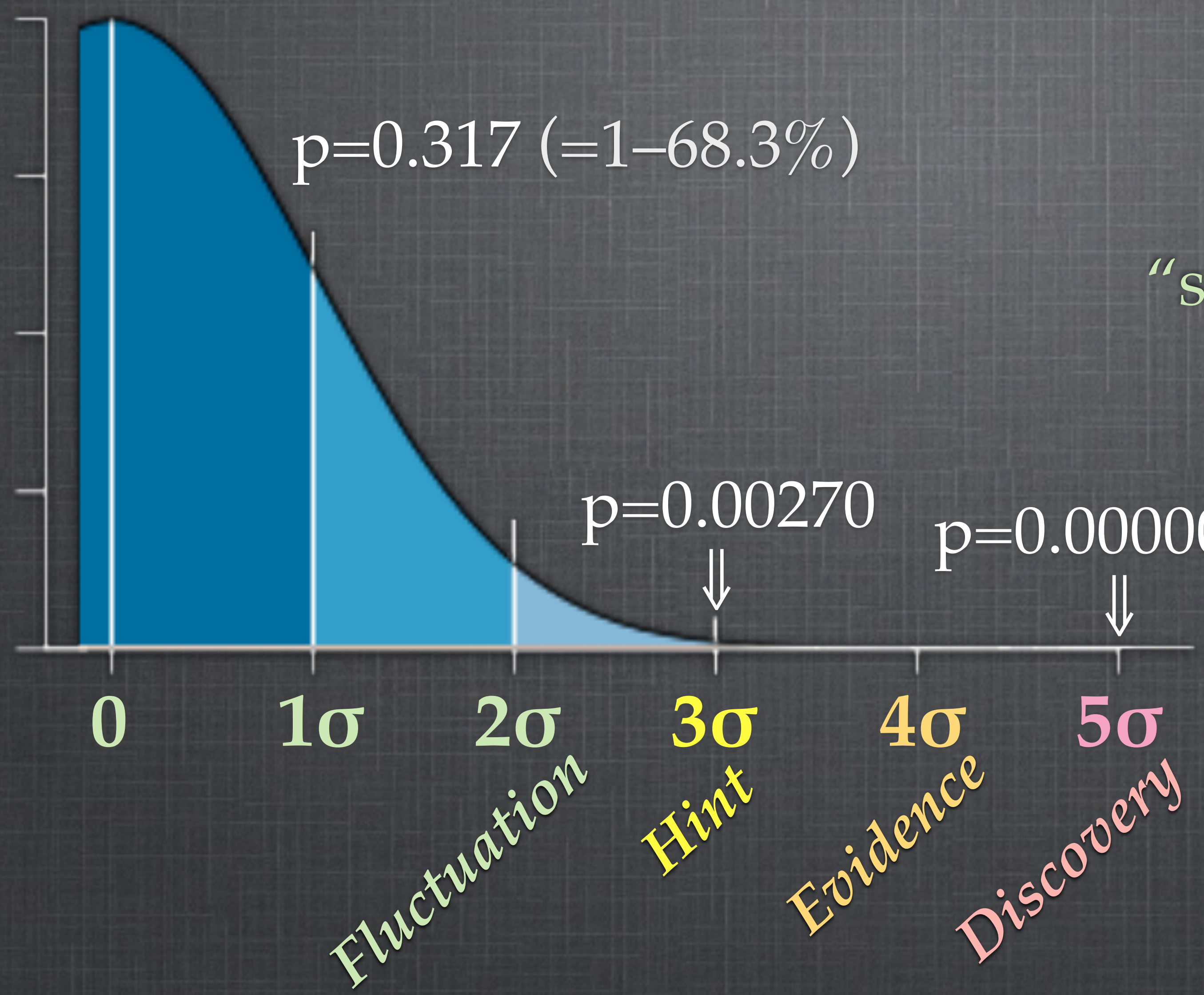
Comment #2

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.

EXCESS BENCHMARKING

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

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



Then convert to # of "sigma" with the definition of standard deviations.

ELEMENTARY PARTICLES

Only 17 in total, so far...

Fermions

SPIN 1/2

QUARKS

u up	c charm	t top
d down	s strange	b bottom

LEPTONS

e electro	μ muon	τ tau
ν_e electron-neutrino	ν_μ muon-neutrino	ν_τ tau-neutrino

Bosons

SPIN 0,1

FORCE CARRIERS

γ Photon	W
g gluon	Z

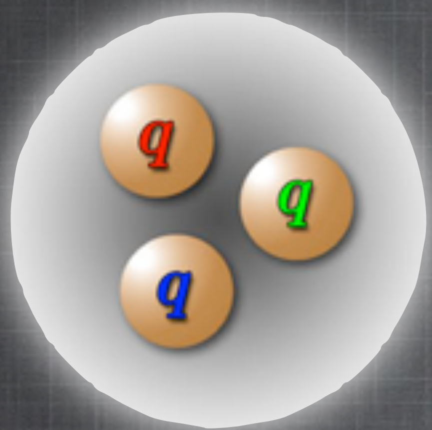
ORIGIN OF MASS

Higgs

The **Standard Model** describes how these elementary particles interact with each other.

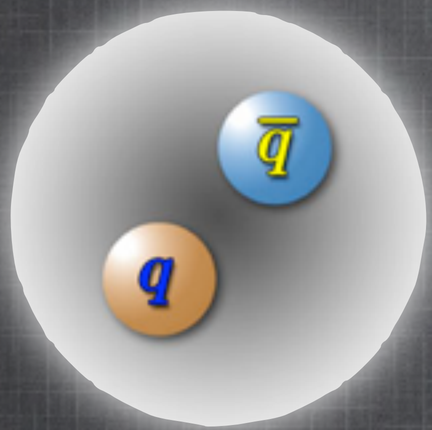
COMPOSITE PARTICLES

Many of them!



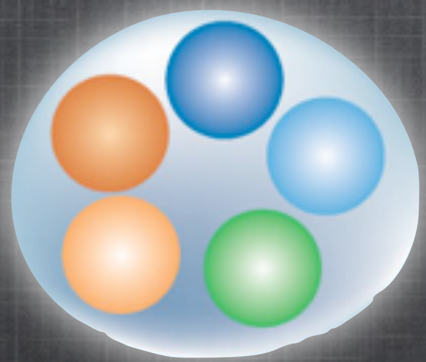
3-quarks

= A baryon, e.g. proton, neutron, ...

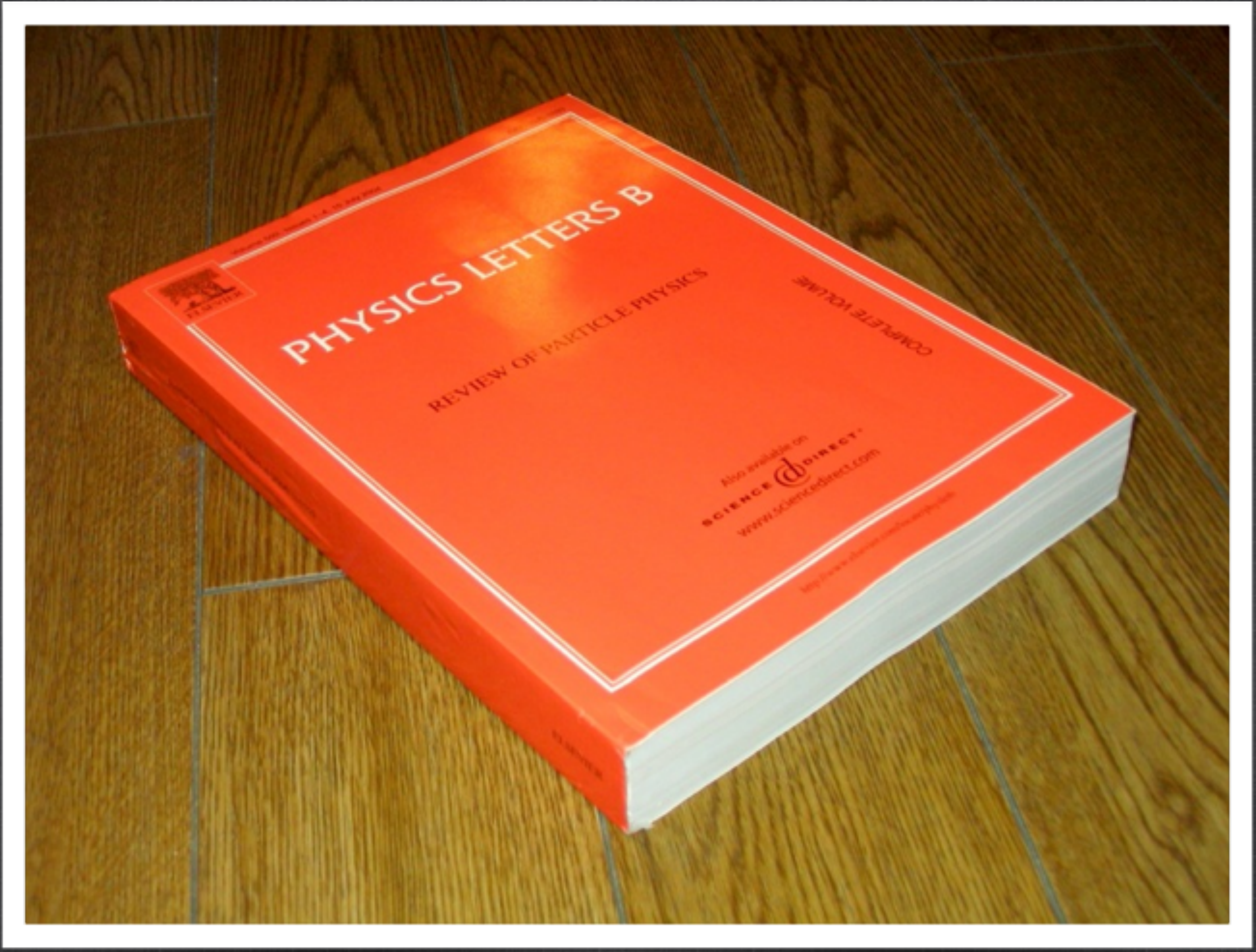


quark + anti-quark

= A meson, e.g. kaon, pion, ...



There could be more possible combinations, such as 4-quark/5-quark states, molecules, etc. But not really confirmed yet.

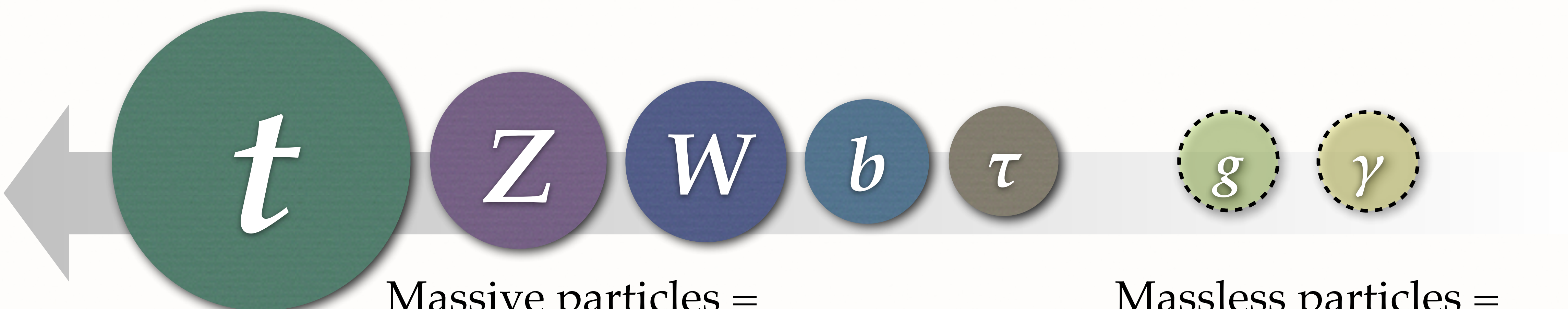


No matter what, the PDG review is always your good friend...

EXPERIMENTAL RESULTS FOR THE HIGGS BOSON

THE HIGGS MECHANISM

- The **Higgs mechanism** was proposed in 1964 by Peter Higgs et al.
- 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.
- After 50 years, (amazingly) it is still the major objective at the LHC!



Massive particles =
strong direct connections with Higgs

Massless particles =
connection with 2nd order loops

AN ANALOGY FOR HIGGS

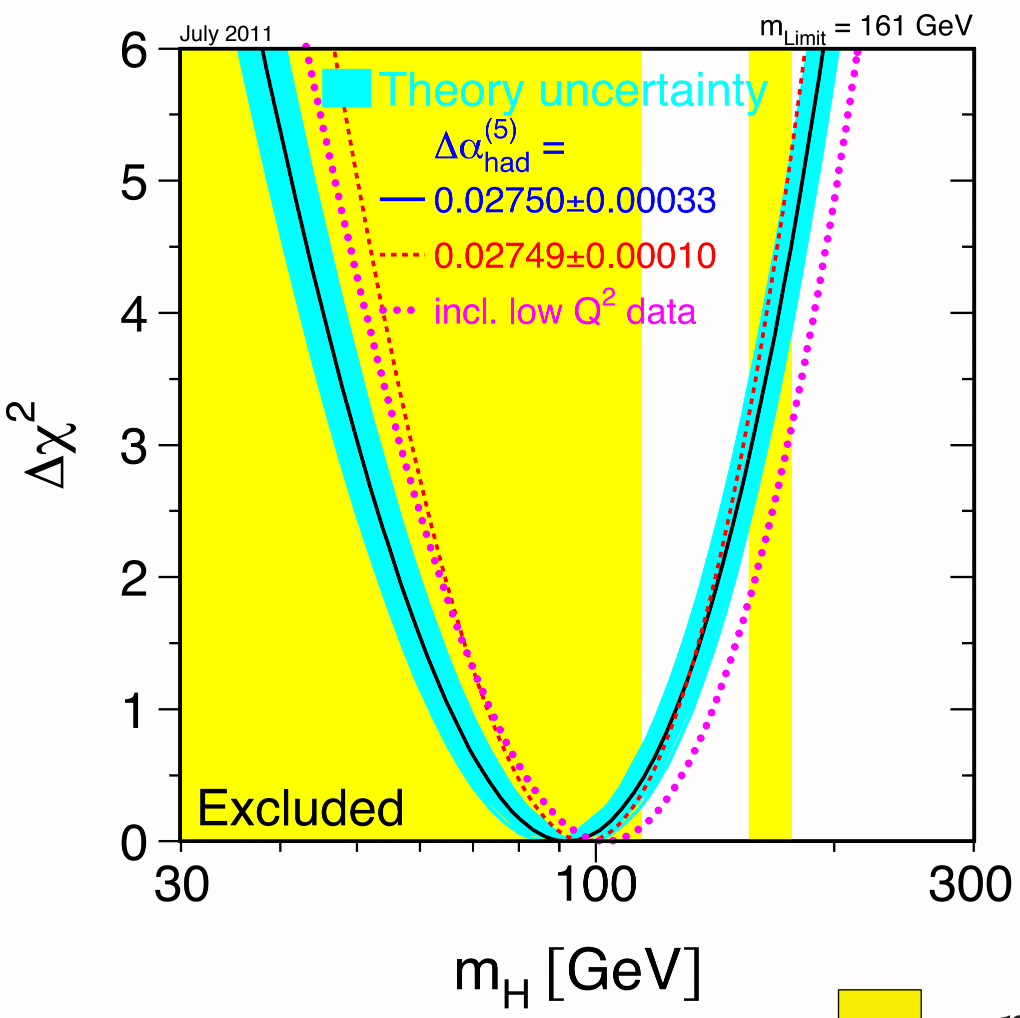
Einstein enters the cocktail party causing a disturbance in the field.

Followers cluster and surround Einstein as this group of people forms a "massive object".

THE HIGGS BOSON

- 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!)

KNOWLEDGE ABOUT HIGGS MASS



- 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 measurements of top, W masses:

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

On the other hand, if this constrained value is different from observed Higgs, then it can be a hint of NP!

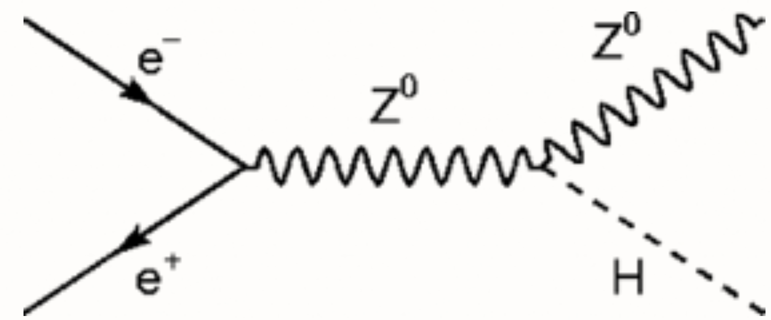
= regions excluded by LEP and Tevatron

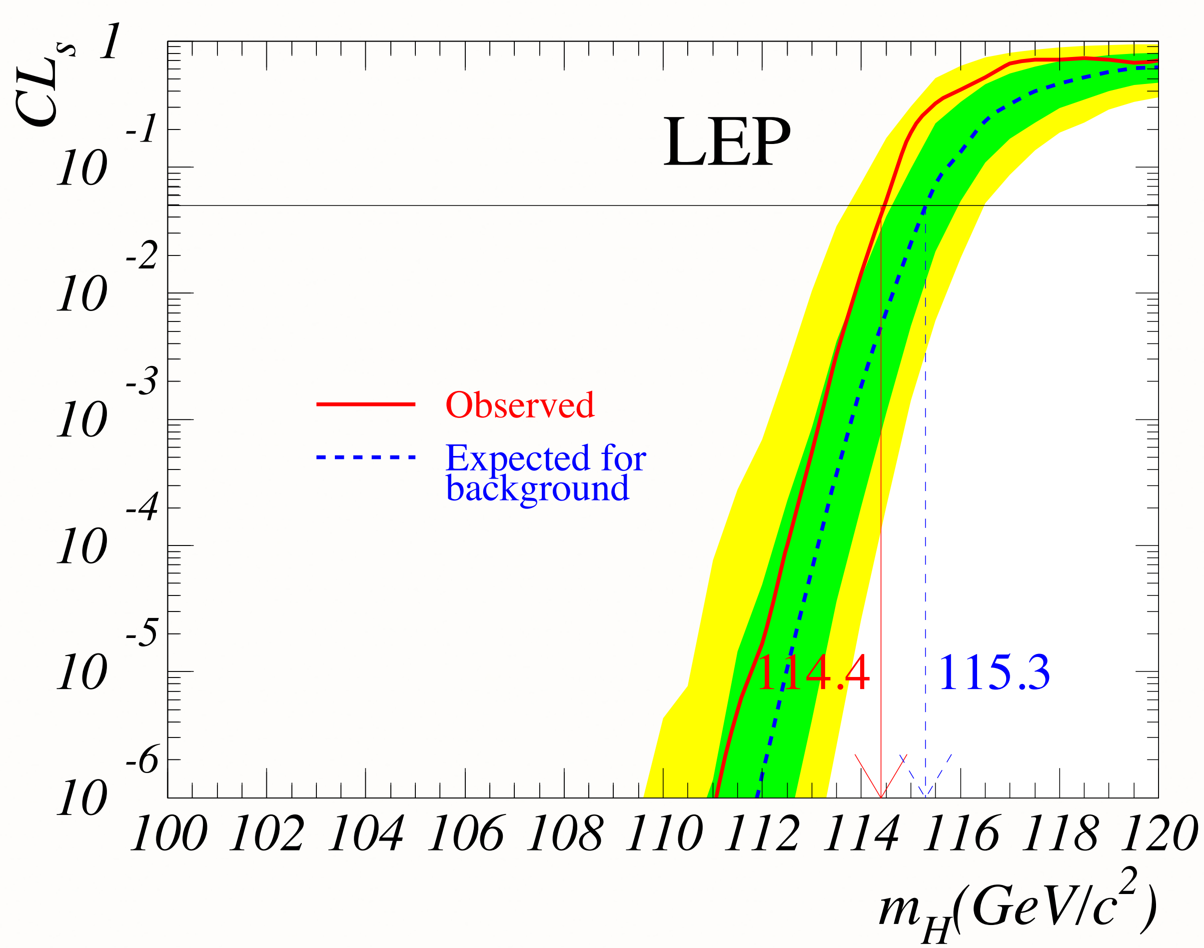
LEP DIRECT SEARCHES

- LEP search in ZH channel – limited the CM energy:

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

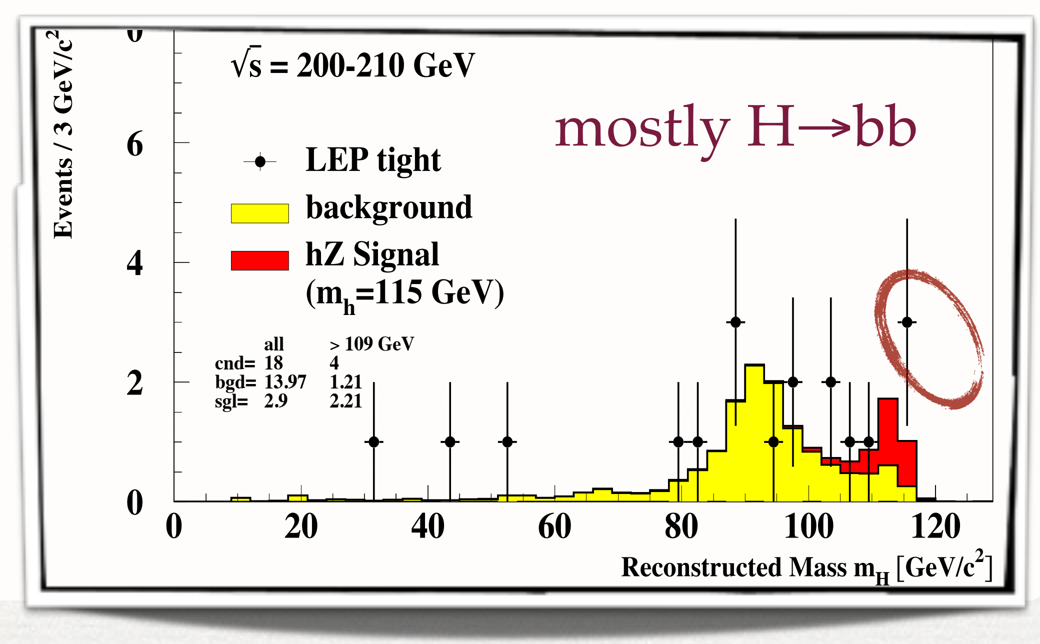
(Maximum Higgs mass reach)





