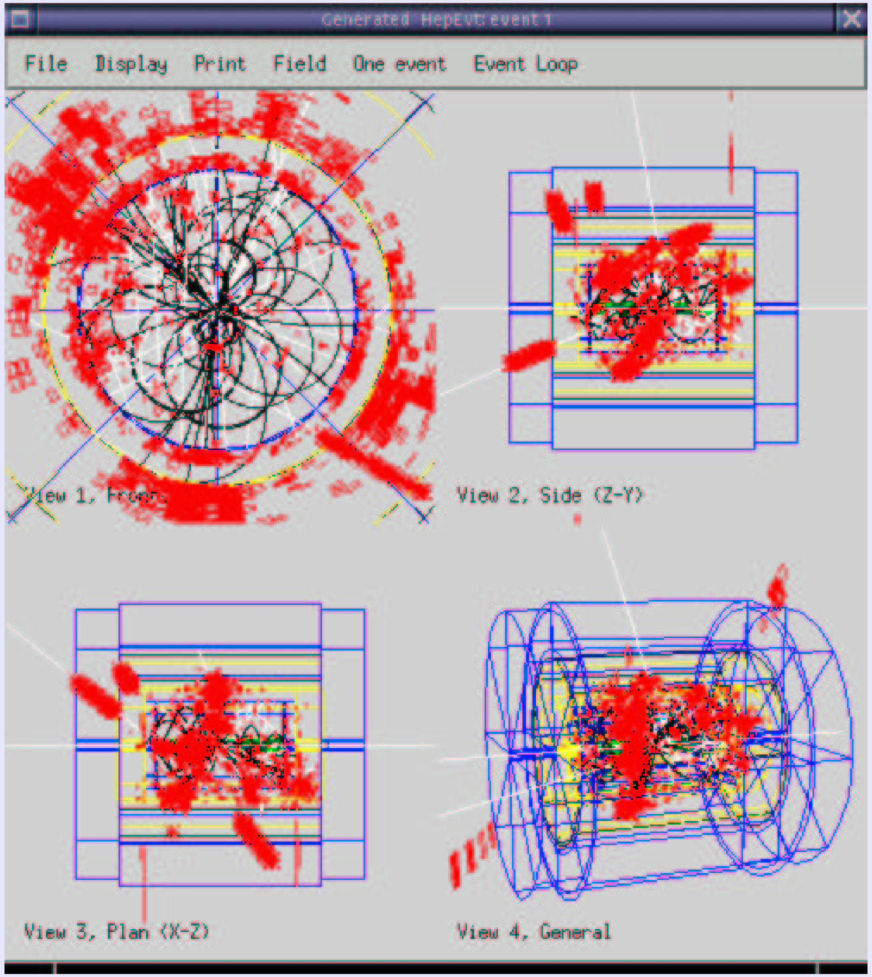
Top/QCD at the Linear Collider: Experimental Aspects



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Loopfest
May 7, 2002

Outline

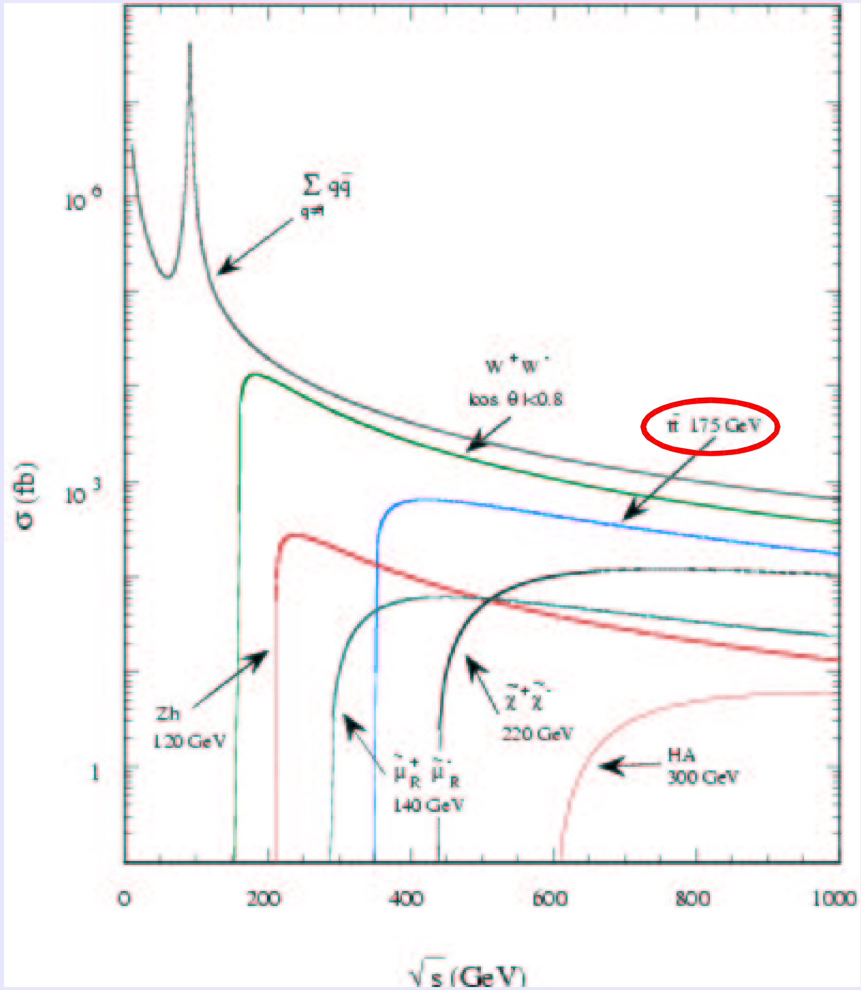
- Top Quark Physics
  - Measurements at threshold
  - Measurements above threshold
- QCD
  - Precision measurement of α_s
  - Q^2 evolution

Machine Parameters

	TESLA(500)	TESLA(800)	NLC(500)	NLC(1000)	Tevatron
E (GeV)	500	800	500	1000	2000
Lum. x 1E33	31	5	20	34	0.1
Rep rate (Hz)	5	3	120	120	--
Bunches/pulse	2820	4500	190	190	--
Bunch sep (ns)	337	189	1.4	1.4	396
$\sigma(x)$ at i.p.	553 nm	391 nm	245 nm	190 nm	30 μm
$\sigma(y)$ at i.p.	5 nm	2 nm	2.7 nm	2.1	30 μm
$\sigma(z)$ at i.p.	0.4 mm	0.3 mm	110 nm	110 nm	30 cm
$\delta B(\%)$	3.3	4.7	4.7	10.2	0
P(e−) (%)	80−90	80−90	80−90	80−90	--
P(e+)(%)	60	60	--	--	--

