Weak effects in heavy quark and di-jet production

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Outline

- Motivation & Leading order processes
- Next-to-leading order corrections $O(\alpha_s^2\alpha)$
- Results & Discussion
- Conclusion & Outlook

Motivation & Leading order processes

Discoveries and Precision at Colliders

- Recent Colliders (examples)
  - Discovery: W and Z boson at the SPS
  - Precision: Z-resonance at the LEP $\longrightarrow$ three generations
  - Discovery: Top-quark at the Tevatron

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Theory $\longrightarrow$ Standard Model

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Theory $\longrightarrow$ Standard Model

- (Near) future Colliders (examples)
  - LHC: Discovery & Precision machine
    $\longrightarrow$ direct and indirect measurements
  - ILC: High Precision machine

Why weak effects in hadronic collisions ?

- Hadron Colliders
  - Provide high energy events
  - Many observables will be measured at 10-20% accuracy

Theory: NLO corrections

- QCD-corrections are dominant
- Weak corrections
  - Smaller coupling: $\alpha < \alpha_s$
  - Large logarithms: Sudakov Logarithms

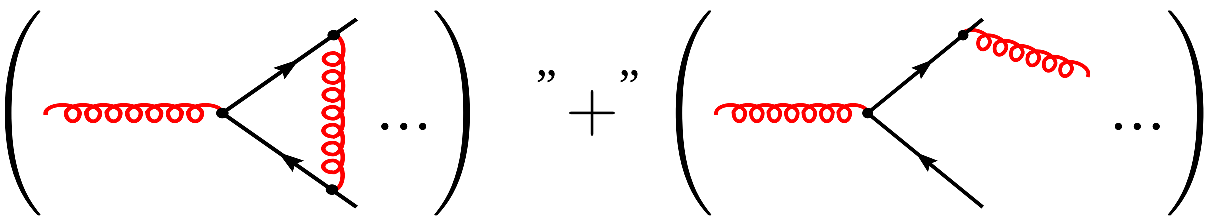
$$\ln^2\left(\frac{E_{cm}}{M_w}\right),\ \ln\left(\frac{E_{cm}}{M_w}\right)$$

(Sudakov 1954)
(Kühn, Penin, Smirnov 1999)
(Ciafaloni, Comelli 1999)
(Denner,Pozzorini 2001)

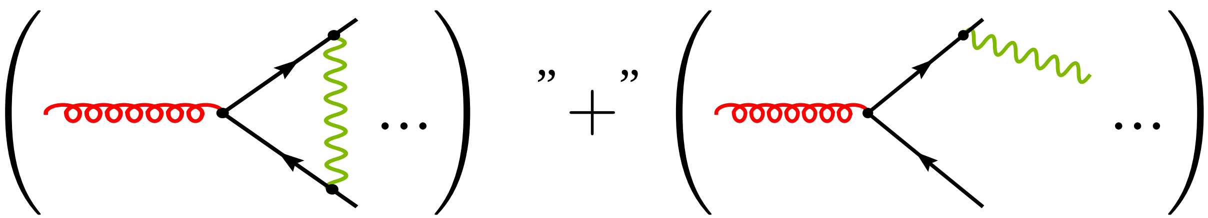
Origin of the Sudakov Logarithms

- Analogy to theories with massless gauge bosons (QCD,QED)
  - Soft and collinear logarithms in virtual corrections
  - Cancellation in the sum of virtual and real contributions

(Bloch, Nordsieck 1937)
(Kinoshita, Lee, Nauenberg 1964)

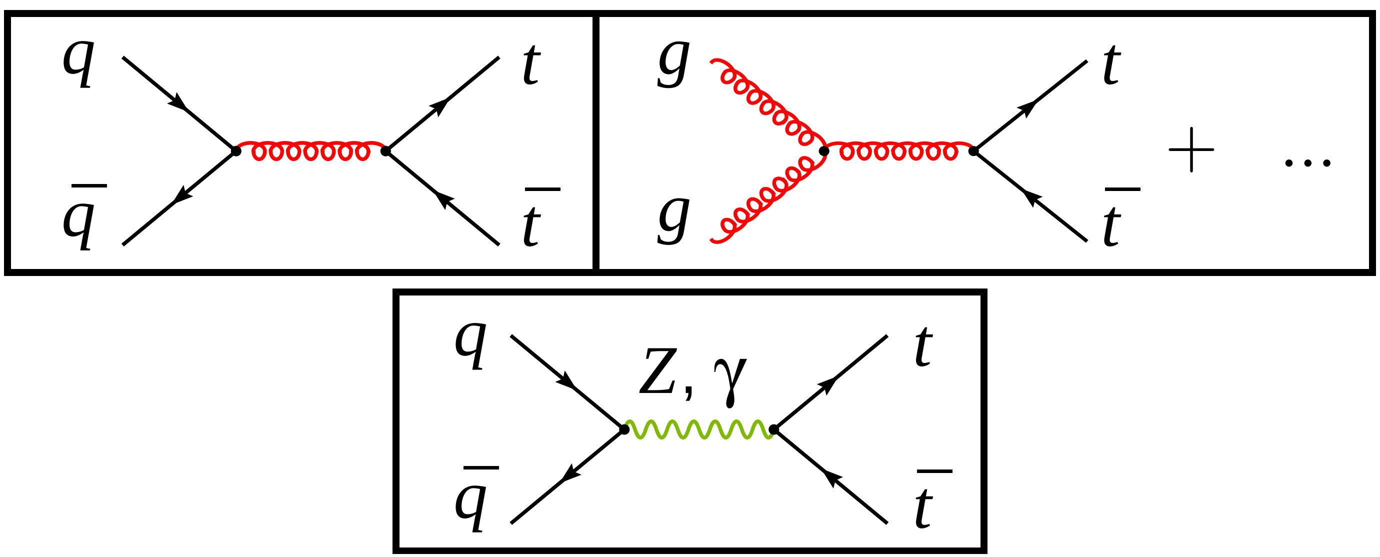


- Weak theory: massive bosons (Z,W)
  - Virtual and real corrections can be separated



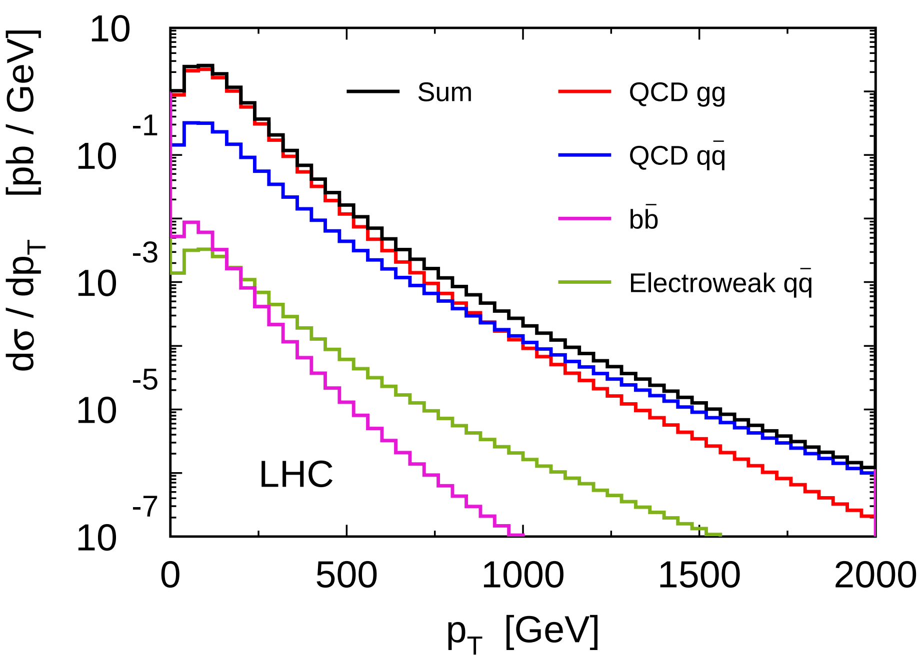
Top-quark pair production

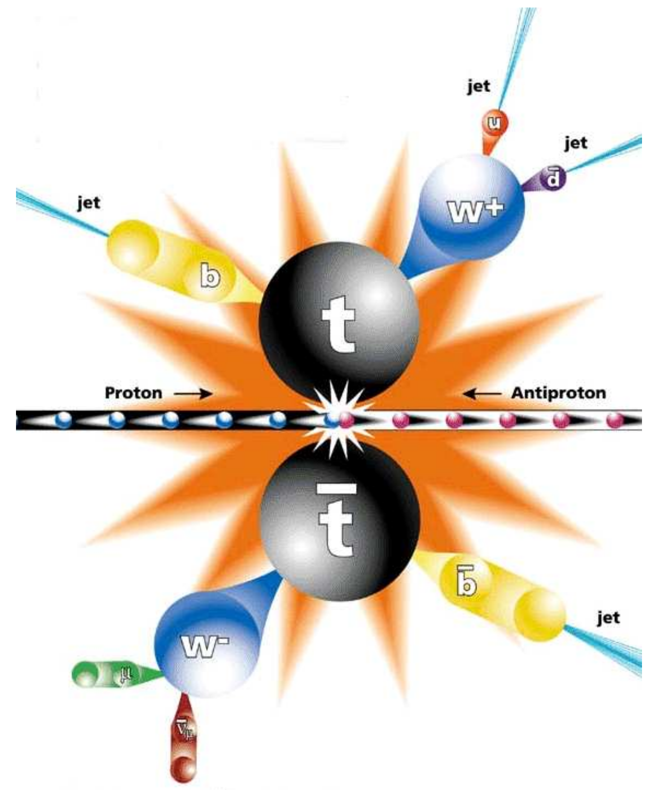
- Top-quark $(m_{\text{top}} \simeq 172.7\ \text{GeV})$
  - Completes the fermion sector of the SM
  - Still not very well measured
  - Probes physics at high mass scale
  - Plays central role in many SM extensions
- $t\bar{t}$-production at Hadron Colliders



