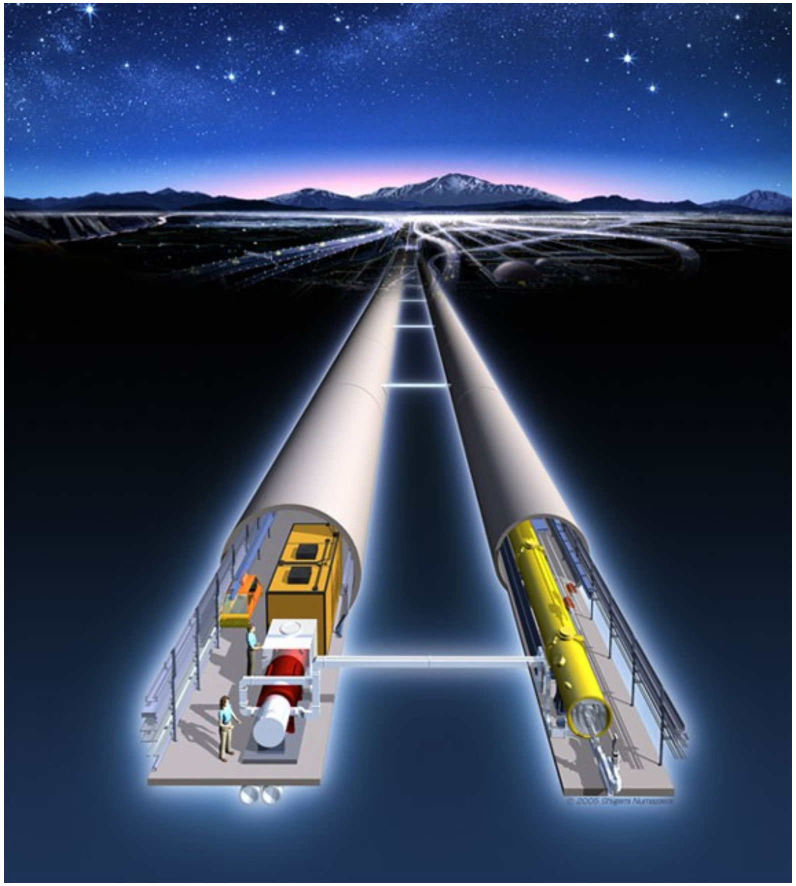
Overview on ILC project

Physics Case and political developments



Roman Pöschl
Directeur de Recherche of CNRS

R.P. is indebted to many authors from whom I have reused their material

Top@LC15 Valencia/Spain – June 2015

Outline of talk

- Chapter 1: Introduction

- Chapter 2: Higgs Physics at the ILC

- Chapter 3: BSM Physics at the ILC

- Chapter 4: Running Scenarios

- Chapter 5: Latest political developments

New reference documents:

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

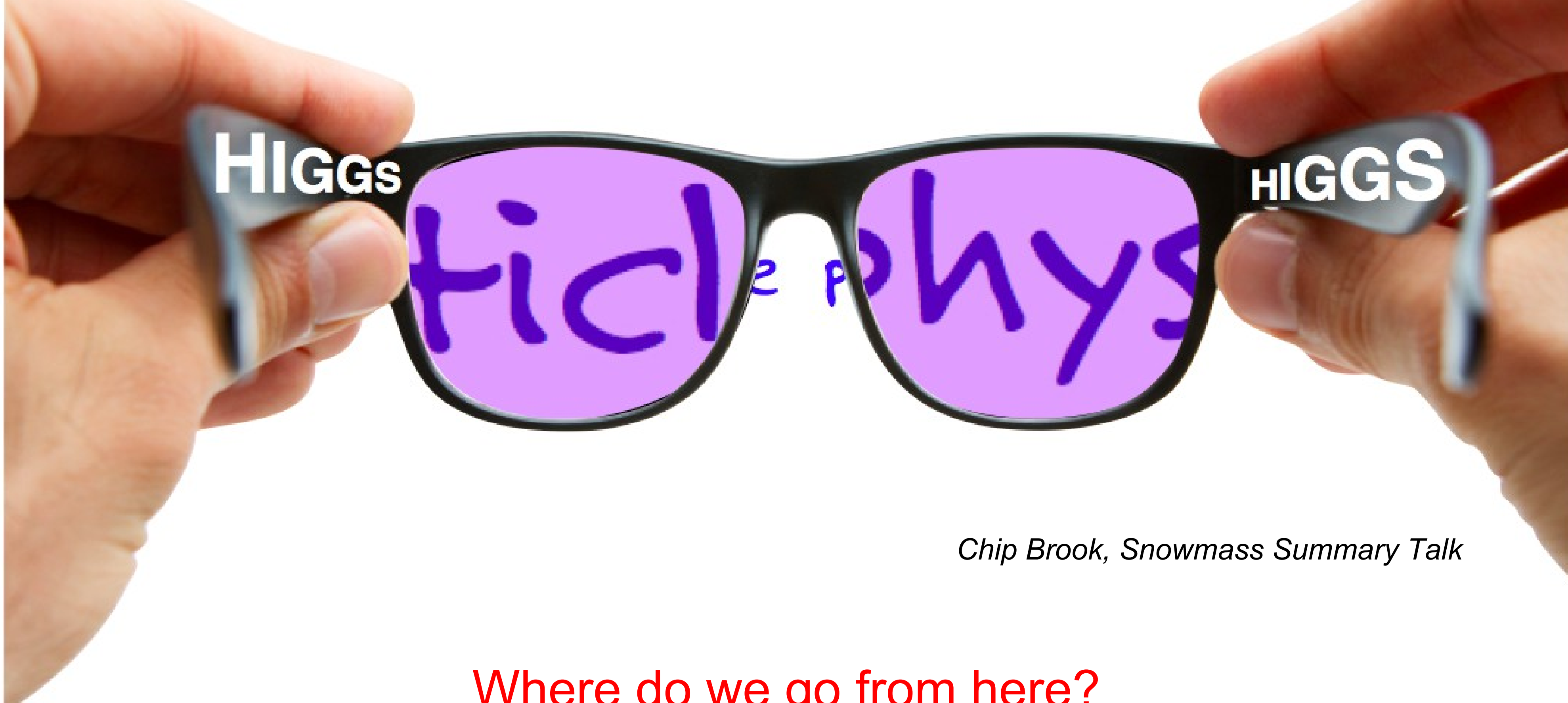
1. Introduction

Coronation of the Standard Model

and

First step on a road yet largely unexplored

Slightly modified citation of Barbieri arXiv:1309.3447



Chip Brook, Snowmass Summary Talk

Where do we go from here?

Open questions

How to make progress?

1) Collisions at energies well above the electroweak scale
- Requires now and in the foreseeable future Hadron colliders
- Direct production of new particles
- Produce large number of rare particles and study rare decays
- First precision measurements of key particles of electroweak theory

-> High energy, High luminosity LHC

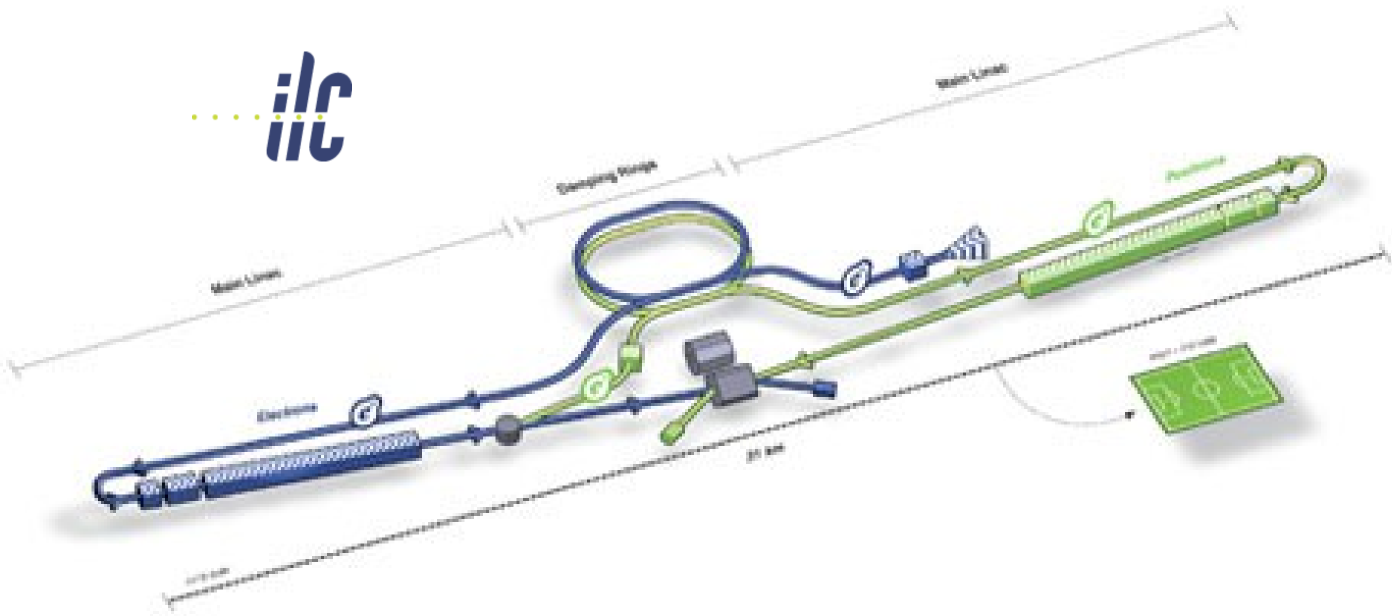
2) e+e-Collisions at energies at the electroweak scale
- Probe the electroweak scale with high precision
- ... in particular particles that carry the “imprint of the Higgs Field such as W, Z and top”

-> LC

3) e+e- collisions at 'smaller' energies
- Requires high luminosity to get sensitive to tiny quantum effects

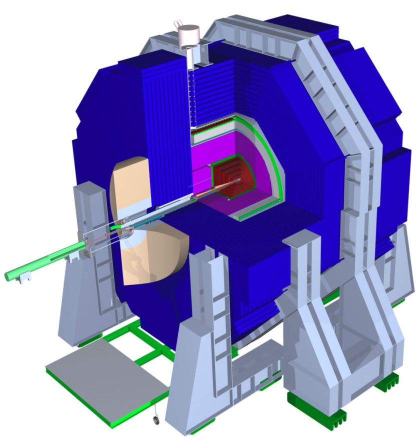
-> SuperKEKB

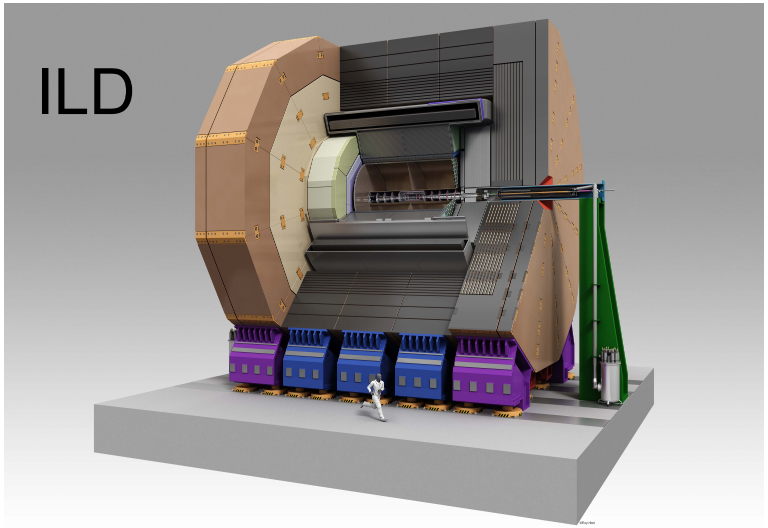
ILC Project - Machine and detectors



ILC design parameters	
$\sqrt{s}$	91-500 GeV
$\mathcal{L}$	2×10^{34} cm^{-2}s^{-1}
P_{e^-}	>80%
P_{e^+}	~30%
Length	~31 km

SiD





Machine TDR in 2013 + DBD for detectors

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

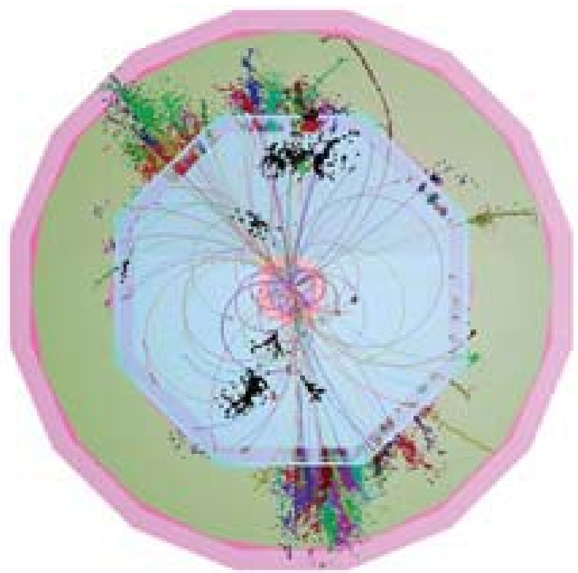
(Quark tagging c/b)

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

(W/Z masses with jets)

Hermeticity : θ_{min} = 5 mrad

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

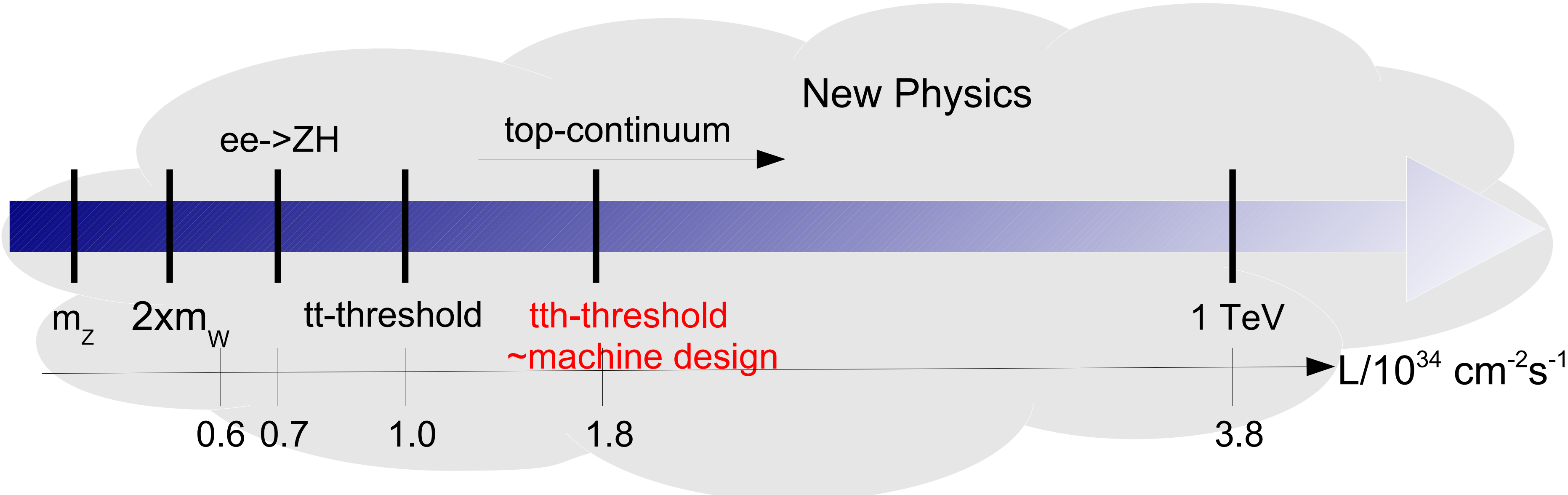


Final state will comprise events with a large number of charged tracks and jets(6+)

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

- Particle Flow Detectors

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

Not covered in this talk

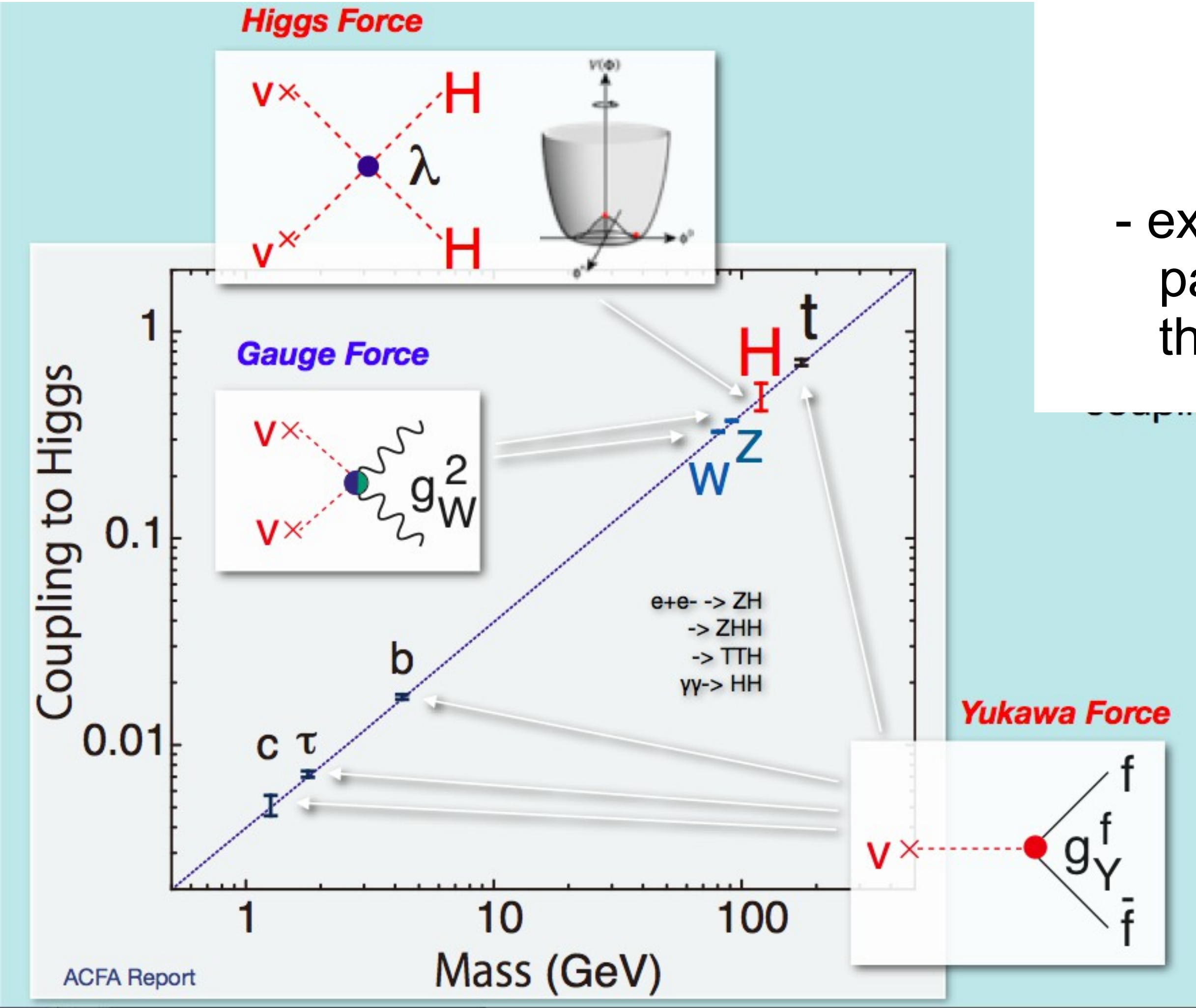
- ILC in GigaZ option
  - Remeasurement of Weak Mixing angle with polarised beams
  - W Mass measurements

- W and Z physics
  - Triple Gauge Boson Couplings
  - Longitudinal Boson Scattering

- Two fermion processes other than ee -> tt

2. Higgs Physics at the ILC

Precision Higgs Physics



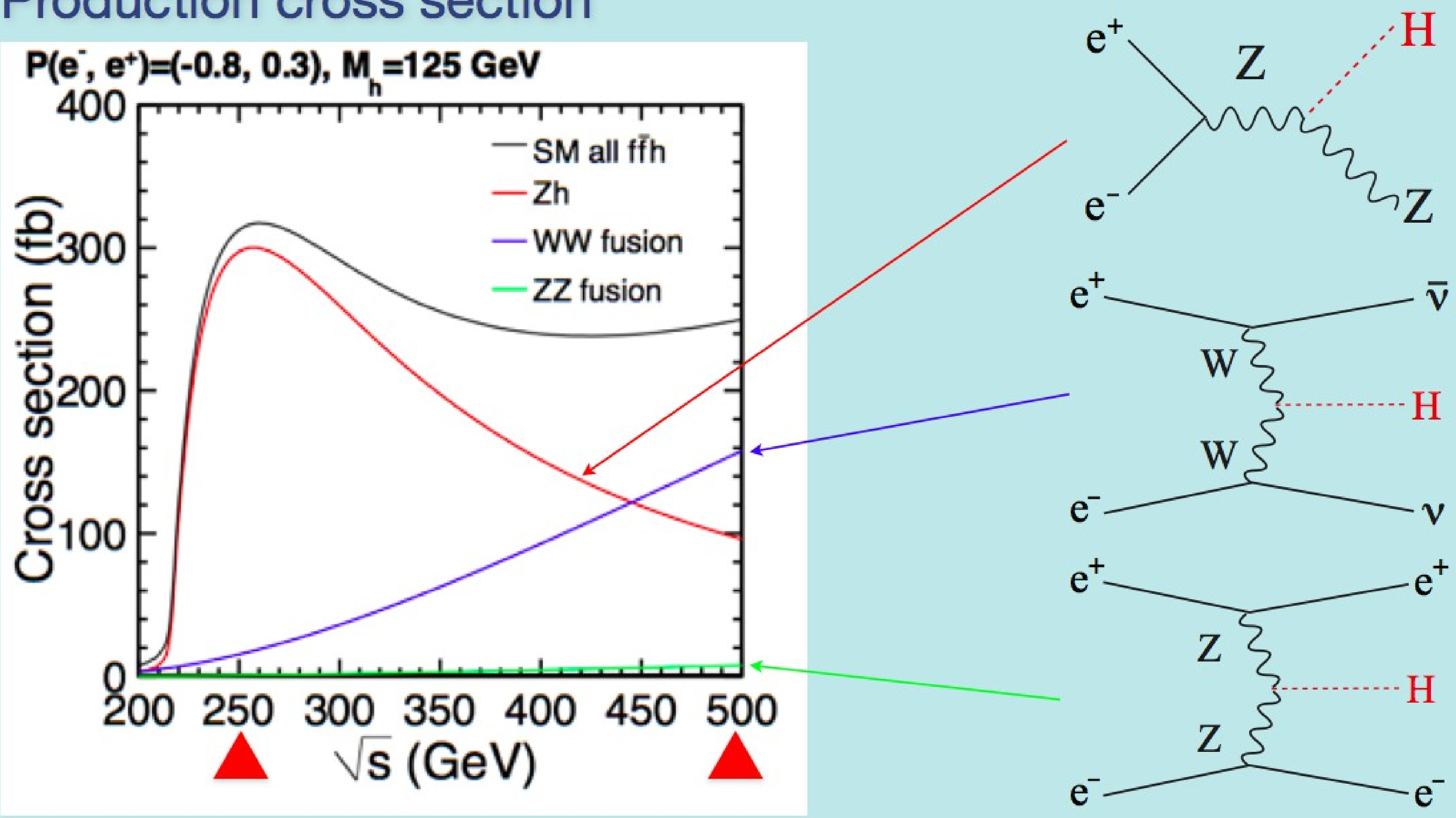
- exact correlation between particle masses couplings to the Higgs in Standard Model

- Any tiny deviation is New Physics

	ΔhVV	$\Delta h\bar{t}t$	$\Delta hb\bar{b}$
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	< 1%	3%	10%[a], 100%[b]
LHC 14 TeV, 3 ab^{-1}	8%	10%	15%

