4th KEK Topical Conference

Top at Future Linear e^+e^- Colliders

Experimental Aspects

Keisuke FUJII : KEK, Japan

Introduction

Top at Threshold

Open Top Region

Top and Higgs

CP Violation

Summary

Top; Its New Features

Fact

Top exists in the mass range

$$M_W < m_t \cong 175 \text{ GeV} \quad \text{(Tevatron)}$$

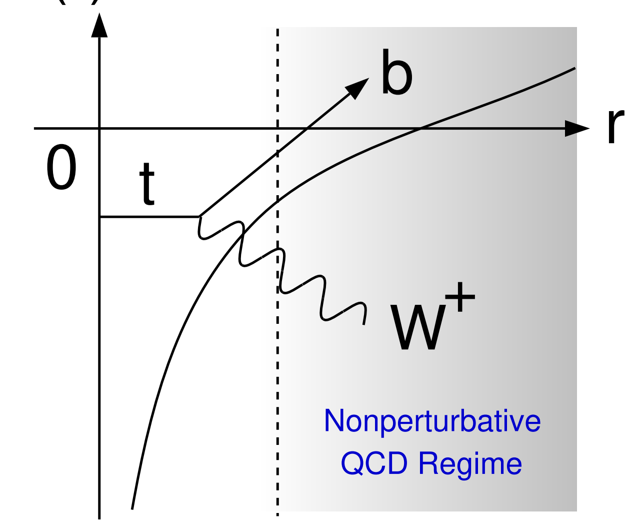
Implications

- We need a 0.5 TeV LC as a top factory.
- There is a chance to see top Yukawa interaction.
- $BR(t \to bW) \cong 100\%$ in SM
  = dominant in most of its extensions

  ------► No problem in its identification
- Γ_t is LARGE ($\Gamma(t \to bW_L)$: LARGE)

Γ_t	m_t
$\cong$ 0.8 GeV	150 GeV
$\cong$ 1.4	175
$\cong$ 2.2	200

------► The most important new feature!



Top decays before entering non-perturbative QCD regime!

Γ_t = Infrared Cutoff

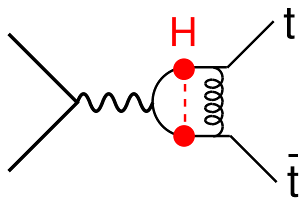
Reliable cross section calculation based on PERTURBATIVE QCD

Fadin-Khoze

------► Clean tests of QCD

α_s measurements

------► Other tiny effects: extractable

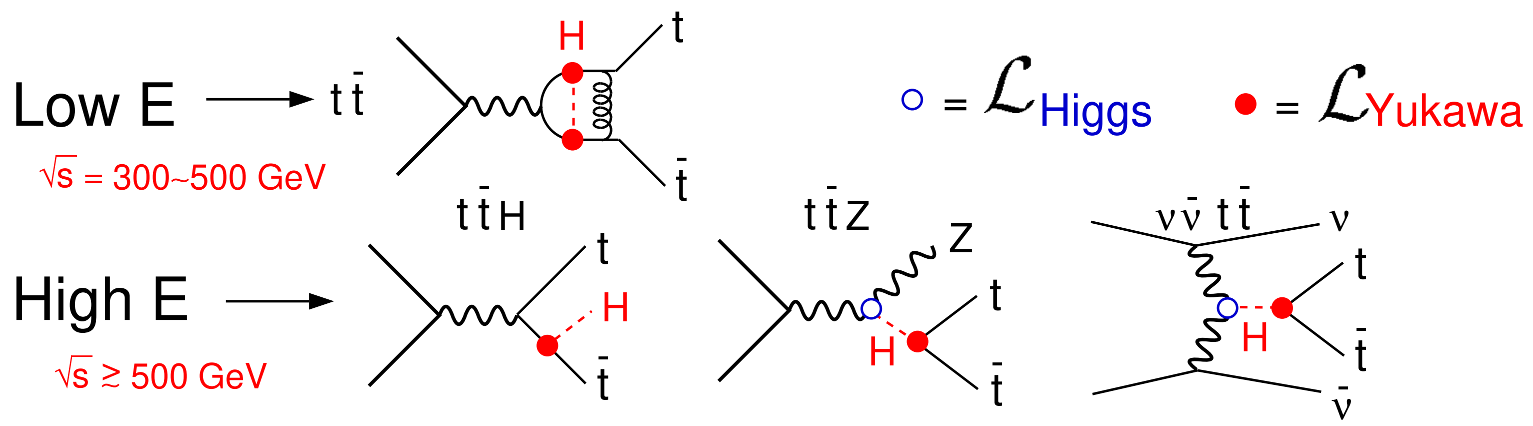


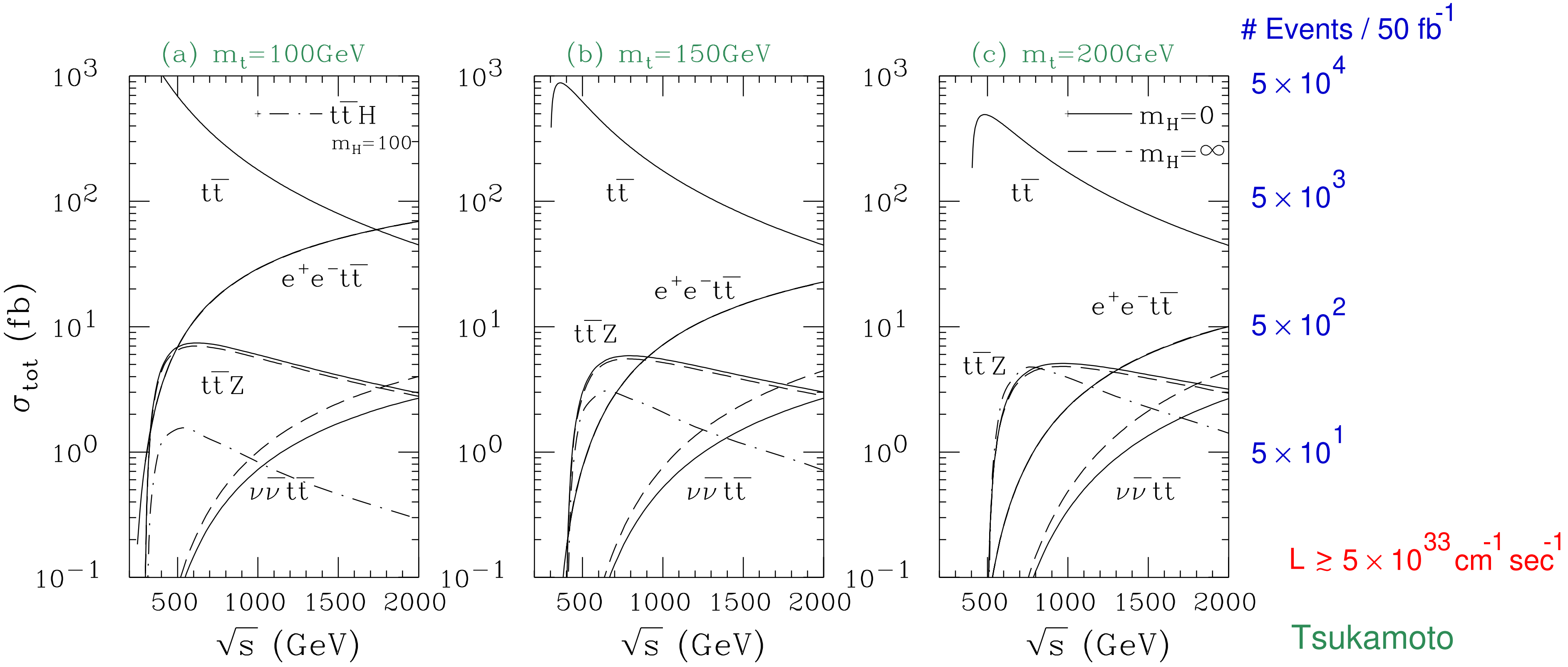
------► $\mathcal{L}_{\text{Yukawa}}$

------► No t-hadron formation

t-polarization: transferred to its daughters!

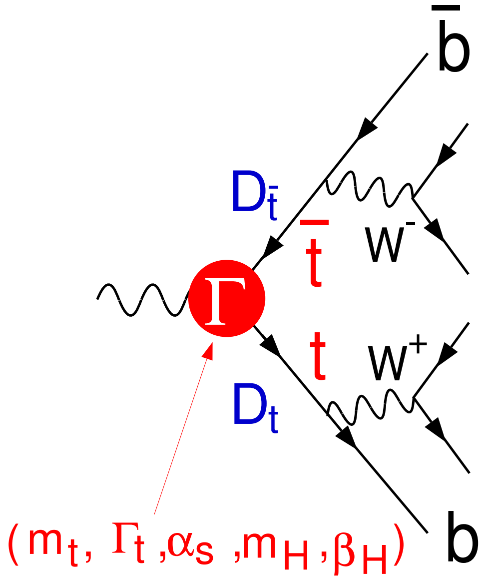
Top Quark Production; Required Energy and Luminosity





Threshold Scan

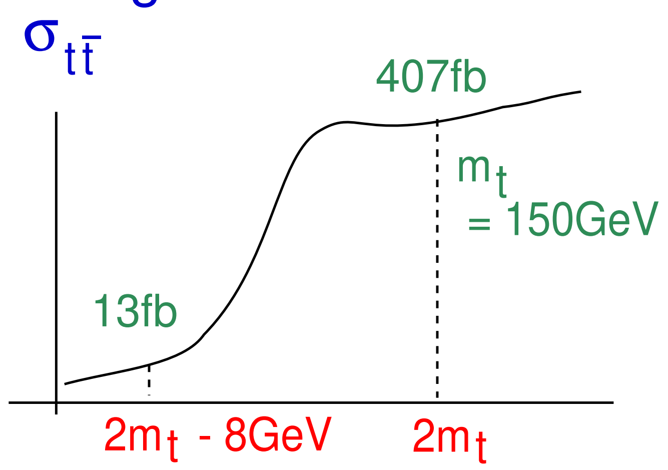
Signal of $t\bar{t}$ Production



2 W's and 2 b's

	BR	Topology
i) bbWW → $q\bar{q}'$, $q\bar{q}'$	45%	6J
ii) bbWW → $l\nu$, $q\bar{q}'$	44%	L+4J
iii) bbWW → $l\nu$, $l\nu$	11%	2L+2J

