VLCW06 (ILC-LHC session), Vancouver, July 19-23, 2006

Top Quark Couplings at Colliders

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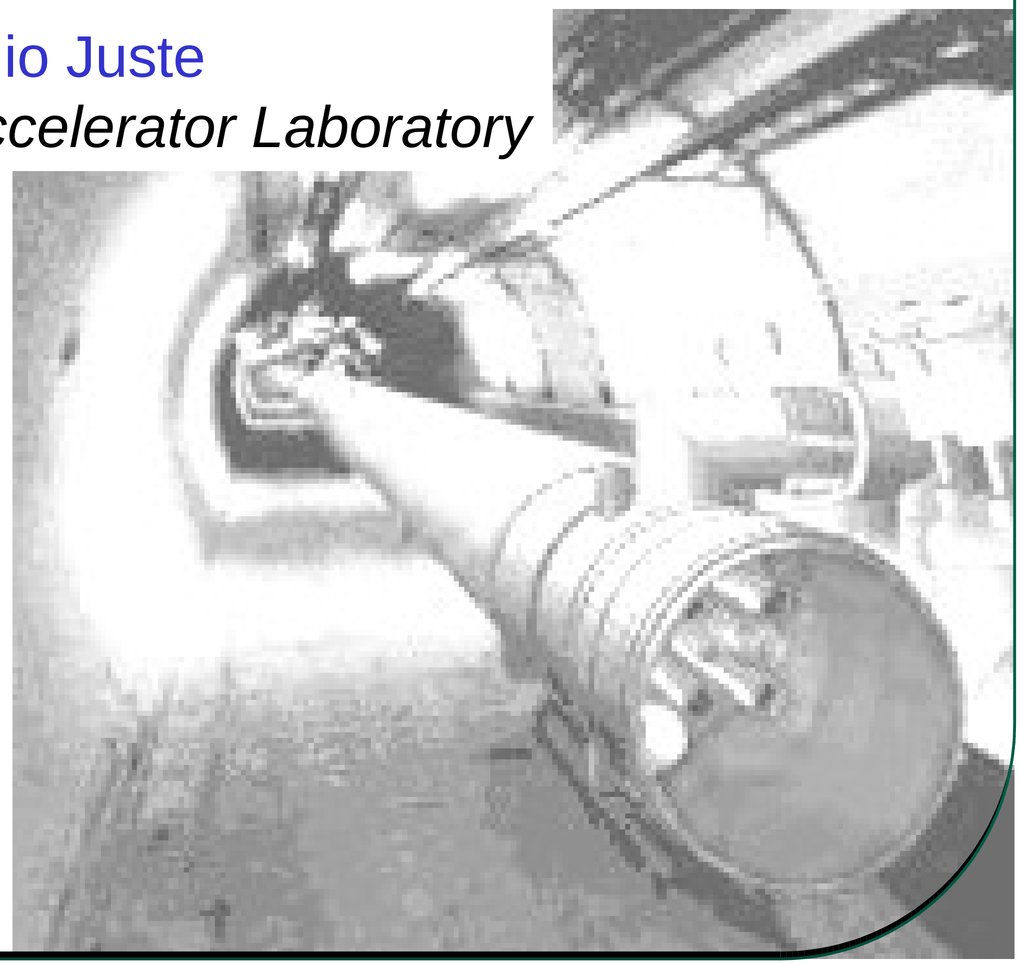
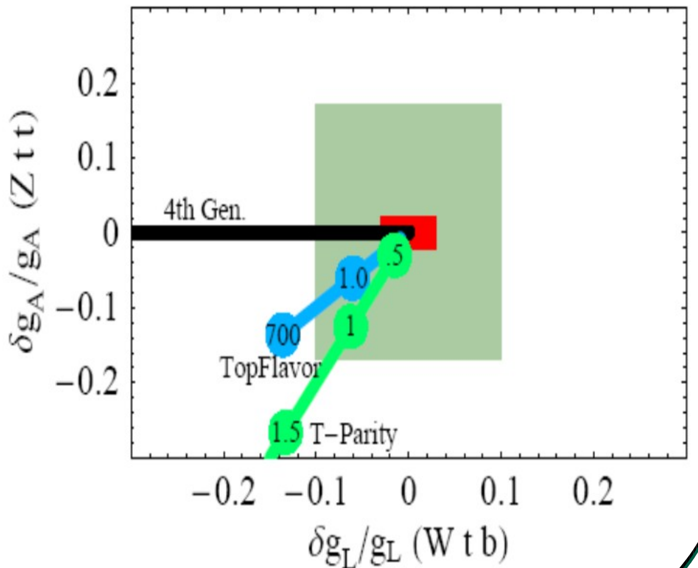


Motivation

- $m_t \sim 175$ GeV $\Rightarrow \lambda_t = \sqrt{2}\, m_t/v \approx 1$
  The top quark may either play a key role in EWSB, or serve as a window to New Physics related to EWSB which might be preferentially coupled to it.
  ⇒The first indication for New Physics might be in the form of modified top quark interactions.
- Anomalous top couplings can manifest themselves affecting many observables:
  - total cross-sections,
  - tt invariant mass distribution,
  - angular distributions of decay products (both tt and single top),
  - rare decays (e.g. flavor-changing neutral current processes),
  - ...
- Many of these observables can be affected by New Physics unrelated to anomalous top quark interactions.
- Different operators can contribute to a given observable.

⇒ Very important to try to disentangle effects and perform cross-checks using different processes

⇒ Analyses must be as model-independent as possible (e.g. allow several couplings to deviate simultaneously)



- A global model-independent analysis combining LHC and ILC measurements has the largest potential to rule/figure out specific models of New Physics.

Top Couplings to Gauge Bosons: g

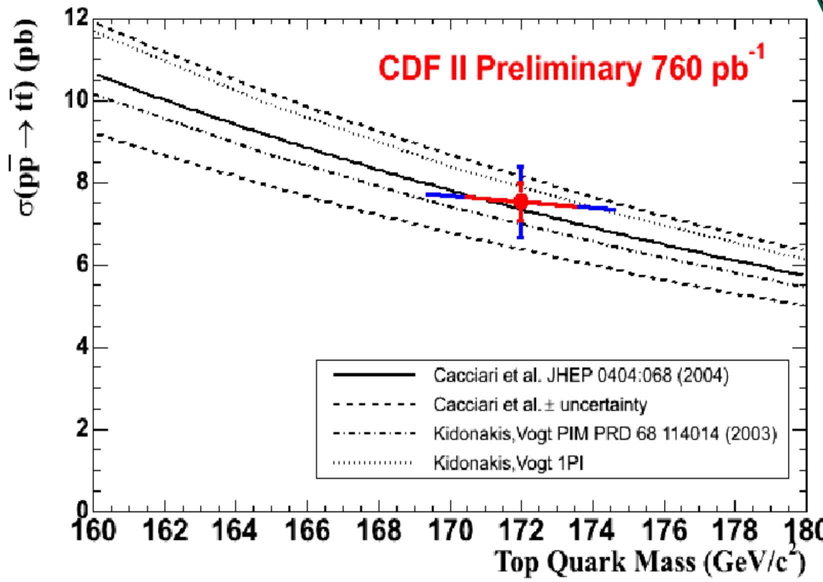
- At hadron colliders, tt production is a direct test of the top coupling to gluons.

  So far Tevatron data is consistent with the SM. However, precision (will be) limited by systematics:

  $\Delta\sigma/\sigma$ (exp) ~ 6.4% (stat) $\oplus$ 7.8%(syst) $\oplus$ 5.7%(lumi) ~ 12%

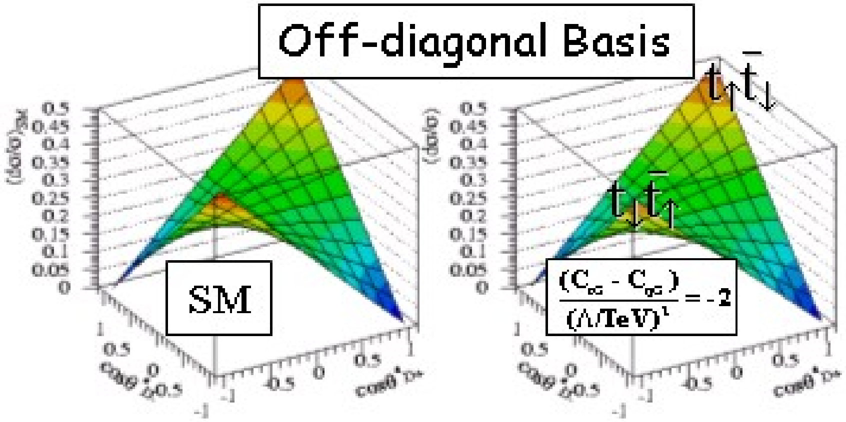
  $\Delta\sigma/\sigma$ (theo) ~ 6.3% (PDF) $\oplus$ 6.5% (scheme) ~ 10%

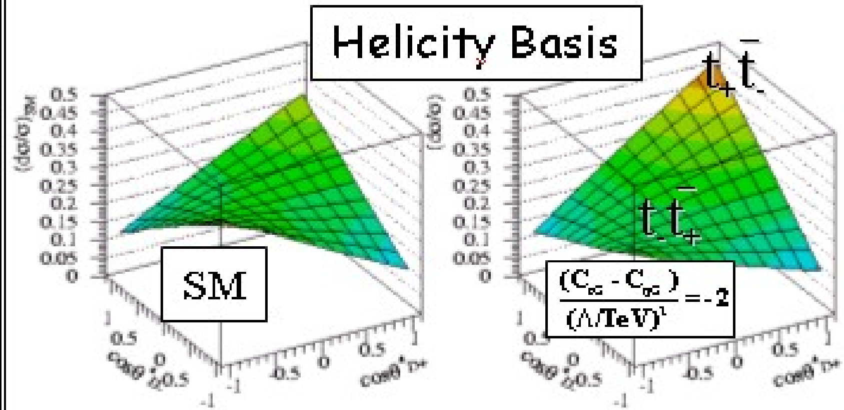
- Must test, not only the effective coupling strength (total rate), but also the presence of a more complicated Lorentz structure. In order to disentangle the effects of the different operators, observables sensitive to different combinations need to be used.



- Correlation between t-t spins can be significantly affected by new Lorentz structures in the g-t-t vertex: make use of weak decays of top to analyze top polarization.
- E.g. axial form factor produces non-zero polarization asymmetry ($N(t_R) \neq N(t_L)$).

Tevatron





Top Couplings to Gauge Bosons: g

- E.g. strong dipole moments from New Physics (e.g. Topcolor, 2HDM,…) can affect the total cross section in addition to other observables (top p_T, spin correlations,…)

$$\mathcal{L} = g_s \bar{t} T_a \left(\gamma_\mu + \frac{i}{2m_t} \sigma_{\mu\nu} (\kappa - i\tilde{\kappa}\gamma_5) q^\nu \right) t G_a^\mu$$

CP-conserving (κ) CP-violating ($\tilde{\kappa}$)

- Some estimates of attainable precision at LHC:

top p_T spectrum (100 fb^{-1}): $|\kappa|<0.05$ @ 95% CL hep-ph/9609311

T_N-odd asymmetry (10 fb^{-1}): $|\tilde{\kappa}|<0.045$ @ 5σ ATL-PHYS-2002-012

- Spin correlation measurements provide additional handles.

$$C = \frac{N_\parallel - N_X}{N_\parallel + N_X}$$

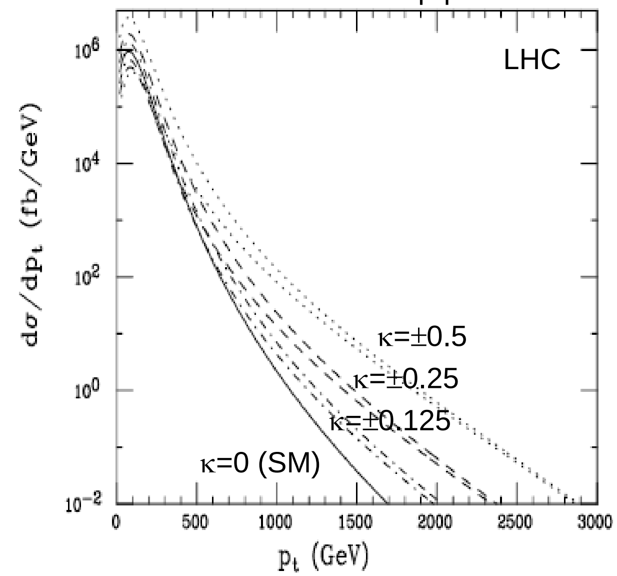
Tevatron: C= -0.4 (helicity), C=-0.8 (off-diagonal)
LHC : C=+0.3 (+0.4 if m_{tt}<550 GeV) (helicity)

- Tevatron sensitivity study (dileptons; 2x4 fb^{-1})
  C = -0.8 ± 0.3(stat)

- LHC sensitivity study (dileptons + lepton+jets; 10 fb^{-1})
  C = 0.422 ± 0.014(stat) ± 0.023(syst)

- Many of these observables can be distorted by new particles instead of anomalous couplings. Very important to find ways to discriminate among the various possibilities.

