Report of the Higgs Working Group

Conveners:
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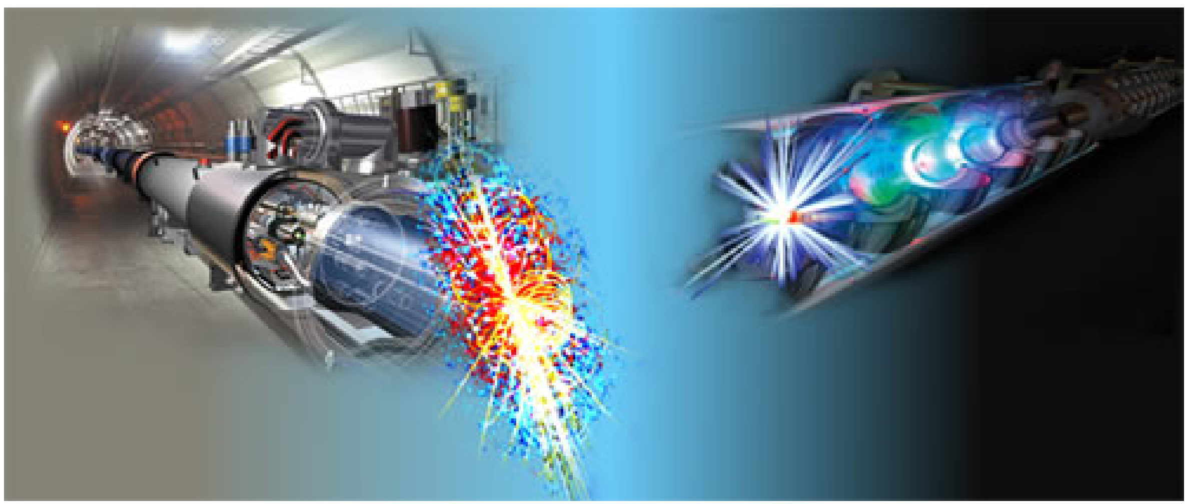
The LHC Early Phase for the ILC @ Fermilab, 14 April 2007



Outline

- Charges for the Higgs working group
- Highlights from the working group sessions—expectations from early LHC running
- Highlights from the working group sessions—theoretical interpretations
- Open questions for the working group
- The next steps

Charge for the Higgs working group

From the workshop web page:

WG I: Only one state, SM-like Higgs boson, at the early stage of LHC

The following questions should be addressed:

- What could be the impact of early LHC results on the choice of the ultimate ILC energy range and the ILC upgrade path? Could there be issues that would need to be implemented into the ILC machine and detectors design from the start?
- Could there be cases that would change the consensus about the physics case for an ILC with an energy of about 500 GeV?
- What are the prospects for LHC/ILC interplay based on early LHC data?

These questions should be investigated within the following classes of possible scenarios of results observed in the initial LHC runs:

- the detection of only one state with properties that are compatible with those of a Higgs boson
- . . .

Expansion of the working group charge

We shall consider the implications of evidence in the first 10 fb^{-1} of LHC data of:

- a Standard Model (SM)-like Higgs boson (i.e., a CP-even scalar state whose properties are consistent with those of the SM Higgs boson, within the accuracy of the observations).

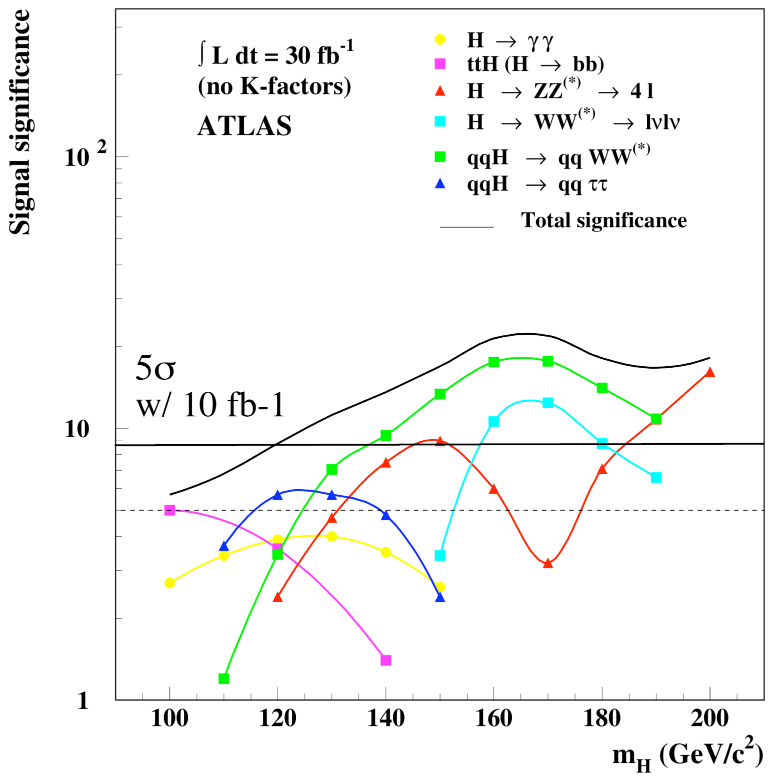
- a scalar boson, whose properties are consistent with a point-like elementary scalar. The interpretation of such a state is consistent with a scalar associated with a weakly-coupled Higgs sector that can arise in some extended model of electroweak symmetry-breaking. Such states could include CP-odd neutral scalars, charged scalars, or scalars of indefinite CP quantum number.

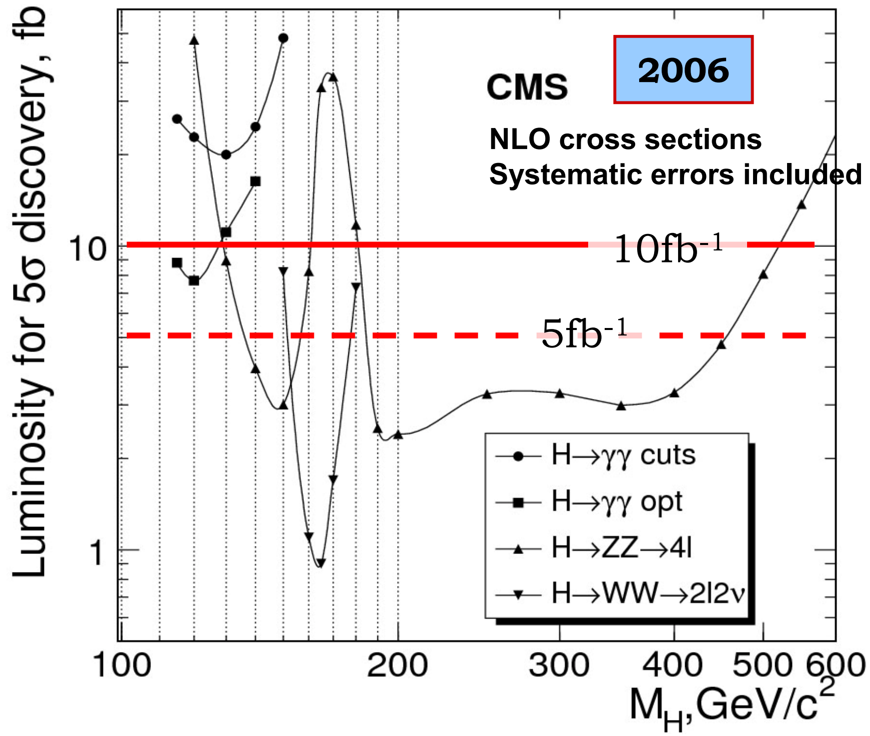
Highlights from the working group sessions: expectations from early LHC running

Main focus of Thursday sessions: one SM-like Higgs boson observed

- $\longrightarrow$ D. Rainwater, "SM Higgs at the LHC with 10 fb^{-1}"
- $\longrightarrow$ B. Mellado, "SM Higgs searches in the early phase of the LHC with ATLAS"
- $\longrightarrow$ A. de Roeck, "SM Higgs searches in the early phase of the LHC with CMS"
- $\longrightarrow$ M. Weber, "Precision calculations for $H \to WW^*/ZZ^* \to 4f$ with PROPHECY4f "
- $\longrightarrow$ P. Nadolsky, "Transverse momentum resummation for background and signal in $H \to \gamma\gamma$ "

What will we know? – Discovery modes: depend on M_H





WBF $\to H \to WW$	Inclusive $H \to \gamma\gamma$
Inclusive $H \to WW \to 2\ell 2\nu$	Inclusive $H \to ZZ \to 4\ell$
Inclusive $H \to ZZ \to 4\ell$	Inclusive $H \to WW \to 2\ell 2\nu$

Evidence in WBF $\to H \to \tau\tau$, $t\bar{t}H(H \to b\bar{b})$

Good mass measurement from ZZ, $\gamma\gamma$ modes.

Highlights

- $H \to \gamma\gamma$ (inclusive, $t\bar{t}H$ with at least 100 fb^{-1})

  $\to$ P. Nadolsky: improved transverse momentum distributions from NNLL-NLO resummation of large logarithms from initial state radiation.