- Need precision on Higgs couplings at 1% level

Production cross section

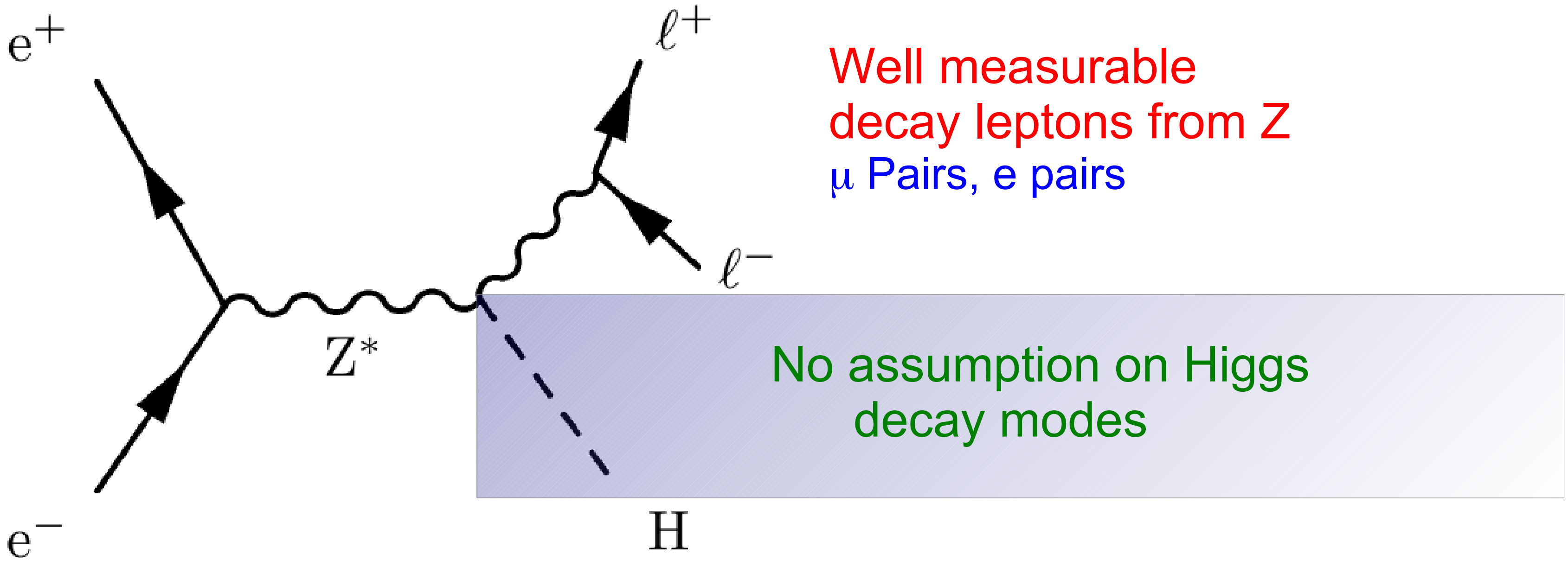


ZH dominates at 250 GeV
(~80k ev: 250 fb^{-1})

ννH takes over at 500 GeV
(~125k ev: 500 fb^{-1})

K. Fujii, LC School 2014

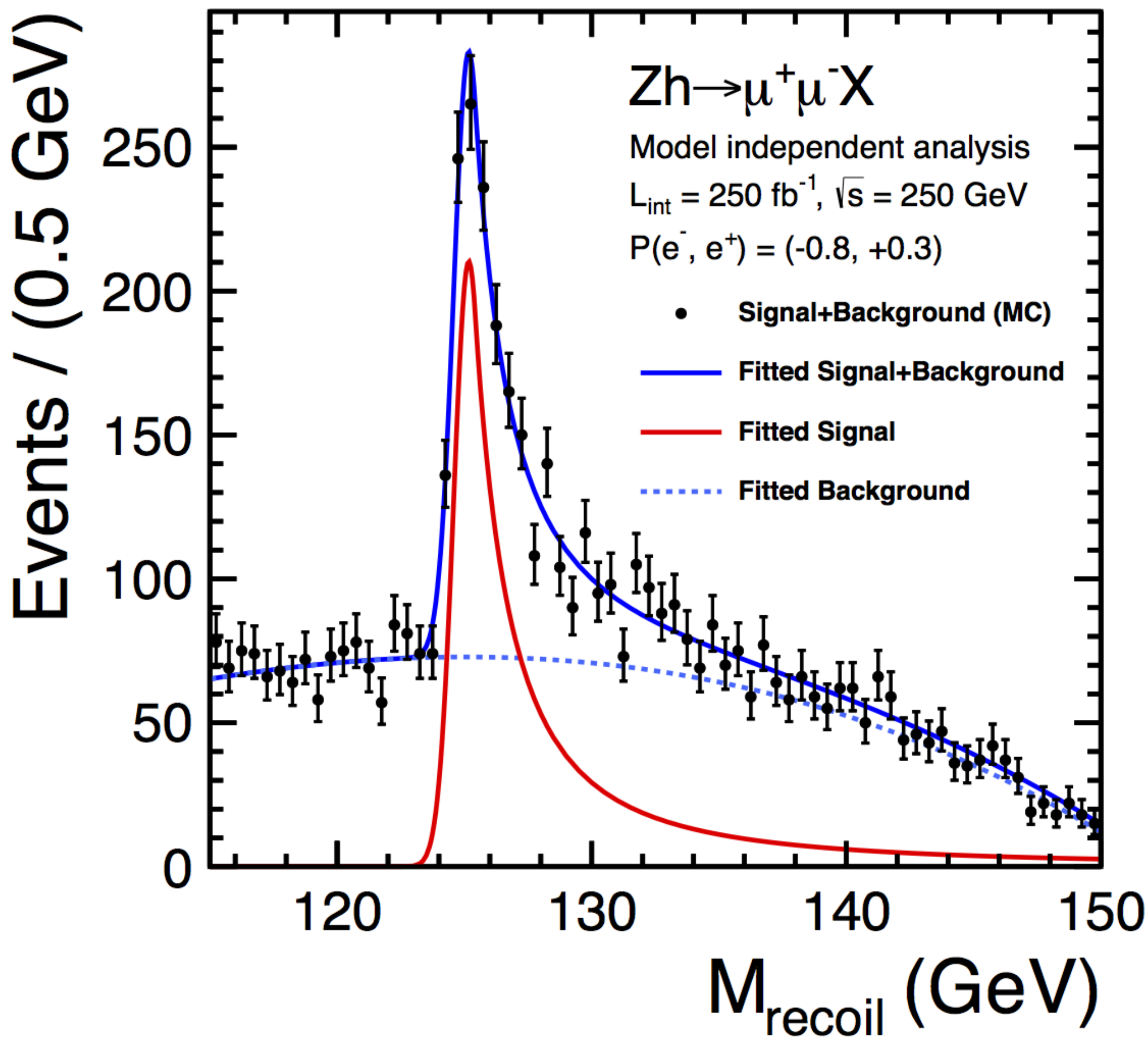
Higgs Mass and ZZH coupling by
Model Independent
measurement



Well measurable decay leptons from Z
μ Pairs, e pairs

Higgs Recoil Mass: $M_h^2 = M_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$

Full simulation study at 250 GeV

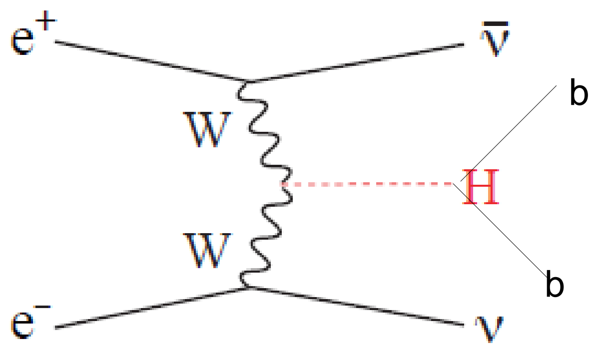


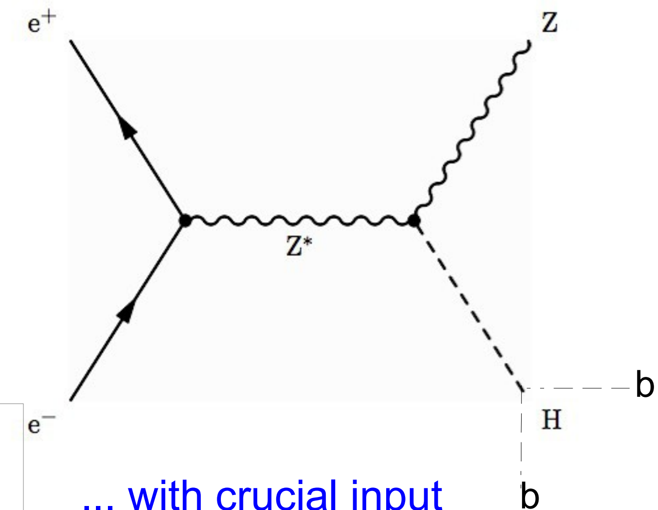
$$M_h = 125.3 \pm 0.03\,\mathrm{GeV}$$

$$\sigma_{ZH} = 10.32 \pm 0.37\,\mathrm{fb},\ 3.6\%$$

The Total Higgs Width

Can be derived from <u>model independant</u> measurements

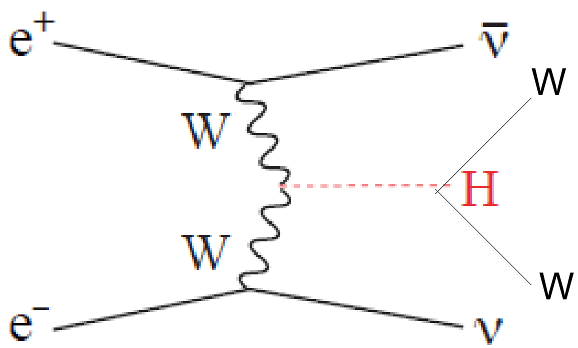


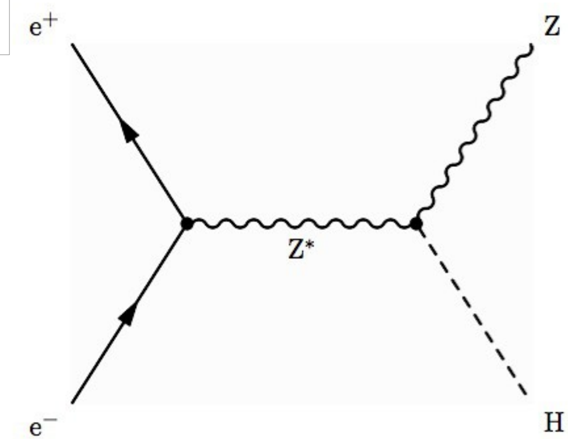


Requires running at 500 GeV

$$\Gamma_t \sim \frac{(\sigma_{\nu\bar{\nu}b\bar{b}}/\sigma_{Zb\bar{b}})^2}{(\sigma_{\nu\bar{\nu}WW}/\sigma_{ZH})} \times \sigma_{ZH}$$

... with crucial input from 250 GeV running



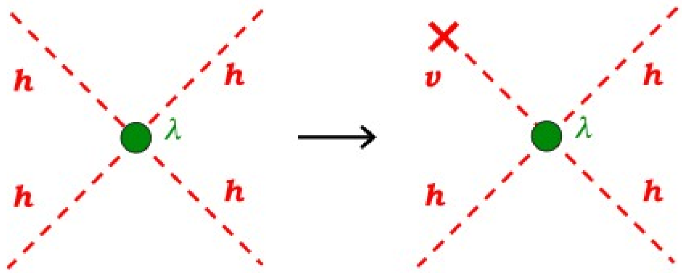


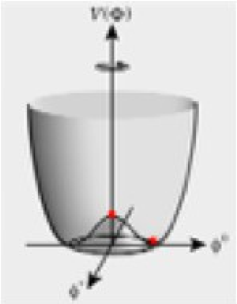
Current prospects - $\delta\Gamma_{tot}$ ~ 5% @ 500 GeV

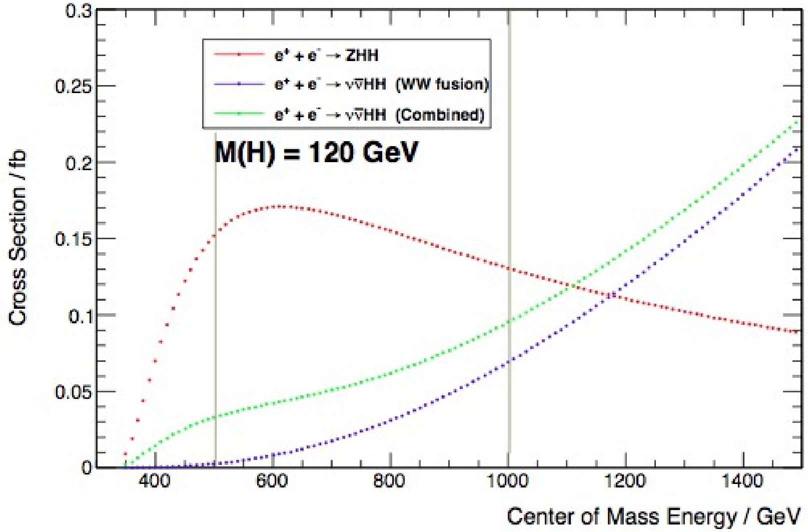
~ 4% @ 1 TeV (2% technically possible)

Higgs self-coupling

Existence of hhh coupling =
Direct evidence of vacuum condensation

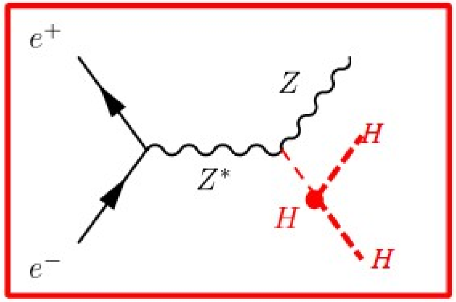




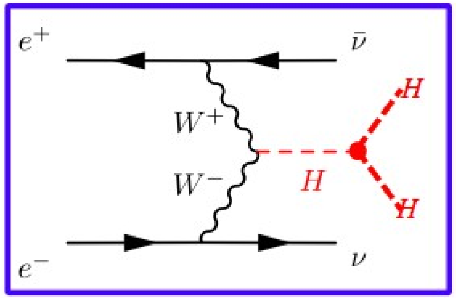


Challenging measurement because of:

- Small cross section (Zhh 0.2 fb at 500 GeV)
- Many jets in the final state
- ***Presence of interference diagrams***



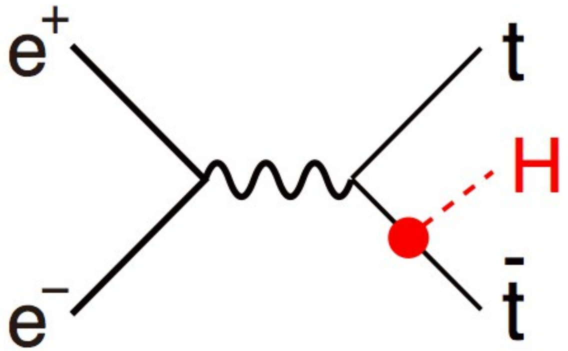
arXiv:1310.0763	ILC500	ILC500-up	ILC1000	ILC1000-up
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000
$\int \mathcal{L}dt$ (fb^{-1})	500	1600‡	500+1000	1600+2500‡
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$
$\sigma(ZHH)$	42.7%		42.7%	23.7%
$\sigma(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%
λ	83%	46%	21%	13%



T. Tanabe, K. Fuji, LCWS14

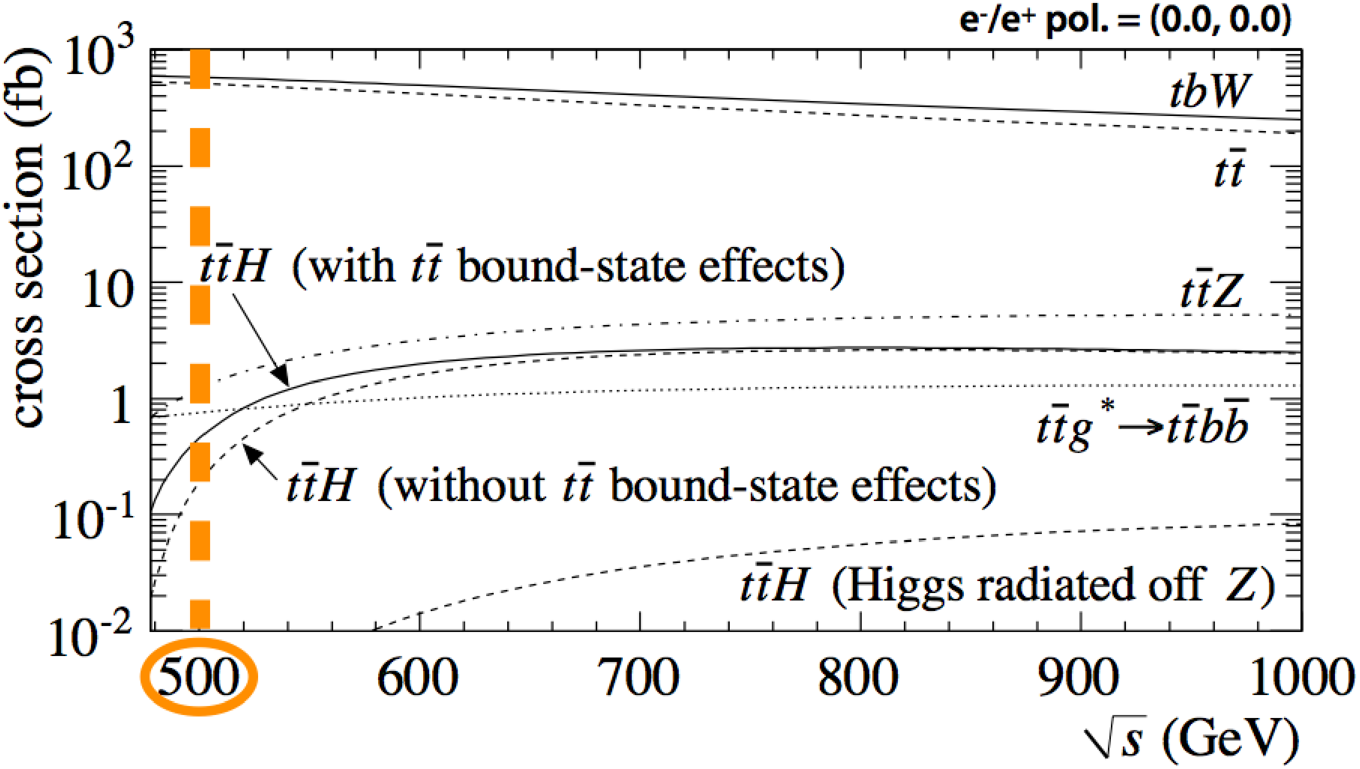
Hard(est) measurement, 10% accuracy seems possible

Top Yukawa Coupling



- Coupling of Higgs to heaviest particle known today

- Up to eight final state jets



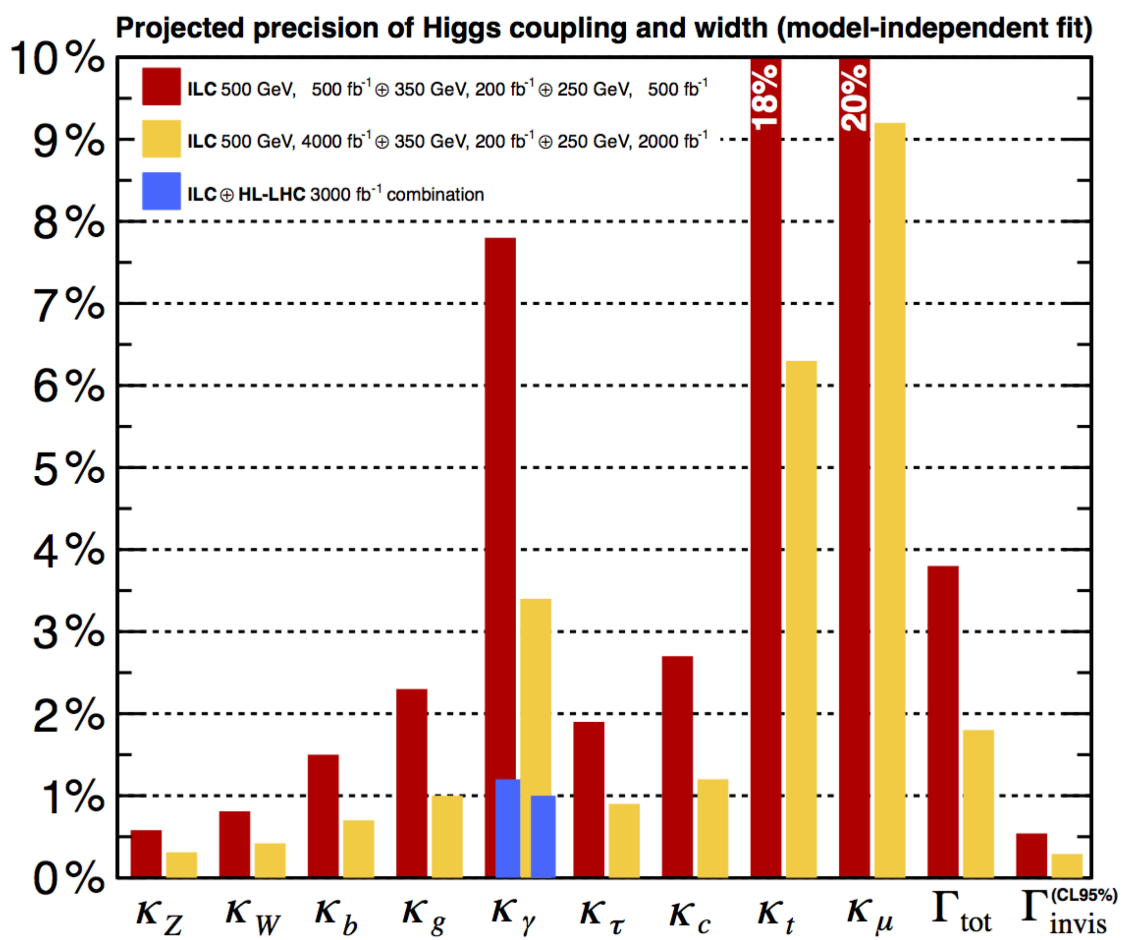
$\Delta g_{ttH} / g_{ttH}$	500 GeV	500 GeV + 1 TeV
Canonical	14%	3.2%
LumiUP	7.8%	2.0%

