Physics at Hadron Colliders

Lecture III

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CERN, Summer Student Lectures, 2010

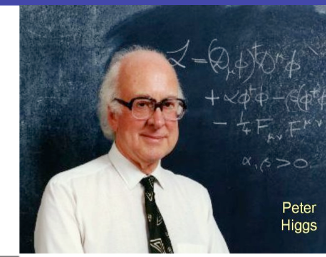
Outline

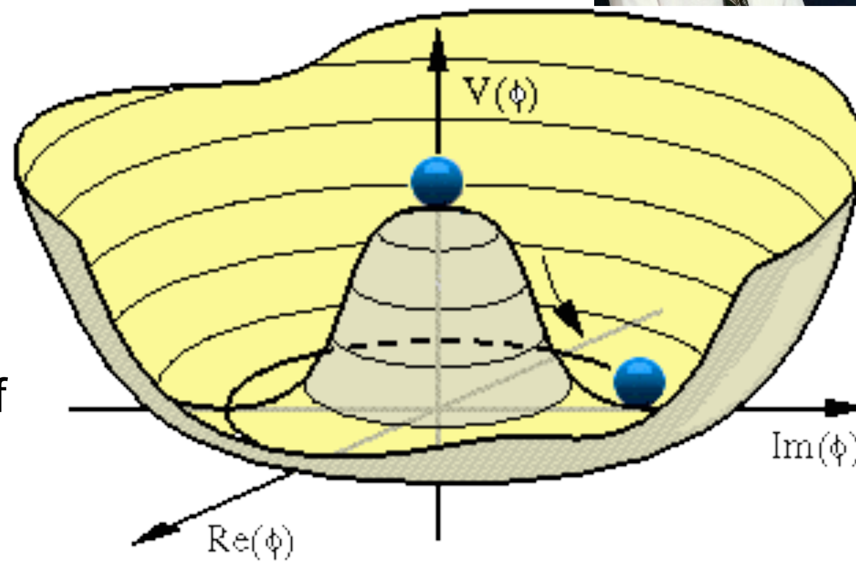
- **Lecture I: Introduction**
  - Outstanding problems in particle physics
    - and the role of hadron colliders
  - Current colliders: Tevatron and LHC
  - Hadron-hadron collisions
- **Lecture II: Standard Model Measurements**
  - Tests of QCD
  - Precision measurements in electroweak sector
- **Lecture III: Searches for the Higgs Boson**
  - Standard Model Higgs Boson
  - Higgs Bosons beyond the Standard Model
- **Lecture IV: Searches for New Physics**
  - Supersymmetry
  - High Mass Resonances (Extra Dimensions etc.)

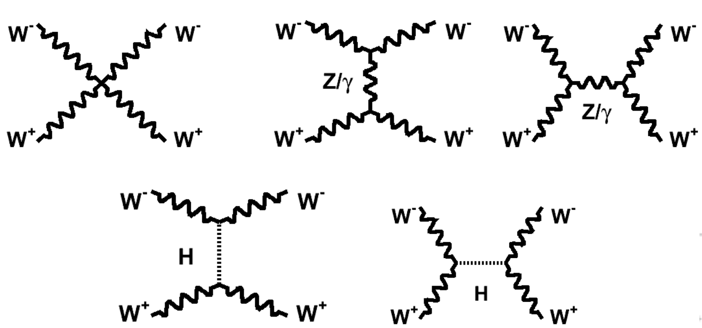
The Higgs Boson

- Electroweak Symmetry breaking
  - caused by scalar Higgs field
- vacuum expectation value of the Higgs field $\langle\Phi\rangle$ =246 GeV/c^2
  - gives mass to the W and Z gauge bosons,
    - $M_W \propto g_W \langle\Phi\rangle$
  - fermions gain a mass by Yukawa interactions with the Higgs field,
    - $m_f \propto g_f \langle\Phi\rangle$
  - Higgs boson couplings are proportional to mass
- Higgs boson prevents unitarity violation of WW cross section
  - $\sigma(pp \rightarrow WW) > \sigma(pp \rightarrow \text{anything})$
    - => illegal!
    - At $\sqrt{s}$=1.4 TeV!

Peter Higgs







$$A \approx g^2 \frac{E^2}{M_W^2}$$

$$A \approx -g^2 \frac{E^2}{M_W^2}$$

Terms which grow with energy cancel for E >> M_H

This cancellation requires M_H < 800 GeV

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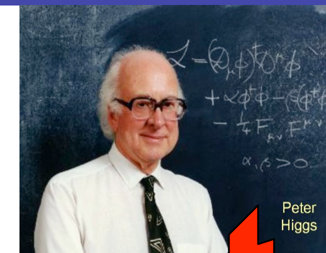
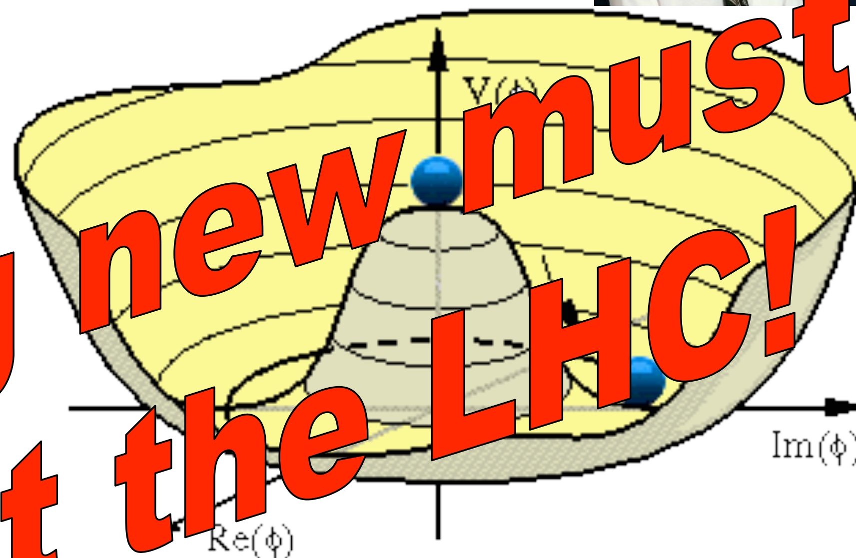
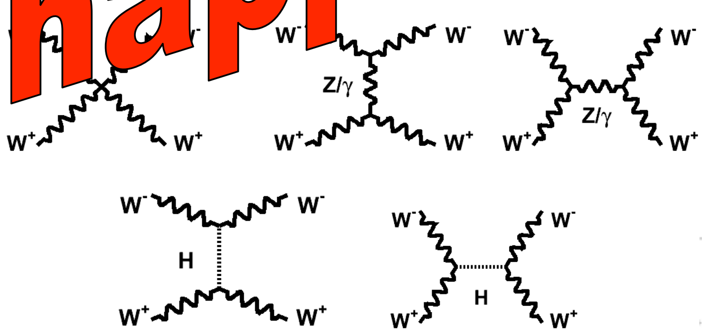




Something new must happen at the LHC!



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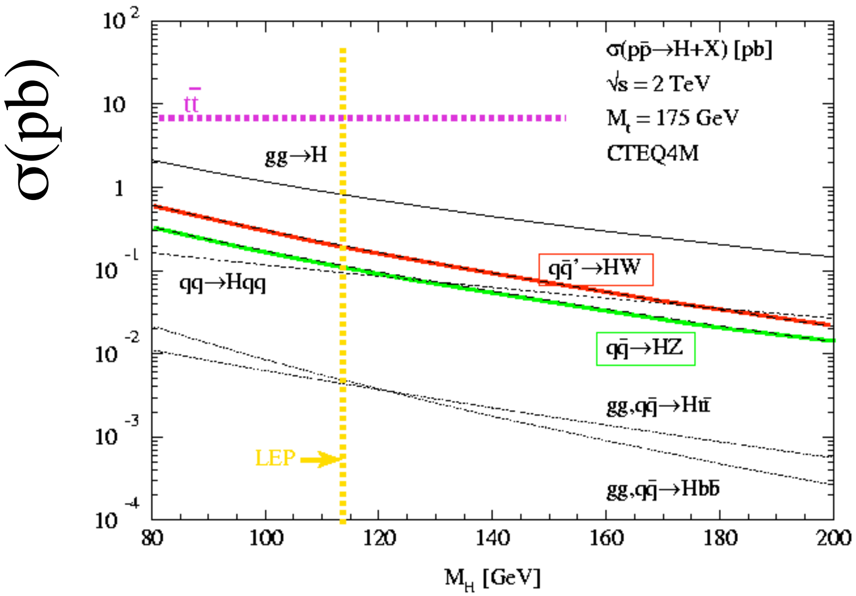
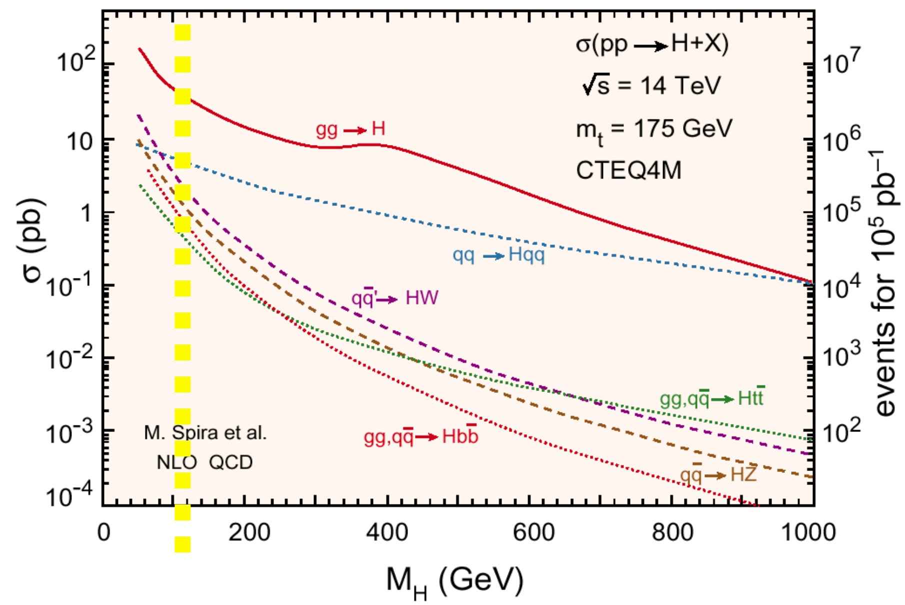
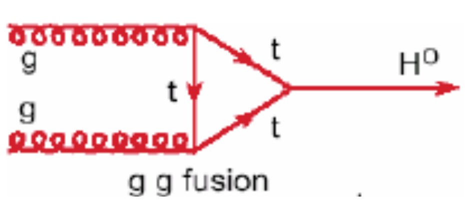
Higgs Production: Tevatron and LHC

