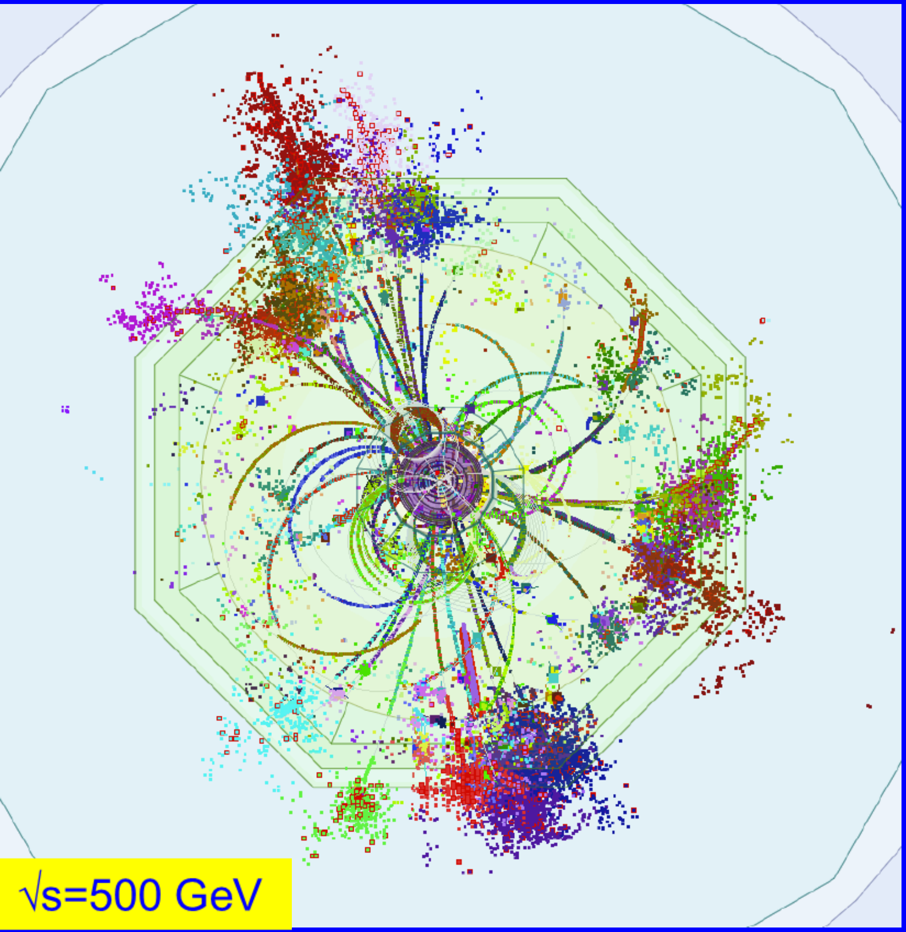
Top Physics at a Future e^+e^- Linear Collider



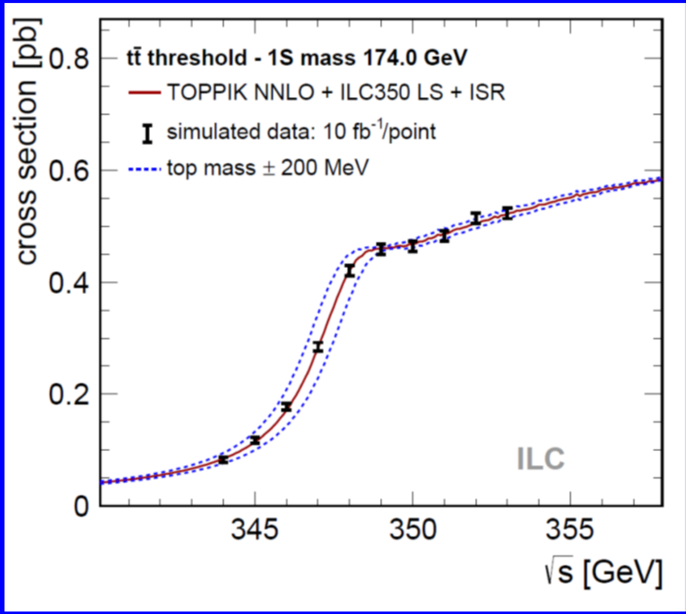
- Linear Colliders (ILC, CLIC)
- Experimentation at ILC
- Top Physics
  - Top mass
  - Top Yukawa coupling
  - Top EW couplings + BSM
  - New physics with tops

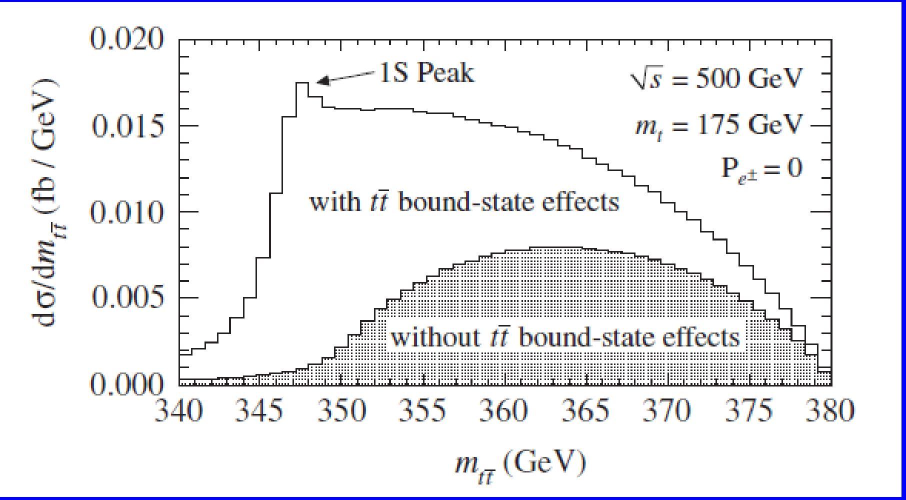
Graham W. Wilson
University of Kansas
DPF2015, Ann Arbor, MI, August 4th 2015

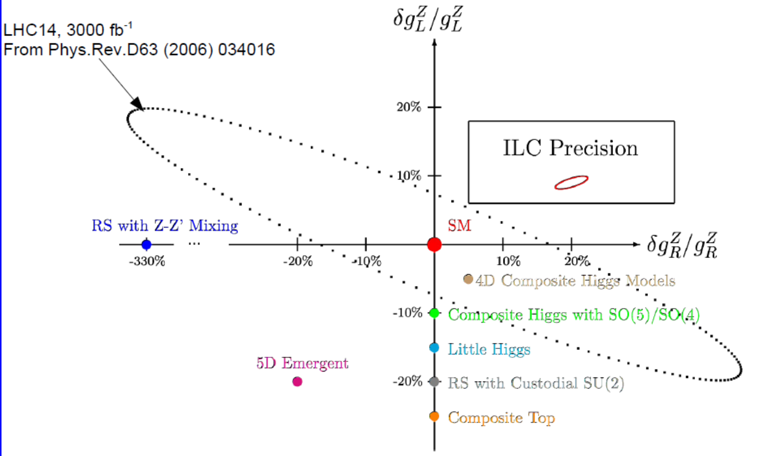
e^+e^- Linear Colliders (ILC/CLIC)

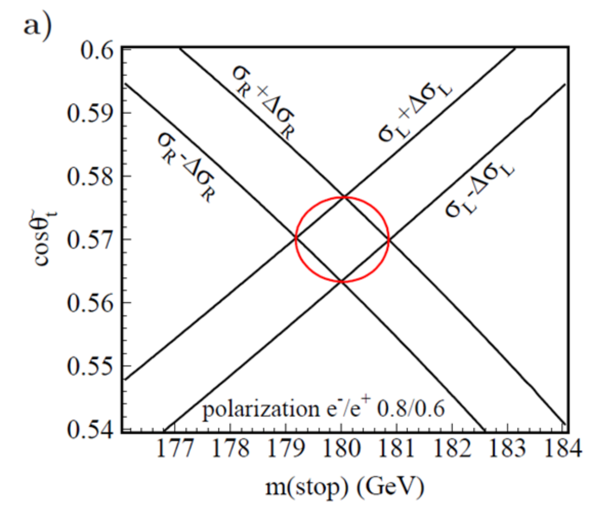
- Only practical way to go significantly above the top pair threshold.
- ILC is based on superconducting RF.
  - ILC under study and development for many years
  - World-wide consensus in 2001 as the next future collider
- ILC initial stage - $\sqrt{s}$ up to 500 GeV, upgradable to 1 TeV
  - Now we have the discovery of the Higgs in 2012
  - ILC technology is mature
  - Japan is in the process of deciding whether to host the ILC as a global project
- CLIC: R&D project at CERN. 2-beam accelerator. Post-LHC option with potential of reaching 3 TeV.

Top Quark Physics Highlights



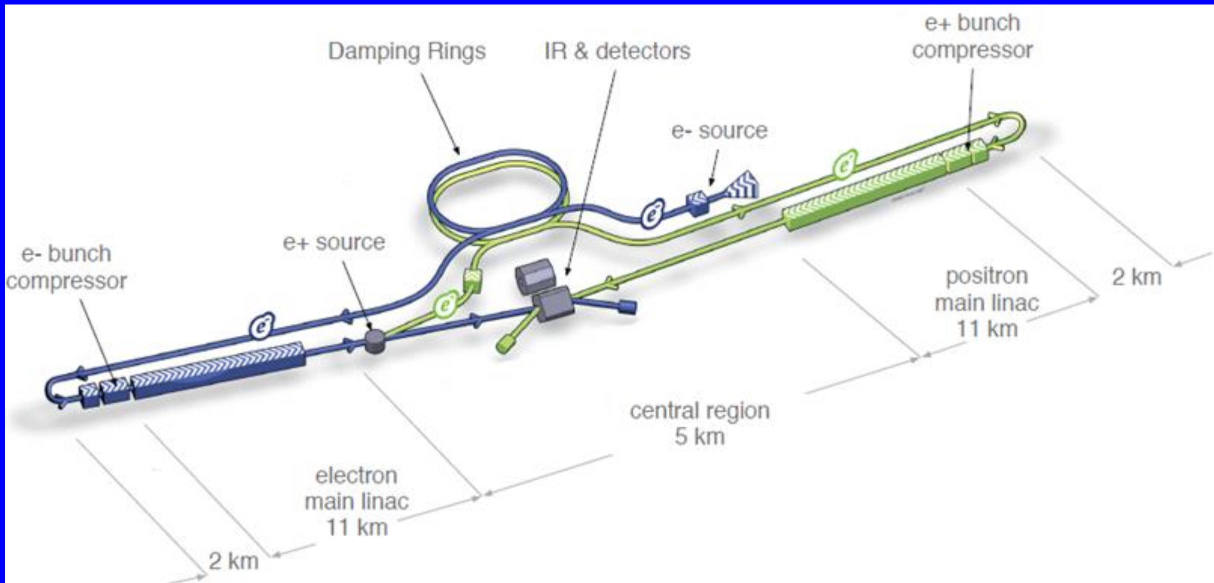


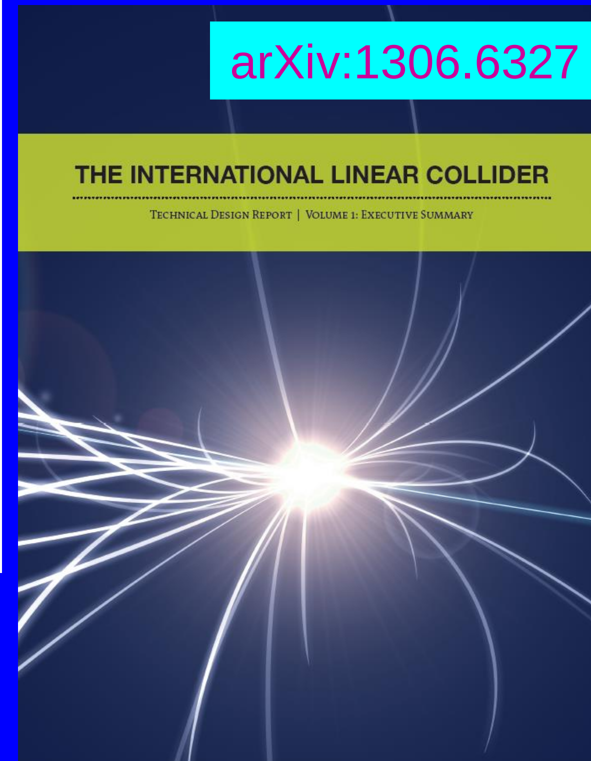


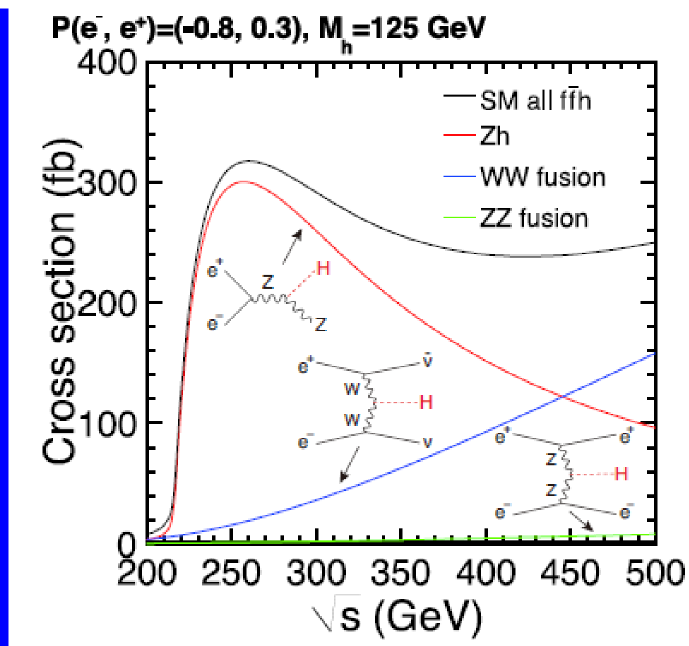


For more info – also see recent LC Top workshops (TopLC15)

International Linear Collider Project

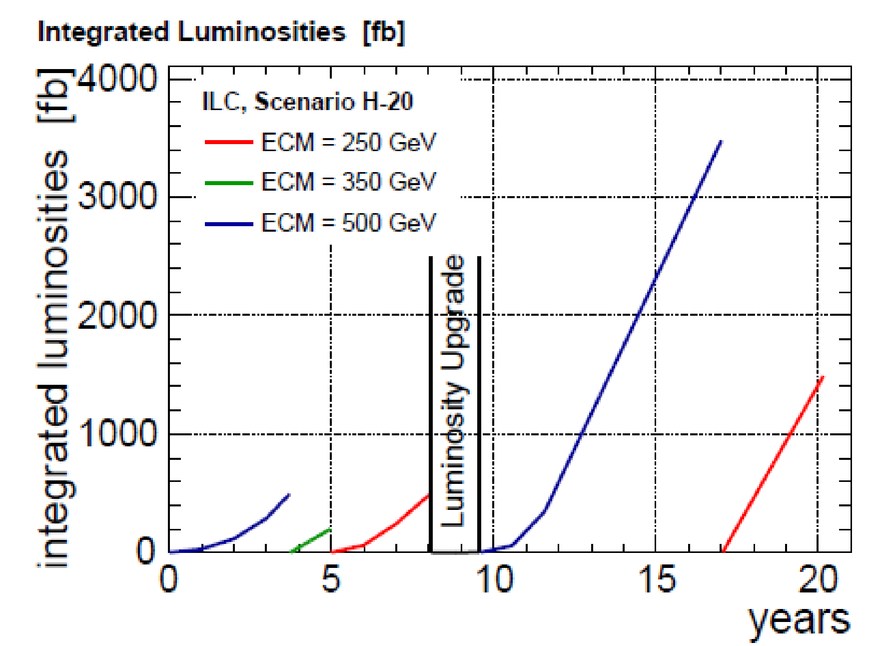






ILC Parameters / Running Scenarios

arXiv: 1506.07830.
See J. Brau talk at DPF for more details.



