

Physics at Hadron Colliders

Lecture III

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CERN, Summer Student Lectures, 2008

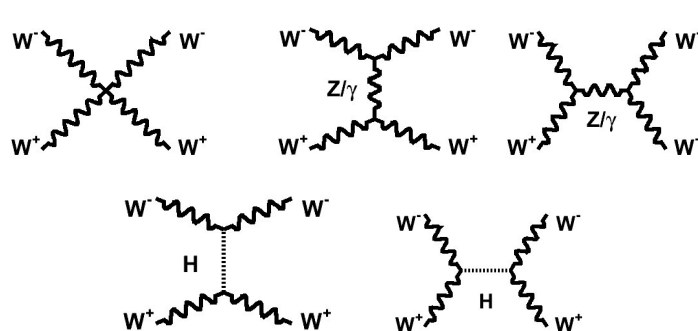
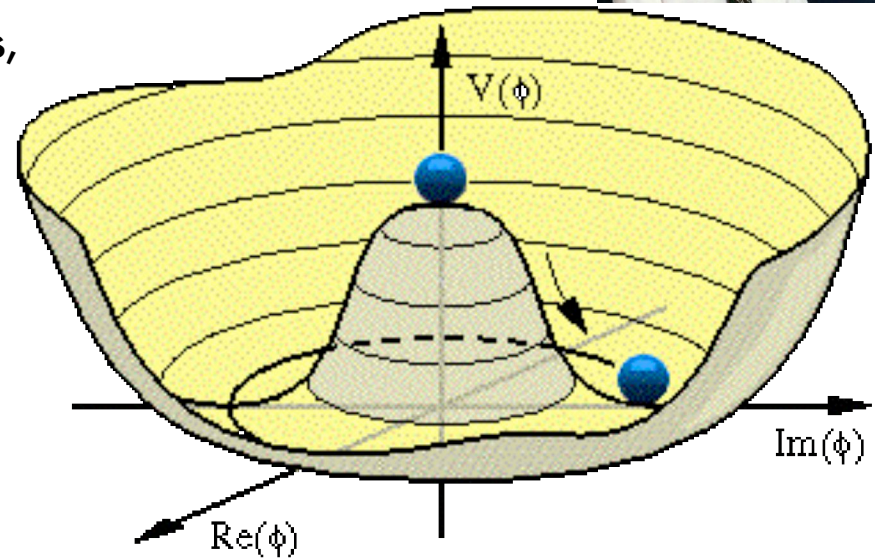
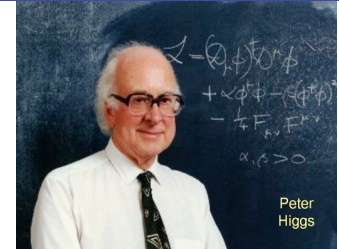
Outline

- **Lecture I: Introduction**
 - Outstanding problems in particle physics
 - and the role of hadron colliders
 - Current and near future 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 $\langle \Phi \rangle = 246 \text{ GeV}/c^2$
 - 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 $\sqrt{s} = 1.4 \text{ TeV}$!

Peter Higgs



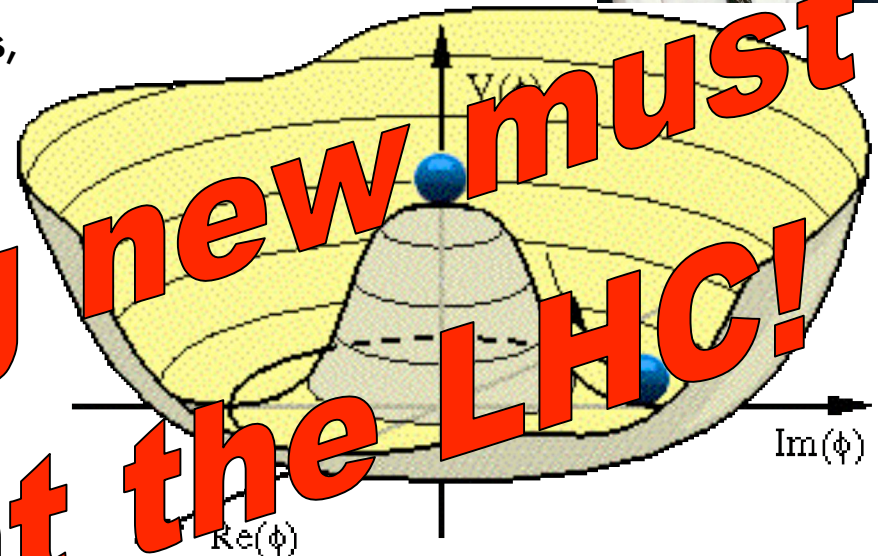
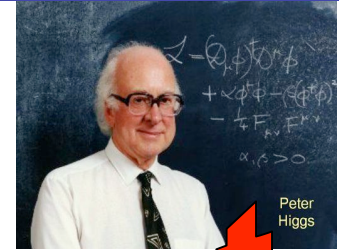
Terms which grow with energy cancel for $E \gg M_H$

This cancellation requires $M_H < 800 \text{ GeV}$

The Higgs Boson

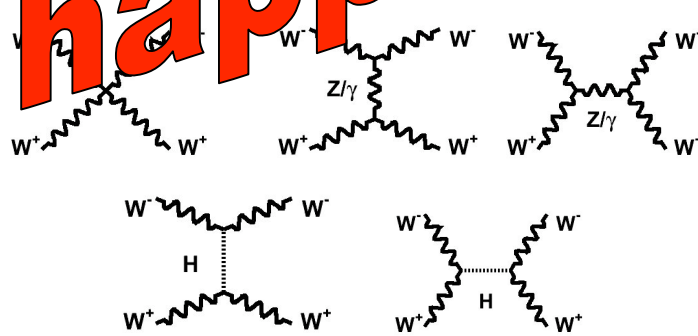
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 - $m_f \propto g_f \langle \Phi \rangle$
 - Higgs boson couplings are proportional to mass
- Higgs boson production via gluon fusion
 - violates unitarity

Peter Higgs



something new must happen at the LHC!

- $\sigma(pp \rightarrow WW) > \sigma(pp \rightarrow \text{anything})$
 - => illegal!
 - At $\sqrt{s} = 1.4 \text{ TeV}$



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

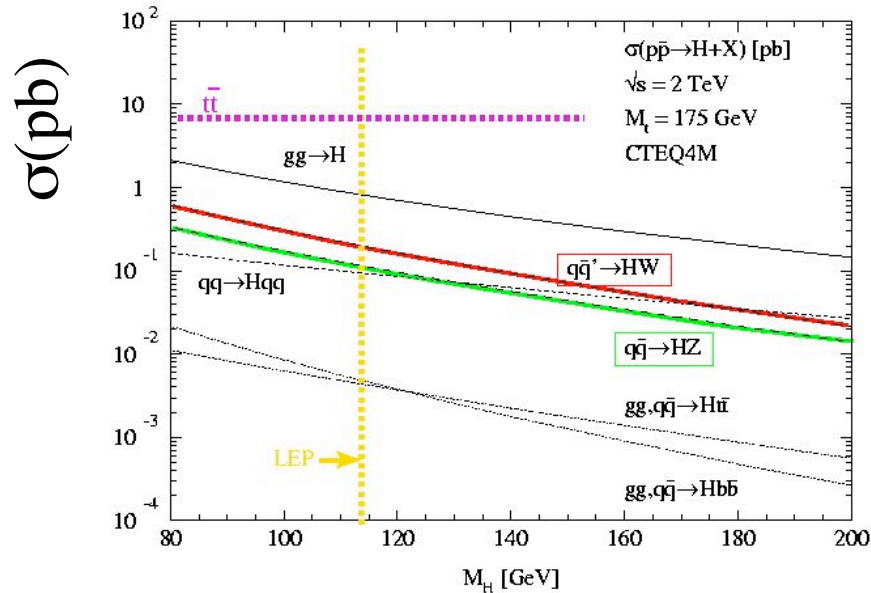
$$A \approx -g^2 \frac{E^2}{M_W^2}$$

Terms which grow with energy cancel for $E \gg M_H$

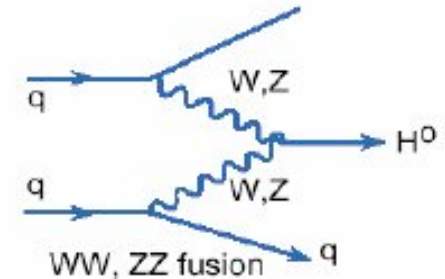
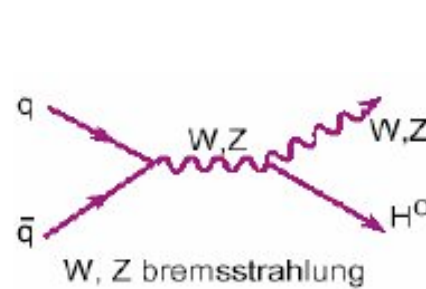
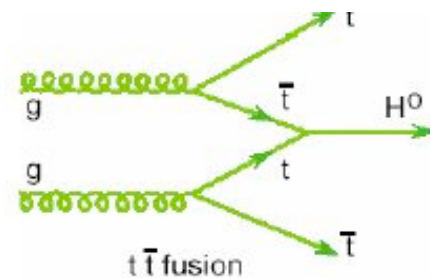
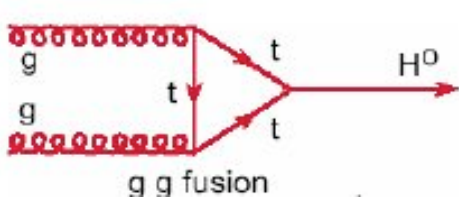
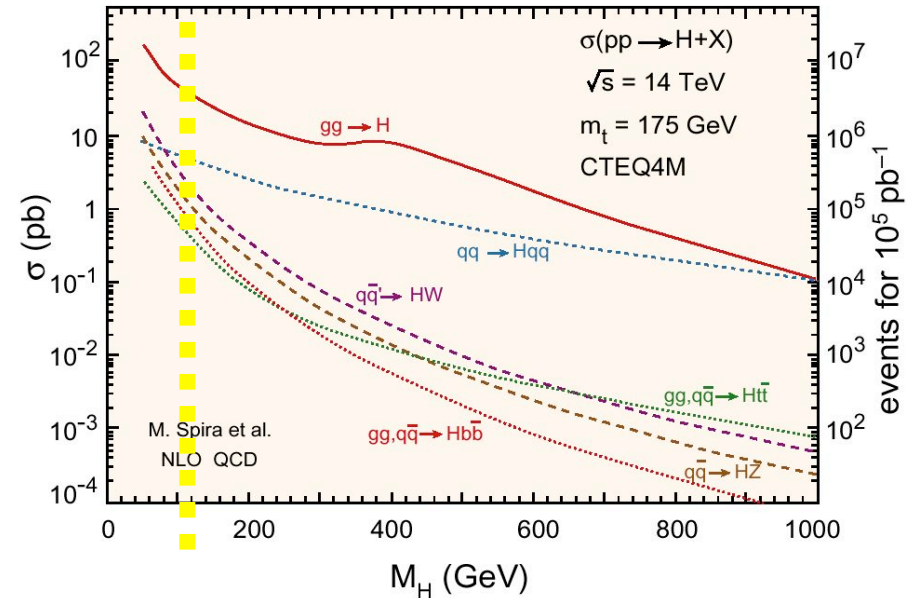
This cancellation requires $M_H < 800 \text{ GeV}$

