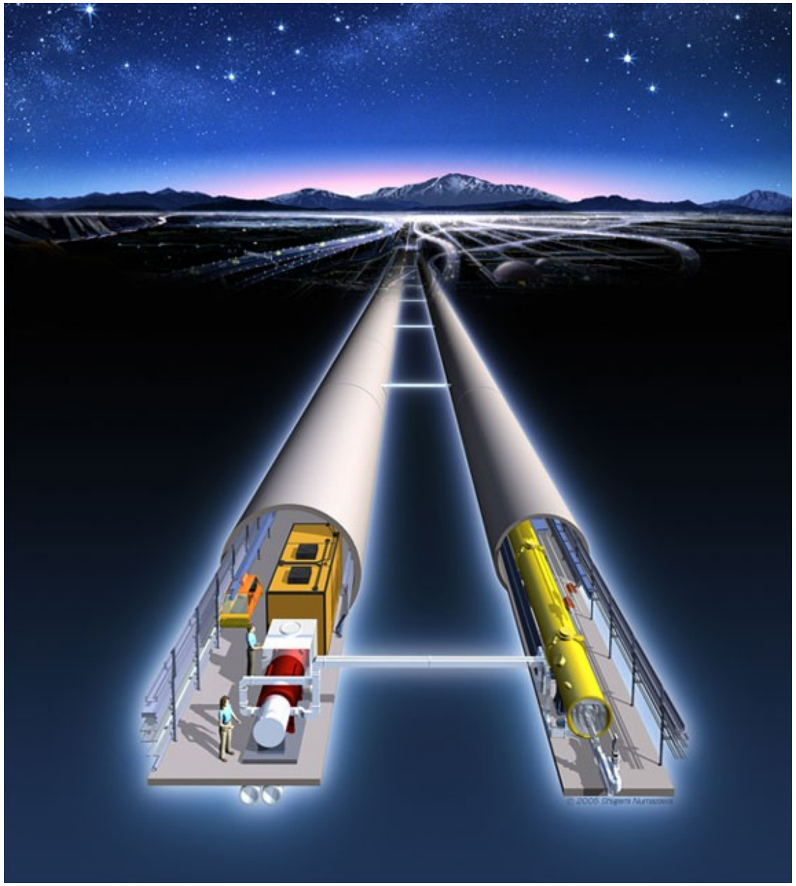
Top quark physics
at
Linear Colliders



Roman Pöschl

On behalf of ...
... Many people contributing to top physics at the LC
... the LC Collaboration

Séminaire LPNHE – July 2015

Message

THERE ARE THINGS KNOWN AND THINGS UNKNOWN AND IN BETWEEN ~~ARE THE DOORS.~~
.. is the top quark
Jim Morrison
American singer-songwriter
QuoteHD.com
(1943-1971)

Outline on talk

- Chapter 1: Introduction
- Chapter 2: Top physics at threshold
- Chapter 3: Top physics in continuum
- Chapter 4: Trends

Latest reference documents:

arxiv:1506.05992 – ILC Physics case (ILC Physics working group)
arxiv: 1506.07830 – Running scenarios (ILC Parameter group)

1. Introduction

What do we know about the top quark

- The top quark is the heaviest known elementary particle
  Discovery in 1995 at Tevatron

- m_t ~ 173 GeV (~m of Gold atom)

- Electrical charge $Q_t = 2/3$

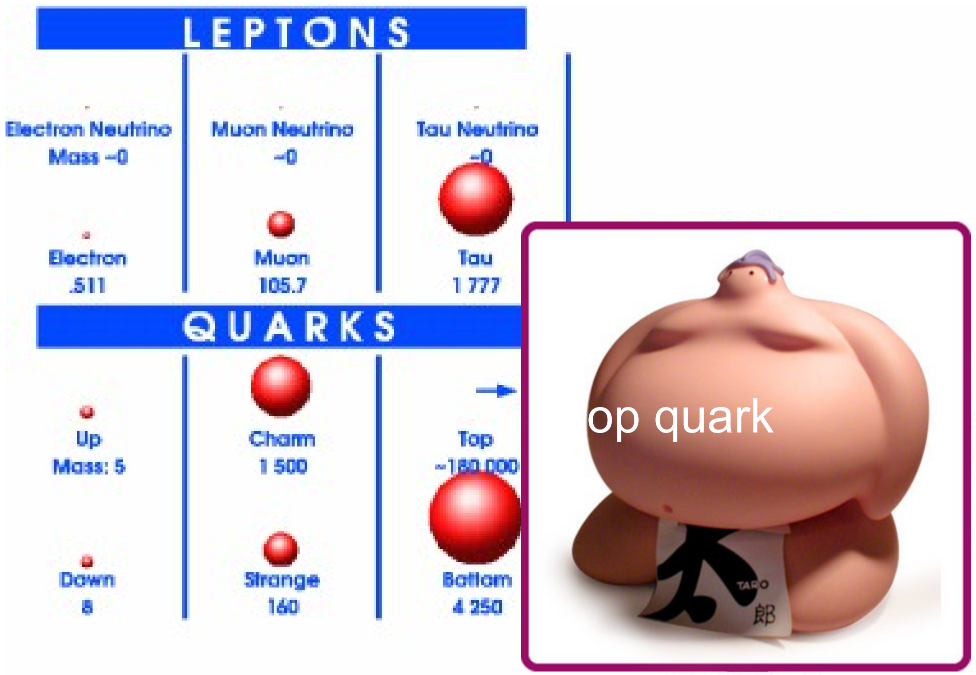
- Spin ½ => fermion

- Lifetime τ ~ $5x10^{-25}$s (SM decays)

- Total width Γ_t ~ 1.5 GeV

- No hadronisation, behaves like a free quark

- Predominant decays
  $t \rightarrow$ Wb (BR~100%)

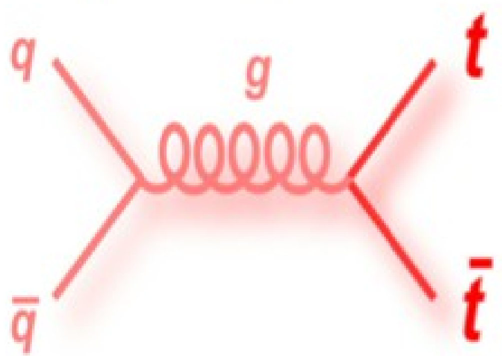


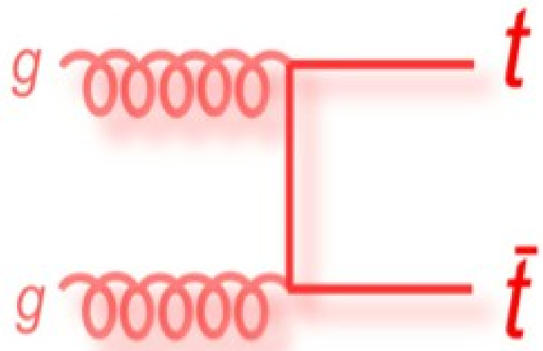
Ideal object for a machine in Japan ;-)

Slide inspired by Lecture of Prof. K. Jakobs,Uni Freiburg

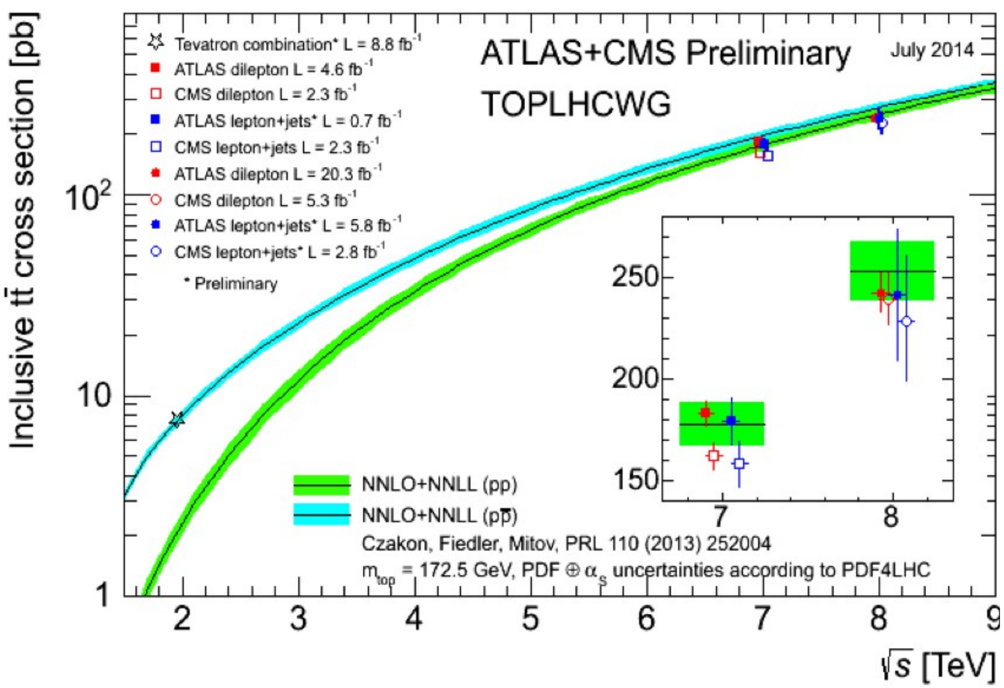
Top quark production at hadron colliders

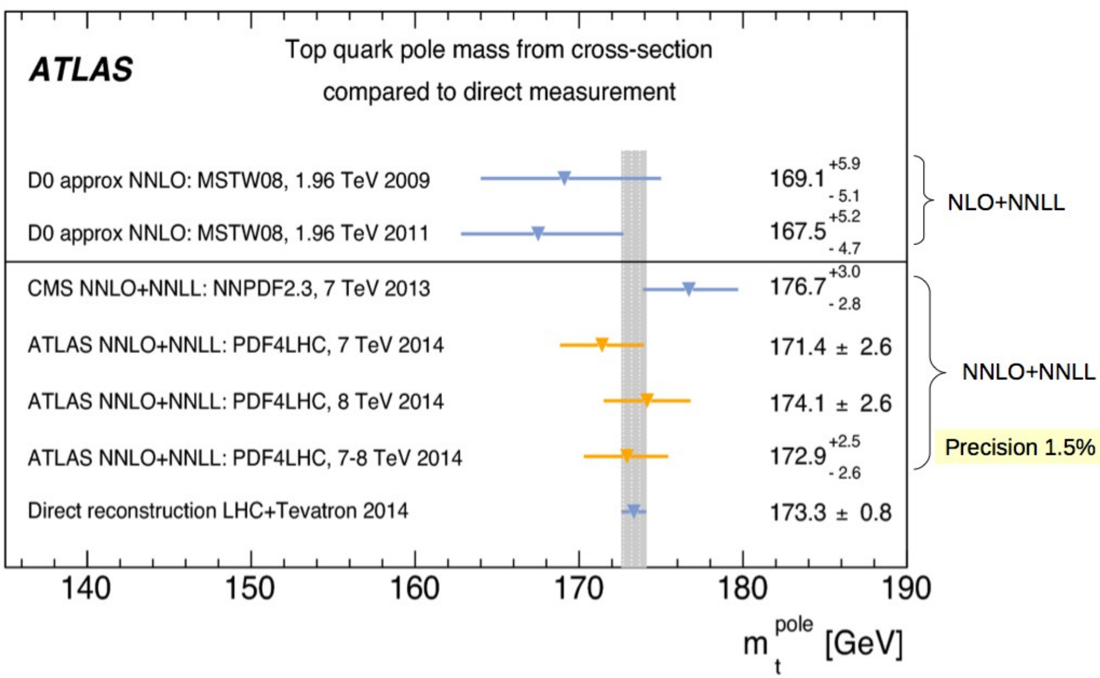
Example diagrams:



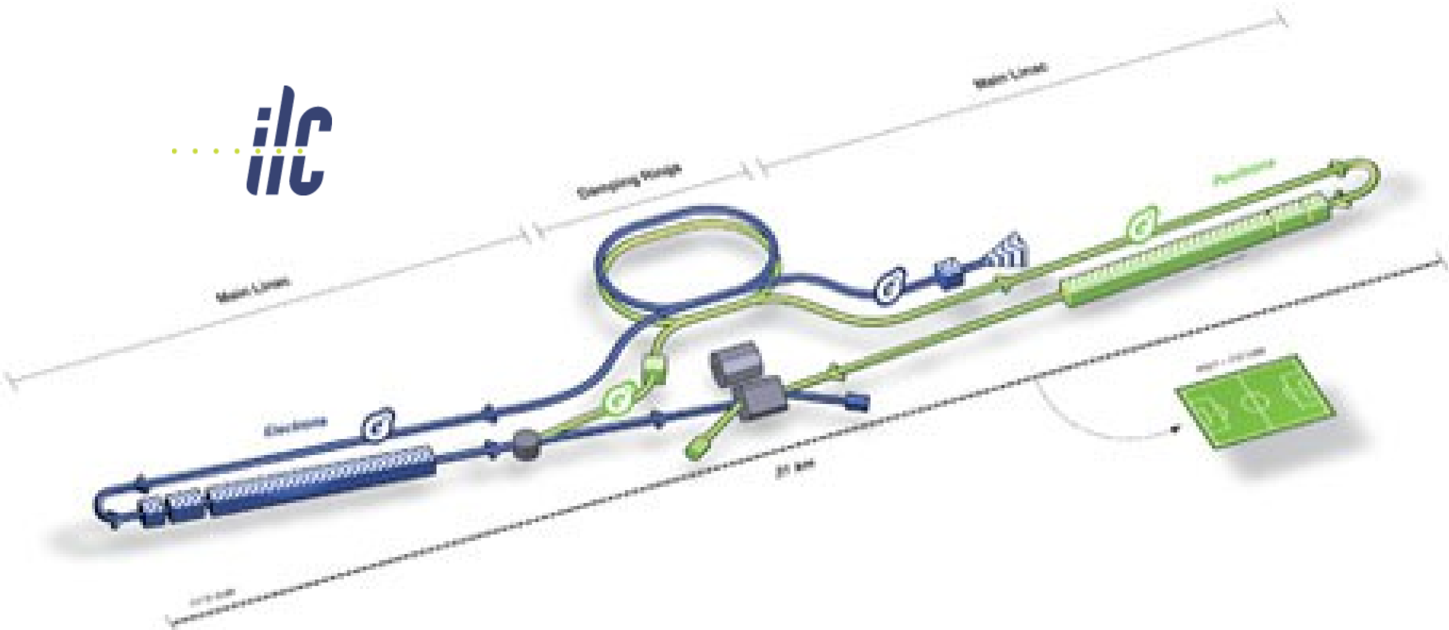


	σ_{gg}/σ_{tot}
Tevatron	$\approx 15\%$
LHC 7 TeV	$\approx 85\%$
LHC 14 TeV	$\approx 90\%$

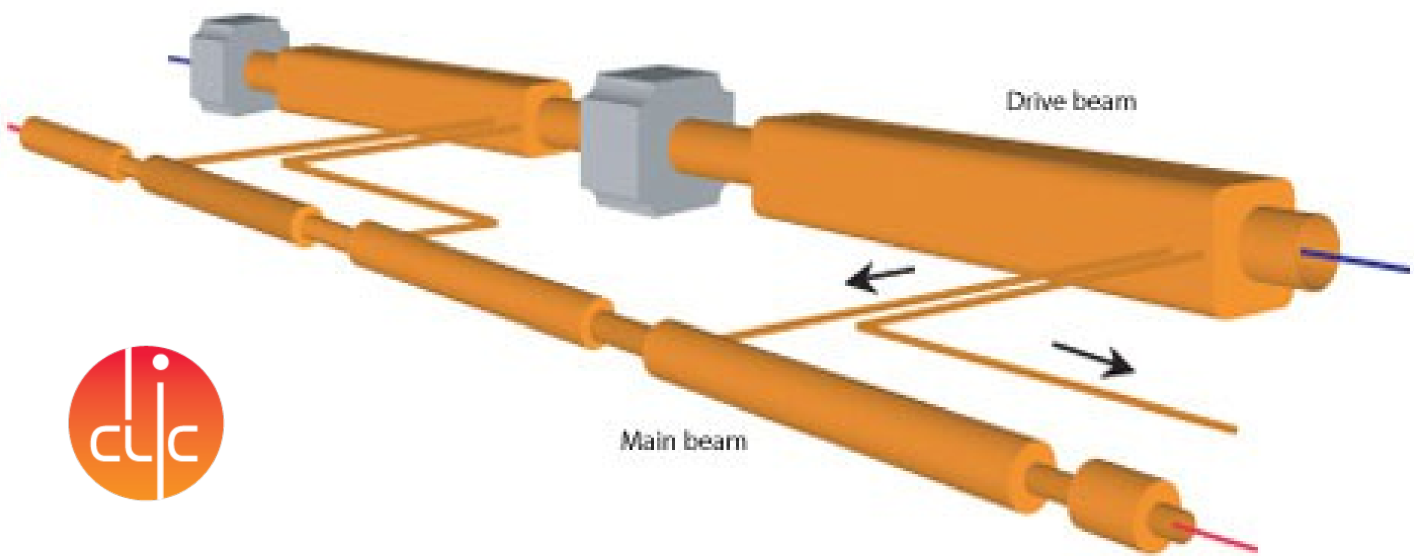




=> High time to see them at lepton colliders!



Energy: 0.1 - 1 TeV
Electron (and positron) polarisation
TDR in 2013
+ DBD for detectors
Footprint 31 km



Energy: 0.5 - 3 TeV

CDR in 2012

Footprint 48km

Detector requirements

Track momentum: $\sigma_{1/p} < 5 \times 10^{-5}$/GeV (1/10 x LEP)

(e.g. Measurement of Z boson mass in Higgs Recoil)

Impact parameter: $\sigma_{d0} < [5 \oplus 10/(p[\mathrm{GeV}]\sin^{3/2}\theta)]$ μm(1/3 x SLD)

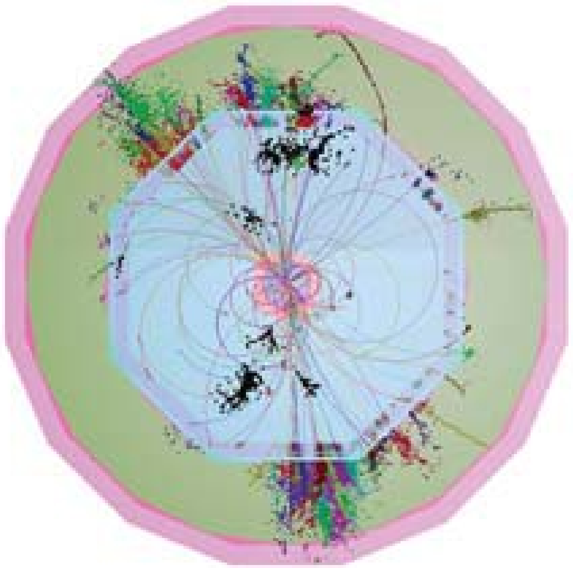
(Quark tagging c/b)

Jet energy resolution : $dE/E = 0.3/(E(\mathrm{GeV}))^{1/2}$ (1/2 x LEP)

(W/Z masses with jets)

Hermeticity : θ_{min} = 5 mrad

(for events with missing energy e.g. SUSY)



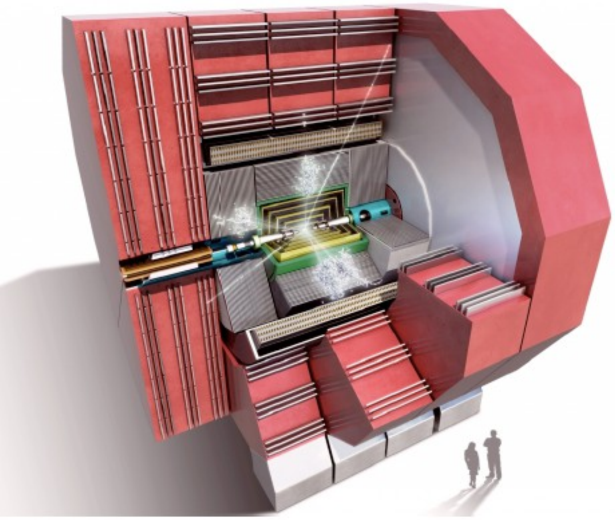
Final state will comprise events with a large number of charged tracks and jets(6+)

- High granularity
- Excellent momentum measurement
- High separation power for particles

