BROOKHAVEN NATIONAL LABORATORY

15th TOPICAL CONFERENCE ON HADRON COLLIDER PHYSICS
HCP2004

Developments in Higgs Physics

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Introduction

The Standard Model is over 35 years old and its essential goal

To describe electroweak interactions with a spontaneously broken $SU(2) \otimes U(1)$ gauge symmetry

has been spectacularly confirmed.

- Renormalizability
- Discovery of Neutral Currents
- Discovery of W and Z bosons
- Precision test of W and Z properties

But ...

The agent of electroweak symmetry breaking remains elusive

What is the Higgs Boson?

In the minimal Standard Model, Electroweak symmetry breaking is accomplished by a single complex scalar doublet, resulting in the three massive gauge bosons $W^{\pm}$, Z, and a single Higgs Boson. The Standard Model Higgs is also responsible for giving mass to quarks and leptons.

In the Supersymmetric Standard Model, there must be at least two scalar doublets resulting in five Higgs scalars: h^0, H^0, A^0, $H^{\pm}$

Where is the Higgs?

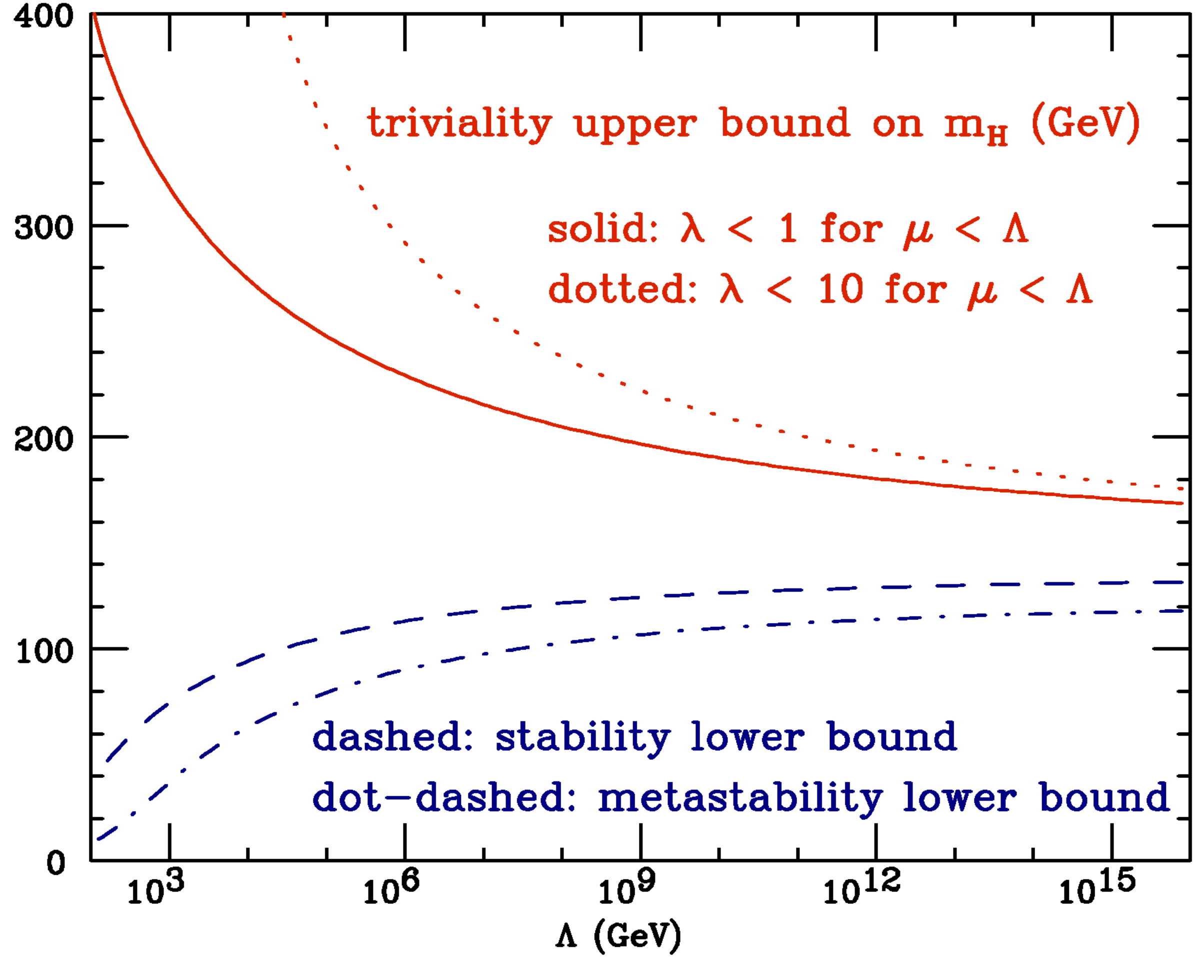
A priori, the mass of the Higgs boson is a free parameter. It can be constrained, however by:

- Theoretical prejudices
- Precision measurements
- Experimental search limits

Theoretical Prejudices

There are three primary considerations determining theoretical prejudices about the mass of the Higgs:

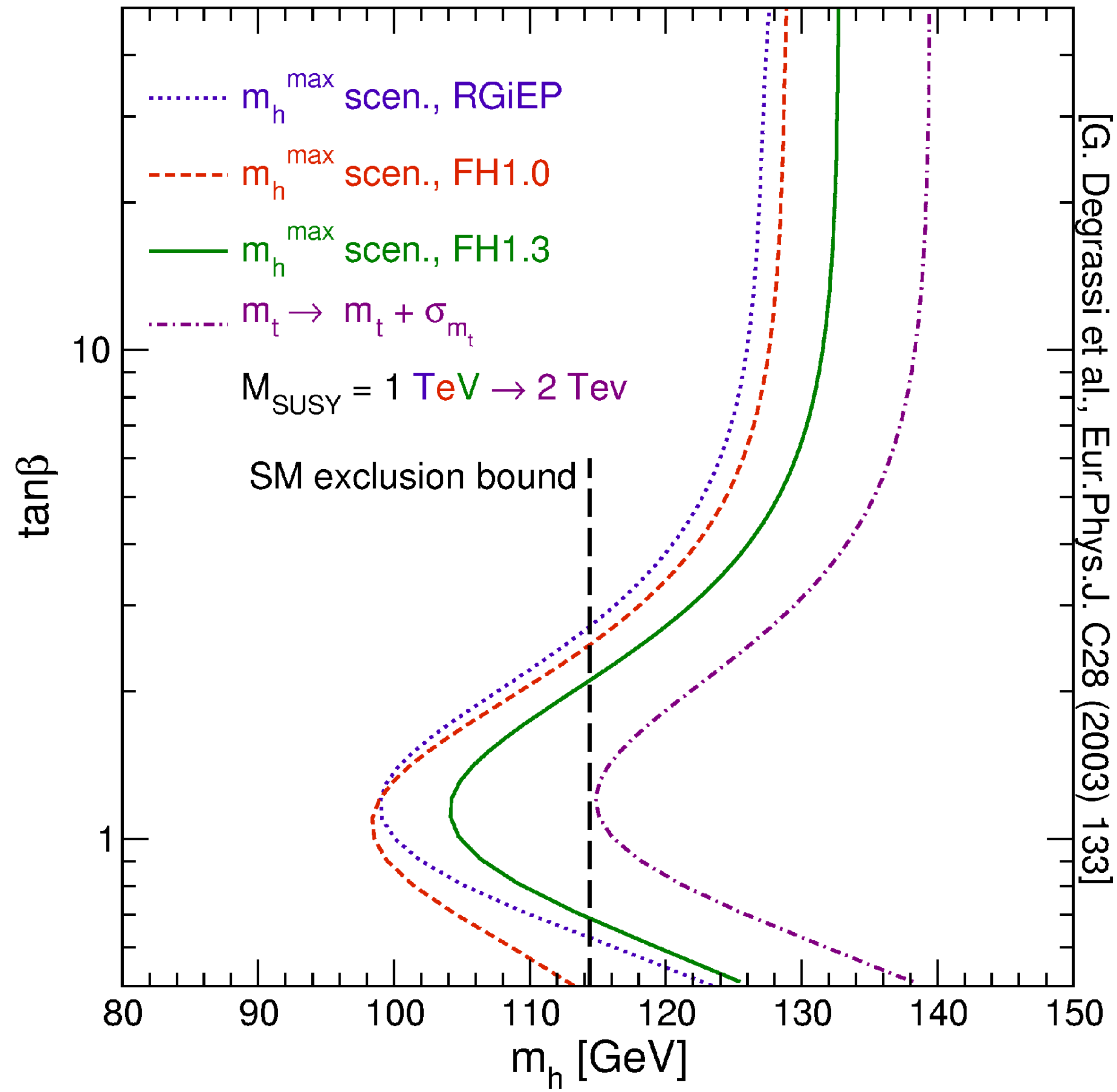
- Vacuum Stability
- Triviality
- Unitarity



[G. Ridolfi, hep-ph/0106300]

Supersymmetric Constraints

In SUSY models, there are further theoretical constraints so that $m_h \leq 135$ GeV.



Direct Search/Precision Constraints

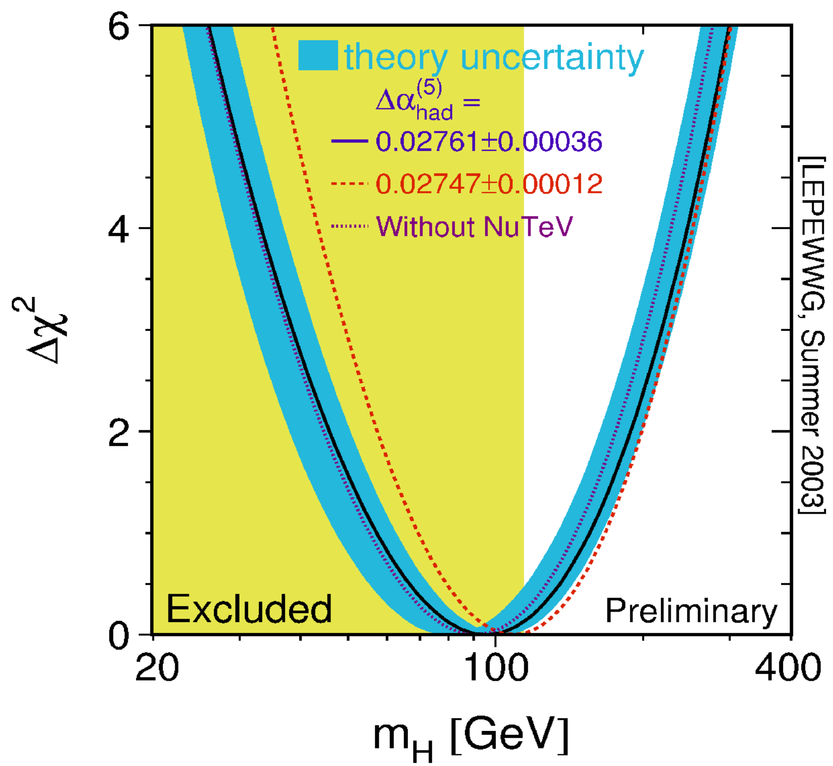
The direct search limit was set by LEP.
Precision Measurements from LEP, SLC, CDF, DØ and NuTeV provide indirect constraints.

As of the Summer of 2003:

LEP Search: $M_H \geq 114.4$ GeV

Precision Fits: $M_H = 96^{+60}_{-38}$ GeV

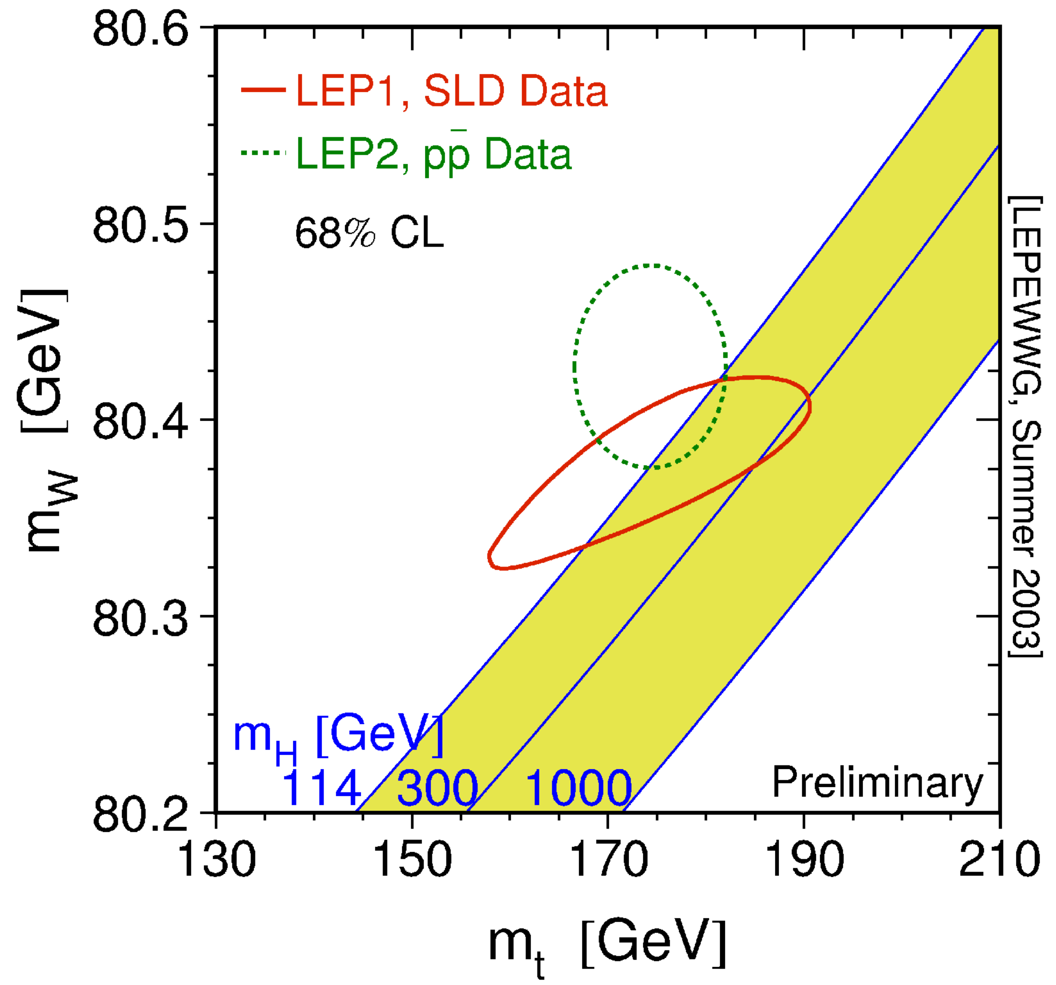
95% CL limit: $M_H < 219$ GeV



Some Parameters are More Equal than Others

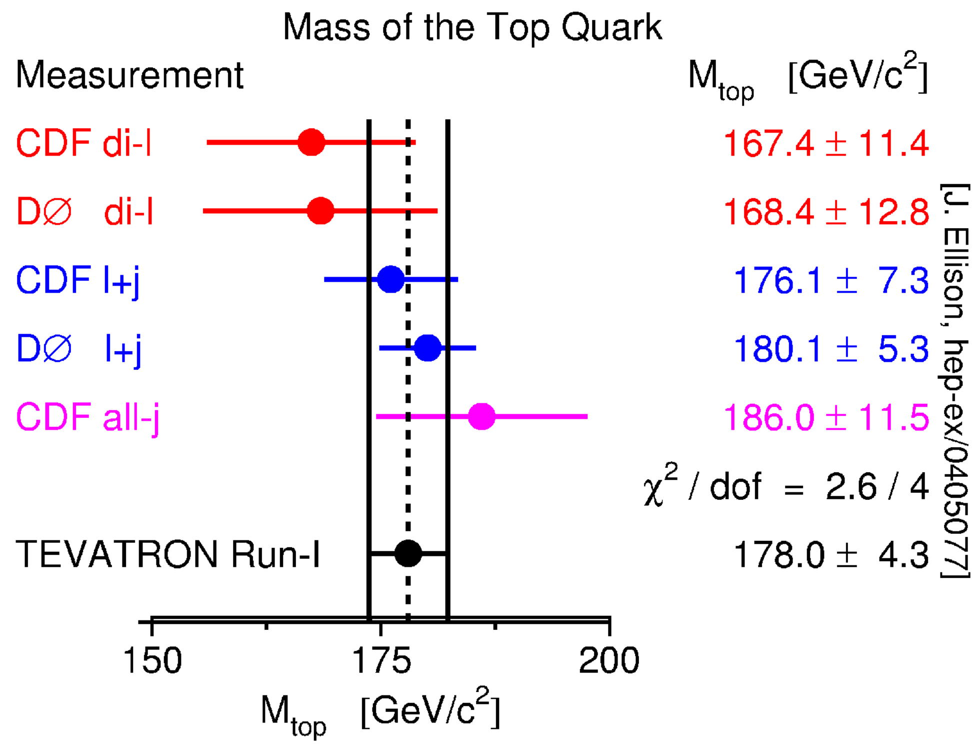
The minimum of the Higgs fit is broad.

Changes to m_W and m_t have a strong effect on the m_H fit.



The top mass has moved!

DØ has reported a new top mass from Run I data of **M_{top} = 180.1 ± 5.3 GeV/c².** This significantly shifts the best fit for the Higgs.



NEW! CDF has just announced a preliminary Run II result (162 pb^{-1}) that agrees with the new world average:

$$M_{top} = 177.8 \pm^{4.5}_{5.0} (\text{stat.}) \pm 6.2\ (\text{syst.})\ \text{GeV}/c^2$$

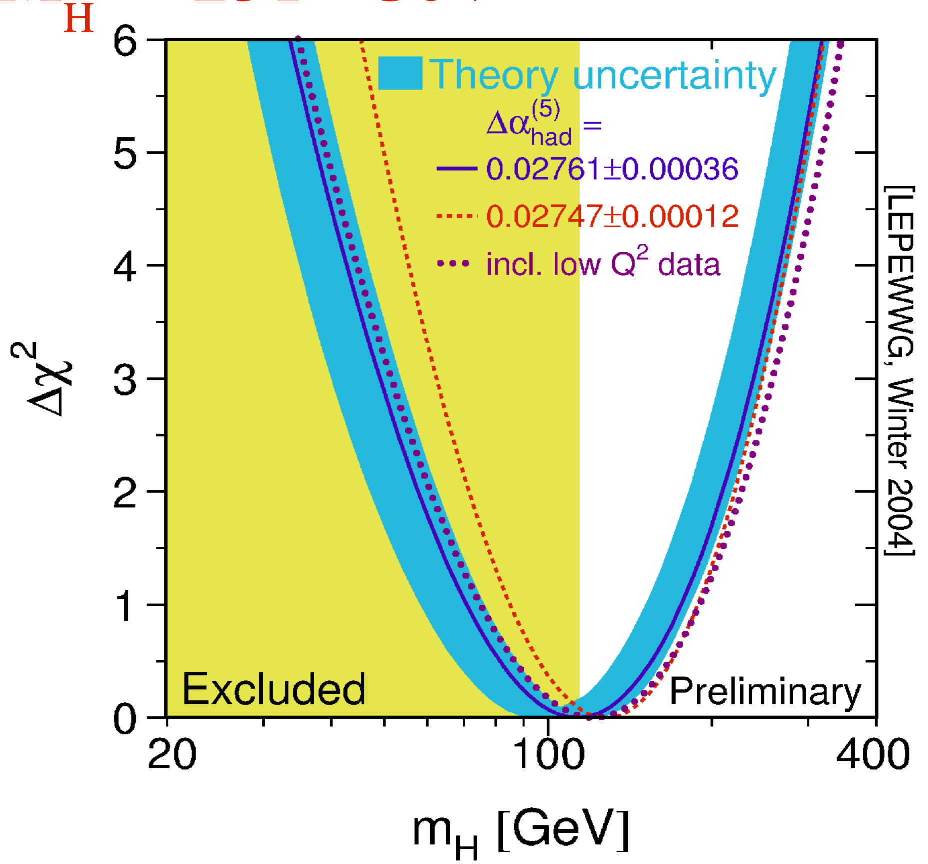
Direct Search/Precision Constraints

LEP Search: $M_H \geq 114.4$ GeV

Precision EW Fits: $M_H = 117^{+67}_{-45}$ GeV

95% CL upper limit: $M_H < 251$ GeV

With the new top mass measurements, the best fit for the Higgs mass is NOT excluded!

