Top pair production near threshold

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Outline

- Introduction and theoretical framework
- Top production near threshold in e^+e^- collisions – QCD effects and parameter variations

  MB, Kiyo, Schuller, 1312.4791 [hep-ph] and in preparation;
  MB, Piclum, Rauh, 1312.4792 [hep-ph];
  MB, ..., Steinhauser, in preparation; MB, Piclum, Rauh, in progress.

- Beyond QCD – Non-resonant effects

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

SFB TR9

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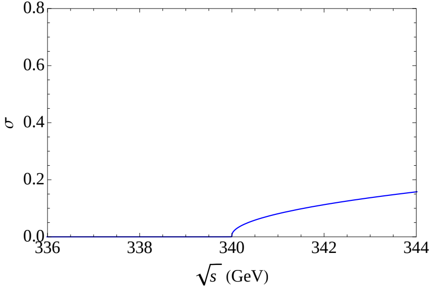
Pair production threshold – Coulomb force and Weak Decay

Ultra-precise mass measurement
Unique QCD dyanmics

Stable top quark, no strong interaction



Pair production threshold – Coulomb force and Weak Decay

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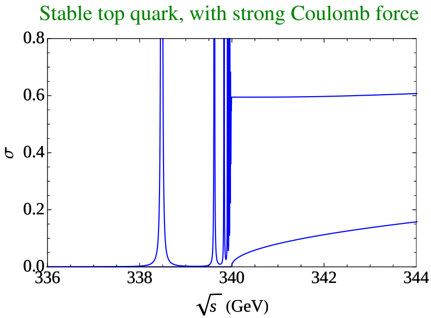
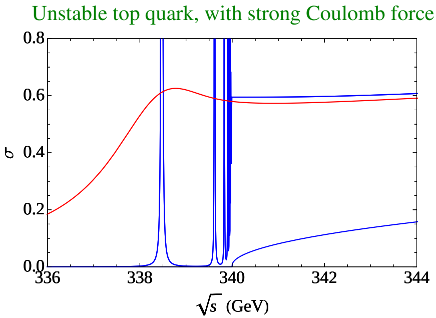


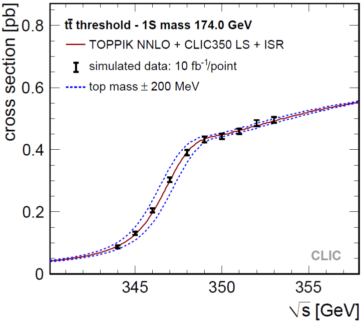
Ultra-precise mass measurement
Unique QCD dyanmics



Smallest structure in particle physics known to exist (10^{-17}m).
Direct "spectroscopic" mass and 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 $10\,\mathrm{fb}^{-1}$ at 10 points.

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

Theory

Non-perturbative but weak coupling. Expansion in α_s and $v = \sqrt{\frac{E}{m}} = \sqrt{\frac{\sqrt{q^2} - 2m_t}{m_t}}$, while $\alpha_s/v = O(1)$

$$R \sim v \sum_k \left(\frac{\alpha_s}{v}\right)^k \cdot \left\{1\,(\text{LO});\, \alpha_s, v\,(\text{NLO});\, \alpha_s^2, \alpha_s v, v^2\,(\text{NNLO});\, \ldots\right\}$$

$$(q_\mu q_\nu - q^2 g_{\mu\nu})\,\Pi(q^2) = i \int d^4x\, e^{iq\cdot x}\, \langle 0|T(j_\mu(x) j_\nu(0))|0\rangle, \qquad j^\mu(x) = [\bar{Q}\gamma^\mu(\gamma_5)Q](x)$$

Summation through Schrödinger equation.

$$\text{Im}\,\Pi(E) = \underbrace{\frac{N_c}{2m^2} \sum_{n=1}^{\infty} Z_n \times \pi\delta(E_n - E)}_{\text{bound states}} + \Theta(E)\, \underbrace{\text{Im}\,\Pi(E)_{\text{cont}}}_{\text{continuum}}$$

$$R \equiv \frac{\sigma_{e^+e^- \to WWb\bar{b}X}}{\sigma_0} = 12\pi e_t^2\, \text{Im}\,\Pi(E + i\Gamma_t) + \text{non-resonant}$$

