Why is ILC so important for top physics ?

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ILC Workshop
Valencia, November 7, 2006
[In Memory of Pedro Pascual]

(with the collaboration of J.A. Aguilar-Saavedra)

Outlook

Why is the top quark important?

The effect of new physics at high scales can be described with an effective Lagrangian involving the SM fields

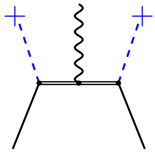
$$\mathcal{L}^{eff} = \mathcal{L}_4 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \ldots$$

$\mathcal{L}_4$		$\rightarrow$	SM Lagrangian
$\mathcal{L}_5$?		$\rightarrow$	Forbidden, if B and L conserved
$\mathcal{L}_6$	$=$	$\sum_x \alpha_x \mathcal{O}_x +$ h.c.	Corrections from scale Λ
$\mathcal{O}_x$		$\rightarrow$	81 operators (up to flavour indices)

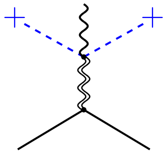
[Buchmüller, Wyler '86]

Top quark heavy ☞ Larger effects expected in its couplings

New physics contributions to top couplings (I)

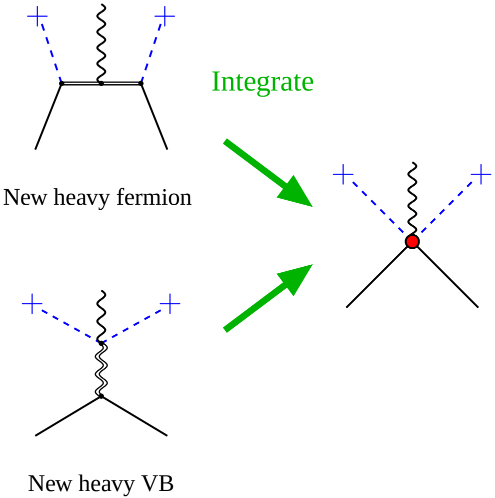


New heavy fermion



New heavy VB

New physics contributions to top couplings (I)



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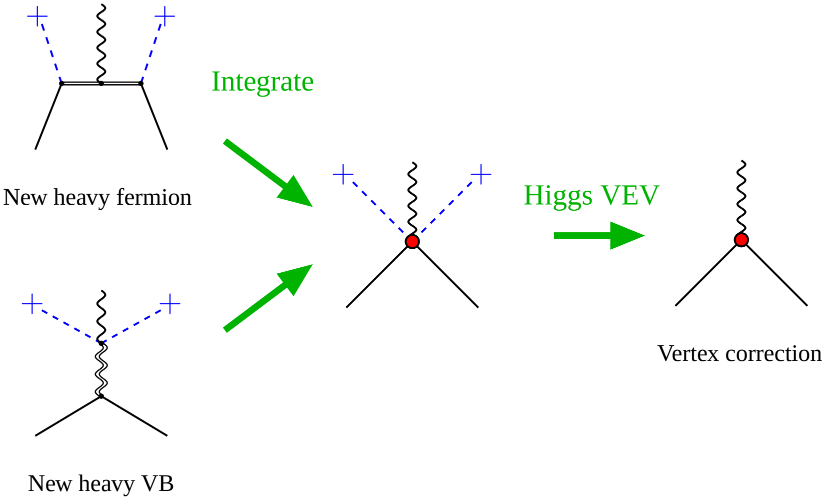
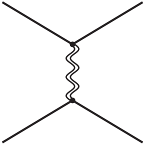


New physics contributions to top couplings (II)



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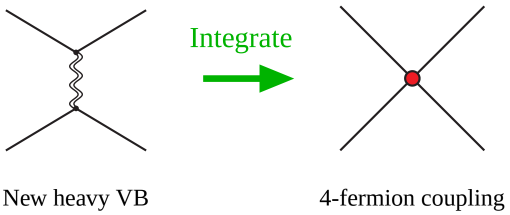
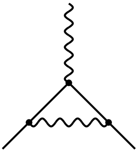
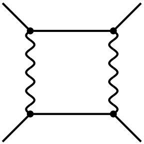


New physics contributions to top couplings (III)

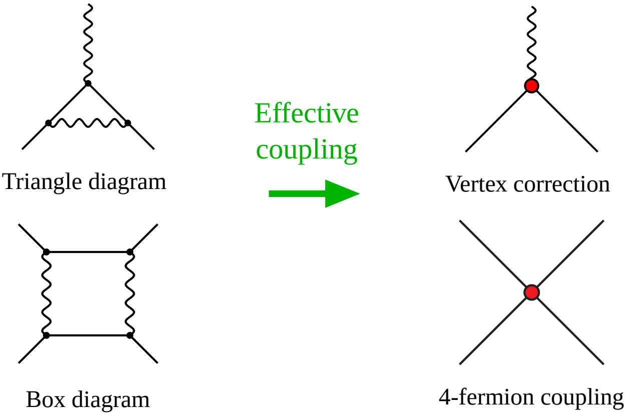


Triangle diagram



Box diagram

New physics contributions to top couplings (III)