Top-quark pair production

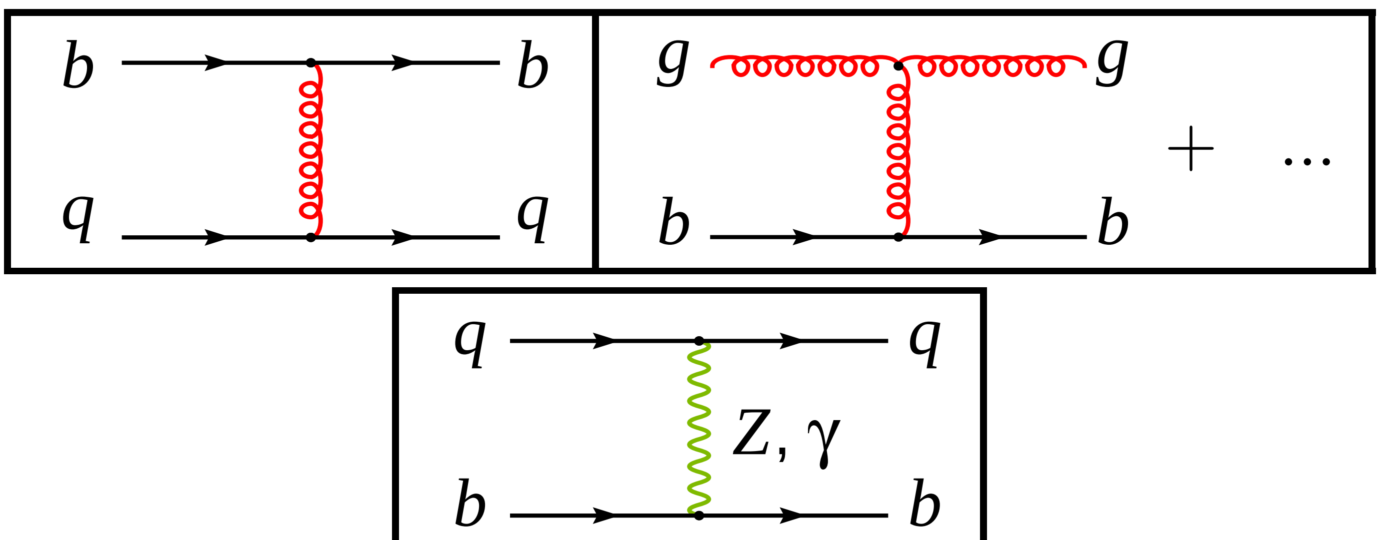
- Experimentally (e.g. $p + \bar{p} \longrightarrow t\bar{t} \longrightarrow b\bar{b} + l\bar{\nu}_l + jj$)
  - Decay channels: di-lepton, semi-leptonic, full hadronic
  - Tevatron: $\frac{\Delta m_t}{m_t} \sim 1\%$
- Leading order $\mathrm{p_T}$ distribution





Bottom jet production

- Bottom-quark ($m_b = 0$)
  - Events with well separated partons ($p_T > 50$ GeV)
  - Background process ($t\bar{t}$, SUSY)
  - Testing the SM at high p_T
- b-jet production at Hadron Colliders

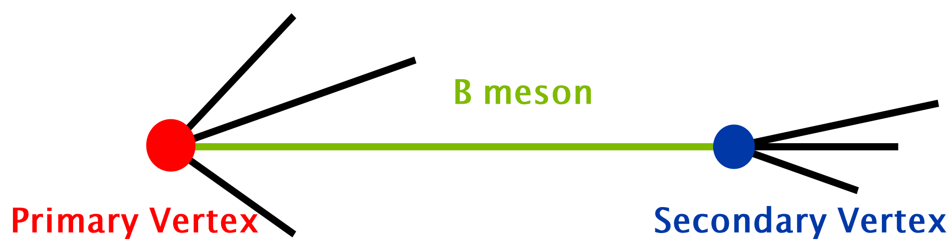


Bottom jet production

- QCD, Mixed and Electroweak contributions

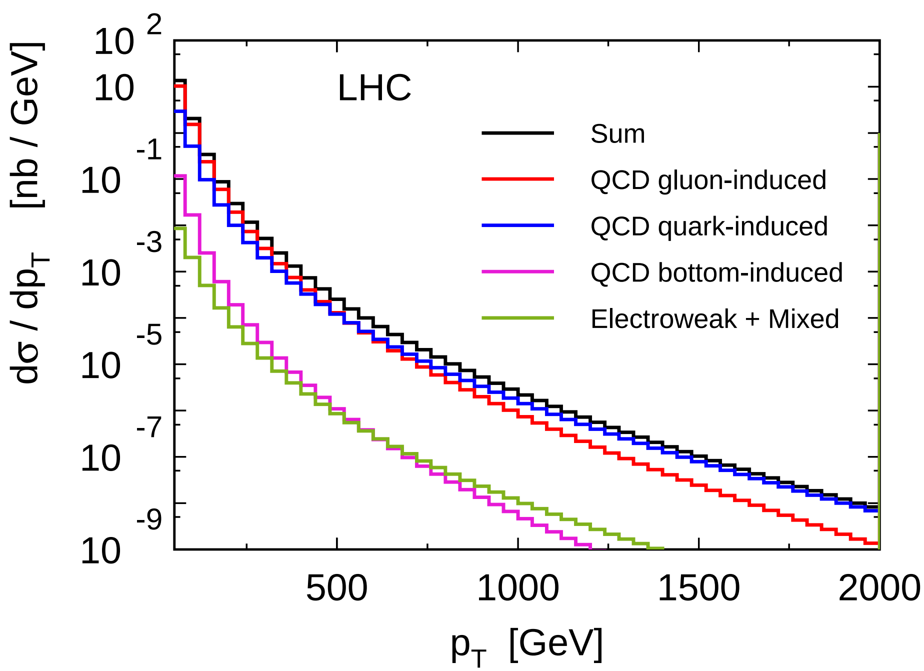
initial state	single b-tag	
quark-induced	$qb \to qb$, $q\bar{b} \to q\bar{b}$, $\bar{q}b \to \bar{q}b$, $\bar{q}\bar{b} \to \bar{q}\bar{b}$	$q\bar{q} \to b\bar{b}$
gluon-induced	$gb \to gb$, $g\bar{b} \to g\bar{b}$	$gg \to b\bar{b}$
pure bottom-induced	$b\bar{b} \to b\bar{b}$, $bb \to bb$, $\overline{bb} \to \overline{bb}$	
	double b-tag	

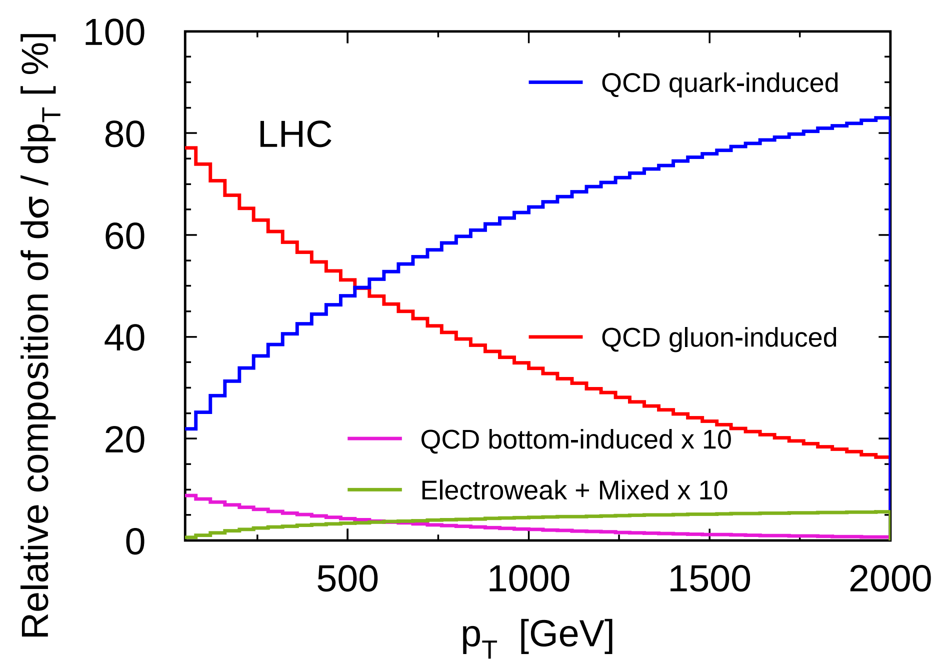
- Experimentally
  - Lifetime of B mesons $\propto 1.5 \times 10^{-12}s$
  - Decay length allows b-jet identification



Bottom jet production

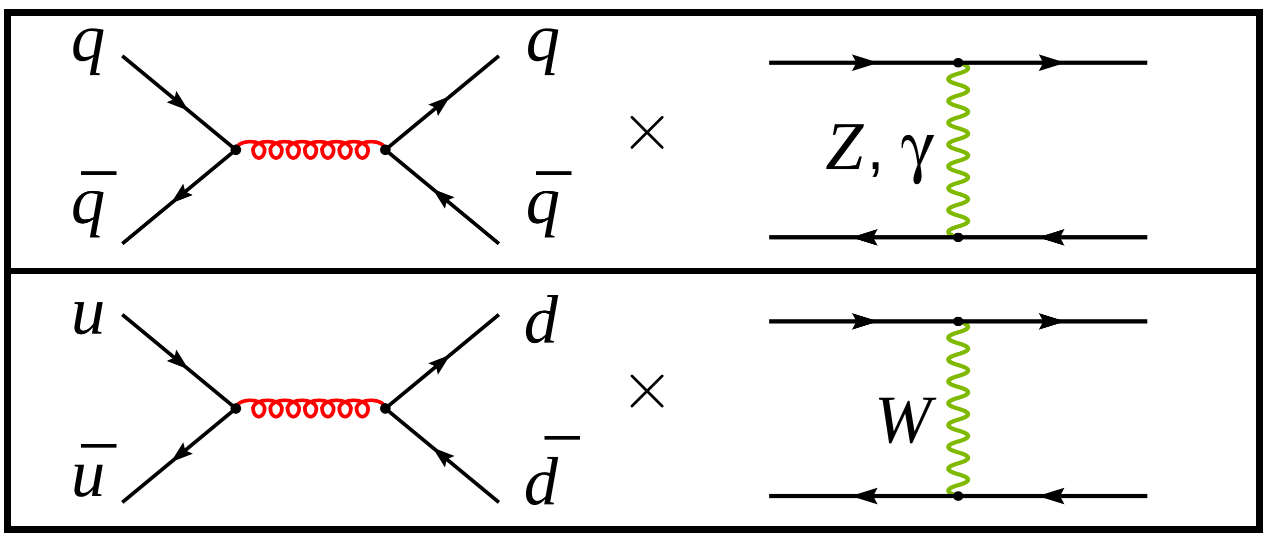
- p_T-distribution at leading order
  - Single b-tag





