MSSM Higgs Production @ Hadron Colliders

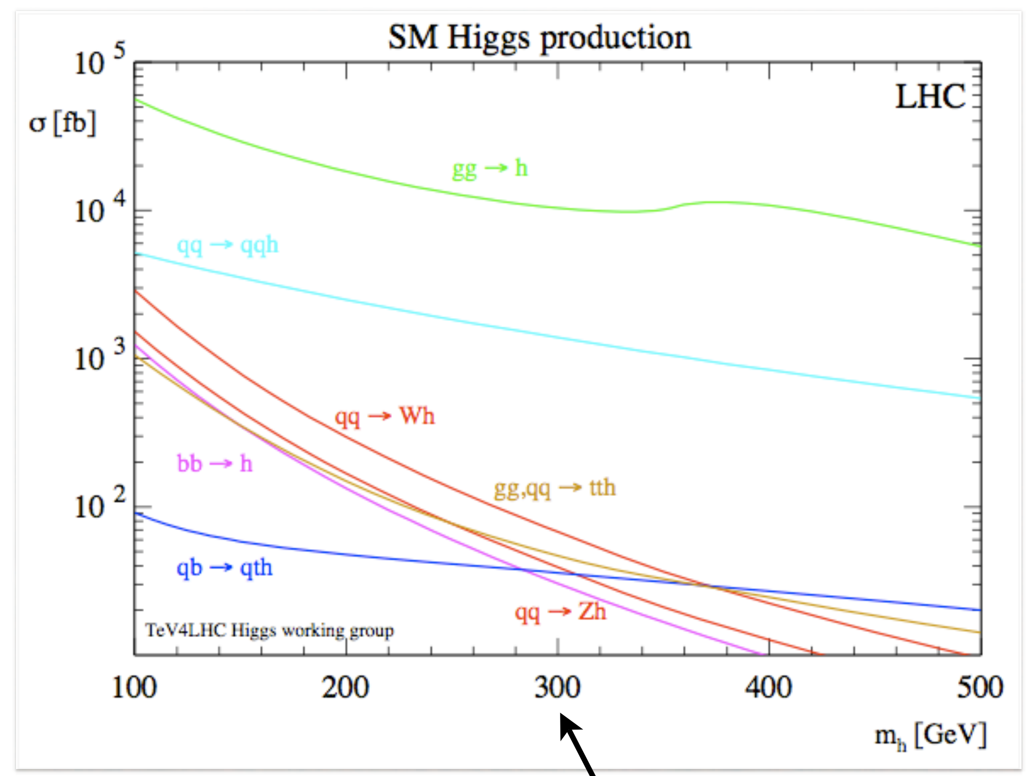
Chris Jackson
Argonne National Laboratory

Outline

- Motivation for SUSY
- Review of MSSM Higgs sector (masses, couplings to SM particles)
- Production of MSSM Higgs bosons at hadron colliders (for large $\tan\beta$)
    - Neutral Higgs bosons in association with bottom quarks
    - Indirect and Direct production of Charged Higgs bosons

SM Higgs Productions at Hadron Colliders

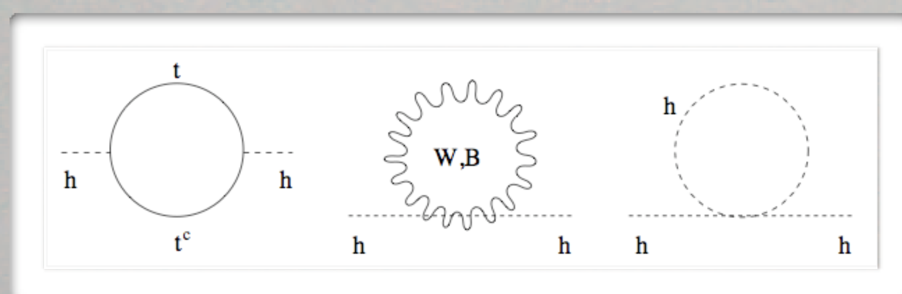
- SM works extremely well! (115 GeV ≤ M_H ≲ 200 GeV)
- "Couples to mass": Production dominated by radiation off HEAVY particles (W's, Z's, tops)
- Main production modes:
  - "gluon fusion" via top loops
  - Associated production w/ W's and Z's
  - Associated production w/ tops



(all known to at least NLO QCD)

Something Beyond the SM?

- General belief: SM is an effective theory valid up to some cutoff scale (Λ)
- Missing pieces:
  - neutrino masses? DM candidate?
  - incorporation of gravity? unification?
- Theorist's "hang up":



Quadratically-divergent! →

$$M_H^2 = M_H^2|_{bare} + \frac{\Lambda^2}{4\pi^2} f(m_t, M_W, M_Z)$$

"Large Hierarchy Problem"

MSSM in a Nutshell

- SUSY: symmetry which relates particles with integer spin (0 and 1) w/ particles of spin 1/2
- SUSY must be "broken" somehow:
  - Preserve gauge-invariance/renormalizability
  - Keep superpartners relatively light (large hierarchy, DM)
- Introduce SUSY-breaking parameters by hand
- Result is a low-energy effective SUSY theory... a.k.a. "Minimal Supersymmetric Standard Model (MSSM)"
- Resolution of large hierarchy problem... scalar top (stop) loops:

$$\Delta M_H^2 = \frac{\lambda_f^2 N_f}{4\pi^2}\left[(m_f^2 - m_S^2)\log\left(\frac{\Lambda}{m_S}\right) + 3m_f^2\log\left(\frac{m_S}{m_f}\right)\right] + \mathcal{O}\left(\frac{1}{\Lambda^2}\right)$$

MSSM Higgs Sector

- MSSM Higgs Sector = Type II Higgs Doublet Model

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \text{ with } Y_{H_1} = -1 \quad , \quad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \text{ with } Y_{H_2} = +1$$

  to cancel gauge anomalies and give masses to both up/down fermions

- The scalar potential:

$$\begin{aligned} V_H \;&=\; (|\mu|^2 + m_{H_1}^2)|H_1|^2 + (|\mu|^2 + m_{H_2}^2)|H_2|^2 - \mu B \epsilon_{ij}(H_1^i H_2^j + \text{h.c.}) \\ &\quad + \frac{g_2^2 + g_1^2}{8}(|H_1|^2 - |H_2|^2)^2 + \frac{1}{2} g_2^2 |H_1^\dagger H_2|^2 \end{aligned}$$

- Some notes:
  - To break EW symmetry, both $\langle H_1 \rangle$ and $\langle H_2 \rangle \neq 0$
  - Quartic couplings given in terms of $SU(2)_L$ and $U(1)_Y$ couplings
  - EWSB requires SUSY breaking

MSSM Higgs Masses

- The neutral components of both Higgs fields acquire vevs:

$$\langle H_1^0 \rangle = \frac{v_1}{\sqrt{2}} \quad , \quad \langle H_2^0 \rangle = \frac{v_2}{\sqrt{2}}$$

$$(v_1^2 + v_2)^2 = v^2 = \frac{4M_Z^2}{g_2^2 + g_1^2} = (246 \text{ GeV})^2$$

- Of the original 8 degrees of freedom, three are “eaten” by the $W^{\pm}$ and Z... leaving 5 physical Higgs bosons:

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

- At tree-level, the entire MSSM Higgs sector can be described by two parameters, e.g. M_A and $\tan\beta$:

$$\tan\beta = \frac{v_2}{v_1} = \frac{(v \sin\beta)}{(v \cos\beta)}$$

- Examples:

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

$$\cos 2\alpha = -\cos 2\beta \, \frac{M_A^2 - M_Z^2}{M_H^2 - M_h^2}$$

Lightest Higgs Mass and Radiative Corrections

- SUSY structure imposes very strong constraints on Higgs masses:

$$M_H > \max(M_A, M_Z)$$

$$M_{H\pm} > M_W$$

$$M_h \leq \min(M_A, M_Z) \cdot |\cos 2\beta| \leq M_Z$$

← Ruled out by LEP!

