Higgs + b Production at the Early LHC

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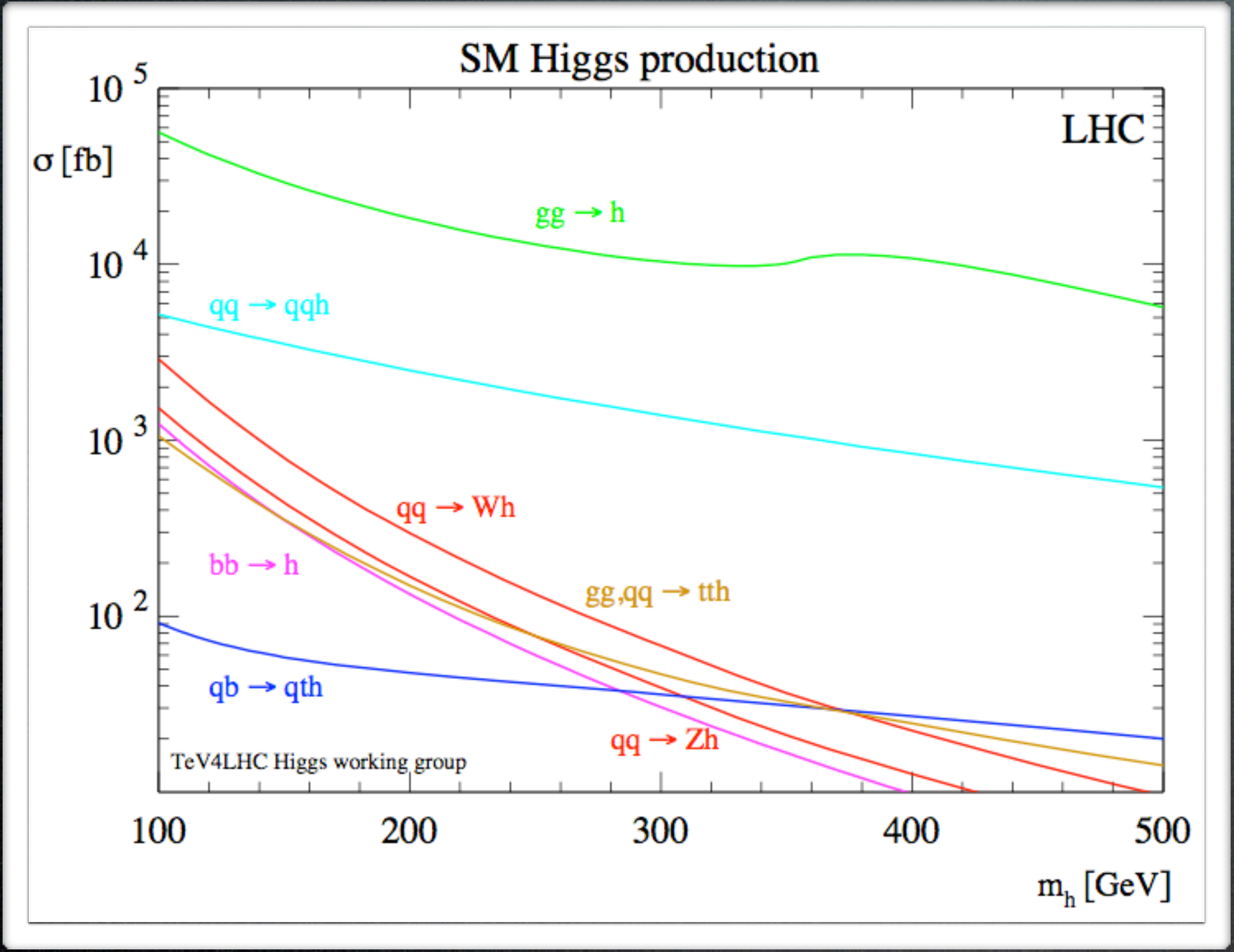
Outline

- Brief review of the MSSM Higgs sector
    - Production at Hadron Colliders
- bbh Experimental issues
- Status of the Standard Model prediction(s) @ NLO in QCD... and effects from NLO EW corrections (NEW!)
    - Different calculational schemes: 4 flavors or 5?
- Including higher-order corrections from SUSY QCD (SQCD)... i.e., loops of squarks and gluinos
    - Effective Lagrangian approach vs. Exact NLO?
- Conclude and outlook

SM Higgs Production @ Hadron Colliders



(from Hahn et al., TeV4LHC Higgs Working Group Report, hep-ph/0607308)

SM Higgs "couples to mass":

- Production dominated by radiation off HEAVY particles (tops, W's, Z's)

Main production modes:

- gluon fusion (gg → h) via top loops
- associated production with W's or Z's
- associated production with pairs of top pairs(?) ("Fat Jet Revival")

All signals (and most backgrounds) known to (at least) NLO in QCD

MSSM Higgs Sector in a Nutshell

MSSM = Two Higgs Doublet Model
At tree-level, Φ_1 (Φ_2) only couples to down- (up-) type quarks

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \phi_2^0 \\ \phi_2^- \end{pmatrix}$$

Electroweak symmetry is broken when BOTH Higgs doublets acquire vacuum expectation values (vevs)

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \qquad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_2 \\ 0 \end{pmatrix}$$

Instead of four degrees of freedom (dof's), there are EIGHT... three of which become the longitudinal dof's for the W and Z

$$M_W^2 = \frac{g^2}{4}\left(v_1^2 + v_2^2\right) \equiv \frac{g^2 v^2}{4}$$

The remaining five dof's make up the physical Higgs bosons of the MSSM

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

MSSM Neutral Higgs Sector

$$h^0 = -(\sqrt{2}\,\Re\,\phi_2^0 - v_2)\sin\alpha + (\sqrt{2}\,\Re\,\phi_1^0 - v_1)\cos\alpha$$

$$H^0 = (\sqrt{2}\,\Re\,\phi_2^0 - v_2)\cos\alpha + (\sqrt{2}\,\Re\,\phi_1^0 - v_1)\sin\alpha$$

$$A^0 = \sqrt{2}(\Im\,\phi_2^0\sin\beta + \Im\,\phi_1^0\cos\beta)$$

Upon diagonalization of the Higgs mass matrix, the mass eigenstates are functions of the original fields and mixing angles

$$M_{H,h}^2 = \frac{1}{2}\left[M_A^2 + M_Z^2 \pm \sqrt{(M_A^2+M_Z^2)^2 - 4M_Z^2 M_A^2\cos^2\beta}\right]$$

$$tan2\alpha = tan2\beta\left(\frac{M_A^2+M_Z^2}{M_A^2-M_Z^2}\right)$$

At tree-level, ENTIRE MSSM Higgs sector described by two parameters: pseudoscalar mass (M_A) and $\tan\beta$ ($\equiv v_1/v_2$)

$$M_h^2 \le M_Z^2\cos 2\beta \le M_Z^2$$

Upper bound on lightest Higgs mass require it be lighter than M_Z! (Experiments ruin everything!)

Radiative Corrections to MSSM Higgs Sector

The contradiction with experimental data is lifted, however, by including corrections to the neutral (scalar) Higgs mass matrix

The dominant corrections come from the top SQUARK sector

In fact, the upper bound on the light Higgs mass-squared is shifted by a top quark mass-squared term

$$M_h^2 \leq M_Z^2 + \frac{3 g^2 m_t^2}{8\pi^2 M_W^2}\left[\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right]$$

The value of M_h is lifted to an experimentally-acceptable range

$$M_h^{max} \simeq 135 - 144 \ GeV$$

These types of corrections also affect the Higgs mixing angle α and the quark masses (i.e., the Yukawa couplings)... which, in turn, affects the couplings of the physical Higgs to gauge bosons and fermions!!!
(More on this later...)

MSSM Higgs Production @ the LHC

Couplings to weak gauge bosons:

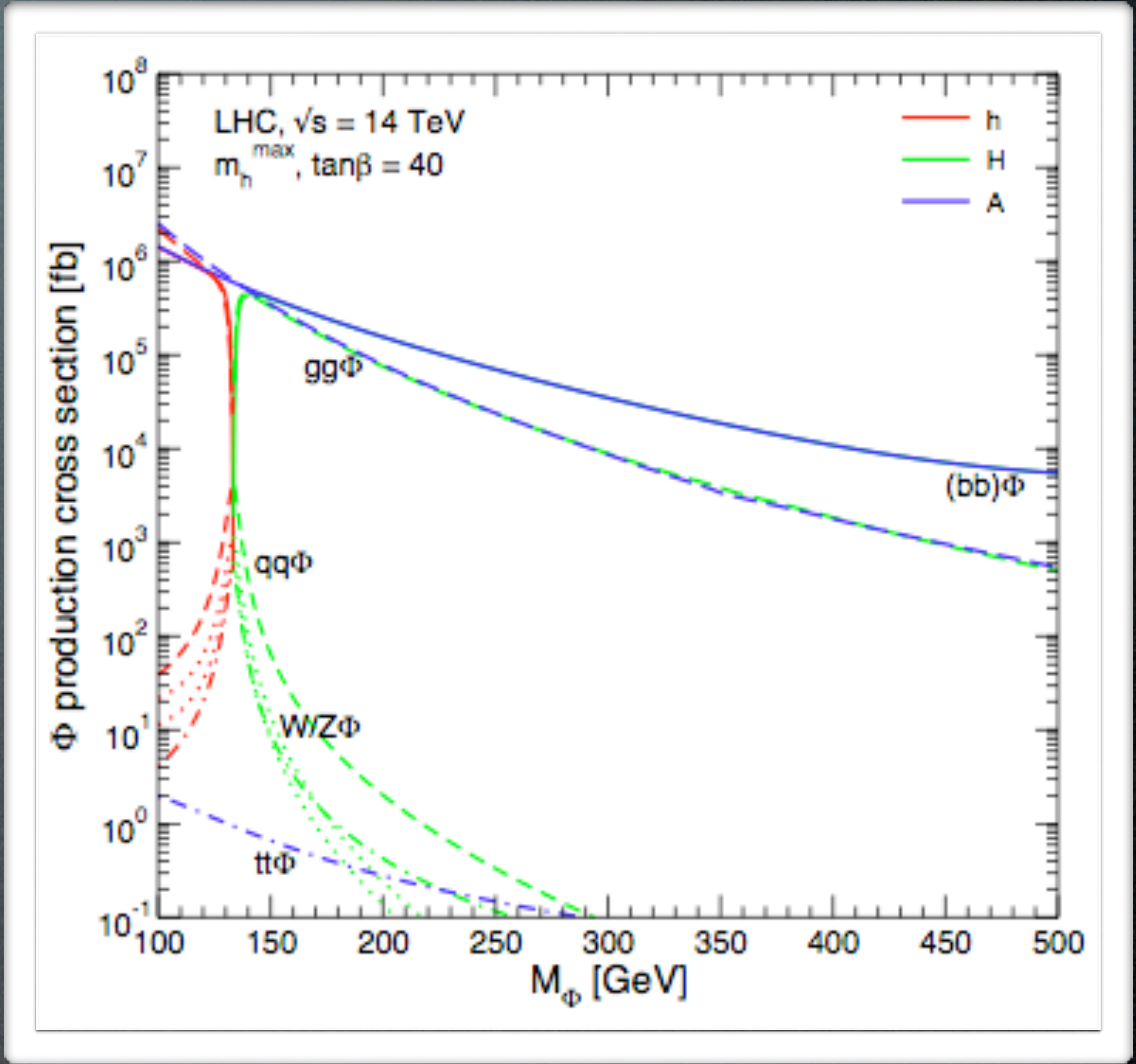
$$g_{hVV}(g_{HVV}) = \sin(\beta-\alpha)(\cos(\beta-\alpha))g_{hVV}^{SM}$$

Couplings to top quarks:

$$g_{htt}(g_{Htt}) = \frac{\cos\alpha}{\sin\beta}\left(\frac{\sin\alpha}{\sin\beta}\right)g_{htt}^{SM}$$

Couplings to bottom quarks:

$$g_{hbb}(g_{Hbb}) = -\frac{\sin\alpha}{\cos\beta}\left(\frac{\cos\alpha}{\cos\beta}\right)g_{hbb}^{SM}$$



For large tanβ, "spectrum" of couplings becomes "inverted" (compared to SM)

Higgs production w/ bottom quarks (very striking!) becomes dominant... and a discovery mode!!!

The Search is on at Fermilab!

