Higgs and Vector Boson Fusion

B.Mellado

University of Wisconsin-Madison

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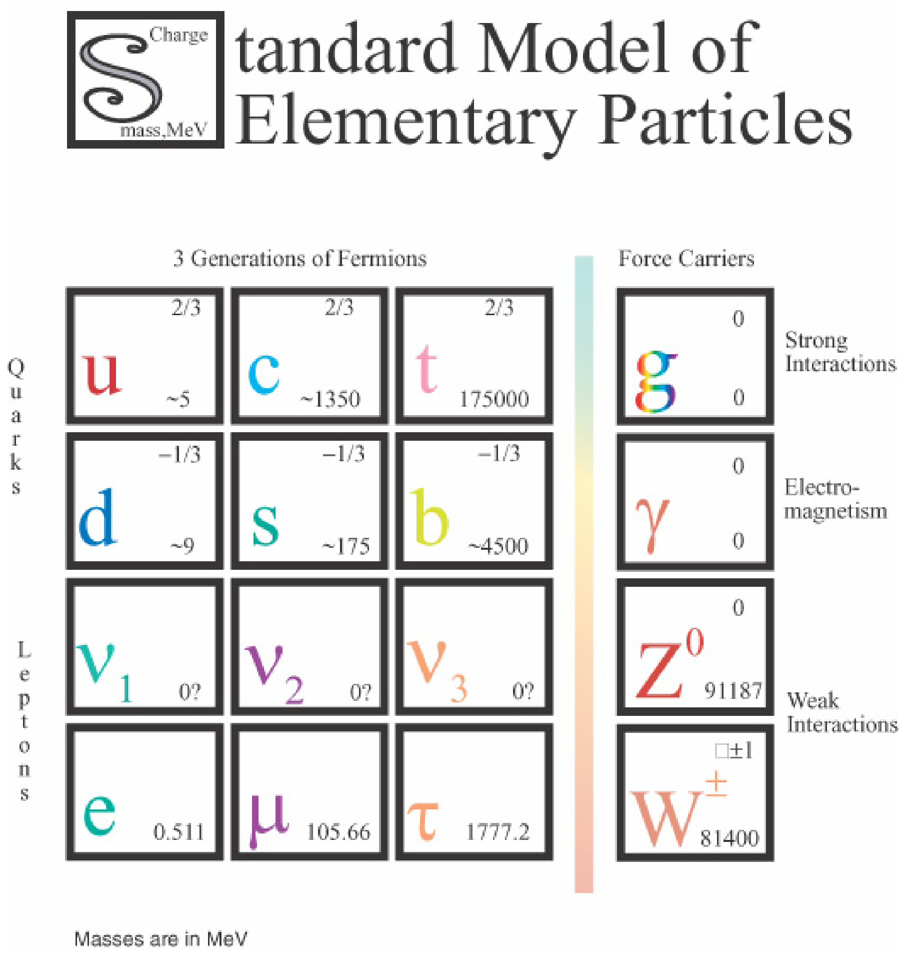
Outline

- Introduction
- SM Higgs at the LHC
  - Feasibility of Inclusive searches
  - Higgs Associated with Hadronic Jets
    - Signal Extraction
- Feasibility of Coupling Measurements
- MSSM Higgs
- Tevatron-LHC Connection
- Outlook and Conclusions

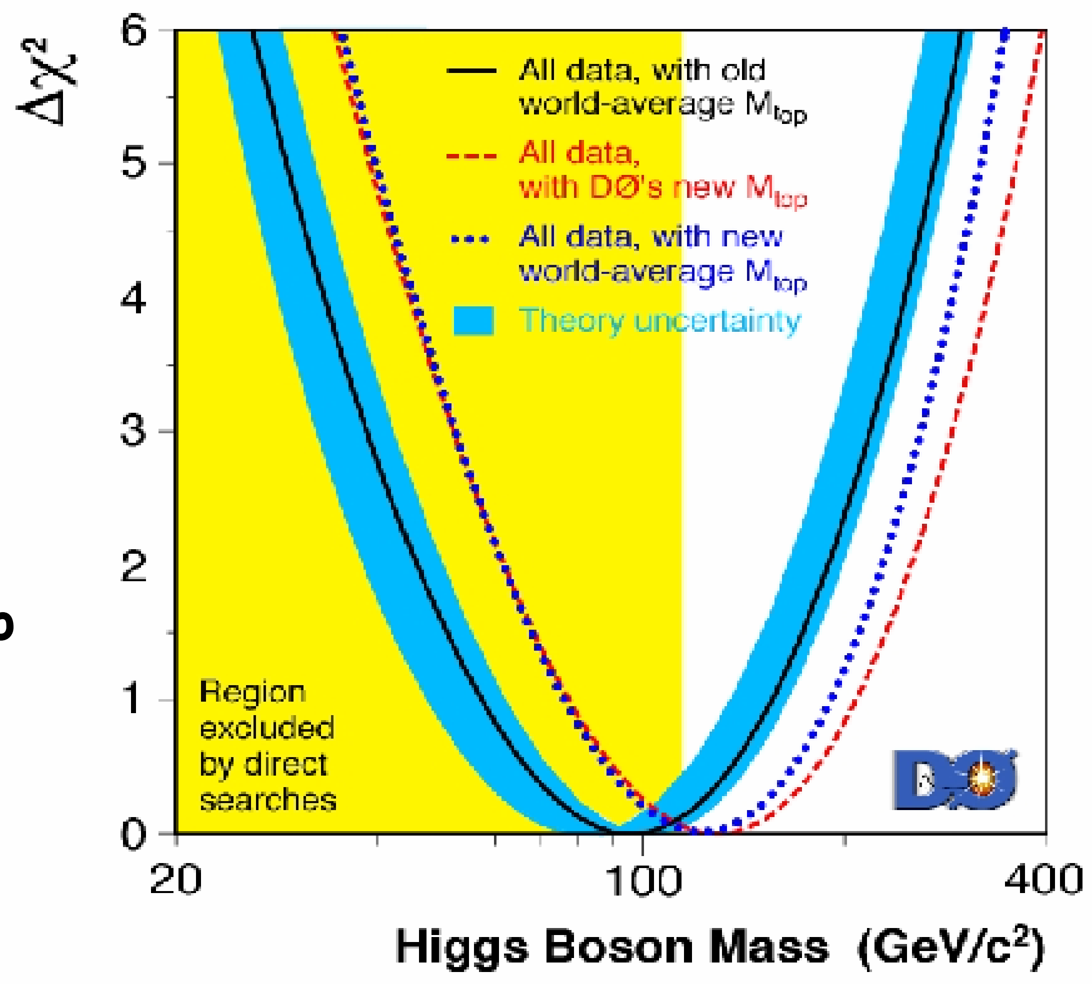
SM Higgs (1)

- **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!**



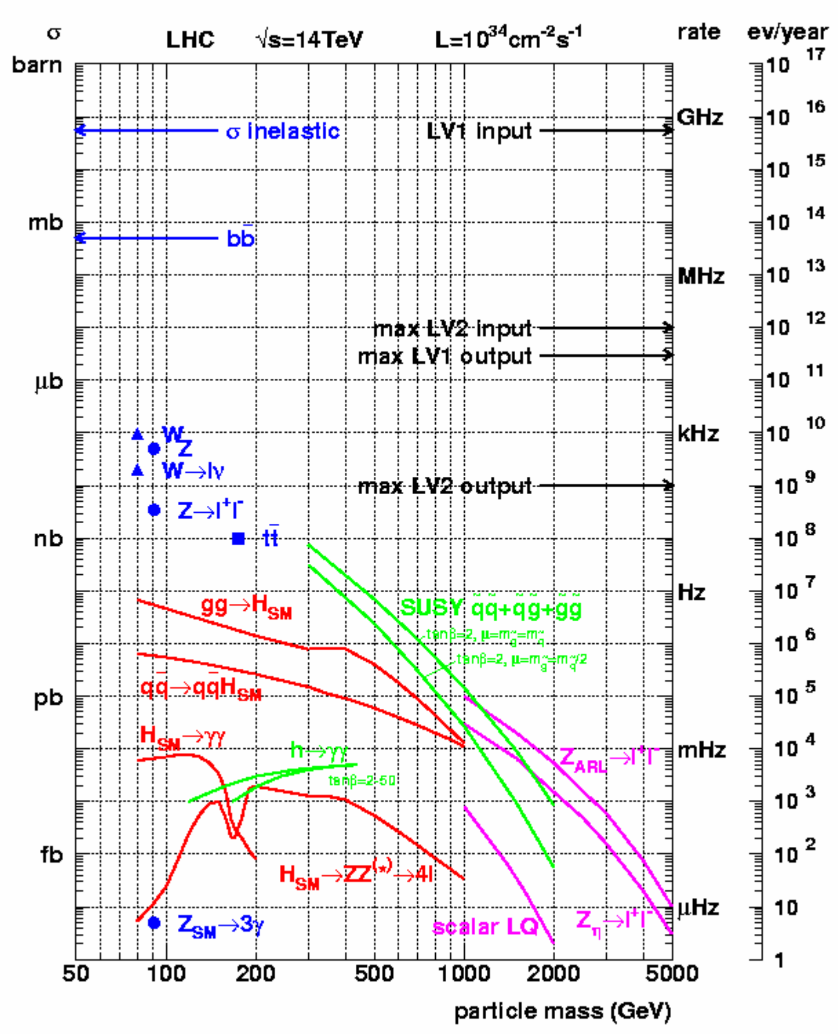
SM Higgs (2)

- **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)
  - With new measurement of top mass at Tevatron
    - M_H=117 GeV with 251 GeV 95% CL exclusion limit
- **Direct Higgs searches remains main focus at LHC**



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 top and jets.

