LHC Higgs Discovery Potential

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- Quick resume of SM Higgs
- The LHC potential
- Comparison with the Tevatron

Disclaimer

The following presentation assumes the world consists of the Standard Model, no more no less
This is not the view of the author.

Other than that, these transparencies represent the authors views and not those of ATLAS, RAL, STFC or even Gavin Davies.

LHC studies are at 14TeV unless otherwise stated

TeV V LHC?

- Who do we believe?

"For Higgs search, I don't expect LHC will be competitive"

- A. Golutvin

"The TeVatron...its a winding down phase"

- J. Campbell

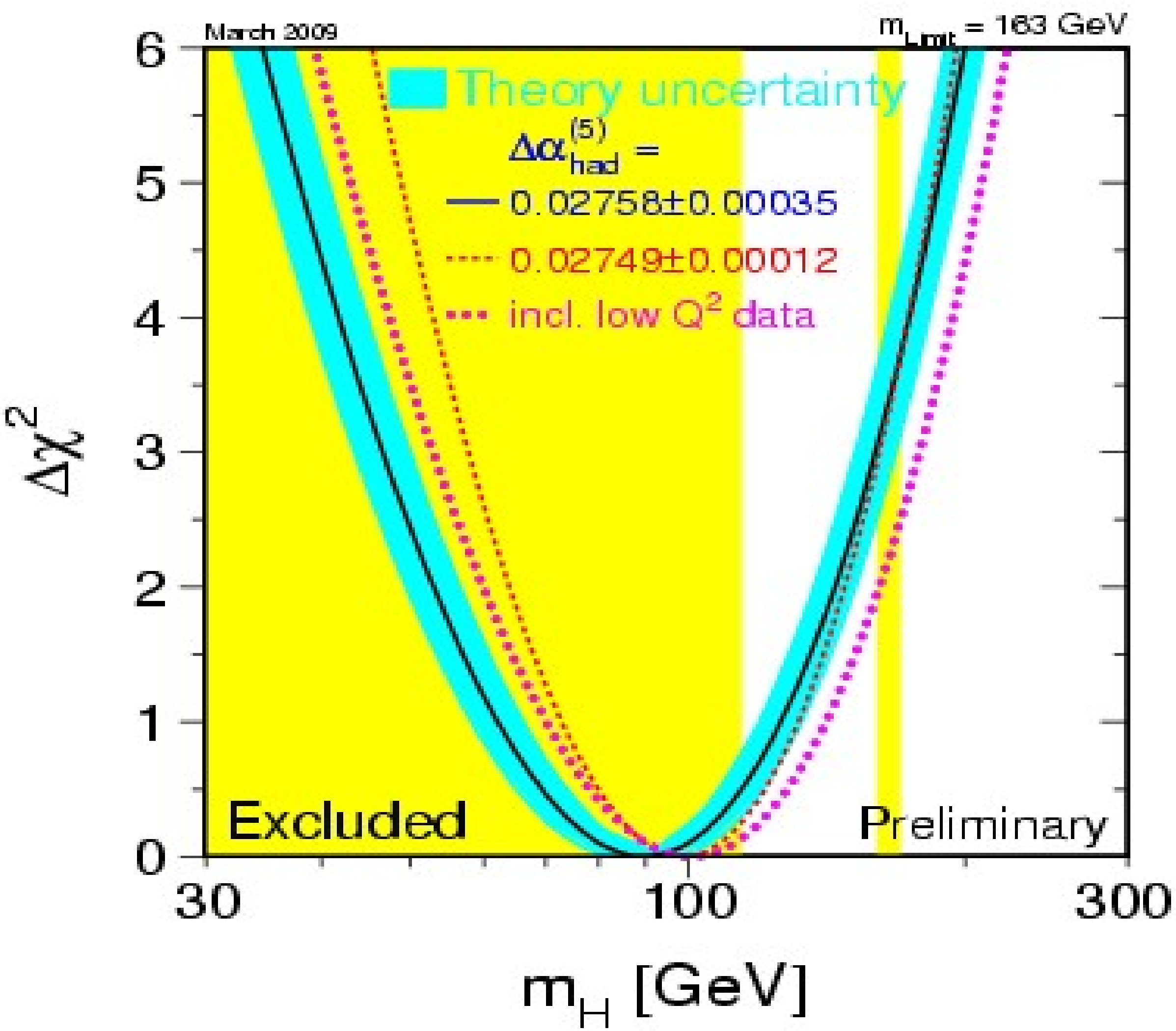
ps: Apologies for mis-representing the above quotations

Why believe in a light Higgs?

- Electroweak fit (Z properties, W and top mass) give at 95%:

  M_H<163GeV/c^2

  M_H<191GeV/c^2
  (with search bound)*
- Will drop with new D0 m_W

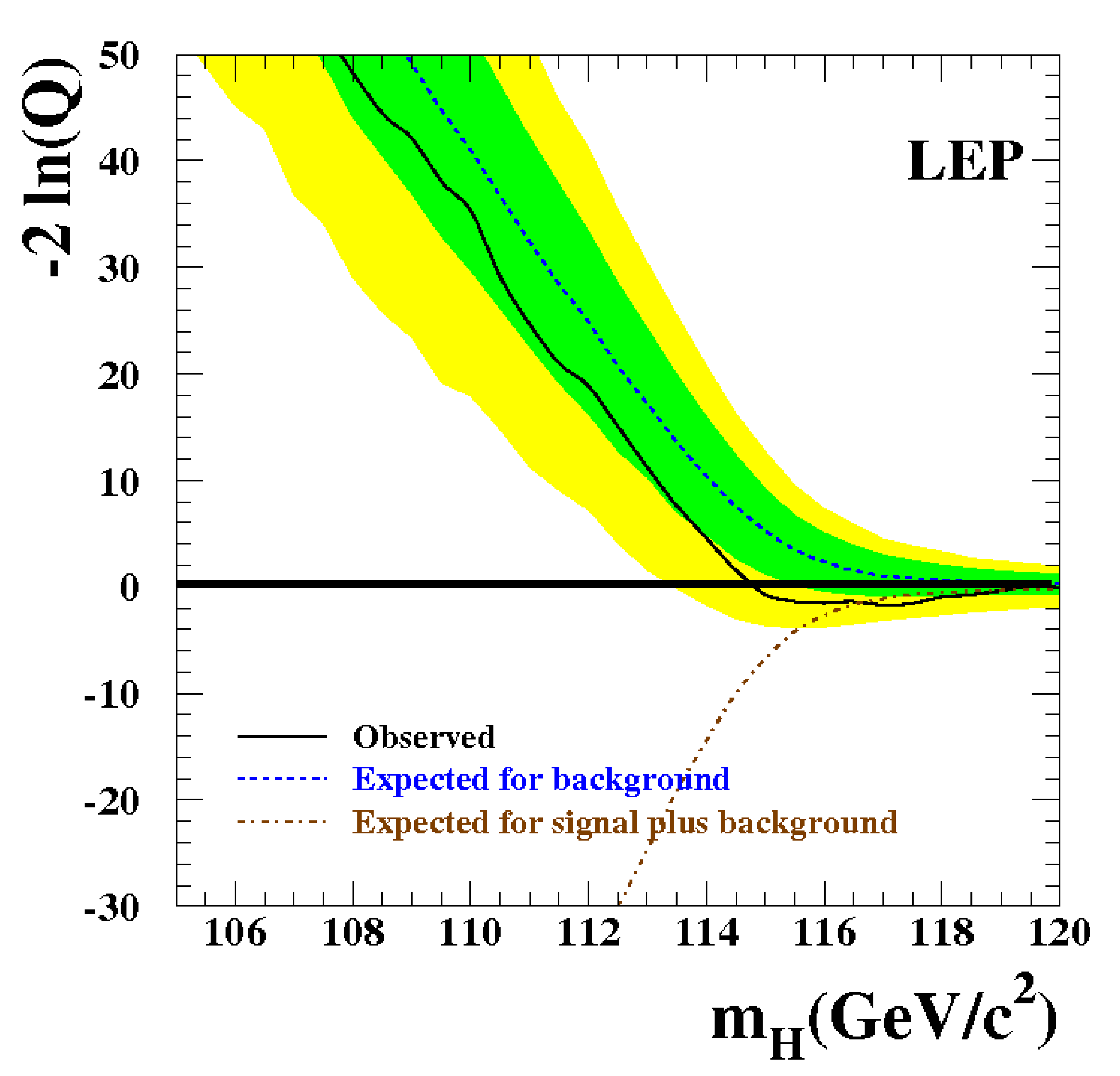


The LEP SM Higgs limit

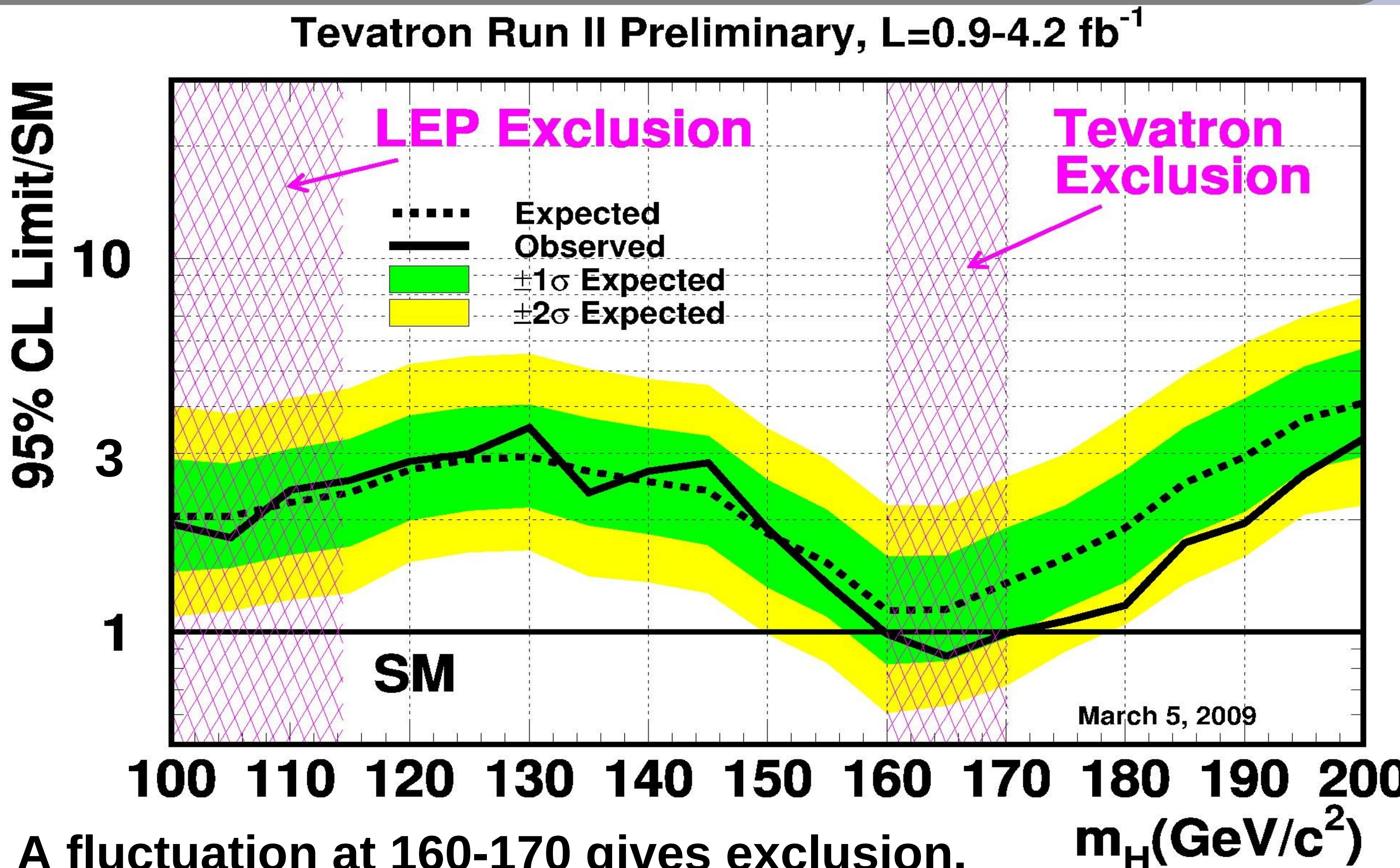
- LEP result:

  M_H>114.4GeV
  (95%CL)

  Excess at 115GeV would happen in 9% cases without signal.
  (But signal remains the best fit)

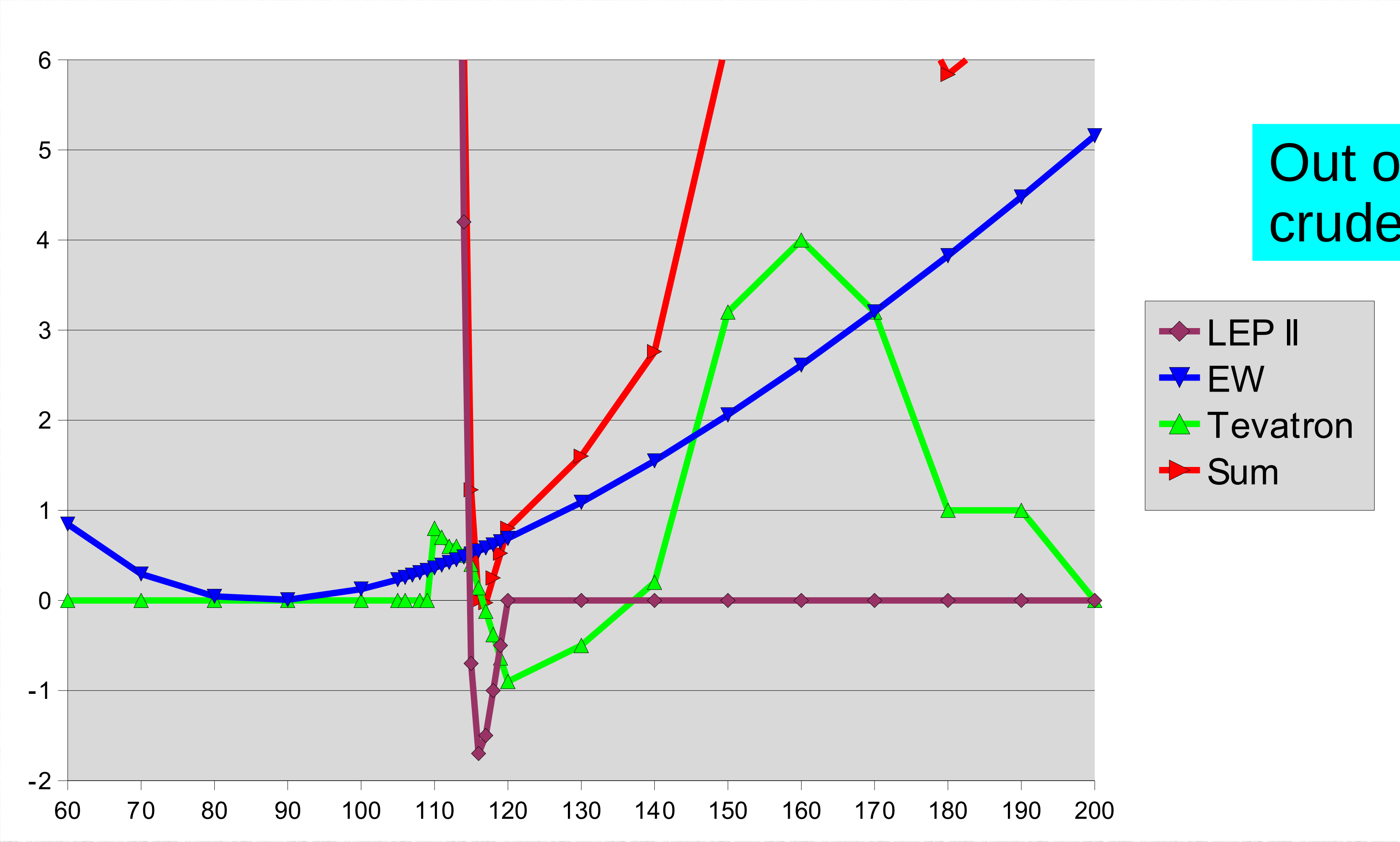


Tevatron Higgs Combination



A fluctuation at 160-170 gives exclusion.

Add likelihoods from EW/LEP/TeV

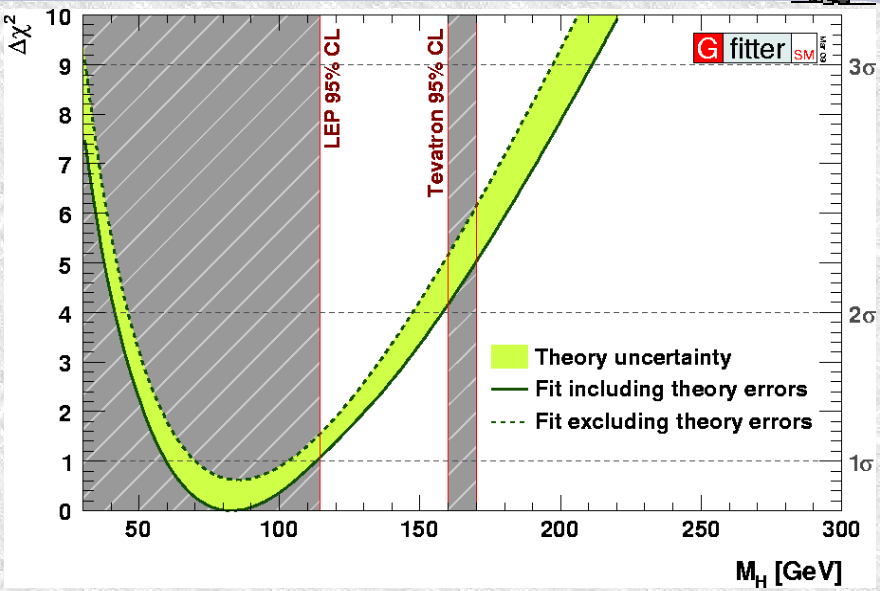


Out of date, crude

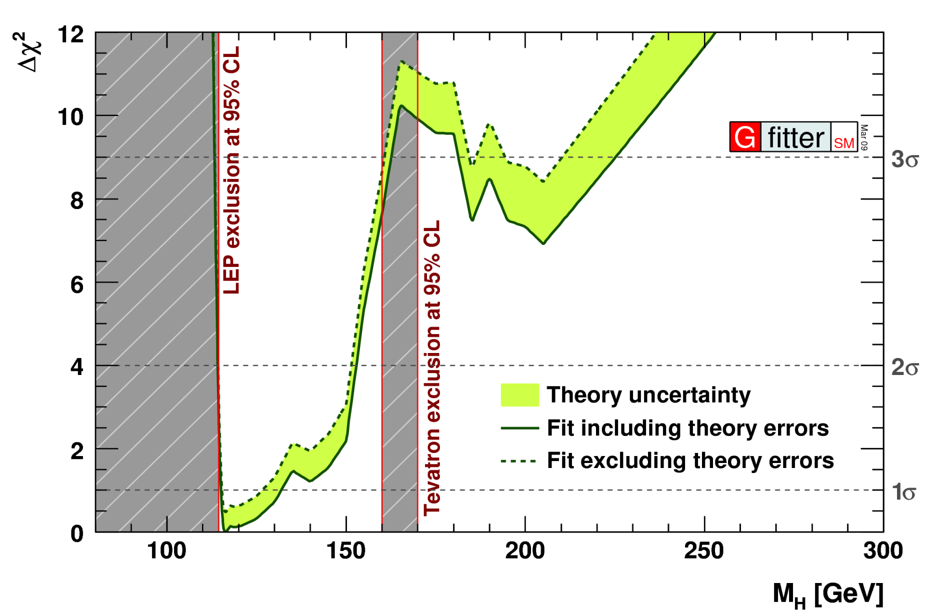
- Higgs mass 115 to 140GeV

Electroweak fit: M_H

- Reproduce EW fit
- But also include search results
  - This is not done correctly
  - Discussion ongoing
- Upper limit ~150 at 95% is conservative.



In any case, Ed Witten thinks it weighs 115GeV, so we don't need to question that.



Coming ~~soon~~: The LHC

- The 14TeV pp energy raises the Higgs cross section
  - Factor 100 c/f 2TeV Tevatron
- Designed for 10^{34} luminosity
  - c/f 3 10^{32} currently at Tevatron
- Decades of preparation continue

Beam – Chamonix Baseline

- 4 TeV 'on the way' to 5TeV
  - No higher in 2010
- Physics at 5TeV on 5TeV
- Starts with low number of bunches, low intensity
  - Increase slowly 1, 4, 12, 43, 156...
- Estimated Integrated luminosity
  - 100pb^{-1} in first 100 days
  - 200pb^{-1} in second 100 days
- End of 2010 run: a month of heavy ions

LHC Possible runs?