- Situation is saved by radiative corrections... the largest of which come from the top (stop) loops:

$$\Delta M_h^2 = \frac{3G_\mu}{\sqrt{2}\pi^2} m_t^4 \log \frac{M_S^2}{m_t^2}$$

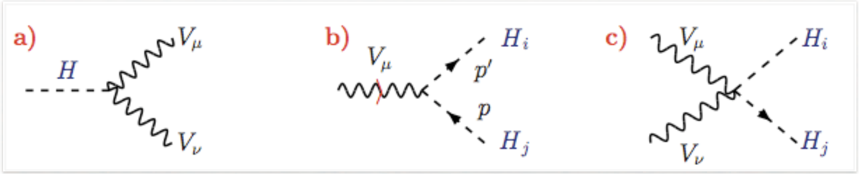
- Quartic (logarithmic) growth w/ top (stop) mass!
- Pushes upper bound on light Higgs mass to ~ 135-140 GeV range

Higgs Couplings to Gauge Bosons

- Couplings obtained from kinetic terms for H_1 and H_2:

$$\mathcal{L}_{\text{kin.}} = (D^\mu H_1)^\dagger (D_\mu H_1) + (D^\mu H_2)^\dagger (D_\mu H_2)$$

- Feynman rules:



$$\begin{array}{llll} Z_\mu Z_\nu h : & i g_Z M_Z \sin(\beta-\alpha) g_{\mu\nu} \quad , & Z_\mu Z_\nu H : & i g_Z M_Z \cos(\beta-\alpha) g_{\mu\nu} \\ W^+_\mu W^+_\nu h : & i g_W M_W \sin(\beta-\alpha) g_{\mu\nu} \quad , & W^+_\mu W^-_\nu H : & i g_W M_W \cos(\beta-\alpha) g_{\mu\nu} \end{array}$$

- Some notes:
  - hVV and HVV couplings are complimentary...

$$G^2_{hVV} + G^2_{HVV} = g^2_{H_{\rm SM}VV}$$

  - CP-invariance forbids AVV and $WZH^\pm$ couplings

Higgs Couplings to Fermions

- SUSY imposes that H_1 (H_2) couples exclusively to down- (up-) type fermions:

$$\mathcal{L}_{\text{Yuk}} = -\lambda_u[\bar{u}P_L u H_2^0 - \bar{u}P_L d H_2^+] - \lambda_d[\bar{d}P_L d H_1^0 - \bar{d}P_L u H_1^-] + \text{h.c.}$$

- Fermions acquire masses when Higgs doublets acquire vevs:

$$\lambda_u = \frac{\sqrt{2}m_u}{v_2} = \frac{\sqrt{2}m_u}{v\sin\beta} \quad , \quad \lambda_d = \frac{\sqrt{2}m_d}{v_1} = \frac{\sqrt{2}m_d}{v\cos\beta}$$

- In terms of physical Higgs bosons:

$$G_{huu} = i\frac{m_u}{v}\frac{\cos\alpha}{\sin\beta}\,, \quad G_{Huu} = i\frac{m_u}{v}\frac{\sin\alpha}{\sin\beta}\,, \quad G_{Auu} = \frac{m_u}{v}\cot\beta\,\gamma_5$$

$$G_{hdd} = -i\frac{m_d}{v}\frac{\sin\alpha}{\cos\beta}\,, \quad G_{Hdd} = i\frac{m_d}{v}\frac{\cos\alpha}{\cos\beta}\,, \quad G_{Add} = \frac{m_d}{v}\tan\beta\,\gamma_5$$

$$G_{H^+\bar{u}d} = -\frac{i}{\sqrt{2}v}V_{ud}^*[m_d\tan\beta(1+\gamma_5) + m_u\cot\beta(1-\gamma_5)]$$

$$G_{H^-u\bar{d}} = -\frac{i}{\sqrt{2}v}V_{ud}[m_d\tan\beta(1-\gamma_5) + m_u\cot\beta(1+\gamma_5)]$$

- Note: enhanced couplings to down-type fermions for large $\tan\beta$

MSSM Higgs Production @ Hadron Colliders

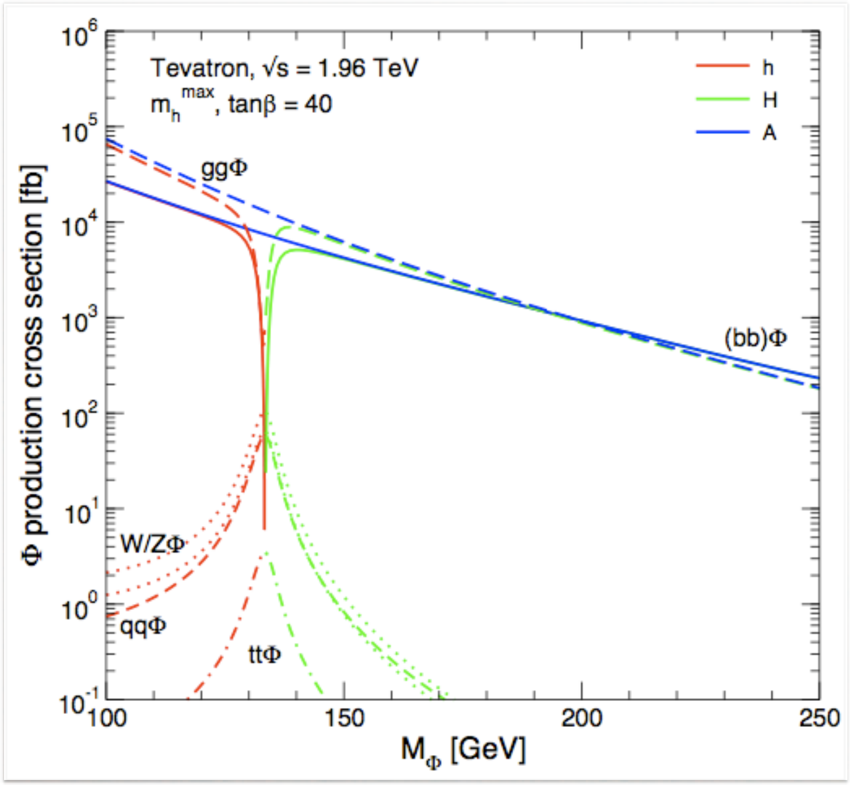
- Production of neutral Higgs bosons proceeds via same channels as in SM:

associated h and H production with W/Z :	$q\bar{q} \to V + h/H$
vector boson fusion for h and H production :	$qq \to V^*V^* \to qq + h/H$
gluon − gluon fusion :	$gg \to h/H/A$
associated production with heavy quarks :	$gg, q\bar{q} \to Q\bar{Q} + h/H/A$