Background



Main BG = WW

σ_{WW}(effective) = 14.2 pb

⟶ $\varepsilon_{WW} \lesssim 1/1000$

Basic Cuts

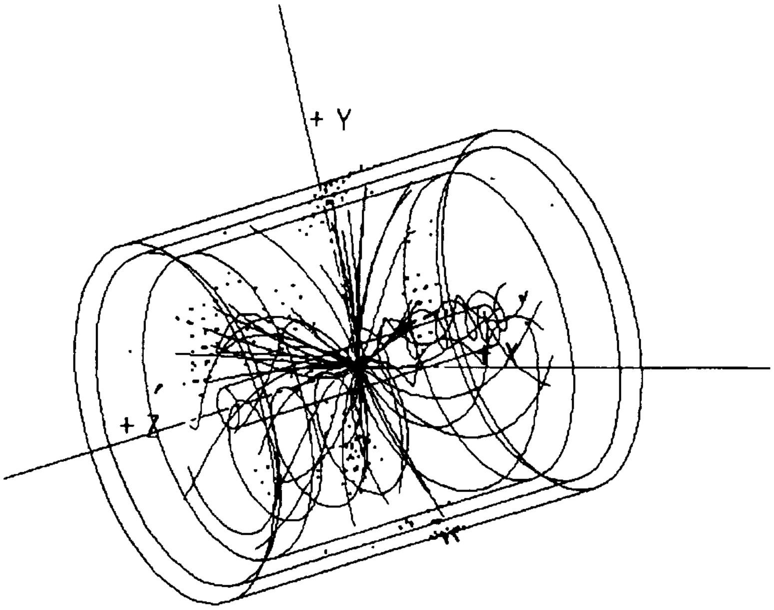
Event Shape	Mass Cuts	Lepton ID
#particles	$m_{2J} \cong m_W$	(ii),(iii)
#jets	$m_{3J} \cong m_t$	+ b-tagging
thrust		

⇢ Easy to get $\begin{cases} \varepsilon_{t\bar{t}} \cong 0.1\text{-}0.3 \\ S/N \cong 5\text{-}10 \end{cases}$

