Higgs boson search at the Tevatron Collider

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- Higgs mechanism and limits
- Higgs boson mass in the MSSM
- Higgs production at 2 TeV
- $M_h < 135$ GeV, $q\bar{q} \to WH, q\bar{q} \to ZH$
- $M_h > 135$ GeV, $H \to WW^*$
- $t\bar{t}H$

Slides available at
`http://theory.fnal.gov/people/ellis/Talks`

Standard Model Higgs boson

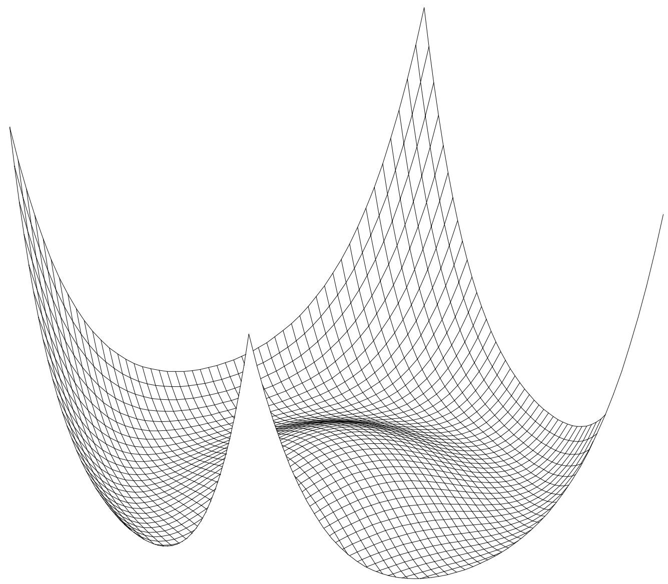
- Higgs boson is a single SU(2) complex doublet field

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} .$$

$$\mathcal{L} = (D_\mu \phi)(D^\mu \phi^\dagger) - \mathcal{V}(\phi^\dagger \phi)$$

The Higgs potential $\mathcal{V}$ is chosen to be of the form

$$\mathcal{V}(\phi^\dagger \phi) = \ \lambda \ (\phi^\dagger \phi)^2 - \mu^2 \phi^\dagger \phi \ .$$



The Higgs field ϕ develops a vacuum expectation value,

$$\langle\phi\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} .$$

$$\phi = U^{-1}(\xi) \begin{pmatrix} 0 \\ (h+v)/\sqrt{2} \end{pmatrix} , \quad U(\xi) = \exp(-iT\cdot\xi/v) \ .$$

$$M_W = g_w v; \quad v = 246 \text{ GeV}$$

• The Higgs mechanism is responsible for the breaking of SU(2)$_L$×U(1) gauge symmetry down to QED and giving mass to the W and Z.

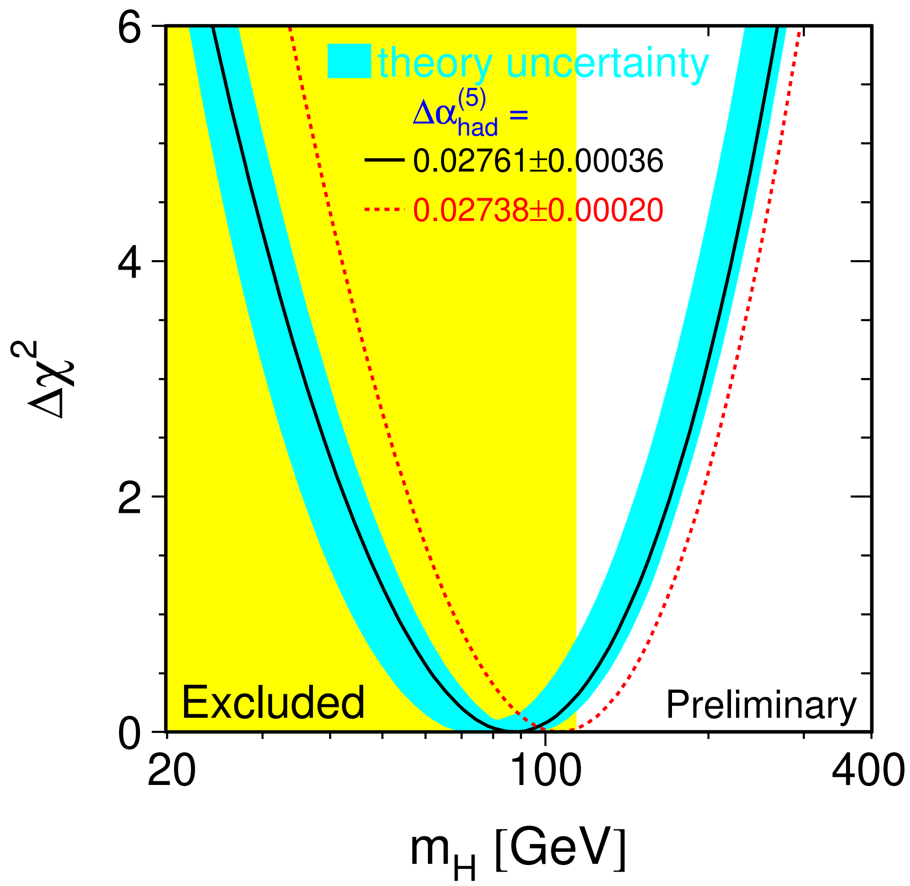
• The mass of the Higgs boson, $M_h = \sqrt{2\lambda}v$, is undetermined.

$$L_Y = h^U \overline{q_L} u_R (\tilde{\phi}) + h^D \overline{q_L} d_R \phi + h^E \overline{l_L} e_R \phi + h.c.$$

• The Yukawa interactions break the global flavour symmetry and give masses to the fermions.

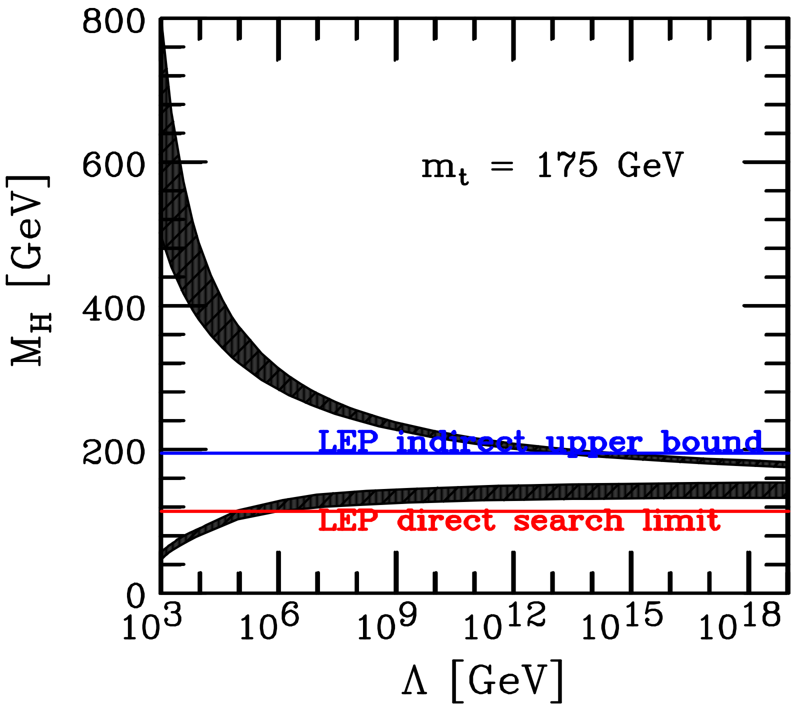
• The Higgs boson coupling to fermions is $\frac{g_w m_f}{2M_w}$.

Indirect bounds from precision electroweak



- $m_h < 196$ GeV at 95% C.L, (Drees LP2001)
- Strong preference for a low mass Higgs
- Note that more than half the χ^2-region is excluded by the direct search limit.

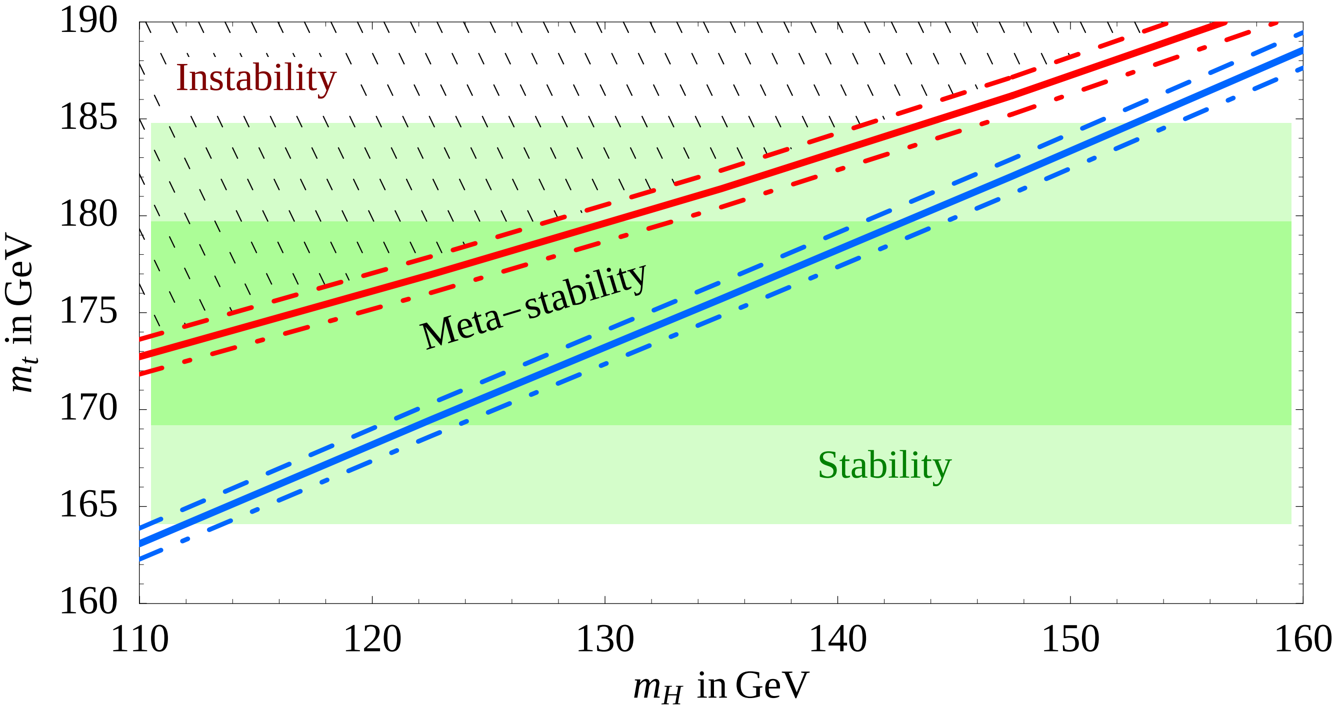
Theoretical Limits on the m_h



- Upper limit on M_h from Landau Pole.
- Lower limit on M_h from vacuum stability, ie when $\mathcal{V}(v) > \mathcal{V}(0)$.
- Lower limit is weakened for lower m_t and/or only requiring only vacuum metastability.
- Could we be stuck in the Planck chimney?

New physics before the Planck scale?

Isidori, Ridolfi, Strumia



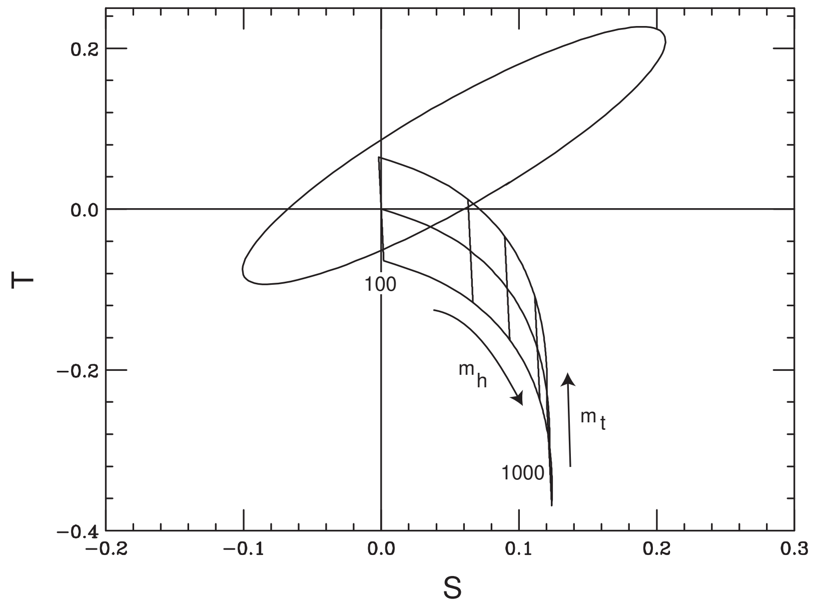
- Would the discovery of a Higgs boson at 115 GeV imply new physics below the Planck scale?
- For $m_h = 115$ GeV,

vacuum is unstable if $m_t > (166 \pm 2)$ GeV

but metastable until $m_t > (175 \pm 2)$ GeV.