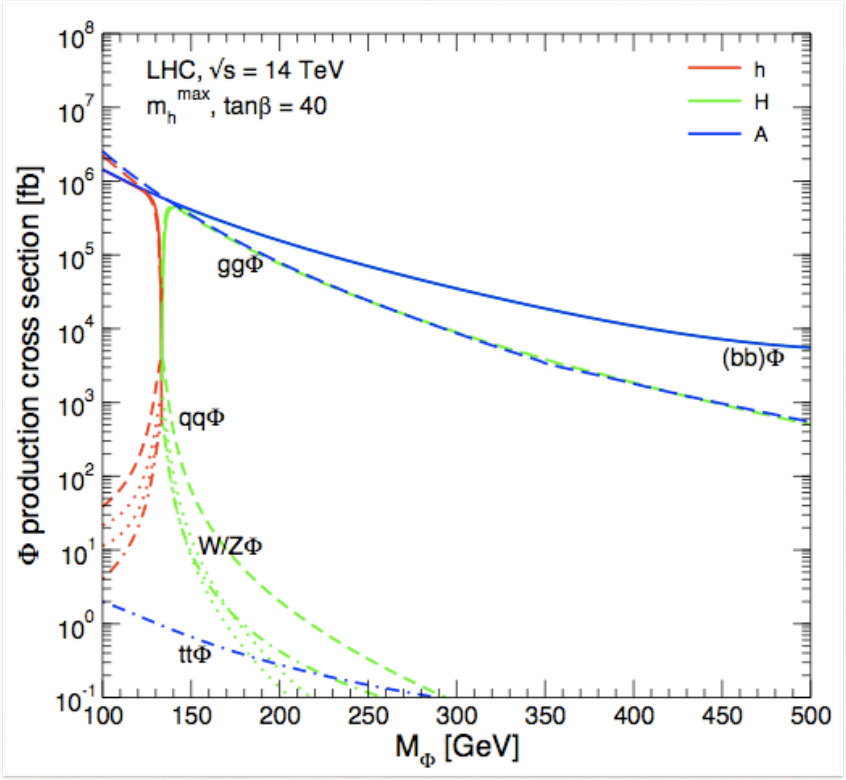
- Note that A cannot be produced in association with V's (CP invariance)
- In the "decoupling" regime ($M_A \gg M_W$), hierarchy of production modes (almost) identical to SM
- However, away from the "decoupling" regime and for large values of $\tan\beta$:
  - Enhanced couplings to bottom quarks implies production of Higgs bosons in association with bottom quarks is important!
  - Possibility of producing charged Higgs either through top quark decays or in association with top/bottom quarks

MSSM Higgs Production @ Hadron Colliders

Tevatron



LHC



(http://maltoni.home.cern.ch/maltoni/TeV4LHC/MSSM.html)

MSSM Higgs Production with Bottom Quarks

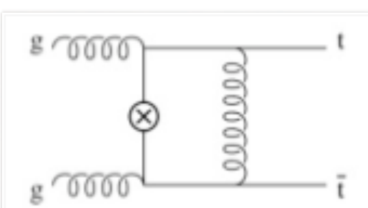
SM Higgs-bottom Production

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

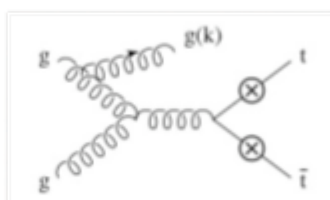
- Tree-level cross sections suffer from stong dependence on μ_R, μ_F

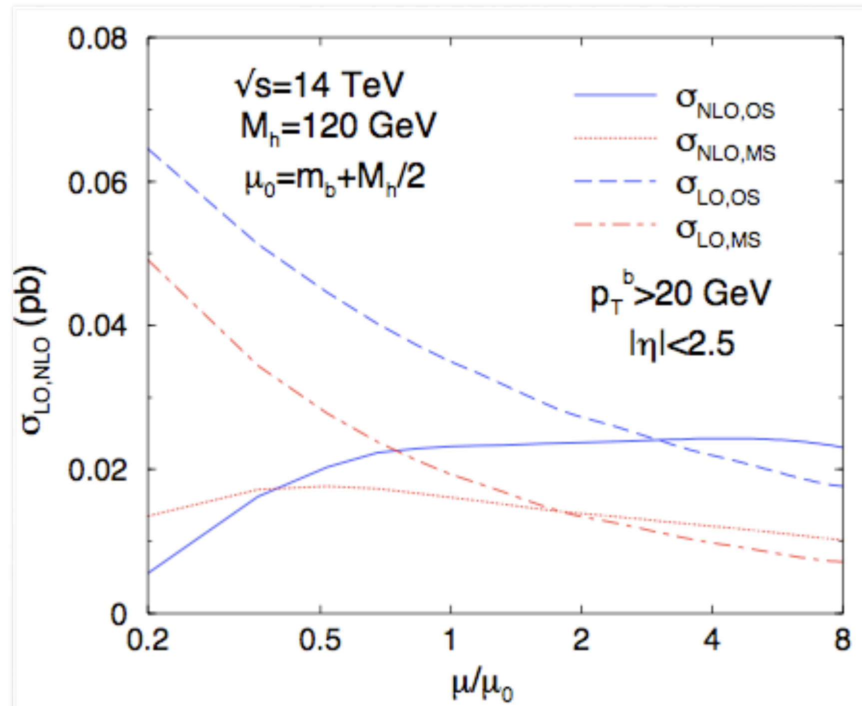
- NLO QCD corrections obtained from pp → tth with m_t → m_b (Dawson et al., Dittmaier et al.)

Virtual



Real



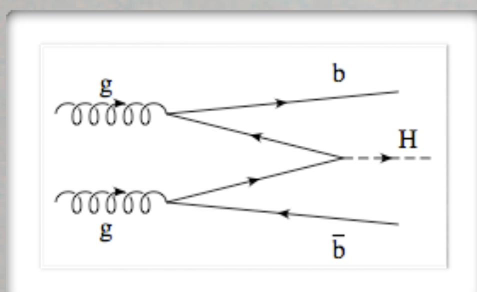


Issues in SM Higgs-bottom Production

Reduced ↓ Background

Larger ↑ Signal

- Ability to "tag" b jets at HC's leads to three distinct modes:
  - "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 PS 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?

