Study of Top Quark Pair Production near the Threshold at the ILC

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Tomohiro Horiguchi

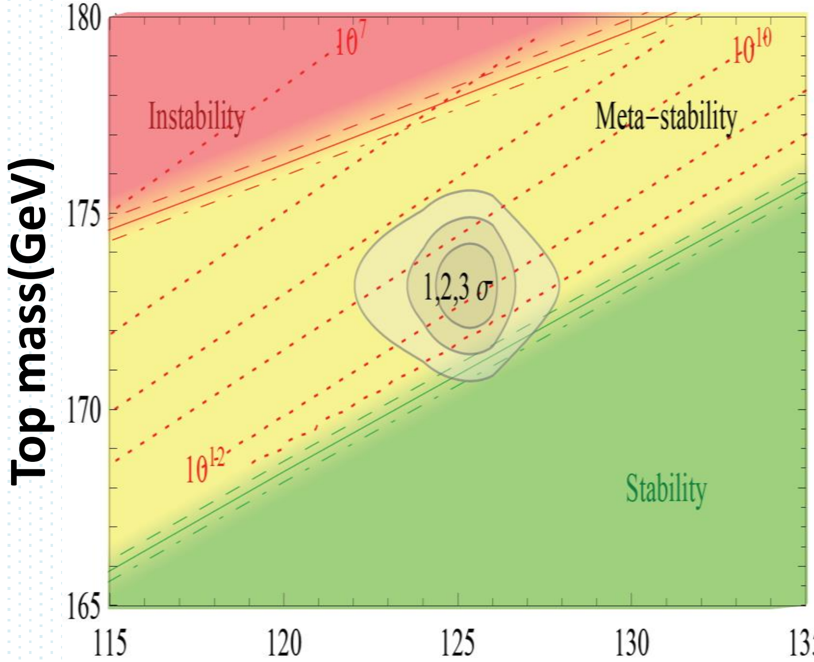
A. Ishikawa, K. Fujii[1], T. Suehara[2], Y. Kiyo[3], Y. Sumino, H. Yamamoto

Tohoku Univ. , [1]KEK, [2]Kyushu Univ. [3]Juntendo Univ.

Our Target

- Top quark mass($\mathbf{m_t}$)
  - $\overline{\text{MS}}$ scheme ($\mathbf{m_t}^{\overline{\mathbf{MS}}}$)
  - Potential subtraction scheme**($\mathbf{m_t}^{\mathbf{PS}}$)
- Decay width($\mathbf{\Gamma_t}$)
  - anomalous coupling
  - exotic decay
- Top quark yukawa coupling(y_t)
- Strong coupling constant α_s
- QCD wave function of top pair system

Vacuum stability



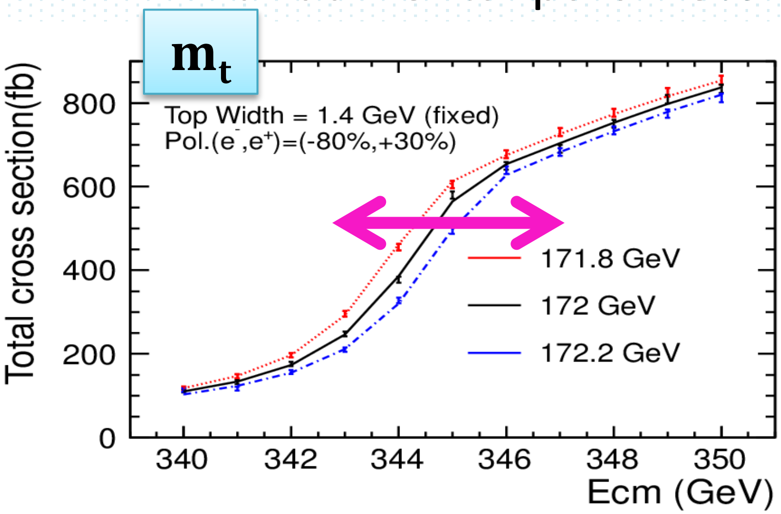
Vacuum stability
JHEP **1210**, 140 (2012)

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

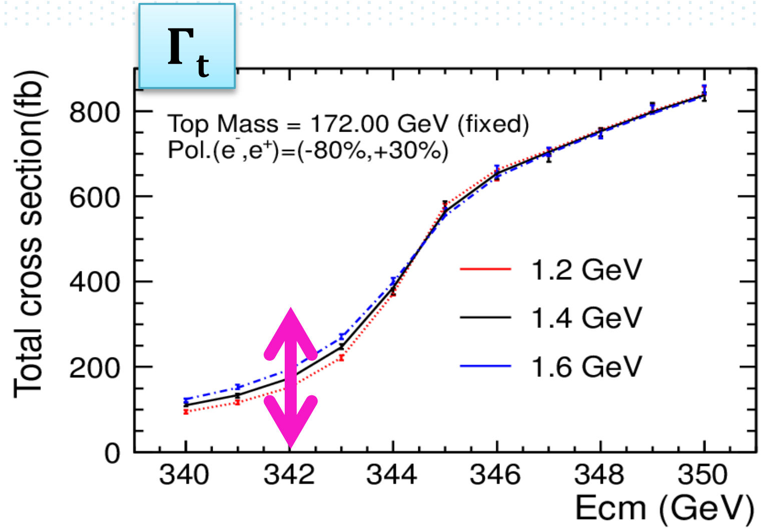
Measuremet of $\mathrm{m_t}$, Γ_t and y_t

