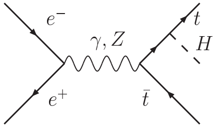
Top-Pair Associated Higgs Production at the ILC



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[hep-ph/0604166], [hep-ph/0504220], . . .

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Outline

- Physical motivation
- Measurement at the ILC at 500 GeV
- Nonrelativistic QCD
- NLL QCD effects
- NLL electroweak effects

Measurement
Motivation

Open questions:

- Generation of mass?
- Electroweak symmetry breaking?

In the SM: Higgs mechanism

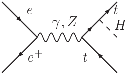
	predicted?	LHC	$\frac{\Delta x}{x}$
Mass	–	$\surd$	1%
Gauge couplings	m_W	$\surd$	5-30%
Self-couplings	$\frac{{m_h}^2}{v^{(2)}}$	–	–
Yukawa couplings	$\frac{m_f}{v}$	top, τ	30-50%

- Couplings discriminate between models
- Need ILC to measure them

Here:

Top Yukawa coupling at ILC

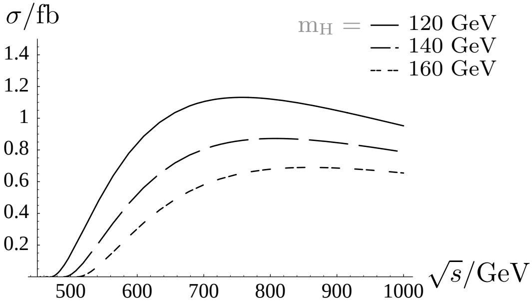
- How?
  - Measurement of $\sigma(e^+e^- \to t\bar{t}H)$



  - Known: Born CS [Gaemers, Gounaris, Djouadi, Kalinowski]
    One-loop CS [Dawson, Reina, Belanger, Dittmaier, Denner, Roth, Weber . . .]

    New: NLL CS in vNRQCD

Total Born CS

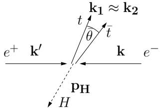


Dedicated Studies:

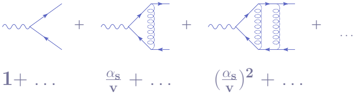
- At 800 GeV: $\delta Y_t / Y_t \approx 5 - 10\%$ [Juste,Gay]
- At 500 GeV: $\approx$ 25% [Juste]

  $2m_t + m_H \geq 475$ GeV $\Rightarrow$ Phase space is small

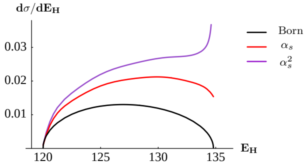
Difficulties for $v \ll 1$:



- Coulomb singularities $\sim (\alpha_s/v)^n$



- $(\alpha_s \log v)^n$ singularities: $\log \frac{E}{p}$, $\log \frac{p}{m}$
- Fixed-order theory breaks down



At 500 GeV: v is always small
Phase space is non-relativistic

$\Rightarrow$ Effective theory

$$\frac{d\sigma}{dE_H} \sim v \sum \left(\frac{\alpha_s}{v}\right)^n (\alpha_s \ln v)^n \left(1\,(LL) + \#\,\alpha_s\,(NLL)\right)$$

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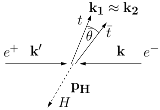

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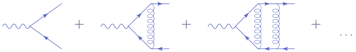

$1 + \ldots \qquad \frac{\alpha_s}{v} + \ldots \qquad \left(\frac{\alpha_s}{v}\right)^2 + \ldots$

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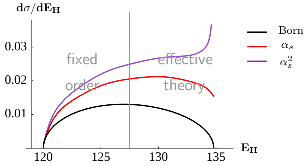

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vNRQCD (velocity Non-Relativistic QCD)
[Luke, Manohar, Rothstein, Stewart, Hoang]

- Power Counting: $\alpha_s \sim v$
- Hierarchy of relevant scales:

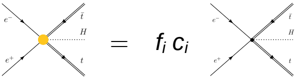
$$m \gg mv \sim \vec{p} \gg mv^2 \sim E_{kin} \sim \mathrm{i}\Gamma_t \gg \Lambda_{QCD}$$

- Infrared regulator Γ_t suppressing hadronization effects
- At LL: $v \approx \sqrt{\frac{E+i\Gamma_t}{m}}$

vNRQCD (velocity Non-Relativistic QCD)
[Luke, Manohar, Rothstein, Stewart, Hoang]

