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Top Quark Measurements at the ILC

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Particle Physics and Cosmology after the discovery of Higgs boson

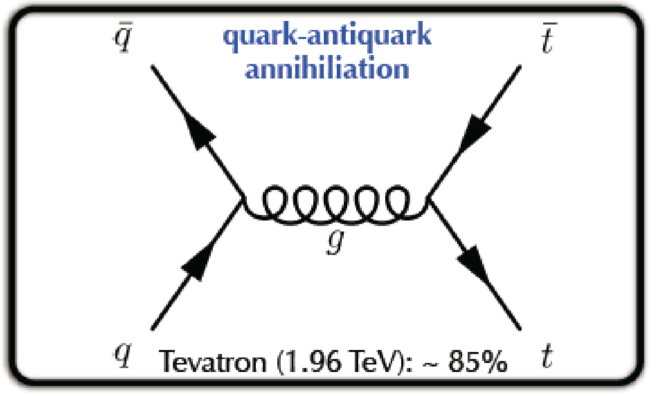
Tohoku Forum for Creativity

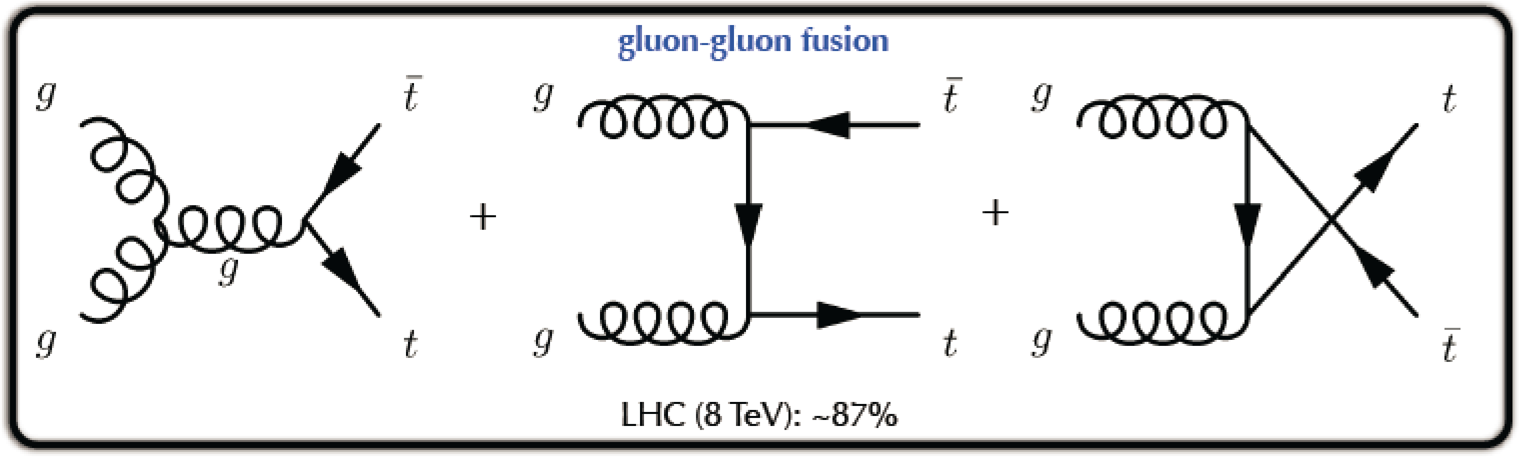
Introduction

- Top quark is the heaviest elementary particle.
  - $m_t = 173.1 \pm 0.9$GeV
- The mass is close to EW scale $v/\sqrt{2} = 174$GeV ($y_t \sim 1$)
  - Top quark may play an important role in EW symmetry breaking
- Top quark decays before hadronization
  - Lifetime is about 5×10^{-25}s
  - Can probe bare quarks

Top Quark at Hadron Colliders

- Top quarks are only studied at hadron colliders.
  - Top quarks are produced from QCD reaction, dominantly quark pairs annihilation at the TeVatron or gluon fusion at the LHC.
  - Initial state energy/polarization is unknown
  - Theoretical uncertainty in QCD is large



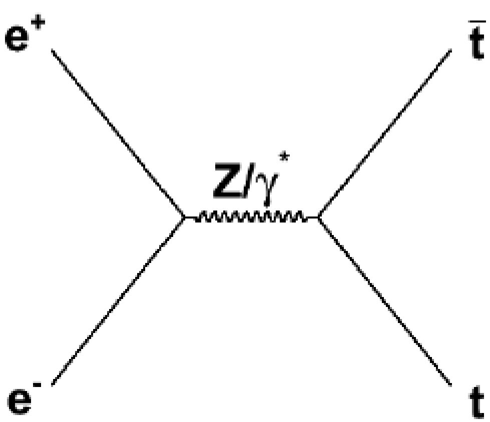


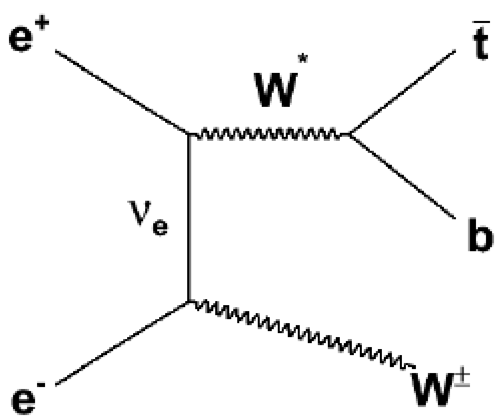
Measurements at Hadron Colliders

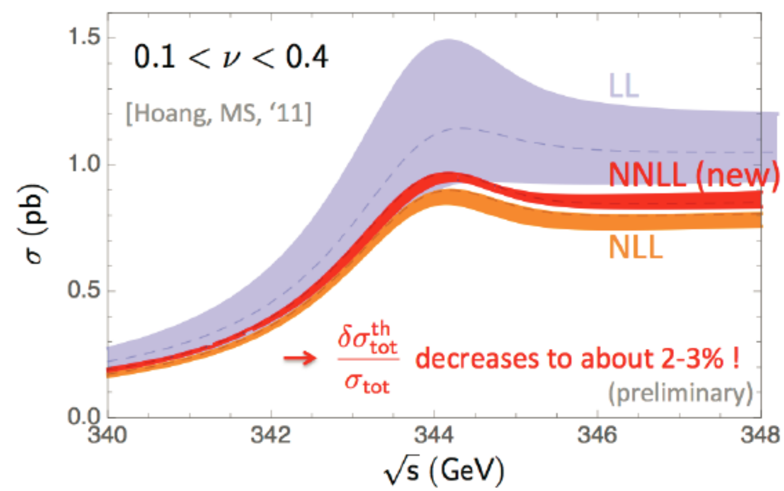
- The properties are partially known
  - Mass in pole “like” scheme which is hard to translate to mass in Msbar scheme : $m_t = 173.1 \pm 0.9$GeV
    - From cross section : $m_t^{MSbar} = 160$ +- 5 GeV
  - Width with indirect method : $\Gamma t = 2.0$ +- 0.5 GeV
  - Spin and charges
  - Coupling to gluon (to axigluon at the TeVatron??)
  - $|V_{tb}|$

