QCD Corrections to $t\bar{t}H$ Production

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Workshop on the Future of Higgs Physics
FNAL, May 2001

- Motivations (discovery, precision studies)
- $p\bar{p} \to t\bar{t}H$ (Run II)
- $pp \to t\bar{t}H$ (LHC)
- $e^+e^- \to t\bar{t}H$ (Tesla/NLC)

Crucial to know first order QCD corrections

- increase/decrease cross section considerably
- reduce μ_r-dependence substantially

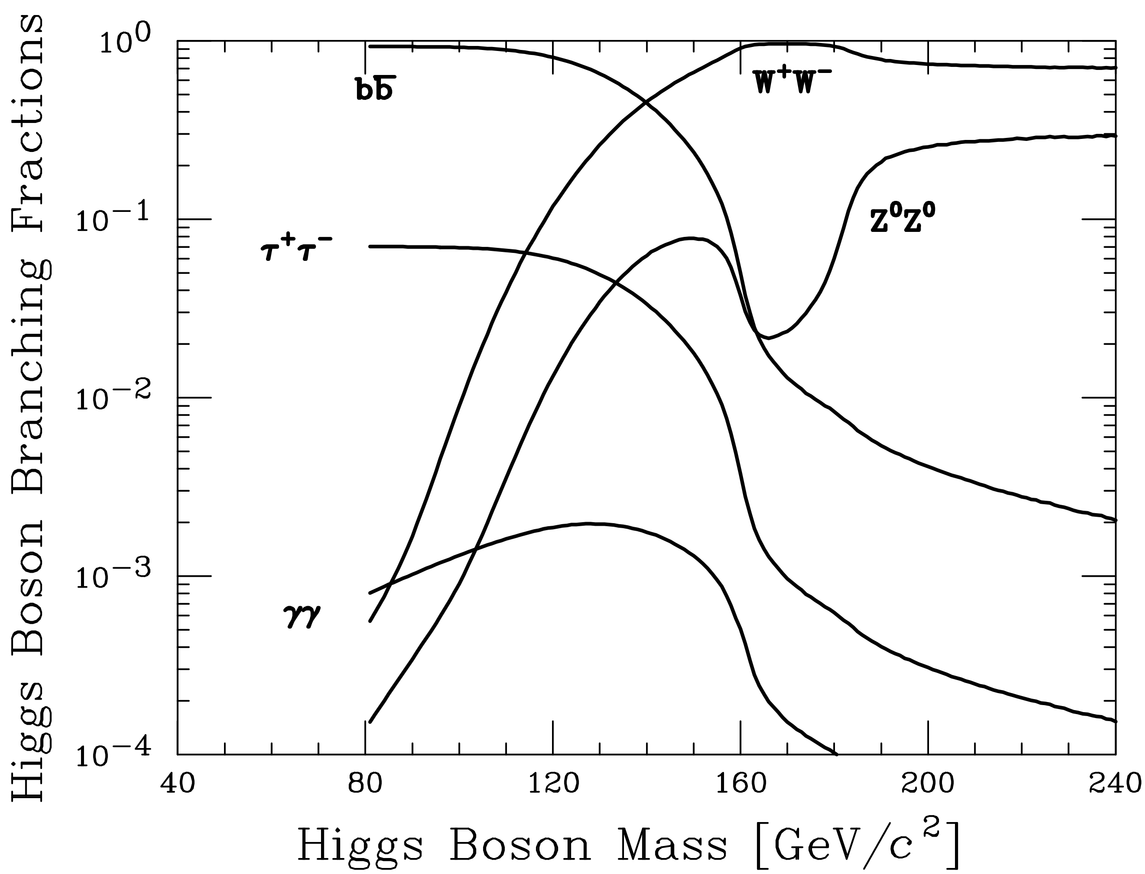
(with S. Dawson)

