



# Top quark pair production near the threshold

**18<sup>th</sup> Dec. 2013 @ ILC annual meeting**

**Tomohiro Horiguchi**

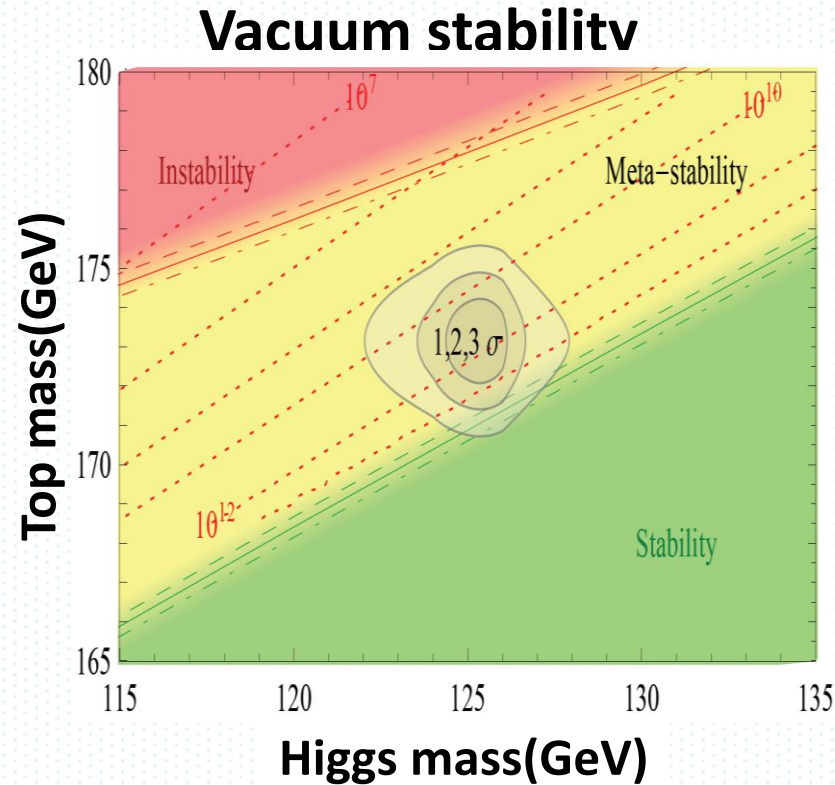
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# Our Target

- Top quark mass( $m_t$ )
  - $\overline{MS}$  scheme ( $m_t^{\overline{MS}}$ )
  - Potential subtraction scheme\*\* ( $m_t^{PS}$ )
- Decay width( $\Gamma_t$ )
  - anomalous coupling
  - exotic decay
- Top quark yukawa coupling( $y_t$ )
- $\alpha_s$
- QCD wave function

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

Using threshold scan technic, measuring the total cross section precisely and fitting it, fundamental parameters are determined !!

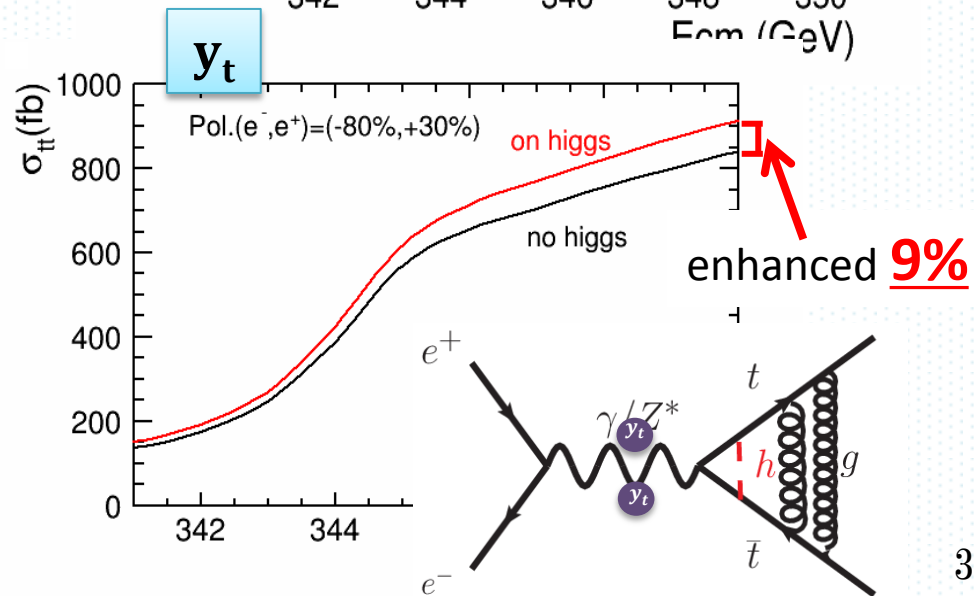
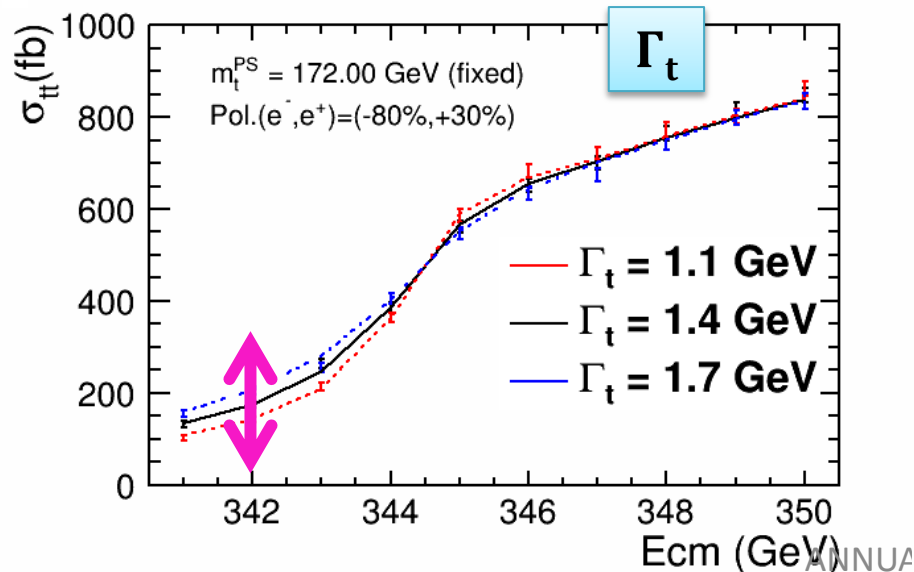
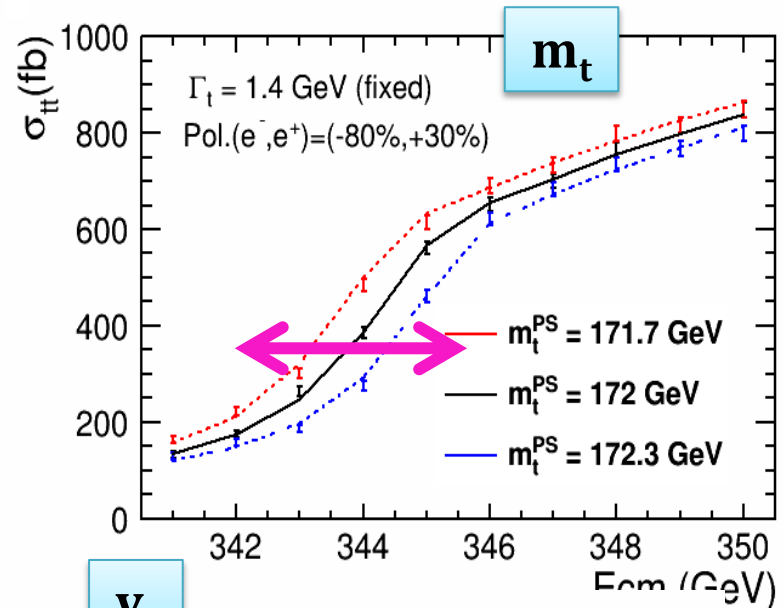
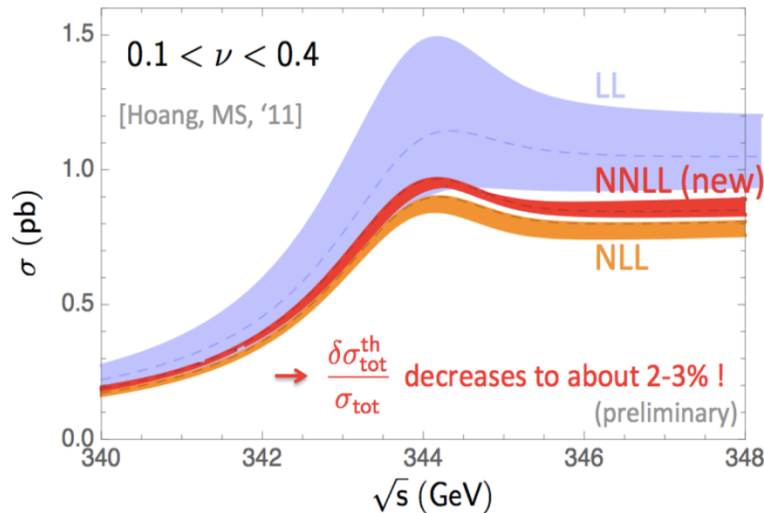


