Higgs Physics in ATLAS

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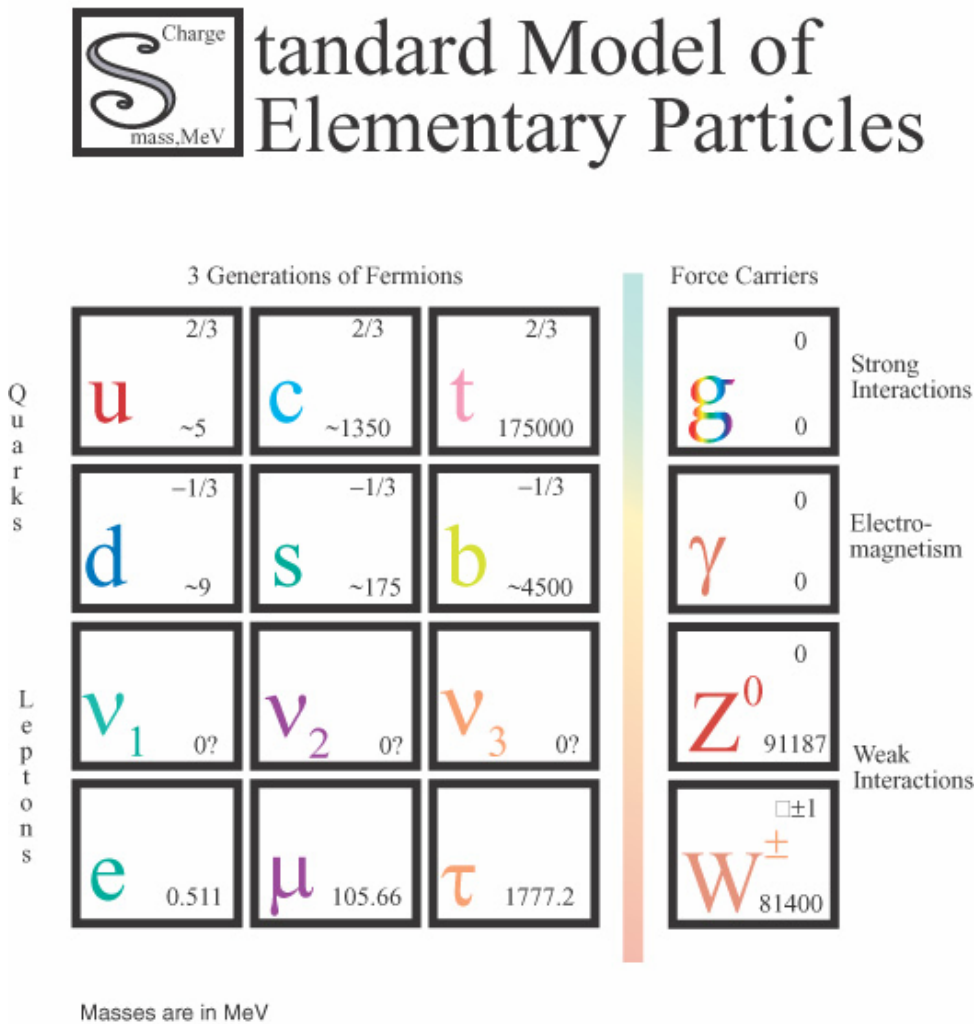
Outline

- Introduction
  - Why is the Higgs so important?
- SM Higgs
  - Status of feasibility studies
  - Production modes at LHC
    - Impact of Vector Boson Fusion (VBF)
  - Experimental issues
- MSSM Higgs
  - Status of feasibility studies

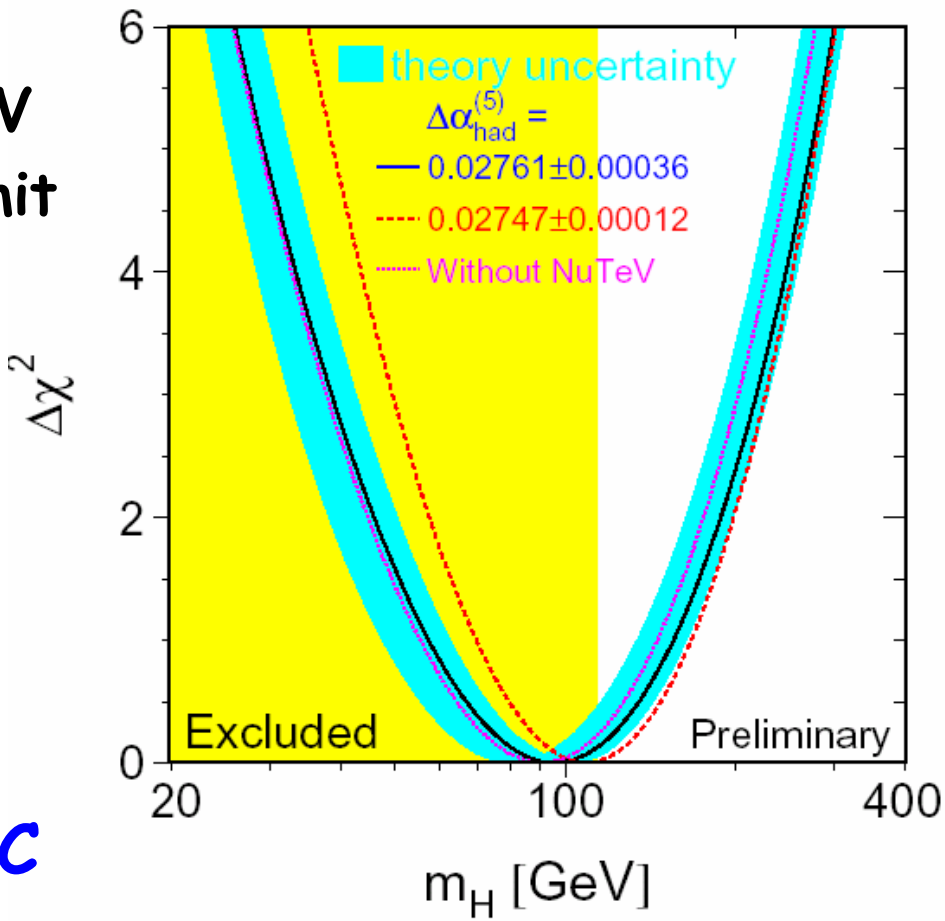
SM Higgs (1)

- **Standard Model:**
  - Huge success in describing the world of elementary particles
  - Many properties of quarks, leptons and forces carriers well established
- **Agent of spontaneous electro-weak symmetry breaking, the Higgs, not observed yet!**



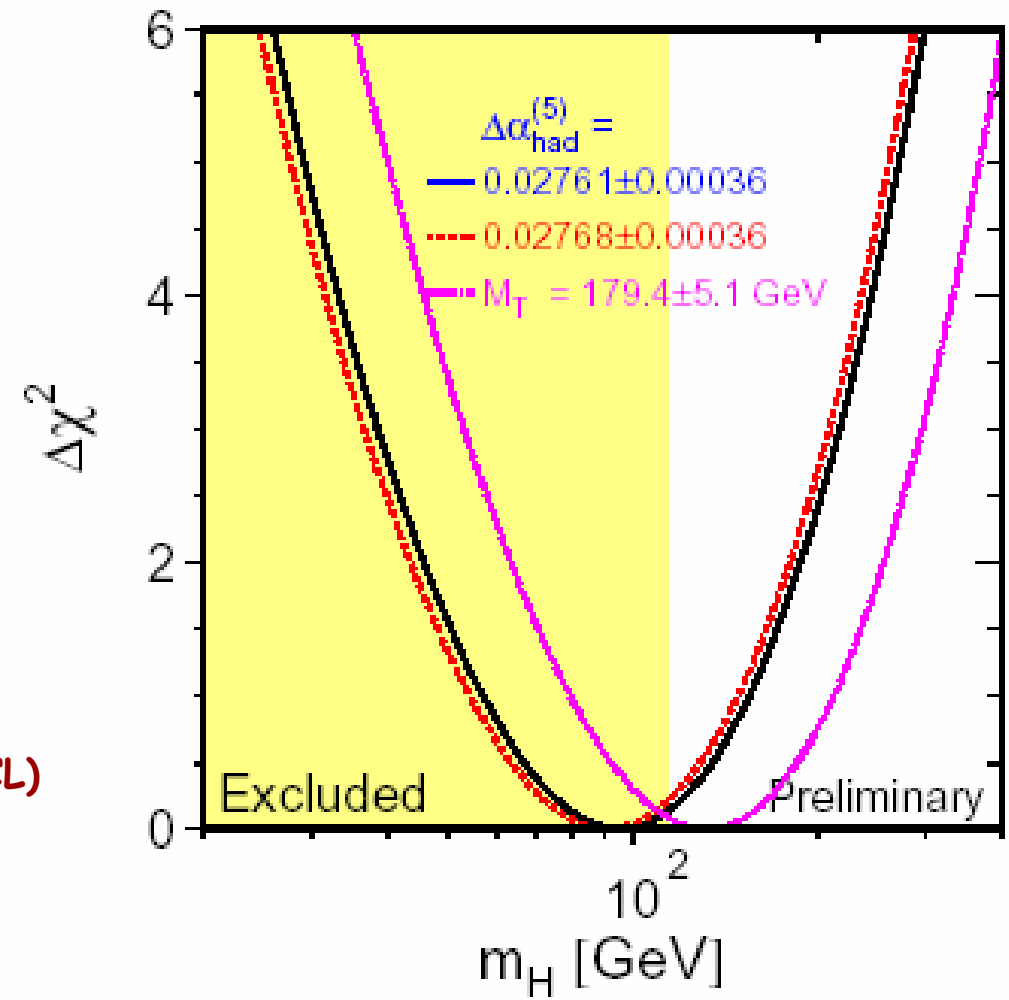
SM Higgs (2)

- Direct searches at LEP
  - Some excess of events consistent with M_H=115 GeV
  - Placed 95% CL exclusion limit at M_H=114 GeV
- Global fit to data
  - Electro-weak parameters sensitive to Log(M_H)
    - $M_H = 91^{+58}_{-37}$ GeV
    - M_H<211 GeV (95% CL)
- Direct Higgs searches remains main focus at LHC



SM Higgs (3)

- Higgs mass sensitive to top mass:
  - New D0 and preliminary CDF RunII measurements
    - M_T=179.4 GeV
  - New EW fit:
    - M_H~130 GeV
    - M_H<280 GeV (95% CL)

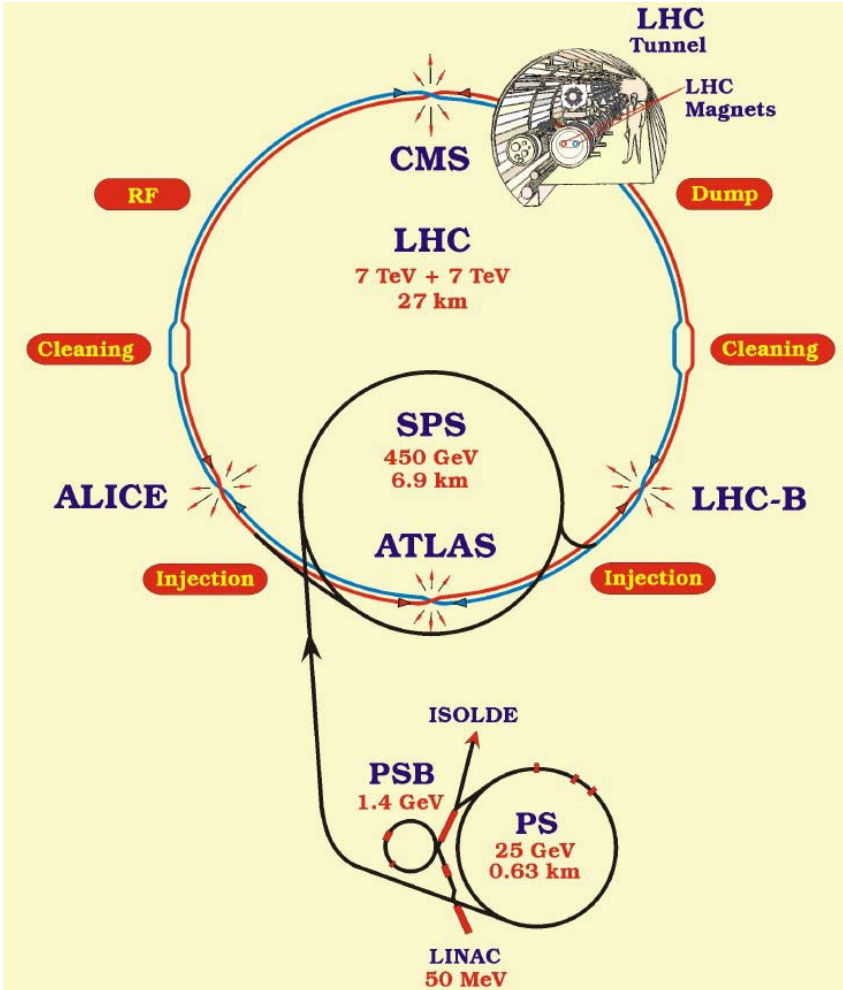


LHC

- **LHC, a p-p collider**

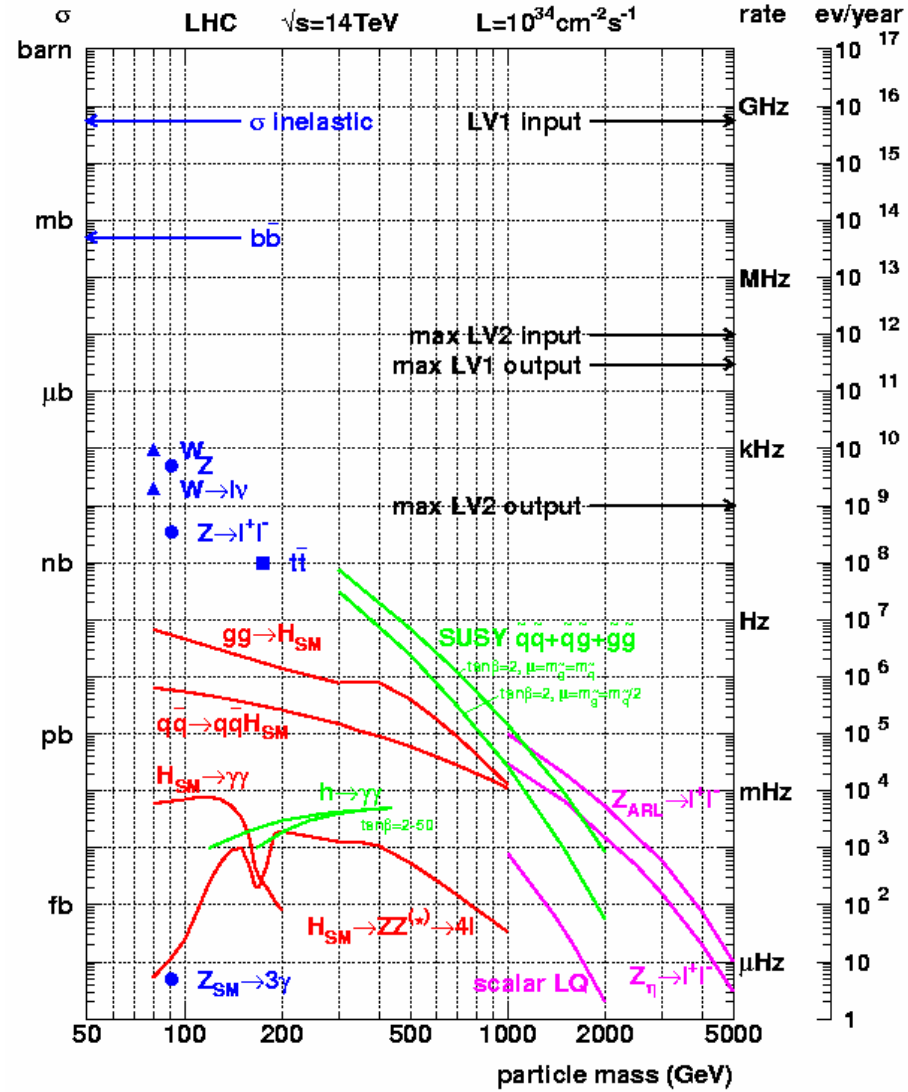
Center of mass E	14 TeV
Design Luminosity	10^{34} cm^{-2} s^{-1}
Luminosity Lifetime	10 h
Bunch spacing	25 ns