Top quark at the ILC

- Top quarks are produced from electroweak reaction
  - Theoretically clean
  - Experimentally easier to reconstruct
- Tunable Beam energy and polarized beam
  - Threshold energy scan is possible
  - Chiral structure can be tested





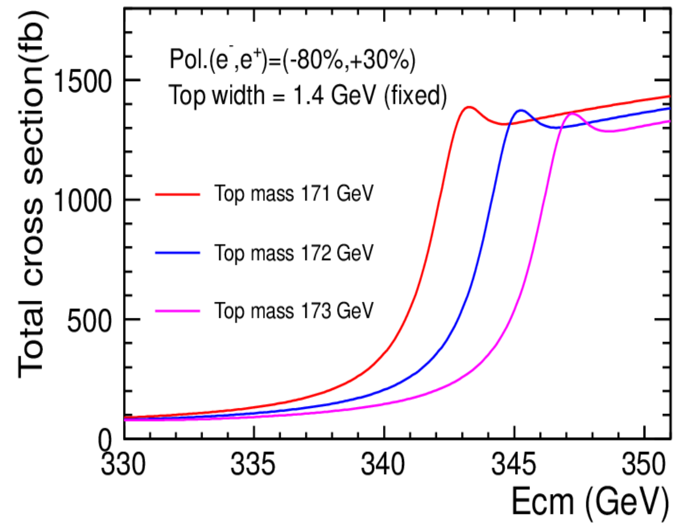


Threshold Scan

- The ttbar cross section is functions of several parameters

$$\sigma_{tt} = f(\sqrt{s}, m_t(yt), \Gamma_t, \alpha_s, m_h,)$$

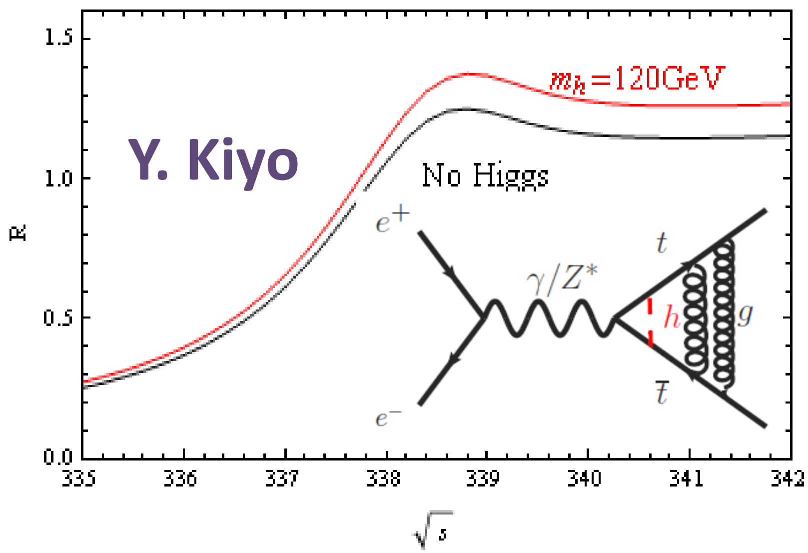
- By scanning the threshold region, those parameter can be determined

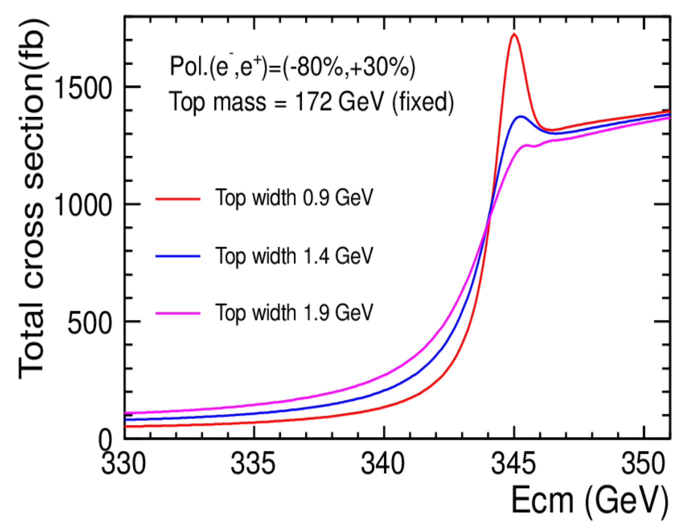


9% enhancement

Uncertainty of σ ~4%

arXiv:hep-ph/9804241





We can measure top yukawa before going to Ecm=500GeV

Experimental Cross Section

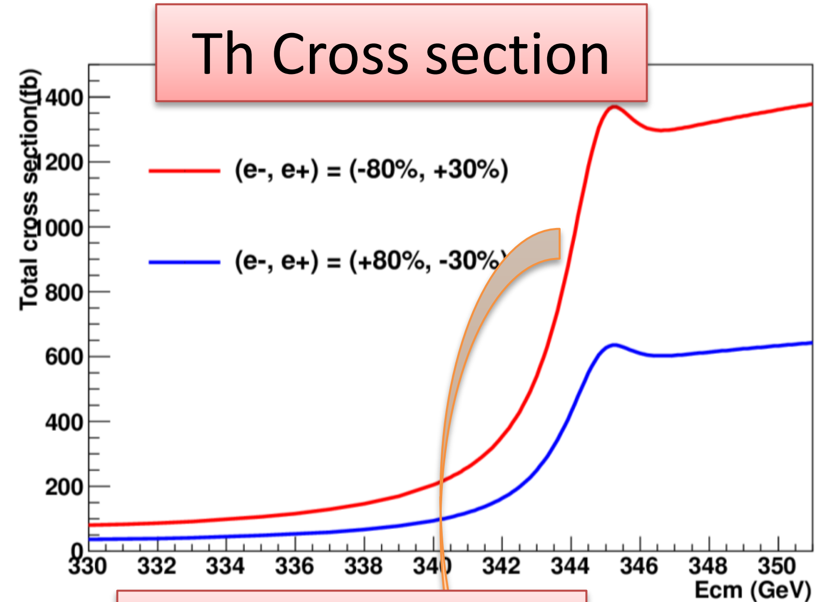
Luminosity spectrum is not δ function !