hep-ph/9609311



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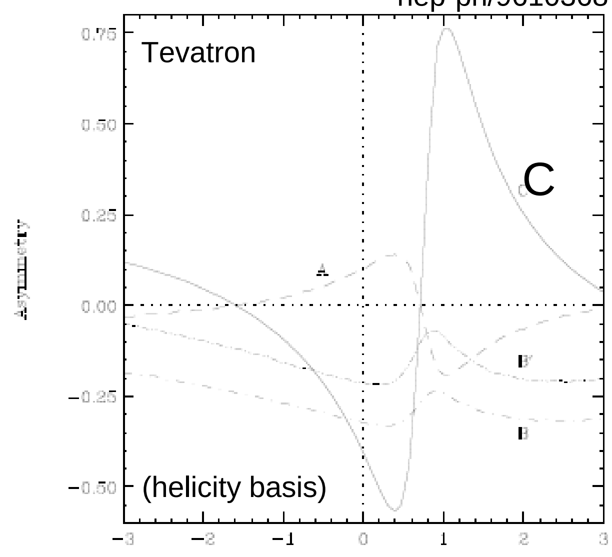
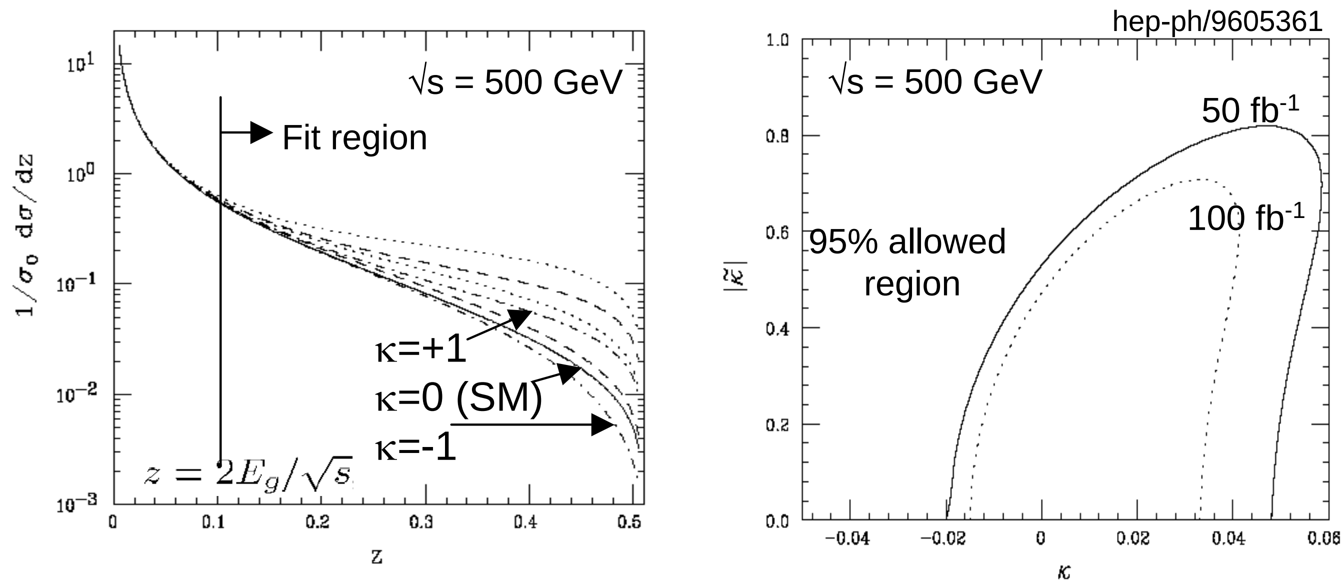


Top Couplings to Gauge Bosons: g

- At the ILC, the main observable explored so far is the energy spectrum of the gluon in $e^+e^- \to t\bar{t}g$.



- Reach in chromo-electric dipole moment ($\tilde{\kappa}$) improves by ~x2 for same integrated luminosity at √s = 1 TeV.
- A-priori it should be possible to find additional observables to increase sensitivity, particularly to the chromo-electric dipole moment.
- Caveat: a global analysis at ILC is needed since the gluon energy spectrum is simultaneously sensitive to electroweak dipole moments (from $tt\gamma$ and ttZ vertices)

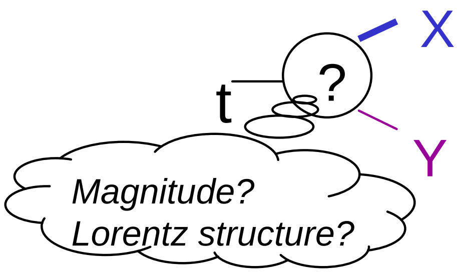
- Nice complementarity between LHC and ILC which should be exploited:
  - LHC more sensitive to chromo-electric dipole moment.
  - ILC more sensitive to chromo-magnetic dipole moment.

Top Couplings to Gauge Bosons: W

- Large m_t ⟺ New Physics (EWSB-related)??

⇒ interactions between the top quark and weak gauge bosons extremely interesting!!

⇒ in a hadron collider only the t-b-W vertex can be sensitively probed



In the SM: X=W 100% of the time, Y=b ~100% of the time ($|V_{tb}|$~1)

$$\Gamma^{\mu}_{tbW} = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^{\mu} \left[f_1^L P_L + f_1^R P_R \right] - \frac{i\,\sigma^{\mu\nu}}{M_W} (p_t - p_b)_{\nu} \left[f_2^L P_L + f_2^R P_R \right] \right\}$$

$f_1^L = \bar{f}_1^L = 1$ with the rest equal to 0 (pure V-A interaction)

If $f_1^{L,R} - \bar{f}_1^{L,R} \neq 0$ *or* $f_2^{L,R} - \bar{f}_2^{R,L} \neq 0 \Rightarrow$ CP-violation

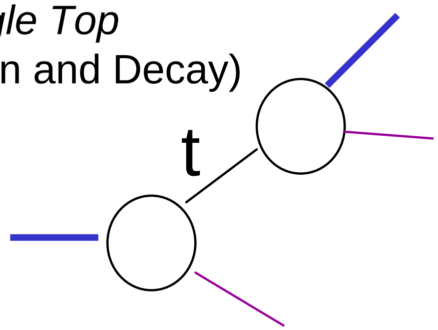
- Relatively stringent indirect constraints (BUT assume no other sources of New Physics):

b→sγ: $|f_1^R|, |f_2^L| < 0.004$ LEP precision data: $|f_1^L| - 1 < 0.02$

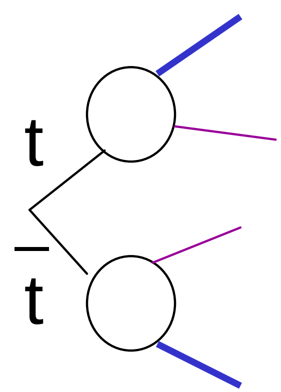
b→sl⁺l⁻: $|f_2^R| < 0.03$

- Charged current interactions <u>define most of the top quark phenomenology</u>:

Single Top
(Production and Decay)



Top Pair
(Decay)



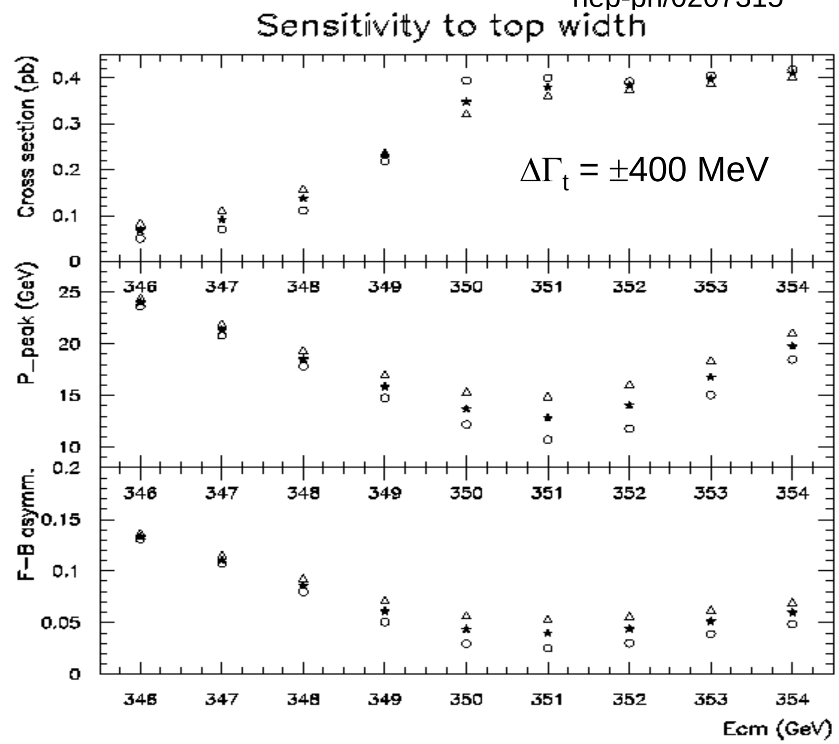
- Top quark width
- Single top quark production rate
- B(t→Wb)
- W helicity in top quark decays
- Top quark polarization
- Anomalous couplings
- Angular (spin) correlations
- Rare decays
- …

Top Quark Width

- In general, there is no easy way to measure the total top quark width in a model independent way.
  e.g. single top cross-section gives $\Gamma(t \to Wb)$.
- Threshold observables in $e^+e^- \to t\bar{t}$ are sensitive to Γ_t:
  - affects peak structure of 1S resonance
  - $p_t^{peak} \uparrow$ as $\Gamma_t \uparrow$ since the top quark decays at shorter distance where the $t\bar{t}$ potential is deeper
  - controls overlap between 1S and 1P states: A_{FB}
- Simultaneous determination of m_t, α_s and Γ_t from fit to threshold observables. Assume 3% theoretical error on σ_{tt} and 9+1 point scan with 30 fb^{-1}/point:
  $\Delta m_t(1S)$=19 MeV, $\Delta\alpha_s$=0.0012, $\Delta\Gamma_t$=32 MeV ,ρ_{ij}<0.5

2% precision!

hep-ph/0207315



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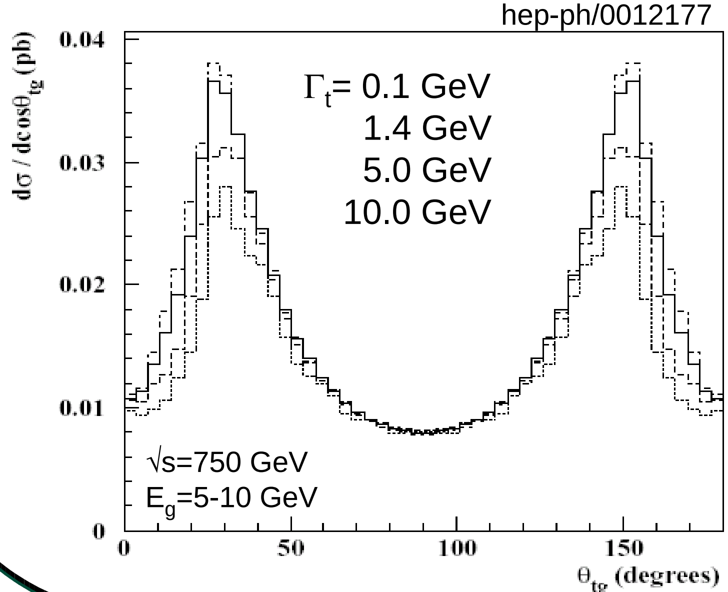
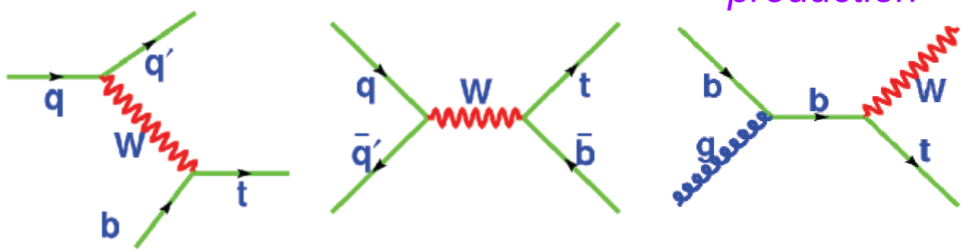


- Large Γ_t leads to interesting effects involving the interplay between the strong and weak interactions: soft gluon ($E_g \sim \Gamma_t$) radiation pattern can be affected by Γ_t.
  - At high energy: production-decay interference dominates
  - Near threshold: decay-decay interference dominates
- No feasibility study available.

Single Top Quark Production

- Main production mechanisms for (SM-like) single top production at a hadron collider:

t-channel   *s-channel*   *associated production*



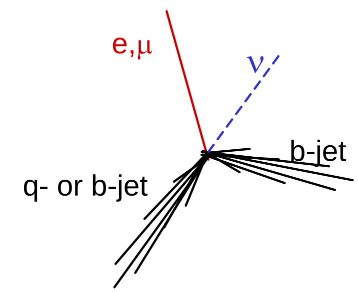
	t-channel	s-channel	associated production
Tevatron:	~1.98 pb	~0.88 pb	~0.09 pb
LHC :	~245 pb	~10 pb	~60 pb

- Experimental signature: similar to tt→lepton+jets but lower jet multiplicity.
- Dominant backgrounds: W+jets, tt

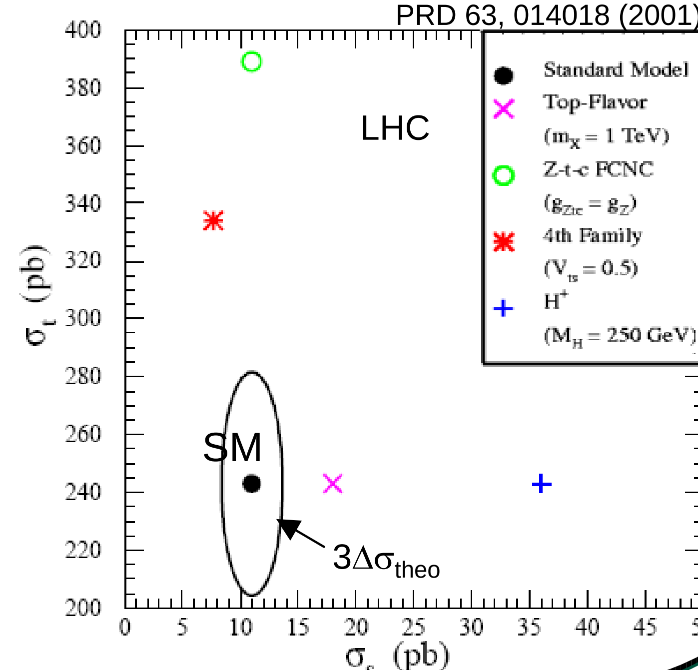
- <u>Motivation</u>:
  - Direct measurement of $|V_{tb}|$ ($\sigma \propto |V_{tb}|^2$)
  - Anomalous couplings in t-b-W vertex
  - s- and t-channels sensitive to different New Physics
  - Top spin physics (~100% polarized top quark)

Not discovered yet

Tevatron Run II upper limits (@ 95% CL):
CDF (695 pb^{-1}): $\sigma_{s(t)} < 3.1(3.2)$ pb, $\sigma_{s+t} < 3.4$ pb
DØ (370 pb^{-1}) : $\sigma_{s(t)} < 5.0(4.4)$ pb



PRD 63, 014018 (2001)



