Higgs Bosons and b Quarks

MCTP Higgs Workshop

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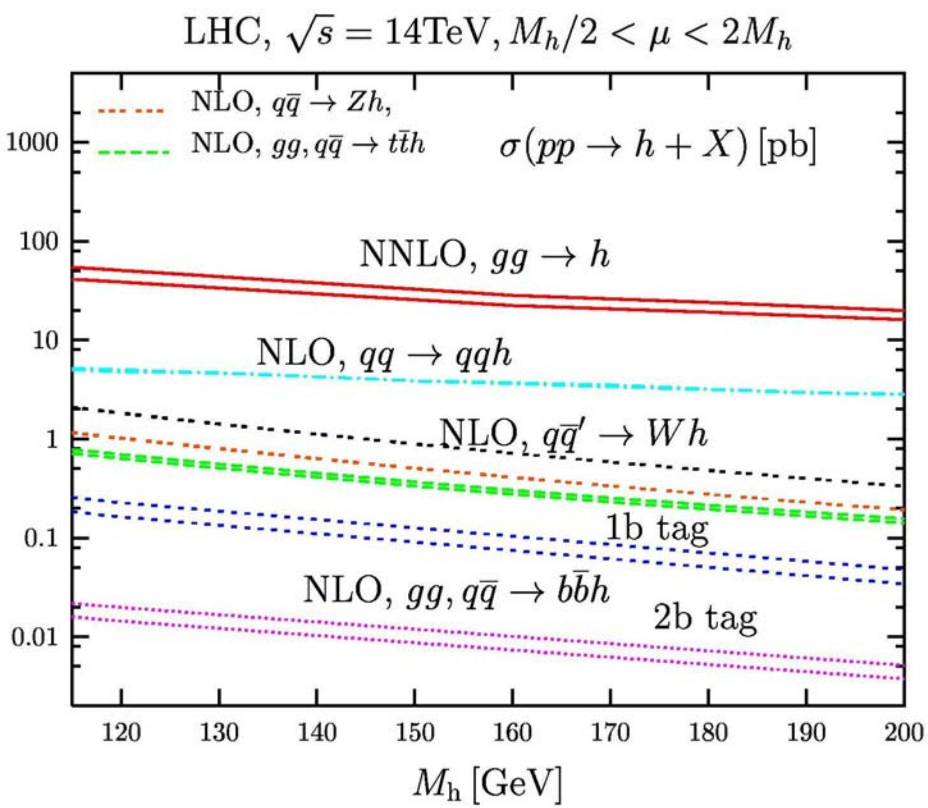
SM Production Mechanisms at LHC

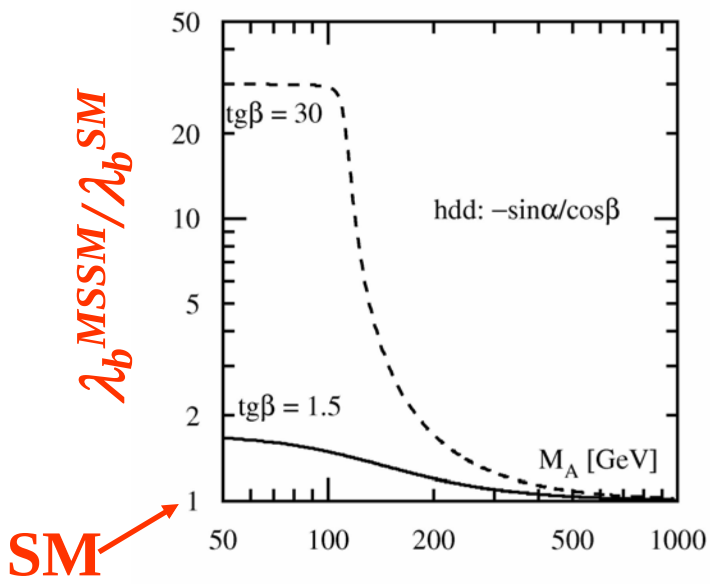


Production with b's very small in SM

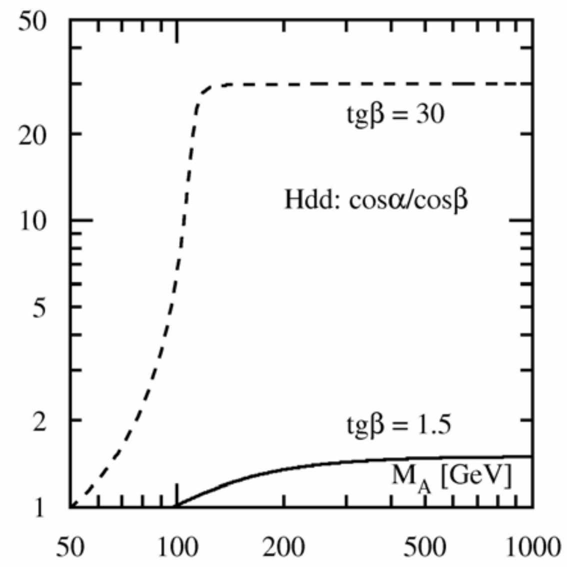
- Information about $b\bar{b}H$ coupling must come from decays
- Progress in extracting $H \to b\bar{b}$ from boosted Higgs techniques [Plehn]

