Higgs Bosons and b Quarks

October, 2007

SLAC ATLAS Forum

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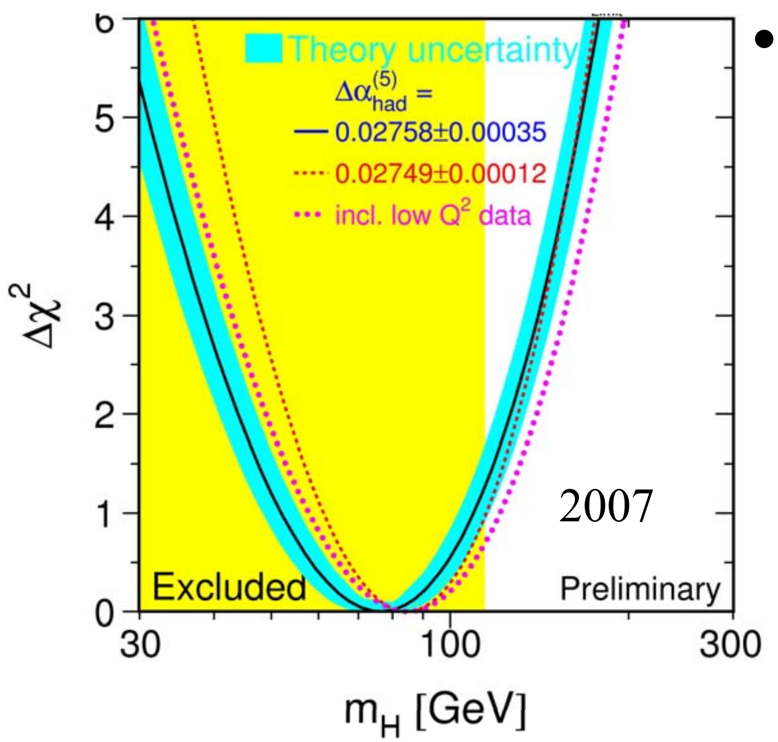
Plan:

- Lightning review of SM Higgs physics
  - Discussion of $gg \rightarrow b\bar{b}h$ vs $bg \rightarrow bh$
  - Emphasize understanding of theoretical assumptions
- MSSM results for $bg \rightarrow bh$
  - Status of current (Summer, 2007) limits
- Effects of squark/gluino loops on $bg \rightarrow bh$
  - Why are these effects interesting?

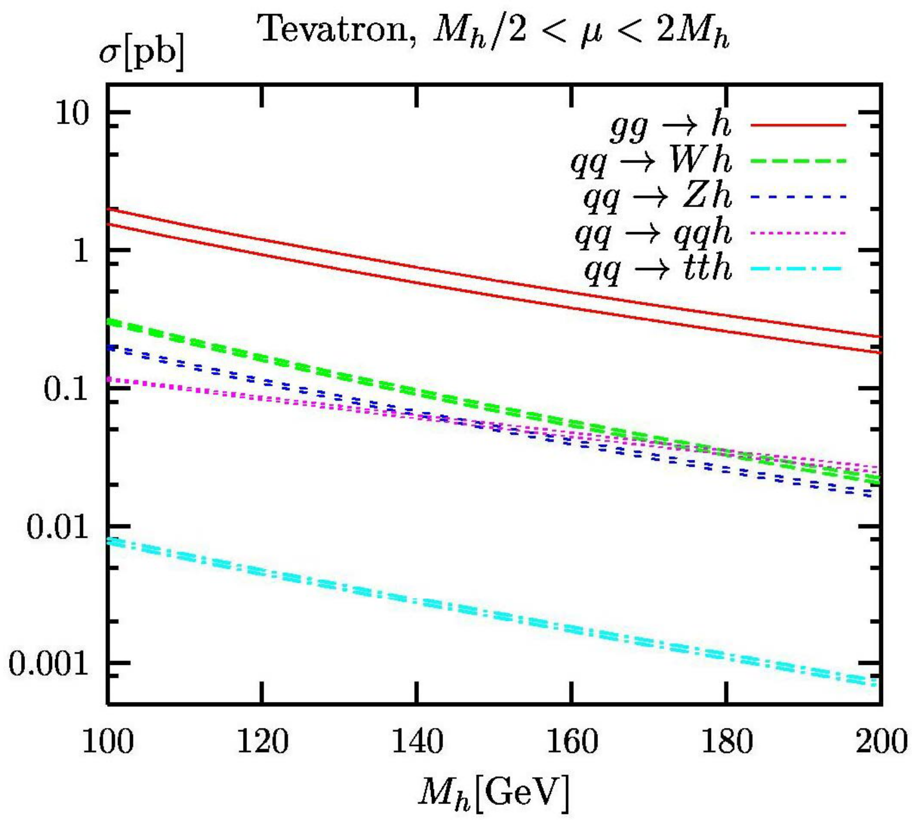
Precision measurements limit Higgs Mass



- LEP EWWG (July, 2007):
  - M_t=170.9 ± 1.8 GeV
  - M_h=76^{+36}_{-24} GeV
  - M_h < 144 GeV (one-sided 95% cl)
  - M_h < 182 GeV (Precision measurements plus direct search limit)

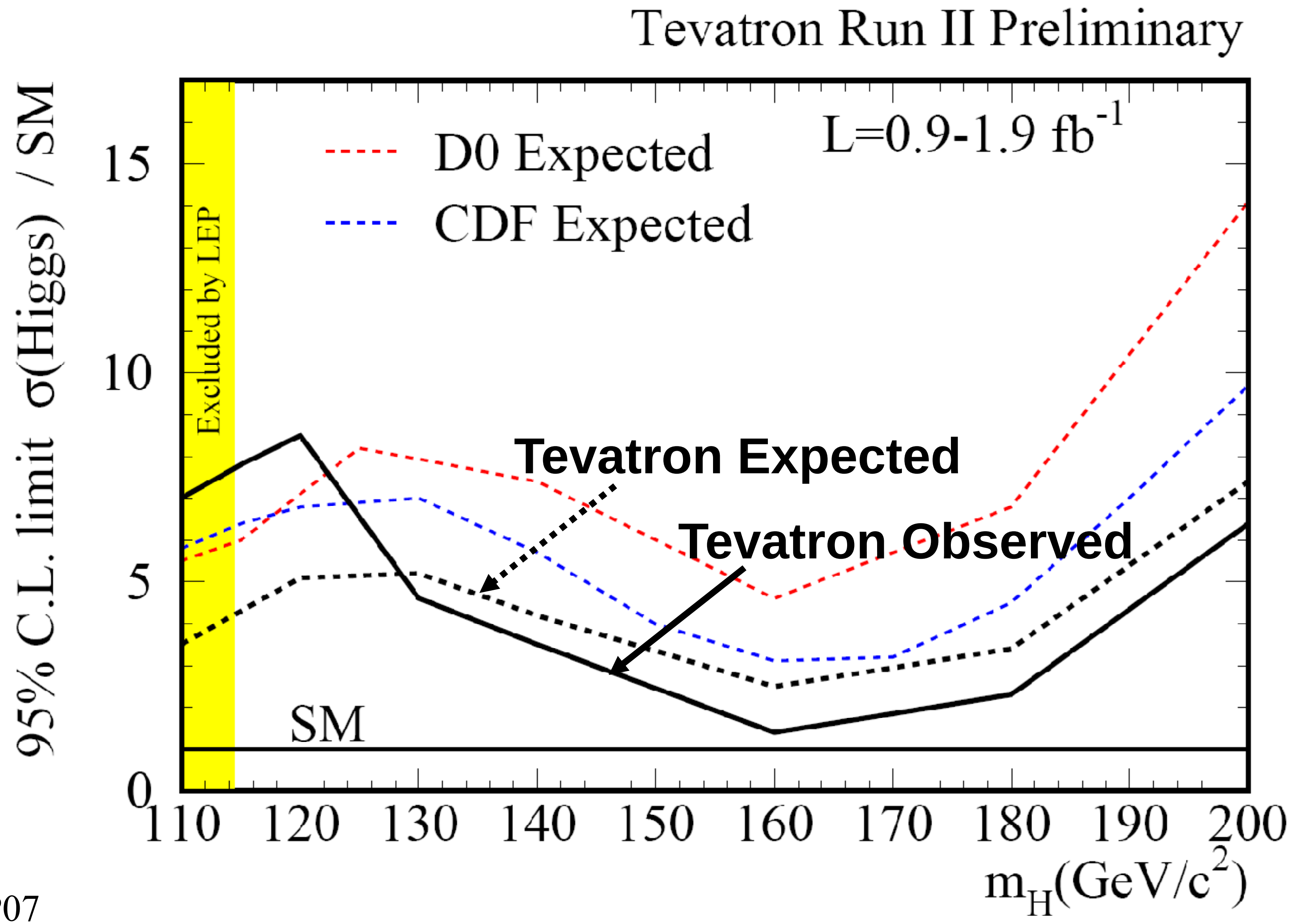
Best fit in region excluded from direct searches

