A qualitative perspective on what is needed for top physics at the ILC

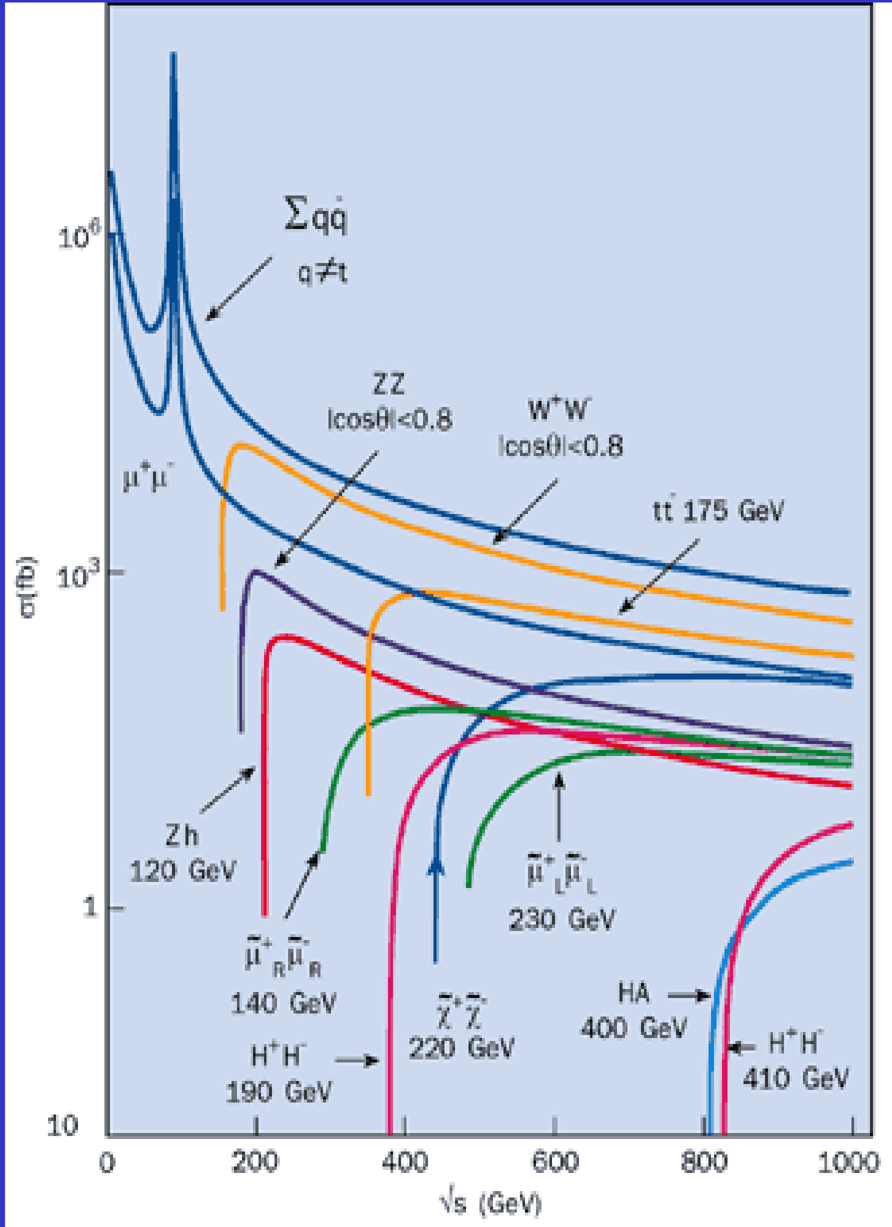
Juan A. Fuster Verdú IFIC-València

ILC-ECFA & GDE meeting

València, 6-10 November 2006

In cooperation with M. Vos and E. Ros

Image by N. Graf



Standard Production of top in e+e-:

$\mathscr{L}$ ~ 500 fb^{-1}

Events ~ 5x10^{5}

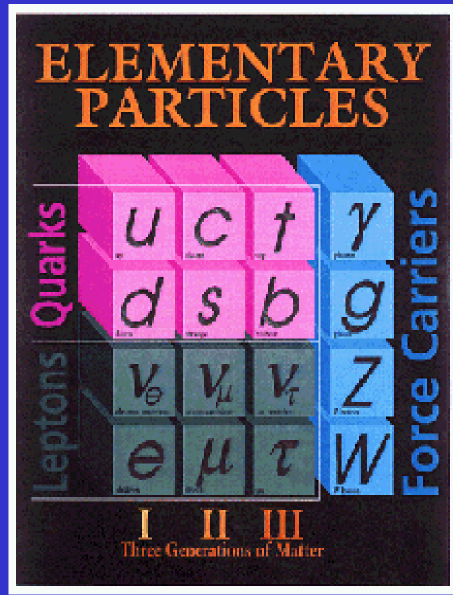
Statistics Low (compared to LHC)

Excellent signal/background ratio

(accurate measurements possible)

Our present knowledge of top

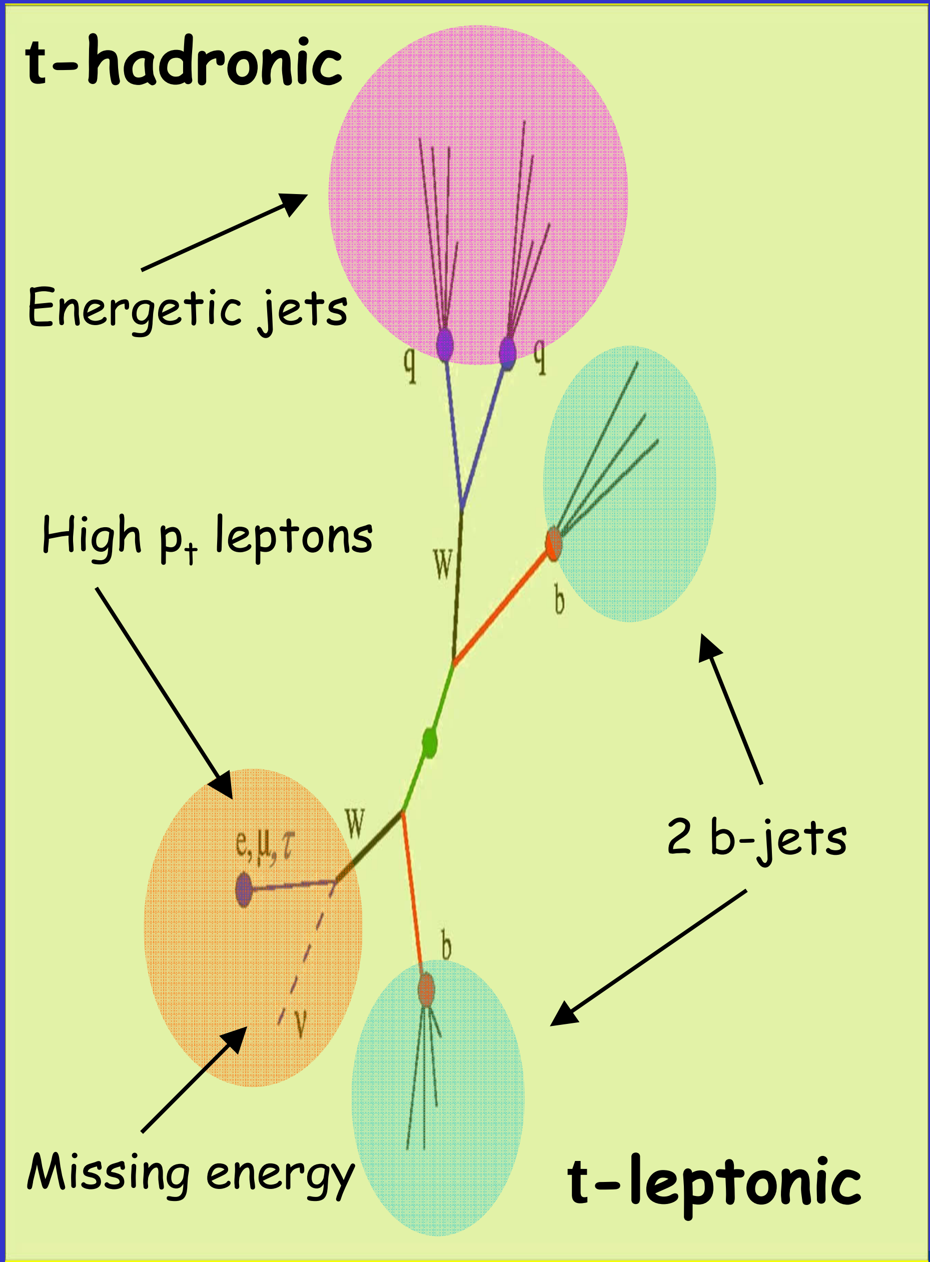
- ✓ The top quark completes the three family structure of the SM
- ✓ It´s massive, "very heavy" — Δm_t ~ 2,1 GeV (CDF+D0)
- ✓ Spin=1/2 — Not directly
- ✓ Charge=+2/3 — -4/3 excluded @ 94% C.L.(D0)
- ✓ Isospin=+1/2 — Not directly
- ✓ $t \rightarrow bW$ — ~100%
- ✓ Large Γ=1.42 GeV (m_b,M_W,a_s,EW corr.)
- ✓ Short lifetime — $c\tau$<53μm @ 95%C.L.(CDF)
- ✓ Couplings: a_t,v_t V_{td} ,V_{ts},V_{tb}, g_{ttH} — not yet measured, ΔV_{tb} ~ 11%



