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

M. Beneke A. Maier J. Piclum T. Rauh

IPPP, Durham University

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Motivation

Linear collider physics goals:

- Determine Higgs boson properties
- BSM physics
- Precision top quark measurements

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- Determine Higgs boson properties
  $\rightarrow$ coupling to top quarks
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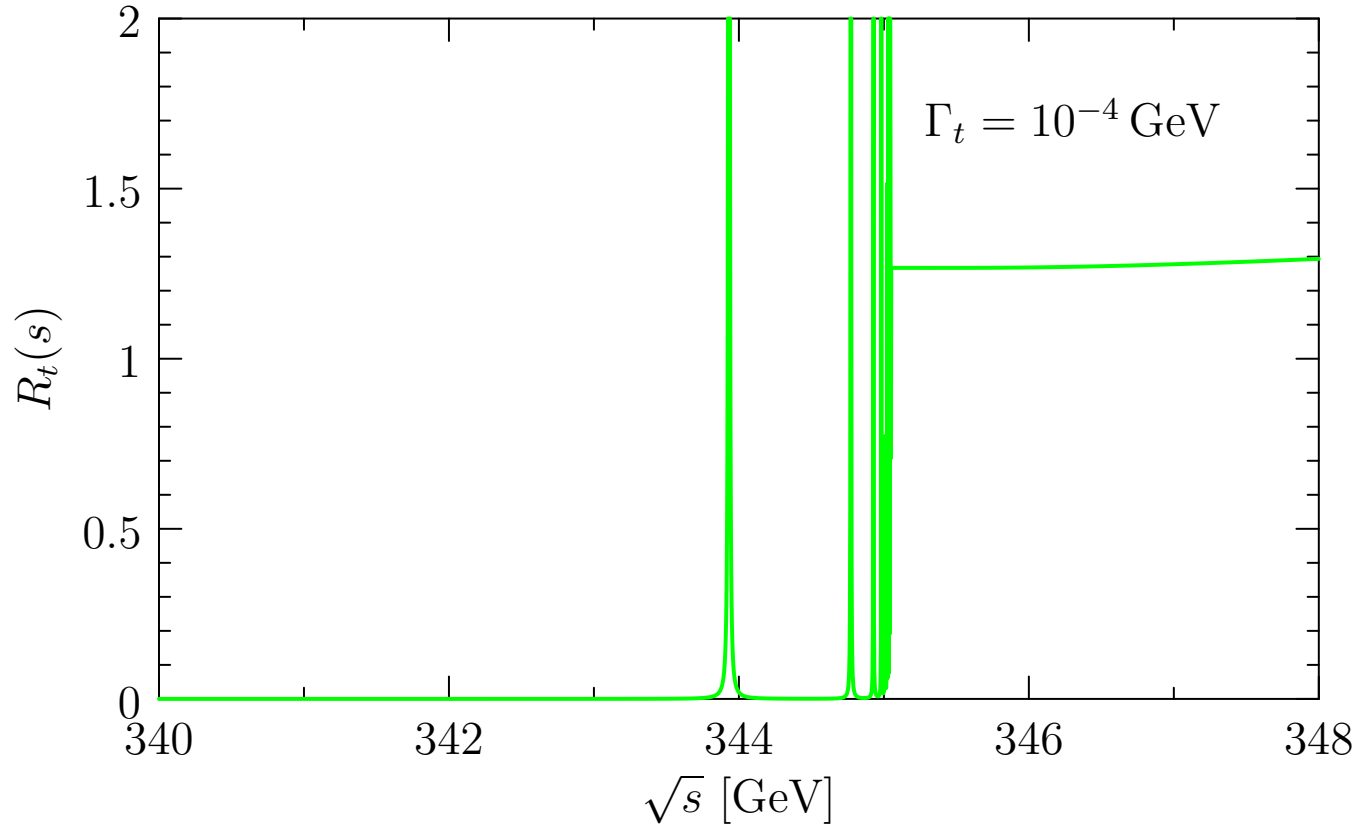
$t\bar{t}$ production near threshold

- Nonrelativistic quarks $v \ll 1$
- Decay during bound state formation

Schrödinger equation with binding potential:



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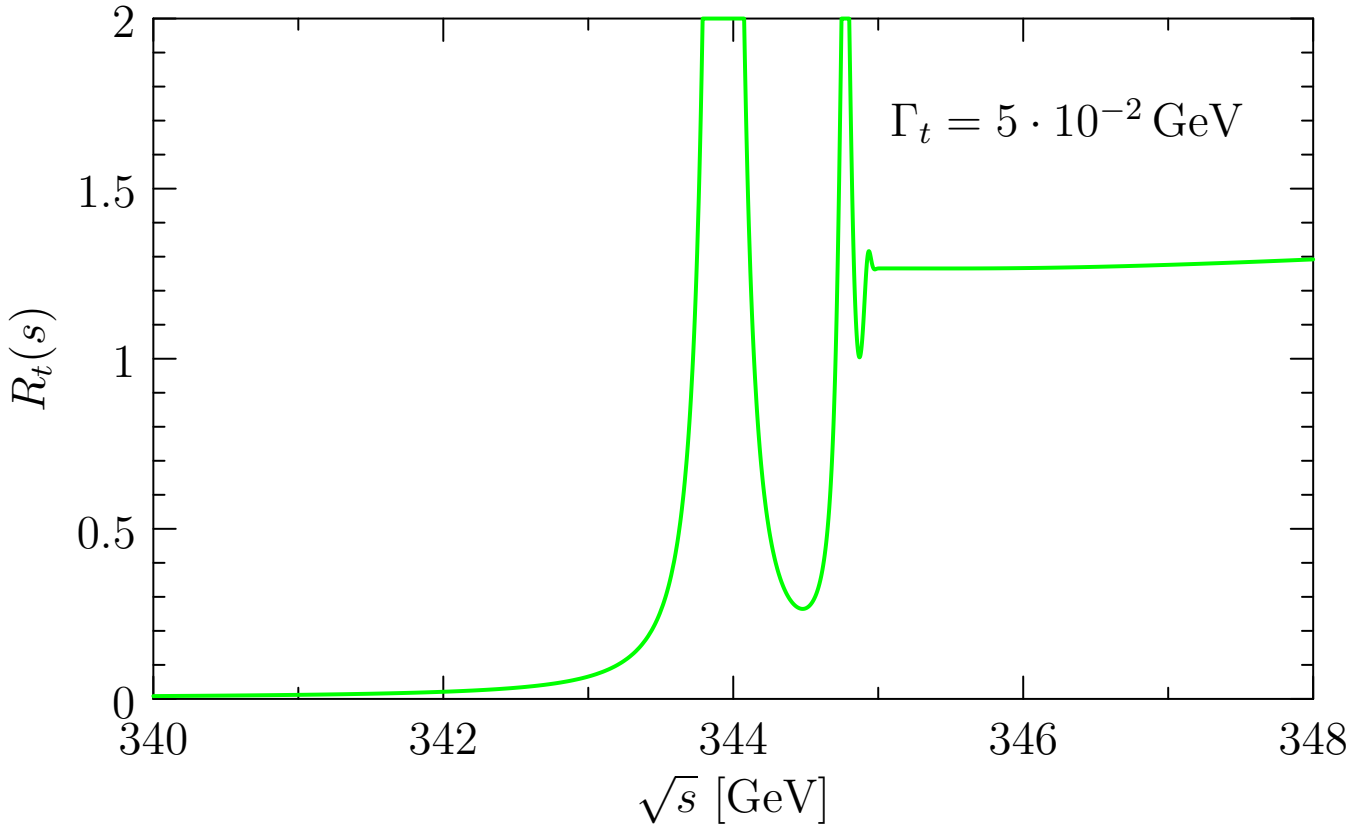