Vacuum stability  
JHEP 1210, 140 (2012)

\*\* Potential subtraction scheme  
arXiv:hep-ph/9804241

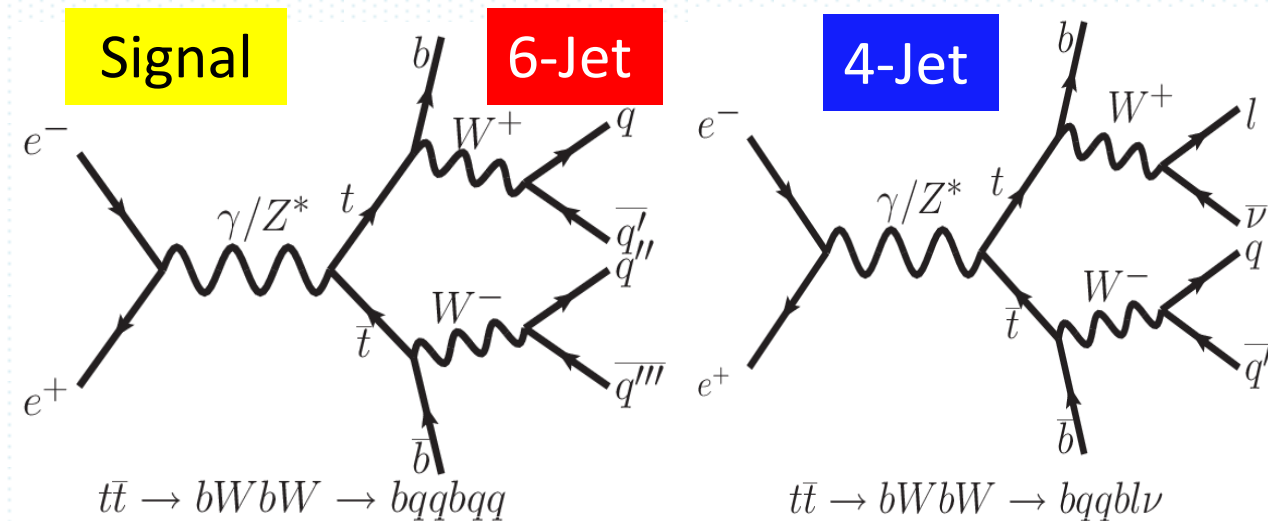
# Measurement of $m_t$ , $\Gamma_t$ and $y_t$

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



# Simulation

Top quark mass	174 GeV
$E_{\text{CM}}$ ( <b>threshold scan</b> )	<u>341 - 350 GeV (every 1 GeV, 10 points)</u>
<u>Polarization</u>	$p(e^+, e^-) = (-30\%, +80\%), (+30\%, -80\%)$ (In this talk, I call them "Right" and "Left")
Integrated Luminosity	5 fb <sup>-1</sup> (each $E_{\text{CM}}$ & pol, total 100fb <sup>-1</sup> ) ✂Running schedule around 350GeV is not determined.
Event Generation	Physsim (LO ,no higgs exchange/on QCD enhancement, on ISR/ beamstrahlung/beam energy spread)
Simulation	ILD_01_v05 ( <b>DBD ver.</b> )