Ref.
European EE500 WG
DESY 92-123A,B
93-123C
Fujii-Matsui-Sumino

Typical 6-Jet Event

a) Tracker's View

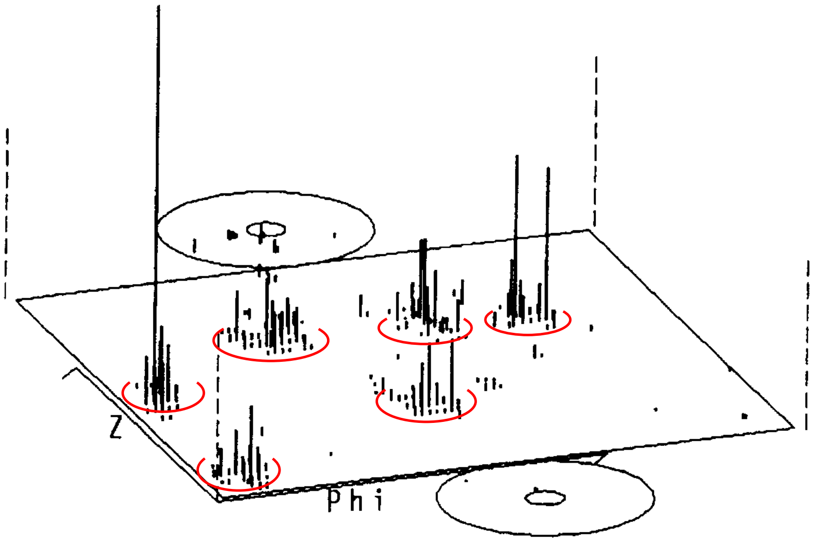


$e^+e^- \rightarrow b\bar{b}W^+W^-$

$W^- \rightarrow q\bar{q}'$

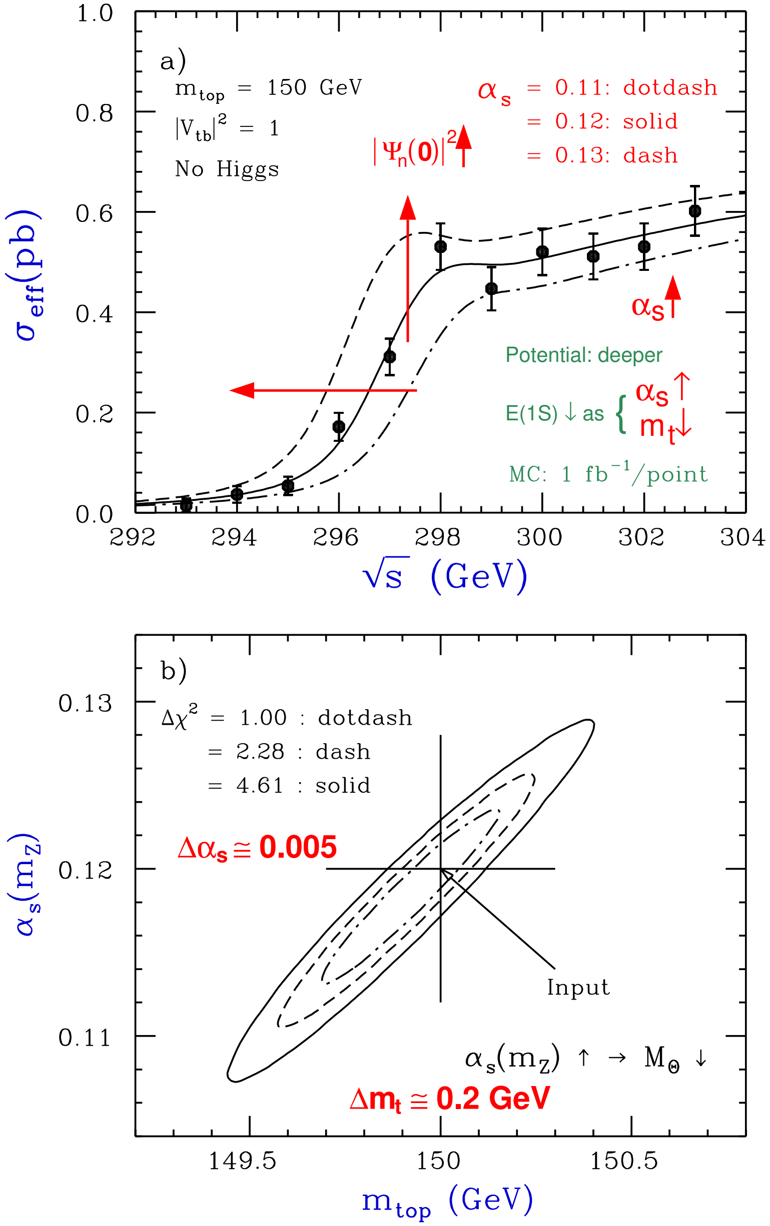
$W^+ \rightarrow q\bar{q}'$

b) Calorimeter's View

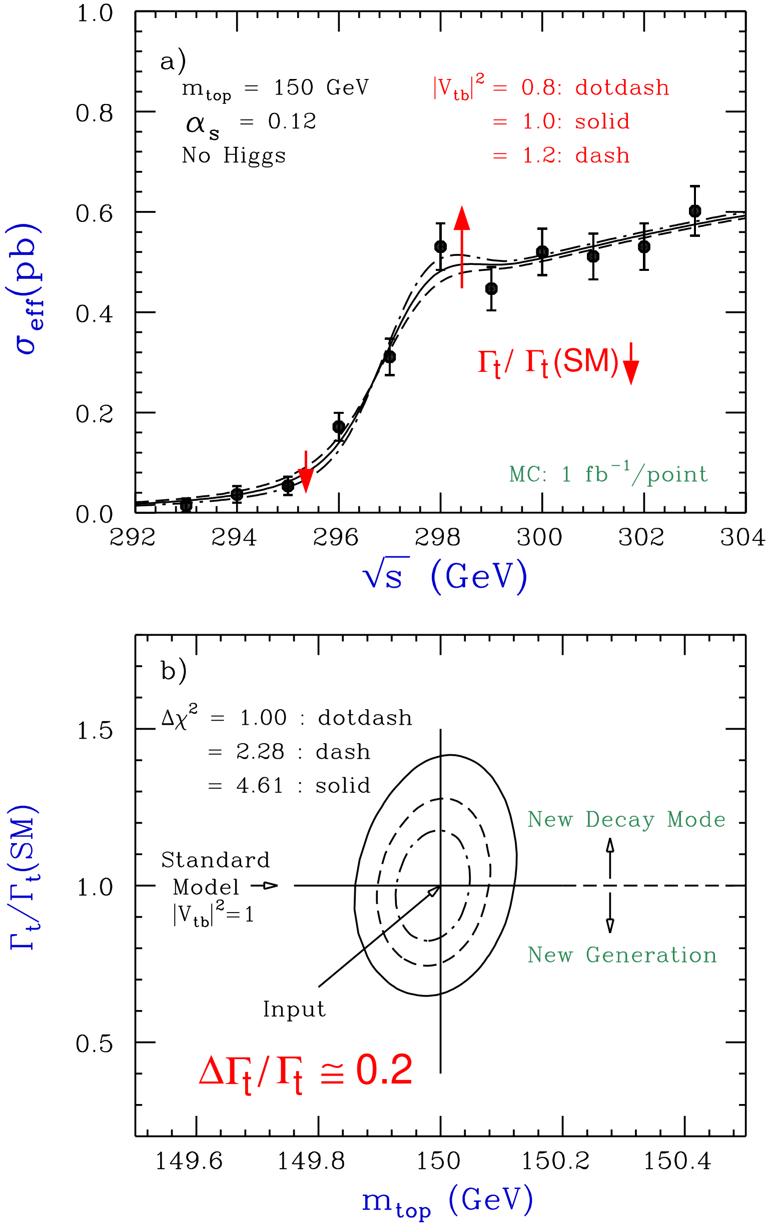


m_t -α_s Fit

~20 days

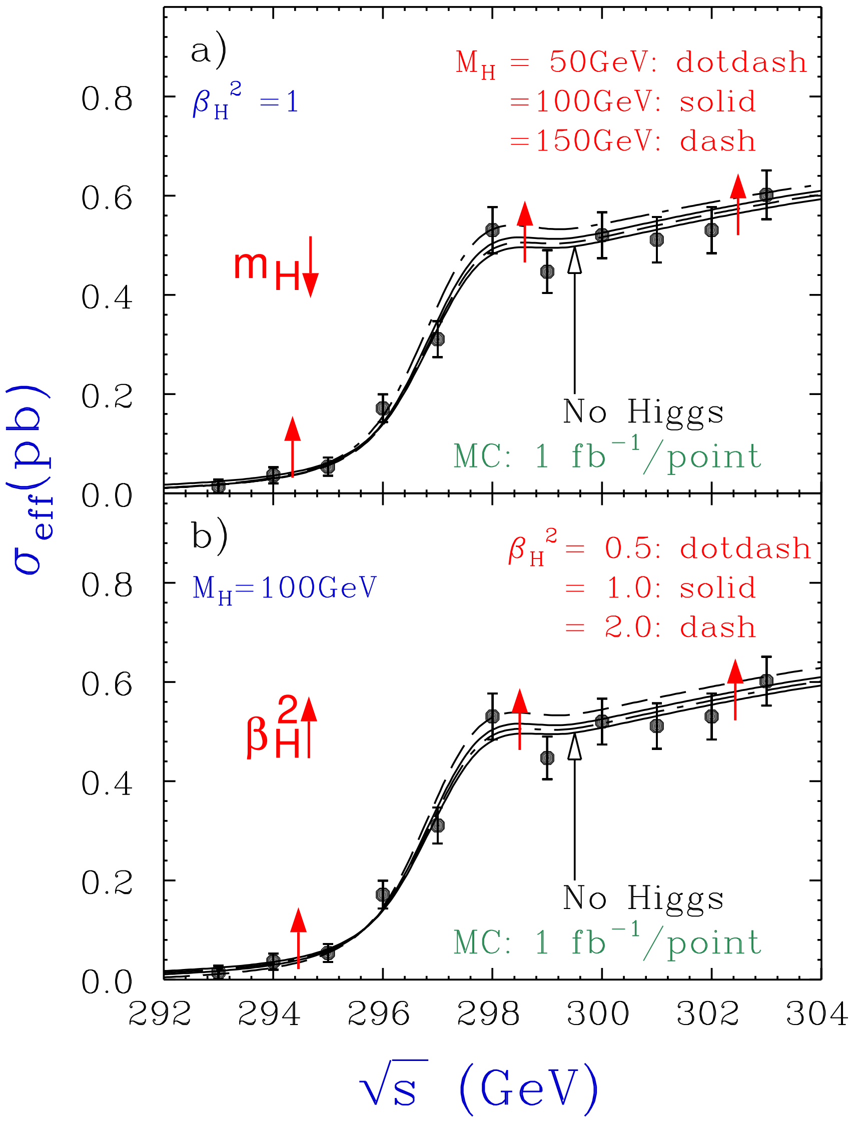


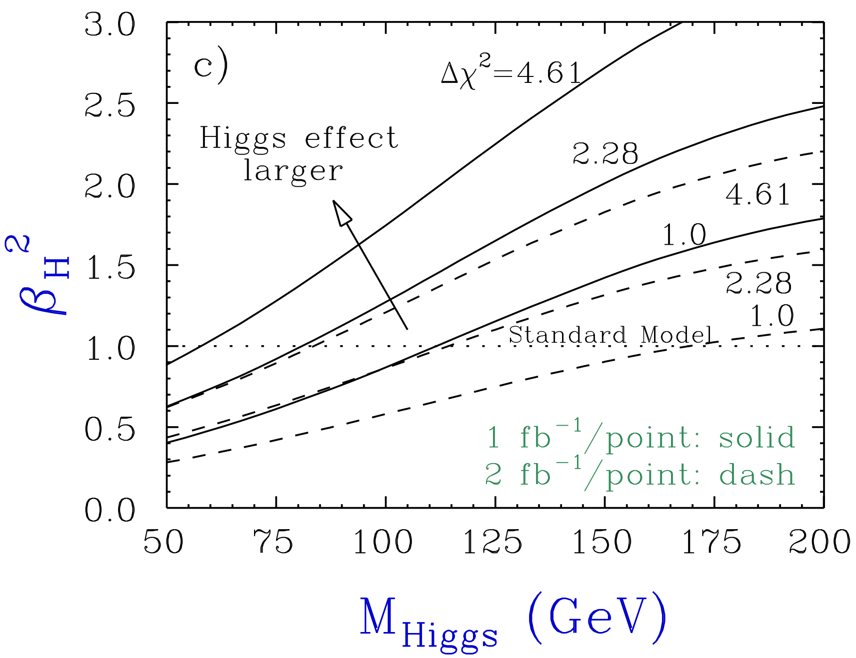
m_t -Γ_t Fit



m_H-β_H^2 Fit

$\beta_H \equiv g_{ttH}/g_{ttH}(SM)$





Input MC data

m_{top}=150GeV

α_s = 0.12

$|V_{tb}|^2$=1

No Higgs

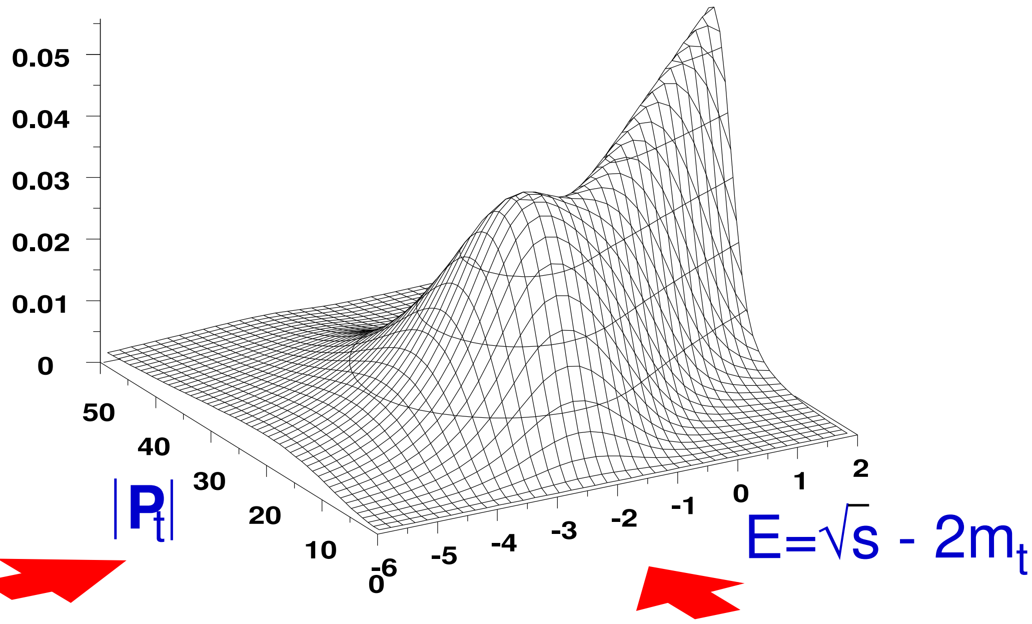
$\Delta\beta_H \cong 0.29$ (m_H= 100GeV:SM)

$$V_{Higgs}(r) = -\frac{\sqrt{2}\,G_F}{4\pi}(\beta_H m_t)^2\,\frac{e^{-m_H r}}{r}$$

Short Range Force

Only changes the overall normalization of the cross section.

Measurement of Top Momentum



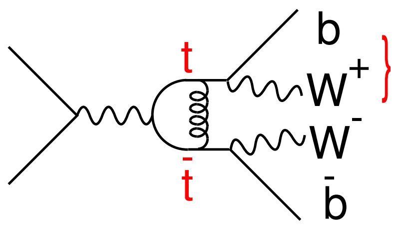
Momentum Dist.

$$\frac{d\sigma_{t\bar{t}}}{d|\mathbf{p}|} \propto \left| \sum_n \frac{\phi_n(\mathbf{p})\ \Psi_n^*(\mathbf{0})}{E - E_n + i\Gamma_n / 2} \right|^2$$

Threshold Scan

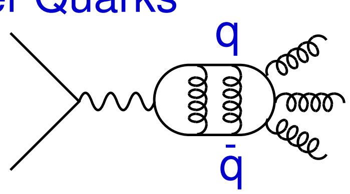
$$\sigma_{t\bar{t}} \propto \mathrm{Im} \sum_n \frac{|\Psi_n(\mathbf{0})|^2}{E - E_n + i\Gamma_n / 2}$$

Top



$\mathbf{p}_{top} = \mathbf{p}_{bW} = \mathbf{p}_{3Jets}$

Other Quarks



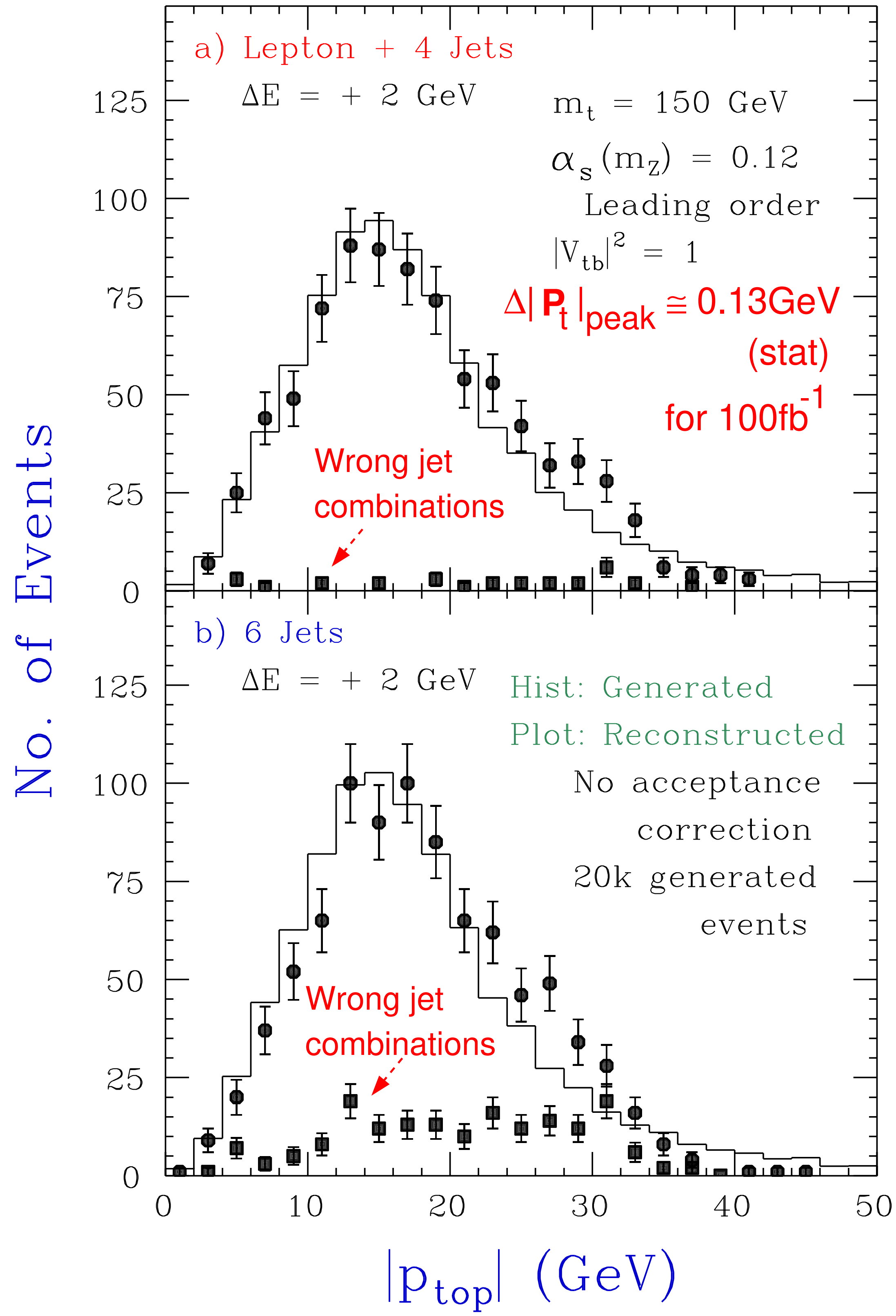
We cannot measure $\mathbf{p}_q$ in the onium!

Momentum measurement ----▸ Additional information on
(E; m_t, Γ_t, α_s, m_H, β_H)

The Higgs exchange only changes the overall normalization!

