Top-Quark Production at Hadron Colliders

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Plan of the Talk

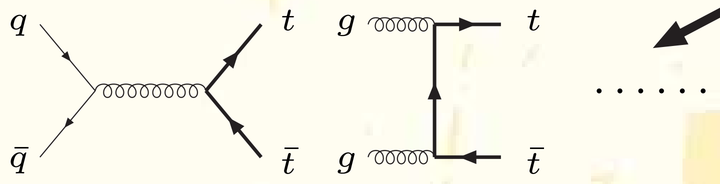
- General Introduction
  - Top Quark at the Tevatron
  - Top Quark at the LHC
- Status of the Theoretical Calculations
  - The General Framework
  - The NLO Corrections
  - Higher-order Corrections
- Conclusions

Top Quark

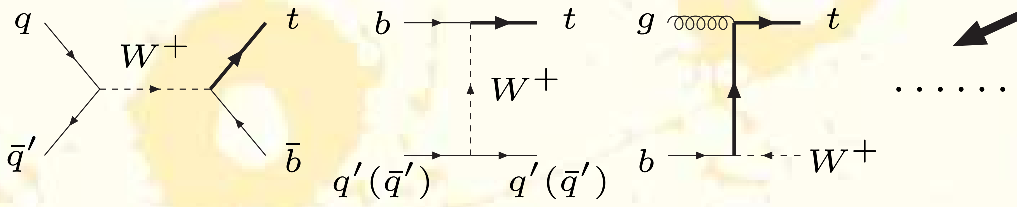
Top Quark

- With a mass of $m_t = 173.3 \pm 1.1$ GeV (July 2010), the TOP quark (the up-type quark of the third generation) is the heaviest elementary particle produced so far at colliders.
- Because of its mass, top quark is going to play a unique role in understanding the EW symmetry breaking $\Rightarrow$ Heavy-Quark physics crucial at the LHC.
- Two production mechanisms
  - $pp(\bar{p}) \to t\bar{t}$
  - $pp(\bar{p}) \to t\bar{b}, tq'(\bar{q}'), tW^-$

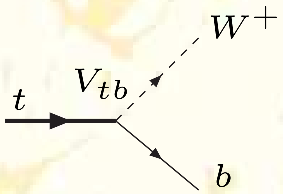
Pair Production



Single Top



- Signal or background for new physics
- Top quark does not hadronize, since it decays in about $5 \cdot 10^{-25}$s (one order of magnitude smaller than the hadronization time) $\Longrightarrow$ opportunity to study the quark as single particle
  - Spin properties
  - Interaction vertices
  - Top quark mass
- Decay products: almost exclusively $t \to W^+ b \quad (|V_{tb}| \gg |V_{td}|, |V_{ts}|)$

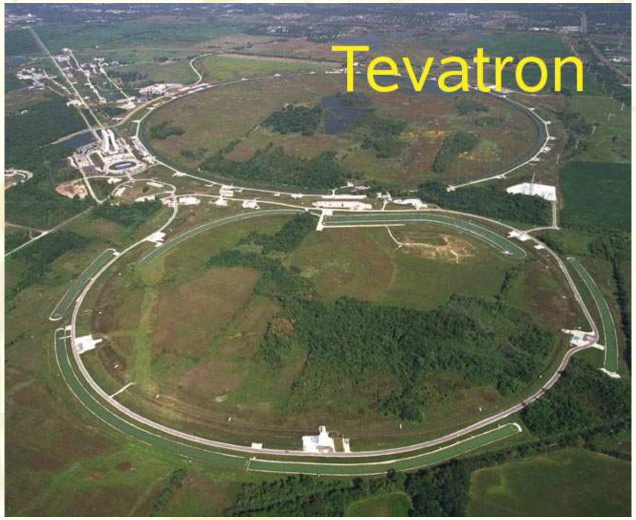


Top Quark

Tevatron	LHC

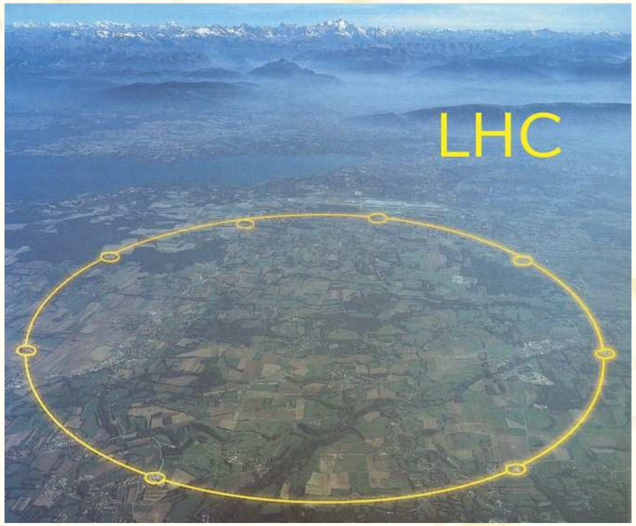
Tevatron

- Up to 2010 the Top quark could be produced and studied only at the Tevatron (discovery 1995)
- $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV
- $L \sim 9\text{fb}^{-1}$ reached in 2010 (12fb^{-1} expected by 2011)
- $\mathcal{O}(10^3)$ $t\bar{t}$ pairs produced so far
- 2009 observation single-top



LHC

- Running since end 2009
- pp collisions at $\sqrt{s} = 7\,(14)$ TeV
- LHC is a factory for HQ ($\mathcal{L} \sim 100\,fb^{-1}/y\,@\,14$ TeV, $t\bar{t}$ at ~1Hz!)
- Recently $\sim 36\text{pb}^{-1}$ @ 7 TeV $\sim \mathcal{O}(10^3)$ $t\bar{t}$ pairs produced so far
- Single top: first measurement June 2011



Top Quark @ Tevatron

Top Quark @ Tevatron

$t\bar{t}$ events measured at Tevatron

$\sigma_{t\bar{t}} \sim$ 7pb

- $p\bar{p} \to t\bar{t} \to W^+bW^-\bar{b} \to l\nu l\nu b\bar{b}$ — Dilepton $\sim 10\%$
- $p\bar{p} \to t\bar{t} \to W^+bW^-\bar{b} \to l\nu q\bar{q}'b\bar{b}$ — Lep+jets $\sim 44\%$
- $p\bar{p} \to t\bar{t} \to W^+bW^-\bar{b} \to q\bar{q}'q\bar{q}'b\bar{b}$ — All jets $\sim 46\%$

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2 high-p_T lept, $\geq$ 2 jets and ME

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NO lept, $\geq$ 6 jets and low ME

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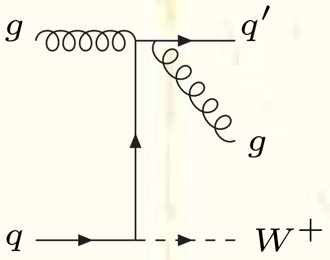
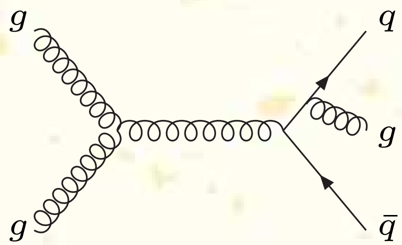
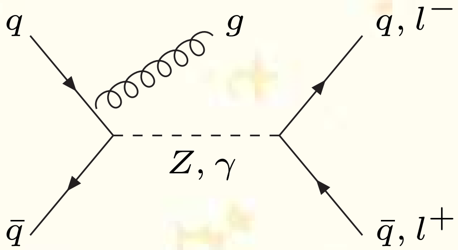
Background Processes



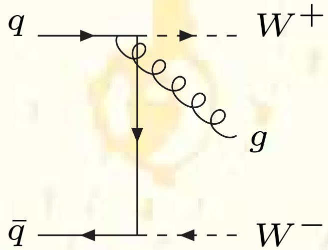
W+jets



QCD



Drell-Yan



Di-boson

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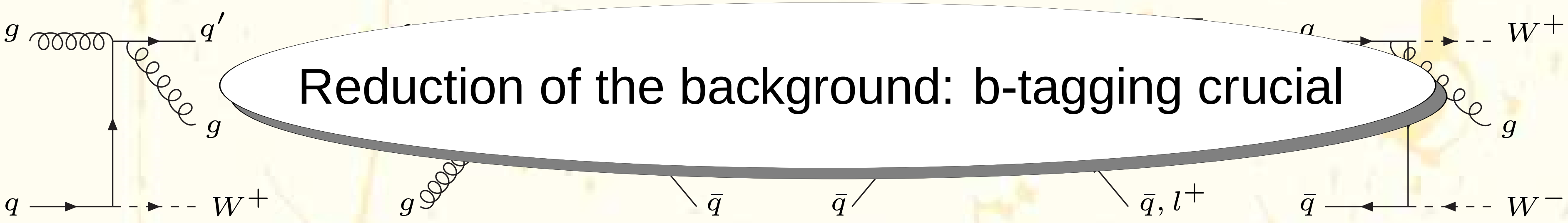
Background Processes

Reduction of the background: b-tagging crucial



W+jets | QCD | Drell-Yan | Di-boson

Top Quark @ Tevatron

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Single-top events measured at Tevatron

$\sigma_t \sim 3\text{pb}$

- $p\bar{p} \to t\bar{q}' \to W^+ b\bar{q}'(\to l\nu b\bar{q}')$ — t-channel $\sim$ 63%
- $p\bar{p} \to t\bar{b} \to W^+ b\bar{b}(\to l\nu b\bar{b})$ — s-channel $\sim$ 30%
- $p\bar{p} \to tW^- \to W^+ bW^-(\to l\nu l\nu b)$ — associate ($\sim$ 7%)

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1 high-p_T lept, 1 bj, 1 j big η + ME

Top Quark @ Tevatron

Single-top events measured at Tevatron

$\sigma_t \sim$ 3pb

- $p\bar{p} \to t\bar{q}' \to W^+ b\bar{q}'(\to l\nu b\bar{q}')$ — t-channel $\sim$ 63%
- $p\bar{p} \to t\bar{b} \to W^+ b\bar{b}(\to l\nu b\bar{b})$ — s-channel $\sim$ 30%
- $p\bar{p} \to tW^- \to W^+ bW^-(\to l\nu l\nu b)$ — associate ($\sim$ 7%)

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1 high-p_T lept, 2 b jets and ME

Top Quark @ Tevatron

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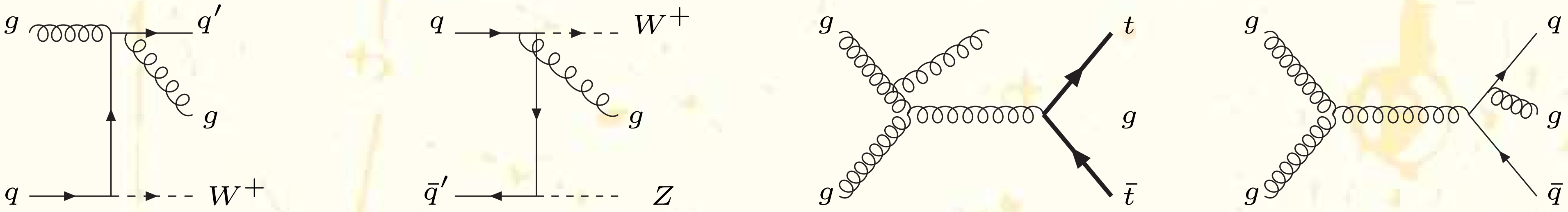
Large Background



