

Electroweak effects in $t\bar{t}$ production near threshold

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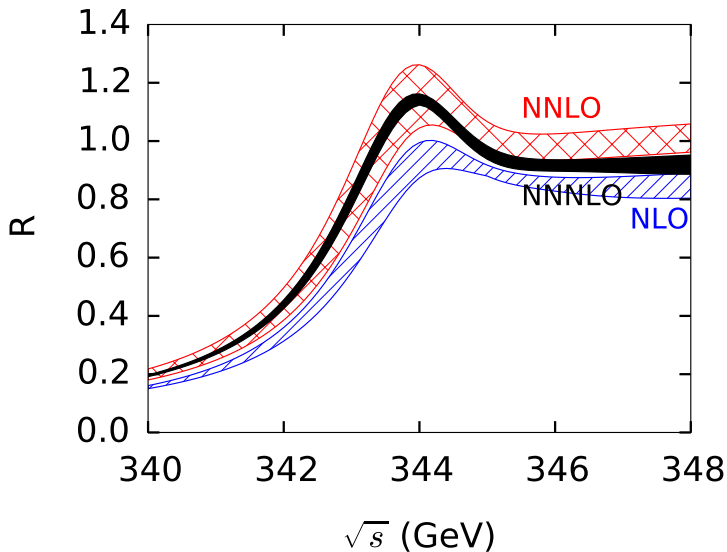
IPPP, Durham University

LCWS 2016

$t\bar{t}$ production in QCD

N^3 LO corrections

[Beneke, Kiyo, Marquard, Penin, Piclum, Steinhauser 2015]



Why corrections beyond QCD?

- ▶ Not included in uncertainty band potentially numerically relevant ($\gtrsim 3\%$)
- ▶ Naïve treatment of width $E_{\text{kin}} \rightarrow E_{\text{kin}} + i\Gamma$ inconsistent at higher orders
- ▶ Yukawa coupling to top quarks

Power counting and modes

Power counting: $v^2 \sim \alpha_s^2 \sim y_t^2 \sim \alpha$

~~~~~ hard:  $p_\mu \sim m_t$

~~~~~ soft:  $p_\mu \sim m_t v$

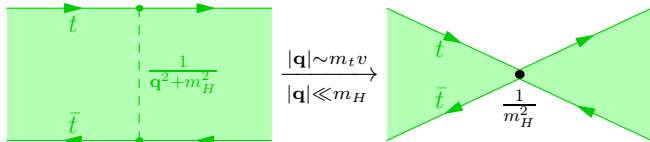
~~~~~ potential:  $E \sim m_t v^2, \vec{p} \sim m_t v$

~~~~~ ultrasoft:  $p_\mu \sim m_t v^2$

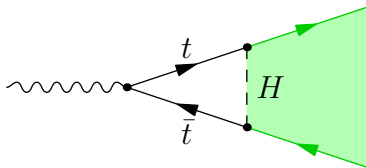
Corrections beyond QCD

[Beneke, AM, Piclum, Rauh 2015]

- ▶ Higgs corrections
 - ▶ Potential (NNNLO):



- ▶ Production current (NNLO + NNNLO):

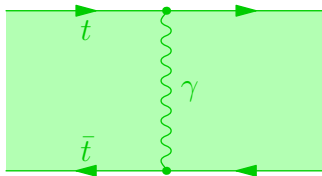


[Grzadkowski, Kühn, Krawczyk, Stuart 1986; Guth, Kühn 1991; Hoang, Reißer 2006; Eiras, Steinhauser 2006]

Corrections beyond QCD

[Beneke, AM, Piclum, Rauh 2015]

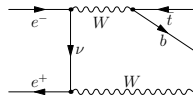
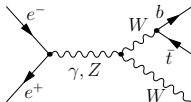
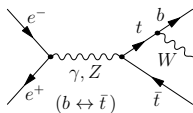
- ▶ Higgs corrections
- ▶ NLO QED Coulomb potential



Corrections beyond QCD

[Beneke, AM, Piclum, Rauh 2015]