Higgs Couplings Very Different in MSSM

Light Higgs



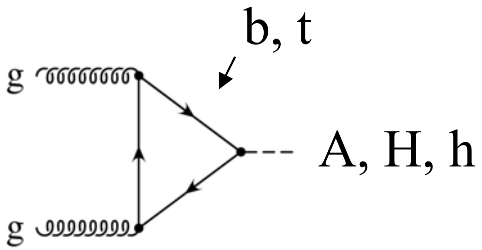
Heavy Higgs

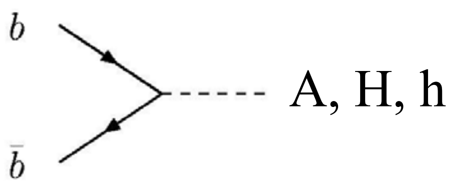


H, A couplings to d, s, b enhanced at large tan β

h couplings to d, s, b enhanced at large tan β for small M_A

Relative Importance of Production Modes





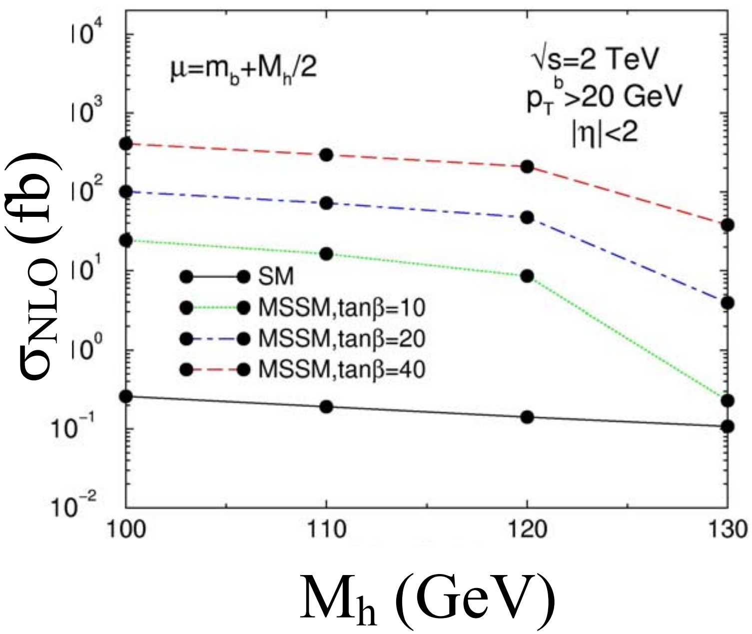
$$\sigma_{gg} = \frac{1}{M_h^2}\left(c_1 \cot^2\beta + c_2\frac{m_b^2}{M_h^2} + c_3\frac{m_b^4}{M_h^4}\tan^2\beta\right)$$

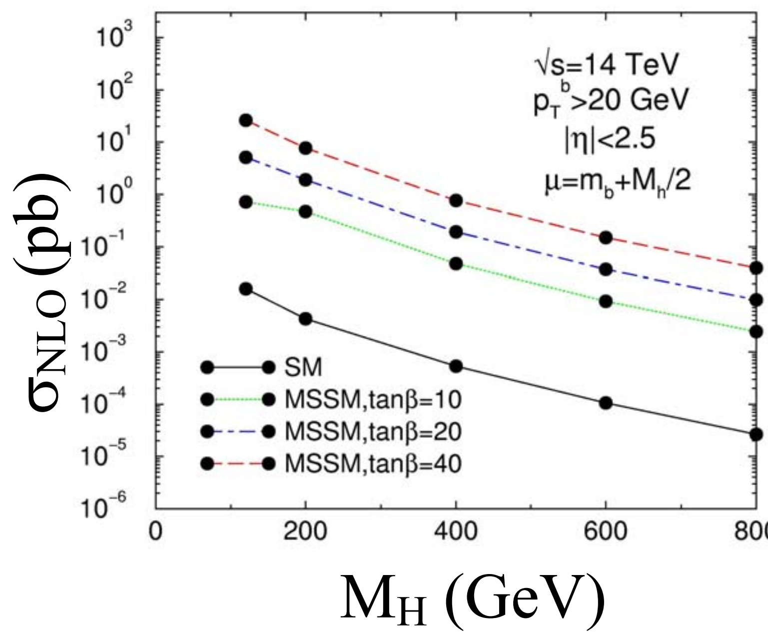
$$\sigma_{bb} = \frac{m_b^2}{M_h^4} c_4 \tan^2\beta$$

⇒ At some tan β, the rates for $b\bar{b}$→A,H,h will be larger than those for gg →A,H,h

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

Rates large even at relatively small tan β

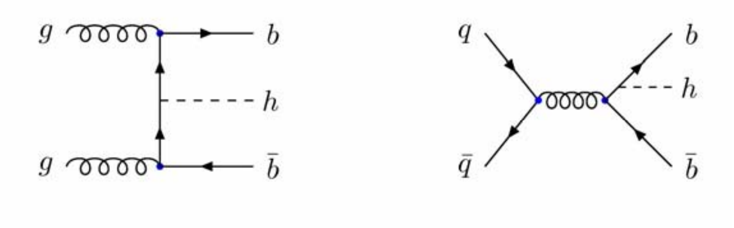




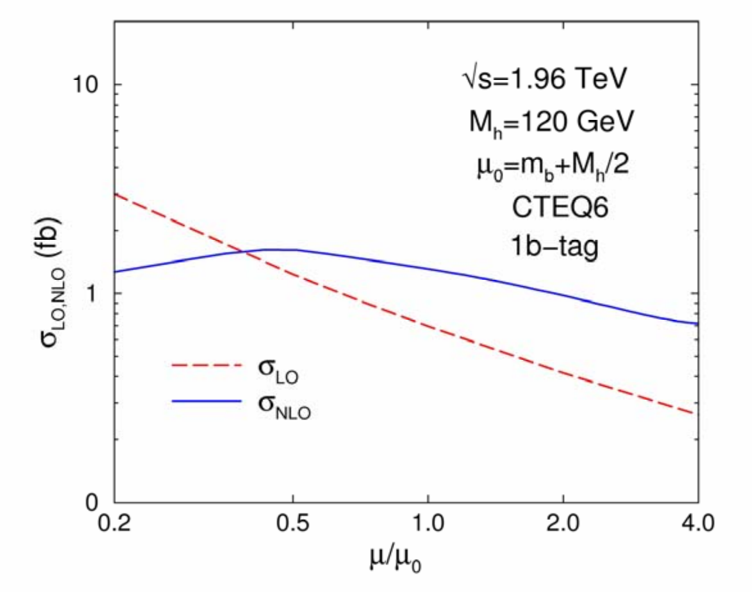
α_{eff} from FeynHiggs with $M_{SUSY}=M_g=\mu=M_2=1$TeV, $A_b=A_t=25$ GeV

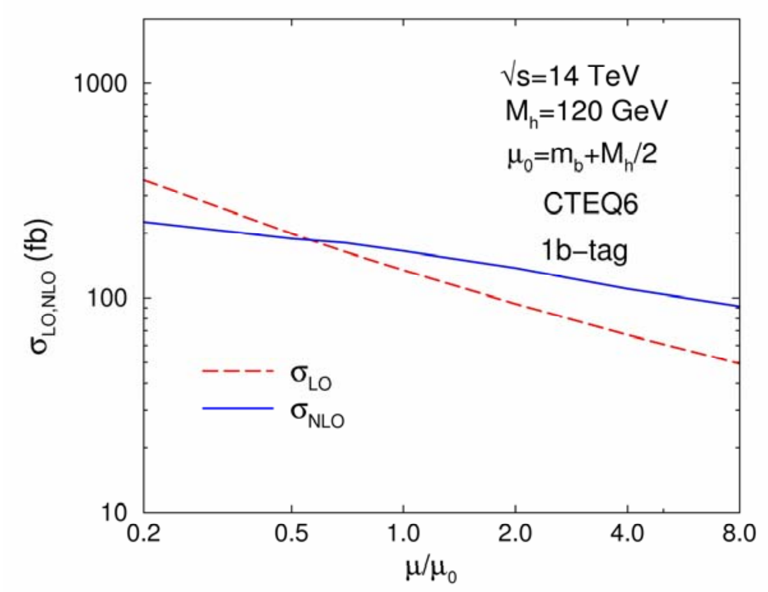
QCD Corrections Important

- NLO corrections improve scale dependence
- NLO QCD corrections large (can't neglect them!)
- In 4 flavor number scheme:



* Corrections don't exist in public code





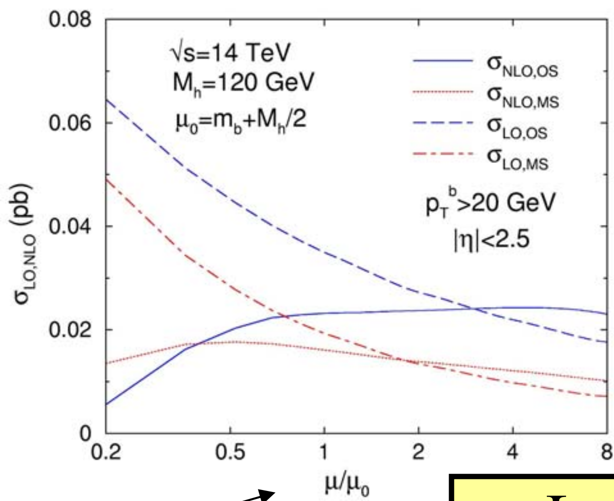
Dawson, Jackson, Reina, Wackeroth, hep-ph/0408077,0508293

Dittmaier, Kramer, Spira, hep-ph/0309204

Residual Scheme Dependence at NLO

- Cross section proportional to b Yukawa, $\lambda_b^2 \approx \left(\frac{m_b^2}{v^2}\right)$
  - $\overline{\text{MS}}$ vs on-shell definitions of b quark mass
  - $\overline{\text{MS}}$ mass depends on physical scale: $\overline{m}_b(\mu) = m_b\left[1 - \frac{\alpha_s}{3\pi}\left(4 + 3\ln\left\{\frac{\mu^2}{m_b^2}\right\}\right)\right]$
  - Difference between schemes is $O(\alpha_s^4)$

$pp \rightarrow b\overline{b}h$



Renormalization scheme dependence

Scale dependence

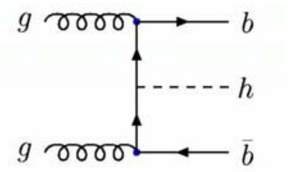
- Large scheme dependence at NLO
- Effect ≈ 10-20%

Theoretical Issues in $b\bar{b}h$ production

Reduced Background ↓ / Larger Signal ↑

- Inclusive mode: No tagged b's
- Semi-inclusive mode: At least one tagged b
- Exclusive mode: Two tagged b's

- Treating b quarks inclusively leads to large collinear logarithms from integration over phase space



$$\Rightarrow \quad \ln\left(\frac{\mu_F^2}{m_b^2}\right), \qquad \mu_F \approx M_h$$

- Expansion parameter becomes $\alpha_s \log(m_b/M_h)$

Two Schemes for PDFs

- 4 flavor number scheme (Fixed Flavor Number Scheme)
  - No b quarks in initial state
  - Lowest order process involving Higgs and b's is $gg \rightarrow b\bar{b}h$
  - No kinematic approximations
- 5 flavor number scheme (Variable Flavor Number Scheme)
  - Define b quark PDFs (absorbs large logarithms)

$$b(x,\mu) = \frac{\alpha_s}{2\pi} \ln\left(\frac{\mu^2}{m_b{}^2}\right) \int_x^1 \frac{dz}{z} P_{bg}\left(\frac{x}{z}\right) g(z,\mu)$$

  - Higgs produced with no p_T at lowest order ($b\bar{b} \rightarrow h$)
  - Higgs p_T generated at higher orders in expansion
  - Both CTEQ and MSTW use this scheme for PDFs

Re-ordering of Perturbation Theory

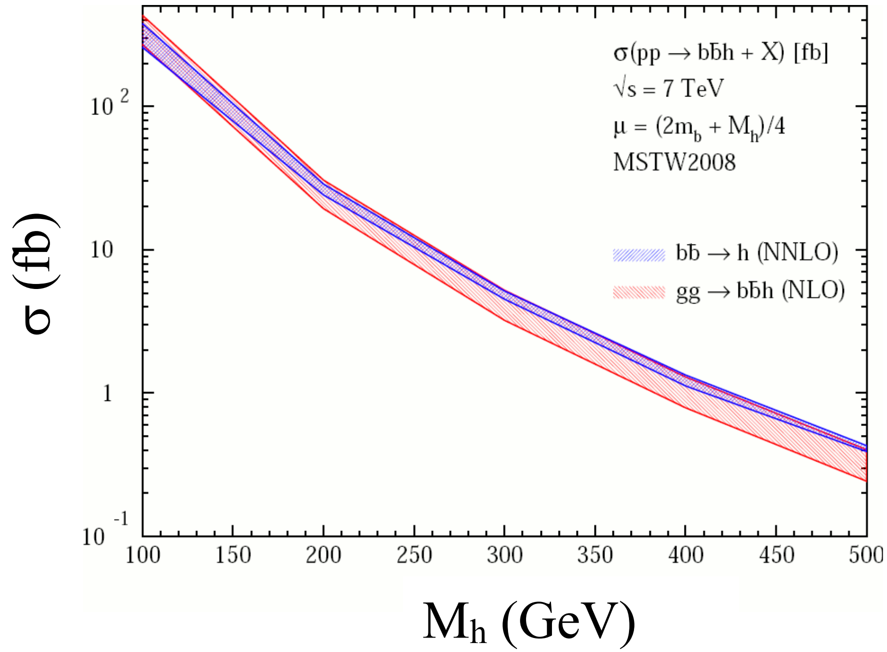
$\Lambda_b = \log(M_h^2/m_b^2)$

- 0 b tag process in 5FNS:
  - LO: $b\bar{b} \rightarrow h$ $O(\alpha_s^2 \Lambda_b^2)$
  - NLO: Virtual + real corrections $O(\alpha_s^3 \Lambda_b^2)$
  - NLO: $bg \rightarrow bh$ $O(\alpha_s^2 \Lambda_b)$, correction of $O(1/\Lambda_b)$
  - NNLO: $gg \rightarrow b\bar{b}h$ $O(\alpha_s^2)$, correction of $O(1/\Lambda_b^2)$
- 1 b tag process in 5FNS:
  - LO process is $bg \rightarrow bh$: Tree level, $O(\alpha_s^2 \Lambda_b)$
  - NLO includes new subprocess: $gg \rightarrow b\bar{b}h$, $O(1/\Lambda_b)$ correction