Evading light Higgs boson bounds

Peskin and Wells

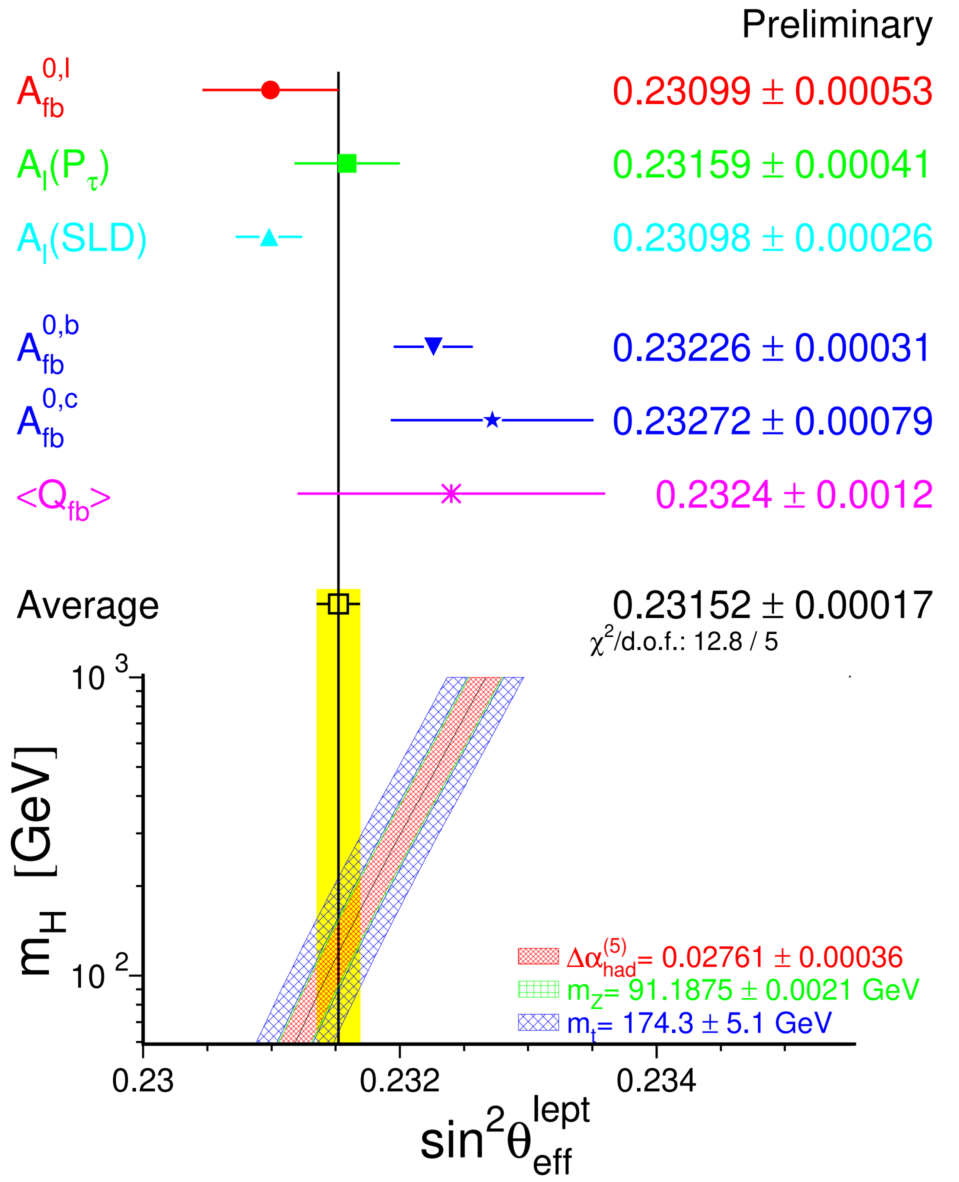


- Models evading light Higgs bounds are constrained in terms of ΔS, (ΔT), the weak isospin conserving (violating) contributions to W and Z loop diagrams.

- Although one cannot foreclose on the Heavy Higgs option, consistency with the low energy constraints frequently requires additional low energy signatures.

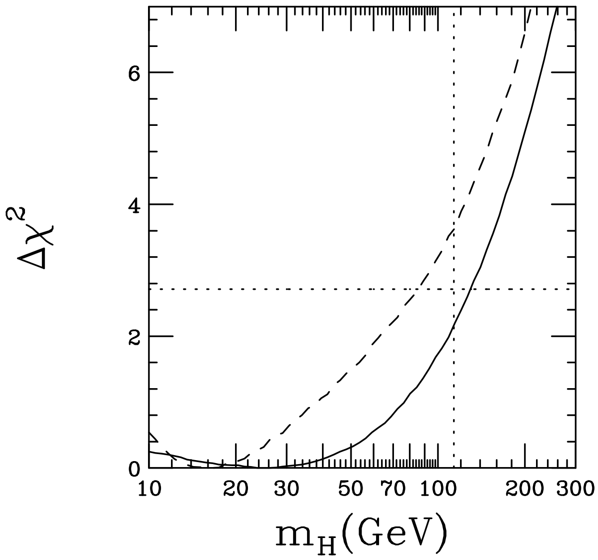
Are the precision electroweak bounds credible?

- Effective weak mixing angles determined from lepton data alone, and from lepton and quark data differ by 3.3 standard deviations, (Drees, Lepton-Photon 2001)



Lose-lose scenario for the standard model?

• Discrepancy caused by statistical fluctuation, systematic error or new physics?
• Systematic error - omit A_b^{FB}, fit becomes excellent ($\chi^2 = 15.4/14$), but central value of m_h falls between 21 and 28 GeV with $m_h < 113.5$ GeV at 92-94% C.L.
• Evidence from the SM fit favouring a light Higgs becomes less credible. (Chanowitz, Winter 2001 data)



• Solid line M_W alone, dashed line M_W, Γ_Z and R_l

Higgs particles in the MSSM

- Mass scales in supersymmetric theories are often elusive.
- An exception is the Higgs particle in the MSSM, whose mass is quite constrained.
- MSSM contains two doublets of Higgs fields

Physical states: $h^0, H^0, A^0, H^\pm$, Goldstones: $G^0, G^\pm$

Input parameters $\tan\beta, M_A^2$

$m_{H,h}^{2,\text{tree}} =$

$\frac{1}{2}\left[M_A^2 + M_Z^2 \pm \sqrt{(M_A^2 + M_Z^2)^2 - 4M_Z^2 M_A^2 \cos^2 2\beta}\right]$

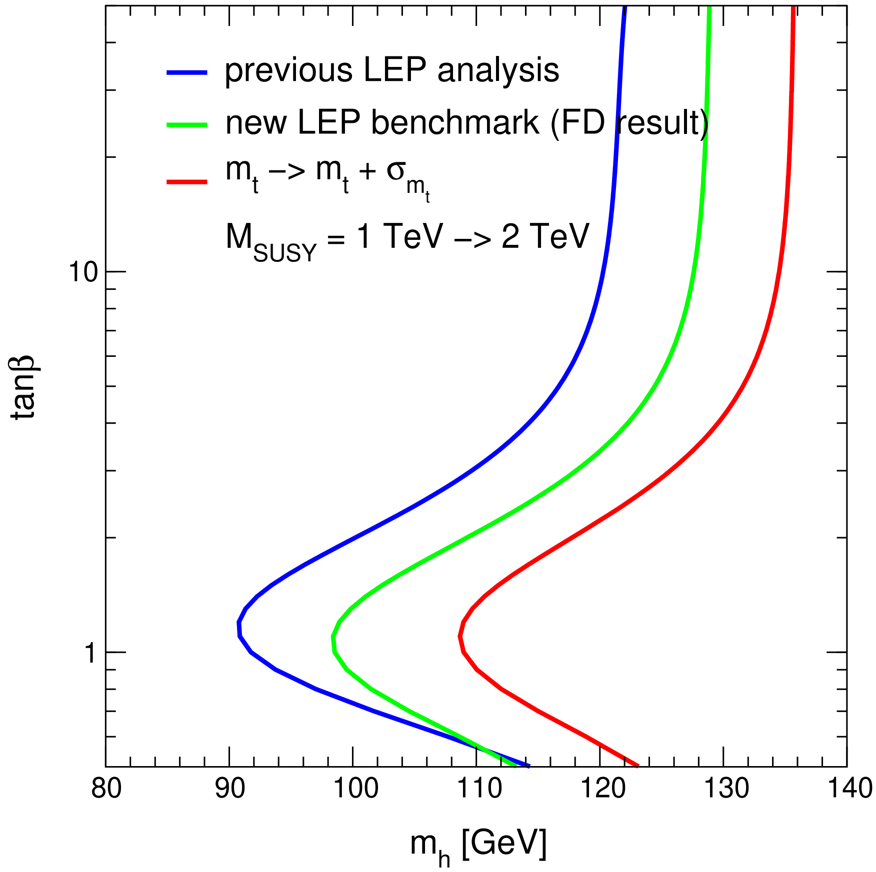
- At tree level $m_h < M_Z$
- Dominant corrections are from $t - \tilde{t}$-sector,

for $\tan\beta > 4$

$$m_h^2 \sim m_Z^2 + \frac{3G_F m_t^4}{\sqrt{2}\pi^2} \ln\left(m_{\tilde{t}}^2/v^2\right)$$

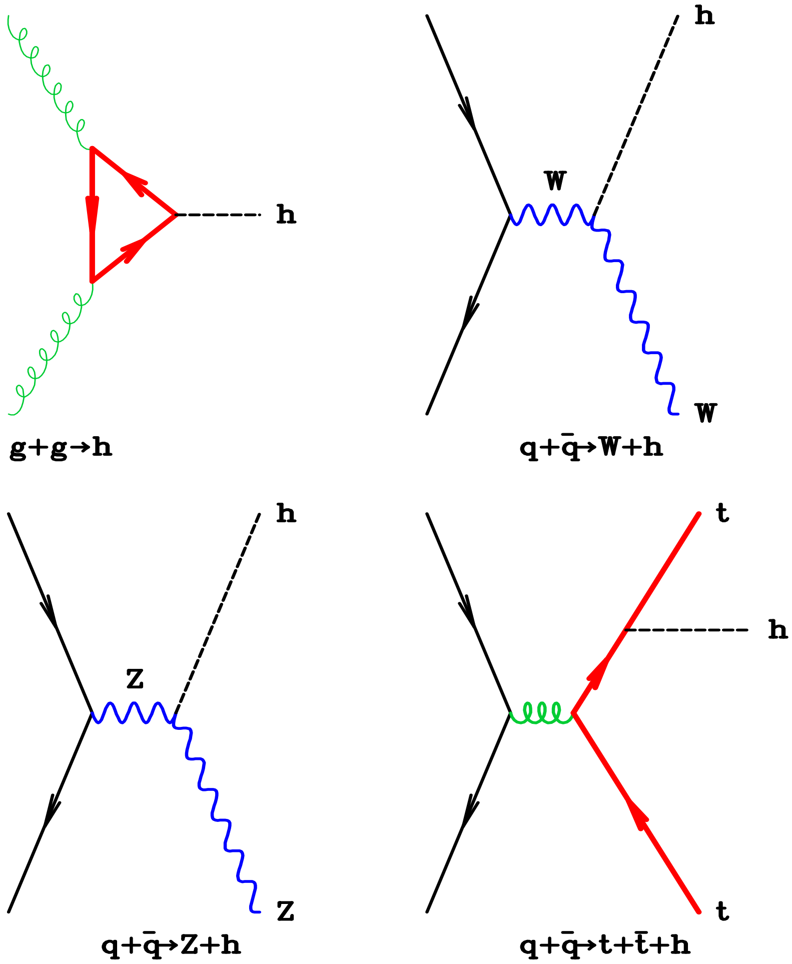
Upper limit on m_h in MSSM

Heinemayer, Hollik, Weiglein



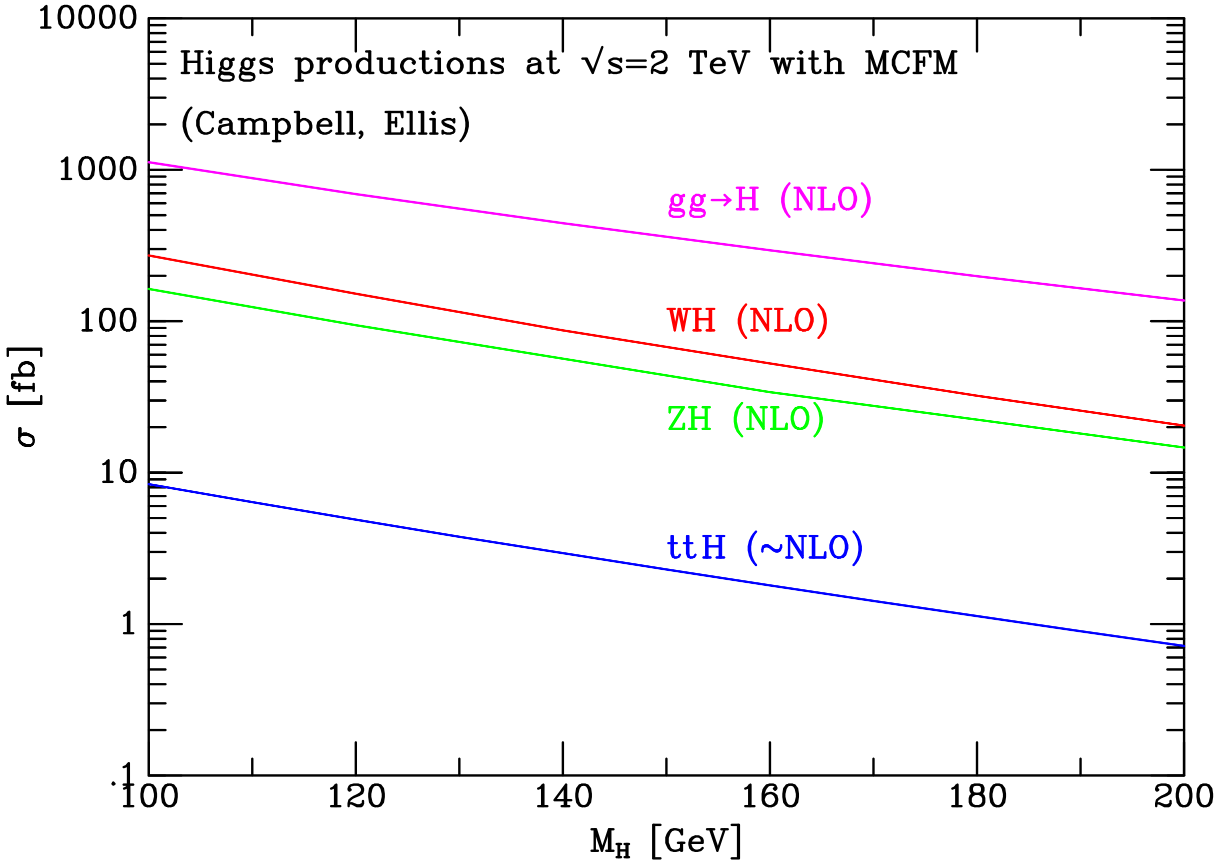
- Two loop calculation $m_h \leq 135$ GeV
- Upper limit for MSSM two doublet model sensitive to value of m_t
- Models with additional representations of particles extend the limit to 205 GeV. Quiros,Espinosa

