TOP PHYSICS at the LINEAR COLLIDER

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Outline

- Introduction: Past, Present and Future
- Linear Collider Specialties
- Top-Antitop at Threshold
- Top-Antitop at Higher Energies
- Summary

The Top Quark in Numbers

- $m_t^? = 174.3 \pm 5.1$ GeV (CDF+D0)
  $m_t^{\rm pole} = 172 \pm 8$ GeV (LEP, ew.precision)

- $\sigma_{p\bar{p}\to t\bar{t}} = \begin{cases} 6.5^{+1.7}_{-1.4}\,pb & \text{(CDF)} \\ 5.9 \pm 1.7\,pb & \text{(D0)} \end{cases}$ assumes SM

- $\left.\begin{array}{l} p_t \text{ spectrum} \\ \text{production process} \end{array}\right\}$ SM-like

- $\frac{B(t\to Wb)}{\Sigma B(t\to Wq)} \sim \frac{|V_{tb}|^2}{|V_{tb}|^2+|V_{ts}|^2+|V_{td}|^2} = 0.99 \pm 0.29$

- $B(t \to W_0 b) = 0.91 \pm 0.39 \quad (\text{SM} = 0.7)$
  $B(t \to W_+ b) = 0.11 \pm 0.15 \quad (\text{SM} = 0)$

- $B(t \to Zq) < 0.33$
  $B(t \to \gamma q) < 0.032$ $\to$ FCNC decays small

$\Rightarrow$ What else do we want?
More precise numbers? More quantities measured?

WHY?

$\Rightarrow$ Let’s have a look into the past and the future.

Pre-Top-Discovery Era $<$ 1995

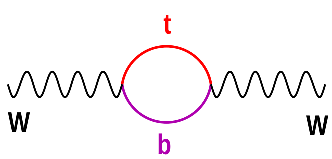
$\Rightarrow \begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} c \\ s \end{pmatrix}_L, \; b$ + ? + gauge symmetry

- **Indirect hits toward $(t,b)_L$ doublet flavor structure**
  - ▷ $\not{C}\not{P}$ in K physics, $B-\bar{B}$ mixing, GIM mechanism
  - ▷ bottom singlet causes FCNC: $\Gamma_{B\to\mu\mu} \sim \Gamma_{B\to\mu\nu X}$

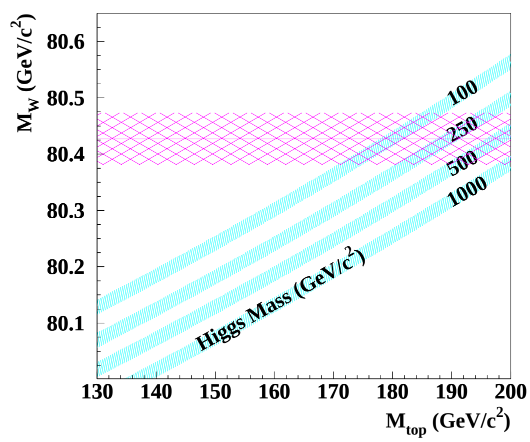
    experiment: $\Gamma_{B\to\mu\mu} < 10^{-5}\,\Gamma_{B\to\mu\nu X}$
  - ▷ isospin of b from $e^+e^- \to b\bar{b}$ angular distr. (PETRA,TRISTAN)

- **Ew precision tests predict m_t from isospin breaking**

$\rightarrow$ top affects M_w by loop effects



▷ predicts m_t range (Higgs model)



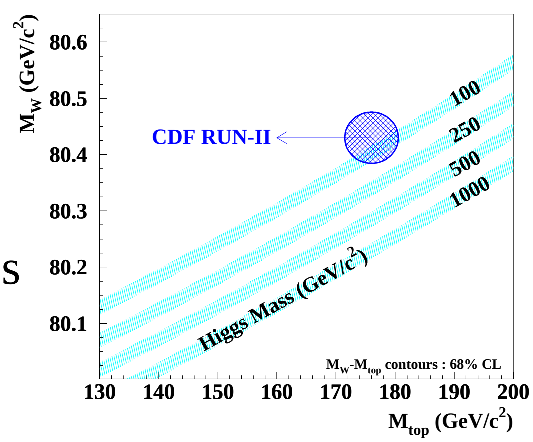
$\rightarrow$ required precision of m_t for a given δM_w

	Run I	Run II	LHC	LC(GIGAZ)
δM_w	40 MeV	20 MeV	20 MeV	6 MeV
δm_t	6 GeV	3 GeV	3 GeV	1 GeV
expected δm_t		2-3 GeV	1-2 GeV	$<$ 0.1–0.2 GeV

Post-Top-Discovery Era > 1995

- **Top precision measurements: top = top ?**
- **Top as unique QCD laboratory:**
  - ▷ $\Gamma_t \sim 1.5$ GeV $\gg \Lambda_{\rm QCD}$: no toponia, T-mesons
    - → dynamics dominated by perturbative QCD
    - → top "almost real": m_t, spin, EDM,… observables
- **Top as tool to uncover true "Next-SM"**
  - ▷ Higgs model: $g_{tth} = \frac{\sqrt{2}m_t}{v}$ ("Goldberger-Treiman")
  - ▷ $4^{\rm th}$ generation: $V_{tb} \ll 1$, $\Gamma_t \ll \Gamma_t^{\rm SM}$
  - ▷ extended gauge groups: new gauge bosons affect top
  - ▷ SUSY: new decay & production mechanisms, $\tilde{t}$, …
  - ▷ Large extra dimensions: KK gravitons ↔ top
  - ▷ etc., etc.