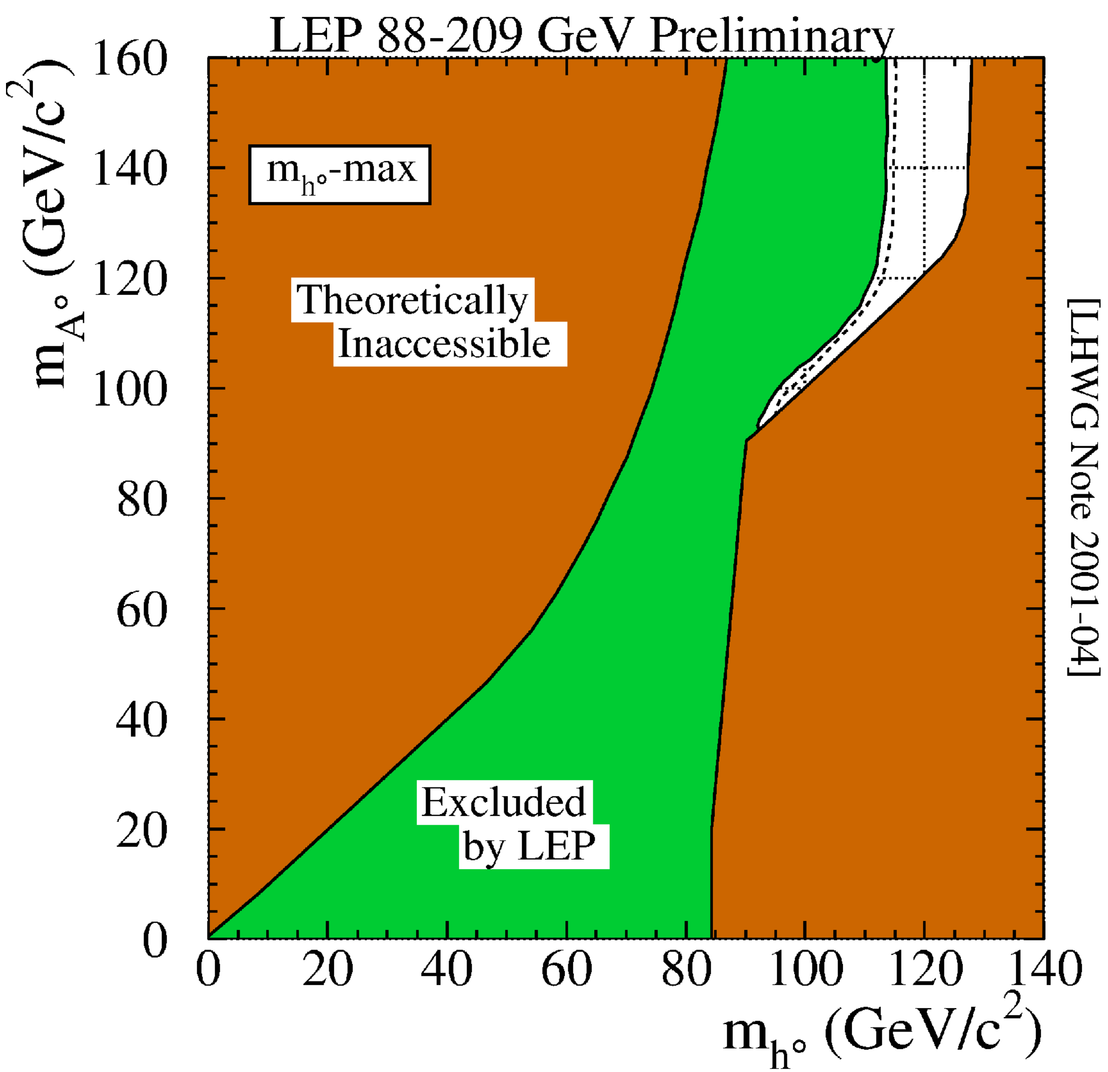


SUSY Higgs Limits

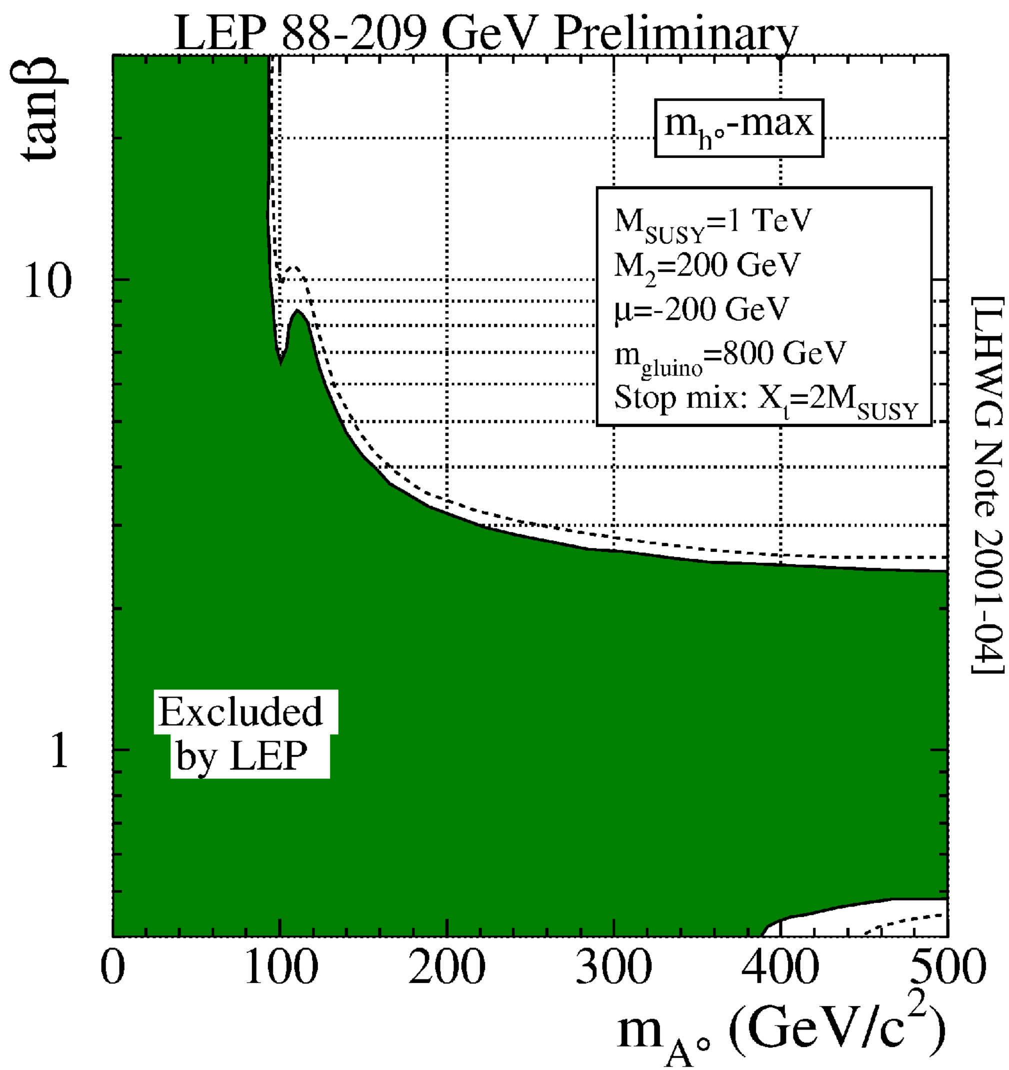
Any limit on SUSY is model dependent.

The most important parameters for the SUSY Higgs sector are m_A, and $\tan\beta$.

In the "m_h-max" scenario:

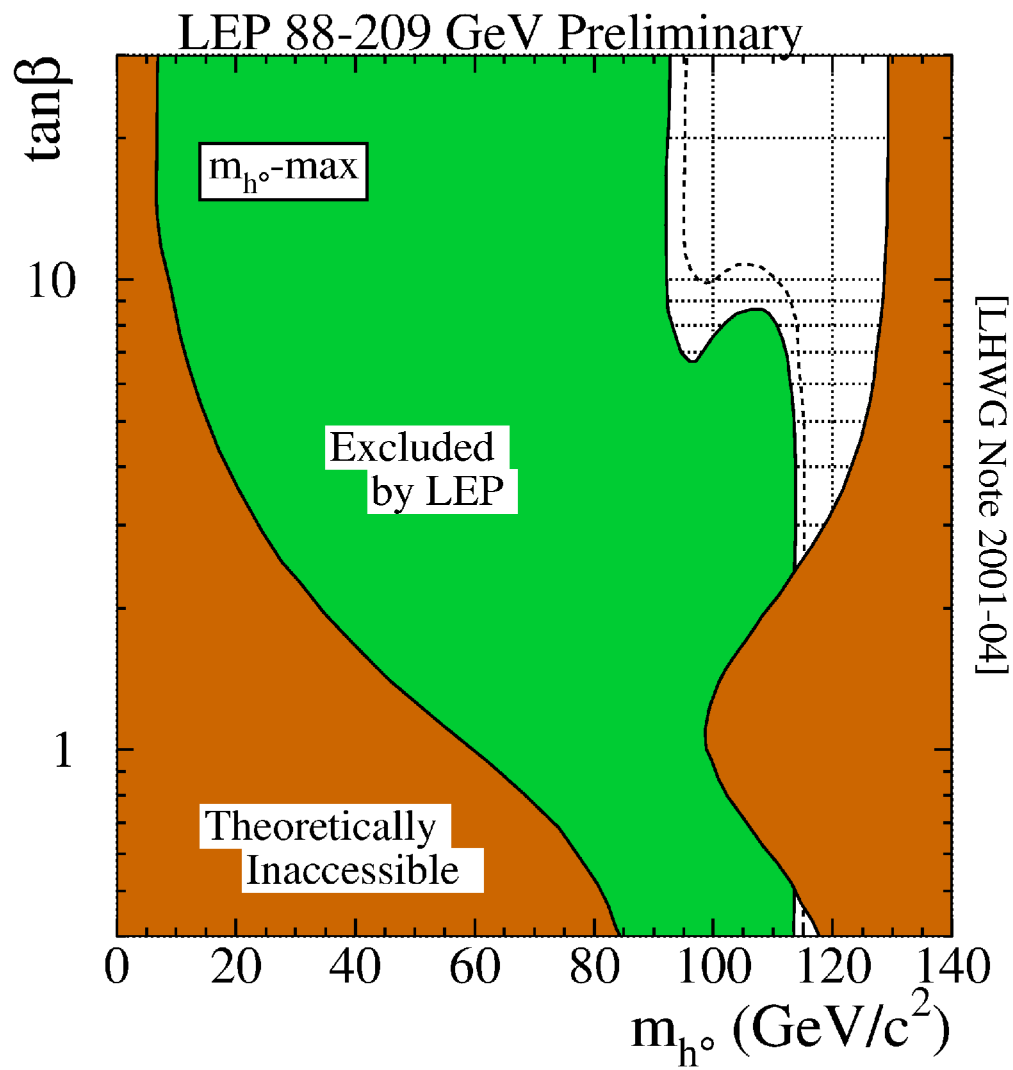


Limits on the Pseudoscalar



SUSY Higgs Limits

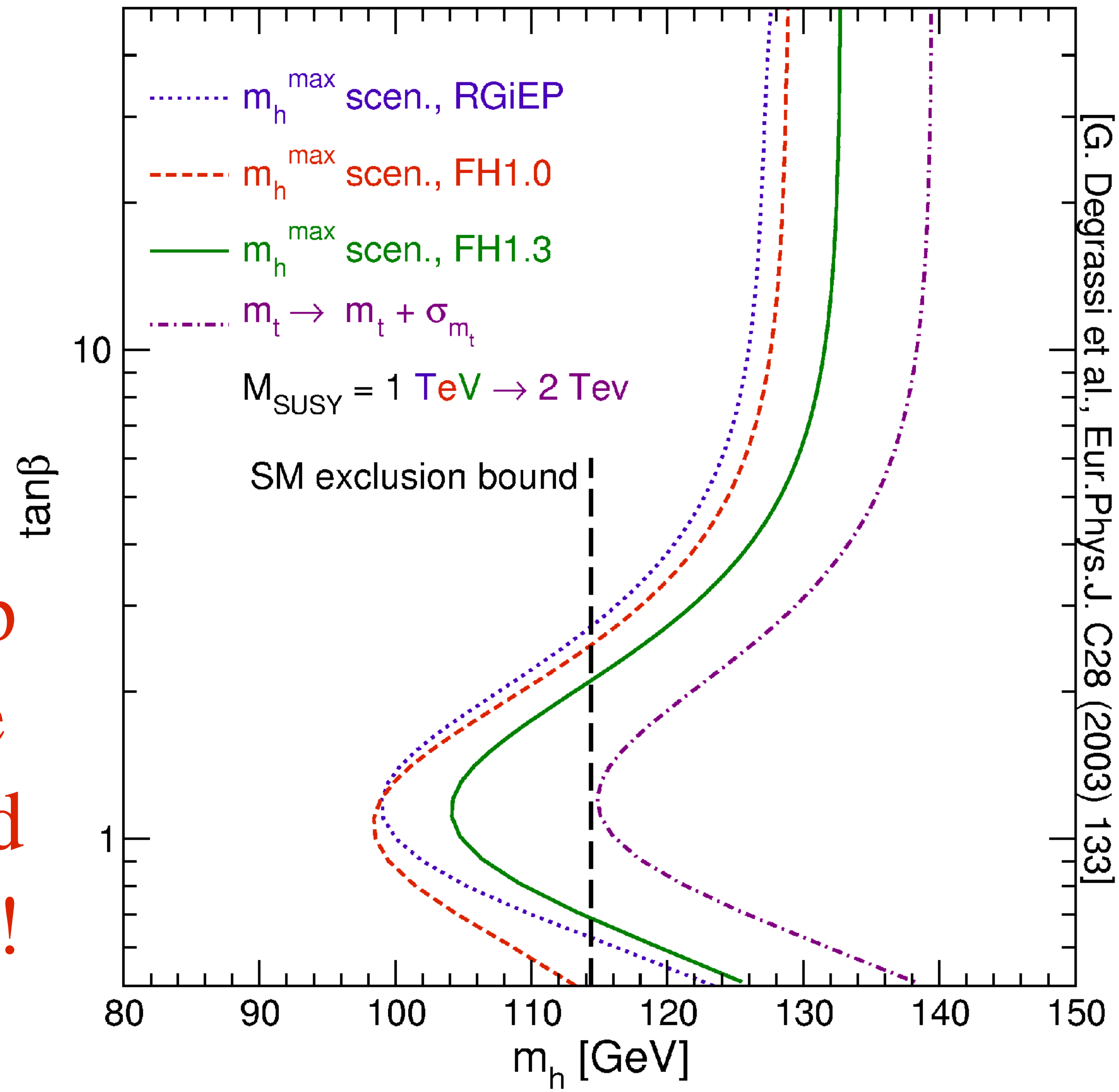
Note the tan β exclusion region.



The limits are weakening!

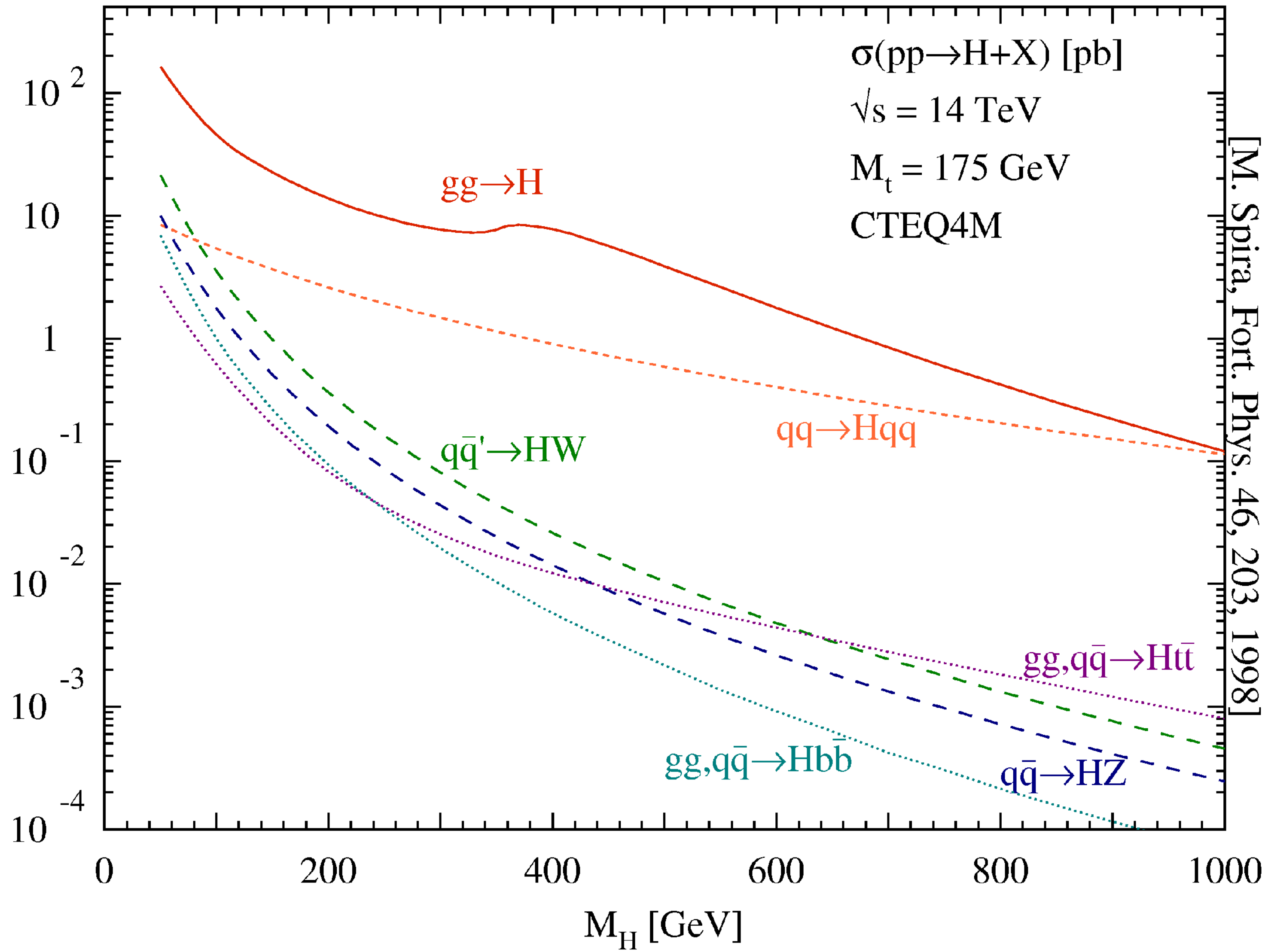
Two-loop corrections to the SUSY Higgs masses weaken the limit from above.

With a shift in the top mass to 179 GeV, the tan β exclusion would completely disappear!

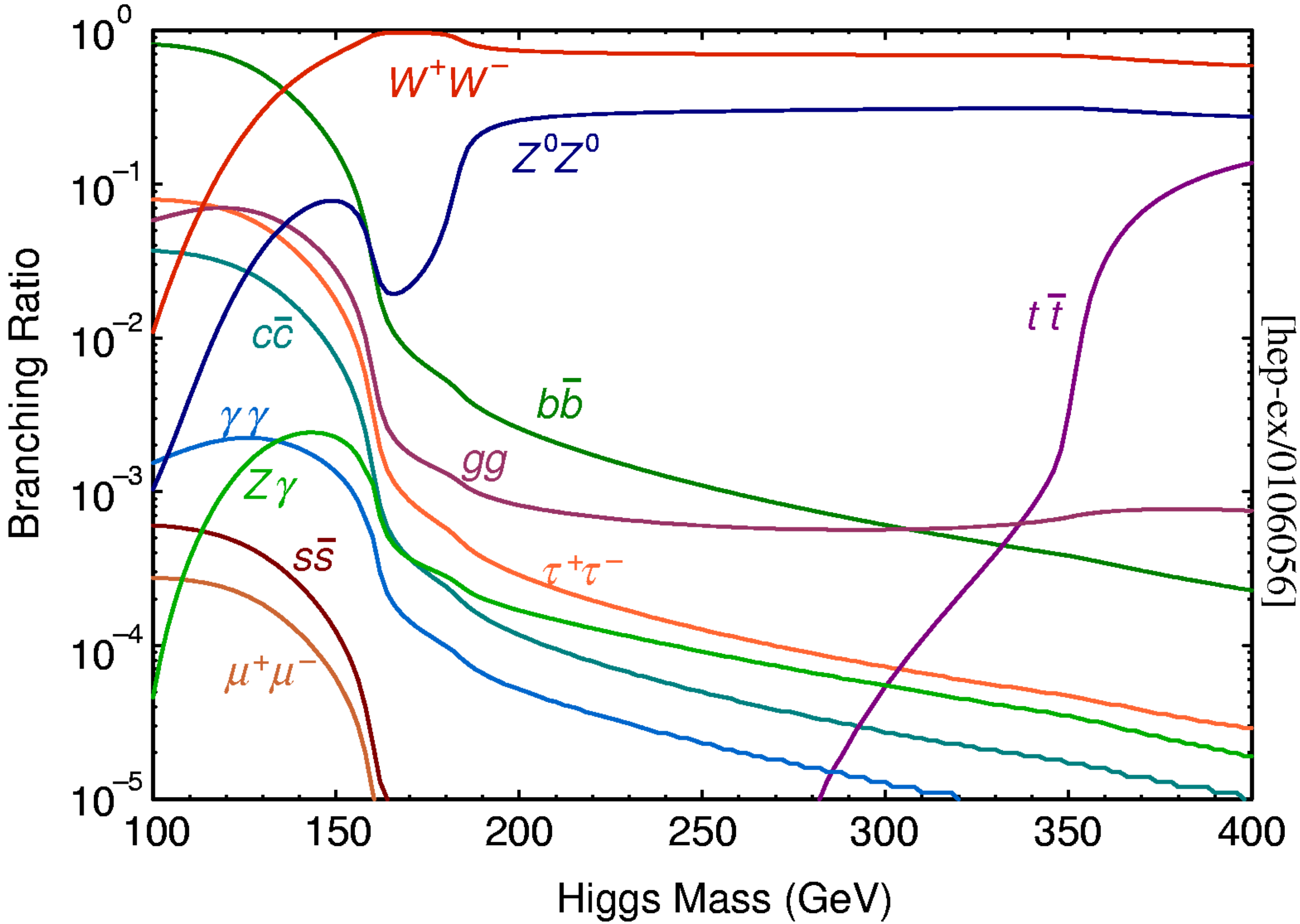


Higgs Production at the LHC

The most important channels are gluon fusion, WBF and $t\bar{t}H$.