Higgs Production: Tevatron and LHC

Tevatron



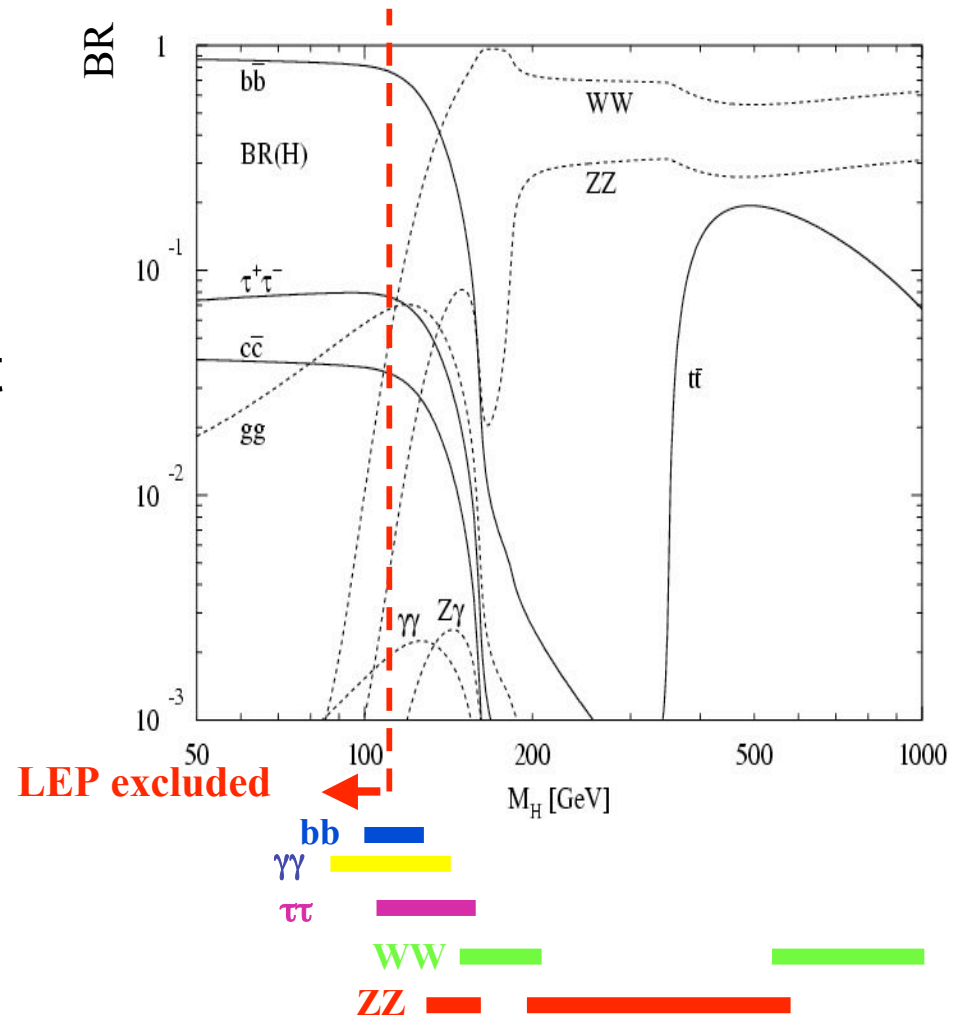
LHC



dominant: $gg \rightarrow H$, subdominant: HW , HZ , Hqq

Higgs Boson Decay

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

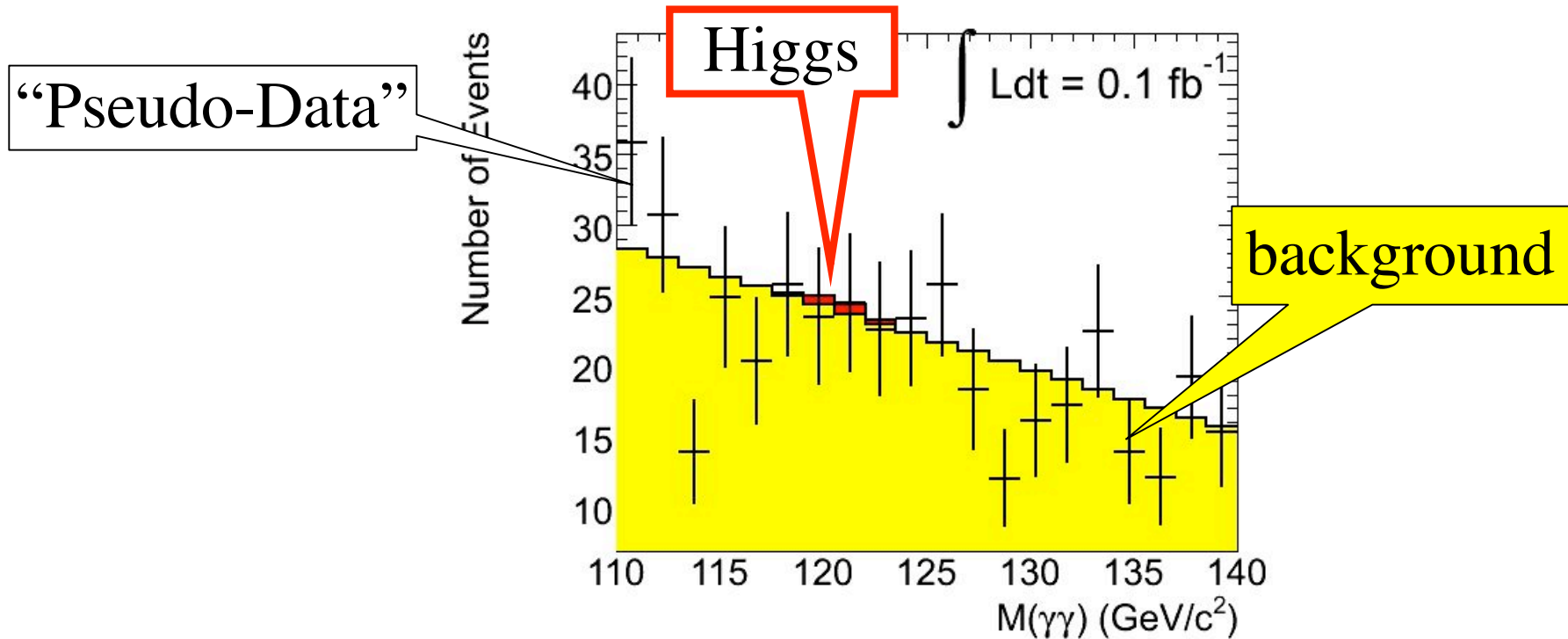


How to make a Discovery

- 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: $\sqrt{N_{\text{Bg}}}$
 - Significance: $S/\sqrt{B}=(N_{\text{Data}}-N_{\text{Bg}})/\sqrt{N_{\text{Bg}}}$
 - Require typically 5σ , corresponds to probability of statistical fluctuation of $\sim 10^{-7}$
 - Increases with increasing luminosity: $S/\sqrt{B} \sim \sqrt{L}$
 - All a lot more complex with systematic uncertainties...

A signal emerging with time

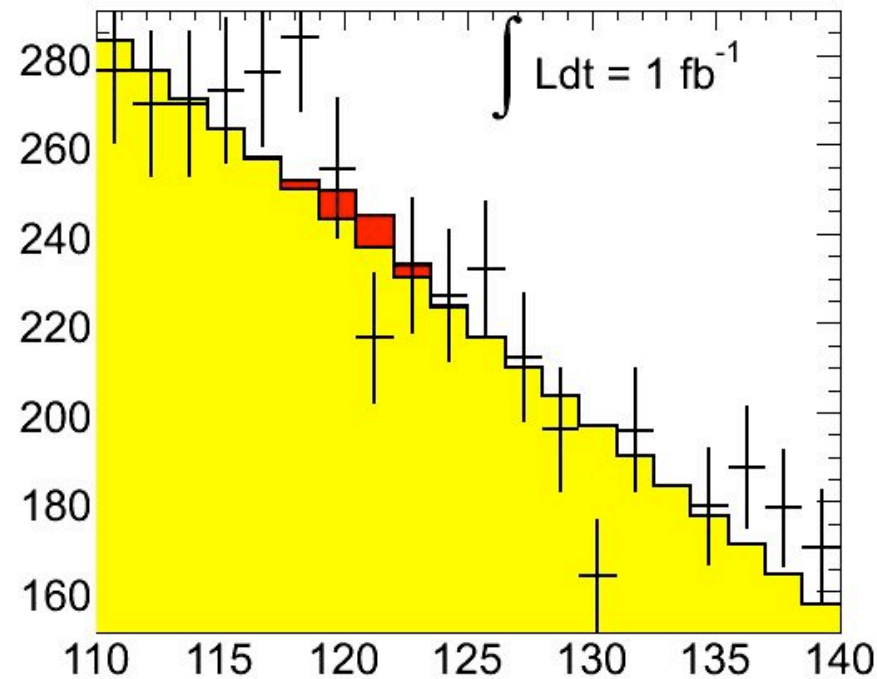
$$\int L dt = 0.1 \text{ fb}^{-1} \text{ (year: 2008/2009)}$$



- Expected Events:
 - $N_{\text{higgs}} \sim 2$, $N_{\text{background}} = 96 \pm 9.8$
 - $S/\sqrt{B} = 0.2$
- No sensitivity to signal

A signal emerging with time...

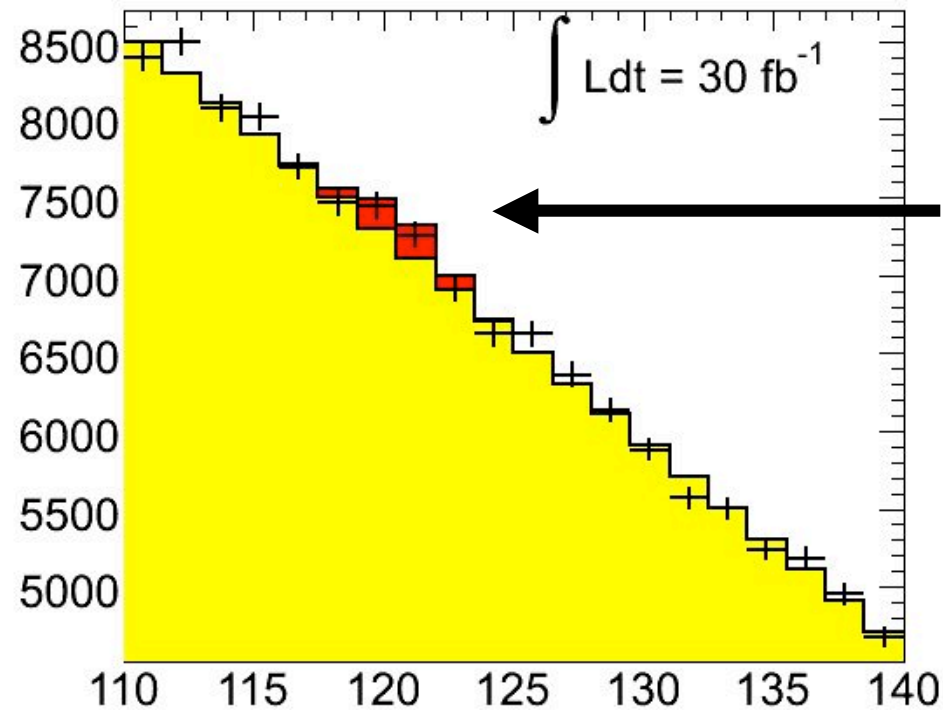
$\int Ldt = 1 \text{ fb}^{-1}$ (year: ~2009)



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

There it is!

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

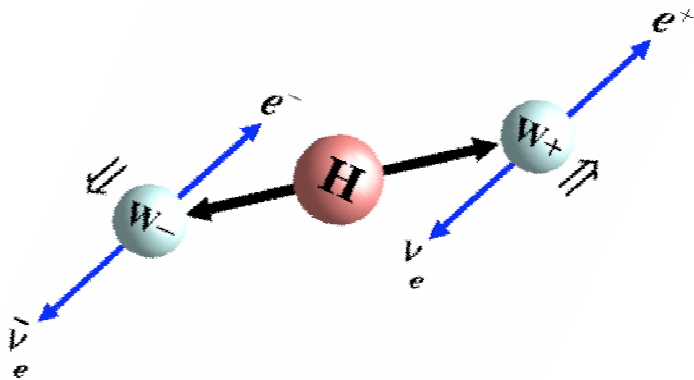


- Expected Events:
 - $N_{\text{higgs}} \sim 700$, $N_{\text{background}} = 28700 \pm 170$
 - $S/\sqrt{B} = 4.1$
- Got it!!!

