Stefan Liebler
DESY Hamburg

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676

Probing the top-quark width through ratios of resonance contributions in $e^+e^- \to W^+W^-b\bar{b}$

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

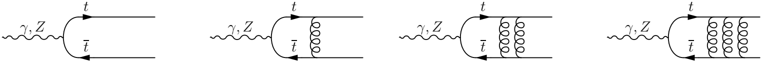
Terascale meeting 2015

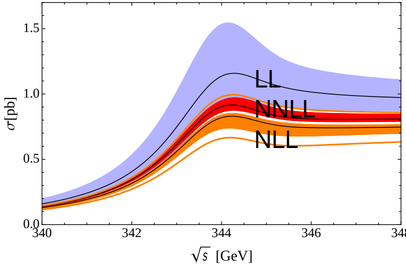
Hamburg - Nov. 2015

DESY

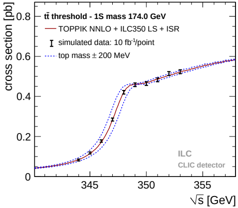
HELMHOLTZ | GEMEINSCHAFT

Disclaimer: A LC offers the most precise measurement of a theoretically well-defined top-quark mass m_t and width Γ_t at the threshold of $e^+e^- \to t\bar{t}$.
Threshold region with non-relativistic $t\bar{t}$: NRQCD





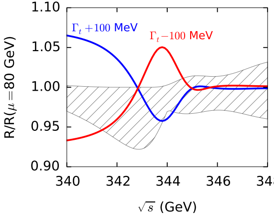
[1309.6323 Hoang Stahlhofen]



[1303.3758 Seidel et al.]

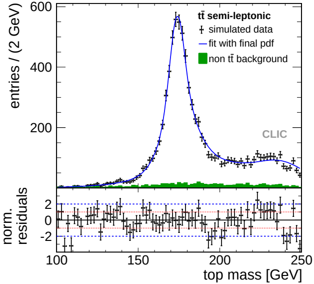
Sensitivity to the top-quark width Γ_t:
Estimated accuracy: $\Delta\Gamma_t \sim 20 - 30$ MeV

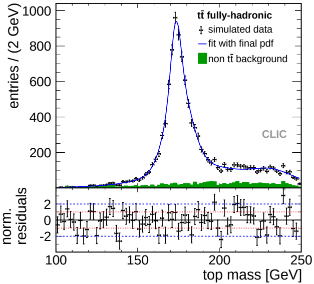
However: LC starts with $\sqrt{s} \geq 500$ GeV!



[1506.06864 Beneke et al.] [1303.3758 Seidel et al.]

In the continuum $\sqrt{s} \geq 500$ GeV the top-quark peak can be resolved:
$e^+e^- \to t\bar{t}$ supplemented with smeared t decays [1303.3758 Seidel et al.]



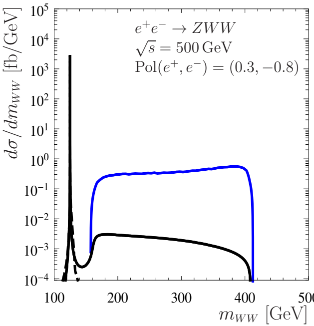


Estimated accuracy: $\Delta\Gamma_t = 100 - 200$ MeV
Higher orders/MC simulation strongly effect the form of the distribution.
Current measurements of Γ_t (e.g. at Tevatron/LHC):

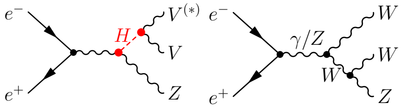
$$\left.\begin{array}{c}\mathrm{BR}(t \to Wb) \text{ through } R = \mathrm{BR}(t \to Wb)/\sum_{q=d,s,b} \mathrm{BR}(t \to Wq) \\ \Gamma(t \to Wb) \propto g_{tbW}^2 \text{ through } g_{tbW} \text{ from single-top production}\end{array}\right\} \to \Gamma_t$$

Current accuracy from this indirect measurement: $\Gamma_t = 1.41^{+0.19}_{-0.14}$ GeV [PDG]

$\to$ Motivation to look for complementary methods of accessing Γ_t at LC!
Inspiration from bounds on Higgs width Γ_H from large off-shell regions in $H \to VV$ with $V \in \{Z, W\}$:



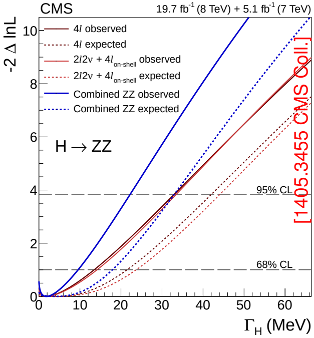
[1502.07970 SL Moortgat-Pick Weiglein]



On-/Off-shell regions scale differently:

$$\sigma_{\text{on}} \sim \frac{(g^{\text{on}}_{\text{prod}} g^{\text{on}}_{\text{decay}})^2}{\Gamma_H^2}, \quad \sigma_{\text{off}} \sim (g^{\text{off}}_{\text{prod}} g^{\text{off}}_{\text{decay}})^2$$

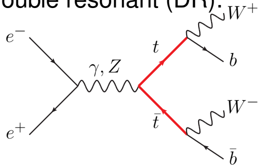
$\to$ Sensitivity through $\sigma_{\text{off}}/\sigma_{\text{on}} \propto \Gamma_H^2$
Assumption: $g^{\text{off}} = g^{\text{on}}$ (model-dependent!)



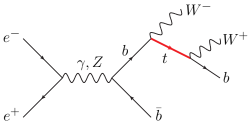
[1405.3455 CMS Coll.]

$\to$ Motivation to look for complementary methods of accessing Γ_t at LC!
For this purpose: $e^+e^- \to W^+W^-b\bar{b}$ at NLO QCD with `Madgraph_aMC@NLO`
[1511.02350 SL Moortgat-Pick Papanastasiou]

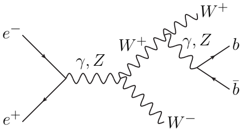
Diagrams at tree-level:
Double resonant (DR):



Single resonant (SR):

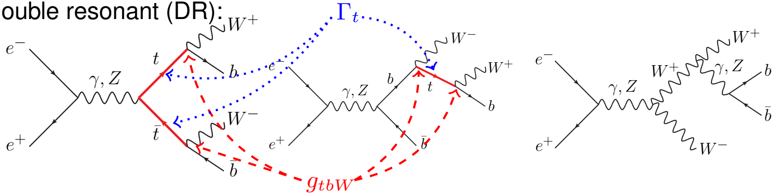


Non resonant:



$\to$ Motivation to look for complementary methods of accessing Γ_t at LC!
For this purpose: $e^+e^- \to W^+W^-b\bar{b}$ at NLO QCD with `Madgraph_aMC@NLO`
[1511.02350 SL Moortgat-Pick Papanastasiou]

Diagrams at tree-level: Single resonant (SR): Non resonant:
Double resonant (DR):



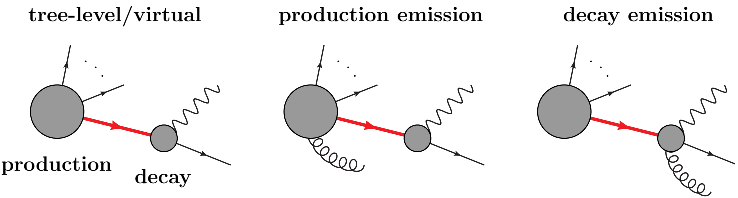
The contributions to single and double resonant regions scale like:

$$\left|\mathcal{M}^{\text{DR}}\right|^2 = \left| \sum_{V\in\{\gamma,Z\}} g_{eeV}\, g_{ttV}\, A_V^{\text{DR}} \right|^2 \frac{g_{tbW}^4}{m_t^2 \Gamma_t^2} + \dots$$

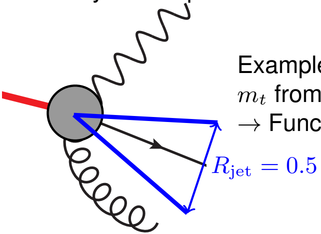
$$\left|\mathcal{M}^{\text{SR}}\right|^2 = \left| \sum_{V} g_{eeV}\, g_{ttV}\, A_V^{\text{DR}} + \sum_{V,j} g_{eeV}\, g_{jjV}\, A_{Vj}^{\text{SR}} + g_{eeW}^2 A_W^{\text{SR}} \right|^2 \frac{g_{tbW}^4}{m_t \Gamma_t} + \dots$$

$\to$ Ratio $\sigma^{\text{SR}}/\sigma^{\text{DR}} \propto \Gamma_t$ independent of g_{tbW}! We stay close to the mass peak!