Example: corrections from heavy fermion exchange

7 (out of 81) dimension six operators generated

6 contribute to top couplings [del Aguila et al. '00]

$$\mathcal{L}_Z = -\frac{g}{2c_W}\left(\bar{u}_L X^{uL}\gamma^\mu u_L + \bar{u}_R X^{uR}\gamma^\mu u_R - 2s_W^2 J_{\rm EM}^\mu\right) Z_\mu$$

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}}\left(\bar{u}_L W^L\gamma^\mu d_L + \bar{u}_R W^R\gamma^\mu d_R\right) W_\mu^+ + \text{h.c.}$$

$$\mathcal{L}_H = -\frac{1}{\sqrt{2}}\bar{u}_L Y^u u_R + \text{h.c.}$$

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$$X^{uL}_{ij} = \delta_{ij} - \frac{v^2}{\Lambda^2} V_{ik} (\alpha^{(1)}_{\phi q} - \alpha^{(3)}_{\phi q})_{kl} V^{\dagger}_{lj}$$

$$\mathcal{L}_Z = -\frac{g}{2c_W} \left(\bar{u}_L X^{uL} \gamma^\mu u_L + \bar{u}_R X^{uR} \gamma^\mu u_R - 2 s_W^2 J^\mu_{\mathrm{EM}} \right) Z_\mu$$

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$$W_{ij}^L = \tilde{V}_{ik}\delta_{kj} + \frac{v^2}{\Lambda^2}\tilde{V}_{ik}(\alpha_{\phi q}^{(3)})_{kj}$$

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}}\left(\bar{u}_L W^L\gamma^\mu d_L + \bar{u}_R W^R\gamma^\mu d_R\right) W_\mu^+ + \mathrm{h.c.}$$

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$$Y^u_{ij} = \delta_{ij}\lambda^u_j - \frac{v^2}{\Lambda^2}\left(V_{ik}(\alpha_{u\phi})_{kj} + \frac{1}{4}\delta_{ij}[V_{ik}(\alpha_{u\phi})_{kj} + (\alpha_{u\phi})^\dagger_{ik}V^\dagger_{kj}]\right)$$

$$\mathcal{L}_H = -\frac{1}{\sqrt{2}}\bar{u}_L Y^u u_R + \mathrm{h.c.}$$

So, why is the top quark important?

Measure top quark couplings ☞ clean window for new physics

- Wtb, Ztt: sizeable corrections $\sim m_t^2/m_T^2$ with new fermions
- FCN top couplings = new physics (tiny in SM)
- Yukawa coupling: test EWSB… after Higgs discovery!
- New scalars: larger coupling to top quark

Measure top mass precisely ☞ *cleanse* window for new physics

- Where top quark loop contributions important: reduce uncertainty!

And investigate top production processes

- New physics coupling to top may appear in m_{tt} distribution

Top quark properties

Quantum numbers	charge spin isospin	Other
Lagrangian parameters	mass SM couplings: Wtb, Ztt, gtt, γtt, Htt Wtd, Wts BSM couplings: Ztq, gtq, γtq, Htq $(q = u, c)$	width $t\bar{t}$ xsec $t\bar{t}$ spin correlations Single t xsec Single t polarisation Rare decays

The top quark: overview

★ Indirect data constrain the top quark to be rather SM-like

- But indirect constraints $\neq$ measurements
- And there is large room for new physics, anyway

★ Measurements at Tevatron limited by statistics

★ LHC statistics excellent, but large systematics

- Example: single top 10% [CMS TDR]
- Example: $t\bar{t}H$ 26% [CMS TDR]

★ ILC systematics expected smaller, but beware:

- Likely, systematics will determine precision too
- It may take work to obtain precise measurements

Precise measurements at Tevatron

- charge

  $Q = -4/3$ excluded at 92% CL [D0 '06]

- mass

  $m_t = 171.4 \pm 1.2$ (stat) ± 1.8 (sys) GeV [CDF+D0 '06]

  SM fit: $m_t = 172.3^{+10.2}_{-7.6}$ GeV, $m_H = 89^{+38}_{-28}$ GeV [PDB '06]

- $t\bar{t}$ xsec

  $\sigma = 7.3 \pm 0.5$ (stat) ± 0.7 (sys) pb ($m_t = 175$ GeV) [CDF '06]