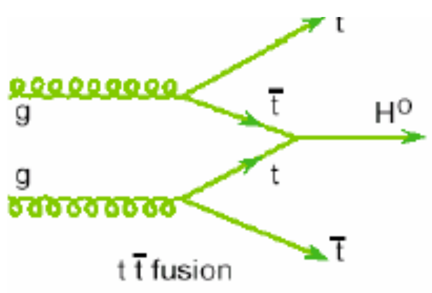
Tevatron

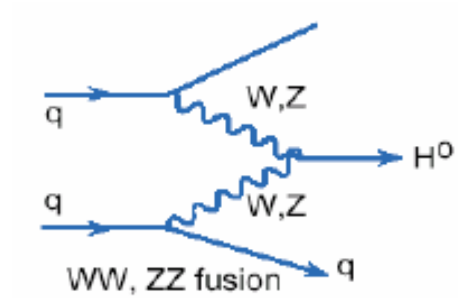


LHC





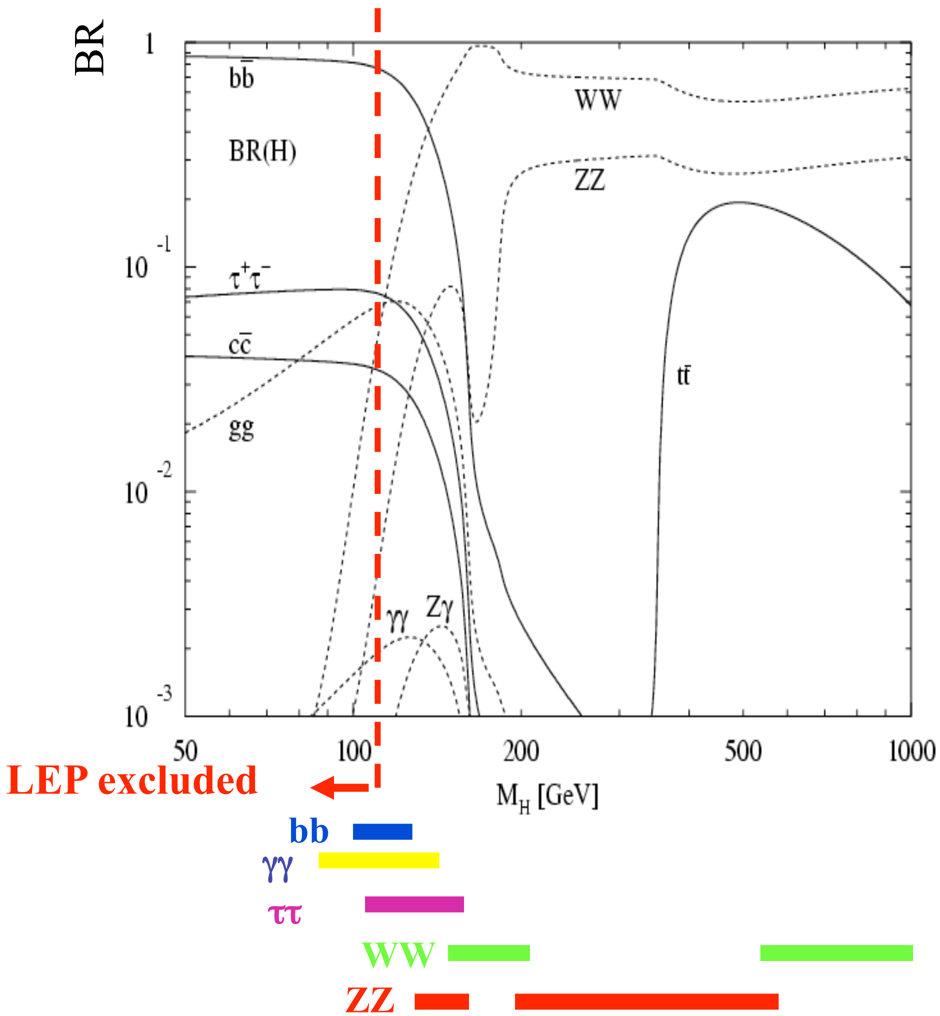




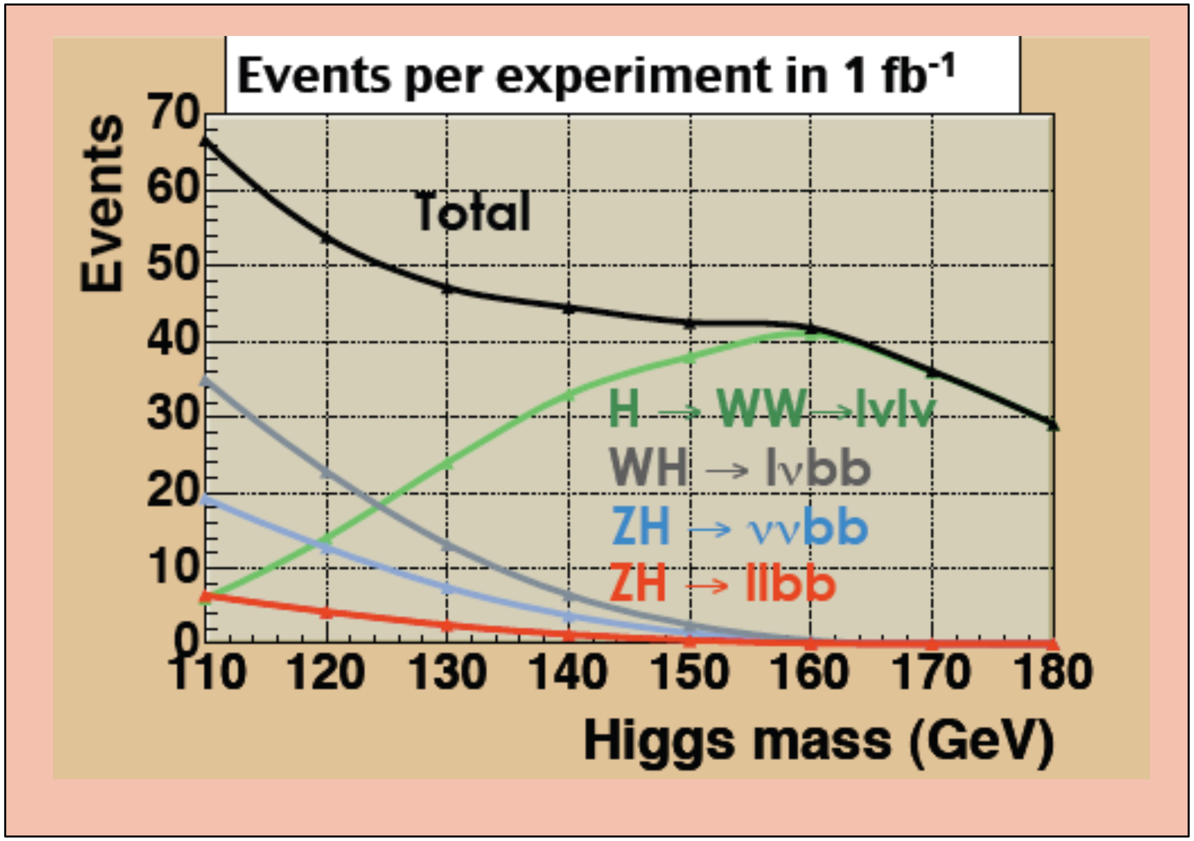
dominant: gg→ H, subdominant: HW, HZ, Hqq

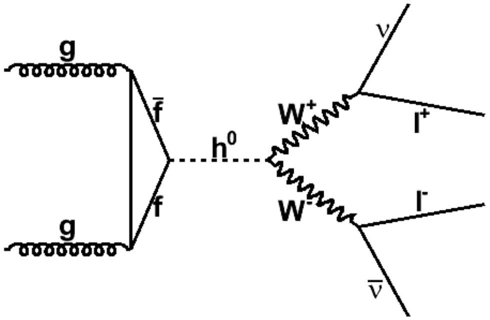
Higgs Boson Decay

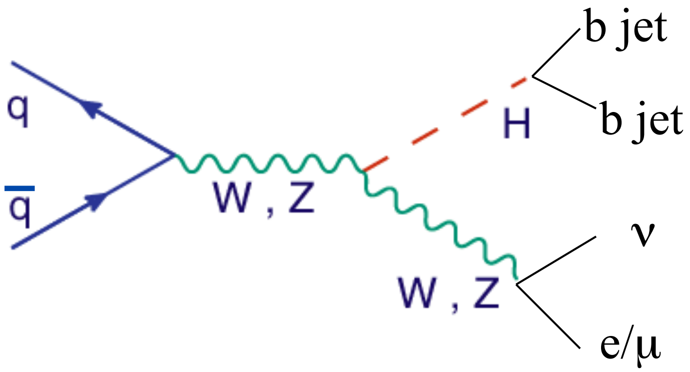
- Depends on Mass
- M_H<130 GeV/c^2:
  - $b\bar{b}$ dominant
  - WW and $\tau\tau$ subdominant
  - $\gamma\gamma$ small but useful
- M_H>130 GeV/c^2:
  - WW dominant
  - ZZ cleanest



Tevatron Discovery Channels







M(H)>125 GeV: WW is best

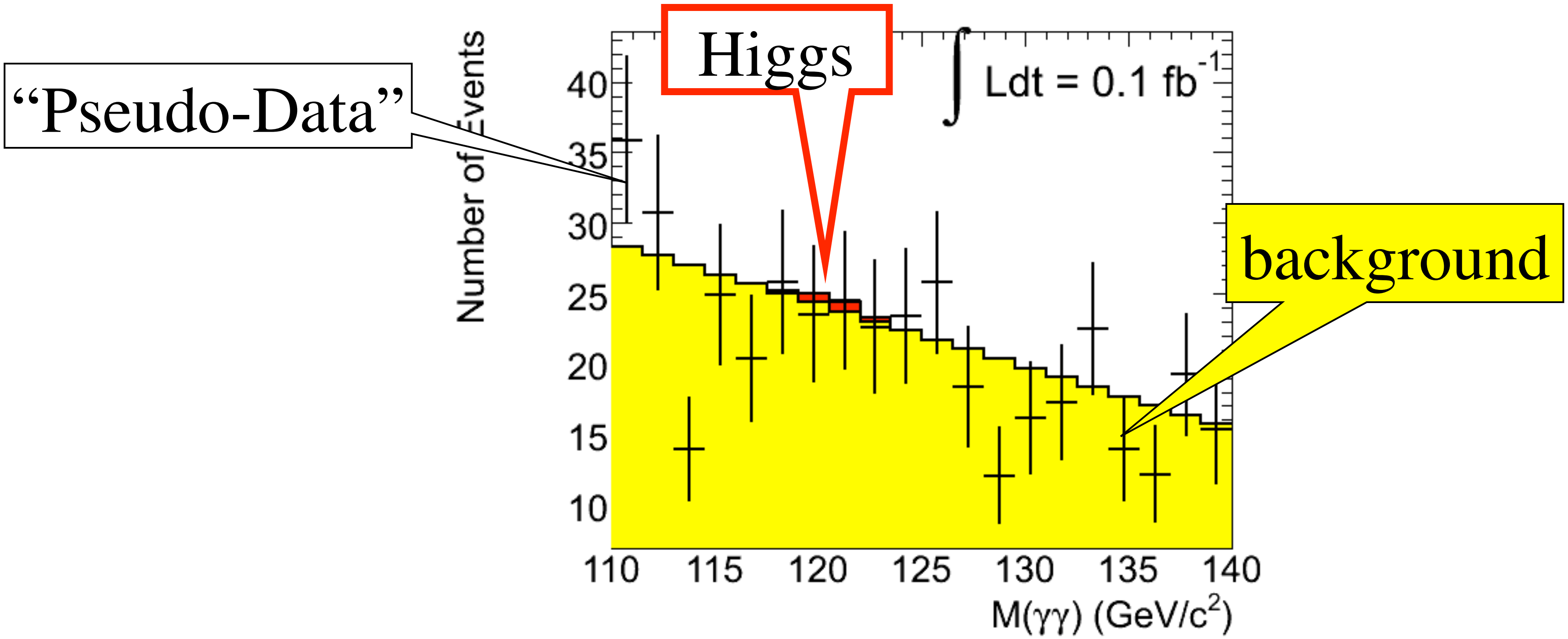
M(H)<125 GeV: WH and ZH become important

How to make a Discovery

- This is a tricky business!
  - Lot's of complicated statistical tools needed at some level
- But in a nutshell:
  - Need to show that we have a signal that is inconsistent with being background
    - Number of observed data events: N_{Data}
    - Number of estimated background events: N_{Bg}
  - Need number of observed data events to be inconsistent with background fluctuation:
    - Background fluctuates statistically: $\sqrt{N_{Bg}}$
  - Significance: $S/\sqrt{B}=(N_{Data}-N_{Bg})/\sqrt{N_{Bg}}$
    - Require typically 5σ, corresponds to probability of statistical fluctuation of 5.7×10^{-7}
    - Increases with increasing luminosity: $S/\sqrt{B} \sim \sqrt{L}$
    - All a lot more complex with systematic uncertainties…

A signal emerging with time

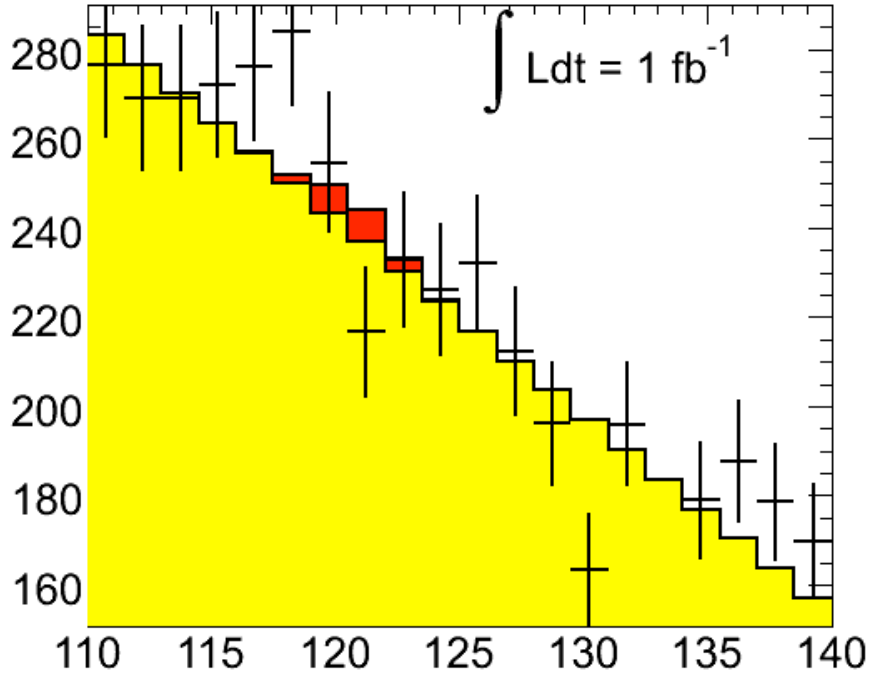
$\int Ldt = 0.1\ fb^{-1}$ (year: 2008/2009)