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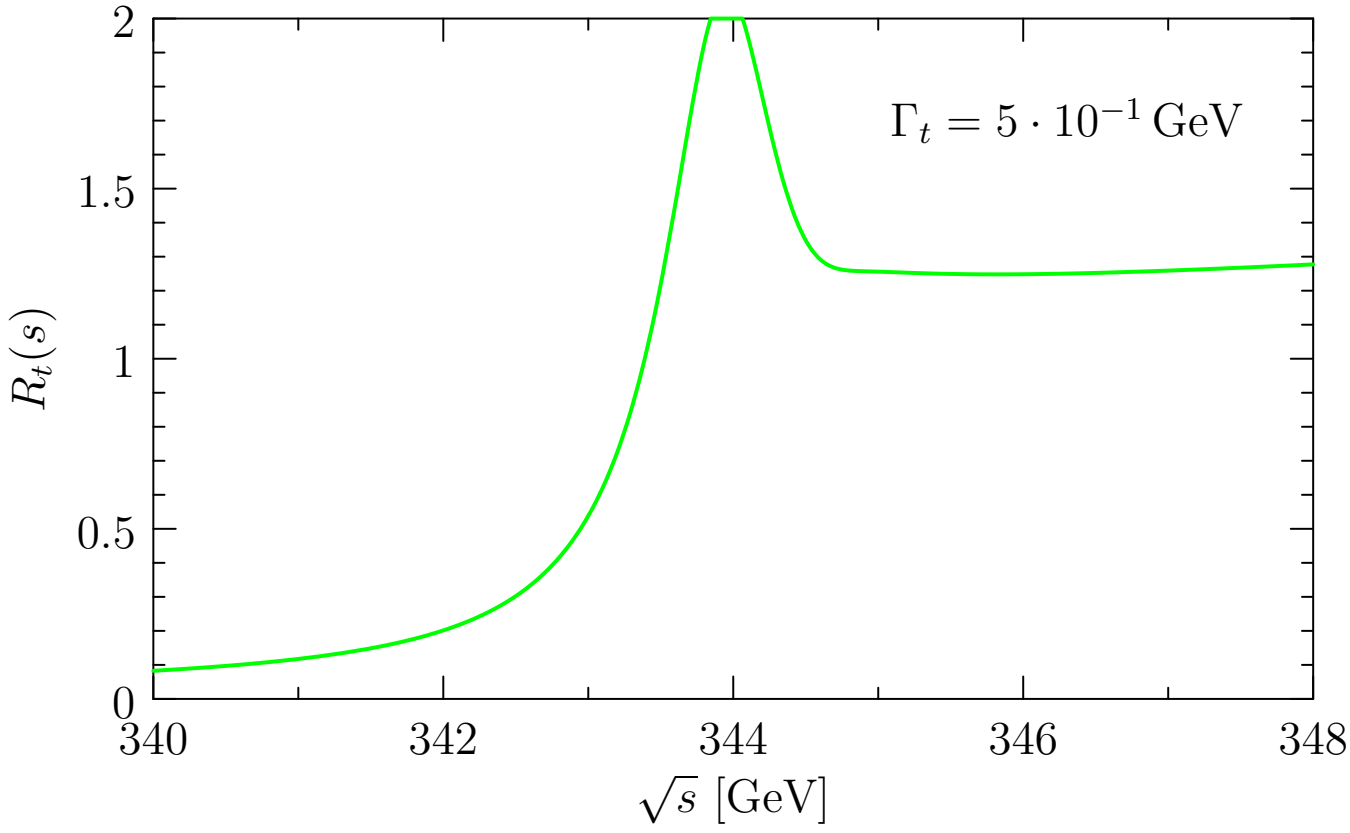

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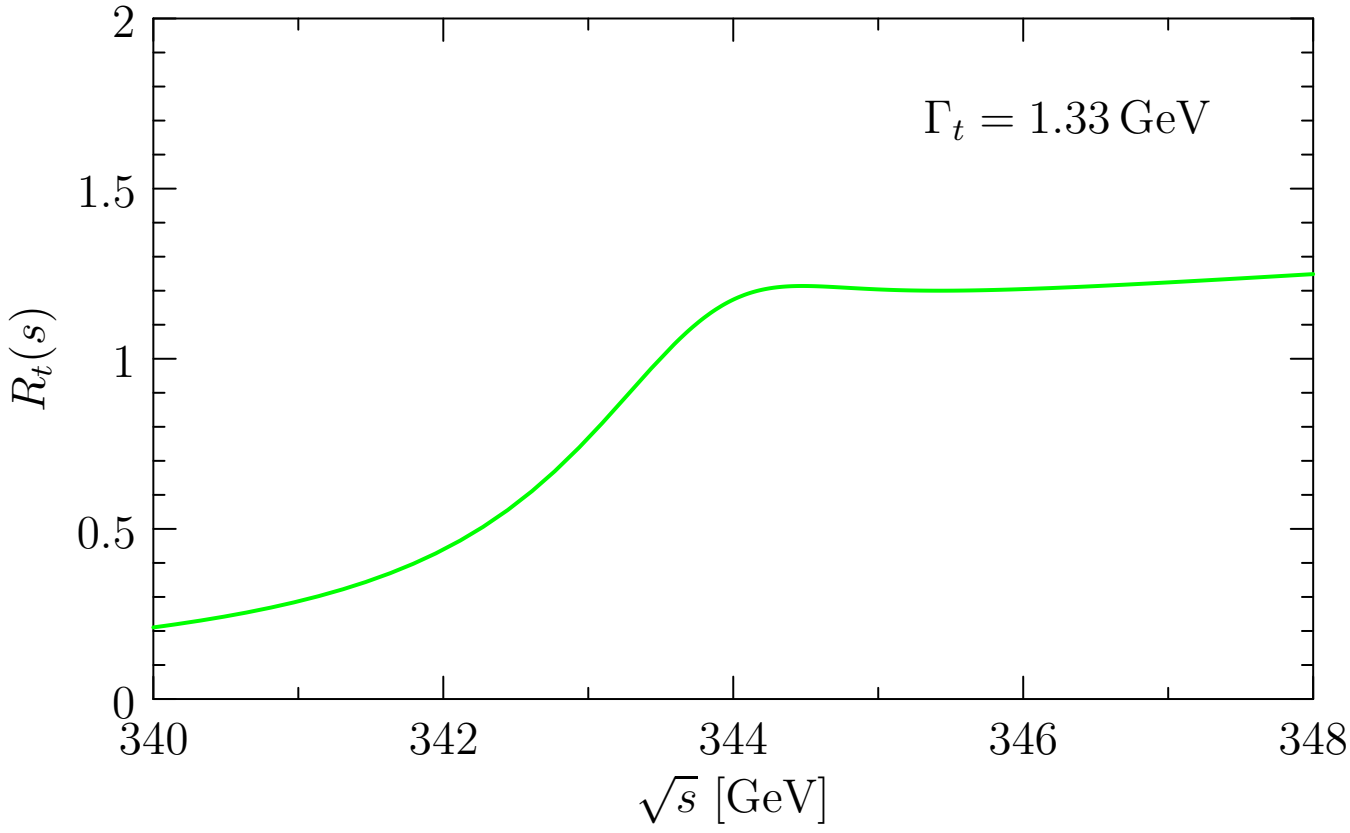
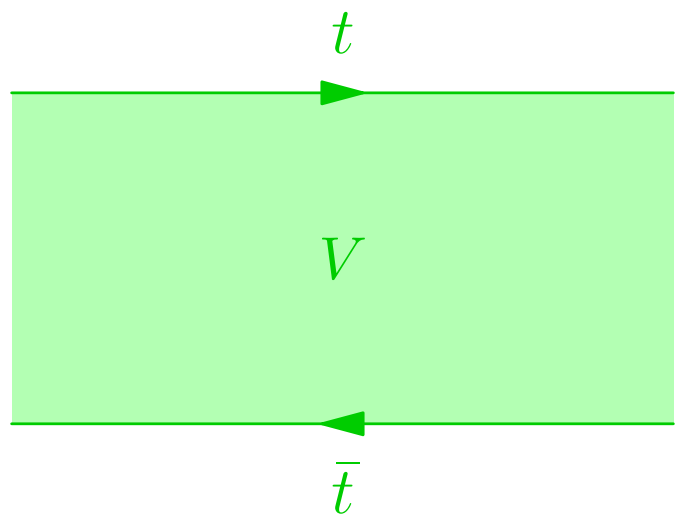
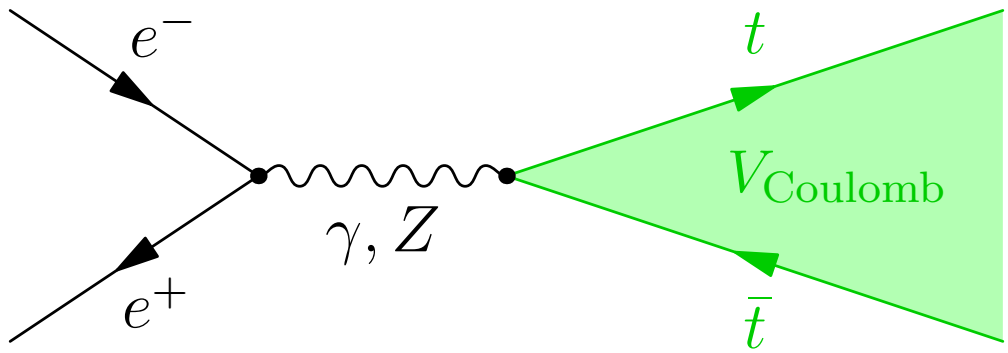



t
V
$\bar{t}$

QCD corrections

Need quantum field theory description:

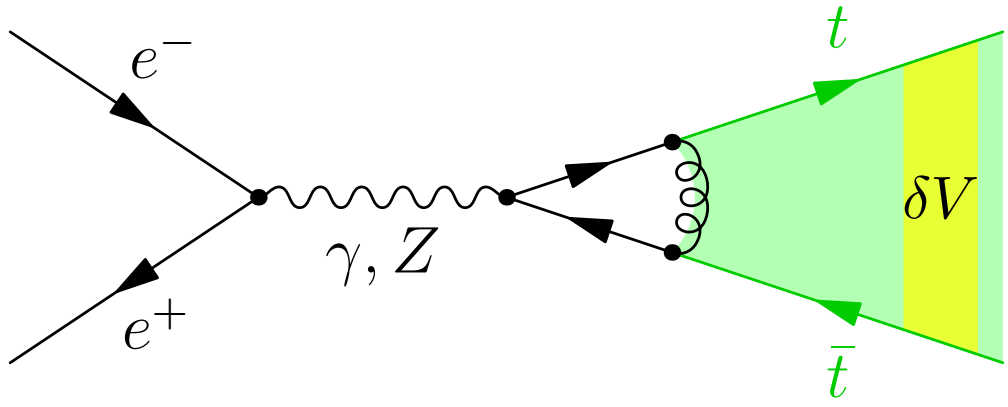
- Creation of particles
- Systematic derivation of potential



QCD corrections

Need quantum field theory description:

- Creation of particles
- Systematic derivation of potential
- Precision: perturbative corrections



Effective QFT framework

Scales: $m_t \gg m_t v \gg m_t v^2$ Coulomb singularity: $\alpha_s \sim v$

- hard modes: $k \sim m_t$
- soft modes: $k \sim m_t v$
- potential modes: $k_0 \sim m_t v^2, \vec{k} \sim m_t v$
- ultrasoft modes: $k \sim m_t v^2$

QCD

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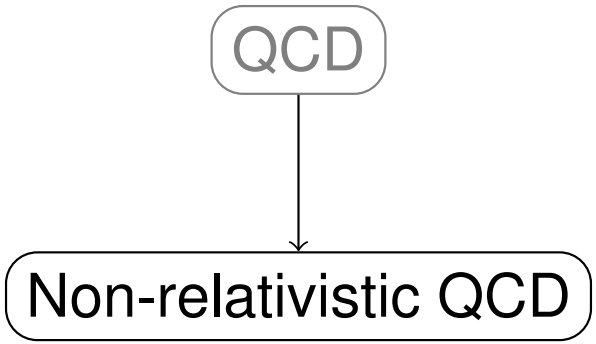

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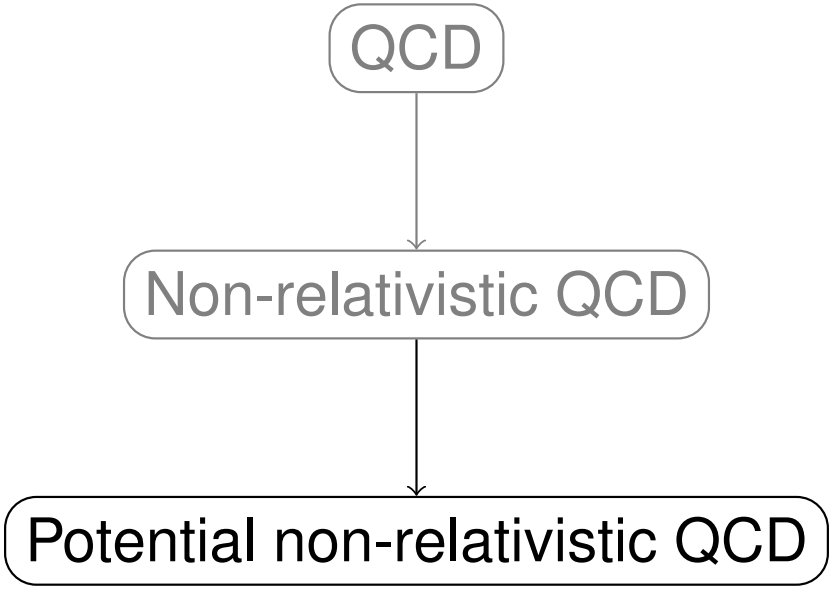
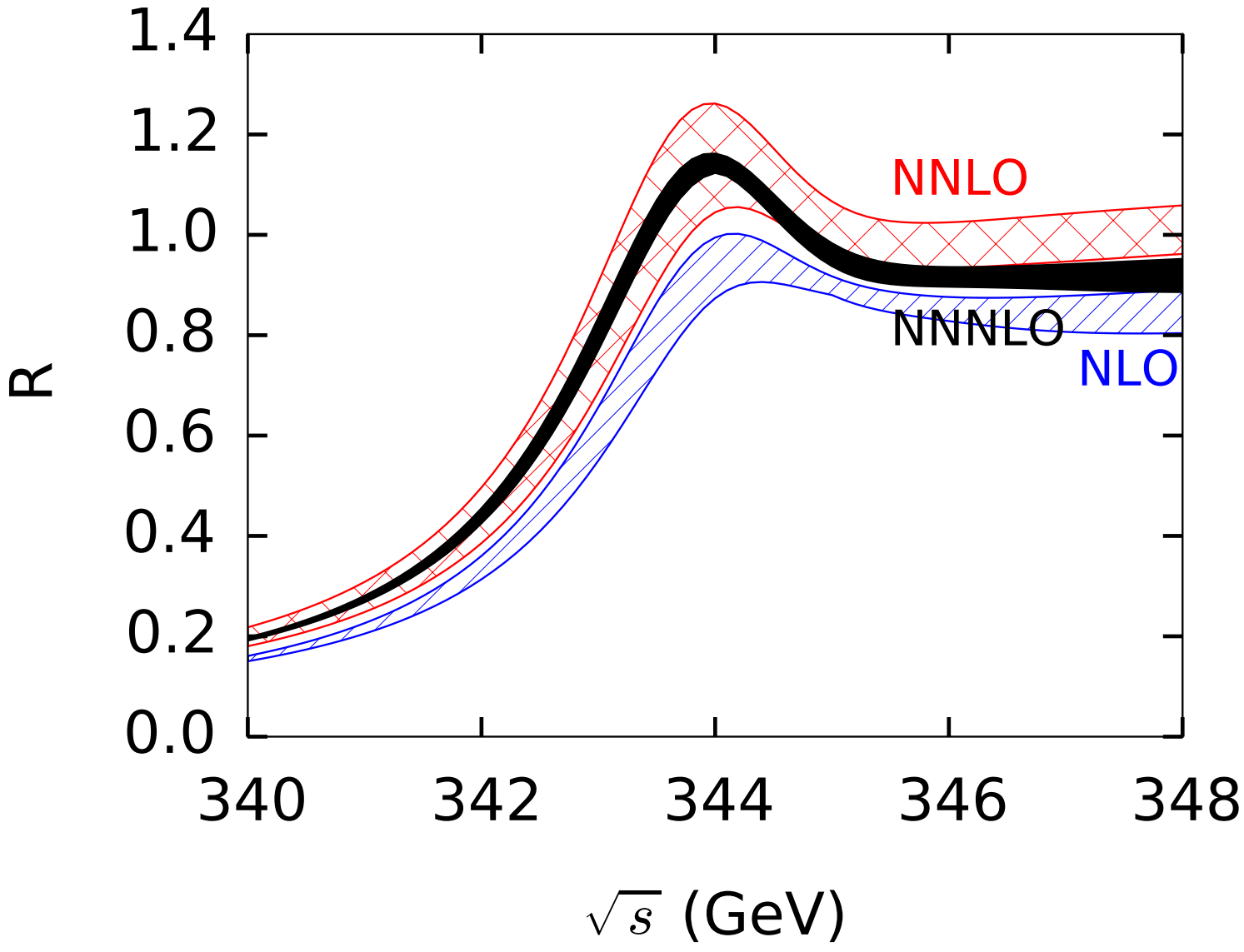
- hard modes: $k \sim m_t$
- soft modes: $k \sim m_t v$
- potential light particle modes
- potential top quark modes: $k_0 \sim m_t v^2, \vec{k} \sim m_t v$
- ultrasoft modes: $k \sim m_t v^2$



Potential non-relativistic QCD

N^{3}LO QCD corrections

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

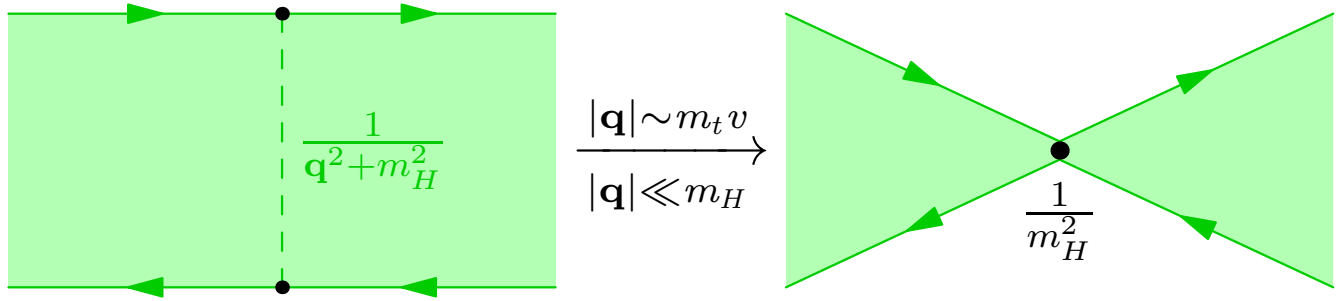


Going beyond QCD

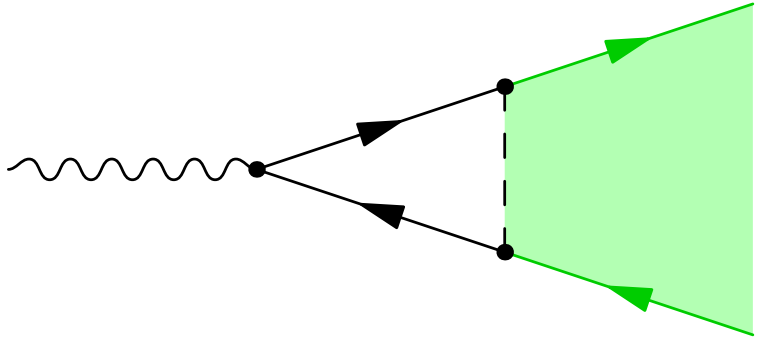
QCD uncertainties under control: $\sim 3\%$