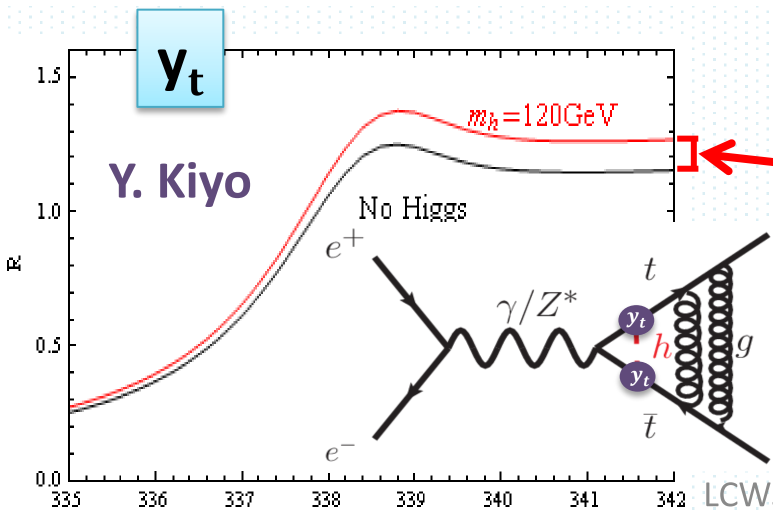
$$\sigma_{tt} = f(\sqrt{s}, m_t, \Gamma_t, \alpha_s, m_h, y_t)$$

Measuring the total cross section precisely and fitting it, fundamental parameters are determined !!



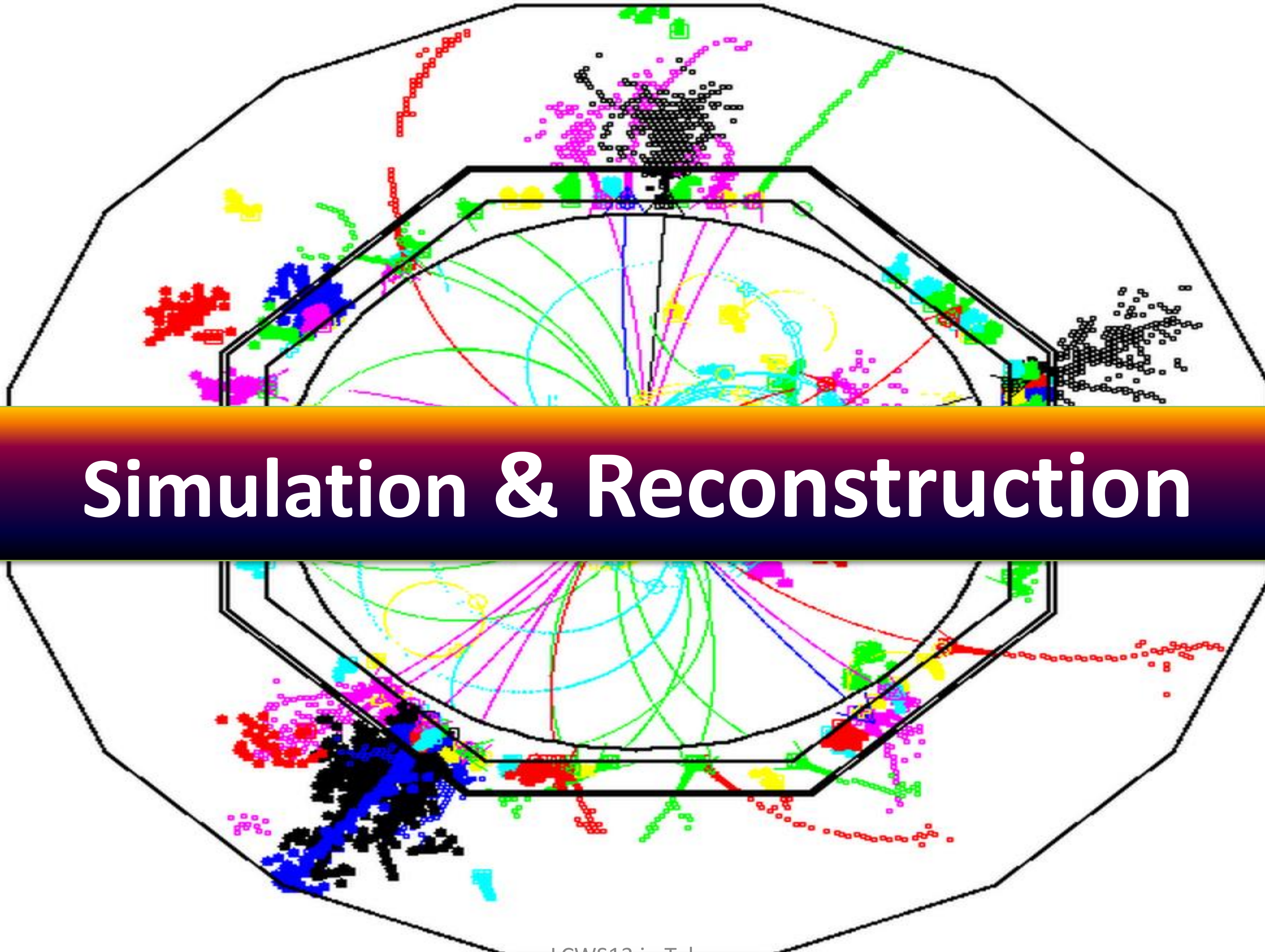
(note. Current theoretical uncertainty in the cross section is about 4% and I hope this will be improved in coming 10 years)