- Baseline scenario for study
- Run plan flexible - will evolve informed by future developments
- Future upgrade to 1 TeV and potentially beyond
- Options for dedicated running with polarized beams at Z-pole and WW threshold

	integrated luminosity with $\mathrm{sgn}(P(e^-),P(e^+)) =$			
	(-,+)	(+,-)	(-,-)	(+,+)
$\sqrt{s}$	[fb^{-1}]	[fb^{-1}]	[fb^{-1}]	[fb^{-1}]
250 GeV	1350	450	100	100
350 GeV	135	45	10	10
500 GeV	1600	1600	400	400

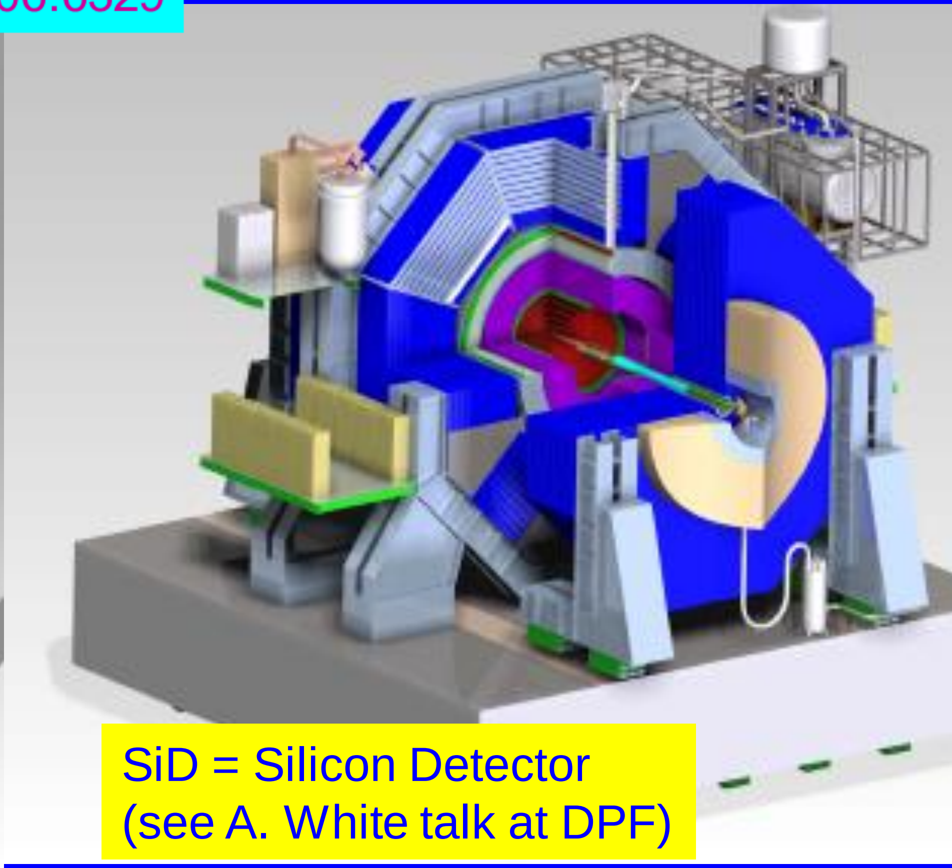
6200 fb^{-1} total

200 fb^{-1} at $\sqrt{s} \approx 350$ GeV

ILC Detectors

arXiv:1306.6329

ILD = International Large Detector



SiD = Silicon Detector
(see A. White talk at DPF)

Modern detectors designed for ILC. Particle-flow for jets.
Similar size to CMS.
ILD centered around a TPC. SiD – silicon tracking.

ILC Physics

- Physics studies at future e^+e^- colliders.
- Seeds were planted in the mid-80's.
- Now a vast literature.
- 3 recent publications.
  - K. Fujii et al
    - arXiv:1506.05992
  - G. Moortgat-Pick et al.,
    - arXiv:1504.01726
  - H. Baer et al,
    - arXiv:1306.6352

Topic	Parameter	Initial Phase	Full Data Set	units
Higgs	m_h	25	15	MeV
	$g(hZZ)$	0.58	0.31	%
	$g(hWW)$	0.81	0.42	%
	$g(hb\bar{b})$	1.5	0.7	%
	$g(hgg)$	2.3	1.0	%
	$g(h\gamma\gamma)$	7.8	3.4	%
		1.2	1.0	%, w. LHC results
	$g(h\tau\tau)$	1.9	0.9	%
	$g(hc\bar{c})$	2.7	1.2	%
	$g(ht\bar{t})$	18	6.3	%, direct
		20	20	%, $t\bar{t}$ threshold
	$g(h\mu\mu)$	20	9.2	%
	$g(hhh)$	77	27	%
	Γ_{tot}	3.8	1.8	%
	Γ_{invis}	0.54	0.29	%, 95% conf. limit
Top	m_t	50	50	MeV (m_t(1S))
	Γ_t	60	60	MeV
	g_L^γ	0.8	0.6	%
	g_R^γ	0.8	0.6	%
	g_L^Z	1.0	0.6	%
	g_R^Z	2.5	1.0	%
	F_2^γ	0.001	0.001	absolute
	F_2^Z	0.002	0.002	absolute
W	m_W	2.8	2.4	MeV
	g_1^Z	8.5×10^{-4}	6×10^{-4}	absolute
	κ_γ	9.2×10^{-4}	7×10^{-4}	absolute
	λ_γ	7×10^{-4}	2.5×10^{-4}	absolute
Dark Matter	EFT Λ: D5	2.3	3.0	TeV, 90% conf. limit
	EFT Λ: D8	2.2	2.8	TeV, 90% conf. limit

Experimentation with ILC

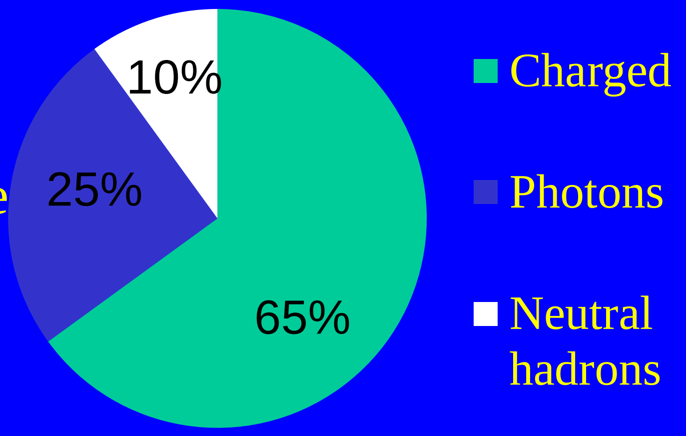
- Physics experiments with e^+e^- colliders are **very different** from a hadron collider.
- Experiments and detectors can be **designed without the constraints** imposed by triggering, radiation damage, pileup.
- **All decay channels** can often be used (not only $H \rightarrow 4l$ etc)
- **Can adjust the initial conditions**, the beam energy, polarize the electrons and the positrons, and measure precisely the absolute integrated luminosity.
- Last – but not least – **theoretical predictions** can be brought under very good control.

Jets Using Particle-Flow

E(jet) = E(charged) + E(photons) + E(neutral hadrons)

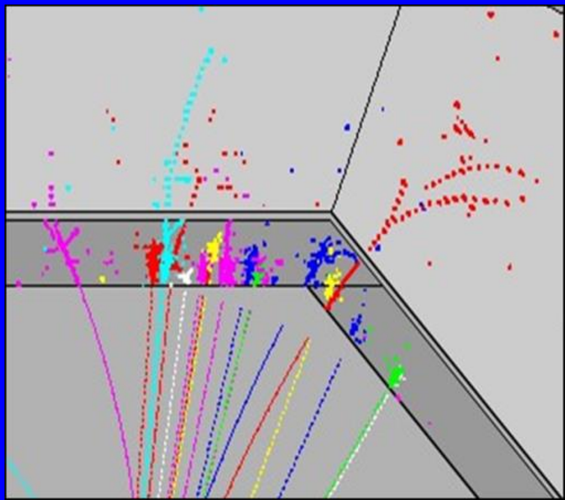
- Outsource **65%** of the event-energy measurement responsibility from the calorimeter to the tracker
  - Emphasize particle separability
  - Leading to better jet energy precision
- Reduce importance of hadronic leakage
  - Now only 10% instead of 75% of the average jet energy is susceptible
- Maximize event information
- Pioneered by LC detector community and CALICE collaboration. Now widely used in CMS

Particle AVERAGEs

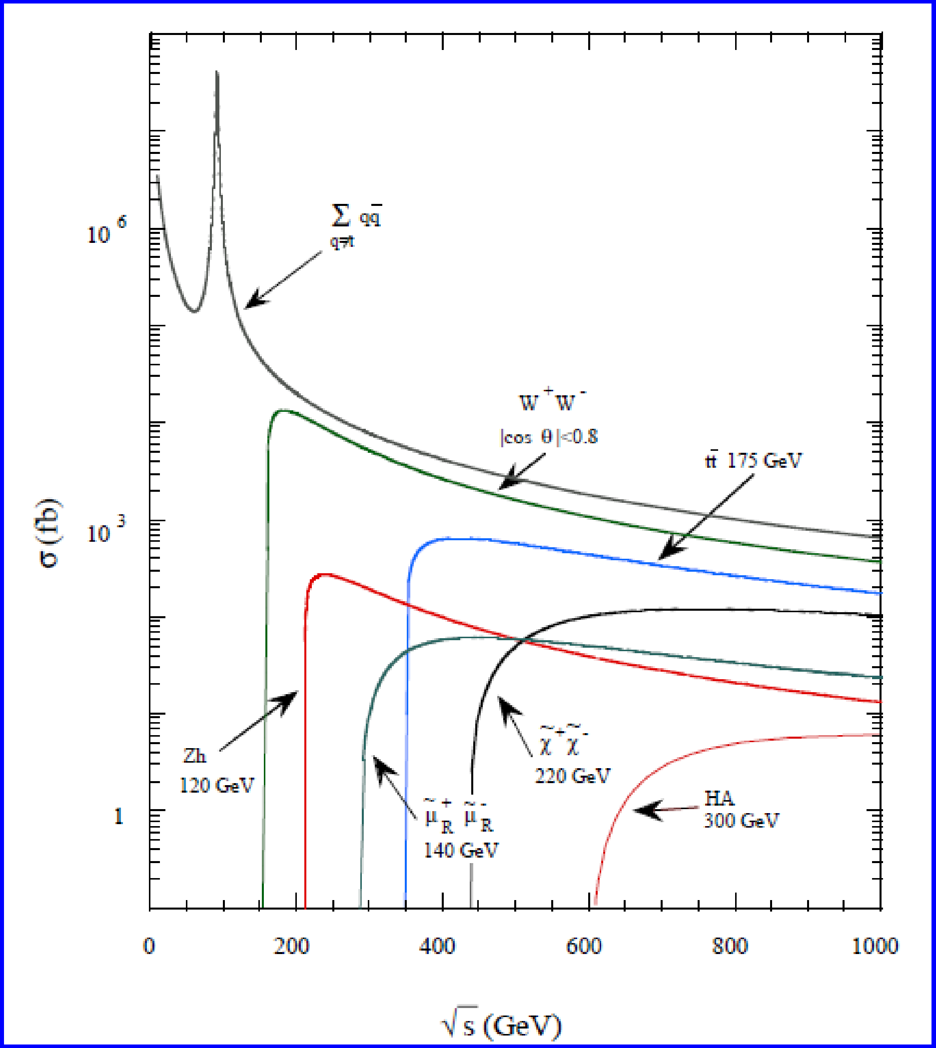


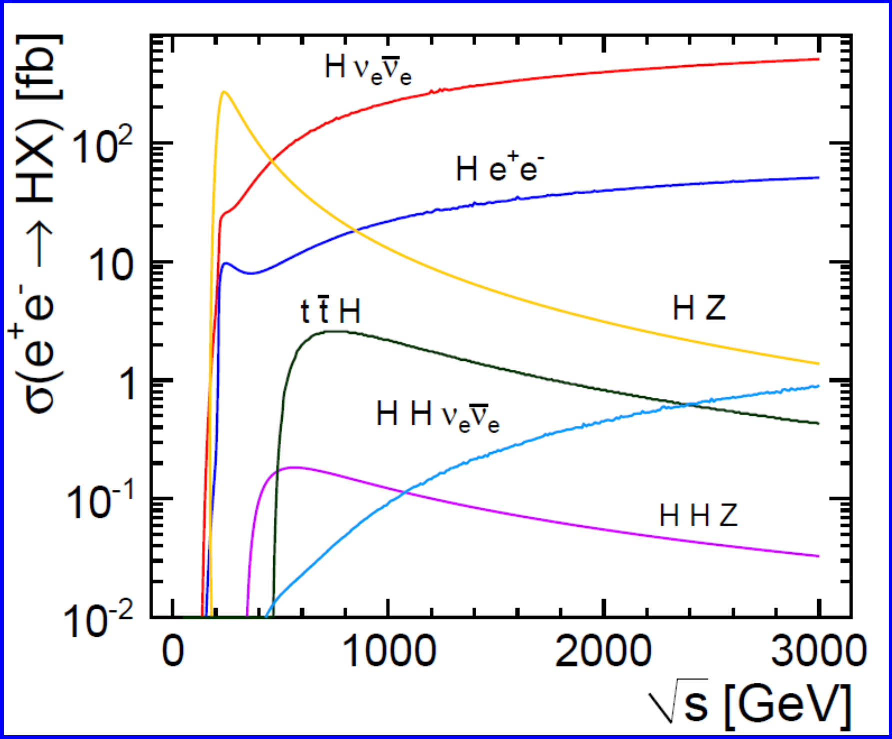
ILD

Jet Energy	rms_{90}	$\mathrm{rms}_{90}/\sqrt{E_{jj}/\mathrm{GeV}}$	σ_{E_j}/E_j
45 GeV	2.4 GeV	24.7 %	(3.66 ± 0.05) %
100 GeV	4.0 GeV	28.3 %	(2.83 ± 0.04) %
180 GeV	7.3 GeV	38.5 %	(2.86 ± 0.04) %
250 GeV	10.4 GeV	46.6 %	(2.95 ± 0.04) %



The e^+e^- Landscape



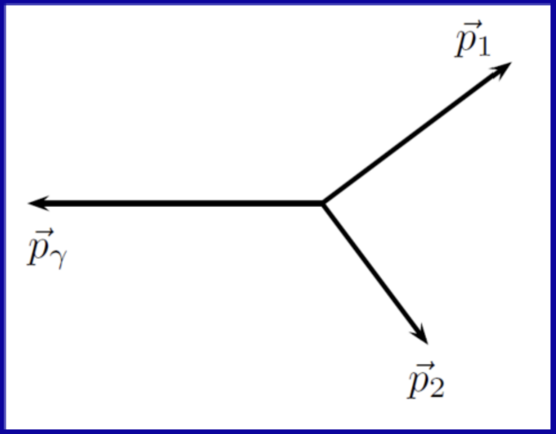


Cross-sections are typically at the pb level. Straightforward to select all top decay modes with little background.