Tools

Non-relativistic effective field theory and threshold expansion (defines the matching procedure!) See arXiv:1312.4791 [hep-ph]

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

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

$$\downarrow$$

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

See mulit-loop fixed-order calculations to match PNRQCD, then perturbation theory in Coulomb background in PNRQCD. Can be extended systematically to any order. 3rd order is current technological limit.

$$\Pi^{(v)}(q^2) = \frac{N_c}{2m^2}\,c_v\left[c_v - \frac{E}{m}\left(c_v + \frac{d_v}{3}\right)\right]G(E) + \ldots$$

$$G(E) = \frac{i}{2N_c(d-1)}\int d^dx\, e^{iEx^0}\,\langle 0|\,T(\,[\chi^\dagger\sigma^i\psi](x)\,[\psi^\dagger\sigma^i\chi](0))|0\rangle_{|\mathrm{PNRQCD}}\,,$$

3rd order ingredients

- Bound state quantities (S-wave)
  - E_n – Kniehl, Penin, Smirnov, Steinhauser (2002); MB, Kiyo, Schuller (2005); Penin, Sminrov, Steinhauser (2005)
  - $|\psi_n(0)|^2$ – MB, Kiyo, Schuller (2007); MB, Kiyo, Penin (2007)
- Matching coefficients
  - a_3 – Anzai, Kiyo, Sumino (2009); Smirnov, Sminrov, Steinhauser (2009)
  - c_3 – Marquard, Piclum, Seidel, Steinhauser (2013) [2009]
- Continuum (PNRQCD correlation function)
  - ultrasoft – MB, Kiyo (2008)
  - potential – MB, Kiyo, Schuller, in preparation (2014) [2007]
  - P-wave – MB, Piclum, Rauh (2013)

Note: logarithmically enhanced 3rd order terms known before or resummed [Hoang et al. 2001-2013; Pineda et al. 2002-2007]
2nd order available since end of 1990s.

I. Top production near threshold in e^+e^- collisions – QCD effects and parameter variations

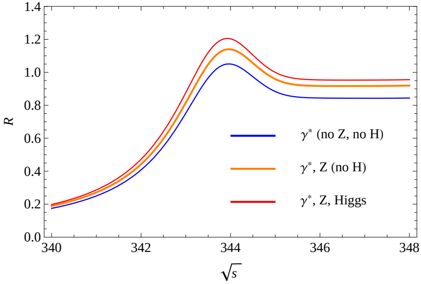
MB, Kiyo, Schuller, 1312.4791 [hep-ph] and in preparation;
MB, ..., Steinhauser, in preparation (third-order QCD);
MB, Rauh, Piclum, in preparation (Higgs, top-Yukawa interaction)

Mass definition, overall result

- Mass definition: Potential-subtracted mass [MB, 1998]

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

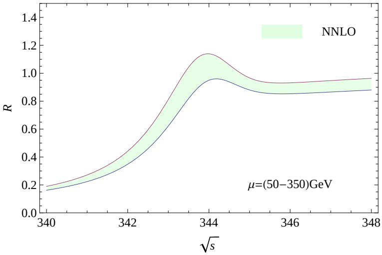
Cancellation of large perturbative contributions from the IR. In the following: $m_{t,\rm PS}(20\,\rm GeV) = 171.5\,\rm GeV$.



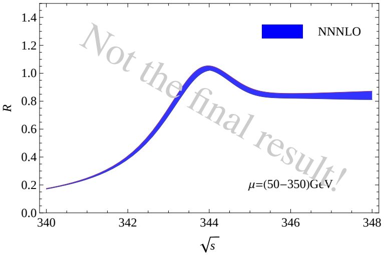
QCD at 3rd order, P-wave (Z only) and Higgs at NLO $\simeq$ NNNLO QCD

Cross section near threshold, from 2nd to 3rd order

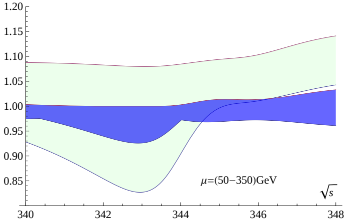
[MB, Signer, Smirnov, 1999]