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

# Top Quark Reconstruction (6-Jet & 4-Jet)

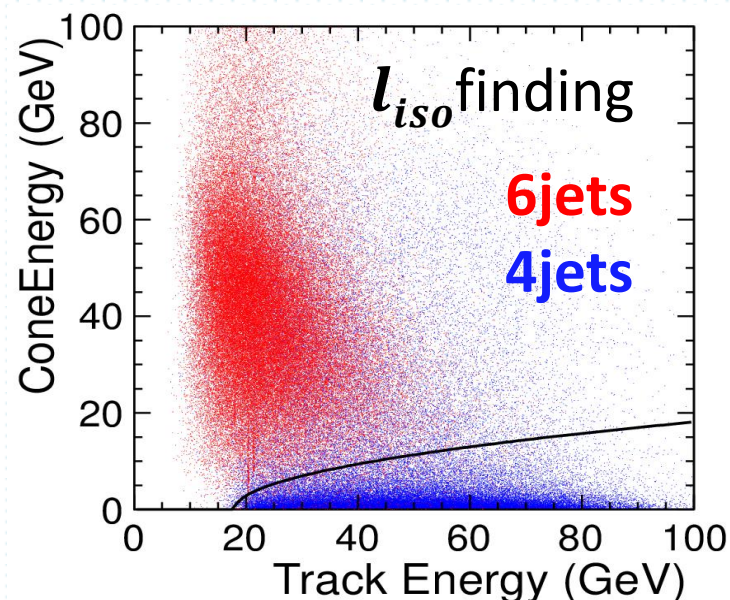
Reconstruction method	6-Jet	4-Jet
Suppressing the background overlay using anti- $k_T$ algorithm ( R=0.7 )		
Finding the Isolated Lepton( $l_{iso}$ )	# of $l_{iso} = 0$	# of $l_{iso} = 1$
Jet clustering using Durham algorithm	Cluster to <b>6jets</b>	Cluster to <b>4jets</b>
2 b-likeness Jets were found using LCFIPlus	-	-
Reconstruction of two W bosons	$q_1 + q_2$ & $q_3 + q_4$	$q_1 + q_2$ & $l_{iso} + \nu$
Reconstruction of two top quarks	-	-
Minimizing the $\chi^2$	①	②

①

$$\chi_{6-Jet}^2 = \frac{(m_{3j^a \text{reco.}} - m_t)^2}{\sigma_t^2} + \frac{(m_{3j^b \text{reco.}} - m_t)^2}{\sigma_t^2} + \frac{(m_{2j^a \text{reco.}} - m_w)^2}{\sigma_w^2} + \frac{(m_{2j^b \text{reco.}} - m_w)^2}{\sigma_w^2}$$

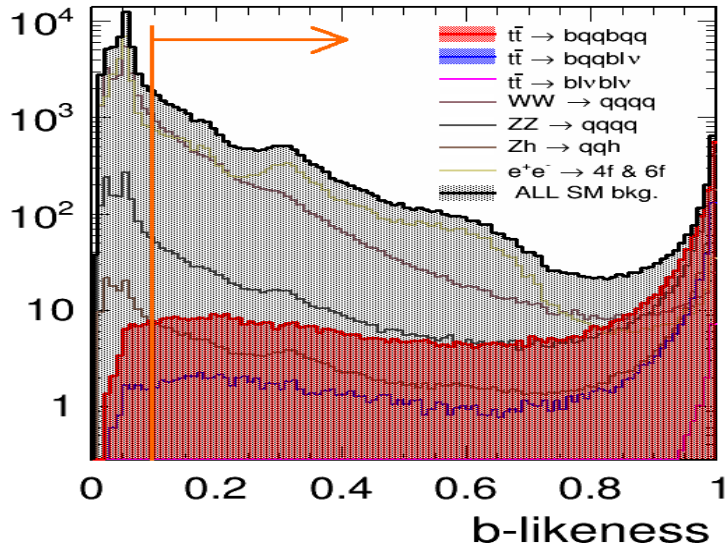
②

$$\chi_{4-Jet}^2 = \frac{(m_{3j \text{reco.}} - m_t)^2}{\sigma_t^2} + \frac{(m_{jl \nu \text{reco.}} - m_t)^2}{\sigma_t^2} + \frac{(m_{2j \text{reco.}} - m_w)^2}{\sigma_w^2}$$

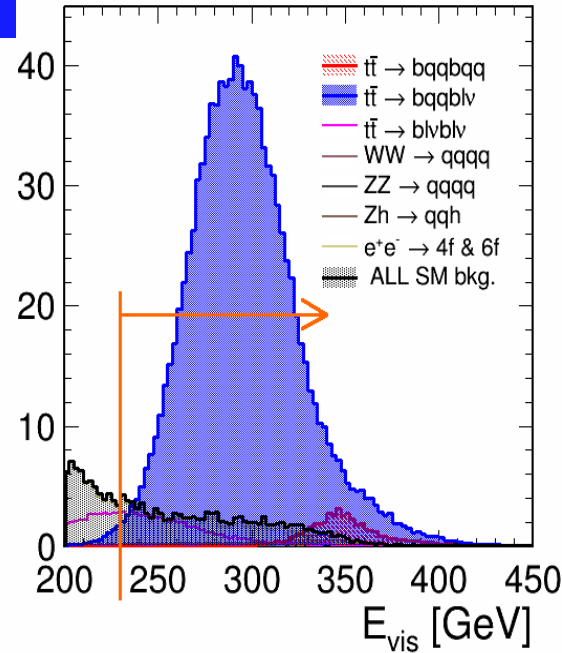
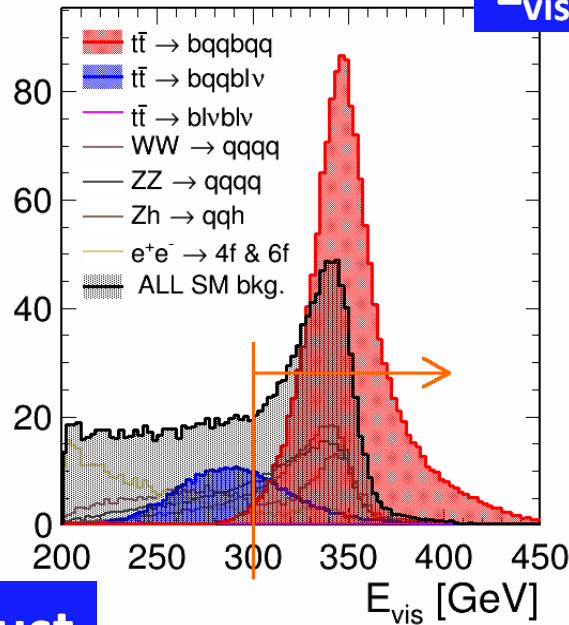