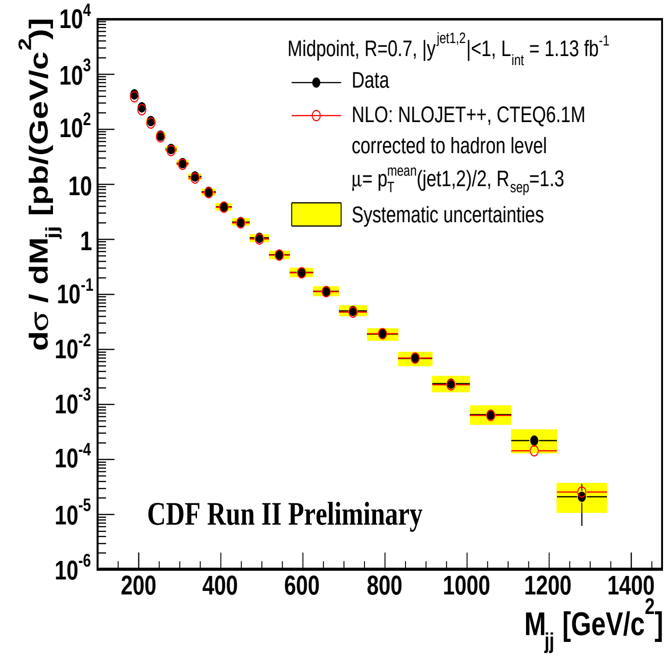
Di-jet production

- Gluon- & light quark-jets ($m_u = m_d = m_s = m_c = 0$)
  - Well separated jets $\mathrm{p_T} > 50$ GeV
  - Indirect new physics search, e.g. Z'
  - Study of jet production rates in the LHC start-up phase
- Di-jet production at Hadron Colliders
  - Processes of $O(\alpha_s^2)$ and $O(\alpha_s \alpha)$!

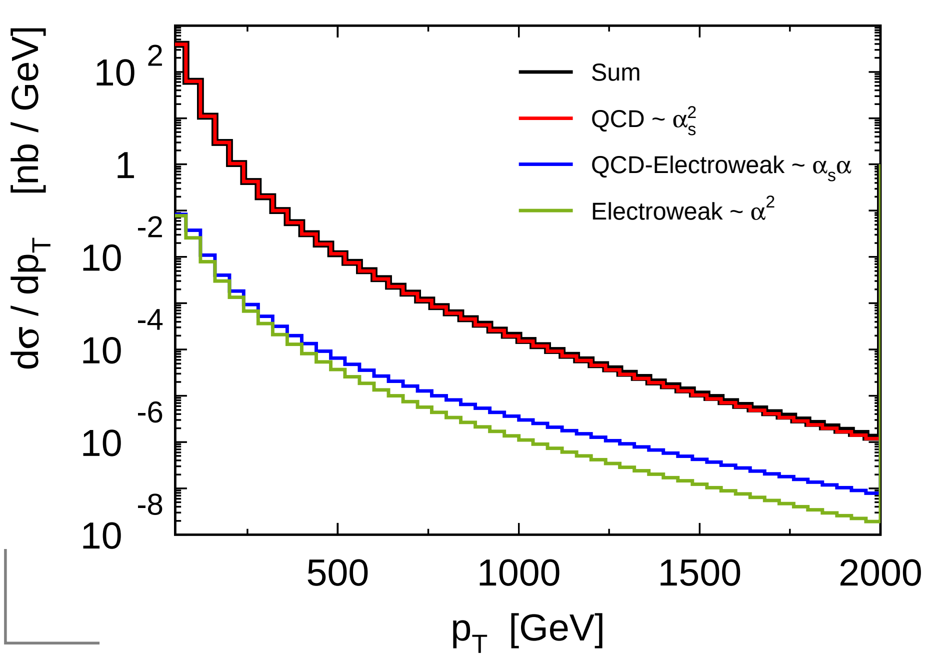


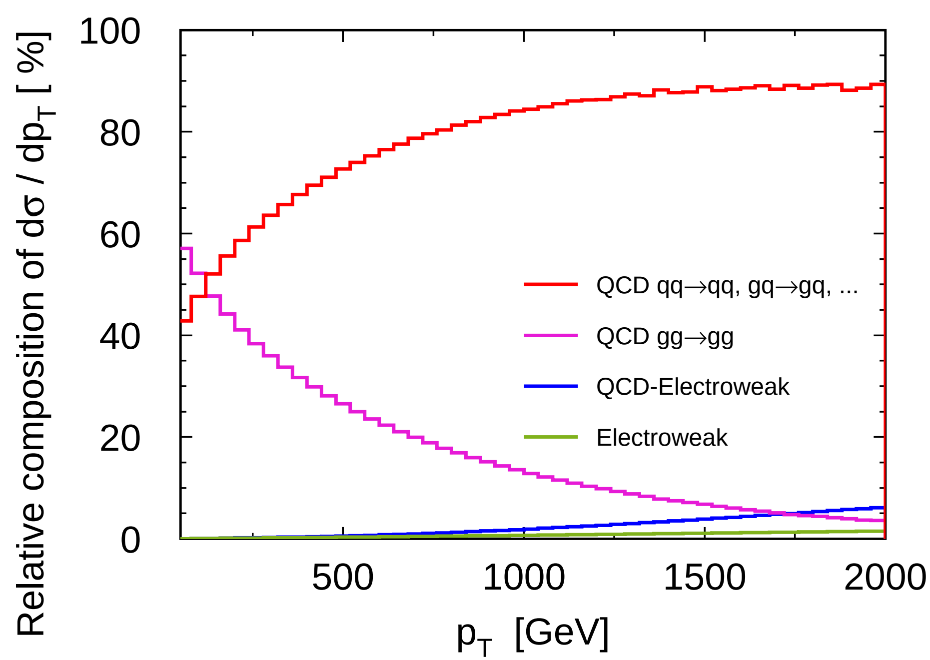
Di-jet production

- Experimentally
  - Tevatron: Di-jet-Masses up to 1 TeV
  - LHC: Di-jet-Masses up to several TeV



- p_T distribution at leading order

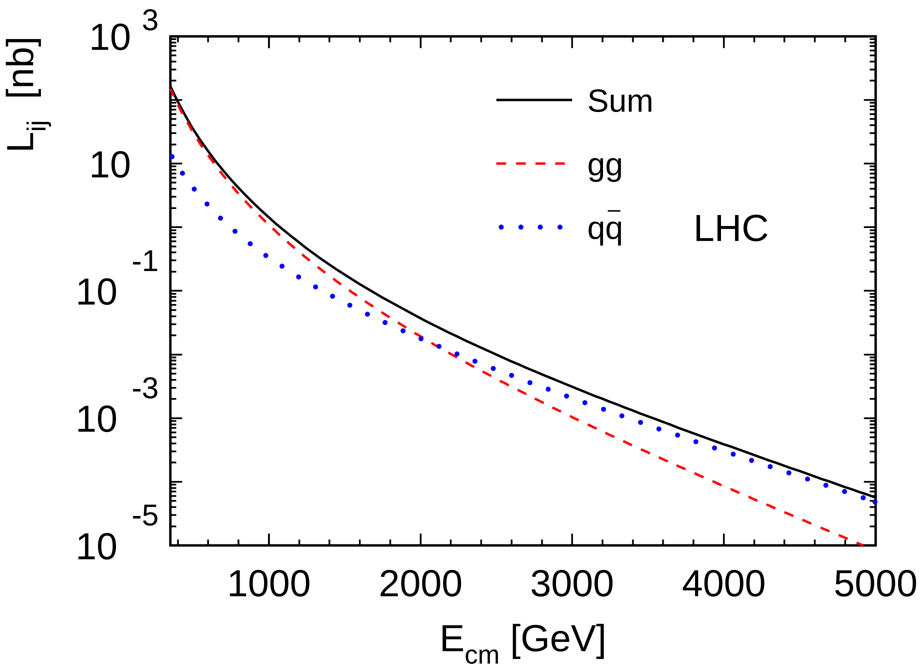




Luminosity at the LHC

- Consider top-quark pair production at LO
  - Define luminosity function:

$$L_{ij}(\tau,\mu_F) = \frac{1}{S}\int_\tau^1 \frac{1}{x_1} f_{i,p}(x_1,\mu_F)\, f_{j,p}\!\left(\frac{\tau}{x_1},\mu_F\right) \quad \text{with } \tau = \frac{E_{cm}^2}{S}$$



Quark density dominates

at high energies!

- Similiar for *b*-jet and di-jet production !