MOTIVATIONS,1

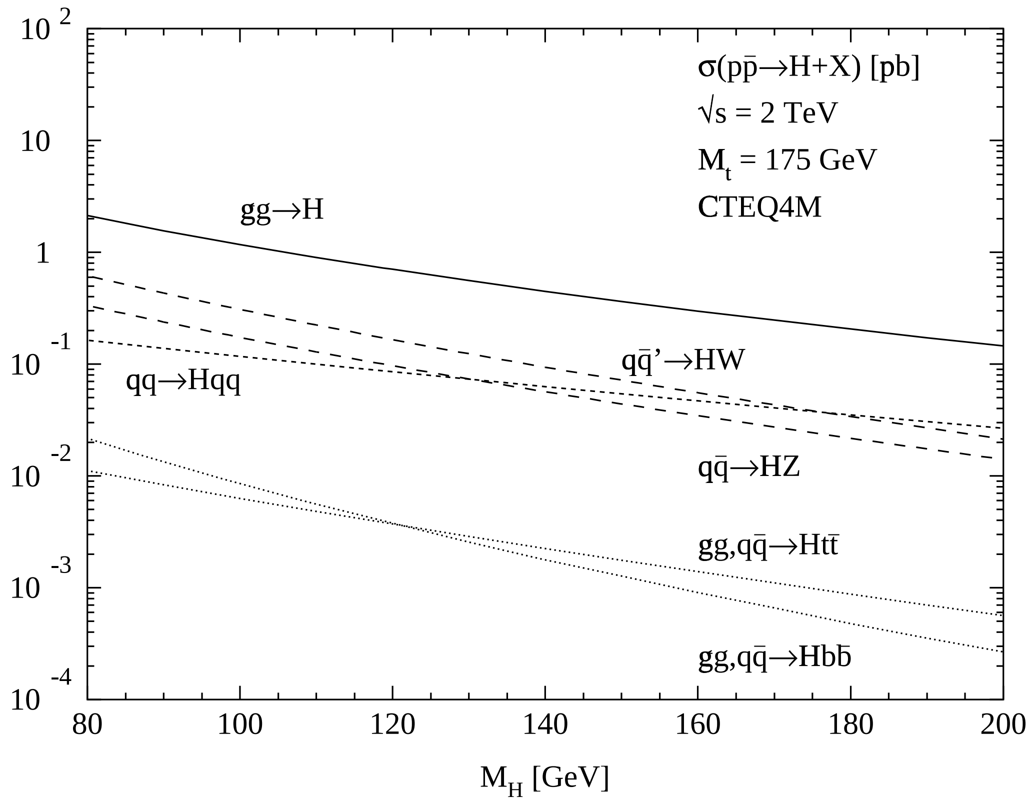
$110 < M_H < 140$ GeV : Crucial Region for future colliders (Tevatron, LHC, NLC)

BUT

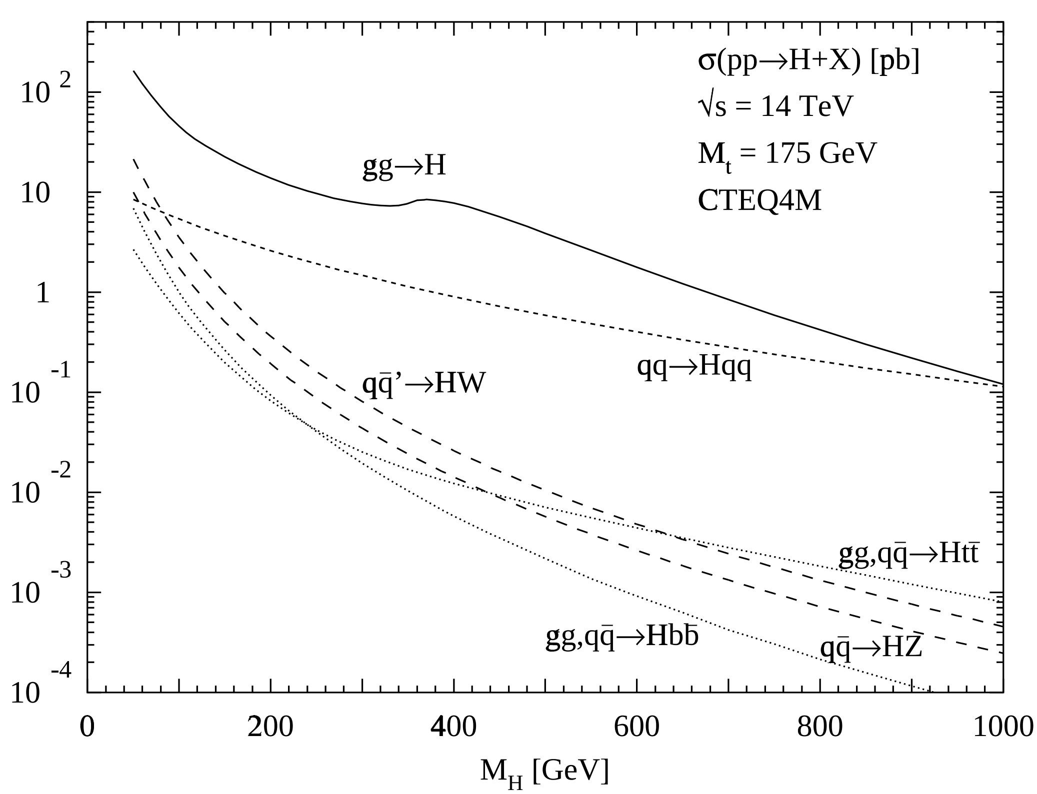
For Hadron Colliders this is a problematic region: non leading production modes will also have to be used to confirm Higgs signal



