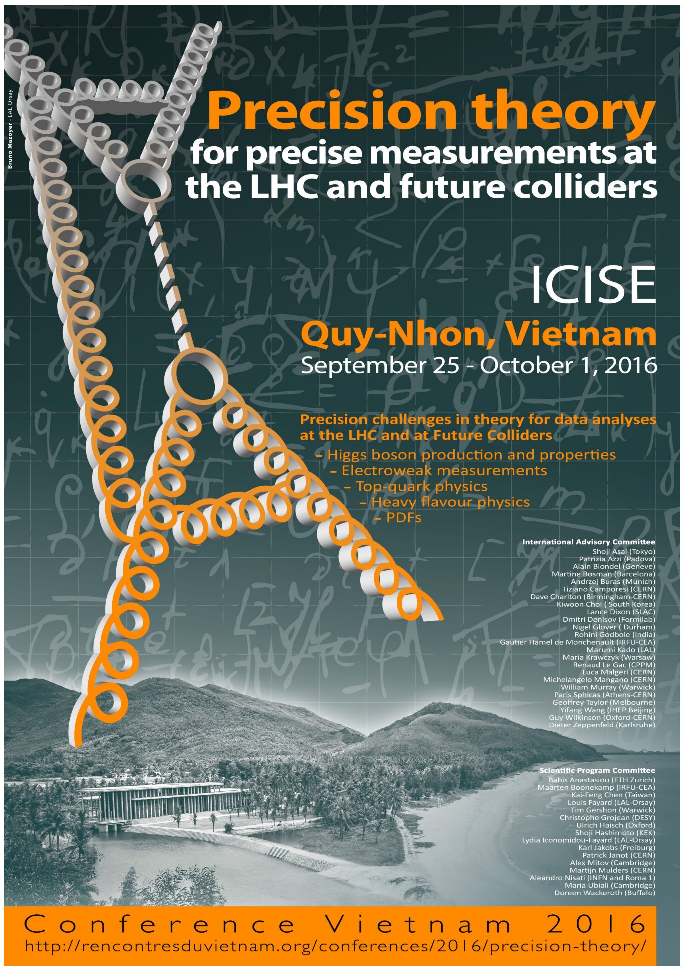
Precision physics at energy frontier e+e- colliders

Logo of German KET Workshop, May 2016



Roman Pöschl
Directeur de Recherche of CNRS

R.P. is indebted to A. Freitas, S. Heinemeyer, F. Richard and F. LeDiberder for useful discussions and to many authors from whom I have reused their material

Precision theory for precision measurements – Quy Nhon/Vietnam Sept. 2016

Outline of talk

- Chapter 1: Introduction

- Chapter 2: Electroweak precision tests

- Chapter 3: Top physics

- Chapter 4: BSM physics

1. Introduction

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

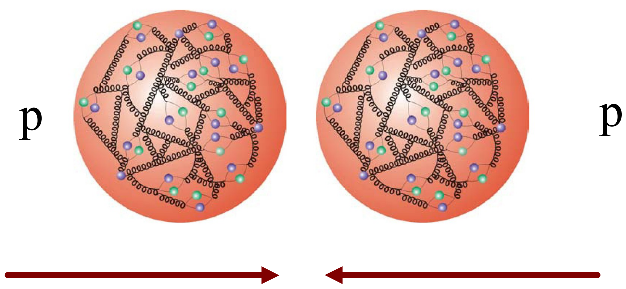
-> High energy, High luminosity LHC

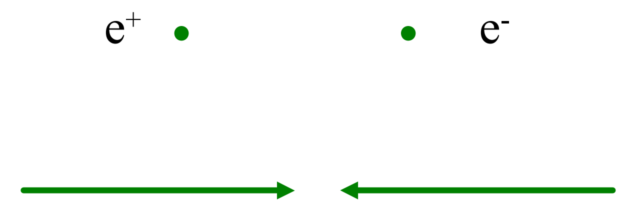
2) e+e-Collisions at energies at the electroweak scale
- Probe the electroweak scale with high precision
- ... in particular particles that carry the “imprint of the Higgs Field such as W, Z and top”

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

-> SuperKEKB

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:

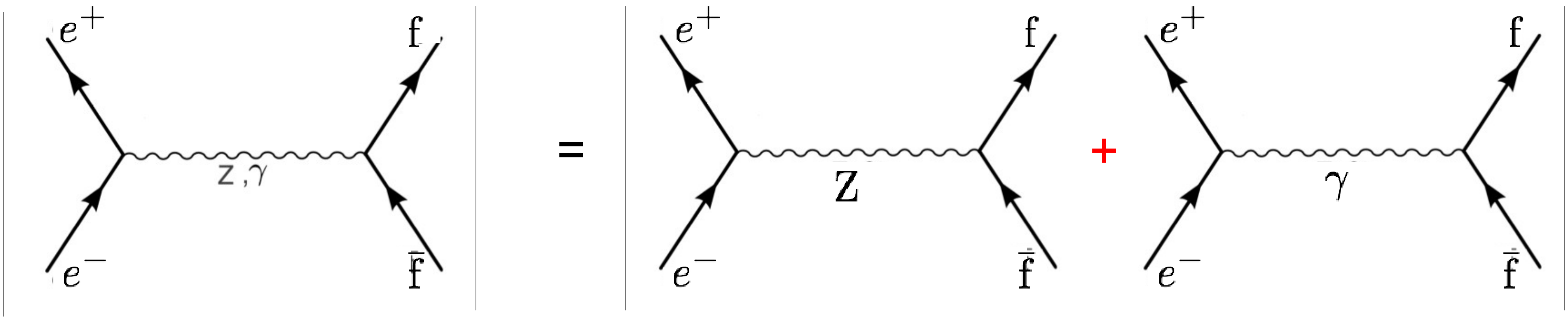
Elementary particle

Well known and adjustable
energy of collision partners

High precision measurements
in a model independent way
with small electroweak backgrounds

Each energy point needs a
new set of machine parameters

Cross section $e^+e^- \to f\bar{f}$



Interference between individual amplitudes of γ and Z exchange

$$\mathcal{M}_Z = -\frac{\sqrt{2}G_F M_Z^2}{s - M_Z^2}\left[\bar{\mathrm{f}}\gamma^\rho\left(c_V^f - c_A^F\gamma^5\right)\mathrm{f}\right] g_{\rho\sigma}\left[\bar{e}\gamma^\sigma\left(c_V^f - c_A^F\gamma^5\right)e\right]$$

$$\mathcal{M}_\gamma = -\frac{e^2}{s}(\bar{\mathrm{f}}\gamma^\nu\mathrm{f})\mathrm{g}_{\mu\nu}(\bar{\mathrm{e}}\gamma^\nu\mathrm{e})$$

Differential cross section:

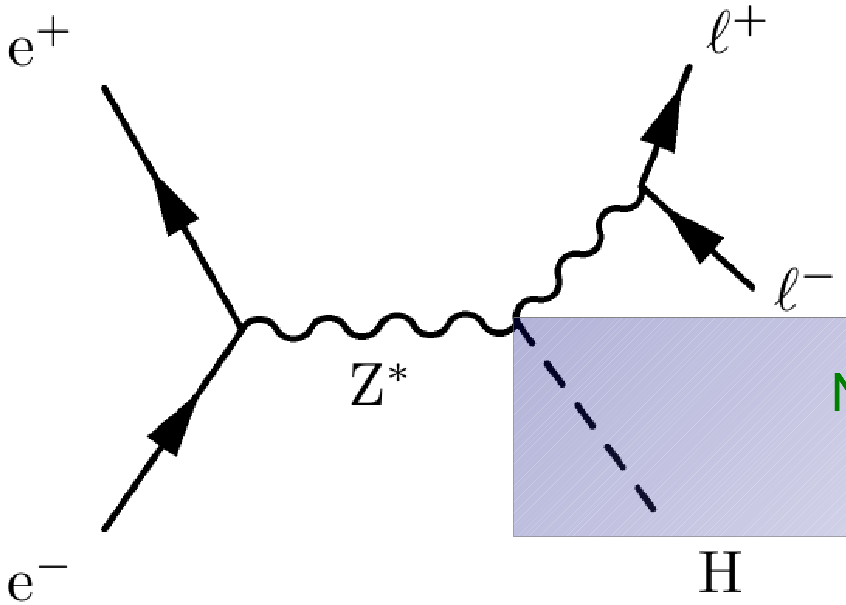
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\left[A_0(1+\cos^2\theta) + A_1\cos\theta\right]\begin{cases} \sim (1+\cos^2\theta) & \text{'Usual' Vector current, symmetric in } \cos\theta \\ \backsim \cos\theta & \text{Axial Vector current, asymmetric in } \cos\theta \end{cases}$$

Weak interaction introduces forward backward asymmetry

=> Asymmetry is intrinsic to electroweak processes!!!

7

Higgs Mass and ZZH coupling by
Model Independent
measurement



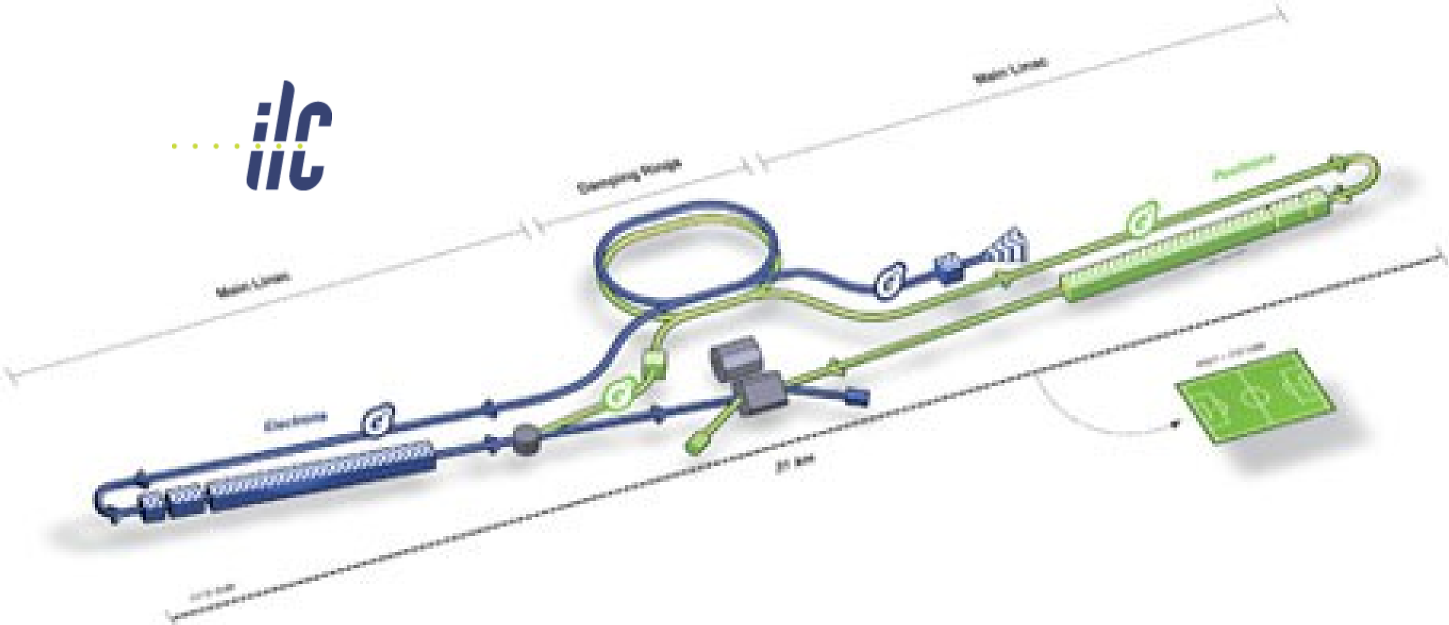
Well measurable
decay leptons from Z
μ Pairs, e pairs