Producing the Higgs at the Tevatron



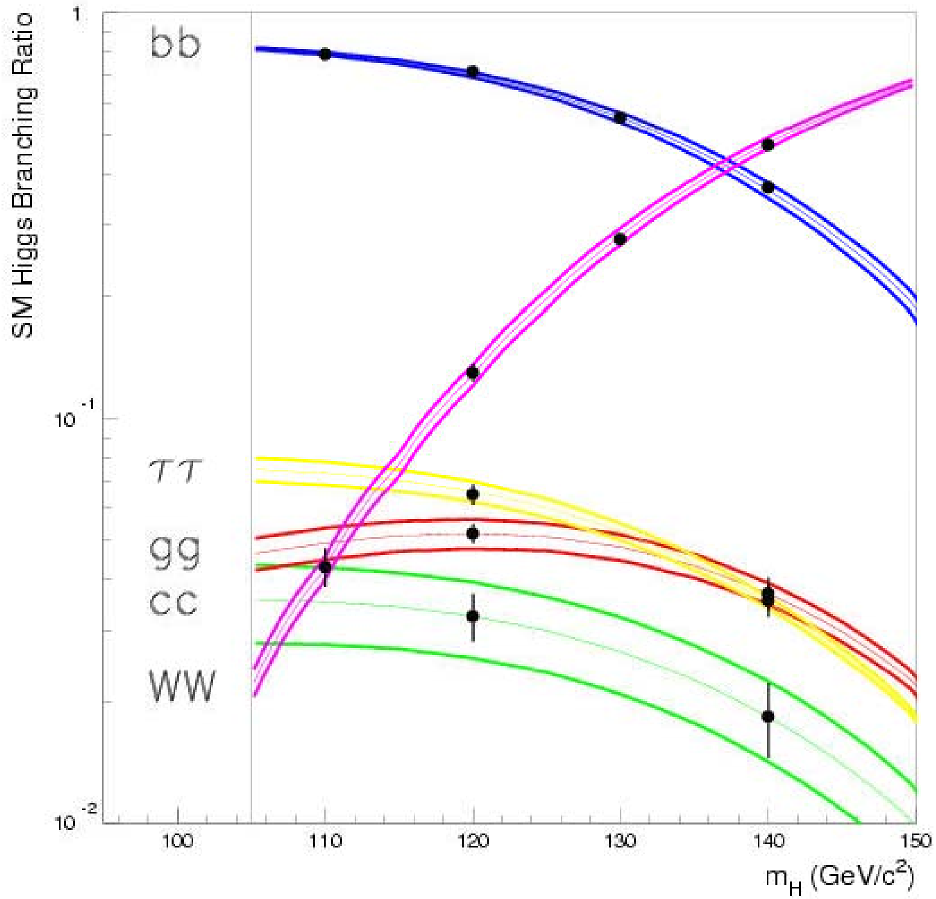
NNLO or NLO rates

$M_h/2 < \mu < M_h/4$

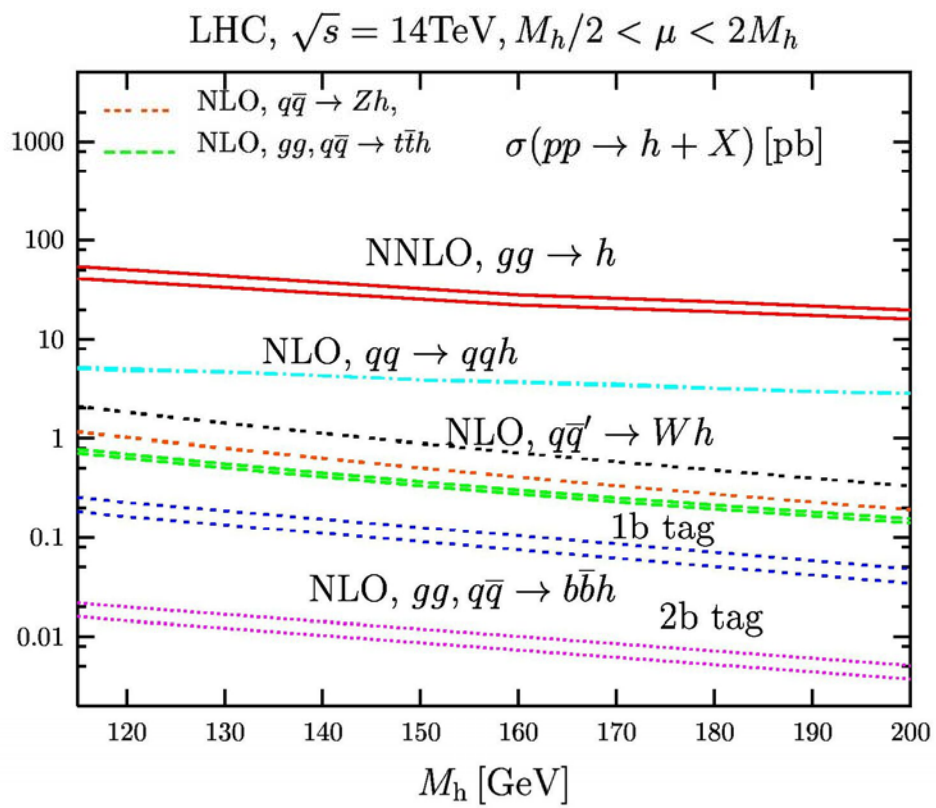


Tevatron Run II Preliminary
L=0.9-1.9 fb-1
D0 Expected
CDF Expected
Excluded by LEP
Tevatron Expected
Tevatron Observed
SM
95% C.L. limit σ(Higgs) / SM
15
10
5
0
110
120
130
140
150
160
170
180
190
200
mH(GeV/c2)

Limits understood from Branching Ratios



SM Production Mechanisms at LHC

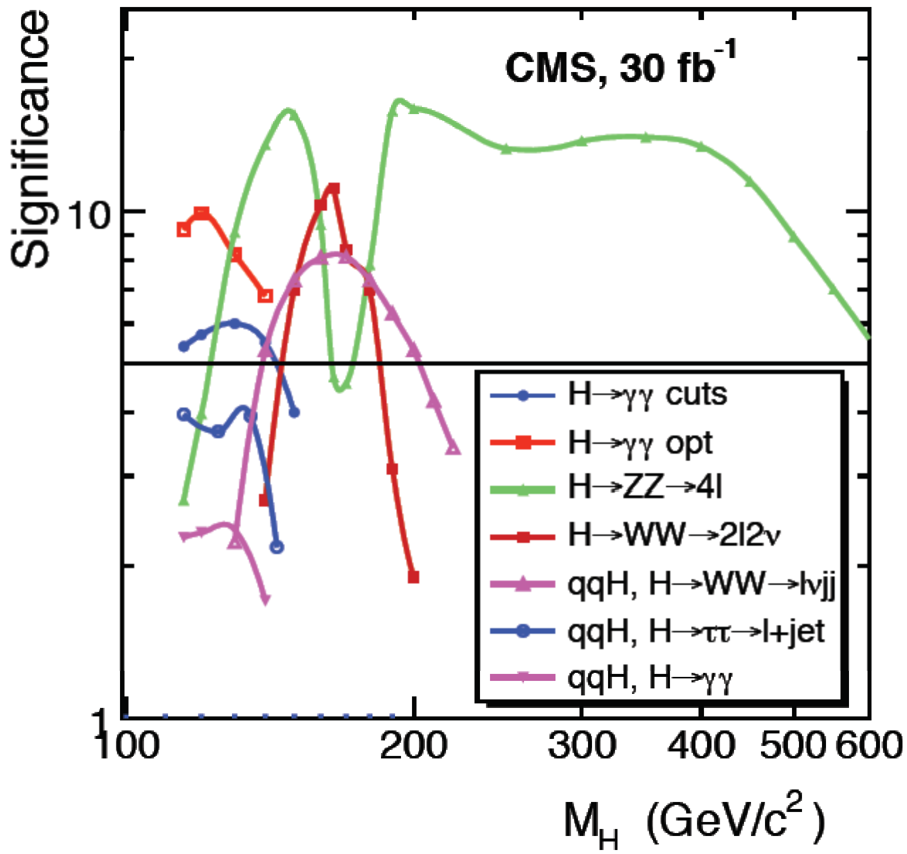


Bands show scale dependence

All important channels calculated to NLO or NNLO

Production with b's very small in SM

SM Higgs, CMS 2007

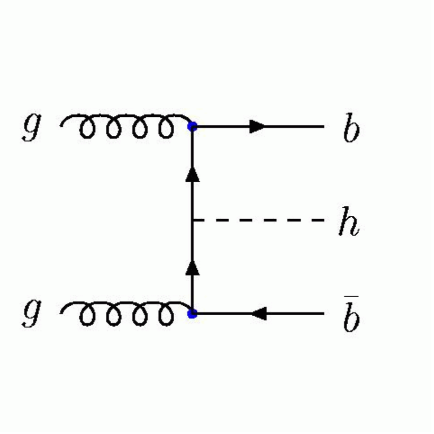


Includes radiative corrections

Higgs + b's aren't discovery mode for SM Higgs

$pp \to b\bar{b}h$

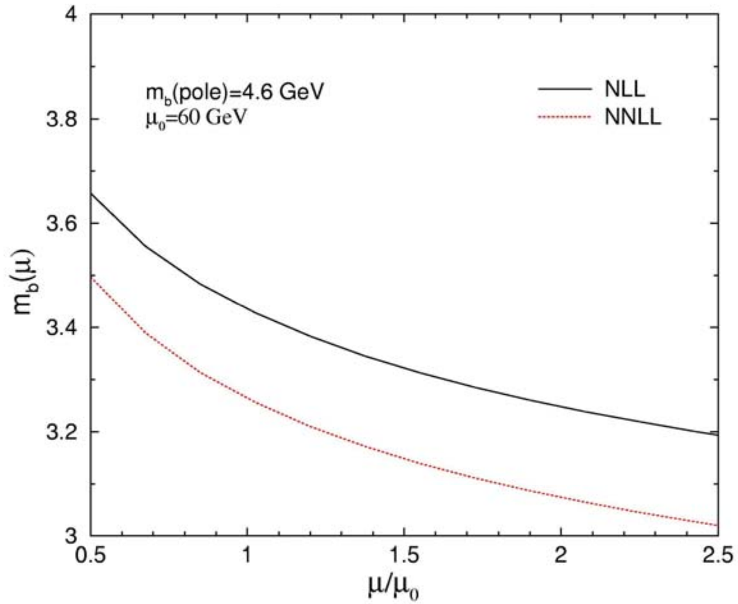
- Why is $b\bar{b}h$ interesting?
  - Direct measurement of b quark Yukawa coupling (enhanced in MSSM at large tan β)
  - Higgs discovery mode in SUSY models at large tan β
  - Theoretical questions about b quark parton distribution functions (PDFs)
- Why do NLO corrections?
  - Improved theoretical reliability
  - Often find large numerical results



Which b mass?

