Higgs Physics and QCD
(part 2)

William Kilgore
Brookhaven National Laboratory

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Outline

- The Standard Model & the Higgs Mechanism

- Agents of Electro-weak Symmetry Breaking

- The Higgs Boson

- QCD and the Higgs – Hadronic Production

- Impact of Radiative Corrections

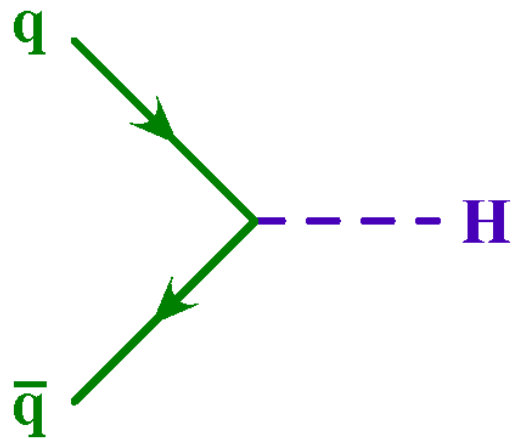- Elements of Precision Higgs Studies

Higgs Production in QCD

How can the Higgs be produced at hadron colliders?

- Quark annihilation?
- Higgs-strahlung?
- Weak boson fusion?
- In association with heavy quarks?
- Through heavy quark loops?

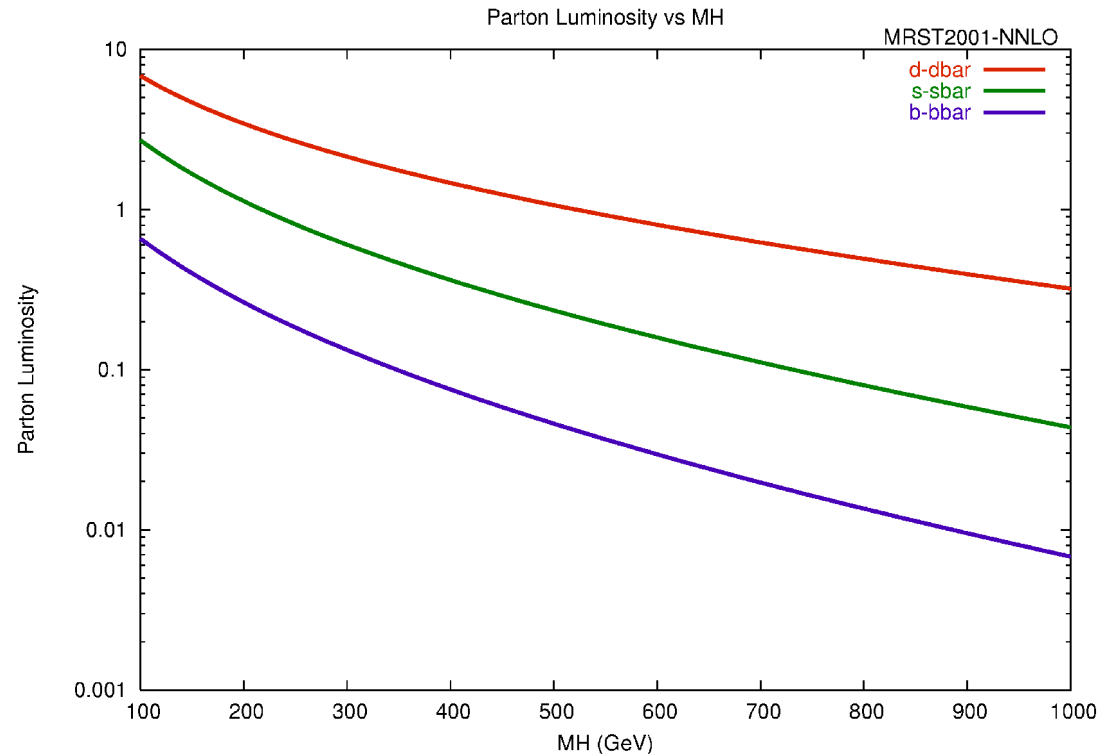Each process plays a role.
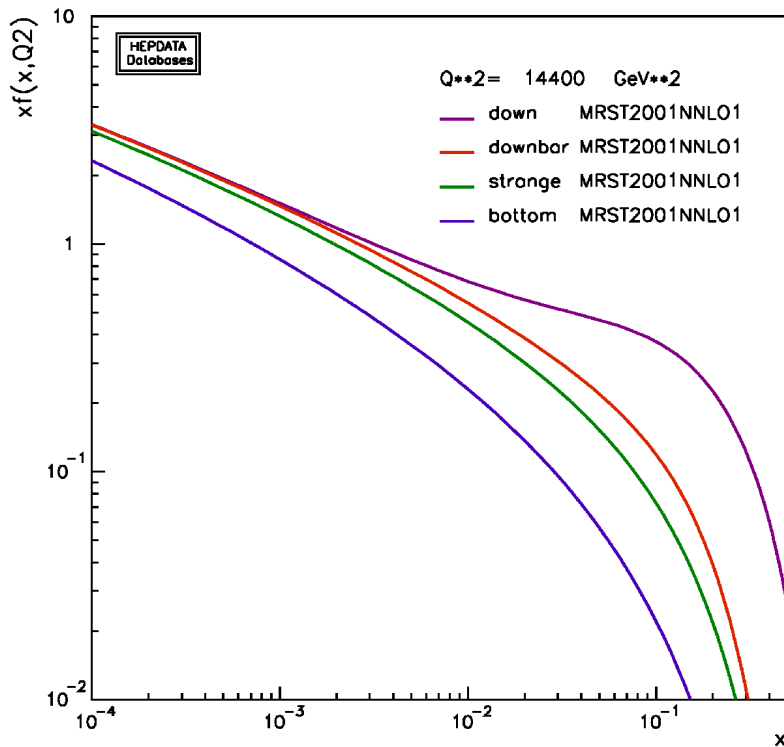
Quark Annihilation

The Higgs couples to mass. The quarks in the proton are much heavier than the electron, but are they heavy enough to produce a viable cross section?

$$\sigma_{\mathrm{LO}}(q\bar{q} \to H) = \frac{\pi G_{\mathrm{F}}}{3\sqrt{2}} \frac{\overline{m}_q^2}{M_H^2} \delta\left(1 - \frac{M_H^2}{\hat{s}}\right)$$

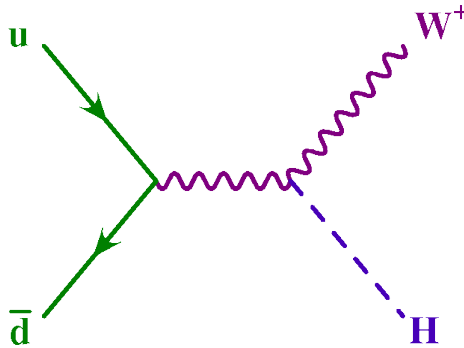$\overline{m}_q$ is the running mass, evaluated at $\mu \sim M_H$.

Quark Annihilation (cont.)

u and d quarks have much larger parton luminosities than s, c or b quarks.

But it's not enough. $m_d^2/m_b^2 \sim 10^{-5}$, even if running is negected !
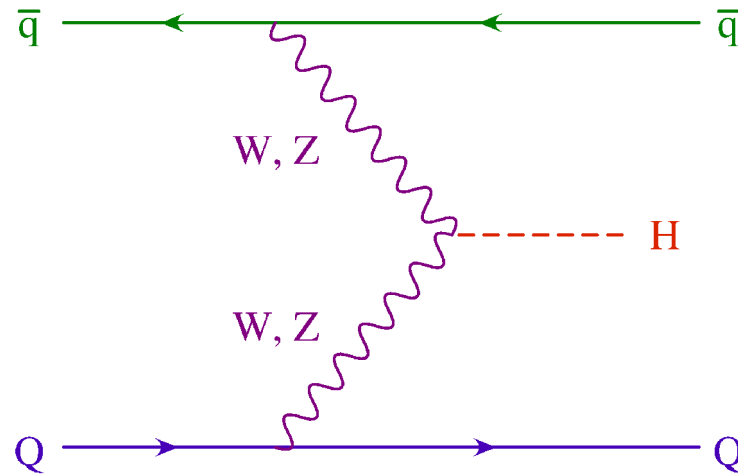
Higgs-strahlung $q\bar{q}{\to}W^{+}H$

Similar to $e^{+}e^{-}{\to}ZH$ Higgs-strahlung. The problem at hadron colliders is that it is a weak process with QCD backgrounds.
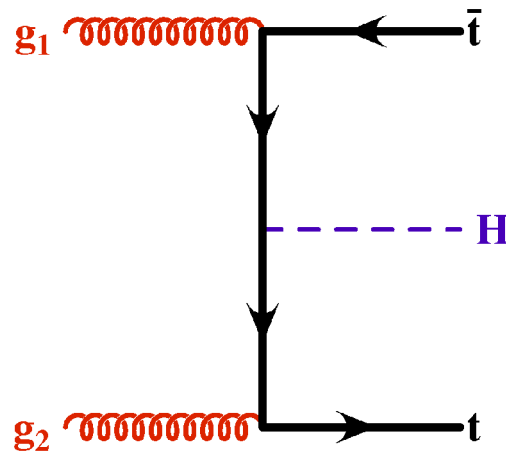
This is the discovery mode at the Tevatron, where it is near the end of the kinematic reach, but it is swamped by gluon induced backgrounds at LHC.

Weak Boson Fusion

Originally used for heavy Higgs studies. Identifiable signal makes it important for lower mass regions as both a discovery channel and a for measuring couplings.
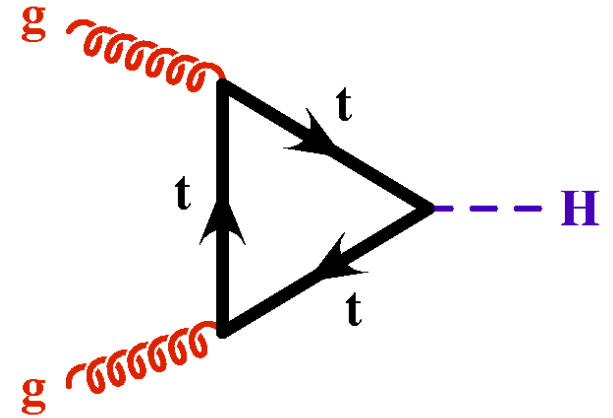
In Association with Heavy Quarks

- pp→t$\bar{\text{t}}$H

  Spectacular signal. C.M. Energy > 450 GeV !   Only viable for low mass region.

- pp→b$\bar{\text{b}}$H

  Closely related to b$\bar{\text{b}}$→H. More later.

Heavy Quark Loops

Somewhat surprisingly, gluon fusion via a virtual top-quark loop dominates Higgs production at hadron colliders.

$$\sigma_{\mathrm{LO}}(gg \to H) = \frac{\pi G_{\mathrm{F}}}{128\sqrt{2}} \left(\frac{\alpha_s(\mu)}{\pi} \right)^2 \tau^2 |1 + (1-\tau)f(\tau)|^2 \, \delta\left(1 - \frac{M_H^2}{\hat{s}} \right)$$

$$f(\tau) = \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau}}, & \tau \geq 1, \\ -\frac{1}{4}\left[\ln \frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi \right]^2, & \tau < 1, \end{cases} \qquad \tau = 4M_t^2/M_H^2,$$

Quark Annihilation vs Gluon Fusion

Comparing b$\bar{\text{b}}$→H to gg→H:

$$\lim_{\tau \to \infty} \sigma_{\text{LO}}(gg \to H) = \frac{\pi G_{\text{F}}}{288\sqrt{2}} \left(\frac{\alpha_s(\mu)}{\pi} \right)^2 \delta \left(1 - \frac{M_H^2}{\hat{s}} \right)$$
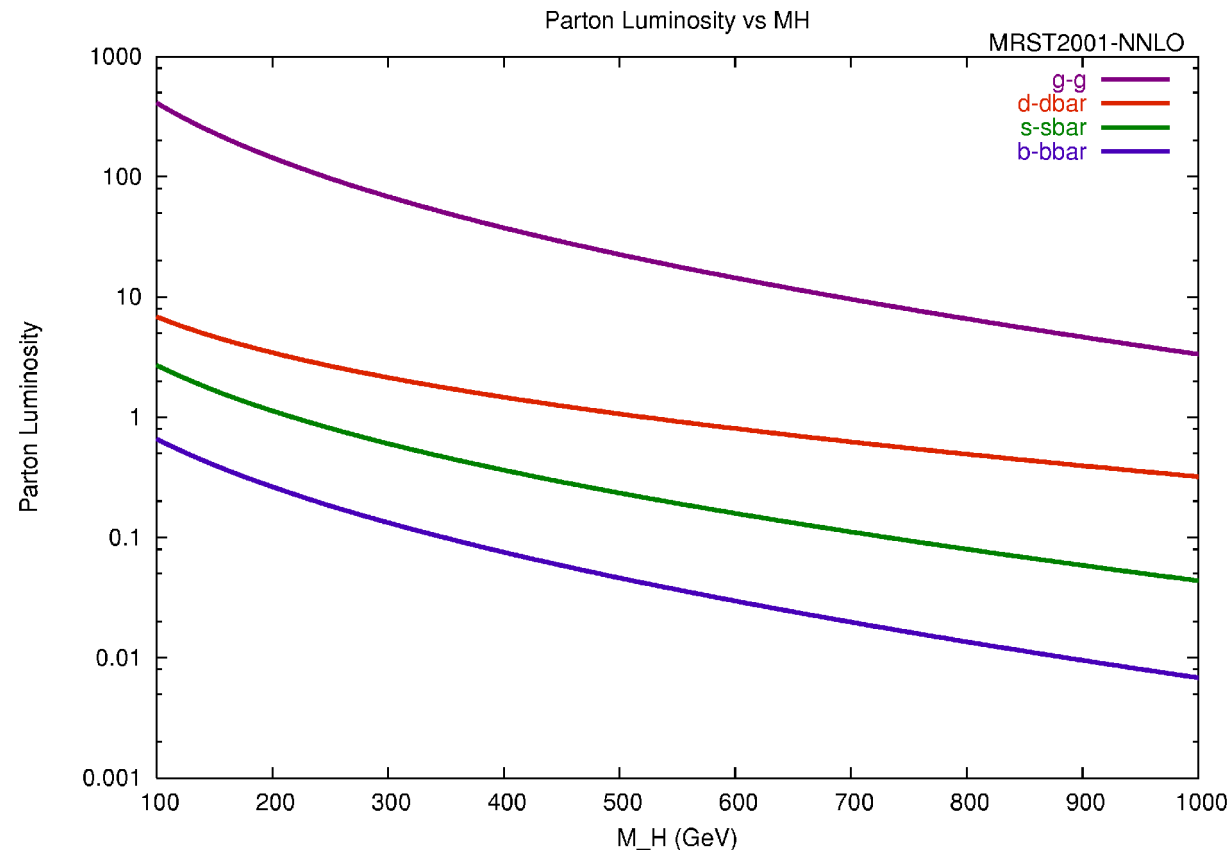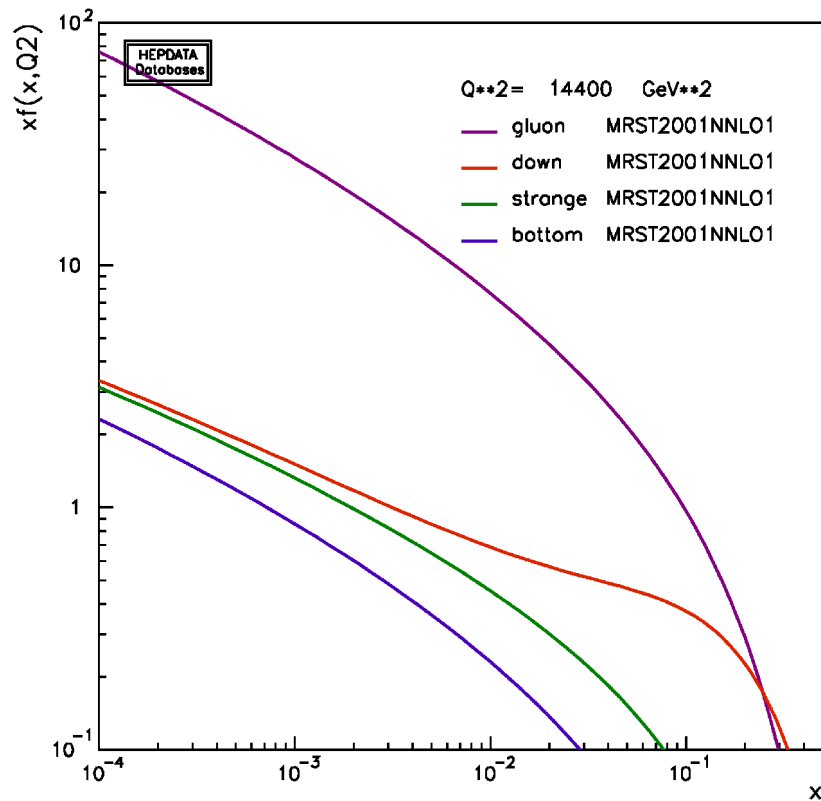
$$\sigma_{\text{LO}}(b\bar{b} \to H) = \frac{\pi G_{\text{F}}}{3\sqrt{2}} \frac{\overline{m}_b^2}{M_H^2} \delta \left(1 - \frac{M_H^2}{\hat{s}} \right)$$

For M_H~120 GeV, $\sigma_{b\bar{b}}/\sigma_{gg} \sim 50$,

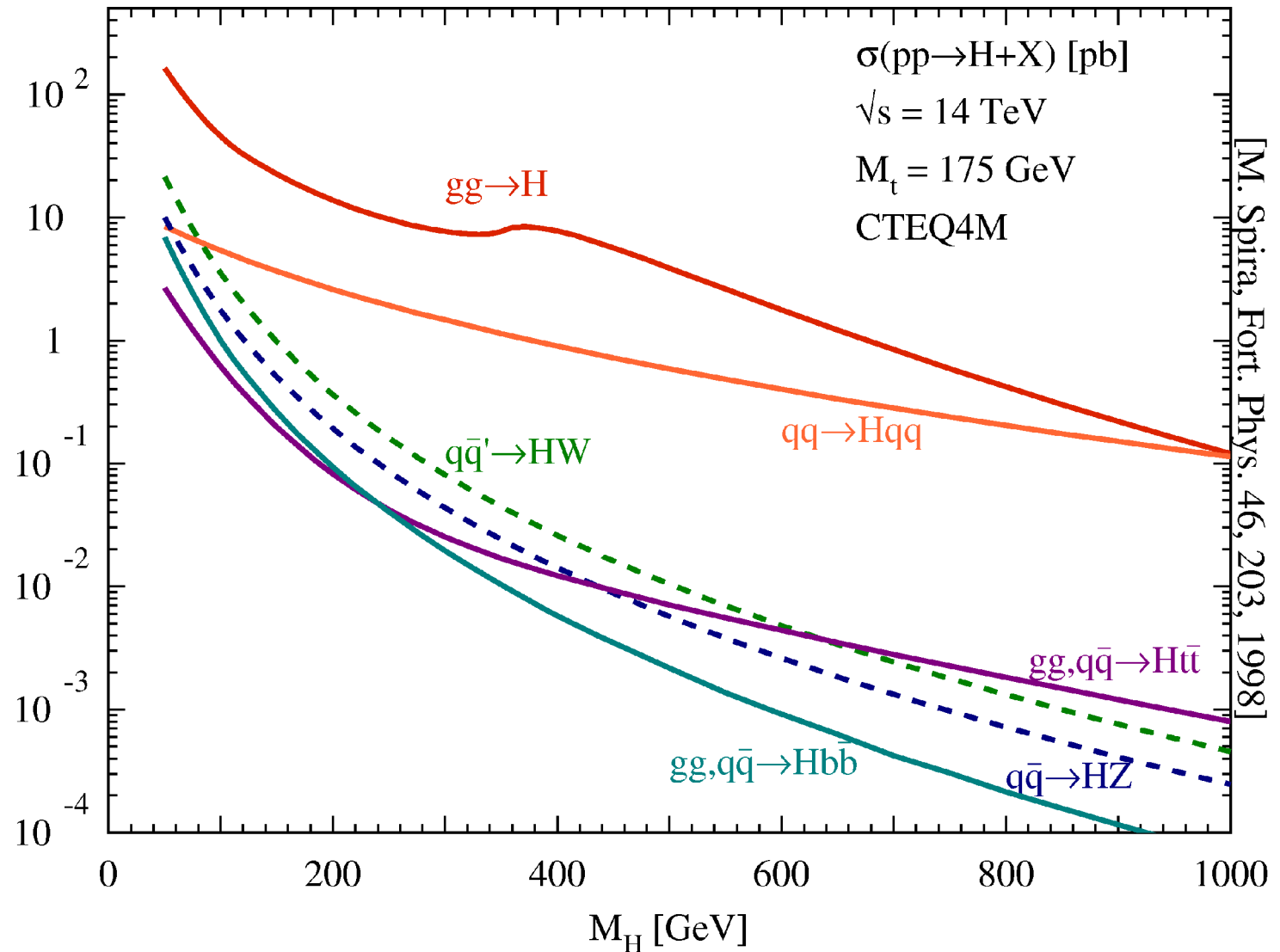For M_H~900 GeV, $\sigma_{b\bar{b}}/\sigma_{gg} \sim 1$.