Higgs production mechanisms



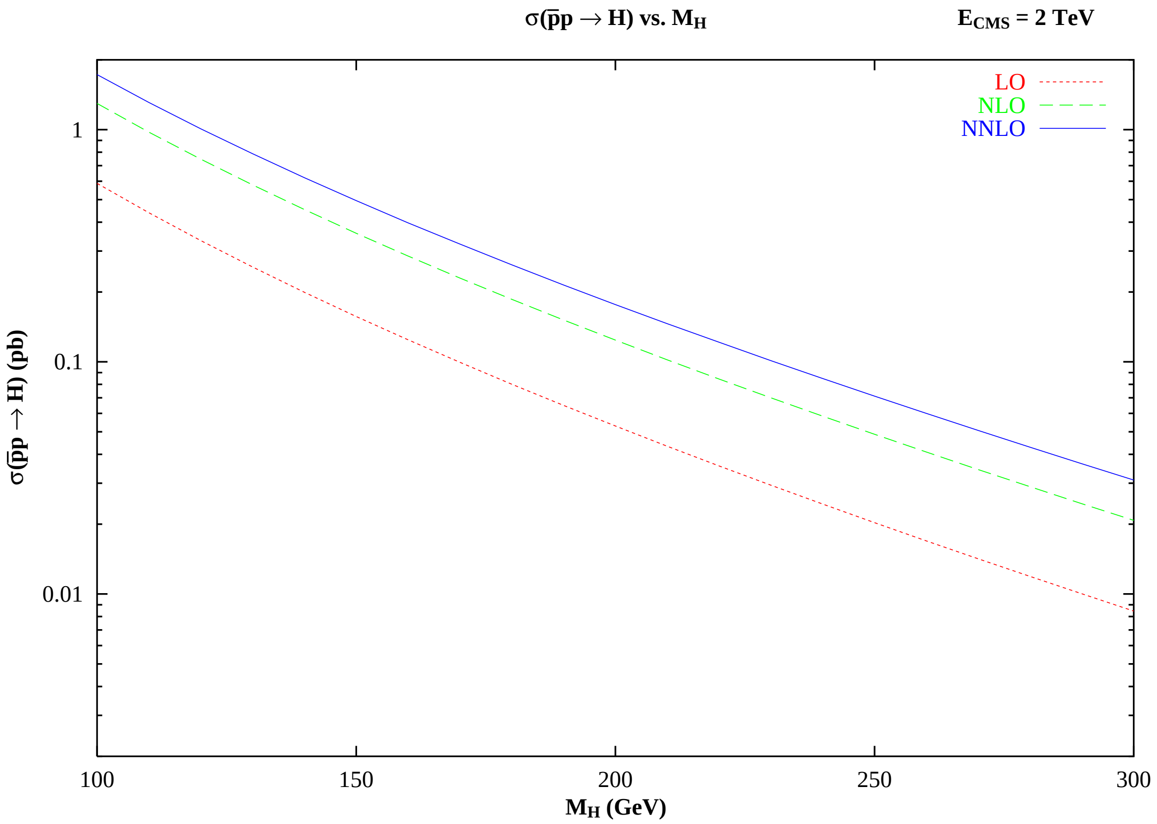
- Important production mechanisms at the Tevatron.

Higgs boson production at 2 TeV



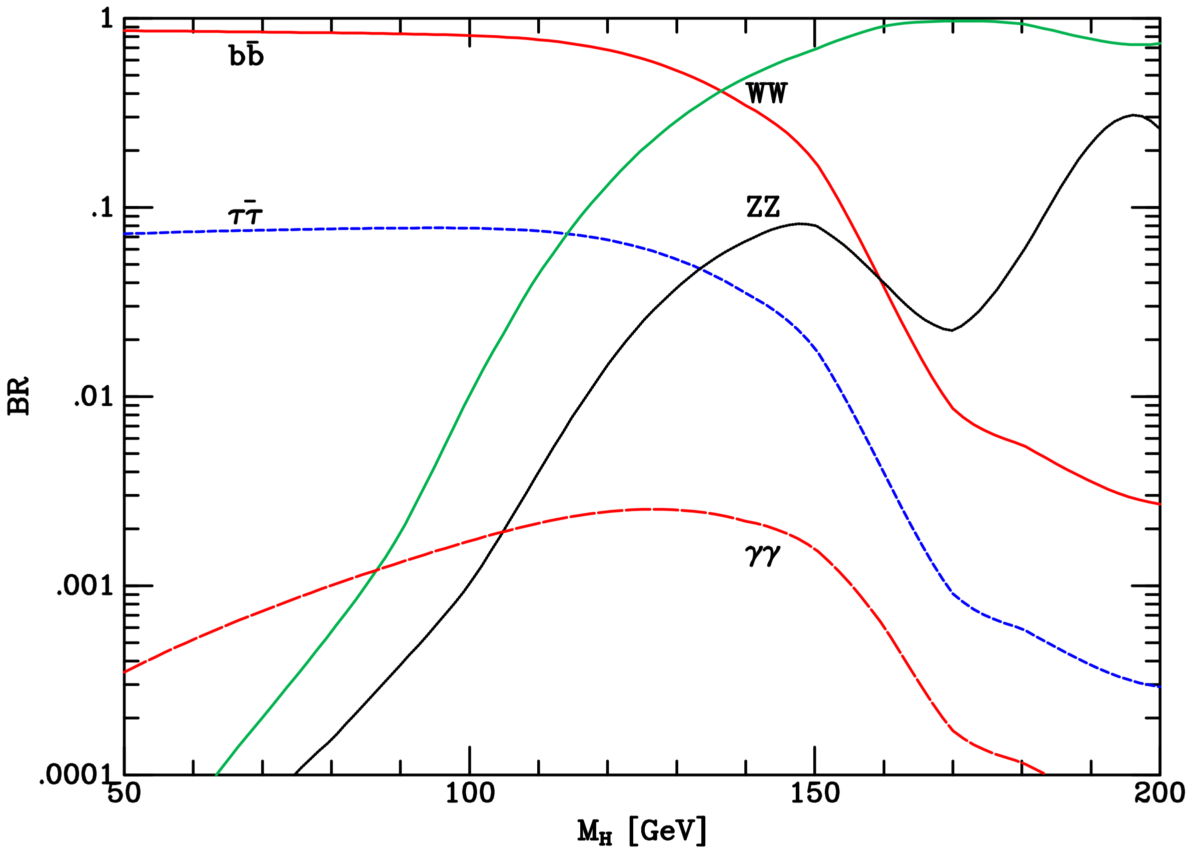
- Higgs cross sections are not so small at the Tevatron.
- Issue of background is crucial.
- Associated production cross sections are more than twenty times smaller than top pair production cross section.

New NNLO result



- Complete NNLO result, (hep-ph/0201206), Harlander,Kilgore
- Substantial increase in cross section
- Uses MRST NNLO (partial) structure functions, (hep-ph/0201127).

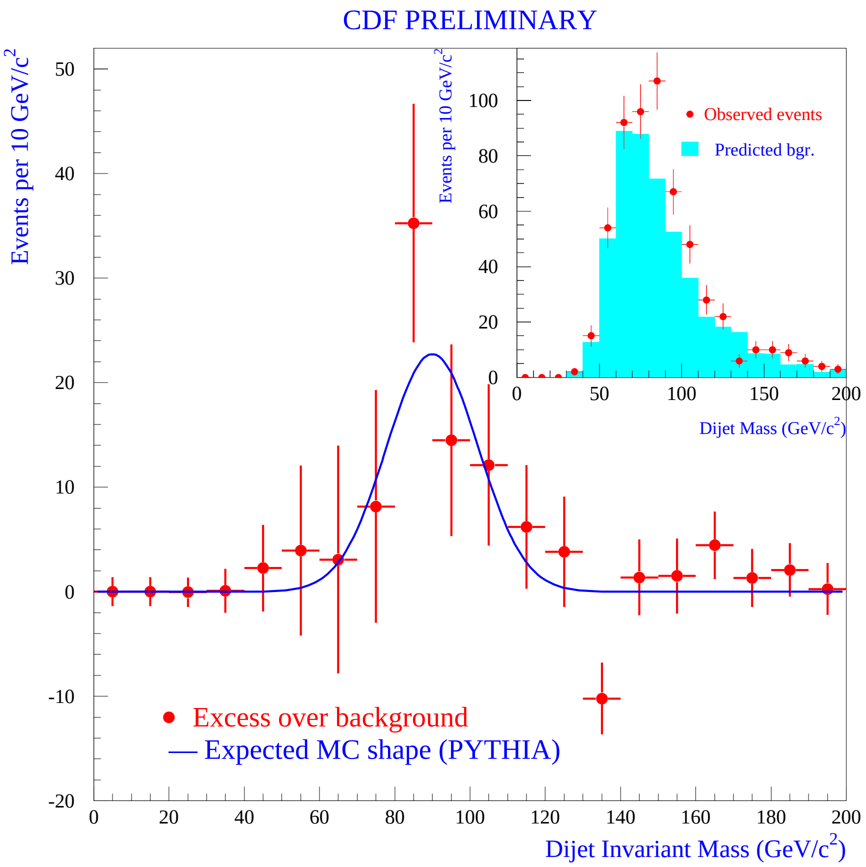
Higgs decay Branching ratios



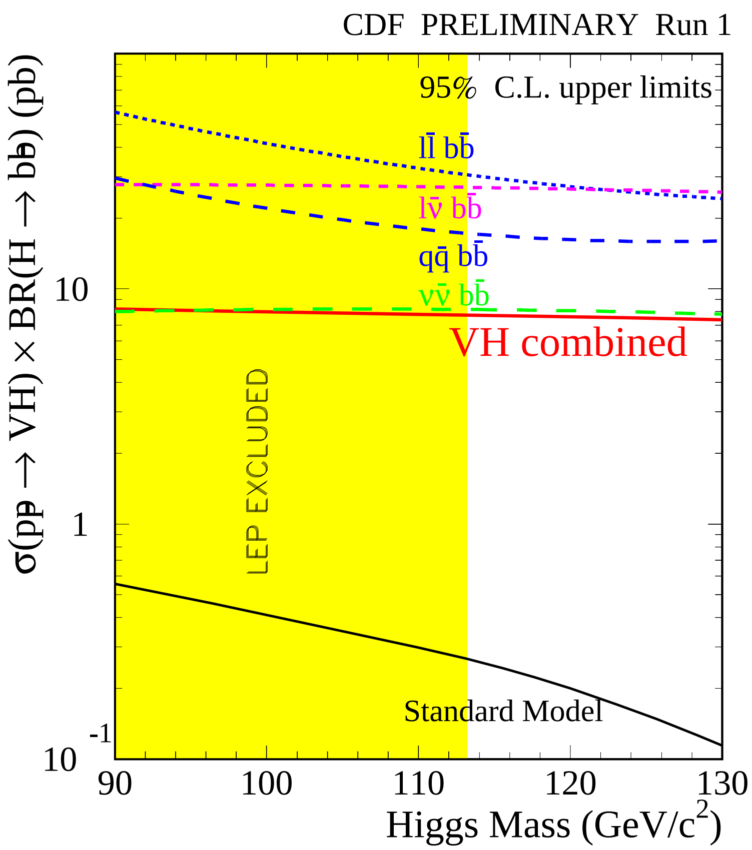
- $m_h \leq 135,\ H \to b\bar{b}$
- $m_h \geq 135,\ H \to WW^*$

$b\bar{b}$ resolution

- The $b\bar{b}$ resolution and b-jet energy scale are crucial.
- In Run II both of these will be *measured* using the decay $Z \to b\bar{b}$.
- A proof of principle is provided by the Run I observation of $Z \to b\bar{b}$ shown below. Curve has an RMS width, $\Delta = 12.3$ GeV