- **Current schedule:**
  - Early 2007 (pilot run)
  - 10 fb^{-1} by end of 2007
  - Starting 2008:
    - 30 fb^{-1} first year
    - Then 100 fb^{-1} per year



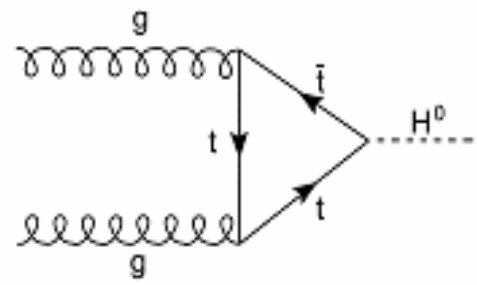
Cross-sections at LHC

- Search for Higgs and new physics hindered by huge background rates
  - Known SM particles produced much more copiously
- This makes low mass Higgs specially challenging. Need to rely on
  - Narrow resonances
  - Complex signatures
    - Higgs in association with tops, W, Z and jets.

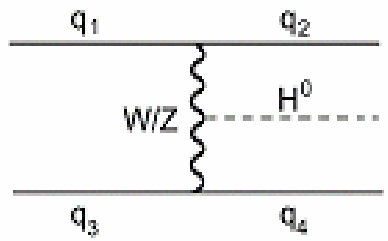


SM Higgs at the LHC (1)

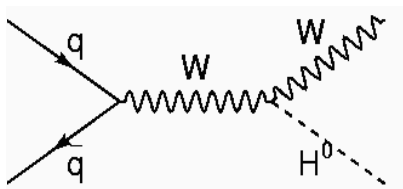
- **Production:**
  - **Direct**
    - **gg → H**
      - Dominant
      - Large background for low masses

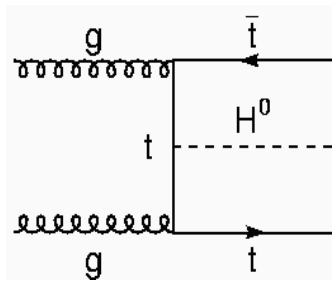


    - **Vector Boson Fusion (VBF) via qq →qqH**
      - Second largest cross-section
      - Distinct final state



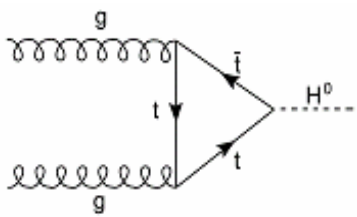
  - **Associated**
    - **ttH, WH, ZH**
      - Interesting final state
      - Small cross-section

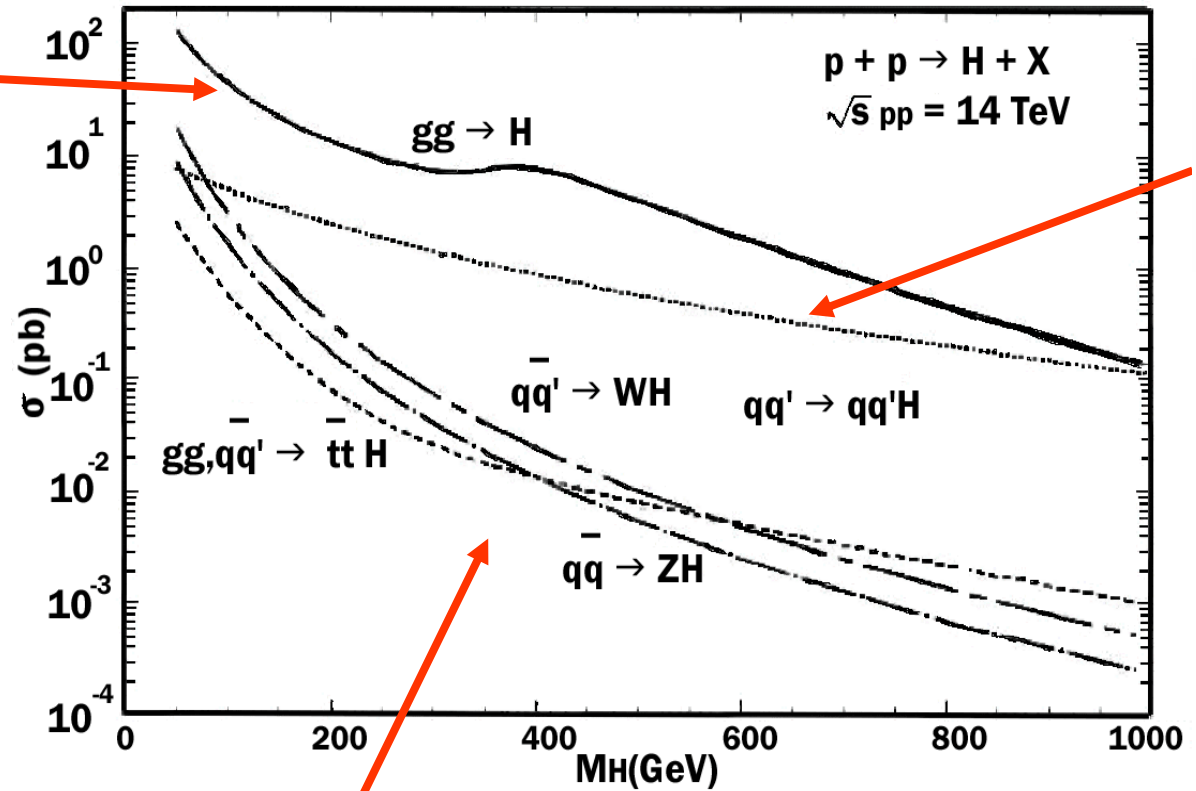




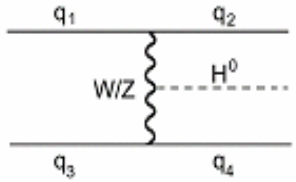
SM Higgs at the LHC (2)

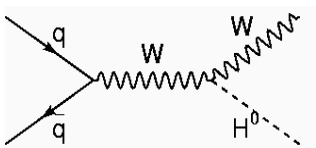
gg→H

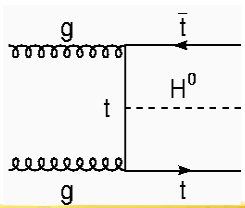




VBF



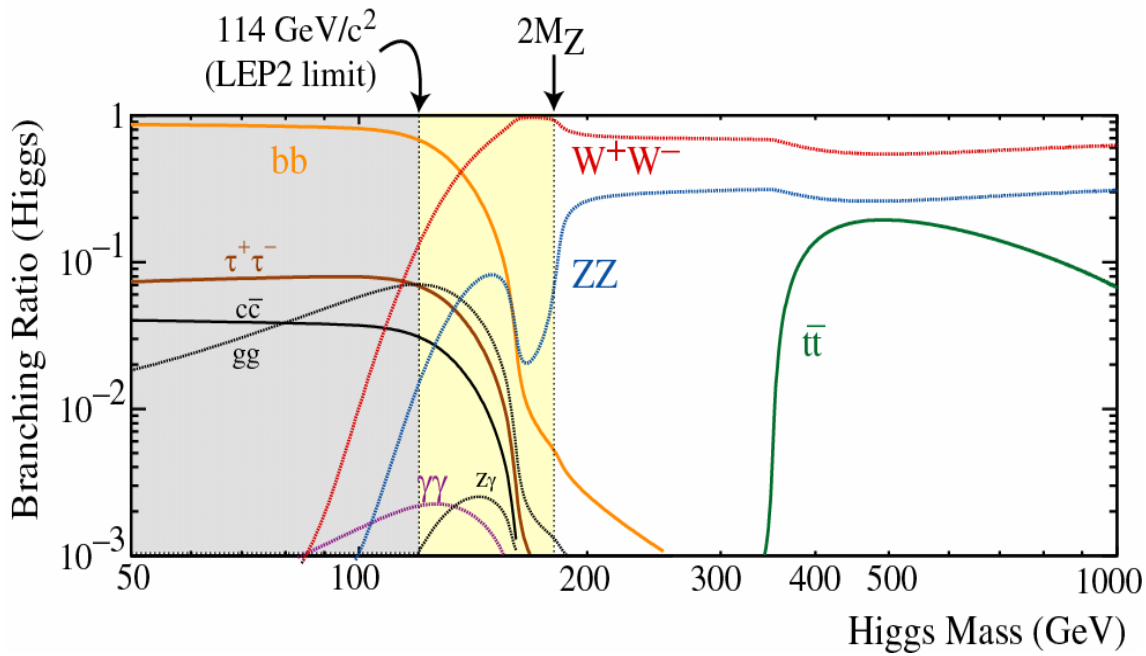




Associated

SM Higgs at the LHC (3)

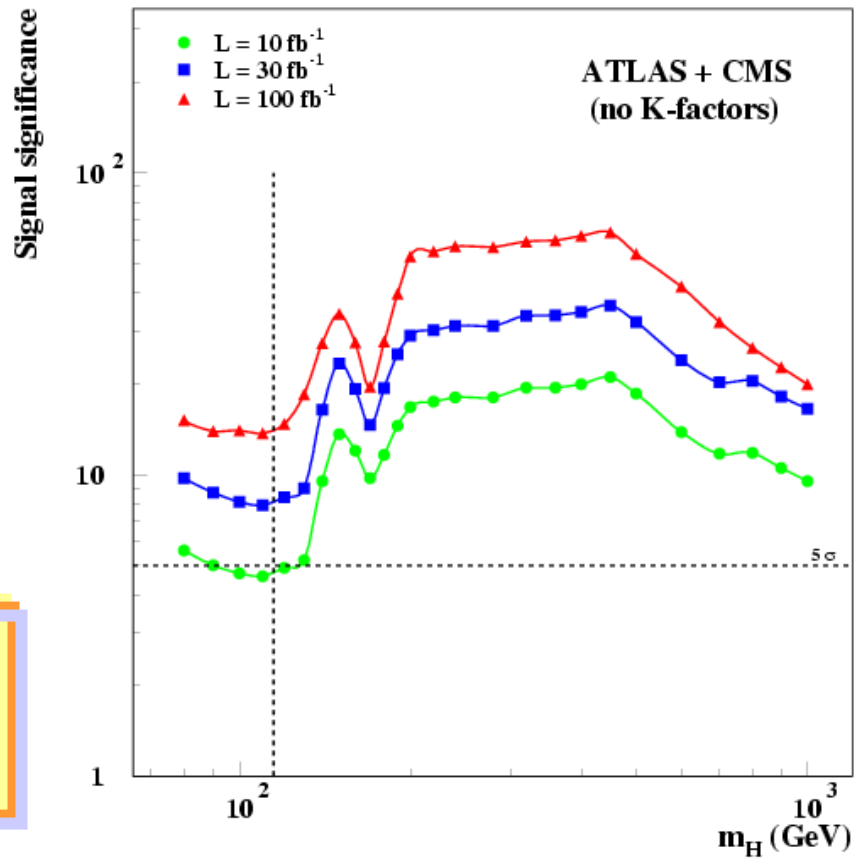
- **Main discovery modes**
  - $M_H < 2M_Z$:
    - $tt\bar{H} \rightarrow lbb+X$
    - $H \rightarrow \gamma\gamma$
    - $H \rightarrow ZZ^* \rightarrow 4l$
    - $H \rightarrow WW^* \rightarrow l\nu l\nu$
    - VBF not included
  - $M_H > 2M_Z$:
    - $H \rightarrow ZZ \rightarrow 4l$
    - $qqH \rightarrow qqZZ \rightarrow qqll\nu\nu$
    - $qqH \rightarrow qqZZ \rightarrow qqlljj$
    - $qqH \rightarrow qqWW \rightarrow qql\nu jj$



Standard analyses: Higgs with forward jets (VBF) looked at only for heavy Higgs

SM Higgs at the LHC (4)

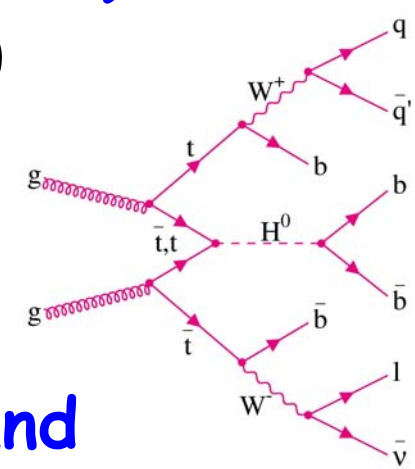
- **Sensitivity**
  - All region excluded @ 95% CL after 1 month
  - Fast discovery for M_H>150 GeV
  - Discovery with 10-15 fb^{-1} for M_H<150 GeV