Two Calculational Schemes

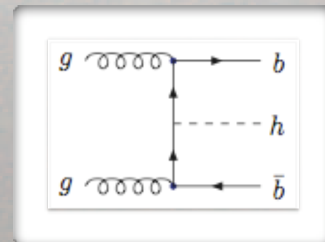
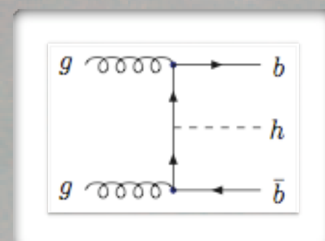
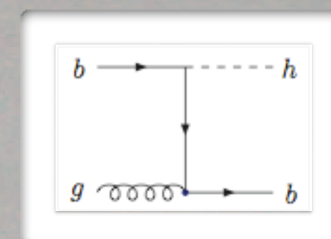
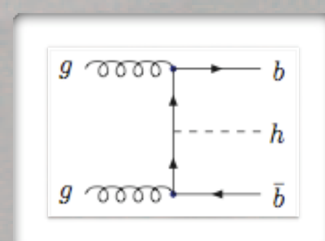
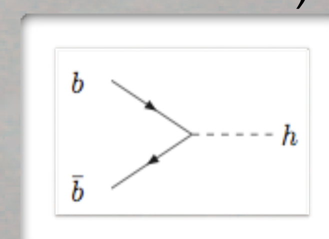
- Five Flavor Number Scheme (5FNS):
  - Assume Λ_b's are the dominant contribution to cross section
  - Introduce bottom quark parton distribution function (PDF):

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

    (effectively, replace g → bb splitting with initial-state b)

  - PT re-ordered to be expansion in α_s AND Λ_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 to b’s?”

Production Mode	4FNS	5FNS
“Exclusive”	 NLO in QCD (Dawson, CJ, Reina & Wackeroth, Dittmaier, Kramer & Spira)	N/A
“Semi-inclusive”	 NLO in QCD	 NLO in QCD (Campbell, Ellis, Maltoni & Willenbrock)
“Inclusive”	 NLO in QCD	 NLO in QCD (Harlander & Kilgore)

MSSM Higgs Production with b Quarks

- Corrections from SUSY can be important (Carena, Wagner et al.)
- Dominant radiative corrections from SUSY to Higgs-b production can be accounted for by including corrections bbh vertex only:

$$g^{MSSM}_{b\bar{b}h^0} = -g^{SM}_{b\bar{b}h}\frac{1}{1+\Delta_b}\left[\frac{\sin\alpha}{\cos\beta} - \Delta_b\frac{\cos\alpha}{\sin\beta}\right]$$

$$g^{MSSM}_{b\bar{b}H^0} = g^{SM}_{b\bar{b}h}\frac{1}{1+\Delta_b}\left[\frac{\cos\alpha}{\cos\beta} + \Delta_b\frac{\sin\alpha}{\sin\beta}\right]$$

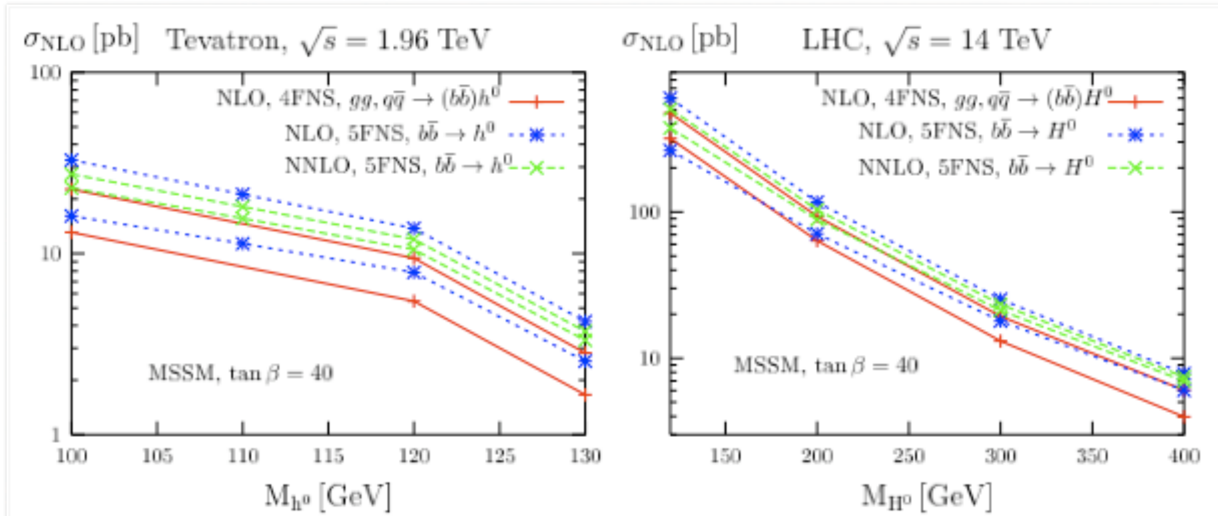
$$\Delta_b = \mu\tan\beta\left[\frac{2\alpha_s(m_t)}{3\pi}M_{\tilde{g}}I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) + \left(\frac{h_t}{4\pi}\right)^2 A_t I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu)\right]$$

- These corrections computed in an Effective Lagrangian approach which assumes bottom quarks are on shell...
  - Valid for Higgs decays or bb → h production
  - What about cases where one of the b's is off-shell (e.g., bg→bh)???

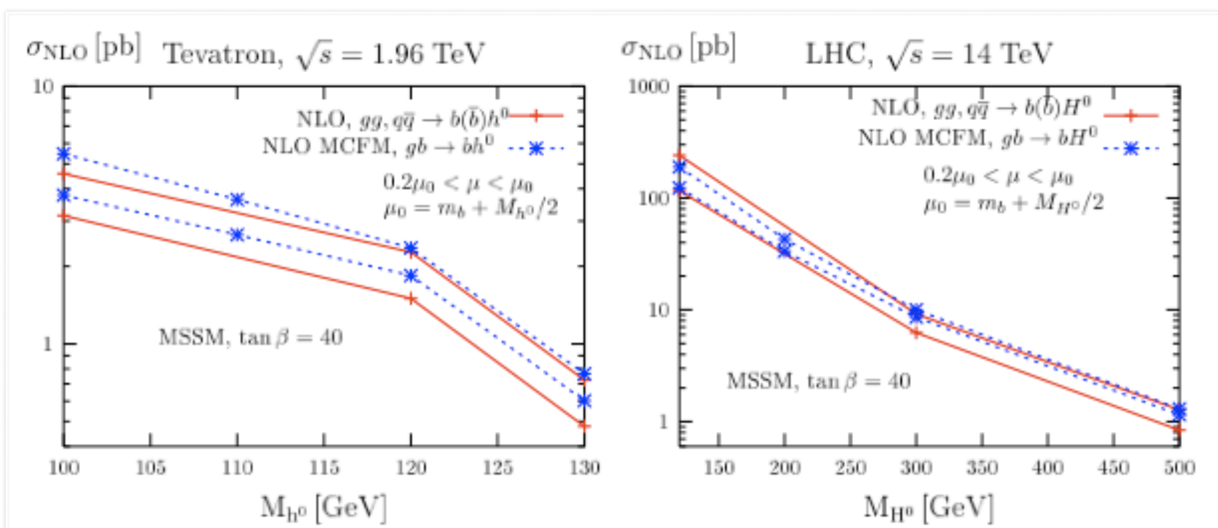
Total Cross Sections: 4FNS vs. 5FNS

(from Dawson, CJ, Reina & Wackeroth, Mod. Phys. Lett. A21, 89 (2006))

