SUSY-QCD Corrections to Higgs Processes

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Overview

- Survey of the MSSM Higgs Sector
- Status of SM QCD Corrections to Higgs Production
- SUSY QCD Corrections:
  - Gluon fusion
  - Production of a Higgs with one b jet
  - Pair Production in Bottom quark fusion
- Summarize and Conclude

Brief Review of MSSM Higgs Sector

- MSSM Higgs Sector = Type II Higgs Doublet Model (2HDM)

$$H_d = \begin{pmatrix} h_d^+ \\ \frac{1}{\sqrt{2}}(v_1 + h_d^0 + i\chi_d^0) \end{pmatrix}, \quad H_u = \begin{pmatrix} \frac{1}{\sqrt{2}}(v_2 + h_u^0 - i\chi_u^0) \\ -h_u^- \end{pmatrix}$$

- After EWSB, W and Z acquire masses and set

$$(v_{SM})^2 = (v_1)^2 + (v_2)^2 = (246\text{ GeV})^2 \rightarrow \boxed{\tan\beta = v_2 / v_1}$$

- Five physical degrees of freedom remain:

$$\boxed{h^0, H^0, A^0, H^\pm}$$

- At tree-level, MSSM Higgs sector described by two parameters $\tan\beta$ and M_A:

$$M_{H^\pm}^2 = M_A^2 + M_W^2$$

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

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

MSSM Higgs Sector (cont.)

- Tree-level relations receive large radiative corrections of order $(m_t)^4$!
  (e.g., $m_h(max) \simeq 130$ GeV)

- These corrections can be accounted for by using effective α and radiatively-corrected Higgs masses (e.g., "FeynHiggs").

- MSSM Higgs interactions with SM matter:

ϕ		g_u^ϕ	g_d^ϕ	g_V^ϕ
SM	H	1	1	1
MSSM	h	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$
	H	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$
	A	$1/\mathrm{tg}\beta$	$\mathrm{tg}\beta$	0

(from Muhlleitner and Spira, hep-ph/0612254)

SUSY QCD Sector

- Concerned with superpartners of gluons ("gluinos") and quarks ("squarks")
- Gluinos receive their mass via "Soft SUSY" breaking parameters... i.e., no direct interactions with Higgs bosons ($m_{\tilde{g}} = M_3$).
- Scalar superpartners of LH and RH fermions mix. Mass eigenstates are related to current eigenstates by mixing angles θ_f :

$$\begin{aligned} \tilde{f}_1 &= \tilde{f}_L \cos\theta_f + \tilde{f}_R \sin\theta_f \\ \tilde{f}_2 &= -\tilde{f}_L \sin\theta_f + \tilde{f}_R \cos\theta_f \, . \end{aligned}$$

$$\sin 2\theta_f = \frac{2m_f(A_f - \mu r_f)}{M^2_{\tilde{f}_1} - M^2_{\tilde{f}_2}}$$

- Note: mixing effects only important for 3rd generation sfermions
- Couplings to MSSM Higgs bosons:

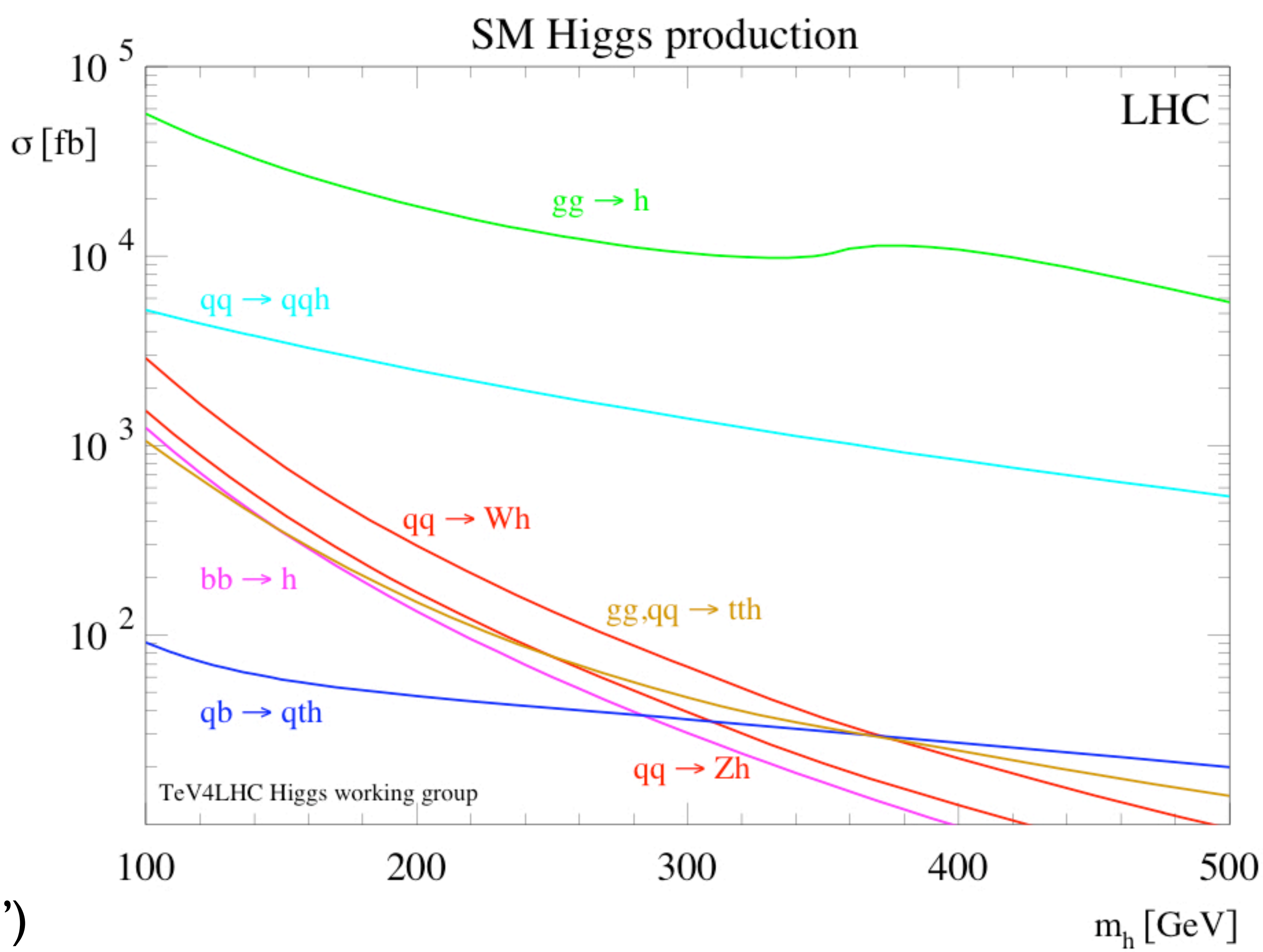
$$\begin{aligned} g^{\phi}_{\tilde{f}_L\tilde{f}_L} &= m_f^2 g_1^{\phi} + M_Z^2 (I_{3f} - e_f \sin^2\theta_W) g_2^{\phi} \\ g^{\phi}_{\tilde{f}_R\tilde{f}_R} &= m_f^2 g_1^{\phi} + M_Z^2 e_f \sin^2\theta_W g_2^{\phi} \\ g^{\phi}_{\tilde{f}_L\tilde{f}_R} &= -\frac{m_f}{2}(\mu g_3^{\phi} - A_f g_4^{\phi}) \, , \end{aligned}$$

$\tilde{f}$	ϕ	g_1^{ϕ}	g_2^{ϕ}	g_3^{ϕ}	g_4^{ϕ}
	h	$\cos\alpha/\sin\beta$	$-\sin(\alpha+\beta)$	$-\sin\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
$\tilde{u}$	H	$\sin\alpha/\sin\beta$	$\cos(\alpha+\beta)$	$\cos\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
	A	0	0	-1	$1/\mathrm{tg}\beta$
	h	$-\sin\alpha/\cos\beta$	$-\sin(\alpha+\beta)$	$\cos\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
$\tilde{d}$	H	$\cos\alpha/\cos\beta$	$\cos(\alpha+\beta)$	$\sin\alpha/\cos\beta$	$\cos\alpha/\cos\beta$
	A	0	0	-1	$\mathrm{tg}\beta$

SM Higgs Production: Status of N^{n}LO Corrections

- Gluon fusion:
  - @ NNLO QCD (large m_t)
  - @ NLO QCD (arbitrary m_t)
  - NNLL soft-gluon resummation
- Weak VBF:
  - @ NLO QCD
- "Higgs-strahlung" (*Wh* or *Zh*):
  - @ NNLO QCD
  - @ NLO EW
- Production with pairs of tops:
  - @ NLO QCD
- Production with bottom quarks:
  - $bb \to h$ @ NNLO QCD ("5FNS")
  - $gg \to bbh$ @ NLO QCD ("4FNS")
  - Excellent agreement between 5FNS and 4FNS

(from T. Hahn et al., hep-ph/0607308)



MSSM Higgs Production

- Gluon fusion:

$$\frac{\Gamma(\phi \to gg)_{\rm MSSM}}{\Gamma(\phi \to gg)_{\rm SM}}$$

ONLY ONE-LOOP SUSY DIAGRAMS!

- "Higgs-strahlung" and Weak VBF:

$$\frac{|g_{\phi VV,\rm MSSM}|^2}{|g_{\phi VV,\rm SM}|^2}, \quad V = W, Z$$

HIGGS PROPAGATOR CORRECTIONS ONLY!