Further corrections $(v^2 \sim \alpha_s^2 \sim y_t^2 \sim \alpha)$:

- Higgs corrections
  - Potential (NNNLO):



  - Production current (NNLO + NNNLO):



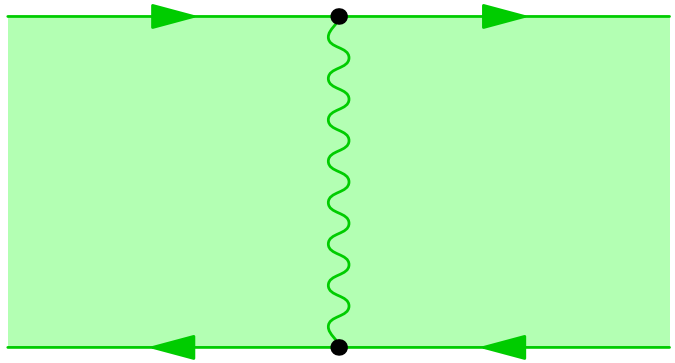
[Grzadkowski, Kühn, Krawczyk, Stuart 1986; Guth, Kühn 1991; Hoang, Reißer 2006; Eiras, Steinhauser 2006]

Going beyond QCD

QCD uncertainties under control: $\sim 3\%$
Further corrections $(v^2 \sim \alpha_s^2 \sim y_t^2 \sim \alpha)$:

- Higgs corrections
- QED Coulomb potential

Starting at NLO:



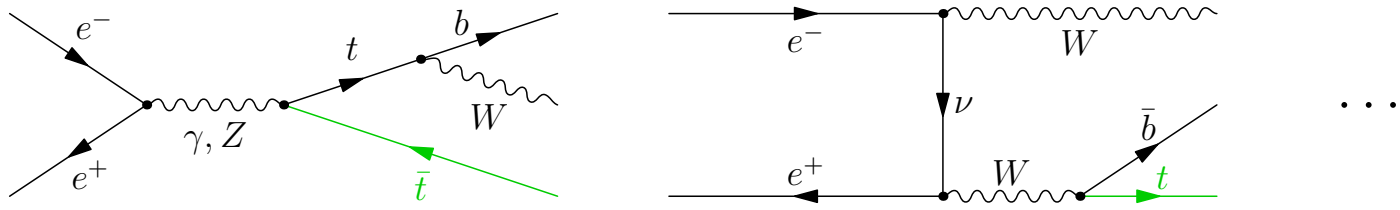
Going beyond QCD

QCD uncertainties under control: $\sim 3\%$
Further corrections $(v^2 \sim \alpha_s^2 \sim y_t^2 \sim \alpha)$:

- Higgs corrections
- QED Coulomb potential
- Nonresonant production

  Actual final state: $W^+ b W^- \bar{b}$

  - NLO: [Beneke, Jantzen, Ruiz-Femenía 2010]

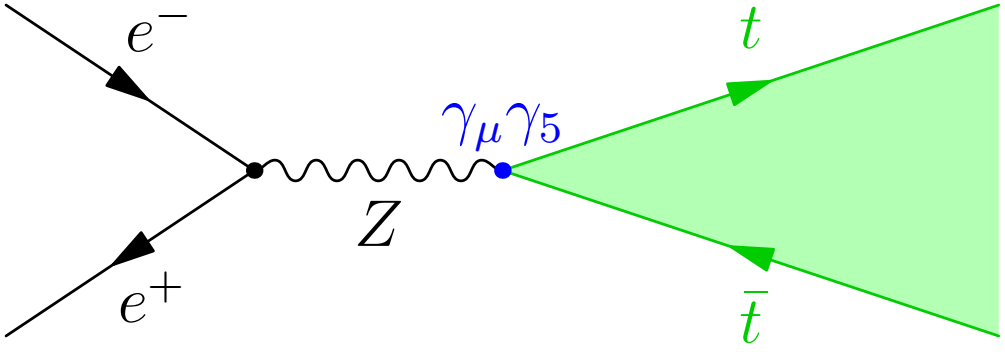


  - NNLO: Partial results [Penin, Piclum 2012; Jantzen, Ruiz-Femenía 2013]
    Work in progress

Going beyond QCD

QCD uncertainties under control: $\sim 3\%$
Further corrections $(v^2 \sim \alpha_s^2 \sim y_t^2 \sim \alpha)$:

- Higgs corrections
- QED Coulomb potential
- Nonresonant production
- P-wave production [Penin Pivovarov 1999; Beneke, Piclum, Rauh 2013]



Small contribution at NNLO and NNNLO: $\lesssim 1\%$

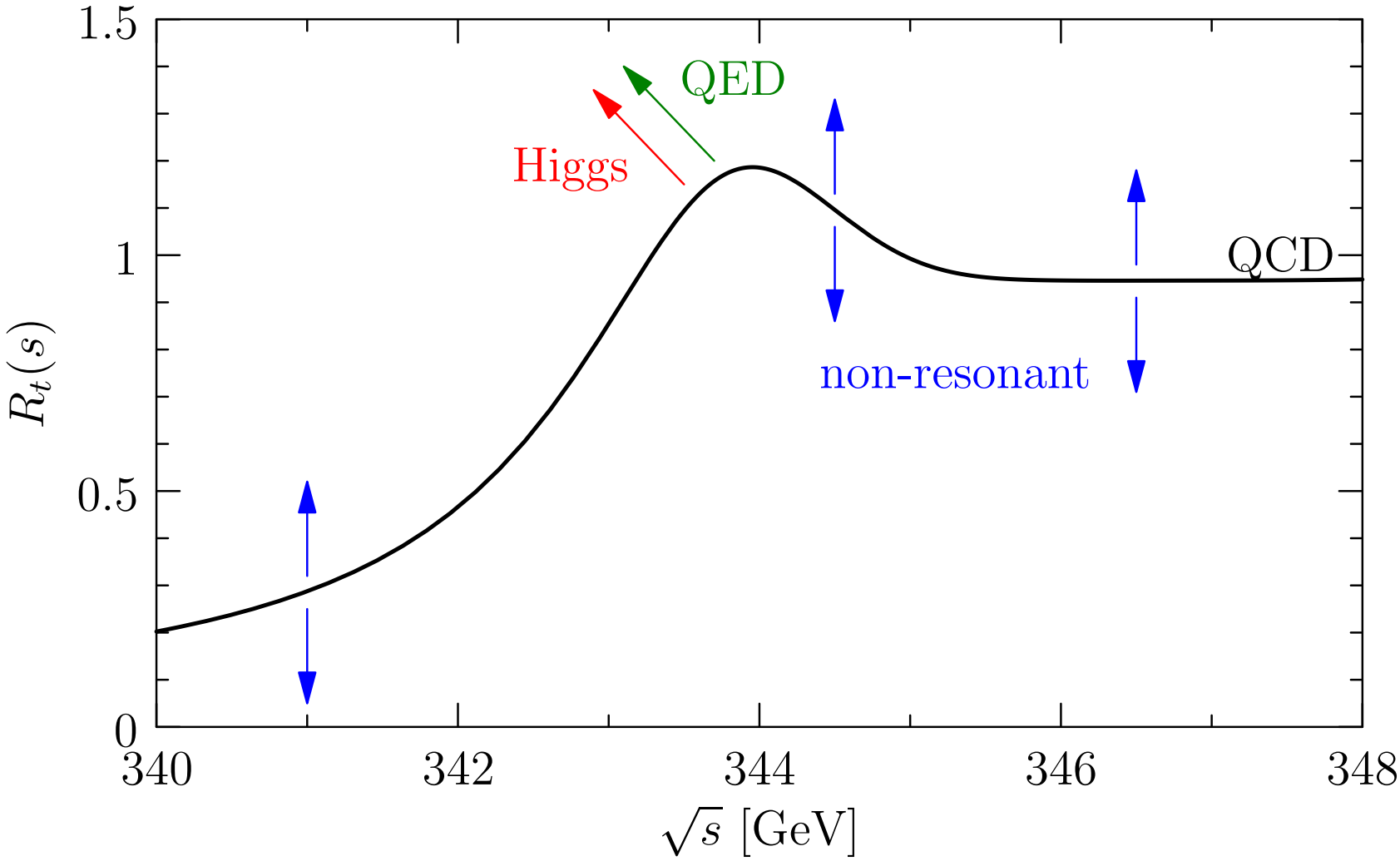
Going beyond QCD

QCD uncertainties under control: $\sim 3\%$
Further corrections $(v^2 \sim \alpha_s^2 \sim y_t^2 \sim \alpha)$:

- Higgs corrections
- QED Coulomb potential
- Nonresonant production
- P-wave production
- Further NNLO electroweak corrections

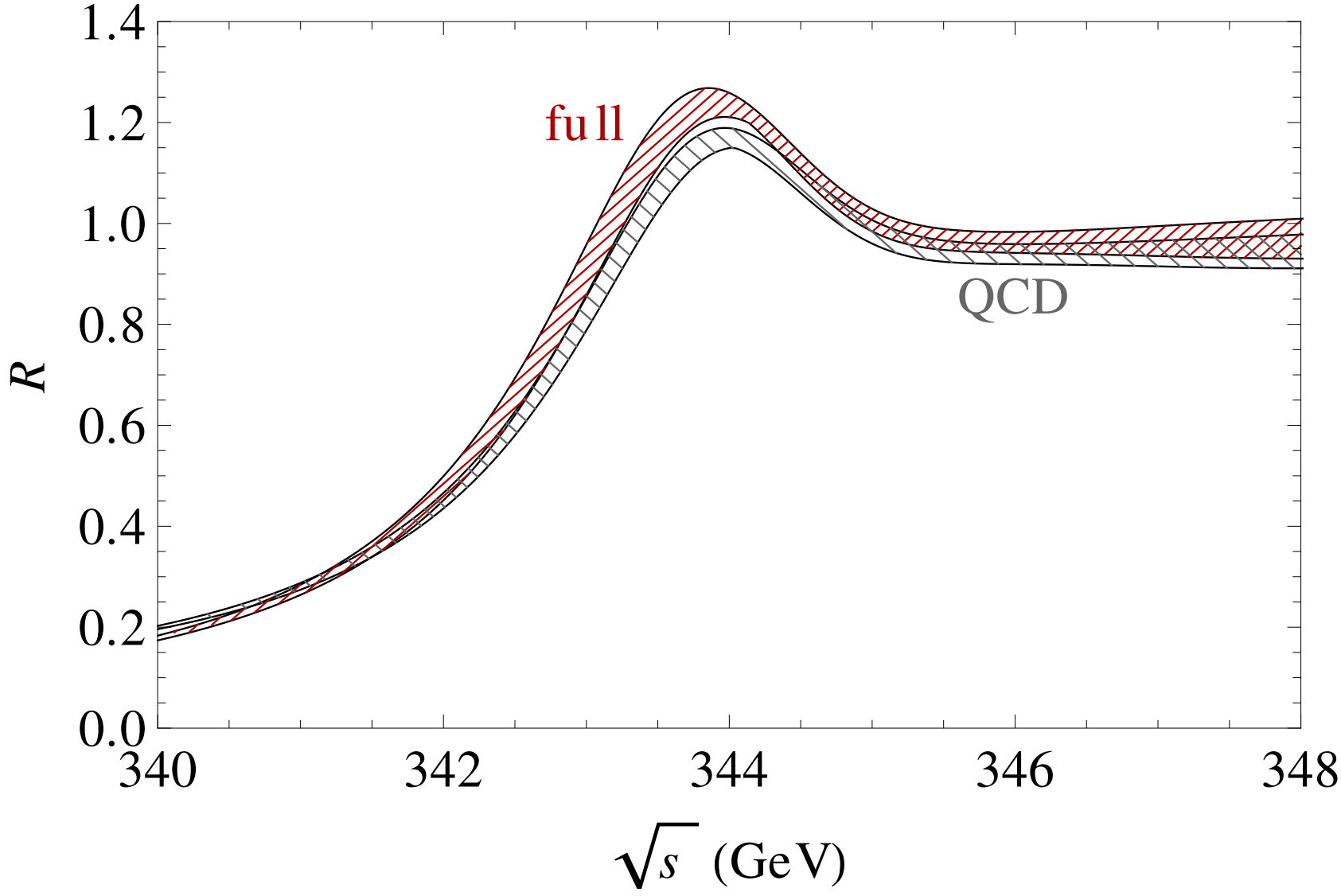
[Grzadkowski, Kühn, Krawczyk, Stuart 1986; Guth, Kühn 1991; Hoang, Reißer 2004 & 2006]