- Expected Events:
  - N_{higgs}~2, $N_{background}$=96 +/- 9.8
  - S/√B=0.2
- No sensitivity to signal

A signal emerging with time…

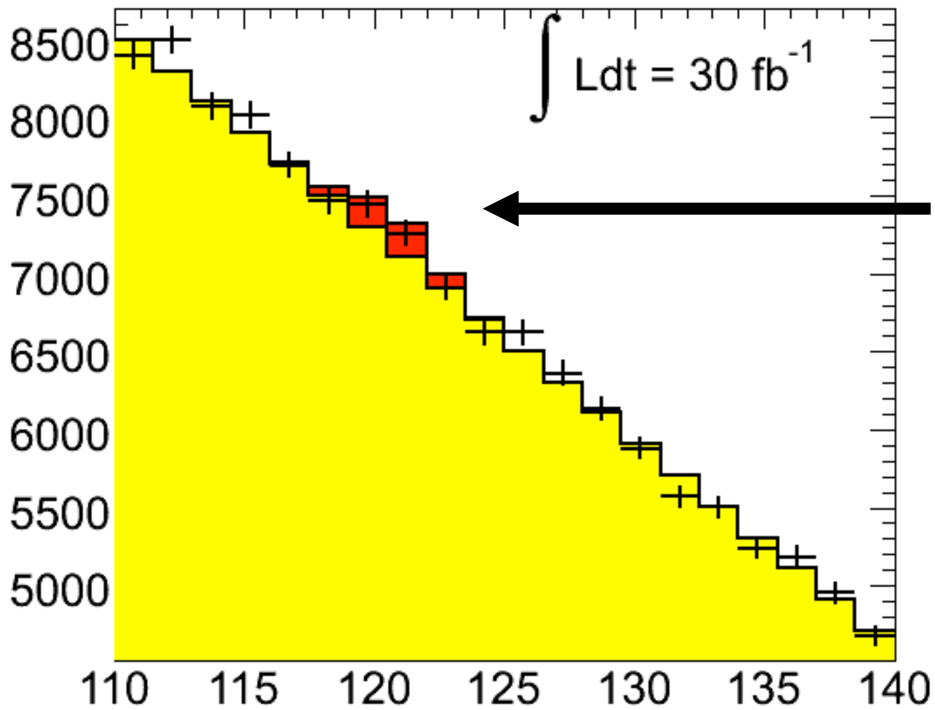
$\int Ldt = 1\ fb^{-1}$ (year: ~2009)



- Expected Events:
  - N_{higgs}~25, $N_{background}$~960 +/- 30
  - $S/\sqrt{B}=0.8$
- Still no sensitivity to signal

There it is!

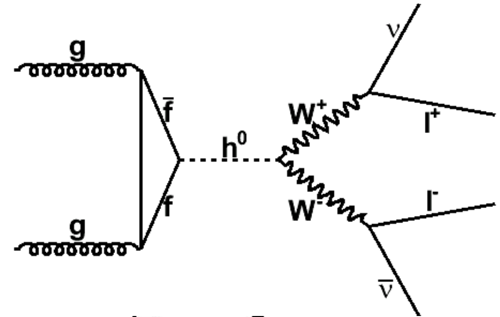
$\int L dt = 30\ fb^{-1}$ (year: 2011/2012?)



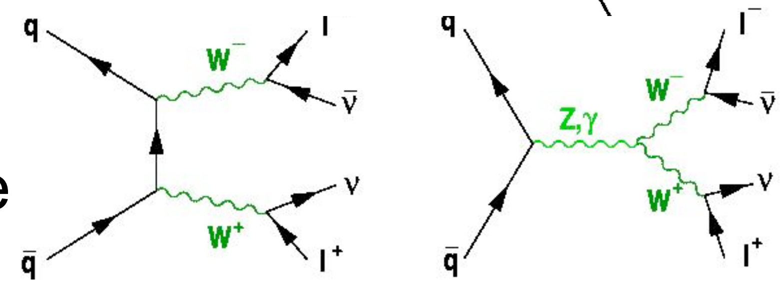
- Expected Events:
  - N_{higgs}~700, $N_{background}$=28700 +/- 170
  - S/√B=4.1
- Got it!!!

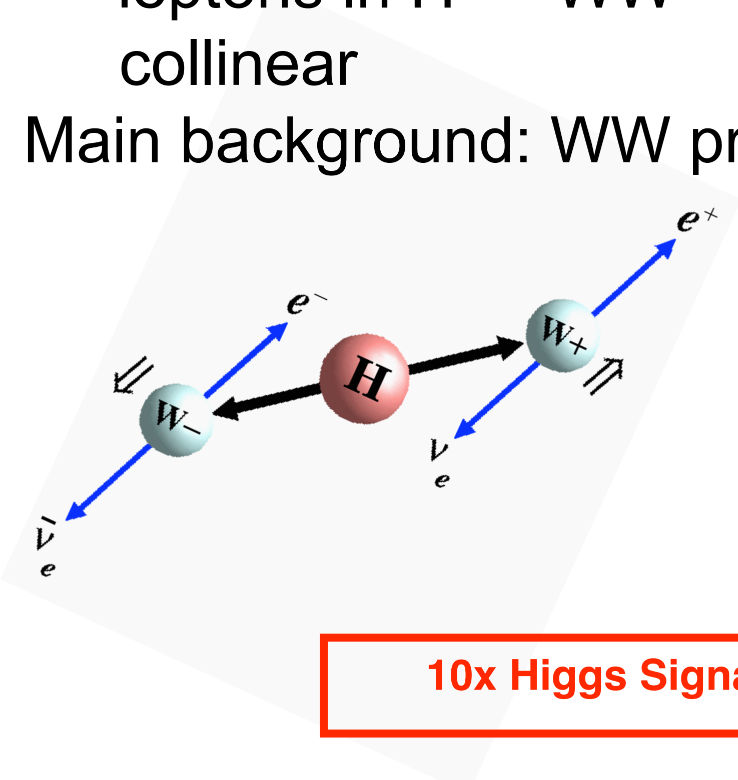
High Mass: m_H>140 GeV

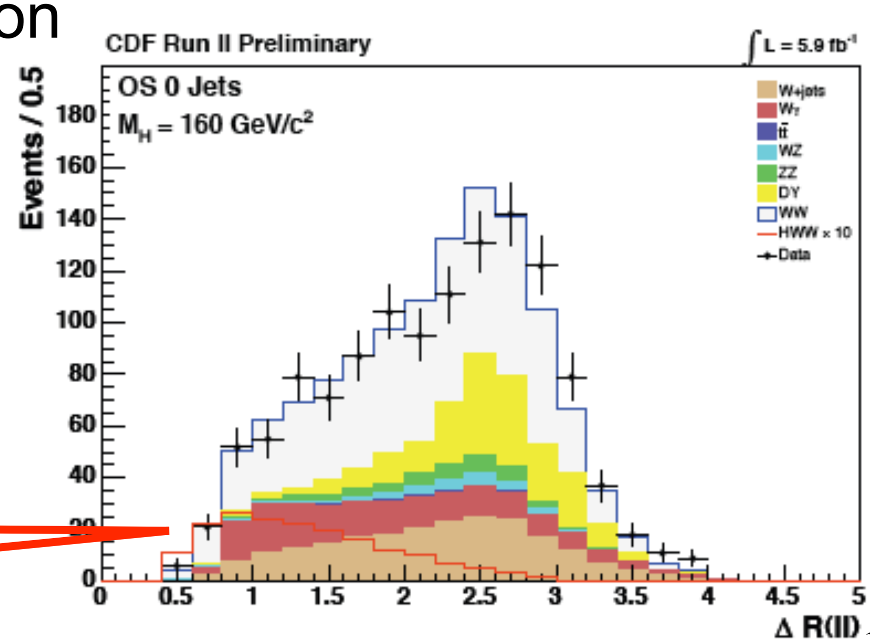
$H \to WW^{(*)} \to l^+l^-\nu\bar{\nu}$



- Higgs mass reconstruction impossible due to two neutrinos in final state
- Make use of spin correlations to suppress WW background:
  - Higgs is scalar: spin=0
  - leptons in $H \to WW^{(*)} \to l^+l^-\nu\nu$ are collinear
- Main background: WW production



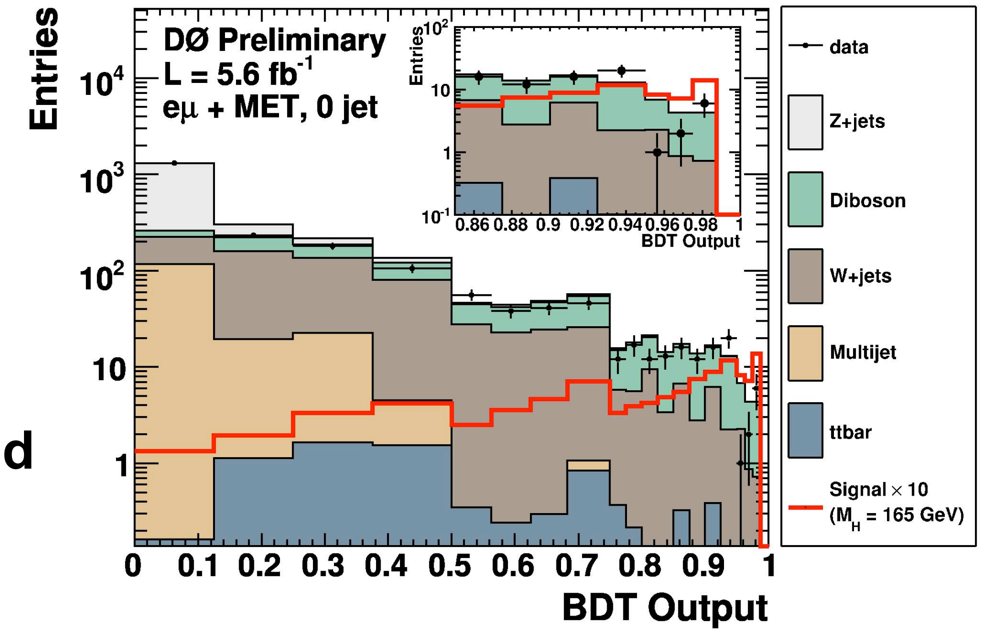




10x Higgs Signal

$H \to WW^{(*)} \to l^+l^-\nu\nu$ (l=e,μ)

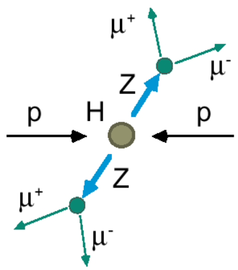
- **Event selection:**
  - 2 isolated e/μ :
    - p_T > 15, 10 GeV
  - Missing E_T >20 GeV
  - Veto on
    - Z resonance
    - Energetic jets

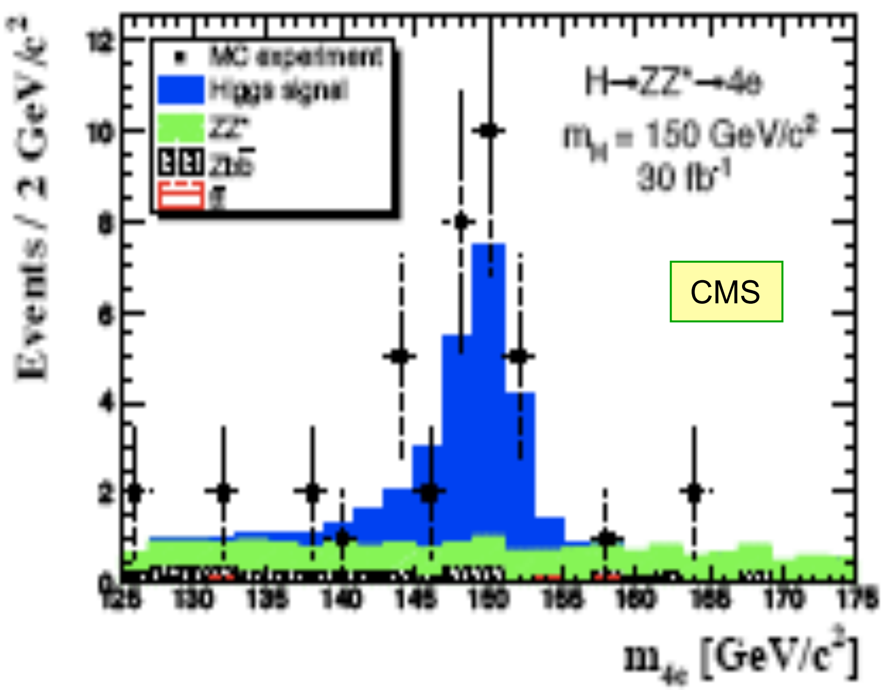


- **Separate signal from background**
  - Use discriminant to enhance sensitivity
  - Many varieties:
    - “Neural Network”, “Boosted Decision Tree”, “Likelihood”,… (see literature)
  - Basically combine many variables into one to exploit as much information as possible