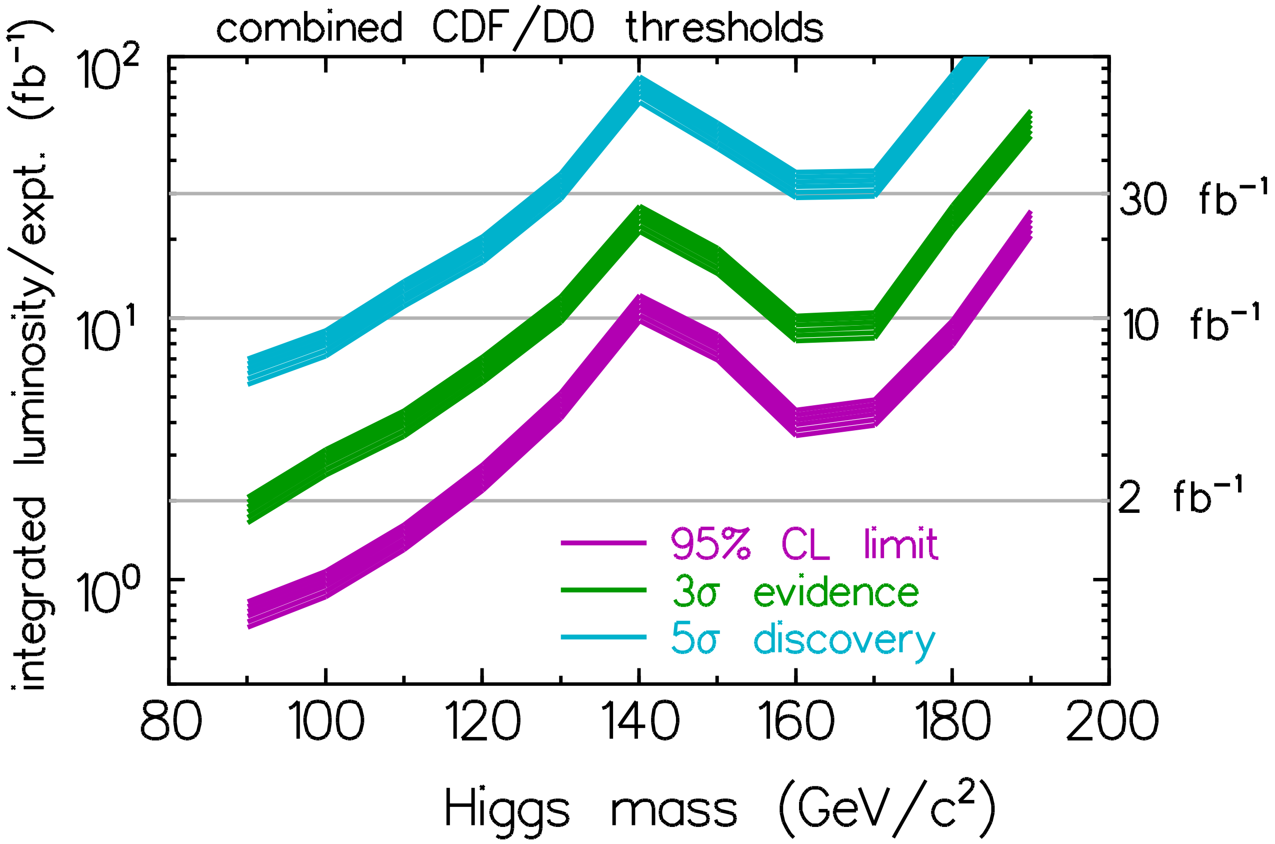
Current limits from CDF and D0



Moneta, hep-ex/0106050

- Upper limits on the production cross sections in the various channels for Run I.
- Sensitivity is still an order of magnitude away from that required in the SM.

Higgs working group results



- Does this contain the most accurate theoretical information?
- $t\bar{t}H$ not included (4.1σ effect for $M_h = 120\text{GeV}$ and 15fb^{-1}/expt).

Scope of the talk

- Aim is to provide the most accurate NLO information on signals and backgrounds, so that relative rates and shapes of cross sections are predicted.
- NLO calculations only contain partial effects of parton showering. For the heavy objects considered here this may be a good approximation.
- No detector effects on backgrounds. So a full assessment of the Higgs reach will not be possible.
- These are preparatory studies which will inform the more complete analysis to be performed when the run II data becomes available.

Description of backgrounds

- Description of the NLO program MCFM[a]
- Backgrounds to WH production (low mass Higgs).
- Backgrounds to ZH production.(low mass Higgs)
- Backgrounds to l^+l^- +missing energy signature (high mass Higgs)
- No MCFM studies yet of $t\bar{t}H$ production, (largest background $t\bar{t}$ + 2 jets) For this process, I will report results from Goldstein et al.

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[a] In collaboration with:
John Campbell and Sinisa Veseli
hep-ph/9810489
hep-ph/9905386
hep-ph/0006304

MCFM Philosophy

- The Tevatron Run II will be sensitive to processes at the femtobarn level.

- Particularly interesting are final states involving heavy quarks, leptons and missing energy.

- Standard model processes which result in these final states often include W, Z or Higgs. Data samples may not be large enough to determine SM backgrounds experimentally.

- MCFM aims to provide a unified description of such processes at NLO accuracy.

- The extension to NLO is made possible in many cases by the recent calculations of virtual matrix elements involving a vector boson and four partons.

MCFM Process List

Included at NLO	
$p\bar{p} \to W^\pm/Z$	$p\bar{p} \to W^+ + W^-$
$p\bar{p} \to W^\pm + Z$	$p\bar{p} \to Z + Z$
$p\bar{p} \to W^\pm/Z + H$	$p\bar{p} \to W^\pm/Z + 1$ jet
$p\bar{p} \to W^\pm + g^\star\,(\to b\bar{b})$	$p\bar{p} \to Z + b\bar{b}$
$p\bar{p} \to W^\pm + 2$ jet	$p\bar{p} \to Z + 2$ jet
$p\bar{p} \to H$	

- Various leptonic and/or hadronic decays of the bosons are included as further sub-processes.
- Where applicable Z includes the Z/γ^* interference, (important e.g. for b'gds to trilepton signatures).
- b-quarks are taken to be massless.
- MCFM v2.1 may be downloaded from

`http://theory.fnal.gov/people/ellis/Programs/`

MCFM LO processes

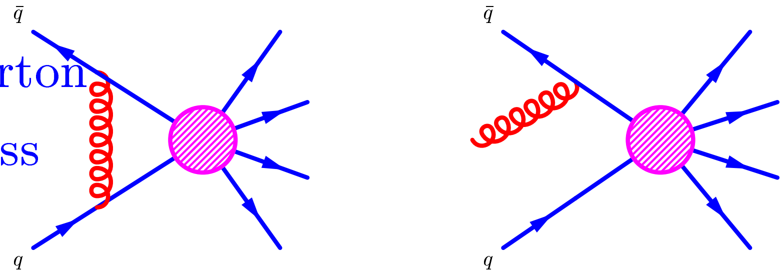
Processes included in MCFM at LO (including vector boson and top decays).

- $p\bar{p} \to t\bar{t}$
- $p\bar{p} \to t\bar{b}$ (single top production)
- $p\bar{p} \to qt\bar{b}$ (single top production, W gluon fusion)
- $p\bar{p} \to t\bar{t}H$
- $p\bar{p} \to W/Z + 3$ jets, ...

Monte Carlo Ingredients - 1

- Helicity amplitudes for the virtual and real ME's

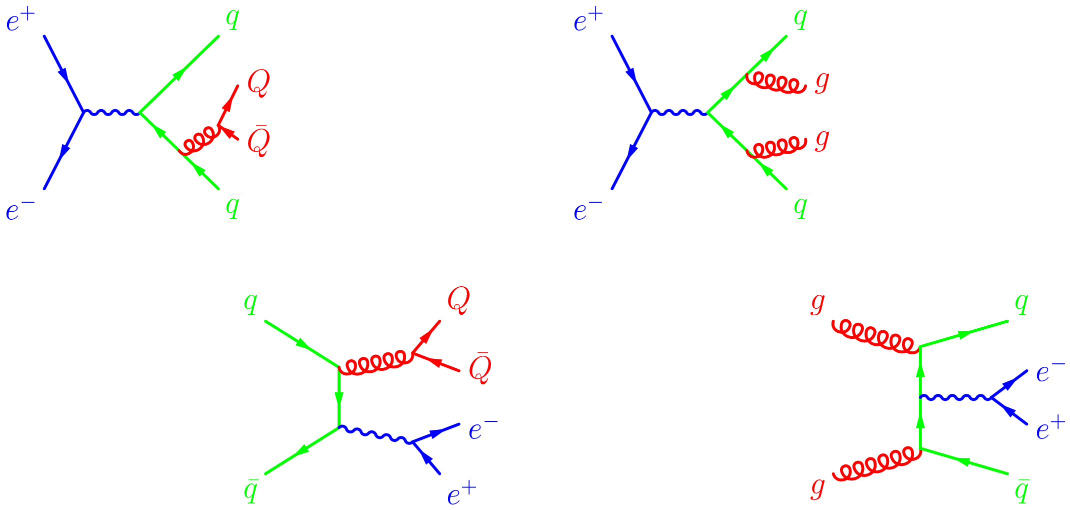
m-parton process



$(m+1)$-parton process

- Many of the NLO matrix elements are obtained by crossing the ones calculated for $e^+e^- \to 4$ jets.

Bern, Dixon, Kosower and Weinzierl, Nucl. Phys. **B489** (1997) 3
Glover and Miller, Phys. Lett. **B396** (1997) 257
Campbell, Glover and Miller, Phys. Lett. **B409** (1997) 503



Monte Carlo Ingredients - 2

- Singular pieces of the real matrix elements must be identified and cancelled by an appropriate set of counter-terms. ERT, Nucl.Phys.**B178** (1981) 421
- MCFM uses the dipole method to cancel the infrared divergences between real and virtual contributions.
  Catani and Seymour, Nucl. Phys. **B485** (1997) 291

$$\begin{aligned}
\sigma^{m+1}_{real} &= \int_{(m+1)} \left(d\sigma_{real} - d\sigma_{counter}\right) + \int_{(m+1)} d\sigma_{counter} \\
&= \text{(integrable terms)} + \sum_{dipoles} \int_m d\sigma \otimes \int_1 dV_{dipole}
\end{aligned}$$

where the 1-dimensional integral over the dipoles leads to soft and collinear divergences (poles in ϵ).

- These poles manifestly multiply m-parton ME's and may be cancelled against poles from the loop diagrams.

Higgs search using MCFM

- Studies using LO Monte Carlos and other event generators show that for a Higgs in the mass range of 100-130 GeV, the most promising channels for discovery at Run II are associated Higgs production.
  Stange et al., Phys. Rev. **D49** (1994) 1354, **D50** (1994) 4491

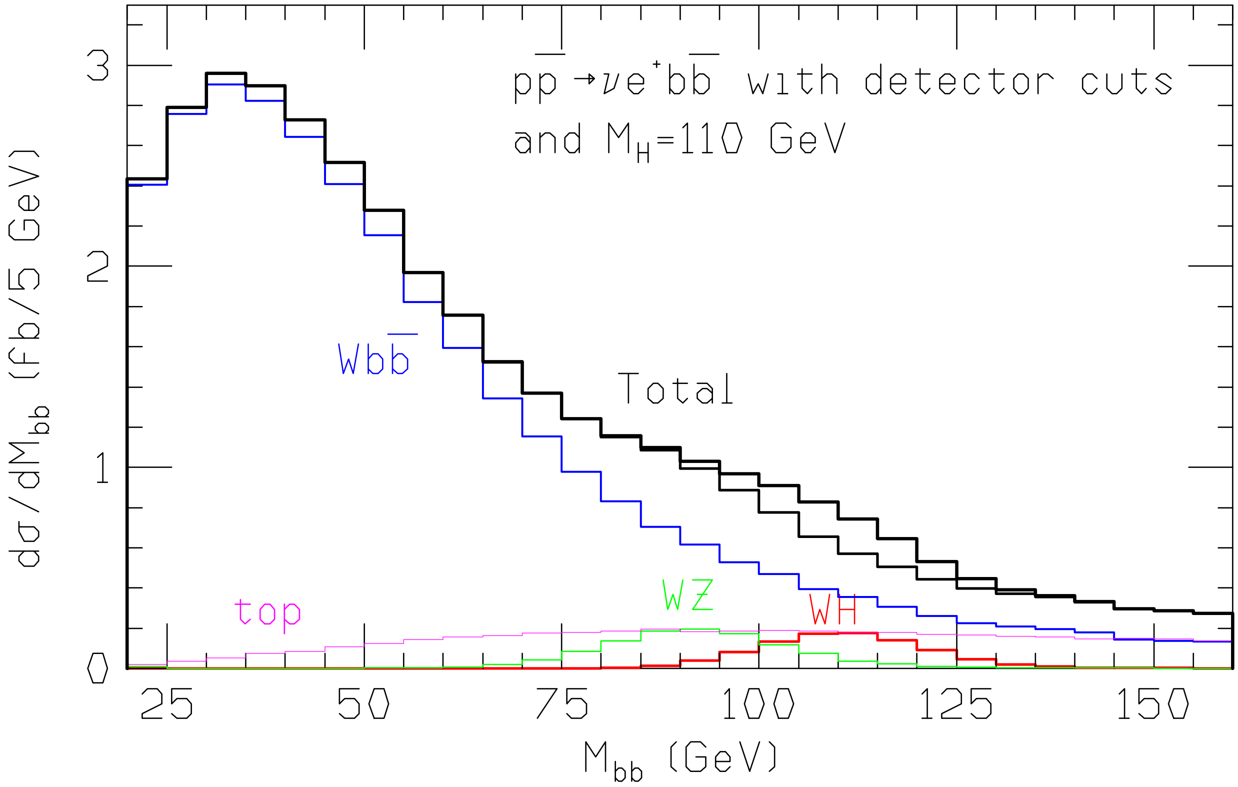
$$p\bar{p} \longrightarrow W(\rightarrow e\nu)H(\rightarrow b\bar{b})$$
$$p\bar{p} \longrightarrow Z(\rightarrow \nu\bar{\nu}, \ell\bar{\ell})H(\rightarrow b\bar{b})$$

- Mass range interesting for the MSSM.
- Backgrounds for the WH signal:

$$\begin{aligned} p\bar{p} &\longrightarrow W\, g^\star(\rightarrow b\bar{b}) \\ p\bar{p} &\longrightarrow W\, Z/\gamma^\star(\rightarrow b\bar{b}) \end{aligned}$$

$$\begin{aligned} p\bar{p} &\longrightarrow t(\rightarrow bW^+)\bar{t}(\rightarrow \bar{b}W^-) \\ p\bar{p} &\longrightarrow W^{\pm *}(t(\rightarrow bW^+)\bar{b}) \\ qg &\longrightarrow q' t(\rightarrow bW^+)\bar{b} \end{aligned}$$

Signal and Backgrounds for $m_h = 110$ GeV



- Double b-tagging efficiency of $\epsilon_{b\bar{b}} = 0.45$
- We have to understand a cocktail of backgrounds, both in normalization and shape. $(WZ \equiv WH)$.