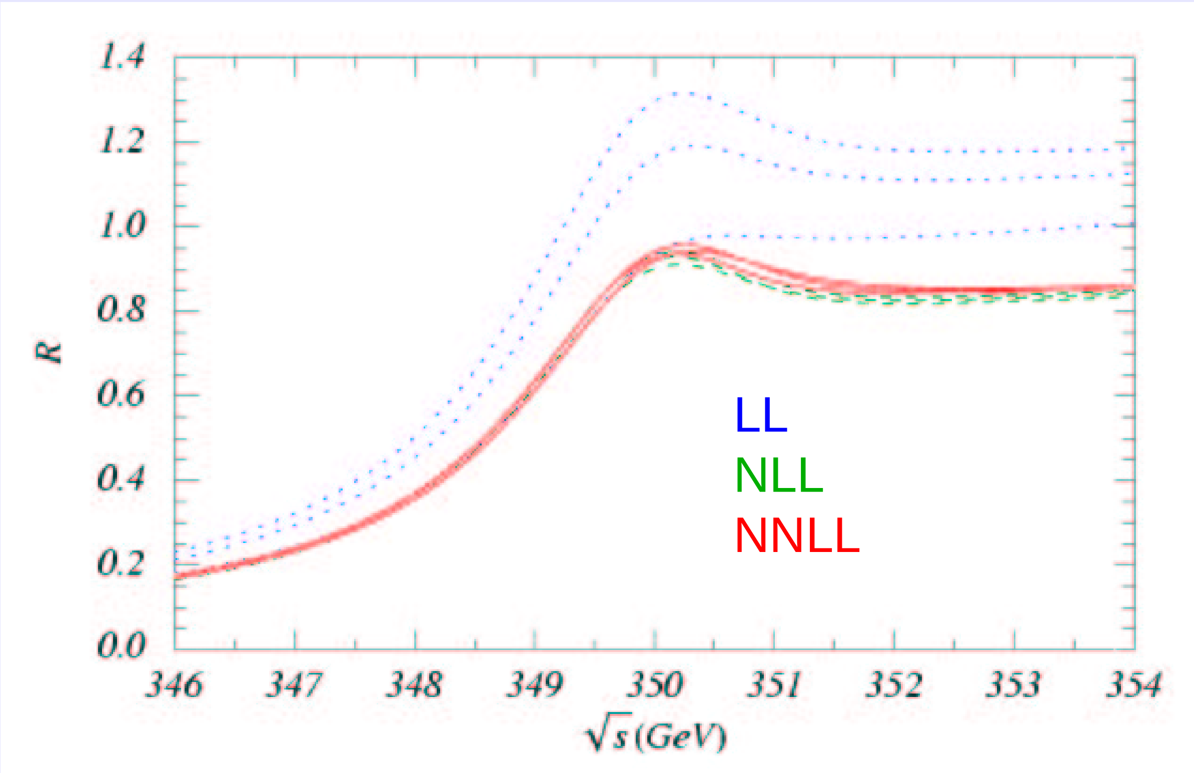
Top Production at the LC

- $\sigma_{tt} \approx 0.6$ pb at $\sqrt{s} = 500$ GeV
- $\Rightarrow$ 200,000 *tt* pairs / year at TESLA design luminosity.
- Why "do top"?
  - $\Gamma_t \sim 1.3$ GeV >> Λ_{QCD}, so top decays before hadronization: Unique opportunity to observe the weak interactions of a bare quark.
  - m_t, Γ_t, g_{tth} etc. are precision EWK parameters.
  - Possible role in EWSB dynamics



Top Quark Threshold

Large top width provides IR cutoff, so can use pQCD to compute threshold cross section. Convergence is sensitive to mass definition used: pole and kinematic masses not IR−safe.