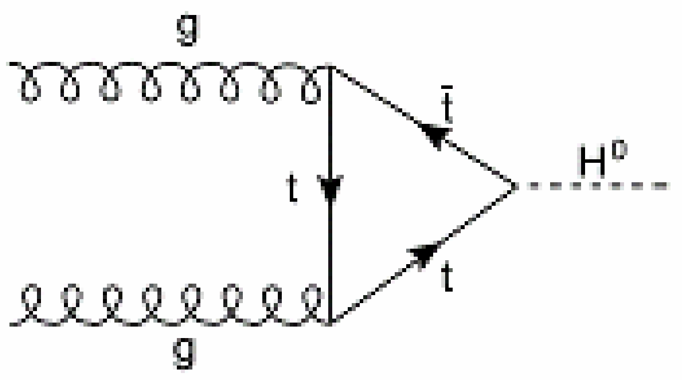


Main Production Mechanisms at the LHC

F.Wilczek PRL39 (1977)

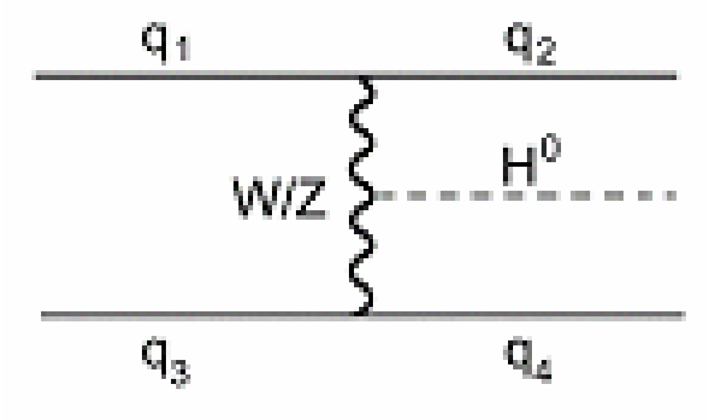
H.M.Georgi, S.L.Glashow, M.E.Machacek and D.V.Nanopoulos

PRL40 (1978)



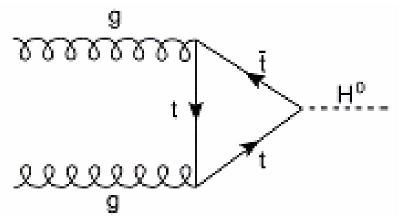
R.Cahn and S.Dawson

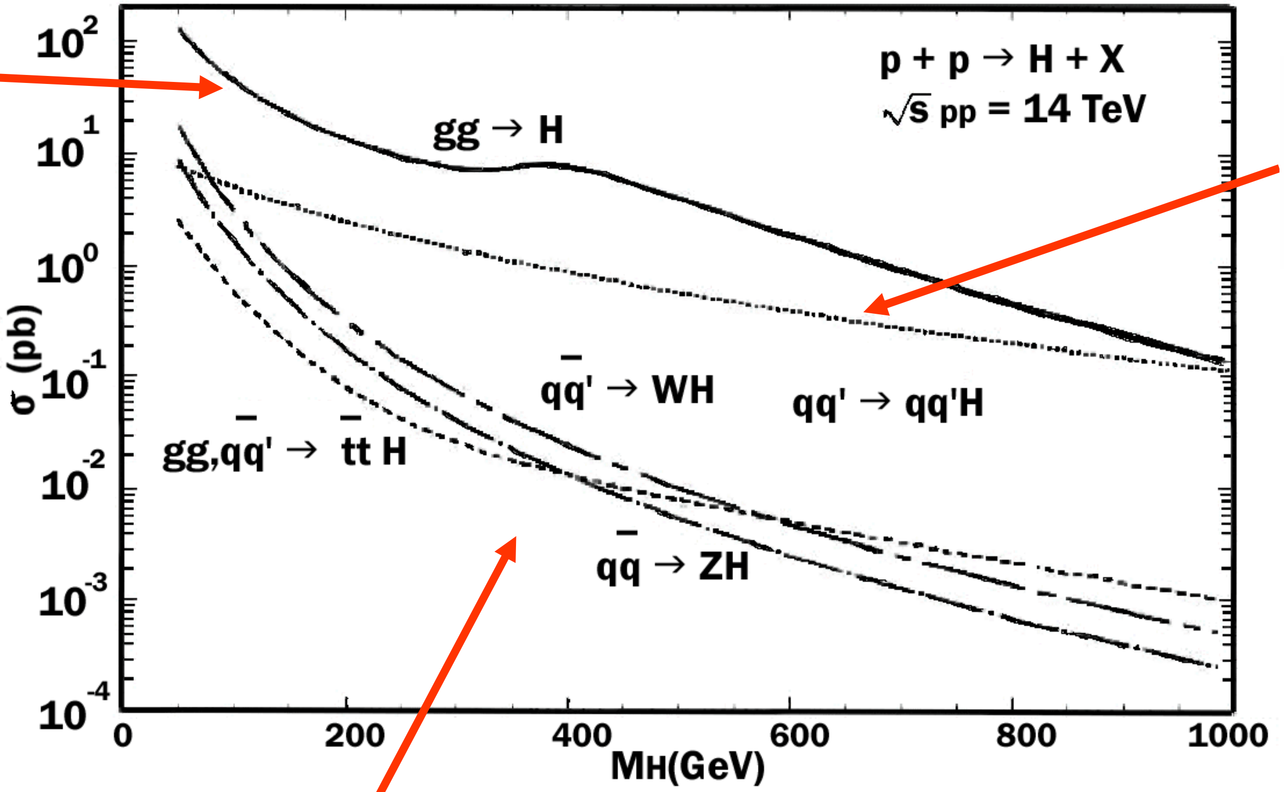
PL 136B 196 (1983)



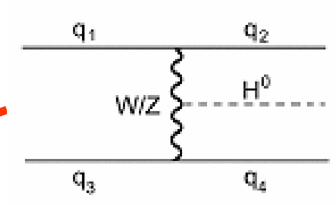
SM Higgs at the LHC

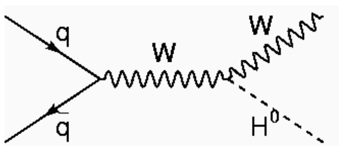
gg→H

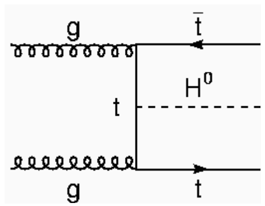




VBF

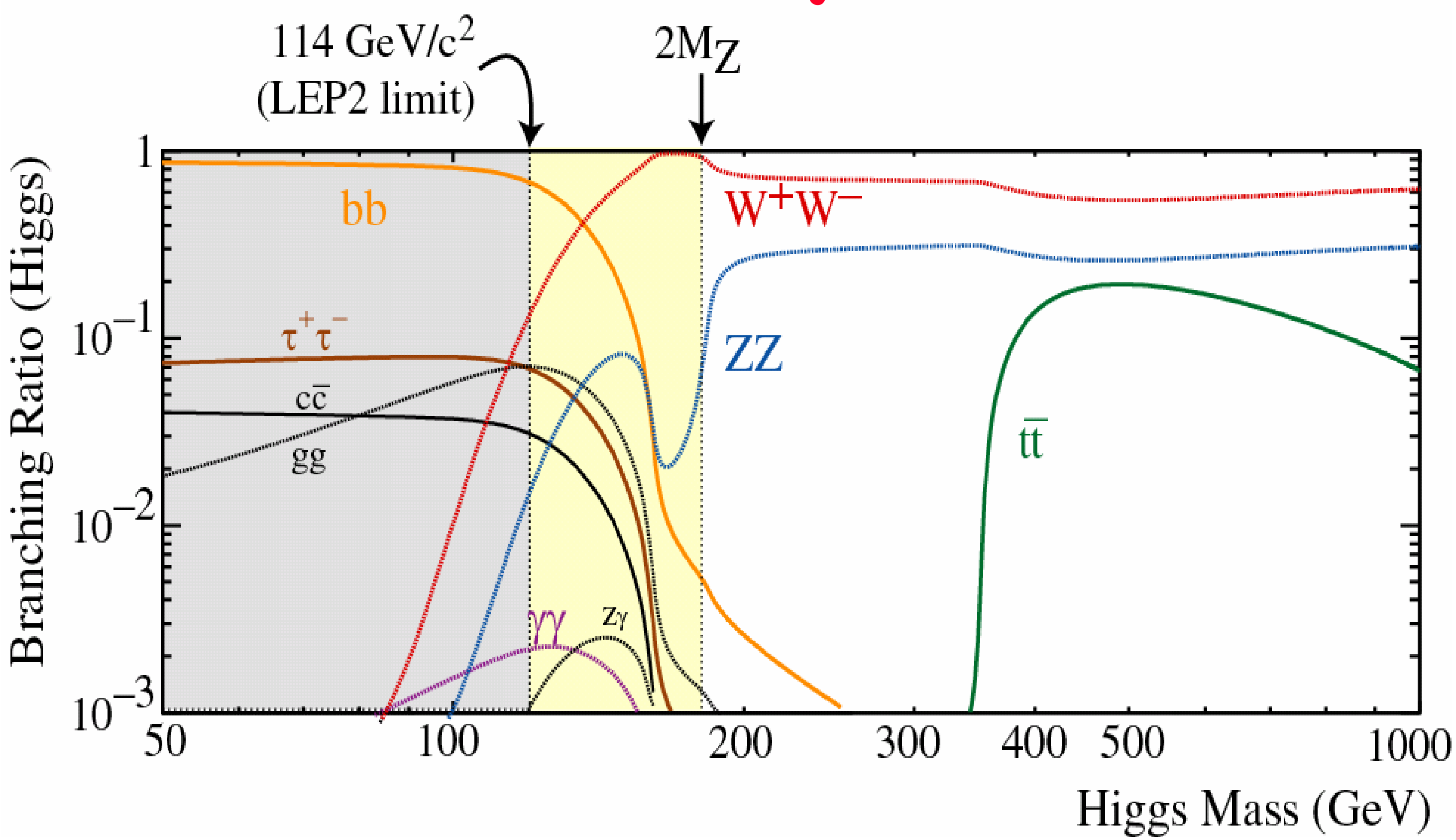






Associated

Main Decay Modes

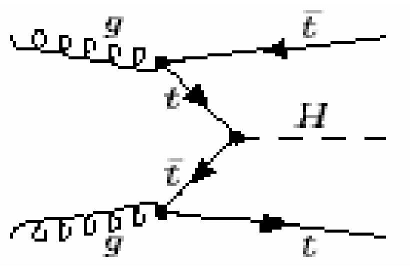


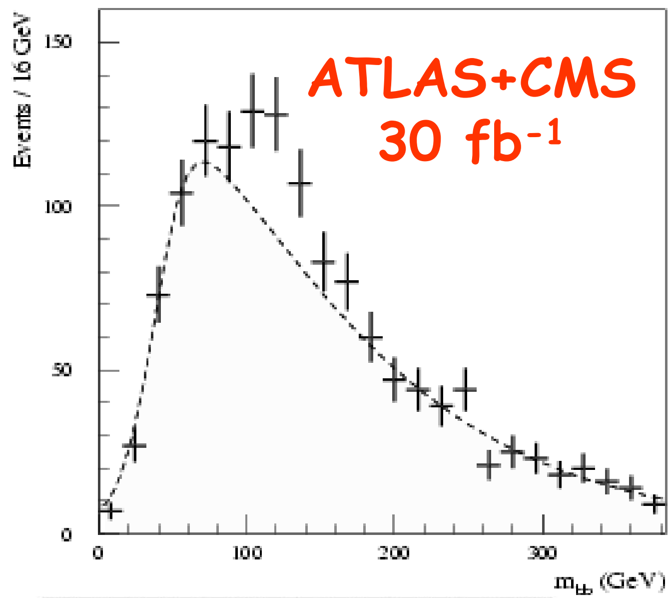
Close to LEP limit:
$H \to bb, \gamma\gamma, \tau\tau$