Cuts for a WH study

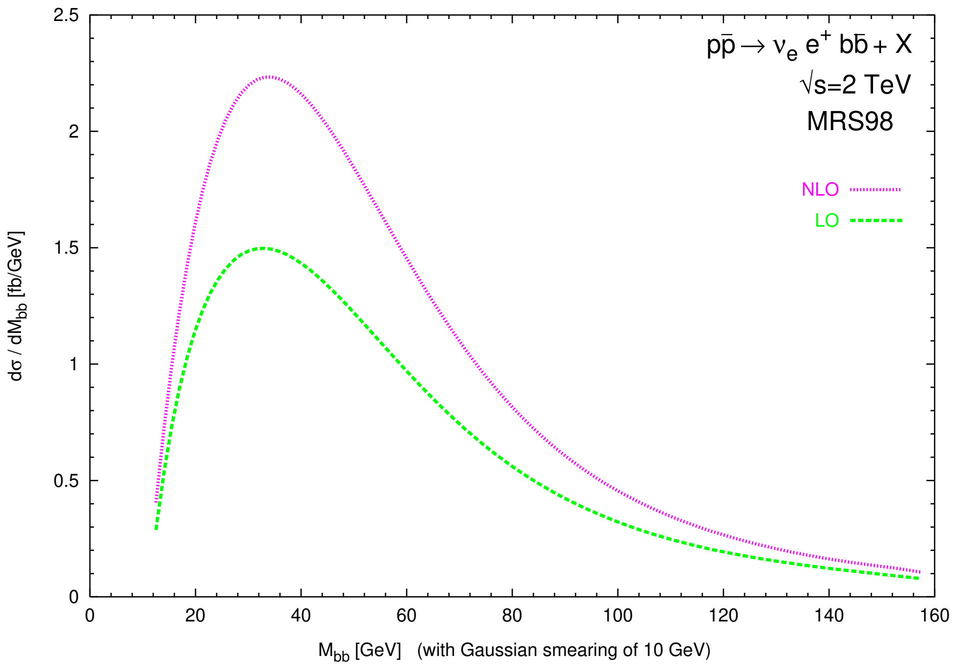
- Use a set of "standard" cuts from the literature

$$
\begin{aligned}
|p_b^T|, |p_{\bar{b}}^T| &> 15 \text{ GeV} \\
|y_b|, |y_{\bar{b}}| &< 2 \, , \\
|p_e^T|, |p_\nu^T| &> 20 \text{ GeV} \\
|y_e| &< 2.5 \, , \\
|p_{jet}^T| &> 20 \text{ GeV} \\
|y_{jet}| &< 2 \, , \\
R_{b\bar{b}}, R_{eb}, R_{e\bar{b}} &> 0.7 \\
|\cos\theta_{b\bar{b}}| &< 0.8
\end{aligned}
$$

- $\theta_{b\bar{b}}$ is the scattering angle of the $b\bar{b}$ system in the Collins-Soper frame
- MRS98 parton distribution functions

$m_{b\bar{b}}$ mass distribution

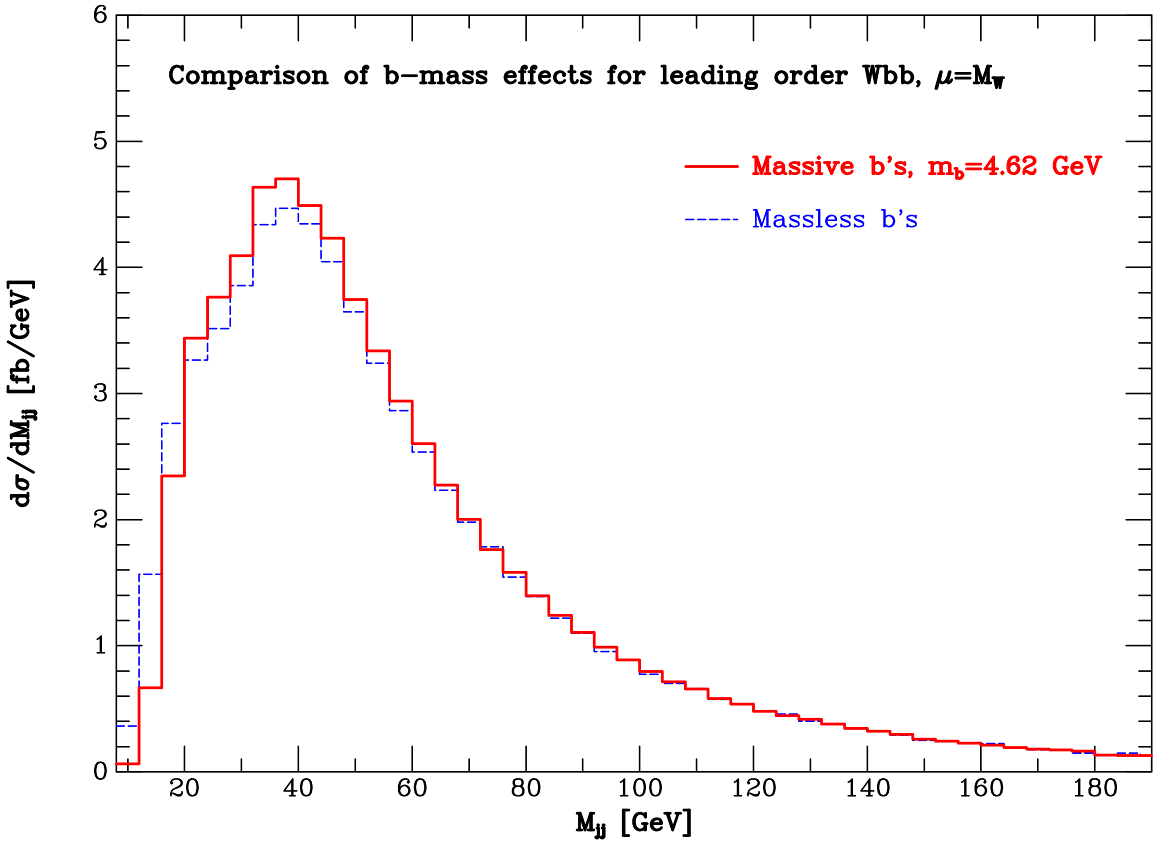
- Examine the $m_{b\bar{b}}$ mass distribution of the largest background at LO and NLO and a scale of 100 GeV



- We see that the actual shape changes very little and the K-factor is around 1.5.
- Calculation performed with $m_b = 0$.

$m_b = 0$ approximation

- Compare the lowest order approximation for m_b zero and non-zero.
- In the interesting region at low mass, matrix-element effects dominate over phase space.



Signal and backgrounds at 2 TeV

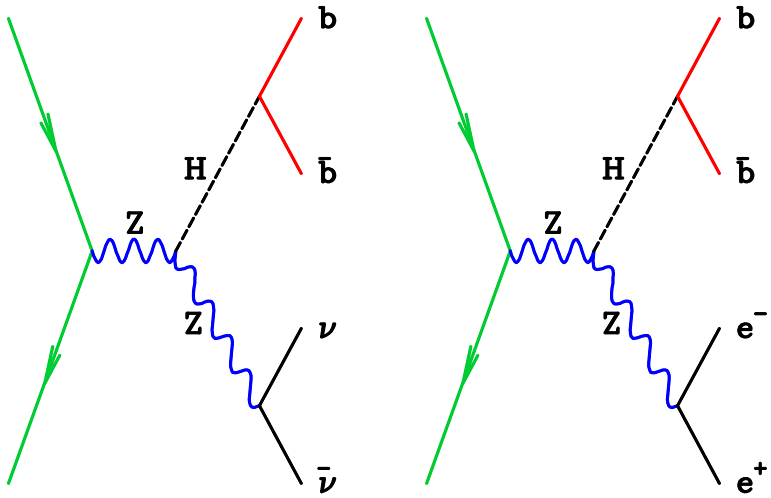
- We take a resolution of $\Delta = 0.1 \times m_h$ and integrate signal and background over the range $m_H - \sqrt{2}\Delta < m_{b\bar{b}} < m_h + \sqrt{2}\Delta$

M_h [GeV]	100	110	120	130
$W^{\pm}H(\to b\bar{b})$	8.8	6.4	4.2	2.5
$W^{\pm}g^{*}(\to b\bar{b})$	22.9	20.3	16.8	14.2
$W^{\pm}Z(\to b\bar{b})$	6.7	4.3	2.0	1.0
$t(\to bW^{+})\bar{t}(\to \bar{b}W^{-})$	4.2	4.7	4.9	5.0
$W^{\pm *}(t(\to bW^{+})\bar{b})$	5.3	6.0	6.2	6.2
$q't(\to bW^{+})$	3.1	3.2	2.9	2.6
Total B	42.1	38.5	32.9	28.8
S/B	0.21	0.17	0.13	0.09
$S/\sqrt{B}$	1.36	1.03	0.73	0.47

Conclusions on WH channel

- In MCFM τ-decay in the $t\bar{t}$ channel is not properly implemented, and may result in an under-estimate of this background
- Our analysis confirms the rates used in the SUSY Higgs study for the WH channel.
- The whole enterprise clearly rests on the ability to control the backgrounds experimentally.

ZH Study



- Primarily $b\bar{b}$+missing energy.
- Similar cuts to WH. Cut also on the missing transverse energy and the azimuthal angles between the direction of the missing energy and the b jets:

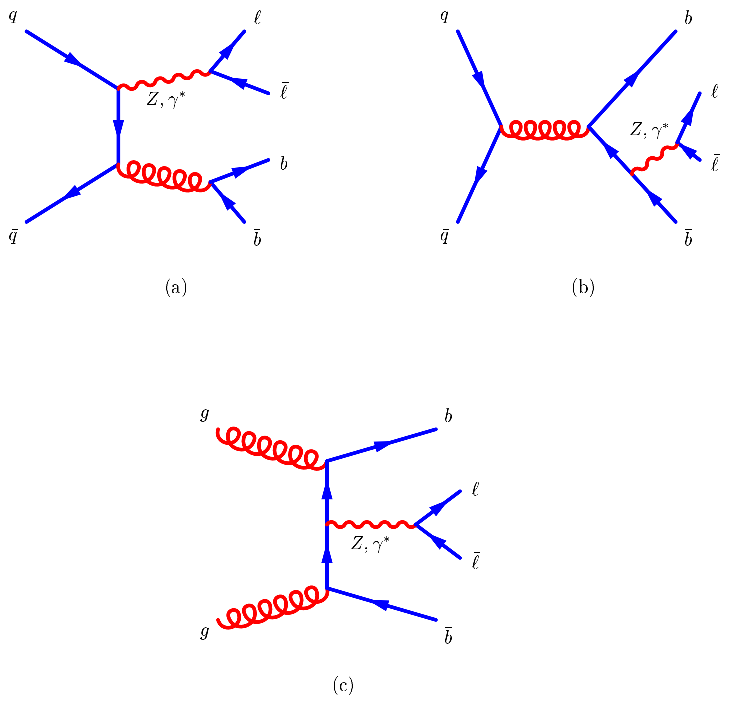
$$
\begin{aligned}
E_T^{miss} &> 35 \text{ GeV} \\
\Delta\phi(E_T^{miss}, jets) &> 0.5
\end{aligned}
$$

Caveat

- A further background to the ZH study could be from ordinary ($p\bar{p} \to b\bar{b}$) events which also contain sufficient missing energy - for example, from a jet that is outside the acceptance region or hits a crack in the detector
- Since the total cross-section for this process is ~ 9 orders of magnitude above the femtobarn signal, even the very small number of events that might fall into this category could be significant
- It is unlikely that even a full shower Monte Carlo would provide a reliable estimate of such a background, much less our NLO Monte Carlo
- Ultimately, we shall have to rely on data to assess the importance of such effects