Next-to-leading order corrections $O(\alpha_s^2\alpha)$

Status of NLO calculations

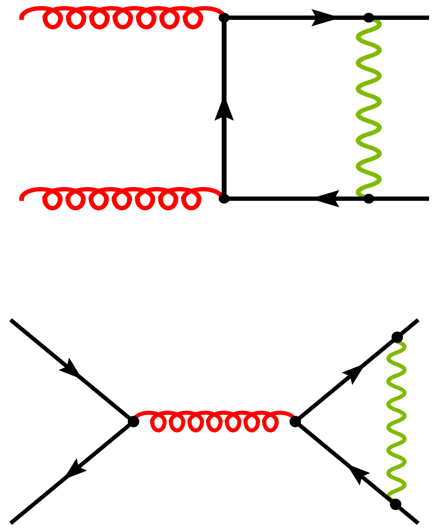
- Top-quark pair production
  - QCD corrections $O(\alpha_s^3)$
    (Dawson, Nason, Ellis 1988)
    (Beenakker, Kuijf, Neerven, Smith 1989)
    (Bernreuther, Brandenburg, Si, Uwer 2004)
  - (Electro-)weak corrections $O(\alpha_s^2\alpha)$
    (Beenakker, Denner, Hollik, Mertig, Sack, Wackeroth 1994)
    (Bernreuther, Fücker, Si 2005, 2006)
    (Kühn, A.S., Uwer 2005, 2006)
    (Hollik, Kollar 2007)
- b-jet production
  - QCD corrections $O(\alpha_s^3)$
    (Dawson, Ellis, Nason 1988)
    (Beenakker, Kuijf, Neerven, Smith 1989)
    (Frixione, Mangano 1997)
  - $b\bar{b}$ production $O(\alpha_s^2\alpha)$
    (Moretti et al 2003)
- Di-jet production
  - QCD corrections $O(\alpha_s^3)$
    (Ellis, Sexton 1985)
    (Aversa et al 1988, 1991)
  - Weak corrections $O(\alpha_s^2\alpha)$
    (Moretti et al 2006)

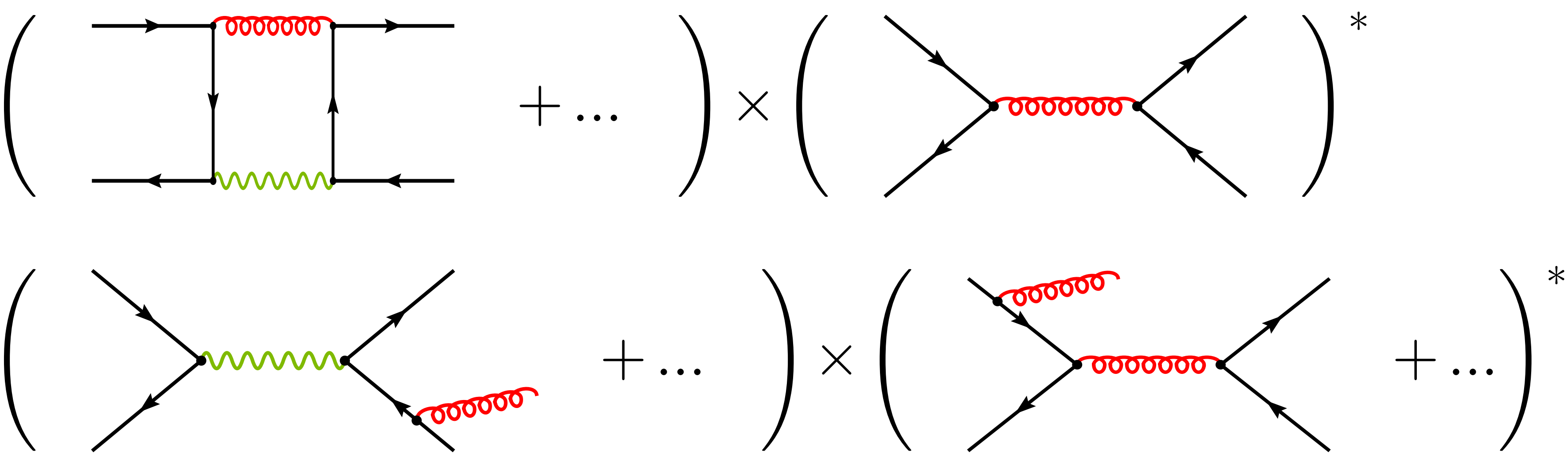
General Remarks

- Corrections of $O(\alpha_s^2\alpha)$ calculated in Feynman-'t Hooft Gauge
- Consider only weak corrections $\longrightarrow$ neglecting photonic contributions
  - Gauge invariant subset
  - Photonic contributions involve no Sudakov Logarithms
- $t\bar{t}$ and b-jet production
  - $O(\alpha)$ corrections to LO α_s^2 processes: $Z, W, \phi, (\chi, H)$
- Di-jet production
  - "$O(\alpha)$ corrections to LO α_s^2 processes: Z, W "
  - "$O(\alpha_s)$ corrections to LO $\alpha_s\alpha$ processes"

Methods: Overview

- Passarino-Veltman reduction
- Scalar Integrals
- Renormalisation
- Real corrections



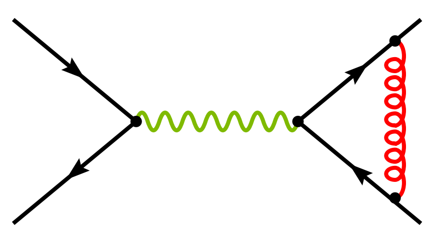


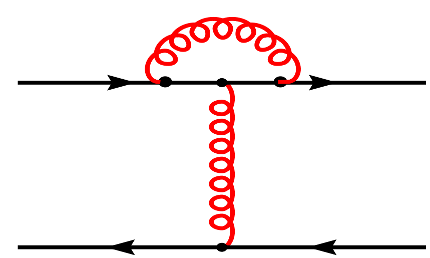
Methods: Renormalisation

- Renormalisation: Counterterm formalism (Denner 1991)

$$\mathcal{L}(\Psi_0, A_0, m_0, g_0) \to \mathcal{L}(\Psi_R, A_R, m_R, g_R) + \mathcal{L}_{ct}(\Psi_R, A_R, m_R, g_R)$$

- $t\bar{t}$ and b-jet production: $O(\alpha)$ corrections
  - On-shell scheme
  - No coupling renormalisation is needed
  - Only wave function and mass renormalisation
- Di-jet production
  - On-shell scheme (like $t\bar{t}$ and b-jet)
  - $\overline{\mathrm{MS}}$ scheme





Methods: Real corrections

- IR singularities
  - Phase-space-slicing (Giele, Glover 1992) (Giele, Glover, Kosower 1993)
  - (Dipole-) subtraction method (Catani, Seymour 1996) (Catani, Dittmaier, Seymour, Troćsányi 2002)
- Virtual corrections considered here
  - Only four quark processes are IR divergent
- IR divergent real corrections to four quark processes
  - Only $q(\bar{q}) \to q(\bar{q}) + g$ splitting must be considered
- $t\bar{t}$ and b-jet production
  - Partonic results are independent from μ_F

Methods: (Dipole-) Subtraction

Dipoles

- Subtraction method in e^+e^- collisions ($e^+e^- \longrightarrow m$)

$$\sigma^{\text{NLO}} = \int_m d\sigma^V + \int_{m+1} d\sigma^R = \int_m \left[d\sigma^V + \int_1 d\sigma^A \right] + \int_{m+1} \left[d\sigma^R - d\sigma^A \right]$$

Integrated dipoles

Methods: (Dipole-) Subtraction

Dipoles

- Subtraction method in e^+e^- collisions ($e^+e^- \longrightarrow m$)

$$\sigma^{\mathrm{NLO}} = \int_m d\sigma^V + \int_{m+1} d\sigma^R = \int_m \left[d\sigma^V + \int_1 d\sigma^A\right] + \int_{m+1} \left[d\sigma^R - d\sigma^A\right]$$

Integrated dipoles

- Dipole method in hadron collisions ($h_1 h_2 \longrightarrow m$)

$$\sigma^{\mathrm{NLO}} = \int_{m+1} d\sigma^R + \int_m d\sigma^V + \int_m d\sigma^C$$

Has same singularity structure as $d\sigma^R$

$$= \int_{m+1} \left[\left(d\sigma^R\right)_{\varepsilon=0} - \left(\sum_{dipoles} d\sigma^{LO} \otimes dV_{dipole} \right)_{\varepsilon=0} \right]$$

Contains all ε poles

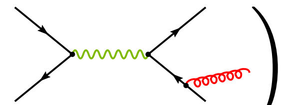
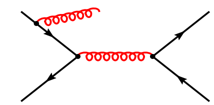
Finite remainder

$$+ \int_m \left[d\sigma^V + d\sigma^{LO} \otimes \mathbf{I}\right]_{\varepsilon=0} + \int dx \int_m d\sigma^{LO}(x) \otimes \left(\mathbf{K}(\mathbf{x}) + \mathbf{P}(\mathbf{x})\right)$$

Methods: Technical Details

- Goal: Compact analytic results for further studies
- Amplitudes, Passarino-Veltman reduction & Renormalisation
  - FORM, MATHEMATICA, MAPLE
- Scalar Integrals
  - FF-LIBRARY, literature, analytical computation
- Numerics & Dipoles
  - FORTRAN 77
  - C/C++

Example

- Real corrections for $q\bar{q} \to b\bar{b}g$ $\Big($  $\Big) \times \Big($  $\Big)^*$

$$
\begin{aligned}
\frac{1}{4}\frac{1}{N^2}\sum_{\text{Spin}}\sum_{\text{Colour}}\left|M^{q\bar{q}\to b\bar{b}g}\right|^2 &= \alpha_s^2\alpha(4\pi)^3\,\frac{N^2-1}{N^2} \\
&\times \Big(g_v^q g_v^b(t_1^2+t_2^2+u_1^2+u_2^2) - g_a^q g_a^b(t_1^2+t_2^2-u_1^2-u_2^2)\Big) \\
&\times \frac{1}{s}\,\frac{1}{s-m_Z{}^2}\,\frac{1}{s+t_1+t_2+u_1+u_2}\,\frac{1}{s+t_1+t_2+u_1+u_2+m_Z{}^2} \\
&\times \frac{1}{s+t_1+u_1}\,\frac{1}{s+t_2+u_1}\,\frac{1}{s+t_1+u_2}\,\frac{1}{s+t_2+u_2} \\
&\times \Big(2s^2+(t_1+t_2+u_1+u_2)(2s-m_Z{}^2)\Big) \\
&\times \Big((t_1+t_2-u_1-u_2)s^2+((t_1+t_2)^2-(u_1+u_2)^2)s \\
&+ (t_1+t_2+u_1+u_2)(t_1t_2-u_1u_2)\Big)
\end{aligned}
$$