  $\sigma = 7.5 \pm 0.9$ pb ($m_t = 172$ GeV) [CDF '06]

  SM prediction (172 GeV): $\sigma = 7.4^{+0.9}_{-1.0}$ pb [Cacciari et al. '04]

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V_{tb} coupling at Tevatron

- Single top not yet observed (0.7 fb^{-1}) [CDF '06]

  $\sigma_{s-\mathrm{ch}} = 0.3^{+2.2}_{-0.3}$ (stat) $^{+0.5}_{-0.3}$ (sys) pb ☞ $\sigma_{s-\mathrm{ch}} \leq 3.2$ pb (95% CL)

  $\sigma_{t-\mathrm{ch}} = 0.6^{+1.9}_{-0.6}$ (stat) $\pm\, 0.1$ (sys) pb ☞ $\sigma_{t-\mathrm{ch}} \leq 3.1$ pb (95% CL)

- $\mathrm{Br}(t \to Wb)/\mathrm{Br}(t \to Wq)$ measured

  ☞ $R \equiv \frac{|V_{tb}|^2}{|V_{td}|^2+|V_{ts}|^2+|V_{tb}|^2} = 1.03^{+0.19}_{-0.17}$ [D0 '06]

  (not a direct measurement of V_{tb})

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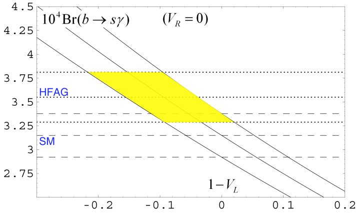
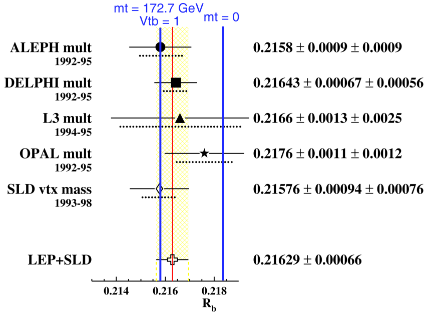
Indirect limits on V_{tb}

- CKM unitarity – if 3×3!
- R_b
- $b \longrightarrow s\gamma$, $\Delta m_B \ldots$



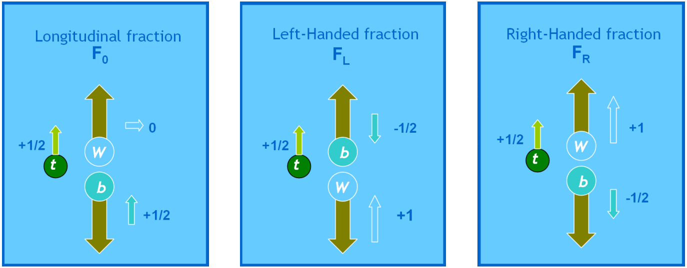
[Misiak, '06]



[LEP EWWG, '05]

Wtb coupling at Tevatron

Non-standard *Wtb* couplings → *W* helicity fractions



SM: $F_0 = 0.703$ $F_L = 0.297$ $F_R = 0.00036$

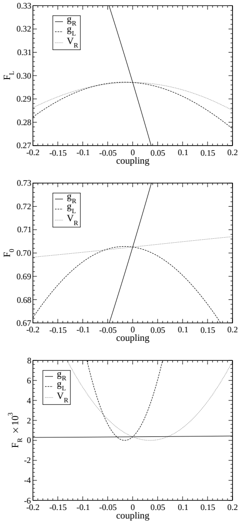
NLO: $F_0 = 0.693$, $F_L = 0.305$, $F_R = 0.0015$ [Do et al., PRD '02]
(small effect even for LHC precision)

Wtb coupling at Tevatron

Most general (on-shell) *Wtb* vertex

$$\begin{aligned}\mathcal{L}_{Wtb} &= -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\,(V_L P_L + V_R P_R)\,t\,W_{\mu}^{-} \\ &\quad -\frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\,(g_L P_L + g_R P_R)\,t\,W_{\mu}^{-} + \text{h.c.}\end{aligned}$$

Anomalous couplings V_R, g_L, g_R ☞ deviations in F_L, F_0, F_R

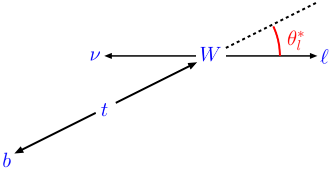


Measurement of W helicity fractions

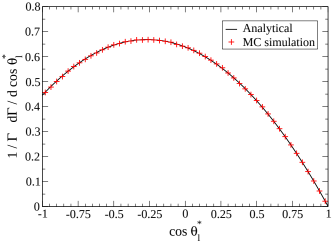
ℓ distribution in W rest frame

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell^*} = \frac{3}{8}(1-\cos\theta_\ell^*)^2\, F_L + \frac{3}{4}\sin^2\theta_\ell^*\, F_0 + \frac{3}{8}(1+\cos\theta_\ell^*)^2\, F_R$$