→ electroweak observables
- ▷ M_w and m_t: predict and check m_h (Higgs model)
- ▷ constrains any new physics



Next-SM Era > 200?

⇒ **Example: SUSY (MSSM)** ⇐

→ test consistency of Next-SM, constrain par. space

- Higgs mass measured, SUSY broken

  $$m^2_{h,\mathrm{light}} = M_z^2 + G_F m_t^4 \ln\left(\frac{m_{\tilde t}}{m_t}\right) + \ldots$$

  → required precision of m_t for a given $\delta m_{h,\mathrm{light}}$

	LHC	LC
$\delta m_{h,\mathrm{light}}$	1 GeV	50 MeV
δm_t	4 GeV	200 MeV
expected δm_t	1-2 GeV	100-200 MeV

- SUSY top decays:

  ▷ $t \to H^+ b,\ \tilde t \tilde\chi^0$

  ▷ FCNC, $\not{C}\!\!\!\not{P}$ top couplings

- Light top squarks $m_{\tilde t} \ll M_{\mathrm{SUSY}}$

  → off-diagonal element $\propto m_t M_{\mathrm{SUSY}}$
  in stop mass matrix

⇒ Aim of future colliders for top physics:
Measure all top properties as accurate as possible!

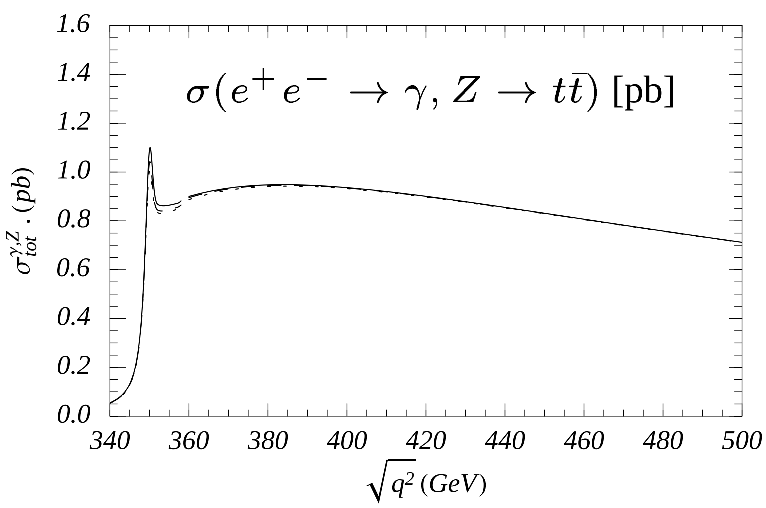
m_t, V_{tb}, Γ_t, g_{tth}, couplings, spin,
rare decays, FCNC, CP-properties,
production mechanism, etc.

Linear Collider and Top Physics

- e^+e^- collider, $E_{\rm cm} = M_z$, 350 GeV – 5 TeV
- Lumi: 10^{34}–$10^{35}\,{\rm cm}^{-2}{\rm s}^{-1} \to 100$–$1000\,{\rm fb}^{-1}/{\rm year}$
- Designs:

TESLA:	supercond.,	$E_{\rm cm}^{\rm max} \sim 1$ TeV
N/JLC:	nor. cond.,	$E_{\rm cm}^{\rm max} \lesssim 1$ TeV
CLIC:	nor. cond.,	$E_{\rm cm}^{\rm max} \lesssim 5$ TeV

- $e^+e^- \xrightarrow{\gamma,Z} t\bar{t}$ main mechanism for $E_{\rm cm} < 1$ TeV



- $e^+e^- \to e\nu tb$, $e^+e^- \to \nu\nu t\bar{t}$ } competitive for $E_{\rm cm} > 1$ TeV, W_L, Z_L scattering! single top!

