International Conference on High Energy Physics

July 22-28, 2010

ICHEP PARIS 2010

Electroweak non-resonant corrections to $e^+e^- \to W^+W^-b\bar{b}$ in the $t\bar{t}$ resonance region

Pedro Ruiz-Femenía

RWTH AACHEN UNIVERSITY

In collaboration with **Martin Beneke** and **Bernd Jantzen**

arXiv: 1004.2188 [hep-ph]

I Top-pair production at linear colliders near threshold

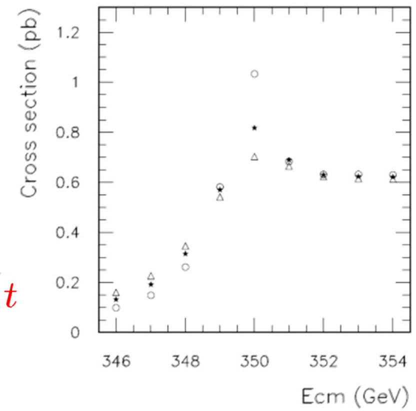
II Evaluation of electroweak non-resonant NLO contributions

III Results & comparisons

IV Conclusions & outlook

FlaviA net

Future linear colliders (ILC/CLIC)
with $\sqrt{s} \gtrsim 2m_t \simeq 350$ GeV will produce lots of $t\bar{t}$ pairs,
allowing for a threshold scan of the top cross section



Martinez, Miquel ´02

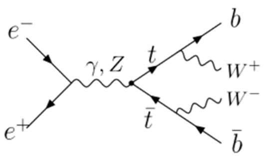
$\hookrightarrow$ Precise determination of the top mass m_t, the width Γ_t and the Yukawa coupling λ_t without the uncertainties ambiguities of hadron colliders $\rightarrow$ $\delta m_t^{\mathrm{exp}} \simeq 30$ MeV

$\rightsquigarrow$ m_t is a crucial input for electroweak precision observables!

Requires also precise theoretical prediction
$\Rightarrow \delta\sigma/\sigma \sim 2-3\%$ ($\delta\sigma \sim 5$ fb below threshold)

QCD corrections are known (almost) up to NNNLO order, but electroweak (EW) NLO contributions due to top decay were missing!

Note: once EW effects are turned on, the physical final state is $W^+W^-b\bar{b}$



$\Rightarrow$ $\sigma(e^+e^- \to W^+W^-b\bar{b})$ in the $t\bar{t}$ resonance region and allow for invariant-mass cuts on reconstructed t, $\bar{t}$

Decay $t \to bW^+$ with $\Gamma_t \approx 1.5$ GeV $\gg \Lambda_{QCD}$
$\Rightarrow t\bar{t}$ is perturbative at threshold

Bigi, Dokshitzer, Khoze, Kühn, Zerwas ´86

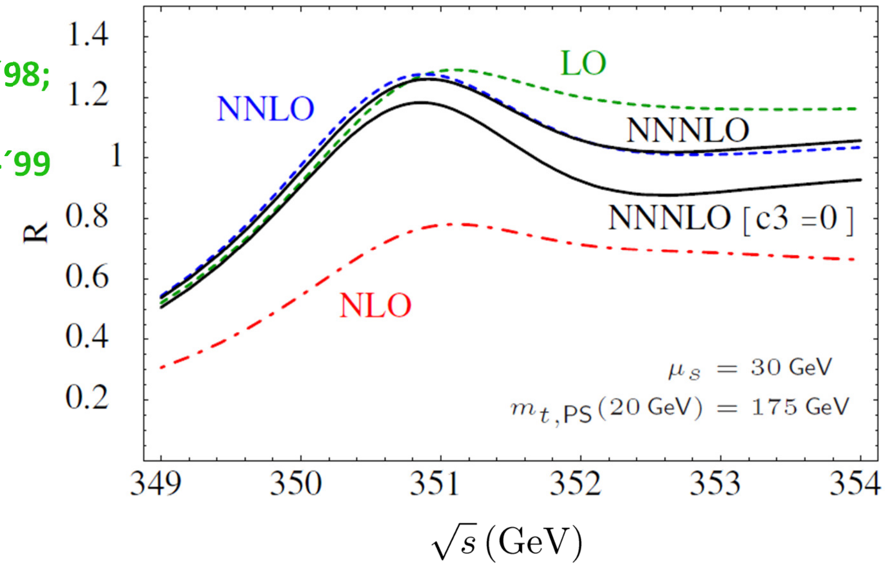
Top quarks move slowly near threshold: $v = \sqrt{1 - \frac{4m_t^2}{s}} \sim \alpha_s \ll 1$