The total cross section is enhanced **9%** by exchanging Higgs boson. So if we can measure total cross section precisely, we can extract **top Yukawa coupling** before going to Ecm=500GeV.

Simulation & Reconstruction



Simulation

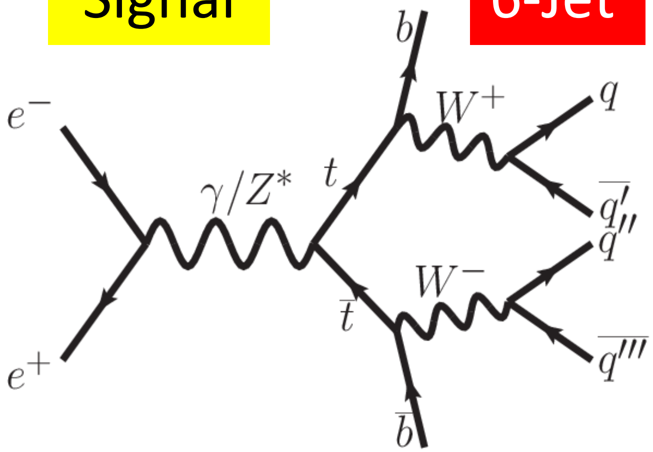
Top quark mass	174 GeV
Center of mass energy (E_{CM}) (threshold scan)	341 - 350GeV (every 1 GeV, 10 points)
Polarization	$p(e^+, e^-) = (-30\%, +80\%), (+30\%, -80\%)$ (In this talk, I call them "Right" and "Left")
Integrated Luminosity	5 fb^{-1} (each E_{CM} & pol, total 100fb^{-1}) ※Running schedule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

Full simulation with the ILD detector is performed.