Single Top Quark Production: Projections

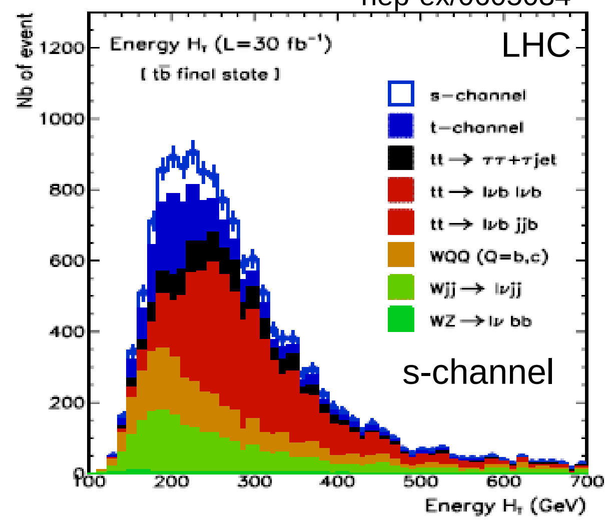
- Tevatron projection for 4 fb^{-1} x 2 experiments (assuming SM):
  S/$\sqrt{B}$ ~ 5σ(3σ) in t-(s-)channel $\Rightarrow (\Delta|V_{tb}|/|V_{tb}|)_{stat}$~9%

- LHC:
  - Much larger σ, better starting S/B than at Tevatron
  - Expectations (CMS, 10 fb^{-1})
    t-channel : Δσ/σ(exp) = 3%(stat) ⊕ 7% (syst) ⊕ 5% (lumi) ~ 9%
    Wt : Δσ/σ(exp) = 6%(stat) ⊕ 16% (syst) ⊕ 5% (lumi)
    s-channel: Δσ/σ(exp) = 18%(stat) ⊕ 31% (syst) ⊕ 5% (lumi)
  - Theoretical uncertainty for <u>inclusive</u> t-channel cross-section: ~4%
    - PDF: +1.3%, -2.2%
    - Scale: 3% PRD 70, 114012 (2004)
    - m_t(±2 GeV): ~1.5%
  - Expected precision on V_{tb} (from t-channel):

$$\frac{\Delta|V_{tb}|}{|V_{tb}|} = \frac{1}{2}\left(\frac{\Delta\sigma^{\exp}}{\sigma^{\exp}} \oplus \frac{\Delta\sigma^{theo}}{\sigma^{theo}}\right) \approx 5\%$$

  - Limits on f_2-type couplings limited to ~0.1-0.2 by systematics on cross section.

hep-ex/0605034



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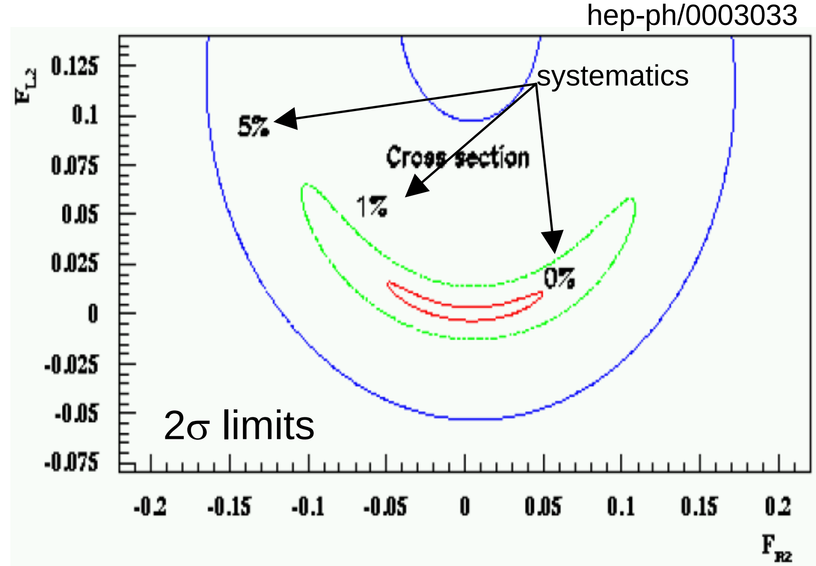
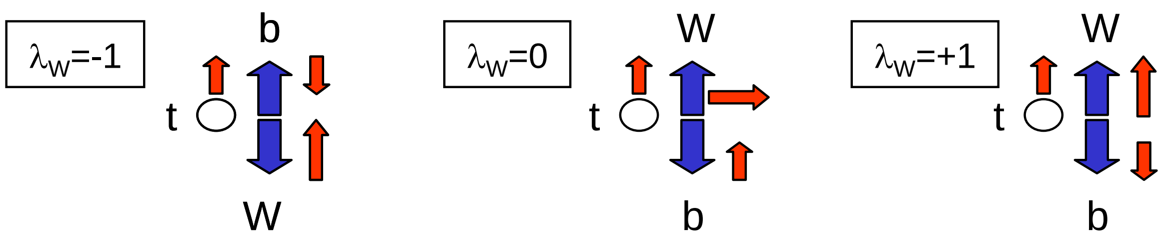
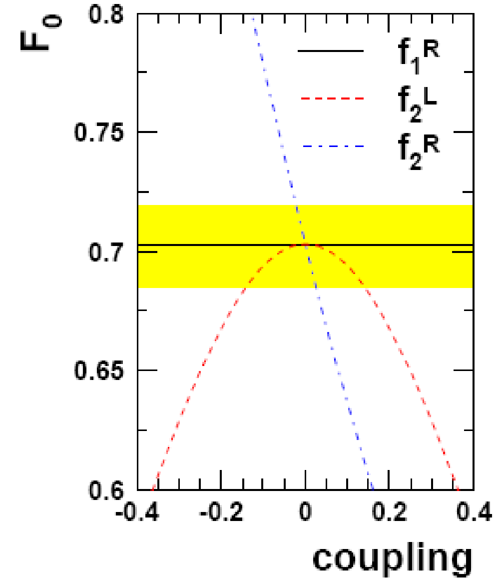


W Helicity in Top Quark Decays

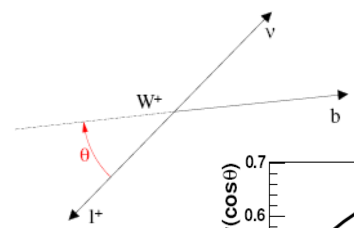
- Use tt events to study the Lorentz structure of the t-b-W interaction.
- Possible W helicity configurations in top quark decays:



SM: $F_- \approx \frac{2M_W^2}{m_t^2 + 2M_W^2} = 0.30$ $\quad F_0 \approx \frac{m_t^2}{m_t^2 + 2M_W^2} = 0.70$ $\quad F_+ = 0$



- W helicity fractions depend on t-b-W Lorentz structure.
- Lepton kinematical distributions rather sensitive to λ_W.



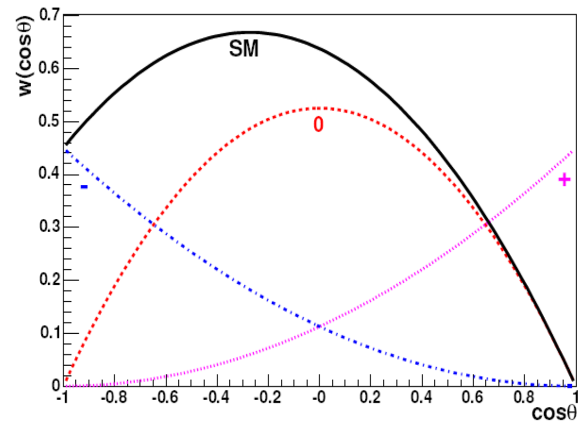
- Projected Tevatron (2x4 fb^{-1}): ΔF_0~0.06, ΔF_+~0.04
- LHC (10 fb^{-1}):

hep-ex/0508061

	Semilep+Dilep
F_L	$0.303 \pm 0.003 \pm 0.024$
F_0	$0.697 \pm 0.004 \pm 0.015$
F_R	$0.000 \pm 0.003 \pm 0.012$

2σ limits hep-ex/0508061

	f_1^R	f_2^L	f_2^R
$t\bar{t}$, LHC (10 fb^{-1}) (Stat.+ Syst.)	0.30	0.13	0.04
single top, LHC (100 fb^{-1}) (Stat.+ 5% Syst.)	0.06	0.07	0.13
$b \to s\gamma, sl^+l^-$, B-factories (indirect)	0.004	0.005	0.4
Z decay, LEP (indirect)	-	-	0.1

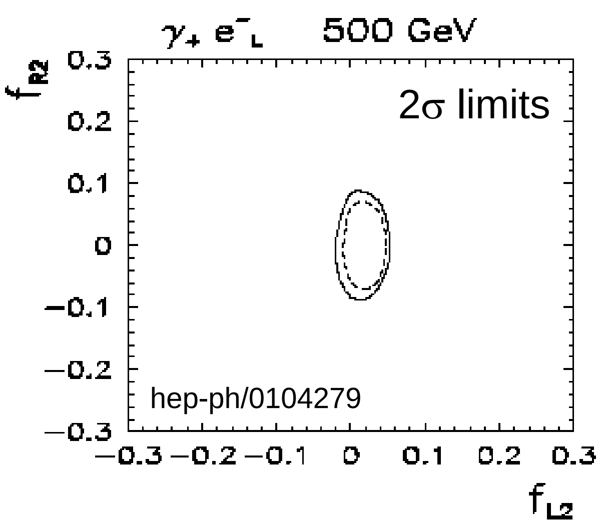


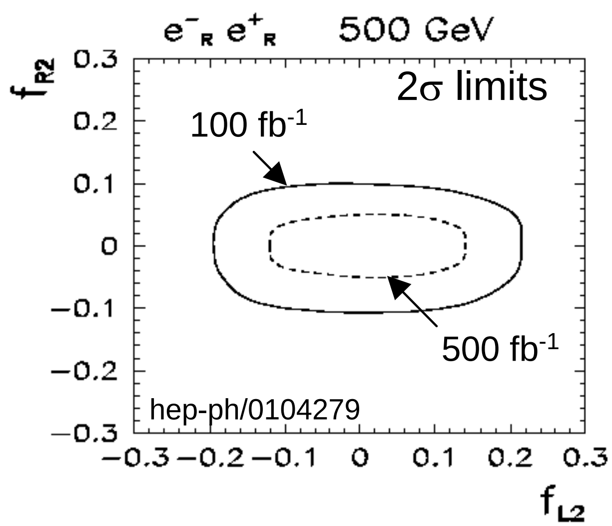
⇒ Caveat: need model-independent measurements (multi-parameter fits)

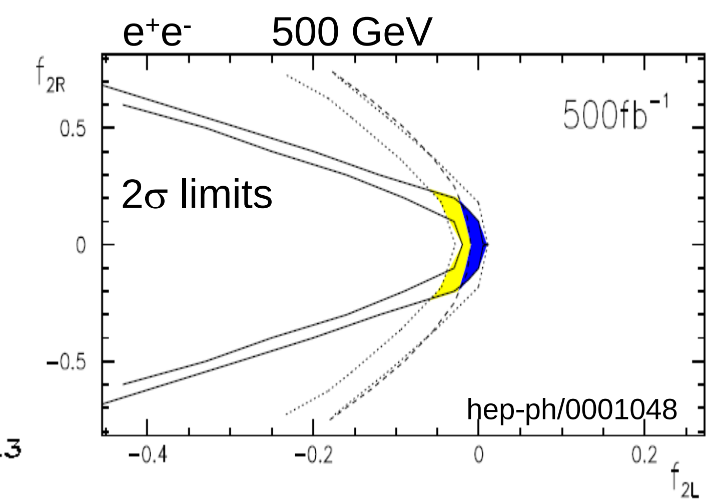
Top Couplings to Gauge Bosons: W

ILC

- Most promising approach is single top quark cross section in polarized γe collisions:
  $\sigma_{\gamma e}$~30-100 fb, no tt background vs σ_{e+e-}~ few fb, large tt background
- Significant sensitivity also from asymmetries in $e^+e^- \to$ tt.



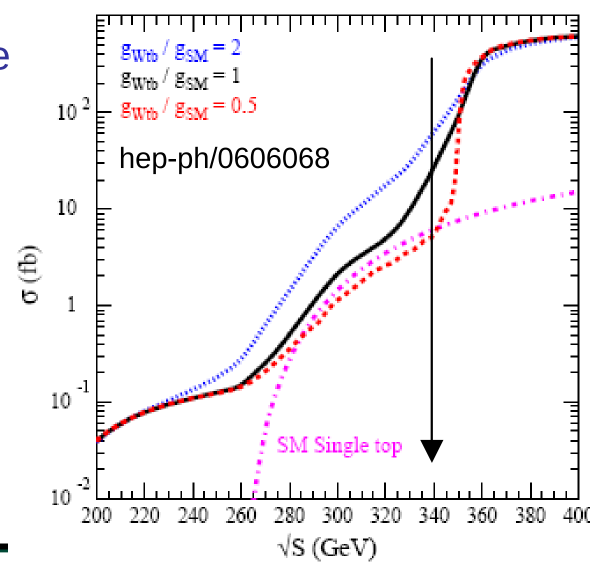


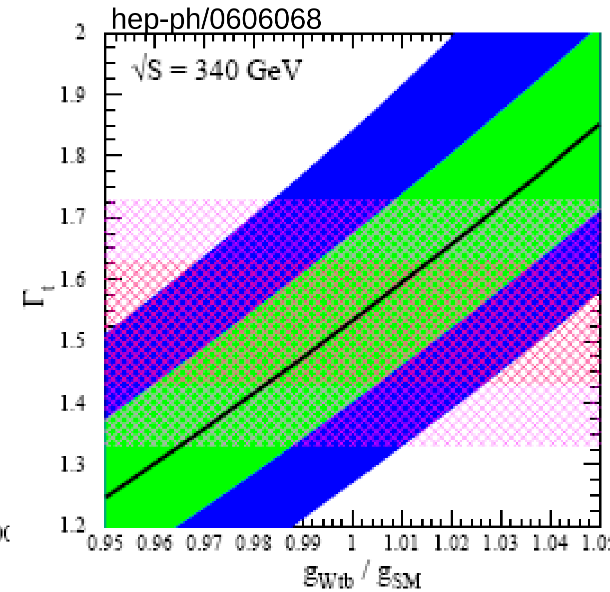


- Another possibility might be the measurement of σ_{tt} just below threshold, in conjunction with the precise Γ_t measurement from the tt threshold scan:

$\sqrt{s}$=340 GeV, L=100 fb^{-1}

$\Delta g_{tbW}/g_{tbW}$ ~2%





Top Couplings to Gauge Bosons: γ and Z

- General t-t-γ and t-t-Z vertices:

$$\mathcal{M}^{\mu(\gamma,Z)} = e\gamma^\mu \left[Q_V^{\gamma,Z} F_{1V}^{\gamma,Z} + Q_A^{\gamma,Z} F_{1A}^{\gamma,Z}\gamma^5\right] + \frac{ie}{2m_t}\sigma^{\mu\nu}k_\nu \left[Q_V^{\gamma,Z} F_{2V}^{\gamma,Z} + Q_A^{\gamma,Z} F_{2A}^{\gamma,Z}\gamma^5\right]$$

  Within the SM: $F_{1V}^{\gamma} = F_{1V}^{Z} = F_{1A}^{Z} = 1$ with the rest equal to 0.