Search for a neutral Higgs boson in association with (at least) ONE b:

$$p\bar{p} \rightarrow b\phi \rightarrow b\tau\tau$$

where ϕ = h, H or A and one τ decays leptonically ($\tau \rightarrow \mu\nu_\tau\nu_\mu$) and the other decays hadronically ($\tau \rightarrow$ jets + ν_τ)

The $b\tau\tau$ final state is less sensitive than bbb to SUSY radiative corrections. Also, the extra b jet in the final state helps reduce the $Z \rightarrow \tau\tau$ background

Dominant backgrounds: tt, Multi-jet and Z + jets ("jets" includes b jets)

"Pre-tag" = a reconstructed primary vertex w/ at least 3 tracks (minimal E_T/p_T cuts)

"b-tagged" = at least ONE b jet (ε_b = 35% and $\varepsilon_{j\rightarrow b}$ = 0.5%)

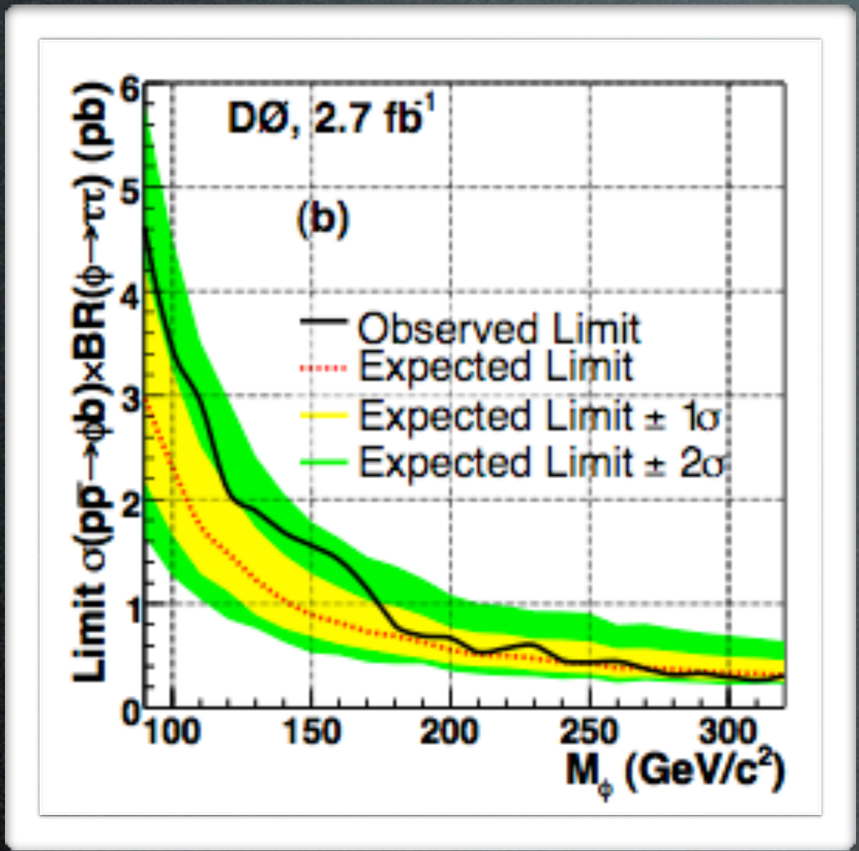
	Pre-tag	*b*-tagged	Final
$t\bar{t}$	66.0 ± 1.3	39.6 ± 0.8	20.3 ± 0.6
Multijet	549 ± 26	38.5 ± 2.3	28.1 ± 1.9
$Z(\rightarrow \tau\tau)$ + jets	1241 ± 8	18.8 ± 0.3	16.3 ± 0.3
Other Bkg	267 ± 6	5.1 ± 0.1	4.1 ± 0.1
Total Bkg	2123 ± 28	102 ± 2.4	68.8 ± 2.0
Data	2077	112	79
Signal	14.4 ± 0.3	4.8 ± 0.1	4.6 ± 0.1

Observed events consistent with SM background...

Current Bounds from DØ

(Phys. Rev. Lett 104, 151801 (2010))

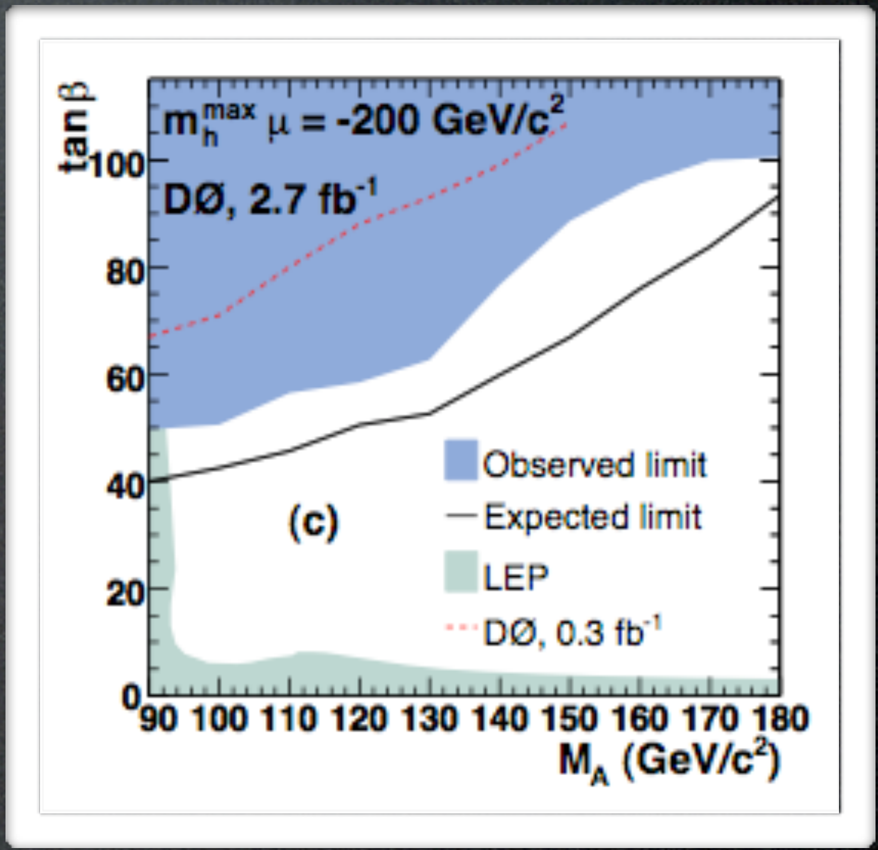
Absence of observable signal, allows constraints to be put on MSSM parameter space...



Results for 2.7 fb^{-1} of data (factor of 8 more data than previous results)

Factor of 3 improvement in bound on MSSM cross section

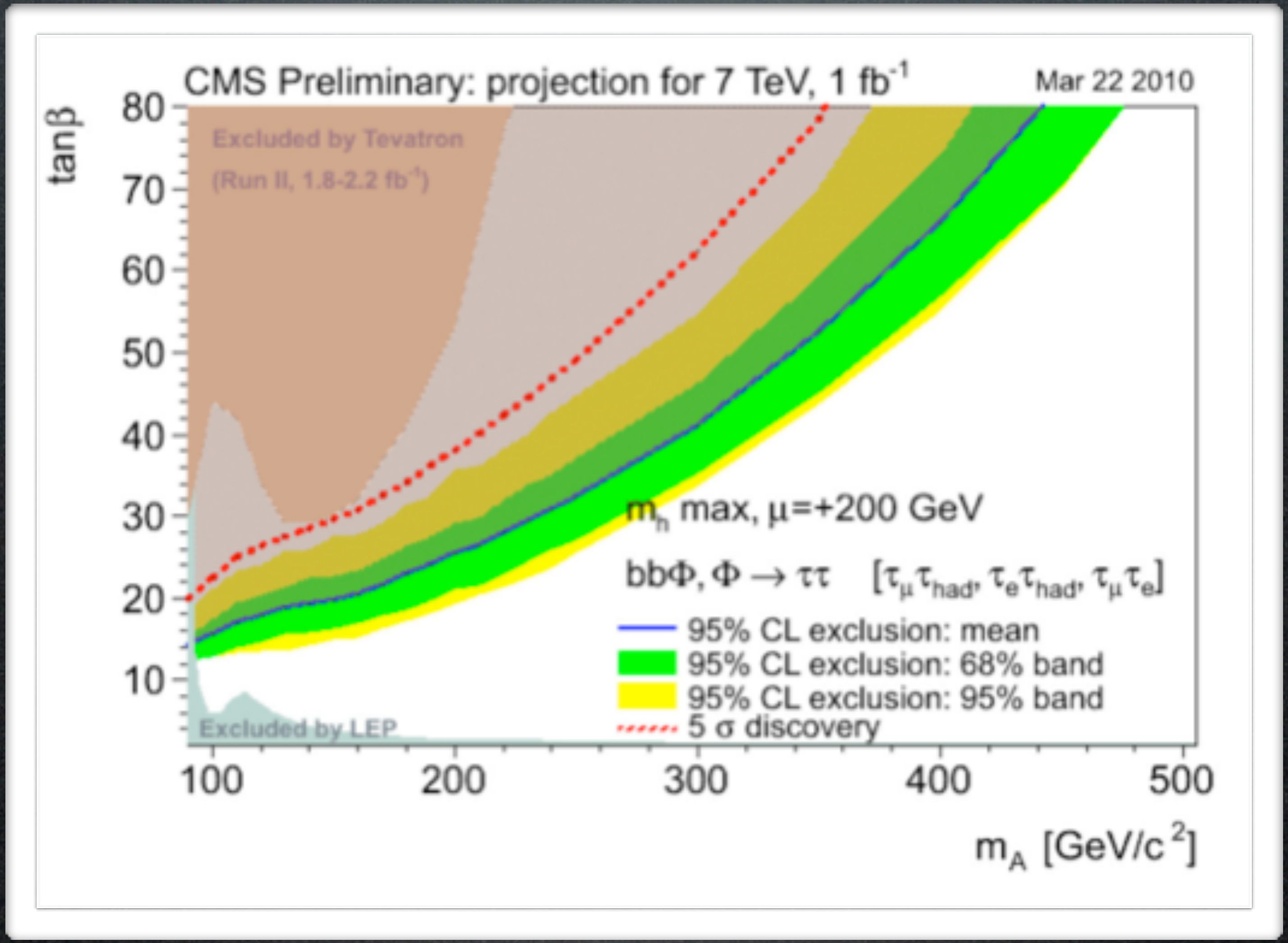
Bounds on cross section can be translated into (rough) bounds on MSSM parameter space (M_A-tanβ plane)



Higgs + b Production at the Early LHC (According to CMS)

Consider same signal process as before (but allow for the possibility that both tau's decay leptonically)

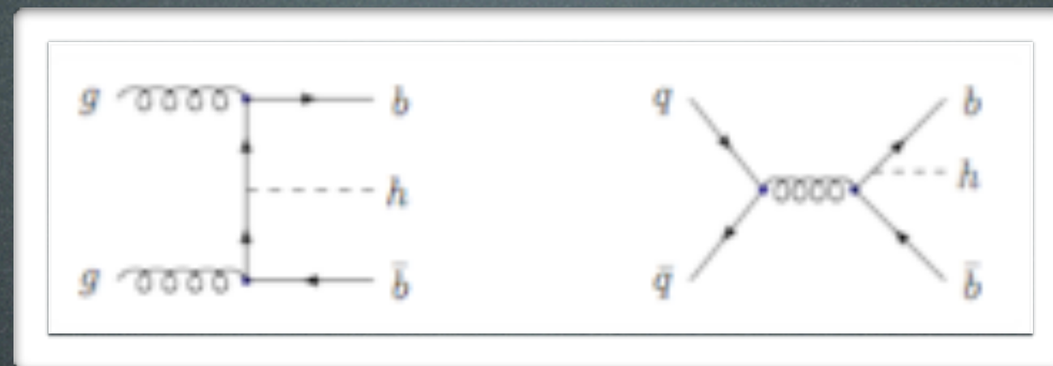
Signal/background event yields obtained by rescaling 14 TeV yields by ratio of cross sections at 7 TeV to 14 TeV



(from CMS Note 2010/008)

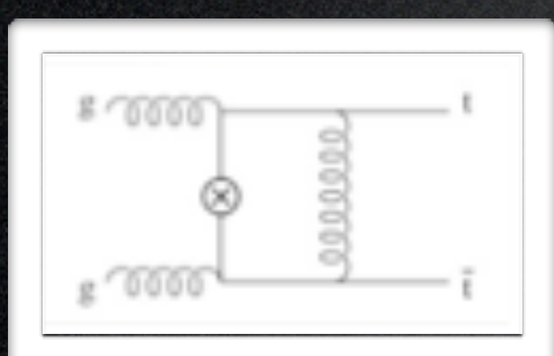
SM Higgs + bottom Production

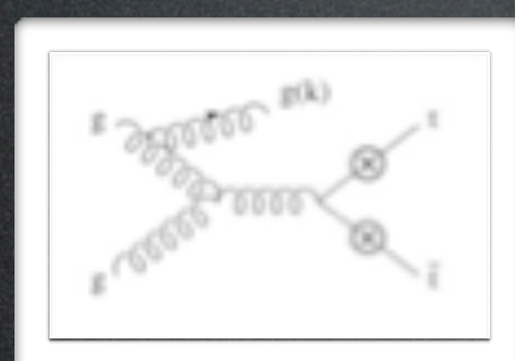
Tree-level production of Higgs + b's proceeds via:

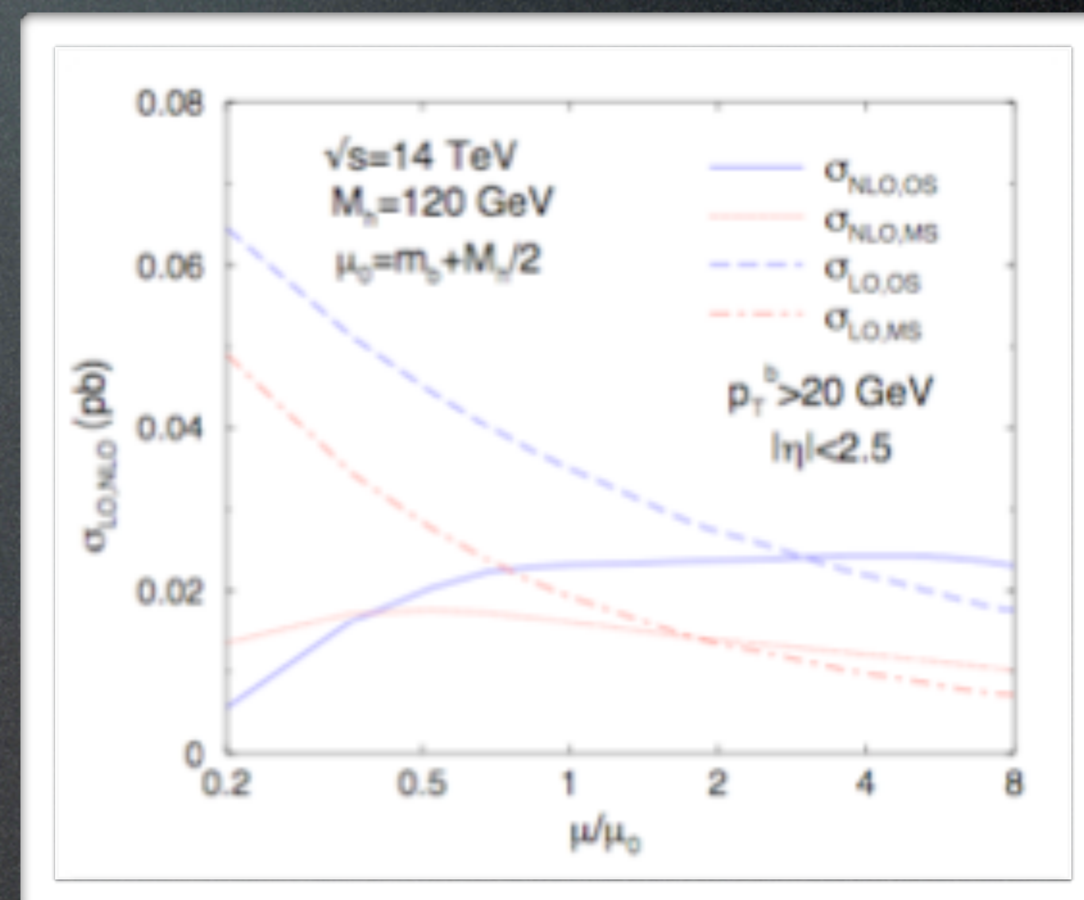


Tree-level cross sections suffer from strong dependence on μ_R, μ_F

NLO QCD corrections obtained from $pp \to tth$ with $m_t \to m_b$
(Dawson et al., Dittmaier et al.)