Combined limit >114.4 GeV
at 95% confidence level

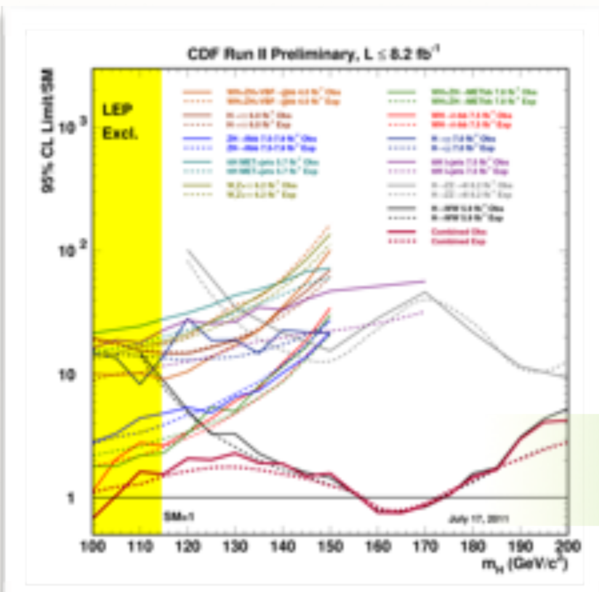
A mild hint found ~118 GeV, but it is hard to concluded ⇓



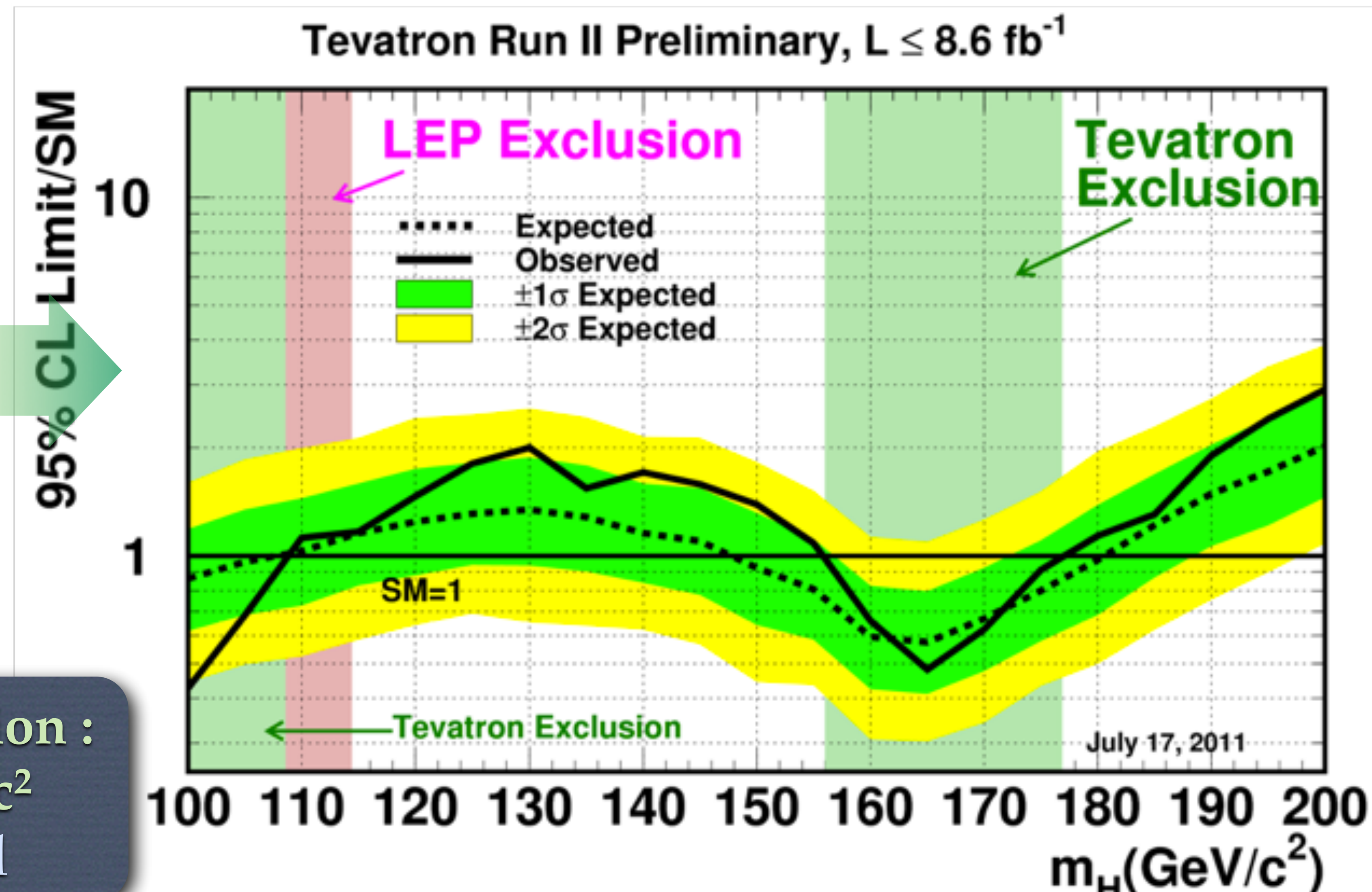
TEVATRON EXCLUSION

(2011, before Higgs discovery)

- Tevatron search is limited by the background level and integrated luminosity. Need to combine many analyses into a single limit plot.



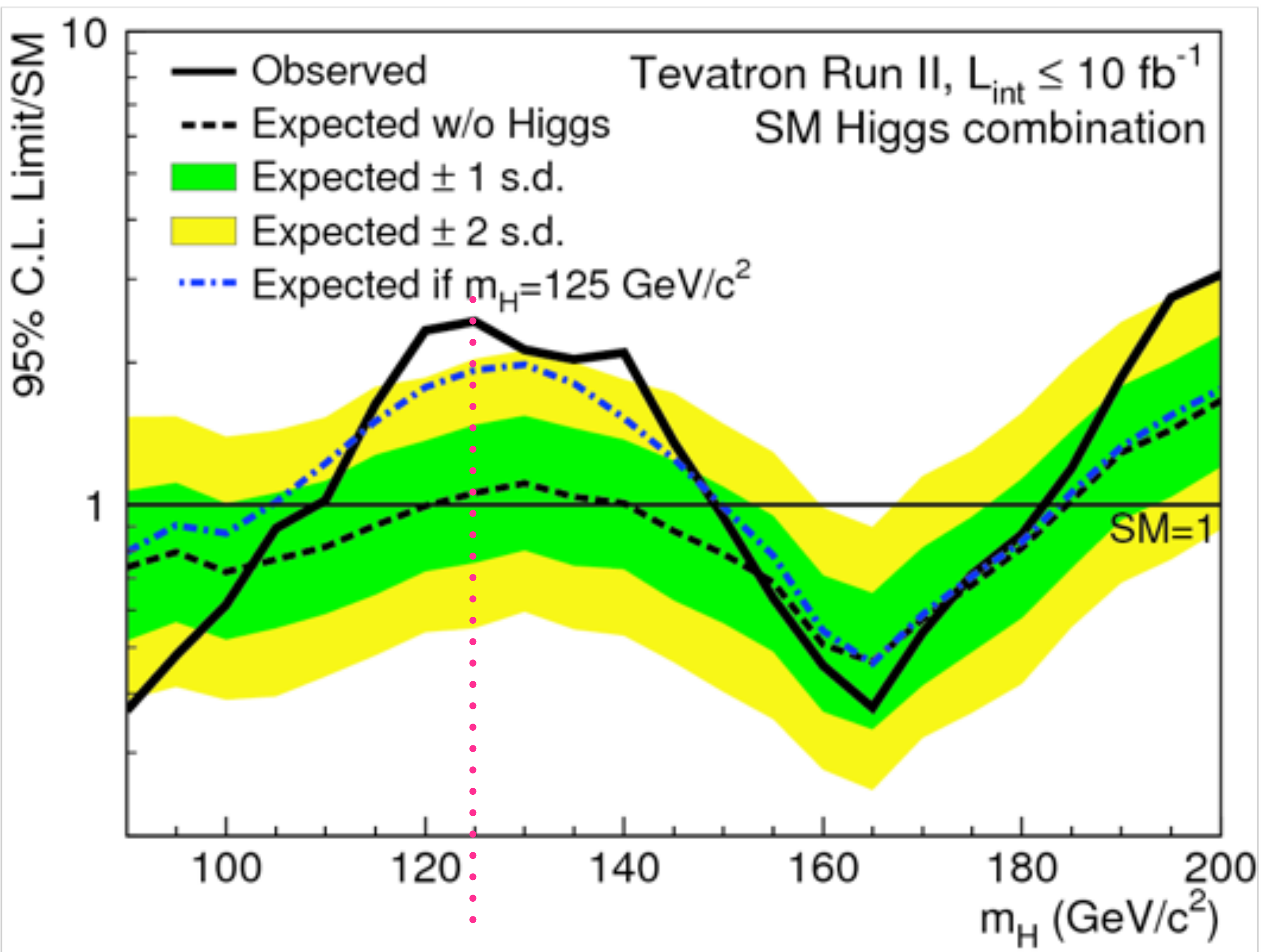
A global combination of 12 search channels



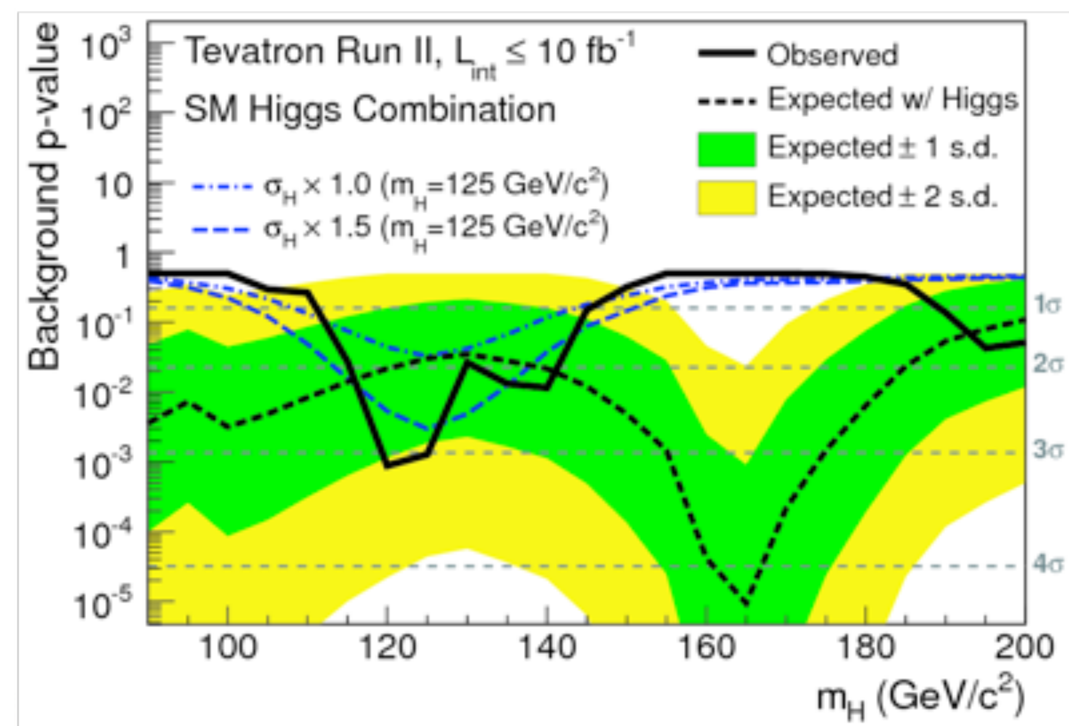
Tevatron combined exclusion : 156 < M(H) < 177 GeV/c^2 at 95% confidence level

TEVATRON RESULTS

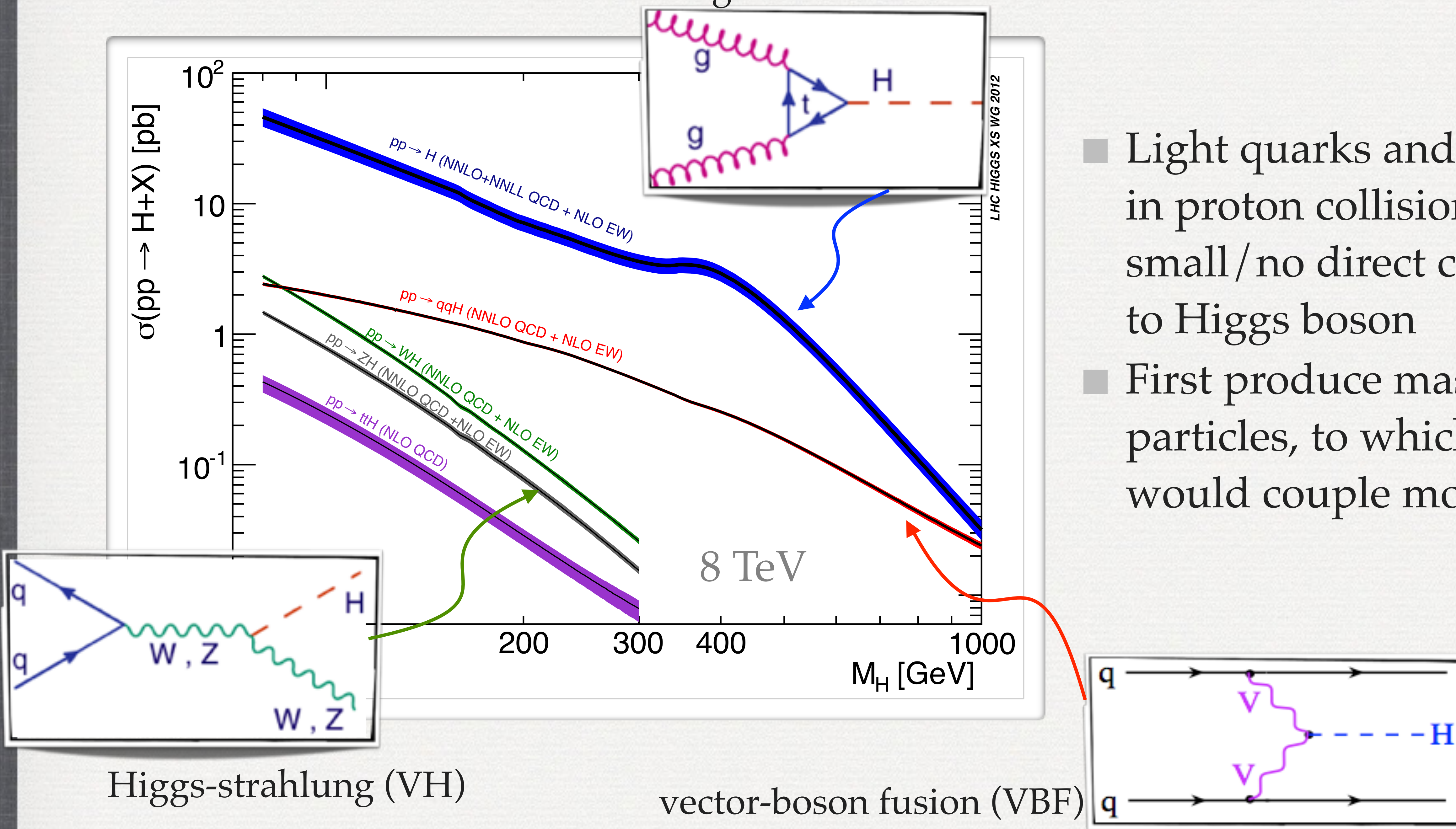
(Final)



"in the mass range between 115 and 140 GeV/c², consistent with the mass of the Higgs boson observed at the LHC. The local significance at m_H=125 GeV/c² is ***3.0σ****, and the median expected significance at that mass is 1.9σ"*



HIGGS PRODUCTIONS AT LHC



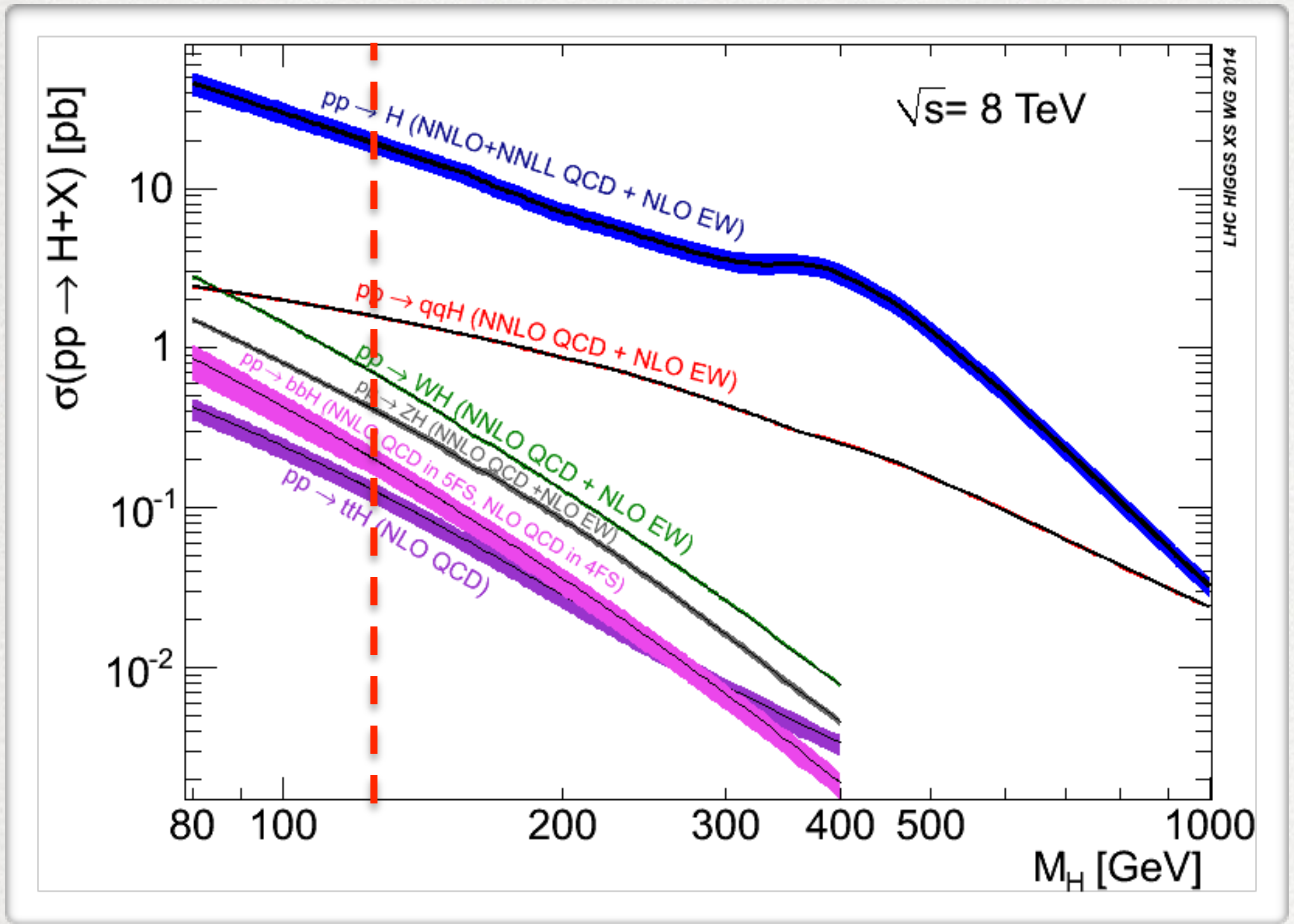
gluon fusion

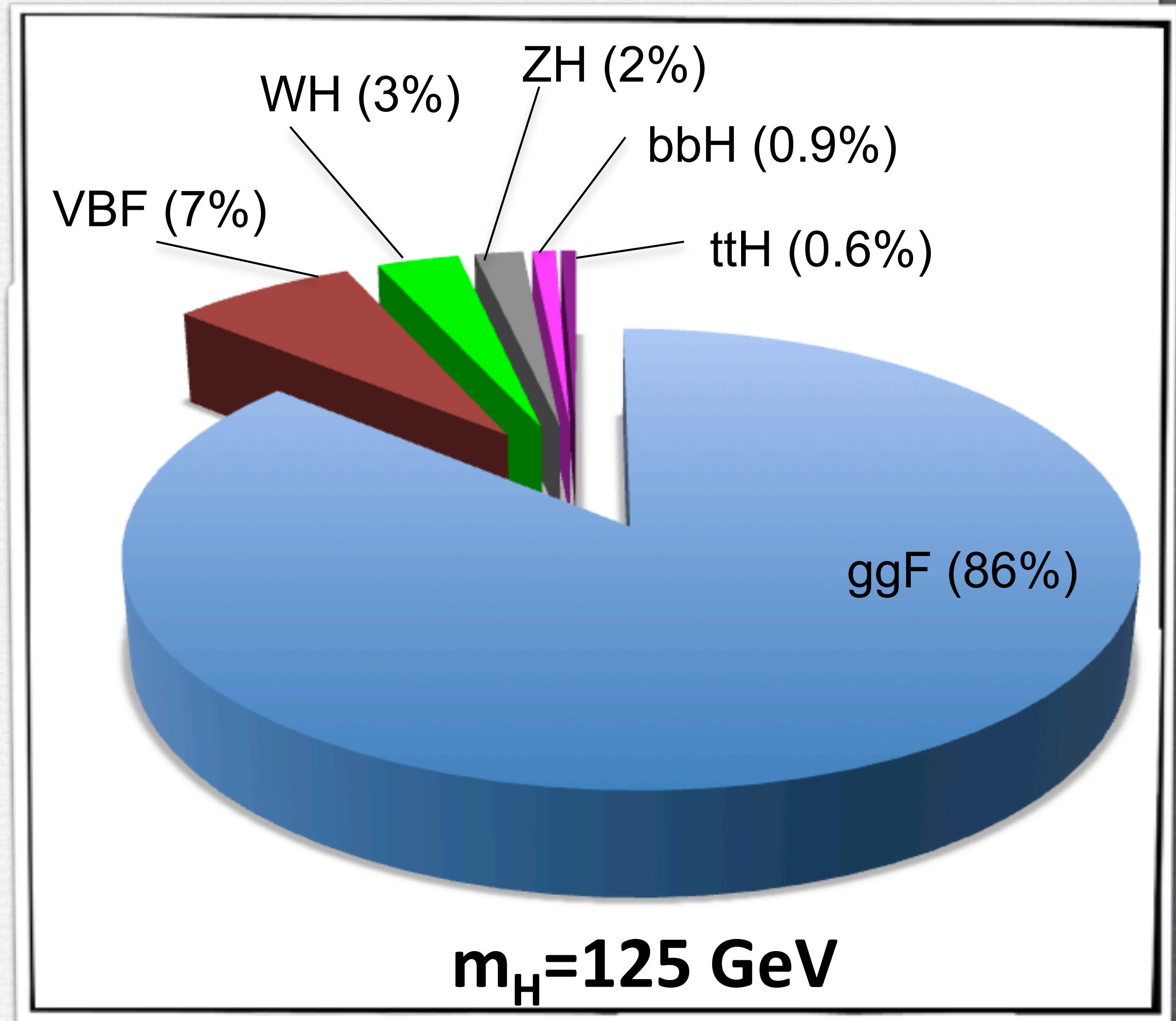
Higgs-strahlung (VH)

vector-boson fusion (VBF)

- Light quarks and gluons in proton collisions have small/no direct coupling to Higgs boson
- First produce massive particles, to which Higgs would couple more easily.

