Associated Higgs boson production with Heavy Quarks

Laura Reina

Les Houches, May 2003

- Motivations (discovery, precision studies)
- $pp \to t\bar{t}H, b\bar{b}H$ (LHC)
- $p\bar{p} \to t\bar{t}H, b\bar{b}H$ (Tevatron,Run II)

with emphasis on

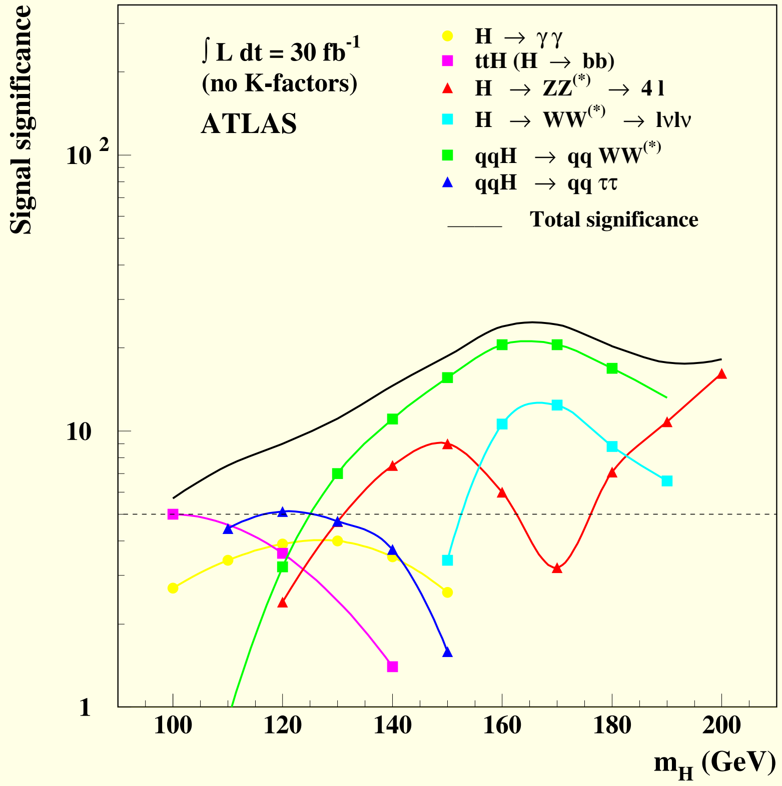
- theoretical predictions (now include NLO QCD)
- relevance to Higgs boson studies

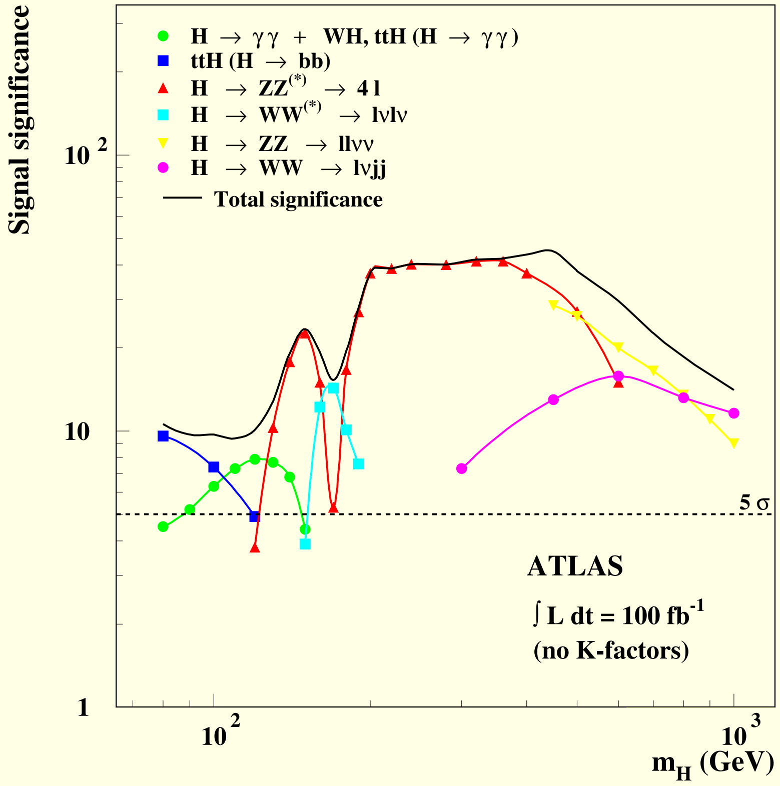
with S. Dawson, C. Jackson, L.H. Orr, and D. Wackeroth

General Framework

- Strong case for a light scalar Higgs boson, both SM and MSSM: focus on $\boxed{M_H < 130 - 140\ \mathrm{GeV}}$.
- $t\bar{t}H$ important for discovery at the LHC.
- $b\bar{b}H$ important for New Physics at both the Tevatron and the LHC (signal is tiny in the SM)
- only $t\bar{t}H$ can measure directly the Top Yukawa Coupling (Y_t): good precision at the LHC, not model independent.
- $t\bar{t}H$ with $H \to b\bar{b}, \tau^+\tau^-, W^+W^-$ measure Y_b/Y_τ and Y_t/Y_g at the LHC in a model independent way.
- Best scenario: combine $Y_t \cdot Y_X$ from the LHC with Y_X measured at a $\sqrt{s} = 500$ GeV Linear Collider

$pp \to t\bar{t}H$ very important for discovery in the low mass region





$\longrightarrow$ $H \to b\bar{b}$: E.Richter-Wąs, M.Sapínski, V.Drollinger, D.Denegri, Th.Müller, Y.Kataoka, . . .