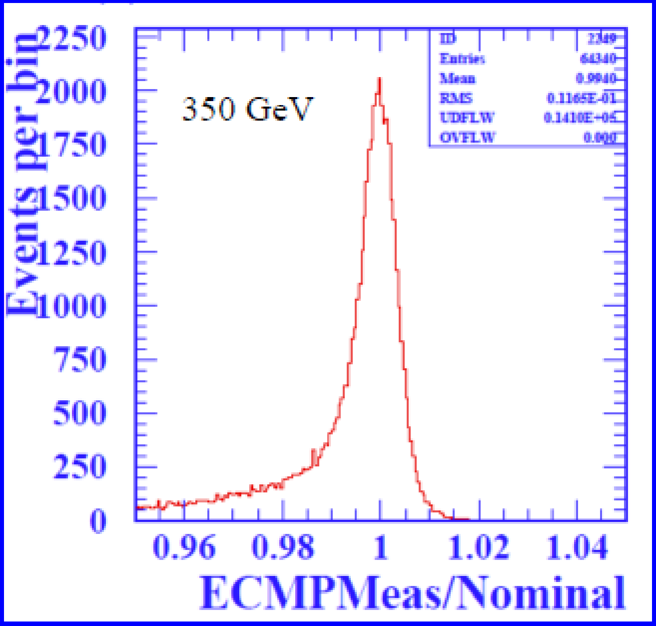
Beam Energy Measurement

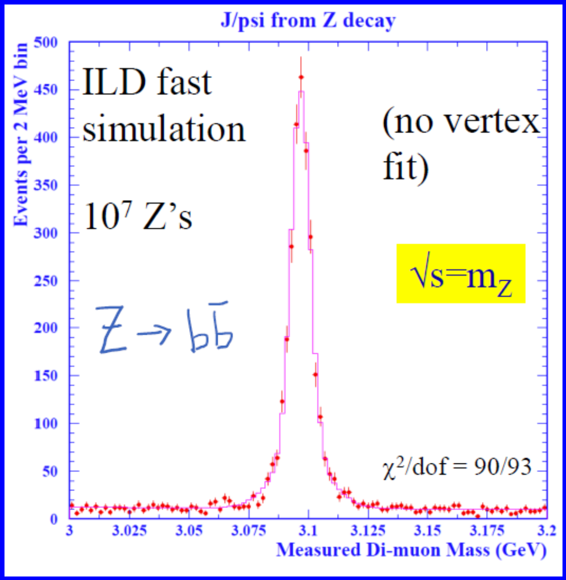
- Critical input to measurements of m_t, m_W, m_H, m_X using threshold scans.
- Standard precision $O(10^{-4})$ for m_t straightforward.
- Targeting precision $O(10^{-5})$ for $m_{W,}$ m_Z
  - Muon momenta based strategy looks feasible

$e^+ e^- \rightarrow \mu^+\mu^-(\gamma)$



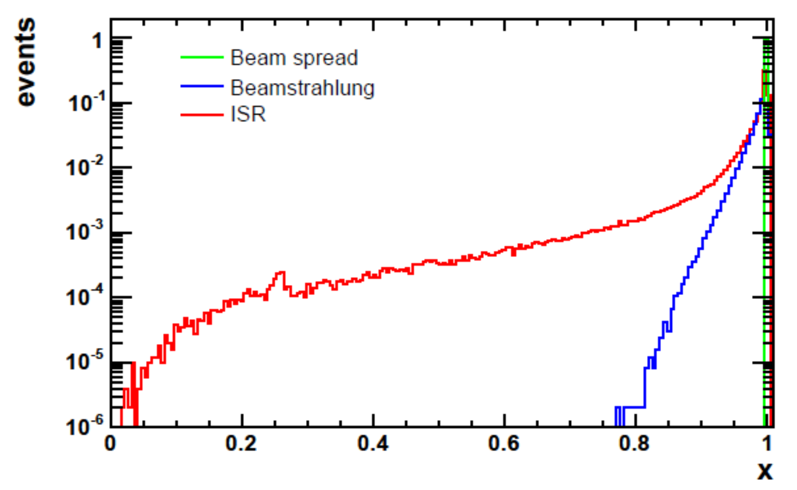
Use muon momenta.
Measure $E_1 + E_2 + |\mathbf{p}_{12}|$ as an estimator of $\sqrt{s}$

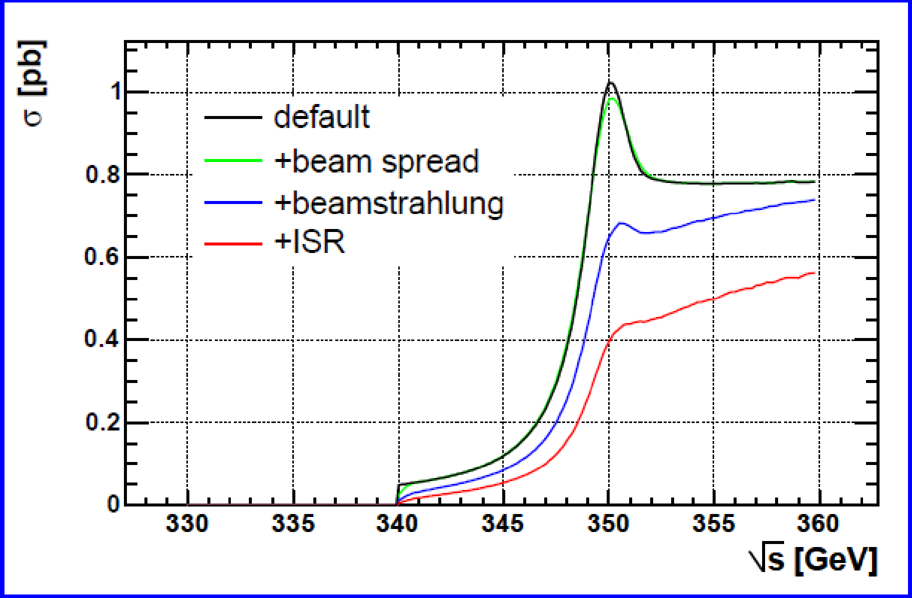


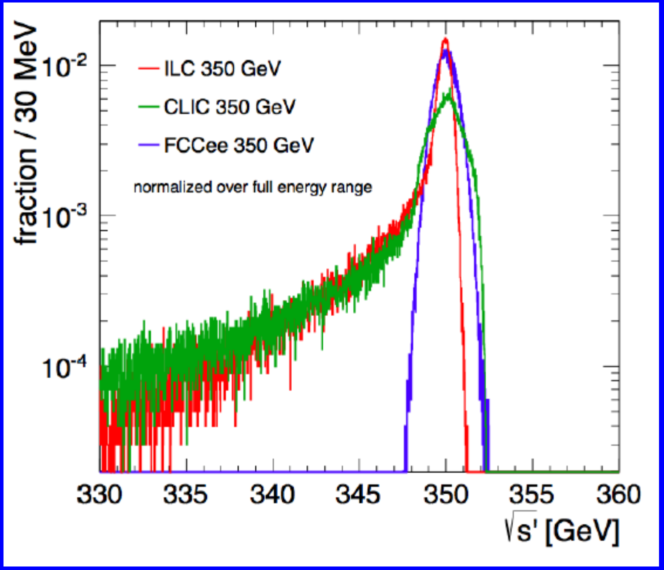


Luminosity Spectrum

- Experimentally accessible measurements are convolved with effects of ISR, beam spread and beamstrahlung







Luminosity sprectrum should be controlled well at ILC (to < 0.2% differentially using Bhabhas - see backup slide))

Polarized Beams

- ILC baseline design has electrons longitudinally polarized to 80%, positrons to 30%.
- Electron polarization to 90% is not out of the question.
- Positron polarization to 60% is under study and possible.
- In contrast to circular colliders, longitudinal polarization is not something that costs luminosity.

$$\sigma(P_{e^-}, P_{e^+}) = \frac{1}{4}\{(1 - P_{e^-})(1 + P_{e^+})\sigma_{LR} + (1 + P_{e^-})(1 - P_{e^+})\sigma_{RL} + (1 - P_{e^-})(1 - P_{e^+})\sigma_{LL} + (1 + P_{e^-})(1 + P_{e^+})\sigma_{RR}\}$$

- With both beams polarized it is straightforward to measure accurately the absolute polarization in-situ for processes where $\sigma_{LL}=\sigma_{RR}=0$.
  - Using the 4 cross-section measurements from the (-+. +-, --, ++) helicity combinations, and the 4 unknowns (σ_U, A_{LR}, P_{e+}, P_{e-}). Assumes same |P| for +ve and –ve helicity of same beam.
- Polarimeters to track relative polarization changes.

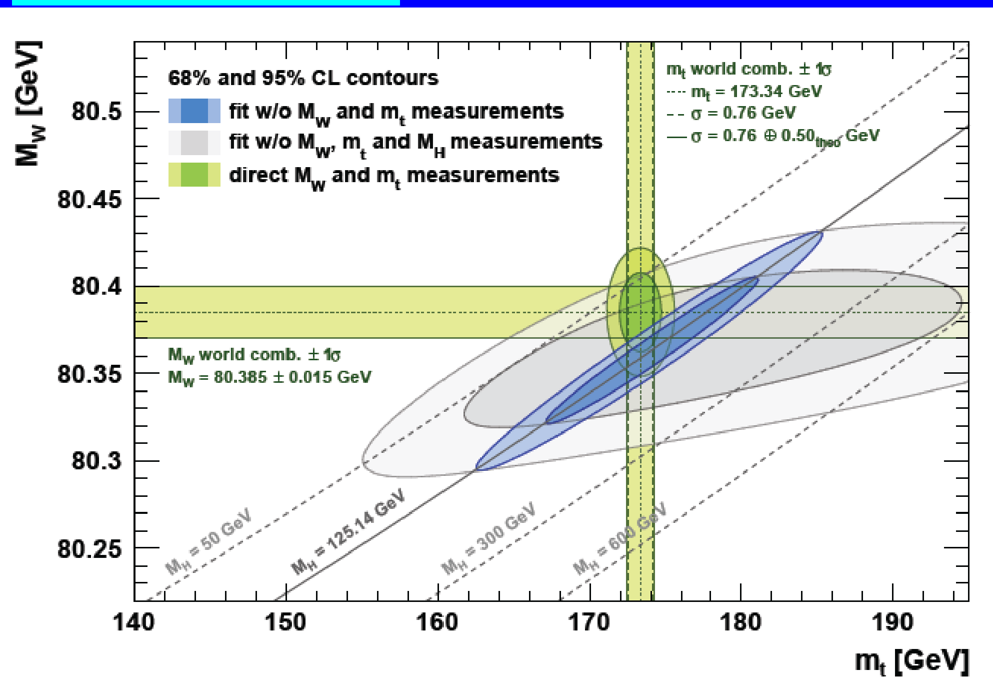
ILC Trigger Requirements

NONE !

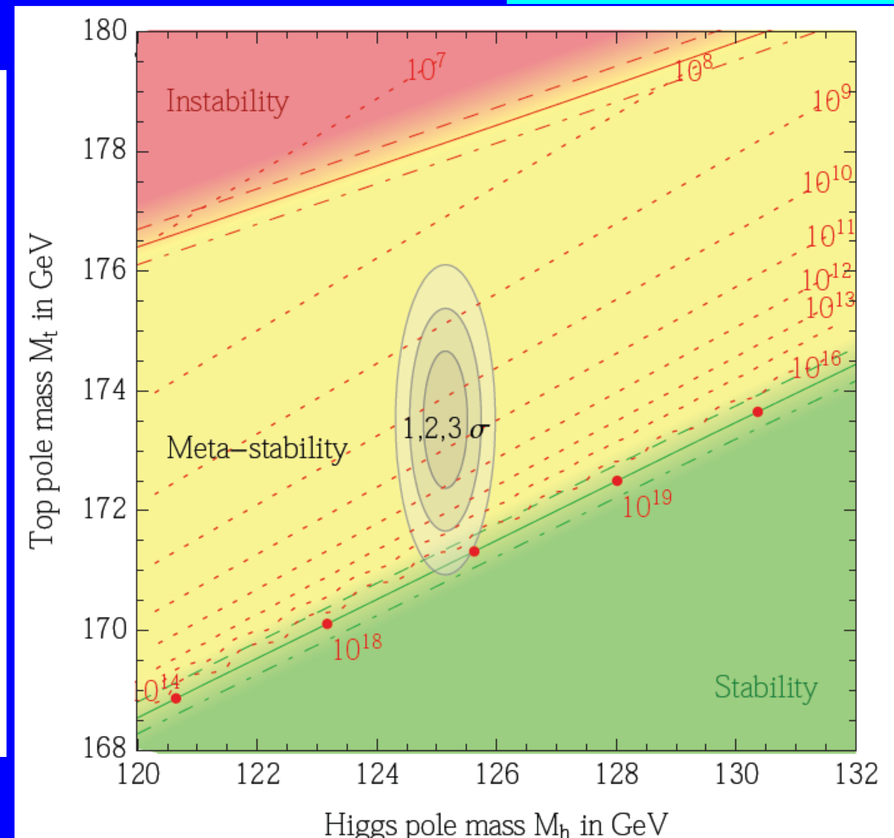
So no biases, no limited acceptance, no inefficiency, no detector constraints.

Top Mass

arXiv:1407.3792



arXiv:1307.3536



A precisely measured and theoretically understood top mass is critical input to assessing the internal consistency of the Standard Model at the quantum level – and for understanding the stability of the universe as we know it today.

W mass also very important. Prospects for sub 3 MeV precision at ILC.