4FNS and 5FNS must agree at high enough order in perturbation theory

Inclusive Cross Section for $b\bar{b} \to h$: 0 b tags

$b\bar{b} \to h$ vs $gg \to b\bar{b}h$



4FNS: NLO QCD

5FNS: NNLO QCD

Agreement best at low M_h

S-ACOT Scheme: $\sigma_{tot} \approx \sigma_{bb} + \sigma_{sub} + \sigma_{gg}$

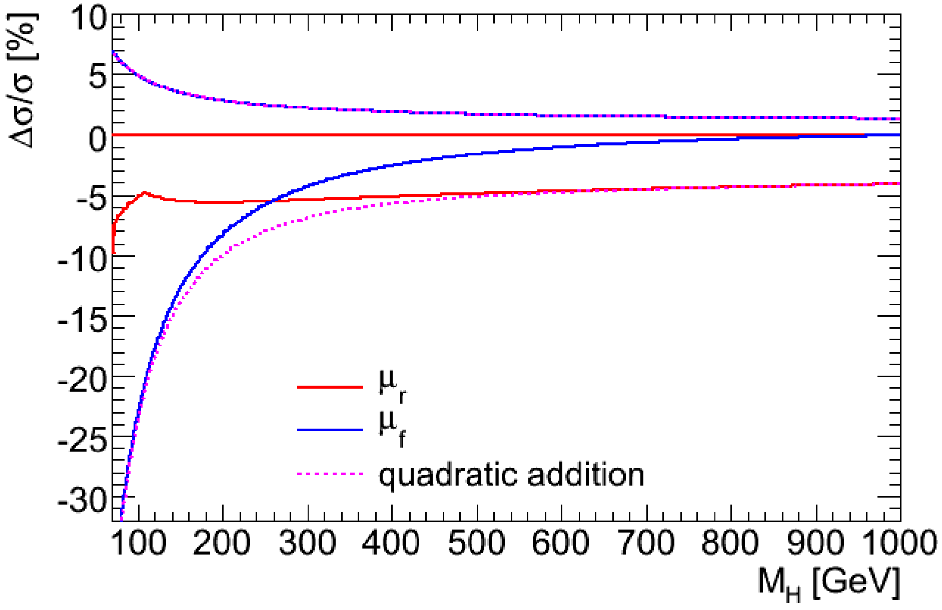
σ_{sub} takes care of double counting from $g \to b\bar{b}$

LHC Higgs cross section group, Freiburg, 3/10

Harlander, Kilgore, hep-ph/0304035; public code bbh@NNLO

Issues with Factorization Scale Dependence?

5FNS, $b\bar{b} \to h$ @NNLO,
MSTW2008, $\sqrt{s}$=7 TeV



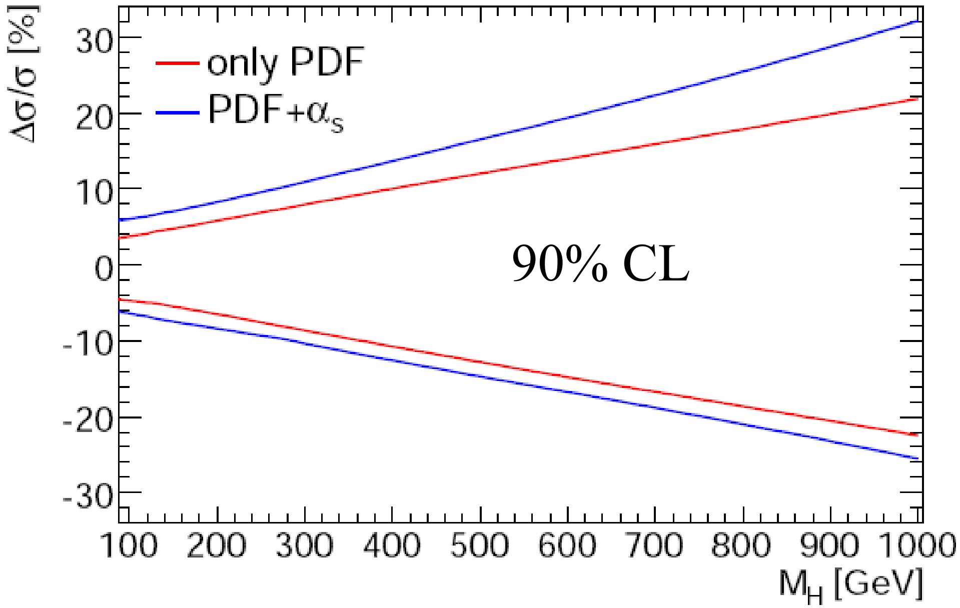
$0.2M_H < \mu_R < 5\ M_H$

$0.1M_H < \mu_F < 0.7\ M_H$

LHC Higgs cross section group, Freiburg, 3/10

PDF uncertainty for $b\bar{b} \rightarrow h$

5FNS, $b\bar{b} \rightarrow h$ @NNLO,
MSTW2008, $\sqrt{s}$=7 TeV



Large PDF uncertainty for heavy Higgs!