Reconstructed Top Momentum Distribution

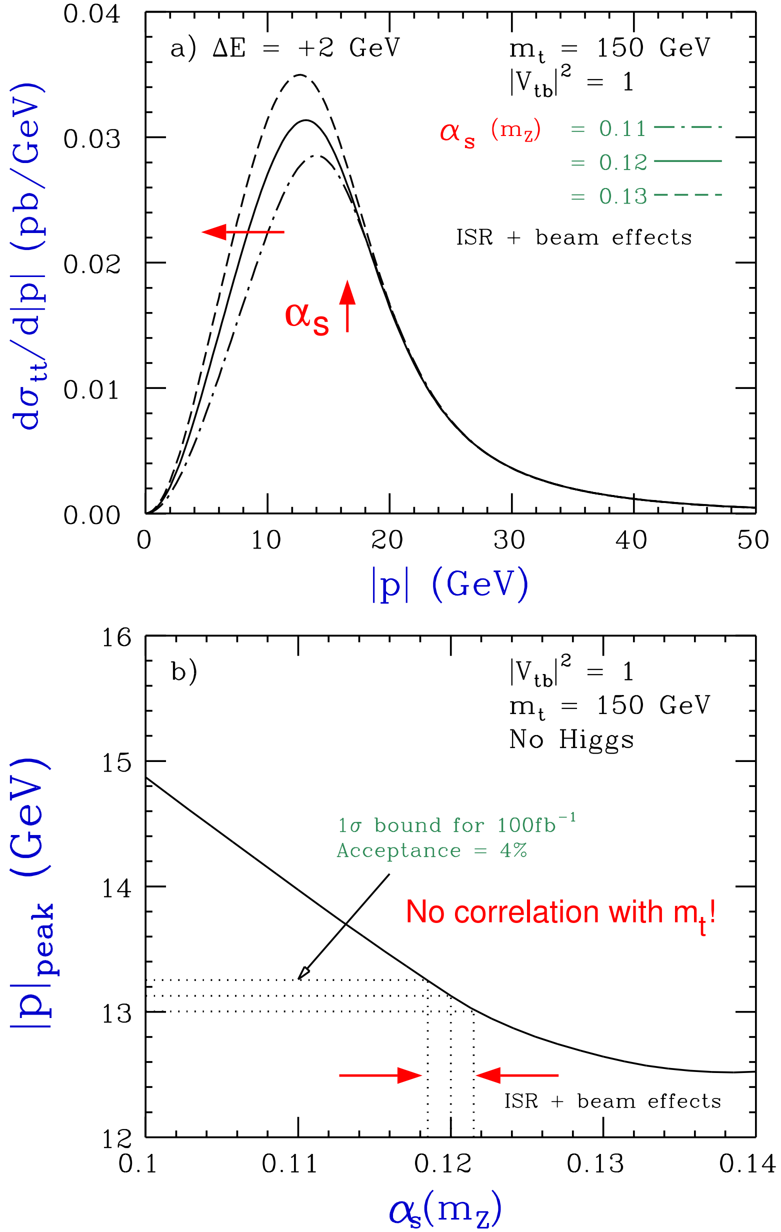
$$\Delta E \equiv \sqrt{s} - \sqrt{s_{1S}}$$



The BG can be eliminated if we can remove charms from bottom candidates!

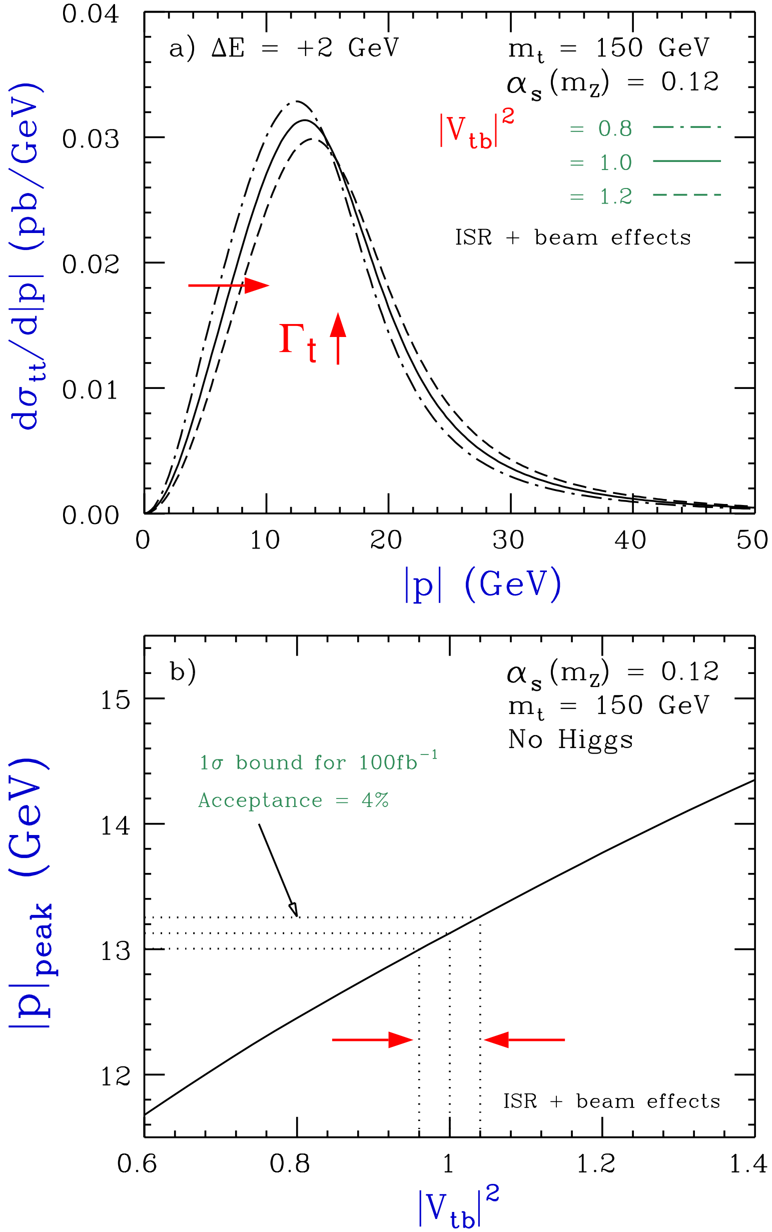
Parameter Determinations

α_s



$\Delta\alpha_s \cong 0.002$ (100fb^{-1}) if $\sqrt{s_{1S}}$, Γ_t : known

Γ_t



$\Delta\Gamma_t / \Gamma_t \cong 0.04$ (100fb^{-1}) if $\sqrt{s_{1S}}$, α_s : known

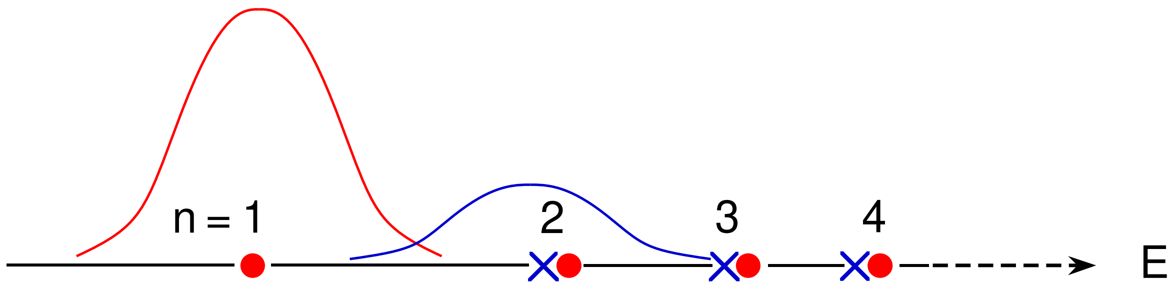
Measurement of FB-Asymmetry

Murayama-Sumino

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

Main Origin of A_{FB} at Threshold

Γ_t : LARGE! ⇢ S-P Interference



● = S-wave resonances

× = P-wave resonances

S-wave O(1)

P-wave O(β)

⇢ O(β) Effect

$^\exists$FB-asymmetry even below threshold!