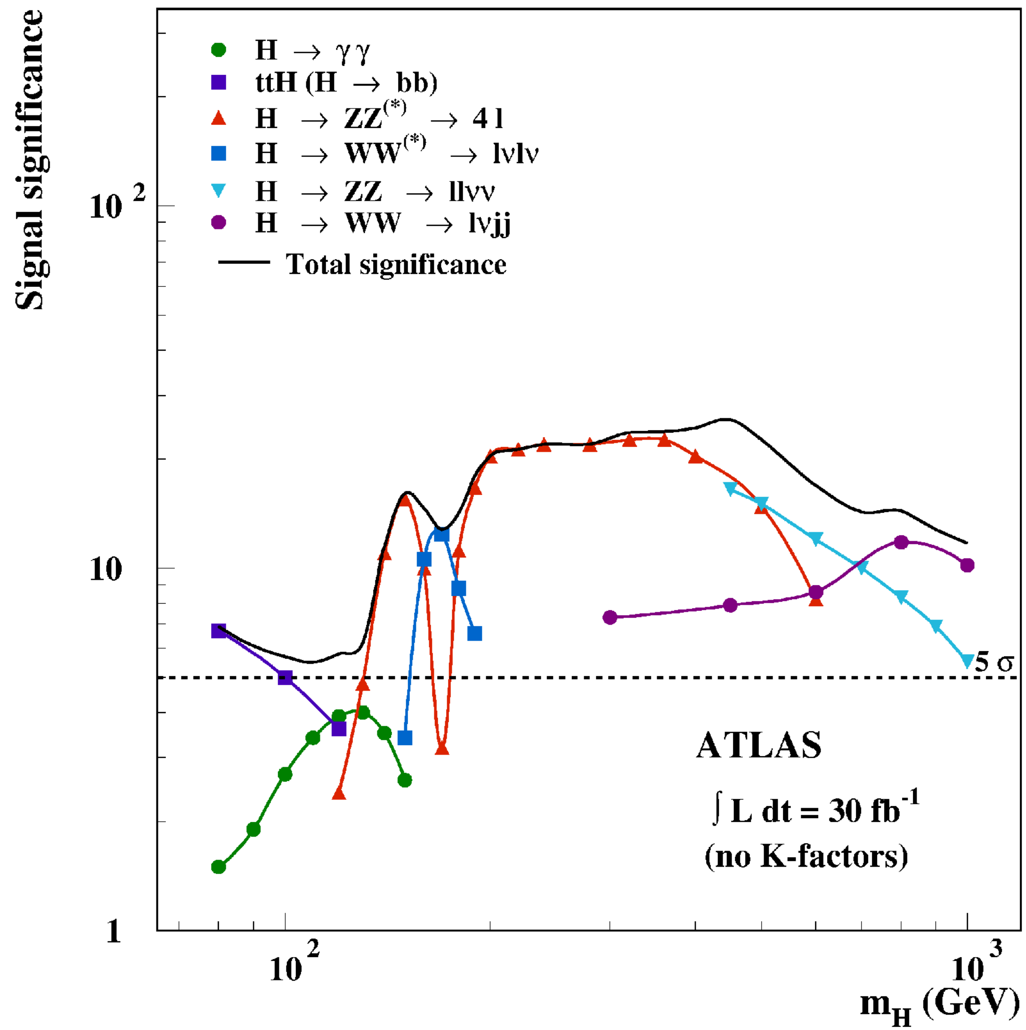


Higgs Branching Ratios



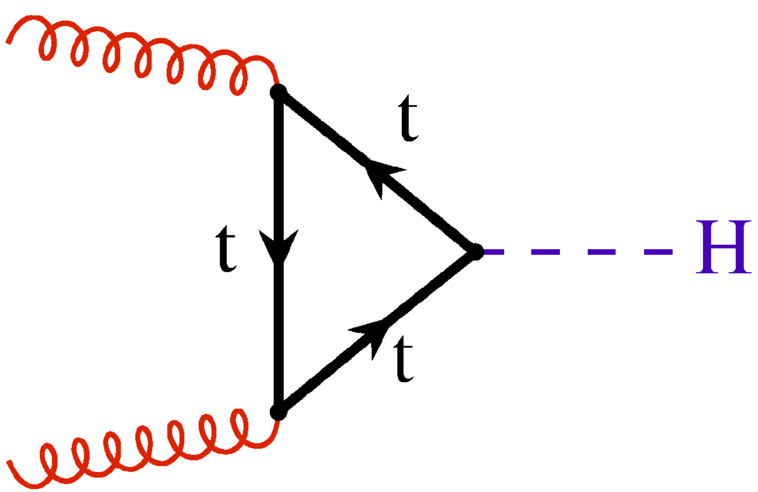
Higgs Discovery requires that you detect the decay products

Inclusive production with decay to $b\bar{b}$ is swamped by QCD production, so we must use rare decays or associated production below the W^+W^- threshold.



Gluon Fusion Dominates Higgs Production

The Higgs boson couples to mass and comes from an electroweak doublet. It seems curious that its production is dominated by gluons, the massless gauge bosons of QCD. The reason: top loops.



The problem for theorists, however, is top loops.

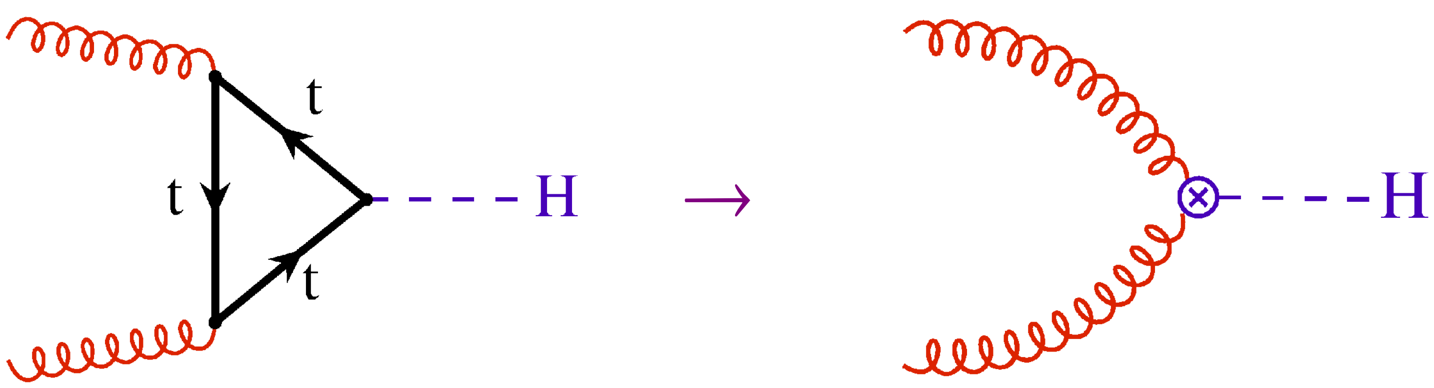
Effective Lagrangian

In the limit that the top quark is very heavy, we can integrate it out and formulate an effective Lagrangian coupling the Higgs to Gluons.

$$\mathscr{L} = C_1 \, H \, G^{a,\mu\nu} \, G^a_{\mu\nu}$$

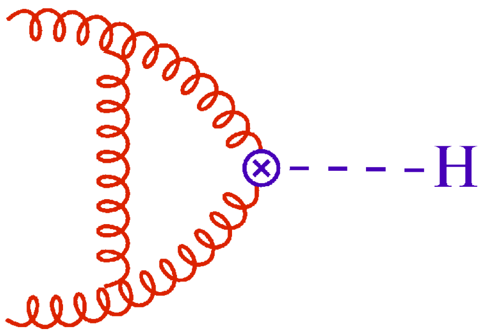
C_1 has been computed to order α_s^4 ! [Chetyrkin, Kniehl, Steinhauser]

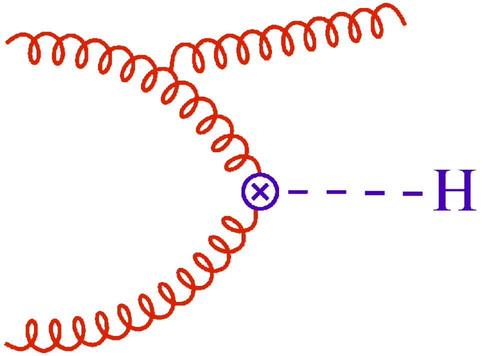
Using the effective Lagrangian greatly simplifies the calculation of radiative corrections.



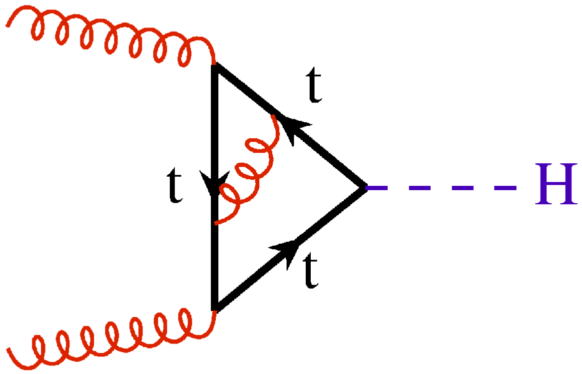
Higher Order Corrections

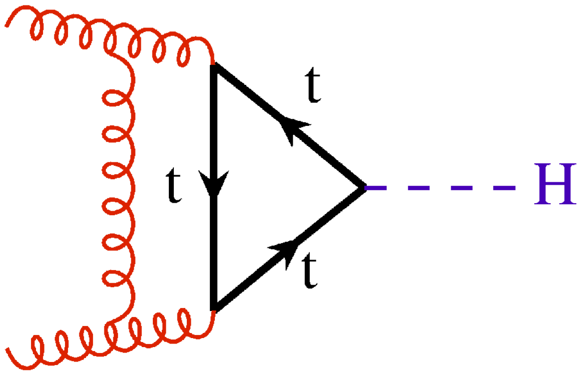
NLO Corrections have been computed in both the effective Lagrangian [Dawson; Djouadi, Spira, Graudenz, Zerwas]



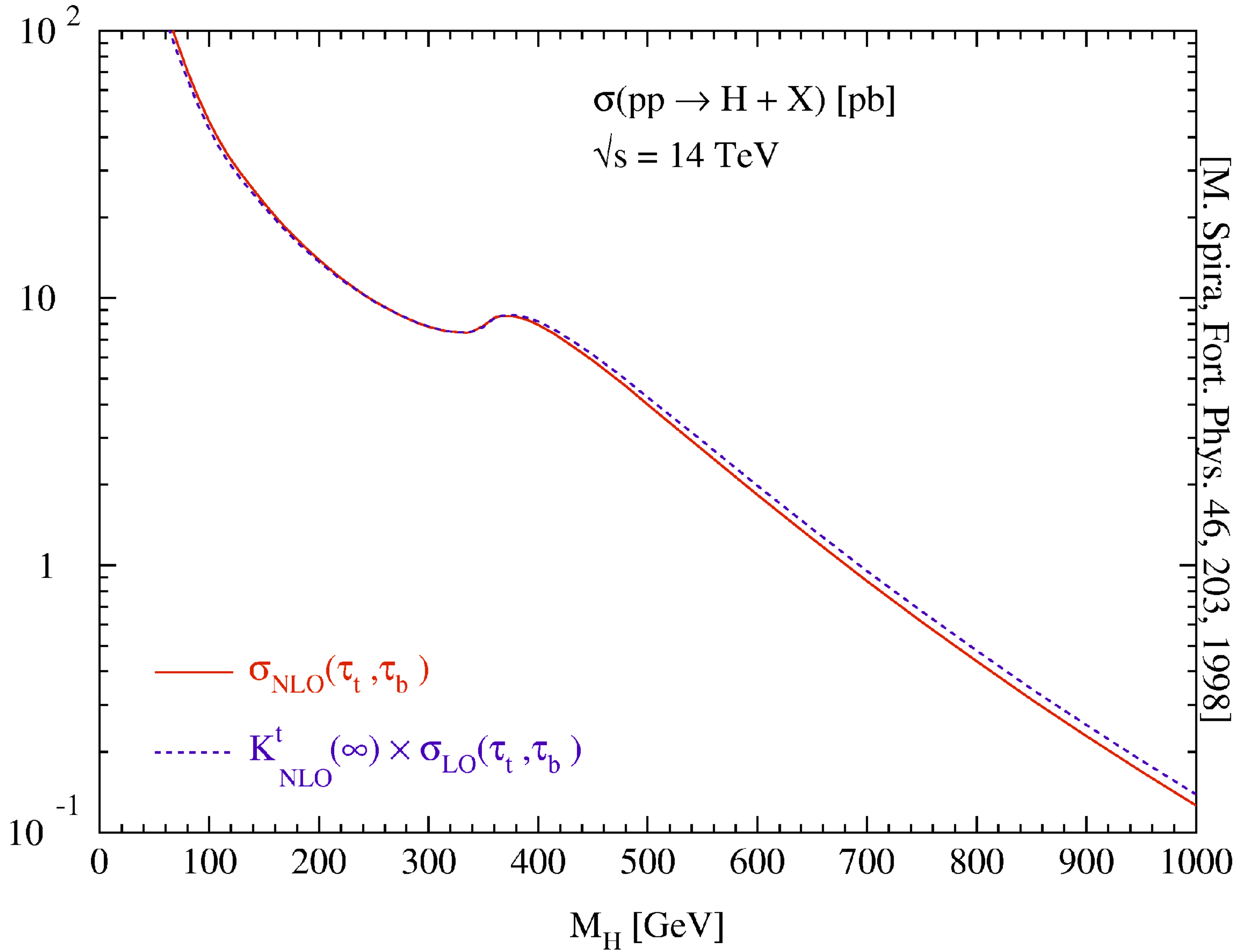


and in the full theory. [Djouadi, Spira, Graudenz, Zerwas]

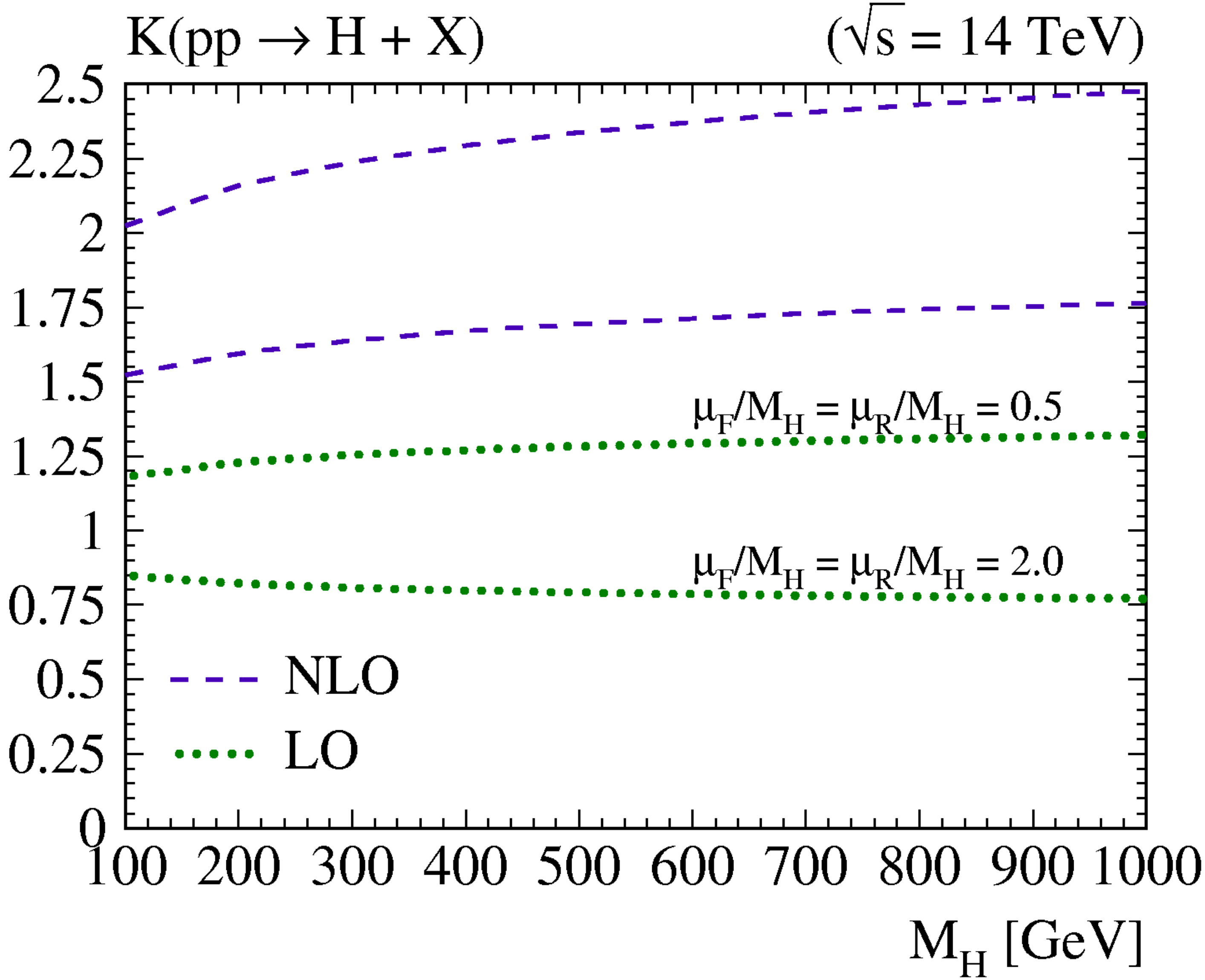




They agree extremely well

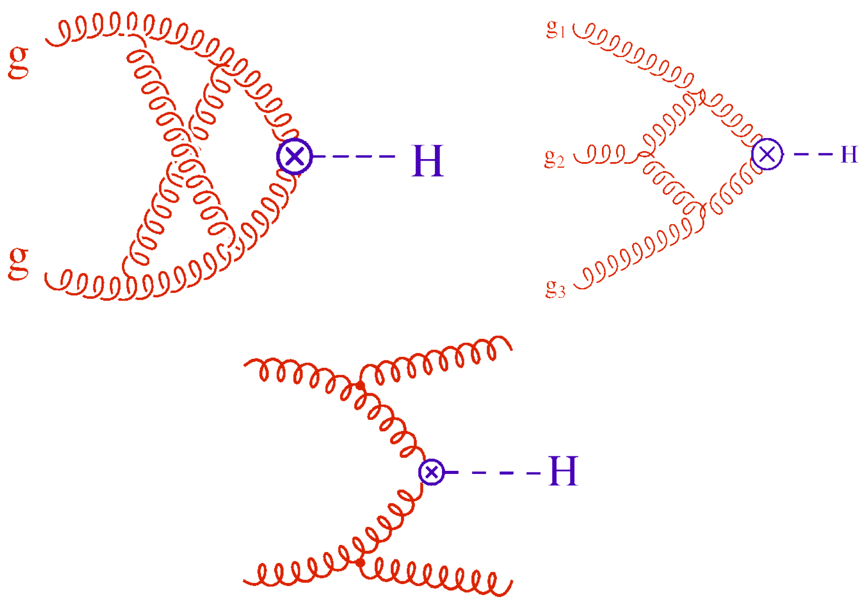


But we need NNLO!