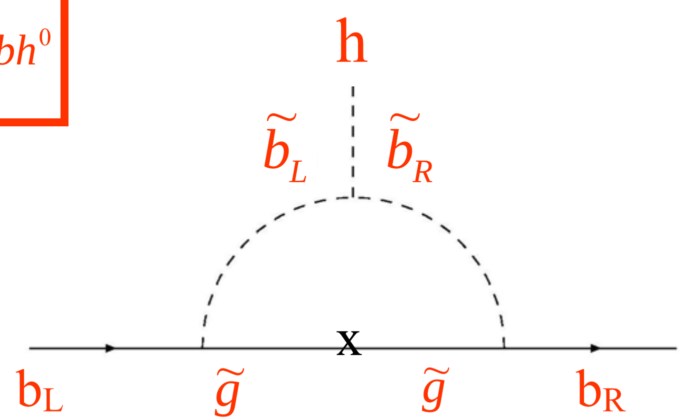
SUSY QCD / Electroweak Corrections

- Compute in effective Lagrangian approach

$$L_{eff} = \frac{\overline{m}_b(\mu)}{v_{SM}}\left(-\frac{\sin\alpha}{\cos\beta}\right)\left(1+\delta_{SQCD}+\delta_{EW}\right)\overline{b}bh^0$$

- SUSY QCD:

$$\delta_{SQCD} \equiv \left(\frac{1}{1+\Delta m_b}\right)\left(1-\frac{\Delta m_b}{\tan\beta\tan\alpha}\right)$$



- Similarly for weak effects: δ_{EW} ~ 2-4%

Effective Lagrangian approach works to 1-3% for $b\overline{b} \to h$ for SQCD and EW effects

Dittmaier et al, hep-ph/0611353

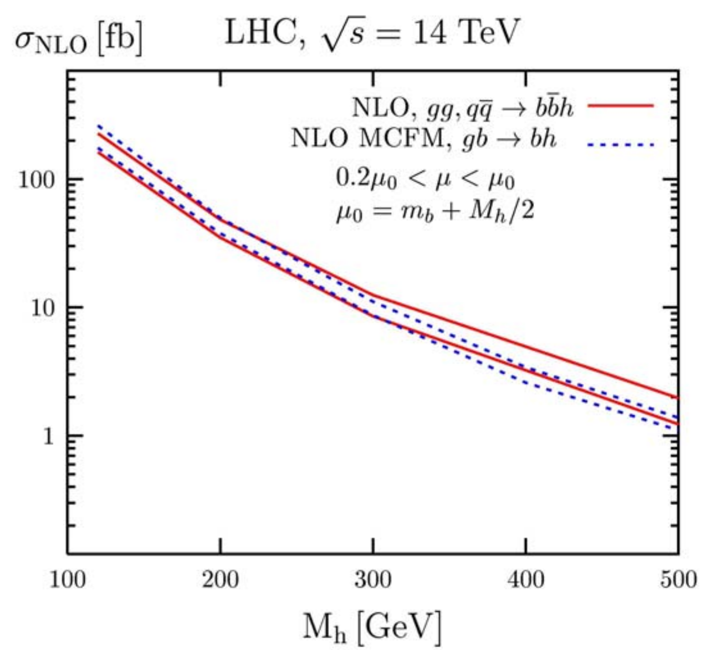
Carena, Garcia, Nierste, Wagner, hep-ph/9912516

Bottom Line: Inclusive 0 b Tag

- Calculate SM in 5FNS to NNLO (using bbh@NNLO)
  - Find MSSM couplings from HDECAY or FeynHiggs
- μ_R uncertainty ~5%
- μ_F uncertainty ~5% for $M_H > 200$ GeV, up to 20% for lighter M_H
- Scheme dependence ~10-20%
- PDF uncertainty ~ 10-20%
- SQCD and EW effects accurately included using effective Lagrangian approach (Δm_b)
  - These may be large

Easier experimentally: bH production

- 4 flavor number scheme
  - NLO QCD
- 5 flavor number scheme
  - NLO QCD [MCFM with top triangle removed]
  - SUSY QCD corrections
  - EW corrections