- $\sigma(bbh) \approx (m_b/v)^2$
- Pole mass (from Υ decays): m_b=4.62 GeV
- MS bar mass:

$$\overline{m}_b(\mu) = m_b\left[1 - \frac{\alpha_s}{3\pi}\left(4 + 3\ln\left\{\frac{\mu^2}{m_b^2}\right\}\right)\right]$$



Makes a big numerical difference which b mass you use

Use $\overline{\text{MS}}$ Renormalization

- Compute the O(α_s) corrections:

$$\Gamma_1(h \to b\bar{b}) = \frac{3M_h}{8\pi}\left(\frac{m_b}{v}\right)^2 \left\{1 + \frac{2\alpha_s}{3\pi}\left[\frac{9}{2} - 3\log\left(\frac{M_h^{\,2}}{m_b^{\,2}}\right)\right]\right\}$$

- Define the running b mass

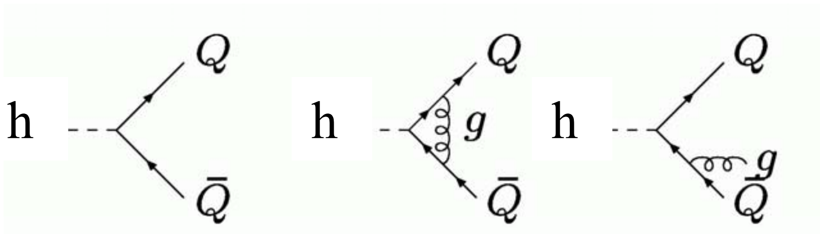
$$\overline{m}_b(\mu) = m_b\left[1 - \frac{\alpha_s}{3\pi}\left(4 + 3\ln\left\{\frac{\mu^2}{m_b^2}\right\}\right)\right]$$

- Large logarithms absorbed to 2-loops

$$\Gamma(h \to b\bar{b}) = \Gamma_0\left\{1 + 5.67\frac{\alpha_s(M_h)}{\pi} + \left(36 - 1.4n_{lf}\right)\frac{\alpha_s(M_h)^2}{\pi^2}\right\}$$

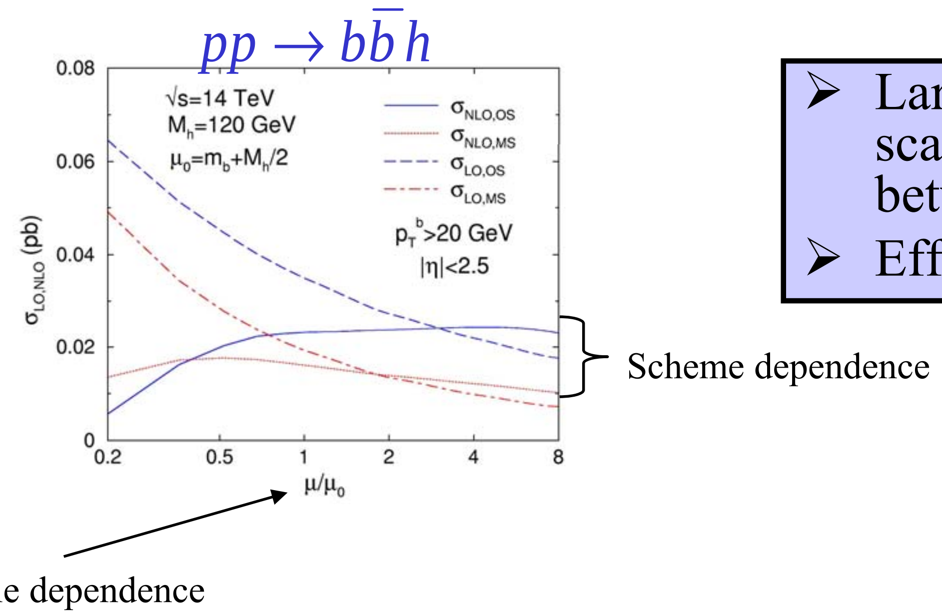
$$\Gamma_0(h \to b\bar{b}) = \frac{3M_h}{8\pi}\left(\frac{\overline{m}_b(M_h)}{v}\right)^2$$

Lore: $\overline{\text{MS}}$ is best!



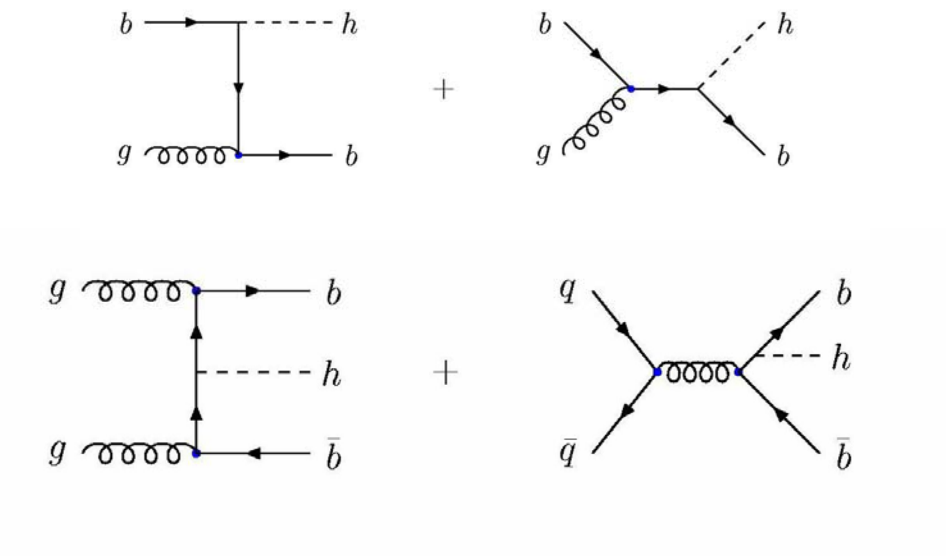
Scale and Scheme Dependence at NLO

- NLO calculations improve scale dependence
  - Scale dependence enters in running of $\alpha_s(\mu)$ and PDFs, $g(\mu)$, as well as $\alpha_s^3\log(\mu)$ contributions
  - Formally, scale dependence is $O(\alpha_s^4)$ but may be numerically large



- ➢ Large remaining scale/scheme dependence between OS and $\overline{MS}$ at NLO
- ➢ Effect ≈ 10-20%

What is the dominant process for Higgs + b Production?



- Answer depends on whether you tag outgoing b’s

- Is there double counting when including b initial state?

The b quark as a parton

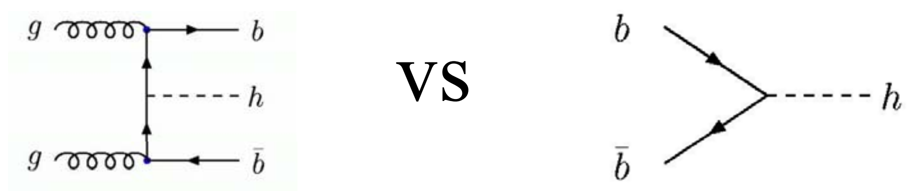
Absorb collinear logs in b quark distributions

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

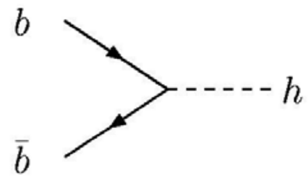
- Altarelli-Parisi evolution of PDFs sums $\alpha_s^n \ln^n(\mu^2/m_b^2)$
- b quark PDF $\approx \alpha_s \ln(\mu^2/m_b^2)$ relative to gluon PDF

Two Schemes for PDFs:

- 4 flavor number scheme (also called fixed flavor number scheme)
  - No b quarks in initial state
  - Lowest order process involving Higgs and b's is $gg \rightarrow b\bar{b}h$
- 5 flavor number scheme (also called variable flavor number scheme)
  - Define b quark PDFs (absorbs large logarithms)
  - Higgs produced with no p_T at lowest order ($b\bar{b} \rightarrow h$)
  - Higgs p_T generated at higher orders in expansion

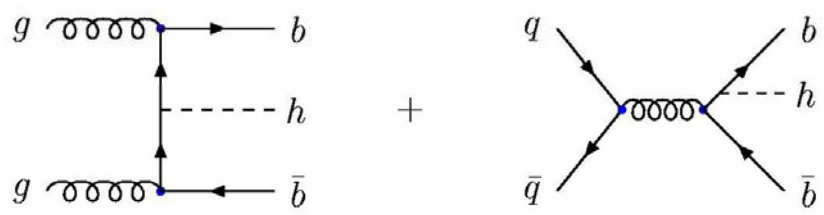


Counting Rules with b PDFs: Reordering of perturbation expansion



$(\alpha_s \ln(M_h^2/m_b^2))^2 \approx .4$

$\alpha_s^2 \ln(M_h^2/m_b^2) \approx .06$



$\alpha_s^2 \approx .01$

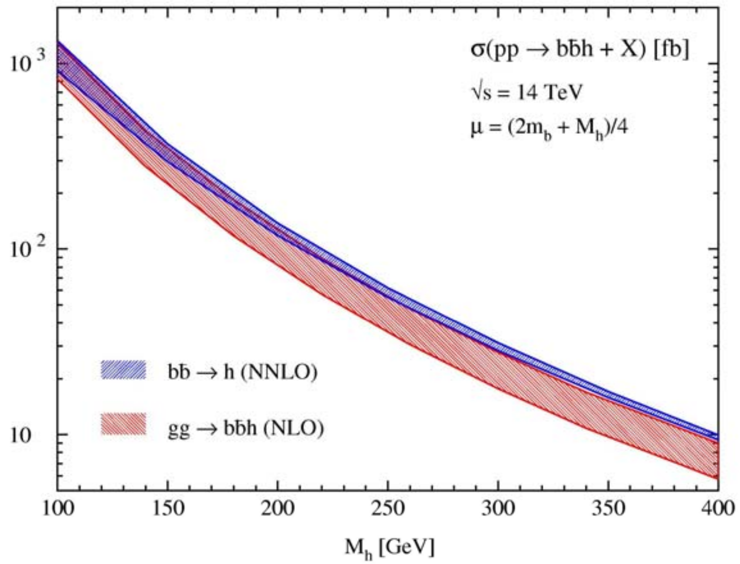
Re-ordering of Perturbation Theory

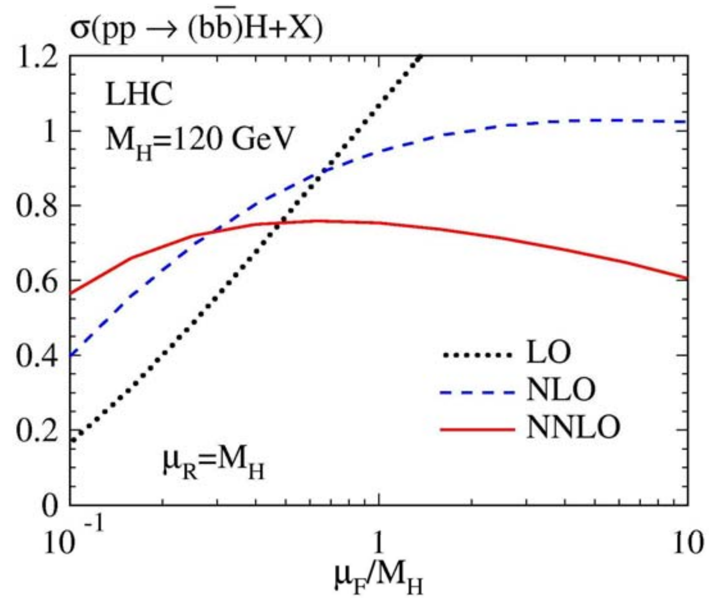
- 0 b tag process in 5FNS:
  - LO: $b\bar{b} \rightarrow h$ $O(\alpha_s^2 \Lambda_b^2)$
  - NLO: Virtual+real corrections $O(\alpha_s^3 \Lambda_b^2)$
  - NLO: $bg \rightarrow bh$ $O(\alpha_s^2 \Lambda_b)$, correction of $O(1/ \Lambda_b)$ to tree level
  - NNLO: $gg \rightarrow b\bar{b}h$ $O(\alpha_s^2)$,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