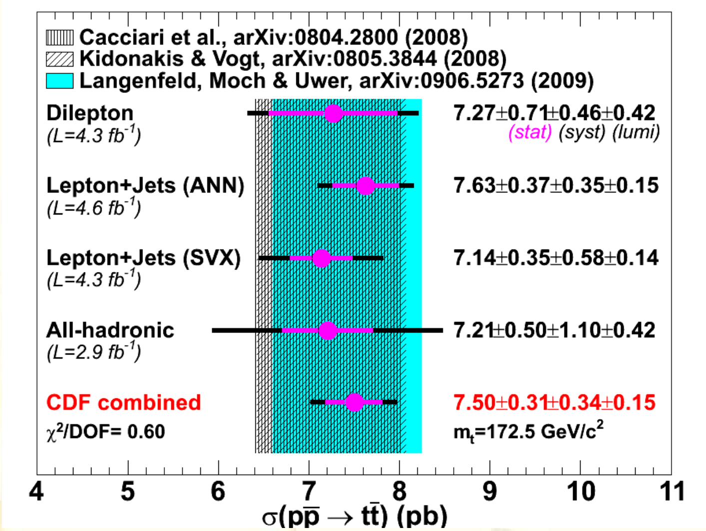
W+jets Di-boson Top Pair QCD

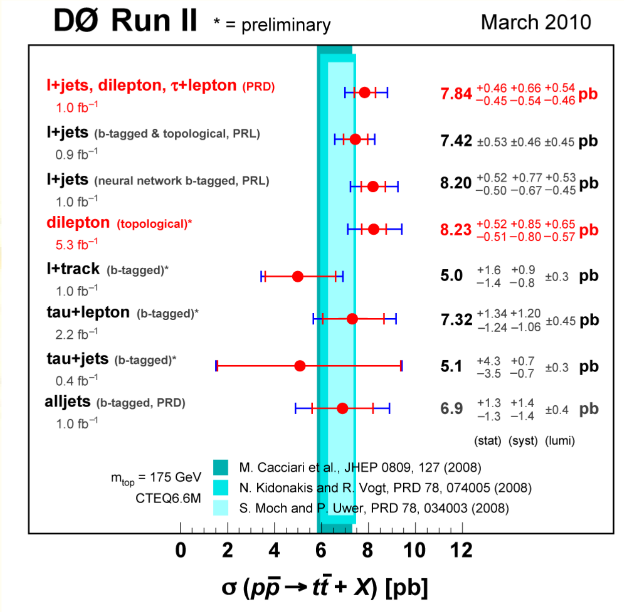
Top Quark @ Tevatron

- Total $t\bar{t}$-pair Cross Section

$$\sigma_{t\bar{t}} = \frac{N_{data} - N_{bkgr}}{\epsilon\, L}$$

  - Good test for the SM (in particular QCD)





Combination CDF-D0 ($m_t = 175$ GeV)

$$\sigma_{t\bar{t}} = 7.0 \pm 0.6\,\text{pb} \qquad (\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} \sim 9\%)$$

using 4.6 fb^{-1} of data

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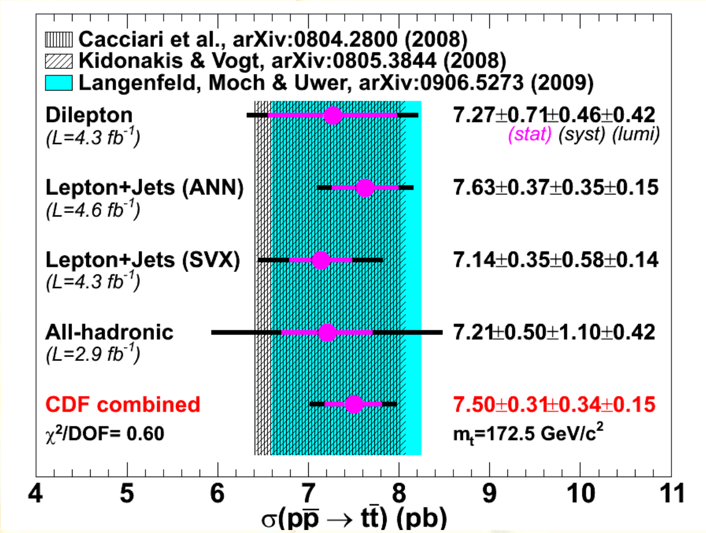

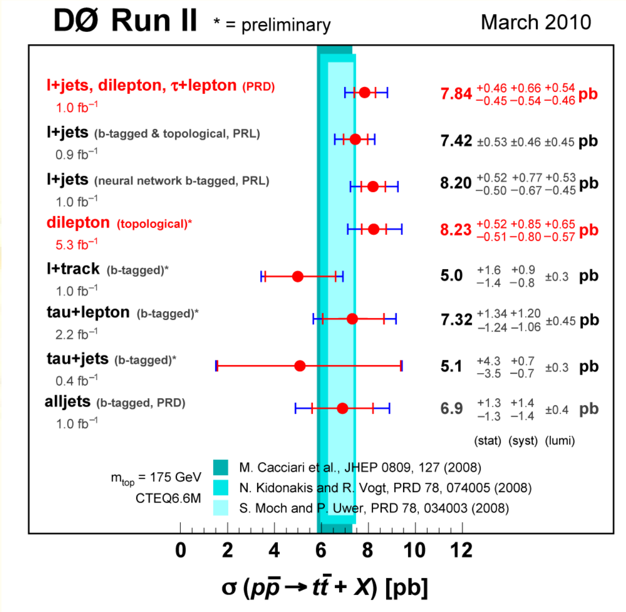

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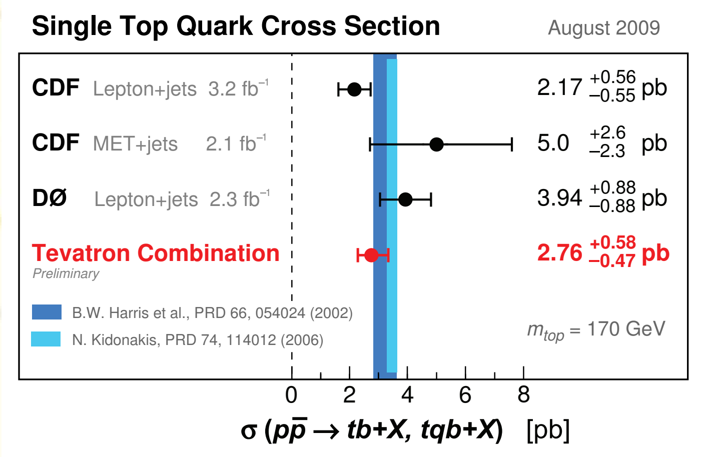
using 4.6 fb^{-1} of data

very recently $\Longrightarrow$ $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} \sim 6.5\%$ (σ_Z for the luminosity)

Top Quark @ Tevatron

- Total Single-Top Cross Section
  - Good test for the SM
  - It is important for the determination of $|V_{tb}|$ (experimental value $|V_{tb}| = 0.88 \pm 0.07$)

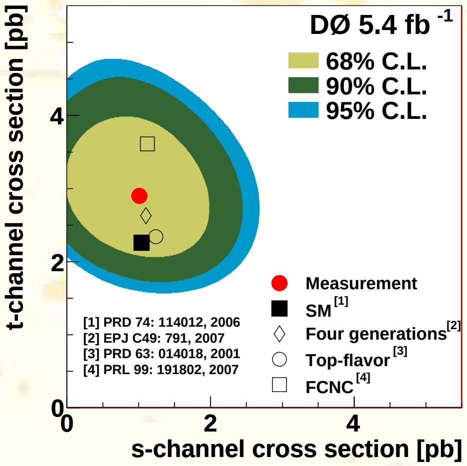


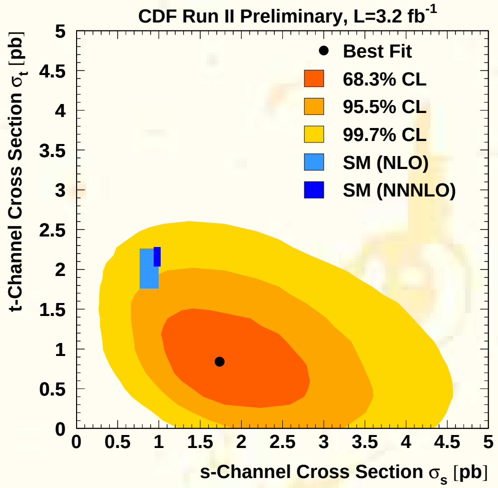
Combination CDF-D0 ($m_t = 170$ GeV)

$$\boxed{\sigma_{s+t} = 2.76^{+0.58}_{-0.47}\ \text{pb} \qquad (\Delta\sigma_t/\sigma_t \sim 20\%)}$$

using 3.2 (CDF) and 2.3 (D0) fb^{-1} of data

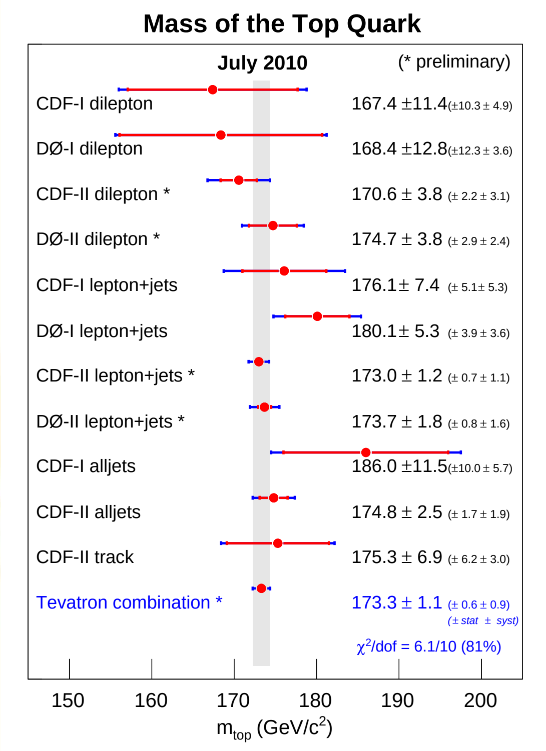
s- versus t-channel





Top Quark @ Tevatron

- Top-quark Mass
  - Fundamental parameter of the SM. A precise measurement useful to constraint Higgs mass from radiative corrections (Δr)
  - Correspondence of the parameter measured at Tevatron: pole mass?
  - Top-quark pole mass is “physically” not well defined: $\mathcal{O}(\Lambda_{QCD})$ ambiguity
  - A possible extraction from precise $\sigma_{t\bar{t}}$



Combination CDF-D0 (July 2010)

$$m_t = 173.3 \pm 1.1\,\text{GeV}\ (0.63\%)$$

- Top-Anti Top Mass Difference @ D0 $\quad \Delta m_t = 3.8 \pm 3.7\,\text{GeV}$

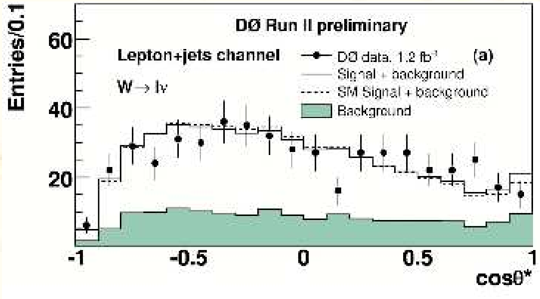
- Top-quark Width $\quad \Gamma_t < 7.6\,\text{GeV}\ (95\%\, CL)$