The Gluon Luminosity is Huge

The large gluon luminosity more than makes up for any suppression from the loop factor!
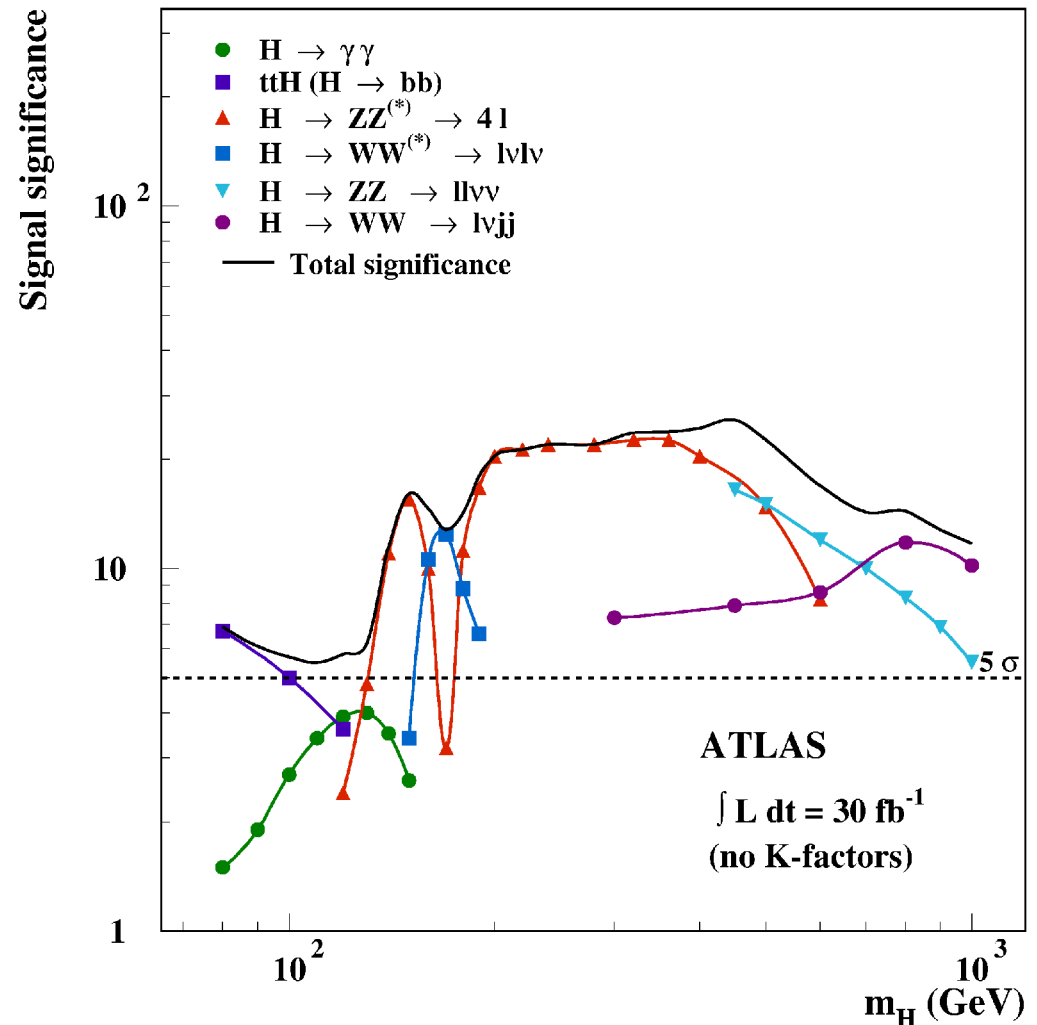
SM Higgs Production at the LHC

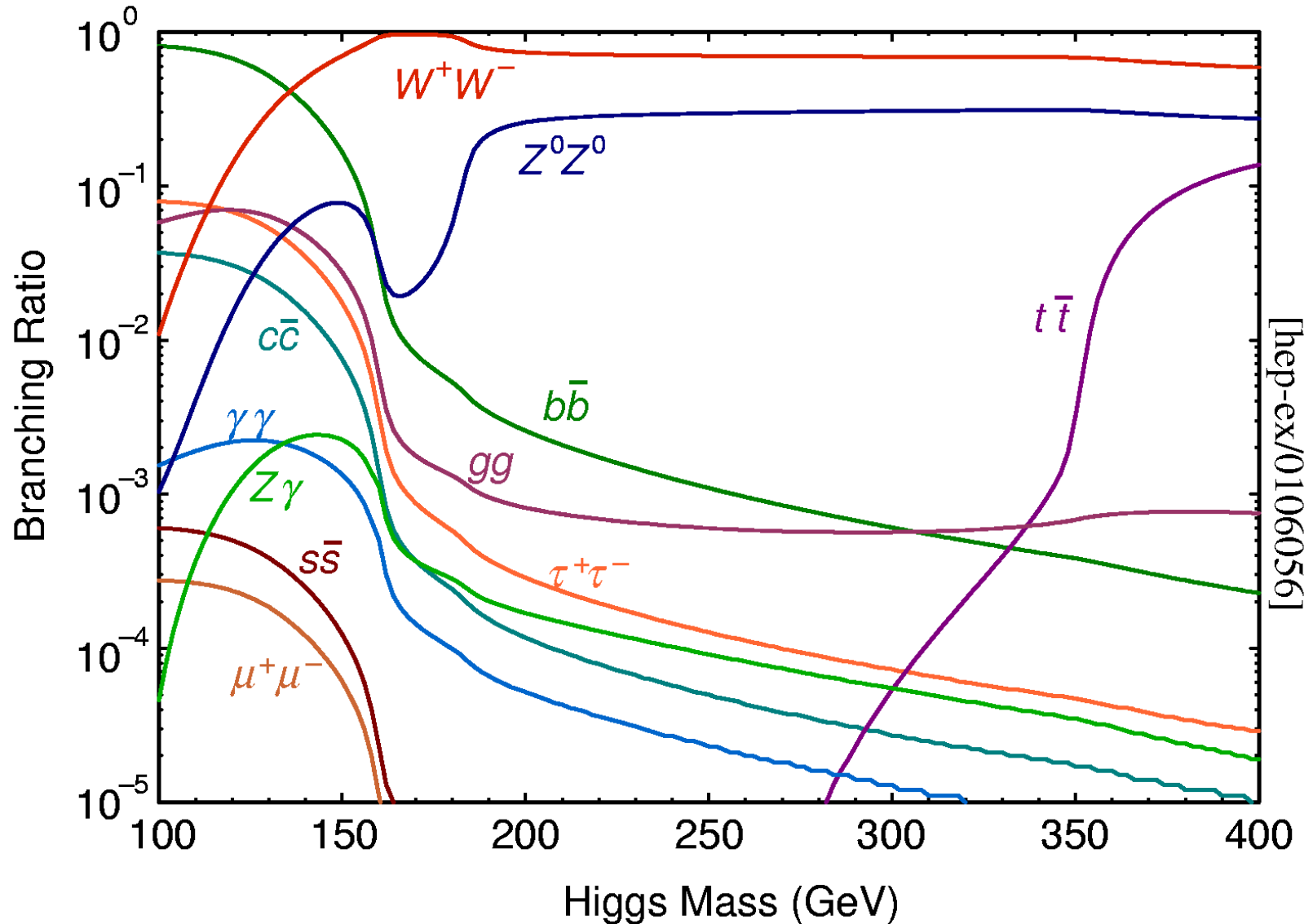The most important channels are gluon fusion, WBF and $t\bar{t}H$.

$\sigma(pp{\rightarrow}H{+}X)$ [pb]

$\sqrt{s} = 14$ TeV

$M_t = 175$ GeV

CTEQ4M

$gg{\rightarrow}H$

$qq{\rightarrow}Hqq$

$q\bar{q}'{\rightarrow}HW$

$gg,q\bar{q}{\rightarrow}Ht\bar{t}$

$gg,q\bar{q}{\rightarrow}Hb\bar{b}$

$q\bar{q}{\rightarrow}HZ$

M_H [GeV]

[M. Spira, Fort. Phys. 46, 203, 1998]

Higgs Discovery requires that you detect the decay products

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

Signal significance

- $H \to \gamma\gamma$
- $ttH (H \to bb)$
- $H \to ZZ^{(*)} \to 4l$
- $H \to WW^{(*)} \to l\nu l\nu$
- $H \to ZZ \to ll\nu\nu$
- $H \to WW \to l\nu jj$
- — Total significance

5 σ

ATLAS

$\int L\, dt = 30\ fb^{-1}$
(no K-factors)

m_H (GeV)

Higgs Branching Ratios

# The Impact of Radiative Corrections

Most processes in QCD must be computed to Next-to-Leading Order (NLO) to get an accurate description of rate and distributions.

This is particularly true of Higgs production. Many of the most important signals have substantial radiative corrections.

In addition to the total rate, differential distributions are needed at higher order and often need resummation.

Gluon Fusion Dominates Higgs Production

The reason: top loops.
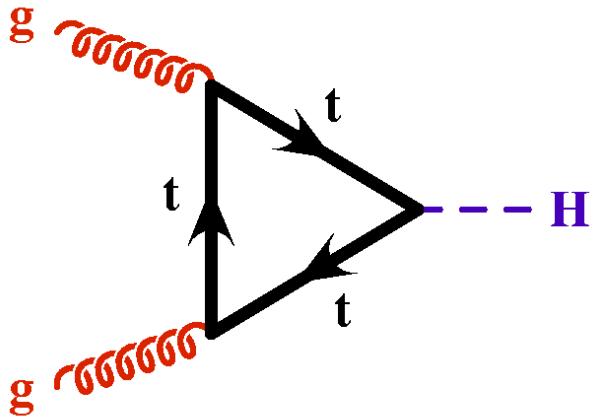
The problem for theorists, however, is top loops.

$$\sigma_{\text{LO}}(gg \to H) = \frac{\pi G_{\text{F}}}{128\sqrt{2}} \left(\frac{\alpha_s(\mu)}{\pi} \right)^2 \tau^2 |1 + (1-\tau)f(\tau)|^2 \, \delta\left(1 - \frac{M_H^2}{\hat{s}} \right)$$

$$f(\tau) = \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau}}, & \tau \geq 1, \\ -\frac{1}{4}\left[\ln \frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi \right]^2, & \tau < 1, \end{cases} \qquad \tau = 4M_t^2/M_H^2,$$
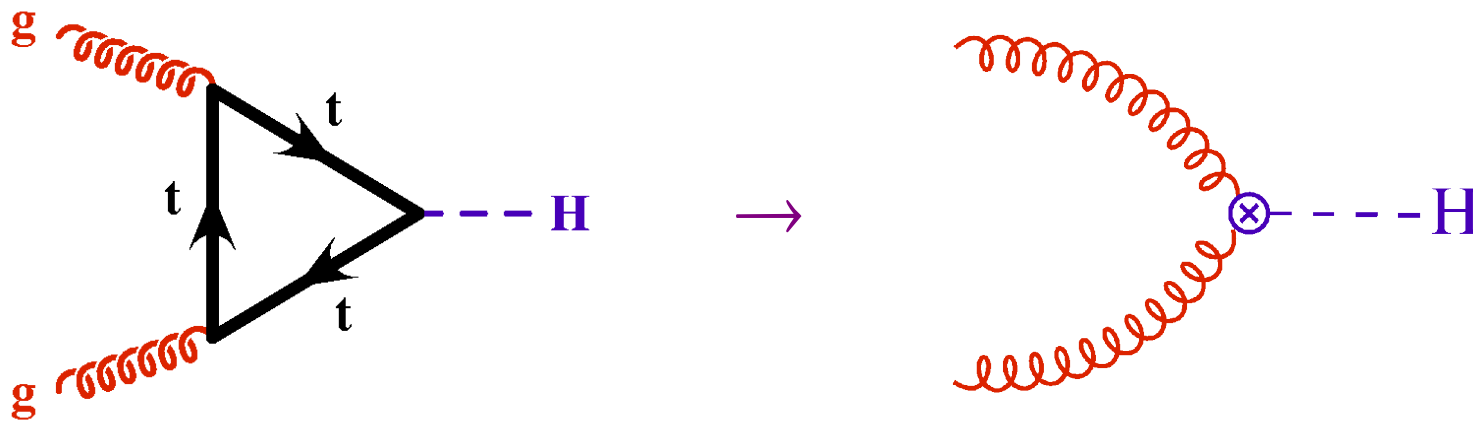
Effective Lagrangian

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.

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

C_1 has been computed to order α_s^4! [Chetyrkin, Kniehl, Steinhauser]
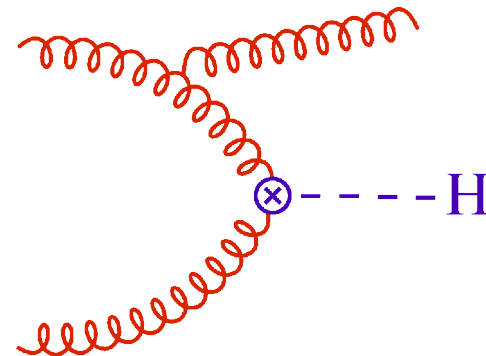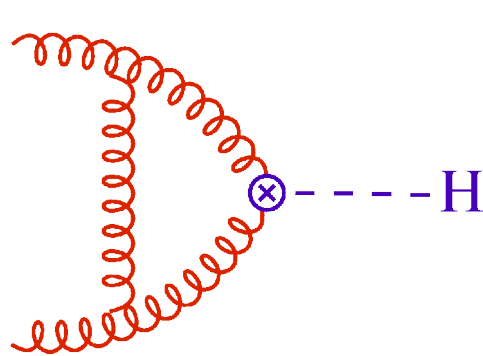
Using the effective Lagrangian greatly simplifies the calculation of radiative corrections.
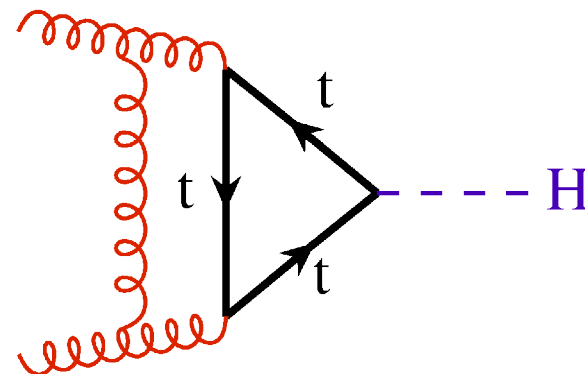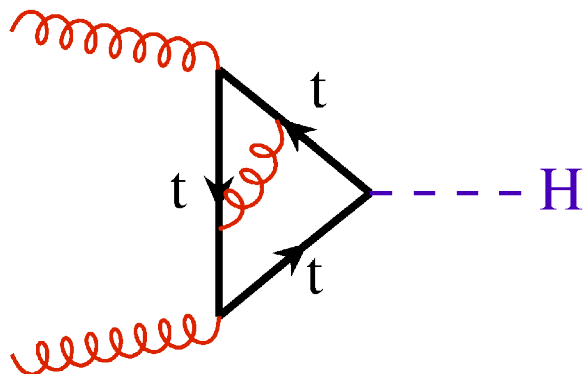
Higher Order Corrections

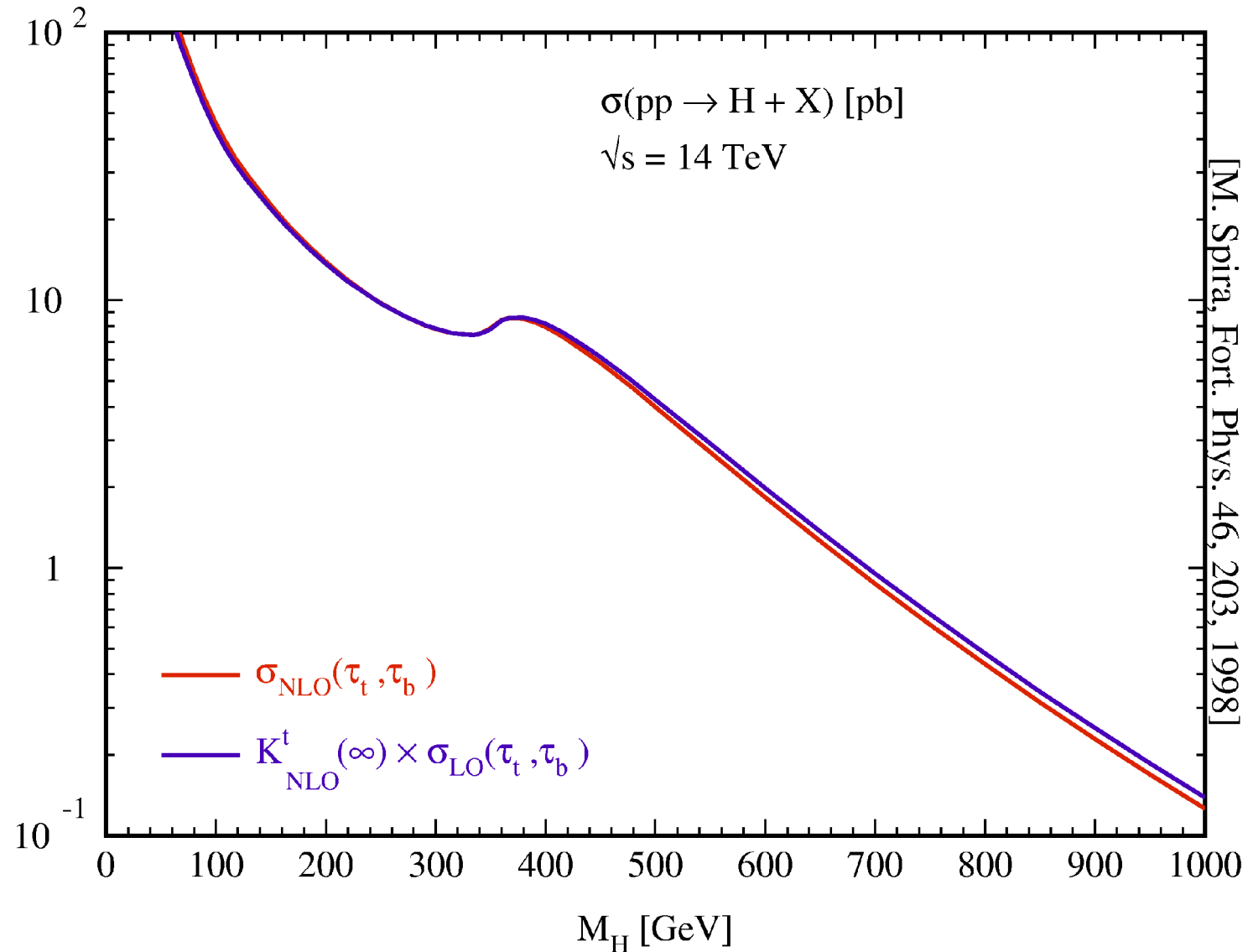NLO Corrections have been computed in both the effective Lagrangian [Dawson; Djouadi, Spira, Graudenz, Zerwas]
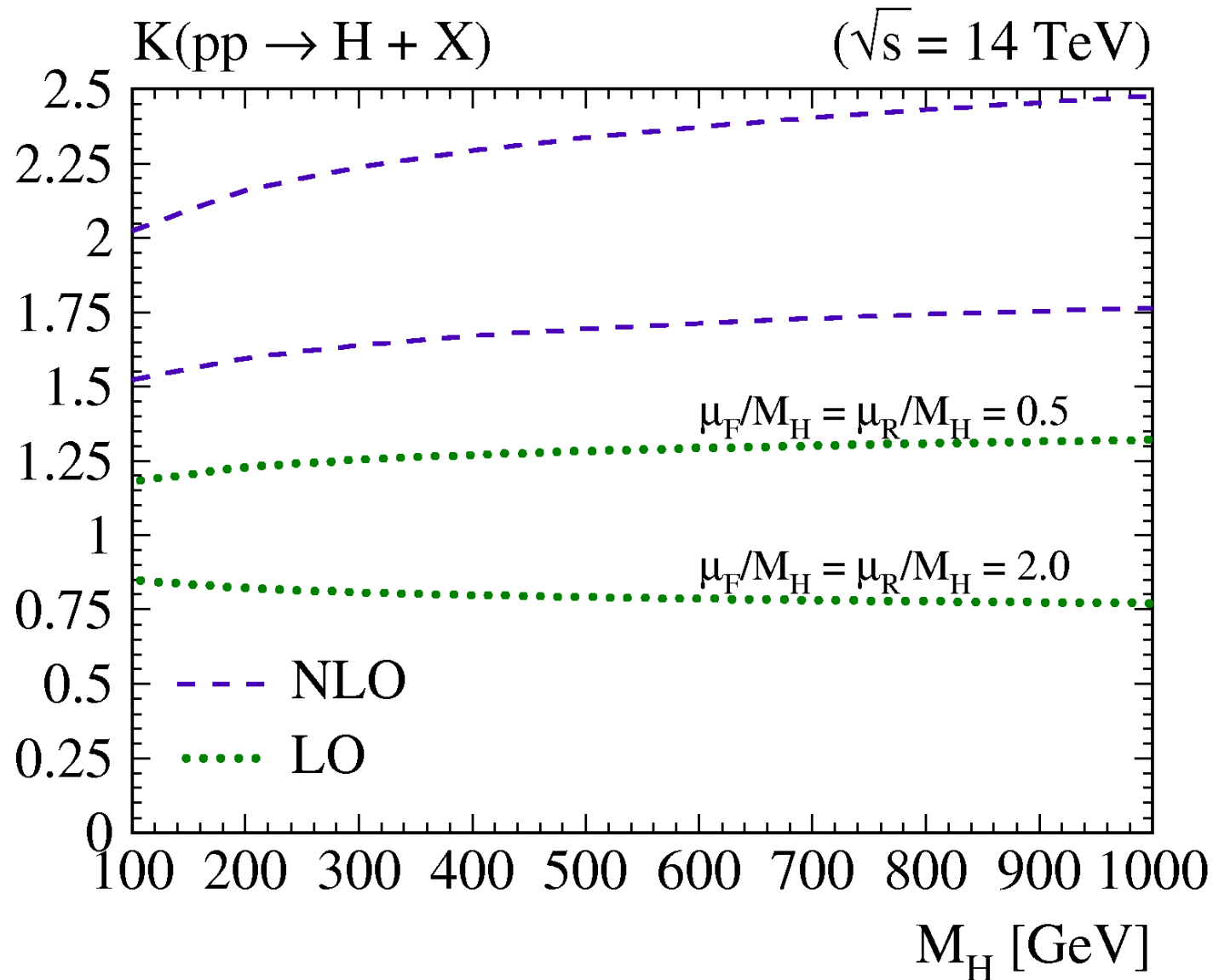

and in the full theory. [Djouadi, Spira, Graudenz, Zerwas]

They agree extremely well

$\sigma(pp \to H + X)$ [pb]

$\sqrt{s} = 14$ TeV

$\sigma_{NLO}(\tau_t, \tau_b)$

$K^t_{NLO}(\infty) \times \sigma_{LO}(\tau_t, \tau_b)$

M_H [GeV]

[M. Spira, Fort. Phys. 46, 203, 1998]

But we need NNLO!