- 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 to LO

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

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





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

Almost no scale dependence at NNLO

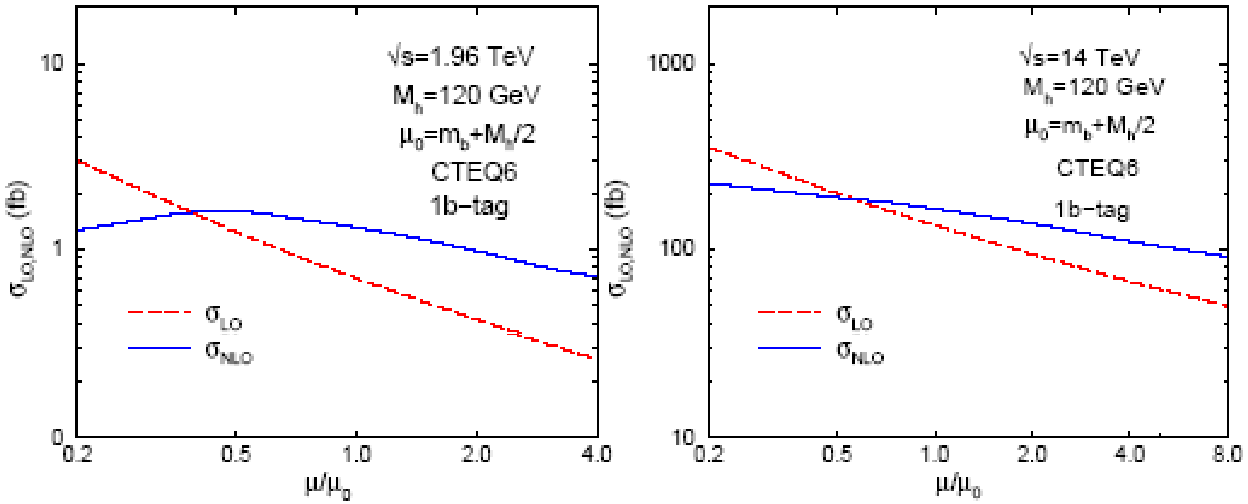
It really doesn't matter which PDF scheme you use

Campbell et al, hep-ph/0405302

Harlander & Kilgore, hep-ph/0304035

What if only 1 b is tagged?

4FNS: $gg \rightarrow b\bar{b}h$



$p_T^b > 20$ GeV

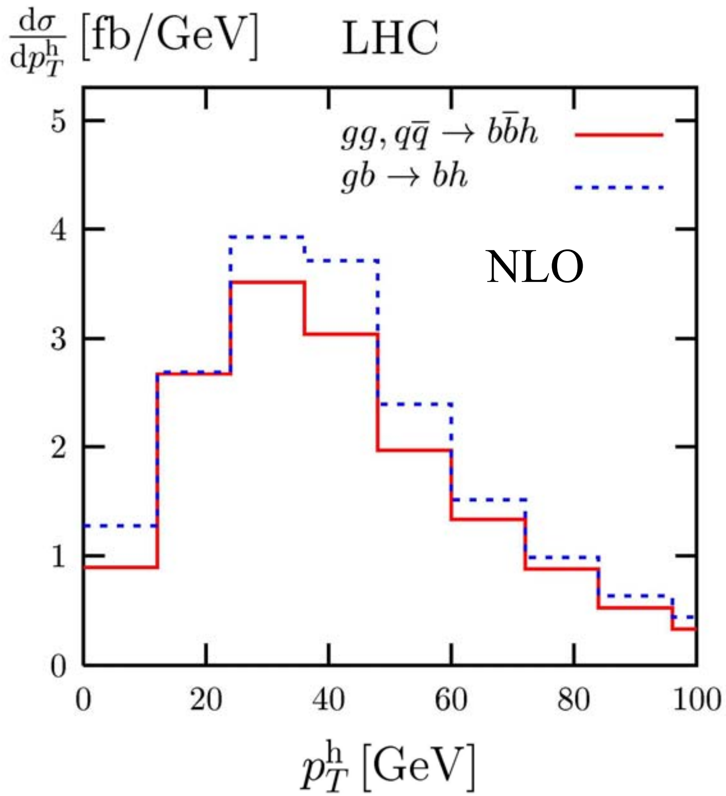
$|\eta| < 2$ (Tevatron), 2.5 (LHC)

$\Delta R > 0.4$

What about distributions?

Compare 4 and 5 Flavor Number PDF Schemes

Higgs plus single b at LHC:

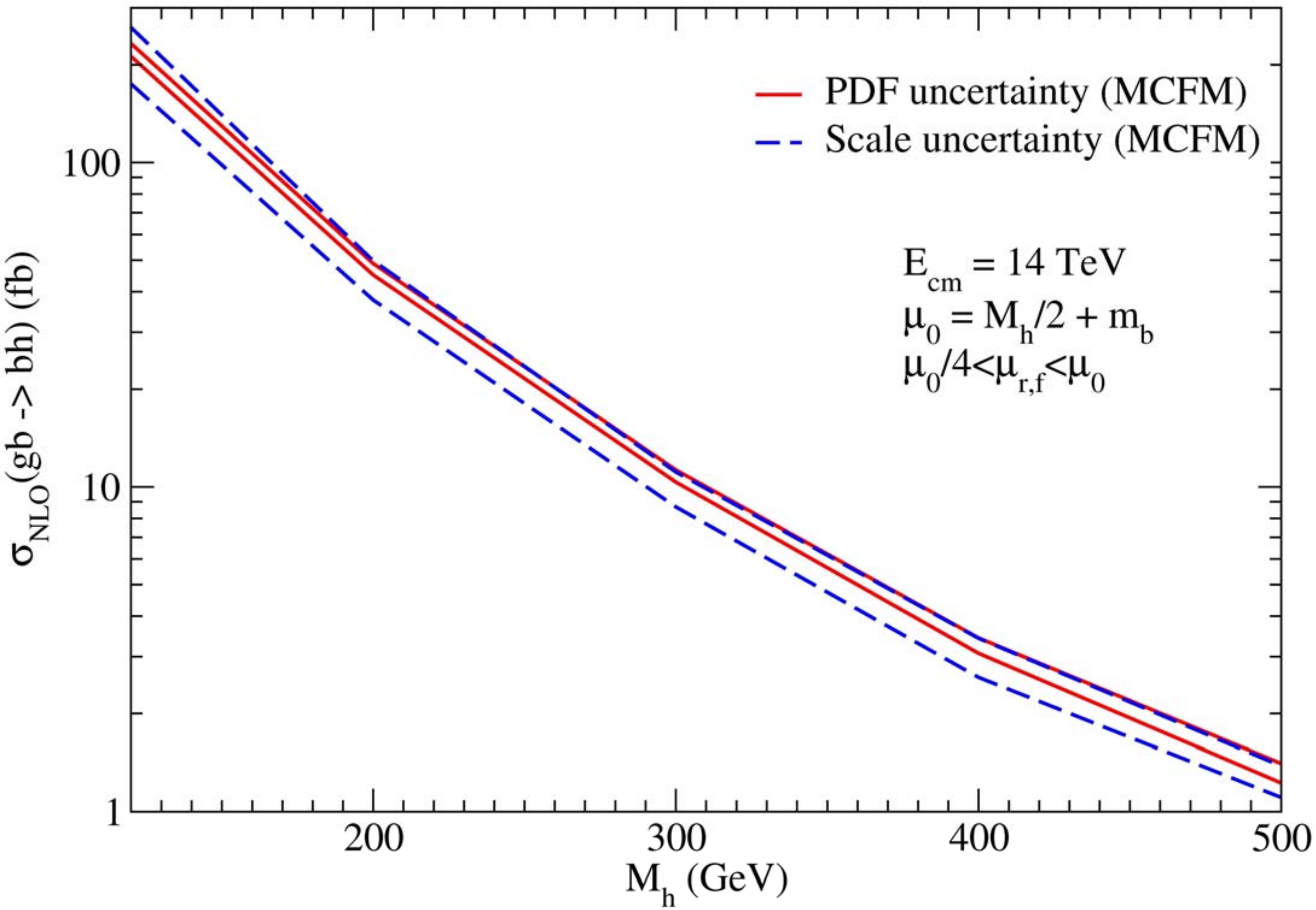


$p_T^b > 20$ GeV

$|\eta| < 2.5$

$\Delta R > 0.4$

Good Theoretical Understanding of Uncertainties



Higgs in the MSSM

- MSSM has 2 Higgs doublets: H_d and H_u

$$H_d = \begin{pmatrix} \varphi_d^+ \\ \varphi_d^0 \end{pmatrix} \qquad H_u = \begin{pmatrix} \phi_u^0 \\ -\phi_u^- \end{pmatrix}$$