Hadron Collider Top Mass

- Impressive progress – systematics limited.
- CDF (l+jets): $172.85 \pm 0.52 \pm 0.98$ GeV
- D0 (l+jets): $174.98 \pm 0.41 \pm 0.63$ GeV
- ATLAS comb: $172.99 \pm 0.48 \pm 0.78$ GeV
- CMS comb: $172.38 \pm 0.14 \pm 0.64$ GeV

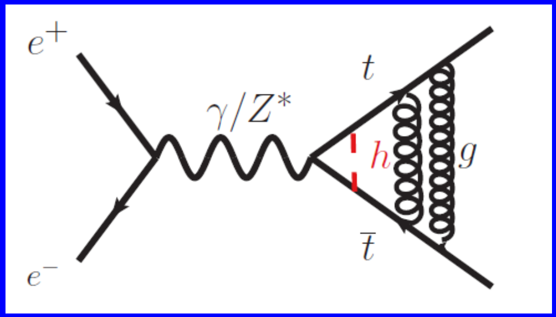
Experiments measure “Monte Carlo masses” based on event kinematics

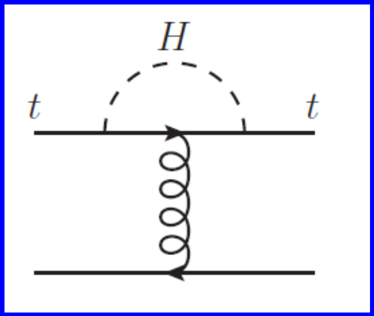
Converting to theoretically well defined masses is not obvious.

Progress beyond 0.5 GeV will be very difficult at hadron colliders - arXiv:1311.2028.
Literature does not exlude error of 1 GeV.

At e^+e^- colliders, in a threshold scan, one can measure the 1S top mass or the pole-subtracted top mass. These can be related to the $\overline{MS}$ mass with high accuracy. (Marquardt et al, arXiv:1502.0103 4-loop order error of 7 MeV (1S), 23 MeV (PS)).

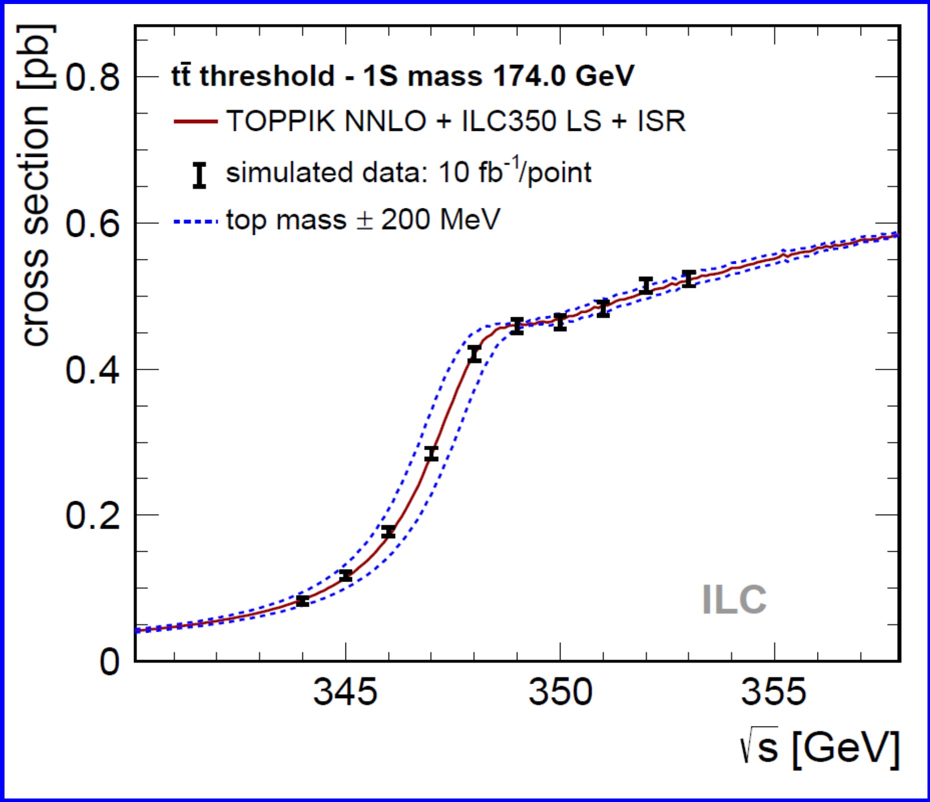
m_t from threshold scan





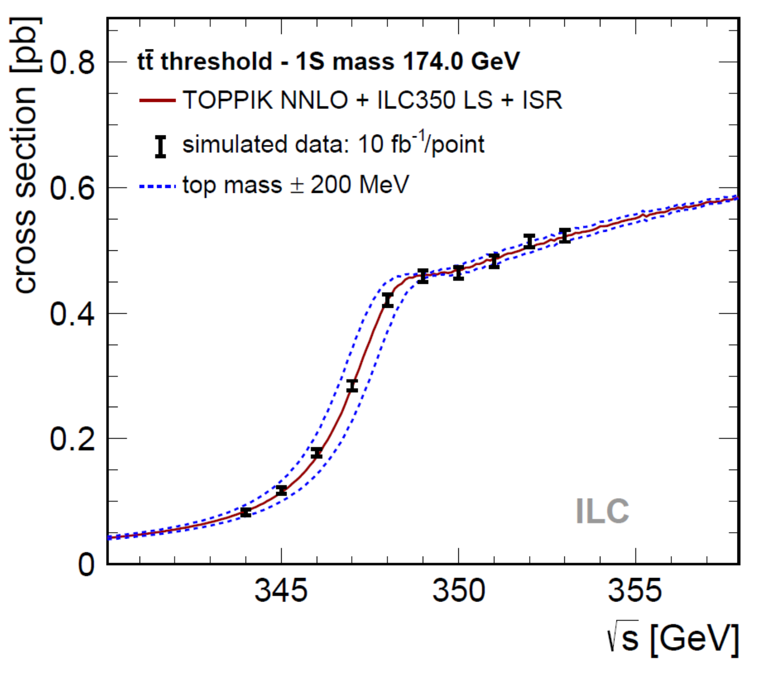
$$\Gamma(t \to b + W^+) = \frac{G_F |V_{tb}|^2 m_t^3}{8\sqrt{2}\pi}\left[1 - \frac{m_W^2}{m_t^2}\right]^2 \left[1 + 2\frac{m_W^2}{m_t^2}\right]$$

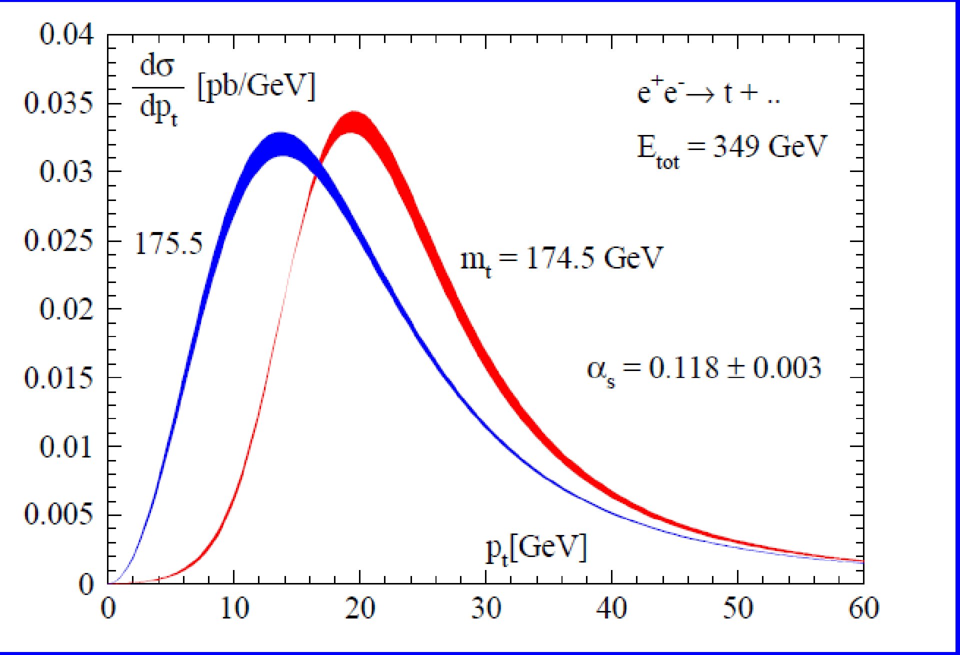
- Threshold cross-section depends on m_t, Γ_t, α_s, y_t .
- Color singlet state, finite top lifetime => accurate and unambiguous theoretical predictions with negligible hadronization effects.
- Width depends on m_t in SM. Expect width of around 1.35 GeV.
- Measure the 1S top mass.
- Prefer a strategy to control the “nuisance” parameters – viz α_s, y_t - they are likely better measured in other ways.

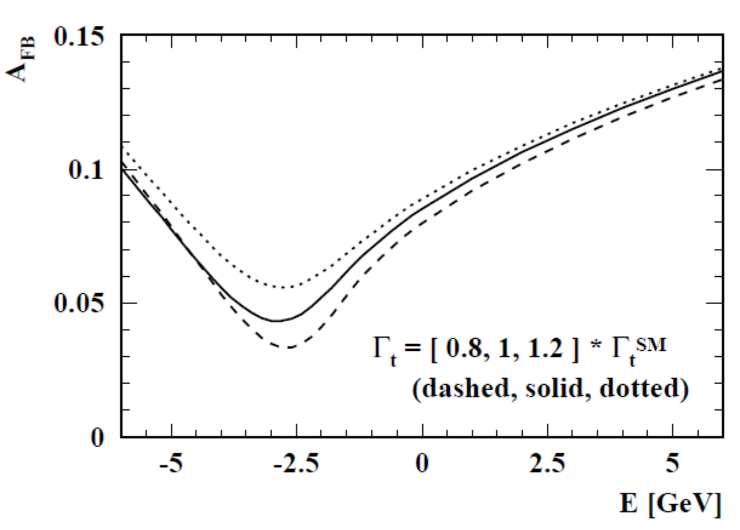


m_t from threshold scan

- Besides the cross-section, the top momentum distributions and A_{FB} are useful tools to assist in interpreting the threshold scan.
- The threshold is a special place, where a QCD bound state can be studied free of non-perturbative effects

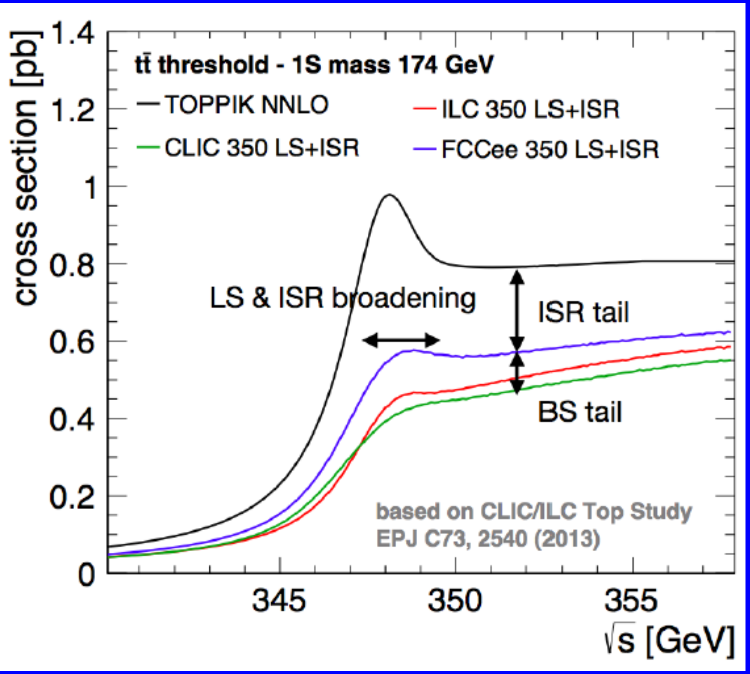


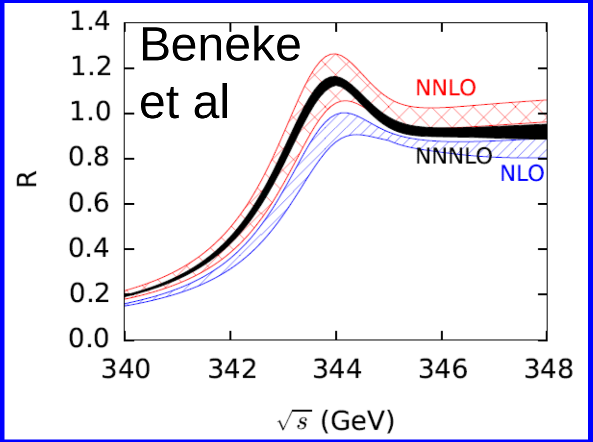




m_t from threshold scan

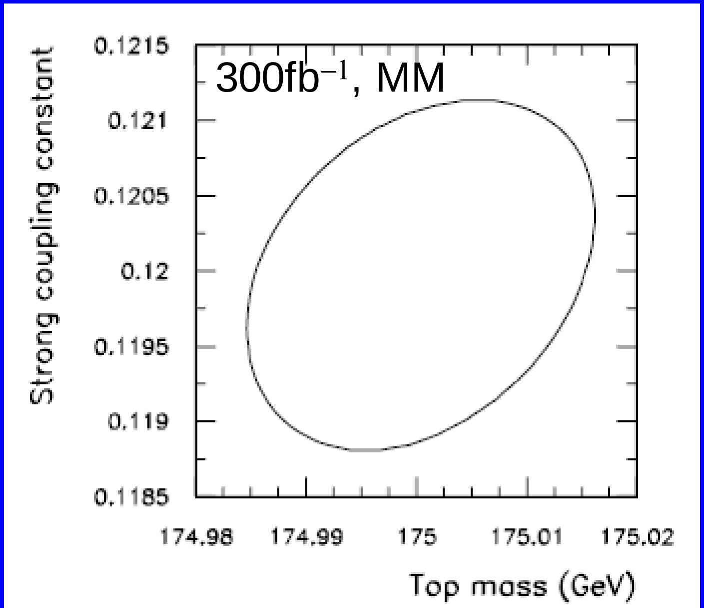
- Many experimental studies.
- Martinez & Miquel, hep-ph/0207315
- T. Horiguchi et al., arXiv:1310.0563
- K. Seidel et al., arXiv:1303.3758
- For nominal ILC, CLIC and FCCee machines (unpolarized beams)
  - Top mass statistical sensitivities per 100 fb^{-1}
  - (1-D) 18 / 21 / 16 MeV for ILC/CLIC/FCCee
- Experimental systematics at ILC under control
- Theoretical error below 50 MeV feasible
  - NNNLO QCD calculation of threshold shape (arXiv:1506.06864)
- Theory systematic currently much greater than foreseen experimental errors for all colliders
- **=> Improvements in theory – highly welcome.**
- ILC will be able to take advantage.





m_t from threshold scan

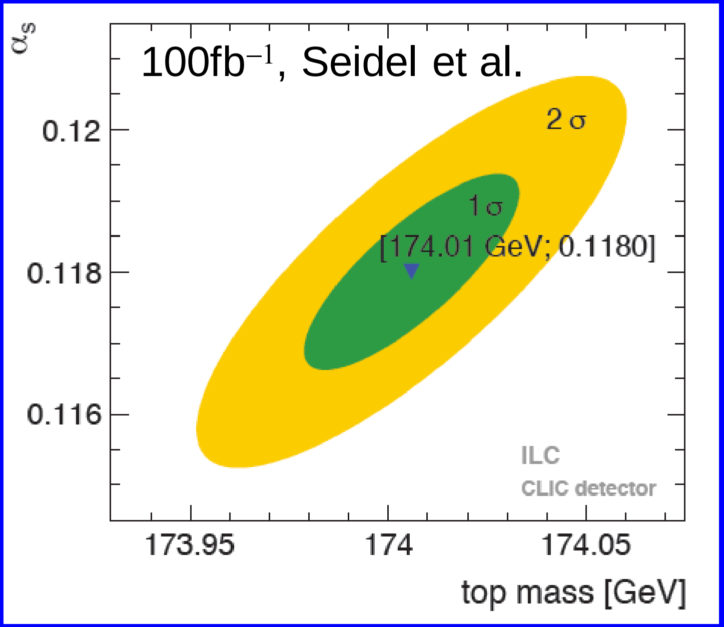
Old study: illustrates potential utility of p(top) distribution (known at NNLO)



m_t 16 MeV
α_S 0.0012, ρ = 0.33
with p(top)

m_t 25 MeV
α_S 0.0019, ρ = 0.76
without p(top)

Threshold scan only.
(known at NNNLO now)



m_t 27 MeV
α_S 0.0008

Better external measurement of α_s and y_t very useful !
Also possible in e+e-.