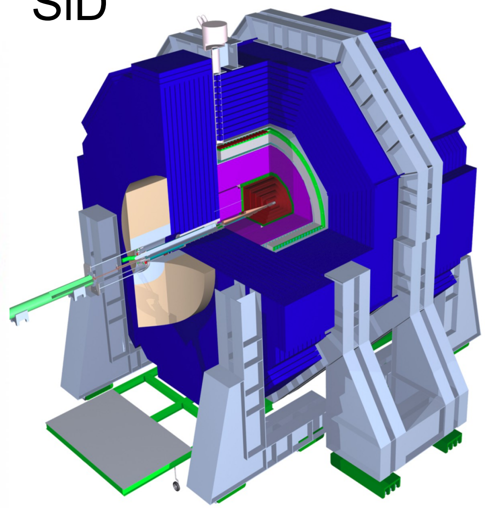
- Particle Flow Detectors

Detector concepts

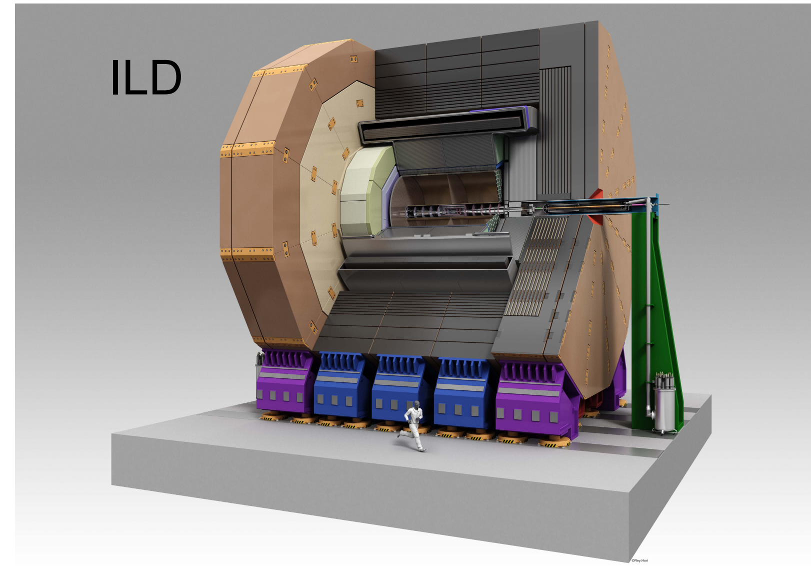
CLIC Detector



SiD



ILD



Highly granular calorimeters

Central tracking with silicon

Inner tracking with silicon

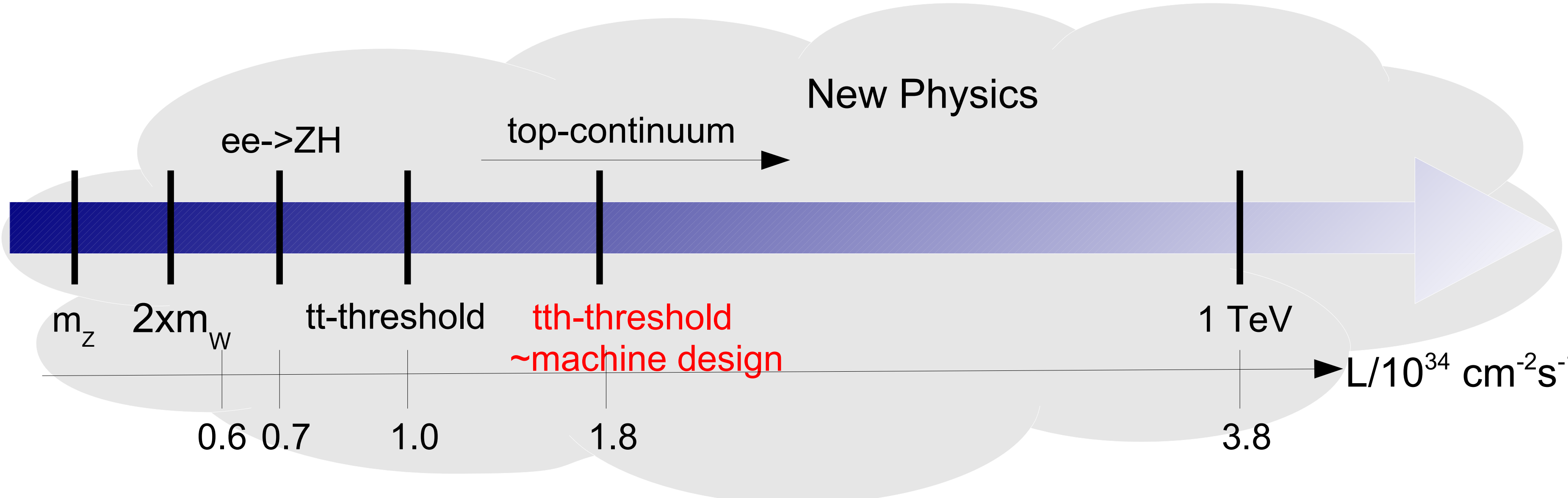
Central tracking with TPC

- CDR 2012
  Revised since

- LOI's Validated by IDAG in 2009
- Publication of **D**etector **B**aseline **D**esign in 2013, together with TDR

Concepts based on input from physics studies and detector R&D organised in R&D collaborations

ILC Physics program

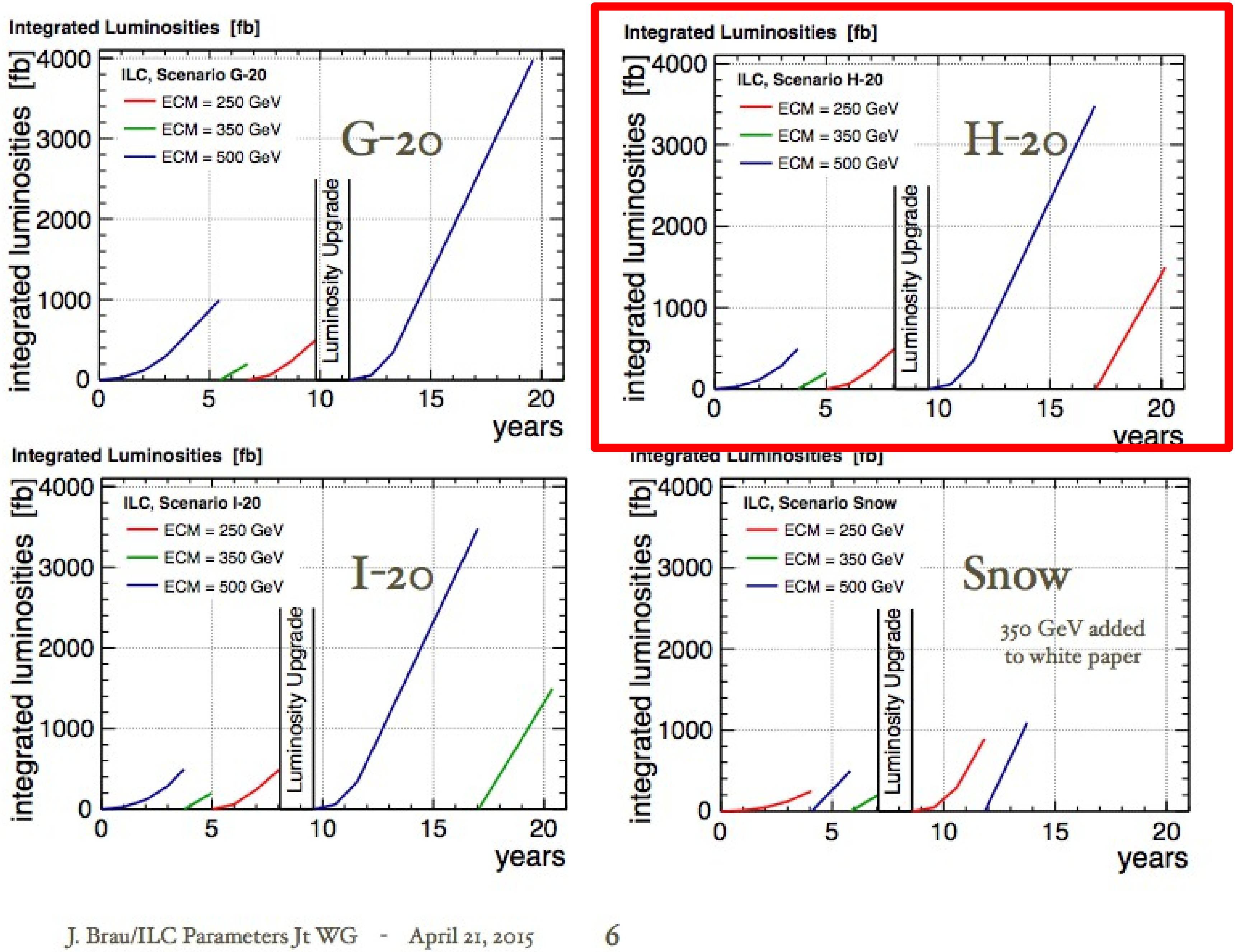


- All Standard Model particles within reach of ILC
  - High precision tests of Standard Model over wide range to detect onset of New Physics
- Machine settings can be “tailored” for specific processes
  - Centre-of-Mass energy
  - Beam polarisation

$$\sigma_{P,P'} = \frac{1}{4}\left[(1 - PP')(\sigma_{LR} + \sigma_{RL}) + (P - P')(\sigma_{RL} - \sigma_{LR})\right]$$

- “Background free” searches for BSM through beam polarisation

ILC Physics program – Running scenarios



ILC Physics program – Running scenarios

	Stage	500			500 LumiUP		
Scenario	$\sqrt{s}$ [GeV]	500	350	250	500	350	250
G-20	$\int \mathcal{L} dt$ [fb^{-1}]	1000	200	500	4000	-	-
	time [years]	5.5	1.3	3.1	8.3	-	-
H-20	$\int \mathcal{L} dt$ [fb^{-1}]	500	200	500	3500	-	1500
	time [years]	3.7	1.3	3.1	7.5	-	3.1
I-20	$\int \mathcal{L} dt$ [fb^{-1}]	500	200	500	3500	1500	-
	time [years]	3.7	1.3	3.1	7.5	3.4	-

	Stage	500			500 LumiUP		
Scenario	$\sqrt{s}$ [GeV]	250	500	350	250	350	500
Snow	$\int \mathcal{L} dt$ [fb^{-1}]	250	500	200	900	-	1100
	time [years]	4.1	1.8	1.3	3.3	-	1.9

For details see: **arxiv: 1506.07830**

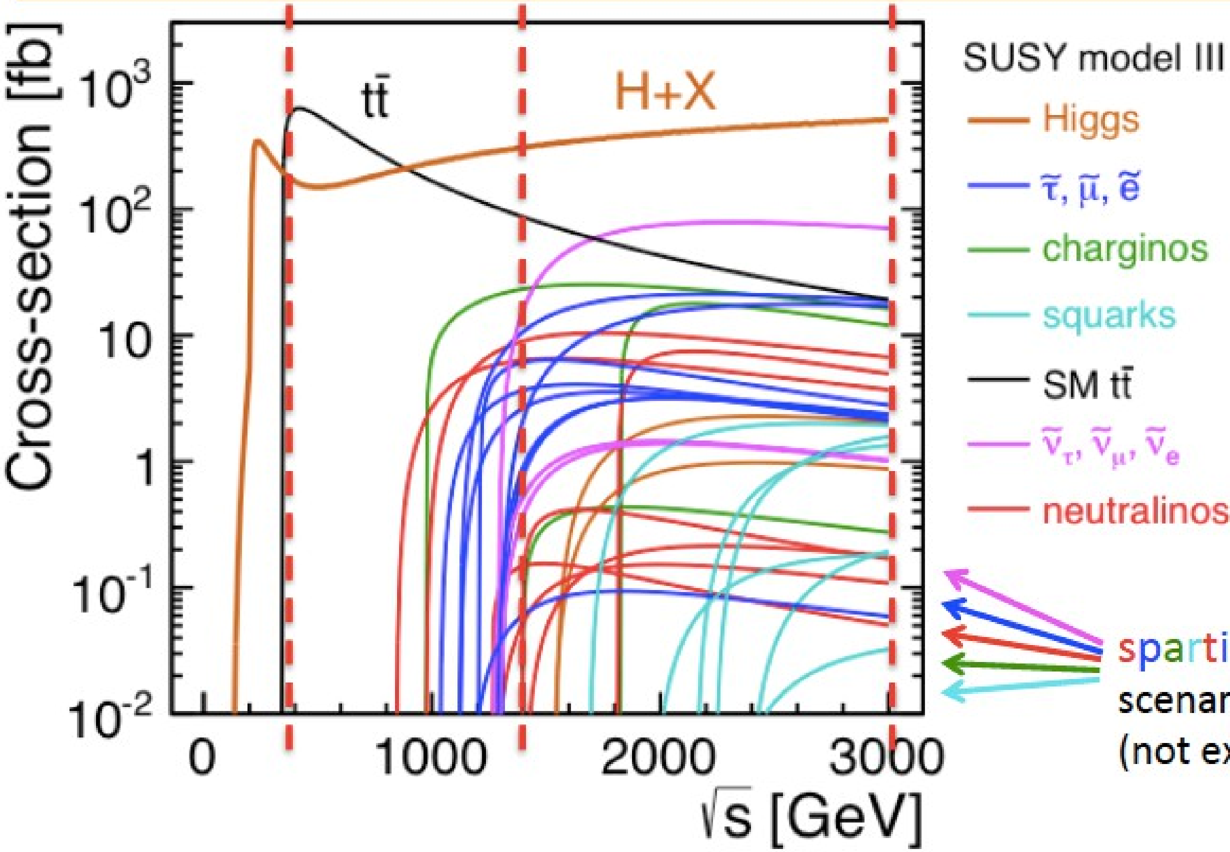
ILC Physics programme privileges early running at 500 GeV
Motivated (among others) by rich top physics programme

CLIC – Staged approach

CLIC: e^+e^- collider, staged approach

- **~380 GeV**, 500 fb^{-1} : precision Higgs and top physics
- **~1.4 TeV**, 1.5 ab^{-1} : targeted at BSM physics, precision Higgs, top
- **~ 3 TeV**, 2 ab^{-1} : targeted at BSM physics, precision Higgs

Exact energies of TeV stages will depend on LHC results

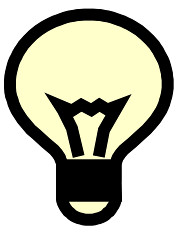


Example of energy staging

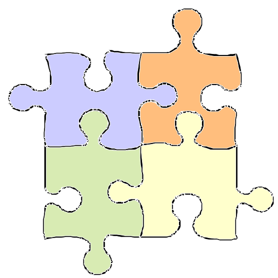
(with an example SUSY model)

sparticles in **SUSY** example scenario
(not excluded by LHC results)

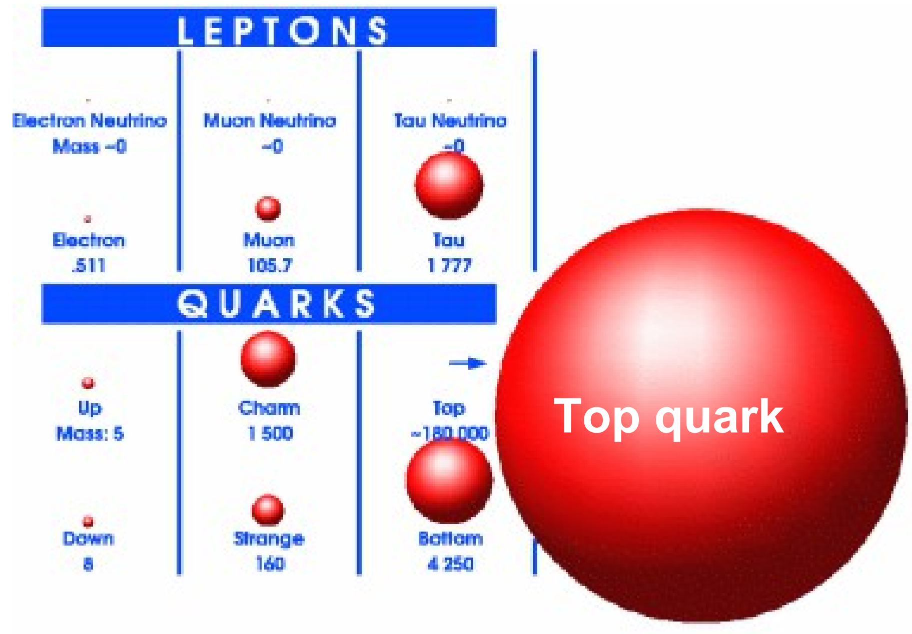
An enigmatic couple



Elementary Scalar?



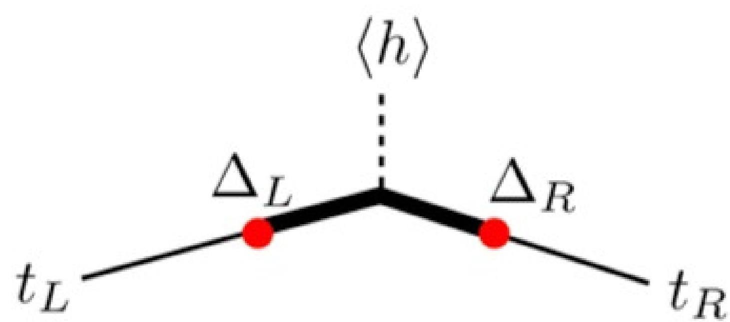
Composite object?



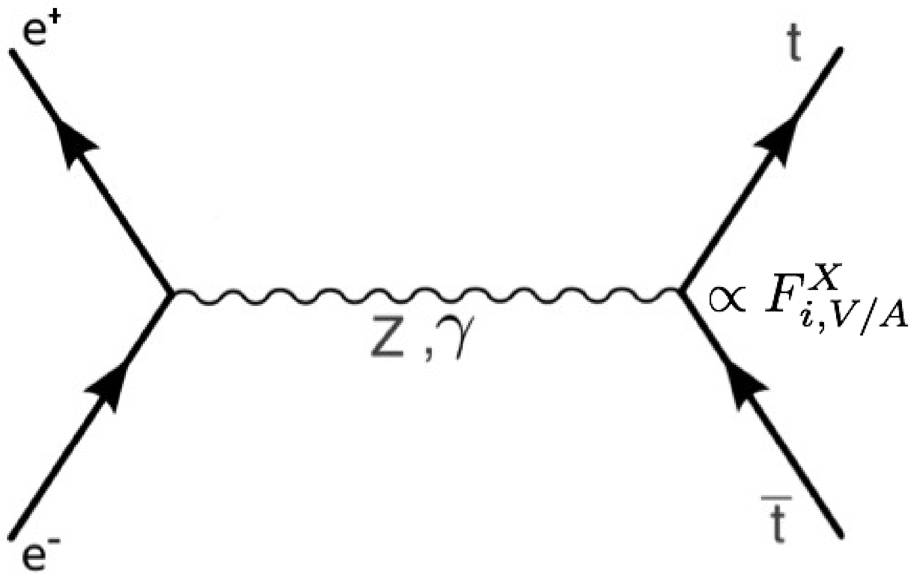
- Higgs and top quark are intimately coupled!
  Top Yukawa coupling O(1) !
  => Top mass important SM Parameter

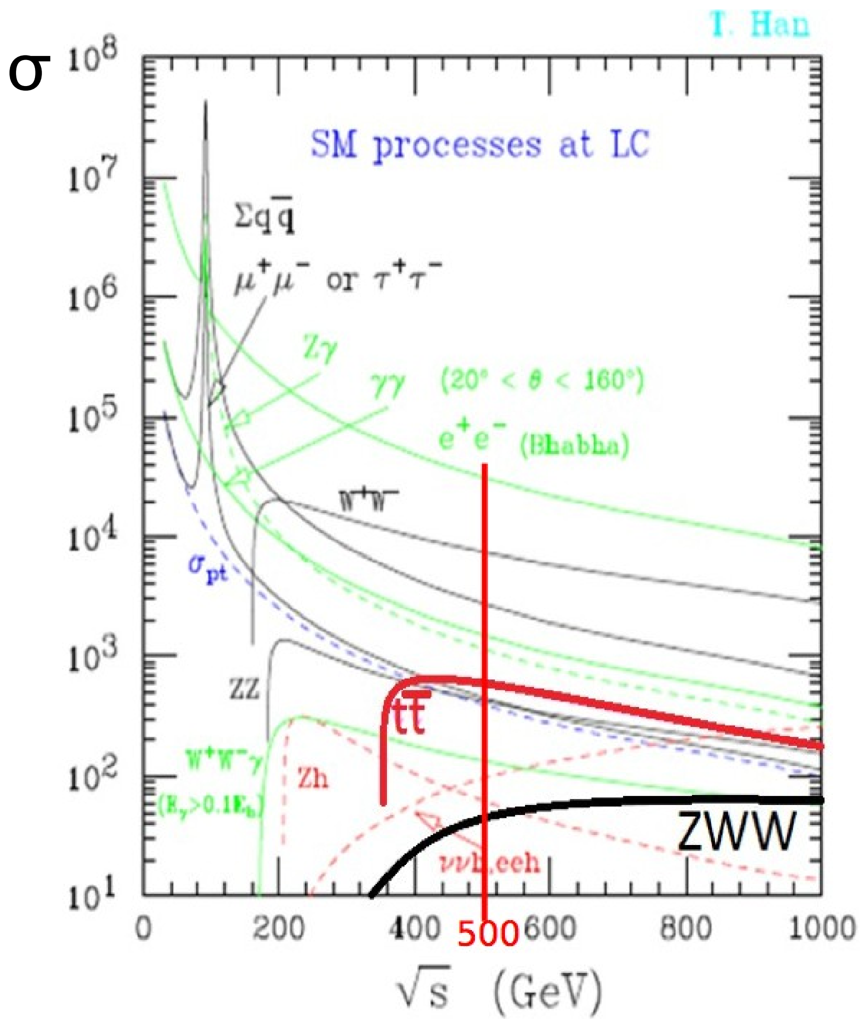
- New physics by compositeness?
  Higgs <u>and</u> top composite objects?

- LC perfectly suited to decipher
  both particles



Courtesy of S. Rychkov





- Top quark production through electroweak processes
  no competing QCD production => Small theoretical errors!