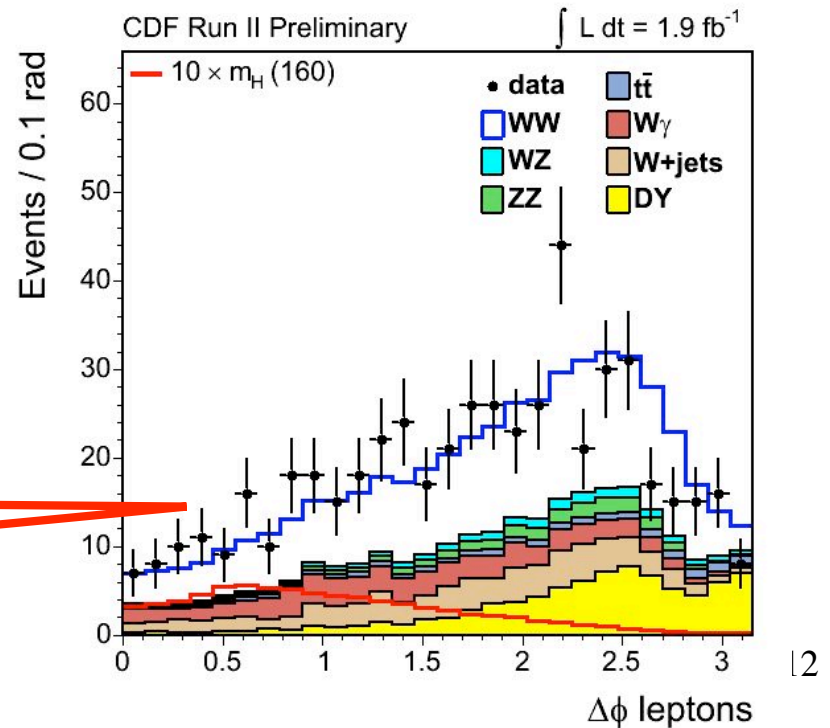
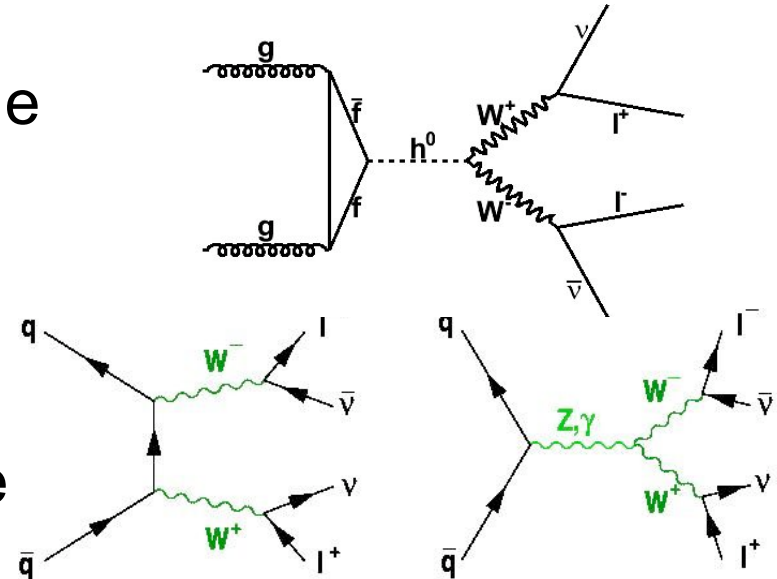
High Mass: $m_H > 140$ GeV

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

- 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 $H \rightarrow WW(*) \rightarrow l^+l^-\nu\bar{\nu}$ are collinear
- Main background: WW production

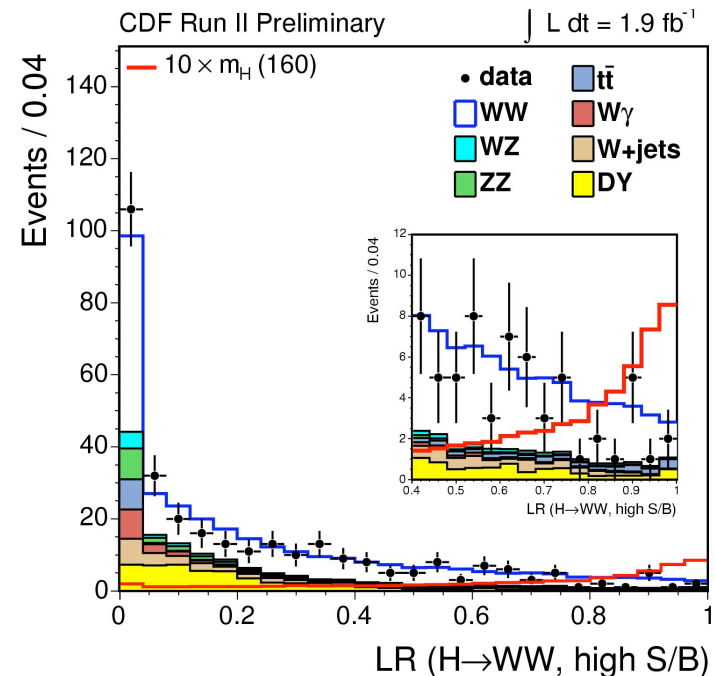
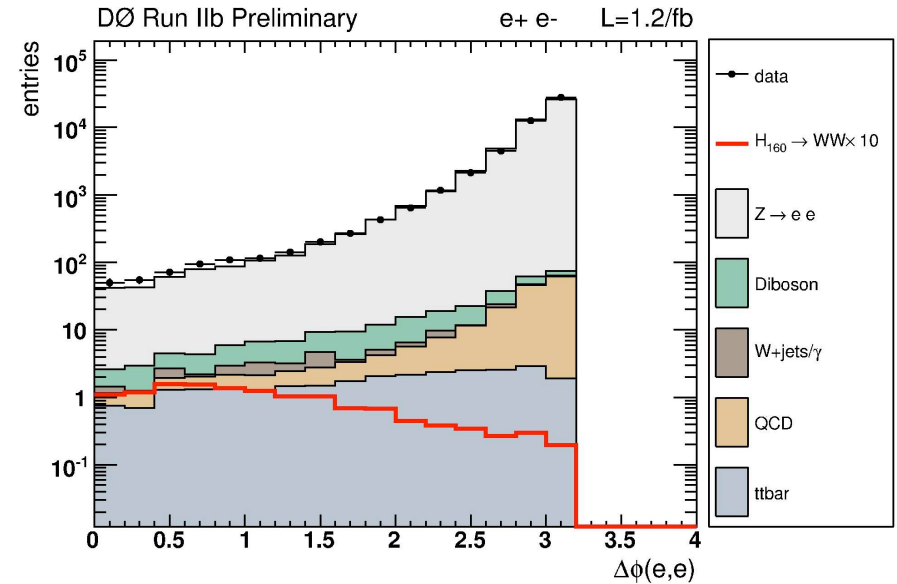


10x 160 GeV Higgs

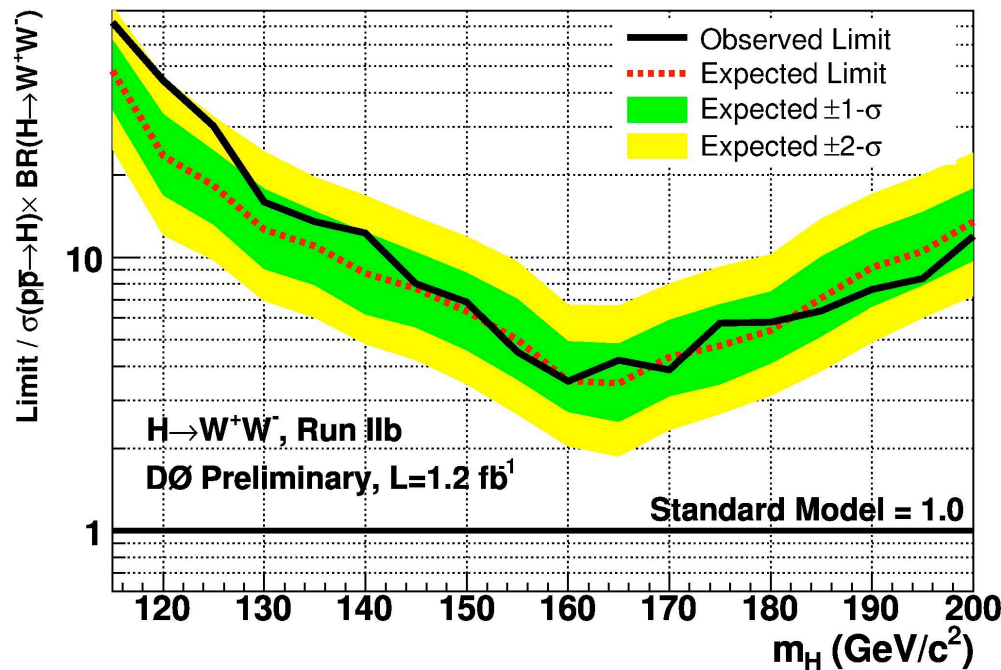


$H \rightarrow WW^{(*)} \rightarrow l^+l^-\nu\nu$ ($l=e,\mu$)

- **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 matrix-element or Neural Network discriminant to enhance sensitivity
- **Main backgrounds**
 - SM WW production
 - Top
 - Drell-Yan
 - Fake leptons
- **No sign of Higgs boson found!**

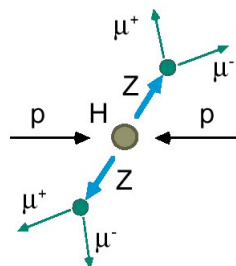


Limits on the Higgs boson cross section



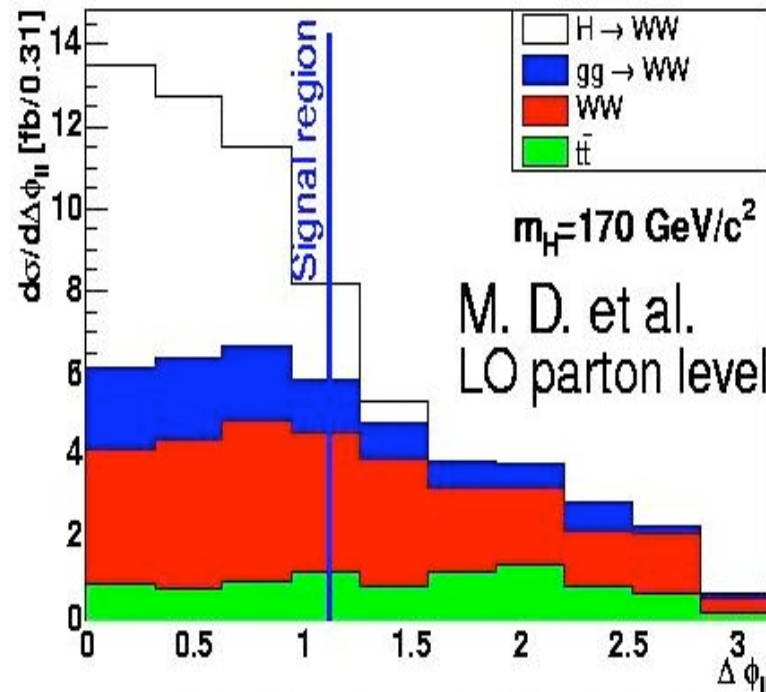
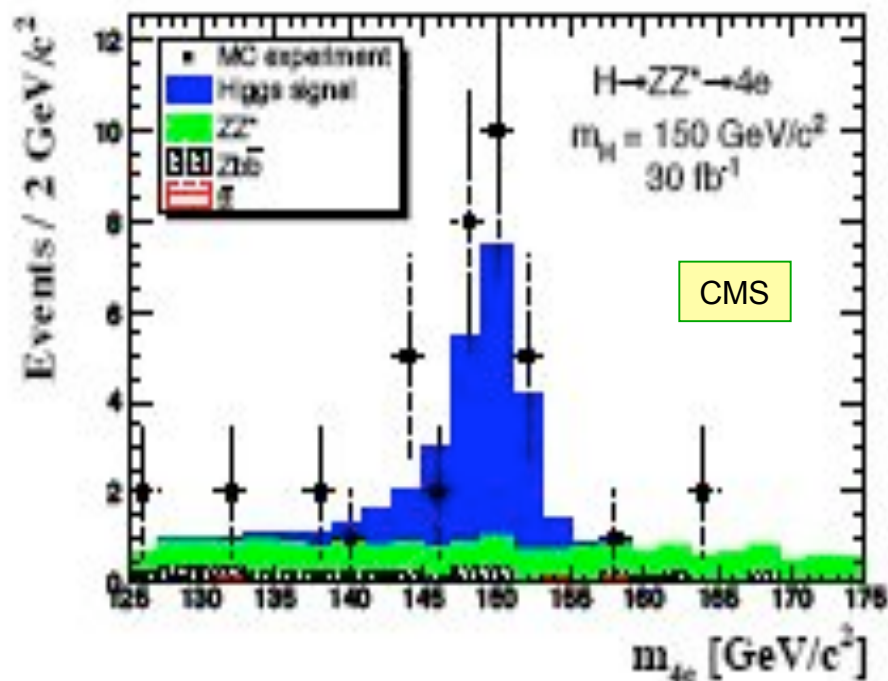
- Lack of observation
 - => an upper limit on the Higgs cross section
 - I.e. if the cross section was large we would have seen it!
- Results presented typically as ratio:
 - Experimental limit / theoretical cross section
 - If this hits 1 we exclude the Higgs boson at that mass!
- In this example: a factor 3 above SM cross section
 - at $M_H=160$ GeV/c²

High Mass Higgs Signals at LHC



$H \rightarrow WW^*$ ($m_H = 170 \text{ GeV}$)