- $t\bar{t}H$, $H \to b\bar{b}$

- $H \to \tau\tau$ (WBF)

- $H \to WW \to 2l\,2\nu$ (inclusive, WBF)

  $\to$ M. Weber: PROPHECY4f, state of the art Monte Carlo generator for $WW/ZZ \to 4f$ including $\mathcal{O}(\alpha)$ and $\mathcal{O}(\alpha_f)$ corrections.

- $H \to ZZ \to 4l$ (inclusive)

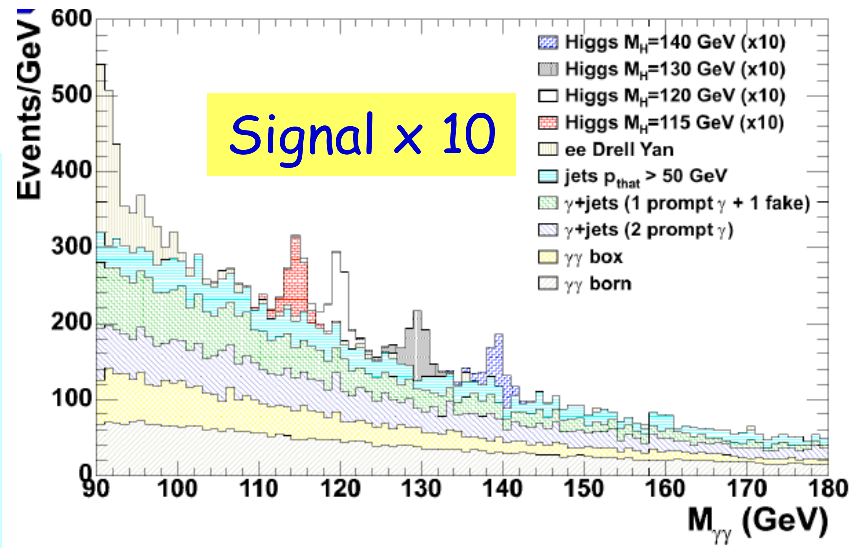
  $\to$ M. Weber: PROPHECY4f, ...

Discovery Potential : $H \to \gamma\gamma$

Significance for SM Higgs
M_H=130 GeV for 30 fb^{-1}

New elements of CMS-PTDR 2006 analysis:

- Cut based analysis
  - Split into categories depending on photon reco quality and position
  - Usage of LLR for discovery, systematic
- Optimized analysis*
  - NN with kinematics and g isolation
  - s/b per event



Final tracker→ all materials
More complete backgrounds

CMS ECAL TDR	CMS PTDR		ATLAS		
NLO count. exp	NLO cut based	NLO optimized*	TDR (LO)	New, NLO Cut based	New, NLO likelihood
~ 7.5	6.0	8.2	3.9	6.3	8.7

S. Dasu, Aspen 07

⇒Still the most promising channel for the low mass Higgs

NNLL/NLO Q_T resummation for $p\overset{(-)}{p} \rightarrow \gamma\gamma X$

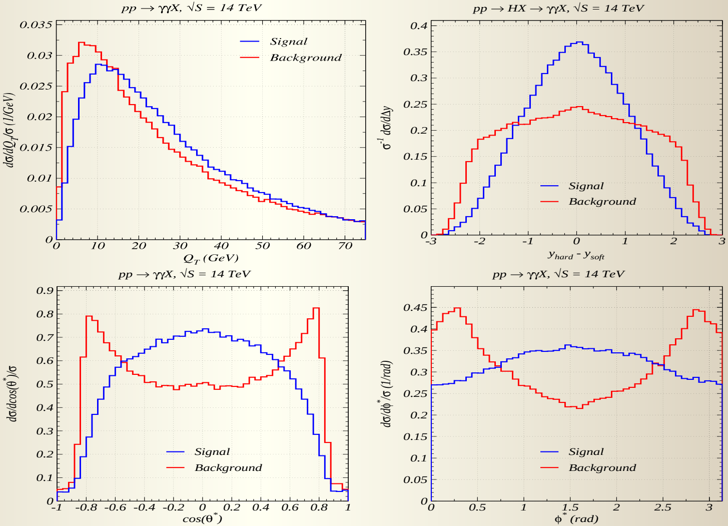
- Our study
  - computes fully differential $\gamma\gamma$ distributions in direct production
  - performs NNLL resummation of $\ln(Q_T/Q)$ logarithms at $Q_T \rightarrow 0$ (in the region with the largest rate)
  - includes essential information about photon fragmentation
  - numerical implementation: improved MC integrator program ResBos (publicly available at http://hep.pa.msu.edu/resum/)

NNLL/NLO distributions for Higgs $\to \gamma\gamma$ signal and background (ResBos, normalized; $M_H = 130$ GeV, $128 < Q < 132$ GeV; ATLAS cuts)

Q_T and $y_{\gamma_1} - y_{\gamma_2}$ in the lab frame

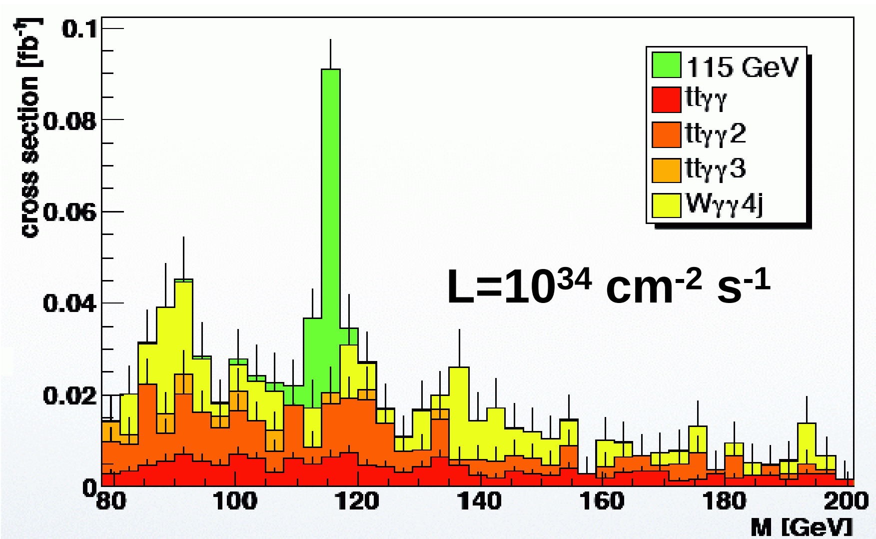
Decay angles θ_*, φ_* in the $\gamma\gamma$ rest frame