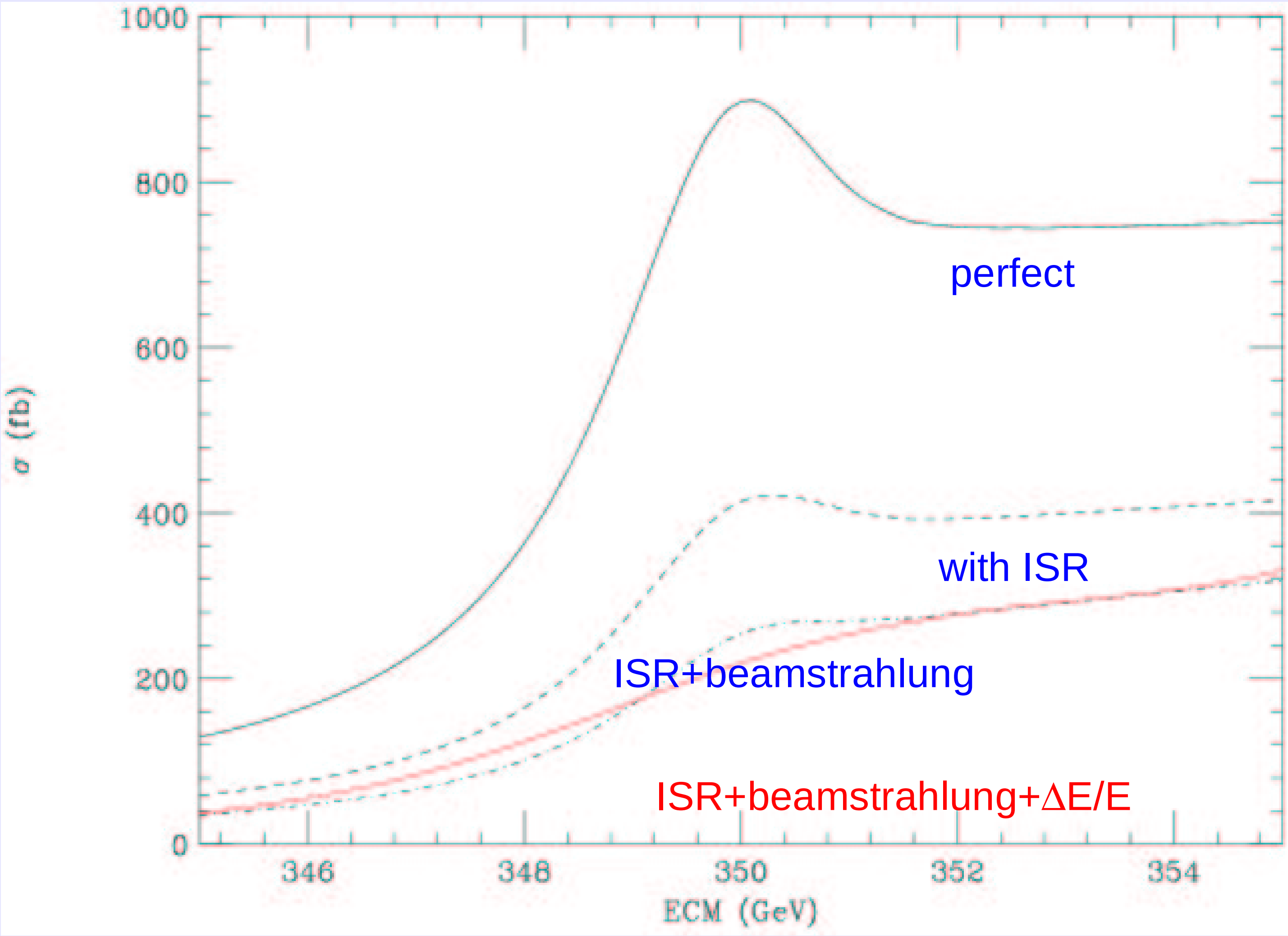


Hoang, Manohar, Stewart, Teubner, hep−ph/0107144

Best results come from using the 1S mass definition (½ the mass of the lowest *tt* bound state, evaluated in the limit $\Gamma_t \to 0$) combined with a velocity resummation.

Also, reduces previous large correlation between m_t and α_s.

Machine Effects on Top Threshold Lineshape

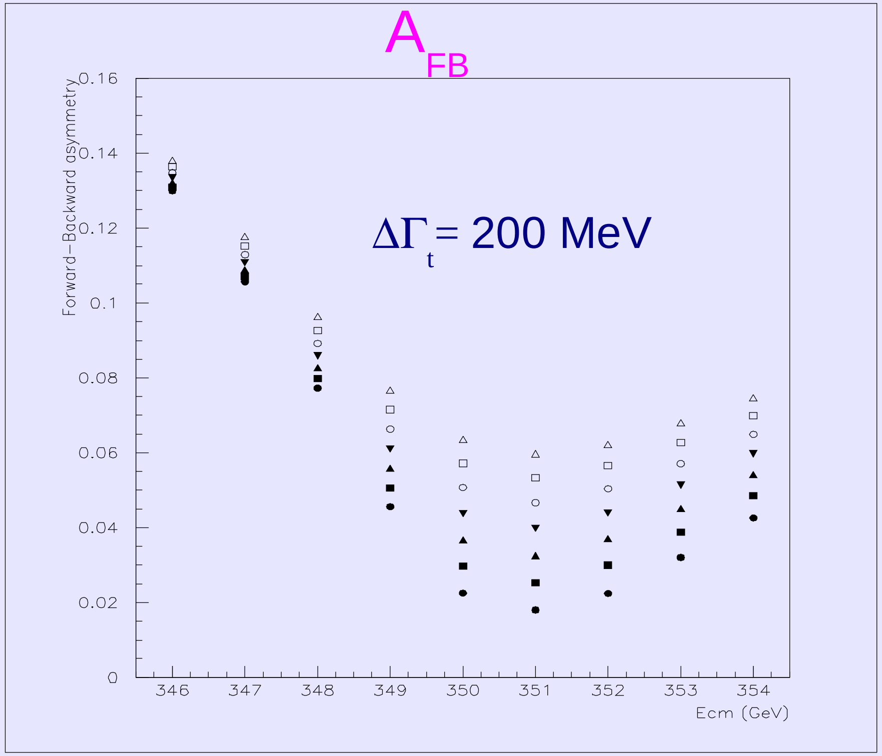


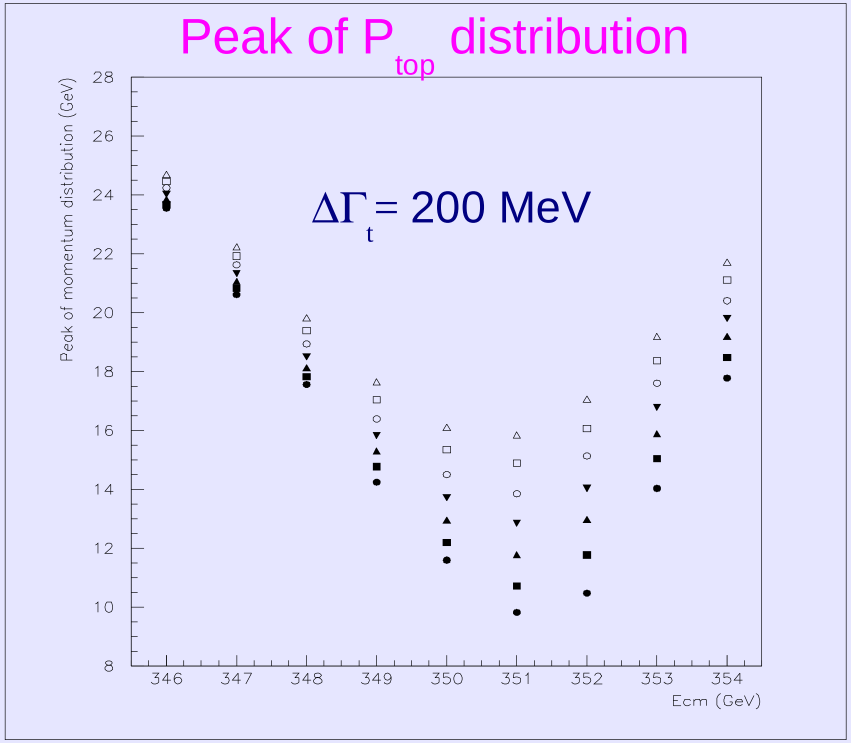
Note: can reduce beamstrahlung at cost of luminosity: optimization issue for experimentalists.

Threshold Measurements

Recent analysis by R. Miquel, M. Martinez (Chicago LCWS '02):

- Assume 300 fb^{-1} and 9 scan points plus one well below threshold for background determination.
- Use the cross section and, in addition, the observables A_{FB} and P_{peak}