- High precision measurements
  - Top quark mass at ~ 350 GeV through threshold scan
  - Polarised beams allow testing chiral structure at ttX vertex
    => Precision on form factors F and couplings g

Relevant cross sections

type	final state	σ 500 GeV	σ 352 GeV
Signal (m_{top} = 174 GeV)	$t\bar{t}$	530 fb	450 fb
Background	WW	7.1 pb	11.5 pb
Background	ZZ	410 fb	865 fb
Background	$q\bar{q}$	2.6 pb	25.2 pb
Background	WWZ	40 fb	10 fb

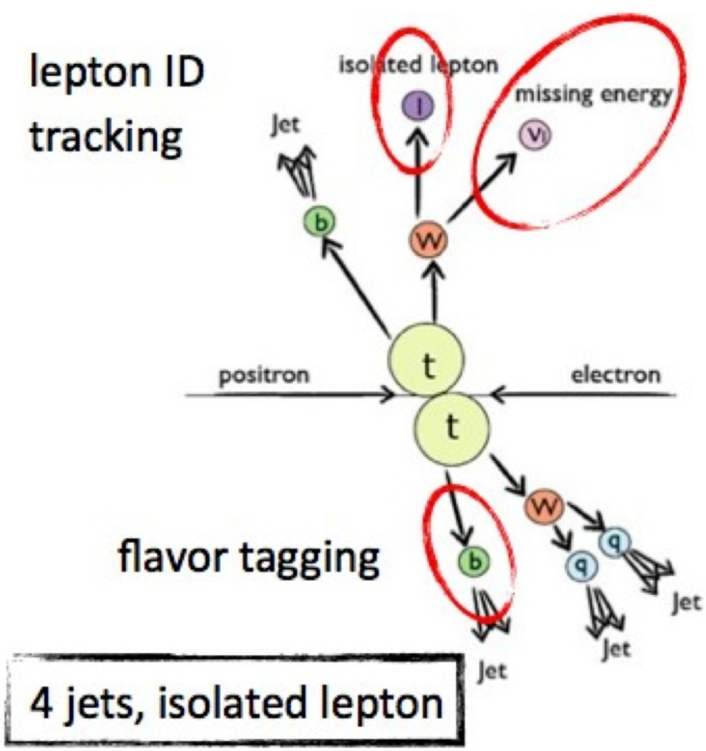
Remarks:

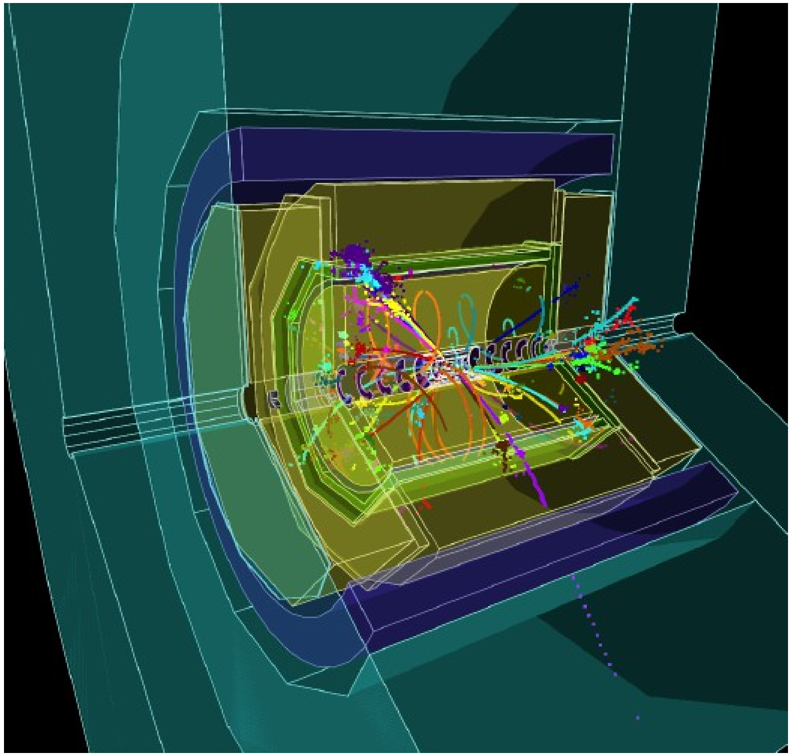
- LC will have polarised beams
  => $(\sigma_{tt})_L$ ~ 1565fb^{-1}, $(\sigma_{tt})_R$ ~ 724fb^{-1} at 500 GeV
- Background varies differently with polarisations
  e.g. WW-Background → 26000fb^{-1} for e_L and 150fb^{-1} for e_R

Elements of top quark reconstruction

Three different final states:
1) Fully hadronic (46.2%) → 6 jets
2) Semi leptonic (43.5%) → 4 jets + 1 charged lepton and a neutrino
3) Fully leptonic (10.3%) → 2 jets + 4 leptons

$$t\bar{t} \rightarrow (bW)(bW) \rightarrow (bqq')(b\ell\nu)$$





Final state reconstruction uses all detector aspects

Results shown in the following are based on <u>full simulation</u> of LC Detectors

Available tools

- Event generator WHIZARD interfaced to PYTHIA

  e^+e^- -> 6f: two beam polarisations: $e_L^- e_R^+$ and $e_R^- e_L^+$

  Events were generated with full simulation and results were scaled for realistic beam polarisation $P, P' = \mp 0.8, \pm 0.3$

$$\sigma_{P,P'} = \frac{1}{4}[(1 - PP')(\sigma_{LR} + \sigma_{RL}) + (P - P')(\sigma_{RL} - \sigma_{LR})]$$

  Full Standard Model background
  Common samples for ILD and SiD studies

- Alternative generators PYTHIA or PHYSIM

- GEANT4 and ILCSoft for detector simulation and reconstruction

- ILD features a full software suite

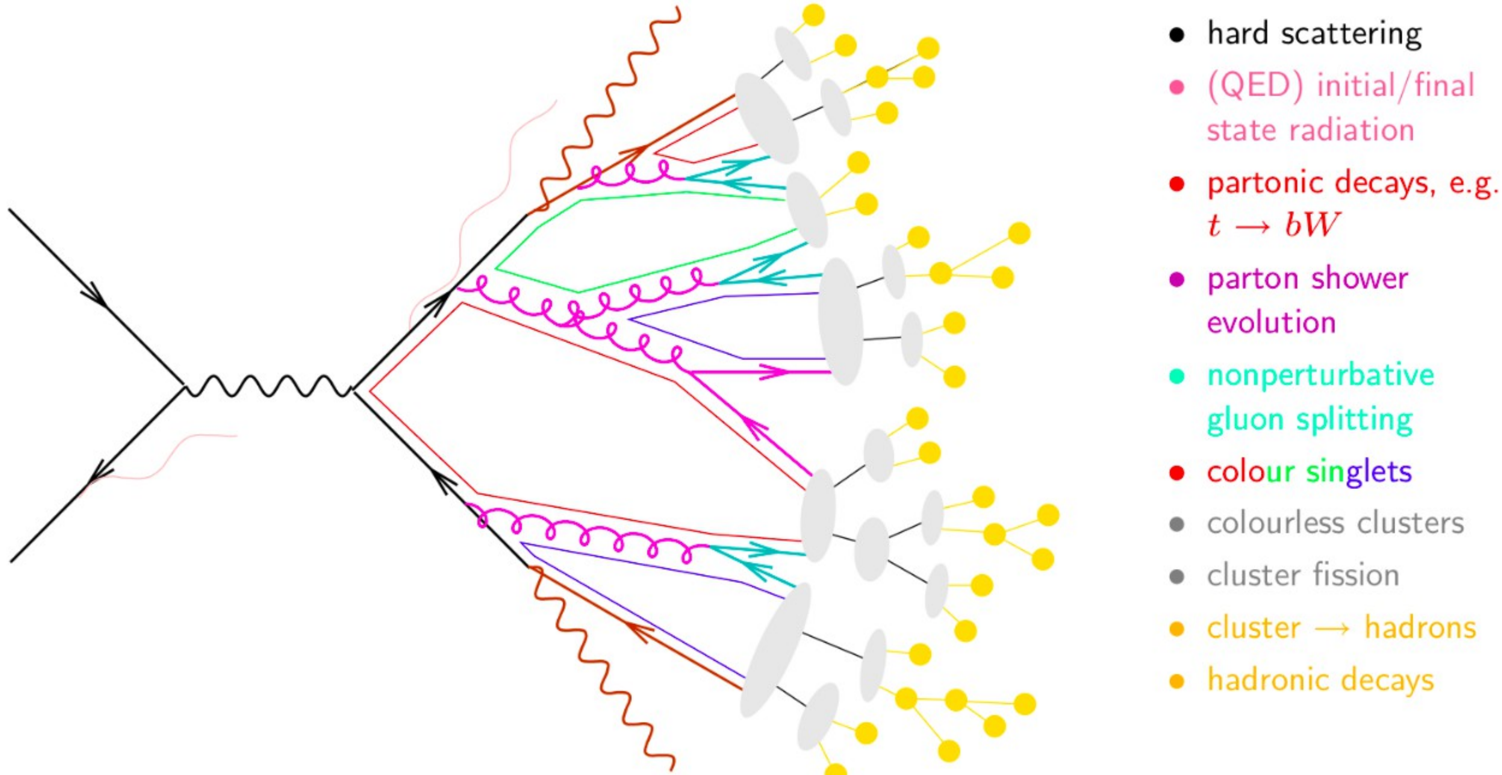
  - Mokka as geometry interface to GEANT4 (Transition to DD4HEP)
  - MARLIN as analysis framework for event reconstruction
  - Interface to toolkits such as PandoraPFA or LCFIVertex

- Detector simulation is based on input from worldwide detector R&D

2. Top physics at threshold

MC mass issues

Extraction of top mass from invariant jet masses (Typical for hadron colliders)



- MC Mass: Mass of (on-shell) top propagator prior to decay => Pole mass

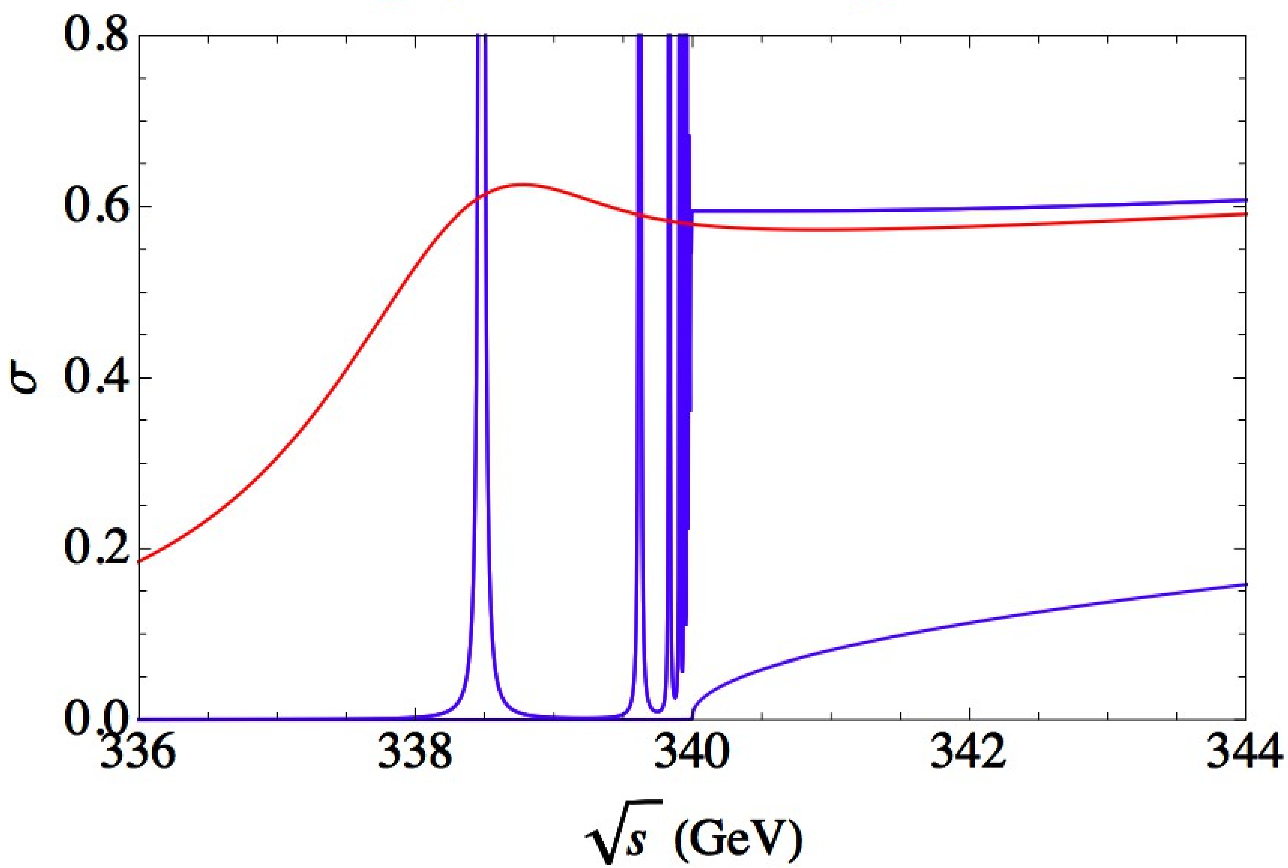
- Pole mass theoretically unsafe when precision reaches O(Λ_{QCD}~1 GeV)

  (Non absorption of soft virtual corrections)

Top pair production at threshold

"Bound states" at tt threshold

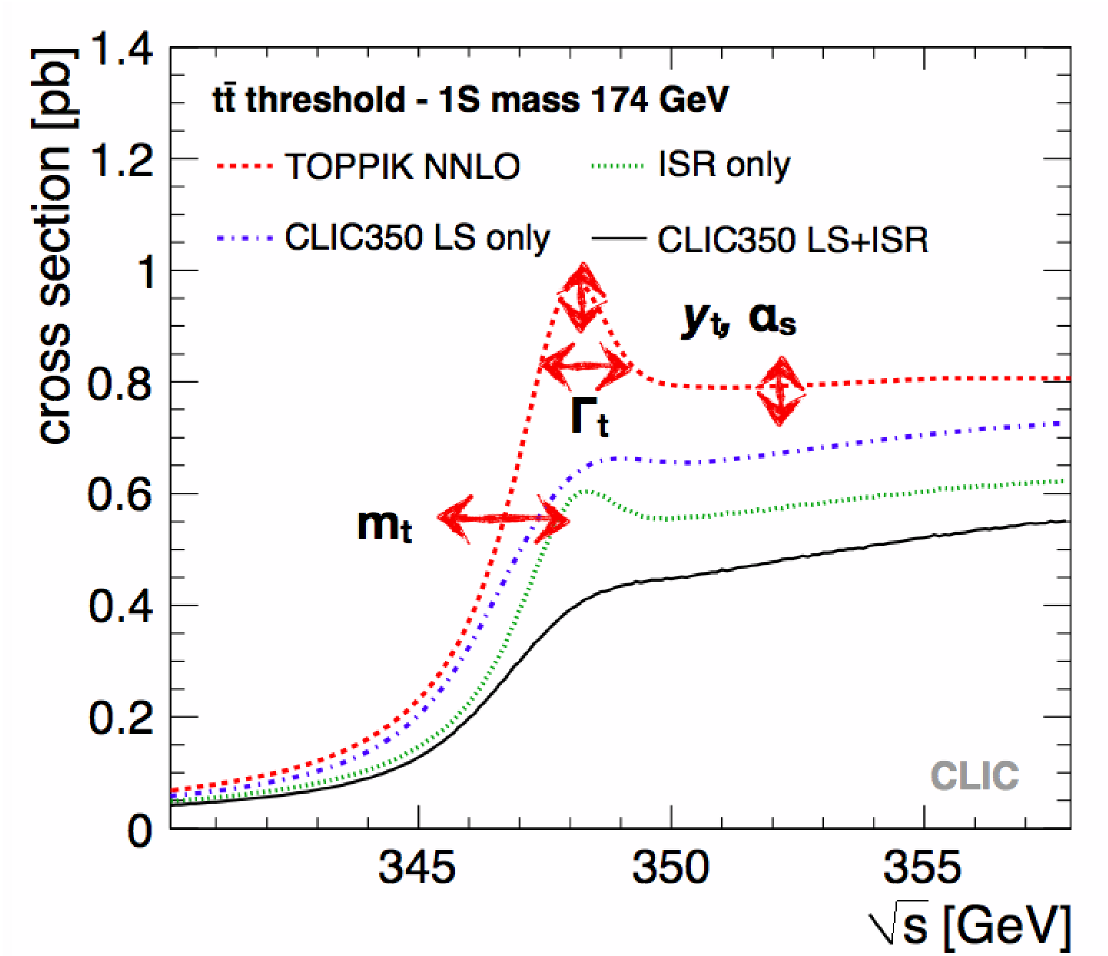
Hydrogen atom of strong interaction



- Size O(10^{-17}m), **smallest object known in particle physics**
  Small scale => Free of confinement effects => Ideal premise for precision calculations
  Measurement of (a hypothetical) 1^3S_1 State

- Decay of top quark smears out resonances in a well defined way

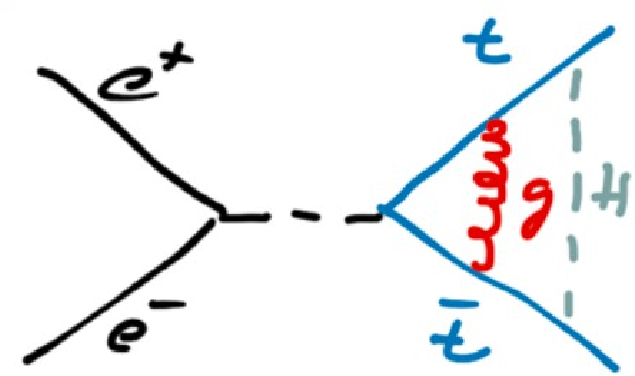
Sensitivity of threshold scans



Cross section around threshold is
Affected by several properties
Of the top quark and by QCD

- Top mass, width Yukawa coupling

- Strong coupling constant



Effects of some parameters are correlated:
Dependence on Yukawa coupling rather weak,
Precise external α_s helps

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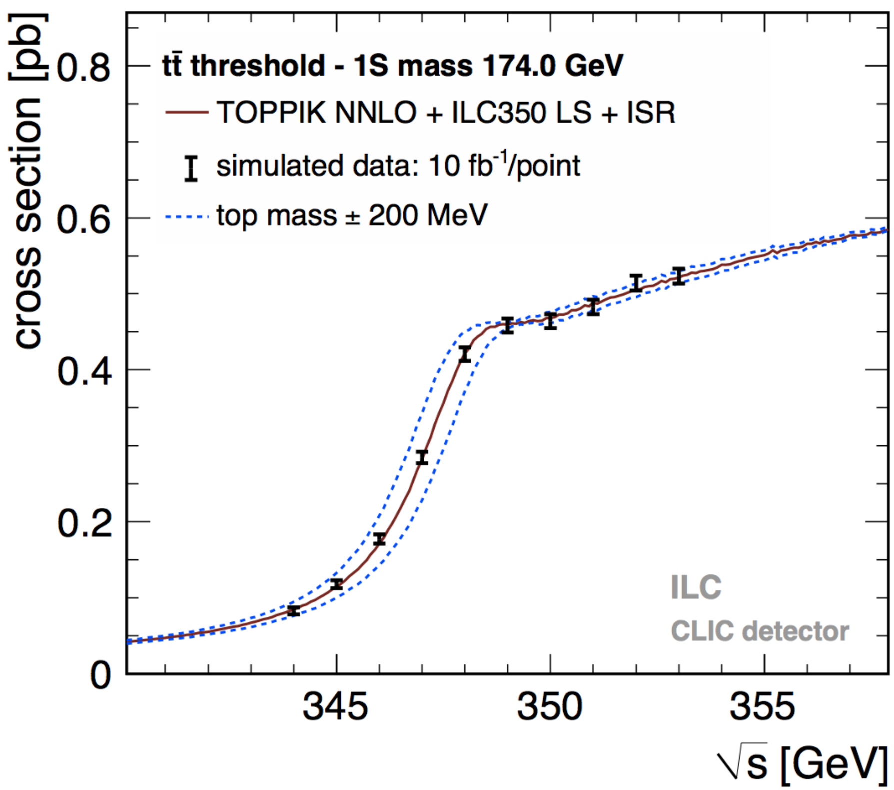
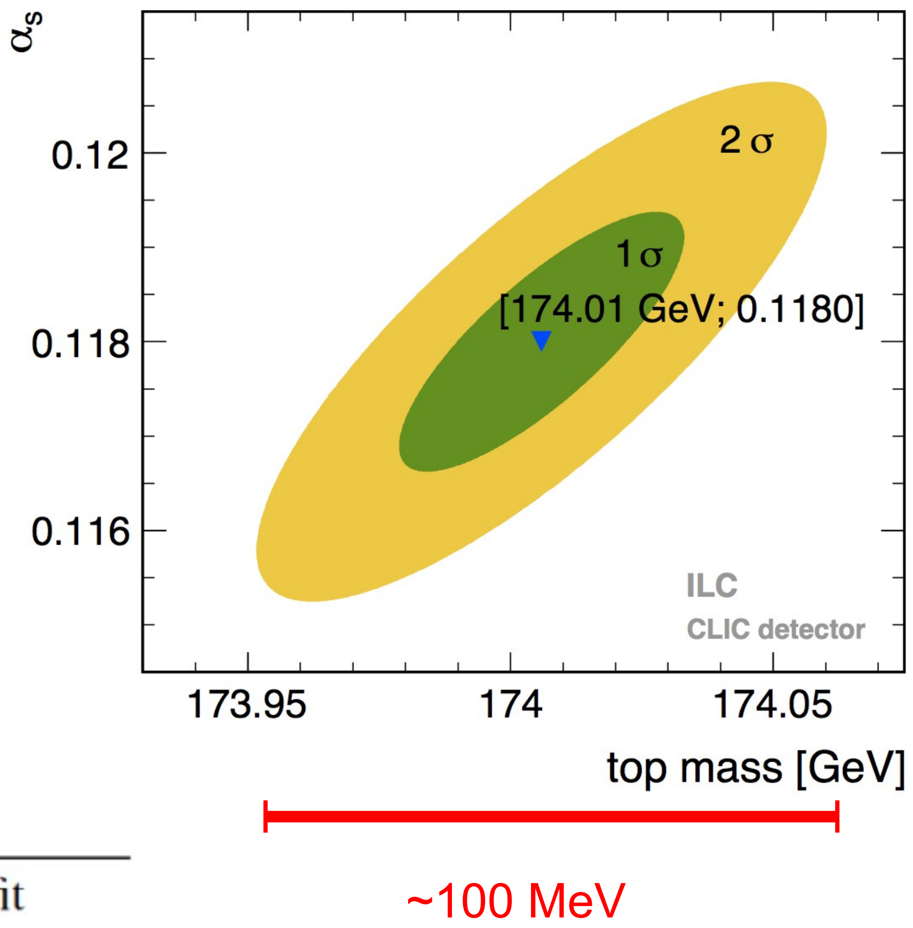
Top quark mass – Results of full simulation studies

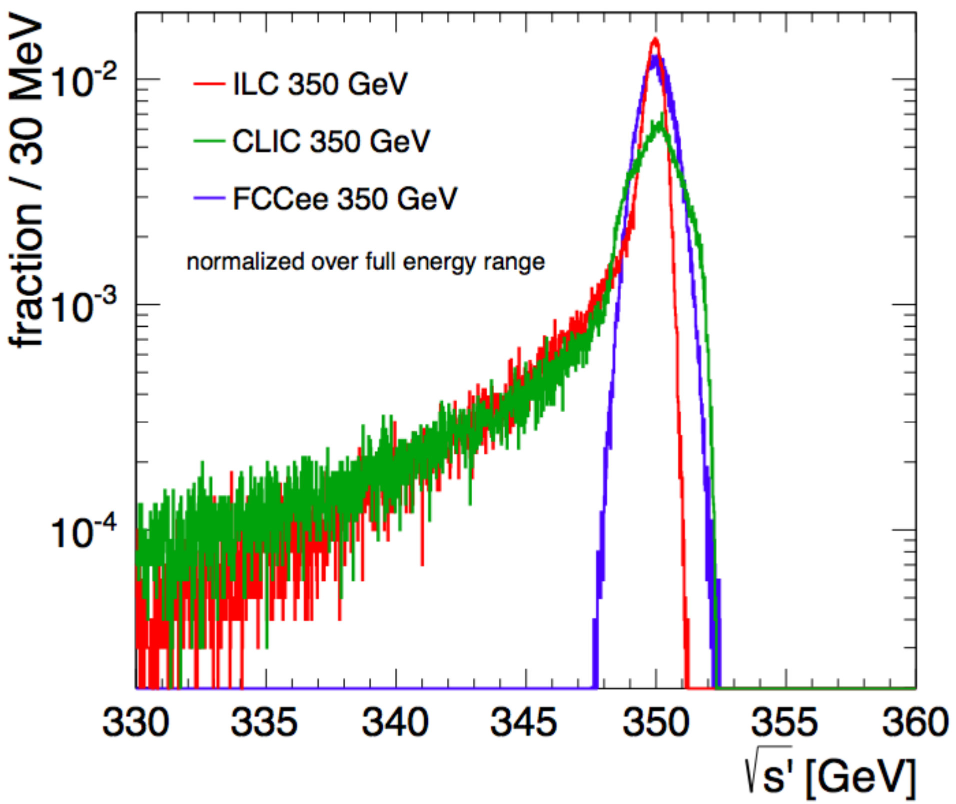
Mass and α_s



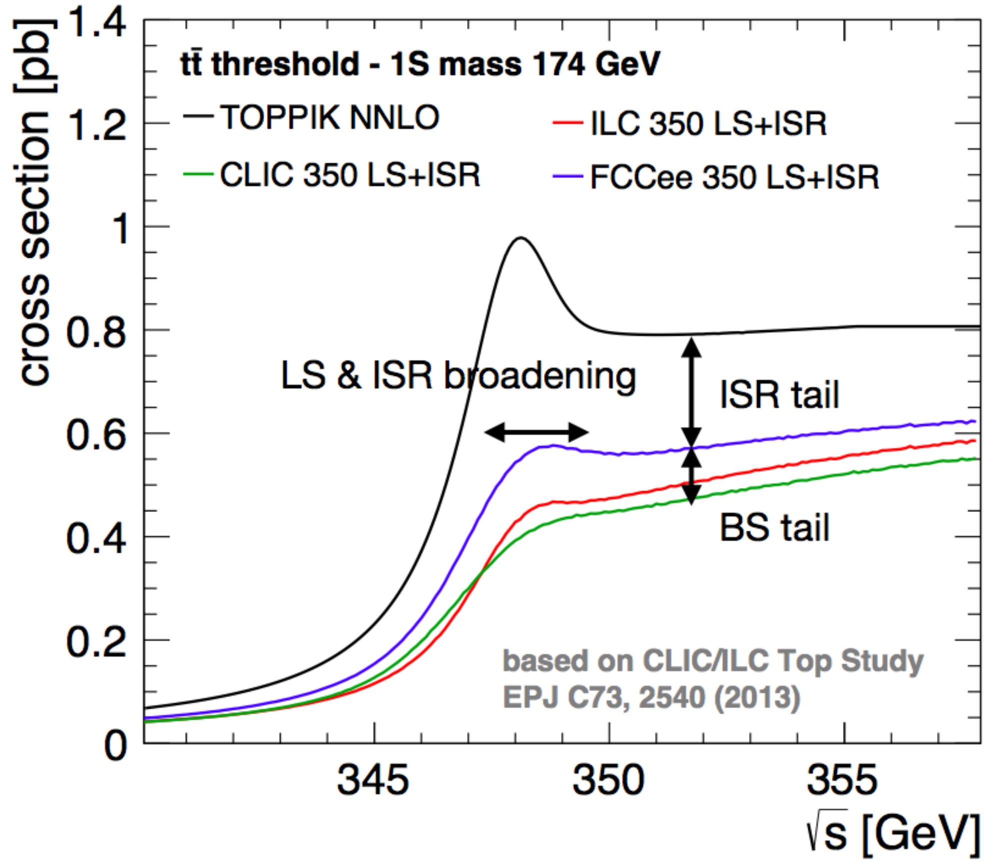


1S top mass and α_s combined 2D fit	
m_t stat. error	27 MeV
m_t theory syst. (1%/3%)	5 MeV / 9 MeV
α_s stat. error	0.0008
α_s theory syst. (1%/3%)	0.0007 / 0.0022

Top quark mass – Results of full simulation studies



Somewhat different luminosity spectra for different machines
- No beamstrahlung in storage ring
- Sharper main peak at ILC broader for CLIC



- Slight changes in statistics due to cross section, changes in sensitivity due to steepness of threshold turn on
- For 100 fb-1, no polarisation, 1D mass fit

16 MeV	→	18 MeV	→	21 MeV (stat.)
FCCee		ILC		CLIC

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Systematic studies - Where are we?