no singularities, in contrast to the fixed-order rate

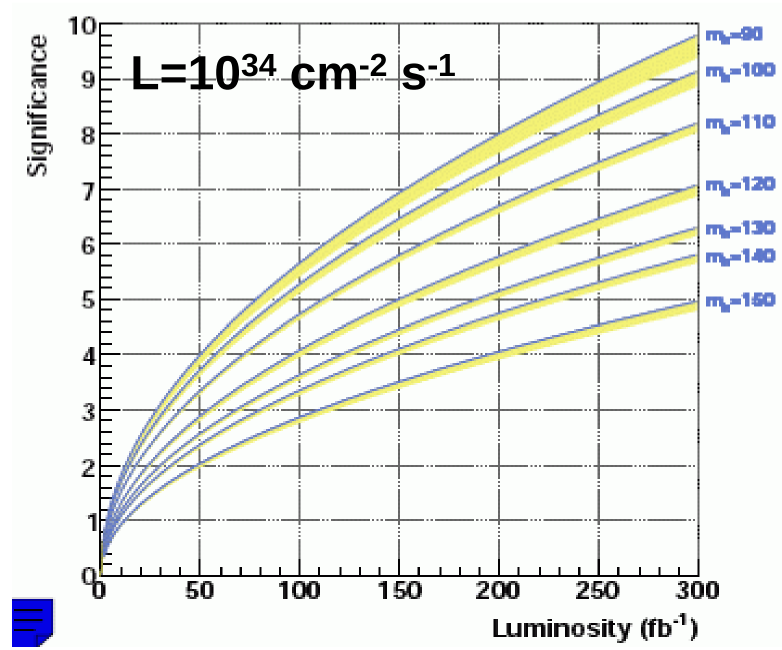


SM H→γγ in associated ttH and WH production at high luminosity

Discovery of tth, h->γγ



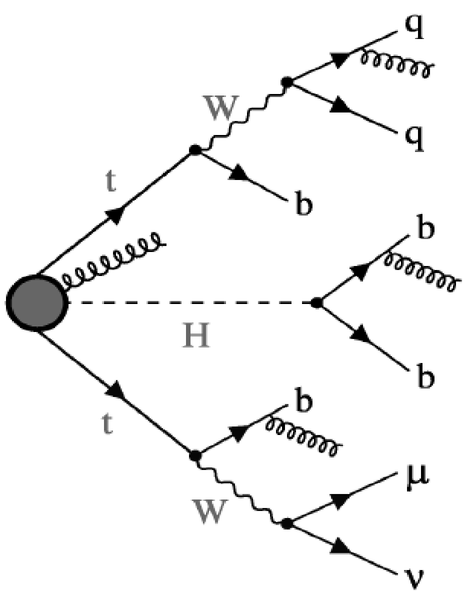
Discovery of Wh, h->γγ

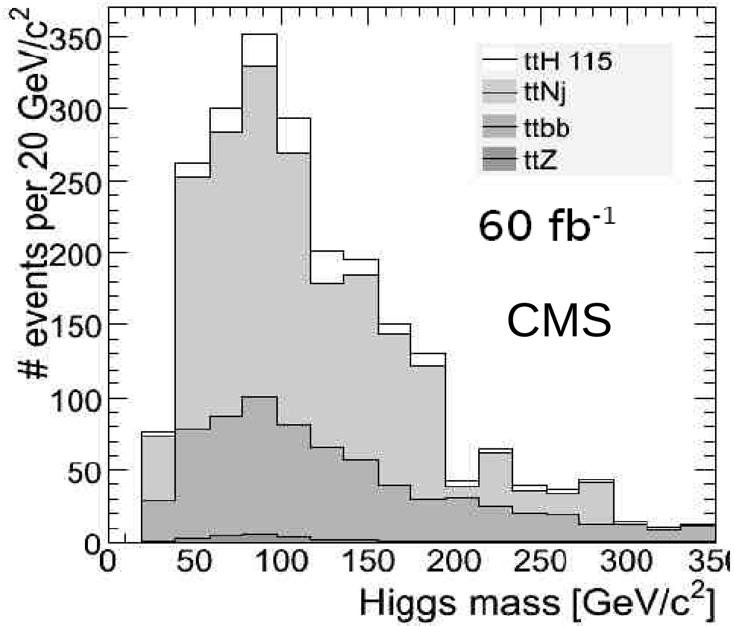


Significance of tth, h->γγ for 100 fb^{-1}

Higgs Boson Mass (GeV)	115	120	130	140
Sig. Selection Eff. (%)	10.7	11.2	11.3	11.3
Number Signal NS	7.42 ±0.33	7.33 ± 0.33	5.96±0.27	4.21±0.19
Total Number Bcgkd	1.61 ±0.53	2.79 ±0.62	1.98±0.66	1.10± 0.51
Total Number Bcgkd from fit w. syst.	2.23±0.34	1.94±0.32	1.60±0.22	1.39±0.22
Signal Significance (ScP)	3.541	3.662	3.257	2.510
Signal Significance (ScP) w. syst.	3.414	3.523	3.184	2.453

ttH, H→bb

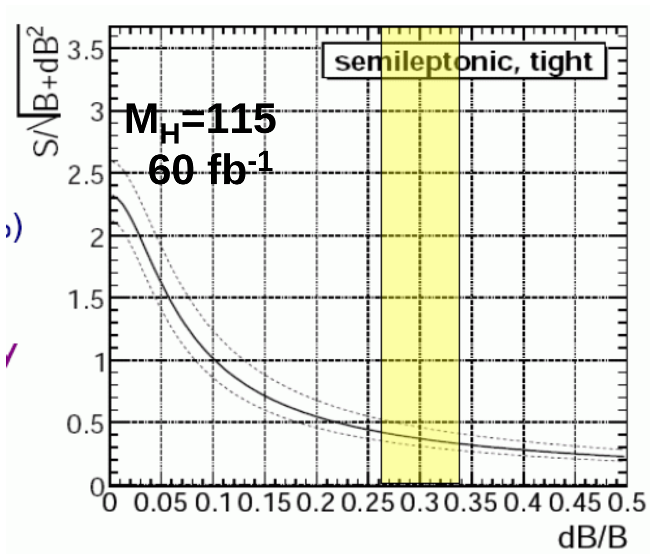




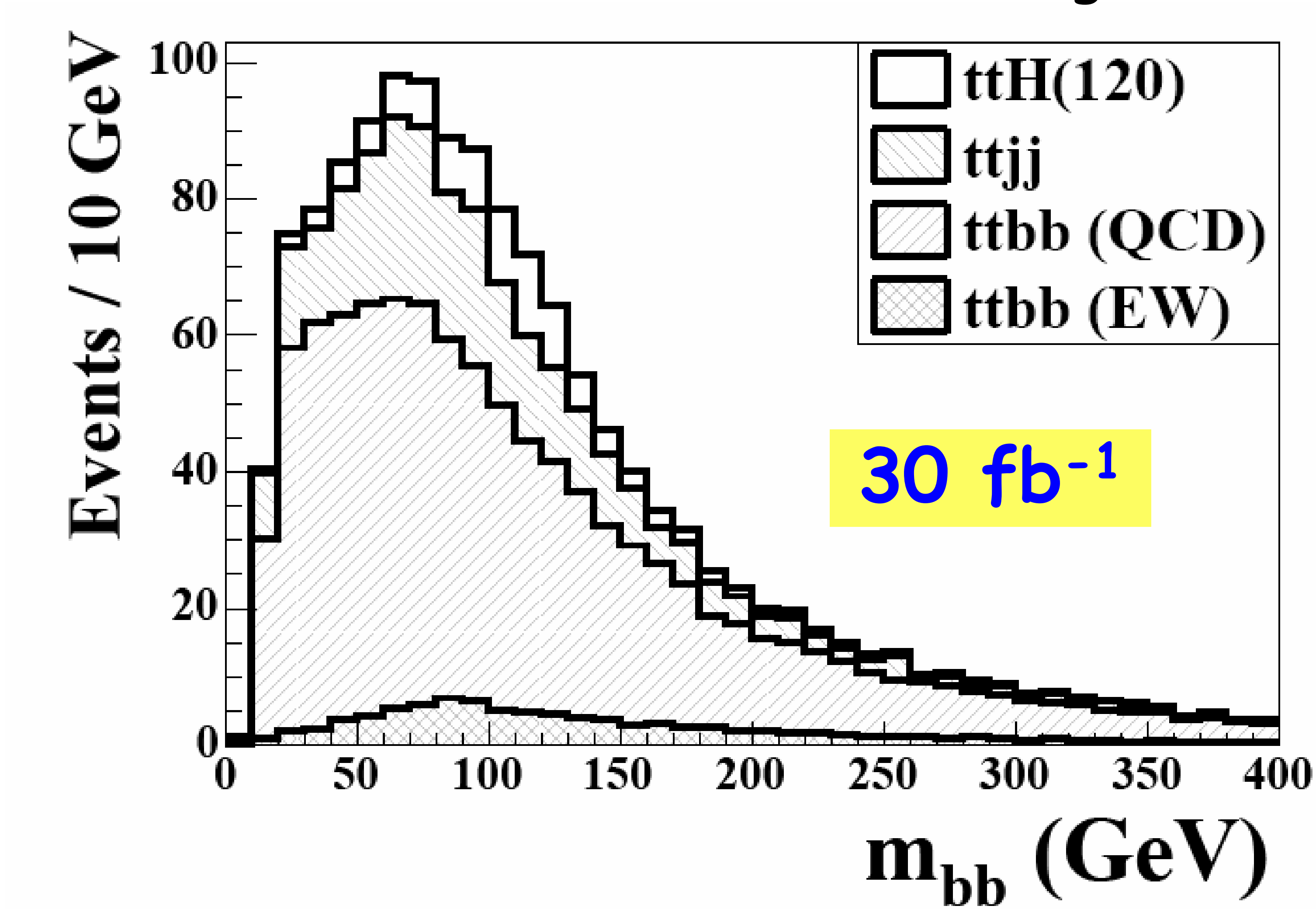
Latest CMS results are more pessimistic for this mode due to:

- effects of systematics
- backgrounds with ME Generator (ALPGEN)
- full detector simulation (b tagging, jet resolution)
- new K factors for signal

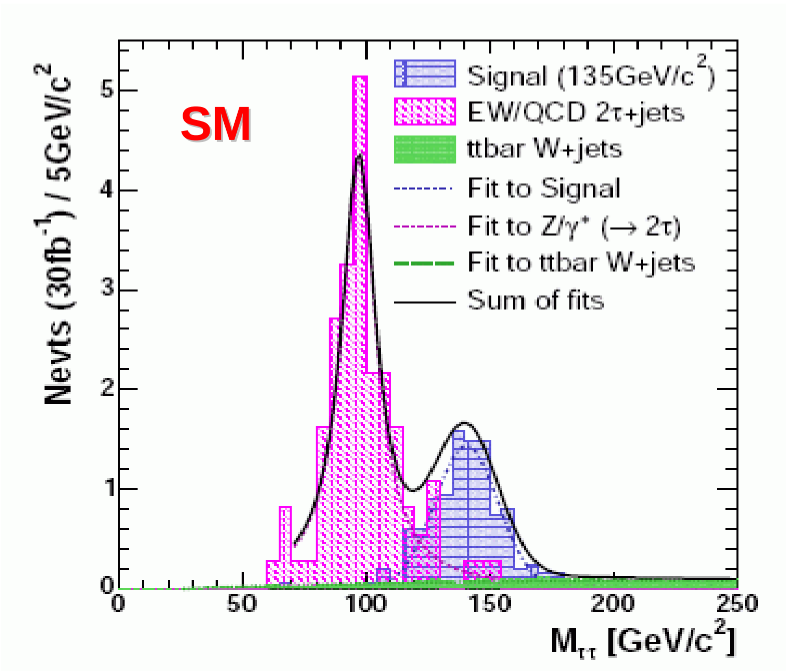
Improvements (eg. Particle Flow) still possible