LC Specialties

- **Statistics:** LC $\sim 10^5$ $t\bar{t}$ pairs $\rightarrow \sigma_{\rm tot} < 1\,{\rm pb}$
  LHC $\sim 10^8$ $t\bar{t}$ pairs $\rightarrow \sigma_{\rm tot} \approx 850\,{\rm pb}$

- $E_{\rm cm}$ **well known, tunable** $\rightarrow$ threshold & continuum
  - ▷ ISR+beam strahlung+energy spread $\Rightarrow$ lumi spect.
  - ▷ tune QCD phases at threshold $\Rightarrow$ CP studies

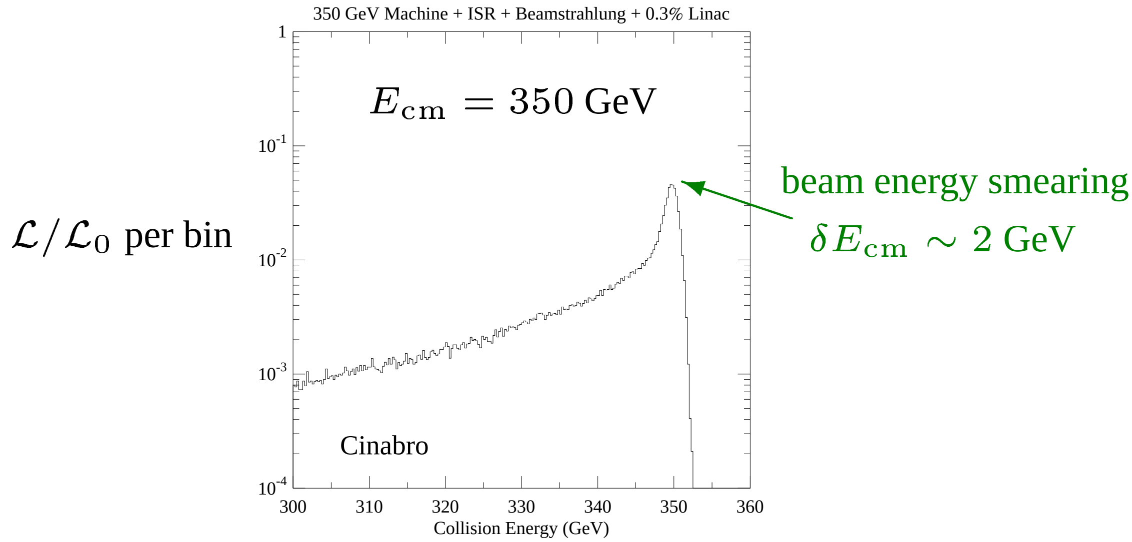
- **Electron beam polarizable:** $\rightarrow$ e^-: 80%
  - ▷ reduction of background (e.g. W^+W^- with RH e^-)
  - ▷ tuning to enhance signals (non-SM) for spin obs.

- **Clean environment:**
  - ▷ smaller background, more events used for physics
  - ▷ systematic uncertainties small

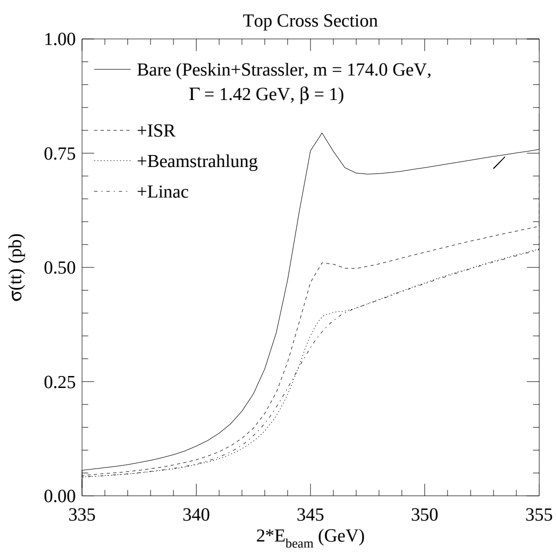
- $\gamma\gamma$, γe **options:**
  - ▷ unique spin configurations
  - ▷ alternative production mechanisms, single top

$\Rightarrow$ I'm going to talk about <u>some</u> interesting aspects of top physics at the LC that take advantage of the special LC features.

Luminosity Spectrum



$\rightarrow$ Lumi spectrum needs to be monitored (Bhabba)
important for $t\bar{t}$ threshold measurements



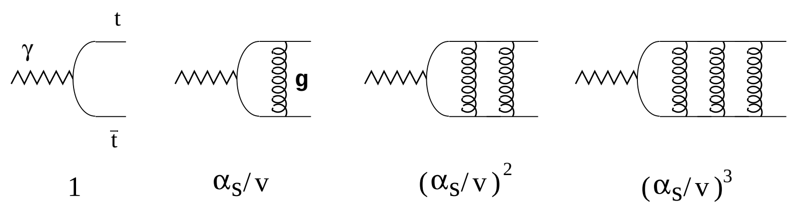
Top Physics at the $t\bar{t}$ Threshold

$$E_{cm} \approx 350\ \mathrm{GeV} \quad \Rightarrow \quad v_{\mathrm{top}} = \sqrt{1 - \frac{4m_t^2}{E_{\mathrm{cm}}^2}} \ll 1$$

$\longrightarrow$ top quarks move with non-relativistic speed

$\longrightarrow$ unique for the Linear Collider!