Issues in SM Higgs + b's Production

Ability to "tag" b jets at hadron colliders leads to 3 distinct modes:

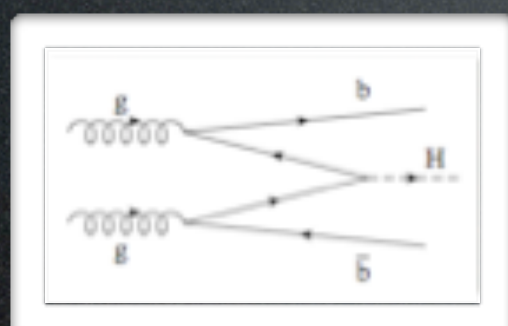
Reduced Background ↓ — Larger Signal ↑

"Inclusive" mode: require NO bottom jets to be tagged

"Semi-inclusive" mode: require at least ONE b jet be tagged

"Exclusive" mode: require BOTH b jets be tagged

However, treating bottom quarks inclusively leads to potentially large (collinear) logarithms from phase space integration:



$$\Lambda_b \equiv \log\left(\frac{\mu_h^2}{m_b^2}\right) \; ; \qquad (\mu_h \simeq M_h)$$

These logs appear at every order in perturbative series

Expansion in α_s becomes one in $\alpha_s\Lambda_b$... convergence of perturbative series?!?

Two Calculational Schemes

Five Flavor Number Scheme (5FNS)

- Assume Λ_b's are the dominant contribution to cross section
- Introduce bottom quark parton distribution function (PDF)

$$b(x,\mu_f) = \frac{\alpha_s(\mu_f)}{2\pi}\Lambda_b \int_x^1 \frac{dy}{y} P_{qg}\left(\frac{x}{y}\right) g(y,\mu_f)$$

- (effectively, replace g → bb splitting with initial-state b quark)
- Perturbative expansion re-ordered to be one in α_s and $1/\Lambda_b$.

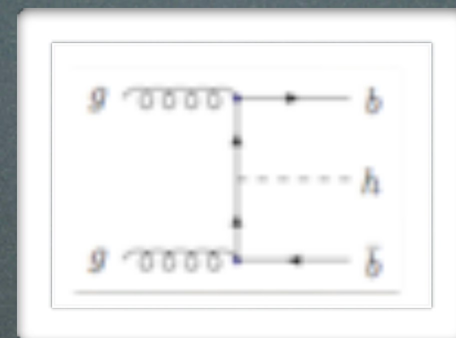
Four Flavor Number Scheme (4FNS)

- No kinematic approximations made
- Cross section for pp → bbh computed at fixed-order with NO special treatment of Λ_b's

“Two b’s or Not Two b’s?”

Production Mode | 4FNS | 5FNS

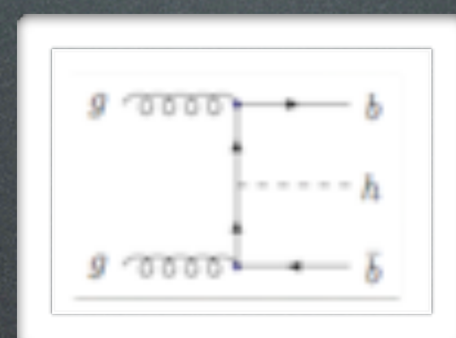
“Exclusive”

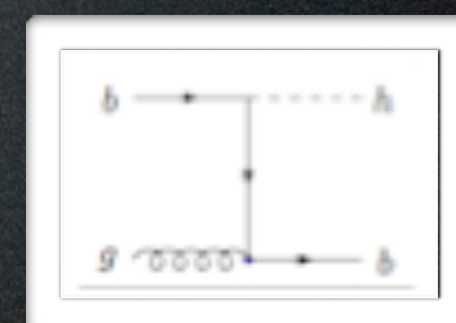


NLO in QCD
(Dawson, CJ, Reina & Wackeroth;
Dittmaier, Kramer & Spira)

N/A

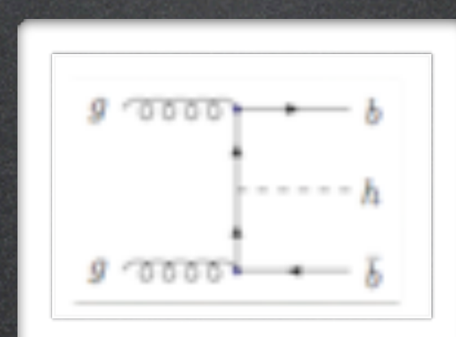
“Semi-inclusive”

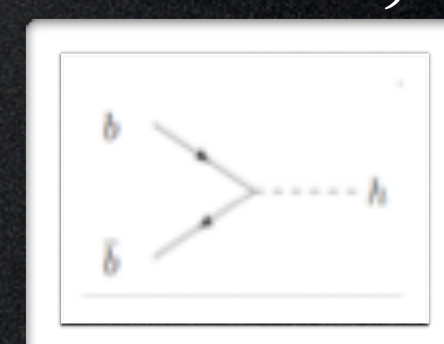




NLO in QCD
(Campbell, Ellis, Maltoni &
Willenbrock)

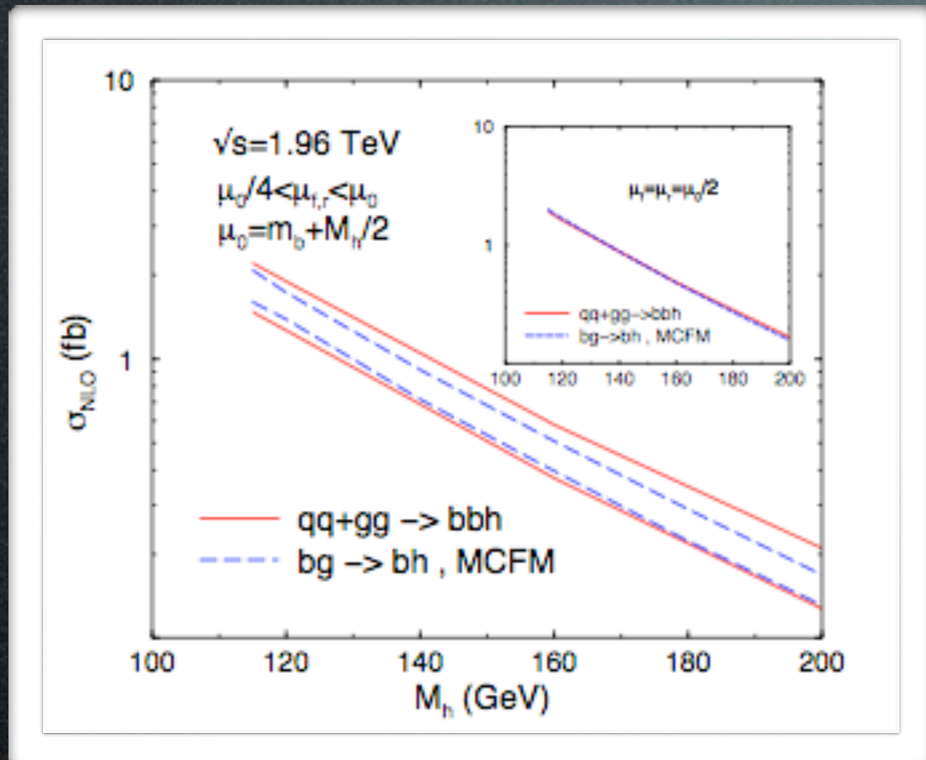
“Inclusive”

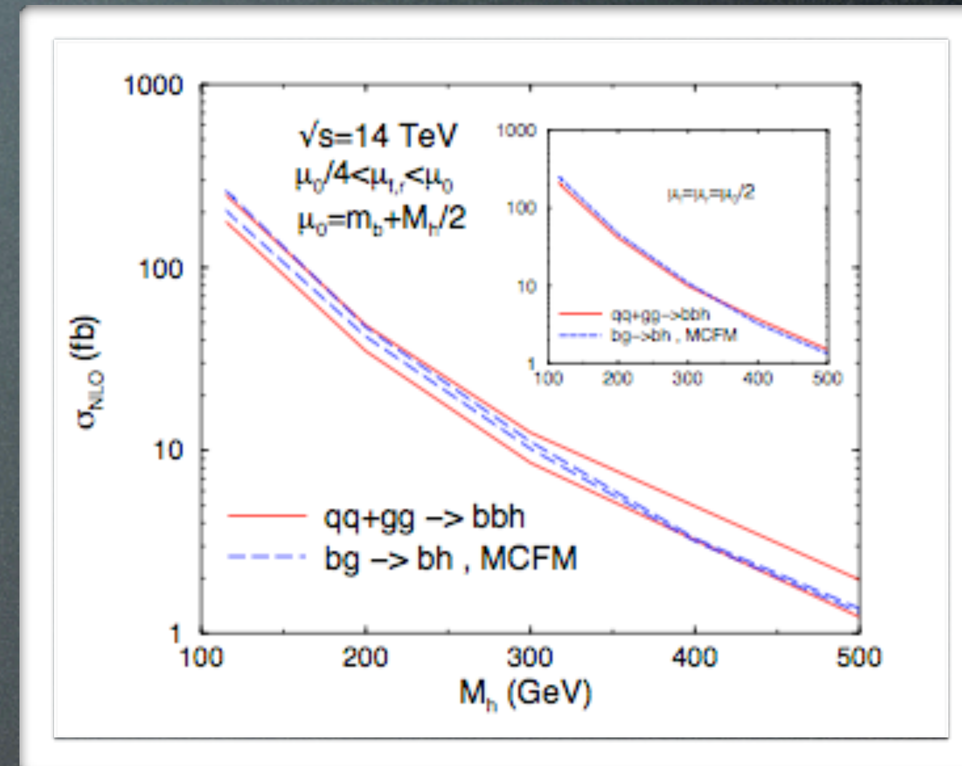


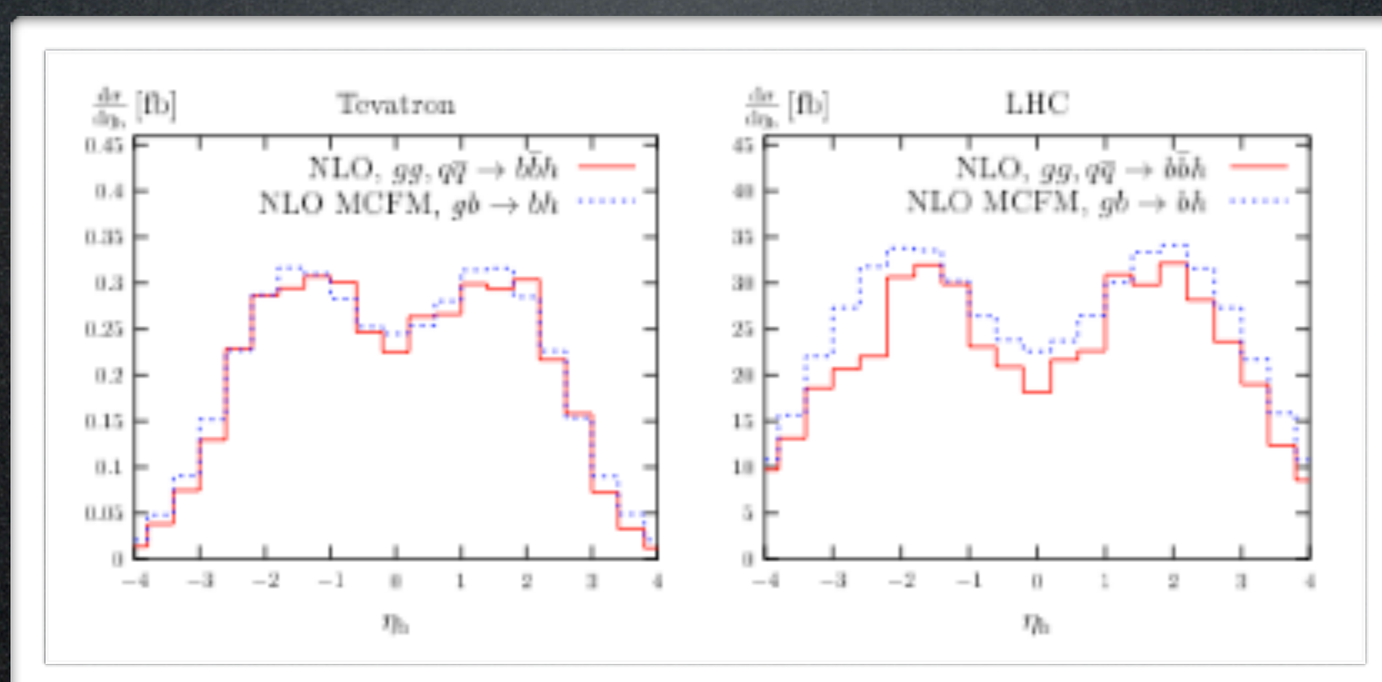


NNLO in QCD
(Harlander & Kilgore)