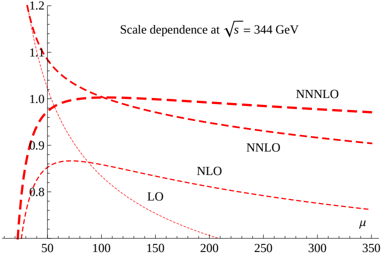


[MB, Kiyo, Schuller; MB ... Steinhauser, in progress]



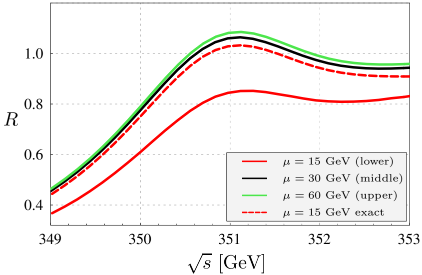
$m_{t,\mathrm{PS}}(20\,\mathrm{GeV}) = 171.5\,\mathrm{GeV},\ \Gamma_t = 1.33\,\mathrm{GeV}$





No convergence for $\mu \lesssim 50\,\text{GeV}$.

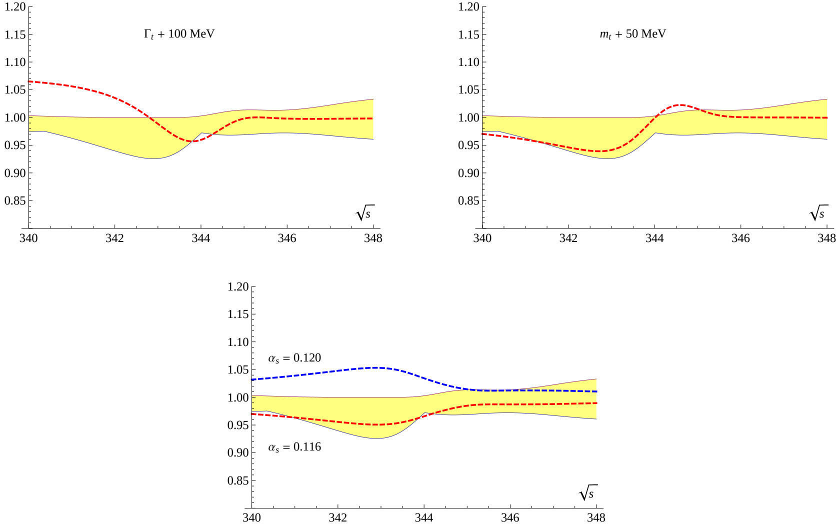
[MB, Kiyo, Schuller (2005)]



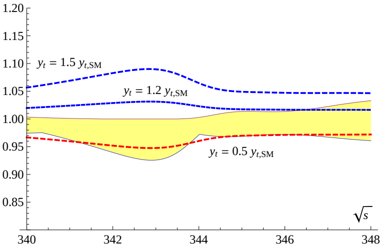
Compare recent NNLO+(N)NLL analysis [Hoang, Stahlhofen, 2013]

Coulomb corrections only (for $m_{t,\text{PS}} = 175\,\text{GeV}$, $\Gamma_t = 1.5\,\text{GeV}$). Scale depedence at third order and exact solution.

Parameter dependence



Yukawa coupling



II. Beyond QCD – non-resonant effects

MB, Jantzen, Ruiz-Femenia 1004.2188 [hep-ph];
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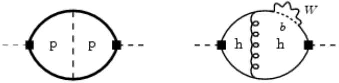
Finte-width divergences and "electroweak effects"

The QCD-only result usually discussed is far from reality

- Finite-width divergences (overall log 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 $e^+e^- \to W^+W^-b\bar{b}$.

$$\sigma_{e^+e^- \to W^+W^-b\bar{b}} = \underbrace{\sigma_{e^+e^- \to [t\bar{t}]_{\text{res}}}(\mu_w)}_{\text{pure (PNR)QCD}} + \sigma_{e^+e^- \to W^+W^-b\bar{b}_{\text{nonres}}}(\mu_w)$$

Non-resonant starts at NLO (overall linear divergence) [MB, Jantzen, Ruiz-Femenia, 2010; Penin, Piclum, 2011]. Finite-width scale dep must cancel. Need consistent dim reg calculation.