- **Top quarks have a lot of time to interact**



"Coulomb singularities"

▷ perturbation theory in α_s breaks down

▷ Bound state dynamics $\Rightarrow$ Schrödinger equation

- **Top decay:** $\Gamma_t \approx 1.5\,\mathrm{GeV} \gg \Lambda_{\mathrm{QCD}}$

▷ no formation of toponia

▷ smooth line-shape for $\sigma(e^+e^- \to t\bar{t})$, 1S peak

▷ $t\bar{t}$ dynamics described by perturbative QCD

- **Top rest system** $= t\bar{t}$ cm system $+\mathcal{O}(v^2)$ corr.

▷ facilitates spin, polarization measurements

- **QCD phases** scale with binding energy $E_{\mathrm{cm}} - 2m_t$

▷ QCD phases are tunable and calculable

▷ QCD phases compete with new $\not{C}\!\!\not{P}$ phases

Top Mass Measurement at Threshold

- **Top mass reconstruction** $\Rightarrow$ standard
- **Threshold Scan**

$\rightarrow$ required: measurement of $\sigma_{\rm tot}$

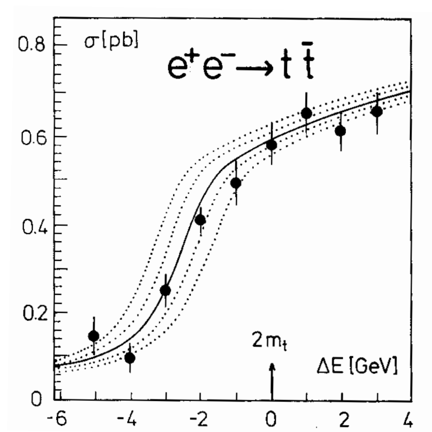
▷ count number of $t\bar{t}$ events

▷ no invariant mass reconstruction

▷ $t\bar{t}$ is in a color singlet state !

$\Rightarrow$ final state interactions, gluon radiation, Bose-Einstein correlation, etc. not relevant

$m_t \pm 200, 400$ MeV



$\rightarrow$ the rise of $\sigma_{\rm tot}$ defines $2m_t$!

▷ measures short-distance "threshold masses", adapted to low virtuality of top, e.g. 1S mass, $m_t^{\rm 1S}$

▷ $t\bar{t}$ is a color singlet $\Rightarrow$ $\delta m_t^{\rm 1S,theory} \ll \Lambda_{\rm QCD}$

▷ $m_t^{\rm 1S}$ can be related precisely to $\overline{\rm MS}$ mass $\overline{m}_t(\overline{m}_t)$

▷ experimental uncertainties:

$\mathcal{L} = 100\,{\rm fb}^{-1}$ distributed to 10 scan points

$\Rightarrow$ $\delta m_t^{\rm 1S,exp} < 100$ MeV (Peralta, Martinez, Miquel)

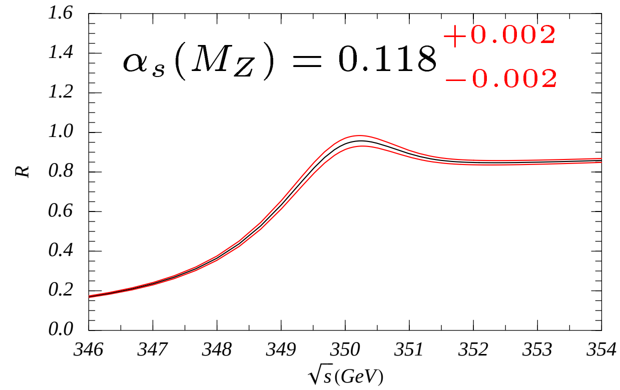
Sensitivity of $\sigma_{\rm tot}^{\rm theory}$ to α_s, $g_{\rm tth}$, Γ_t