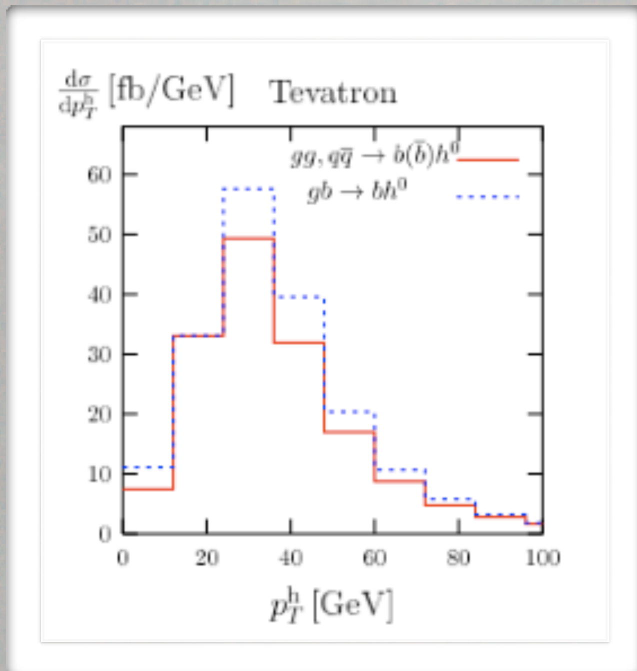
Inclusive



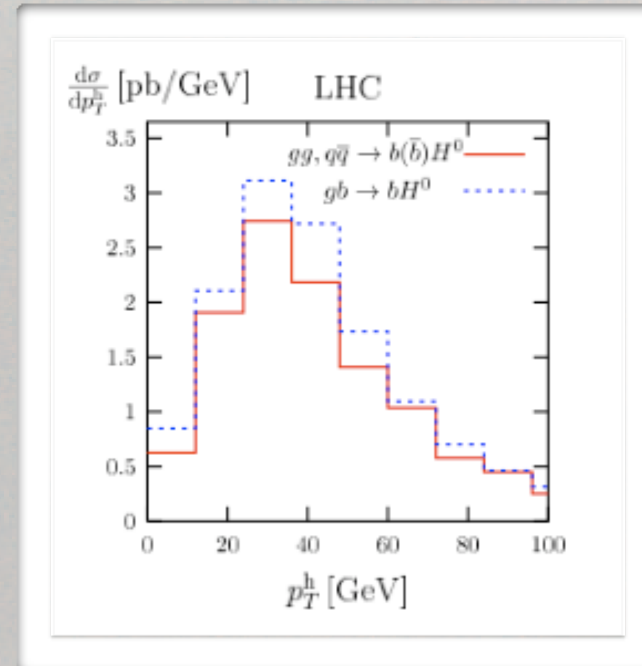
Semi-inclusive

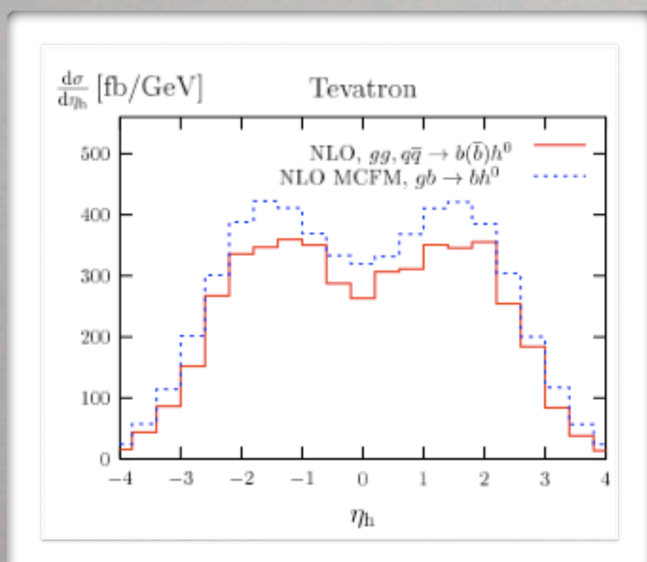


Distributions for "Semi-inclusive" Mode

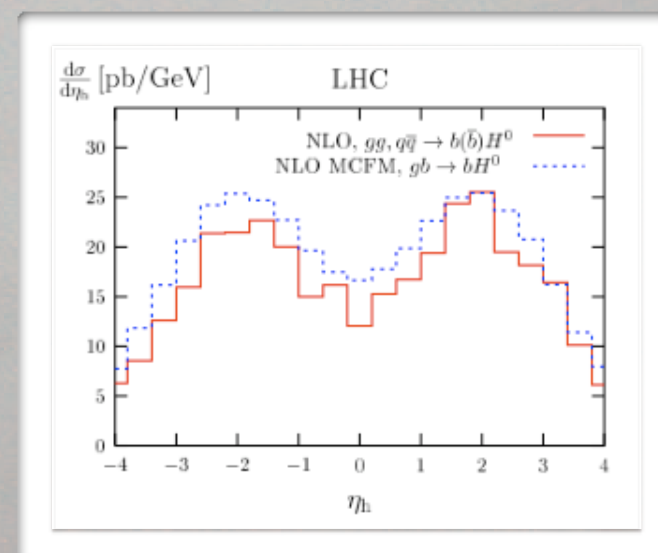


Higgs p_T





Higgs pseudorapidity



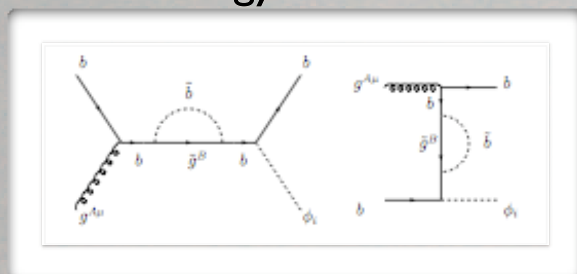
Complete SQCD Corrections to bh Production

Dawson and CJ, Phys. Rev. D77, 015019 (2008))

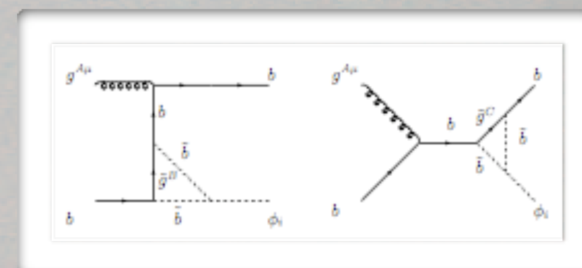
- Compute full SUSY QCD (SQCD) corrections and test “Effective Lagrangian Approach” for including dominant corrections