Signal and Background

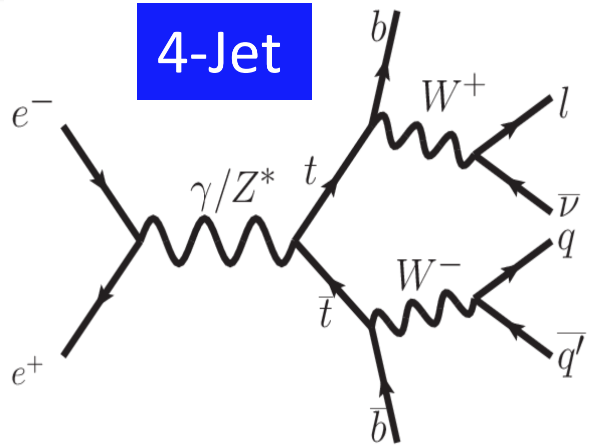
Signal

6-Jet



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

4-Jet

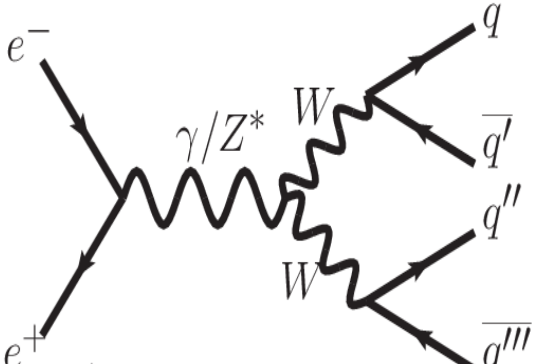


$t\bar{t} \to bWbW \to bqqbl\nu$

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

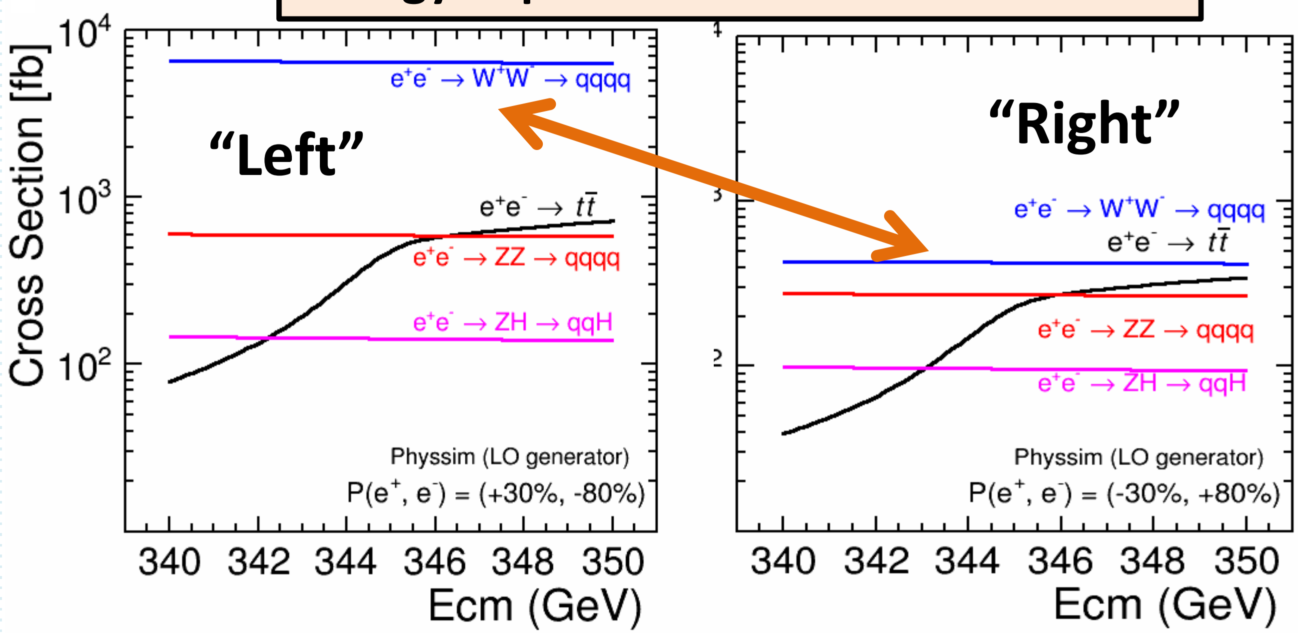
Main BG.

WW, ZZ, ZH



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

Energy dependence of the cross section



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

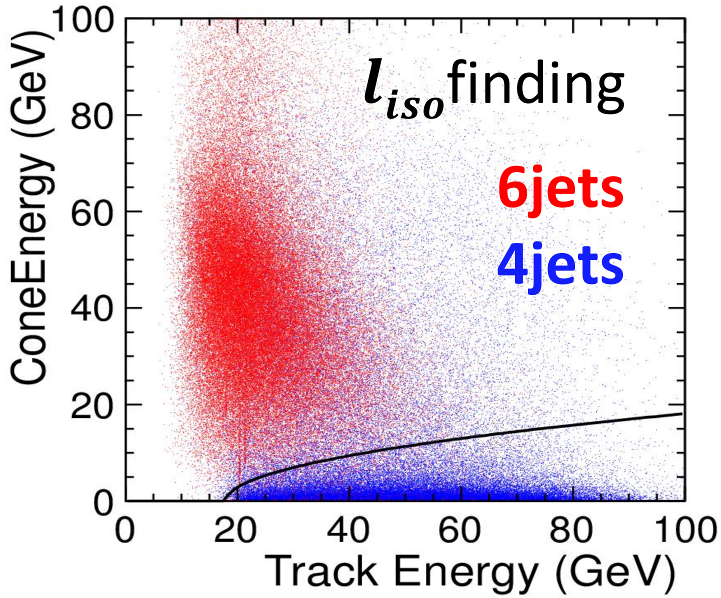
Reconstruction method	6-Jet	4-Jet
Suppressing the background overlay using anti-k_T algorithm		
Finding the Isolated Lepton(l_{iso})	# of l_{iso} = 0	# of l_{iso} = 1
Jet clustering using Durham algorithm	Cluster to 6jets	Cluster to 4jets
2 b-likeness Jets were found using LCFIPlus	-	-
Reconstruction 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 χ^2	①	②