- Production with Bottom Quarks:

bb → h:

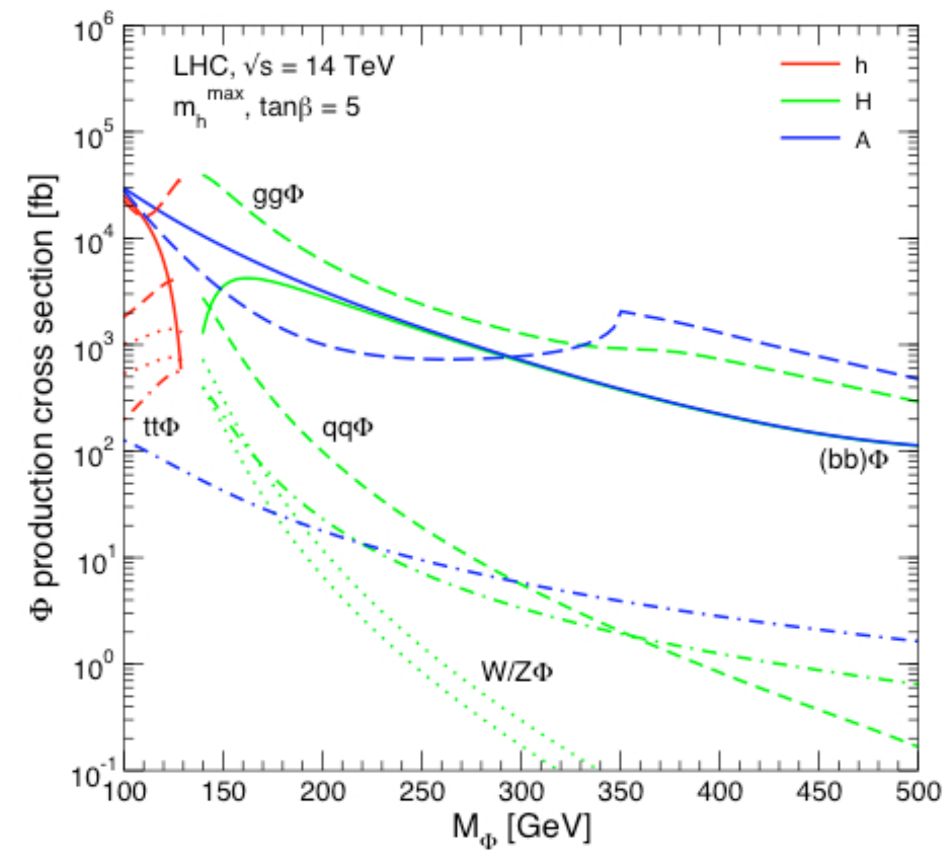
$$\frac{\Gamma(\phi \to b\bar{b})_{\rm MSSM}}{\Gamma(\phi \to b\bar{b})_{\rm SM}}$$

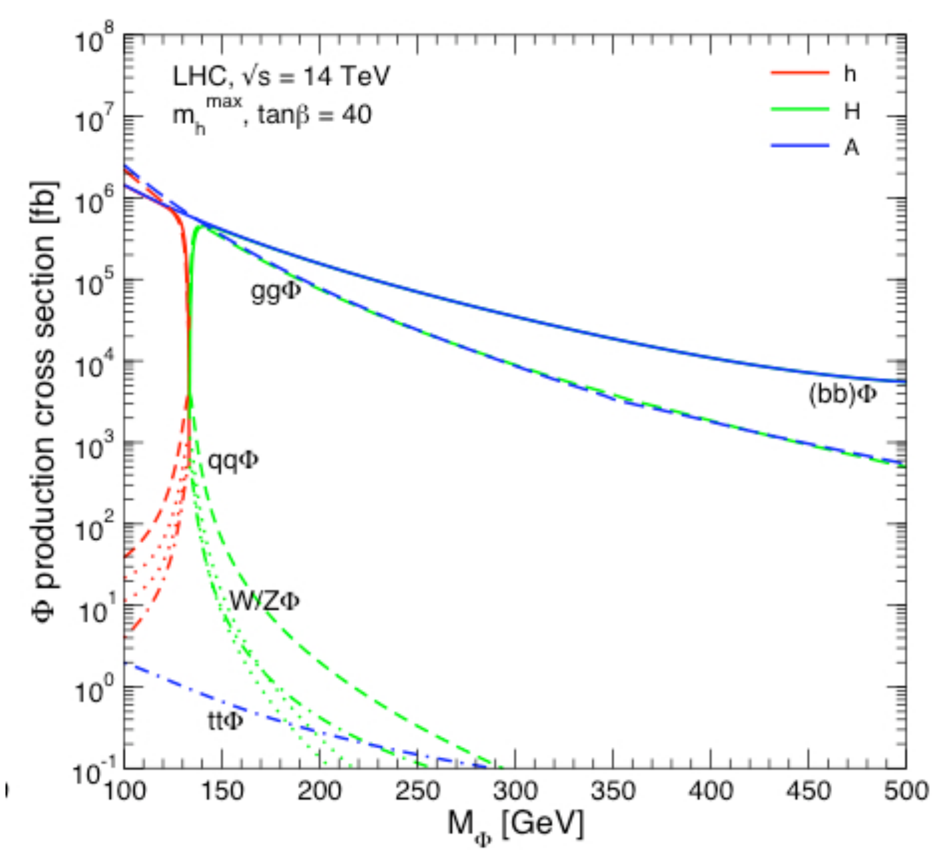
INCLUDES FULL QCD + SQCD CORRECTIONS

gg → bbh:

$$\left(\frac{g^{MSSM}_{b\bar{b}h}}{g^{SM}_{b\bar{b}h}}\right)^2$$

INCLUDES SQCD CORRECTIONS TO bbh VERTEX... BUT, FOR ON-SHELL QUARKS!

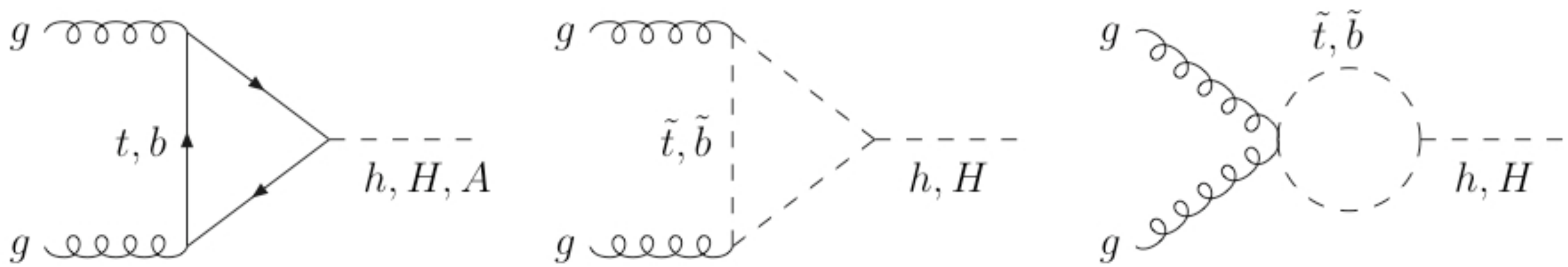




SQCD Corrections to Gluon Fusion

Gluon Fusion in SQCD

- In the MSSM, gluon fusion @ LO proceeds via heavy quark and squark loops:



- Pure SM QCD corrections to the quark loop amplitudes:

  - $O(\alpha_s^2)$ → S. Dawson; Djouadi, Spira and Zerwas
  - $O(\alpha_s^3)$ → Chetyrkin, Kniehl and Steinhauser; Kramer, Laenen and Spira
  - $O(\alpha_s^4)$ → Chetyrkin, Kniehl and Steinhauser

- Full SQCD corrections with arbitrary (s)quark and Higgs masses = "Hard Work" (G.W. Bush)

  - Two-loop integrals with up to 3 different mass scales!!

  - Progress is being made!
    (see Anastasiou, Beerli and Daleo, arXiv:0803.3065)

Gluon Fusion @ NLO in SQCD: EFT Approach

- Effective Field Theory Approach (Harlander & Steinhausser, hep-ph/0409010)

  - Good for "most" of MSSM parameter space:

    1) neglect effects from bottom loops (work in "Decoupling limit")

    2) neglect sbottom loops (minimal mixing and degenerate masses)

    3) Appropriate for light higgs only ($m_h^2 \ll (2\, m_{loop})^2$)

- Effective Lagrangian constructed from full theory by integrating out the top quark and all SUSY partners (stops and gluino):

$$\mathcal{L}_{\rm eff} = -\frac{h}{v}\, C_1^{\rm B}\, \mathcal{O}_1^{\rm B}\,, \qquad \mathcal{O}_1^{\rm B} = \frac{1}{4} G_{a,\mu\nu}^{\rm B} G_a^{{\rm B},\mu\nu}$$

  where:

$$C_1 = -\frac{\alpha_s}{3\pi}\left[c_1^{(0)} + \frac{\alpha_s}{\pi} c_1^{(1)} + \mathcal{O}(\alpha_s^2)\right]$$

- C_1 coefficient extracted by matching to ggh vertex calculated in the full MSSM

Gluon Fusion in the EFT Approach (cont.)

- The LO coefficient:

$$c_1^{(0)} = c_{1,t}^{(0)} + c_{1,\tilde{t}}^{(0)}\,, \qquad c_{1,t}^{(0)} = \frac{\cos\alpha}{\sin\beta}\,,$$

$$c_{1,\tilde{t}}^{(0)} = \frac{\cos\alpha}{\sin\beta}\left[\frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2}\right) + \frac{\sin^2 2\theta_t}{8}\left(1 - \frac{m_{\tilde{t}_1}^2}{2m_{\tilde{t}_2}^2} - \frac{m_{\tilde{t}_2}^2}{2m_{\tilde{t}_1}^2}\right)\right]$$
$$+ \frac{1}{8}\mu_{\rm SUSY}\, m_t \frac{\cos(\alpha-\beta)}{\sin^2\beta}\, \sin 2\theta_t \left[\frac{1}{m_{\tilde{t}_1}^2} - \frac{1}{m_{\tilde{t}_2}^2}\right]$$
$$+ \frac{c_1^{\rm EW} + c_2^{\rm EW}}{16}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2}\right) + \frac{c_1^{\rm EW} - c_2^{\rm EW}}{16}\cos 2\theta_t\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} - \frac{m_t^2}{m_{\tilde{t}_2}^2}\right)$$

- $\sin^2(2\theta_t)$ term < 0 : top and stop contributions can cancel each other!

