# Higgs Searches at the LHC

eilam gross, Weizmann Institute of Science

Acknowledgements: ATLAS, CMS and LHC-HCG
and Ohad Silbert, Raz Alon for their assorted help

# The Higgs Car

Layman: What drives the SM car?

Theorist: The Higgs engine

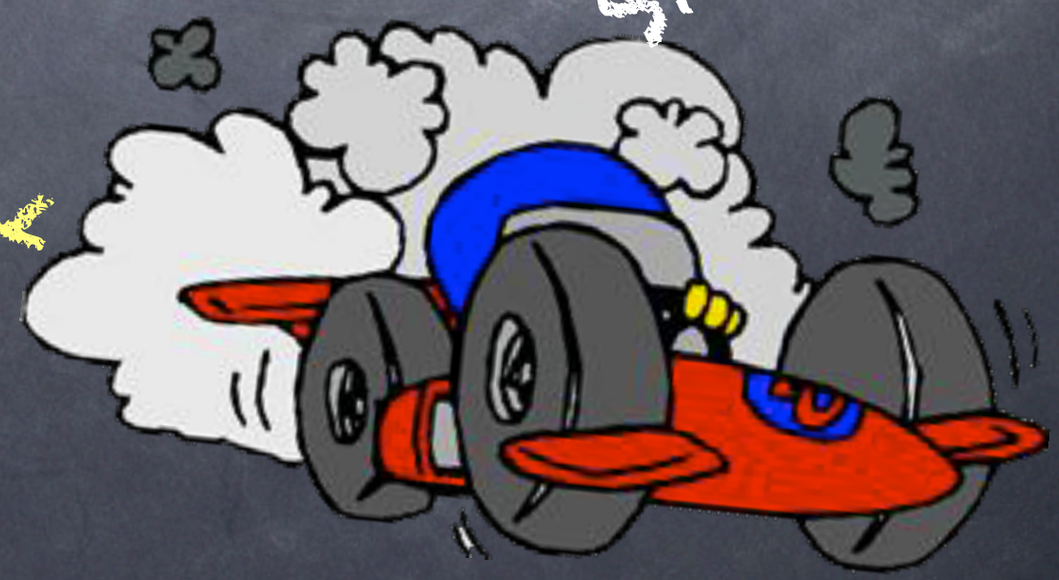
LHC


Layman: How fast does it go?

Theorist: Don't know, if it's a standard model, it must be no more than ~160 GeV

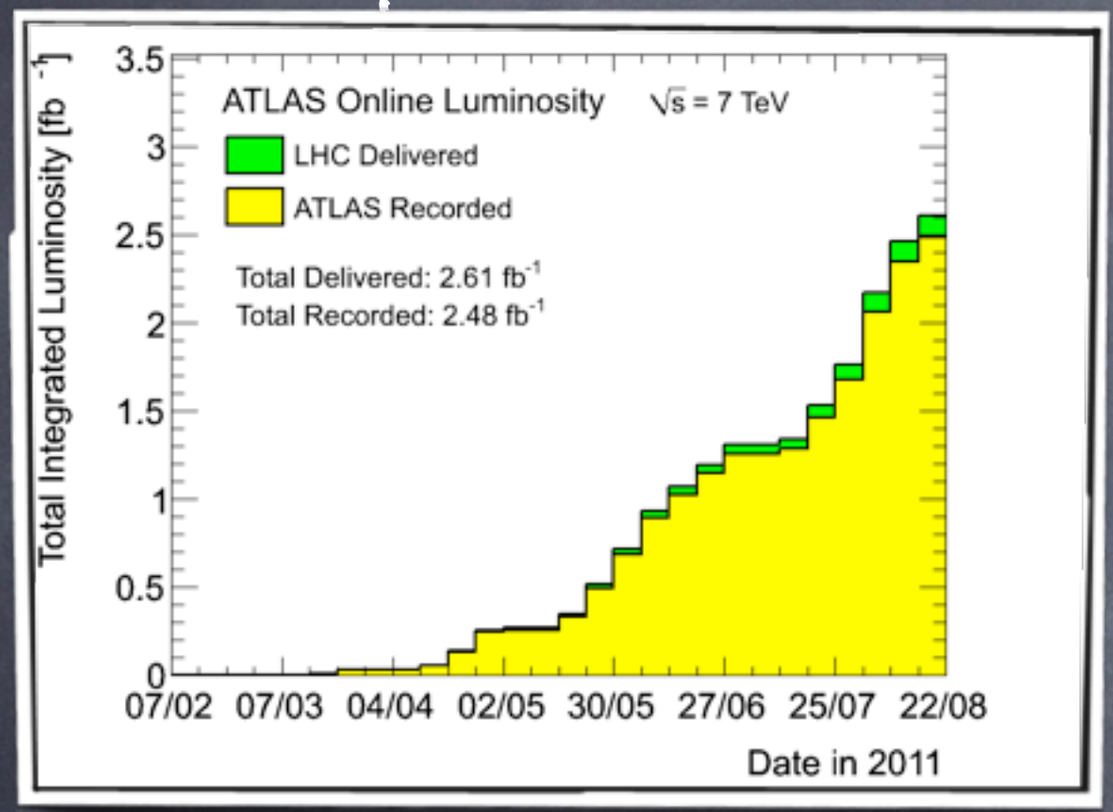
Experimentalist:
Let's get it and check the engine....

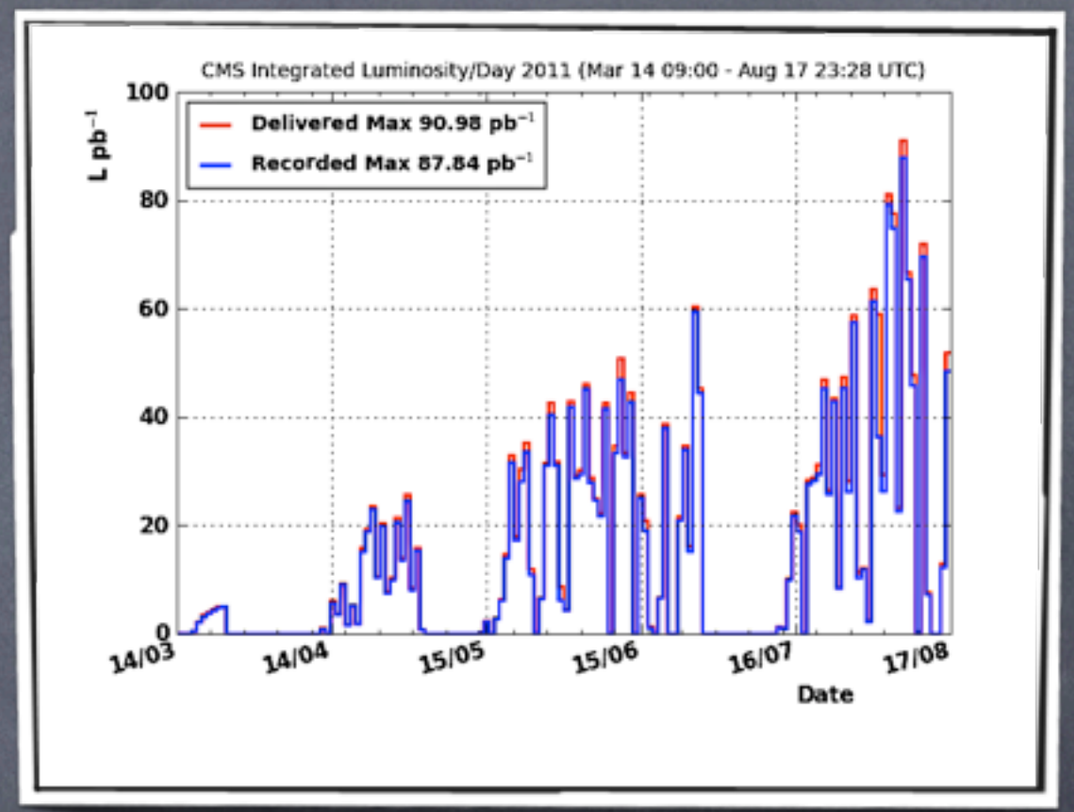
SM



# 2011 - Oh What a Year

- The new thumb rule:
  ~500 $pb^{-1}$/week and more to come

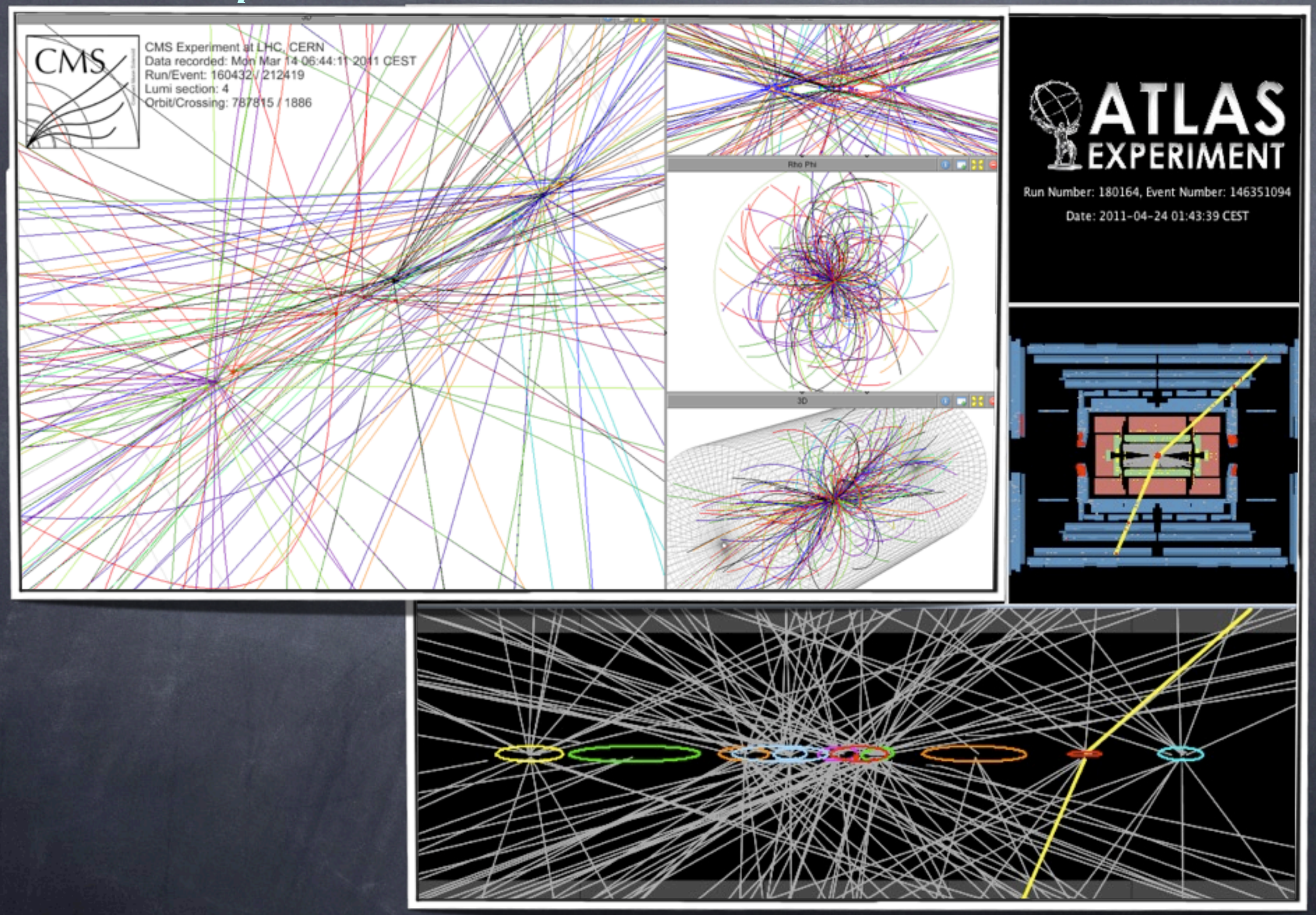


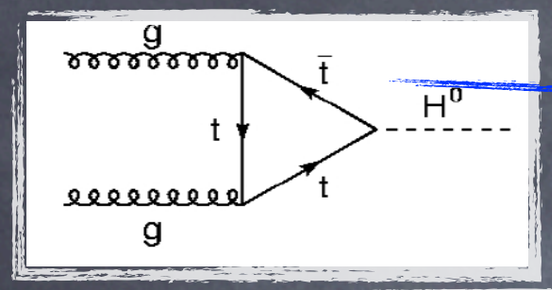

- 50 ns bunch trains with 6-8 interactions/crossing
- The analyses presented here are based on 1-2.3 $fb^{-1}$/experiment

# Pile Up - A Managable Nuisance

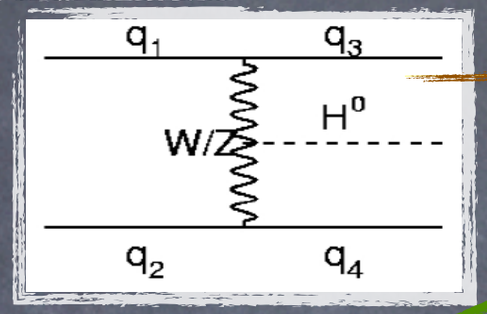
V. Sharma

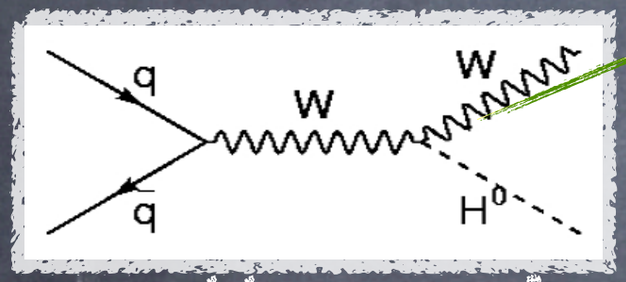


# Higgs Production

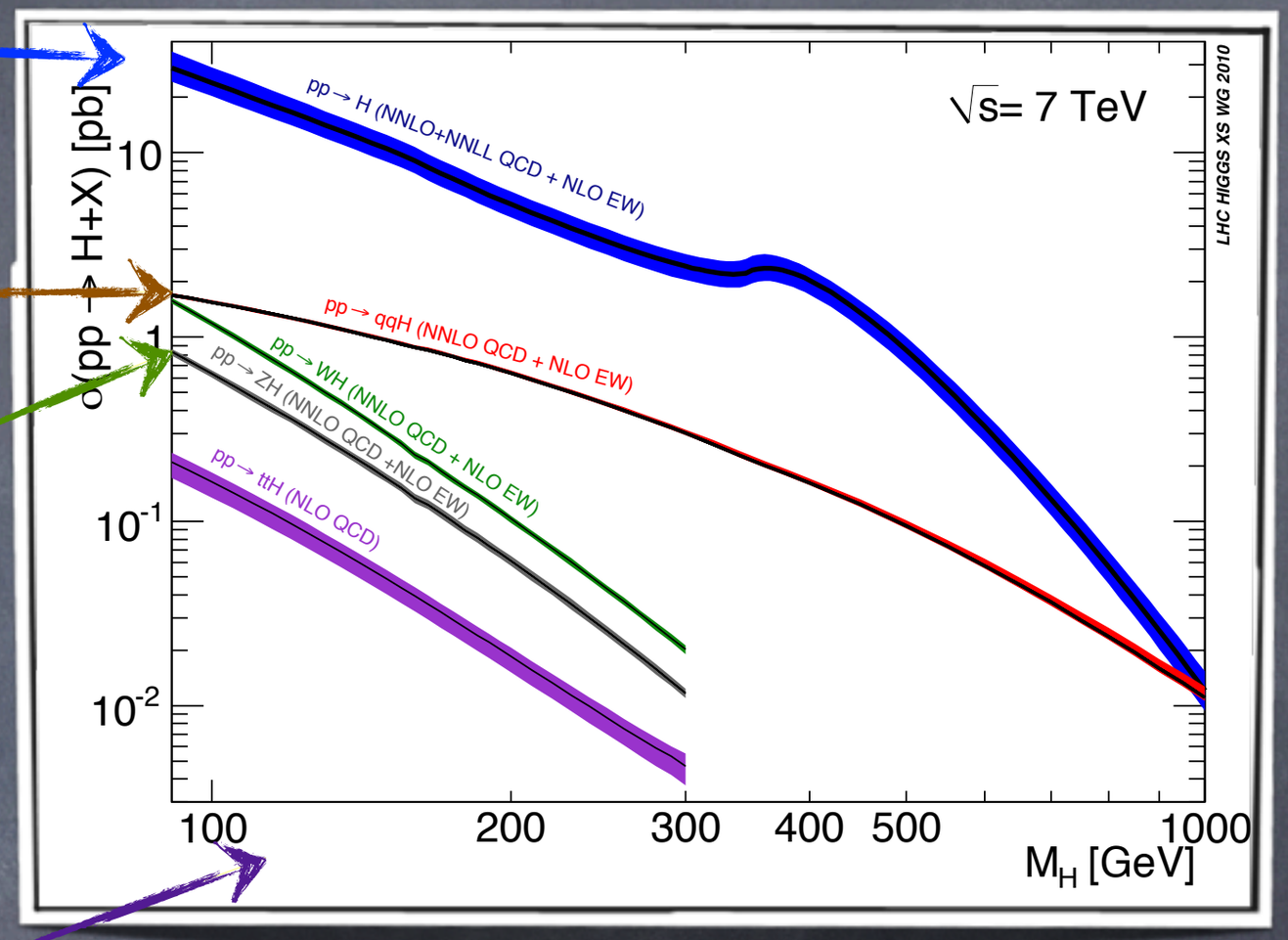


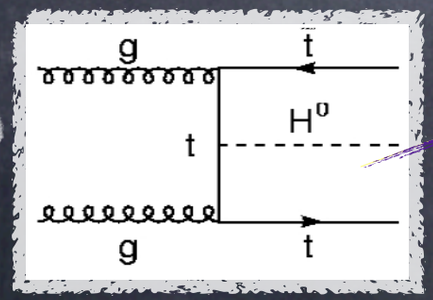

is x10 then



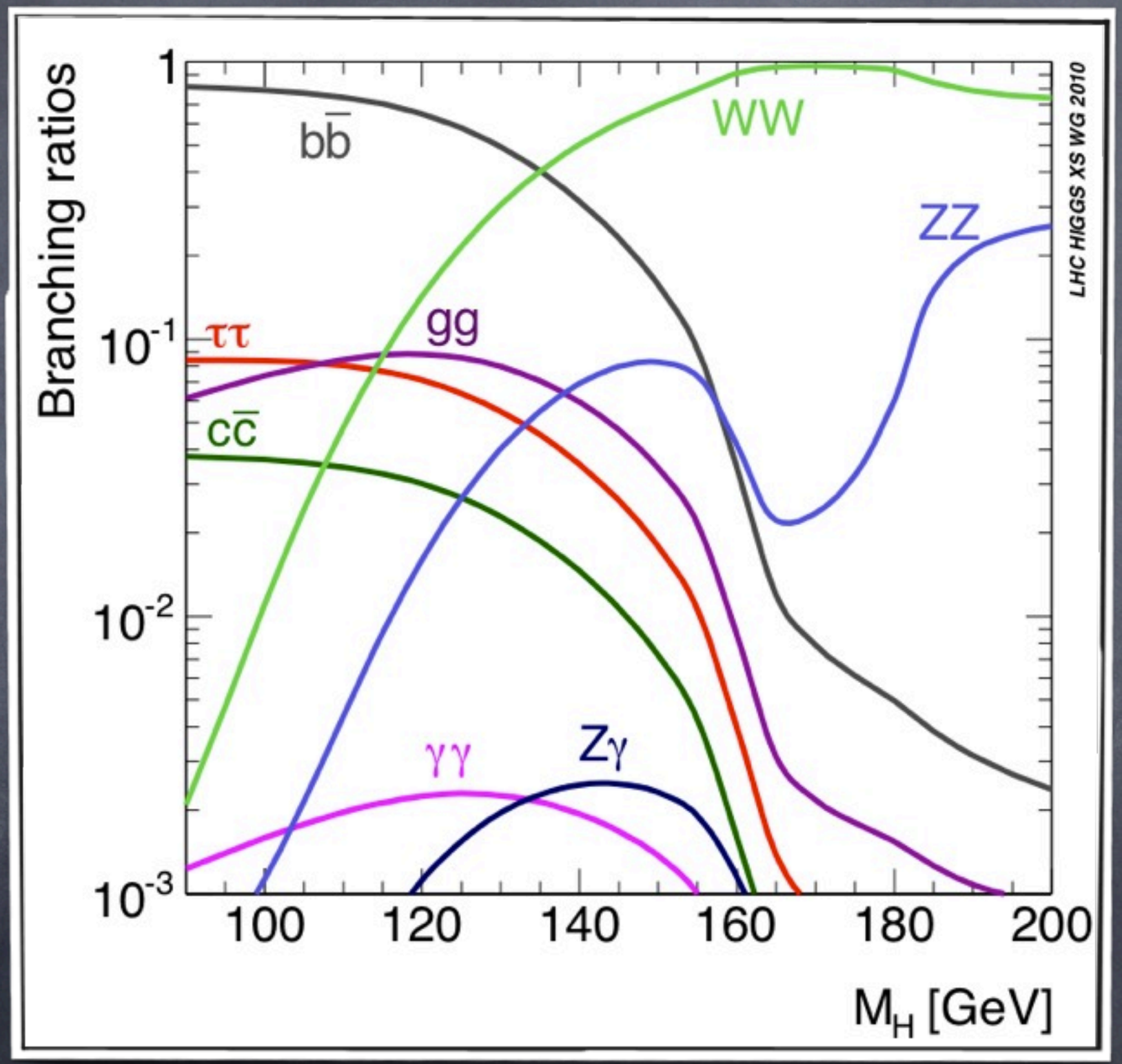

is even smaller, yet distinct



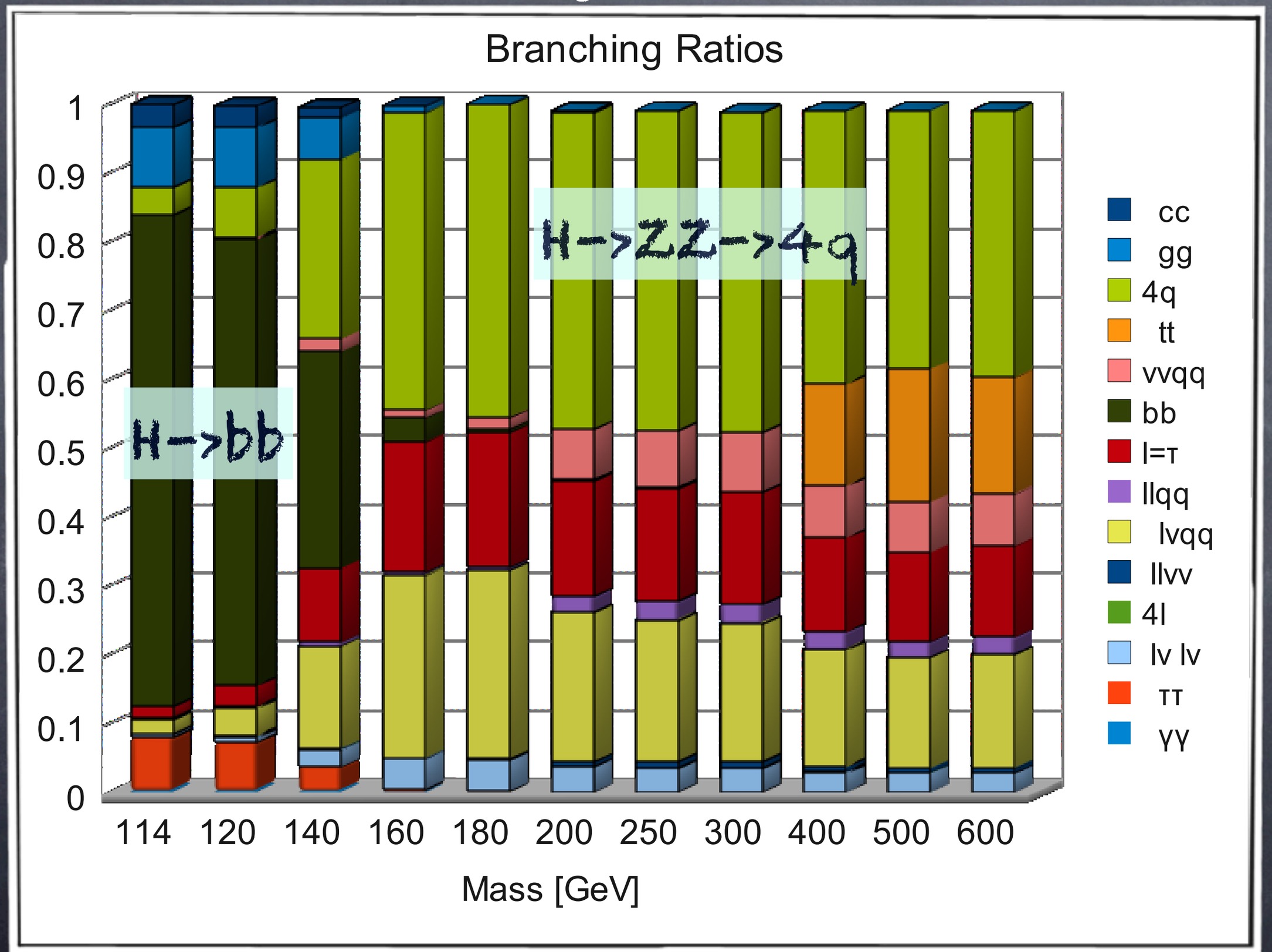




is the smallest and also difficult

# Branching Ratios



# All Ingredients



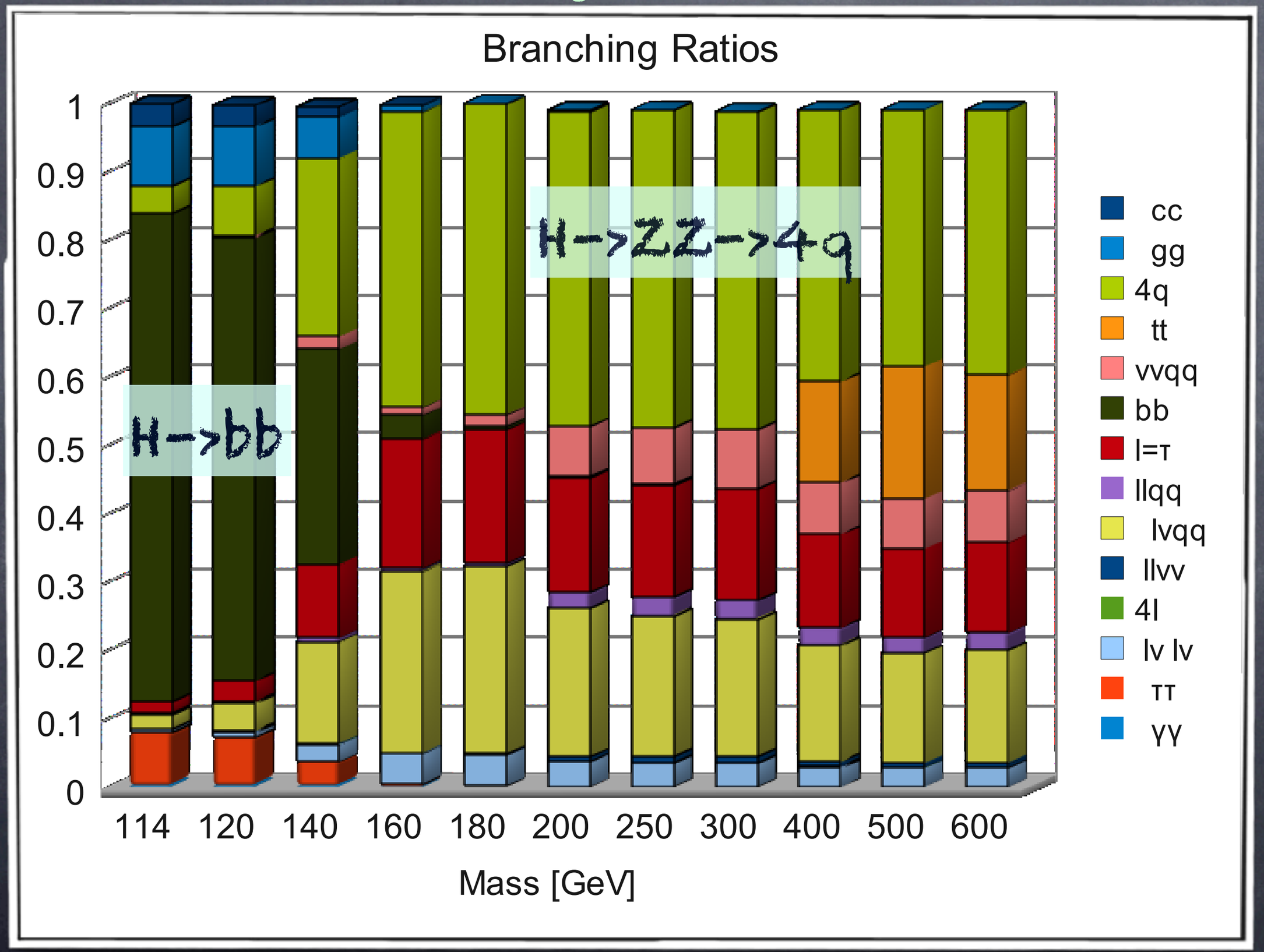
# The Killing Trigger

- For a channel to be usable, we must be able to trigger it
- Most efficient and clean triggers are lepton based

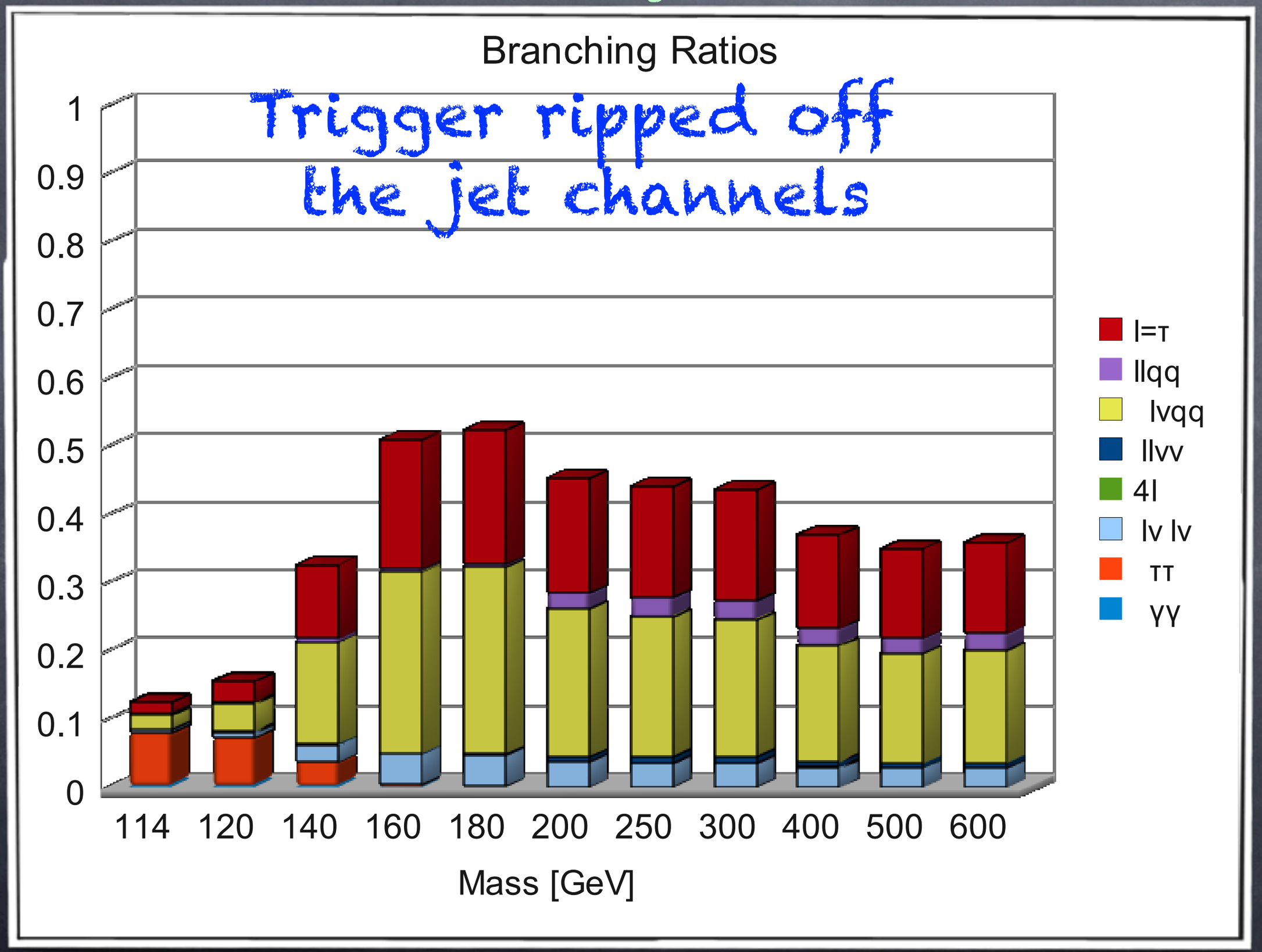
| Channel | | Trigger |
|---|---|---|
| $\gamma\gamma$ | | Diphoton |
| $\tau\tau$ | | Single lepton (+isolated jet),Dilepton |
| WH | | Single lepton |
| ZH | | Single lepton (ATLAS,CMS);<br>Dielectron (CMS) |
| WW<br>($l\nu l\nu$) | 0-jet | Single lepton (ATLAS, CMS);<br>Dilepton (CMS) |
| | 1-jet | Single lepton (ATLAS, CMS);<br>Dilepton (CMS) |
| | VBF* | Single lepton, dilepton |
| WW**<br>($l\nu qq$) | 0-jet | Single lepton |
| | 1-jet | Single lepton |
| ZZ ($llll$) | | Single lepton (ATLAS);<br>Single lepton (early data), dilepton (CMS) |
| ZZ ($ll\nu\nu$) | | Single lepton (ATLAS);<br>Dilepton (CMS) |
| ZZ ($llqq$) | | Single lepton |
| ZZ ($ll\tau\tau$) * | | Dilepton |