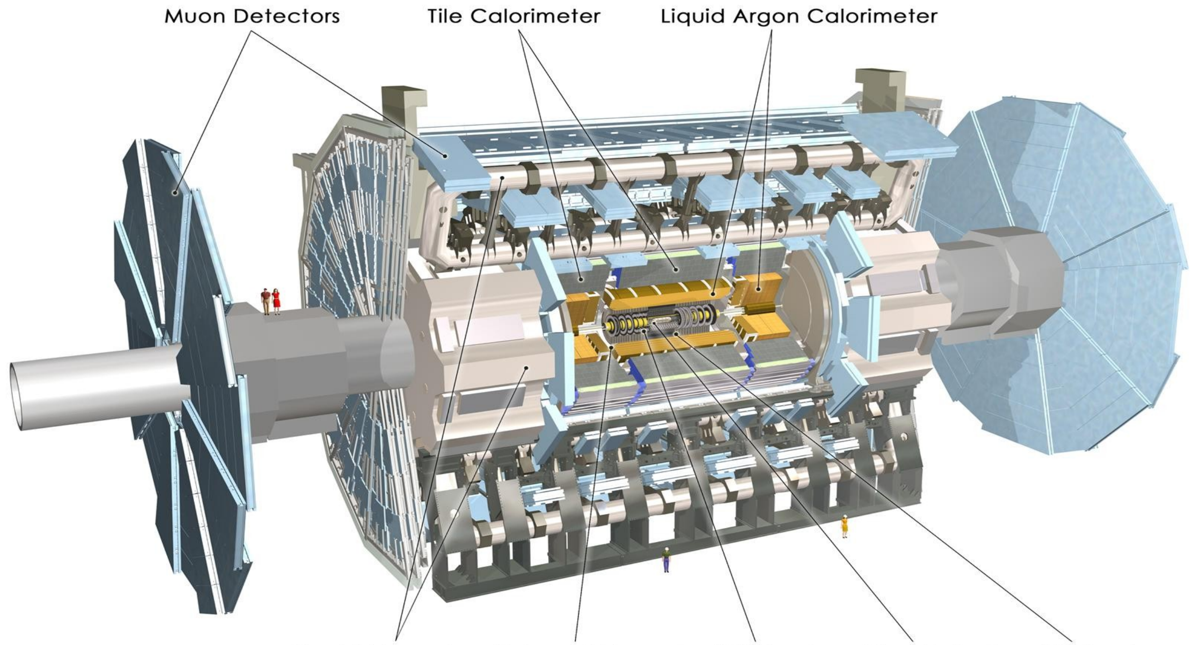
- Don't shoot me...just random guesses

Year	Energy TeV	Luminosity	Luminosity, fb^{-1}	
			Per year	Total
2009-10	10	Up to 10^{32}	0.2	0.2
2011	12	10^{33}	8	8.2
2012	14	10^{33}	8	16.2
2013-2015	14	10^{34}	80	258
2018+ SLHC	14	10^{35}	800	1058

- $30fb^{-1}$ often used: Nominal first 3 years

General Purpose Detectors ATLAS & CMS

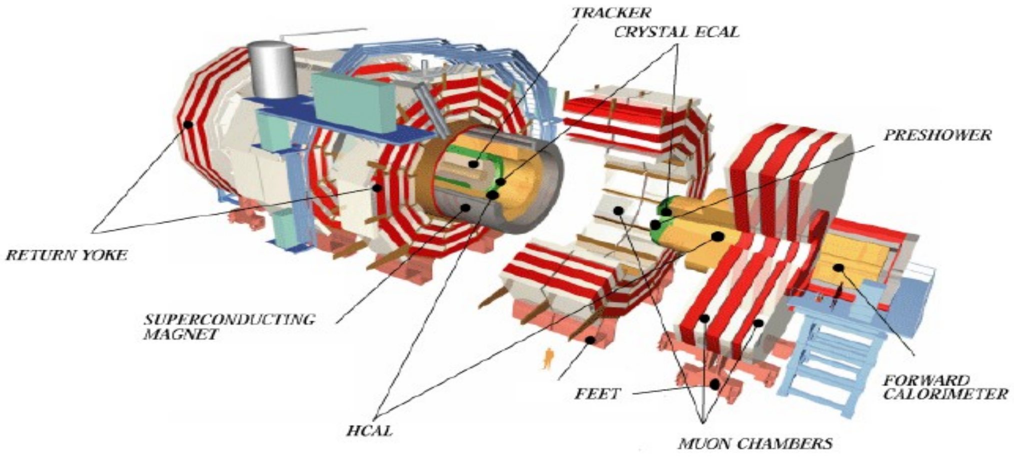
General Purpose Detectors



CMS

The CMS Experiment

ATLAS



Detector Comparison

	ATLAS	CMS
Magnetic field	2 T solenoid + toroid (0.5 T barrel 1 T end-cap)	4 T solenoid + return yoke
Tracker	Si pixels, strips + TRT $\sigma/p_T \approx 5\text{x}10^{-4}p_T + 0.01$	Si pixels, strips $\sigma/p_T \approx 1.5\text{x}10^{-4}p_T + 0.005$
EM Calorimeter	Pb+LAr $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	PbWO4 crystals $\sigma/E \approx 2\text{-}5\%/\sqrt{E} + 0.005$
Hadronic Calorimeter	Fe+scint. / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Cu+scintillator (5.8λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	σ/pT ≈ 2% @ 50GeV to 10% @ 1TeV (ID+MS)	σ/pT ≈ 1% @ 50GeV to 5% @ 1TeV (ID+MS)
Trigger	L1 + RoI-based HLT (L2+EF)	L1+HLT (L2 + L3)

For details see:

G. Aad et al (ATLAS Collaboration) J. Instrum. 3. s08003 (2008)
S.Chatrchysn (CMS Collaboration) J. Instrum. 3. s08004 (2008)

Rates?

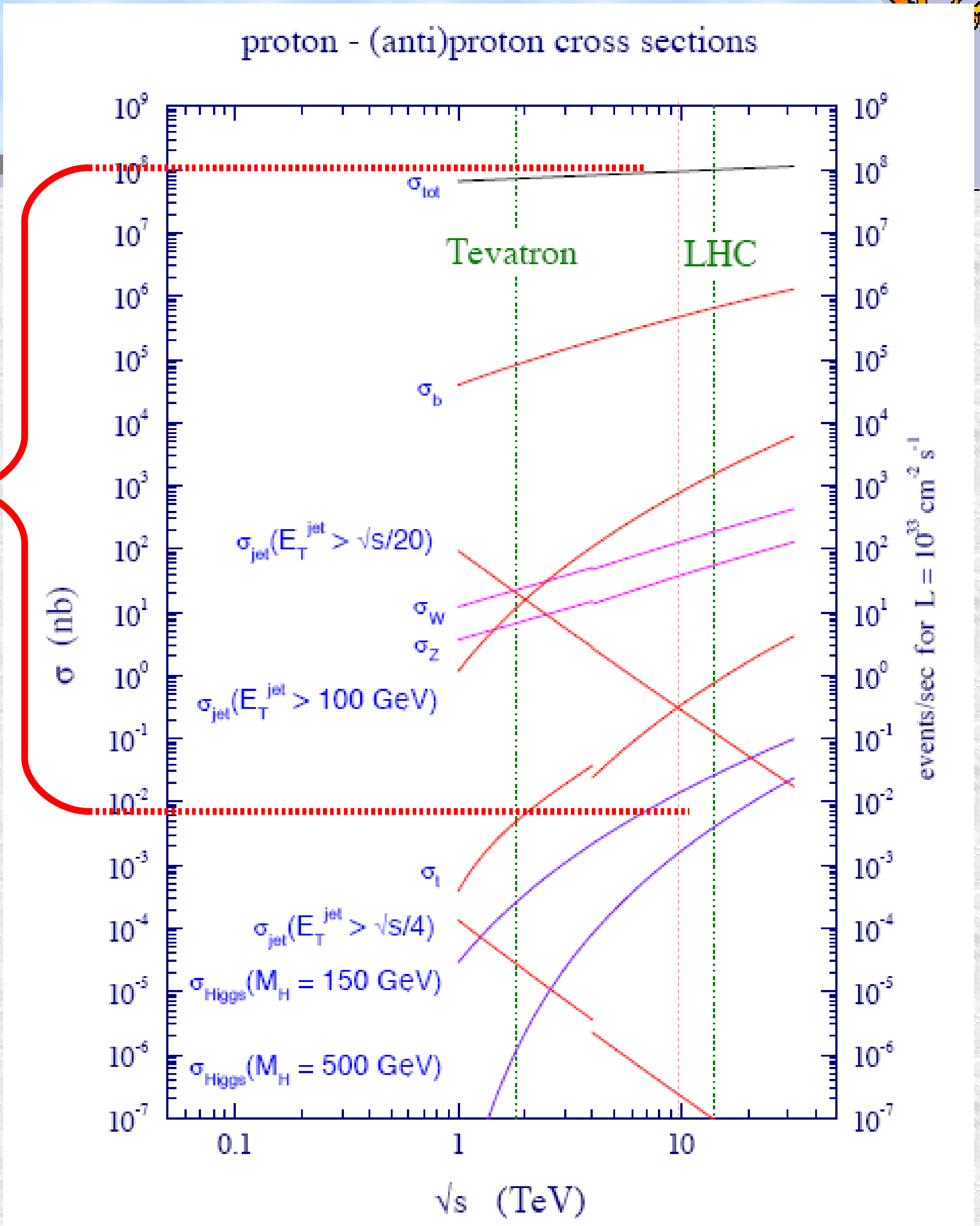
- LHC backgrounds!

Every event at a lepton collider is physics; every event at a hadron collider is background

Sam Ting

10^{10}

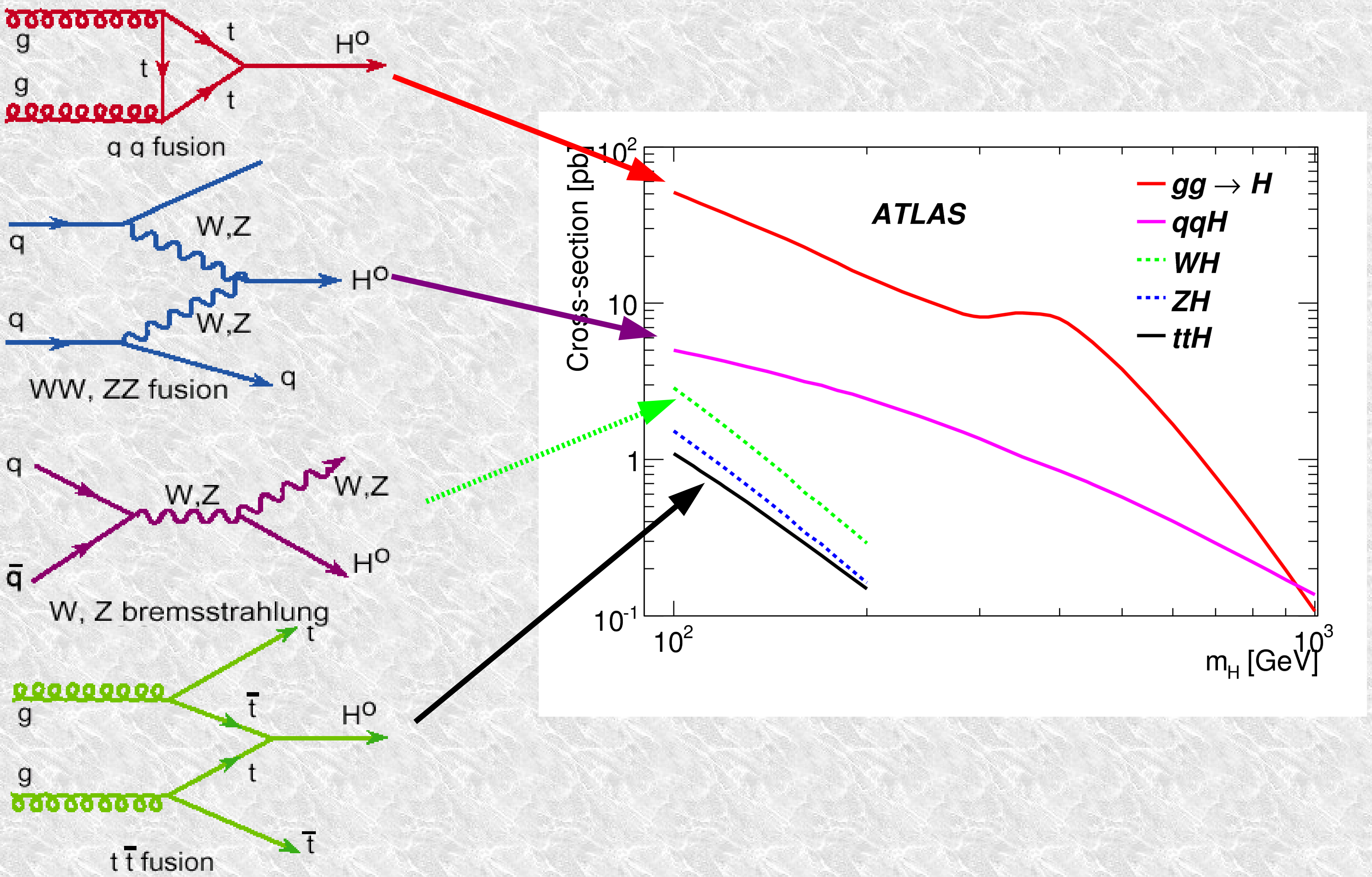
- σ_{Higgs} ~10^{2-3} x Tevatron



Higgs relative rates

- Generally Higgs rates 100 x TeVatron
- Total background roughly constant
- So 200pb^{-1} at LHC is much better than 20fb^{-1} at TeVatron, right?
- Wrong
  - *Relevant* backgrounds often rise faster than signal
  - Different channels become relevant

Higgs production



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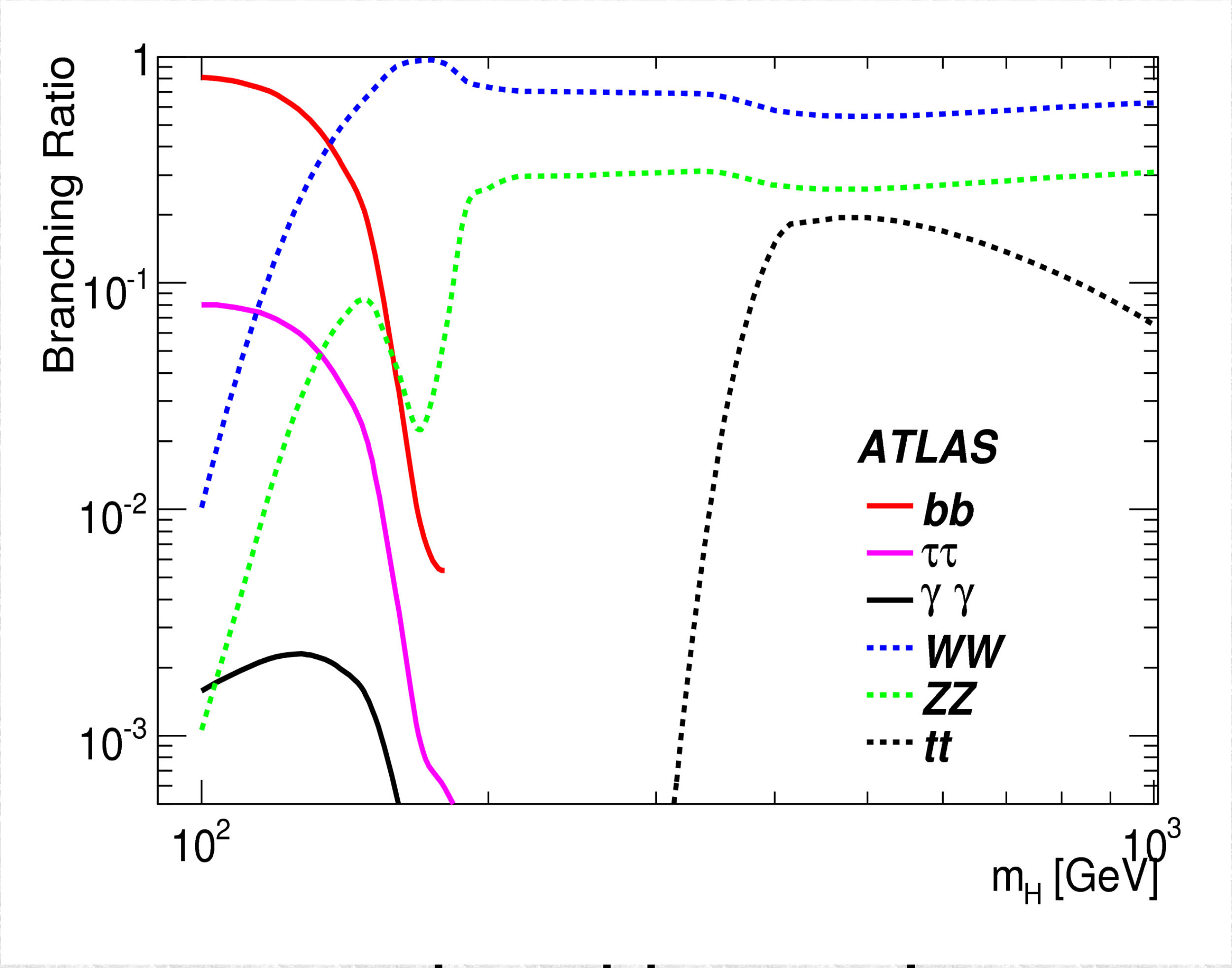
Higgs Decay

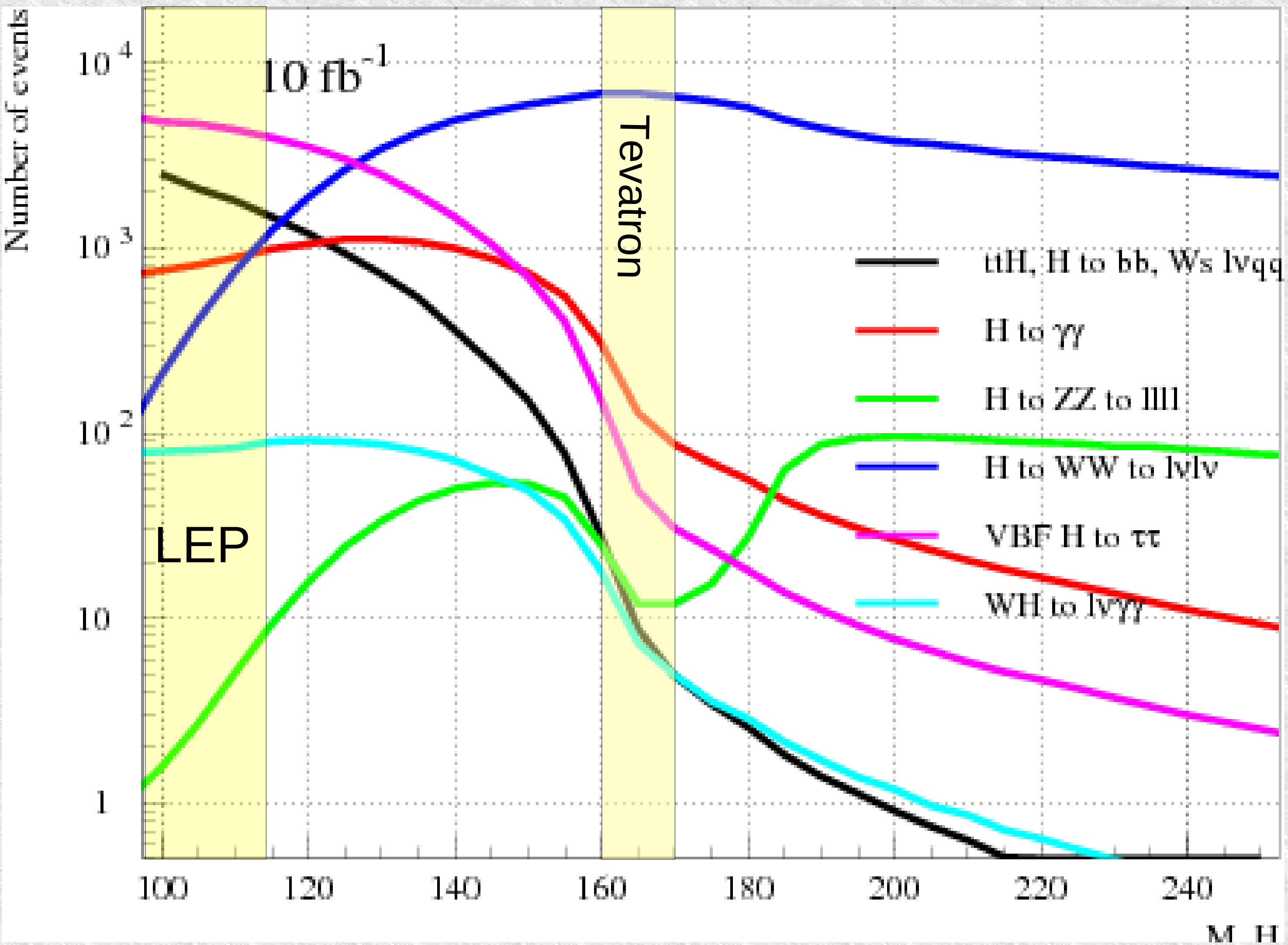


- Only decays considered for analysis are shown

How to find the thing

- If Higgs boson is heavy (>140GeV/c^2)
  - Serious decays to WW, ZZ
  - These have clear leptonic decay modes
  - ZZ→4l is frankly nicer, but WW→lνlν more common
  - The discovery is not too difficult.
- If Higgs boson is light (<140GeV/c^2)
  - (and it is)
  - Use rare H→γγ
  - Or VBF H→ττ – can trigger leptons
  - H→bb is dominant mode – can we find it?
    - Not without something to make it stand out
    - ttH, Z/W+H?

Rates in channels used



- Rates in major channels
- No cuts, just branching ratios
- l: e or μ
- Thousands of events to look for...
    - Far less will pass cuts

Summary of '2 sigma' modes

LHC

	ZZ	WW	γγ	ττ	bb
gg→H	X	X	X		
VBF		X	X	X	
Z/W+H			X		?
ttH					?