$\hookrightarrow$ sum $\left(\frac{\alpha_s}{v}\right)^n$ from "Coulomb gluons" to all orders $\rightarrow$ **NRQCD**

$$R = \frac{\sigma_{t\bar{t}}}{\sigma_{\mu^+\mu^-}} = v \sum_n \left(\frac{\alpha_s}{v}\right)^n \left(\{1\}_{\rm LO} + \{\alpha_s, v\}_{\rm NLO} + \{\alpha_s^2, \alpha_s v, v^2\}_{\rm NNLO} + \dots\right)$$

Further RG improvement by summing also $(\alpha_s \ln v)^m$: LL, NLL, ...

- NNLO QCD corrections
  Hoang, Teubner ´98-´99; Melnikov, Yelkhovsky ´98; Yakovlev ´98; Beneke, Signer, Smirnov ´99; Nagano, Ota, Sumino ´99; Penin, Pivovarov ´98-´99
- NNLO & (partial) NNLL
  Hoang, Manohar, Stewart, Teubner ´00-´01; Hoang ´03; Pineda, Signer ´06
- (partial) NNNLO
  Beneke, Kiyo, Schuller ´05-´08 → see figure



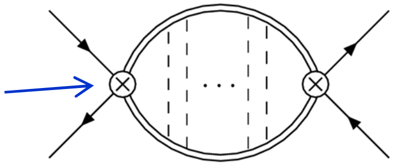
Effective field theory (EFT) for pair production of unstable particles near threshold, based on separation of resonant and nonresonant fluctuations

Hoang, Reisser ´05 ⟺ Beneke, Chapovsky, Khoze, Signer, Zanderighi ´01-´04; Actis, Beneke, Falgari, Schwinn, Signer, Zanderighi ´07-´08

- power counting for finite width effects: $\frac{\Gamma_t}{m_t} \sim \alpha_{\text{EW}} \sim \alpha_s^2 \sim v^2 \ll 1$
- hard modes $\sim m_t$ (including top decay products) are integrated out
  $\rightsquigarrow$ EFT with potential (nearly on-shell) top quarks and ultrasoft gluons
- Extract cross section for $e^+e^- \to W^+W^-b\bar{b}$ from appropriate cuts of the $e^+e^- \to e^+e^-$ forward-scattering amplitude:

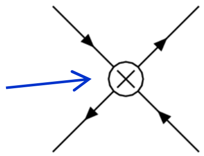
resonant contributions

$t\bar{t}$ production operators $\mathcal{O}_p^{(k)}$



non-resonant contributions

4-electron operators $\mathcal{O}_{4e}^{(k)}$



$\Rightarrow$ Hard corrections encoded in matching coefficients of operators

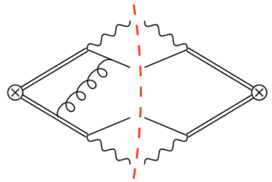
Electroweak effects at LO

- Replacement rule: $E = \sqrt{s} - 2m_t \to E + i\Gamma_t$ Fadin, Khoze ´87

Electroweak effects at NLO

- Exchange of "Coulomb photon": trivially extension of QCD corrections

- Gluon exchange involving the bottom quarks in the final state $\Rightarrow$ these contributions vanish at NLO for the total cross section, Fadin, Khoze , Martin ´94; Melnikov, Yakovlev ´94
  also negligible if loose top invariant-mass cuts are applied



- Non-resonant (hard) corrections to $e^+e^- \to W^+W^-b\bar{b}$ which account for the production of the Wb pairs by highly virtual tops or with only one or no top
  $\hookrightarrow$ **topic of this talk!**

Also:
the resonant **NNLO** corrections produce "finite-width divergences" $\propto \frac{\alpha_s \Gamma_t}{\epsilon}$
which must be cancelled by non-resonant NNLO contributions !