No assumption on Higgs
decay modes

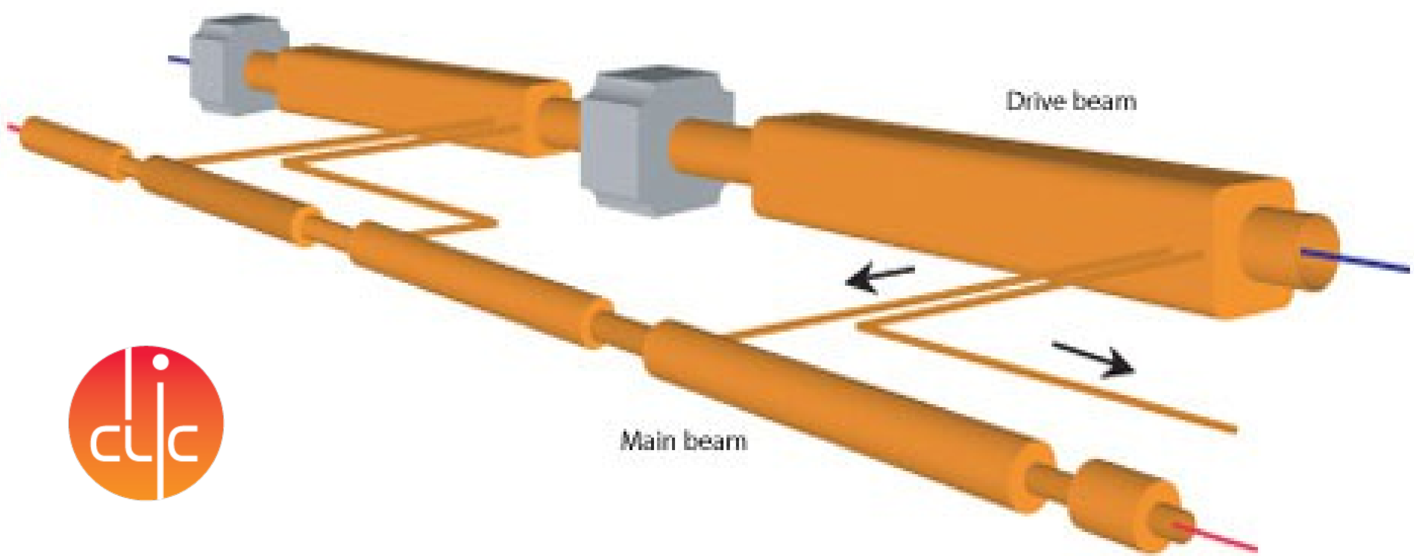
Higgs Recoil Mass: $M_h^2 = M_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$

More details on Higgs physics at e+e- colliders see talk by Junping Tian

Linear Electron-Positron Colliders Projects



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

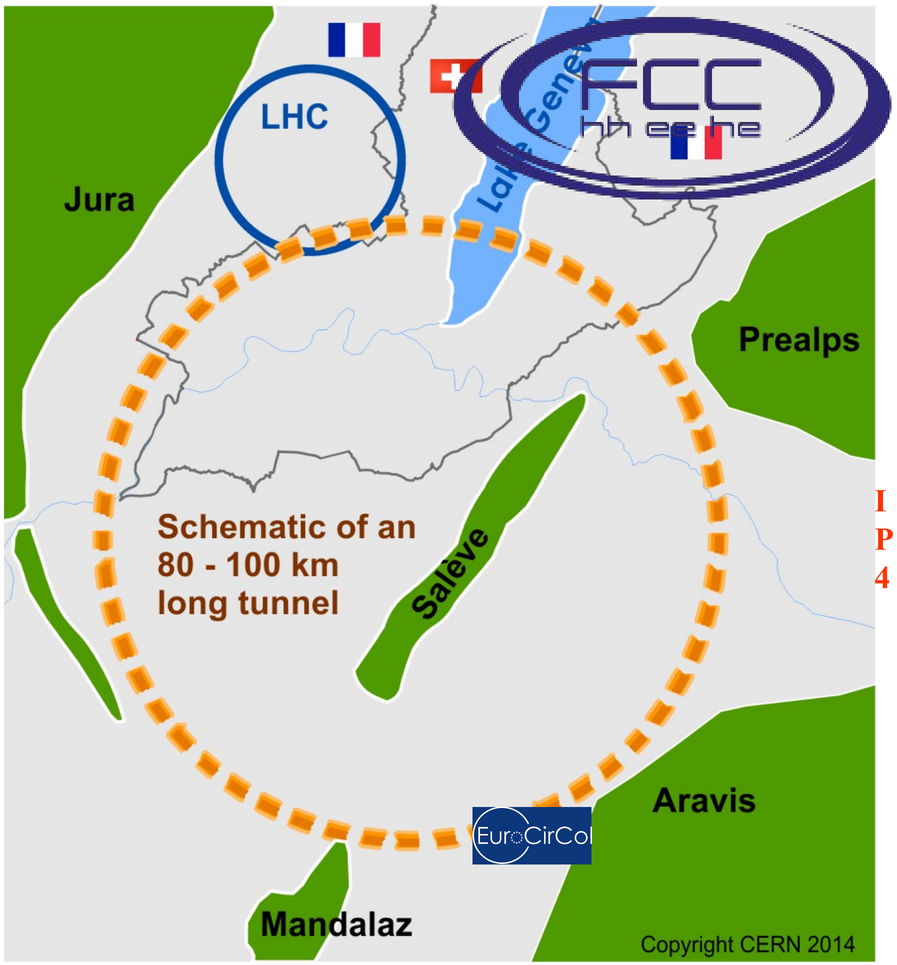


Energy: 0.5 - 3 TeV

CDR in 2012

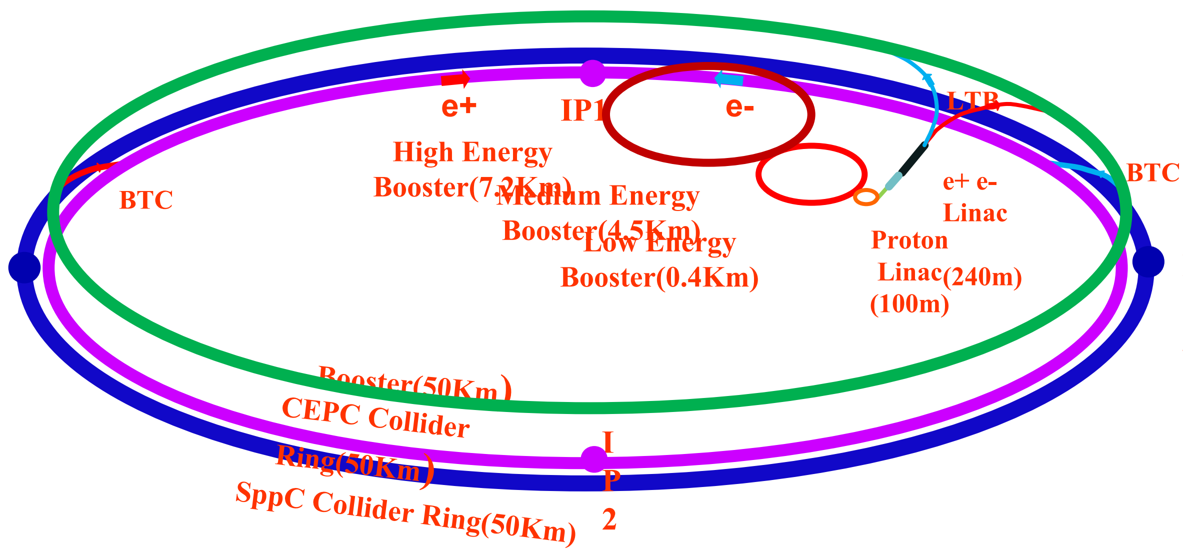
Footprint 48km

Circular Electron-Positron Colliders Proposals



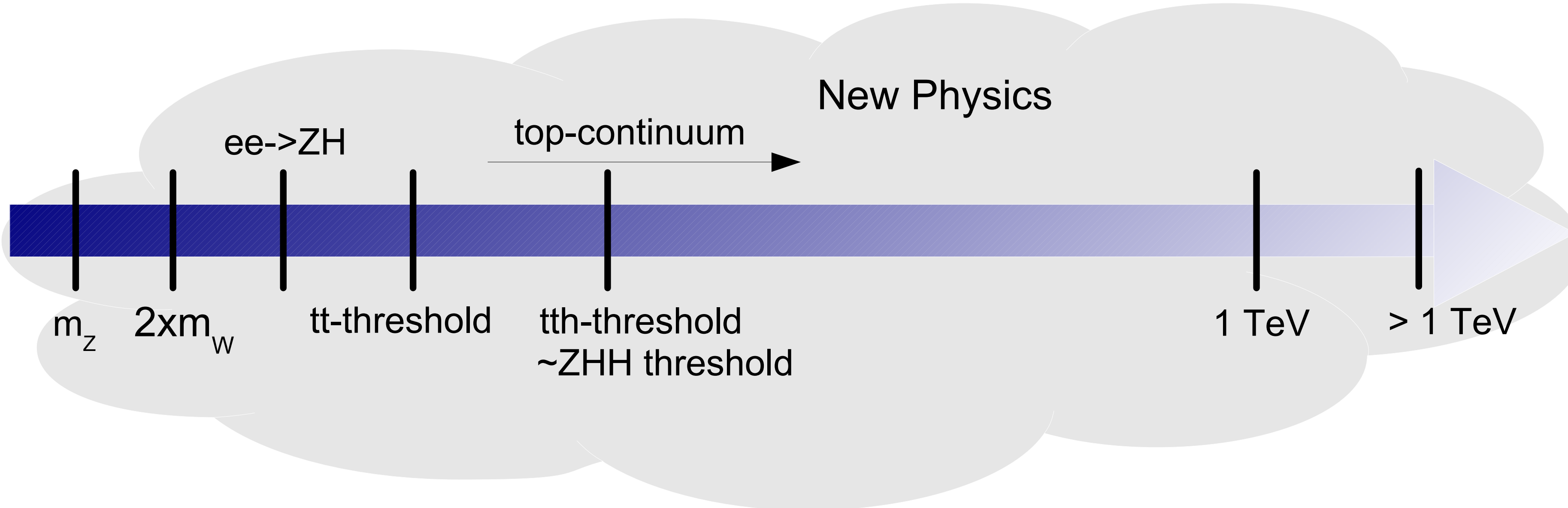
- ~100 km storage rings
- Coupled to hadron collider proposal
- 90 – 350 GeV cms energy
- No long. beam polarisation
- CDR Phase