Consistency

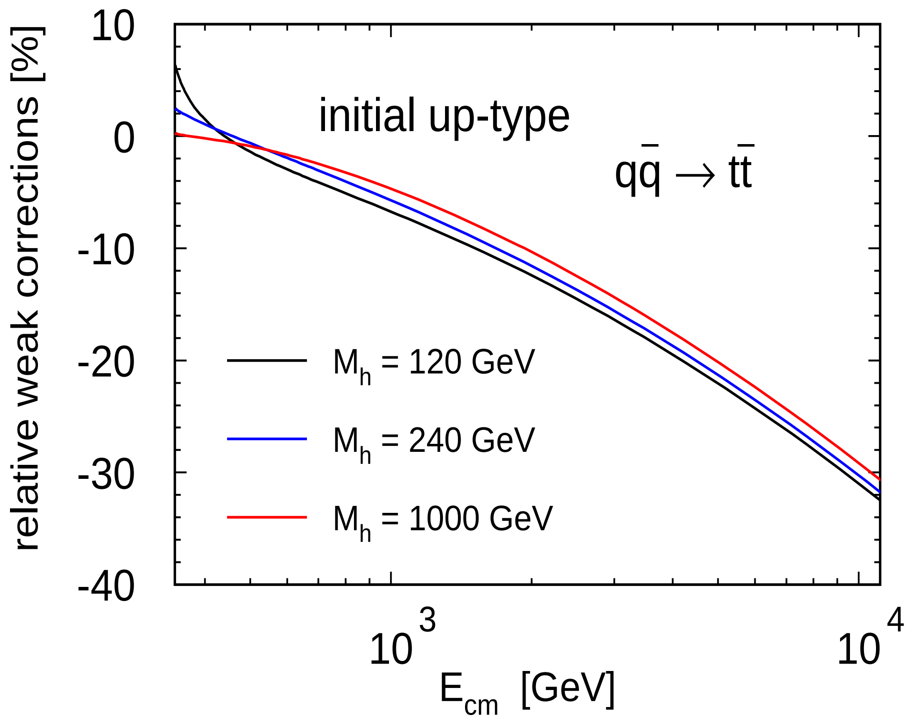
- $t\bar{t}$ production
  - Cancellation of the IR and UV poles, ... ✓
  - Independent calculation by Peter Uwer ✓
  - Parallel work ✓ (W. Bernreuther, M. Fücker, Z.G. Si)
  - Literature ✓ (Beenakker, Denner, Hollik, Mertig, Sack, Wackeroth 1994) (Grzadkowski, Kühn 1987) (Kniehl, Kühn 1989) (Jezábek, Kühn 1993)
    $\longrightarrow$ No aggreement with Moretti et al 2006
- b-jet production
  - Cancellation of the IR and UV poles, ... ✓
  - Crossing symmetries ✓
  - Independent calculation by Peter Uwer (✓)
  - Literature

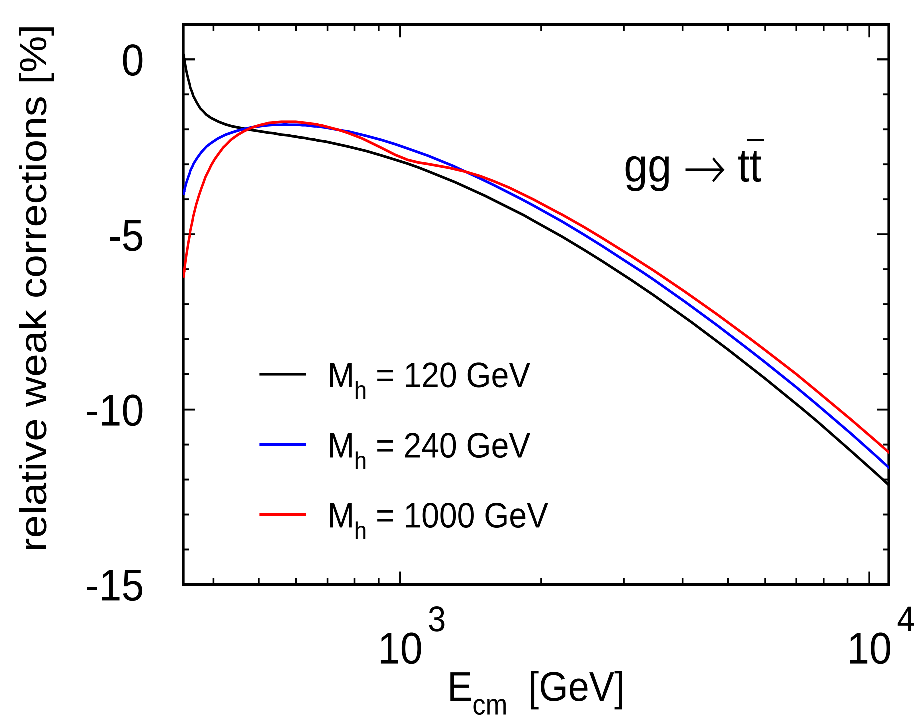
Status of di-jet production

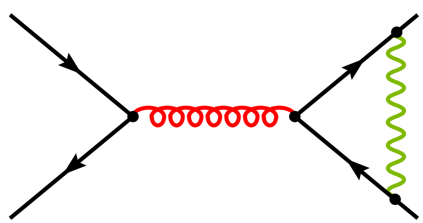
- Virtual Corrections ✓
- Real Corrections ✓
- Renormalisation ✓
- Subtraction method in progress

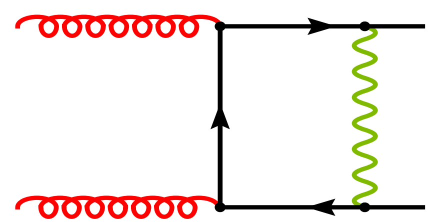
Results & Discussion

Partonic results for $t\bar{t}$ production







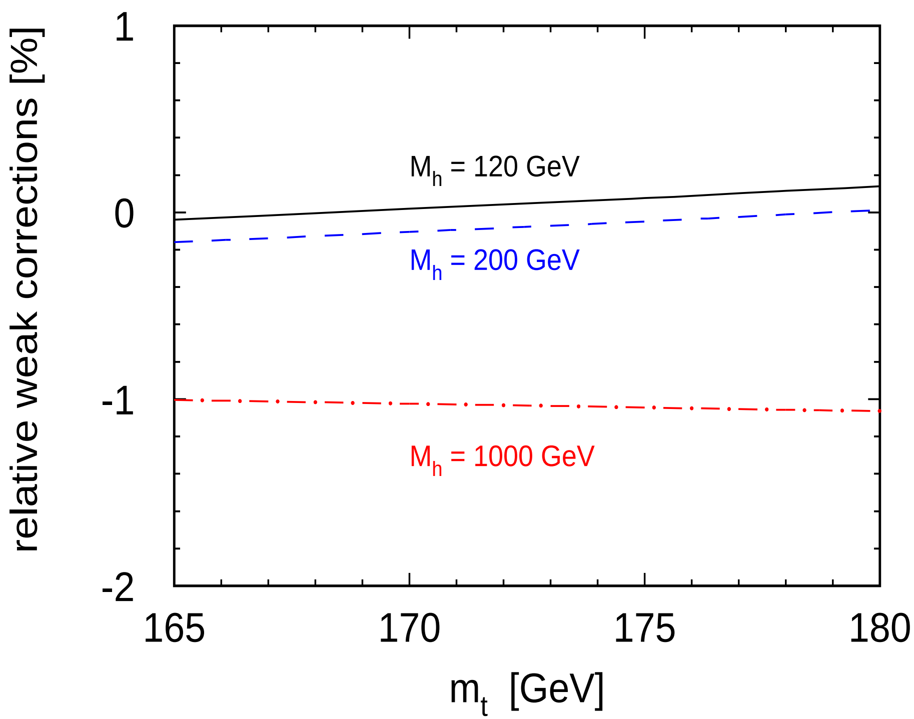


- Quark-induced processes receive larger corrections

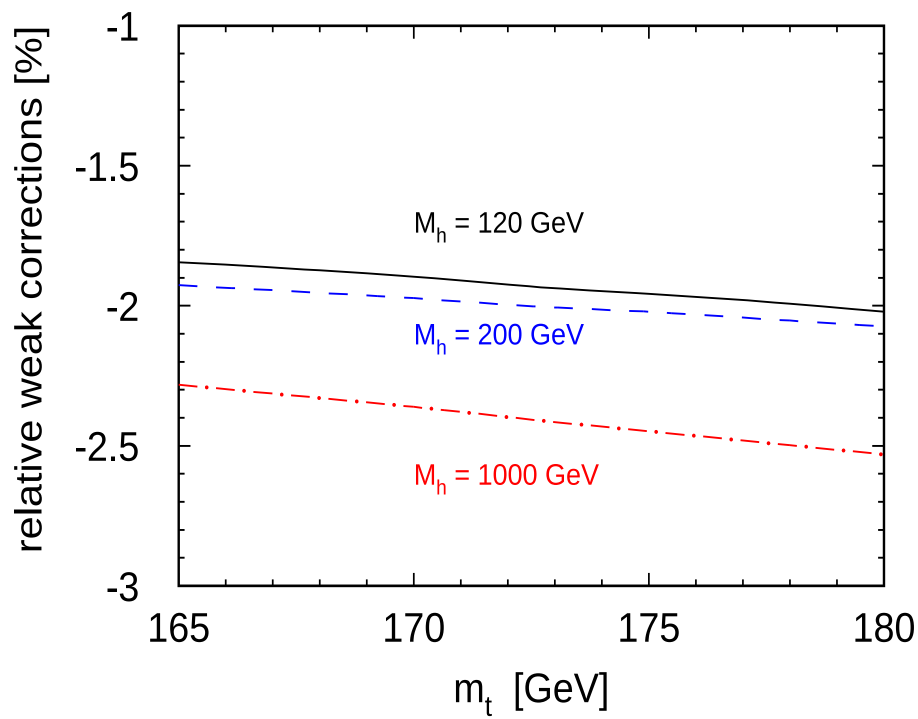
Total hadronic cross section for $t\bar{t}$