4FNS vs. 5FNS Comparison for the Semi-inclusive Case



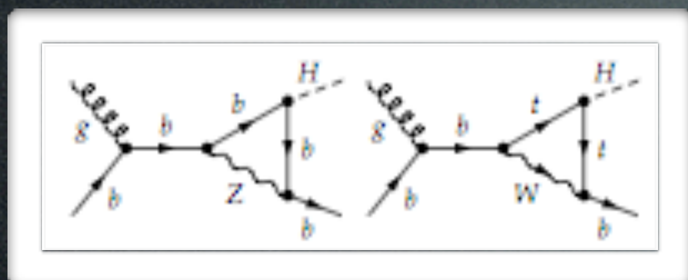


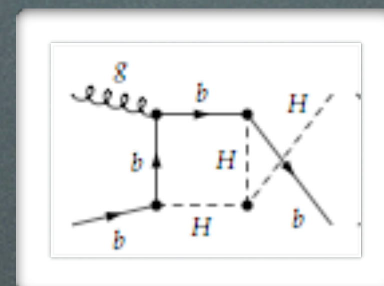


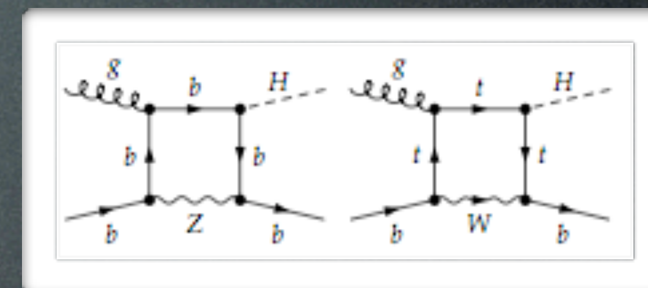
SM Electroweak Corrections

(Dawson and Jaiswal, PRD81, 073008 (2010))

Considered the NLO EW corrections to the 5FNS process gb → bh:







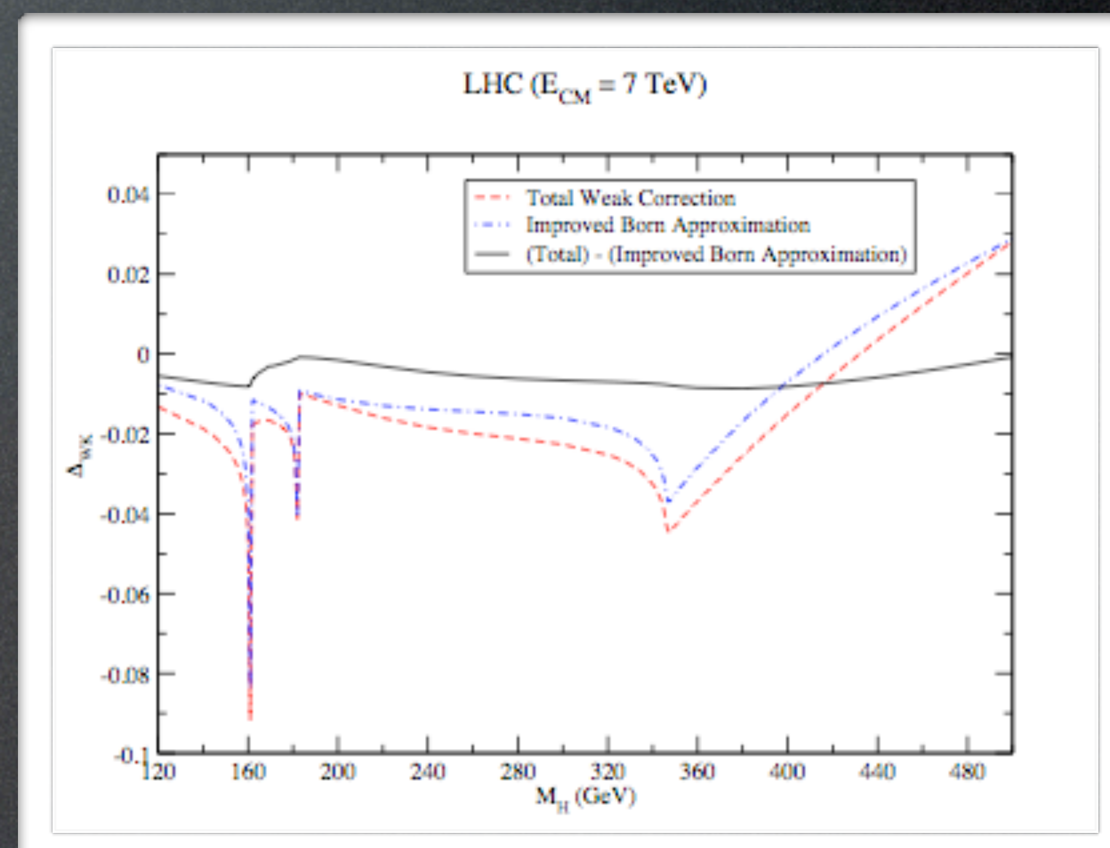
$$\sigma(bg \to bH)_{NLO} = \sigma(bg \to bH)_0 \left(1 + \Delta_{QCD} + \Delta_{QED} + \Delta_{WK}\right)$$

SM EW corrections are typically small (~ few percent level)

Except…

1) at "threshold" regions

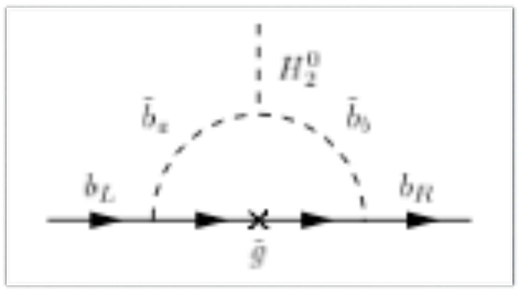
2) for a very heavy Higgs (for M_h = 1 TeV, ΔEW ~ 20%)



Converting SM Predictions into SUSY Predictions

To obtain SUSY results (for large tanβ) from SM results, not enough to rescale Yukawas by tree-level expressions

$$g^{LO}_{hbb} = -\frac{\sin\alpha}{\cos\beta} g^{SM}_{hbb} \qquad g^{LO}_{Hbb} = \frac{\cos\alpha}{\cos\beta} g^{SM}_{hbb}$$



One-loop corrections involving SUSY particles can have significant effects on Yukawa couplings
(Carena Mrenna & Wagner, PRD60:075010 (1999))

These types of corrections induce couplings between bottom quarks and the up-type Higgs doublet

$$\mathcal{L} \simeq h_b b\bar{b} H_1^0 + \Delta h_b b\bar{b} H_2^0$$

$$m_b \rightarrow h_b v_1 \left[1 + \Delta(m_b) \right]$$

$$\Delta(m_b) = \frac{2\alpha_s}{3\pi} M_{\tilde{g}}\, \mu \tan\beta\, I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, M_{\tilde{g}})$$

The induced couplings can provide significant shifts to the bottom quark mass for large tanβ...
even though they are loop-suppressed!!!

SUSY QCD Corrected Yukawa Couplings

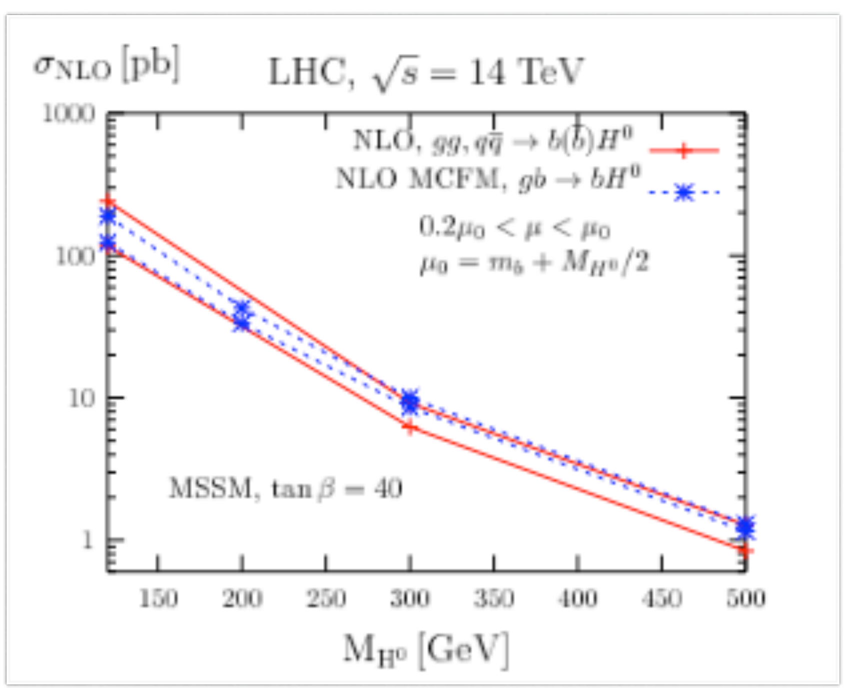
In turn, the shift in m_b leads to a shift in the Yukawa couplings between bottom quarks and the physical Higgs bosons

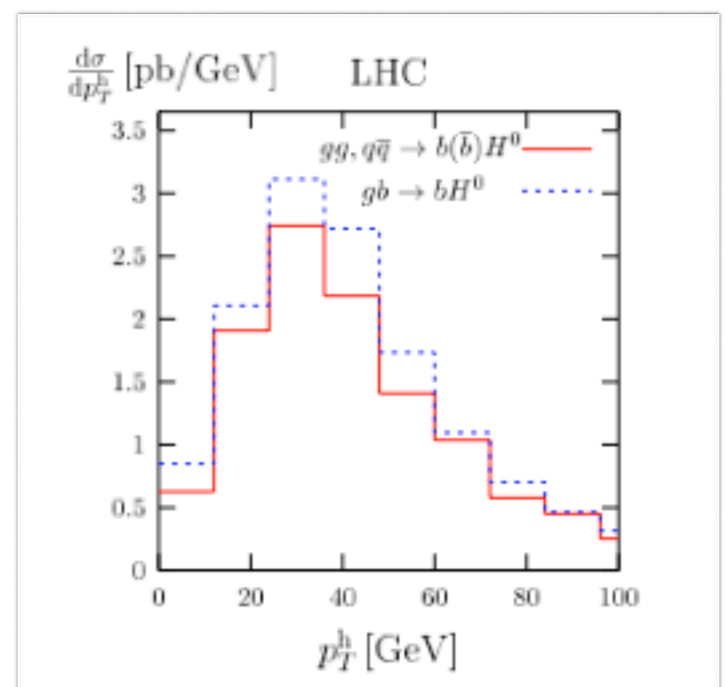
$$g_{hbb} = -\frac{\sin\alpha}{\cos\beta}\frac{1}{(1+\Delta(m_b))}\left[1 - \frac{\Delta(m_b)}{\tan\alpha\tan\beta}\right] g_{hbb}^{SM}$$

$$g_{Hbb} = \frac{\cos\alpha}{\cos\beta}\frac{1}{(1+\Delta(m_b))}\left[1 + \frac{\Delta(m_b)\tan\alpha}{\tan\beta}\right] g_{hbb}^{SM}$$

$$\sigma_{MSSM} = \left(\frac{g_{b\bar{b}h}^{MSSM}}{g_{b\bar{b}h}^{SM}}\right)^2 (\sigma_{SM} - \sigma_{SM}^t) + \left(\frac{g_{t\bar{t}h}^{MSSM}\, g_{b\bar{b}h}^{MSSM}}{g_{t\bar{t}h}^{SM}\, g_{b\bar{b}h}^{SM}}\right)\sigma_{SM}^t$$

Rescale cross section by the SQCD-corrected Yukawas

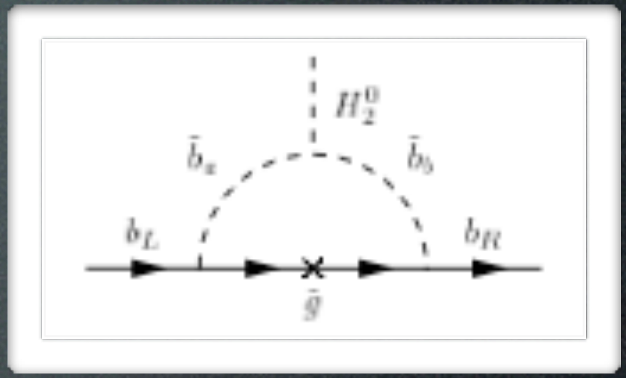




Computing the Full SUSY QCD Corrections

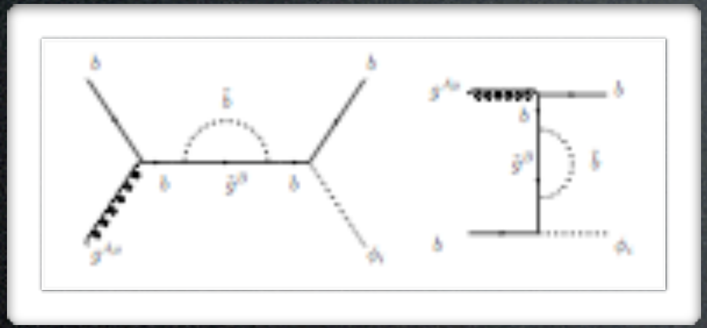
(CJ and S. Dawson, PRD77, 015019 (2008))

Effective Lagrangian Approach assumes bottom quarks are on-shell. This works fine for inclusive 5FNS ($bb \to h$) or Higgs decay ($h \to bb$)