No Higgs Signal found here

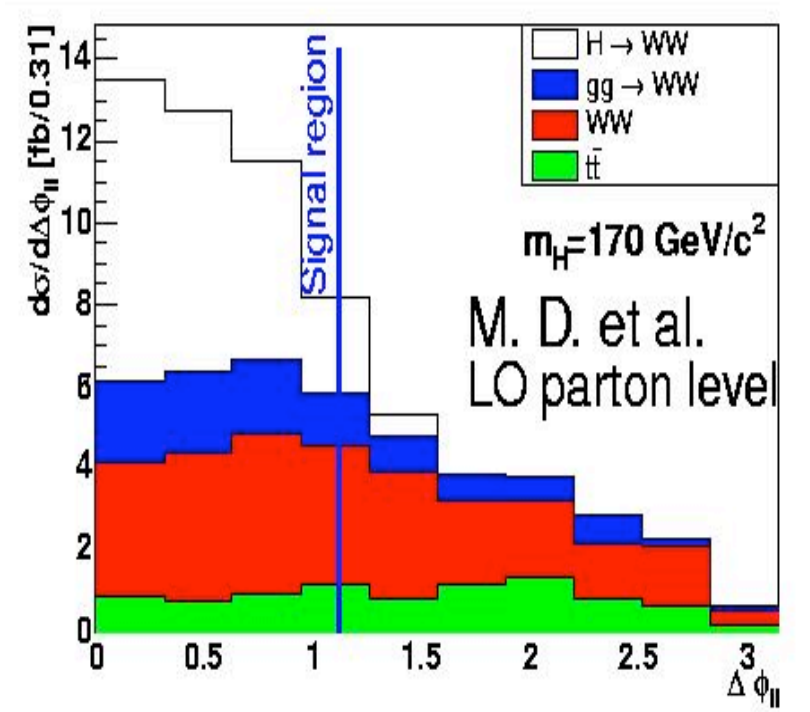
High Mass Higgs Signals at LHC





H→WW* (m_H=170 GeV)

ATLAS

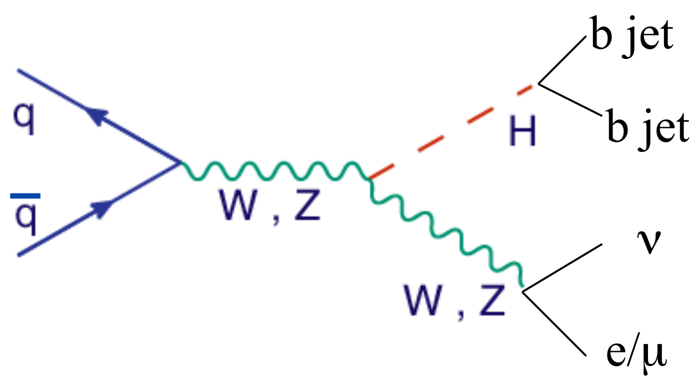


Clean signals on rather well understood backgrounds

Low Mass: m_H<140 GeV

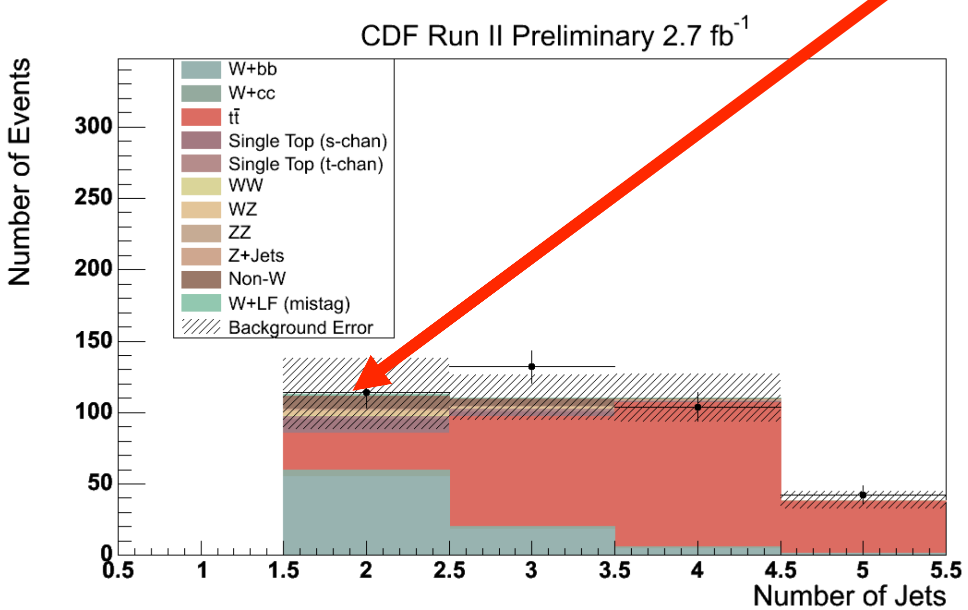
- Tevatron:
  - WH($\rightarrow$bb), ZH($\rightarrow$bb)
- LHC:
  - H($\rightarrow\gamma\gamma$), qqH($\rightarrow\tau\tau$/WW*), ttH($\rightarrow$bb)

WH→lνbb



- **WH selection:**
  - 1 or 2 tagged b-jets
  - electron or muon with p_T > 20 GeV
  - E_T^{miss} > 20 GeV

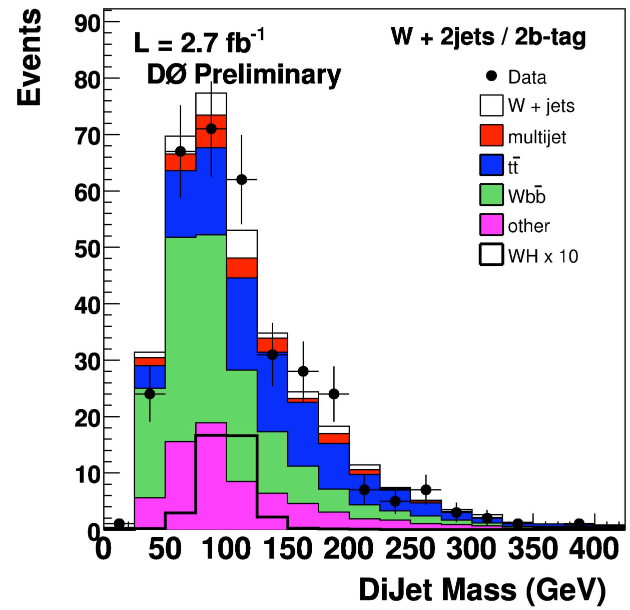
Looking for 2 jets

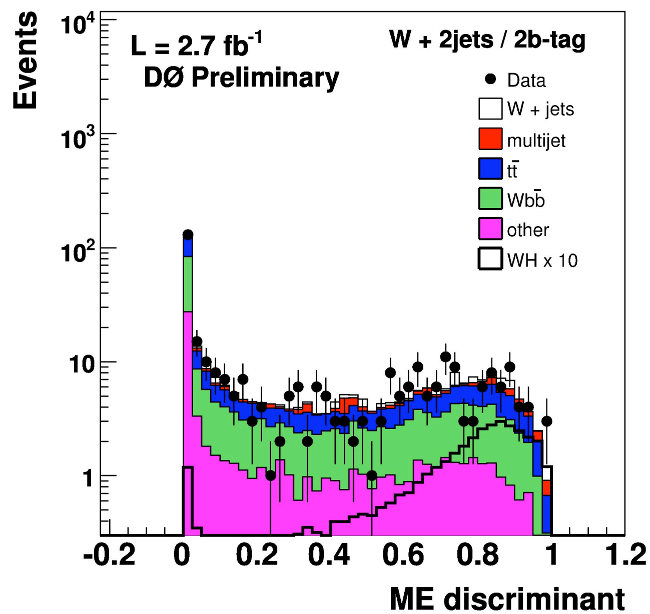


Expected Numbers of Events for 2 b-tags:
WH signal: 1.6
Background: 110±25

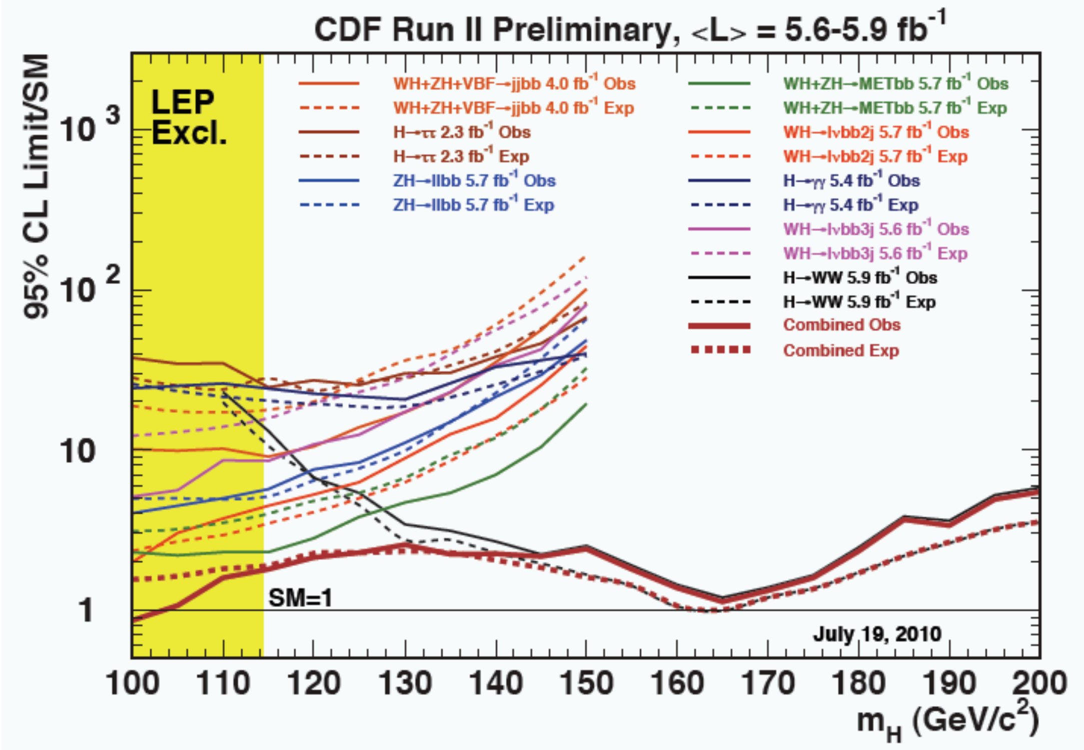
WH Dijet Mass distributions

- Use discriminant to separate signal from backgrounds:
  - Invariant mass of the two b-jets
    - Signal peaks at m(bb)=m_H
    - Background has smooth distribution
  - More complex:
    - Neural network or other advanced techniques
- Backgrounds still much larger than the signal:
  - Further experimental improvements and luminosity required
  - E.g. b-tagging efficiency (40->60%), *NN/ME selection*, higher lepton acceptance
- Similar analyses for ZH