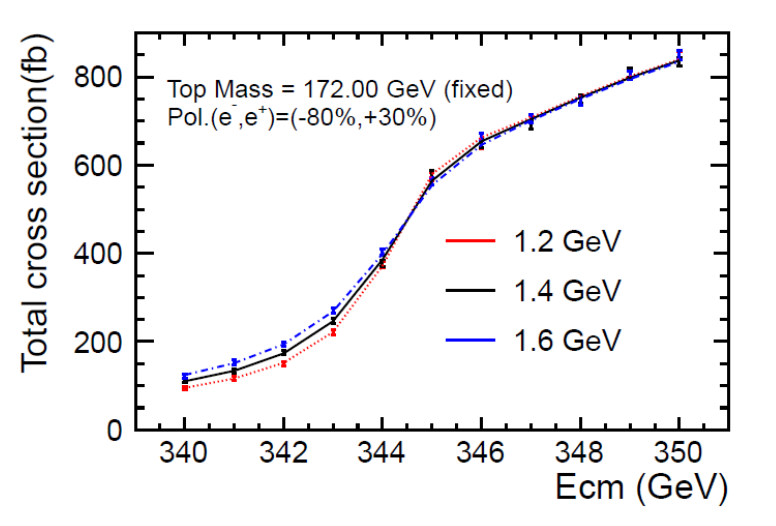
m_t from threshold scan

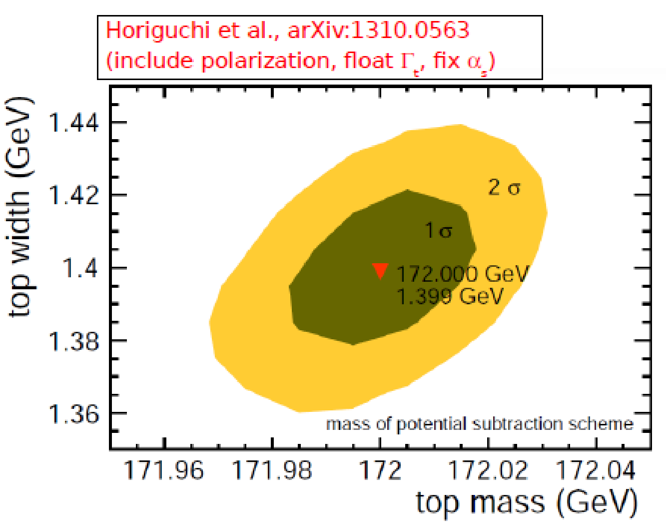
Horiguchi et al

5 fb^{-1}

6-jet only!

E_{CM}= 350(GeV) on "Left"	$t\bar{t}$ 6-Jet	$t\bar{t}$ 4-Jet	$t\bar{t}$ 2-Jet	WW	ZZ	ZH	$S_{6-\text{Jet}}$
Generated	3288	3167	763	65328	6008	1389	11.6
btag1 >0.1, btag2 >0.1	3136	3004	725	7567	2832	982	23.2
thrust <0.84	3090	2882	645	867	917	815	32.2
Visible Energy >310(GeV)	3063	1194	37	434	573	577	39.9
nlep = 0	3021	399	3	429	571	571	42.8
Y_{45} >0.0012 , Y_{56} >0.0007	2956	331	2	174	176	193	47.8
p_t^{miss} >38(GeV)	2942	160	0	173	175	192	48.7
nPFOs = 95	2917	137	0	115	143	170	49.4





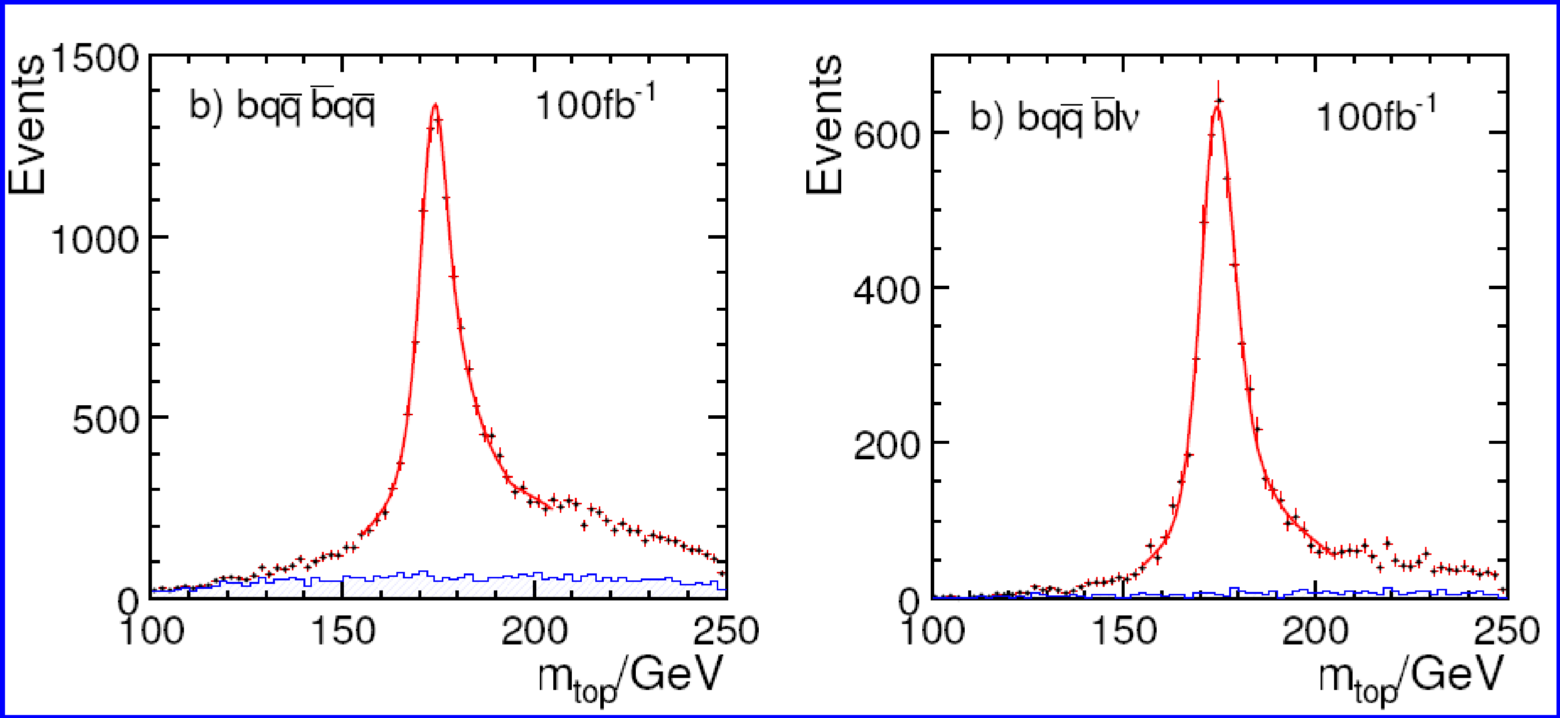
	PS Mass (GeV)	Width (GeV)
"Left" (110 fb^{-1})	172.000 ± 0.020	1.399 ± 0.026
"Right" (110 fb^{-1})	172.000 ± 0.028	1.398 ± 0.038
"Left" + "Right" (220 fb^{-1})	172.000 ± 0.016	1.399 ± 0.021

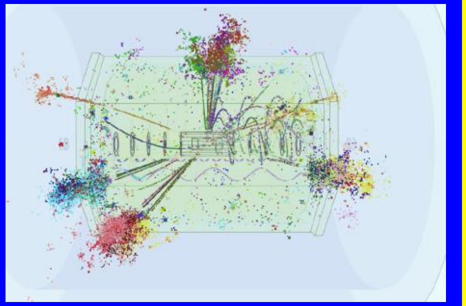
Stat. Errors: (α_S fixed)
16 MeV (PS mass),
21 MeV (width), 4.2% on y_t

m_t from top-pair production above threshold

$\sqrt{s}$ = 500 GeV. ILC Full simulation

Electroweak production of top quarks





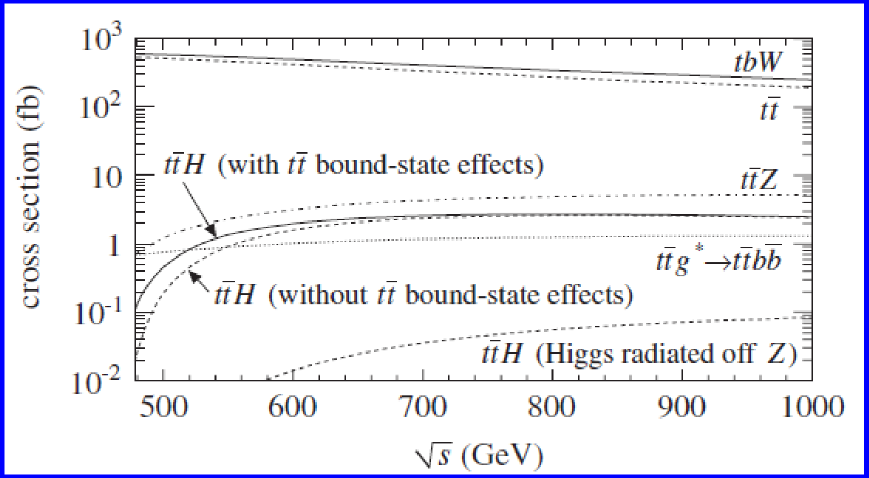
Analysis uses particle-flow reconstruction, b-tagging, and kinematic fit.

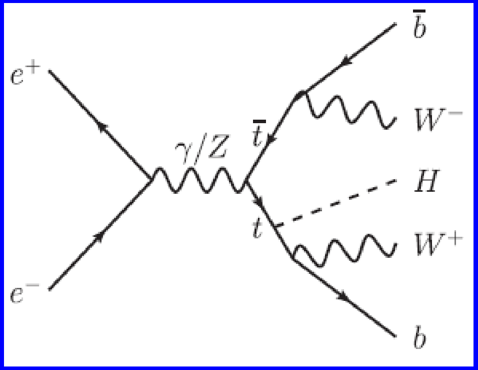
Result: statistical error of 10 MeV for 4000 fb^{-1}

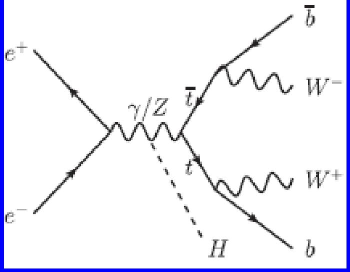
(Factor of 2.5 improvement in sensitivity over hadronic-only study of PRD 67, 074011 (2003).

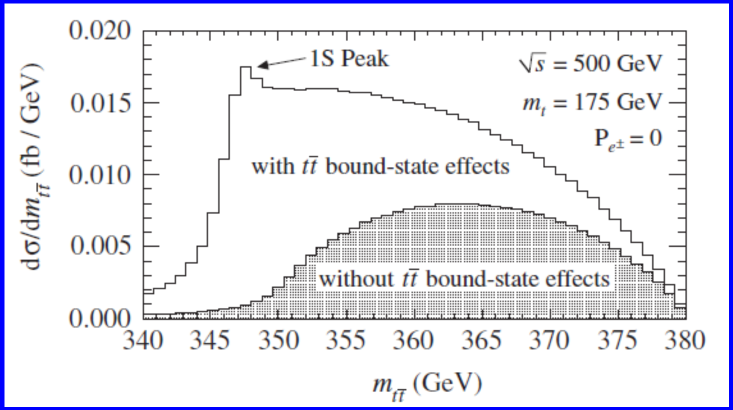
Top Yukawa Coupling

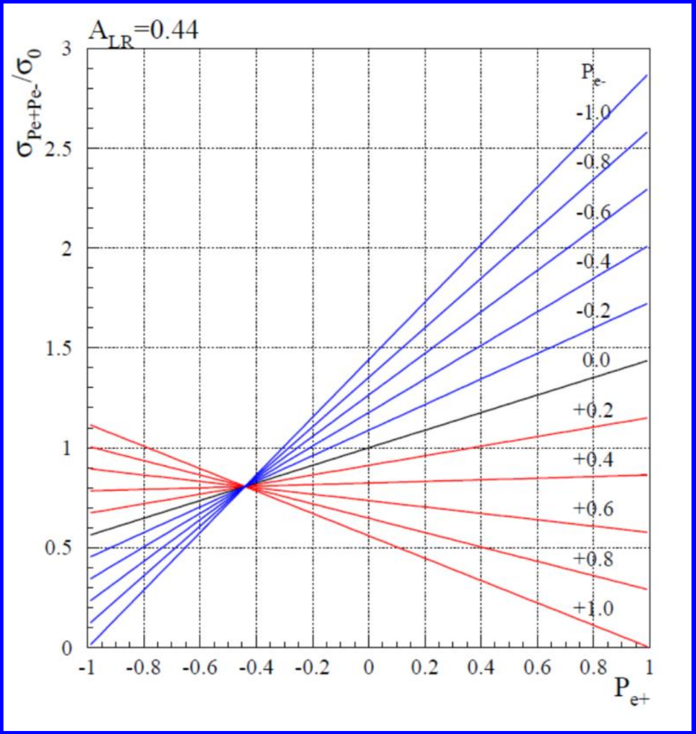
Direct measurement of top quark – Higgs Yukawa interaction







