Top-Antitop Threshold Production at Linear Collider

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Topics discussed

- Introduction
  - *threshold production at a glance*
- Status of theoretical analysis
  - *NNNLO QCD corrections*
- Top phenomenology
  - *top quark mass and width determination*
- Theoretical challenges

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- Phenomenology
  - *most precise determination of top quark properties such as*

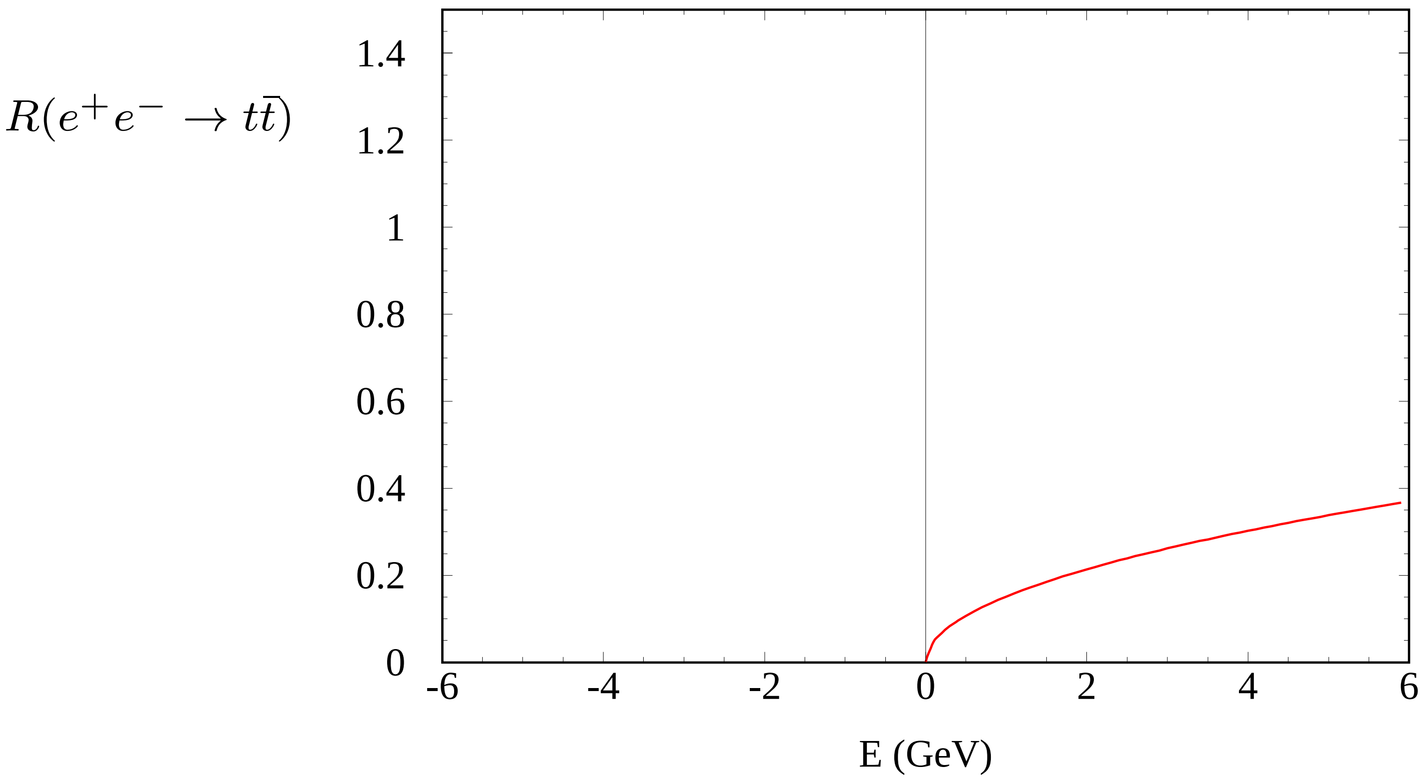
    mass, width, vector couplings

↪ *probe of Higgs sector, traces of new physics, vacuum stability*

$t\bar{t}$ at threshold

- Nonrelativistic top quark $v \ll 1$
- Coulombic effects $(\alpha_s/v)^n$
- Unstable top quark $\Gamma_t \gg \Lambda_{QCD}$