For M_H>135 GeV:
$H \to WW$ & $H \to ZZ$

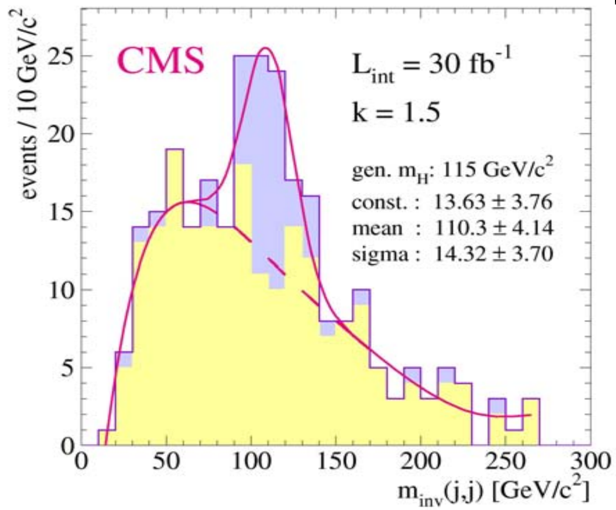
SM Higgs via ttH

- **Complex channel ($H \to bb$):**
  - One lepton (trigger)
  - 4 b-jets + 2 jets
    - b-tagging essential
    - Need to know well background (ttjj)





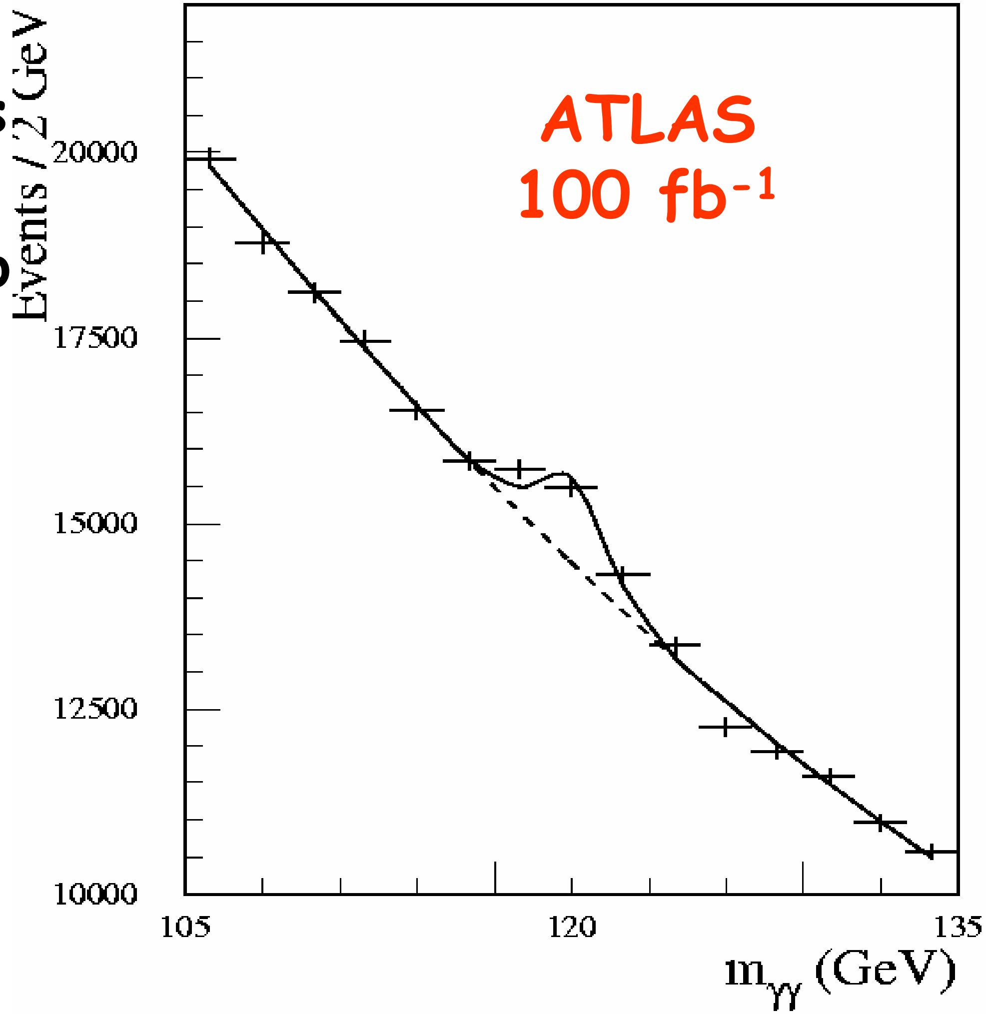
- **Good for discovery and Yukawa coupling determination**
  - $80 < M_H < 120$ GeV



- **Background extraction is hard**
  - With systematic errors, potential seriously diminished

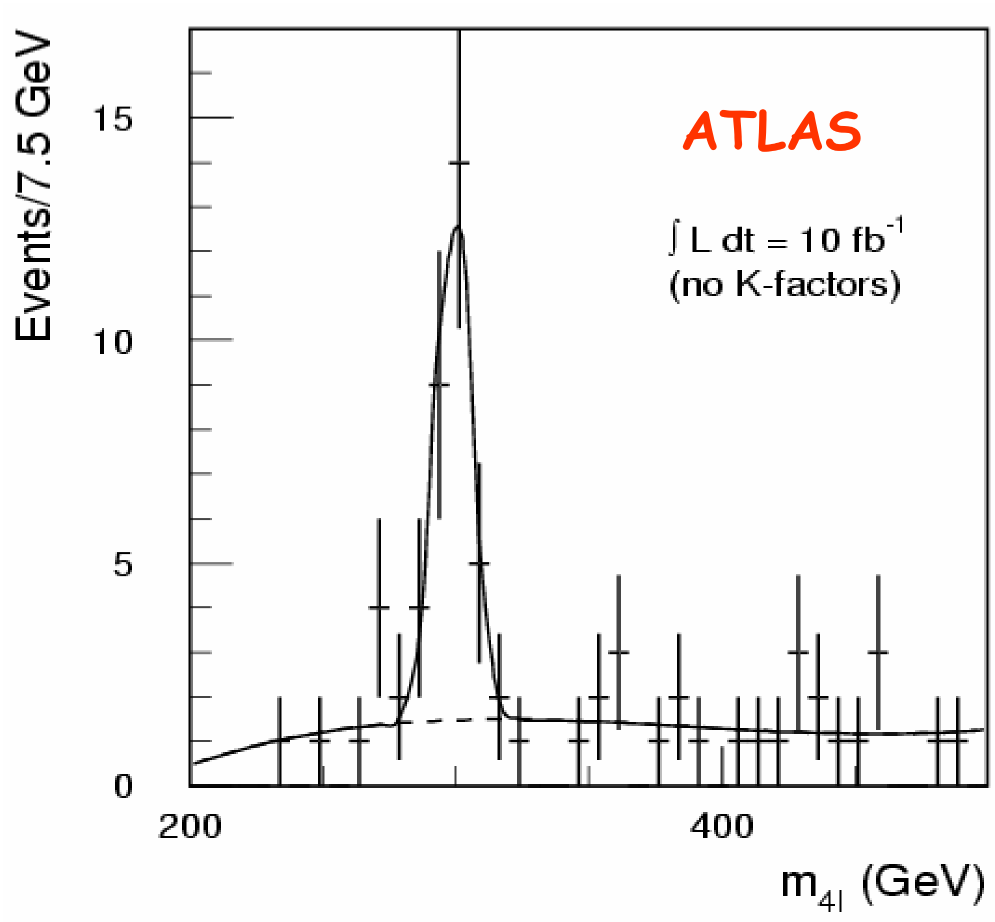
SM Higgs, $H \rightarrow \gamma\gamma$

- **Need good calorimetry**
  - Achieve ~1% resolution in Higgs mass reconstruction
  - Need to control energy scale to better than 0.5%
- **Background**
  - Non-resonant $\gamma\gamma$ production
  - Easily determined from side bands
- **Good for discovery of low mass Higgs and mass measurement**



SM Higgs, H->ZZ->4l

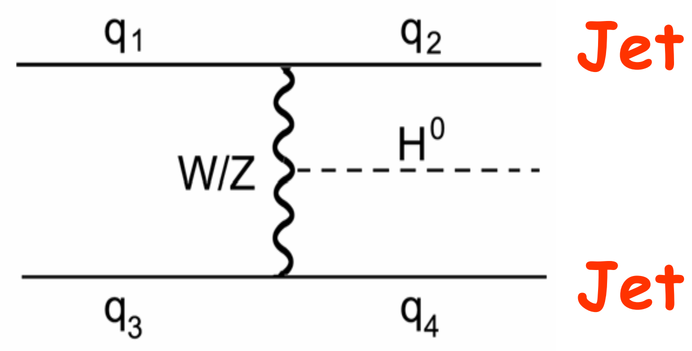
- **Very clean signature**
  - Narrow resonance
  - Small background contribution
- **Main experimental issues**
  - Lepton isolation
    - Zbb and ttbb rejection
- **Good for discovery in wide Higgs mass range**
  - $120 < M_H < 600$ GeV



