Top quark pair production cross section in e^+e^- and hadronic collisions

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LC13: Exploring QCD from the infrared regime to ... LHC and Linear Colliders
Trento, Italy, Sep 16-20, 2013

Outline

- Top production at the LHC – NNLL resummed

  MB, P. Falgari, S. Klein, C. Schwinn, 1109.1536 [hep-ph];
  MB, P. Falgari, S. Klein, J. Piclum, C. Schwinn, M. Ubiali, F. Yan, 1206.2454 [hep-ph] (TOPIXS program)

- Top production near threshold in e^+e^- collisions

  MB, Kiyo, Schuller, hep-ph/0501289; MB, Kiyo, 0801.3464 [hep-ph];
  MB, Kiyo, Schuller, in preparation.

- Effective field theory of unstable particle production and non-resonant effects

  MB, Jantzen, Ruiz-Femenia 1004.2188 [hep-ph]; Jantzen, Ruiz-Femenia 1307.4337 [hep-ph]

- ... could be like any other quark, just happens to be a bit more massive.
  - SM
  - simple, perhaps unexciting

$\Longrightarrow$ Precision studies of top quark properties (mass, width) through inclusive production, FB and charge asymmetries, invariant mass, p_T (momentum) spectra etc.

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  - or to a strongly coupled sector (partial compositeness)
  - have new flavour-changing interactions
  - determine the fate of the Universe

Search for anomalous couplings, anomalies in production and decay.

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This is not a review ... focus on recent progress in inclusive production.

Total top-pair production cross section

Hadronic production (LHC)

- Benchmark for QCD calculations of hadronic processes. Now the most precisely predicted purely hadronic cross section.
- Theoretically clean but not very precise mass determination.
- Template for searches for unknown particles with missing transverse momentum.
- Constraint on gluon distribution in the proton in a momentum fraction region relevant to Higgs production.

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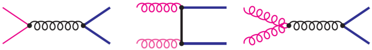
e^+e^-

- Very precise and clean mass measurement and width measurement at threshold
- Couplings above threshold

I. Hadronic production



dominant at Tevatron   dominant at LHC

NLO correction is large (50% at LHC)
[NLO QCD: Nason, Dawson, Ellis (1988), Beenakker et al. (1989)]
Data requires precision beyond NLO

	NLO	CDF	D0
Tevatron	$6.68\,^{+0.36+0.23}_{-0.75-0.22}$	$7.50^{+0.48}_{-0.48}$	$7.56^{+0.63}_{-0.56}$
	NLO	ATLAS	CMS
LHC (7 TeV)	$158.1\,^{+19.5+6.2}_{-21.2-6.8}$	$177 \pm 3^{+8}_{-7} \pm 7$	$166 \pm 2 \pm 11 \pm 8$
LHC (8 TeV)	$226.2\,^{+27.8+9.8}_{-29.7-9.1}$	$241 \pm 2 \pm 31 \pm 9$	$227 \pm 3 \pm 11 \pm 10$

$\sigma_{t\bar{t}}$ (in pb). NLO: $m_t = 173.3$ GeV. MSTW2008NLO, PDF+α_s error at 68% CL; independent μ_r and μ_f variations.

Theoretical progress beyond NLO

$$\sigma_{\text{had}}(\sqrt{s}, m_t) = \sum_{i,j=q,\bar{q},g} \int dx_i dx_j \, f_i(x_i) f_j(x_j) \, \hat{\sigma}_{ij}(\sqrt{\hat{s}}, m_t) \qquad \hat{s} = x_i x_j s$$

$$\beta = \sqrt{1 - 4m_t^2/\hat{s}}$$

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$$\beta = \sqrt{1 - 4m_t^2/\hat{s}}$$

NLO [NLO QCD: Nason, Dawson, Ellis, 1988, Beenakker et al., 1989]
NLL resummed [Catani et al.; Berger, Contopanagos; Kidonakis, Smith, Vogt, 1996; Bonciani et al., 1998]