# Event Selection

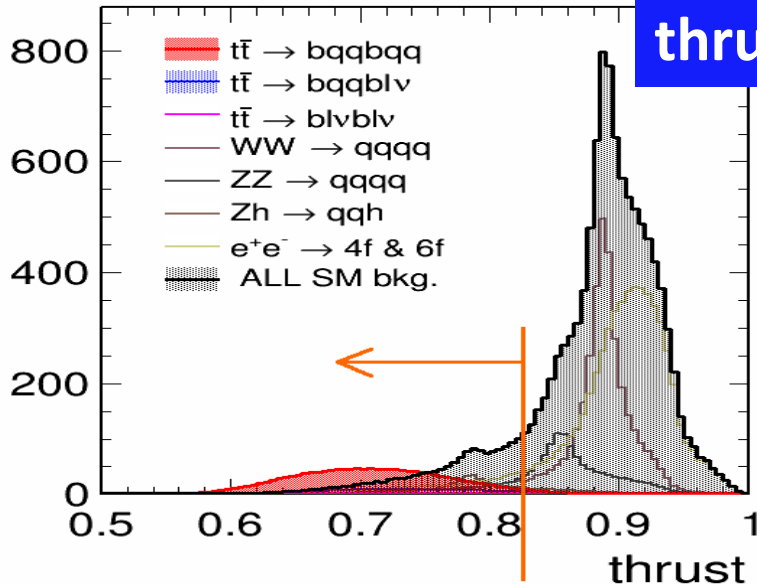
**btag**



**$E_{vis}$**



**thrust**



➤ Other useable cuts

- Y value cut
- missing  $P_T$
- Top mass
- # of PFOs

# Selection Table 6-Jet @350GeV

Left	tt6j	tt4j	tt2j	WW	ZZ	ZH	6f	$S_{6j}$
Generated	1643	1583	381	32664	3004	694	65408	8.2
# of lepton = 0	1591	358	18	32076	2956	638	35005	5.9
btag > 0.1 × 2	1513	340	17	3580	1395	472	6056	13.1
Thrust<0.84	1491	320	14	407	454	392	716	24.2
Evis>300 GeV	1475	114	0	205	294	295	58	29.8
missPt<38GeV	1469	58	0	204	292	292	56	30.2
$m_t > 100\text{GeV} \times 2$	1462	56	0	173	245	246	45	31
y45 > 0.0015 y56 > 0.0007	1411	36	0	65	67	76	33	34.3
# of pfos<86	1398	31	0	41	57	70	32	<b>34.6</b>

Right	tt6j	tt4j	tt2j	WW	ZZ	ZH	6f	$S_{6j}$
Generated	786	757	182	2162	1386	468	4379	10.4
# of lepton = 0	760	171	8	2122	1365	431	2290	9
btag > 0.065 × 2	745	167	8	537	772	343	650	13.1
Thrust<0.84	734	157	6	64	204	284	89	18.7
Evis>300 GeV	725	55	0	32	125	213	13	21.3
missPt<38GeV	722	28	0	32	124	211	12	21.5
$m_t > 100\text{GeV} \times 2$	719	27	0	27	105	178	11	22
y45 > 0.0015 y56 > 0.0007	693	18	0	10	29	57	10	24.2
# of pfos<86	686	15	0	6	23	52	10	<b>24.4</b>

$$\int \mathcal{L}(t) dt = 5(\text{fb}^{-1})$$

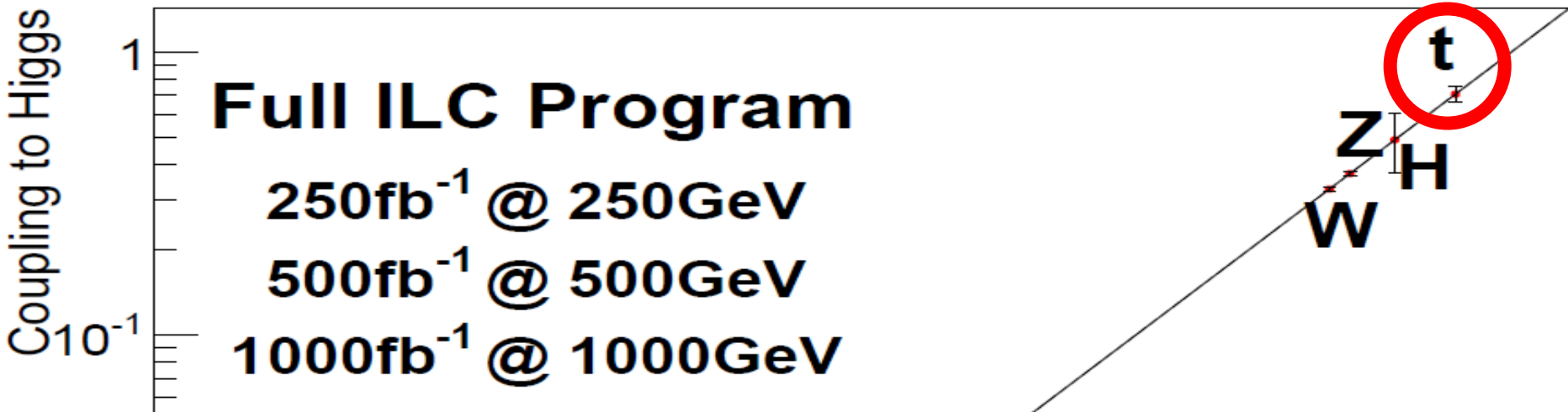
$$S = \frac{N_{Sig}}{\sqrt{N_{Sig} + N_{BG}}}$$