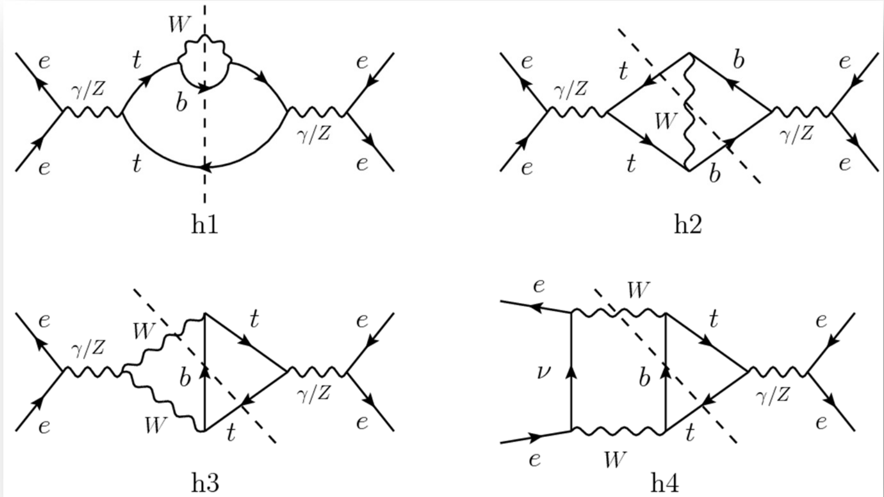
II. Evaluation of EW non-resonant NLO contributions

Non-resonant corrections at NLO:

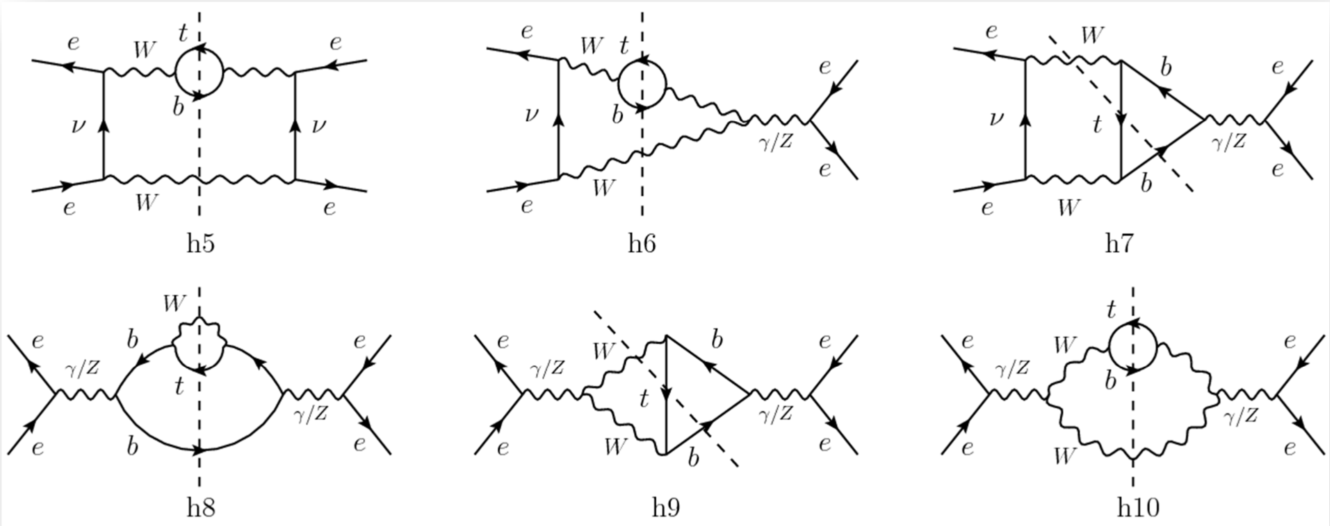
$\Rightarrow$ cuts through $bW^+\bar{t}$ (see diagrams) and $\bar{b}W^-t$ (not shown) in the 2-loop forward scattering amplitude

- treat loop-momenta as hard:
  $p_t^2 - m_t^2 \sim \mathcal{O}(m_t^2) \gg \Sigma(p_t^2) \sim m_t^2 \alpha_{\text{EW}}$
  $\to \Gamma_t = 0$
- suppressed w.r.t. LO $(\sim v)$ by
  $\alpha_{\text{EW}}/v \sim \alpha_s$
- expansion in
  $$\delta = \frac{s - 4m_t^2}{4m_t^2}$$
  $\hookrightarrow$ at NLO:
  $s = 4m_t^2$

[but keep the full s-dependence in γ/Z propagators]



bW^+ from highly virtual top



bW^+ without intermediate top

Form of non-resonant contributions

In terms of the invariant mass of the bW^+ system, $p_t^2 = (p_b + p_{W^+})^2$, ($p_t \to$ also momentum of the top line for h1-h4) diagrams h1-h10 read:

$$\int_{\Delta^2}^{m_t^2} dp_t^2 \, (m_t^2 - p_t^2)^{1/2-\epsilon} \, H_i\left(\frac{p_t^2}{m_t^2}, \frac{M_W^2}{m_t^2}\right)$$

with $\Delta^2 = M_W^2$ for the total cross section

[Phase-space factor $(m_t^2 - p_t^2)^{1/2-\epsilon}$ in dim. reg. regularizes the end-point singularity for h1]