- Diagrams involving gluinos and sbottoms:

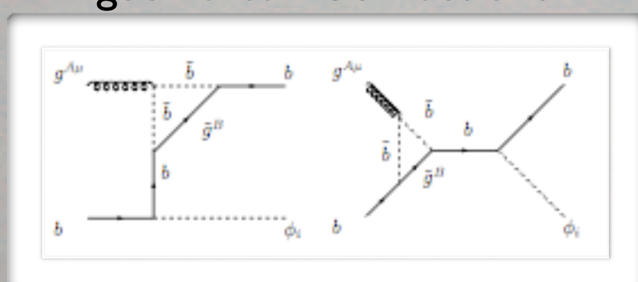
Self-energy Corrections



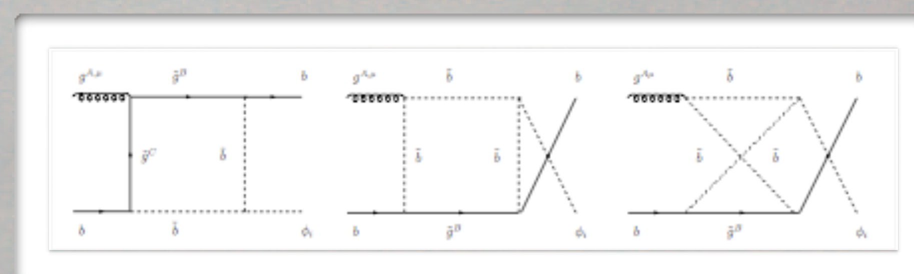
bbh Vertex Corrections

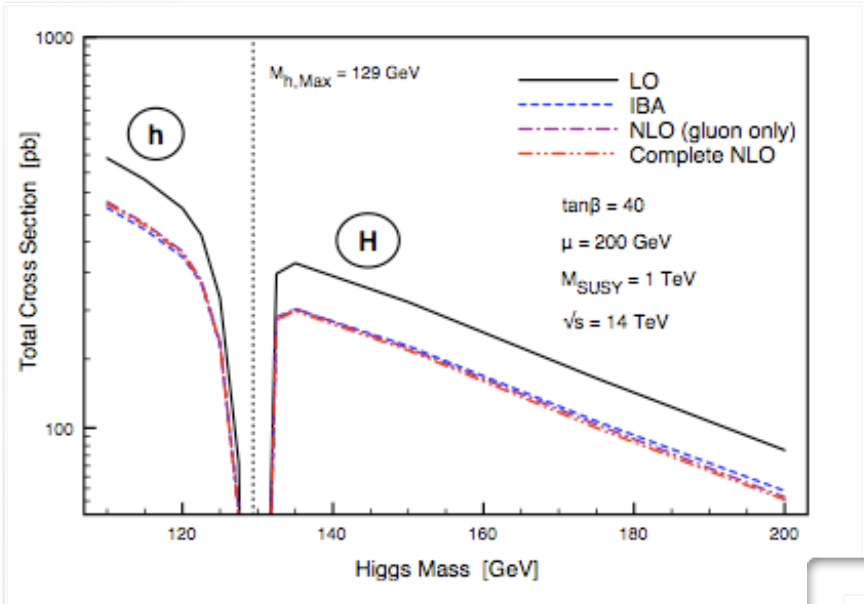


gbb Vertex Corrections



Box Corrections

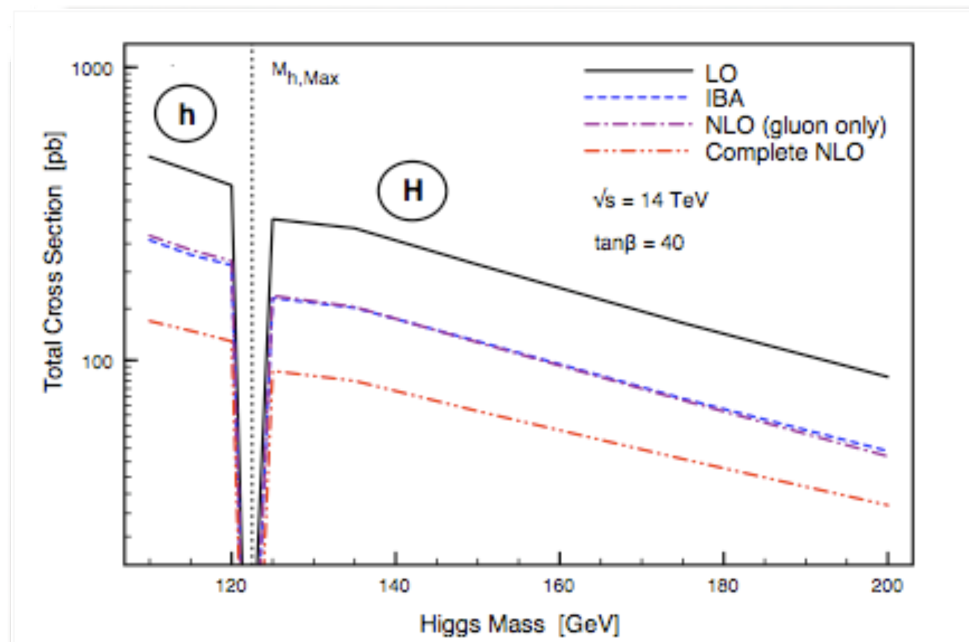




Heavy SUSY Spectrum:

$m_g = m_{b1} = m_{b2} = 1$ TeV

Good agreement between EFT ("IBA") approach and full SQCD



Light SUSY Spectrum:

$m_g = m_{b1} = 250$ GeV
$m_{b2} = 350$ GeV

Large difference between EFT and full SQCD!

MSSM Charged Higgs Production

The Production of Charged Higgs Bosons

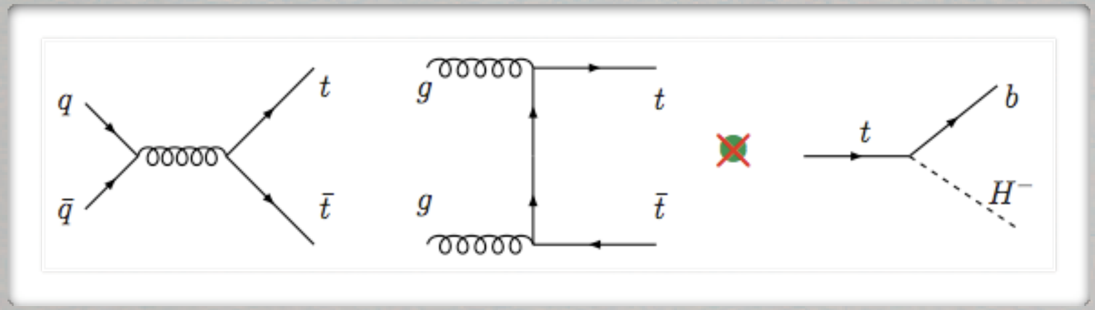
- Discovery of $H^{\pm}$ ... unambiguous evidence of extended Higgs sector
- Searches at LEP: $M_{H^{\pm}} > 79.3$ GeV
- Within MSSM, limit on $M_{H^{\pm}}$ can be obtained from limits on M_A

$$M_{H^{\pm}}^2 = M_A^2 + M_W^2 \longrightarrow M_{\mathrm{A}} > 93.4\ \mathrm{GeV} \longrightarrow M_{\mathrm{H}^{\pm}} \gtrsim 120\ \mathrm{GeV}$$