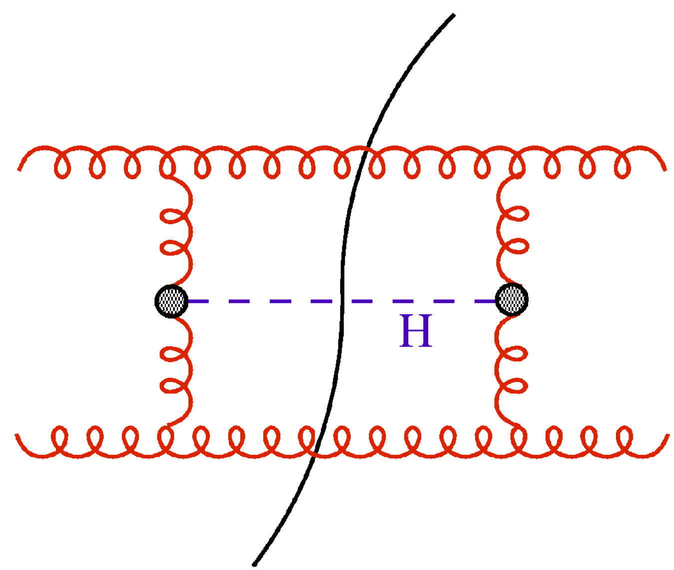


Higgs Production at NNLO

In recent years, the Higgs production cross section has been computed to NNLO in the effective theory by three groups using very different methods.



[Harlander, WK;
Ravindran, Smith, van Neerven]

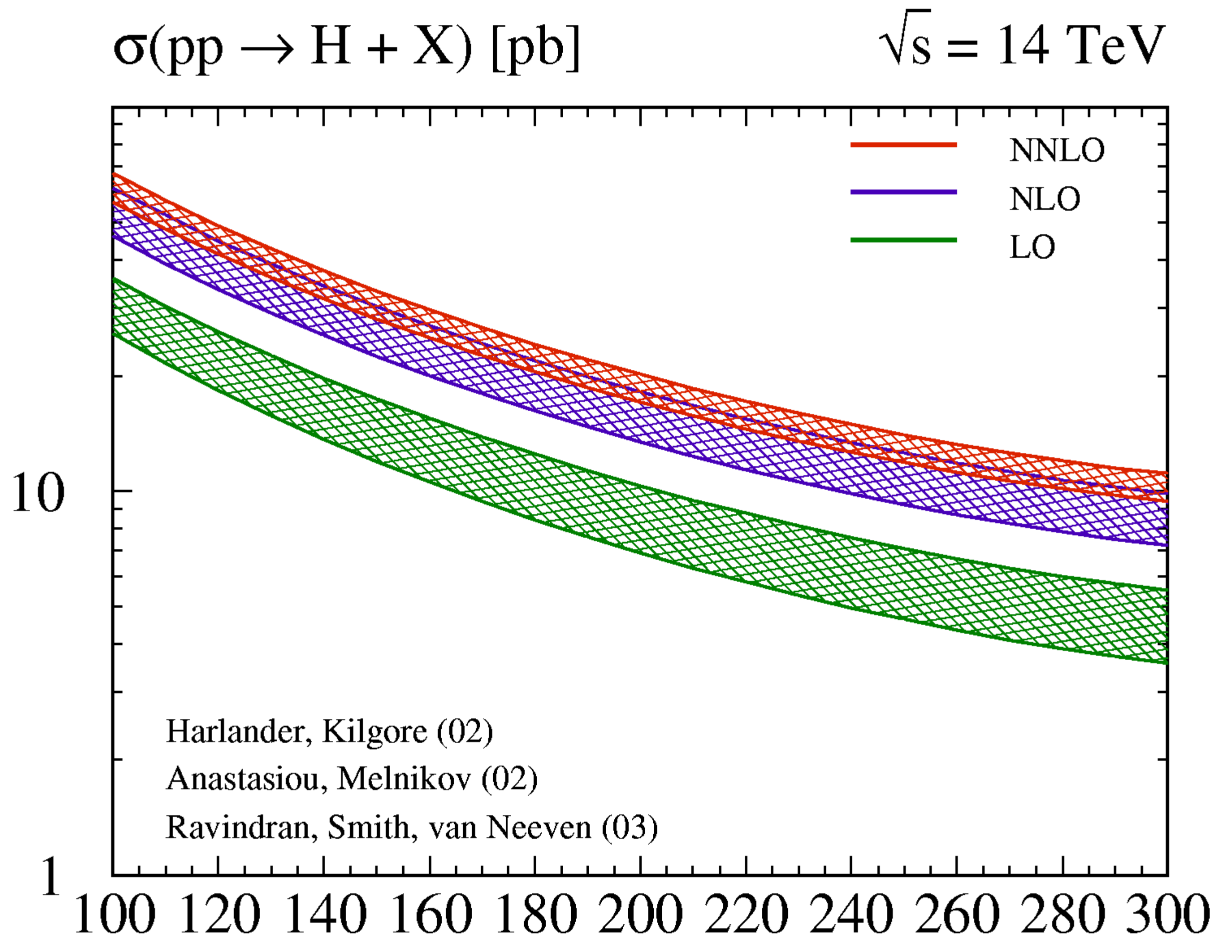


[Anastasiou & Melnikov]

All groups agree exactly

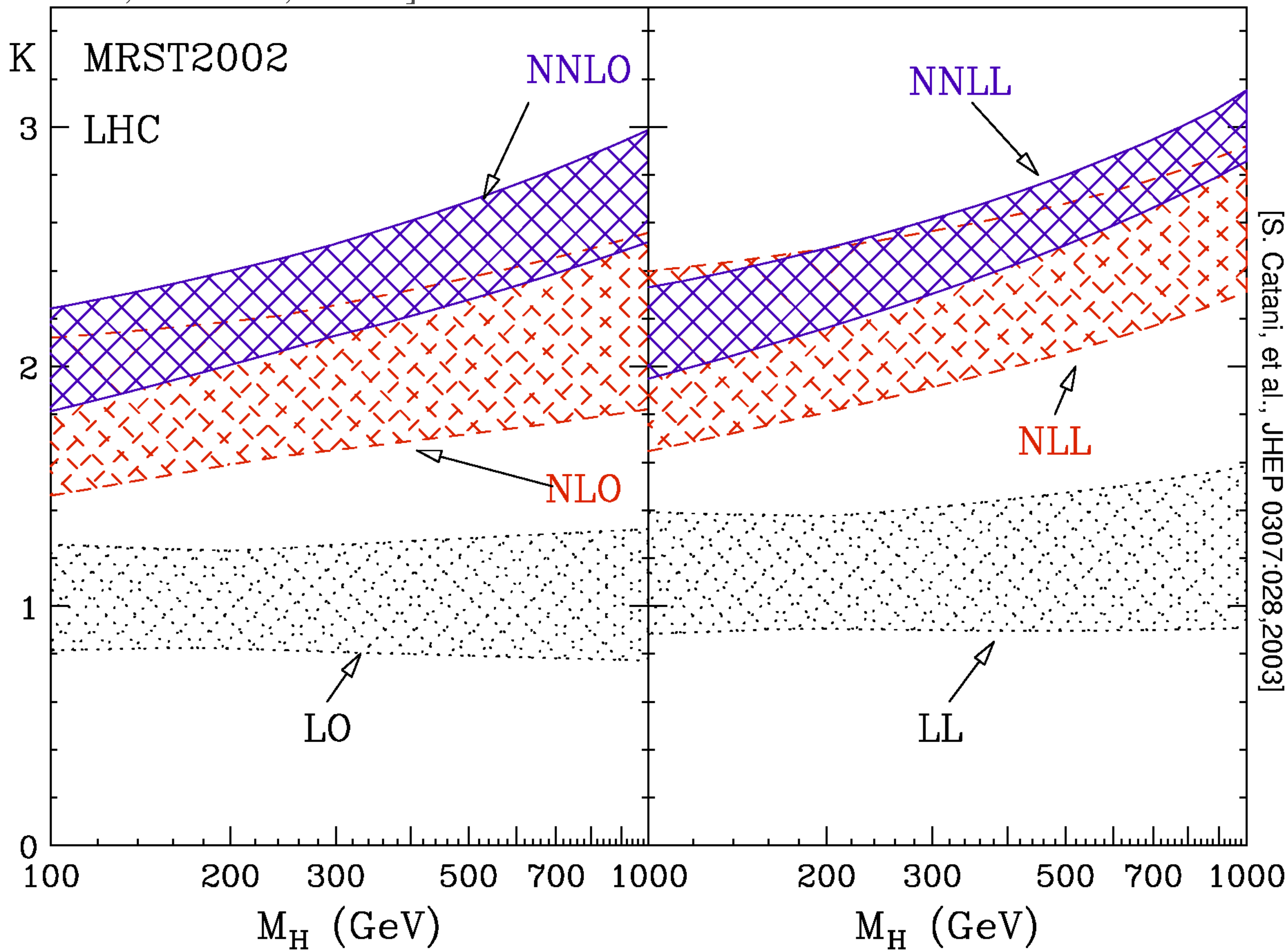
$$
\begin{aligned}
\Delta_{ggA}(x) = & \left[\frac{741}{8} + \frac{139}{2}\zeta_2 - \frac{165}{4}\zeta_3 - \frac{9}{20}\zeta_2^2\right]\delta(1-x) - \left[\frac{101}{3} - 33\,\zeta_2 - \frac{351}{2}\,\zeta_3\right]\mathscr{D}_0(x) + \left[139 - 90\,\zeta_2\right]\mathscr{D}_1(x) - 33\,\mathscr{D}_2(x) + 72\,\mathscr{D}_3(x) \\
& - (144x - 72x^2 + 72x^3)\ln^3(1-x) - (297 - 381x + 348x^2 - 330x^3)\ln^2(1-x) - \frac{9}{2}\frac{(31 - 30x + 93x^2 - 94x^3 + 31x^4)}{1-x}\ln^2(1-x)\ln(x) \\
& + \left[\frac{(2027 - 2735x + 2182x^2 - 2583x^3)}{4} + (180x - 90x^2 + 90x^3)\zeta_2\right]\ln(1-x) + 3\frac{(88 - 211x + 312x^2 - 365x^3 + 187x^4)}{1-x}\ln(1-x)\ln(x) \\
& + 9\frac{(7 + 3x + 19x^2 - 3x^3 - 19x^4 + 9x^5)}{1-x^2}\ln(1-x)\ln^2(x) + 36\frac{(1 - 6x - 13x^2 - 6x^3 + x^4)}{1+x}\ln(1-x)\mathrm{Li}_2(1-x) \\
& - 18\frac{(1 + 2x + 3x^2 + 2x^3 + x^4)}{1+x}\ln(1-x)\mathrm{Li}_2(1-x^2) - \frac{9}{2}\frac{(24 - 38x + 8x^2 + 54x^3 - 19x^4 + 9x^5)}{1-x^2}\mathrm{Li}_3(1-x) \\
& - \frac{9}{2}\frac{(27 + 35x + 75x^2 - 29x^3 - 78x^4 + 6x^5)}{1-x^2}\mathrm{Li}_3\left(-\frac{(1-x)}{x}\right) + \frac{9}{8}\frac{(1 + 2x + 3x^2 + 24x^3 + 16x^4)}{1+x}\mathrm{Li}_3(1-x^2) \\
& - \frac{9}{8}\frac{(1 + 2x + 3x^2 - 8x^3 - 8x^4)}{1+x}\mathrm{Li}_3\left(-\frac{(1-x^2)}{x^2}\right) - \frac{9}{2}\frac{(7 + 14x + 21x^2 + 8x^3 + 4x^4)}{1+x}\left[\mathrm{Li}_3\left(\frac{1-x}{1+x}\right) - \mathrm{Li}_3\left(-\frac{1-x}{1+x}\right)\right] \\
& - \frac{3}{4}\frac{(317 - 398x - 87x^2 + 300x^3 - 121x^4)}{1-x}\mathrm{Li}_2(1-x) + \frac{9}{2}\frac{(11 + 31x + 59x^2 - 25x^3 - 65x^4 + 11x^5)}{1-x^2}\mathrm{Li}_2(1-x)\ln(x) \\
& + \frac{(42 + 36x - 63x^2 - 33x^3)}{4}\mathrm{Li}_2(1-x^2) + \frac{9}{4}\frac{(5 + 10x + 15x^2 - 2x^4)}{1+x}\mathrm{Li}_2(1-x^2)\ln(x) + \frac{3}{4}\frac{(21 + 23x + 41x^2 - 37x^3 - 44x^4 + 4x^5)}{1-x^2}\ln^3(x) \\
& - \frac{3}{8}\frac{(154 - 365x + 675x^2 - 827x^3 + 374x^4)}{1-x}\ln^2(x) - \frac{1}{8}\frac{(2213 - 5599x + 6603x^2 - 7003x^3 + 4342x^4)}{1-x}\ln(x) \\
& + 9\frac{(9 - 2x + 27x^2 - 34x^3 + 9x^4)}{1-x}\zeta_2\ln(x) - \frac{(16309 - 20611x + 23819x^2 - 22749x^3)}{48} + \frac{3}{4}(319 - 277x + 233x^2 - 363x^3)\zeta_2 - \frac{351}{2}(2x - x^2 + x^3)\zeta_3 \\
& + n_f\left\{\left[-\frac{689}{72} + l_{Ht} - \frac{5}{3}\zeta_2 + \frac{5}{6}\zeta_3\right]\delta(1-x) + \left[\frac{14}{9} - 2\,\zeta_2\right]\mathscr{D}_0(x) - \frac{10}{3}\mathscr{D}_1(x) + 2\,\mathscr{D}_2(x) - \frac{2}{9}(8 - 12x + 3x^2 - 17x^3)\,\zeta_2\right. \\
& + \frac{2}{9}(8 - 12x + 3x^2 - 17x^3)\ln^2(1-x) + \frac{8}{3}(x + x^2)\ln^2(1-x)\ln(x) - \frac{(922 - 294x + 249x^2 - 1570x^3)}{108}\ln(1-x) \\
& - \frac{2}{9}\frac{(17 + 7x + 21x^2 - 61x^3 + 25x^4)}{1-x}\ln(1-x)\ln(x) - \frac{8}{3}(x + x^2)\ln^2(x)\ln(1-x) + \frac{16}{3}(x + x^2)\ln(1-x)\,\mathrm{Li}_2(1-x) \\
& - \frac{(2 + 14x + 17x^2)}{6}\mathrm{Li}_3(1-x) - \frac{(2 - 34x - 31x^2)}{12}\mathrm{Li}_3\left(-\frac{(1-x)}{x}\right) .+ \frac{1}{36}\frac{(68 - 302x + 21x^2 + 227x^3 + 4x^4)}{1-x}\mathrm{Li}_2(1-x) \\
& + \frac{(2 - 50x - 47x^2)}{12}\mathrm{Li}_2(1-x)\ln(x) + \frac{(2 + 6x + 9x^2)}{72}\ln^3(x) + \frac{1}{72}\frac{(68 + 100x + 69x^2 - 351x^3 + 132x^4)}{1-x}\ln^2(x) \\
& \left. + \frac{1}{216}\frac{(1282 - 382x + 117x^2 - 3041x^3 + 2384x^4)}{1-x}\ln(x) - \frac{8}{3}(x + x^2)\zeta_2\ln(x) + \frac{(12707 - 606x + 1641x^2 - 17774x^3)}{1296}\right\}
\end{aligned}
$$

Higgs Cross Section at NNLO



Threshold resummation

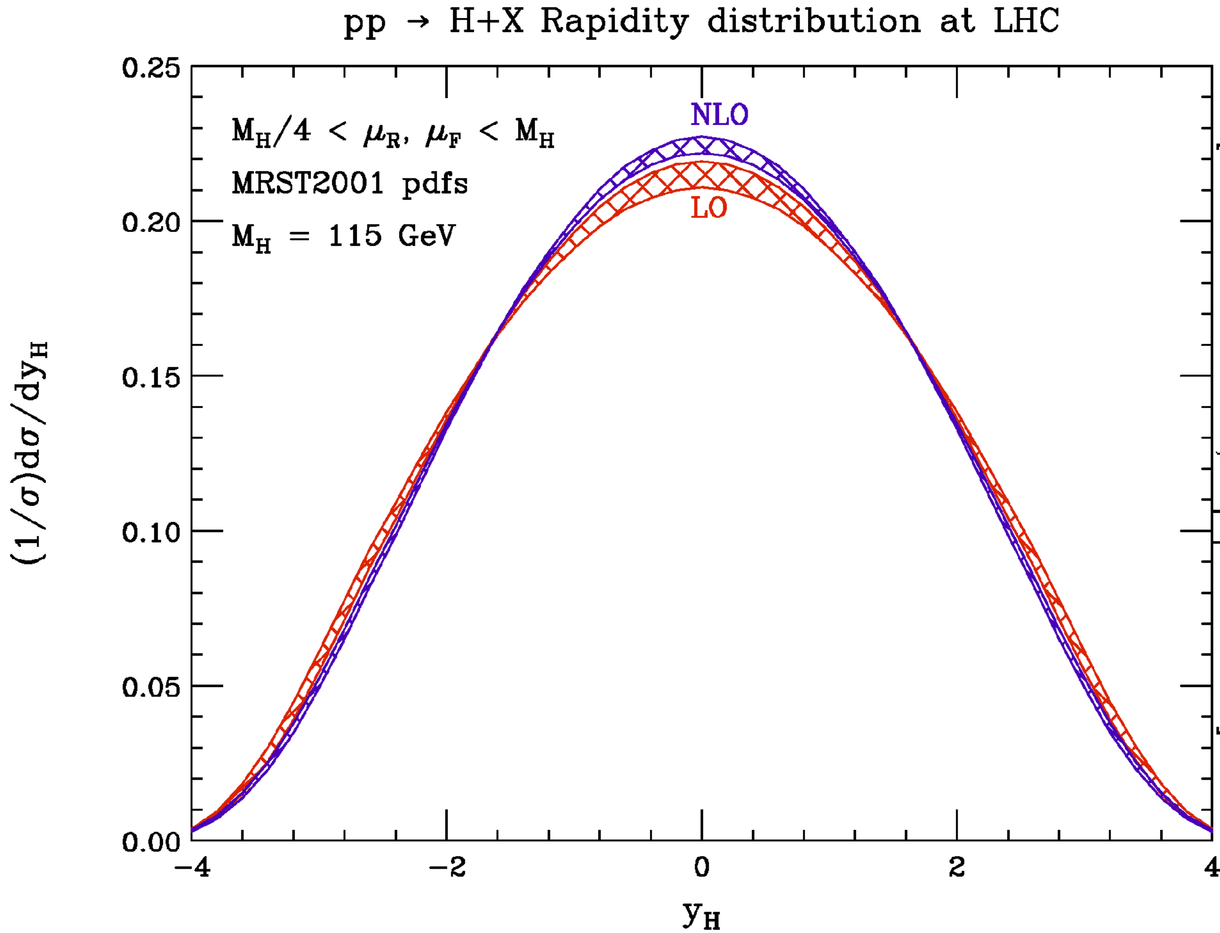
[Catani, de Florian, Grazzini, Nason]



Higgs Distributions at NNLO

Using the cutting method, NNLO distributions can be computed. [Anastasiou, Dixon, Melnikov, Petriello]

NNLO distributions for Drell-Yan exist, only NLO for Higgs so far.



[C.Anastasiou et al., hep-ph/0211141]

Higgs at Finite Q_T

Signal identification as well as the signal to background ratio can be improved by looking at Higgs production at finite Q_T. In the effective theory, this has been computed to NLO.