For instance, if we sit inbetween n=1 and 2

Γ_t ↑

$|E_1 - E_2|$ ↓

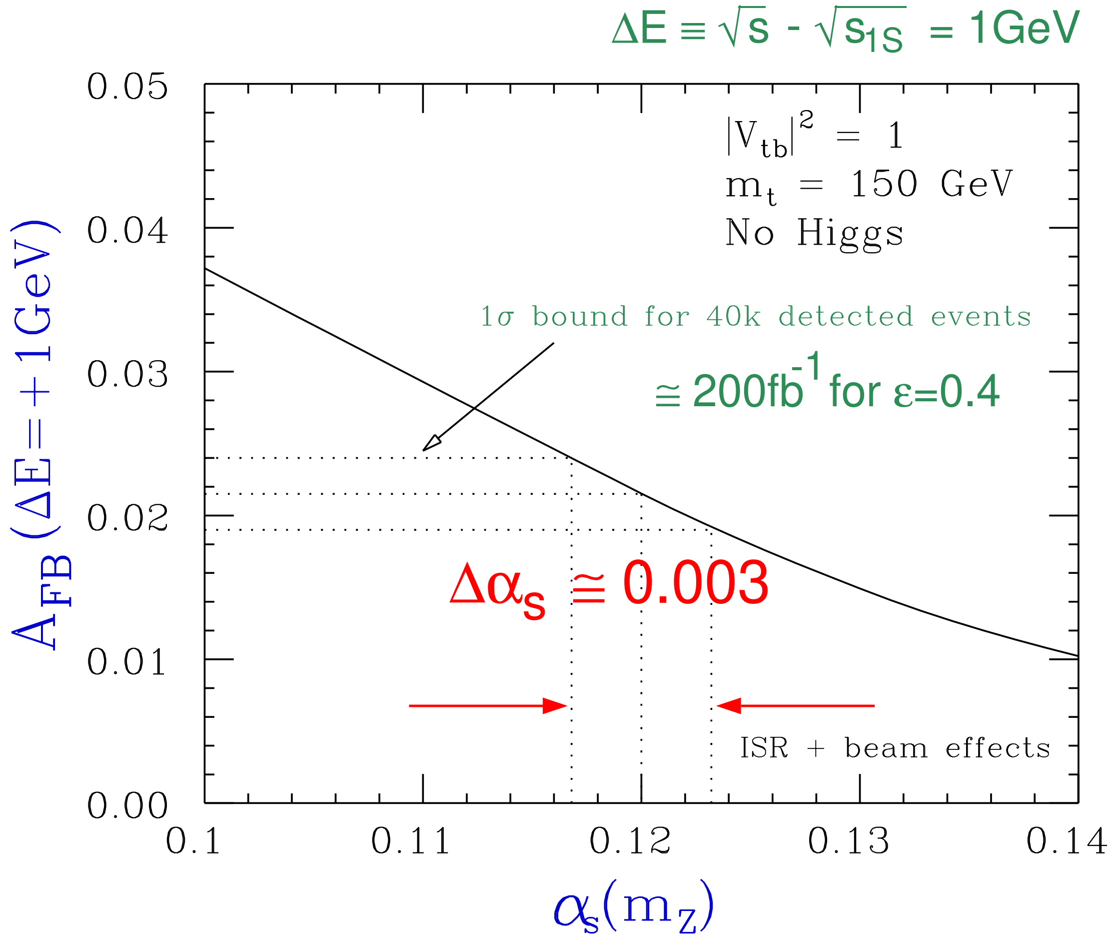
⇢ Interference ↑

Function of α_s

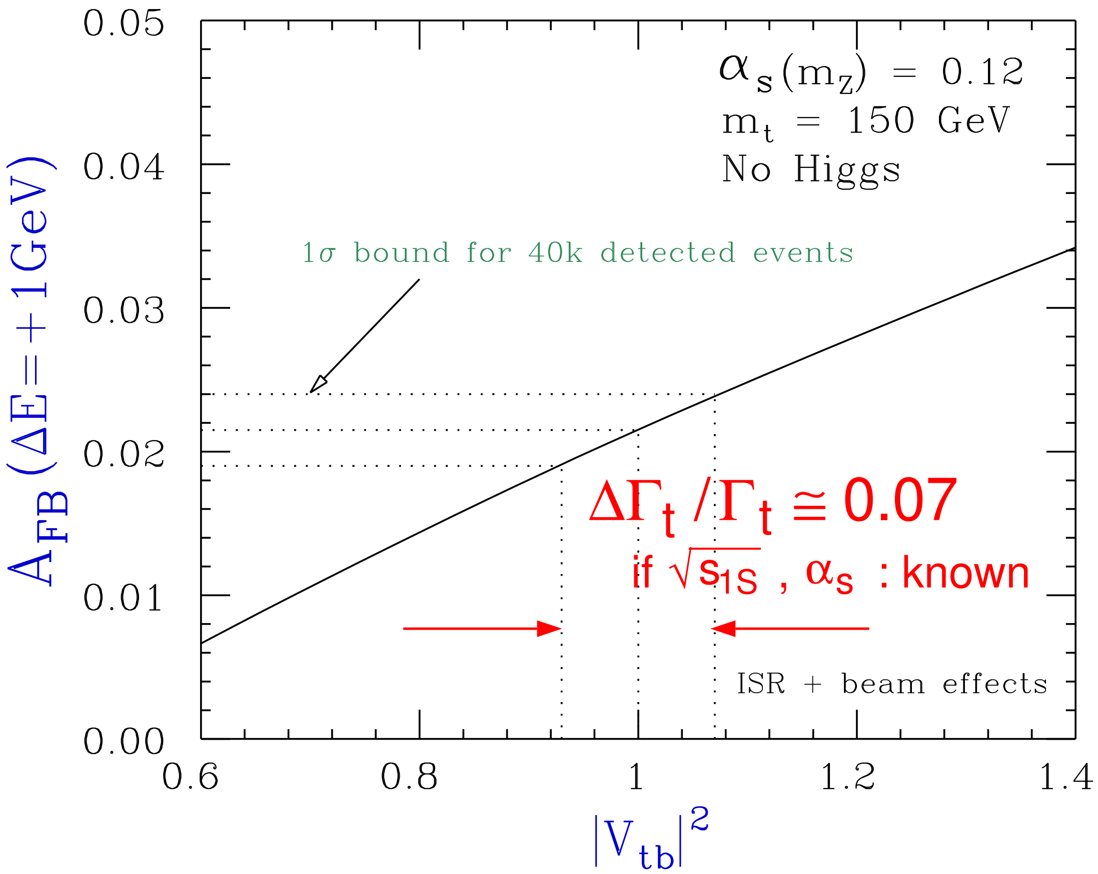
⇢ Measurements of α_s and Γ_t

Parameter Determination

$\boxed{\alpha_s}$



$\boxed{\Gamma_t}$



Open Top Region

$e^+e^- \longrightarrow t\,\bar{t}$

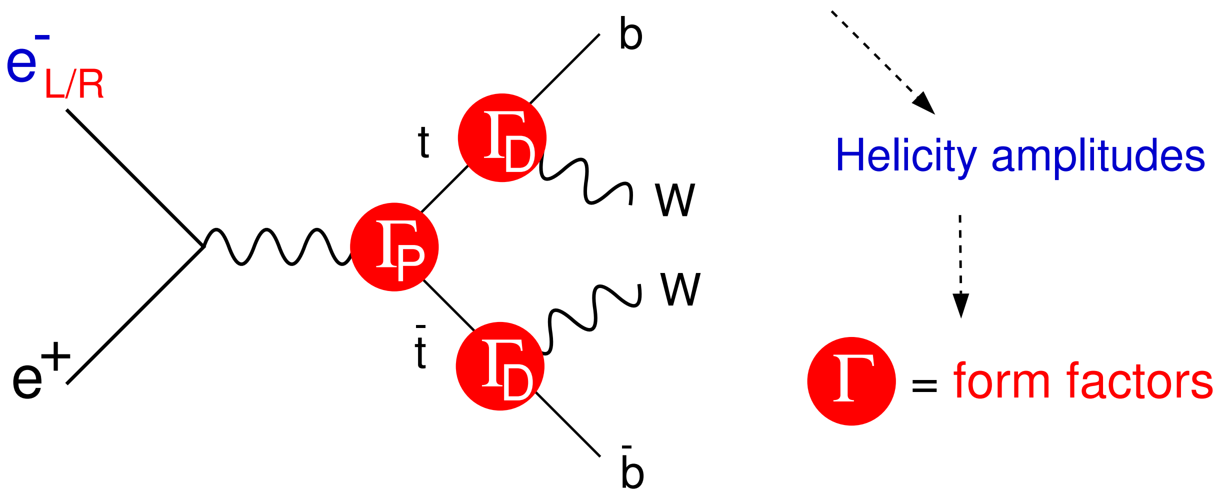
Key Points

Top decays before forming a top hadron!

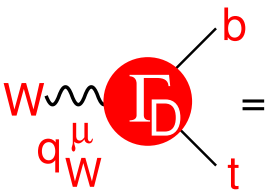
⇢ angular analysis

⇢ Top spin measurable!

Highly polarized electron beam available!



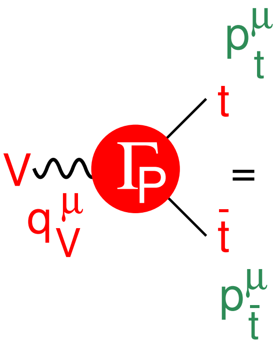
Form Factors at tbW Vertex



$$= \mathcal{L}^{tbW}_{int} = \frac{g_W}{\sqrt{2}} \Big[W^-_\mu \; \bar{b}\, \gamma^\mu \left(F^W_{1L} P_L + F^W_{1R} P_R \right) t - \frac{1}{v} \left(\partial_\nu W^-_\mu\right) \bar{b}\, \sigma^{\mu\nu} \left(F^W_{2L} P_L + F^W_{2R} P_R \right) t + \text{h.c.}$$

$$P_{L/R} = \tfrac{1}{2}\left(1 \mp \gamma^5\right) \qquad \sigma^{\mu\nu} = \tfrac{i}{2}\left[\gamma^\mu, \gamma^\nu\right] \qquad v = \left(\sqrt{2} G_F\right)^{1/2}$$

Form Factors at $t\bar{t}V$ Vertex

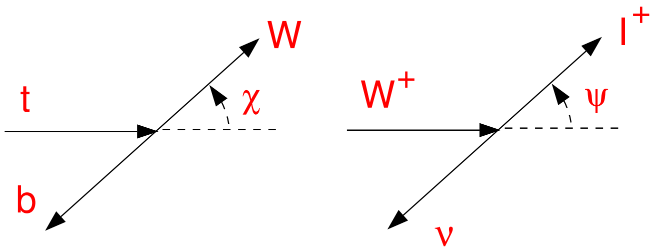


$$= \mathcal{L}^{t\bar{t}V}_{int} = g_W \Big[V_\mu \; \bar{t}\, \gamma^\mu \left(F^V_{1L} P_L + F^V_{1R} P_R \right) t - \frac{1}{v} \left(\partial_\nu V_\mu\right) \bar{t}\, \sigma^{\mu\nu} \left(F^V_{2L} P_L + F^V_{2R} P_R \right) t$$

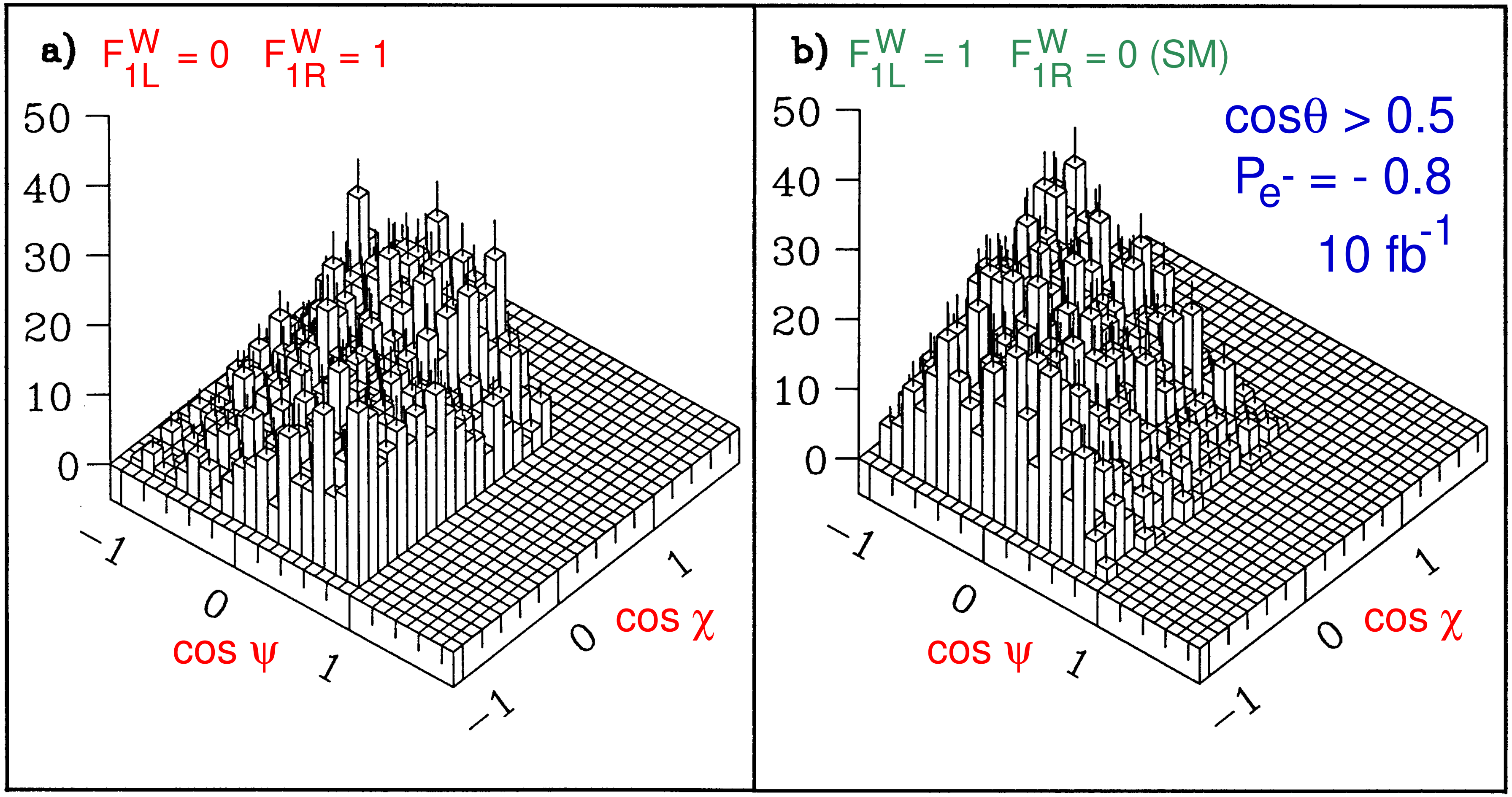
Form Factors at tbW Vertex

For $m_t = 140$ GeV
$\sqrt{s} = 400$ GeV
10 fb^{-1}

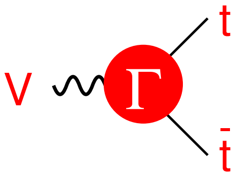
$\dashrightarrow$ $\Delta F \cong \pm\, 0.05$