## Statistical error

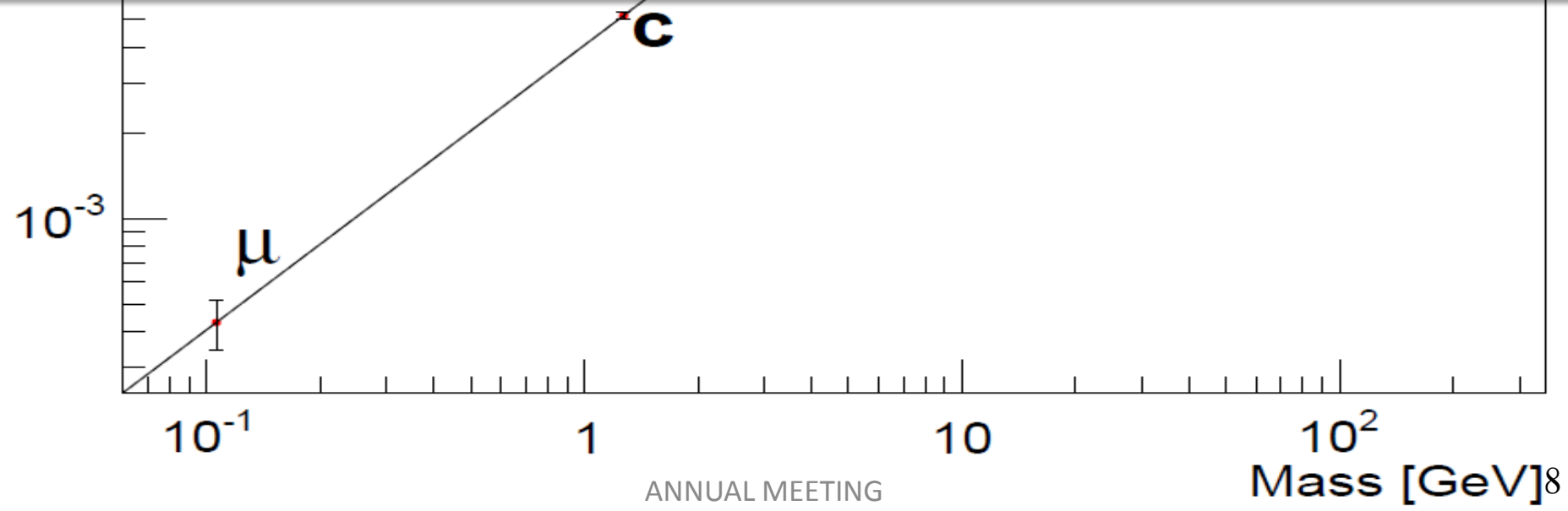
$$\frac{\delta\sigma_{t\bar{t}}}{\sigma}_{\text{Left}} = 2.9\%$$

$$\frac{\delta\sigma_{t\bar{t}}}{\sigma}_{\text{Right}} = 4.1\%$$

6f: 6 fermion final state except ttbar



# Measurement of Top Quark Yukawa Coupling





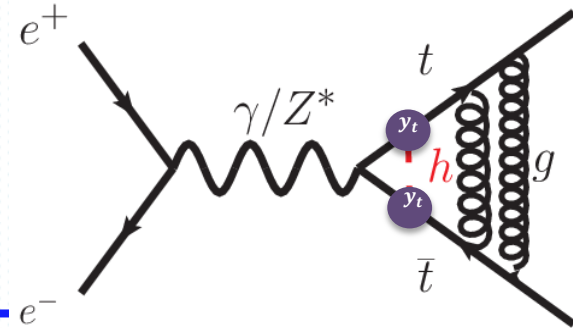
# The Statistical Error of $y_t$

Using the significances of the **all  $E_{CM}$**  (341 – 350 GeV) for **each polarization**, the statistical error of  $y_t$  is estimated.

The cross section is enhanced about **9%** by exchanging the Higgs boson !!

$$\sigma_{t\bar{t}} \propto |\mathcal{M}_{no\ higgs\ exchange} + y_t^2 \mathcal{M}_{higgs\ exchange}|^2$$

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



Stat. Error (50 fb <sup>-1</sup> )	6-Jet (Left)	6-Jet (Right)	4-Jet (Left)	4-Jet (Right)	6-Jet + 4-Jet (Left)	6-Jet + 4-Jet (Right)	Combined (100 fb <sup>-1</sup> )
$\frac{\delta\sigma}{\sigma}$	1.2%	1.7%	1.3%	1.9%	0.9%	1.3%	
$\frac{\delta y_t}{y_t}$	7.2%	10.2%	8.0%	11.3%	5.4%	7.6%	<b>4.4%</b>

# Measurement of Top Quark “Mass” and “Width”

# Fit - convolution -

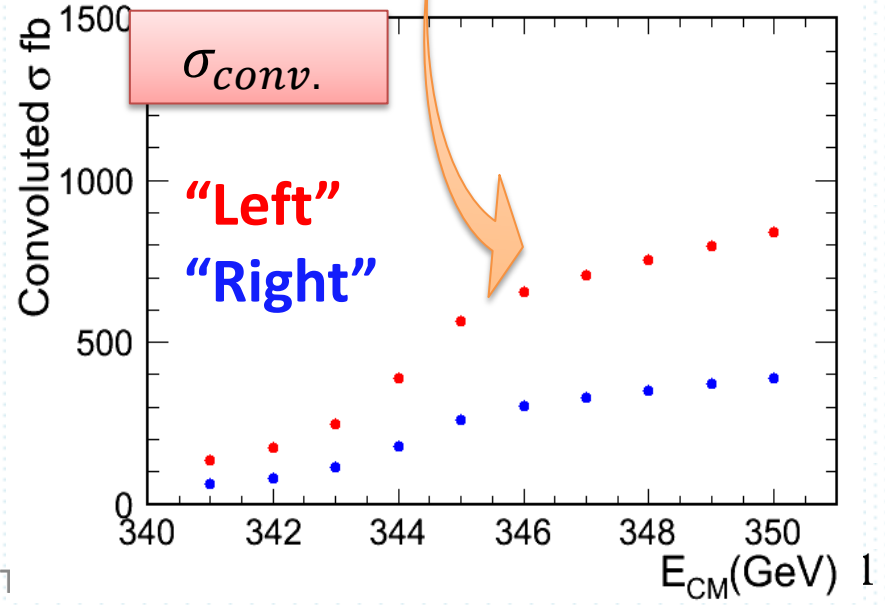
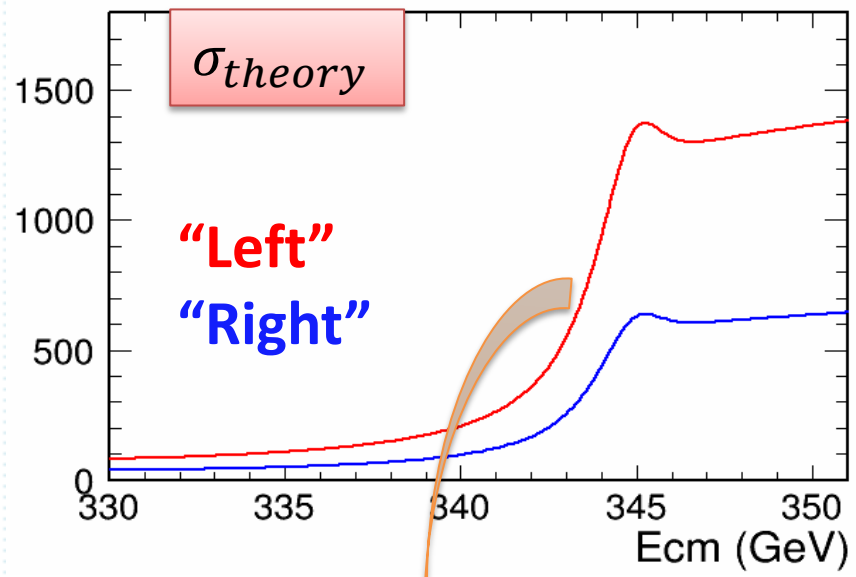
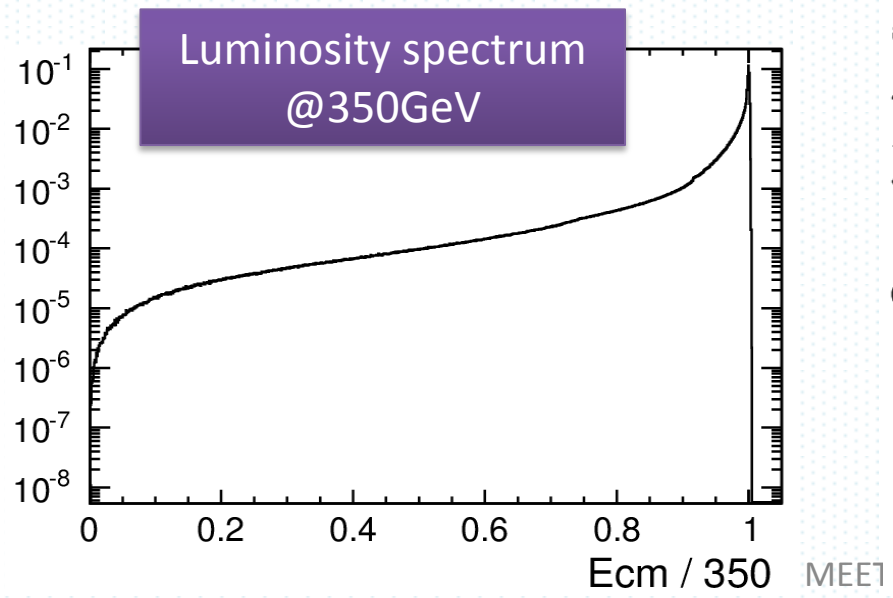
© We must consider **“Beam effects”** around threshold.