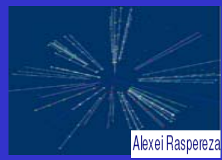
$$\tau_{had} = L_{QCD}^{-1} > \tau_{decay}$$

→ "t-quarks are produced and decay as free particles"

NO top hadrons



$t \rightarrow Wb$ → $qq'b$ (68%), $\ell\nu b$ (32%)



$t\bar{t}$ final states (standard model):

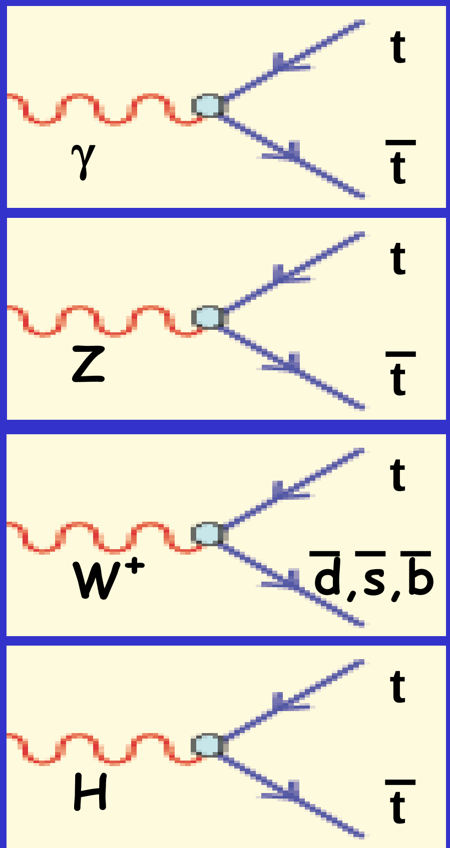
- ~46% 6 jets (2b)
- ~44% 4jets (2b) + lepton + neutrino
- ~10% 2jets (2b) + leptons + neutrinos
- (complicated topologies !!)

Detector capabilities required (very much demanding):

- b,c,τ-tagging in energetic b,c,τ-jets
- High energetic jet reconstruction
- W mass reconstruction (jets, leptons)
- Missing energy, ie, hermiticity
- Reconstruction of lepton direction
- Precise lepton identification (τ also)

ILC: Accurate measurements of SM-top parameters:

Top couplings



q_t = +2/3 |e|

Natural in e+e-

a_t , v_t

V_{td} , V_{ts} , V_{tb}

g_{ttH} ,

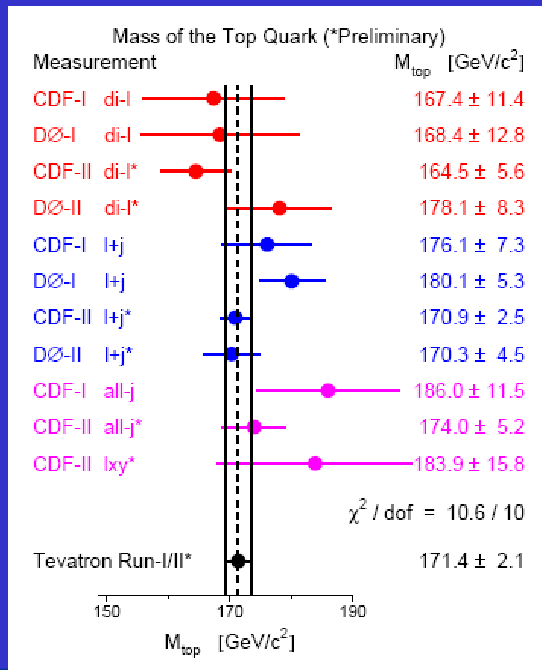
top Yukawa Coupling

σ_{tt} ($e^+e^- \longrightarrow$ tt)

Γ_{tt}

m_t (1‰)

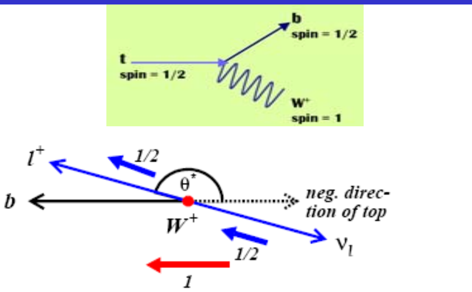
(at threshold and above)



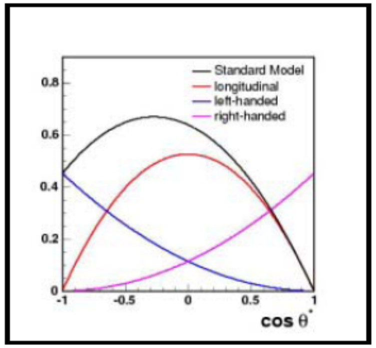
ILC: Accurate measurements of SM-top parameters:

Polarizations and Asymmetries

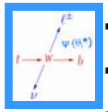
Darien Wood, ICHEP'06, "Electroweak Physics"



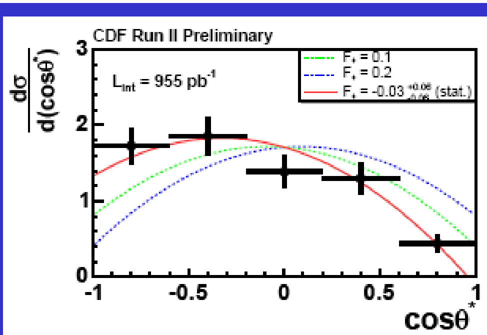
$$\frac{1}{N}\frac{dN}{d\cos\Psi} = \frac{3}{2}\left[F_0\left(\frac{\sin\Psi}{\sqrt{2}}\right)^2 + F_L\left(\frac{1-\cos\Psi}{2}\right)^2 + F_R\left(\frac{1+\cos\Psi}{2}\right)^2\right]$$

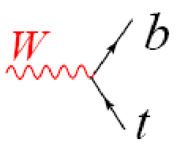


SM prediction of helicity fractions (assuming M_t=175GeV):