NNLO Corrections

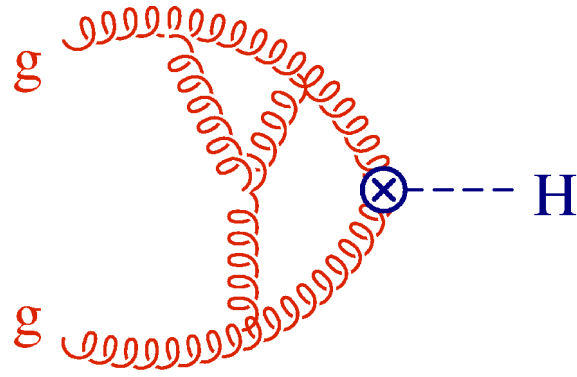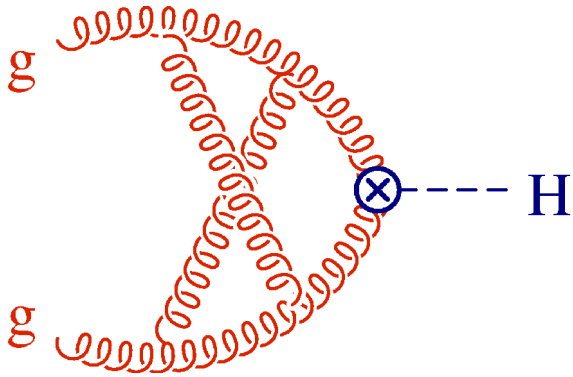For NNLO corrections, we assume that the Effective Lagrangian provides a good description of Higgs Production, especially in the most interesting mass range (< 200 GeV).

NNLO Corrections combine three components
- Virtual corrections to two loops
- Single Real Emission corrections to one loop
- Double Real Emission corrections

Virtual Corrections:
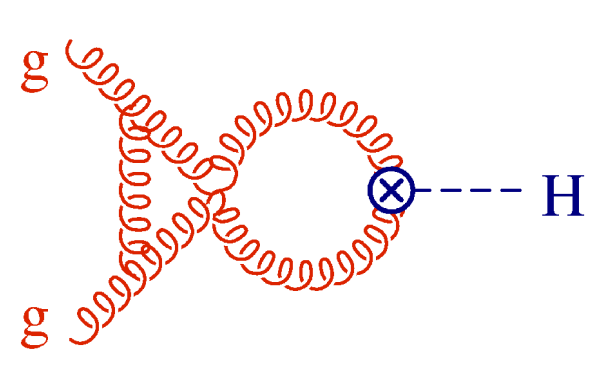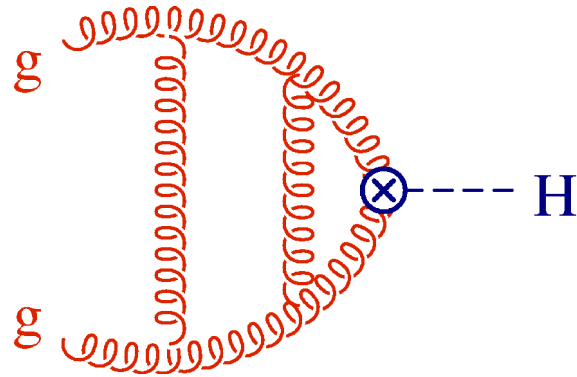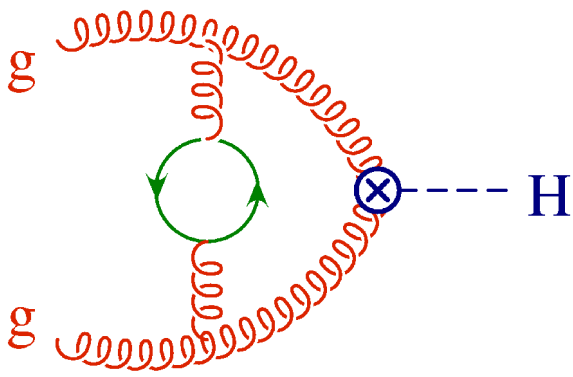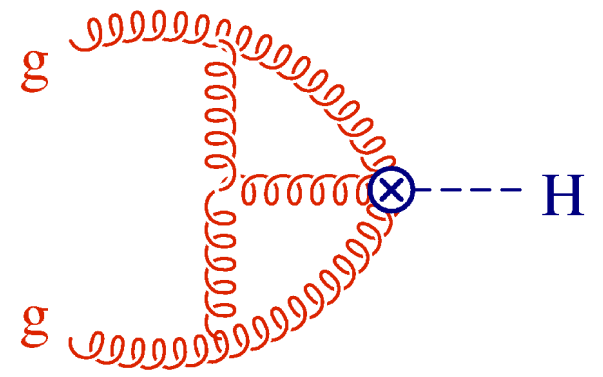
One-Loop Single Real Emission:
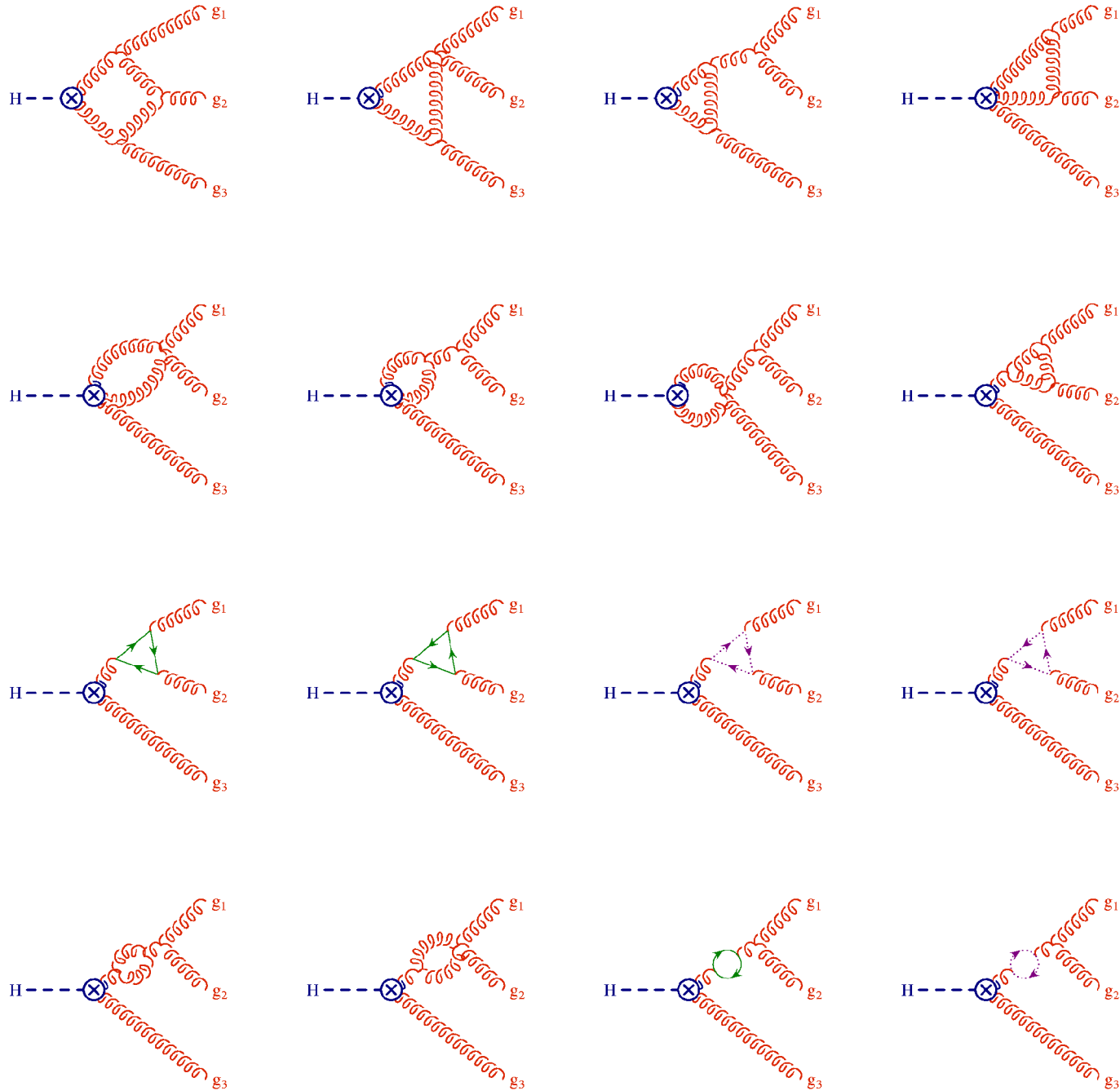
Double Real Emission:
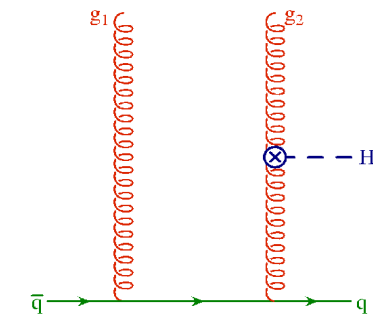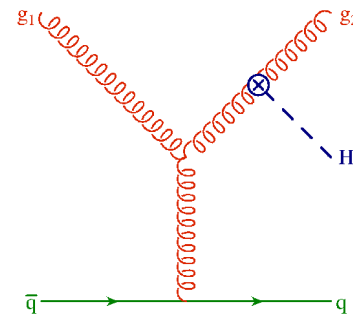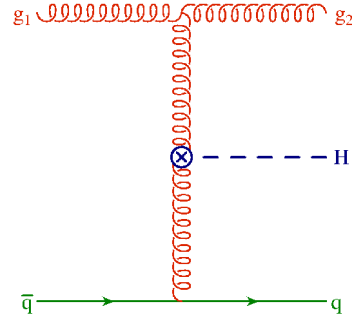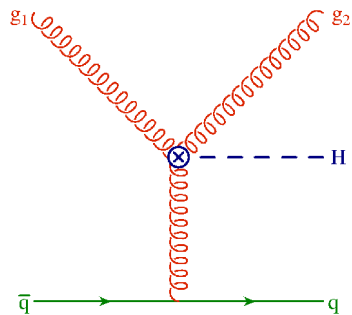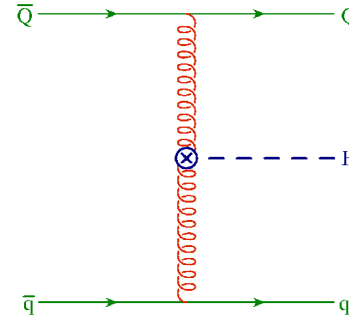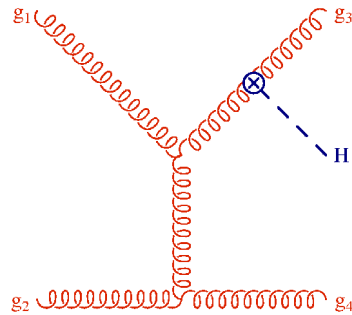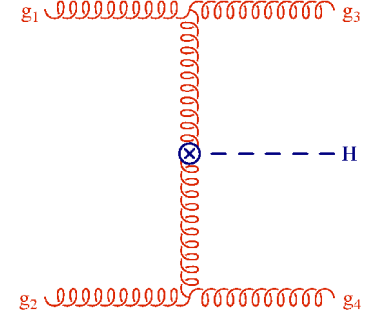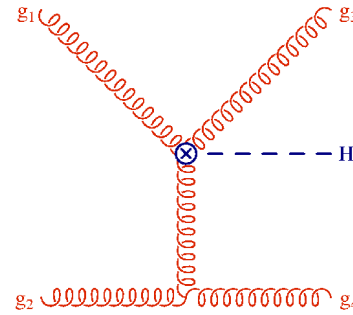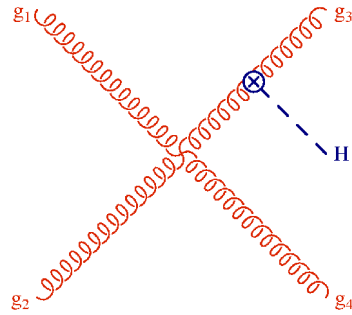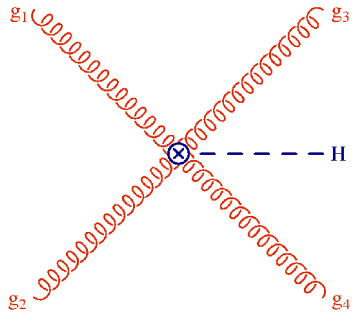
Higgs Production at NNLO

In recent years, the Higgs production cross section has been computed to NNLO in the effective theory by three groups using very different methods.
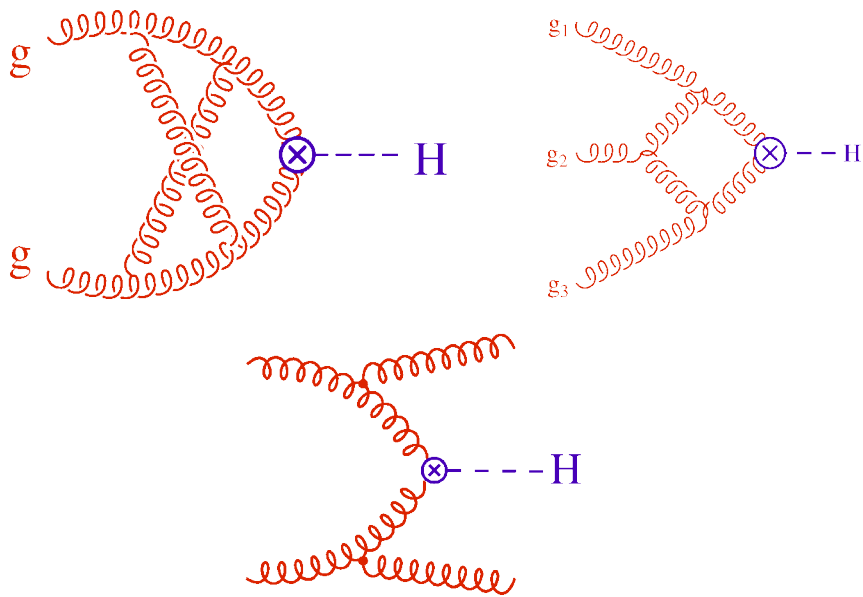
[Harlander, WK;
Ravindran, Smith, van Neerven]
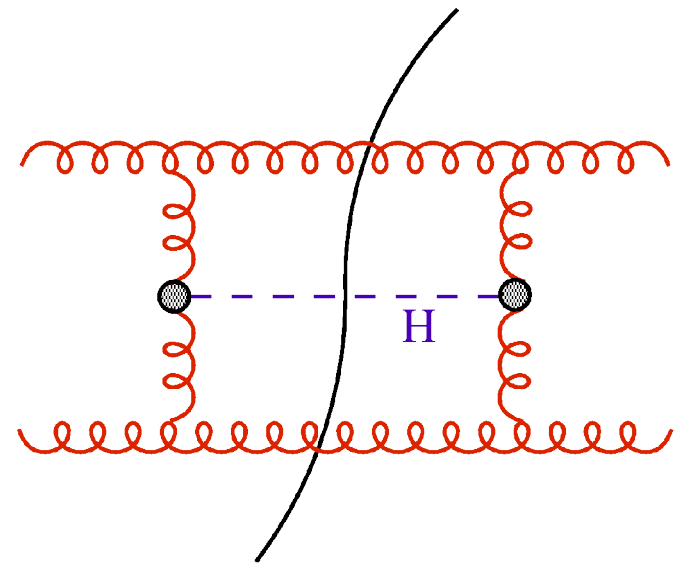
[Anastasiou & Melnikov]

All groups agree exactly

$$\Delta_{ggA}(x) = \left[\frac{741}{8} + \frac{139}{2}\zeta_2 - \frac{165}{4}\zeta_3 - \frac{9}{20}\zeta_2^2\right]\delta(1-x) - \left[\frac{101}{3} - 33\zeta_2 - \frac{351}{2}\zeta_3\right]\mathcal{D}_0(x) + \left[139 - 90\zeta_2\right]\mathcal{D}_1(x) - 33\mathcal{D}_2(x) + 72\mathcal{D}_3(x)$$

$$- (144x - 72x^2 + 72x^3)\ln^3(1-x) - (297 - 381x + 348x^2 - 330x^3)\ln^2(1-x) - \frac{9}{2}\frac{(31 - 30x + 93x^2 - 94x^3 + 31x^4)}{1-x}\ln^2(1-x)\ln(x)$$

$$+ \left[\frac{(2027 - 2735x + 2182x^2 - 2583x^3)}{4} + (180x - 90x^2 + 90x^3)\zeta_2\right]\ln(1-x) + 3\frac{(88 - 211x + 312x^2 - 365x^3 + 187x^4)}{1-x}\ln(1-x)\ln(x)$$

$$+ 9\frac{(7 + 3x + 19x^2 - 3x^3 - 19x^4 + 9x^5)}{1-x^2}\ln(1-x)\ln^2(x) + 36\frac{(1 - 6x - 13x^2 - 6x^3 + x^4)}{1+x}\ln(1-x)\mathrm{Li}_2(1-x)$$