α_s larger

$\Rightarrow$ binding force larger

$$V_{\rm QCD}(r) = -\frac{3\,\alpha_s}{4\,r}$$

$\Rightarrow$ $\sigma_{\rm tot}$ enhanced

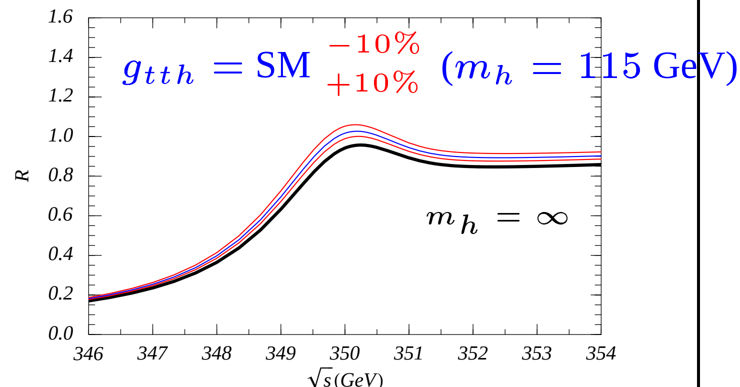


$g_{\rm tth}$ larger

$\Rightarrow$ binding force larger

$$V_h(r) = -\frac{g_{\rm tth}}{4\,r}\,e^{-m_h r}$$

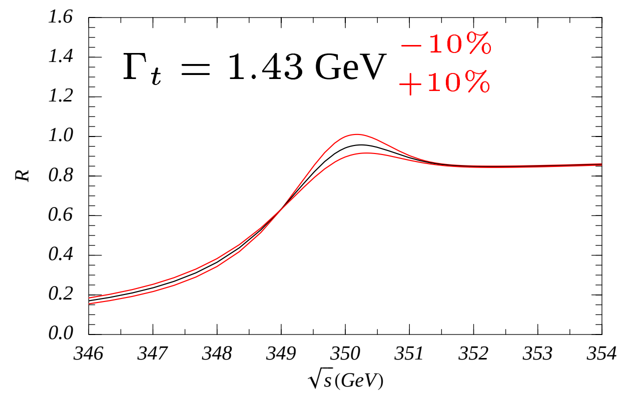
$\Rightarrow$ $\sigma_{\rm tot}$ enhanced



Γ_t smaller

$\Rightarrow$ peak more pronounced

(see also F-B asymmetry)

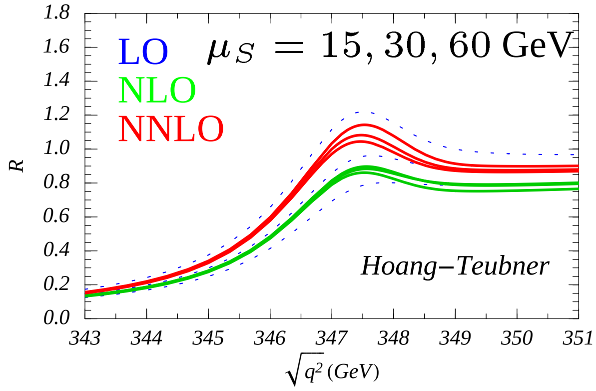


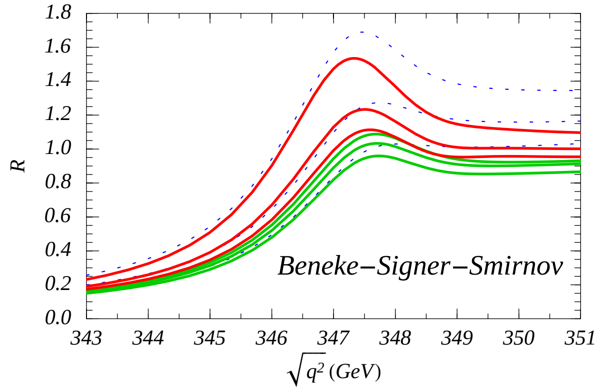
- Comparison: experimental uncertainties

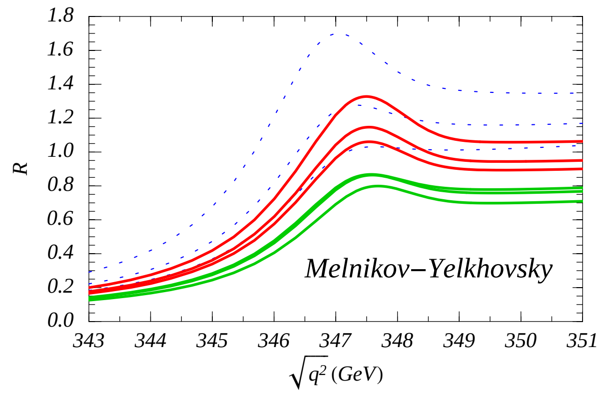
$$\begin{array}{lrcl} \mathcal{L} = 100\,\text{fb}^{-1}: & \delta\alpha_s(M_Z) & \lesssim & 0.002 \\ (< 2000) & \delta\Gamma_t/\Gamma_t & \lesssim & 5-10\% \\ & \delta g_{tth}/g_{tth} & \lesssim & 5-10\% \end{array}$$

Theoretical Situation for $\sigma_{\rm tot}$

$\Rightarrow$ Until 2000 a number of NNLO calculations had been carried out







also:

Sumino et al.