Top Quark @ Tevatron

- W helicity fractions $F_i = B(t \to bW^+(\lambda_W = i))$ $(i = -1, 0, 1)$ measured fitting the distribution in θ^* (the angle between l^+ in the W^+ rest frame and W^+ direction in the t rest frame)

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{4}F_0 \sin^2\theta^* + \frac{3}{8}F_-(1-\cos\theta^*)^2 + \frac{3}{8}F_+(1+\cos\theta^*)^2$$

$$F_0 + F_+ + F_- = 1$$



$$\boxed{F_0 = 0.66 \pm 0.16 \pm 0.05 \quad F_+ = -0.03 \pm 0.06 \pm 0.03}$$

$\Longrightarrow$ Ok with SM prediction at NNLO: $F_0 = 0.687(5)$ $F_+ = 0.0017(1)$ $F_- = 0.311(5)$

A. Czarnecki, J. G. Körner, J. H. Piclum, Phys. Rev. D 81 (2010) 111503(R)

- Spin correlations measured fitting the double distribution
(θ_1 (θ_2) is the angle between the dir of flight of l_1 (l_2) in the $t(\bar{t})$ rest frame and the $t(\bar{t})$ direction in the $t\bar{t}$ rest frame)

$$\frac{1}{N}\frac{d^2N}{d\cos\theta_1\, d\cos\theta_2} = \frac{1}{4}(1 + \kappa\cos\theta_1\cos\theta_2)$$

$$\boxed{\kappa = 0.32^{+0.55}_{-0.78}}$$

$\Longrightarrow$ Ok with QCD prediction at NLO: $\kappa = 0.389$

W. Bernreuther, A. Brandenburg, Z. G. Si, P. Uwer, Phys. Rev. Lett. 87 (2001) 242002

Top Quark @ Tevatron

- FB Asymmetry

$$A_{FB}^{lab\,(\text{or }t\bar{t})} = \frac{N(y_t(\text{or }\Delta y) > 0) - N(y_t(\text{or }\Delta y) < 0)}{N(y_t(\text{or }\Delta y) > 0) + N(y_t(\text{or }\Delta y) < 0)}$$

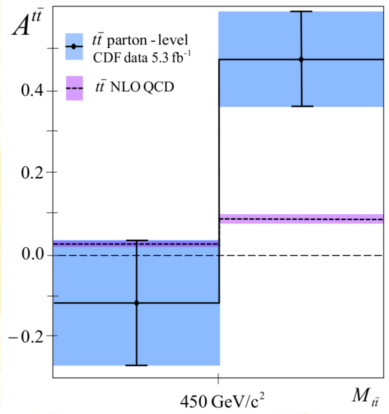
- At LO top and anti-top quarks have identical distribution. A_{FB} starts at $\mathcal{O}(\alpha_S^3)$
- CDF $(5.3\, fb^{-1})$

$A_{FB}^{(lab)} = (15.0 \pm 5\, stat \pm 2.4\, syst)\,\%$

$A_{FB}^{(t\bar{t})} = (15.8 \pm 7.2\, stat\, \pm 1.7\, syst)\,\%$

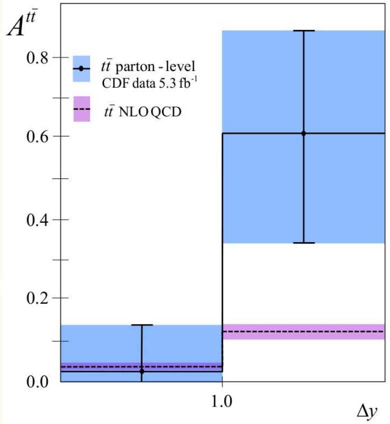
$A_{FB}^{(t\bar{t})}(M_{t\bar{t}} < 450\text{GeV}) = (-11.6 \pm 14.6\, stat\, \pm 4.7\, syst)\,\%$

$A_{FB}^{(t\bar{t})}(M_{t\bar{t}} > 450\text{GeV}) = (47.5 \pm 10.1\, stat\, \pm 4.9\, syst)\,\%$



- D0 $(4.3\, fb^{-1})$

$A_{FB}^{(t\bar{t})} = (8.0 \pm 4.0\, stat\, \pm 1\, syst)\,\%$ (uncorrected)



- THEORY

$A_{FB}^{(lab)} = (5.1 \pm 0.6)\,\%$ (NLO QCD+EW, Kühn and Rodrigo '98)

$A_{FB}^{(t\bar{t})} = (7.8 \pm 0.9)\,\%$ (NLO QCD+EW, Kühn and Rodrigo '98)

$A_{FB}^{(t\bar{t})} = (7.24^{+1.04+0.2}_{-0.67-0.27})\,\%$ (NLO + NNLL, Ahrens et al. '11)

Top Quark @ Tevatron

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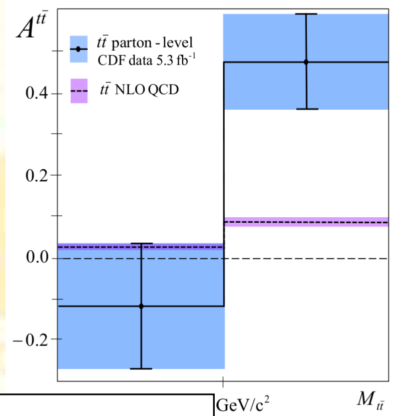

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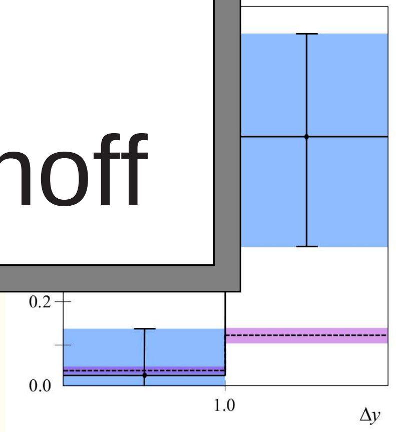
See the

Talk by S. Westhoff



Top Quark @ Tevatron

Tevatron searches of physics BSM in top events

- New production mechanisms via new spin-1 or spin-2 resonances: $q\bar{q} \to Z' \to t\bar{t}$ in lepton+jets and all hadronic events. Bumps in the invariant-mass distribution (excluded at 95% CL vector resonances with mass in the range 450–1500 GeV)
- Top charge measurements (recently excluded exotic top-quark with $Q_t = -4/3$)
- Anomalous couplings
$$L = -\frac{g}{\sqrt{2}}\bar{b}\left\{\gamma^\mu (V_L P_L + V_R P_R) + \frac{i\sigma^{\mu\nu}(p_t - p_b)_\nu}{M_W}(g_L P_L + g_R P_R)\right\} t W_\mu^-$$
  - From helicity fractions
  - From asymmetries in the final state
- Forward-backward asymmetry
- Non SM Top decays. Search for charged Higgs: $t \to H^+ b \to q\bar{q}' b (\tau \nu b)$
- Search for heavy $t' \to W^+ b$ in lepton+jets (recently excluded t' with $m_{t'} < 360$ GeV)

Top Quark @ Tevatron

Tevatron searches of physics BSM in top events

- New pr $\rightarrow t\bar{t}$ in lepton- (excluc eV)
- Top ch $/3$)
- Anoma

  $L = -$

  - F
  - F
- Forwar

No Evidence
of New Physics so far

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Top Quark @ LHC

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- CMS $\boxed{\sigma_{t\bar{t}} = 194 \pm 72(stat.) \pm 24(syst.) \pm 21(lumi.)\text{ pb}}$ arXiv:1010.5994
  - Only di-lepton channel: e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\pm$
  - Based on 3.1 pb^{-1} of data (11 events, 2.1 ± 1.0 background)
  - Background (Drell-Yan ...) estimated from data and/or modeled with MADGRAPH
  - Selection efficiency of signal events: MADGRAPH + PYTHIA + CMS detector simulation
- ATLAS $\boxed{\sigma_{t\bar{t}} = 145 \pm 31^{+42}_{-27}\text{ pb}}$ arXiv:1012.1792
  - Lepton+jet and di-lepton channels
  - Based on 2.9 pb^{-1} (37 events in l+j and 9 in di-l, 12.2 ± 3.9 and 2.5 ± 0.6 background)
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very recently CMS $\Longrightarrow$ 36 pb^{-1} analyzed, arXiv:1105.5661, arXiv:1106.0902

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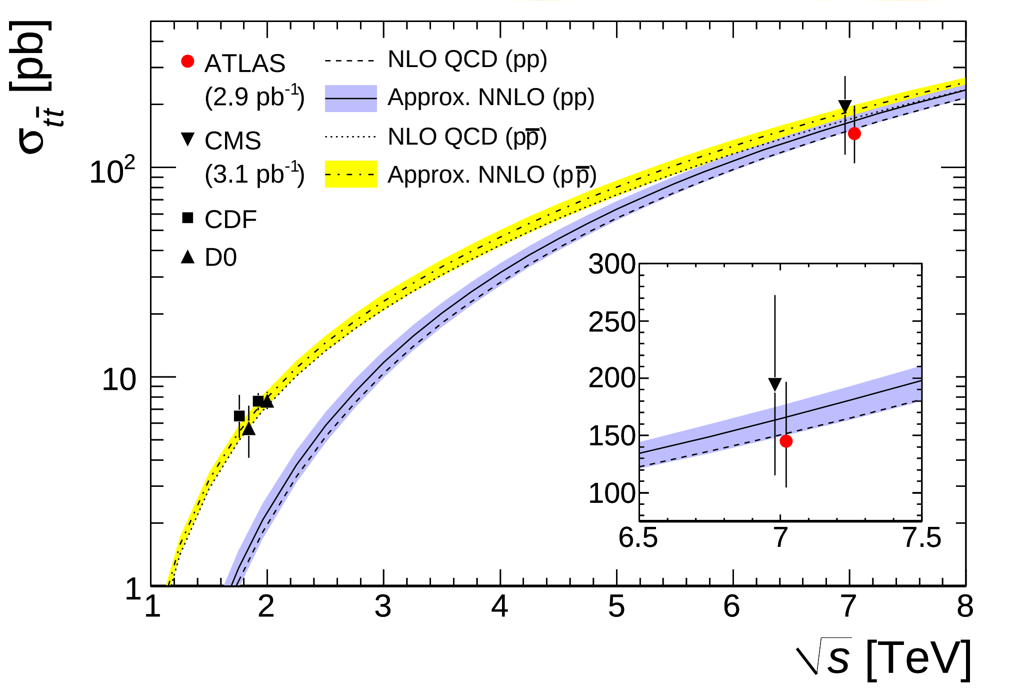

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Top Quark @ LHC

Very recently, new results became available from CMS about the measurement of the t-channel single-top production cross section at $\sqrt{s} = 7$ GeV, analysing 36 pb^{-1}:

- CMS $\boxed{\sigma_t = 83.6 \pm 29.8(stat. + syst.) \pm 3.3(lumi.)\text{ pb}}$ arXiv:1106.3052
  - The measurement uses the decay channels: $t \to e\nu b$, $t \to \mu\nu b$, and $t \to \tau\nu b$, with leptonic τ decays
  - Background: $t\bar{t}$, single-top s and tW channels, and $W/Z + jets$ estimated with MADGRAPH. Di-boson production, multi jets QCD estimated with PYTHIA. + full simulation of the detector response with GEANT4