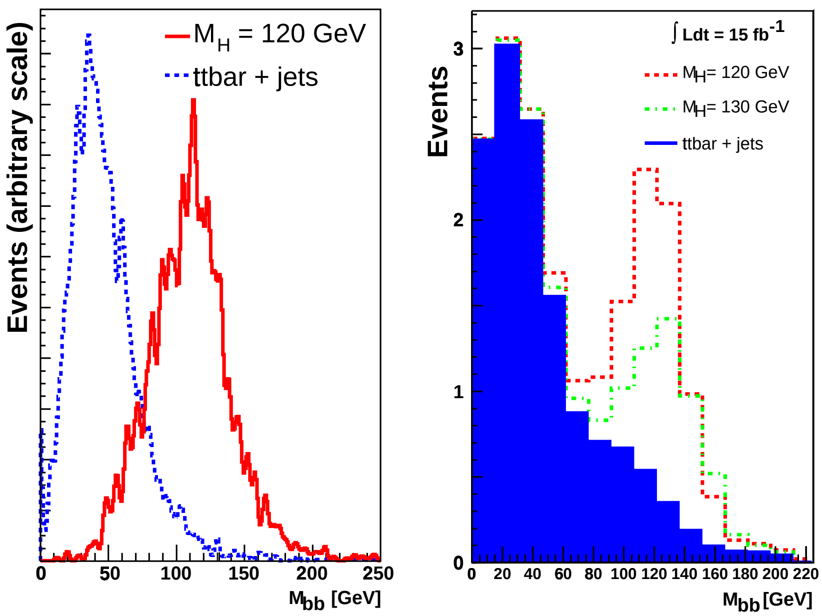
Tevatron, SM Higgs



LHC, SM Higgs



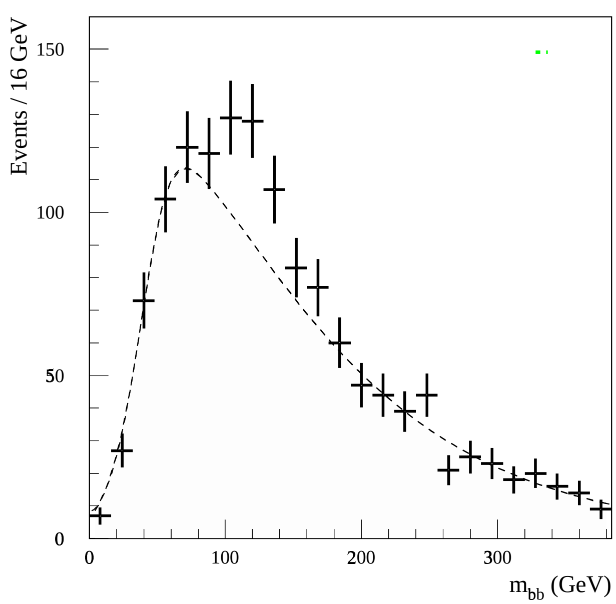
Tevatron, $p\bar{p} \to t\bar{t}h_{SM}$



Goldstein etal.
hep-ph/0006311

LHC, $pp \to t\bar{t}h_{SM}$

LHC top working group

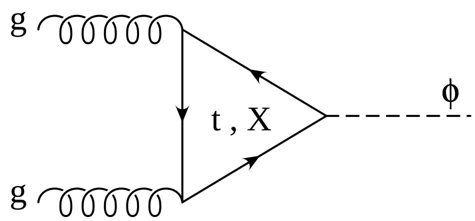


MOTIVATIONS, 2

Precision studies : measure the Top Yukawa coupling in $pp\,,\, e^+e^- \to t\bar{t}\phi$