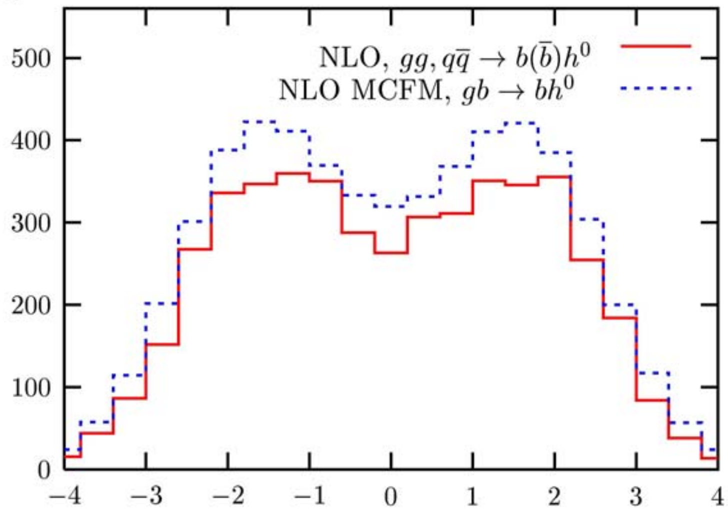


Consistent results for total cross sections

Compare Distributions: Single b Tag

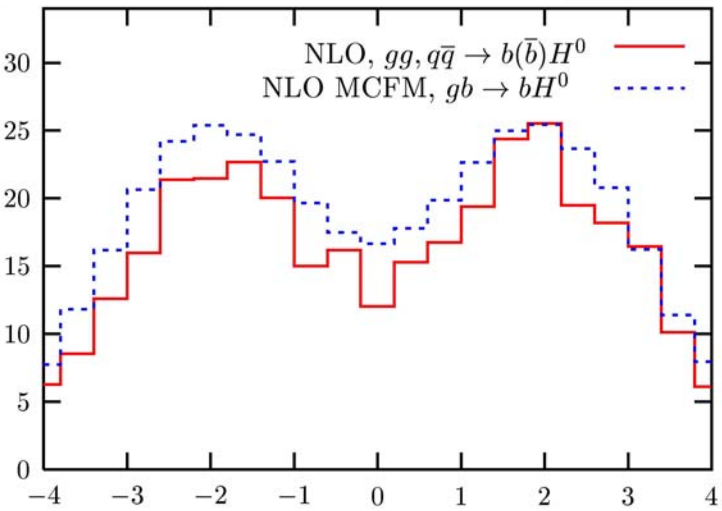
- 4FNS vs 5FNS: Important differences

$d\sigma/d\eta_h$ (fb/GeV)   Tevatron



η_h

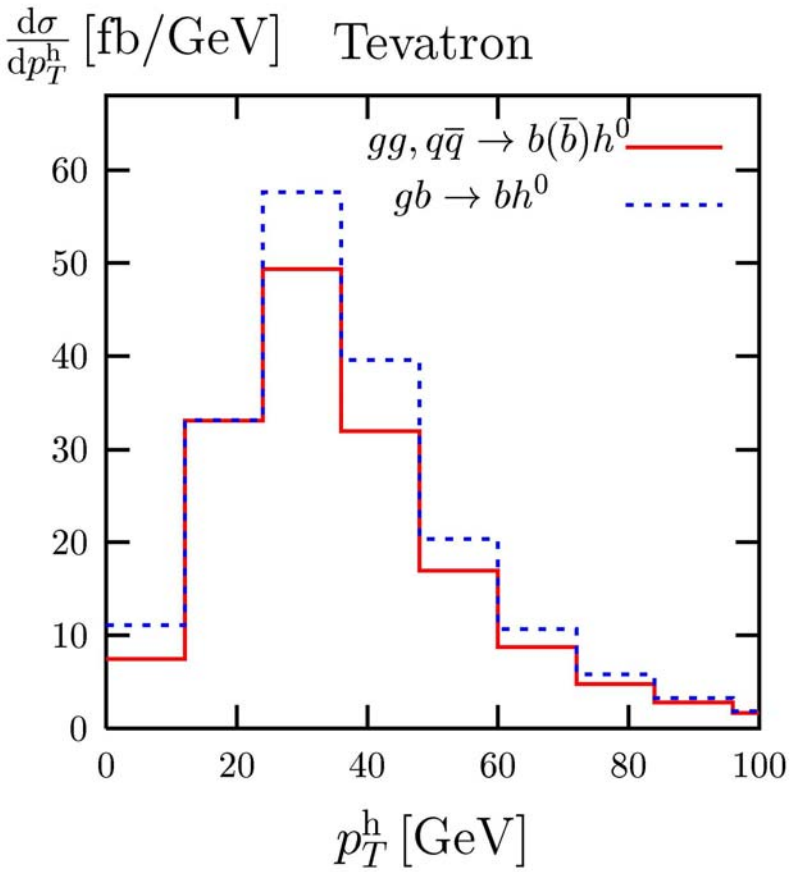
$d\sigma/d\eta_h$ (pb/GeV)   LHC $\sqrt{s}$=14 TeV

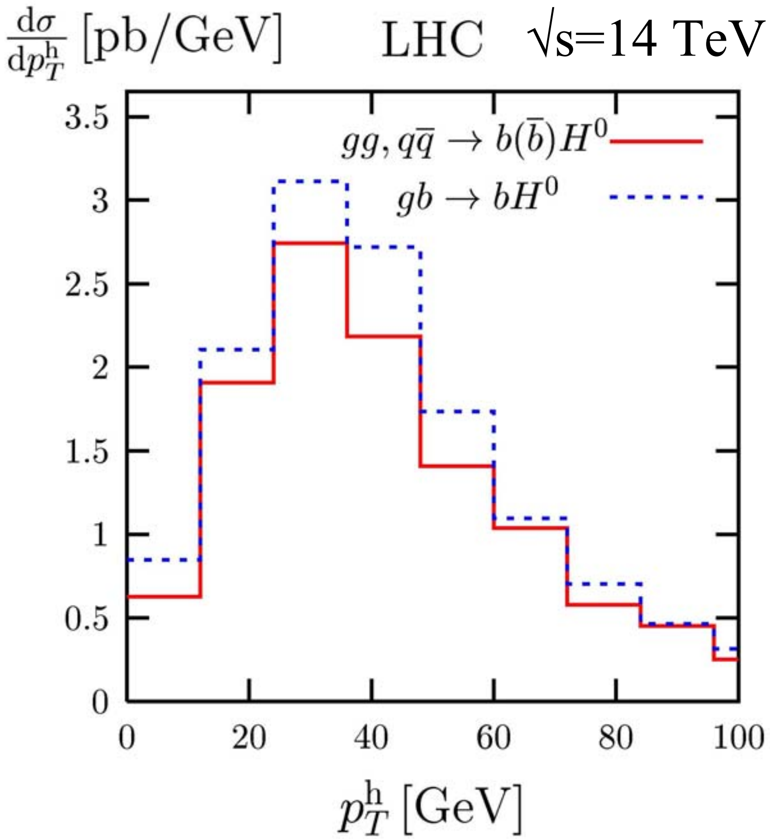


η_h

MSSM with M_h=120 GeV, tan β=40

Compare distributions: Single b tag





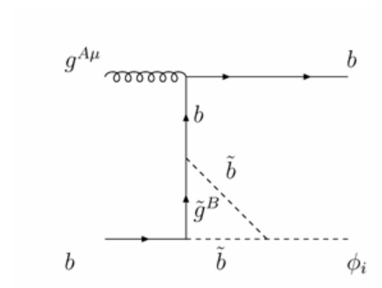
MSSM with M_h=120 GeV, tan β=40

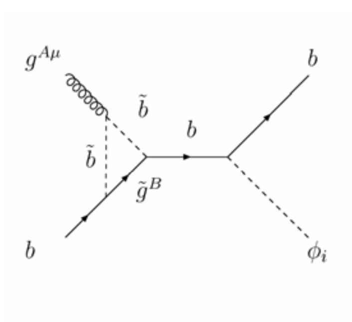
Calculate SUSY QCD Corrections to bg→bh

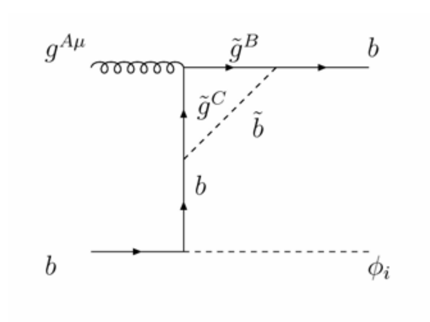
- Approach 1: Improved Born Approximation (Δm_b)

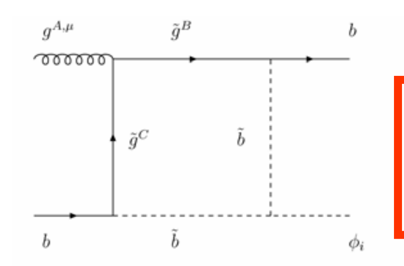
$$g_{hbb} \equiv \frac{m_b}{v_{SM}}\left(\frac{1}{1+\Delta m_b}\right)\left(-\frac{\sin\alpha}{\cos\beta}\right)\left(1-\frac{\Delta m_b}{\tan\beta\tan\alpha}\right) \qquad \sigma_{IBA} = \left(\frac{g_{hbb}}{g_{hbb}^{SM}}\right)^2 \sigma_{LO}$$

- Approach 2: $O(\alpha_s^2)$ NLO calculation
  - Use g_{hbb} as above, so subtract off double counting
  - Include all contributions from squark/gluino loops