$$- 18\frac{(1 + 2x + 3x^2 + 2x^3 + x^4)}{1+x}\ln(1-x)\mathrm{Li}_2(1-x^2) - \frac{9}{2}\frac{(24 - 38x + 8x^2 + 54x^3 - 19x^4 + 9x^5)}{1-x^2}\mathrm{Li}_3(1-x)$$
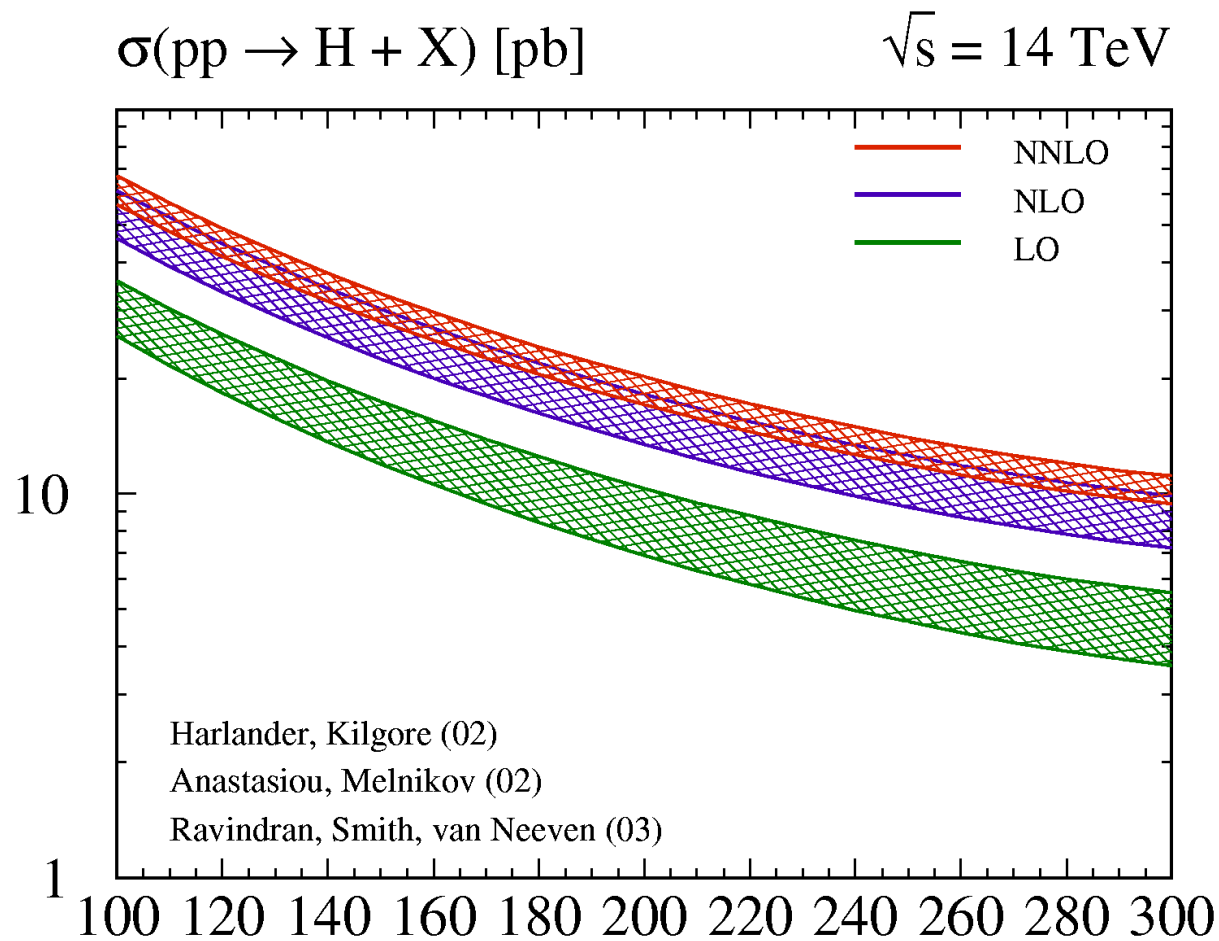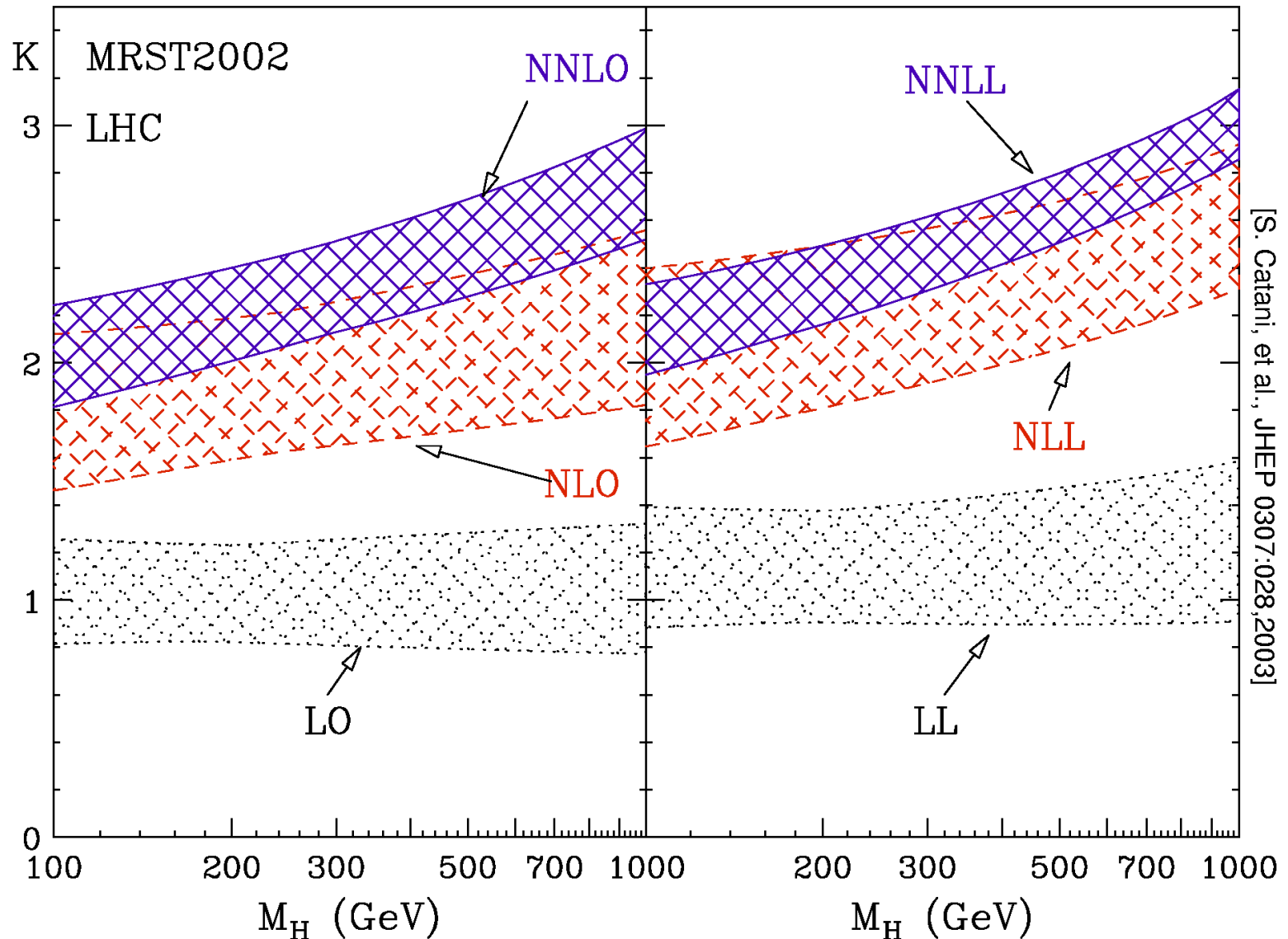
$$- \frac{9}{2}\frac{(27 + 35x + 75x^2 - 29x^3 - 78x^4 + 6x^5)}{1-x^2}\mathrm{Li}_3\left(-\frac{(1-x)}{x}\right) + \frac{9}{8}\frac{(1 + 2x + 3x^2 + 24x^3 + 16x^4)}{1+x}\mathrm{Li}_3(1-x^2)$$

$$- \frac{9}{8}\frac{(1 + 2x + 3x^2 - 8x^3 - 8x^4)}{1+x}\mathrm{Li}_3\left(-\frac{(1-x^2)}{x^2}\right) - \frac{9}{2}\frac{(7 + 14x + 21x^2 + 8x^3 + 4x^4)}{1+x}\left[\mathrm{Li}_3\left(\frac{1-x}{1+x}\right) - \mathrm{Li}_3\left(-\frac{1-x}{1+x}\right)\right]$$

$$- \frac{3}{4}\frac{(317 - 398x - 87x^2 + 300x^3 - 121x^4)}{1-x}\mathrm{Li}_2(1-x) + \frac{9}{2}\frac{(11 + 31x + 59x^2 - 25x^3 - 65x^4 + 11x^5)}{1-x^2}\mathrm{Li}_2(1-x)\ln(x)$$

$$+ \frac{(42 + 36x - 63x^2 - 33x^3)}{4}\mathrm{Li}_2(1-x^2) + \frac{9}{4}\frac{(5 + 10x + 15x^2 - 2x^4)}{1+x}\mathrm{Li}_2(1-x^2)\ln(x) + \frac{3}{4}\frac{(21 + 23x + 41x^2 - 37x^3 - 44x^4 + 4x^5)}{1-x^2}\ln^3(x)$$

$$- \frac{3}{8}\frac{(154 - 365x + 675x^2 - 827x^3 + 374x^4)}{1-x}\ln^2(x) - \frac{1}{8}\frac{(2213 - 5599x + 6603x^2 - 7003x^3 + 4342x^4)}{1-x}\ln(x)$$

$$+ 9\frac{(9 - 2x + 27x^2 - 34x^3 + 9x^4)}{1-x}\zeta_2\ln(x) - \frac{(16309 - 20611x + 23819x^2 - 22749x^3)}{48} + \frac{3}{4}(319 - 277x + 233x^2 - 363x^3)\zeta_2 - \frac{351}{2}(2x - x^2 + x^3)\zeta_3$$

$$+ n_f\left\{\left[-\frac{689}{72} + l_{Ht} - \frac{5}{3}\zeta_2 + \frac{5}{6}\zeta_3\right]\delta(1-x) + \left[\frac{14}{9} - 2\zeta_2\right]\mathcal{D}_0(x) - \frac{10}{3}\mathcal{D}_1(x) + 2\mathcal{D}_2(x) - \frac{2}{9}(8 - 12x + 3x^2 - 17x^3)\zeta_2\right.$$

$$+ \frac{2}{9}(8 - 12x + 3x^2 - 17x^3)\ln^2(1-x) + \frac{8}{3}(x + x^2)\ln^2(1-x)\ln(x) - \frac{(922 - 294x + 249x^2 - 1570x^3)}{108}\ln(1-x)$$

$$- \frac{2}{9}\frac{(17 + 7x + 21x^2 - 61x^3 + 25x^4)}{1-x}\ln(1-x)\ln(x) - \frac{8}{3}(x + x^2)\ln^2(x)\ln(1-x) + \frac{16}{3}(x + x^2)\ln(1-x)\mathrm{Li}_2(1-x)$$

$$- \frac{(2 + 14x + 17x^2)}{6}\mathrm{Li}_3(1-x) - \frac{(2 - 34x - 31x^2)}{12}\mathrm{Li}_3\left(-\frac{(1-x)}{x}\right) . + \frac{1}{36}\frac{(68 - 302x + 21x^2 + 227x^3 + 4x^4)}{1-x}\mathrm{Li}_2(1-x)$$

$$+ \frac{(2 - 50x - 47x^2)}{12}\mathrm{Li}_2(1-x)\ln(x) + \frac{(2 + 6x + 9x^2)}{72}\ln^3(x) + \frac{1}{72}\frac{(68 + 100x + 69x^2 - 351x^3 + 132x^4)}{1-x}\ln^2(x)$$

$$+ \frac{1}{216}\frac{(1282 - 382x + 117x^2 - 3041x^3 + 2384x^4)}{1-x}\ln(x) - \frac{8}{3}(x + x^2)\zeta_2\ln(x) + \frac{(12707 - 606x + 1641x^2 - 17774x^3)}{1296}\right\}$$

Higgs Cross Section at NNLO

$\sigma(pp \to H + X)$ [pb] $\sqrt{s} = 14$ TeV

NNLO
NLO
LO

10

Harlander, Kilgore (02)
Anastasiou, Melnikov (02)
Ravindran, Smith, van Neeven (03)

1
100 120 140 160 180 200 220 240 260 280 300

Threshold resummation

[Catani, de Florian, Grazzini, Nason]

Higgs Distributions at NNLO

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

Distributions for Drell-Yan exist at NNLO. For Higgs, they are known only to NLO so far.

pp → H+X Rapidity distribution at LHC

$M_H/4 < \mu_R, \mu_F < M_H$
MRST2001 pdfs
$M_H = 115$ GeV

NLO
LO

$(1/\sigma)d\sigma/dy_H$

y_H
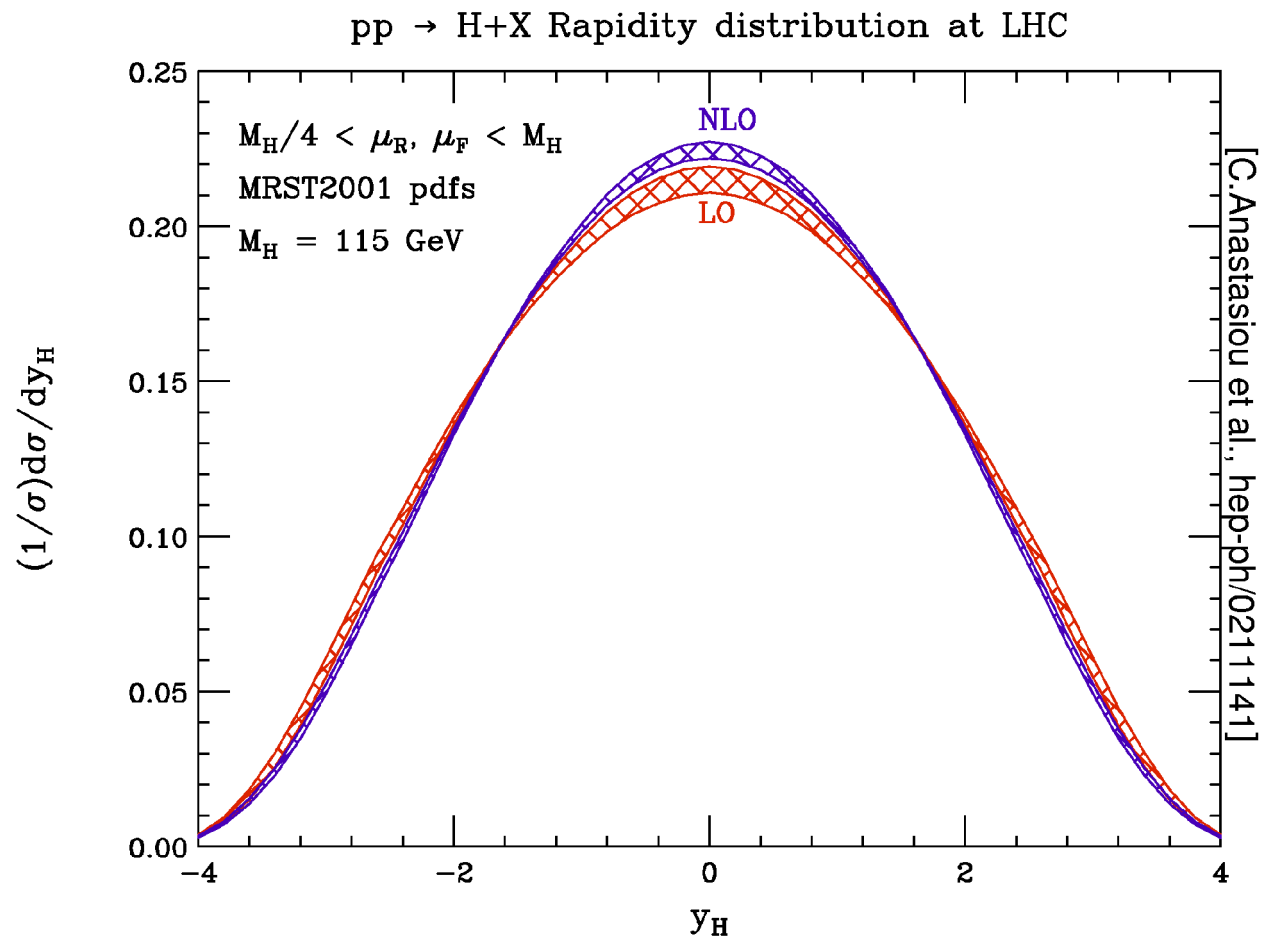
Higgs at Finite Q_T

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 is known at NLO.

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

The background, $\gamma\gamma$ + jet, is also known at 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]
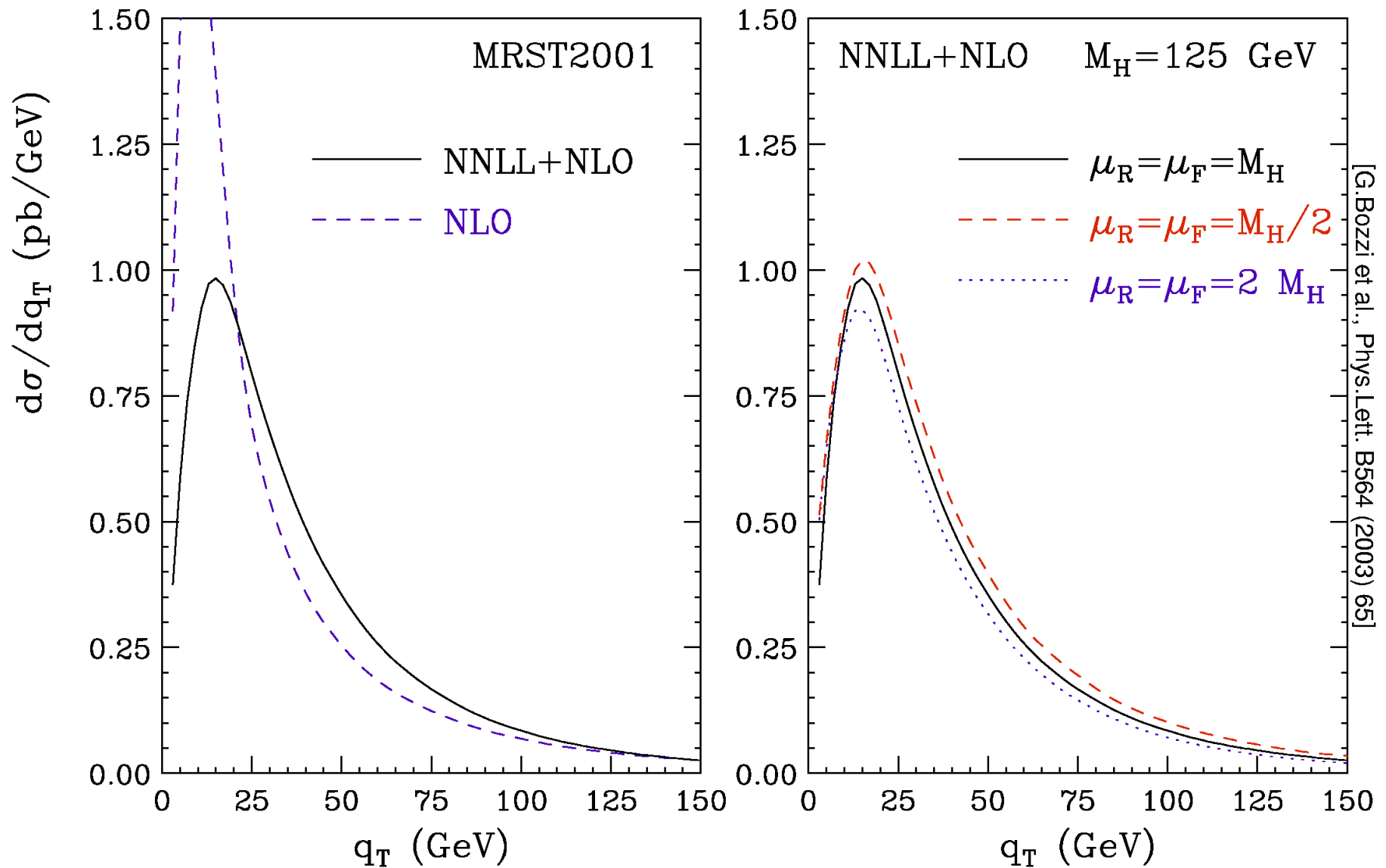
Joint Threshold and Q_T Resummation

sqrt(s)=14 TeV, M_H=125 GeV, CTEQ5M

- - - recoil

—— joint, η=1

[A.Kulezsa, et al., hep-ph/0309264]
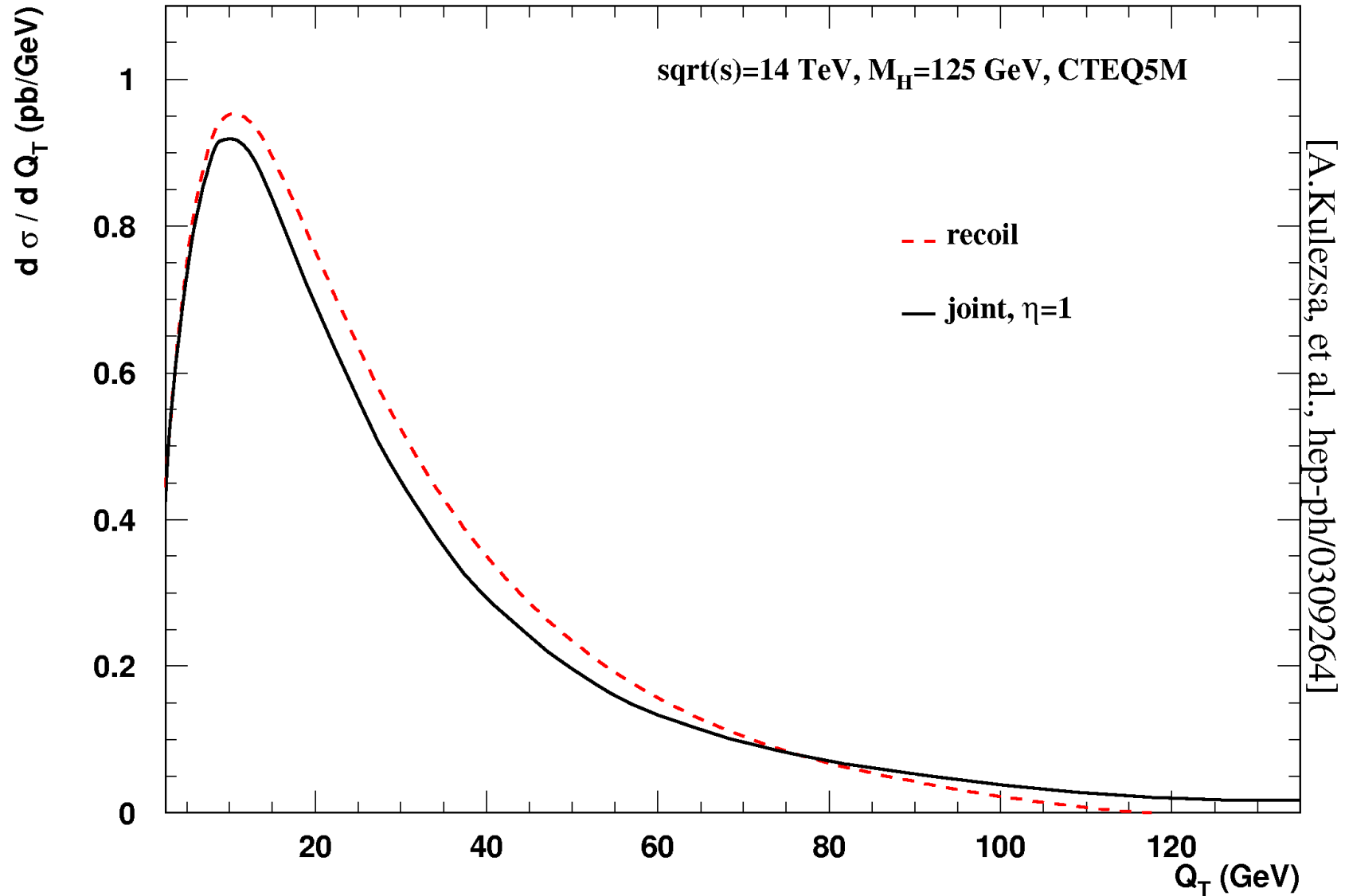
t̄tH production at NLO