The single-top cross section can be used as a test of the unitarity of the CKM matrix. Under the assumption $|V_{td}|, |V_{ts}| \ll |V_{tb}|$ the following value is found:

$\boxed{|V_{tb}| > 0.68}$ at the 95% CL

- ATLAS $\boxed{\sigma_t = 76\,^{+41}_{-21}\text{ pb}}$ ATLAS-CONF-2011-027
  - Using 156 pb^{-1}. 1 lepton + ME_T + 1 b jet and 1 add jet

Top Quark @ LHC: Perspectives

- $t\bar{t}$ Cross Section
  - With $100\,\text{pb}^{-1}$ of accumulated data an error of $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} \sim 15\%$ is expected
  - After 5 years (in the high-luminosity high-energy pahe) of data taking an error of $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} \sim 5\%$ is expected
- Single-top Cross Section
  - With $10\,\text{fb}^{-1}$ of accumulated data an error of $\Delta\sigma_t/\sigma_t \sim 10-20\%$ is expected
- Top Mass
  - With $1\,\text{fb}^{-1}$ Mass accuracy: $\Delta m_t \sim 1-3$ GeV
- Top Properties
  - W helicity fractions and spin correlations with $10\,\text{fb}^{-1} \Longrightarrow$ 1-5%
  - Top-quark charge. With $1\,\text{fb}^{-1}$ we could be able to determine $Q_t = 2/3$ with an accuracy of $\sim 15\%$
- Sensitivity to new physics
  - all the above mentioned points
  - Narrow resonances: with $1\,\text{fb}^{-1}$ possible discovery of a Z' of $M_{Z'} \sim 700$ GeV with $\sigma_{pp\to Z'\to t\bar{t}} \sim 11$ pb

ATLAS CSC book

Theoretical Framework: QCD

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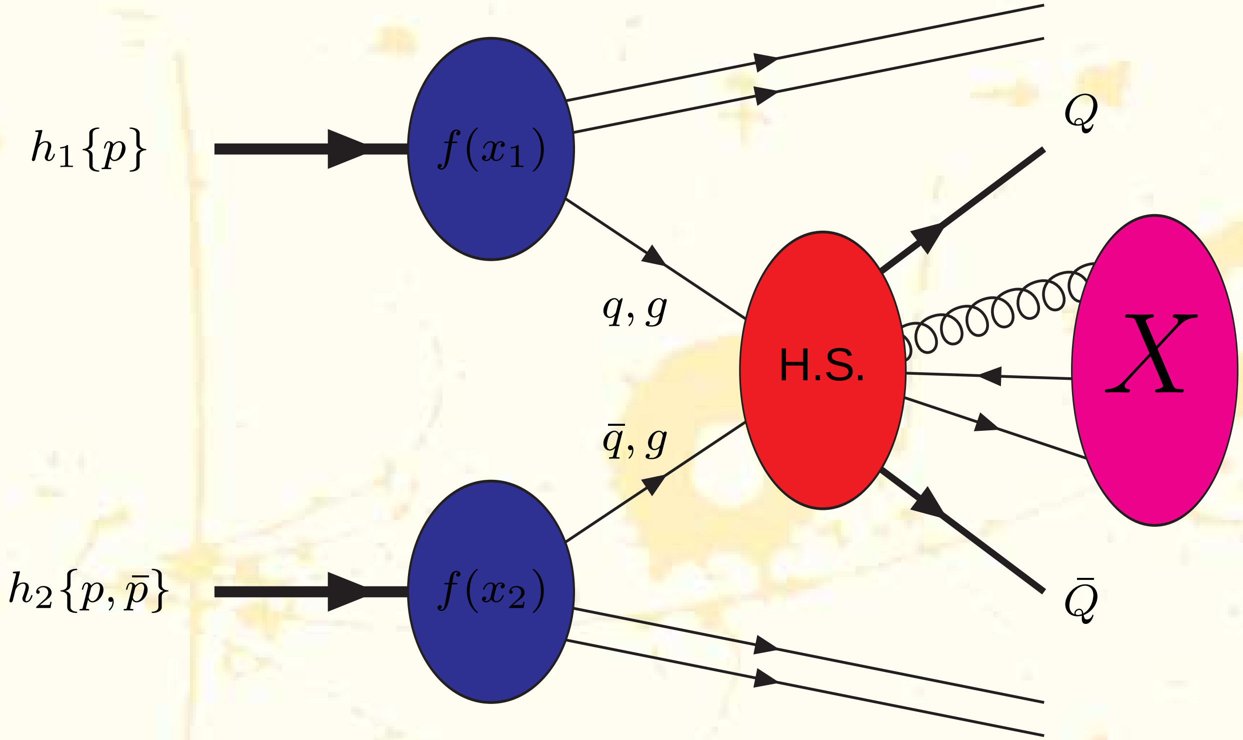
Let us consider the heavy-quark production in hadron collisions $h_1 + h_2 \rightarrow Q\bar{Q} + X$

According to the FACTORIZATION THEOREM the process can be sketched as follows:



$$\sigma_{h_1,h_2} = \sum_{i,j} \int_0^1 dx_1 \int_0^1 dx_2 f_{h_1,i}(x_1, \mu_F) f_{h_2,j}(x_2, \mu_F)\ \hat{\sigma}_{ij}\left(\hat{s}, m_t, \alpha_s(\mu_R), \mu_F, \mu_R\right)$$

$$s = \left(p_{h_1} + p_{h_2}\right)^2\ ,\ \hat{s} = x_1 x_2 s$$

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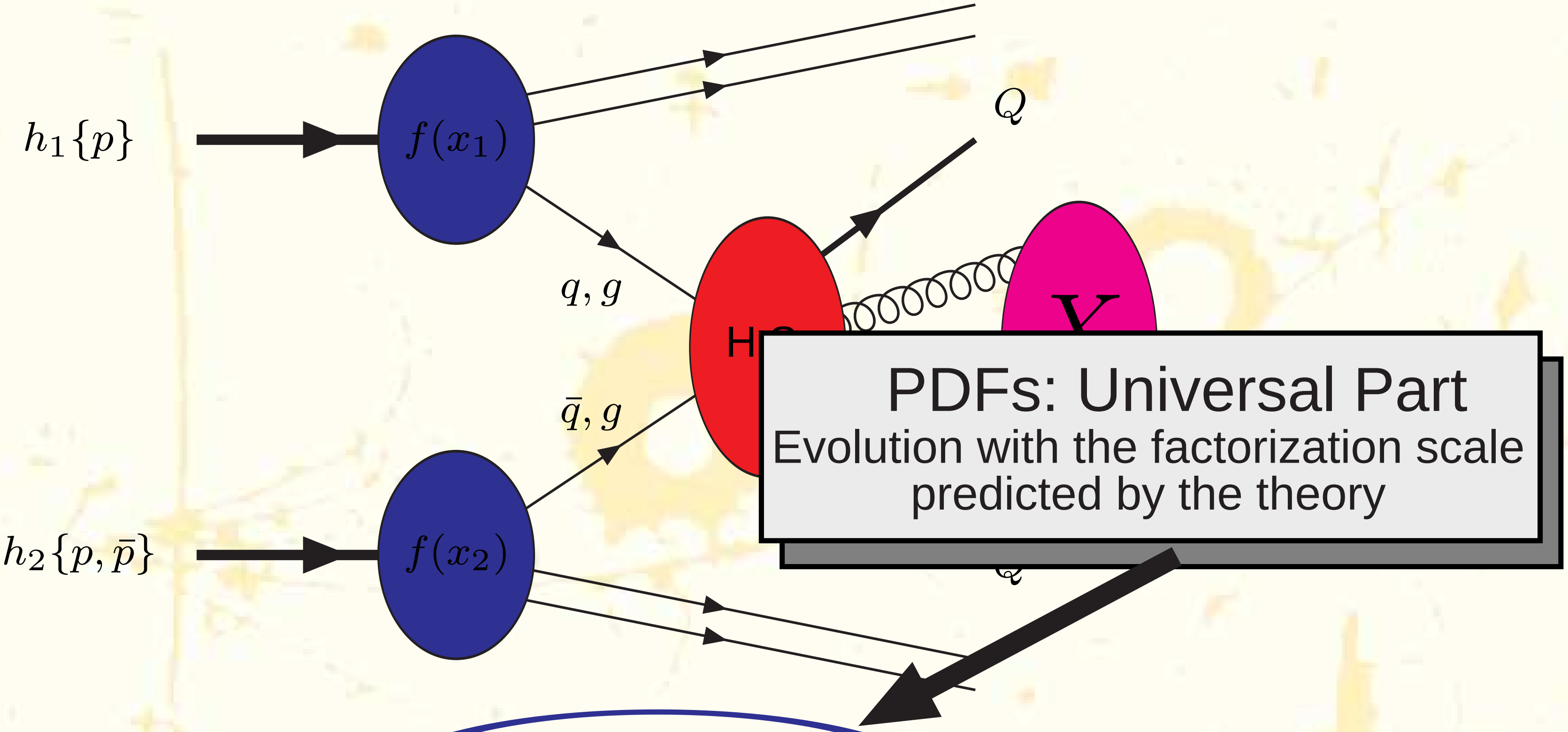

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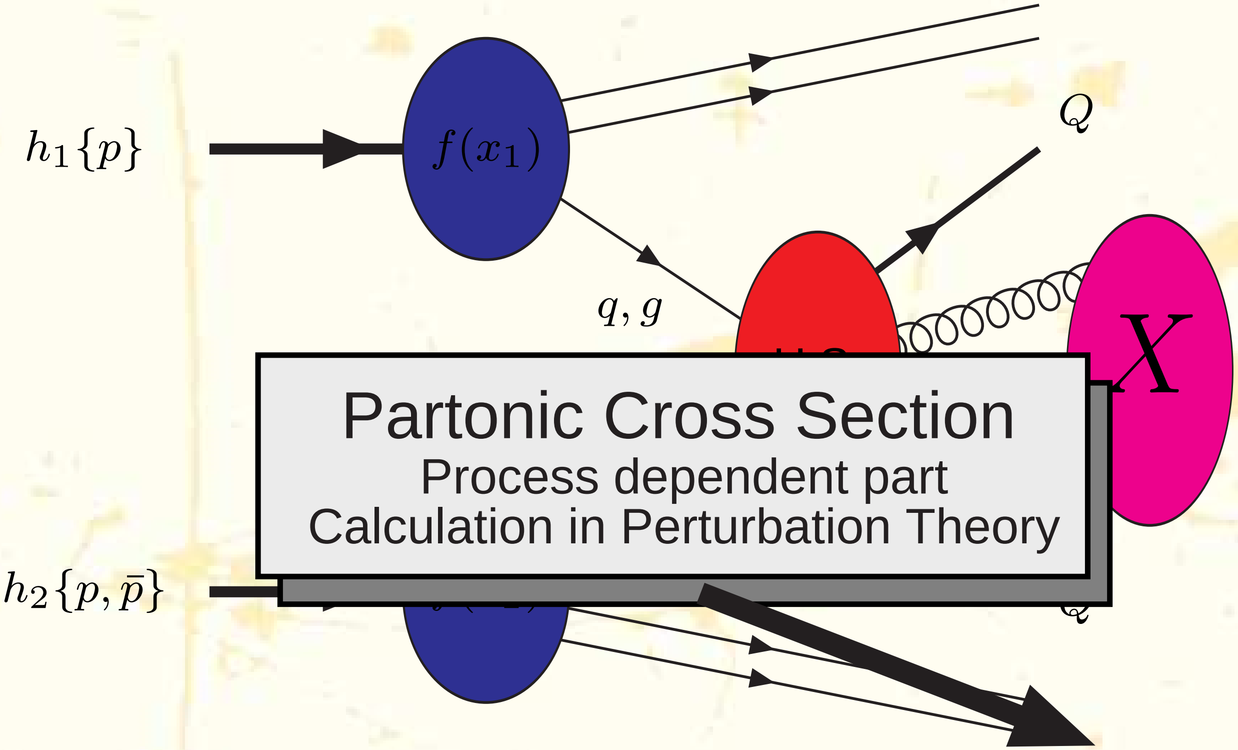