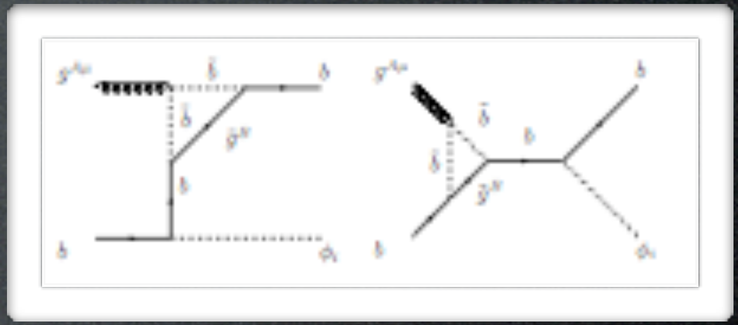


Need to compute full SUSY QCD corrections (i.e., corrections from loops of sbottoms and gluinos) to $gb \to b\phi$ (ϕ = h, H or A)

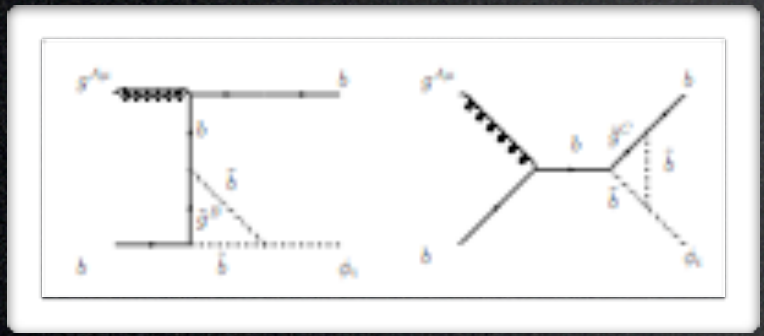
Self-energy Corrections



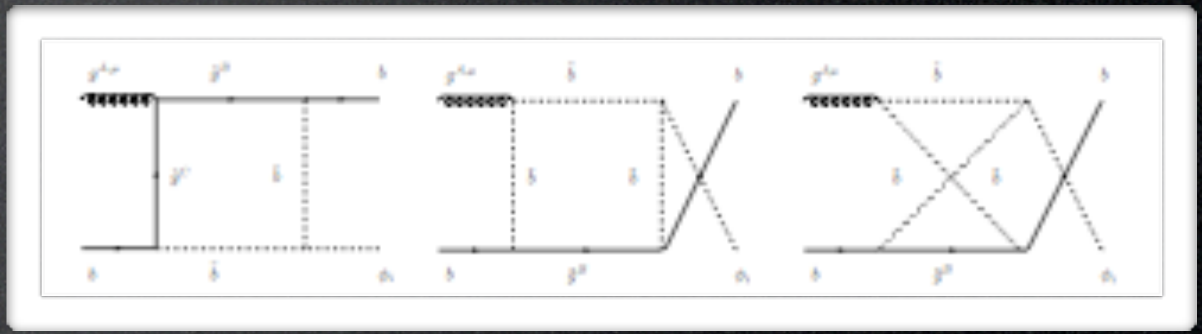
gbb Vertex Corrections



bbφ Vertex Corrections



Box Corrections



Three Scenarios

In the following, I'll consider three scenarios:

"Very Heavy" (or "Pessimistic") scenario:

M_{SUSY} = 5 TeV and Max. $M_h \approx$ 127 GeV

"Heavy" (or "Semi-Pessimistic"/ "Semi-Optimistic") scenario:

M_{SUSY} = 1 TeV and Max. $M_h \approx$ 131 GeV

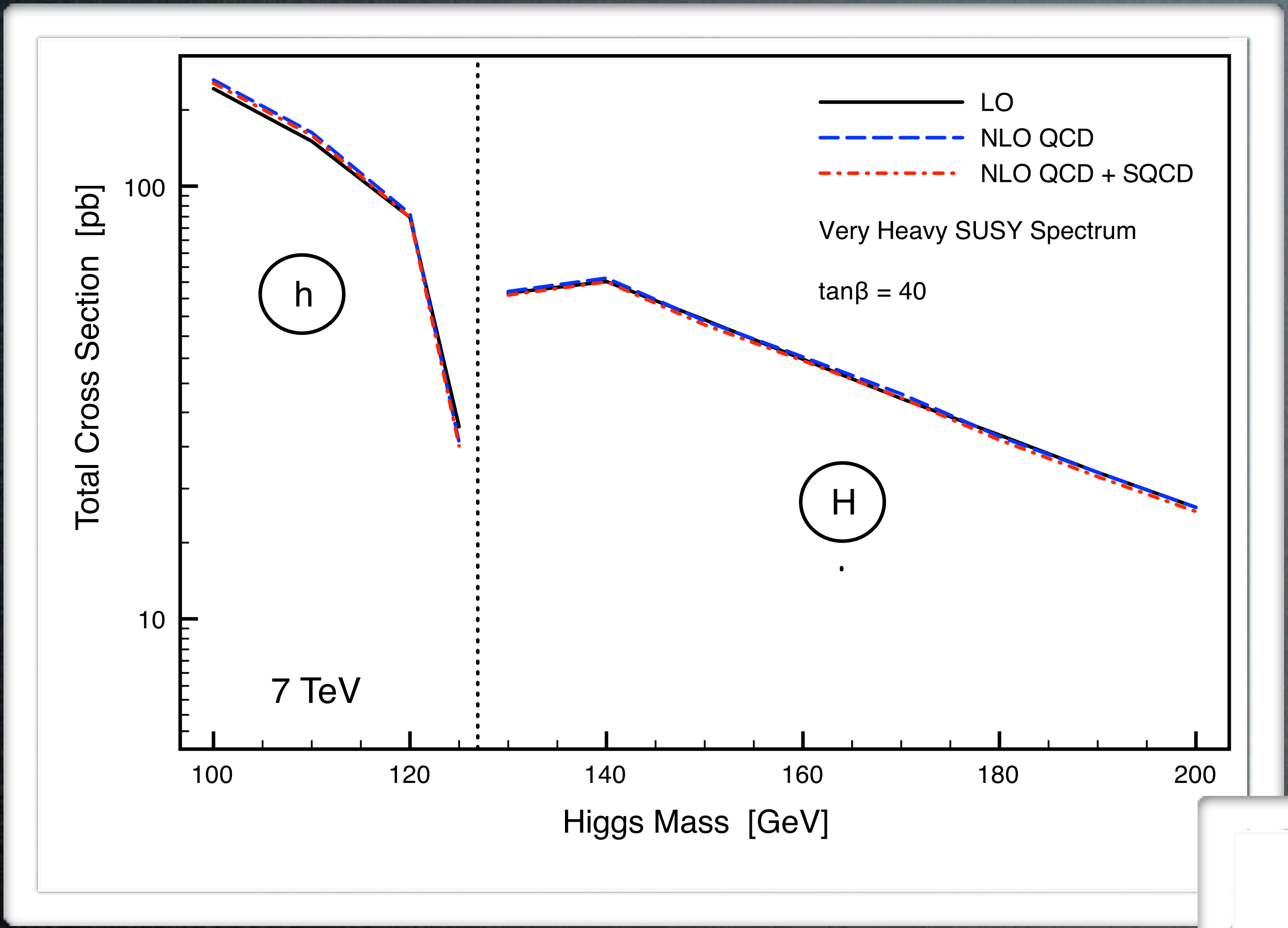
"Light" (or "Optimistic") scenario:

M_{SUSY} = 500 GeV and Max. $M_h \approx$ 127 GeV

For all three scenarios, we consider large $\tan\beta$ and positive SUSY μ parameter

All plots assume $\mu_{R,F} \approx M_h/4$ and $\sqrt{s}$ = 7 TeV...
cross sections scale as $1/s^2$

Results for the “Very Heavy” Scenario



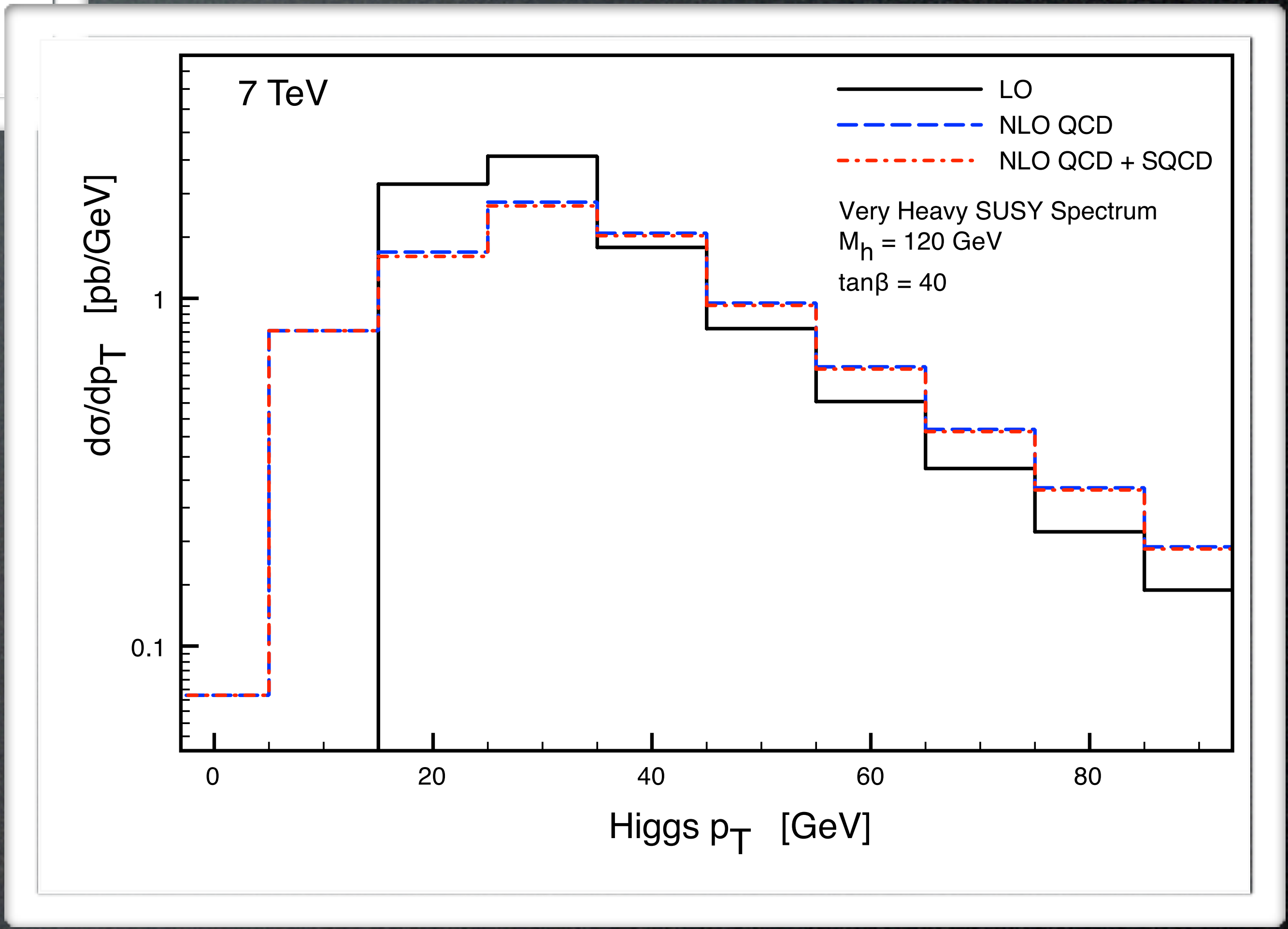
$M_{SUSY} \approx 5$ TeV

“LO” and “NLO QCD” include effects from SQCD-corrected Yukawa couplings

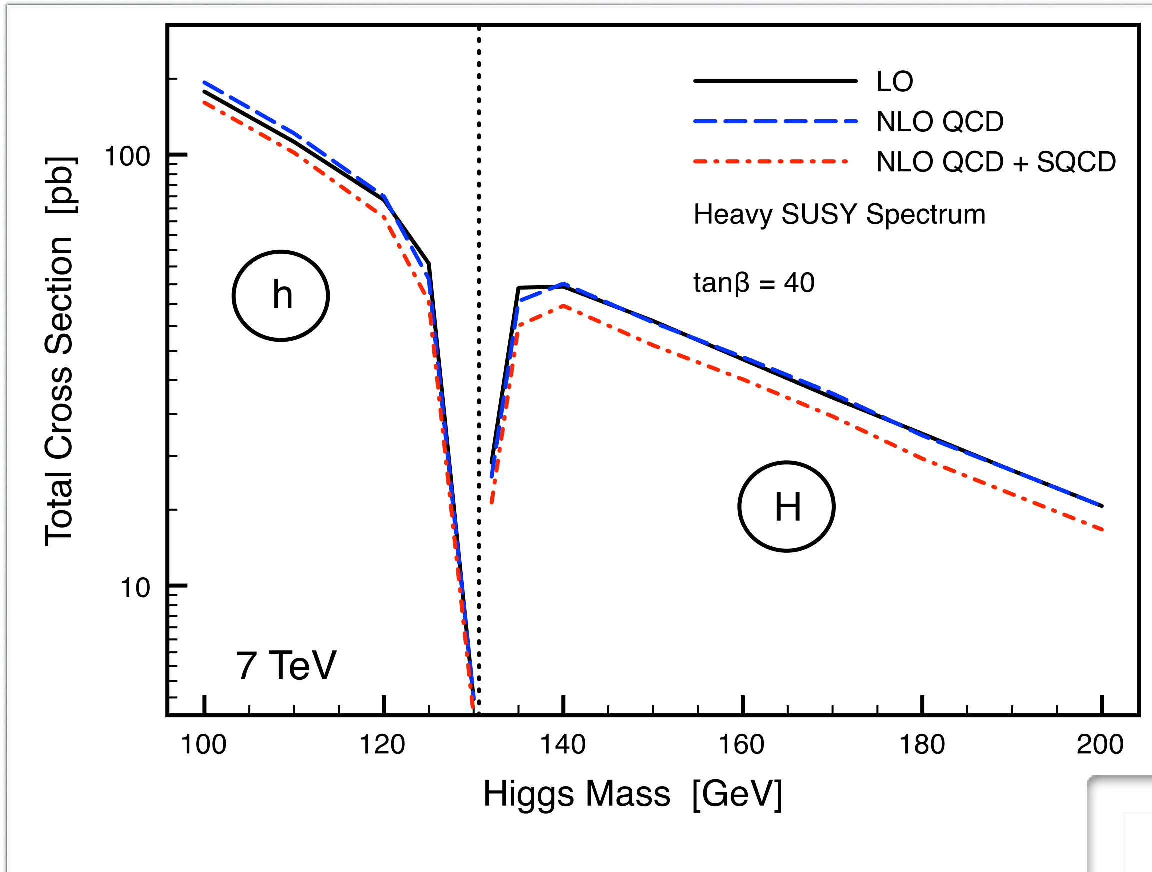
“NLO SQCD” includes all other SQCD corrections (gbb vertex, boxes, etc.)