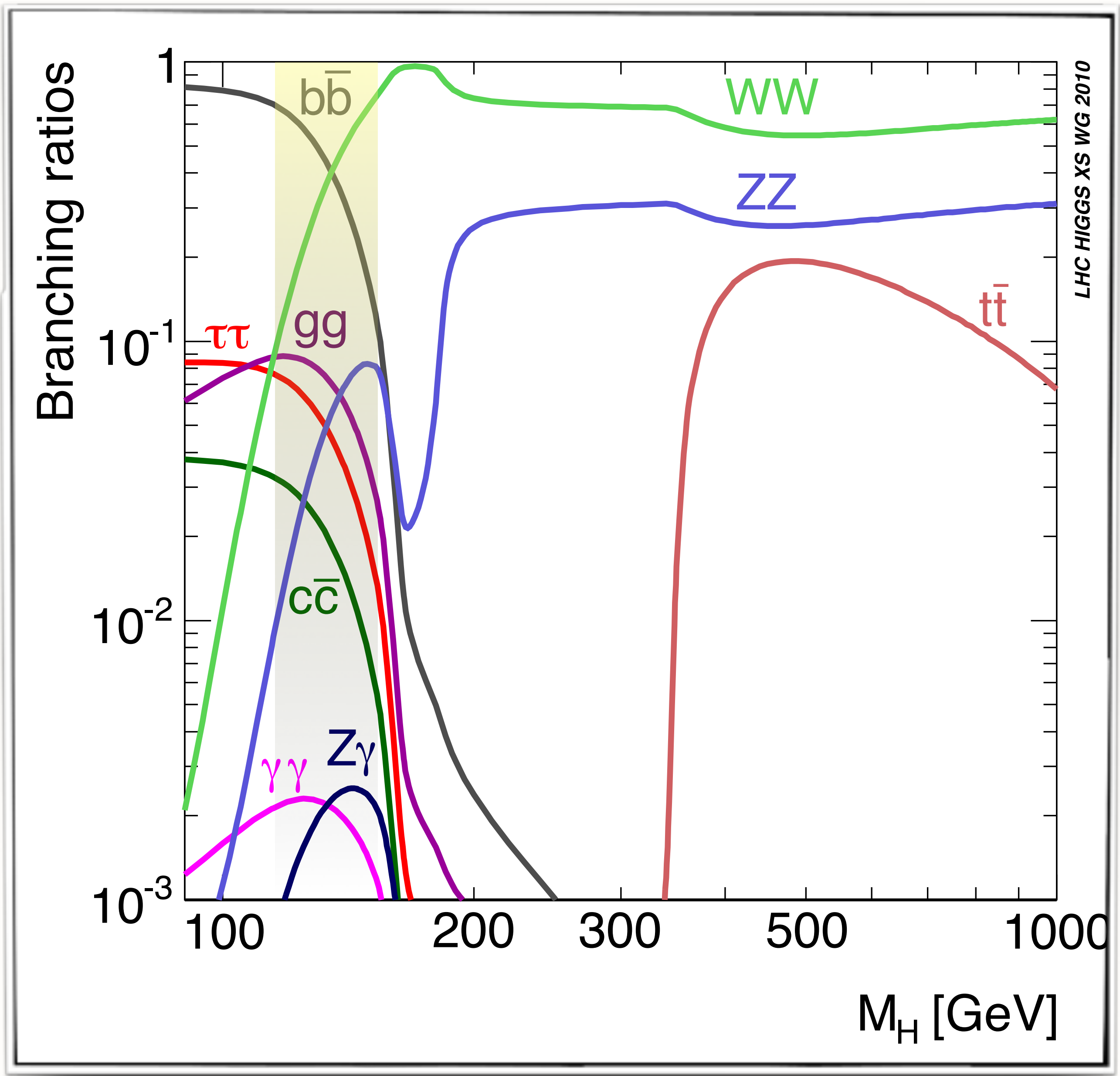
HIGGS PRODUCTIONS AT LHC





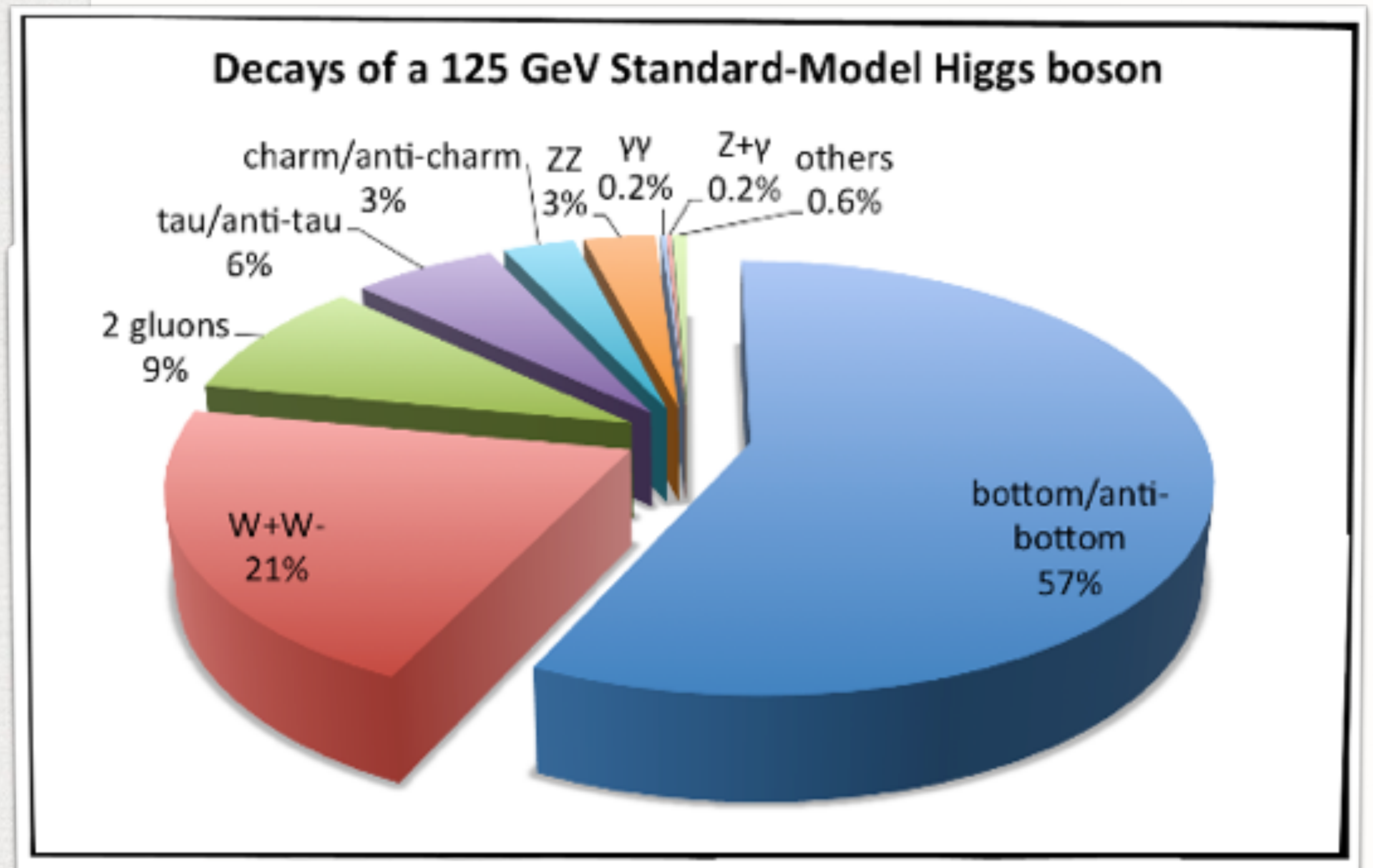
- Dominated by gluon fusion, while the vector-boson fusion and Higgs-strahlung channels are also very useful.
- All production modes to be exploited.

DECAY OF THE HIGGS BOSON



- Higgs boson likes to decay to the heaviest kinematically allowed pair of particles.
- WW* and ZZ* decays do not drop out immediately if M(H)<2M(W) or 2M(Z)
- gg, γγ, Zγ are only possible with loops of top and W.

DECAY OF THE HIGGS BOSON



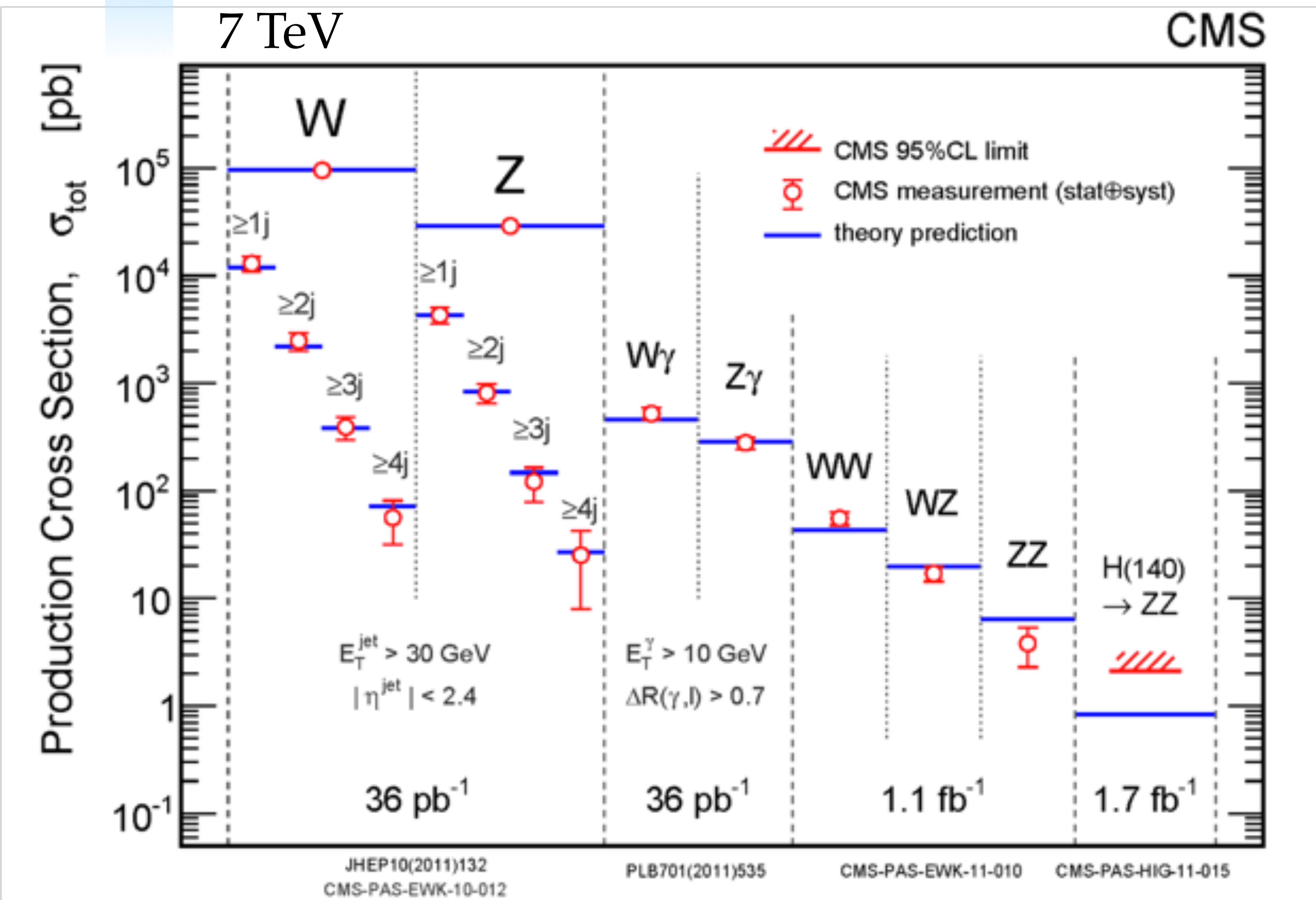
- Five promising decay channels exploited:
  - Fermions: **H→bb, ττ**
  - Bosons: **H→ZZ, WW, γγ**

  (and further divided into many production and sub-decay channels.)
- Rich in signatures at low mass region.
- H→bb and ττ channels are very challenging due to the huge background.

THE CHALLENGE

dijet 10^8 pb

Huge background from known SM processes



Events produced per year per experiment

dijet ~500,000,000,000

W ~500,000,000

Z ~150,000,000

top ~800,000

WW ~200,000

ZZ ~35,000

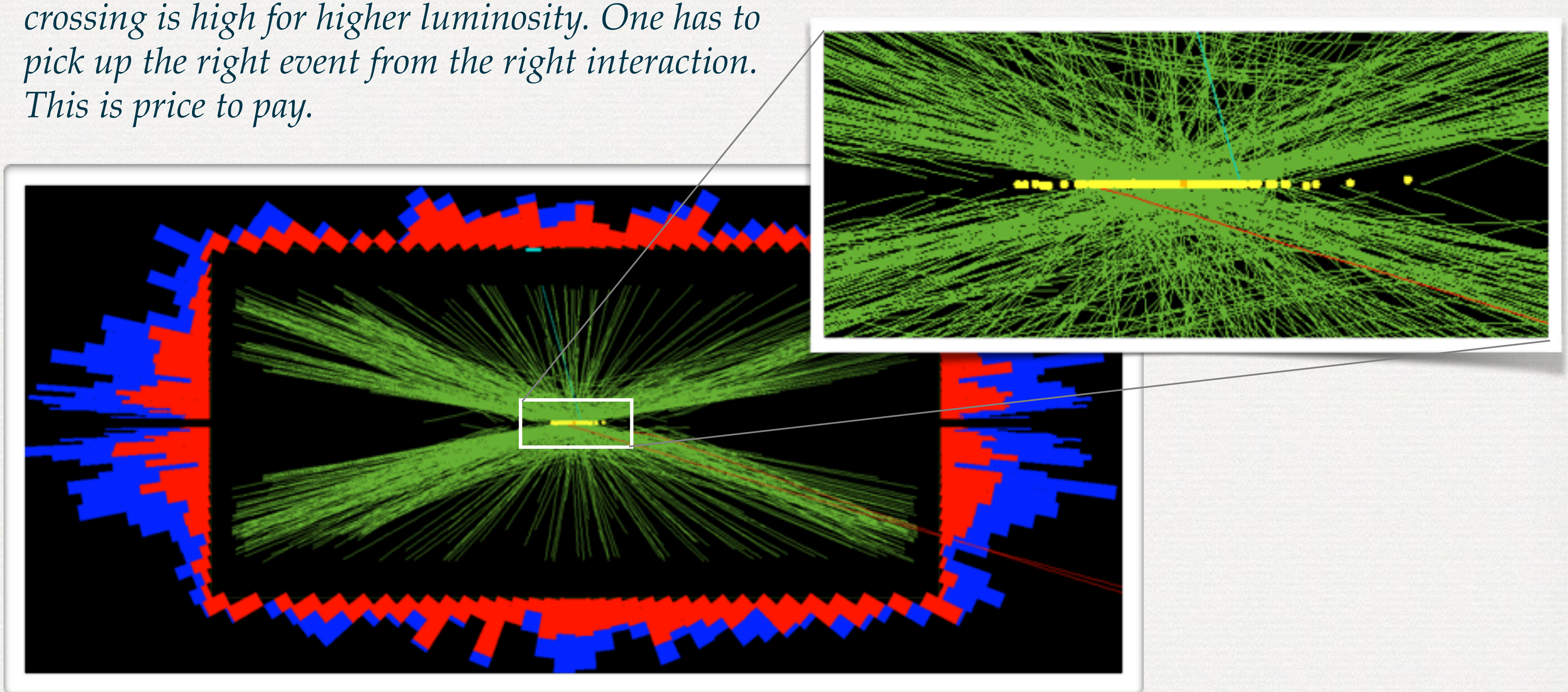
Higgs ~50,000

(but only few hundreds visible)

It's not too far from finding a needle in a haystack...

THE CHALLENGE

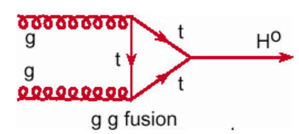
The detectors record more than one interaction in a single snapshot. Number of interactions per crossing is high for higher luminosity. One has to pick up the right event from the right interaction. This is price to pay.

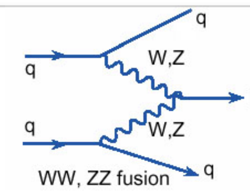


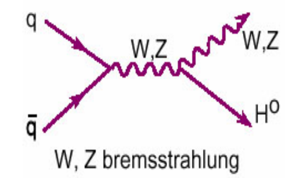
An event with 78 reconstructed vertices;
Luminosity goes high, but pile-up also goes very high!

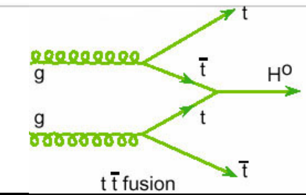
ALL HIGGS EVENTS IN LHC RUN-I

m_H=125 GeV









observed?	Decays		ggF (19.3 pb)	VBF (1.6 pb)	VH (1.1 pb)	ttH (0.13 pb)
			86%	7%	5%	0.6%
✓	ZZ → 4l	0.00014	77			
✓	γγ	0.0023	1,300			
✓	WW → lνlν	0.0028	1,500			
✓	ττ	0.062	34,000			
✓	bb	0.56	270,000	42,000		
	μμ	0.00021	120			
	Zγ → 2l γ	0.00011	61			
	γ*γ→ 2μ γ	2×10^{-5}	11			
	invisible	0.0012	663 (too small S/B at LHC, unless there is BSM)			
	other	0.37	200,000 (deemed not feasible at LHC)			

TOTAL PRODUCED: 500K events

- before acceptance
- before reconstruction efficiency
- before event selection efficiency

STATE OF EXPERIMENTAL AFFAIRS

Main focus today...

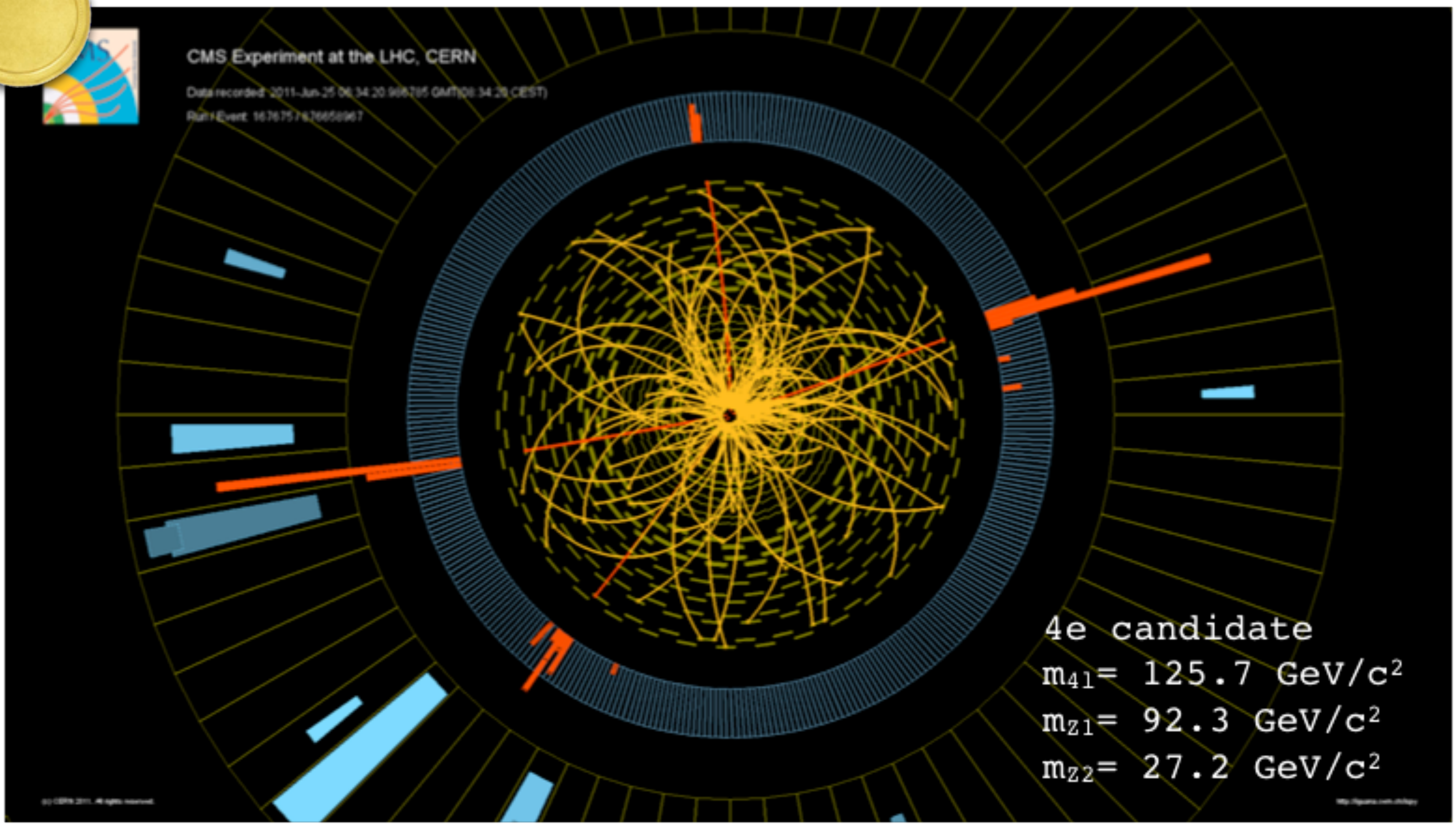
1. **Establish the 125 GeV Higgs boson in main decay channels**
   - H→WW, ZZ, γγ, ττ, bb
2. **Precision measurements of the properties:**
   - mass/width/spin-parity
   - production & decay rates
   - Look for difficult or rare processes, e.g. Zγ, ttH, etc.
3. **Searches associated with Higgs sector:**
   - More Higgs bosons? (extended Higgs sector, such as MSSM)
   - Exotic decays? (e.g. invisible decay, flavor violating decays, etc.)
   - New process with Higgs in the final state? (e.g. X→HH, t→cH)

So far all observations are consistent with the SM...