$$\phi_d^0 = \frac{1}{\sqrt{2}}\left(v_1 + h_d^0\right)$$

$$\phi_u^0 = \frac{1}{\sqrt{2}}\left(v_2 + h_u^0\right)$$

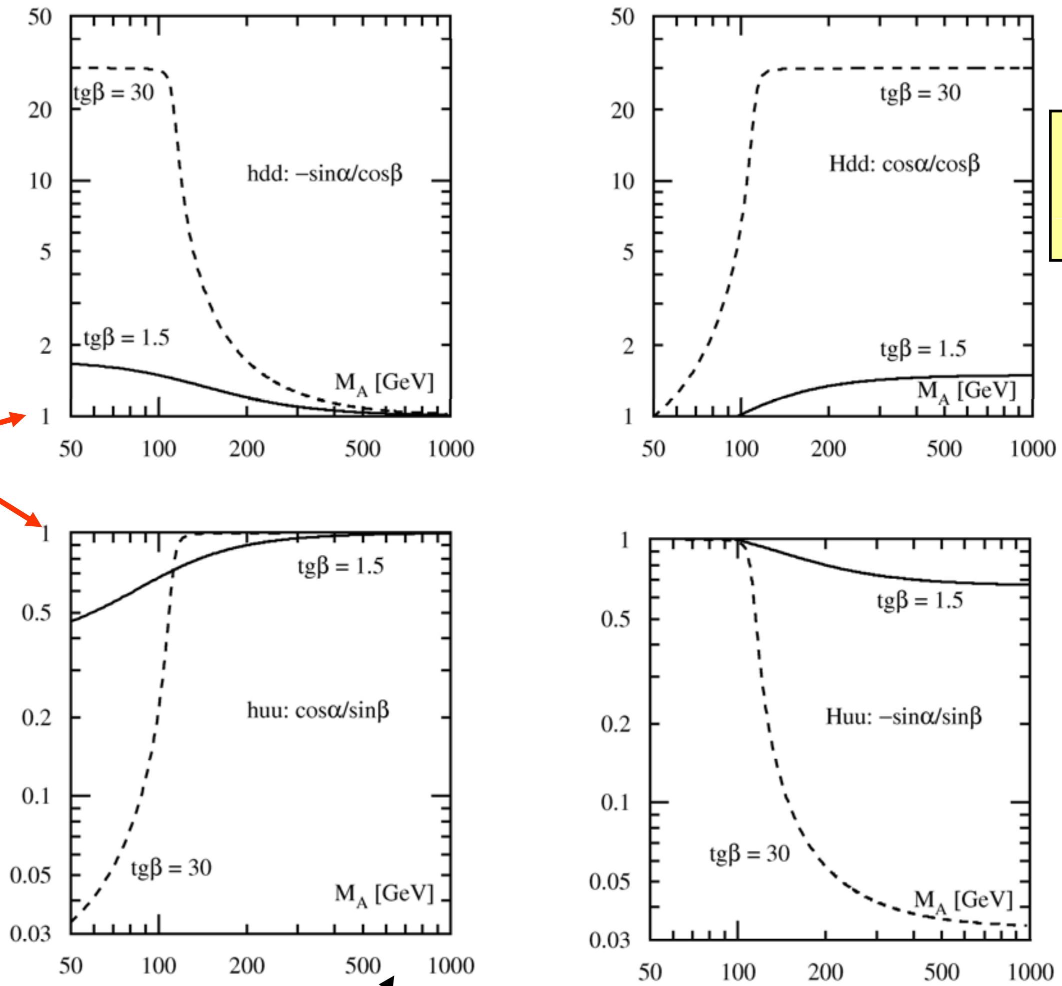
- Physical CP-Even Higgs bosons

$$\begin{pmatrix} h^0 \\ H^0 \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h_u{}^0 \\ h_d{}^0 \end{pmatrix}$$

- Pseudoscalar, A^0, and two charged Higgs, $H^\pm$

Higgs Couplings very different in MSSM

Light Higgs **Heavy Higgs**



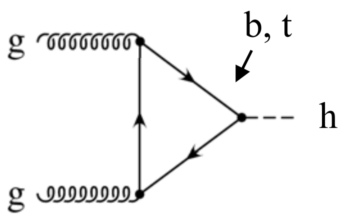
SM

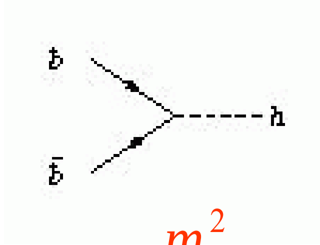
Decoupling limit

Couplings to d, s, b enhanced at large tan β

Couplings to u, c, t suppressed at large tan β

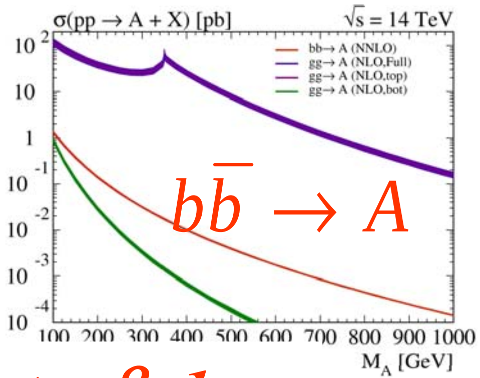
Large tan β Changes Relative Importance of Production Modes



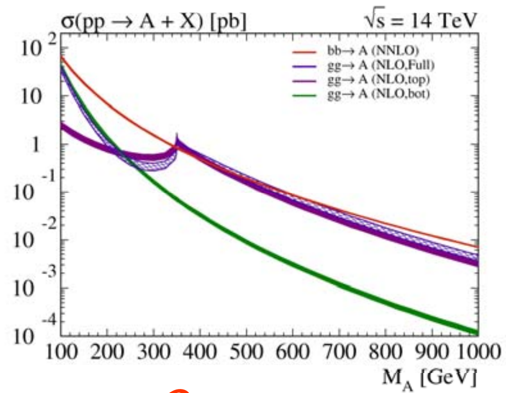


$$\sigma_{gg} = \frac{1}{M_h^2}\left(c_1 \cot^2\beta + c_2 \frac{m_b^2}{M_h^2} + c_3 \frac{m_b^4}{M_h^4} \tan^2\beta \right)$$

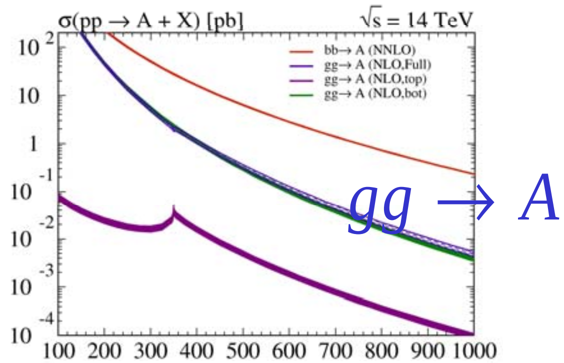
$$\sigma_{bb} = \frac{m_b^2}{M_h^4} c_4 \tan^2\beta$$



tanβ=1



tanβ=7



tanβ=40

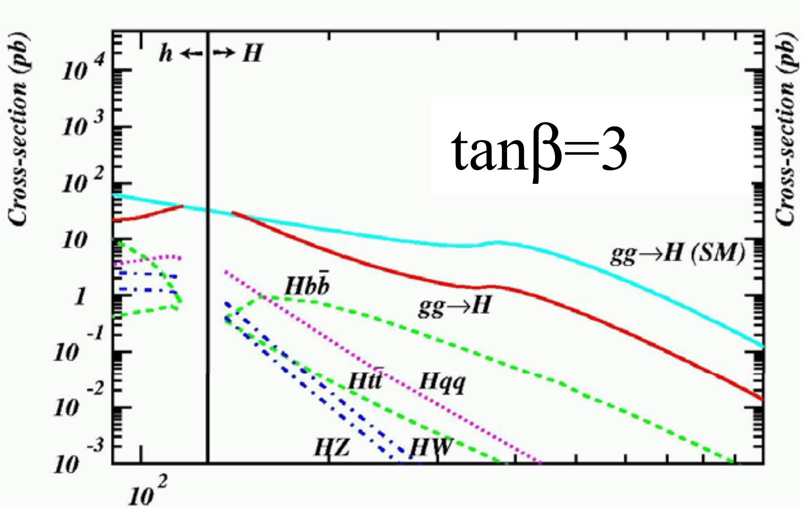
tanβ ≥ 7, $b\bar{b}$ production mode dominates

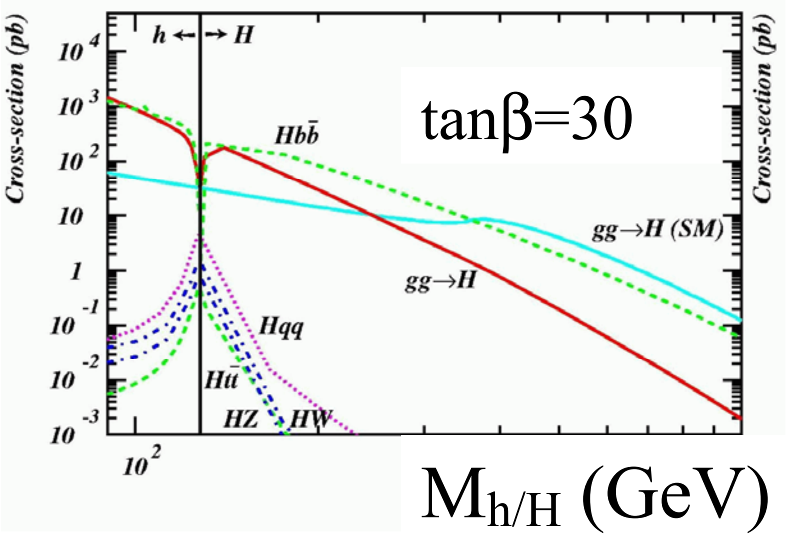
Kilgore

Production of SUSY Higgs Bosons

- For large tan β, dominant production mechanism is with b's
- bbh can be 10x's SM Higgs rate in SUSY for large tan β

LHC





$M_{h/H}$ (GeV)

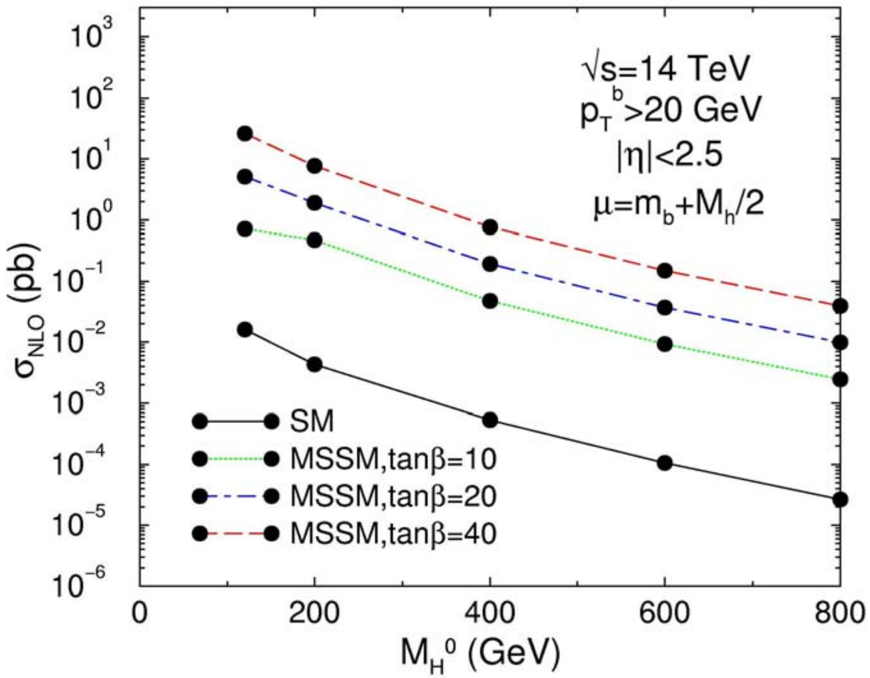
SUSY Higgs are produced with b's!