↓

NNLO$_{\rm approx}$ [MB, Czakon, Falgari, Mitov, Schwinn, 2009; MB, Falgari, Klein, Schwinn, 2010; Aliev et al., 2010; from 1PI/1PM distributions: Ahrens et al., 2010/11; Kidonakis, 2010]

↓

NNLL resummed [MB, Falgari, Klein, Schwinn, 2011 (soft and Coulomb); Cacciari, Czakon, Mangano, Mitov, Nason, 2011 (soft) (Top++); MB, Falgari, Klein, Piclum, Schwinn, Ubiali, Yan, 2012 (TOPIXS); from 1PI/1PM distributions: Ahrens et al., 2010/11]

↓

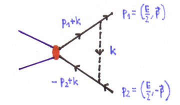
NNLO [Bärnreuther, Czakon, Mitov, 2012 ($q\bar{q}$); Czakon, Fiedler, Mitov, 2013 (gg)]

↓

NNLO + NNLL [2013 v2 versions of (Top++) and (TOPIXS)]

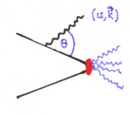
Fixed-order PT not applicable for threshold production (non-relativistic)

- Coulomb force



$$A \sim A_0 \times \frac{g^2}{\beta}$$

- Inhibited (soft) radiation



$$A \sim A_0 \times g^2 \ln^2 \beta$$

Resummation: breakdown of perturbation theory at small β

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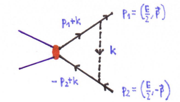

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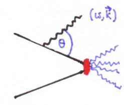
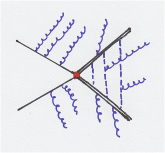


$$A \sim A_0 \times g^2 \ln^2 \beta$$

Perturbation theory breaks down due to the emergence of small scales $M\beta, M\beta^2 \ll M, \sqrt{\hat{s}}$.
Sum the series of enhanced quantum fluctuations to all orders:

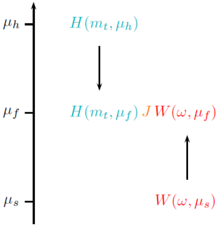
$$\begin{aligned} \sigma &= \sigma_0 \left[1 + g^2 \left\{ \frac{1}{\beta}, \ln^{2,1} \beta \right\} + g^4 \left\{ \frac{1}{\beta^2}, \frac{\ln^{2,1} \beta}{\beta}, \ln^{4,3,2,1} \beta \right\} + \ldots \right] \\ &= \sigma_0 \sum_{k=0} \left(\frac{\alpha_s}{\beta} \right)^k \exp \Big[\underbrace{\ln \beta \, g_0(\alpha_s \ln \beta)}_{\text{(LL)}} + \underbrace{g_1(\alpha_s \ln \beta)}_{\text{(NLL)}} + \underbrace{\alpha_s g_2(\alpha_s \ln \beta)}_{\text{(NNLL)}} + \ldots \Big] \\ &\quad \times \left\{ 1 \text{ (LL,NLL)}; \alpha_s, \beta \text{ (NNLL)}; \alpha_s^2, \alpha_s \beta, \beta^2 \text{ (NNNLL)}; \ldots \right\} \end{aligned}$$

$$\hat{\sigma}(\beta,\mu) = \sum_i H_i(M,\mu) \int d\omega \sum_{R_\alpha} J_{R_\alpha}(E - \frac{\omega}{2})\, W_i^{R_\alpha}(\omega,\mu)$$



- Factorization and resummation with non-relativistic and soft-collinear EFT.
- Summation of $\ln\beta$ terms by SCET RGE equation in x-space, not moment space. [Becher, Neubert (2006); Becher, Neubert, Xu (2007)]
- Match to fixed-order result to describe the region $\beta \sim 1$

$$\hat{\sigma}^{\text{NNLL}}_{\text{matched}} = [\hat{\sigma}^{\text{NNLL}} - \hat{\sigma}^{\text{NNLL}}_{\text{exp. to NNLO}}] + \hat{\sigma}^{\text{NNLO}}$$