Yakovlev

- ▷ peak position under control

  $\longrightarrow \delta m_t^{\rm theo} < 100\text{–}200$ MeV

- ▷ large normalization uncertainties: $\frac{\delta\sigma_{t\bar t}}{\sigma_{t\bar t}} \sim 20\%$

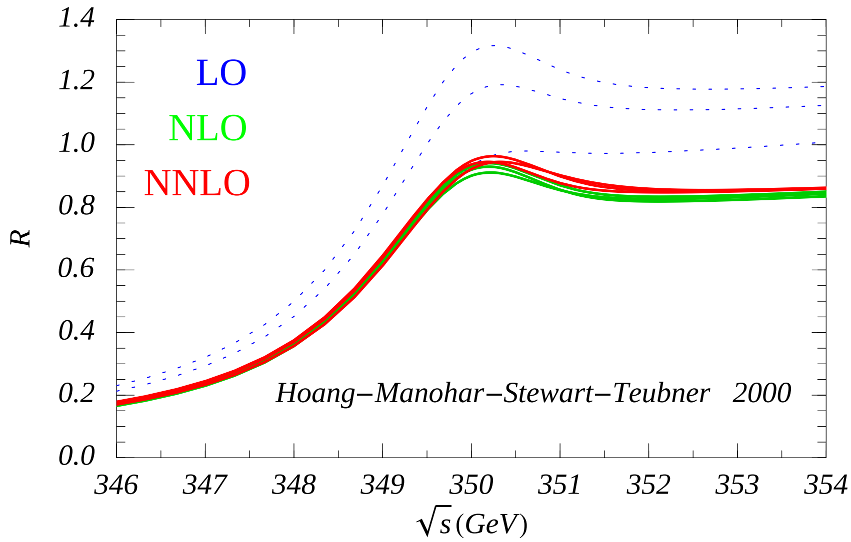
  $\longrightarrow$ measurements of α_s, Γ_t, g_{ttH} in jeopardy

  old experimental studies appeared unrealistic

New Calculation of the Cross Section

⇒ 2000: New renormalization group improved calculation at NNLL order

→ summation of $(\alpha_s \ln v)^n$ to all orders



$m_t^{1S} = 175$ GeV

$\Gamma_t = 1.43$ GeV $\qquad \nu = 0.15$–0.4

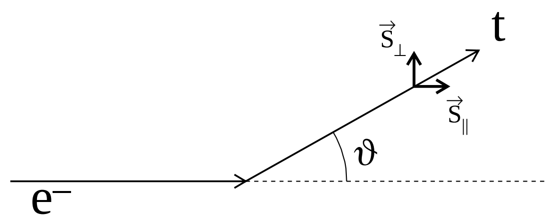
$\alpha_s(M_Z) = 0.118$

▷ peak position under control
$\longrightarrow \delta m_t^{\rm theo} < 100$–$200$ MeV

▷ small normalization uncertainties: $\frac{\delta\sigma_{t\bar{t}}}{\sigma_{t\bar{t}}} \sim 2\%$
$\longrightarrow$ measurements of α_s, Γ_t, g_{tth} at the % level are feasible

Top Polarization

⇒ **Top rest system = e^+e^- c.m. system**



$\vec{s}_N = \vec{s}_{||} \times \vec{s}_\perp$

$P_{||}$: dominated by S-wave

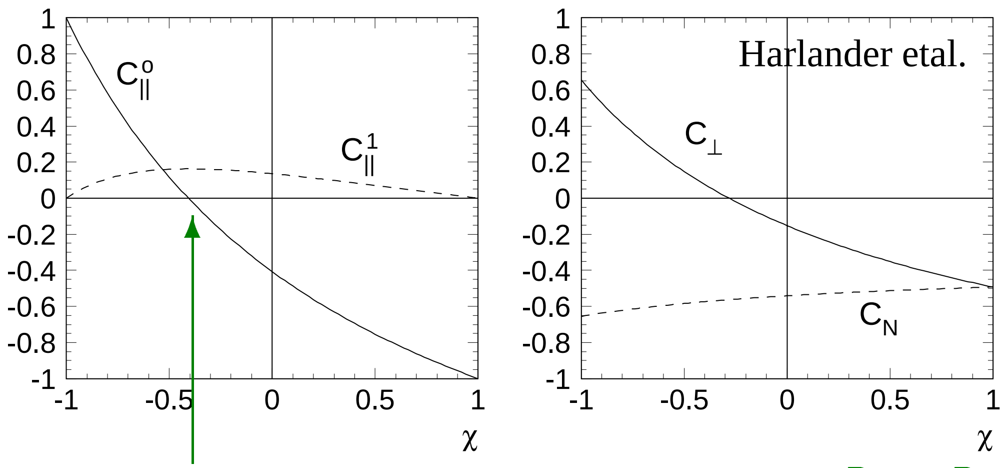
$P_\perp,\ P_N$: sensitive to QCD phases

sensitive to T-odd $\gamma t\bar{t}$, $Zt\bar{t}$ couplings

(EDM's)

- **Top polarization can be tuned by e^-, e^+ polarization**

$$\mathcal{P}_{||}(\boldsymbol{p},E,\chi) = C^0_{||}(\chi) + C^1_{||}(\chi)\,\varphi_{\rm R}(p,E)\,\cos\vartheta$$
$$\mathcal{P}_\perp(\boldsymbol{p},E,\chi) = C_\perp(\chi)\,\varphi_{\rm R}(p,E)\,\sin\vartheta$$
$$\mathcal{P}_{\rm N}(\boldsymbol{p},E,\chi) = C_{\rm N}(\chi)\varphi_{\rm I}(p,E)\,\sin\vartheta$$



