TOP QUARK PHYSICS AND THE LINEAR COLLIDER

André H. Hoang
CERN / MPI Munich

Top Thinkshop^2, Nov. 10-12 2000, Fermilab

- Introduction → Top precision physics
- Linear Collider Specialities
- Top-anti Top threshold
- Higher Energies
- Summary

Top Quark in numbers → Tevatron

$m_t = 174.3 \pm 5.1$ GeV (CDF + DØ) $\qquad$ 172 ± 8 GeV (ew.prec.)

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

$BR(t \to W_0 b) = 0.91 \pm 0.39$ $\quad$ (SM = 0.7) $\quad$ ← Yukawa dominates! (Higgs mechanism?)

$BR(t \to W_+ b) = 0.11 \pm 0.15$ $\quad$ (SM = 0)

$BR(t \to Zq) < 0.33$

$BR(t \to \gamma q) < 0.032$

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

p_t spectrum
production process } SM-like

→ What else do we want?
More precise numbers? More quantities measured?
Why?

→ Let's have a look into the past and into the future.

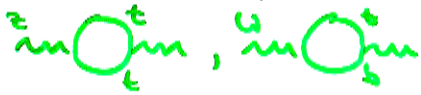
Pre-Top-Discovery Era $\rightarrow \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L, b$? + gauge symmetry

⇒ indirect hints towards flavor structure • anomalies

- $\not{CP}$ in K physics ($\rightarrow$ GIM mechanism), B-$\bar{B}$ mixing
- bottom singlet model leads to FCNC: $\Gamma(B \to \mu\mu) \sim \Gamma(B \to \mu\nu + X)$
  experiment: $\Gamma_{\mu\mu} < 10^{-5}\, \Gamma_{\mu\nu+X}$
- isospin of b from $e^+e^- \to b\bar{b}$ angular distr.: $I_b = -\frac{1}{2}$ (PETRA)

⇒ experimental hints for existence of top $\rightarrow \begin{pmatrix} t \\ b \end{pmatrix}_L$ weak doublet

⇒ electroweak precision observables predict top mass range



$\Rightarrow M_W, \sin^2\theta_W \rightsquigarrow m_{top}$ from isospin breaking

Post-Top-Discovery Era (> 1995)

⇒ top as tool to uncover more structure of "Next-SM"
magnifying glas, window to higher energies
→ lot of room for speculations

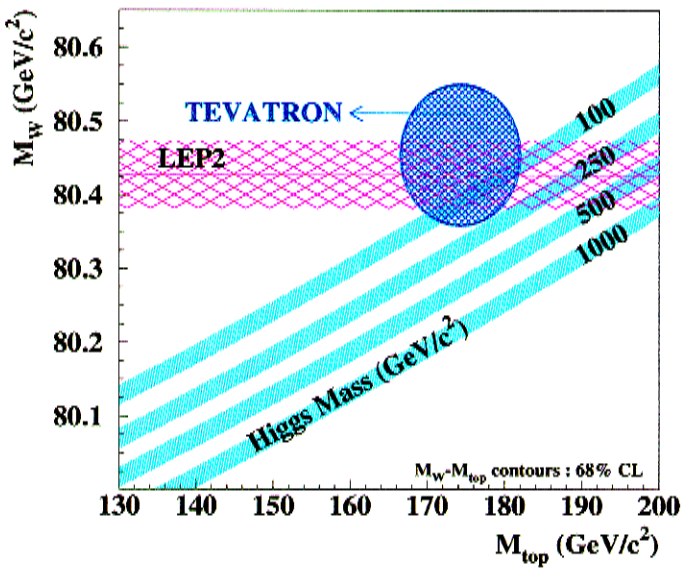
⇒ top as tool to understand QCD

Mechanism of Mass Generation:

- Higgs model predicts $g_{ttH} = \sqrt{2}\,\frac{m_t}{v}$ ("Goldberger-Treiman")
  predicts m_H from e.w. precision observables
- other models have alternative pridictions (TC theories)

Structure of Next-SM: → indirect hints

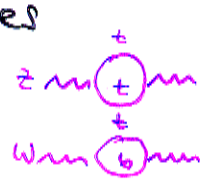
- exotic quarks, 4th generation ⇒ $V_{tb} \ll 1$, $\Gamma_t \ll \Gamma_t^{SM}$
- FCNC, GIM-suppressed in SM ⇒ visible effects ⇔ new physics
- composite top, new strong interactions ⇒ top substructure, resonances
- extended gauge groups (weak or strong)
- SUSY: new decays, production mechanisms, static properties
- electroweak precision observables
- rare decays (other)



Electroweak Precision Observables

→ top quark affects the relation of e.w. observables through loop corrections

$\alpha_{em}, G_F, M_Z, M_W \Rightarrow$ e.g. $\Delta r \sim G_F m_t^2$



- constrains new physics
- predicts m_h

	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

⇑

required uncertainty in m_{top} for a given uncertainty in M_W for given m_h

Top as unique QCD laboratory: SM: $\Gamma_t \sim G_F m_t^3 \sim 1.5\,\text{GeV} \gg \Lambda_{QCD}$

- hadronization strongly suppressed, ~~t-mesons~~, ~~toponium~~
- top is almost "real" particle: m_t, spin, EDM, etc. → physical observables

→ learn about limitations of this concept

→ use precision as tool to find hints for Next-SM

⇒ Era of top precision physics

- top particularly sensitive to Next-SM structure
- restrict allowed (parameter) space of extensions / alternatives to SM
- learn about QCD

Next-SM Era (> 2000 + ?)

SUSY (as an example)

- if Higgs particle(s) found, mass(es) measured

MSSM → $m_{h,light}^2 \approx M_Z^2 + G_F m_t^4 \ln\left(\frac{m_{\tilde{t}}^2}{m_t}\right)$

"Higgs precision observables"

required precision in m_t for a given uncertainty in m_h

	LHC	LC
δm_h	1 GeV	50 MeV
δm_t	4 GeV	200 MeV

⇒ constrain stop masses

- SUSY top decays: $t \to H^+ b$, $\tilde{t}\tilde{\chi}^0$
  FCNC → loop effects

etc... etc...