Applying invariant-mass cuts

Restrict invariant masses of the reconstructed $t, \bar{t}$: $|\sqrt{p_{t,\bar{t}}^2} - m_t| \leq \Delta M_t$

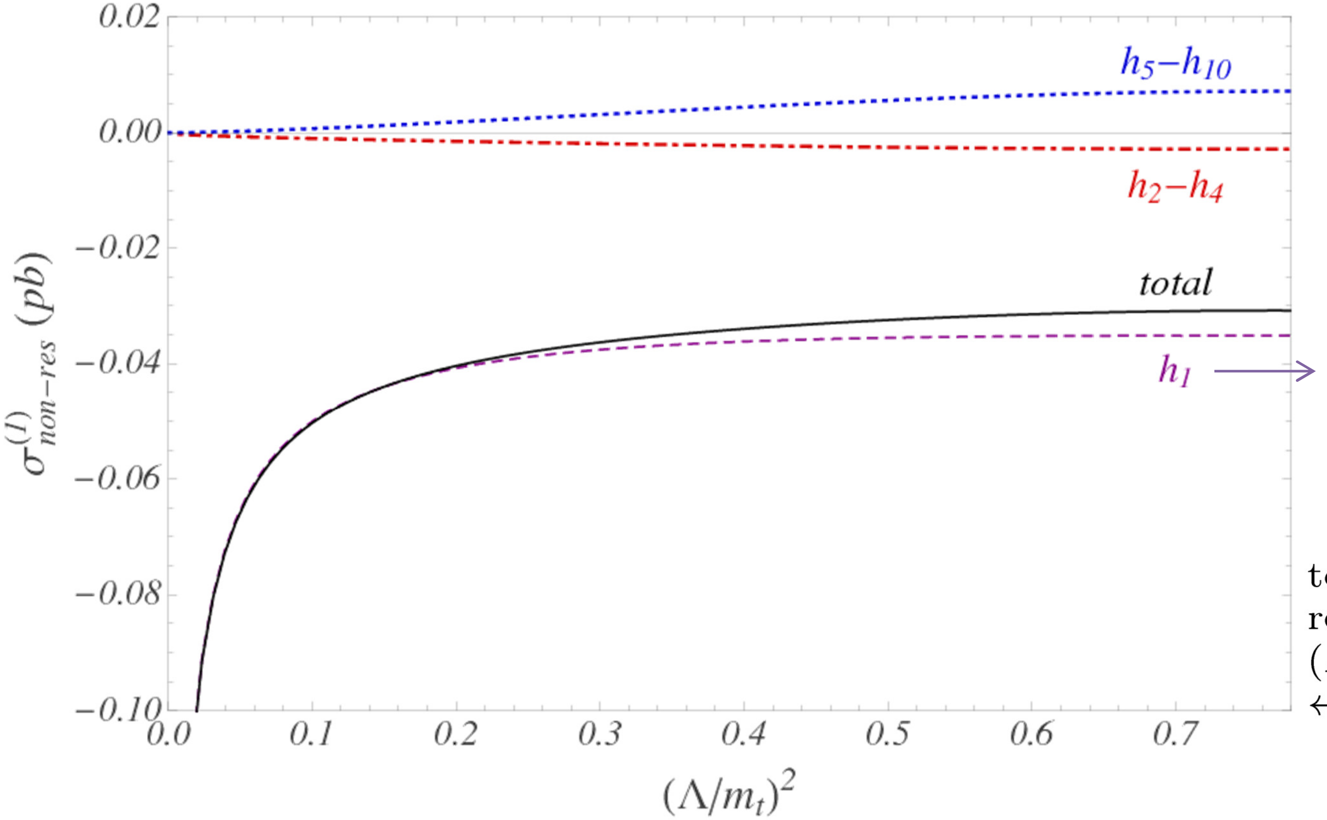
$\hookrightarrow$ lower integration limit $\Delta^2 = m_t^2 - \Lambda^2$ where $\Lambda^2 = (2m_t - \Delta M_t)\Delta M_t$

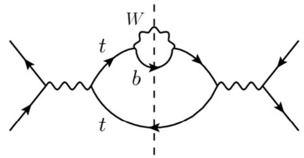
We focus on loose cuts with $\Lambda^2 \gg m_t \Gamma_t$ (corresponding to $\Delta M_t \gg \Gamma_t$)