- Studies are not complete but quite some information is already available
  - At threshold: Results will be systematically limited

- So far most complete study on the mass
  - Expected statistical uncertainty (depending on strategy and integrated luminosity) **10 – 30 MeV**

- Experimental systematics
  - Beam energy: **~30 MeV** or lower
  - Non-ttbar background, selection efficiencies (Assuming < 5% background uncertainty, 0.5% knowledge on signal slection): **~ 15 MeV**
  - Luminosity spectrum (studied for CLIC LS with reconstruction of spectrum via Bhabha
  - Scattering, scaling from 3 TeV studies, full study on the way): **10 MeV**
  - Single top contamination: **< 30 MeV**

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Systematic studies - Where are we?

Key factor theory uncertainties
So far use naive estimates assuming 3% uncertainty on cross section
Impact on mass: **~55 MeV**

- Recent NNNLO QCD calculations promising to reduce this error considerably!

Uncertainties from strong coupling constant
When not included in the fit: ~ 3 MeV per 10^{-4} uncertainty on α_s today → **~18 MeV**

In addition impact on the conversion from 1S/PS masses used at threshold to MSbar mass
Currently: **~50 MeV**

However relation between masses known to four-loop order by now
=> Further significant reduction expected
=> to be propagated into analysis

=> Including of newest theory results into LC projections within ~next year
(if manpower available)

=> Now at point where results become sensitive to effects other than QCD

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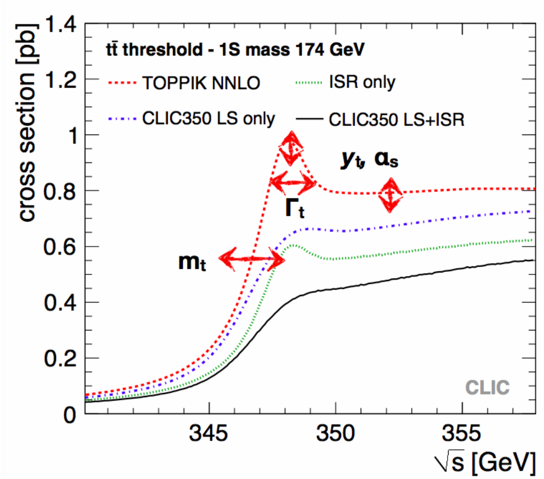
Simultaneous determination of m_t, Γ_t and y_t

Stat. Error (m_t, Γ_t :MeV/y_t:%)	6-Jet			4-Jet		
	m_t^{PS}	Γ_t	y_t	m_t^{PS}	Γ_t	y_t
Left($50fb^{-1}$)	47	65	9.6	52	71	11
Right($50fb^{-1}$)	68	94	14	75	106	16
Left ($50fb^{-1}$) + Right($50fb^{-1}$)	**39**	**53**	**7.9**	**43**	**59**	**9.1**

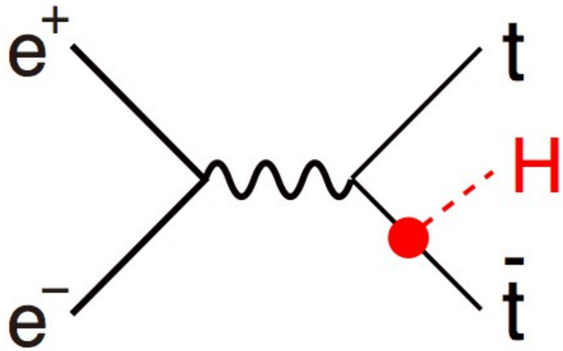
Update of: arxiv 1310.0563

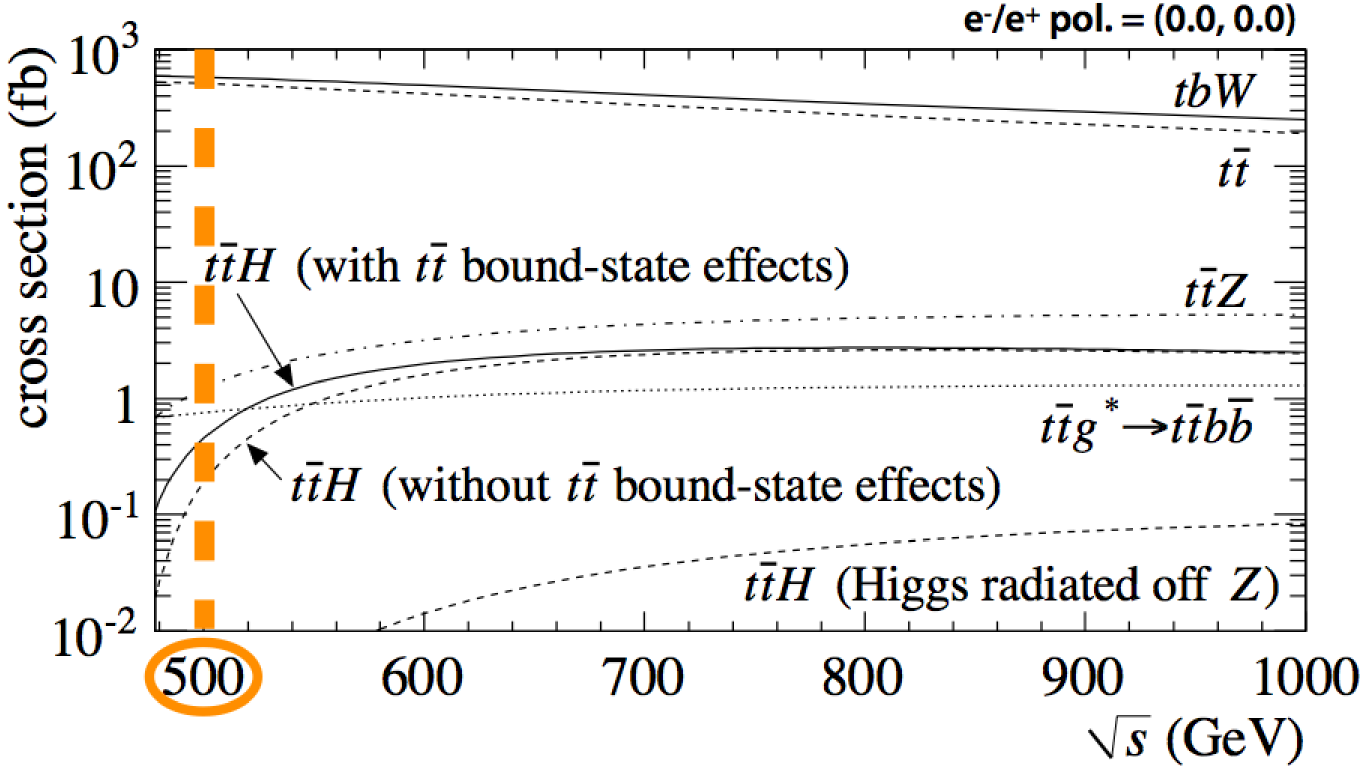


Combined ALL		
m_t^{PS}(GeV)	Γ_t(GeV)	y_t
172±0.029	1.4±0.039	5.9 %

- Competitive determination of three parameters
- y_t suffers however from large theory uncertainties (~20%)
  => Indirect determination may not be conclusive
- Systematic studies on e.g. beam spectrum ongoing
  Important for top width

Top Yukawa Coupling





- Coupling of Higgs to heaviest particle known today

- Up to eight final state jets

$\Delta g_{ttH}/g_{ttH}$	H20 - 500	H20 – 500 Lumi Up
Standard ILC	18%	6.3%
ILC @ √s = 550 GeV	~9%	~3%

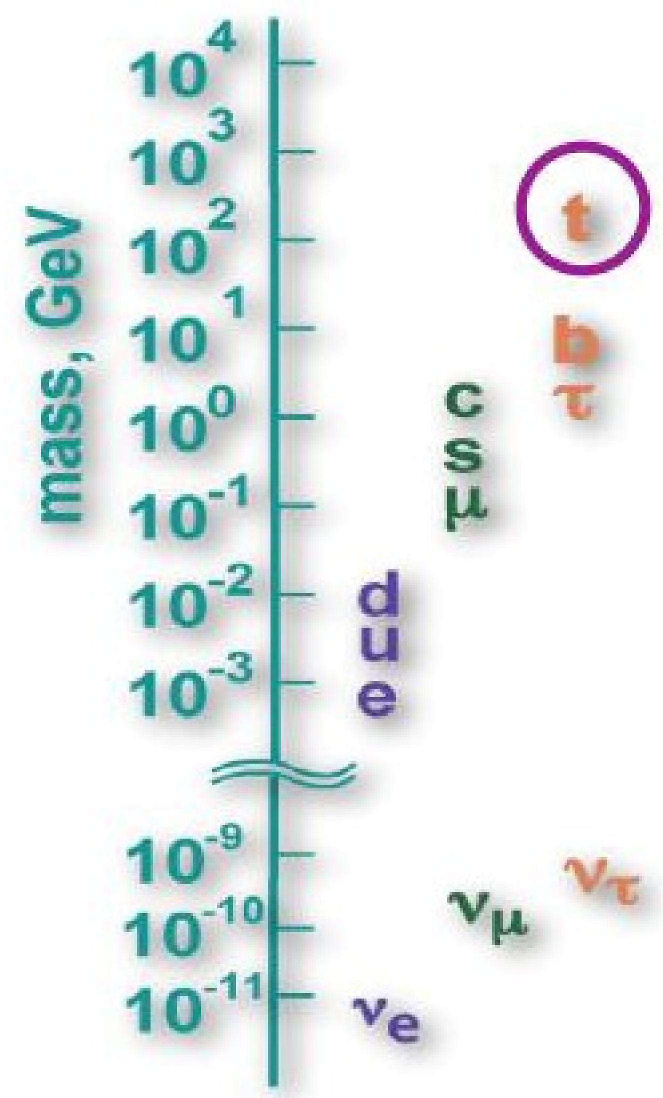
← ILC 2015 (Standard ILC)

← Technically possible (ILC @ √s = 550 GeV)

Running at 1 TeV would allow precision at the 1 – 2% level

3. Top physics in continuum - Couplings

Top Quark and Flavor Hierarchy



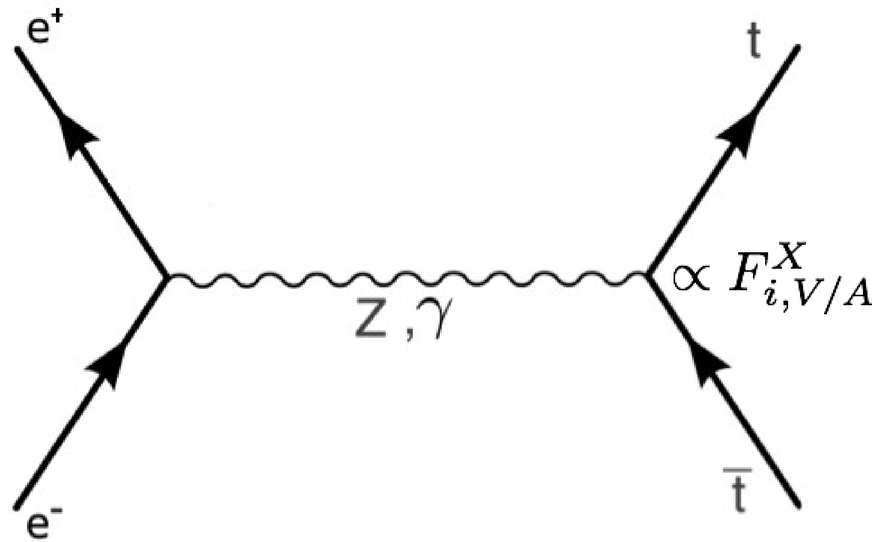
- SM does not provides no explanation for mass spectrum of fermions (and gauge bosons)

- Fermion mass generation closely related to the origin electroweak symmetry breaking

- Expect residual effects for particles with masses closest to symmetry breaking scale
  - A_{FB} anomaly at LEP for b quark

Strong motivation to study chiral structure of top vertex in high energy e+e- collisions

Testing the Chiral Structure of the Standard Model



$$\Gamma^{ttX}_{\mu}(k^2,q,\overline{q}) = -ie\left\{\gamma_\mu\left(F^X_{1V}(k^2)+\gamma_5 F^X_{1A}(k^2)\right)+\frac{\sigma_{\mu\nu}}{2m_t}(q+\overline{q})^\mu\left(iF^X_{2V}(k^2)+\gamma_5F^X_{2A}(k^2)\right)\right\}, \quad (2)$$

Pure γ or pure Z^0 : $\sigma \backsim (F_i)^2 \Rightarrow$ No sensitivity to sign of Form Factors

Z^0/γ interference : $\sigma \backsim (F_i) \Rightarrow$ Sensitivity to sign of Form Factors

Disentangling

At ILC **no** separate access to ttZ or ttγ vertex, but ...

ILC 'provides' two beam polarisations

$$P(e^-) = \pm 80\% \qquad P(e^+) = \mp 30\%$$

There exists a number of observables sensitive to chiral structure, e.g.

$$\sigma_I \qquad A^t_{FB,I} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)} \qquad (F_R)_I = \frac{(\sigma_R)_I}{\sigma_I}$$

x-section — Forward backward asymmetry — Fraction of right handed top quarks

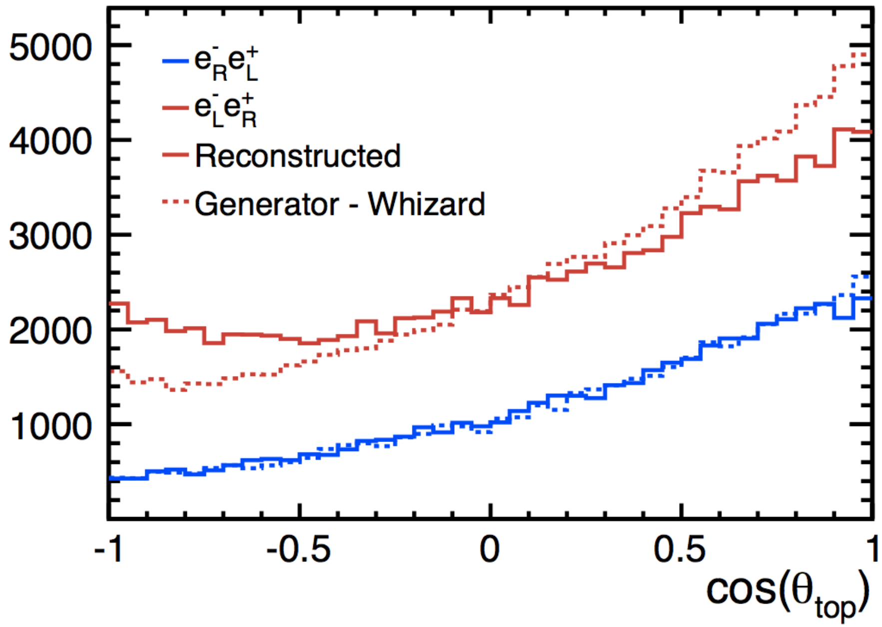
⇩

Extraction of relevant unknowns

$$F^{\gamma}_{1V},\ F^{Z}_{1V},\ F^{\gamma}_{1A} = 0,\ F^{Z}_{1A}$$
$$F^{\gamma}_{2V},\ F^{Z}_{2V}$$

or equivalently $g^{\gamma}_{L},\ g^{\gamma}_{R},\ g^{Z}_{L},\ g^{Z}_{R}$

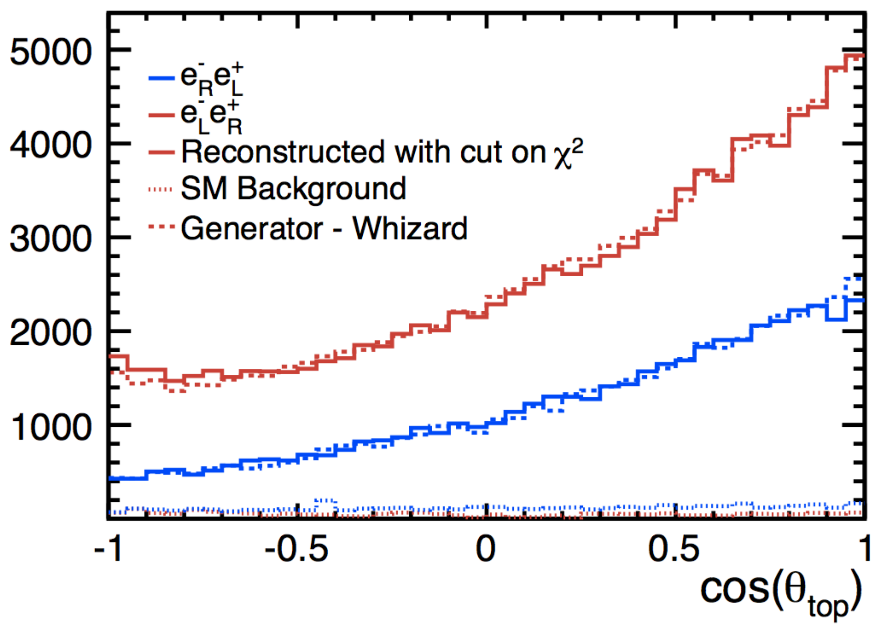
arxiv:1505.06020



Ambiguities in case of left handed electron beams Due to V-A structure at ttX vertex

Precise reconstruction of θ_{top} in case of right handed electron beams

Remedy to address ambiguities:
Select cleanly reconstructed events by χ^2 analysis
or
Reconstruction of b quark charge



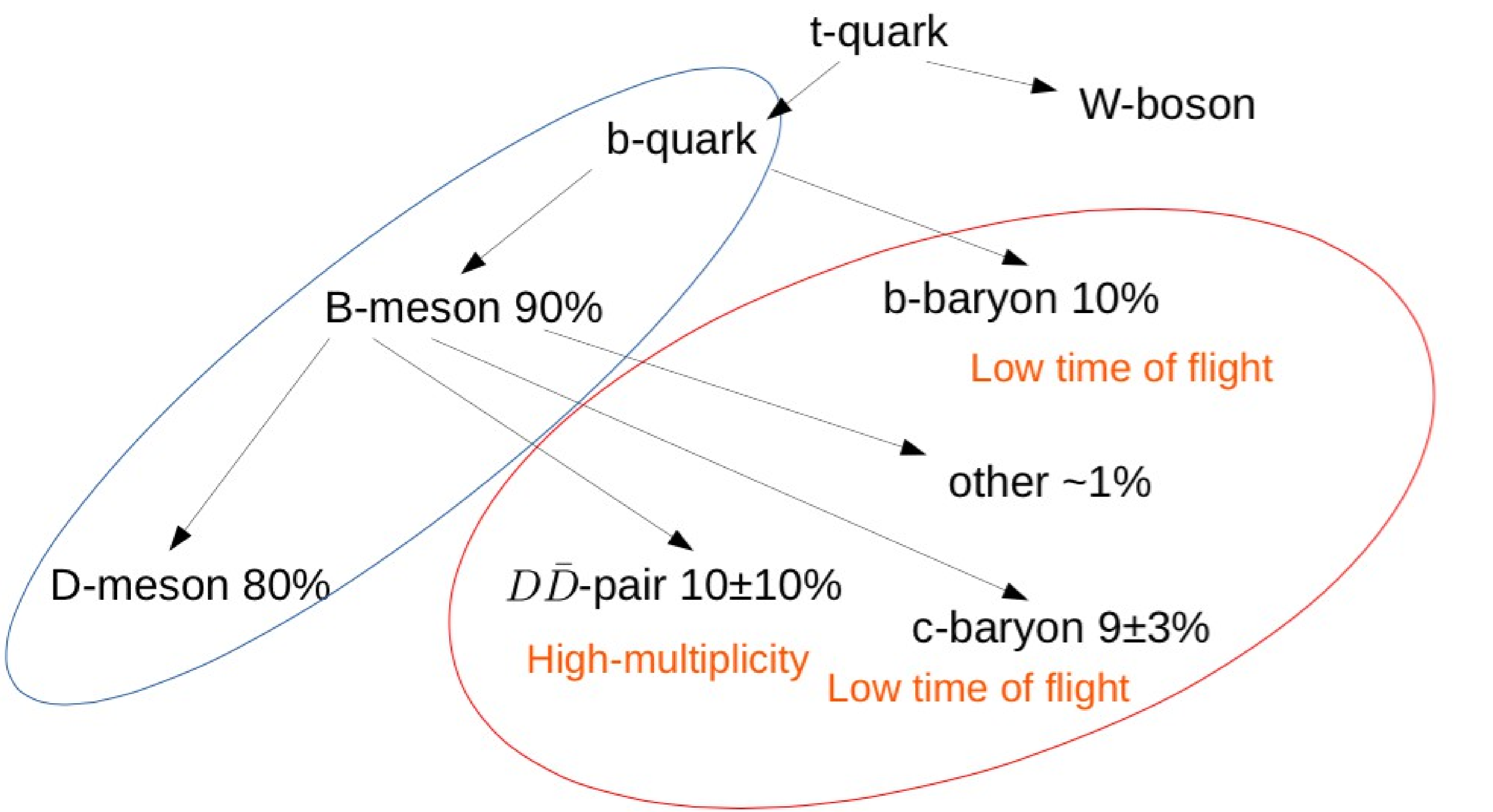
Precise reconstruction for both beam polarisations