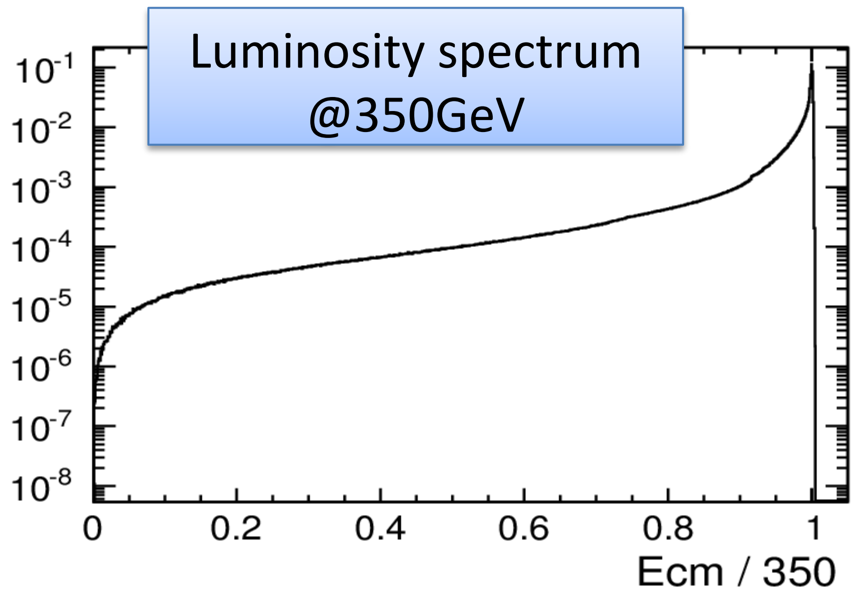
Need to convolute theoretical cross section with luminosity spectrum

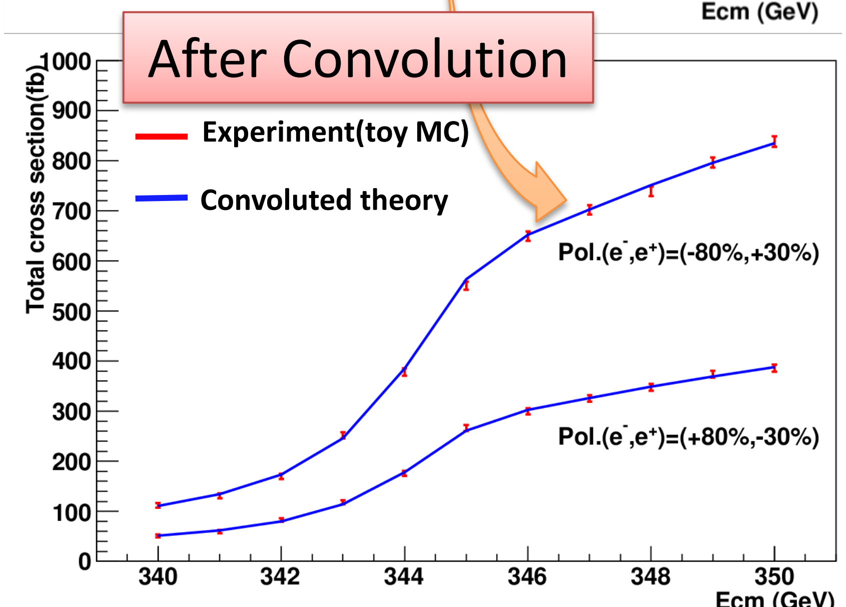
$$\sigma_{conv.}(\sqrt{s}) = \int_0^1 \mathcal{L}(t)\ \sigma_{th}(\sqrt{s} - t)dt$$

$\mathcal{L}$: Luminosity Spectrum, $\sqrt{s}$: center of mass energy

σ_{th} : theoretical cross section, $\sigma_{conv.}$: cross section after convolution







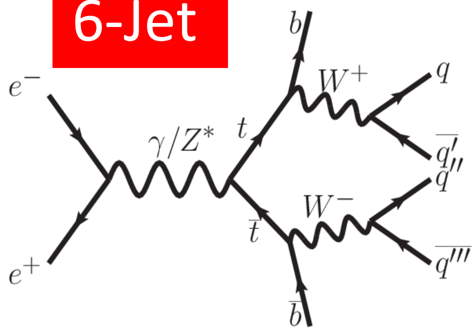
Assumptions for Threshold Scan

- Since the running scenario is not fixed at ttbar threshold, the assumptions of integrated luminosity, energy points and polarizations are different among analyses.
  - Possible polarization configurations, “RL”, “LR” and “L”: $\boldsymbol{p}(\boldsymbol{e}^-, \boldsymbol{e}^+) = (+\mathbf{80}\%, -\mathbf{30}\%), (-\mathbf{80}\%, +\mathbf{30}\%)\ , (-\mathbf{80}\%, \mathbf{0}\%)$
- Case A : 220fb^{-1}
  - Ecm = 340 ~ 350 GeV, every 1GeV, “LR” and “RL”, 10fb^{-1} for each
  - Potential subtraction scheme : m_t^{PS} = 174GeV
- Case B : 100fb^{-1}
  - Ecm = 344~353 GeV, every 1GeV, “L”, 10fb^{-1} for each
  - 1S mass scheme : m_t^{1S} = 174GeV