Higgs in Association with Hadronic Jets (or with jet veto)

SM Higgs + ≥2jets at the LHC

- D.Zeppenfeld, D.Rainwater, et al. proposed to search for a Low Mass Higgs in association with two jets with jet veto
  - Central jet veto initially suggested in V.Barger, K.Cheung and T.Han in PRD 42 3052 (1990)

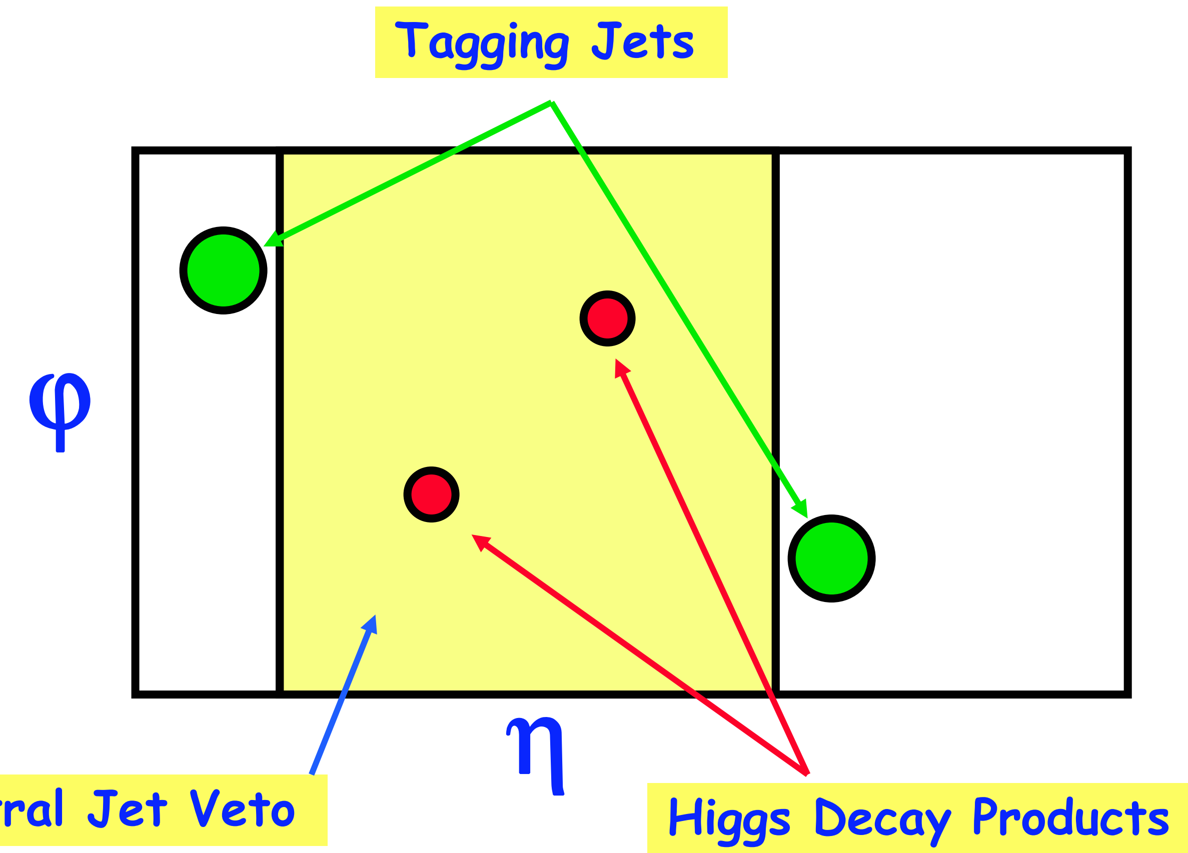


$\eta_{J1} \cdot \eta_{J2} < 0$

$\Delta\eta_{JJ} > 3.5 \div 4$

$M_{JJ} > 500 \div 700\text{GeV}$

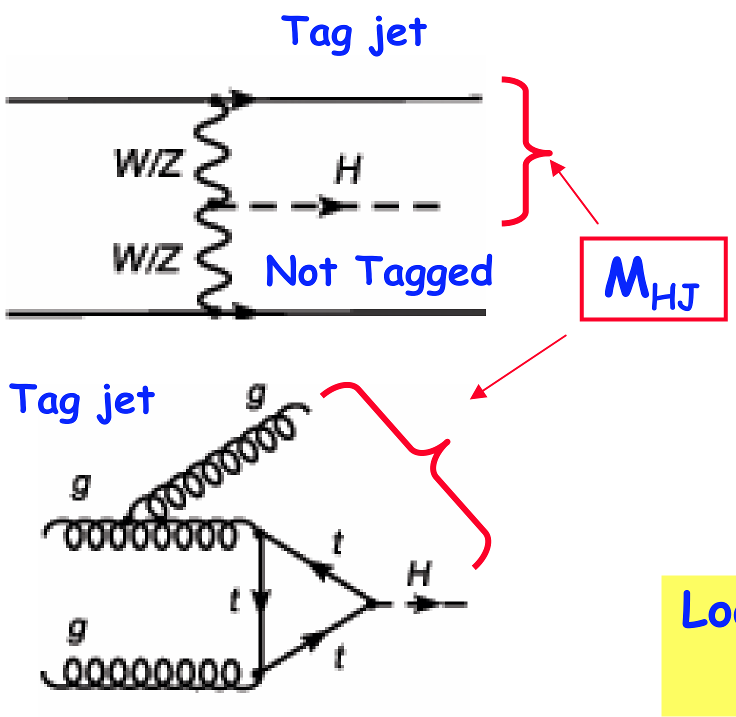
c.j.v.

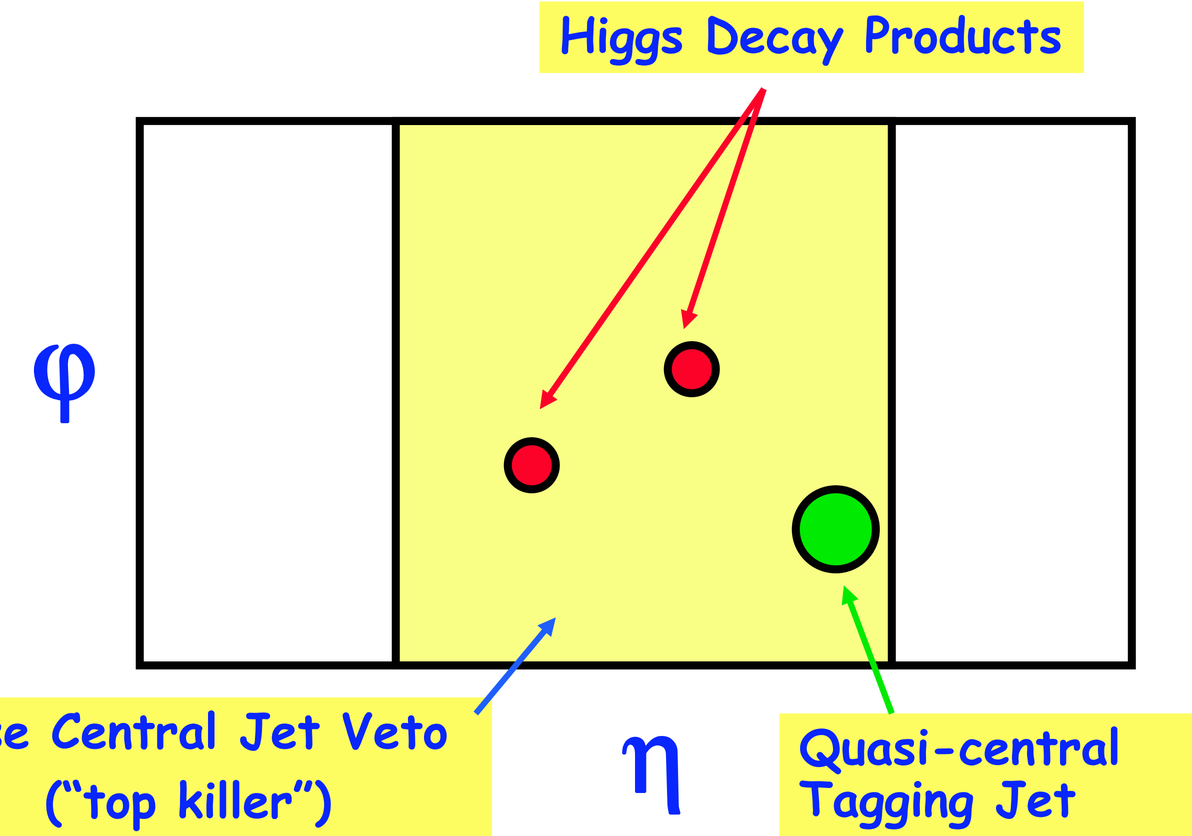


SM Higgs + ≥1jet at the LHC

1. Large invariant mass of leading jet and Higgs candidate
2. Large P_T of Higgs candidate
3. Leading jet is more forward than in QCD background

S.Abdullin et al PL B431 (1998) for $H \to \gamma\gamma$
B.Mellado, W.Quayle and Sau Lan Wu (hep-ph/0406095) for $H \to \tau\tau$ and $H \to WW^{(*)}$