* CMS only / ** ATLAS only

# All Ingredients

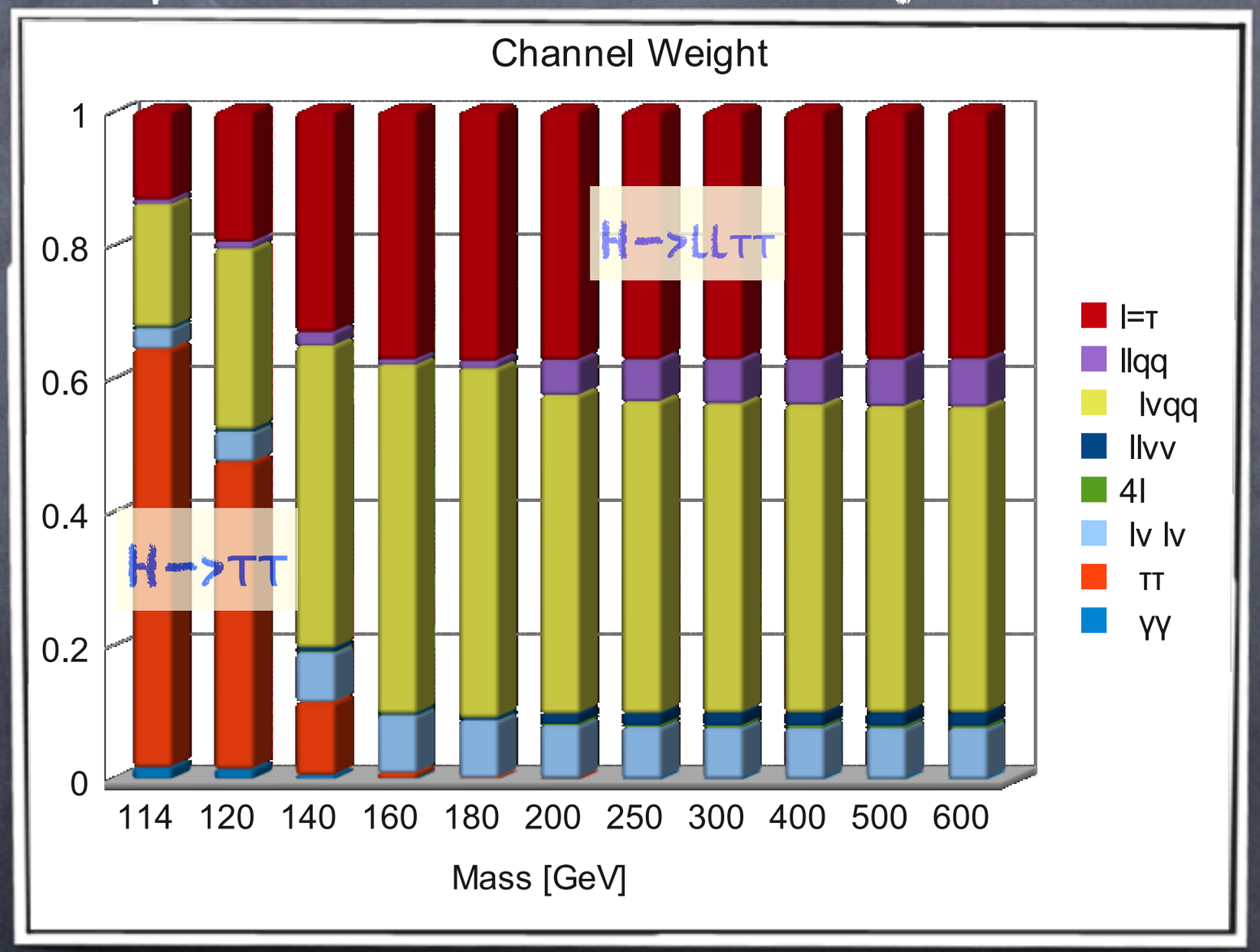


# Usable Ingredients

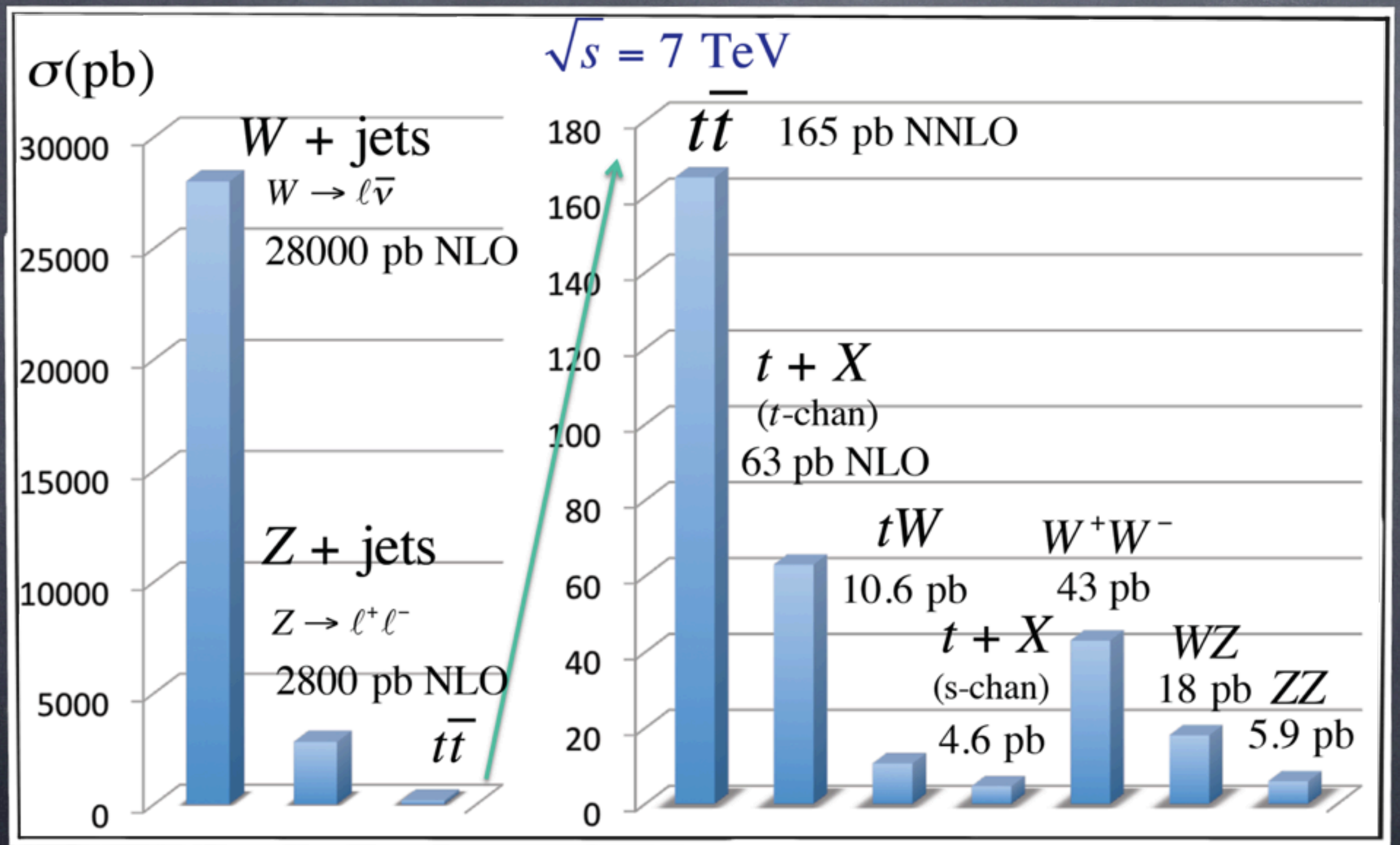


# Usable Apparent Channels Weight

- Here we normalize the usable channels BRs
- Looks like tau tau is the best channel to probe LEP. Is it really so?
- Tau-> (low pT) lepton or hadrons, not so easy to trigger



# The BG: Powers of Ten




Vivek Sharma

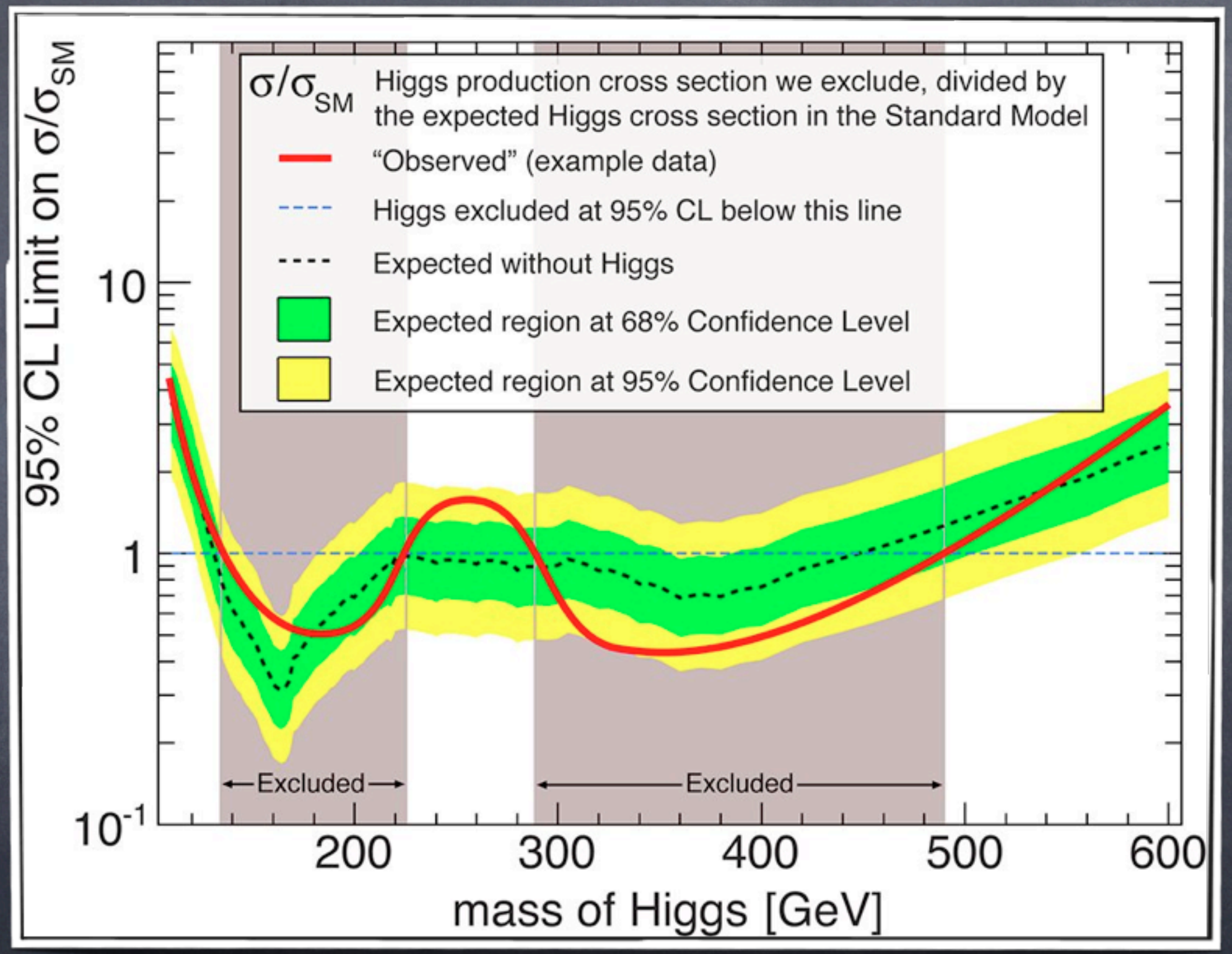
# A nano statistical interlude

## Understanding The Yellow and Green Bands

eilam gross, WIS, LHC2TSP, August 2011

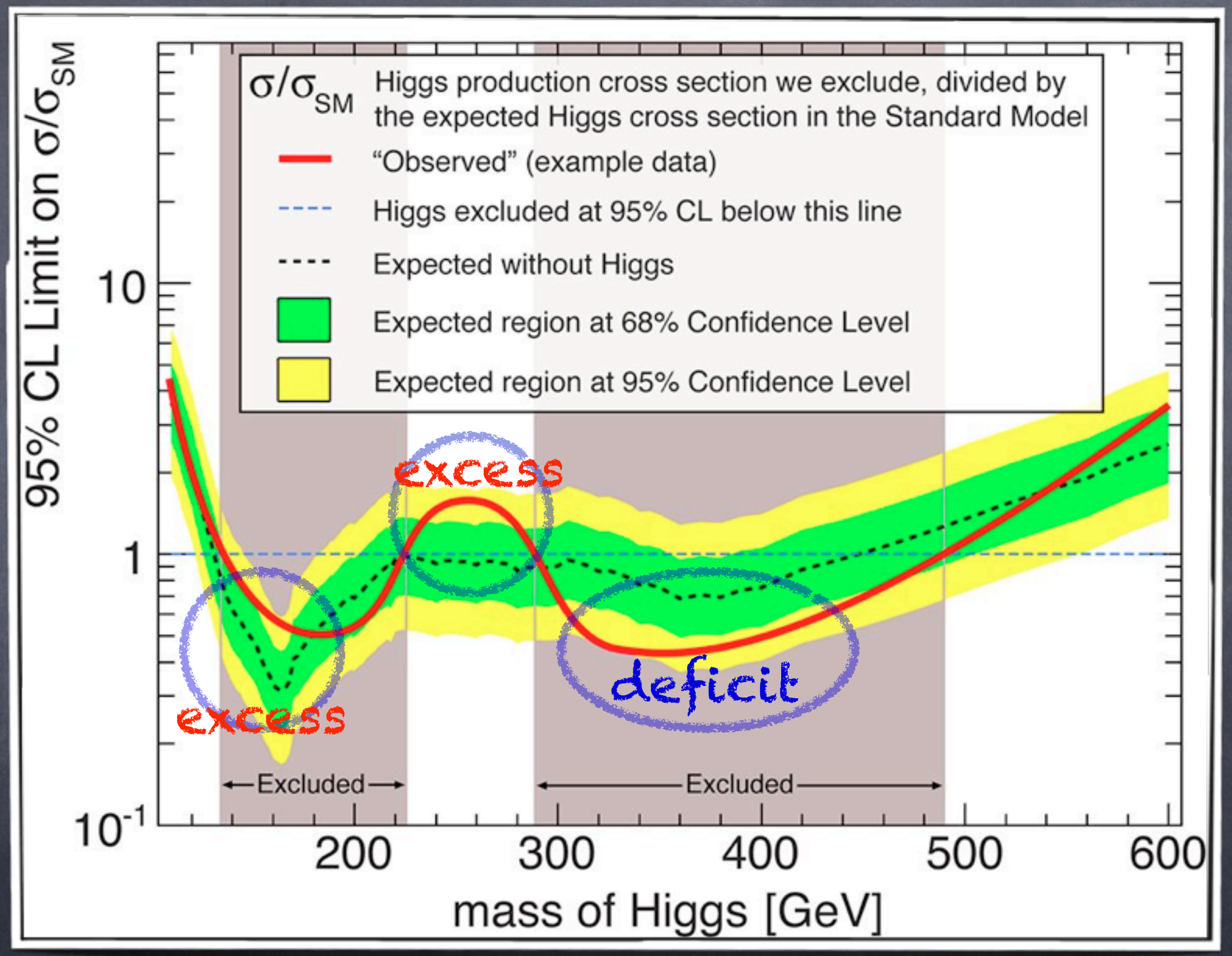
# Understanding The Yellow and Green Bands

$$\mu = \frac{\sigma}{\sigma_{SM}}$$



# Understanding The Yellow and Green Bands

$$\mu = \frac{\sigma}{\sigma_{SM}}$$



# Channels Weight

$$\mu = \frac{\sigma}{\sigma_{SM}}$$

- Asymptotically

CCGV, EPJC 71 (2011) 1-19.

$$\mu_{up,obs} = \hat{\mu} + \sigma_{\mu_{up}} \cdot 1.64,$$

$$\mu_{up,exp} = \hat{\mu}_A + \sigma_{\mu_{up}} \cdot 1.64 = \sigma_{\mu_{up}} \cdot 1.64 \rightarrow \frac{1.64}{s/\sqrt{s+b}}$$

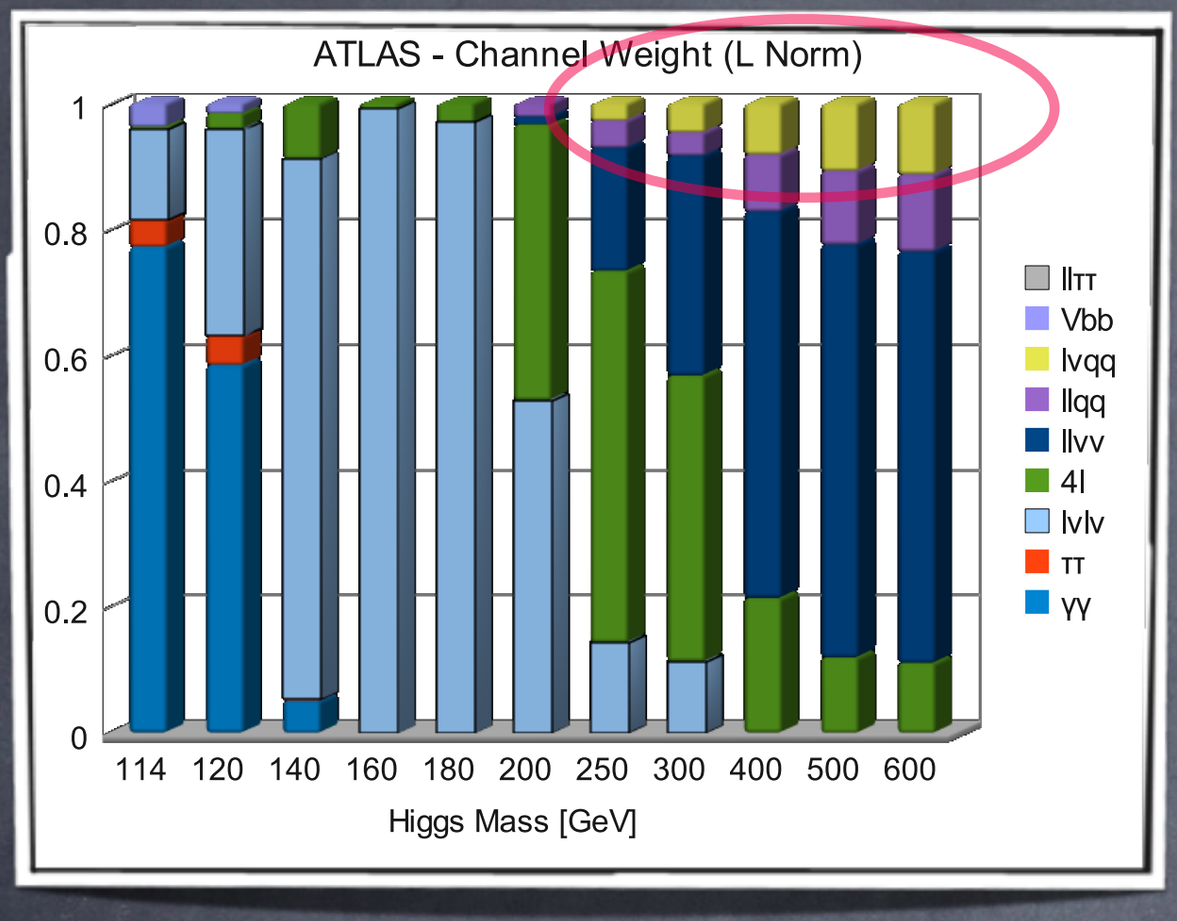
$$\mathrm{w}_i = \left(\frac{\mu_{up,\exp,C}}{\mu_{up,\exp,i}}\right)^2 = \left(\frac{\frac{1}{\mu_{up,\exp,i}}}{\sqrt{\sum\left(\frac{1}{\mu_{up,\exp,i}}\right)^2}}\right)^2 \rightarrow \frac{\left(s_i/\sqrt{s_i+b_i}\right)^2}{\sum_i\left(s_i/\sqrt{s_i+b_i}\right)^2}$$

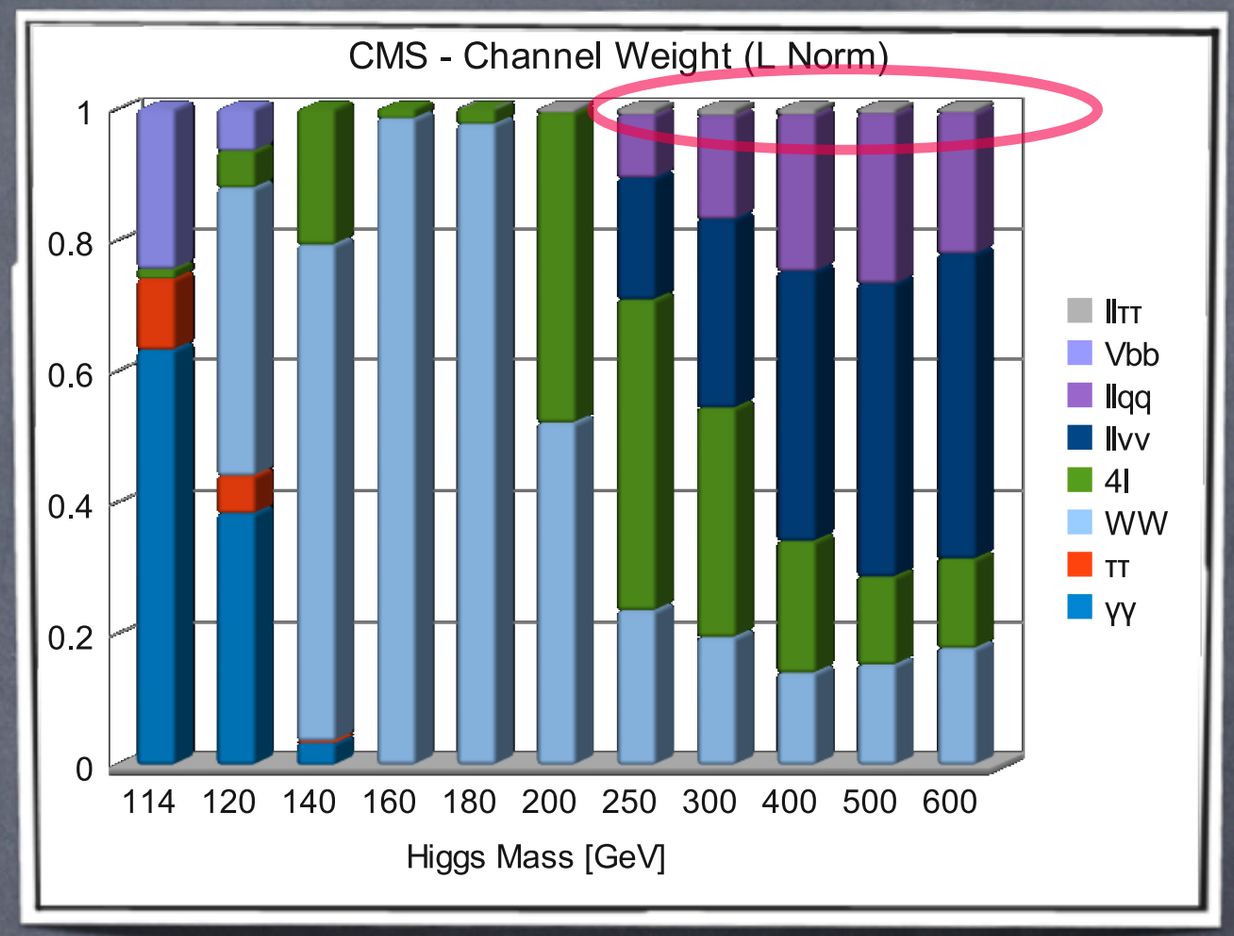
Luminosity normalized:

$$\mu_{up,\exp,i}(\mathcal{L}_i) \rightarrow \mu_{up,\exp,i}(\mathcal{L}_0) = \mu_{up,\exp,i}(\mathcal{L}_i)\sqrt{\frac{\mathcal{L}_i}{\mathcal{L}_0}}$$

If we normalize individual channels to the same luminosity, the weight, $w_i$ is independent of the luminosity