①

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

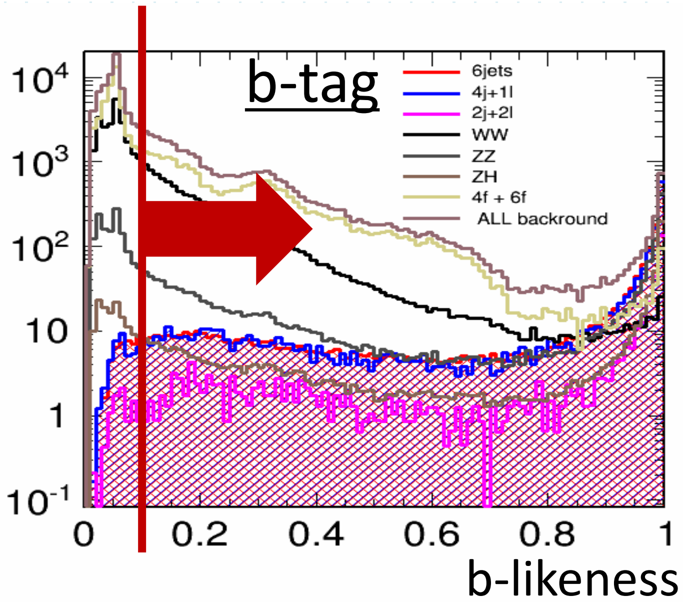
②

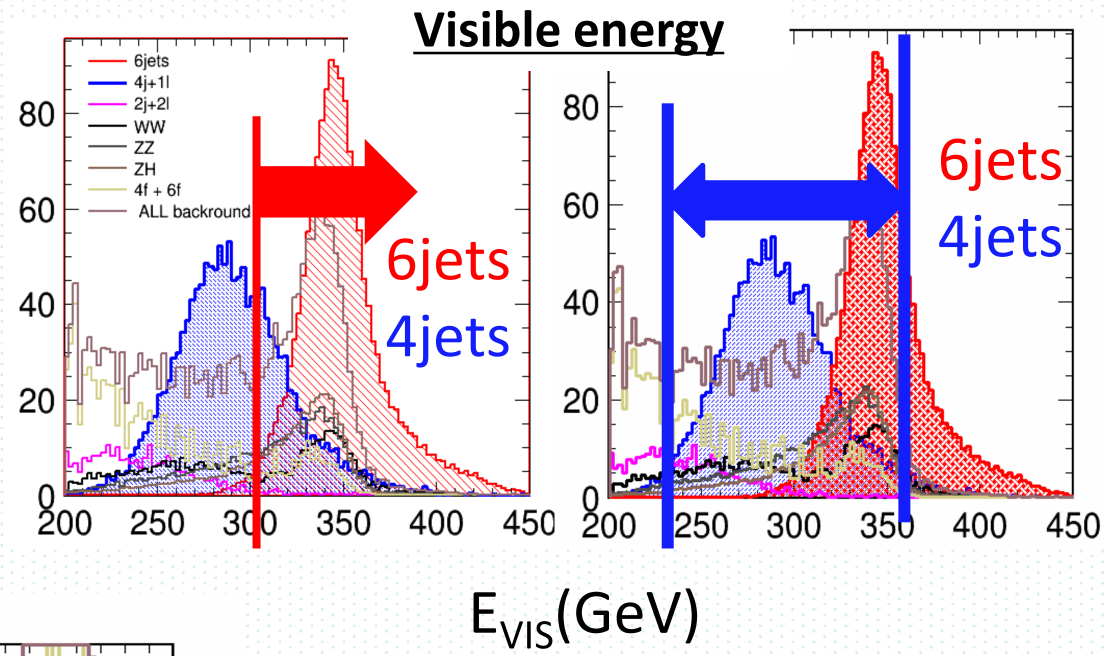
$$\chi^2_{4-\text{Jet}} = \frac{(m_{3j\text{reco.}} - m_t)^2}{\sigma_t^2} + \frac{(m_{jl\nu\text{reco.}} - m_t)^2}{\sigma_t^2} + \frac{(m_{2j\text{reco.}} - m_w)^2}{\sigma_w^2}$$

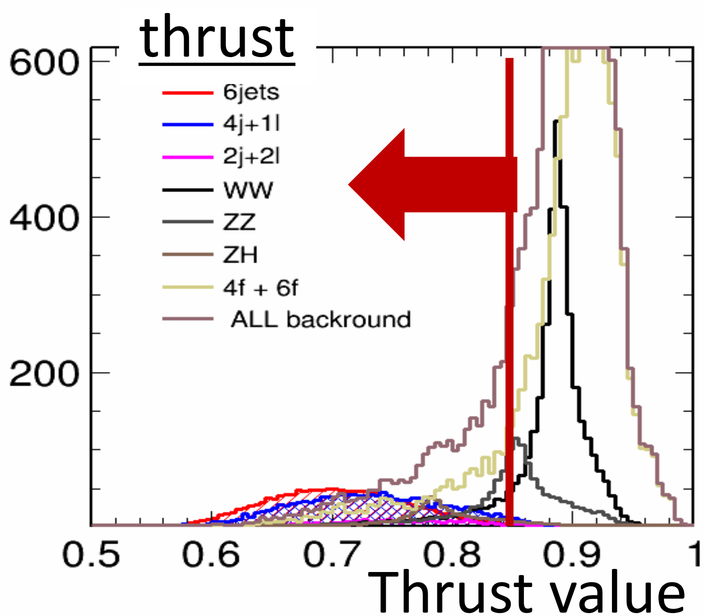


Event selection

Event Selection







- 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>100GeV × 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	**34.6**

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>100GeV × 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	**24.4**

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

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

Statistical error

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

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

6f: 6 fermion final state except ttbar

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 < 360 GeV	1048	45	50	8	6	12	77	29.6
missPt < 38 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 # of pfos < 160	1006	9	31	0	1	6	30	**30.5**

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 < 360 GeV	517	22	25	1	3	10	12	21.2
missPt < 38 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 # of pfos < 160	496	4	16	0	0	5	6	**21.6**