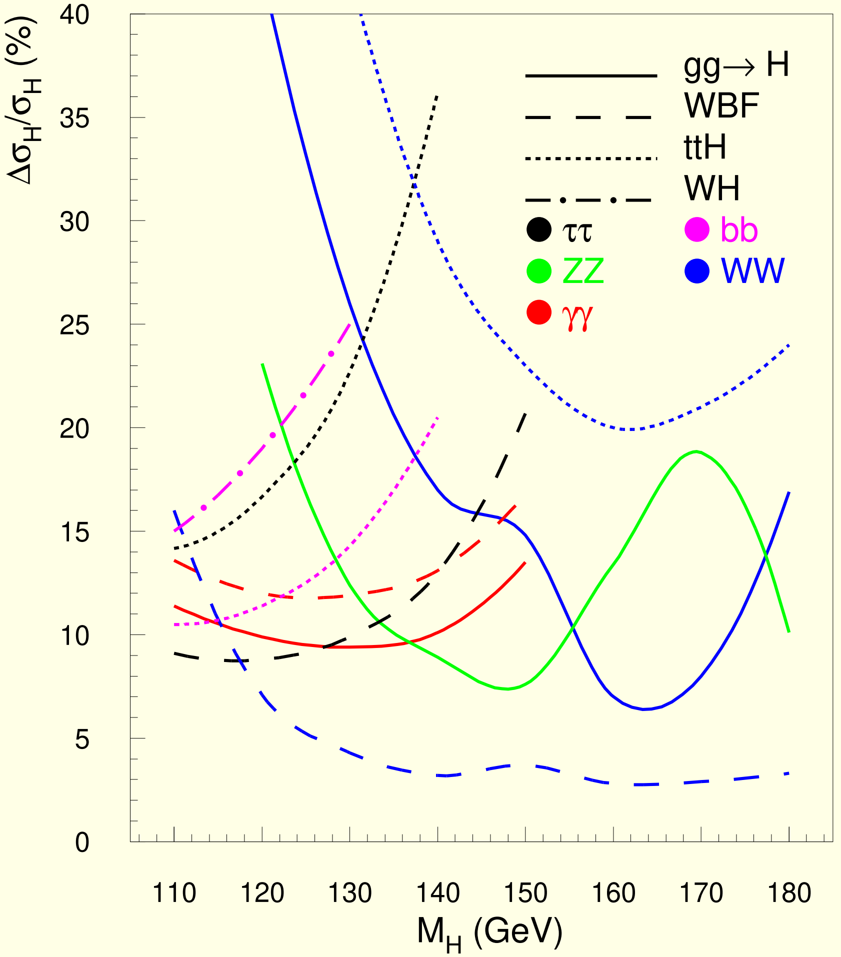
$\longrightarrow$ $H \to \tau^+\tau^-$: E.Gross, L.Živcović, A.Ito, . . .

$\longrightarrow$ $H \to W^+W^-$: J.Levêque,J.B. de Vivie, V.Kostioukhine, A.Rozanov Y.Matsumoto, . . .