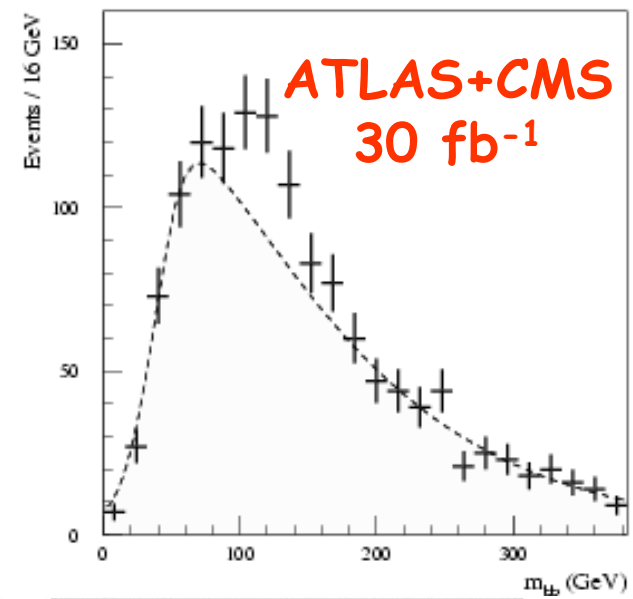


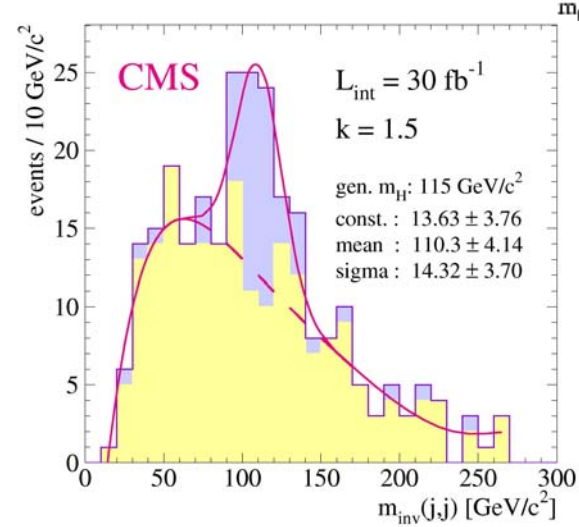
✓ VBF processes not used for low and medium M_H

SM Higgs via ttH

- Complex channel (H→bb):
  - One lepton (trigger)
  - 4 b-jets + 2 jets
    - b-tagging essential
    - Need to know well background (ttjj)
- Good for discovery and Yukawa coupling determination
  - 80 < M_H < 120 GeV
- CMS study:
  - Use likelihood for t decays and kinematics

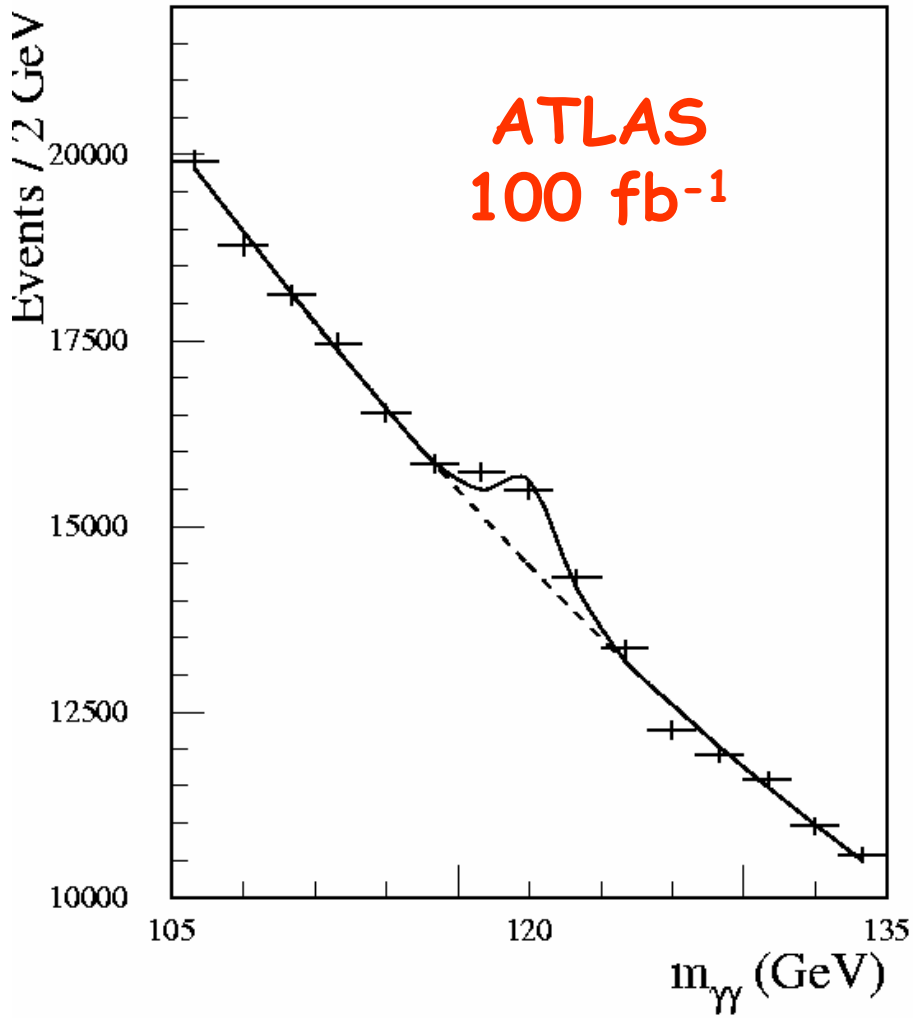






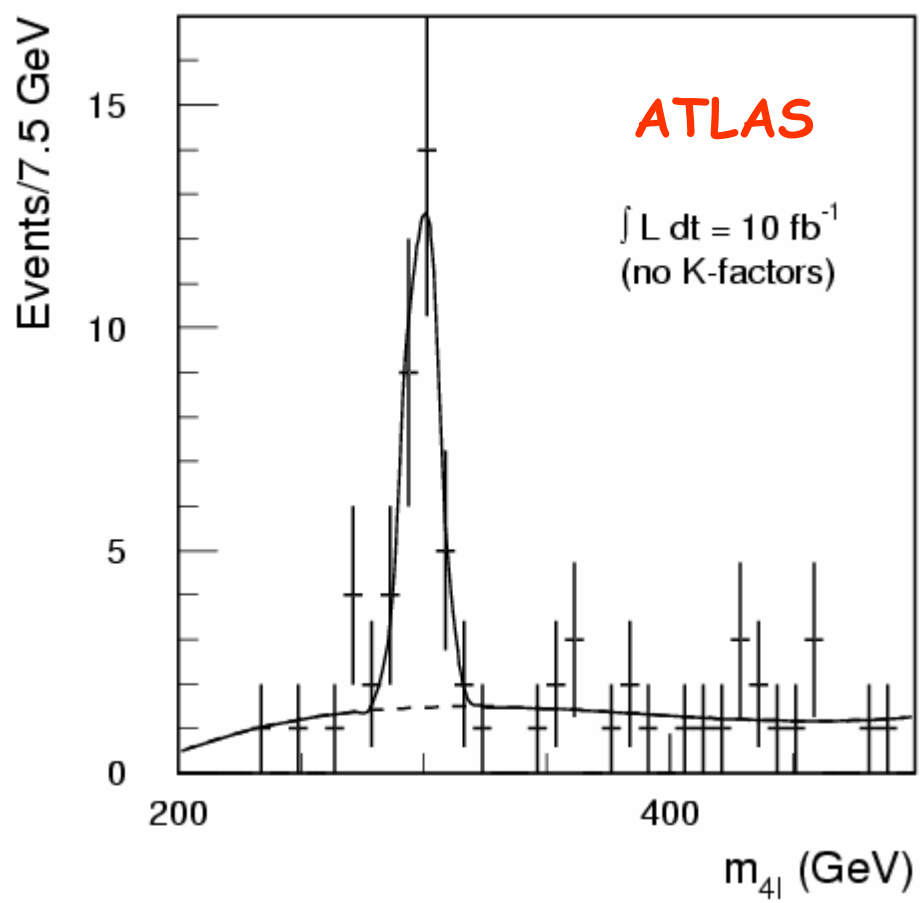
SM Higgs, $H \rightarrow \gamma\gamma$

- Need good calorimetry
  - Achieve ~1% resolution in Higgs mass reconstruction
- Need good rejection against jets
- Background
  - Non-resonant $\gamma\gamma$ production
  - Easily determined from side bands
- Good for discovery of low mass Higgs
  - $100 < M_H < 150$ GeV



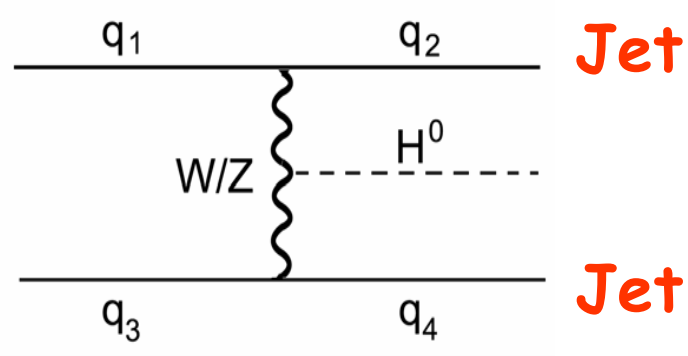
SM Higgs, H->ZZ->4l

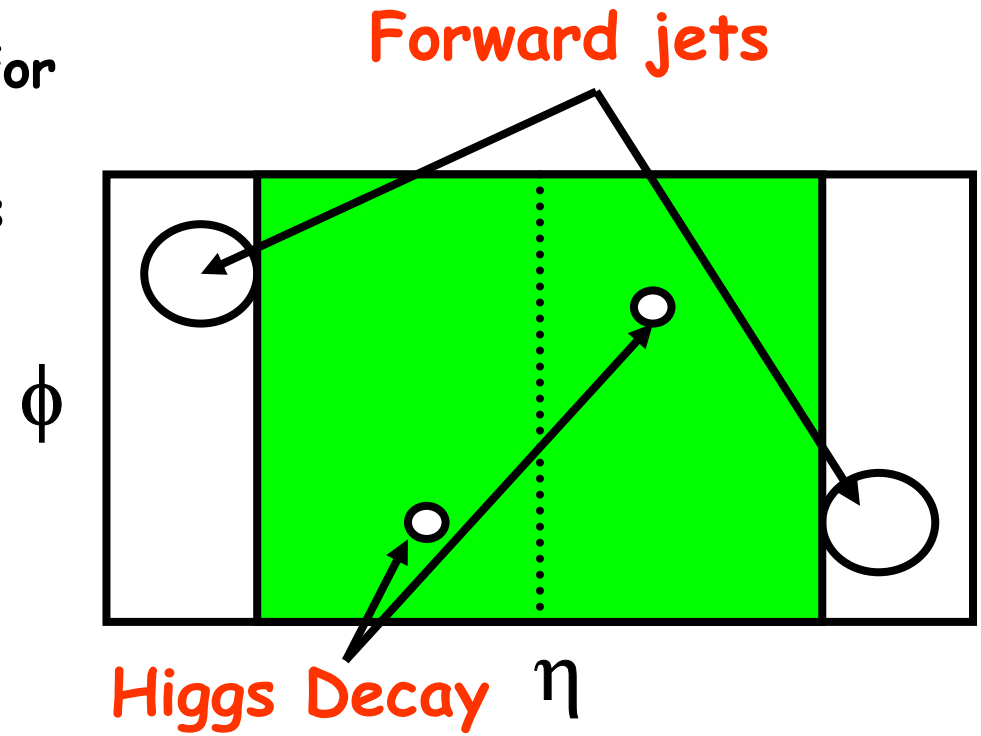
- Very clean signature
  - Narrow resonance
  - Small background contribution
- Main experimental issues
  - Lepton isolation
    - Zbb and ttbb rejection
- Good for discovery in wide Higgs mass range
  - 120 < M_H < 600 GeV



Low Mass Higgs via VBF (1)

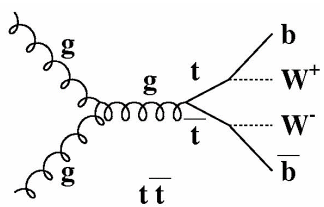
- Wisconsin Pheno (D.Rainwater, D.Zeppenfeld et al.):
  - Two high P_T jets with large $\Delta\eta$ separation
  - Strong discovery potential for low Higgs mass
  - Can measure Higgs couplings
  - Invisible decays
- Hadron level analyses very promising:
  - CMS & ATLAS seriously looking into VBF modes

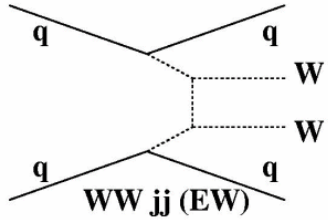




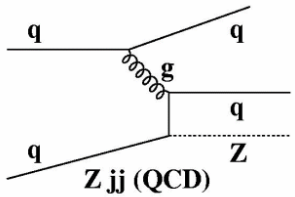
Low Mass Higgs via VBF (2)

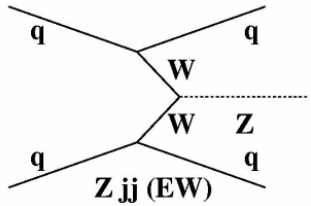
- H->WW*->llνν,lνqq. Strong for M_H>120 GeV
  - Main background:
    - tt EW WWjj
    - W + 4 jets



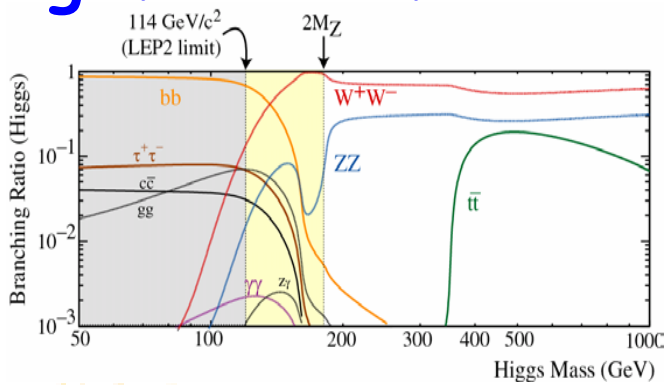


- H->ττ->ll,lh (+ptmiss). Good around LEP limit
  - Main background
    - QCD and EW Zjj