⇒ test consistency of model
constrain parameter space for yet undiscovered parts
fix final structure of model

⇒ Era of top precision physics

Aim of future colliders for top physics:

→ measure all top properties as accurate as possible

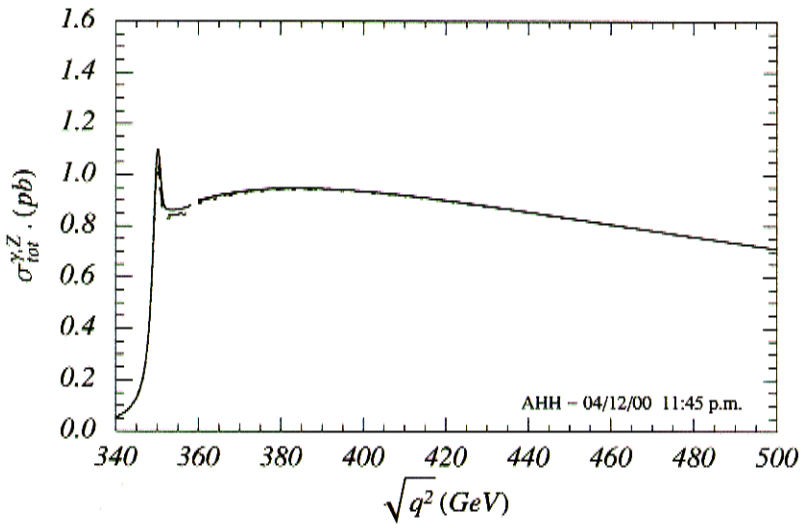
→ keep an eye on discoveries

m_t, V_{tb}, Γ_{total}, g_{ttH}, $\alpha_s(\text{top})$, spin, anomalous couplings, rare decays, FCNC, CP properties

The Linear Collider and Top Physics

- e^+e^- collider, $E_{cm} \sim 350$ GeV – 5 TeV
- luminosity: several 10^{33} – several 10^{34} $cm^{-2}s^{-1}$ → sev. 10 – sev 100 fb^{-1}/year
- 3 designs: TESLA – supercond. structure, $E_{cm}^{max} \sim 1$ TeV
  N/JLC – normal cond., $E_{cm}^{max} \lesssim 1$ TeV
  CLIC – normal cond., $E_{cm}^{max} < 5$ TeV, higher lumi
- $e^+e^- \to \gamma, Z \to t\bar{t}$ main production mechanism for $E_{cm} \lesssim$ TeV
- $e^+e^- \to e\nu\, tb$ competitive at high energies $\gtrsim 1$ TeV
  $e^+e^- \to \nu\nu\, t\bar{t}$ longitudinal W_L, Z_L scattering! single top!

$\sigma(e^+e^- \xrightarrow{\gamma,Z} t\bar{t})$



LC Specialities

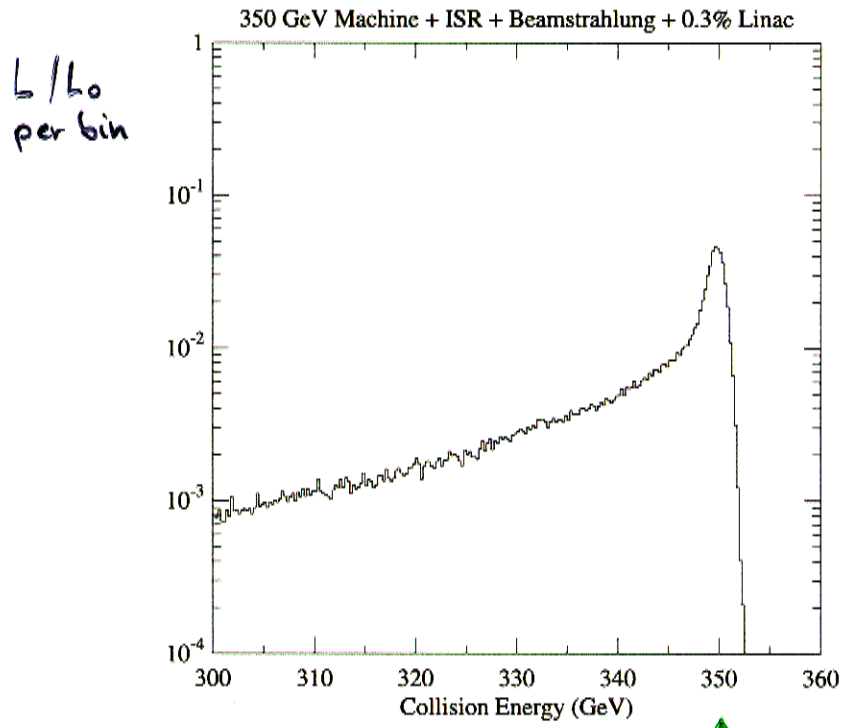
- less statistics than LHC ~ 10^5 $t\bar{t}$ pairs

- E_{cm} well known, can be tuned → $t\bar{t}$ threshold ⊕ continuum
  ISR + beam strahlung + beam energy spread ⇒ Lumi spectrum
  most relevant for threshold
- electron beam polarizable → e^-: 80%
  → reduction of background (e.g. W^+W^- with r.h. e^-)
  → tuning instrument to enhance signals (non-SM)
  → most relevant for top polarization measurements
- clean environment
  → more events can be used for physics, small backgrounds
  → systematic uncertainties small
- $\gamma\gamma$, γe options
  → new unique spin configurations of top
  → alternative top production mechanisms, single top, "TC-sensitive"

→ I'm going to talk about some interesting aspects of top physics at the LC.