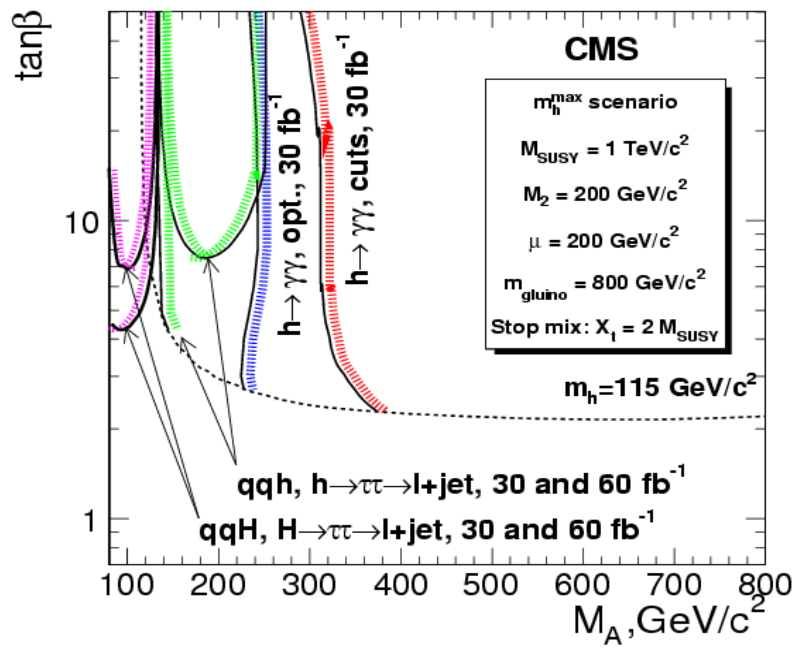


- May achieve 3-5σ effect for M_H=120 GeV and 30 fb^{-1}
  - Need to address issues related to background shapes and differences in hadronic scales for light and b-jets



Full simulation analysis of qqH, H→ττ →l+jet





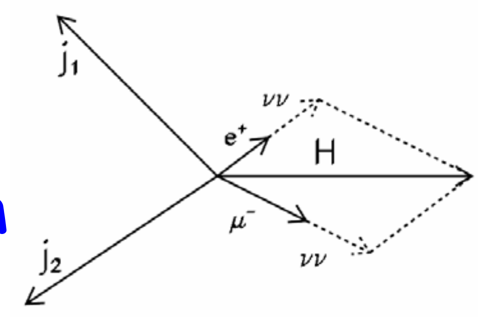
discovery light h in MSSM

Discovery in Standard Model

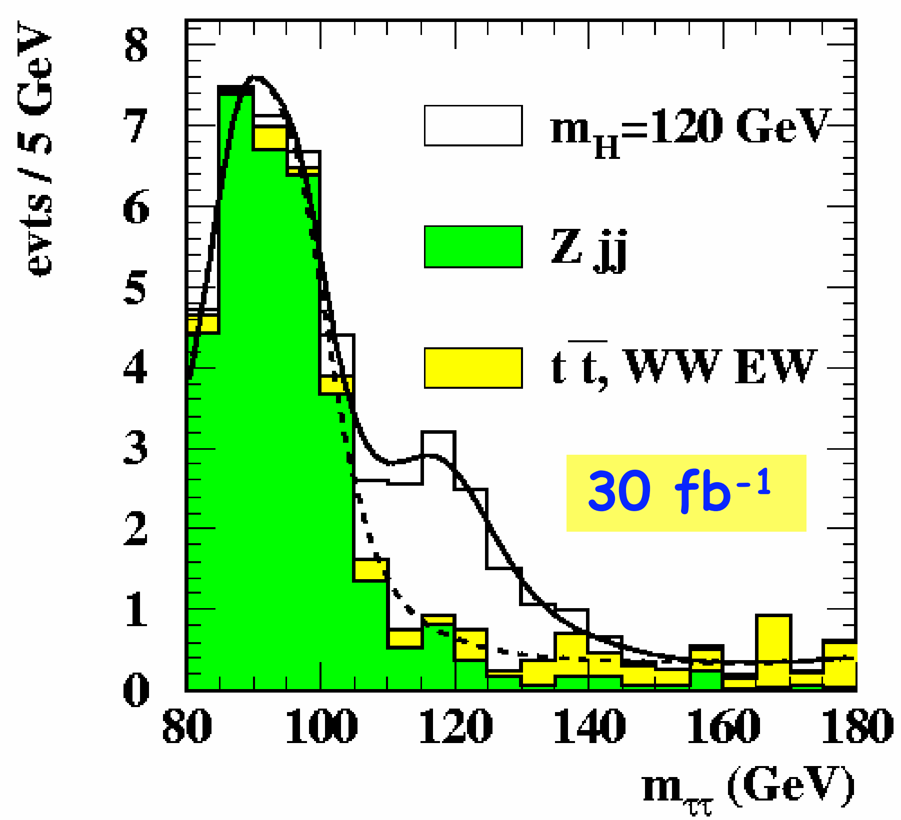
M_H [GeV]	115	125	135	145
Production σ [fb]	4.65×10^3	4.30×10^3	3.98×10^3	3.70×10^3
$\sigma\times BR(H\to\tau\tau\to lj)$ [fb]	157.3	112.9	82.38	45.37
N_S at 30 fb^{-1}	10.5	7.8	7.9	3.6
N_B at 30 fb^{-1}	3.7	2.2	1.8	1.4
Significance at 30 fb^{-1} ($\sigma_B = 7.8\%$)	3.97	3.67	3.94	2.18
Significance at 60 fb^{-1} ($\sigma_B = 5.9\%$)	5.67	5.26	5.64	3.19

Low Mass SM H→ττ+jets

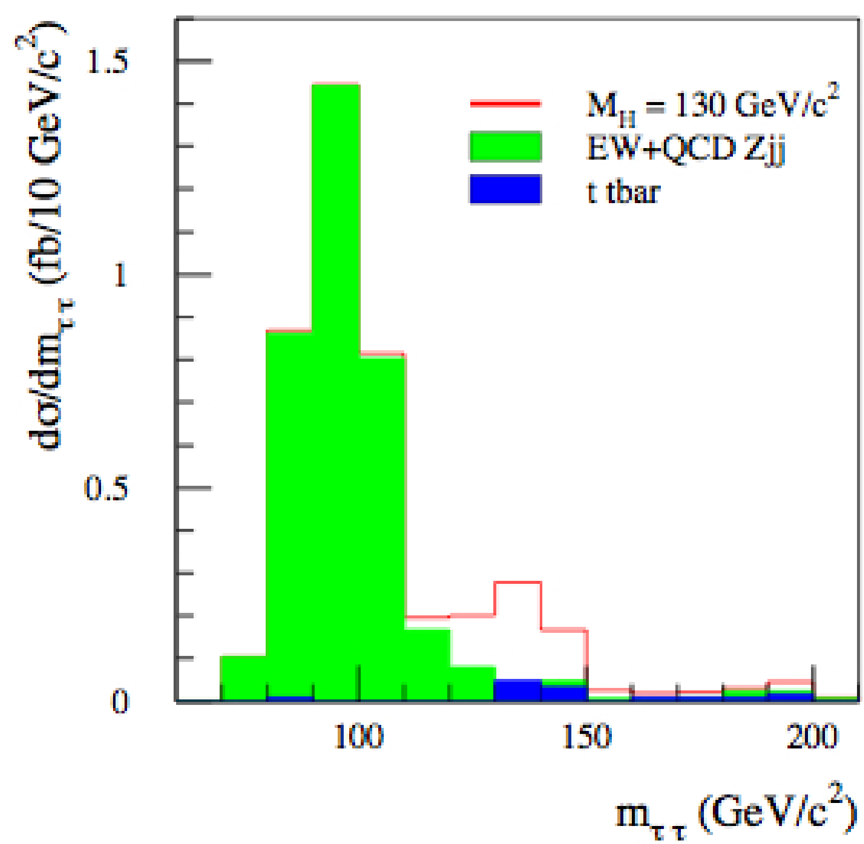
- Reconstruct Higgs mass with collinear approxim



$H(\rightarrow\tau\tau\rightarrow ll)$ +≥2jets (VBF)