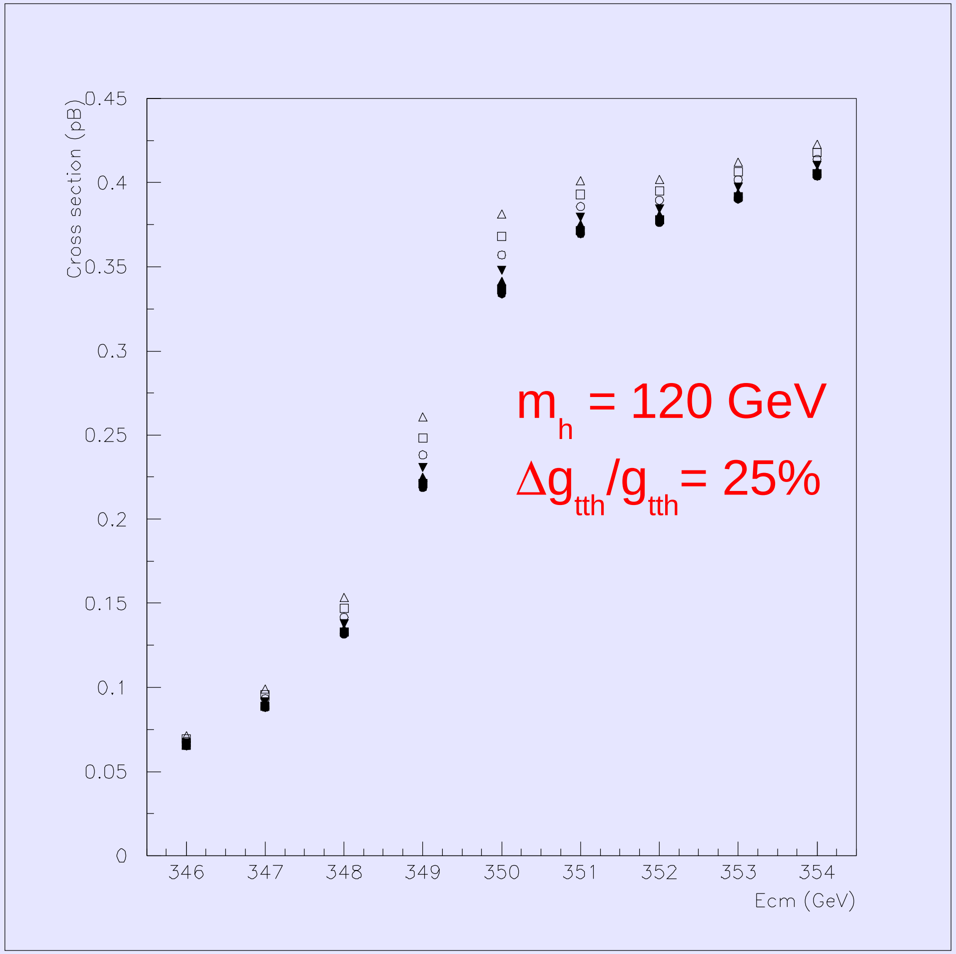


Threshold Results

- Mass: Δm_t = 16 MeV, $\Delta\alpha_s$ = 0.0011
  - Using cross section only: Δm_t = 24 MeV, $\Delta\alpha_s$ = 0.0017.
  - Γ_t, g_{tth} fixed at SM values; assume m_h=120 GeV, $\alpha_s(M_Z)$=0.120.
  - Theory error: ~100 MeV.
- Width: allow to vary in a 3−parameter fit.
  - $\Delta\Gamma_t$ = 32 MeV, Δm_t = 18 MeV, $\Delta\alpha_s$ = 0.0015
  - 2% exp. uncertainty on width

Top−Higgs Yukawa Coupling at Threshold

- Small effect in all observables, diminishes rapidly for m_h>120 GeV
- If all other parameters fixed (best−case scenario), find $\Delta g_{tth}/g_{tth}$= +17%−24%
- Fit m_t, Γ_t, g_{tth} simultaneously with 0.001 constraint on α_s:
  $\Delta g_{tth}/g_{tth}$= +33% −57%
  (with correlations up to 85%)
  Also Δm_t=30 MeV, $\Delta\Gamma_t$=33 MeV.
- ⇒This measurement looks hard.

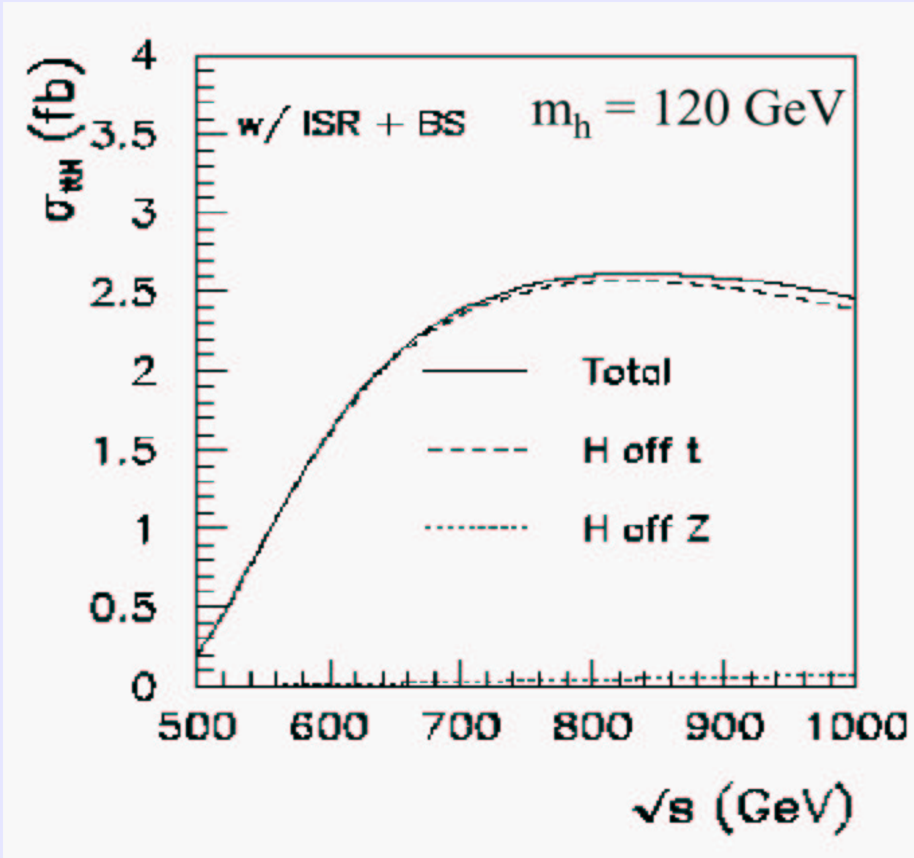


Loopfest Wish List for Top Threshold

- Measurements may be dominated by theory systematics.
- Much progress in recent years on threshold cross section. How much more can calculation be improved? Better quantification of systematics?
- Improved calculations of other threshold observables (NLL calculations currently used for A_{FB}, P_{peak}, e.g.)