  CP-conserving (F_{2V}) CP-violating (F_{2A})

  Strong EWSB models (e.g. technicolor): F_{2V}~5-10%
  SUSY/MHDM models: F_{2A}~0.1-1%

- At a hadron collider, EW-mediated top pair production is hopeless. The most promising process to study the t-t-γ and t-t-Z couplings SEPARATELY is ttγ and ttZ production. Rate too small at Tevatron.

t-t-γ at LHC

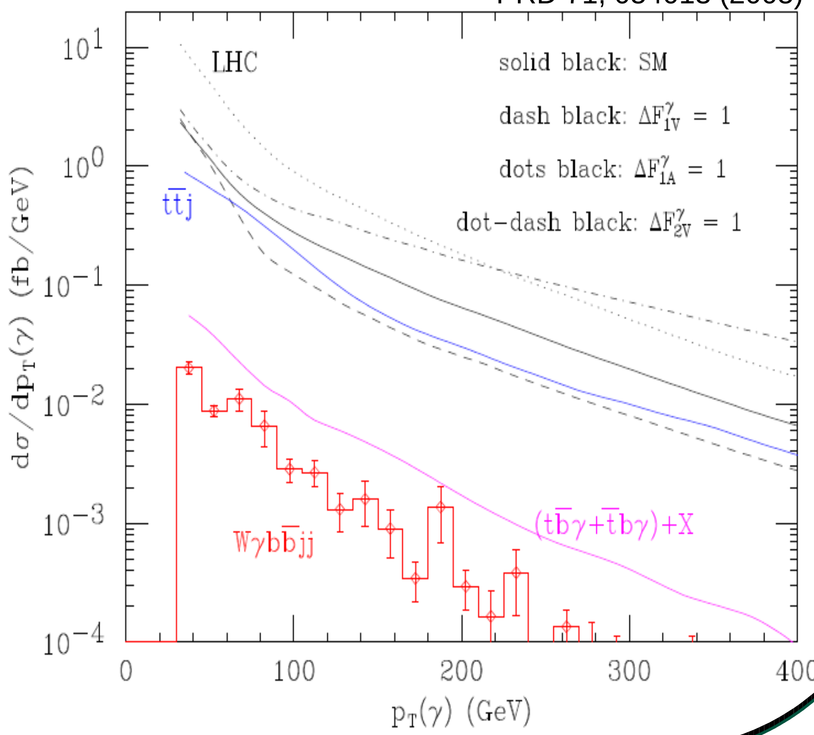
PRD 71, 054013 (2005)

- pp→lνjjbbγ+X final state
- Signal: pp→ttγ+X →lνjjbbγ+X
- Rather detailed background evaluation
- Observables: σ and $p_T(\gamma)$ distribution (assume 30% normalization uncertainty)

- Multi-parameter fits (2 couplings at a time)

  $\Delta F_{1V,A}$ ~ 10% (5%) with 30 fb^{-1} (300 fb^{-1})

  $\Delta F_{2V,A}$ ~ 20-30% (5-20%) with 30 fb^{-1} (300 fb^{-1})

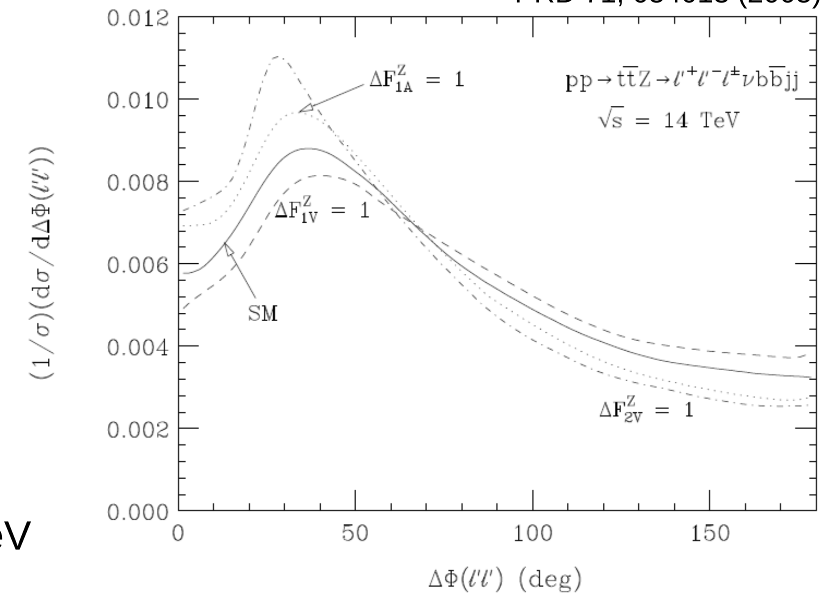


Top Couplings to Gauge Bosons: γ and Z

t-t-Z at LHC

- Signal: pp$\to$ttZ+X
- Several final states considered:
  - ttZ$\to$ lνjjbb+(Z$\to$)ll, jjjjbb+(Z$\to$)ll
    Observables: σ, p_T(Z) and $\Delta\Phi$(ll; from Z)
    Rather small background.
  - ttZ$\to$ jjjjbb+(Z$\to$)$\nu\nu$
    Observables: σ, Missing p_T(~ p_T(Z))
    tt-related backg dominates up to MET~300 GeV

PRD 71, 054013 (2005)

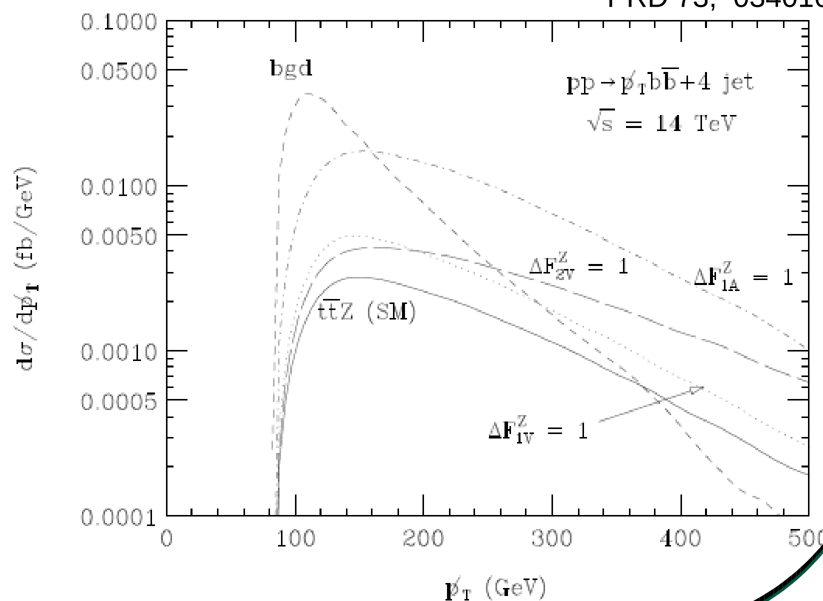


- Multi-parameter fits (2 couplings at a time)

PRD 73, 034016 (2006)

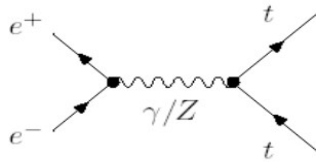
300 fb^{-1} (LHC)			
coupling	$\not{p}_T b\bar{b}+4j$	$2\ell+3\ell$	combined
ΔF^Z_{1V}	–	$+0.84$ -0.43	$+0.75$ -0.36
ΔF^Z_{1A}	$+0.12$ –	$+0.16$ -0.13	$+0.096$ -0.112
ΔF^Z_{2V}	$+0.59$ -0.55	$+0.47$ -0.47	$+0.38$ -0.39
ΔF^Z_{2A}	$+0.57$ -0.58	$+0.48$ -0.49	$+0.40$ -0.40

PRD 73, 034016 (2006)



Top Couplings to Gauge Bosons: γ and Z

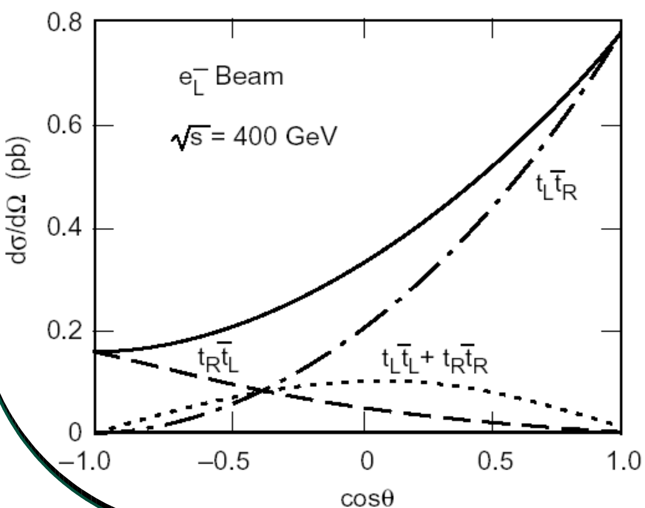
- ILC: the top pair production rate is directly sensitive to BOTH t-t-γ and t-t-Z vertices.

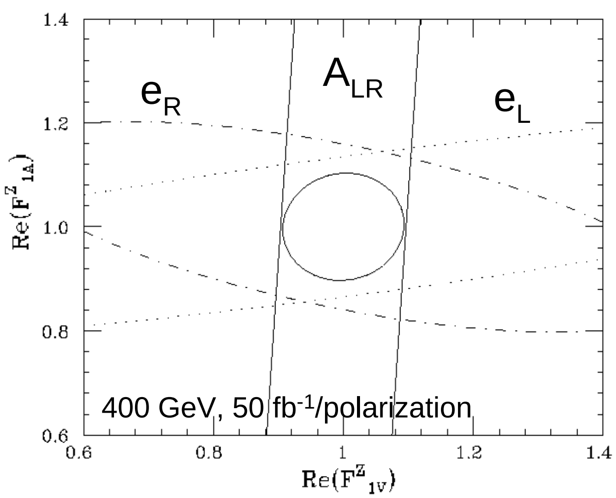


- Polarization is an important tool to disentangle among different couplings:
  - High sensitivity both at threshold (highly polarized top quarks) and continuum
  - Inclusive polarization observables: e.g. $A_{LR} = (\sigma_L - \sigma_R)/(\sigma_L + \sigma_R)$
  - Angular distributions of final state products

hep-ex/0106057

coupling	e^+e^-		LHC, 300 fb^{-1}
$\Delta\widetilde{F}^{\gamma}_{1V}$	$+0.047$ -0.047	200 fb^{-1}	$+0.043$ -0.041
$\Delta\widetilde{F}^{\gamma}_{1A}$	$+0.011$ -0.011	100 fb^{-1}	$+0.051$ -0.048
$\Delta\widetilde{F}^{\gamma}_{2V}$	$+0.038$ -0.038	200 fb^{-1}	$+0.038$ -0.035
$\Delta\widetilde{F}^{\gamma}_{2A}$	$+0.014$ -0.014	100 fb^{-1}	$+0.16$ -0.17
$\Delta\widetilde{F}^{Z}_{1V}$	$+0.012$ -0.012	200 fb^{-1}	$+0.34$ -0.72
$\Delta\widetilde{F}^{Z}_{1A}$	$+0.013$ -0.013	100 fb^{-1}	$+0.079$ -0.091
$\Delta\widetilde{F}^{Z}_{2V}$	$+0.009$ -0.009	200 fb^{-1}	$+0.26$ -0.34
$\Delta\widetilde{F}^{Z}_{2A}$	$+0.052$ -0.052	100 fb^{-1}	$+0.35$ -0.35





- LHC competitive with ILC for most t-t-γ couplings.
- A-priori precision t-t-Z couplings only possible at ILC.
- Caveat: multi-parameter fits will be required at the ILC to disentangle effects at t-t-γ and t-t-Z vertices (no realistic analysis available).