To separate SR from DR reconstruct the invariant mass of the t, $M(W, J_b)$. What happens at NLO QCD? Virtual and real corrections $\to$ More radiation.

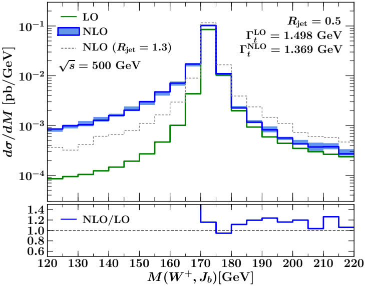


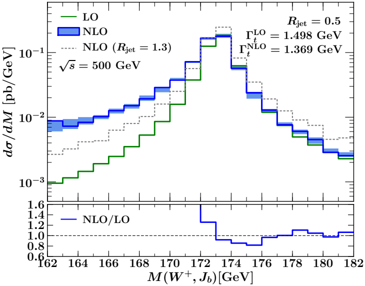
Fixed order analysis with partons clustered into jets ($b \to J_b$) with k_t-algorithm:



Example for decay emission: To reconstruct m_t from $M(W, J_b)$ capture the gluon in J_b.
$\to$ Function of R_{jet}

Reconstructed top-quark mass spectrum at NLO QCD:

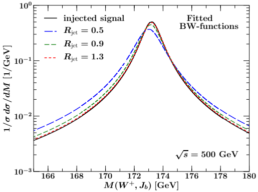




K-factors (=NLO/LO) are strongly dependent on $M(W, J_b)$ and $R_{\rm jet}$.

$\to$ Peak distribution is distorted at higher orders.

Interlude: Effect on the reconstructed Γ_t value from lineshape fitting



Input values: $m_t = 173.2$ GeV, $\Gamma_t = 1.369$ GeV

Reconstructed values:

$R_{\rm jet} = 0.5$: $m_t = 173.00$ GeV, $\Gamma_t = 1.92$ GeV

$R_{\rm jet} = 0.9$: $m_t = 173.14$ GeV, $\Gamma_t = 1.55$ GeV

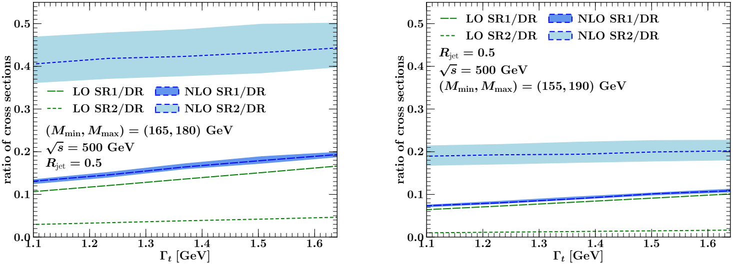
$R_{\rm jet} = 1.3$: $m_t = 173.20$ GeV, $\Gamma_t = 1.30$ GeV

also non-pert. effects: [0711.2079 Fleming et al.]

Define double and single resonant regions with interval $(M_{\text{min}}, M_{\text{max}})$:

$$\begin{aligned}
\text{DR:}\quad & M(W^+, J_b) \in [M_{\text{min}}, M_{\text{max}}] \text{ and } M(W^-, J_{\bar{b}}) \in [M_{\text{min}}, M_{\text{max}}] \\
\text{SR1:}\quad & M(W^+, J_b) \in [M_{\text{min}}, M_{\text{max}}] \text{ and } M(W^-, J_{\bar{b}}) > M_{\text{max}} \\
& \text{or } M(W^+, J_b) > M_{\text{max}} \text{ and } M(W^-, J_{\bar{b}}) \in [M_{\text{min}}, M_{\text{max}}] \\
\text{SR2:}\quad & M(W^+, J_b) \in [M_{\text{min}}, M_{\text{max}}] \text{ and } M(W^-, J_{\bar{b}}) < M_{\text{min}} \\
& \text{or } M(W^+, J_b) < M_{\text{min}} \text{ and } M(W^-, J_{\bar{b}}) \in [M_{\text{min}}, M_{\text{max}}]\,.
\end{aligned}$$

Following our findings SR1 ($M(W, J_b) > m_t$) is less affected by NLO corr.!