▸ m_{bl}

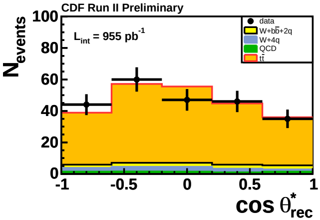


SM prediction (MC LO)



CDF 955 pb^{-1}

[Chwalek et al. (CDF), '06]



Measurement of W helicity fractions

One-parameter fit to experimental data [Chwalek et al. (CDF), '06]

Assuming $F_R = 0$ ➜ $F_0 = 0.59 \pm 0.12\ (\text{stat})^{+0.07}_{-0.06}\ (\text{sys})$

Assuming $F_0 = 0.7$ ➜ $F_R = -0.03 \pm 0.06\ (\text{stat})^{+0.04}_{-0.03}\ (\text{sys})$

- ★ No useful limits on anomalous couplings yet
- ★ Precision dominated by statistics
  - ☞ will be greatly improved at LHC
- ★ Systematics reduced with other observables: helicity ratios and asymmetries
- ★ Important measurement: constrain new physics in top decays in order to search for new physics in production

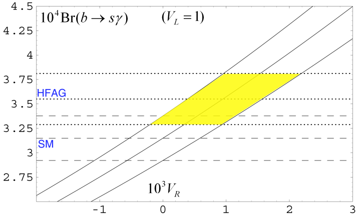
Note: indirect limits on *Wtb* couplings

Indirect limits from $b \to s\gamma$

Constraint: $V_R + 20V_R^2 \sim \pm 10^{-3}$

[Larios et al., ’99]

- ★ Indirect limit $\neq$ measurement
  Assumes no other new physics
- ★ Two regions allowed
  - $V_R \simeq -0.05$ (cancellation)
  - $V_R \sim \pm 10^{-3}$
- ★ First region excluded at 90% CL by LHC (see later)



[Misiak, ’06]

Top quark properties — after Tevatron

Quantum numbers	charge spin isospin	**Other** width $t\bar{t}$ xsec $t\bar{t}$ spin correlations Single t xsec Single t polarisation Rare decays
Lagrangian parameters	mass SM couplings: Wtb Ztt gtt γtt Htt Wtd Wts BSM couplings: Ztq gtq γtq Htq $(q = u, c)$	

Precise measurements at LHC

- mass

  $\Delta m_t \simeq 1$ GeV combining several channels [CMS TDR]
  (stat $\oplus$ sys, dominated by systematics)

- V_{tb}

  Single top: $\Delta\sigma_{t-\mathrm{ch}}/\sigma_{t-\mathrm{ch}} = 10\%$ [CMS TDR]
  (3% stat $\oplus$ 4% th $\oplus$ 5% sys $\oplus$ 5% lum)

  ☞ $\Delta V_{tb}/V_{tb} = 5\%$

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Wtb anomalous couplings at LHC

Precision dominated by systematics

already for 10 fb^{-1} See

New observables ☞ smaller sys.

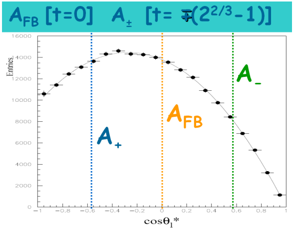
[Aguilar-Saavedra et al., '06]

- Helicity ratios $\rho_{R,L} \equiv F_{R,L}/F_0$

  extracted from fit to $\cos\theta_\ell^*$ distribution

- Angular asymmetries

$$A_t = \frac{N(\cos\theta_\ell^* > t) - N(\cos\theta_\ell^* < t)}{N(\cos\theta_\ell^* > t) + N(\cos\theta_\ell^* < t)}$$



$t = 0$ ☞ A_{FB}

$t = -(2^{2/3} - 1)$ ☞ A_+

$t = (2^{2/3} - 1)$ ☞ A_-

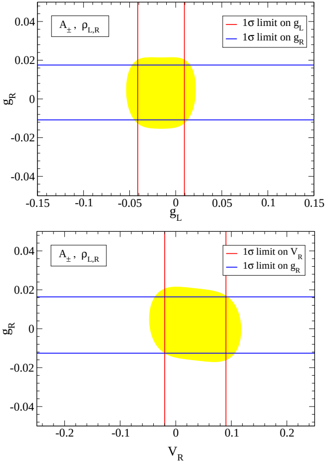
Combined limits up to 3.2× better than from F_L, F_0, F_R

Wtb anomalous couplings at LHC

Combination of $A_\pm$, $\rho_{R,L}$

- Limits $2-4\%$ on anomalous couplings already for 10 fb^{-1}
- More observables required to rule out cancellations
- Overall scale (V_{tb}) uncertainty $\sim 5\%$

  ☞ ILC measurement of V_{tb} required!