- Efficiency Penalty for e_L
- ε_{tot}: $e_R \sim 50\%$, $e_L \sim 30\%$

Precision on $A_{FB} \sim 2\%$

Top quark decay chain

- Hadronization and decay modes of b-quark:

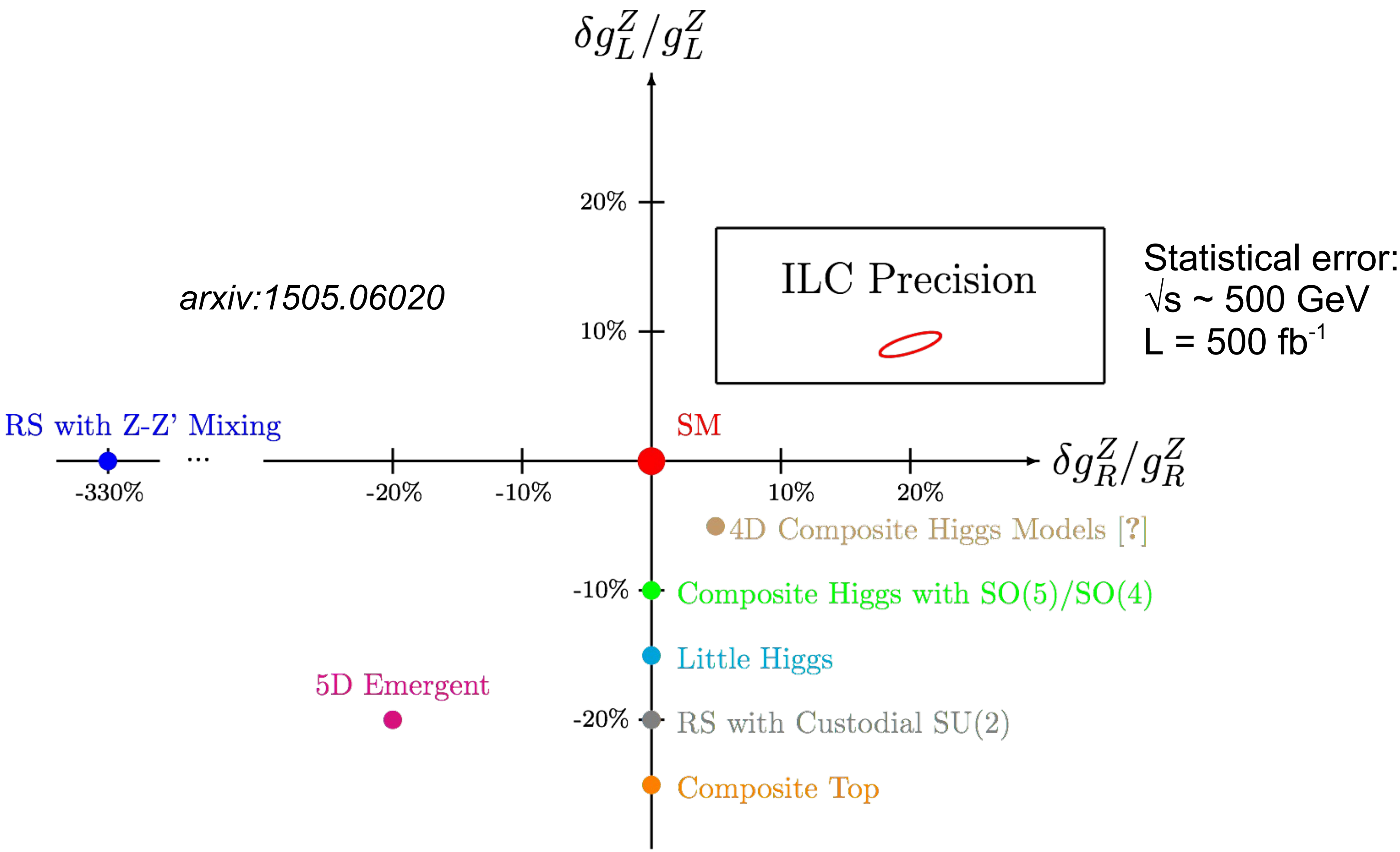


> 70% of the tops lead to “straightforward” reconstructable final states
Exploiting this observation is subject of PhD thesis at LAL

Collaboration within French-Japanese TYL/FJPPL research programme

Sensitivity to New Physics

Top is primary candidate to be a messenger new physics in many BSM models
Incorporating compositeness and/or extra dimensions

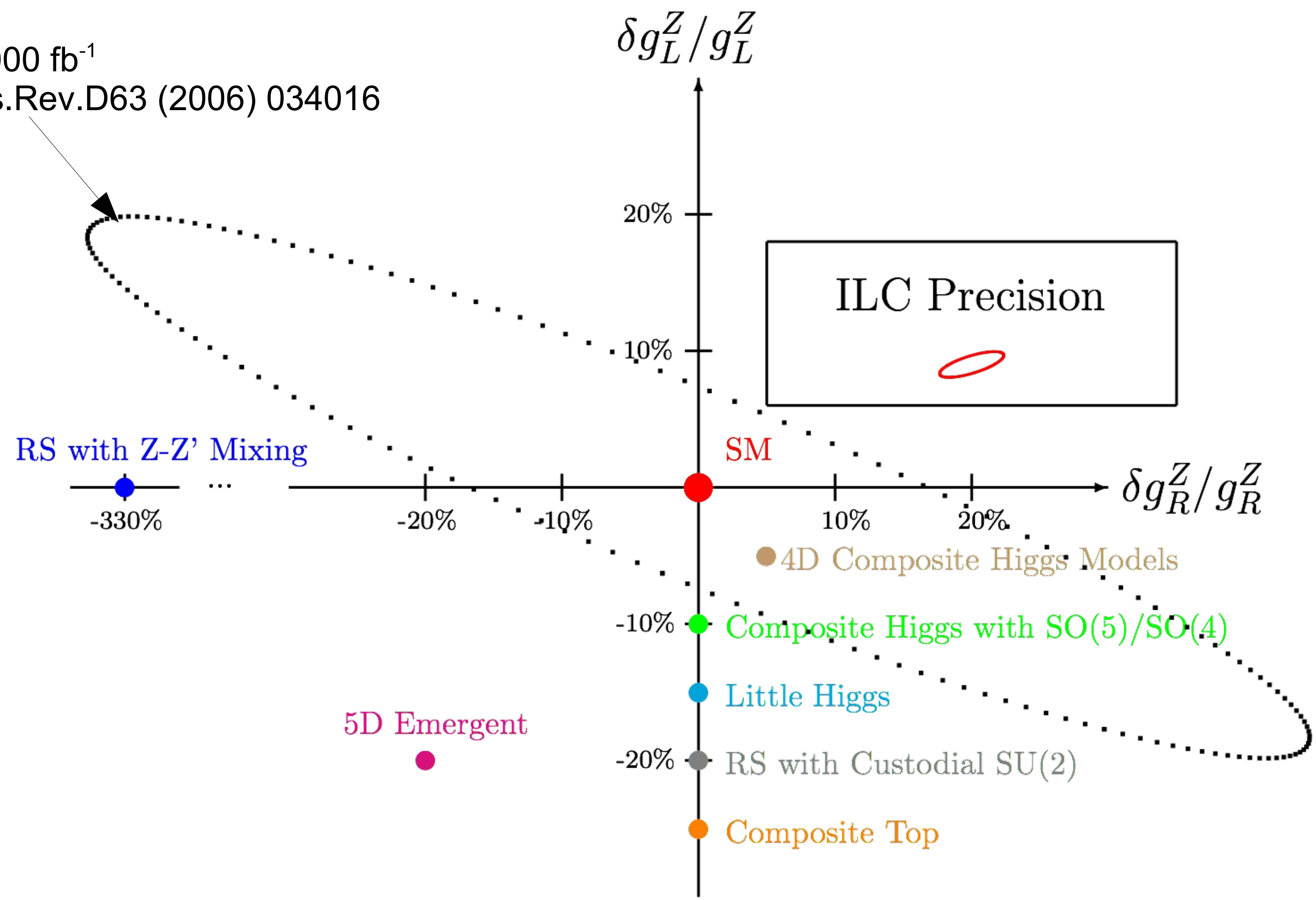


Precision expected for top quark couplings will allow to distinguish between models

Remark: All presented models are compatible with LEP elw. precision data

What about LHC perspectives?

LHC14, 3000 fb^{-1}
From Phys.Rev.D63 (2006) 034016



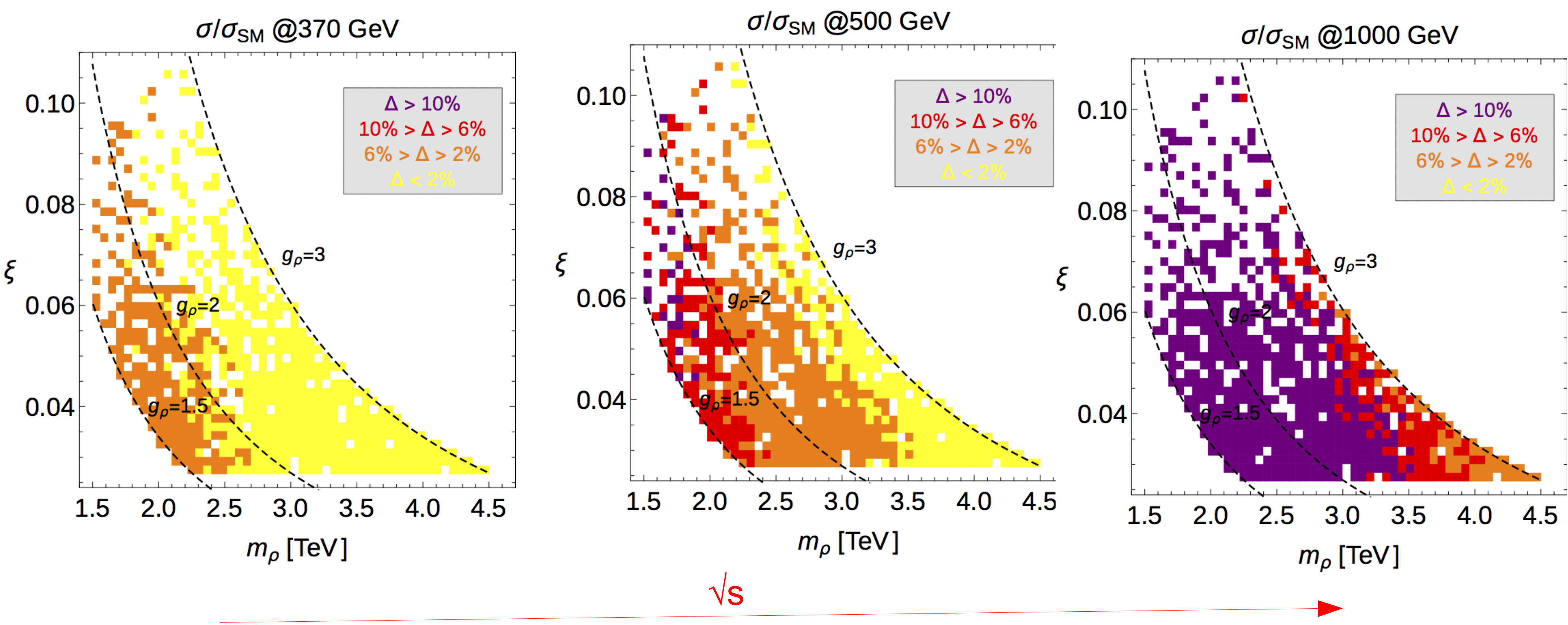
Linear Collider will outperform LHC results

- Particular poor constraint on g_R (this holds also for flavor physics results)
- LHC LO QCD analysis, ~30% improvement through NLO QCD
- LHC may still be capable to exclude models

The merit of higher energies

Example: Sensitivity to $M_{Z'} = M_\rho$ in 4D Higgs Composite Model, arxiv: 1504.05407

$$\frac{\delta g_I}{g_I} \sim \xi \sim \left(\frac{v g_\rho}{M_\rho}\right)^2$$

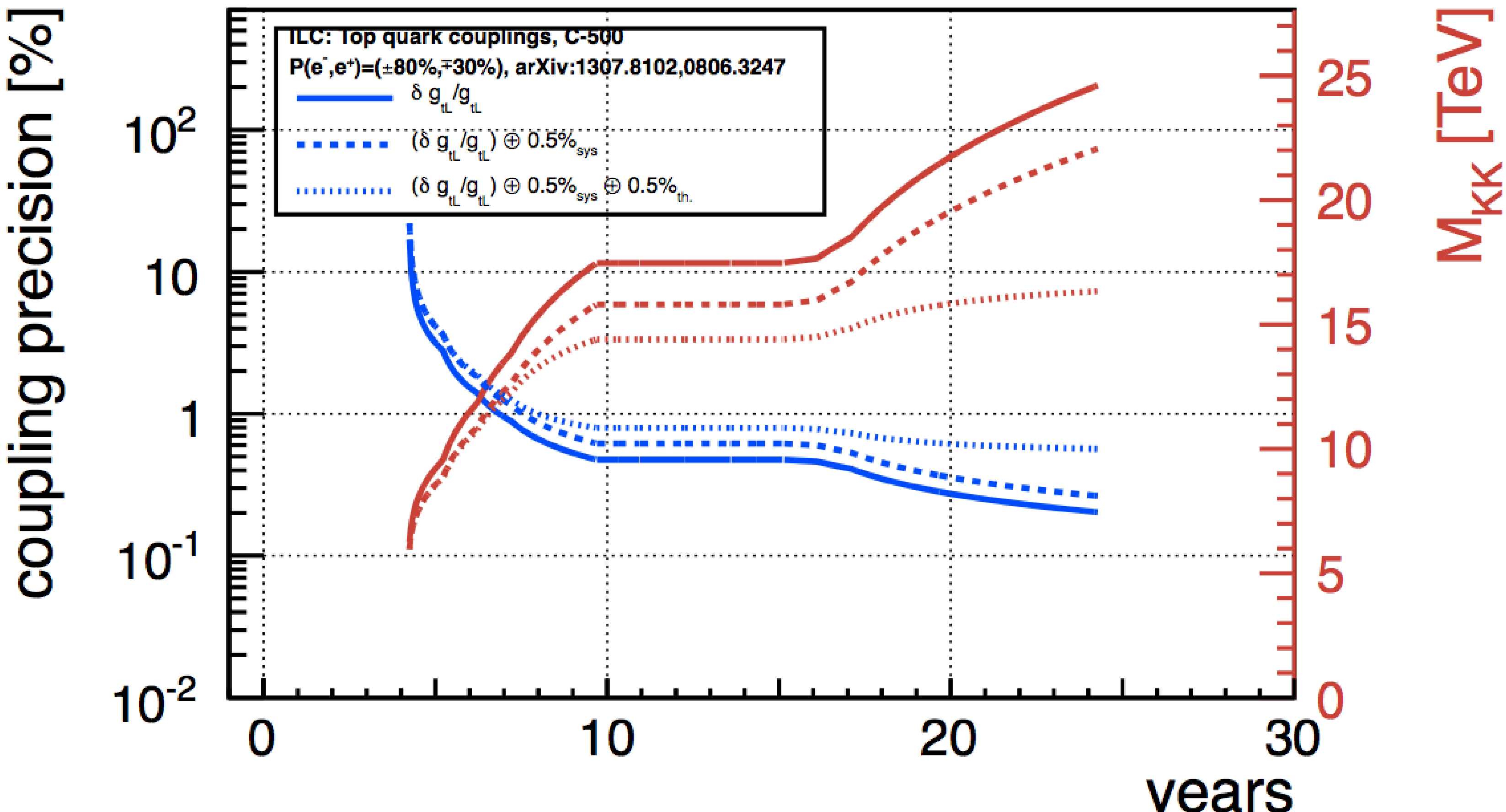


Effects observed at smaller energies may be amplified at higher energies

Example for physics reach

New physics reach for typical BSM scenarios with composite Higgs/Top and or extra dimensions

Based on phenomenology described in Pomerol et al. arXiv:0806.3247



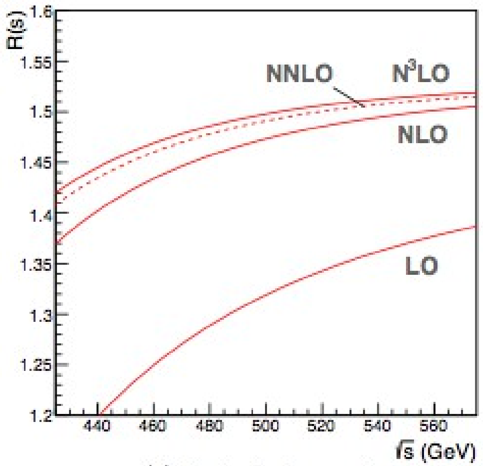
Can probe scales of ~25 TeV in typical scenarios

(… and up tp 80 TeV for extreme scenarios)

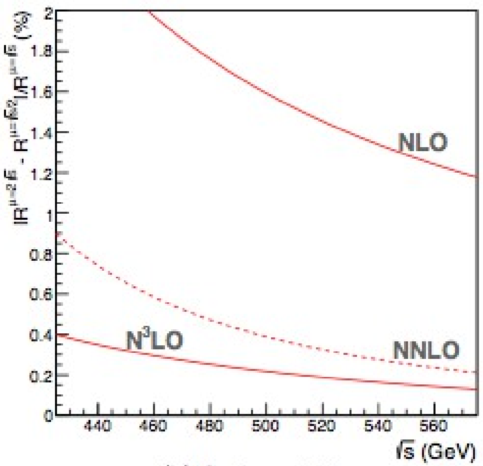
=> Important guidance for e.g. 100 TeV pp-collider

Theoretical uncertainties

- QCD corrections are known up to N^3LO



(a) Perturbation series

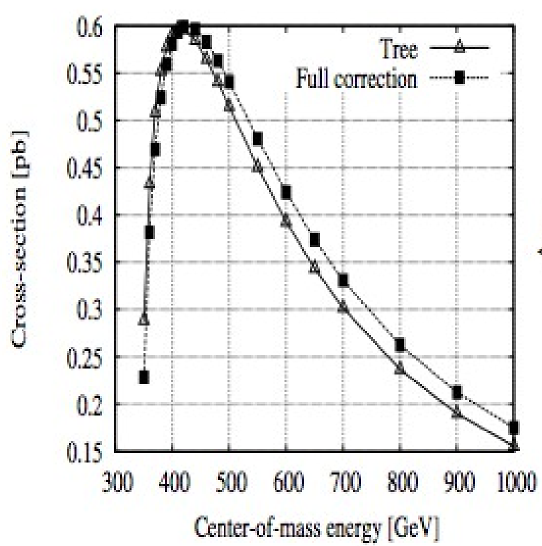


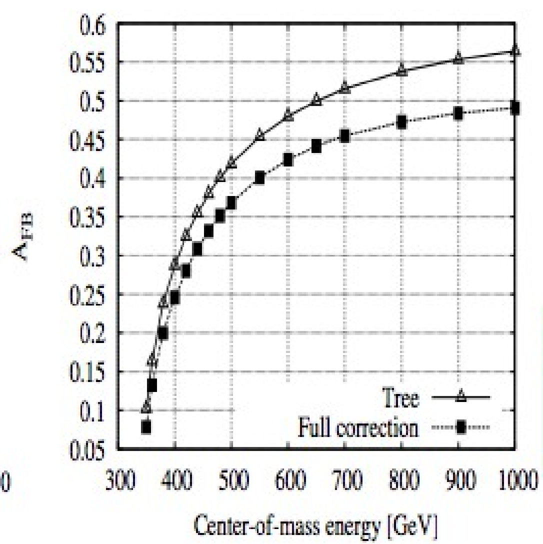
(b) Scale variations

QCD correction (N^3LO) is at the per mil level

Kiyo, Maier, Maierhofer, Marquard, NCP B823 ('09)
Bernreuther, Bonciani, Gehrmann, Heinesch, Leineweber. NPB750 ('06)
Hoang, Mateu, Zebarjad, NPB813 ('09)