THE "BIG FIVE" CHANNELS

- **Undeniable observation (>5σ)**
  - $H \to ZZ^{(*)} \to 4l$
  - $H \to \gamma\gamma$, $\tau\tau$, bb
- **Very strong evidence (>3σ)**
  - $H \to WW^{(*)} \to 2l2\nu$
  - $H \to \tau\tau$
- **Some evidence**
  - $H \to bb$

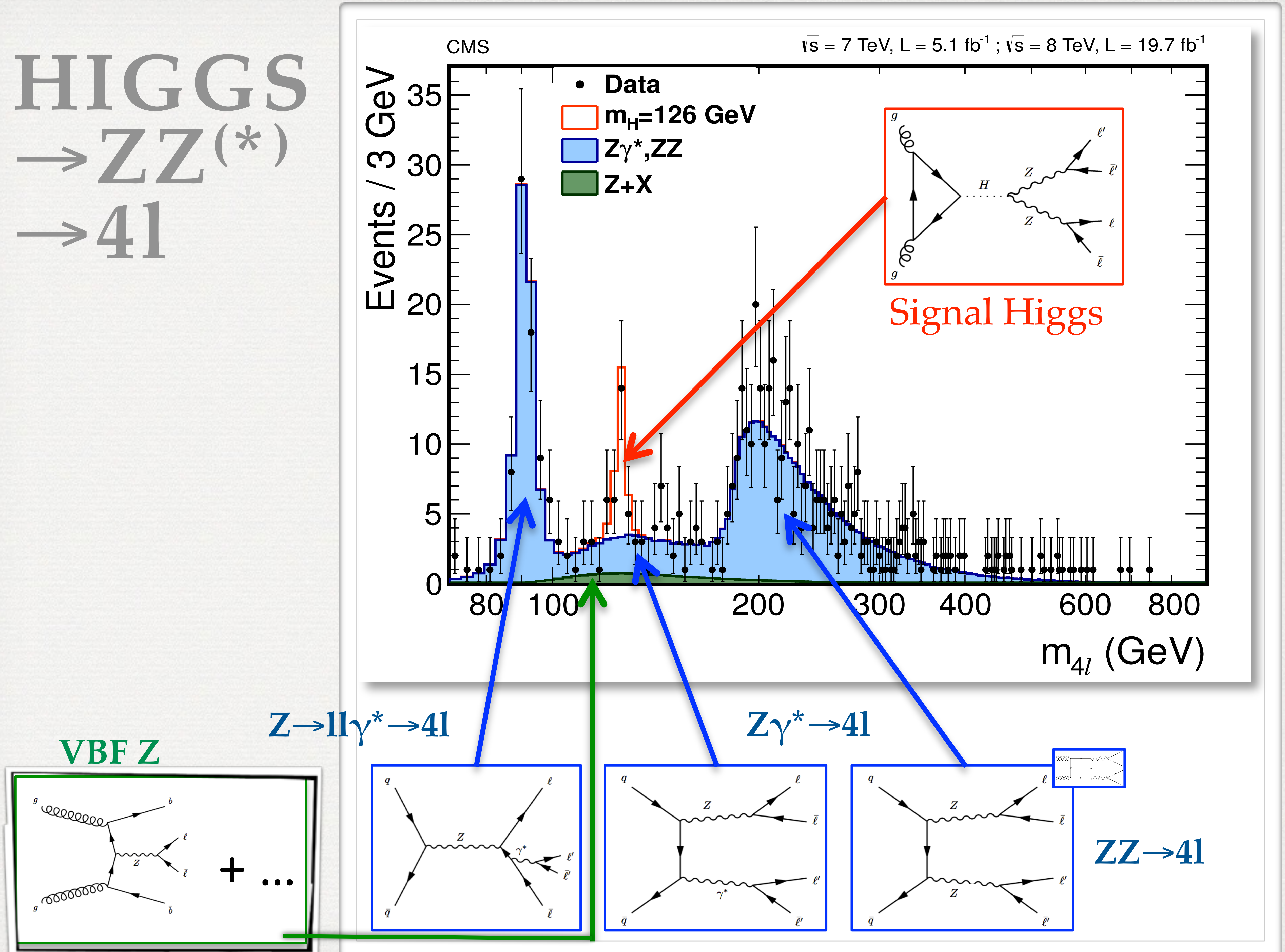
$H \rightarrow ZZ^{(*)} \rightarrow 4l$



$H \rightarrow ZZ^{(*)} \rightarrow 4l$: SIGNAL & BACKGROUND

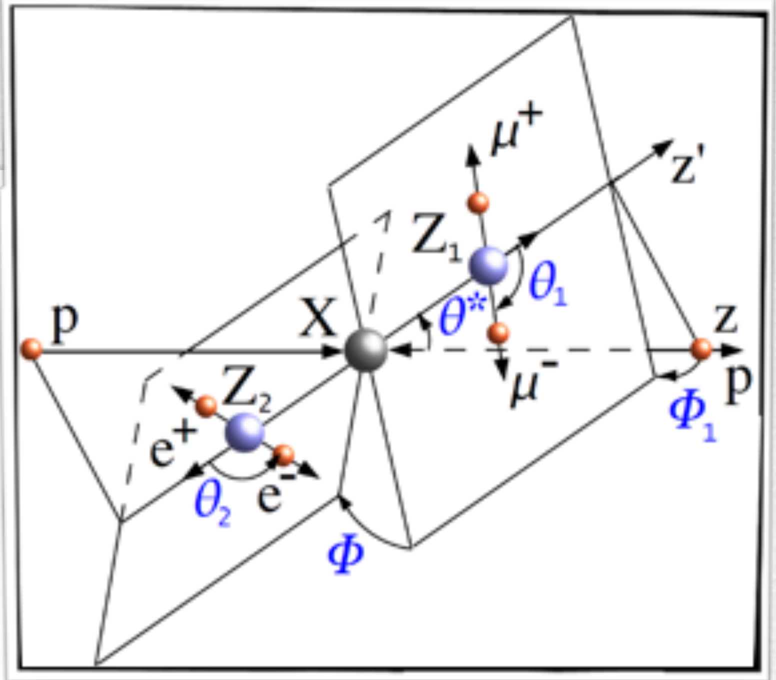
- **Event selection strategy:**
  - 4 leptons (as low p_T as possible).
  - split events into 4e, 4μ, 2e2μ channels, which have different mass resolutions and S/B rates.
- **Background sources:**
  - direct ZZ production (dominant) — a well calculated EWK process, modeling with MC.
  - reducible with "fake" leptons, model with data–driven method.
- **Other analysis features:**
  - Small event yield: ~20 events.
  - high S/B ratio, better than 2:1 (best among the all!)
  - Excellent mass resolution: ~1–2%

HIGGS →ZZ$^{(*)}$ →4l


CMS
√s = 7 TeV, L = 5.1 fb-1 ; √s = 8 TeV, L = 19.7 fb-1
Events / 3 GeV
Data
mH=126 GeV
Zγ*,ZZ
Z+X
m4l (GeV)
Signal Higgs
Z→llγ*→4l
Zγ*→4l
ZZ→4l
VBF Z
+ ...

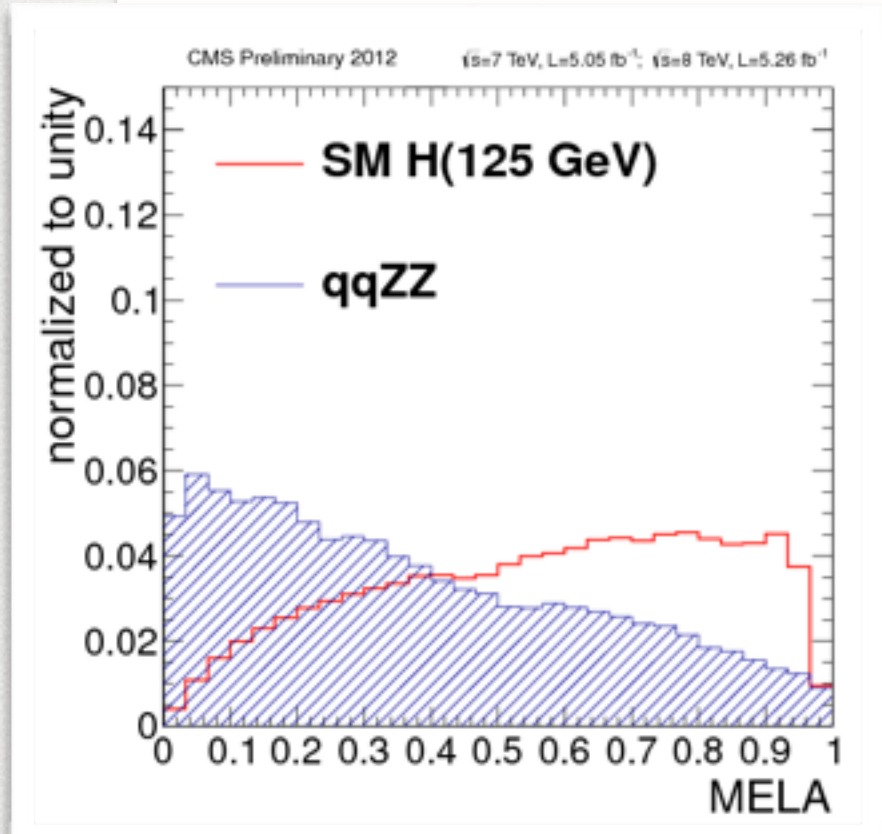
KINEMATIC DISCRIMINANT

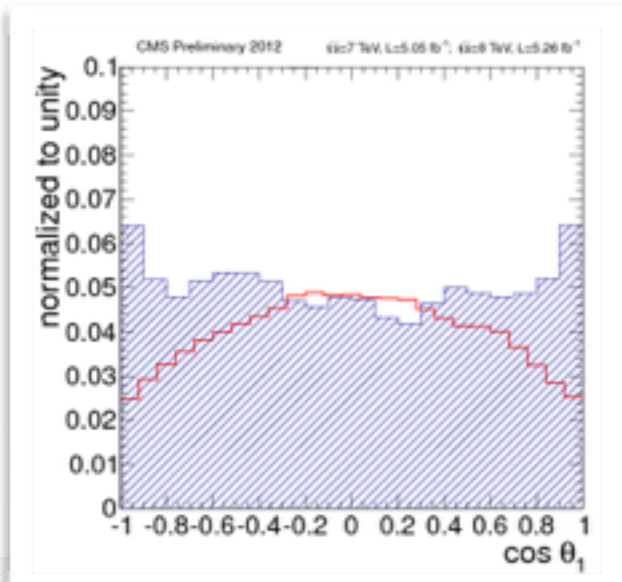
Ref. PRD 81, 075022 (2010)

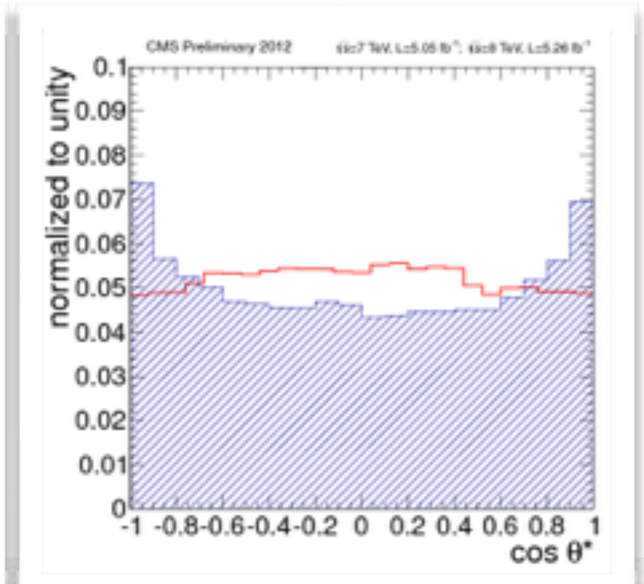


- **"MELA" (matrix element likelihood analysis)**
  - Use the full kinematic information given by the $ZZ^{(*)}$ events (full decay angles).
  - Discriminating between different "Higgs" hypotheses (spin, CP state, etc.)

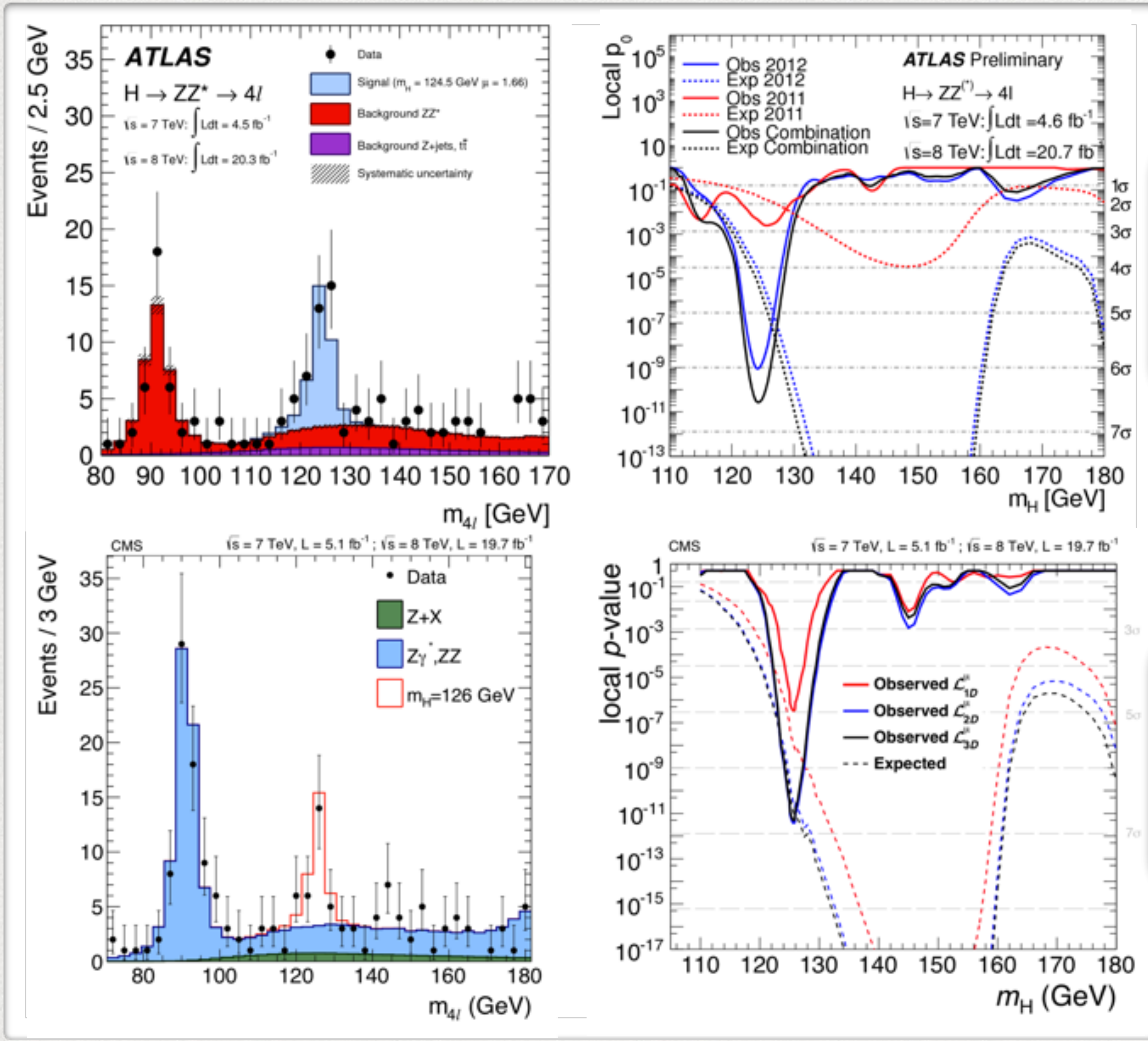
$$\mathbf{MELA} = \left[\mathbf{1} + \frac{\mathcal{P}_{\mathbf{bkg}}(\mathbf{m_1}, \mathbf{m_2}, \theta_1, \theta, \mathbf{\Phi}, \theta^*, \mathbf{\Phi_1} | \mathbf{m_{4\ell}})}{\mathcal{P}_{\mathbf{sig}}(\mathbf{m_1}, \mathbf{m_2}, \theta_1, \theta, \mathbf{\Phi}, \theta^*, \mathbf{\Phi_1} | \mathbf{m_{4\ell}})}\right]^{-1}$$







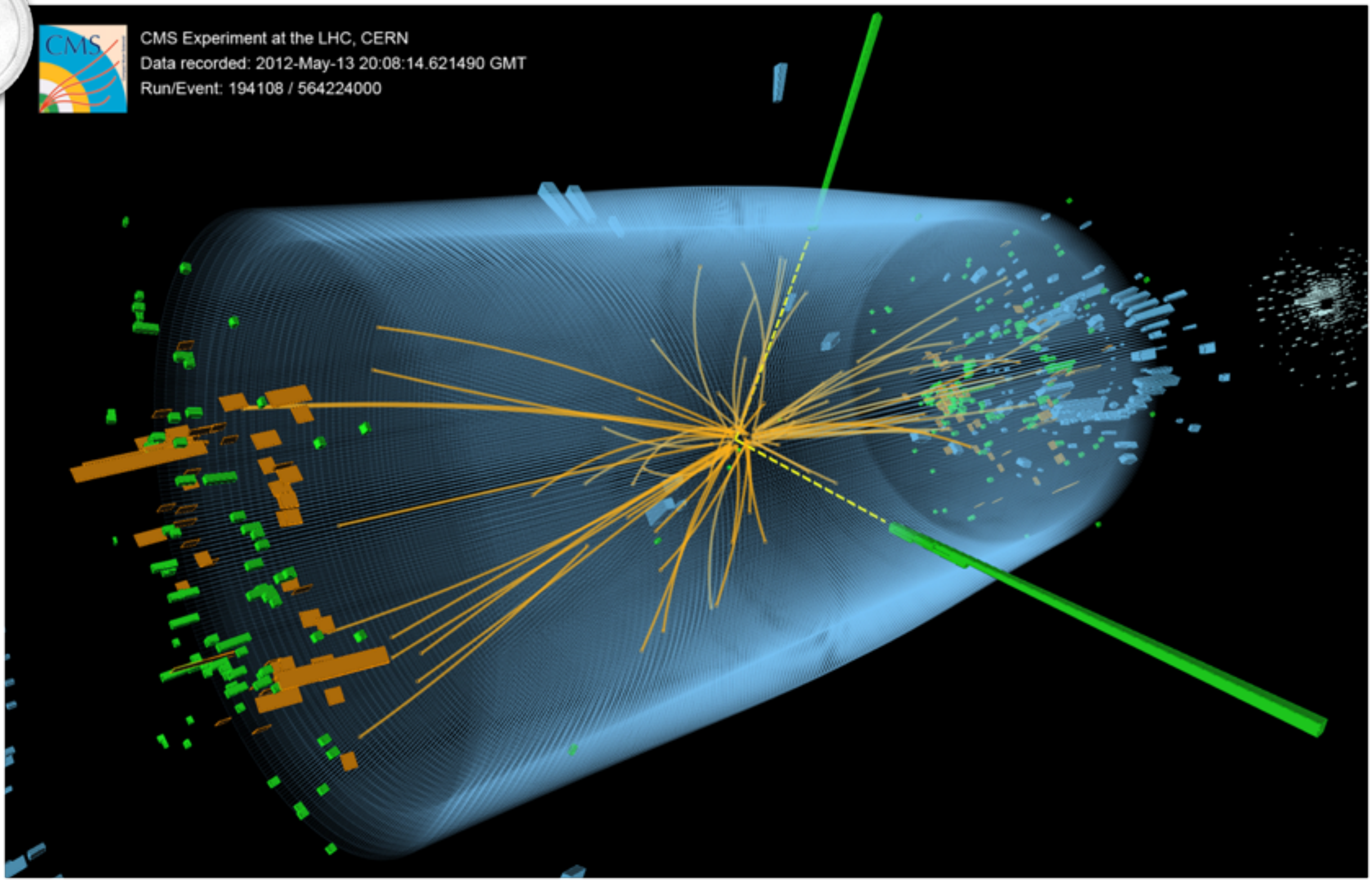
$H \to ZZ^{(*)} \to 4l$ RESULTS



ATLAS
$Z_{obs} = 6.6\ \sigma$
$\mu = 1.7 \pm 0.5$
$M(H) = 124.5 \pm 0.5$ GeV
$\Gamma_H < 2.6$ GeV @ 95% CL

CMS
$Z_{obs} = 6.7\ \sigma$
$\mu = 0.9 \pm 0.3$
$M(H) = 125.6 \pm 0.4$ GeV
$\Gamma_H < 3.4$ GeV @ 95% CL