For the “Very Heavy” case, the rest of the SQCD corrections decouple and the effective Lagrangian approach is VERY ACCURATE.

$\Delta_{SQCD} \approx$ -2-3% for full range of Higgs masses considered



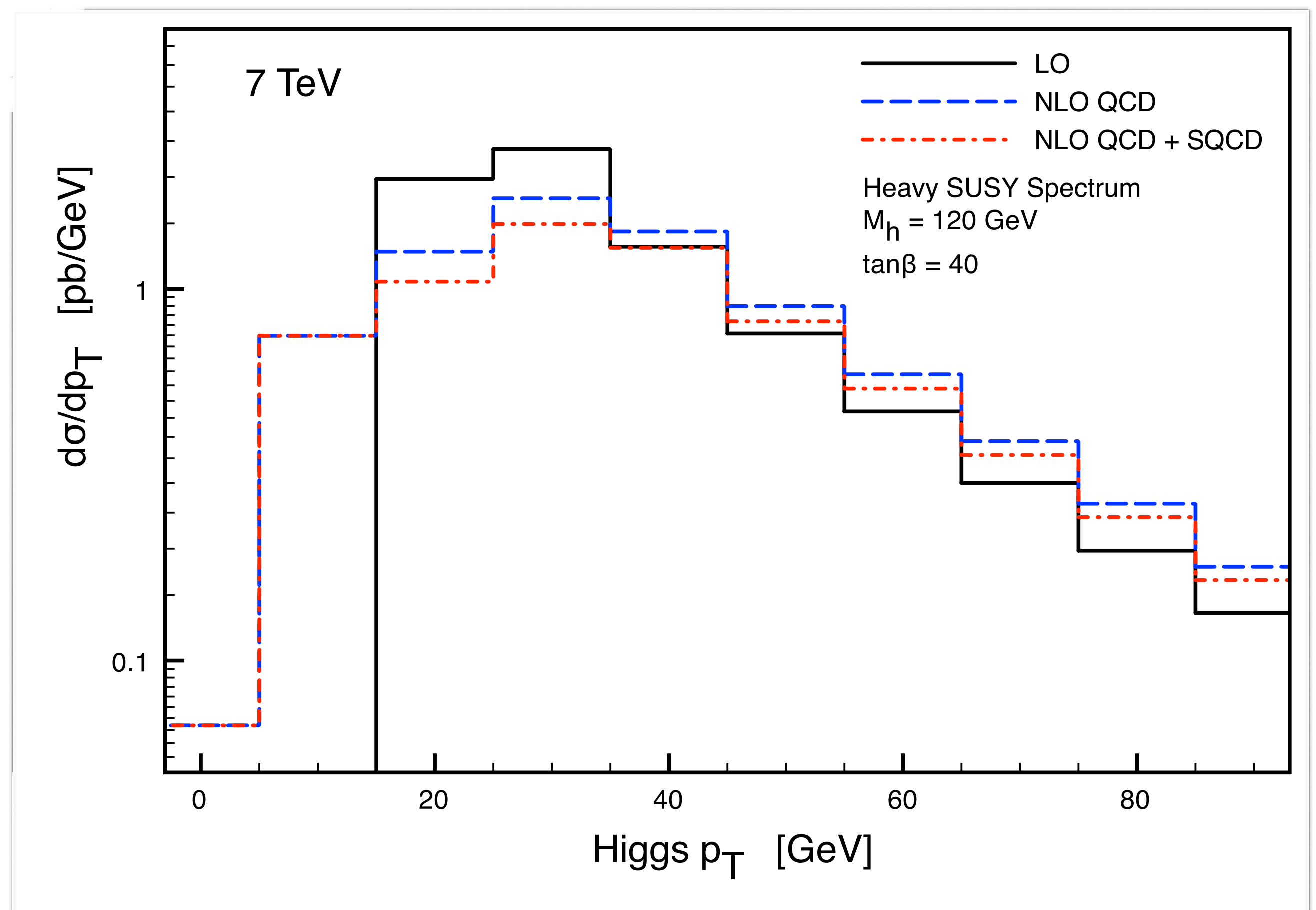
Results for the "Heavy" Scenario



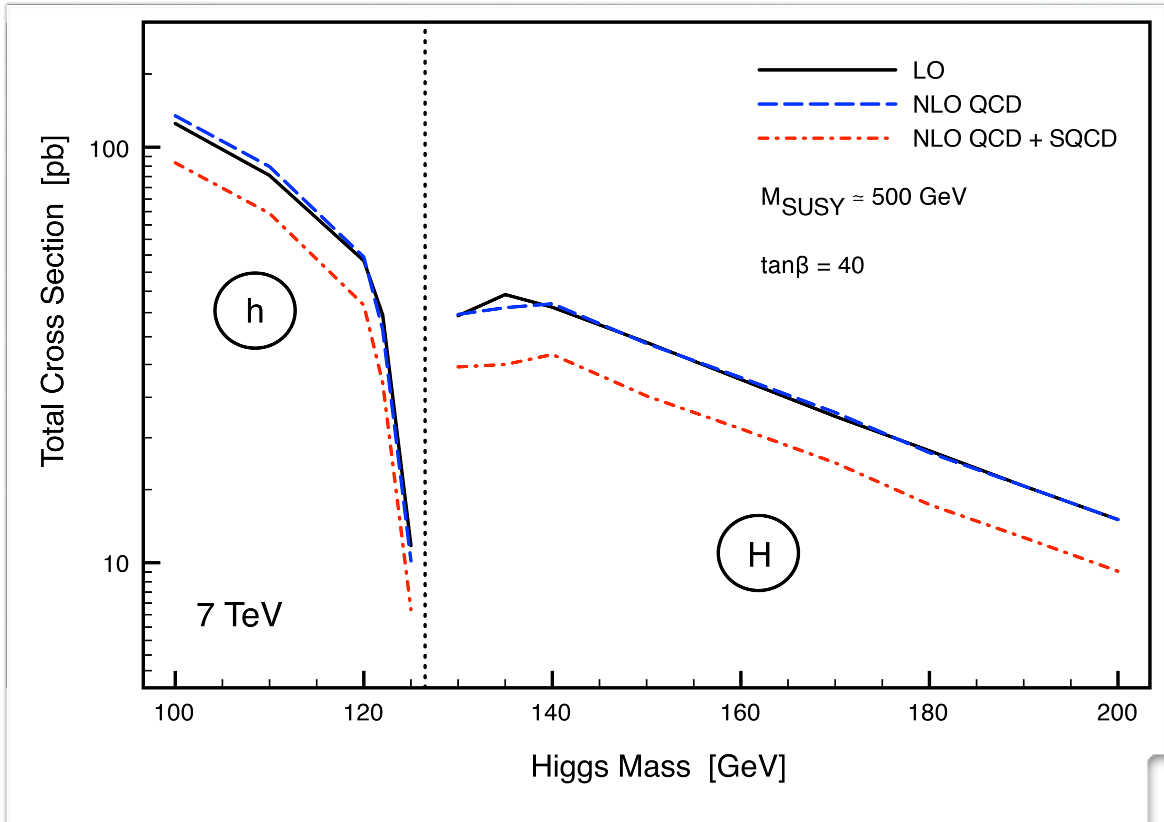
$M_{SUSY} \approx 1$ TeV

For $\mu > 0$, the full NLO SQCD corrections REDUCE the total cross section

$\Delta_{SQCD} \approx -10\%$ for the full mass range considered



Results for the "Light" SUSY Scenario



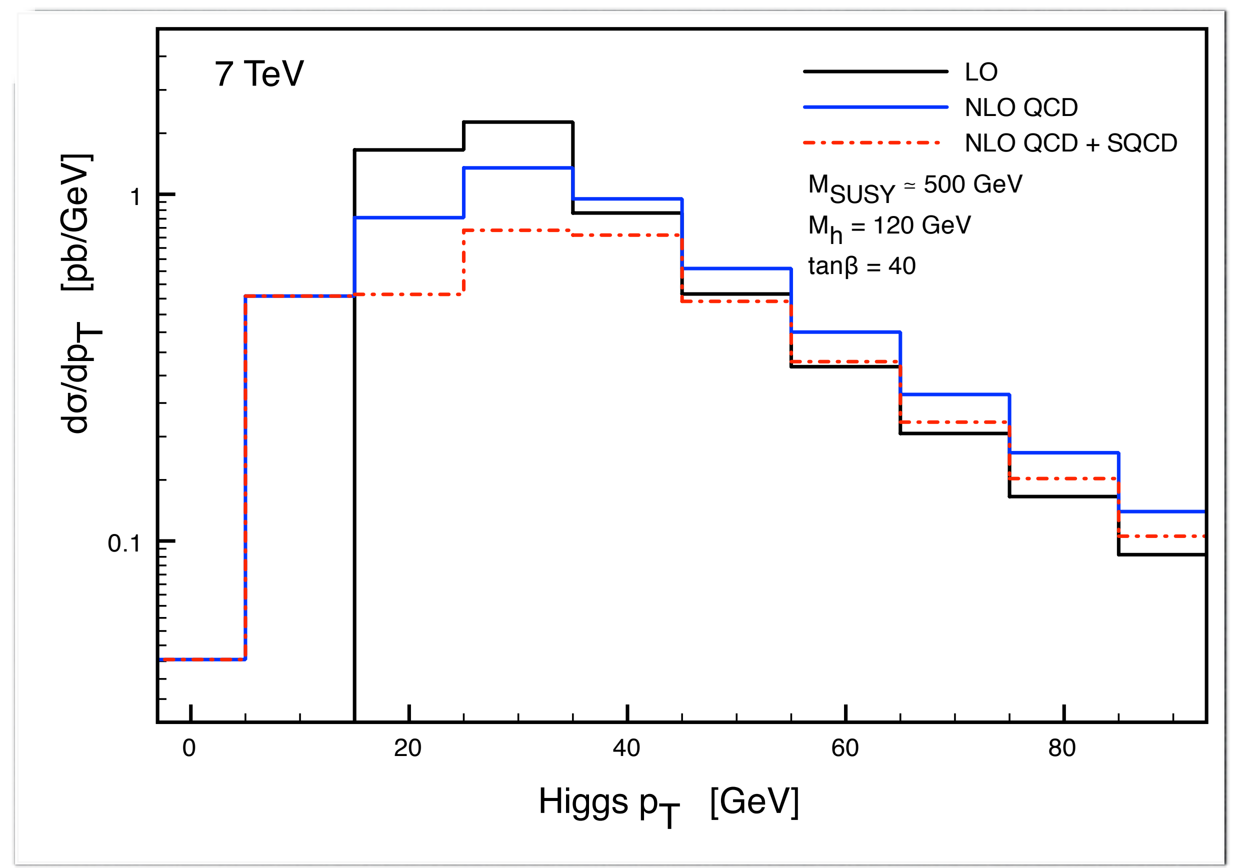
$M_{SUSY} \simeq 500$ GeV

NLO SQCD corrections DRASTICALLY REDUCE the total rate!

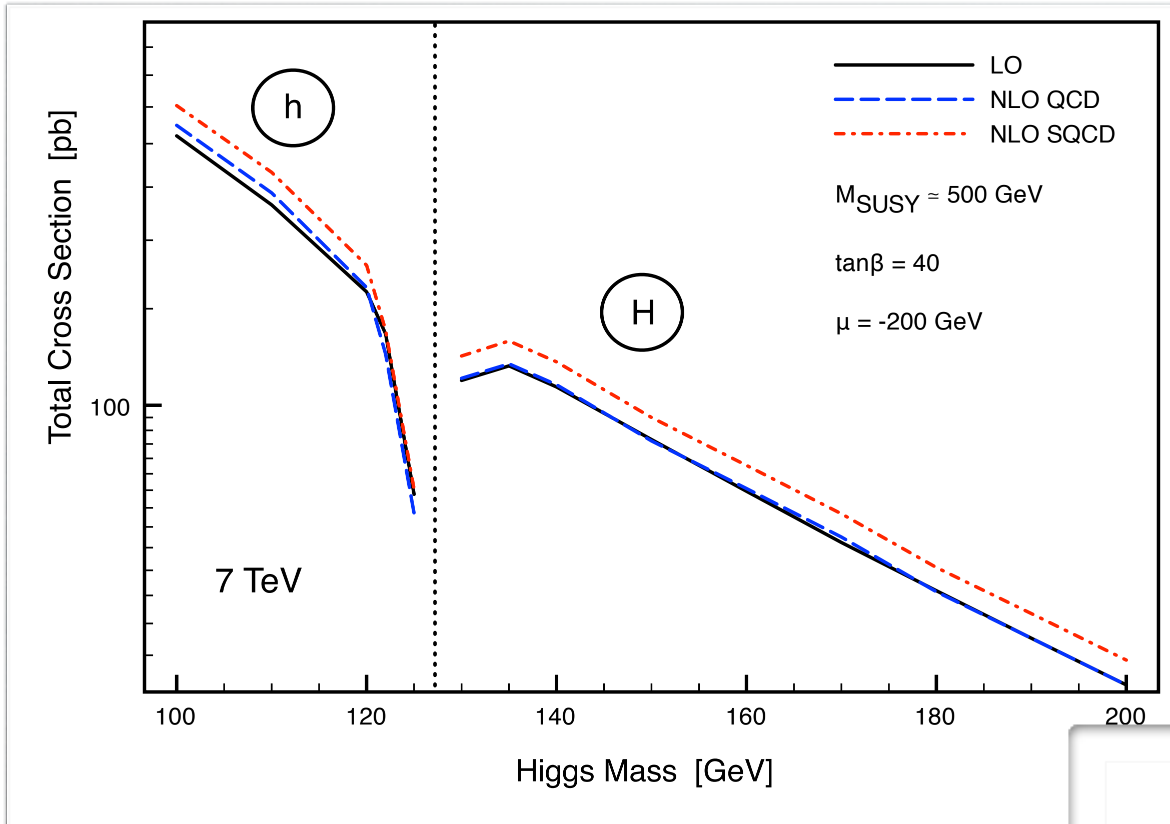
$\Delta_{SQCD} \approx$ -20-25% for the full mass range considered

Signal in the low p_T region severely degraded...