# CMS vs ATLAS channel weights

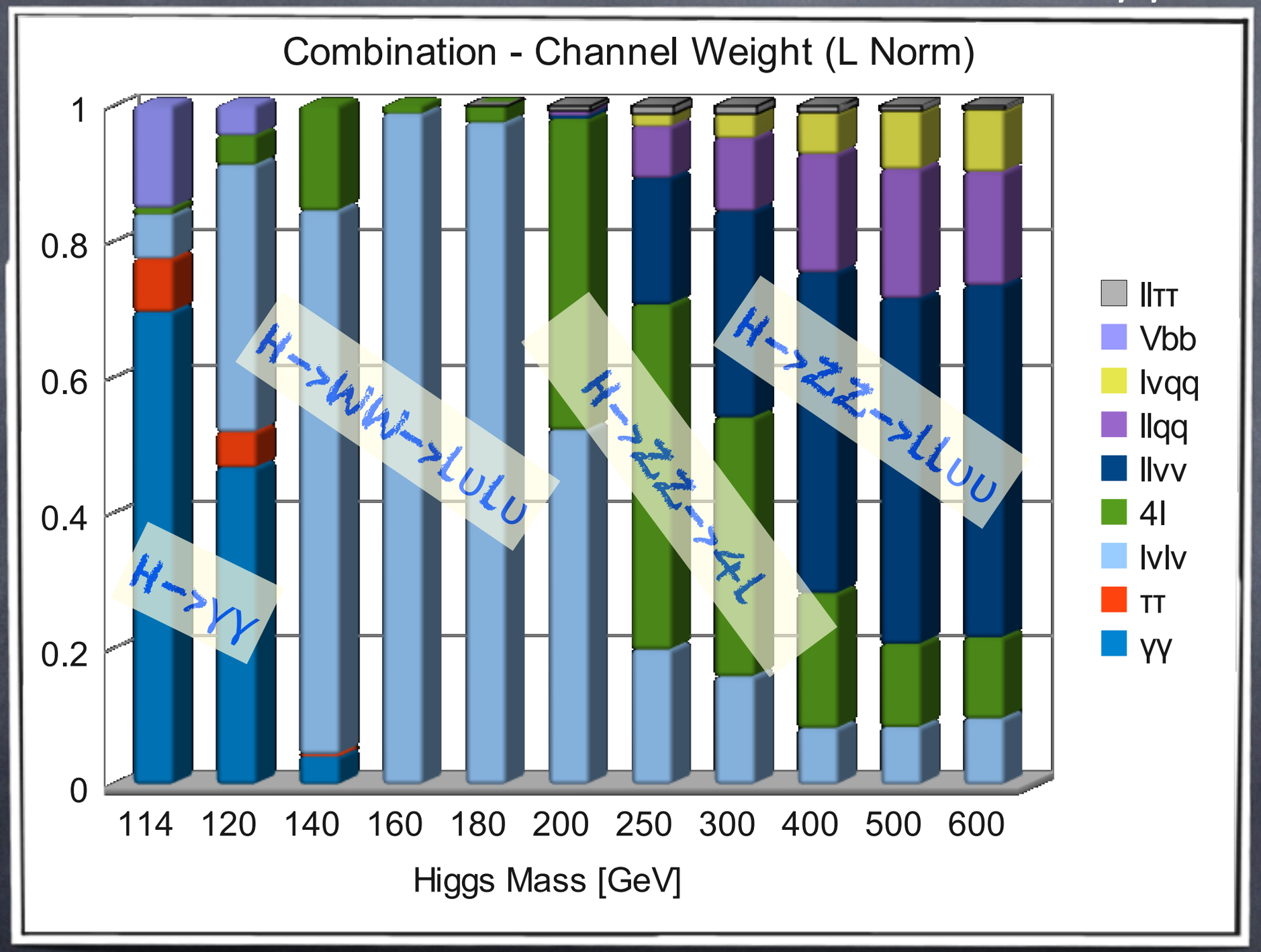



- Spot the differences

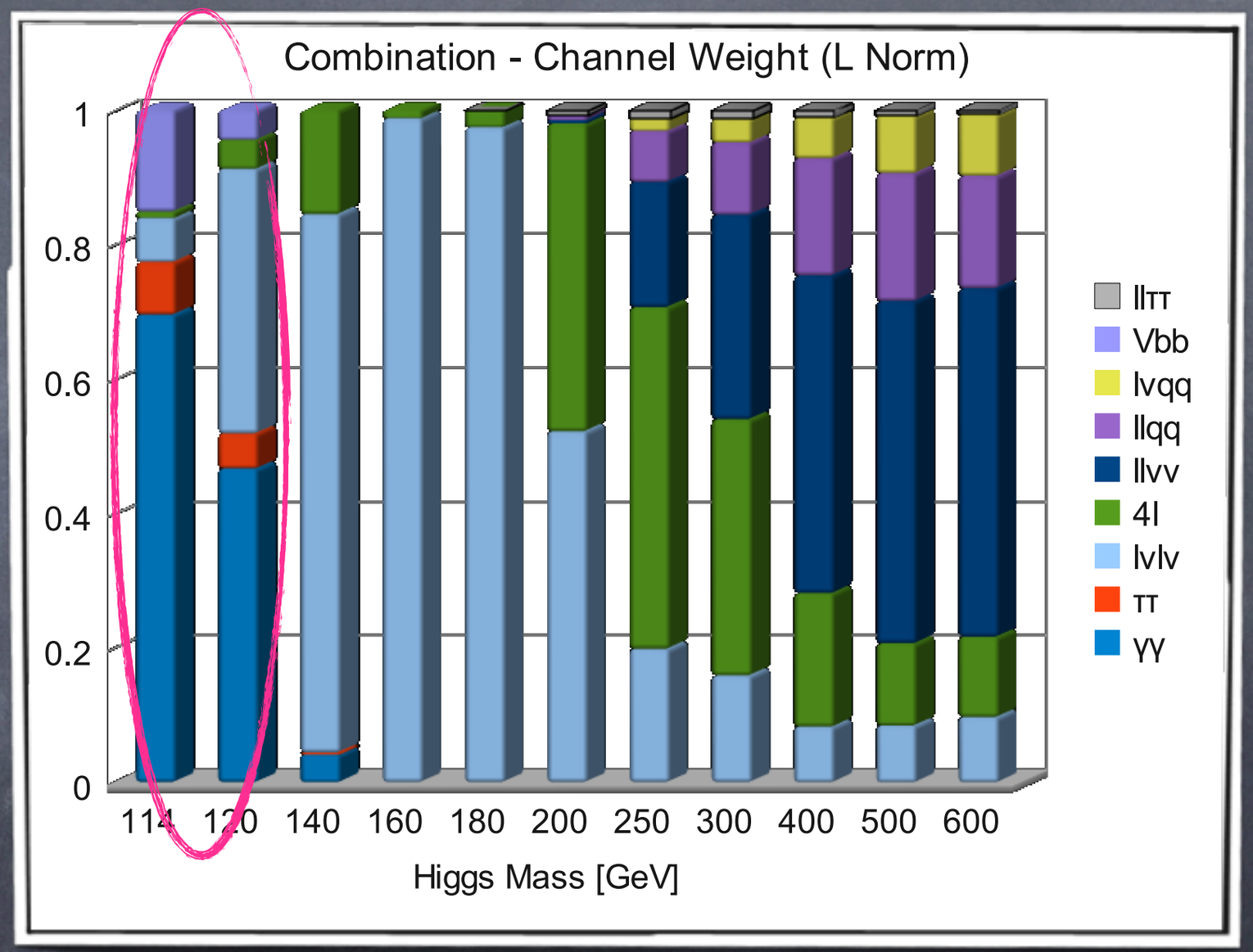
# ATLAS+CMS Channels Weight

- Distinct mass regions γγ, lνlν, 4l, llνν+llqq



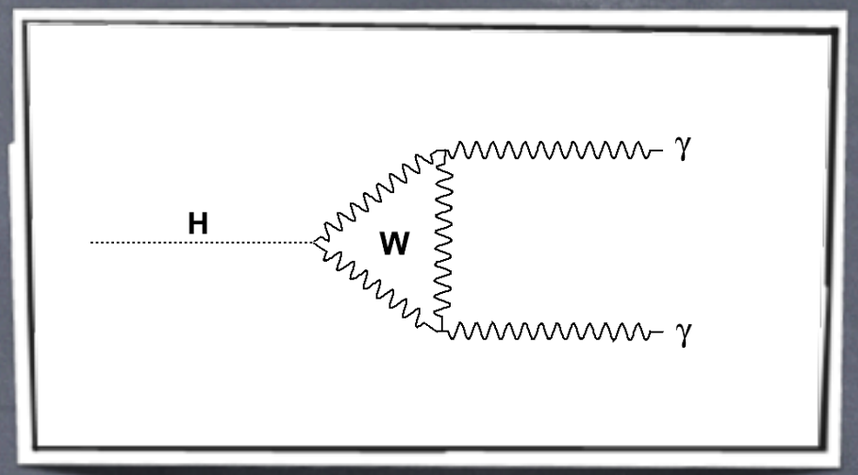
# Probing the LEP Edge

- The LEP edge 114-140 GeV
- Probing channels: H->γγ, Vbb, ττ

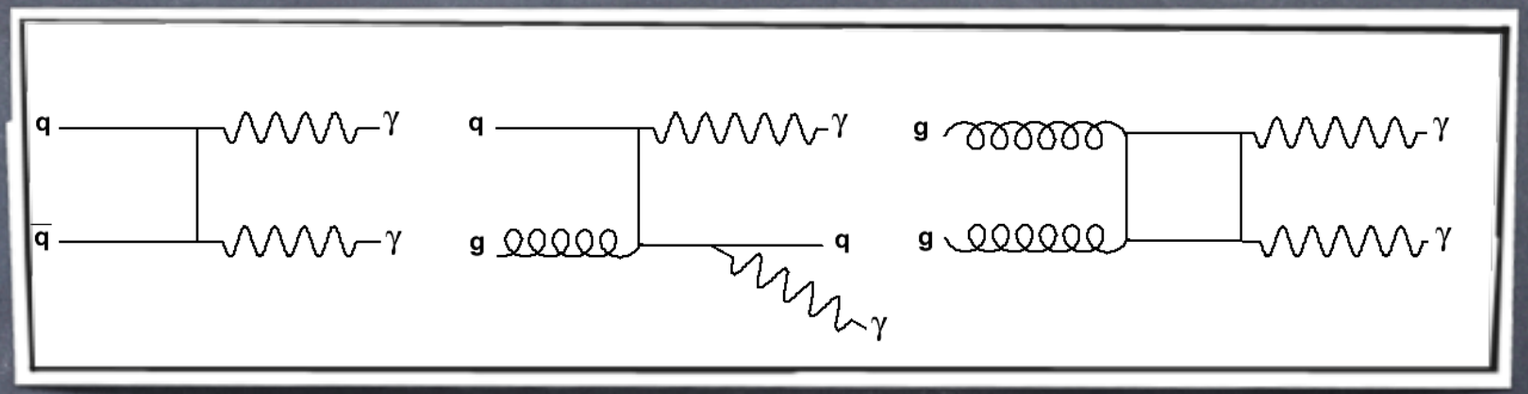


# H->γγ Probing LEP 114 GeV

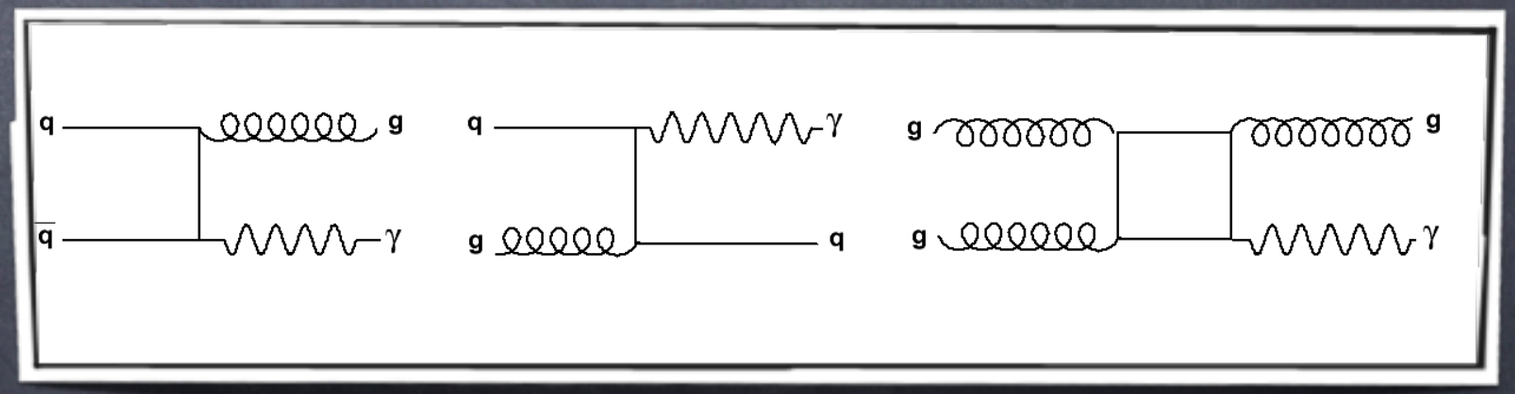
- Though its the most important channel for very low mass Higgs, σ×BR=0.04pb




- Large irreducible BG from pp->γγ+X (continuum)

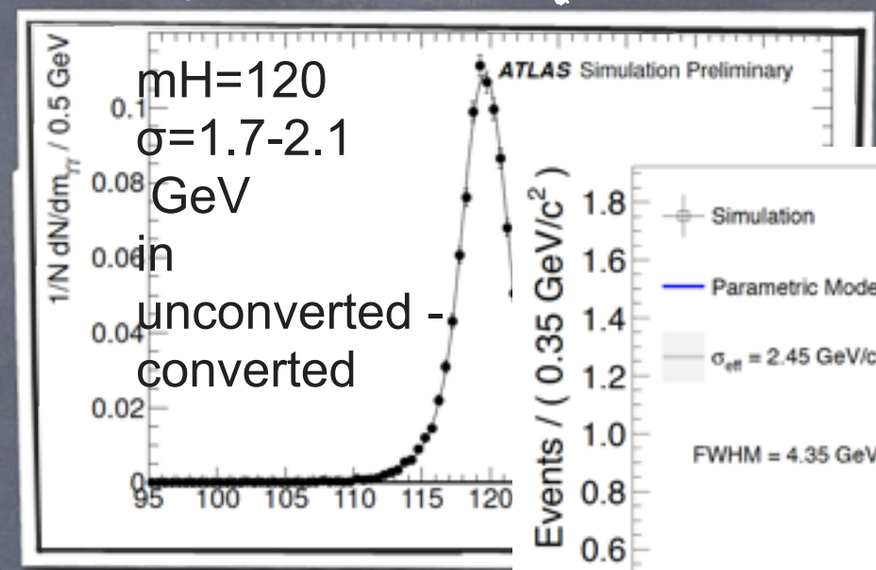


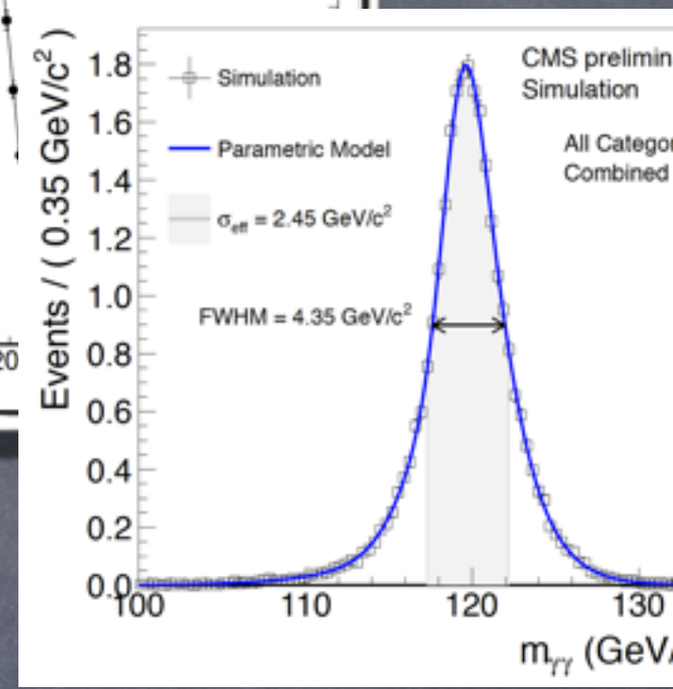

- Large BG from fakes pp->γj, jj+X

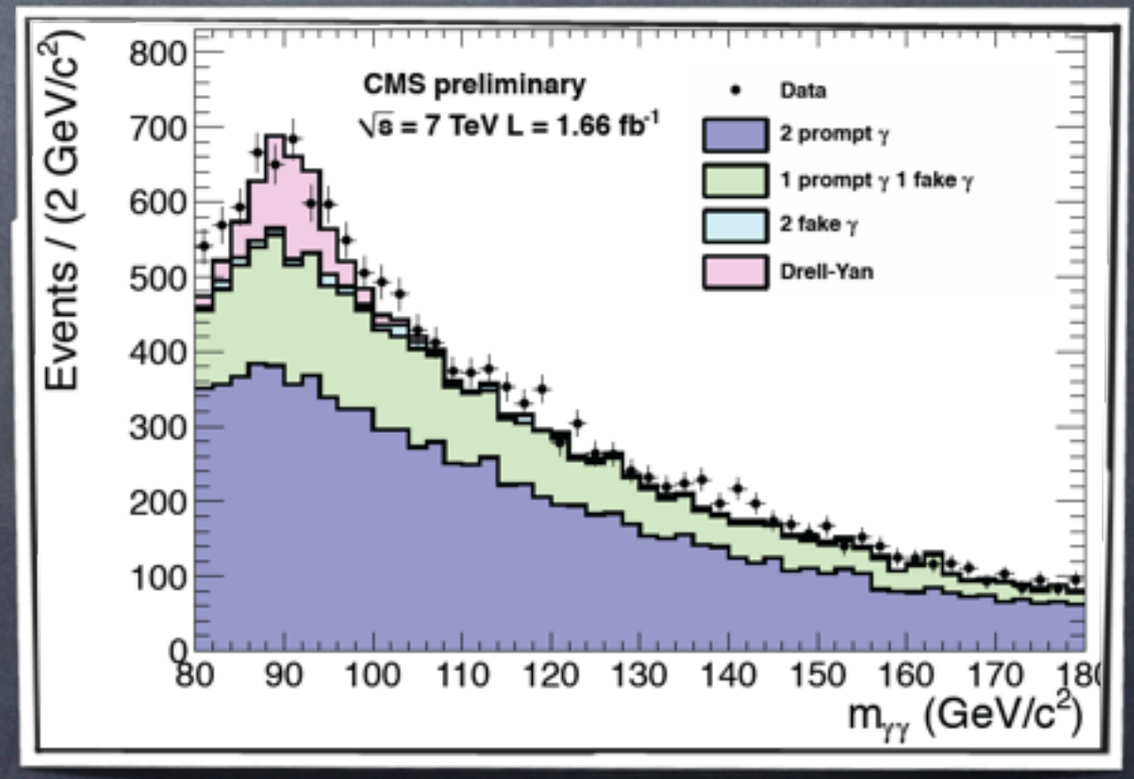


# H->γγ Probing LEP 114 GeV

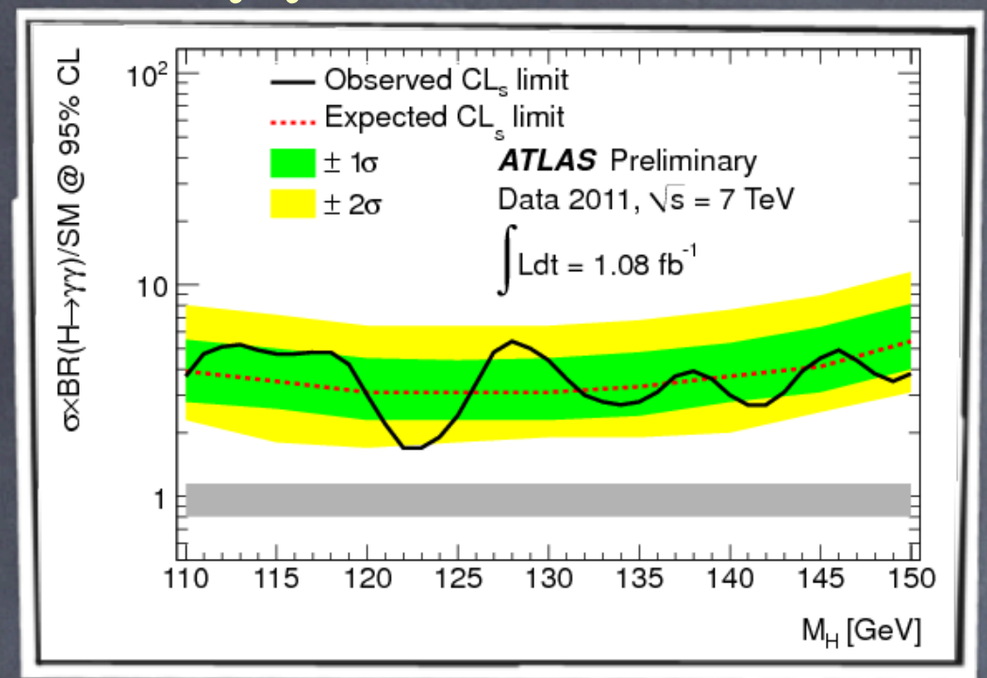
- Clean signature: 2 energetic isolated photons->narrow mass peak
- A narrow peak is searched for over a large, smooth background.
- Data are split into categories based on direction of photons (detector region) and conversion mode (which affect γγ mass resolution, which is excellent)
- A fit is performed to the background side band under the BG only hypothesis (only data is considered)



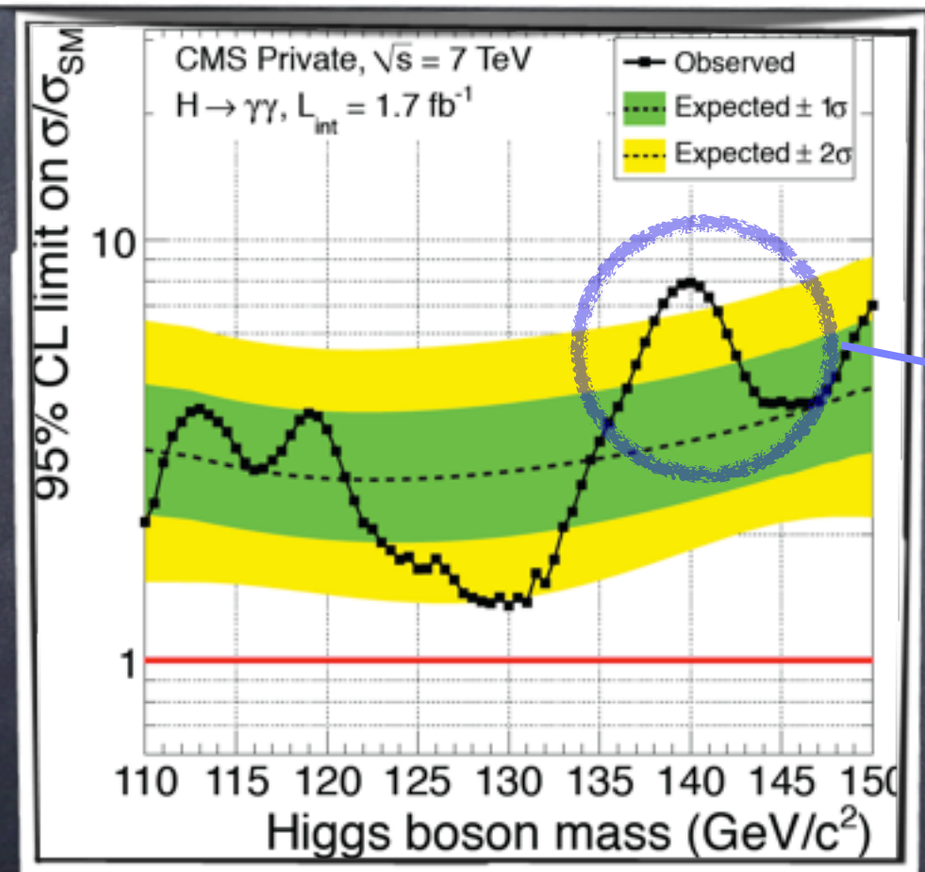



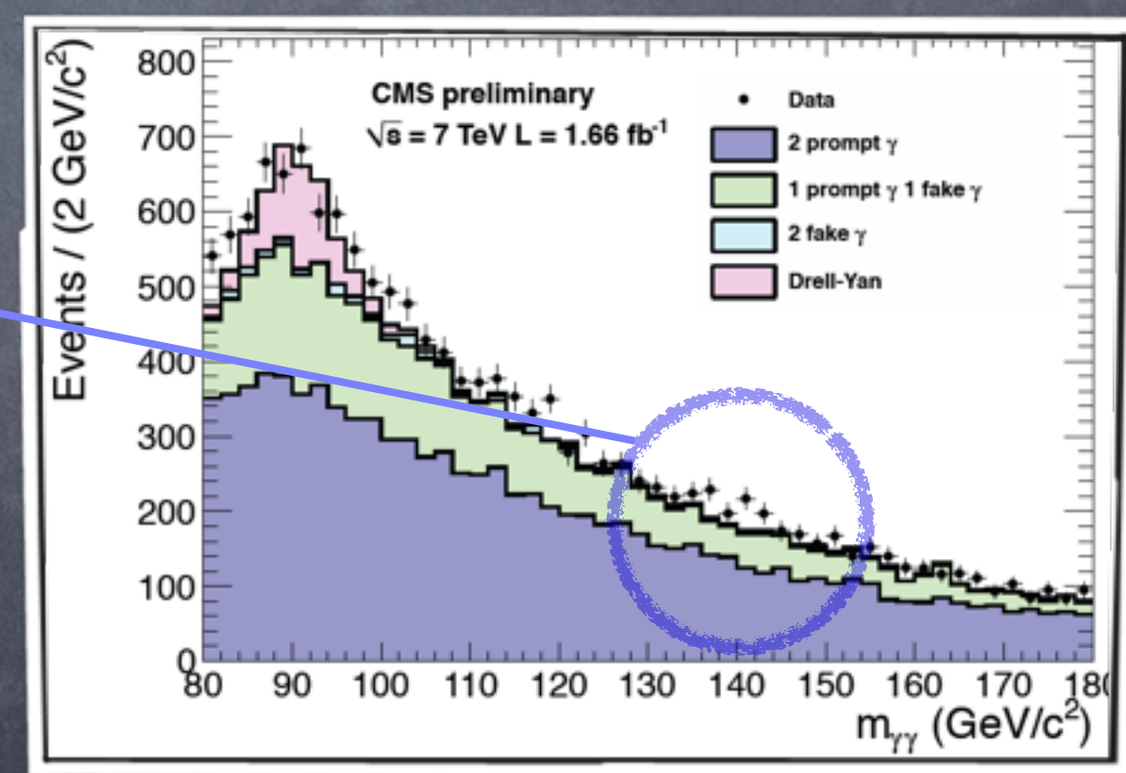



# H->γγ Probing LEP 114 GeV



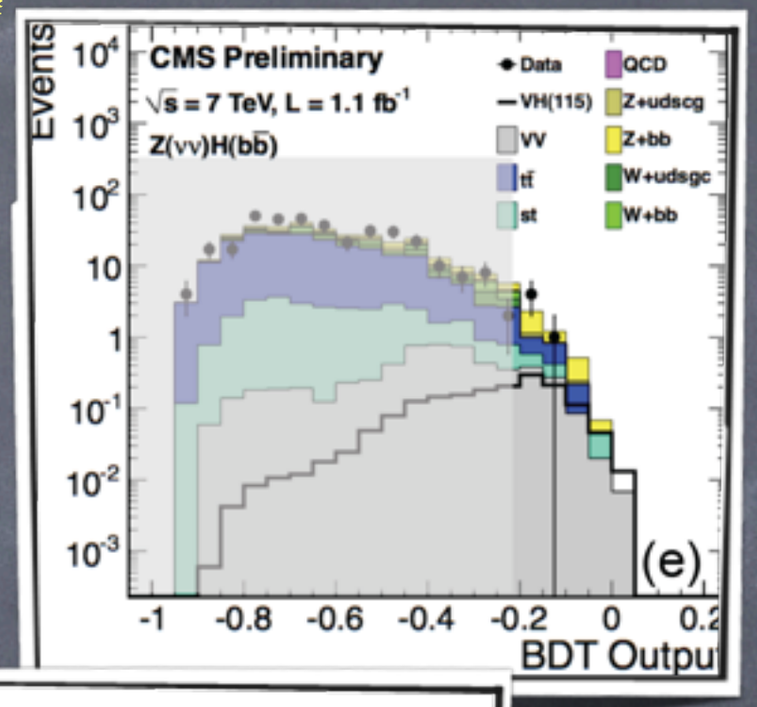

- 114 GeV expected sensitivities ATLAS 3.6xSM, CMS 2.9xSM
- projected illustrative current combined @ 114 expected ~2xSM
- Need a few more fb$^{-1}$/experiment to close the 114 GeV gap

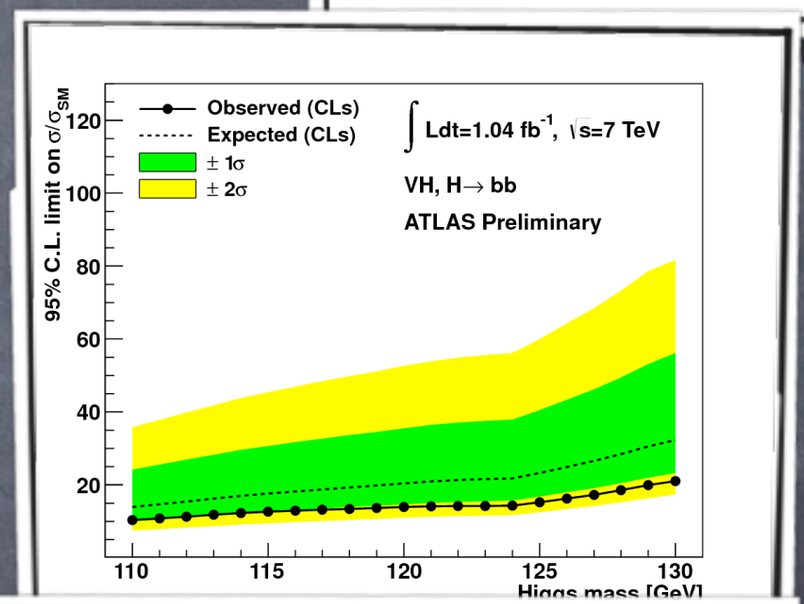


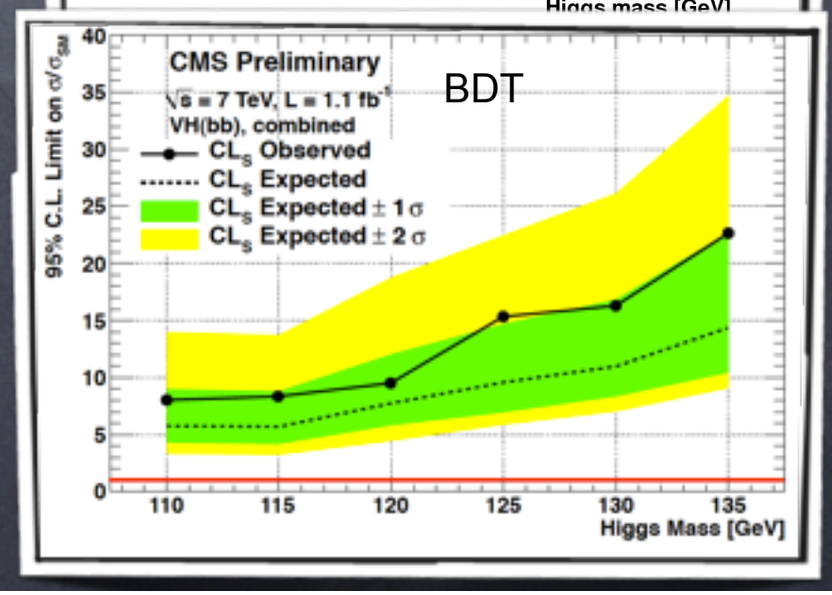



# Probing Deeper: W/ZH->W/Zbb

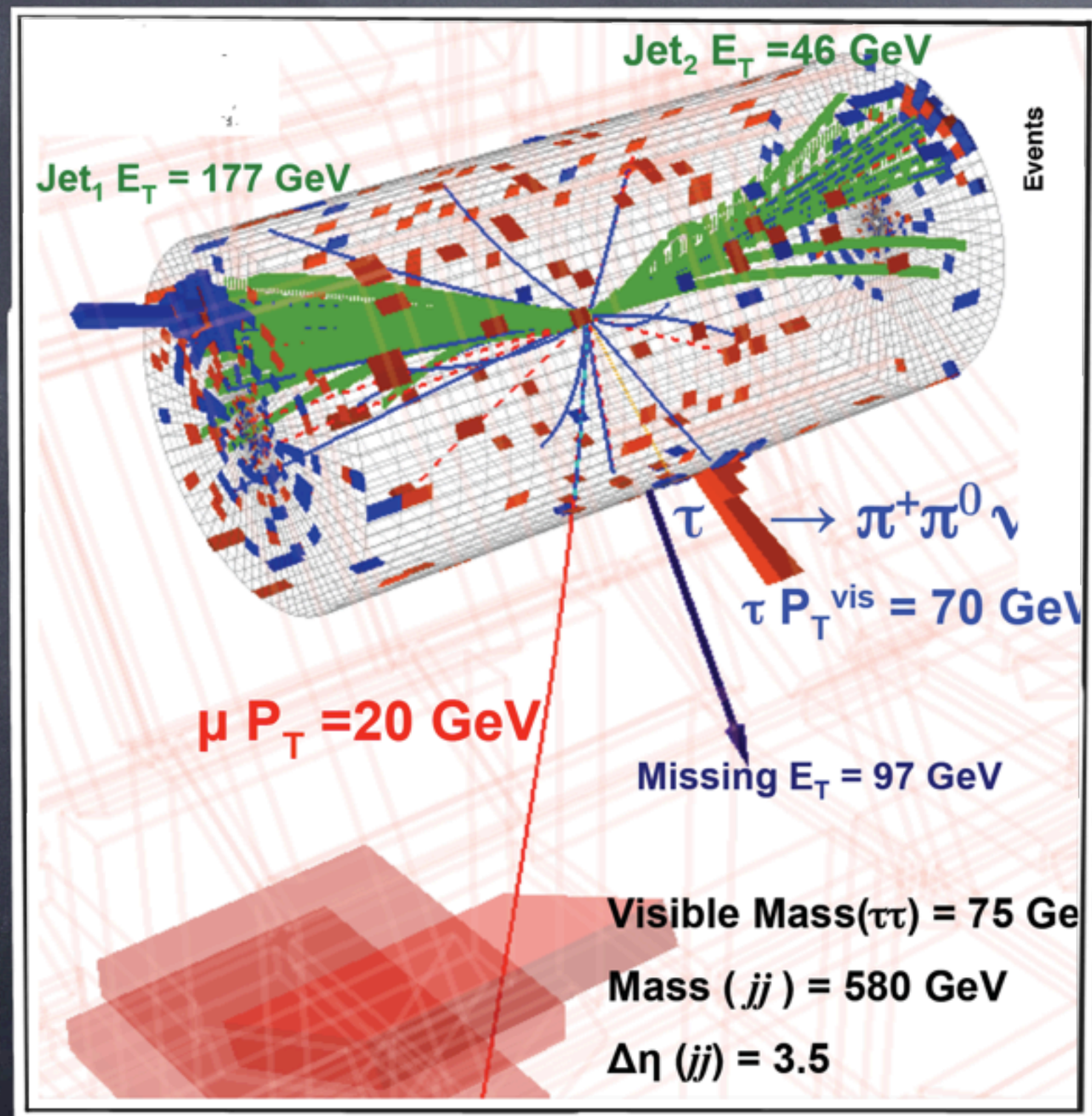
- H->bb is the dominant decay of a low mass Higgs. It also extremely important to measure Higgs couplings.
- Multi-jet background kills its inclusive production
- W/ZH is feasible for low Higgs mass channels: Lubb,LLbb and uubb (CMS only)
- Signature
  lepton,MET and b-tag
- Z/W+jets and tt BG can be reduced by requiring boosted Higgses with combined b-tag (CMS)
- Jet substructure is an analysis option (ATLAS have not yet implemented any boosted feature)
- CMS introduce two analyses,
  cut & count and BDT; ATLAS are using a shape analysis based on $m_{bb}$
- Sensitivity is 6-10xSM (CMS) @ 110-130 GeV