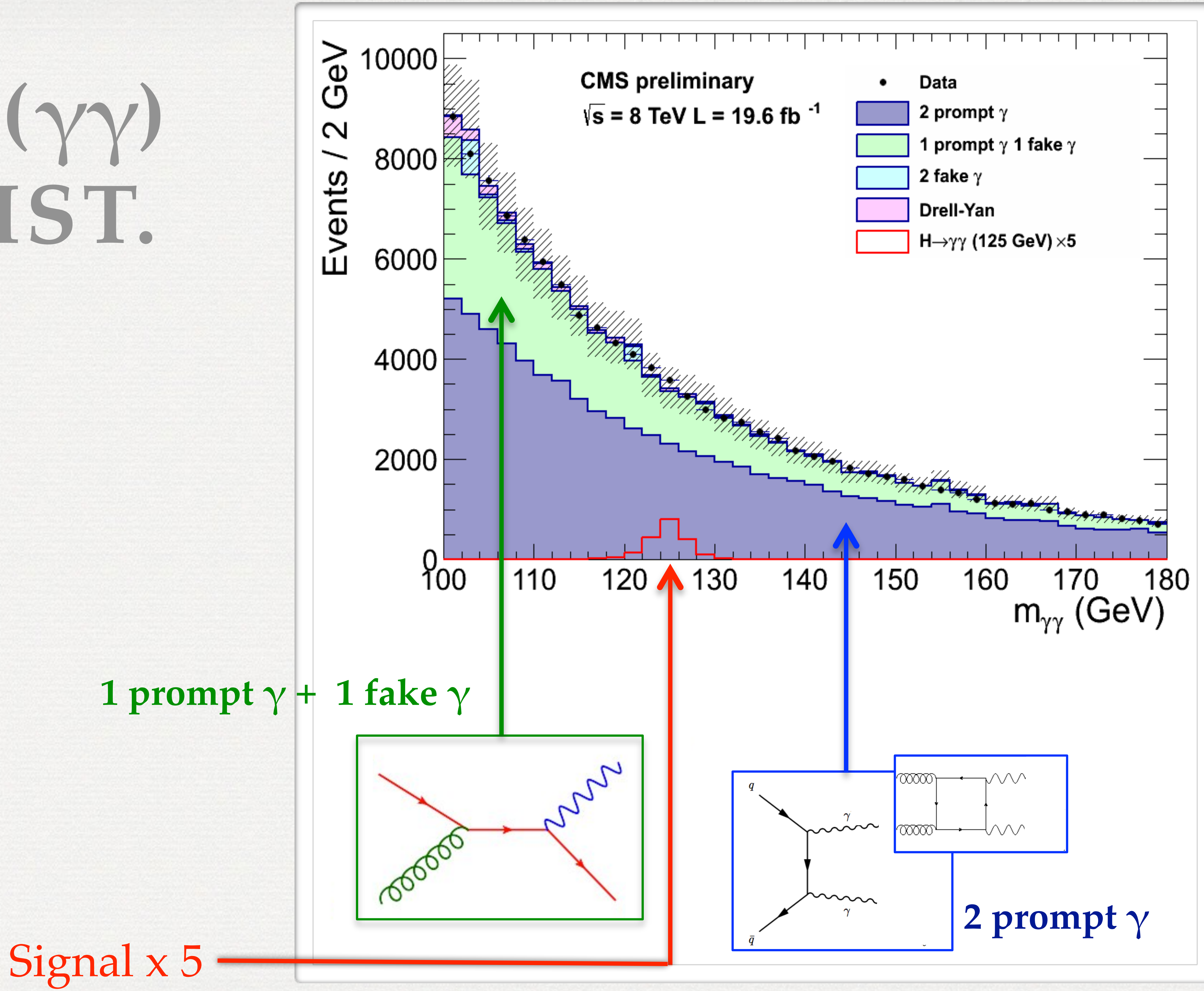
$H \rightarrow \gamma\gamma$



H→γγ: SIGNAL & BACKGROUND

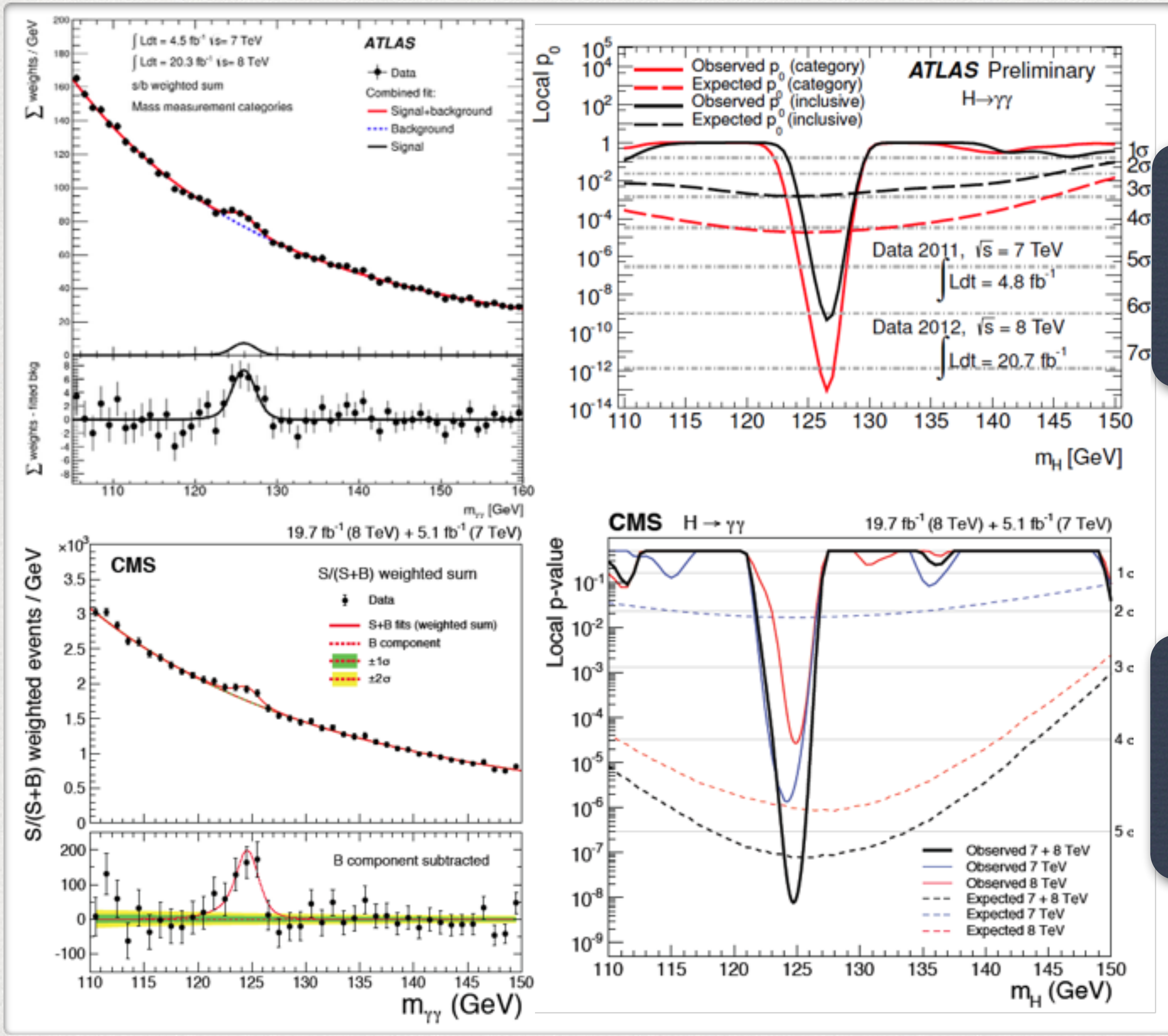
- **Event selection strategy:**
  - 2 high−p_T photons, the vertex is determined from recoiling charged particles. The invariant mass is the key observable.
  - Split events into exclusive categories: dijet/MET/e/μ tagged
  - Untagged events are further sorted into number of classes based on the quality of photons.
- **Background sources:**
  - 70% from prompt γγ, 30% from jet+γ, ...
  - Data−driven from M(γγ) sidebands.
- **Other analysis features:**
  - fairly high event yield: ~470 events.
  - high background with a S/B ratio of 1:20.
  - Good mass resolution: ~1−2%

M(γγ) DIST.



CMS preliminary
√s = 8 TeV L = 19.6 fb -1
Data
2 prompt γ
1 prompt γ 1 fake γ
2 fake γ
Drell-Yan
H→γγ (125 GeV) ×5
Events / 2 GeV
0
2000
4000
6000
8000
10000
100
110
120
130
140
150
160
170
180
mγγ (GeV)
1 prompt γ + 1 fake γ
Signal x 5
2 prompt γ

H→γγ RESULTS



ATLAS

$Z_{obs} = 7.4\ \sigma$

$\mu = 1.3 \pm 0.3$

$M(H) = 126.0 \pm 0.5$ GeV

$\Gamma_H < 5.0$ GeV @ 95% CL

CMS

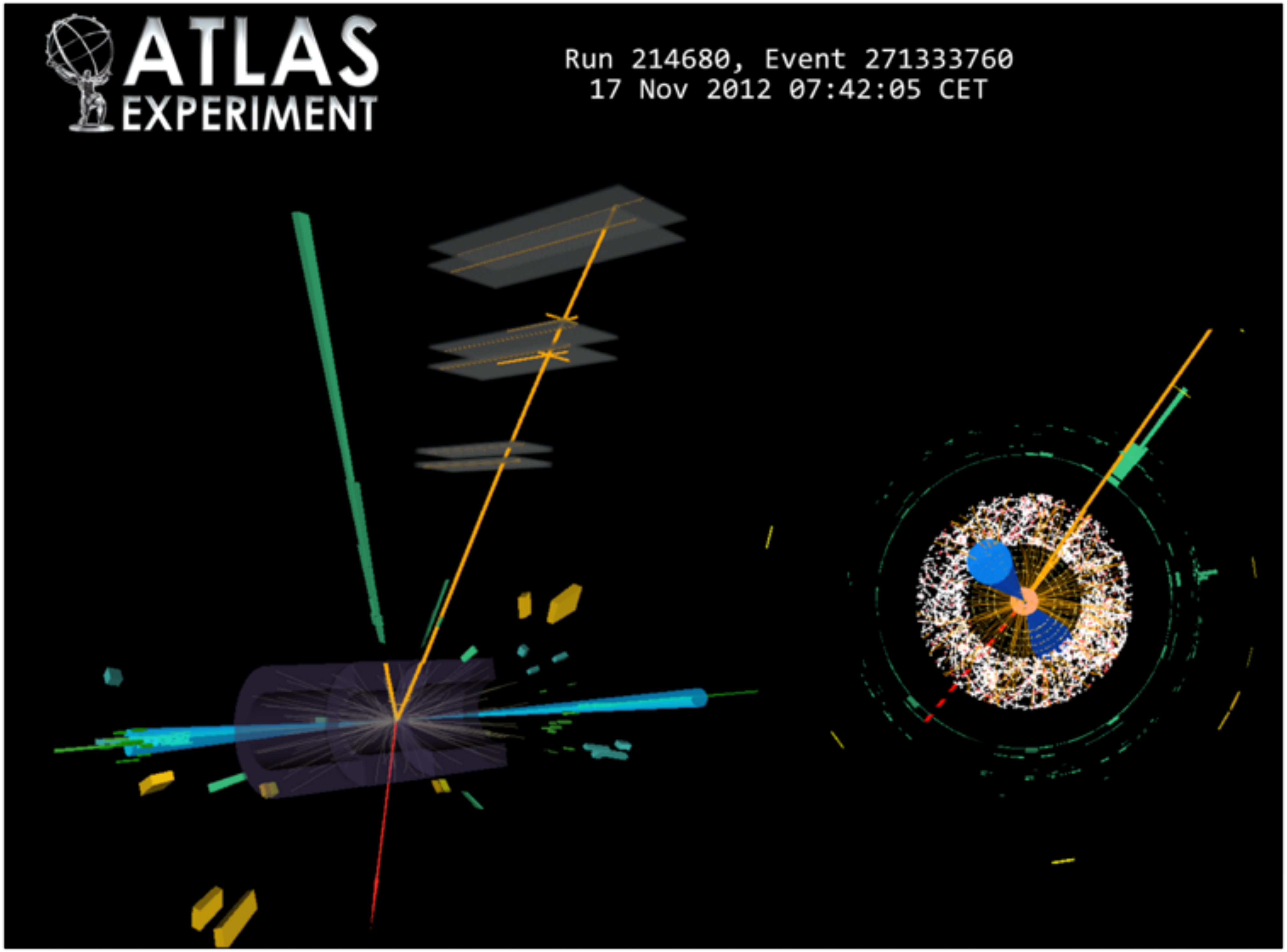
$Z_{obs} = 5.7\ \sigma$

$\mu = 1.1 \pm 0.3$

$M(H) = 124.7 \pm 0.4$ GeV

$\Gamma_H < 3.4$ GeV @ 95% CL

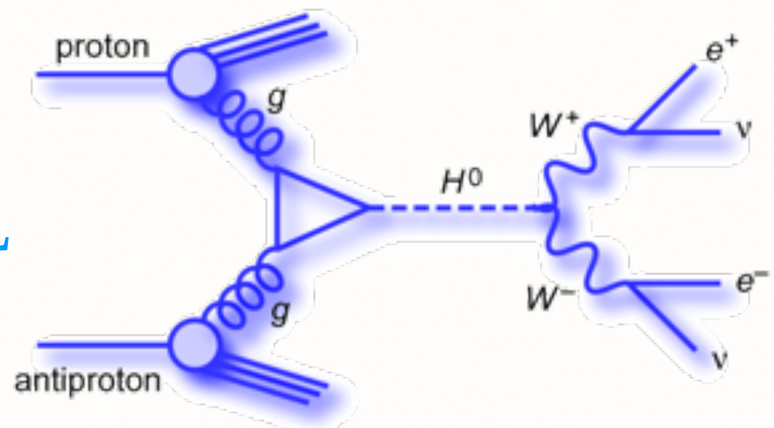
$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$

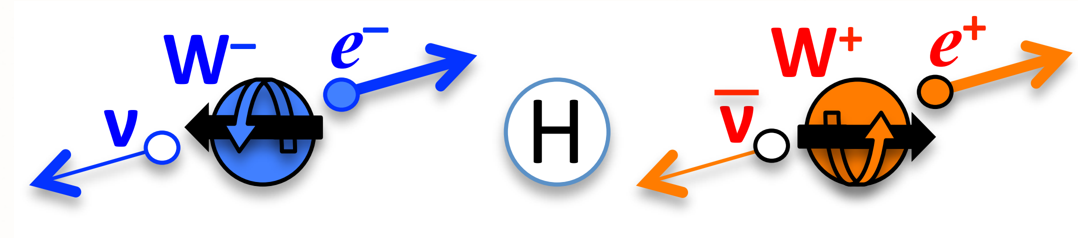


$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$: SIGNAL & BACKGROUND

- **Signal signature:**
  - 2 leptons from 2 W's (one on-shell, one off-shell)
  - Missing energy from the 2 neutrinos.
  - Discriminating observables: M_T, M(ll)
  - split events into exclusive categories: untagged with 0/1 jet, VBF dijet tag, VH dijet, WH 3l3ν tag, ZH tag.
- **Background sources:**
  - WW, top, Drell-Yan, W+jets, Wγ, determined from data
  - ZW, ZZ, small contribution, modeled with MC
- **Other analysis features:**
  - large event yield: ~270 events.
  - not too good S/B ratio of only ~1:10.
  - poor mass resolution: ~20%

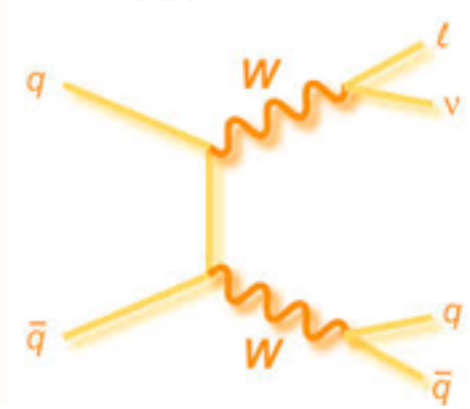
SIGNAL





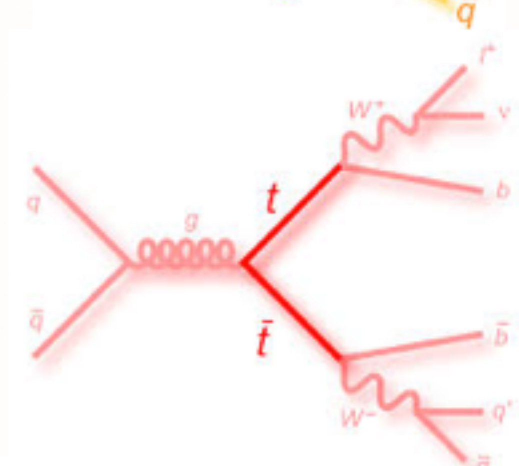
Scaler (spin 0) Higgs ⇒
small dilepton mass

irreducible
WW



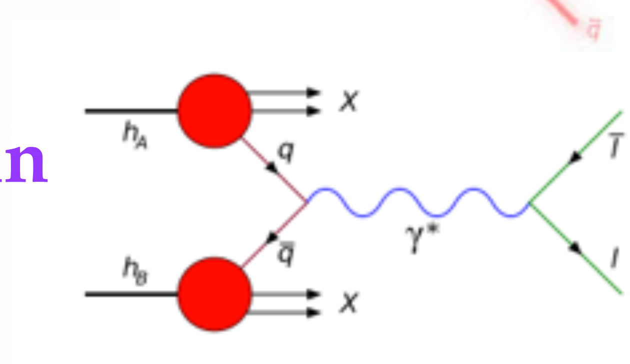
use high M(ll) region to predict the
overall WW event rate

top pair
WWbb

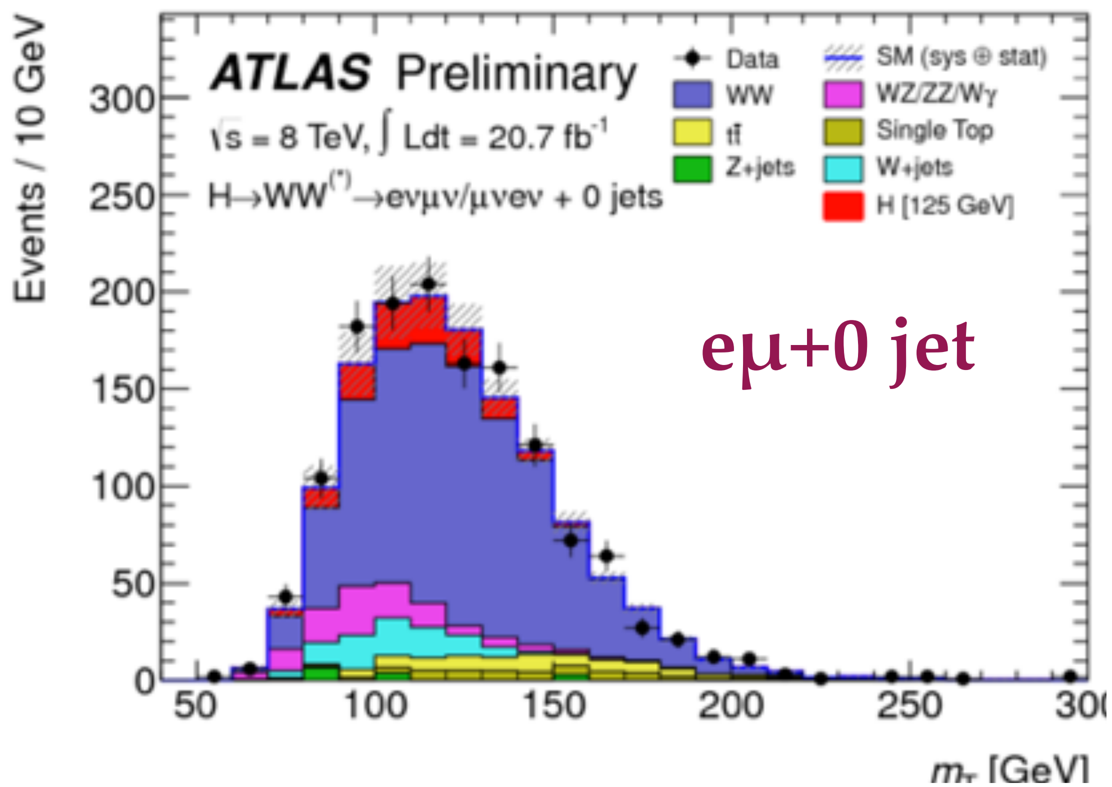


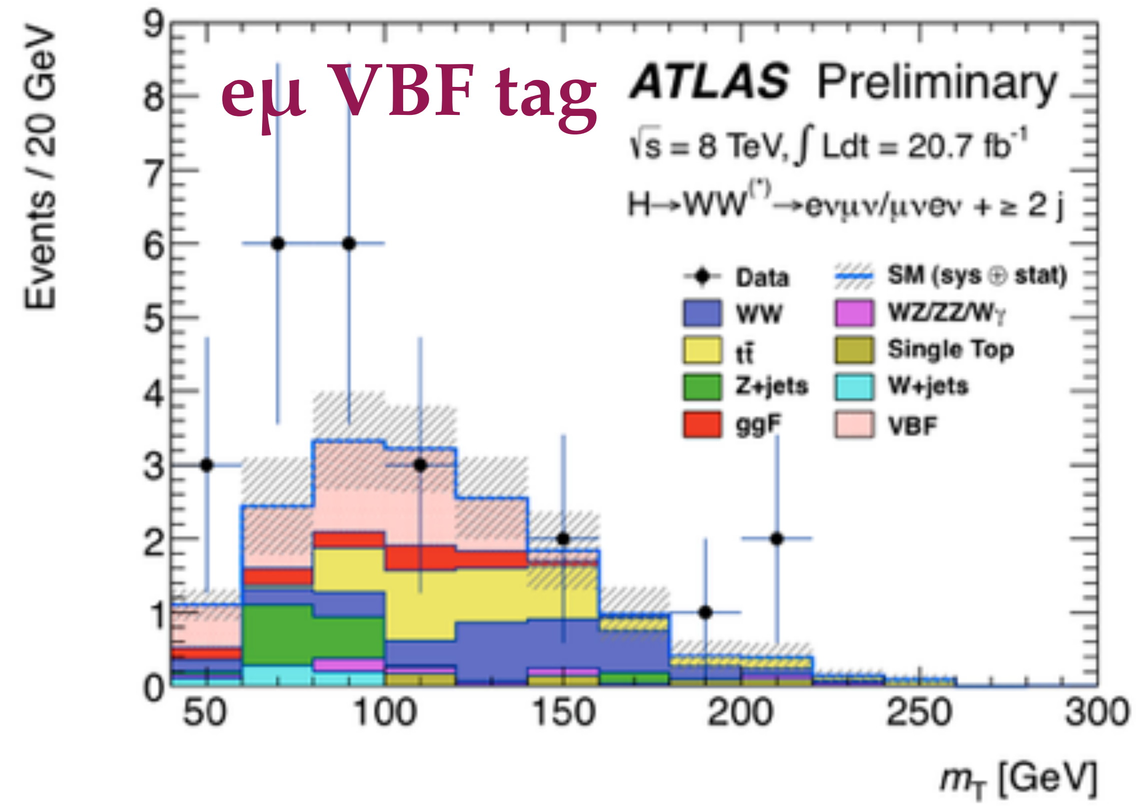
Veto the additional (b-)jets;
use the events with b–jets predict the
background rate in the signal region

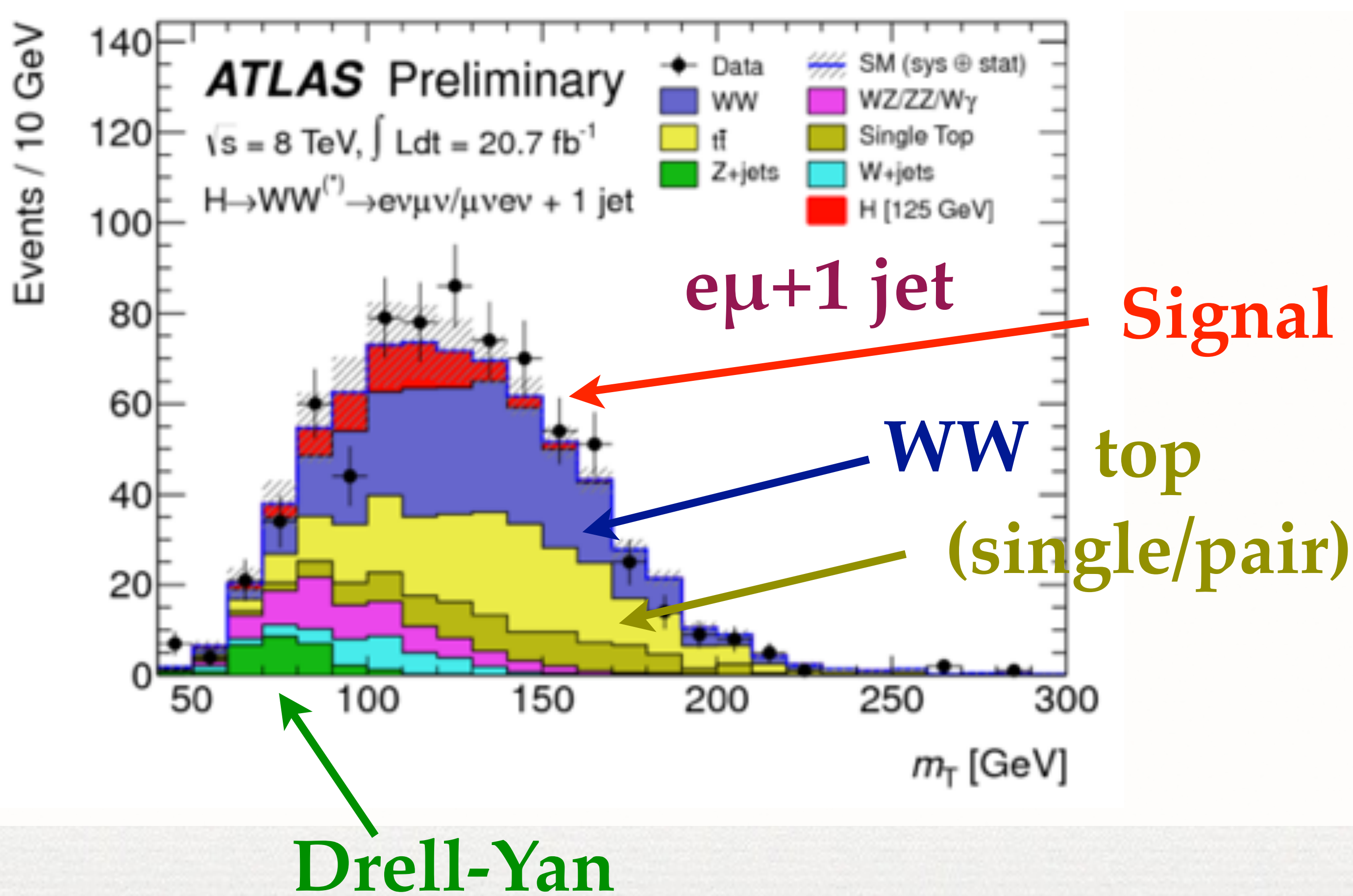
Drell-Yan
l^+l^-



Ask for MET;
eμ channel is much cleaner than ee and μμ
Use the Z peak ee and μμ to predict
off–peak background yields.