Signal and Backgrounds

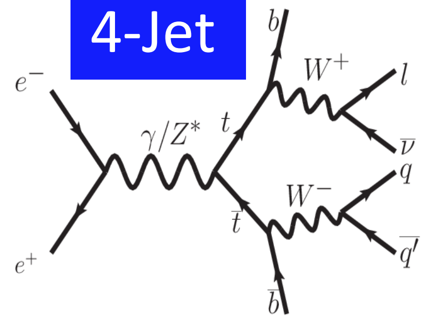
Signal

6-Jet



$t\bar{t} \to bWbW \to bqqbqq$

4-Jet

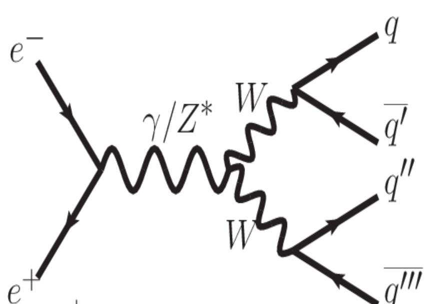


$t\bar{t} \to bWbW \to bqqbl\nu$

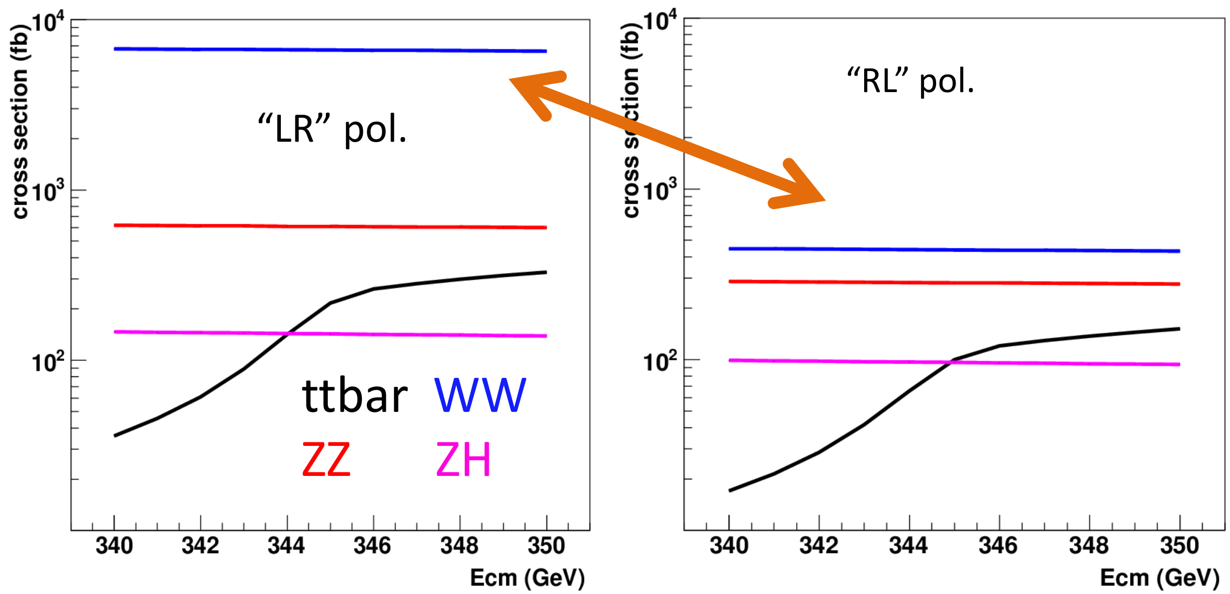
Branching Fractions	
6-Jet	45%
4-Jet	44%
2-Jet	11%

Backgrounds

$e^+e^- \rightarrow WW, ZZ, ZH$



$e^+e^- \to WW \to qqqq$

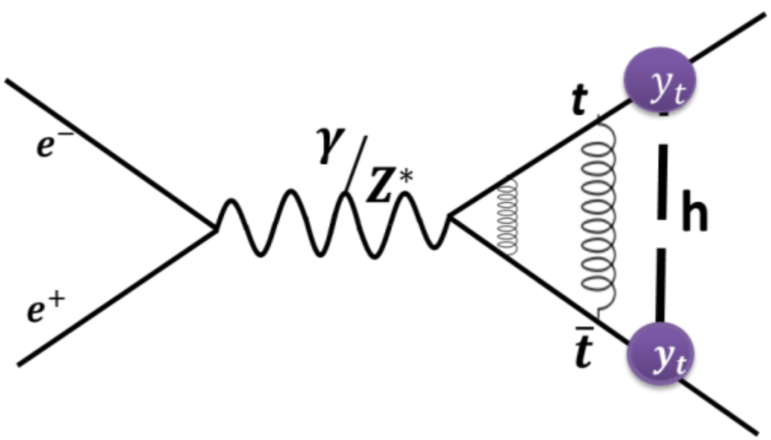


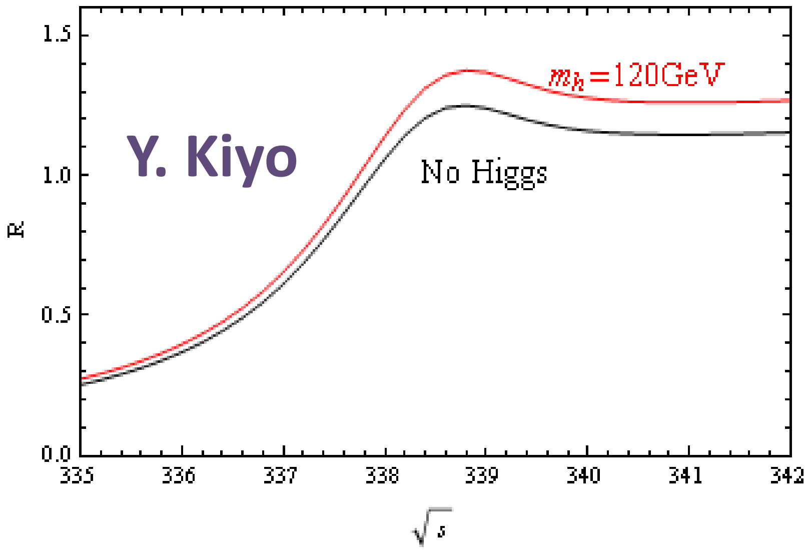
Top Yukawa

- Enhancement due to Higgs exchange is 9%
- Almost no Ecm dependence

$$\sigma \propto \left| \mathcal{M}_{no\ higgs\ exchange} + y_t^2 M_{higgs\ exchange} \right|^2$$

$$\frac{\delta y_t}{y_t} \sim \frac{109 \times \frac{1}{2} \times \frac{\delta\sigma}{\sigma}}{9}$$