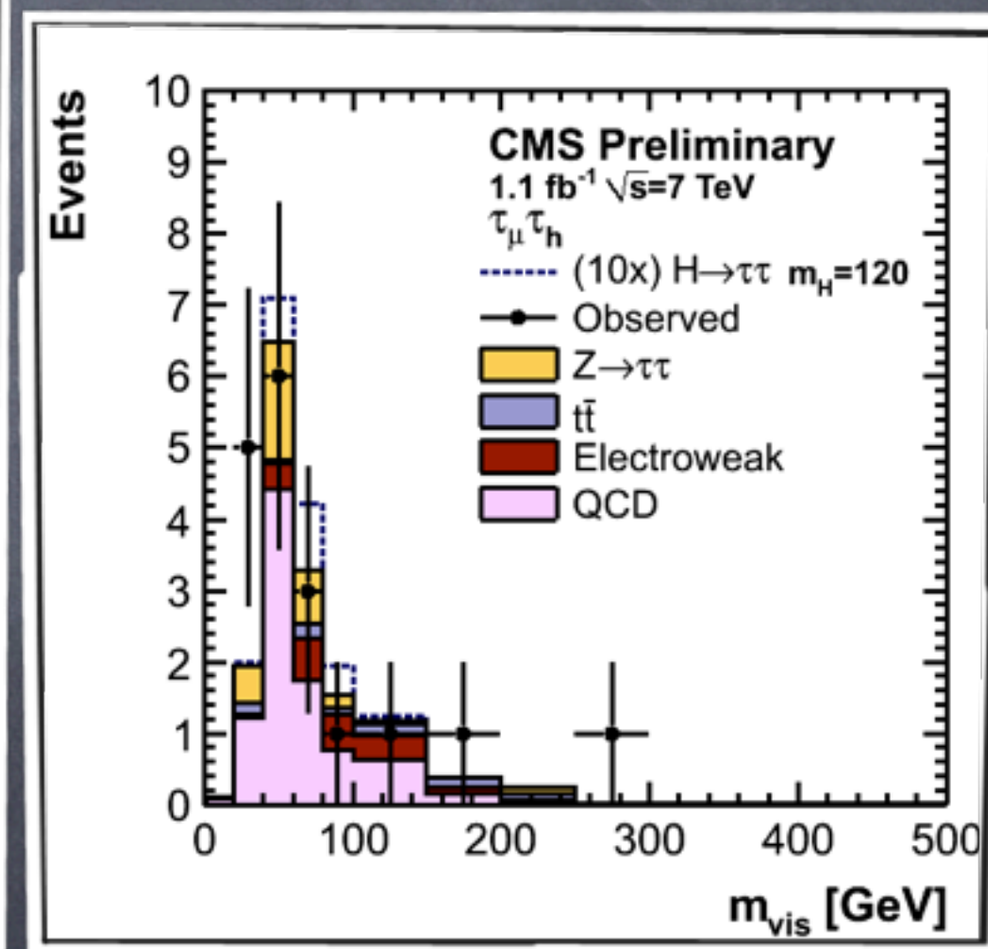



# H->ττ

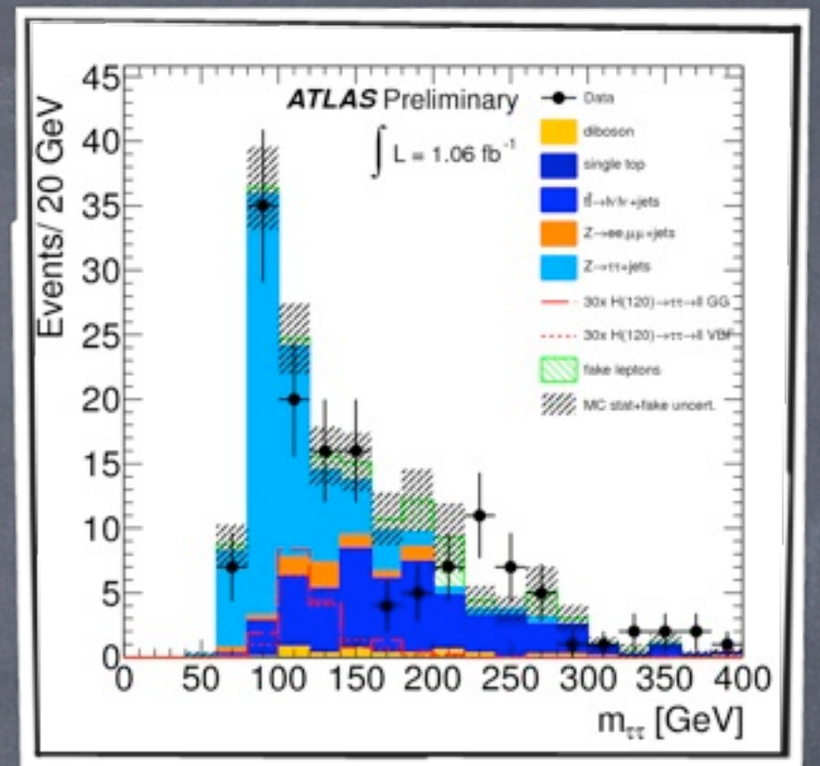


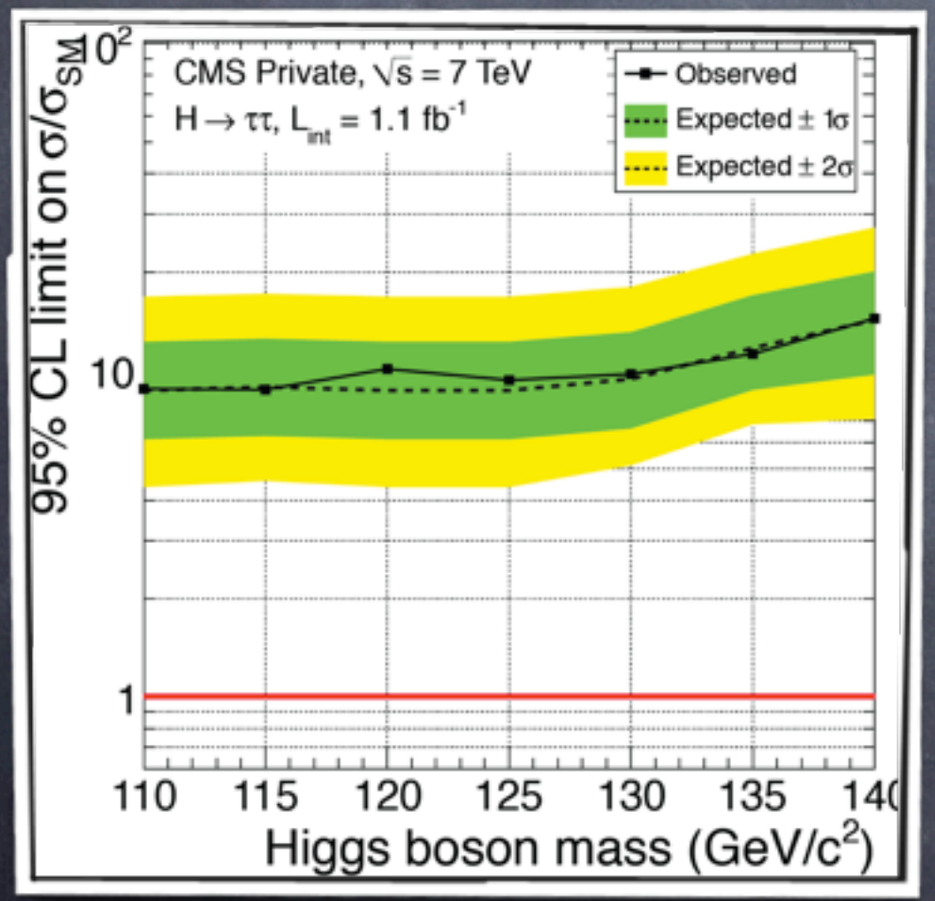

- VBF (CMS)
  clean and sensitive
- 2 tagged back to back forward jets and two tagged taus

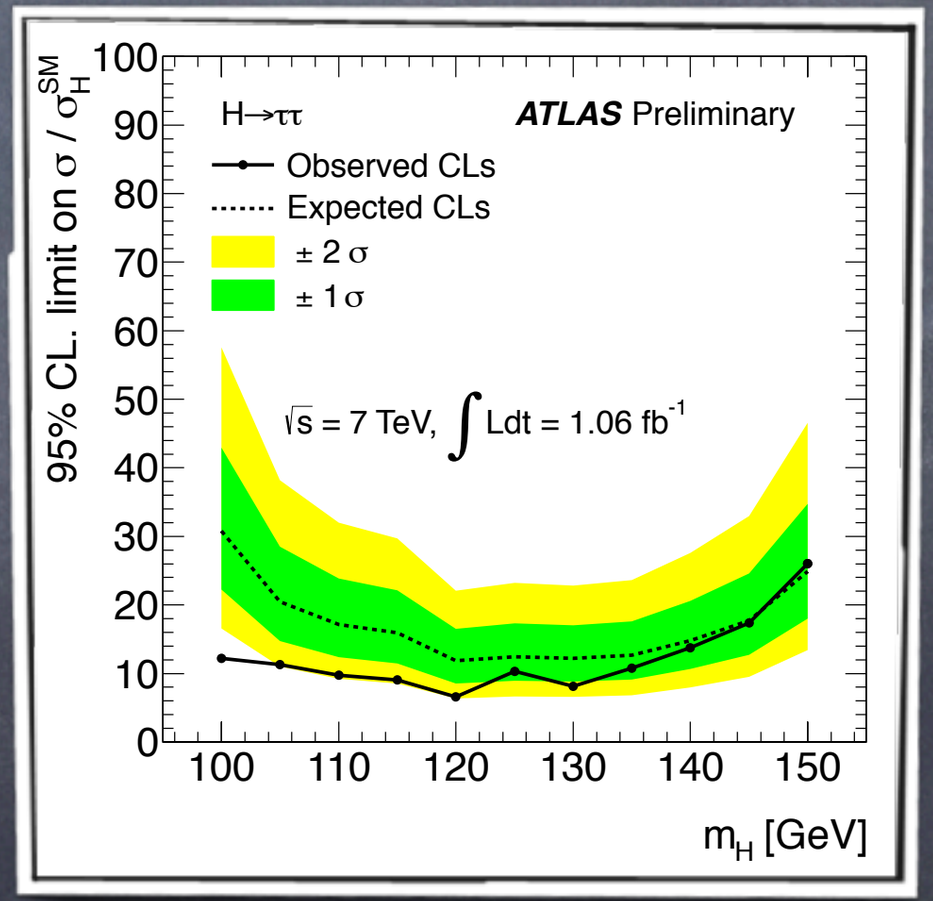


# H->ττ

- Non VBF - ll+jets(ATLAS), eμ(CMS), lh
- Dominant BG: Data driven tt and Z->ττ (using Embedding (ATLAS), using Z->ll (CMS) )
- QCD, W+jets from data



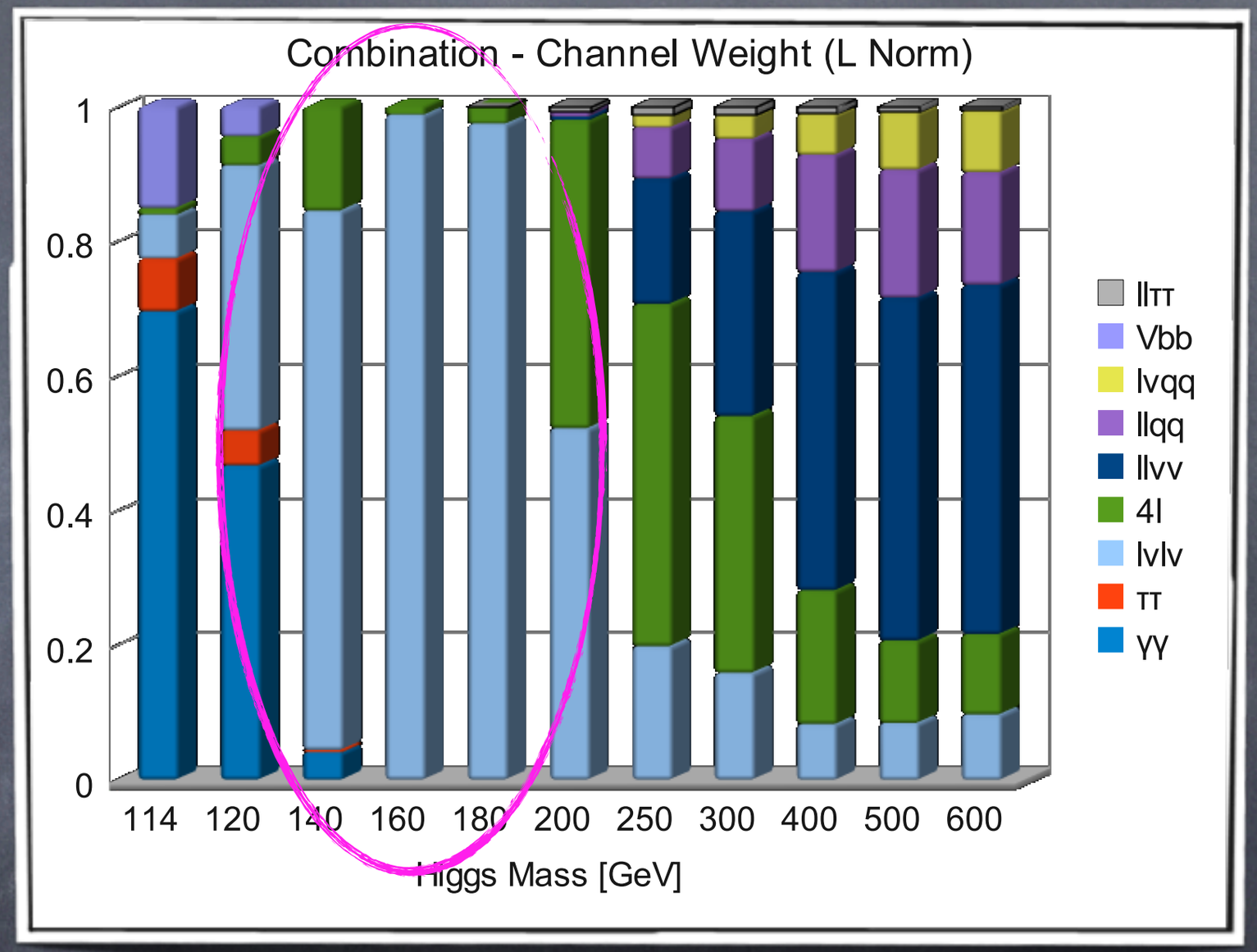




Sensitivity > x 10 SM

CMS has a downward fluctuation which improves the observed limit

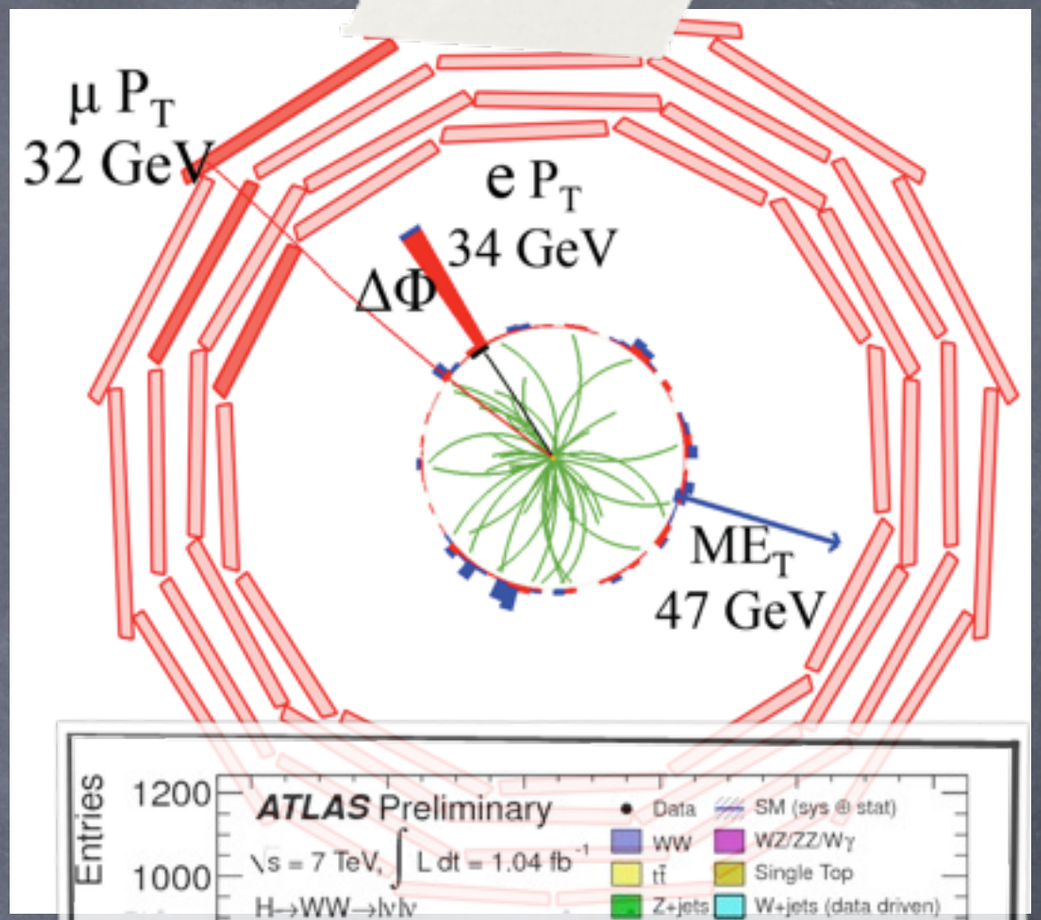
# "TEVATRON++" mass region

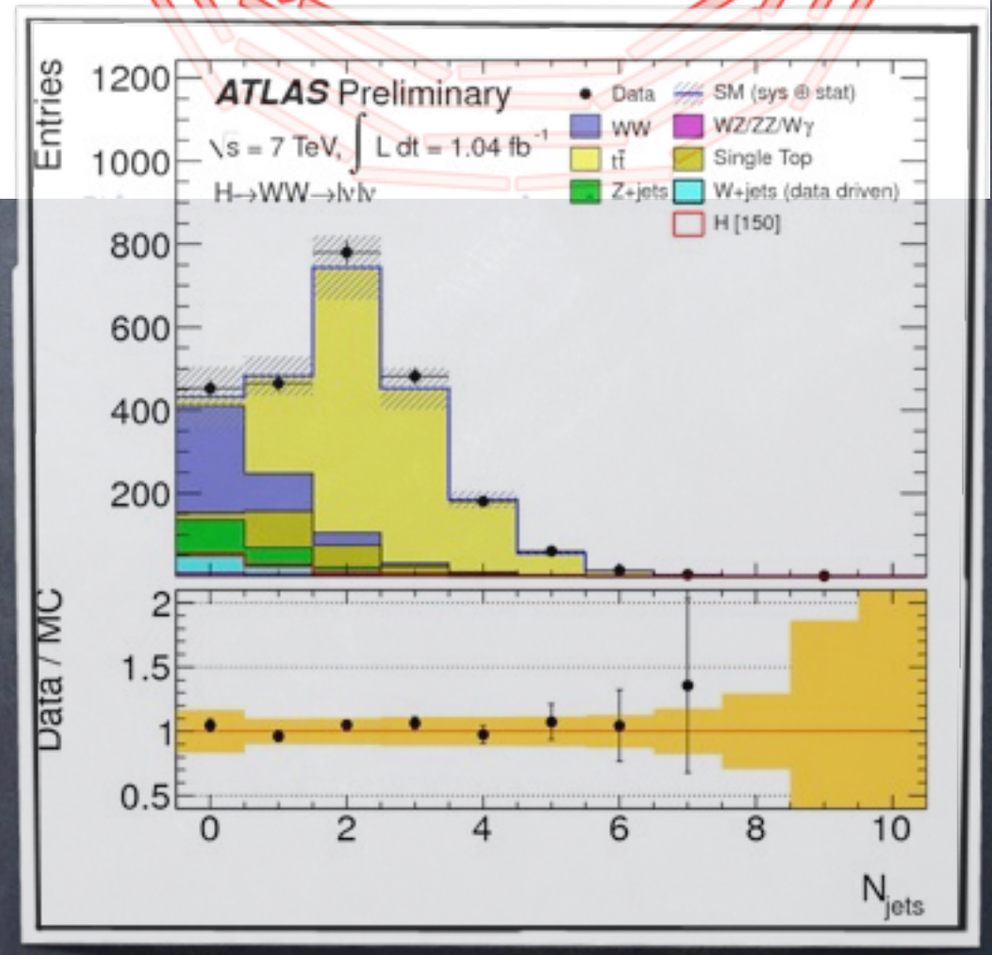
- "TEVATRON++" mass region 140-200 GeV
- Probing channel: H->WW->LuLu



# H->WW->lνlν

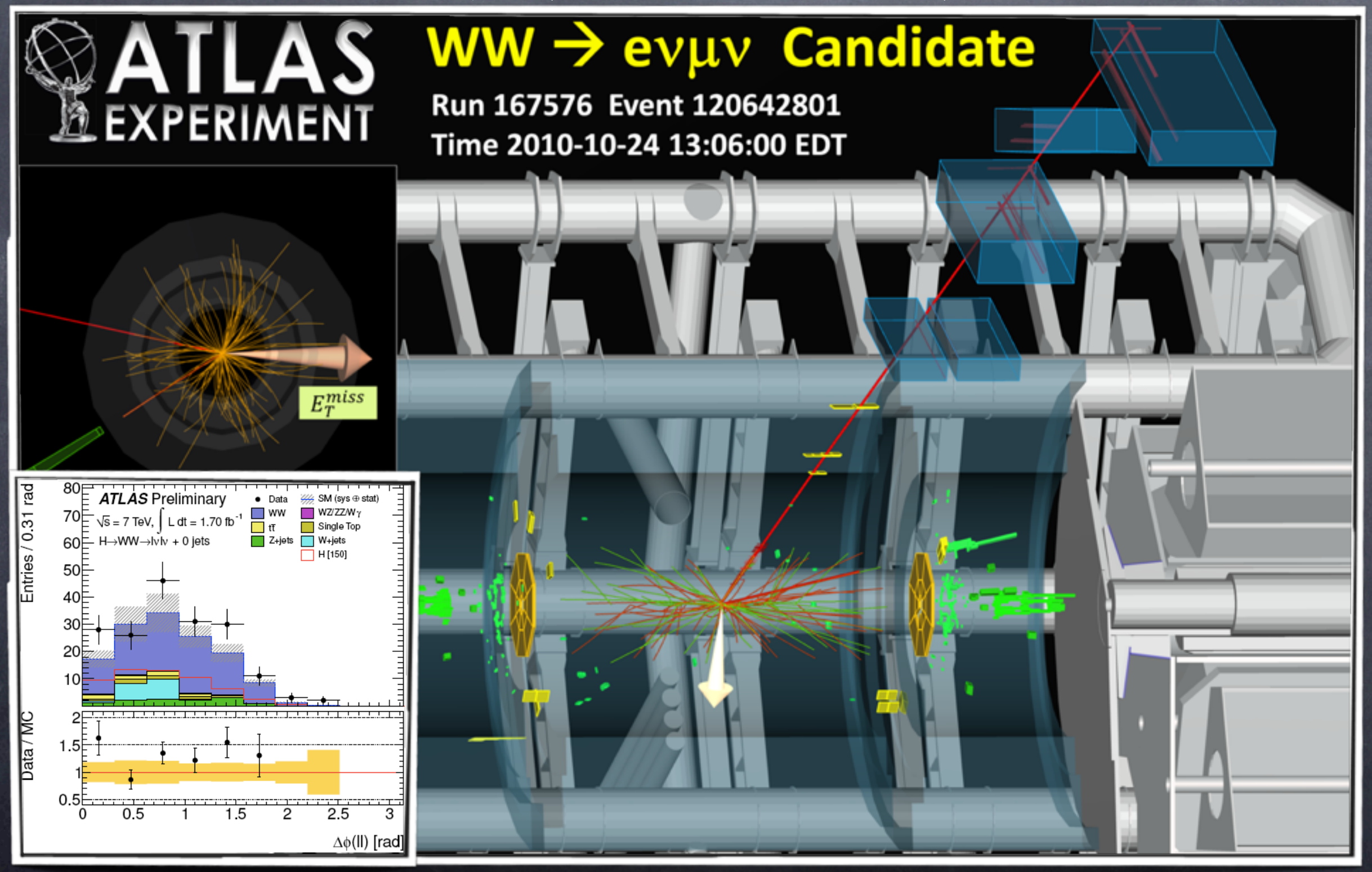
- The cjannel is challenging (2 neutrinos- no mass reconstruction)
- Signature: 2 high pT opposite sign isolated leptons with large MET
- 3 bins: +0,1 and 2 jets (VBF)



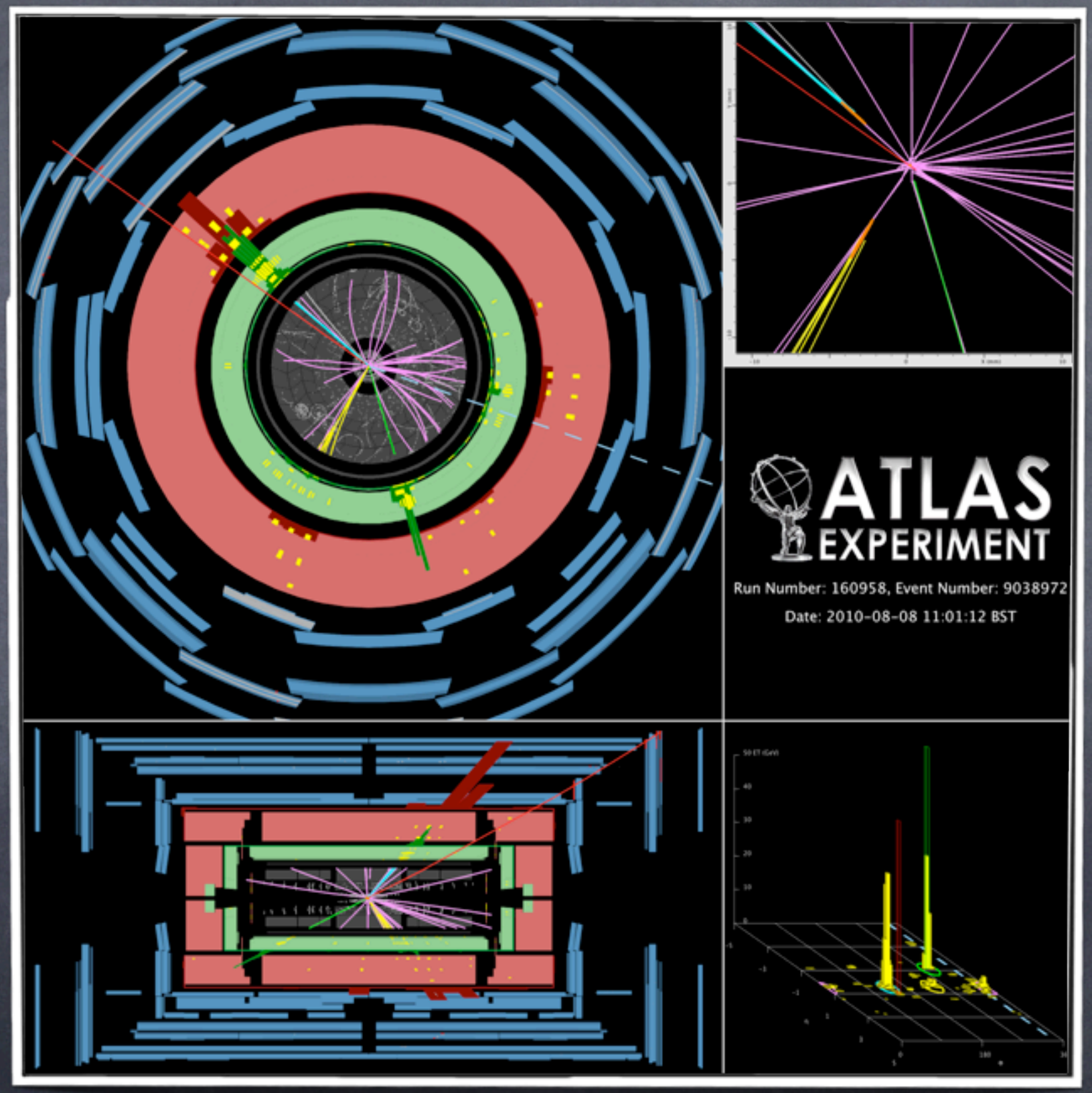
# WW->eμ Irreducible BG

- WW can be reduced by exploiting the Higgs spin, require small $\Delta\Phi_{ll}$



# ATLAS WW->eμ background: tt->eμ

Event display of a top pair e-mu dilepton candidate with two b-tagged jets.
The electron is shown by the green track pointing to a calorimeter cluster, the muon by the long red track intersecting the muon chambers, and the missing ET direction by the dotted line on the XY view. The secondary vertices of the two b-tagged jets are indicated by the orange ellipses on the zoomed vertex region view.

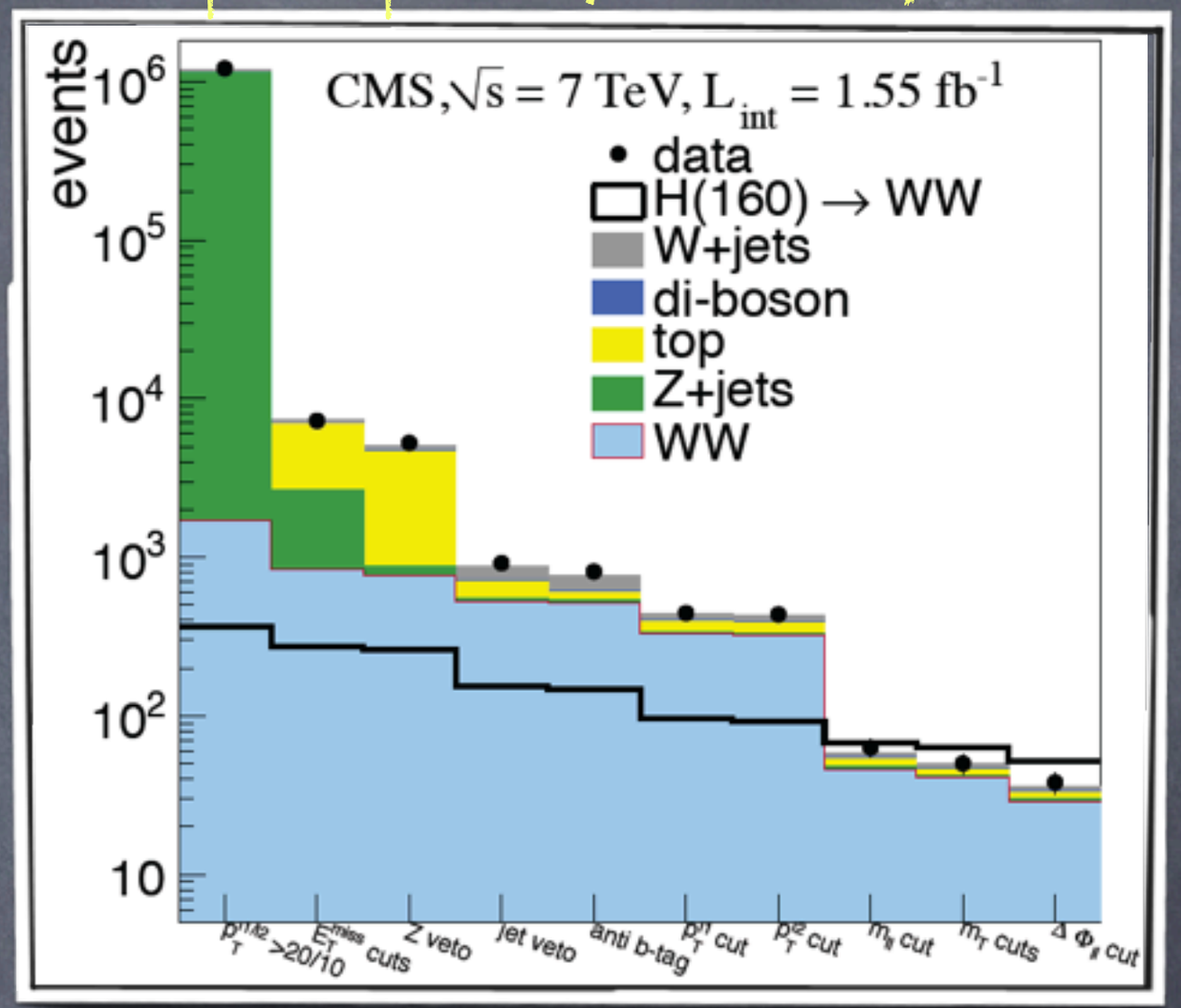



Reject by b-tag veto

# H->WW->lνlν

- BG: WW, W+jets, DY, top
- Irreducible WW BG can be slightly reduced requiring small $\Delta\Phi_{ll}$
- Large MET and Z Veto against DY
- b-tag veto to remove top contamination

in this plot expected (data driven) vs data



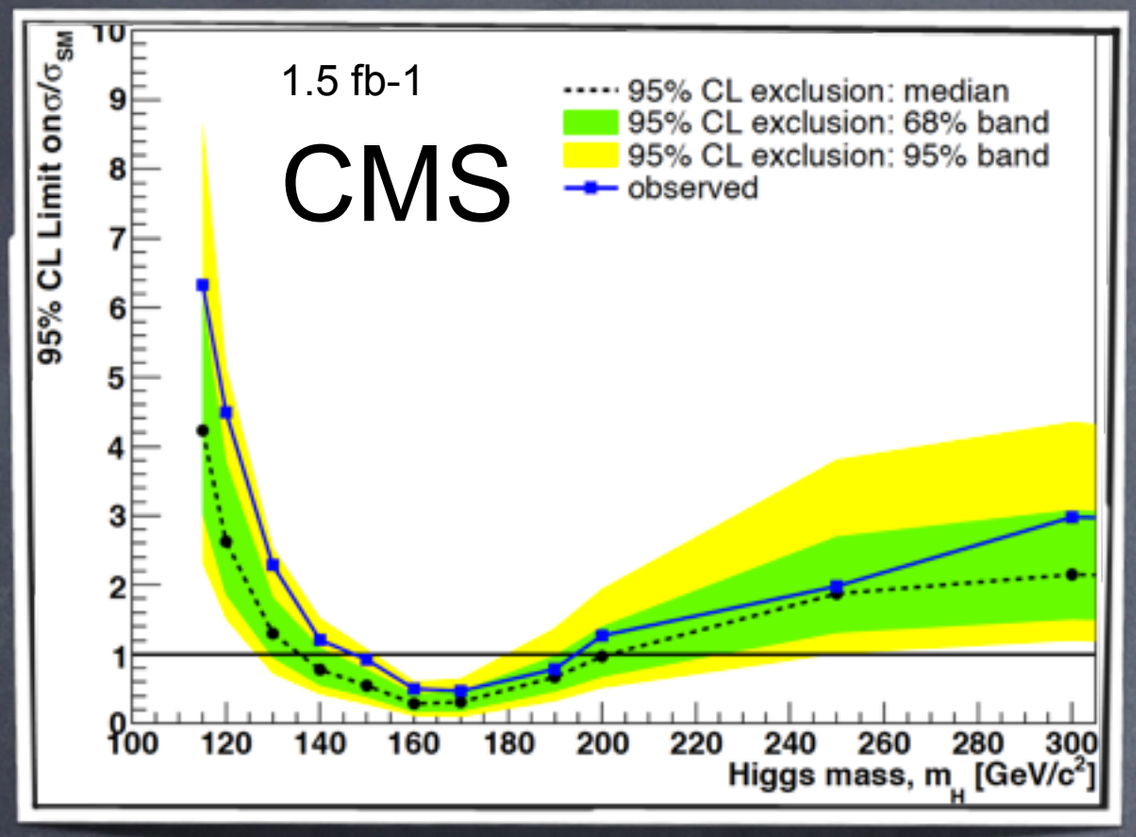

- Finally mass dependent cuts are applied (e.g. ATLAS $0.75m_H<m_T<m_H$)