← ILC TDR

← Technically possible

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

Individual Couplings to the Higgs

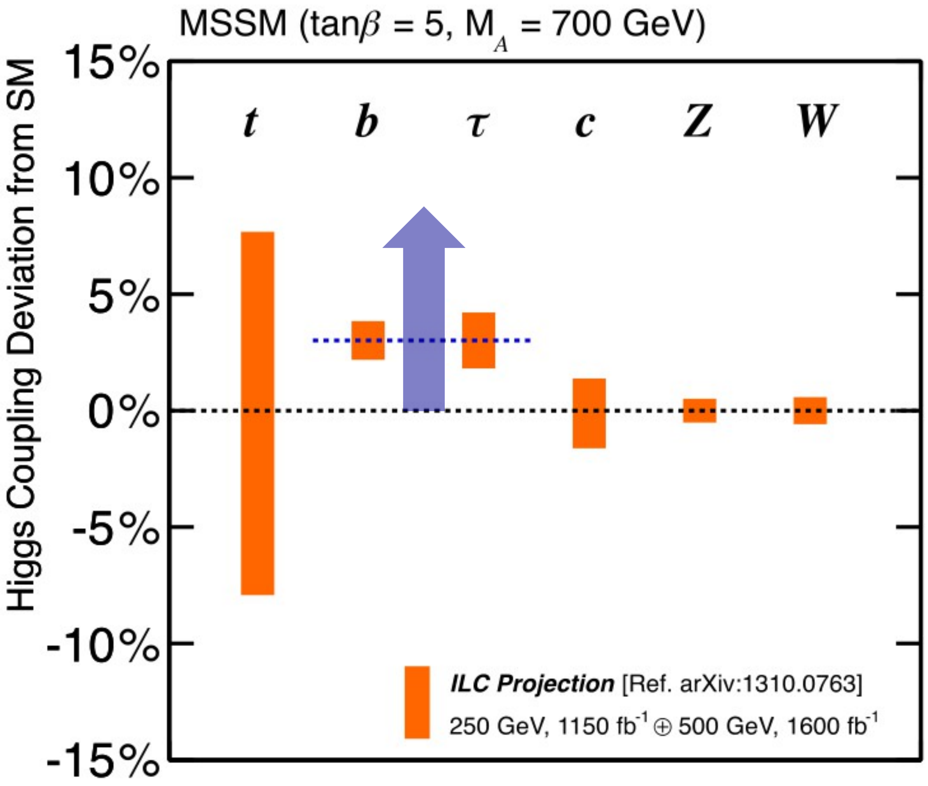


arxiv:1506.05992

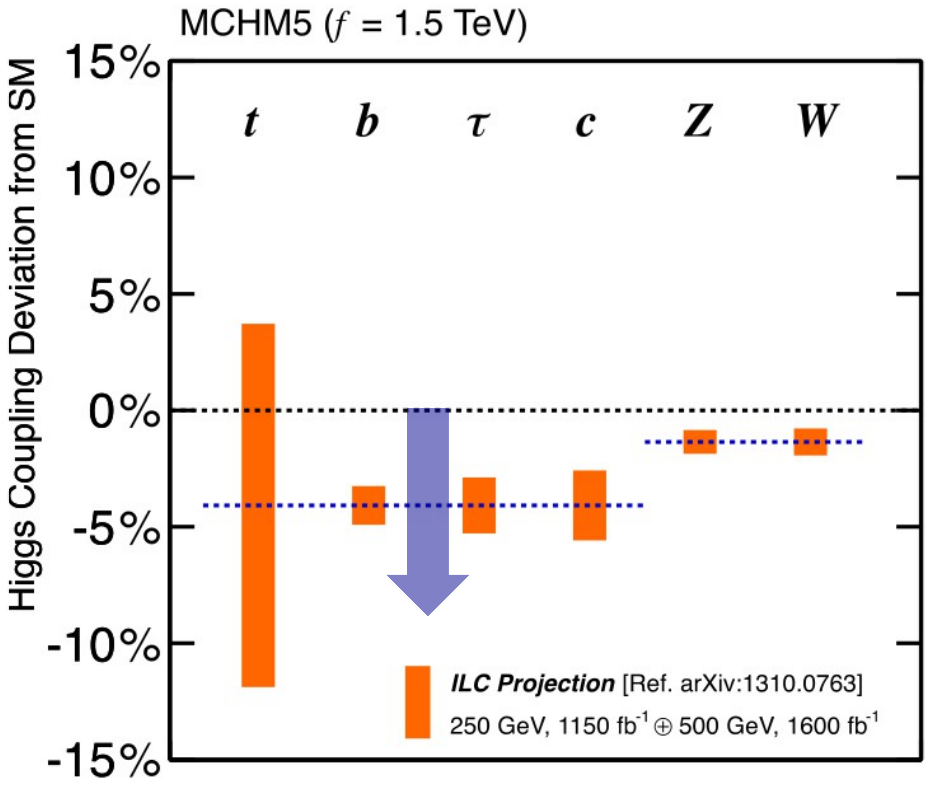
- Precise measurements of relevant Higgs couplings
- Precision matters: Detect deviations, for example due to extended Higgs sectors (SUSY,composite, ...):Expected on the 10% - 15% level in fermions,on the few % level in gauge bosons in typical Two-Higgs-Doublet models (Chapter 4)

Elementary v.s. Composite

Supersymmetry (MSSM)



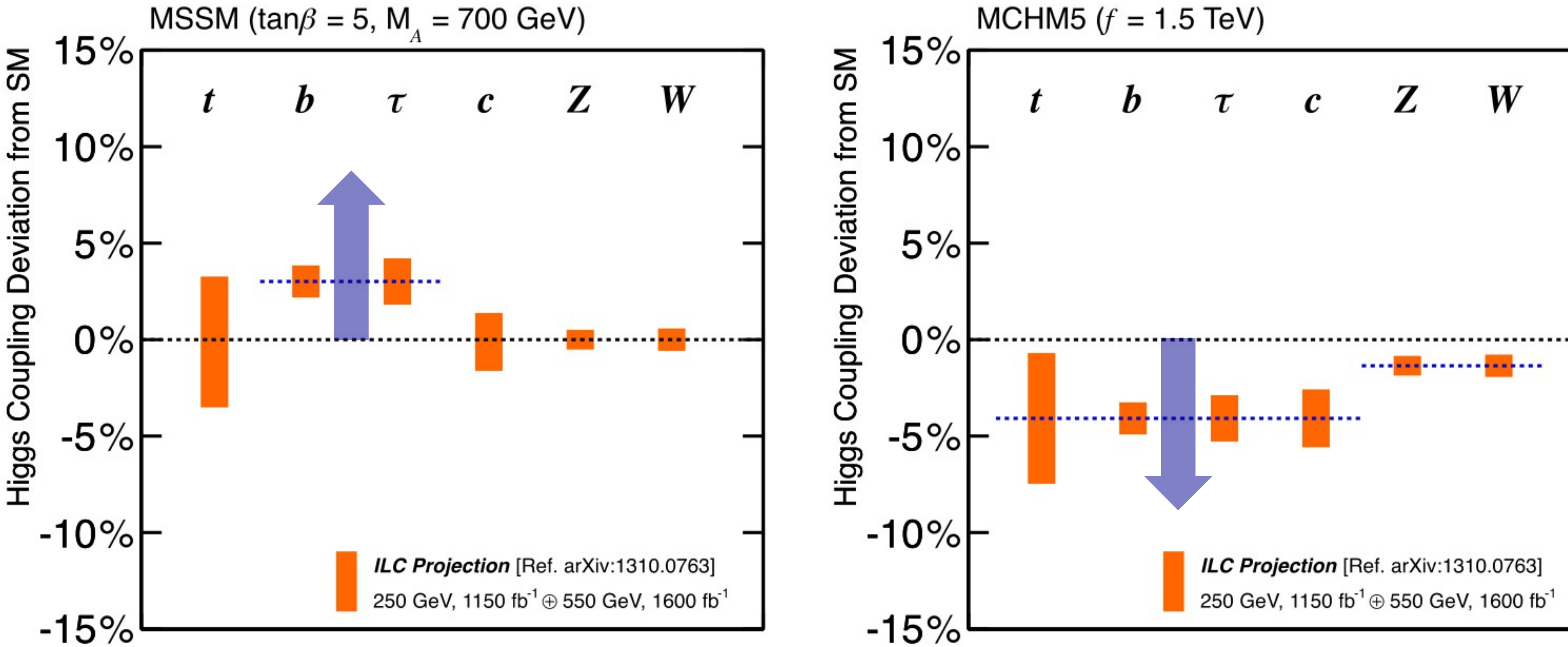
Composite Higgs (MCHM5)



ILC 250+500 LumiUP

Elementary v.s. Composite

Supersymmetry (MSSM) / Composite Higgs (MCHM5)

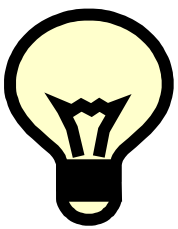


ILC 250+550 LumiUP

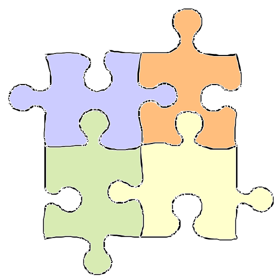
Top physics at the ILC

Very brief since this is the Top workshop

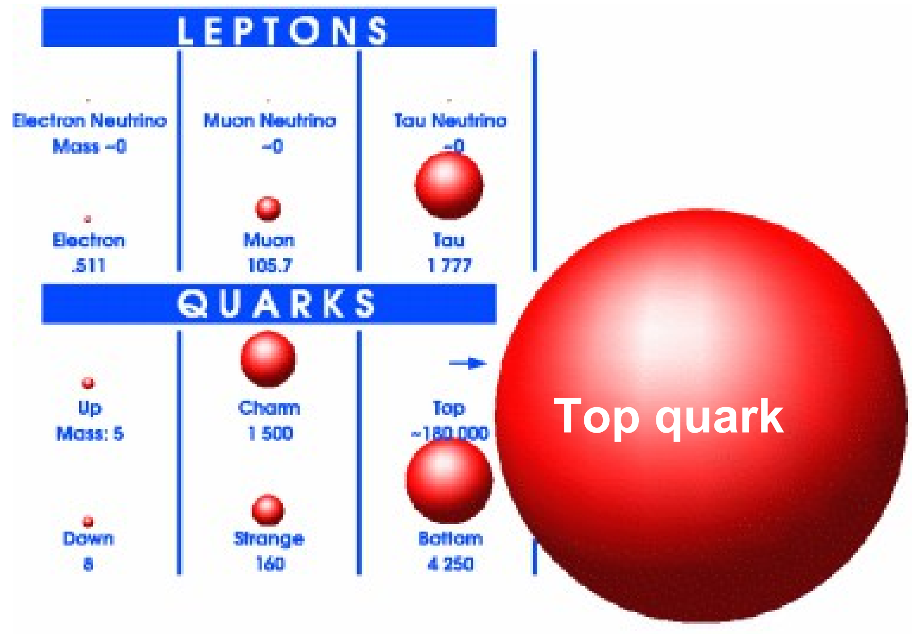
An enigmatic couple



Elementary Scalar?



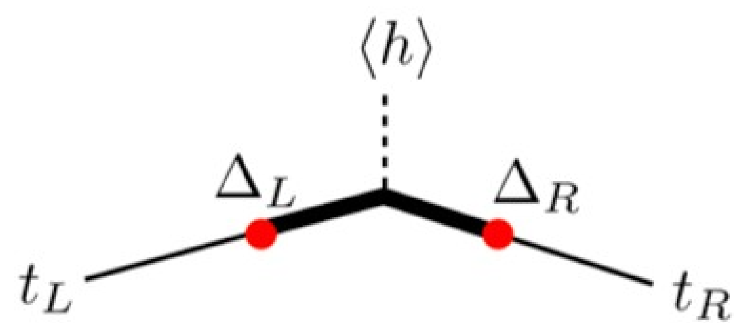
Composite object?



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

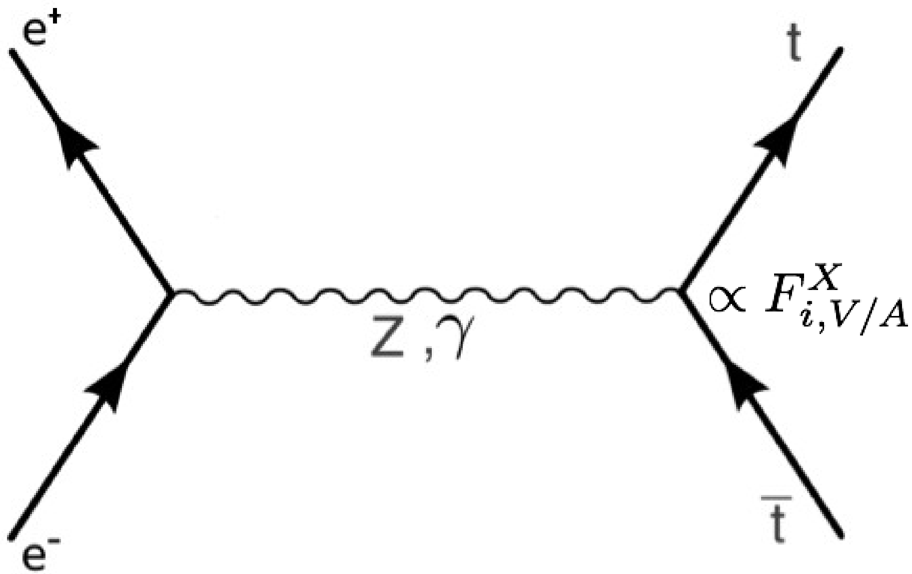
- New physics by compositeness?
  Higgs <u>and</u> top composite objects?

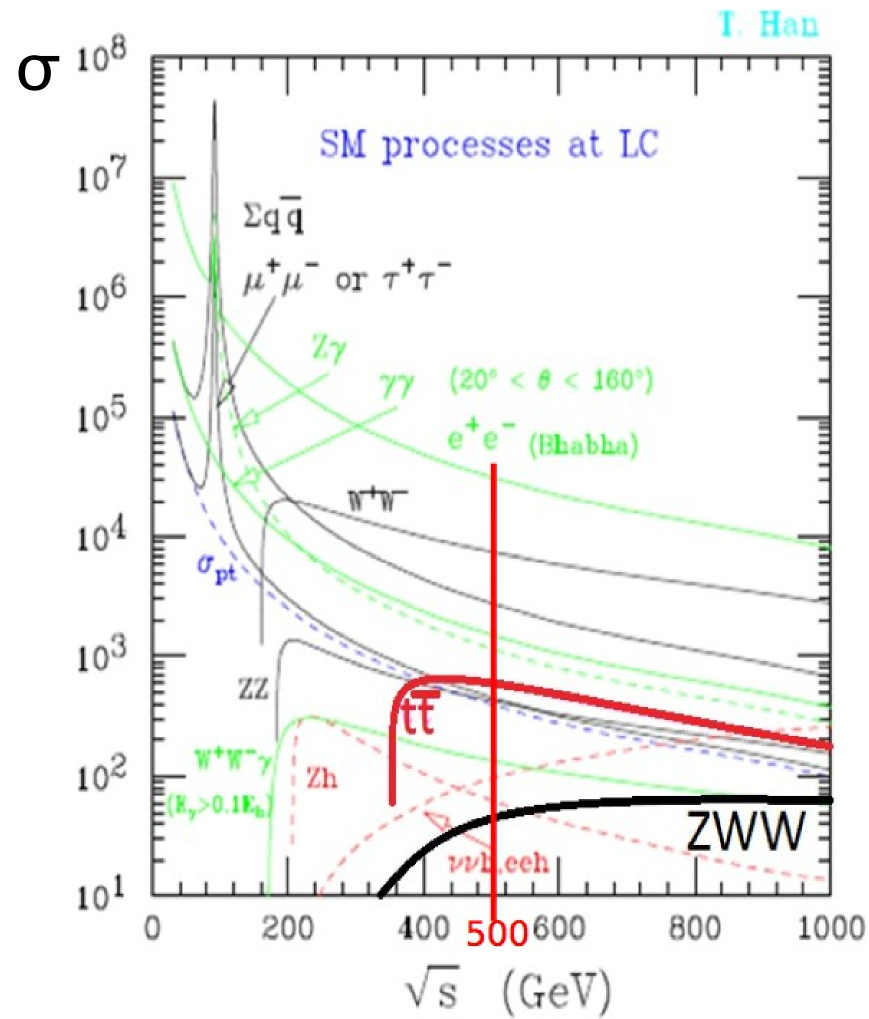
- LC perfectly suited to decipher
  both particles



Courtesy of S. Rychkov

Top Quark Physics at Electron-Positron Colliders





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

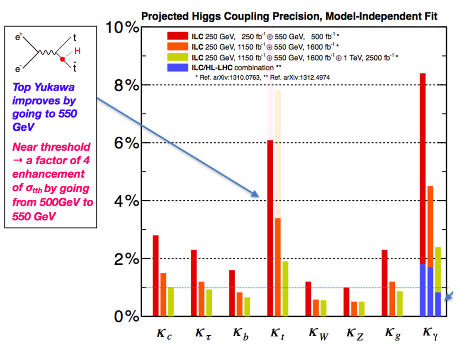
- High precision measurements
  -Top quark mass at ~ 350 GeV through threshold scan
  - Polarised beams allow testing chiral structure at ttX vertex
    => Precision on form factors F

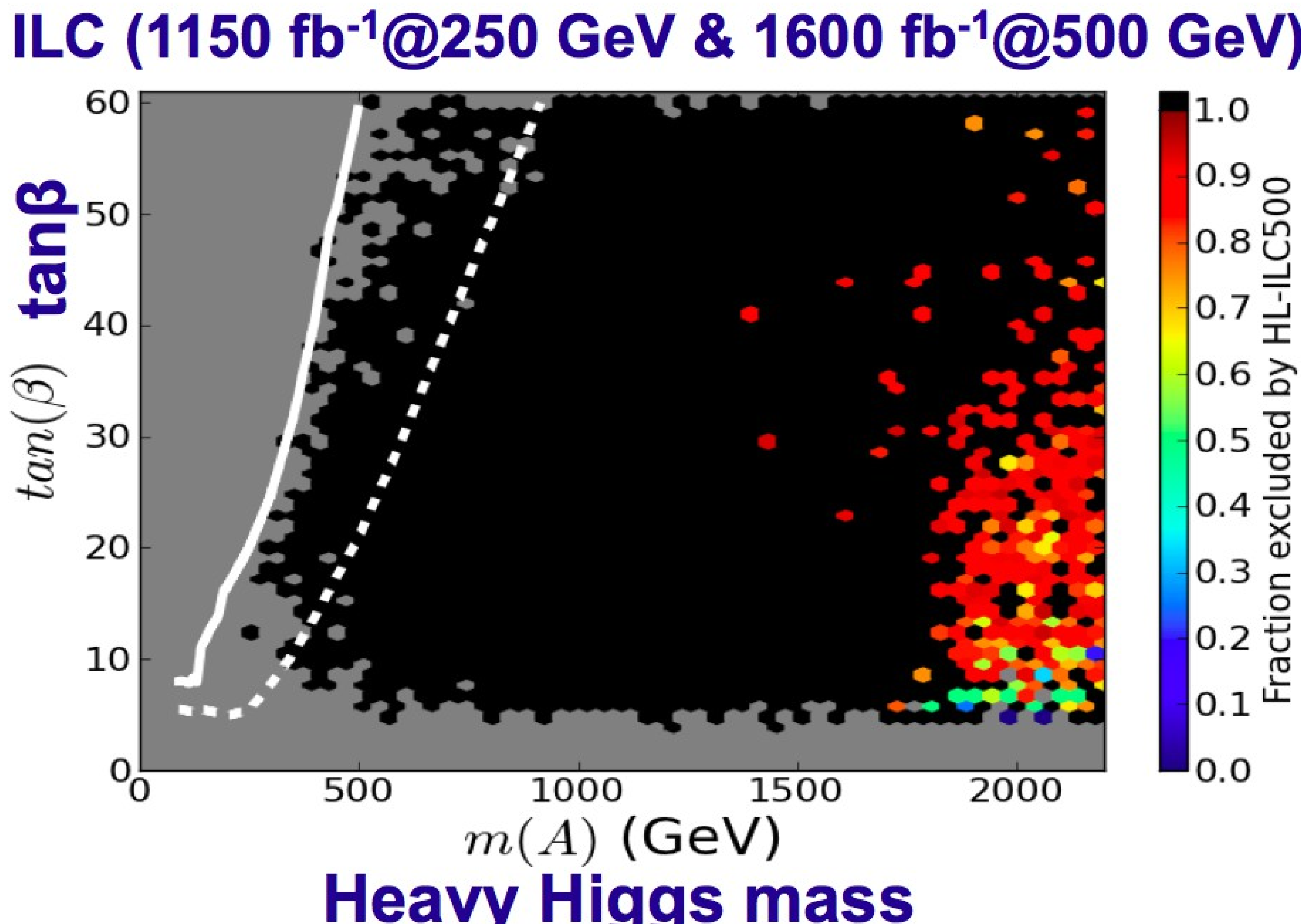
4. BSM Physics at the ILC

Supersymmetric Higgs Boson (MSSM)

Exclusion of pMSSM points via Higgs Couplings – arXiv 1407.7021

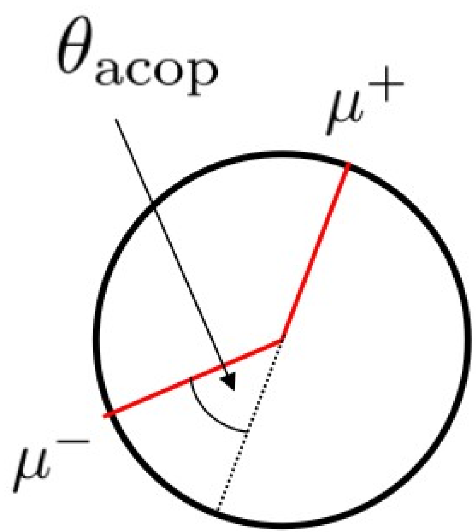
See Chapter 2

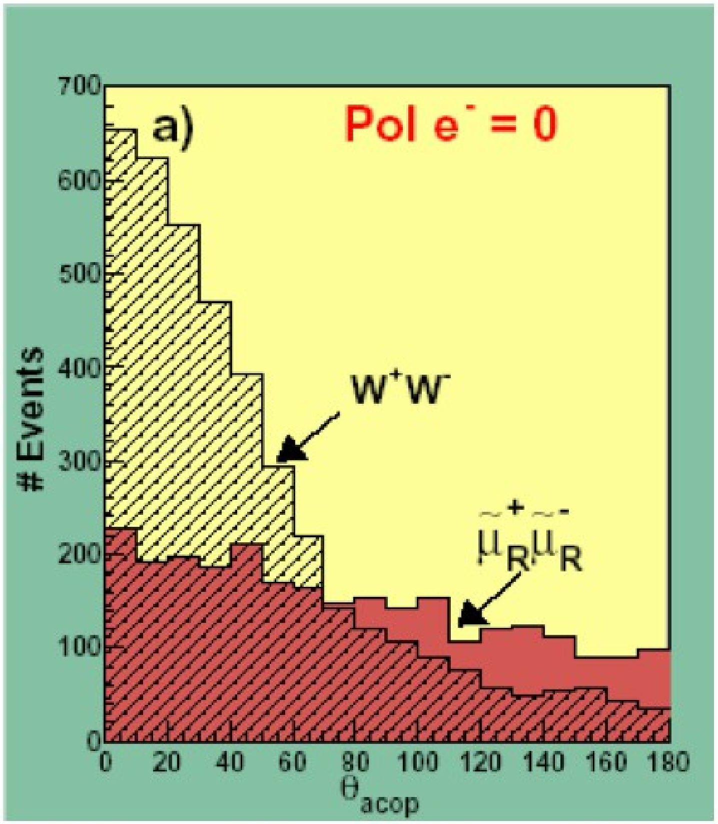




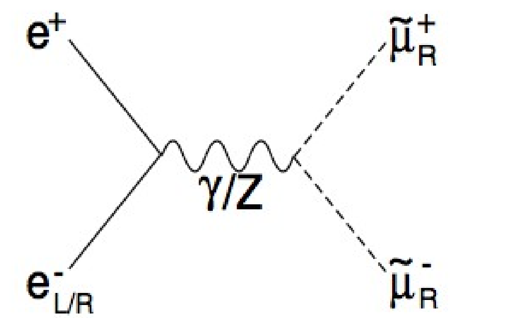
Precision Higgs coupling measurements are sensitive probe for heavy Higgs Bosons m_A ~ 2 TeV reach for any tanβ in high energy e+e- collisions