The LHC can measure most SM Higgs couplings at 15-20%

Under some model dependent assumptions

And ratios of couplings with no assumptions



$\longleftarrow$ mostly $200\,\text{fb}^{-1}$

- Below 130-140 GeV

  $gg \to H\ ,\ H \to \gamma\gamma, WW, ZZ$

  $qq \to qqH\ ,\ H \to \gamma\gamma, WW, ZZ, \tau\tau$

  $\boxed{q\bar{q}, gg \to t\bar{t}H\ ,\ H \to b\bar{b}, \tau\tau}$

- Above 130-140 GeV

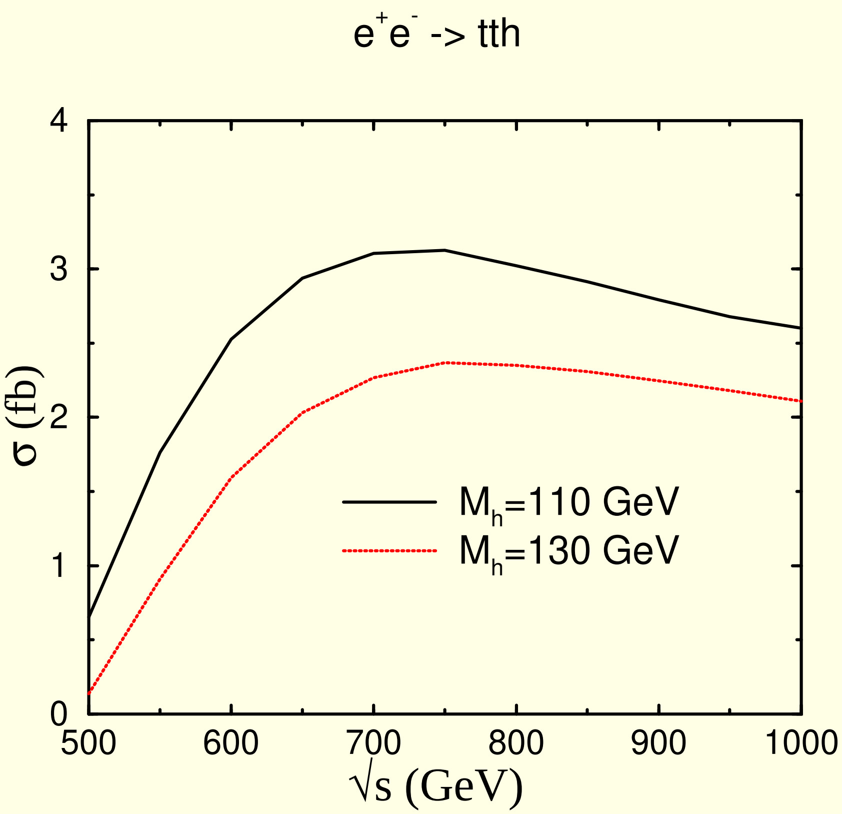
  $gg \to H\ ,\ H \to WW, ZZ$

  $qq \to qqH\ ,\ H \to \gamma\gamma, WW, ZZ$

  $\boxed{q\bar{q}, gg \to t\bar{t}H\ ,\ H \to WW}$

$\boxed{t\bar{t}H}$: F.Maltoni, D.Rainwater, S.Willenbrock, A.Belyaev, L.R.

LC: measure Y_t via $e^+e^- \to t\bar{t}H$



Optimal scale $\sqrt{s} \simeq 700 - 800$ GeV:

$\longrightarrow \ \sqrt{s} = 800$ GeV: $\frac{\delta g_{tth}}{g_{tth}} \simeq 5.5\%$

$\longrightarrow \ \boxed{\sqrt{s} = 500 \text{ GeV: } \frac{\delta g_{tth}}{g_{tth}} \simeq 30\%}$

$M_H = 120$ GeV, $1000\,\text{fb}^{-1}$

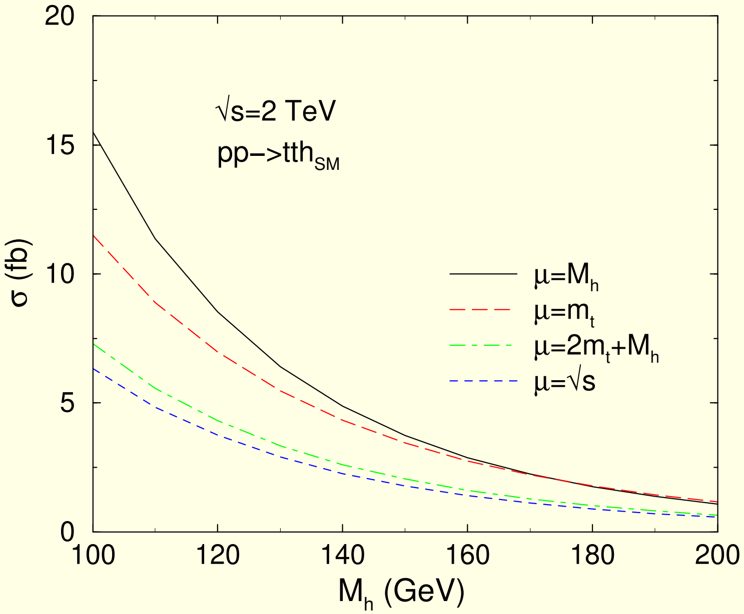
A.Juste, G.Merino; A.Gay;

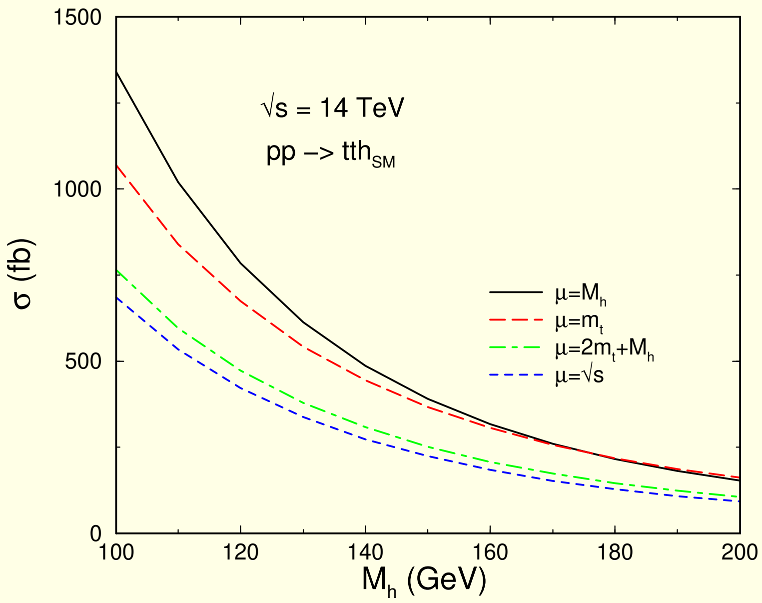
H.Baer, S.Dawson, L.R.