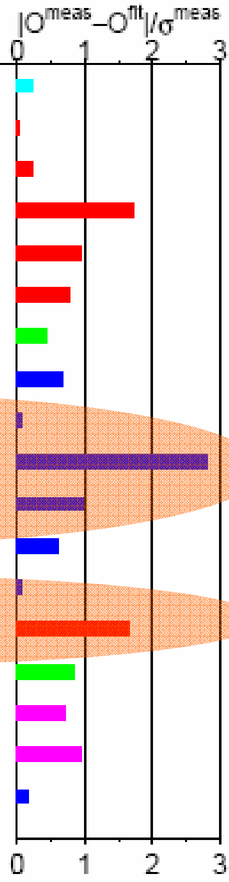
- SM(LO): F_0=0.703 , F_L=0.297 , F_R=3.6x10^{-4}
- (NLO): F_0=0.695 , F_L=0.304 , F_R=0.001





	F_0	F_R
CDF (~700 pb^{-1}) [prelim]		-0.02±0.07
CDF (955 pb^{-1}) [prelim]	0.61±0.12(stat)±0.04(syst)	-0.06±0.06(stat)±0.03(syst)
CDF (955 pb^{-1}) [prelim]	$0.59\pm0.12(stat)\pm^{0.07}_{0.06}$ (syst)	$-0.03\pm0.06(stat)\pm^{0.04}_{0.03}$ (syst)
DØ (370 pb^{-1}) [prelim]		0.08±0.08(stat)±0.05(syst)

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21585
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.392 ± 0.029	80.371
Γ_W [GeV]	2.147 ± 0.060	2.091
m_t [GeV]	171.4 ± 2.1	171.7

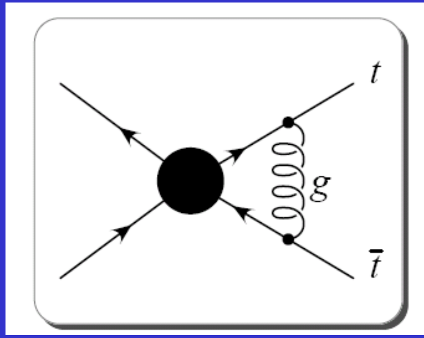


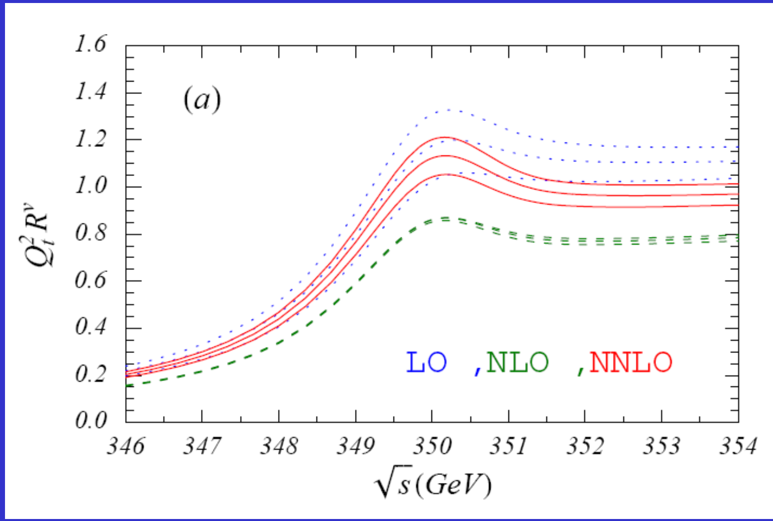
Asymmetries of heavy fermions are the most problematic

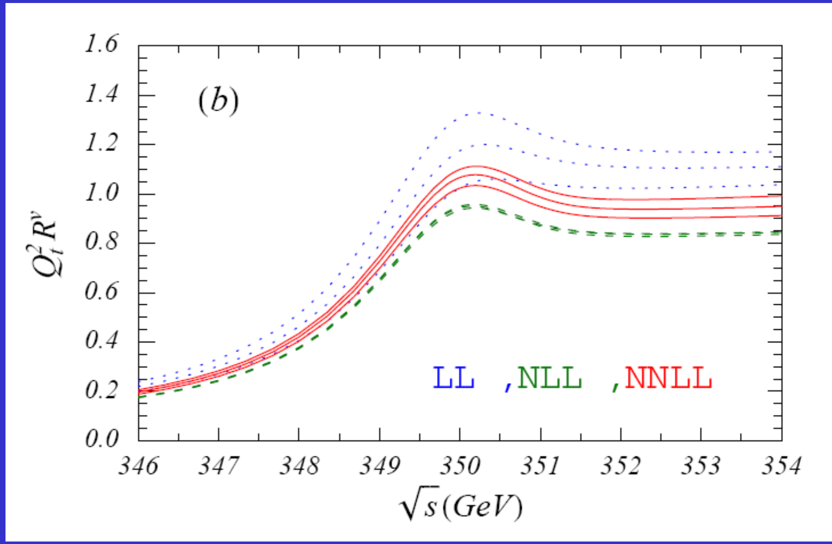
What will happen with top ?

ILC: Top cross section at threshold, theoretical issues:

- ✓ Theoretical issues for top-at-threshold:
- ✓ Coulomb potential, toponium bound state
- ✓ Theoretical interpretation of threshold scan mass
- ✓ NNLO, NNLL calculations available.





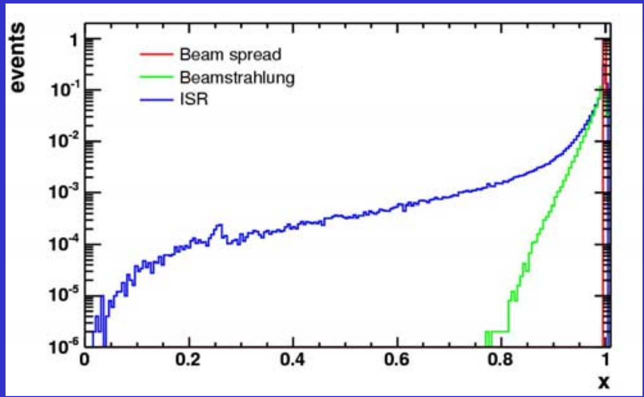


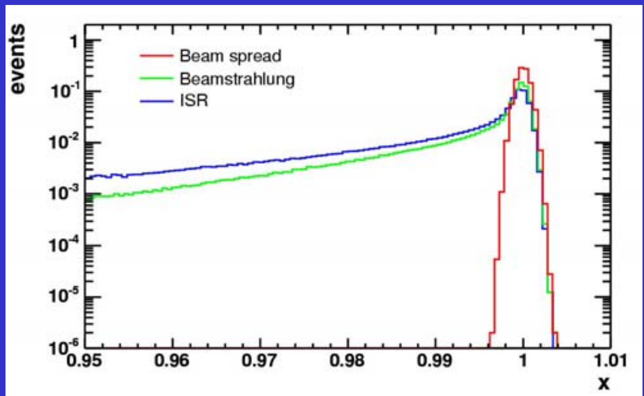
Vector current induced cross section with fixed M^{1S}_t