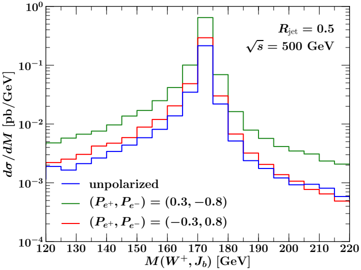


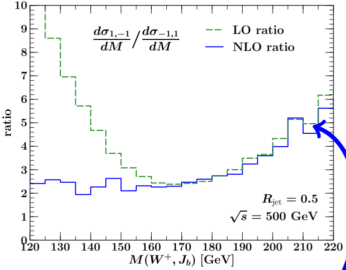
Uncertainty band from $\mu_R \in [0.5, 2]m_t \rightarrow$ SR1/DR is best suited for $\propto \Gamma_t$.

Improvements on the sensitivity on Γ_t:
Polarization of the initial state (P_{e^+}, P_{e^-})

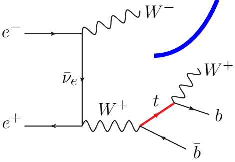
$$\sigma = \frac{1}{4}\left(1 - P_{e^+}\right)\left(1 + P_{e^-}\right)\sigma_{-1+1} + \frac{1}{4}\left(1 + P_{e^+}\right)\left(1 - P_{e^-}\right)\sigma_{+1-1}$$

with σ_{-1+1} = XS for left-handed electron, right-handed positron, etc.
The formula also holds for diff. XS and at NLO QCD!



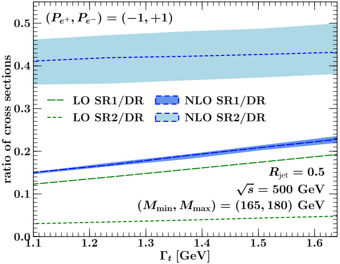


Sensitivity increase for σ_{-1+1}
due to increased gradient of SR1/DR.

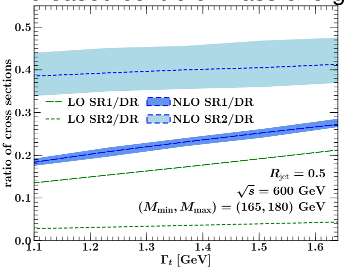


Improvements on the sensitivity on Γ_t:

Polarization:



Increased centre of mass energy:



$\sqrt{s}$ [GeV]	Pol.	R_{jet}	$(M_{\text{min}}, M_{\text{max}})$ [GeV]	$\Delta\Gamma_t^{\text{theo}}$ [GeV]	$\Delta\Gamma_t$ [GeV]
500	unpol.	0.5	$(165, 180)$	0.11	0.19
500	unpol.	1.3	$(165, 180)$	0.19	0.27
500	unpol.	0.5	$(160, 185)$	0.10	0.20
500	unpol.	1.3	$(160, 185)$	0.19	0.31
500	unpol.	0.5	$(155, 190)$	0.09	0.25
500	unpol.	1.3	$(155, 190)$	0.20	0.36
500	$(-1, +1)$	0.5	$(165, 180)$	0.07	0.14
600	unpol.	0.5	$(165, 180)$	0.12	0.18

with scale uncertainty

with error of ± 0.005 $(5-10\%)$ on SR1/DR

Conclusions:

▷ LC offers clean measurement of m_t and Γ_t at threshold with $\Delta\Gamma_t \sim 20$ MeV!

LC runs first at higher energies, where possible options to extract Γ_t are:

▷ Top-quark width can be reconstructed from lineshape fitting!

$\rightarrow$ Fit is influenced by higher orders and MC modeling, $\Delta\Gamma_t \sim 100$ MeV.

▷ Top-quark width can be obtained from ratios of single and double resonant regions in $e^+e^- \rightarrow W^+W^-b\bar{b}$, shown at NLO QCD, $\Delta\Gamma_t \sim 100$ MeV.

Assumption: Couplings are SM-like, in particular $g_{t\bar{t}V}$.

Alternative: Use ratios with Γ_t as input to constrain $g_{t\bar{t}V}$.

A detailed simulation is on order!

For more details on $e^+e^- \rightarrow W^+W^-b\bar{b}$ at NLO QCD
see our paper [1511.02350 SL Moortgat-Pick Papanastasiou] and listen to:

$e^+e^- \rightarrow t\bar{t}$ at threshold: Jan Piclum, Thomas Rauh
NLO calculations with WHIZARD (incl. $e^+e^- \rightarrow W^+W^-b\bar{b}$): Christian Weiss
Top physics sessions, e.g. top-quark width from lineshape at LHC: Philipp Stolte
NLL threshold resummation in $t\bar{t}$ production with WHIZARD: Bijan Chokoufe Nejad

Thank you!