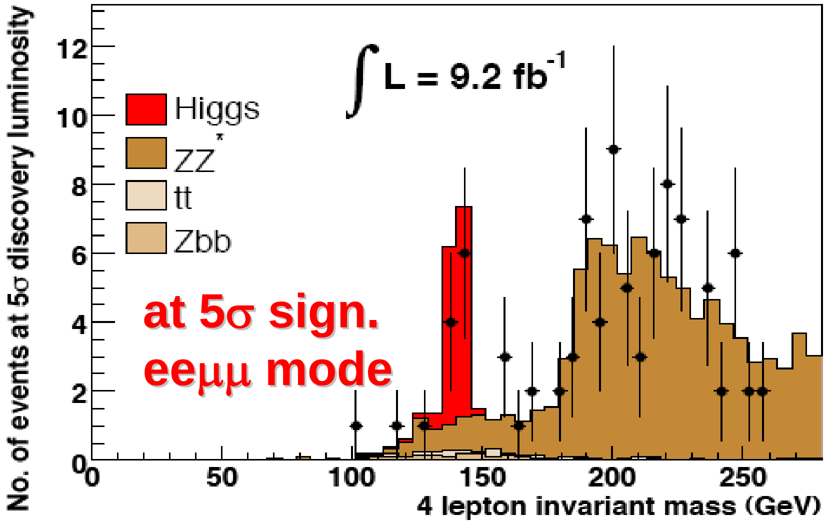


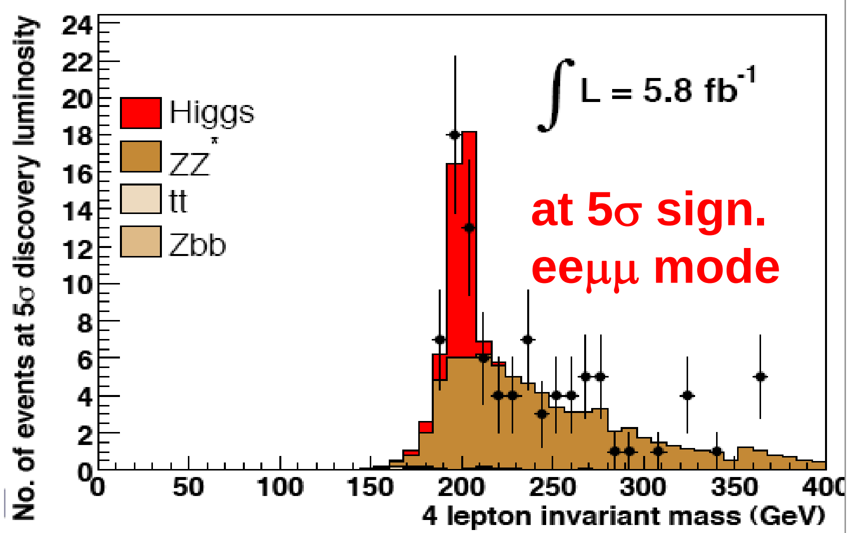
$H(\rightarrow\tau\tau\rightarrow lh)$ +≥2jets (VBF)



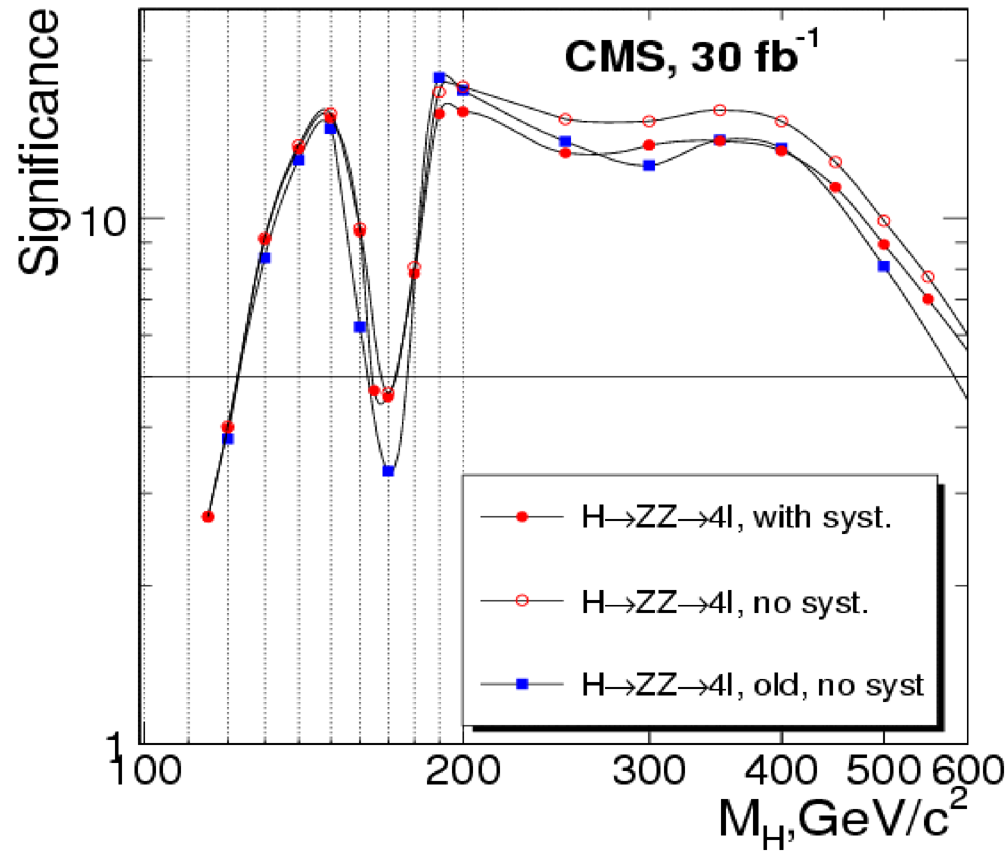
Higgs: $H \rightarrow ZZ \rightarrow$ 4 leptons

ZZ background: NLO K-factor depends on mass of 4l
Background from side bands or from ZZ/Z;
(gg->ZZ is added as 20% of LO qq->ZZ)