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]
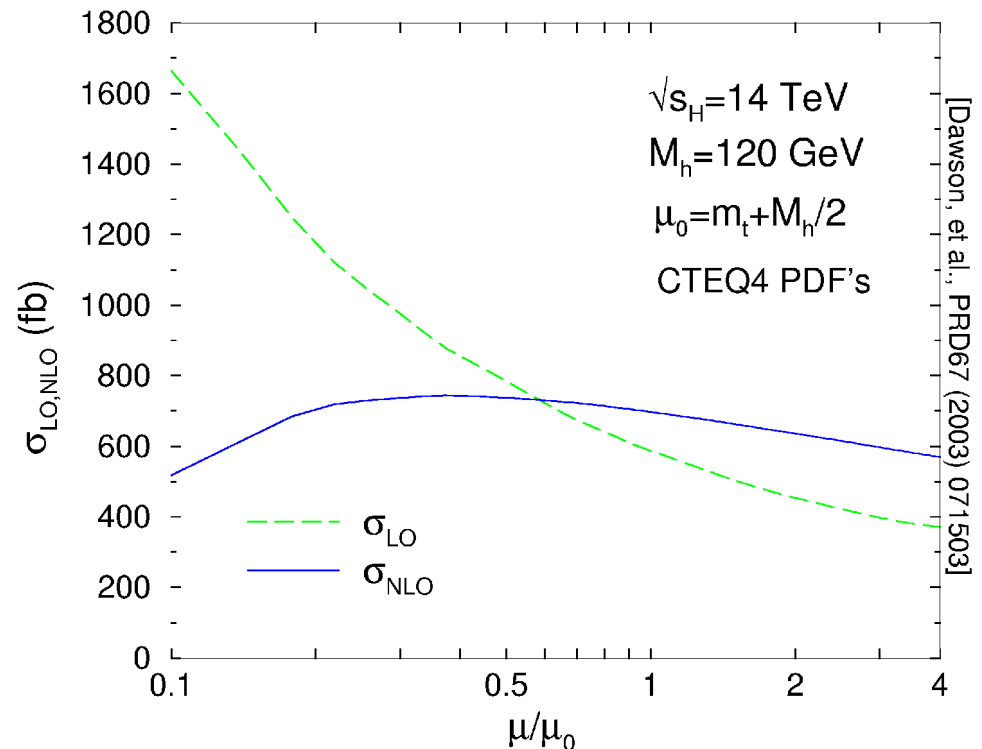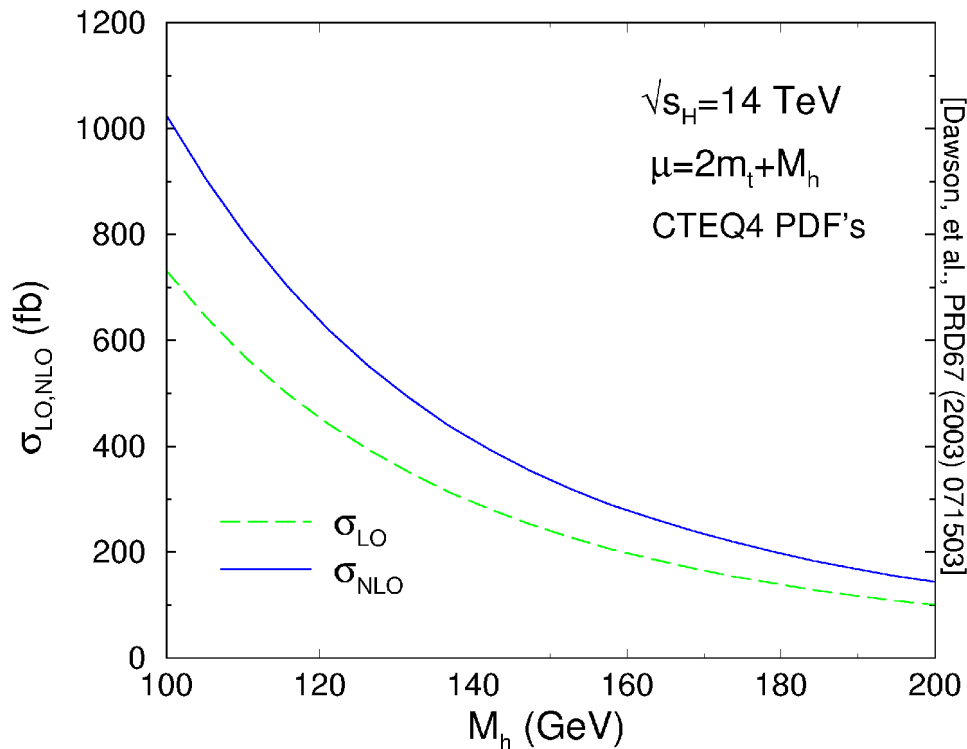
Weak Boson Fusion
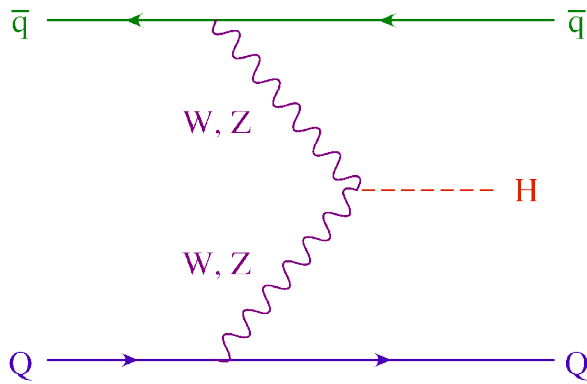
NLO corrections have been known for some time.   [Han, Willenbrock]

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

Offers discovery potential in the low to intermediate mass range and allows one to measure Higgs couplings. [Hagiwara, Kauer, Plehn, Rainwater, Zeppenfeld]

$gg{\rightarrow}H{+}2j$ background computed with m_t dependence.   [Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld]

Higgs Discovery through Weak Boson Fusion
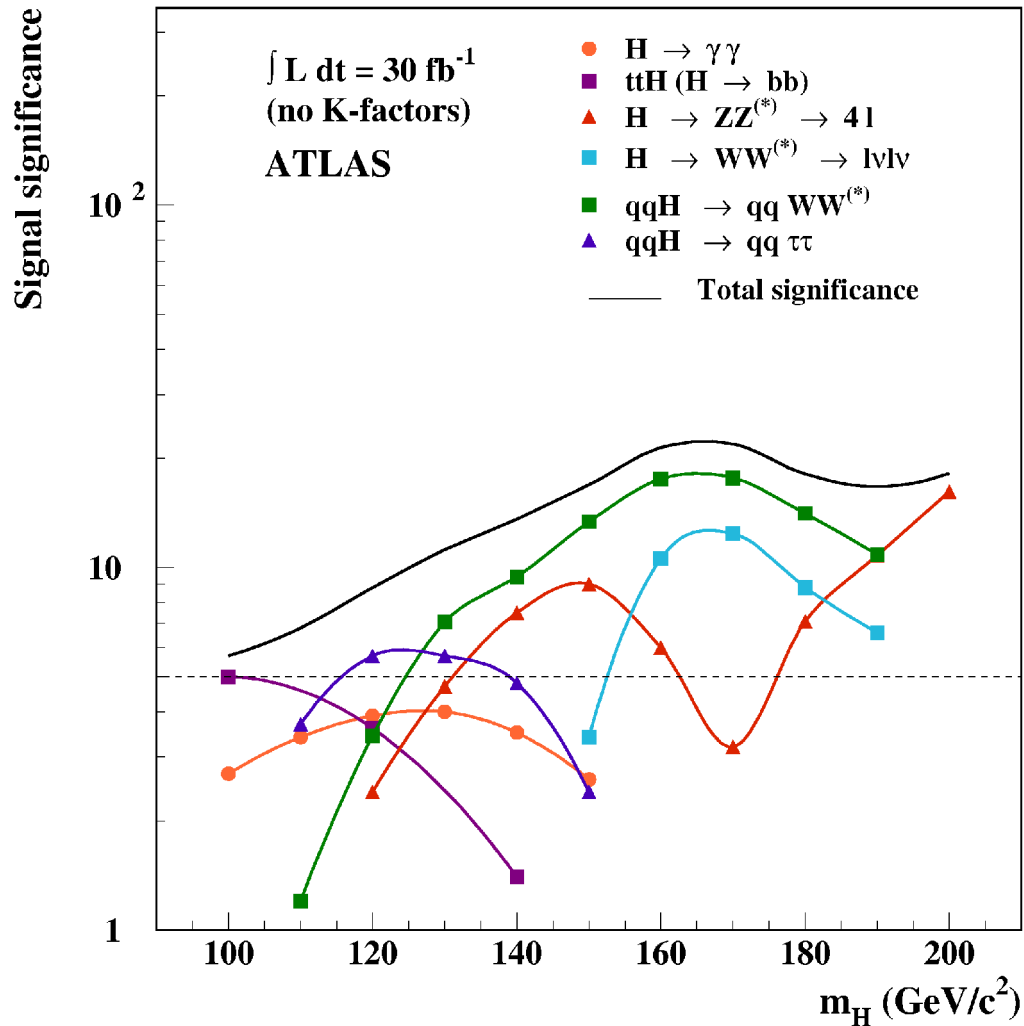
Expected precision in $\sigma \cdot BR$
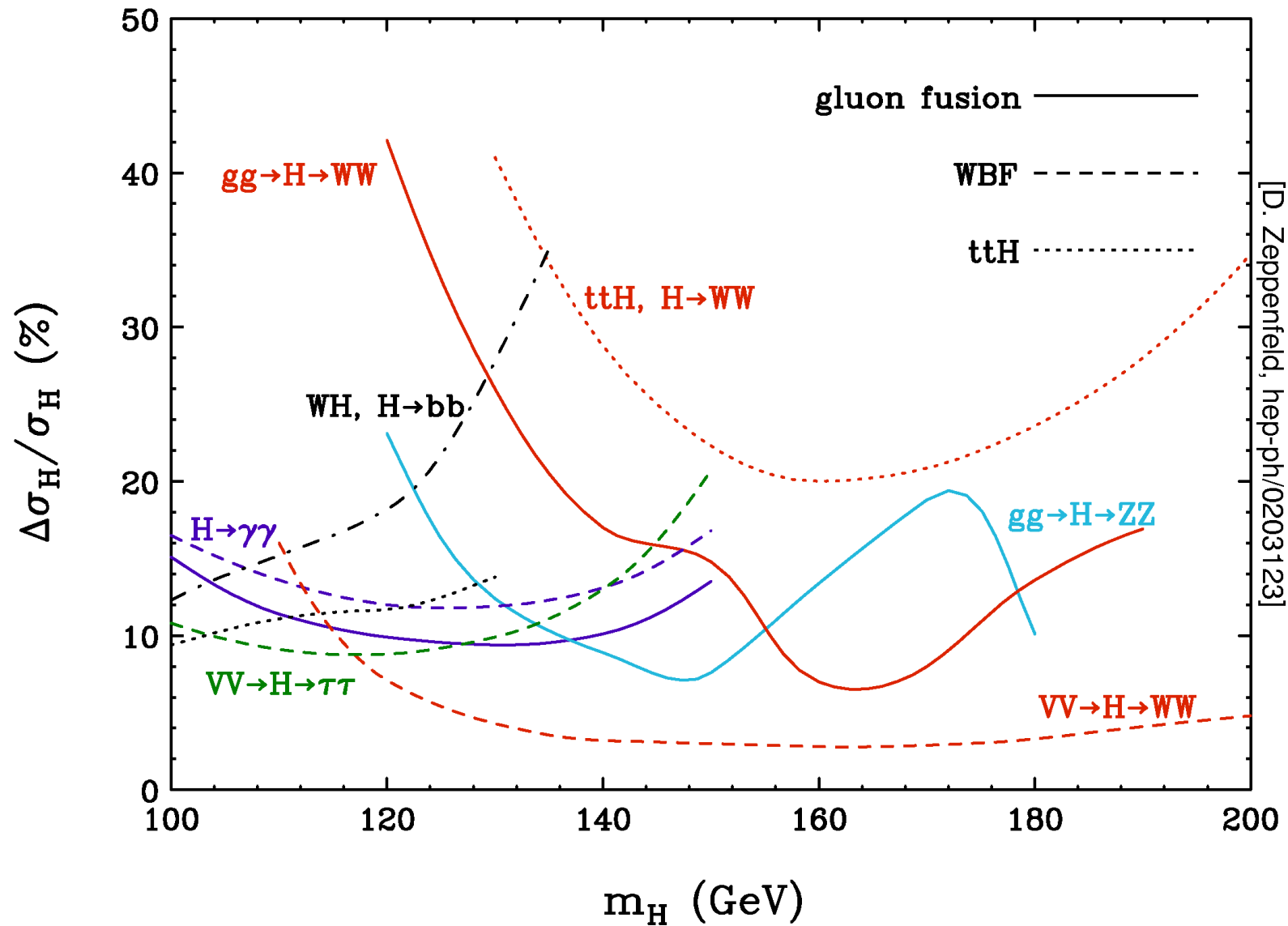
Expected Precision of Absolute couplings
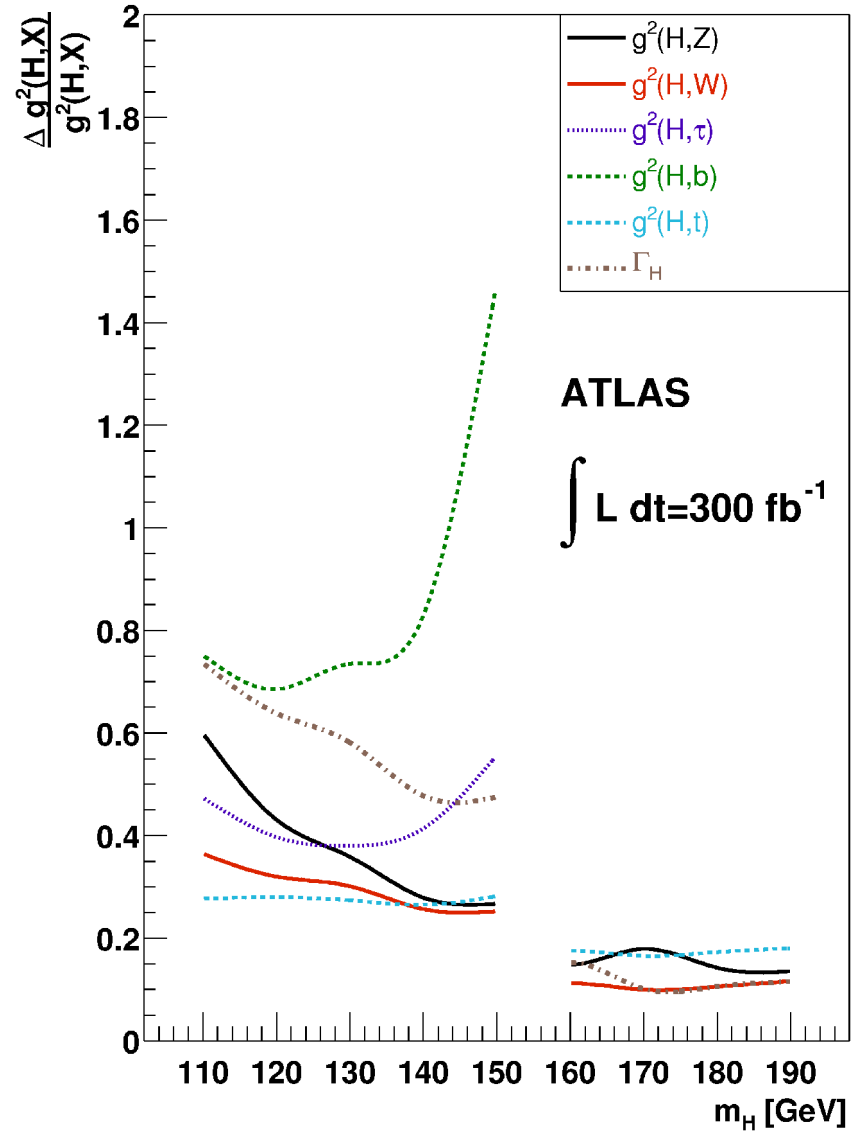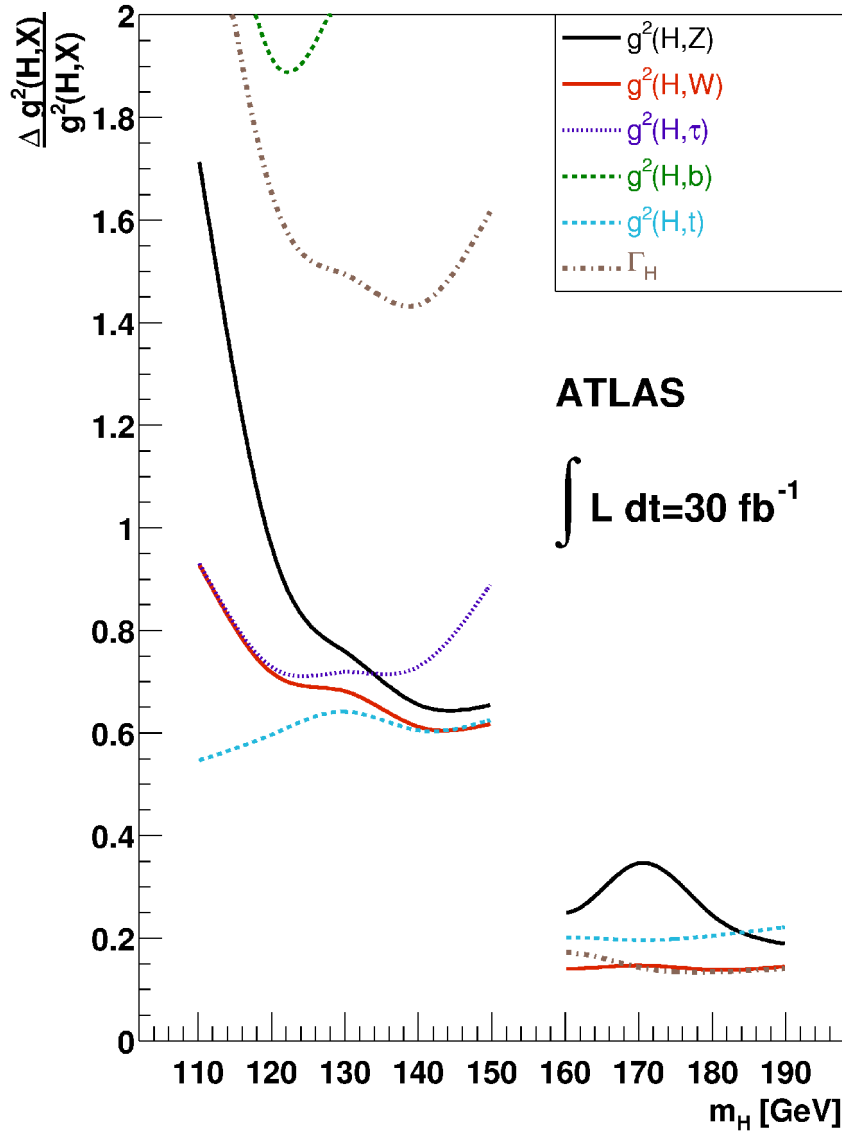
Supersymmetric Higgs Boson Production

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.