- ▶ Higgs corrections
- ▶ NLO QED Coulomb potential
- ▶ Nonresonant production ($e^+e^- \rightarrow W^+W^-b\bar{b}$)
 - ▶ NLO: [Beneke, Jantzen, Ruiz-Femenia 2010]



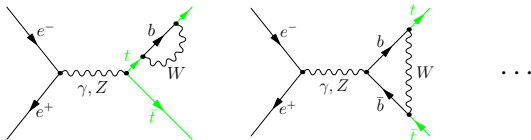
- ▶ NNLO: Partial results [Penin, Piclum 2012; Jantzen, Ruiz-Femenia 2013]
not included in analysis

Corrections beyond QCD

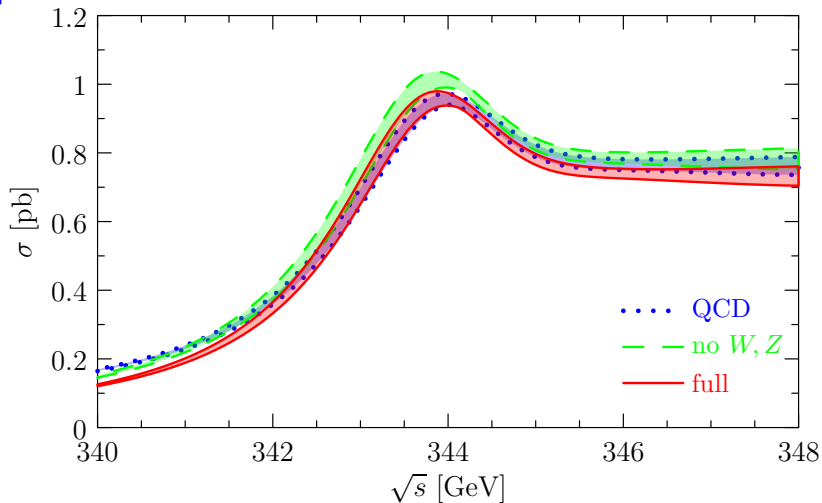
[Beneke, AM, Piclum, Rauh 2015]

- ▶ Higgs corrections
- ▶ NLO QED Coulomb potential
- ▶ Nonresonant production ($e^+e^- \rightarrow W^+W^-b\bar{b}$)
- ▶ **New:** hard NNLO electroweak corrections (W, Z)

[Grzadkowski, Kühn, Krawczyk, Stuart 1986; Guth, Kühn 1991; Hoang, Reißer 2004 & 2006]



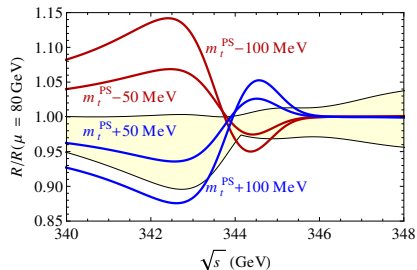
Impact on the cross section



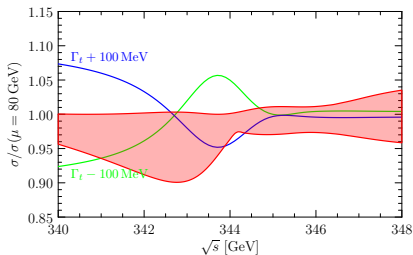
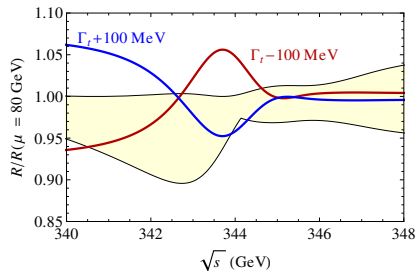
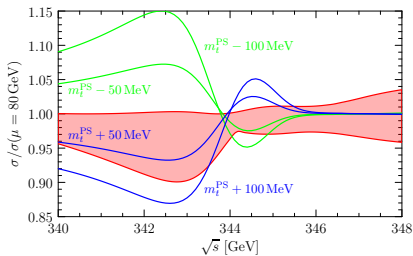
$$m_t^{\text{PS}}(20 \text{ GeV}) = 171.5 \text{ GeV}, \quad \Gamma_t = 1.33 \text{ GeV}, \quad m_H = 125 \text{ GeV}, \\ \alpha_s(m_Z) = 0.1177, \quad \alpha(m_Z) = 1/128.944, \quad m_W, m_Z$$