- LC : measure all Y_X except Y_t at the $2 - 5\%$ level
- LHC: from $\boxed{t\bar{t}H} \longrightarrow Y_t \cdot Y_X \longrightarrow Y_t$

$p\bar{p}, pp \to t\bar{t}H$: Need for NLO calculation

Tree level cross section have very strong μ-dependence





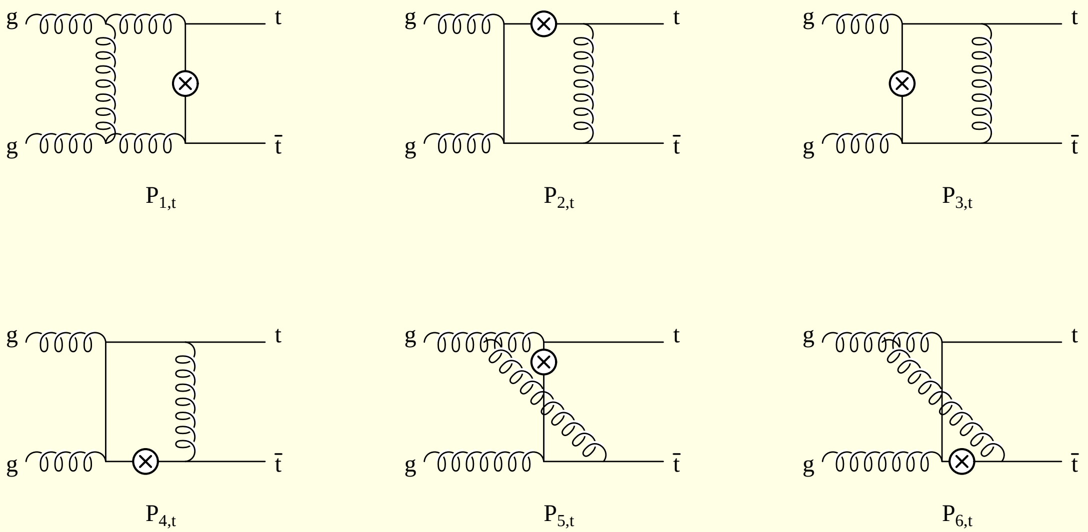
$\sigma(p\bar{p}, pp \to t\bar{t}H)$ calculated at $\mathcal{O}(\alpha_s^3)$: results confirmed by two groups:

- W.Beenakker, S.Dittmaier, M.Krämer, B.Plümper, M.Spira, P.M.Zerwas (PRL 87(2001), NPB 653(2003))

- S.Dawson, L.R., D.Wackeroth (PRL 87(2001), PRD 65(2002))
- S.Dawson, C.Jackson, L.H.Orr, L.R., D.Wackeroth(PRD 67(2003), hep-ph/0305087)

$p\bar{p}, pp \to t\bar{t}H$: $\mathcal{O}(\alpha_s)$ virtual corrections

Main challenge: Pentagon scalar and tensor integrals with several external and internal massive particles

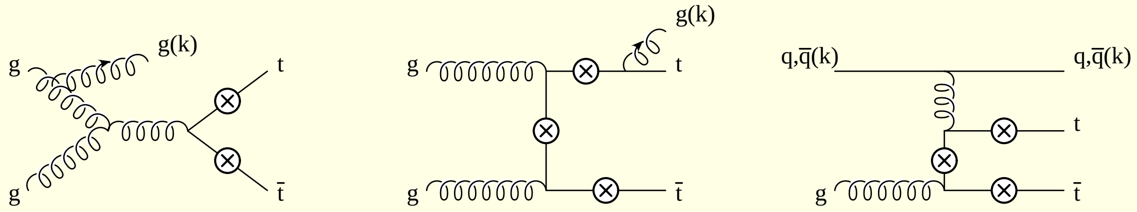


- Scalar pentagon integrals: reduced to linear combination of five box scalar integrals (Z.Bern,L.J.Dixon, D.A.Kosower; A.Denner)

- Tensor pentagon integrals: numerical instabilities (due to Gram determinant spurious singularities) treated both analytically and numerically.

$p\bar{p}, pp \longrightarrow t\bar{t}H$: $\mathcal{O}(\alpha_s)$ real corrections

Real gluon emission IR singularities for $2 \rightarrow 4$ process:



Phase Space Slicing $\longrightarrow$ isolate the region of the $t\bar{t}h + g(q,\bar{q})$ phase space where $s_{ik} \rightarrow 0$

$$s_{ik} = 2p_i \cdot k = 2E_i k^0 (1 - \beta_i \cos\theta_{ik})$$

$$\longrightarrow \quad \text{two cut-off method}: \begin{cases} \delta_s & (k^0 < \delta_s \sqrt{s}/2) \\ \delta_c & (1 - \cos\theta_{ik}) < \delta_c) \end{cases}$$