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

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

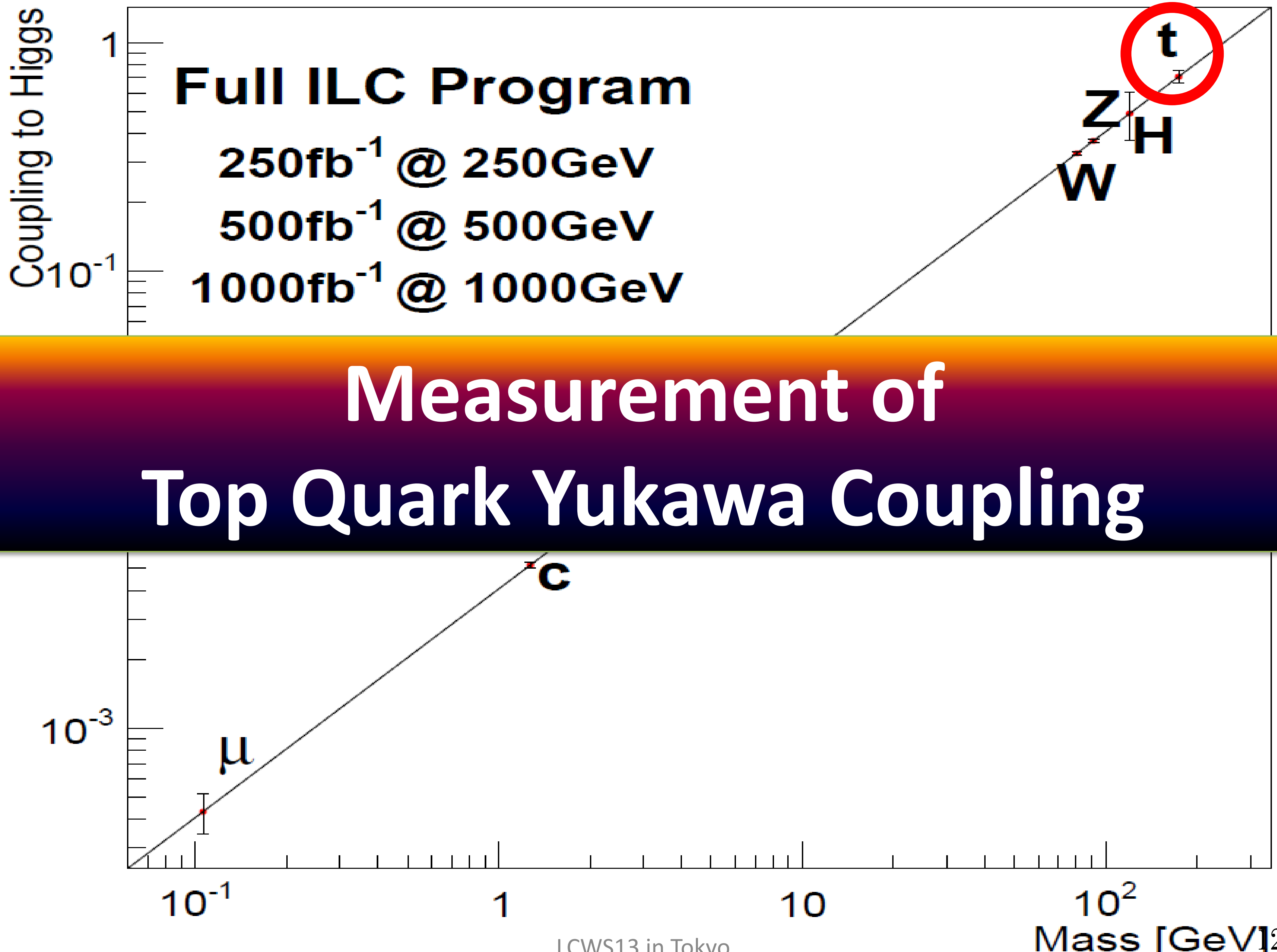
$$S = \frac{N_{Sig}}{\sqrt{N_{Sig} + N_{BG.}}}$$

Statistical error

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

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

Measurement of Top Quark Yukawa Coupling



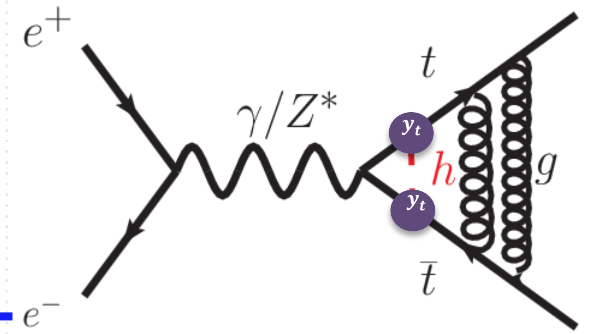
The Statistical Error of Top Quark Yukawa Coupling

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 !!

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

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



Stat. Error (50 fb^{-1})	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^{-1})
$\frac{\delta\sigma}{\sigma}$	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%	4.4%

Measurement of Top Quark “Mass” and “Width”