- Electroweak corrections are known at one-loop level

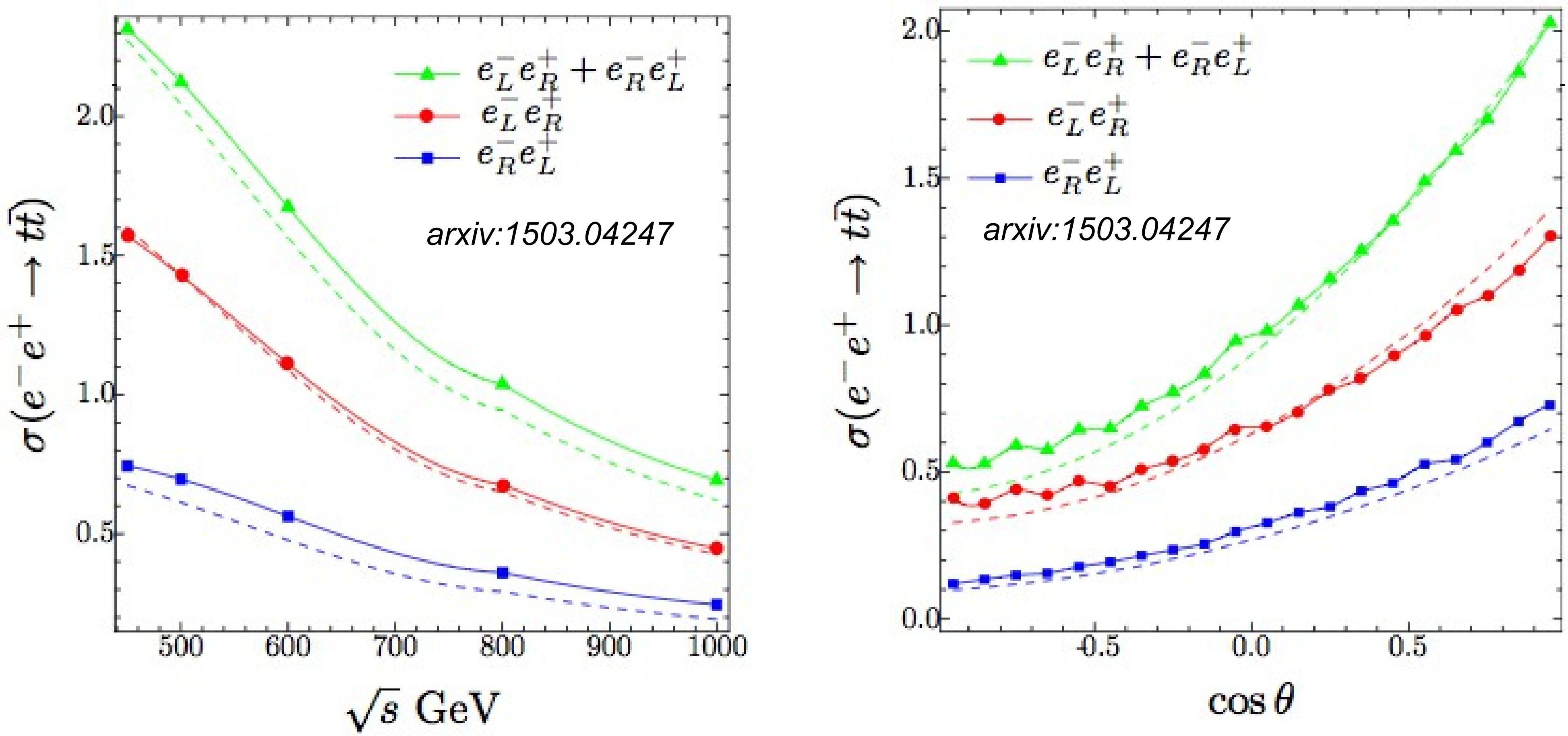




EW correction at one-loop is ~5% for cross section ~10% for A_{FB}

Fleischer, Leike, Riemann, Werthenbach, EJPC31 ('03)
Kheim, Fujimoto, Ishikawa, Kaneko, Kato, arXive:1211.1112

Detailed look at higher order elw. corrections - GRACE



- Electroweak corrections manifest themselves differently for different beam polarisations

-

Beam polarisation important asset to disentangle SM and effects of new physics

Configuration $e_R^- e_L^+$ seems to lead to "simpler" corrections

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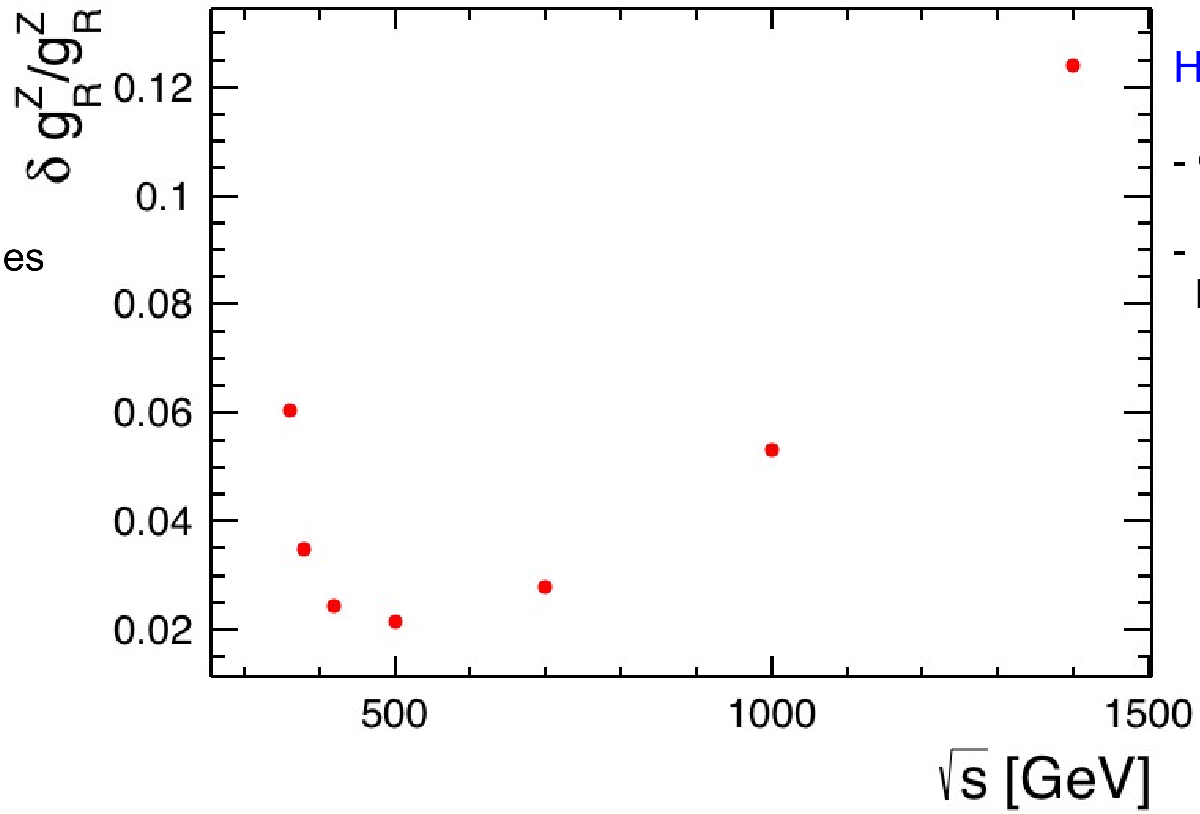
Different centre of mass energies

... simplified discussion

Small cms energies:

- Vanishing axial vector coupling
- large QCD uncertainties ... and
- Lumi decreases at linear colliders



High cms energies:

- Quickly decreasing cross section
- ... partially compensated by increasing luminosity

Broad minimum between 400 and 700 GeV

$\sqrt{s}$ ~ 500 GeV is “sweet spot” for coupling measurements

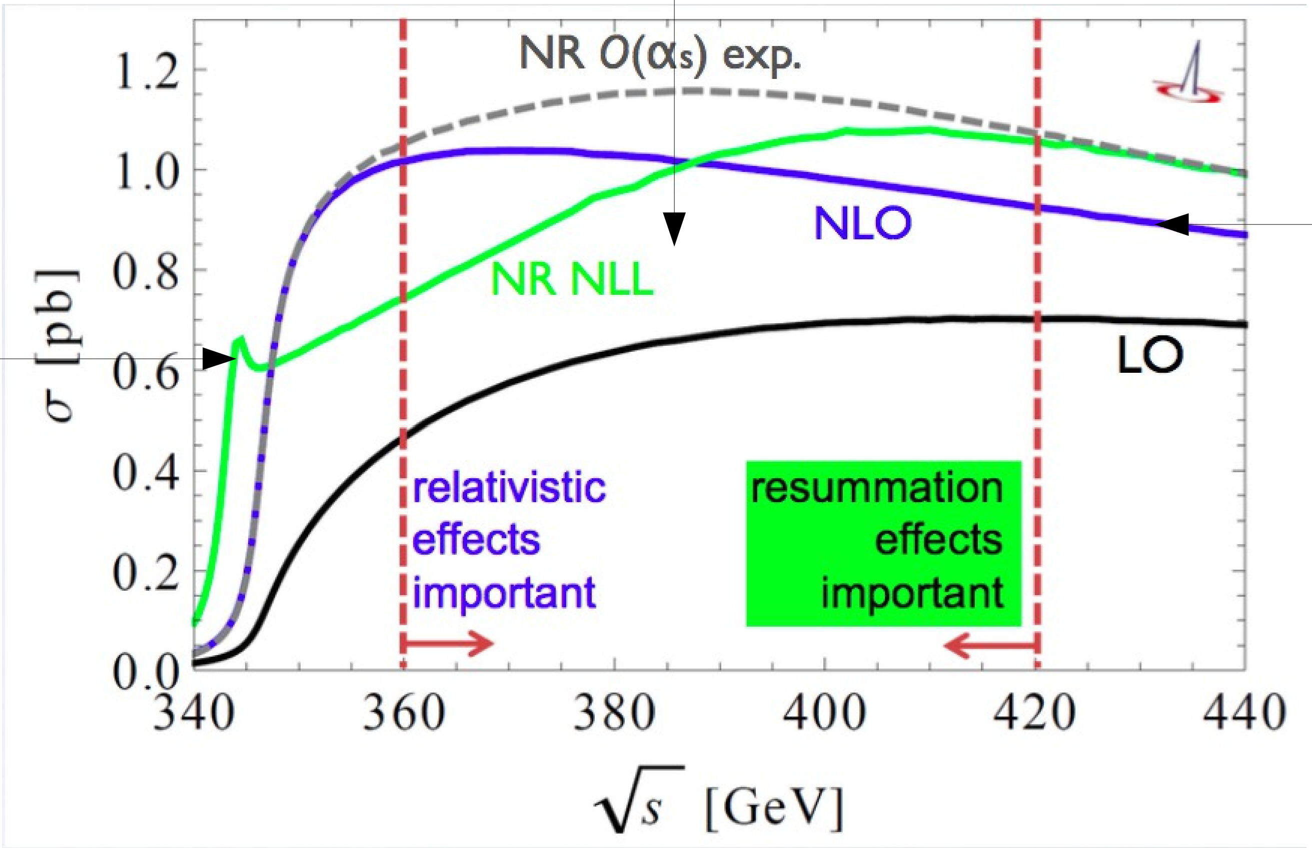
However:

- Sensitivity to CP violating Higgs at smaller cms energies
- New physics at higher energies may increase cross section (see above)

Complicated transition region

Transition region
Difficult to match non-relativistic QCD at threshold
With relativistic QCD in continuum

Threshold region
Theoretically
well under control



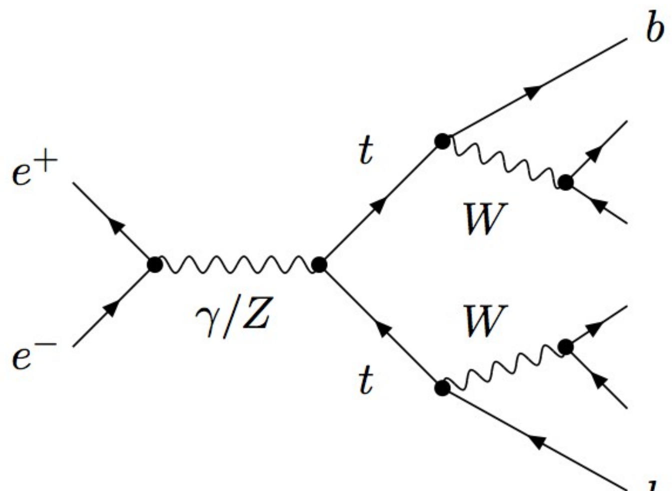
Continuum
Theoretically
well under control

Considerable theory uncertainties suggest
to avoid transition region for precision physics

4. Trends

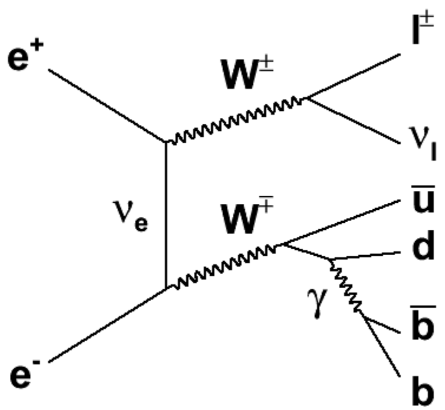
Closer look at ttbar production

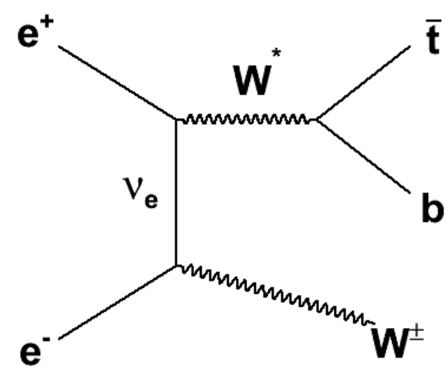
That's what we are interested in



Top pair production is effectively ee->6f process

That's what is also contributing to final state!



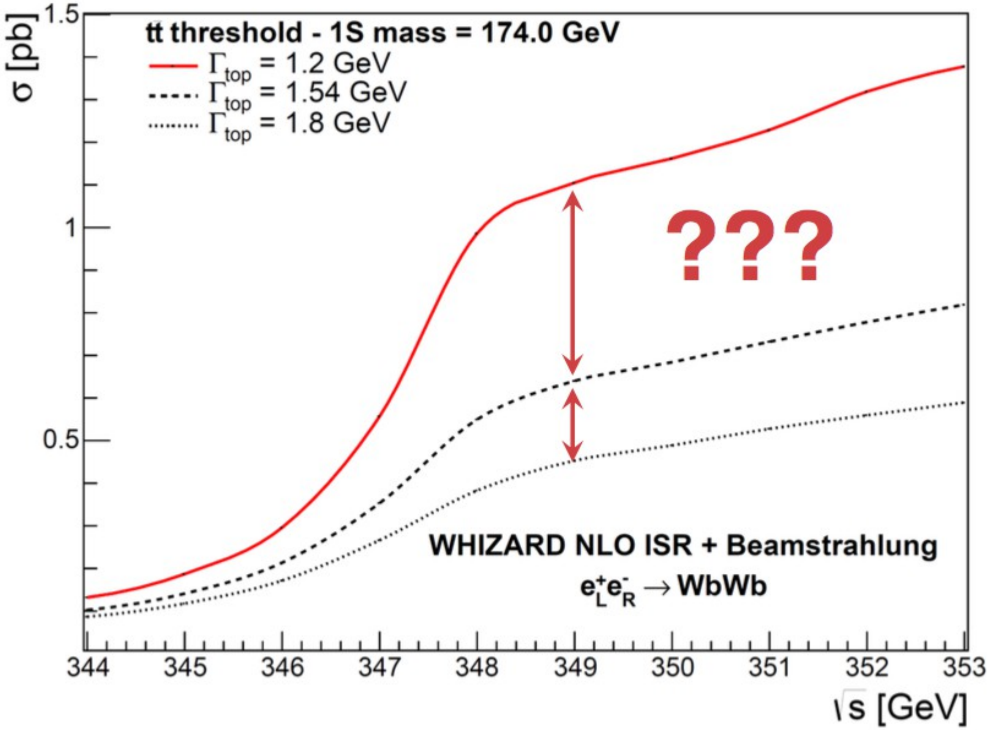


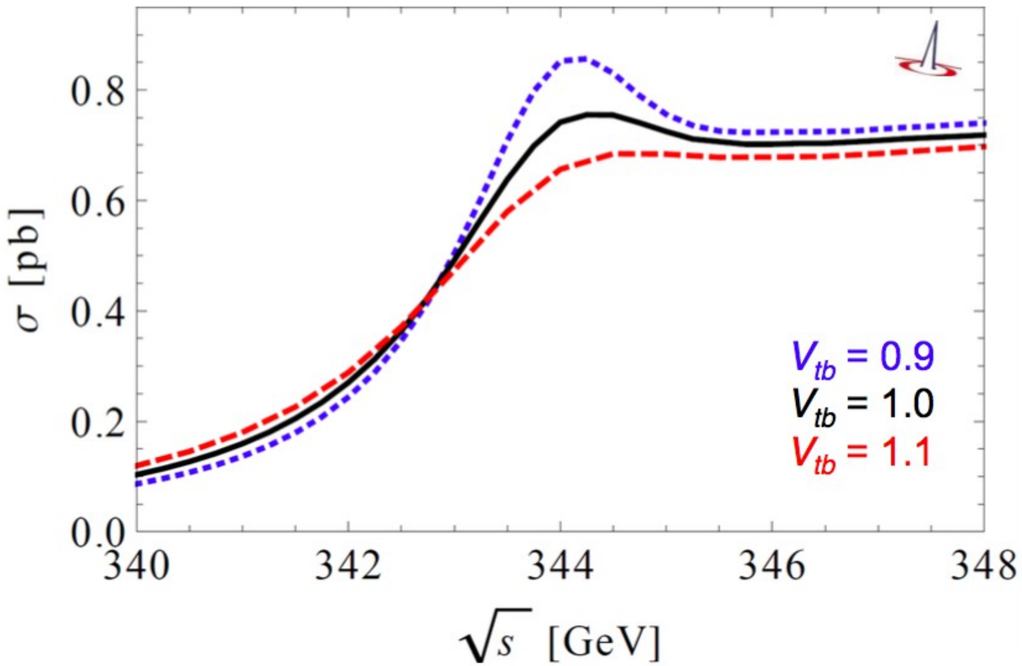
+ s-channel, t-channel only relevant for eL

- Can one really speak about a ttbar cross section?
- If only 6f is relevant: What are relations to ttX couplings?

Top width and V_{tb}

Study with WHIZARD generator





- "Erratic" behaviour of theory prediction when using Γ_t as free parameter

- Using V_{tb} as free parameter leads to more benign behaviour

Experimentally observable final state requires proper definition of theory parameters

Top couplings with matrix element method

For details see arxiv: 1503.04247

Basic idea: Final state top polarisation cointains information about factors

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

=> different sensitivities in different individual matrix elements:

$$\omega_i = \frac{\partial |\mathcal{M}|^2(\alpha)}{\partial \alpha_i}_{|\alpha^0} \frac{1}{|\mathcal{M}|^2(\alpha^0)}$$

For each α_i (=FF) there is one (measurable) ω_i

Using full matrix element information -> Full event reconstruction

$$\mathrm{dLips} \propto \mathrm{d}\cos\theta_t\ \mathrm{d}\cos\theta_b\ \mathrm{d}\phi_b\ \mathrm{d}\cos\theta_{\bar{b}}\ \mathrm{d}\phi_{\bar{b}}\ \mathrm{d}\cos\theta_{l^+}\ \mathrm{d}\phi_{l^+}\ \mathrm{d}\cos\theta_{l^-}\ \mathrm{d}\phi_{l^-}\ \mathrm{d}q_t^2\ \mathrm{d}q_{\bar{t}}^2\ \mathrm{d}q_W^2$$

Matrix element method – First results

Parton level analysis (with GRACE generator) using fully leptonic final state

Simultaneous extraction of 10 FF **including CP violating FFs**

$\mathcal{R}e\,\delta\tilde{F}^{\gamma}_{1V}$	$\mathcal{R}e\,\delta\tilde{F}^{Z}_{1V}$	$\mathcal{R}e\,\delta\tilde{F}^{\gamma}_{1A}$	$\mathcal{R}e\,\delta\tilde{F}^{Z}_{1A}$	$\mathcal{R}e\,\delta\tilde{F}^{\gamma}_{2V}$	$\mathcal{R}e\,\delta\tilde{F}^{Z}_{2V}$	$\mathcal{R}e\,\delta\tilde{F}^{\gamma}_{2A}$	$\mathcal{R}e\,\delta\tilde{F}^{Z}_{2A}$	$\mathcal{I}m\,\delta\tilde{F}^{\gamma}_{2A}$	$\mathcal{I}m\,\delta\tilde{F}^{Z}_{2A}$
0.0037	−0.18	−0.09	+0.14	+0.62	−0.15	0	0	0	0
	0.0063	+.14	−0.06	−0.13	+0.61	0	0	0	0
		0.0053	−0.15	−0.05	+0.09	0	0	0	0
			0.0083	+0.06	−0.04	0	0	0	0
				0.0105	−0.19	0	0	0	0
					0.0169	0	0	0	0
						0.0068	−0.15	0	0
							0.0118	0	0
								0.0069	−0.17
									0.0100

No particular improvement through beam polarisation

- No background, no smearing

- Needs experimental study – You?

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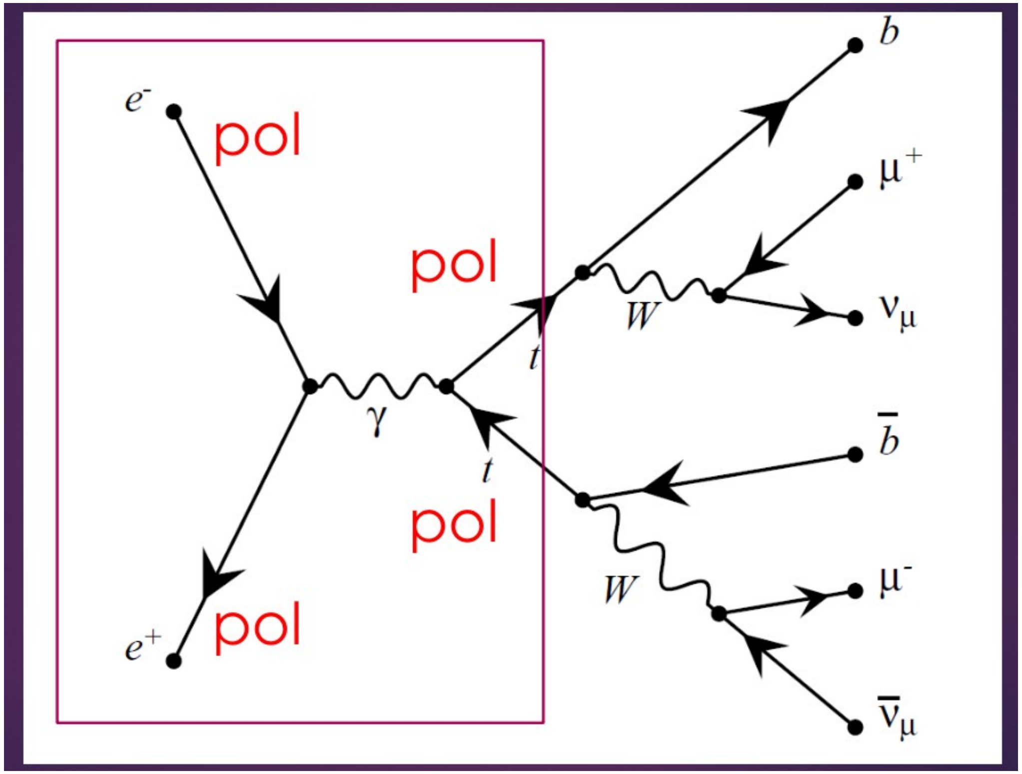
Full six fermion final state

Elw. Corrections for polarised beams



Target:

- $e^+e^- \to t\bar{t} \to b\bar{b}f\bar{f}f\bar{f}$ @ ILC
- Full *O*(α) electroweak corrections
- Beam polarization effects
- Finite width effects of top-quarks
- Matrix elements

- Event generation ?
- $O(\alpha^2)$ electroweak corrections ???