Petradza



Form Factors at ttV Vertex



$$= g_W \left[V_\mu \, \bar{t} \, \gamma^\mu \left(F^V_{1L} P_L + F^V_{1R} P_R \right) t - \frac{1}{v} \left(\partial_\nu V_\mu \right) \bar{t} \, \sigma^{\mu\nu} \left(F^V_{2L} P_L + F^V_{2R} P_R \right) t \right]$$

MC Conditions

$m_t = 140\,\mathrm{GeV}$

$\sqrt{s} = 500\,\mathrm{GeV}$ $\xrightarrow{50\,\mathrm{fb}^{-1}}$ 30k events

$P_{e^-} = 0$

Use both L+4J and 2L+2J modes ($L = e/\mu$)

Ladinsky-Yuan

Form Factor	68%CL Bound	90%CL Bound
F^Z_{1L}	$(1.00 \pm 0.03) \times \mathrm{SM}$	$(1.00 \pm 0.08) \times \mathrm{SM}$
F^Z_{1R}	$(1.00 \pm 0.05) \times \mathrm{SM}$	$(1.00 \pm 0.18) \times \mathrm{SM}$
F^Z_2	0.000 ± 0.004	0.00 ± 0.02

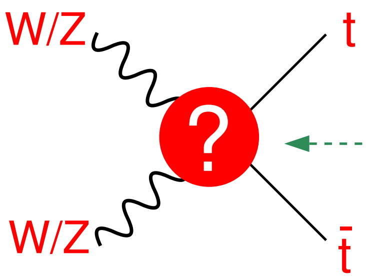
Or in terms of (W)MDM or (W)EDM

Atwood-Soni
Ladinsky-Yuan

$$\delta(\mathrm{MDM}) \cong 10^{-18} - 10^{-19} \ \mathrm{e\,cm}$$

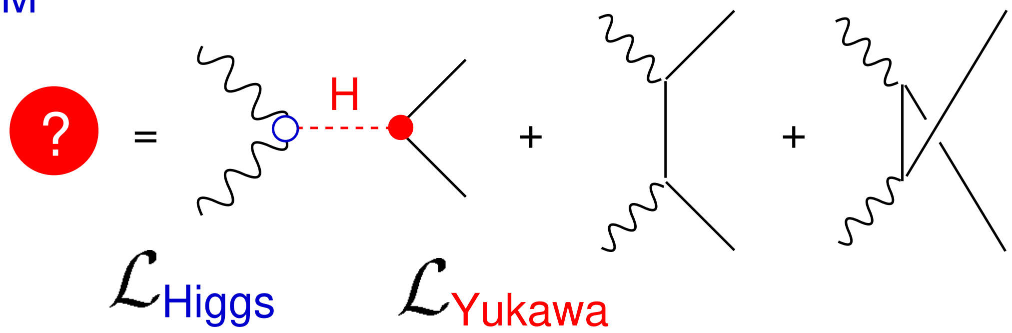
$$\delta(\mathrm{EDM}) \cong 10^{-18} - 10^{-19} \ \mathrm{e\,cm}$$

How to Test SSB Physics



Depends on models to generate top mass

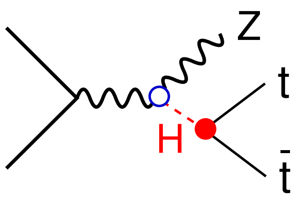
In SM



Heavy Higgs Decaying Into Top

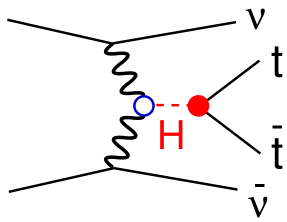
The 1st chance might be

$$e^+ e^- \longrightarrow t\,\bar{t}\,Z$$

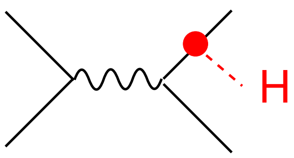


while at higher energies

$$e^+ e^- \longrightarrow \nu\,\bar{\nu}\,t\,\bar{t}$$



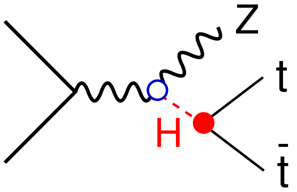
Light Higgs off Top



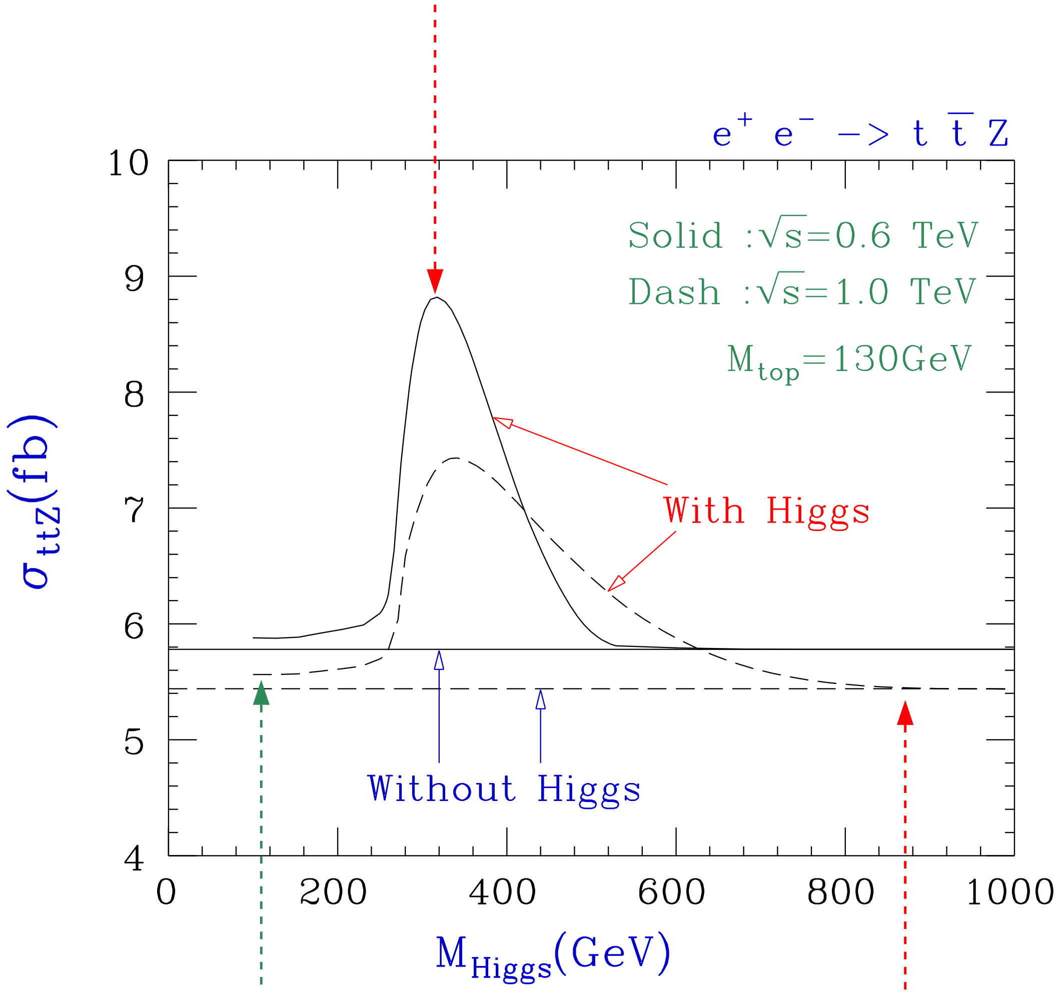
$$e^+ e^- \longrightarrow t\,\bar{t}\,H$$

Direct measurement of Top Yukawa coupling !

$e^+e^- \rightarrow t\bar{t}Z$



Real Higgs dominates !



Only a Small Effect from Virtual Light-Higgs !

No Virtual Heavy Higgs Effect !

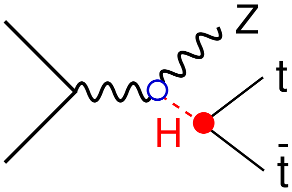
Assume

$m_H = 300$ GeV $\quad m_t = 130$ GeV

and see if how well we can determine the top Yukawa coupling.

Determination of Top Yukawa Coupling

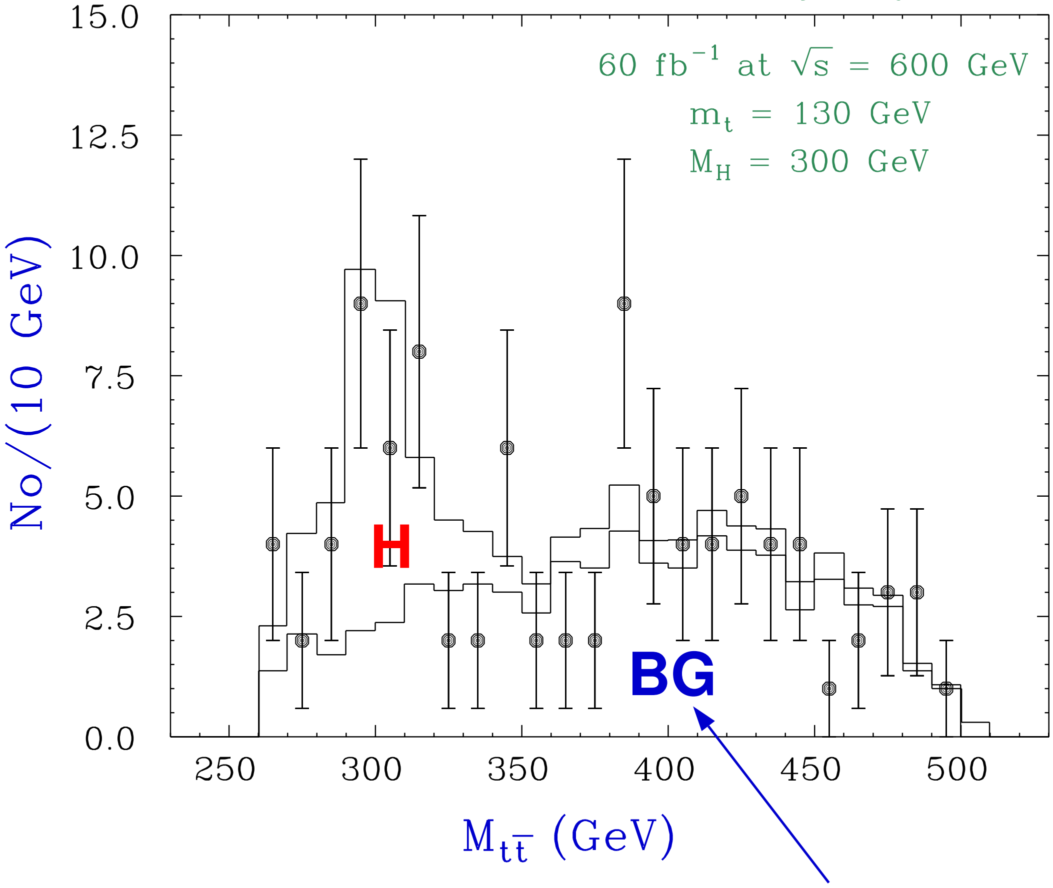
Signal to Look For



$\dashrightarrow$ 8 Jets

Look at $M_{t\bar{t}}$ and count # Higgs bosons

Tauchi-Fujii-Miyamoto



BG from non-Higgs diagrams!