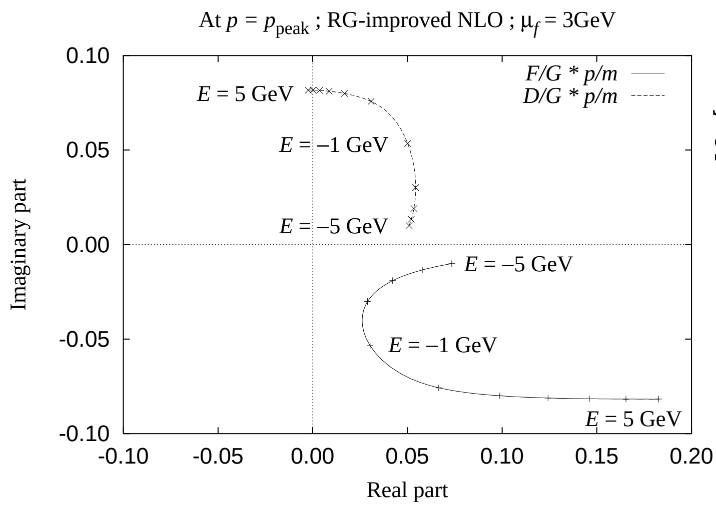
$C^0_{||} = 0$

$E_{\rm cm} = 2m_t$

QCD phases only

$\chi = \frac{P_{e^+} - P_{e^-}}{1 - P_{e^+}P_{e^-}}$

- **Top polarization can be tuned by changing $E_{\rm cm}$**
  $\to$ QCD phases change with $E = E_{\rm cm} - 2m_t$



Jezabek, Nagano, Sumino

- **Sensitivities for ~~CP~~ top EDM ($t\bar{t}\gamma$), Z-EDM ($t\bar{t}Z$), chromo-EDM ($t\bar{t}G$)**

$$\text{e.g. } \mathcal{L}_{\rm EDM} = -\frac{e d_{t\gamma}}{2m_t}(\bar{t} i \sigma^{\mu\nu}\gamma_5 t)\partial_\mu A_\nu$$

	LHC (10 fb^{-1})	LC (500 GeV) (50 fb^{-1})	LC ($t\bar{t}$ threshold) (50 fb^{-1})
EDM ($d_{t\gamma}$)	-	10^{-1} – few 10^{-2}	10^{-1}
Z-EDM (d_{tZ})	-	10^{-1} – few 10^{-2}	10^{-1}
chr.-EDM (d_{tg})	10^{-2} – few 10^{-3}	$\mathcal{O}(1)$	10^{-1}

Top Physics at Higher Energies

$$E_{cm} \gtrsim 2m_t + 10 \text{ GeV}$$

- **Top mass**
  - ▷ invariant mass reconstruction for single top
  - ▷ top still slow for $E_{\rm cm} = 500$ GeV
  - ▷ limitation: $\rightarrow$ top colored, on-shell pole unphysical (interconnection, jet energy, gluon radiation, ...)

    $\Rightarrow \delta m_t^{\rm syst} > \Lambda_{\rm QCD} \sim 300$ MeV

    ECFA/DESY (1991): $\delta m_t = 500$ MeV

    G.P. Yeh (1999): $\delta m_t = 200$ MeV (no systematics)

- **Top Yukawa coupling** $\rightarrow e^+e^- \rightarrow t\bar{t}H$

  Juste etal. (1999): $E_{\rm cm} = 800$ GeV, $m_h = 120$ GeV, $\mathcal{L} = 1000\,{\rm fb}^{-1}$ ($\sim$ 3 years á $10^{34}\,{\rm cm}^{-2}{\rm s}^{-1}$)

  $\Rightarrow \delta g_{tth}/g_{tth} \sim 5.5\%$ ($q\bar{q}b\bar{b}b\bar{b}\ell\nu$, $q\bar{q}q\bar{q}b\bar{b}b\bar{b}$ channels)

  $\rightarrow$ LHC: $\delta g_{tth}/g_{tth} < 16\%$, $\mathcal{L} = 100\,{\rm fb}^{-1}$

- **Strong coupling**
  - ▷ $\sigma_{\rm tot}$ maximal for $E_{\rm cm} \approx 400$ GeV

    $\rightarrow \alpha_s$ from radiative corrections

    $\rightarrow$ systematic error dominated by luminosity spectrum

    Bernreuther (1999): $\delta\alpha_S(M_z) \sim 0.007$

- **FCNC top-charm-γ/Z coupling**

  ▷ consider $e^+e^- \to t\bar{c} + \bar{t}c$ instead of rate top decay

  $\to$ sensitivity kinematically enhanced

  Han,Hewett (1998): $\mathcal{L} = 500\,\text{fb}^{-1}$, $E_{\text{cm}} = 500$ GeV

  sensitivities on FCNC couplings $< 1\%$ achievable

  $\to$ competitive to LHC from rare decay $t \to c\gamma/Z$

- **Top decays in new light particles** (1991 studies)

  $t \to H^+ b$: 3σ disc. for all $\tan\beta$ (favored in MSSM)

  $\mathcal{L} = 10\,\text{fb}^{-1}$, $E_{\text{cm}} = 500$ GeV,

  $m_t = 150$ GeV, $m_{H^+} = 50$ GeV

  $t \to \tilde{t} + \tilde{\chi}^0$: needs $\mathcal{L} = 30\,\text{fb}^{-1}$ for 3σ

- **Spin correlations & anomalous couplings**

  ▷ top spin configuration via lepton angular distr.