CEPC



- ~50 km storage rings
- Coupled to hadron collider proposal
- 90 – 240 GeV cms energy
- No long. beam polarisation
- (Pre-)CDR Phase

e+e- Physics program

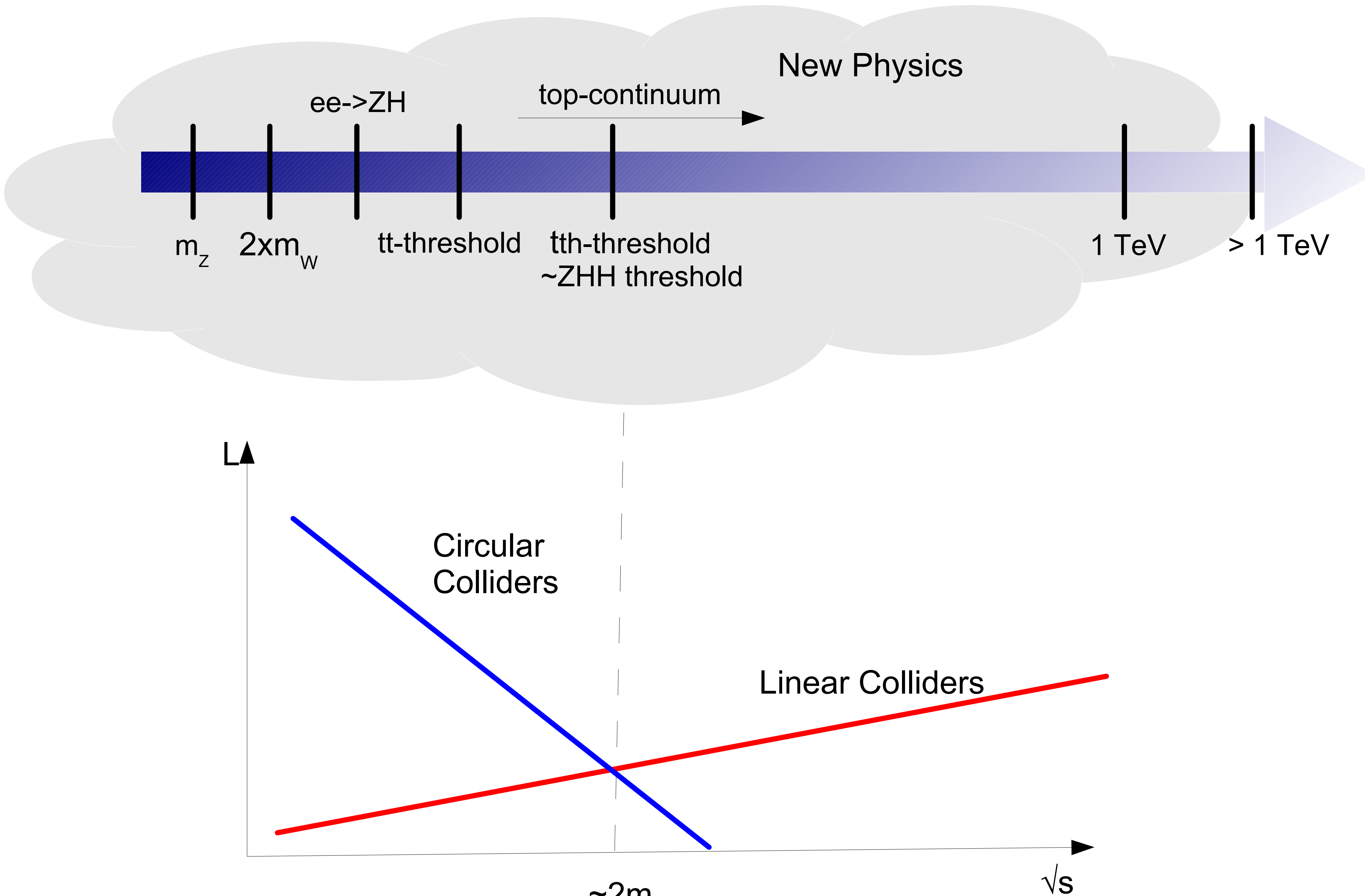


- All Standard Model particles within reach of planned e+e- colliders
  - High precision tests of Standard Model over wide range to detect onset of New Physics
- Machine settings can be “tailored” for specific processes
  - Centre-of-Mass energy
  - Beam polarisation

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

- “Background free” searches for BSM through beam polarisation

e+e- Physics program



e+e- collisions - Tools?

Theory

Loop calculations (prospect on 3-loops)

... to distinguish new effects from ordinary effects, how many are needed?

Global Fits

... to assure consistency of results

New models

... as concrete manifestations of new physics

Effective field theory

... for generic effects of new physics

Experiment

Better accelerators

- Higher accelerating gradients
- Beam polarisation
- Nanosize beams

Better detectors

- 4π hermetic
- Highly granular devices

New analysis techniques

... multi-variate techniques (must however not replace first two points)

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)

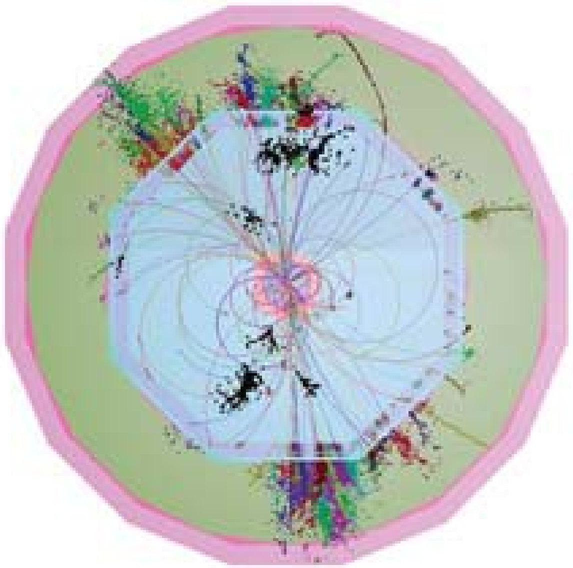
(Quark tagging c/b)

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

(W/Z masses with jets)

Hermeticity : $\theta_{min} = 5$ 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

2. Electroweak precision tests

Electroweak Precision Data

Copied from deBlas, Higgs-Hunting 2016

- Precise measurements of W&Z properties taken at e+e- colliders

$$M_Z,\ \Gamma_Z,\ \sigma^0_{had},\ \sin^2\theta^{\rm lept}_{\rm eff},\ P^{Pol}_\tau,\ A_f,\ A^{0,f}_{FB},\ R^0_f$$

Z-Pole observables
SLD/LEP
0.002 - O(1%)

$$M_W,\ \Gamma_W$$

W-observables
LEP2
0.02 - O(1%)

- Tevatron/LHC but in future also from e+e- colliders

$$M_W,\ \Gamma_W$$

0.02-O(1%)

$$m_t$$

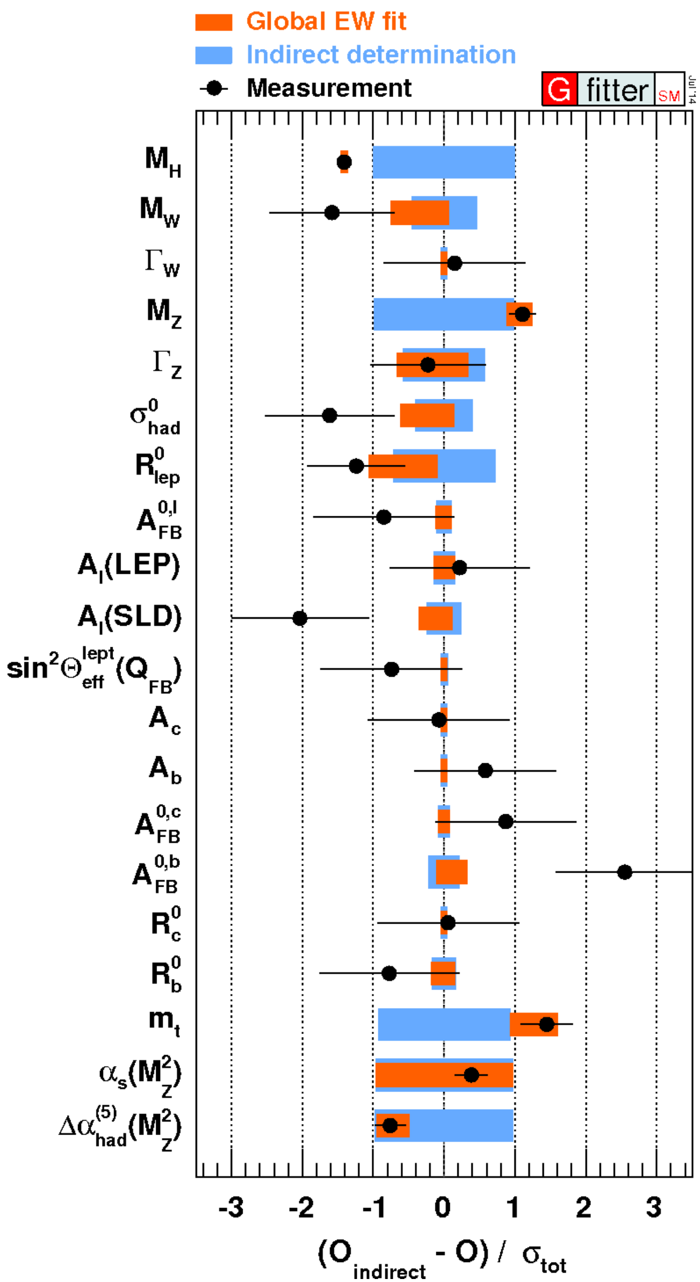
0.4%

$$M_H$$

0.2%

Note competitive measurements of $\sin^2\theta^2_{\rm eff.}$ by LHC

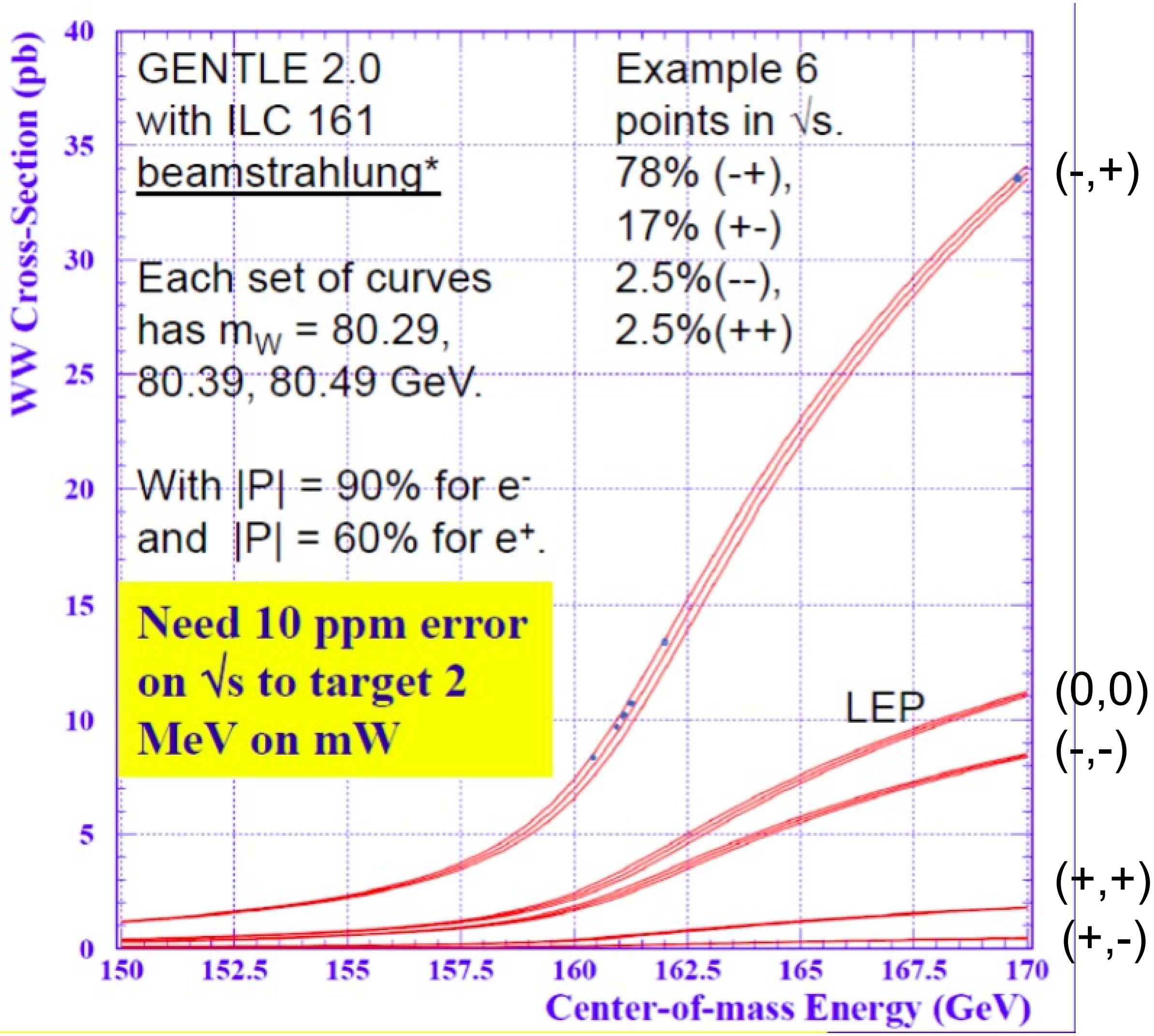
Electroweak precision data – Overall status