Using luminosity spectrum,  
theoretical cross section is convoluted.

$$\sigma_{conv.}(\sqrt{s}) = \int \mathcal{L}(t)\sigma_{th}(t)dt$$

$\mathcal{L}$ : luminosity spectrum,  $\sqrt{s}$ : nominal  
 $\sigma_{th}$ : theoretical  $\sigma$ ,  $\sigma_{conv.}$ : convoluted  $\sigma$   
 $t(=\sqrt{s'/s})$  where  $\sqrt{s'}$  is collision energy.



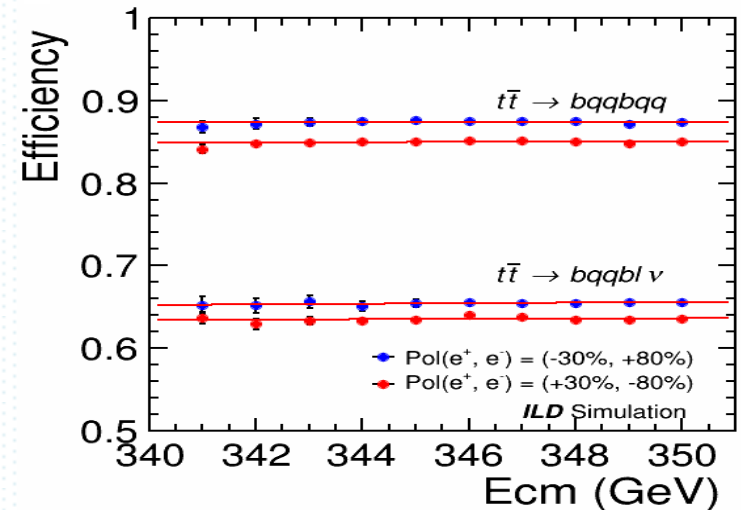
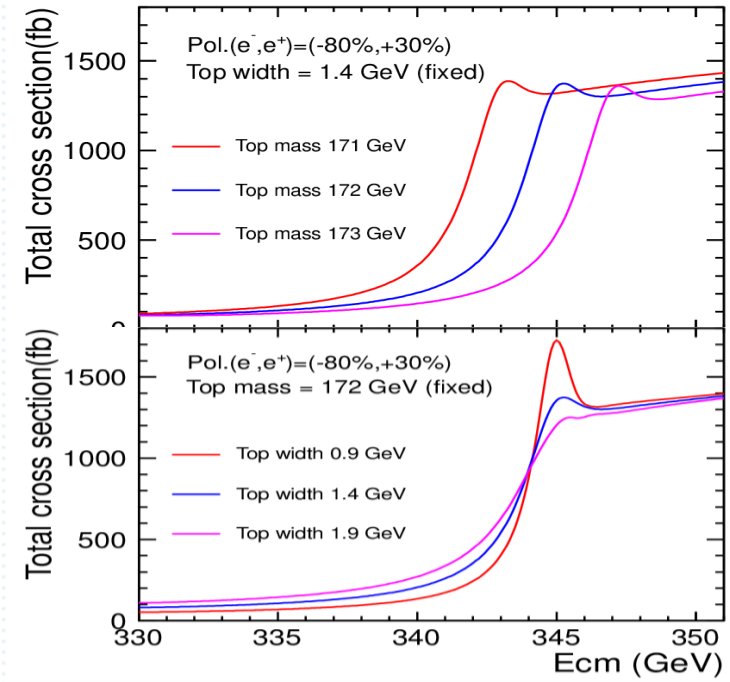
# Fit -toyMC

## ➤ Template of theoretical cross section:

- Floating  $m_t^{\text{PS}}$ ,  $\Gamma_t$  and  $E_{\text{CM}}$
- Fixed  $\alpha_s$  and  $y_t$
- The set center value  
 $(m_t^{\text{PS}}, \Gamma_t) = (172.000, 1.400)$

## ➤ Fitting with NNLO convoluted theoretical cross section using Toy-MC method:

- Using the efficiency of LO analysis, experimental cross section was scaled to NNLO calculation.
- 2-D fitting  $(m_t^{\text{PS}}, \Gamma_t)$  by interpolating and minimizing the cross section.