Results for $Zb\bar{b}$

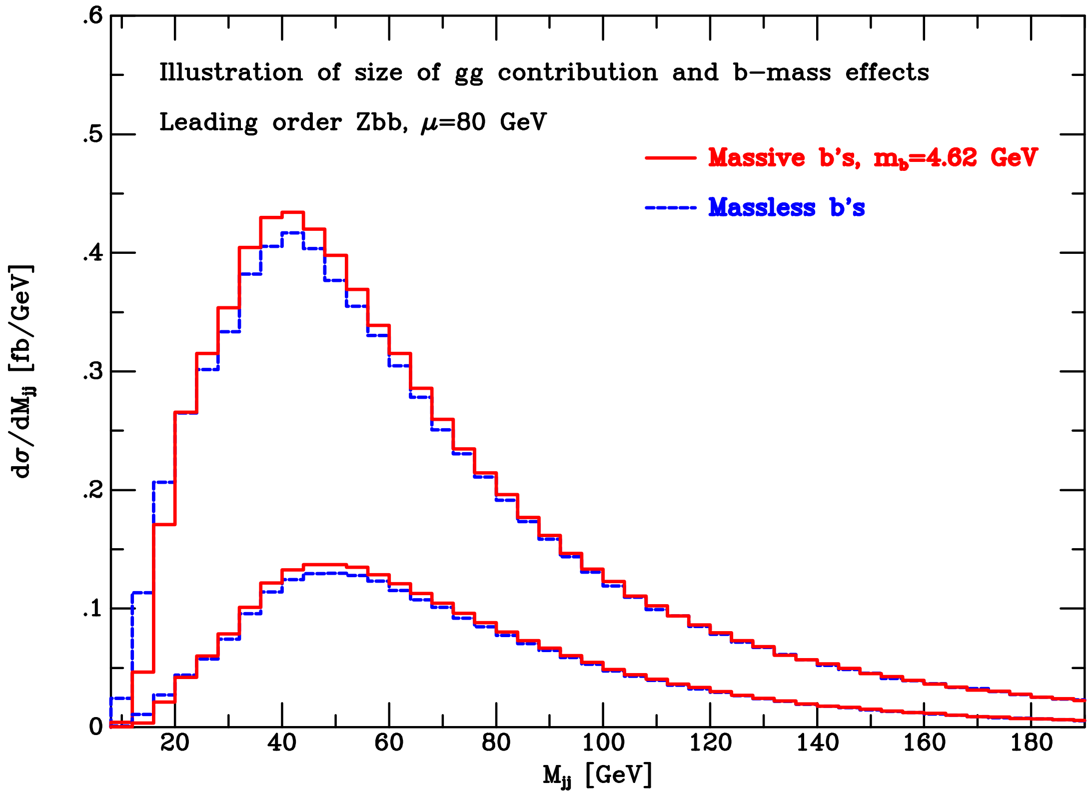
- New results include radiative corrections, relevant for a further Higgs search in the channel ZH.
- The required matrix elements are very similar to the $Wb\bar{b}$ case,



with additional contributions from gg initial states.

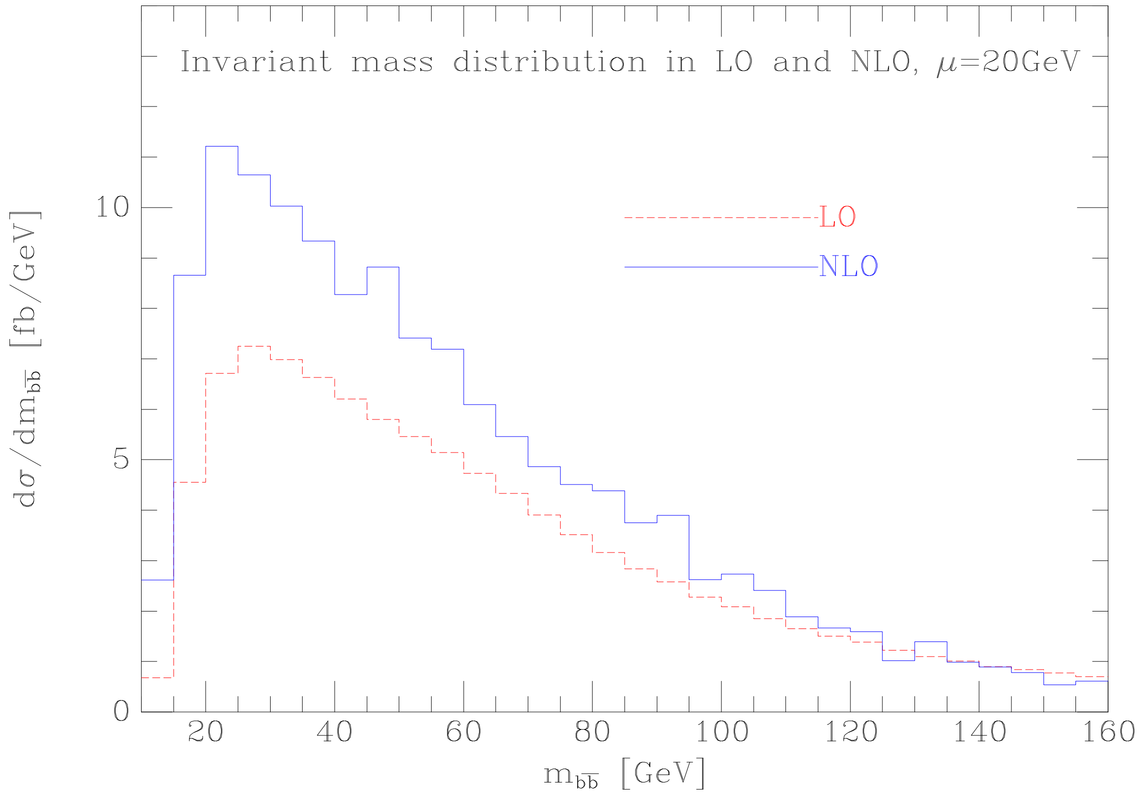
The gg sub-process in LO

- A $b\bar{b}$ pair with a large invariant mass can be produced by the gg initial state process, without off-shell propagators.
- Test of $m_b = 0$ approximation



$m_{b\bar{b}}$ mass distribution for $Zb\bar{b}$

- For a 'conventional' scale of 100 GeV, there is a large K-factor in the region of interest, around 1.8.

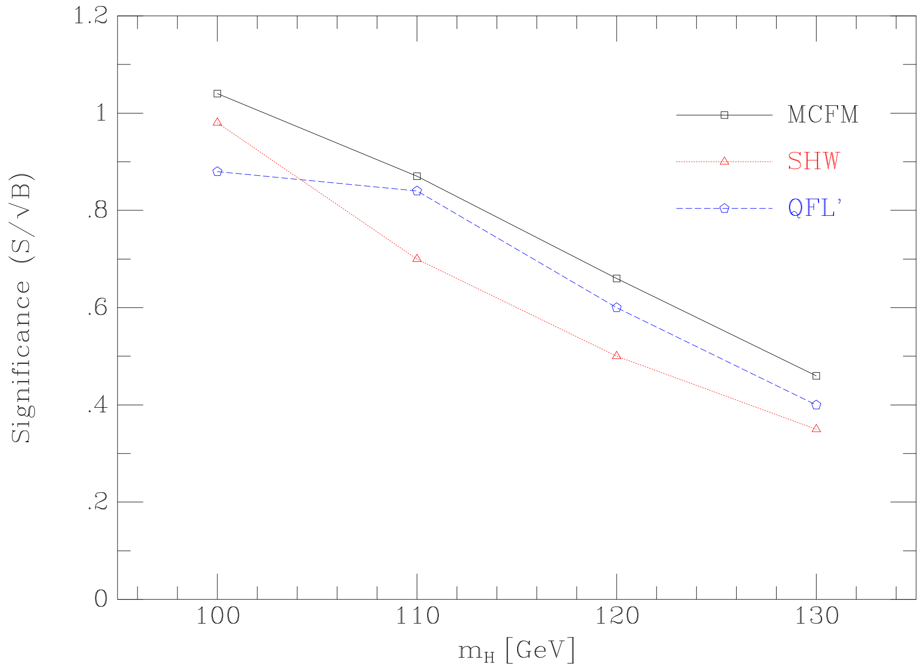


- The entire distribution is changed both in shape and normalization - perhaps suggesting that this scale choice is no longer appropriate ($\rightarrow$ new gg processes).

Z Channel: Signal and backgrounds

m_H [GeV]	100	110	120	130
$Z^0(\to \nu\bar{\nu})H(\to b\bar{b})$	5.8	4.4	2.9	1.8
$W(\to \ell\nu)H(\to b\bar{b})$	0.7	0.5	0.3	0.2
Total S	6.5	4.9	3.2	2.0
$Z^0(\to \nu\bar{\nu})g^*(\to b\bar{b})$	23.3	21.0	17.5	15.8
$Z^0(\to \nu\bar{\nu})Z(\to b\bar{b})$	10.8	6.9	3.3	1.4
$W^\pm(\to \ell\bar{\nu})g^*(\to b\bar{b})$	2.7	2.4	1.6	1.1
$W^\pm(\to \ell\bar{\nu})Z(\to b\bar{b})$	1.4	0.8	0.4	0.2
$W^{\pm *}(\to t(\to bW^+)\bar{b})$	0.6	0.6	0.6	0.6
$q't(\to bW^+)\bar{b}$	0.2	0.2	0.2	0.2
Total B	39.0	31.9	23.6	19.3
S/B	0.17	0.15	0.14	0.11
$S/\sqrt{B}$	1.04	0.87	0.66	0.46

Significance compared with SUSY Higgs study

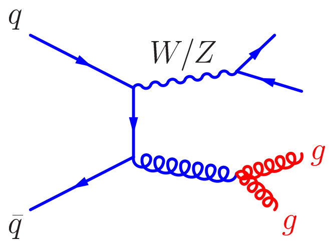


- MCFM overestimates significance because of lack of detector effects (misidentification of leptons).
- Susy Higgs study overestimates significance because of underestimate of $Zb\bar{b}$ background. Our guess is that this could be a 20% effect.

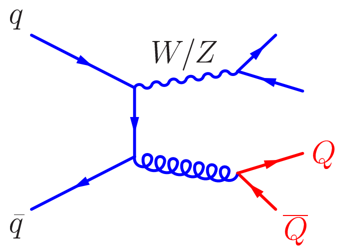
$W + 2$ jets

- Separate the diagrams by colour structure:

At lowest order we have

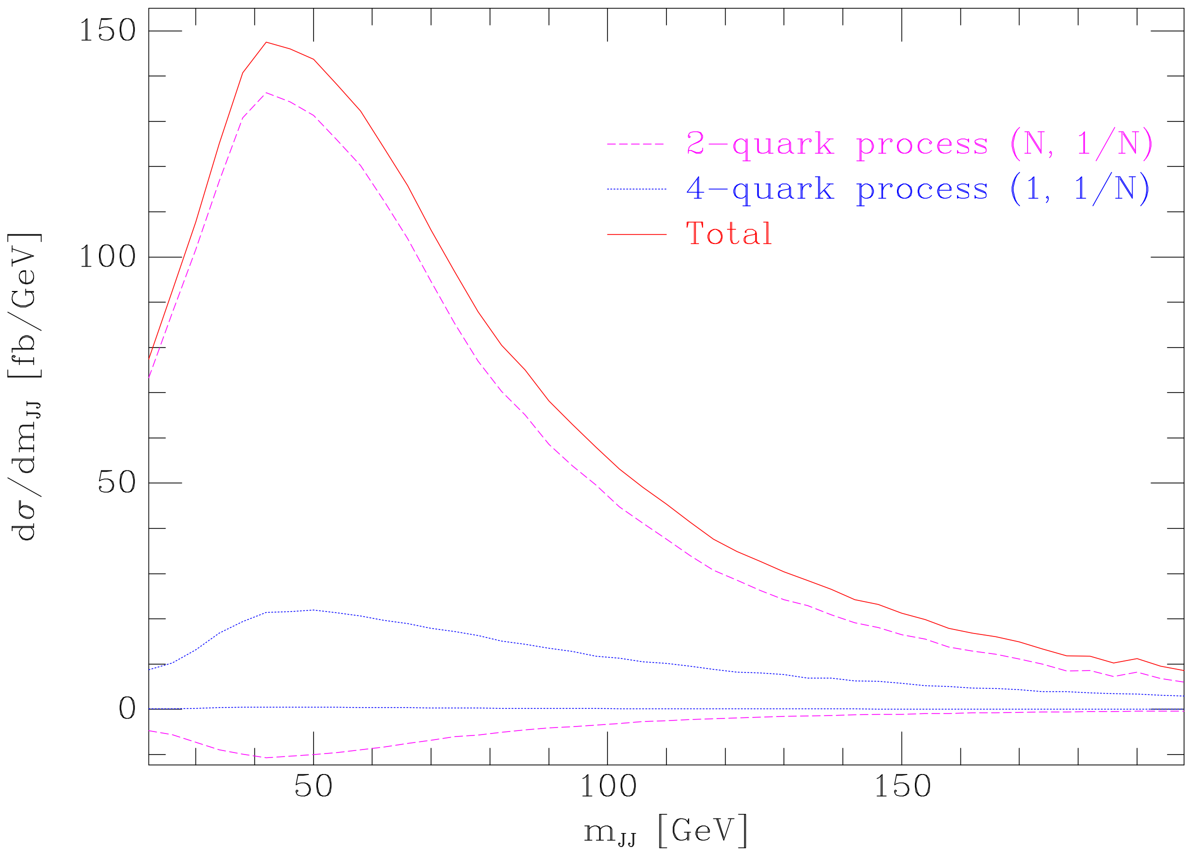


$\propto N,\ 1/N$

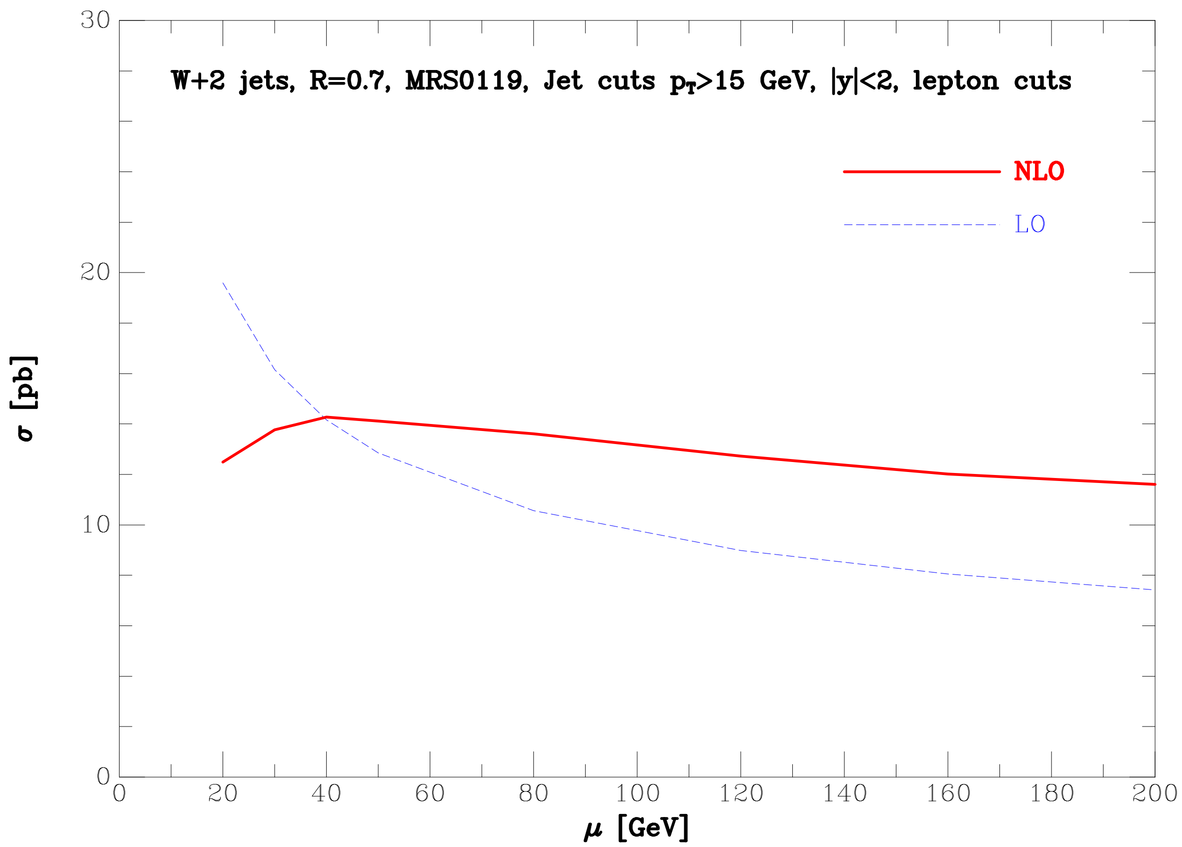


$\propto 1,\ 1/N \times \delta_{qQ}$

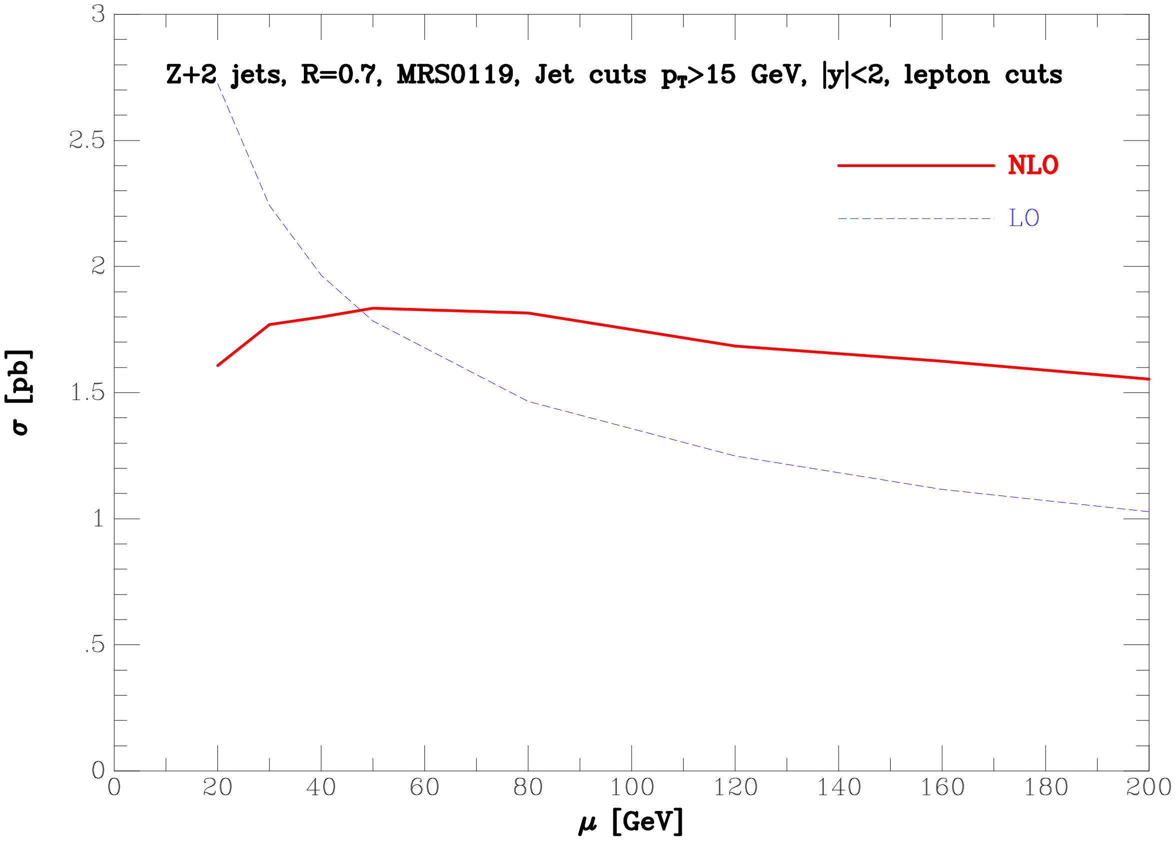
- Typical distribution, standard set of cuts



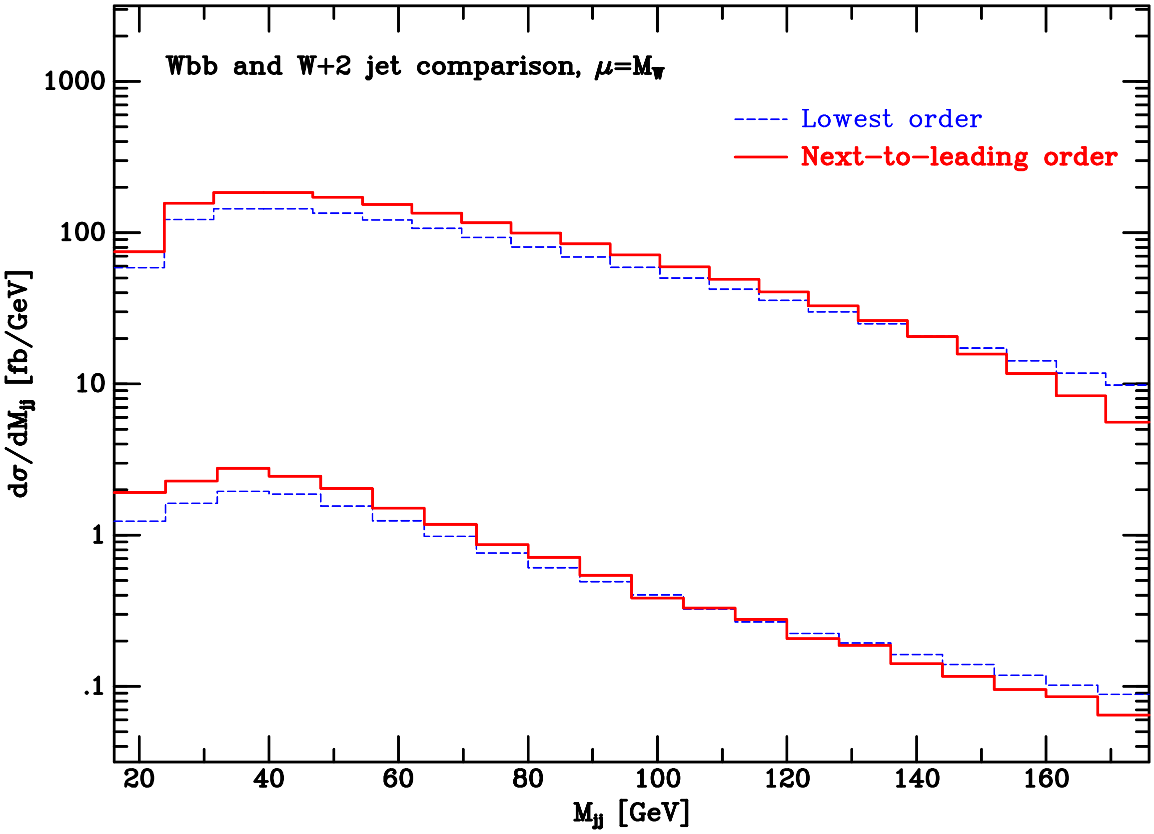
$W+2$ jets: scale dependence



Z+2 jets: scale dependence

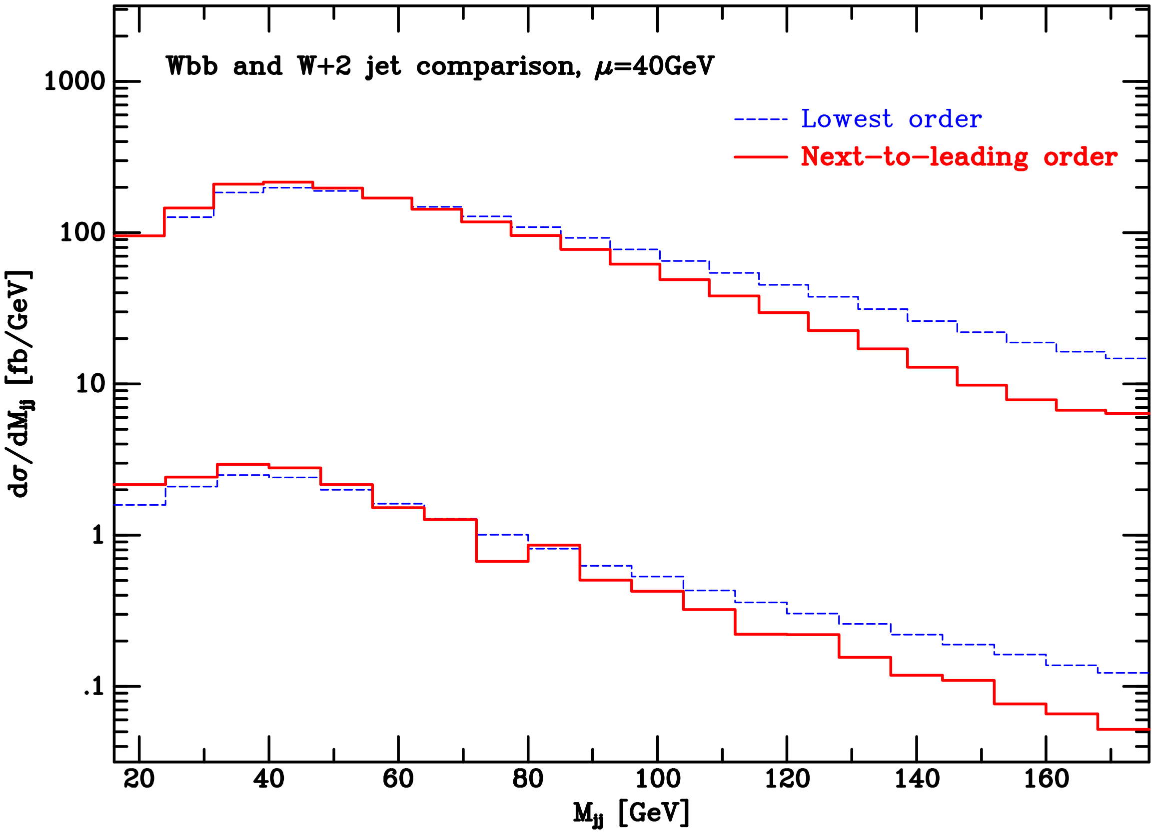


$W + b\bar{b}$ vs $W + 2$ jets



- $\mu = 40$ GeV

$W + b\bar{b}$ vs $W + 2$ jets



- $\mu = 40$ GeV
- Ratio seems $W + b\bar{b}$ to $W + 2$ jets seems well predicted.

Higher mass Higgs

Basic idea (Han, Turcot, Zhang): exploit the $H \to W^* W$ decay in the higher mass region.