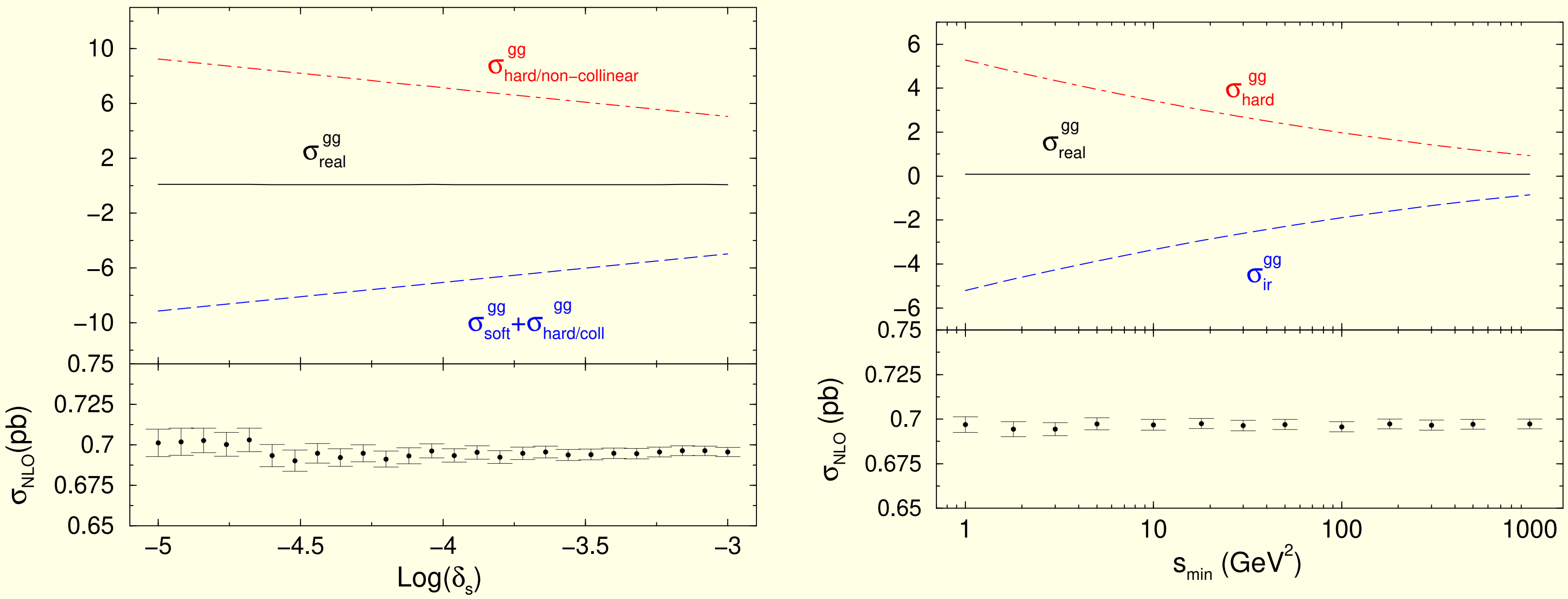
$$\longrightarrow \quad \text{one cut-off method}: s_{min} \quad (s_{ik} < s_{min})$$

- 2CM : L.Bergmann, J.Owens, B.Harris (review), ...
- 1CM : W.Giele, N.Glover, D.A.Kosower, S.Keller, E.Laenen

Compute $\mathcal{O}(\alpha_s)$ real cross section:

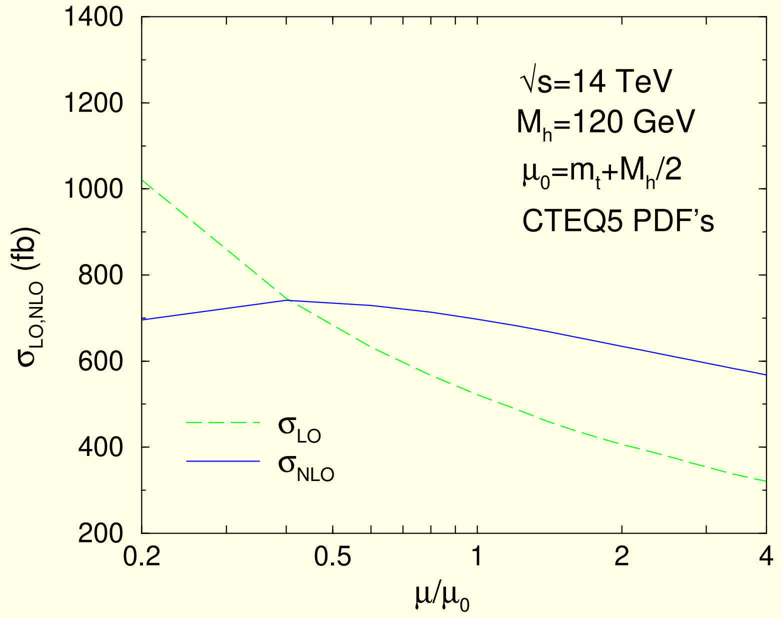
- analytically, below the cut-off(s)
- numerically, above the cut-off(s)

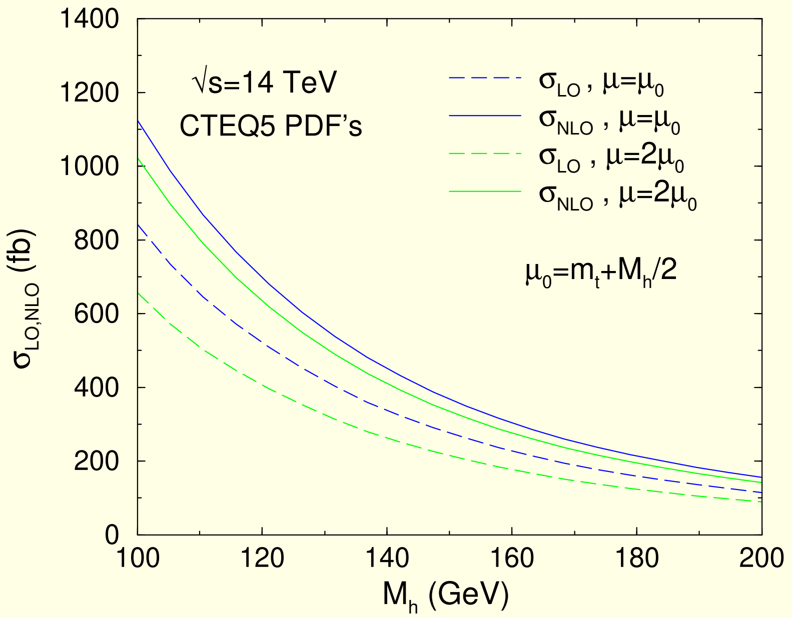
Cross section is cutoff(s) independent



(LHC, $M_h = 120$ GeV)