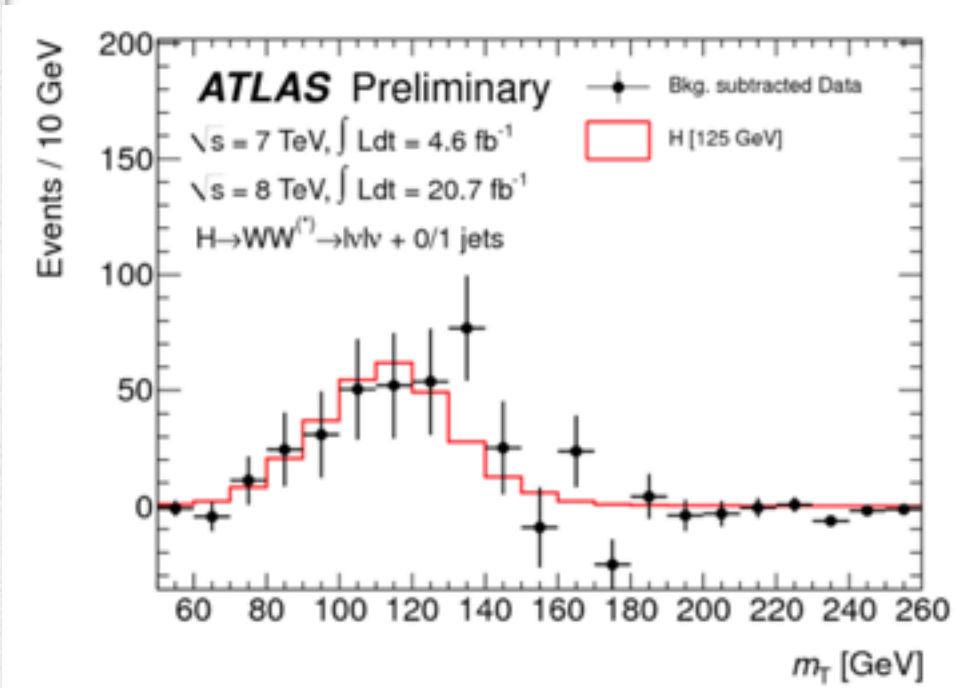


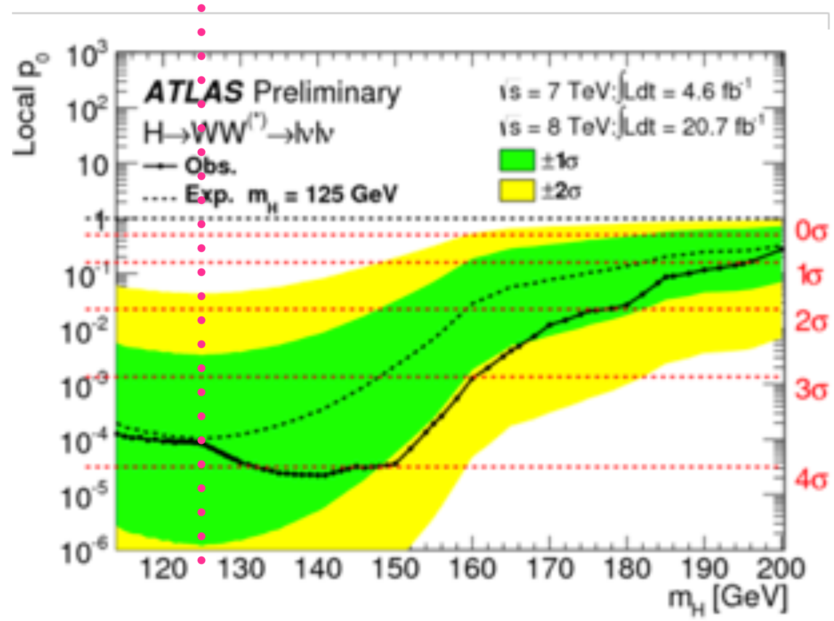


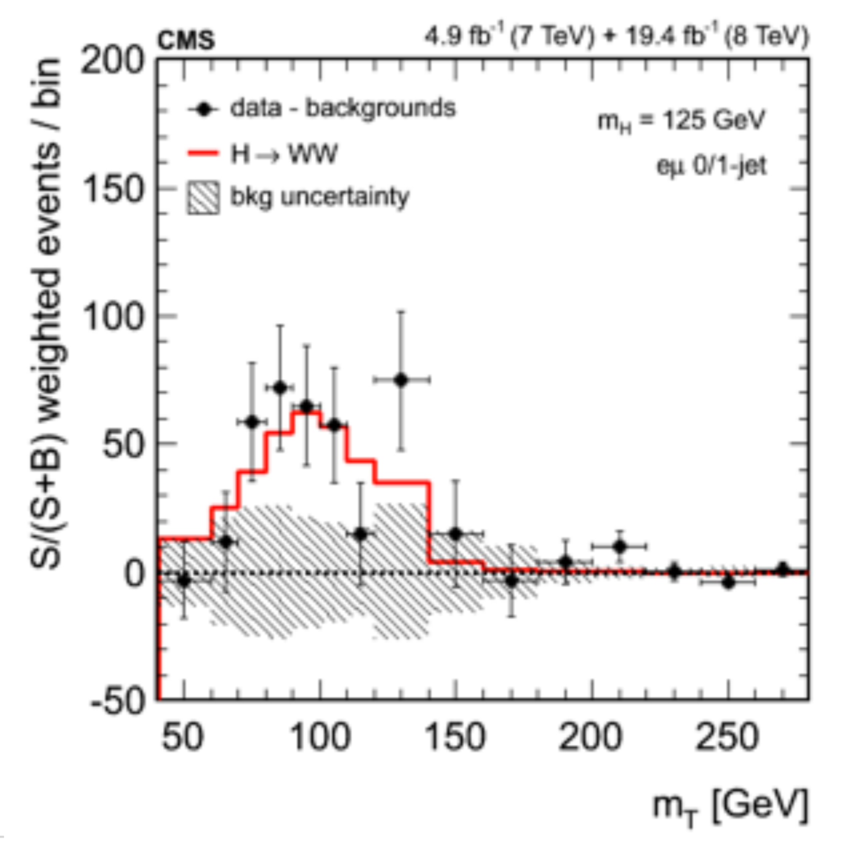


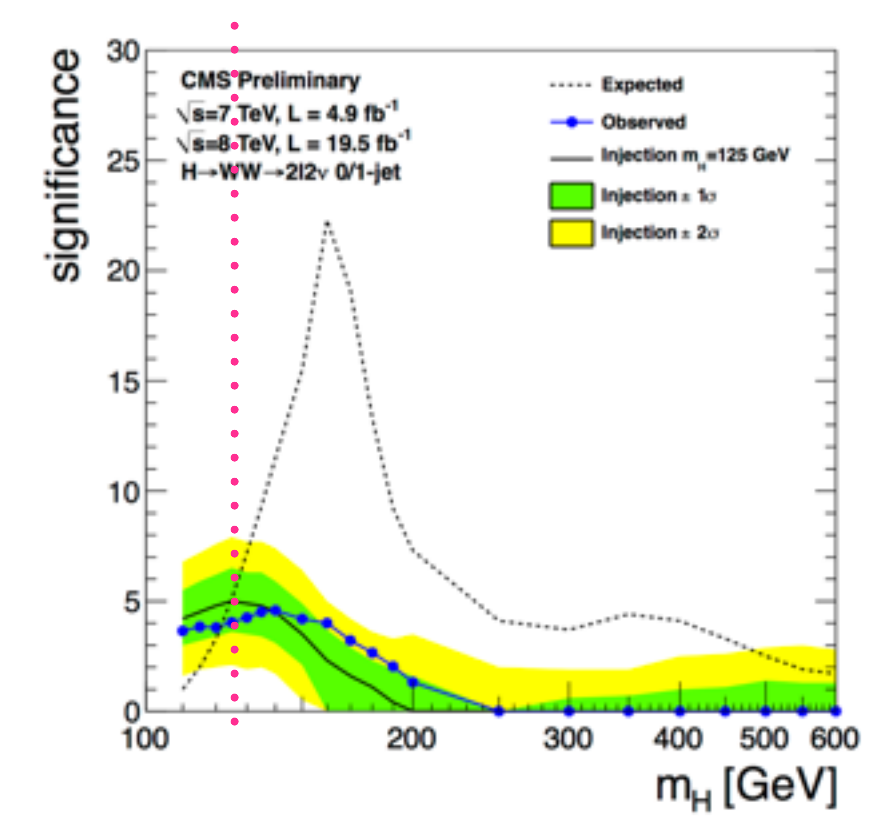
One can clearly see the background component changes with different additional jet requirements!

H→WW$^{(*)}$→lνlν RESULTS









ATLAS $Z_{obs} = 3.8\ \sigma$

$\mu = 1.0 \pm 0.3$

@ M(H) = 125 GeV

Fitted M(H) =139 ± 13 GeV

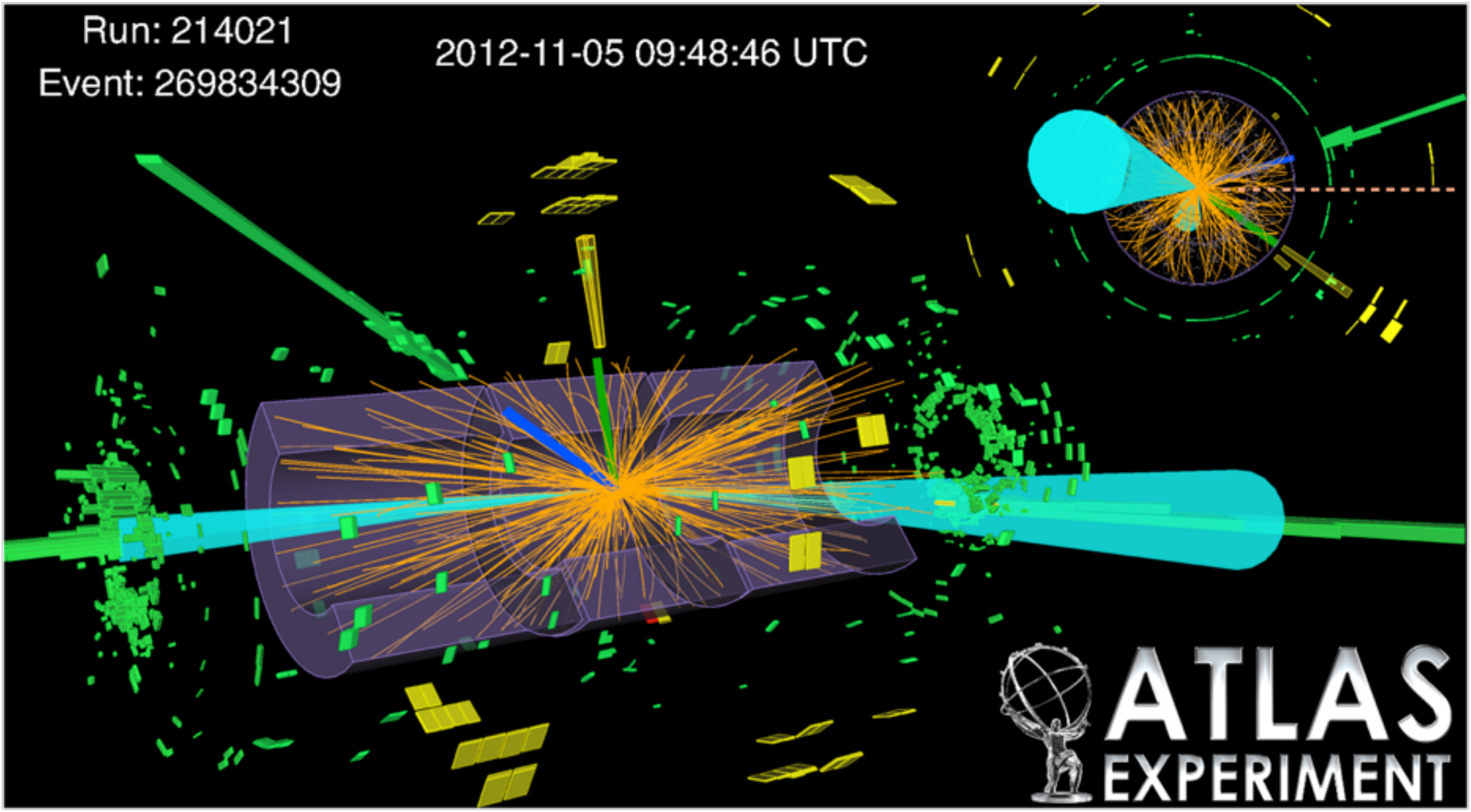
CMS $Z_{obs} = 4.3\ \sigma$

$\mu = 0.7 \pm 0.2$

@ M(H) = 125.6 GeV

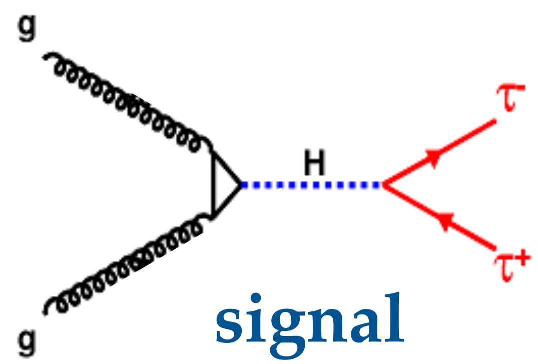
Fitted M(H) =128 ± 6 GeV

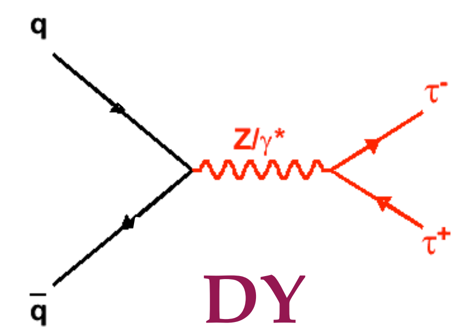
H→ττ


Run: 214021
Event: 269834309
2012-11-05 09:48:46 UTC
ATLAS
EXPERIMENT

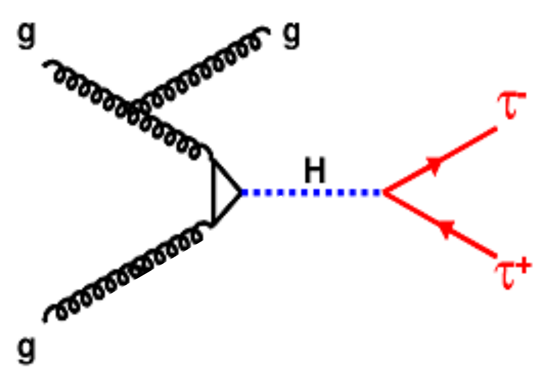
$H \rightarrow \tau\tau$: THE SIGNATURE

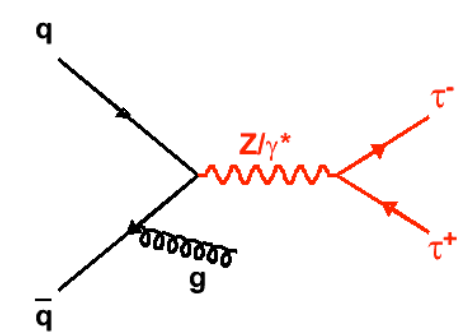
Drell–Yan background is too large to compete.



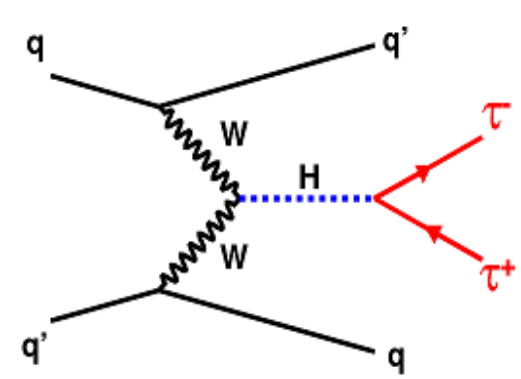


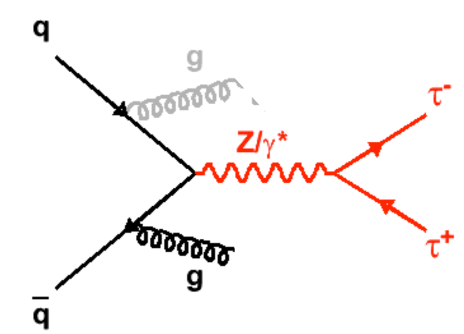
Ask for 1 more jet (DY gets suppressed more)





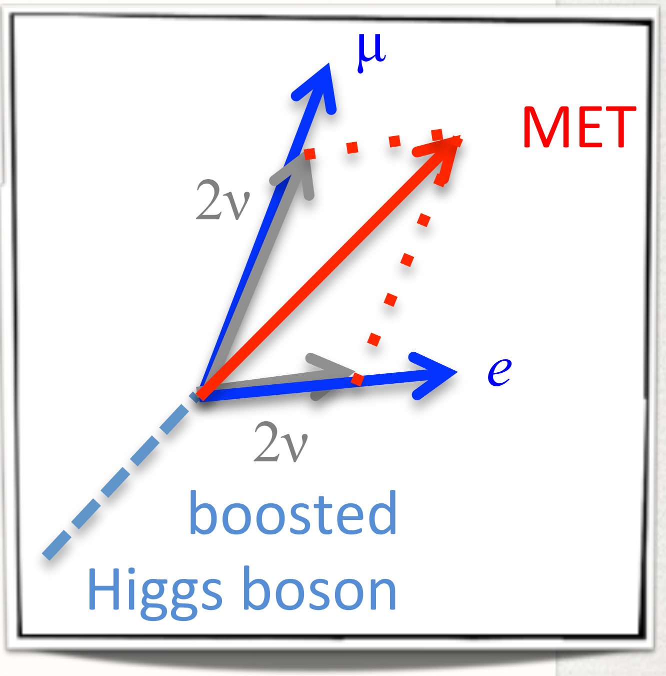
Ask for 2 VBF–like jets (DY gets suppressed a lot)

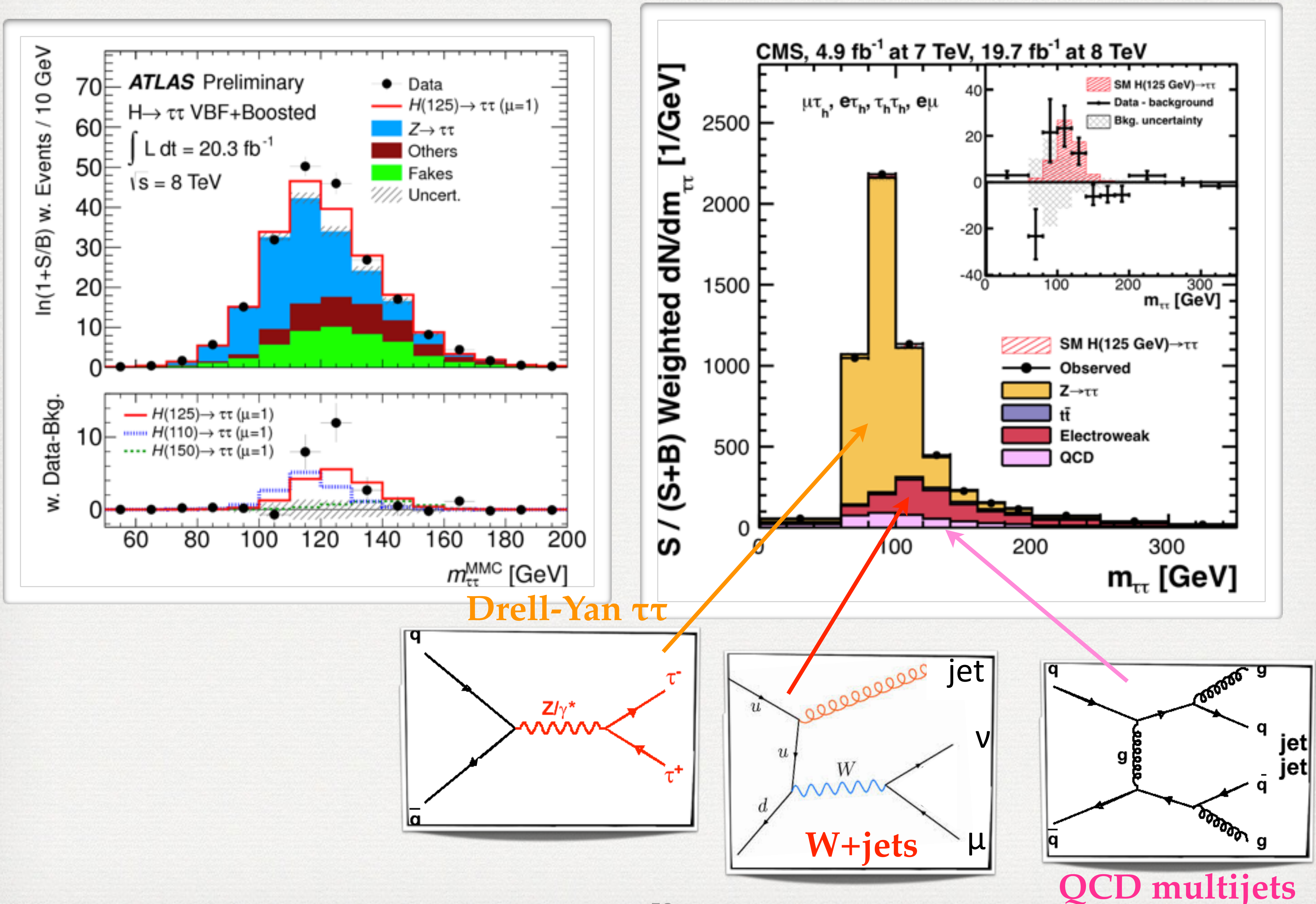




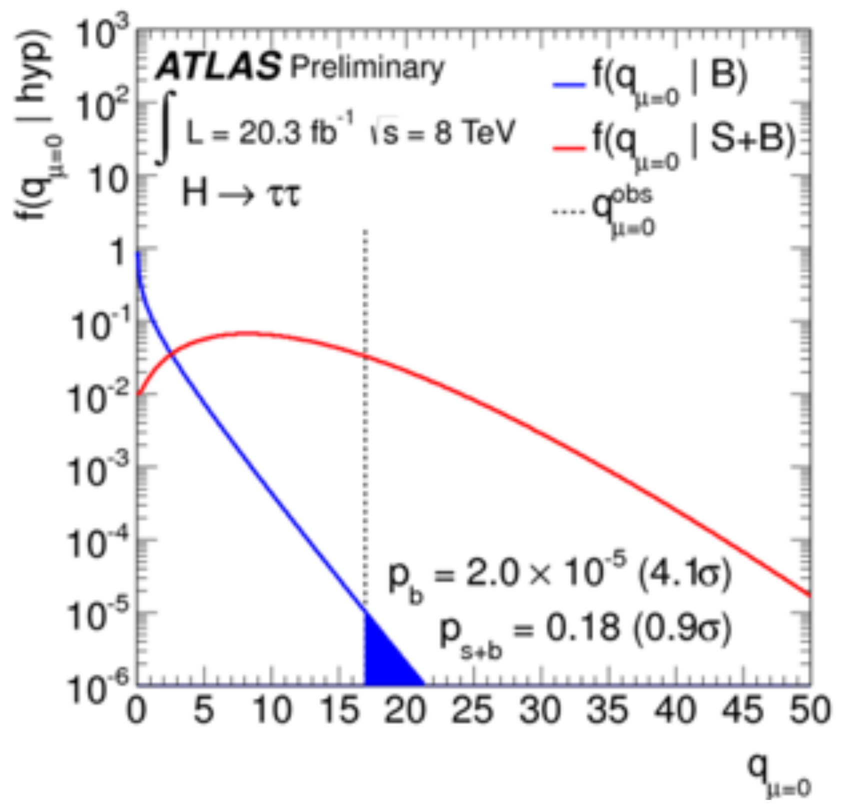
$H\rightarrow\tau\tau$: SIGNAL & BACKGROUND