- Lagrangian includes the fields of all resonant degrees of freedom $\rightarrow$ Schrödinger equation in the CMS
- Effective creation and annihilation currents:

$$\mathbf{O_p} = f_0\, c_0(\mu, \sqrt{s}, m_H) \left(\psi_{\vec{p}}^{\dagger}\ \tilde{\chi}_{-\vec{p}}\right) + f_1\, c_1(\mu, \sqrt{s}, m_H) \left(\psi_{\vec{p}}^{\dagger}\ \vec{\sigma}\ \tilde{\chi}_{-\vec{p}}\right)$$



- Wilson coefficients contain the non-resonant contributions
  - RGE running: $c(\mu) = c(m_t) \cdot u(m_t, \mu)$

NLL QCD Effects

Cross section $\sigma(e^+e^- \to t\bar{t}H)$

$$\frac{d\sigma}{dE_H}(E_H \approx E_H^{\max}) \quad \sim \quad \Big[f_0^2\, c_0^2(\mu, \sqrt{s}, m_t, m_H) + f_1^2\, c_1^2(\mu, \sqrt{s}, m_t, m_H) \Big] \, \mathrm{Im}\, G^{\mathrm{NLL}}_{\mathrm{Coulomb}}$$

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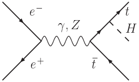
$f_{0,1}^2$: electroweak information in the endpoint

$$\sim \left(\frac{d\sigma_{0,1}}{dE_H}\right)_{Born} \text{ for } E_H \to E_{H,max}$$



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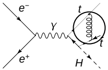
$c^2_{0,1}$: hard QCD corrections in the endpoint



[Denner, Dittmaier, Roth Weber]

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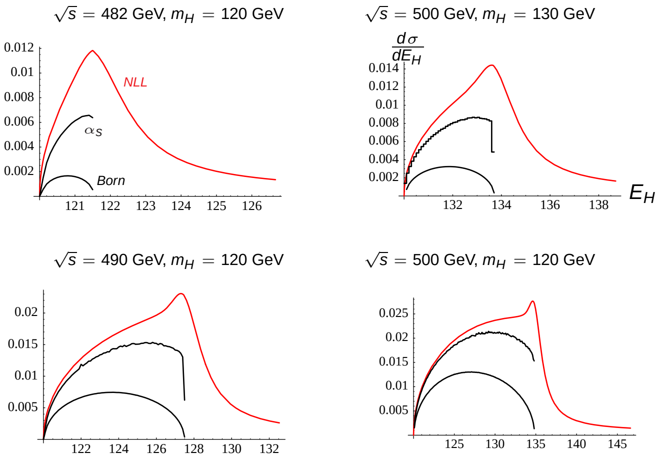
Known:

- Renormalization group running of $c_{0,1}$
- $G^{\mathrm{NLL}}_{\mathrm{Coulomb}}$

New:

- Matching conditions $f_{0,1},\ c_{0,1}(\mu = m_t)$
- Inclusion of e^+e^- polarization
- Formula for σ_{tot}
- Top-decay effects
- Phase space matching

NLL QCD Effects
Differential Cross Section



$\Rightarrow$ Behavior far from threshold is well reproduced

$\Rightarrow$ Increase of total cross section

e^+e^- Polarization

Cross section depends on the helicity of e^+ and e^-:

Total cross section:

$$\sigma_{pol} = \sigma_{\text{unpol}} \left[1 - P_- P_+ - A_{LR}(P_+ - P_-)\right]$$

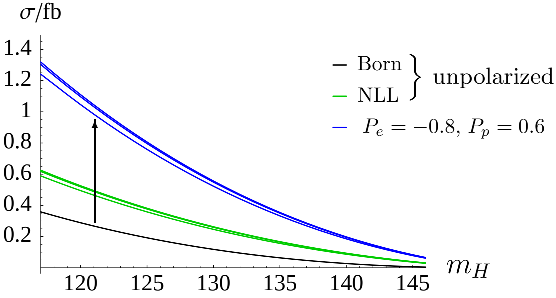
$P_\pm$: degree of $e^\pm$ polarization

left-right asymmetry: $A_{LR} = \frac{\sigma^- - \sigma^+}{\sigma^- + \sigma^+}$

$\Rightarrow$ Increase of σ_{tot} by polarization possible

e^+e^- Polarization

Total Cross Section for $\sqrt{s} = 500$ GeV, $m_t = 175$ GeV



$\sim$ 400% increase vs. unpolarized Born cross section

$\Rightarrow$ Decrease of statistical uncertainty by $\sim$ 50%

Electroweak effects

Top Decay

Power Counting:

$$g \sim g' \sim v \sim \alpha_s$$

Top decay:

At LL: $E \rightarrow E + \mathrm{i}\Gamma_t$

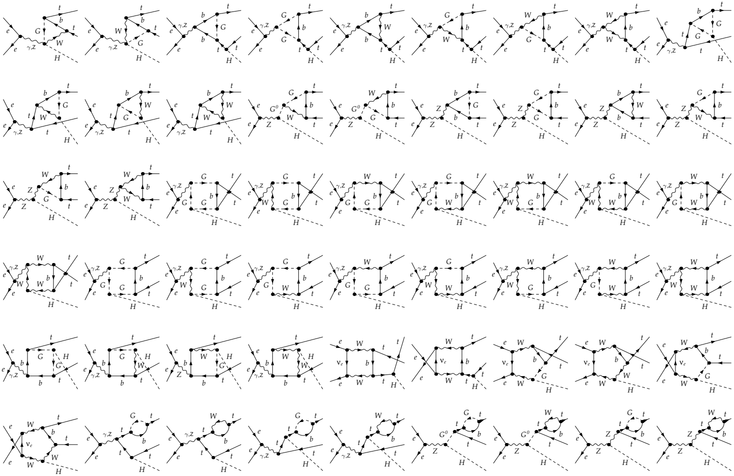
At NNLL: Imaginary Wilson coefficients

Tops decay into $b - W$-pairs

- Cutkosky: Identify cuts corresponding to bW-cuts
- At $t\bar{t}$ threshold: Gram determinant often vanishes
  $\Rightarrow$ Use appropriate reduction method [Denner,Dittmaier]

Electroweak Effects
Top Decay

The relevant diagrams for $t\bar{t}H$



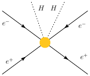
Electroweak Effects

- Sensitivity to Re[G]

  Optical Theorem: $\sigma_{\rm tot} \sim {\rm Im}[c_W\, G]$

$$G^{\rm LL}_{\rm Coulomb}(0,0,E) = \frac{m_t^2}{4\,\pi}\left\{iv - c_F\,\alpha_s\left[\frac{1}{4\epsilon} + \ln\left(\frac{-i m_t v}{\mu}\right) + \psi(1 - \frac{i\, c_f\, \alpha_s}{2v})\right]\right\}$$

$\Rightarrow$ RGE running of new operator



- Phase Space Matching:

  double-resonant region: NR expansion is valid

  $\Rightarrow$ Cut on Q^2 of the tops

Electroweak Effects

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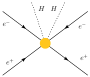
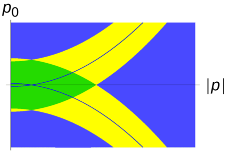


- Phase Space Matching:

[Hoang, Reisser, Ruiz-Femenia]

$p_0 < \Lambda \ll m_t$



double-resonant region: NR expansion is valid

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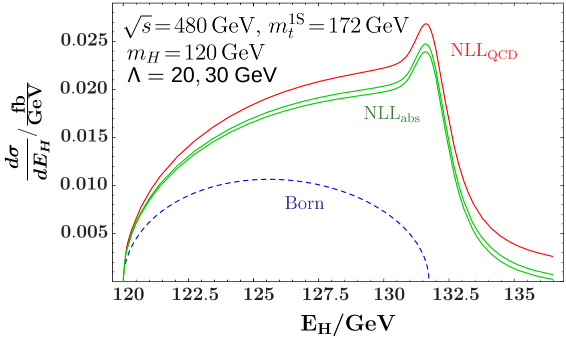
Electroweak Effects
Results



Numerical effect: 10-15%

CS goes to zero above threshold

Conclusion

- Top Yukawa coupling for test of EWSB
- ILC at 500 GeV: Phase space is non-relativistic $\Rightarrow$ vNRQCD
- Completed:
  - Strong and electroweak matching conditions at $\mathcal{O}(NLL)$
  - Effects of e^+e^- polarization
  - Formula for the total cross section
  - Electroweak NLL decay effects
  - Phase space matching
- Increase of total cross section of up to 400%
  - $\delta Y_t / Y_t \approx 10 - 15\%$ might be possible