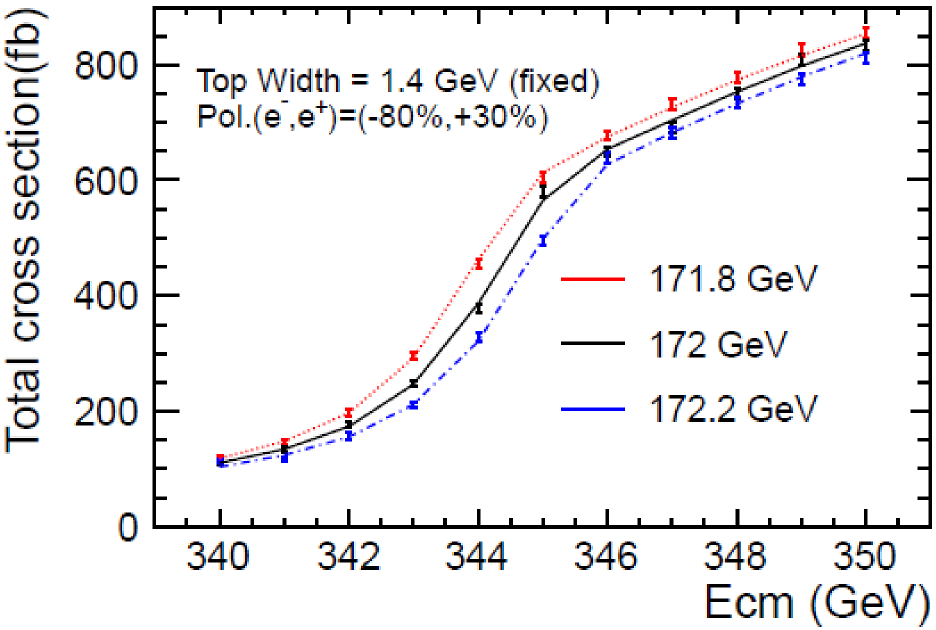


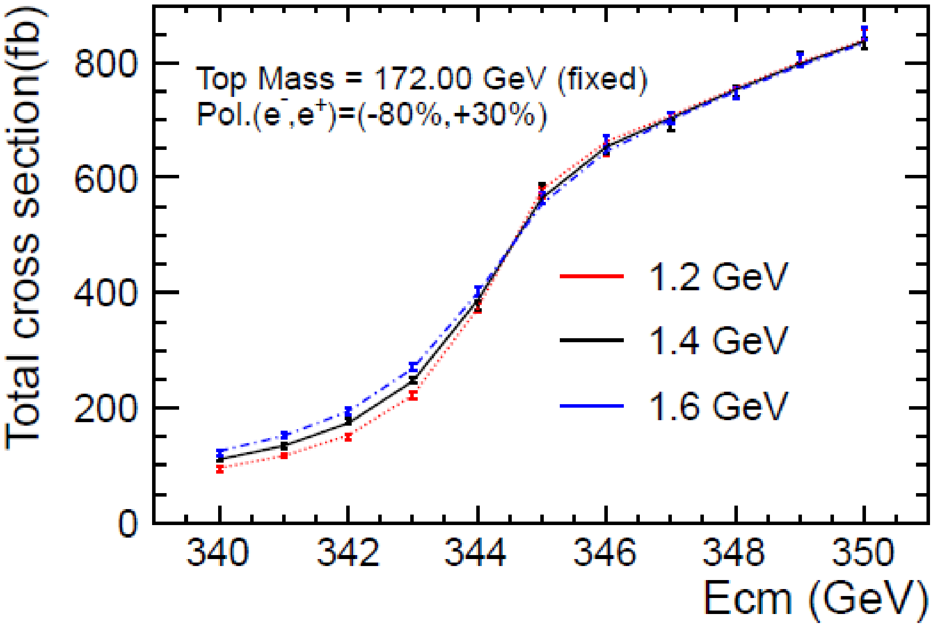
Sensitivity to Top Yukawa : Case A

Stat error	6-Jet (Left)	6-Jet (Right)	4-Jet (Left)	4-Jet (Right)	Combined ALL
Cross section	0.8%	1.2%	0.9%	1.3%	
Top yukawa	5.0%	7.2%	5.1%	7.9%	3.0%

Fits to Mass and Width : Case A

Clear discrimination of 200MeV differences for mass and width

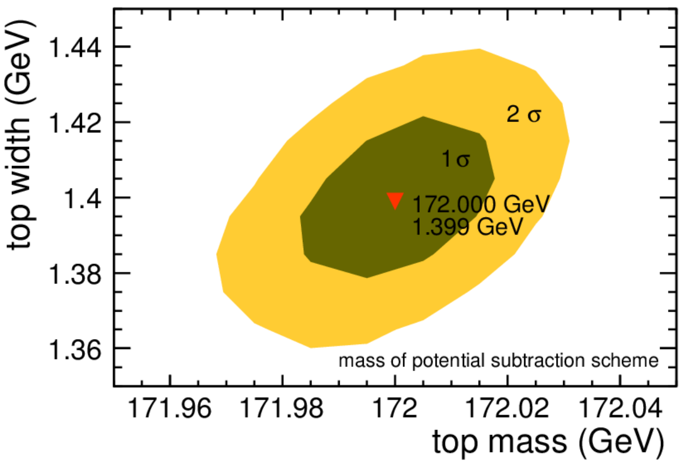




Results on Mass and Width

Input s
m_t^{PS} = 172 GeV
Γ_t = 1.4GeV

	6-Jet		4-Jet		combined	
Stat error (MeV)	δm_t^{PS}	$\delta\Gamma_t$	δm_t^{PS}	$\delta\Gamma_t$	δm_t^{PS}	$\delta\Gamma_t$
Left (110fb^{-1})	23	29	24	30	---	---
Right (110fb^{-1})	34	42	33	42	---	---
L+R (220fb^{-1})	20	24	19	25	14	17

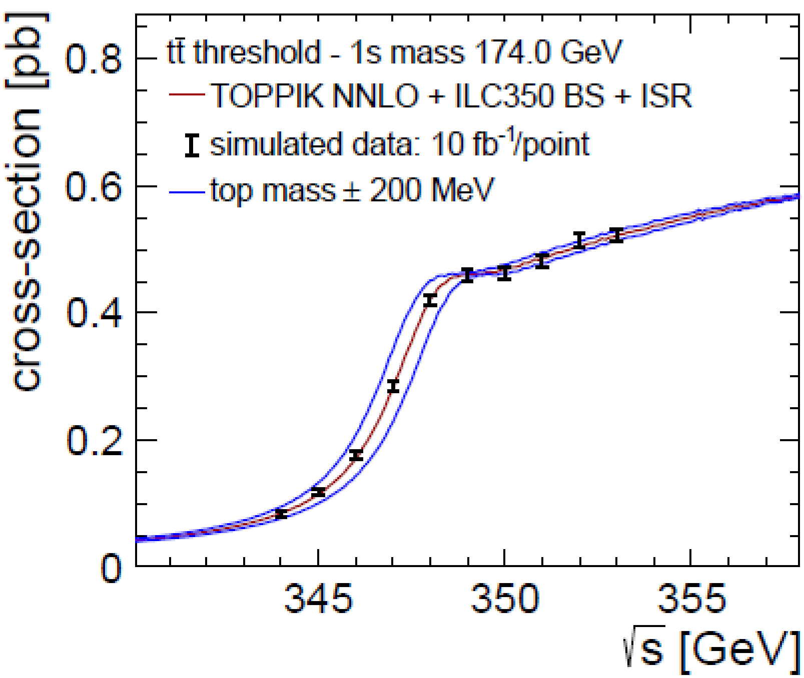


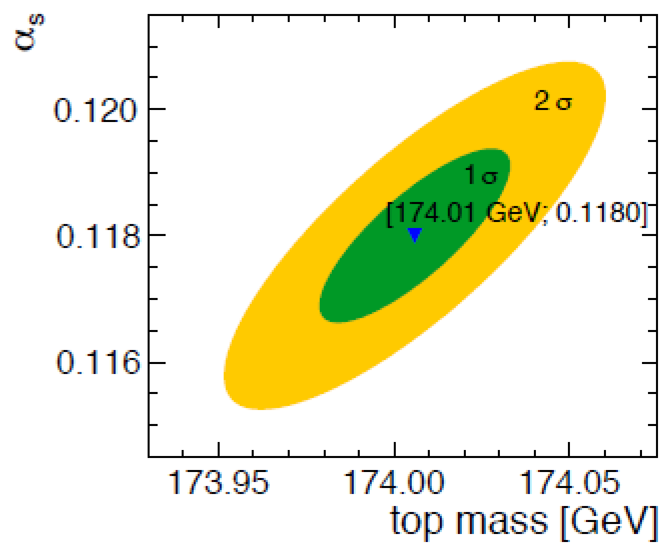
Stat error of top mass and width are 14MeV and 17MeV