- direct measurement

  ($\phi \to gg$ or $gg \to \phi$: possible spurious contributions from heavy new particles)



- high sensitivity to the $t\bar{t}\phi$ coupling: probe new physics

- spectacular signature : $W^+W^-b\bar{b}b\bar{b}$

NLC :

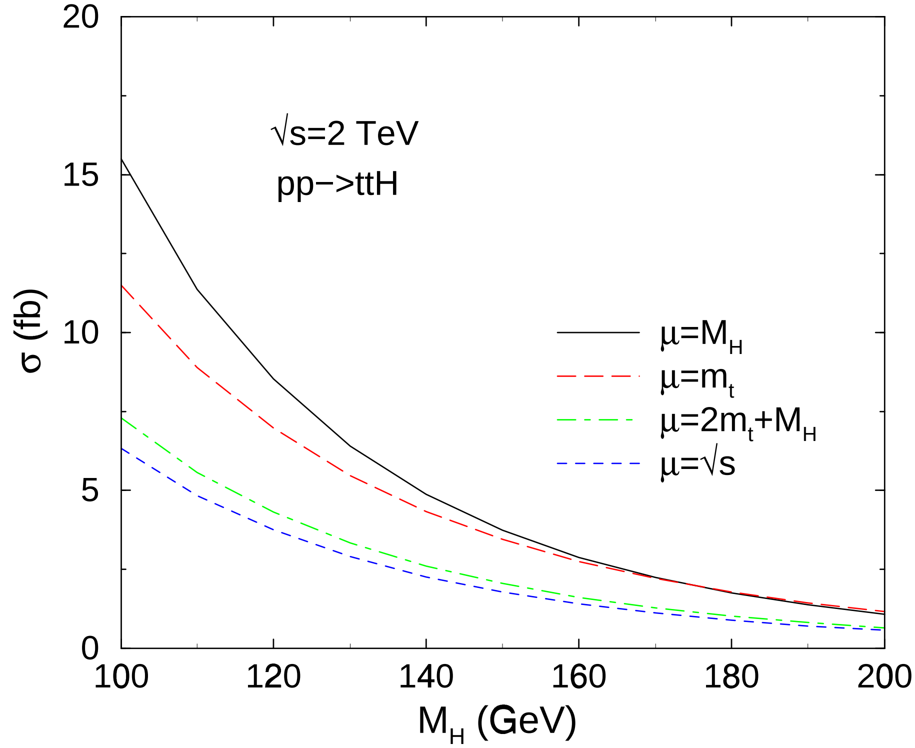
$$\frac{\delta g_{tth}}{g_{tth}} \simeq 5.5\%$$

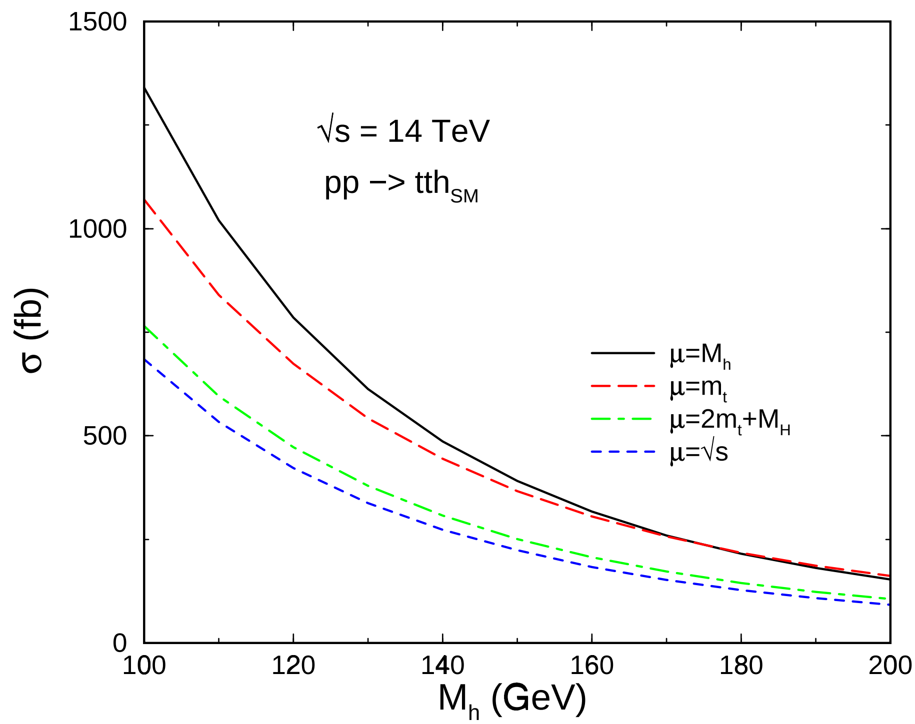
LHC :