Example: Smuon pair production

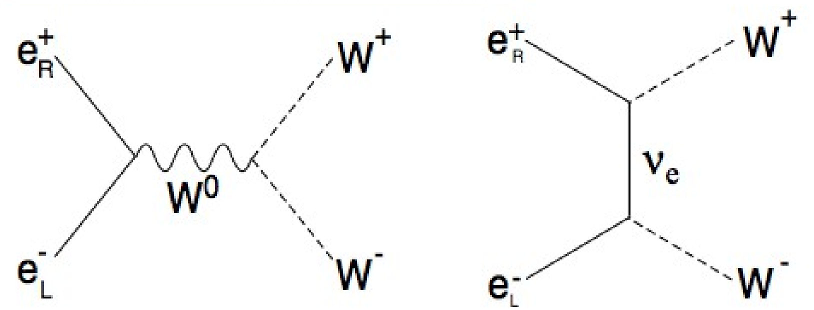




signal



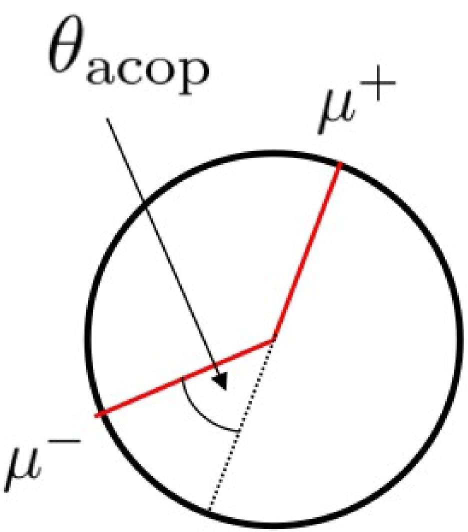
SM background

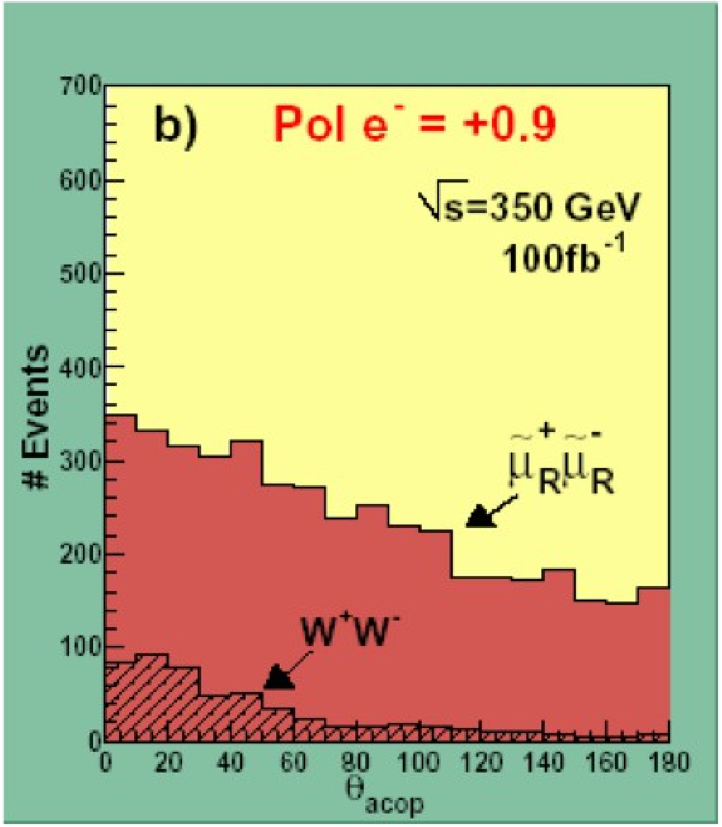


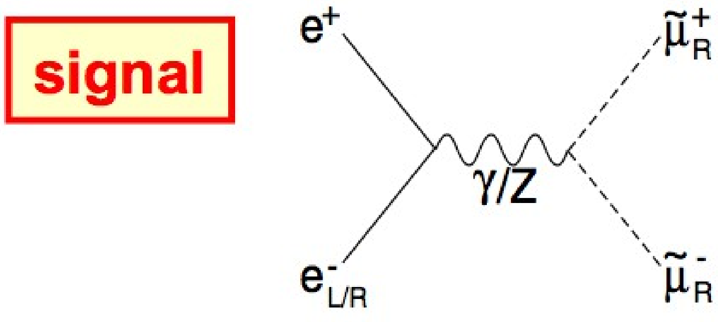
M. Thomson, IoP Meeting 2007

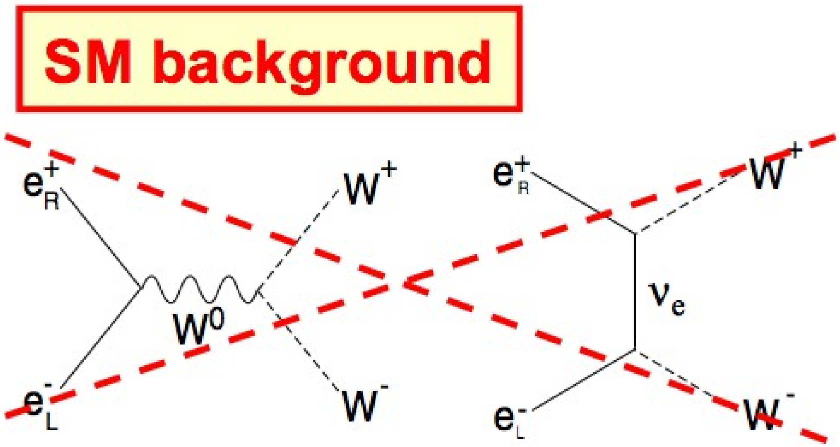
Strong SM Background

Example: Smuon pair production





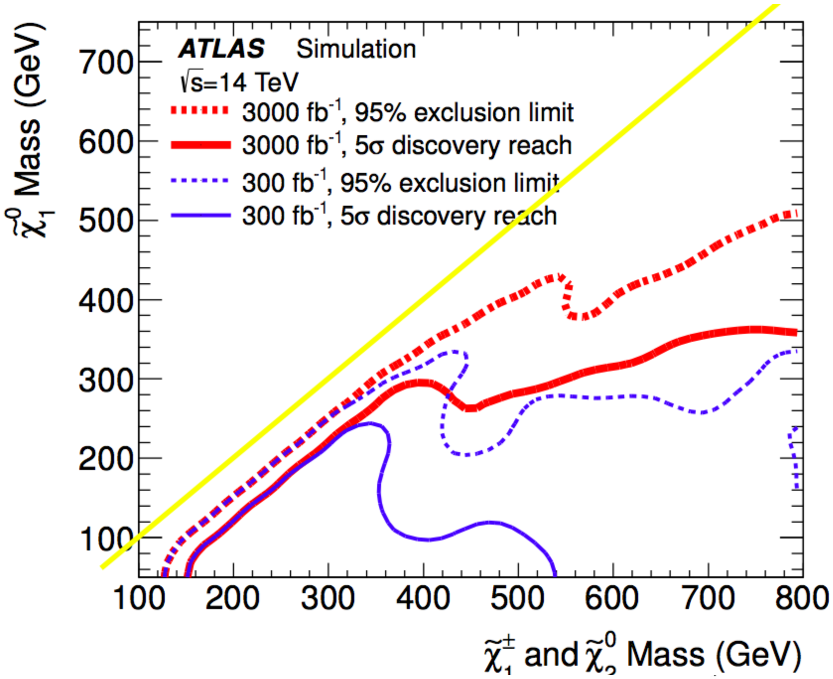


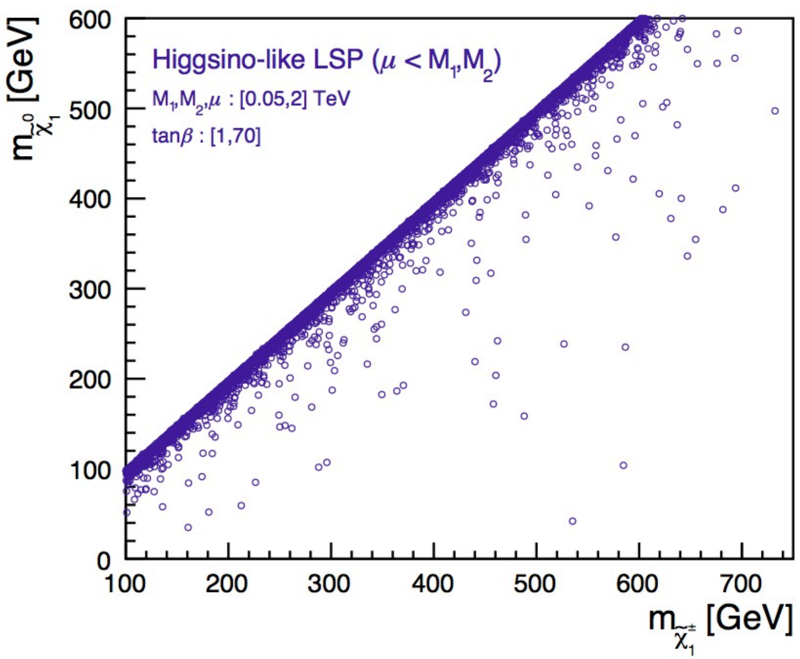


M. Thomson, IoP Meeting 2007

Strong background suppression through beam polarisation

Direct searches





- Hadron colliders have a great potential to discover supersymmetric particles
  - coloured and neutral

- Hadron colliders cannot exclude low mass SUSY with light neutralino and chargino(s) Degenerated in mass

- Example: scenario with light higgsinos μ ~ O(v)

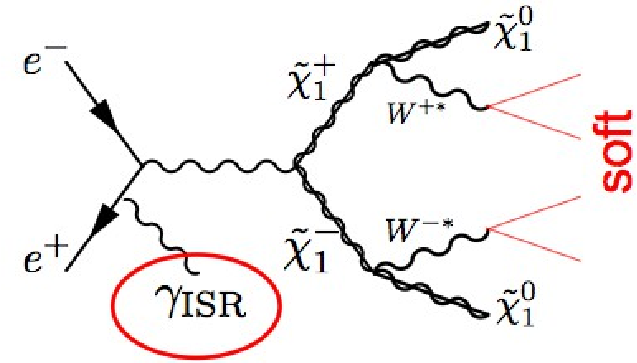
Study of Higgsino pair production, with ISR tag

Benchmark models with

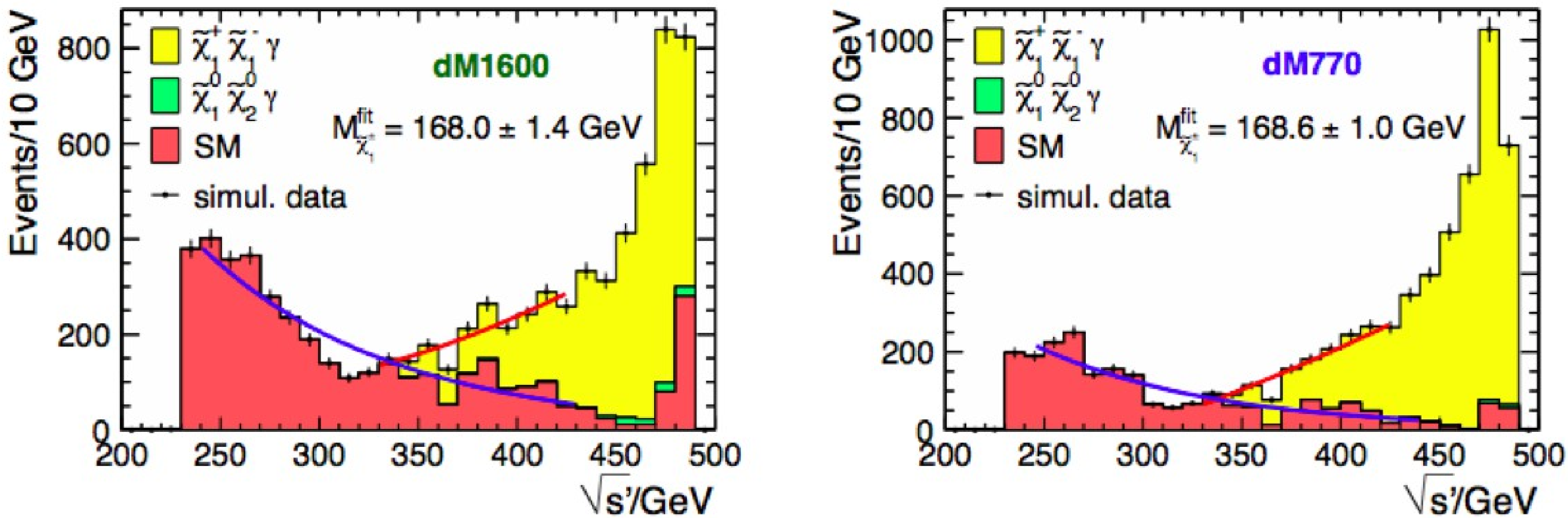
m(NLSP) – M(LSP) = 1.6 GeV and 0.8 GeV

$$\sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-) = 78.7\ (77.0)\ \text{fb}$$

$$\Delta M = 1.60\ (0.77)\ \text{GeV}$$



Berggren, Bruemmer, List, Moortgat-Pick, Robens, Rolbiecki, Sert, EPJ C73 (2013) 2660 [arXiv:1307.3566]



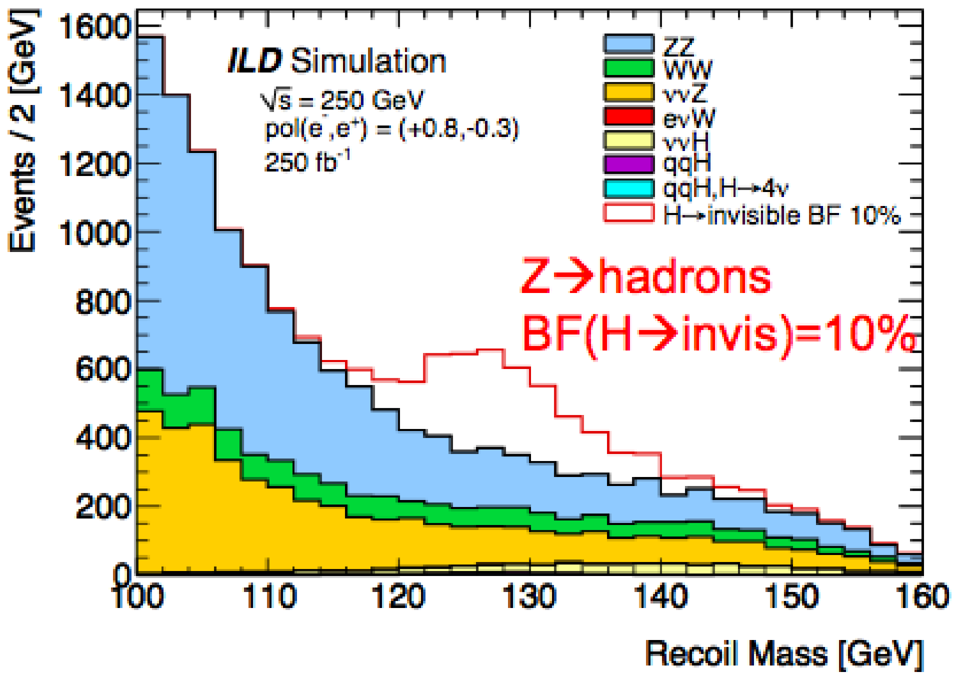
√s=500 GeV, Lumi=500 fb^{-1}, P(e-,e+)=(-0.8,+0.3) → LSP mass resolution ~1%

Clear signal => ILC covers important corner of phase space for SUSY Searches

WIMP and Dark Matter Searches

WIMP searches at colliders are complementary to direct/indirect searches.
Examples at the ILC:

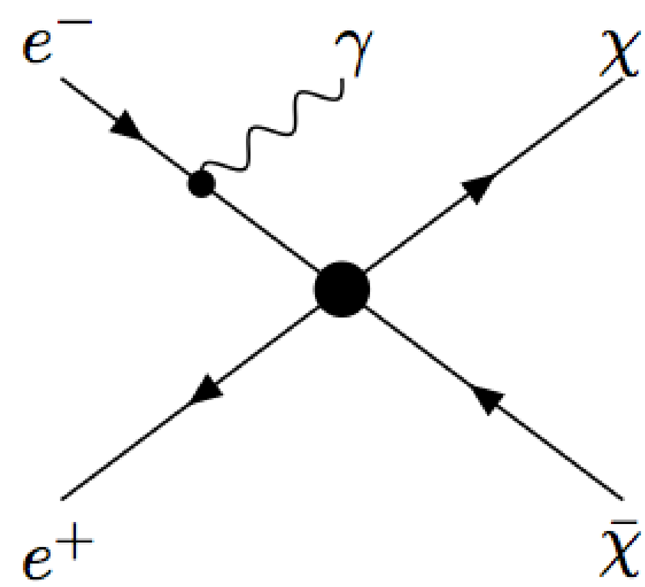
Higgs Invisible Decays



BR(H→invis.) < 0.4% at 250 GeV, 1150 fb^{-1}

Impact of jet energy resolution

Monophoton Searches



→ DM mass sensitivity nearly half √s

Soft photons, forward detectors

Tomohiko Tanabe
ILD Meeting 2014

Dark Matter Search – A spectacular example

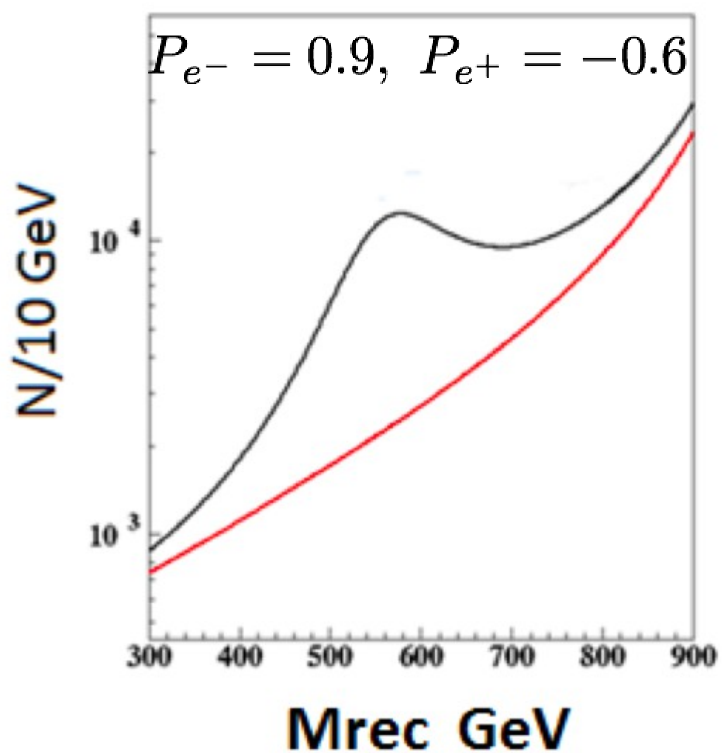
arXiv:1411.0088

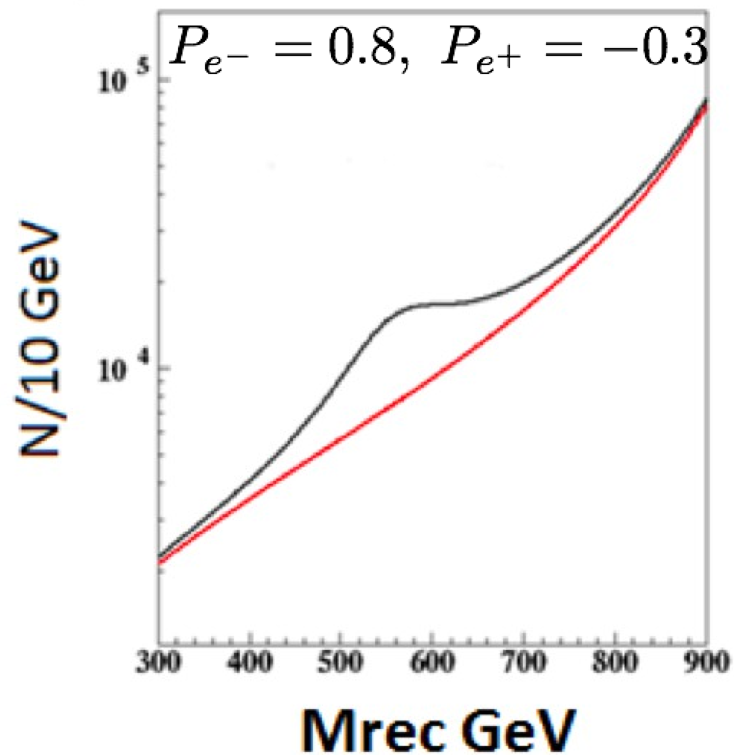
Z' with vector couplings to Dirac type Dark Matter X and axial couplings to ordinary matter

$$\sigma v = |g_V^X|^2 K^2 \sum_f n_{cf} |g_A^f|^2 \frac{2m_X^2 + s}{12\pi\left[(s - m_{Z'}^2) + (m_{Z'}\Gamma_{Z'})^2\right]}$$

-> Monophoton search
-> Background suppression through polarised beams

$$\sqrt{s} = 1\,\text{TeV},\quad m_{Z'} = 550\,\text{GeV},\quad L = 1\,\text{ab}^{-1},\quad K^2 = 0.1$$

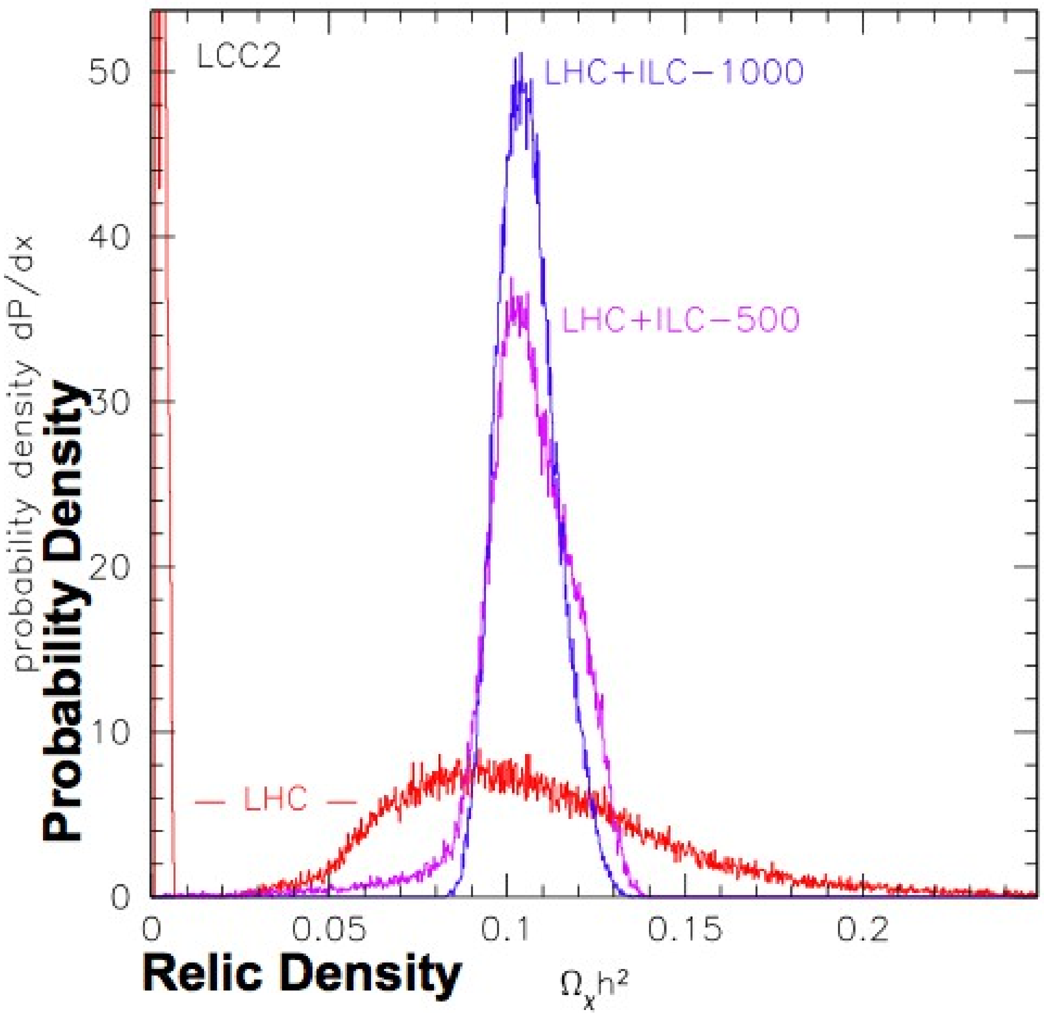




Connection to relic dark matter density

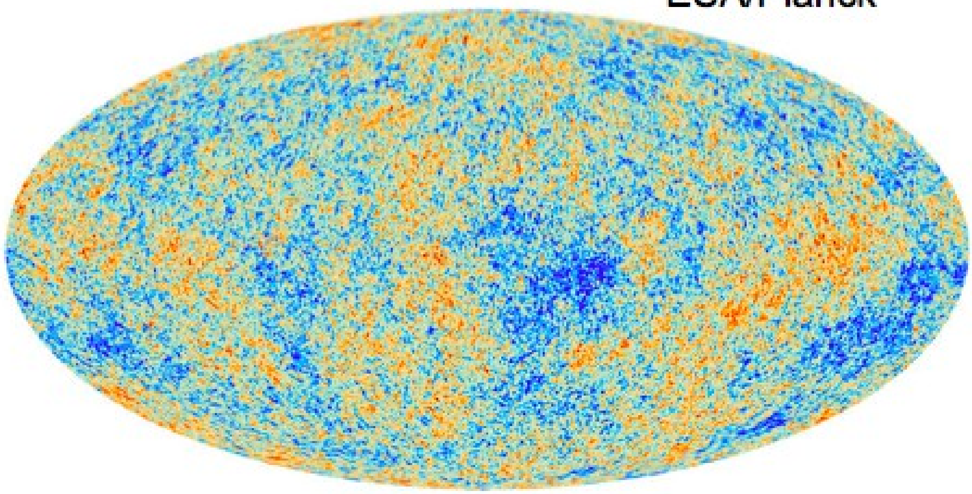
WMAP/Planck (68% CL)

$\Omega_c h^2 = 0.1196 \pm 0.0027$



Baltz, Battaglia, Peskin, Wizansky
PRD74 (2006) 103521, arXiv:hep-ph/0602187

ESA/Planck



Once a DM candidate is discovered, need to check the consistency with the measured DM relic abundance.