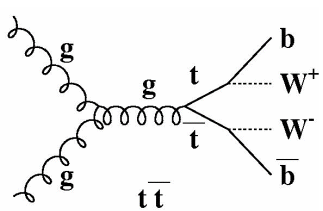


- H->bb. Useful for Yukawa coupling measurement
- H->γγ
  - Main background
    - real and fake non-resonant γγ

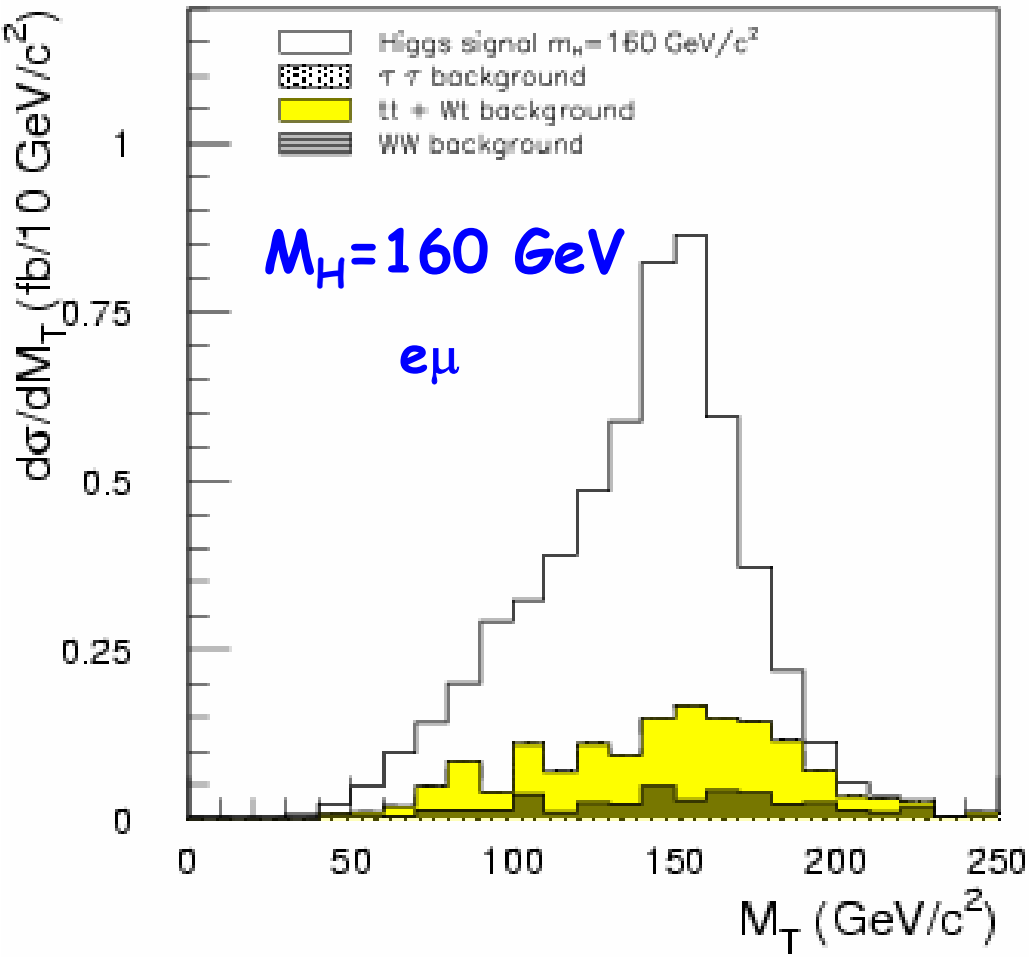


VBF H->WW* (1)

- **Background: tt, EW WWjj**
  - Understanding of tt production is crucial



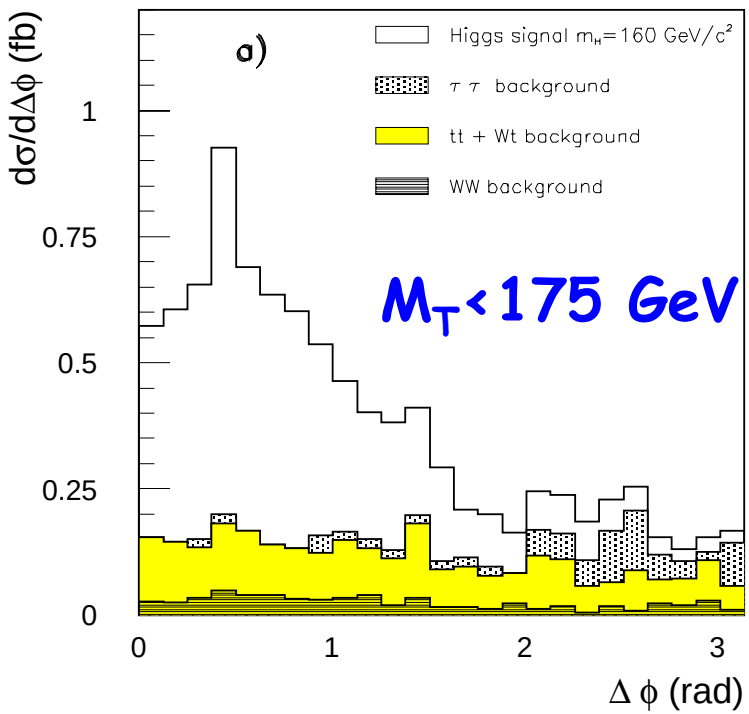
- **Background suppression:**
  - Well separated forward jets + central jet veto
  - <u>b-jet veto</u>
  - Lepton angular correlations



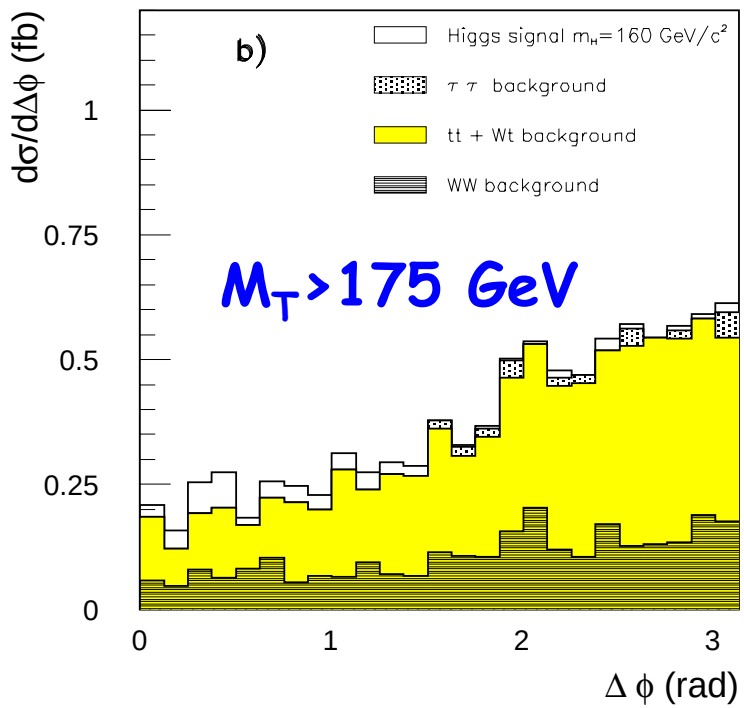
VBF H->WW* (2)

- Evidence of Spin-0 resonance in H->WW->ll modes
  - Look into difference in ϕ between leptons

Signal Region

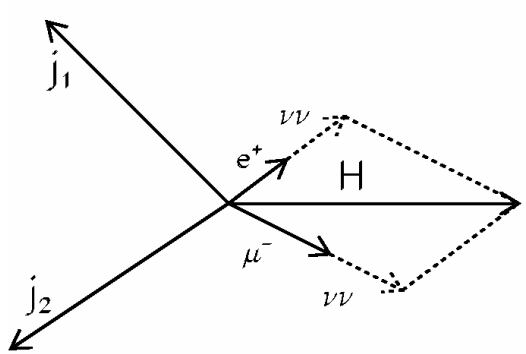


Outside Signal Region



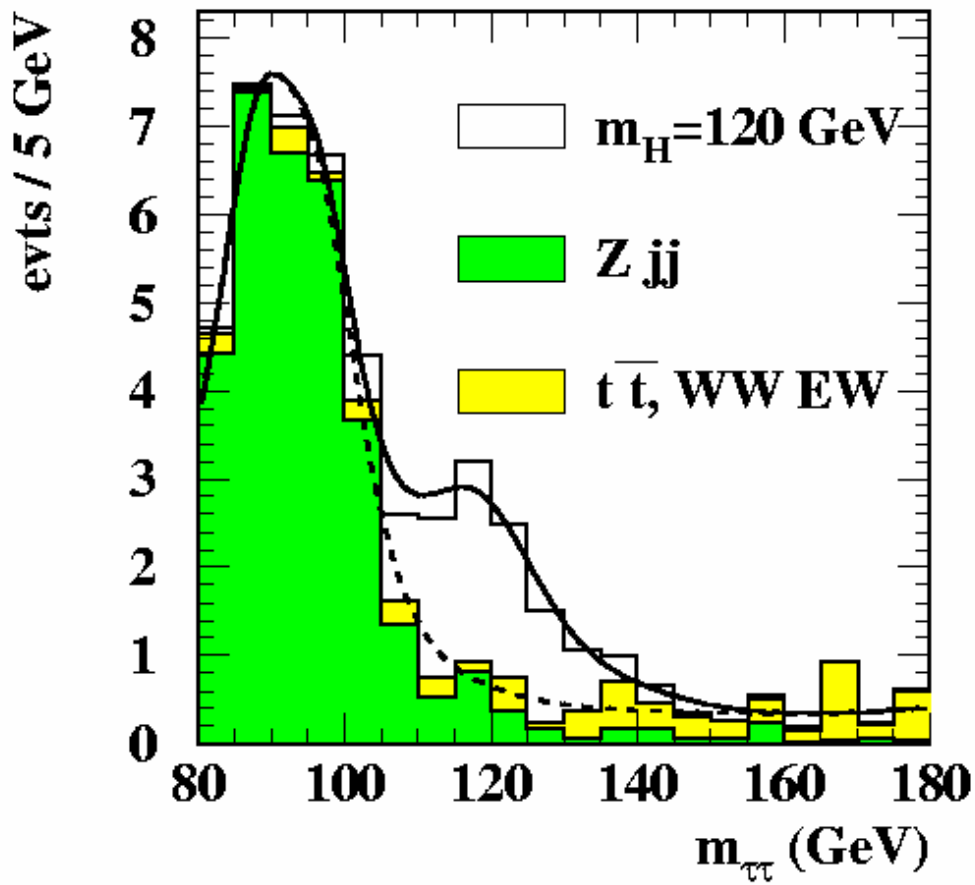
VBF H->ττ

- H→ττ analyses (ττ->ll,lh):
  - $M_{\tau\tau}$ reconstruction using collinear approximation
    - Mass resolution ~10%



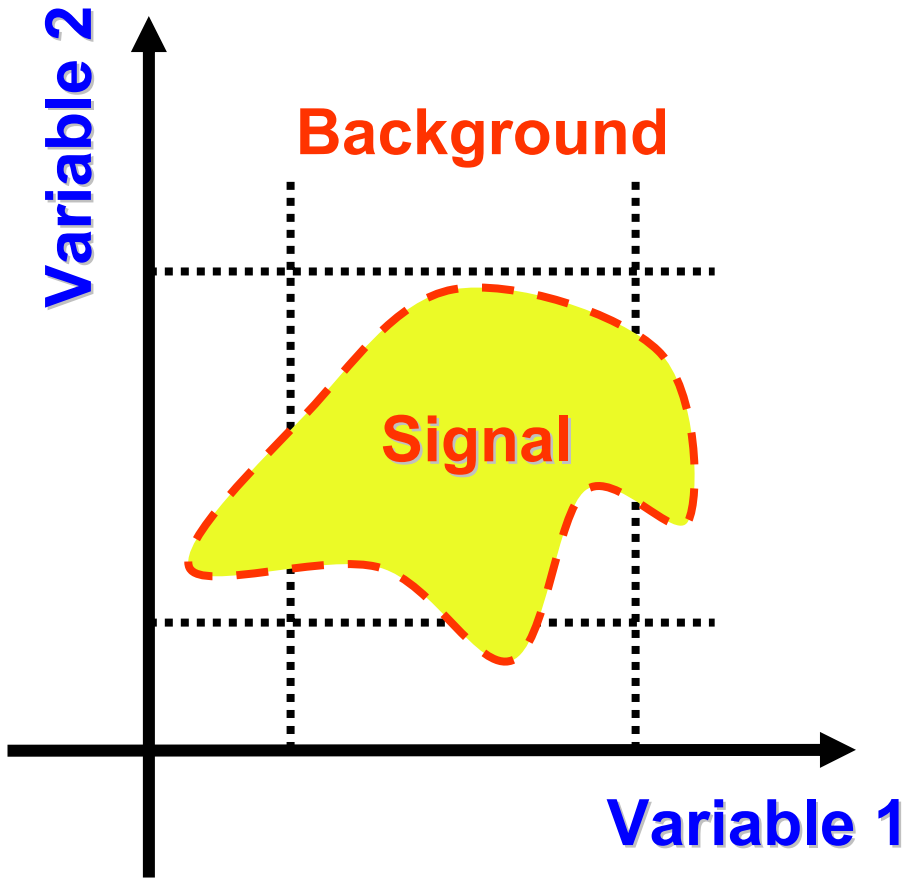
  - Main backgrounds
    - EW & QCD Zjj
    - tt and W production