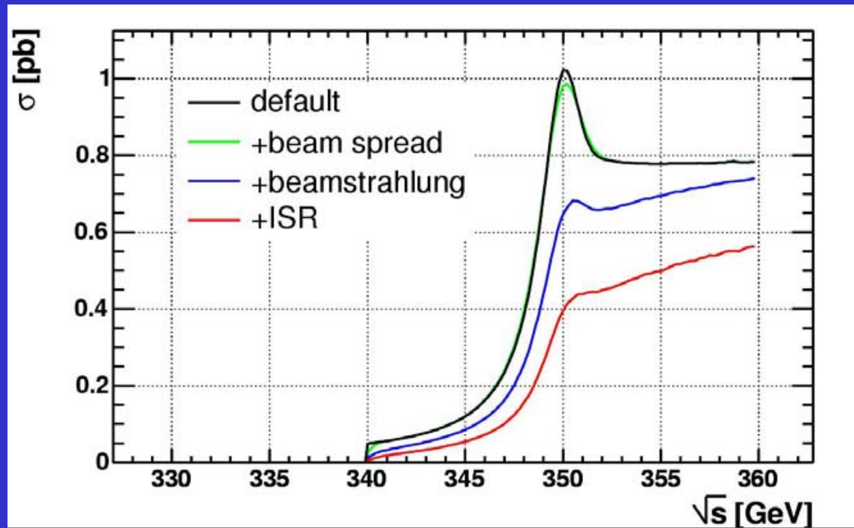
(a) fixed order, (b) Renormalization Group improved (A.H. Hoang, A.V. Manohar, I.W. Stewart, T. Teubner)

ILC: Top cross section, experimental issues:

Figures from S. Boogert, experimental top threshold scan, Snowmass 08/2005







- Effect on top cross section:

$$\sigma^{\mathrm{obs}}(\sqrt{s}) = \frac{1}{L_0}\int_0^1 L(x)\,\sigma(x\sqrt{s})\,\mathrm{d}x$$

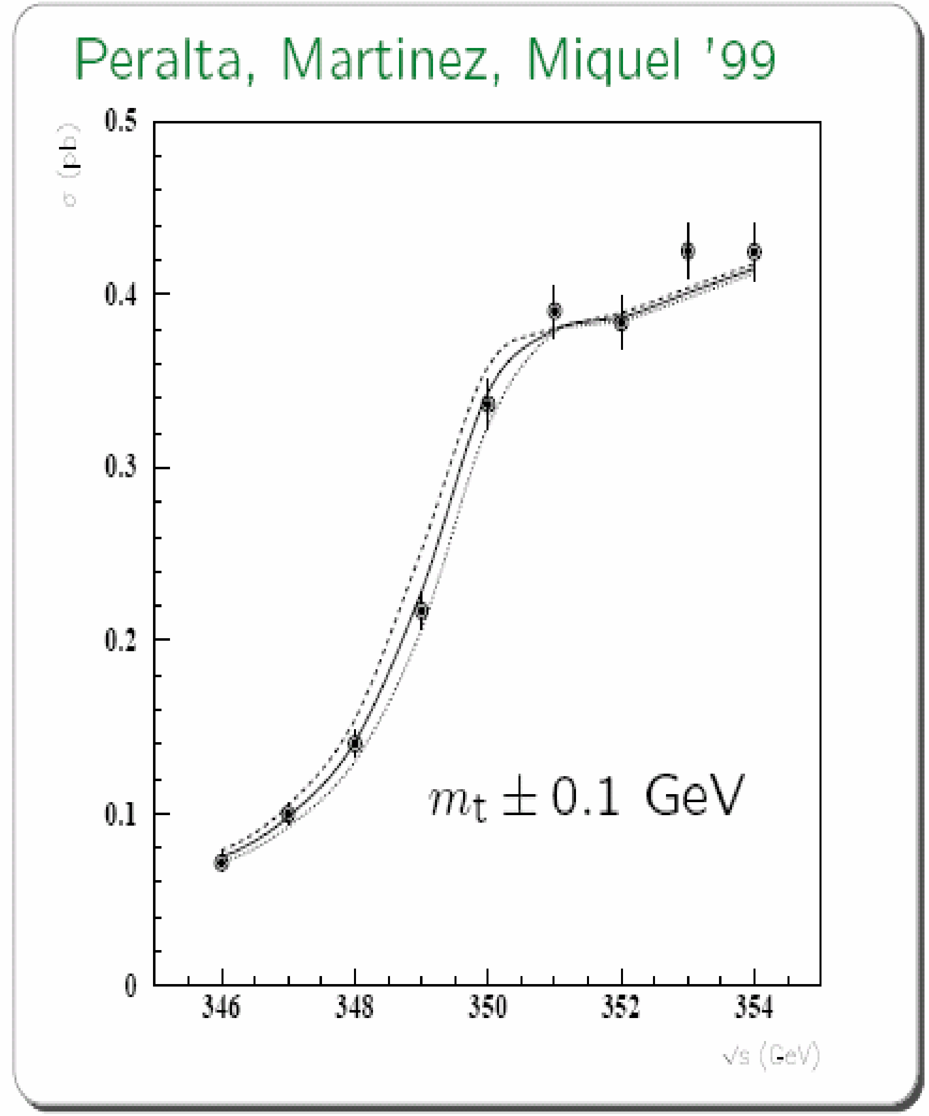
Top threshold is the benchmark for high precision analysis. Impressive progress but many details remain to be clarified to make error estimes (th+Exp) more reliable.

Accurate simulations including beam effects are needed for threshold scan

(T. Teubner, Ambleside Linear Collider Physics Summer School)

ILC: Top cross section:

- ✓ Measurement of tt cross section at various points around the production threshold. Fit top mass (and width).
- ✓ Total error top mass expected < 100 MeV or better.
- ✓ Complementary kinematic reconstruction of top anti-top events above threshold expected to yield good statistical uncertainty



ILC: CKM matrix elements from t decays

As an experimental requirement:

Clean isolation of the decay (ok at ILC)

Excellent quark flavour identification (b,c, uds)

Parton charge (efficient track reconstruction, track-to-vertex association, down to low p_T)

CKM from top decays,
Letts, Mattig '01

($\mathscr{L}$ ~ 300 fb^{-1})

			now	ILC
		V_{td}	0.0074 ± 0.0008	± 0.026
		V_{ts}	0.0406 ± 0.0027	$\pm \mathbf{0.006}$
		V_{tb}	$1.0 \quad \pm 0.11$	$\pm \mathbf{0.005}$

ILC: Top couplings to Z and γ

- 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   CP-violating

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

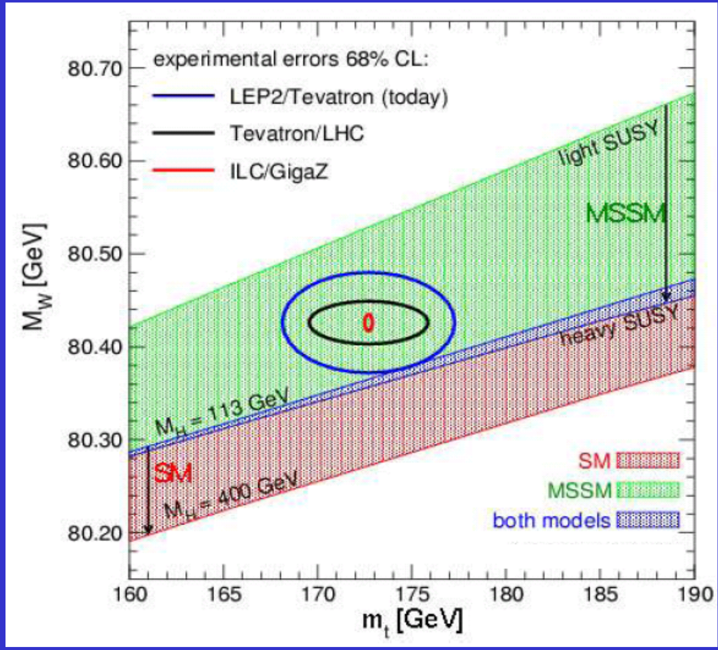
See Aurelio Juste talk at Vancouver: for Ztt ILC better than LHC

for γtt ILC comparable to LHC

ILC: top and SUSY

No need to stress the importance of precision measurements of Standard Model parameters to constrain theory.