Luminosity Spectrum

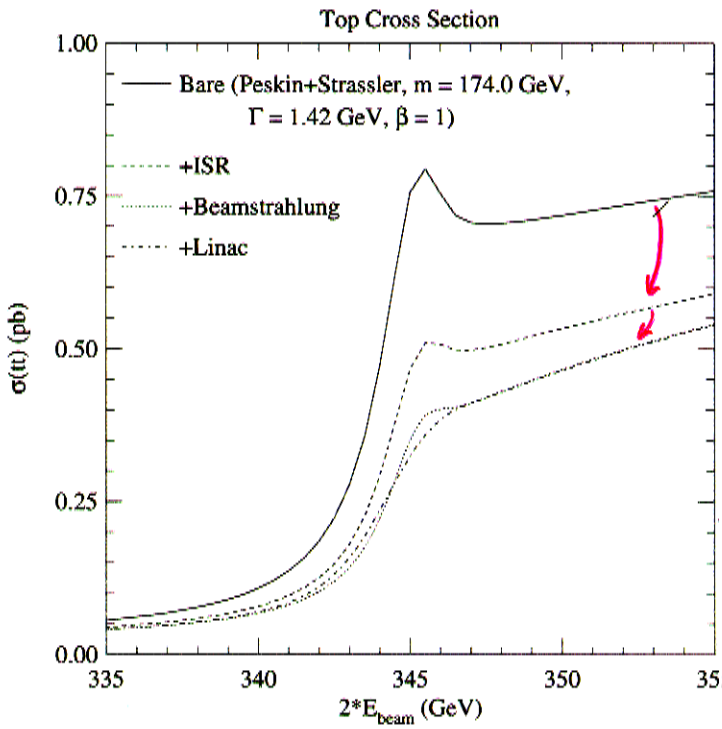
$E_{c.m.} = 350$ GeV



Cinabro

beam energy smearing
$\delta E_{cm} \sim 2$ GeV

→ luminosity spectrum needs to be monitored → Bhabha scattering
important for threshold $t\bar{t}$ measurement


Top Cross Section
Bare (Peskin+Strassler, m = 174.0 GeV,
Γ = 1.42 GeV, β = 1)
+ISR
+Beamstrahlung
+Linac
σ(tt) (pb)
1.00
0.75
0.50
0.25
0.00
335
340
345
350
355
2*E_beam (GeV)

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

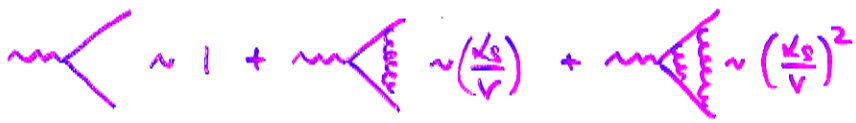
→ does not exist at any other collider !

General physics situation

$$E_{c.m} \simeq 350 \text{ GeV} \quad \Longrightarrow \quad v_{top} = \sqrt{1-\frac{4m_t^2}{q^2}} \ll 1$$

→ tops move with non-relativistic speed

- top quarks have a lot of time to interact



"Coulomb singularities"
→ expansion in α_s breaks down

⇒ bound state dynamics
non-relativistic Schrödinger equation

- no toponia due to e.w. top decay $t \to bW$: $\Gamma_t \sim 1.5\,\text{GeV} \gg \Lambda_{QCD}$
  ⇒ smooth lineshape for $\sigma(e^+e^- \to t\bar{t})$, 1S peak visible
  ⇒ beam effects leads to smearing + luminosity loss

- $t\bar{t}$ c.m. system = top rest system + $O(v^2)$ corrections
  ⇒ interpretation of spin, polarization measurements facilitated

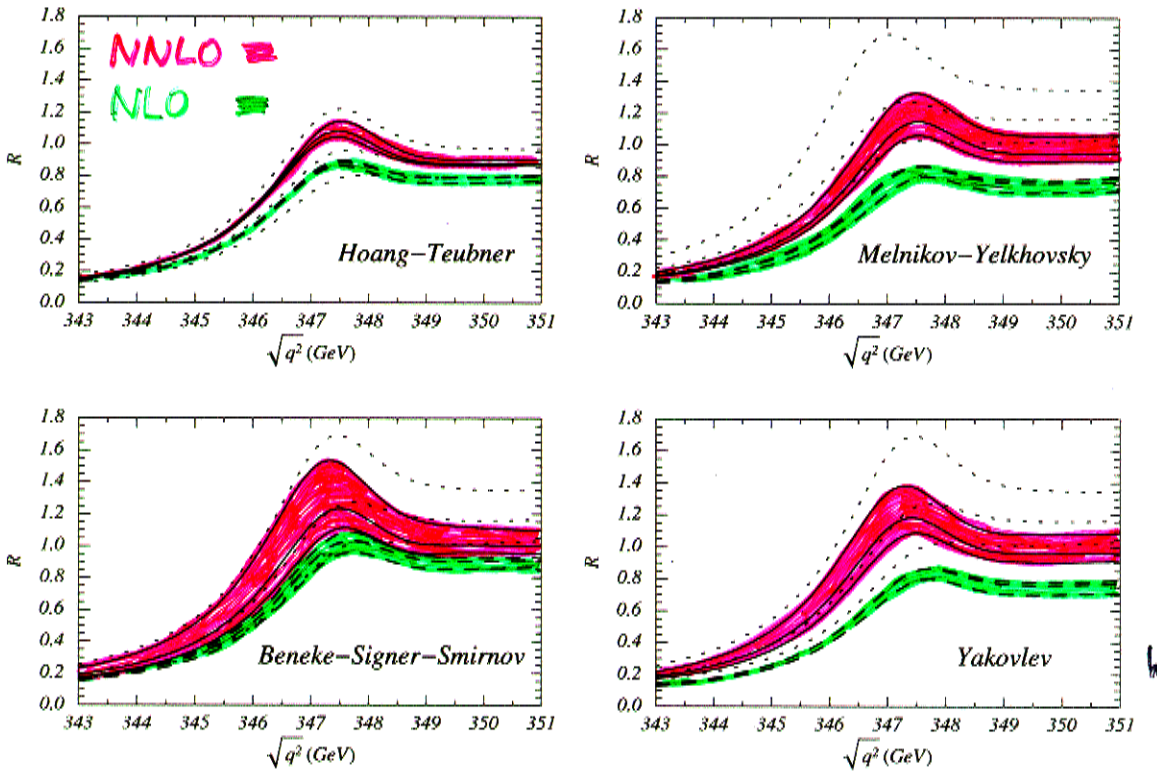
- large QCD phases by resummation of diagrams
  → compete with possible non-SM $\not{CP}$ phases
  → QCD phases are calculable, tunable functions of $E_{c.m.}$