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:

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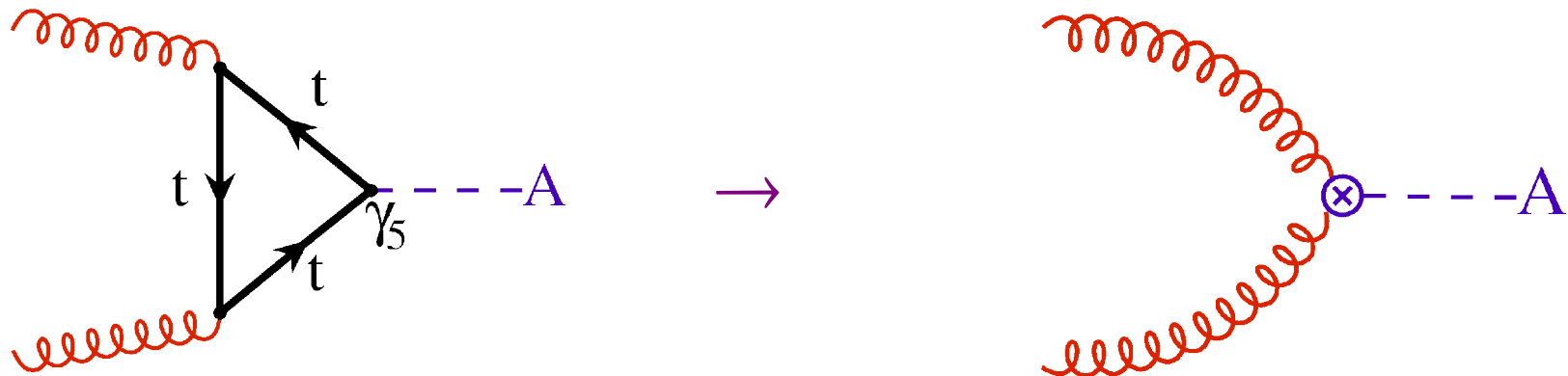
SUSY Higgs Production

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
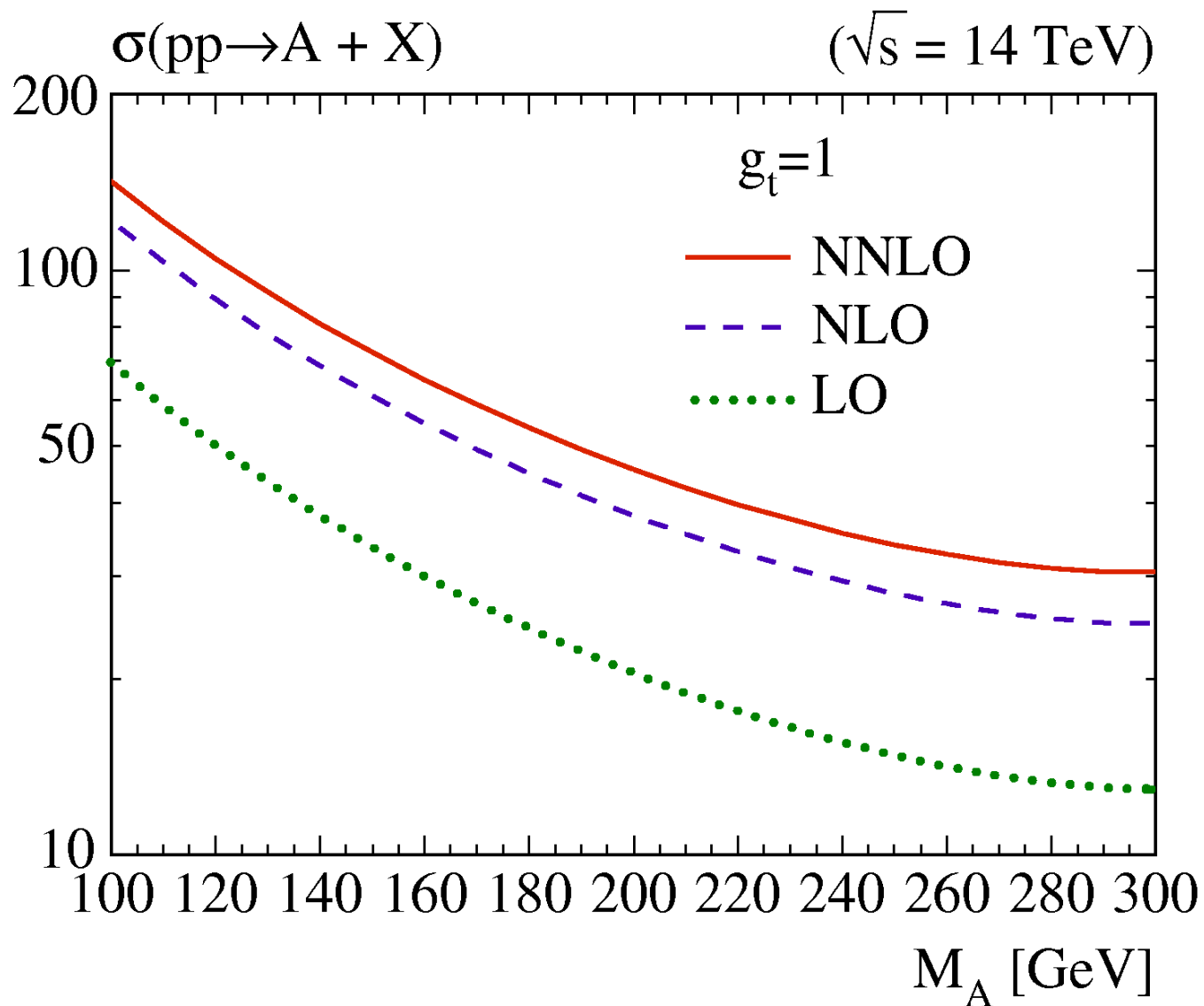
H/A Couplings

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

For $\tan \beta$ much larger than 1, b-quark interactions are important. But an effective Lagrangian from integrating out the b-quark to produce ~100 GeV Higgs bosons is unjustifiable! 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.

Fixed vs. Variable Flavor Number

The question arises whether one should work in the Fixed Flavor Number Scheme (FFNS) or a Variable Flavor Number Scheme (VFNS).

A FFNS has a fixed number (say 3) of "active" flavors. Heavy flavor production only occurs through gluon splitting. While well-defined, FFNS seems forced if $Q^2 \gg m_q^2$. In addition, $\ln(Q/m_q)$ terms become problematic.

A VFNS recognizes thresholds and changes the number of "active" flavors with Q^2.

Parton Distributions in VFNS

Logarithmic terms arise from forward emission of on-shell b-quarks
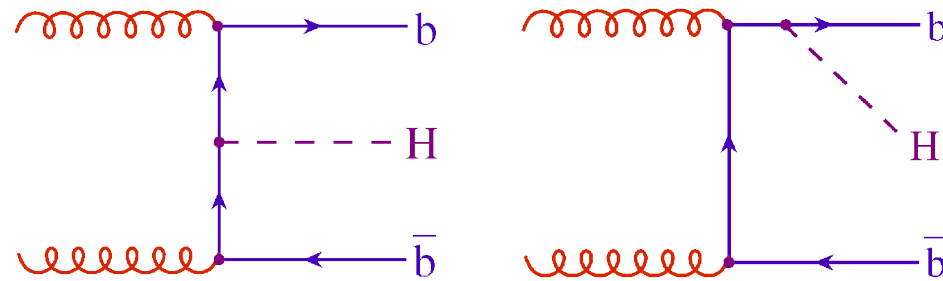
In VFNS, the lowest order terms are b$\bar{\text{b}}$→H. Parton evolution resums the logarithmic terms.

Worries about the VFNS

At leading order, the inclusive cross section for $b\bar{b} \to H$ is much bigger than $gg \to b\bar{b}H$.
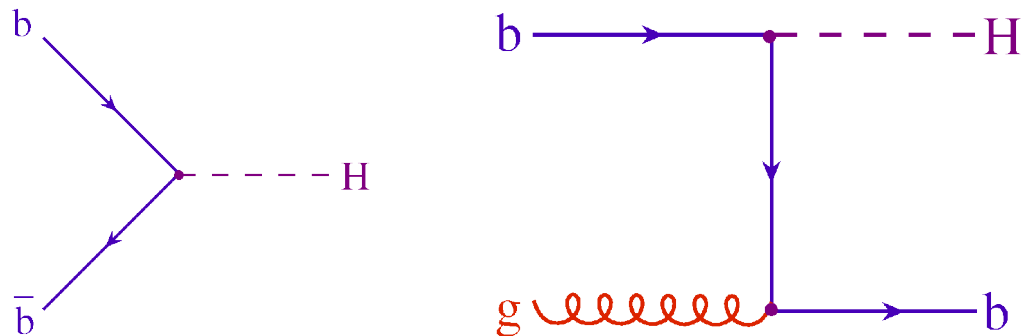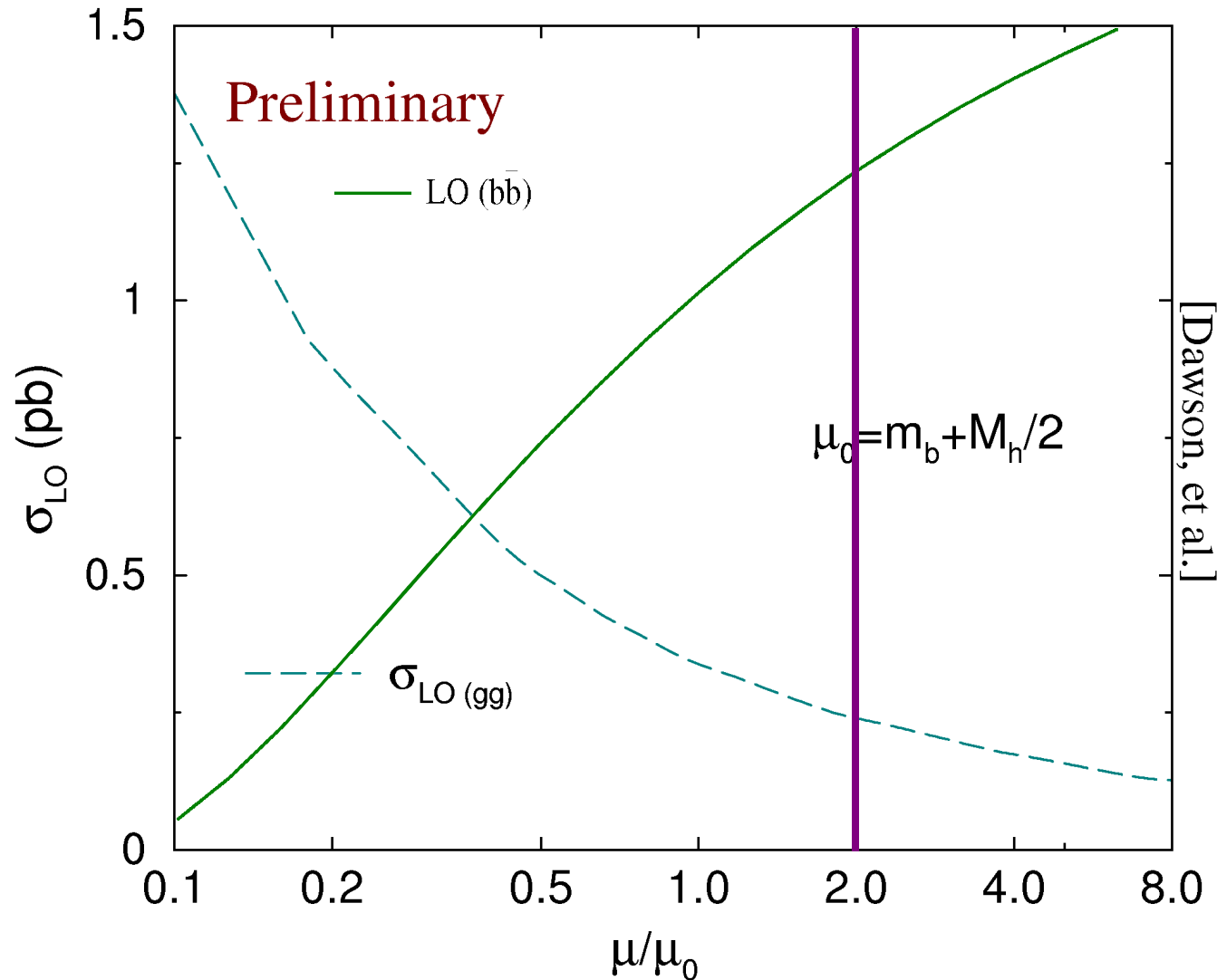
Power Counting in the VFNS

The key to obtaining a consistent calculation is to properly count the powers of α_s and $\ln(M_H/m_b)$. The leading contribution in $b\bar{b}\rightarrow H$ is not order 1 but order $\alpha_s^2 \ln^2(M_H/m_b)$. To all orders in perturbation theory, the inclusive Higgs production cross section is: ($\mu_F \sim M_H$)

$$\sigma_{bb} = \sum_{n=0}^{\infty} (\alpha_s\ln(M_H/m_b))^n \{$$

$$\alpha_s^2[c_{n0} \ln^2(M_H/m_b) + c_{n1} \ln(M_H/m_b) + c_{n2}]$$

$$+ \alpha_s^3 c_{n3} + \alpha_s^4 c_{n4} + \alpha_s^5 c_{n5} + ... \}$$

Inclusive Higgs production in VFNS

[Harlander, WK]

The lowest order calculation to include all terms at order α_s^2 and the resummed collinear logs is NNLO. Since all collinear logs are resummed in the PDFs, the b-quark mass is ignored, except in Yukawa couplings. Other b-quark mass effects are suppressed by factors of m_b^2/M_H^2.

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

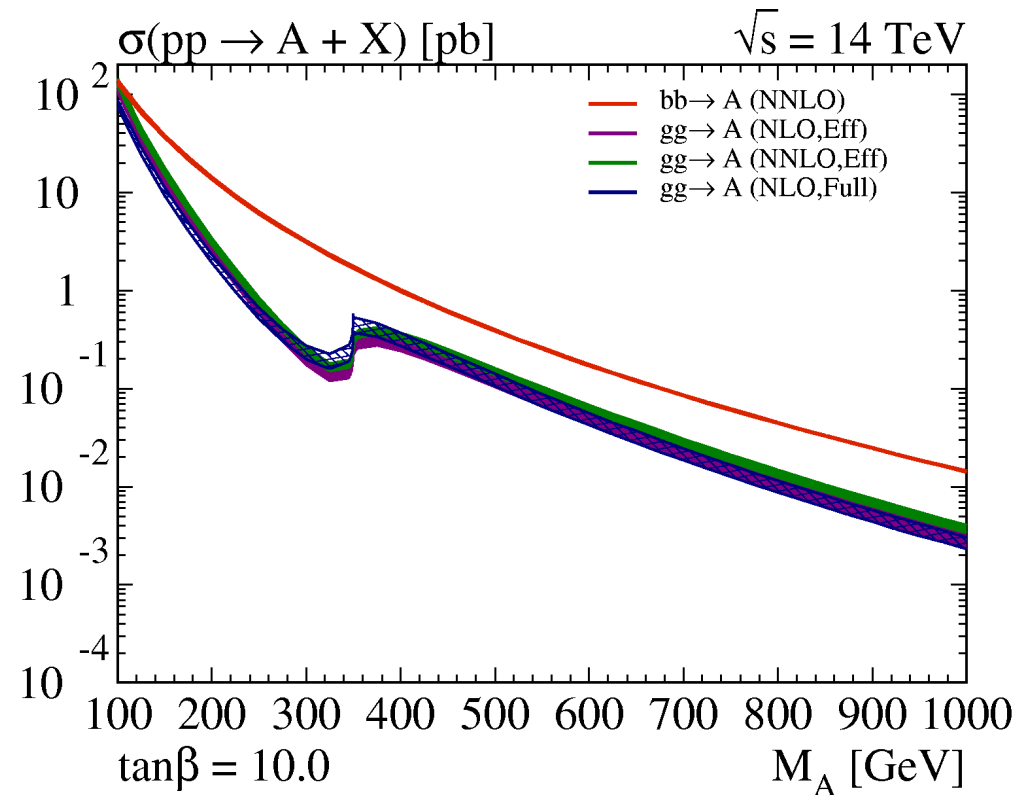$$\sigma_{b\bar{b}} \sim m_b^2/M_H^2 \; \tan^2\beta \qquad \text{while}$$

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

b̄b→A versus gg→A

At small tan β, b quark fusion is tiny.

At large tan β, it dominates.

$\sigma(pp \to A + X)$ [pb] $\sqrt{s} = 14$ TeV

- bb→ A (NNLO)
- gg→ A (NLO,Eff)
- gg→ A (NNLO,Eff)
- gg→ A (NLO,Full)

tanβ = 1.0 M_A [GeV]

$\sigma(pp \to A + X)$ [pb] $\sqrt{s} = 14$ TeV

- bb→ A (NNLO)
- gg→ A (NLO,Eff)
- gg→ A (NNLO,Eff)
- gg→ A (NLO,Full)

tanβ = 10.0 M_A [GeV]
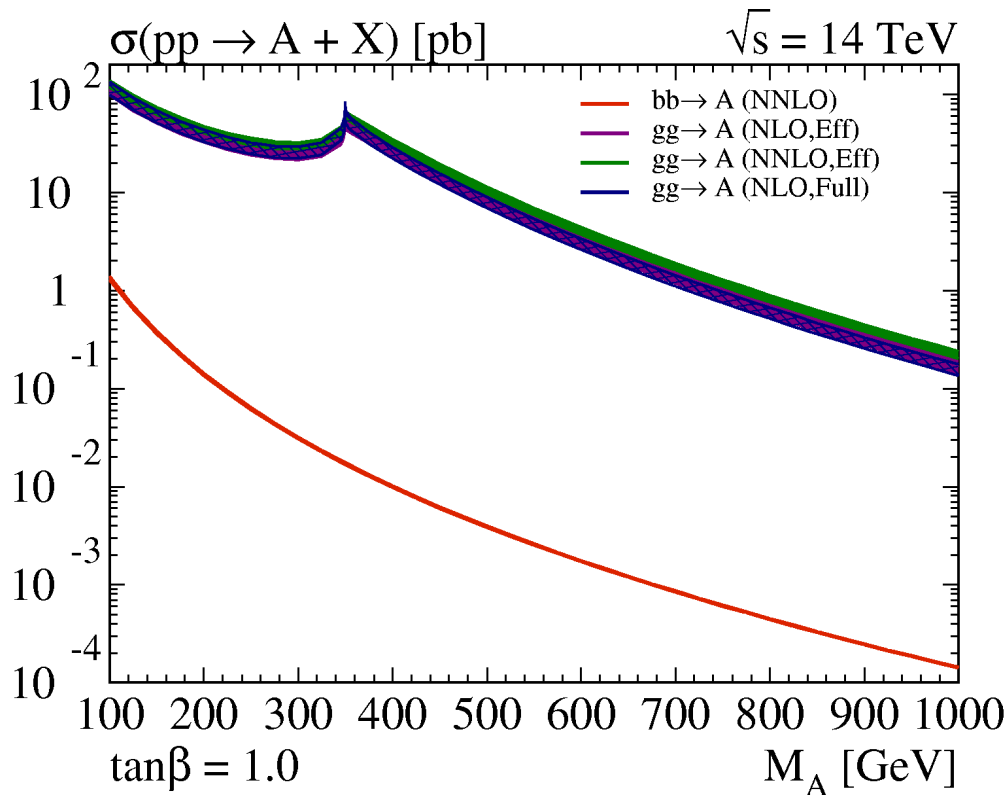
Scale Dependence of b̄b→H/A at LHC
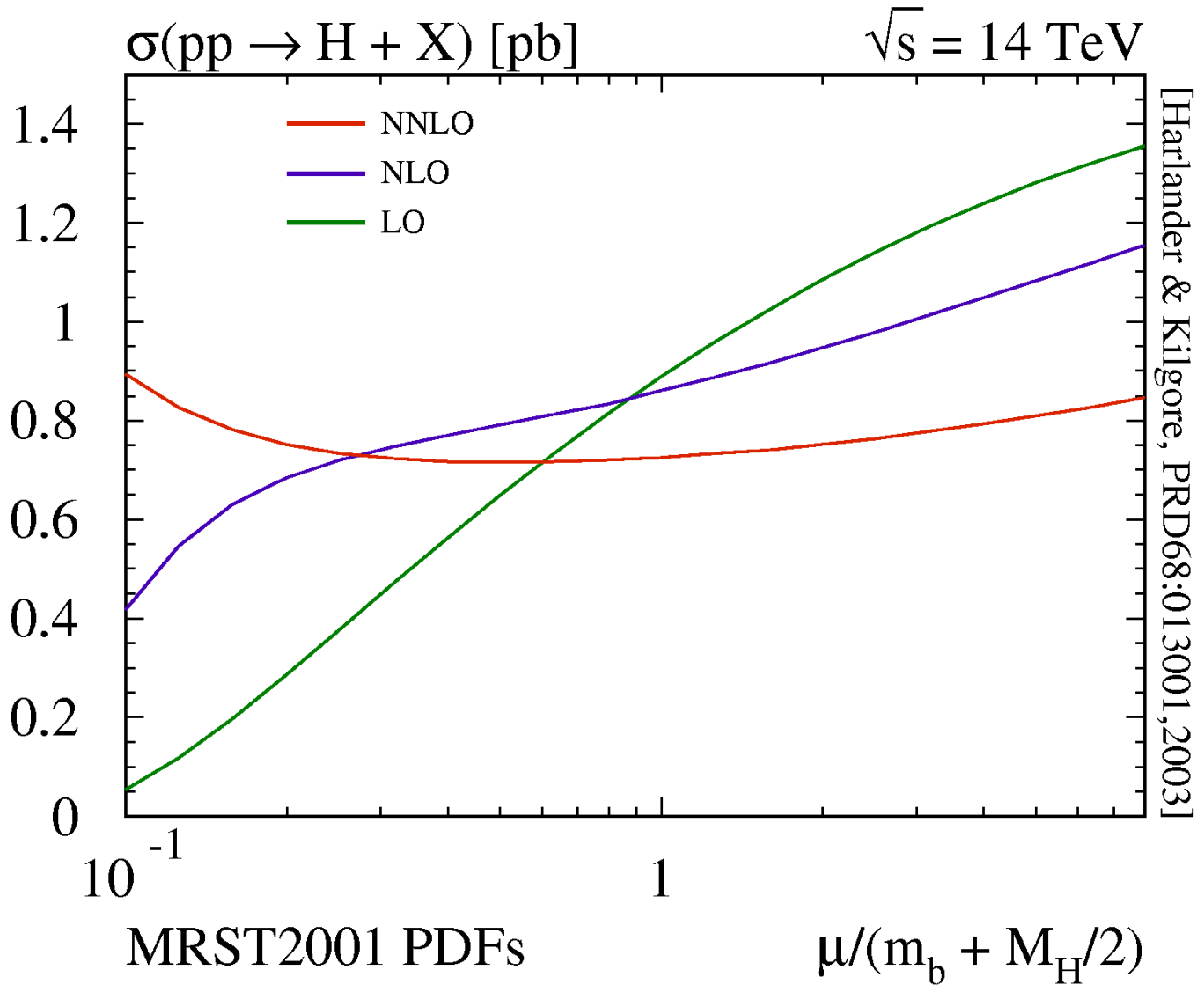
Results for gg→bb̄H @ NLO

This calculation goes to order α_s^3 and includes more of the log-enhanced terms.
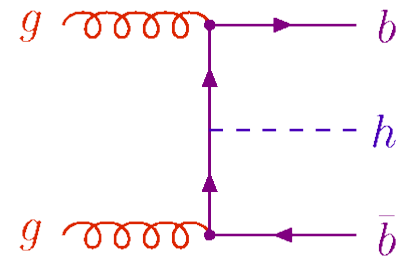
This result is flexible in that it can be applied to the