The top mass may reveal to be one of the most important ones.



Top decay t-> Wb (~100% in SM), W-> e, μ, τ (Branching ratios 10% per lepton)

For 2 doublet Higgs sector, with light charged Higgs boson H^+, top decay t -> H^+b becomes competitor. $H^+ \to \tau\, \nu$ (branching ratio ~ 1 for tan Beta > 10 and $mH^+ < m_t - m_b$)

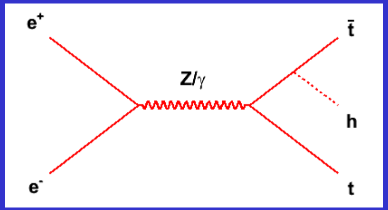
Measure Br.R. (**t** -> $\mu\, \nu$ b) / Br. R.(**t** -> $\tau\, \nu$ b), calibrate with W production.

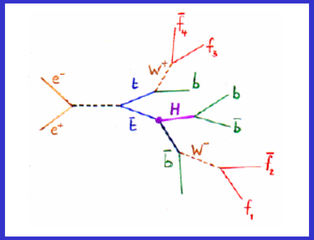
Experimental requirement: precisely reconstruct missing energy and t - decays (including hadronically decaying τ–jets)

ILC: top Yukawa coupling to Higgs

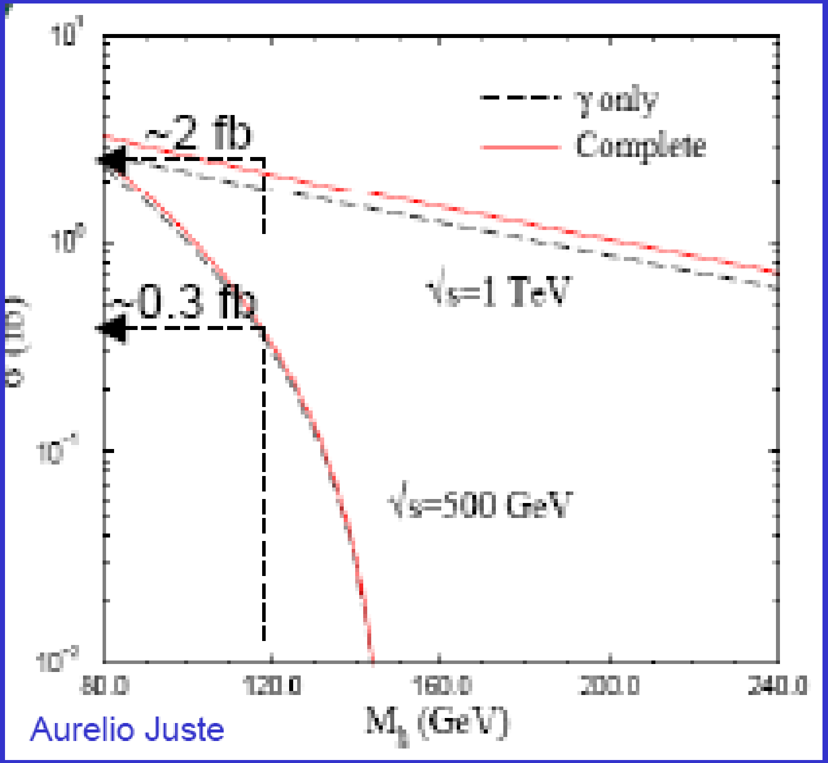
tt production cross-section at threshold is sensitive to **tt**h Yukawa coupling.

For m_h = 115 GeV, a variation of 14% in SM Yukawa coupling leads to a 2% change in normalization of the cross section near the 1S peak.





Very complicated topology



6jets +2bjets+leptons+missing energy

4jets +2bjets

2jets + 4bjets + leptons + neutrinos

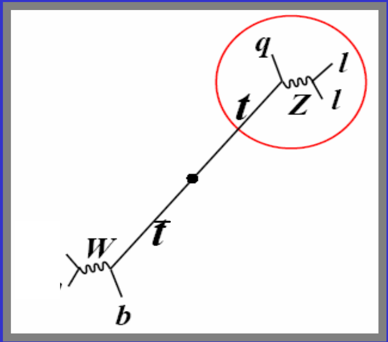
$$\frac{\Delta g_{ttH}}{g_{ttH}} \sim 15\%,\ m_h \sim 120\ \text{GeV}$$

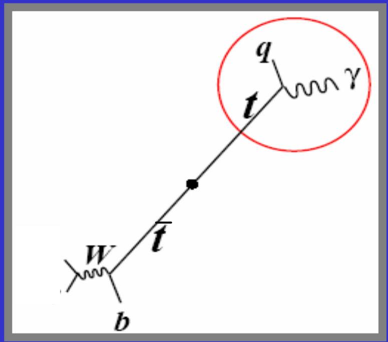
(E_{beam} ~ 250 GeV, $\mathscr{L}$ ~1000 fb^{-1})

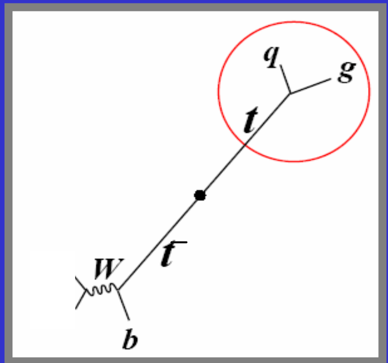
(with polariztion 60%e+,-80%e-)

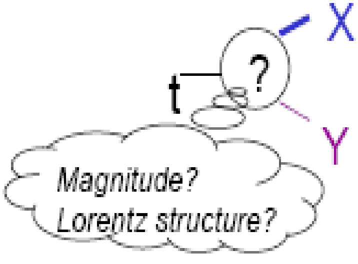
Aurelio Juste

ILC: t and exotic physics, rare decays, FCNC









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 $f_1^{LR} - \bar{f}_1^{LR} \neq 0$ or $f_2^{LR} - \bar{f}_2^{RL} \neq 0 \Rightarrow$ CP-violation

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

hep-ph/0102197

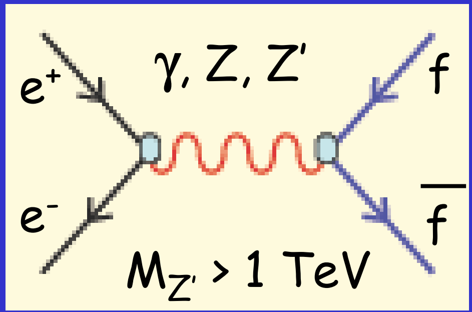
$\sqrt{s}$ = 500 GeV
L = 100 fb^{-1}

	(P(e⁻),P(e⁺)) = (0,0) No pol. 95%	3σ	(P(e⁻),P(e⁺)) = (-0.8,0) Pol. e^- 95%	3σ	(P(e⁻),P(e⁺)) = (-0.8,+0.45) Pol. $e^- e^+$ 95%	3σ	
$Br(t \to \gamma q)$	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
$Br(t \to Zq)$ (γ_μ)	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
$Br(t \to Zq)$ $(\sigma_{\mu\nu})$	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.