$$\frac{\delta g_{tth}}{g_{tth}} \simeq 16\%$$

Need for NLO calculation

LO calculation have very strong μ-dependence





Status of QCD corrections

- $\sigma(e^+e^- \to t\bar{t}h)$ calculated at $O(\alpha_s)$:
  - $\sqrt{s} = 500$ GeV : K=1.4-2.4
  - $\sqrt{s} = 1$ TeV : K=0.8-0.9

  Dittmaier, Krämer, Liao, Spira, Zerwas

  L.R., S.Dawson

- $\sigma(p\bar{p} \to t\bar{t}h)$ calculated at $O(\alpha_s^3)$

  Beenakker, Dittmaier, Krämer, Pluemper, Spira, Zerwas

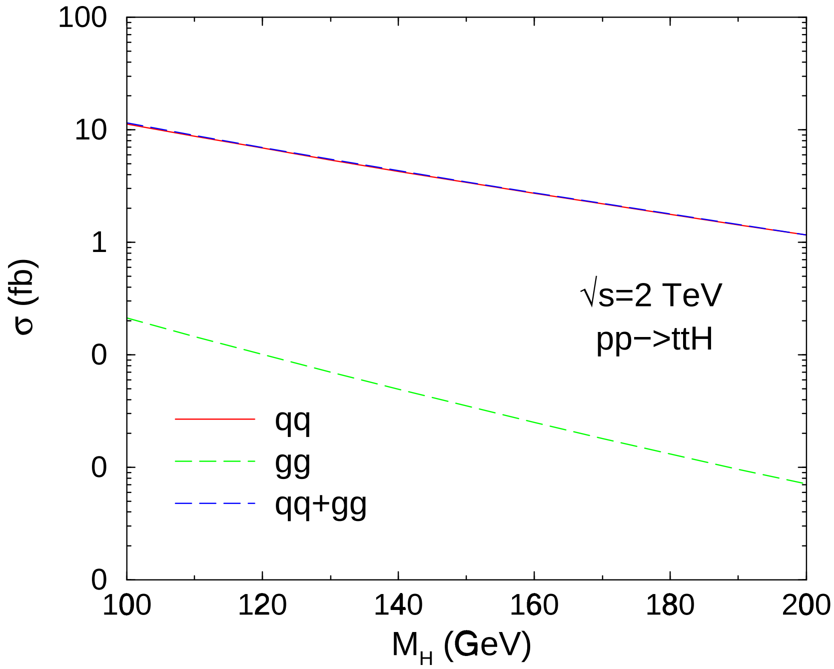
  S.Dawson, L.R.