Impact of NNLO and resummation [TOPIXS]

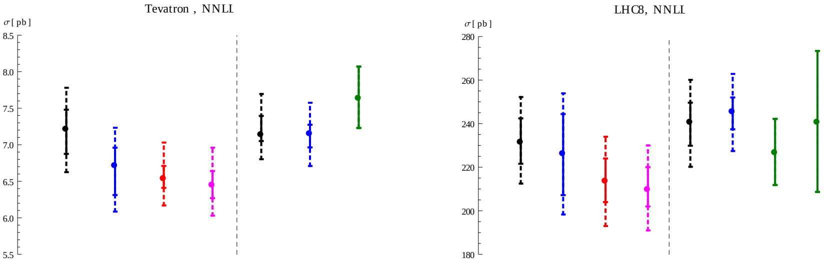
$\sigma_{t\bar{t}}$[pb]	Tevatron	LHC ($\sqrt{s}$ =7 TeV)	LHC ($\sqrt{s}$ =8 TeV)
NLO	$6.68^{+0.36+0.23}_{-0.75-0.22}$	$158.1^{+19.5+6.8}_{-21.2-6.2}$	$226.2^{+27.8+9.2}_{-29.7-8.3}$
NNLO_{app}	$7.06^{+0.26+0.29}_{-0.34-0.24}$	$161.1^{+12.3+7.3}_{-11.9-6.7}$	$230.0^{+16.7+9.7}_{-15.7-9.0}$
NNLO	$7.01^{+0.27+0.29}_{-0.37-0.24}$	$167.1^{+\ 6.7+7.7}_{-10.7-7.1}$	$239.1^{+9.2+10.4}_{-14.8-9.6}$
NNLL	$7.15^{+0.24+0.30}_{-0.10-0.25}$	$168.5^{+\ 6.3+7.7}_{-\ 7.5-7.2}$	$241.0^{+8.7+10.5}_{-11.1-9.7}$

$m_t = 173.3$ GeV, $\alpha_s(M_Z) = 0.1171$, (N)NLO MSTW08 PDFs, first error theoretical uncertainty, second PDF+α_s at 68% CL.
Theoretical error: independent soft/hard/Coulomb scale variations, resummation ambiguities.

- Tevatron ($q\bar{q}$)
  significant resummation/NNLO effect [+8%],
  reduction of theoretical uncertainty [8% $\rightarrow$ 3%] (excluding PDF + α_s error),
  threshold approximation worked well.

- LHC (gg)
  small resummation [+1%]/significant NNLO effect [+4%],
  significant reduction of theoretical uncertainty [13% $\rightarrow$ 4.5%],
  threshold expansion did not work that well.

Comparison of NNLL results



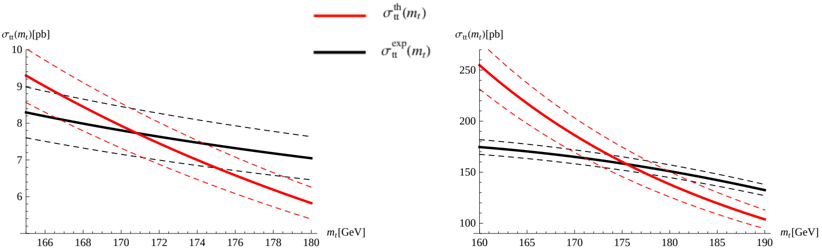
left of dashed: NNLO$_{\text{app}}$ + NNLL
MB, Falgari, Klein, Schwinn 2011; TOPIXS 1.0 ($m_t = 173.3$ GeV)
Cacciari, Czakon, Mangano, Mitov, Nason 2011 ($m_t = 173.3$ GeV)
Ahrens, Ferroglia, Neubert, Pecjak, Yang 2011 (1PI, $m_t = 173.1$ GeV)
Ahrens, Ferroglia, Neubert, Pecjak, Yang 2011 (PIM, $m_t = 173.1$ GeV)

right of dashed: NNLO + NNLL
Piclum; 2013 update of MB, Falgari, Klein, Piclum, Schwinn, Ubiali, Yan 2012; TOPIXS 2.0 ($m_t = 173.3$ GeV)
Czakon, Fidler, Mitov, 2013 `top++2.0` ($m_t = 173.3$ GeV)