$e^+e^- \to t\bar{t}$ threshold cross section



$$\alpha_s,\ \Gamma_t = 0$$

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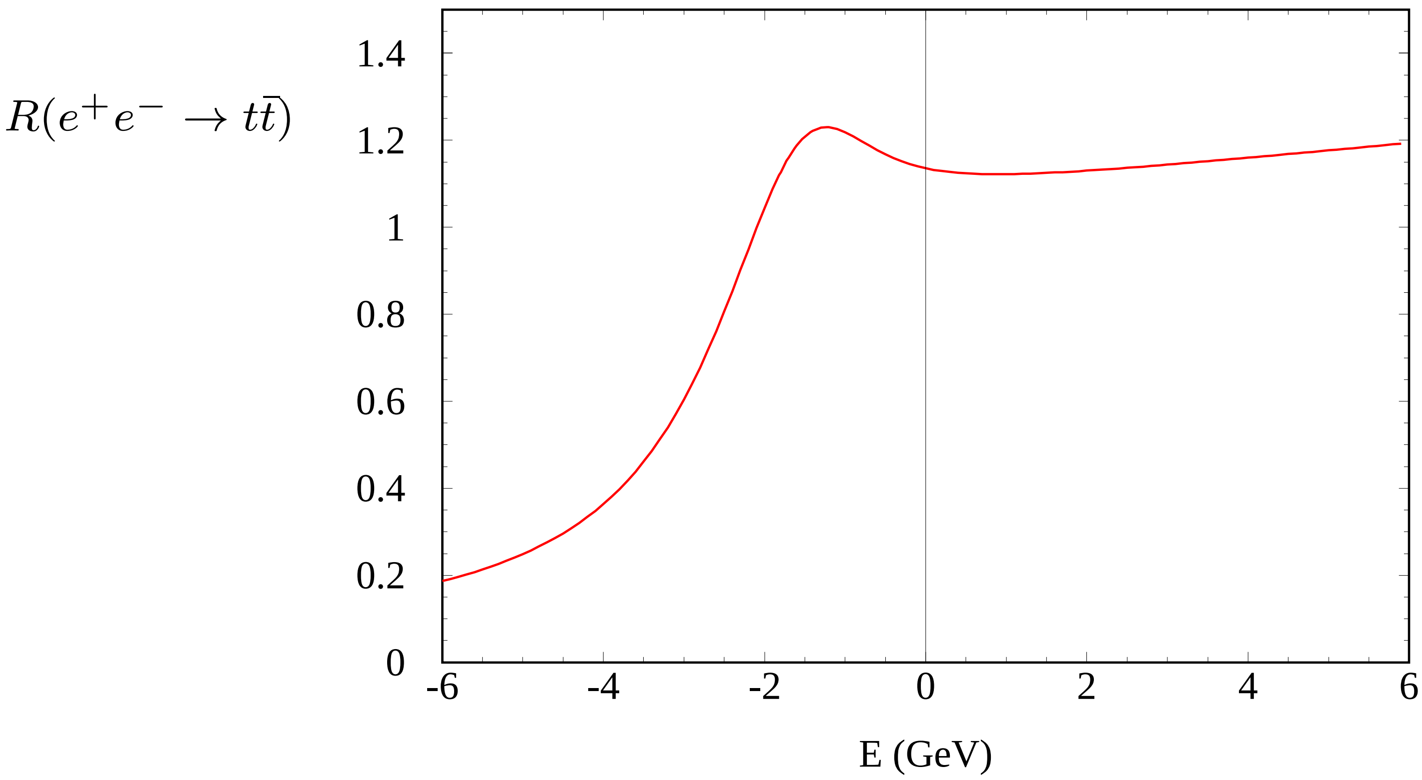

$$R_{\rm res} \propto \alpha_s^3/\Gamma_t$$

$$E_{\rm res} \propto m_t$$

Heavy Quarkonium at NNLO

- Apparent slow convergence!
- Possible reasons:
  - *Renormalons* $n!(\beta_0 \alpha_s)^n$
  - *Threshold logs* $\alpha_s^n \ln^m \alpha_s$