Fits to Top mass and α_s : Case B

1S top mass and α_s combined 2D fit	
m_t stat. error	27 MeV
m_t theory syst. (1%/3%)	5 MeV / 9 MeV
α_s stat. error	0.0008
α_s theory syst. (1%/3%)	0.0007 / 0.0022

PDG α_s = 0.1184 ±0.0007 (0.6%)



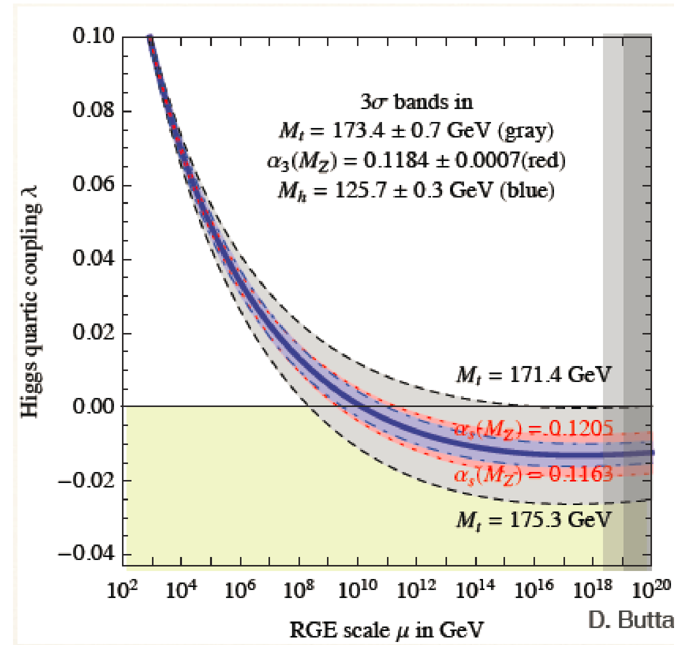


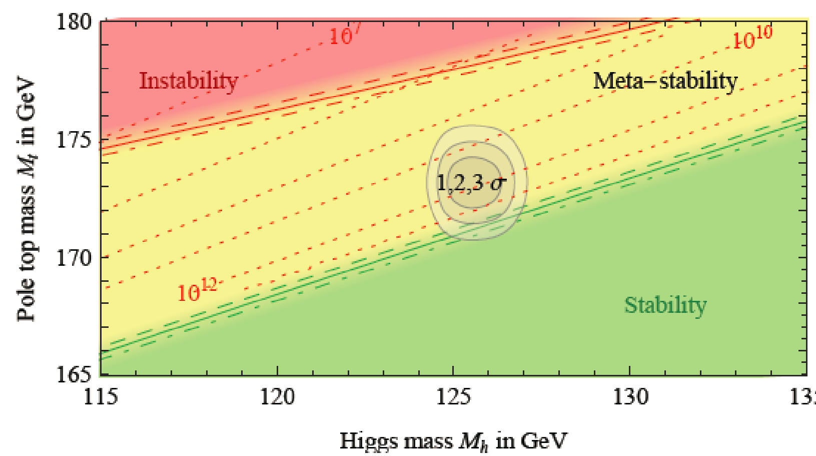
Vacuum Stability Current Status

- Vacuum stability can be discussed with top mass and Higgs mass

$$16\pi^2\beta_\lambda = 12\lambda^2 - 12y_t^4 + \dots$$

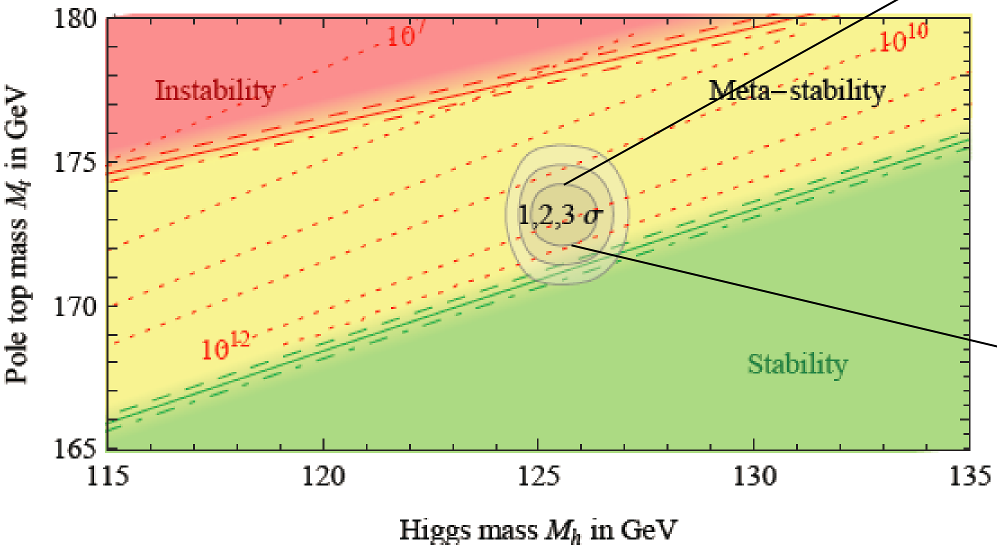
- Our vacuum might be meta-stable from current world averages of top mass and Higgs mass in the SM!
  - top mass from cross section
- But the uncertainties on masses are large so we can not conclude the fate of our universe.