ATLAS

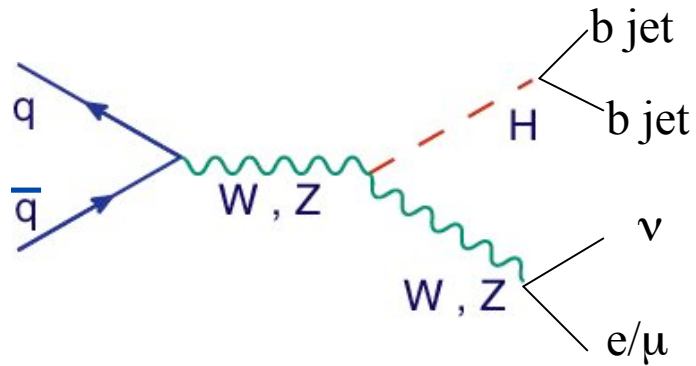


Clean signals on rather well understood backgrounds

Low Mass: $m_H < 140$ GeV

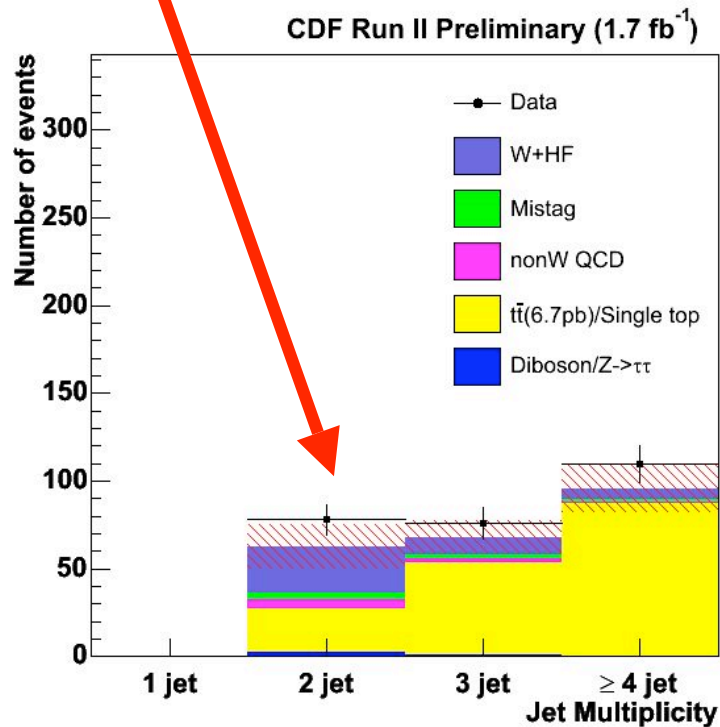
- Tevatron:
 - $WH(\rightarrow bb)$, $ZH(\rightarrow bb)$
- LHC:
 - $H(\rightarrow \gamma\gamma)$, $qqH(\rightarrow \tau\tau/WW^*)$, $ttH(\rightarrow bb)$

WH \rightarrow $l\nu bb$



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

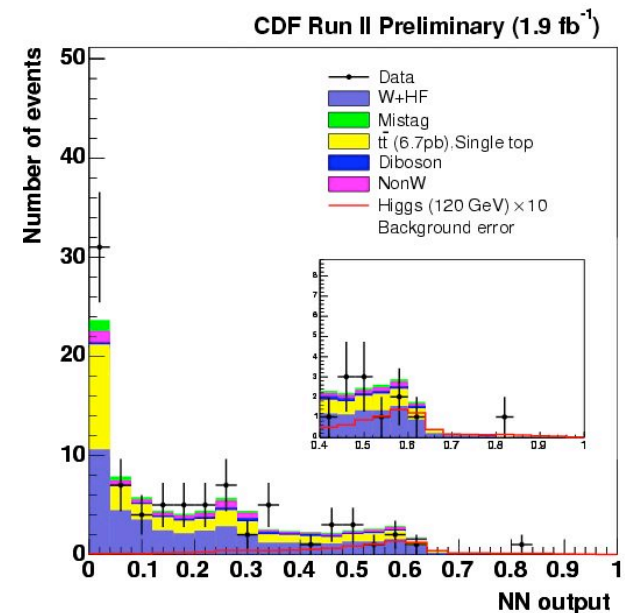
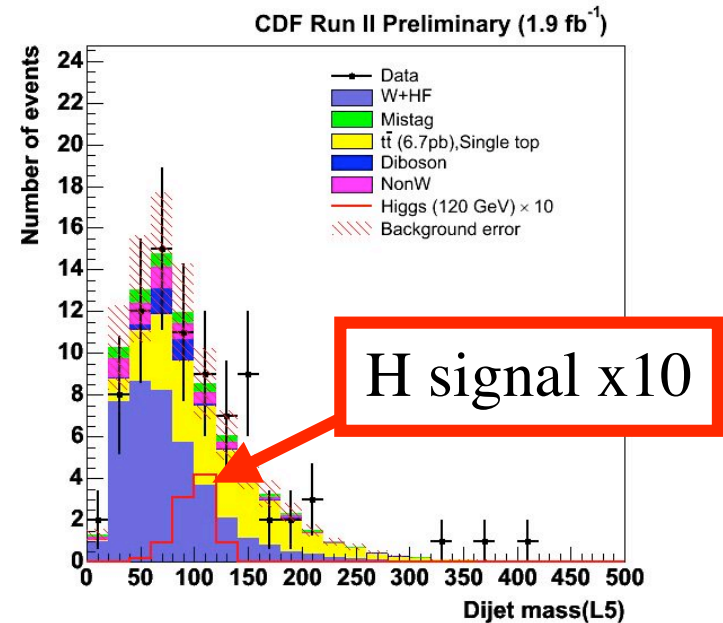
Looking for 2 jets



Expected Numbers of Events:
 WH signal: 1.5
 Background: 131 ± 50

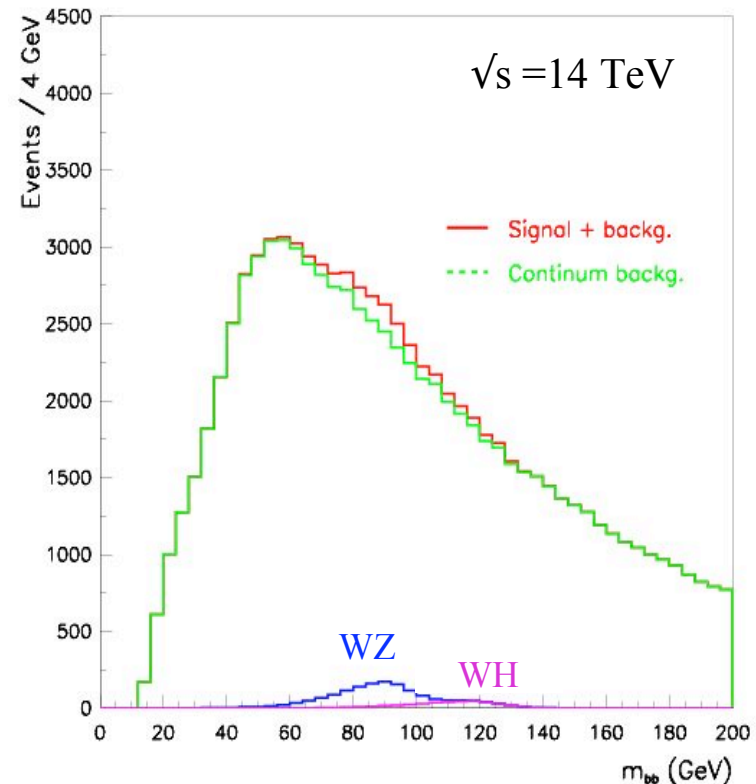
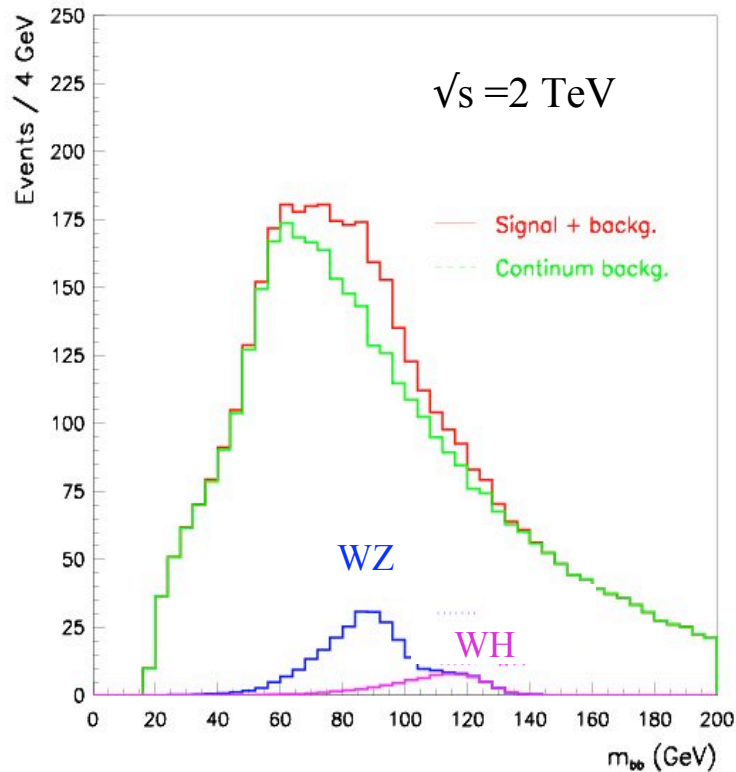
WH Dijet Mass distributions

- 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 selection*, higher lepton acceptance
- Similar analyses for ZH



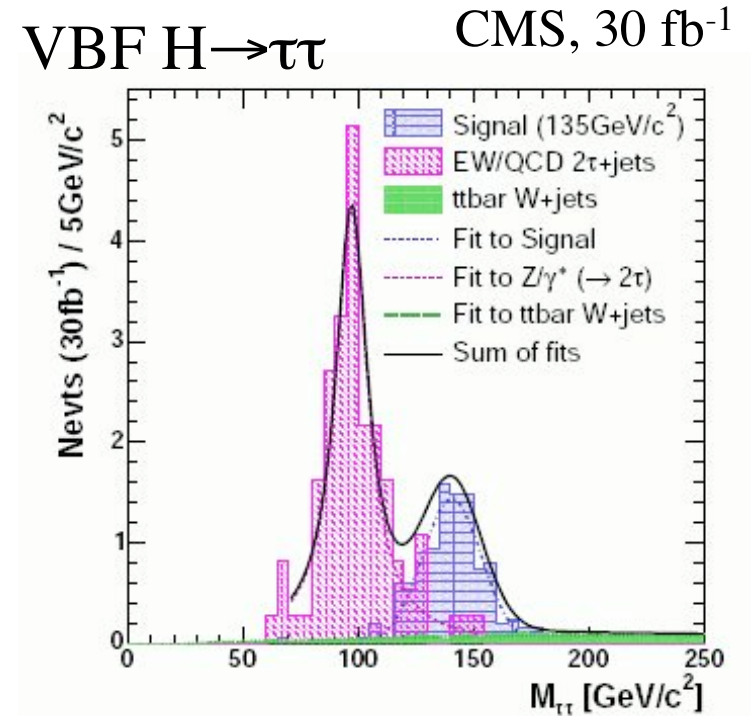
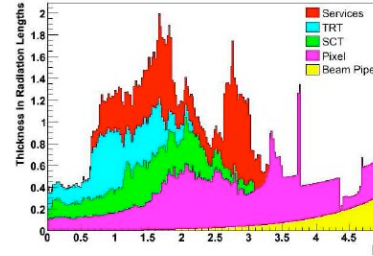
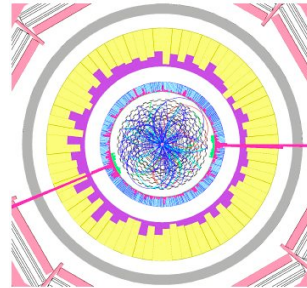
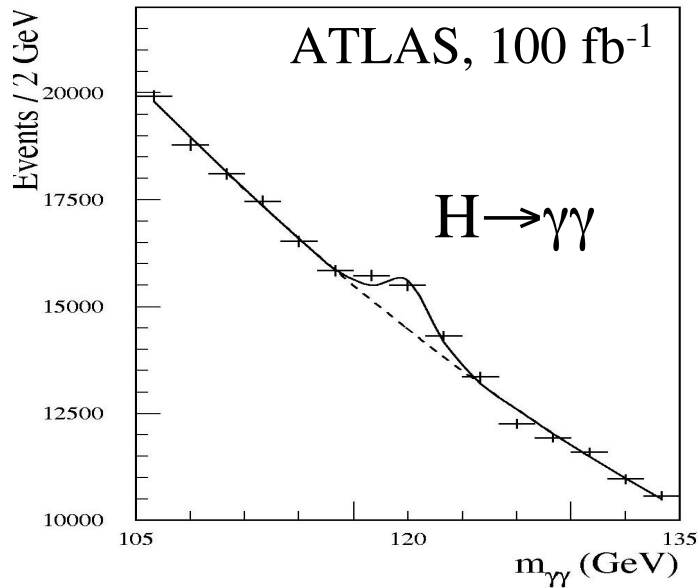
Higgs at Low Mass: Tevatron vs LHC