# Fit -Result-

Stat. Error (MeV)	6-Jet		4-Jet	
	$m_t^{PS}$	$\Gamma_t$	$m_t^{PS}$	$\Gamma_t$
Left(50fb <sup>-1</sup> )	28	40	33	48
Right(50fb <sup>-1</sup> )	42	63	48	67
Left (50fb <sup>-1</sup> ) + Right(50fb <sup>-1</sup> )	<b>23</b>	<b>34</b>	<b>27</b>	<b>39</b>

## Combined ALL

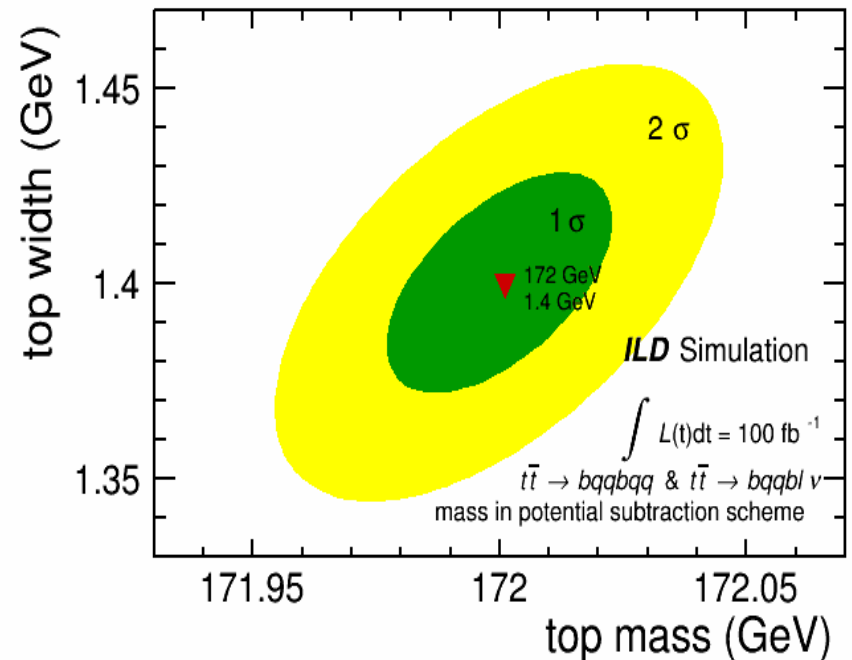
$m_t^{PS}$ (GeV)	$\Gamma_t$ (GeV)
$172.001 \pm 0.018$	$1.399 \pm 0.026$

### ⊙ PS → MS mass

$$m_t^{\overline{MS}} \sim m_t^{PS} - \frac{4}{3\pi}(m_t^{PS} - 20)\alpha_s + \dots$$

$$m_t^{\overline{MS}} = 160^{+5}_{-4} \text{ (GeV) } \text{ PDG}$$

$$m_t^{\overline{MS}} = 163.800 \pm 0.017 \text{ (stat.) (GeV)}$$



# Summary and Plan

## ➤ Summary

- We have estimated the statistical error of  $y_t$ ,  $m_t$  and  $\Gamma_t$  using 6-Jet and 4-Jet final state for two polarization at the ILC.
- $5 \text{ fb}^{-1} \times 20$  points,  $100 \text{ fb}^{-1}$ 
  - ✓ ( $10 E_{\text{CM}}$   $\times$  2 polarization states, Left and Right)

$\Delta y_t / y_t$	<b>4.4 %</b>
$m_t^{\text{PS}}$	$172.001 \pm \mathbf{0.018}$ (GeV)
$m_t^{\overline{\text{MS}}}$	$163.800 \pm \mathbf{0.017}$ (GeV)
$\Gamma_t$	$1.399 \pm \mathbf{0.026}$ (GeV)

## ➤ Plan

- $A_{\text{FB}}$

**backup**

# Top quark

- Discovered at Tevatron in 1995
- Top quark has much heavier than any other quarks.
  - $\sim 173\text{GeV} \Rightarrow$  connected to EWSB ??
- Large  $\Gamma_t$  and short life time

$$\Gamma_t \simeq \frac{G_F m_t^3}{8\sqrt{2}\pi} |V_{tb}|^2 \sim 1.5 [\text{GeV}] \gg \Lambda_{\text{QCD}}$$

- perturbative QCD & decaying before hadronization
- We can not measure its mass at hadron colliders!!
  - $173.5 \pm 0.6 \pm 0.8 \text{ GeV}$  (PDG)  $\leftarrow$  we don't know what this mass is.
  - Top quark has color. The top mass measurement using invariant mass reconstructed from jets must has uncertainty.
  - We want to know top quark mass which has clear theoretical definitions.  $M_{\text{sbar}}$  mass  $160 \pm 5 \text{ GeV}$  (PDG)

**We can determine the top mass measuring the top pair production near threshold !!!**



# Signal and Background

Signal

6-Jet

4-Jet

Branching Ratio

6-Jet

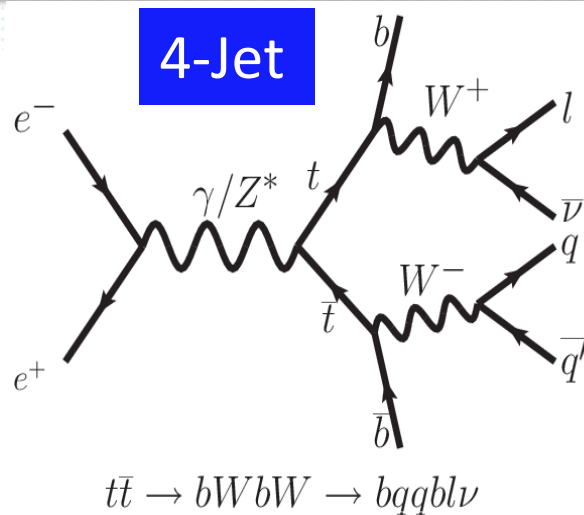
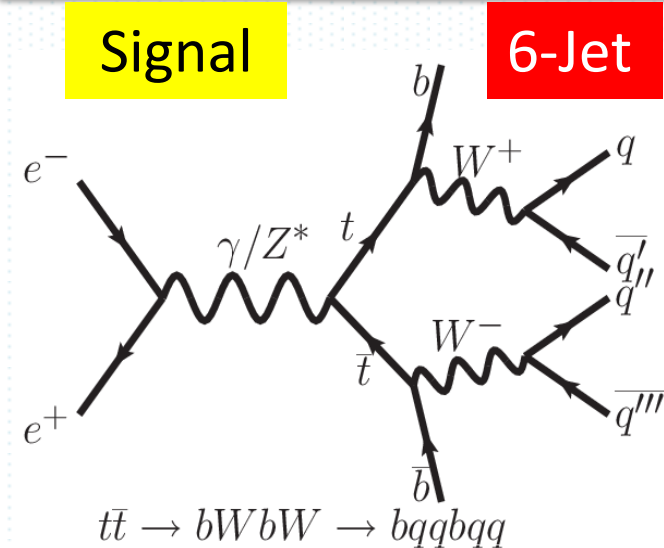
45%