Experiments: CDF/D0 2012 combined; CMS/ATLAS-CONF-2012-149

Error bars: solid – theory, dashed – PDF (+α_s) added
PDF set: MSTW 2008 NNLO

Experimental cross section depends on assumed m_t.



Maximize joint likelihood $f(m_t) = \int d\sigma\, f_{\rm th}(\sigma|m_t) \cdot f_{\rm exp}(\sigma|m_t)$.

$m_t = (171.5^{+5.4}_{-6.2})$ GeV (Tevatron data)

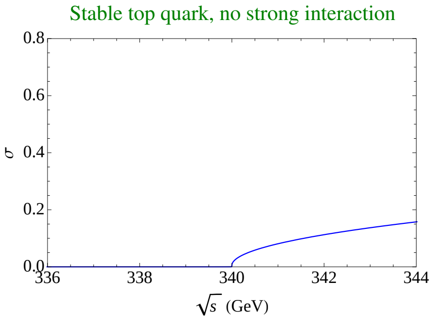
$m_t = (176.1^{+5.3}_{-4.7})$ GeV (CMS data [1208.2671])

Consistent with top decay mass reconstruction!
($m_t = 173.2 \pm 0.8$ GeV)

See also Langenfeld et al. (2009), D0, CDF, ...

II. Threshold production in e^+e^-

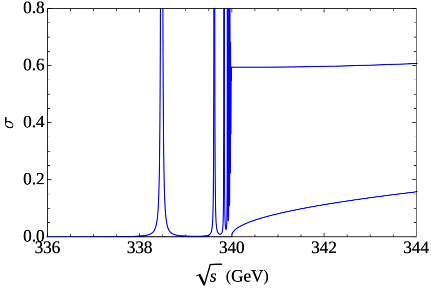
Ultra-precise mass measurement
Unique QCD dyanmics



Pair production threshold – Coulomb force and Weak Decay

Ultra-precise mass measurement
Unique QCD dyanmics

Stable top quark, with strong Coulomb force



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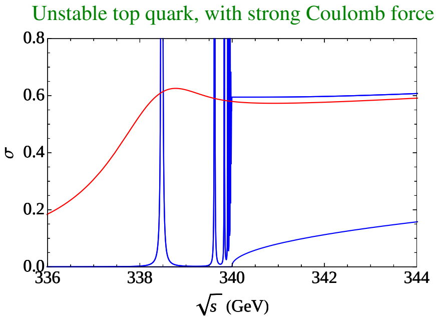
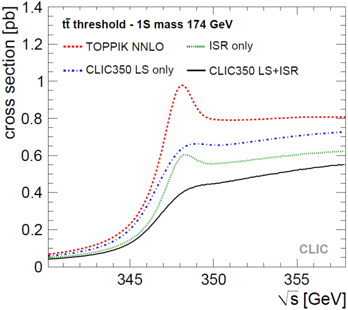
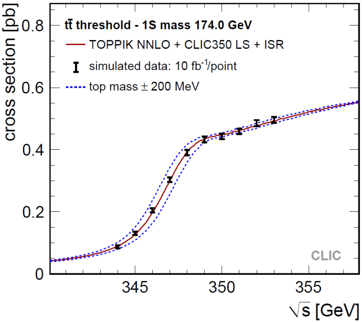


Smallest <u>structure</u> in particle physics known to exist (10^{-17}m).
Direct "spectroscopic" width measurement.