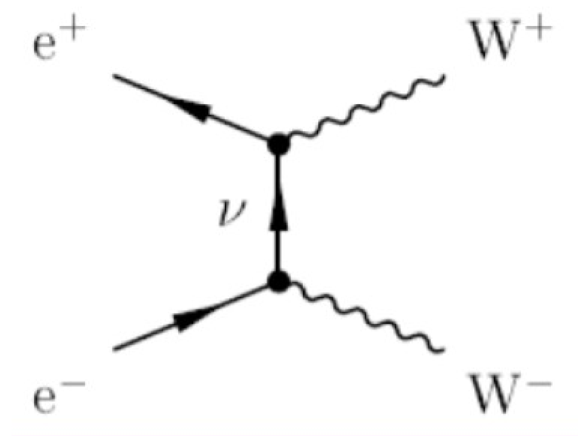


- Consistency between fit and measured values for vast majority of precision observables

With one notable exception!!!!
(see later)

Example: Future W mass measurement



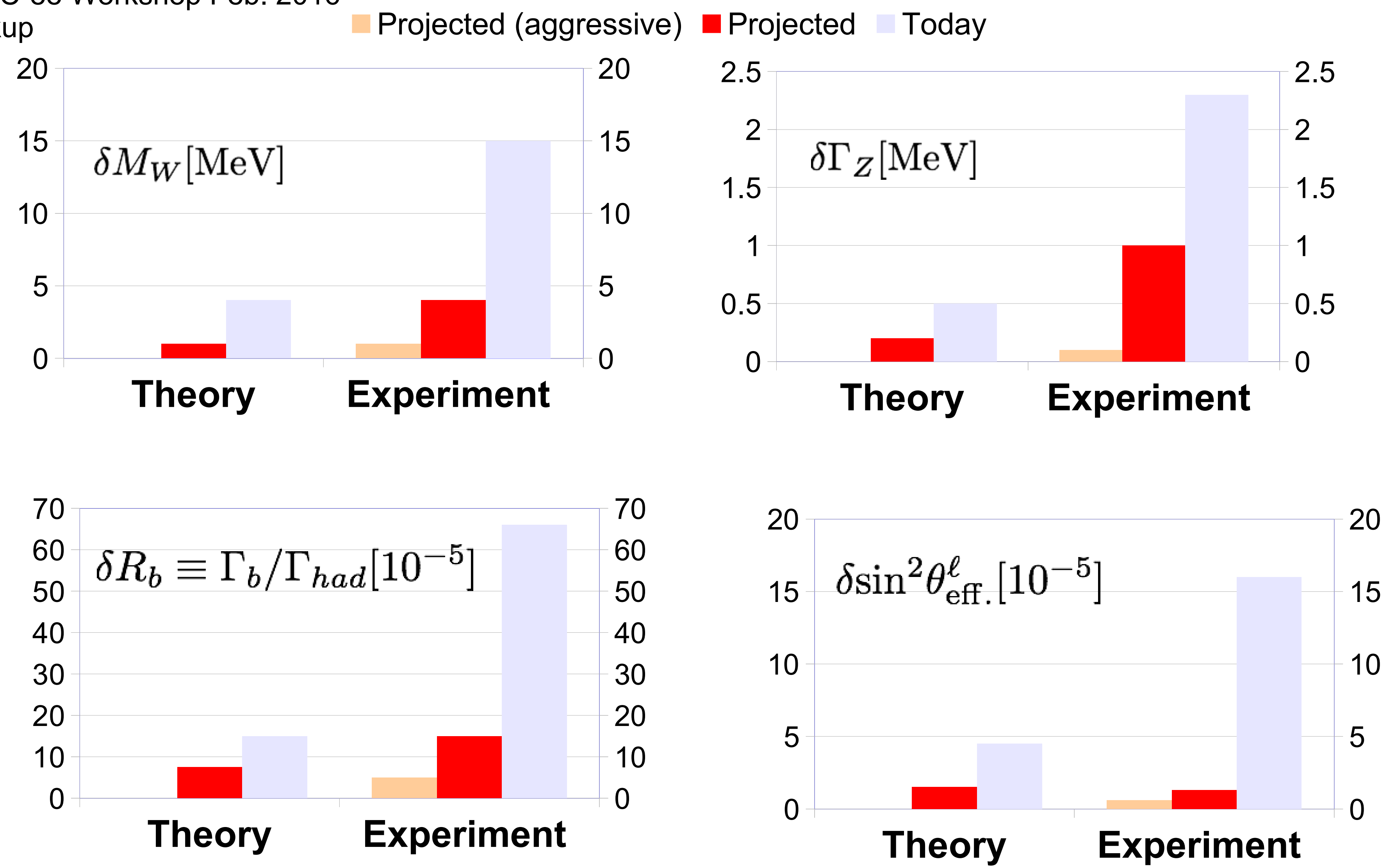


- Robust method
- Beam polarisation essential
- Need extreme good control of beam energy

G. Wilson

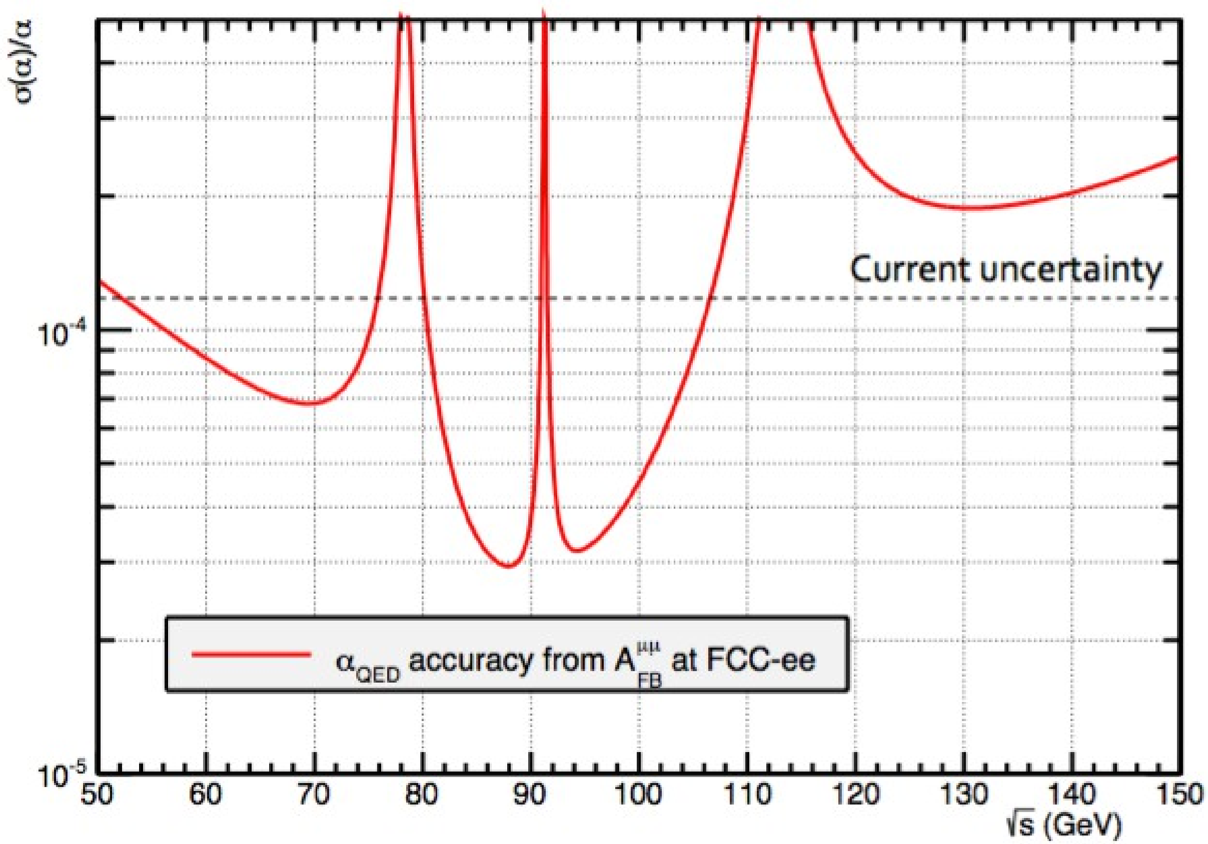
Projected development of precision

à la Freitas, FCC-ee Workshop Feb. 2016
Details -> backup



- Optimistic/aggressive scenario will lead to theory dominated errors
- Theory errors may become guide line for planning of future projects

Prospects for alpha_QED in high statistics e+e- running

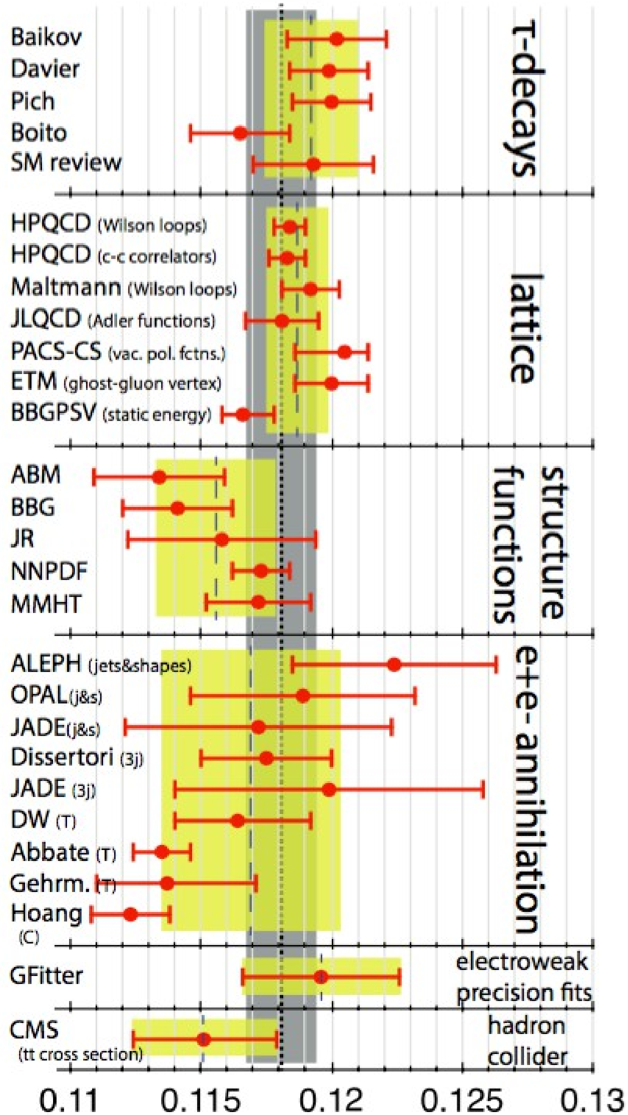


- Combining measurements slightly above and below the Z-Pole to reduce experimental errors
- Most optimistic experimental prospection arrives at $d\alpha/\alpha$ $3x10^{-5}$
- Puts challenge on theory, current prospect $\sim 10^{-4}$