- Double tag mode
- Single tag mode
- Inclusive mode

But it still suffers from un-resummed log-enhanced terms in (semi-)inclusive modes.
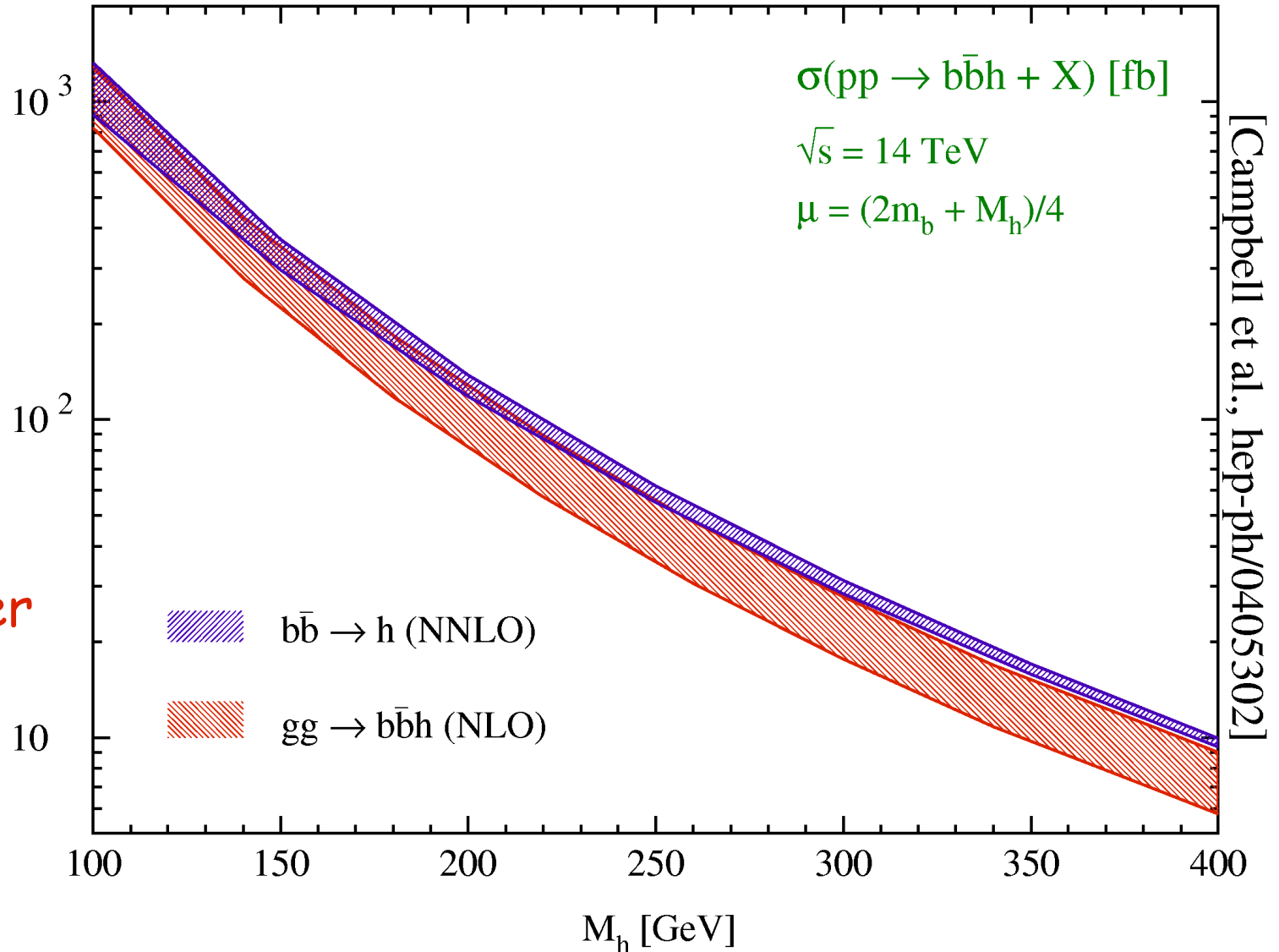
[Dittmaier, Krämer, Spira; Dawson, Jackson, Reina, Wackeroth]

Results for inclusive gg→bb̄H

The good behavior of bb̄→H and the favorable comparison to gg→bbH largely settles the controversy over b parton distributions.

$\sigma(pp \rightarrow b\bar{b}h + X)$ [fb]

$\sqrt{s} = 14$ TeV

$\mu = (2m_b + M_h)/4$

$b\bar{b} \rightarrow h$ (NNLO)

$gg \rightarrow b\bar{b}h$ (NLO)

M_h [GeV]

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

Results for inclusive gg→b̄bH

Preliminary

$\sqrt{s}$=14 TeV
M_h=120 GeV
μ_0=m_b+M_h/2

CTEQ6

no b−tag

[Dawson, et al.]

$\sigma_{LO,MS}$
$\sigma_{NLO,MS}$

$\sigma_{LO,NLO}$ (pb)

μ/μ_0
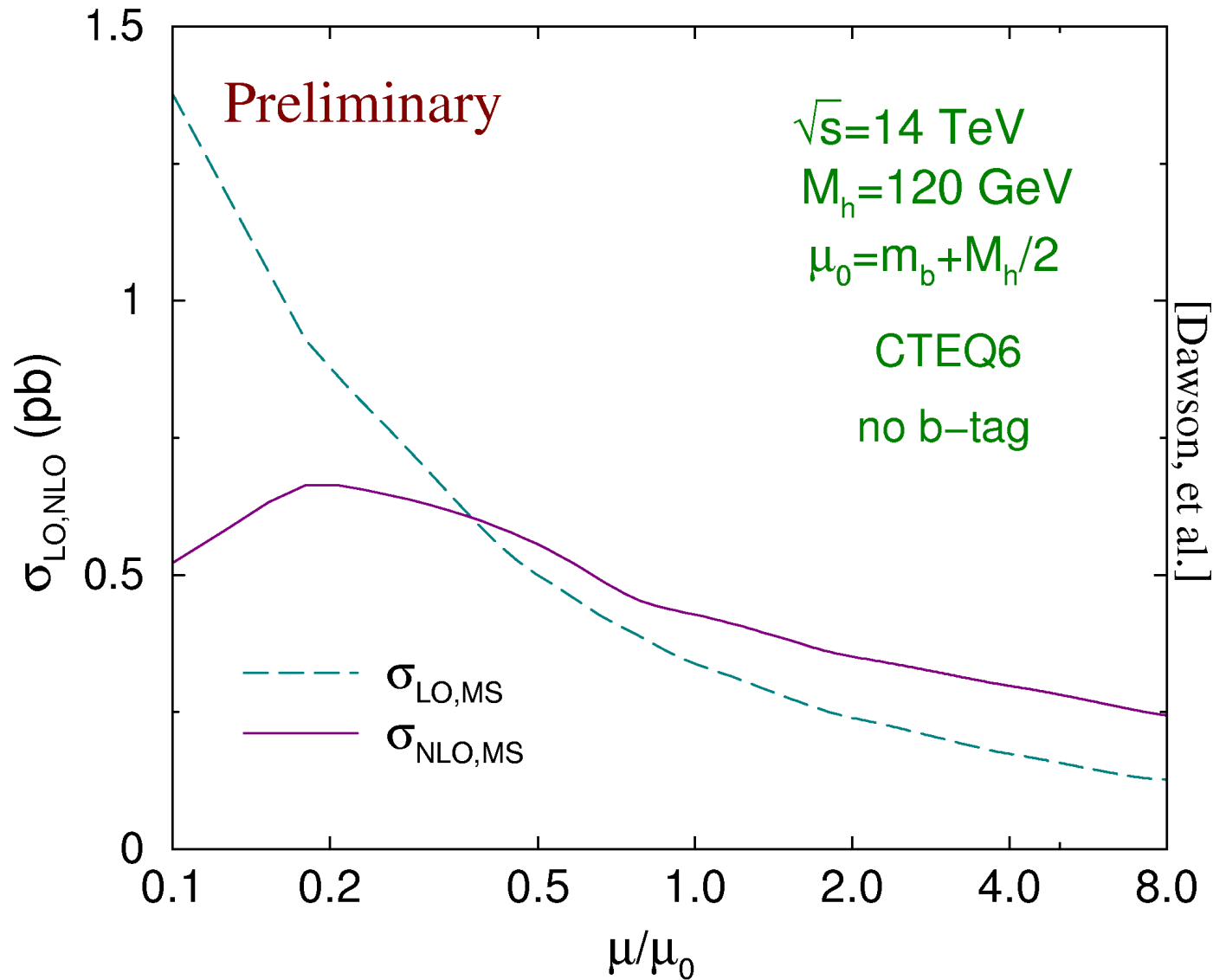
Compare b$\bar{\text{b}}$→H to gg→b$\bar{\text{b}}$H
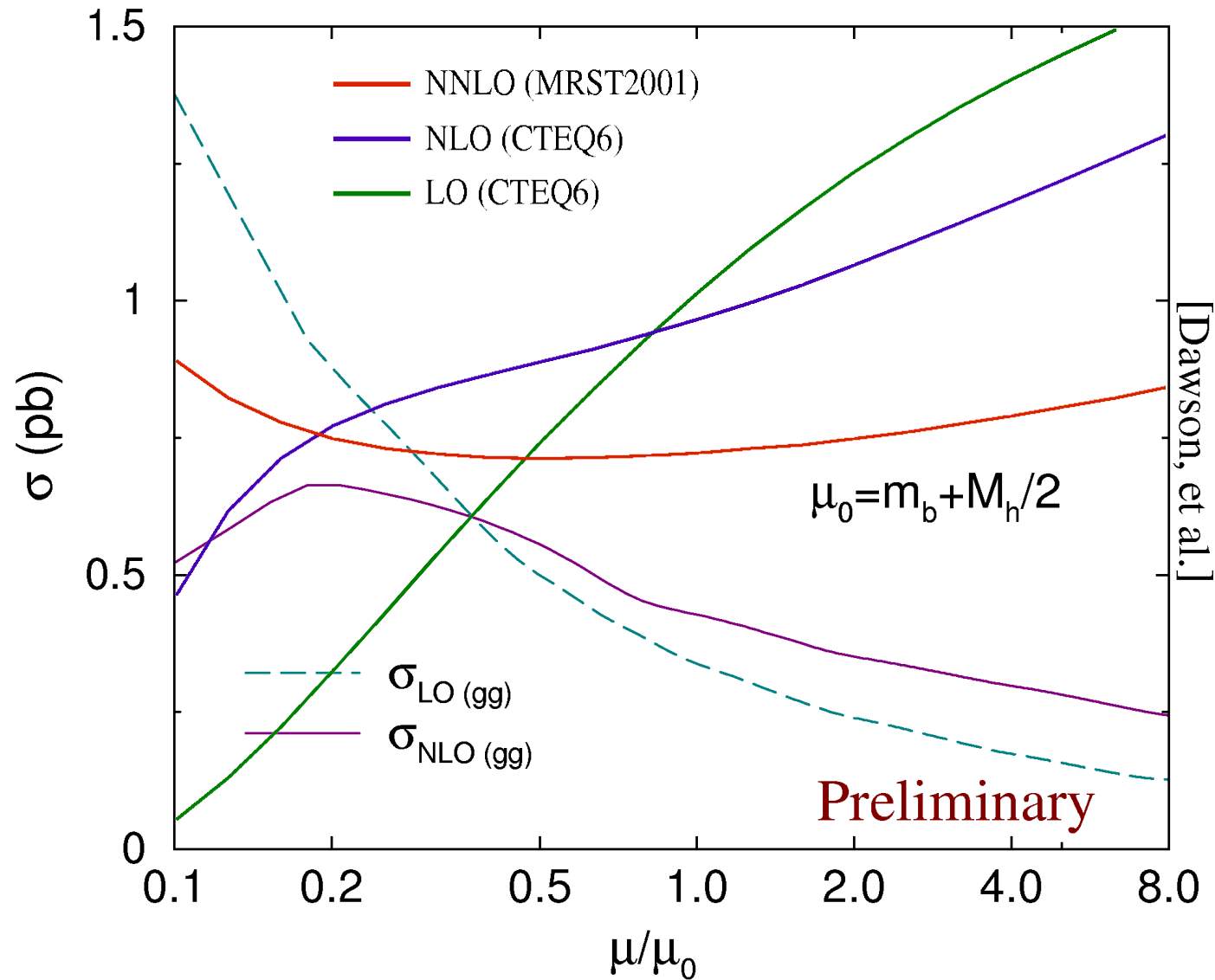
Higgs + b quark Production

H+b production may be more promising. The b tag and the Higgs Q_T greatly improve detection efficiency.
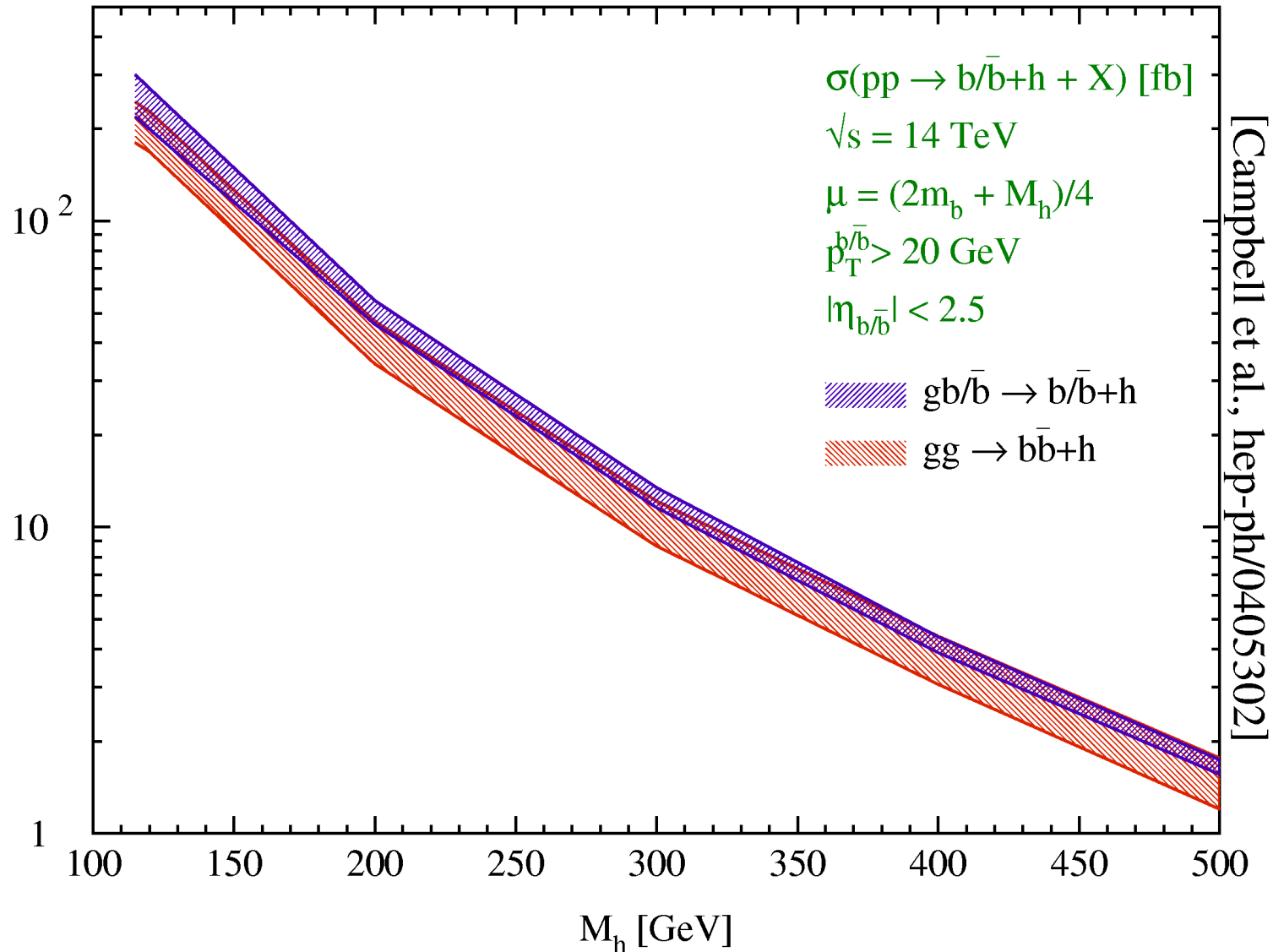
With only one b quark in the initial state, NLO is sufficient to obtain a reliable result.

pp→hb @ LHC

m_h=120 GeV
$p_T(b)$>15 GeV
$|\eta(b)|$<2.5

NLO

LO

$\sigma(\mu)/\sigma_{NLO}(\mu=m_h)$

μ/m_h

[Campbell, et al., PRD67 095002]
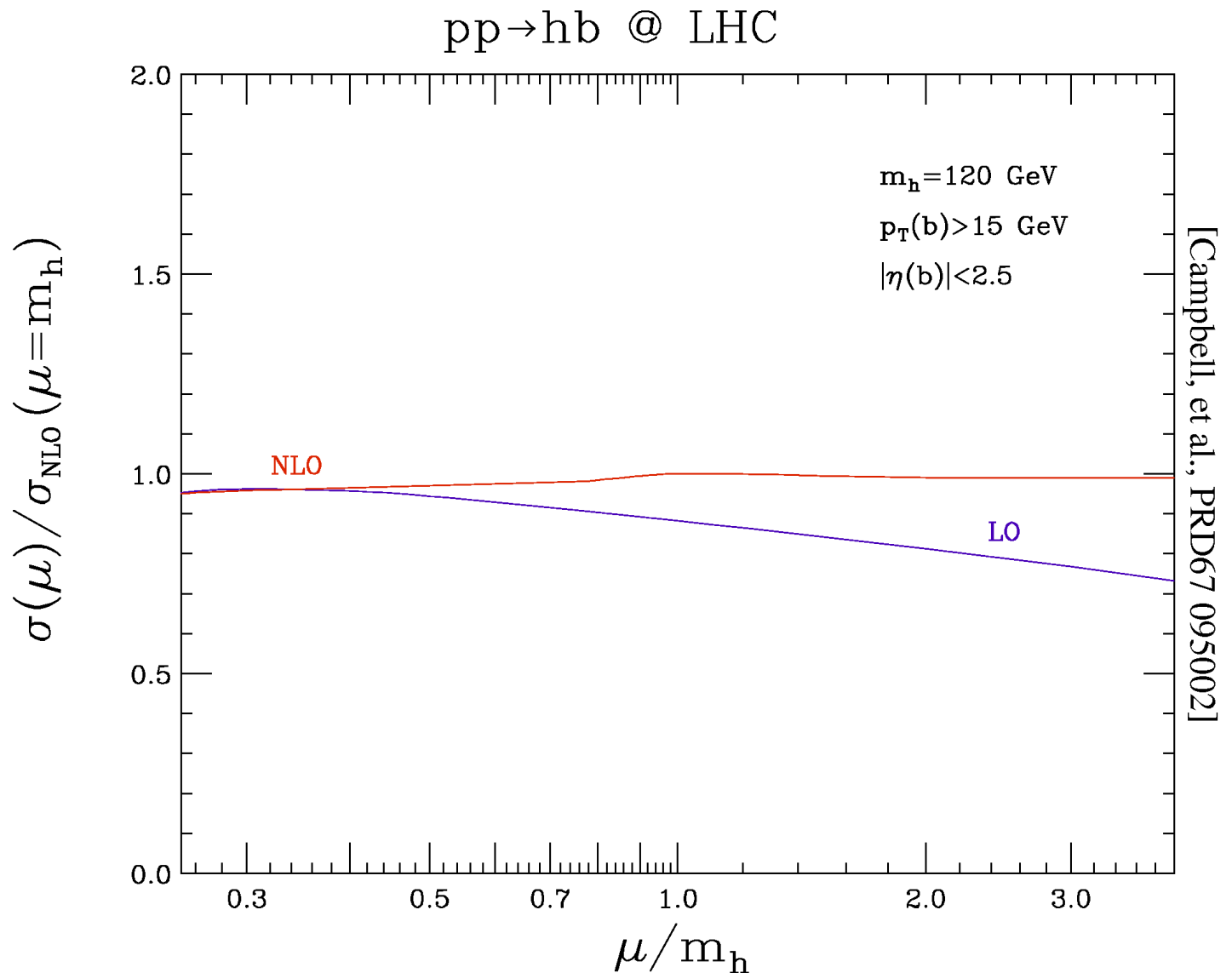
[Campbell, Ellis, Maltoni, Willenbrock]

Compare bg→bH to gg→b̄bH

$\sigma(pp \rightarrow b/\bar{b}+h + X)$ [fb]

$\sqrt{s} = 14$ TeV

$\mu = (2m_b + M_h)/4$

$p_T^{b/\bar{b}} > 20$ GeV

$|\eta_{b/\bar{b}}| < 2.5$

$gb/\bar{b} \rightarrow b/\bar{b}+h$

$gg \rightarrow b\bar{b}+h$

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

M_h [GeV]

gg→bb̄H with two tagged b quarks

√s=14 TeV
M_h=120 GeV
$\mu_0 = m_b + M_h/2$

$\sigma_{NLO,OS}$
$\sigma_{NLO,MS}$
$\sigma_{LO,OS}$
$\sigma_{LO,MS}$

p_T^b >20 GeV
$|\eta|$<2.5

[Dawson, et al., hep-ph/0311067]

$\sigma_{LO,NLO}$ (pb)

μ/μ_0

gg→bb̄H with two tagged b quarks

$\sigma(pp \rightarrow b\bar{b}h + X)$ [fb]