- $t\bar{t}$ system, dynamics can be described by perturbative methods due to large top width
  ⇒ non-perturbative effects strongly suppressed

Theoretical Situation

- NLO QCD: σ_{tot}, $\frac{d\sigma}{d|\vec{p}_t|}$, F-B asymmetry, top polarization
- NNLO QCD: σ_{tot}, $\left(\frac{d\sigma}{d|\vec{p}_t|}\right)$ ⇒ NNLO corrections ≈ NLO corrections
  large scale dependence

σ_{tot}



hep-ph/0001286

→ large normalization uncertainty $\frac{\delta\sigma_{tot}}{\sigma_{tot}} \sim 20\%$

→ m_t measurement not affected, but danger of feed-in of normalization uncertainties after beam effects taken into account

→ measurement of quantities that influence normalization pessimistic

α_s, Γ_{top}, g_{ttH}, polarization → large theoretical uncertainties

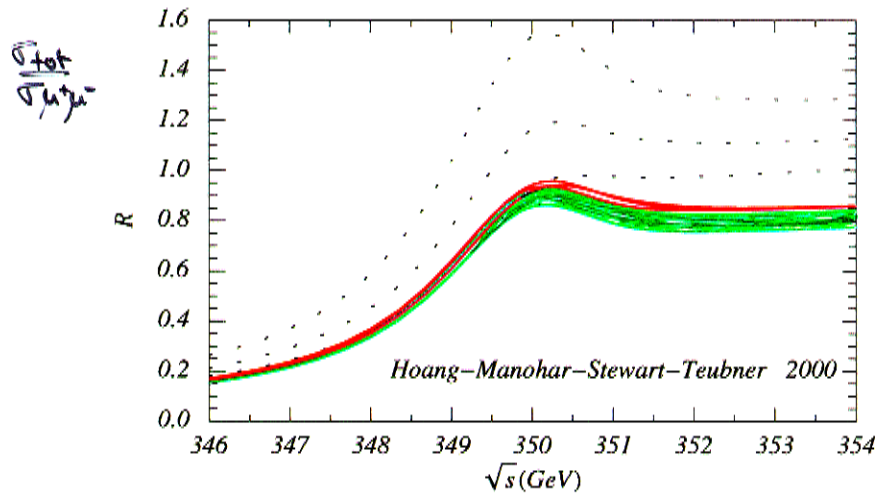
⇒ many old experimental studies (< 1998) appeared unrealistic because no theoretical uncertainties were taken into account

⇒ but: situation is about to be changed!

→ new NNLL order calculation of σ_{tot}

Scale hierarchy: $m_t \gg m_t v$ (momentum) $\gg m_t v^2$ (energy)

⇒ resummation of $\ln\left(\frac{m}{mv}\right)$, $\ln\left(\frac{m}{mv^2}\right)$, $\ln\left(\frac{mv}{mv^2}\right)$ at NNLL order in vNRQCD } → parallel sessions



$m_t^{1S} = 175$ GeV
$\alpha_s(M_Z) = 0.118$
$\Gamma_t = 1.43$ GeV
$v = 0.1 - 0.4$

- NNLL corrections smaller than NLL ones
  NNLL corrections behave naturally
- $\frac{\delta\sigma_{tot}}{\sigma_{tot}} \lesssim 2\%$ ⇒ normalization uncertainties are an order of magnitude smaller than for NNLO results !
- NLL/NLO calculations do not underestimate the theoretical uncertainties

⇒ many old experimental studies (<1998) appear realistic even though theoretical uncertainties have not been taken into account

Capability of measurements for a threshold run ($\mathcal{L} \sim 100\,fb^{-1}$)

$\delta m_t \lesssim 100$ MeV (even with NNLO results)

$\delta\alpha_s(M_Z) \sim 0.002$
$\delta g_{ttH} \sim (0.05 - 0.1)\, g_{ttH}$
$\delta\Gamma_t \sim (0.05 - 0.1)\,\Gamma_t$
} ECFA/DESY studies <1998

EDM, Z-EDM : sensitivity $\mathcal{O}(1\%)$ Jezabek, Sumino 1999

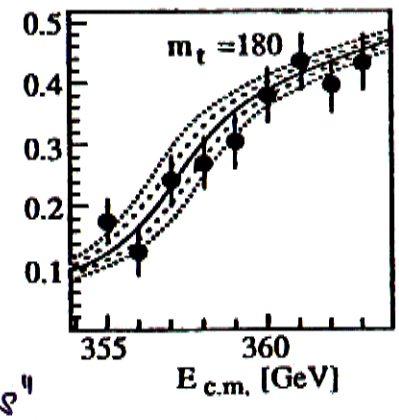
Top Mass Determination from the Threshold Scan

⇒ required: measurement of σ_{tot}

- counting # of $t\bar{t}$ events
- no reconstruction

→ $t\bar{t}$ are in a color singlet state; no dependence on final state interactions, gluon radiation, Bose-Einstein correlation, etc.

m_t = 180 GeV ± 400, 200 MeV



⇒ the rise of σ_{tot} defines $2m_t$!

- leads to so-called "threshold masses" e.g. 1S, PS mass
- $t\bar{t}$ is in color singlet ⇒ threshold masses do not contain an ambiguity of $\mathcal{O}(\Lambda_{QCD})$, can be determined with uncertainties smaller than Λ_{QCD} (Hoang et al, Beneke)

[this is different for the invariant mass distribution!]