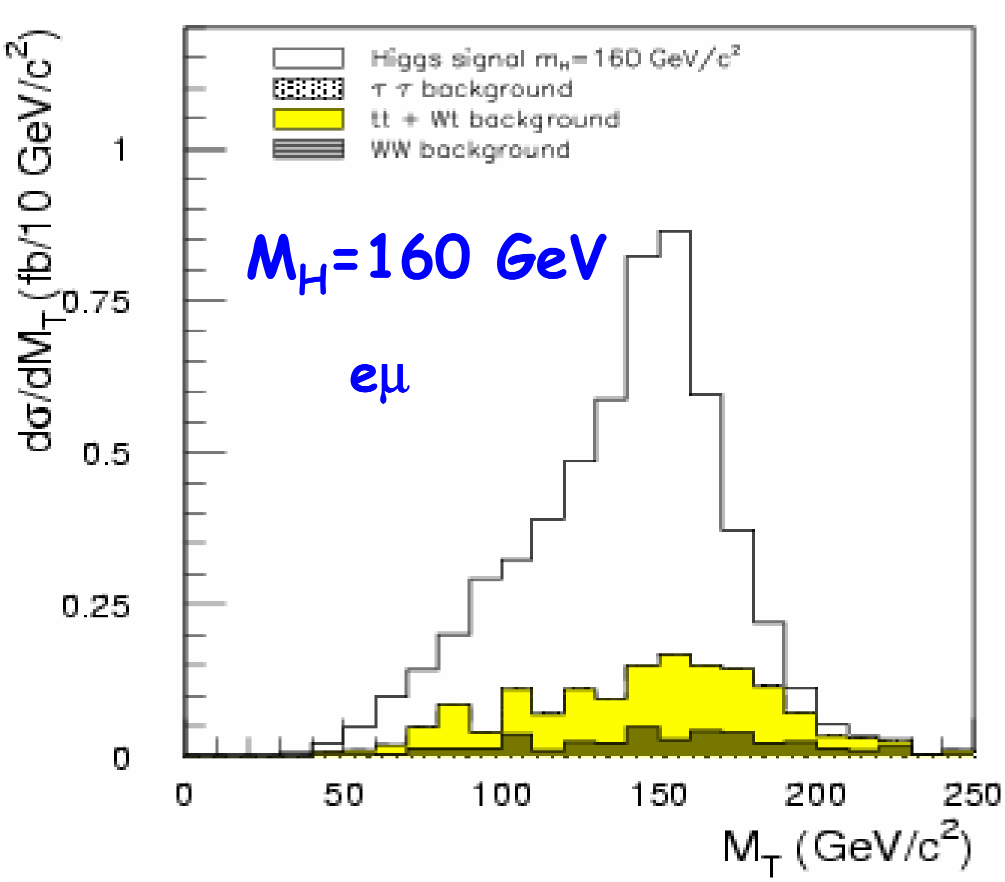




$H \rightarrow WW^{(*)}$ with Jets (or with jet veto)

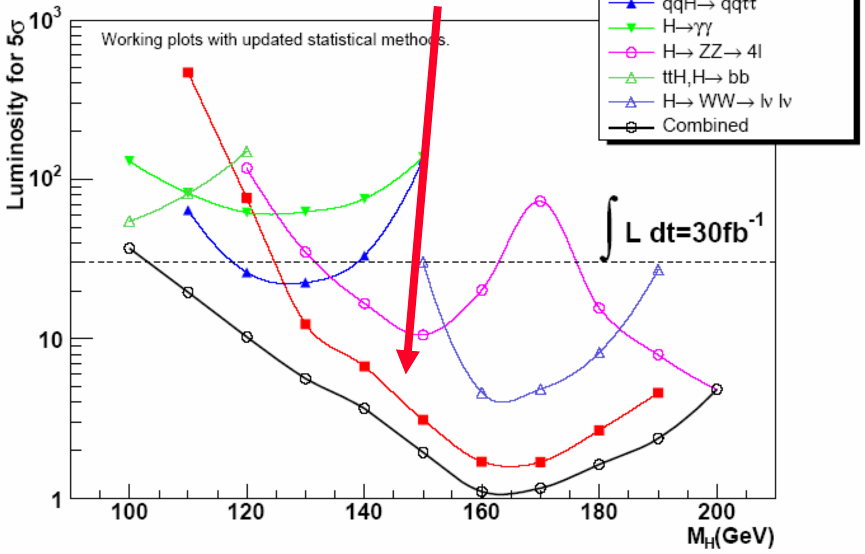
- **Most powerful decay channel for $125 < M_H < 180$ GeV**
- **Background: pp->WW+X, including tt production**
- **Background suppression:**
  - **Jet veto (b-jet veto)**
  - **Lepton angular correlations**
  - **Jet angular correlations**

$H \rightarrow WW^{(*)}$ +≥2jet

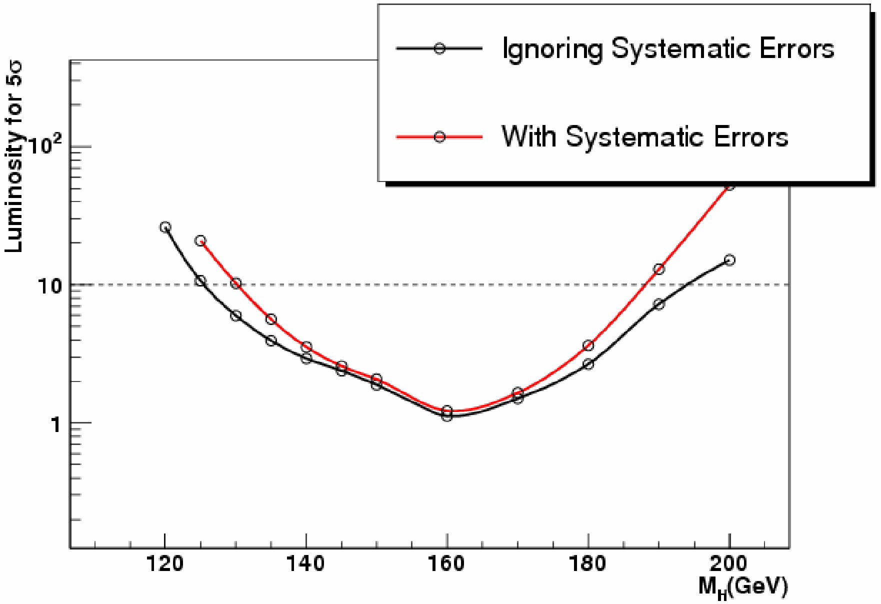


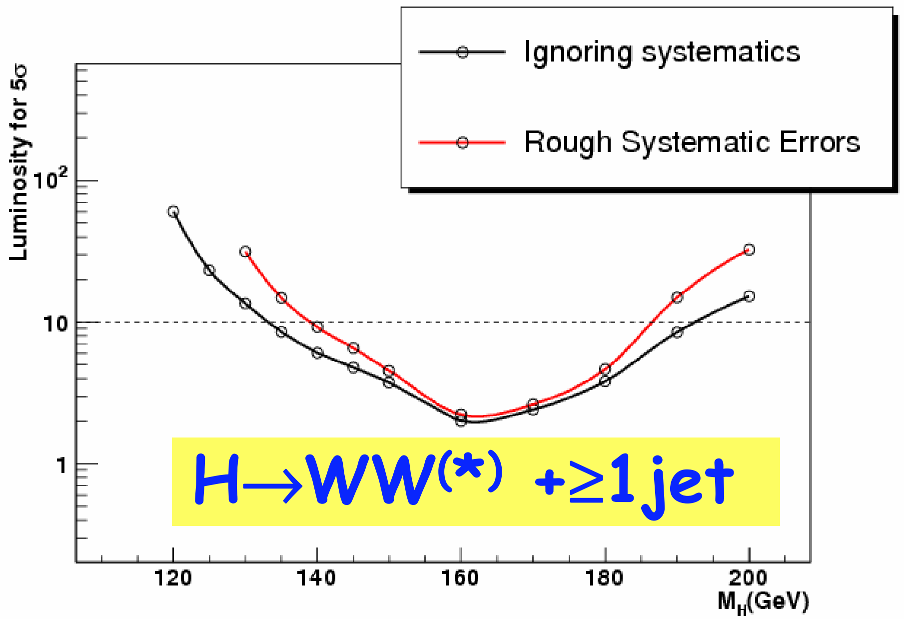
- **Most powerful decay channel for $125<M_H<180$ GeV**
  - Three non-overlapping analysis defined
  - Background subtraction using data