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Cross Section: LO (stable top)

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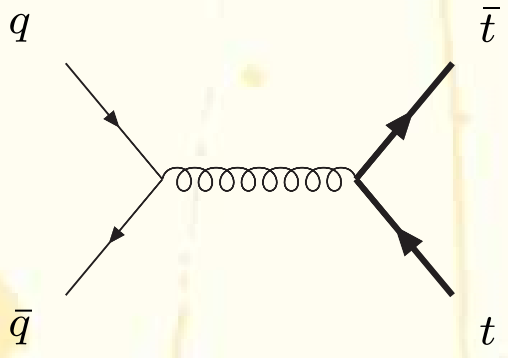
Top-Antitop production at leading order, partonic diagrams:

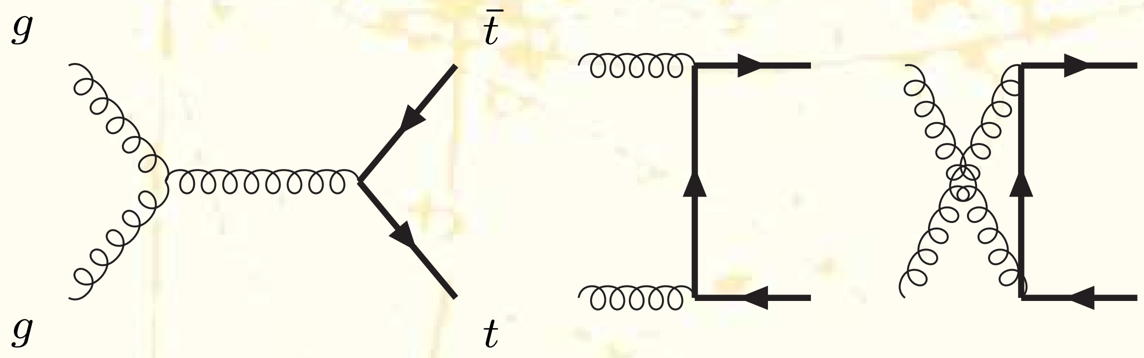
$$q(p_1) + \bar{q}(p_2) \longrightarrow t(p_3) + \bar{t}(p_4)$$



Dominant at Tevatron

$\sim 85\%$

$$g(p_1) + g(p_2) \longrightarrow t(p_3) + \bar{t}(p_4)$$



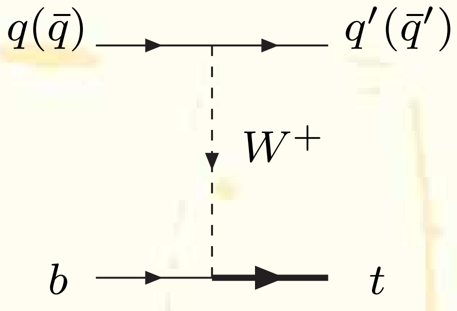
Dominant at LHC

$\sim 90\%$

Cross Section: LO (stable top)

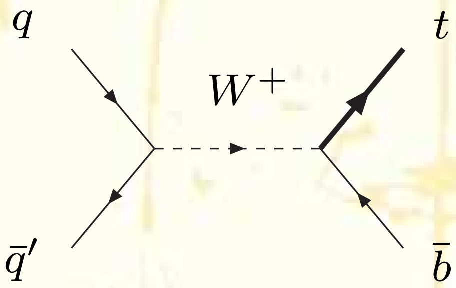
Single-top production at leading order, partonic diagrams:

t-channel: $q(\bar{q}) + b \longrightarrow q'(\bar{q}') + t$



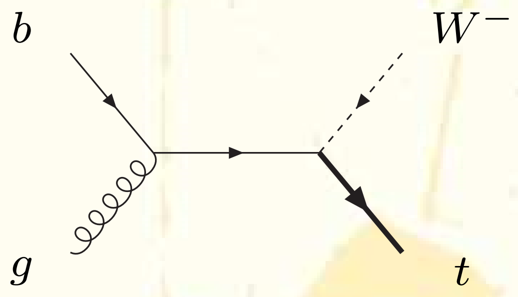
Dominant at Tevatron and LHC $\sim 60 - 70\%$

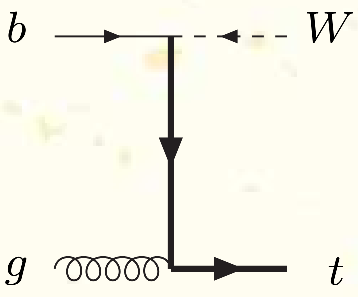
s-channel: $q + \bar{q}' \longrightarrow \bar{b} + t$



Second at Tevatron $\sim 30\%$

associated tW^- production: $g + b \longrightarrow t + W^-$ (five-flavour scheme)





Second at LHC $\sim 20\%$

Cross Section: NLO (stable top)

$t\bar{t}$ Fixed Order

- NLO QCD corrections quite sizable: + 25% at Tevatron and +50% at LHC.

  Nason, Dawson, Ellis '88-'90; Beenakker, Kuijf, van Neerven, Smith '89-'91;
  Mangano, Nason, Ridolfi '92; Frixione et al. '95; Czakon and Mitov '08

- NLO EW corrections small: - 1% at Tevatron and -0.5% at LHC.

  Beenakker *et al.* '94 Bernreuther, Fuecker, and Si '05-'08
  Kühn, Scharf, and Uwer '05-'06; Moretti, Nolten, and Ross '06.

Single-top Fixed Order

- NLO QCD corrections to the t-channel: + 9% at Tevatron and +5% at LHC.

  Bordes, van Eijk '95; Stelzer, Sullivan, Willenbrock '97-'98;
  Harris, Laenen, Phaf, Sullivan, Weinzierl '02; Sullivan '04-'05

- NLO EW corrections t-channel: <1% at Tevatron and <1% at LHC.

  Beccaria, Macorini, Renard, Verzegnassi '06; Beccaria et al. '08

- NLO QCD corrections to the s-channel: + 47% at Tevatron and +44% at LHC.

  Smith, Willenbrock '96; Harris, Laenen, Phaf, Sullivan, Weinzierl '02; Sullivan '04-'05

- NLO QCD corrections to the tW-channel: + 10% at LHC.

  Giele, Keller, Laenen '96; Zhu '02

Cross Section: NLO + resumm (stable top)

- The QCD corrections to processes involving at least two large energy scales ($\hat{s}, m_t^2 \gg \Lambda_{QCD}^2$) are characterized by a logarithmic behavior in the vicinity of the boundary of the phase space

$$\sigma \sim \sum_{n,m} C_{n,m} \alpha_S^n \ln^m (1-\rho) \qquad m \leq 2n$$

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Inelasticity parameter

$$\rho = \frac{4m_t^2}{\hat{s}} \to 1$$

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  Resummation $\Longrightarrow$ improved perturbation theory

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$t\bar{t}$ cross section

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- Next-to-Next-to-Leading-Logs (NNLL) — Moch and Uwer '08; Beneke et al. '09-'10; Czakon et al. '09; Kidonakis '09; Ahrens et al. '10

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Very energetic tops with SCET (for the moment not in hadronic collisions)

Fleming et al. '08; Jain et al. '08; Hoang et al. '08; Hornig et al. '11; Kelley et al. '11

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- Next-to-Next-to-Leading-Logs (N... Kidonakis '11

See the
Talk by B. Pecjak

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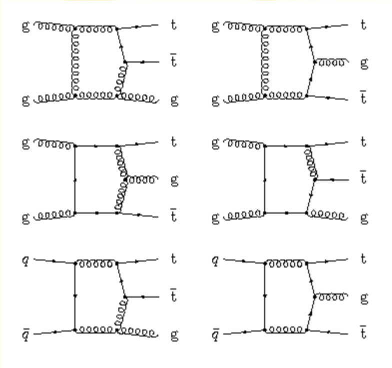
Distributions

Distributions

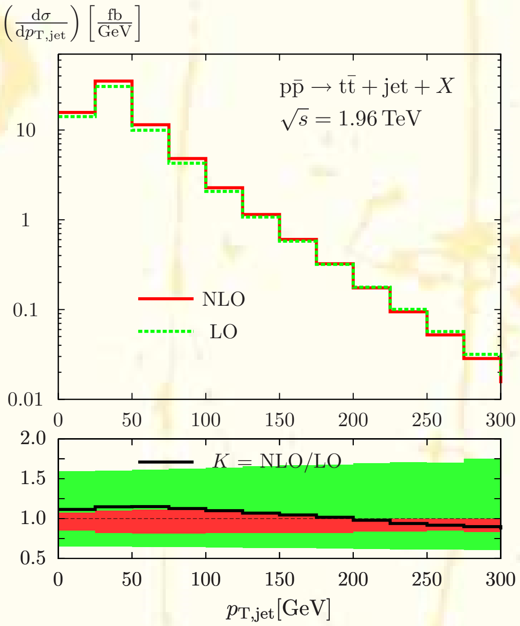
- $pp(\bar{p}) \to t\bar{t} + 1\,jet$
  - Important for a deeper understanding of the $t\bar{t}$ prod (possible structure of the top-quark)
  - Technically complex involving multi-leg NLO diagrams

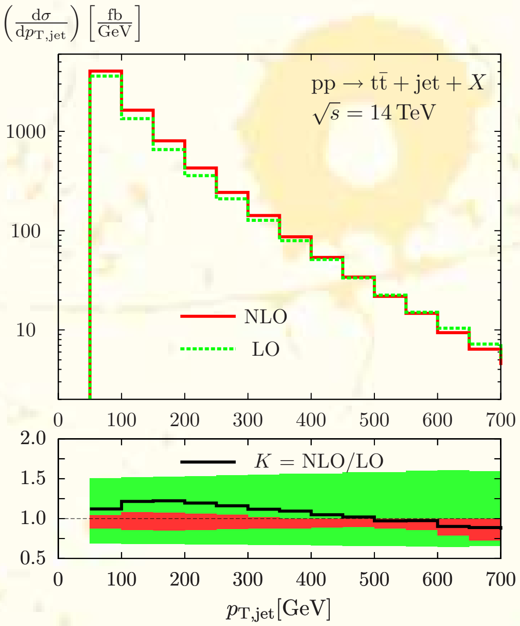


$$\sigma_{t\bar{t}+j}(LHC) = 376.2^{+17}_{-48}\ \text{pb}$$

$$\sigma_{t\bar{t}+j}(Tev) = 1.79^{+0.16}_{-0.31}\ \text{pb}$$

$$\sigma^{CDF}_{t\bar{t}+j} = 1.6 \pm 0.2\,(\text{stat}) \pm 0.5\,(\text{syst})\ \text{pb}$$