- Signal processes

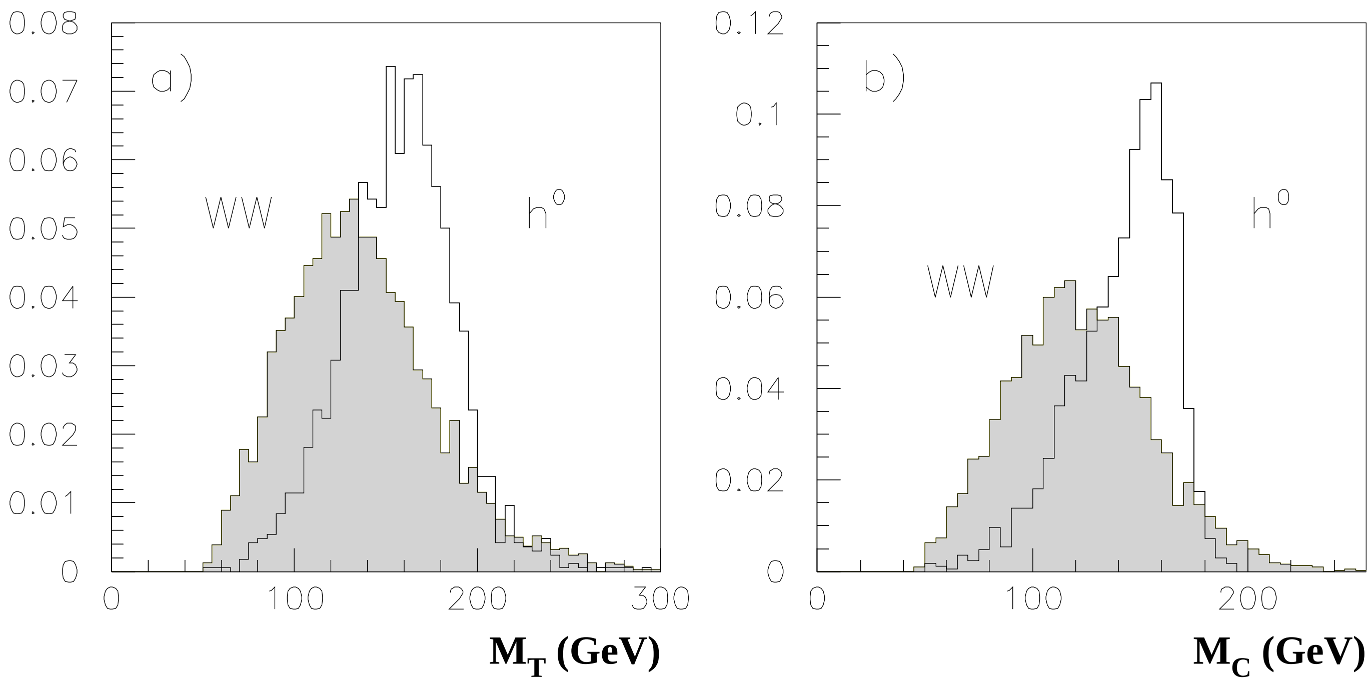
$gg \to H \to WW^*$
$ZH \to ZWW^*$
$WH \to WWW^*$

- Experimental signatures

$l^+ l^- +$ missing energy $(\nu\bar{\nu})$
$l^\pm l^\pm jj$
$l^\pm l^\mp l'^\pm$

- Main backgrounds $WW, WZ, t\bar{t}$

Dilepton + missing energy channel



- $M_T = 2\sqrt{P_T^2(ll) + m^2(ll)}$
- $M_C = \sqrt{P_T^2(ll) + m^2(ll)} + \not{E}_T$
- Some kinematic discrimination between signal and background

MCFM Results on High-mass Higgs

- The only experimental signature which can be usefully analysed in MCFM is l^+l^- + missing energy. (This is the most significant according to HTZ)

Signal (m_h)	140	150	160	170	180	190
$\sigma_{\rm cuts}$ (fb)	4.36	5.32	6.12	5.15	3.90	2.47
$\sigma_{\rm total}$ (pb)	0.181	0.206	0.215	0.180	0.143	0.0976

Background	WW	$t\bar{t}$	ZZ	WZ
$\sigma_{\rm cuts}$ (fb)	185	9.55	2.48	10.4
$\sigma_{\rm total}$ (pb)	13.0	6.82	1.56	3.96

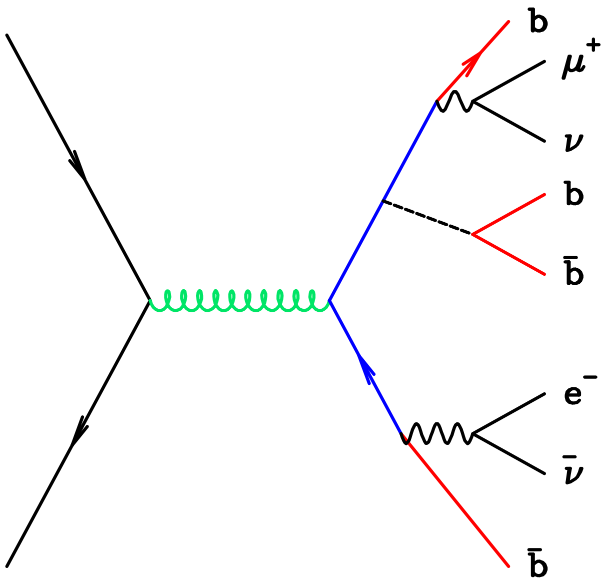
Table 1: Signal and background cross-sections for a Higgs search with di-lepton final states. The total cross sections (without leptonic decays from the vector bosons) are also shown.

Comparison with HTZ

- We find that all the backgrounds due to the di-boson processes are larger than in Han,Turcot and Zhang (HTZ) because we have normalized to the $O(\alpha_s)$ cross-sections which are about 30% bigger than the Born cross-sections..
- Our signal cross sections are also larger than HTZ by about 20%; the net effect on $S/\sqrt{B}$ may be small.
- The $gg \to H$ rate used is NLO. Further increase from the NNLO corrections (Harlander,Kilgore).
- The background from the WZ-class of events is twice as big as in HTZ because of our inclusion of the $W\gamma^*$ contribution.

$t\bar{t}H$

- The production of a Higgs boson in association with a $t\bar{t}$-pair gives a dramatic signature. Goldstein et al



- For $m_h < 135$ GeV the final state contains 4 b-quarks. • Assume a 70% b-tagging efficiency

92% probability to tag $\geq$ 2-jets

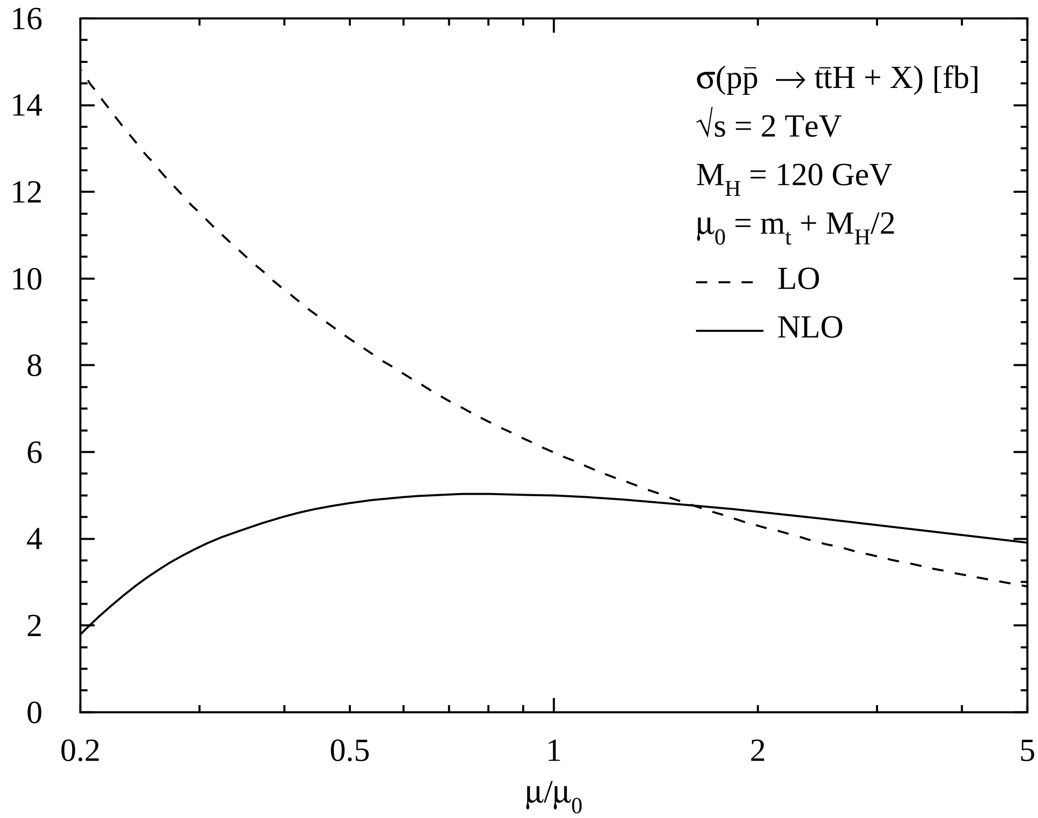
65% probability to tag $\geq$ 3-jets

24% probability to tag all 4 b-jets

$t\bar{t}H$-cross section

- The cross section has been calculated to NLO

$\sigma \sim 10^{(1.85 - M_h[\mathrm{GeV}]/100)}$ [fb] Beenakker et al, Dawson et al



- The radiative corrections reduce the scale uncertainty of the cross section.

$t\bar{t}H$-backgrounds (Goldstein et al)

- Background estimates include $p_T > 20$ [GeV] and are uncertain by $\pm 50\%$.

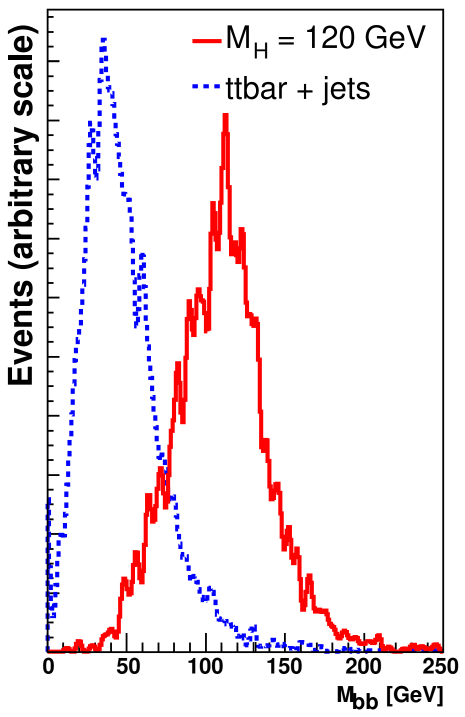
Signal and Backgrounds	σ [fb]
$t\bar{t}H, H \to b\bar{b}$	4
$t\bar{t} + jj$	1030
$t\bar{t} + b\bar{b}(c\bar{c})$	27
$t\bar{t} + Z, Z \to b\bar{b}$	1.5
$WZ + jj, Z \to b\bar{b}$	10

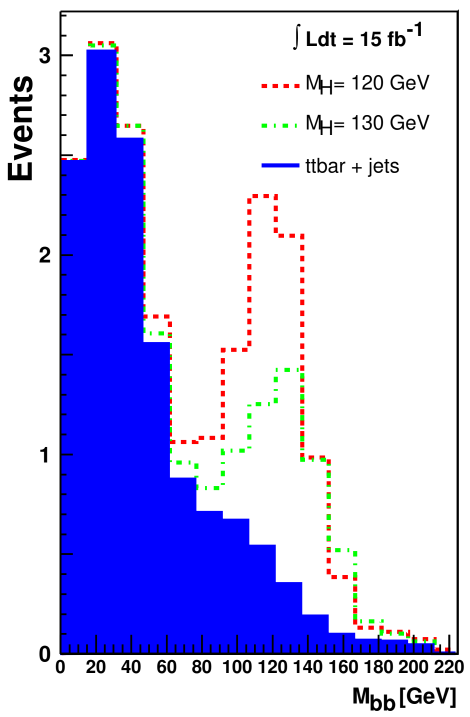
- In 15 fb^{-1}, 3-b tags gives 19 signal and 140 bkgd, 4-b tags gives 7 signal and 40 background.

$t\bar{t}H$-signal

- Form invariant masses of all combinations of jets
- Separation in 4th highest mass combination.
- Mass distribution after top mass reconstruction.
- Conclude that 15fb^{-1} gives a 2.8 σ effect at

$M_h = 120$ GeV.





Conclusions

- The precision electroweak bounds on the Higgs boson mass should be viewed with scepticism.
- Our work underscores the importance of having an experimental determination of the $Zb\bar{b}$ and $Wb\bar{b}$ background, by relating them to $Vb\bar{b}$ events at lower $m_{b\bar{b}}$ or V + 2jet events.
- We find that the rates used in the (HTZ) analysis too low, but the radiative corrections lead to little net change in $S/\sqrt{B}$.
- The SUSY Higgs workshop Higgs limits represent an extrapolation of what can be expected, after a lot of work understanding backgrounds.
- Other measurements in Run IIa with 2 fb^{-1} (yielding $\Delta m_t = 2.5$ GeV and $\Delta m_W = 40$ MeV) will improve indirect limits, constraints on MSSM etc.

- The Higgs boson should not be viewed as an end, but as a beginning; in natural models it appears accompanied by other physics.
- More luminosity is the panacea for all background ills.