  ▷ Off-diagonal basis: (Parke, Shadmi)

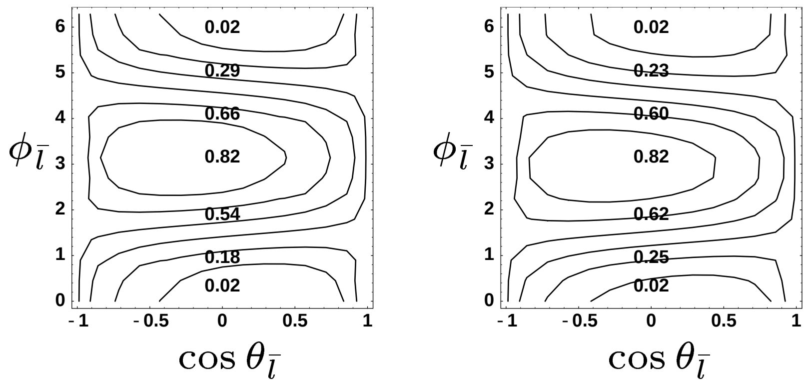
  - spin basis in which non-SM are easy to detect
  - SM: $e^-_L e^+_R \to t_\uparrow \bar{t}_\downarrow$ contains $\sim 100\%$ of events for any energy
  - not affected by QCD radiative corrections
  - does not exist at the LHC due to gluon fusion!

Double diff. angular distr. of leptons from top decay

(Kiyo,Kodaira,Morii,Nasuno,Parke)

- **Helicity Basis**

SM — EDM+Z-EDM (0.2)



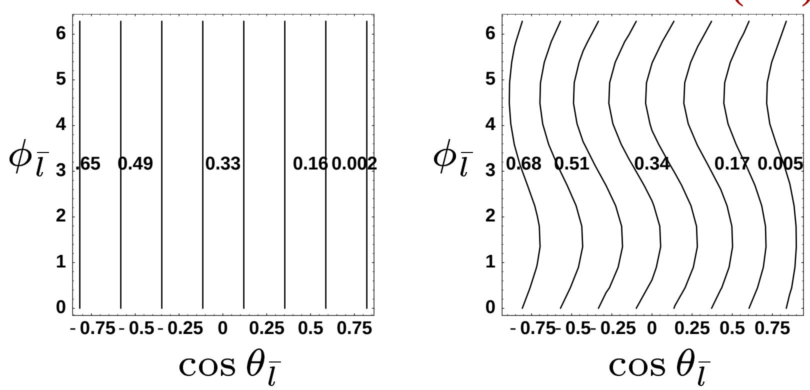
$e_L^- e^+ \to t\bar{t}$

$E_{\rm cm} = 400$ GeV

$\to$ anomalous effects barely visible

- **Off-diagonal bases** $\to \phi_{\bar{l}}$ and $\cos\theta_{\bar{l}}$ in different system

SM — EDM+Z-EDM (0.2)



$e_L^- e^+ \to t\bar{t}$

$E_{\rm cm} = 400$ GeV

$\to$ anomalous effects clearly visible

$\to$ asymmetry: $A \sim \int_0^{\pi} d\phi_{\bar{l}} - \int_{\pi}^{2\pi} d\phi_{\bar{l}}$

$\to$ QCD contributions to A: $<0.5\%$

$\to$ anomalous coupling $\mathcal{O}(0.1)$ detectable

Conclusions & Outlook

- Top quark is a window to ”New Physics”
  m_t large $\rightarrow$ EWSB, non-SM effects
- Top quark lifetime $\ll 1/\Lambda_{\rm QCD}$
  $\rightarrow$ unique QCD laboratory
  $\rightarrow$ almost ”real particle” $\rightarrow$ ew physics
- Measure top quark as precise as possible
  $\Rightarrow$ be prepared for surprises
- Linear Collider: versatile instrument for precision top studies (and much more !)
  $\rightarrow$ complementary/competitive to hadron colliders

  $\triangleright$ $E_{\rm cm}$ tunable, well known $\rightarrow t\bar{t}$ threshold

  $\triangleright$ clean, background-low environment

  $\triangleright$ LC: 10^5 tops $\longleftrightarrow$ LHC: 10^8 tops

  $\triangleright$ beam polarization

  $\triangleright$ $\gamma\gamma$, γe options