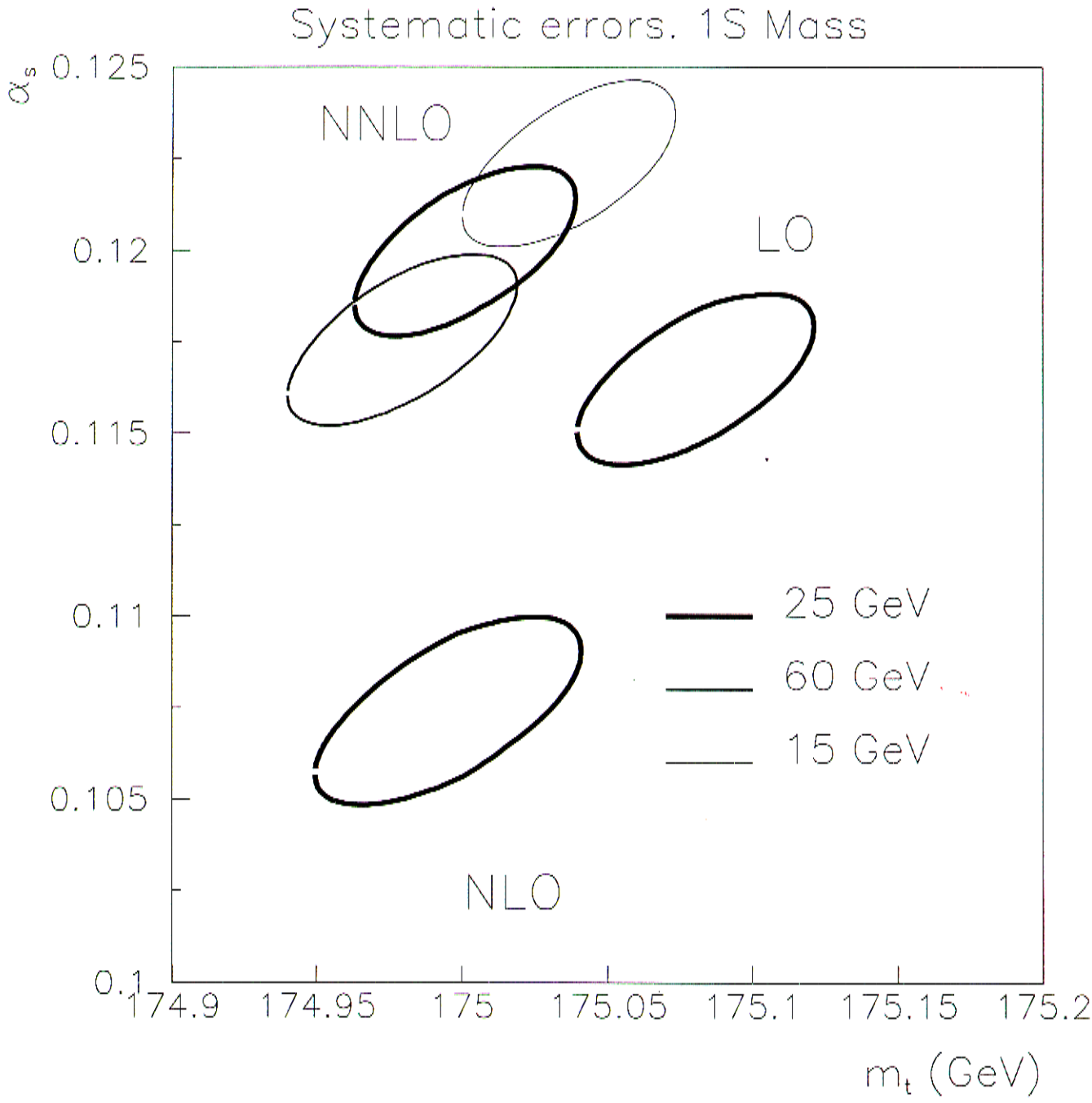
- threshold masses have a well convergent pert. relation to the $\overline{MS}$ mass that is used at high energies

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

$\delta m_t^{1S,PS} < 100$ MeV

ECFA/DESY WG
Peralta, Martinez, Miquel

→ Analysis using NNLO calculations for σ_{tot}



Peralta, Martinez

→ $\delta\alpha_s(M_Z)^{sys} \sim 0.01$

$\updownarrow$

$\delta\alpha_s(M_Z)^{NA} \simeq 0.003 - 0.004$

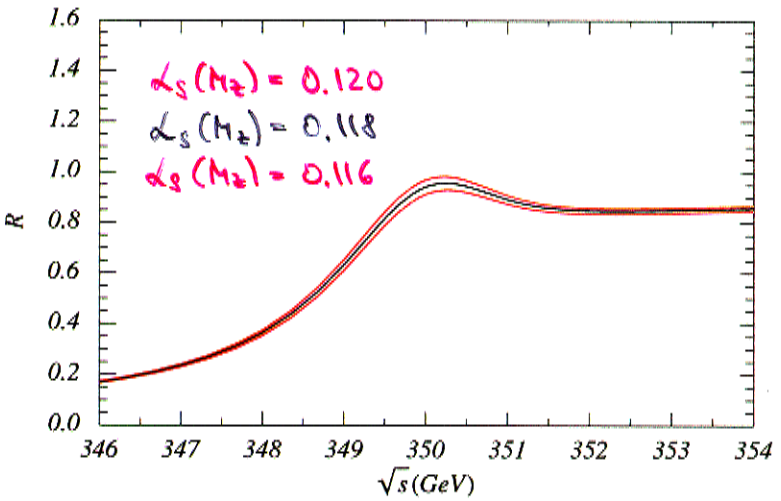
Sensitivity of σ_{tot} on small changes in $\alpha_s(M_Z)$, g_{ttH}, Γ_{top}