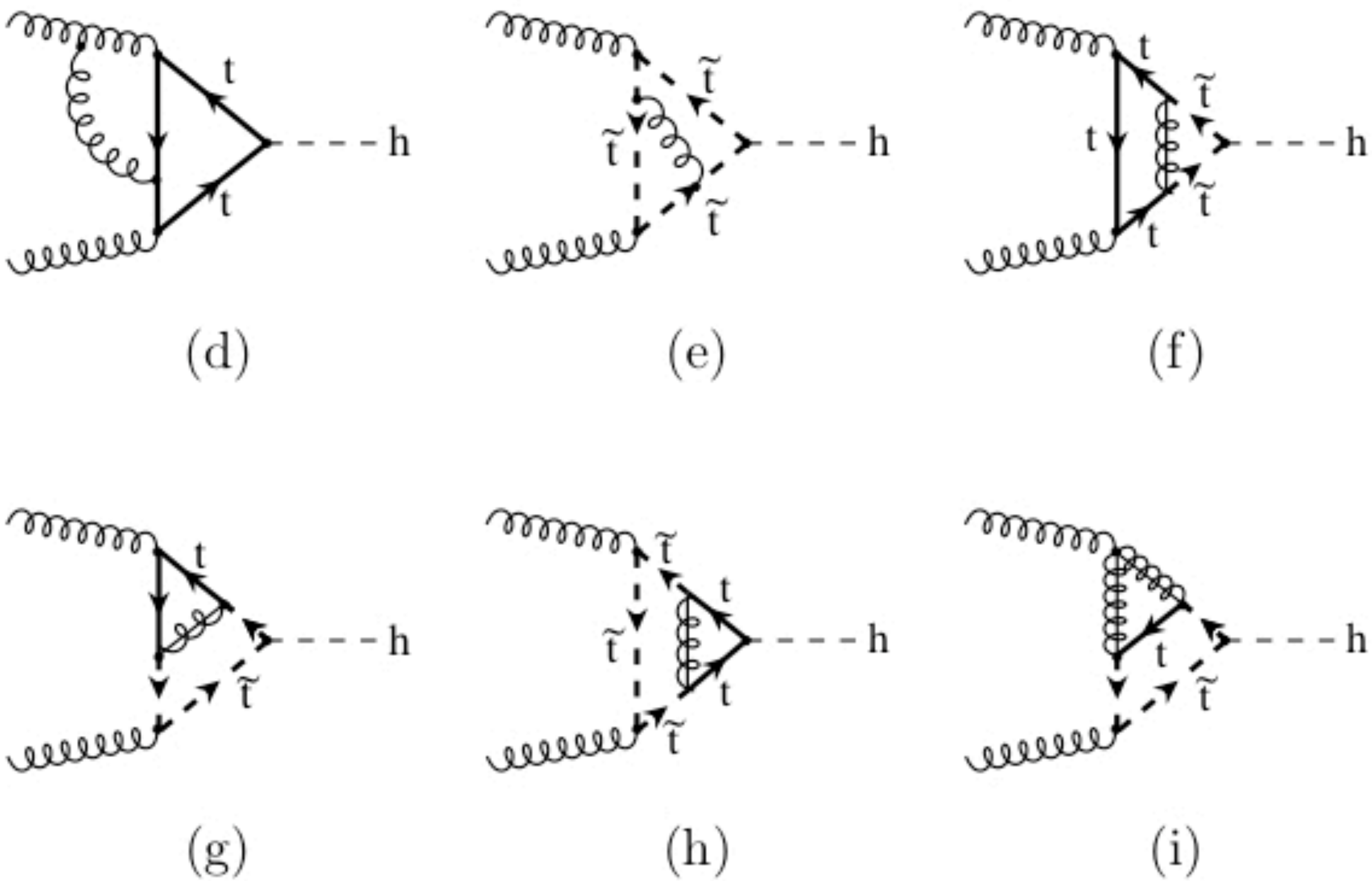
- $c_1^{(1)}$ provided in the form of a FORTRAN code ("evalcsusy.f")

- Two scenarios:

  - "Snowmass Point and Slope 1a" ($\tan\beta = 10$, etc.)

  - "Gluophobic" scenario: parameters chosen s.t. LO cancellation is large

Corrections to ggh Vertex



Three types of contributions:

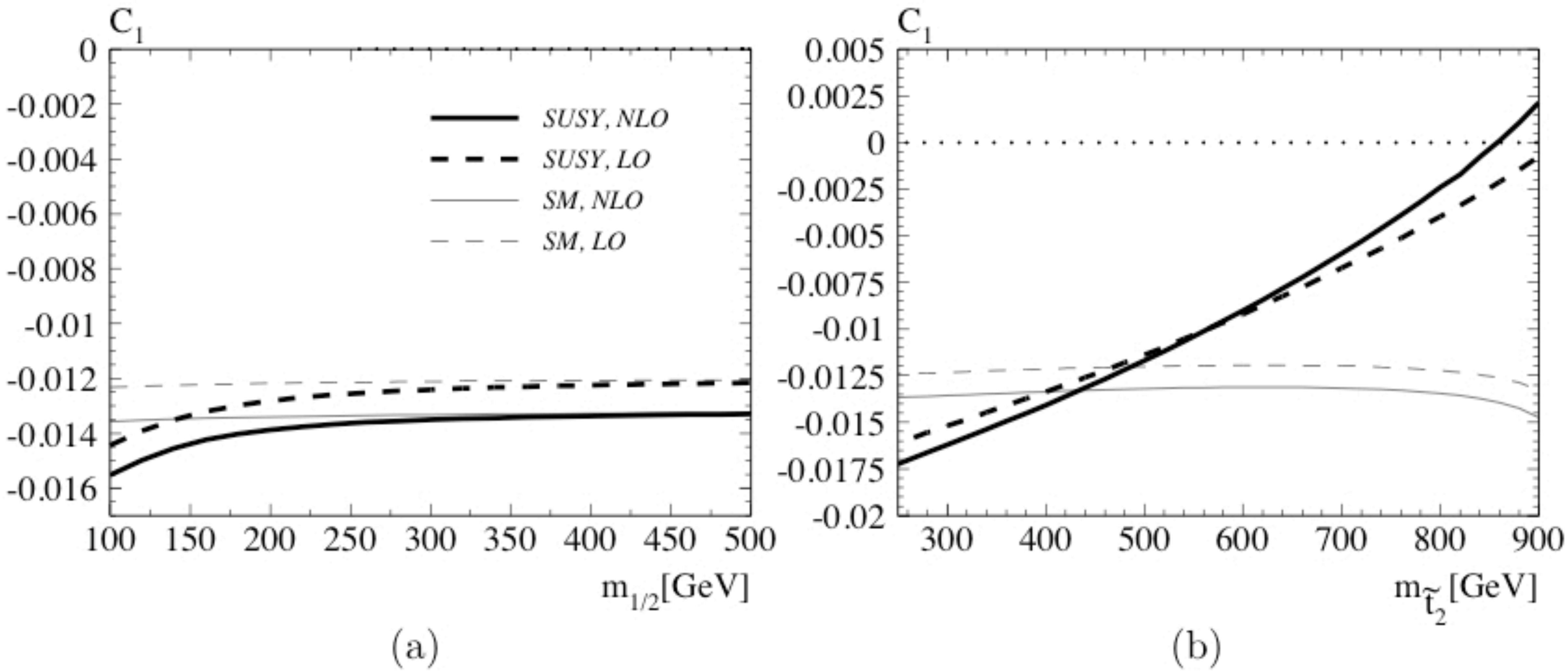
- Pure top contributions (separately finite)

- Pure stop contributions

- Mixed top/stop/gluino contributions

Sum is UV finite

C_1 @ NLO in SQCD



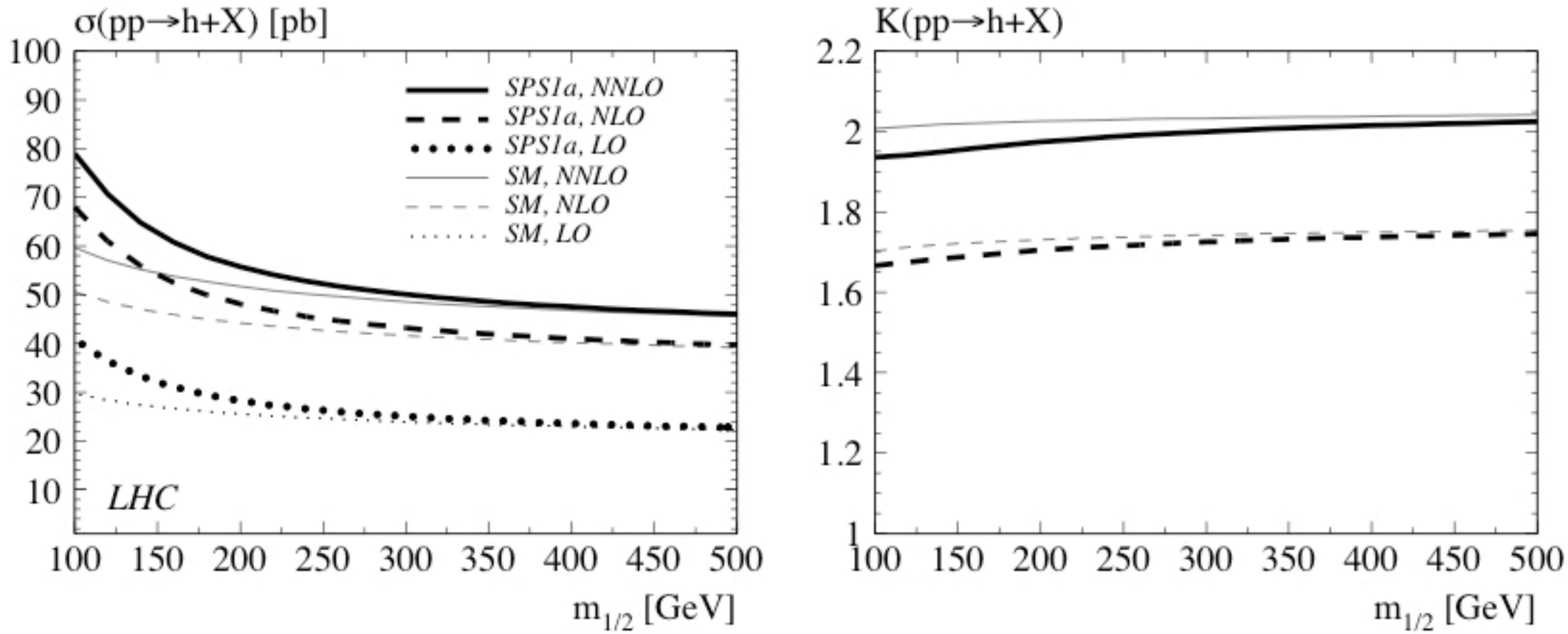
SPS1a Scenario:

- NLO/LO ≃ 8 %
- SQCD corrections negligible over most of $m_{1/2}$ range
- SUSY/SM ≃ 15 % around $m_{1/2}$ = 100 GeV

"Gluophobic" Scenario:

- Large variation of C_1
- LO (NLO) changes sign around m_{t_2} ≃ 900 (850) GeV
- NLO corrections significant at edges

NLO SQCD Cross Section: SPS1a



(a) (b)

Hadronic Cross setion @ LHC:

- MSSM/SM ≃ 34% for $m_{1/2}$ = 100 GeV

- Difference decreases rapidly for larger $m_{1/2}$

K Factor @ LHC:

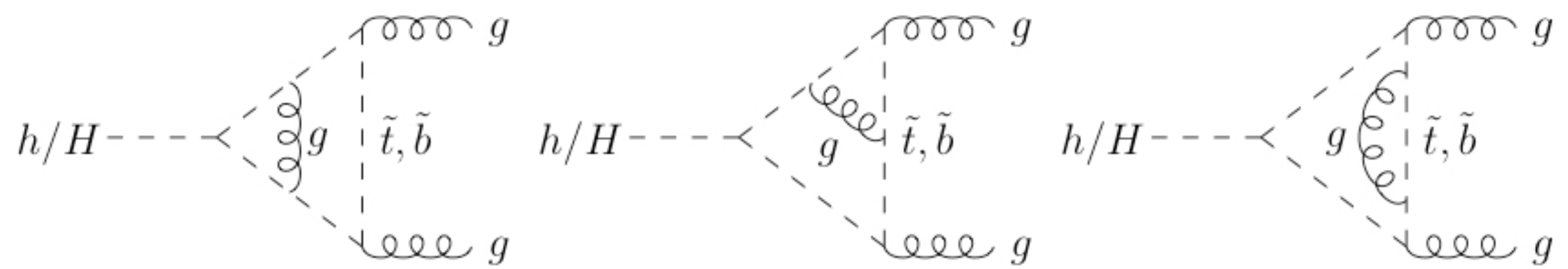
- NLO K factor ≃ 1.7

- Difference between SM and MSSM mainly a LO effect

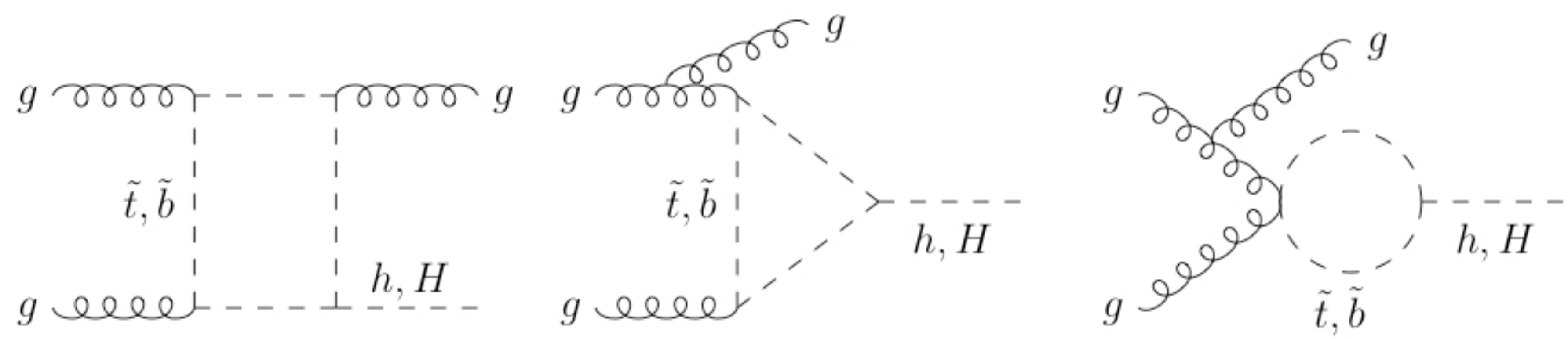
Gluon Fusion, Take Two: Squark Loops @ NLO QCD

- First step towards a full NLO SQCD calculation: compute pure SM QCD corrections to gluon fusion via squark loops (both stop and sbottom) (Muhlleitner and Spira, hep-ph/0612254)