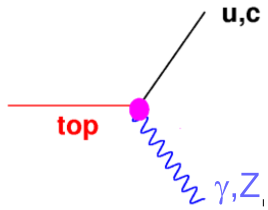
Top Couplings to Gauge Bosons: FCNC

- Within the SM, neutral current interactions are flavor-diagonal at tree level.
  FCNC loop-induced and tiny: $B(t\to cg) \approx 10^{-10}$, $B(t\to c\gamma) \approx 10^{-12}$
  $B(t\to cZ) \approx 10^{-12}$, $B(t\to cH) \approx 10^{-7}$
  Can be significantly enhanced in models beyond the SM ($\sim$x10^3-10^4).
  } Observation would be a clear signal of New Physics!
- Indirect constraints (rare decays, EW precision data,…) restrict FCNC but model-dependent.
- Search strategies so far:

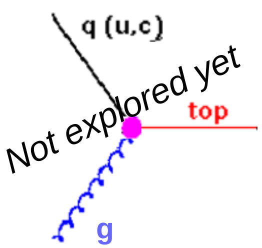
$p\bar{p}$ collisions

CDF Run I (@ 95% CL):
$B(t\to c\gamma)+B(t\to u\gamma)<3.2\%$
$B(t\to cZ)+B(t\to uZ)<33\%$

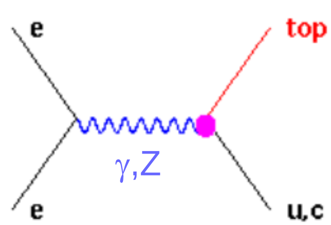
Anomalous top decays in tt events



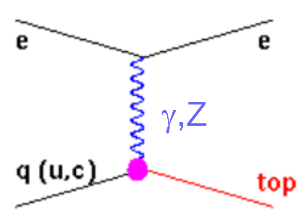
Anomalous single top production

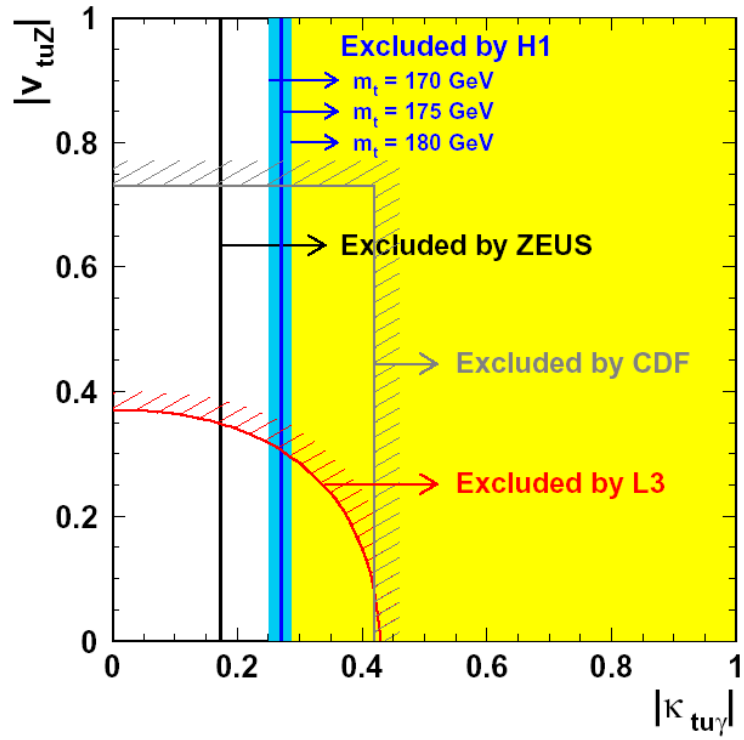


e^+e^- collisions



$e^\pm p$ collisions



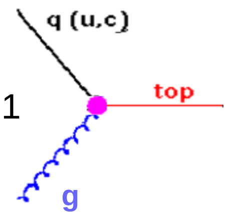


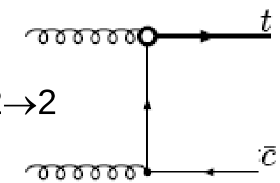
- Existing direct constraints still rather weak.
- Improvements by at least x10 expected in the very near future (Tevatron Run II, HERA II)

Top Couplings to Gauge Bosons: FCNC

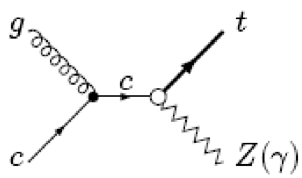
LHC

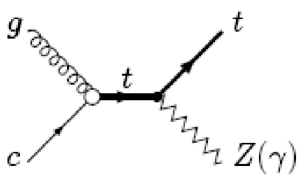
- tqg: via anomalous single top production

2→1 

2→2 

- tqγ/Z: via anomalous tV production and $t \to Vq$ in tt events.





Best 3σ discovery limits
(hep-ph/0003033)

95% upper limits
(ATL-PHYS-PUB-2005-009)

	Tevatron	LHC		95% upper limits
$\sqrt{s}$(TeV)	2	14		
$\mathcal{L}$(fb^{-1})	2	100		100
tug	3.3×10^{-4}	3.2×10^{-6}	2→1	4.3×10^{-4} (decay)
tcg	3.5×10^{-3}	2.1×10^{-5}	2→1	4.3×10^{-4} (decay)
$tu\gamma$	3.5×10^{-3}	3.9×10^{-6}	tV	
	–	4.8×10^{-5}	decay	1.8×10^{-5} (decay)
$tc\gamma$	–	3.5×10^{-5}	tV	
	–	4.8×10^{-5}	decay	1.8×10^{-5} (decay)
tuZ	3.2×10^{-2}	1.1×10^{-4}	tV	
	1.1×10^{-2}	1.9×10^{-4}	decay	6.5×10^{-5} (decay)
tcZ	–	4.8×10^{-4}	tV	
	1.1×10^{-2}	1.9×10^{-4}	decay	6.5×10^{-5} (decay)
	–	6.7×10^{-1}	$t\,t$	

ILC: both anomalous production ($e^+e^- \to tq$) and decay ($e^+e^- \to tt$; $t \to Vq$) can be explored.

hep-ph/0102197

$\sqrt{s}$ = 500 GeV
L = 100 fb^{-1}

	(P(e⁻),P(e⁺)) = (0,0) No pol.		(P(e⁻),P(e⁺)) = (-0.8,0) Pol. e^-		(P(e⁻),P(e⁺)) = (-0.8,+0.45) Pol. e^- e^+		
	95%	$3\,\sigma$	95%	$3\,\sigma$	95%	$3\,\sigma$	
$\mathrm{Br}(t \to \gamma q)$	3.9×10^{-5}	5.9×10^{-5}	3.2×10^{-5}	3.3×10^{-5}	1.9×10^{-5}	1.8×10^{-5}	tq
	3.3×10^{-4}	3.2×10^{-4}	5.0×10^{-4}	3.2×10^{-4}	4.0×10^{-4}	2.6×10^{-4}	decay
$\mathrm{Br}(t \to Zq)\ (\gamma_\mu)$	7.9×10^{-4}	1.2×10^{-3}	7.1×10^{-4}	7.5×10^{-4}	4.4×10^{-4}	4.2×10^{-4}	tq
	5.4×10^{-3}	3.5×10^{-3}	8.0×10^{-3}	2.6×10^{-3}	6.3×10^{-3}	2.0×10^{-3}	decay
$\mathrm{Br}(t \to Zq)\ (\sigma_{\mu\nu})$	6.3×10^{-5}	9.4×10^{-5}	5.7×10^{-5}	6.0×10^{-5}	3.5×10^{-5}	3.4×10^{-5}	tq
	5.7×10^{-3}	3.7×10^{-3}	8.3×10^{-3}	2.7×10^{-3}	6.5×10^{-3}	2.1×10^{-3}	decay

- Sensitivity better from production than from decay since, despite the lower S/B, σ is larger.
- Beam polarization very useful to improve limits from production.
- $\gamma\gamma \to tc$ would allow to study FCNC with higher σ (~x100) and lower SM bckg.

LHC/ILC complementarity

Top Coupling to Scalars: Higgs

- The top-Higgs Yukawa coupling is the largest coupling of the Higgs boson to fermions (g_{ttH} ~ 0.7 vs g_{bbH} ~ 0.02). Precise measurement important since the top quark is the only "natural" fermion from the EWSB standpoint.

- A number of production and decay channels are expected to be available at the LHC for detailed measurements of the Higgs boson properties:

$$gg \to H \text{ with } H \to \gamma\gamma,\, ZZ,\, WW$$
$$qq \to qqH \text{ with } H \to \gamma\gamma,\, \tau\tau,\, WW$$
$$q\bar{q}, gg \to t\bar{t}H \text{ with } H \to b\bar{b}, \tau\tau, WW$$
$$q\bar{q} \to WH \text{ with } H \to b\bar{b}$$

- Each cross-section measurement is proportional to the product of squares of Yukawa couplings: e.g. $\sigma_{tth,h\to bb} \propto g^2_{tth}\, g^2_{bbh}$

- To determine the top-Higgs Yukawa coupling with good accuracy:
  - Need to be able to minimize systematic uncertainties (both experimental and theoretical) that plague cross-section estimates at hadron colliders:

    ⇒ experimental systematics: luminosity, reconstruction efficiencies, etc

    ⇒ availability of theoretical predictions at higher order in QCD

    ⇒ PDF uncertainties

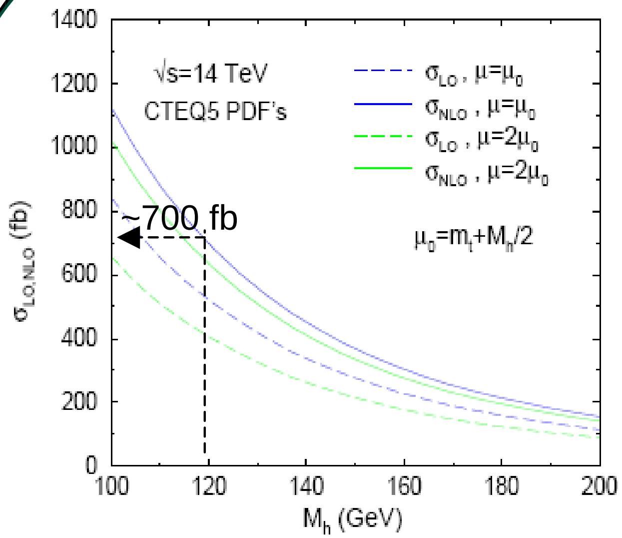
    Ratio of cross-sections (large cancellations of systematics) ⇒ ratios of Yukawa couplings (already extremely useful to start probing the nature of the Higgs boson)

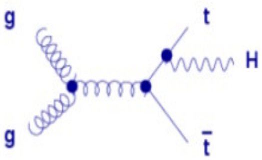
  - For an absolute measurement, need to have a measurement of the Yukawa couplings in each decay mode considered: g_{bbh}, $g_{\tau\tau h}$, g_{WWh} . Two possibilities:

    ⇒ internal (derived from other LHC measurements). Requires some theoretical assumptions.

    ⇒ external (from high precision model-independent measurements at the LC)

Top Coupling to Scalars: Higgs

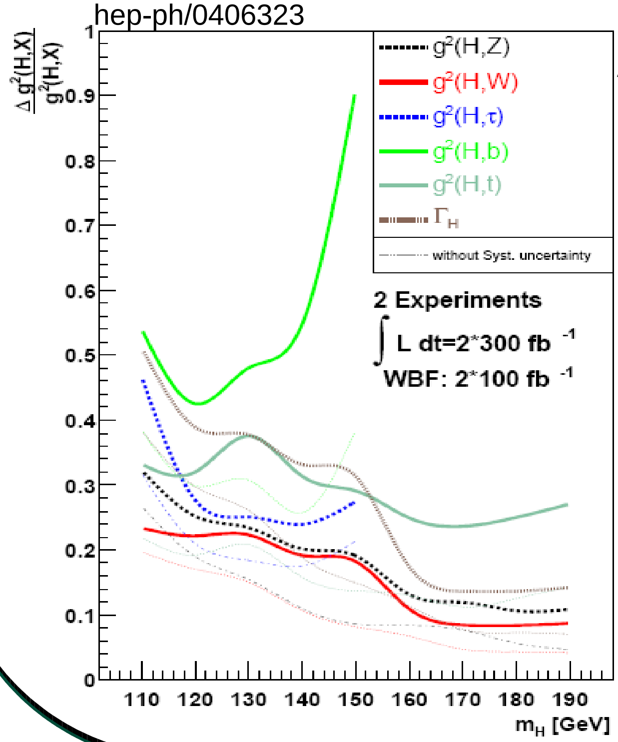




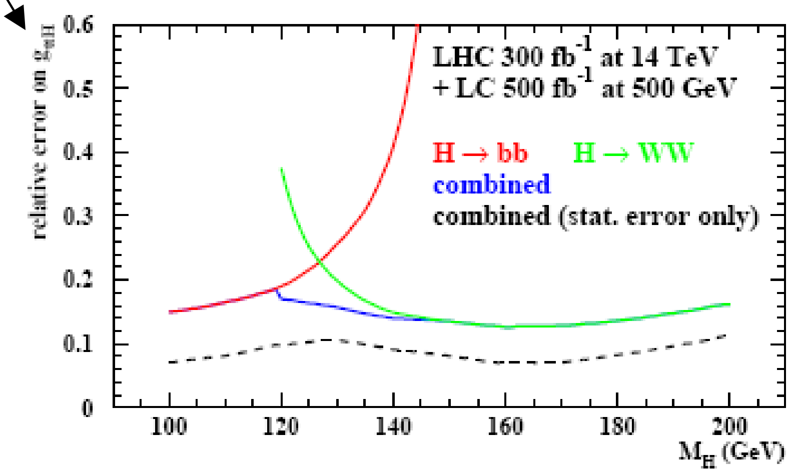
LHC:

- σ_{tth} ~ 700 fb (m_h=120 GeV, $\mu=m_t+m_h/2$)
  $\Rightarrow$ ~7(70)k events/year at low(high) luminosity
- Estimated overall theoretical uncertainty: ~15-20%
- Spectacular signatures:
  - tth(h→bb)→l+2j+4b
  - tth(h→WW) → $l^\pm l^\pm$+4j+2b, 3l+2j+2b
  - tth(h→ττ) →l+2τ_h+2j+2b, $l^\pm l^\pm$+τ_h+2j+2b, 3l+τ_h+2b

hep-ph/0406323

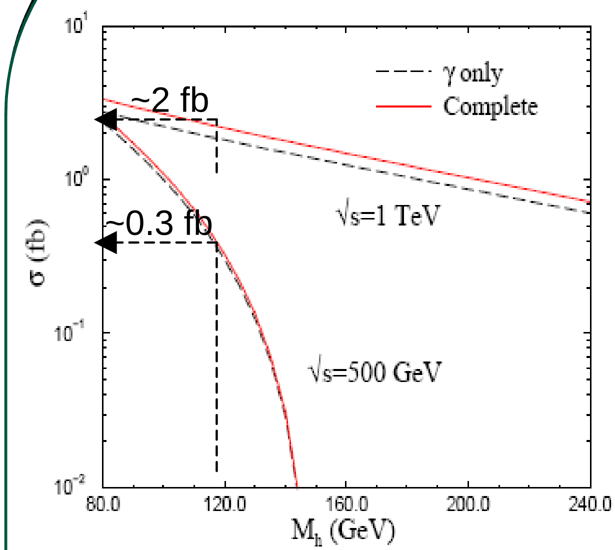


- Global fit to LHC measurements: assume $g^2_{HVV}\leq 1.05\, g^2_{HVV}$(SM) (valid in general multi-Higgs doublet models)
  $\Rightarrow \Delta g_{tth}/g_{tth}$~15% for m_h=120-190 GeV
- Model-independent determination use percent-level B(h →bb) and B(h →WW) from ILC: ~same precision

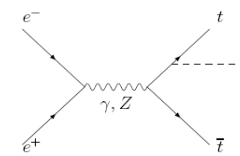


hep-ph/0410364

Top Coupling to Scalars: Higgs



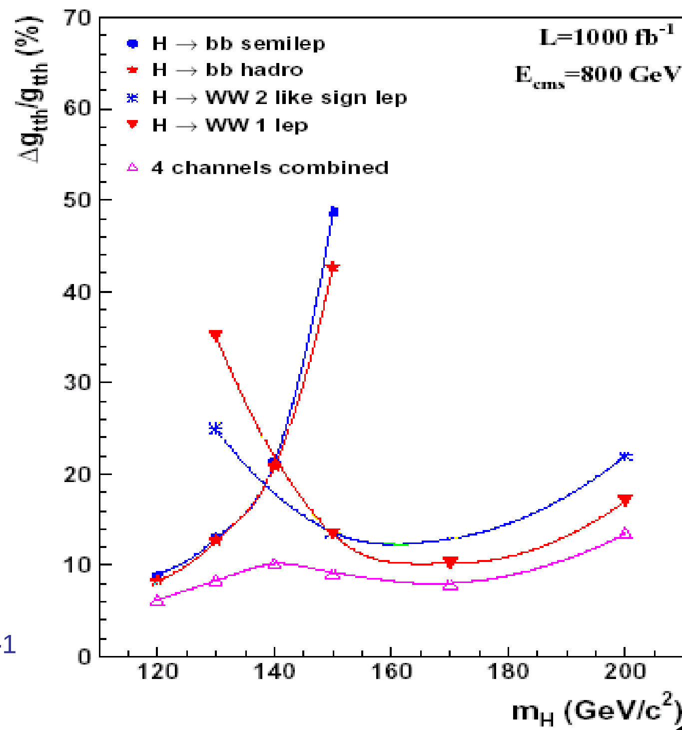
ILC:



- σ_{tth} ~ 0.2(2.5) fb at √s=500(800) GeV (m_h=120 GeV)
- Estimated theoretical uncertainty: ~10%
- High luminosity required (≥1 ab^{-1}) for a precise measurement:
  ⇒ ~40(500) events/year at 2×10^{34} $cm^{-2}s^{-1}$
- Signatures studied:
  - tth(h→bb) → l+2j+4b, 4j+4b
  - tth(h→WW) → l+6j+2b, $l^{\pm}$ $l^{\pm}$+4j+2b
- Use of b-tagging and sophisticated multivariate analyses crucial.