*Maximal Mixing

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

Enhancement in MSSM

Note log scale!

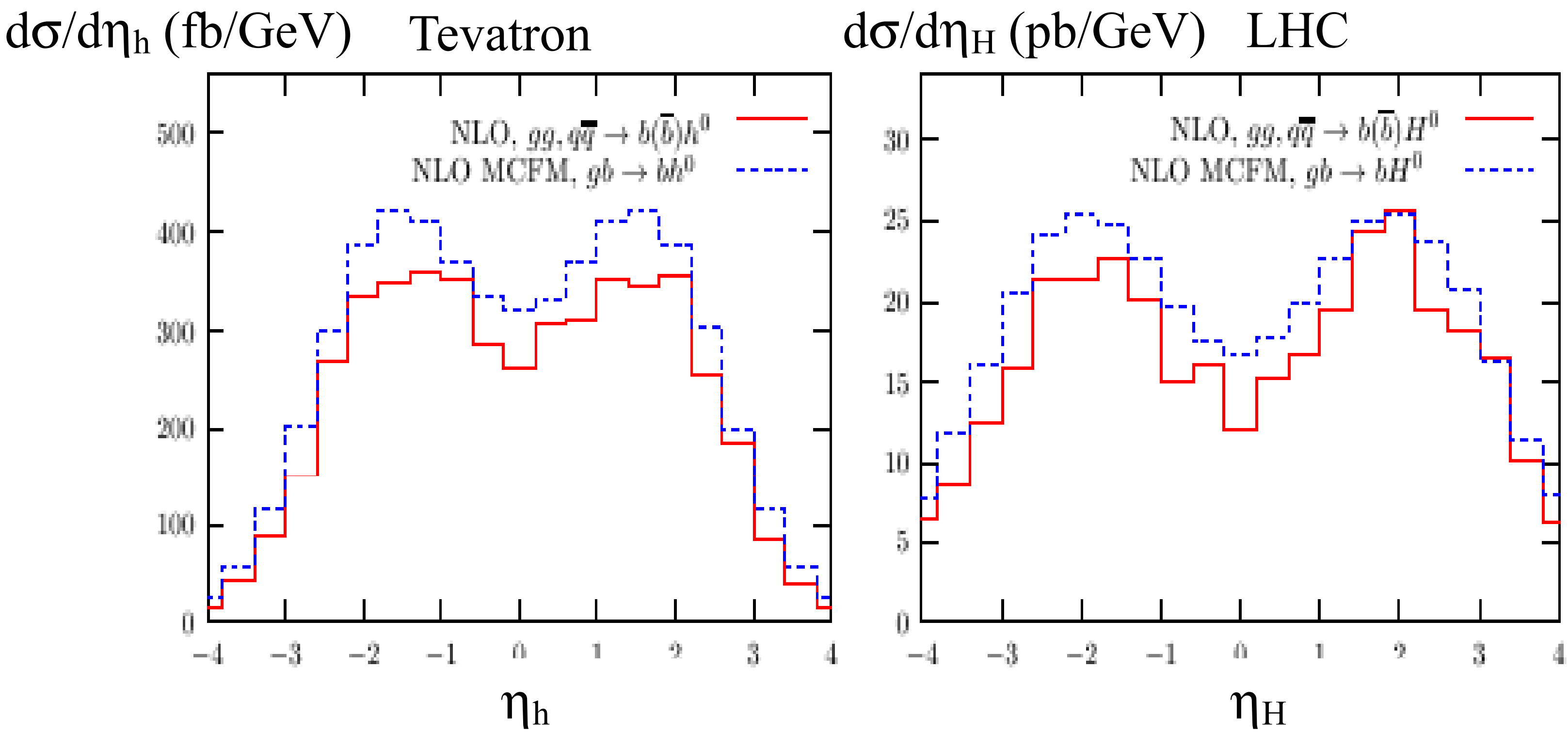


This is why the calculation is interesting!

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

Can observe heavy MSSM scalar Higgs boson

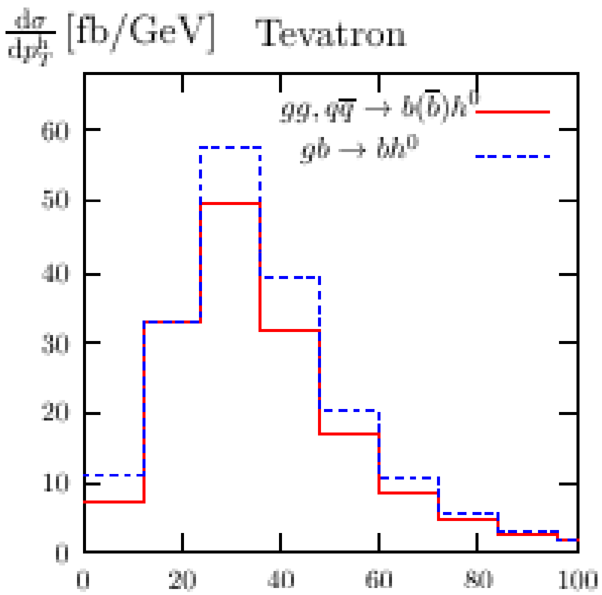
Single b tag



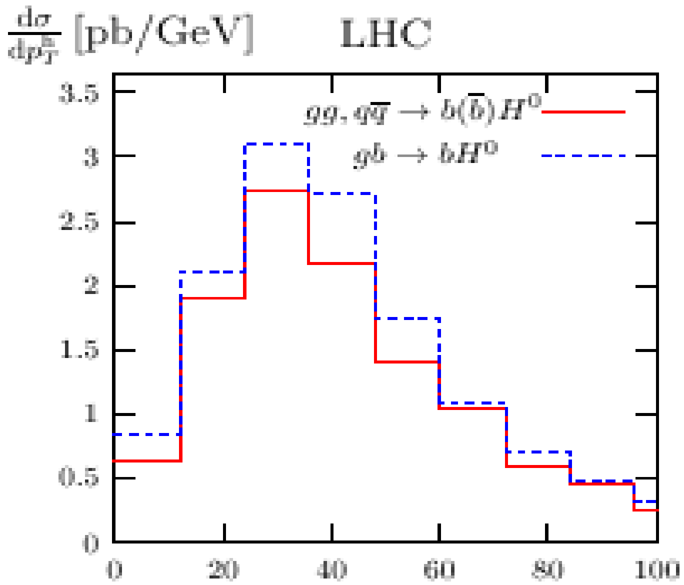
MSSM with M_h=M_H=120 GeV, tan β=40

Single b tag

NLO



p_T^h (GeV)



p_T^H (GeV)

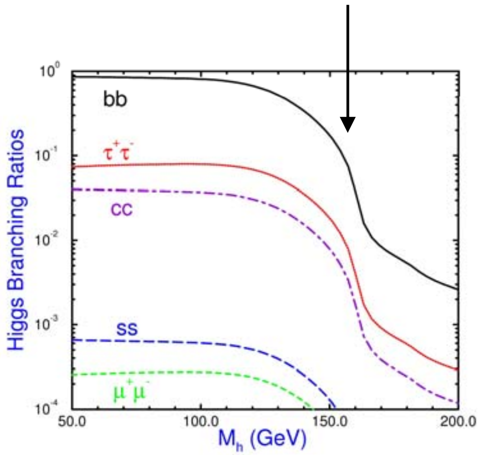
MSSM with M_h=M_H=120 GeV, tan β=40

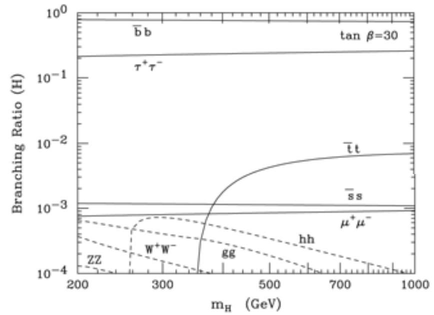
Higgs Decays also affected at large tan β

- SM: Higgs branching rates to bb and $\tau^+\tau^-$ turn off as rate to W^+W^- turns on (M_h > 160 GeV)

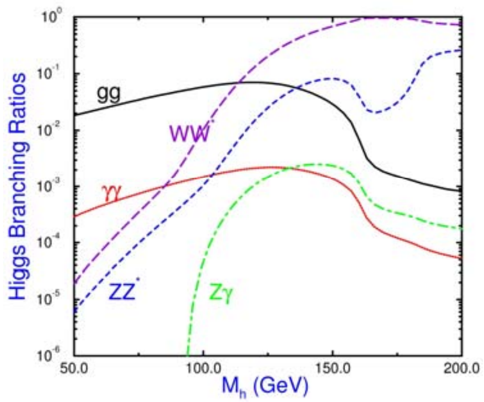
•MSSM: At large tan β, rates to bb and $\tau^+\tau^-$ stay large