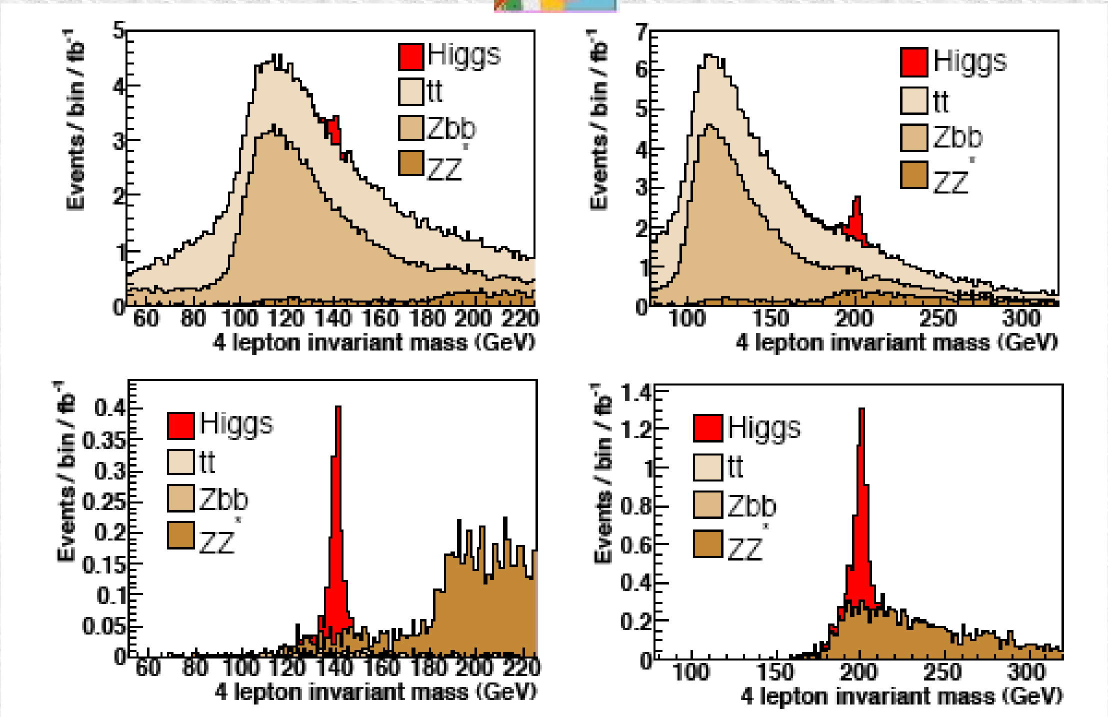
TeVatron

	ZZ	WW	γγ	ττ	bb
gg→H		X			
VBF					
Z/W+H					X
ttH					

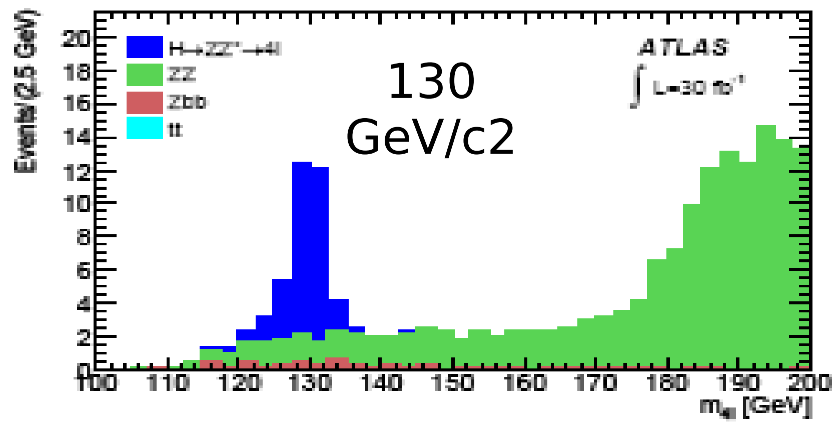
$h \rightarrow 4l$

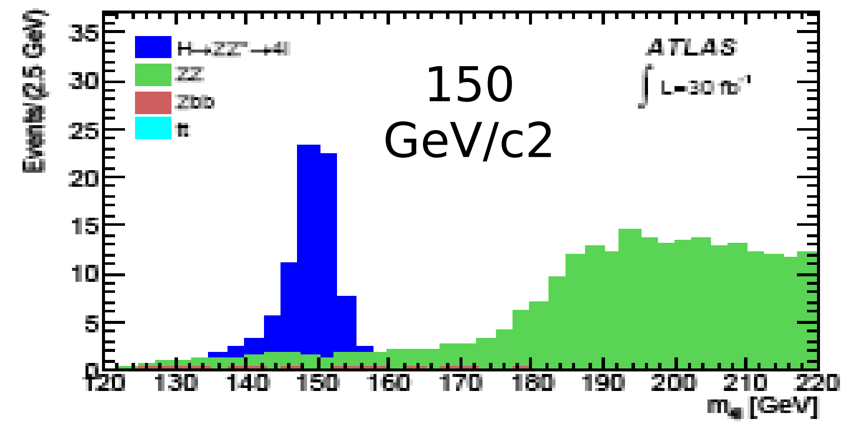
$H \rightarrow ZZ \rightarrow l^+l^-l^+l^-$

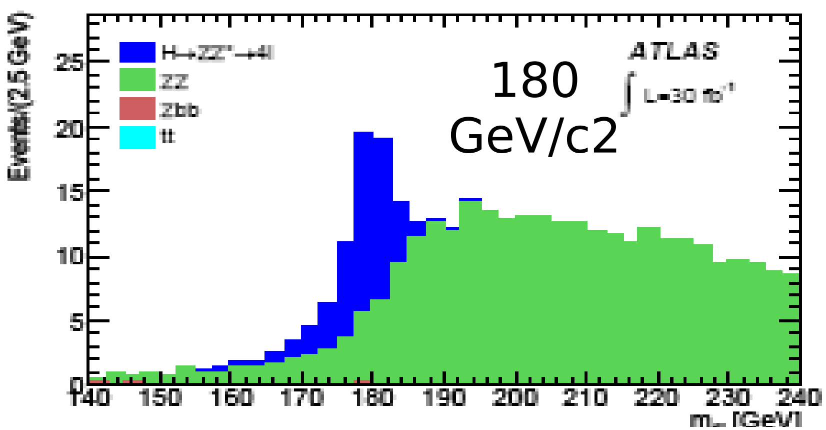
- Golden channel m_H>130GeV/c^2 (except 170)
- Good mass resolution, trigger
  - One or (>200GeV) two on-shell Z's
- Backgrounds:
  - Irreducible QCD ZZ to llll
  - Reducible Zbb, tt
  - Estimate with sidebands
- Multivariate (p_t, η) methods for low m_H

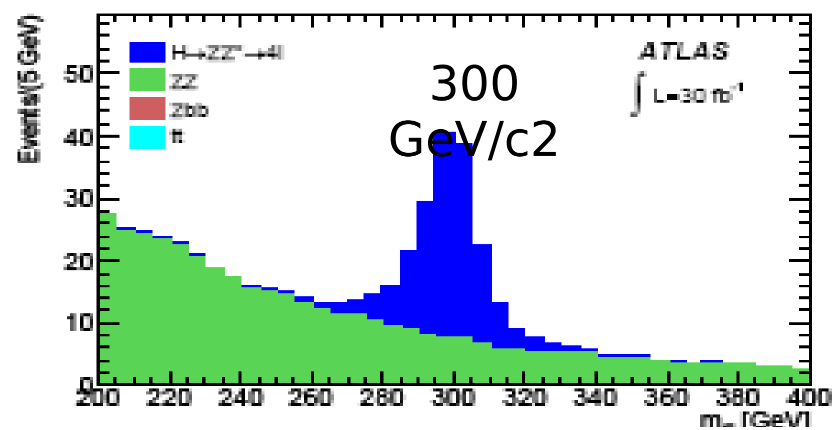


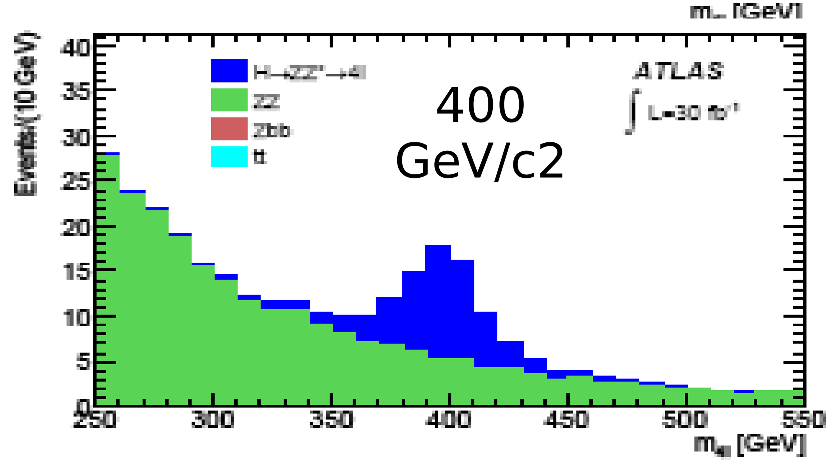
H $\Rightarrow$ZZ$\Rightarrow l^+l^-l^+l^-$

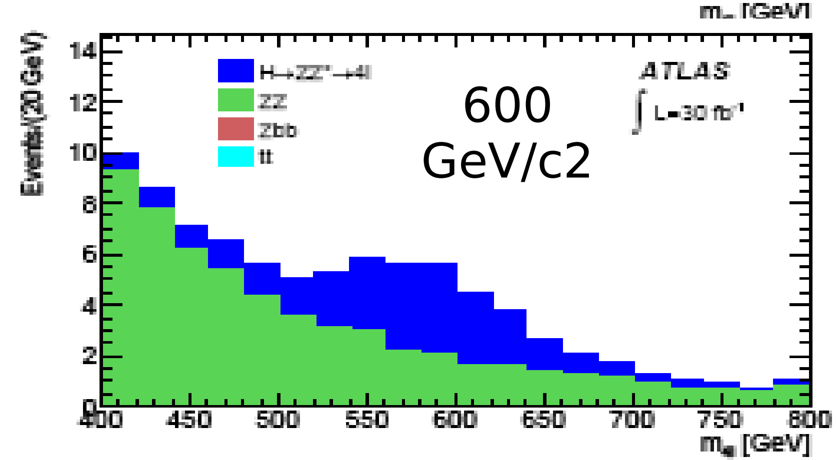




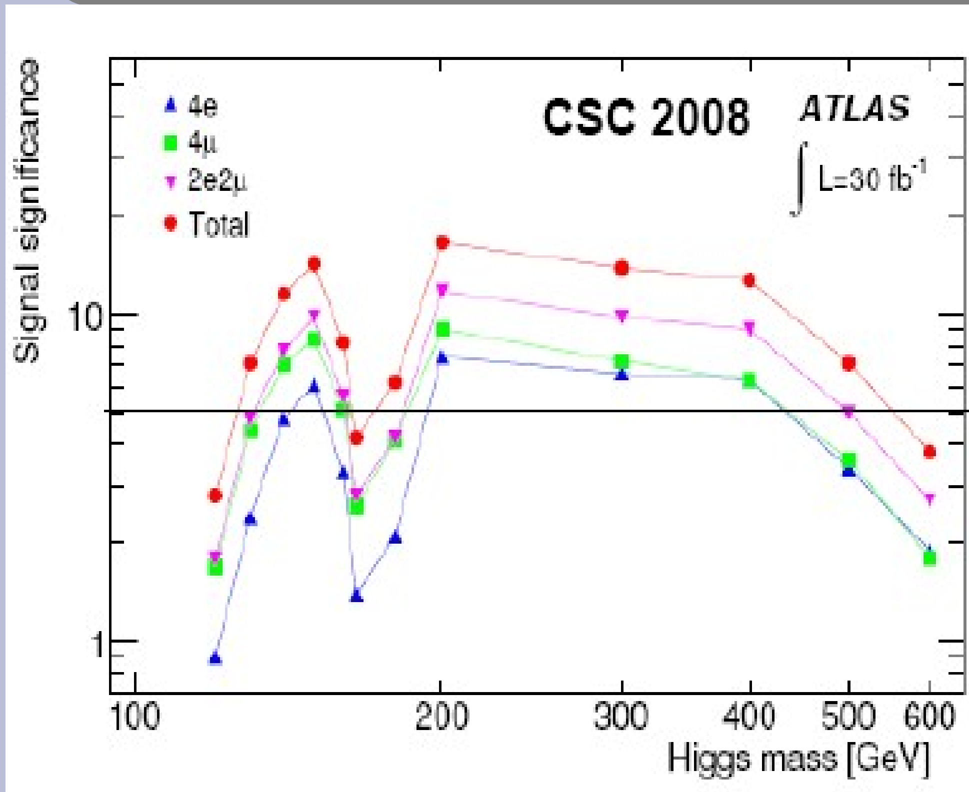


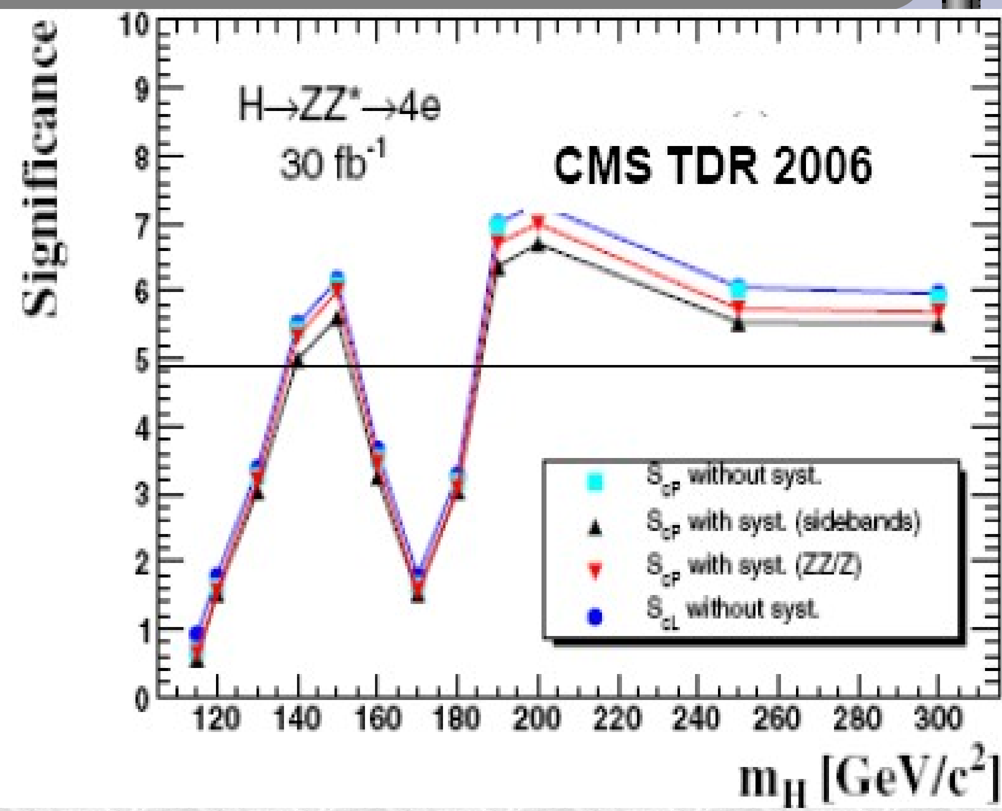






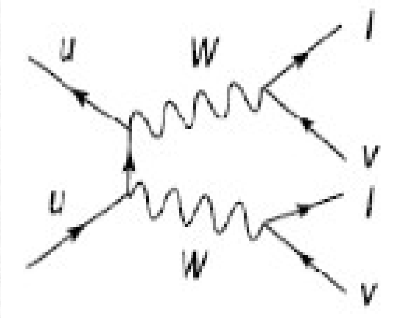
H to llll significance

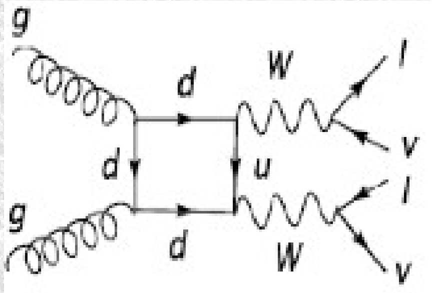


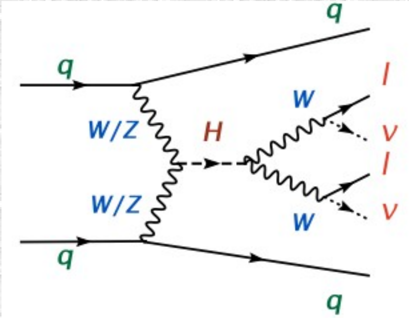


- Atlas expect 5σ here 130 to 500 (nearly)
- CMS recently re-optimised for 1fb^{-1}

h→ww$^{(*)}$



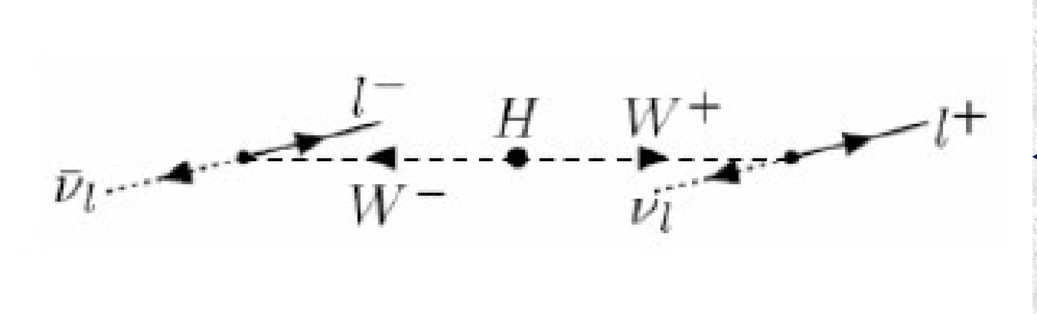




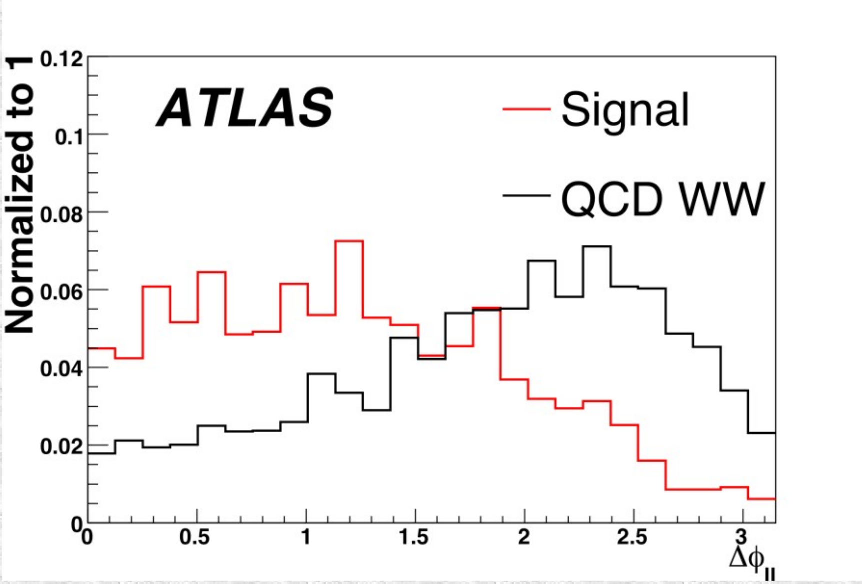
h→WW→lνlν

- c/f ZZ, leptonic branching ratio of W's much higher
  - Relatively common
  - Especially 160-180 when ZZ suppressed
- But...two neutrinos means no nice mass peaks.
  - Not for the W
  - Or for the Higgs
  - But the pT spectrum is distinctive
- Spin correlation of the Ws pushes leptons in similar directions
- ATLAS plots for eμ only at this stage

Spin correlation Higgs to WW$^{(*)}$

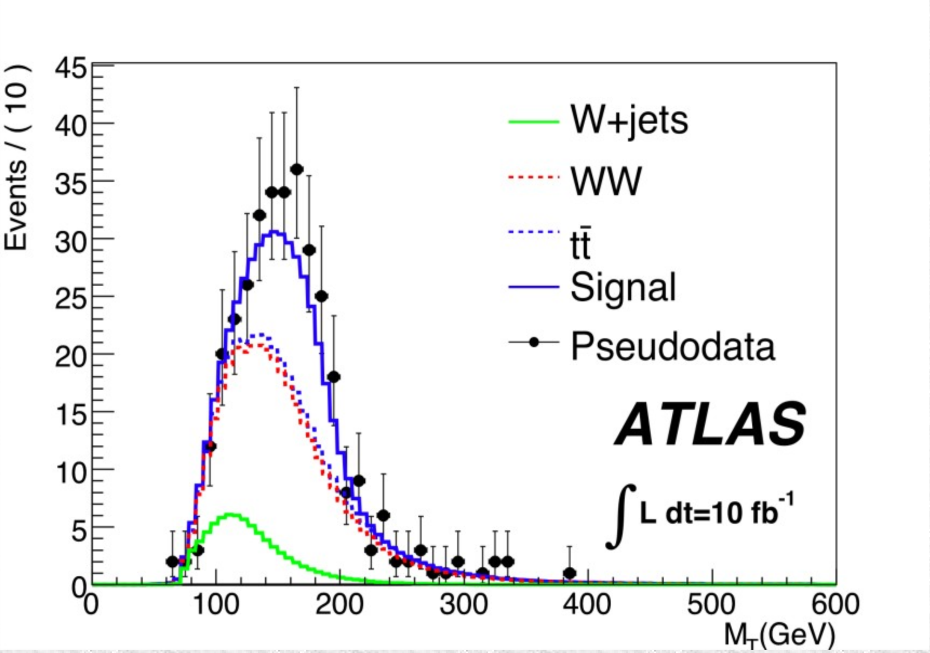


In the signal the decay creates a correlation between the spins of the Ws (in the rest frame of the Higgs) which in turn translates into a correlation between the leptons produced in the W decays and can be used to suppress backgrounds.