$\sqrt{s}$ = 14 TeV

$\mu = (2m_b + M_h)/4$

$p_T^{b/\bar{b}} > 20$ GeV

$|\eta_{b/\bar{b}}| < 2.5$

- - - LO

——— NLO

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

M_h [GeV]
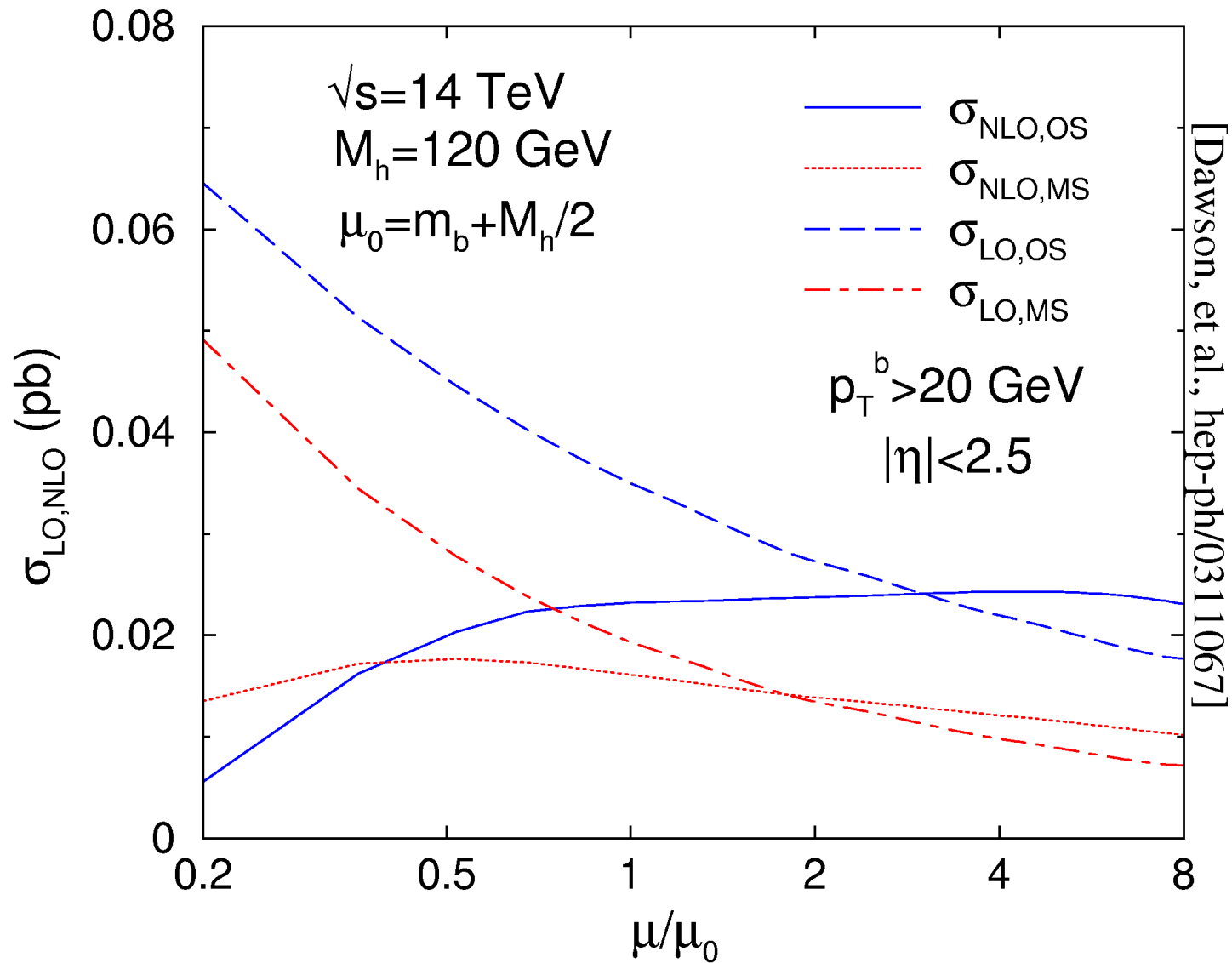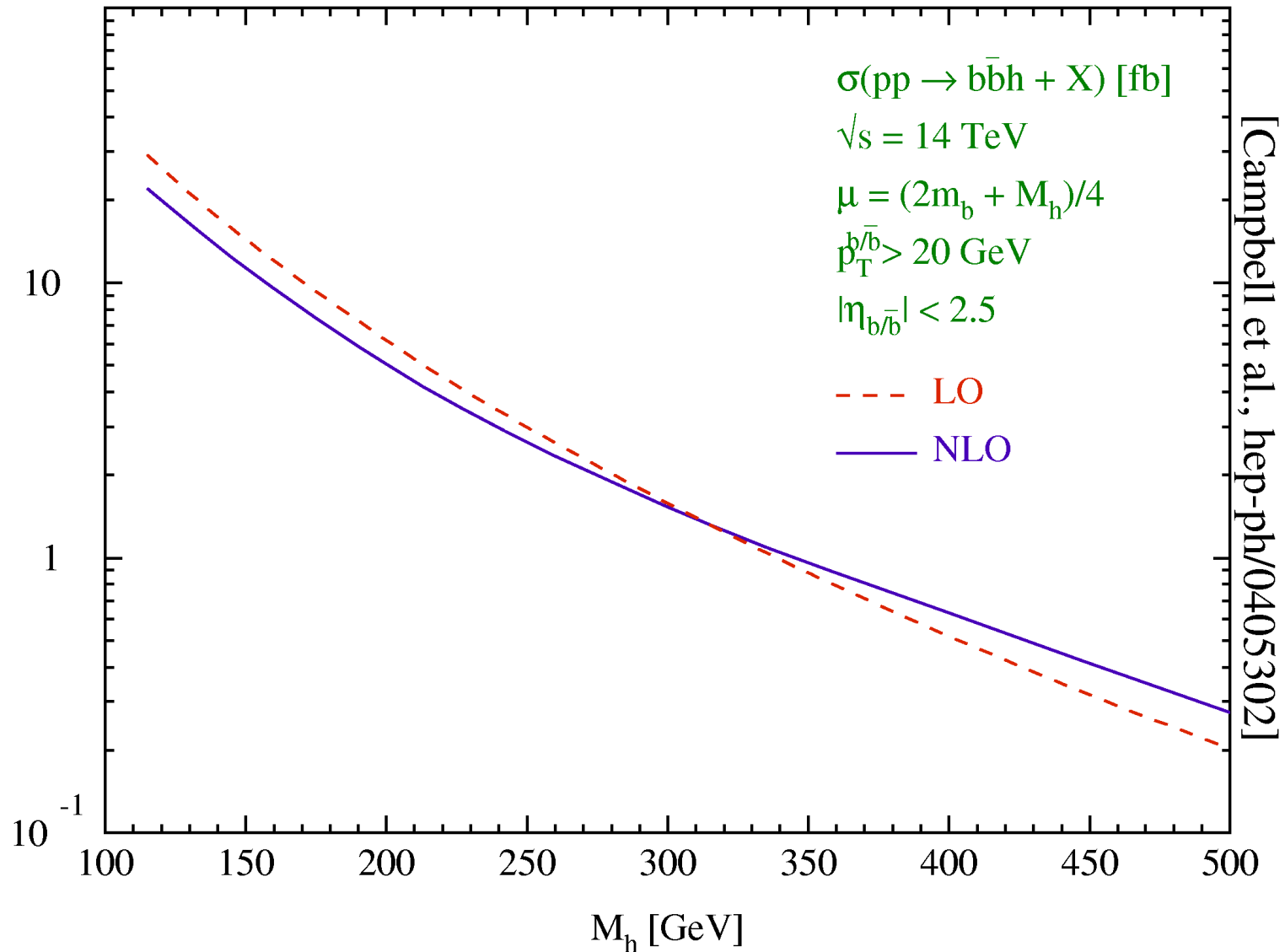
Finding SUSY Higgs at LHC
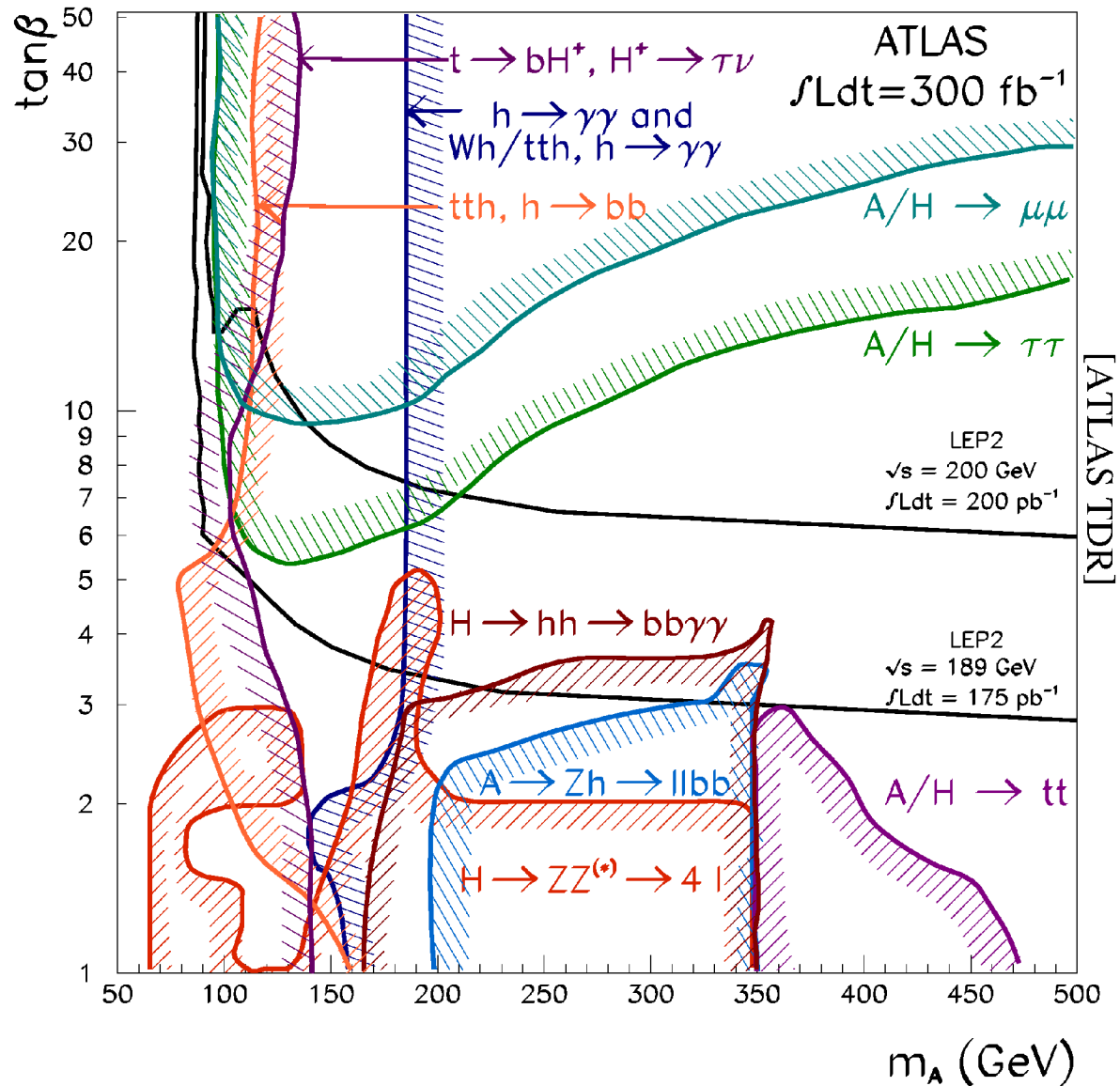
Higgs Bosons at a Linear Collider:

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.
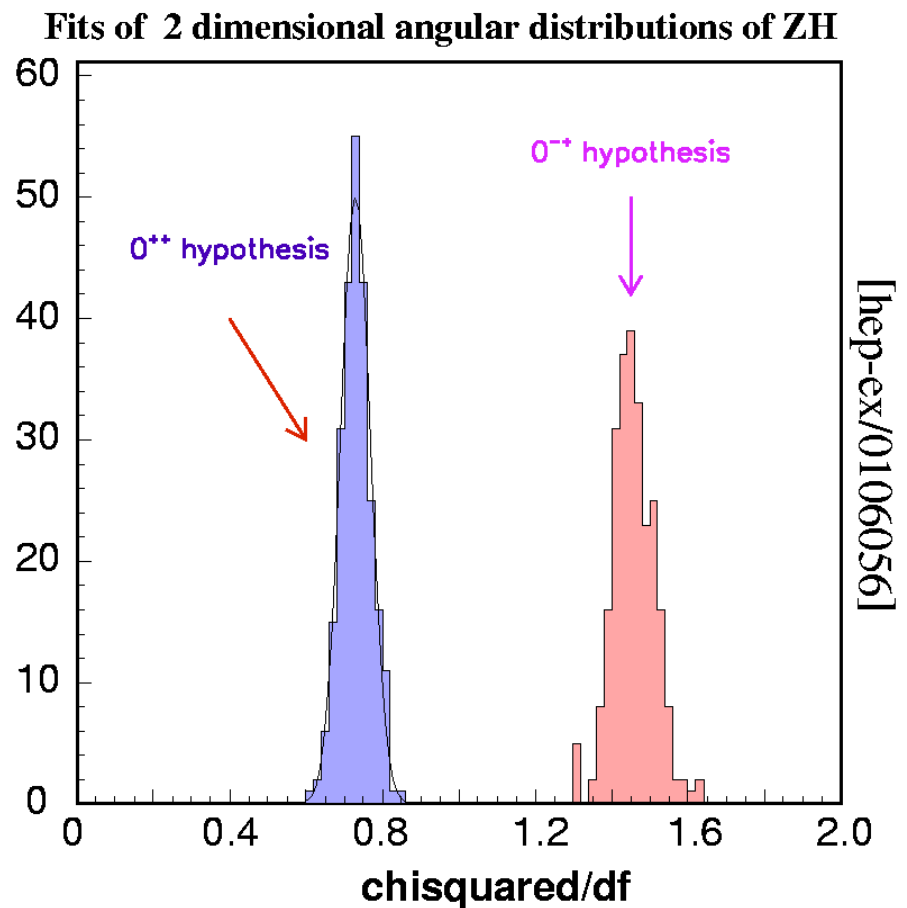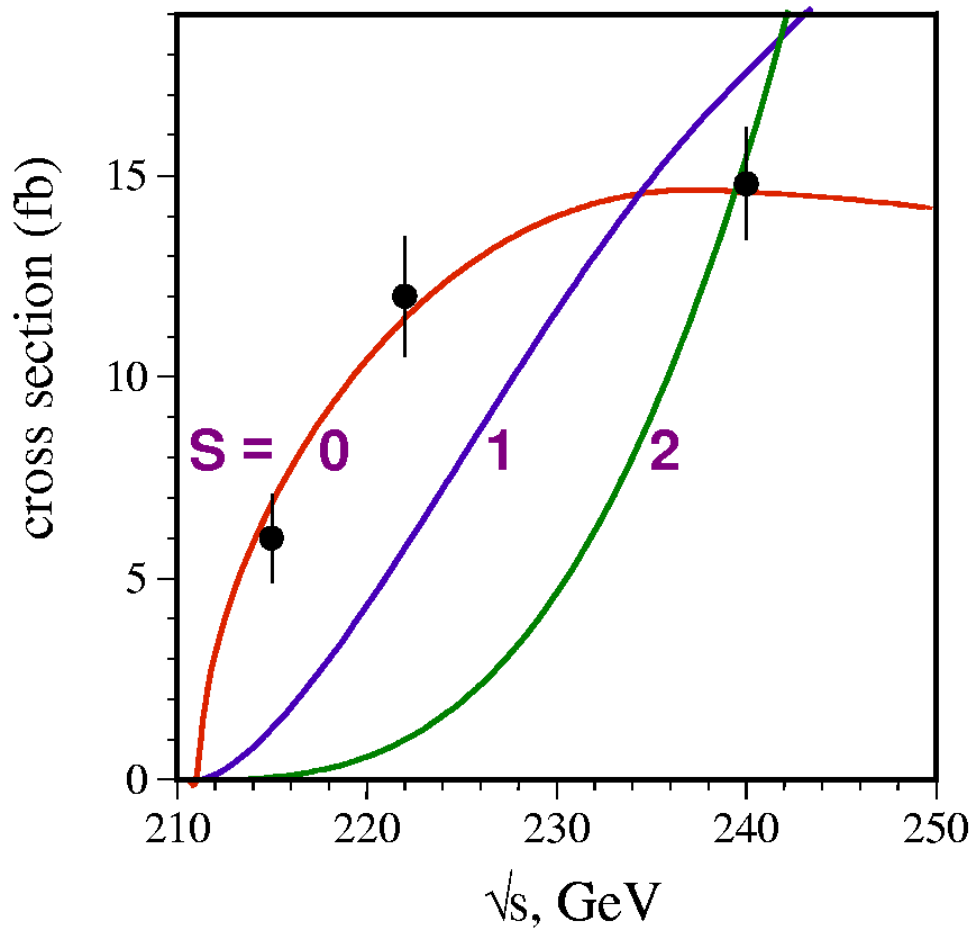
Higgs Couplings at a Linear Collider

If the Higgs mass is below ~160 GeV, many branching ratios can be precisely measured.
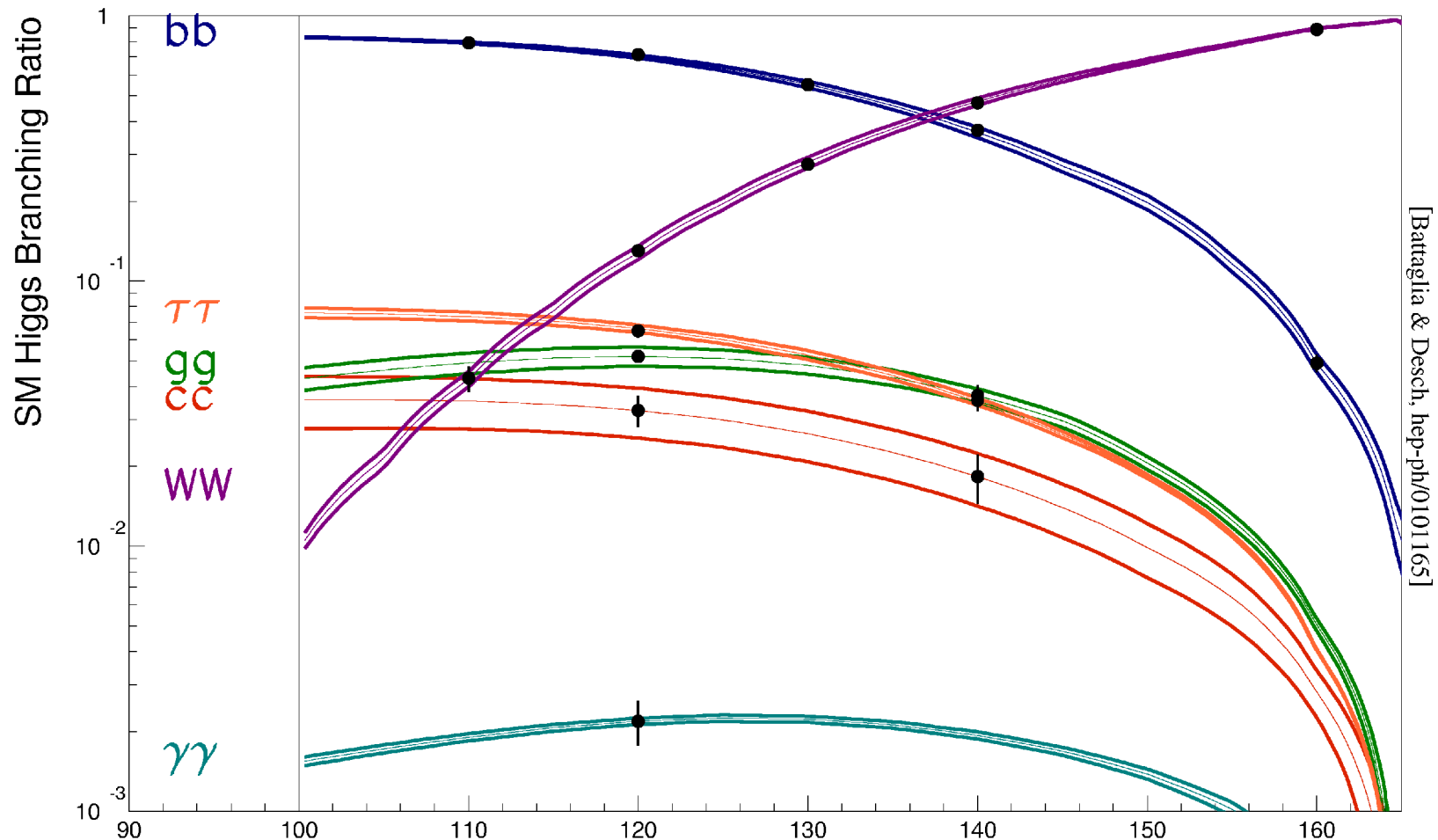
Spin and CP at a Linear Collider

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

Conclusions

The nature of electroweak symmetry breaking is the most important question in particle physics.

This has been true for ~ 20 years. It is still true.

The discovery of the agent of electroweak symmetry will likely be made at the LHC.

The Tevatron can find evidence and perhaps set important limits, but it will be difficult to make a definitive observation.

Conclusions (continued)

Radiative corrections and resummations will play an essential role in the discovery and exploration of the symmetry breaking sector of the Standard Model.

Higher order corrections can do more than provide a more accurate calculation. They can also clarify difficult issues.