- Searches at Tevatron (to this point) haven't placed any further generic bound on charged Higgs mass
- LHC will extend searc up to ~ 600 GeV region
- Two scenarios:
  - Light $H^{\pm}$: charged Higgs produced from top quark decays
  - Heavy $H^{\pm}$: charged Higgs produced directly in association with top (and bottom) quarks

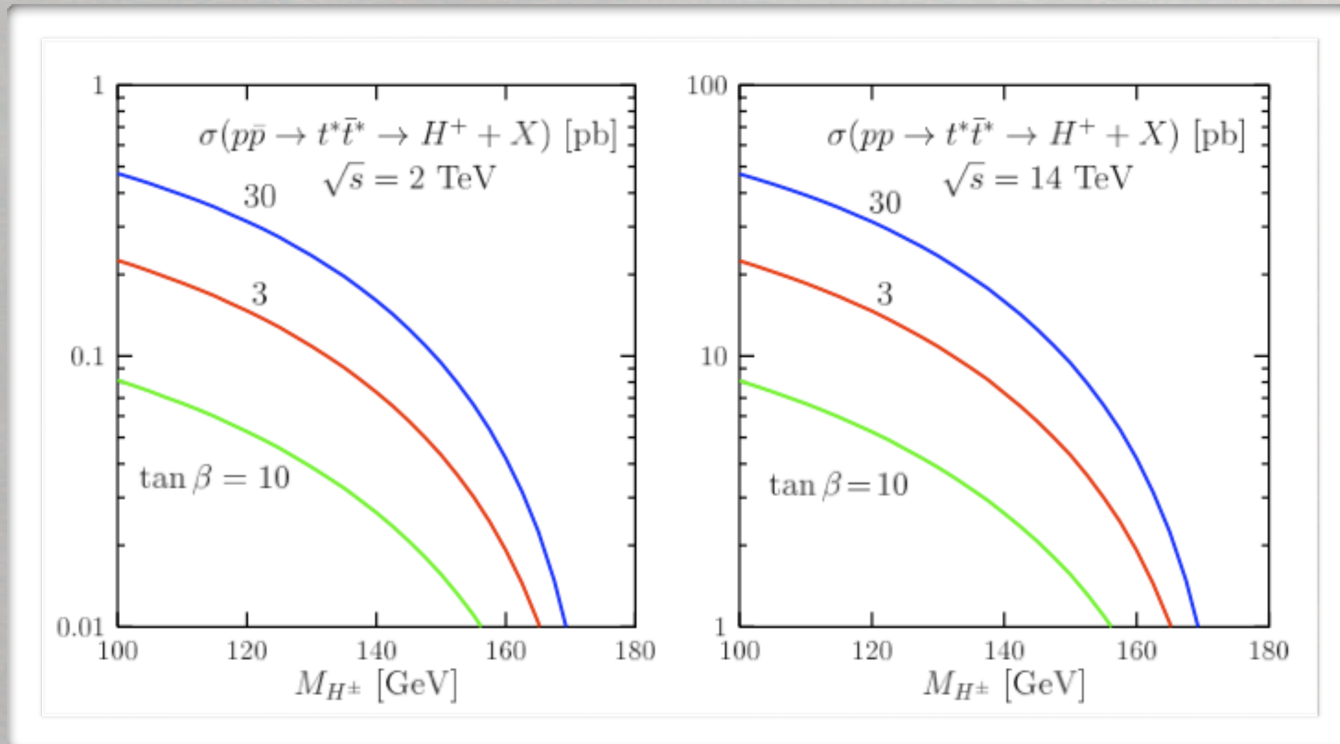
Charged Higgs Production from Top Decays

- If $M_{H^\pm} < m_t - m_b$, $H^\pm$ can be produced in the decay of the top quark ($t \rightarrow bH^+$):
    - For large $\tan\beta$, decays into bH^+ can be competitive with bW^+ decays
    - With SM and SUSY radiative corrections, Br ($t \rightarrow bH^+$) ~ 20%
- Main production mode would be through production of top pairs:



- Tevatron: top pair cross section ~ 5 pb $\rightarrow$ 10^4 top pairs (w/ 2 fb^{-1})
- LHC: top pair cross section ~ 1 nb $\rightarrow$ 10^8 top pairs (w/ 100 fb^{-1})
- For Br ($t \rightarrow bH^+$) $\gtrsim$ 1%, this means more than 10^2 $H^\pm$ at the Tevatron... and 10^6 $H^\pm$ at the LHC!

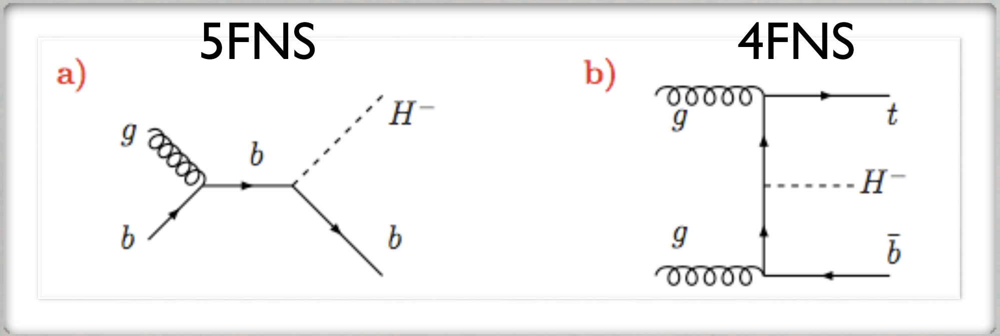
Charged Higgs Production from Top Decays



- For small ($\lesssim$ 3) and large ($\gtrsim$ 30) values of tanβ, production rates are huge!
- For intermediate tanβ (~10), H+tb coupling is not enhanced enough... and rates are rather small
- Note strong suppression at $M_{H^\pm} \sim m_t$ kinematic threshold