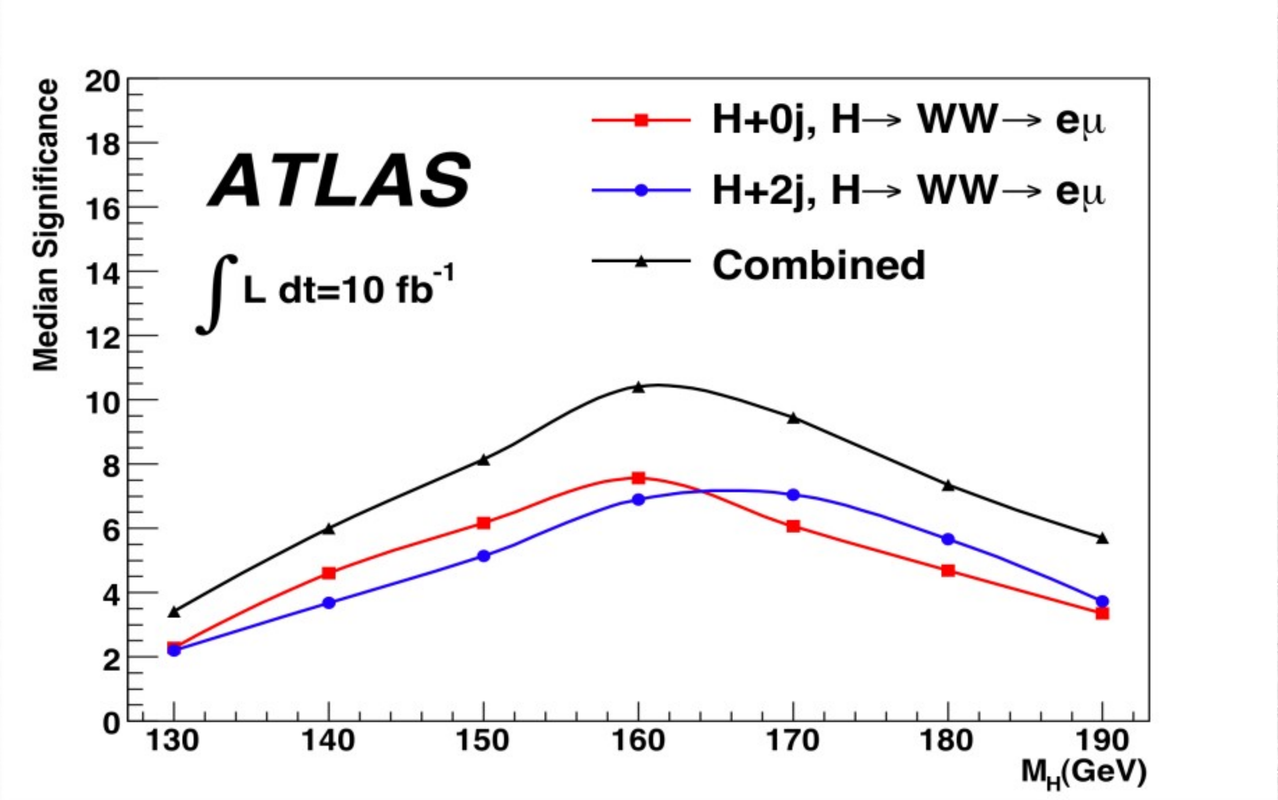
Higgs to WW(*)

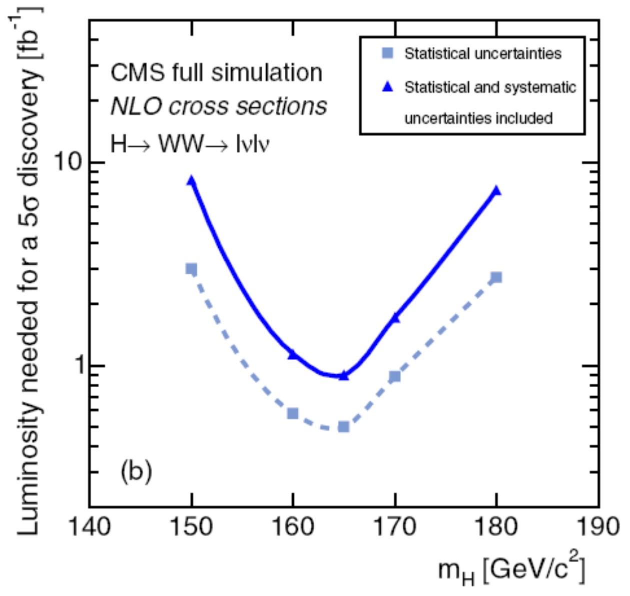
- M_T distribution shows important discrimination
- Production mechanism adds more
  - Gluon fusion dominate
  - VBF has distinctive forward jets
- Backgrounds:
  - WW is 'irreducible'
  - tt is dominant reducible

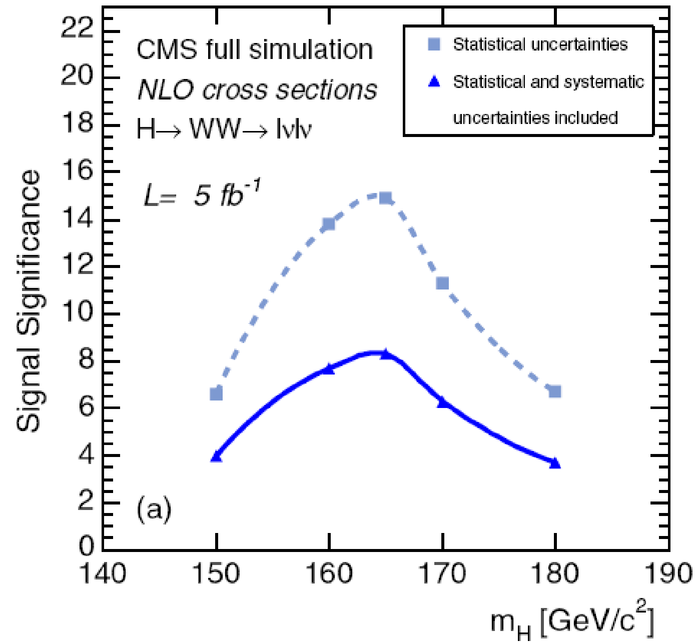


Understanding the backgrounds is critical

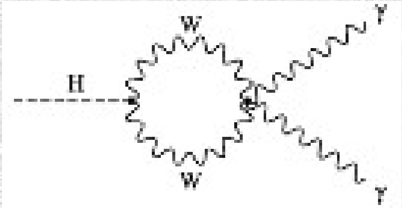
Signal significance

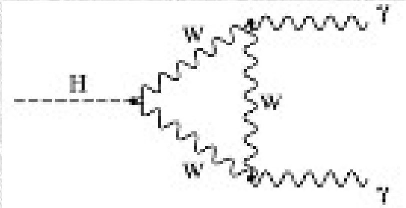


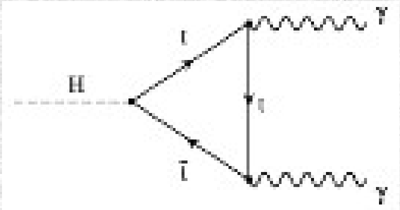




$h \rightarrow \gamma\gamma$



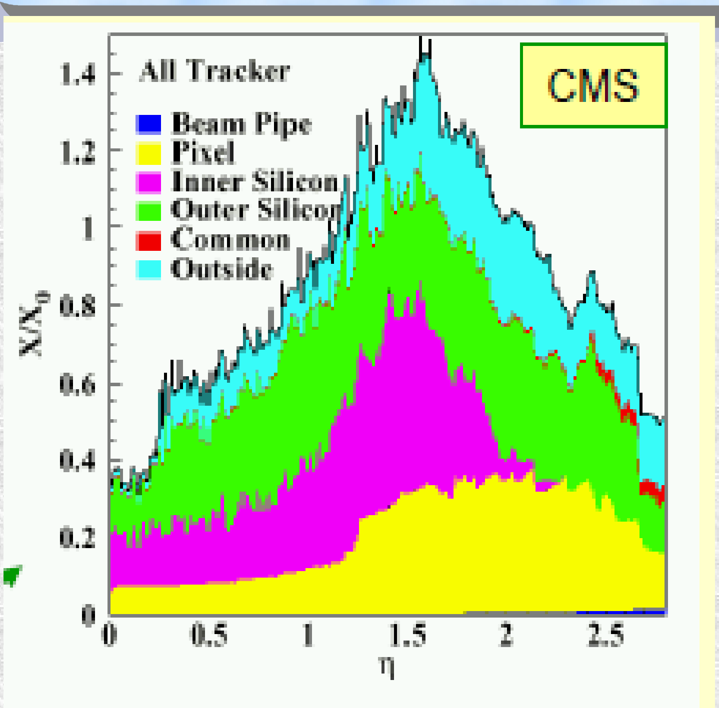




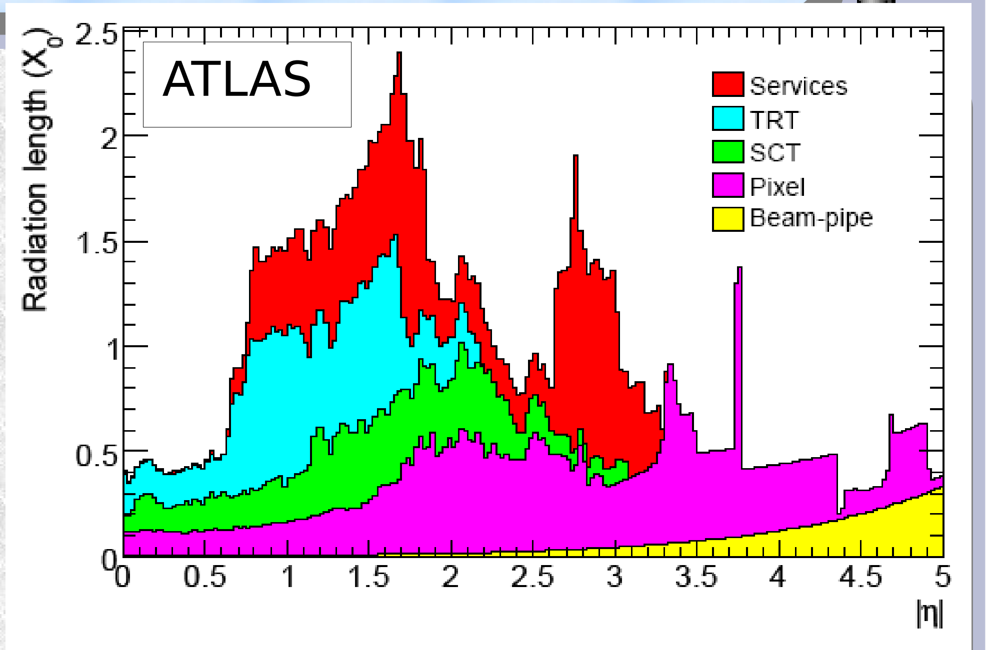
γγ properties

- Good sensitivity around LEP limit 115-140 GeV/c^2
- BF = 0.2% in the range of Higgs mass between 120-140 GeV
- Very clean signature on a smooth background
- Irreducible prompt backgrounds from continuum production of di-photons (gg,qq → γγ)
- Reducible backgrounds come from γ+jet where one of the particles from the jet is misidentified as a photon and jet-jet events.
  - Important because of the large QCD cross-sections
- Needs excellent rejection against jet-jet and gamma-jet events (typically 10^{-3} at 80% efficiency)
- Need a good knowledge of conversions because of the high fraction of events with at least one converted photon and hence degraded energy resolution. Note that about 60% of all events have at least one converted photon.
- Needs good mass reconstruction resolution from both energy and angular reconstruction
- Needs a good knowledge of material in front of the calorimeter

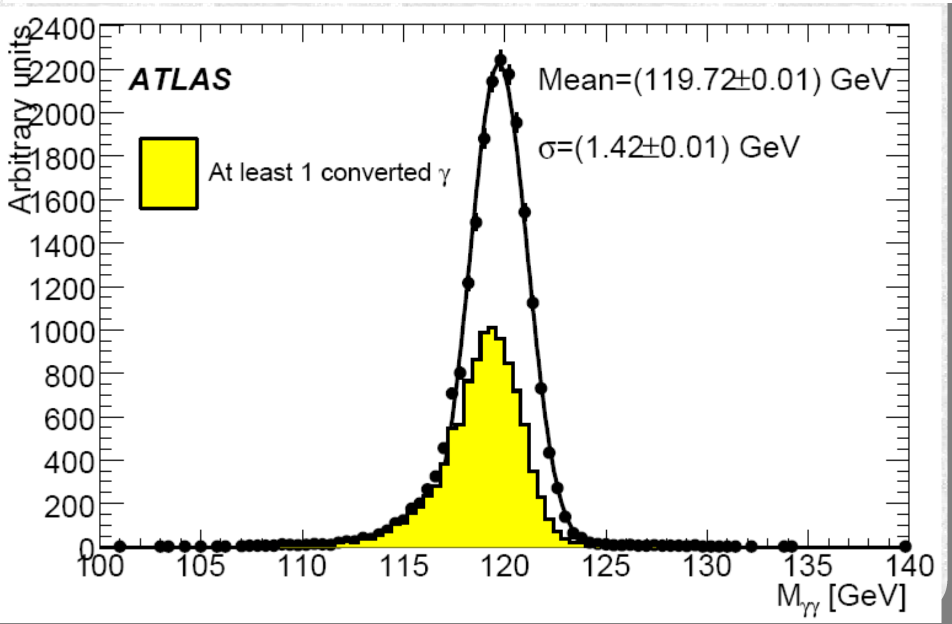
Material Distributions



[CDF: 20% X_0 in silicon tracker. D0: $4X_0$ before cal.]



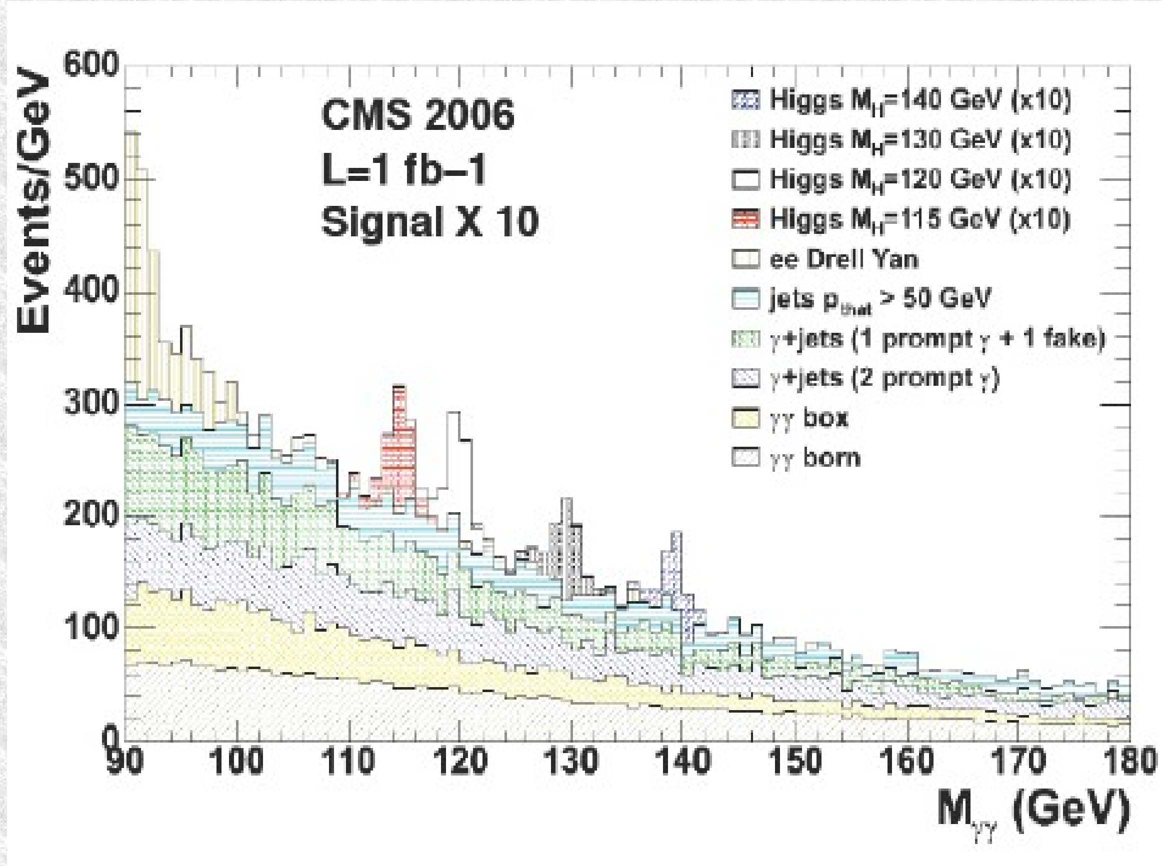
Good knowledge of the material before the Calorimeter is essential in understanding conversions



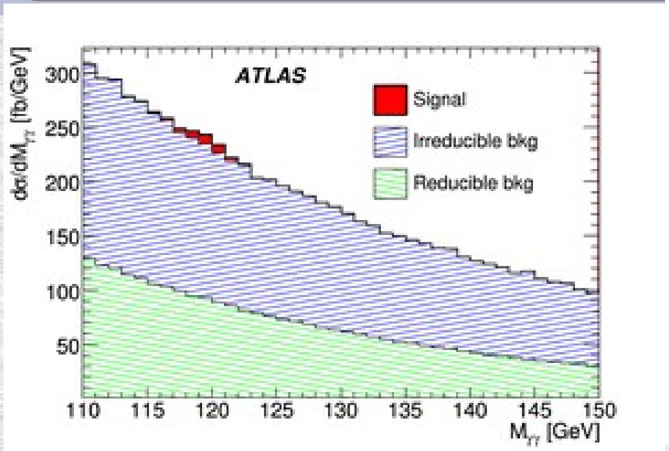
The effect of conversions on the reconstruction of 120 GeV Higgs mass in the ATLAS experiment

H→γγ

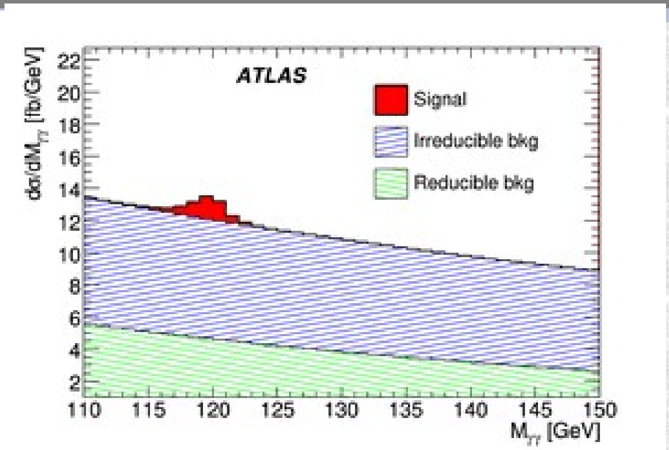
- Rare (10^{-3}) decay mode – top loop
- But trigger, mass resolution are good
- Large backgrounds of γγ, γ-jet and jet jet
- Jet rejection 10^3 required
- CMS resolution 0.5GeV best
- Production mechanism can be used to improve signal-to-background