4-Jet

44%

2-Jet

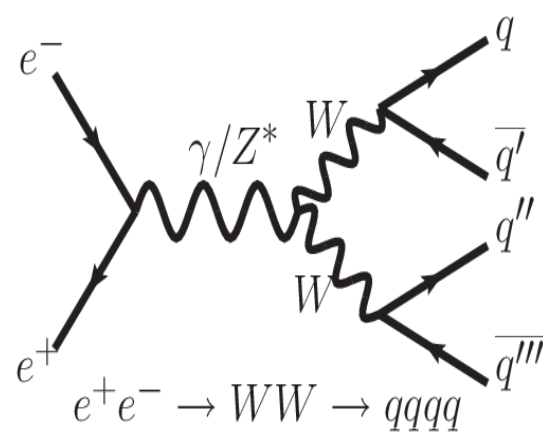
11%



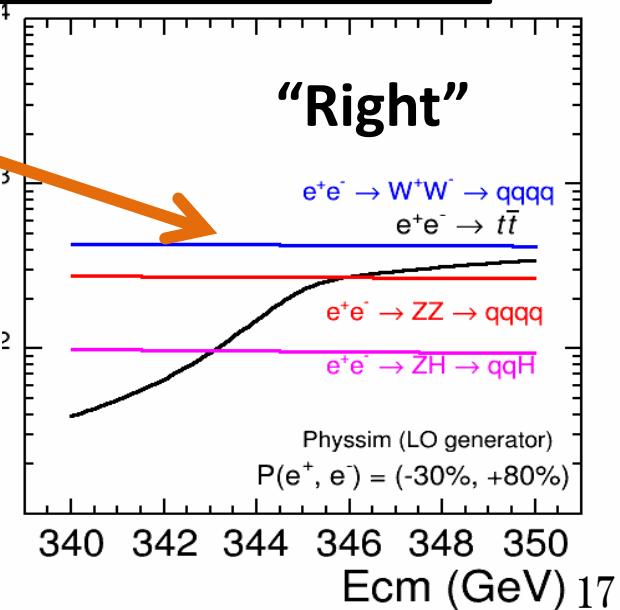
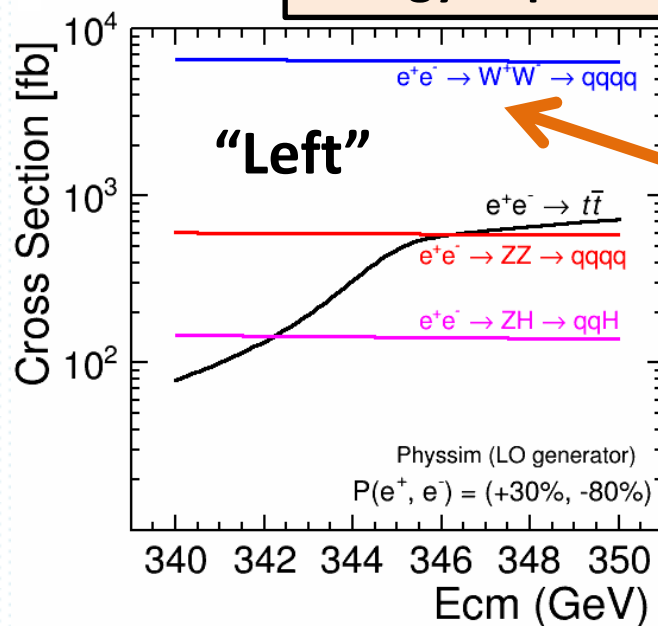
6-Jet	45%
4-Jet	44%
2-Jet	11%

Main BG.

WW, ZZ, ZH



Energy dependence of the cross section



# Event selection

# Selection Table 4-Jet @350GeV

Left	tt4j	tt6j	tt2j	WW	ZZ	ZH	6f+4f	$S_{4j}$
Generated	1583	1643	381	32664	3004	694	65408	7.9
# of lepton = 1	1203	67	112	742	59	51	30003	6.7
btag > 0.1 × 2	1122	63	106	55	16	17	1330	21.6
Thrust < 0.845	1092	63	92	10	7	14	201	28.4
230 < Evis GeV	1048	45	50	8	6	12	77	29.6
missPt > 9 GeV	1027	16	49	1	2	8	75	29.9
$m_t > 100$ GeV × 2	1011	10	40	0	1	7	45	30.2
# of pfos > 50	1006	9	31	0	1	6	30	<b>30.5</b>

Right	tt4j	tt6j	tt2j	WW	ZZ	ZH	6f+4f	$S_{4j}$
Generated	757	786	182	2162	1386	468	4379	10
# of lepton = 1	576	31	53	50	27	35	2018	10.9
btag > 0.065 × 2	554	30	51	7	9	14	161	19.2
Thrust < 0.845	539	30	45	1	3	12	30	20.9
230 < Evis GeV	517	22	25	1	3	10	12	21.2
missPt > 9 GeV	506	7	24	0	1	7	12	21.4
$m_t > 100$ GeV × 2	498	4	20	0	0	6	8	21.5
# of pfos > 50	496	4	16	0	0	5	6	<b>21.6</b>

4f: the total # of events semi-leptonic decay of ZZ, WW  
 6f: 6 fermion final state except ttbar

$$\int \mathcal{L}(t) dt = 5(\text{fb}^{-1})$$

$$S = \frac{N_{Sig}}{\sqrt{N_{Sig} + N_{BG}}}$$

## Statistical error

$$\frac{\delta\sigma_{t\bar{t}}}{\sigma}_{\text{Left}} = 3.3\%$$

$$\frac{\delta\sigma_{t\bar{t}}}{\sigma}_{\text{Right}} = 4.6\%$$