$\rightsquigarrow$ cut has no effect in the resonant contributions

[In contrast: for tight cuts with $\Lambda^2 \sim m_t \Gamma_t$ ($\Delta M_t \sim \Gamma_t$), non-resonant contributions vanish and cuts only affect the resonant contributions]

Non-resonant NLO contributions: from numeric integration over p_t^2 (and over one angle for some diagrams), the integrand is an analytic function of p_t^2/m_t^2 and M_W^2/m_t^2; cut-dependence enters through the integration limit





total cross section reached for $(\Lambda/m_t)^2 = 1 - M_W^2/m_t^2 = 0.78$

Parameters: on-shell (pole) masses, $m_t = 172$ GeV, $\Gamma_t = \Gamma_t^{\mathrm{tree}} = 1.46550$ GeV, α and $\sin^2\theta_W$ from G_F, M_W, M_Z

"Phase-space matching" method

Hoang, Reisser , RF ´10
arXiv: 1002.3223

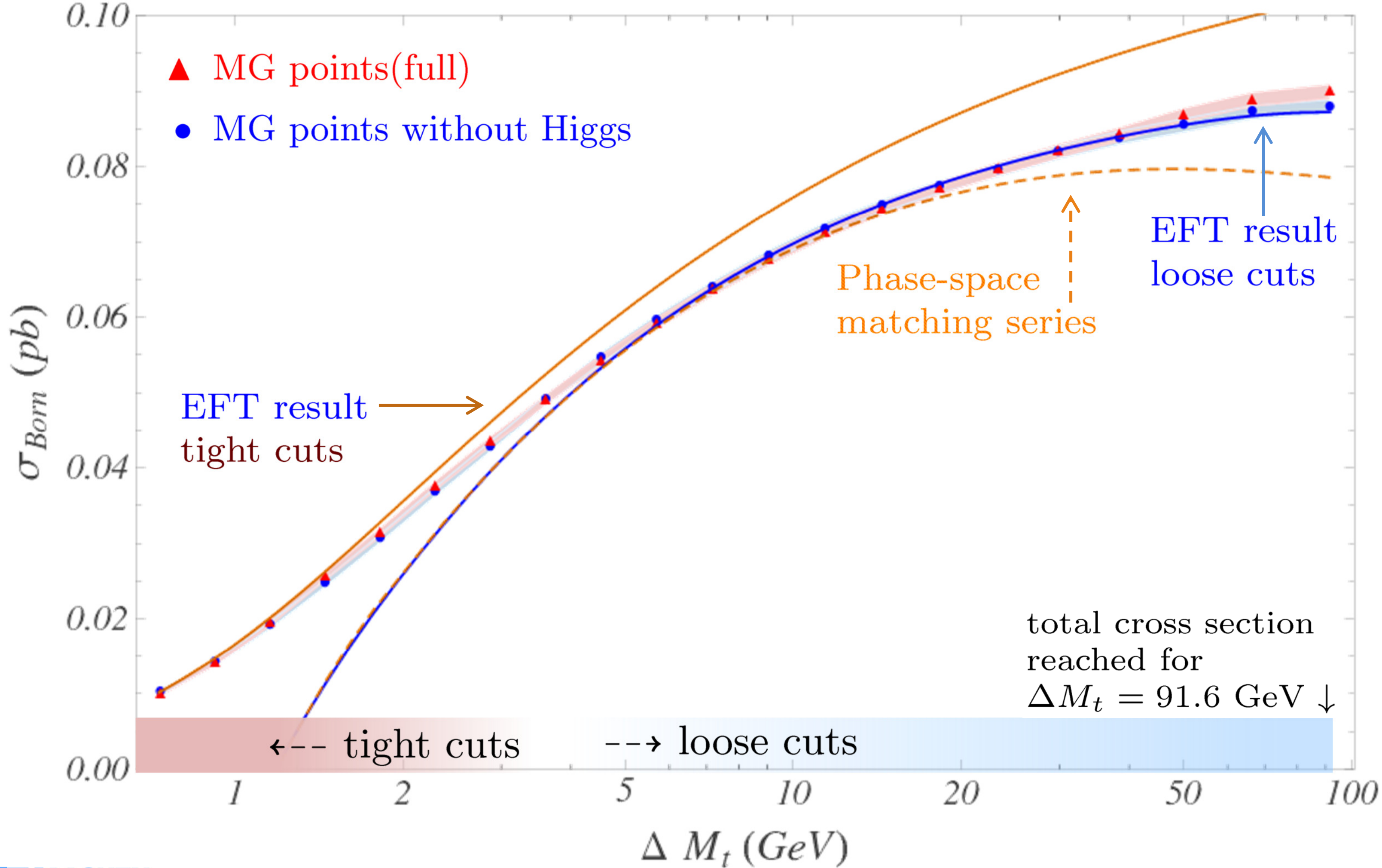
- Non-resonant contributions obtained for moderate invariant-mass cuts, $m_t\Gamma_t \ll \Lambda^2 \ll m_t^2$, as a series:

$$\frac{\Gamma_t}{\Lambda}\sum_{n,\ell}\left[\left(\frac{m_t\Gamma_t}{\Lambda^2}\right)^n \times \left(\frac{\Lambda^2}{m_t^2}\right)^\ell\right] \qquad n,\ell = 0,1,\ldots$$

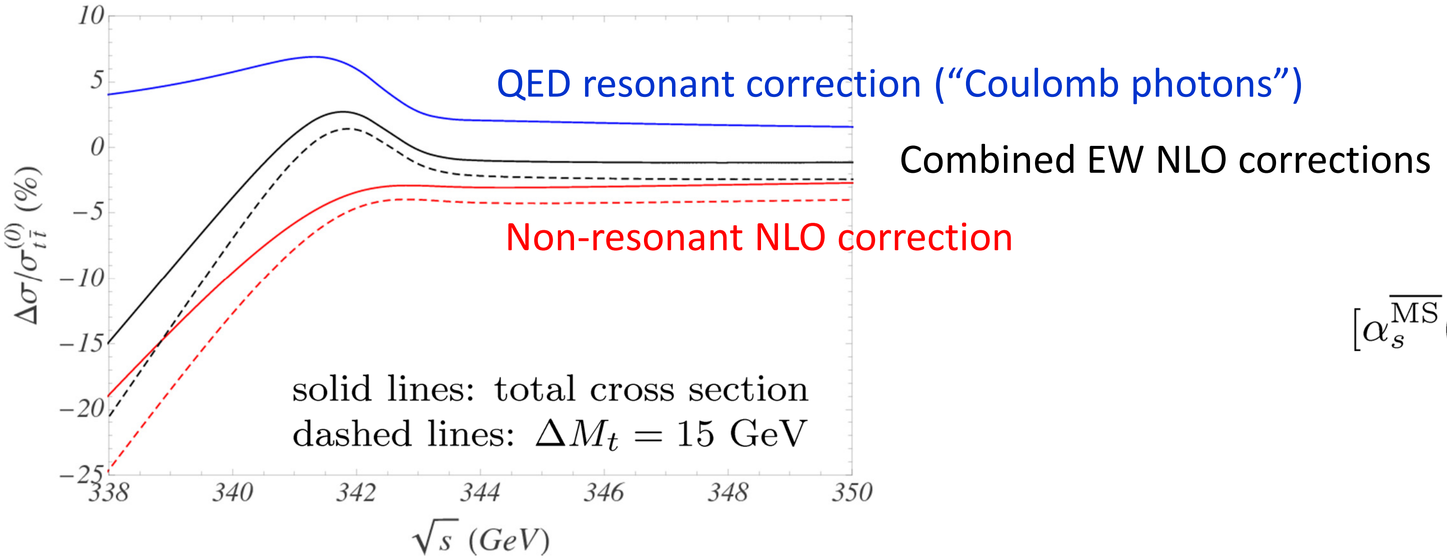
- NLO, NNLO and (partial) $\mathrm{N}^3\mathrm{LO}$ contributions obtained ✓
- Assumption: non-resonant background processes are small (✓ at NLO!)
- Beyond NLO, phase-space matching approach cannot be applied to larger cuts up to the total cross section ×
- Expansion of our result in $(\Lambda/m_t)^n$ agrees with first two terms in series above [higher powers receive contributions from non-t diagrams h5-h10, which are not taken into account in the phase-space matching approach]

↪ generated 10^4 events for $e^+e^- \to W^+W^-b\bar{b}$ with MadGraph (MG) for $s = 4m_t^2$, and analyzed dependence on the bW invariant-mass cut ΔM_t