H-> ττ->ll
30 fb^{-1}



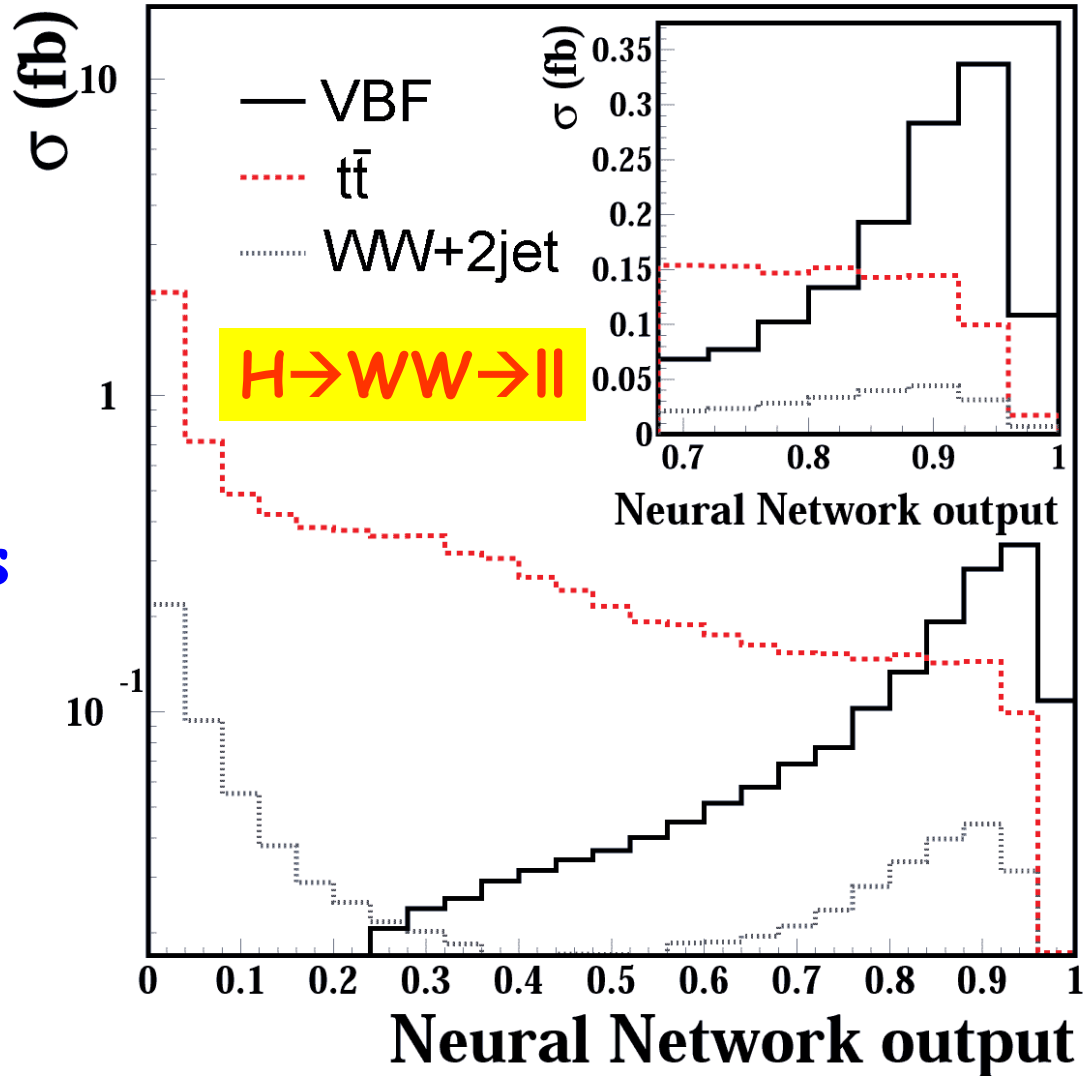
Multivariate Analysis (1)

- Classical cut analysis uses rectangular signal-like phase space
- Contour if signal-like phase space may be of any shape
- Disadvantage of cut analysis gets larger with increasing number of discriminating variables
- Use Neural Networks as a multivariate tool



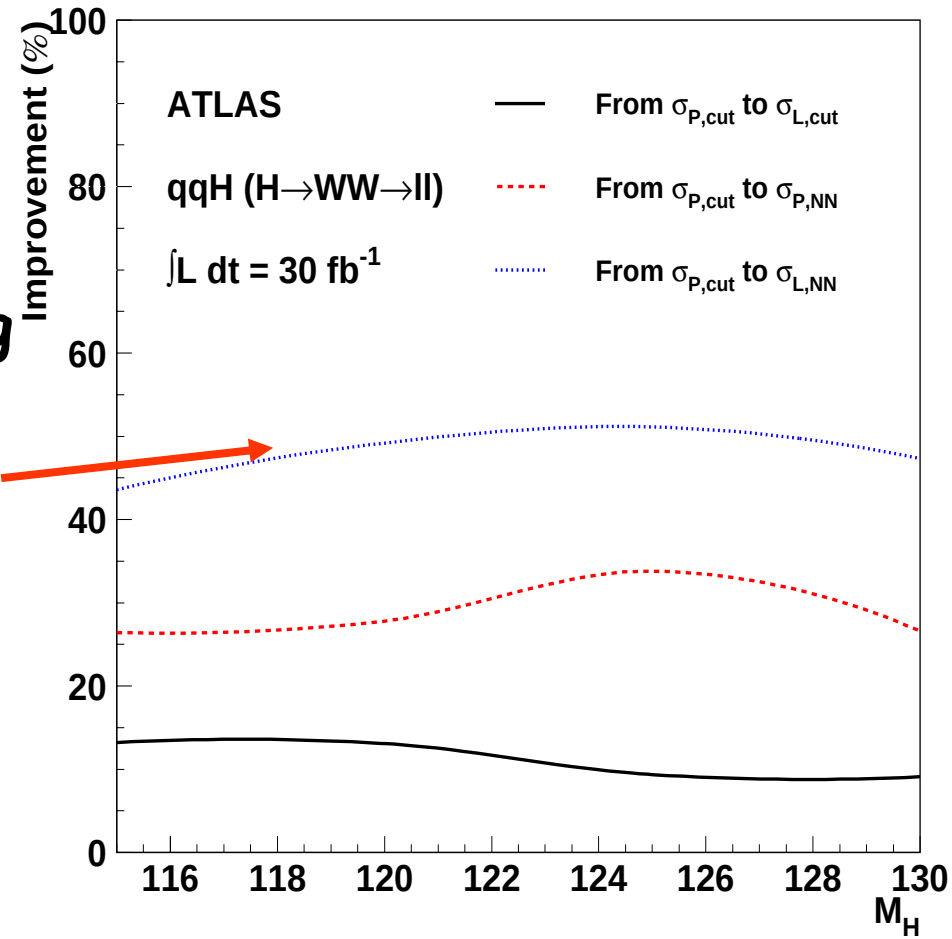
Multivariate Analysis (2)

- Complex final state (VBF)
  - Two forward jets
  - Two leptons
  - Missing momentum
- Classical cut analysis misses correlations
- Ideal for multivariate analysis



Multivariate Analysis (3)

- Signal significance improvement with neural network based analysis:
  - Neural network output used as a discriminating variable
  - Results improve by 45-50%

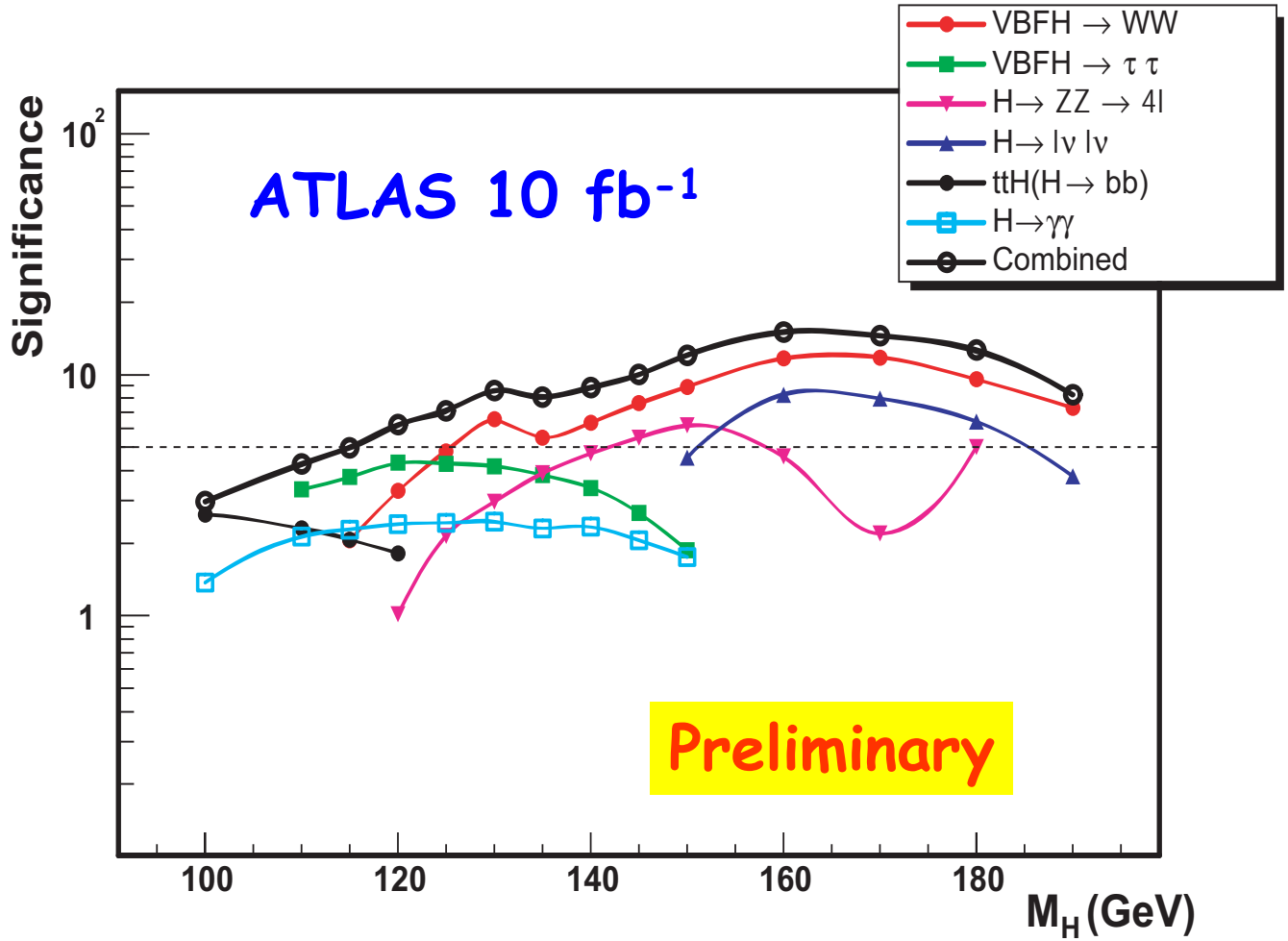


$$H \rightarrow W^+W^- \rightarrow l^+\nu l^-\nu$$

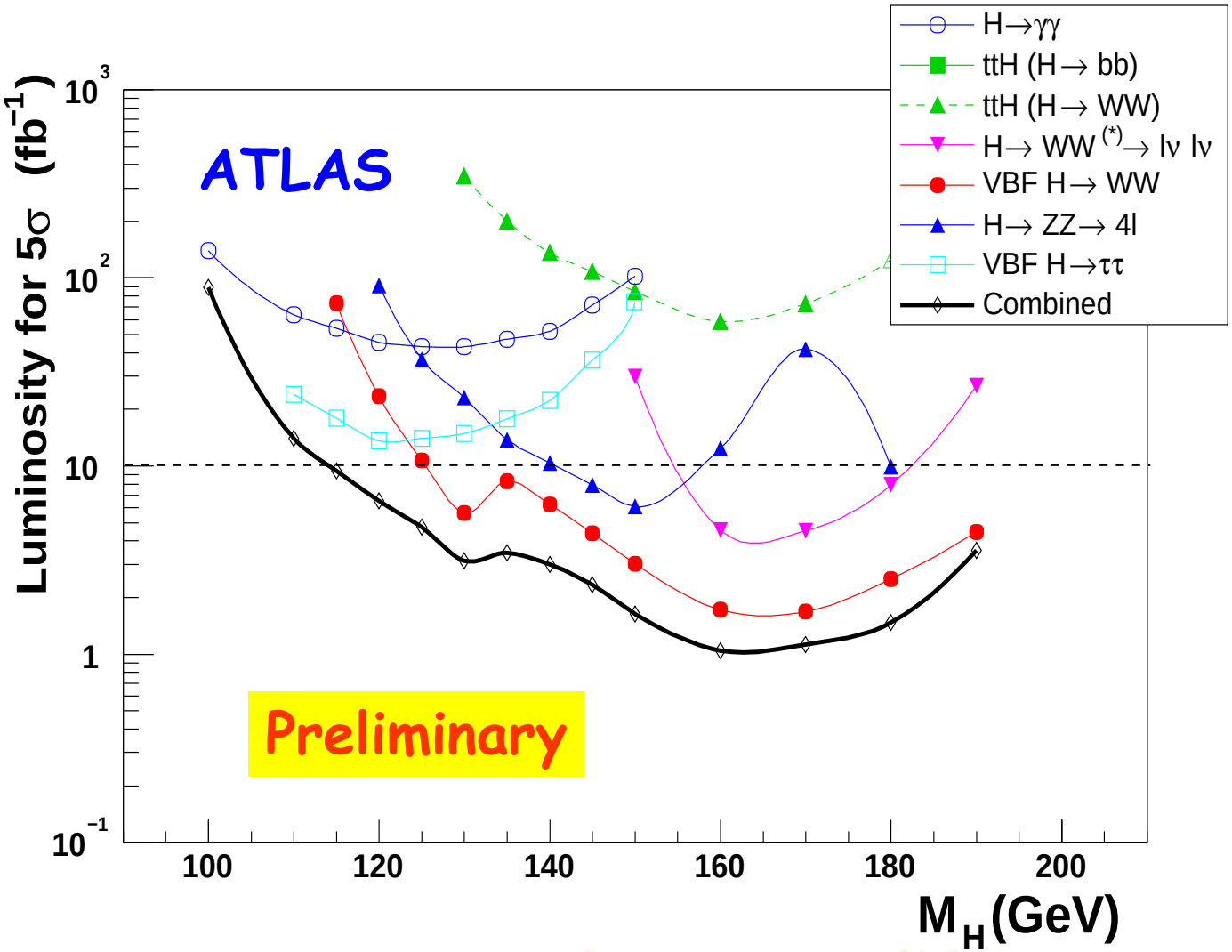
$$H \rightarrow \tau^+\tau^- \rightarrow l^+\nu\nu l^-\nu\nu$$

$$H \rightarrow \tau^+\tau^- \rightarrow l\nu\nu h\nu$$

- ***One experiment may reach a 5σ signal significance with only 10 fb^{-1} of data***