α_s larger

$\Rightarrow$ binding force larger

$$V(r) = -\frac{C_F \alpha_s}{r}$$

$\Rightarrow$ σ_{tot} enhanced

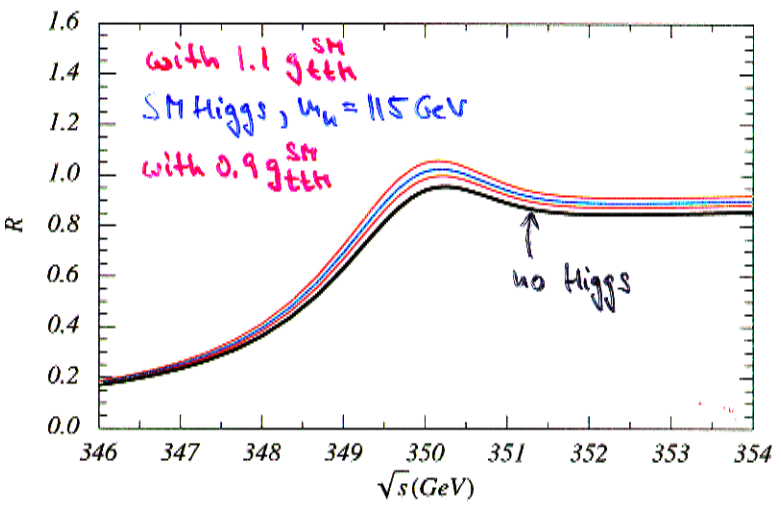


top Yukawa coupling larger

$\Rightarrow$ binding force larger

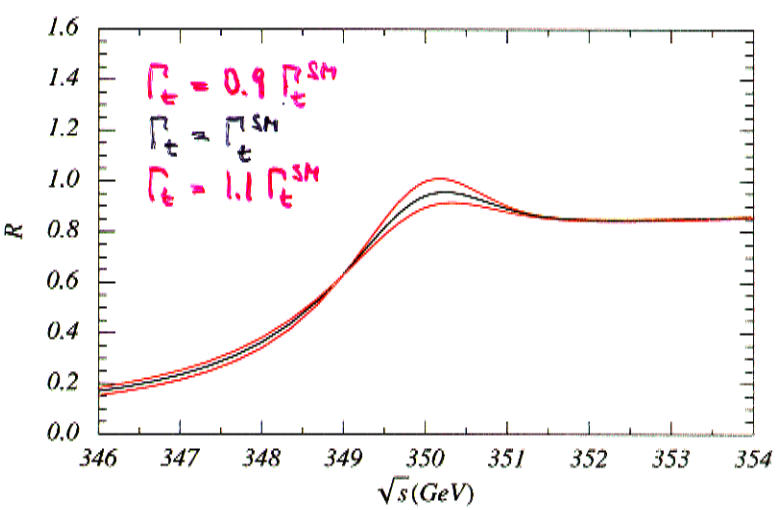
$$V^{higgs}(r) = -\frac{g_{ttH}^2}{r} e^{-m_H r}$$

$\Rightarrow$ σ_{tot} enhanced



top width smaller

$\Rightarrow$ peak more pronounced



$\rightarrow$ the changes in σ_{tot} caused by the variations of α_s, g_{ttH}, Γ_t shown here are $\gtrsim$ the normalization uncertainties of the NNLL total cross section

$\rightarrow$ luminosity spectrum !!! ☺

Sensitivity of the F-B asymmetry on changes in $\sqrt{s}$, Γ_t, m_t

$$A_{FB} = \frac{1}{\sigma_{tot}} \left[\int_0^1 d\cos\theta - \int_{-1}^0 d\cos\theta \right] \frac{d\sigma}{d\cos\theta} \sim \text{axialvector coupling} \times \frac{\text{P-wave}}{\text{S-wave}} \text{ formfactors}$$

→ small statistics

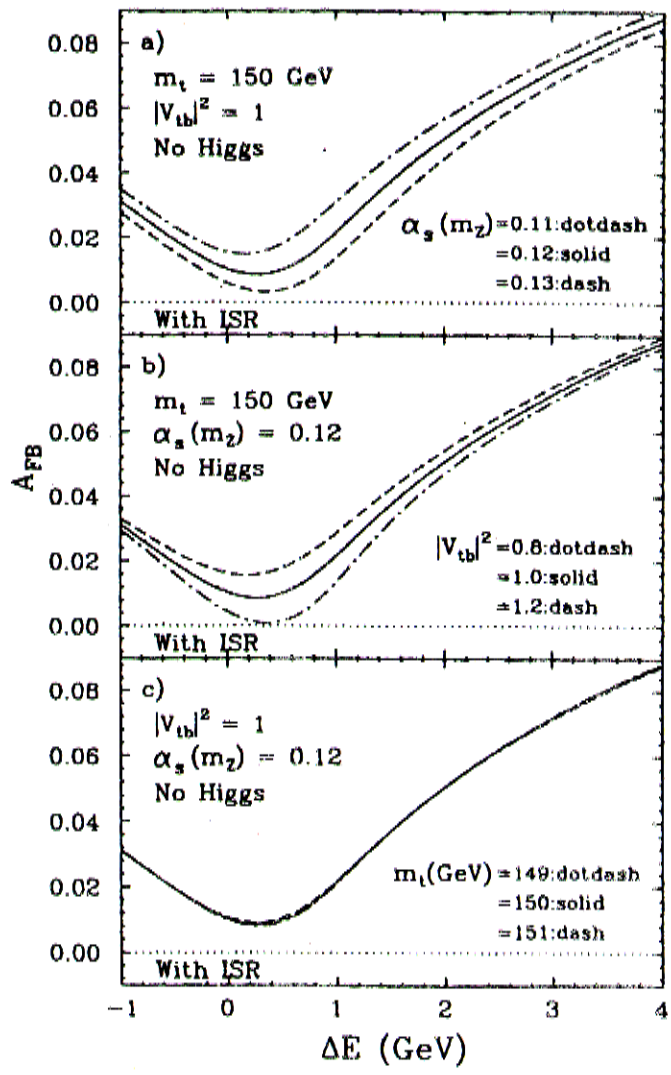
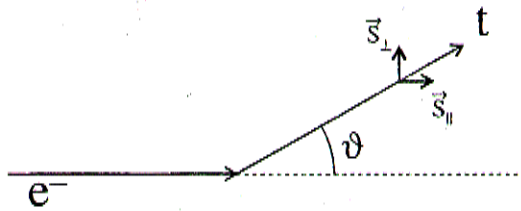


FIG. 28. Forward-backward asymmetry as a function of ΔE, showing the dependence on (a) $\alpha_s(m_Z)$, (b) $|V_{tb}|^2$, and (c) m_t. These include the initial state radiation but not the beam effects.