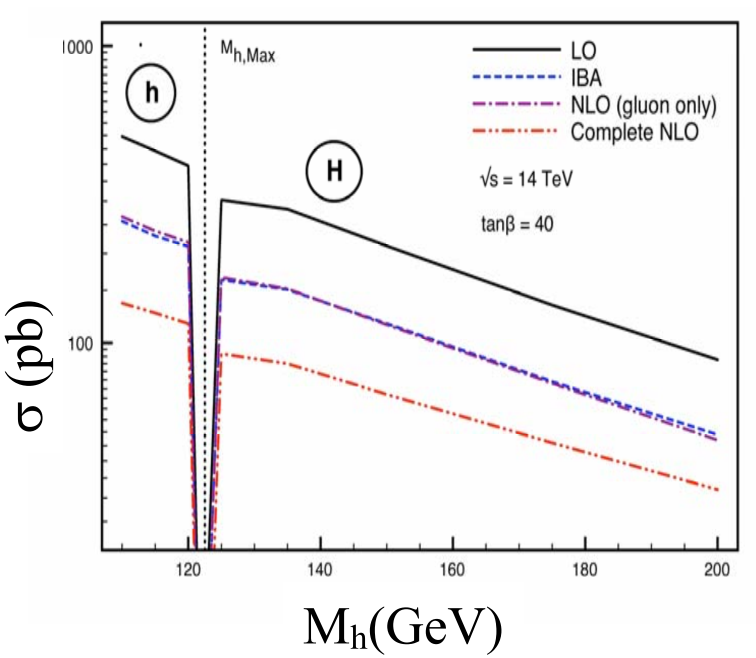


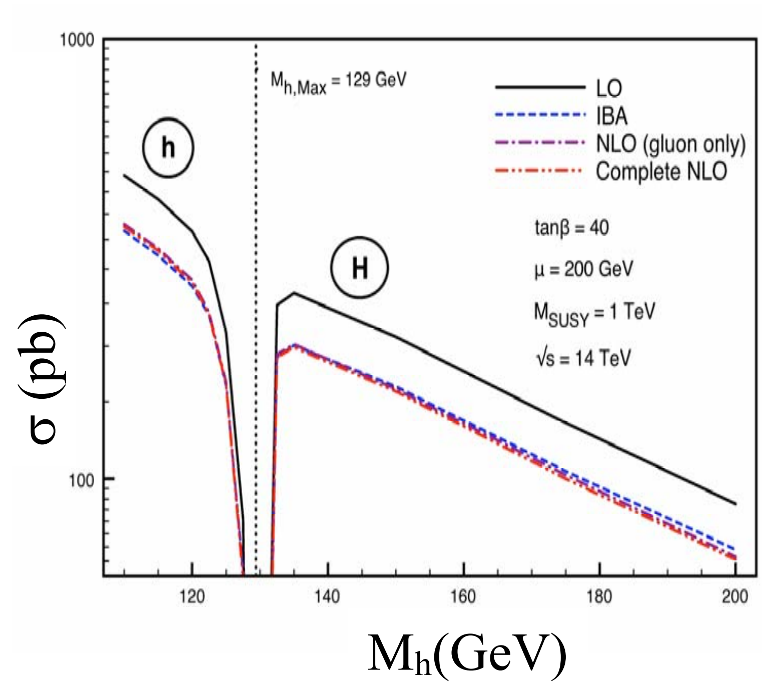




Many contributions not included in IBA

Non-Decoupling of SQCD for Light SUSY
($pp \rightarrow bH$)





$\tilde{m}_g = \tilde{m}_b = 250\ GeV$

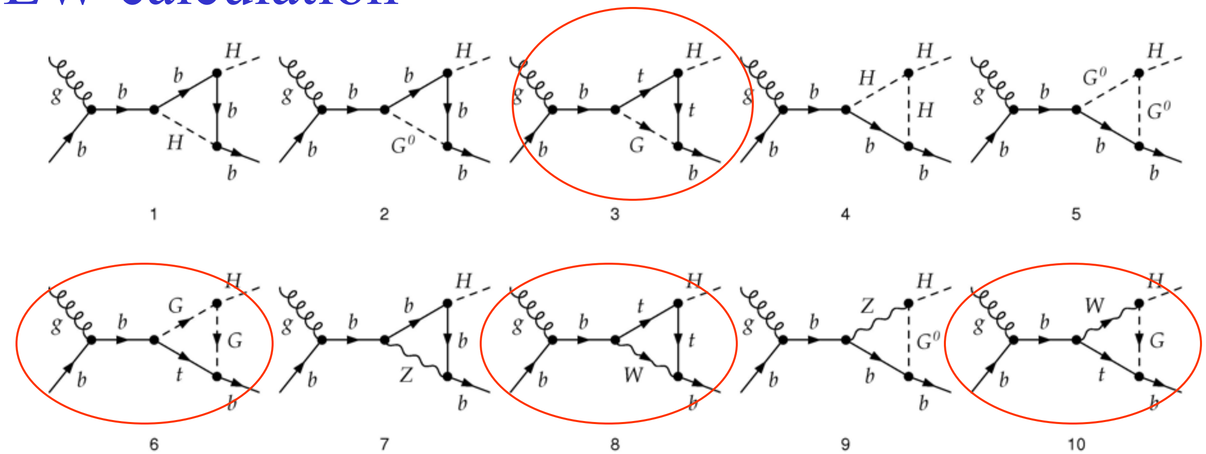
$\tilde{m}_g = \tilde{m}_b = 1\ TeV$

Improved Born Approximation fails for light SUSY particles

Dawson & Jackson, arXiv:0709.4519

Do Electroweak Corrections Matter?