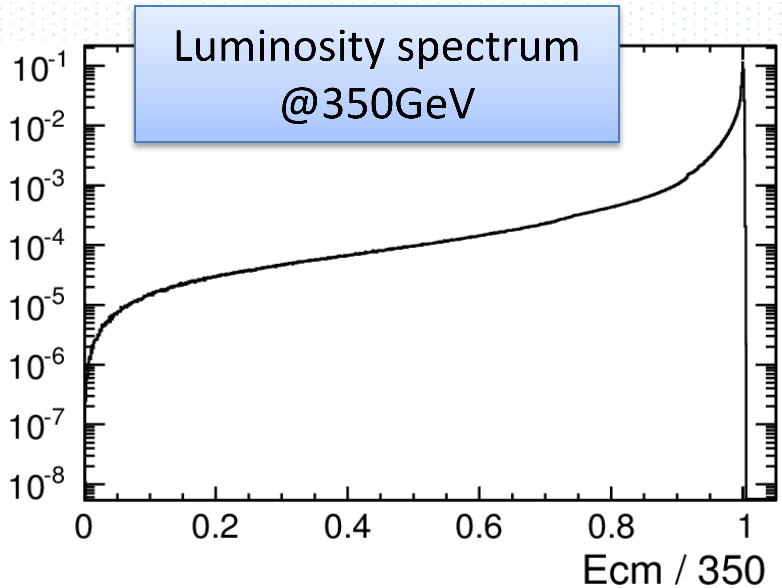
Fit - convolution -

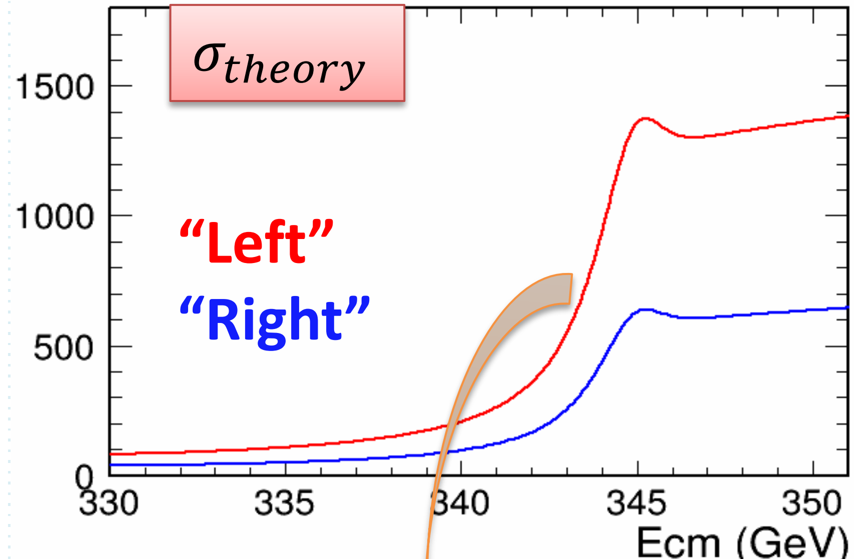
◎We must consider “Beam effects” around threshold.

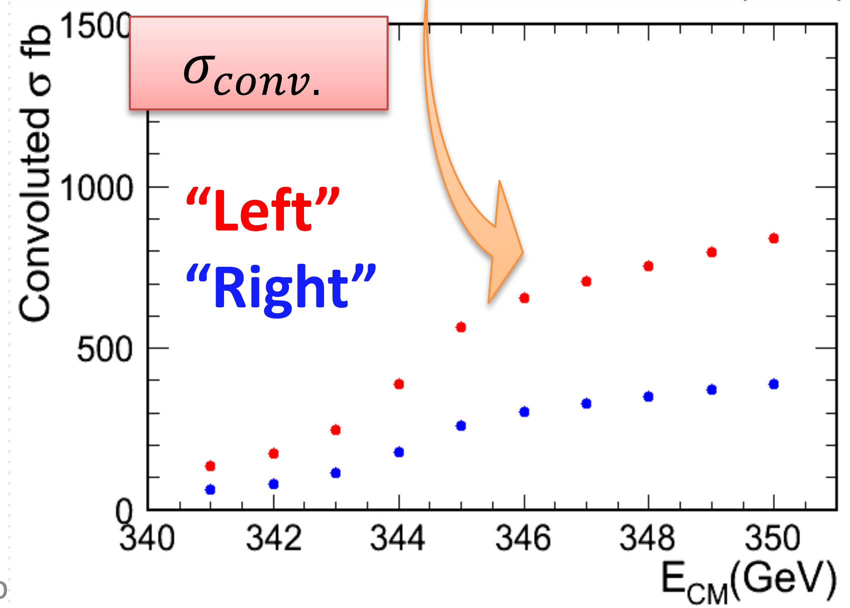
Using luminosity spectrum,
theoretical cross section is convoluted.