Top Quark Polarization



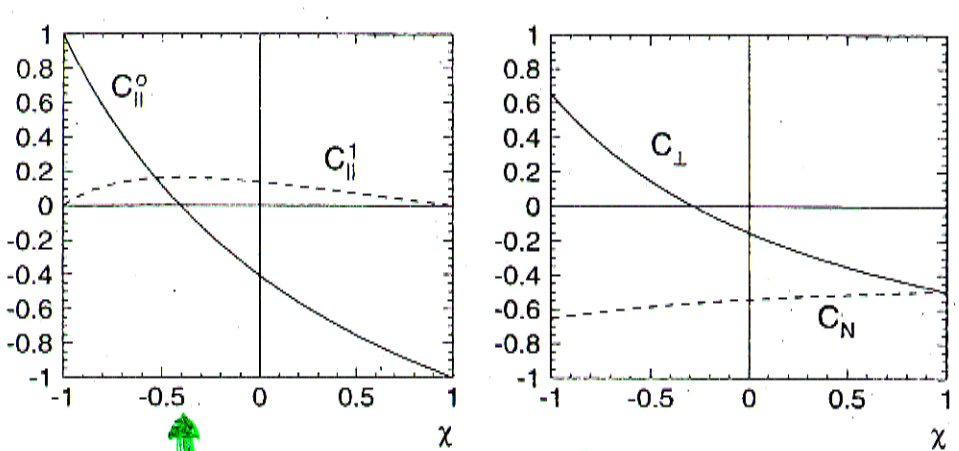
$$\vec{s}_N = \vec{s}_\parallel \times \vec{s}_\perp$$

$P_\parallel$: dominated by S-wave

P_T , P_N : sensitive to T-odd $\gamma t\bar{t}$, $Zt\bar{t}$ couplings
(EDM , Z-EDM)
sensitive to QCD phases

$\Rightarrow$ top polarization can be tuned by changing $P_{e^\pm}$
top polarization can be tuned by slightly changing E_{cm}.
(phases change with $\Delta E \sim 1\,\text{GeV} \sim \Gamma_t$)

$$\begin{aligned}
\mathcal{P}_\parallel(\mathbf{p},E,\chi) &= C_\parallel^0(\chi) + C_\parallel^1(\chi)\,\varphi_R(\mathbf{p},E)\,\cos\vartheta \\
\mathcal{P}_\perp(\mathbf{p},E,\chi) &= C_\perp(\chi)\,\varphi_R(\mathbf{p},E)\,\sin\vartheta \\
\mathcal{P}_N(\mathbf{p},E,\chi) &= C_N(\chi)\varphi_I(\mathbf{p},E)\sin\vartheta\,,
\end{aligned}$$

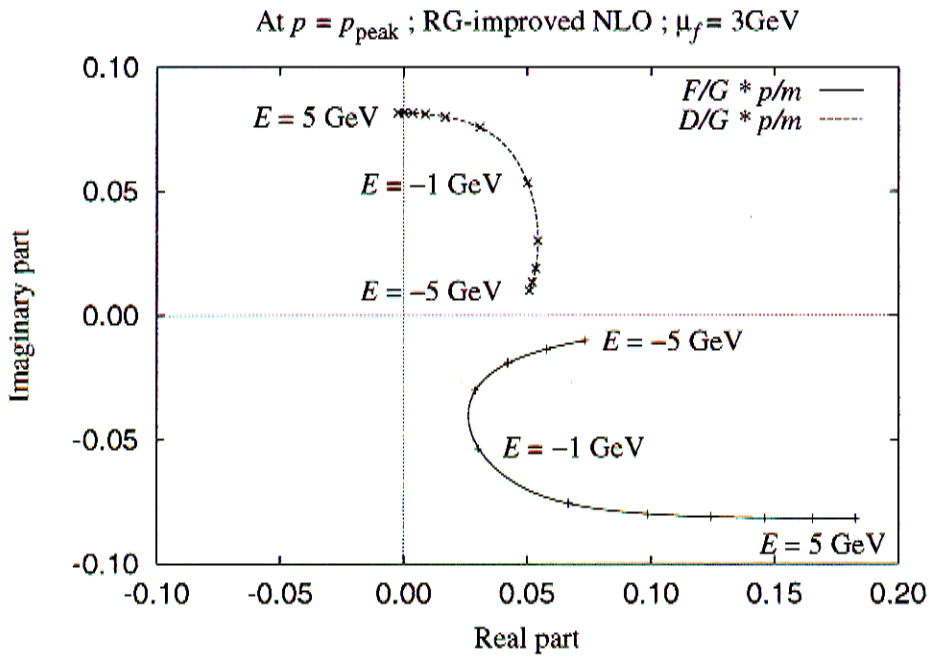


Hartander, Jezabek, Kühn, Peter

$C_\parallel^0 = 0$

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

→ tuning of QCD phases by changing $E_{c.m.}$



$E = E_{cm} - 2m_t^{LS}$

Jezabek, Nagano Sumino

→ sensitivities for top EDM, Z-EDM, chromo-EDM

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

		δd_{tg}	$\delta d_{t\gamma}$	δd_{tZ}
LHC (10 fb^{-1})		10^{-2} – a few$\times 10^{-3}$	-	-
e^+e^- LC	open top	$\mathcal{O}(1)$	10^{-1} – a few$\times 10^{-2}$	10^{-1} – a few$\times 10^{-2}$
(50 fb^{-1})	$t\bar{t}$ threshold	10^{-1}	10^{-1}	10^{-1}

Table 1: The results of studies of sensitivities to the anomalous couplings expected in future experiments. For e^+e^- linear colliders (LC), "open top" denotes the results of studies performed at $\sqrt{s} = 500$ GeV. These results are taken from [3]-[19].

Top Physics at Higher Energies

$\Rightarrow E_{c.m.} \gtrsim 2m_t + 10$ GeV

Top Mass

→ invariant mass reconstruction for single top

- top quarks still slow for $\sqrt{s} = 500$ GeV
- theoretical limitation → top is color triplet
  pole is unphysical (e.g. interconnection, jet energy scale, etc..)
  ⇒ $\delta m_t > \Lambda_{QCD} \sim 200 - 300$ MeV
  ECFA/DESY (1991) : $\delta m_t = 500$ MeV
  G.P. Yeh (Sitges) $\delta m_t = 200$ MeV (systematics ?)