Sensitivity to Top Yukawa Coupling

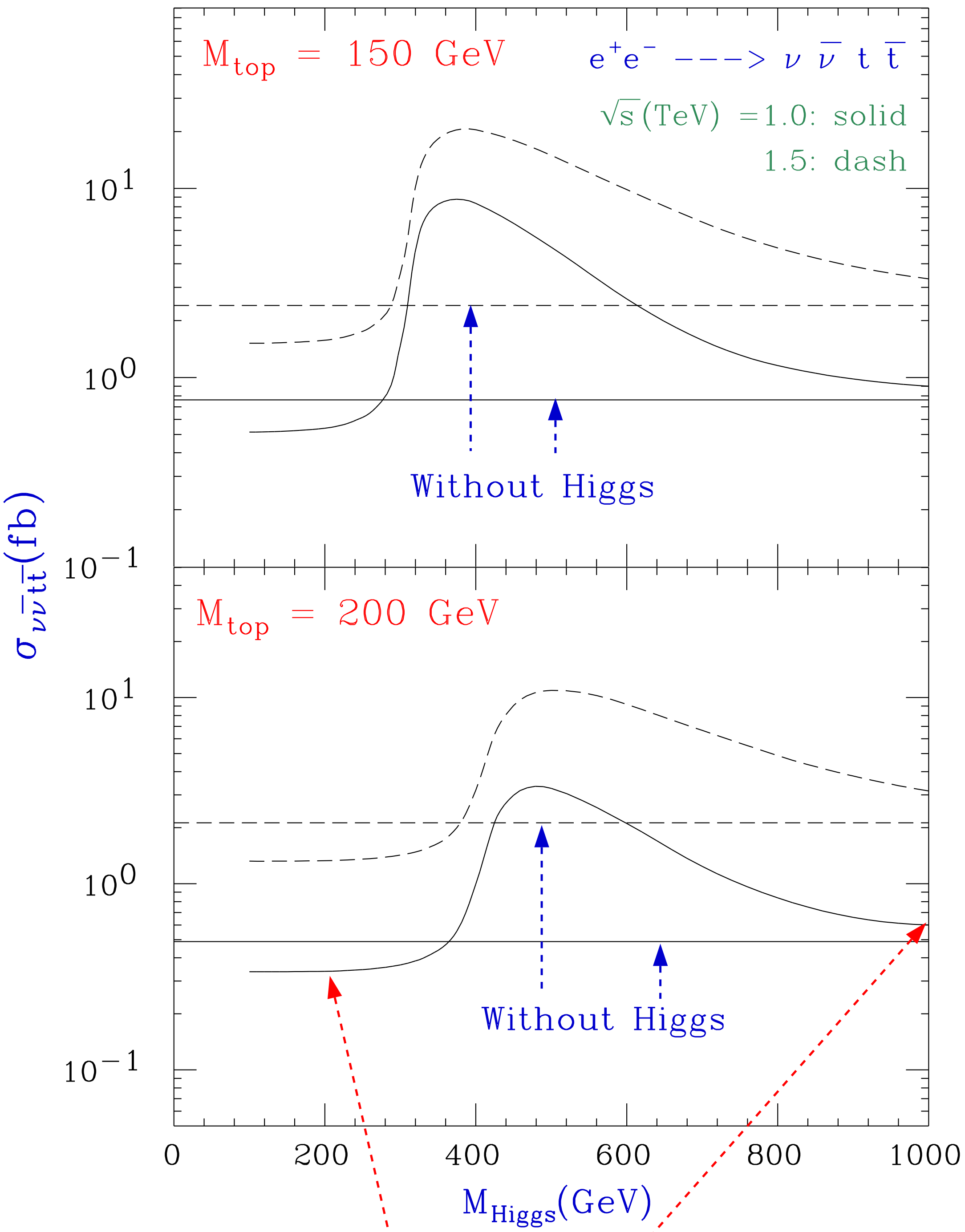
$$S(H) \propto \beta_H^2$$

S(H) = 27

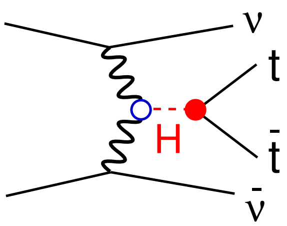
BG = 9

$\dashrightarrow$ $\Delta\beta_H / \beta_H \cong 0.1$

$e^+e^- \rightarrow \nu\bar{\nu}\, t\bar{t}$



∃ Virtual Higgs Effect !



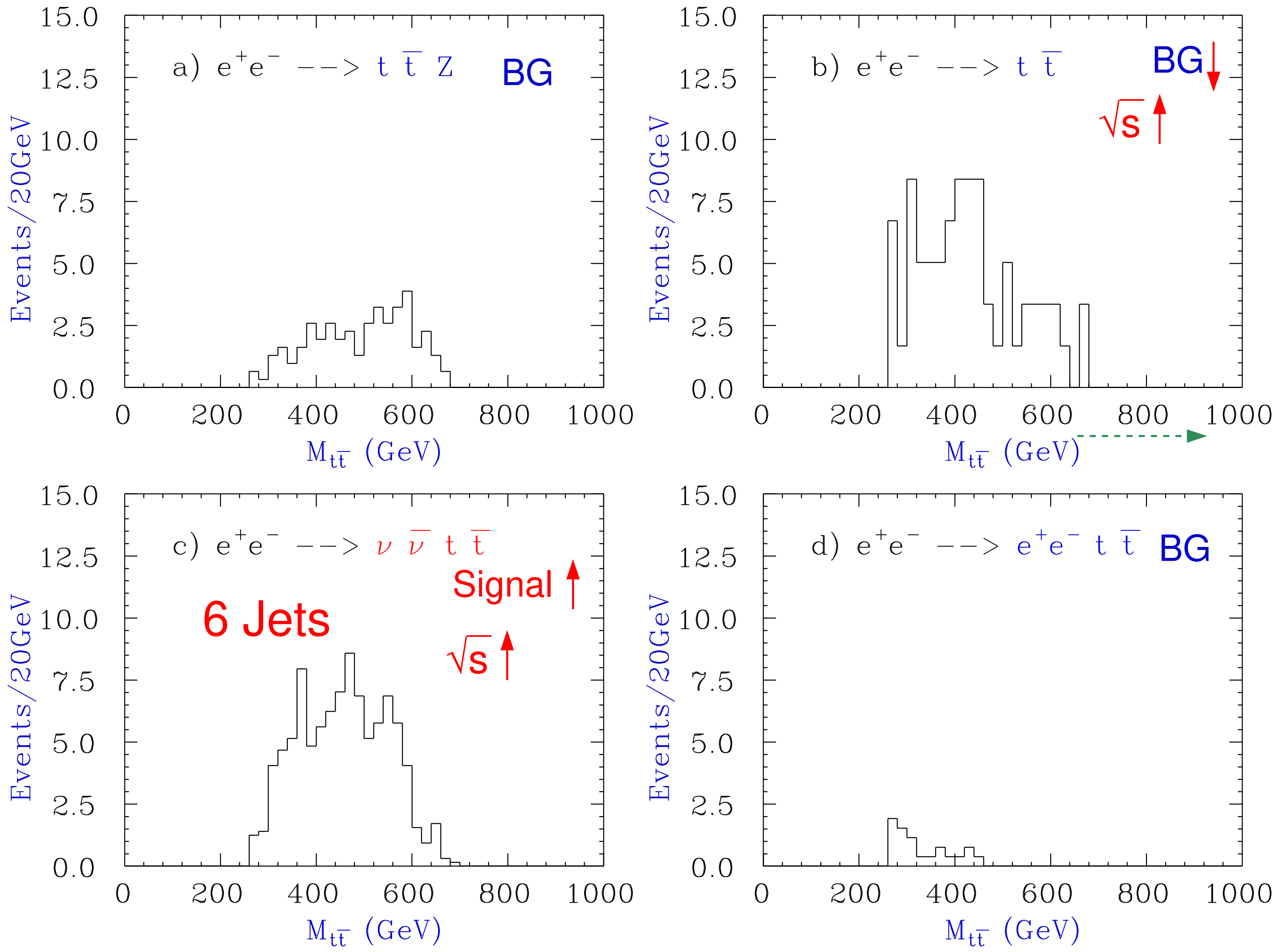
Assume

$m_H = 600$ GeV $\quad m_t = 150$ GeV

and see if how well we can determine the top Yukawa coupling.

Measurement of Top Yukawa Coupling

Tsukamoto



$m_H = 600\,\mathrm{GeV}$

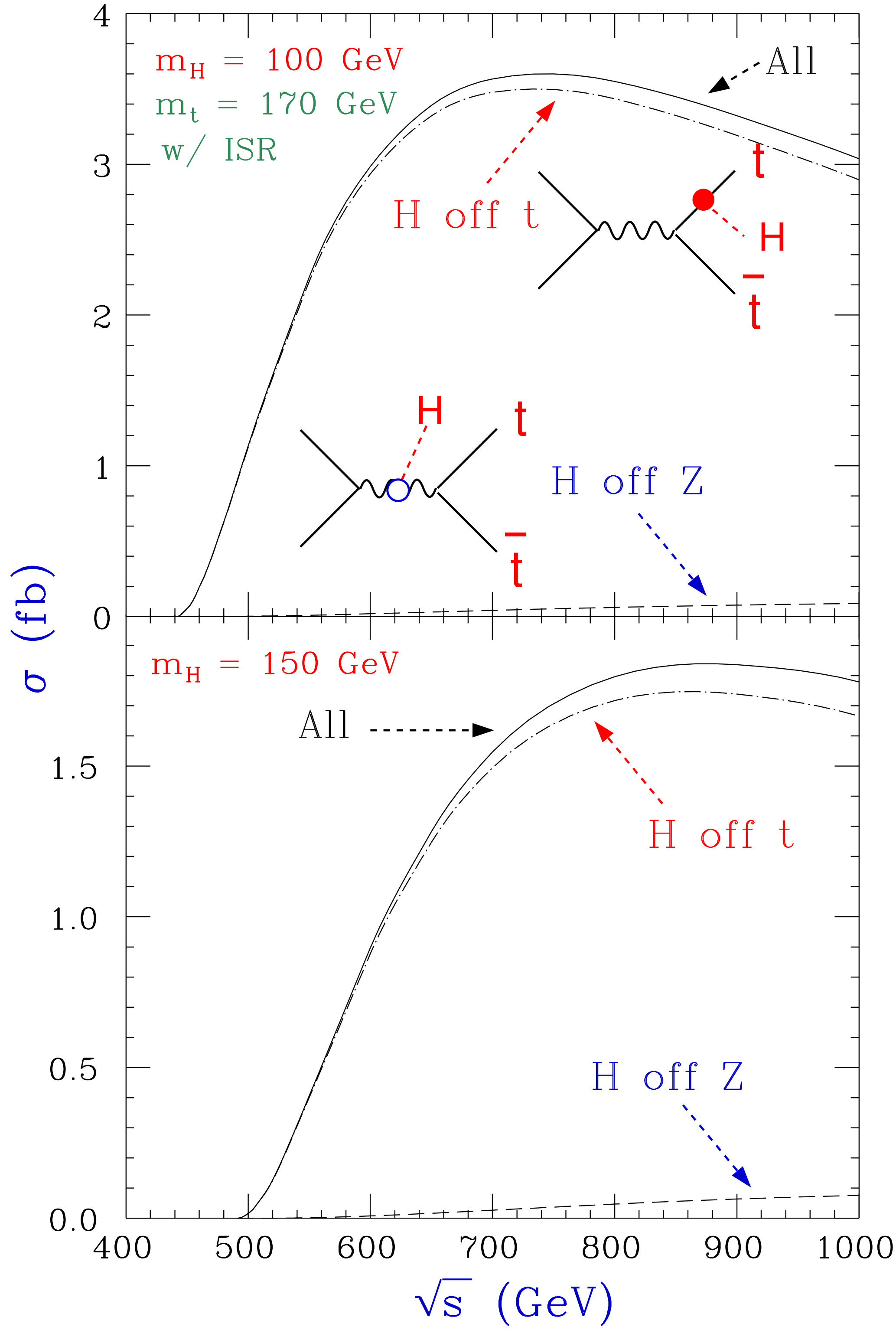
$m_t = 150\,\mathrm{GeV}$

$\sqrt{s} = 1\,\mathrm{TeV}$

$300\,\mathrm{fb}^{-1}$

Sensitivity to Top Yukawa Coupling ⟶ S = 96, BG = 143 ⟶ $\Delta\beta_H / \beta_H \cong 0.1$

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



Higgs-strahlung diagrams dominate !