Virtual Corrections



Real Corrections

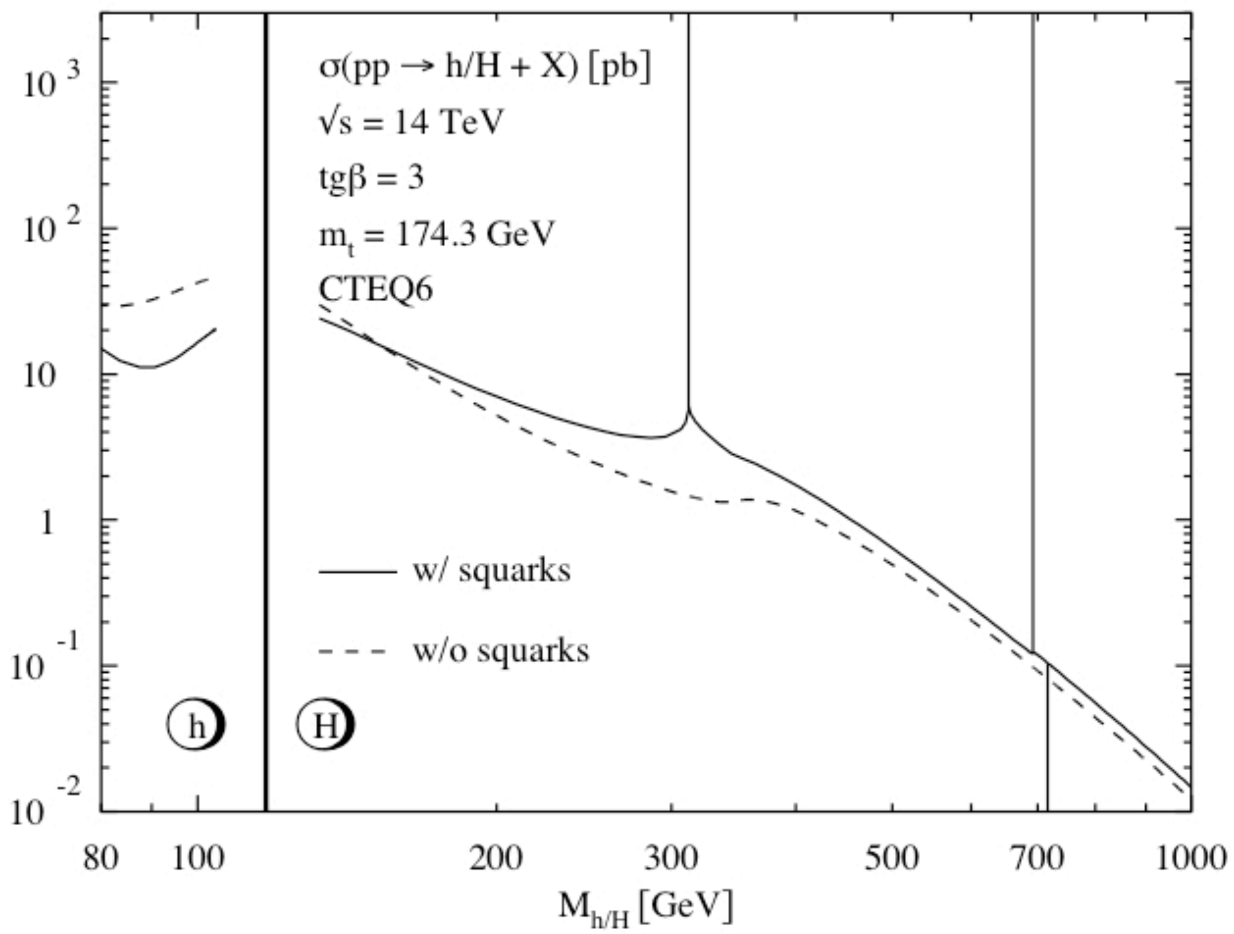


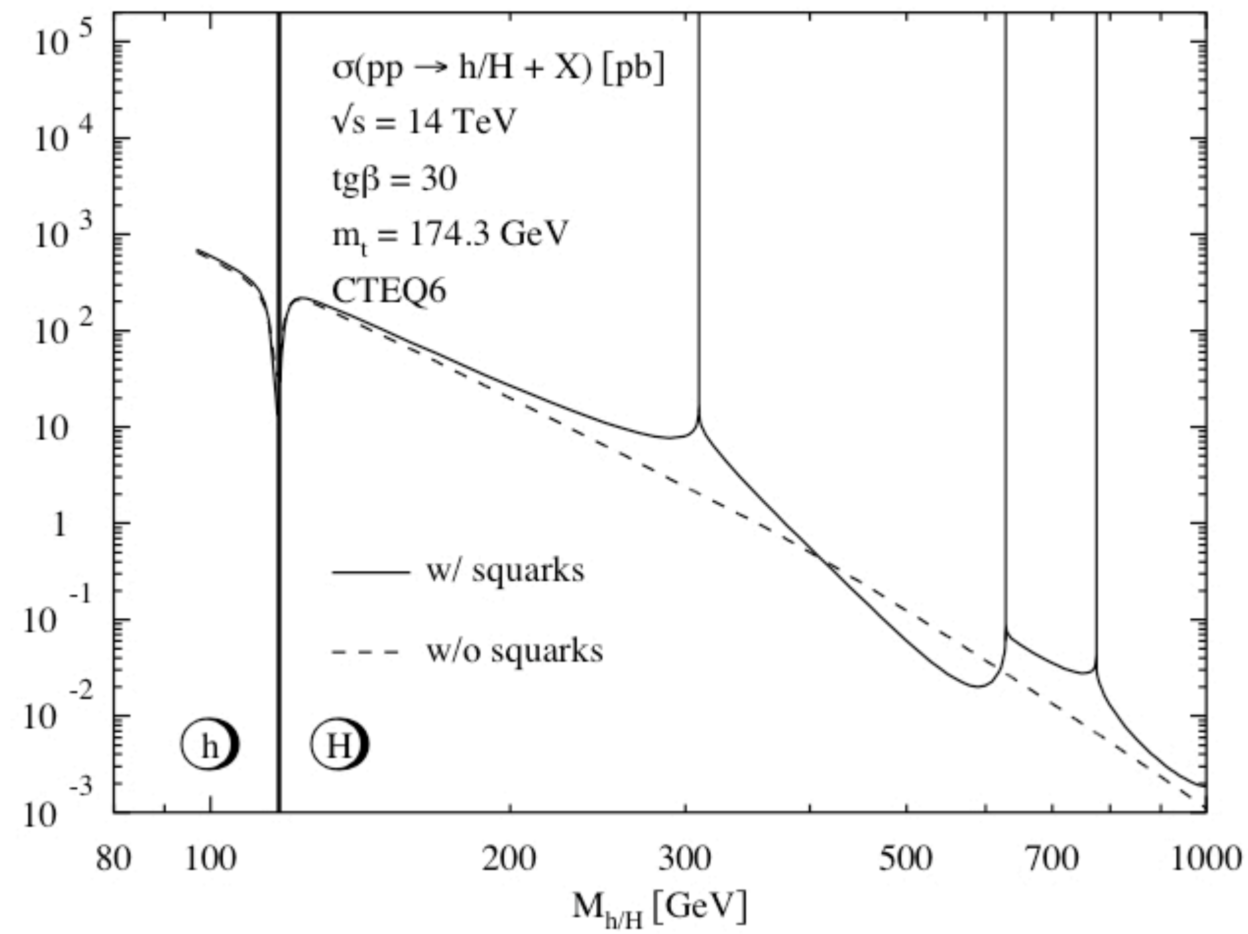
- Hadronic cross section takes the form:

$$\sigma(pp \to h/H + X) = \sigma_0^{h/H} \left[1 + C^{h/H} \frac{\alpha_s}{\pi} \right] \tau_{h/H} \frac{d\mathcal{L}^{gg}}{d\tau_{h/H}} + \Delta\sigma_{gg}^{h/H} + \Delta\sigma_{gq}^{h/H} + \Delta\sigma_{q\bar{q}}^{h/H}$$

- Considered the "gluophobic" scenario

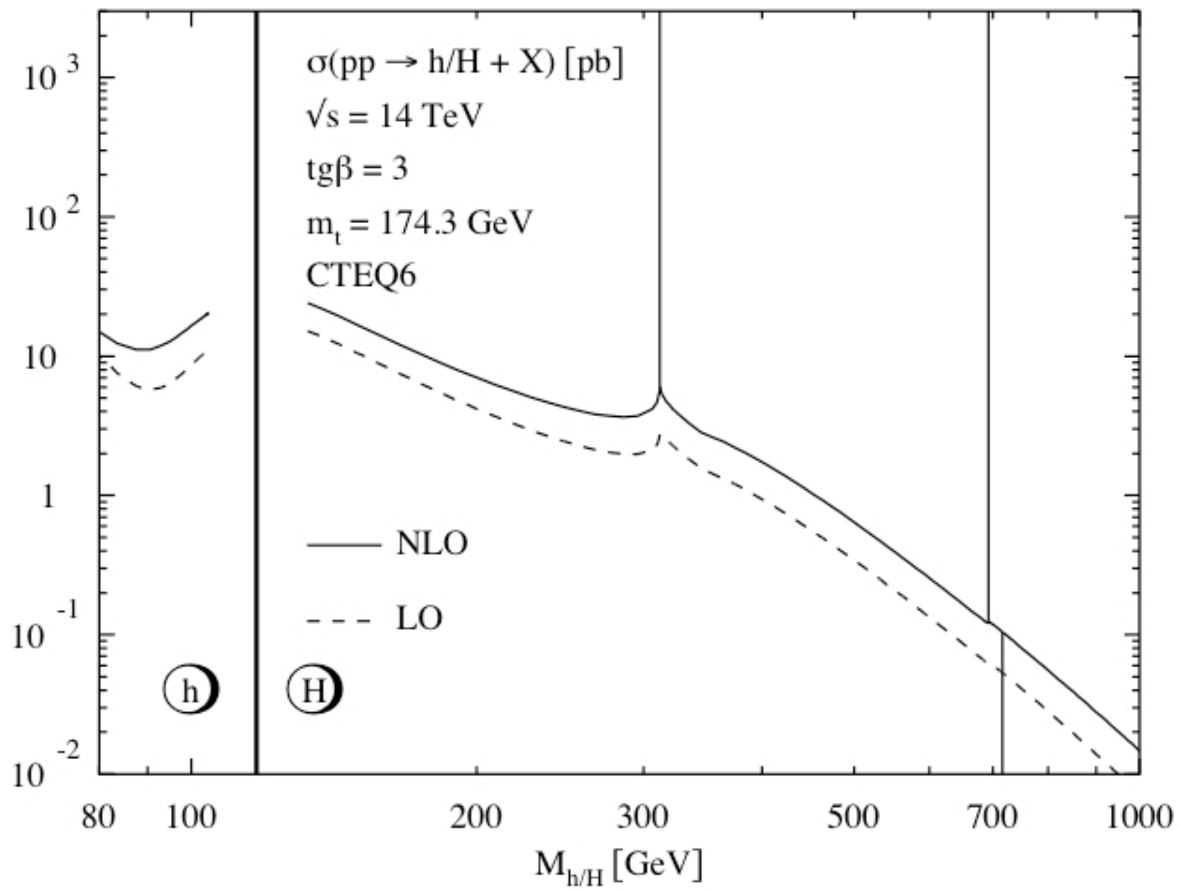
Squark Mass Effects in Gluon Fusion

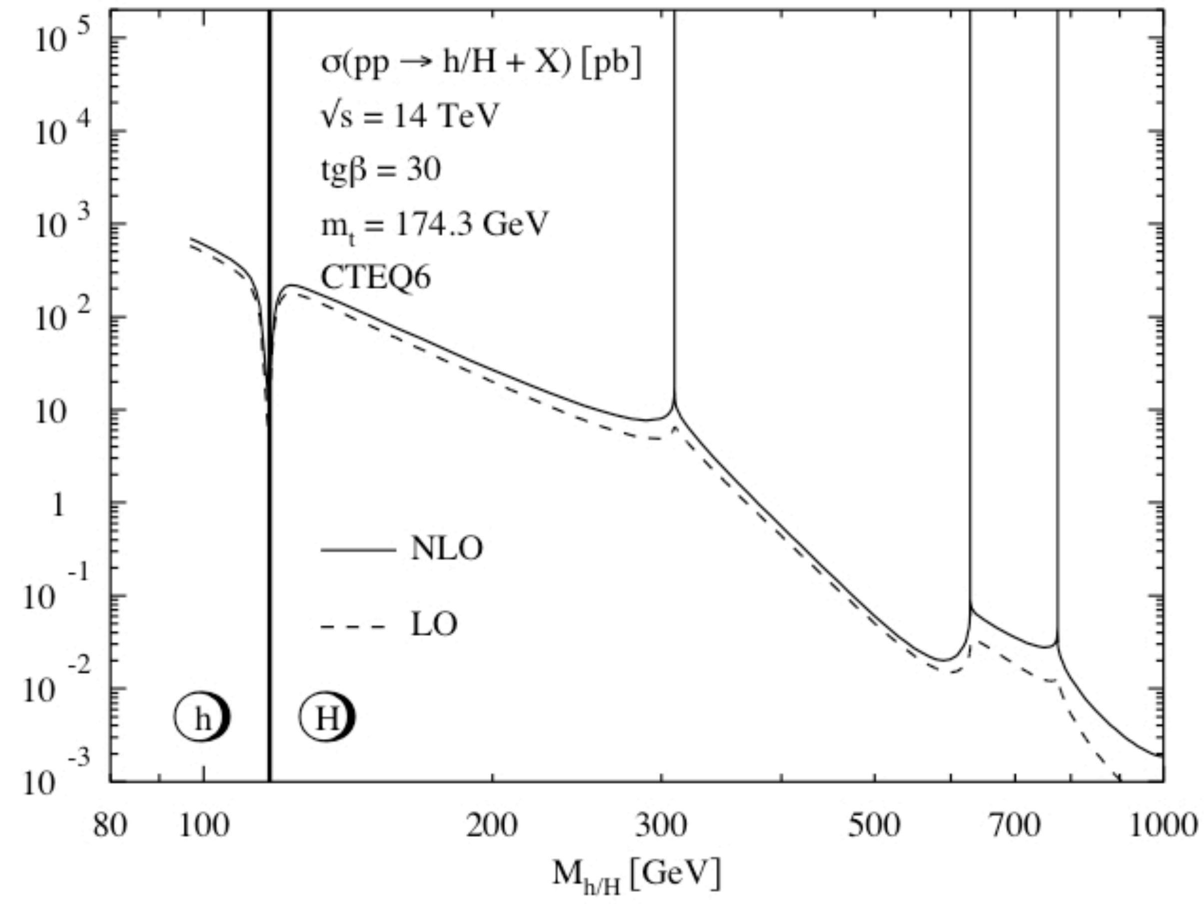




- "Spikes" = squark mass thresholds (t_1t_1, b_1b_1 and b_2b_2 respectively)
- "Gluophobic" scenario: squark loops alter c.s. by up to factors of 3!
- ... especially in regions close to and beyond squark mass thresholds.
- "Feature holds in other MSSM scenarios."

Squark Loop Effects: LO vs. NLO





- QCD+SQCD corrections increase c.s. by 10-100%
- ... but, can be significantly larger in regions of large destructive interference
- Residual scale-dependence lowered from 50% to 20%
- K factors develop squark mass dependence up to 20% (larger than top mass dependence!)