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Renormalon contribution (→ 26.7)

➥ ***Full N^{3}LO analysis is mandatory***

Heavy Quarkonium at N^3LO

- Theory challenges
  - *multiscale problem*
  - *bound state dynamics*
- *Formula of Success*

pNRQCD + Dim.Reg. = N^3LO

- *effective field theory of pNRQCD* A. Pineda, J.Soto, ...
  - *scale separation: QCD $\longrightarrow$ Schrödinger equation*
- *dimensional regularization*
  - *simple matching $\longrightarrow$ crucial for multiloop calculation*

Heavy Quarkonium at N^{3}LO

- Main N^{3}LO ingredients
  - $\mathcal{O}(\alpha_s^3)$ *spectrum*

    A. Penin, M. Steinhauser, Phys.Lett. B538 (2002) 335
  - *ultrasoft contribution*

    M. Beneke, Y. Kiyo, A. Penin, Phys.Lett. B653 (2007) 53
  - *3-loop static potential*

    A. Smirnov, V. Smirnov, M. Steinhauser Phys.Rev.Lett. 104 (2010) 112002

    C. Anzai, Y. Kiyo, Y. Sumino, Phys.Rev.Lett. 104 (2010) 112003
  - *3-loop vector current*

    P. Marquard, J. Piclum, D. Seidel, M. Steinhauser, Phys.Rev. D89 (2014) 034027
  - *4-loop mass relation*

    P. Marquard, A. Smirnov, V. Smirnov, M. Steinhauser,

    Phys.Rev.Lett. 114 (2015) 142002

Heavy Quarkonium at N^{3}LO

- Peak position

$$E_{res} = E_{res}^{LO}\left[1 + 3.201\alpha_s + 16.434\alpha_s^2 + (15.300\ln\alpha_s + 84.858)\,\alpha_s^3\right]$$