P. Janot, arxiv:1512.05544

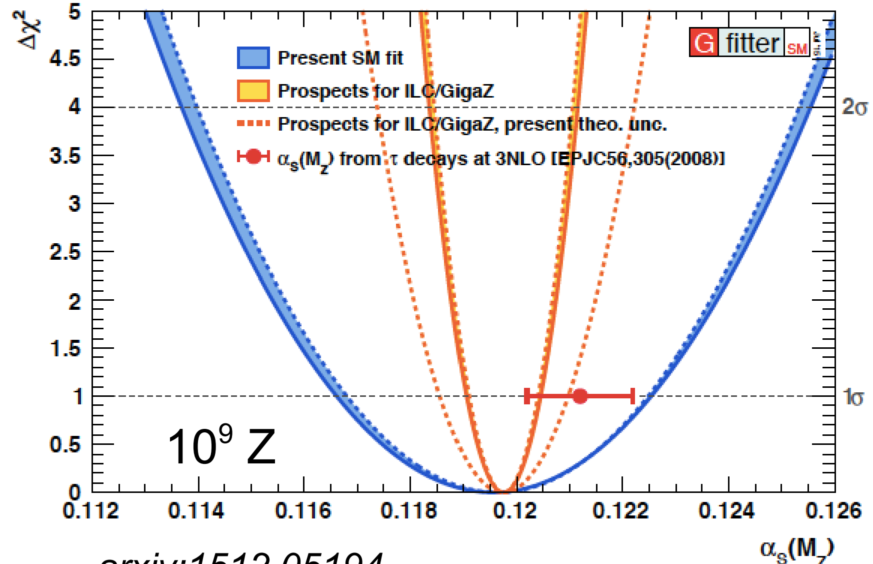
Uncertainty driver α_s

Current status



Dominated by lattice QCD

Prospects Z-running



arxiv:1512.05194

Electroweak fit with updated EWPO: and theory uncertainties

$\delta\, \alpha_s(M_Z) \sim 0.0007$ for 10^9Z

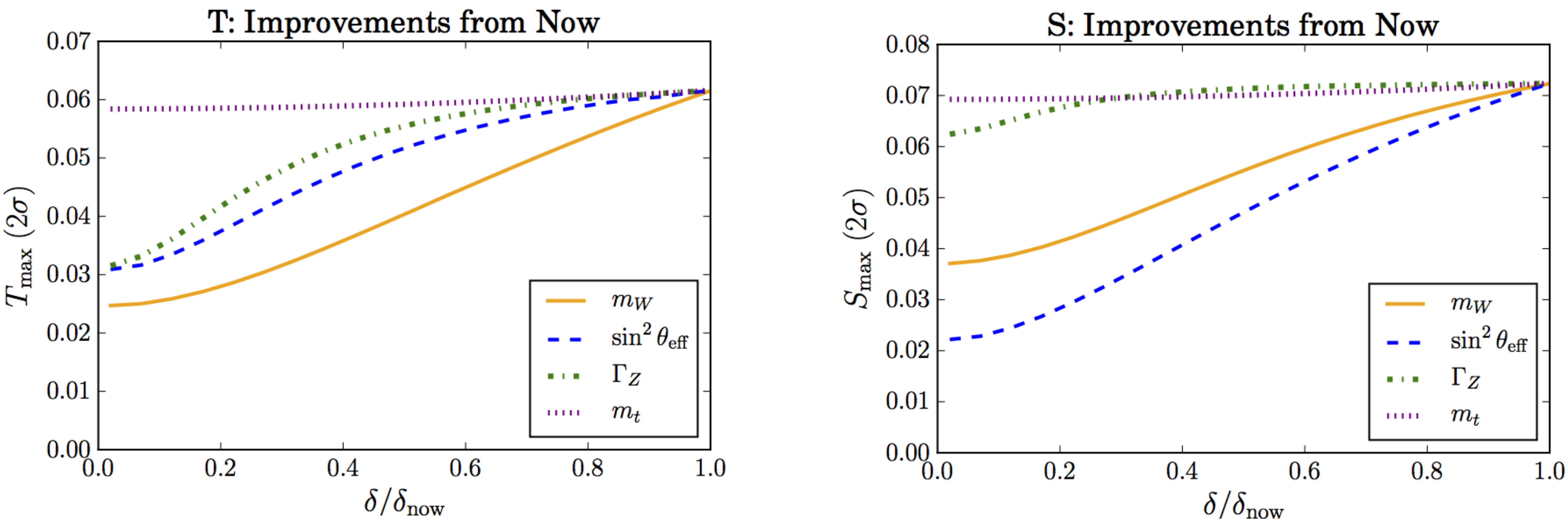
$\delta\, \alpha_s(M_Z) \sim 0.0003(16)$ for 10^{12}Z

Prospects Lattice

$\delta\alpha_s(MZ) \sim 0.0003$

Impact on oblique parameters?

à la M. Reece 1609.03018



- T depends mainly on M_W
  - Threshold scan around $2M_W$ (with polarised beams), see above

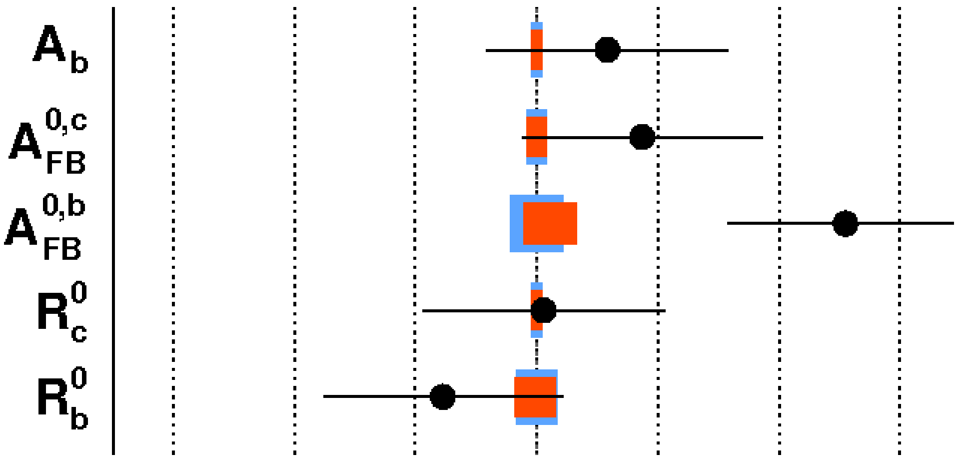
-

- S depends mainly on $\sin^2\theta^2_{\rm eff}$.
  - Ultra-high statistics sample ee-> ff at Z-mass or smaller sample exploiting beam polarisation (Remember LEP and SLC times)

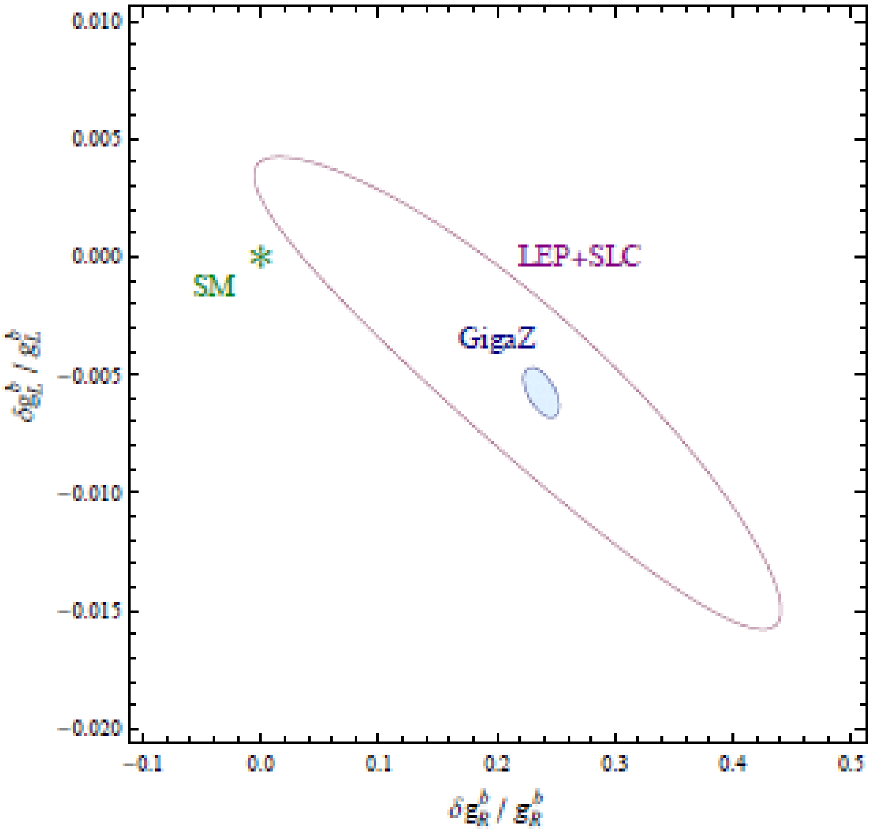
- Precision on S and T seems to saturate at $\delta/\delta_{now} \approx 0.1 - 0.2$

LEP Anomaly on A^b_{FB}

~3σ in heavy quark observable A^b_{FB}



Projection with 10^9 Z



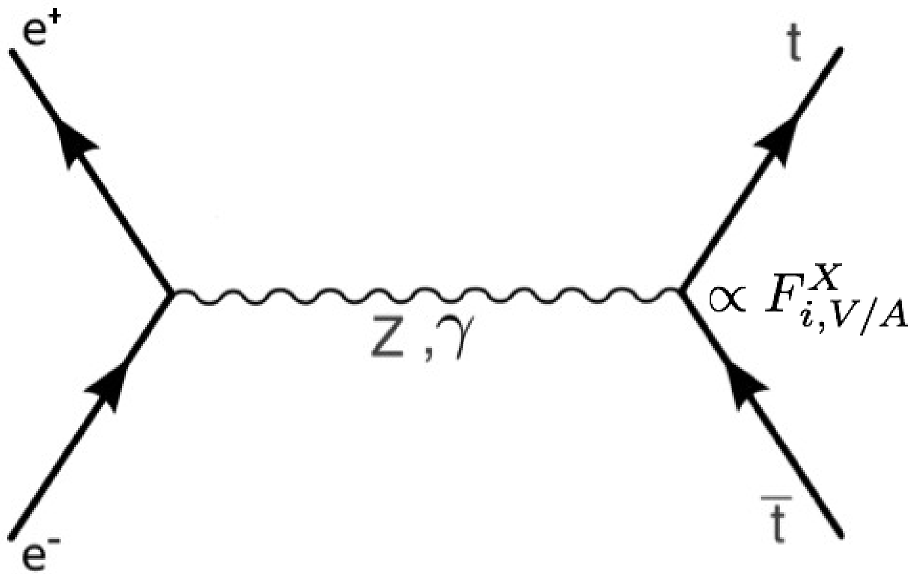
- Is tension due to underestimation of errors or due to new physics?