Expected shape changes



Results

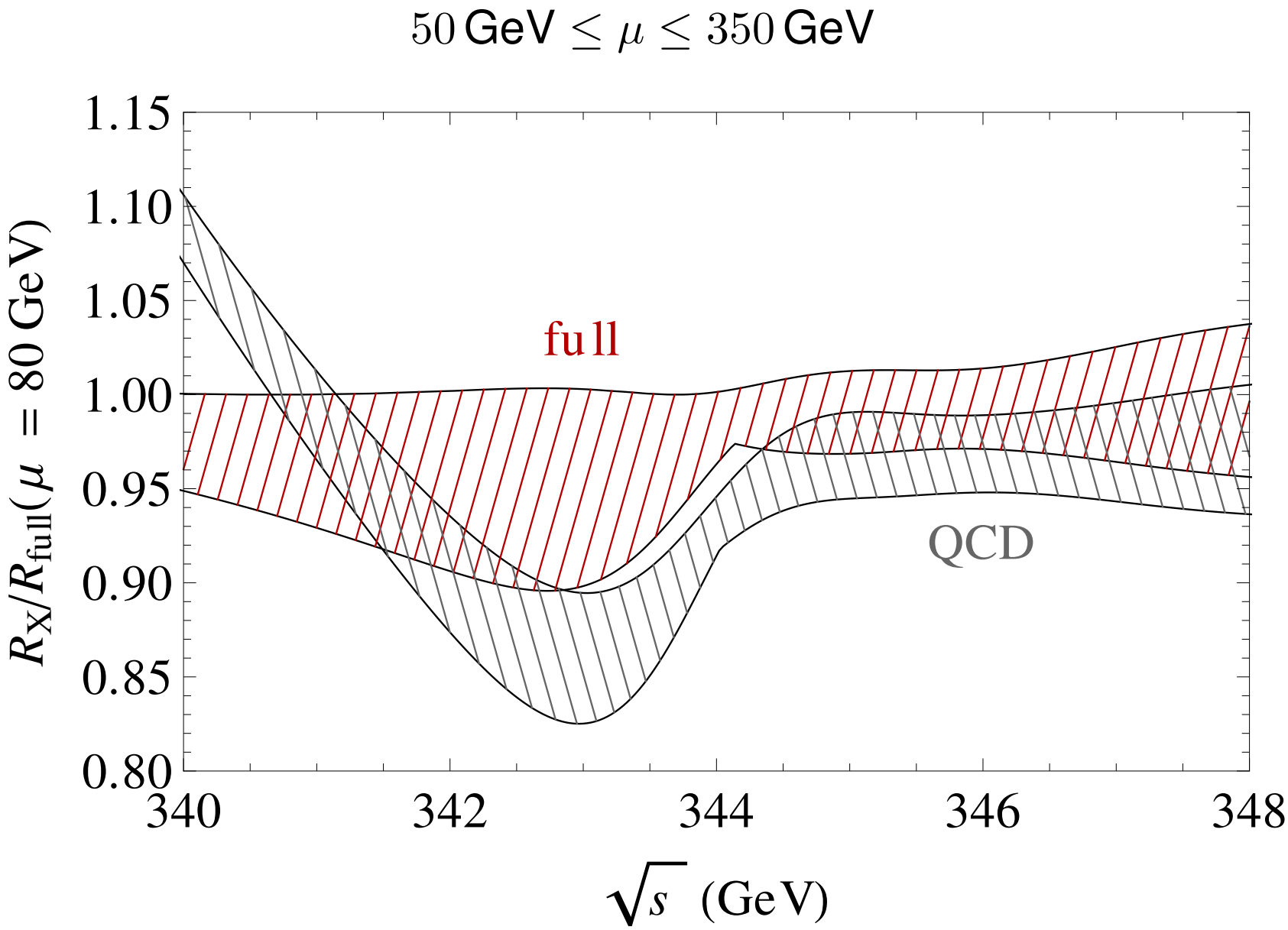
Impact on the cross section



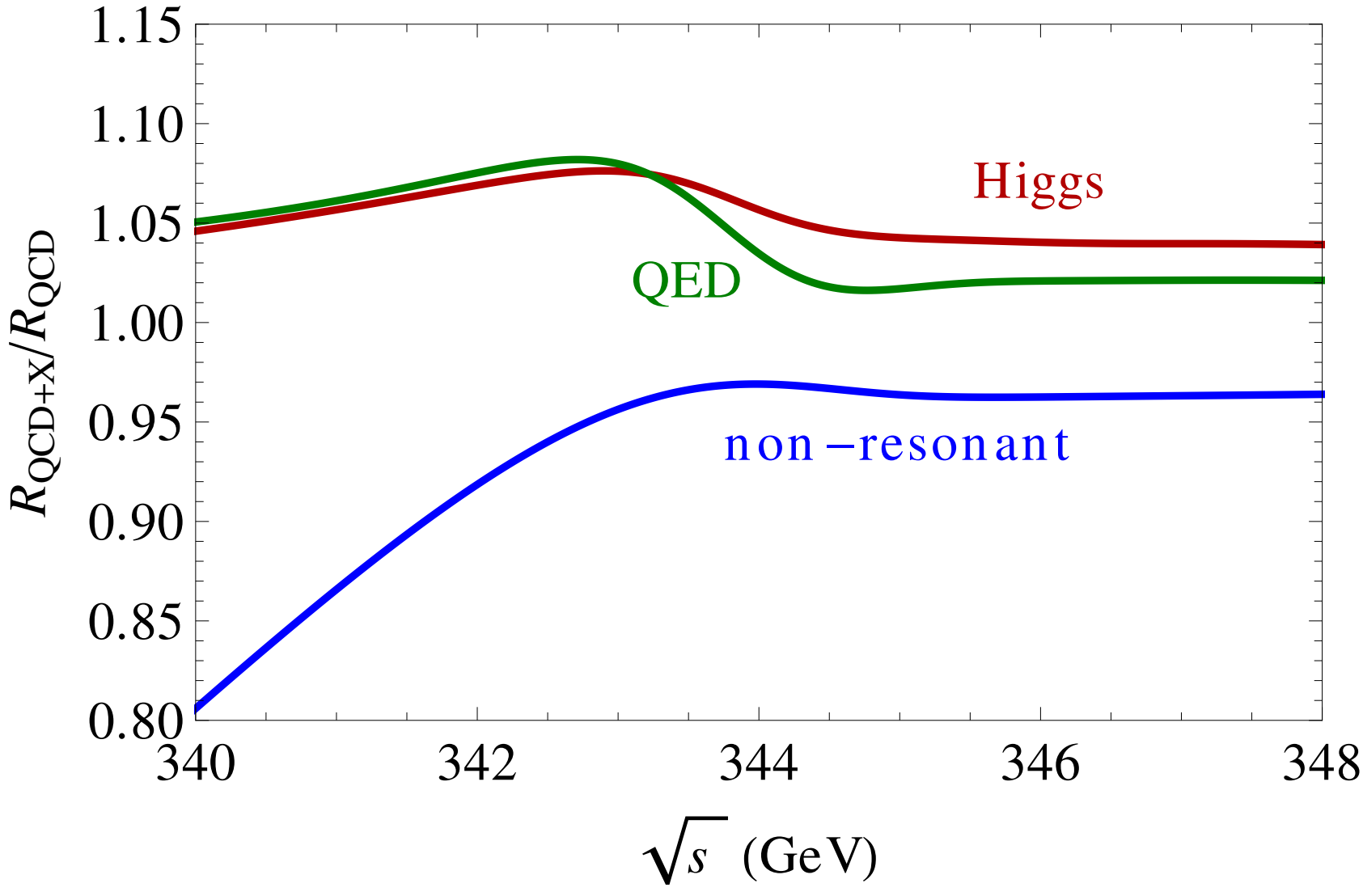
$m_t^{\rm PS}(20\,{\rm GeV}) = 171.5\,{\rm GeV}\,,$ $\Gamma_t = 1.33\,{\rm GeV}\,,$ $m_H = 171.5\,{\rm GeV}\,,$

$\alpha_s(m_Z) = 0.1185\,,$ $\alpha(m_Z) = 1/128.944$ m_W, m_Z

Scale uncertainty

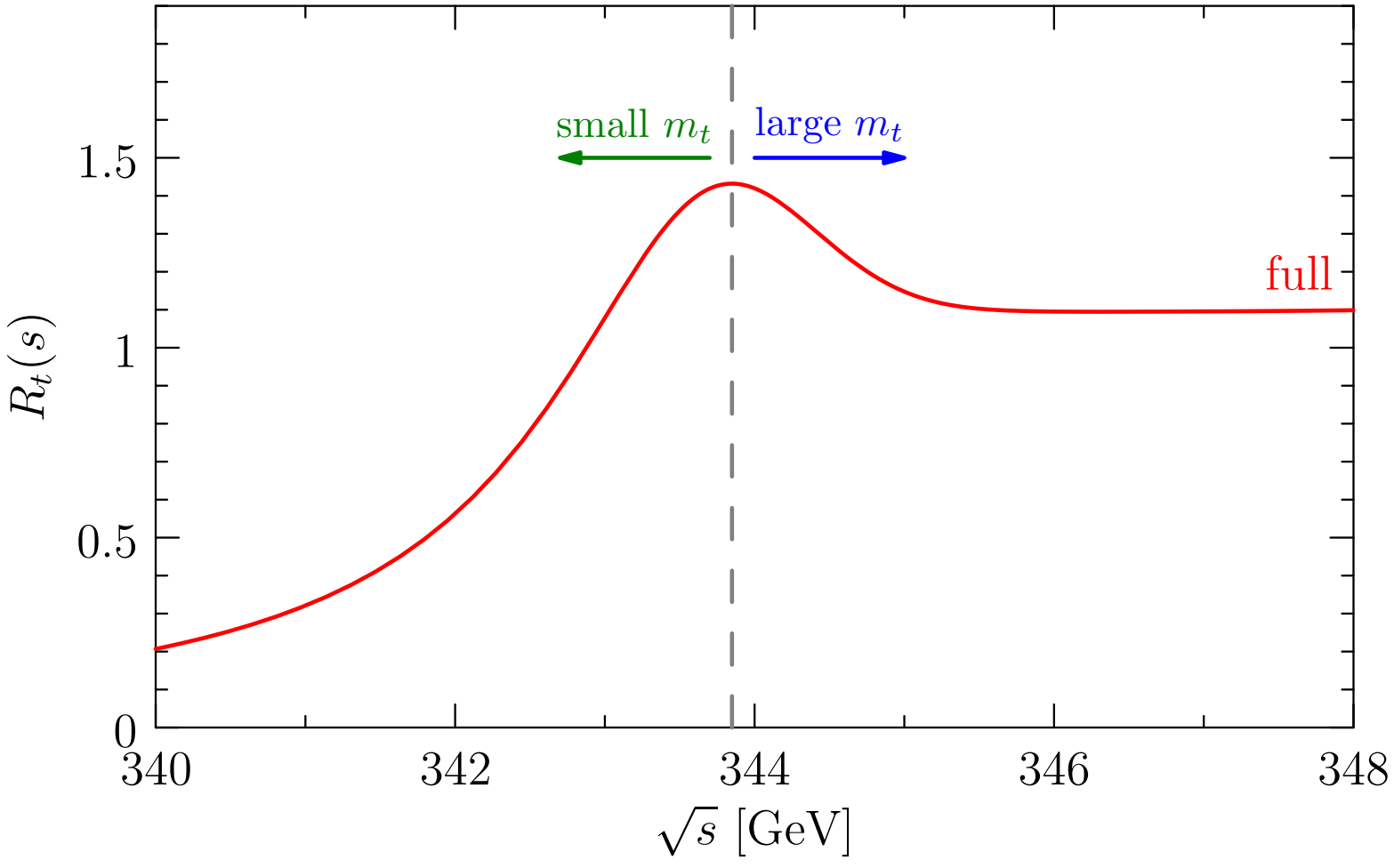


Individual contributions



Extracting parameters

- Mass m_t in well-defined mass scheme (PS, 1S, $\overline{\text{MS}}$):