[Aguilar-Saavedra et al., ATL–COM ’06]

Measurement of Ztt, γtt couplings at LHC

Ztt vertex

$$\mathcal{L}_{Ztt} = -\frac{g}{2c_W}\bar{t}\,\gamma^\mu \left(X_{tt}^L P_L + X_{tt}^R P_R - \frac{4}{3}s_W^2 \right) t\, Z_\mu - \frac{g}{2c_W}\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(g_L^Z P_L + g_R^Z P_R\right) t\, Z_\mu$$

SM: $X_{tt}^L = 1$
rest: zero

γtt vertex

$$\mathcal{L}_{\gamma tt} = -e\,\bar{t}\,\gamma^\mu \left(Q_t + Q_t^A \gamma_5\right) t\, A_\mu - e\,\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{m_t}\left(g_V^\gamma + g_A^\gamma \gamma_5\right) t\, A_\mu$$

SM: $Q_t = 2/3$
rest: zero

Measurement of Ztt, γtt couplings at LHC

Processes: $t\bar{t}Z$ and $t\bar{t}\gamma$ (parton-level analysis) [Baur et al., ’05, ’06]

$\Delta X_{tt}^L, \Delta X_{tt}^R \simeq 0.13 \oplus \Delta\,(\text{sys})$

$\Delta Q_t \simeq 0.05 \oplus \Delta\,(\text{sys})$ ☞ Complement jet charge measurement

Limits poorer on rest of couplings

- ★ Limits obtained for 300 fb^{-1}
- ★ Limits include 30% xsec uncertainty
- ★ Sys. expected $\gtrsim$ 5% from Wtb analysis
  (perhaps optimistic: harder environment in high luminosity phase)

Top Yukawa coupling at LHC

Top Yukawa coupling in $t\bar{t}H$ production

Old estimates: precision $\Delta\lambda_t/\lambda_t = 12 - 15\%$ [Weiglein et al., '04]

Most recent calculations: $t\bar{t}H$, $H \to b\bar{b}$ will not be seen:
significance 0.75σ for $m_H = 115$ GeV and 60 fb^{-1} [CMS TDR]

Main reason: $t\bar{t}nj$ background larger than expected See

$t\bar{t}H, H \to \gamma\gamma$ ➜ $\Delta\lambda_t/\lambda_t \simeq 20\% \oplus \Delta\sigma\,(\mathrm{sys})/2$
(significance extracted from data in [CMS TDR])

$t\bar{t}H, H \to W^+W^-$ not likely to be useful

Spin correlations in $t\bar{t}$ production

Top quarks (almost) unpolarised in $t\bar{t}$ production but with spins correlated

$$C \equiv \frac{\sigma(t_R\bar{t}_R) + \sigma(t_L\bar{t}_L) - \sigma(t_R\bar{t}_L) - \sigma(t_L\bar{t}_R)}{\sigma(t_R\bar{t}_R) + \sigma(t_L\bar{t}_L) + \sigma(t_R\bar{t}_L) + \sigma(t_L\bar{t}_R)} \simeq 0.326$$

[Bernreuther et al,. NPB ’04]

LHC precision: $\Delta C = 0.024$ [Hubaut et al., EPJC ’05]

Spin correlations may allow to:

- Detect non-standard gtt couplings
- Determine parity of a resonance decaying to $t\bar{t}$

after anomalous Wtb couplings constrained with other observables

Top quark properties after LHC

Quantum numbers	charge spin isospin	Other
Lagrangian parameters	mass SM couplings: Wtb Ztt gtt γtt Htt Wtd Wts BSM couplings: Ztq gtq γtq Htq $(q = u, c)$	width $t\bar{t}$ xsec $t\bar{t}$ spin correlations Single t xsec Single t polarisation Rare decays

Precise measurements at ILC

Top mass and width measurements

Threshold scan at $\sqrt{s} \simeq 2m_t$ (fast sim.) [Martinez, Miquel, EPJC '03]

Observables: $\left[\begin{array}{l} \sigma \\ \text{Peak of } |\vec{p}| \text{ distribution} \\ \text{FB asymmetry} \end{array}\right.$ ☞ extract m_t, Γ_t, λ_t