$H \to WW^{(*)}$ +≥2jet



$H \to WW^{(*)}$ with jet veto



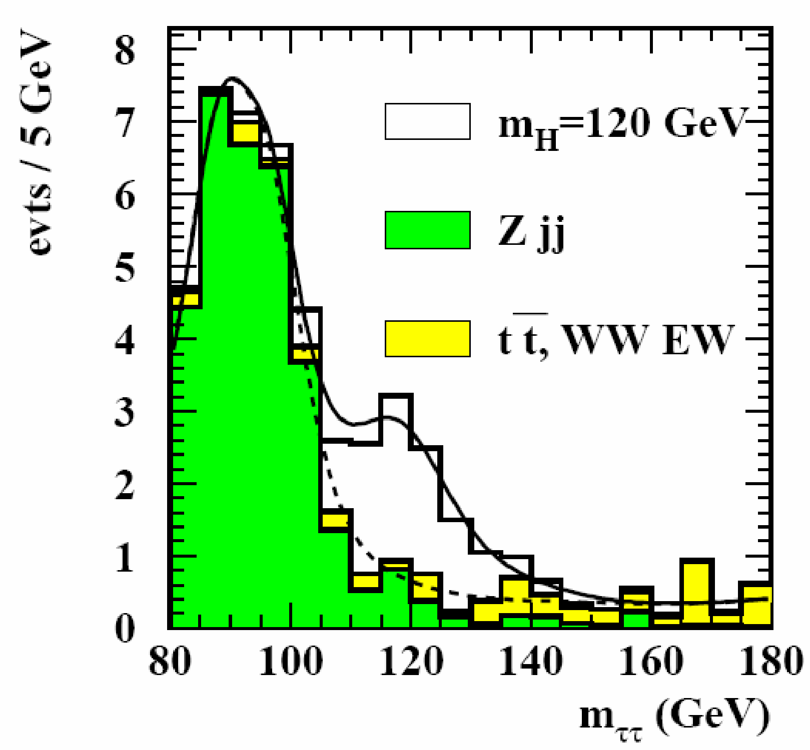


$H \to WW^{(*)}$ +≥1jet

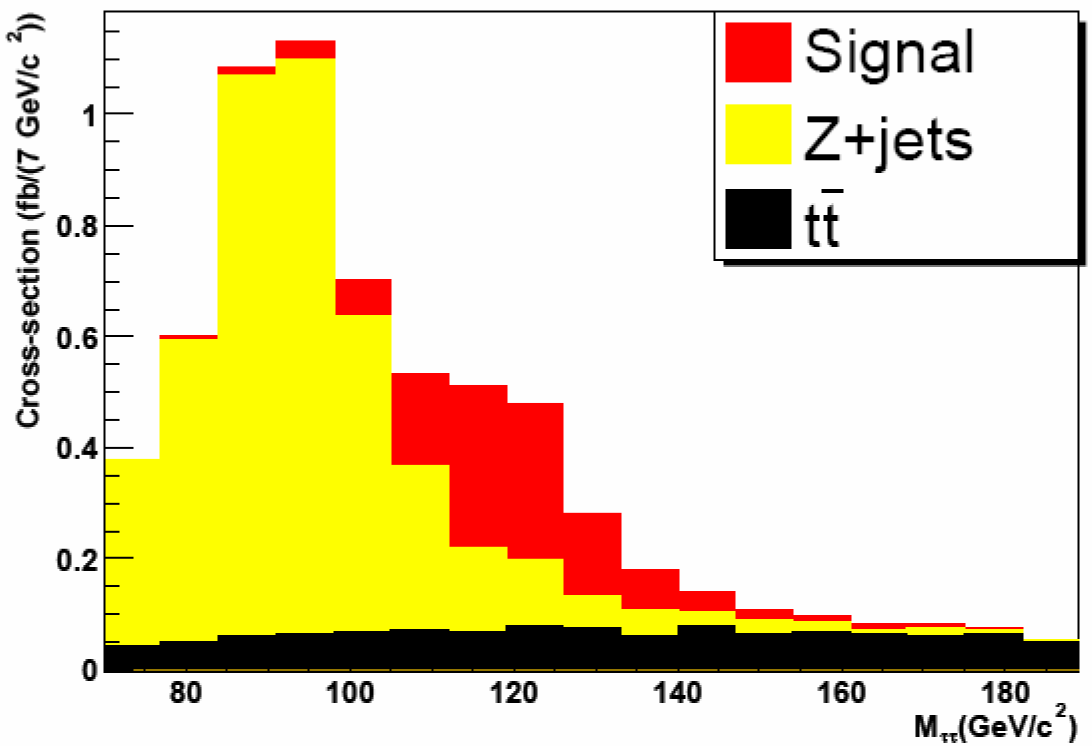
$H \to \tau\tau$ with Jets

- Carries about 50% of sensitivity of LHC experiments for a Higgs close to the LEP Limit

$H(\to\tau\tau\to 2l)$ $+\geq 2$jets (VBF)



$H(\to\tau\tau\to 2l)$ $+\geq 1$jet



Two independent ways of extracting $Z\to\tau\tau$ shape

- Data driven and MC driven
- Similar procedure has been defined for $H\to WW^{(*)}$

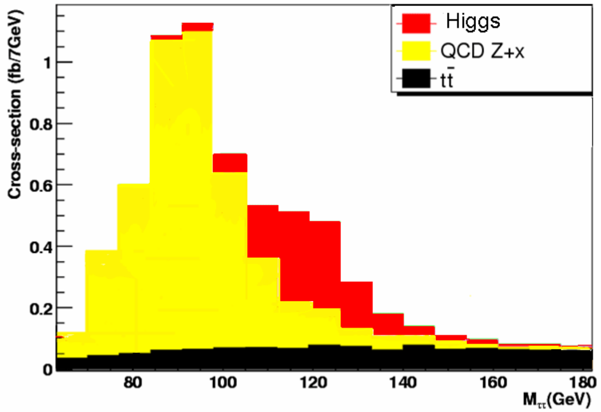
Control Sample 1
$Z\to ee,\mu\mu$
Loose cuts on Jets

MC extrap. is validated

Control Sample 3
$Z\to ee,\mu\mu$
Tight cuts on Jets

$85<M_{ll}<95$ GeV

Determine shape and normalization of $Z\to\tau\tau$ background



Replace $Z\to ee,\mu\mu$ by $Z\to\tau\tau$

Control Sample 2
$Z\to\tau\tau$
Loose cuts on Jets

MC extrap.

Signal Region
$Z\to\tau\tau$
Tight cuts on Jets

$M_{ll}<75$ GeV

M_{HJ}, $\Delta\eta_{JJ}$

Coupling Measurements and MSSM Higgs

If observed, LHC can throw light on the size of the Higgs couplings to vector bosons and fermions

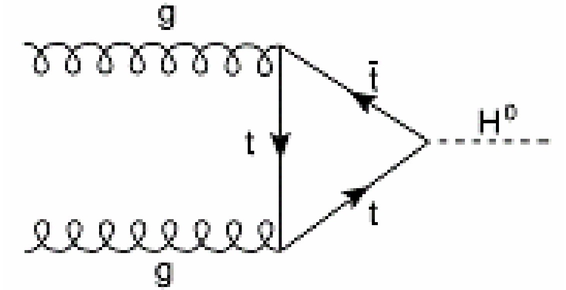
- Depends strongly on the precision with which we can predict the production cross-section

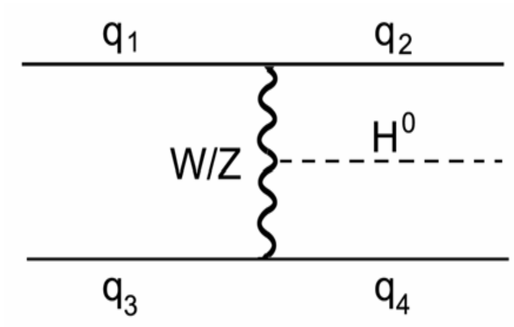
W.Kilgore & R.Harlander
C.Anastasiou & K.Melnikov
V.Ravindran, J.Smith & W.L. van Neerven

Residual 15-20% uncertainty in NNLO calculation

T.Han, G.Valencia, S.Willenbrock PRL69 (1991)
T.Figy, C.Oleari, D.Zeppenfeld PRD68 (2003)

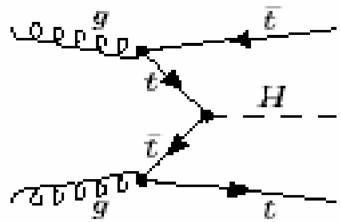
NLO K factor ~1.05÷1.1, small theoretical uncertainty <5%





S.Dawson, L.H.Orr, L.Reina, and D.Wackeroth Phys. Rev. D 67, 071503

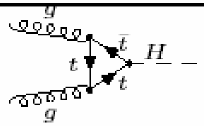
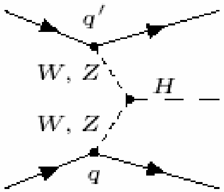
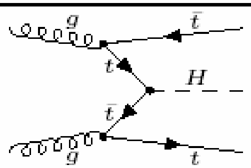
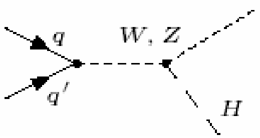
NLO K factor ~1.3, residual uncertainty of ~10÷15%



Extraction of Couplings

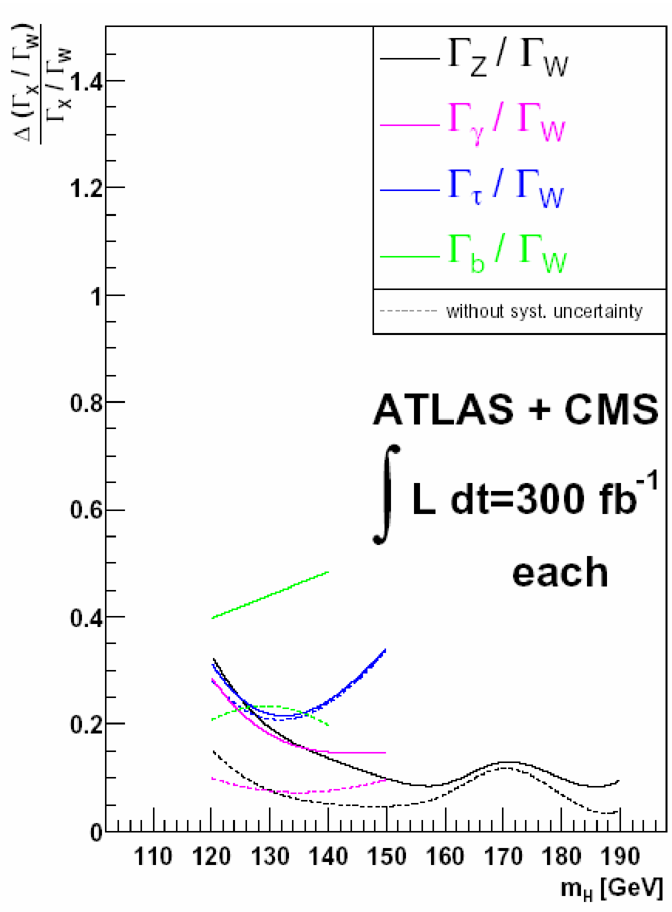
- **ATLAS attempted a model independent global fit to cross-sections of known channels to extract Higgs couplings**
  - **Big role of Higgs searches associated with two hard jets**