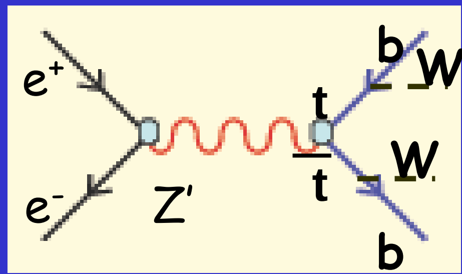
ILC: t and exotic physics, Z' resonances

Even, if Z' discovered at LHC in leptonic decays



→ $\bar{f}\gamma^{\mu}(v_f' - a_f'\gamma^5)f$

↓ f=t



Very important to make accurate measurements of the couplings to discrimante between Z' models (very difficult at LHC):

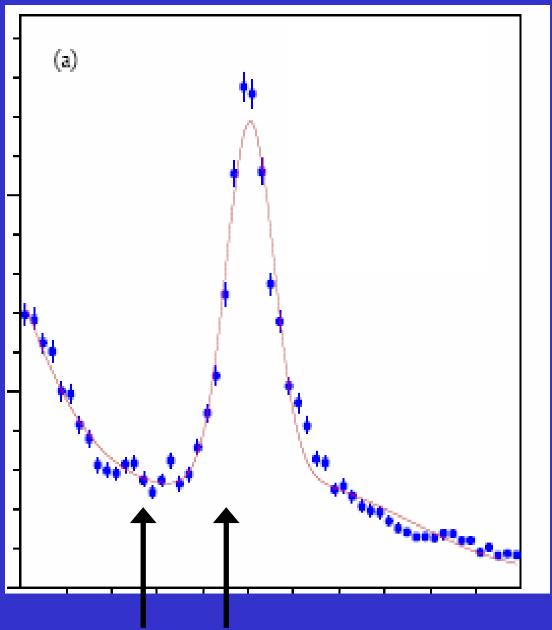
SM Z'

LR symmetric models

Little Higgs

Extra dimensions

Effective symmetries



Depending on the beam energy it will be more or less difficult to extract couplings ! Energy crucial !!

Key Observables

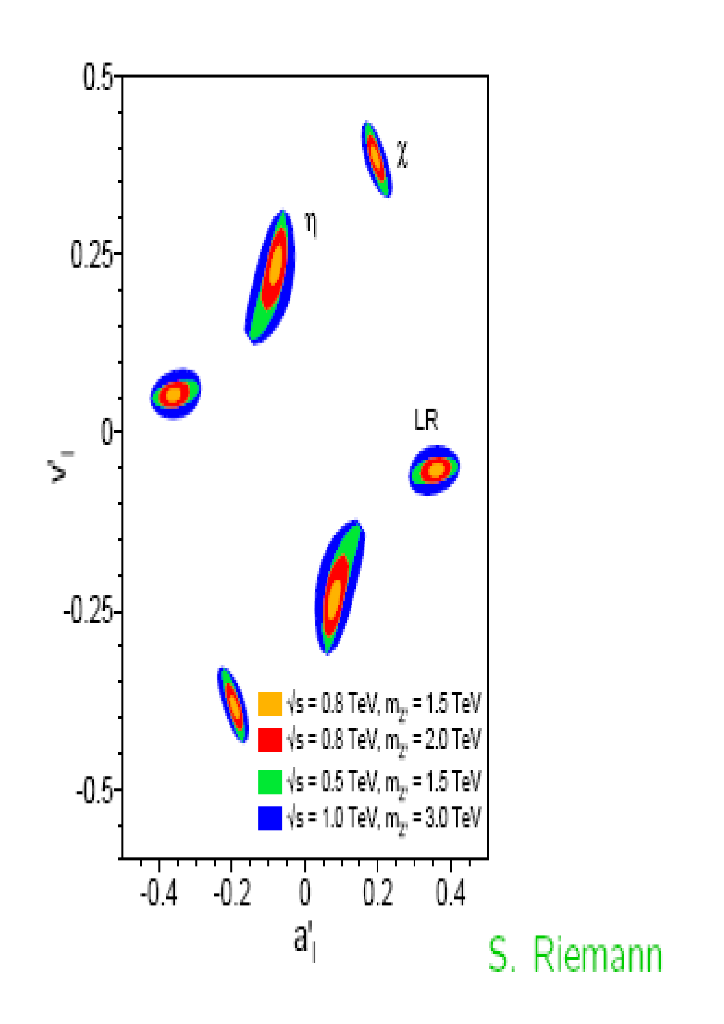
$\sigma_t \sim (v_t')^2 + (a_t')^2 \quad A_f^{FB} \sim \dfrac{2v_f' a_f'}{(v_t')^2 + (a_t')^2}$

Polarization studies also possible (like τ at LEP)

(if all decay productis recosntructed)

Polarized beams very beneficial !

ILC: t and exotic physics, Z' resonances, possibilities



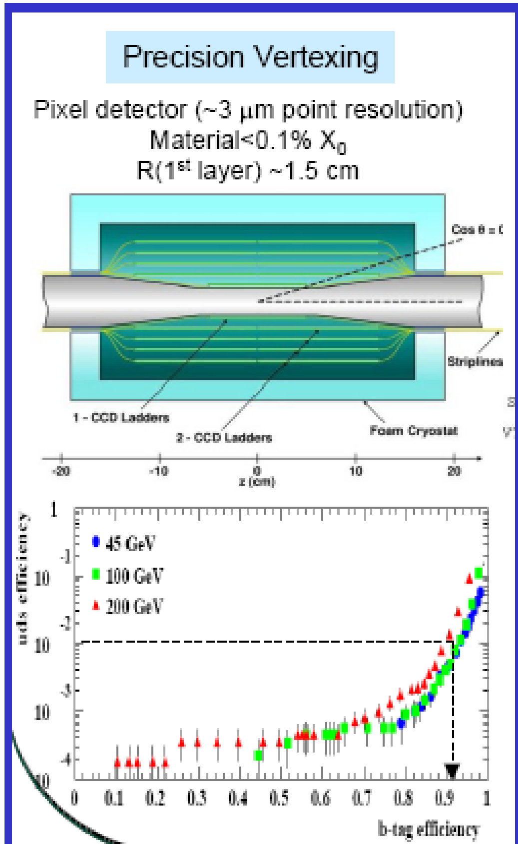
Energy	Observables	Δ(%)	Deviation From SM
500 (GeV)	R_t	0.2	+24
500 (GeV)	A_t^{LR}	0.1	+200

Resolving the A_b^{FB} puzzle in an extra dimensional model

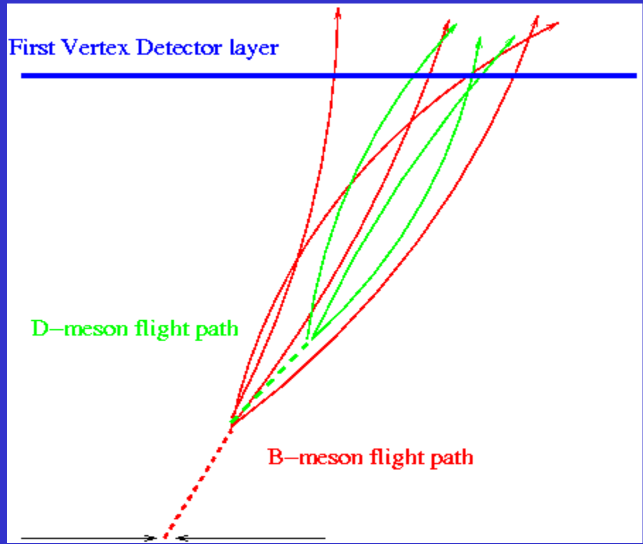
(A. Djouadi, G. Moreau, F. Richard)

(E_{beam} ~ 250 GeV, $\mathscr{L}$ ~500 fb^{-1})