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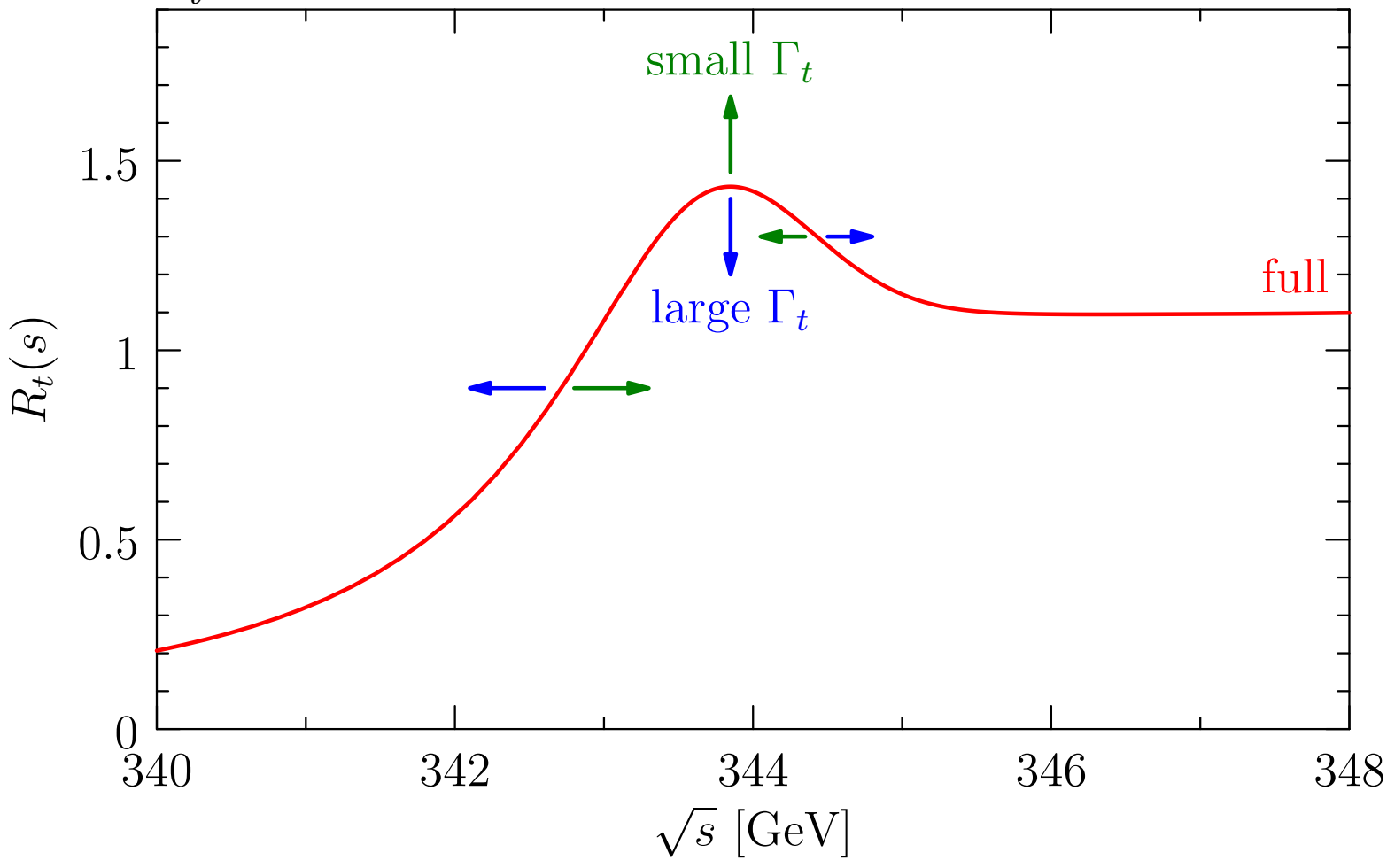
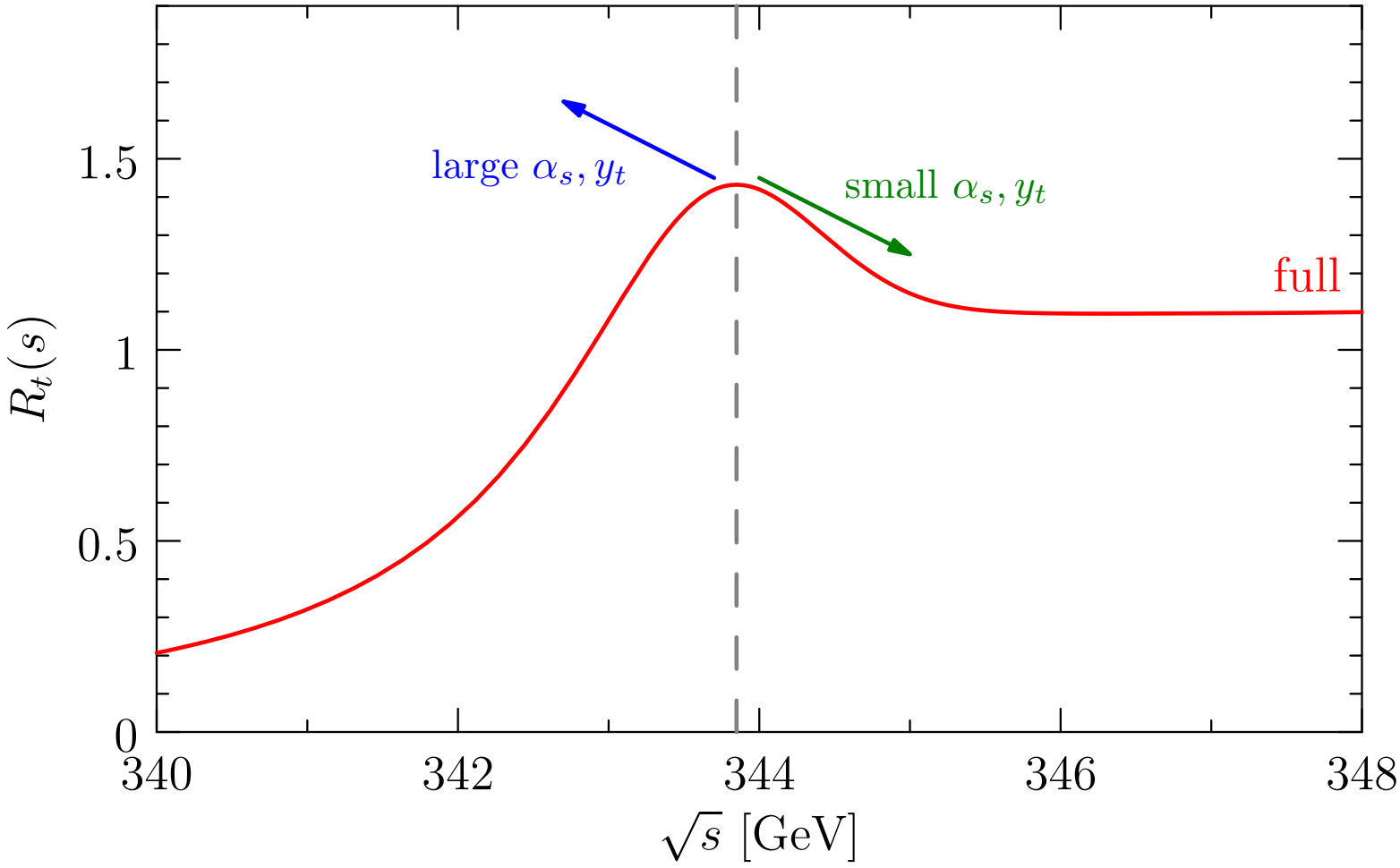
- Mass m_t in well-defined mass scheme (PS, 1S, $\overline{\text{MS}}$):
- Width Γ_t