[de Florian, Grazzini, Kunszt; Ravindran, Smith, van Neerven; Glosser, Schmidt]

The background process $\gamma\gamma$ + jet has also been computed to NLO

[Del Duca, Maltoni, Nagy, Trócsányi]

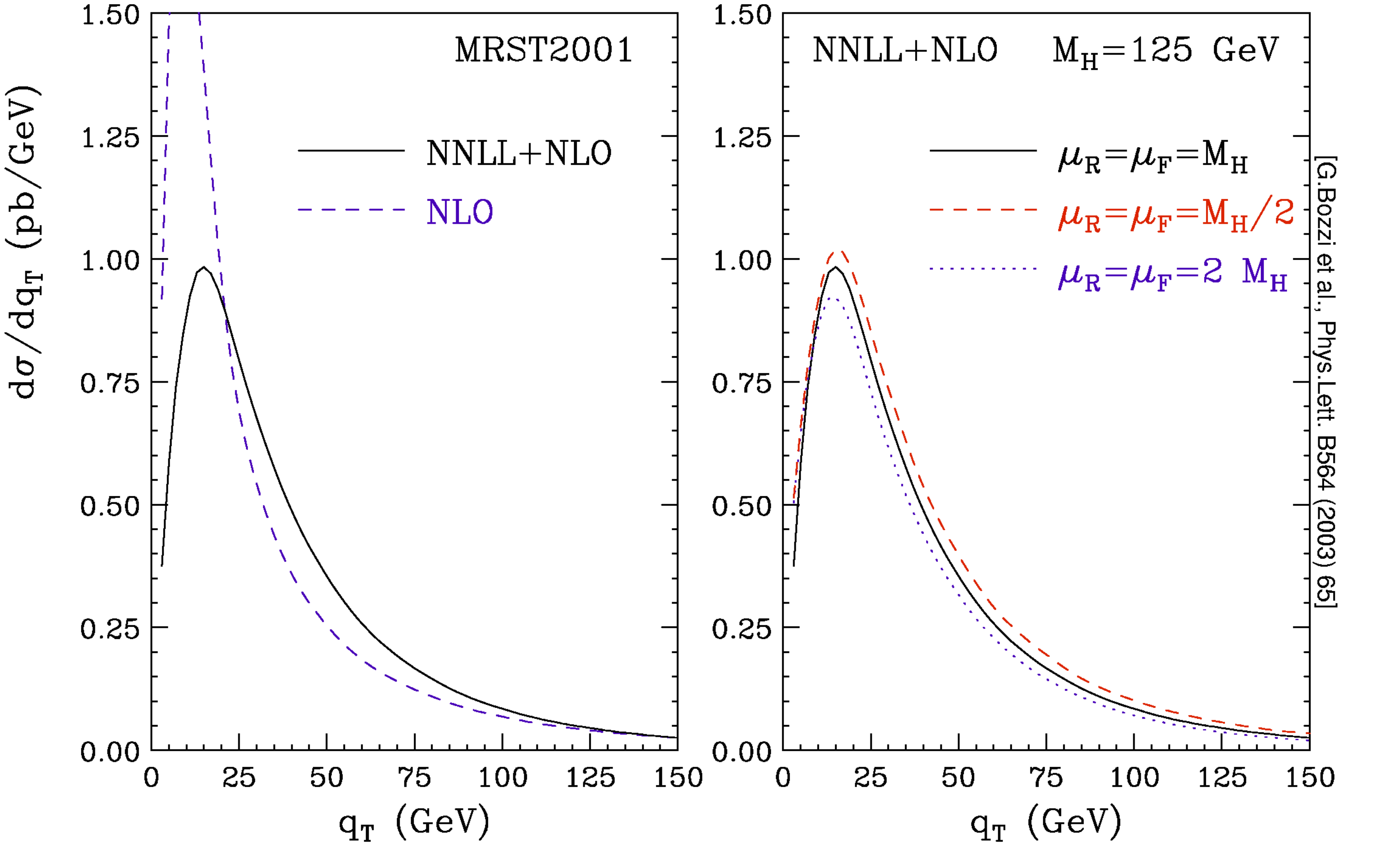
The Higgs Q_T can be resummed alone

[Balázs, Yuan; Berger, Qiu; Bozzi, Catani, de Florian, Grazzini]

or in conjunction with threshold resummation

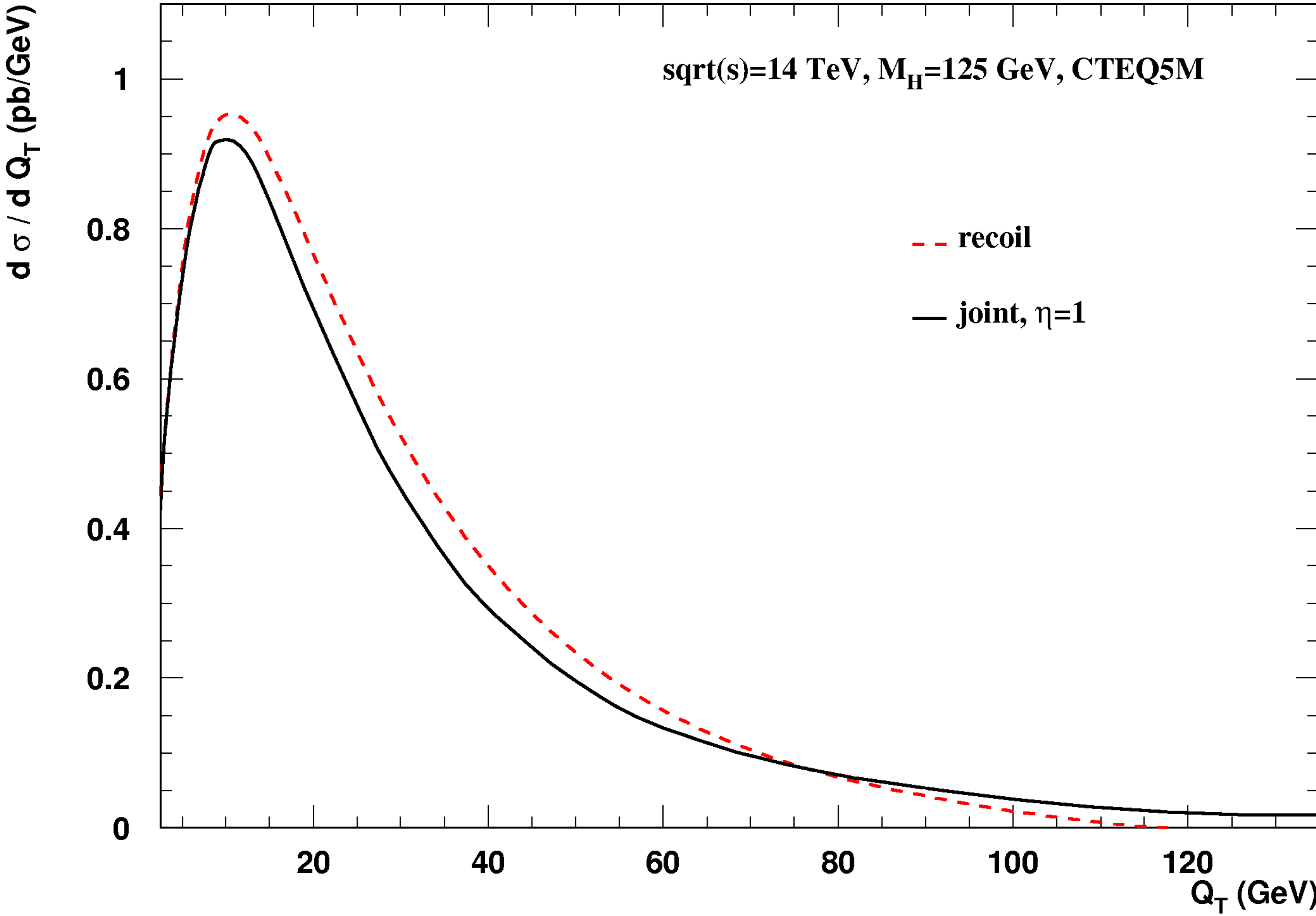
[Kulesza, Sterman, Vogelsang]

Q_T Resummation



[G.Bozzi et al., Phys.Lett. B564 (2003) 65]

Joint Threshold and Q_T Resummation



[A.Kulezsa, et al., hep-ph/0309264]

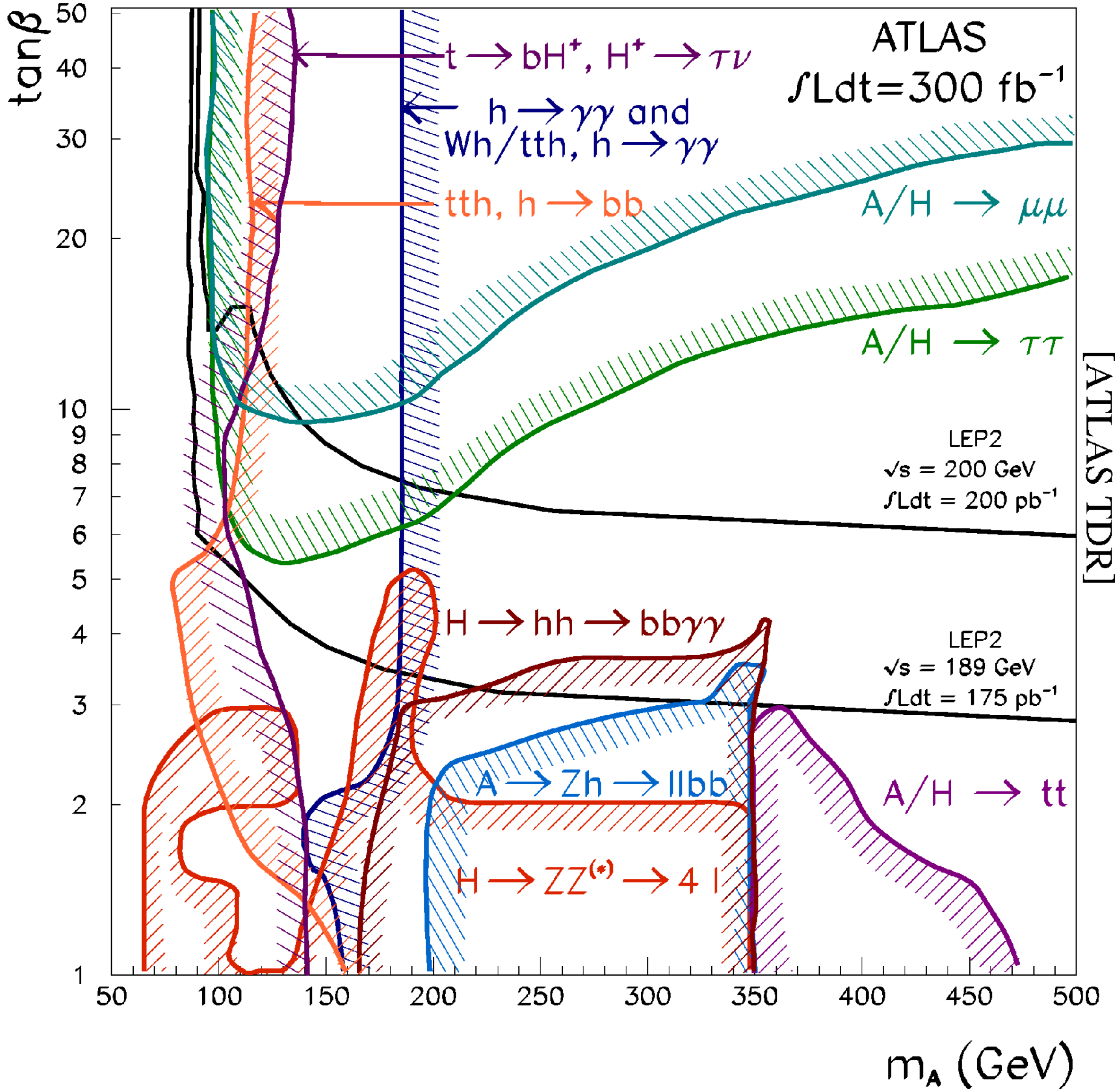
Supersymmetric Higgs Boson Production

In the Minimal Supersymmetric Standard Model (MSSM) there are two Higgs doublets, with vacuum expectation values v_u, v_d. After symmetry breaking, there are 5 physical Higgs Scalars:

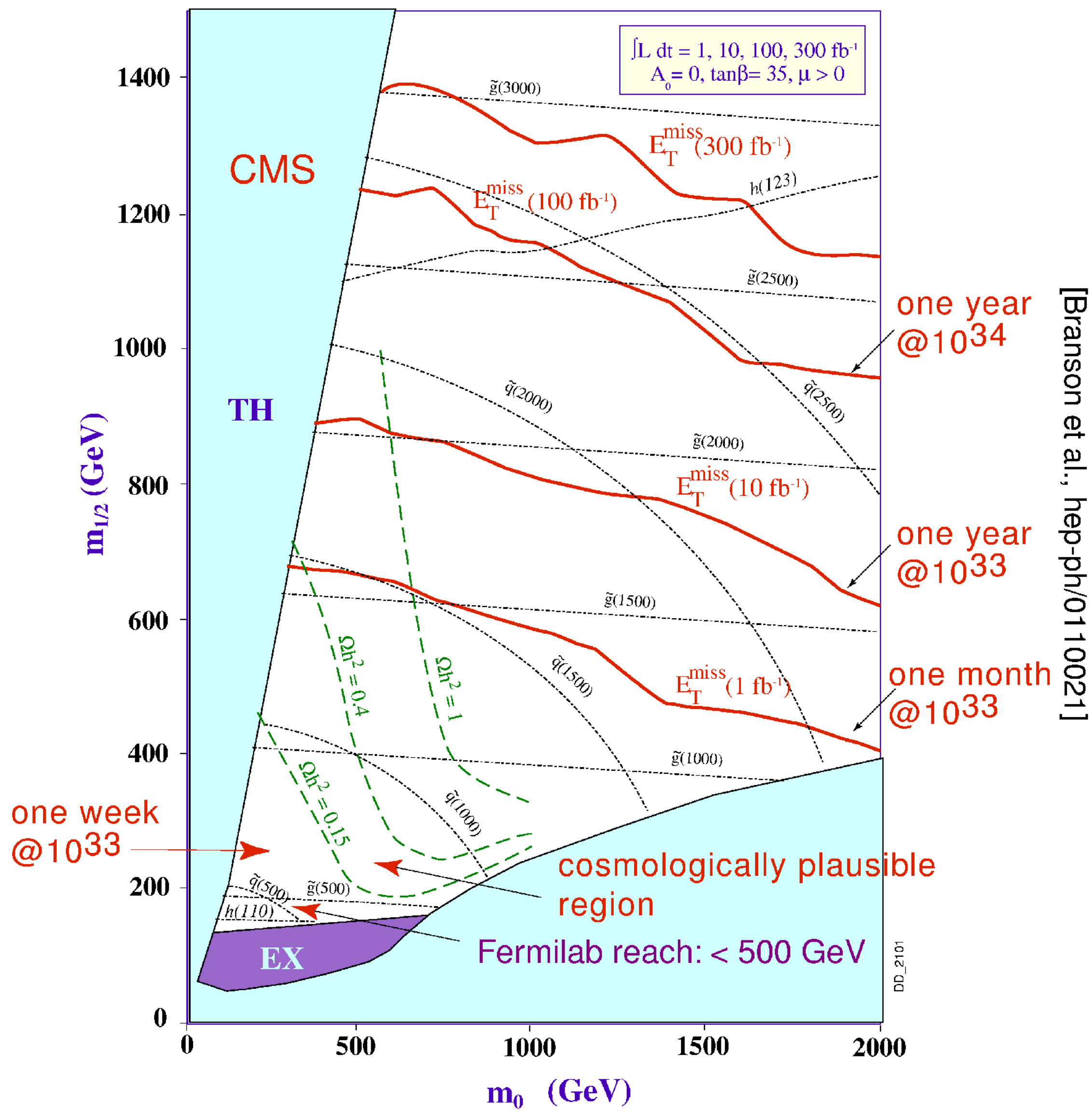
$$h^0,\ H^0,\ A^0,\ H^\pm$$

In the "decoupling" limit, the light neutral scalar, h^0, has properties almost identical to the Standard Model Higgs. The heavy scalar, H^0, and the pseudoscalar, A^0, have very different interactions.

Finding SUSY Higgs at LHC



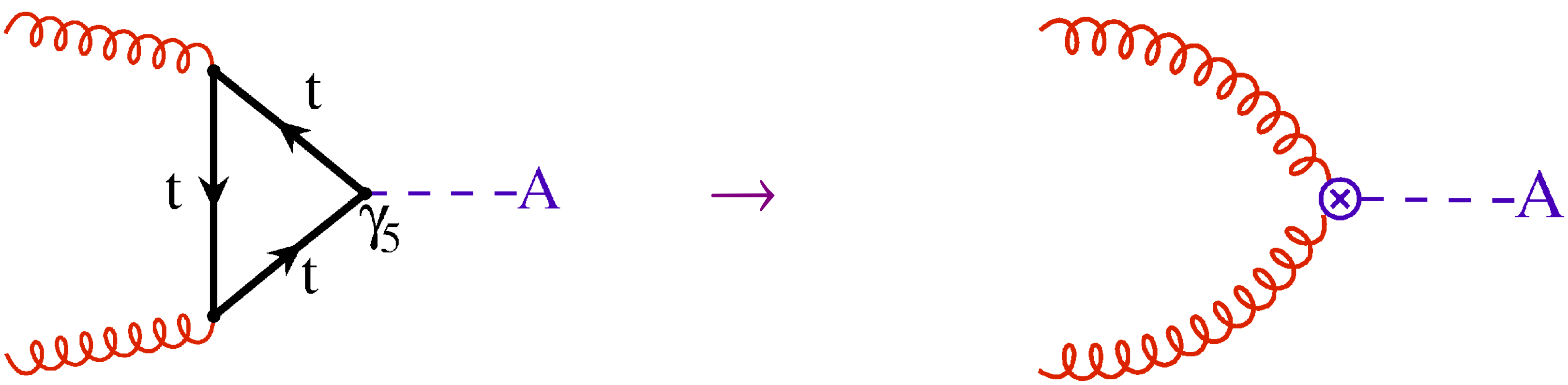
We will likely see super-partners first



Pseudoscalar Production

Gluon fusion is also very important to pseudoscalar production and can also be described by an effective Lagrangian in which the top quark is integrated out. This effective Lagrangian coupling the pseudoscalar to gluons is:

$$\mathscr{L} = C_1 A\, \varepsilon_{\mu\nu\alpha\beta}\, G^{a,\mu\nu}\, G^{a,\alpha\beta} + \ldots$$



SUSY Higgs Production

SUSY Higgs production has also been computed using massive fermions to NLO.

[Spira, Djouadi, Graudenz, Zerwas]

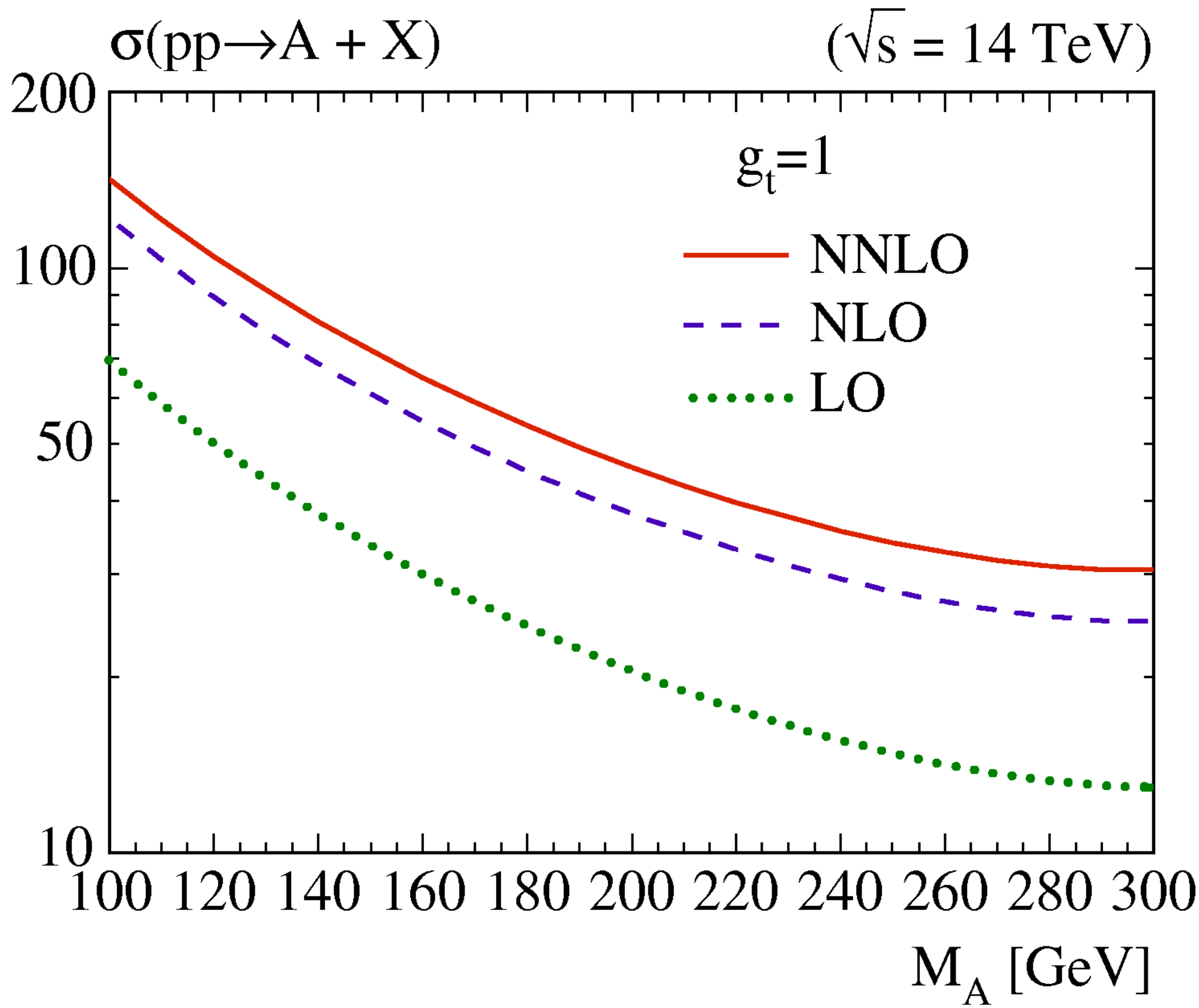
NNLO Pseudoscalar production is computed in the same way as scalar production. But the effective Lagrangians are only valid for top quark loops! The same three groups again obtained exact analytic agreement.