- Expected precision:
  √s=800 GeV, L=1000 fb^{-1}
  $\Delta g_{ttH}/g_{tth}$ ~ 6(10)% for m_H=120(190) GeV

hep-ph/9910301
hep-ph/0604034



- Ongoing study to estimate precision at √s=500 GeV:
  - For now just focusing on h→bb decay channel
  - Consider σ_{tth} enhancement due to:
    - Large QCD resummation effects near tt threshold: ~x2.4 for m_h=120 GeV
    - Use of beam polarization: ~x2.1 for ($P(e^-)$,$P(e^+)$) = (-0.8,+0.6)

hep-ph/0512246

Anticipate: $(\Delta g_{ttH}/g_{tth})_{stat}$~10% for m_H=120 GeV, L=1000 fb^{-1}

Conclusions

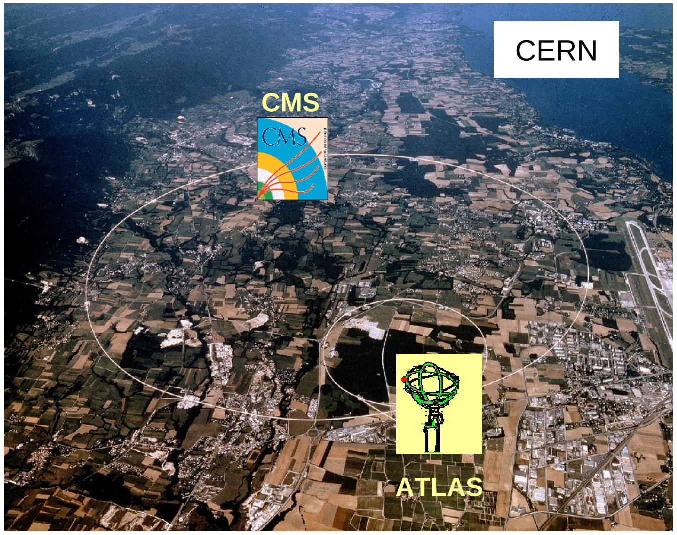
- Elucidation of the dynamics responsible for EWSB constitutes the main goal for particle physics research in the next 20 years. The top quark, by virtue of its large mass, may provide clues on the EWSB mechanism.
- Fully exploiting this opportunity requires precision and model-independent measurements of the top quark interactions.
- On this topic, there is a strong synergy between LHC and ILC which remains essentially unexplored:
  - how would measurements at the LHC affect the ILC physics program?
  - how would measurements at the ILC help interpret and exploit the LHC discoveries?
  - how would the combination of measurements at both machines help point to the correct underlying theory of EWSB?

Backup

Future Colliders

LHC: very near future (2007)

Colliding beams	p-p
$\sqrt{s}$ (TeV)	14
Typical L ($cm^{-2}s^{-1}$)	$10^{33} \rightarrow 10^{34}$
Bunch crossing (ns)	25
Interactions/crossing	$2.3 \rightarrow 23$



Tevatron ($1\text{-}3\times10^{32}$ $cm^{-2}s^{-1}$)	1-3 fb^{-1}/year
LHC (10^{33}-10^{34} $cm^{-2}s^{-1}$)	10-100 fb^{-1}/year
ILC (2×10^{34} $cm^{-2}s^{-1}$)	200 fb^{-1}/year

(*) 1 year ≡ 10^7 s

ILC: hopefully not too far future (~2015?)

Baseline Machine

- $e^+ e^-$ collisions
- $(\sqrt{s})_{max}$= 500 GeV but can operate at at any $\sqrt{s}$ in the range 200-500 GeV
- 500 fb^{-1} in first 4 years of running
- Possibility of energy scans at any $\sqrt{s}$ in whole energy range
- Possibility to go down to Z peak for calibration
- Beam energy precision < 0.1%
- $P(e^-) \geq 80\%$ in whole energy range
- 2 interaction regions

Upgrade

- $(\sqrt{s})_{max} \sim$ 1 TeV
- 1000 fb^{-1} in ~3-4 years

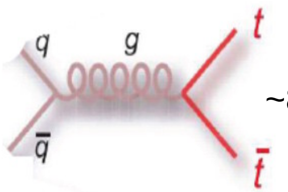
Options (relevant to Top Physics)

- Additional 500 fb^{-1} at $\sqrt{s}$ = 500 GeV in 2 years
- $P(e^+) \geq 50\%$ in whole energy range
- $e^- \gamma$ and $\gamma\gamma$ collisions

Top Quark Production in p-$\overset{(-)}{p}$ Collisions

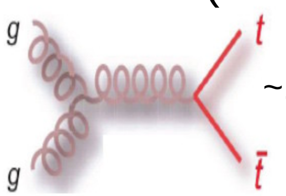
Tevatron (LHC)

Strong Interaction



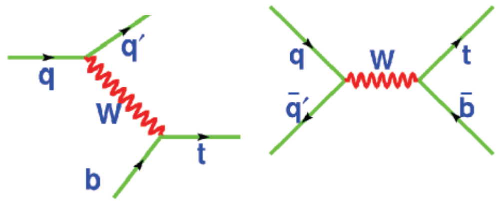
~85%(13%)

σ~7(800) pb

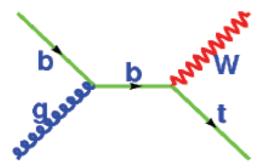


~15%(87%)

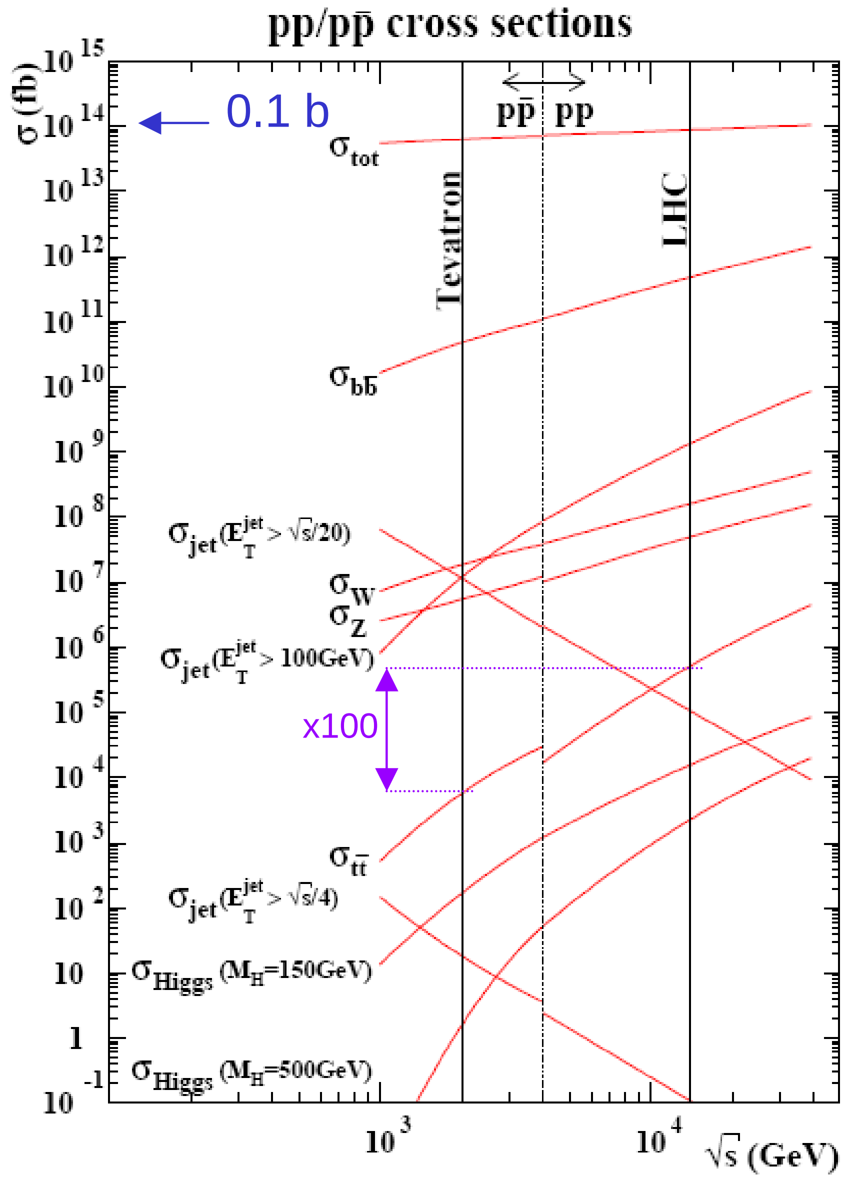
Electroweak Interaction



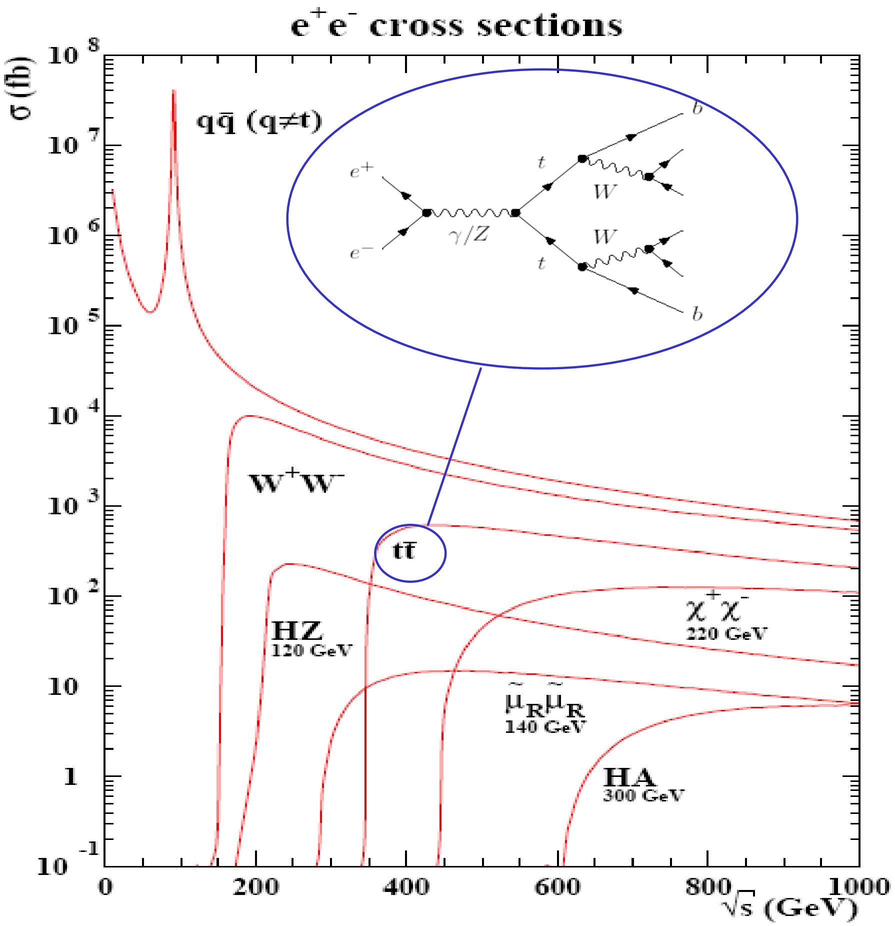
σ~3.0(300) pb



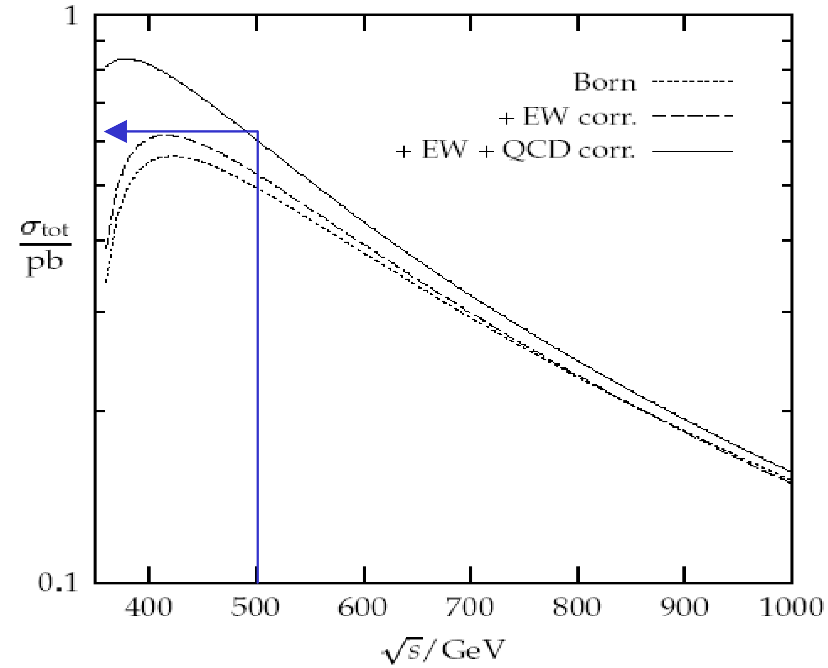
- Dominant production mechanism is in pairs, mediated by the strong interaction.
  Electroweak production of single top quarks not discovered yet.
- Tevatron (@ 10^{32} cm^{-2}s^{-1}): 7k(3k) events/year
  LHC (@ 10^{33} cm^{-2}s^{-1}): 8M(3M) events/year
- Experimental conditions (e.g. at Tevatron):
  …like drinking from a fire hose:
  σ_{inel} ~ 70 mb ⇒ 7 M events/s @ 10^{32} cm^{-2}s^{-1}
  …like panning for gold: $\sigma_{inel}/\sigma_{t\bar{t}} \sim 10^{10}$
  ⇒ ~ 1 $t\bar{t}$ event/24 min @ 10^{32} cm^{-2}s^{-1}
  ⇒ high luminosity and highly efficient and selective triggers crucial