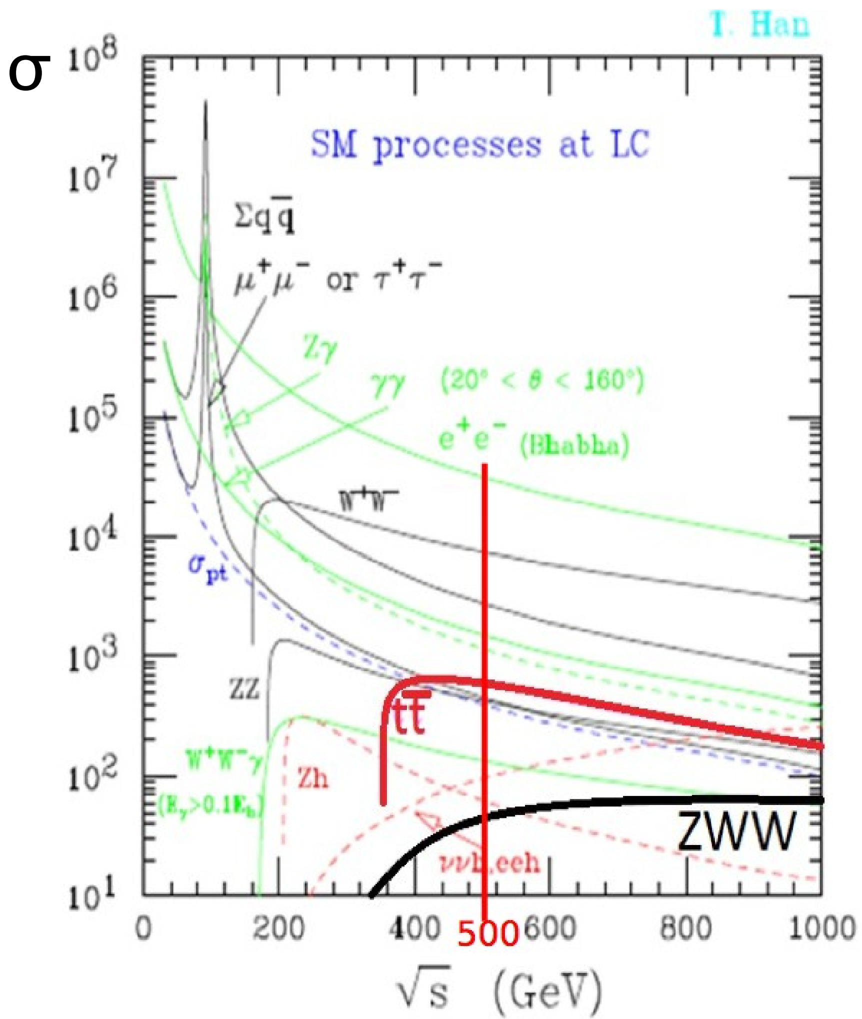
- High precision e+e- collider will give final word on anomaly

- In case it will persist polarised beams will allow for discrimination between effects on left and right handed couplings (Remember $Zb_l b_l$ is protected by cross section)

3. Top physics

Top Quark Physics at Electron-Positron Colliders



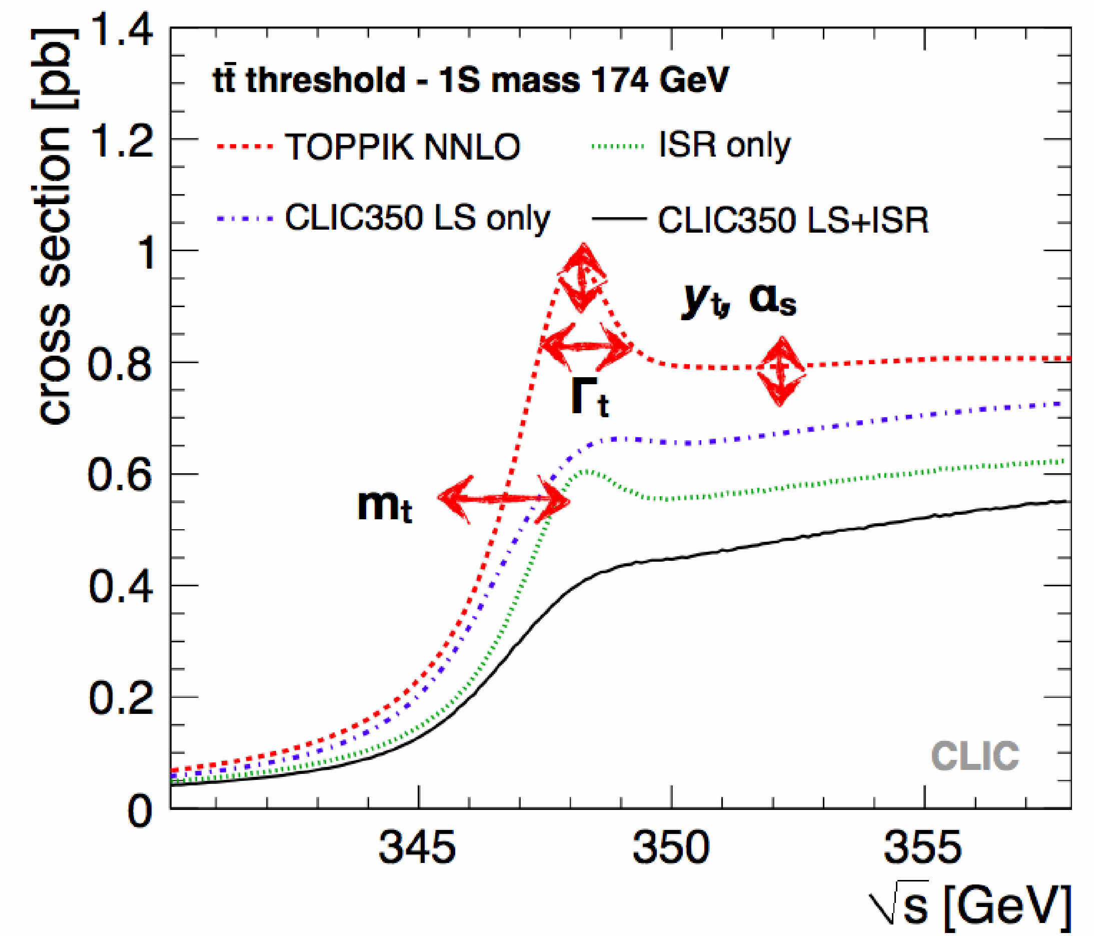


- Top quark production through electroweak processes
  no competing QCD production => Small theoretical errors!

- 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

Threshold scan

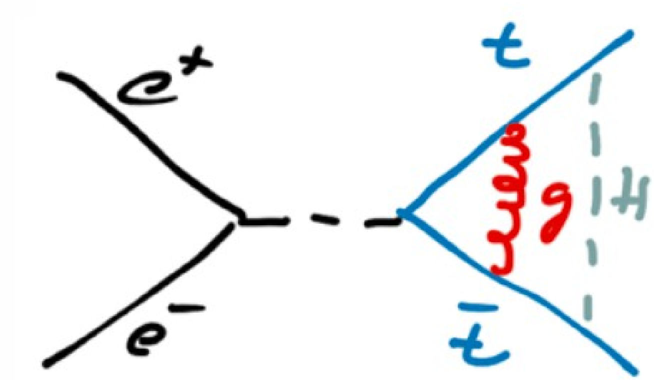
Small size of ttbar “bound state” at threshold ideal premise for precision physics



Cross section around threshold is affected by several properties of the top quark and by QCD

- Top mass, width Yukawa coupling

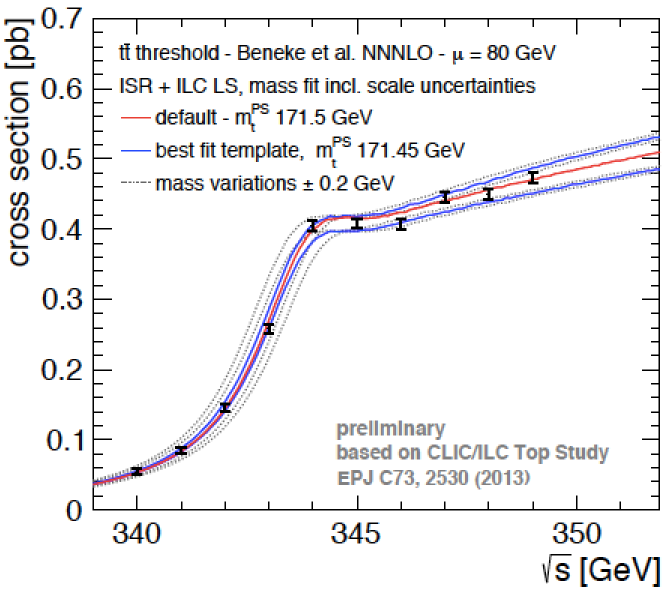
- Strong coupling constant

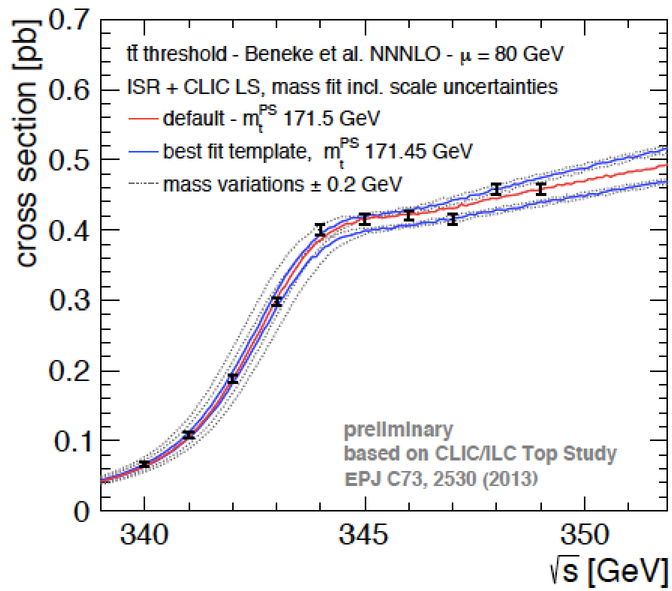


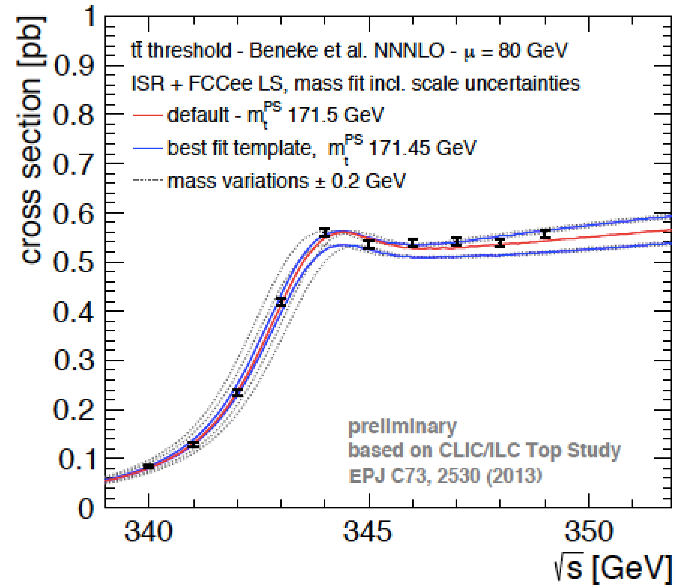
Effects of some parameters are correlated:
Dependence on Yukawa coupling rather weak,
Precise external α_s helps