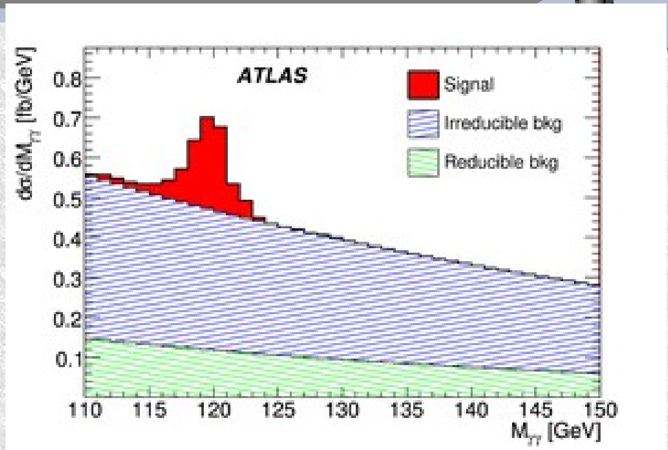
Higgs to γγ



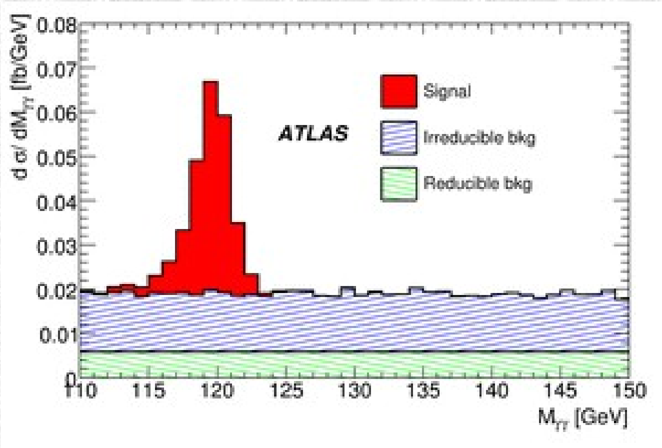
Inclusive analysis



Higgs plus 1 jet analysis

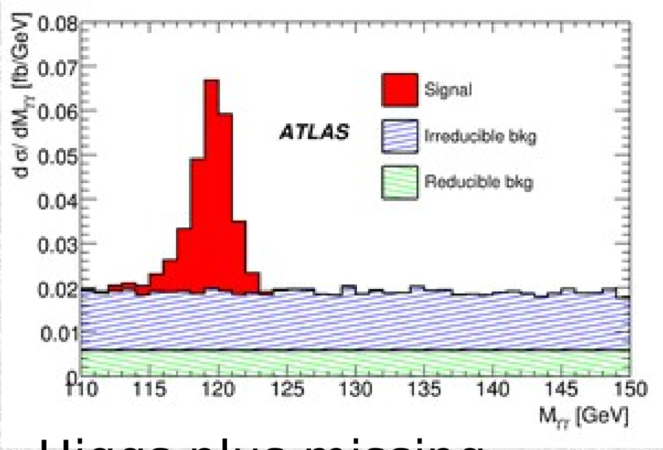


Higgs plus 2 jet analysis



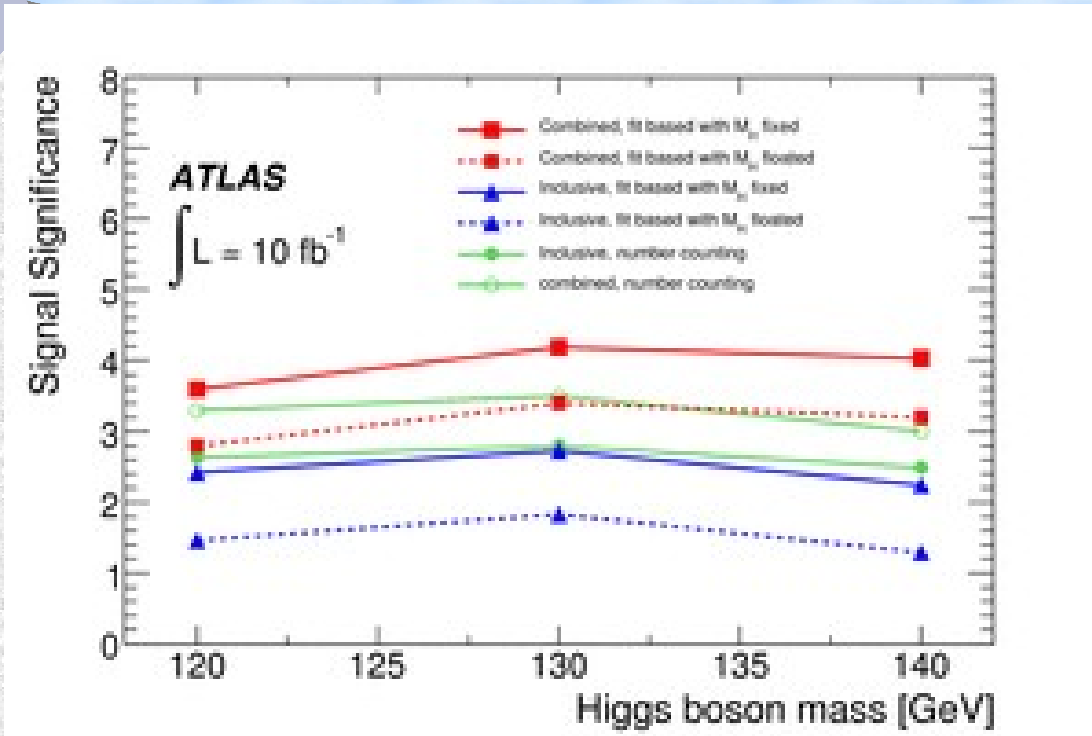
Higgs plus 1 lepton

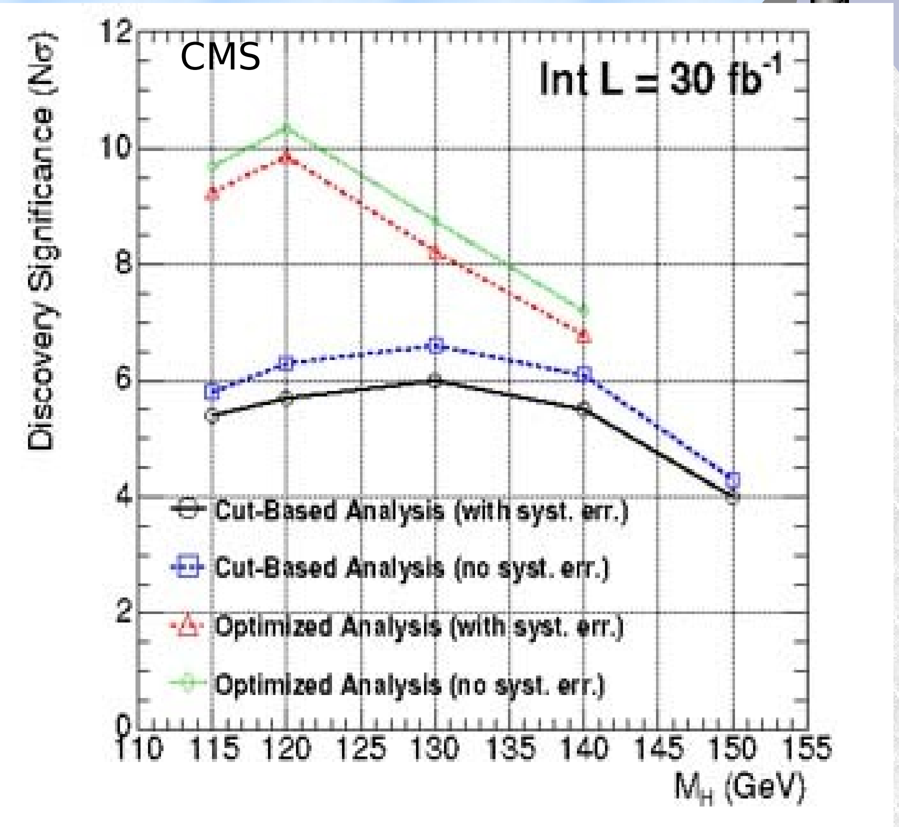
Cross section in fb.
s/b varies dramatically



Higgs plus missing energy

H to γγ significance



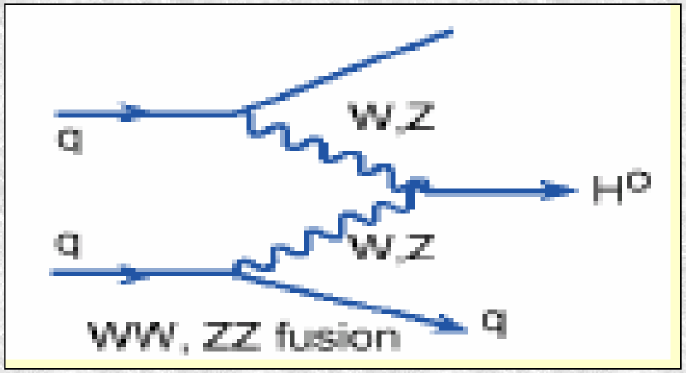


ATLAS : various analyses including Events counting and combined fits

CMS: optimized : neural network with kinematics as input, using cluster size

Note that additional reach gained from the superior energy resolution of the CMS calorimeter is matched in ATLAS by the ability to point the clusters back to the IP

$h \rightarrow \tau^+\tau^-$



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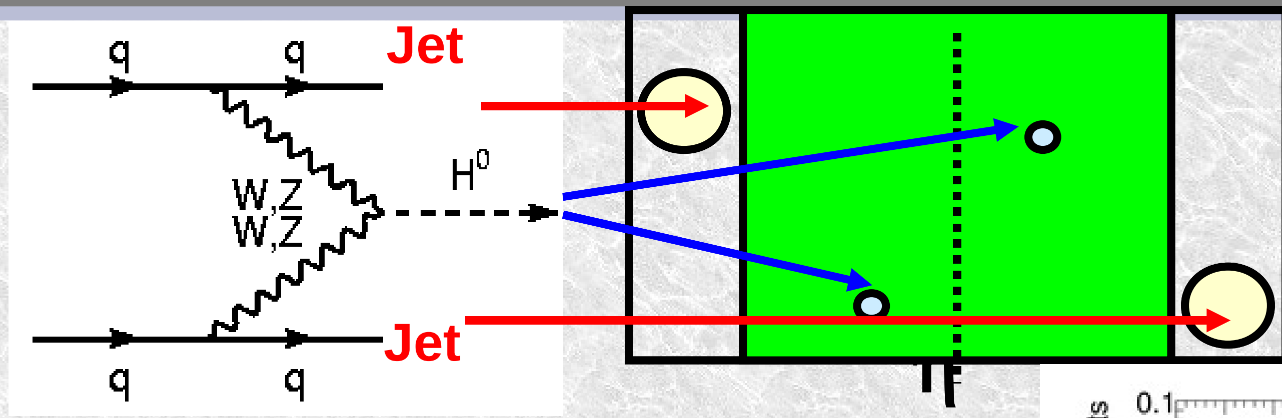
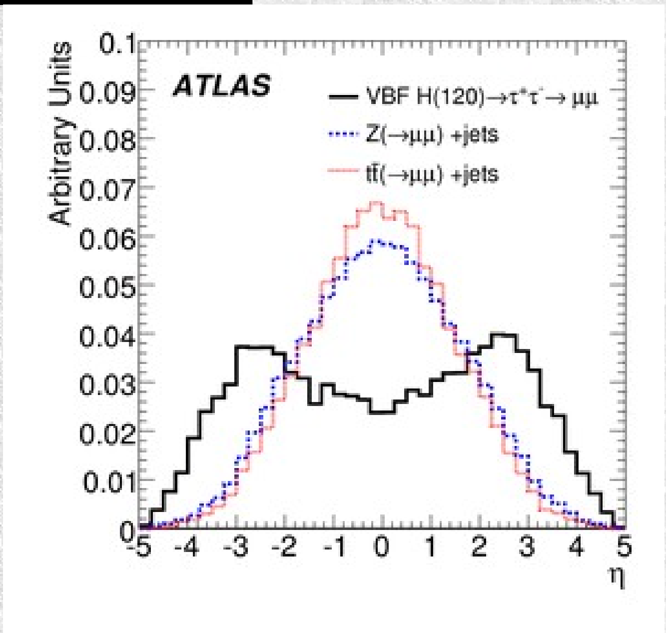
Boson fusion: qq→qqH→ττ



Low
mass

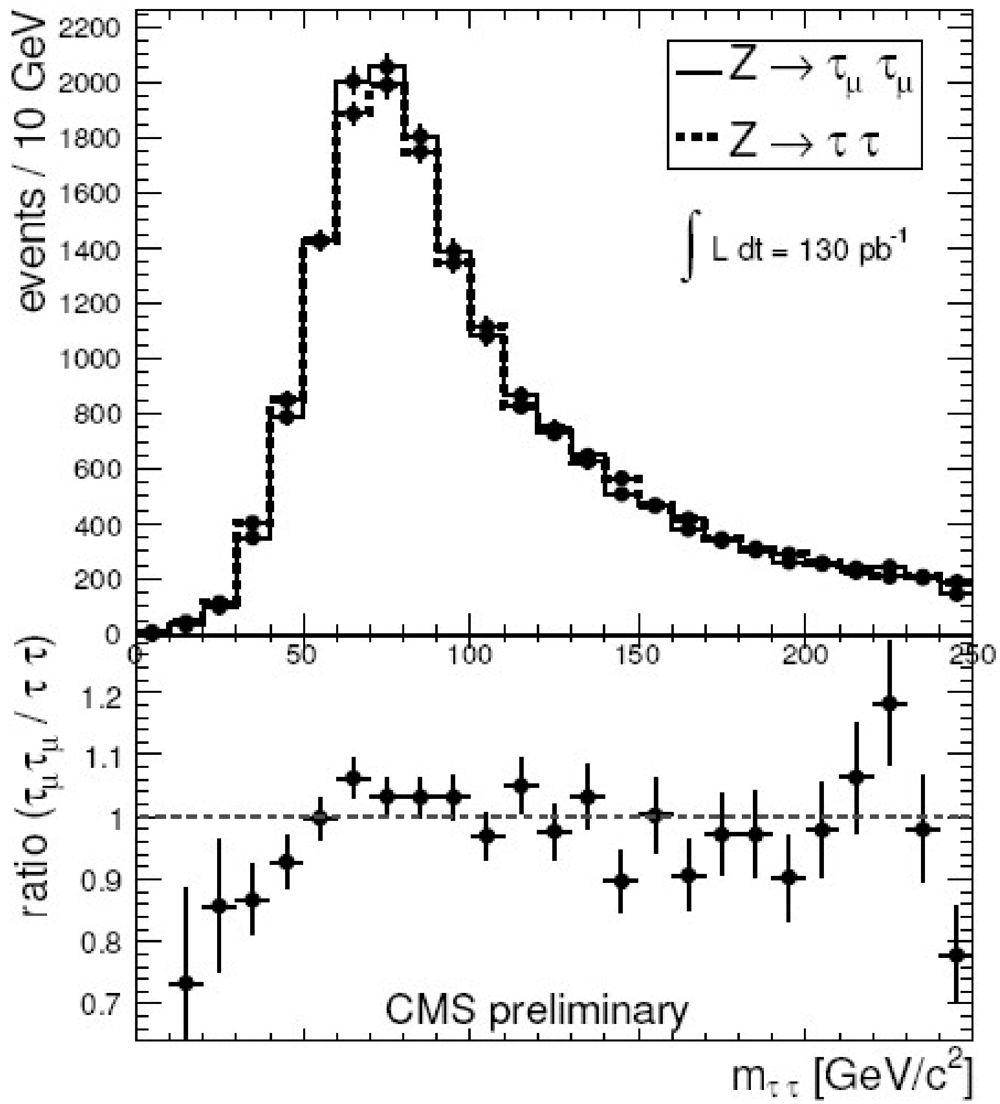


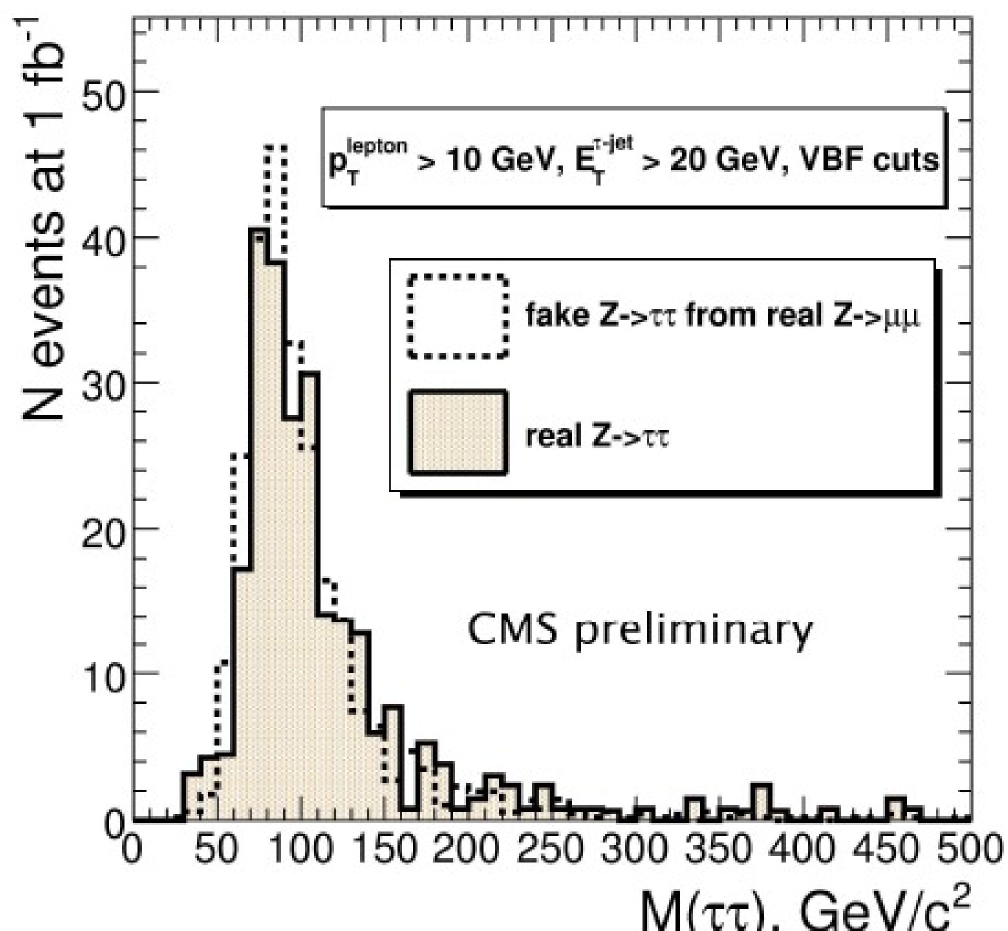
- Two forward jets, P_T like $M_W/2$
- Higgs products central
- No colour-flow → suppressed central jets
- Z→ττ plus two jets background

- τ τ →lν l'ν ', lν+jet final states (τ hadronic ident.)
- τ τ mass reconstruction: need P_t^{miss}, boosted Higgs

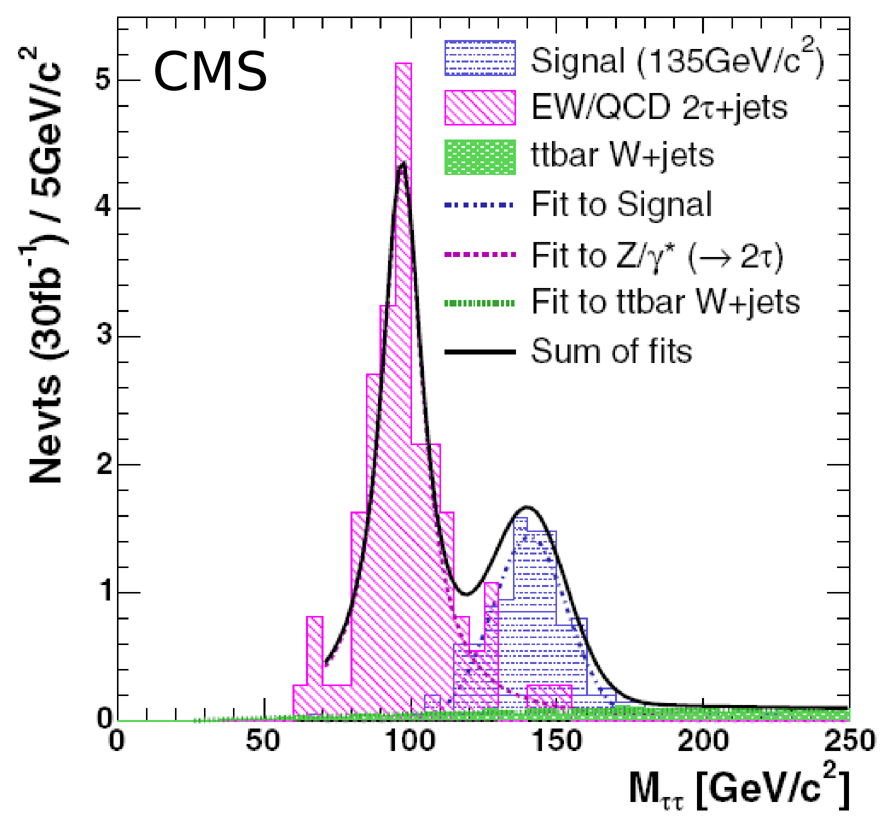
H →ττ: Data driven background

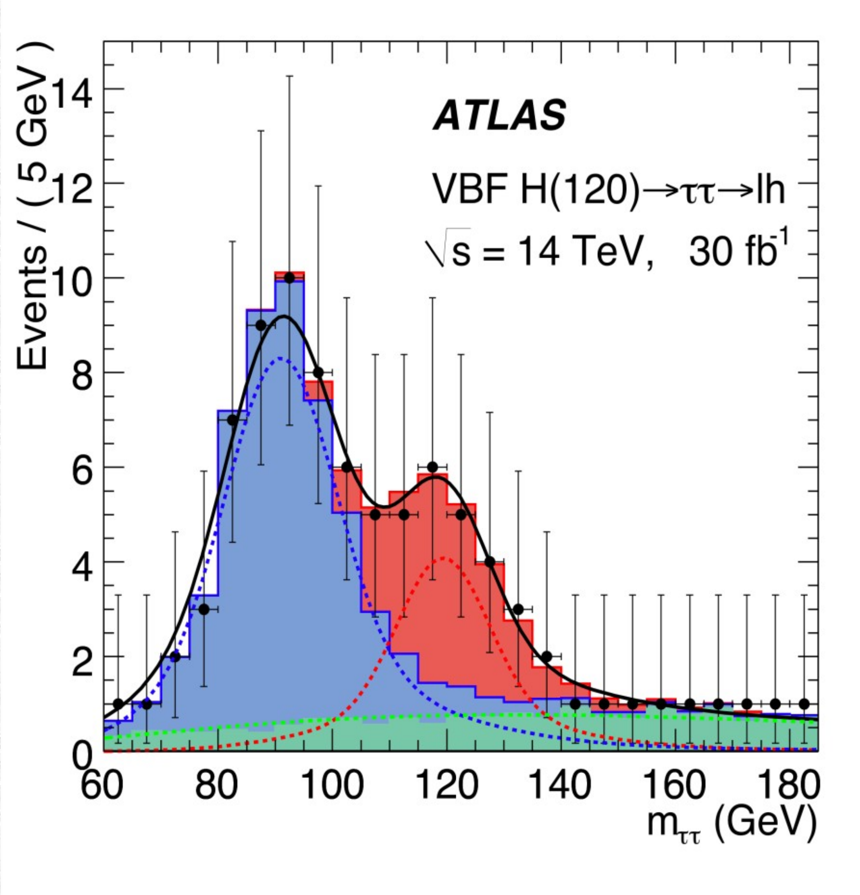
- Data Z→μμ; replace μ by MC τ





H to tau tau

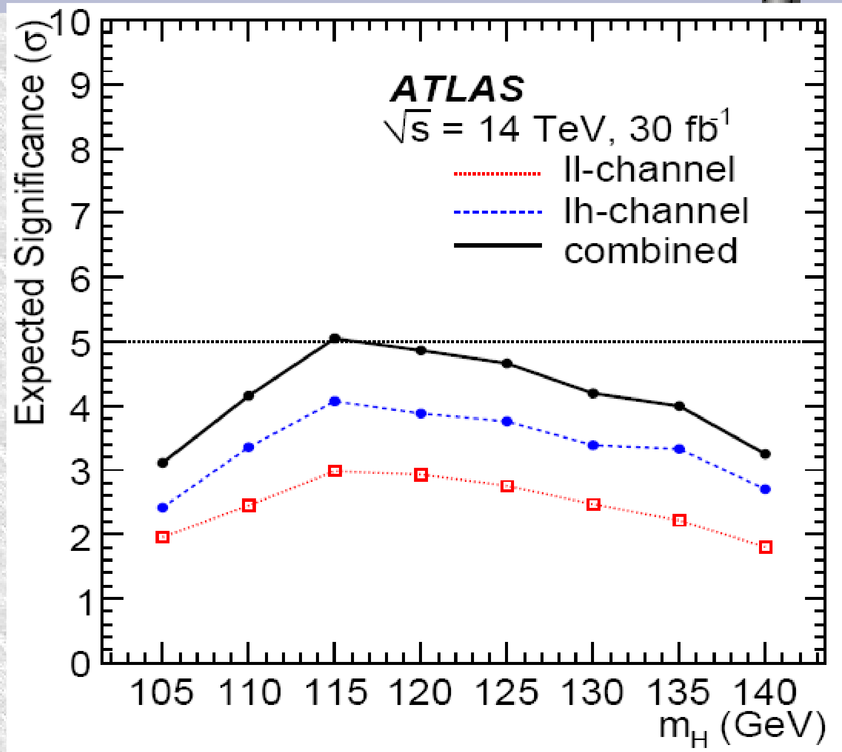




Examples of fits to the invariant Mass distributions for Signal plus Background.
The CMS distribution is on the left and the ATLAS on the right.
The **CMS** is for a **135 GeV** signal and the **ATLAS** is for the **120 GeV** Signal