LHC, $pp \to t\bar{t}H$: NLO cross section



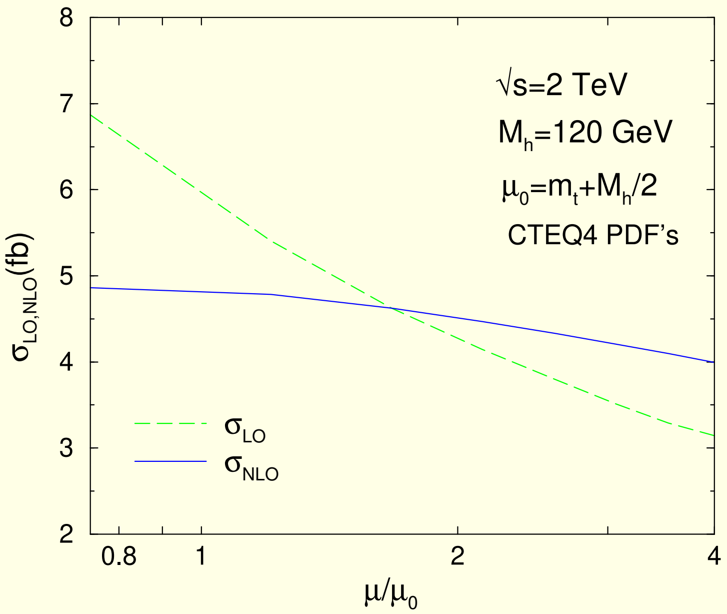


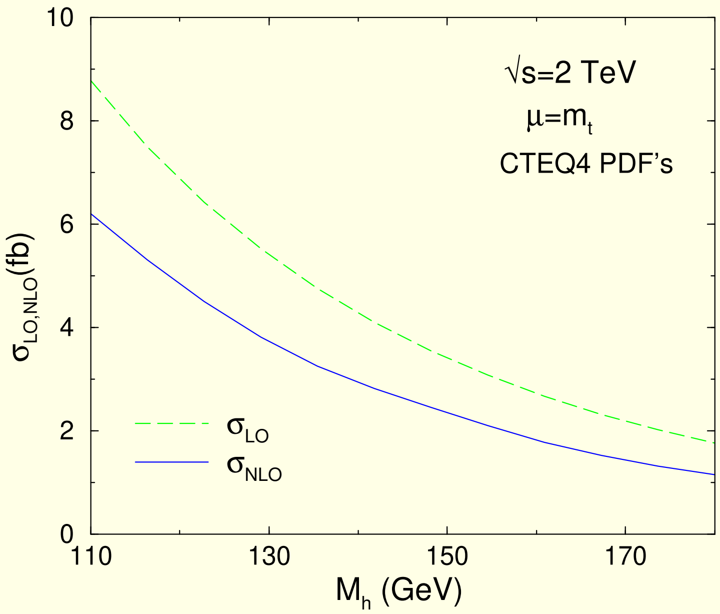
Theoretical uncertainty reduced to about 15%

S.Dawson, C.Jackson, L.H.Orr, L.R., D.Wackeroth

$$K = \frac{\sigma_{NLO}}{\sigma_{LO}} > 1$$ for most values of μ and M_H

Tevatron, $p\bar{p} \to t\bar{t}H$: NLO cross section





S.Dawson, L.R., D.Wackeroth

$$K = \frac{\sigma_{NLO}}{\sigma_{LO}} < 1 \qquad \text{for most values of } \mu \text{ and } M_H$$

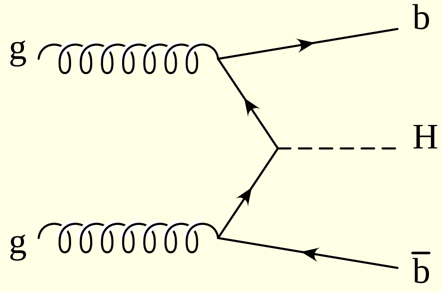
Interesting only for high luminosity

Studied by: J.Goldstein, C.S.Hill, J.Incandela, S.Parke, D.Rainwater, D.Stuart

$p\bar{p}, pp \longrightarrow b\bar{b}H$

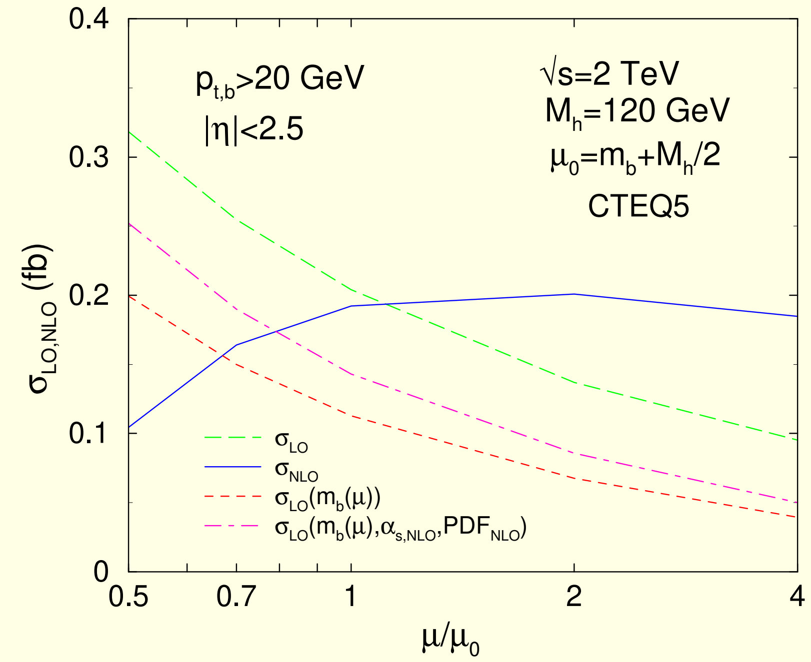
Possible signals of New Physics at RUN II