SQCD Corrections in Higgs Production with Bottom Quarks

MSSM Higgs Production with a Single b

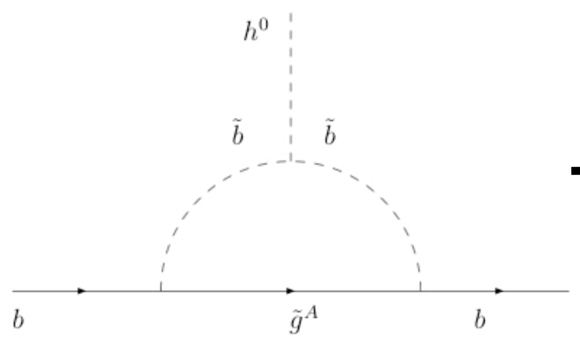
- Discovery mode at Tevatron (w/ h → bb) and important at LHC (w/ H → ττ)

- QCD corrections in full agreement!
  - "5FNS" = gb → bh [Campbell, Ellis, Maltoni and Willenbrock]

  - "4FNS" = gg → b(b)h [Dawson et al.; Dittmaier et al.]

- Claim: most important SUSY corrections come from bbh vertex

  - Computed in EFT approach [Carena et al.]:



$$g_{hbb} \to g_{hbb} \frac{1 - \Delta_b/(\tan\beta \tan\alpha)}{1 + \Delta_b}$$

  - where:

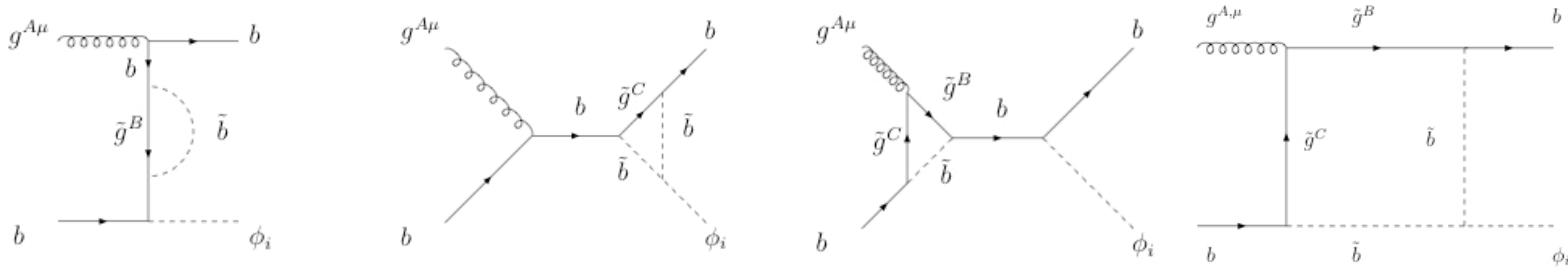
$$\Delta_b = \frac{2\alpha_s(\mu_R)}{3\pi} m_{\tilde{g}} \mu \tan\beta I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}})$$

Sums all SQCD corrections to bbh vertex to all orders!

  - But, Δ_b computed in $m_h^2 \ll (M_{SUSY})^2$ limit and w/ on-shell bottom quarks

Complete SQCD Corrections to gb → bφ

- Goal: compute full SQCD corrections and test EFT claim [S. Dawson and CBJ]
- Virtual corrections:



- Define various cross sections:

"IBA"

$$\frac{d\hat{\sigma}_{IBA}}{dt} \equiv \frac{d\hat{\sigma}_{Born}}{dt}\left(\frac{g_{b\bar{b}\phi}}{g^{LO}_{b\bar{b}\phi}}\right)^2$$

"Gluon Only" = QCD Corrected c.s.

$$\sigma_{NLO}(pp \to b\phi)_{QCD} \equiv \left(\frac{g_{b\bar{b}\phi}}{g^{LO}_{b\bar{b}\phi}}\right)^2 \sigma_{LO}(pp \to b\phi) + \delta\sigma_{QCD}(pp \to b\phi)$$

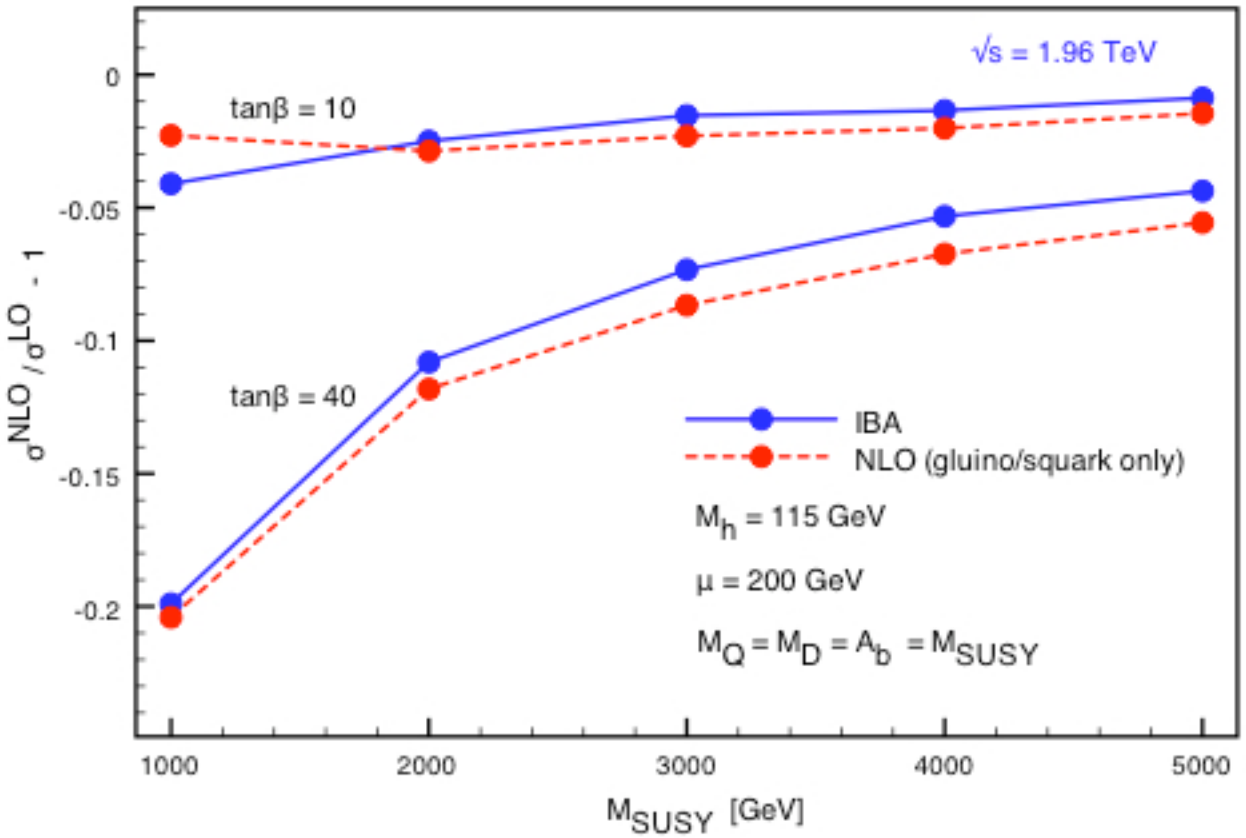
"Gluino/Squark Only" = SQCD Corrected c.s.

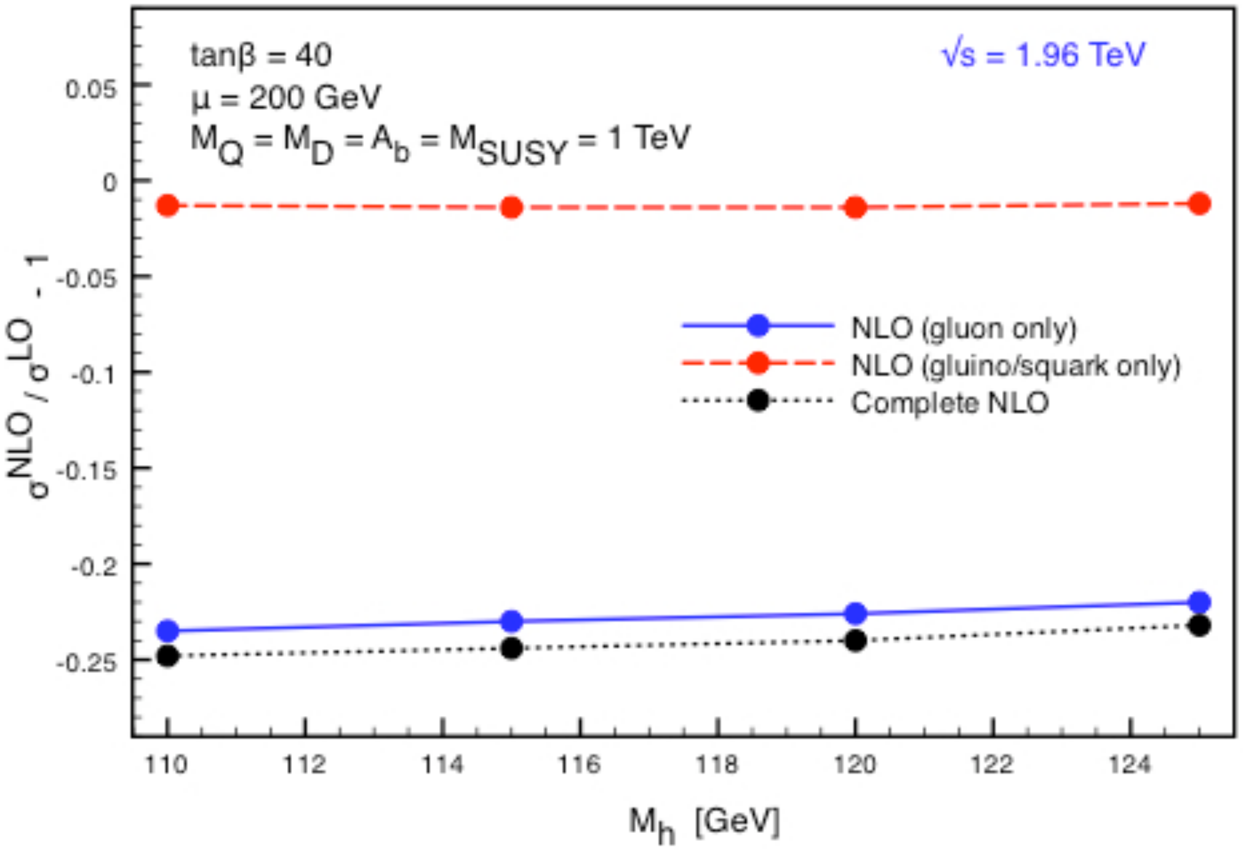
$$\sigma_{NLO}(pp \to b\phi)_{SQCD} = \int dx_1 dx_2 \left[g(x_1,\mu)b(x_2,\mu)\int dt\left(\frac{d\hat{\sigma}_{SQCD}}{dt}\right) + (x_1 \leftrightarrow x_2)\right]$$