- $\sigma(pp \to t\bar{t}h)$ at $O(\alpha_s^3)$: work in progress

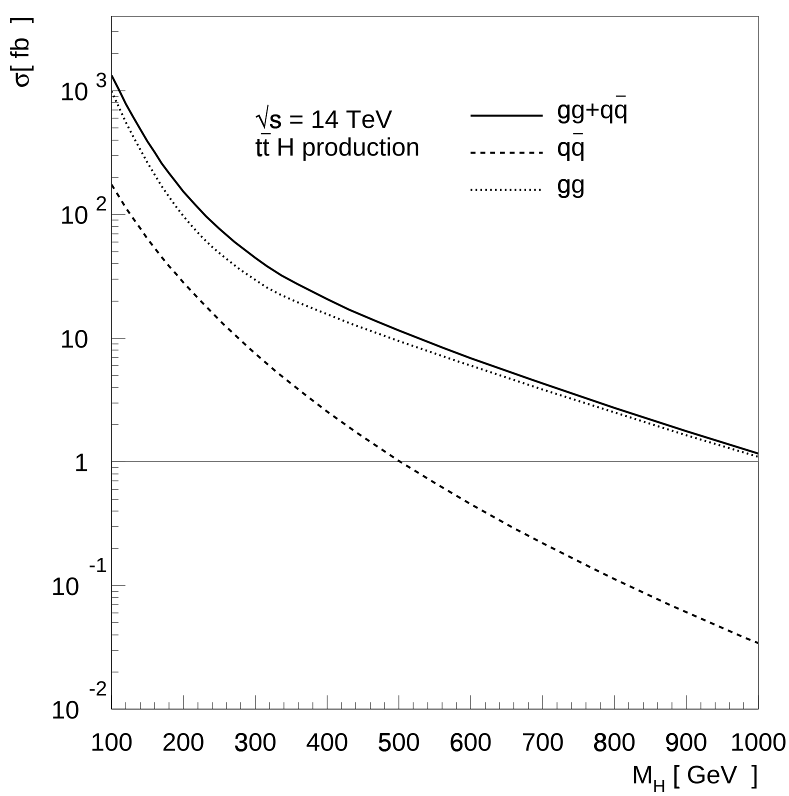
  Beenakker, Dittmaier, Krämer, Pluemper, Spira, Zerwas

  S.Dawson, L. Orr, L.R., D. Wackeroth

$pp \to ttH$: dominant channel $qq \to ttH$



$pp \to t\bar{t}H$: dominant channel $gg \to t\bar{t}H$



General Approach

NLO cross section:

$$\sigma_{\mathcal{H}_1\mathcal{H}_2} = \sum_{a,b} \int dx_1 dx_2 \mathcal{F}_a^{\mathcal{H}_1}(x_1)\mathcal{F}_b^{\mathcal{H}_2}(x_2)\sigma_{ab}^{NLO}(x_1, x_2)$$

where

$$\sigma_{ab}^{NLO} = \sigma_{ab}^{LO} + \alpha_s \delta\sigma_{ab}^{NLO} + O(\alpha_s^2)$$

NLO correction $\delta\sigma_{ab}^{NLO}$ made off:

- one loop virtual corrections to $q\bar{q} \to t\bar{t}H$
- real one gluon emission: $q\bar{q} \to t\bar{t}H + g$

We use Phase Space Slicing as proposed by:

Giele and Glover, PRD 46 (1992) 1980

Giele, Glover, and Kosower NPB 403 (1993) 633

extended to massive quarks by

Keller and Laenen, PRD 59 (1999) 114004

. . .

- Cross all partons to final state:

$$q\bar{q} \to t\bar{t}H \quad \text{becomes} \quad H \to q\bar{q}t\bar{t}$$

- Compute virtual corrections $\longrightarrow \sigma_{virtual}$
  - renormalize UV divergences
  - calculate IR divergences

- Compute real gluon emission using PSS
  - introduce a cut-off parameter s_{min} (GeV^2)
  - partons are considered soft/collinear if

$$s_{ij} = 2p_i \cdot p_j < s_{min}$$

$\sigma_{hard} \longrightarrow$ all $s_{ij} > s_{min}$, numerical

$\sigma_{ir} = \sigma_{soft} + \sigma_{collinear} \longrightarrow$ analytic

- Cross $q\bar{q}$ to initial state, H to final state:
  - flip signs of s_{ij} invariants accordingly
  - add $\sigma_{crossing} \longrightarrow$ use crossing functions

$$\Downarrow$$

$$\sigma_{real} = \sigma_{hard} + \sigma_{ir} + \sigma_{crossing}$$

$$\delta\sigma^{NLO} = \sigma_{virtual} + \sigma_{real}$$

About σ_{real}

GGK+KL$\longrightarrow$ systematic approach to factorization of soft+collinear divergences.