$\Delta m_t = 19$ MeV	$\Delta\Gamma_t = 32$ MeV	$\Delta\alpha_s = 0.0012$	$\Delta\sigma$ (th) $= 3\%$ λ_t known or H heavy
$\Delta m_t = 31$ MeV	$\Delta\Gamma_t = 34$ MeV	$\Delta\lambda_t/\lambda_t = ^{+0.35}_{-0.65}$	$\Delta\sigma$ (th) $= 1\%$ $\Delta\alpha_s = 0.001$ known

$m_t = 1S$ mass (convertible to $\overline{\text{MS}}$ mass)

Precise measurements at ILC

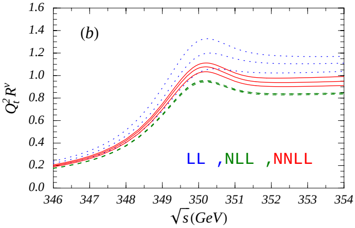
Goal: $\Delta\sigma_{t\bar{t}}$ (th) $= 3\%$ ☞ Excellent experimental precision requires small theoretical uncertainties

$t\bar{t}$ pair at threshold: non-relativistic, velocity $v = \sqrt{1 - 4m_t^2/s} \ll 1$

Multi-gluon diagrams: contributions $\propto (\alpha_s/v)^n$, $(\alpha_s \log v)^n$ must be summed

Electroweak corrections have same size

Present theoretical uncertainty: 6%



[Hoang et al., PRD ’02]
[Hoang, APPB ’03]

V_{tb} measurement at ILC

- $e^+e^- \to tW^-\bar{b}$ below $t\bar{t}$ threshold [Batra, Tait, PRD '06]

  $\Delta V_{tb}/V_{tb} \simeq 4.2\% \oplus \Delta\sigma\,(\text{sys})/2$ (for $\Delta\Gamma_t = 50$ MeV)

- $e\gamma \to \nu\bar{t}b$ at 500 GeV [Boos et al., EPJC '01]

  $\Delta V_{tb}/V_{tb} \simeq 1\% \oplus \Delta\sigma\,(\text{sys})/2$

★ ISR, beamstrahlung, beam spread not included

★ Systematic uncertainties $\Delta\sigma\,(\text{sys}) = 5\%$? (LHC 10%)

★ e^+e^- not likely to improve LHC measurement

★ $e\gamma$ measurement limited by systematics ☞ NNLO?

Measurement of Ztt, γtt couplings at ILC

Process: $e^+e^- \longrightarrow t\bar{t}$

Fast simulation [Abe et al., '01]

$\Delta X_{tt}^L, \Delta X_{tt}^R \simeq 0.02 \oplus \Delta\,(\text{sys})$

$\Delta Q_t \simeq 0.05 \oplus \Delta\,(\text{sys})$ (same as LHC)

- ★ Limits assume all other anomalous couplings zero
- ★ Good precision for Z: requires good theoretical predictions

Measurement of Ztt, γtt couplings at ILC

General model-independent analysis challenging:

- Production involves exchange of Z, γ $(4+4$ couplings$)$
- Decay $t \longrightarrow Wb$ invoves 4 couplings too

Strategy:

- Use LHC bounds on anomalous Wtb couplings (likely, much more stringent)
- Use information from $t\bar{t}\gamma$ at LHC (similar precision expected)
- Analyse various CM energies to disentangle γ^μ and $\sigma^{\mu\nu}q_\nu$

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→ LHC–ILC complementarity

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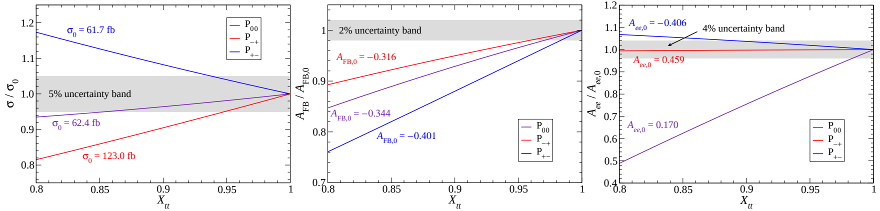
LHC–ILC complementarity

Example: X_{tt}^L dependence of observables

Total xsec — FB asymmetry — Sample spin asymmetry



- ★ Statistical errors $\lesssim 0.5\%$ for $L = 1000$ fb^{-1} and any beam polarisation
- ★ Reasonable (?) systematic errors: $\Delta\sigma/\sigma = 5\%$ $\quad \Delta A_{\text{FB}}/A_{\text{FB}} = 2\%$ $\quad \Delta A_{ee}/A_{ee} = 4\%$
- ★ Precision $\Delta X_{tt}/X_{tt} \simeq 0.02$ for P_{00} or P_{+-}
- ★ A_{ee} very sensitive for P_{00}