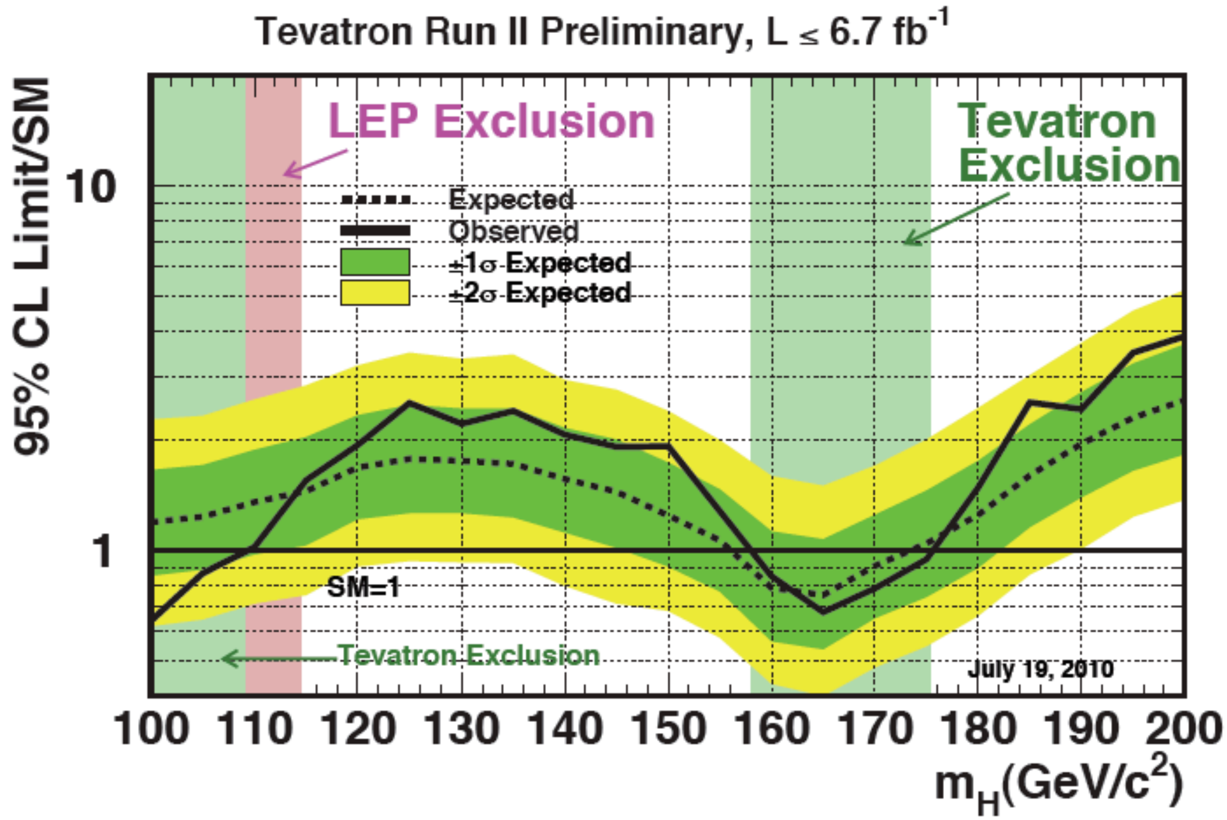


Tevatron Limits on the Higgs boson cross section



- Lack of observation
  - => an upper limit on the Higgs cross section
  - I.e. if the cross section was large we would have seen it!
- Results presented typically as ratio:
  - Experimental limit / theoretical cross section
  - If this hits 1.0 we exclude the Higgs boson at that mass!
- In this example from CDF only
  - Higgs boson excluded <104 GeV/c^2

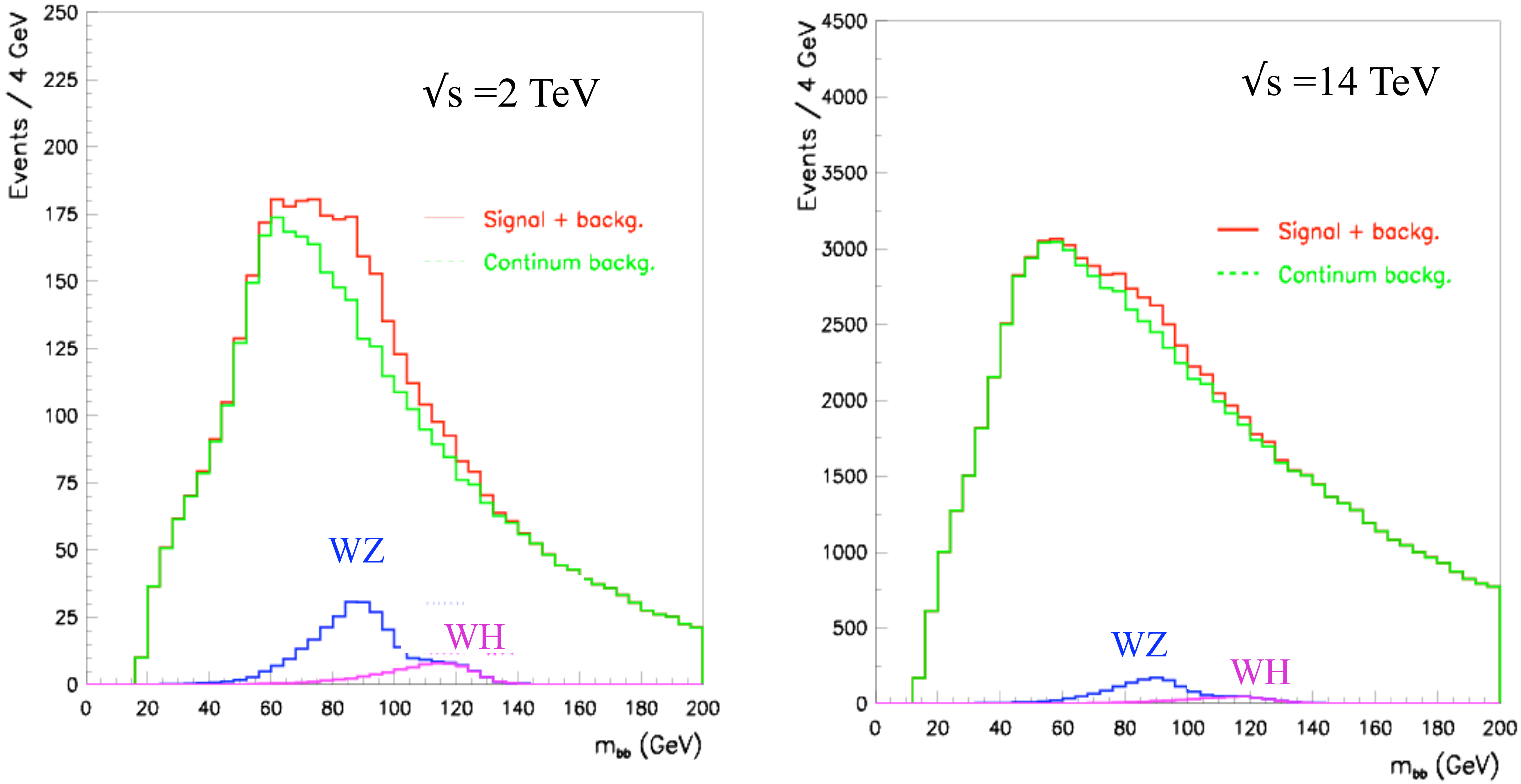
Tevatron Combined Status



- Combine CDF and DØ analyses from all channels at low and high mass
  - Exclude m_H=158-175 GeV/c^2 at 95% C.L.
  - m_H=120 GeV/c^2: limit/SM=1.5

Higgs at Low Mass: Tevatron vs LHC

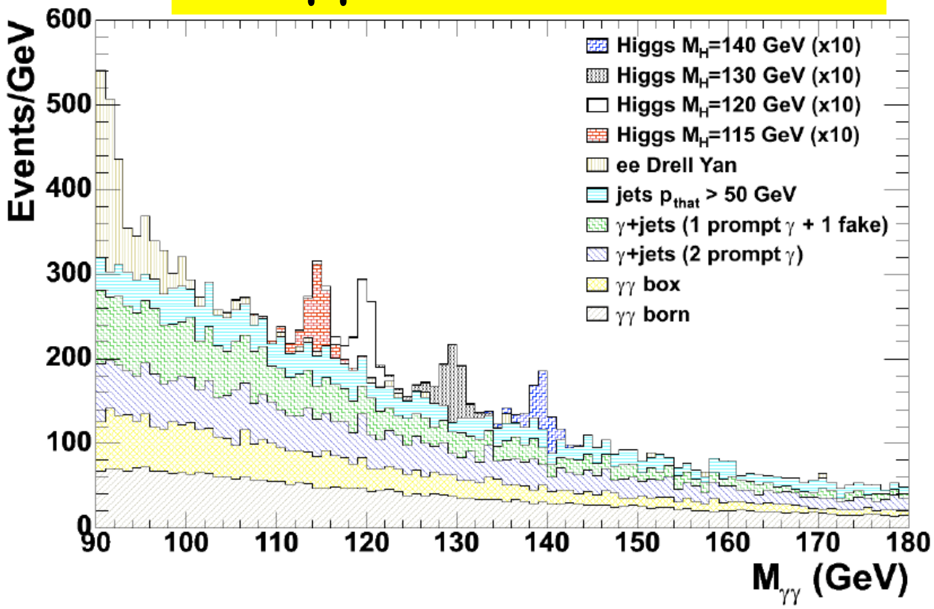
$M_H = 120$ GeV, 30 fb^{-1}



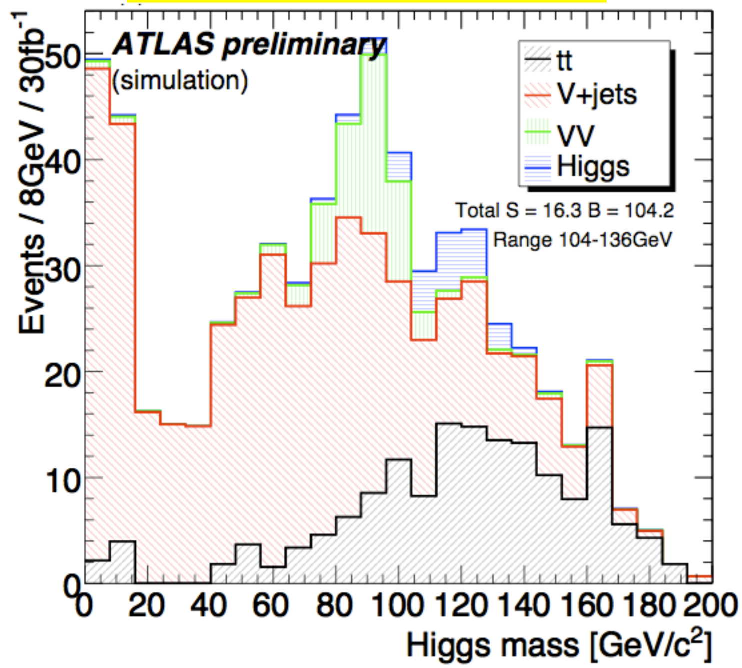
- WH channel:
  - Much larger backgrounds at LHC than at Tevatron
  - Use other channels / make harder selections