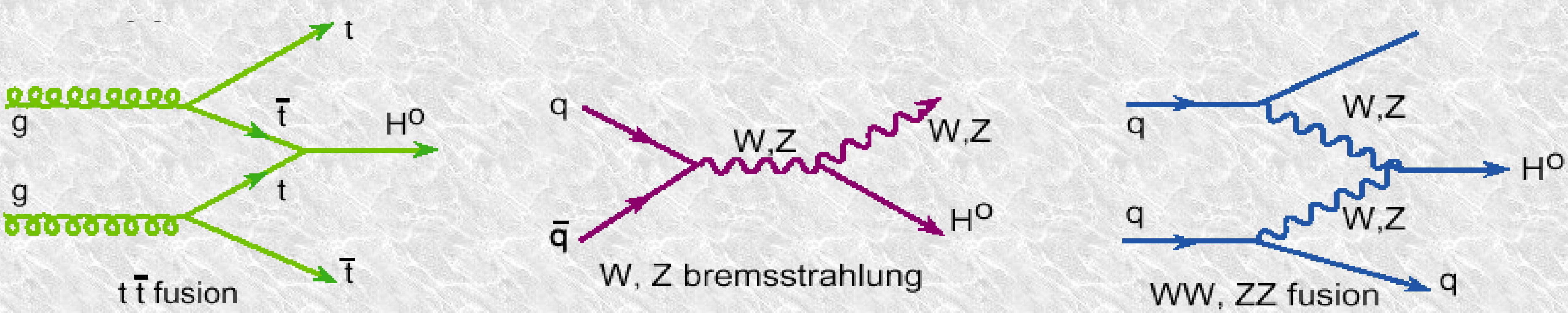
H to tau tau sensitivity

CMS significance				
MH (GeV)	**115**	**125**	**135**	**145**
N_{signal} ($30fb^{-1}$)	10.5	7.79	7.94	3.63
N_{bgrd} ($30fb^{-1}$)	3.70	2.21	1.84	1.42
Sig ($30fb^{-1}$) No uncertainty	4.04	3.71	3.98	2.19
Sig ($30fb^{-1}$) (σB = 7.8%)	3.97	3.67	3.94	2.18
Sig ($60fb^{-1}$) (σB = 5.9%)	5.67	5.26	5.64	3.19



similar in CMS , slightly tighter cuts (pile-up included
L = 2 10^{33} cm^{-2} s^{-1})

$h \rightarrow b^{+}b^{-}$

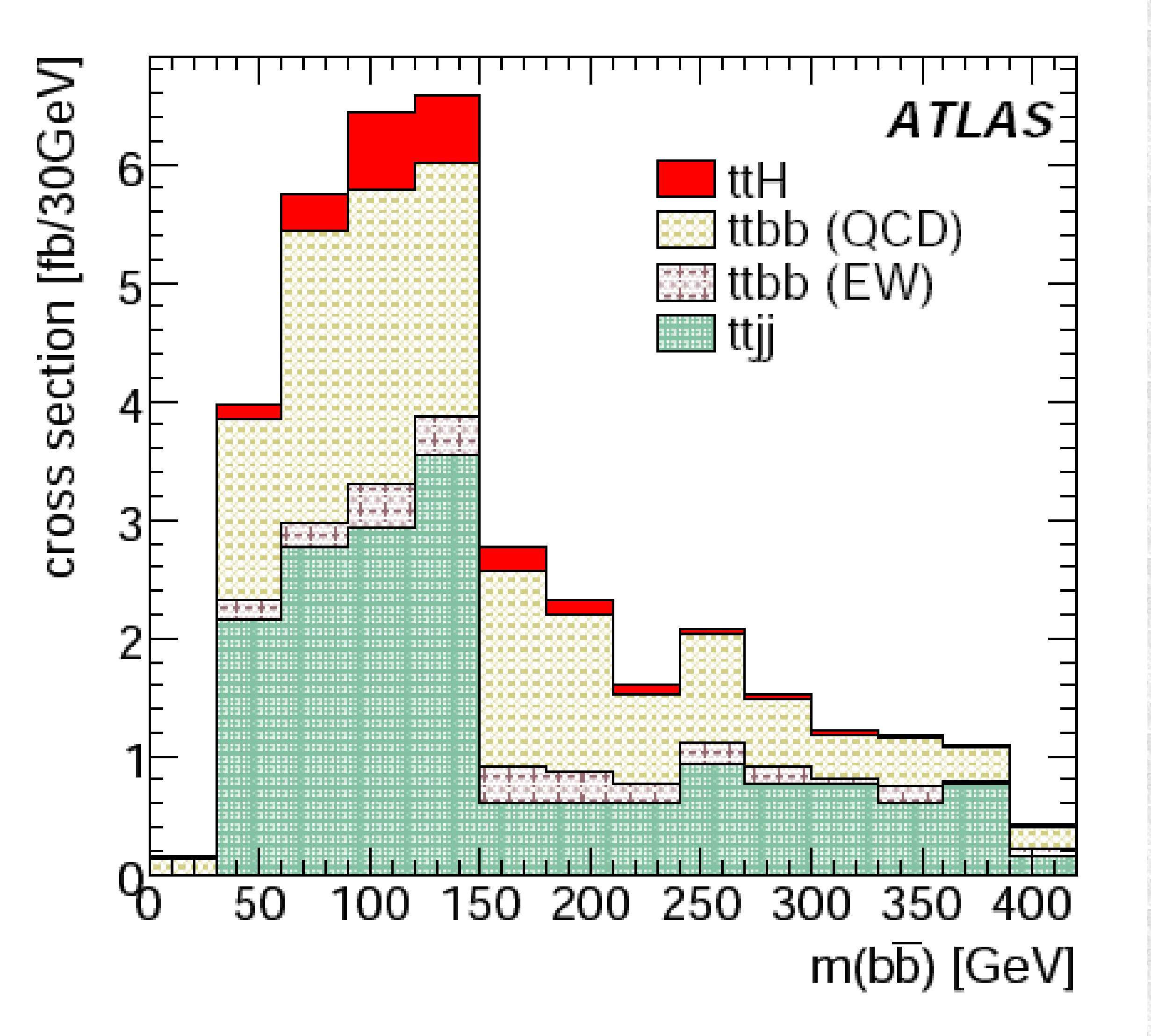


ttH, H to bb

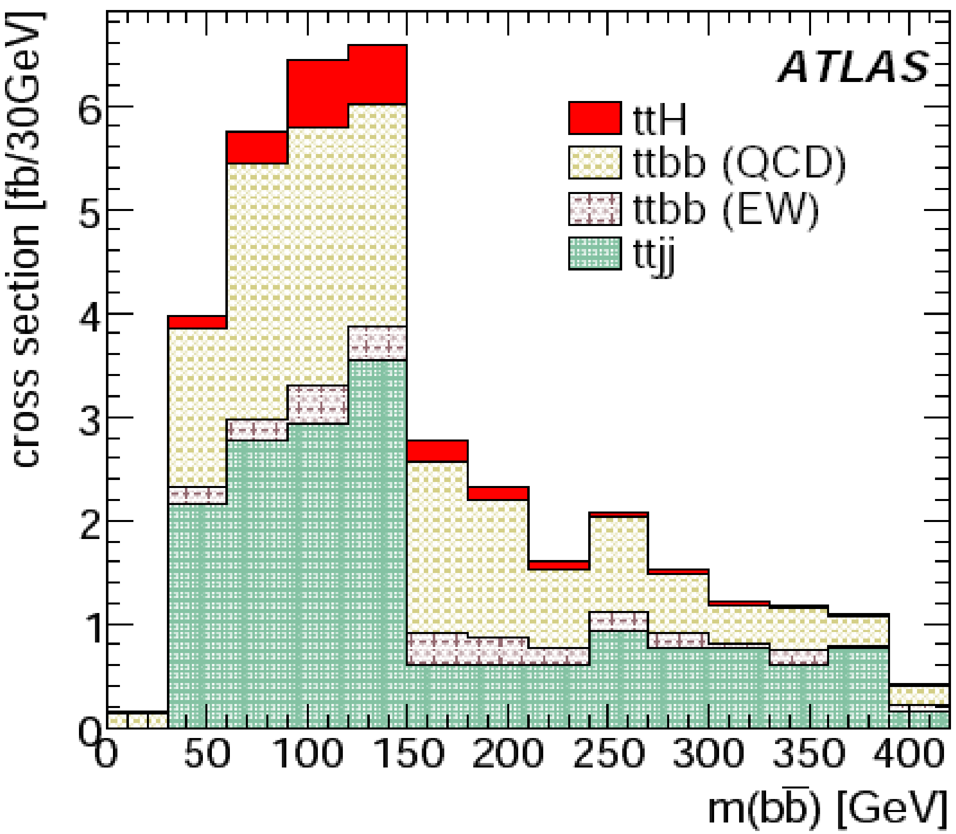
- s/b poor
  - Improving simulations always seems to add complication

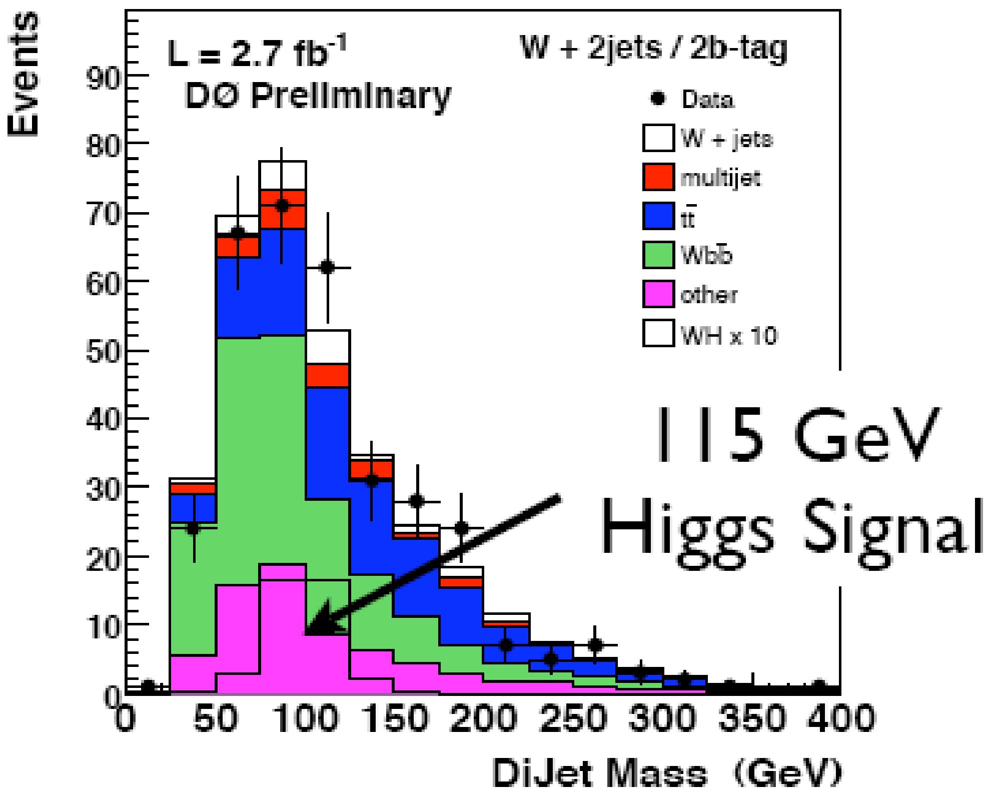
'Dead';
S. Heinemeyer, Seattle, Jan 2009

ArXiV: 0905:0110
ttbb k-factor 1.8
Increases the background
[Signal too, by 1.25]



ttH, H to bb: Doesn't lie down





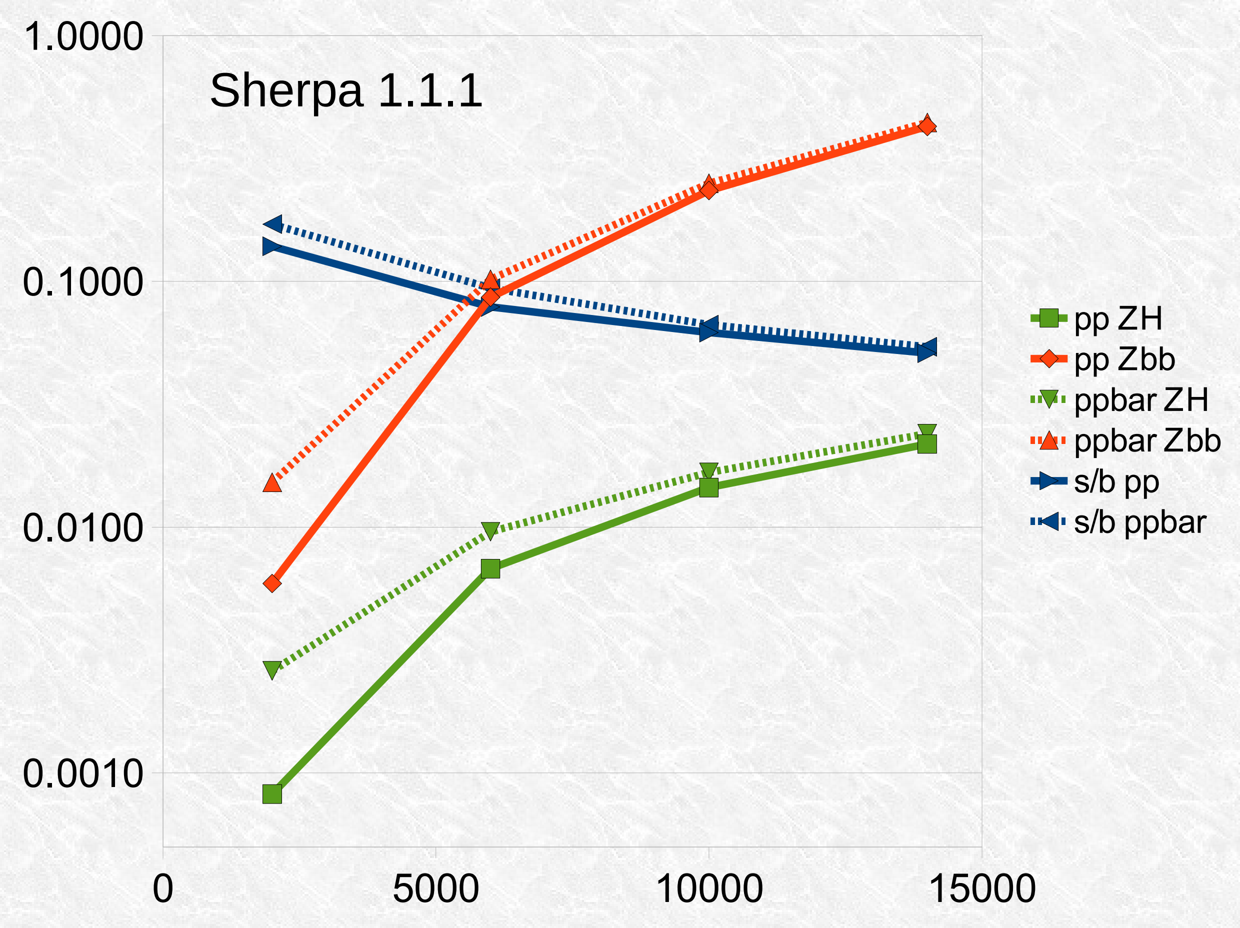
- Looks not much worse than Wbb at TeVatron to me
- Wait – TeVatron plot has signal shown times 10!

H to bb: Episode 4, a new hope

- WH/ZH at LHC being revived via subjet analysis
  - Butterworth et al., PRL 100:242001 (2008)
  - Now being fully analysed
  - Also NN etc. approaches being pursued again
- VBF Hγ production unexpectedly promising
  - Gabrielli et al., Nucl. Phys. B781: 64-84, 2007
  - Extra photon enhances quark nature
  - Suppresses glue based bb production
  - VBF tag jets also enhance signal to background
  - Being vigorously pursued

Why is VH missing at LHC?

- Z/W+H provides low mass result at TeVatron
- Why not at LHC?
  - More phase space for gluons

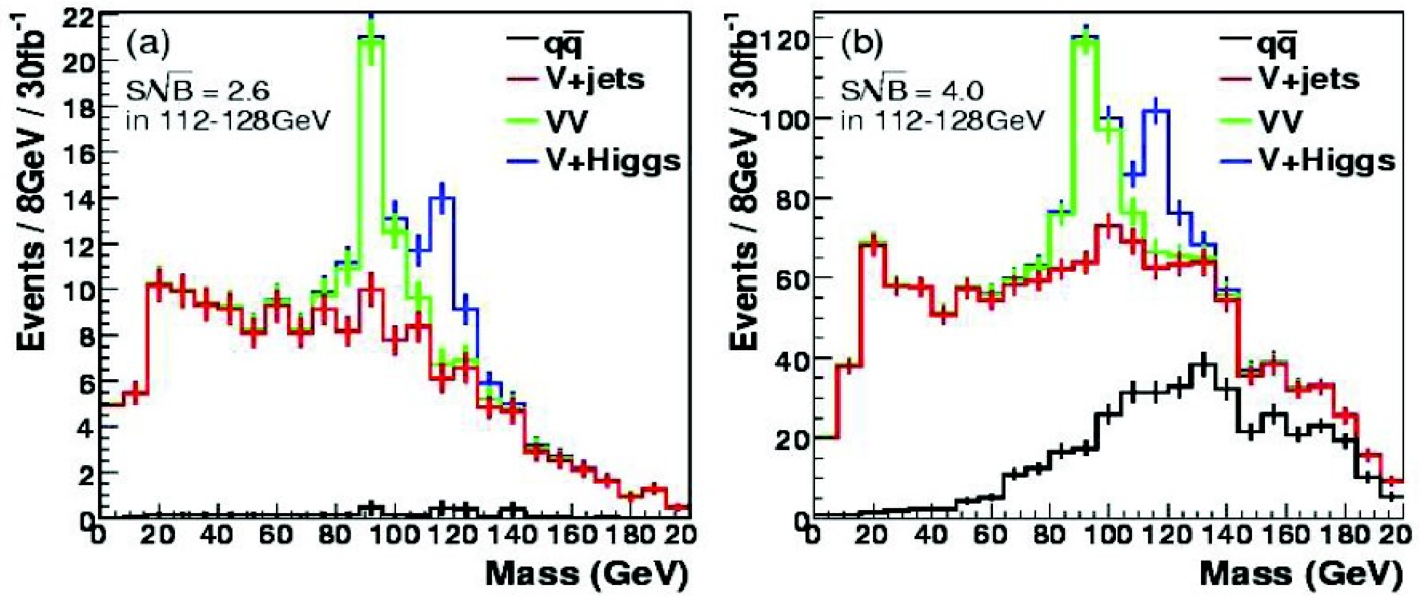


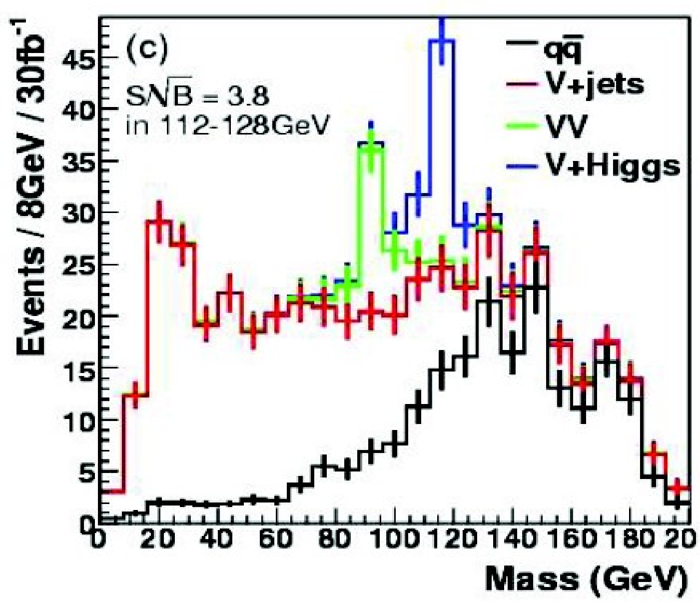
- Signal to backgrounds falls by factor 4.