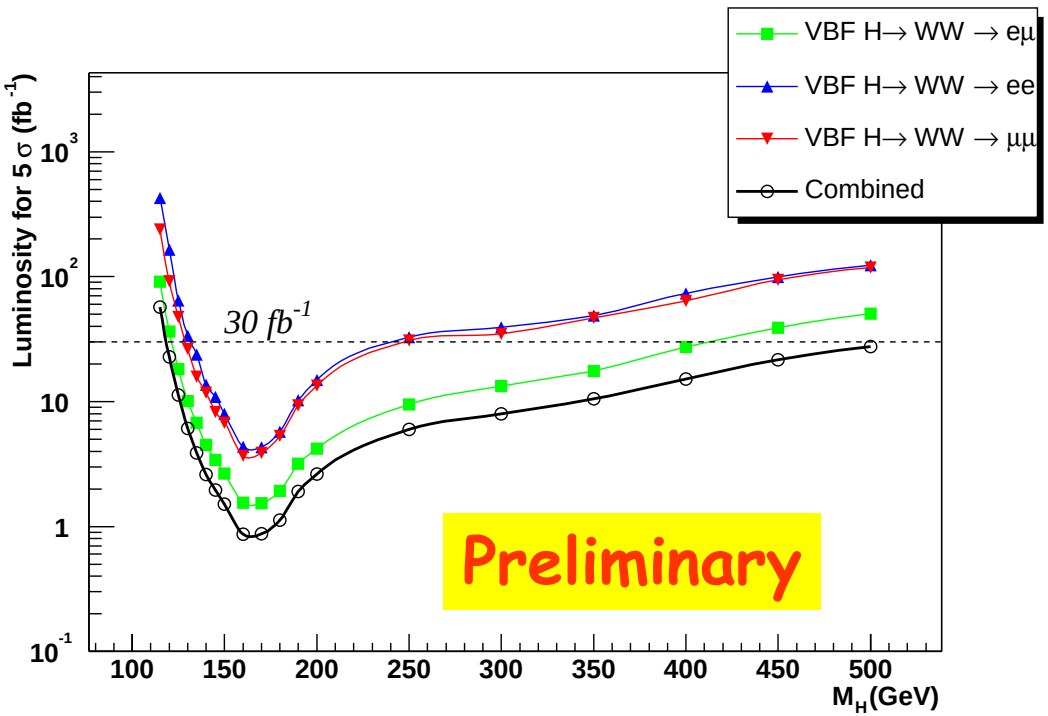


"Luminosity" plot

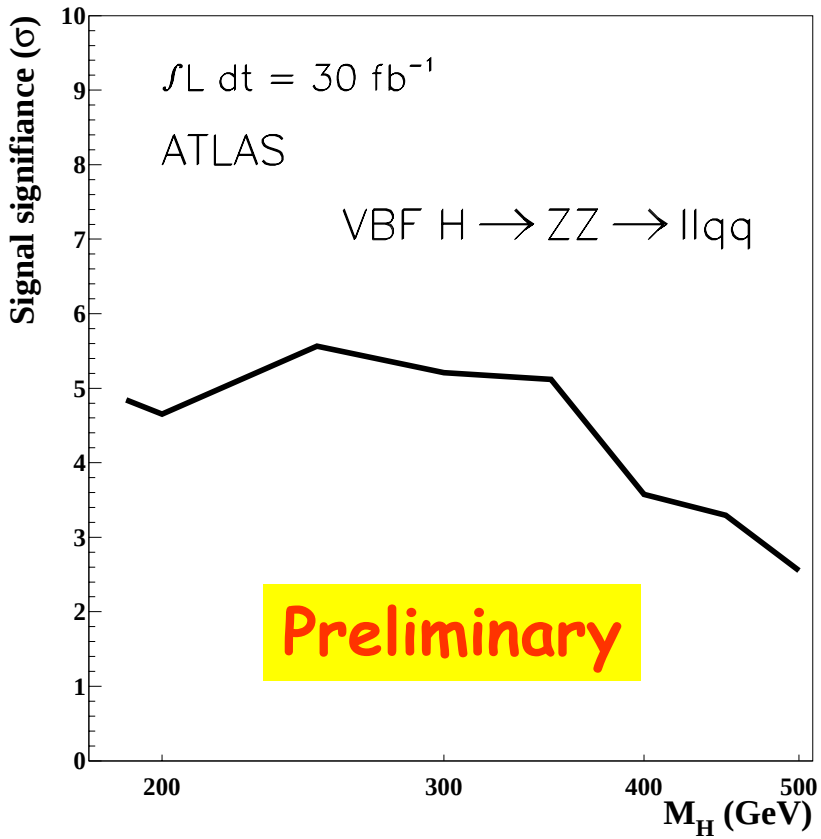


VBF for Intermediate Masses

VBF H->WW->ll



VBF H->ZZ->llqq



MC's for VBF

- VBF analysis is an exclusive search
  - Two hard and well separated jets (tagging jets)
  - Veto on third jet in central region of the detector.
    - Need to distinguish between QCD and EW processes
- Severe requirements on MC:
  - Simulate X+3j
- A lot of MC development needed before turn on!

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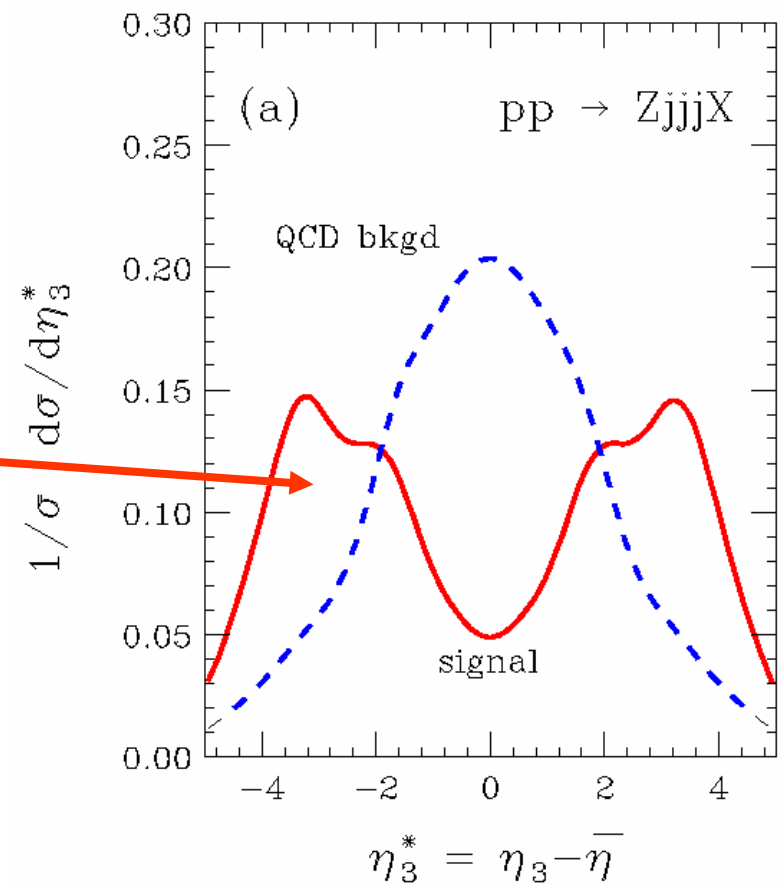
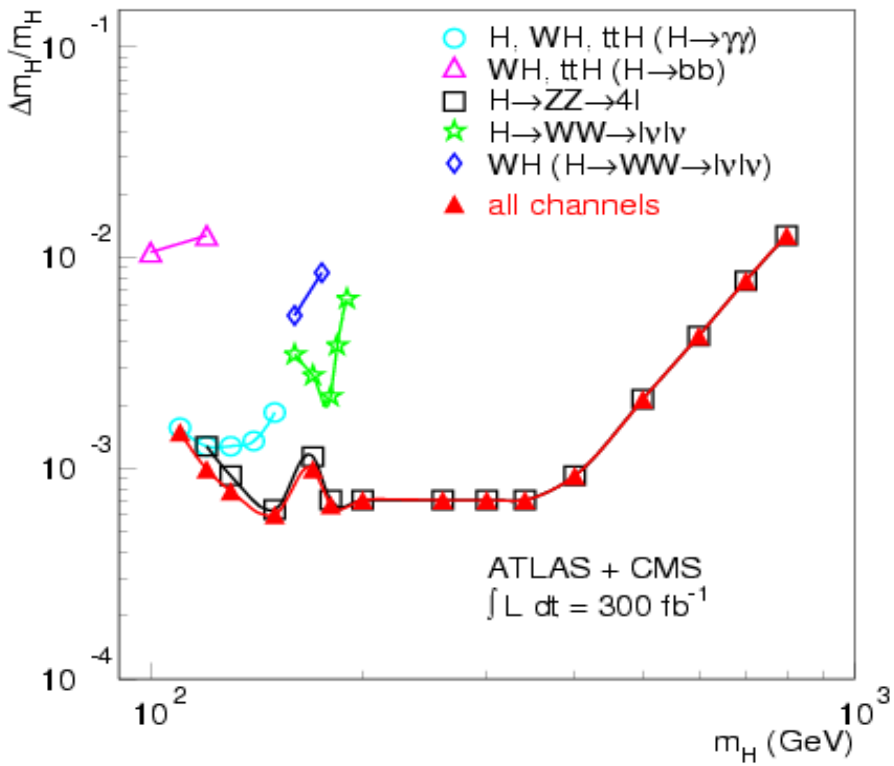


SM Higgs Mass

- Determined best with
  - H->ZZ->4l
  - H->γγ
  - Resolution ~1%
  - Electro-magnetic energy scale uncertainty ~0.1%
    - Calibration with Z->ee
- Higgs width grows fast with mass
  - Precision decreases for heavy Higgs



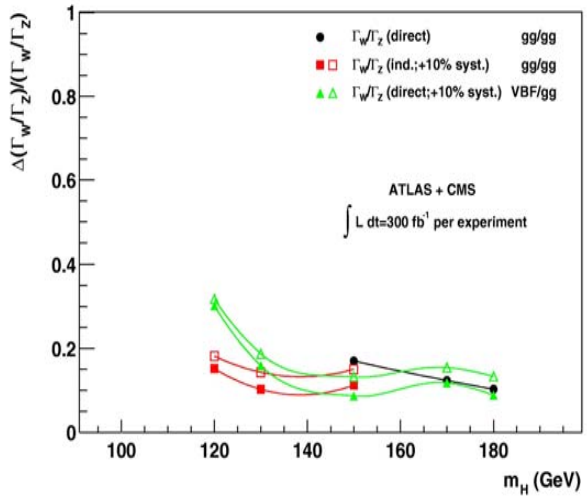
Coupling Measurements

- **Ratio of boson-boson couplings**
  - Direct (QCD corrections cancel)

$$\frac{\sigma \times BR(H \to WW^*)}{\sigma \times BR(H \to ZZ^*)} = \frac{\Gamma_g \Gamma_W}{\Gamma_g \Gamma_Z} = \frac{\Gamma_W}{\Gamma_Z}$$

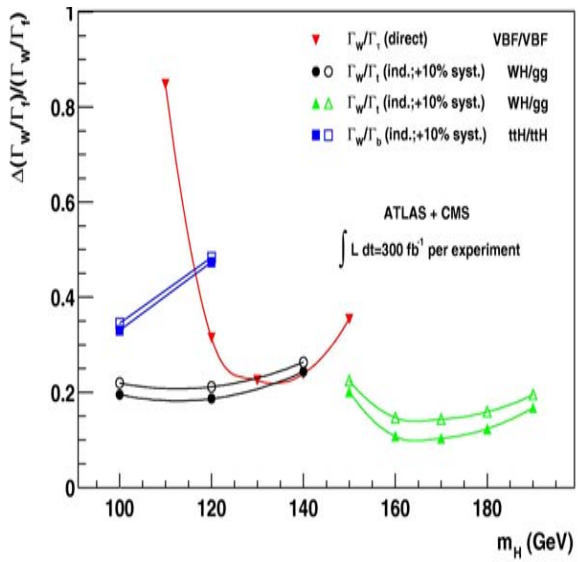
  - VBF (QCD corrections don't cancel)

$$\frac{\sigma \times BR(qqH \to qqWW^*)}{\sigma \times BR(H \to ZZ^*)} = \frac{\Gamma_W}{\Gamma_Z}$$



- **Ratio of boson-fermion couplings**
  - Direct (VBF)

$$\frac{\sigma \times BR(qqH \to qqWW)}{\sigma \times BR(qqH \to qq\tau\tau)} = \frac{\Gamma_W \Gamma_W}{\Gamma_W \Gamma_\tau} = \frac{\Gamma_W}{\Gamma_\tau}$$



- **VBF not fully exploited**

Major Experimental Issues (1)

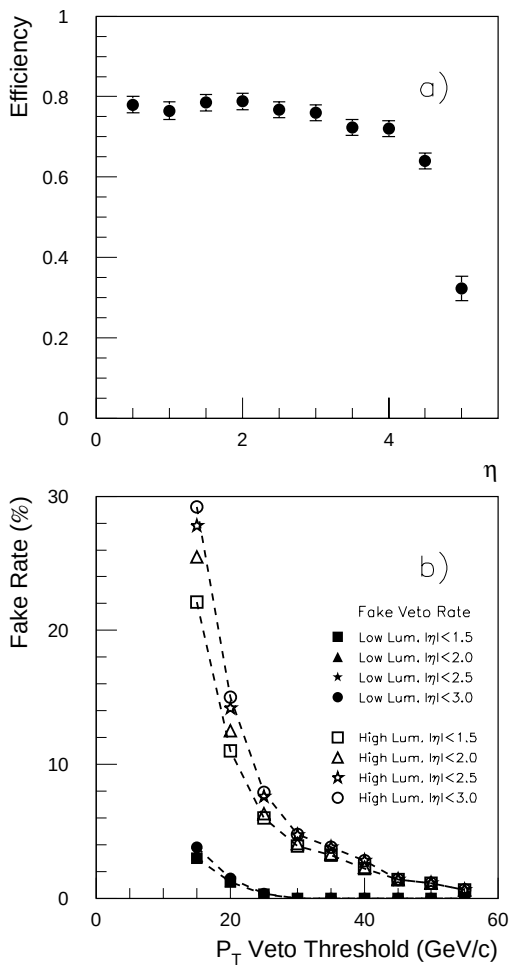
ttH, H->bb	$80<M_H<120$	b-tagging, jet calibration
H->γγ (+0,1,2 jets)	$100<M_H<150$	γ calibration, γ/jet separation
H->ZZ*, Z->4l	$120<M_H<180$	Lepton isolation, efficiency
H->ττ, τ->l,h (+2 jets)	$110<M_H<150$	ττ reconstruction VBF issues, Ptmiss
H->WW* W->lν,qq (+2 jets)	$110<M_H<180$	Lepton isolation VBF issues, Ptmiss