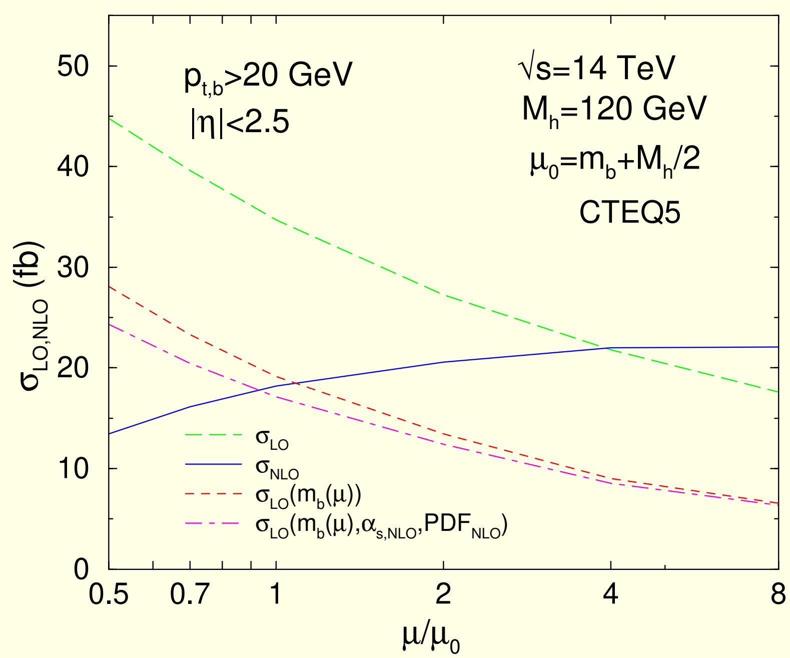
- Main candidate for new physics: SUSY (large $\tan\beta$).
- At high $\sqrt{s}$ b-quark in the initial state: resum big $\ln(M_H^2/m_b^2)$ in b-quark PDF.
- Perturbative series ordered in Leading and SubLeading powers of $\alpha_s \ln(M_H^2/m_b^2)$. Need to consider (avoiding double counting)
  - ▷ $b\bar{b} \rightarrow H$ (known at NNLO)
    (R.Harlander, W.Kilgore; D.Dicus, T.Stelzer, Z.Sullivan, S.Willenbrock)
  - ▷ $bg \rightarrow bH$ (known at NLO)
    (J.Campbell, R.K.Ellis, F.Maltoni, S.Willenbrock)
  - ▷ $gg \rightarrow b\bar{b}H$ (known at NLO)



Exclusive cross section for $p\bar{p}, pp \to b\bar{b}H$

Use high p_T b-quarks to suppress background: need NLO $(q\bar{q})gg \to b\bar{b}H$