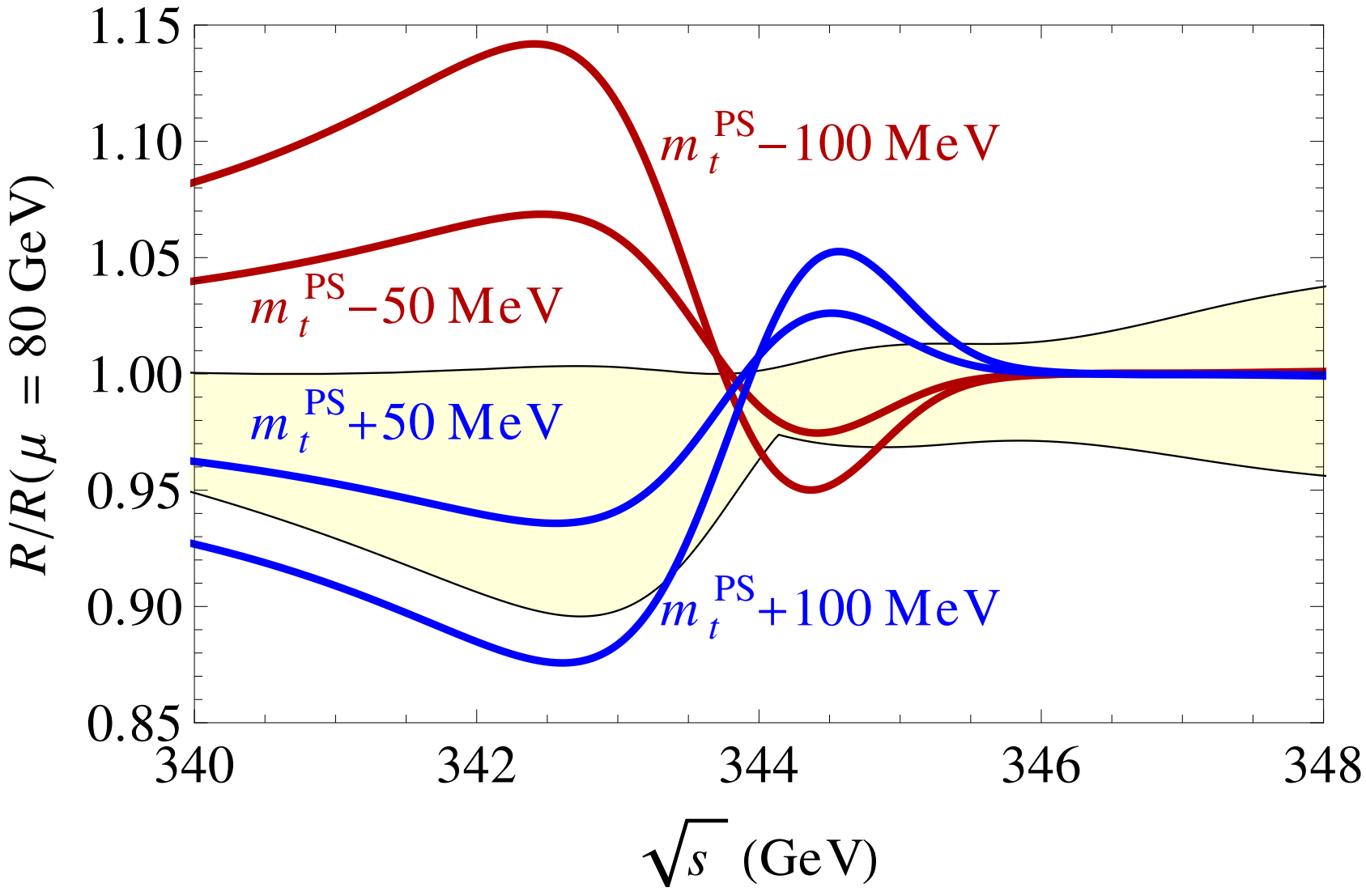
Extracting parameters

- Mass m_t in well-defined mass scheme (PS, 1S, $\overline{\text{MS}}$):
- Width Γ_t
- Top Yukawa coupling y_t: Peak position and height
- Strong coupling constant $\alpha_s(M_Z)$: Peak position and height



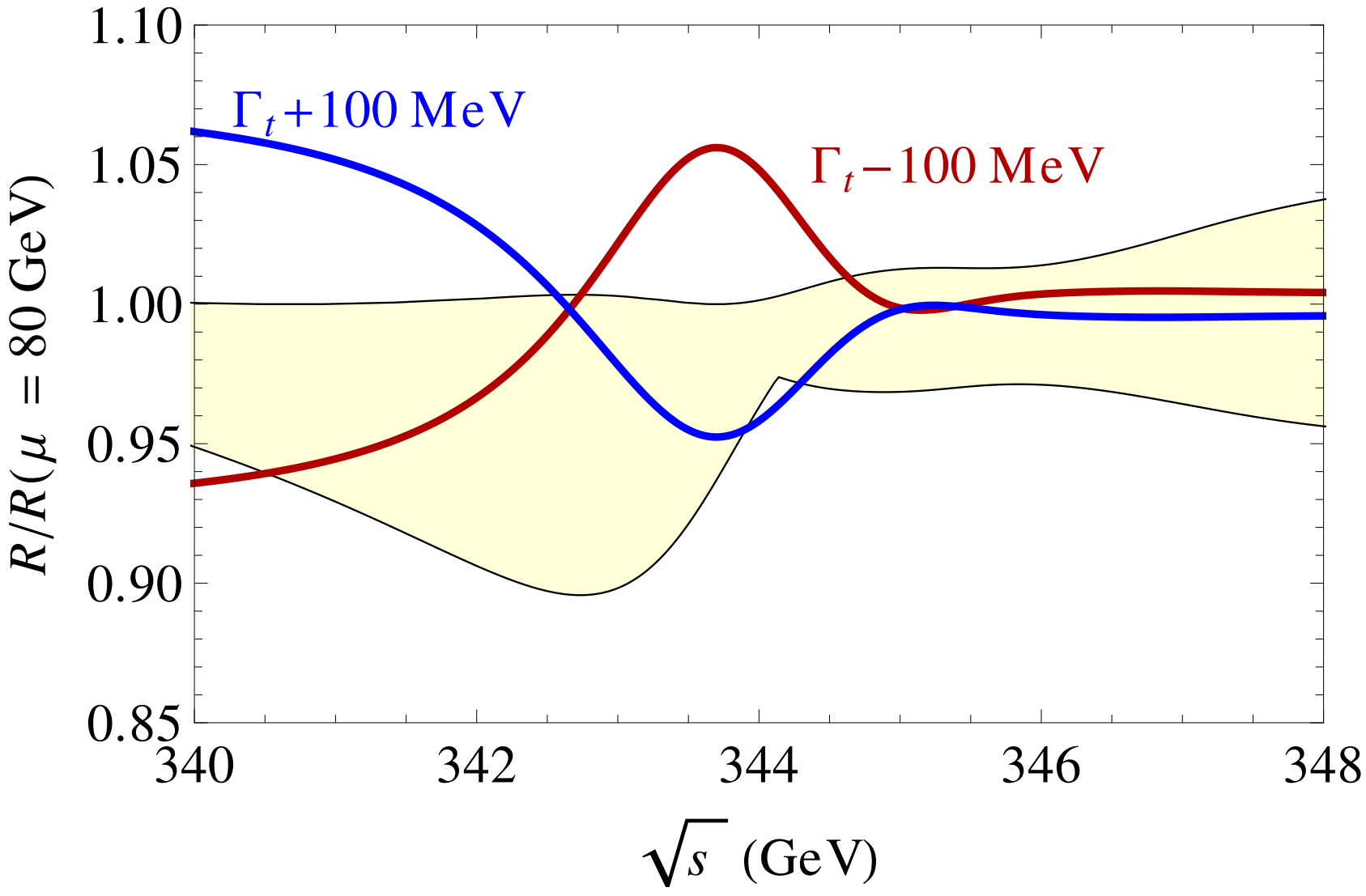
Extracting parameters

Top mass



Extracting parameters

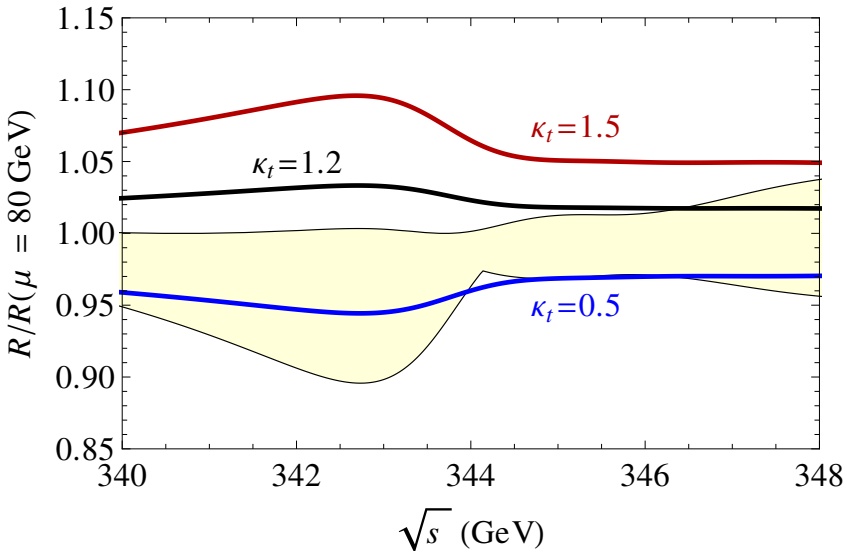
Top width

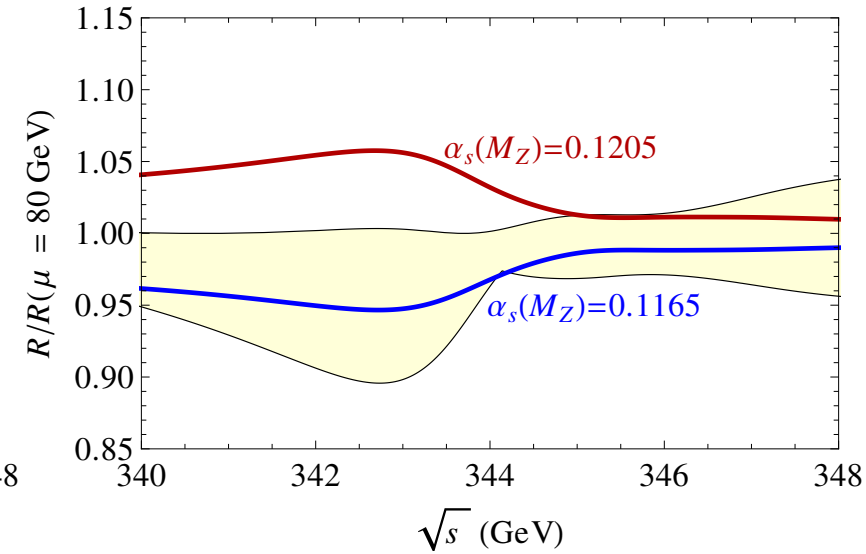


Extracting parameters

Top Yukawa and strong coupling

$$\kappa_t = y_t / y_t^{\mathrm{SM}}, \qquad y_t^{\mathrm{SM}} = \frac{\sqrt{2} m_t}{v}$$





Conclusions

- $t\bar{t}$ threshold scan at core of LC physics programme
- Theory uncertainties under control $\sim 3\%$
- Electroweak corrections significant; up to 10%
- Precise values for top mass, width
- Extraction of Yukawa coupling and α_s possible
  (but maybe not combined?)
- Updated experimental analysis needed

Outlook

- NNLO electroweak effects
- Renormalisation group improvement
- Publish code

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