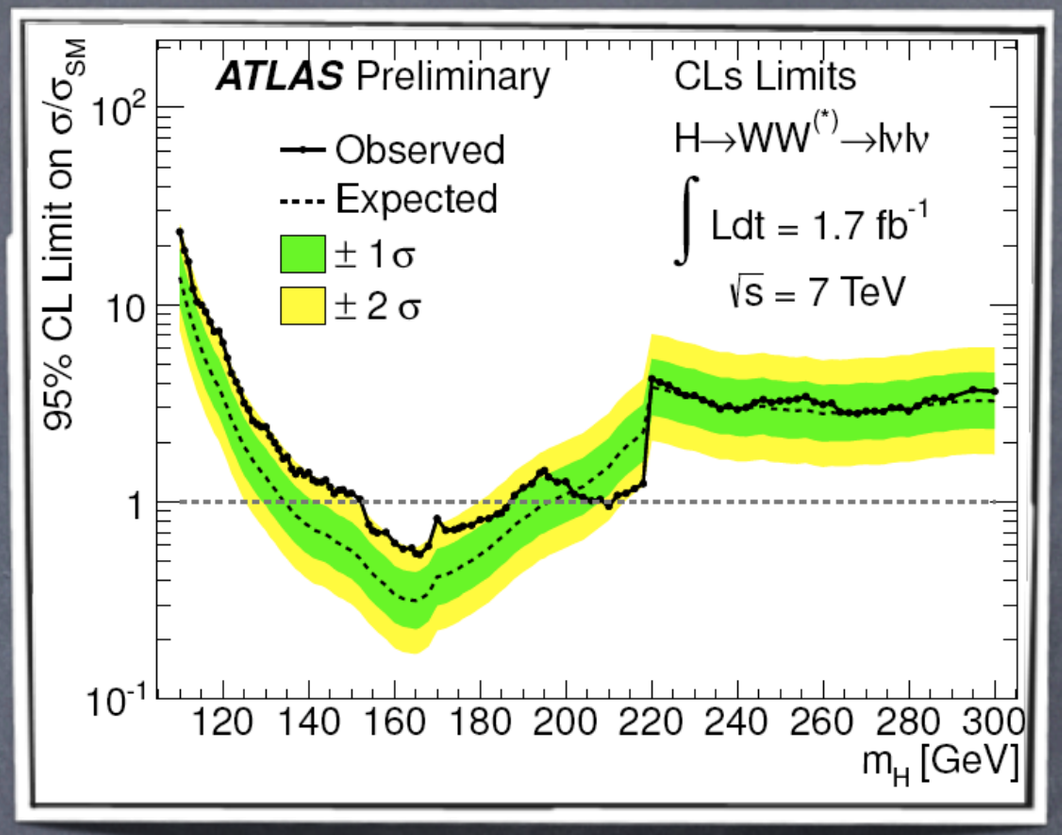
# H->WW->lνlν

- Background is estimated from control samples in various sophisticated ways
- A control region is defined rich in the measured BG (e.g. WW or top), contaminations are being subtracted and then the BG is extrapolated to the signal region (mostly using MC)
- Example: b-tag is inverted to estimate Top BG
- (CMS) DY estimated by inverting Z-veto
- W+jets and QCD multi-jet BG are data driven (estimating fakes)

# H->WW->lνlν Limits

- Results are counting based



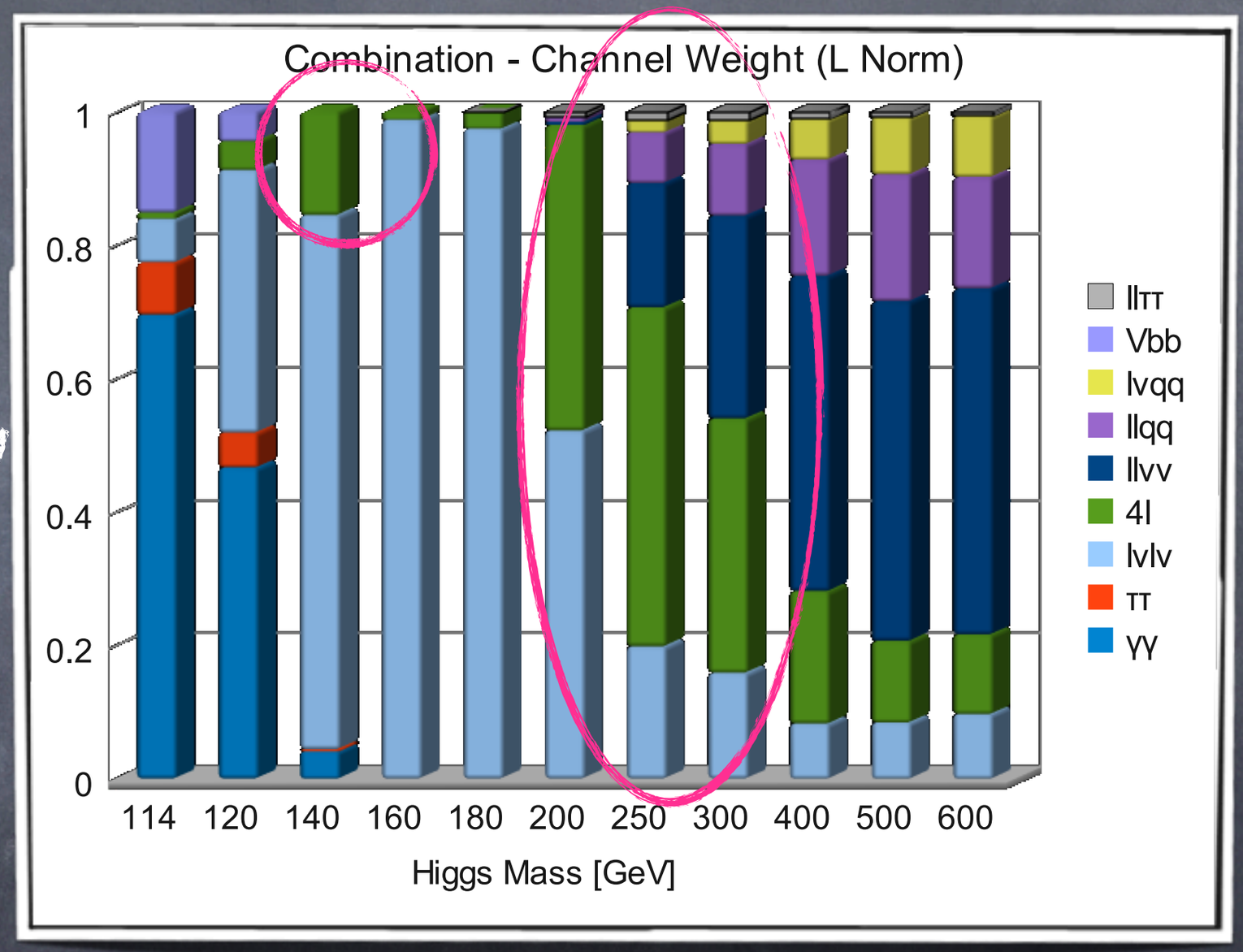

Obs: 154<mH<186 Obs: 147<mH<194

Exp: 135<mH<196 Exp: 136<mH<200

Both cut based ATLAS: only +0,1 jets

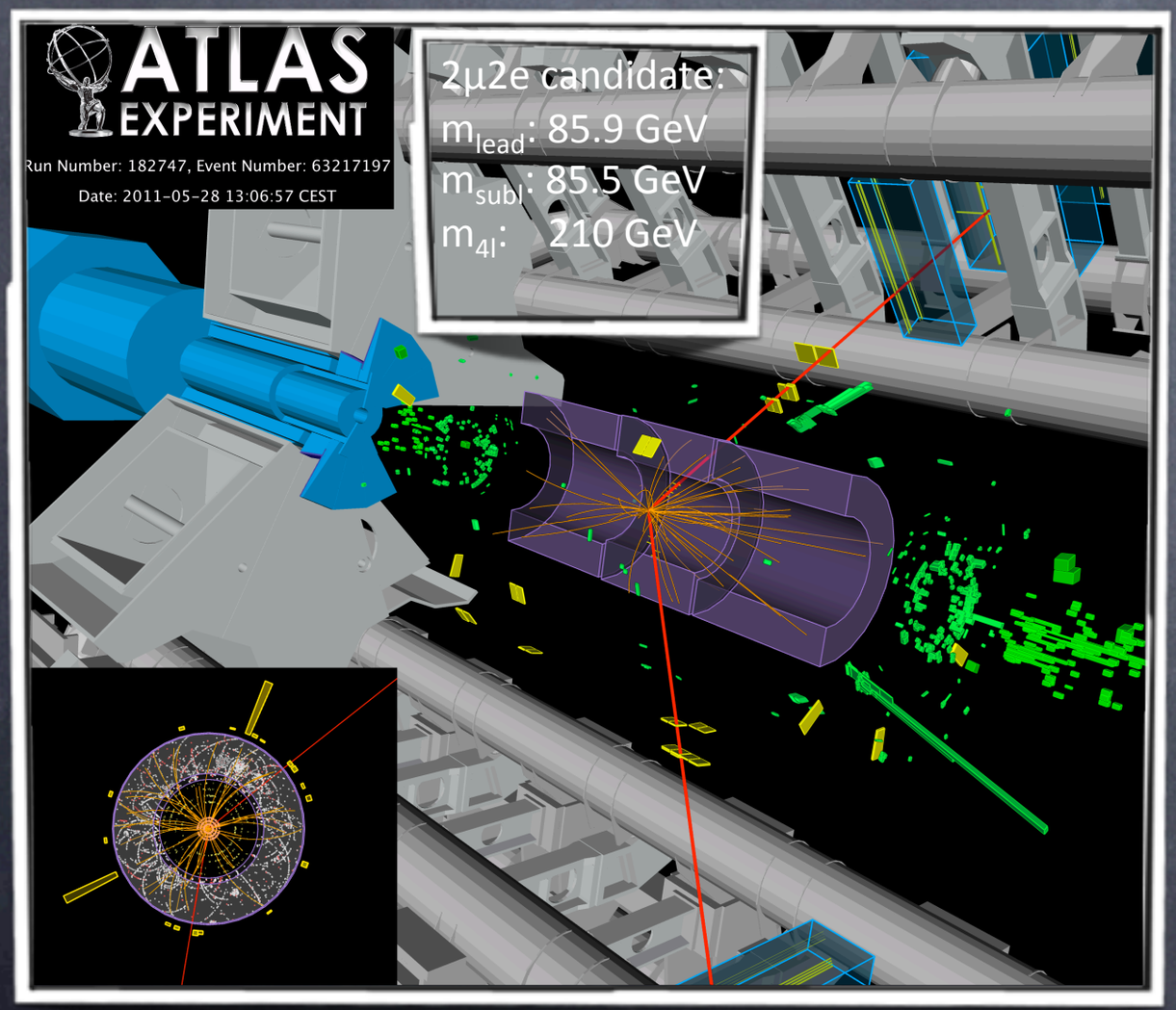
# The Golden Channel - H->ZZ->4l

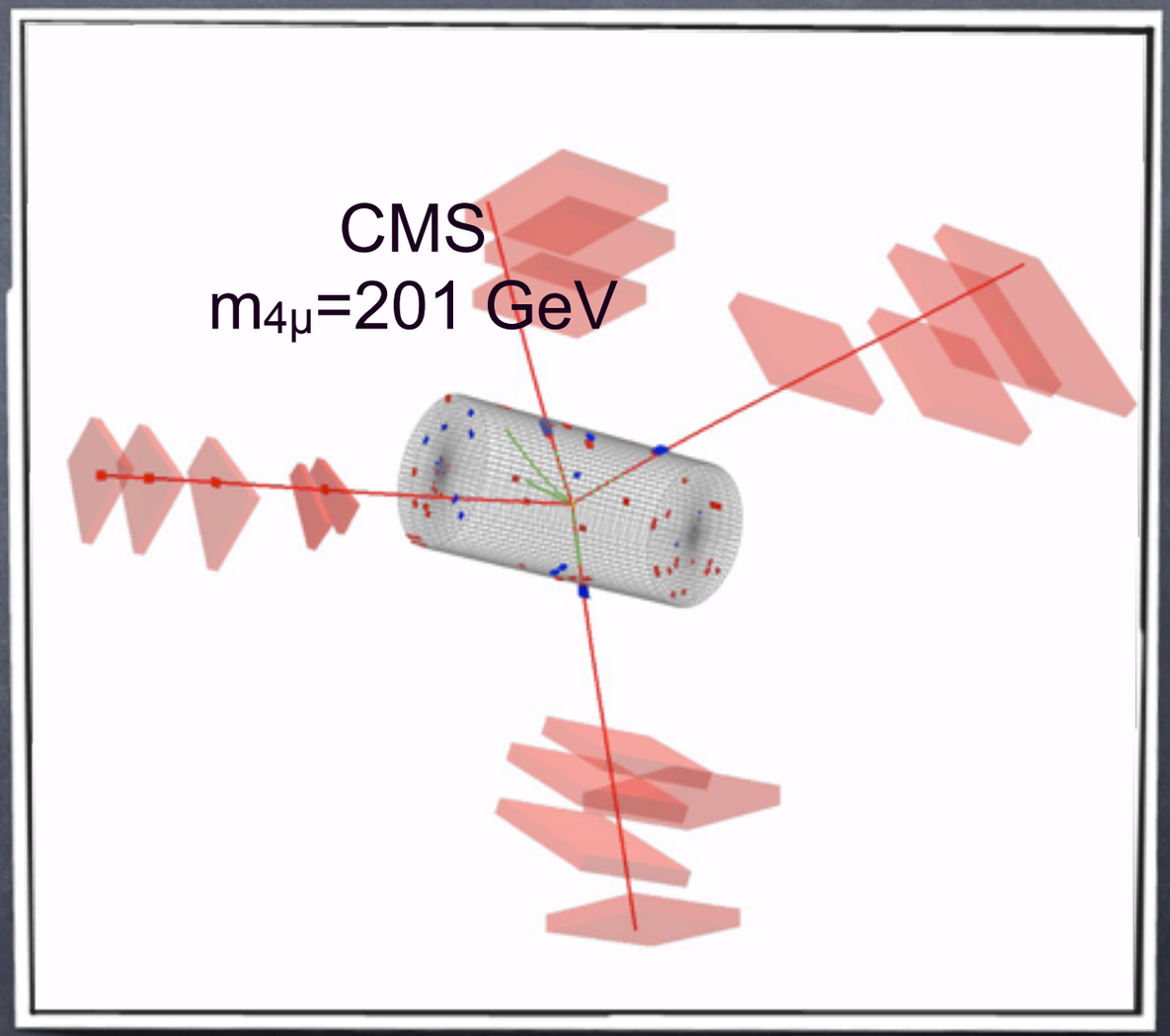
- Around 140 and above 200 GeV
- Probing channel: H->ZZ->4l



# The Golden Channel: H->ZZ->4l

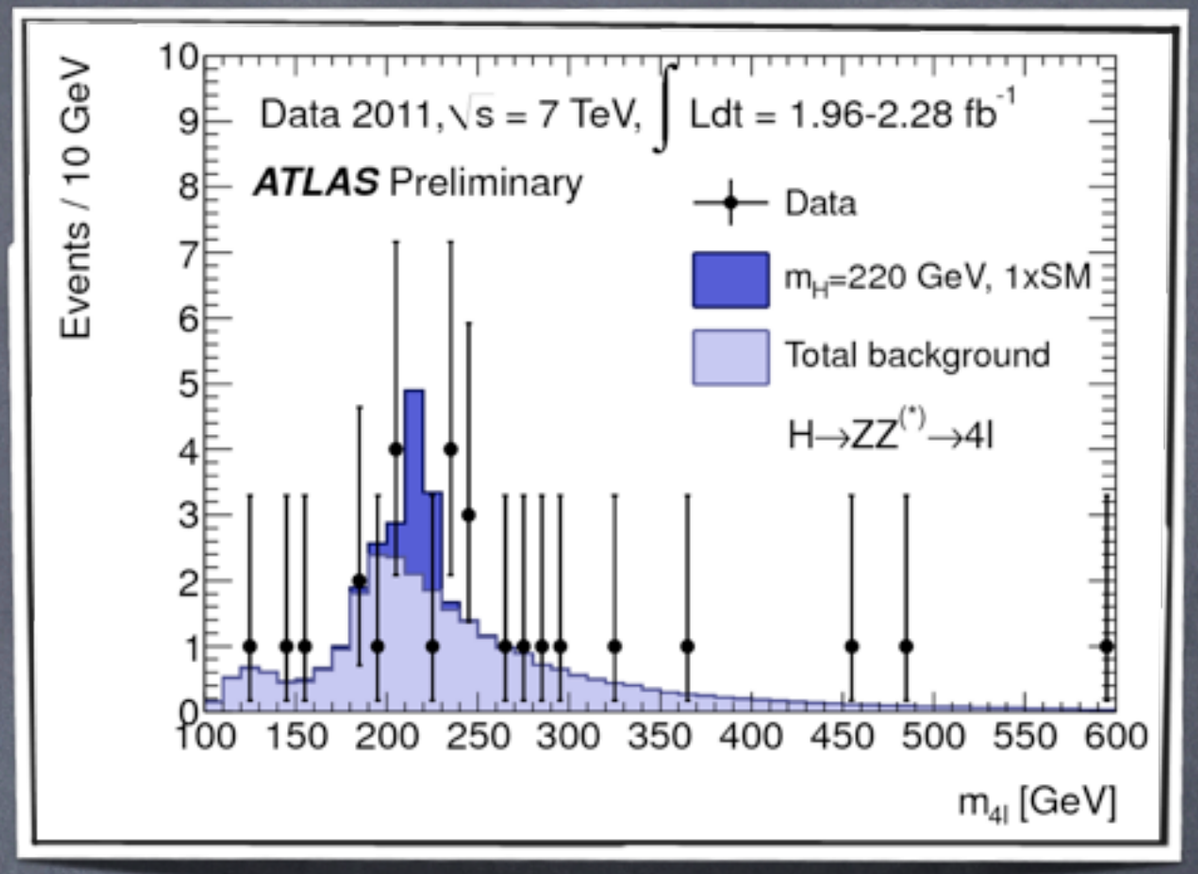
- CLEAN but very low rate, yet probably most trustable
- All information is available, one can fully reconstruct the kinematics and the masses ($m_{2l}$, $m_{4l}$)
- Signature: Two pairs of same flavor high pT opposite charged isolated leptons, one or both compatible with Z



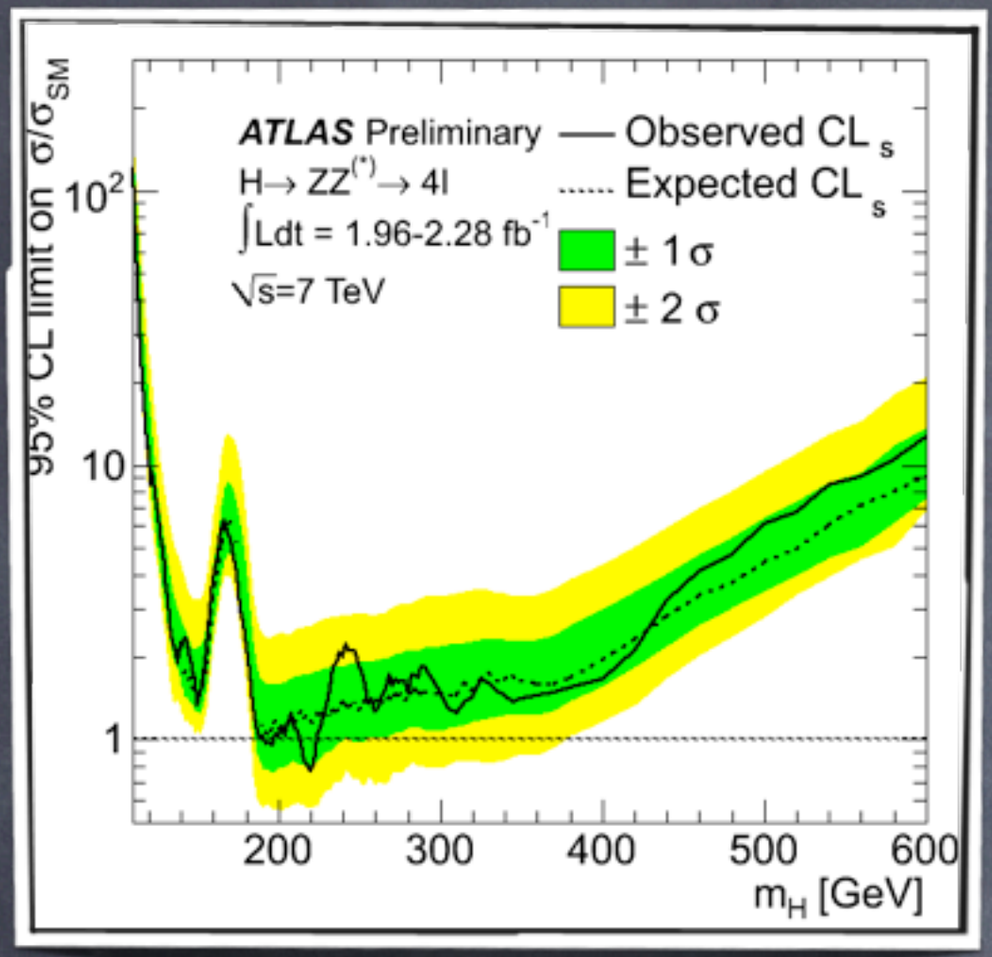



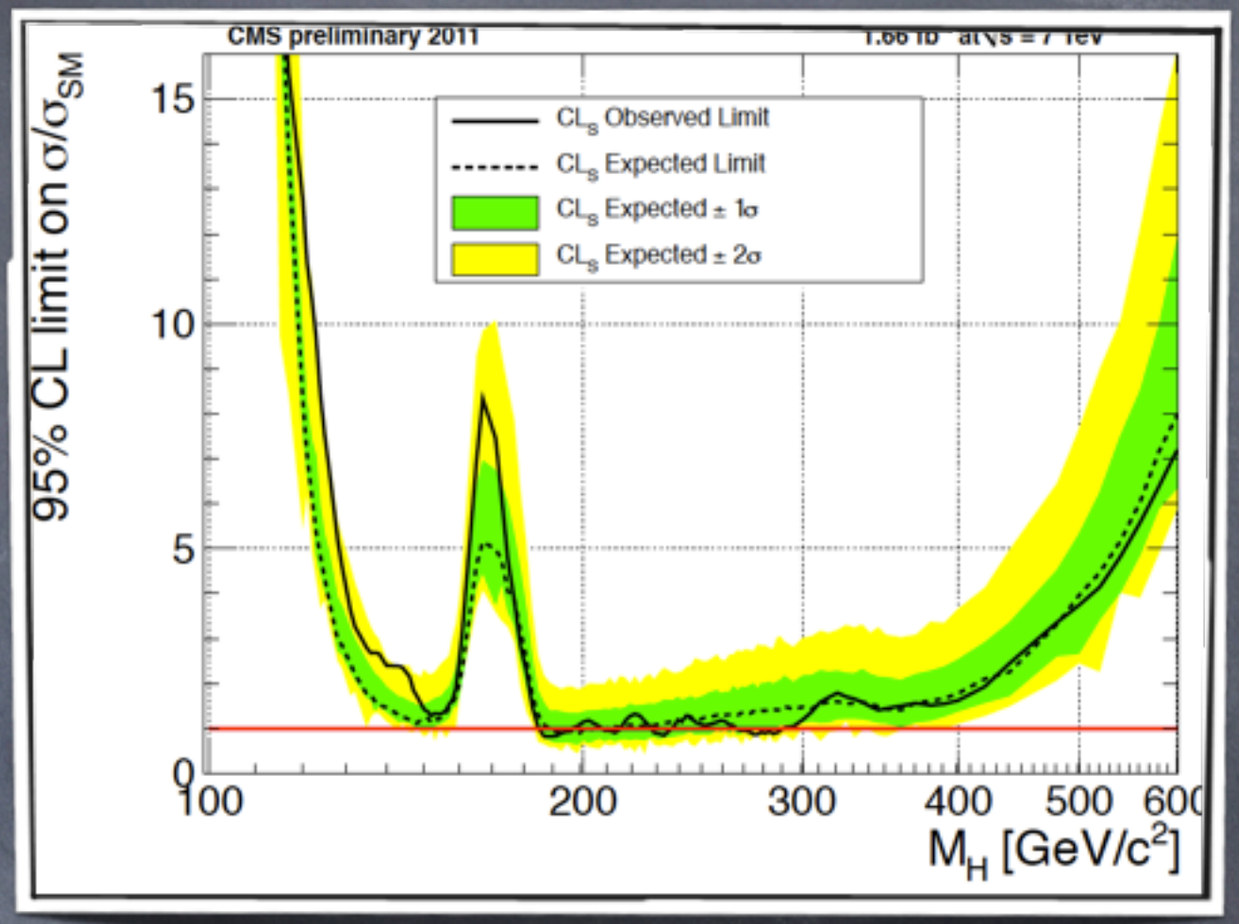
# The Golden Channel: H->ZZ->4l

- A distinct signature due to the excellent mass resolution
- Highly sensitive to lepton ID performance
- Irreducible BG from ZZ
- Z+jets (Z+bb) BG estimated from data
- Reducible BG: tt, Zbb removed by isolation and small impact parameter (for $m_{4l}<2m_Z$) requirements



# The Golden Channel: H->ZZ->4L

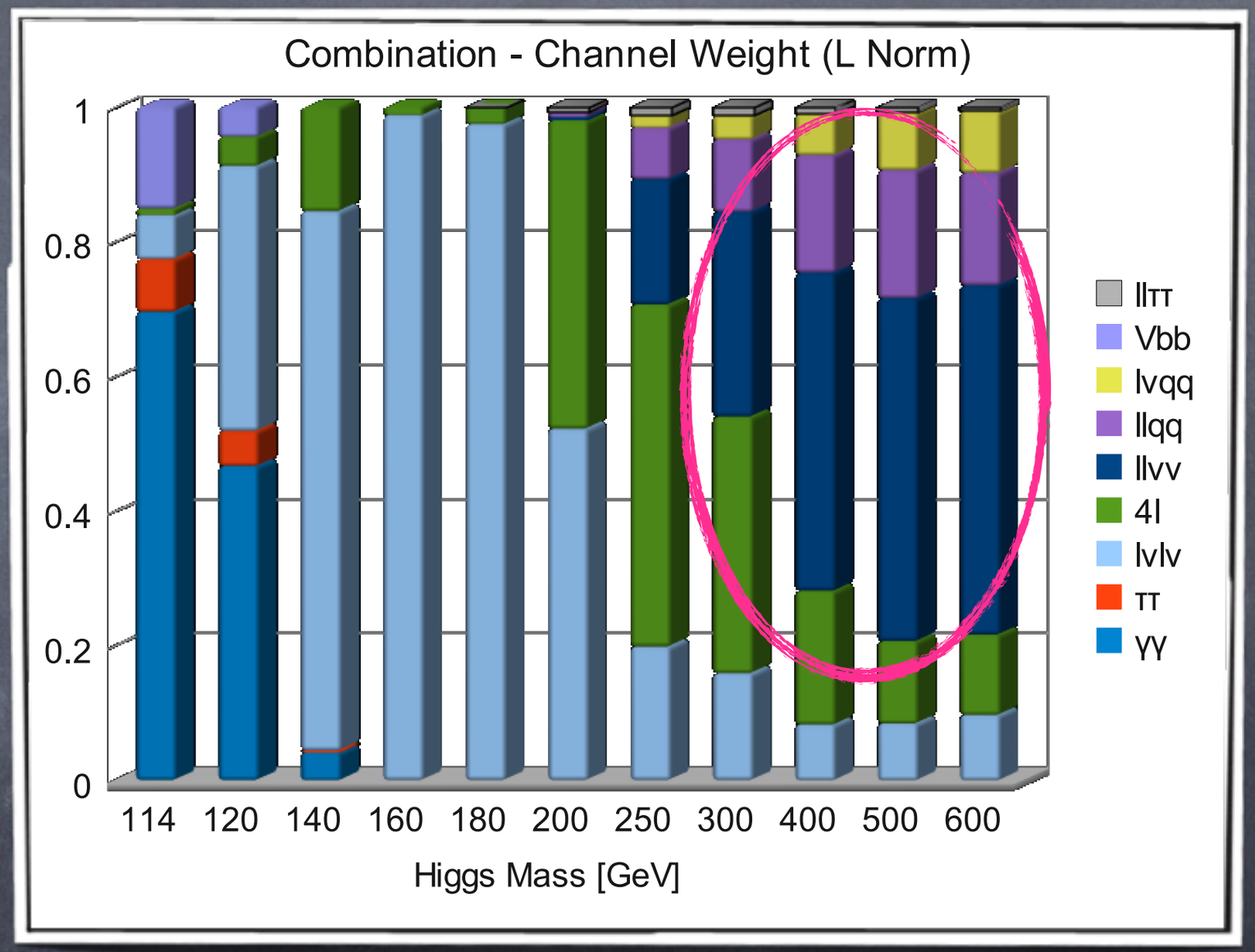



- Both experiments are getting closer to exclude
- There is no real excess anywhere
- A projected illustrative combination shows that the combined sensitivity range is 190<mH<300 and the region 190<mH<340 is rather unlikely already

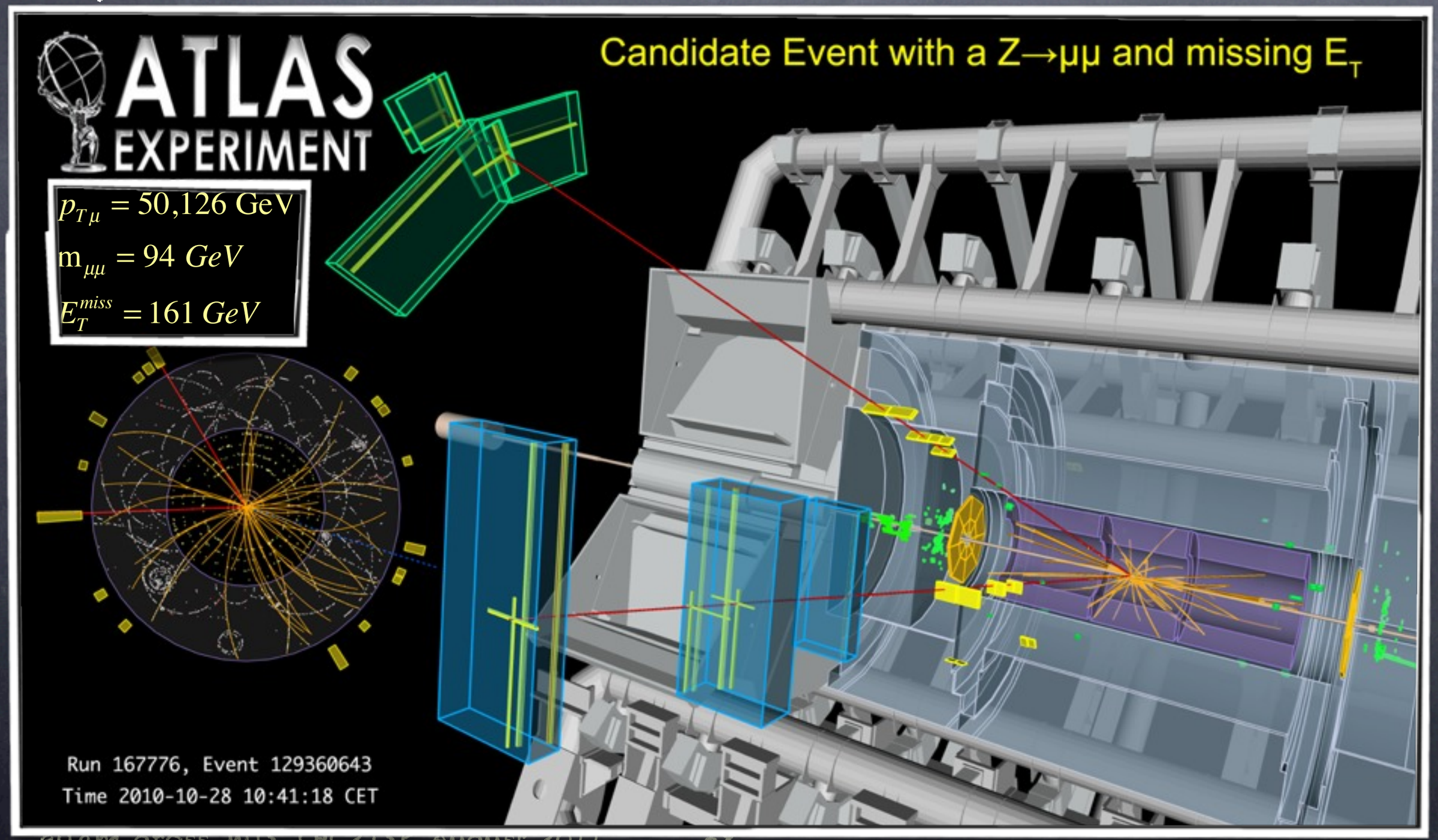
# Heavy Higgses

- mH>300
- Probing channels:
  H->ZZ->llvv
  H->ZZ->llqq
  and 4l



# Heavier Higgs: H->LLνν

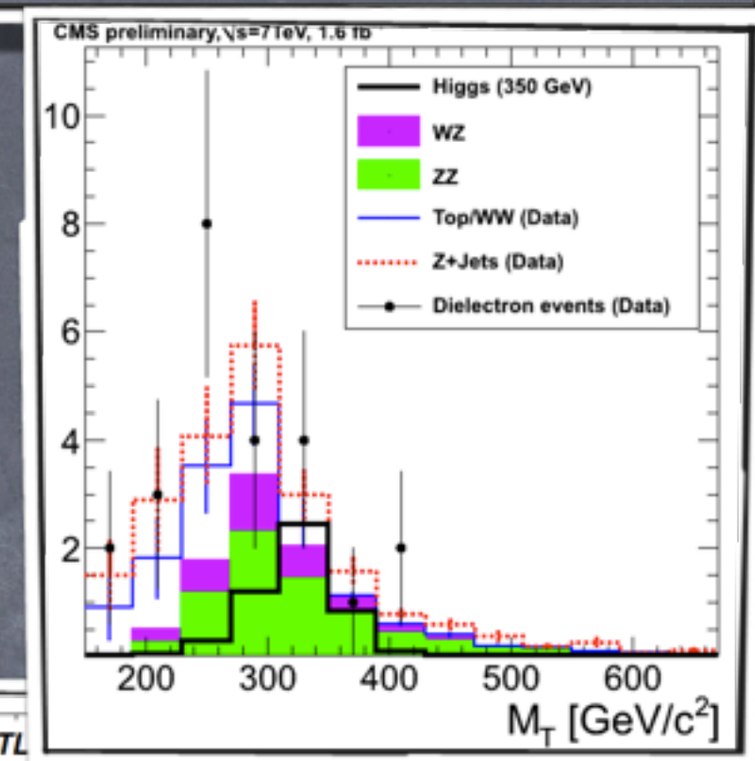
- Signature: two high pT opposite charged isolated leptons with high MET