Low Mass Higgs Signals at LHC

H->γγ: CMS with 30 fb^{-1}

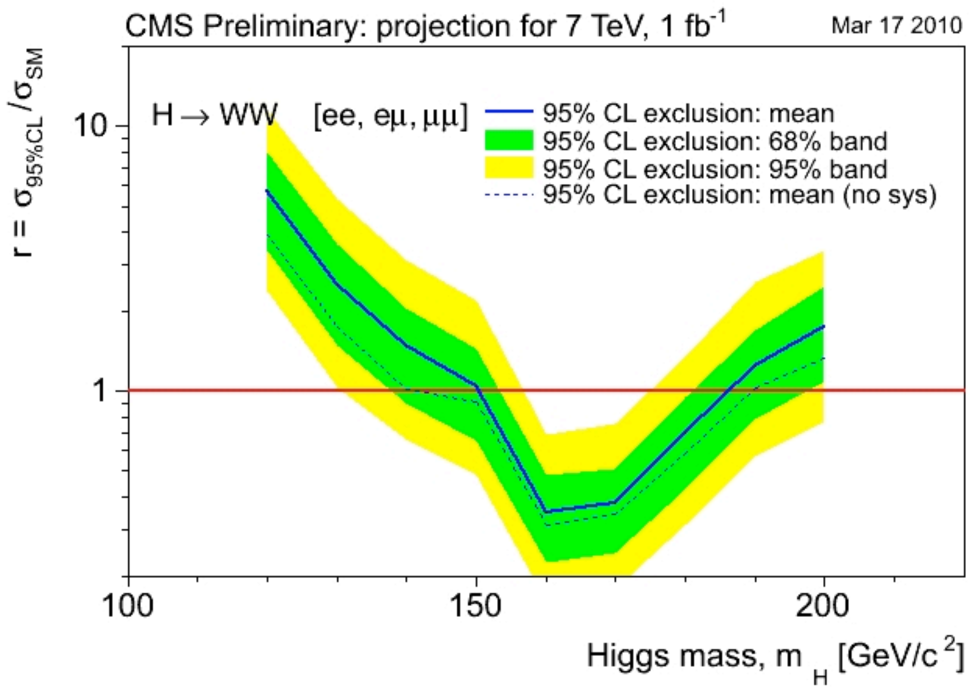


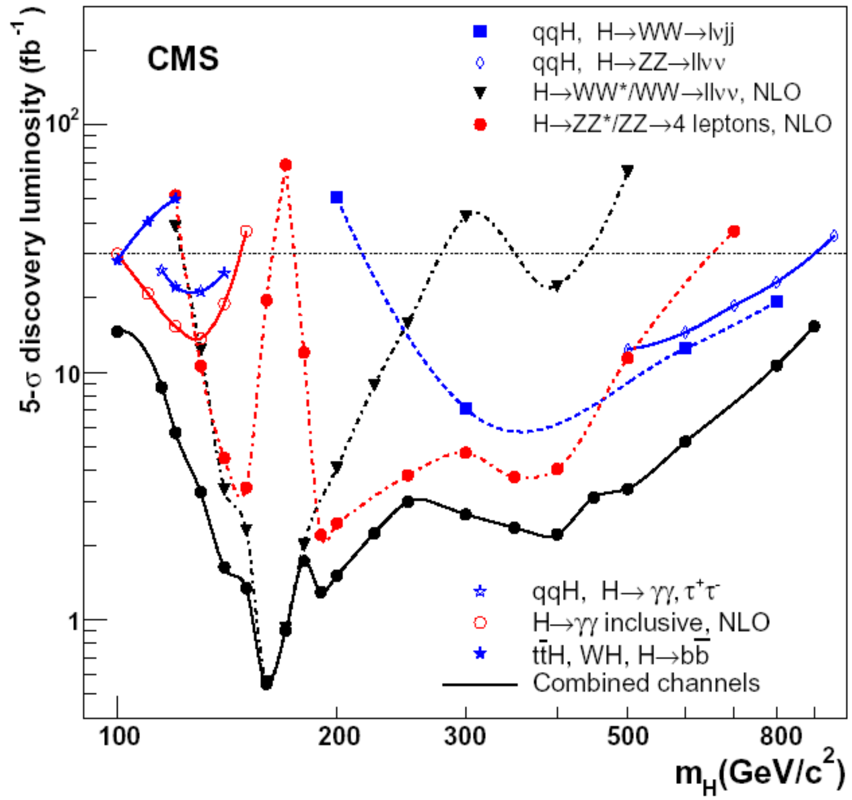
WH: ATLAS 30 fb^{-1}



- Main observation channels:
  - H→γγ
  - qqH→qqττ
  - W/Z+H with H->bb
- Discovery is very difficult
  - Requires at least 10 fb^{-1} (2013?)

LHC SM Higgs Discovery Potential





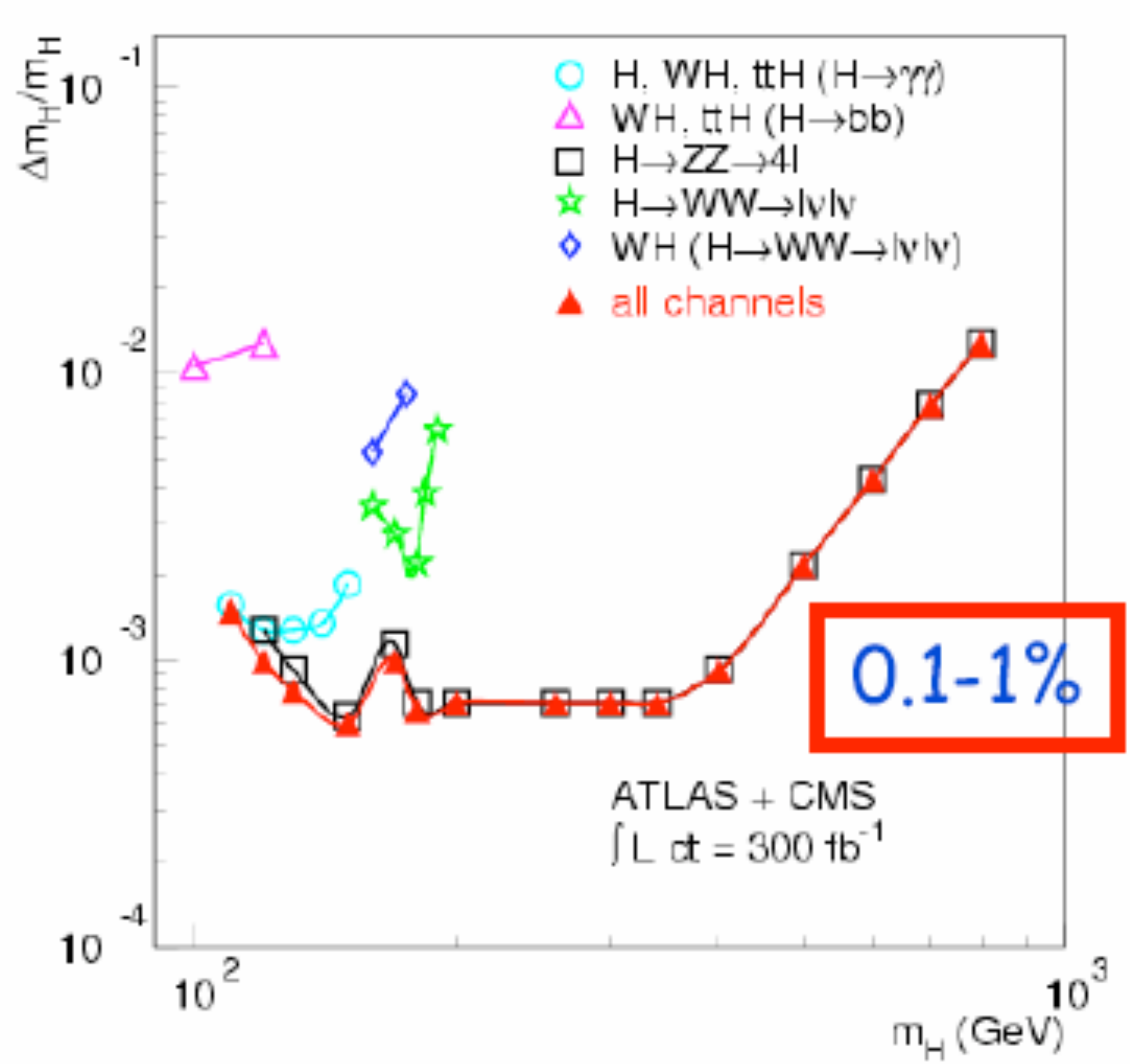
- **Exclusion similar to Tevatron with 1 fb^{-1} at high mass**
- **Discovery with L~4 fb^{-1} at high mass: m_H>150 GeV/c^2**
- **Harder at low mass: many channels contribute**

- **At latest with 30 fb^{-1} we will know if Higgs boson exists**

How do we know what we have found?

- After discovery we need to check it really is the Higgs boson
- Measure it’s properties:
  - The mass
  - The spin (very difficult…)
  - The branching ratio into all fermions
    - Verify coupling to mass
  - The total width (very difficult…)
    - Are there invisible decays?
- Check they are consistent with Higgs boson

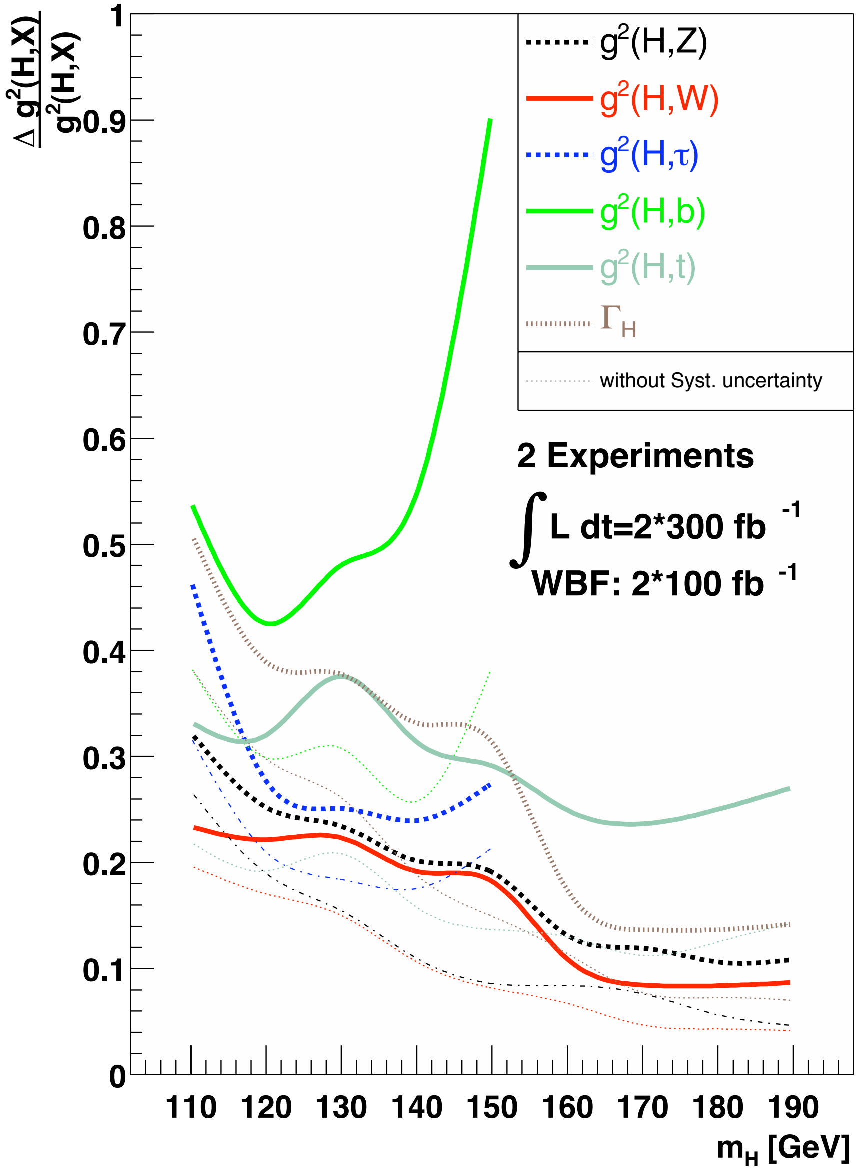
Mass



$\Delta m_H/m_H$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{2}
10^{3}
m_H (GeV)
H, WH, ttH (H→γγ)
WH, ttH (H→bb)
H→ZZ→4l
H→WW→lνlν
WH (H→WW→lνlν)
all channels
ATLAS + CMS
∫L dt = 300 fb^{-1}
0.1-1%

Coupling Measurements at LHC

Duehrssen et al hep-ph/0407190

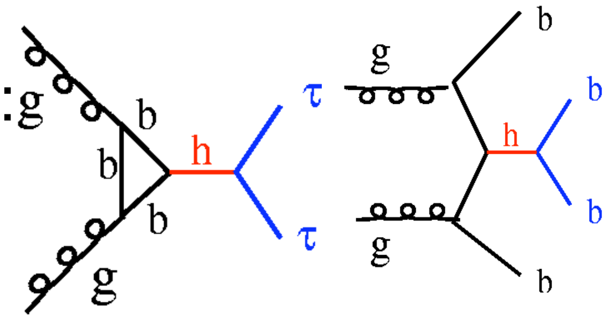


- Measure couplings of Higgs to as many particles as possible
  - $H \to ZZ$
  - $H \to WW$
  - $H \to \gamma\gamma$
  - $H \to bb$
  - $H \to \tau\tau$
- And in different production modes:
  - $gg \to H$ (tH coupling)
  - $WW \to H$ (WH coupling)
- Verifies that Higgs boson couples to mass

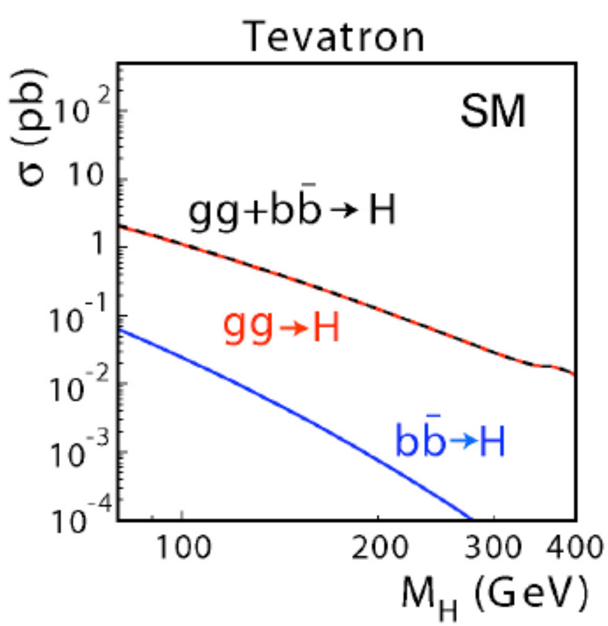
Non Standard-Model Higgs Bosons

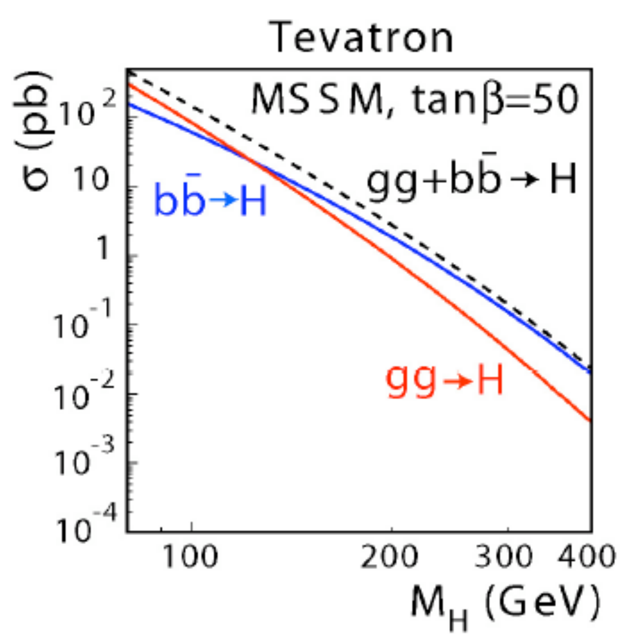
Higgs in Supersymmetry (MSSM)