Threshold scan at ILC

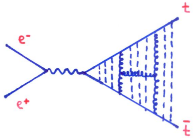
Additional smearing of the resonance due to beam luminosity spectrum (collider-specific) and ISR





Most recent study for ILC/CLIC [Seidel, Simon, Tesai, Poss, 2013] assumes $10\,\text{fb}^{-1}$ at 10 points.

$$[\delta m_t]_{\text{thr}} = 27\,\text{MeV} \qquad \text{[simultaneous fit of } \alpha_s\text{]}$$



- All-order summation since α_s/v can be large.
  Well-defined framework (EFT) to combine relativistic and boundstate effects.

- Mass definition: abandon the pole mass!
  Potential-subtracted mass [MB, 1998]

$$m_{\mathrm{PS}}(\mu_f) \equiv m_{\mathrm{pole}} + \frac{1}{2} \int_{|\vec{q}\,|<\mu_f} \frac{d^3\vec{q}}{(2\pi)^3}\, \tilde{V}_{\mathrm{Coulomb}}(\vec{q}\,)$$

Cancellation of large perturbative contributions from the IR.

- High orders:
  NNLO calculations find large uncertainty [up $\pm 25\%$] in the cross section in the resonance peak region (MB, Signer, Smrinov; Hoang, Teubner; Melnikov,Yelkovsky; Yakovlev; Nagano et al.; Penin, Pivovarov, 1998/99).
  Maybe less after $\log(v)$ resummation [$\pm 3\%$] (Hoang et al., 2002; Hoang, Stahlhofen, 2011)

Basic techniques worked out end of 1990s but the next order is hard!

In the absence of electroweak corrections

$$(q_\mu q_\nu - q^2 g_{\mu\nu})\,\Pi(q^2) = i\int d^4x\, e^{iq\cdot x}\,\langle 0|T(j_\mu(x)j_\nu(0))|0\rangle, \qquad j^\mu(x) = [\bar{t}\gamma^\mu t](x)$$

$$R \equiv \frac{\sigma_{t\bar{t}X}}{\sigma_0} = 12\pi e_t^2\,\mathrm{Im}\,\Pi(s)$$

Relevant scales: $m_t \approx 175\,\mathrm{GeV}$ (hard), $m_t\alpha_s \approx 30\,\mathrm{GeV}$ (soft, potential) and the ultrasoft scale (us) $m_t\alpha_s^2 \approx 2\,\mathrm{GeV}$.

$$\mathcal{L}_{\mathrm{QCD}}\,[Q(h,s,p),\ g(h,s,p,us)] \qquad \mu > m_t$$

$$\downarrow$$

$$\mathcal{L}_{\mathrm{PNRQCD}}\,[Q(p),\ g(us)] \qquad \mu < m_t v$$

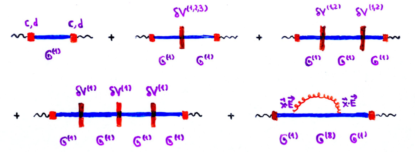
The ultrasoft scale appears explicitly only at NNNLO. A complete calculation of the (non-logarithmic) NNNLO correction is therefore needed.

Matching of currents and interactions (potentials and ultrasoft)

$$j^i = c_v\, \psi^\dagger \sigma^i \chi + \frac{d_v}{6m_t^2} \psi^\dagger \sigma^i\, \mathbf{D}^2 \chi + \ldots$$
$$\mathcal{L}_{\rm QCD} \to \mathcal{L}_{\rm PNRQCD}$$