M.Duhrssen ATL-PHYS-2003-30

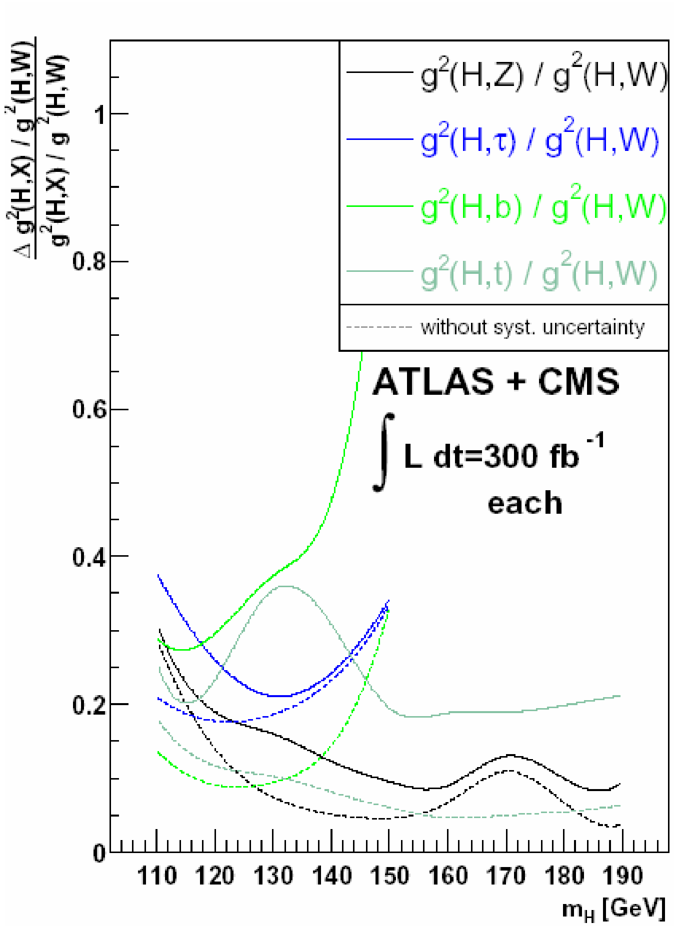
Production		Decay	mass ranges
	Gluon-Fusion $(gg \rightarrow H)$	$H \rightarrow ZZ \rightarrow 4l$	110 GeV - 200 GeV
		$H \rightarrow WW \rightarrow l\nu\, l\nu$	110 GeV - 200 GeV
		$H \rightarrow \gamma\gamma$	110 GeV - 150 GeV
	WBF $(qq\,H)$	$H \rightarrow ZZ \rightarrow 4l$	110 GeV - 200 GeV
		$H \rightarrow WW \rightarrow l\nu\, l\nu$	110 GeV - 190 GeV
		$H \rightarrow \tau\tau \rightarrow l\nu\nu\, l\nu\nu$	110 GeV - 150 GeV
		$H \rightarrow \tau\tau \rightarrow l\nu\nu\, \mathrm{had}\nu$	110 GeV - 150 GeV
		$H \rightarrow \gamma\gamma$	110 GeV - 150 GeV
	$t\bar{t}H$	$H \rightarrow WW \rightarrow l\nu\, l\nu\, (l\nu)$	120 GeV - 200 GeV
		$H \rightarrow b\bar{b}$	110 GeV - 140 GeV
		$H \rightarrow \tau\tau$ (not included)	110 GeV - 150 GeV
		$H \rightarrow \gamma\gamma$	110 GeV - 120 GeV
	WH	$H \rightarrow WW \rightarrow l\nu\, l\nu\, (l\nu)$	150 GeV - 190 GeV
		$H \rightarrow \gamma\gamma$	110 GeV - 120 GeV
	ZH	$H \rightarrow \gamma\gamma$	110 GeV - 120 GeV

Extraction of Couplings (cont)

Relative Branching Ratios

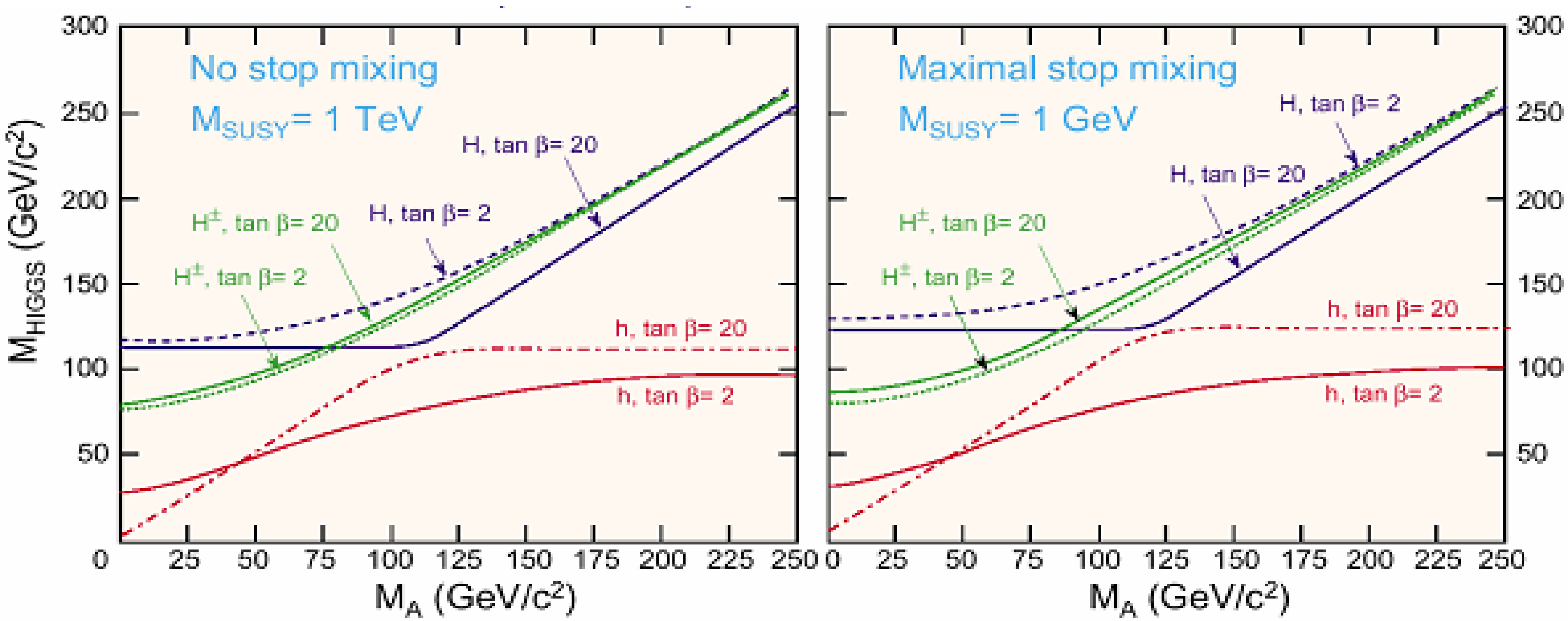


Relative Couplings



MSSM Higgs

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



MSSM Higgs (cont)

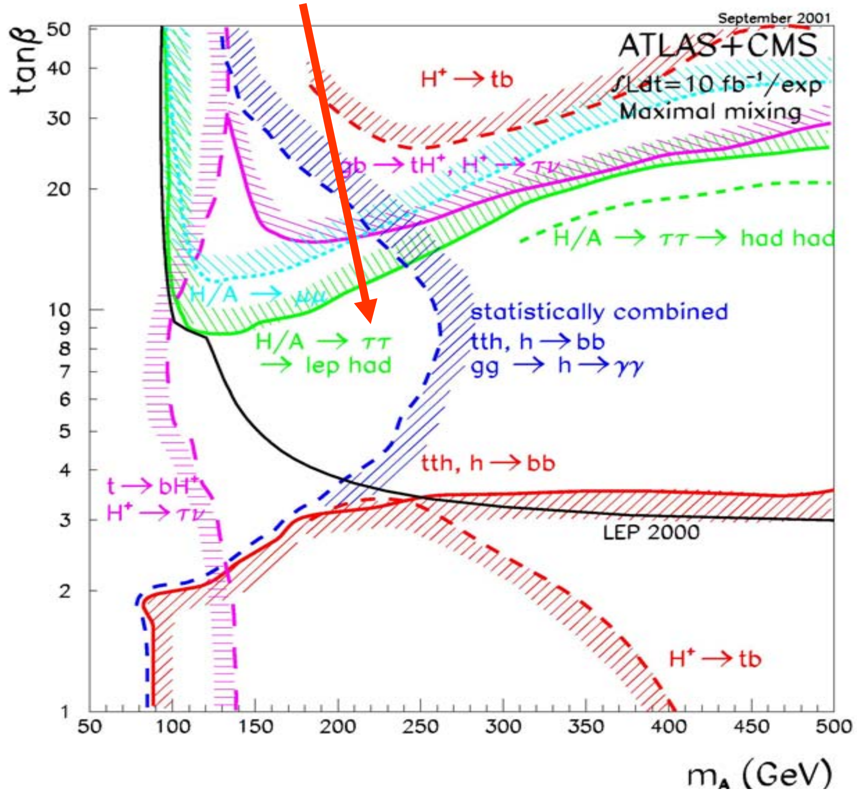
- Large multiplicity of discovery modes:
  - SUSY particles heavy:
    - SM-like: $h\rightarrow\gamma\gamma$, bb, $\tau\tau$, WW; $H\rightarrow 4l$
    - MSSM-specific: $A/H\rightarrow\mu\mu,\tau\tau$, tt; $H\rightarrow hh$, $A\rightarrow Zh$; $H^{\pm}\rightarrow\tau^{\pm}\nu$
  - SUSY accessible:
 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