- Minimal Supersymmetric Standard Model:
  - 2 Higgs-Fields: Parameter $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$
  - 5 Higgs bosons: h, H, A, $H^{\pm}$
- Neutral Higgs Boson:
  - Pseudoscalar A
  - Scalar H, h
    - Lightest Higgs (h) very similar to SM



$$\sigma \times BR_{SUSY} = 2 \times \sigma_{SM} \times \frac{\tan\beta^2}{(1+\Delta_b)^2} \times \frac{9}{[9+(1+\Delta_b)^2]}$$

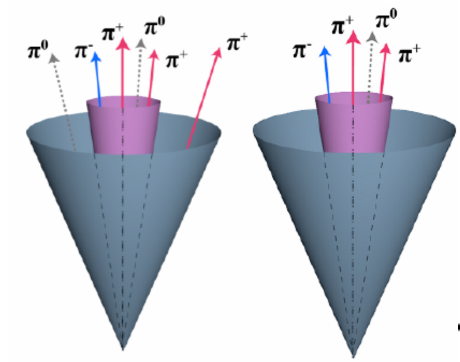


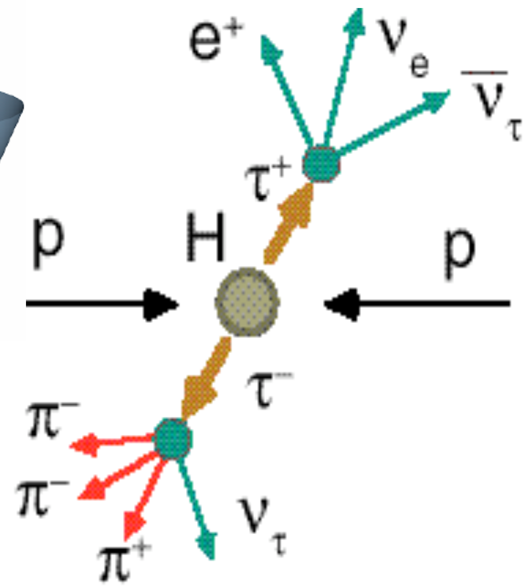


C. Balazs, J.L. Diaz-Cruz, H.J.He, T.Tait and C.P. Yuan, PRD 59, 055016 (1999)

MSSM Higgs Selection

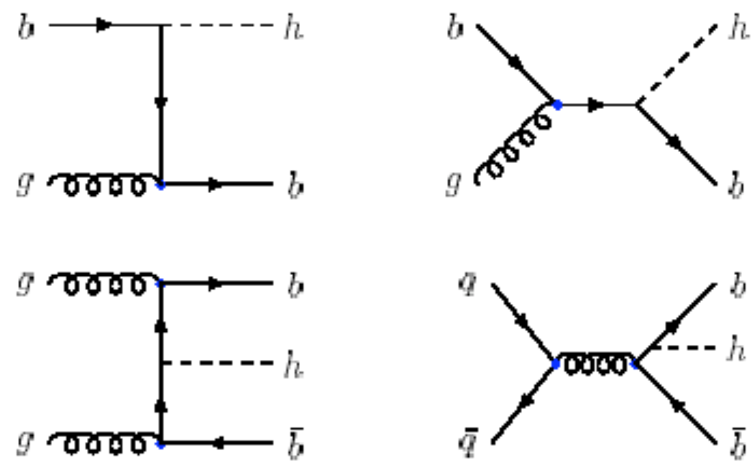
- $pp \rightarrow \Phi + X \rightarrow \tau\tau + X$:
  - One τ decays to e or μ
  - One τ decays to hadrons or e/μ
  - They should be isolated
  - Efficiency: ~50%
  - Fake rate ~0.1-1%
    - 10-100 times larger than for muons/ electrons



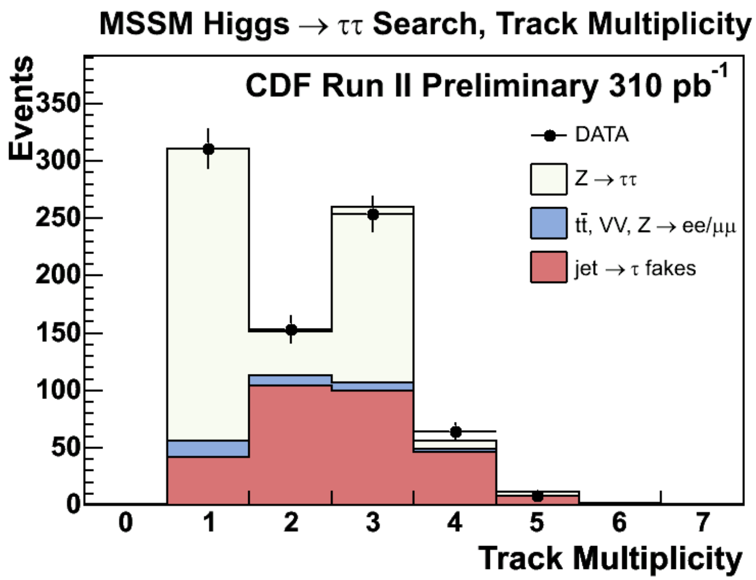


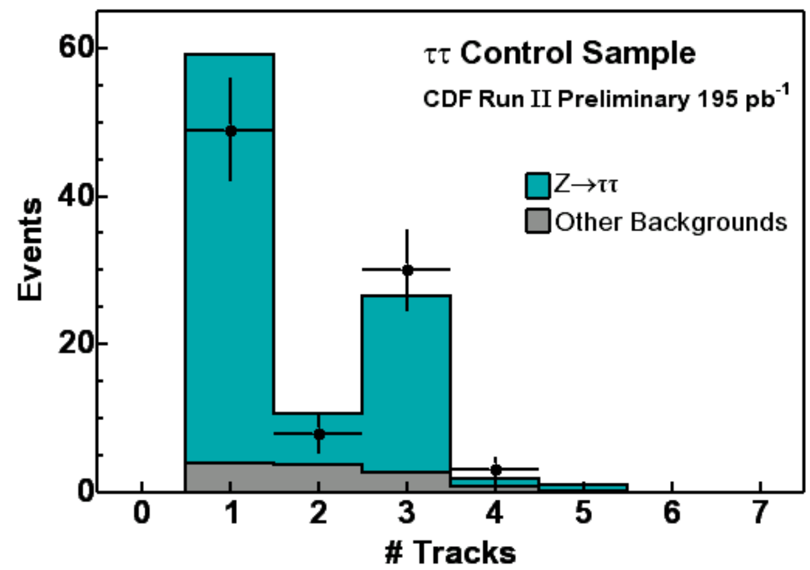
- $pp \rightarrow \Phi b + X \rightarrow bbb + X$:
  - Three b-tagged jets
    - E_T>35, 20 and 15 GeV
  - Use invariant mass of leading two je to discriminate against background

Φ =h/H/A

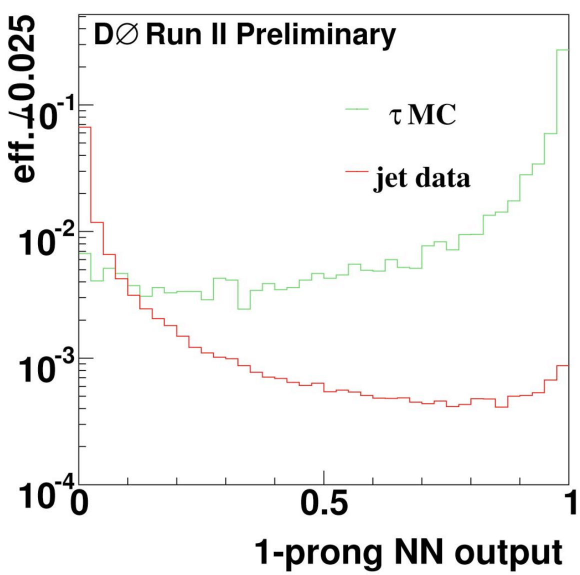


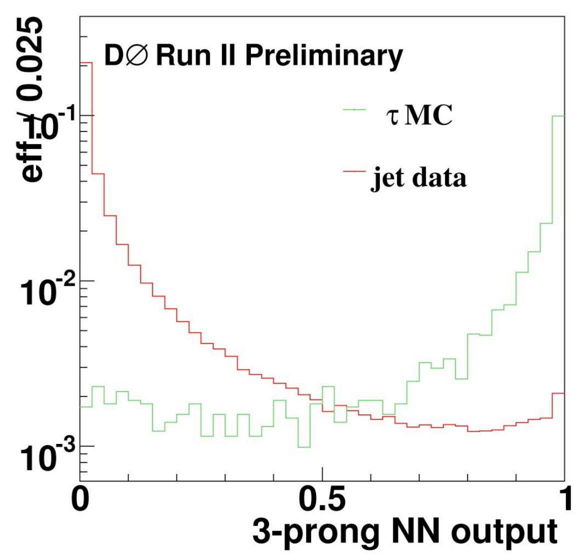
Tau Signals!





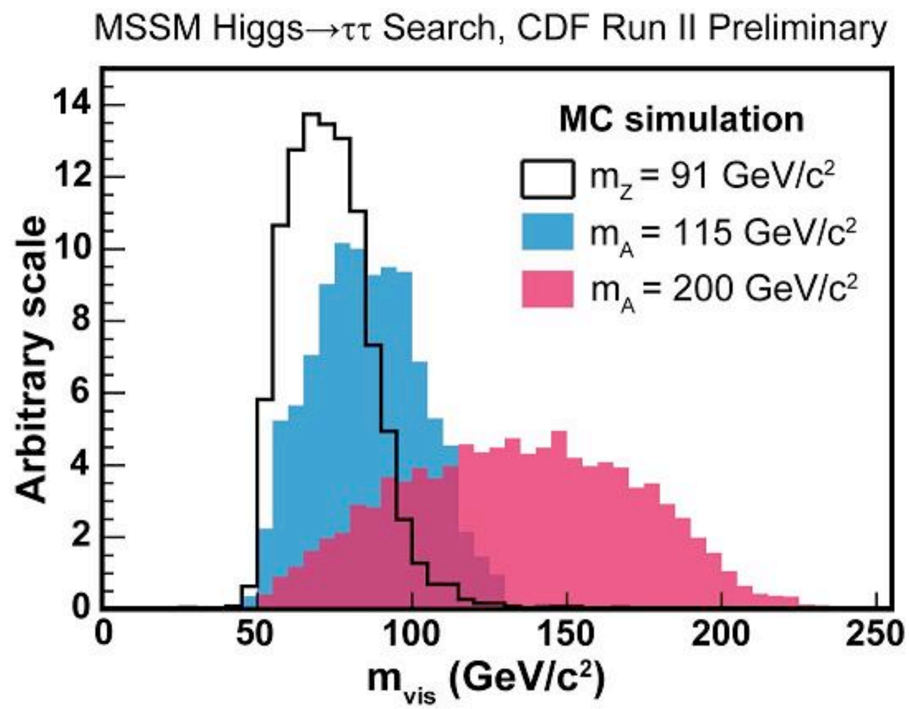
- Clear peaks at 1 and 3 tracks:
  - Typical tau signature
- DØ use separate Neural Nets for the two cases:
  - Very good separation of signal and background