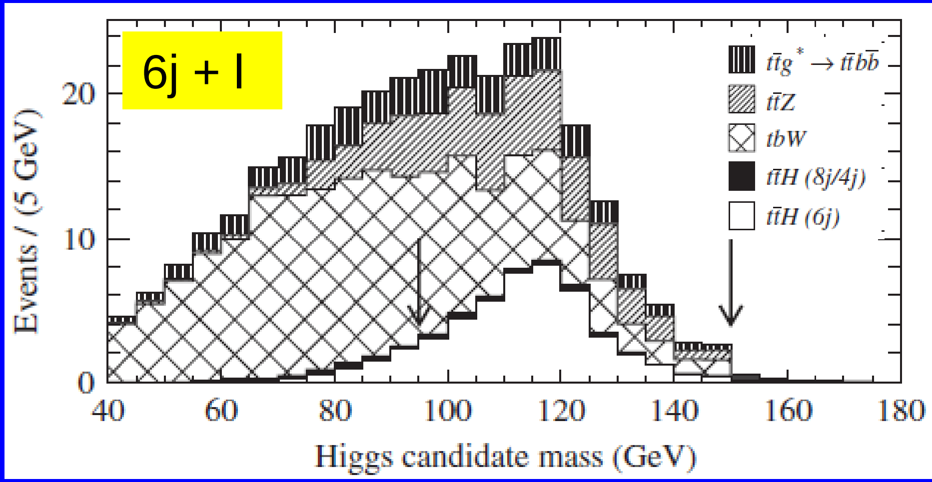


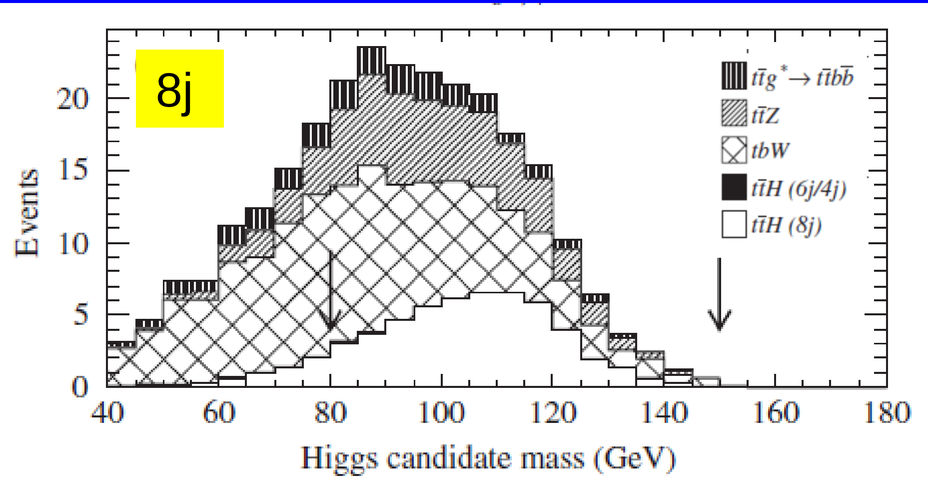


Old studies focused on measurement well above ttH threshold with energy upgraded ILC (800 GeV, 1000 GeV).
Juste (2005) hep-ph/0512246 emphasized the potential already with 500 GeV ILC (threshold enhancement + make more use of polarization)

Top Yukawa Coupling

Studies at √s=500 GeV for ILC
Cut-based. Yonamine et al., PRD84 (2011) 014033.
ttH, H → bb





Almost identical sensitivity in 6j+l and 8j channel.
Expect measurement to be statistics limited with systematics under control.

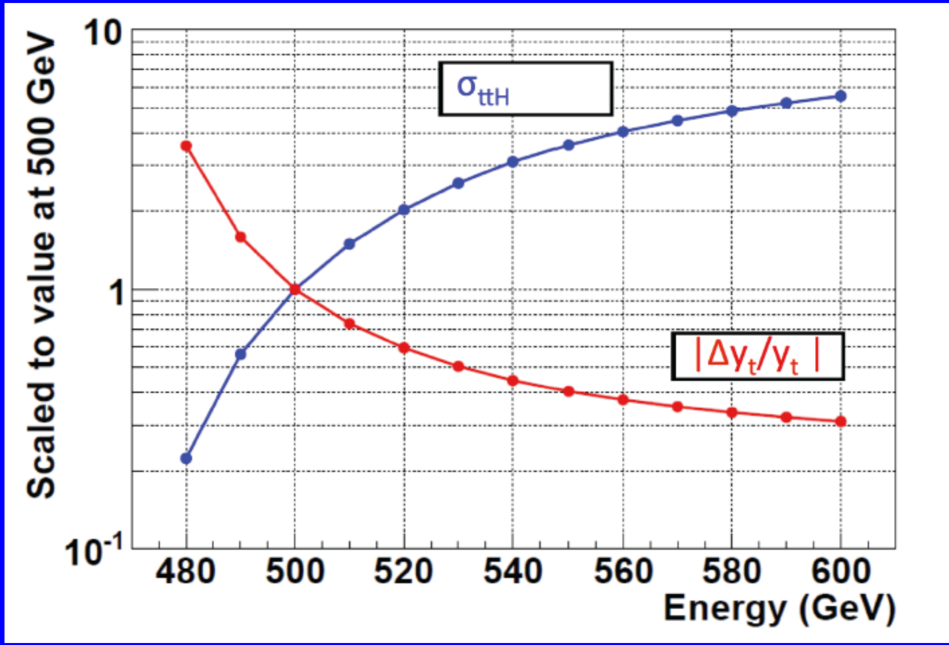
With ILC run plan (arXiv:1506:07830)
projected error on y_t from this initial analysis is 6.3%.

By including other channels (many with much less background), and using more sophisticated analyses, significant improvements expected in eventual sensitivity.

Top Yukawa Coupling

- ttH in e^+e^- collider needs sufficient $\sqrt{s}$
- Near ttH threshold, the cross-section rises steeply, so serious consideration should be given to extending the upper CoM energy reach of the initial machine from 500 GeV to ≈ 550 GeV.
- At 550 GeV, expected error on y_t reduced by factor of 2.5 from 6.3% to 2.5%

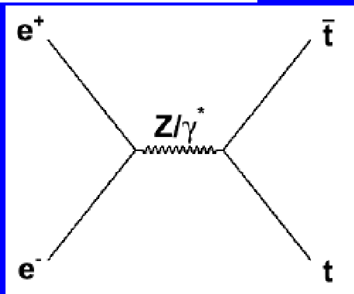
y_t from ttH cross-section



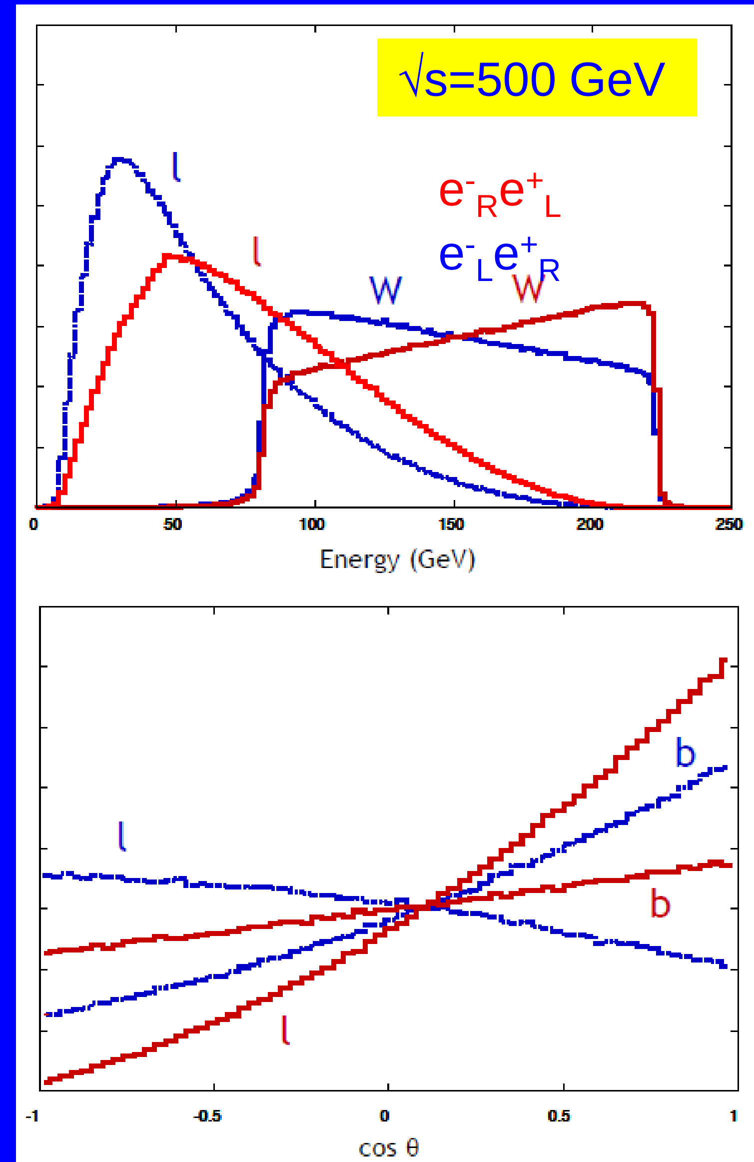
My bottom-line. Expect that the ILC can measure y_t to better than 2.5%.

Top Electroweak Couplings

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



HC production of tt is QCD. ttγ and ttZ can be explored at LHC.



Not much knowledge of the top-quark EW couplings. New physics effects very possible.

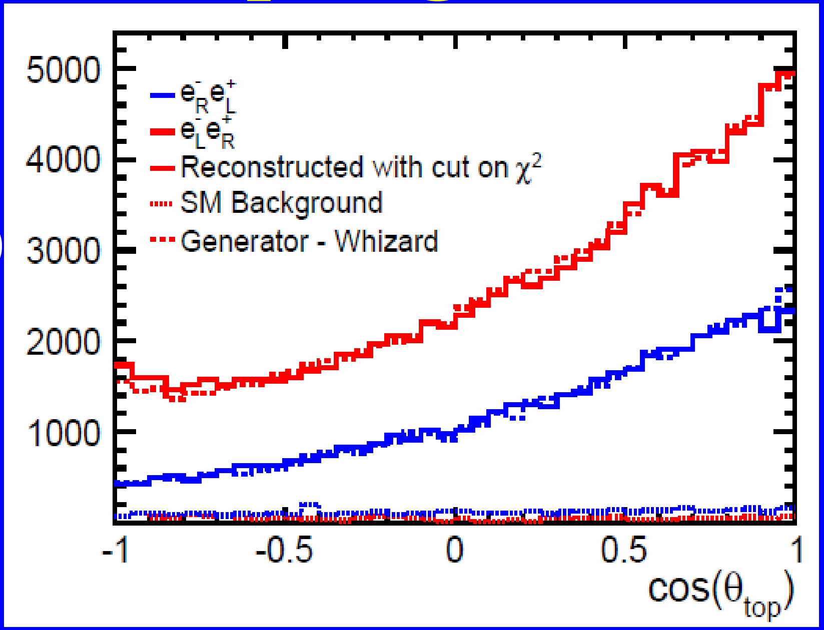
Top production in e^+e^- is an ideal lab for analyzing weak and EM couplings using initial and final state polarization (akin to τ polarization studies)

General Lagrangian has up to 10 form factors, F

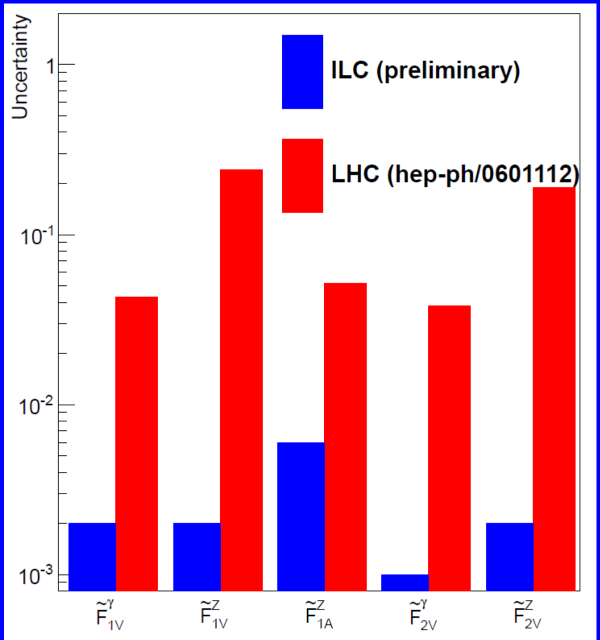
$$\begin{aligned}
\mathcal{M}(e_L\bar{e}_R \to t_L\bar{t}_R)^{\gamma/Z} &= c_L^{\gamma/Z}[F_{1V}^{\gamma/Z} - \beta F_{1A}^{\gamma/Z} + F_{2V}^{\gamma/Z}](1+\cos\theta)e^{-i\phi} \\
\mathcal{M}(e_L\bar{e}_R \to t_R\bar{t}_L)^{\gamma/Z} &= c_L^{\gamma/Z}[F_{1V}^{\gamma/Z} + \beta F_{1A}^{\gamma/Z} + F_{2V}^{\gamma/Z}](1-\cos\theta)e^{-i\phi} \\
\mathcal{M}(e_L\bar{e}_R \to t_L\bar{t}_L)^{\gamma/Z} &= c_L^{\gamma/Z}\gamma^{-1}[F_{1V}^{\gamma/Z} + \gamma^2(F_{2V}^{\gamma/Z} + \beta F_{2A}^{\gamma/Z})]\sin\theta e^{-i\phi} \\
\mathcal{M}(e_L\bar{e}_R \to t_R\bar{t}_R)^{\gamma/Z} &= c_L^{\gamma/Z}\gamma^{-1}[F_{1V}^{\gamma/Z} + \gamma^2(F_{2V}^{\gamma/Z} - \beta F_{2A}^{\gamma/Z})]\sin\theta e^{-i\phi} \\
\mathcal{M}(e_R\bar{e}_L \to t_L\bar{t}_R)^{\gamma/Z} &= -c_R^{\gamma/Z}[F_{1V}^{\gamma/Z} - \beta F_{1A}^{\gamma/Z} + F_{2V}^{\gamma/Z}](1-\cos\theta)e^{i\phi} \\
\mathcal{M}(e_R\bar{e}_L \to t_R\bar{t}_L)^{\gamma/Z} &= -c_R^{\gamma/Z}[F_{1V}^{\gamma/Z} + \beta F_{1A}^{\gamma/Z} + F_{2V}^{\gamma/Z}](1+\cos\theta)e^{i\phi} \\
\mathcal{M}(e_R\bar{e}_L \to t_L\bar{t}_L)^{\gamma/Z} &= c_R^{\gamma/Z}\gamma^{-1}[F_{1V}^{\gamma/Z} + \gamma^2(F_{2V}^{\gamma/Z} + \beta F_{2A}^{\gamma/Z})]\sin\theta e^{i\phi} \\
\mathcal{M}(e_R\bar{e}_L \to t_R\bar{t}_R)^{\gamma/Z} &= c_R^{\gamma/Z}\gamma^{-1}[F_{1V}^{\gamma/Z} + \gamma^2(F_{2V}^{\gamma/Z} - \beta F_{2A}^{\gamma/Z})]\sin\theta e^{i\phi}
\end{aligned}$$

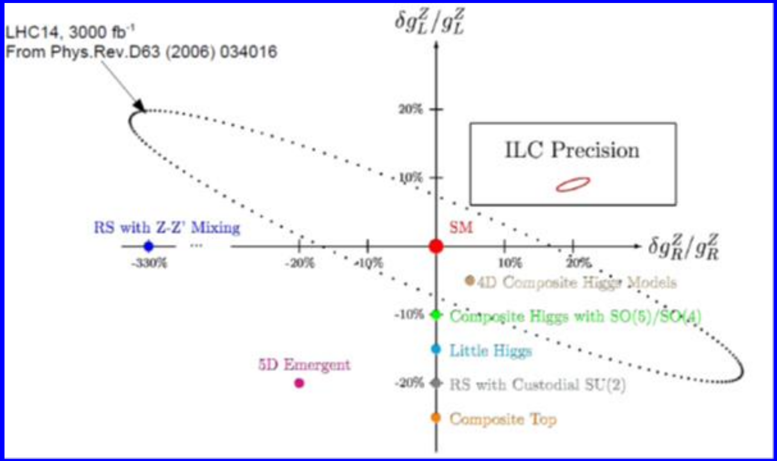
Top Electroweak Couplings

Fast evolving field.
Several recent studies.
Examples:
Amjad et al, arXiv:1307.8102 (σ, A_{FB}, helicity angle (lepton in t RF) with 2 beam polarizations)
Khiem et al, arXiv:1503.04247 (Full reconstruction + ME analysis proof of principle)
Janot, arXiv:1503.01325 (x, cosθ)



Possibilities to do complete kinematic reconstruction of events.