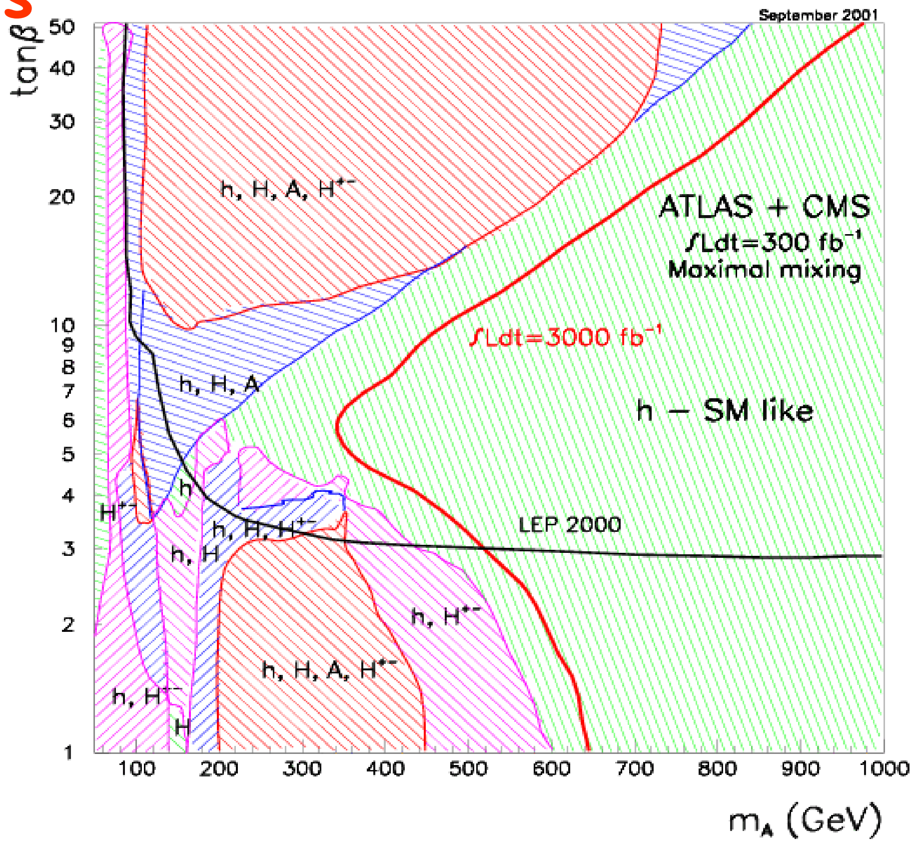
MSSM Higgs Discovery Potential

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

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

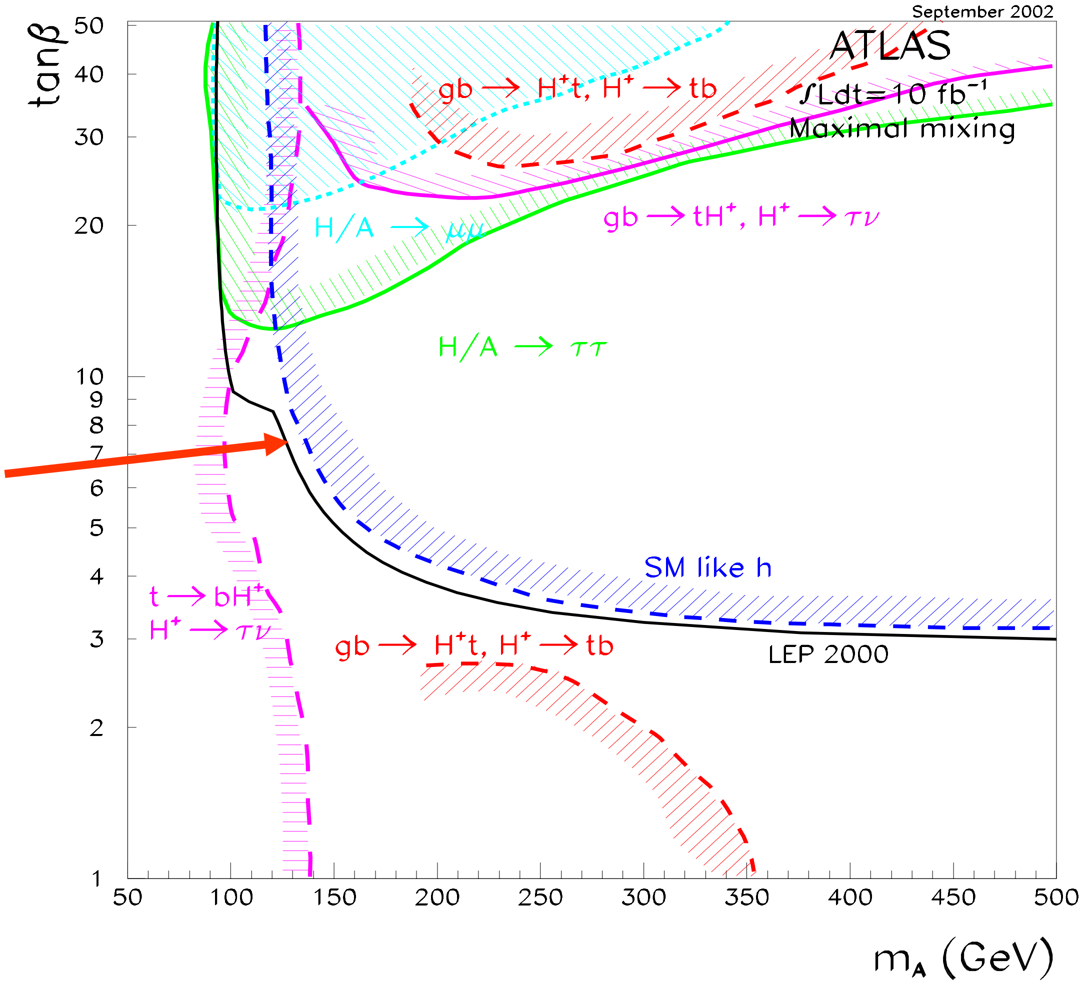
5 σ Contours





MSSM Higgs and VBF

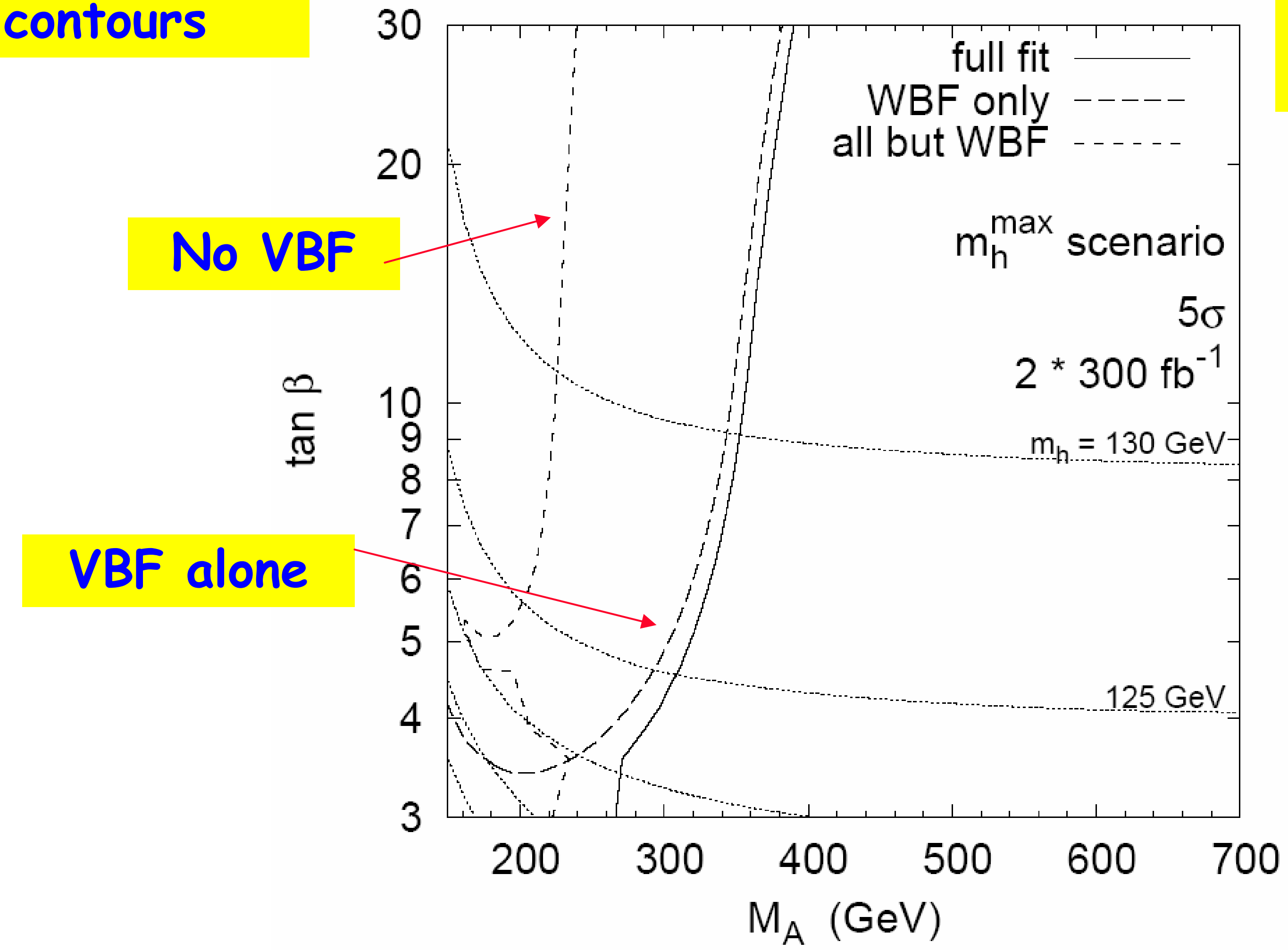
- The addition of VBF modes in MSSM searches enhances sensitivity to low mass Higgs
  - One experiment with 10 fb-1 covers almost entirely MSSM plane
  - Only light Higgs (h)



Central role of VBF distinguishing between SM and MSSM h via extraction of couplings

5σ exclusion contours

Zeppefeld et.al. Phys.Rev. D70 (2004) 113009



The Connection Between the Tevatron and the LHC

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 (+1,2 jets)	$110<M_H<150$	ττ reconstruction VBF issues, Ptmiss
H->WW* W->lν,qq (0,1,2 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

Tevatron/LHC Connection

- **Tevatron will help understand faster experimental and theoretical issues at the LHC (already highlighted in at first workshop)**
  - Lepton identification, jet algorithms, missing E_T reconstruction, b-tagging, τ reconstruction, etc…
  - Background studies
    - Better theoretical understanding of $\gamma\gamma$ continuum
    - W/Z production + jets, jet veto (Zeppenfeld plots)
      - Central point in this Tevatron/LHC connection
    - Top production, tt+jet, flavor content of jets associated with tops.
    - Underlying event, pile up.
  - Parton density functions
  - Etc..

Outlook and Conclusions

- The search of a SM Higgs at the LHC is robust
  - A SM can be observed with multiple channels
- Higgs in association with jets will play a central role in the observation of a light Higgs at the LHC
  - Use event topology to suppress QCD backgrounds
  - Well defined data driven background subtraction
- The identification of Higgs via VBF is fundamental to extract Higgs couplings
  - Helps distinguish between SM and MSSM light higgs
- The connection between Tevatron and LHC is vast
  - Study of Z/W + jets is most relevant