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



- WH channel:
 - Much larger backgrounds at LHC than at Tevatron
 - Not the best channel at the LHC! => use other ones

Low Mass Higgs Signals at LHC



■ Main observation channels:

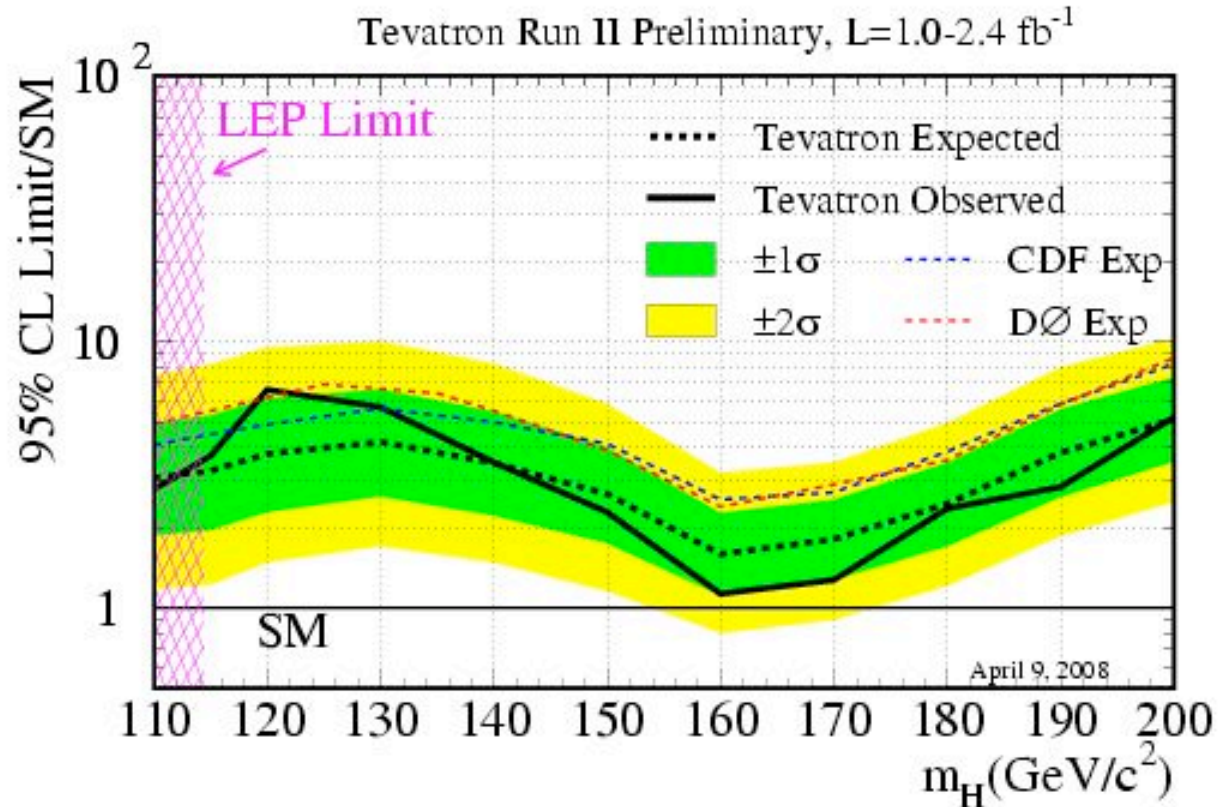
- $H \rightarrow \gamma\gamma$
- $qqH \rightarrow qq\tau\tau$
- $ttH \rightarrow ttbb$

■ Total $S/\sqrt{B}=4.2$

- $m_H=115$ GeV/c²

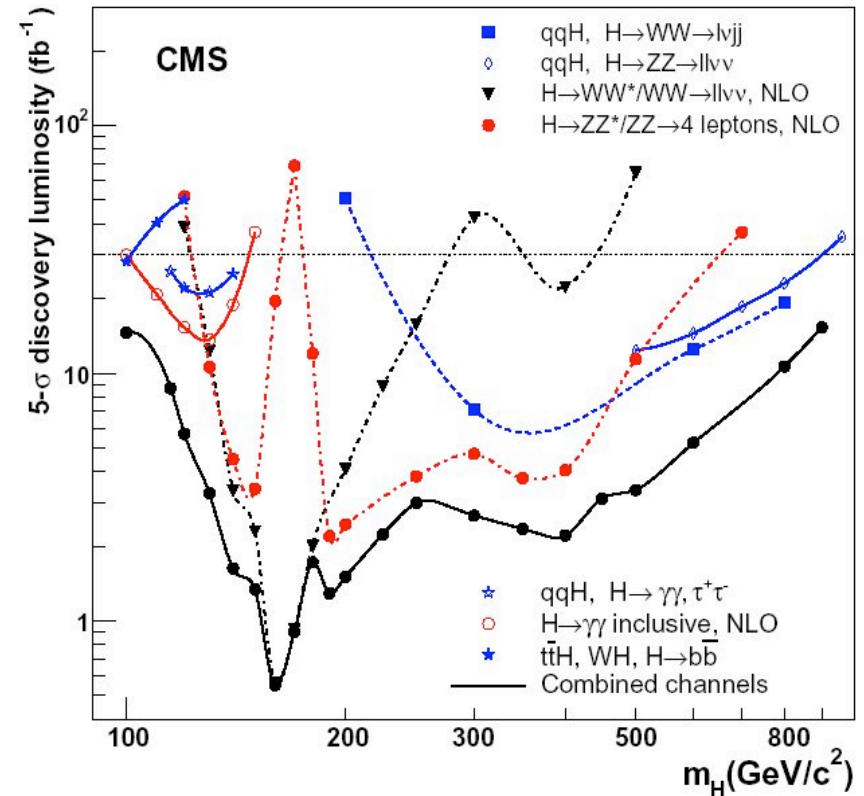
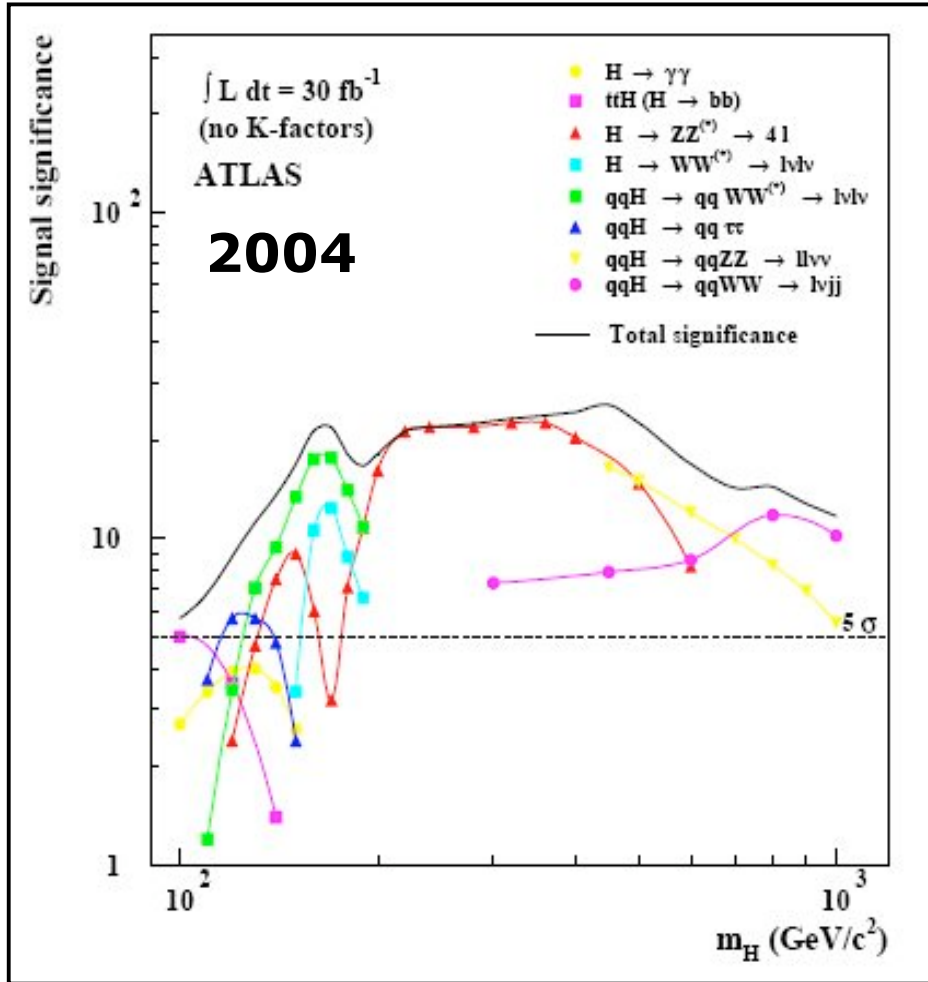
	$H \rightarrow \gamma\gamma$	$ttH \rightarrow ttbb$	$qqH \rightarrow qq\tau\tau$
S (115)	150	15	10
B	3900	45	10
S/\sqrt{B}	2.4	2.2	2.7

Tevatron Combined Status



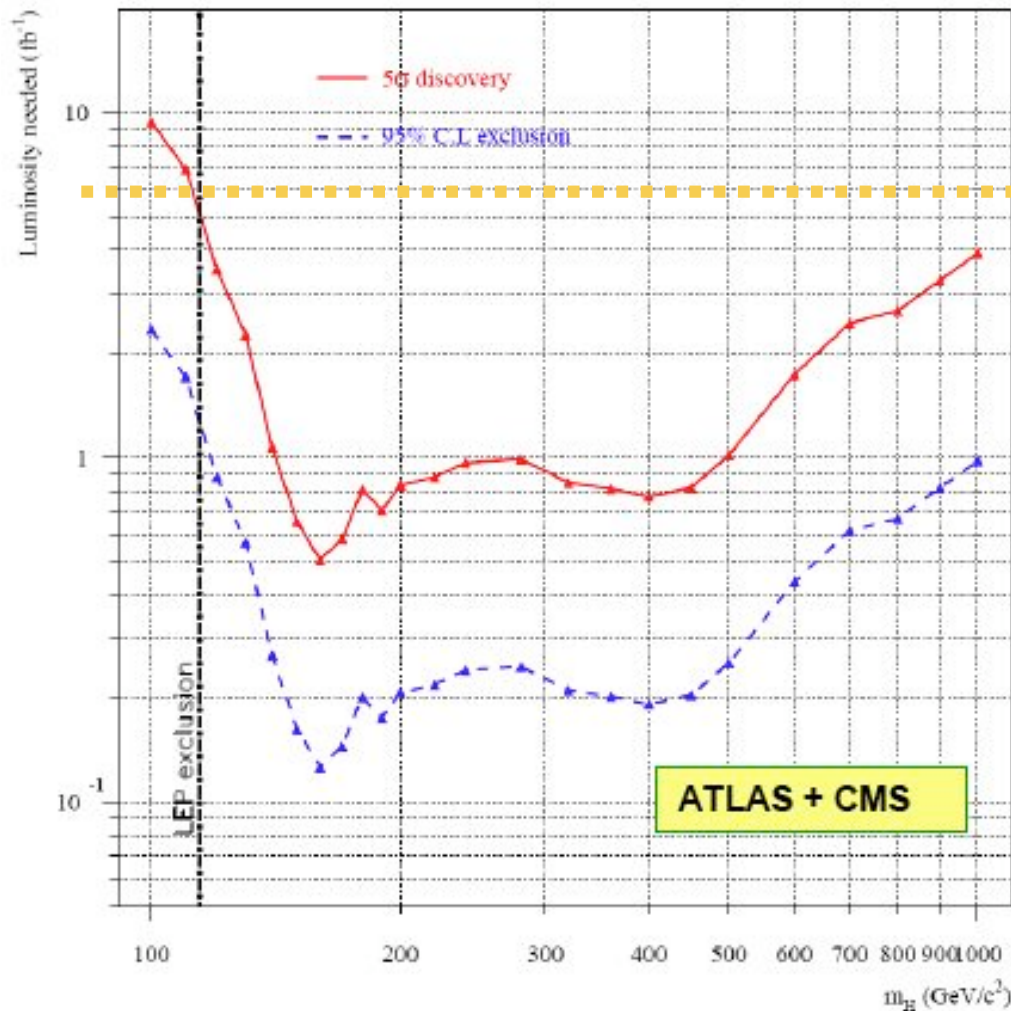
- Combine CDF and DØ analyses from all channels at low and high mass
 - $m_H=160 \text{ GeV}/c^2$: limit/SM=1.1 (that is close!! => watch this)
 - $m_H=115 \text{ GeV}/c^2$: limit/SM=3.7