☞ Use LHC input on anomalous *Wtb* couplings

Top Yukawa coupling measurement at ILC

Light Higgs ☞ $t\bar{t}H$ not seen at LHC
λ_t must be measured at ILC

For $m_H \lesssim 120$ GeV ➜ Small phase space for $t\bar{t}H$ at 500 GeV

Non-relativistic effects large: xsec $\sim 2\times$ larger than LO

[Hoang, Farrell, PRD '06]

For 1000 fb^{-1} $\Delta\lambda_t/\lambda_t \simeq 15\% \oplus \Delta\sigma\,(\text{sys})/2$ (fast simulation)

[Juste '06]

- ★ Additional improvement with beam polarisation
- ★ ILC $\neq$ LHC but… Beware $t\bar{t}nj$!

FCNC in top sector

Expectations and LHC precision

	SM	QS	2HDM	MSSM	$\not R$ SUSY	LHC
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	2×10^{-6}	3×10^{-5}	4.7×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	2×10^{-6}	1×10^{-6}	1.7×10^{-5}
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	8×10^{-5}	2×10^{-4}	in progress
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	10^{-5}	$\sim 10^{-6}$	

ILC: single FCNC top production $e^+e^- \to t\bar{q}$

Again, LHC–ILC complementarity

- ★ Likely, ILC with polarised beams more sensitive to γtc and Ztc of $\sigma^{\mu\nu}$ type
- ★ LHC low efficiency for c tagging, better at ILC
- ★ ILC does not disentangle Z, γ couplings, LHC does

Top quark properties — after ILC

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Example I

New quark singlet T

- Present limit: $m_T \geq 258$ GeV

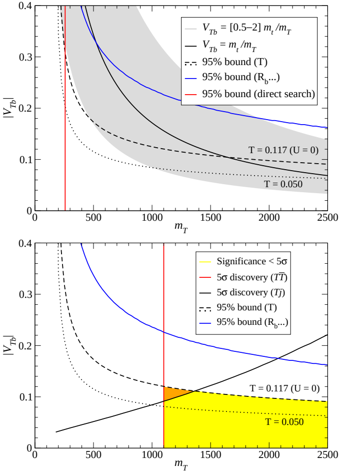
$$\longrightarrow \left[\begin{array}{lr} V_{Tb} \leq 0.31 & (0.46) \\ V_{tb} \geq 0.95 & (0.89) \\ X_{tt}^L \geq 0.91 & (0.79) \end{array} \right.$$

- LHC does not see it: $m_T \geq 1.3$ TeV

$$\longrightarrow \left[\begin{array}{lr} V_{Tb} \leq 0.11 & (0.16) \\ V_{tb} \geq 0.994 & (0.987) \\ X_{tt}^L \geq 0.988 & (0.974) \end{array} \right.$$

ILC precision $\Delta X_{tt}/X_{tt} \lesssim 1\%$ required

Δ (stat) $= 0.5\%$, reduce systematics!



[Aguilar-Saavedra, PLB '05]

Example II

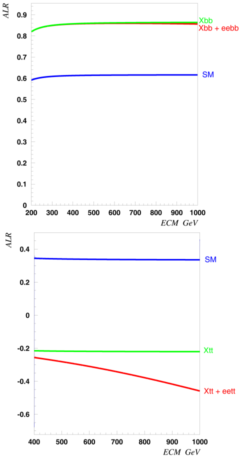
New gauge bosons

Large effects in

$$A_{LR} = \frac{\sigma(e^+_L e^-_R) - \sigma(e^+_R e^-_L)}{\sigma(e^+_L e^-_R) + \sigma(e^+_R e^-_L)}$$

$\Delta A_{LR}/A_{LR} \simeq 0.1\% \oplus \Delta$ (sys) for 1000 fb^{-1}

Δ (sys) $= 1 - 2\%$?