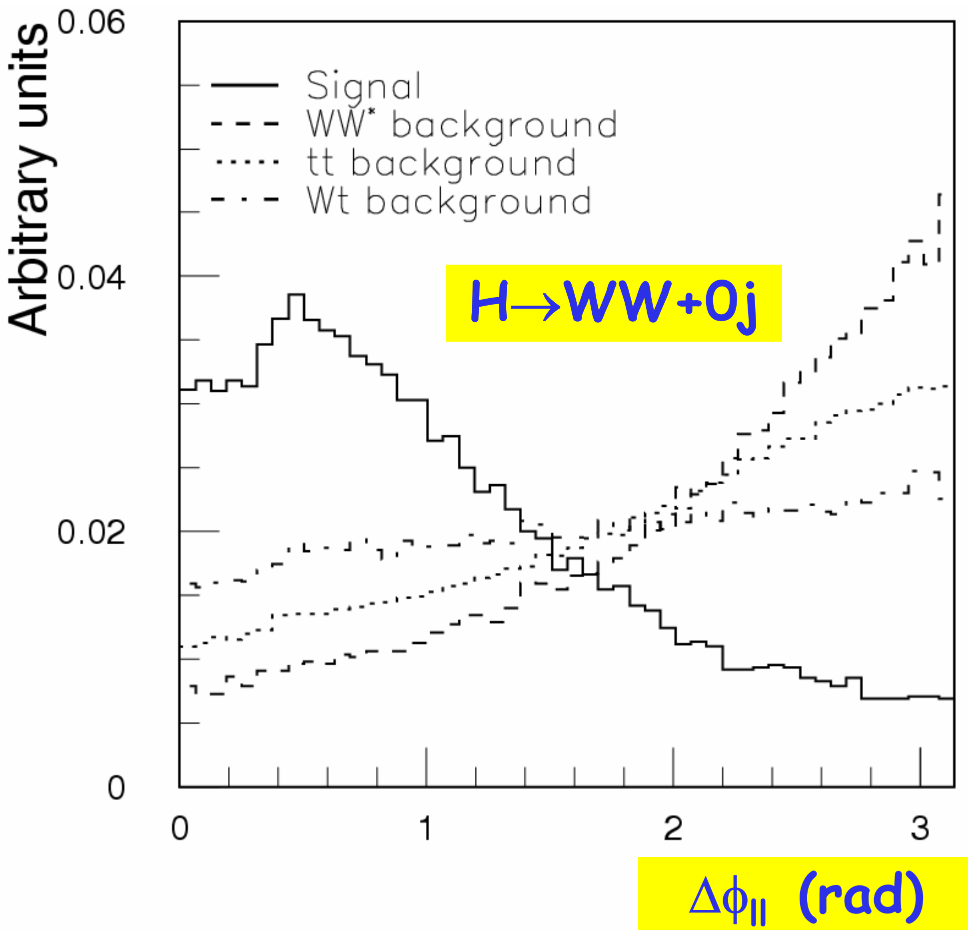


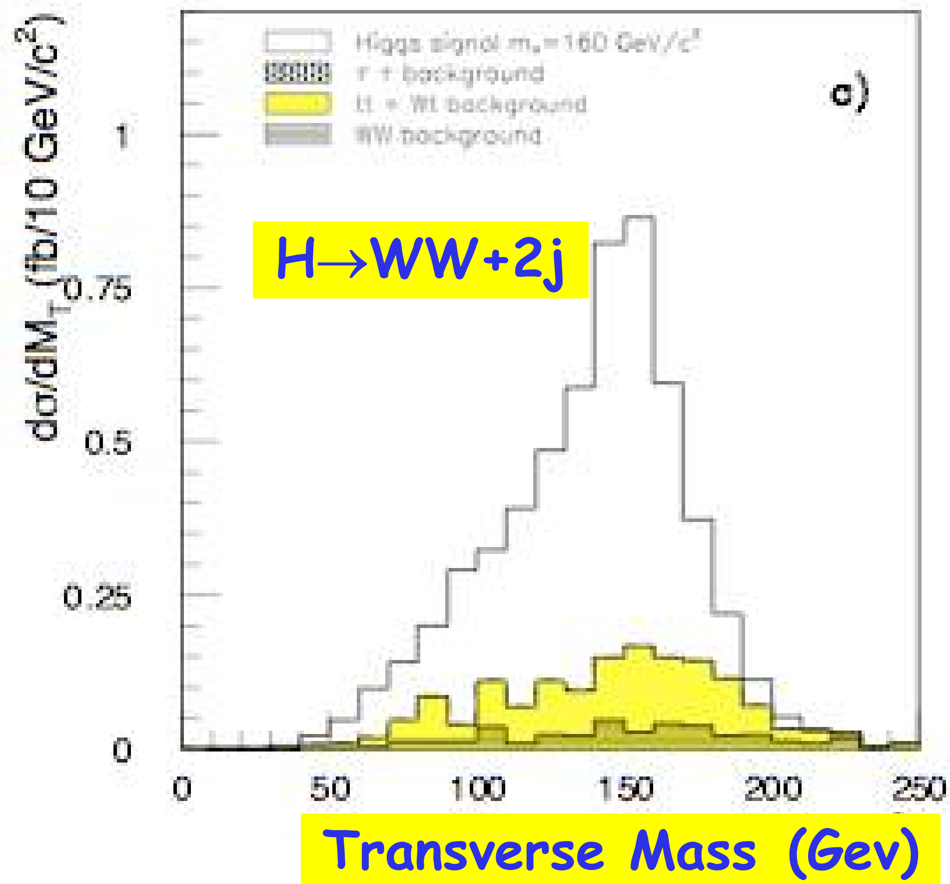
Combined 4μ, 4e, eeμμ signal significance



SM Higgs $H \rightarrow WW^{(*)} \rightarrow 2l2\nu$

- **Strong potential due to large signal yield, but no narrow resonance. Left basically with event counting experiment**





PROPHECY4F

Features of Monte Carlo generator PROPHECY4F

- $\mathcal{O}(\alpha)$ and $\mathcal{O}(\alpha_s)$ calculation of $H \to WW/ZZ \to 4f$
  partial widths and distributions

- non-collinear-safe observables possible

- corrections beyond $\mathcal{O}(\alpha)$
  higher order final state radiation, large m_{H} effects

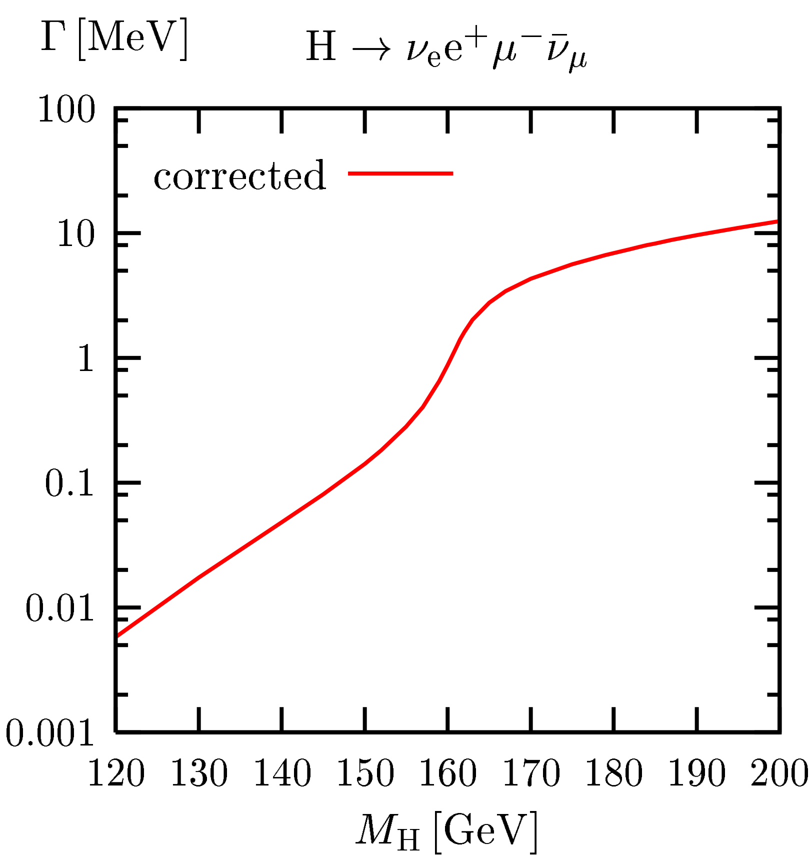
- improved Born approximation for partial widths
  includes: Coloumb singularity, leading effects for $m_{\mathrm{H}}, m_{\mathrm{t}} \gg m_{\mathrm{W}}$, fitting constant

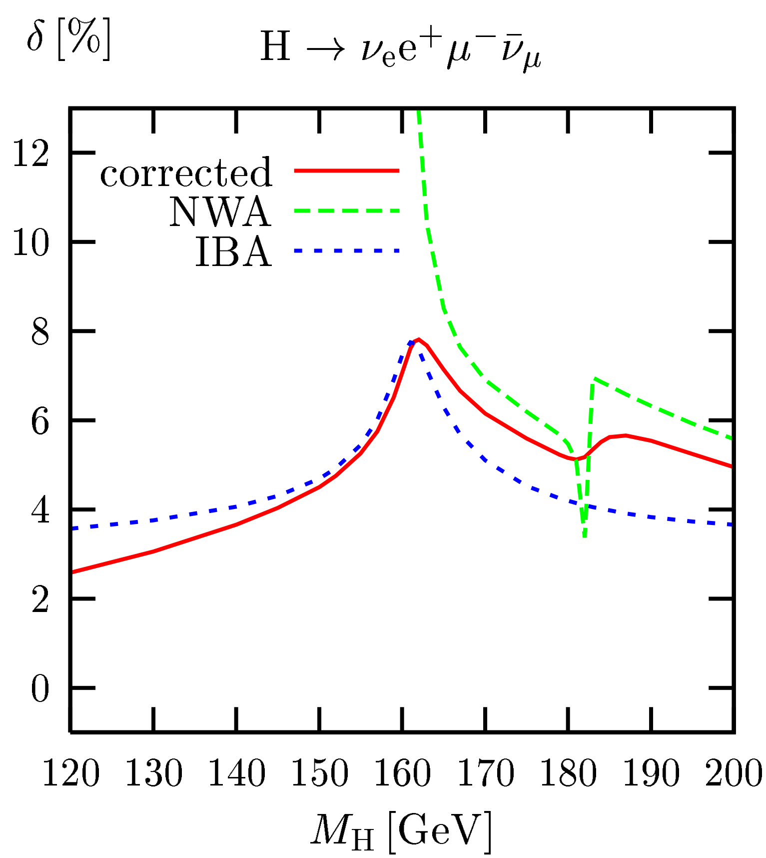
- phase space integration
  multi channel Monte Carlo integration [Berends,Kleiss,Pittau '94]
  adaptive weight optimization [Kleiss, Pittau '94]