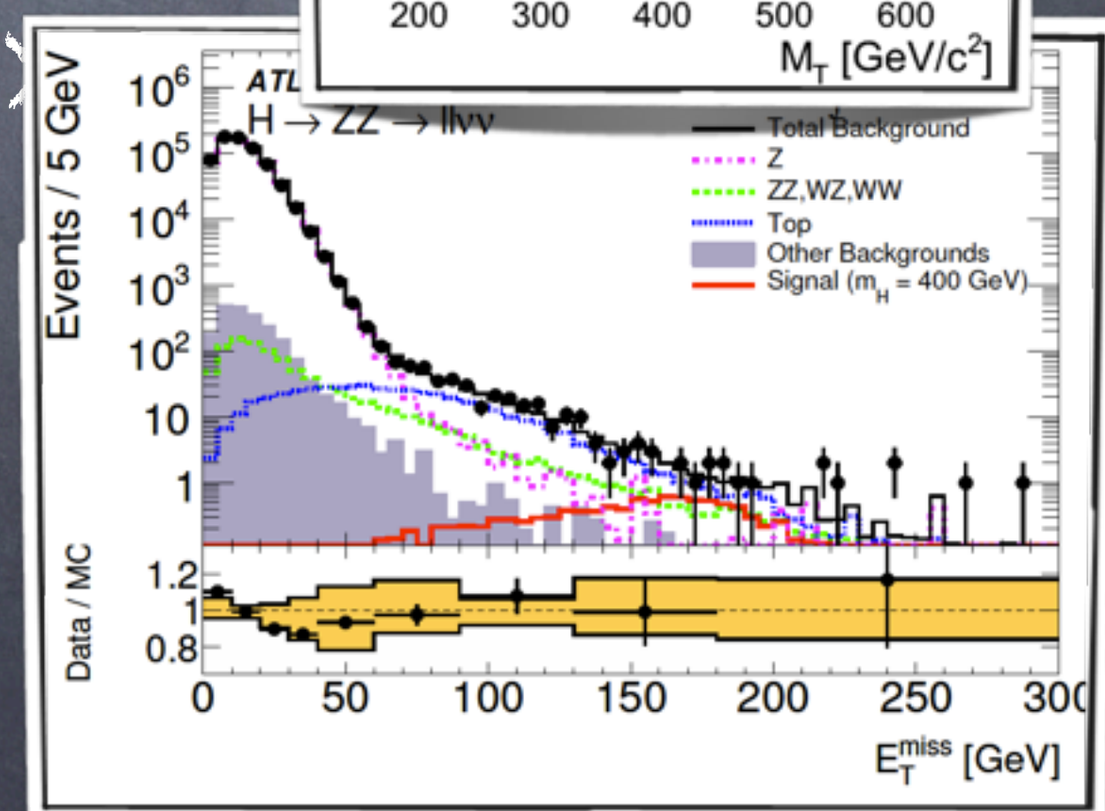


# Heavier Higgs: H->llνν

$$m_T^2 \equiv \left(\sqrt{\vec{p}_{TZ}^{\,2} + m_Z^2} + \sqrt{|\,\vec{p}_T^{\,miss}\,|^2 + m_Z^2}\right)^2 - (\vec{p}_{TZ} + \vec{p}_T^{\,miss})^2$$

- Main BG: irreducible di-Boson ZZ,WZ & WW
- Reducible, measured or verified with data control samples: QCD, W/Z+jets (suppressed by MET) and top (rejected by anti b-tag)
- Discriminating variables: $\Delta\Phi_{ll}$,MET and Transverse mass (two mass bins (ATLAS) and mass dependent cuts (CMS)).

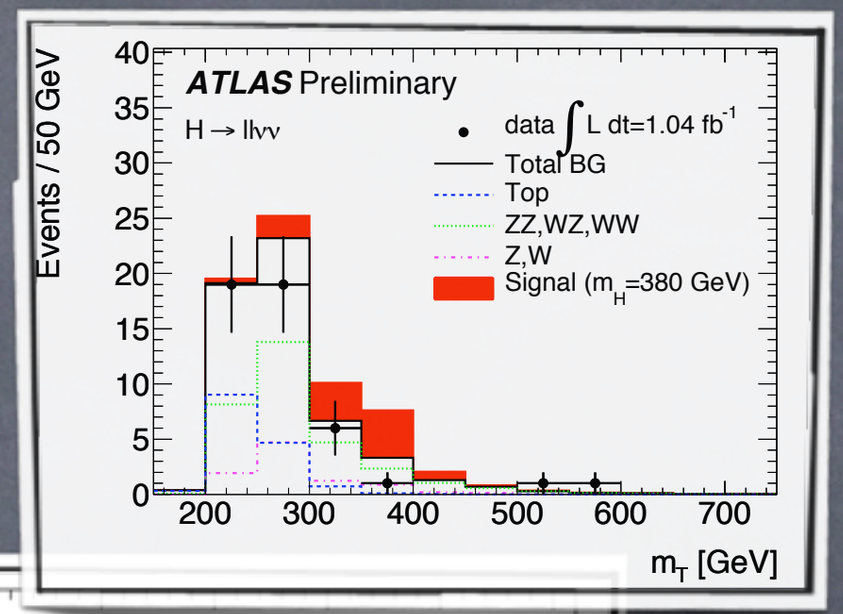


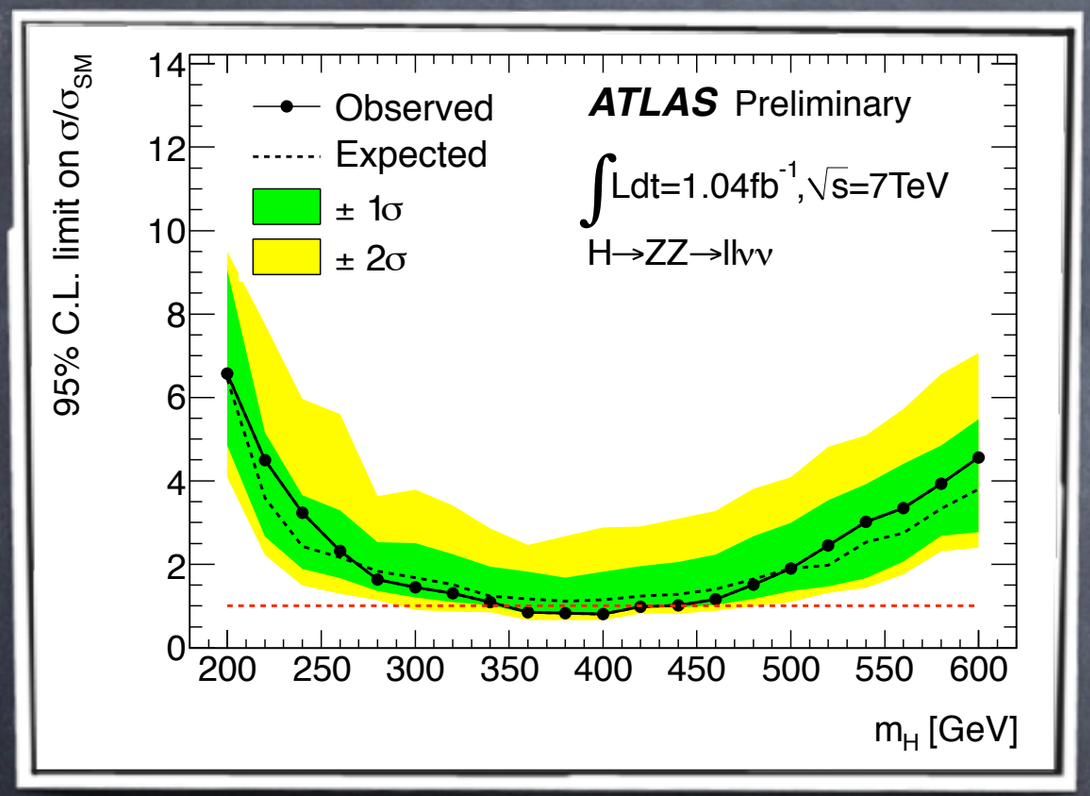



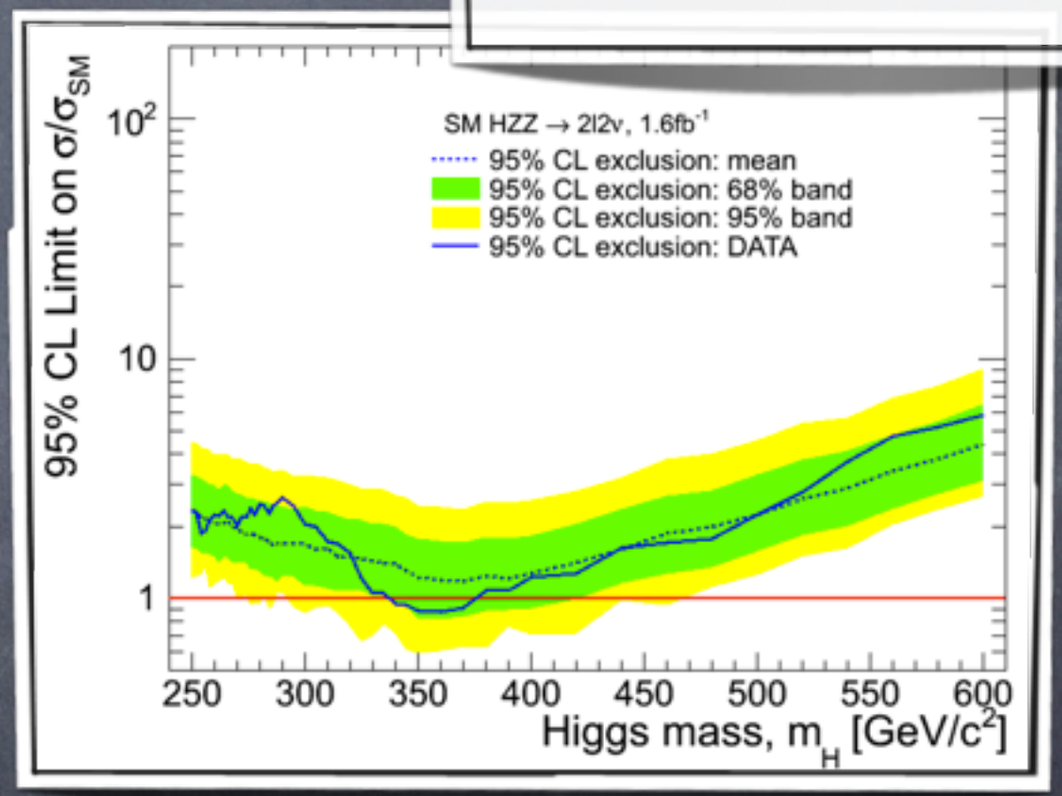
# Heavier Higgs: H->LLνν

- $$m_T^2 \equiv \left(\sqrt{\vec{p}_{TZ}^{\,2} + m_Z^2} + \sqrt{|\,\vec{p}_T^{\,miss}\,|^2 + m_Z^2}\right)^2 - (\vec{p}_{TZ} + \vec{p}_T^{\,miss})^2$$

- Final analysis by counting (CMS) or $m_T$ shape (ATLAS)



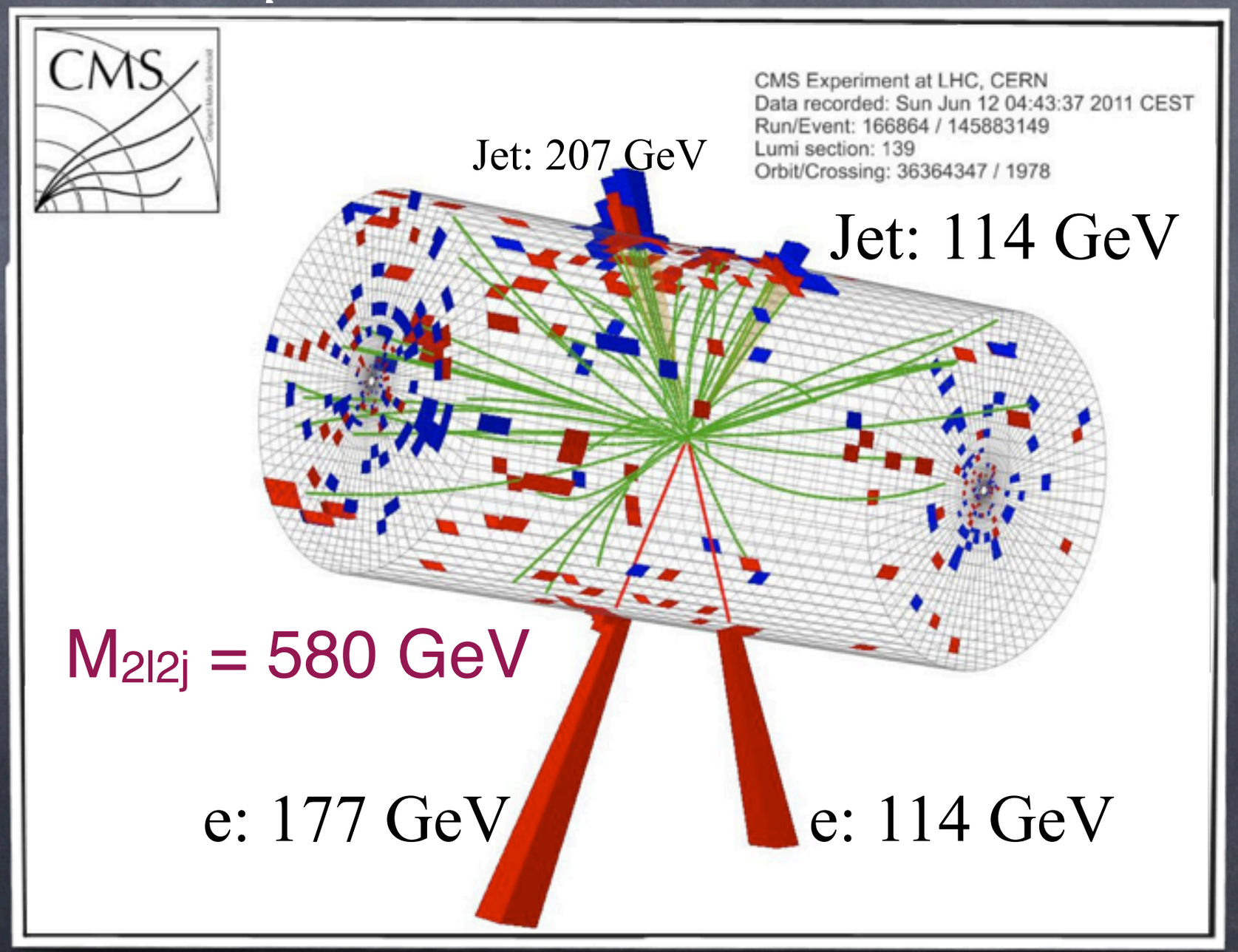




Obs: excl 350<mH<450

Obs: excl 340<mH<375

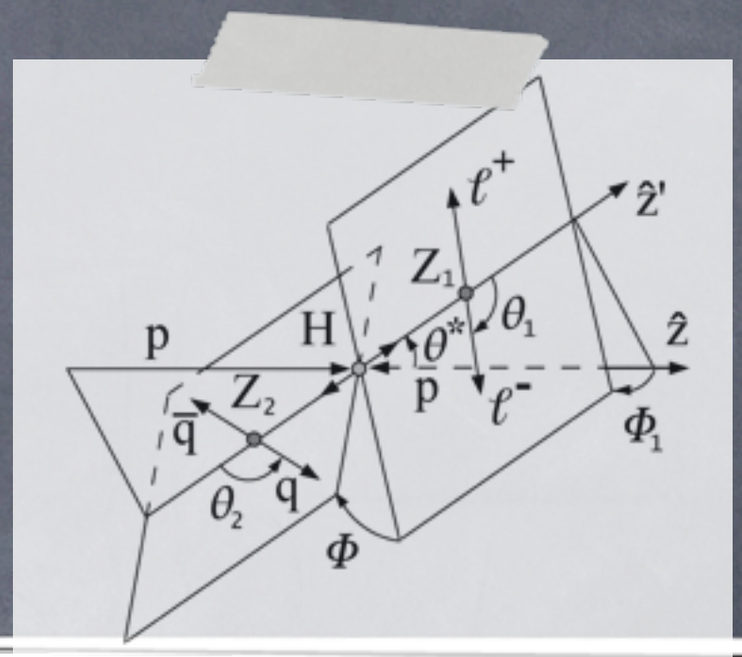
# Heavier Higgs: H->LLqq

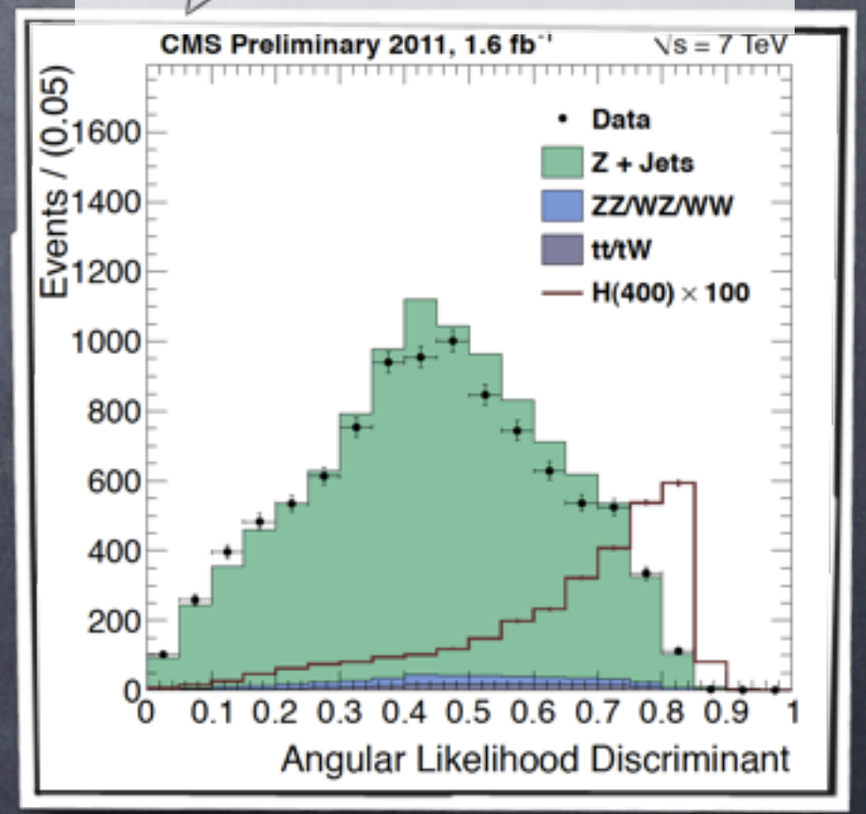
- Clear signature: Exactly one pair of oppositely charged same flavor leptons and a pair of jets.
  both pairs compatible with a Z boson. Low MET



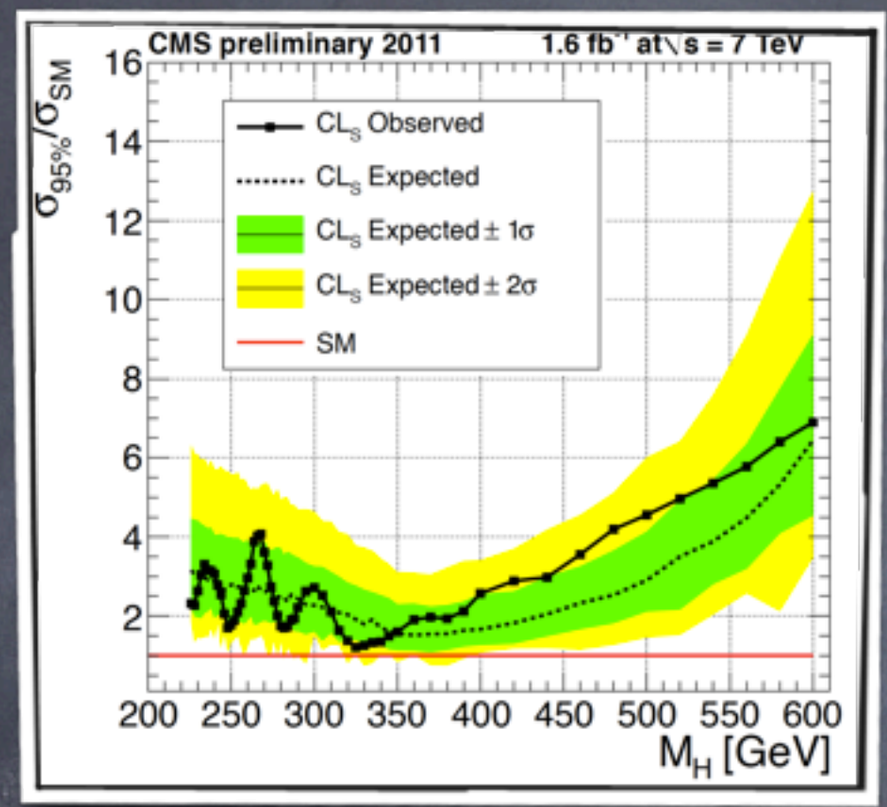
# Heavier Higgs: H->LLqq

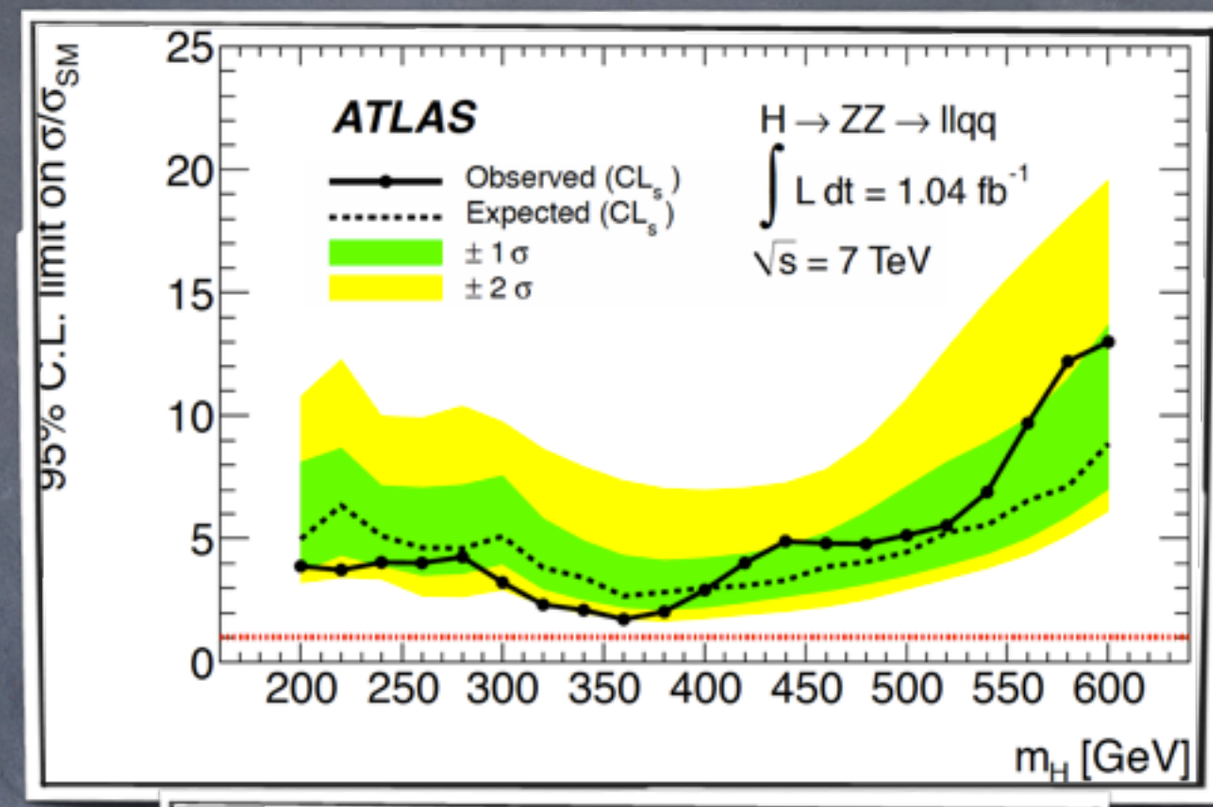
- Even though this channel has the highest rate of all H->ZZ final states, it has less weight due to High Z+jets BG
- Strategy:
  - "Bump search" in $m_{LLqq}$ distribution
  - Use b-tagged bins (ATLAS 0+1,2; CMS 0,1,2 b-tagged jets)
  - CMS are using spin related angular variables
  - Use side bands in $m_{LL}$ and $m_{jj}$ to measure the Z+jets BG



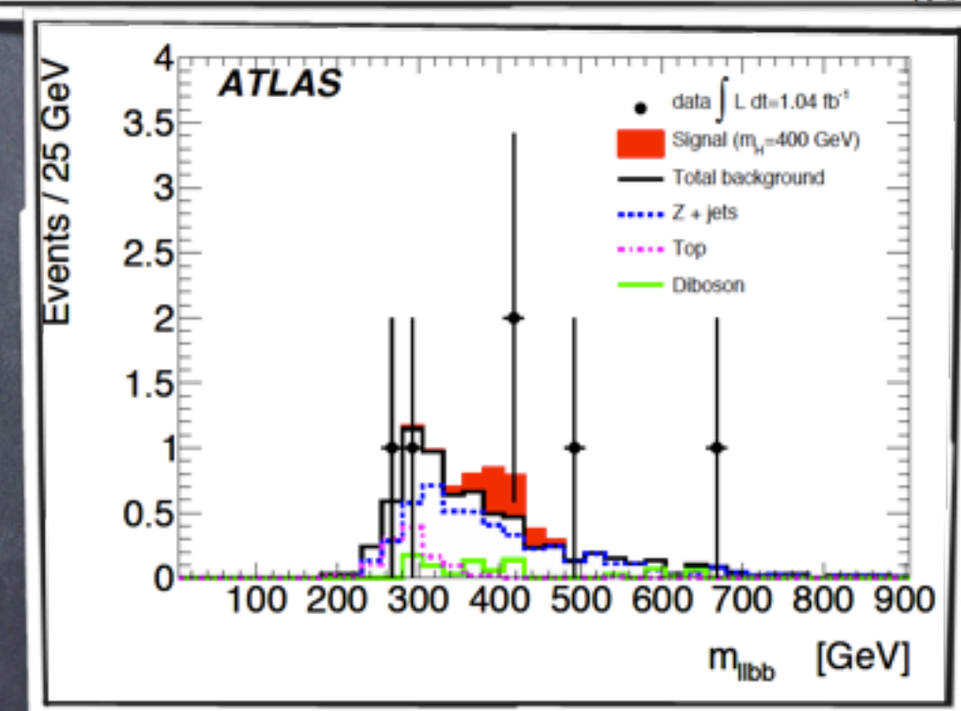



# Heavier Higgs: H->llqq

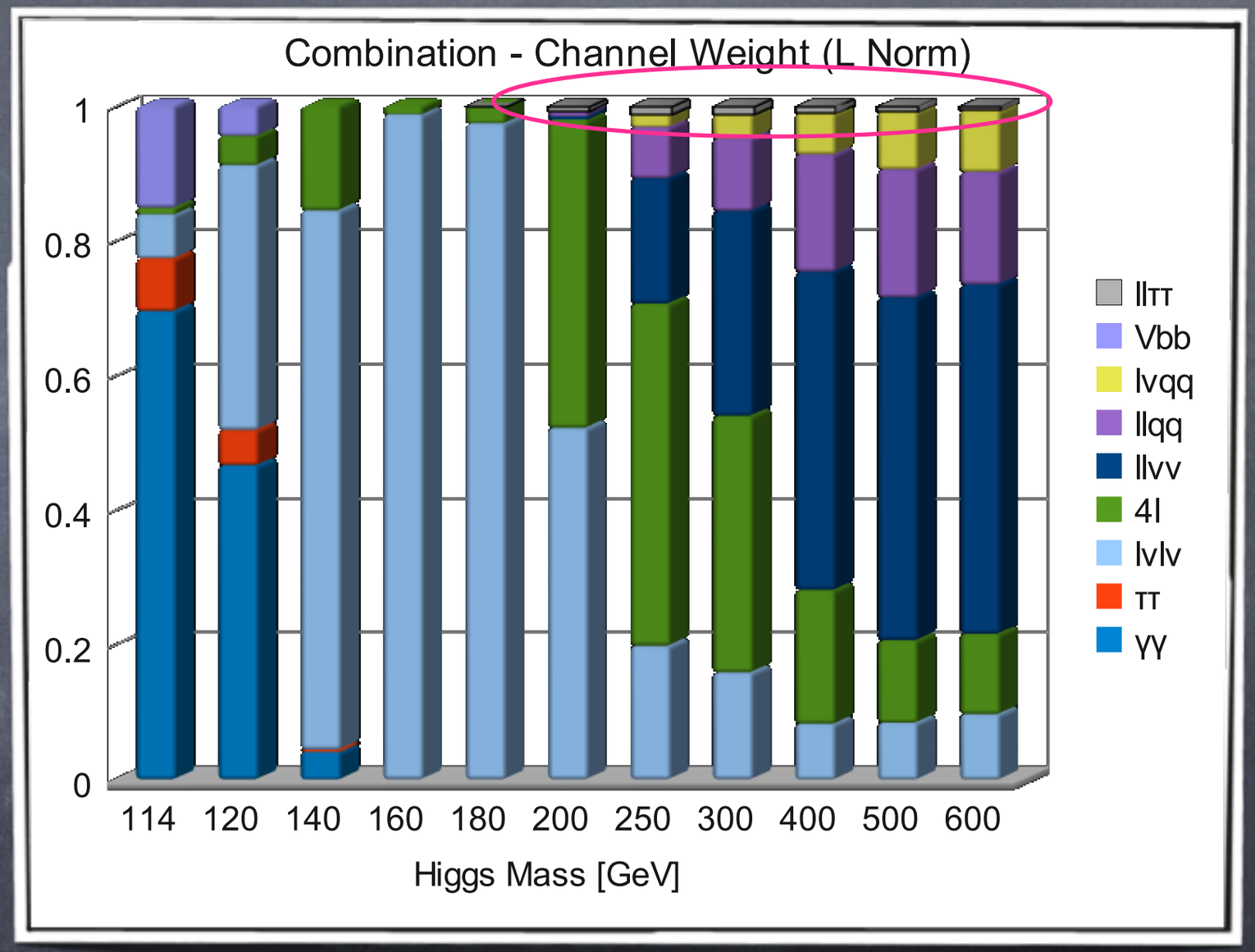



- This channel is approaching a sensitivity for exclusion
- Both experiments almost touch the SM exclusion line due to a downwards fluctuation of the data