F. Simon, Top@LC15 Valencia

Top threshold scans at different e+e- colliders







ILC

Fit uncertainty:
28.5 MeV (18 MeV stat)

Scale uncertainty:
40 MeV

CLIC

Fit uncertainty:
31 MeV (21 MeV stat)

Scale uncertainty:
42 MeV

FCC-ee

Fit uncertainty:
27 MeV (15 MeV stat)

Scale uncertainty:
40 MeV

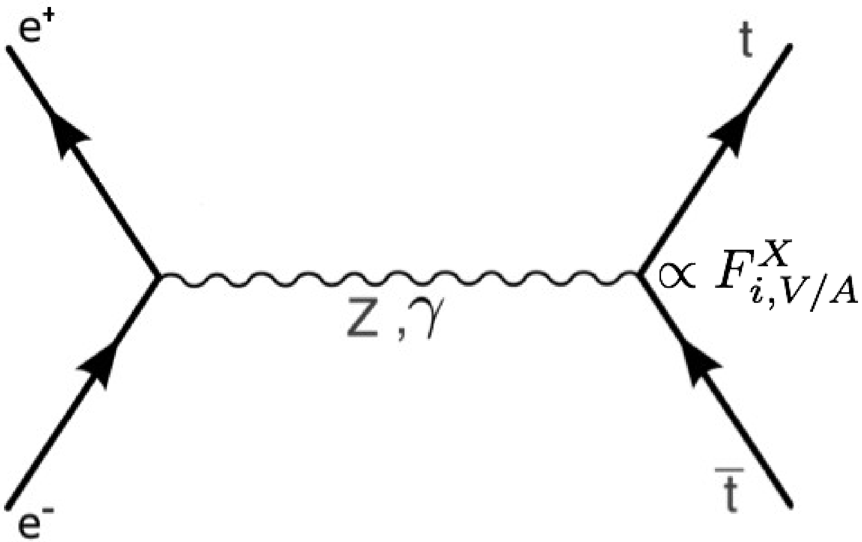
More details on top mass in e+e- collisions by A. Hoang and M. Beneke

F. Simon Top@LC16

Testing the electroweak top vertices

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

- Expect residual effects for particles with masses closest to symmetry breaking scale



Manifestation of New Physics:

- Modification of Ztt coupling
  Mixing between top and partners
  Mixing Z/Z'

- s-channel exchange of New Z'
  Including interference effects

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

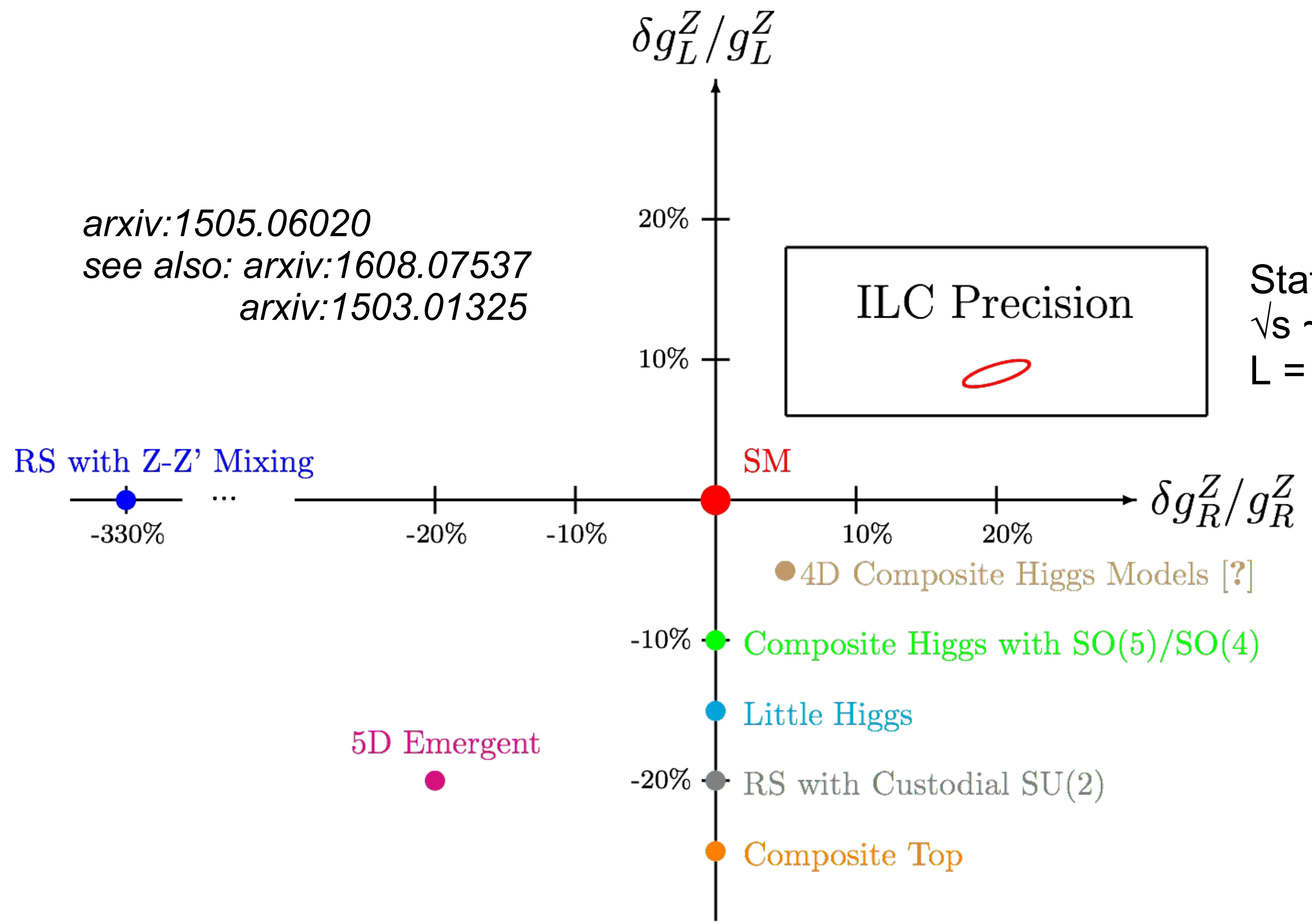
Pure γ or pure Z^0 : $\sigma \backsim (F_i)^2 \Rightarrow$ No sensitivity to sign of Form Factors

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

Sensitivity to New Physics

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

arxiv:1505.06020
see also: arxiv:1608.07537
arxiv:1503.01325



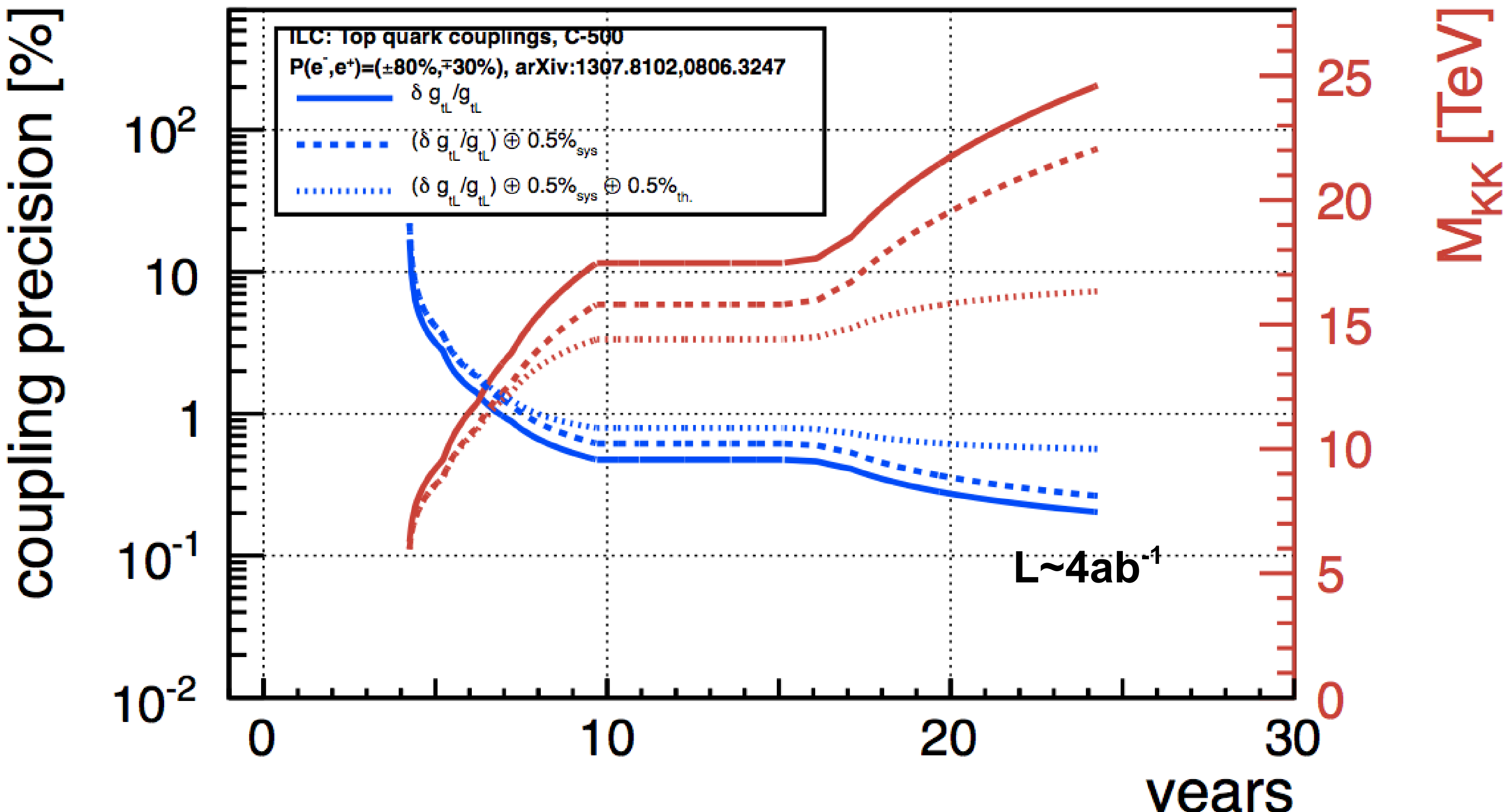
Statistical error:
$\sqrt{s}$ ~ 500 GeV
L = 500 fb^{-1}

Precision expected for top quark couplings will allow to distinguish between models
Remark: All presented models are compatible with LEP elw. precision data