Heavy H^0 MSSM BRs



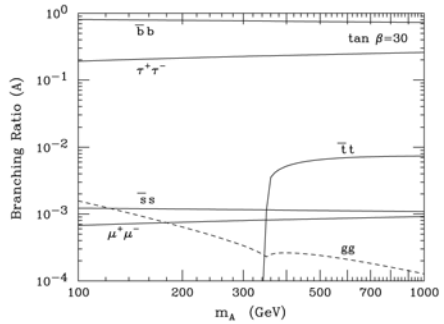


SM



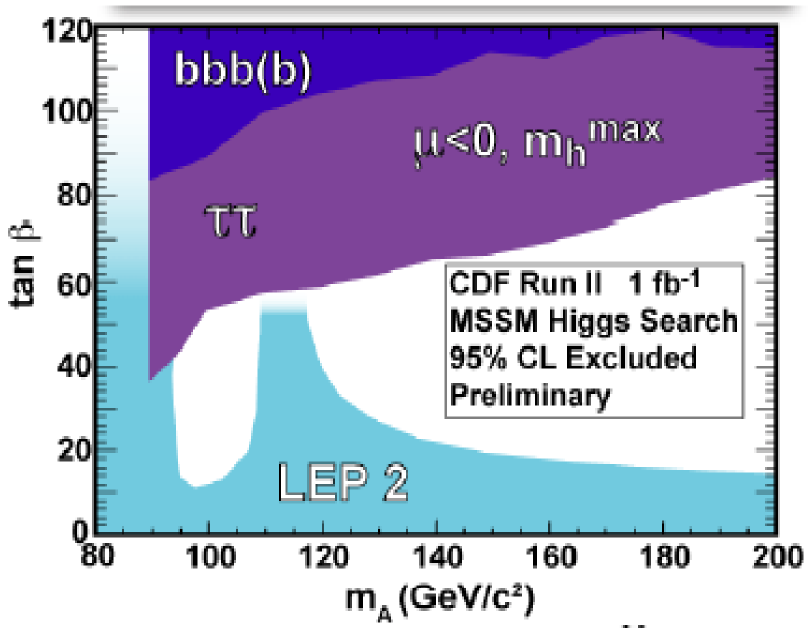
Rate to bb and $\tau^+\tau^-$ almost constant in MSSM

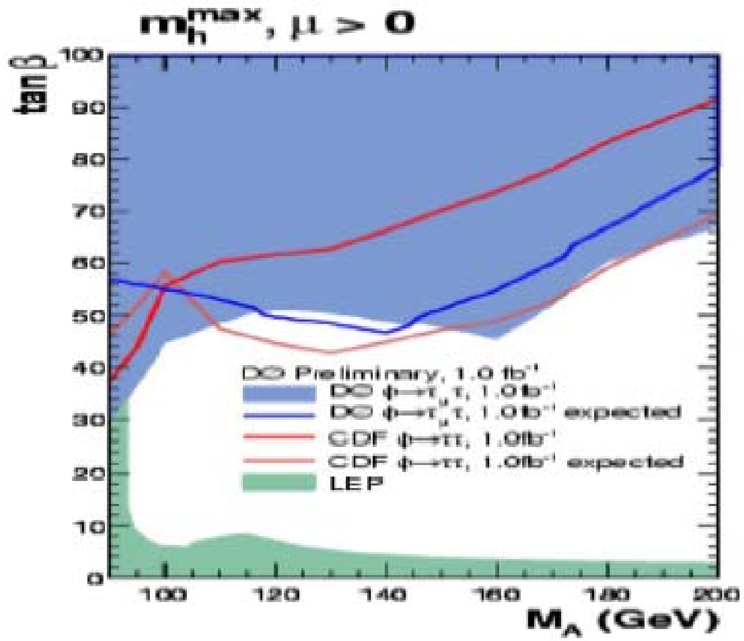
A^0 MSSM BRs



MSSM limits from bg→bh (1 fb^{-1})

LP, 2007

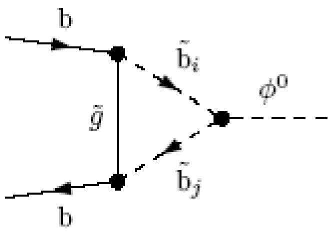




30 fb^{-1} CMS expects to get to tan β ~ 15 through bh; $h \to \tau^+\tau$, $h \to bb$

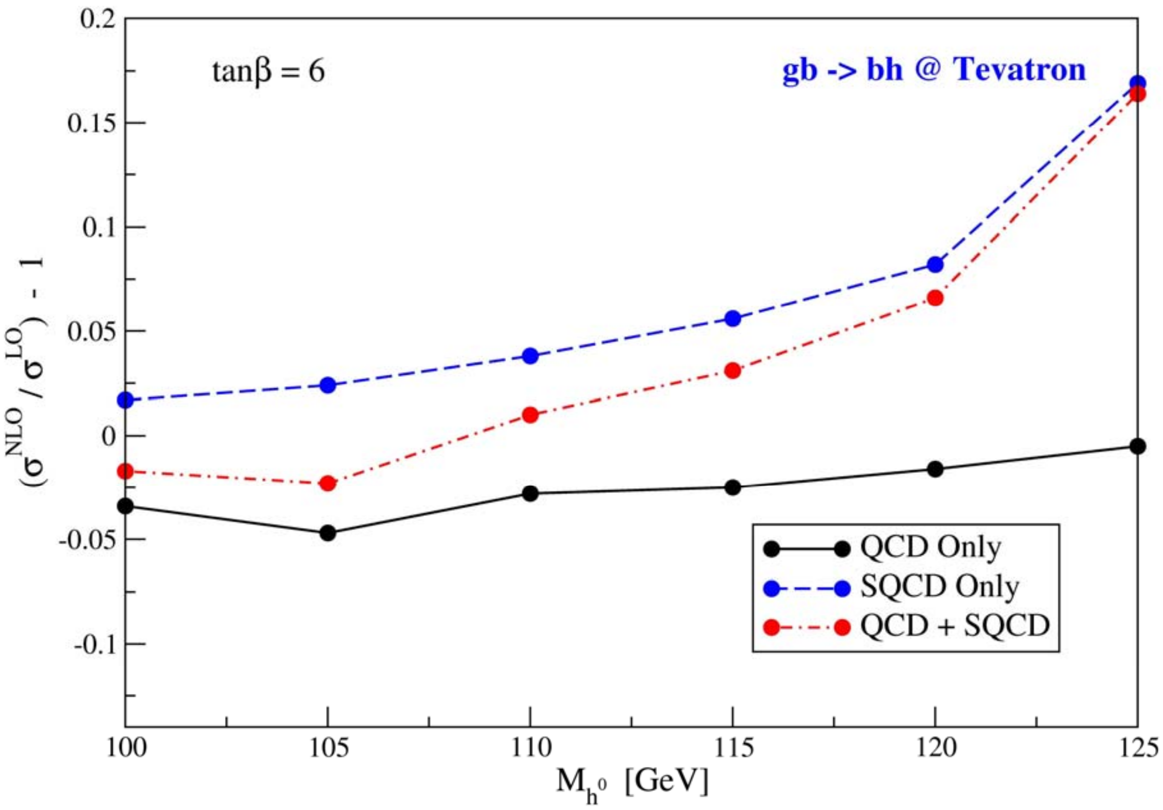
A Reliable Prediction

- We have bg →bh at QCD NLO
  - PDF/scale/scheme uncertainties ~ 10-20%
- Are squark/gluino contributions relevant?
  - Important for bb→H, A at LHC
  - For some parameters as large as -50% effects
  - Squark/gluino effects almost completely described by *Improved Born Approximation*