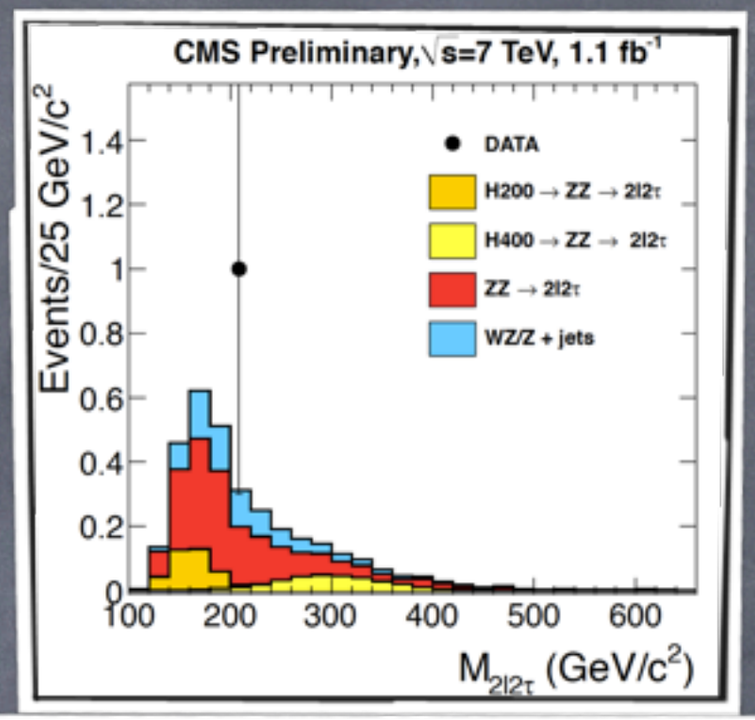


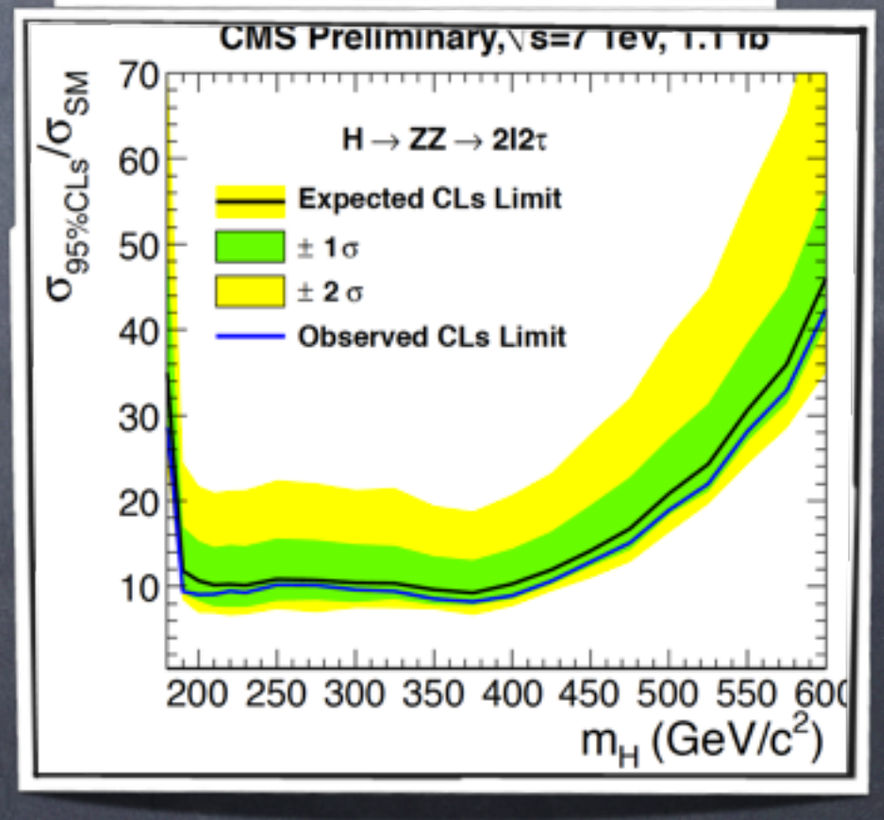
# CMS "exclusive": ZZ->llττ



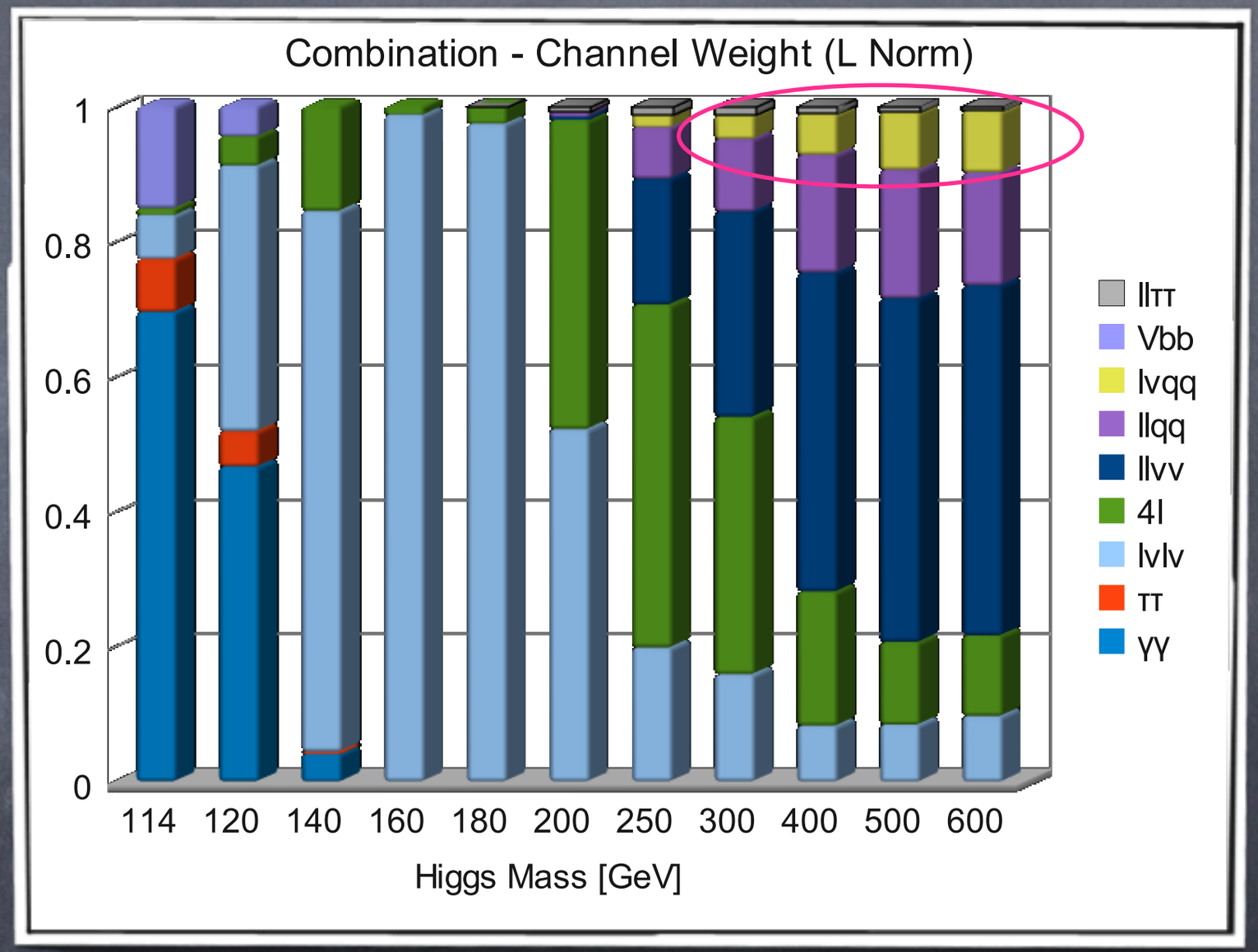
# CMS "exclusive": ZZ->llττ

- Serach performed by CMS
- Signature: ee or μμ from Z and a pair of taus.
- Major BG ZZ, WZ and Z+jets estimated with data driven ways.
- For tau leptonic decays only eμ final states are considered (to avoid overlap with 4l)
- ONE event survived in the eeeTh final state
- Sensitivity ~x10 SM 200-400 GeV



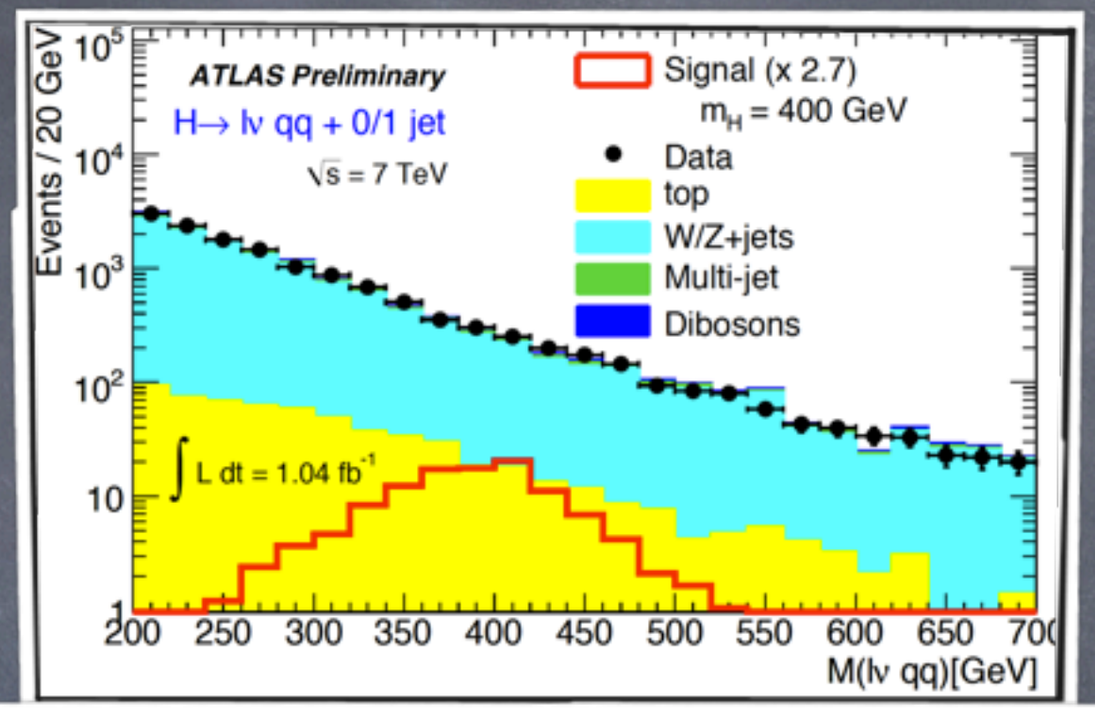



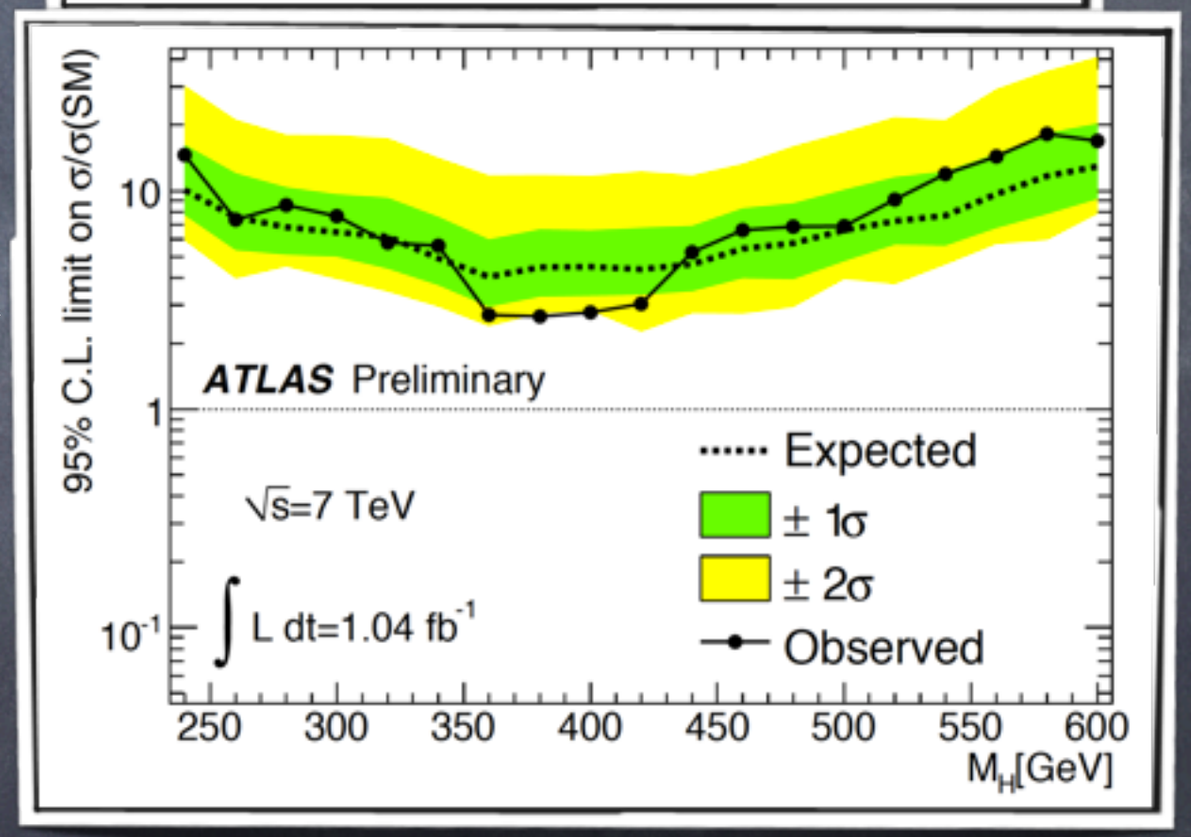
# ATLAS "exclusive": WW->lνqq



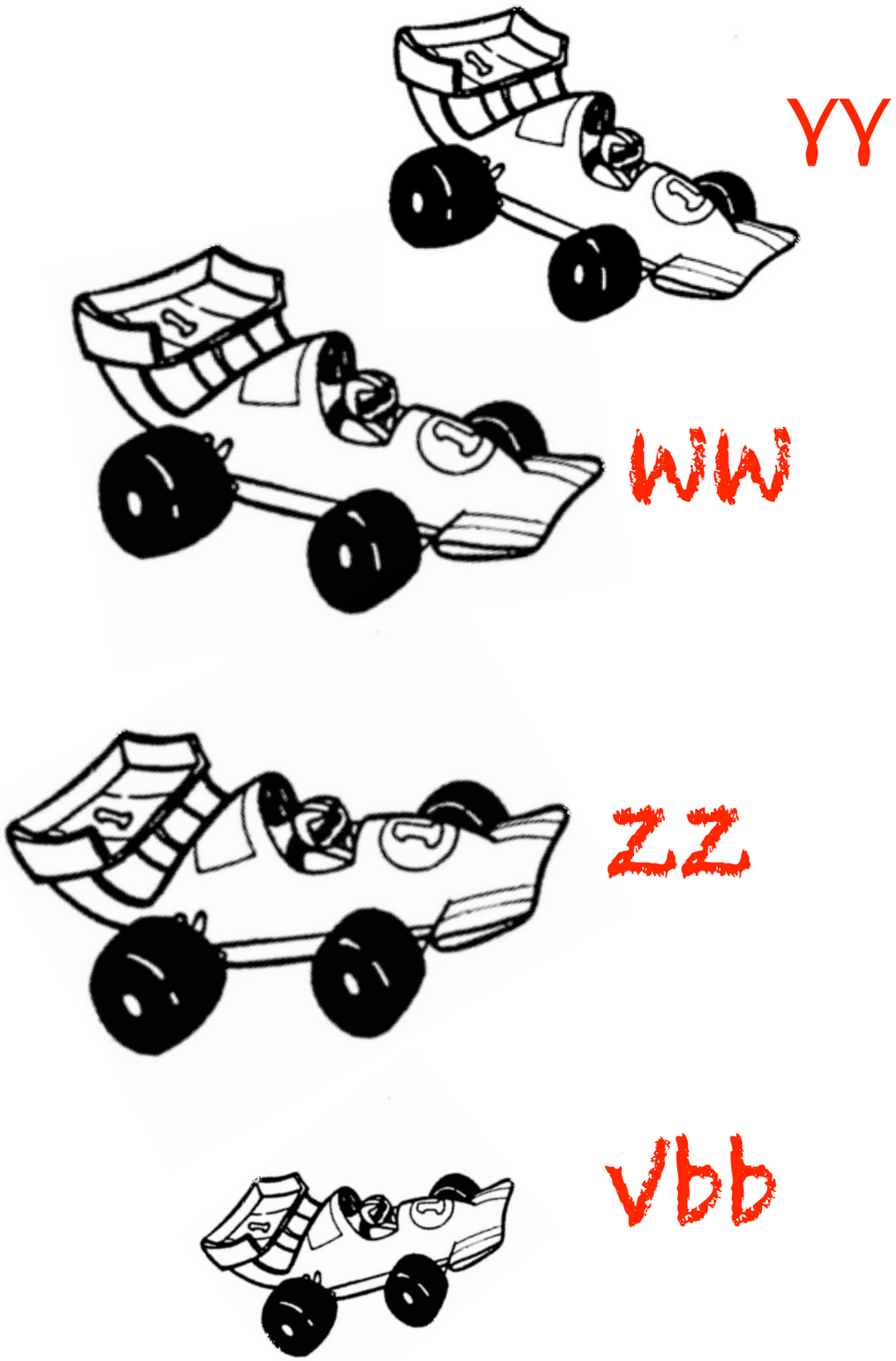
# ATLAS "exclusive": WW->lνqq

- Signature : One and only one high pT isolated lepton accompanied with high $E_T^{miss}$ and a pair of high pT jets compatible with a W boson.
- One can solve for the $p_z^{\nu}$ using $m_{l\nu}=m_Z$ and find $m_{l\nu qq}$
- Shape based analysis ($m_{l\nu qq}$), two bins (+0,+1 jet); Main BG W+jets derived from data
- Anti b-tag against top
- Sensitivity is ~ x4 SM @350-450 GeV



# All for one - Combine forces

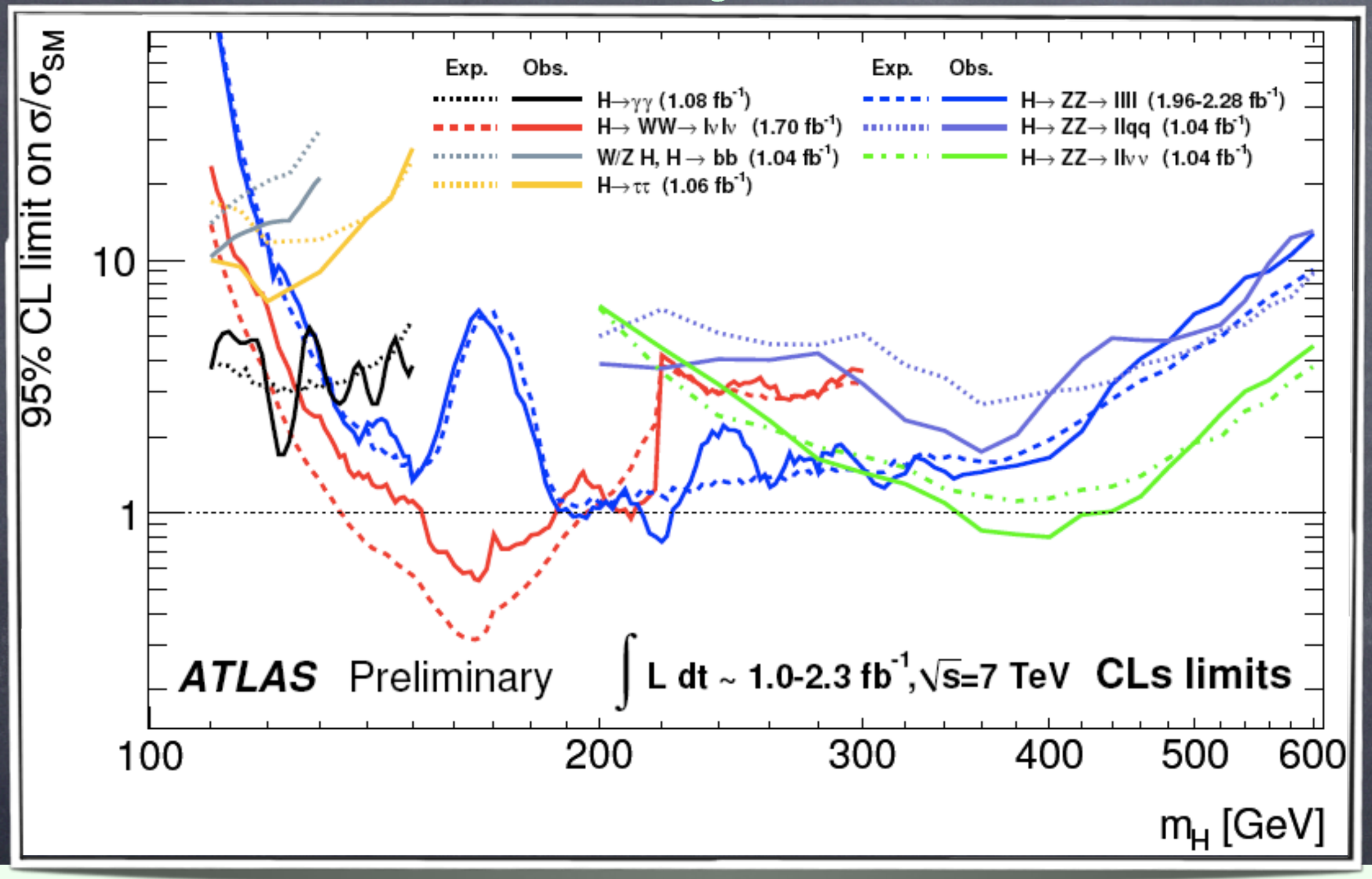



SM car; powered by the Higgs?

# Disclaimer

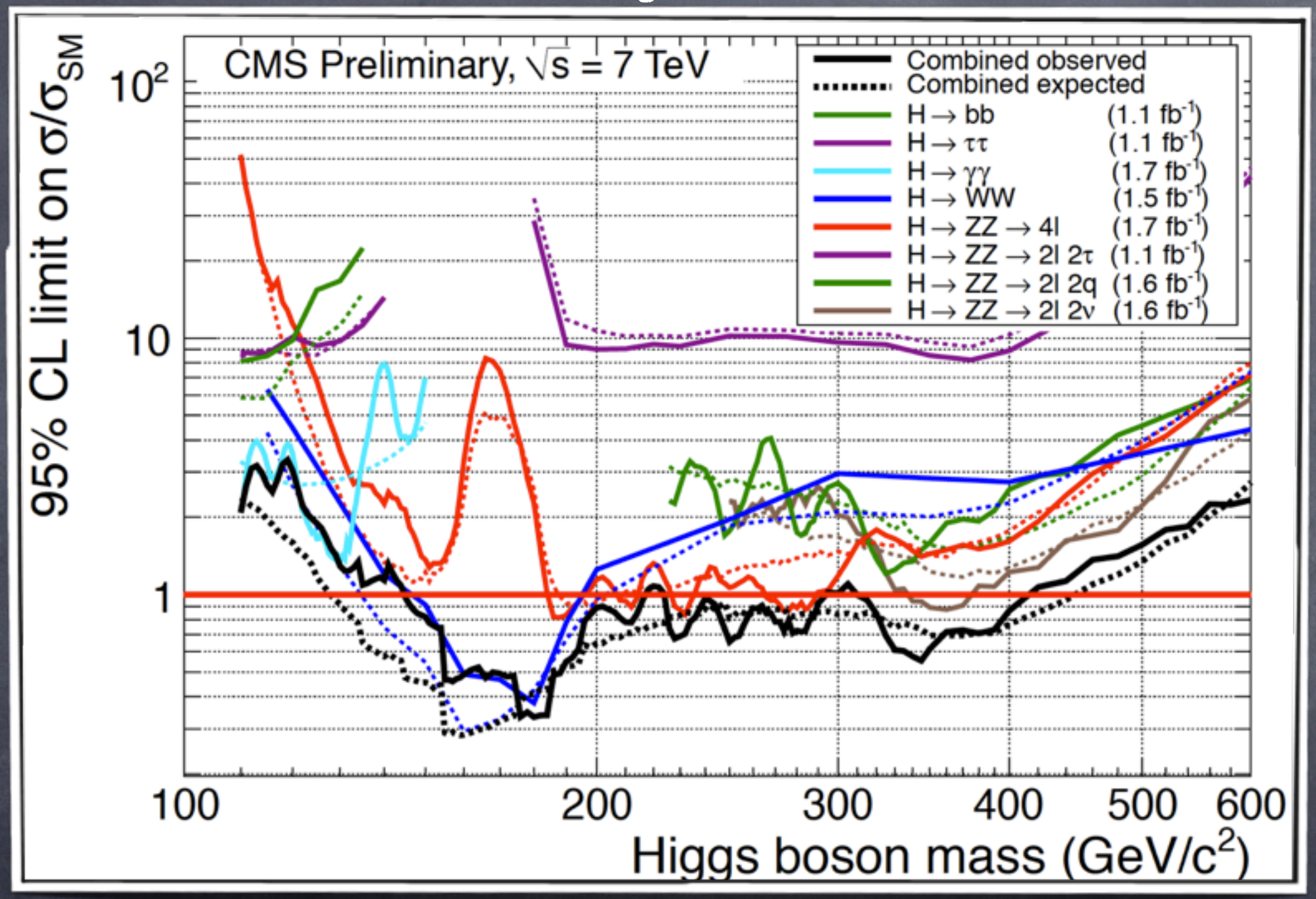
- Correlated uncertaintoes (Jet energy scales, Luminosity etc... taken into account)
- When data driven methods are used, systematics are not correlated
- Theory uncertaintes are carefully taken into account across channels using the recommendation of the LHC cross section group (see talk by R. Tanaka)