Partial widths: leptonic

$$\mathbf{H} \to \nu_{\mathrm{e}} \mathrm{e}^+ \mu^- \bar{\nu}_\mu$$

G_μ-scheme





NWA: narrow width approximation

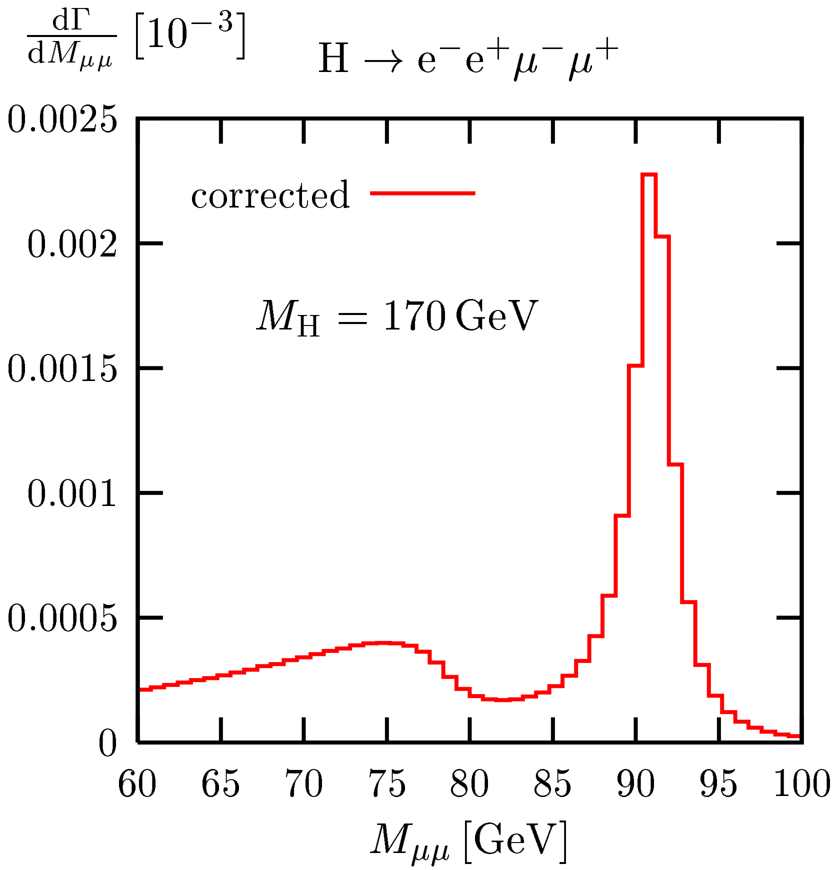
IBA: improved Born approximation

Distributions: invariant mass

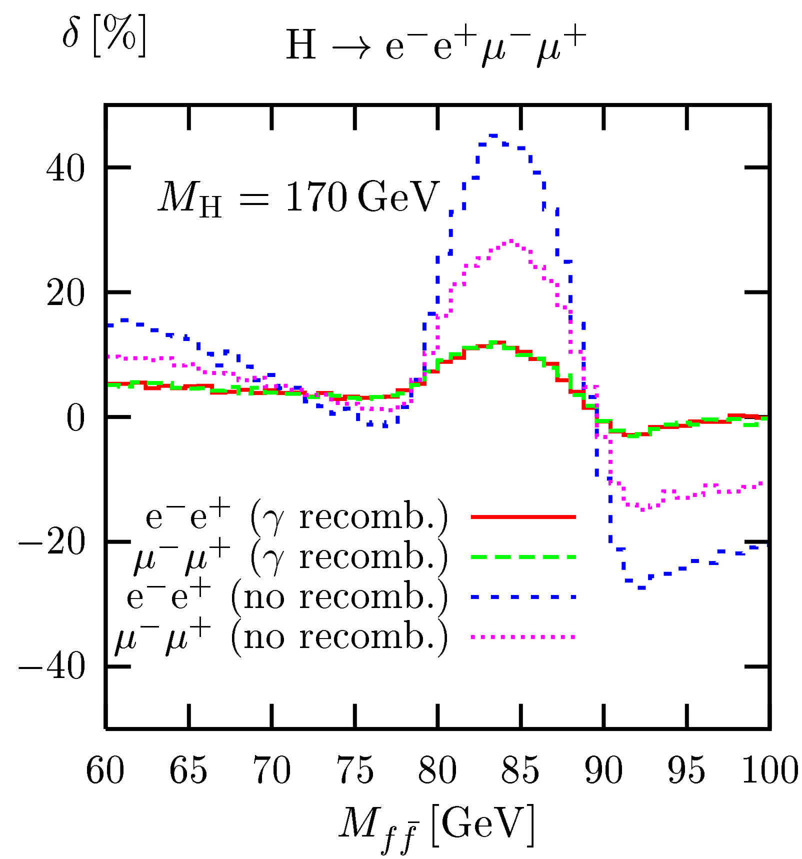
$\mathbf{H \to e^- e^+ \mu^- \mu^+}$

G_μ-scheme, $m_H = 170$ GeV

invariant mass distribution



relative corrections



photon recombination: if $m_{f\gamma} < 5$ GeV

→ large corrections from photon recombination in Z reconstruction

Constraints on SM-like Higgs from early LHC data

- Measuring M_H drastically reduces the parameter space of all models.
- Observation/non-observation of additional states is crucial.
- 10^{-1} fb not enough for a detailed coupling analysis, but measurements of relevant rates put bounds on couplings (HWW, HZZ, $H\tau\tau$, and indirectly $Ht\bar{t}$, HXX).
- 10^{-1} fb not enough for study of the Higgs potential.

$$\Downarrow$$

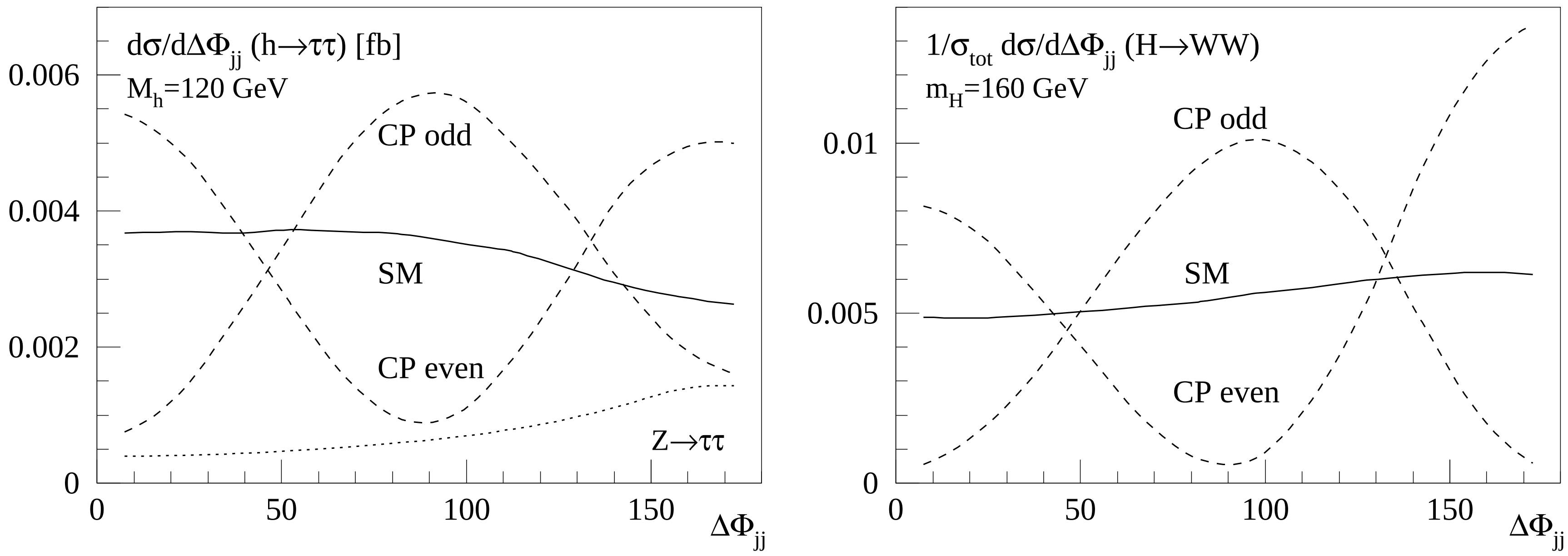
possible to establish consistency with the SM

So what can we do at LHC?

WBF production measures vertex structure (indep. of decay)

CP & spin determination: [hep-ph/0105325,0609075]

$g^{\mu\nu}$ of $SU(2)$ v. $\Phi W^{\mu\nu} W_{\mu\nu}$ D-5 operators (CP-even/odd)



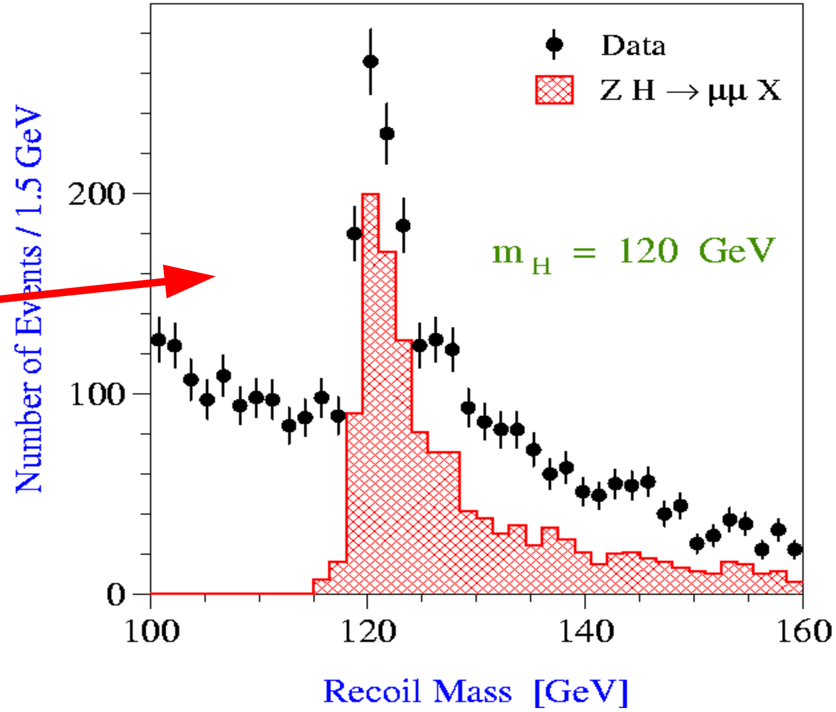
- need about 10x lumi past discovery to bin ϕ_{jj}