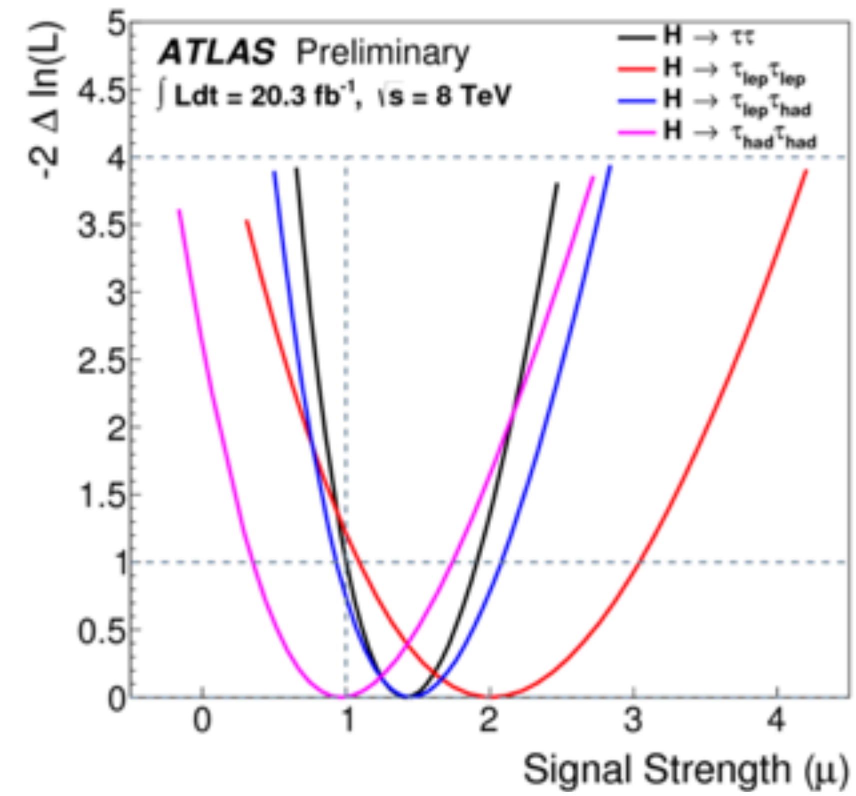
- **Signal signature:**
  - Selecting di-tau candidates ($e\tau_h$, $\mu\tau_h$, $e\mu$, ee, $\mu\mu$, $\tau_h\tau_h$) + MET [τ_h = hadronic tau decays]
  - key observable is the di-tau mass (with MET included).
  - Event categorizing: VBF-tag, 1-jet tag
- **Background sources:**
  - $Z\rightarrow\tau\tau$, $Z\rightarrow ee$, top pair, W−jets, QCD multijets, estimated with data−driven method.
  - di−boson, estimated with MC
- **Other analysis features:**
  - Event yield: ~400 events.
  - Very poor S/B ratio ~1:50.
  - poor mass resolution: ~10% ($\tau_h\tau_h$), ~15% ($\tau_h l$), ~20% (ll)

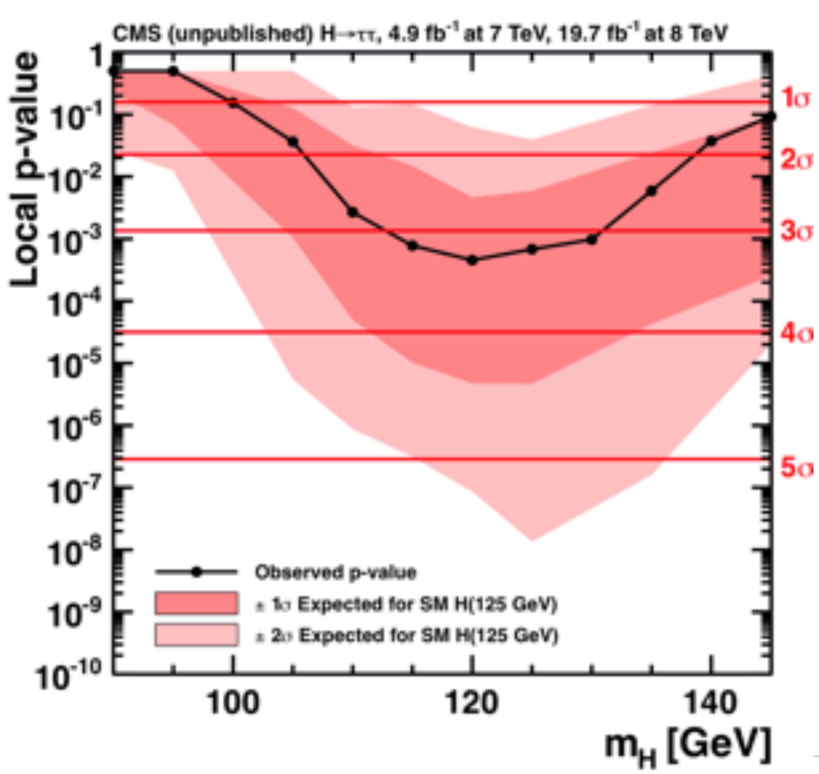


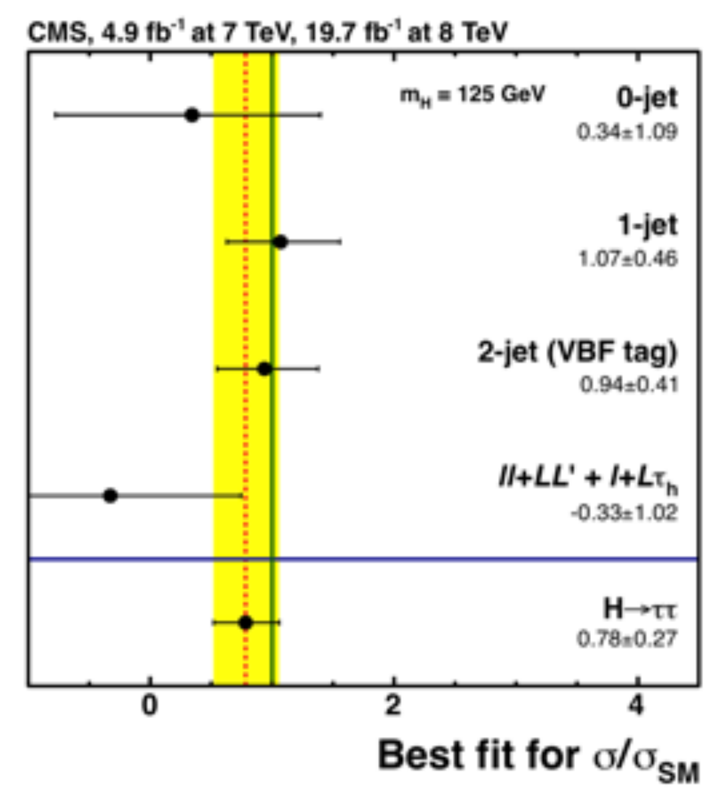

ATLAS Preliminary
H→ ττ VBF+Boosted
∫ L dt = 20.3 fb-1
√s = 8 TeV
Data
H(125)→ ττ (μ=1)
Z→ ττ
Others
Fakes
Uncert.
ln(1+S/B) w. Events / 10 GeV
w. Data-Bkg.
H(110)→ ττ (μ=1)
H(150)→ ττ (μ=1)
m_ττ^MMC [GeV]
CMS, 4.9 fb-1 at 7 TeV, 19.7 fb-1 at 8 TeV
μτh, eτh, τhτh, eμ
SM H(125 GeV)→ττ
Data - background
Bkg. uncertainty
Observed
Z→ττ
tt̄
Electroweak
QCD
S / (S+B) Weighted dN/dm_ττ [1/GeV]
m_ττ [GeV]
Drell-Yan ττ
Z/γ*
τ-
τ+
jet
ν
W
μ
W+jets
jet
jet
QCD multijets

H→ττ RESULTS







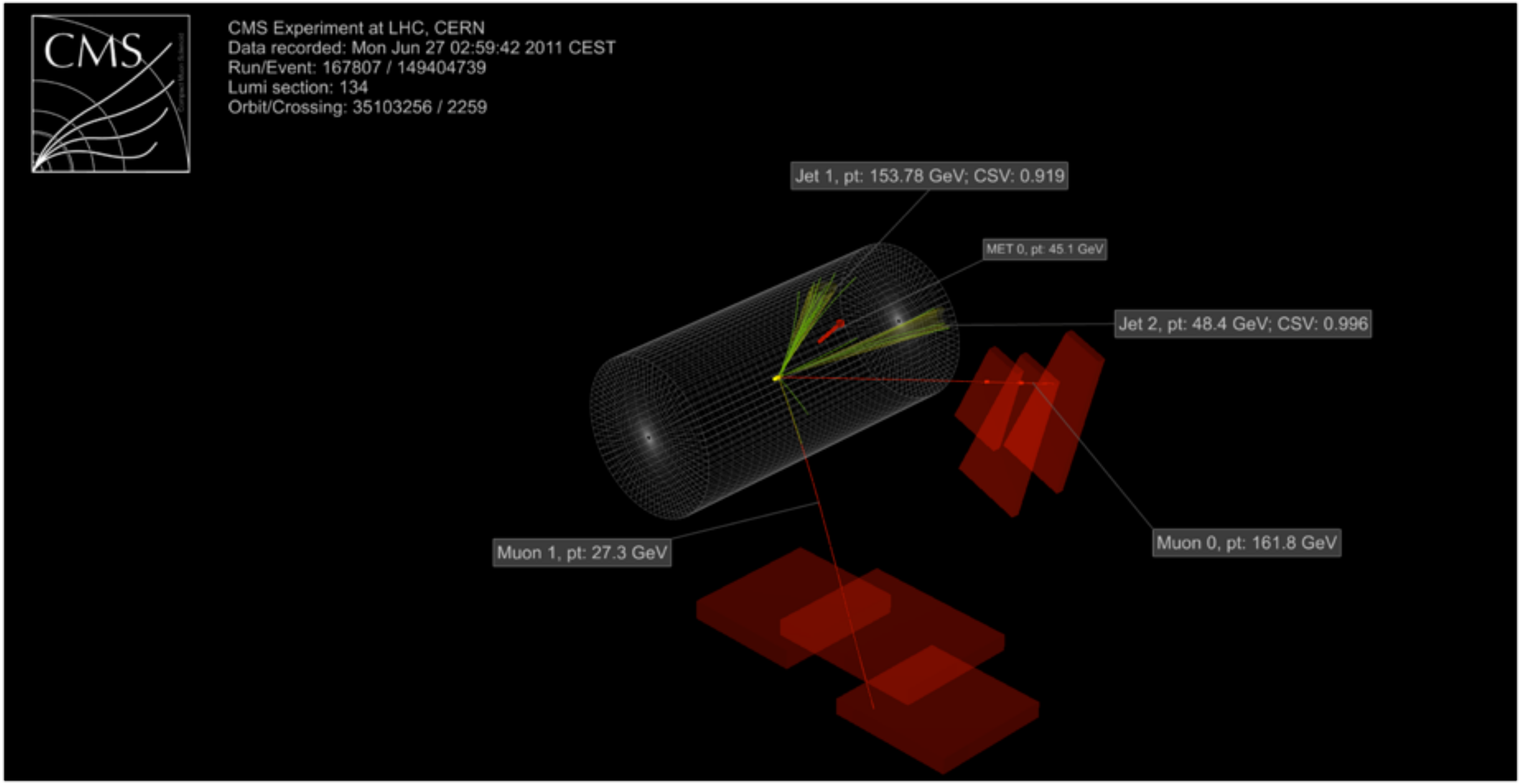


ATLAS $Z_{obs} = 4.1\,\sigma$
$\mu = 1.4 \pm 0.5$
@ M(H) = 125 GeV

CMS $Z_{obs} = 3.2\,\sigma$
$\mu = 0.8 \pm 0.3$
@ M(H) = 125 GeV

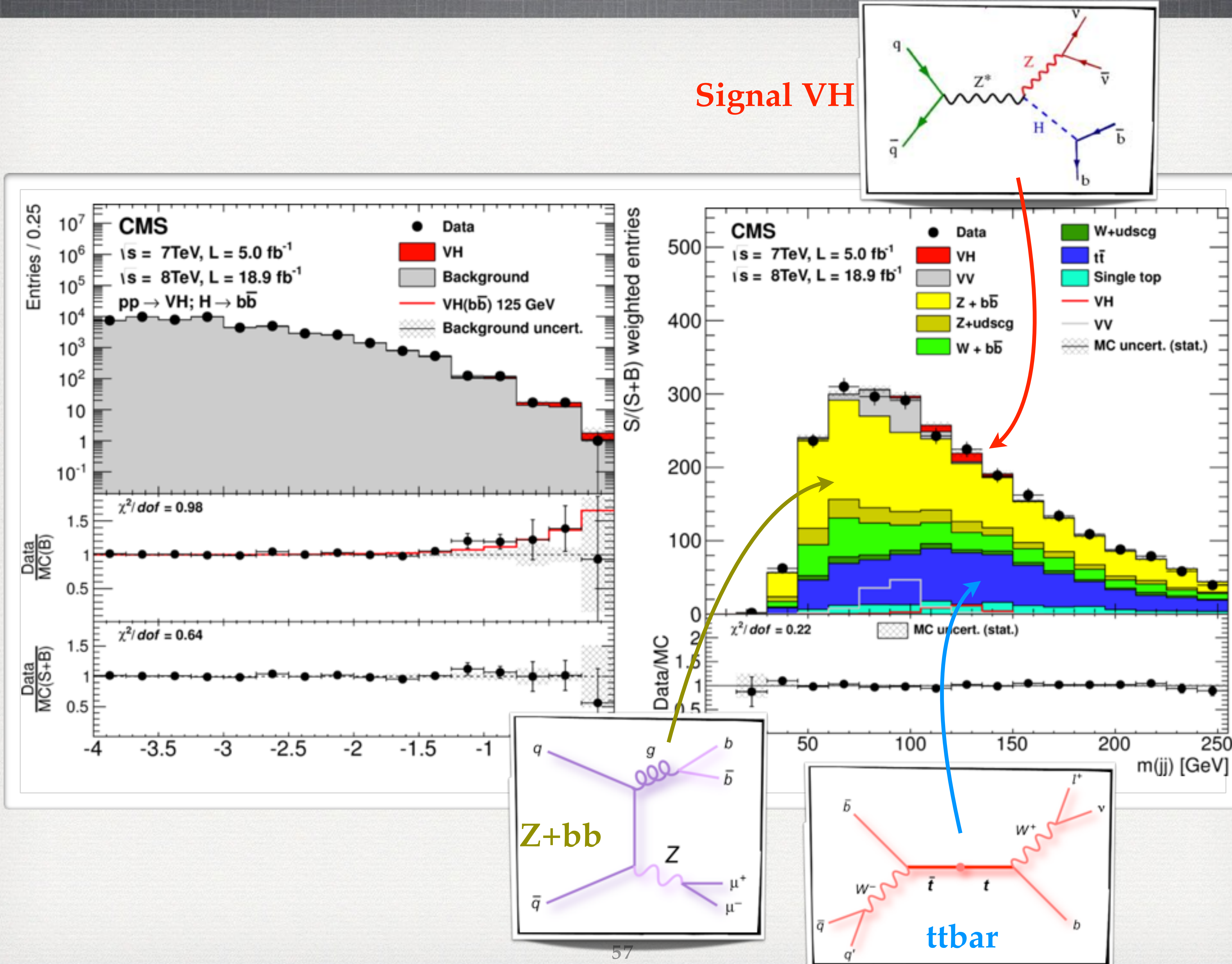
Fitted M(H) =122 ± 7 GeV

H→bb

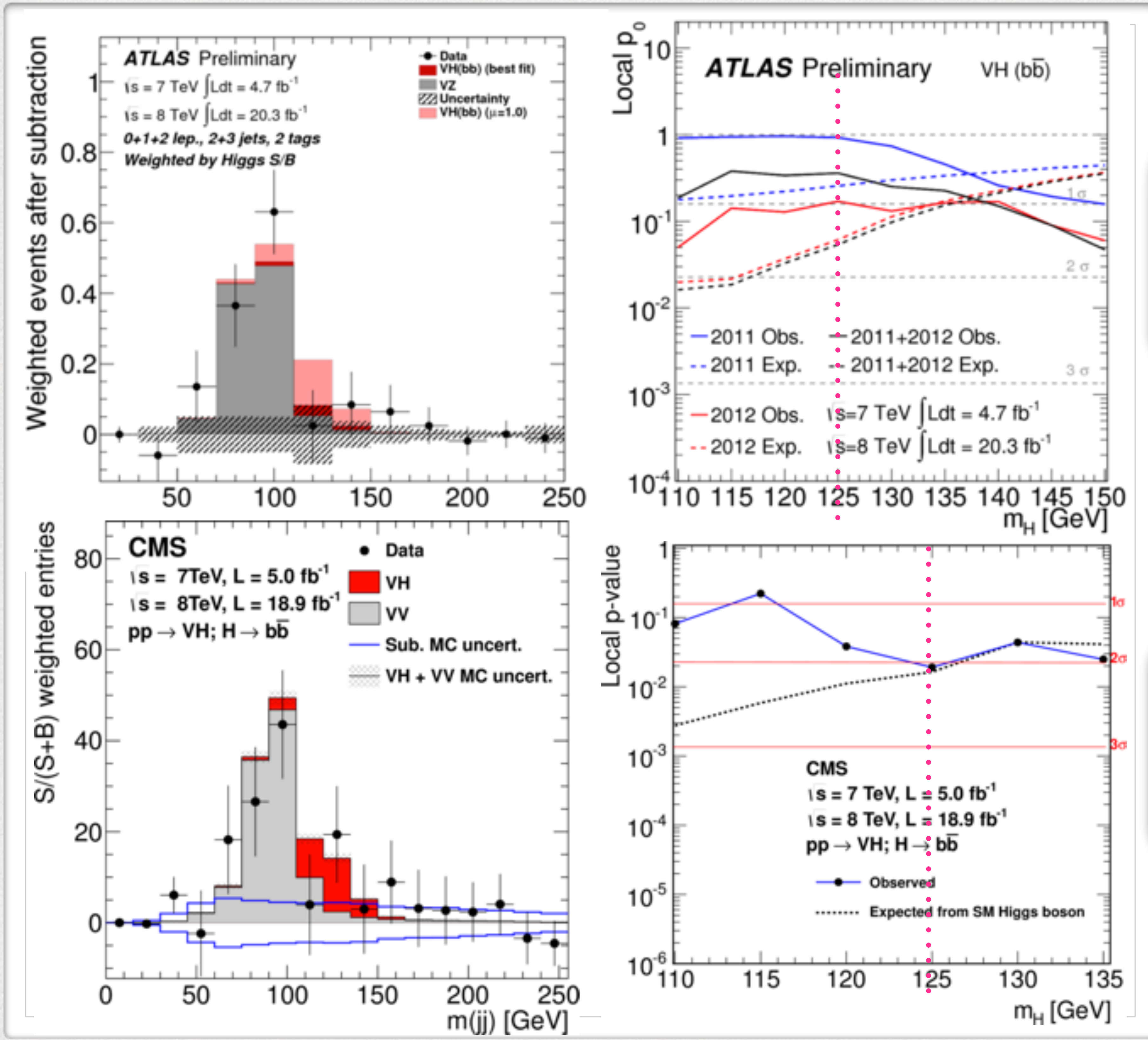

CMS
CMS Experiment at LHC, CERN
Data recorded: Mon Jun 27 02:59:42 2011 CEST
Run/Event: 167807 / 149404739
Lumi section: 134
Orbit/Crossing: 35103256 / 2259
Jet 1, pt: 153.78 GeV; CSV: 0.919
MET 0, pt: 45.1 GeV
Jet 2, pt: 48.4 GeV; CSV: 0.996
Muon 1, pt: 27.3 GeV
Muon 0, pt: 161.8 GeV

H→bb: SIGNAL & BACKGROUND

- **Signal signature:**
  - The background from QCD multijet process is very large, so only targeting VH productions.
  - Selecting two b−tagged jets + W or Z, splitting into Z(νν), Z(ll), W(lν) categories.
  - Key observables: BDT with many observables included (CMS), or di-bjet mass (ATLAS).
- **Background sources:**
  - W+bb, Z+bb, top pair, V+jets, single−top, estimated from data control regions
  - di−boson, estimated with MC.
- **Other analysis features:**
  - Small signal yield: ~60 events.
  - Poor S/B ratio ~1:20, Ok mass resolution: ~10%


Signal VH
Z+bb
ttbar
CMS
√s = 7TeV, L = 5.0 fb⁻¹
√s = 8TeV, L = 18.9 fb⁻¹
pp → VH; H → bb̄
Data
VH
Background
VH(bb̄) 125 GeV
Background uncert.
Entries / 0.25
χ²/dof = 0.98
Data / MC(B)
χ²/dof = 0.64
Data / MC(S+B)
S/(S+B) weighted entries
VV
Z + bb̄
Z+udscg
W + bb̄
W+udscg
tt̄
Single top
MC uncert. (stat.)
χ²/dof = 0.22
Data/MC
m(jj) [GeV]