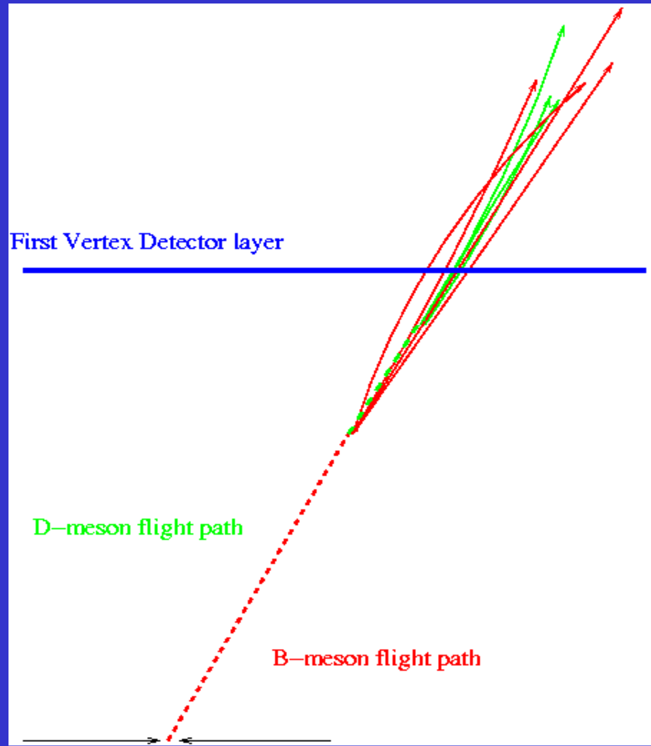
Main background being ZWW events, accurate reconstruction of Z mass needed (particle flow)



Flavour tagging at ILC



"soft b-jet"

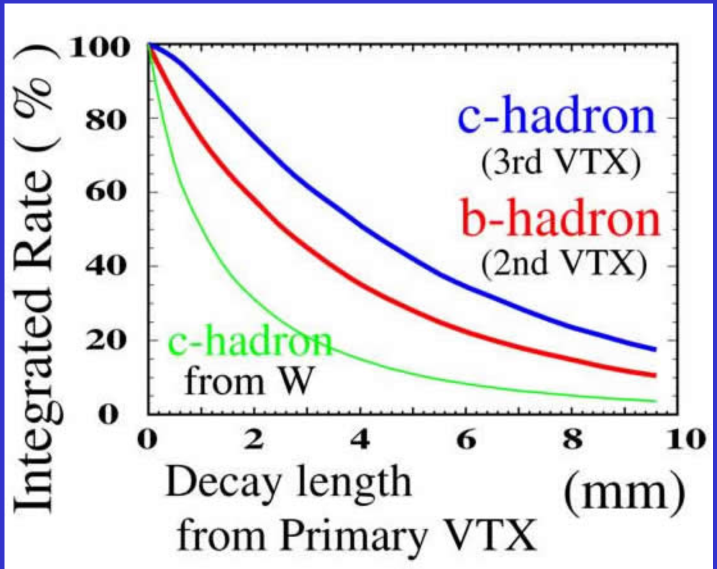


"hard b-jet"

- ✓ Typically b-tagging becomes "easier" for larger jet energy (more and stiffer tracks, boost leads to greater displacement of the vertex for the same lifetime)
- ✓ True only up to the point where a negative effect kicks in: the dense environment in collimated jet, with B/D decay vertex very close to first layer, leads to problems in hit-to-track assignment, merging of hits etc.

Flavour tagging at ILC

How close do our secondary vertices get?

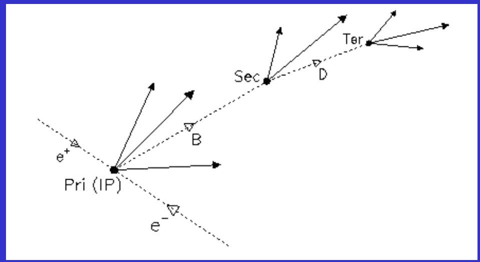


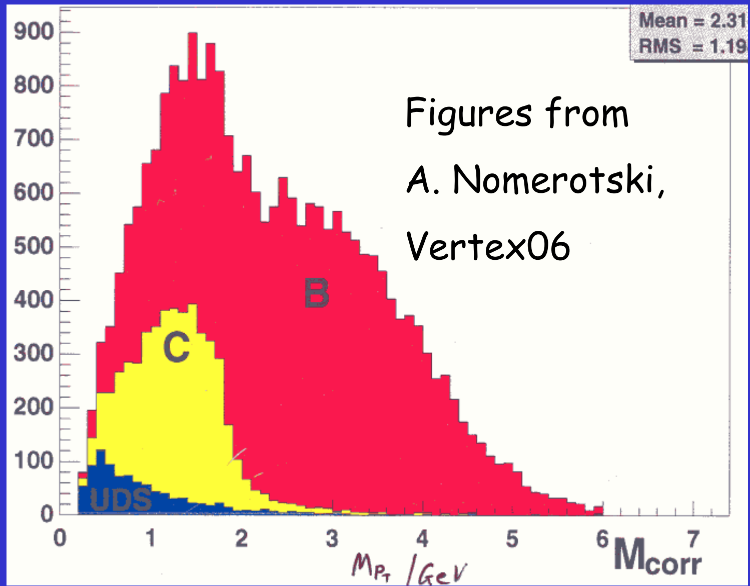
- ✓ Illustration: decay length of B-hadrons with 40-50 GeV (ACFA report)
- ✓ Typical values for top (produced at rest) decay products: jet energy ~ $m_t/2$
- ✓ decay length (distance PV-SV) = $\beta\, \gamma\, c\, \tau$
- ✓ (b-jets: $\langle c\tau \rangle$ ~ 450 μm, $\langle \beta\gamma \rangle$ ~ 20)
- ✓ (τ-jets: $\langle c\tau \rangle$ ~ 80 μm, $\langle \beta\gamma \rangle$ ~ 50)

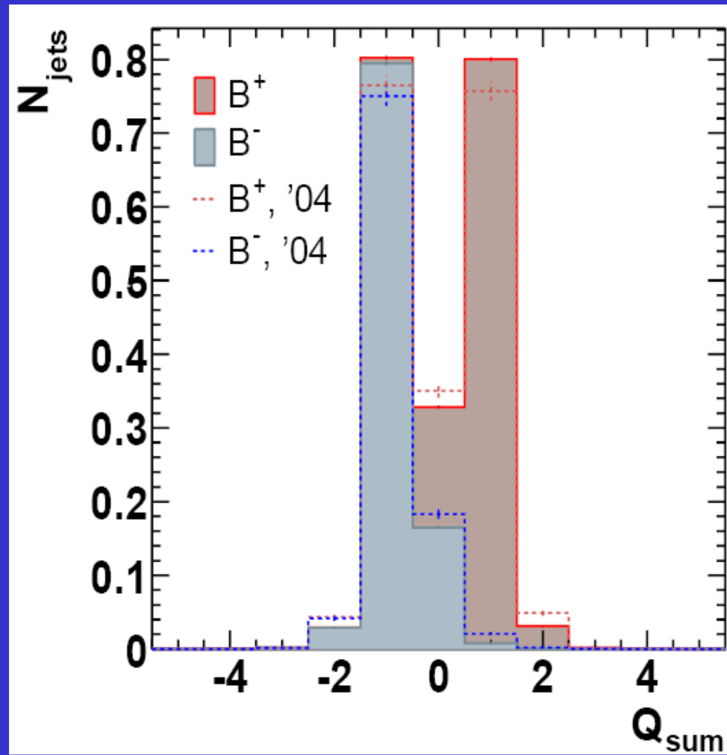
A good fraction of B-hadrons from top decay at rest (and charmed hadrons formed in the B-decay) come very close to the first vertex layer. For large M_{tt} events….

τ-leptons travel much less before decay, and the (charged) decay products are typically few. However, high energy τ-jets are extremely collimated.