→ ILC's precise measurements of the mass and cross sections provide crucial input.

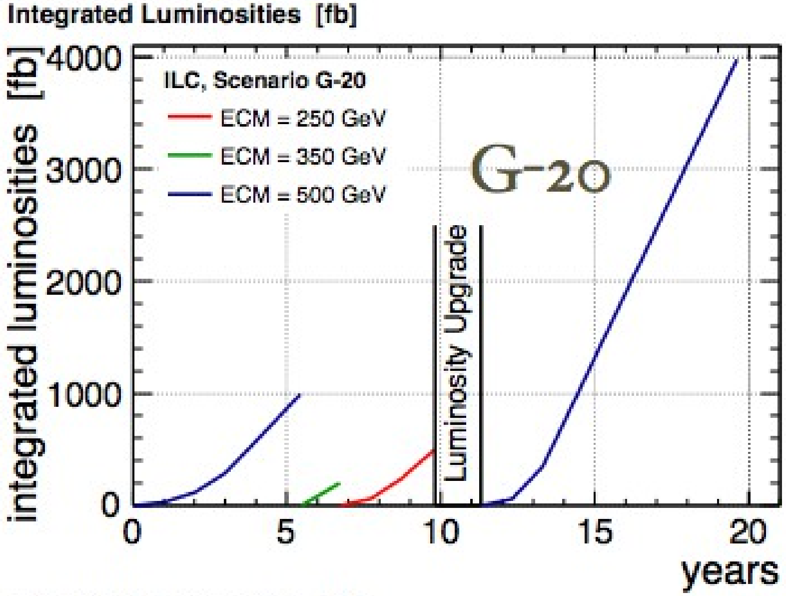
Tomohiko Tanabe
ILD Meeting 2014

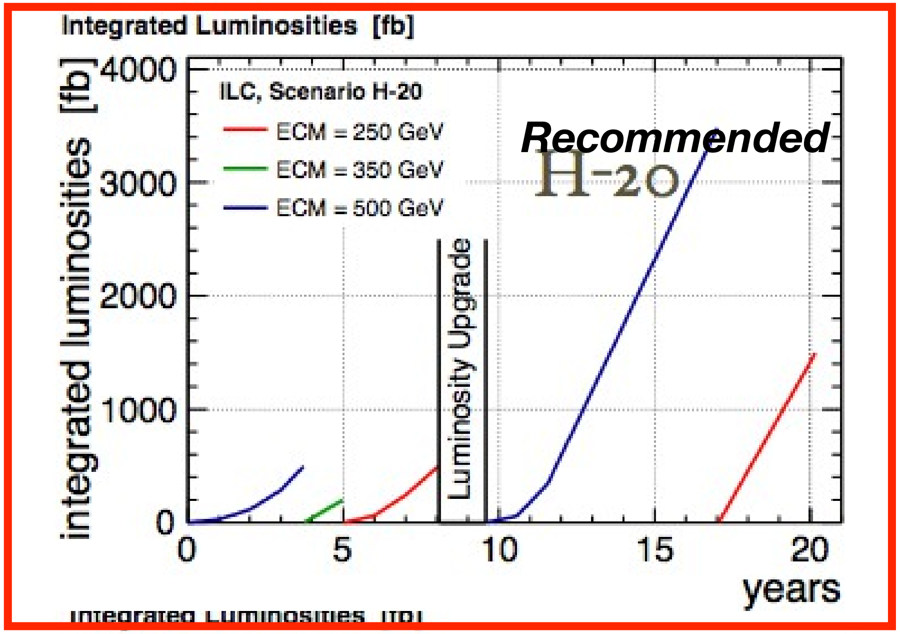
4. Definition of Running Scenarios

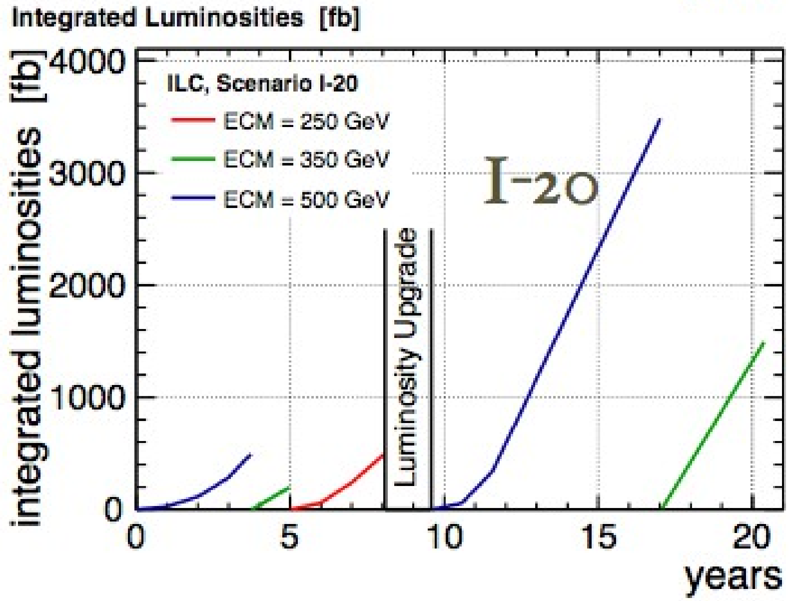
arxiv: 1506.07830

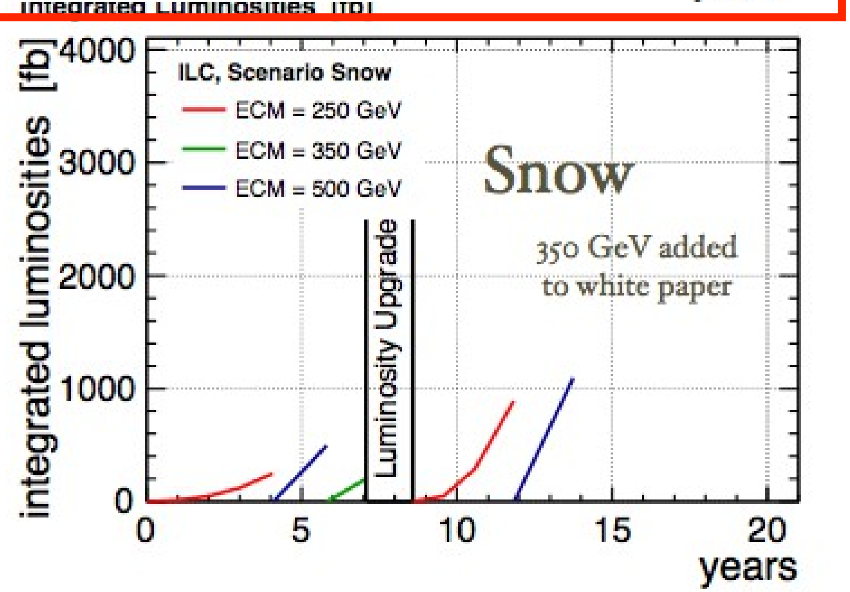
(Nearly) All slides stolen from Keisuke

Discussed Running Scenarios









J. Brau/ILC Parameters Jt WG - April 21, 2015 6

Running Scenarios in Numbers

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

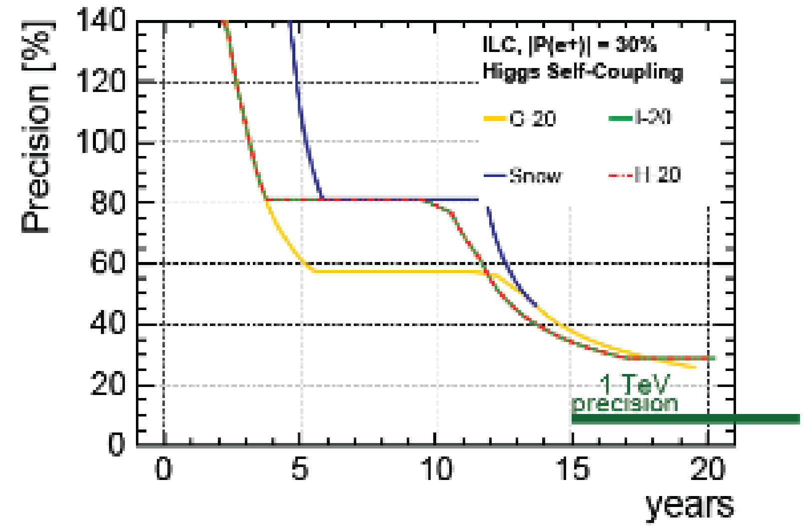
	Stage	500			500 LumiUP		
Scenario	$\sqrt{s}$ [GeV]	250	500	350	250	350	500
Snow	$\int \mathscr{L} dt$ [fb^{-1}]	250	500	200	900	-	1100
	time [years]	4.1	1.8	1.3	3.3	-	1.9

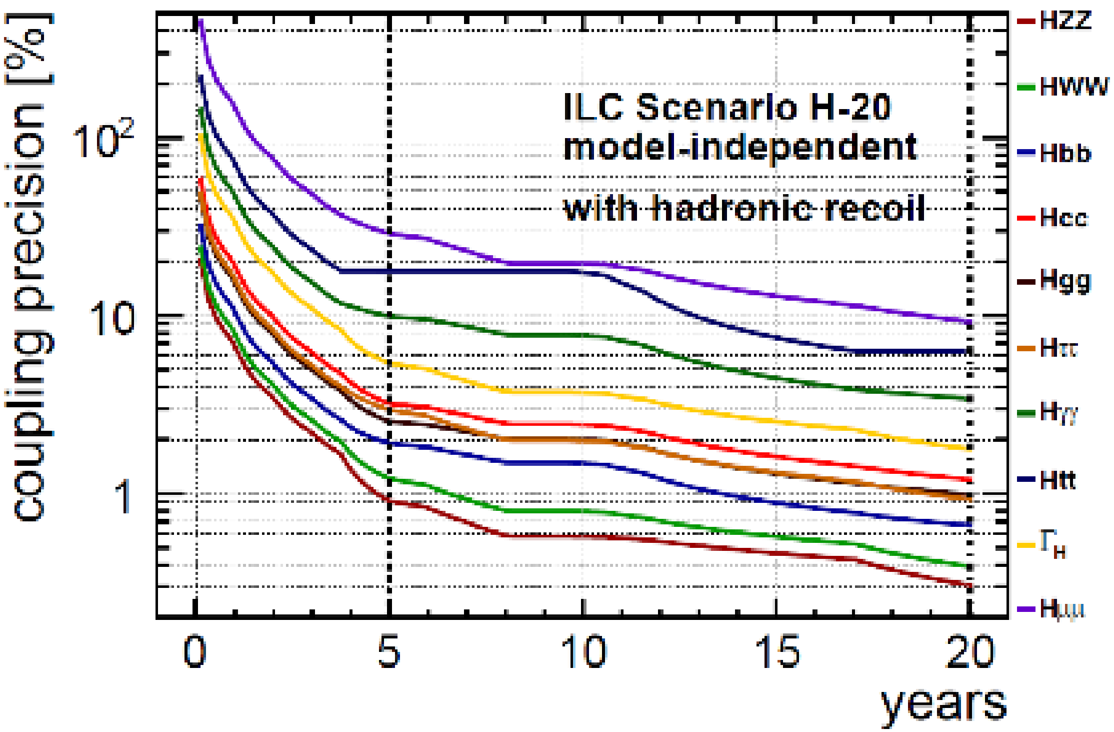
Higgs Measurements

Higgs Measurements

H-20

	first phase	lumi upgrade	total
250 GeV	500 fb^{-1}	1500 fb^{-1}	2 ab^{-1}
350 GeV	200 fb^{-1}		0.2 ab^{-1}
500 GeV	500 fb^{-1}	3500 fb^{-1}	4 ab^{-1}
time	8.1 yrs	10.6 yrs	20.2 yrs*





Self-coupling reaches <30% for SM case. <15% if lamda=2xSM

ILC parameter WG report *Jim BRAU*

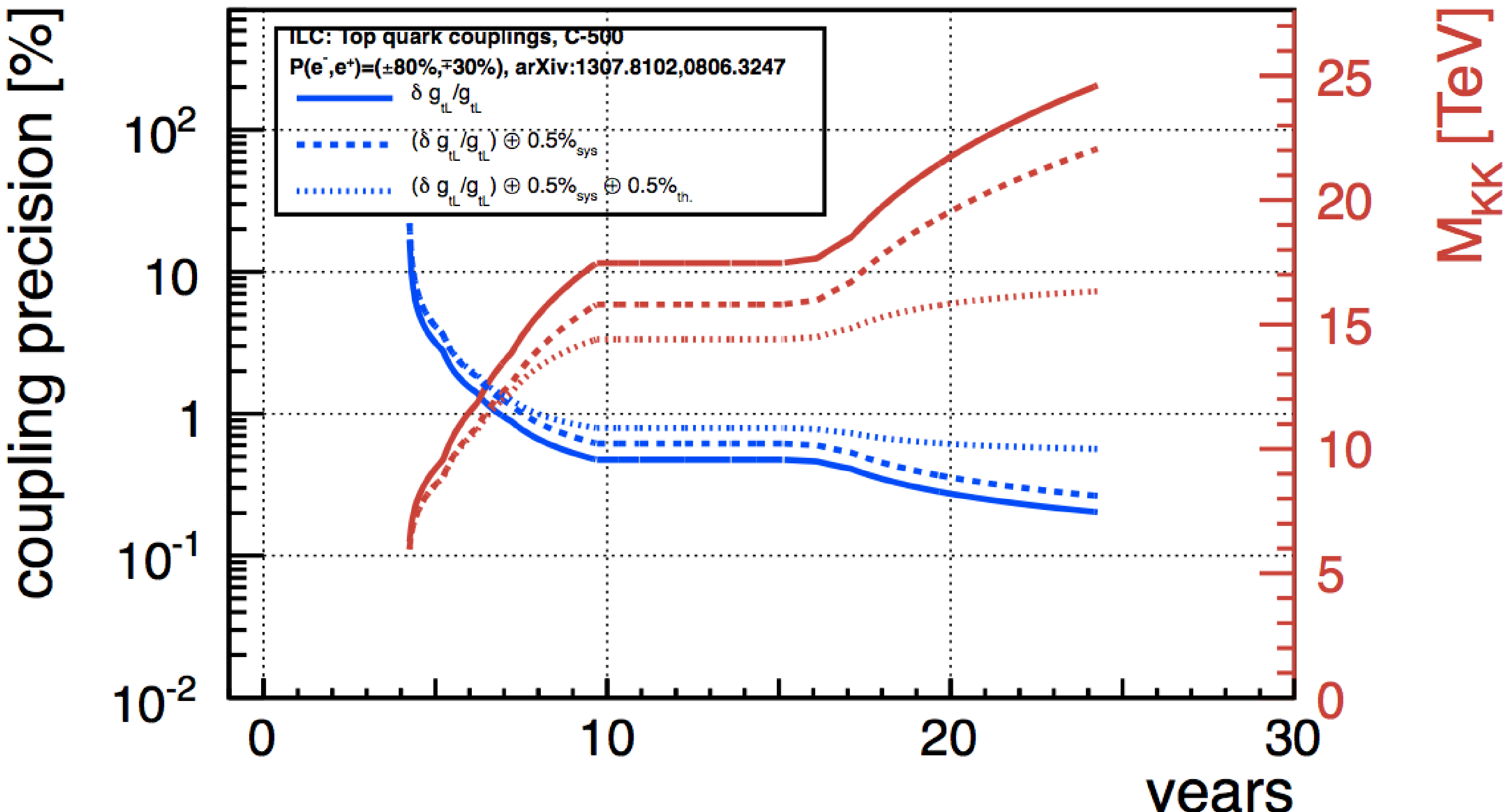
Most couplings reach <1%

11

Example for physics reach – ttZ coupling

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

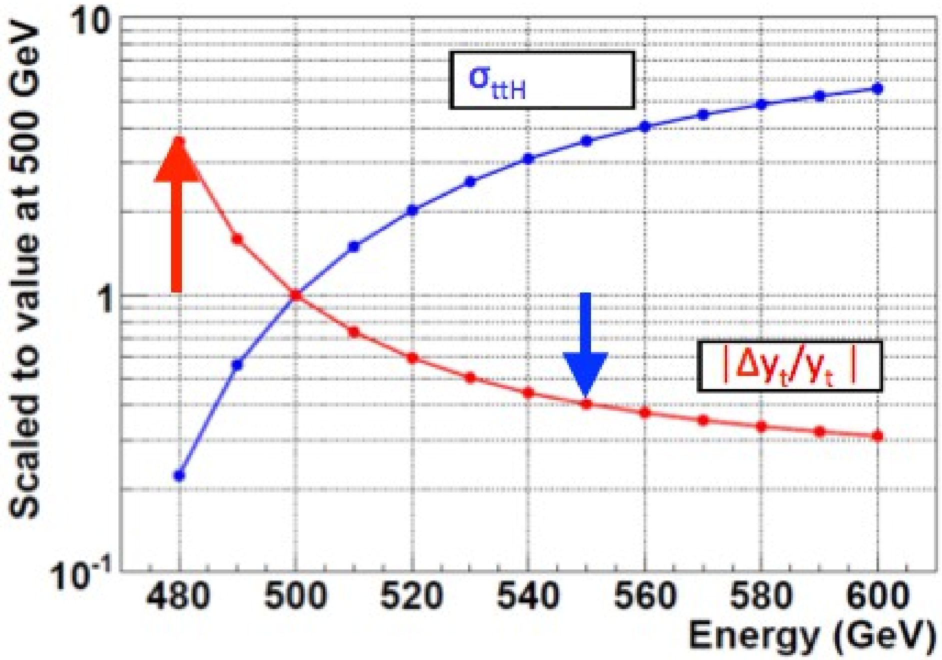


Can probe scales of ~25 TeV in typical scenarios

(… and up tp 80 TeV for extreme scenarios)

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

500 GeV vs. 550 GeV & ttH



550 GeV is 2.4 precision improvement over 500 GeV
- Failing to achieve 500 GeV loses reach quickly

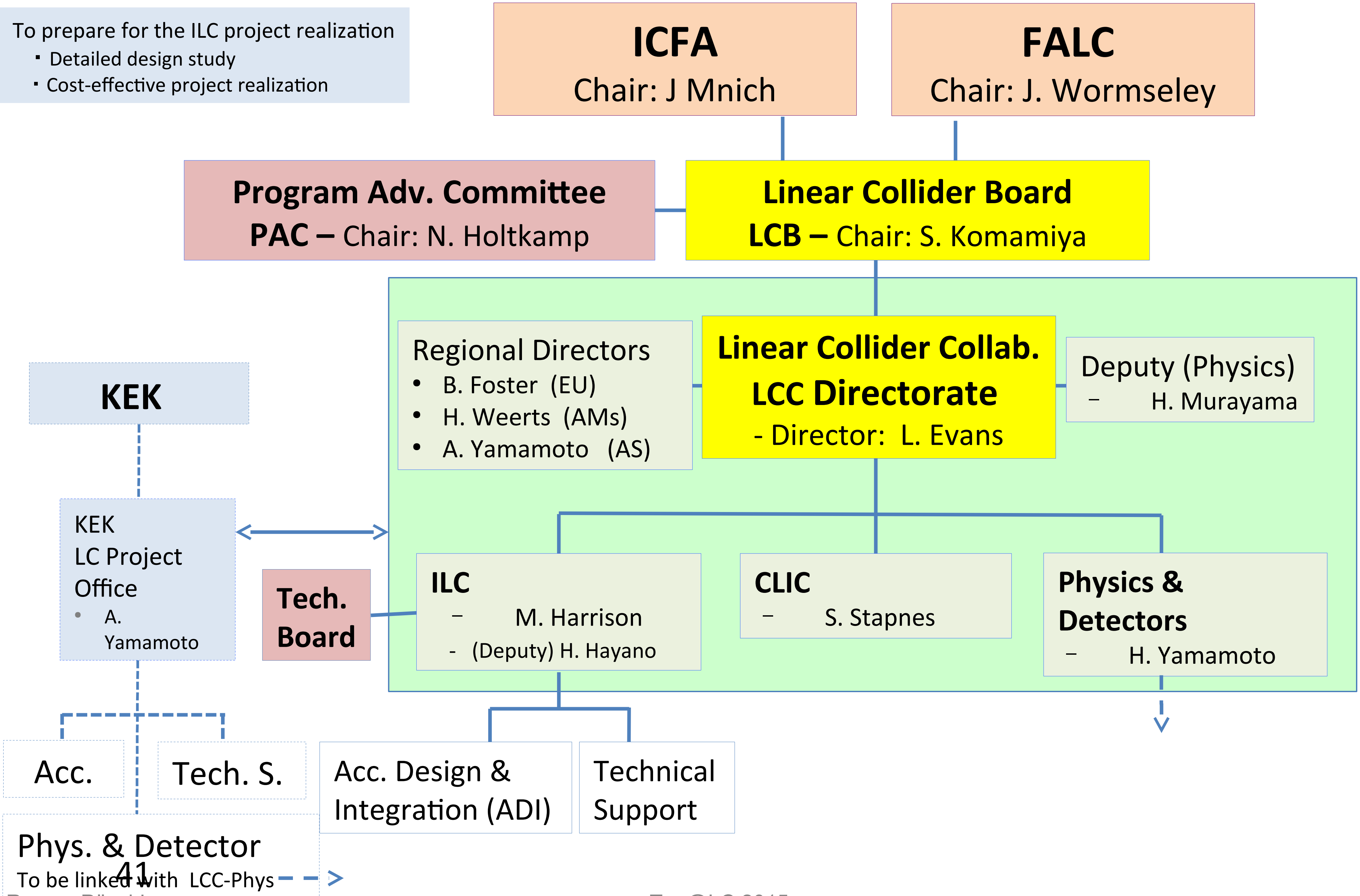
J. Brau/ILC Parameters Jt WG - April 21, 2015 14