- use color ordered amplitudes

$$\begin{aligned} \mathcal{A}(H\to q\bar{q}t\bar{t}+g) &\simeq \delta_{f_t f_{\bar{t}}}\delta_{f_q f_{\bar{q}}}\cdot \\ \Big(\delta_{c_t c_{\bar{q}}}T^a_{c_q c_{\bar{t}}}B_1(t,\bar{t},q,\bar{q},k) &+ T^a_{c_t c_{\bar{q}}}\delta_{c_q c_{\bar{t}}}B_2(t,\bar{t},q,\bar{q},k)\Big) \\ -\frac{1}{N}\Big(\delta_{c_t c_{\bar{t}}}T^a_{c_q c_{\bar{q}}}B_3(t,\bar{t},q,\bar{q},k) &+ T^a_{c_t c_{\bar{q}}}\delta_{c_q c_{\bar{q}}}B_4(t,\bar{t},q,\bar{q},k)\Big) \end{aligned}$$

- calculate the soft and collinear approximation of

$$\int dPS_g|\mathcal{A}(H\to q\bar{q}t\bar{t}+g)|^2$$

keeping both leading and sub-leading terms in N, and find

$$\sigma_{ir}=\sigma_{soft+collinear}=\int dPS_3(S_F+C_F)|A_{LO}|^2$$

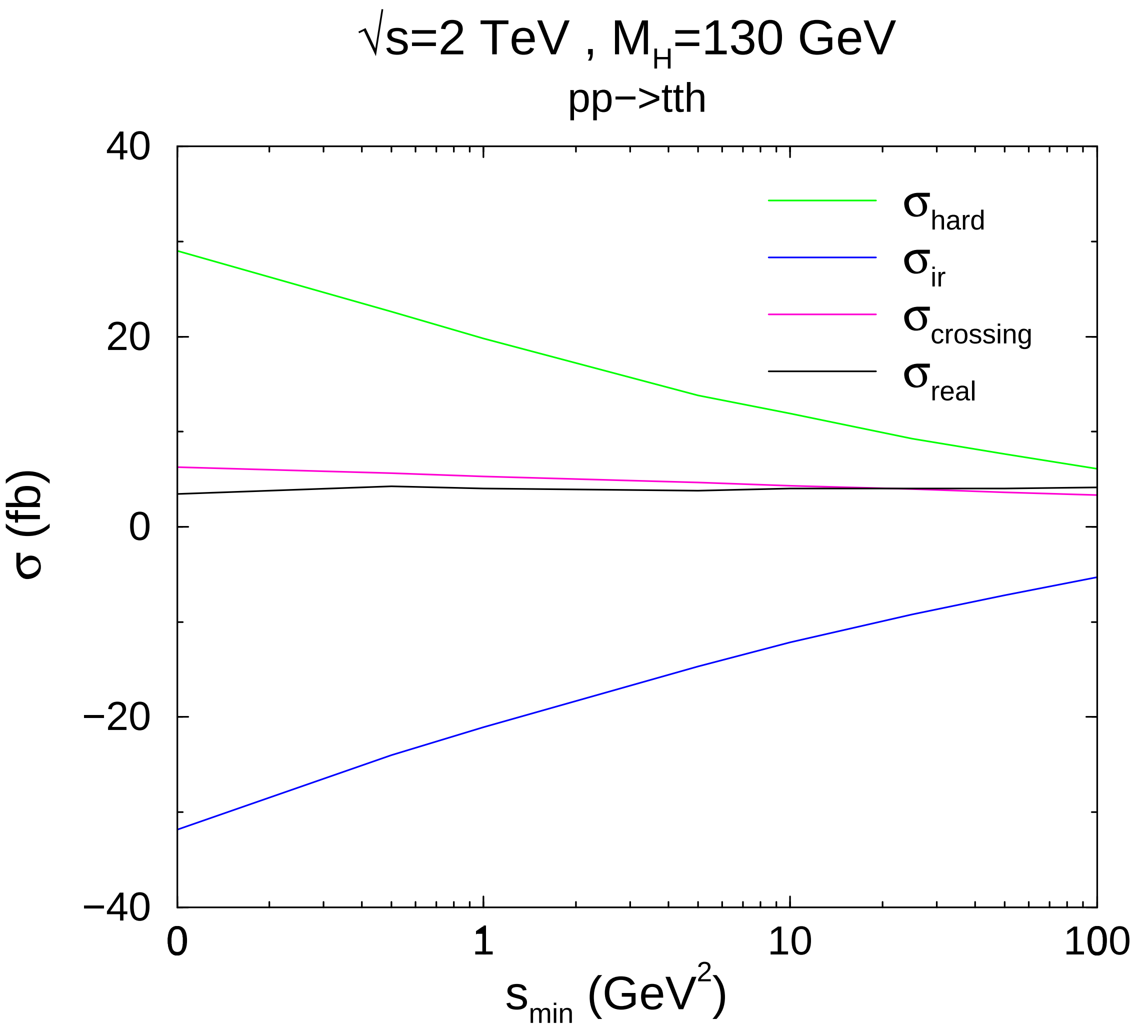
where both S_F and C_F are s_{min}-dependent.