Bottom-line: An e^+e^- collider is the appropriate tool for bringing Z-like understanding to top physics.

New Physics Associated with the Top Quark

- You may have the impression that the absence of discoveries besides the Higgs at the LHC do not augur well for an e^+e^- collider at modest $\sqrt{s}$.
  - The LHC strong suit is strongly interacting particles.
  - But even for the stop, the most restrictive and easy to interpret limits are still from LEP.

$\tilde{t}$ — scalar top (stop) PDG

Mass $m > 95.7$ GeV, CL = 95% LEP

$[\tilde{t} \to c\tilde{\chi}_1^0,\ m_{\tilde{t}} - m_{\tilde{\chi}_1^0} > 10$ GeV, all $\theta_t]$

Mass $m > 650$ GeV, CL = 95% LHC

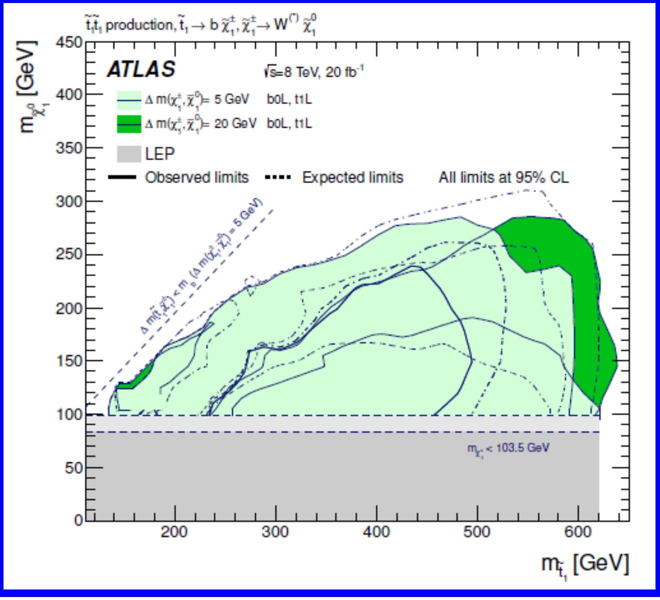
$[1\ \ell^{\pm} + \text{jets} + \not{E}_T,\ \tilde{t} \to t\tilde{\chi}_1^0$ simplified model, $m_{\tilde{\chi}_1^0}$=0 GeV$]$

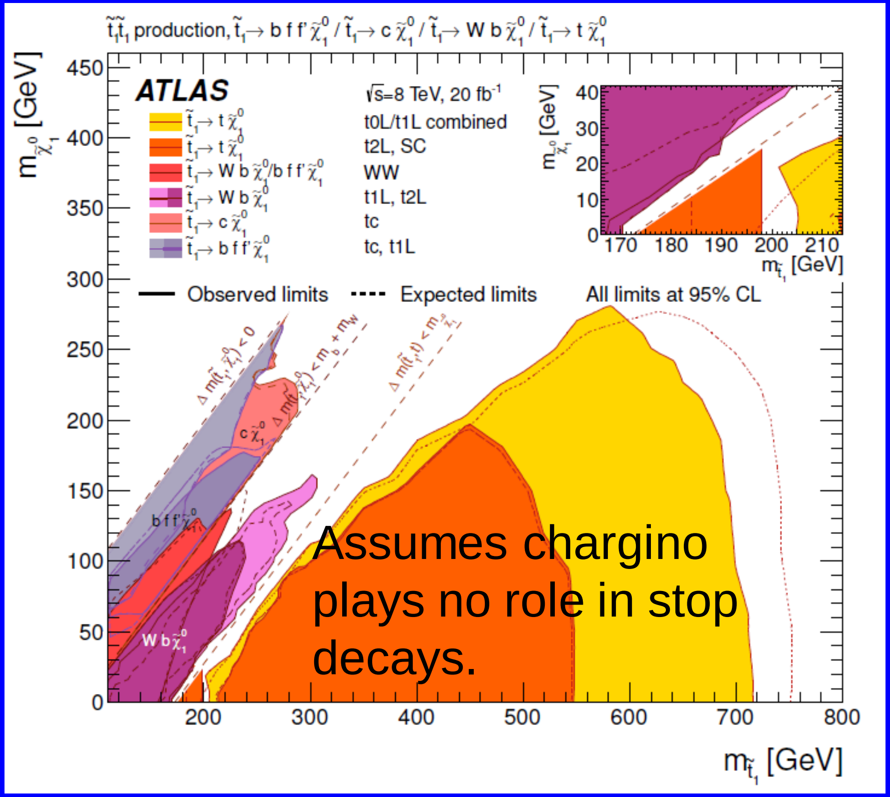
Mass $m_{\tilde{\chi}_1^0} > 46$ GeV, CL = 95% LEP

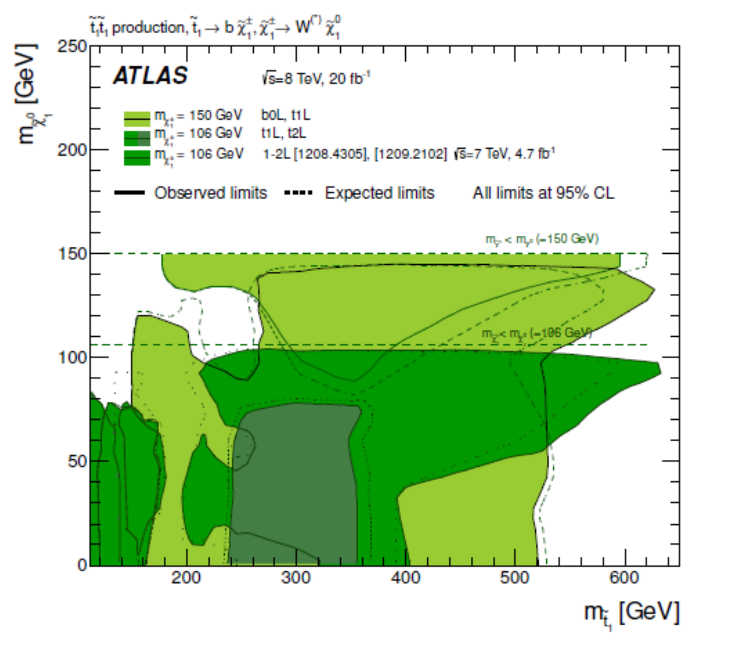
$[$all $\tan\beta$, all m_0, all $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}]$

LHC limits on stop

- Impressive – many specific possibilities are indeed excluded - but need legal counsel to understand the fine print.
- My conclusion – most restrictive stop mass lower limit still from LEP.
- Stop could be as light as 110 GeV

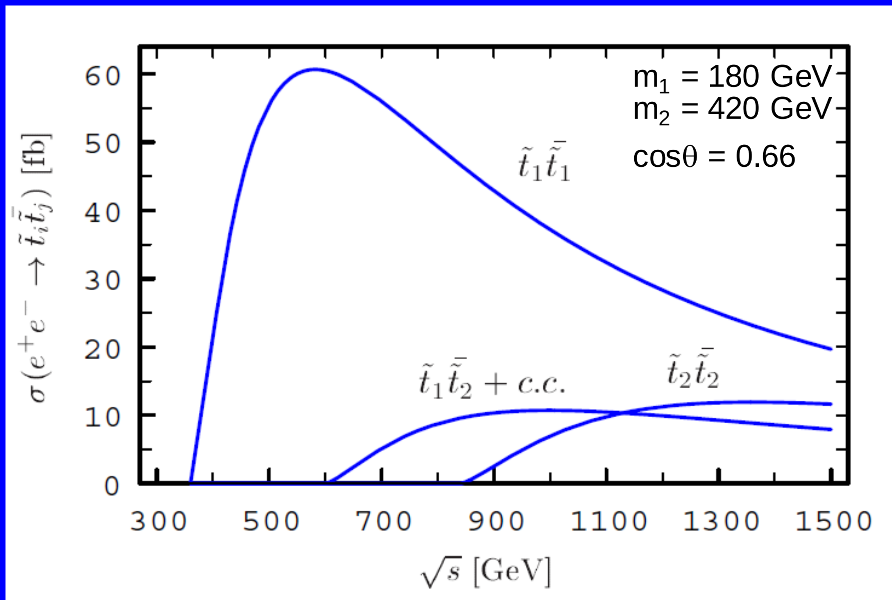




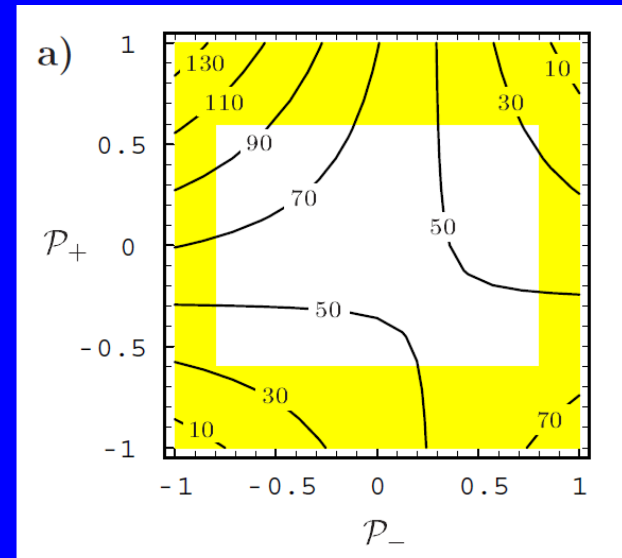


Stop at ILC

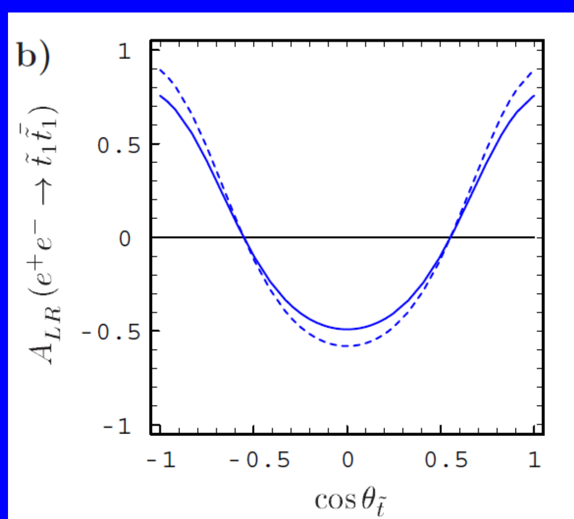
$\tilde{t}_1 = \tilde{t}_L \cos\theta_{\tilde{t}} + \tilde{t}_R \sin\theta_{\tilde{t}}$ $\tilde{t}_2 = \tilde{t}_R \cos\theta_{\tilde{t}} - \tilde{t}_L \sin\theta_{\tilde{t}}$

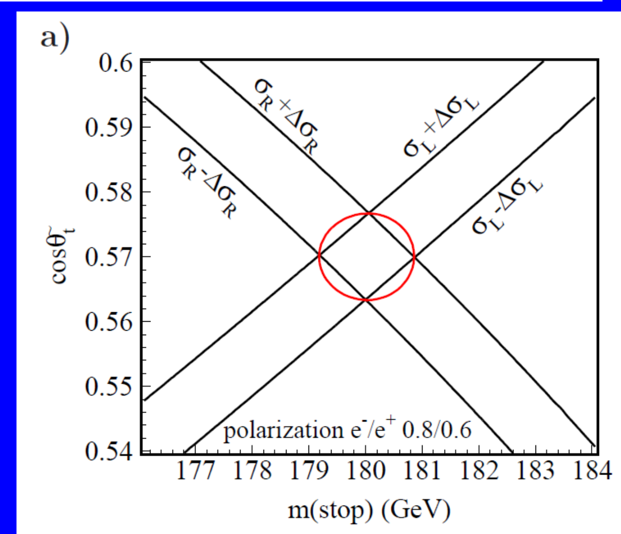


σ(fb) for t_1t_1 at √s=500 GeV



$$A_{LR} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$





Polarized beams allow measurement of the mixing angle, and can obtain $m(t_2)$.