Flavour tagging at ILC II

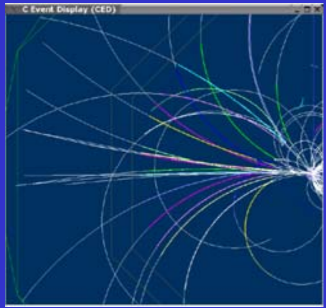




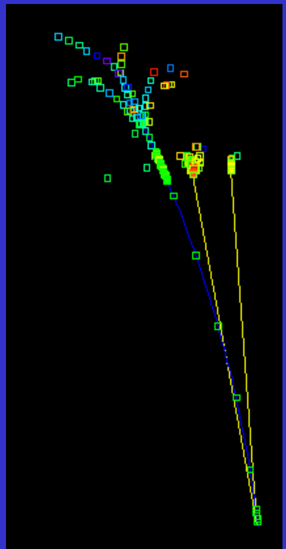


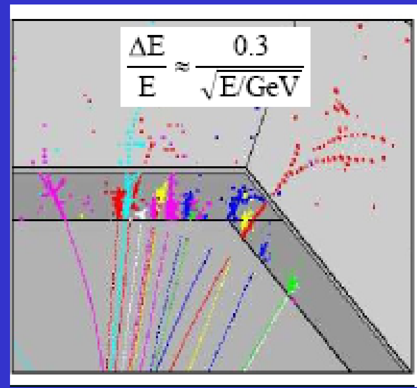
✓Impact parameter is not the end of it: secondary (and tertiary) vertex reconstruction allows to determine decay vertex properties. Vertex sign determination allows to distinguish jets containing B^+ and B^- , of utmost importance for asymmetries.

✓One lost track (or one fake) ruins it all. Tracking efficiency (and fake control) is crucial! Reconstruction needs to be tested on realistic Monte Carlo (including pattern recognition).



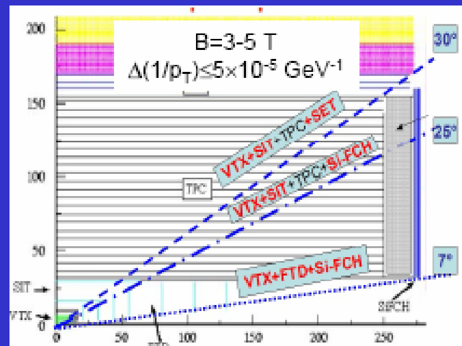
Particle Flow – Jet Energy reconstruction ILC





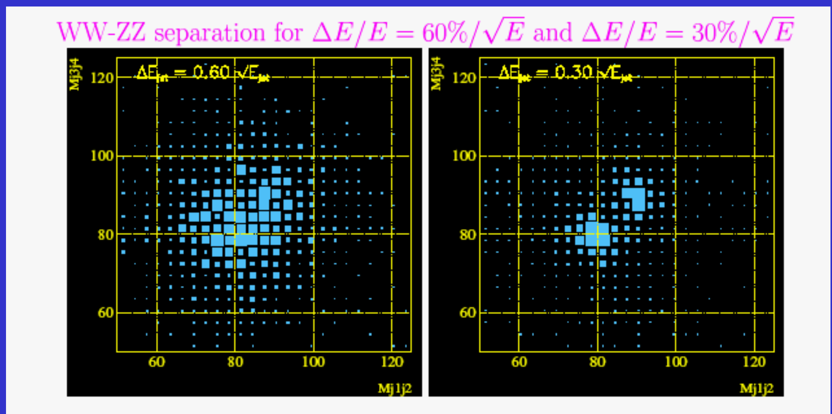
Jet Reconstuction:

- Track momentum resolution important but not only
- Two track separation essential
- Track association to calorimeters and vertex



Jets in top topologies:

- Essential to have very good jet-jet invariant mass resolution (W-Z separation, etc..)
- Energetic jets imply high collimation requiring granularity



Resolution on the jets δE_{jet}	2-3 better than LHC
Granularity/segmentation of the calorimeter	>250 x LHC

Reconstructiog multi-jet final states (from LEP knowledge)

" we know that they are not fully understood in generators, specially when *heavy quarks are involved*"

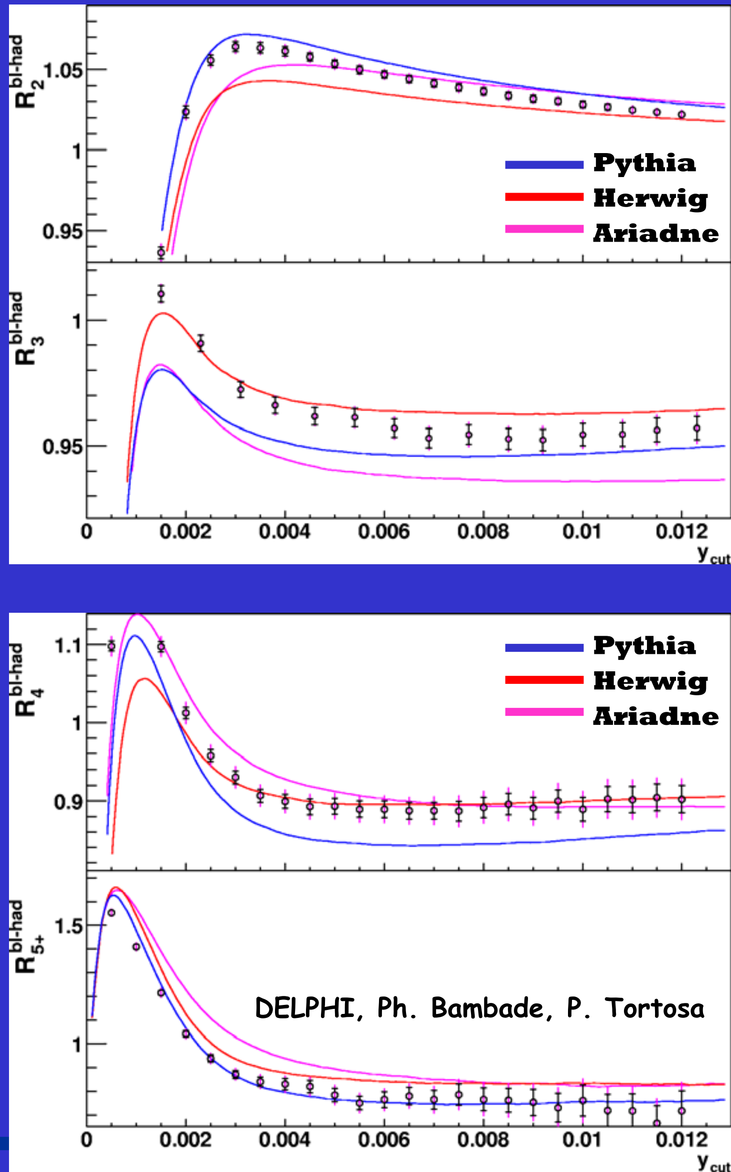
Double rates ($R_n^{b\ell} = R_n^b / R_n^\ell$)

$$R_n^{b\ell}(y_c) = \frac{\sigma_{nj}^{Z^0 \to b\bar{b}(n-2)g}(y_c) / \sigma_{tot}^{Z^0 \to b\bar{b}}}{\sigma_{nj}^{Z^0 \to \ell\bar{\ell}(n-2)g}(y_c) / \sigma_{tot}^{Z^0 \to \ell\bar{\ell}}}$$

Cancel systematics. Small hadronisation corrections, partial cancellation of higher order terms

Cancel EW effects.

- No generator describes all rates at the same time
- In general there are more heavy quark jets than predicted



Understanding top/background final states will need improved generator descriptions for heavy quark initiated jets

Conclusions

Top physics are very rich and its exploitation is very detector performance demanding (vertexing, tracking, calorimetry and flavour identification)

Due, mainly, to its large mass studying its phenomenology is not only interesting for Standard Model measurements but also to evaluate the existence of many new physics scenarios

ILC complements with LHC also for top

A lot of work though extremely challenging waiting for us ...