$t\bar{t}H$ production and the Top Yukawa Coupling

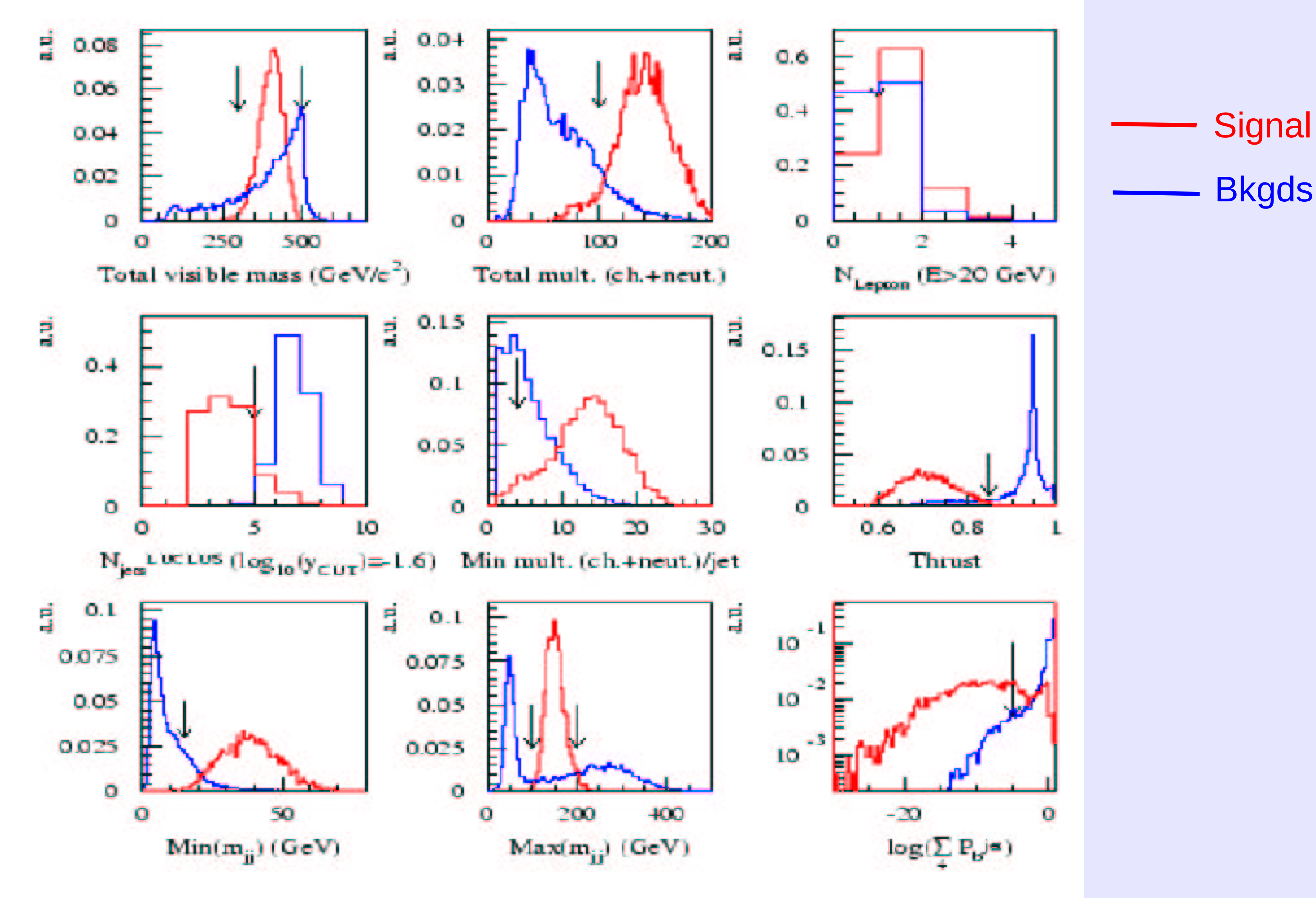
- $e^+e^- \rightarrow$ ttH $\rightarrow$ WbWb bb
- Very complicted final state:
  - Up to 8 jets
  - 4 b's
  - Many kinematic constraints
- Tiny cross section (~2 fb), with backgrounds ~3 orders of magnitude higher.
- Interfering backgrounds from EWK (ttZ), QCD (g→bb)
- Non−interfering backgrounds
  - Dominantly $e^+e^- \rightarrow$ tt
  - Formally smaller number of partons, but can enter the selection due to hard gluon radiation, detector effects, and their very large cross sections



$t\bar{t}H$ Analysis Strategy (Juste, Merino)

- Lots of luminosity: 1 ab^{-1} at 500 GeV
- Loose preselection on semileptonic final states (9 event variables)
  - Retains ~45% of signal while reducing bkgs by 2−3 orders of magnitude.
  - Still have only ~36 signal events, ~3800 bkgd events, about half of which are tt.
- Then apply multivariate analysis to remaining events. Neural net that uses the 9 preselection variables plus 14 more.

ttH Preselection



ttH Sensitivity

- For the semileptonic channel, L=1 ab^{-1}, m_H=120, find

$$\left(\frac{\Delta g_{ttH}}{g_{ttH}}\right)_{stat} \approx 0.33$$

- Only N~11 signal events, ~54 background events survive.
- Assuming √2 improvement from fully hadronic channel,

$$\left(\frac{\Delta g_{ttH}}{g_{ttH}}\right)_{stat} \approx 0.23$$

- NB: K−factors not used for signal or bkgd processes. Know K~1.5 for ttH @ 500 GeV (Dawson and Reina; Dittmaier et al.); would improve sensitivity by 22%. K−factors for backgrounds?
- Factor of 3−4 improvement at √s = 800 GeV.

Top Production/Decay Form Factors

General neutral−current couplings:

$$\Gamma^{\mu}_{t\bar{t}\gamma,Z} = ie\left\{ \gamma^{\mu}\left[F^{\gamma,Z}_{1V} + F^{\gamma,Z}_{1A}\gamma^5\right] + \frac{i\sigma^{\mu\nu}q_{\nu}}{2m_t}\left[F^{\gamma,Z}_{2V} + F^{\gamma,Z}_{2A}\gamma^5\right]\right\}$$

SM: only F^{γ}_{1V}, F^{Z}_{1V}, F^{Z}_{1A} are nonzero.