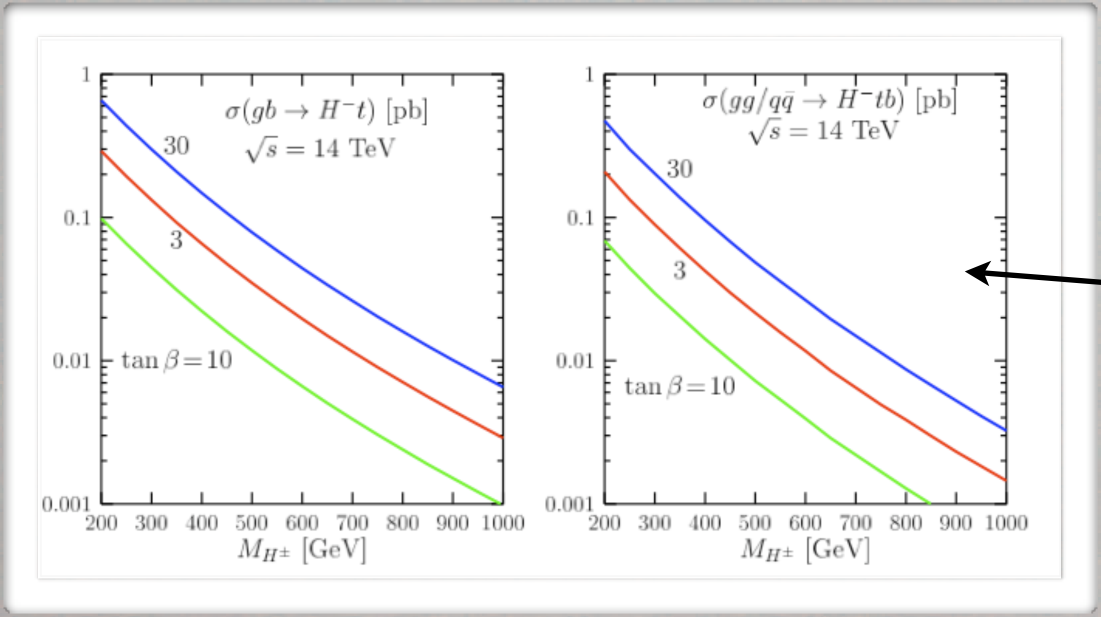
Direct Production of $H^{\pm}$ at the LHC

- For $M_{H^{\pm}} > m_t$, charged Higgs bosons can be produced directly via:



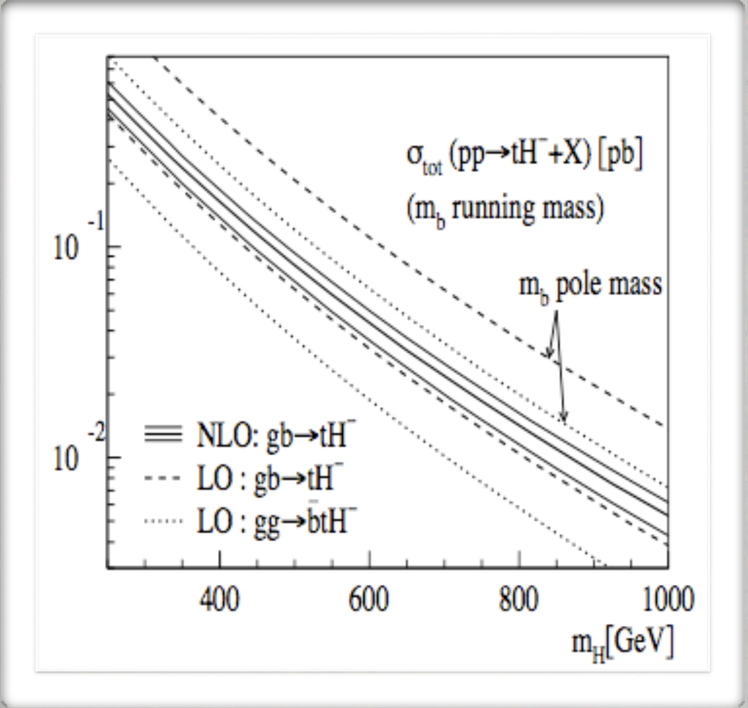
- Only important at LHC... PS-suppressed at Tevatron

- At tree-level:



5FNS c.s. larger than 4FNS c.s. by a factor of ~ 2-3

NLO QCD Corrections to $H^{\pm}$ Production



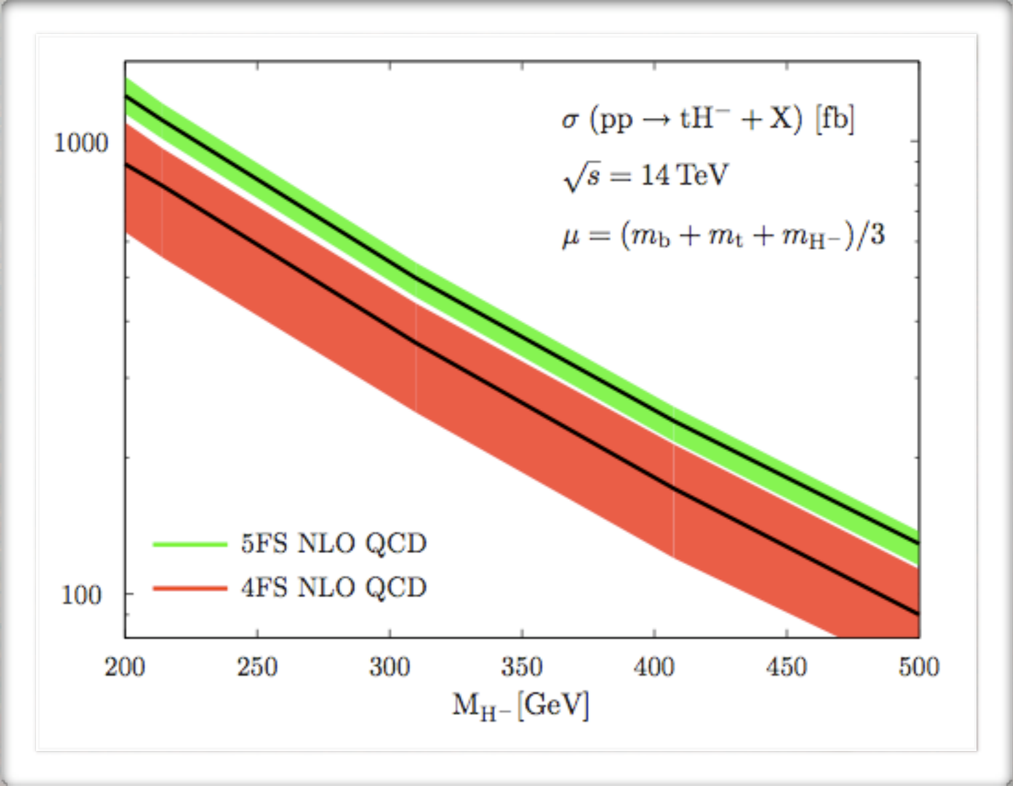
5FNS NLO QCD Corrections:
Plehn, PRD67, 014018 (2003)
Zhou, PRD67, 075006 (2003)
Berger et al., PRD71, 115012 (2005)

4FNS NLO QCD+SQCD Corrections:
Dittmaier et al., arXiv:0906.2648

Multi-scale calculation!

5FNS > 4FNS by 40%

Consistent within uncertainties(?)



Conclusions

- The MSSM Higgs sector is within our grasp!
- On-going searches @ Tevatron
- "LHC Alive!" (almost)
- Striking signatures:
  - Neutral Higgs production in association w/ b quarks
  - Charged Higgs production
- Go out there and find 'em!!!