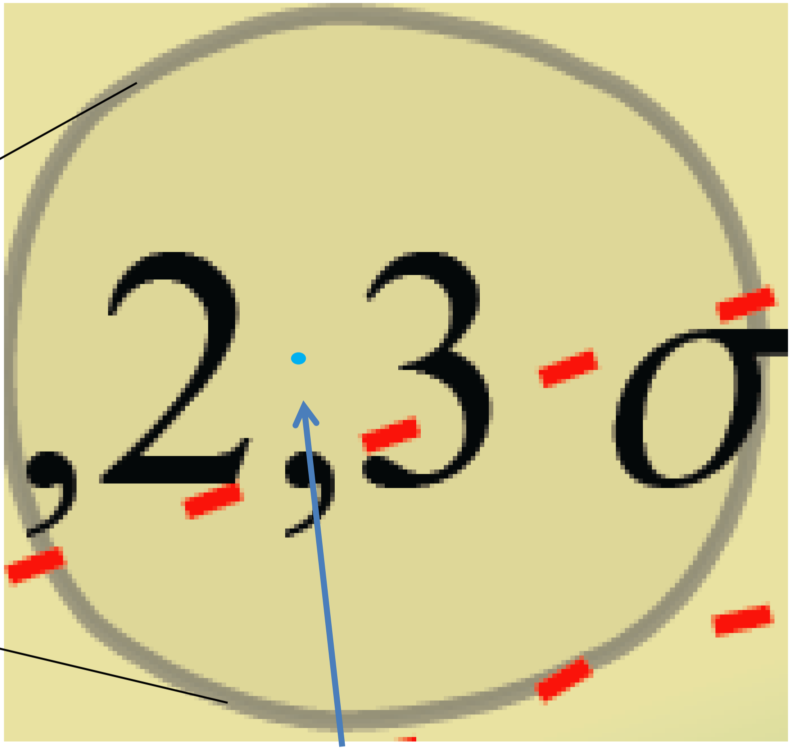




Vacuum Stability Future

- Systematic error should be considered
  - Luminosity spectrum < 100MeV??
  - Theoretical uncertainty ~ 100MeV





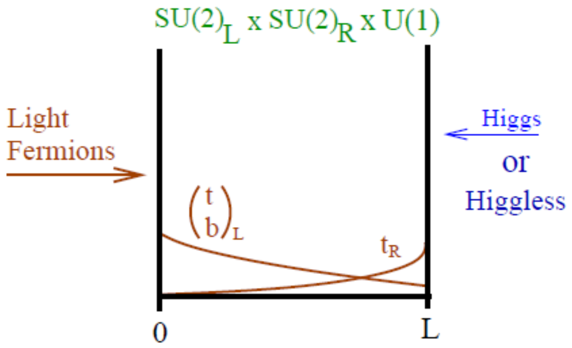
$\Delta M_H = \pm 37$ MeV
$\Delta m_t^{pole} = \pm 17$MeV

Only Stat error.

Stat error of Higgs mass is by Watanuki with recoil with μμh

Form Factor Measurements

- In Warped Extra Dimension model (bulk RS1), wave functions of heavy particles are close to IR brane while wave functions of light particles are localized at UV brane.
- Heavy top mass is explained by an overlap of right handed top quark and Higgs wave functions in the 4th spatial dimension direction.
  - Couplings of left and right handed tops to Z is different



- In some composite models, Higgs and top quark are composite.

- These can be searched with form factor measurements

Form Factors

$$\Gamma_\mu^{ttX}(k^2, q, \overline{q}) = ie\left\{\gamma_\mu \left(\widetilde{F}_{1V}^X(k^2) + \gamma_5 \widetilde{F}_{1A}^X(k^2)\right) + \frac{(q-\overline{q})_\mu}{2m_t}\left(\widetilde{F}_{2V}^X(k^2) + \gamma_5 \widetilde{F}_{2A}^X(k^2)\right)\right\}$$

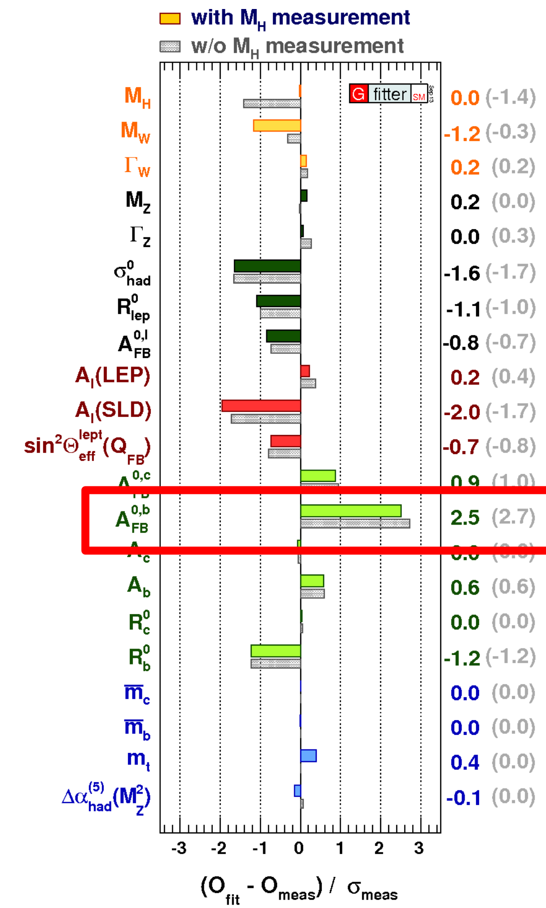
$$X = \gamma, Z$$

$$\widetilde{F}_{1V}^X = -\left(F_{1V}^X + F_{2V}^X\right), \qquad \widetilde{F}_{2V}^X = F_{2V}^X, \qquad \widetilde{F}_{1A}^X = -F_{1A}^X, \qquad \widetilde{F}_{2A}^X = -iF_{2A}^X$$

- Only $F_{1V}^\gamma(k^2)$, $F_{1V}^Z(k^2)$ and $F_{1A}^Z(k^2)$ are non-zero in the SM

$$F_{1V}^{\gamma,SM} = -\frac{2}{3},\ F_{1A}^{\gamma,SM} = 0,\ F_{1V}^{Z,SM} = -\frac{1}{4s_wc_w}\left(1-\frac{8}{3}s_w^2\right),\ F_{1A}^{Z,SM} = \frac{1}{4s_wc_w}$$

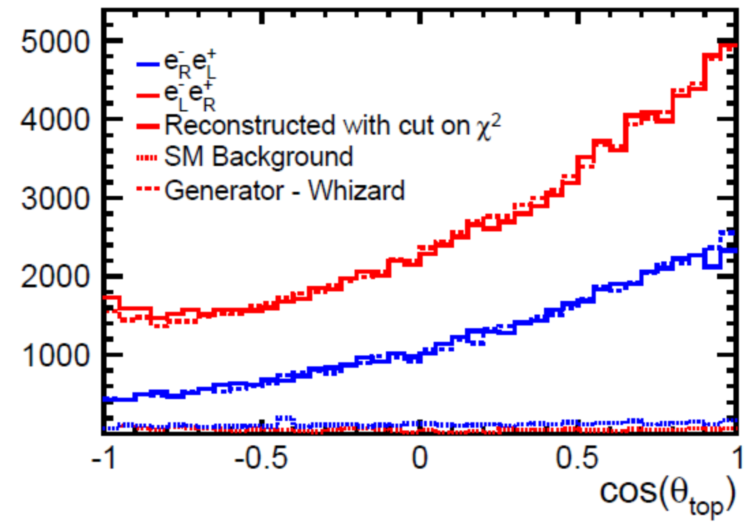
- $F_{2V}^{\gamma,Z}(k^2)$ are dipole moment form factors.
- Modified vertex could explain the discrepancy of $A_{FB}^{0,b}$ at LEP
- Interference of γ and Z allows a determination of relative sign.
  - Polarization are very powerfull tool
  - It is difficult at the LHC where form factors are measured from ttZ and ttγ