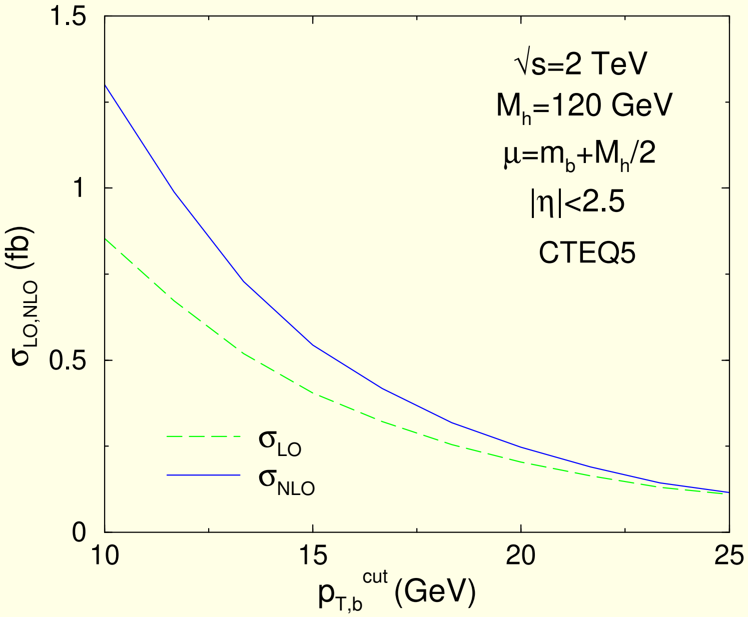


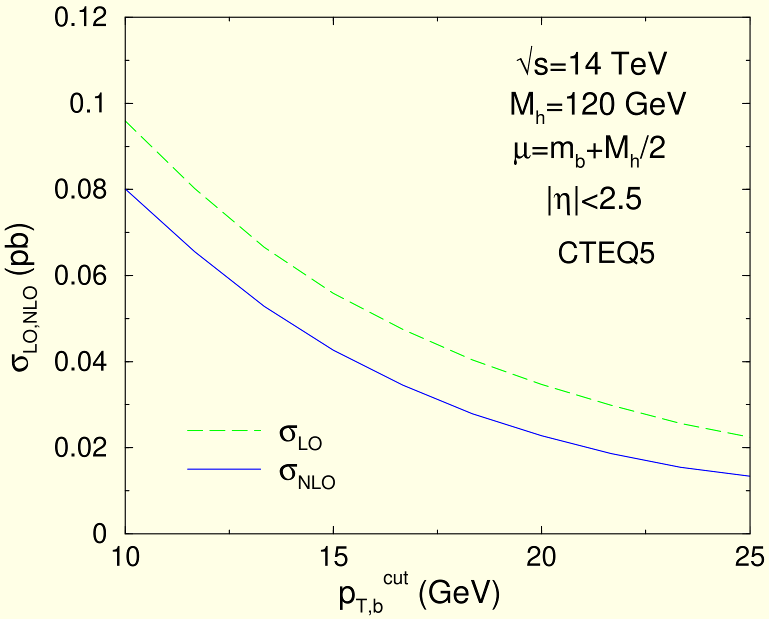
S.Dawson, C.Jackson, L.R., D.Wackeroth (**preliminary**)

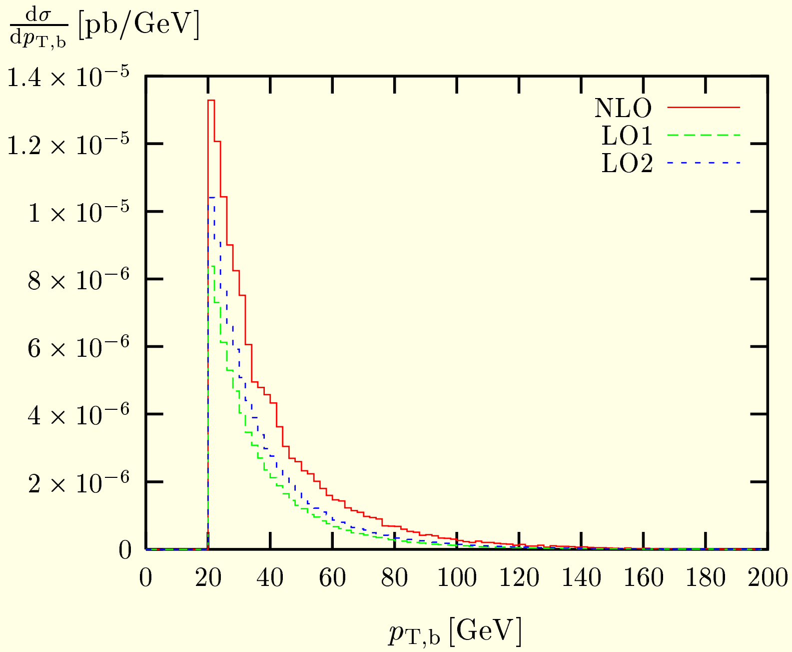
Cross section very small in the SM, enhanced in the MSSM for large $\tan\beta$

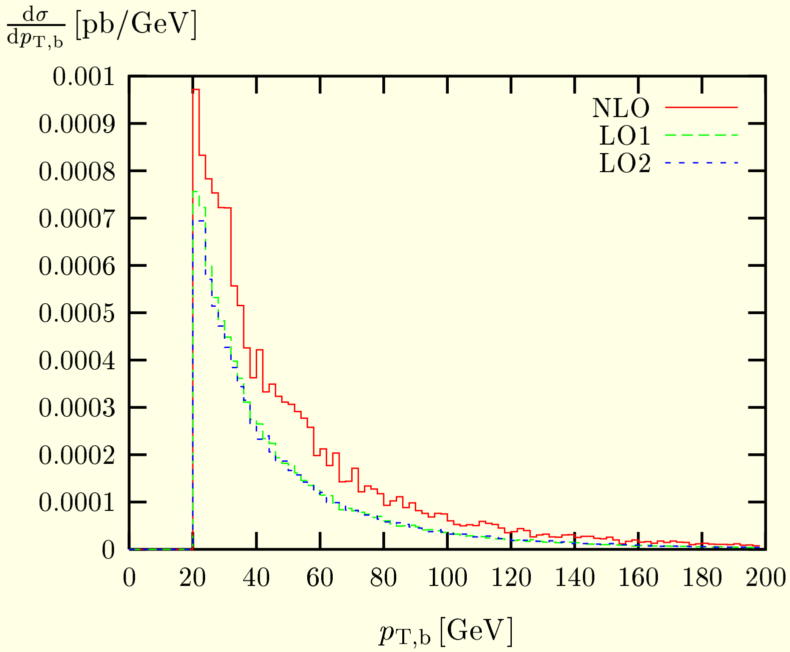
$$\sigma_{MSSM} = \left[\frac{Y_b^{MSSM}}{Y_b^{SM}}\right]^2 \sigma_{SM} \qquad \text{(roughly)}$$

Strong dependence on p_t^b cuts (**preliminary**)









Conclusions

- $t\bar{t}H$, $b\bar{b}H$ very interesting production modes at present and future colliders:
  - ▷ discover/confirm the Higgs boson
  - ▷ measure the Higgs boson couplings
  - ▷ SM? New Physics?
- Top Yukawa coupling: the LHC can play a crucial role and complement a $\sqrt{s}=500$ GeV LC .
- Enhanced $b\bar{b}H$: possible signal of New Physics at the Tevatron.
- Crucial to have calculated NLO QCD corrections: theoretical uncertainty greatly reduced.
- Exclusive $b\bar{b}H$ production: preliminary results.
- Inclusive $b\bar{b}H$ production: several issues are being discussed at this workshops.
- Generalize the NLO calculation to the full MSSM Higgs sector.