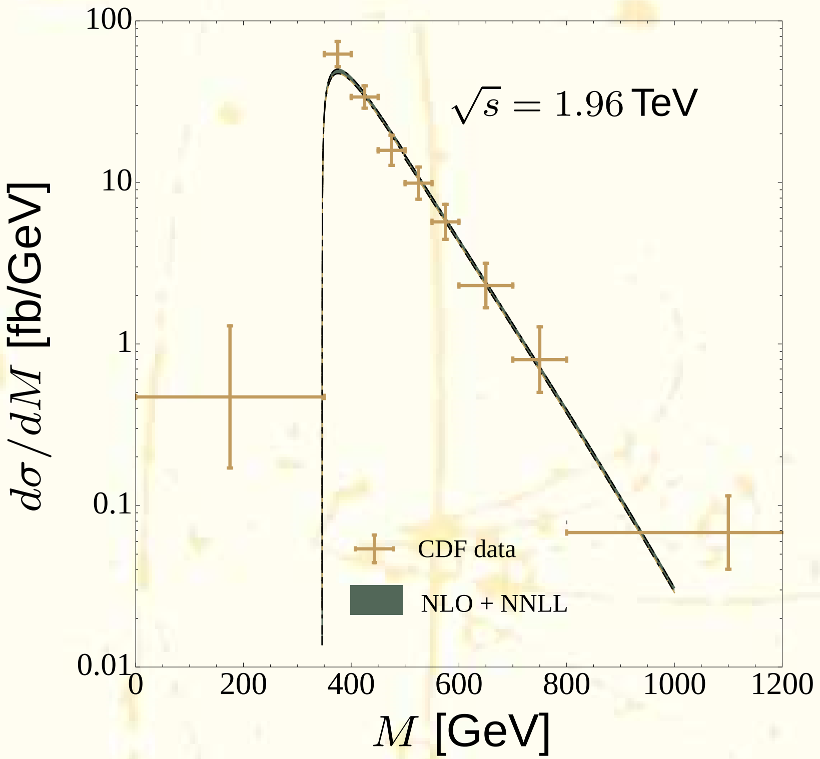


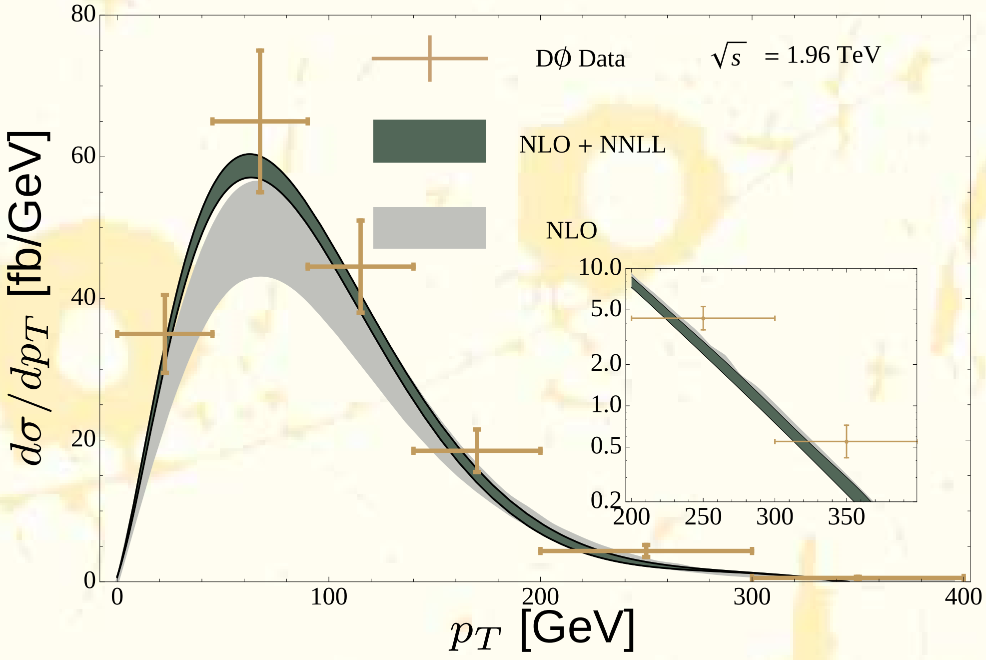
S. Dittmaier, P. Uwer and S. Weinzierl,
Phys. Rev. Lett. 98 (2007) 262002
Eur. Phys. J. C **59** (2009) 625

confirmed by G. Bevilacqua, M. Czakon, C.G. Papadopoulos, M. Worek, Phys.Rev.Lett. 104 (2010) 162002
K. Melnikov and M. Schulze, Nucl.Phys. B840 (2010) 129-159

Distributions

- Invariant mass and p_T distributions: NLO + resummed (SCET) NNLL comparison with CDF and D0 data

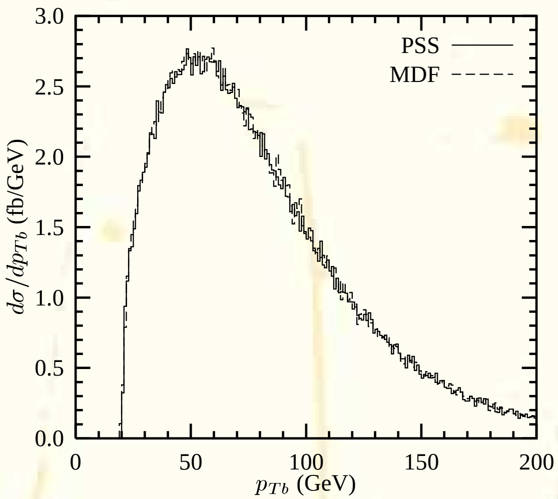




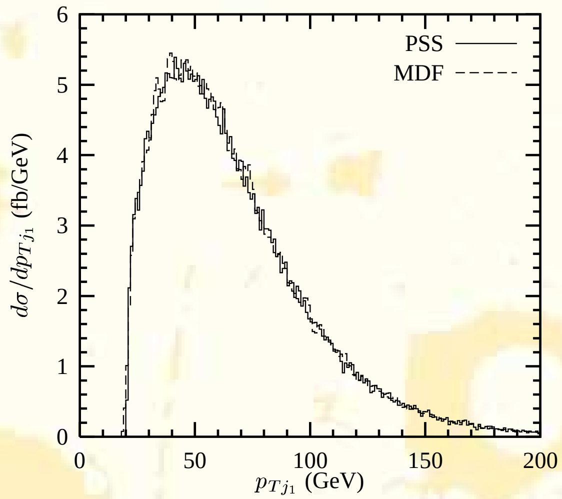
V. Ahrens, A. Ferroglia, M. Neubert, B. D. Pecjak, and L. L. Yang, JHEP 1009 (2010) 097
V. Ahrens, A. Ferroglia, M. Neubert, B. D. Pecjak, and L. L. Yang, arXiv:1103.0550
N. Kidonakis, arXiv:1105.3481

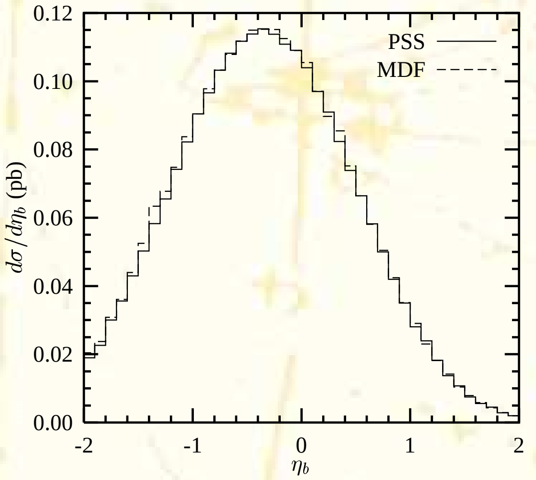
Distributions

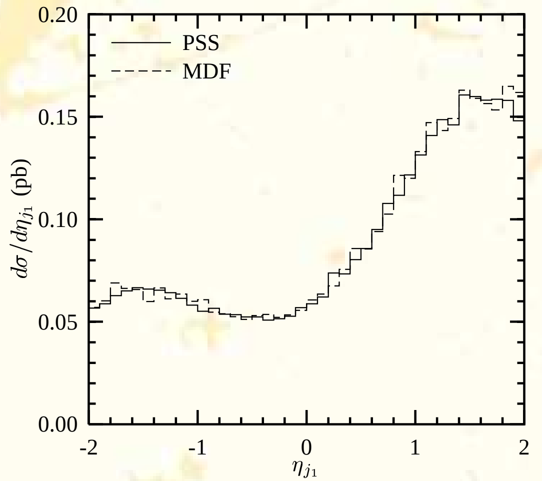
s-channel



t-channel







B. W. Harris, E. Laenen, L. Phaf, Z. Sullivan, S. Weinzierl, Phys. Rev. **D66** (2002) 054024

Tools @ NLO

The corrections at NLO for the $t\bar{t}$ and single-top productions are implemented in a series of public codes

- MCFM

  J. M. Campbell, R. K. Ellis, Phys. Rev. **D60** (1999) 113006

- MC@NLO

  S. Frixione, B. R. Webber, JHEP **0206** (2002) 029

- POWHEG

  S. Frixione, P. Nason, C. Oleari, JHEP **0711** (2007) 070

NLO with decay Products: Fact. Corrections

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- The calculations shown so far consider a stable top (anti-top) quark. Advantage: reduction in the complexity of a NLO calculation
- In “reality” the out states are leptons and hadrons $\Longrightarrow$ experiments put cuts on leptons and hadrons. Desirable a description of the process in terms of actual out states

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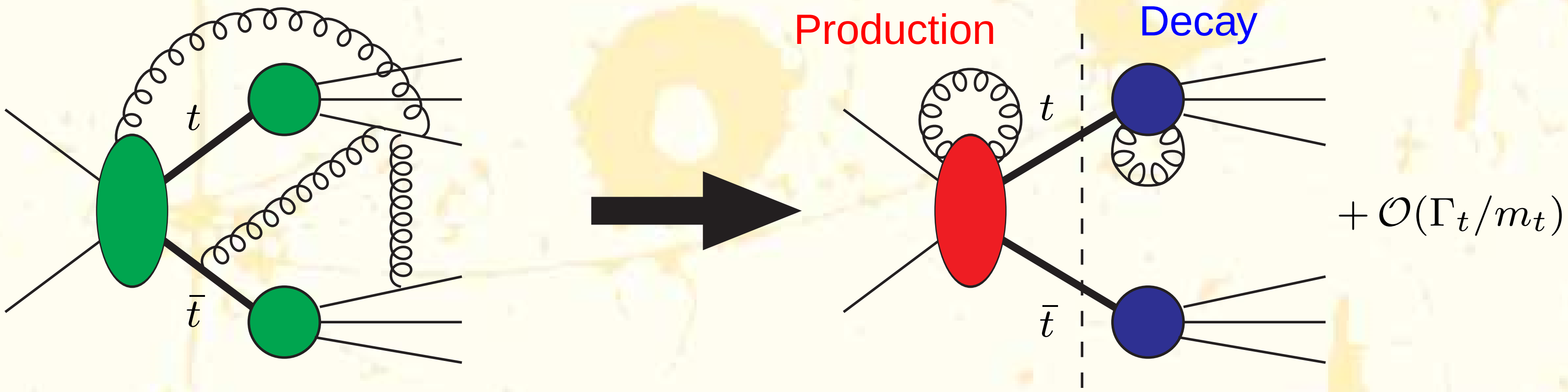
- In "reality" the out states are leptons and hadrons $\Longrightarrow$ experiments put cuts on leptons and hadrons. Desirable a description of the process in terms of actual out states
- Factorizable corrections do not mix production and decay stages!