5. Latest Political Developments

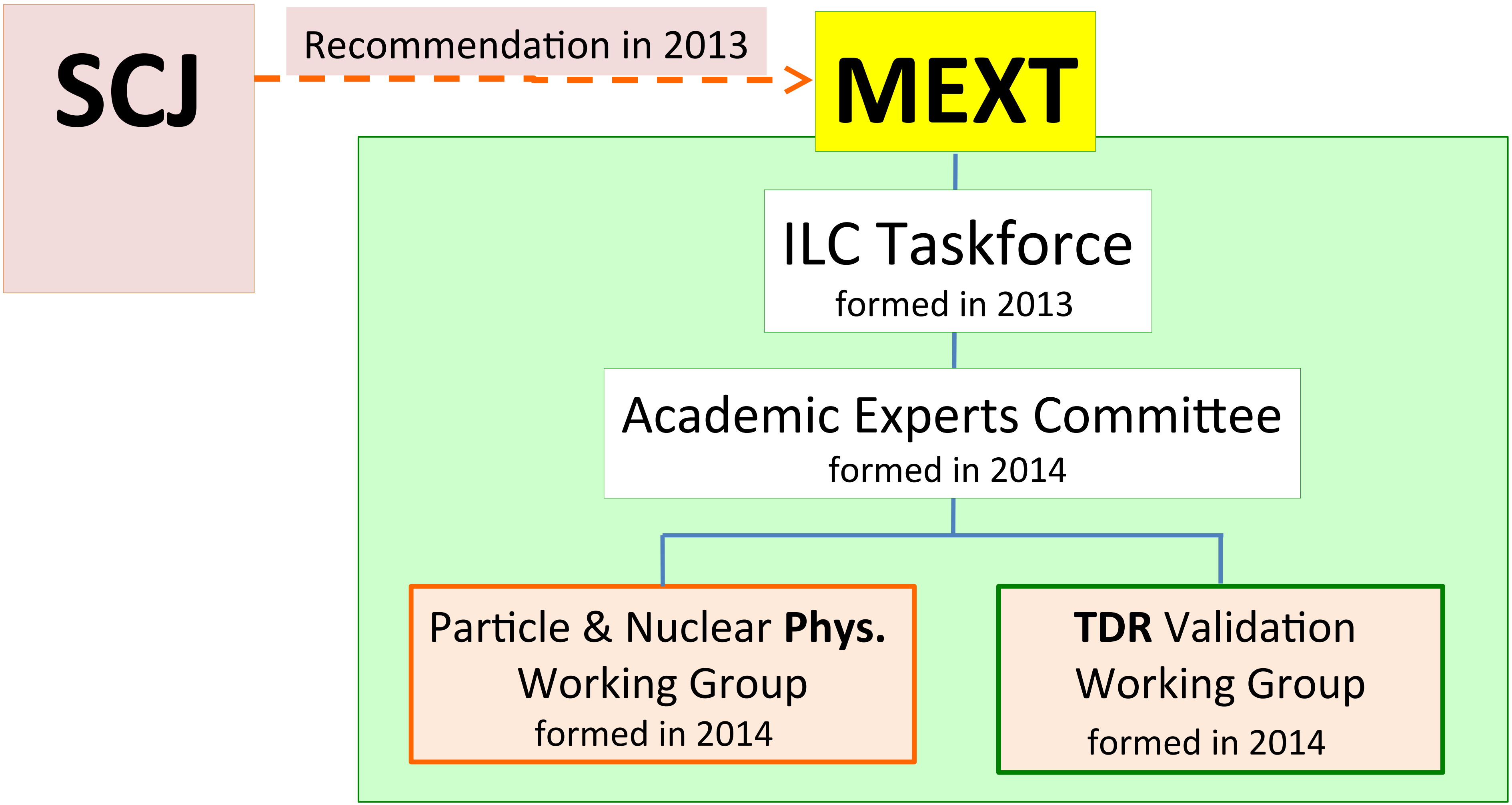
(Personal selection by R.P. Reusing partially material from Keisuke)

ILC in Linear Collider Collaboration

To prepare for the ILC project realization
- Detailed design study
- Cost-effective project realization



ILC Evaluation by MEXT



Both working groups have issued interim reports in Spring 2015
Only available in Japanese! Unofficial translations exist

Academic Experts Committee is about to distill overall interim report from these individual reports

Known Keypoints from Interim Reports

See talks by Sachio Komamiya (PAC Meeting) and Yasuhiro Okada (ALCW2015)

- Optimal strategy for ILC has to be clarified in view of results of the current LHC running
- TDR demonstrates that physics goals can be achieved but re-assessment concerning cost risks may be necessary
- Economical impact factor of ILC 2.12
  - evaluated based on study by NOMURA Research Industries
- Public understanding, i.e. acceptance of project by general public and other scientific communities needs to be assured

All of the above are no show-stoppers but motivate further and more work to promote the ILC case

Visit of NOMURA Research Industries

Example France: Visit of LAL, CEA/IRFU and IN2P3 Headquarter

Keypoints in NOMURA Report (Thanks to Emi Kou):
France has capability to contribute to a project at the scale of the ILC
France (and other countries) expect clear signal from Japanese gouvernment to go further

PAC Meeting in April 2015

- 13/4/15 – 15/4/15 at LAL Orsay

- PAC chaired by Norbert Holtkamp and Michel Davier

- Scientific excellency of project was pointed out

- How to resolve "conflict" between current suspension and continuation of needed R&D
  Accelerator and detector need further support to realise the next steps towards project

Tokyo Event

- 22/4/15 at Tokyo, 300 participants, Ito auditorium was extremely well filled

- Notes by Lyn Evans, Ryu Shionoya (President of Diet member group for the Promotion of the ILC), Hiroya Masuda (Japanese Policy Council)

- Very interesting and balanced panel discussion!
  Joachim Mnich (DESY), Lyn Evans, Jonathan Bagger (TRIUMF), Hiroake Aihara (Vice-president University of Tokyo)

  Key points:
  - ILC has outstanding scientific potential
  - Need clear signal from Japan to go further (Evans)
  - ILC is on its way but patience is needed (Aihara)

Tokyo Statement

Statement on "Towards the realisation of the International Linear Collider"

22 April 2015, Tokyo

At the ILC Tokyo Symposium, held on 22 April 2015 at the Ito International Hall, Tokyo, Japan, the Linear Collider Collaboration (LCC) and the participants around the world at the Asian Linear Collider Workshop (ALCW) 2015 decided to issue a statement confirming their conviction of the scientific justification for a prompt realisation of the International Linear Collider (ILC).

1) The ILC's role in particle physics is to explore with exquisite detail the time just after the beginning of the Universe. This research is unique and indispensable for adeep understanding of how our Universe began, how it evolved, and how it works today. We are eager to build and work at the facility.

2) The technical feasibility of the ILC has been demonstrated in the Technical Design Report. The ILC is ready to be built following the completion of an engineering-design phase. The project is now in a phase where governmental involvement should lead to a decision to realize the project. In this context we express our appreciation of the ongoing project assessment being undertaken by the Japanese government.

3) The ILC is one of the largest scientific projects ever proposed, on a similar scale to the Large Hadron Collider project and that its realisation as an international project requires the establishment of an international framework for sharing the cost and expertise among countries. We therefore intend to facilitate discussions between governments and funding authorities to achieve this goal as soon as possible.

Lyn Evans
Director of the LCC, on behalf of the LCC and scientists at the ALCW 2015.

Japanese Delegations in the US and Europe

Japanese-US Consultations (see also ILC Newsline) end of April 2015:

- Meeting at Hudson Institute (American Think Tank) Between Japanese Diet Members and US Congress and DOE representatives

- Agreement of actions to enhance US-Japanese Scientific cooperation on big projects

- Preparation of an US-Japanese Caucus on these issues

- Diner with Shinzo Abe, Moniz and Holdren

Contacts in Europe (as far as I can tell!):

- ILC case was brought forward at the occasion of the 35th Japan-EC Parliamentary Conference

- French scientists (M. Winter, M. Titov, O. Napoly and F. LeDiberder) had the occasion to Talk to Koska-san (Head of the Friendship Association)

- Meeting with members of French Assemblee Nationale had to be reported to a later date but intention to talk exist

Summary

- The ILC is versatile machine for precision physics in the range m_Z – 1 TeV
  Polarised beams to test chiral theory!

- Higgs and top quark are physics guaranteed
  (My conviction) both are messengers to New Physics

- Discovery potential for Supersymmetry and Dark Matter
  Sensitivity in phase space left by LHC and Dark Matter Experiments

- Running scenarios defined by Parameter group

- Technologies are getting mature
  ILC is ready to be constructed
  Well advanced detector technologies
  In both cases further funding is needed to make next steps
  AIDA2020 is welcomed support by Europe (~2.5 MEUR for LC Detector "R&D")
  Cost remains an issue

- Political discussions at many levels
  MEXT process is heading towards interim report
  Meetings between Japanese and American and European Delegations

Backup ....

ILC Basic Parameters and Comments

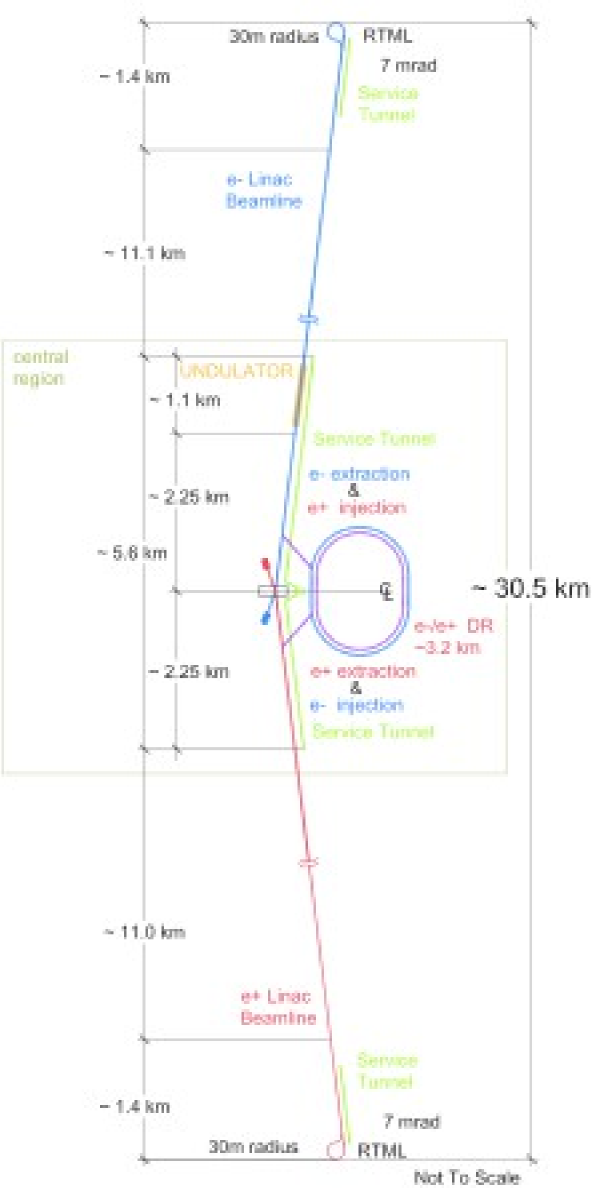
ILC design parameters		Comment
$\sqrt{s}$	91-500 GeV	500 GeV is baseline Option to upgrade to 1 TeV
$\mathcal{L}$	$2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	~Factor 4 technically possible
P_{e^-}	>80%	Proven by SLC
P_{e^+}	upto 30%	~Conservative estimate
Length	~31 km	Current site allows for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

- Discussion on possible running scenarios has started

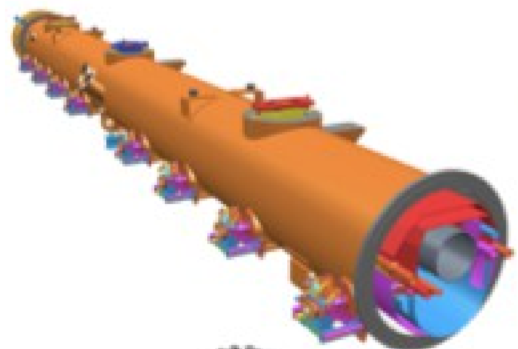
- Luminosity and running time to achieve at a ~25 years research programme
  That includes running at 250 GeV, 350 GeV, 500 GeV and 1 TeV

- 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

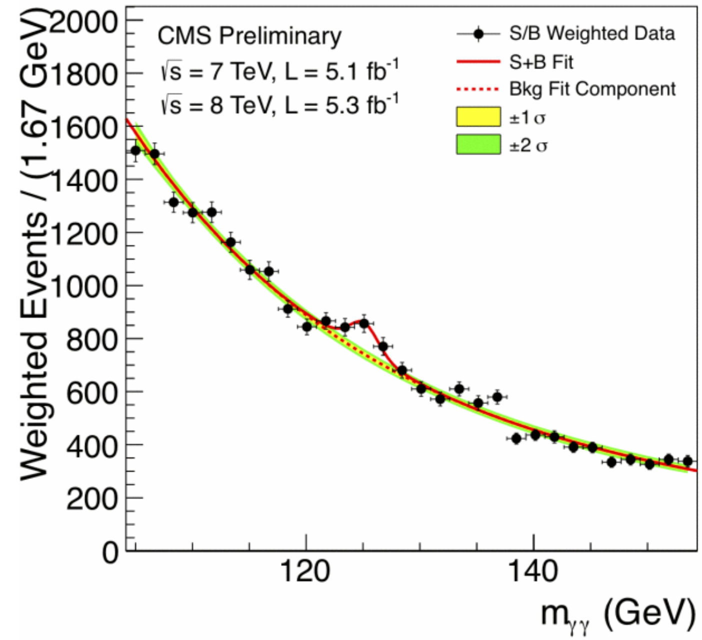
Luminosity

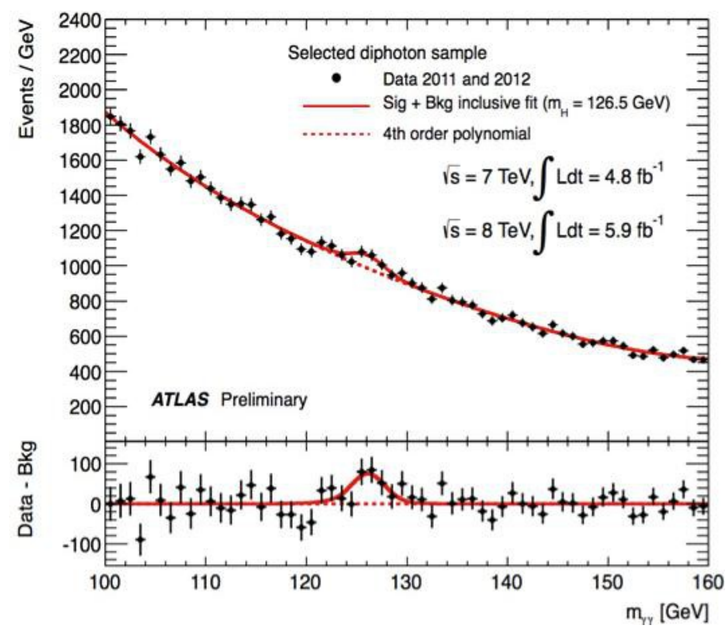
$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}} \sqrt{\frac{\delta_{BS}}{\varepsilon_{n,y}}} H_D$$

η_{RF} ~ 40% for SCRF technology

-> efficient technology

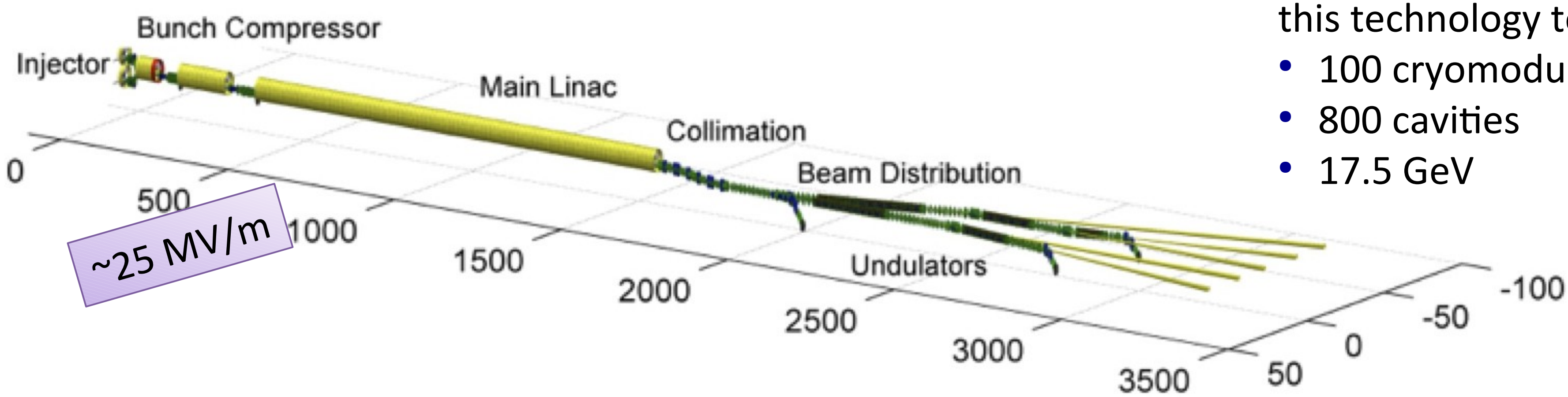
4th of July 2012





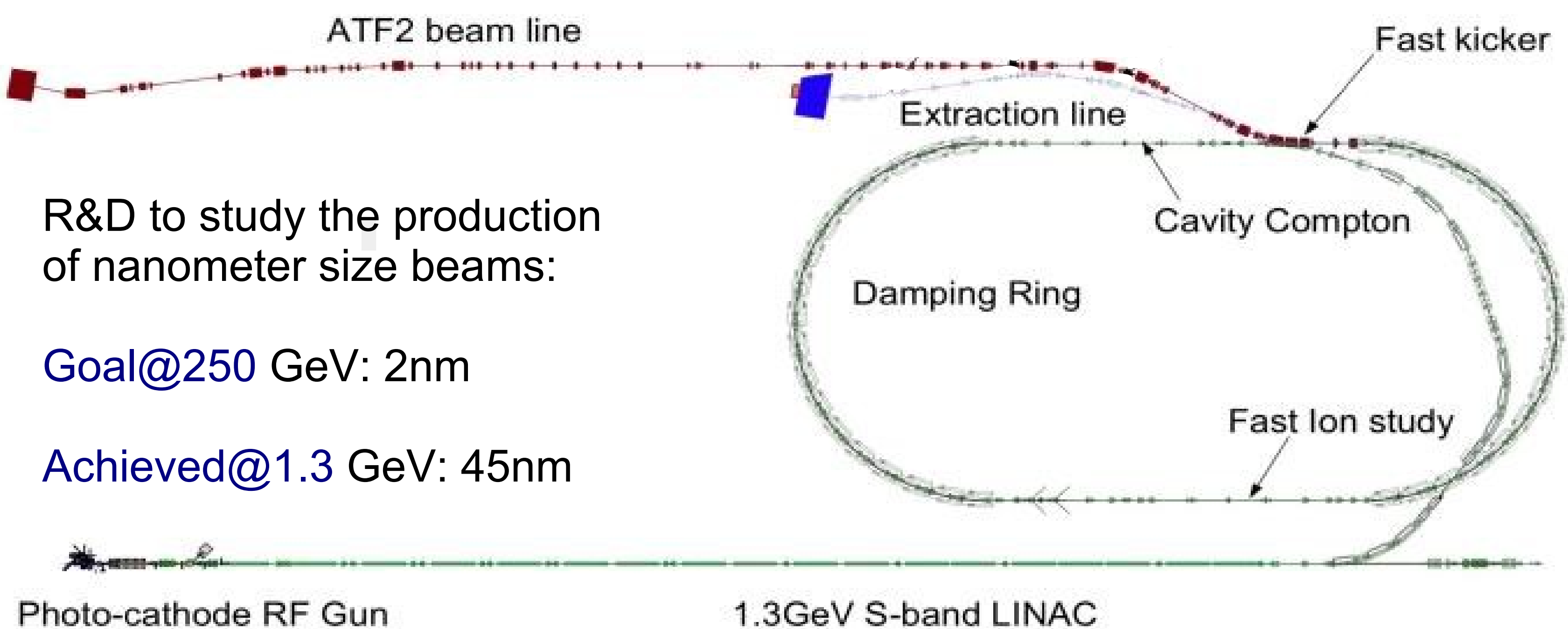
Accelerator - Test and reality

European XFEL Project: Location DESY Hamburg, Start 2015



Largest deployment of this technology to date
- 100 cryomodules
- 800 cavities
- 17.5 GeV

ATF at KEK Japan:

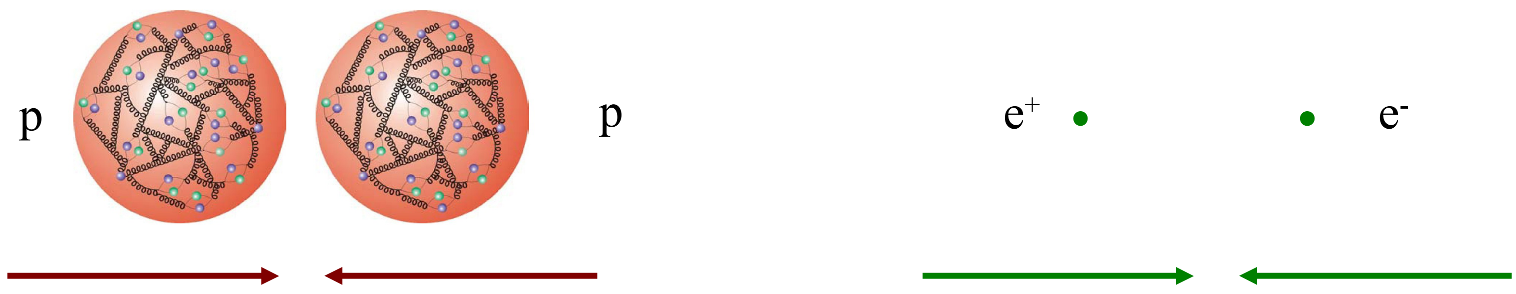


R&D to study the production of nanometer size beams:

Goal@250 GeV: 2nm

Achieved@1.3 GeV: 45nm

Why e+e- collisions?



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

How do the particles get their masses?