Top Production in e+e- Collisions



- Top pair production via γ/Z exchange dominates



σ_{tt}~0.6 pb at √s=500 GeV
⇒ ~120k events/year (L=2x10^{34}cm^{-2}s^{-1})

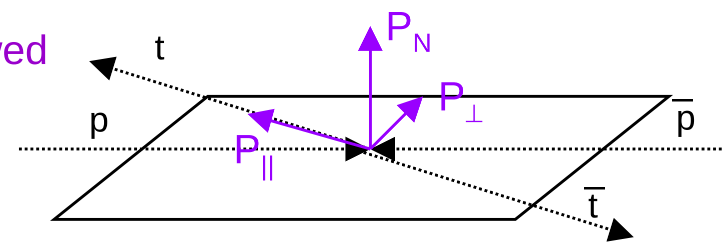
Experimentation at an e$^+$e$^-$ collider:

- "clean environment"
  - well defined initial state
  - relatively simple event topologies
  - precise theoretical calculations
- "democracy of cross sections"
  ⇒ low backgrounds
- excellent experimental accuracy (high precision detectors, full event reconstruction,…)

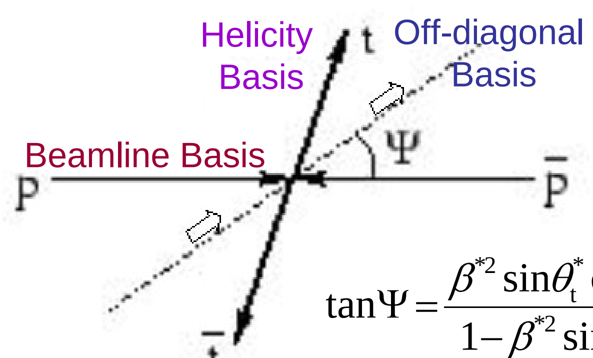
Spin Issues in Top Production

Strong interaction: Top Pair Production

- C and P conserving ➔ only transverse polarization allowed
  $P_{||} = P_{\perp} = 0$
  P_N ~ few % in SM from QCD effects at the loop level



Net polarization of top quarks very small: $N(t_\uparrow) = N(t_\downarrow)$...
BUT large asymmetry, $C = \frac{N_{||} - N_X}{N_{||} + N_X}$, if proper spin quantization axes chosen:



$$\tan\Psi = \frac{\beta^{*2}\sin\theta^*_t\cos\theta^*_t}{1-\beta^{*2}\sin^2\theta^*_t}$$

(*) valid for $q\bar{q} \to t\bar{t}$

	Tevatron	LHC	ILC (500 GeV)
P_X	90% / 70% / 90%	34%	95% / 79% / 99%
C	-0.80 / -0.39 / -0.81	0.32	-0.91 / -0.58 / -0.98

- β=0 (at threshold) ➔ Ψ= 0 (Beamline Basis)
- β=1 (ultra-relativistic) ➔ $\Psi=\theta_t^*$ (Helicity Basis)
- any β (at Tevatron <β>~0.6) (Off-diagonal Basis)

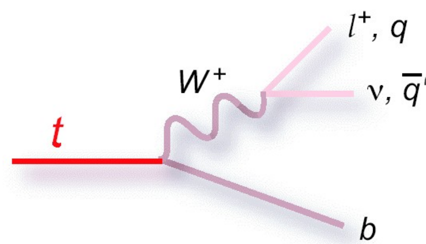
Electroweak interaction:

- Single Top Production: V-A weak interaction ➔ $P_{||}\uparrow\uparrow$
- Top Pair Production in e^+e^-: the EW interaction leads to sizeable $P_{||}$ and $P_\perp$ at tree level.
  Also, can use beam polarization to produce samples of highly polarized top quarks.

Top Quark Decay

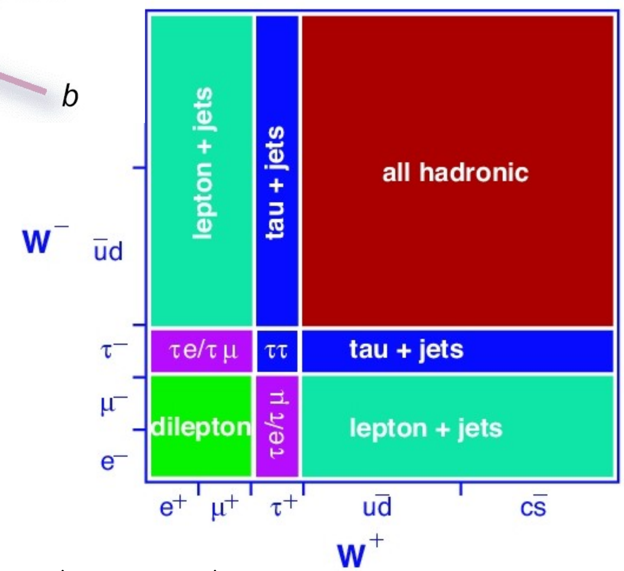
Within the SM:

- $m_t > m_W + m_b \Rightarrow$ dominant 2-body decay $t \to Wb$
  ($t \to Ws$, Wd CKM suppressed)
  Assuming unitarity of 3-generation CKM matrix:
  $|V_{tb}| = 0.9990\text{-}0.9992$ @ 90% CL $\Rightarrow$ B($t \to Wb$) ~ 100%
- $\Gamma_t^{SM} \approx 1.4$ GeV at $m_t = 175$ GeV $\Gamma_t >> \Lambda_{QCD}$
  Top decays before top-flavored hadrons or tt-quarkonium bound states can form.

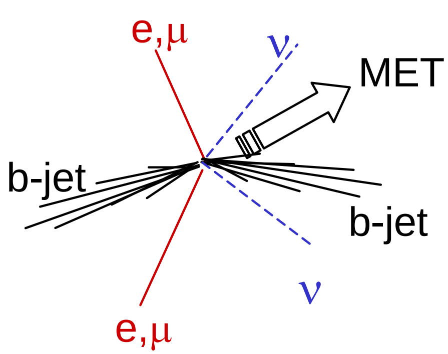


B($W \to q\bar{q}$) ~ 67%
B($W \to l\bar{\nu}$) ~ 11%, l=e,μ,τ

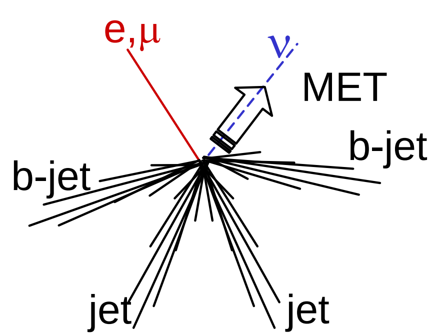
$t\bar{t}$ decay modes



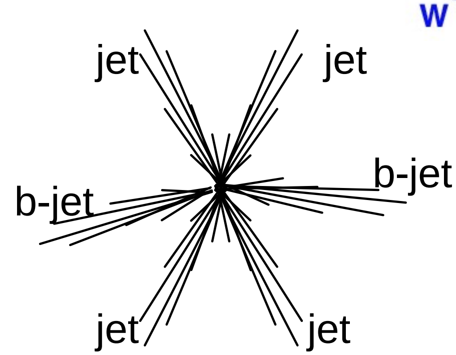
Typical final state signatures in top quark pair production:



Dilepton
(BR~5%, low bckg)



Lepton+jets
(BR~30%, moderate bckg)



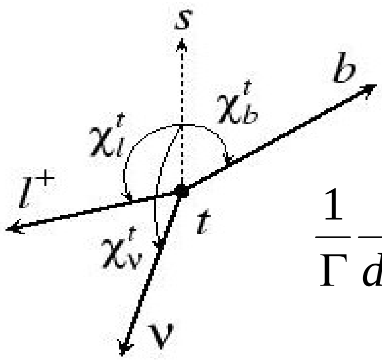
All-hadronic
(BR~46%, huge bckg)

$\Rightarrow$ Top Physics requires multipurpose detectors!

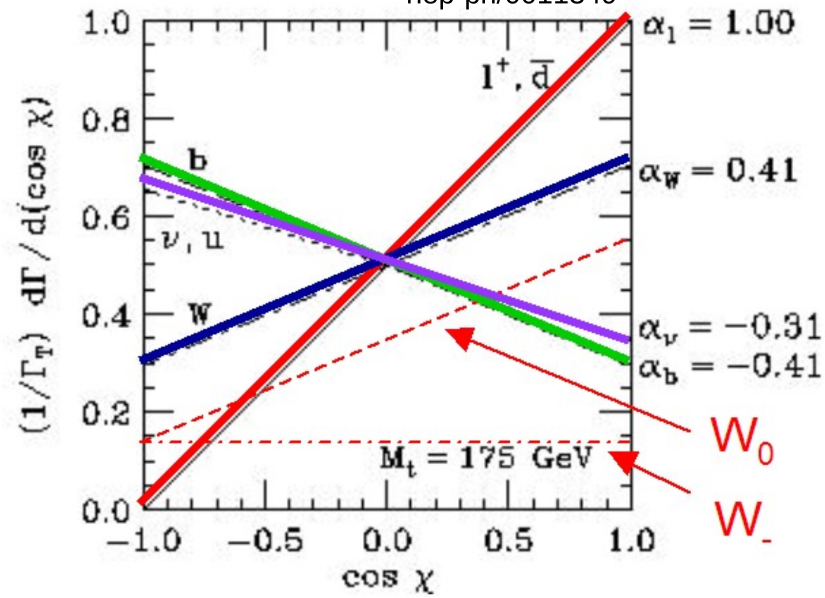
Spin Issues in Top Decay

- Decays like a "free quark"

  ➔ spin efficiently transmitted to the final state



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\chi_i^t} = \frac{1}{2}\left(1+\alpha_i\cos\chi_i^t\right)$$



- The production mechanism of t t correlates the spin

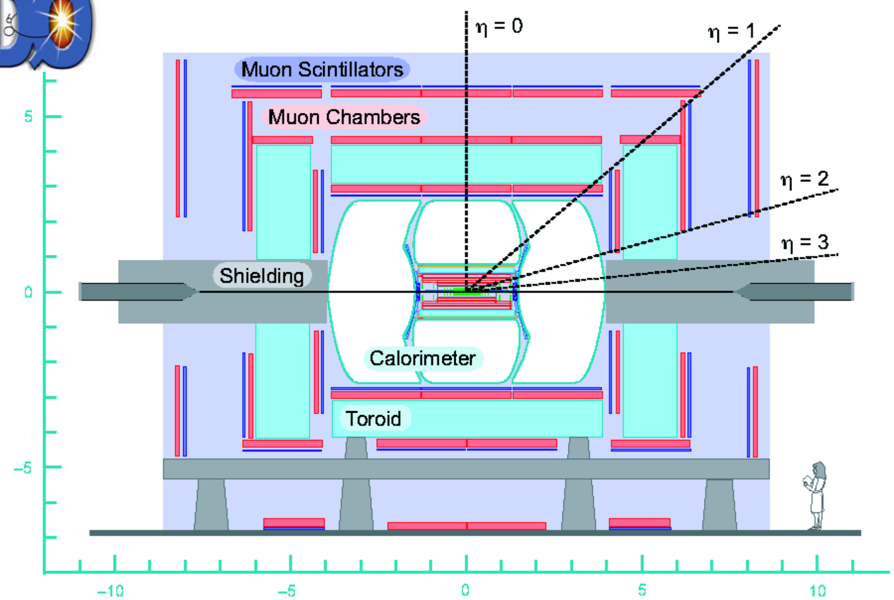
  The t($\bar{t}$) decay products are strongly correlated with the t($\bar{t}$) spin

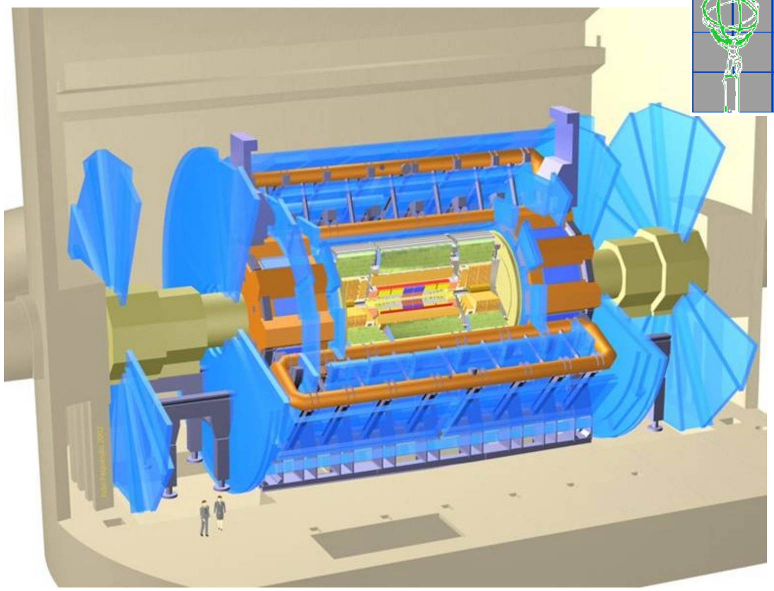
  ➔ Angular correlations between t and t decay products