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

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



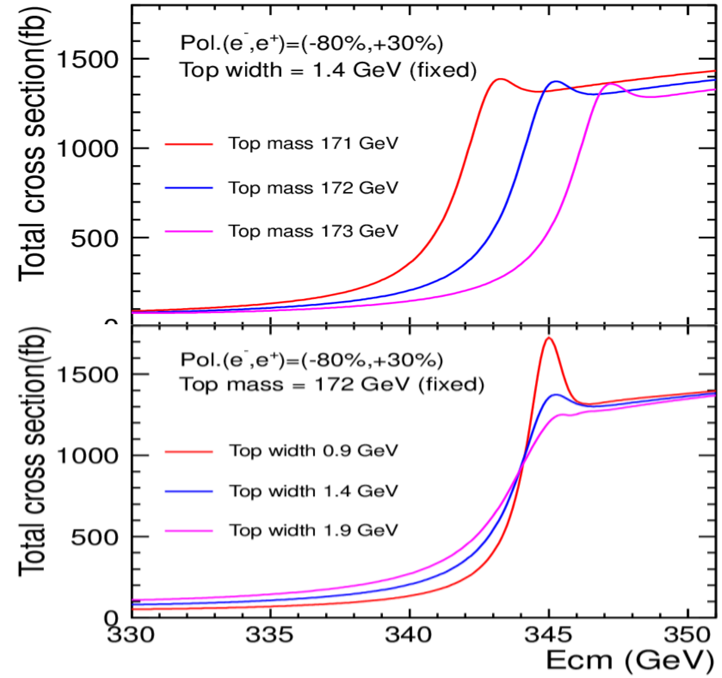


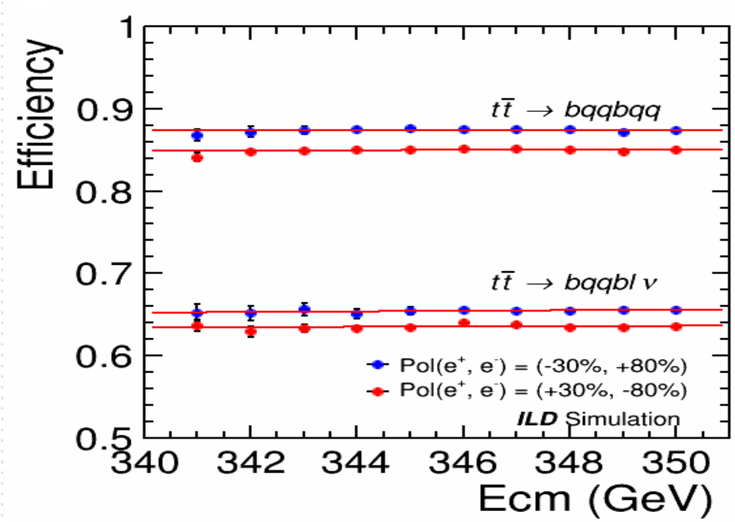


Fit -toyMC

- **<u>Template of theoretical cross section:</u>**
  - Floating m_t^{PS}, Γ_t and E_{CM}
  - Fixed α_s and y_t
  - The set center value
    $(m_t^{PS}, \Gamma_t) = (172.000, 1.400)$

- **<u>Fitting with NNLO convoluted theoretical cross section using Toy-MC method:</u>**
  - Using the efficiency of LO analysis, experimental cross section was scaled to NNLO calculation.
  - Its random number depend on Poisson distribution was generated.
  - 2-D fitting (m_t^{PS}, Γ_t) by interpolating and minimizing the cross section.





Fit -Result-

Stat. Error (MeV)	6-Jet		4-Jet	
	m_t^{PS}	Γ_t	m_t^{PS}	Γ_t
Left($50fb^{-1}$)	28	40	33	48
Right($50fb^{-1}$)	42	63	48	67
Left ($50fb^{-1}$) + Right($50fb^{-1}$)	**23**	**34**	**27**	**39**

Combined ALL

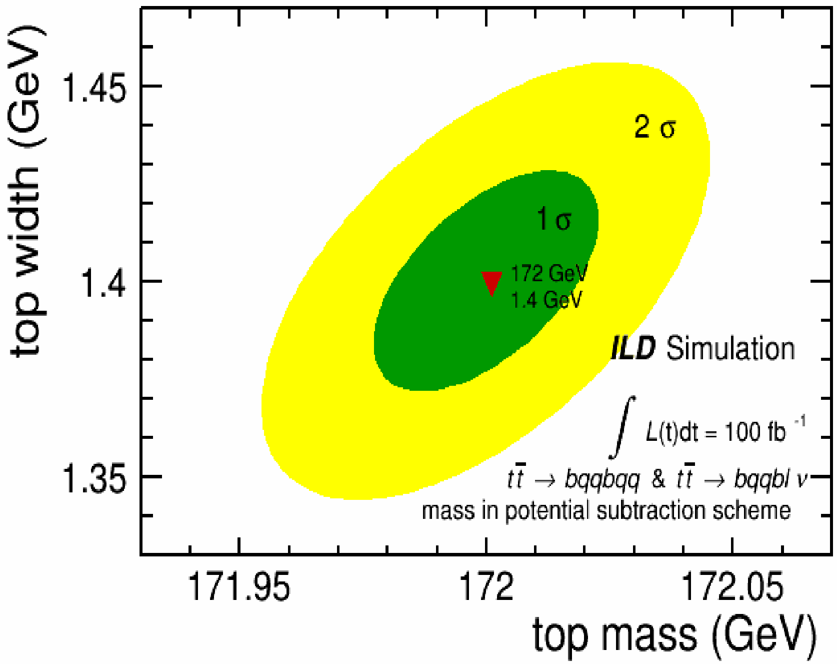
m_t^{PS}(GeV)	Γ_t(GeV)
172.001±0.018	1.399±0.026

◎PS→$\overline{MS}$ mass

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

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

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



Summary and Plan

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

$\Delta y_t/y_t$	**4.4 %**
m_t^{PS}	172.001 ± **0.018** (GeV)
$m_t^{\overline{MS}}$	163.800 ± **0.017** (GeV)
Γ_t	1.399 ± **0.026** (GeV)

- Plan
  - Start the QCD wave function analysis, A_{FB}