- Small corrections

TEVATRON

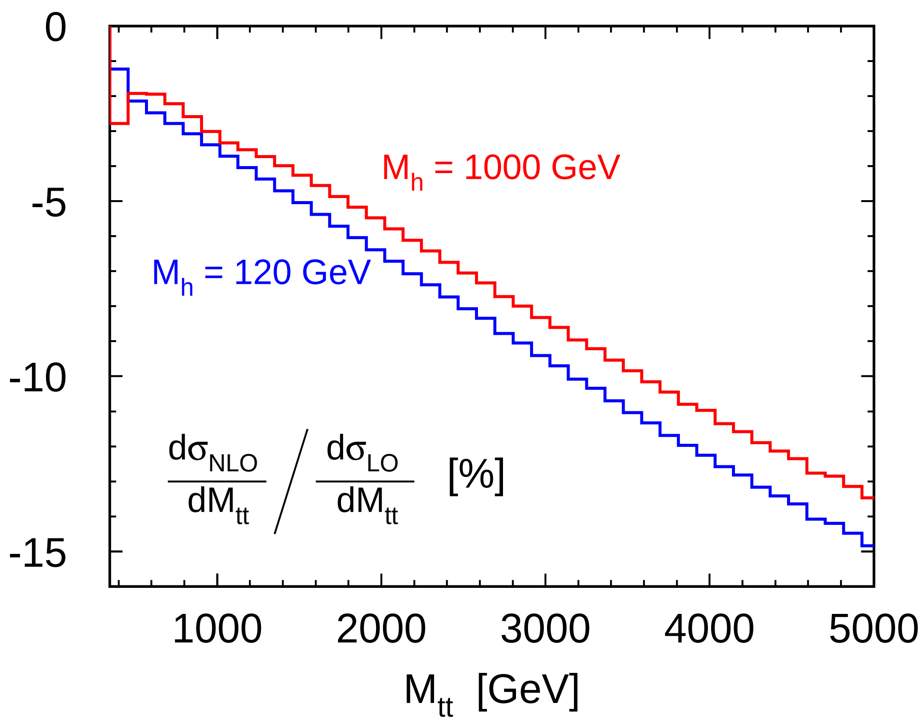


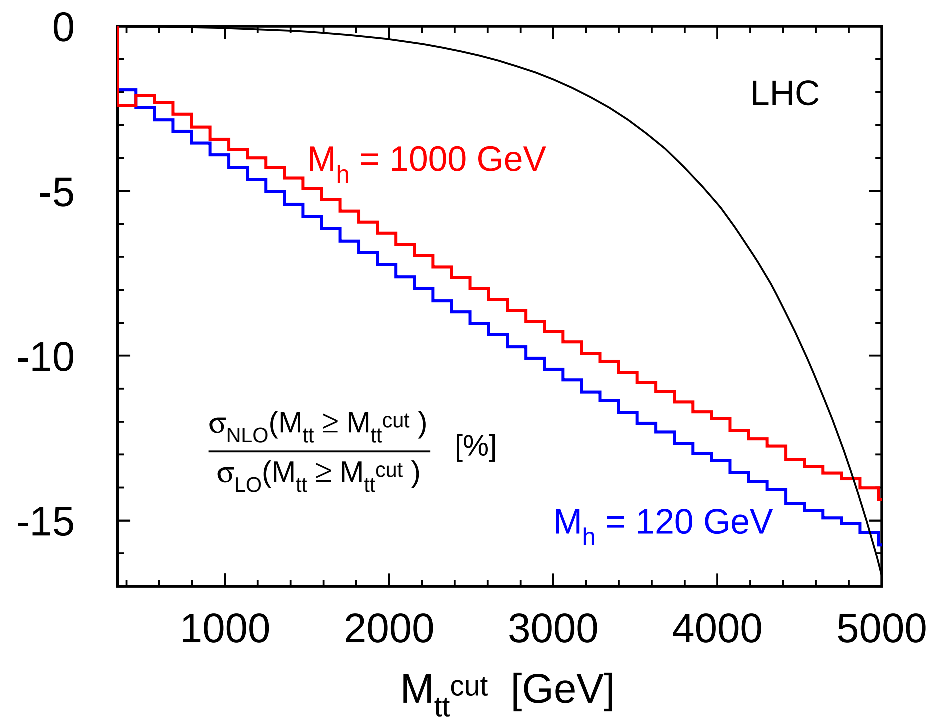
LHC



$t\bar{t}$ production at the LHC

- Relative corrections to $M_{t\bar{t}} = \sqrt{(k_t + k_{\bar{t}})^2}$

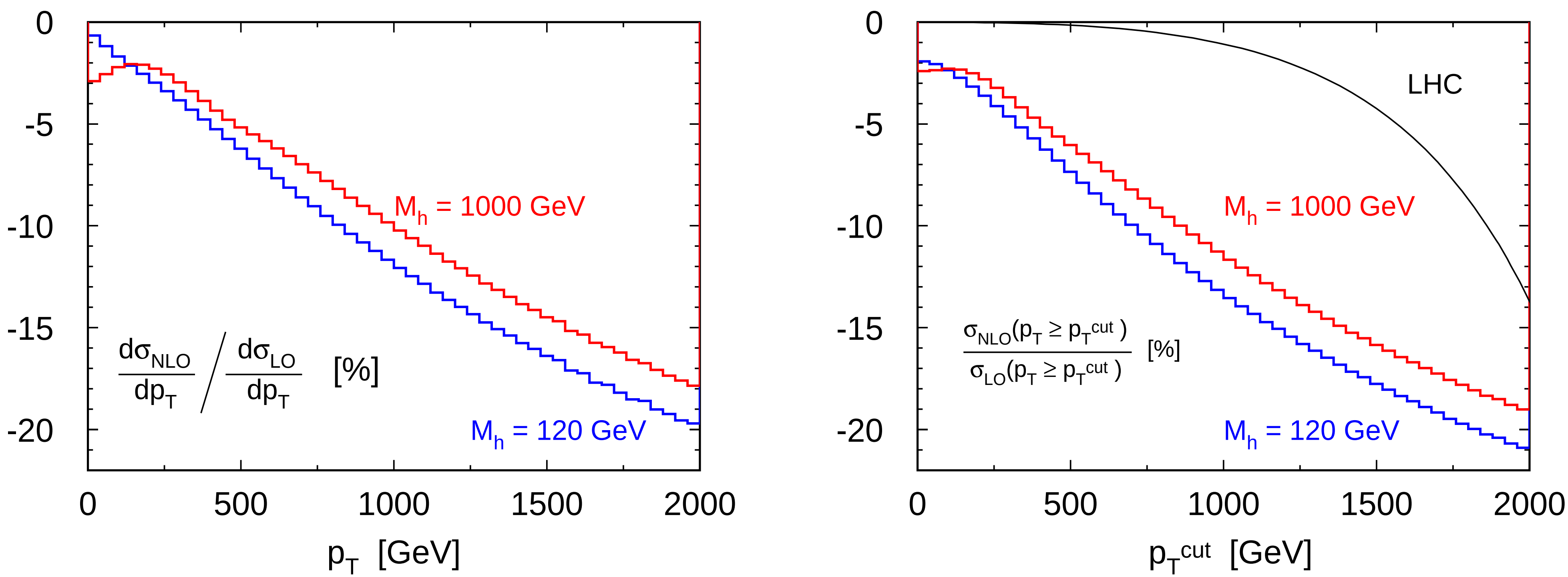




$$\int \mathcal{L}\, dt = 200\text{fb}^{-1}$$

$t\bar{t}$ production at the LHC