$$\begin{aligned}\mathcal{L}_{\rm PNRQCD} \;=\;& \psi^\dagger \Big(iD_0 + i\frac{\Gamma_t}{2} + \frac{\boldsymbol{\partial}^2}{2m} + \frac{\boldsymbol{\partial}^4}{8m^3} \Big) \psi + \chi^\dagger \Big(iD_0 - i\frac{\Gamma_t}{2} - \frac{\boldsymbol{\partial}^2}{2m} - \frac{\boldsymbol{\partial}^4}{8m^3} \Big) \chi \\ & + \int d^{d-1}\mathbf{r} \left[\psi^\dagger \psi\right](x+\mathbf{r}) \left(-\frac{\alpha_s C_F}{r} + \delta V(r, \boldsymbol{\partial}) \right) \left[\chi^\dagger \chi\right](x) \\ & - g_s \psi^\dagger(x) \boldsymbol{x}\boldsymbol{E}(t, \mathbf{0}) \psi(x) - g_s \chi^\dagger(x) \boldsymbol{x}\boldsymbol{E}(t, \mathbf{0}) \chi(x)\end{aligned}$$

- Three-loop matching required for the hard vertex c_v [Marquard, Piclum, Seidel, Steinhauser, unpublished] and the Coulomb potential [Anzai, Kiyo, Sumino, 2009; Smirnov, Smirnov, Steinhauser, 2009].



where

$$G_c^{(1,8)}(\boldsymbol{r},\boldsymbol{r}',E) = \frac{my}{2\pi} e^{-y(r+r')} \sum_{l=0}^{\infty} (2l+1)(2yr)^l (2yr')^l P_l\left(\frac{\boldsymbol{r}\cdot\boldsymbol{r}'}{rr'}\right) \sum_{s=0}^{\infty} \frac{s!L_s^{(2l+1)}(2yr)L_s^{(2l+1)}(2yr')}{(s+2l+1)!(s+l+1-\lambda)}$$

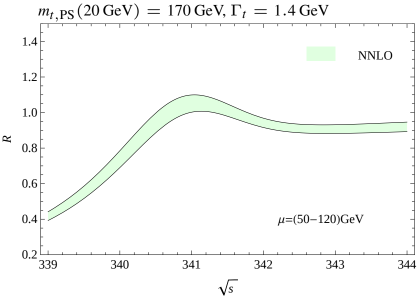
$$y = \sqrt{-m(E+i\epsilon)},\ \lambda = \frac{m\alpha_s}{2y} \times \{C_F\ (\text{singlet});\ C_F - C_A/2\ (\text{octet})\}$$

The ultrasoft contribution is ($D = d - 1$)

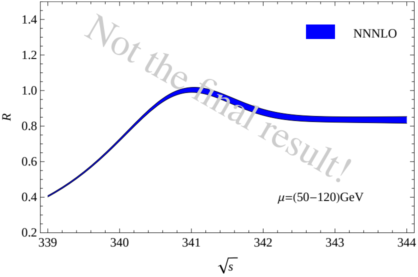
$$\delta G_{\text{us}} = (-i)(ig_s)^2 C_F \int \frac{d^d k}{(2\pi)^d} \frac{-i}{k^2} \left(\frac{k^i k^j}{k_0^2} - \delta^{ij}\right) \int \prod_{n=1}^{6} \frac{d^D p_n}{(2\pi)^D}\, i\tilde{G}^{(1)}(p_1,p_2;E)\, i\tilde{G}^{(8)}(p_3,p_4;E+k^0)\, i\tilde{G}^{(1)}(p_5,p_6;E)$$

$$\times\, i\left[\frac{2p_3^i}{m_t}(2\pi)^D \delta^{(D)}(p_3-p_2) + (ig_s)^2 \frac{C_A}{2} \frac{2(p_2-p_3)^i}{(p_2-p_3)^4}\right] i\left[-\frac{2p_4^j}{m_t}(2\pi)^D \delta^{(D)}(p_4-p_5) + (ig_s)^2 \frac{C_A}{2} \frac{2(p_4-p_5)^j}{(p_4-p_5)^4}\right]$$

Difficulty is the extraction of the divergence in dim. reg.