[Harlander, WK; Anastasiou, Melnikov; Ravindran, Smith, van Neerven]

For scalar Higgs production in SUSY, you can also add squark/gluino effects.

[Harlander, Steinhauser; Dawson, Djouadi, Spira]

Pseudoscalar Production in Gluon Fusion



H/A Couplings

For the pseudoscalar (and for H^0 in the decoupling limit) the couplings to "up-type" fermions are suppressed by $\tan\beta \equiv v_u/v_d$ while those to "down-type" fermions are enhanced by $\tan\beta$. This presents a problem for gluon fusion calculations:

For $\tan\beta$ significantly larger than 1, b-quark interactions are important. But ... one cannot formulate an effective Lagrangian by integrating out the b-quark to produce ~100 GeV Higgs bosons! An NNLO calculation would require massive 3-loop diagrams.

A new production mode at large tan β

The importance of b-quark couplings at large tan β suggests a new inclusive production mechanism:

$$b\bar{b} \to H$$

Since b-quark distributions are generated by gluon splitting the true parent process is

$$gg \to b\bar{b}H$$

The b-quark distribution resums large logs associated with the gluon splitting, but is fully consistent only if calculated to high enough order to include the parent process.

In this case, one must compute to NNLO.

$b\bar{b} \to H/A$ at NNLO

One can ignore the b-quark mass in this calculation, except where it enters into the Yukawa couplings. Other b-quark mass effects are suppressed by factors of m_b^2/M_H^2.

In the $m_b \to 0$ limit, the partonic cross sections for $b\bar{b} \to H$ are identically equal to those for $b\bar{b} \to A$.

$b\bar{b} \to H/A$ can dominate at large $\tan\beta$ because

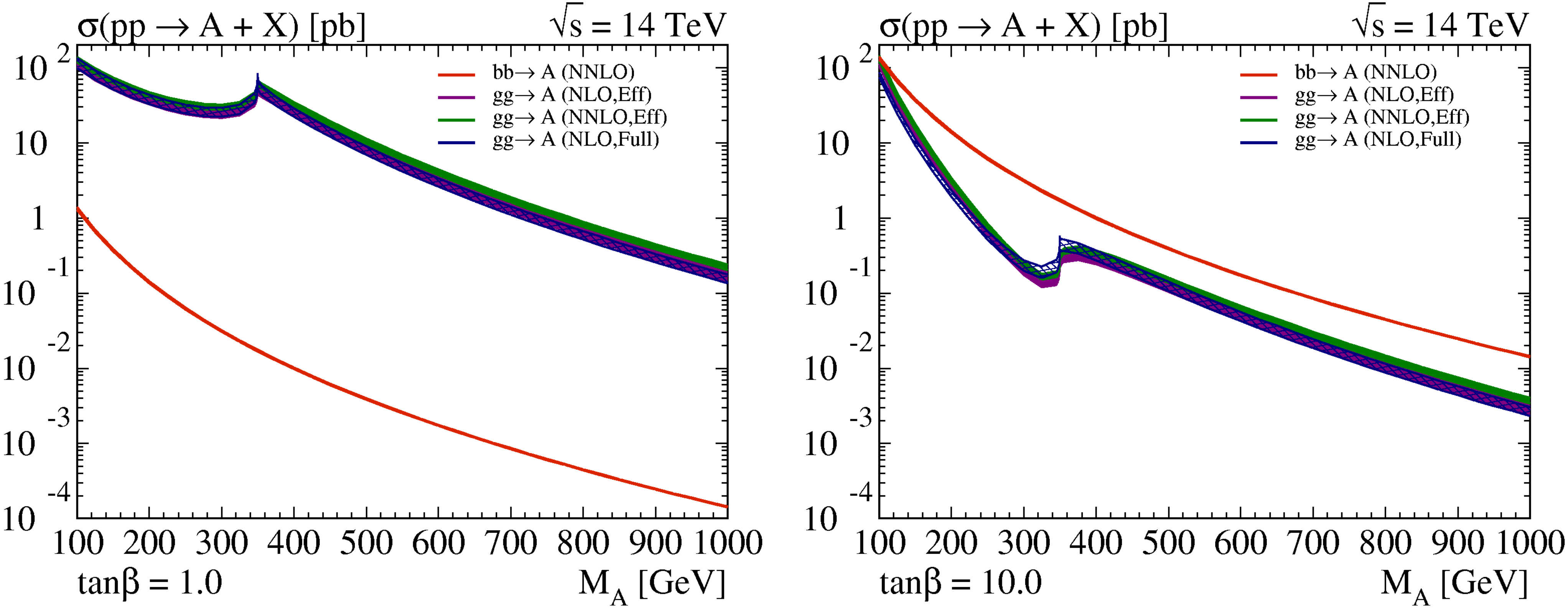
$\sigma_{bb} \sim m_b^2/M_H^2 \tan^2\beta$ while

$\sigma_{gg} \sim A \cot^2\beta + B\, m_b^2/M_H^2 + C\, m_b^4/M_H^4 \tan^2\beta$

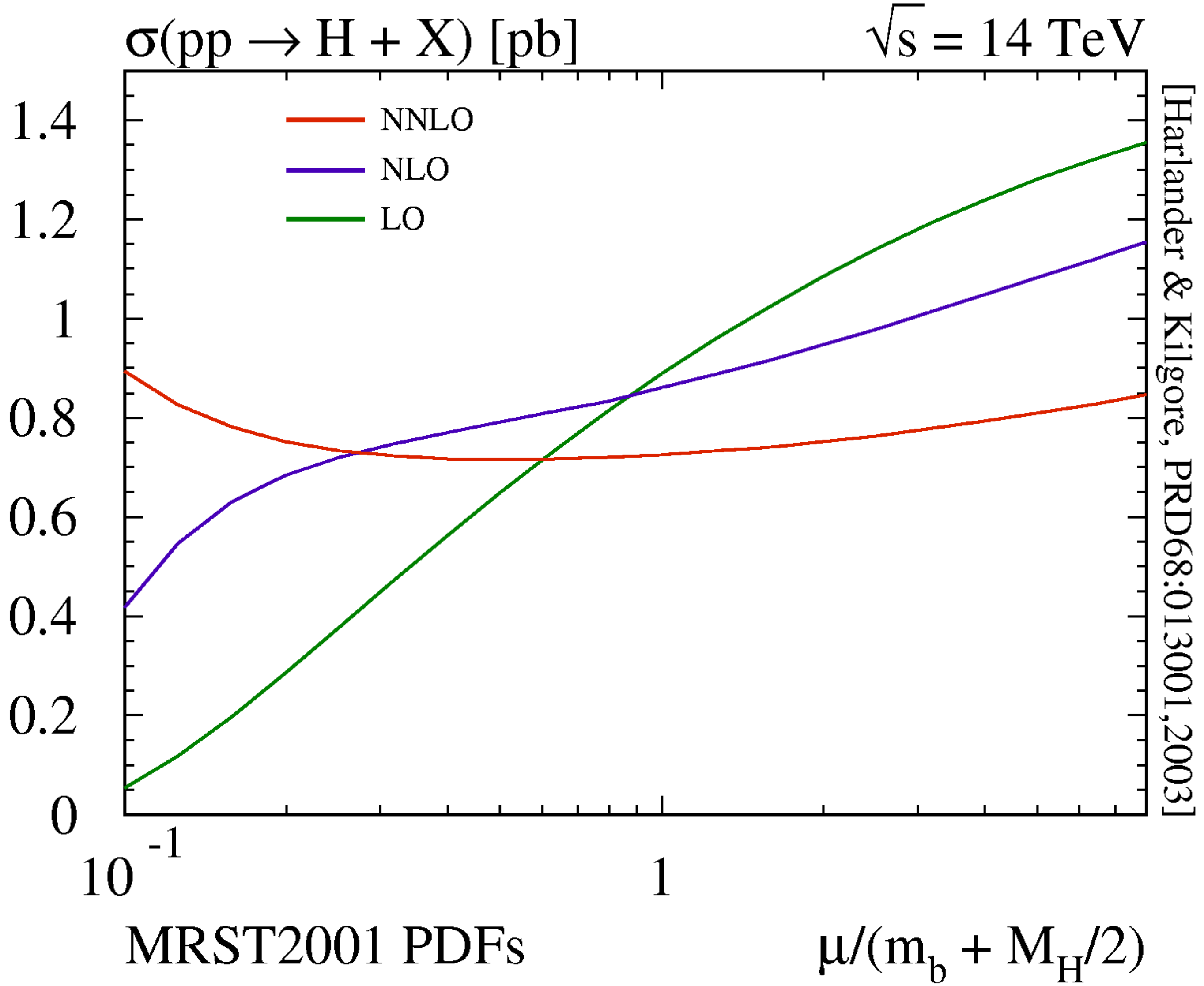
$b\bar{b}\rightarrow A$ versus $gg\rightarrow A$

At small tan β, b quark fusion is tiny.

At large tan β, it dominates.

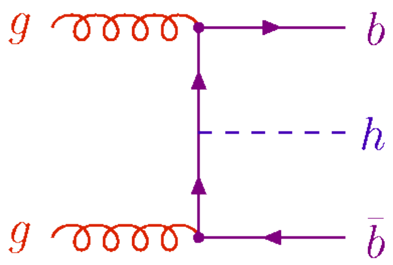


Scale Dependence of $b\bar{b} \to H/A$ at LHC



Results for gg→b$\bar{b}$H @ NLO

This calculation goes to order α_s^3 and includes more of the log-enhanced terms.



This result is flexible in that it can be applied to the

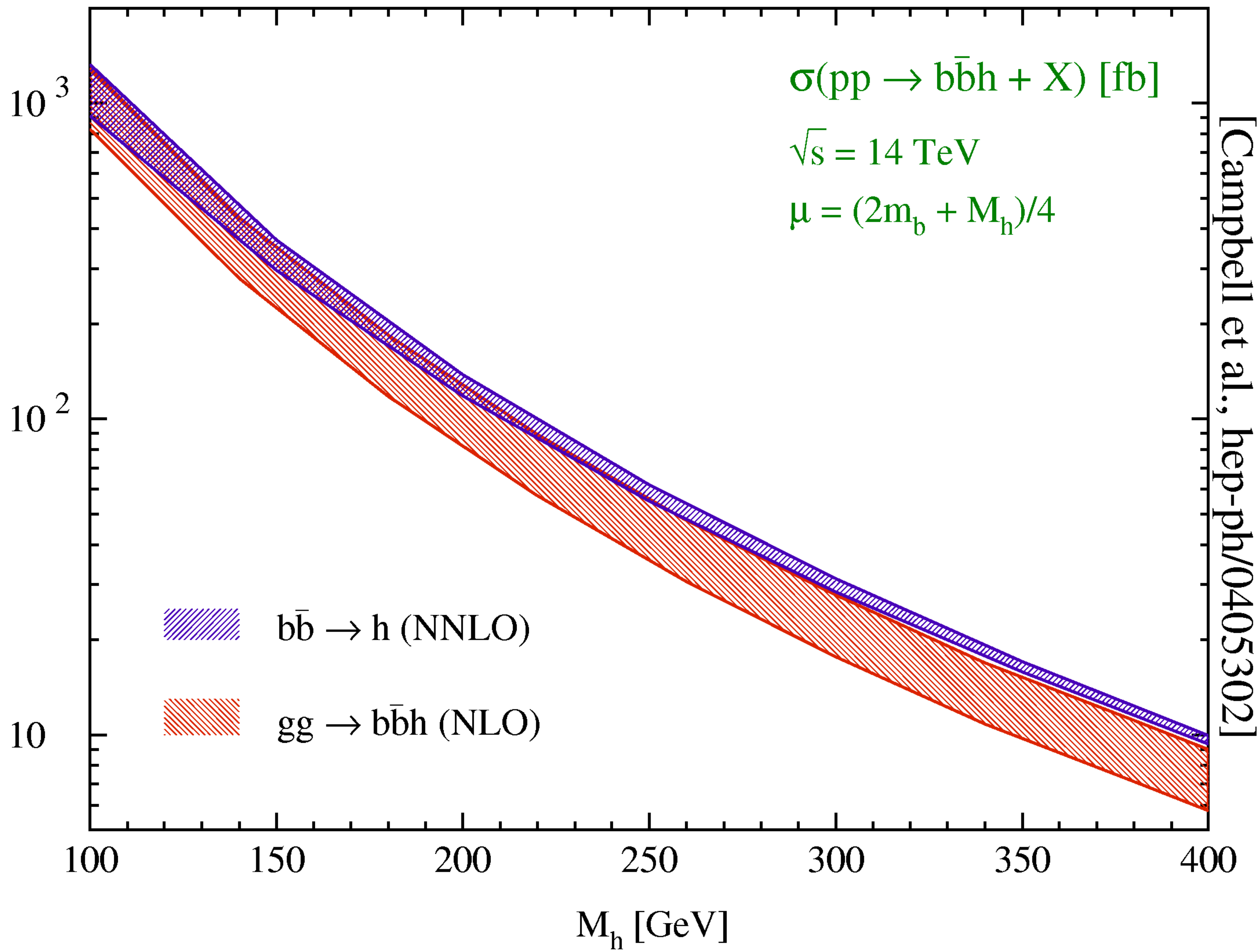
- Double tag mode
- Single tag mode
- Inclusive mode

But it still suffers from un-resummed log-enhanced terms in (semi-)inclusive modes.

[Dittmaier, Krämer, Spira; Dawson, Jackson, Reina, Wackeroth]

Results for inclusive $gg \to b\bar{b}H$

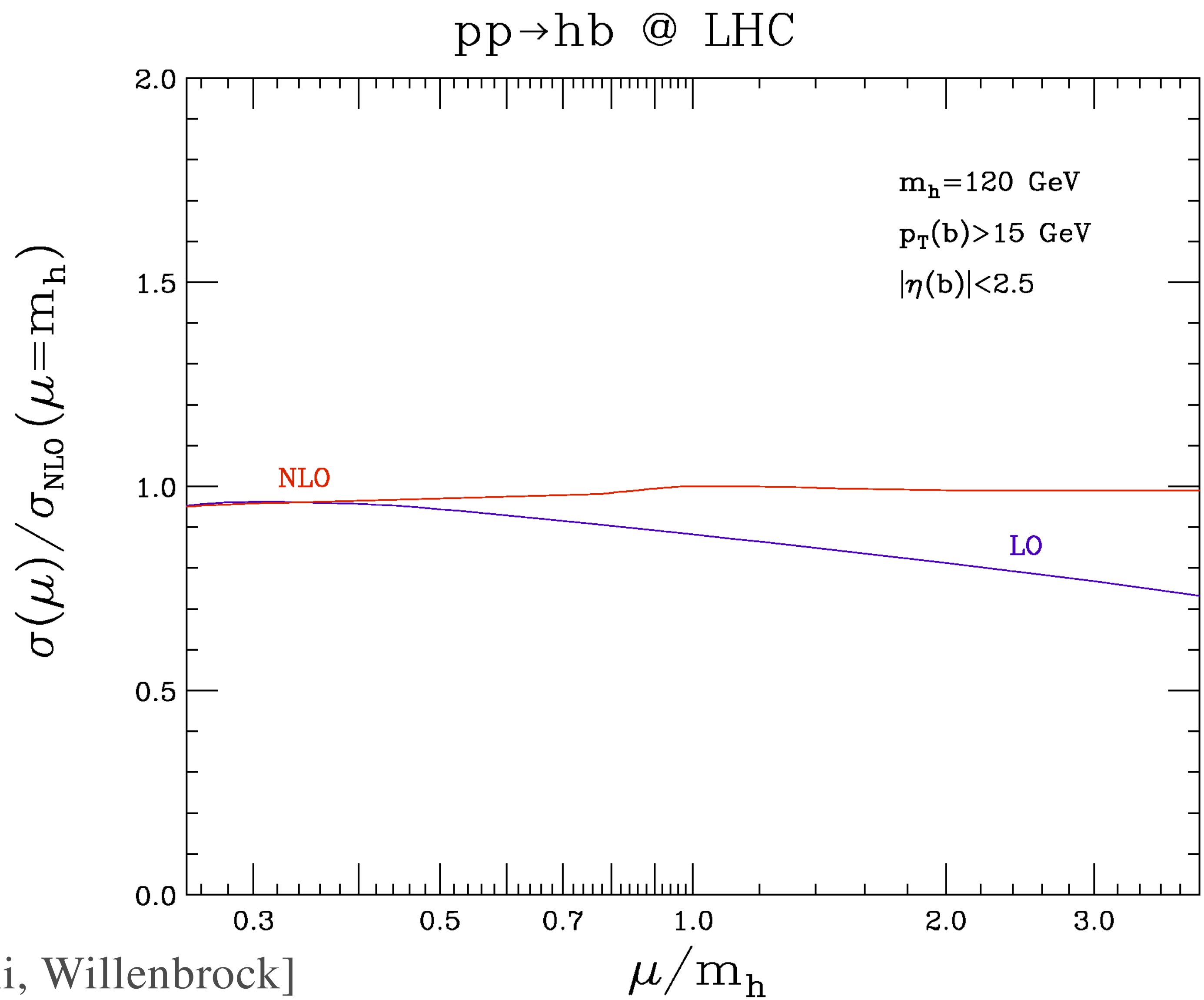
The good behavior of $b\bar{b} \to H$ and the favorable comparison to $gg \to b\bar{b}H$ largely settles the controversy over b parton distributions.



Higgs + b quark Production

A more promising channel may be H+b production. The extra b tag and the Higgs transverse momentum greatly improve detection efficiency.

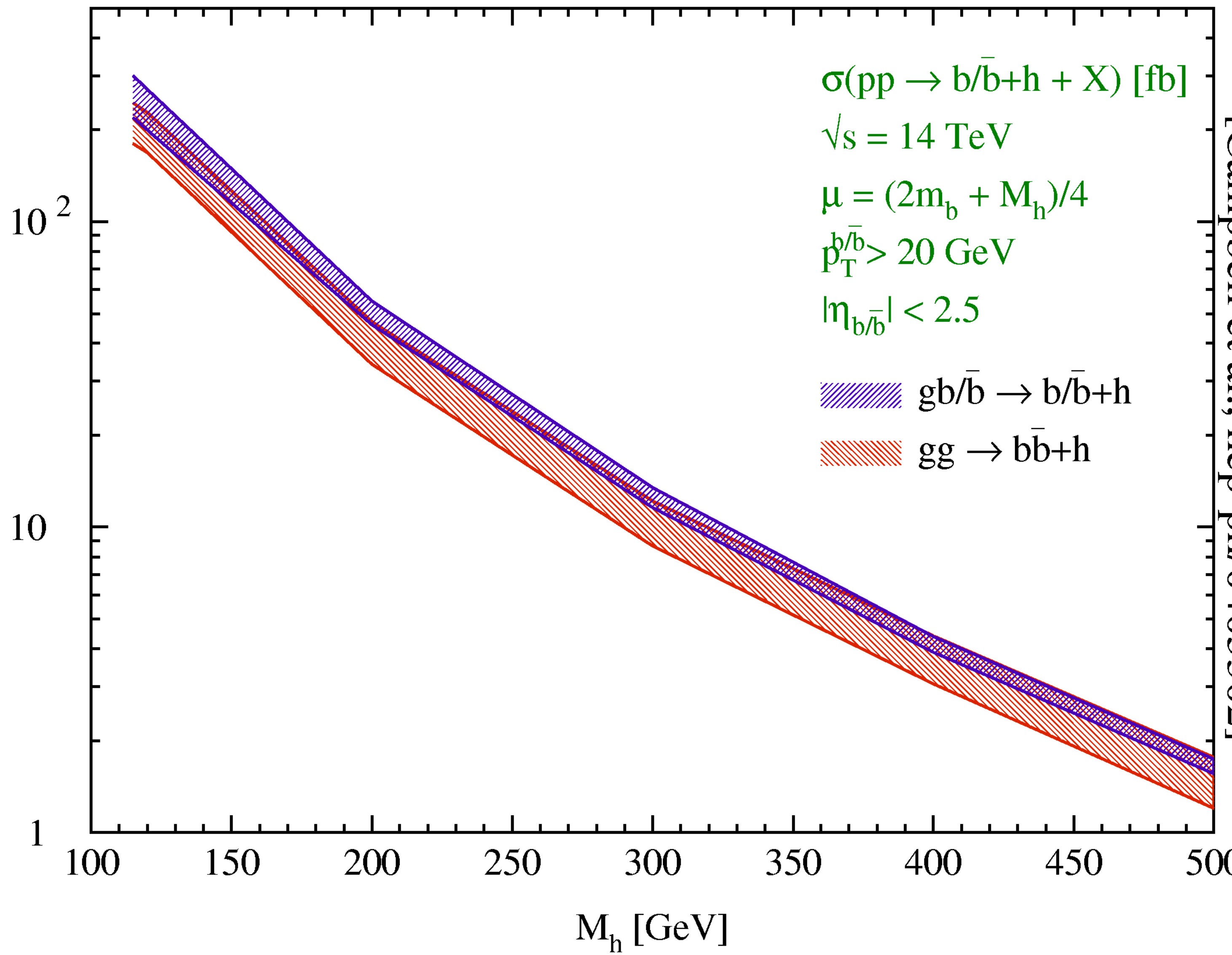
With only one b quark in the initial state, NLO is sufficient to obtain a reliable result.