LHC SM Higgs Discovery Potential



- Fast discovery for high mass, e.g. $m_H > 150 \text{ GeV}/c^2$
- Harder at low mass many channels contribute

Ultimate sensitivity



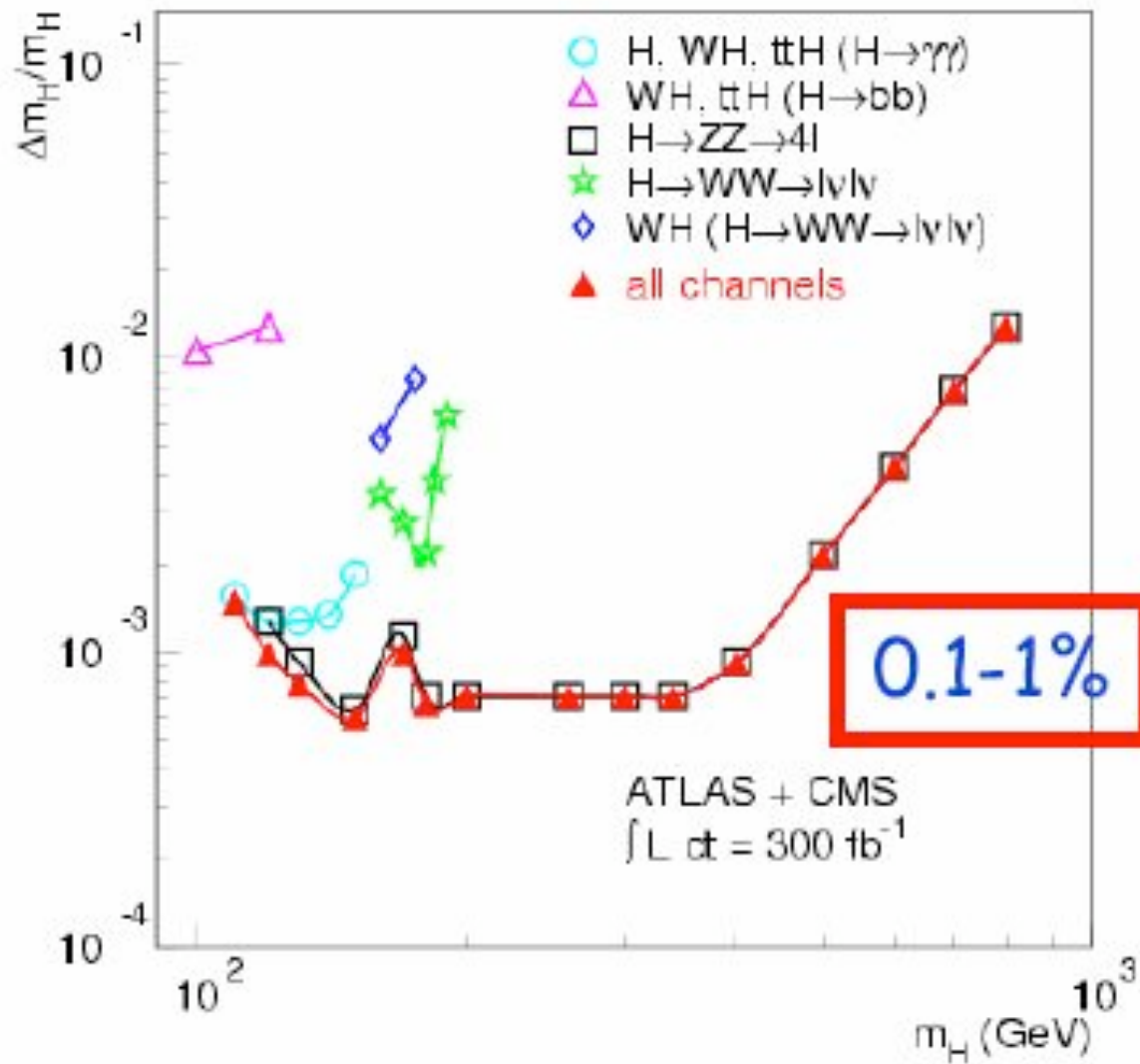
$\int L dt = 6 \text{ fb}^{-1}$

- With 6 fb⁻¹ of LHC data will know if Higgs boson exists
 - in 2-4 years already (hopefully)!

How do we know what we have found?

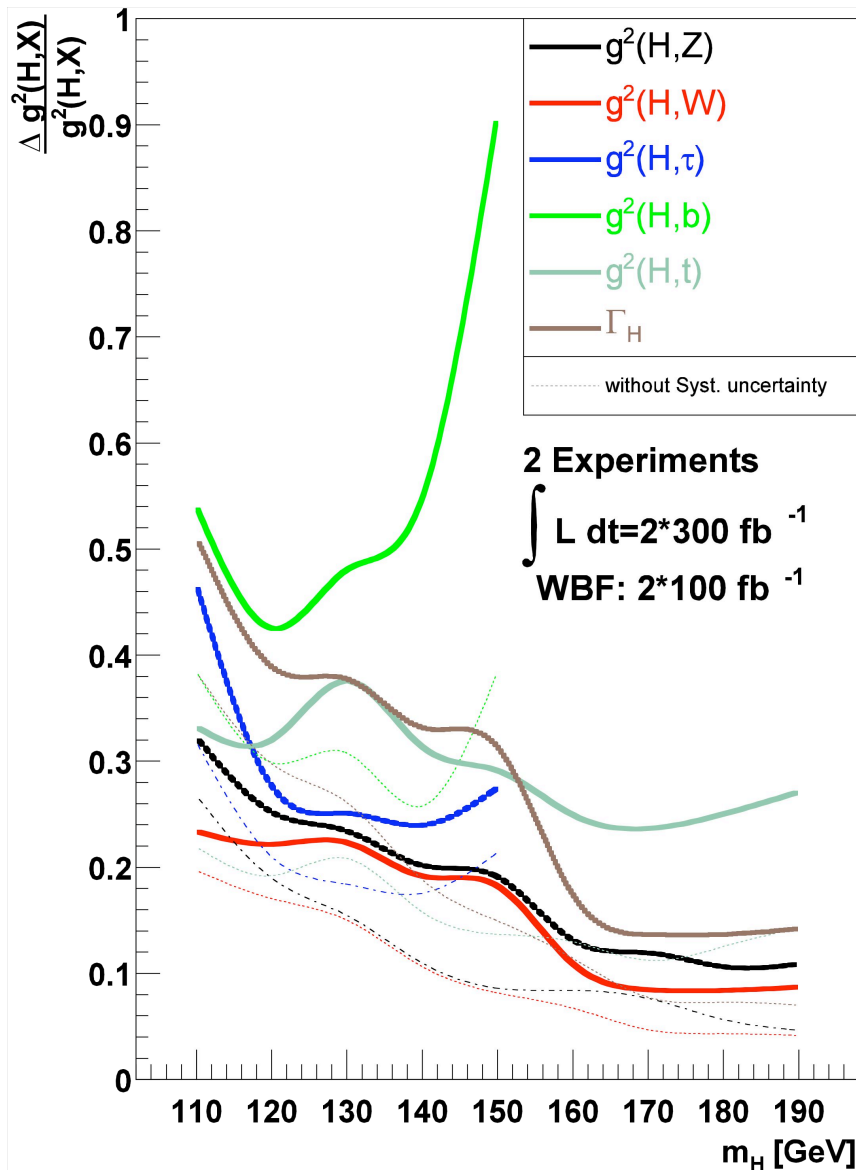
- After discovery we need to check it really is the Higgs boson
- Measure it's properties:
 - The mass
 - The spin (very difficult...)
 - The branching ratio into all fermions
 - Verify coupling to mass
 - The total width (very difficult...)
 - Are there invisible decays?
- Check they are consistent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

Mass



Coupling Measurements at LHC

Duehrssen et al hep-ph/0407190



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

Non Standard-Model Higgs Bosons

Higgs in Supersymmetry (MSSM)

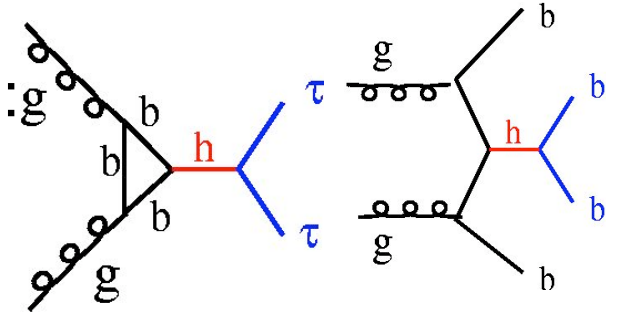
- Minimal Supersymmetric Standard Model:
 - 2 Higgs-Fields: Parameter $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$

- 5 Higgs bosons: h, H, A, H^\pm

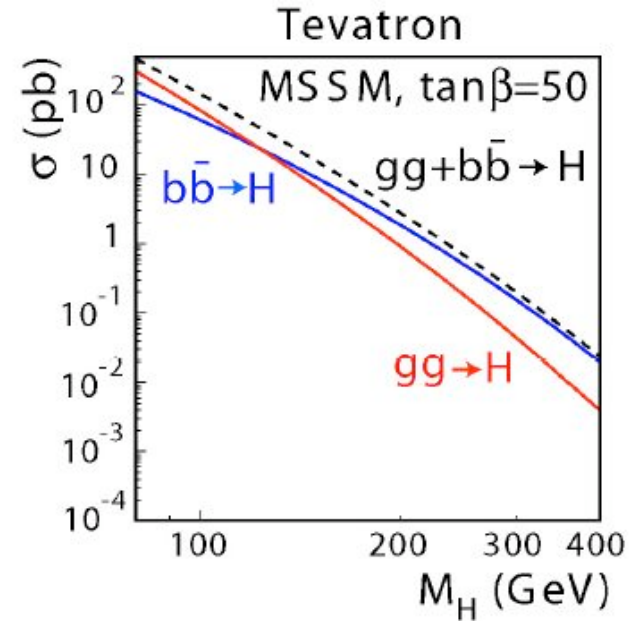
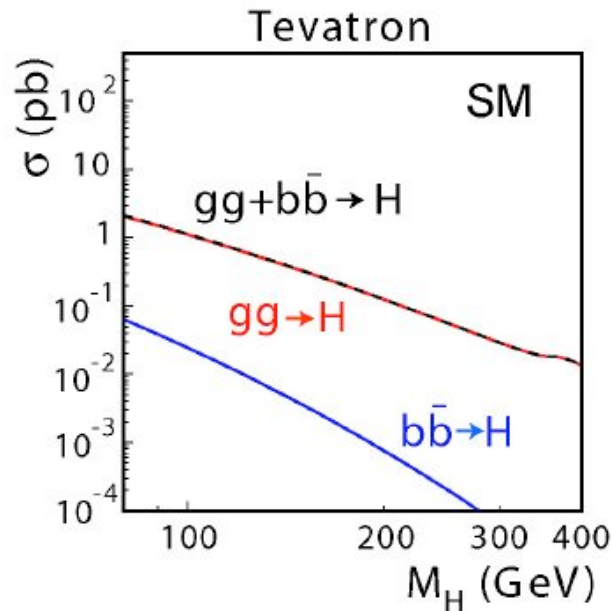
- Neutral Higgs Boson:

- Pseudoscalar A
- Scalar H, h

- Lightest Higgs (h) very similar to SM

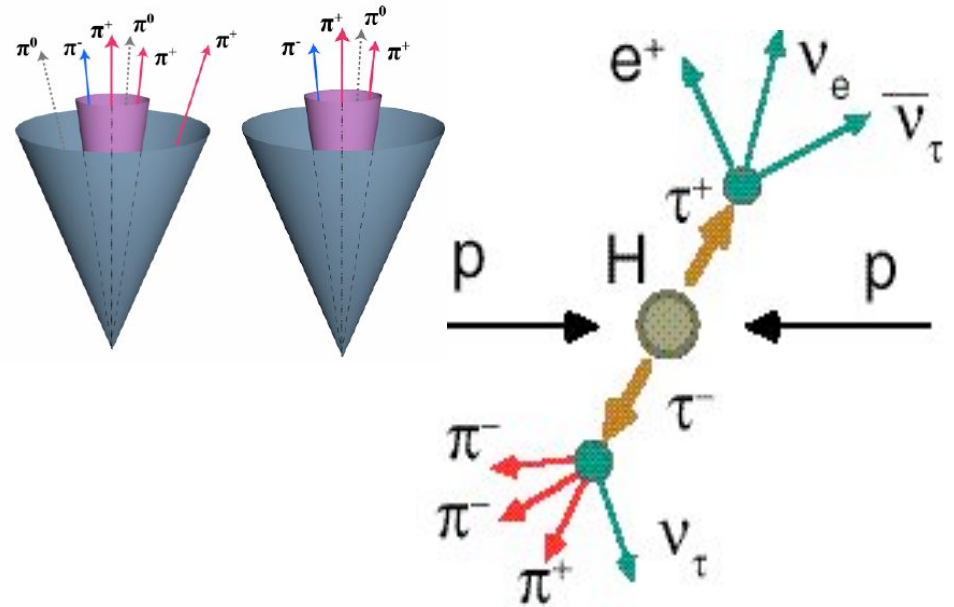


$$\sigma \times BR_{SUSY} = 2 \times \sigma_{SM} \times \frac{\tan\beta^2}{(1 + \Delta_b)^2} \times \frac{9}{[9 + (1 + \Delta_b)^2]}$$



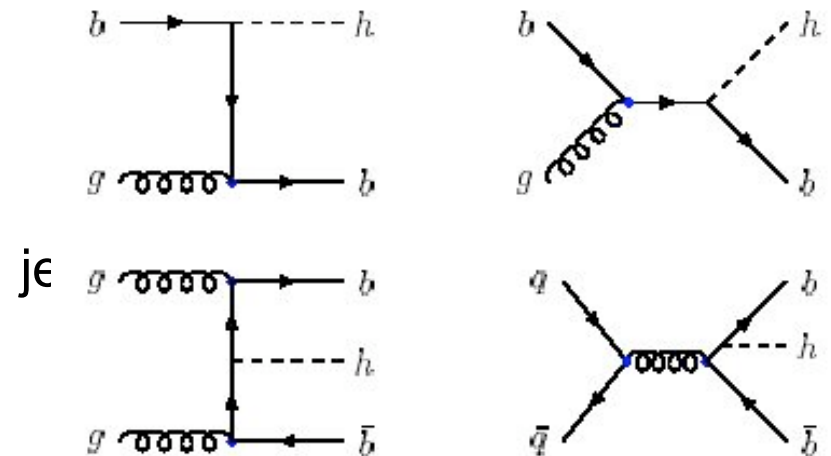
MSSM Higgs Selection

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

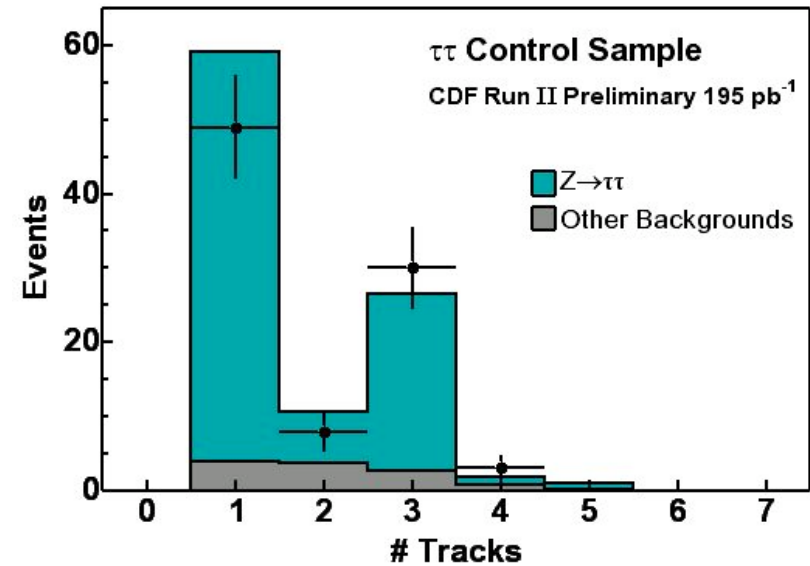
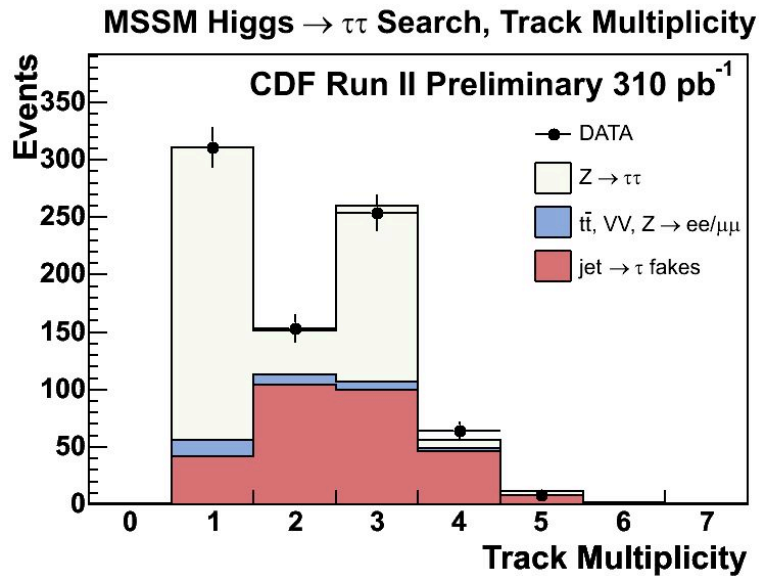


- $pp \rightarrow \Phi b + X \rightarrow bbb + X$:
 - Three b -tagged jets
 - $E_T > 35, 20$ and 15 GeV
 - Use invariant mass of leading two to discriminate against background

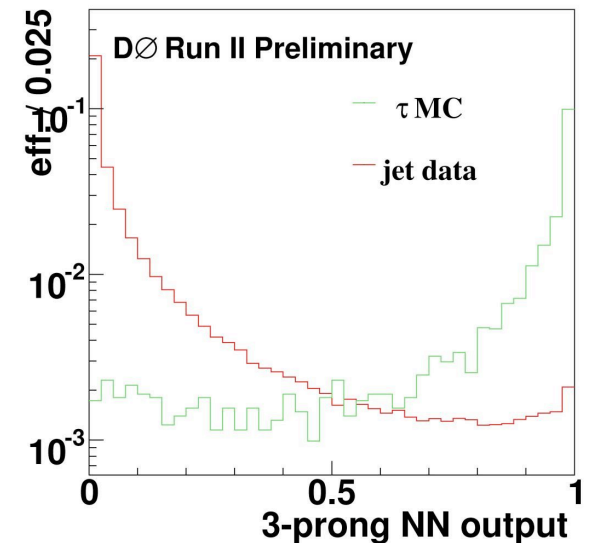
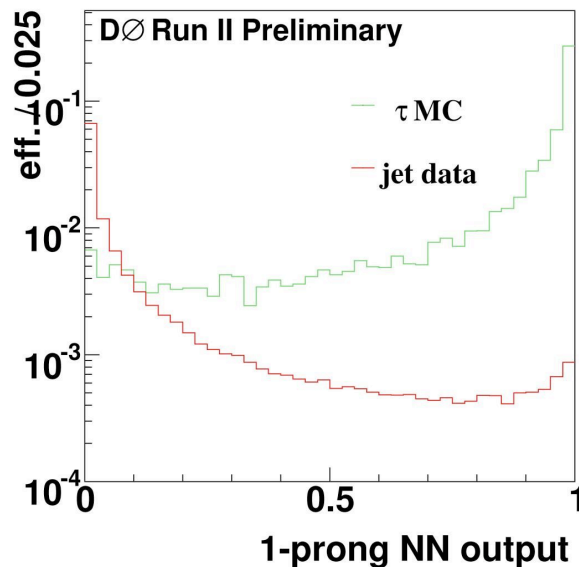
$$\Phi = h/H/A$$



Tau Signals!

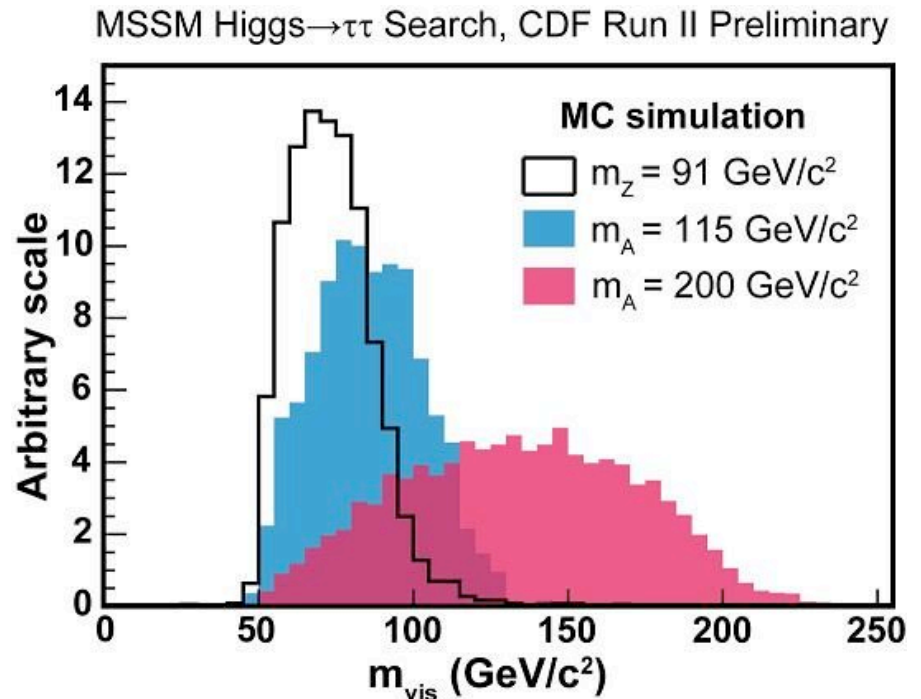


- Clear peaks at 1 and 3 tracks:
 - Typical tau signature
- DØ use separate Neural Nets for the two cases:
 - Very good separation of signal and background

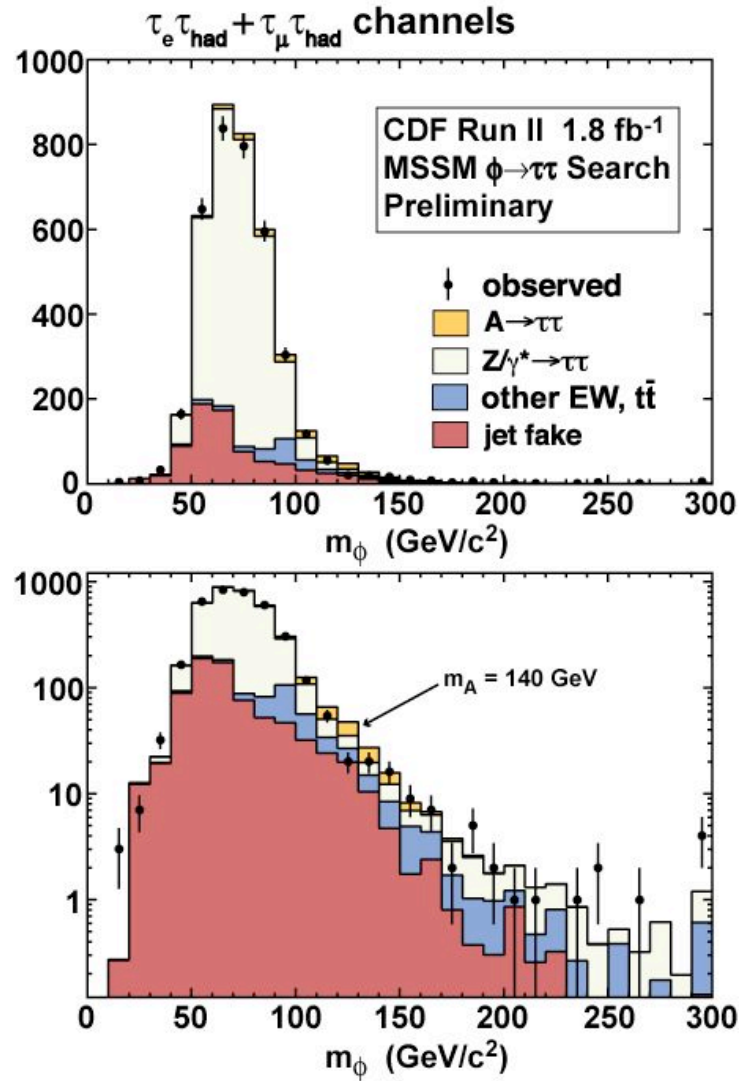


Di-tau Mass reconstruction

- Neutrinos from tau-decay escape:
 - No full mass reconstruction possible
- Use “visible mass”:
 - Form mass like quantity:
 $m_{\text{vis}} = m(\tau, e/\mu, \cancel{E}_T)$
 - Good separation between signal and background
- Full mass reconstruction possible in boosted system, i.e. if $p_T(\tau, \tau) > 20 \text{ GeV}$:
 - Loose 90% of data statistics though!
 - Best is to use both methods in the future