[MB, Signer, Smirnov, 1999]



[MB, Kiyo, Schuller, in progress]

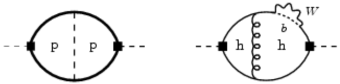
III. Non-resonant effects

Finte-width divergences and "electroweak effects"

The QCD-only result usually discussed is far from reality

- Finite-width divergences (overall divergence, already at NNLO):

$$[\delta G(E)]_{\text{overall}} \propto \frac{\alpha_s}{\epsilon} \cdot E$$



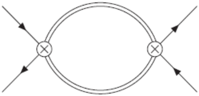
Since $E = \sqrt{s} - 2m_t + i\Gamma$, the divergence survives in the imaginary part:

$$\text{Im}\,[\delta G(E)]_{\text{overall}} \propto m_t \times \frac{\alpha_s \alpha_{ew}}{\epsilon}$$

- Electroweak effect. Must consider $e^+e^- \to W^+W^-b\bar{b}$.
  Significant "non-resonant" background from off-shell top decay (unless tight invariant mass cuts are applied), not described by NRQCD.
  Starts at NLO [MB, Jantzen, Ruiz-Femenia, 2010; Penin, Piclum, 2011]

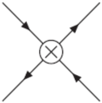
- QED effects [Pineda, Signer, 2006; MB, Jantzen, Ruiz-Femenia, 2010], electroweak absorptive parts [Hoang, Reisser, 2004], initial state radiation (formalism in [MB, Falgari, Schwinn, Signer, Zanderighi]).

Unstable particle EFT provides a systematic expansion of the amplitude in powers of Γ/m.



Resonant contributions

Production of an on-shell, non-relativistic $t\bar{t}$ pair and subsequent decay $t \to W^+ b$.



Non-resonant contributions

Off-shell lines. Full theory diagrams expanded around $s = 4m_t^2$.

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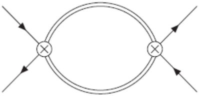

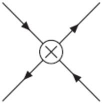

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Non-resonant contributions

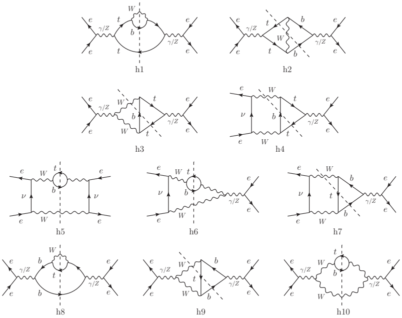
Off-shell lines. Full theory diagrams expanded around $s = 4m_t^2$.

$$i\mathcal{A} = \sum_{k,l} C_p^{(k)} C_p^{(l)} \int d^4x \, \langle e^- e^+ | \mathrm{T}[i\mathcal{O}_p^{(k)\dagger}(0)\, i\mathcal{O}_p^{(l)}(x)] | e^- e^+ \rangle + \sum_k C_{4e}^{(k)} \langle e^- e^+ | i\mathcal{O}_{4e}^{(k)}(0) | e^- e^+ \rangle$$

$$\mathcal{O}_p^{(v)} = \bar{e}_{c_2} \gamma_i e_{c_1} \, \psi_t^\dagger \sigma^i \chi_t \qquad \mathcal{O}_{4e}^{(k)} = \bar{e}_{c_1} \Gamma_1 e_{c_2} \, \bar{e}_{c_2} \Gamma_2 e_{c_1},$$

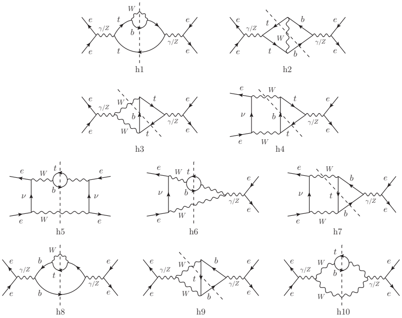
$$\mathcal{O}_p^{(a)} = \bar{e}_{c_2} \gamma_i \gamma_5 \, e_{c_1} \, \psi_t^\dagger \sigma^i \chi_t$$

$$\sigma_{\text{non-res}} = \frac{1}{s} \sum_k \mathrm{Im}\left[C_{4e}^{(k)}\right] \langle e^- e^+ | i\mathcal{O}_{4e}^{(k)}(0) | e^- e^+ \rangle$$