"Complete NLO" = QCD + SQCD

$$\sigma_{NLO}(pp \to b\phi)_{QCD+SQD} \equiv \sigma_{NLO}(pp \to b\phi)_{SQCD} + +\delta\sigma_{QCD}$$

Testing the EFT Claim





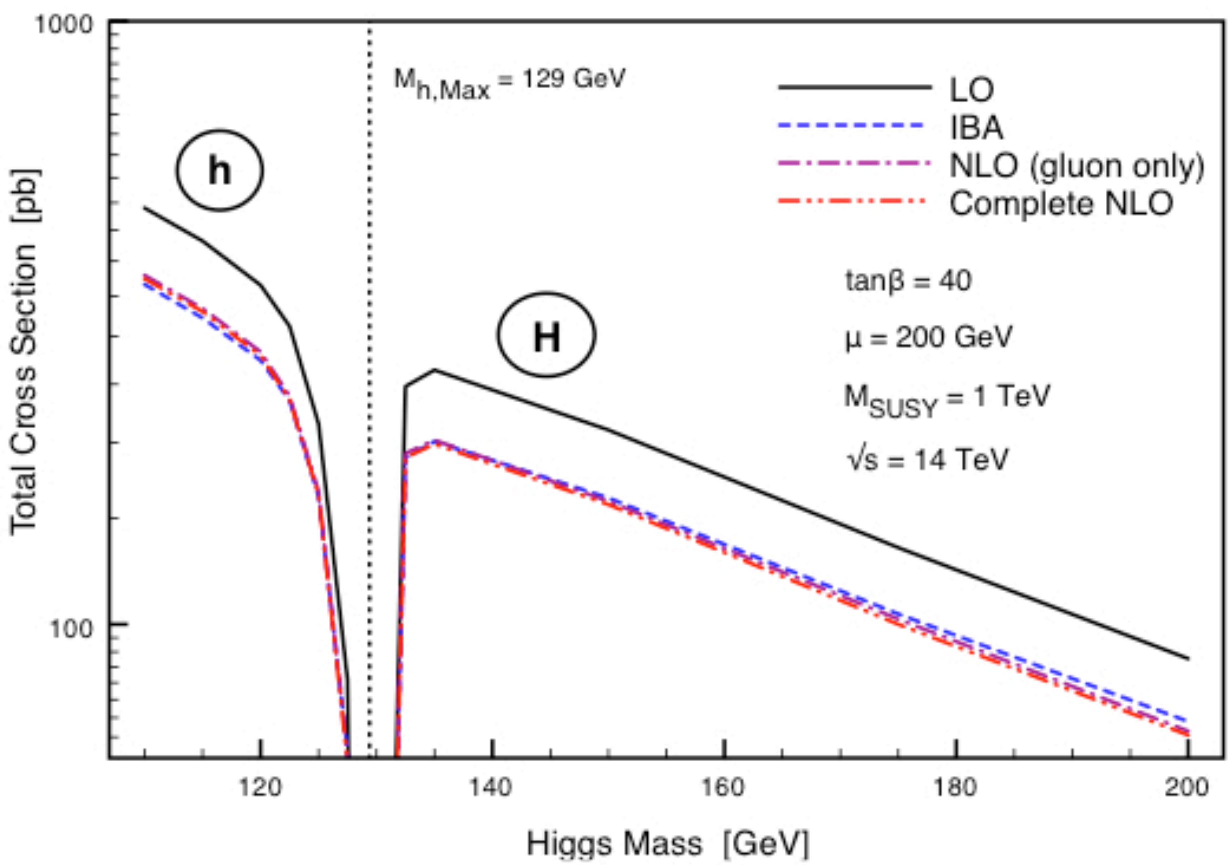
IBA vs. Gluino/Squark Only:

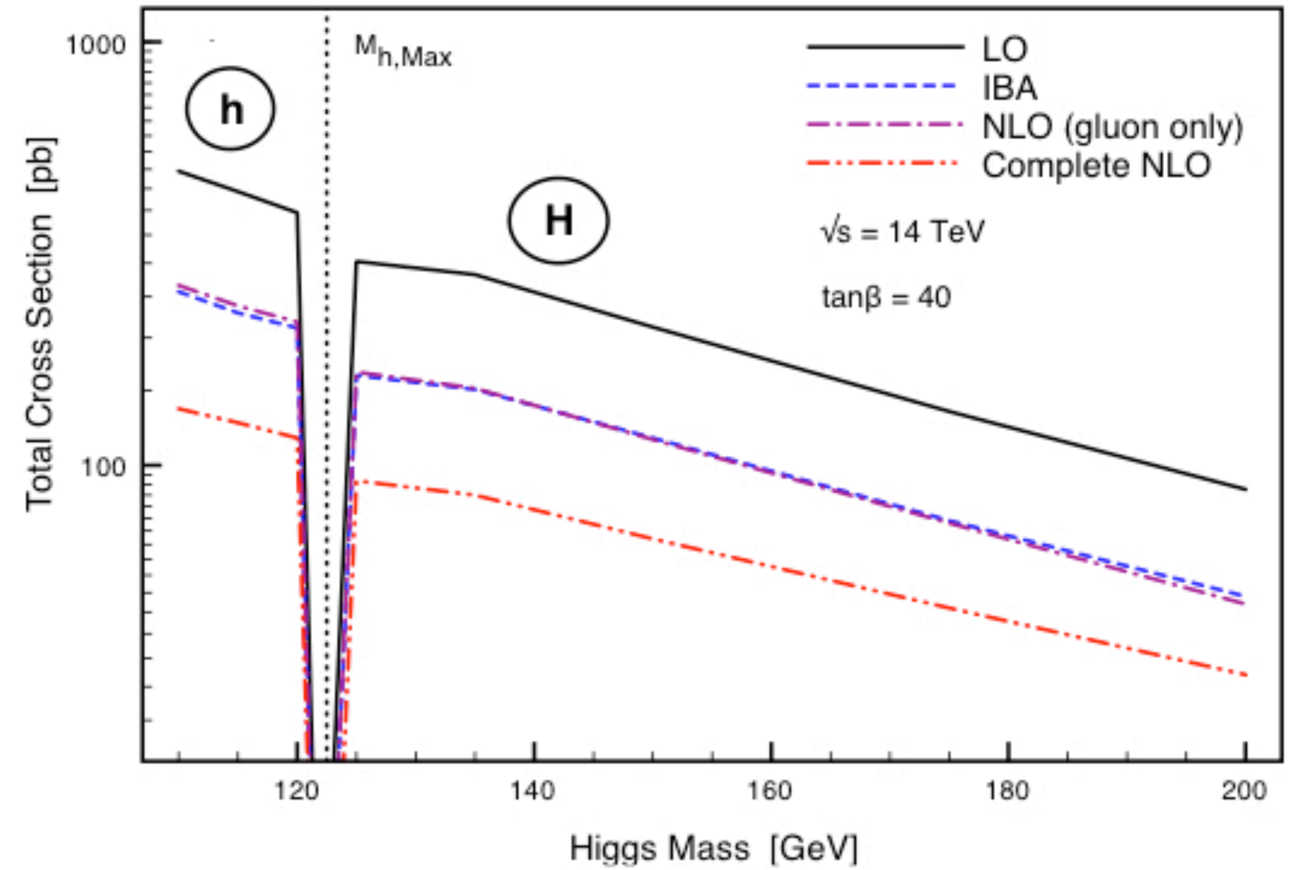
- Light Higgs @ Tevatron
  (similar results for all Higgs at both machines)
- Difference at percent level
  (IBA works for large M_{SUSY})
- Results approach "decoupling limit"

QCD vs. SQCD:

- Note: large M_{SUSY} (see next slide...)
- QCD corrections dominate!
- SQCD at 1-2% level

gb → bφ @ the LHC





Large M_{SUSY} Scenario:

- Almost all of NLO corrections accounted for by EFT approach
- Additional SQCD corrections tiny
- ... QCD corrections too!

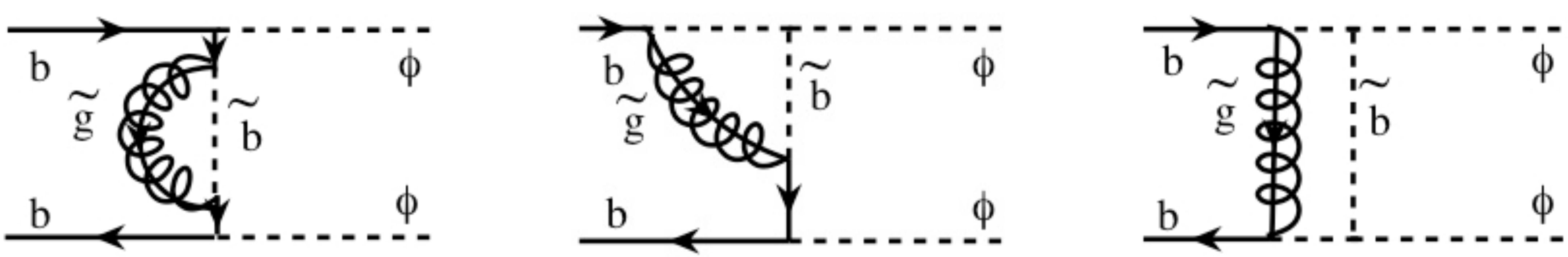
"More Optimistic" Scenario:

- $m_g = m_{b1} = 250$ GeV, $m_{b2} = 350$ GeV
- Still QCD corrections tiny, but...
- SQCD corrections dominate and significantly reduce c.s. !