Closing Remarks

- e^+e^- collisions are unique (very different from LHC)
- An e^+e^- collider like ILC will offer a new precision probe of top quark physics that can revolutionize our understanding of the heaviest quark
  - m_t to better than 50 MeV in the unique laboratory of the threshold
  - Yukawa coupling to 2.5%
  - Some windows to direct new physics: stop, FCNC.
  - Measurements of top electroweak couplings to the <1% level
  - Constraints on many models of new physics associated with the top
- ILC opportunity – carpe diem

Backup Slides

Other lepton collider ideas

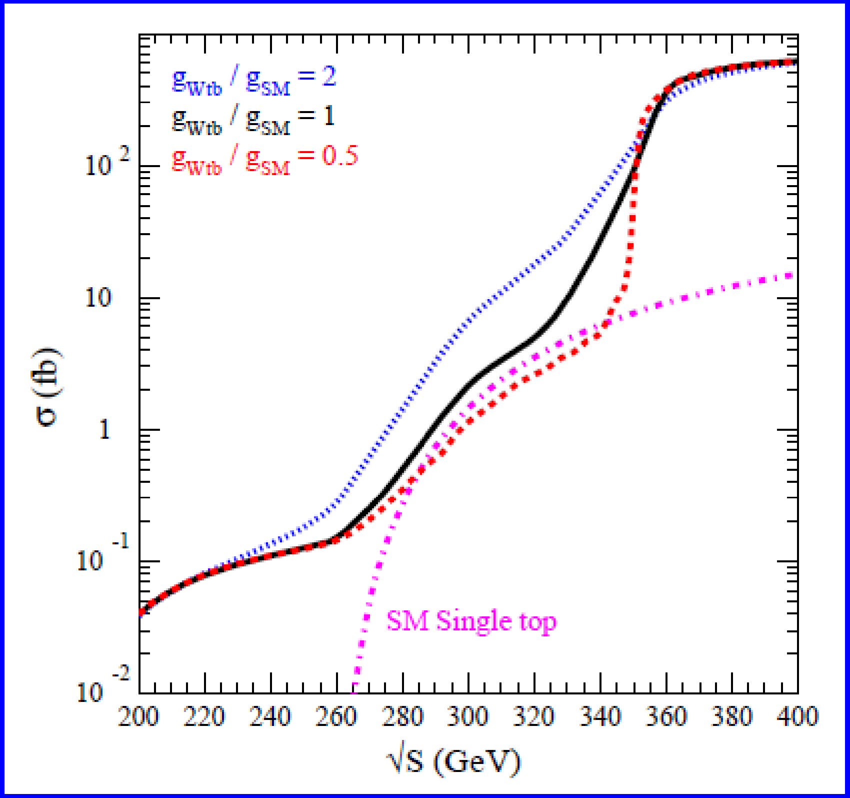
- CLIC
- FCC-ee
- CEPC
- Muon-Collider

I did not include much discussion of these other possibilities as none of them are competitive with ILC in time-scales, physics reach and technology maturity.

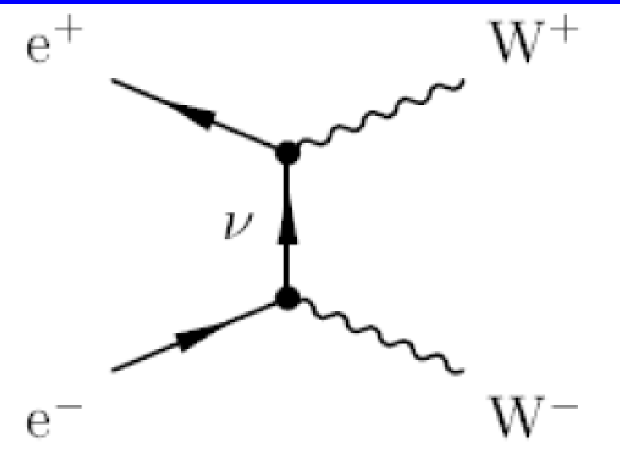
From the top physics perspective, CLIC, is also of some interest.

Wtb coupling study

- Batra and Tait



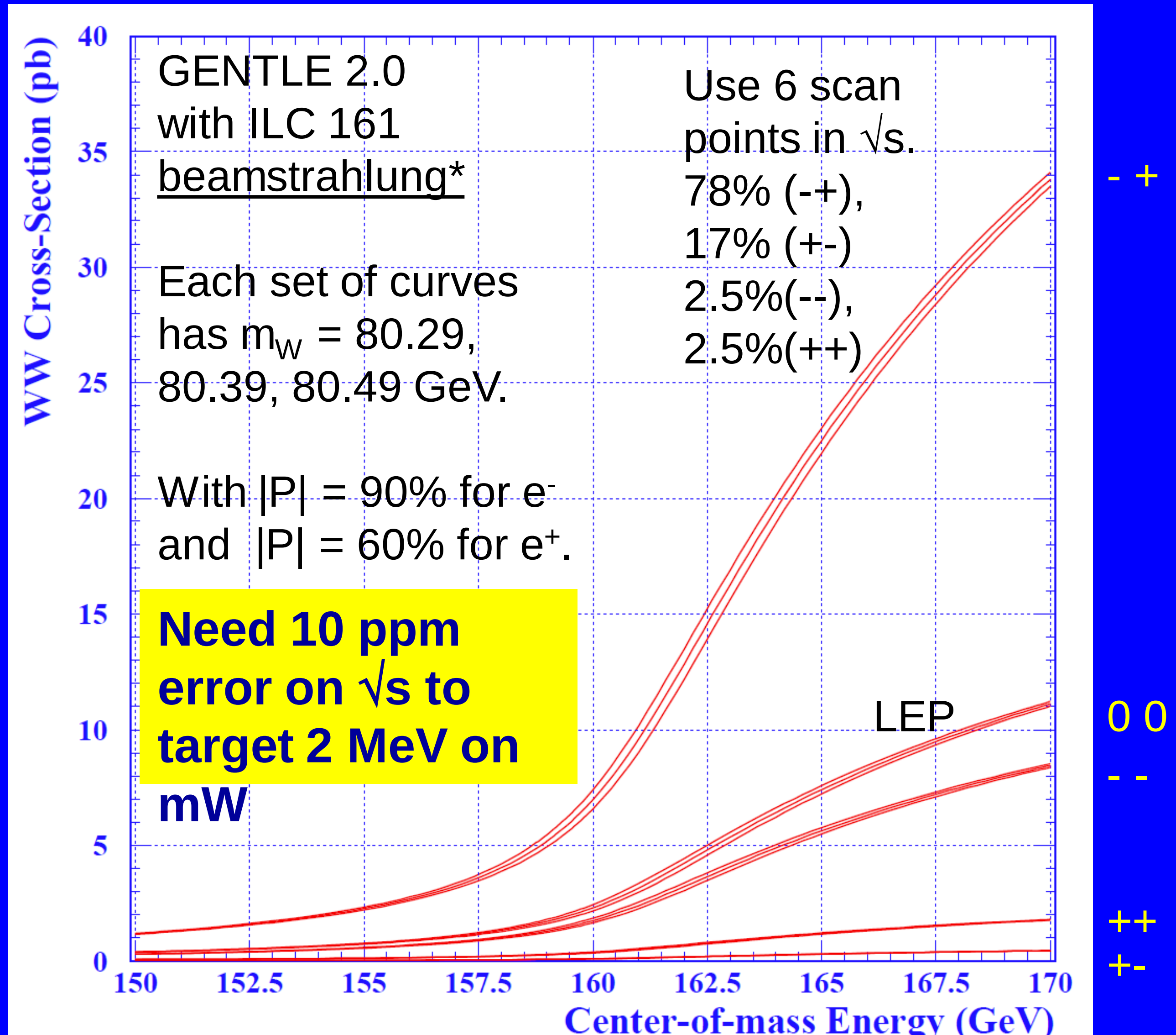
ILC Polarized Threshold Scan



Use (-+) helicity combination of e$^-$ and e$^+$ to enhance WW.

Use (+-) helicity to suppress WW and measure background.

Use (--) and (++) to control polarization (also use 150 pb qq events)



Experimentally very robust. Fit for eff, pol, bkg, lumi

m_W Prospects

1. Polarized Threshold Scan
2. Kinematic Reconstruction
3. Hadronic Mass

Method 1: Statistics limited.

Method 2: With up to 1000 the LEP statistics and much better detectors. Can target factor of 10 reduction in systematics.

Method 3: Depends on di-jet mass scale. Plenty Z's for 3 MeV.

1

ΔM_W [MeV]	LEP2	ILC	ILC
$\sqrt{s}$ [GeV]	161	161	161
$\mathcal{L}$ [fb^{-1}]	0.040	100	480
$P(e^-)$ [%]	0	90	90
$P(e^+)$ [%]	0	60	60
statistics	200	2.4	1.1
background		2.0	0.9
efficiency		1.2	0.9
luminosity		1.8	1.2
polarization		0.9	0.4
systematics	70	3.0	1.6
experimental total	210	3.9	1.9
beam energy	13	0.8	0.8
theory	-	(1.0)	(1.0)
total	210	4.0	2.1

2

ΔM_W [MeV]	LEP2	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	172-209	250	350	500
$\mathcal{L}$ [fb^{-1}]	3.0	500	350	1000
$P(e^-)$ [%]	0	80	80	80
$P(e^+)$ [%]	0	30	30	30
beam energy	9	0.8	1.1	1.6
luminosity spectrum	N/A	1.0	1.4	2.0
hadronization	13	1.3	1.3	1.3
radiative corrections	8	1.2	1.5	1.8
detector effects	10	1.0	1.0	1.0
other systematics	3	0.3	0.3	0.3
total systematics	21	2.4	2.9	3.5
statistical	30	1.5	2.1	1.8
total	36	2.8	3.6	3.9

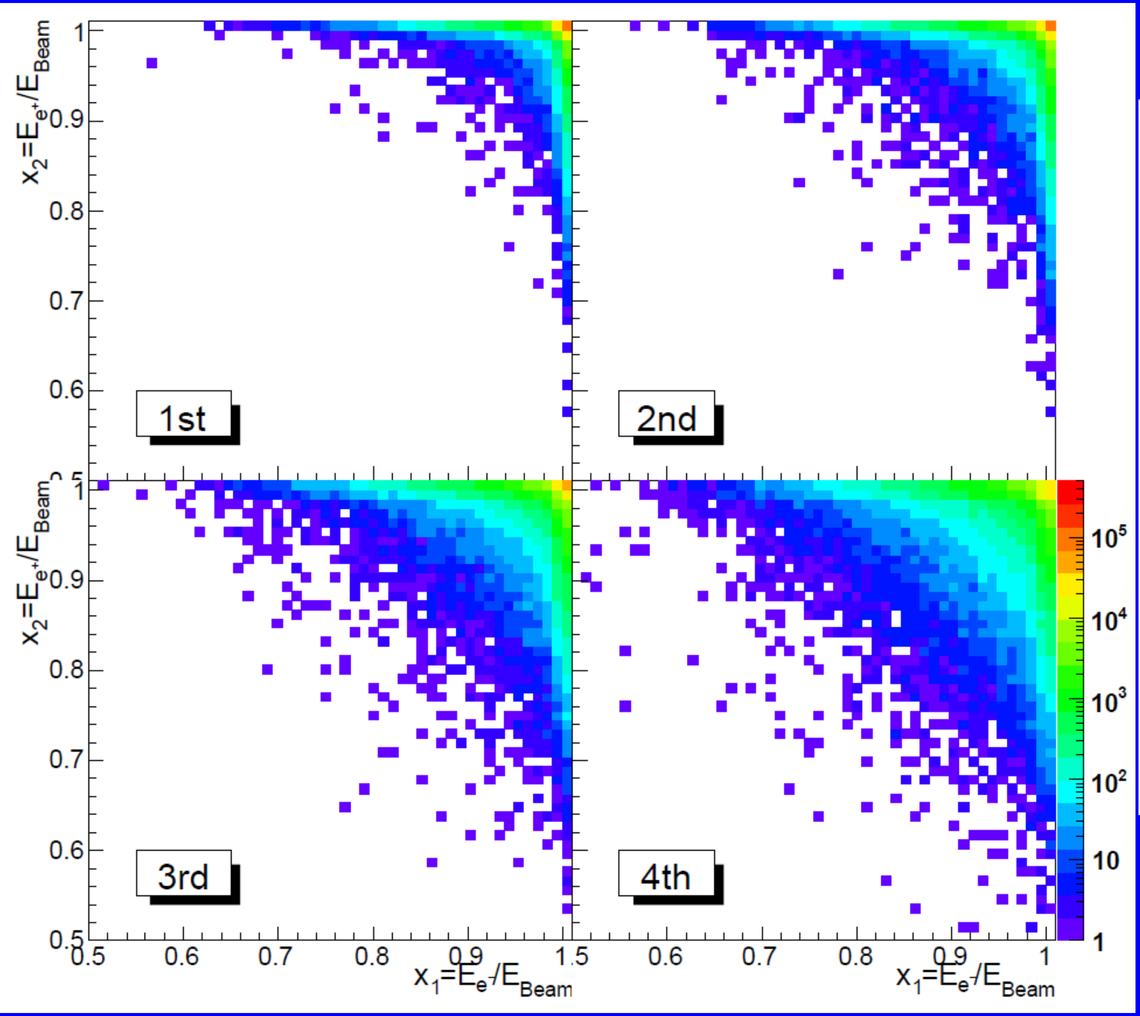
3

ΔM_W [MeV]	ILC	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	250	350	500	1000
$\mathcal{L}$ [fb^{-1}]	500	350	1000	2000
$P(e^-)$ [%]	80	80	80	80
$P(e^+)$ [%]	30	30	30	30
jet energy scale	3.0	3.0	3.0	3.0
hadronization	1.5	1.5	1.5	1.5
pileup	0.5	0.7	1.0	2.0
total systematics	3.4	3.4	3.5	3.9
statistical	1.5	1.5	1.0	0.5
total	3.7	3.7	3.6	3.9

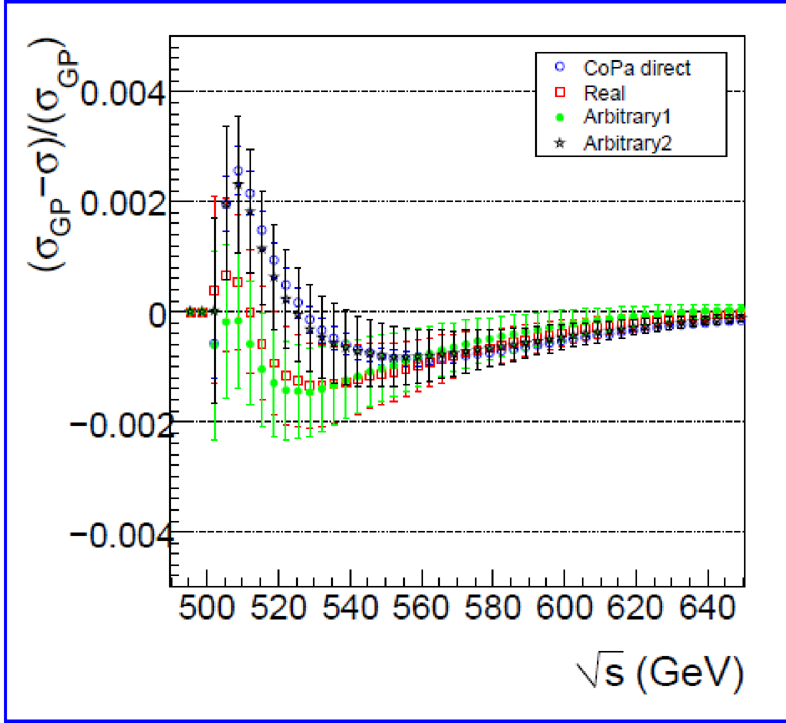
See attached document for more detailed discussion

Luminosity Spectrum Measurement

Use Bhabhas



See A. Sailer DESY Thesis-09-011



Expect that the differential luminosity will be controlled at or better than 0.2%.