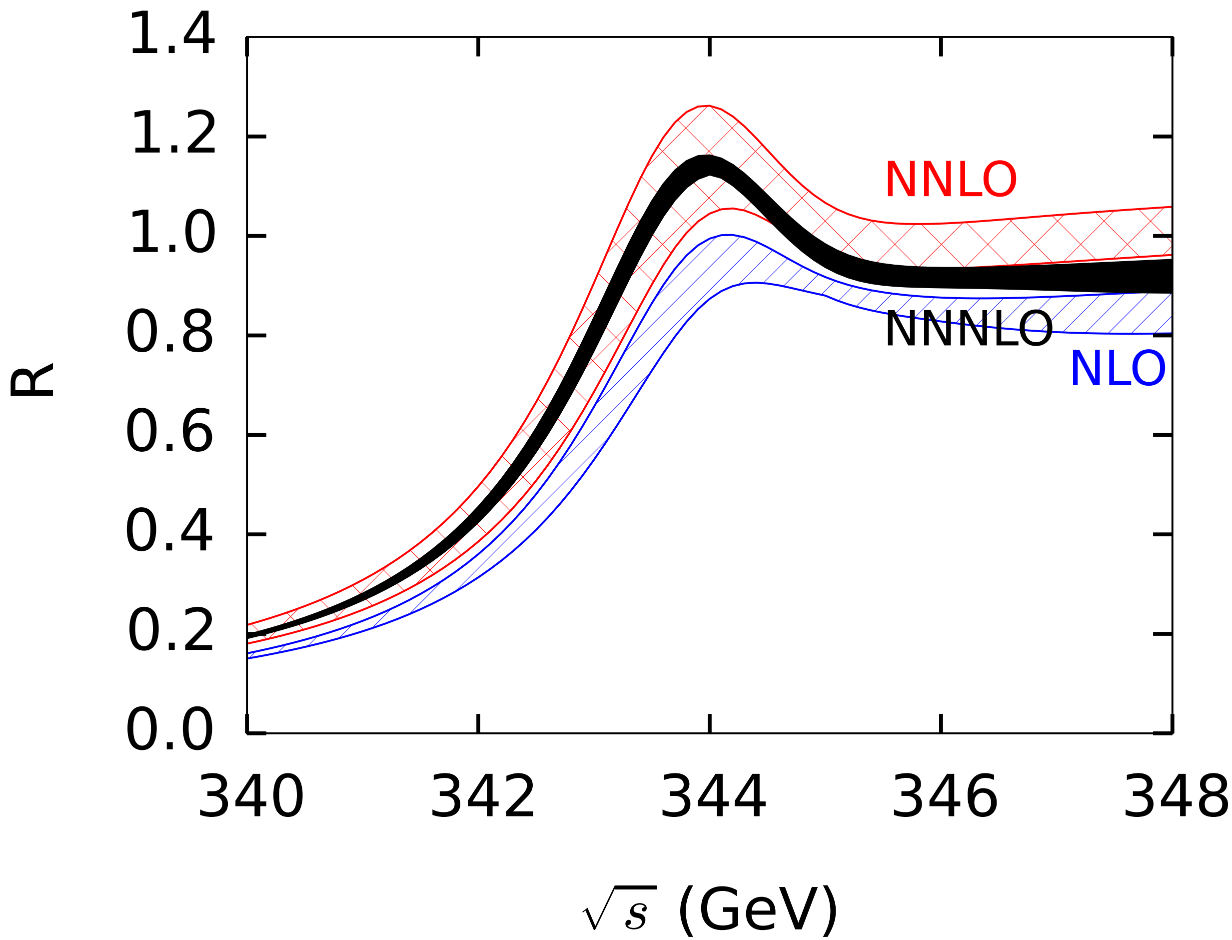
- Peak cross section

$$\begin{aligned} R_{res} &= R_{res}^{LO}\Big[1 - 2.131\alpha_s + (-7.256\ln\alpha_s + 8.375)\alpha_s^2 \\ &\quad - \left(16.352\ln^2\alpha_s + 0.682\ln\alpha_s + 66.793\right)\alpha_s^3\Big] \end{aligned}$$