"Optimistic" SUSY scenario not so "optimistic" for Higgs searches! :(



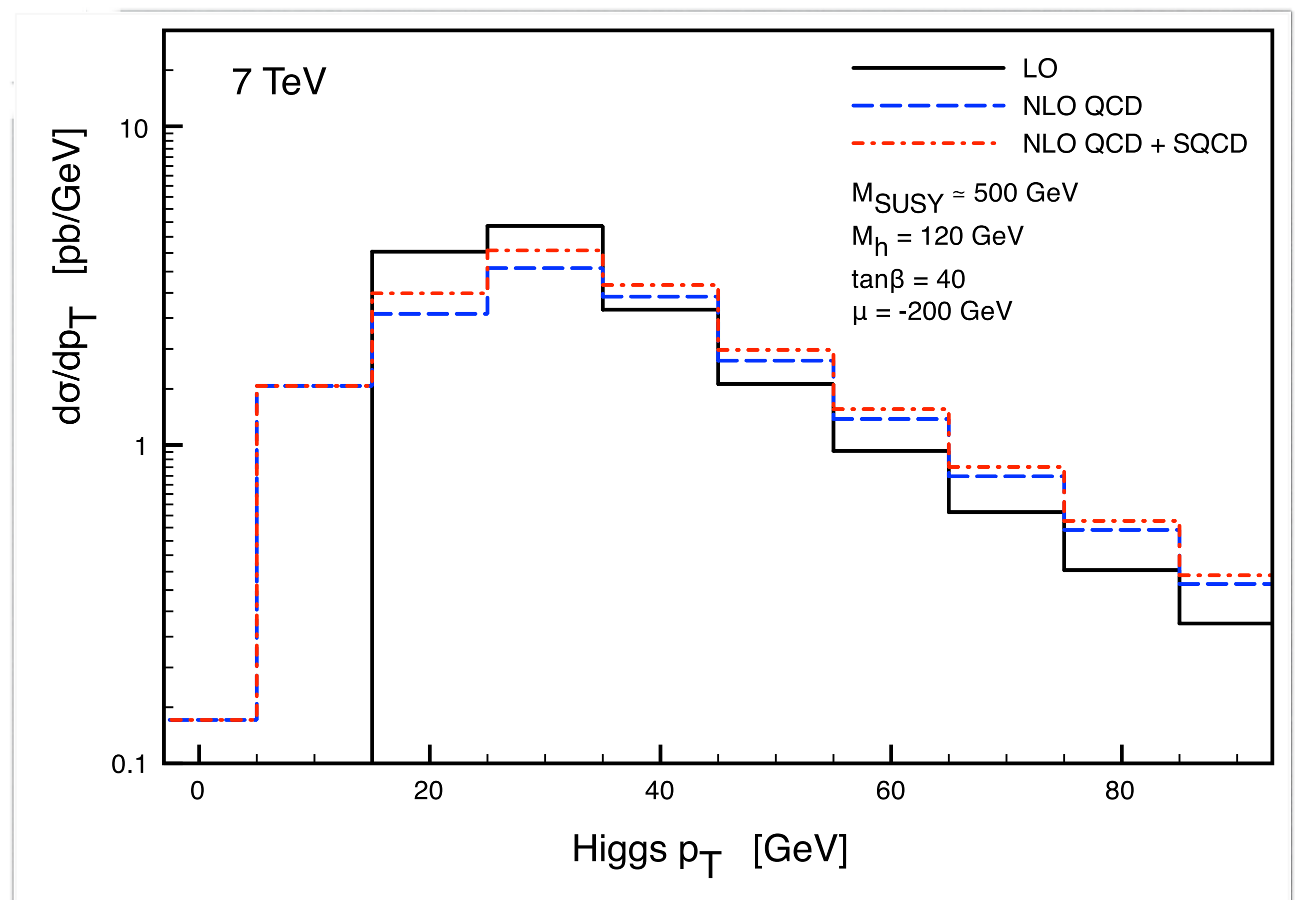
Results for “Light” Scenario w/ Negative μ



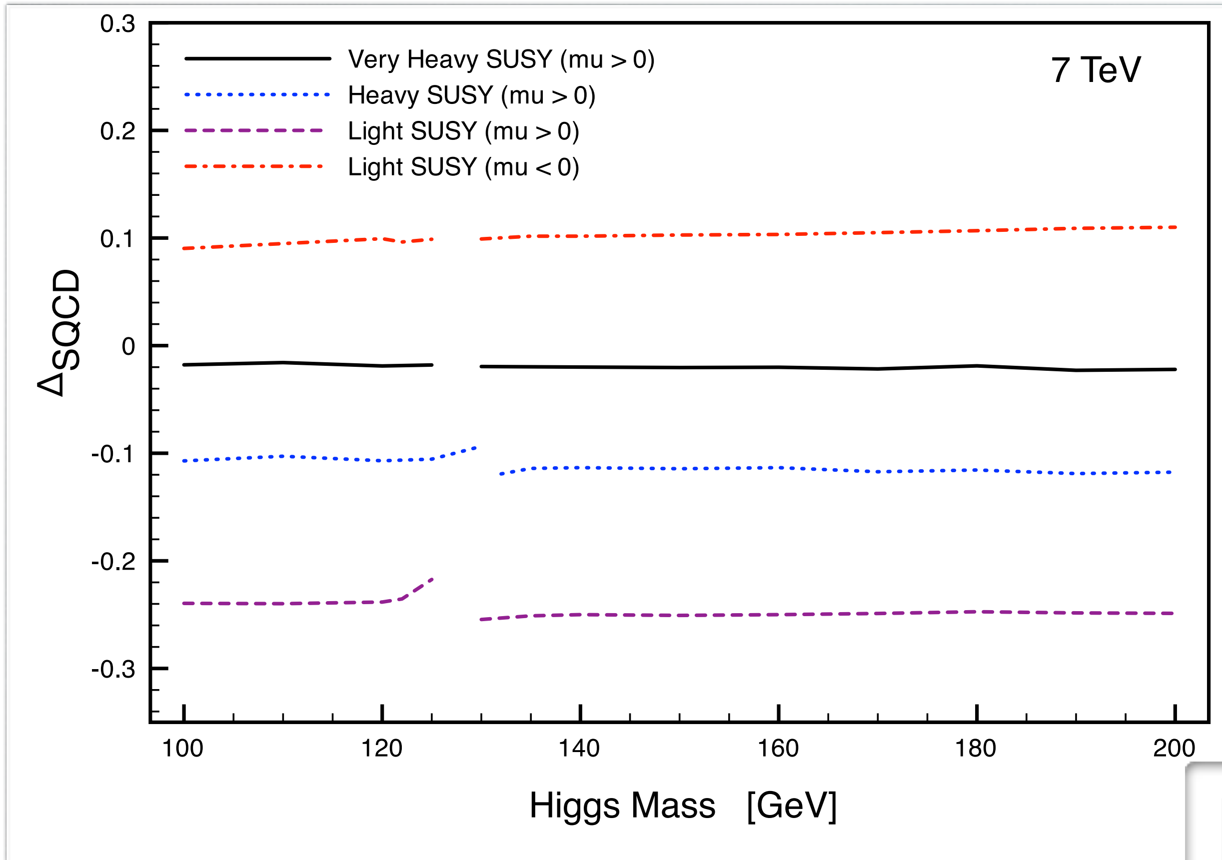
$M_{SUSY} \simeq 500$ GeV

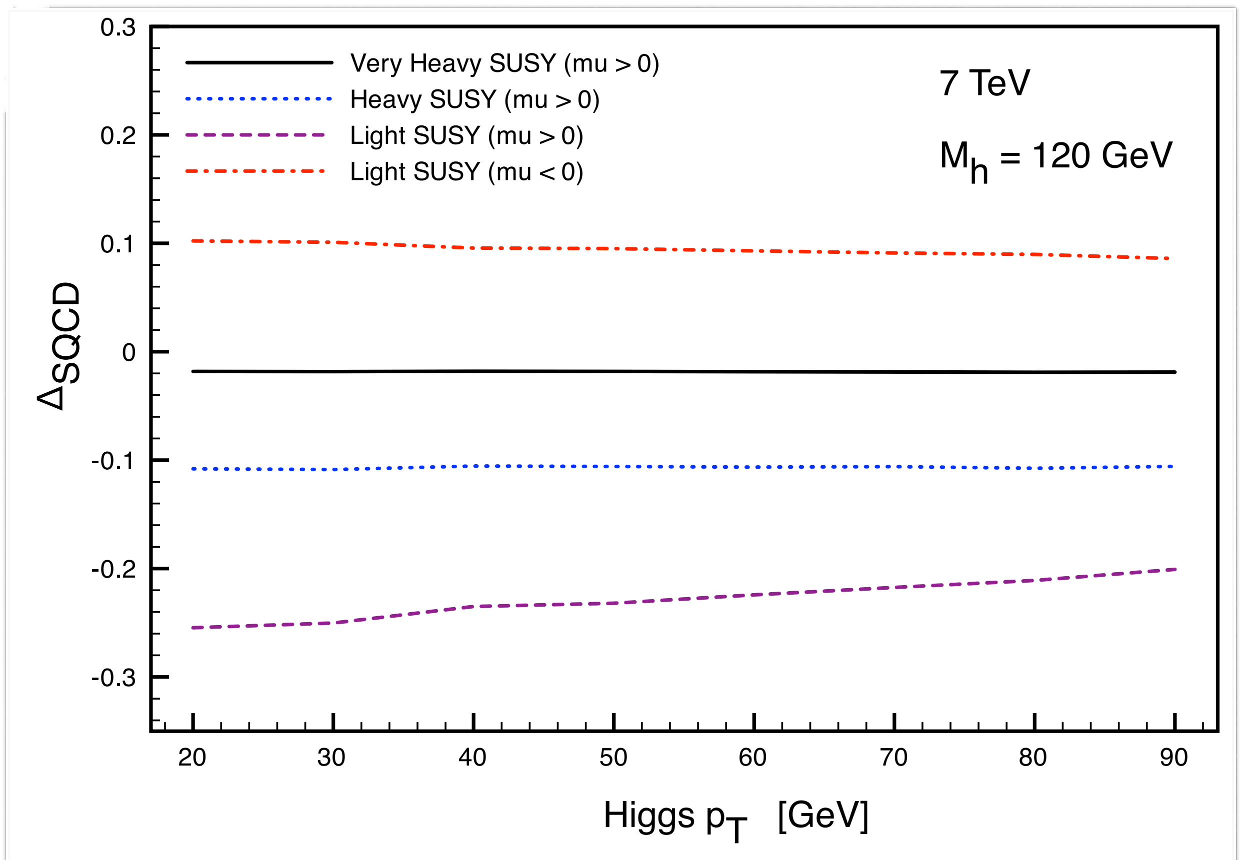
For $\mu < 0$, NLO SQCD corrections enhance the rate!

$\Delta_{SQCD} \approx +10\%$ for the full mass range considered



Summary of NLO SQCD Results





Conclusions/Outlook

SUSY Higgs production in association with bottom quarks is a discovery mode at both the Tevatron and LHC (even the "early" LHC!)

D∅ is already using this channel to bound the MSSM parameter space... and CMS claims they can do even better at 7 TeV and 1 fb^{-1}

On the theoretical side, comparisons between the two calculational schemes (4FNS and 5FNS) show almost exact agreement for SM QCD corections

Very important to consider the SUSY QCD corrections... especially for more "optimistic" SUSY scenarios!!!

Observation of bh production could tell us about the size of SQCD corrections... and about the SUSY parameter space (sign of μ?)