Goal for accuracy < 1%

Collaboration within French-Japanese TYL/FJPPL research programme

Summary

- A LC is the right machine for **Rediscovery of the top quark** by precision physics

  Production top pairs in electroweak production!!!

  Essential pillar of LC physics program

  Experimental programme can take full advantage of flexible running (cms energy)

- Full simulation available for LC detectors

  => Great deal of realism and confidence in perspectives

- Precision on top mass reach 50 MeV regime (200 fb^{-1} or less needed)

  Effort was driven by experimental study, now need to feedback newest theory insights

- Direct and indirect observation of tth

  Full exploitation of LC potential allow for 1-2% precision on g_{ttH}

- Precision on form factors and couplings of the order of 1% with minimal ILC running scenario

  Sensitivity to new physics up to several 10 TeV

  Main experimental challenge is control of migrations in A_{FB}

  Beam polarisation is major asset for control of theoretical and experimental ambiguities

- Start to address full 6 fermion final state instead of tt only

- Keeping all the promises is hardest task in coming years

  Need full understanding of systematics for optimal detector and machine design

Open topics – Non exhaustive

- Get a good guess on systematic errors

- Feed conclusions into machine and detector design
  (Remember total uncertainty needs to remain e.g. ~ 0.1% for coupling studies)

- Understanding aspects of 6 fermion final state (experimentally and theoretically)

- Explore full potential of measurement of CP violation

- Impact of higher order electroweak corrections

- Experimental study of matrix element method

- Pros and cons of effective field theory and full /new physics models

- Monitoring and reacting to latest LHC results

Top quark physics at LC - Organsation

- Regular workshops, so far three

- May 2012 in Paris (ENS Chimie)
  http://events.lal.in2p3.fr/conferences/Top-Quark-Physics/Contacts.html

- March 2014 in Paris (LPNHE)
  https://agenda.linearcollider.org/event/6296/program

- June 2015 at IFIC Valencia
  http://ific.uv.es/~toplc15/index.html

- 2016 ??? maybe Japan

- Mailing list: topatlc-l@listserv.in2p3.fr (40 persons registered)

- (Small) funding by LIA TYL/FJPPL => Structuring of French-Japanese Collaboration

- Sessions at Linear Collider Meetings

- Presence at international conferences

Backup ....

ILC Basic Parameters and Comments

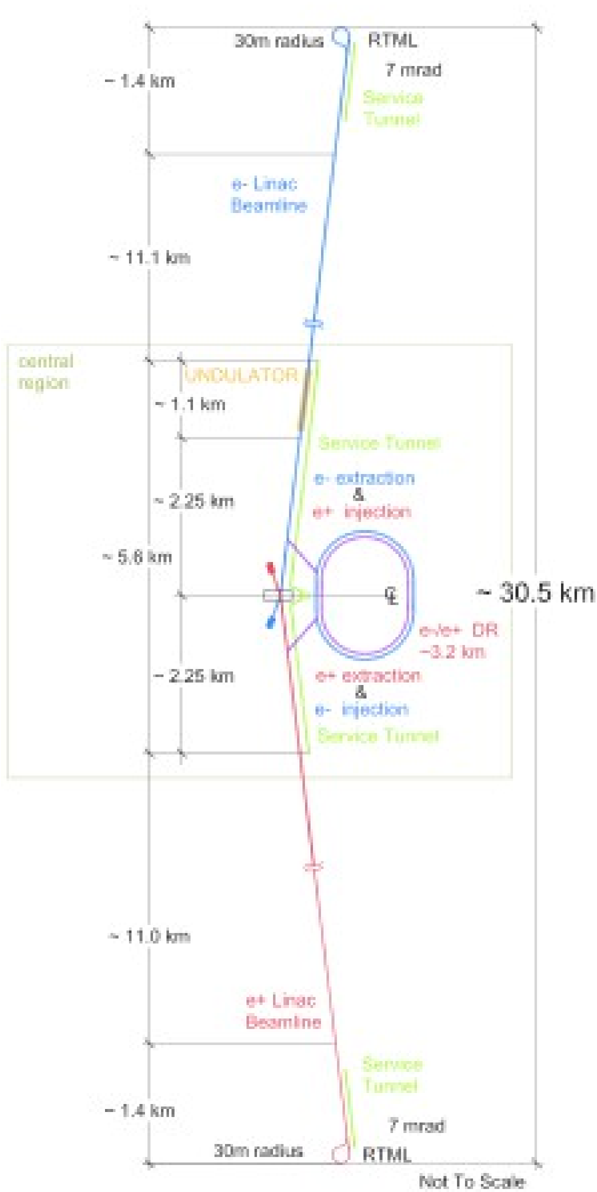
ILC design parameters		Comment
$\sqrt{s}$	91-500 GeV	500 GeV is baseline Option to upgrade to 1 TeV
$\mathcal{L}$	2×10^{34} cm^{-2}s^{-1}	~Factor 4 technically possible
P_{e^-}	>80%	Proven by SLC
P_{e^+}	upto 30%	~Conservative estimate
Length	~31 km	Current site allows for 50km

- Discussion on possible running scenarios has started

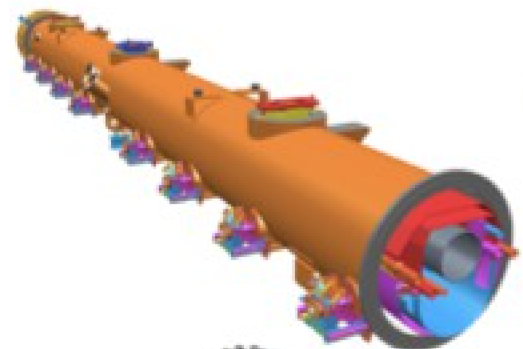
- Luminosity and running time to achieve at a ~25 years research programme
  That includes running at 250 GeV, 350 GeV, 500 GeV and 1 TeV

- No official statement yet but integrated luminosities indicated in following
  transparencies are realistic

ILC in a Nutshell



N. Walker, ILC School 2013



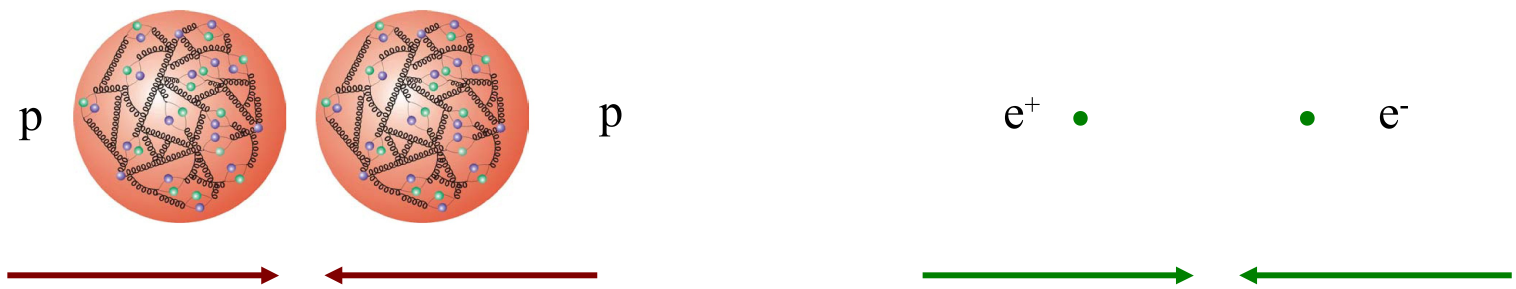
- **SCRF Technology**
  - 1.3GHz SCRF with 31.5 MV/m
  - 17,000 cavities
  - 1,700 cryomodules
  - 2×11 km linacs

Luminosity

$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}} \sqrt{\frac{\delta_{BS}}{\varepsilon_{n,y}}} H_D$$

η_{RF} ~ 40% for SCRF technology

-> efficient technology



Proton:

Composed particle (hadron)
Unknown energy of collision partners
Parasitic reactions
Strong interaction
=> Considerable physics background
Advantage: Scan of energy Range within one experiment

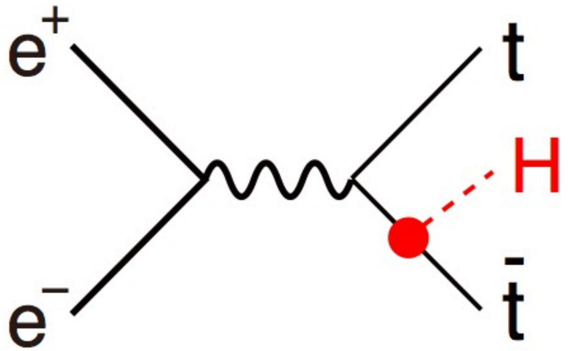
Electron:

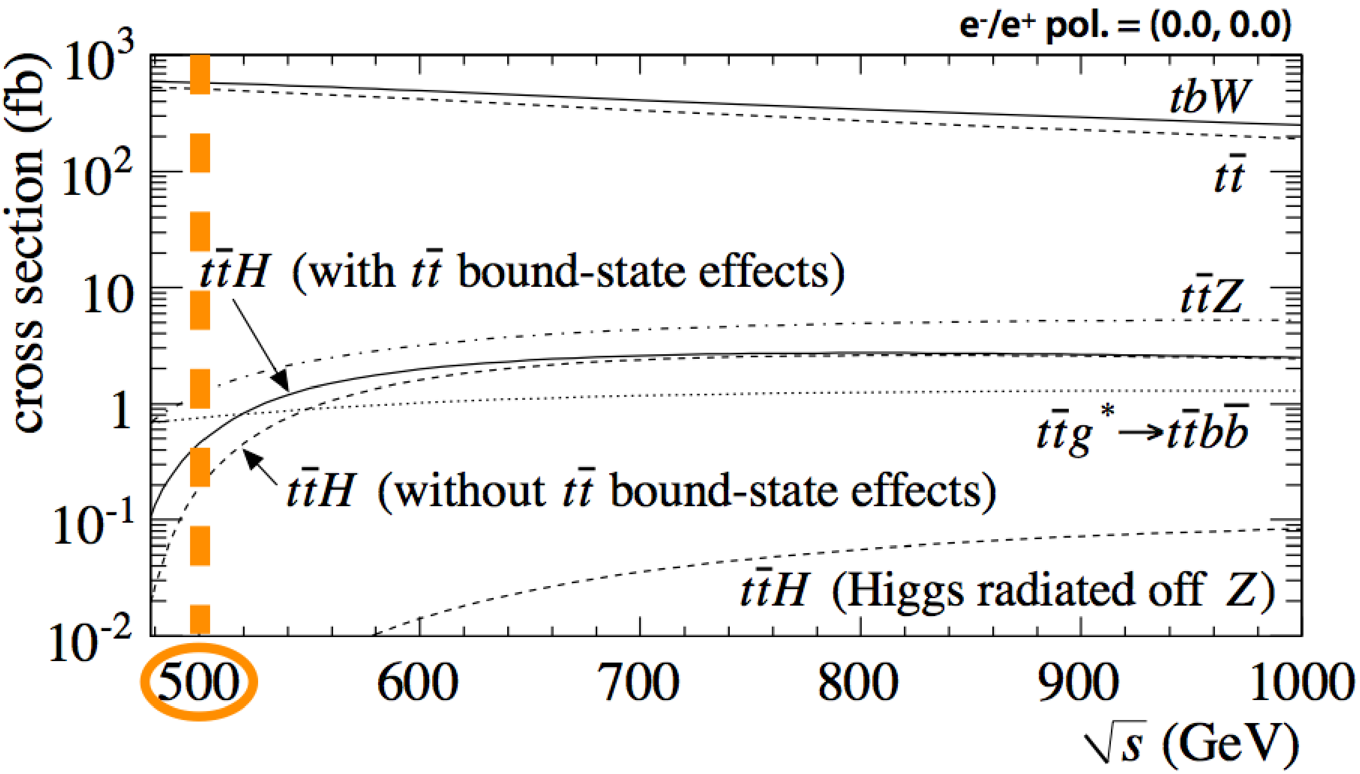
Elementary particle
Well known and adjustable energy of collision partners

Each energy point needs a New set of machine parameters

High precision measurements

Top Yukawa Coupling





- Coupling of Higgs to heaviest particle known today

- Up to eight final state jets

$\Delta g_{ttH} / g_{ttH}$	500 GeV	500 GeV + 1 TeV
Canonical	14%	3.2%
LumiUP	7.8%	2.0%

◄ ILC TDR

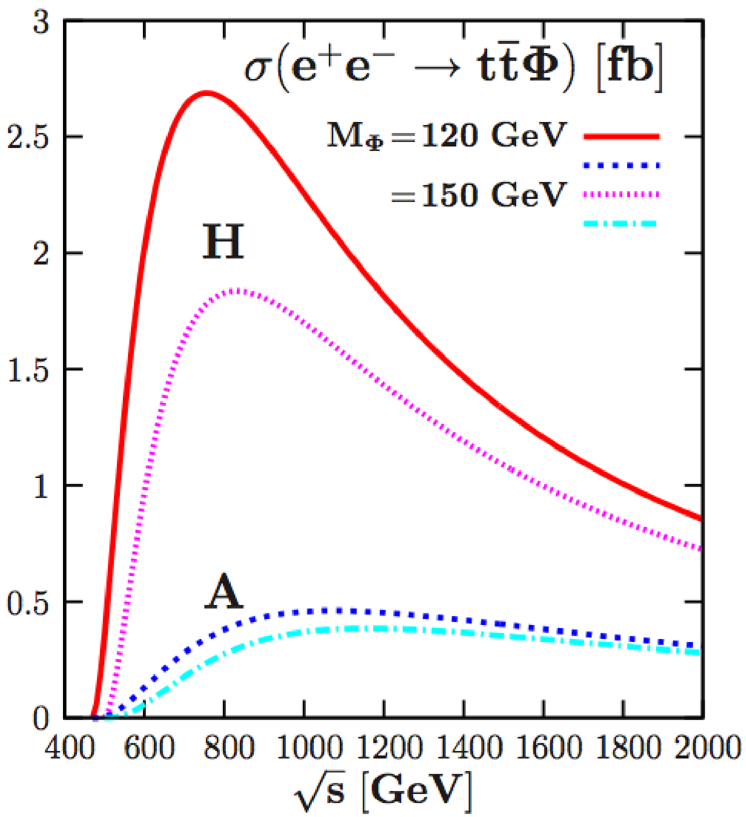
◄ Technically possible

R. Horiguchi et al.
T. Tanabe, T. Price

Higgs Quantum Numbers – CP via tth

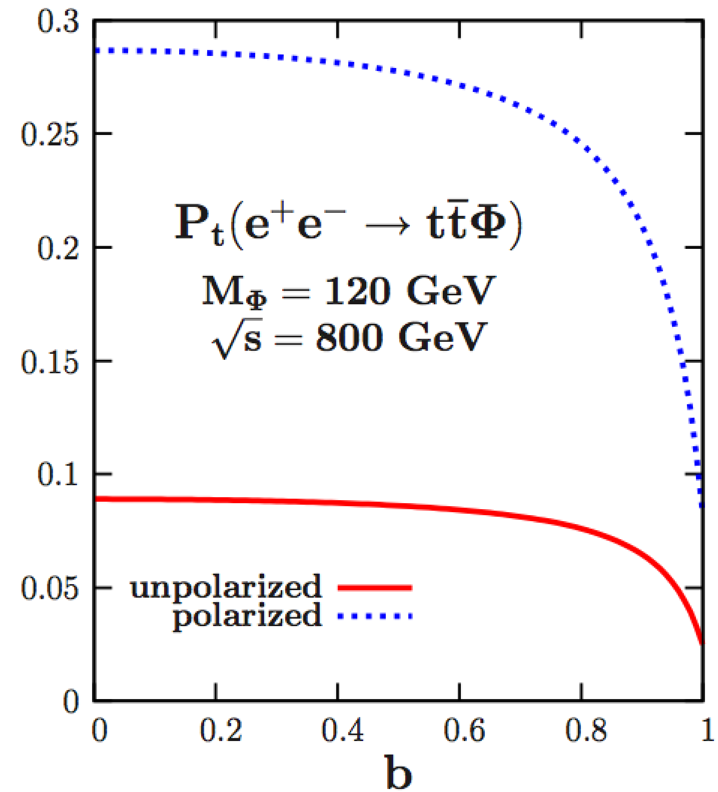
Direct coupling of top quark to CP odd and CP even scalar

Cross section



Dramatic differences for
CP odd and CP even scalar

Top quark polarisation



Sensitivity to CP odd admixture b
Merit of beam polarisation

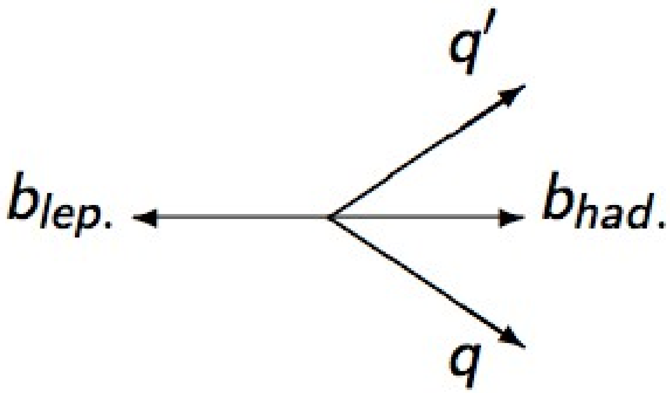
Determination of CP nature of scalar boson in an unambiguous way

Godbole et al., LCWS07

Experimental challenge b-charge reconstruction - Motivation

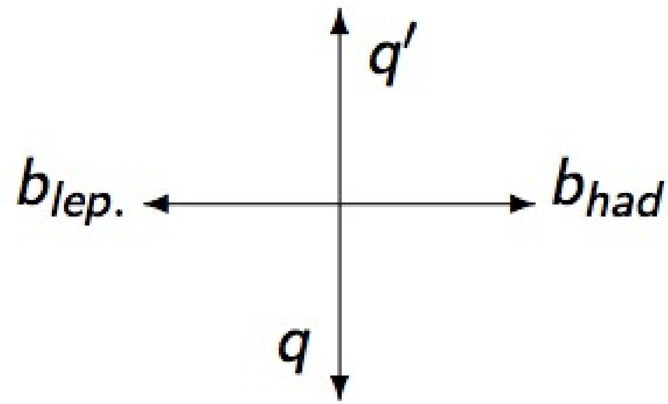
- To measure A_{FB} in fully hadronic decays there is no choice

- In semi-leptonic decays there is the charged lepton but ….



Right handed electron beam:

- mainly right handed tops In final state (V-A)
- Hard W in flight direction of Top and soft b's
- Flight direction of t from flight direction of W



Left handed electron beam:

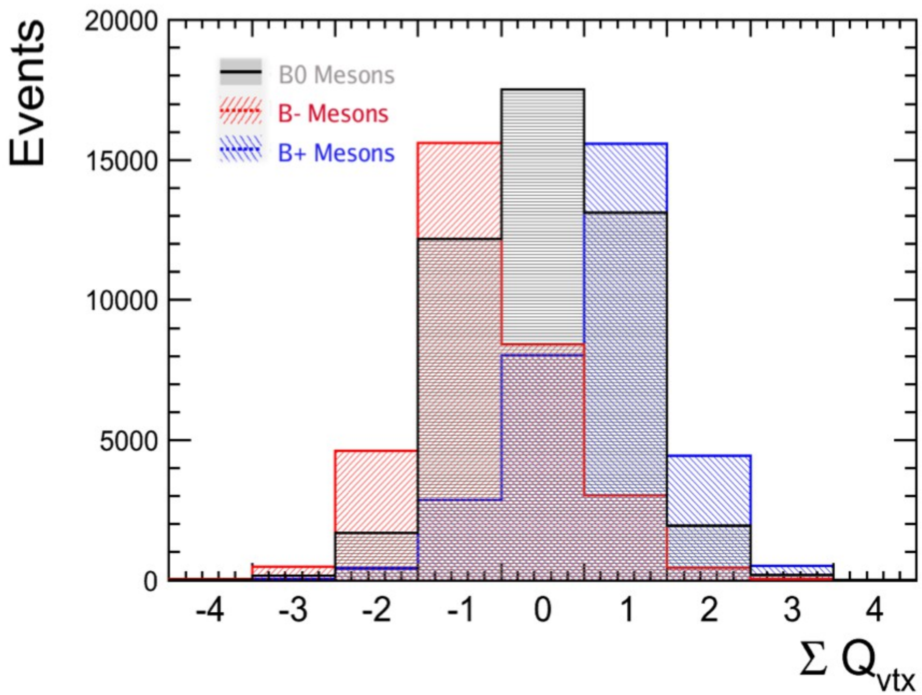
- mainly left handed tops
- Hard b in flight direction of Top and soft W's
- Flight direction of t from flight direction of b

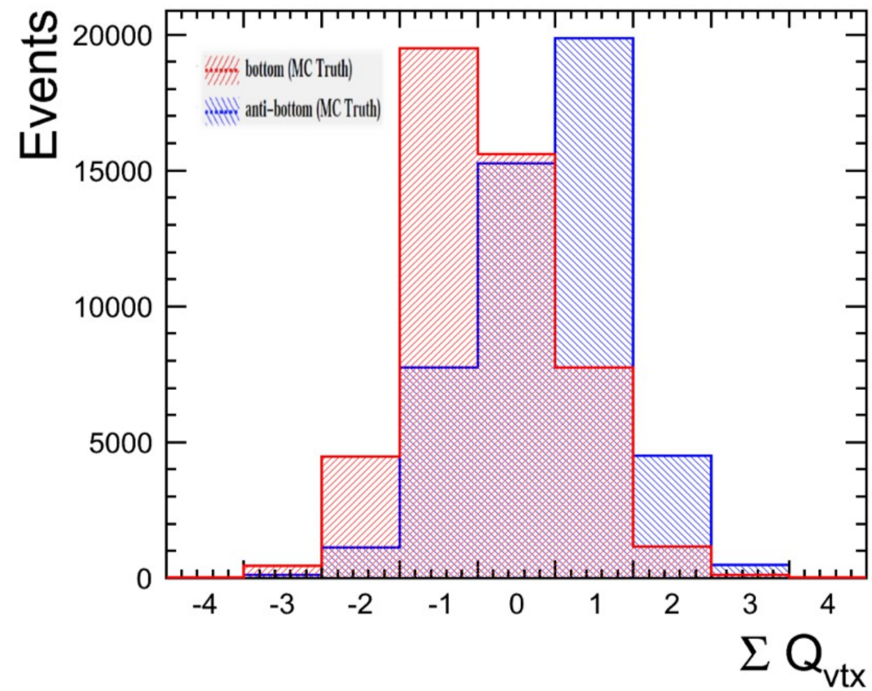
=> Wrong association ↔ top flip

Measurement of b-charge to resolve ambiguities

Measurement of b quark charge

(N.B. At example of fully hadronic analysis, PhD M.S. Amjad)