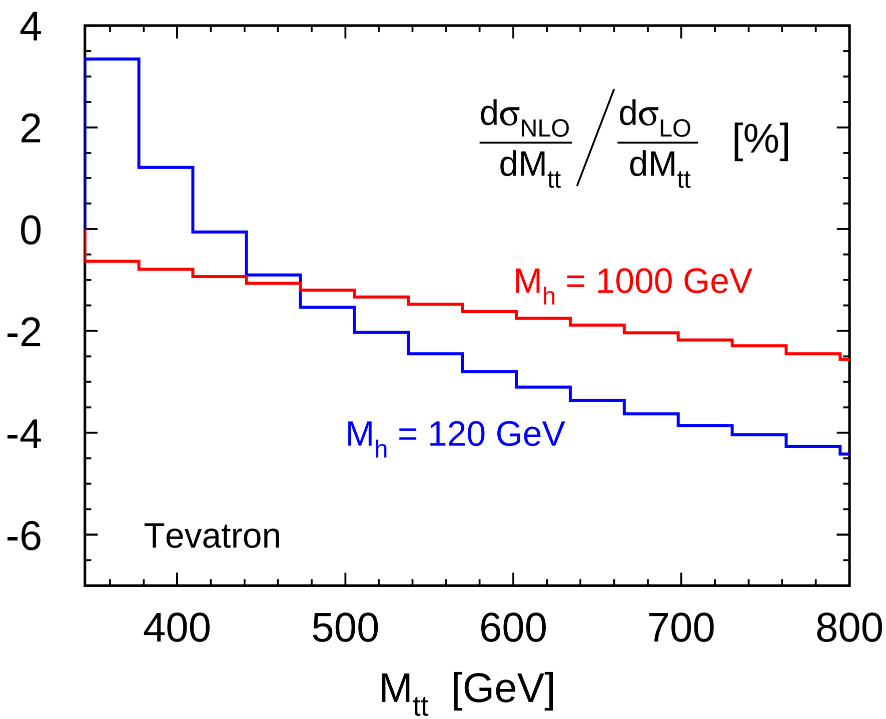
- Relative corrections to p_T

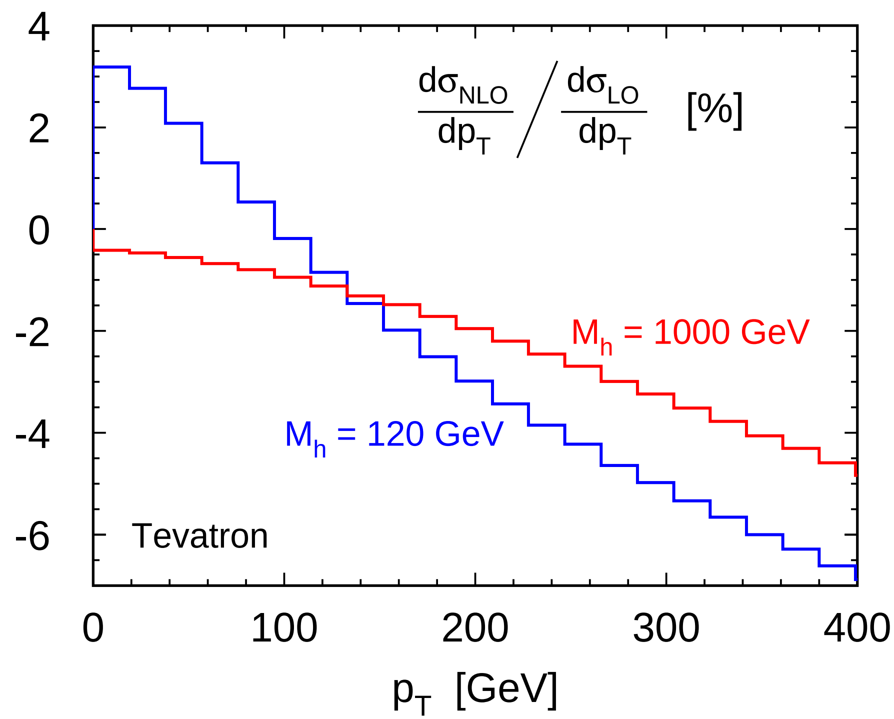


$$\int \mathcal{L}\, dt = 200 \text{fb}^{-1}$$

$t\bar{t}$ production at the Tevatron

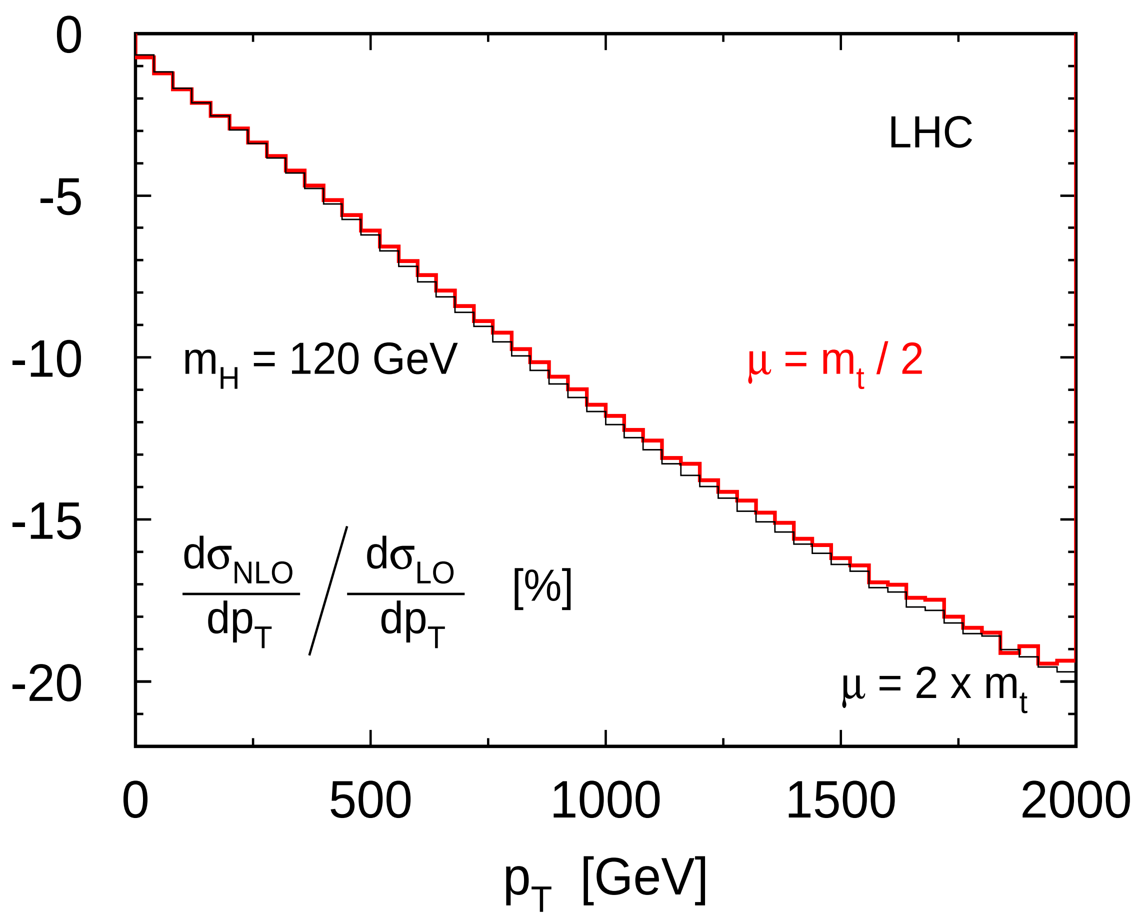
- Relative corrections





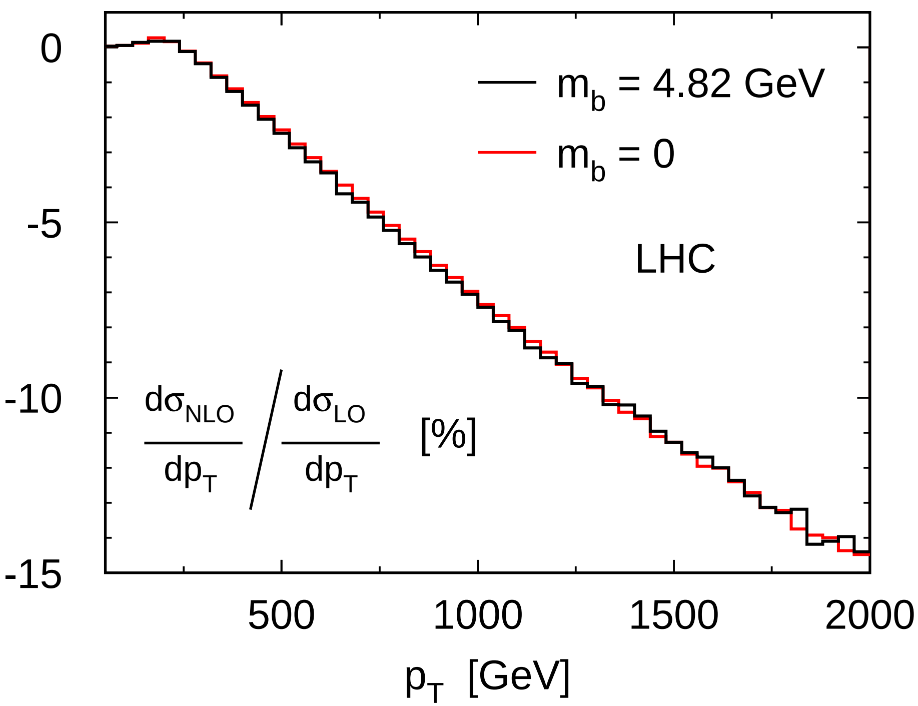
Scale Dependence for $t\bar{t}$ production