F_{2V} ⇒ weak magnetic dipole moment (≠ 0 in some strong EWSB models)

F_{2A} ⇒ weak electric dipole moment, violates CP. (≠ 0 in some SUSY models)

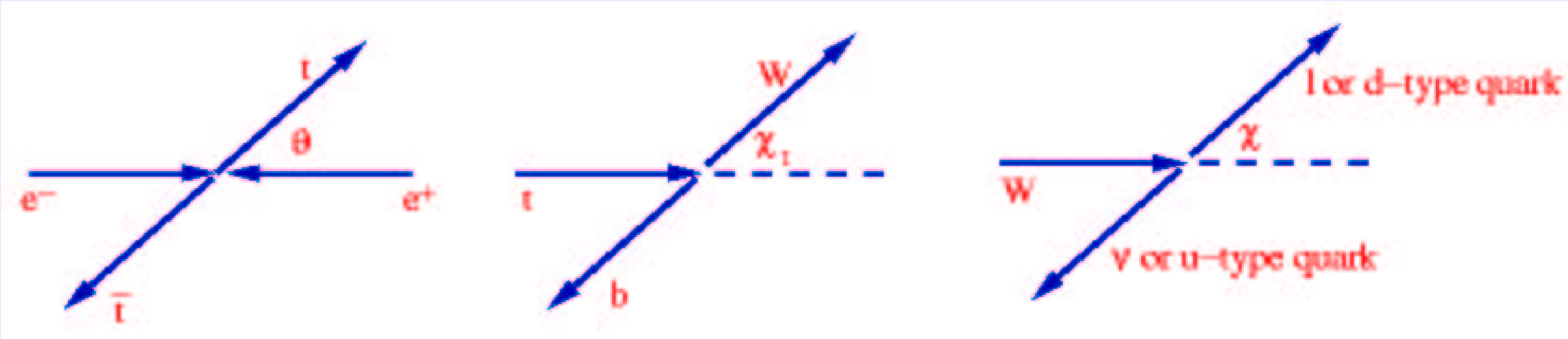
General charged−current couplings:

$$\Gamma^{\mu}_{tbW} = \frac{-g}{\sqrt{2}} V_{tb}\left\{ \gamma^{\mu}\left[F_{1L}P_L + F_{1R}P_R\right] + \frac{i\sigma^{\mu\nu}q_{\nu}}{2m_t}\left[F_{2L}P_L + F_{2R}P_R\right]\right\}$$

SM: only F_{1L} is nonzero.

Couplings Measurement

Information about the form factors is encoded in the helicity angles:



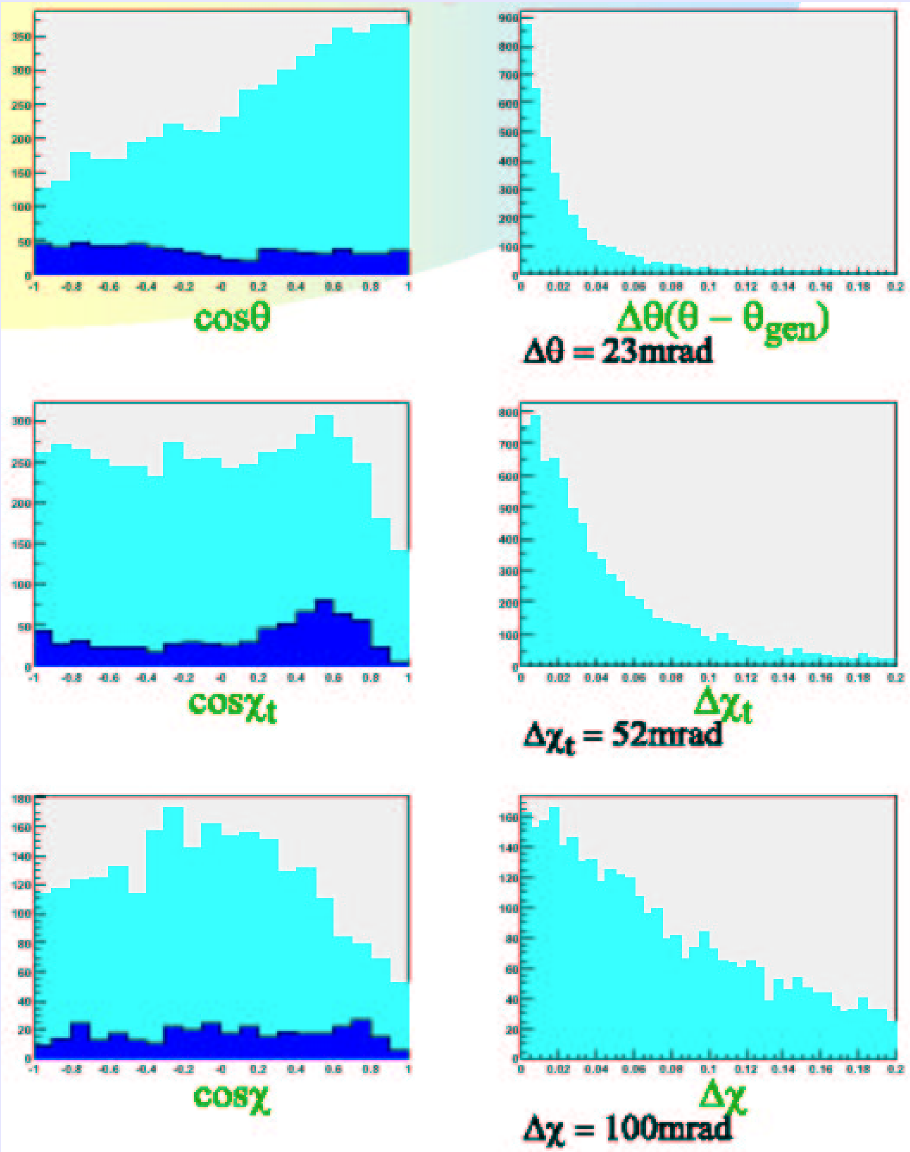
Focus on the semileptonic (4−jet) final state:

- Charge of lepton tags t or $\bar{t}$
- Can also use charge of b−tagged jet (ε=57%, purity = 83%)
- Four−momentum of the leptonic t−quark from the opposite hadronically−decaying top.

Analysis strategy (M. Iwasaki, 2002): assume 100 fb^{-1} at $\sqrt{s}$ = 500 GeV

- Force 4−jet final state using JADE clustering algorithm (ε = 60%)
- Cut on 2−jet invariant mass (W identification) and 3−jet mass (top ID) (50%)
- b−tag using SLD−esque algorithm ZVTOP. (67%)

Reconstructed Helicity Angles and Results



Axial form factors from maximum likelihood analysis:

68% C.L. sensitivities

	F^{γ}_{1A}	F^{Z}_{1A}	F^{γ}_{2A}	F^{Z}_{2A}
$P_{e^-} = -0.8$	0.011	0.013	0.016	0.049
$P_{e^-} = -0.8, P_{e^+} = 0.5$	0.009	0.011	0.021	0.033
No polarization	0.011	0.014	0.013	0.059
$P_{e^-} = +0.8$	0.011	0.015	0.014	0.052

Vector form factors from L−R asymmetry (200 fb^{-1})