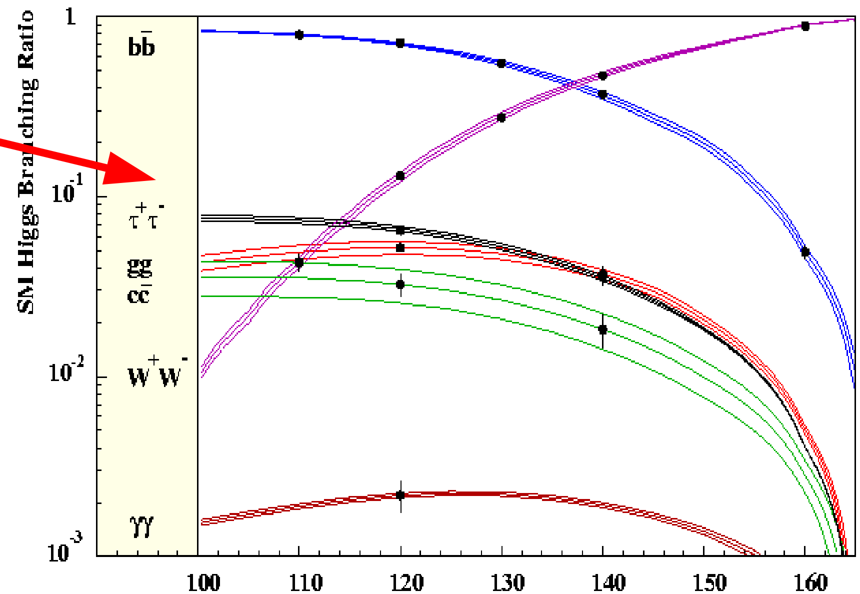
$\longrightarrow$ distributions not vulnerable to NLO QCD [hep-ph/0608158]

$\longrightarrow$ contamination from $gg \to Hgg$ is an issue

Requirements on Detector Driven by Higgs Program

- Excellent momentum resolution ($\delta p/p^2 = 5\cdot 10^{-5}$[GeV^{-1}c])
  - ➔ ZH➔$\mu\mu$(ee)X (model independent analysis)
- Excellent performance of VXD (σ_{d0}= 5μm$\oplus$10μm/p[GeV/c]$\cdot\sin^{3/2}\theta$), high track finding efficiency down to low track momentum (p ~ 500 MeV)
  - ➔ H➔bb,cc,gg,$\tau\tau$ decays (branchings, parity)
  - ➔ Vtx charge ➔ reduction of combinatorics (e.g. HHZ 6jet)
- Precise jet reconstruction in multi-jet final states ($\delta E/E$ = 30%/$\sqrt{E}$)
  - ➔ Higgs self-couplings (HHZ process)
  - ➔ Other signals: HA,HZ➔4jets(6jets)





Higgs Physics at ILC

- Early analyses, evaluating ILC potential for determination of (SM-like) Higgs profile, include simulation of following measurements
  - Higgs mass, width;
  - Couplings to fermions, gauge bosons, self-couplings;
  - Quantum numbers (spin, parity)
- Most of these analyses are done with fast simulation program SIMDET (must be revised with full & detailed simulation and realistic reconstruction)
- Though beamstrahlung (reducing $\sqrt{s}$) is taken into account , other beam-induced effects (e.g. impact e+e- pair background on pattern recognition in VTX detector) are not studied in detail
- Assumed centre-of-mass energies: 350, 500, 800(1000) GeV depending on channel (an issue optimal ILC running strategy still to be addressed)
- Analyses were ment to give an approximate estimate on achievable precision of Higgs measurements and maybe provide a bit too optimistic forecast
- In the following selected analyses are reviewed

Highlights from the working group sessions: theoretical interpretations

Main focus of Thursday sessions: BSM with a SM-like Higgs

→ S. Belyaev, "Light MSSM Higgs boson scenario and its test at hadron colliders"

→ G. Shaughnessy, "Phenomenology of the SM with a scalar singlet"

→ G. Huang, "$H \to aa$ at the LHC"

LHS: features/consequences

- **Light MSSM Higgs ~ 50 GeV mass is allowed!**
  - ***Light Charged Higgs***
    - small ZZh coupling and large $WH^{+}h$ coupling
  - ***Intermediate – large μ and A_t***
    - Large $\mu>0$ and intermediate-heavy gluino provide non-universal corrections to tau and bottom Yukawa couplings suppressing Br(H->bb)
  - ***Intermediate-high tanβ***
    - provides futher suppression of Br(H->bb), in agreement with b->sγ. Light stop and charginos!
- **$H^{+}A$: LHC covers the whole LHS parameter space, suggested process is independent of tanβ**
- **Correlation with Yukawa-enhanced processes, ILC precision tests**
- **Important tests from B-physics experimets!**
- **Different look at fine-tuning problem (especially for ~90 GeV M_H)**

Summary

SM Higgs + 1 scalar singlet:

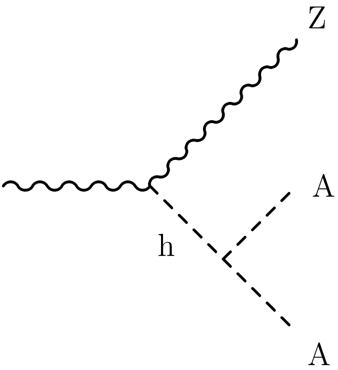
Case A: Singlet mixes with SM Higgs

- Traditional discovery modes weakened if $H \to SS$ open
- H discovery may be possible via 4b or $2b+2\tau$ modes

Case B: $S \to -S$ (stable singlet)

- DM candidate
- $H \to$ inv:
  - Discovery potential reduced (traditional modes)
  - Opportunity for discovery via invisible modes

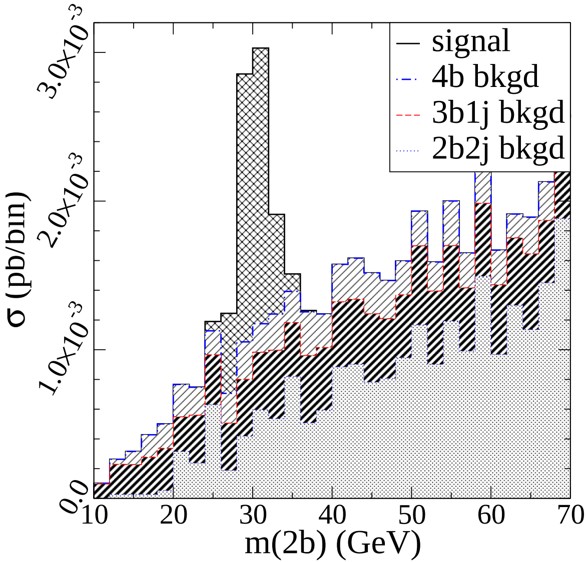
Decay Chain



- $W/Z \rightarrow l\nu_l/l + l-$
- $H \rightarrow AA$
- $A, A \rightarrow b\bar{b}, \tau\bar{\tau}$

- Signal compromised by smaller σ and W, Z leptonic BR.
- Background suppressed by 2 or more orders of magnitude.

Signal vs. Background



Open questions for the Higgs working group

Scenarios for SM-like Higgs discovery at the LHC

- Low mass SM-like Higgs ($M_H \lesssim 2M_Z$ GeV):

  $\longrightarrow$ what can be improved in order to extract as much as possible from the first 10 fb^{-1} of data (e.g, $t\bar{t}H$, $H \to b\bar{b}$)
  $\longrightarrow$ what is most important in view of the ILC?
  $\longrightarrow$ what is the value added of Tevatron data?

- Intermediate mass SM-like Higgs ($180 \lesssim M_H \lesssim 2M_t$ GeV):

  $\longrightarrow$ How much precision do we need?
  $\longrightarrow$ Is there any sensitivity to $H \to tt^*$ (below $t\bar{t}$ threshold)?

- Heavier SM-like Higgs ($M_H \gtrsim 2M_t$):

  $\longrightarrow$ Implications for the ILC precision Higgs program?

Important theoretical input

- State-of-the-art Higgs computations

  $\longrightarrow$ How accurate are current predictions of Higgs production and decay processes and the relevant backgrounds?
  $\longrightarrow$ Do we need to do better? Identify the highest priority needs.

- The decoupling limit: Many models of physics beyond the SM possess significant parameter regimes in which the lightest Higgs scalar closely resembles the SM Higgs boson.

  $\longrightarrow$ What are the first order corrections to the SM-like Higgs properties?
  $\longrightarrow$ Do the systematics of the corrections to the SM-like Higgs observables distinguish among various possible models?
  $\longrightarrow$ Can this be exploited by a precision Higgs program at the ILC?

Next steps

- → We will have a webpage soon!
- → List of important experimental and theoretical studies needed to address the open questions.
- → Provide a central location for various links to the relevant ATLAS, CMS and ILC Higgs studies.
- → Identify ongoing working group projects and contact information for project authors.
- → Incorporate subject areas of the newly expanded working group charge. Identify possible connections to other working group activities.
- → Be prepared ahead of time in anticipation of the next meeting of this workshop in the fall of 2007.