EFT result: resonant LO+NNLO $(\alpha_s = 0)$ + non-resonant NLO

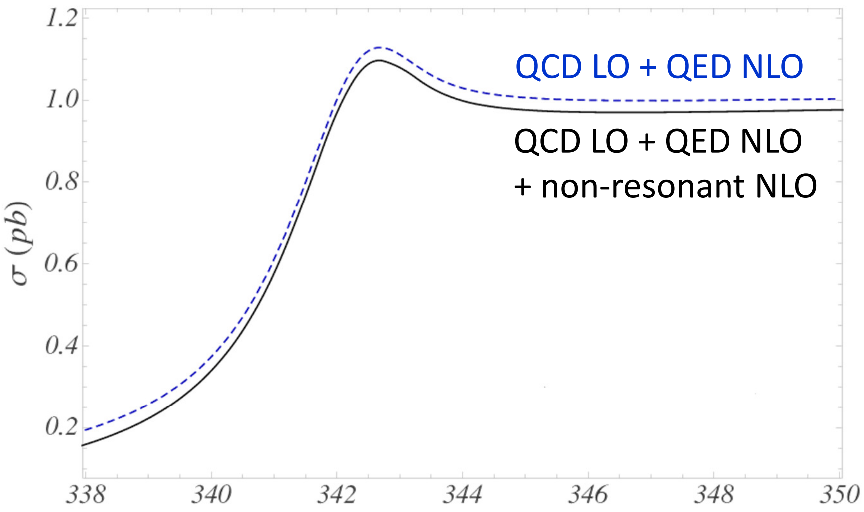


Relative sizes of EW NLO corrections w.r.t. LO (including resummation of Coulomb gluons $\propto (\alpha_s/v)^n$)

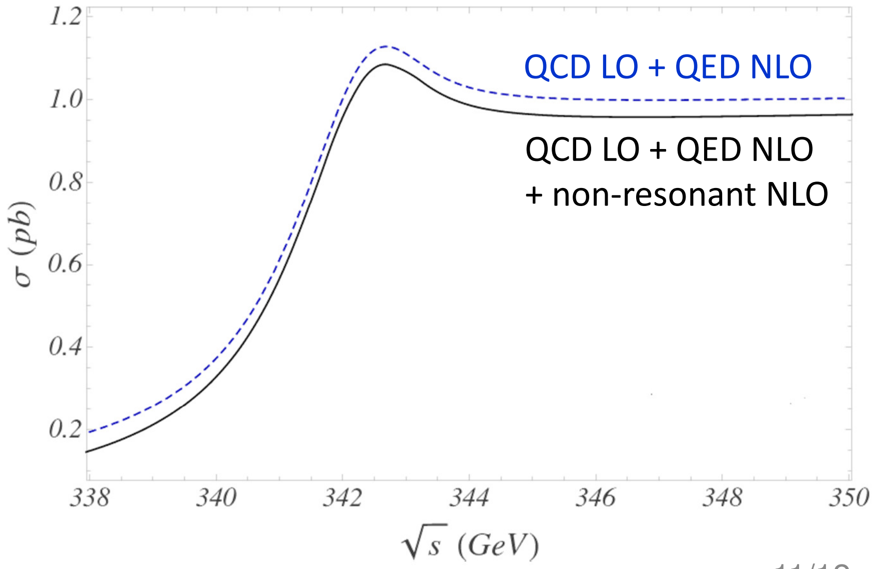


$[\alpha_s^{\overline{\text{MS}}}(30\,\text{GeV}) = 0.142]$

Total cross section



Cross section with $\Delta M_t = 15$ GeV



IV. Conclusions & outlook

EW non-resonant corrections to $e^+e^- \to W^+W^-b\bar{b}$ in the $t\bar{t}$ resonance region

- NLO completed by EW non-resonant contributions for total cross section and with top invariant-mass cuts
- correction of ~ -30 fb (-3% above and up to -20% below threshold) for the total cross section, even more with invariant-mass cuts

  $\hookrightarrow$ can be added to existing QCD results to improve accuracy of theoretical prediction