(Fixed jet thresholds, mass windows)

Subjet Z/W+H; generator level

- Higgs, Z p_T>200GeV
- 5% of signal survives
- Background is manageable
- 6σ for 30fb^{-1} in generator
- Being studied fully





Top-left: ZH, Z→ll
Top-right: WH→lν
Bottom left: ZH, Z→νν

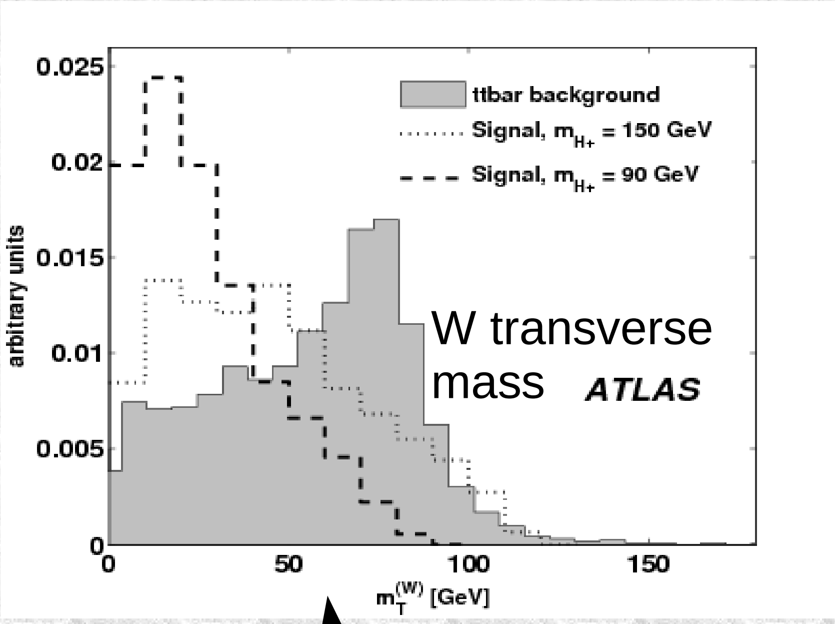
MSSM

Well – charged Higgs

Charged Higgs

- Charged Higgs search is ATLAS low-luminosity Higgs discovery channel
- Low mass H+ produced in top decay
- e.g.

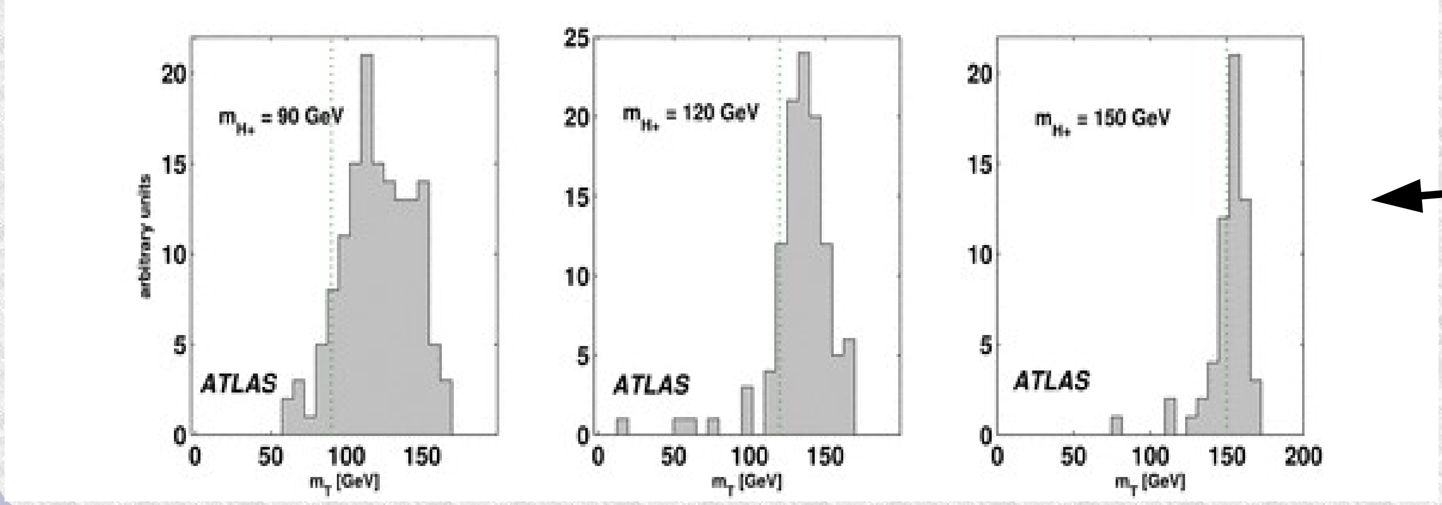
  $tt \to (Wb)(Hb) \to (l\nu b)(qqb)$



$M_W{}^T$ distribution

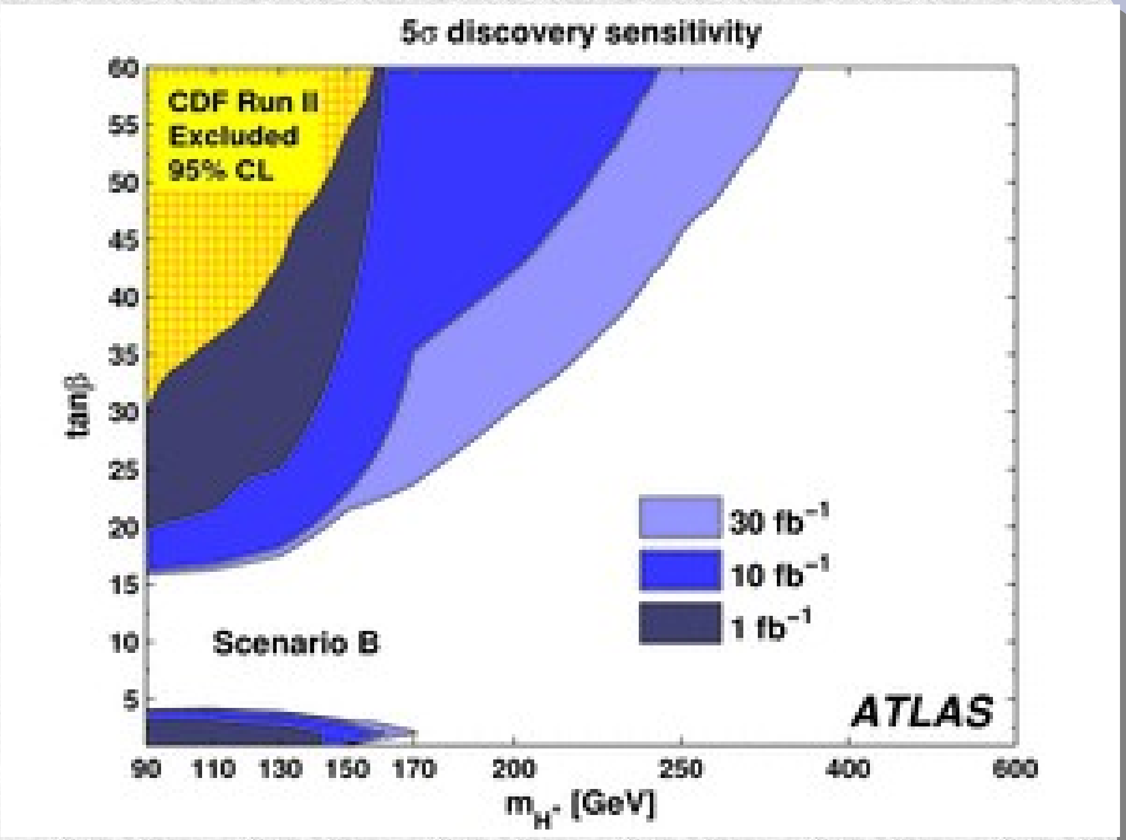
M_H distributions;

Arbitrary units



Charged Higgs sensitivity

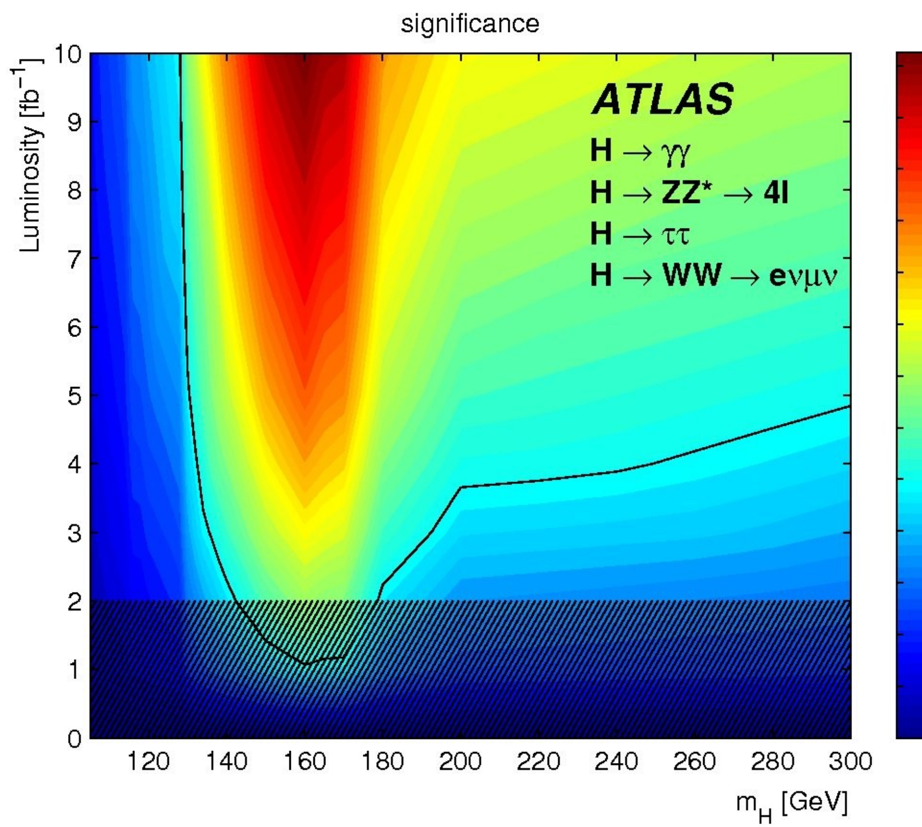
- Join low mass H+ with $m_{H+} > m_t$
- Allow for systematics
- Background is largely from top
  - Gain w.r.t TeVatron is good

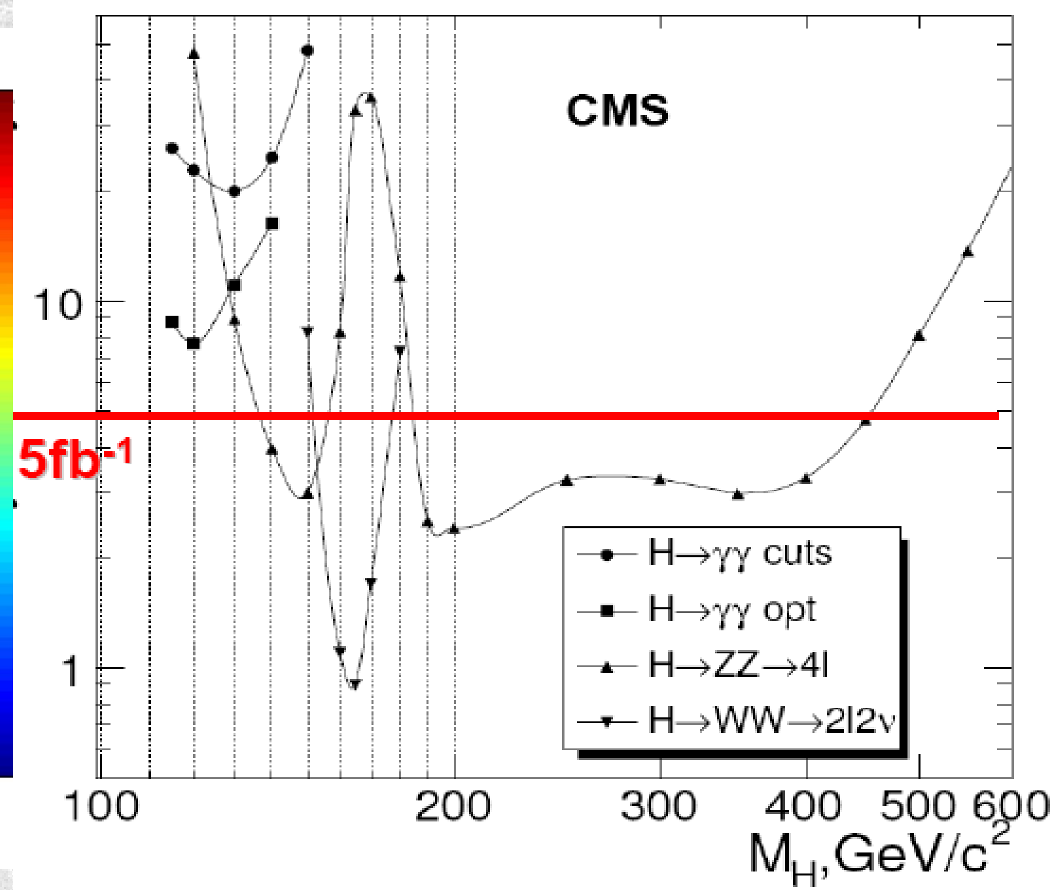


- There is only small 5 sigma discovery region
  - 14TeV, 1fb
- Perhaps worth combining CMS+ATLAS?

Combine Channels

SM Discovery

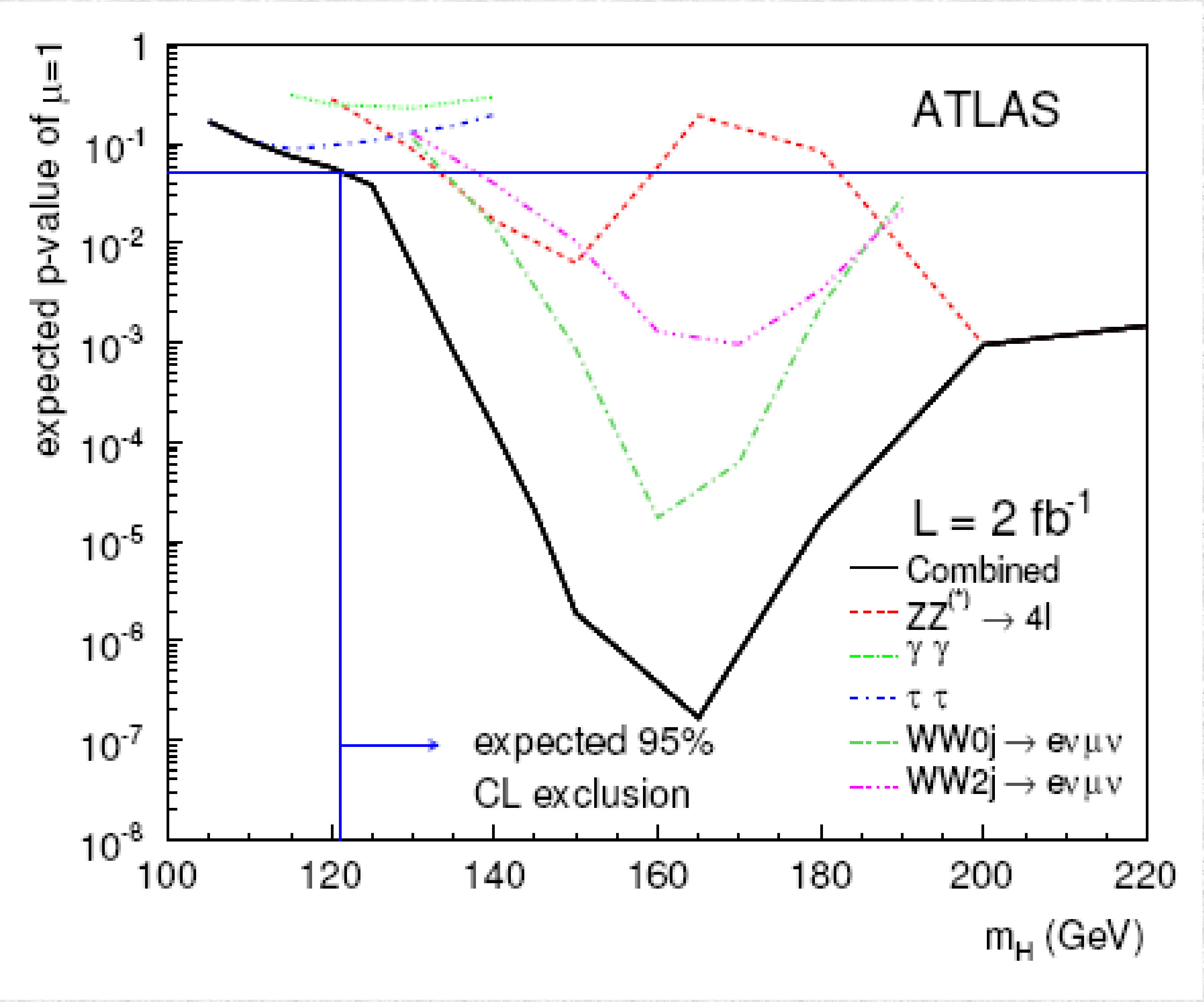




2fb^{-1} allows a Higgs from 143-179 GeV to be found (ATLAS)
As the Higgs weighs less than this, it will take longer...
3fb^{-1} allows exclusion down to 115.

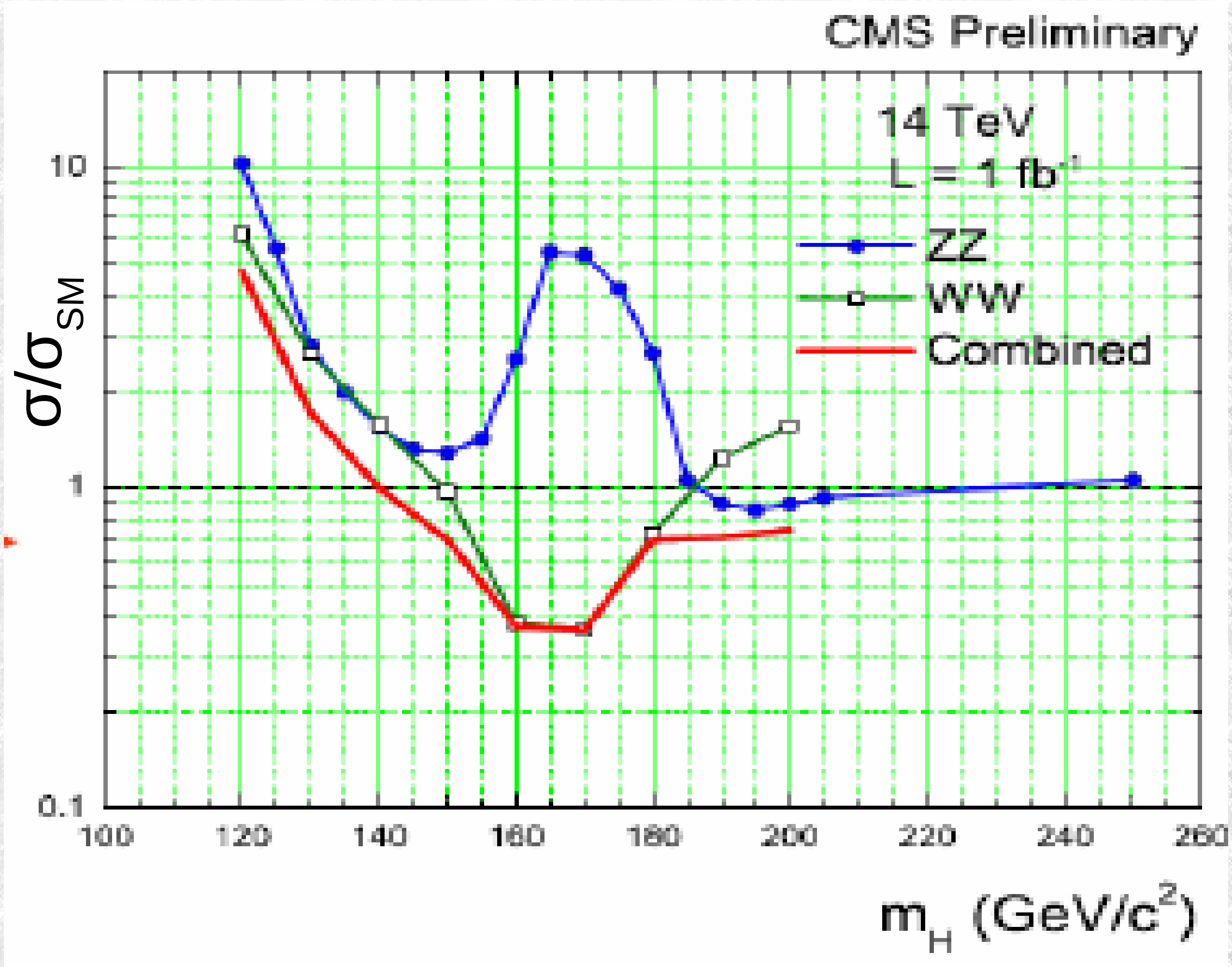
Contributions of channel

- Low mass region has contributions from:
  - ττ
  - γγ
  - llll
- We have ignored ttH
- Can ZH+WH help?