Major Experimental Issues (2)

H->ZZ, Z->4l	$180<M_H<600$	Lepton isolation, efficiency
H->ZZ, Z->llνν	$500<M_H<1000$	Lepton isolation, Ptmiss, forward jets
H->WW* W->lν,qq (+2 jets)	$180<M_H<1000$	Lepton isolation VBF issues, Ptmiss
H->ZZ, Z->llqq (+2 jets)	$180<M_H<500$	Lepton isolation VBF issues

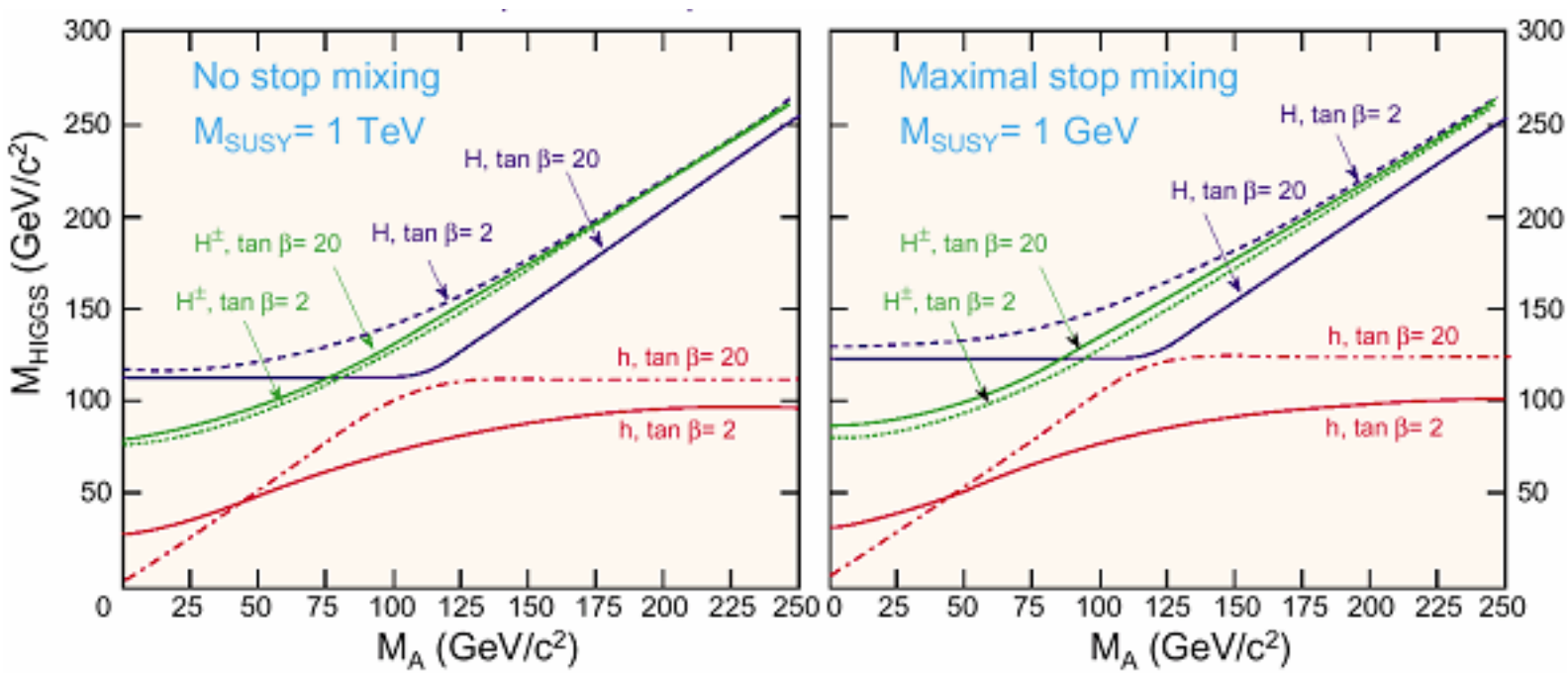
VBF Experimental Issues

- Tagging forward jets:
  - Efficiencies critical
    - Double tag efficiency ~50%
  - Jet calibration
- Central jet veto:
  - Pile up effects introduce fake central jets
    - Effect small at low luminosity
    - Serious concern at high luminosity
- Need to improve analysis based on more realistic full simulation



MSSM Higgs (1)

- Minimal super-symmetric extension of Higgs sector
  - Five Higgs: h (light), H, A, $H^{\pm}$ (heavy)
  - Parameter space reduced to two: M_A, $\tan\beta$
  - Theoretical limit on light MSSM Higgs: h<135 GeV



MSSM Higgs (2)

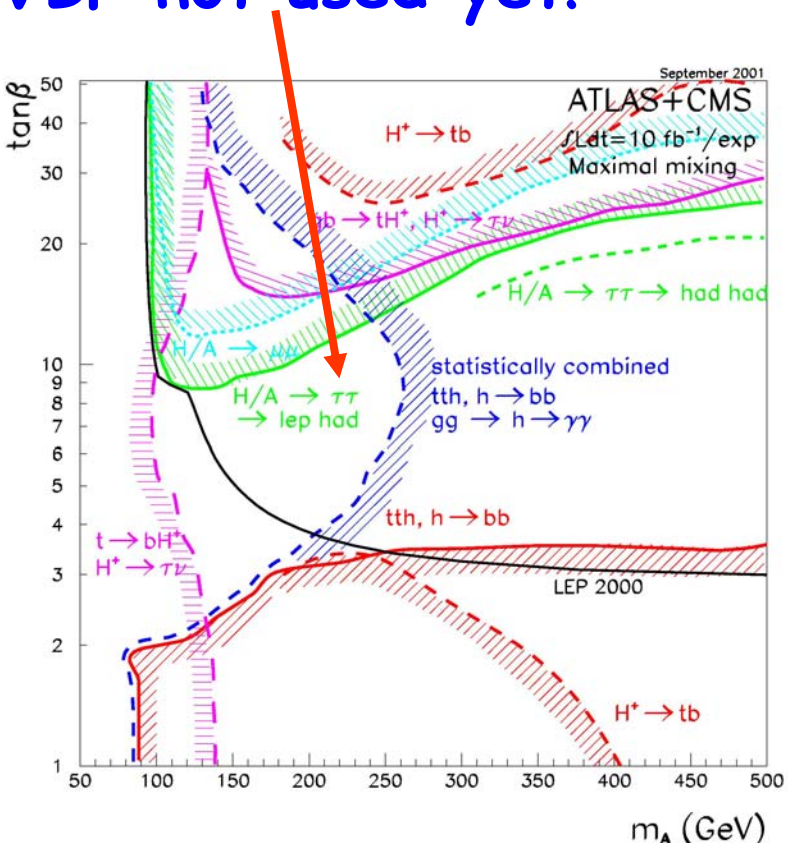
- Large multiplicity of discovery modes:
  - SUSY particles heavy:
    - SM-like: $h \to \gamma\gamma, bb, \tau\tau, WW$; $H \to 4l$
    - MSSM-specific: $A/H \to \mu\mu, \tau\tau, tt$; $H \to hh$, $A \to Zh$; $H^{\pm} \to \tau^{\pm}\nu$
  - SUSY accessible:
    - $H/A \to \chi^0_2 \chi^0_2$, $\chi^0_2 \to h\, \chi^0_1$
    - Small impact on Higgs branching ratio to SM particles
- Consider different MSSM scenarios
  - Different upper limits to light MSSM Higgs (h)

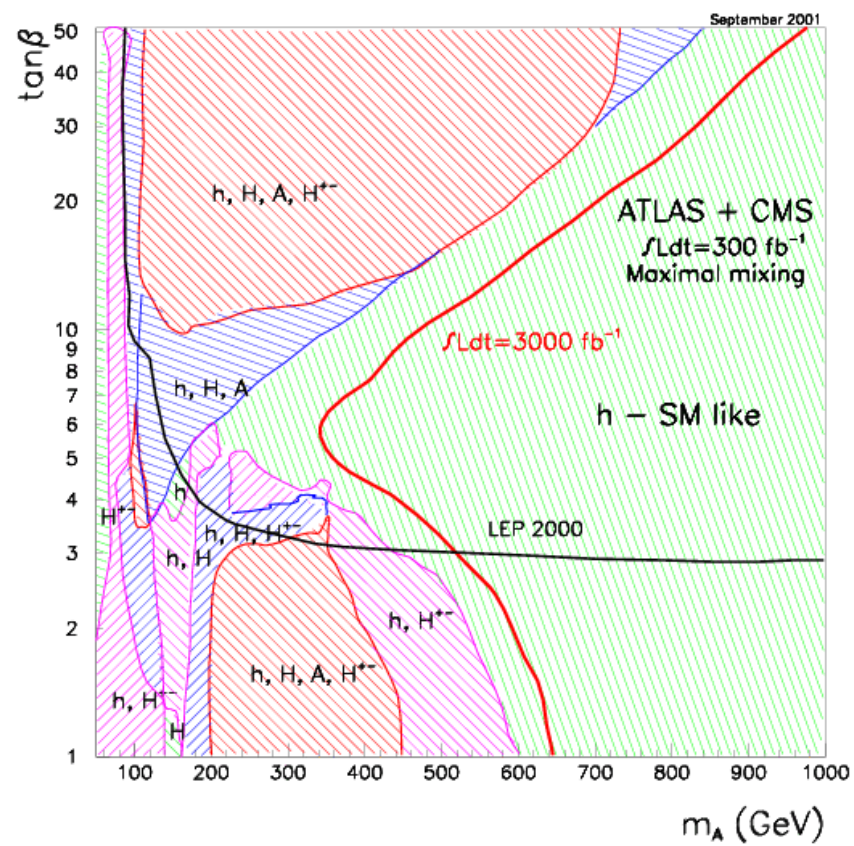
MSSM Higgs Discovery Potential

- Most of plane explored with 10 fb^{-1}
- >1 MSSM Higgs observable:
  - Disentangle SM and MSSM
- VBF not used yet!

4 Higgs observable
3 Higgs observable
2 Higgs observable
1 Higgs observable

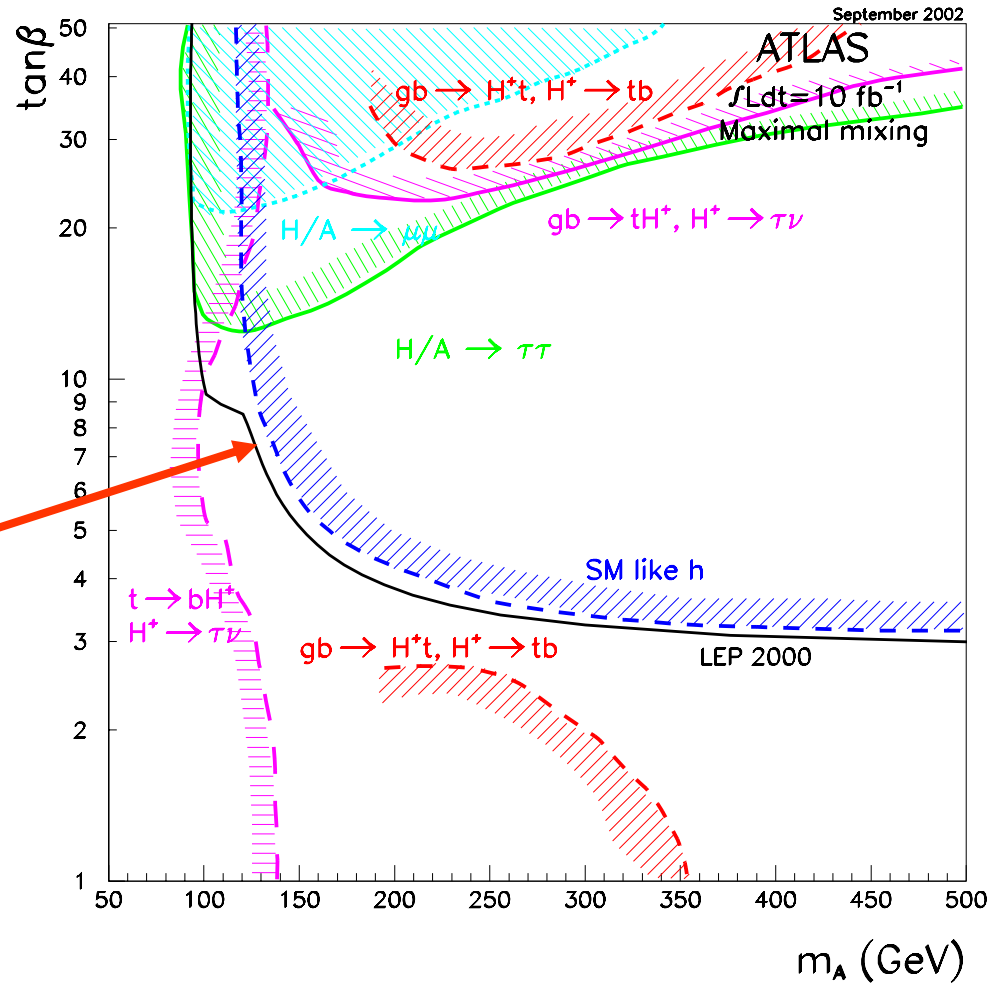
5 σ Contours





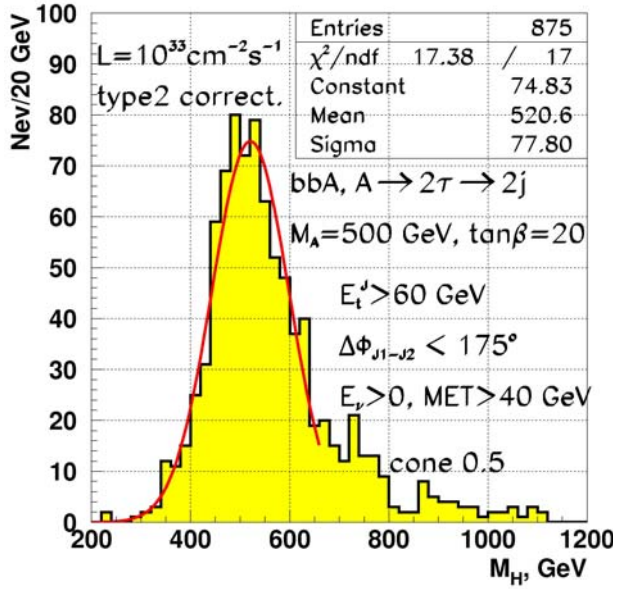
MSSM Higgs and VBF

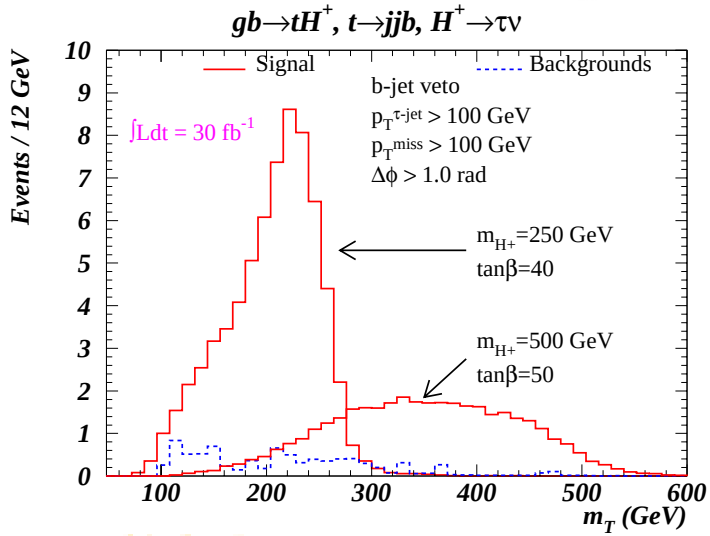
- The addition of VBF modes in MSSM searches enhances sensitivity to low mass Higgs
  - One experiment with 10 fb-1 covers <u>almost entirely</u> MSSM plane
  - Only light Higgs (h)