$$\lim_{\Gamma_t/m_t \to 0} \frac{1}{(p_t^2 - m_t^2)^2 + m_t^2 \Gamma_t^2} = \frac{\pi}{m_t \Gamma_t} \delta(p_t^2 - m_t^2)$$



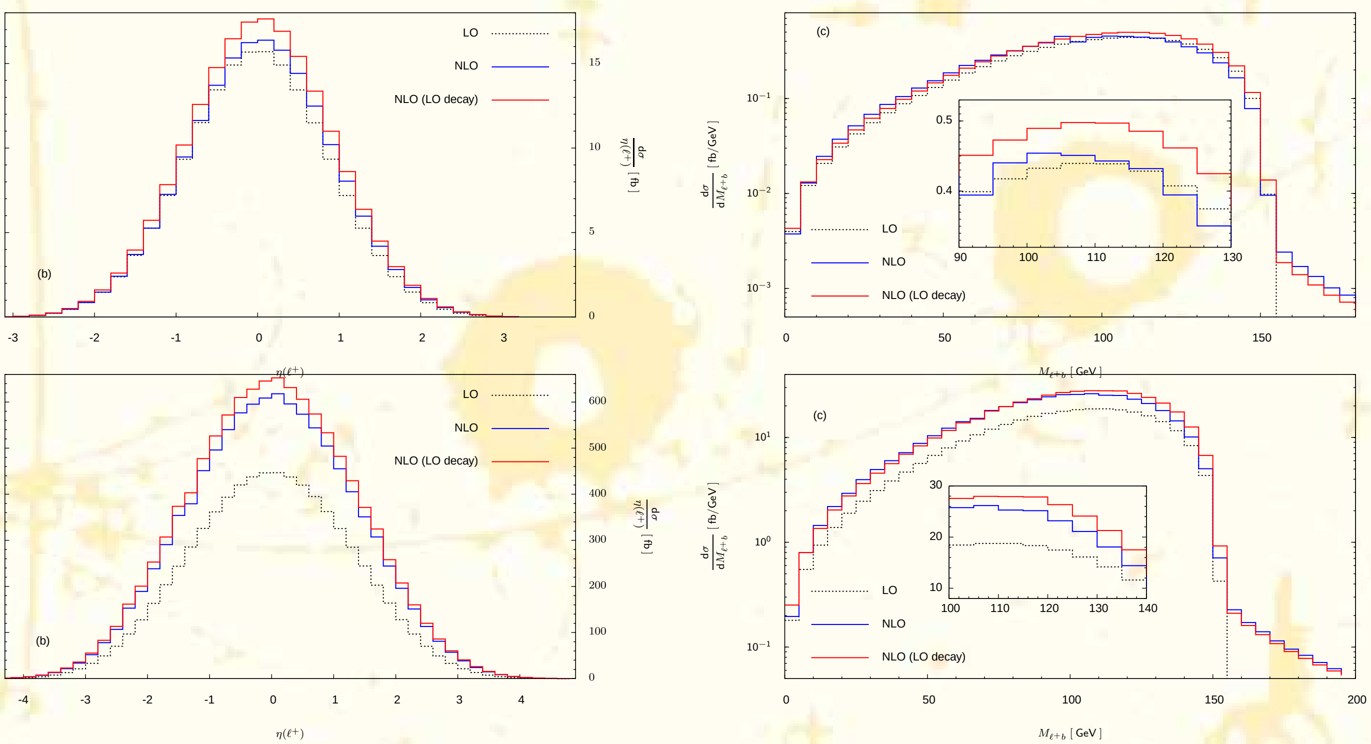
- The non-factorizable corrections do not decouple, but in sufficiently inclusive observables they become small: $\sim \mathcal{O}(\Gamma_t/m_t)$ Fadin, Khoze, Martin '94; Aeppli, van Oldenborgh, Wyler '94; Melnikov, Yakovlev '94; Beenakker, Berends, Chapovsky '99
- One can keep track of the spin of the top and anti-top and compute spin correlations

NLO with decay Products: Fact. Corrections

- NLO corrections to various kinematic distributions for Tevatron and LHC (Bernreuther et al. include also EW corrections)

Tevatron

LHC

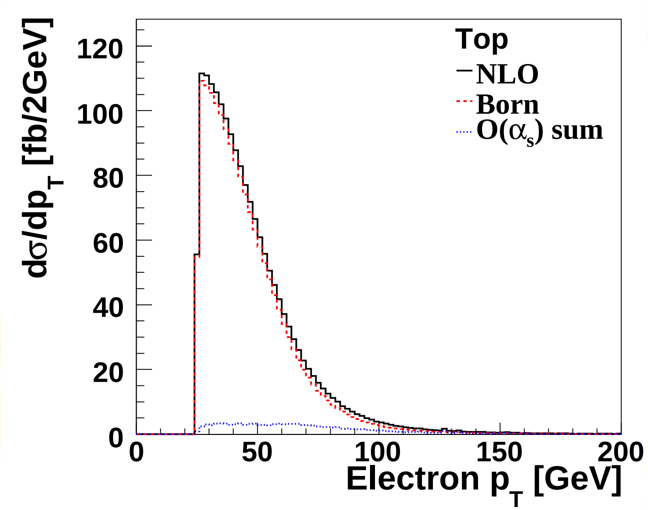


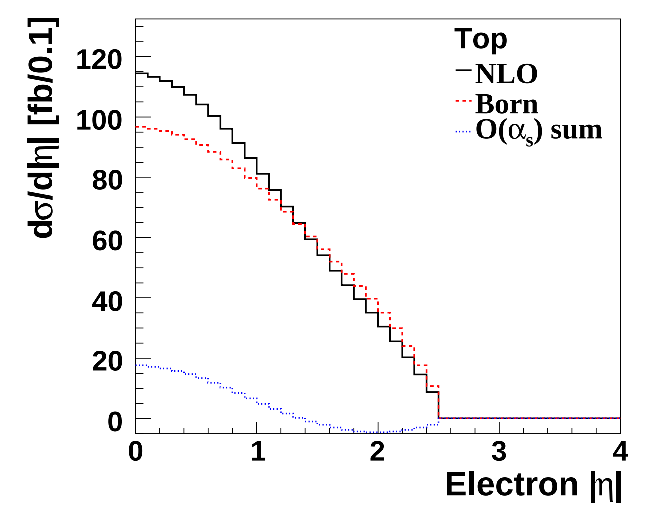
- NB: the study can be extended at NNLO

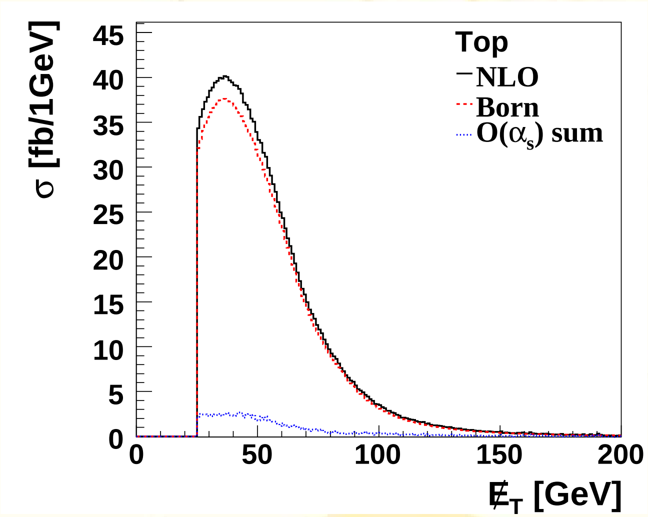
W. Bernreuther et al., Nucl.Phys. B690 (2004) 81
W. Bernreuther and Z. Si, Nucl.Phys. B837 (2010) 90-121
K.Melnikov and M. Schulze, JHEP 0908 (2009) 049

NLO with decay Products: Fact. Corrections

- Single-top production and decay in the t channel at the LHC



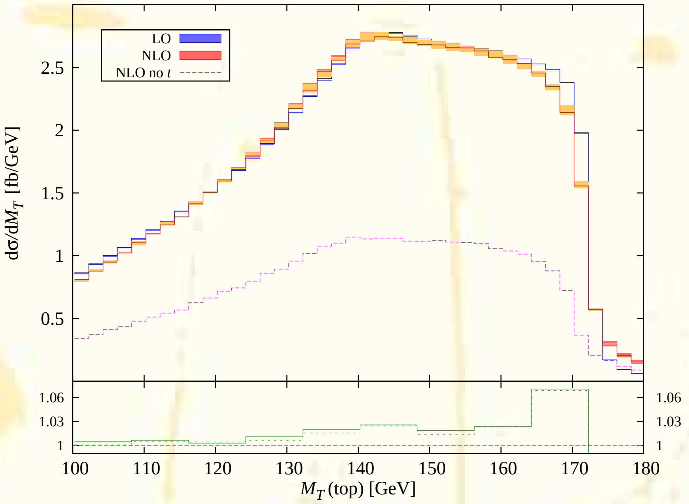


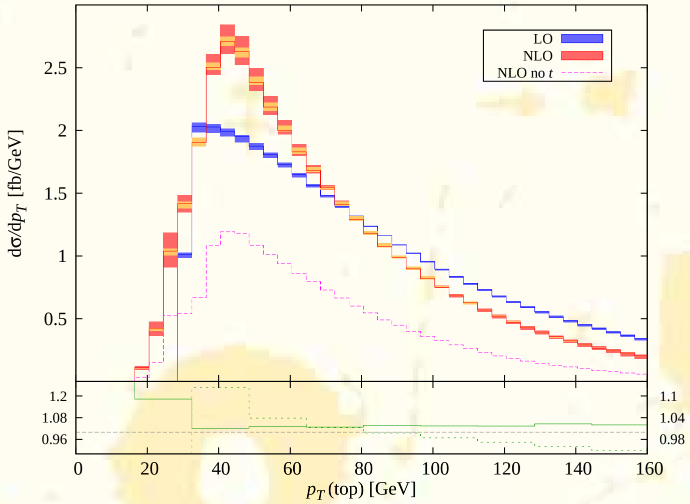


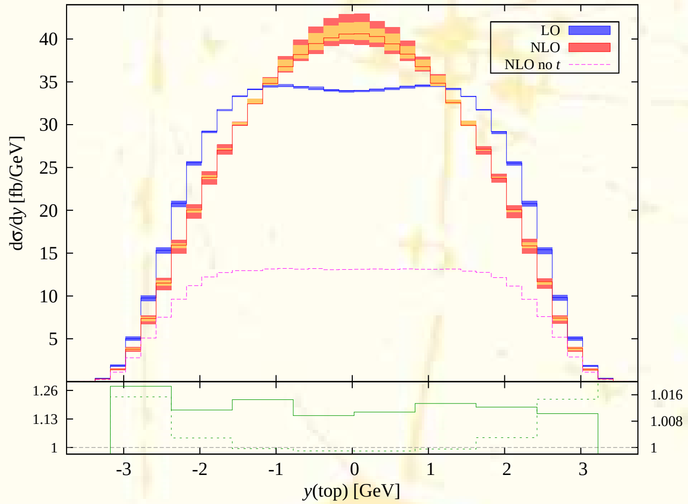
R. Schwienhorst, C. -P. Yuan, C. Mueller, Q. -H. Cao, Phys. Rev. **D83** (2011) 034019.