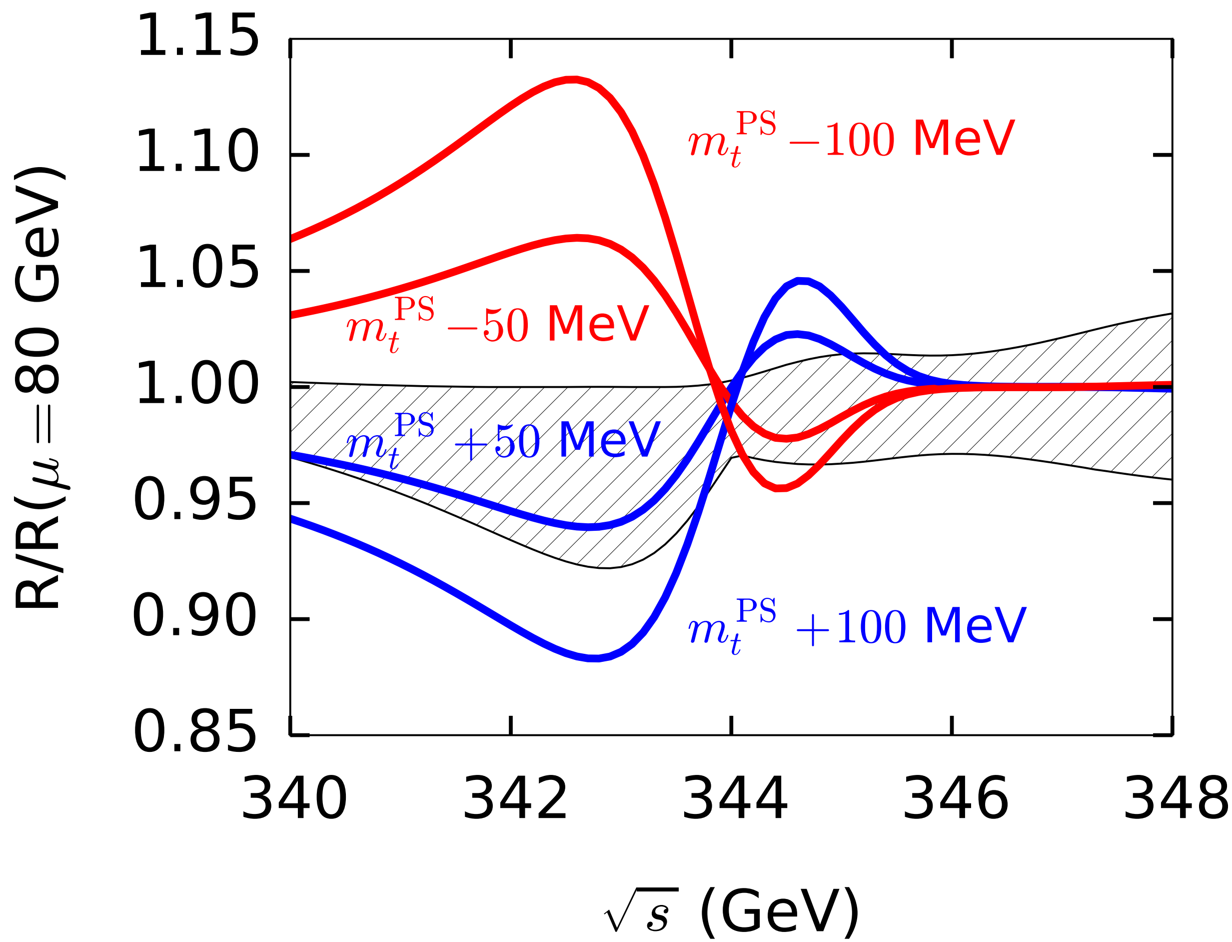
N^3LO cross section

M.Beneke, Y.Kiyo, P.Marquard, A.Penin, J.Piclum, M.Steinhauser,

Phys.Rev.Lett. 115 (2015) 192001



Top mass sensitivity



Pole *vs* a short distance mass

- Renormalon in mass relation

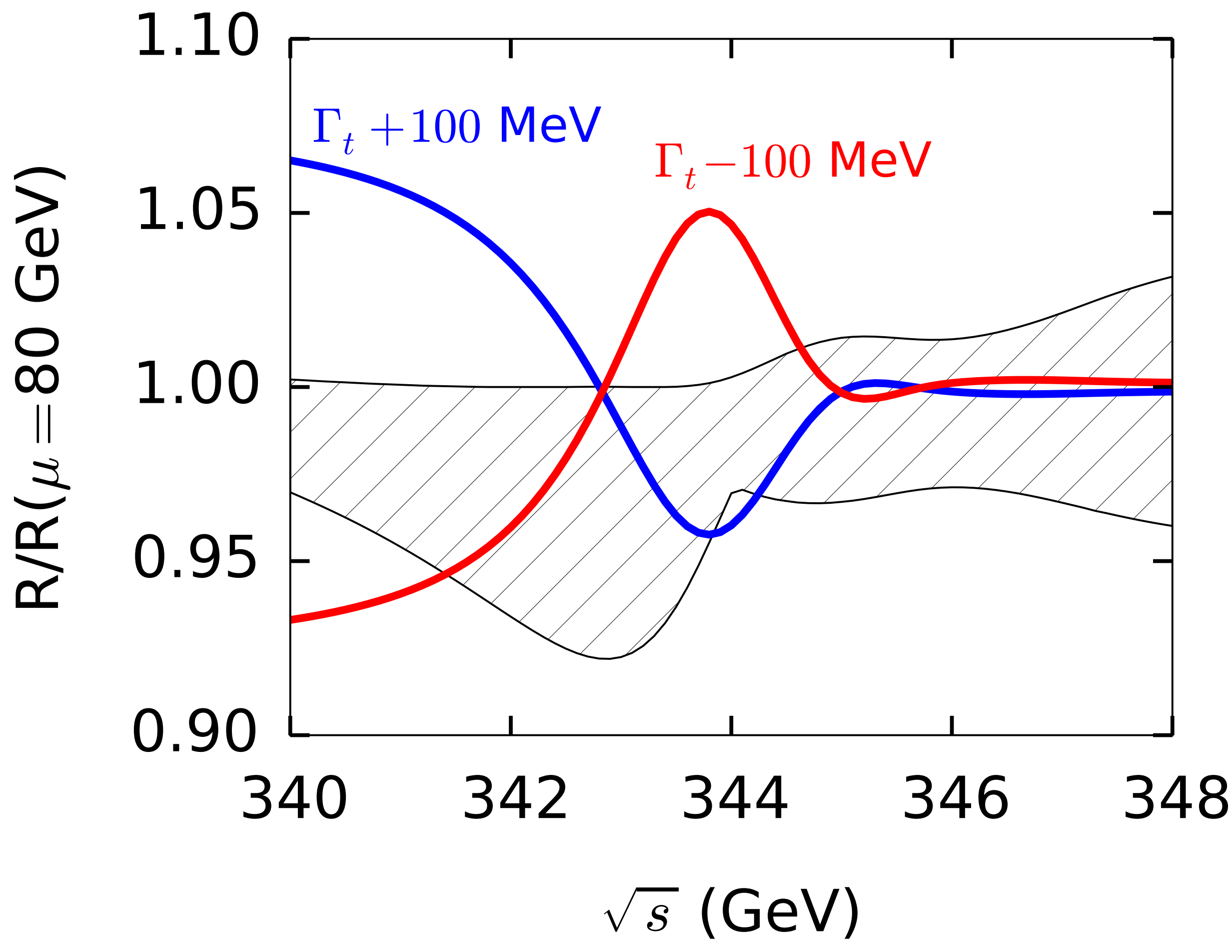
$$m_t = \bar{m}_t(\bar{m}_t)\left(1 + 0.424\alpha_s + 0.835\alpha_s^2 + 2.37\alpha_s^3 + 10.6\alpha_s^4 + \ldots\right)$$

➥ *intrinsic uncertainty in pole mass* $\delta m_t \approx 70\ \mathrm{MeV}$

M. Beneke, P. Marquard, P. Nason, M. Steinhauser, arXiv:1605.03609 [hep-ph]

(talk by Peter Marquard)

Top width sensitivity



Finite width effects

- Resonant approximation V.Fadin, V.Khoze, JETP Lett. 46 (1987) 525

$$\delta(\boldsymbol{p}^2 - m_t E) = \frac{1}{\pi} \frac{\Gamma_t}{(\boldsymbol{p}^2/m_t - E)^2 + \Gamma_t^2}$$

not consistent in pNRQCD beyond LO!

- Non-resonant contribution (up to 10%)
  - *NLO* M. Beneke, B. Jantzen, P. Ruiz-Femenia, Nucl. Phys. B840 (2010) 186
  - *NNLO* A. Penin, J. Piclum, JHEP 1201 (2012) 034

see the next talk

N^{3}LO top phenomenology

✔ Top quark mass

QCD uncertainty $\begin{cases} 40 \text{ MeV for } \overline{MS} \text{ mass} \\ 80 \text{ MeV for pole mass} \end{cases}$

✔ Top quark width

QCD uncertainty 30 *MeV*

✔ Top quark vector coupling

QCD uncertainty 3%

✘ Top quark Higgs coupling

QCD uncertainty *factor 2*

Summary

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- Top threshold production
  - *complete N^3LO result*

    after 15 years, one of only two in collider physics
  - *stabilization of the QCD series, small errors*
  - *prospect of ultimate precision for top quark*

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- To be addressed
  - *high order logarithmic corrections*
  - *non-QCD effects* *(talk by Andreas Maier)*
  - *realistic simulations* *(talk by Marcel Vos)*