MSSM Higgs Pair Production from Bottom Quark Fusion

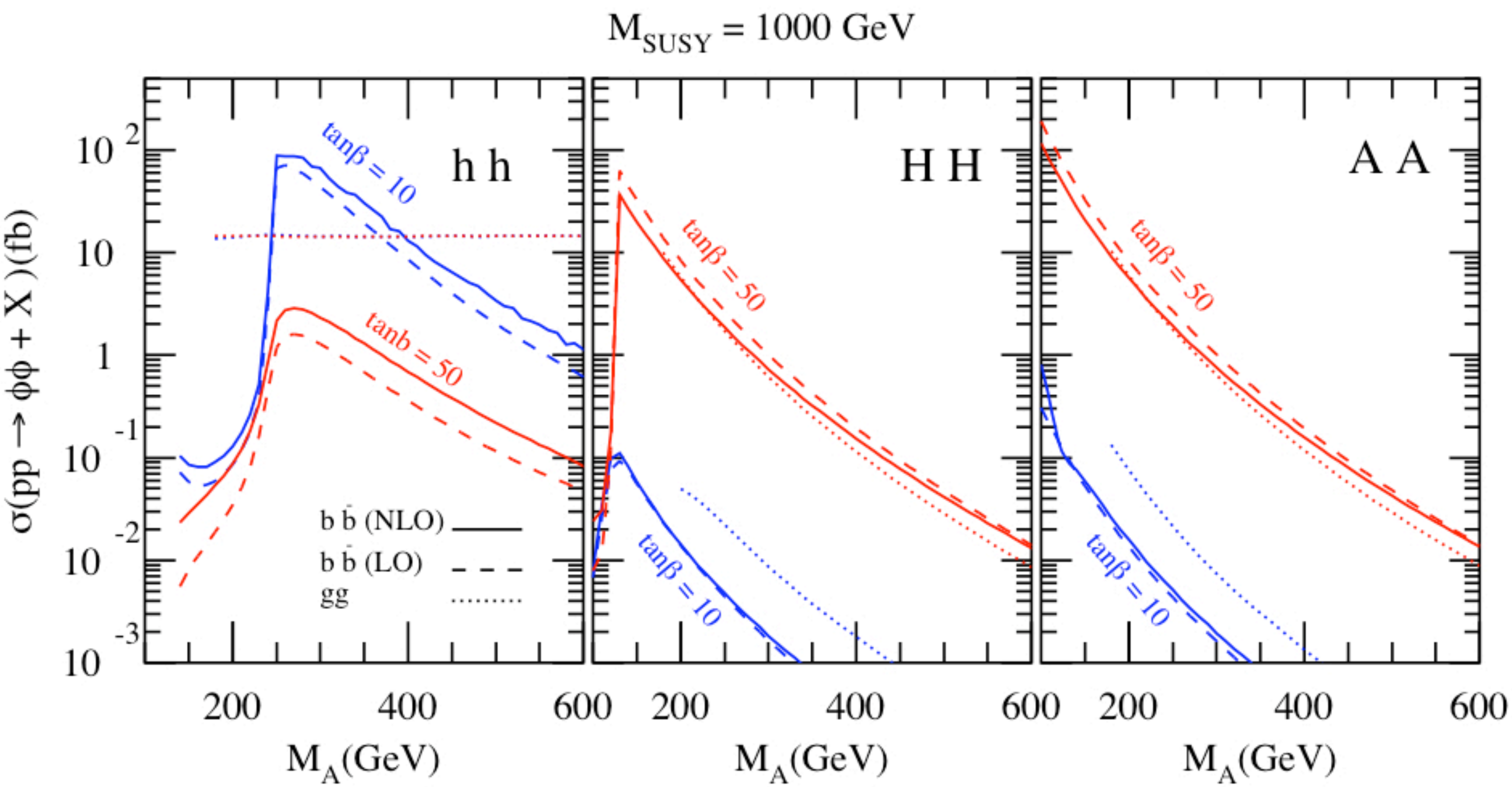
[S. Dawson, C. Kao and Y. Wang]

- Production rate for light Higgs from bb fusion > gg fusion channel for $\tan\beta \leq 35$ and moderate values of M_A ($M_A \simeq 300$ GeV)
- Prospect for measuring the Higgs tri-linear coupling
- QCD corrections significantly increase the total cross section [S. Dawson, C. Kao and Y. Wang]
- SQCD corrections:



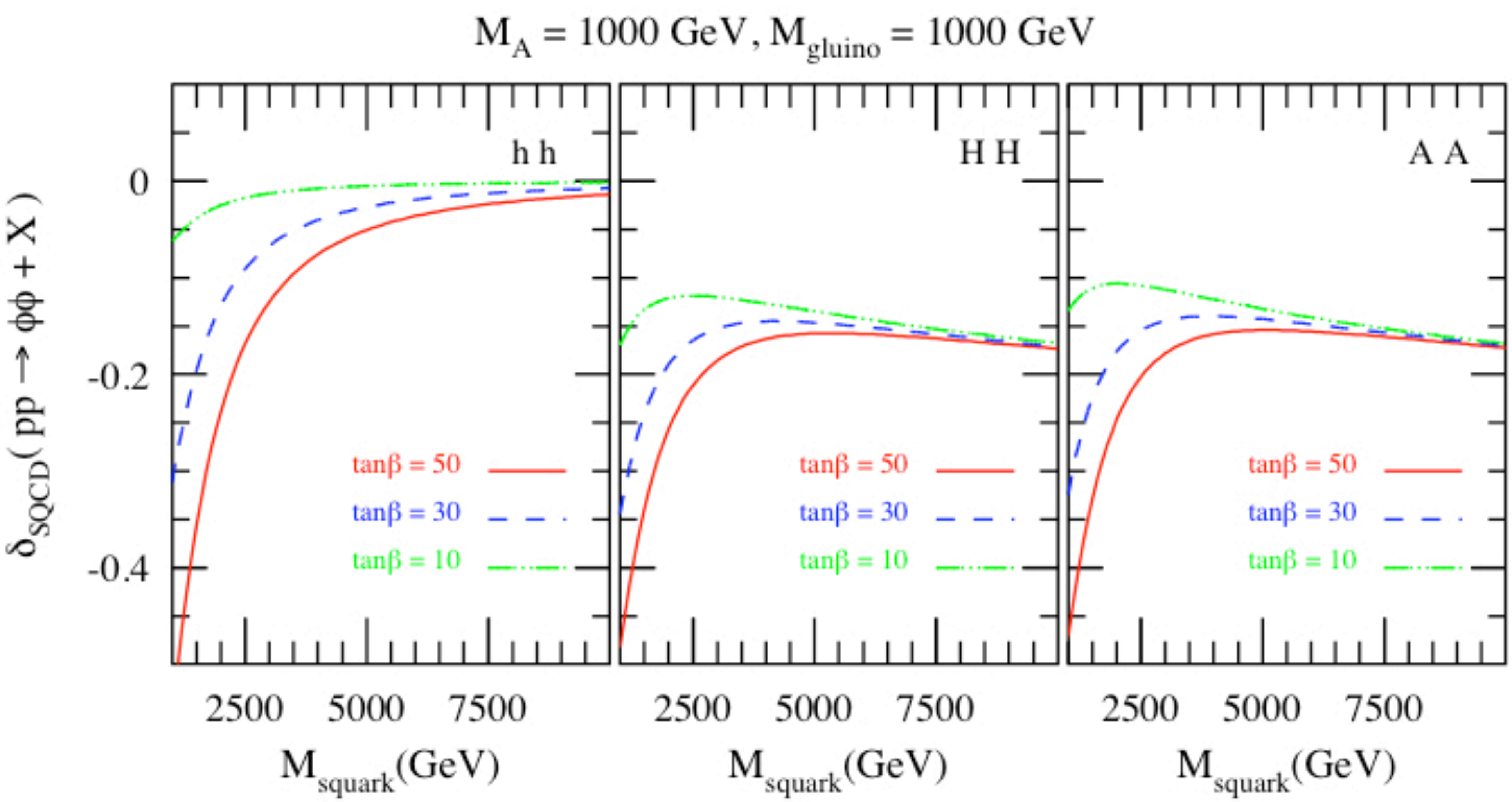
- Study results for both the MSSM and mSUGRA scenarios
- Compared results for bb → hh to gg → hh [Plehn, Spira and Zerwas; Bendezu and Kniehl]

Gluon Fusion vs. Bottom Quark Fusion



- For tanβ = 10:
  - Cross section for hh production can be much larger for bb
  - HH, AA production suppressed compared to gg
- For tanβ = 50;
  - hh channel in b quark fusion suppressed compared to gg
  - HH,AA comparable in both channels

SQCD Corrections with Heavy Squarks



- NLO SQCD cross section normalized to Born cross section
- Cross section for hh approaches decoupling for large squark masses (similar to gb → bh behavior)
- Cross sections for HH/AA approach non-zero constant

Summary

- QCD corrections to all MSSM Higgs production processes now under complete control (some @ NNLO QCD, NLO EW, etc.)

- Recently, a lot of effort going into SUSY corrections.

- Gluon fusion:
  - EFT approach:
    - ✓ valid for "most" of MSSM parameter space
    - ✓ SQCD corrections typically small

  - QCD corrections to Squark loops
    - ✓ Corrections can be quite large around squark mass thresholds

  - Ongoing effort to calculate full two-loop amplitudes in SQCD

- Production with Bottom Quarks:
  - $gb \to b\varphi$: EFT approach valid for large SUSY masses, but inadequate for more "optimistic" scenarios

  - $bb \to \varphi\varphi$: SQCD corrections significant for several regions of MSSM parameter space

Fate of the MSSM Higgs Sector?

Annie Taylor

Became first person to ride
a barrel over Niagara Falls
on Oct. 24, 1901...
and survive.

Charles Stephens

Englishman Charles G. Stephens equipped his wooden barrel with an anvil for ballast. Charles tied himself to the anvil for security. After the plunge, Chucks right arm was the only item left in the barrel.