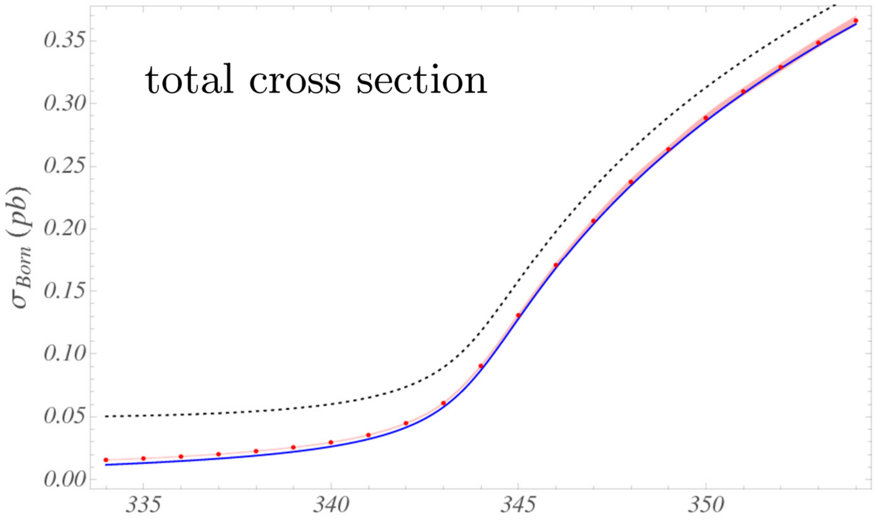
- Good agreement with tree-level Madgraph cross section for loose and tight cuts
- Complementary to phase-space matching approach for intermediate cuts

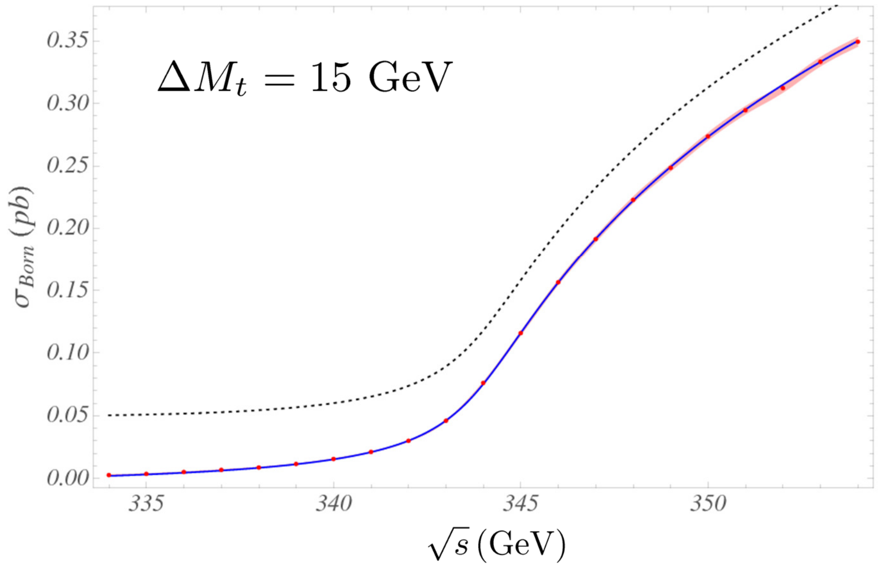
Future improvements

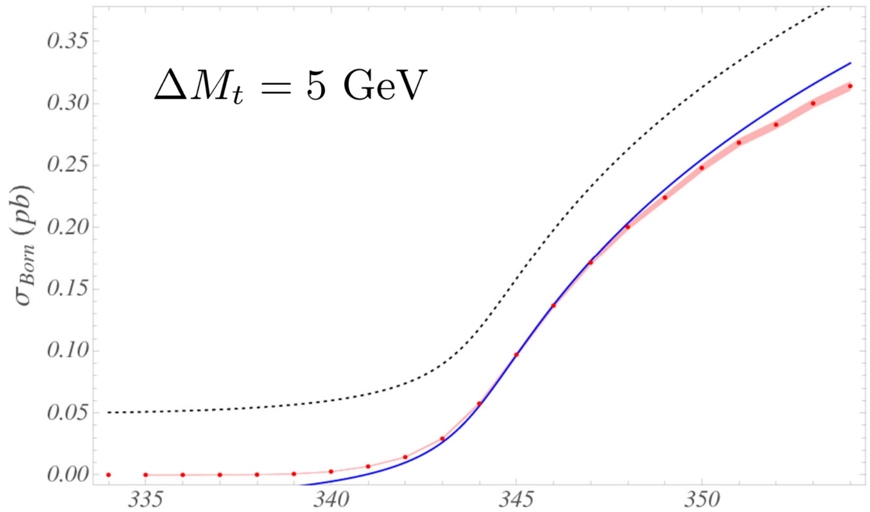
- add initial-state radiation and convolution with electron distribution functions
- add gluon exchange to non-resonant contributions → full EW NNLO corrections

Backup slides

$e^+e^- \to W^+W^-b\bar{b}$ tree-level cross section: energy dependence for different ΔM_t invariant-mass cuts







MG (full) points & error band,

EW NNLO tree-level contributions (solid-blue) [resonant + non-resonant],

only resonant contributions (dotted-black)