H→ττ RESULTS



ATLAS $Z_{obs} = 0.3\ \sigma$

$\mu = 0.2 \pm 0.6$

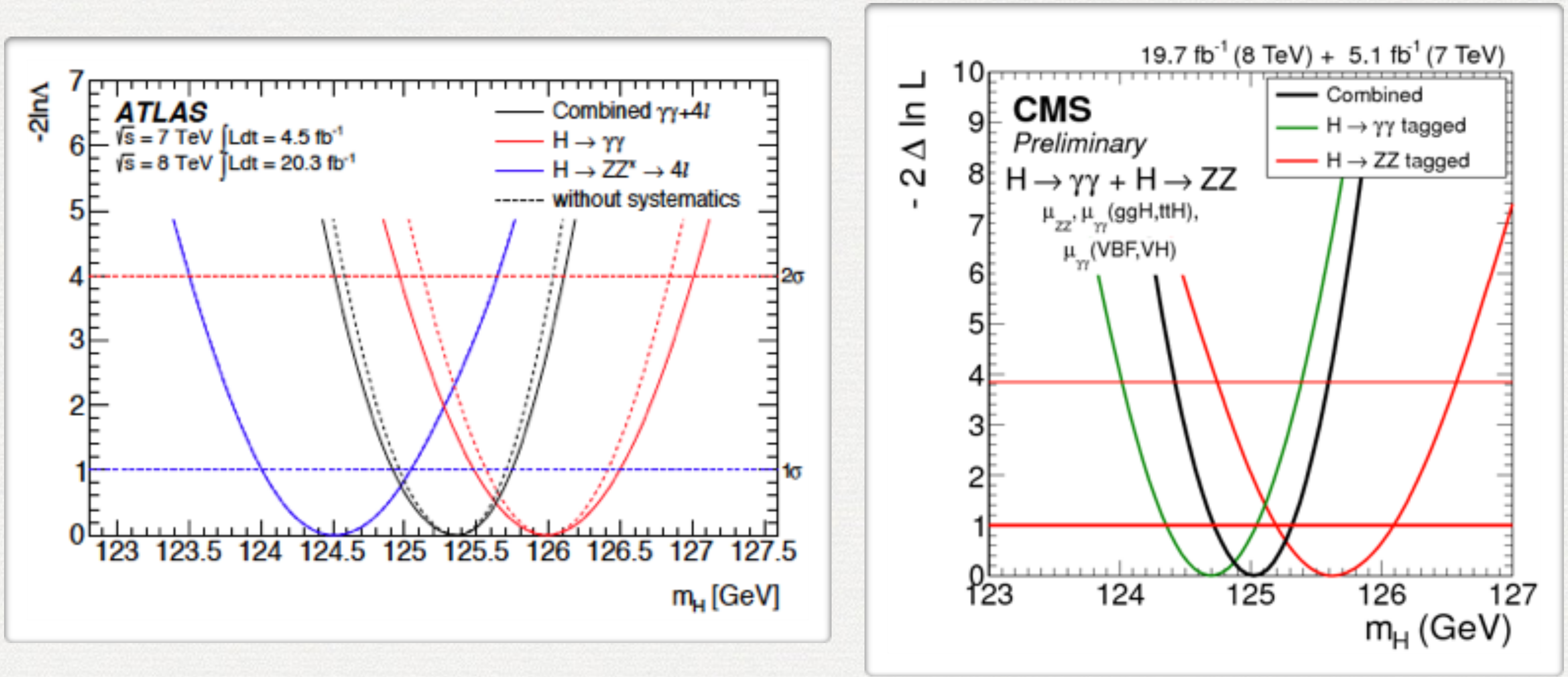
@ M(H) = 125 GeV

CMS $Z_{obs} = 2.1\ \sigma$

$\mu = 1.0 \pm 0.5$

@ M(H) = 125 GeV

COMBINING H→4l & H→γγ



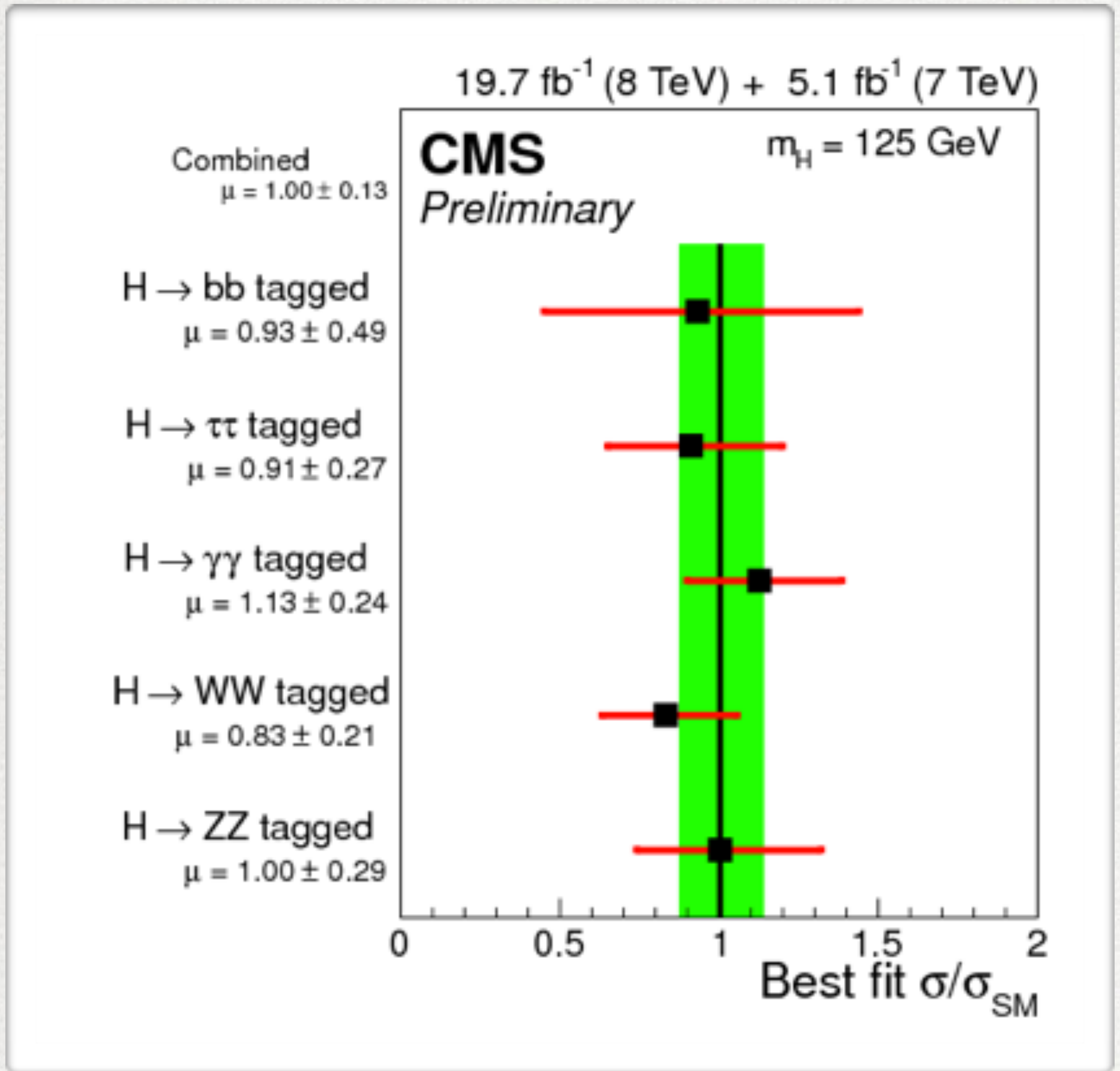
- A narrow resonance is seen with high significance in the best two channels: 4l and γγ. Results are consistent with single particle.
- Combined mass measurements:

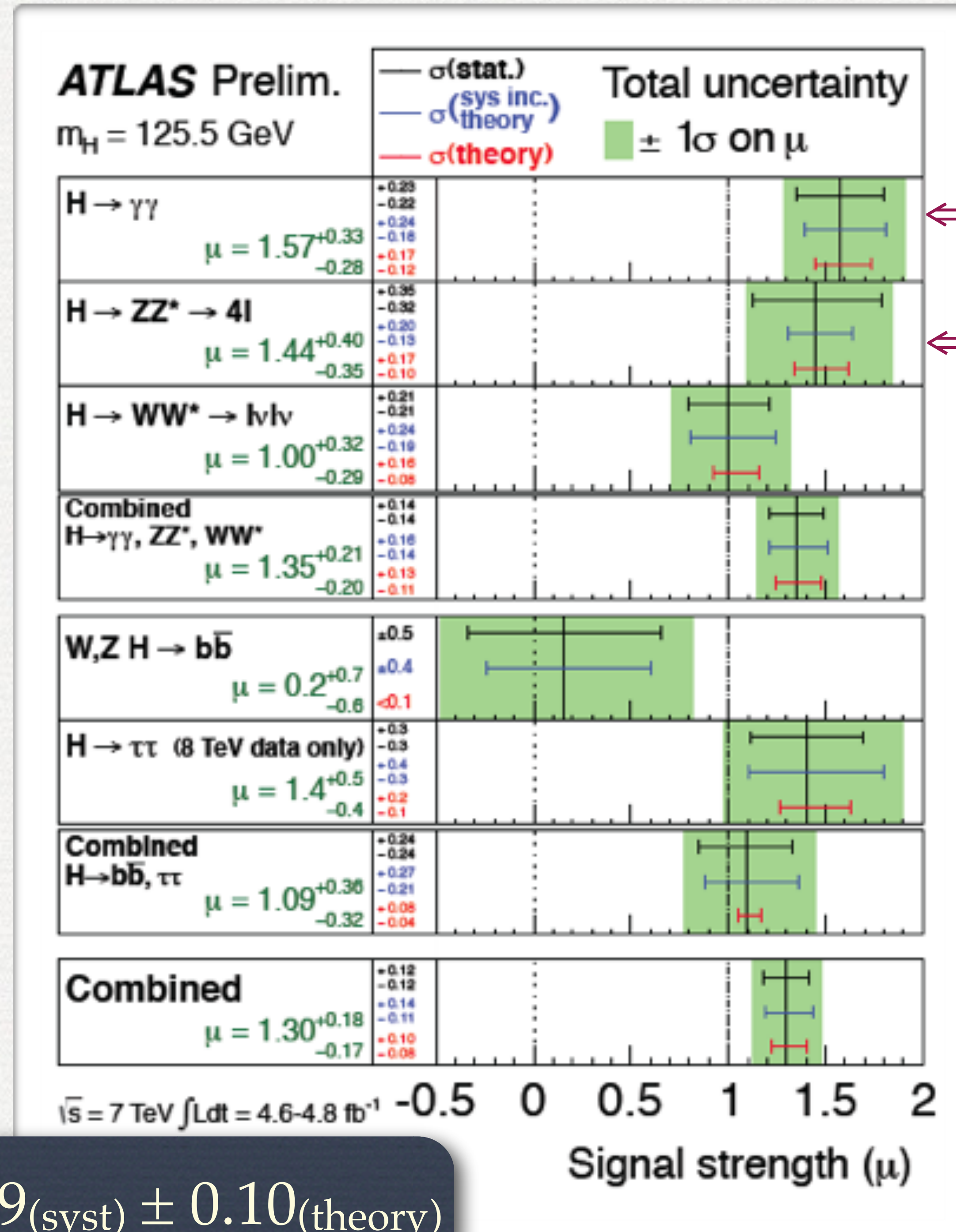
ATLAS $m = 125.36 \pm 0.37\ (stat) \pm 0.18\ (syst)$ GeV

CMS $m = 125.03 \pm 0.27\ (stat) \pm 0.14\ (syst)$ GeV

better then 3% precision!

BIG-5 COMBINED





⇐ new $\mu=1.3\pm0.3$

⇐ new $\mu=1.7\pm0.5$

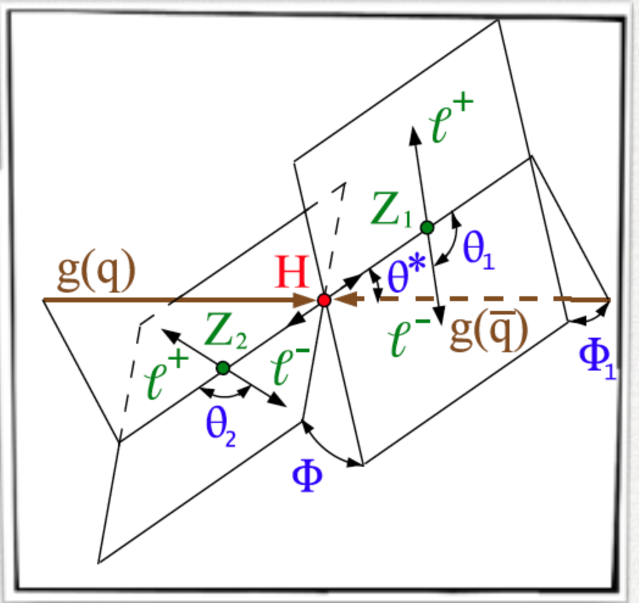
ATLAS $\mu = 1.30 \pm 0.12_{(stat)} \pm 0.09_{(syst)} \pm 0.10_{(theory)}$

CMS $\mu = 1.00 \pm 0.09_{(stat)} \pm 0.07_{(syst)} \pm 0.08_{(theory)}$

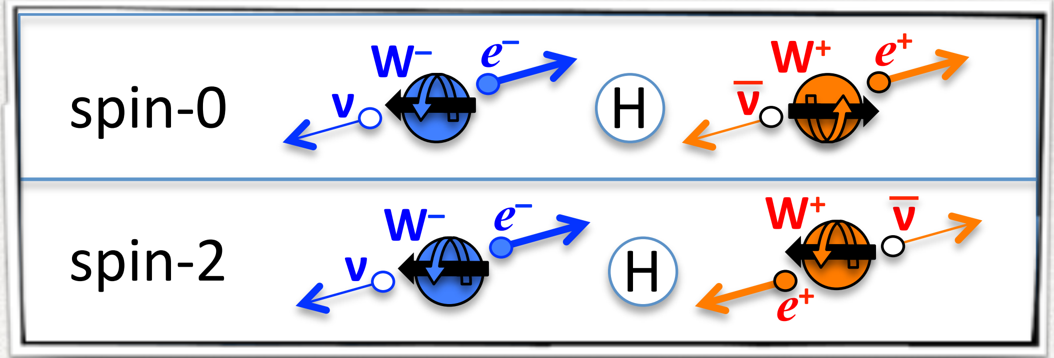
Experimental precision is already comparable with TH uncertainty!

SPIN–PARITY TESTS

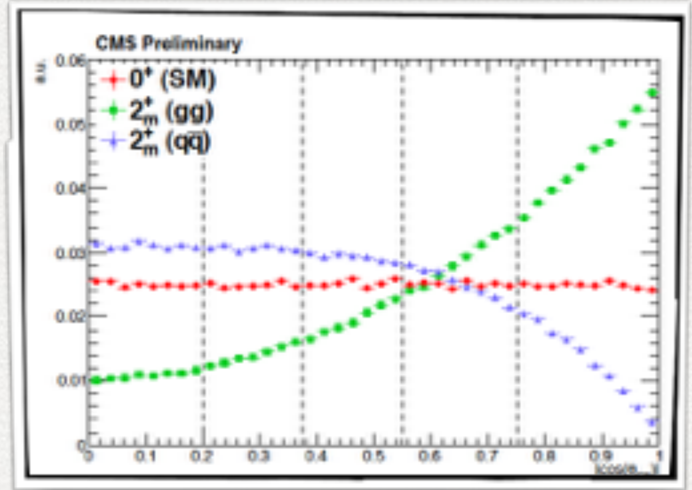
- **$H \rightarrow ZZ^{(*)} \rightarrow 4l$**
  - The four lepton system contains the full information.
  - Use the lepton momenta to compute matrix elements or train MVA for distinguishing different hypothesis.



- **$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$**
  - dilepton angle is sensitive to spin of the decaying boson.

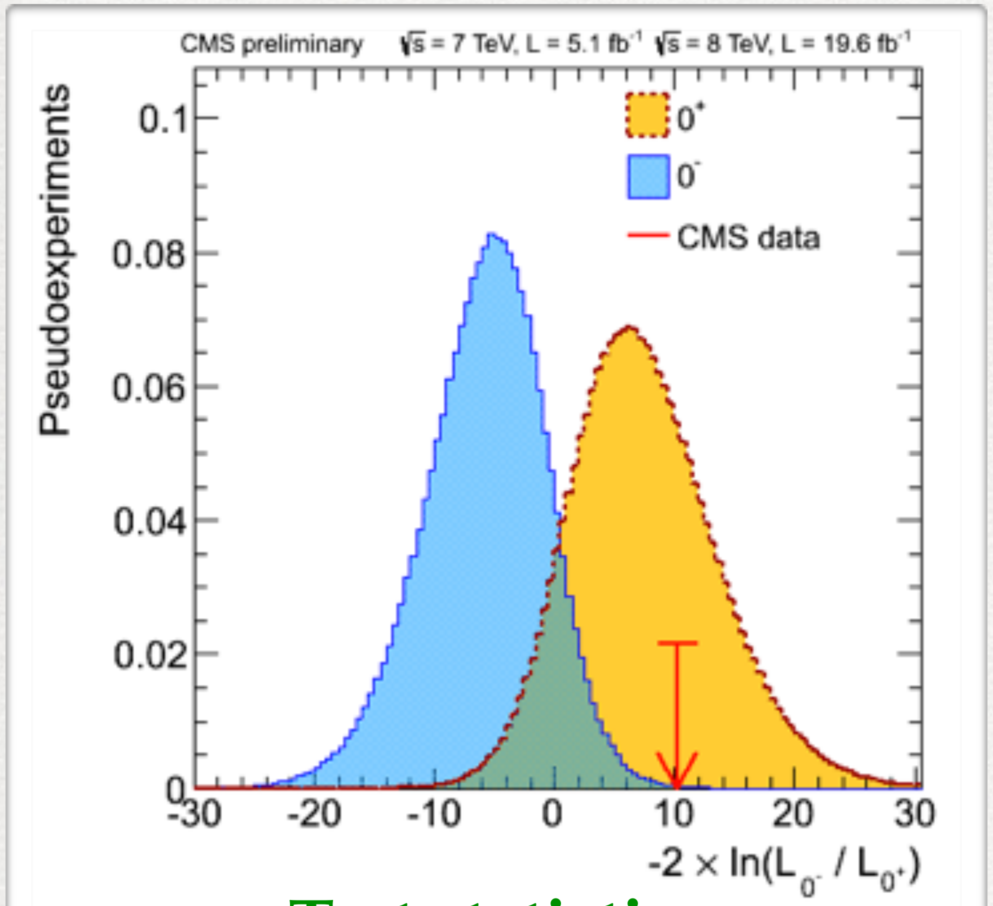


- **$H \rightarrow \gamma\gamma$**
  - J=1 forbidden (Landau–Yang theorem)
  - Decay helicity angle is the only variable sensitive to J^P information at the leading order.

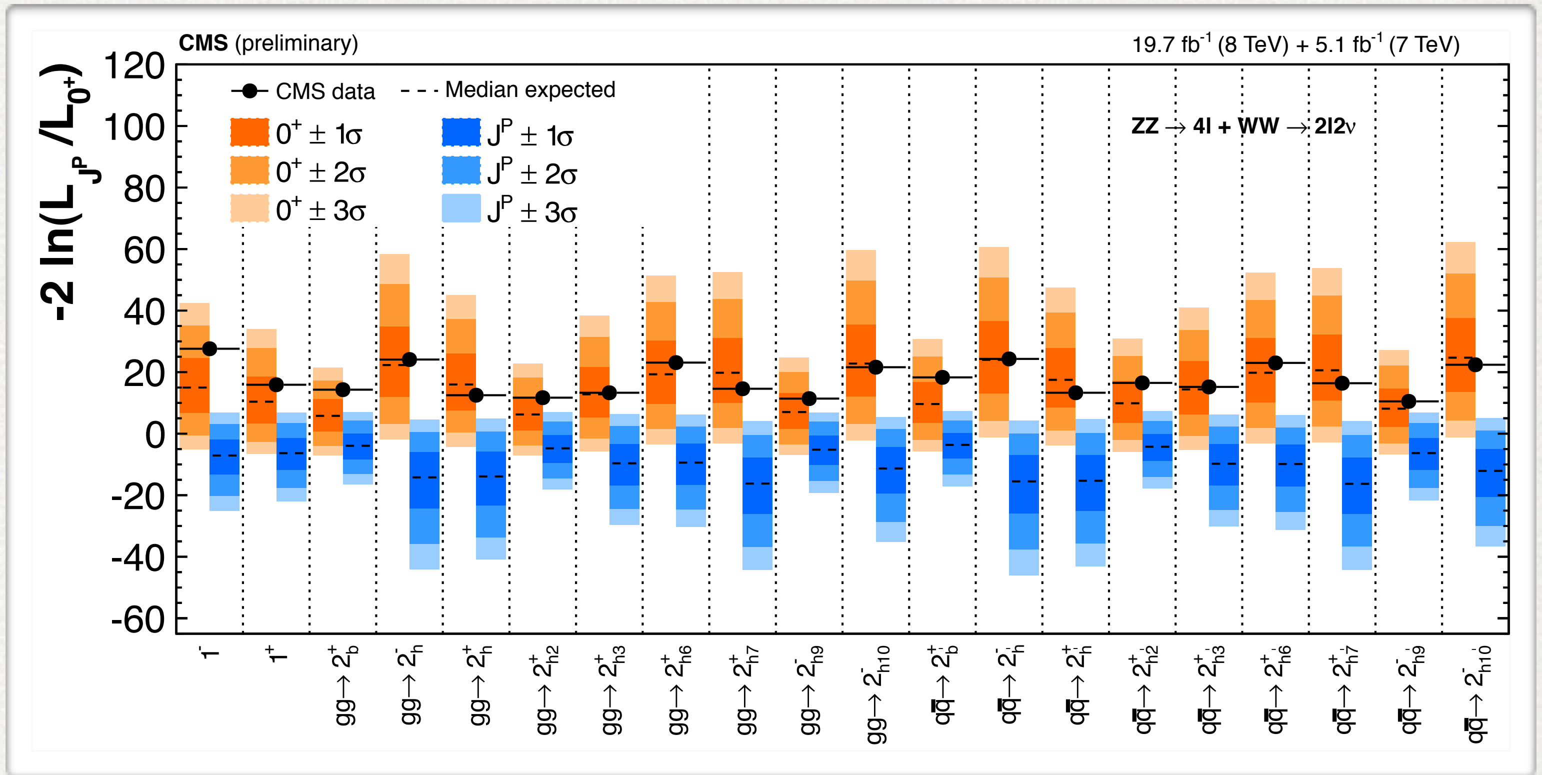


SPIN–PARITY TESTS

- Data are compatible with 0^+ in all tests, better than $\pm 1.5\sigma$ for any other spin-parity hypotheses.
- Data is incompatible with 0^-, $1^\pm$, nine J=2 models at the level of 3σ or higher.



Test statistics distributions



In short – very much like the SM!

SUMMARY

- A new boson is reliably observed in $ZZ^{(*)}$, $\gamma\gamma$, $WW^{(*)}$, $\tau\tau$, with evidence for bb as well.
- The measured mass is 125 GeV.
- The overall signal strength and the spin-parity are consistent with the standard model Higgs (sign...)
- Topics which are not covered today:
  - Couplings are consistent with SM as well.
  - Higgs rare decay: $Z\gamma$ and $\mu\mu$, still below the sensitivity.
  - Higgs rare production: ttH, just about to show up in data.
  - No other new bosons, whether it's neutral, charged, or even doubly−charged, observed (yet).

BACKUP SLIDES