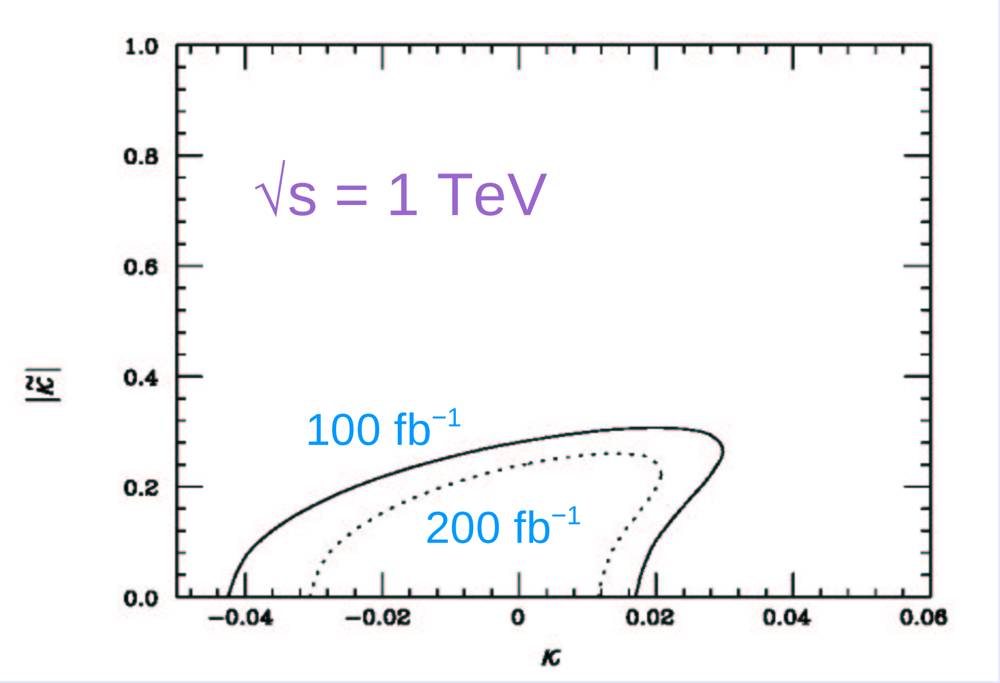
- $F_{1V}^{\gamma} \sim 0.05$
- $F_{1V}^{Z} \sim 0.01$
- $F_{2V}^{\gamma} \sim 0.04$
- $F_{2V}^{Z} \sim 0.01$

Top Quark Strong Moments

- Top may play a role in new strong interactions, which can modify top couplings through higher−dimension operators.
- Simplest, CP−conserving form:
- $\kappa, \tilde{\kappa}$ both zero in SM.

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

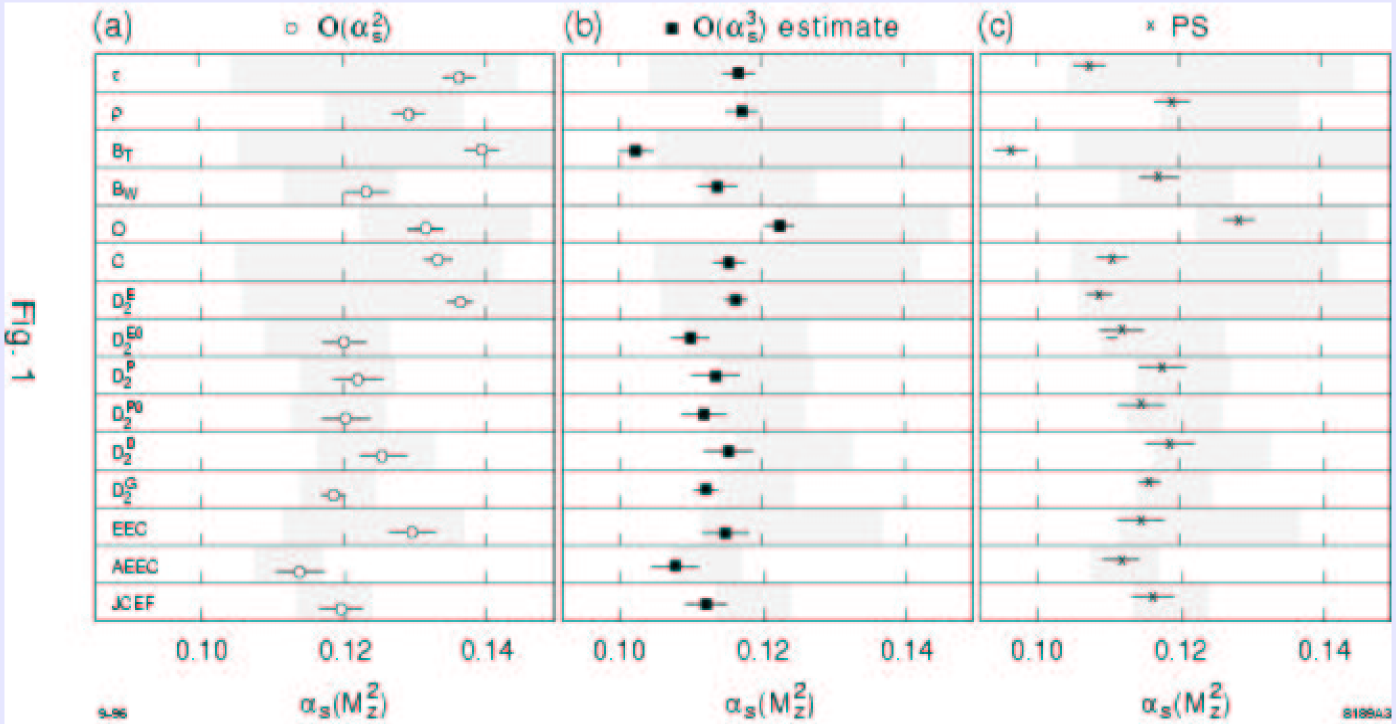
Affects energy spectrum and angular distribution of hard gluon radiation above threshold.



Precision Measurement of α_s

- Why?
  - RG extrapolation of the gauge couplings constrains / tests physics at the GUT scale. Currently limited by ~few percent uncertainty on α_s.
  - Measure Q^2−dependence over wide range to test QCD or reveal new physics.
- Main technique: event shape observables
  - E.g. thrust, sphericity, jet masses, jet rates...
  - Fit each observable to a pQCD prediction, allowing α_s to vary.
  - Statistical uncertainties currently ~0.001, experimental systematics at level of ~0.001−0.004.