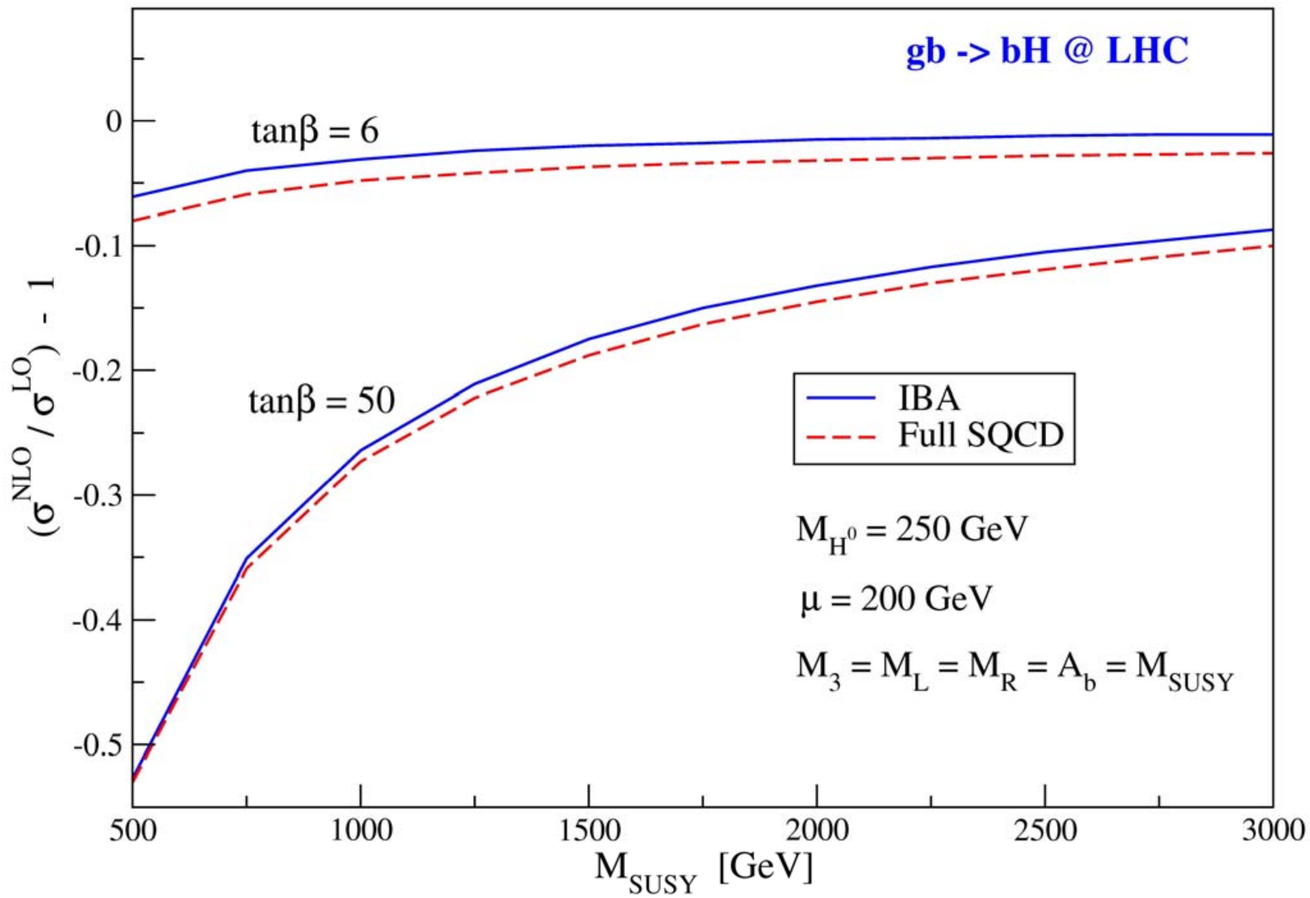


Dittmaier et al, hep-ph/0611353

Need SQCD for Reliable Predictions

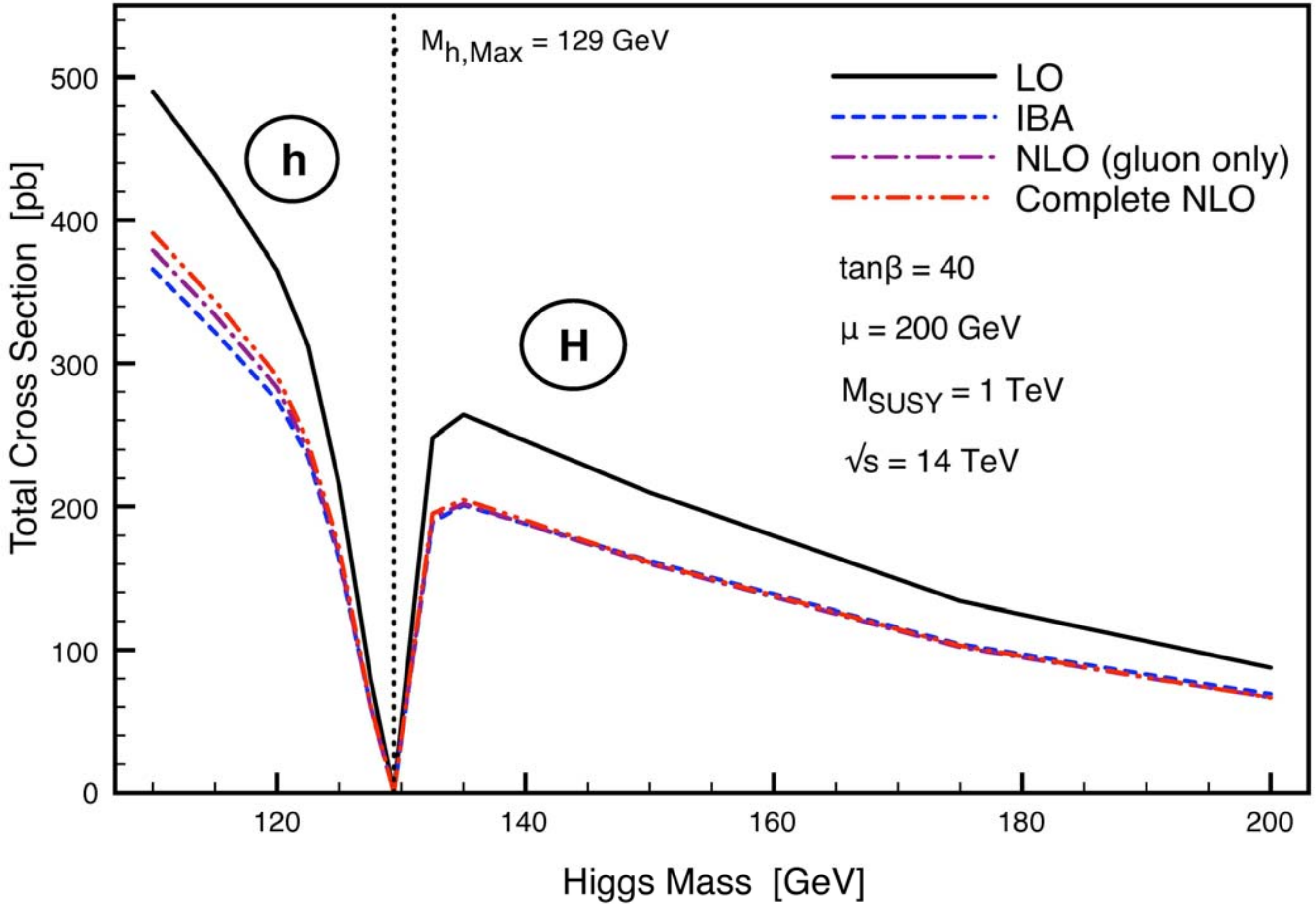


Squark/gluino loops important for large tan β and small M_{SUSY}



Note slow approach to decoupling limit for large tanβ

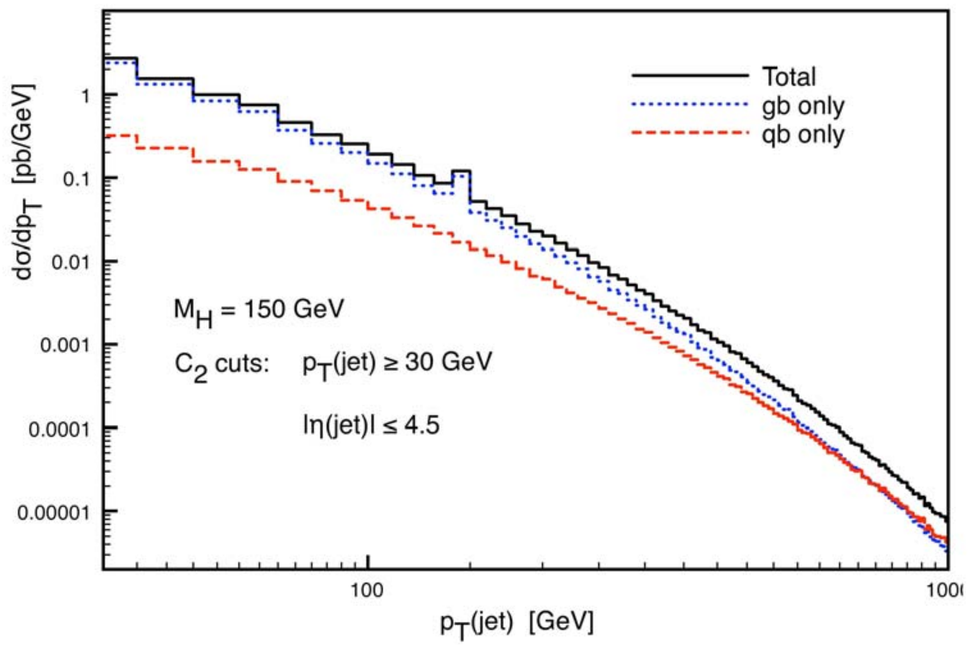
$gb \to b\phi$



Dawson, Jackson, hep-ph/0709.4519

Can gb→bϕ +jet be useful?

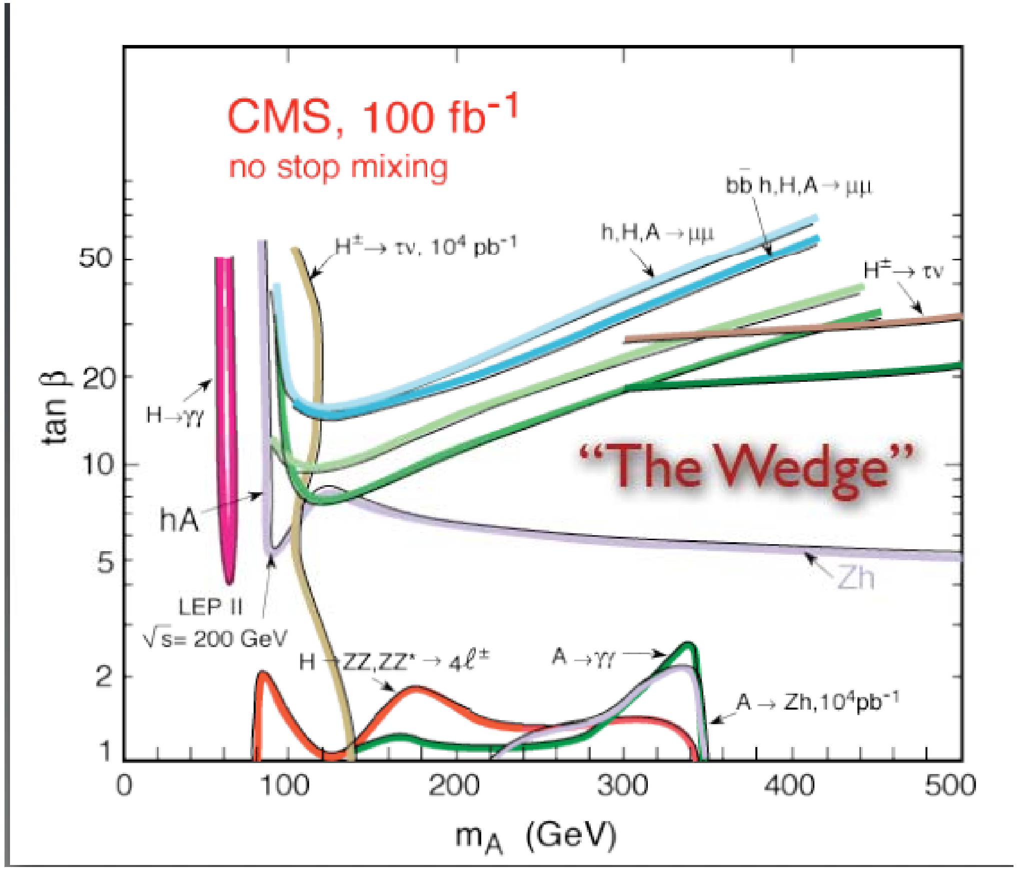
- LHC



More soon…..

Conclusions

- In the MSSM Higgs and b quarks go together at large tan β
- Higgs production with b's is dominant mechanism for tan $\beta > 7$
- Theoretical understanding of b PDFs: compatible answers in 4FNS and 5FNS for PDFs
- SUSY QCD corrections can be the same size as QCD corrections



CMS, 100 fb-1
no stop mixing
"The Wedge"
H→γγ
hA
LEP II
√s= 200 GeV
H±→ τν, 10⁴ pb-1
h,H,A → μμ
bb h,H,A → μμ
H±→ τν
Zh
H → ZZ,ZZ* → 4ℓ±
A → γγ
A → Zh,10⁴pb-1
tan β
m_A (GeV)