From QCD $t\bar{t}$ threshold to a realistic prediction

At 3rd order QCD effects under control. Then

- $\sigma_{e^+e^-\to W^+W^-b\bar{b}_{\rm nonres}}(\mu_w)$ to (at least) NNLO in consistent scheme. Mostly inclusive.

  NLO [MB, Jantzen, Ruiz-Femenia, 2010; Penin, Piclum, 2011]
  Partial results only at NNLO [Hoang, Reisser, Ruiz-Femenia, 2010; Jantzen, Ruiz-Femenia, 2013]

- QED effects (from NLO) [Pineda, Signer, 2006; MB, Jantzen, Ruiz-Femenia, 2010]

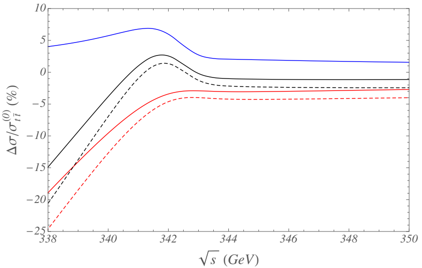
- Electroweak matching coefficients absorptive parts [Hoang, Reisser, 2004]

- Initial state radiation (formalism in MB, Falgari, Schwinn, Signer, Zanderighi, 2007).

Finally, need four-loop (formally even five-loop) relation between the pole and the MSbar mass to convert the precise value for the PS mass to an equally precise value of the MSbar mass.

Non-resonant corrections at NLO

[MB, Jantzen, Ruiz-Femenia, 2010]

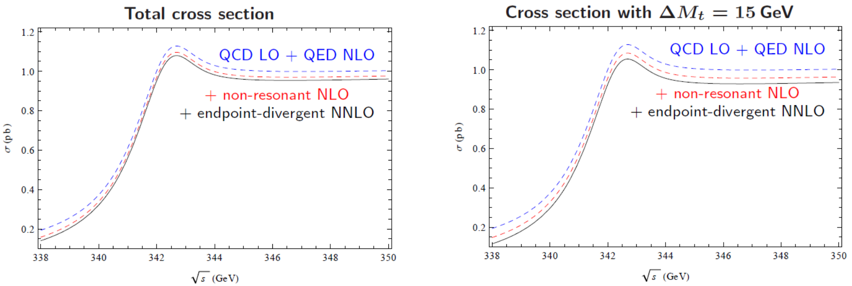


QED and non-resonant corrections relative to the $t\bar{t}$ LO cross section in percent: $\sigma^{(1)}_{\rm QED}/\sigma^{(0)}_{t\bar{t}}$ (upper solid blue), $\sigma^{(1)}_{\rm non\text{-}res}/\sigma^{(0)}_{t\bar{t}}$ for the total cross section (lower solid red) and $\Delta M_t = 15$ GeV (lower dashed red). The relative size of the sum of the QED and non-resonant corrections is represented by the middle (black) lines, for $\Delta M_{t,\rm max}$ (solid) and $\Delta M_t = 15$ GeV (dashed). $m_{t,\rm pole} = 172$ GeV.

Large correction below threshold.
Much larger than QCD scale-dependence at 3rd order ($\pm(2-3)\%$)

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

NLO + NNLO singular terms [Jantzen, Ruiz-Femenia, 2013; see also Hoang, Reisser, Ruiz-Femenia, 2010]
(Singular refers to expansion in Λ/m_t where Λ is an invariant mass cut such that $m_t\Gamma_t \ll \Lambda^2 \ll m_t^2$.)



NNLO non-resonant still -2% at threshold and larger below.
Accurate description of region below peak is required for precise determination of m_t.

Summary

I $e^+e^- \to t\bar{t}X$ cross section near threshold now computed at NNNLO in (PNR)QCD

- Sizeable 3rd order corrections and reduction of theoretical uncertainty.
- Parameter dependences $(m_t, \Gamma_t, y_t, \alpha_s)$ can be studied.

II Realistic predictions for $e^+e^- \to W^+W^-b\bar{b}$ near top-pair threshold

- NLO available, including cuts invariant mass cuts.
  Should (and can) be done to NNLO. Residual uncertainty should then be small.
- ISR should be done by theorists.
  Known in principle, in practice accuracy may not yet be sufficient.

III What is limiting the mass measurement: statistics? experimental systematics? theory? Still open.