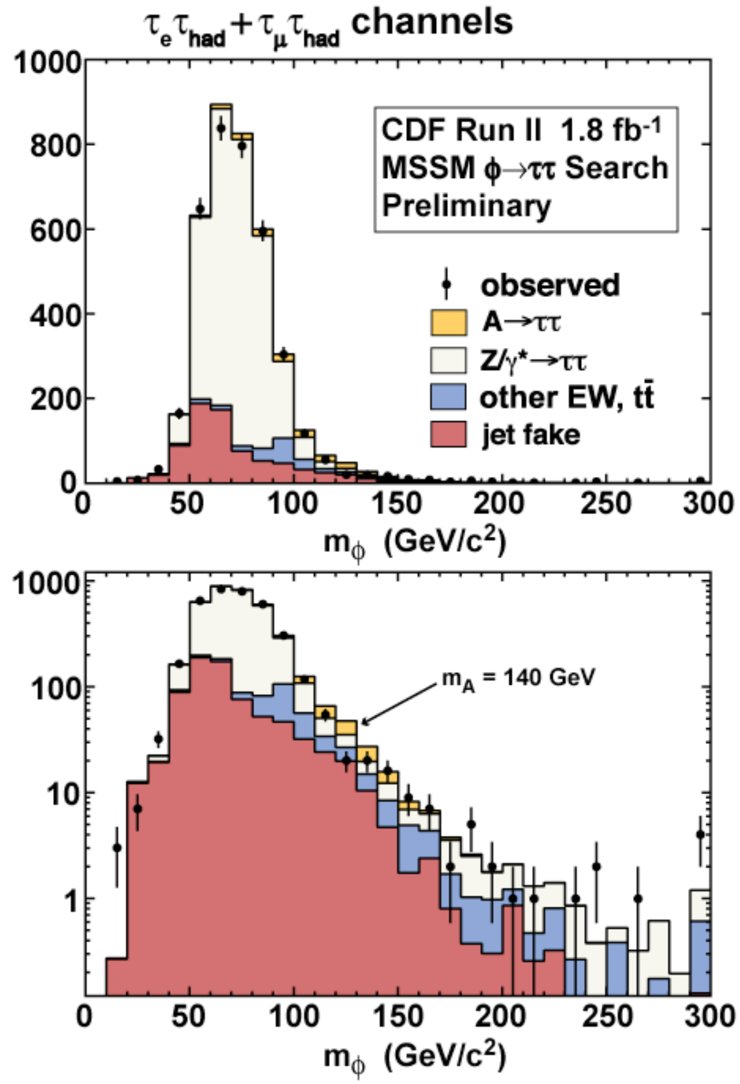


Di-tau Mass reconstruction

- Neutrinos from tau-decay escape:
  - No full mass reconstruction possible
- Use "visible mass":
  - Form mass like quantity: $m_{vis}=m(\tau, e/\mu, \not{E}_T)$
  - Good separation between signal and background
- Full mass reconstruction possible in boosted system, i.e. if $p_T(\tau, \tau)>20$ GeV:
  - Loose 90% of data statistics though!
  - Best is to use both methods in the future

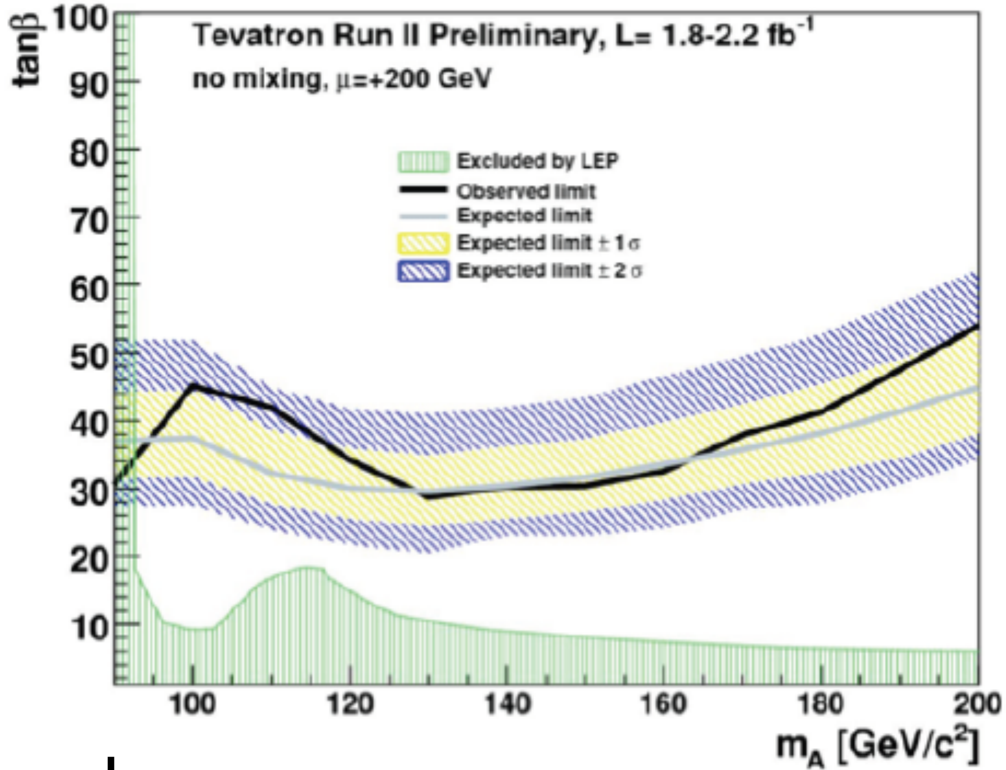


Di-Tau Higgs Boson Search



- Data agree with background prediction

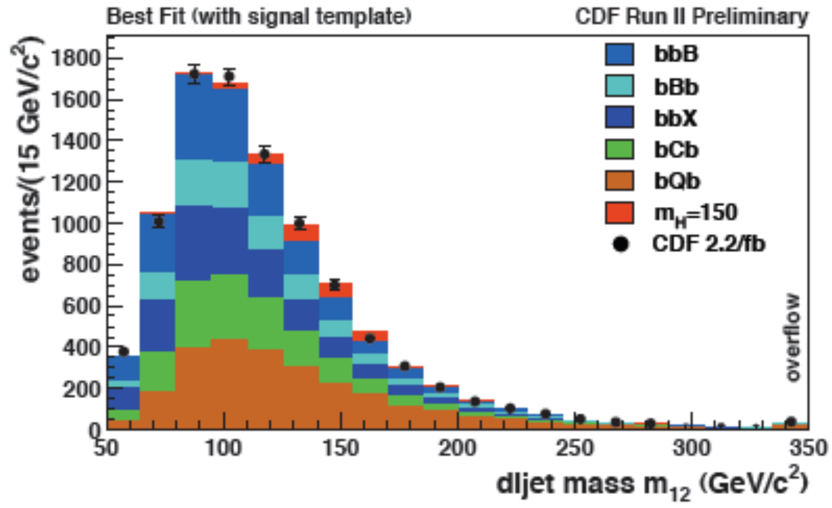
Limits on the MSSM Higgs

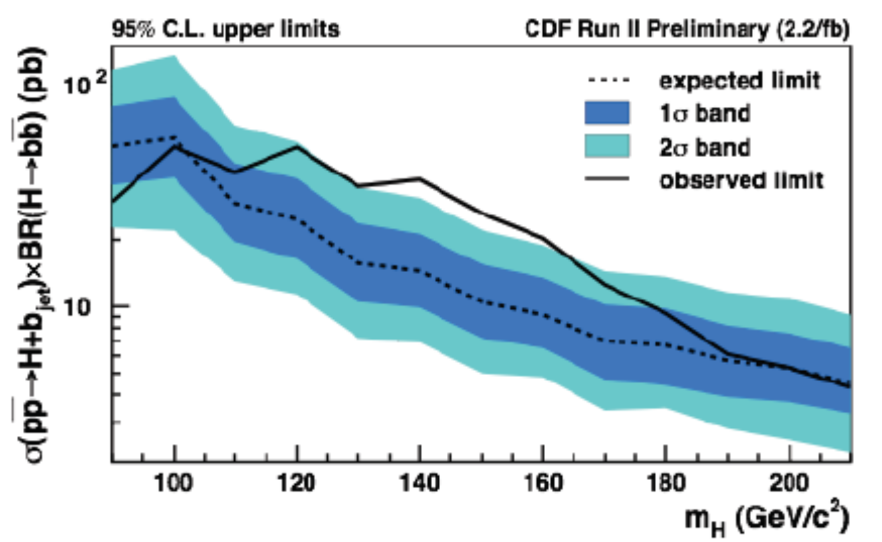


- Data agree with background
  - Use to put an upper limit on the cross section
  - Translate into SUSY parameter space using theoretical cross section prediction
    - E.g. exclude tanβ>30 for m_A=140 GeV/c^2

MSSM Higgs in 3b-jets channel

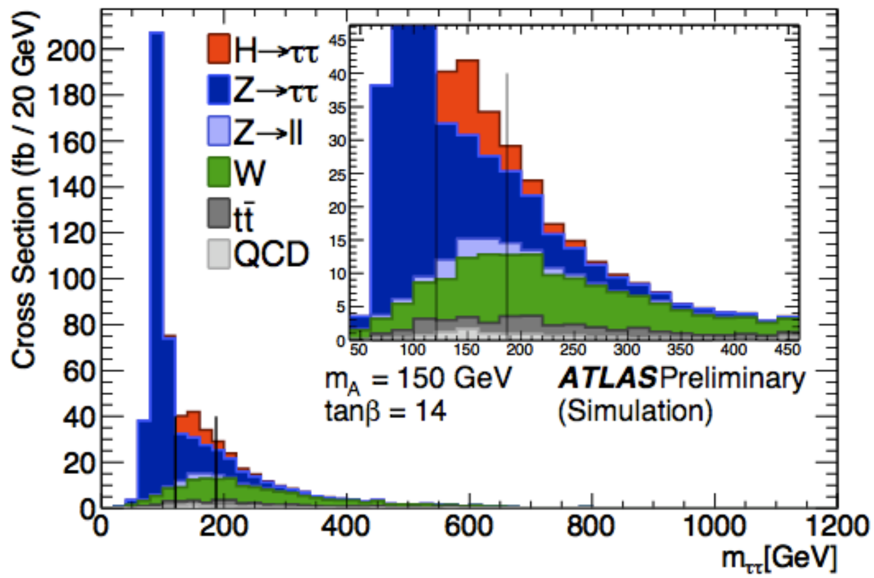
- Use events with 3 b-jets
- Invariant mass of leading two jets
  - Sensitive to m_A
- Data show an excess near 140 GeV
  - Probability of statistical fluctuation:
    - At 140 GeV: 0.9%
    - Anywhere: 5.7%
- Excess observed as weaker limit near ~140 GeV.
- Analyze more data / check what D0 and LHC find!!

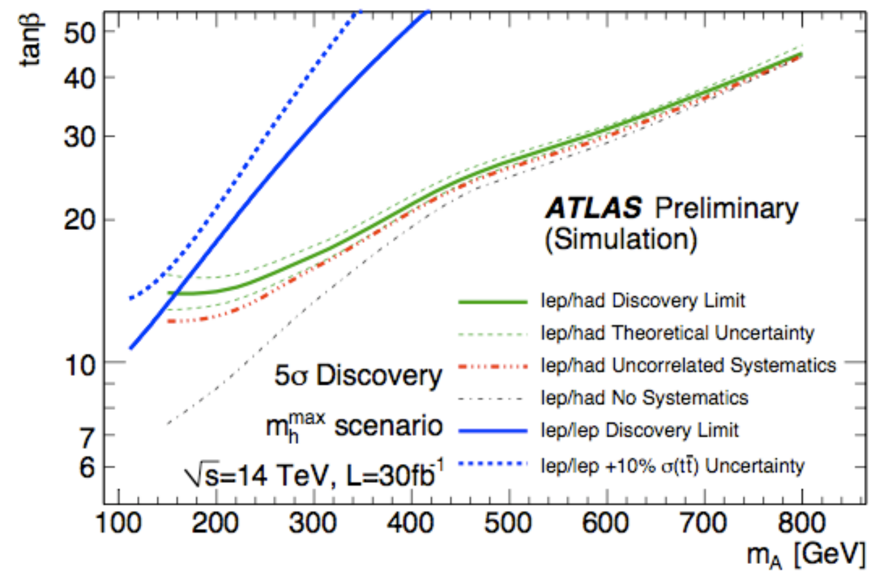




MSSM Higgs Bosons at LHC

30 fb^{-1}





- Similar analysis to the Tevatron experiments can be done at LHC
- With 30 fb^{-1} probe values of tanβ=15-40 for masses up to 800 GeV

Conclusions

- The Higgs boson is the last missing piece in the Standard Model
  - And arguably the most important SM particle
- Searches ongoing at the Tevatron
  - 95% exclusion in mass range 158-175 GeV
- LHC will find the Higgs boson if it exists
  - With >5σ significance
  - And measure some of it's properties
- If the Higgs boson does not exist
  - Some other mechanism must kick in to prevent unitarity violation => something has to be found at the LHC
- There might be more than one Higgs boson
  - E.g. in supersymmetry
  - They can be found too (hopefully)