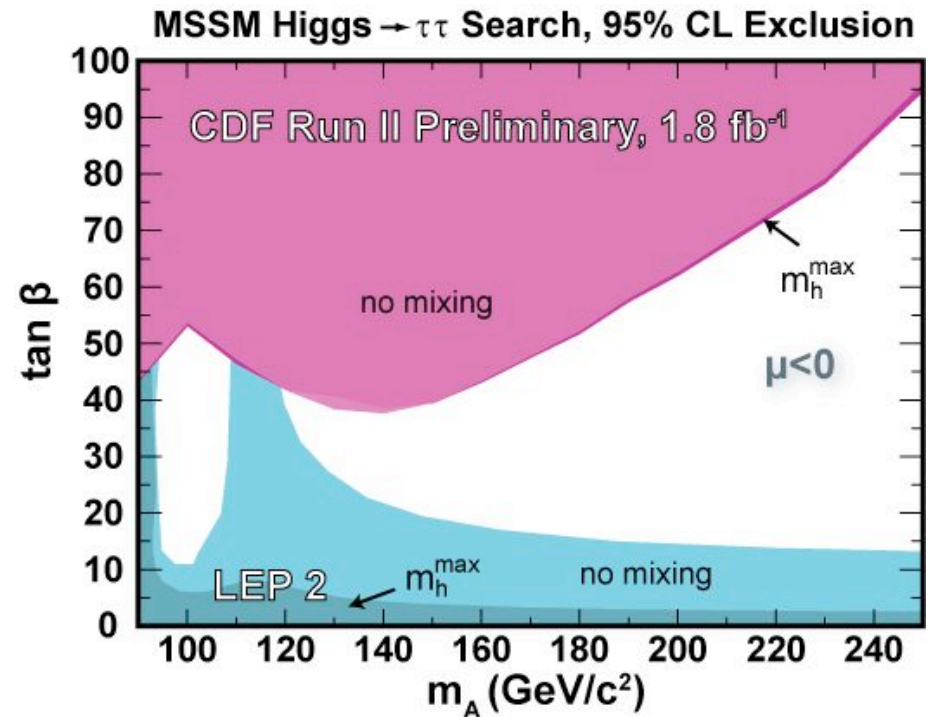
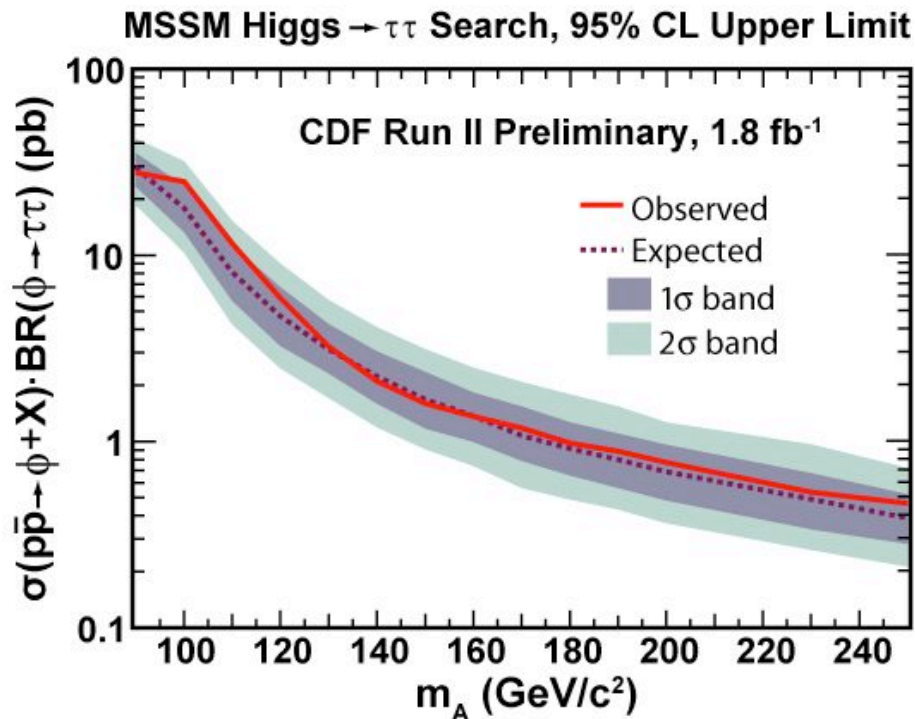


Di-Tau Higgs Boson Search



- Data agree with background prediction

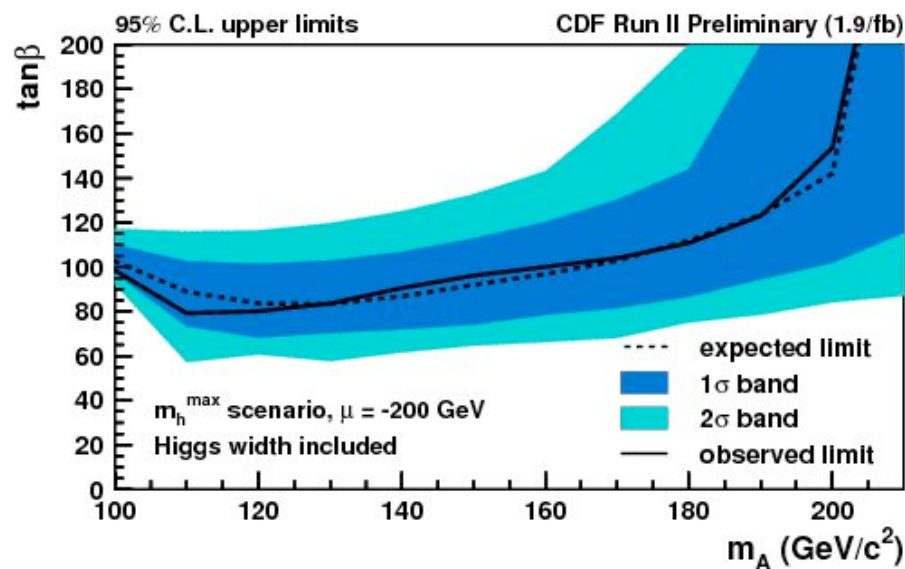
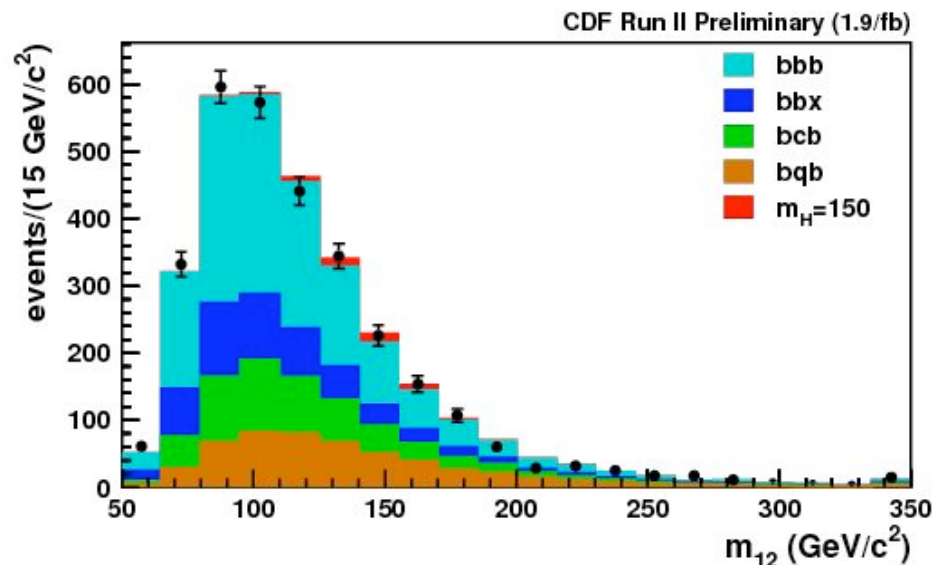
Limits on the MSSM Higgs



- 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 $\tan\beta$ for $m_A=140$ GeV/c²

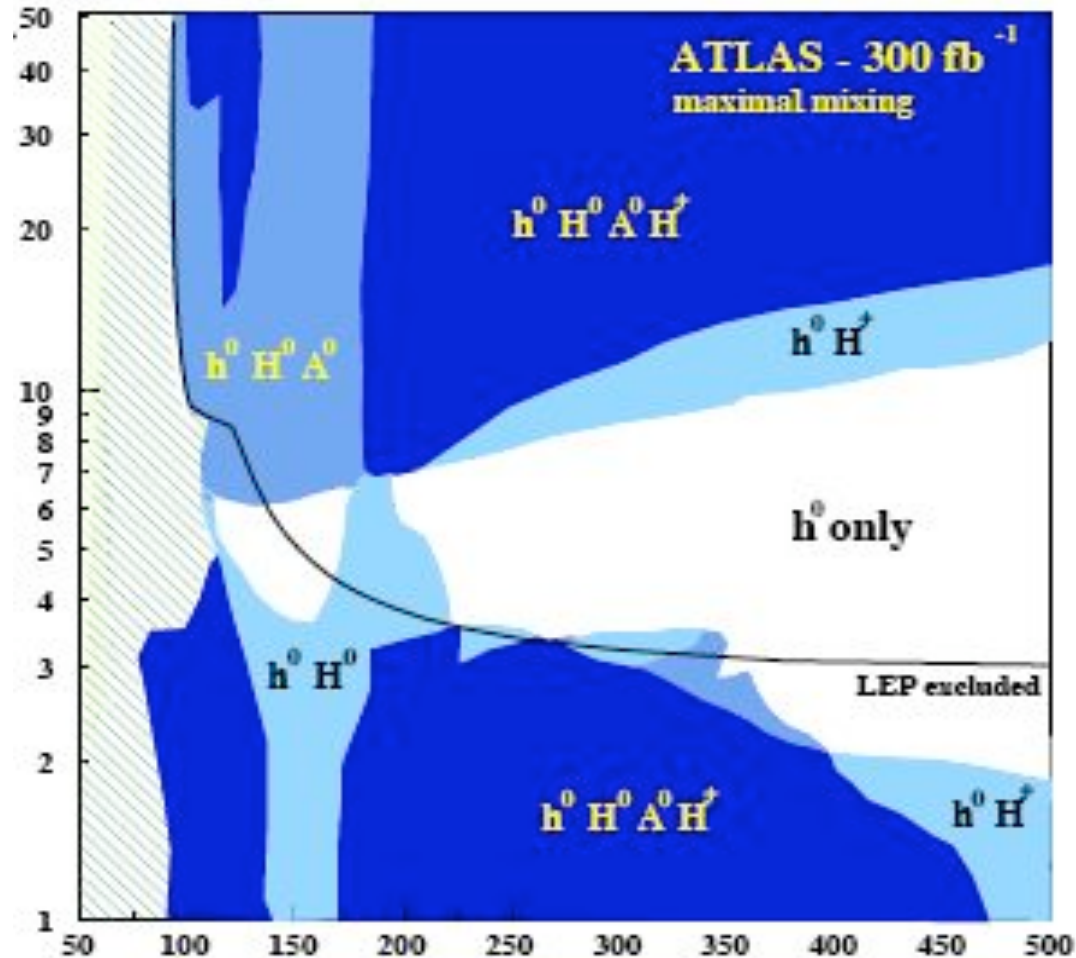
MSSM Higgs in 3b-jets channel

- Use events with 3 b-jets
- Invariant mass of leading two jets
 - Sensitive to m_A
- Data also agree with background
- Constrain again $\tan\beta$ vs m_A
 - Constraint weaker than in di-tau mode



MSSM Higgs Bosons at LHC

300 fb⁻¹



- At least one Higgs boson definitely observable 😊
- Often only one Higgs boson observable 😞

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
 - Chance of a 3σ evidence
- LHC will find the Higgs boson if it exists
 - With $>5\sigma$ significance
 - And measure some of its properties
- If it Higgs boson does not exist
 - Some other mechanism must kick in to prevent unitarity violation
- There might be more than one Higgs boson
 - E.g. in supersymmetry
 - They can be found too (hopefully)