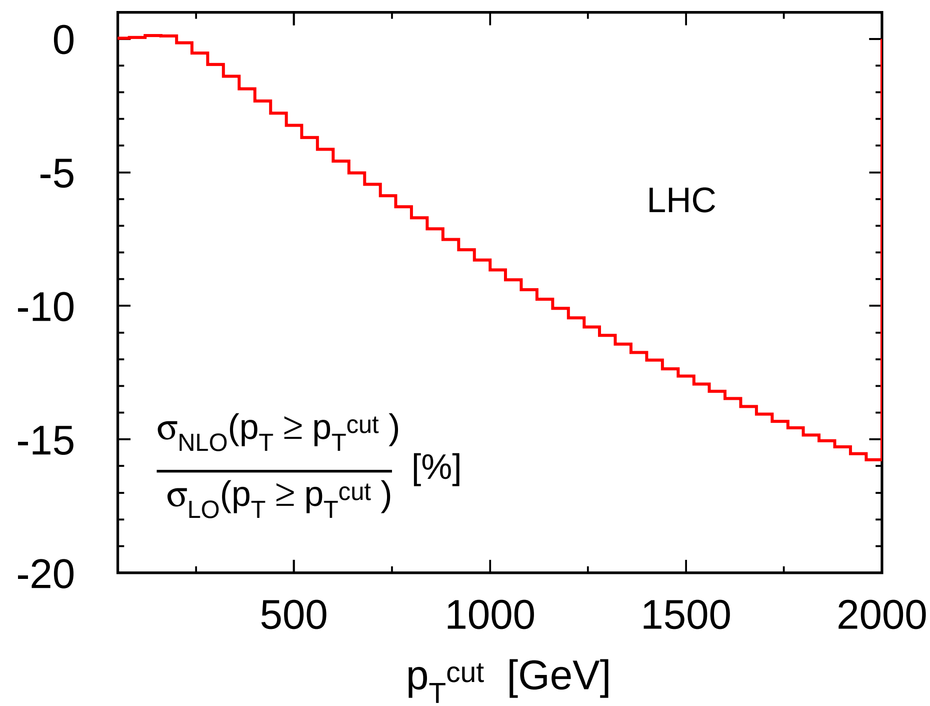
- $\mu = \mu_R = \mu_F$



b-jet production at the LHC

- Preliminary results
- Relative corrections to p_T: double *b* tag





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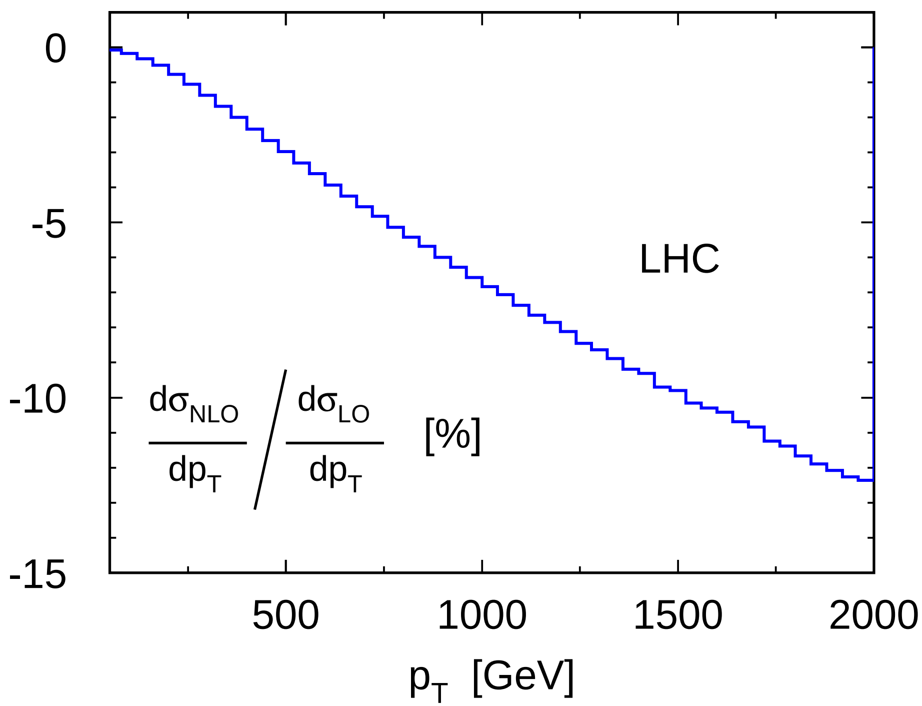
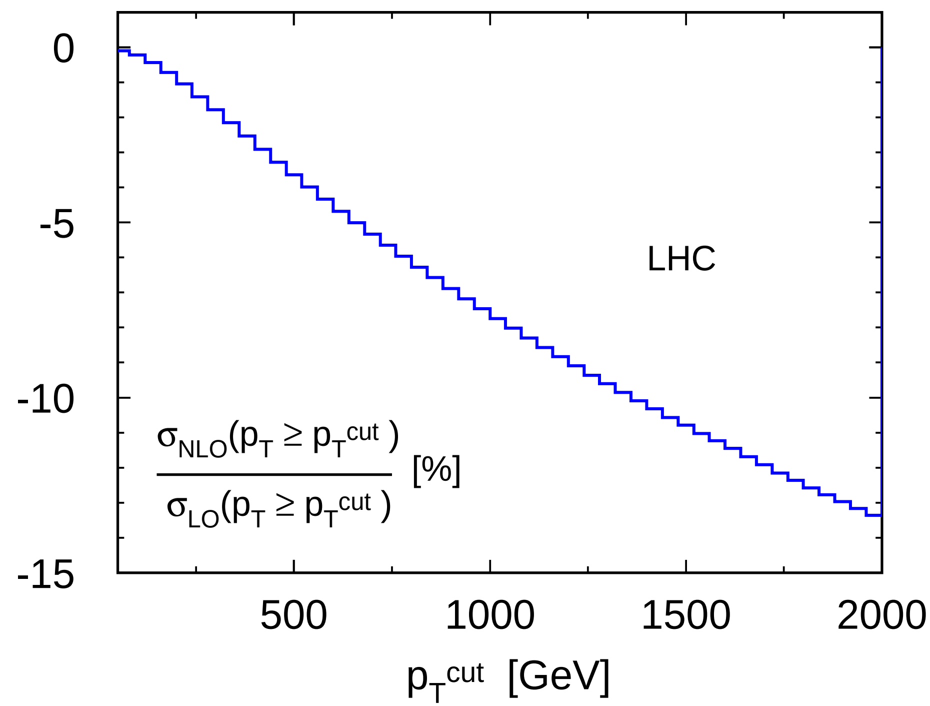
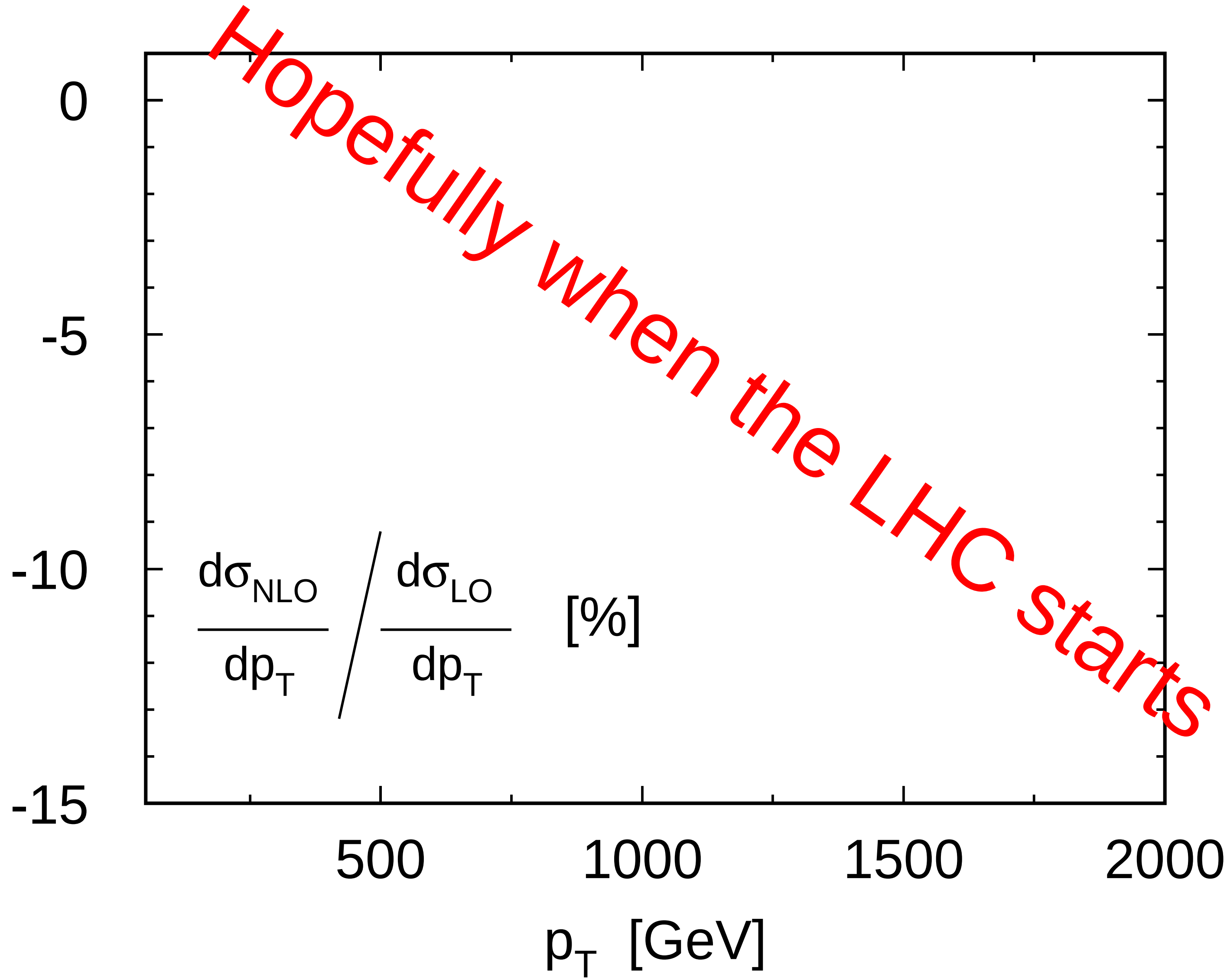




Di-jet production

- Preliminary prediction



Discussion: General remarks

- Small corrections to total cross sections
- Important corrections for differential distributions at high energies
  - Statistics ?
  - Precision ?
- Weak boson emission ? (Baur 2006)
- Parton distribution functions
  - Error for light quark-PDF's $\sim$ 10 % (2 TeV)
  - Error for gluon-PDF's $\sim$ 50 % (2 TeV)

Discussion

- $t\bar{t}$ production
  - NLO corrections to the "real" process $(p+p \longrightarrow t\bar{t} \longrightarrow b\bar{b} + l\bar{\nu}_l + jj)$?
  - NNLO corrections ?
- b-jet production
  - Bottom-quark PDF's are not measured up to now
  - Uncertainity on the jet energy-scale
- Di-jet production
  - Uncertainity on the jet energy-scale
- ... .

Conclusion & Outlook

Conclusion

- Heavy quark and di-jet production
  - Standard Model ?
  - New physics ?
- Weak corrections are important for differential distributions
  - Top-quark pair production: $15-20\%$
  - b-jet production: $10-15\%$
  - Analytic results for further studies

Outlook

- b-jet production
  - Study further observables
- Di-jet production
  - Data taking starts already in the LHC warm up phase
  - Weak corrections should be known