Top mass and width

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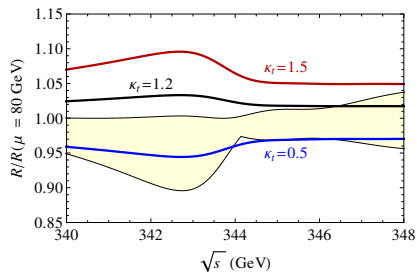
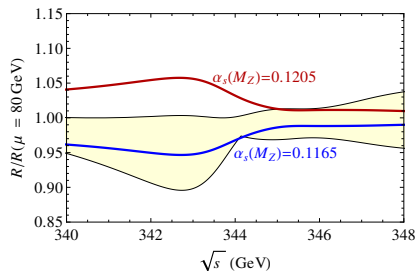


Today

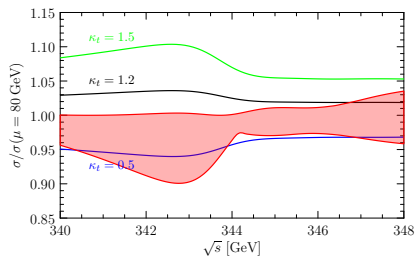
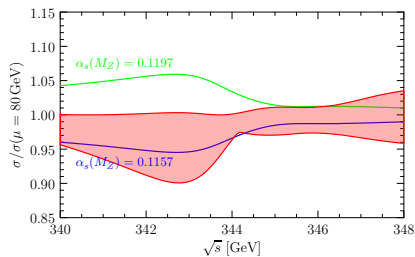


Strong coupling and top Yukawa coupling

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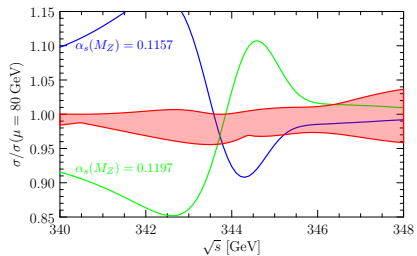


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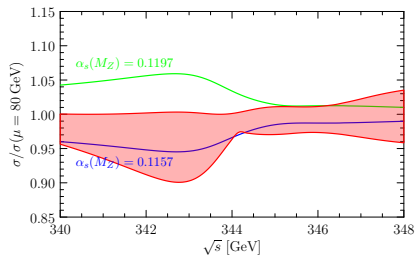


\overline{MS} vs. PS mass

\overline{MS} scheme



PS scheme



QQbar_threshold

[Beneke, Kiyo, AM, Piclum 2016]

Public C++ library for $e^+e^- \rightarrow Q\bar{Q}$ near threshold:

- ▶ N³LO QCD and partial electroweak corrections
- ▶ Top and bottom quarks
- ▶ Includes Mathematica package
- ▶ Excessive Extensive options:
 - ▶ Mass schemes: PS, 1S, \overline{MS} , pole
 - ▶ Loose invariant Wb mass cut: $(m_t - m_{Wb})^2 \gg \Gamma_t m_t$
 - ▶ Coarse and fine-grained control over contributions
 - ▶ ...

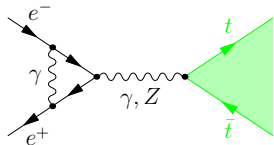
```
Needs["QQbarThreshold"];
LoadGrid[GridDirectory <> "ttbar_grid.tsv"];
Plot[
  TTbarXSection[
    sqrt, {80., 350.}, {171.5, 1.33},
    "N3LO"
  ],
  {sqrt, 340, 348}
]
```

```
#include <iostream>
#include "QQbar_threshold/QQbar_threshold.hpp"
using namespace QQbar_threshold;
int main(){
  load_grid(grid_directory() + "ttbar_grid.tsv");
  std::cout << ttbar_xsection(
    344., {80., 350.}, {171.5, 1.33}, N3LO
  ) << '\n';
}
```

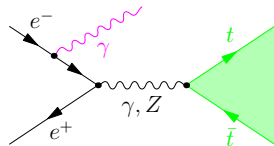
What is missing?