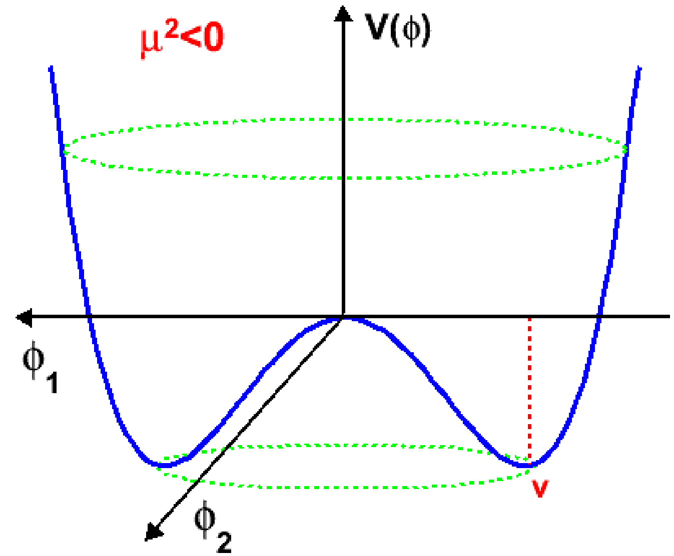
Higgs Mechanism

Scalar field which doesn't vanish in the vacuum

Choice in SM: Doublet Field $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ 4 degrees of freedom

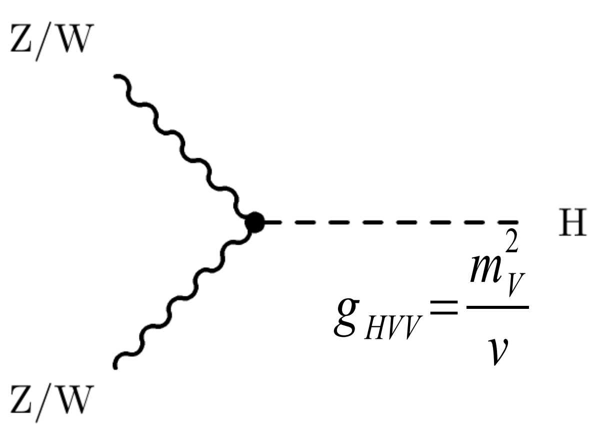
Higgs Boson

Longitudinally degrees of W,Z Bosons

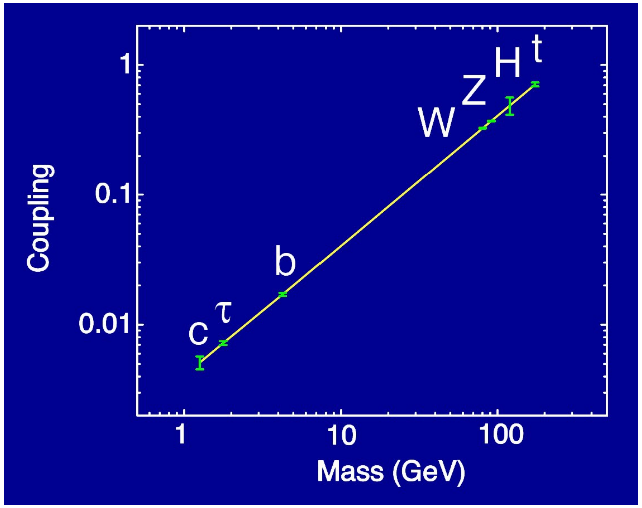


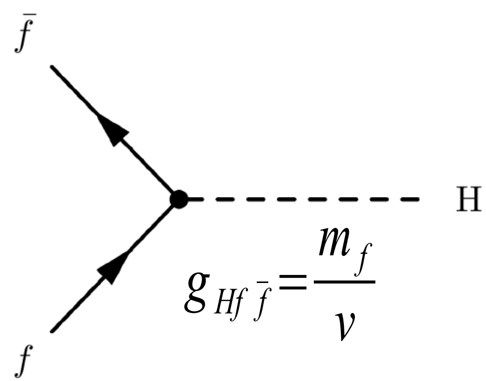
Couplings to Higgs Boson in Standard Model

Increase with particle mass



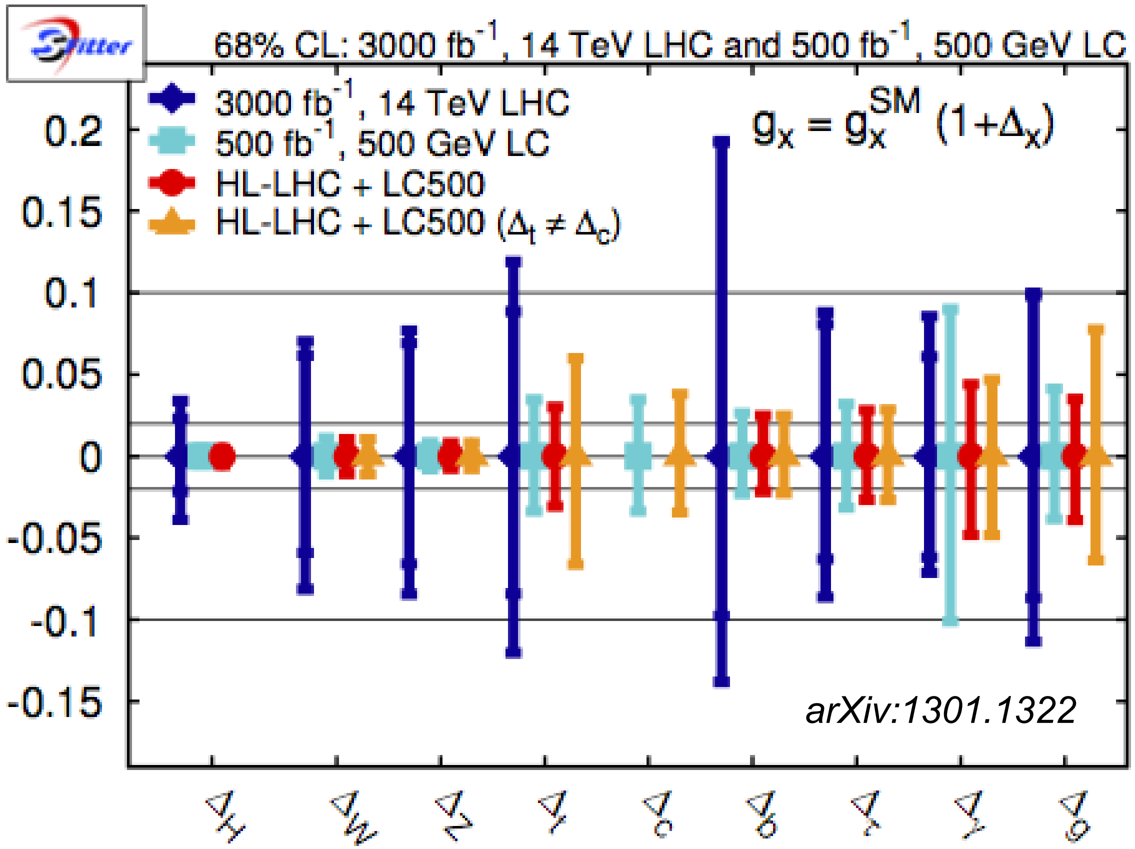
$$g_{HVV} = \frac{m_V^2}{v}$$





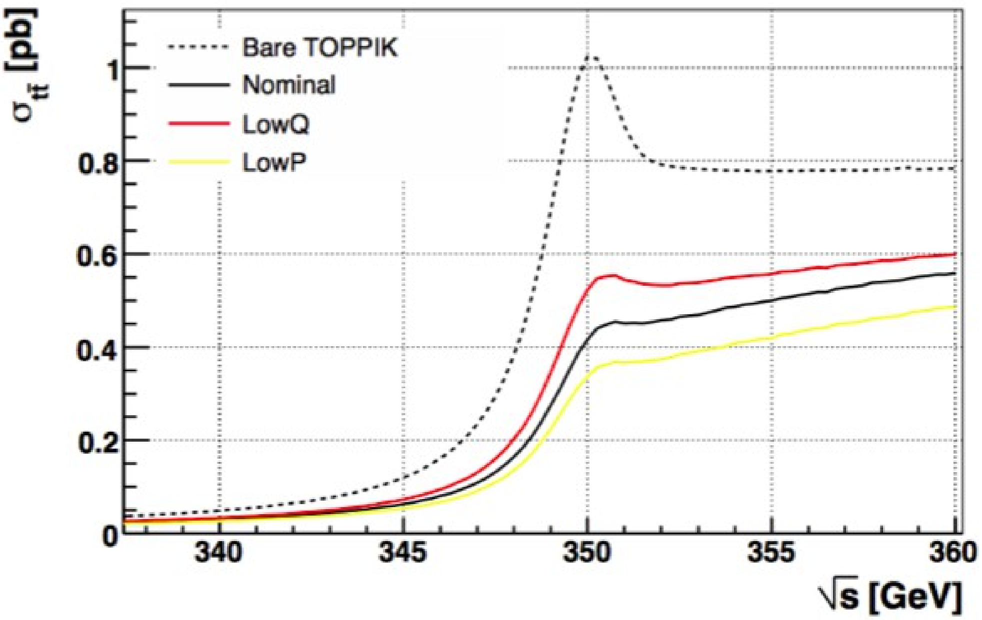
$$g_{Hf\bar{f}} = \frac{m_f}{v}$$

Individual Couplings to the Higgs



- A e+e- machine (Linear Collider) running at several energies will provide precise measurements of relevant Higgs couplings: Possibility to confirm the Higgs mechanism of the SM
- Precision matters: Detect deviations, for example due to extended Higgs sectors (SUSY,composite, ...):Expected on the 10% - 15% level in fermions,on the few % level in gauge bosons in typical Two-Higgs-Doublet models

Total tt Cross Section in e+e- Collisions



Principle: m_t from $\sigma_{tt}(m_t)$

Advantages:

- count number of $t\bar{t}$ events
- color singlet state
- background is non-resonant
- physics well understood (renormalons, summations)
- Top decay protects from non-pert effects

Much of the discriminating power of the approach related to the strong mass-dependence (ttbar resonance).

Peak position very stable in theory predictions (threshold mass scheme).

Typical results:

$\rightarrow \delta m_t^{\mathrm{exp}} \simeq 50$ MeV

$\rightarrow \delta m_t^{\mathrm{th}} \simeq 100$ MeV

What mass?

$\sqrt{s}_{\mathrm{rise}} \sim 2m_t^{\mathrm{thr}}$ + pert.series

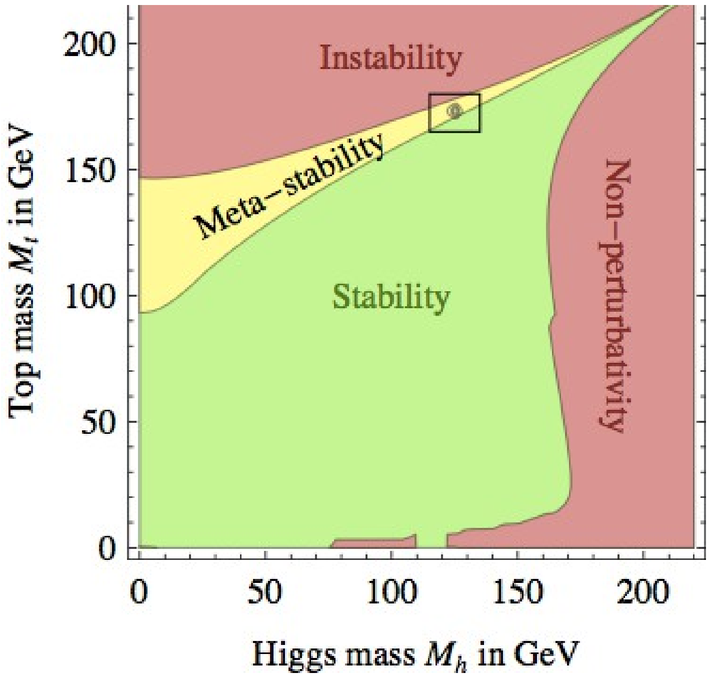
(short distance mass: 1S $\leftrightarrow \overline{\mathrm{MS}}$)

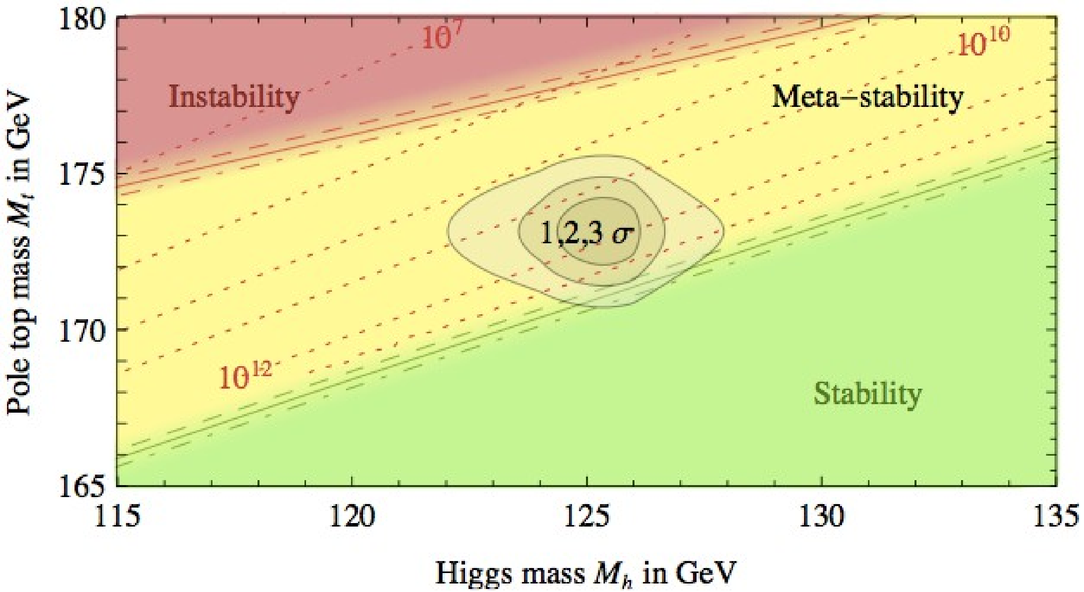
A. Hoang

Vacuum stability and Top Quark Mass

Degrassi et al. arXiv:1205.6497

$$M_h\ [\mathrm{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\mathrm{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\mathrm{th}}\ .$$

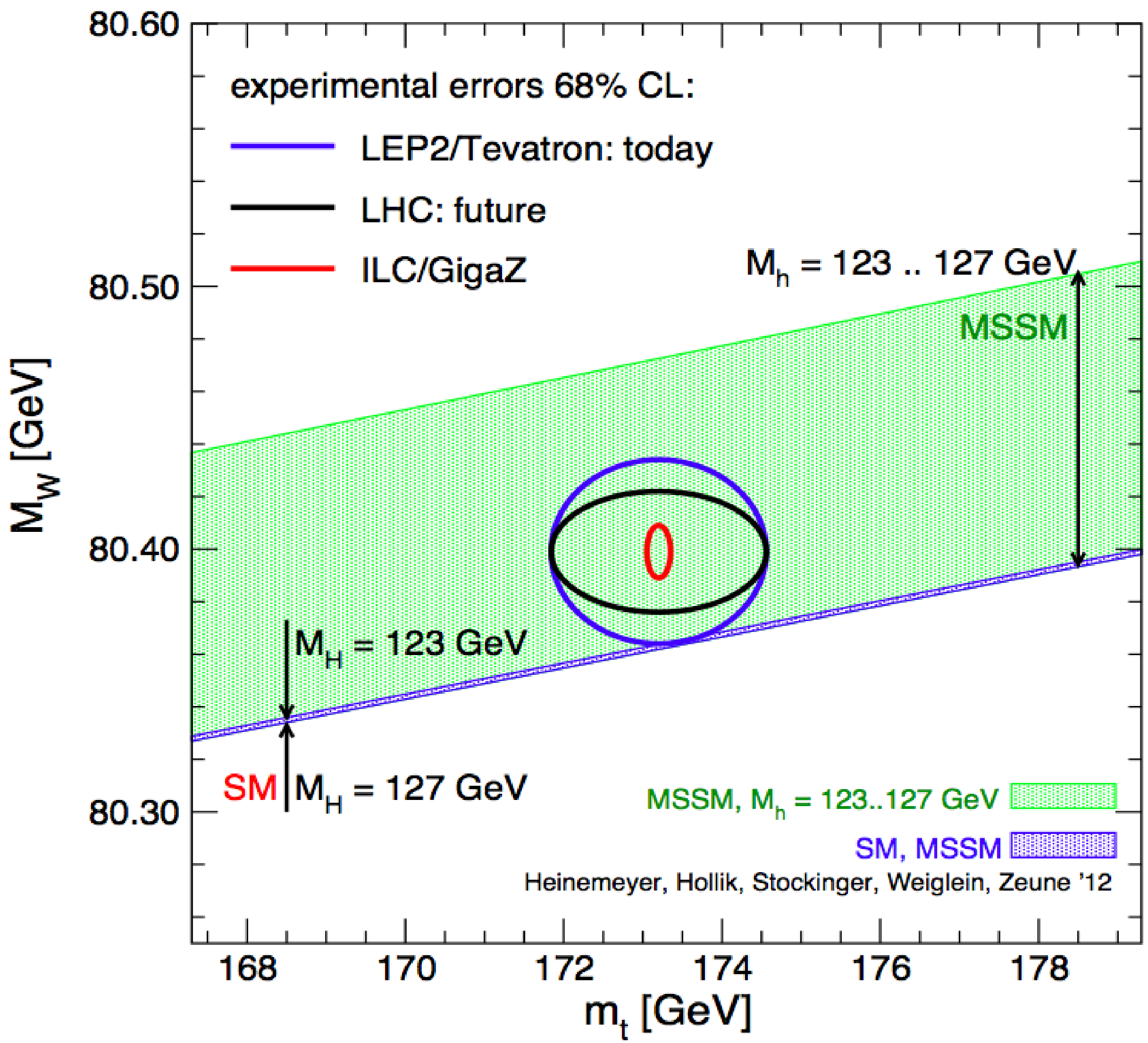




Type of error	Estimate of the error	Impact on M_h
M_t	experimental uncertainty in M_t	±1.4 GeV
α_s	experimental uncertainty in α_s	±0.5 GeV
Experiment	**Total combined in quadrature**	±1.5 GeV
λ	scale variation in λ	±0.7 GeV
y_t	$\mathcal{O}(\Lambda_{\mathrm{QCD}})$ correction to M_t	±0.6 GeV
y_t	QCD threshold at 4 loops	±0.3 GeV
RGE	EW at 3 loops + QCD at 4 loops	±0.2 GeV
Theory	**Total combined in quadrature**	±1.0 GeV

Uncertainty on **(pole)** top quark mass dominates uncertainty on stability conditions

Top Mass, Higgs Mass and BSM – SM vs. MSSM



Precise Top (and W) mass crucial to test compatibility of measured Higgs mass

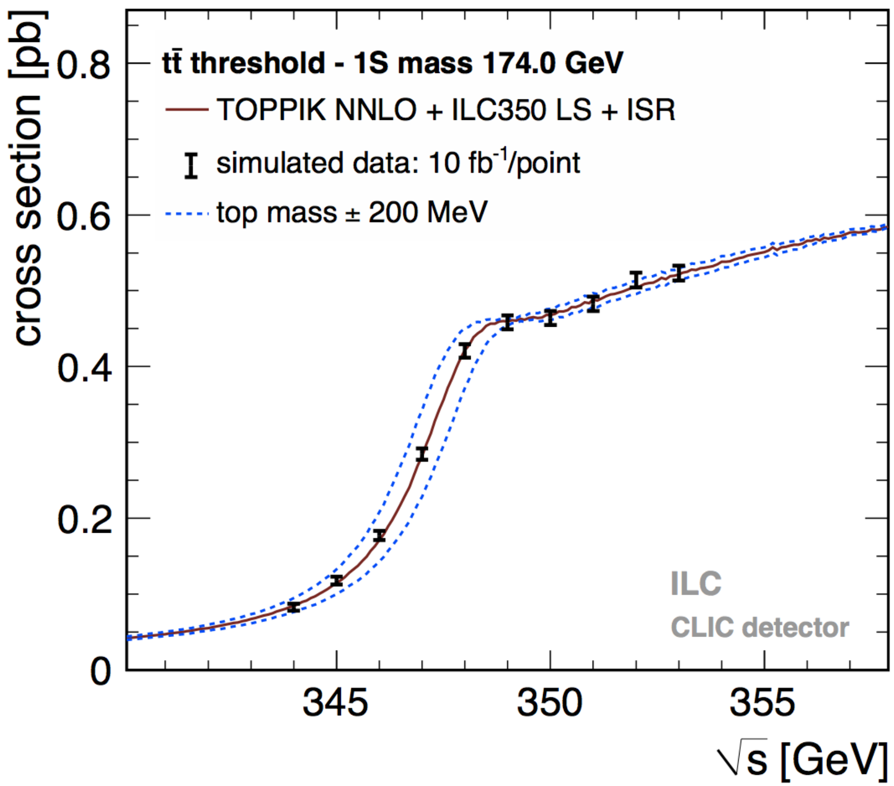
MS might not be sufficient to explain Higgs mass

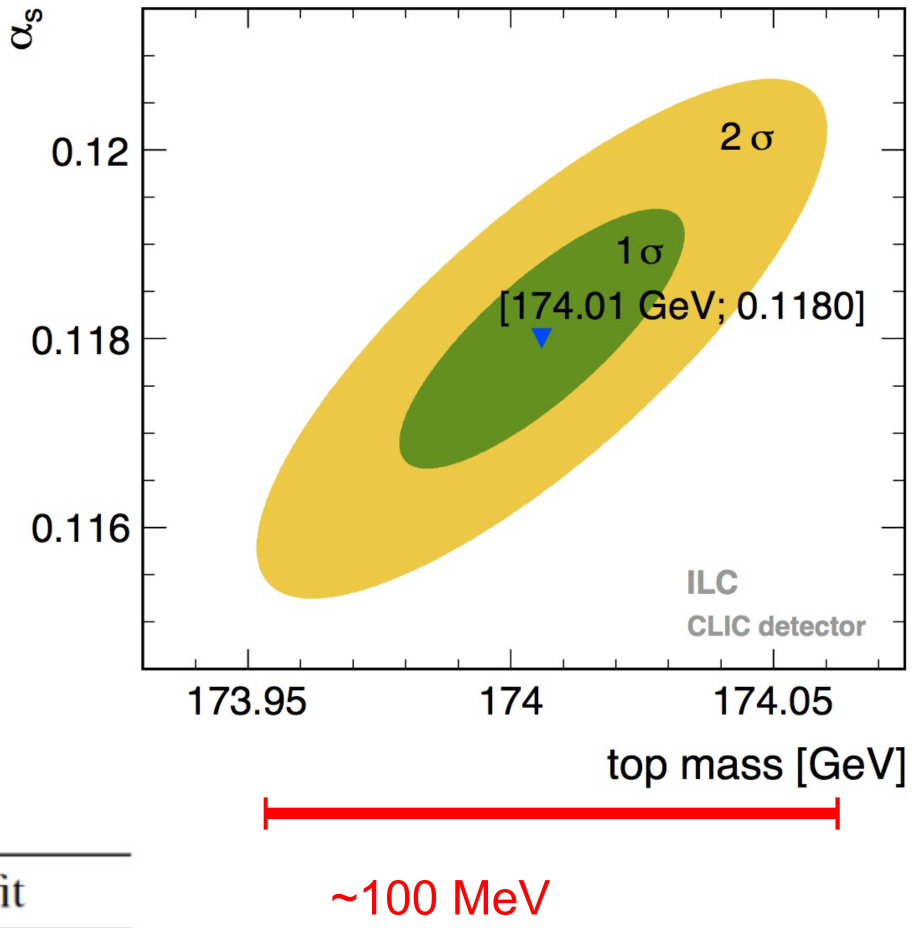
LHC may not reach sufficient discriminative power

A lepton collider will

Mass and α_s

EPJC C73 (2013) 2530





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

Disentangling

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

ILC 'provides' two beam polarisations

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

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

σ_I

x-section

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

Forward backward asymmetry

$$(F_R)_I = \frac{(\sigma_{t_R})_I}{\sigma_I}$$

Fraction of right handed top quarks

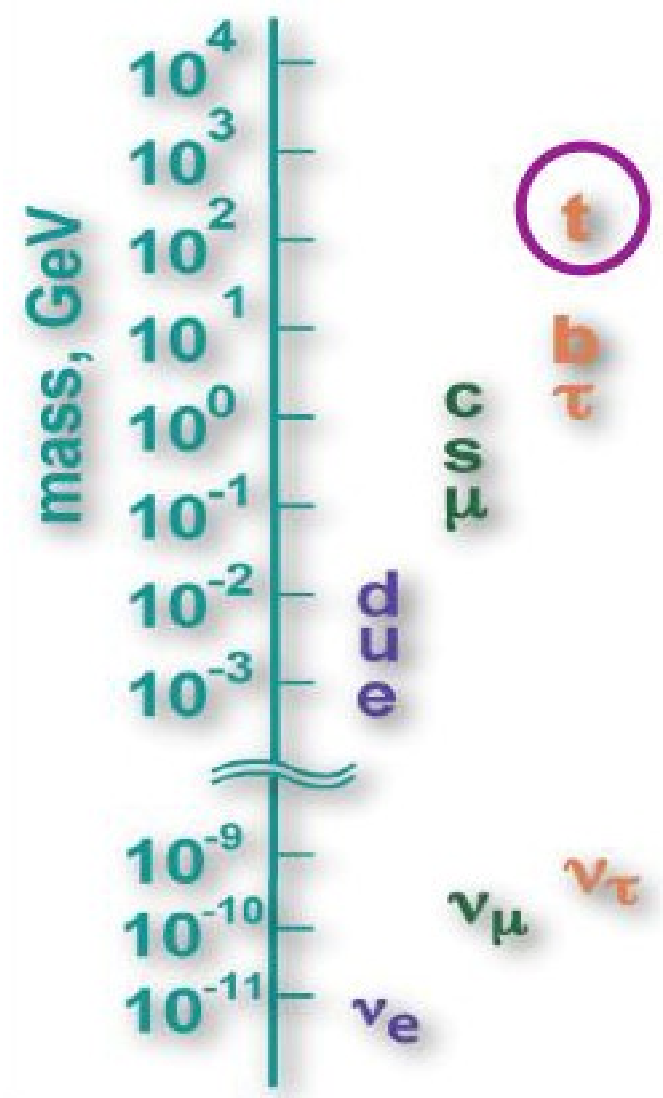
⇩

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

Top Quark and Flavor Hierarchy



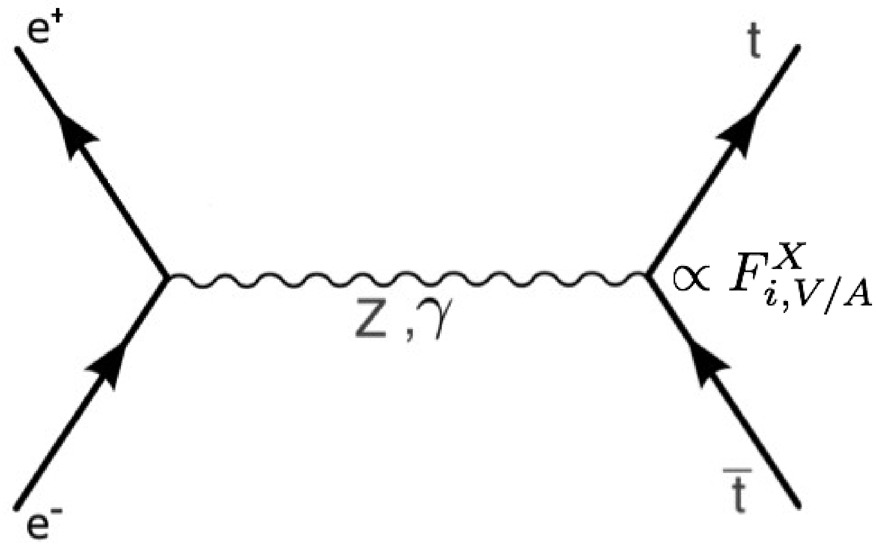
- SM does not provides no explanation for mass spectrum of fermions (and gauge bosons)