What about 10TeV?

- CMS AN 2009/20
- 200pb^{-1} at 10TeV
- Sensitive to the region the TeVatron just excluded



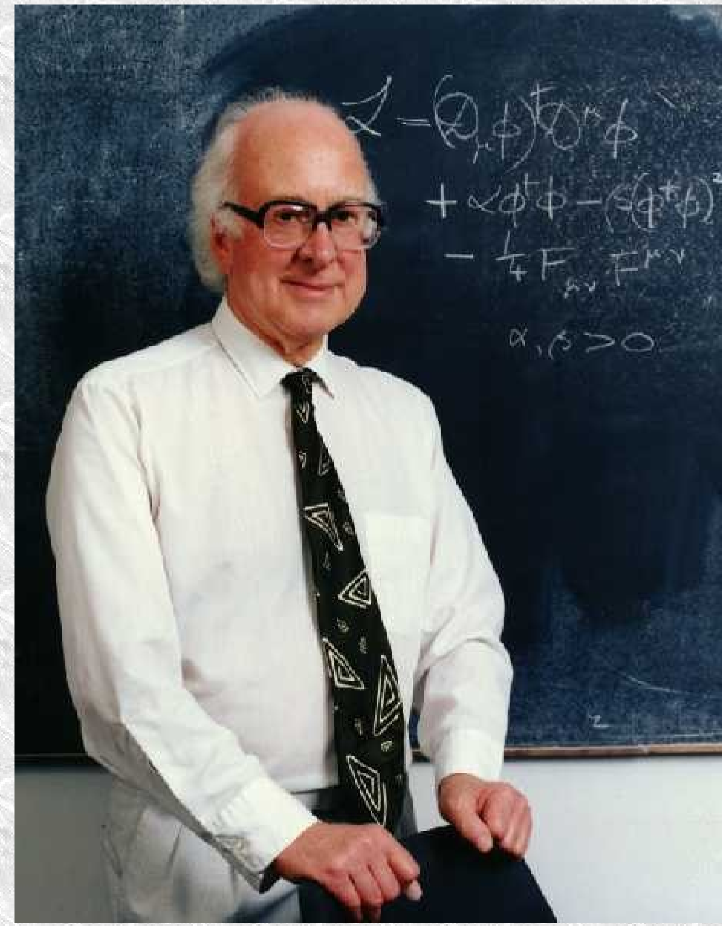
Comparison with TeVatron

- Tevatron is running well, pp-bar at 2TeV collision energy
  - $6fb^{-1}$ delivered
  - Records broken all the time
- CDF and D0 are in great shape
  - A stream of top quality Run II results coming out.
  - W mass
  - Top mass
  - Ω_b
- Now sensitive to SM Higgs
  - But they exclude the sensitive region
  - Factor 2 from data sets *4
  - Need to be cleaver AND lucky to get a discovery now

Would you believe the SM excluded at 2 sigma?

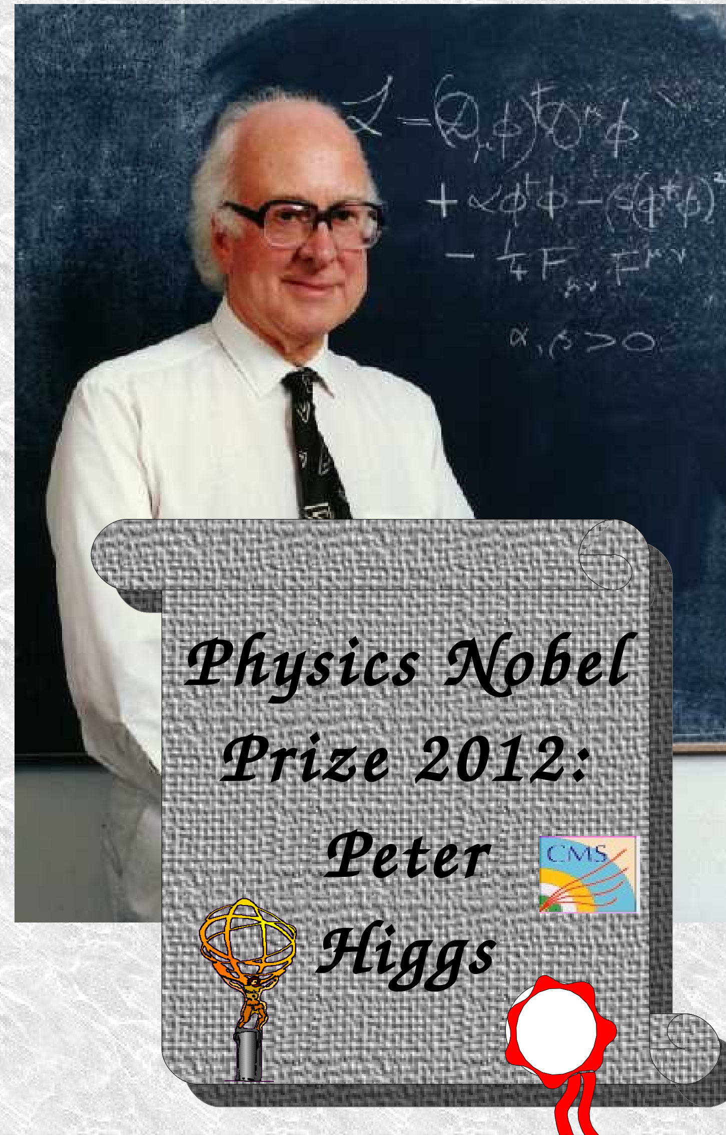
Conclusions

- We are knocking at the door
- But it is 2012 before we will get an answer.



Conclusions

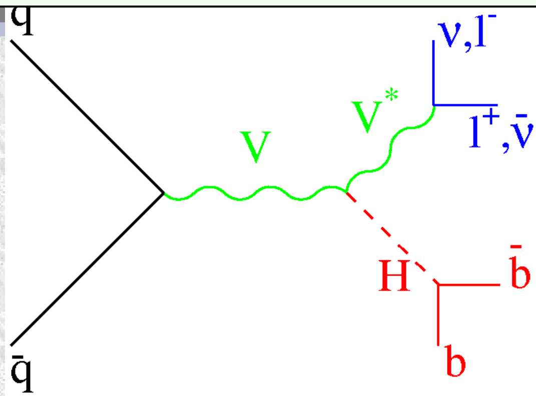
- We re knocking at the door
- But it is 2012 before we will get an answer.



Bonus Slides

Slide from 2001

Same process as at LEP:

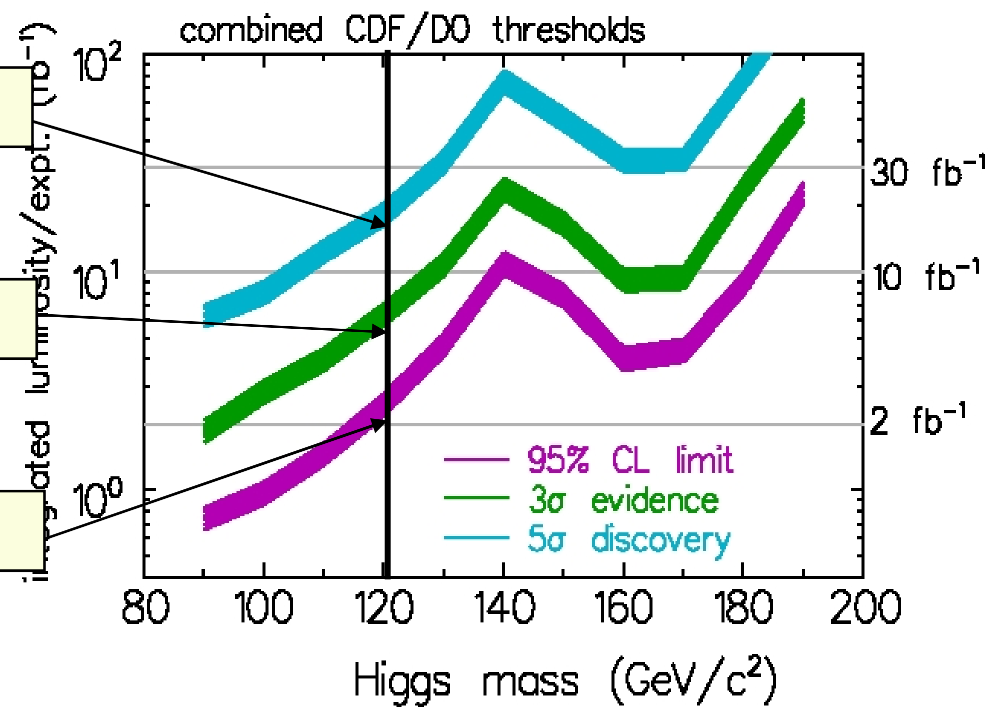


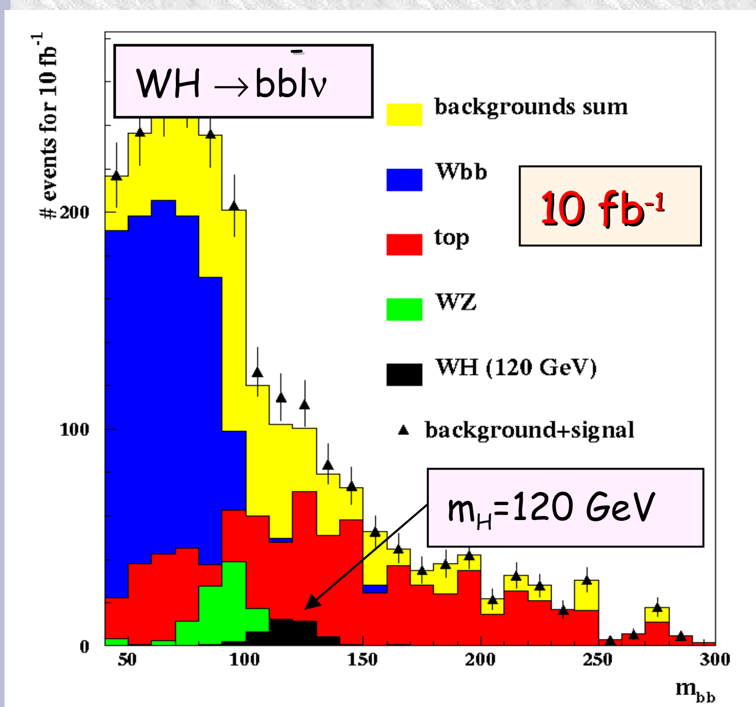
Produced: 50 events / fb^{-1}

5σ in 2007

3σ in 2004

2σ in 2002



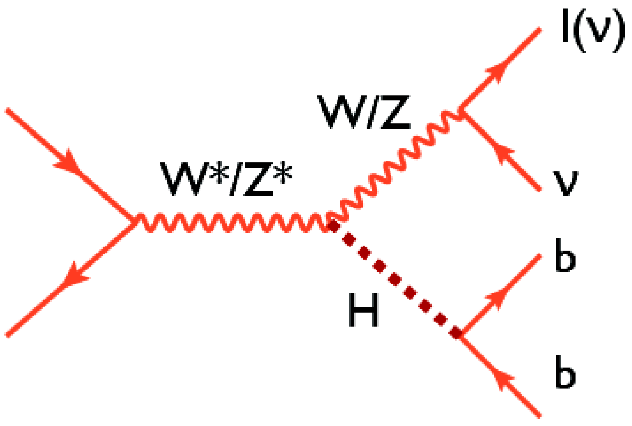


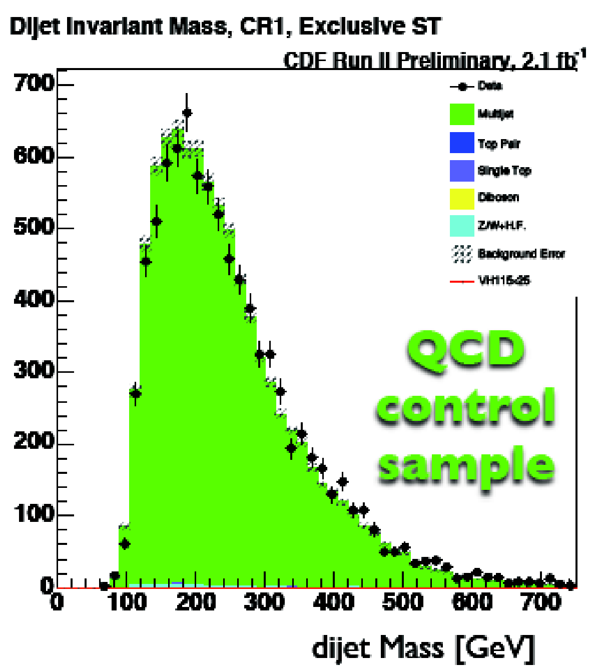
- Should confirm LEP hints;
- Much more difficult environment;
- Somewhat later; (3σ from 2004 to 2007);
- No detailed studies of the Higgs mechanism…
- Difficult above 115 GeV/c^2.

W/Z+H → ννbb Search

- Signature: 2 high p_T b-jets and large missing E_T from undetected $Z \rightarrow \nu\nu$ decay.
  - ➡ Accept $WH \rightarrow l\nu bb$ where lepton is not found (~50% of total signal)
- Both CDF and DØ analyzed 2.1 fb^{-1} for this search.

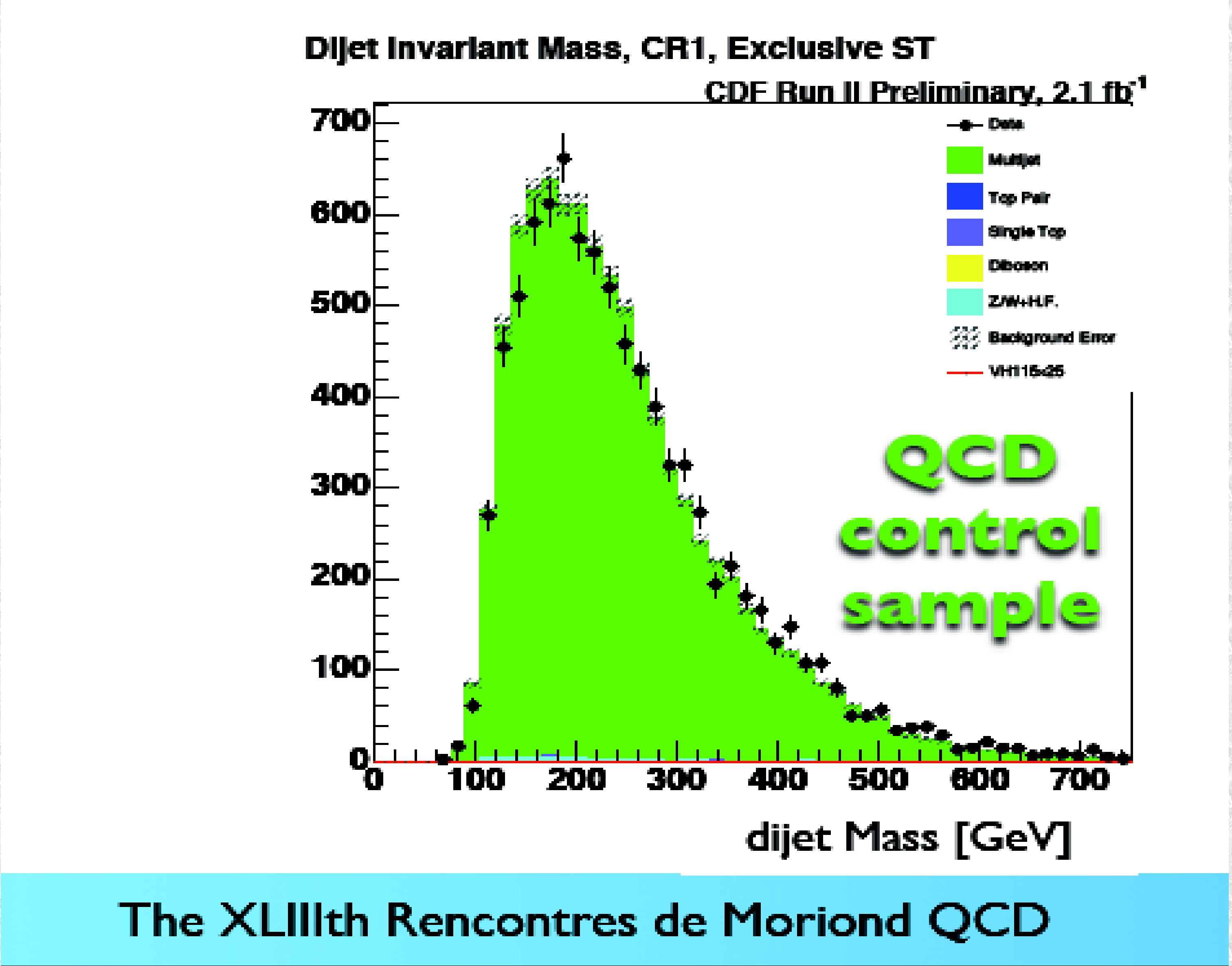
	Missing E_T	Jets
DØ	$ME_T > 50$ GeV	≥2 jets, ($\Delta\Phi$(jet1, jet2) < 165° jets $P_T > 20$ GeV, $\lvert\eta^{jet}\rvert < 2.5$
CDF	$ME_T > 50$ GeV	≥2 jets, jet $P_T >$ (35)20 GeV, $\lvert\eta^{jet}\rvert < 2.0$





- Background dominated by QCD multijet production. Difficult to model in MC ⇒ Use Data!
- Define multijet and W+jets dominated control samples test backgrounds.
- Events sorted by number of tagged jets similar to WH and ZH→llbb search.

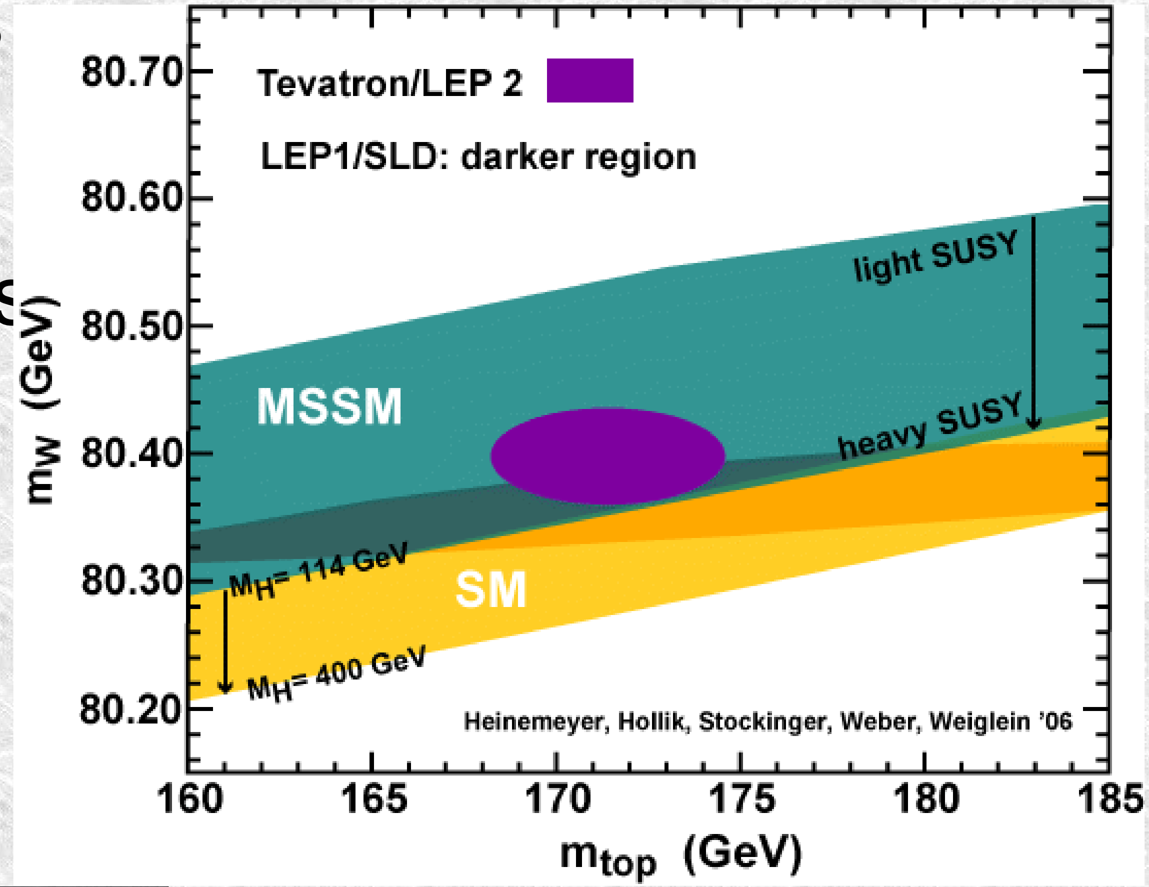
Look at control



- 10% off around 120GeV.
- This is not good enough for s/b 1/10

Supersymmetry

- EW fit result favours SUSY region:
  - Heavy SUSY
- SUSY has two Higgs doublets
  - 5 Higgses
- Two parameters:
  - M_A, $\tan\beta$



$$M^2_{H^0,h} = \frac{1}{2}\left[M_A^2 + M_Z^2 \pm \sqrt{M_A^2 + M_Z^2 \; - 4M_A^2 M_Z^2 \cos^2 2.}\right]$$

$$\Rightarrow M_h^2 + M_{H^0}^2 = M_A^2 + M_Z^2$$

$$M_H^2 = M_A^2 + M_W^2$$

Including Run II CDF $M_{W,}$ not m_T