Initial state radiation

Photon corrections to initial state:



γ hard, hard-collinear



γ ultrasoft, (ultra)soft-collinear

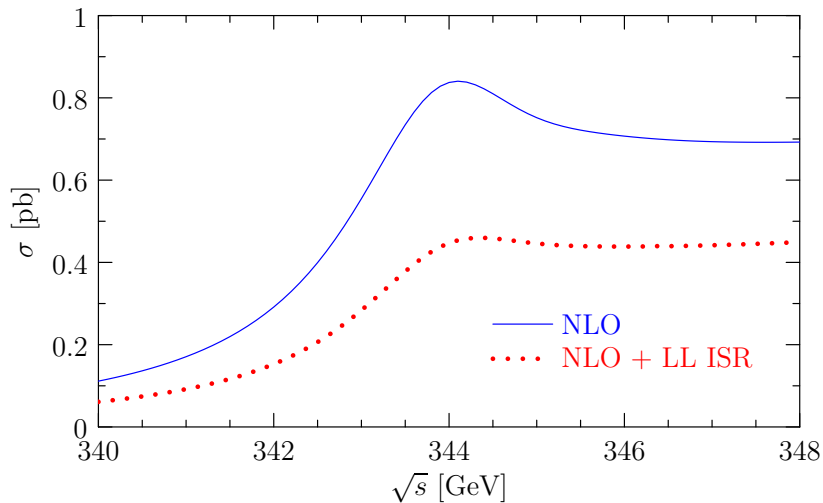
\leftrightarrow large logarithms $\log^2 \frac{m_t}{m_e}$, resummed into structure functions

[Fadin, Kuraev 1985; Fadin, Khoze 1987]

$$\sigma(s) = \int_0^1 dx_1 \int_0^1 dx_2 \Gamma_{ee}(x_1) \Gamma_{ee}(x_2) \hat{\sigma}(x_1 x_2 s)$$

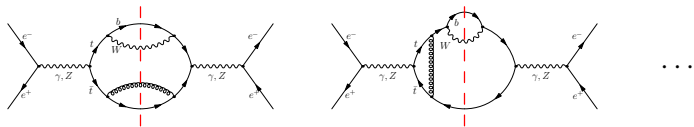
What is missing?

Initial state radiation

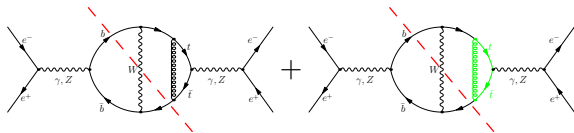


What is missing?

NNLO non-resonant production



- ▶ Naïve expansion in $\Gamma_t \rightarrow 0$
 \Rightarrow *endpoint divergences* as $p_{t,\bar{t}}^2 \rightarrow m_t^2$
- ▶ Mostly automatised calculation (modified MadGraph 5)
+ manual calculation of endpoint divergent contributions
- ▶ Divergences cancel against resonant part, [Jantzen, Ruiz-Femenía 2013]
e.g. hard NNLO electroweak corrections:



What is missing?

Width in nonrelativistic expansion

Position of complex pole: $p_{t,\bar{t}}^2 = M_*^2 \equiv m_t^2 - im_t\Gamma_t$

⇒ Kinetic terms in nonrelativistic theory:

$$\mathcal{L}_{\text{kin},\psi} = \psi^\dagger \left(i\partial^0 + \frac{\vec{\partial}^2 + im_t\Gamma_t}{2m_t} + \frac{(\vec{\partial}^2 + im_t\Gamma_t)^2}{8m_t^3} + \dots \right) \psi$$

Time dilatation: $\Gamma_{t\bar{t}} < 2\Gamma_t$

Conclusions

High-precision theory prediction for $e^+e^- \rightarrow t\bar{t}$ near threshold:

- ▶ NNNLO QCD + NNNLO Higgs + partial NNLO electroweak
- ▶ Public code `QQbar_threshold`
- ▶ Complete NNLO electroweak corrections in the near future

Open questions:

- ▶ Matching to fixed-order (relativistic) cross section
- ▶ Combination with $\log \alpha_s$ resummation