[Djouadi et al., ’06]

Example III

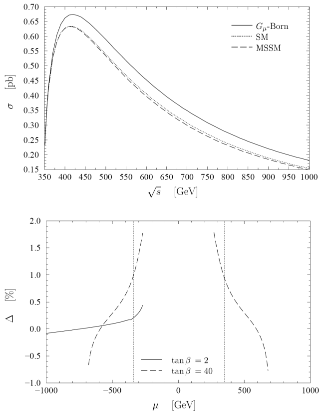
SUSY

Assume worst scenario:

SUSY not seen at ILC

☞ effects $\lesssim 2\%$ in $\sigma(e^+e^- \to t\bar{t})$

Need more precision (or new observables) to see heavy SUSY indirect effects



[Guasch et al., '00]

Summary

Precision expected

	Tevatron	LHC	ILC
m_t	2.2 GeV	1 GeV	$\lesssim$ 50 MeV
V_{tb}	–	0.05	$\lesssim 0.02^*$?
Wtb anom	–	0.02 – 0.04	?
X_{tt}	–	≥ 0.13	0.02
Q_t	–	≥ 0.05	≥ 0.05
λ_t	–	–	≥ 0.15
Γ_t	–	–	$\lesssim$ 50 MeV

* $e\gamma$ collisions

Alternative: m_{bl} distribution

$$m_{bl}^2 \simeq \frac{m_t^2 - M_W^2}{2}(1 + \cos\theta_\ell^*)$$

☞

- measure F_0, F_L, F_R for known m_t
- measure m_t for SM values of F_0, F_L, F_R (m_t in final states $b \to J/\Psi \to \ell\ell$) [CMS TDR]

Back

Angular distributions and asymmetries at LHC

Statistical and systematic errors

F_0	0.699	± 0.004 (stat)	± 0.020 (sys)	2.9%
F_L	0.299	± 0.004 (stat)	± 0.019 (sys)	6.4%
F_R	0.0021	± 0.0030 (stat)	± 0.0033 (sys)	–
ρ_L	0.4274	± 0.0080 (stat)	± 0.0356 (sys)	8.3%
ρ_R	0.0004	± 0.0021 (stat)	± 0.0016 (sys)	–
$A_{\rm FB}$	-0.2231	± 0.0035 (stat)	± 0.0130 (sys)	5.8%
A_+	0.5472	± 0.0032 (stat)	± 0.0099 (sys)	1.8%
A_-	-0.8387	± 0.0018 (stat)	± 0.0028 (sys)	0.33%

Back Next

Angular distributions and asymmetries at LHC

Source	F_0	F_L	F_R	ρ_L	ρ_R	A_{FB}	A_+	A_-
MC generator	0.0018	0.0014	0.0004	0.0006	0.0000	0.0035	0.0015	0.0006
PDFs	0.0045	0.0017	0.0027	0.0046	0.0008	0.0021	0.0005	0.0014
Top mass	0.0065	0.0060	0.0006	0.0124	0.0007	0.0034	0.0039	0.0005
ISR+FSR	0.0142	0.0131	0.0011	0.0218	0.0001	0.0046	0.0049	0.0011
b tag eff.	0.0080	0.0069	0.0011	0.0126	0.0003	0.0039	0.0046	0.0004
E_b scale	0.0019	0.0024	0.0004	0.0061	0.0002	0.0021	0.0017	0.0005
E_j scale	0.0030	0.0038	0.0005	0.0074	0.0002	0.0038	0.0023	0.0014
Back.	0.0002	0.0000	0.0002	0.0001	0.0000	0.0001	0.0000	0.0001
Pile-up	0.0087	0.0084	0.0003	0.0175	0.0002	0.0080	0.0051	0.0006
b frag.	0.0012	0.0015	0.0004	0.0078	0.0011	0.0045	0.0000	0.0012
Total Δsys.	0.0206	0.0188	0.0033	0.0356	0.0016	0.0130	0.0099	0.0028

Back

Effect of higher orders in $t\bar{t}H$

$t\bar{t}H$ ($\to \ell\nu bbbbjj$) and main backgrounds at pre-selection $\ell = e, \mu$

	σ	N	ε (%)		σ	N	ε (%)
$t\bar{t}H$	118.7 fb	166.0	4.6	$t\bar{t}3j$	54.0 pb	1900	0.12
$t\bar{t}$	143.2 pb	1475	0.034	$t\bar{t}4j$	27.4 pb	1195	0.15
$t\bar{t}j$	142.7 pb	2370	0.055	$t\bar{t}5j$	12.8 pb	$1067^{(k)}$	0.19
$t\bar{t}2j$	95.9 pb	2443	0.085	$t\bar{t}b\bar{b}$	564.9 fb	1648	4.7

$N = \#$ events $\quad \varepsilon \equiv N/N_{\text{gen}} =$ eff. [Aguilar-Saavedra, '06]

ε grows with n (larger b mistag probability)

nj by PYTHIA ➔ $\sigma = 138.7$ fb $\quad N = 2076 \quad \varepsilon = 0.050\%$

☞
- Full $t\bar{t}nj$ cross section 3.4× larger than $t\bar{t}$+ PYTHIA
- $t\bar{t}nj$ at pre-selection 5.0× larger than $t\bar{t}$+ PYTHIA

Back