Events $\propto \beta_H^2$

Determination of Top Yukawa Coupling

Assume

$m_H = 100$ GeV $\quad m_t = 170$ GeV

$100\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 700$GeV

and see if how well we can determine the top Yukawa coupling.

Signal

L+6 Jets or 8 Jets
with >2 b-taggs

$\sigma_{t\bar{t}H} \cong 3.6$ fb $\qquad \epsilon_{t\bar{t}H} \cong (0.304 + 0.203) = 0.51$

BG

$\sigma_{t\bar{t}Z} \cong 4.4$ fb $\qquad \epsilon_{t\bar{t}Z} \cong (0.114 + 0.066) = 0.18$

Sensitivity to Top Yukawa Coupling

$$\left\{ \begin{array}{l} S = 183 \\ B = 79 \\ S/N \cong 2.3 \end{array} \right\} \xrightarrow{S(H) \propto \beta_H^2} \Delta\beta_H / \beta_H \cong 0.1$$

Preliminary: No optimization of selection cuts yet !

CP Violation in Top Physics

Key Points

Top is heavy and has almost no mixing with other generations

SM CP violation: extremely small

$\dashrightarrow$ Any CP violation in top physics = BSM !

Large top mass

$\dashrightarrow$ Higgs sector CP might be sizable

No hadronization

$\dashrightarrow$ Top spin: measurable

Example of CP Violation Signals

1) EDM

EDM $\neq 0$

Experimental Sensitivity

$\delta(\text{EDM}) \cong 10^{-18} - 10^{-19}$ e cm

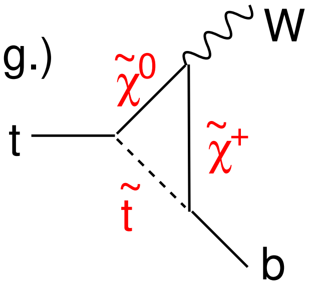
2) PRA

$$\frac{\Gamma(t\to bW) - \Gamma(\bar{t}\to\bar{b}W)}{\Gamma(t\to bW) + \Gamma(\bar{t}\to\bar{b}W)} \neq 0$$

$$\updownarrow \quad \sum_{X} \Gamma(t\to X) = \sum_{\bar{X}} \Gamma(\bar{t}\to\bar{X})$$

Asymmetry in Ugly decays

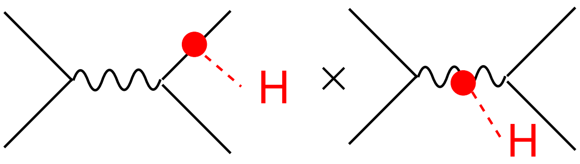
e.g.)



$\delta(\text{PRA}) \cong O(10^{-2})$?

3) $t\,\bar{t}\,H$

$$\langle \mathbf{p}_- \cdot (\mathbf{p}_t \times \mathbf{p}_{\bar{t}}) / s^{3/2} \rangle \neq 0$$



$\delta(\text{Correlation}) \cong$?

And a lot more theorist's papers, but almost no MC studies with detector simulation by experimentalists!

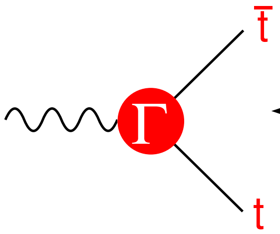
Need more studies !

Summary

Top at Threshold

Key Point

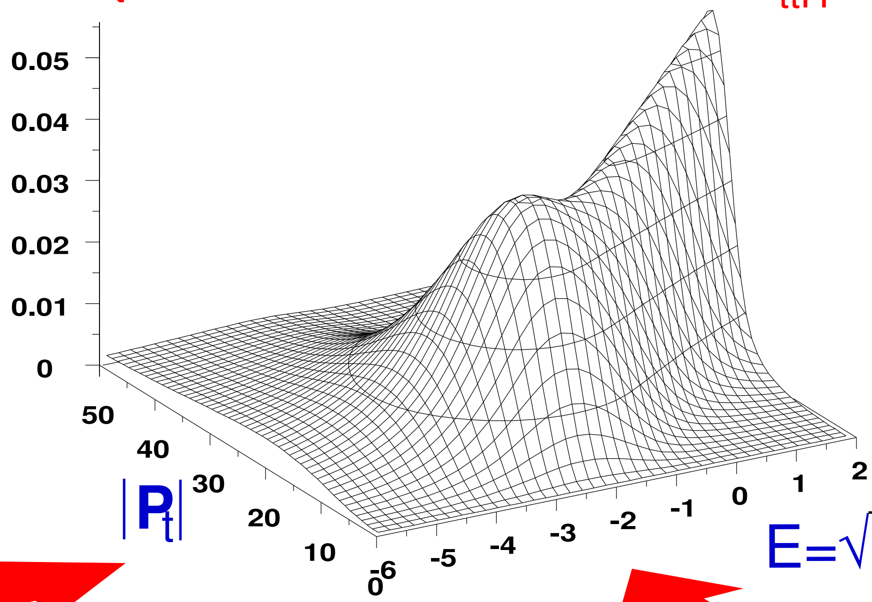
Large Γ_t = Infrared Cutoff ⇢ Reliable theoretical predictions



Essentially all the physics in G!

⟷ $G\,(E;\, m_t,\ \Gamma_t, \alpha_s, m_H, \beta_H)$

$\beta_H \equiv g_{ttH}/g_{ttH}(SM)$



$E=\sqrt{s} - 2m_t$

Momentum Dist.

$$\frac{d\sigma_{t\bar{t}}}{d|\mathbf{p}|} \propto \left|\langle \mathbf{p} | G | \mathbf{x}=\mathbf{0}\rangle\right|^2$$

$$\approx \left| \sum_n \frac{\phi_n(\mathbf{p})\ \Psi_n^*(\mathbf{0})}{E - E_n + i\Gamma_n / 2} \right|^2$$

$100\ \mathrm{fb}^{-1}$ if E_{1S}: known

$\Delta\alpha_s \cong$ **0.002**

$\Delta\Gamma_t/\Gamma_t \cong$ **0.04**

S-wave part of G

Threshold Scan

$$\sigma_{t\bar{t}} \propto \mathrm{Im}\langle \mathbf{x}=\mathbf{0} | G | \mathbf{x}=\mathbf{0}\rangle$$

$$\approx \mathrm{Im} \sum_n \frac{|\Psi_n(\mathbf{0})|^2}{E - E_n + i\Gamma_n / 2}$$

$10\ \mathrm{fb}^{-1}$ m_t=150 GeV

$\Delta m_t \cong$ **0.2 GeV**

$\Delta\alpha_s \cong$ **0.005**

$\Delta\Gamma_t/\Gamma_t \cong$ **0.2**

$\Delta\beta_H \cong$ **0.29**

(m_H=100GeV:SM)

$$\frac{d\sigma_{t\bar{t}}}{d\cos\theta} \ (\text{or } A_{FB})$$

P-wave part of G

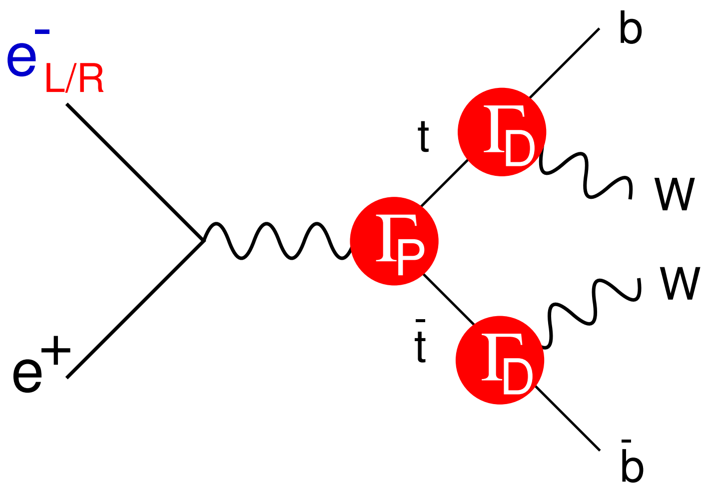
⇢ Yet another way to measure α_s and Γ_t

Open Top Region

$e^+ e^- \longrightarrow t\,\bar{t}$

Key Points

Top decays before forming a top hadron!
⇢ angular analysis
⇢ Top spin measurable!
Highly polarized electron beam available!



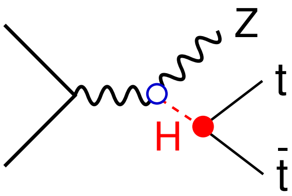
Helicity amplitudes

Γ = form factors

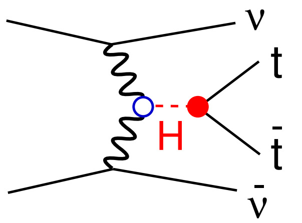
$\Delta F_D \cong 0.05$ (10 fb^{-1})
$\Delta F_P \cong 0.005$-0.05 (50 fb^{-1})

Top and Higgs

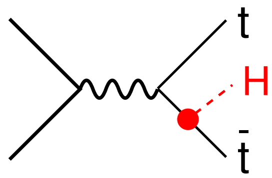
$e^+ e^- \longrightarrow t\,\bar{t}\,Z$



$e^+ e^- \longrightarrow \nu\bar{\nu}\; t\,\bar{t}$



$e^+ e^- \longrightarrow t\,\bar{t}\,H$



Useful when $H \rightarrow t\,\bar{t}$ allowed

Useful for a light Higgs

$\Delta\beta_H / \beta_H \cong 0.1 \sim 0.2$ 100 fb^{-1}

CP Violation

A lot of possibilities
But needs verification by realistic MC simulations