NLO with decay Products: Fact. Corrections

- Off-shell effects for t- and s-channel single-top production at Tevatron and LHC







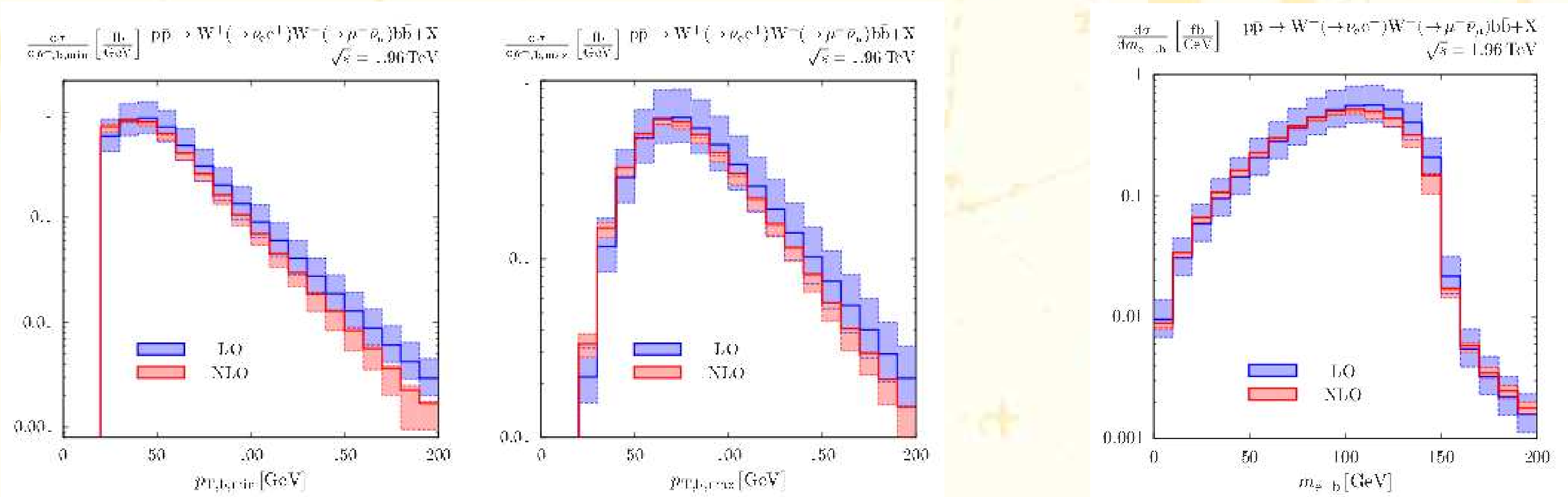
P. Falgari, F. Giannuzzi, P. Mellor, A. Signer, Phys. Rev. **D83** (2011) 094013.

NLO with decay Products: Full Calculation

NLO with decay Products: Full Calculation

Finally, very recently two groups computed the full set of NLO corrections to $\boxed{pp \to WWbb}$

- Calculation technically challenging (~ 1500 Feynman diagrams, up to 6 external legs)
- The direct calculation confirms that for inclusive quantities the non-factorizable corrections are of $\mathcal{O}(\Gamma_t/m_t)$
- Possibility to study many distributions imposing realistic experimental cuts



(Plots S. Pozzorini's ZH 2011 talk)

A. Denner, S. Dittmaier, S. Kallweit, and S. Pozzorini, Phys. Rev. Lett. 106 (2011) 052001
G. Bevilacqua, M. Czakon, A. van Hameren, C. G. Papadopoulos, M. Worek, JHEP 1102 (2011) 083

Towards the NNLO

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Experimental requirements for $\sigma_{t\bar{t}}$:

- Tevatron $\Delta\sigma/\sigma \sim 9\% \Longrightarrow$ already < $(\Delta\sigma/\sigma)_{TH}$
- LHC (14 TeV, high luminosity) $\Delta\sigma/\sigma \sim 5\% \ll (\Delta\sigma/\sigma)_{TH}$!!

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Different groups presented approximated higher-order results for $\sigma_{t\bar{t}}$

- Including scale dep at NNLO, NNLL soft-gluon contributions, Coulomb corrections

$$\sigma_{t\bar{t}}^{\mathrm{NNLOappr}}(\mathrm{Tev}, m_t = 173\ \mathrm{GeV}, \mathrm{MSTW2008}) = 7.08\ {}^{+0.00+0.36}_{-0.24-0.27}\ \mathrm{pb}$$

$$\sigma_{t\bar{t}}^{\mathrm{NNLOappr}}(\mathrm{LHC}, m_t = 173\ \mathrm{GeV}, \mathrm{MSTW2008}) = 163\ {}^{+7+9}_{-5-9}\ \mathrm{pb}$$

Kidonakis, Vogt ’08; Moch, Uwer ’08; Langenfeld, Moch, Uwer ’09, M. Aliev, et al. ’11
Kidonakis, arXiv:1105.3481

- Mean between integration of the invariant mass and p_T distributions at NLO+NNLL

$$\sigma_{t\bar{t}}^{\mathrm{NNLO\ appr}}(\mathrm{Tev}, m_t = 173.1\ \mathrm{GeV}, \mathrm{MSTW2008}) = 6.63\ {}^{+0.07+0.63(0.33)}_{-0.41-0.48(0.25)}\ \mathrm{pb}$$

$$\sigma_{t\bar{t}}^{\mathrm{NNLO\ appr}}(\mathrm{LHC}, m_t = 173.1\ \mathrm{GeV}, \mathrm{MSTW2008}) = 155\ {}^{+8+14(8)}_{-9-14(9)}\ \mathrm{pb}$$

V. Ahrens, A. Ferroglia, M. Neubert, B. D. Pecjak, L. L. Yang, arXiv:1105.5824

Towards the NNLO

For the single-top cross section we have:

- t-channel. $m_t = 173$ GeV, MSTW2008.

$$\sigma^{\mathrm{NNLO\,appr}}_{t \text{ or } \bar{t}}(\mathrm{Tev}) = 1.04\,^{+0.00}_{-0.02} \pm 0.06 \;\; \mathrm{pb}$$

$$\sigma^{\mathrm{NNLO\,appr}}_{t}(\mathrm{LHC}) = 41.7\,^{+1.6}_{-0.2} \pm 0.8 \;\; \mathrm{pb}$$

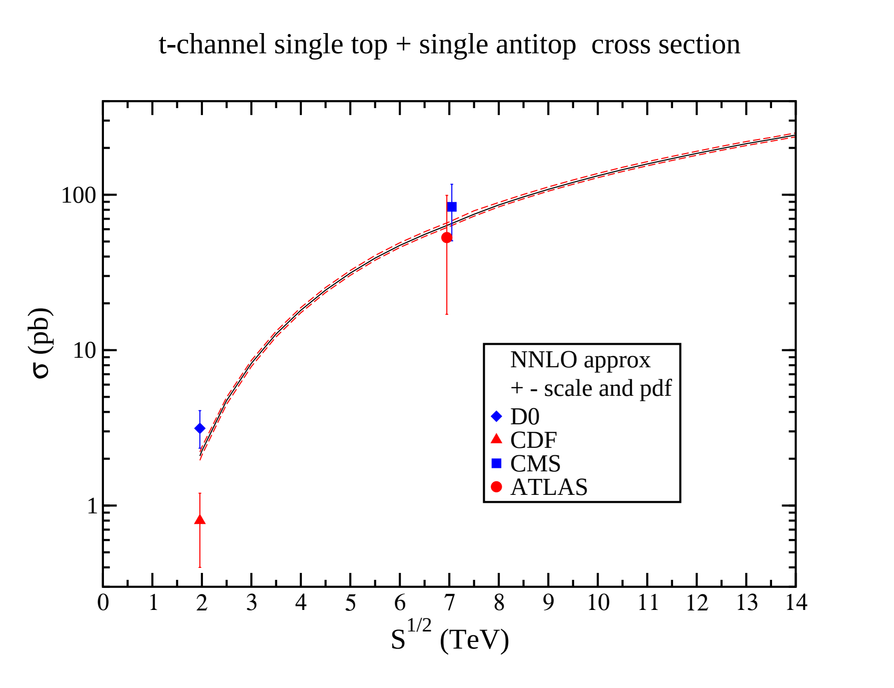
$$\sigma^{\mathrm{NNLO\,appr}}_{\bar{t}}(\mathrm{LHC}) = 22.5\; \pm 0.5^{+0.7}_{-0.9} \;\; \mathrm{pb}$$

- s-channel. $m_t = 173$ GeV, MSTW2008.

$$\sigma^{\mathrm{NNLO\,appr}}_{t \text{ or } \bar{t}}(\mathrm{Tev}) = 0.523\,^{+0.01+0.030}_{-0.005-0.028} \;\; \mathrm{pb}$$

$$\sigma^{\mathrm{NNLO\,appr}}_{t}(\mathrm{LHC}) = 3.17\; \pm 0.06^{+0.13}_{-0.10} \;\; \mathrm{pb}$$

$$\sigma^{\mathrm{NNLO\,appr}}_{\bar{t}}(\mathrm{LHC}) = 1.42\; \pm 0.01^{+0.06}_{-0.07} \;\; \mathrm{pb}$$



Kidonakis, arXiv:1105.3481

Exact NNLO for $t\bar{t}$ ... in progress

The NNLO calculation of the top-quark pair hadro-production requires several ingredients:

- Virtual Corrections
  - two-loop matrix elements for $q\bar{q} \to t\bar{t}$ and $gg \to t\bar{t}$

    Czakon '08, R. B., Ferroglia, Gehrmann, Maitre, von Manteuffel, Studerus '08-'10, Ferroglia, Neubert, Pecjak, Yang '09
  - interference of one-loop diagrams

    Körner et al. '05-'08; Anastasiou and Aybat '08
- Real Corrections
  - one-loop matrix elements for the hadronic production of $t\bar{t}$ + 1 parton
  - tree-level matrix elements for the hadronic production of $t\bar{t}$ + 2 partons

    Dittmaier, Uwer and Weinzierl '07-'08, Bevilacqua, Czakon, Papadopoulos, Worek '10, Melnikov, Schulze '10
- Subtraction Terms
  - Both matrix elements known for $t\bar{t} + j$ calculation, BUT subtraction up to 1 unresolved parton, while in a complete NNLO computation of $\sigma_{t\bar{t}}$ we need subtraction terms with up to 2 unresolved partons.

    Need of an extension of the subtraction methods at the NNLO.

    Gehrmann-De Ridder, Ritzmann '09, Daleo et al. '09, Boughezal et al. '10, Glover, Pires '10

    Recently double real in $\sigma_{t\bar{t}}$.

    Czakon '10, Anastasiou, Herzog, Lazopoulos '10

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**See the
Talk by A. von Manteuffel**

Conclusions

- In the last 15 years, Tevatron explored top-quark properties reaching a remarkable experimental accuracy. The top mass could be measured with $\Delta m_t/m_t = 0.63\%$ and the production cross section with $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} = 9\%$. Other observables could be measured only with bigger errors. First evidence of single top production.

- At the LHC the situation will further improve. Many observables will be measured with an extraordinary accuracy. The production cross section of $t\bar{t}$ pairs is expected to reach the accuracy of $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} = 5\%$!!

- This experimental precision requires a complete and precise theoretical analysis. Many groups are contributing to this effort.