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\chi_i^t\, d\cos\chi_j^{\bar{t}}} = \frac{1}{4}\left[1+\frac{N_{\parallel}-N_X}{N_{\parallel}+N_X}\alpha_i\alpha_j\cos\chi_i^t\cos\chi_j^{\bar{t}}\right]$$

Use polarization properties of the top quark as additional observables for testing the SM and to probe for New Physics

The Generic Hadron Collider Detector





- CDF and DØ detectors:
  - Central tracking system embedded in a solenoidal field
    - Silicon vertex detector
    - Tracking chamber/fiber tracker
  - Preshowers
  - Electromagnetic and hadronic calorimeters
  - Muon system
- Data taking efficiency: ≥85%
- Run II results presented here: 160-350 pb^{-1}

- Hadron collider experiments (including ATLAS and CMS) have "similar" performance:

e/γ: $\sigma(E)/E \sim 5\text{-}15\%/\sqrt{E}$

jet: $\sigma(E)/E \sim 60\text{-}80\%/\sqrt{E}$

track: $\sigma(1/p_T) \sim 0.2\text{-}1.4 \times 10^{-3}$ GeV^{-1}

impact parameter resolution: ~10-15 μm

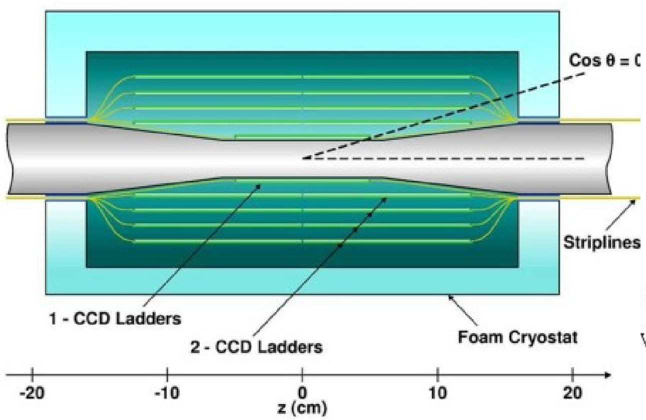
flavor ID: $\varepsilon_b \sim 50\%\text{-}60\%$, $\varepsilon_{mistag} \sim 1\%$

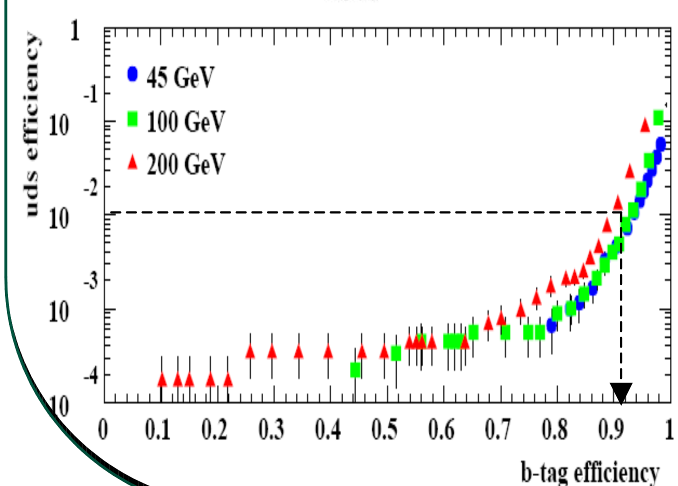
The Generic ILC Detector

- High resolution detector, based on the experience from LEP/SLD and R&D for the LHC.
- Detector design largely driven by performance optimization for Higgs physics.

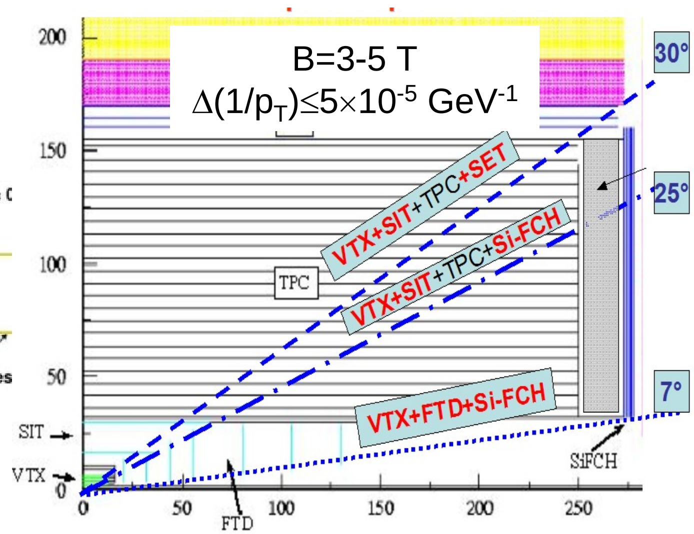
Precision Vertexing

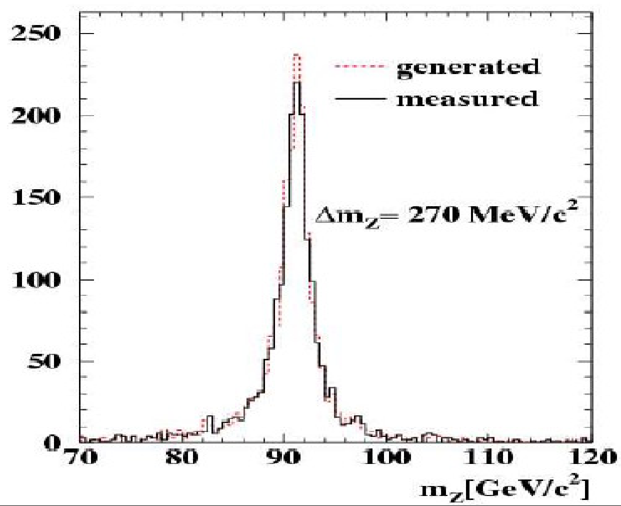
Pixel detector (~3 μm point resolution)
Material<0.1% X_0
R(1st layer) ~1.5 cm



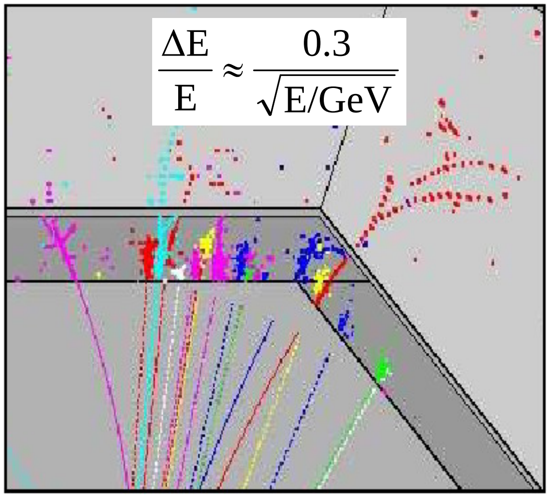


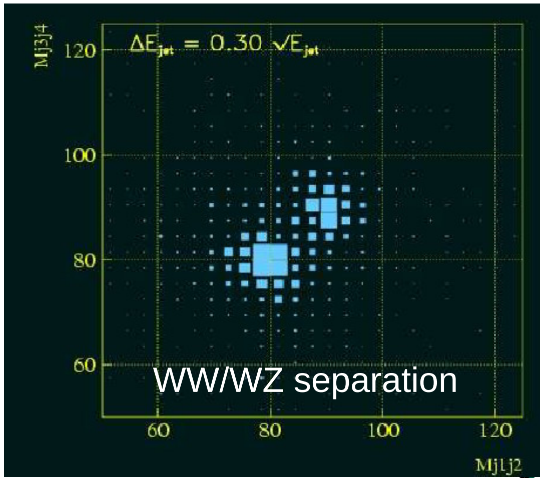
Precision Global Tracking





Optimized Calorimetry for Energy Flow





Top Pair Production in e^+e^- at Threshold

- Large Γ_t:
  - $1/\Gamma_t$ >> revolution time of top quark so toponium bound states cannot form
  - Provides IR cutoff, so can use non-relativistic pQCD to compute σ_{tt} near threshold.

    QCD potential essentially Coulombic:

$$V(r) \sim -C_F \frac{\alpha_s(1/r)}{r}$$

- Remants of toponium S-wave resonances induce a fast rise of σ_{tt} near threshold.

  Basic parameters: σ_{tt} $(m_t, \alpha_s, \Gamma_t)$

- Convergence of calculation is sensitive to m_t definition used: pole mass is not IR-safe

  $\Rightarrow \sigma_{tt}^{peak}$ not stable vs $\sqrt{s}$

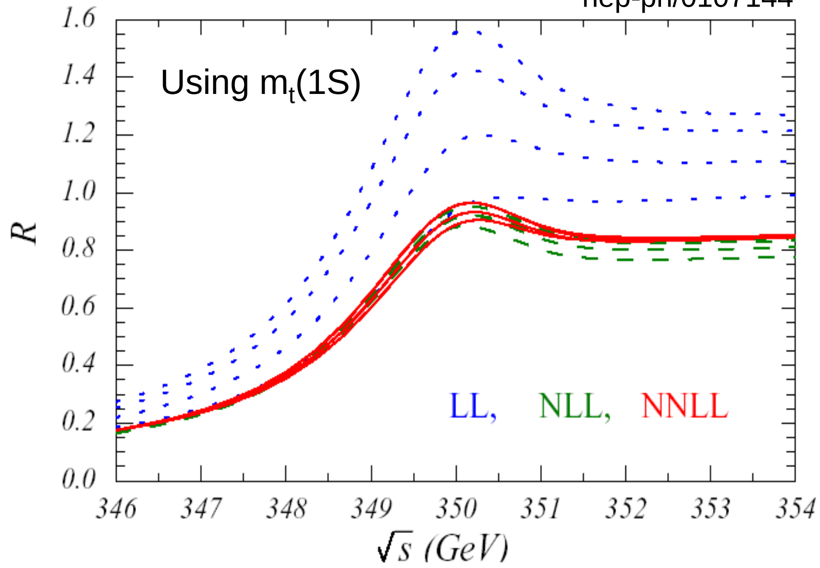
  Solution is to use threshold masses:
  e.g. 1S mass (1/2 the mass of the lowest $t\bar{t}$ bound state in the limit $\Gamma_t \rightarrow 0$).

  High accuracy in absolute normalization requires velocity resummation (NNLL):

$$(\Delta\sigma_{tt})_{QCD} \leq 3\%$$

- Important to take into account previously neglected %-level effects: non-factorizable corrections, EW box- and triangle-diagrams, W width, interfering backgrounds…

hep-ph/0107144



- Additional observables with different degree of sensitivity to m_t, α_s, Γ_t can also be computed/measured:

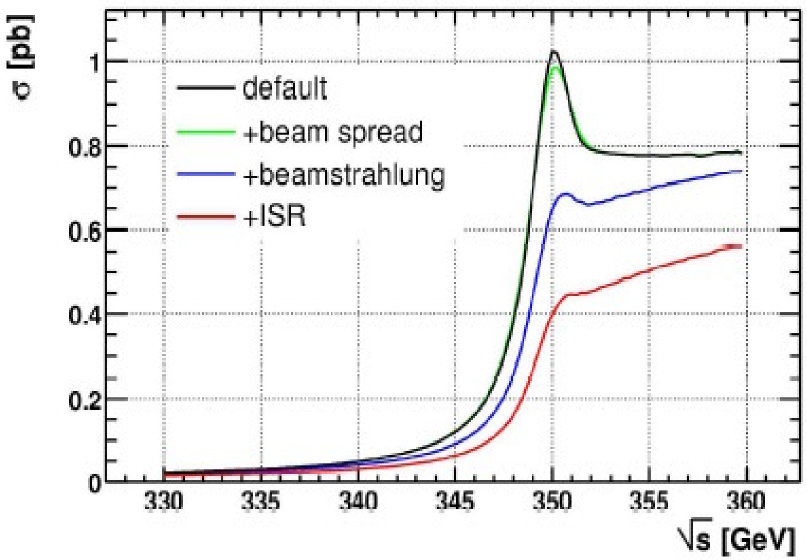
Mainly sensitive to α_s and Γ_t

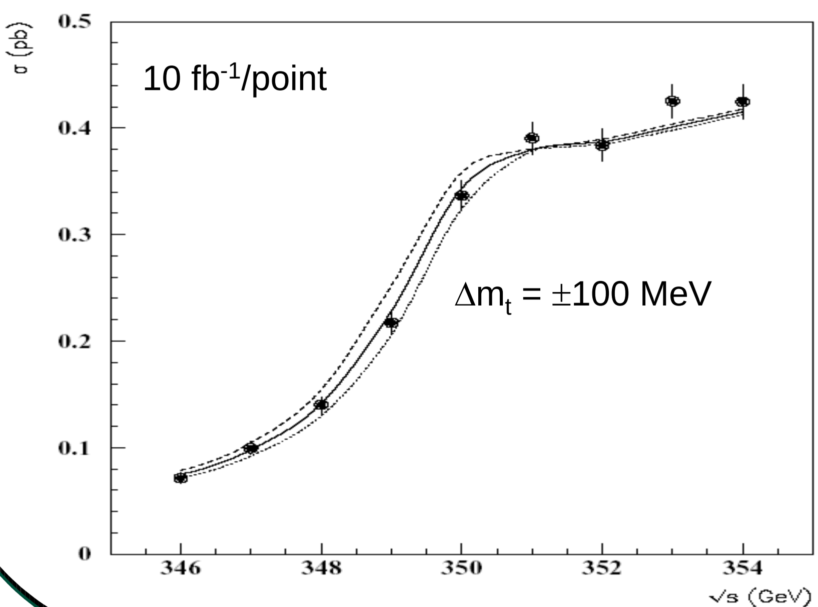
p_t : p_t^{peak} rather insensitive to ISR effects

A_{FB} : due to interference between S- and P-wave states.

- Simultaneous determination of parameters possible when using all threshold observables.

Top Pair Production at Threshold (cont'd)





- Lineshape significantly distorted due to:
  - Beam energy spread: ~0.1%
  - Beamstrahlung: coherent radiation due to beam-beam interactions. Must be measured precisely (acollinearity in Bhabha events).
  - Bremsstrahlung (ISR): can be calculated accurately

- Strategy: perform scan in √s around the threshold region and compare measurement of various observables to theoretical predictions as a function of model parameters.

For instance (hep-ph/0207315):

- 300 fb^{-1} uniformly distributed among 10 points, one of them well below the threshold to measure the background.
- Consider lepton+jets and alljets final states: ε_{tt}~40%, σ_{bckg}~0.0085 pb