Theory Uncertainty Dominates



P. N. Burrows, hep−ex/9612008

Points: measured values with exp. errors

Gray bands: theory uncertainty

Ratio Method (GigaZ)

- Measure inclusive ratios $\Gamma_Z^{had}/\Gamma_Z^{lept}$, $\Gamma_\tau^{had}/\Gamma_\tau^{lept}$, which depend on α_s through radiative corrections.
- LEP data (16M Z's): $\Delta\alpha_s$ = ±2.5% (stat.) ±1% (exp. syst.)
- GigaZ: $\Delta\alpha_s$ = ±0.4% (stat.)
- Theory uncertainties controversial: 1−2%, maybe as high as 5%.
- If theory uncertainties clarified/improved, this could be a competitive ~1%−level measurement.

α_s Wish List

- What we have:
  - 5 partons at tree level
  - 4 partons at one loop
  - parts of 3 parton amplitudes at 2 loops
  - Ratio method calculated to NNLO
- What we need for a 1% measurement:
  - Full NNLO calculation of jet rates!
  - For ratio method, need NNNLO calculation, as well as NLO(?) EWK corrections.
  - This is left as an exercise...

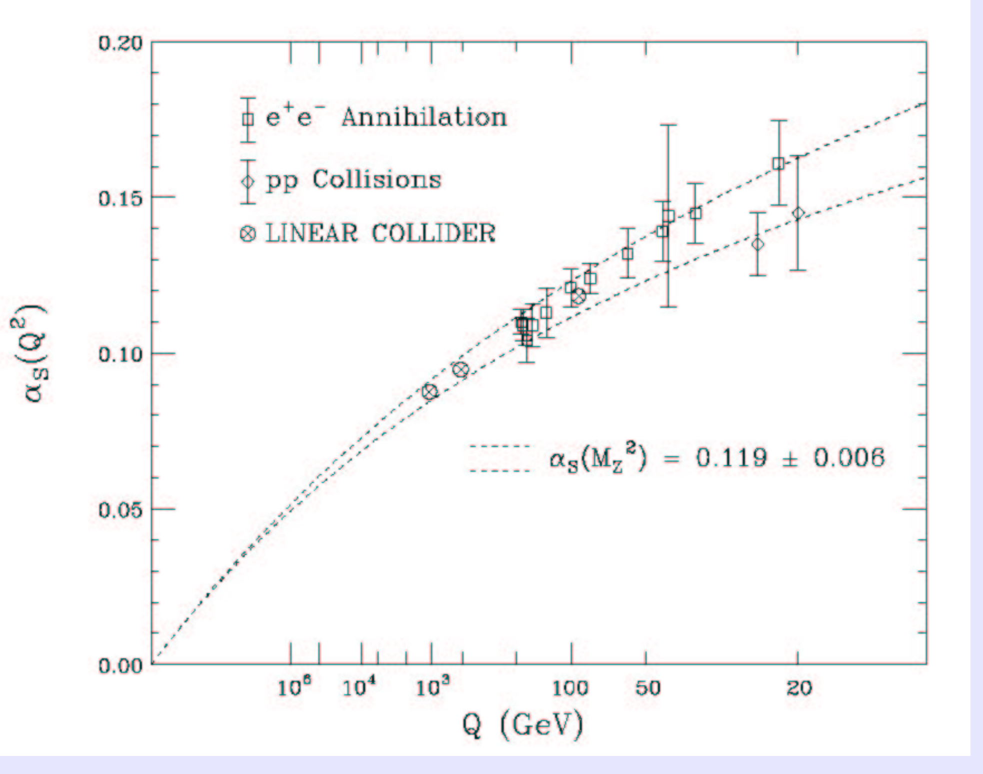
Q^2 Evolution of α_s

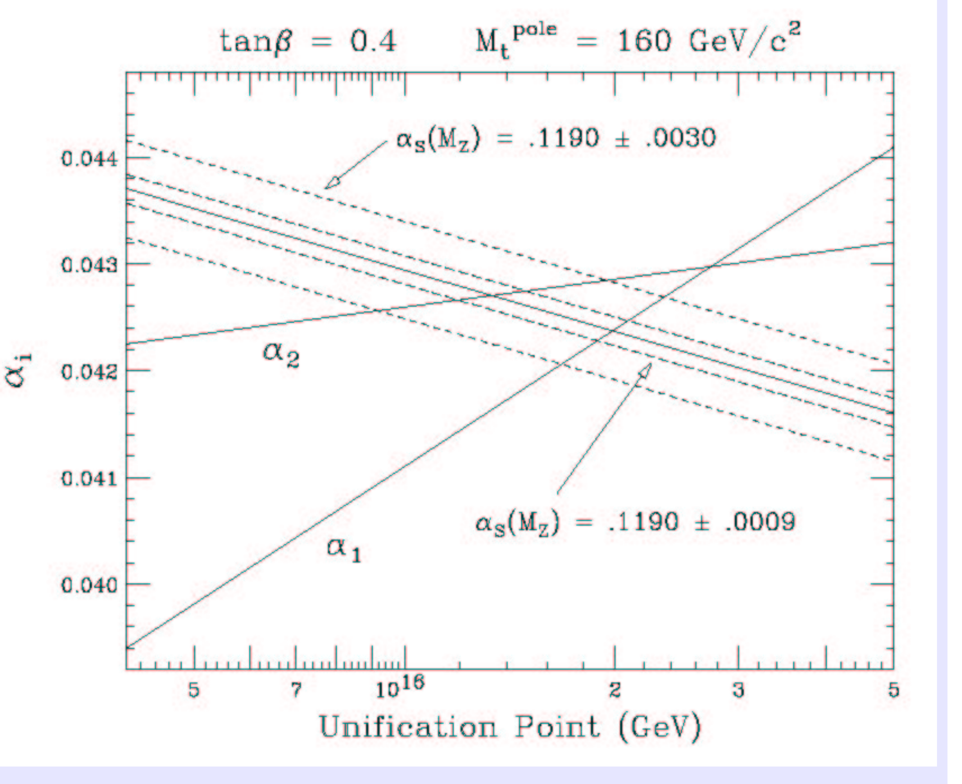
- For the preceding measurements, we normalize to $\alpha_s(M_Z^2)$, using the QCD β−function to connect measurements at different scales.
- But want to test this running explicitly, since the β−function itself is an important prediction of QCD.
- Linear collider is well−suited to high−precision measurements under similar experimental conditions over a large lever arm in Q^2.

Measurement of Q^2 Evolution

- LC at $\sqrt{s}$=91, 500, 1000 GeV
- Use jet rates/shapes at all energies, and ratio technique at Z pole.
- Assume 1% theory uncertainty.

Resulting improvement in extrapolation to GUT scale with 1% measurement:





Conclusions

- Top and QCD illustrate many of the challenges and rewards of the LC physics program.
- At the same time, they only scratch the surface of the physics we hope to do there!
- We need calculations and theories worthy of the machine and detectors we are going to build.
- For the LC physics program to reach its potential, your help is essential!