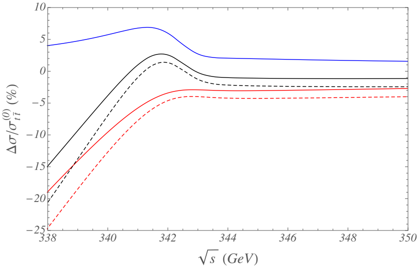
Equivalent to the dimensionally regulated $e^+e^- \to bW^+\bar{t}$ process with $\Gamma_t = 0$, expanded in the hard region around $s = 4m_t^2$.

Non-resonant corrections at NLO



Equivalent to the dimensionally regulated $e^+e^- \to bW^+\bar{t}$ process with $\Gamma_t = 0$, expanded in the hard region around $s = 4m_t^2$.

[MB, Jantzen, Ruiz-Femenia, 2010]

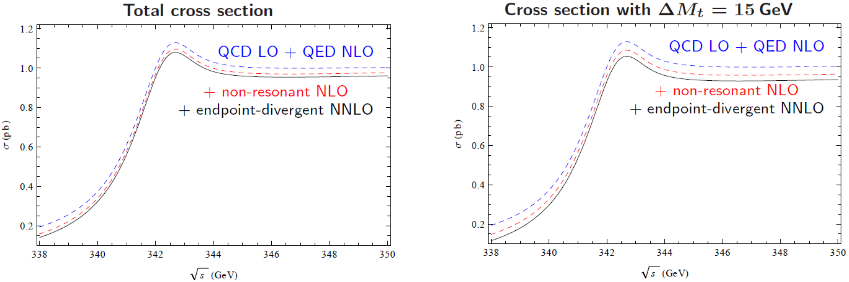


QED and non-resonant corrections relative to the $t\bar{t}$ LO cross section in percent: $\sigma^{(1)}_{\text{QED}}/\sigma^{(0)}_{t\bar{t}}$ (upper solid blue), $\sigma^{(1)}_{\text{non-res}}/\sigma^{(0)}_{t\bar{t}}$ for the total cross section (lower solid red) and $\Delta M_t = 15$ GeV (lower dashed red). The relative size of the sum of the QED and non-resonant corrections is represented by the middle (black) lines, for $\Delta M_{t,\text{max}}$ (solid) and $\Delta M_t = 15$ GeV (dashed)

Large correction below threshold.
Invariant mass cuts can be applied within the EFT framework.

$e^+e^- \to W^+W^-b\bar{b}$ near $s = 4m_t^2$

NLO + NNLO singular terms [Jantzen, Ruiz-Femenia, 2013]



“Realistic” cross section calculations almost completed.
ISR corrections should be applied in the theoretical prediction, not the experimental simulation.

Summary

- Hadronic $t\bar{t}$ cross section now computed at NNLO+NNLL (soft + Coulomb)

  Theoretical uncertainty: 3% (Tevatron), 4.5% (LHC)
  PDF + α_s uncertainty (68% CL): 5%

  Best predicted purely hadronic cross section. PDF error dominates. Solid constraint on "light" new physics.

  Well-defined determination of m_t with a present error of $(4-5)$ GeV, consistent with the top mass reconstruction from decay products.

  Outlook: differential NNLO; NNNLL resummation.

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Outlook: differential NNLO; NNNLL resummation.

II $e^+e^- \to t\bar{t}X$ cross section near threshold now computed at NNNLO.

Sizeable 3rd order corrections and reduction of theoretical uncertainty.
Ultra-precise mass measurement.

Realistic predictions for $e^+e^- \to W^+W^-b\bar{b}$ near top-pair threshold available with sufficient accuracy, including cuts.

Outlook: NNNLO code; complete NNLO non-resonant.