Heavy MSSM Higgs

- **bbH/A→ττ→had had νν:**
  - Full simulation studies
    - Trigger efficiency
    - τ-jets efficiency
    - Mass reconstruction
      - 15% resolution
      - Reconstruction efficiency
- **gb→tH±, H±→τ±ν:**
  - Only transverse mass
  - Almost background free
    - 100% τ polarization enhances signal

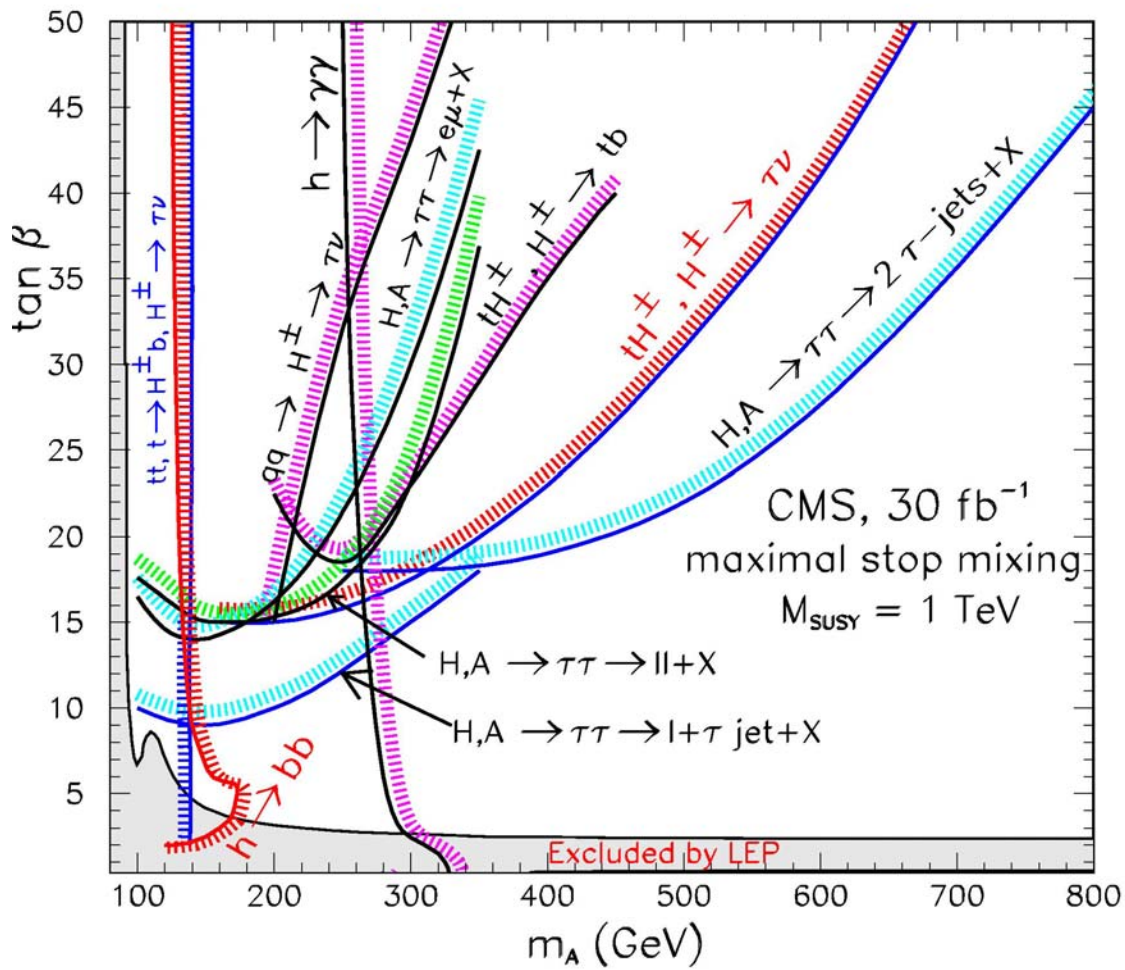




Sensitivity to Heavy Higgs (1)

- Sensitivity to heavy MSSM Higgs dominated by τ in final state
- Little sensitivity to intermediate tan β with SM decays
- Need new scenarios
  - SUSY
    - Higgs decays
    - From cascade

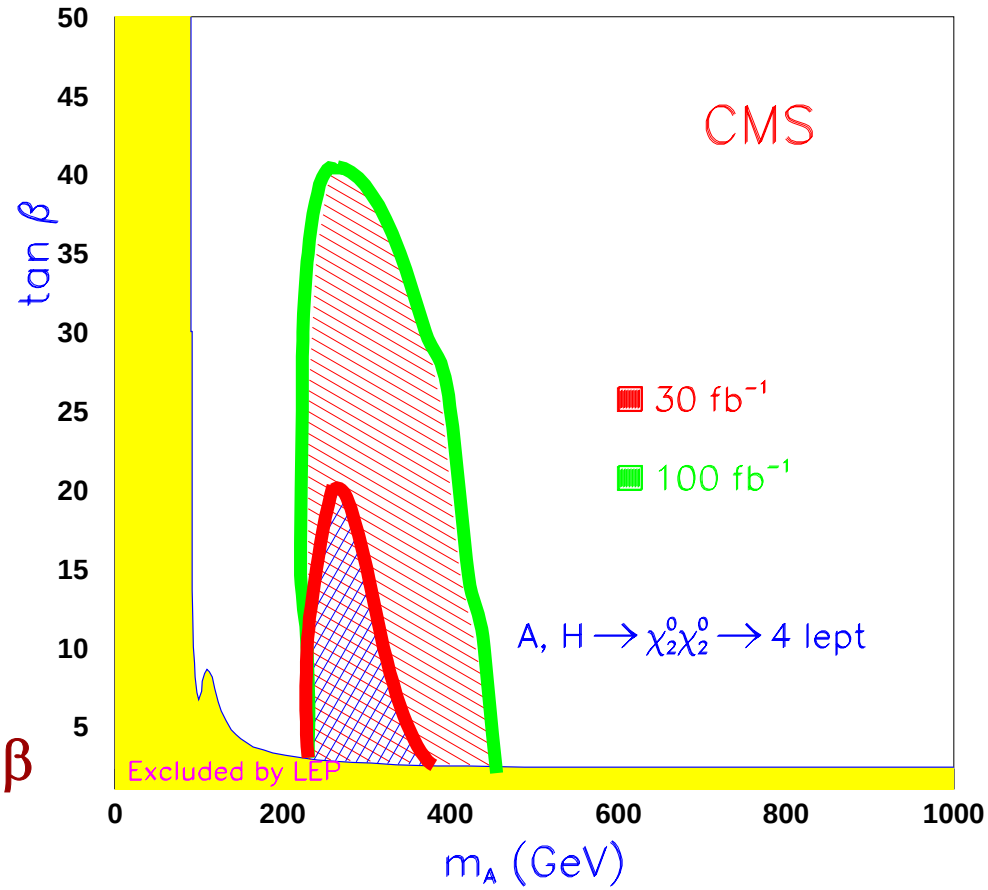
5 σ Contours



Sensitivity to Heavy Higgs (2)

- $H/A \rightarrow \chi^0_2\ \chi^0_2 \rightarrow 4l + E_t^{miss}$
  - Look for isolated e,μ and E_t^{miss}
  - Strong background suppression:
    - SM (ZZ, tt)
    - MSSM (sνsν)
  - MSSM plane:
    - $230 < M_A < 450$ GeV
    - Low and medium tan β

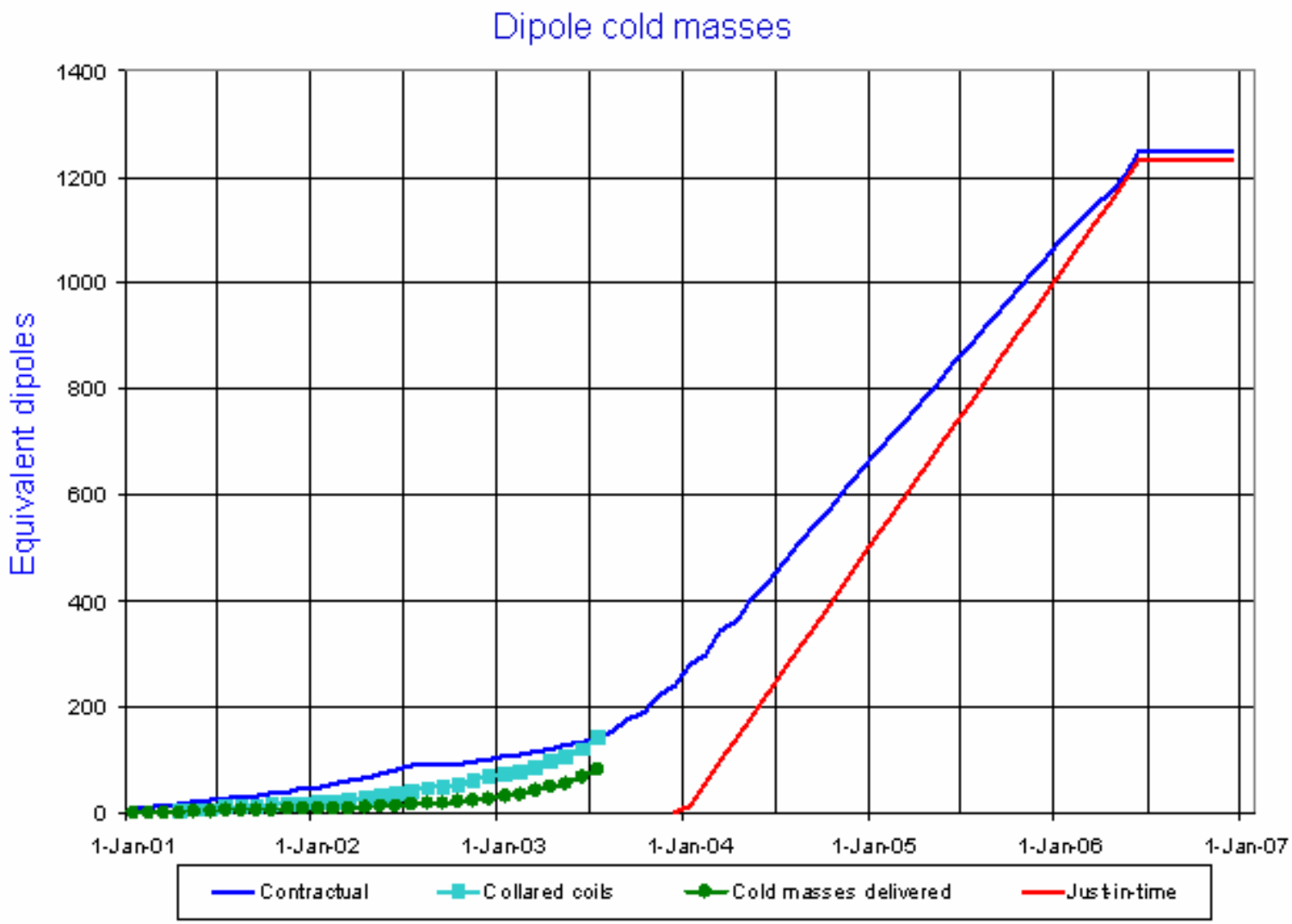
5 σ Contours



Software Development

- Higgs will be observed with more than one channel
- Higgs searches spans over a number of final states
  - Leptons, photons, Ptmiss, jets, taus
- Need to understand a lot of experimental issues
  - Lepton/γ identification, isolation, calibration, rejection against jets
  - Tau reconstruction, rejection against jets
  - Missing momentum, b-tagging
  - Forward jets and central jet veto: calibration, tagging efficiency, rejection against pile-up, underlying event
- Most of the studies based on full simulation date back to TDR. A lot of work needs to be done

Summary

- SM Higgs may be observed with 10 fb^{-1}
  - Known channels ($H \rightarrow bb, \gamma\gamma, 4l$...) well assessed
  - Vector Boson Fusion significantly enhances sensitivity for Higgs of low mass:
    - Forward jet tagging efficiency crucial
    - Neural Nets enhance signal significance by ~50%
    - A lot of MC development needed before turn on!
- Most of MSSM plane explored with 10 fb^{-1}
  - VBF enhances sensitivity to light MSSM Higgs
  - Sensitivity to heavy Higgs dominated by channels with τ in final state
- Lots of software development to be done before turn on!

The LHC is coming!