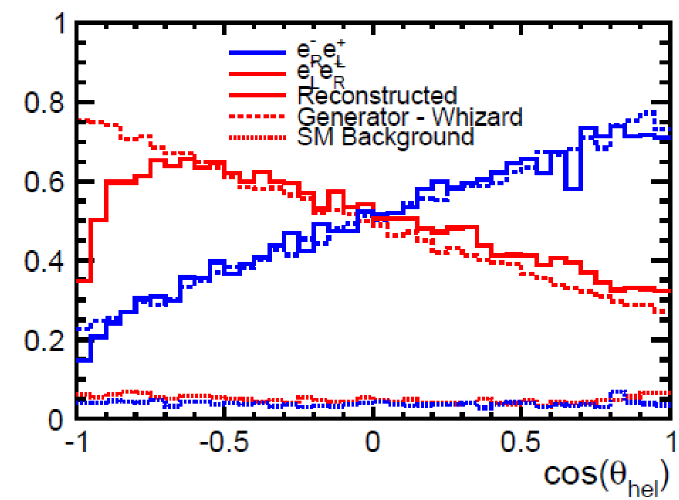
Plot inspired by Eberhardt et al. [arXiv:1209.1101]

Angular Analysis

- $\sigma(\text{Ecm}, \theta_{top}, \theta_{hel})$
- Top quark charge is measured with lepton (4jet+lepton final states)
- Polar angle of top quark can be measured with very small bias.
  - Forward-Backward Asymmetry



- Helicity angle of top quark is also measured with small bias at +-1 that can be easily corrected.
  - Determination of a fraction of t_L and t_R
  - Ri $$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{hel}} = \frac{1 + a_t \cos\theta_{hel}}{2}$$ nriched

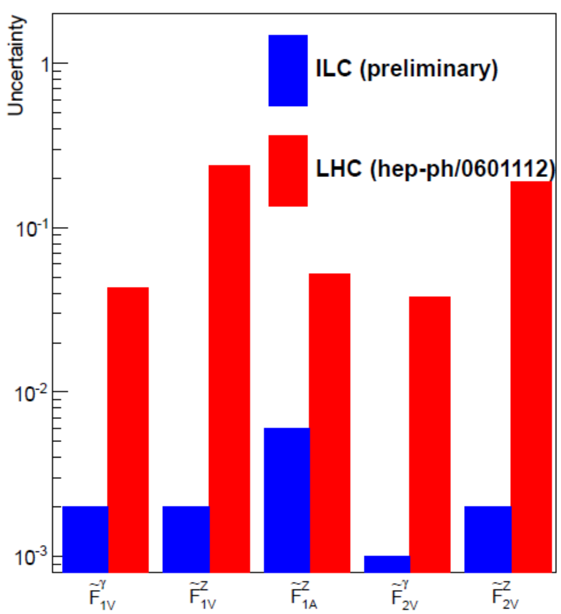


CP Conserving Couplings

- We assume Ecm = 500GeV and 500fb^{-1}
  - About 100,000 top pair events.
- From, differential cross section, CP conserving couplings are extracted
- All couplings are measured less than 1% precisions
  - Which new physics parameter space is excluded?

Coupling	LHC [40] $\mathcal{L} = 300$ fb^{-1}	e^+e^- [52] $P_{e^-} = \pm 0.8$	e^+e^- [45] $\mathcal{L} = 500$ fb^{-1}, $P_{e^-,+} = \pm 0.8, \mp 0.3$
$\Delta\widetilde{F}^{\gamma}_{1V}$	$^{+0.043}_{-0.041}$	$^{+0.047}_{-0.047}$, $\mathcal{L} = 200$ fb^{-1}	$^{+0.002}_{-0.002}$
$\Delta\widetilde{F}^{Z}_{1V}$	$^{+0.24}_{-0.62}$	$^{+0.012}_{-0.012}$, $\mathcal{L} = 200$ fb^{-1}	$^{+0.002}_{-0.002}$
$\Delta\widetilde{F}^{Z}_{1A}$	$^{+0.052}_{-0.060}$	$^{+0.013}_{-0.013}$, $\mathcal{L} = 100$ fb^{-1}	$^{+0.006}_{-0.006}$
$\Delta\widetilde{F}^{\gamma}_{2V}$	$^{+0.038}_{-0.035}$	$^{+0.038}_{-0.038}$, $\mathcal{L} = 200$ fb^{-1}	$^{+0.001}_{-0.001}$
$\Delta\widetilde{F}^{Z}_{2V}$	$^{+0.27}_{-0.19}$	$^{+0.009}_{-0.009}$, $\mathcal{L} = 200$ fb^{-1}	$^{+0.002}_{-0.002}$

$\widetilde{F}^{\gamma}_{1A}$ is fixed to zero



CP Violating Couplings

- If 125GeV is CP mixture states, a few % CP Violating couplings are possible at Ecm~370GeV.
- Has not been done at the ILC
  - Roman Poeschel, Yuichiro Kiyo et al started the analysis.

Summary

- From a threshold scan
  - Measure top quark mass with 14MeV stat error which draws a definitive conclusion of vacuum stability in the SM
    - Systematic uncertainty is ~100MeV?
    - And higgs mass less than 50MeV
  - Measure top quark width with 17MeV stat error
    - Allows to search for anomalous couplings
  - Measure top yukawa before going to Ecm=500GeV, ttH production.
- At higher energy,
  - Stat error of CP conserving form factors are estimated which is much better than LHC
  - One question to theorists. Which new physics parameter space is excluded?

backup

CP Violating Couplings at TESLA

- But done at the TESLA

Coupling	LHC [40] $\mathcal{L} = 300\ \text{fb}^{-1}$	e^+e^- [51] $\mathcal{L} = 300\ \text{fb}^{-1},\ P_{e^{-,+}} = -0.8$
$\Delta\text{Re}\,\widetilde{F}_{2A}^{\gamma}$	$^{+0.17}_{-0.17}$	$^{+0.007}_{-0.007}$
$\Delta\text{Re}\,\widetilde{F}_{2A}^{Z}$	$^{+0.35}_{-0.35}$	$^{+0.008}_{-0.008}$
$\Delta\text{Im}\,\widetilde{F}_{2A}^{\gamma}$	$^{+0.17}_{-0.17}$	$^{+0.008}_{-0.008}$
$\Delta\text{Im}\,\widetilde{F}_{2A}^{Z}$	$^{+0.035}_{-0.035}$	$^{+0.015}_{-0.015}$