Top Yukawa Coupling

hep-ph/9910301

Juste, Merino (Sitges): "realistic simulation"
$E_{cm} = 800$ GeV, $m_h = 120$ GeV, $\mathcal{L} = 1000\ fb^{-1}$ (~3 years à $10^{34} cm^{-2} s^{-1}$)
⇒ $\delta g_{ttH}/g_{ttH} \sim 5.5\%$ ($q\bar{q}b\bar{b}b\bar{b}\ell\nu + q\bar{q}q\bar{q}b\bar{b}b\bar{b}$ channels)

Strong Coupling

- $\sigma_{t\bar{t}}$ at E_{cm} with largest cross section : $E_{cm} \simeq 380$ GeV
  → α_s from QCD radiative corrections
  → limiting factor: luminosity measurement
  Bernreuther (1999): $\delta\alpha_s(M_Z) \sim 0.007$

Rare Decays – FCNC (old studies)

BR ($t \to cH$, $c\tilde{\chi}^0$) sensitivity $< 1\%$
$t \to cZ, \gamma$?

Top Decays in new light particles (1991 studies)

$t \to H^+ b$: 3σ discovery for all $\tan\beta$ (favored by MSSM)
$\mathcal{L} = 10\ fb^{-1}$, $E_{cm} = 500$ GeV, $m_t = 150$ GeV, $m_{H^+} \sim 50$ GeV

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

Spin Correlations + anomalous couplings

→ $t\bar{t}$ produced in unique spin configurations that can be directly measured by angular distr. of decay leptons from W's

→ advantageous: use spin basis in which non-SM effects are easy to detect

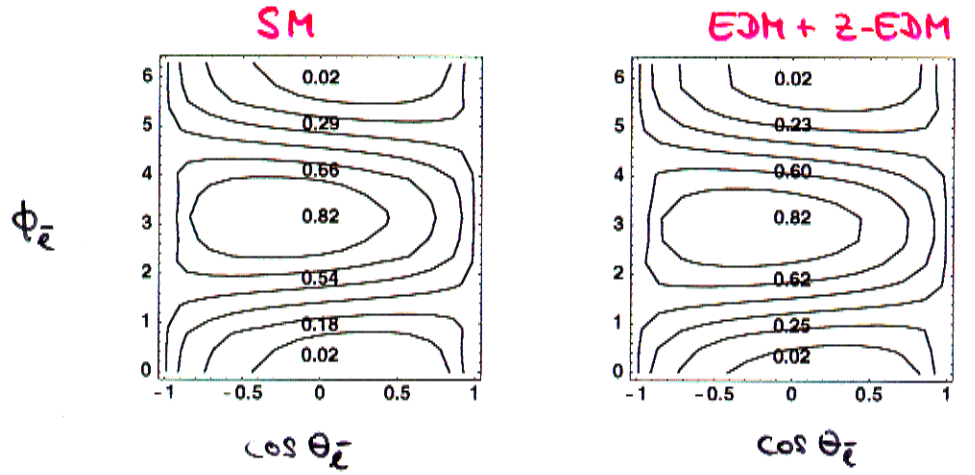
"off-diagonal basis" (Parke, Shadmi)

- for any energy $e^-_L e^+_R \to t_\downarrow \bar{t}_\uparrow$ contains ~100% of events
- only valid in the SM → new physics affects subdominant channels
- QCD phases have little effect (Kiyo, Parke, et al)
- off-diagonal basis accounts for fact that tops are neither at threshold nor at ultra-high energies ($m_t = 0$)

→ Double differential angular distribution of $\bar{\ell}$ from top decay

(Kiyo, Kodaira, Morii
Nasuno, Parke)

helicity basis

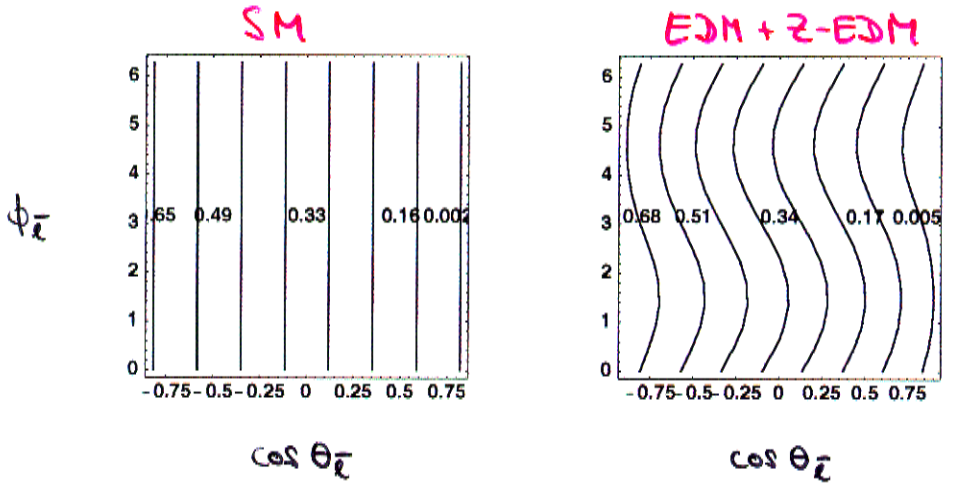


$e^-_L e^+ \to t\bar{t}$

$E_{cm} = 400$ GeV

→ anomalous effect barely visible

off-diagonal basis → $\phi_{\bar{\ell}}, \theta_{\bar{\ell}}$ defined differently



→ anomalous effect clearly visible

→ asymmetry can be easily defined $A \sim \int_0^{\pi} d\phi_{\bar{\ell}} - \int_{\pi}^{2\pi} d\phi_{\bar{\ell}}$

→ QCD contribution to asymmetry $< 0.5\,\%$

→ can be used to search for anomalous effects in production (EDM, etc.) and decay (V+A).

Summary

→ top quark is a window to "new physics"
large top mass ⟷ EWSB

→ measure all top quark properties as precise as possible
→ be prepared for surprises

→ <u>Linear Colliders:</u> versatile instrument to study top (and much more)

- $E_{c.m.}$ variable, well known
- clean e^+e^- environment
- beam polarization
- $\gamma\gamma$, γe modes

→ precision top studies ←
complementary to hadron colliders

MANY INTERESTING RESULTS
TO COME !