[Campbell, et al., PRD67 095002]

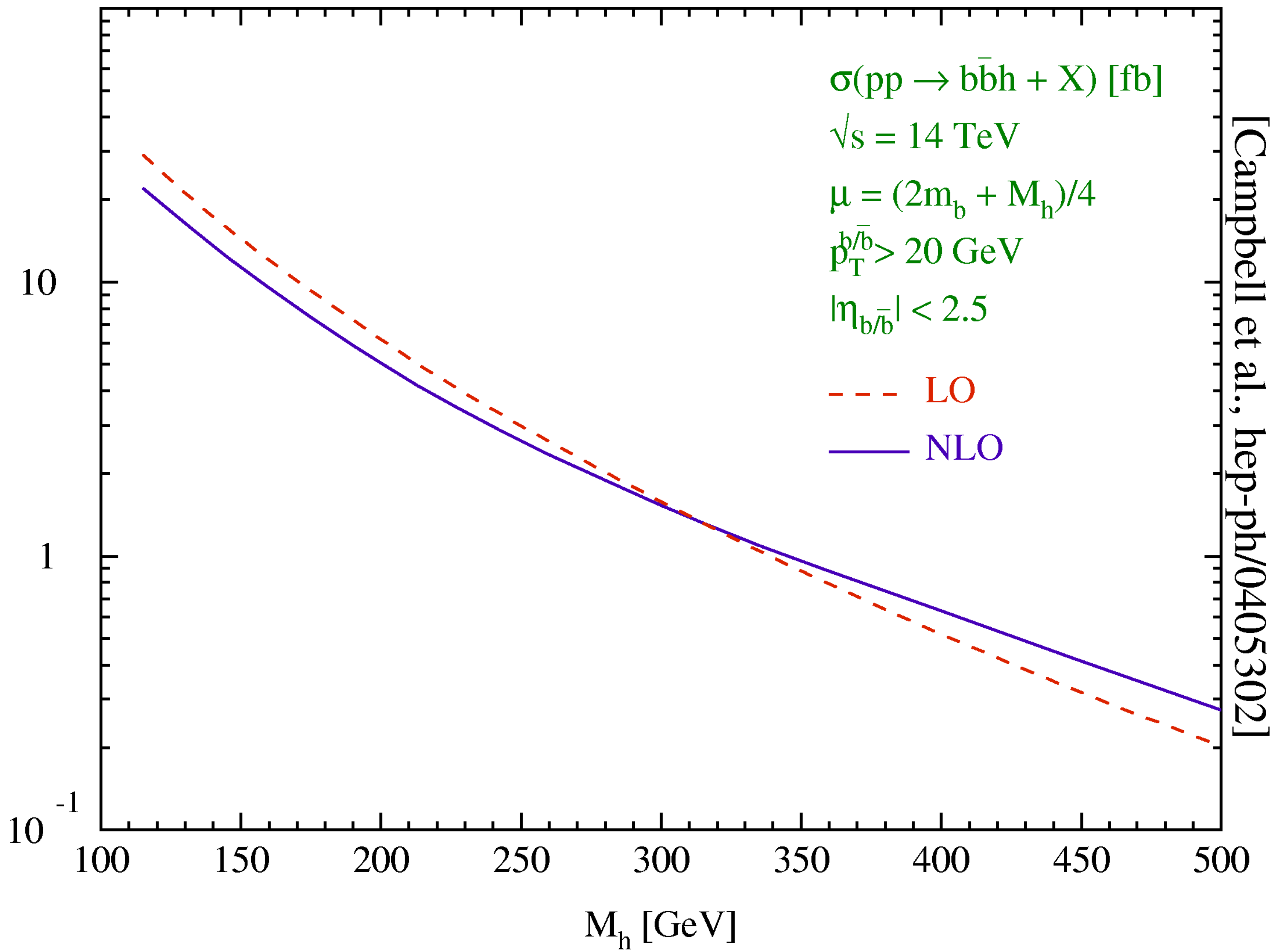
[Campbell, Ellis, Maltoni, Willenbrock]

Compare bg→bH(NLO) to gg→b$\bar{b}$H(NLO)

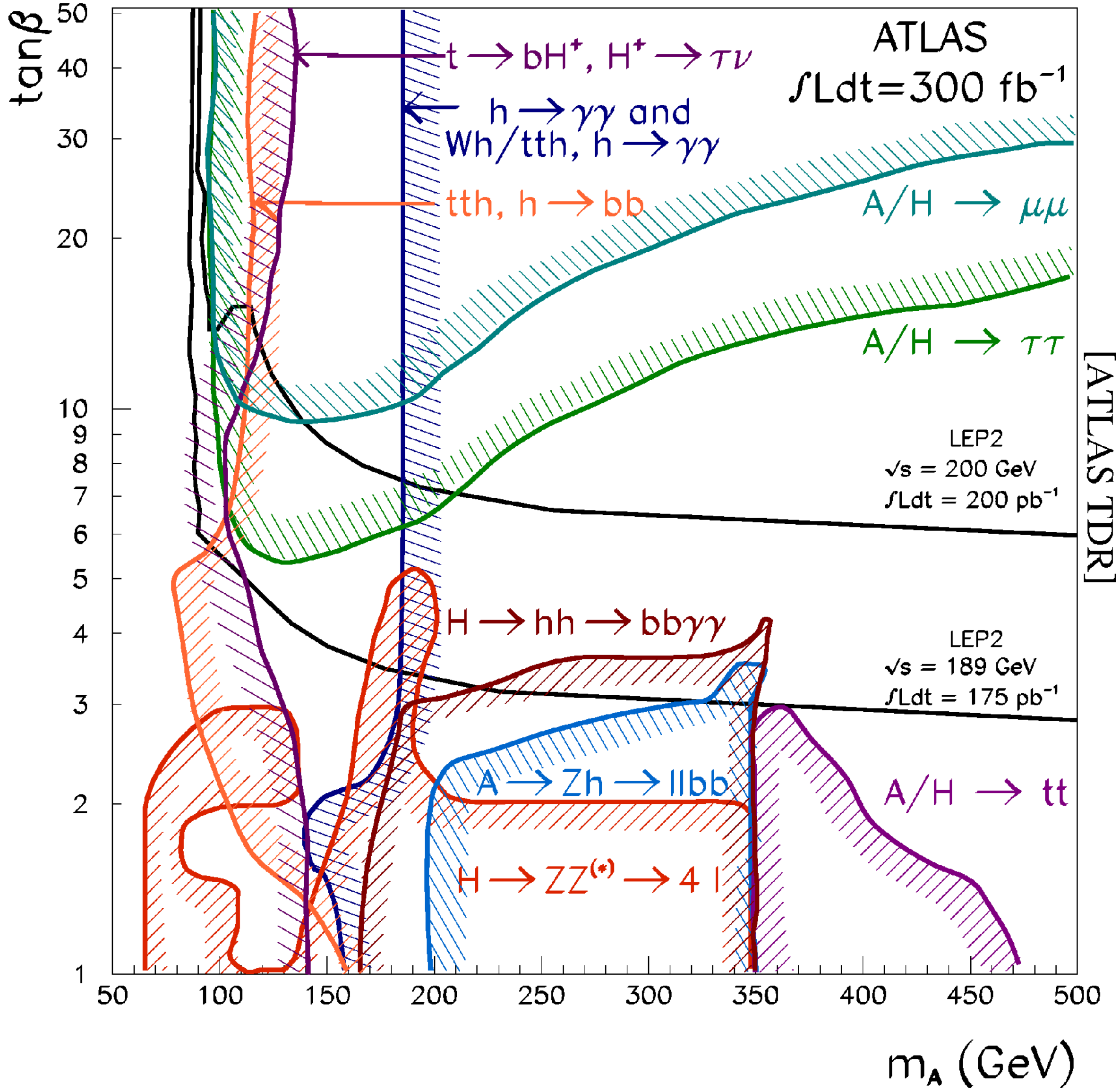


[Campbell et al., hep-ph/0405302]

$gg \rightarrow b\bar{b}H$ with two tagged b quarks

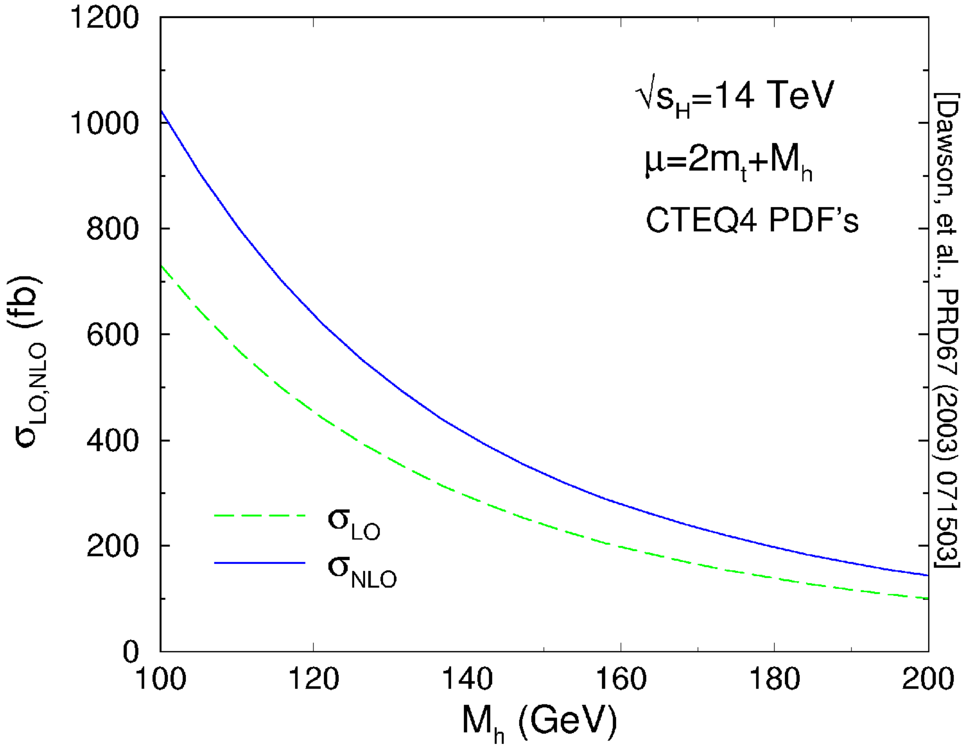


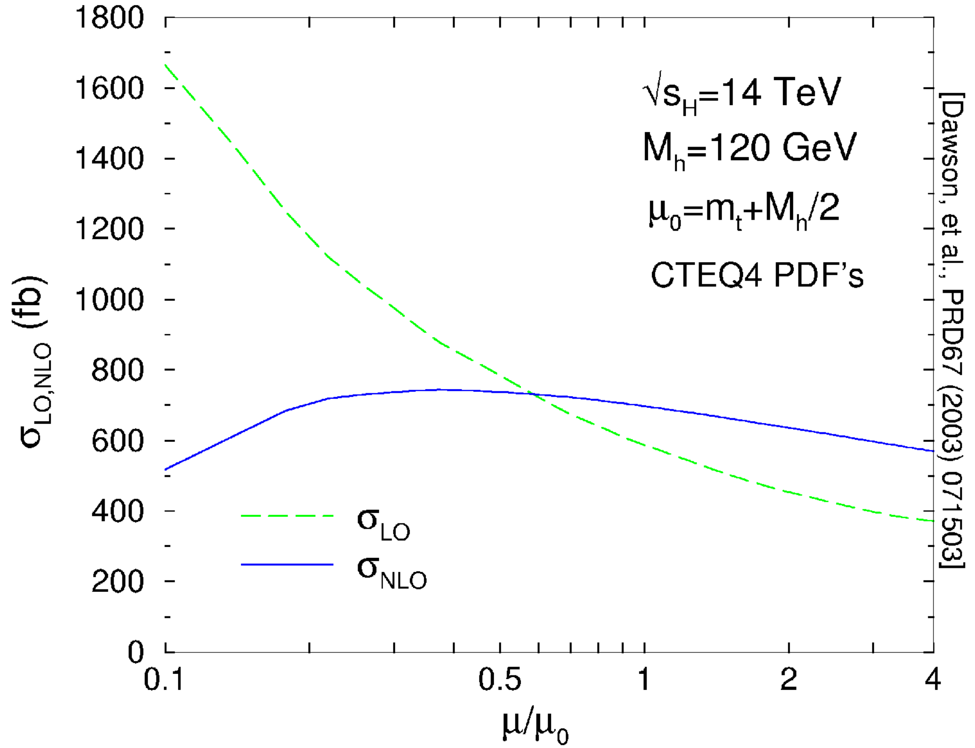
Finding SUSY Higgs at LHC



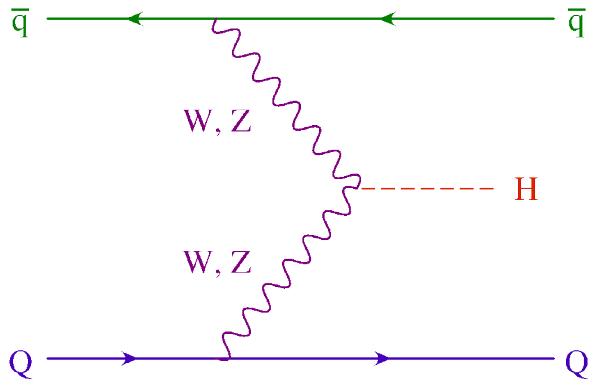
$t\bar{t}H$ production at NLO

This process serves as a discovery mode for a light Higgs and gives information on the top Yukawa coupling. [Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas; Dawson, Jackson, Orr, Reina, Wackeroth]





Weak Boson Fusion



NLO corrections have been known for some time.

[Han, Willenbrock]

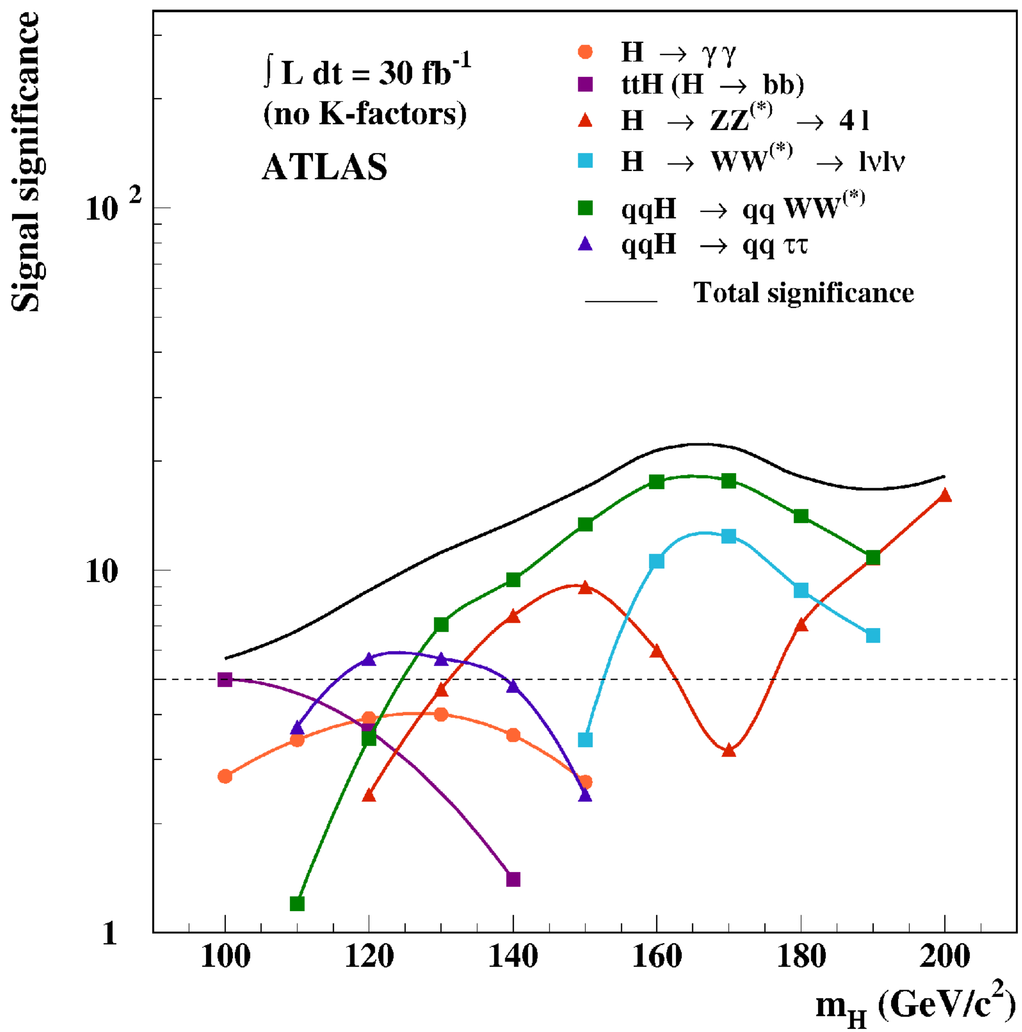
Recently implemented in multi-purpose Monte-Carlo calculation. [Figy, Oleari, Zeppenfeld

Offers discovery potential in the intermediate mass range and gives a good handle on measuring couplings. [Hagiwara, Kauer, Plehn, Rainwater, Zeppenfeld]

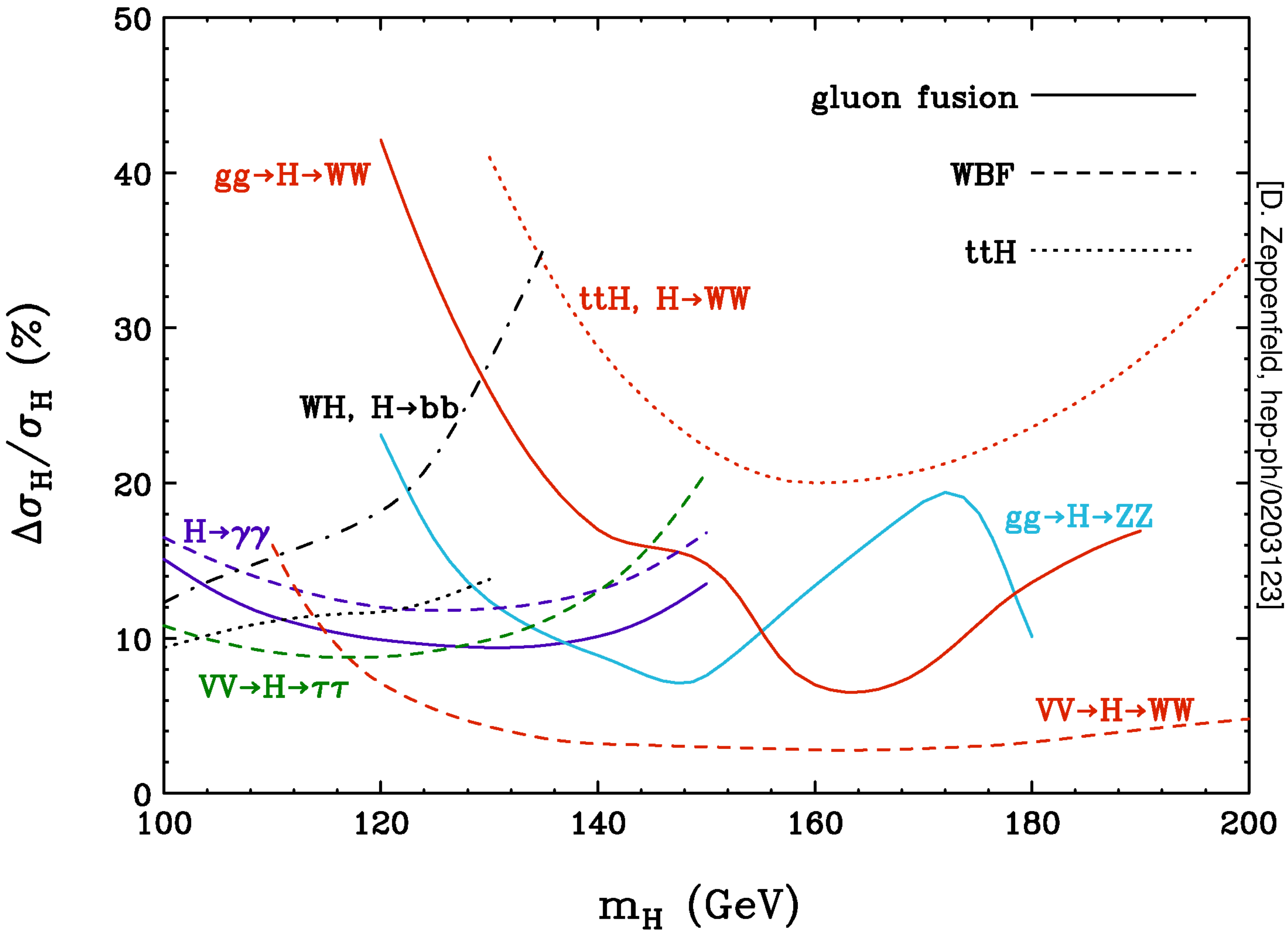
$gg \to H+2j$ background computed in full theory.

[Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld]

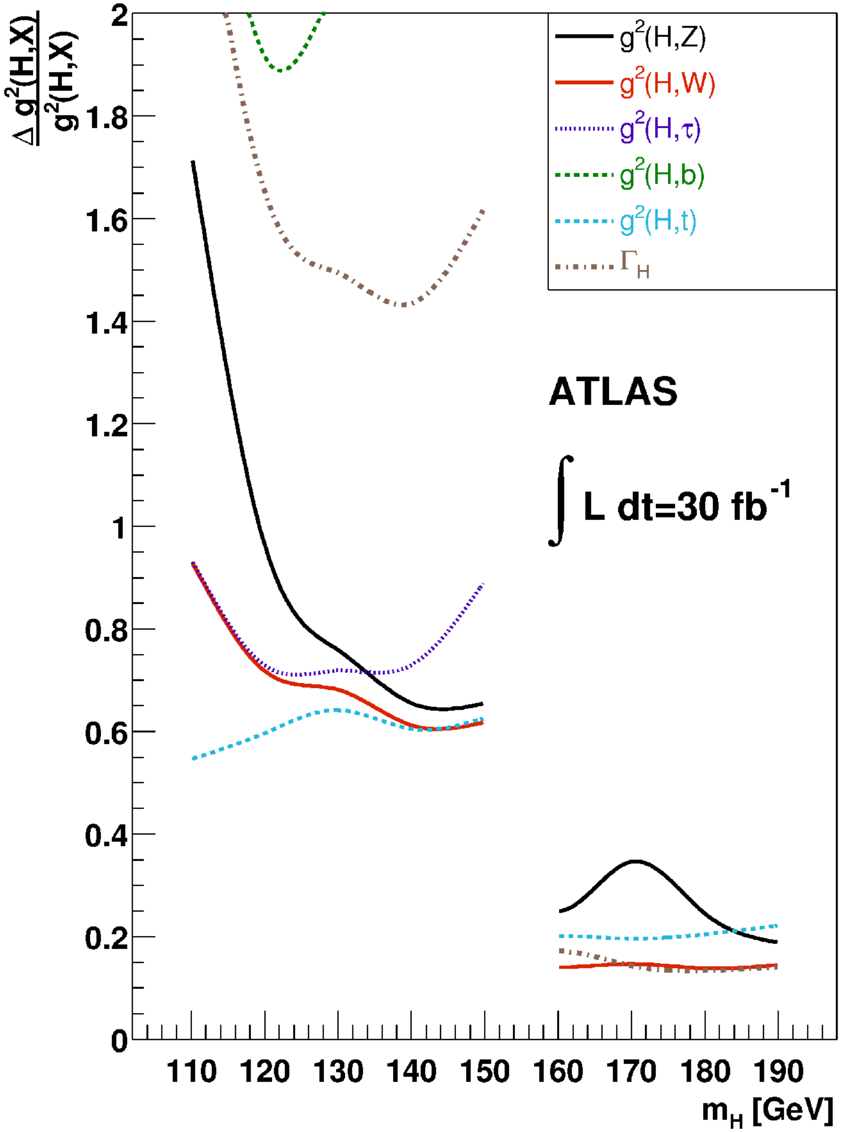
Higgs Discovery through Weak Boson Fusion

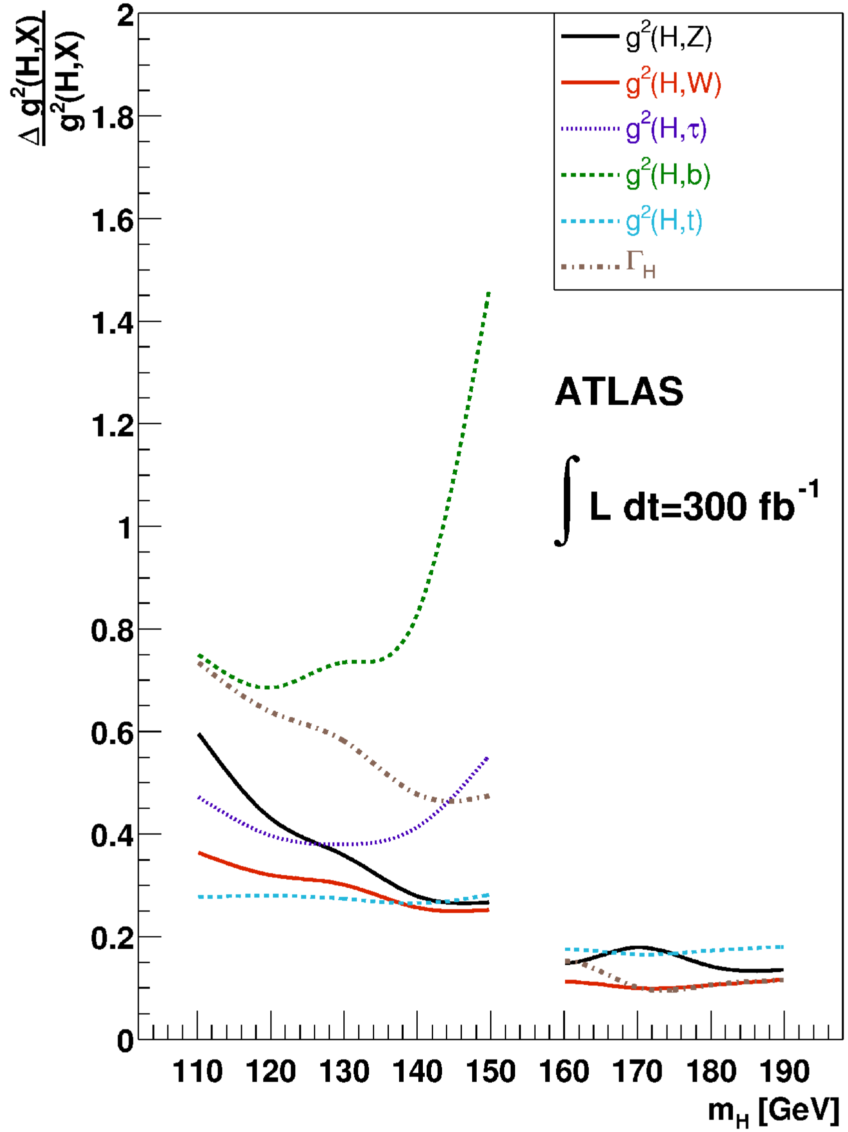


Expected precision in $\sigma \cdot BR$



Expected Precision of Absolute couplings





LHC Summary

We are well positioned to discover the Higgs at the LHC. Some signals will take years of running to develop, but we know how to attack the problem.

We will be able to measure couplings and branching ratios with reasonable precision, but hadronic uncertainties in both detection and in the production cross section will limit precision.

Conclusions

There has been great progress in Higgs physics in the last few years.

- Inclusive production is known to NNLO.
- Some distributions at NNLO are coming.
- Threshold, Q_T and joint resummations are known.
- b-quark distributions established as consistent.
- Associated production processes known to NLO.
- Important backgrounds also known to NLO.

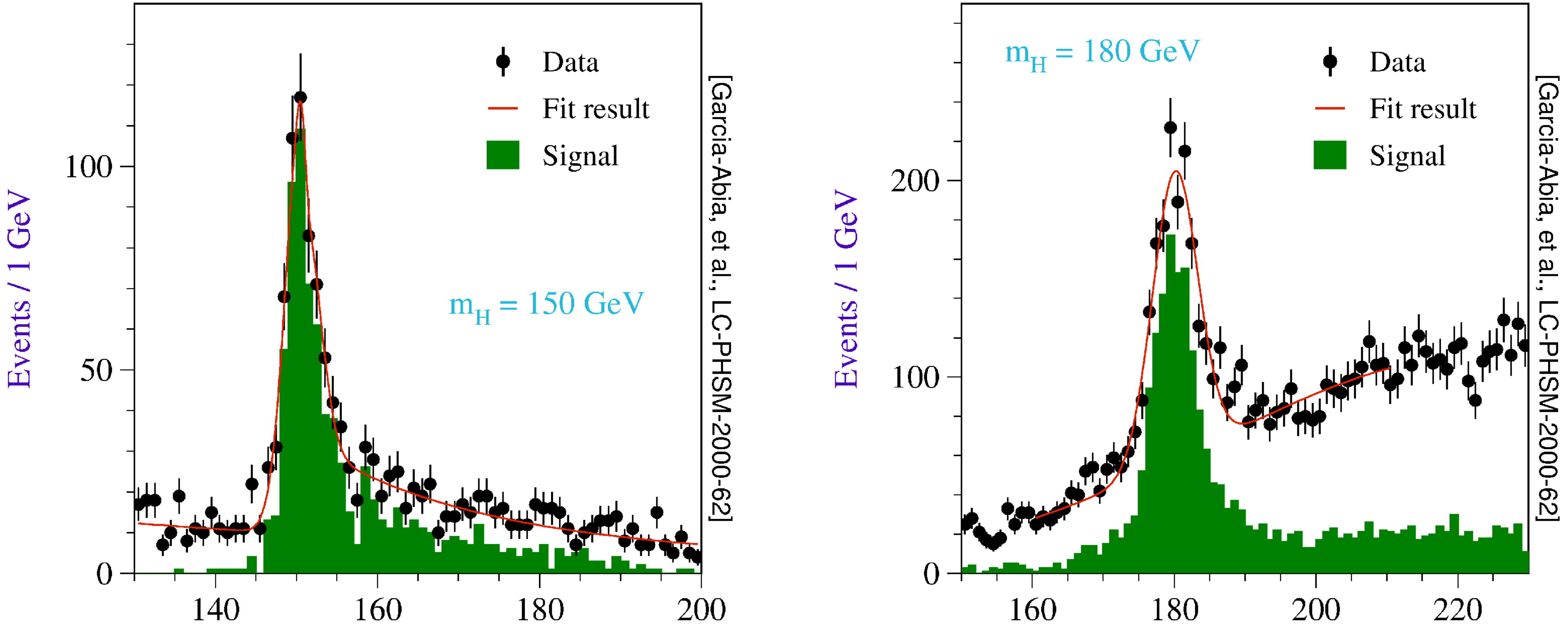
Higgs Bosons at a Linear Collider:

We want to measure all we can at the LHC, but we should remember the importance of the Linear Collider to the program of Higgs studies.

The Linear Collider will be able to measure Higgs properties with phenomenal precision and will allow us to fully understand those components of the symmetry breaking sector that are within its kinematic reach.

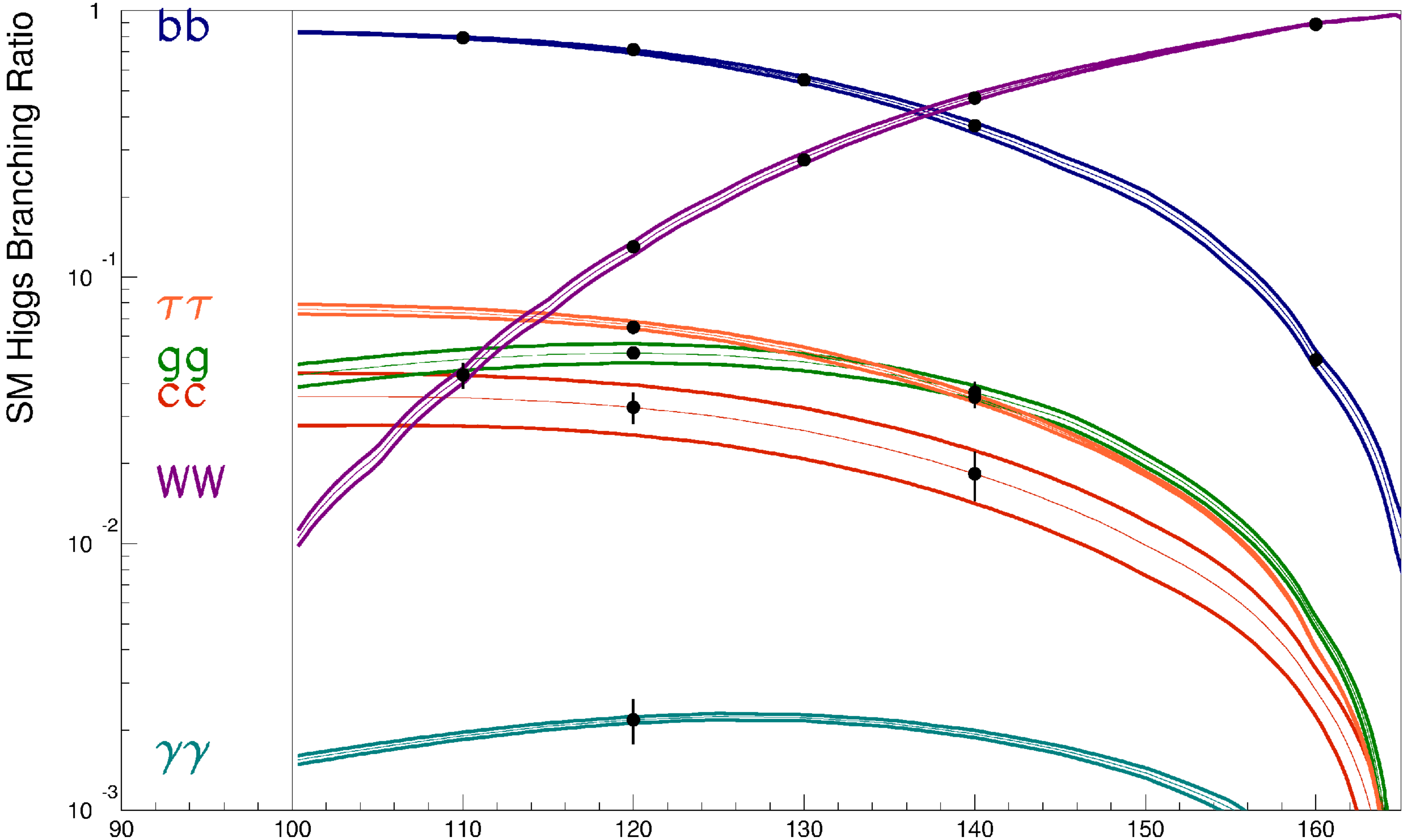
Higgs Discovery at a Linear Collider

The linear collider would be a good discovery machine within its kinematic reach.



Higgs Couplings at a Linear Collider

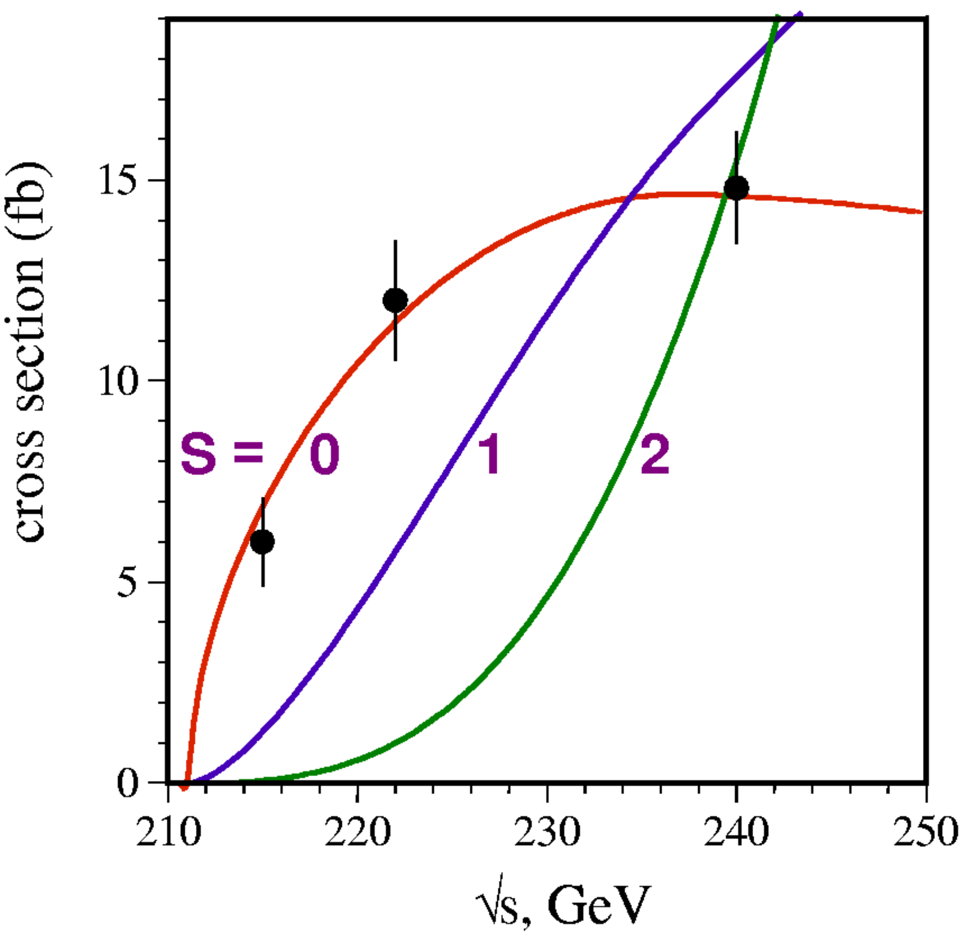
If the Higgs mass is below ~160 GeV, many branching ratios can be precisely measured.

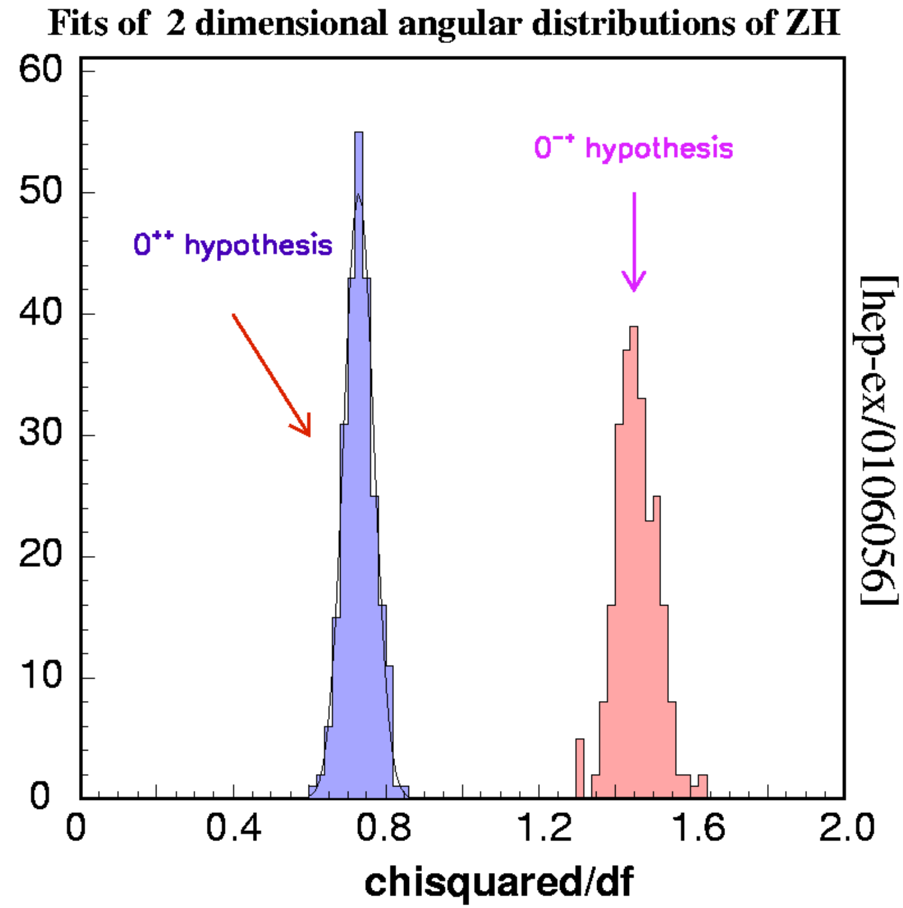


[Battaglia & Desch, hep-ph/0101165]

Spin and CP at a Linear Collider

The spin and CP quantum numbers can also be definitively measured at a linear collider





[hep-ex/0106056]