On-going work ("to do" list):

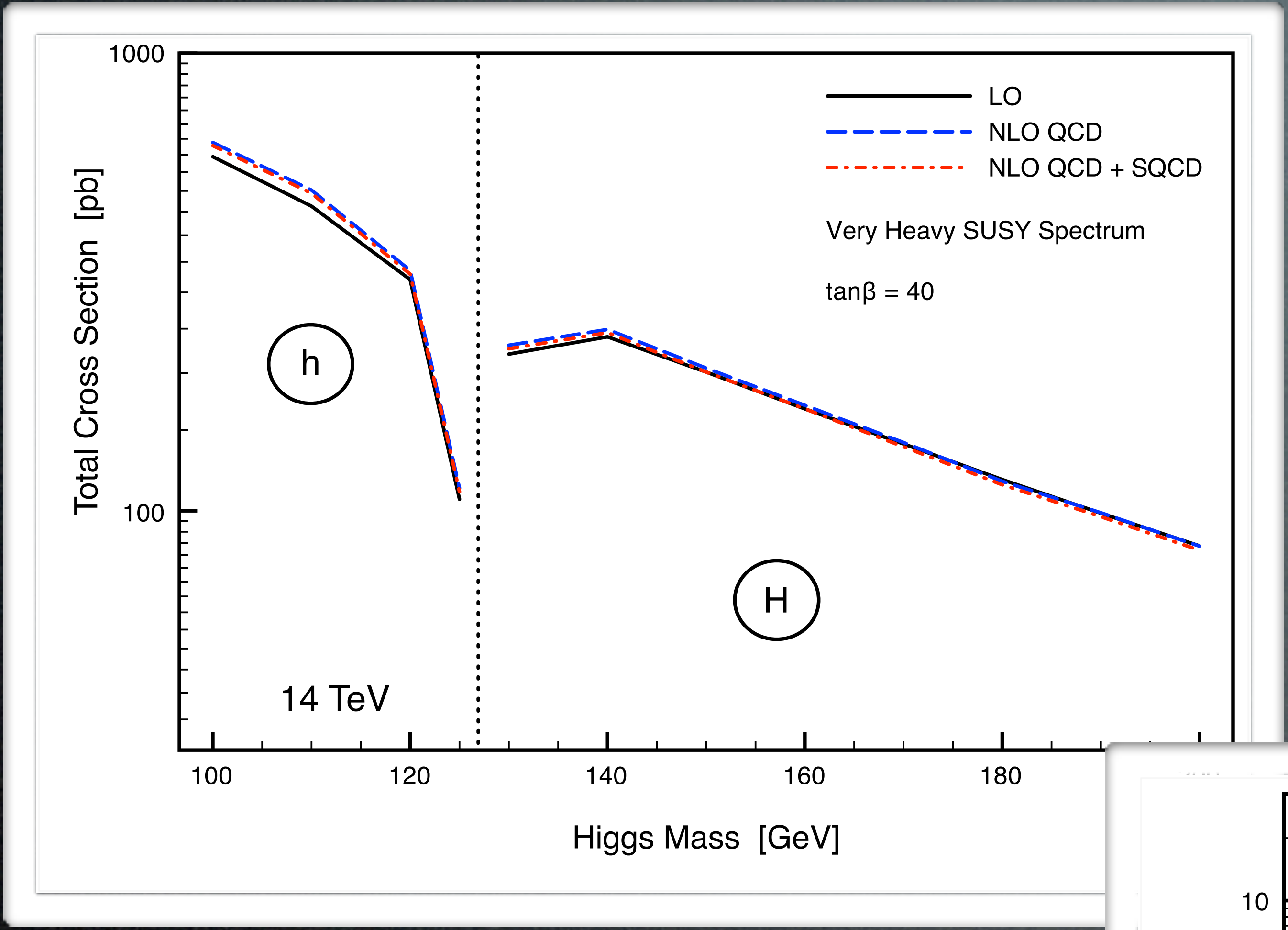
- Trying to interface SQCD code with MCFM
- Incorporating bbh in an event generator (e.g., POWHEG)

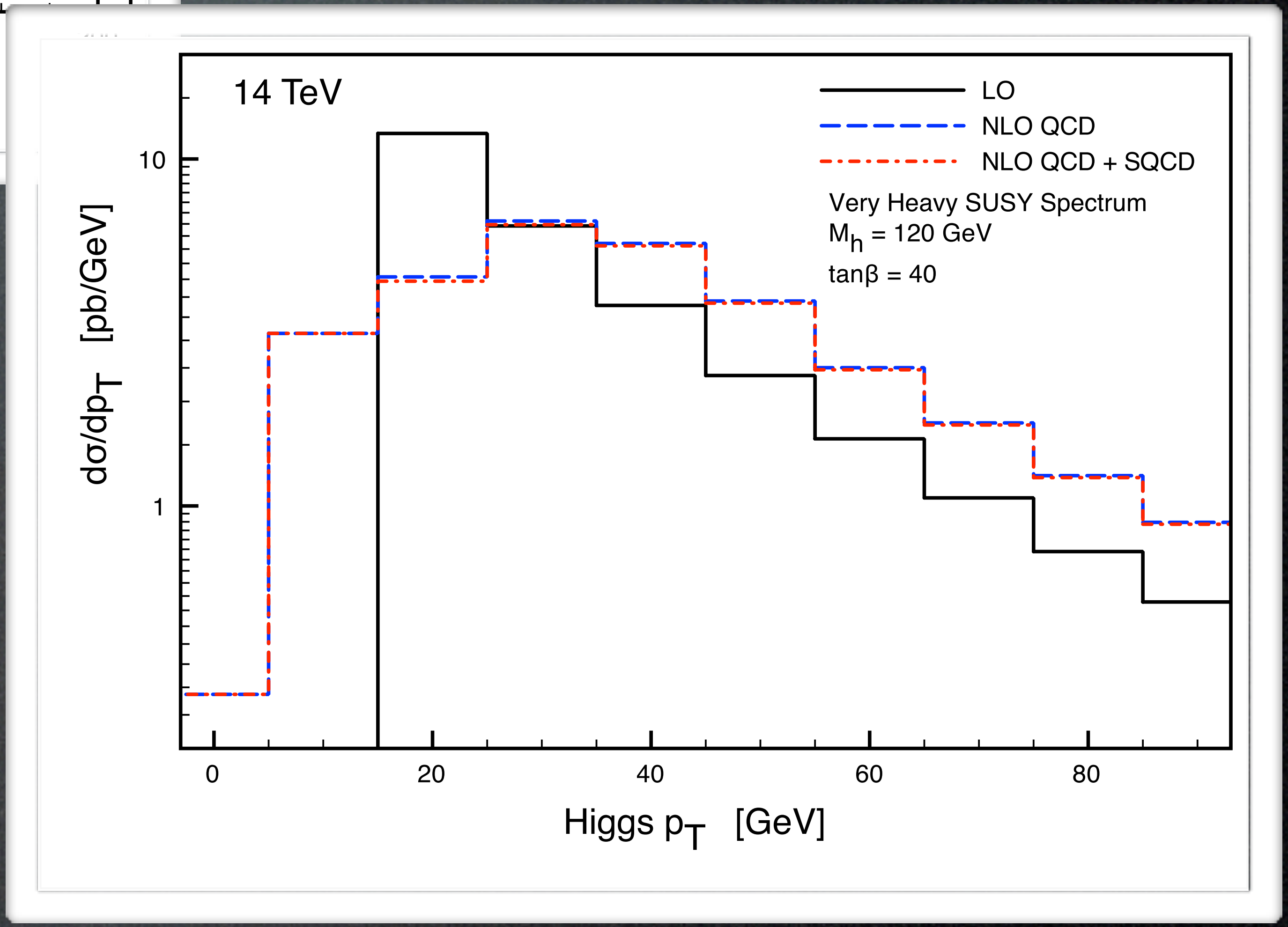
Thanks!

The truth is out there.

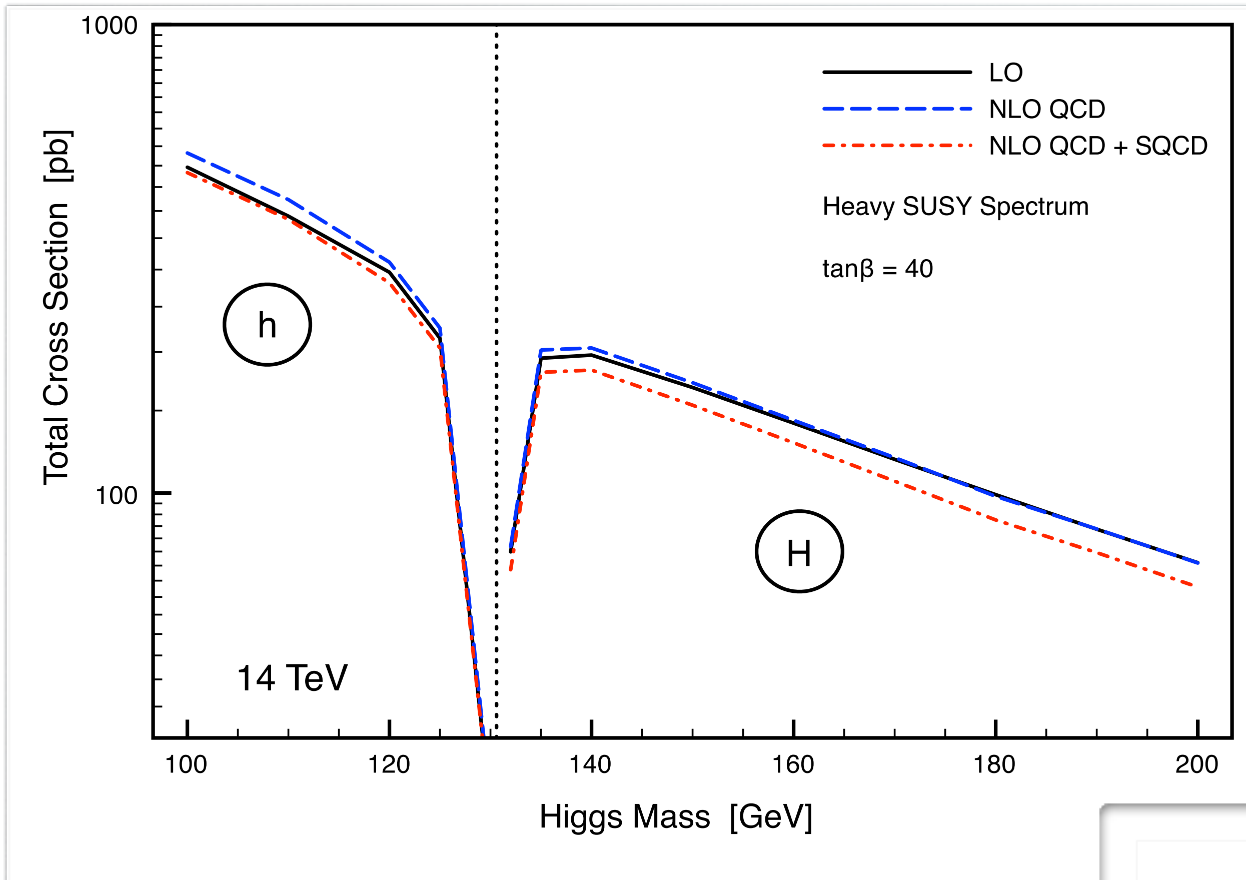
Back up slides

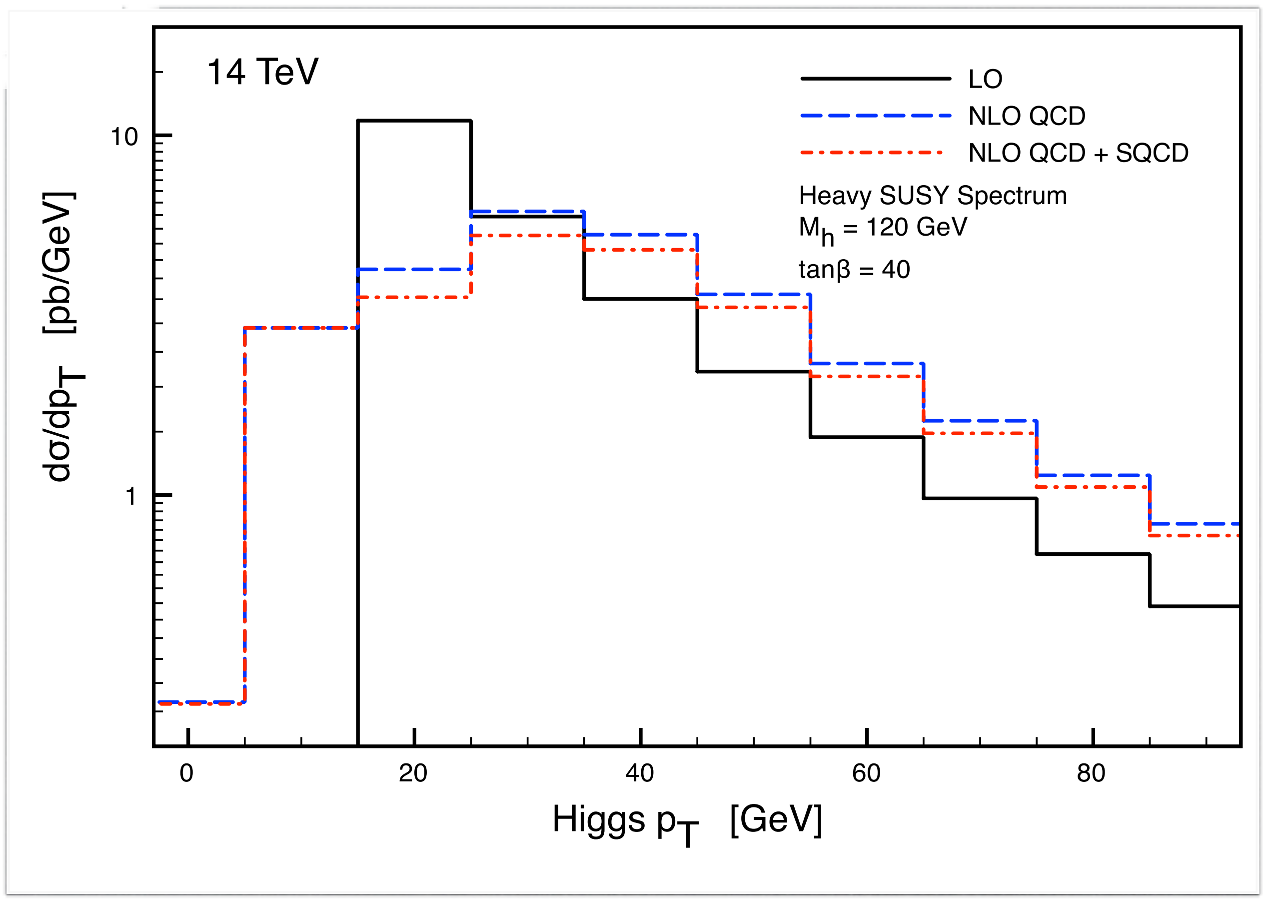
“Very Heavy” Scenario @ 14 TeV





“Heavy” Scenario @ 14 TeV





"Light" Scenario @ 14 TeV