# ATLAS ingredients



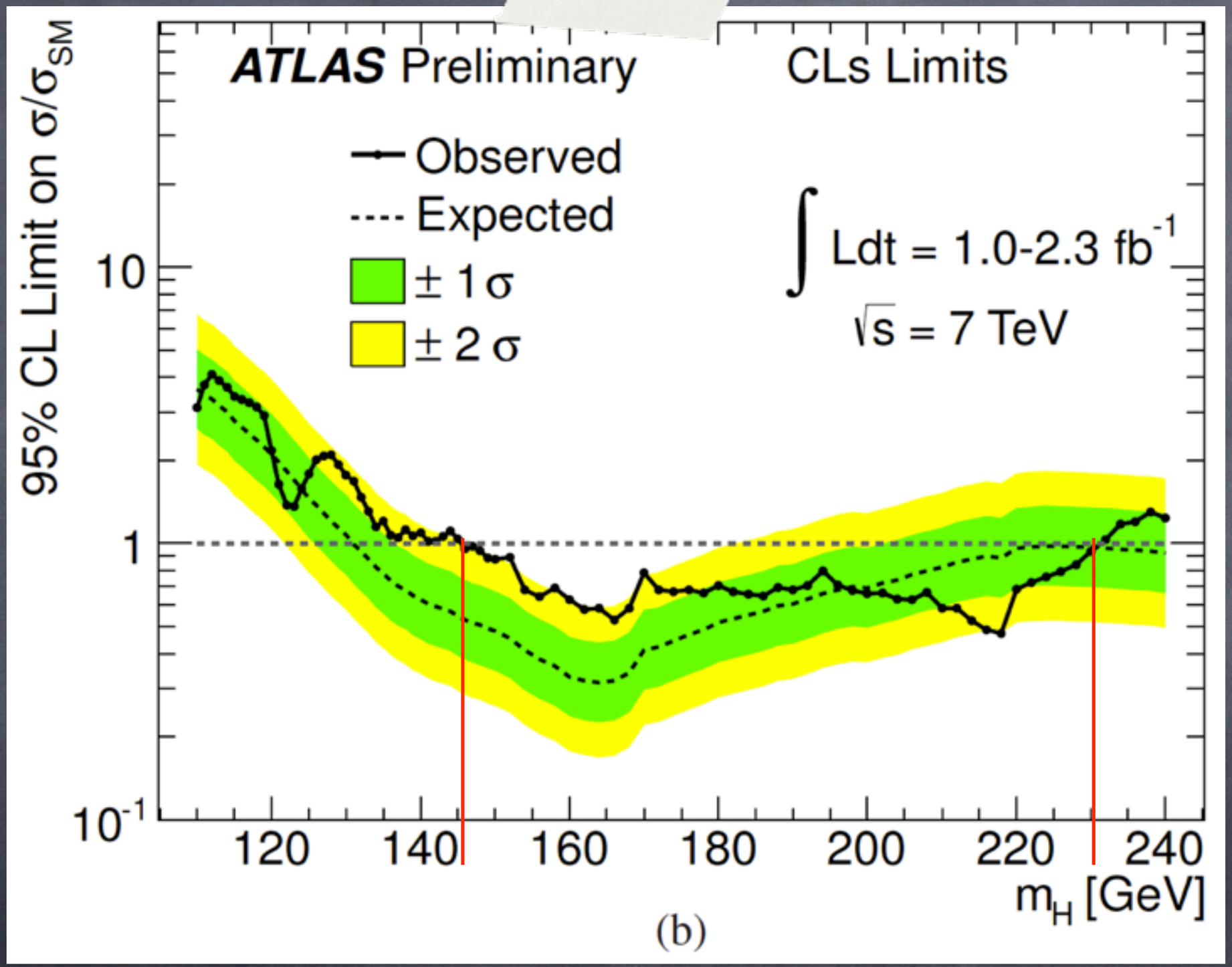

- Limit in low mass completely driven by H->γγ, then lνlν, 4l and llνν

# CMS Ingredients



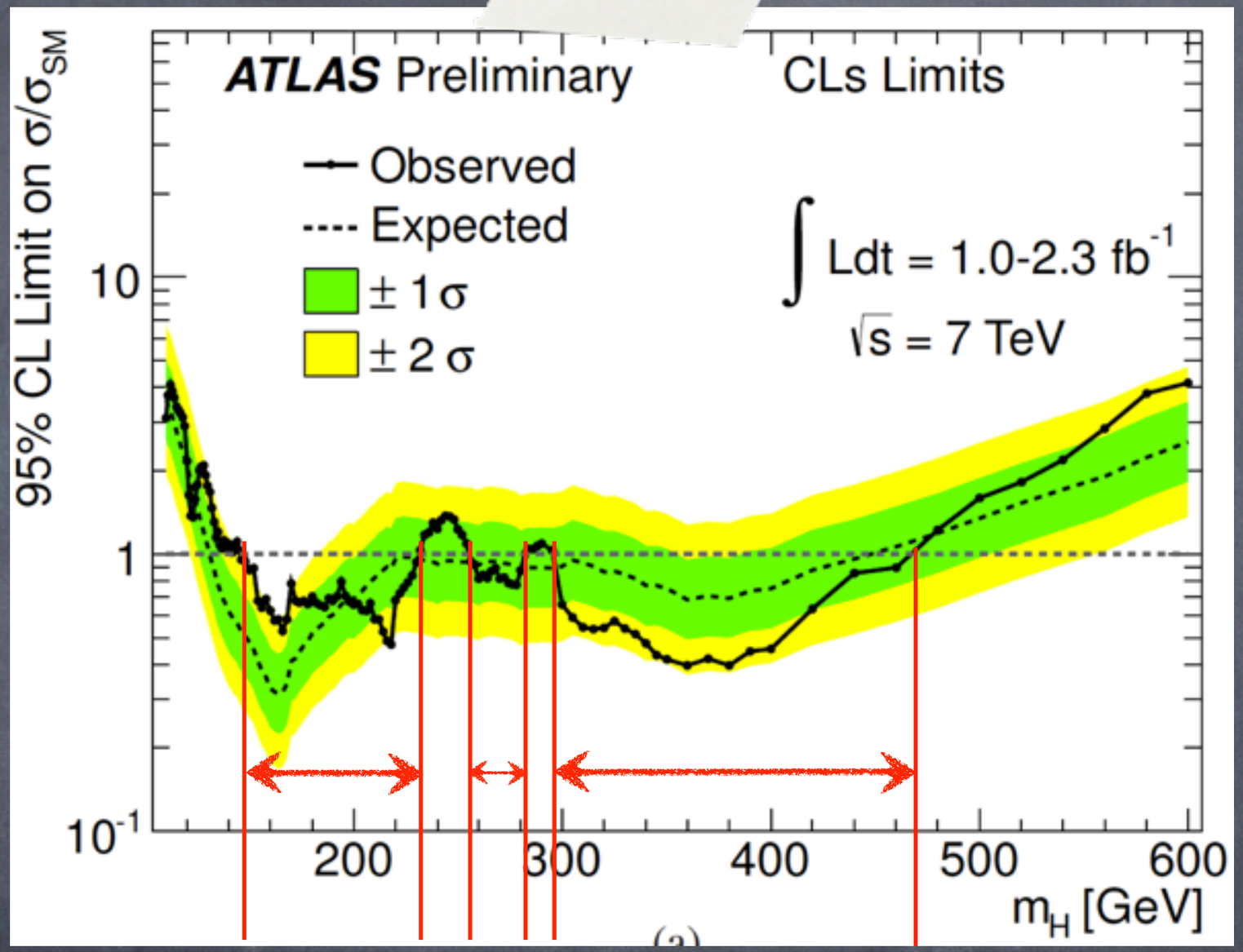

- Limit in low mass completely driven by H->γγ, then lulu, 4l and llνν

# And, ATLAS: first, Low Mass



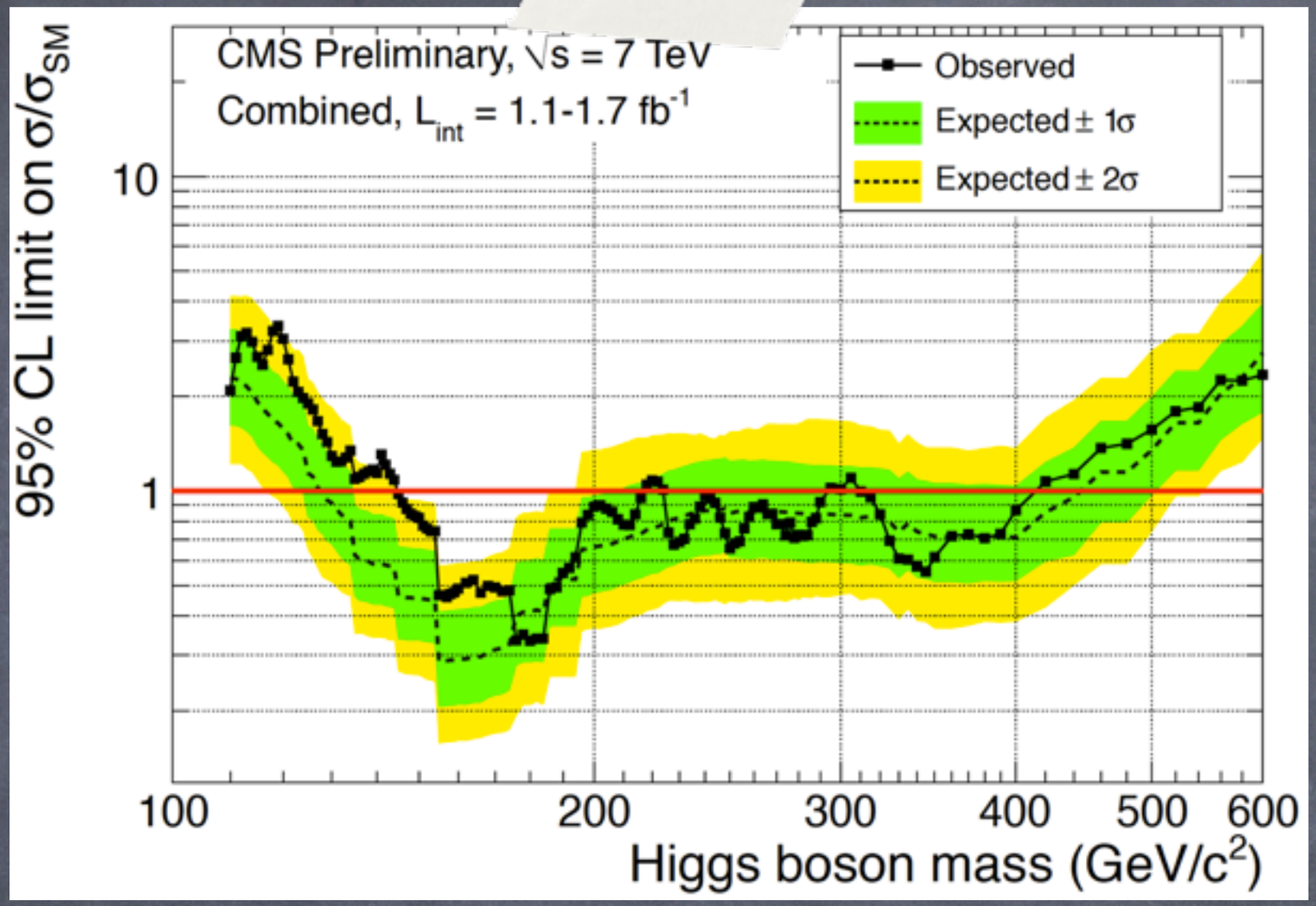

- exp. exclusion:>130, obs. exclusion: 146-232

# And, ATLAS: full range




- exp. exclusion:~130-444
- obs. exclusion: 146-232, 256-282, 296-466

# CMS, Full Range




- exp. exclusion:~130-440
- obs. exclusion: 145-216, 226-288, 310-400

# Local p-values

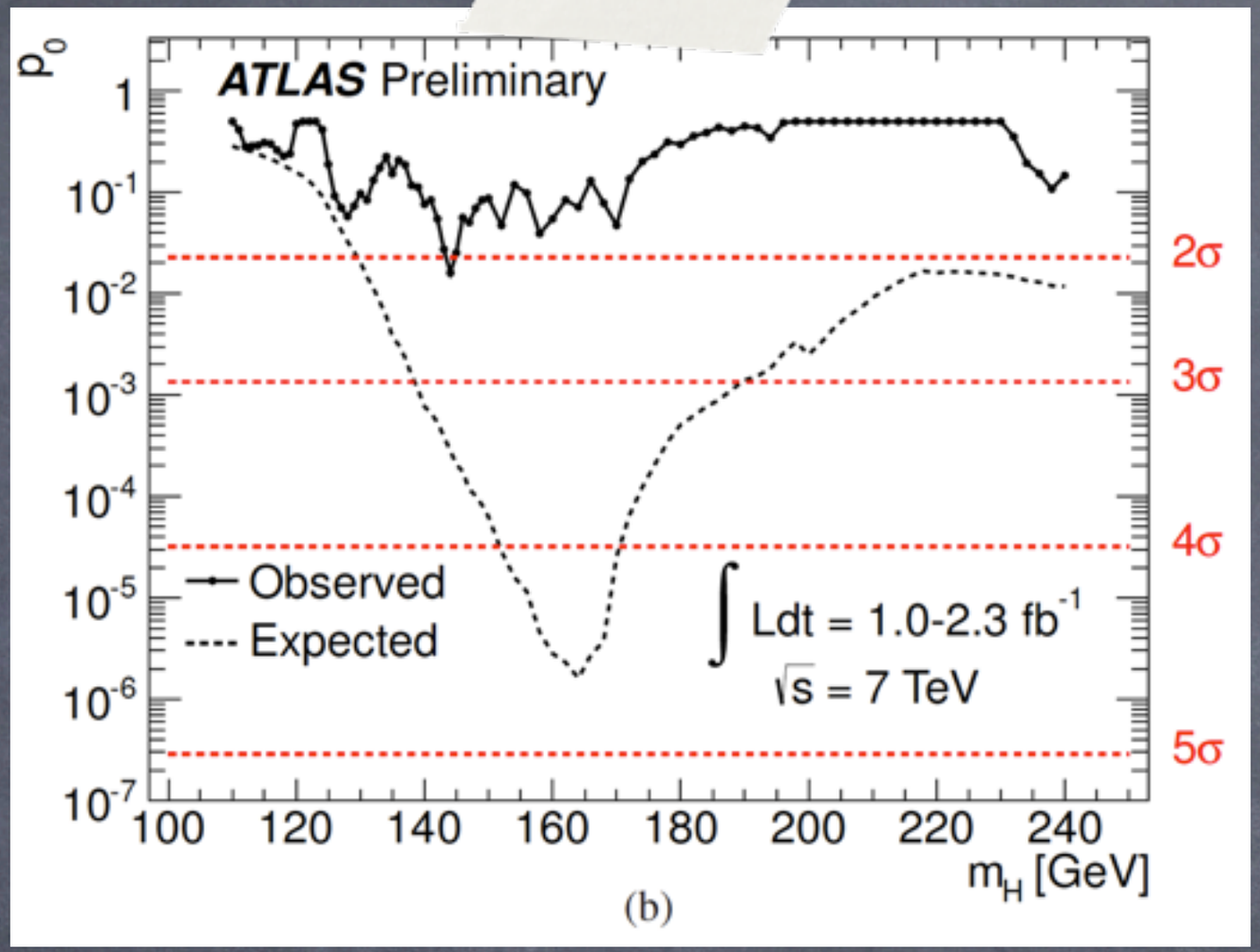
- The local p-value is the probability that the backround only will fluctuate up to the observed local significance ($Z_{max}$) or more.

- An approximate way to calculate the LEE, i.e. the probability to see an excess anywhere in the search mass range above some $Z_{max}$ is calculated via the most famous formula in the world ☺

$$p_{global} = p_{min} + N_0 e^{-Z_{max}^2/2}$$

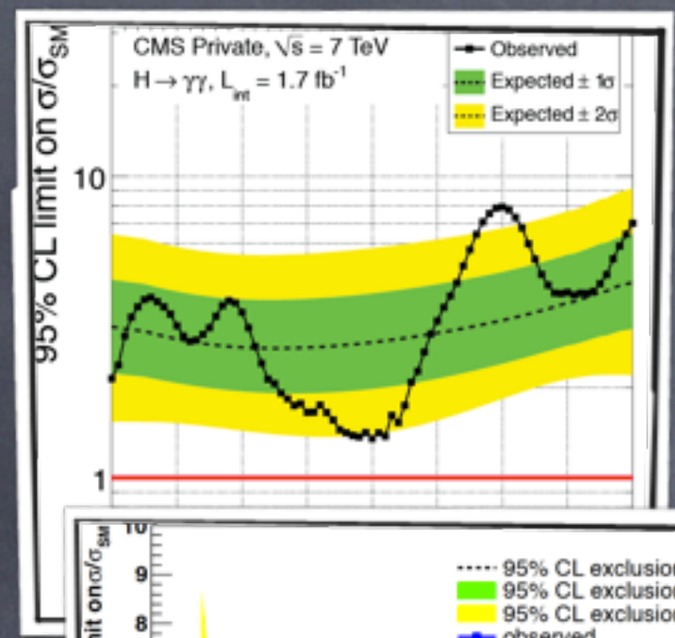
$N_0$ is the average number of upcrossings at Z=0 which is estimated from data, and $Z_{max}$ is the local significance. Formula is asymptotically accurate for increasing $Z_{max}$

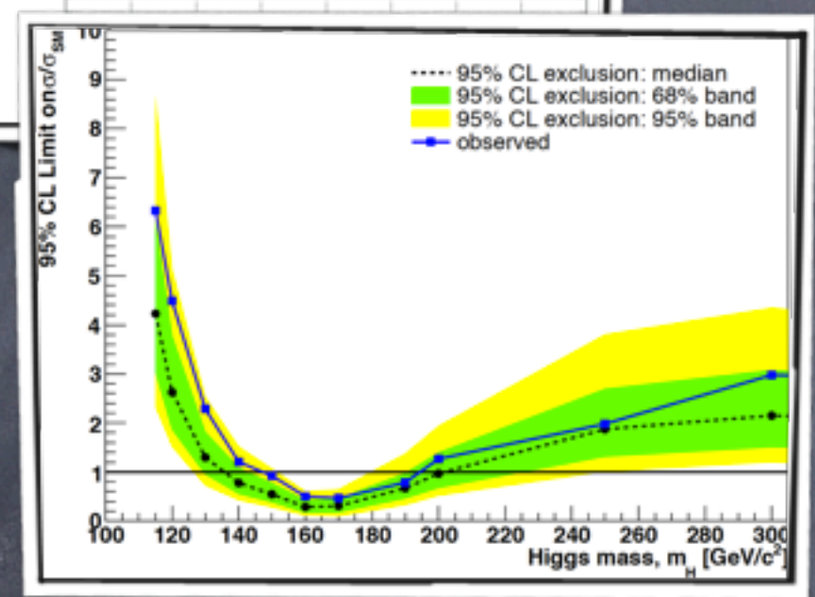
# Discovery?

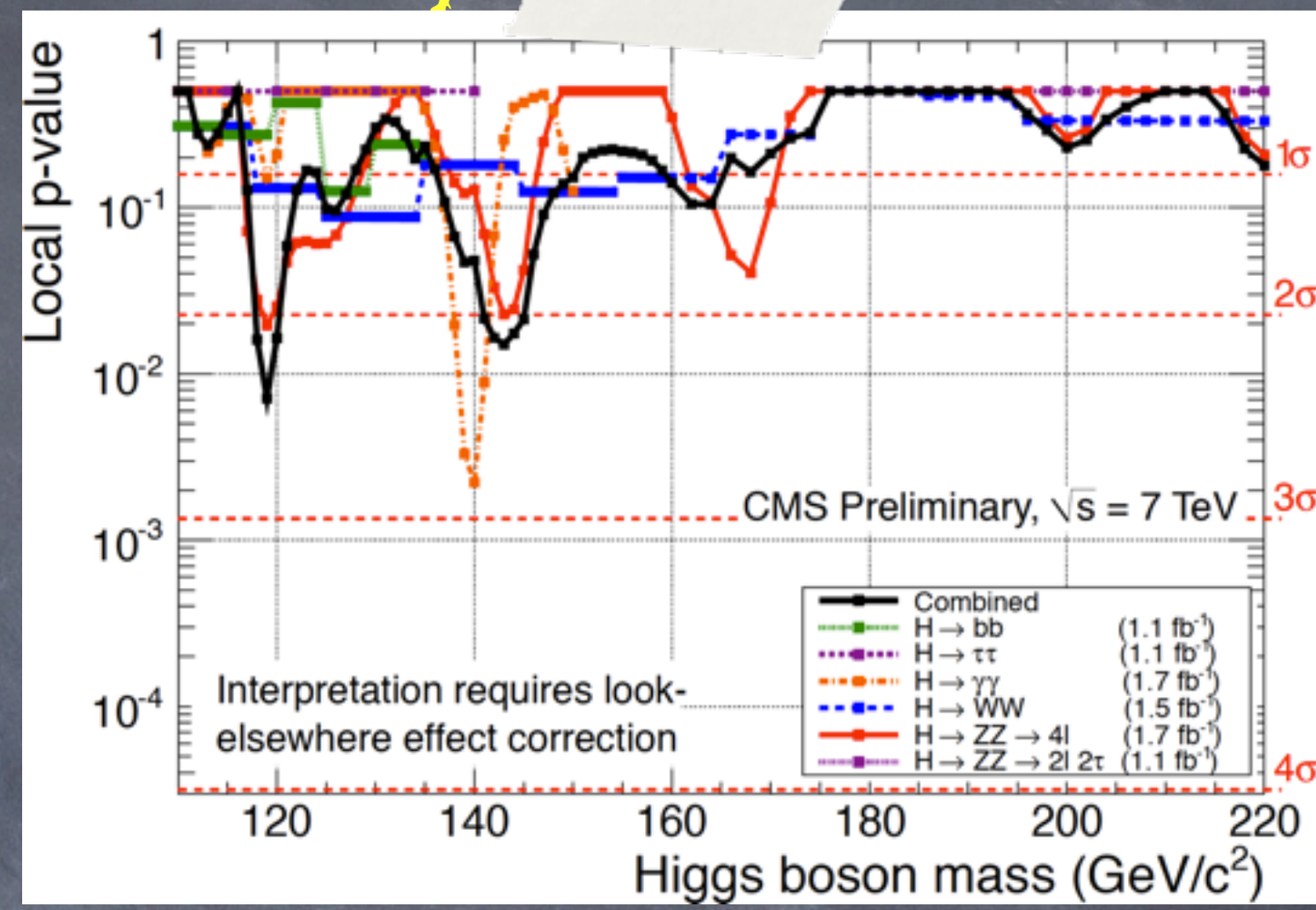



- No incompatibility with the SM is seen in ATLAS.

# Discovery?



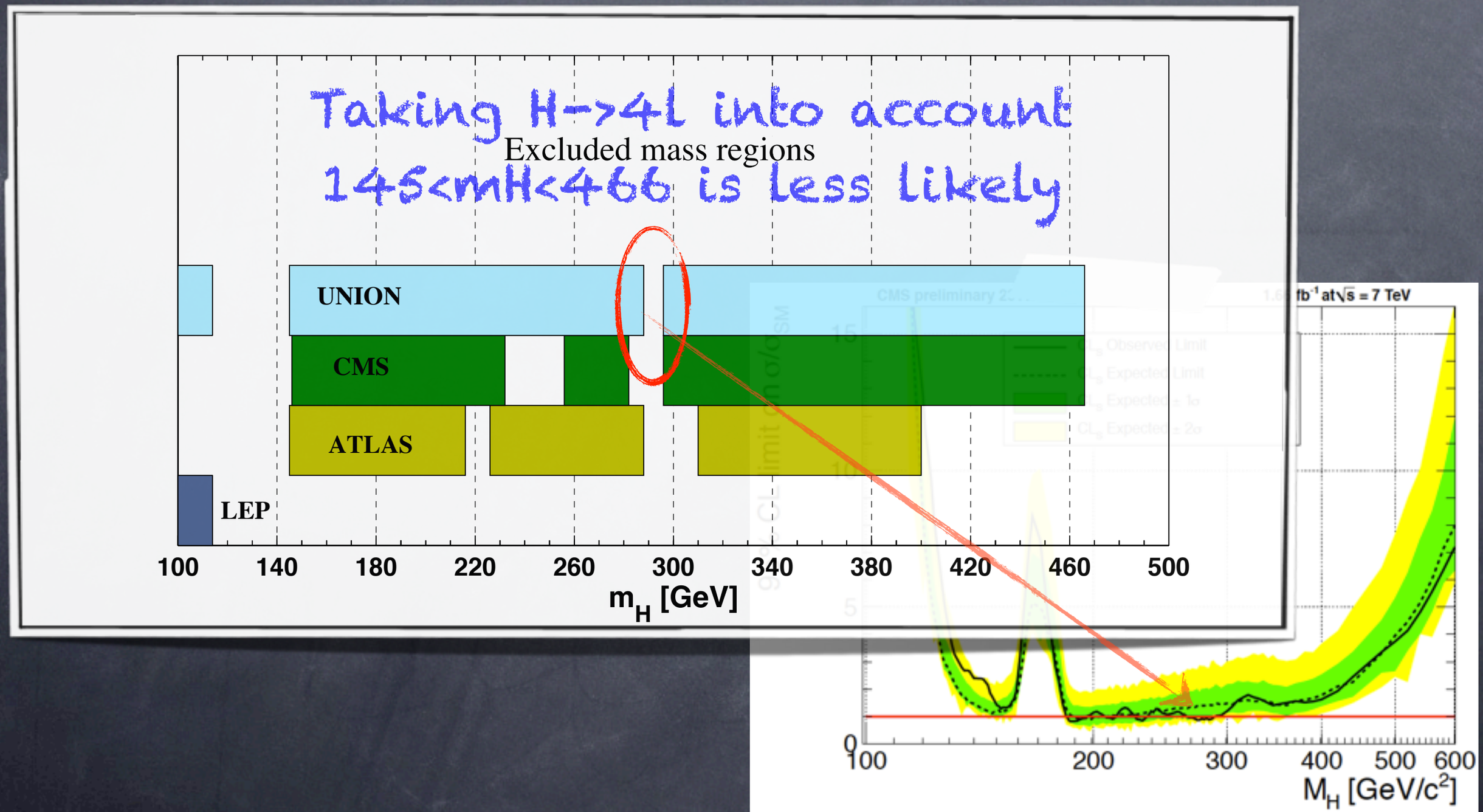




- A local moderate (yet genuine) 2.3σ excess is seen in CMS aroudn 120. The probability to observe such an excess or more anywhere in the mass range is ~40%.
  LEE washes out the excess....
- The excess @ 120 and 160 is incompatible with SM Higgs. (@120 compatible with 0.6xSM)
- There is 2.8σ with H->γγ which is reduced to 1.7σ with the LEE

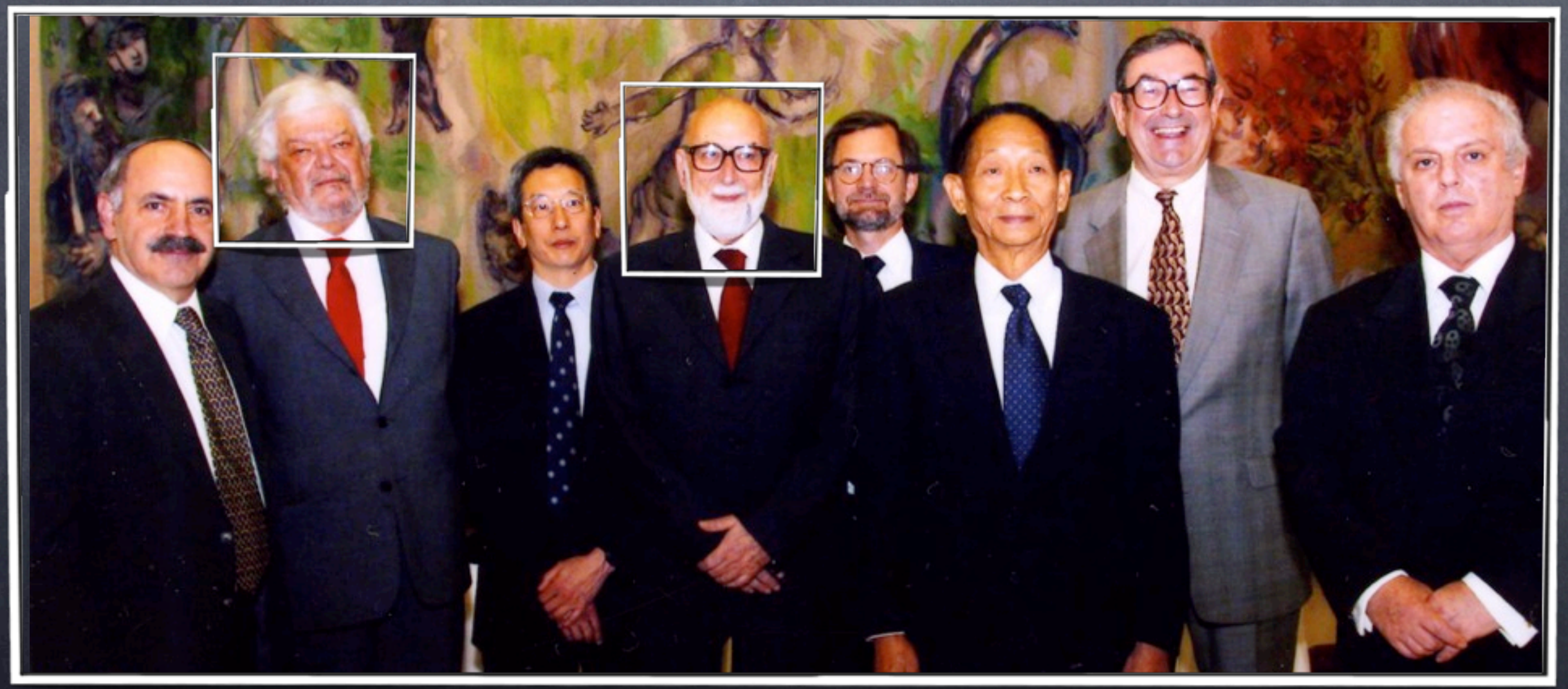
# Summary

- Including the 4l current results, it is unlikely that the SM Higgs is in the range 145<mH<460 GeV



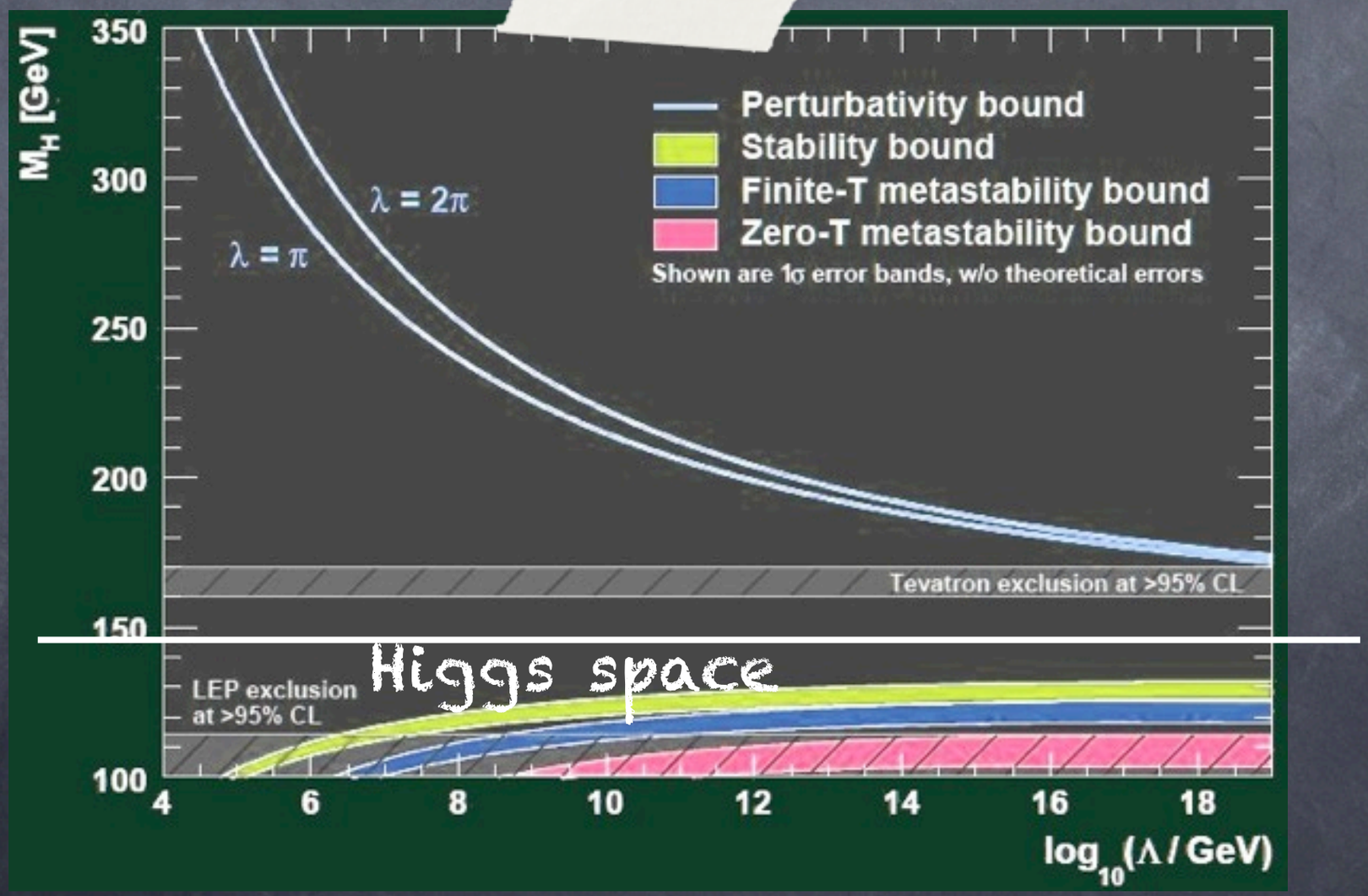
# A Prelude to the Nobel Prize

- The 2004 Wolf prize, awarded by the Wolf Foundation, is often thought to be the most prestigious prize in physics after the Nobel prize (in the pic. Brout & Englert).



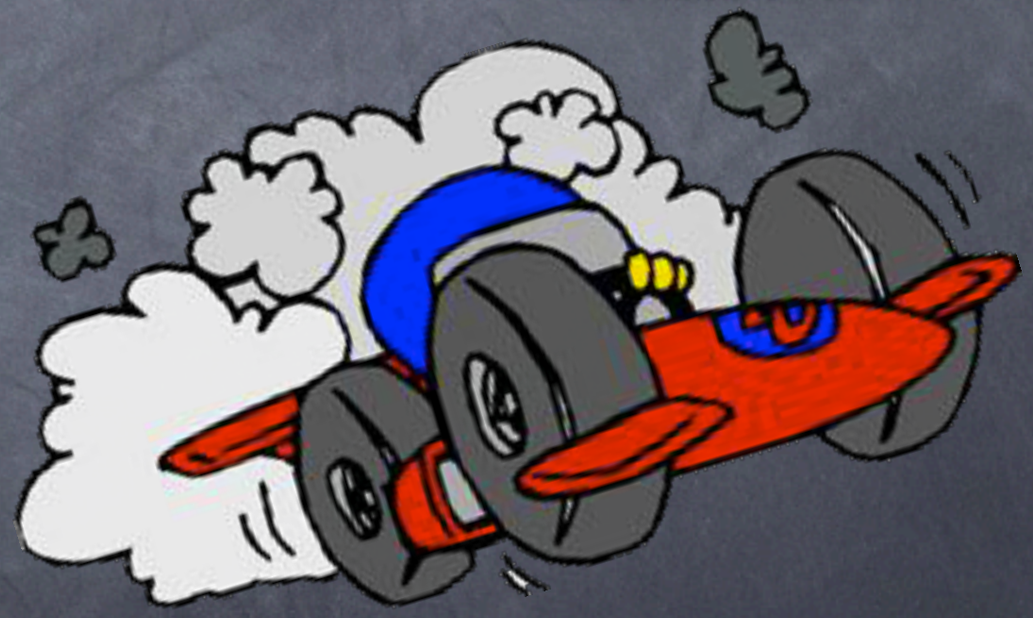
# Nightmare Scenario I: SM Higgs, period.

- Not much living space is left for the Higgs boson
- Yet, if all bounds are well established, the SM Higgs could be EXACTLY where it is supposed and expected to be 130-145 GeV



# Nightmare Scenario II: No Higgs

- Not much living space is left for the Higgs boson
- If there is no engine, how does the SM car drives so smooth and fast?



# 2011-2012 Miraculous Years

- 2011-2012 are the Higgs Miraculous Years
  OR 2011-2012 are the LHC Miraculous Years

- The SM Higgs is probably light mH<145 GeV
  OR we are on our way to discover an MSSM Higgs

- The LHC is approaching a sensitivity to discover a light Higgs, be it SM or (maybe even a bit more likely) MSSM or...

- The "other" less weighted channels (Vbb, Lvqq, ...) get more weight as we fail to discover the SM Higgs boson, keep searching,
  leave no stone unturned!

- I think from any point of view (SM, EXotic, SUSY, Higgs .....) this is the prime time for any High Energy Physicist

- Don't worry be happy ☺

# Backup

# Systematics

- A careful study of systematics was performed in both experiments
- Systematics were taken into account within the limit machinery base on the PL, including correlations across channels with nuisance parameters such as Luminosity and JES etc.....

| Channel | | Systematics |
|---|---|---|
| $\gamma\gamma$ | | id eff ~ 11% |
| $\tau\tau$ | | JES ~10%, $\tau$ES~15%(ATLAS); Lumi,$\tau$id~6%(CMS) |
| WH | | btag eff ~10-16% (ATLAS);<br>JER~10% (CMS) |
| ZH | | btag eff ~10-16% (ATLAS);<br>JER~10% (CMS) |
| WW<br>($l\nu l\nu$) | 0-jet | JES~6 (ATLAS)<br>WW,W+jets norn~10-30% (CMS) |
| | 1-jet | JES~6 (ATLAS)<br>WW,W+jets norn~10-30% (CMS) |
| | VBF* | WW,W+jets norn~10-30% (CMS) |
| WW**<br>($l\nu qq$) | 0-jet | JES~18% |
| | 1-jet | JES~18% |
| ZZ ($llll$) | | L=3.7-4.5%, eid~2-3% |
| ZZ ($ll\nu\nu$) | | MET~6.6%, JES~6% (ATLAS)<br>Z+jets norm~19-57% (CMS) |
| ZZ ($llqq$) | | JES~10% (ATLAS)<br>btag~13-18% e reco~4.5% |
| ZZ ($ll\tau\tau$) * | | Z+jets estimation ~30% |

* CMS only / ** ATLAS only

# Channels Nano Review

Marumi Kado

| Channel | | btag (veto) | Jets | MET (GeV) | Shape | Mass Range (GeV/$c^2$) | Main backgrounds |
|---|---|---|---|---|---|---|---|
| gg | | | | | $M_{gg}$ | 110-150 | gg (from sidebands) |
| tt | | ✓ | ✓ | | $M_{tt}$ | 110-140 | Z from data driven methods |
| WH | | ✓ | 2 | | $M_{bb}$ | 110-130 | Top (3j - high $M_{bb}$) and W+jets (low $M_{bb}$) |
| ZH | | ✓ | 2 | | $M_{bb}$ | 110-130 | Z+jets (low $M_{bb}$) |
| WW (lnln) | 0-jet | | 0 | >30 | | 110-600 | WW (control region $M_{ll}$) |
| | 1-jet | veto | 1 | >30 | | 110-600 | Top (from reverse btag) and WW ($M_{ll}$ CR) |
| | VBF* | veto | 2 | >30 | | 110-600 | Top from CS |
| WW** (lnqq) | 0-jet | | 0 | >30 | $M_{WW}$ | 200-600 | W+jets (sidebands) |
| | 1-jet | veto | 1 | >30 | $M_{WW}$ | 200-600 | W+jets (sidebands) |
| ZZ (llll) | | IP | | | $M_{4l}$ | 110-600 | ZZ (from MC), Z+jets and top (CR) |
| ZZ (llnn) | | ✓ | | >30 | $M_T$ | 200-600 | VV(from MC) and top (MC and checks) |
| ZZ (llqq) | | ✓ | 2 | <50 | $M_{llqq}$ | 200-600 | Z+jets (from MC) and top (from MC) |
| ZZ (lltt) * | | | ✓ | | $M_{lltt}$ | 200-400 | Z+jets (CR) ZZ normalization (from data) |

* CMS only / ** ATLAS only