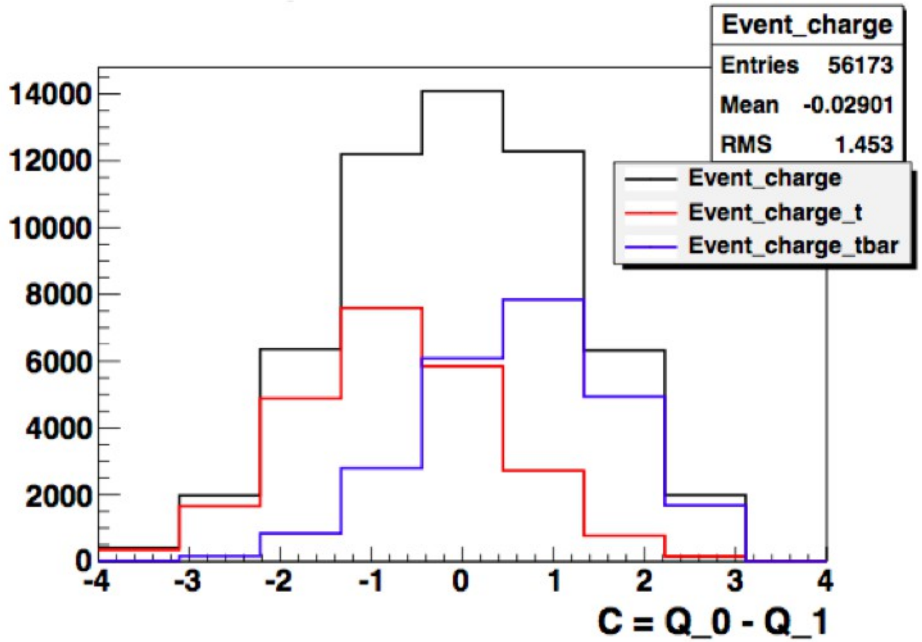
- LC vertex and tracking system should allow for determination of b-meson (b-quark) charge

- B-quark charge measured correctly in about 60% of the cases
  Can be increased to 'arbitrary' purity on the expense of smaller statistics
- However ~25% are “accidentally” correct measurements

- LC software (`LCFIPlus` package) not yet optimised for vertex charge measurement

Optimisation of b-quark charge is major topic in ongoing studies and real challenge of LC detectors

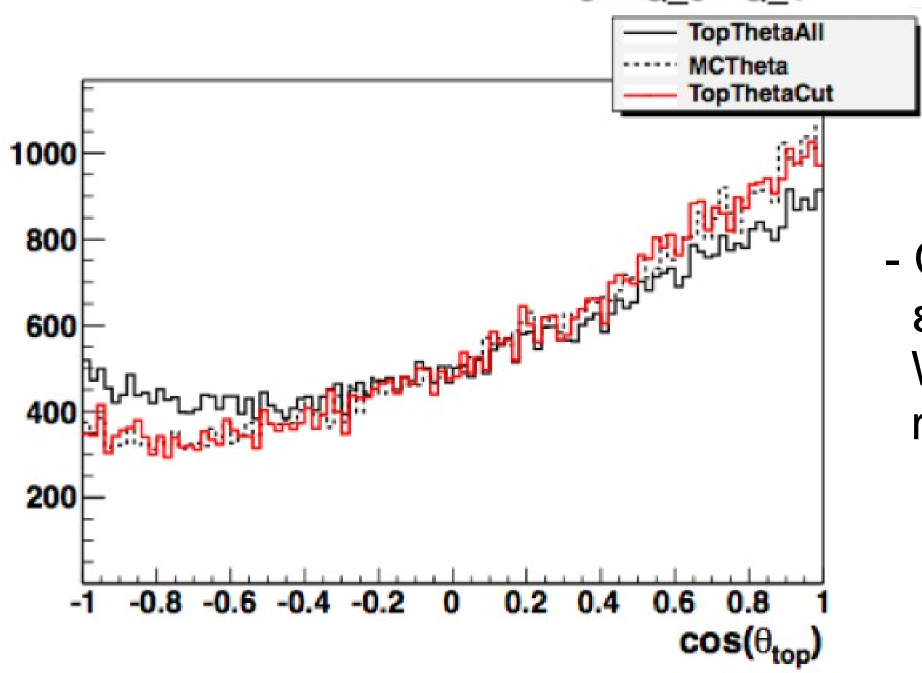
Top polar angle using b quark charge – Semi leptonic case



Event charge C = b1 -b2

In SL can compare charge C with lepton charge to select clean sample

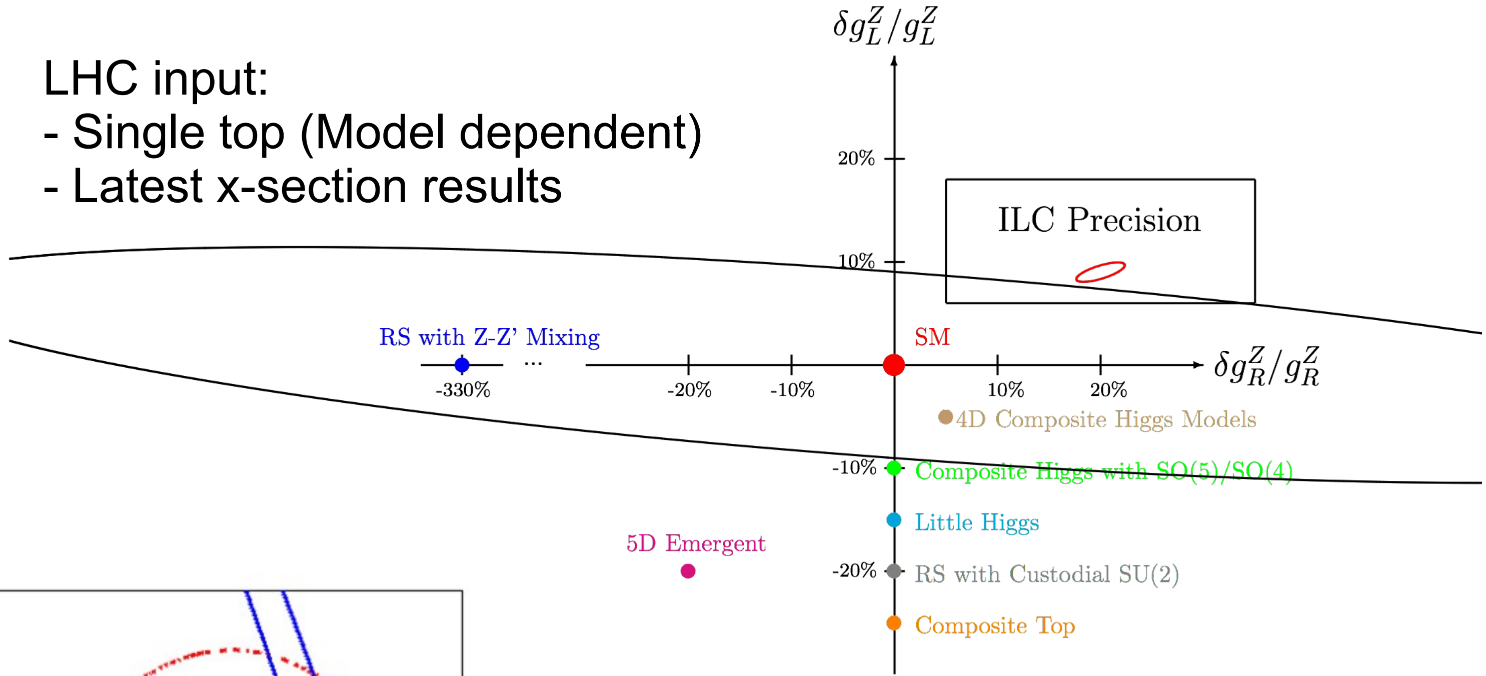
Use only events with correct C or C=0 (plus another cut on the Lorentz Factor)

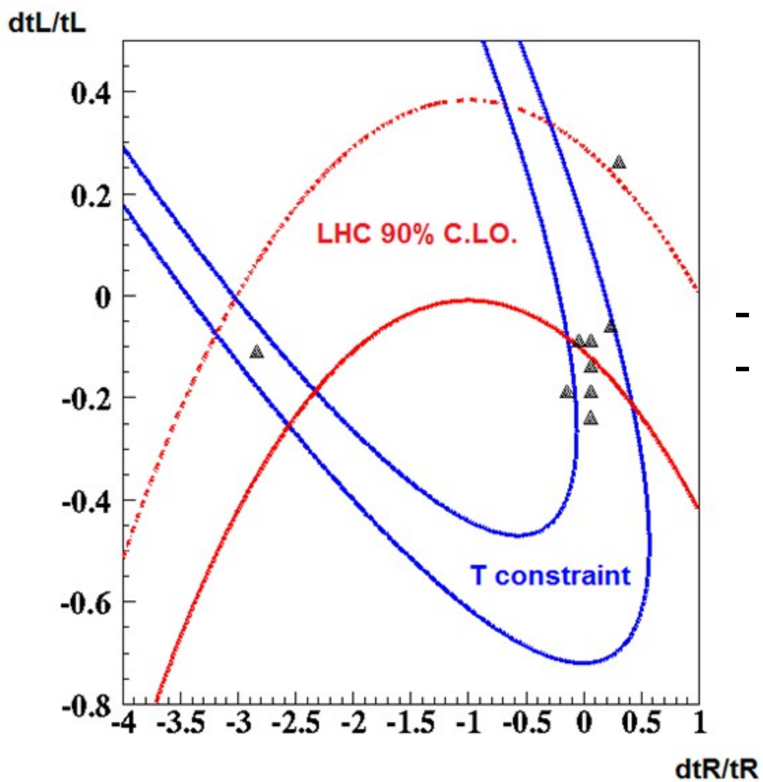


- Clean reconstruction of top quark direction
  $\varepsilon \sim 30\%$
  Will improve with improving charge reconstruction

Comparison with current LHC results

LHC input:
- Single top (Model dependent)
- Latest x-section results





- Result based on latest x-section results
- Takes into account possible sign flip of couplings

CP Violation – Role of Higgs exchange?

Study by Francois Richard

Higgs sector

- It should be noted that for what concerns the Higgs sector (non-minimal) contribution there could be a much larger enhancement for the 3d generation **df~m³f** at one-loop
- Higgs exchange is larger near threshold and the sensitivity for Re(F2A) drops to 0 at 500 GeV

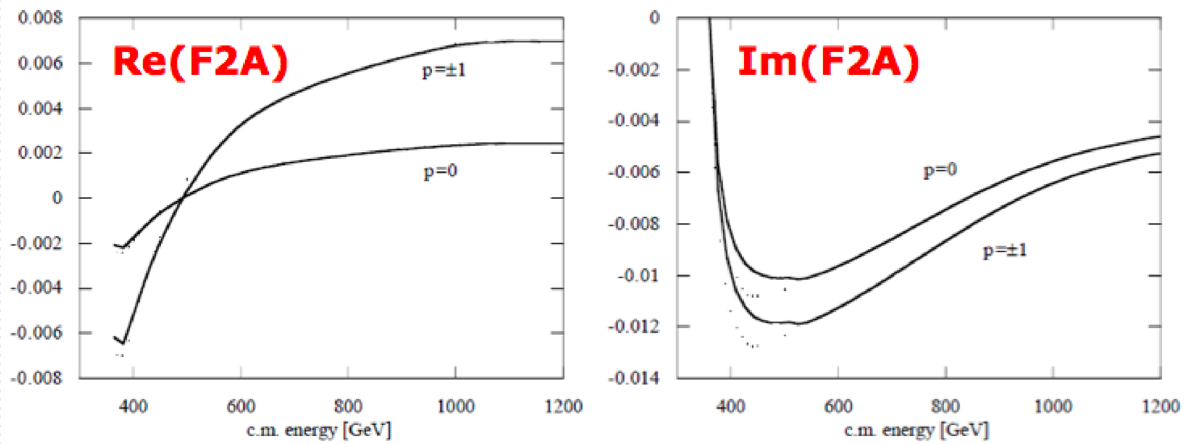
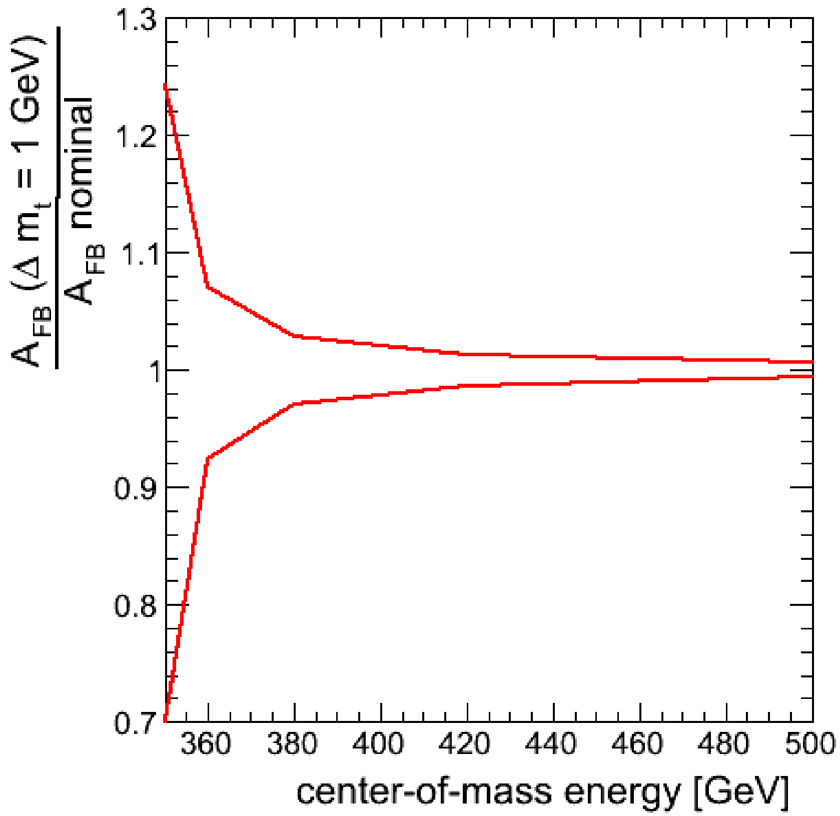


Fig 1: Ratios r_1 (left figure) and r_2 (right figure) for the optimized dispersive and absorptive observables $\mathcal{O}_\pm(i)$, $i = 1, 2$ defined in [6] for $m_t = 180$ GeV, $m_{\varphi_1} = 100$ GeV, and $\gamma_{CP} = 1$.

8

Exchange of CP Violating Higgs is most probable source of CP violation In tt production (dixit Werner Bernreuther)

From threshold to continuum



Influence of the top quark mass on x-sec and A_{FB}

- very pronounced below $\sqrt{s}$ = 360 GeV
- 2.9%/GeV at $\sqrt{s}$ = 380 GeV
- 1.3%/GeV at $\sqrt{s}$ = 420 GeV
- 0.6%/GeV at $\sqrt{s}$ = 500 GeV

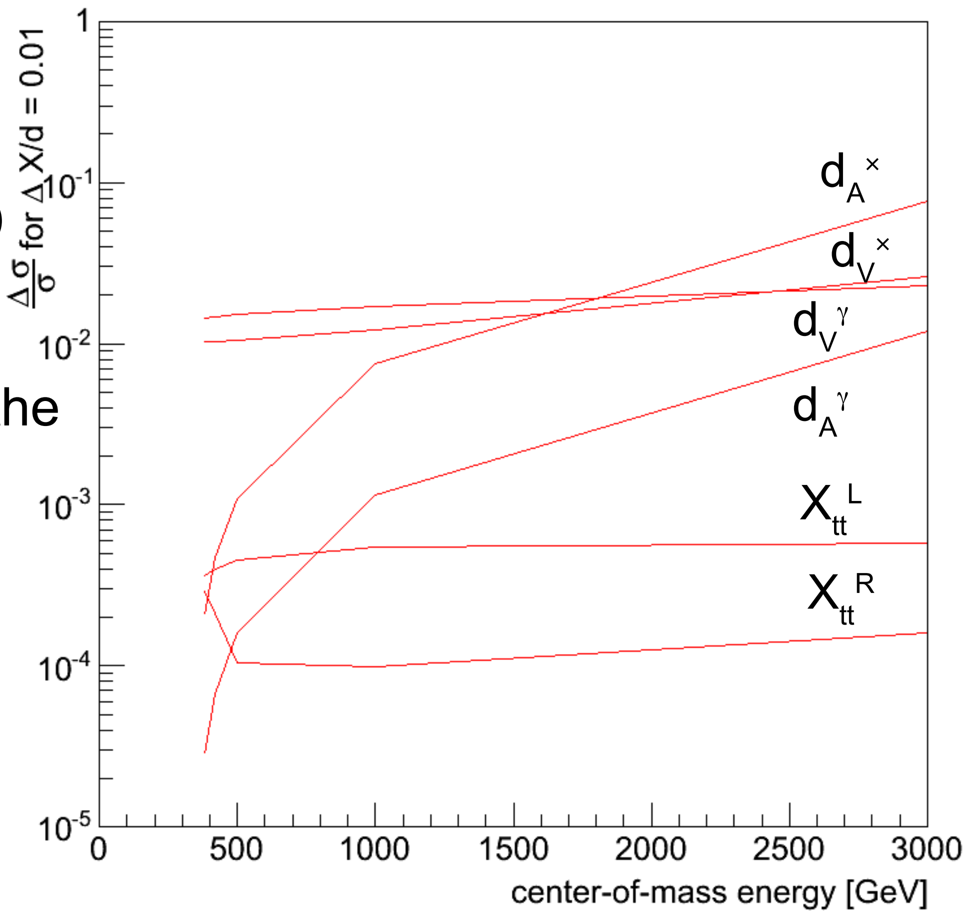
With the assumption of a 100 MeV pole mass measurement at threshold, the remaining uncertainty is one per mil or less above 420 GeV

Impact of x-section on New Physics

Dimension 6 effective operators
(~equivalent role to anomalous form factors)
have been implemented in WHIZARD...

Allow to map the dependence on √s of the impact of new physics on given observable

May help to explore the sensitivity of new/additional observables



Potential systematic uncertainties

- Luminosity: Critical for cross section measurements
  Expected precision 0.1% @ 500 GeV

- Beam polarisation: Critical for asymmetry measurements
  Expected to be known to 0.1% for e- beam
  and 0.35% for e+ beam

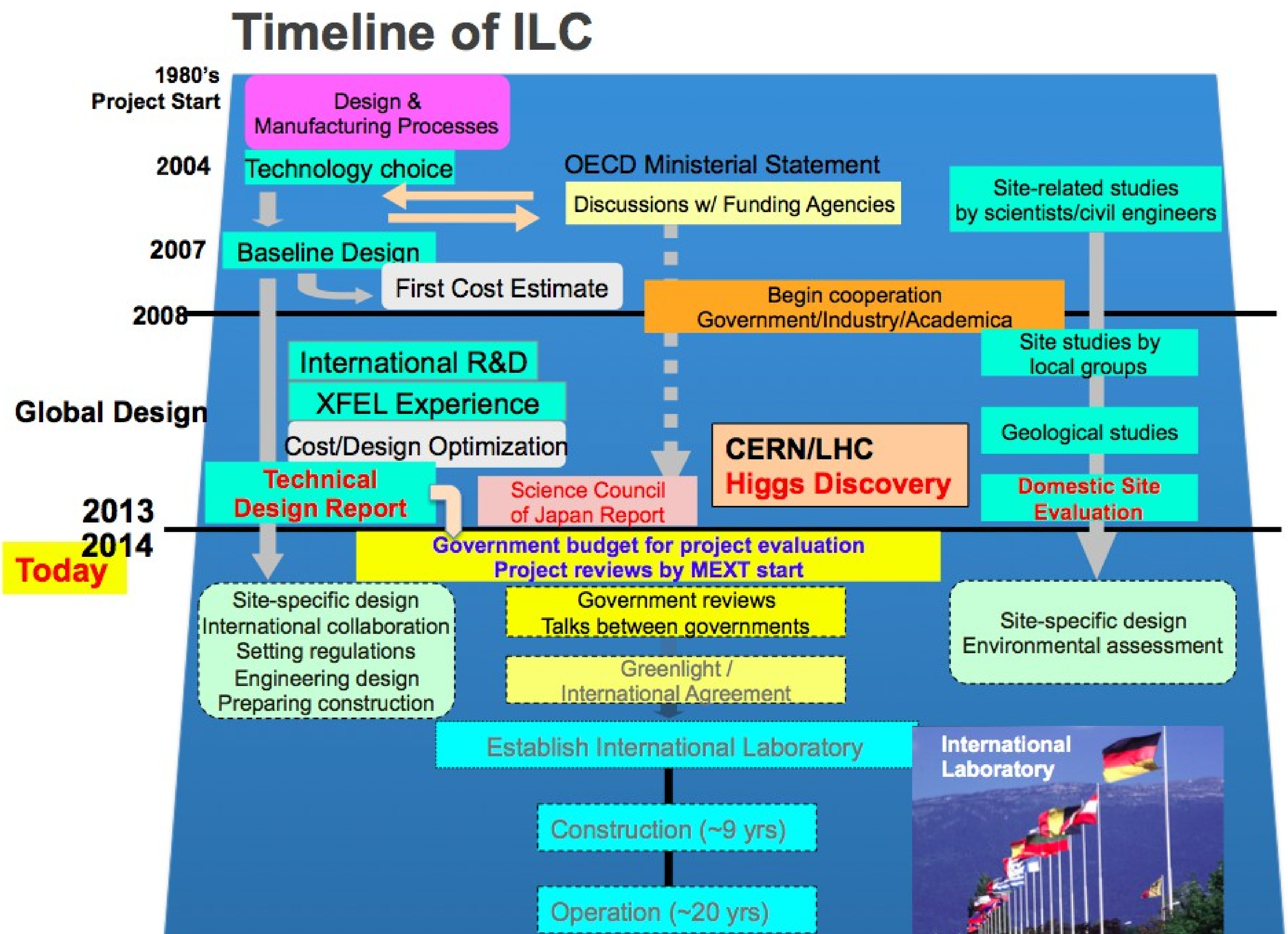
- Migrations/Ambiguities: Critical for A_{FB}:
  PFLOW important for selection of 'clean events' but maybe subleading w.r.t. jet clustering
  Control of b charge is most relevant topic !!!!

- Other effects: b-tagging, passive material etc.
  LEP1 claims 0.2% error on R_b -> guiding line for LC

Under discussion with theory groups:

- Consideration full 6f final state (Interference with single top and ZWW)
- Electroweak NLO predictions (Correction LO → NLO ~ 15%)
- Update and maintenance of event generators (WHIZARD, MADGRAPH etc.)

ILC Roadmap



Remark R.P.: MEXT report in March 2016