- add $\sigma_{crossing}$ to correct for mismatch between initial state and final state collinear divergences $\longrightarrow$ extra s_{min}-dependence

$$\mathcal{F}^{\mathcal{H}}_a(x)=f^{\mathcal{H}}_a(x,\mu_F)+\alpha_s C^{\mathcal{H}}_a(x,\mu_F)+O(\alpha_s^2)$$

Crucial: check s_{min}-independence of σ_{real}

$$\sigma_{real} = \sigma_{hard} + \sigma_{ir} + \sigma_{crossing}$$



About $\sigma_{virtual}$

- Reduce each diagram in terms of scalar integrals of the form:

$$\int \frac{d^n k}{(2\pi)^n} \frac{1}{\left[(k^2 - m_1^2)\left((k+p_1)^2 - m_2^2)^2\right)\cdots\right]}$$

$\rightarrow$ three external massive particle

$\rightarrow$ several massive internal propagators

- finite integrals: compute them numerically

- UV-divergent integrals: easy

- IR-divergent integrals : difficult

Example: pentagon scalar integral

$$E0 = \int \frac{d^n k}{(2\pi)^n} \frac{1}{N_1 N_2 N_3 N_4 N_5}$$

use method proposed by:

Bern, Dixon, and Kosower,

PLB 302 (1993) 299, NPB 412 (1994) 751

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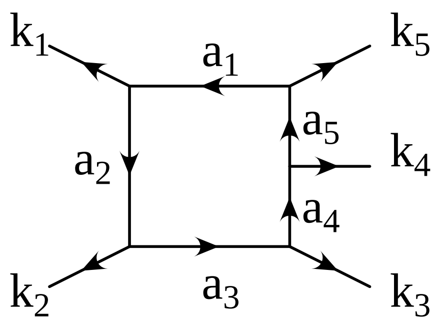

$$E0 = \frac{1}{16\pi^2}(4\pi\mu^2)^\epsilon \Gamma(3+\epsilon) \int d^5 a_i \frac{\delta(1-\sum_{i=1}^5 a_i)}{[\mathcal{D}(a_i)]^{3+\epsilon}}$$

where

$$\mathcal{D}(a_i) = \sum_{i,j=1}^{5} S_{ij} a_i a_j$$

$$S_{ij} = \frac{1}{2}(M_i^2 + M_j^2 - p_{ij}) \quad , \quad p_{ij} = k_i + k_{i+1} + \cdots + k_{j-1}$$

scalar pentagon $\longrightarrow \sum$ scalar boxes

$$I_n = \frac{(-1)^n}{2}\left[\sum_{i=1}^{n} c_i I_{n-1}^{(i)} + (n-5+2\epsilon) c_0 I_n^{6-2\epsilon}\right]$$

$$\Downarrow$$

$$E0 = -\frac{1}{2}\left[\sum_{i=1}^{5} c_i D0^{(i)} + 2\epsilon c_0 D0^{6-2\epsilon}\right]$$

Conclusions

- $t\bar{t}H$ very interesting production mode at present and future colliders:
  - discover/confirm the Higgs
  - SM? New Physics?

- Crucial to know the impact of QCD corrections

- $\sigma(p\bar{p} \to t\bar{t}H)$ calculated at NLO: comparing results

- $\sigma(pp \to t\bar{t}H)$ coming soon.