- 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



$$\Gamma_\mu^{ttX}(k^2,q,\overline{q}) = -ie\left\{\gamma_\mu\left(F_{1V}^X(k^2)+\gamma_5F_{1A}^X(k^2)\right)+\frac{\sigma_{\mu\nu}}{2m_t}(q+\overline{q})^\mu\left(iF_{2V}^X(k^2)+\gamma_5F_{2A}^X(k^2)\right)\right\}, \tag{2}$$

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

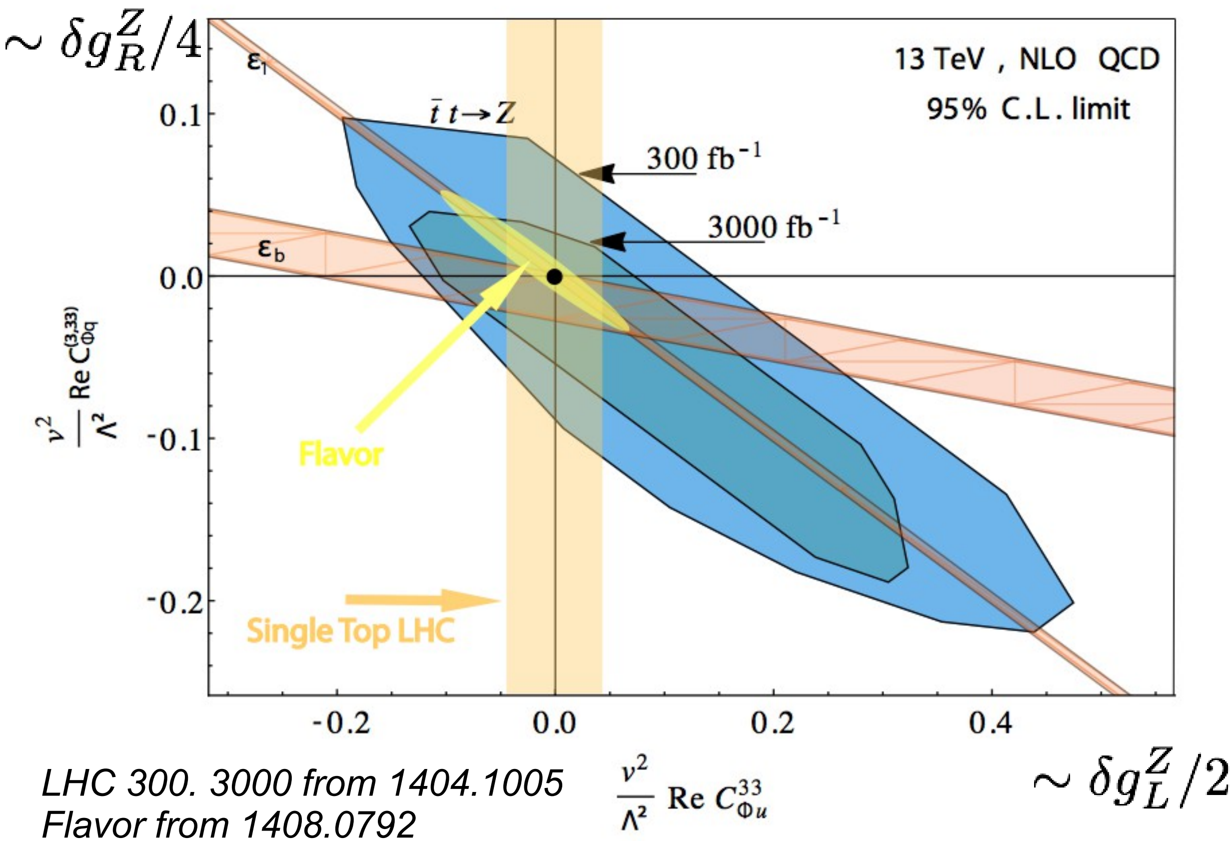
Z^0/γ interference : $\sigma \backsim (F_i) \Rightarrow$ Sensitivity to sign of Form Factors

Results of full simulation study at $\sqrt{s}$ = 500 GeV and L=500 fb^{-1}

ArXiv: 1307.8102

Precision cross section ~ 0.5%, Precision A_{FB} ~ 2%, Precision λ_t ~ 3-4%

Accuracy on SM Z couplings compared with other experiments



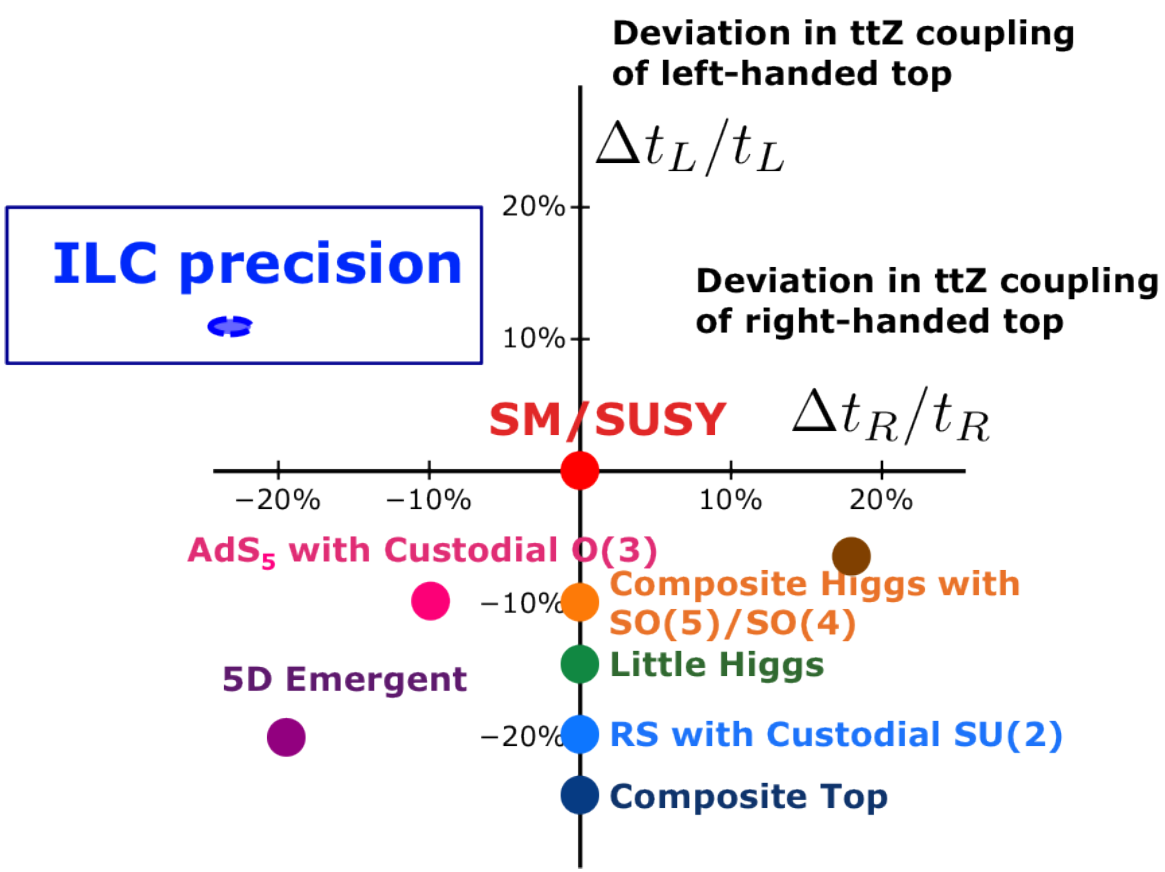
LHC 300. 3000 from 1404.1005
Flavor from 1408.0792
LHC Single top added by F. Richard

- ILC with polarised beams outperforms all present and future experiments (Stringent limits only from LEP)
- Before ILC single top at LHC and B factories can deliver complementary information
- In particular g_R can only be constrained by ILC!
- Maintaining this high level still requires substantial experimental and theoretical work

ILC promises to be high precision machine for electroweak top couplings

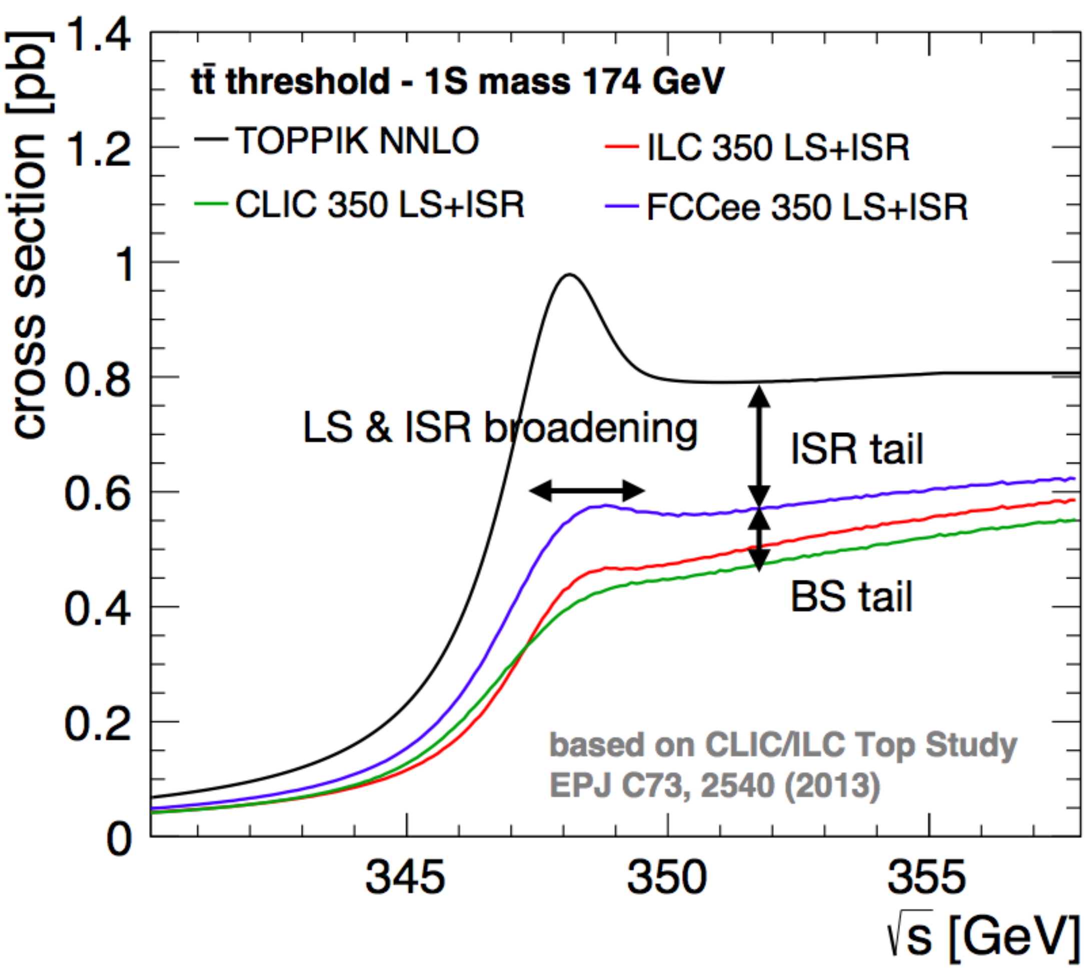
Sensitivity to New Physics

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 beween models

Top Quark Mass – Influence of Luminosity Spectrum



- Initial State Radiation
  Lowers effective L at top energy
- BeamStrahlung
  Lowers effective L
  at top energy
  Not at FCCee Gaussian spectrum
- Luminosity spectrum & Initial State Radiation broadening
  Smearing of cross section
  Due to beam energy spread
  ILC and FCCee comparable
  Worse at CLIC

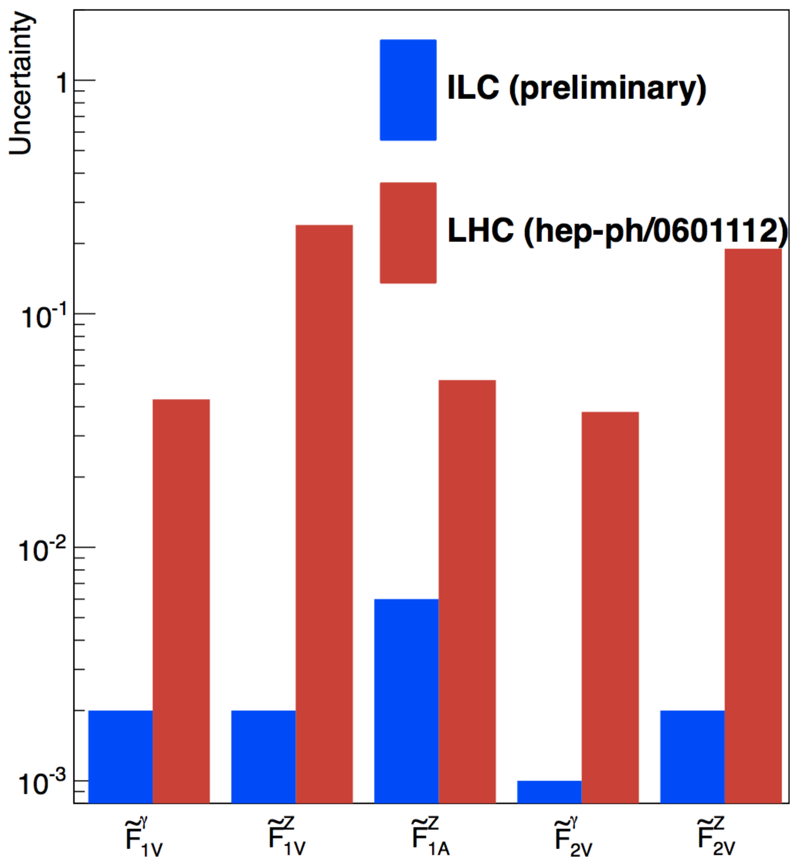
1) Main effect on L spectrum is ISR
   => Reduces Luminosity, smears out 1s bound state peak
2) LC somewhat smaller L due to BeamStrahlung

F. Simon
AWLC14

ArXiv: 1307.8102

Precision: cross section ~ 0.5%, Precision A_{FB} ~ 2%, Precision λ_t ~ 3-4%

Accuracy on CP conserving couplings



- ILC might be up to two orders of magnitude more precise than LHC ($\sqrt{s}$ = 14 TeV, 300 fb^{-1})
  Disentangling of couplings for ILC
  One variable at a time For LHC
  However LHC projections from 8 years old study

- Need to control experimental (e.g. Top angle) and theoretical uncertainties (e.g. Electroweak corrections)
  -> Dedicated work has started

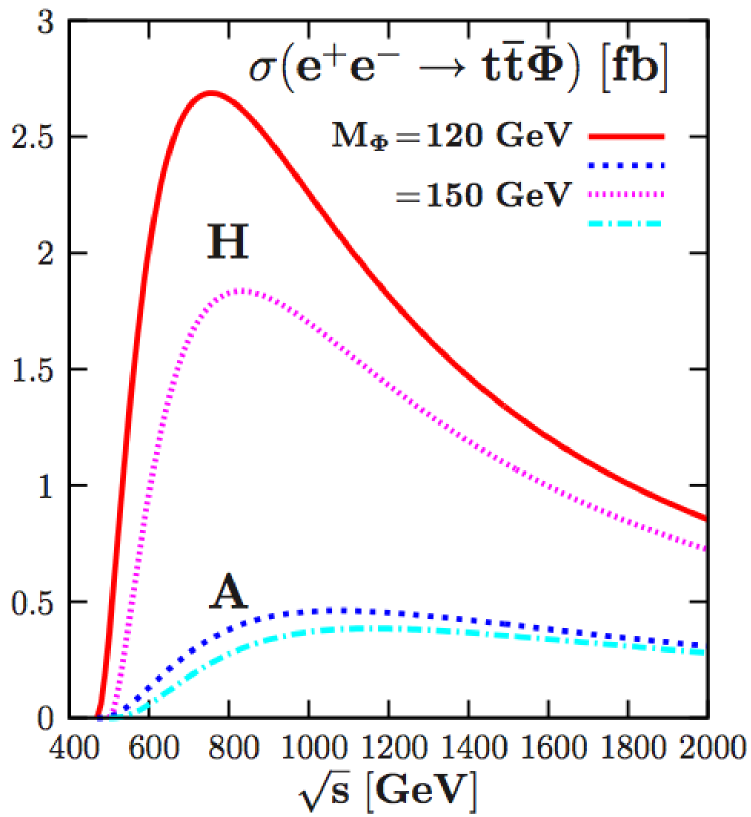
- Potential for CP violating couplings at ILC under study

ILC promises to be high precision machine for electroweak top couplings

Higgs Quantum Numbers – CP via tth

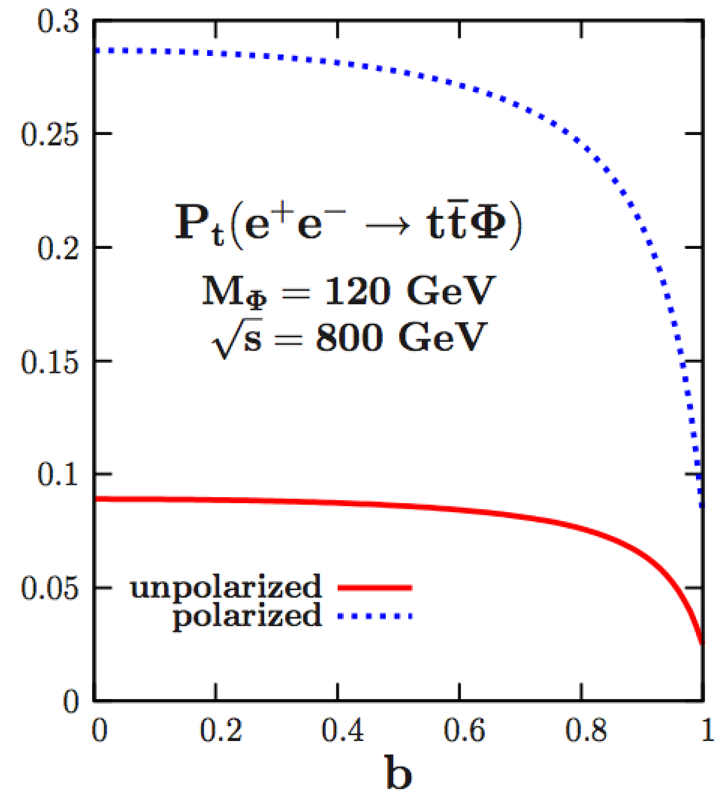
Direct coupling of top quark to CP odd and CP even scalar

Cross section



Dramatic differences for
CP odd and CP even scalar

Top quark polarisation

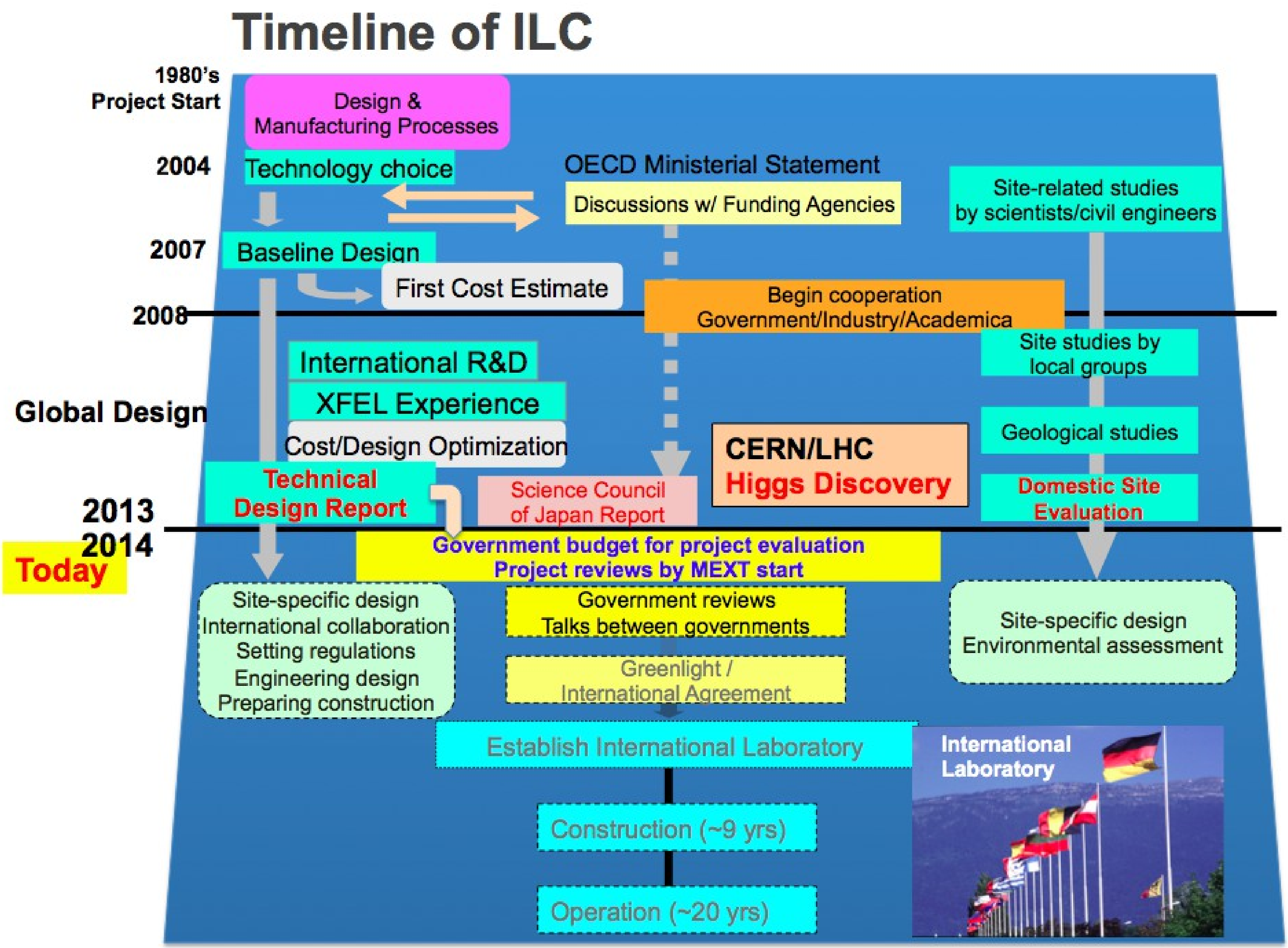


Sensitivity to CP odd admixture b
Merit of beam polarisation

Determination of CP nature of scalar boson in an unambiguous way

Godbole et al., LCWS07

ILC Roadmap



Remark R.P.: MEXT report in March 2016