- Lowest order rate for $bg \rightarrow bh$ vanishes for $m_b=0$
- At 1-loop, there are diagrams which do NOT vanish in $m_b=0$ limit
- Full EW calculation



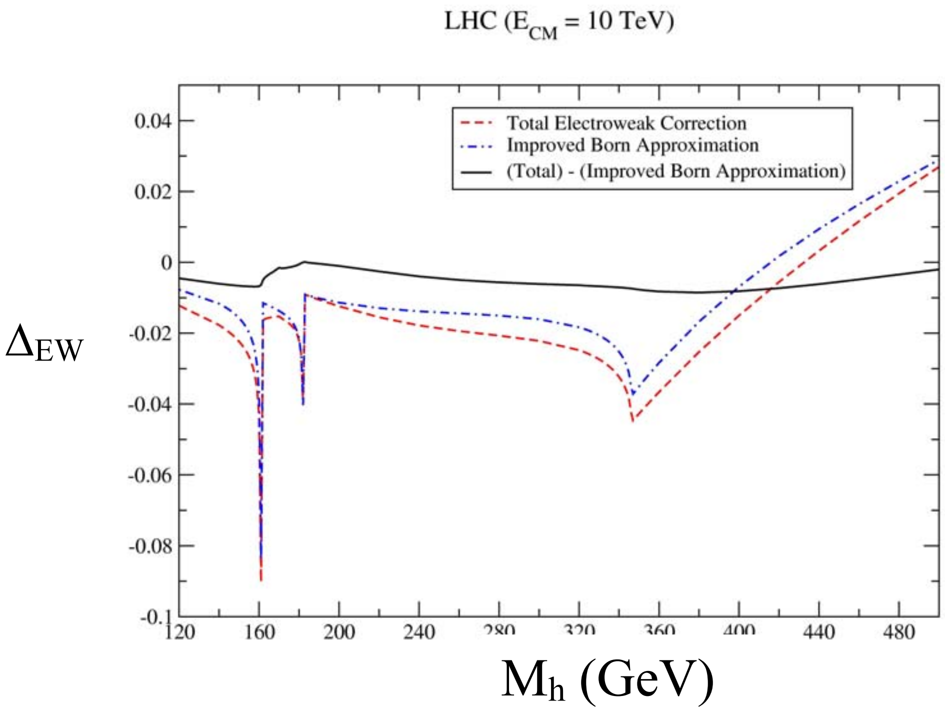
Plus many more diagrams…..

Mrenna, Yuan, hep-ph/9507235

EW Corrections to pp → bh

$$\sigma(pp \to bH) = \sigma_0\left(1 + \Delta_{QCD} + \Delta_{SQCD} + \Delta_{EW}\right)$$

Improved Born Approximation captures weak corrections accurately

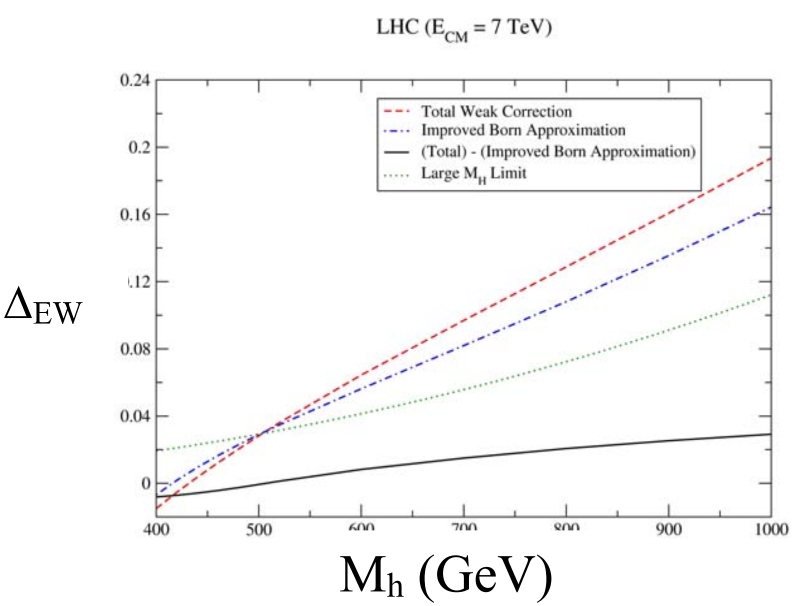


Dawson & Jaiswal, arXiv:1002.2672

EW corrections in large M_h limit

- Dominant contributions from $b\bar{b}h$ vertex
  - No contributions which grow with M_h from triangle or box diagrams

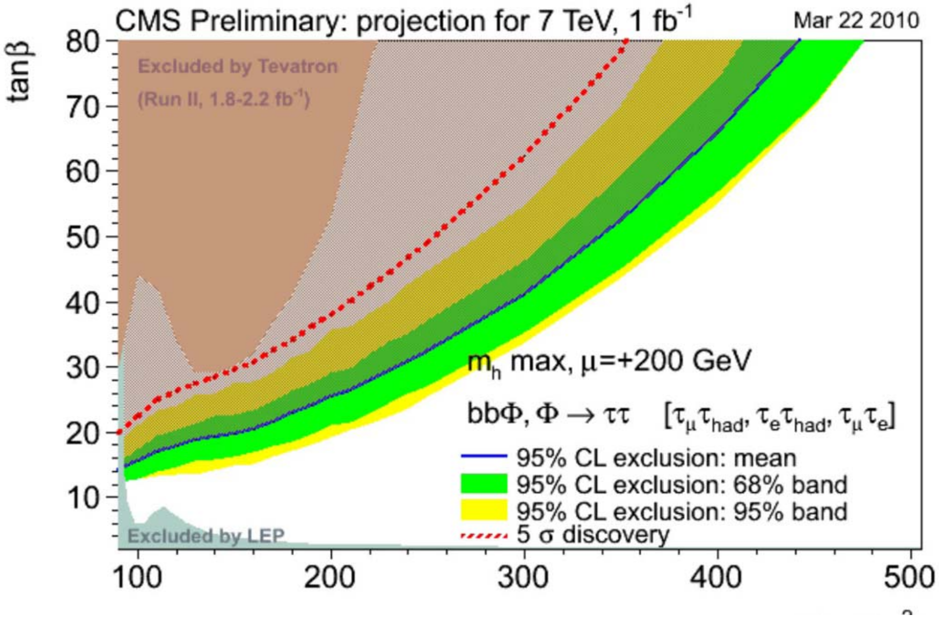
$$\sigma(bg \to bh) \approx \sigma_0 \left(1 + \frac{M_h^2}{32\pi v^2} \left[13 - 2\pi\sqrt{3} \right] \right)$$



- Need log(M_h) pieces to reproduce full calculation
- Corrections O(18%) for M_h~1 TeV

Dawson & Jaiswal, arXiv:1002.2672 [hep-ph]

LHC Expectations



M_A (GeV)

QCD and theory uncertainties will change this!

Conclusions

- Compatible answers in 4FNS and 5FNS for total cross sections
  - Distributions in single b tag case slightly different
- EW corrections important at large M_h
  - EW corrections for both 0 and 1 b tag can be included with effective Lagrangian
- SUSY QCD corrections can be important for light SUSY
  - For heavy SUSY can include SQCD in effective Lagrangian for single b tag
  - Effective Lagrangian works for all SUSY masses for 0 b tag
- Uncertainties from scheme dependence, PDFs, scale uncertainty significant