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

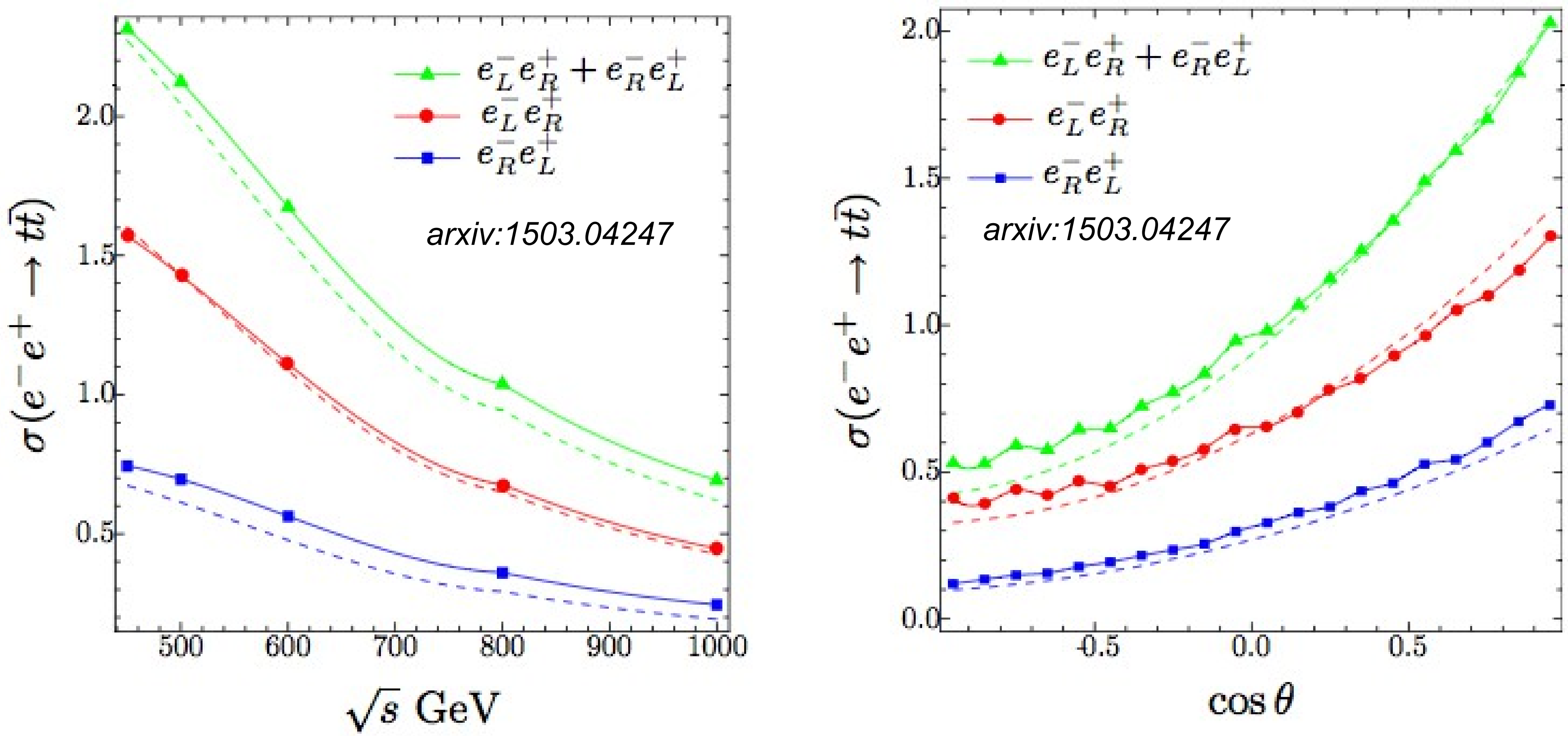


Can probe scales of ~25 TeV in typical scenarios

(… and up tp 80 TeV for extreme scenarios)

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

Detailed look at higher order elw. corrections - GRACE



- Electroweak corrections manifest themselves differently for different beam polarisations

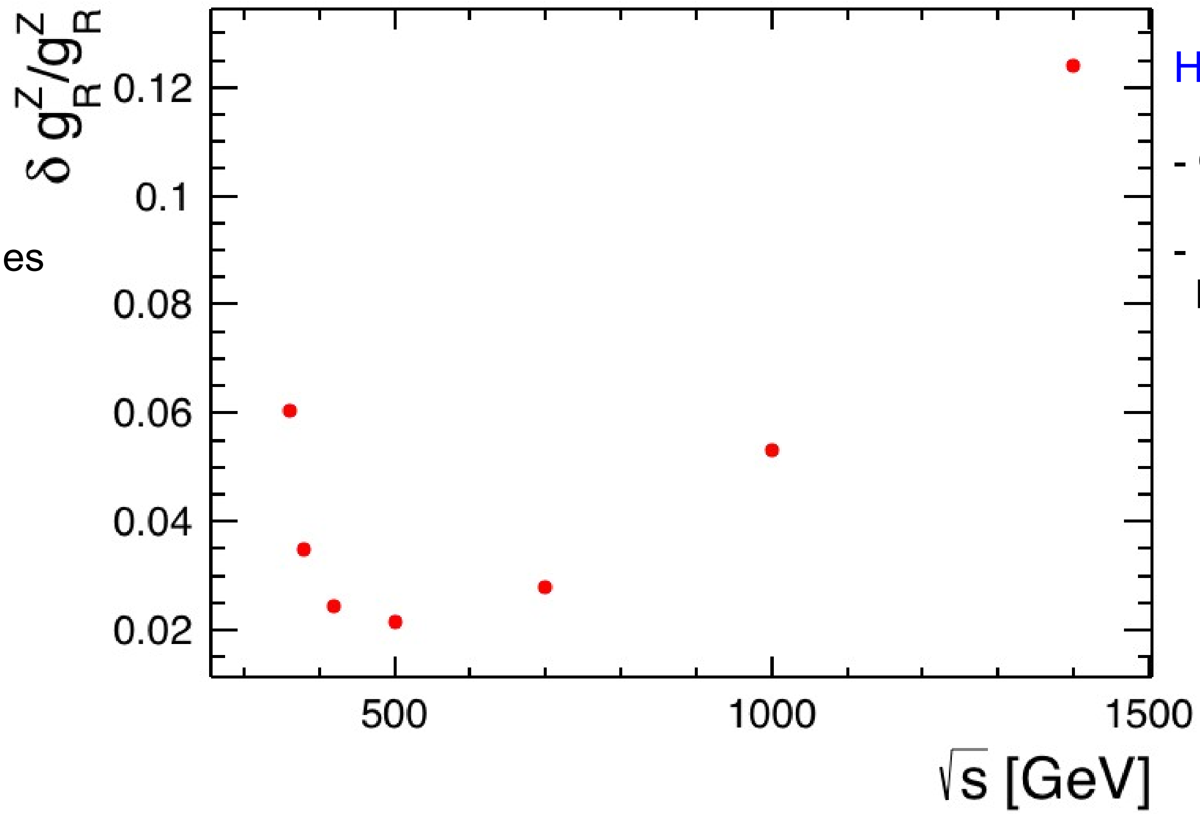
Beam polarisation important asset to disentangle SM and effects of new physics
Configuration $e_R^- e_L^+$ seems to lead to “simpler” corrections

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

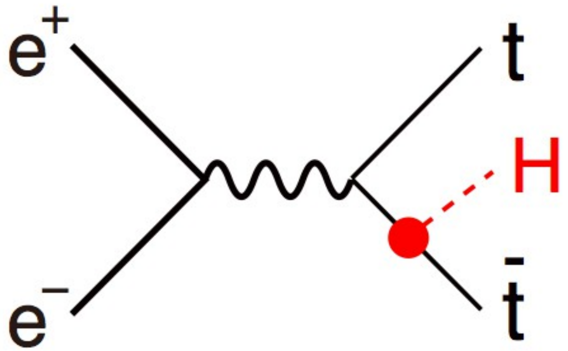
Broad minimum between 400 and 700 GeV

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

However:

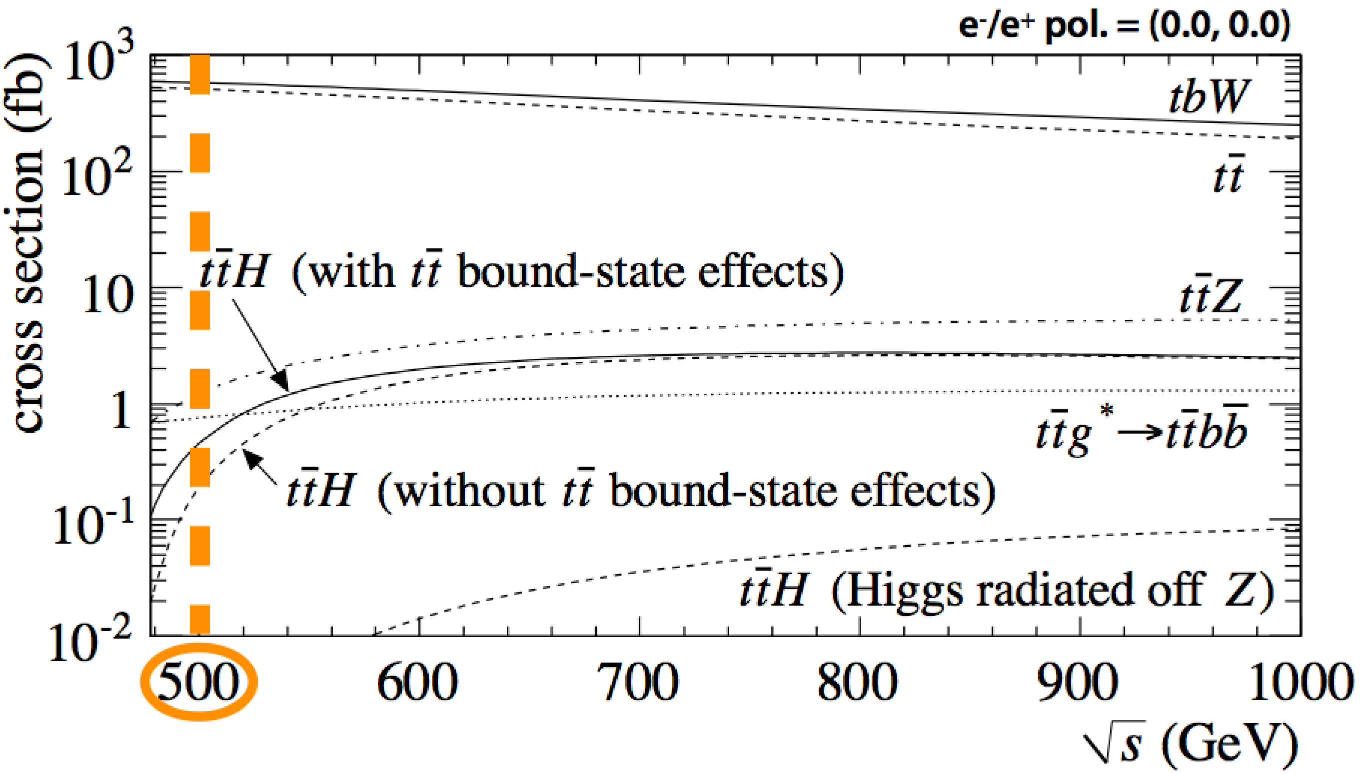
- Sensitivity to CP violating Higgs at smaller cms energies
- New physics at higher energies may increase cross section

Top Yukawa Coupling



- Coupling of Higgs to heaviest particle known today

- Up to eight final state jets



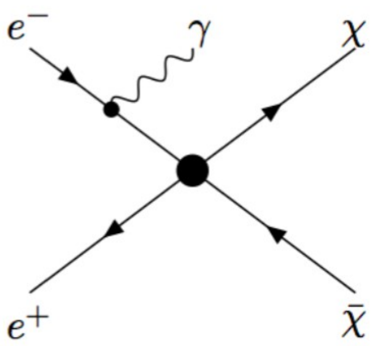
ΔgttH / gttH	500 GeV	+ 1 TeV
Snowmass	7.8%	2.0%
H20	6.3%	1.5%

4. BSM Physics at e+e- colliders

Dark Matter Search – A spectacular example

arXiv:1411.0088

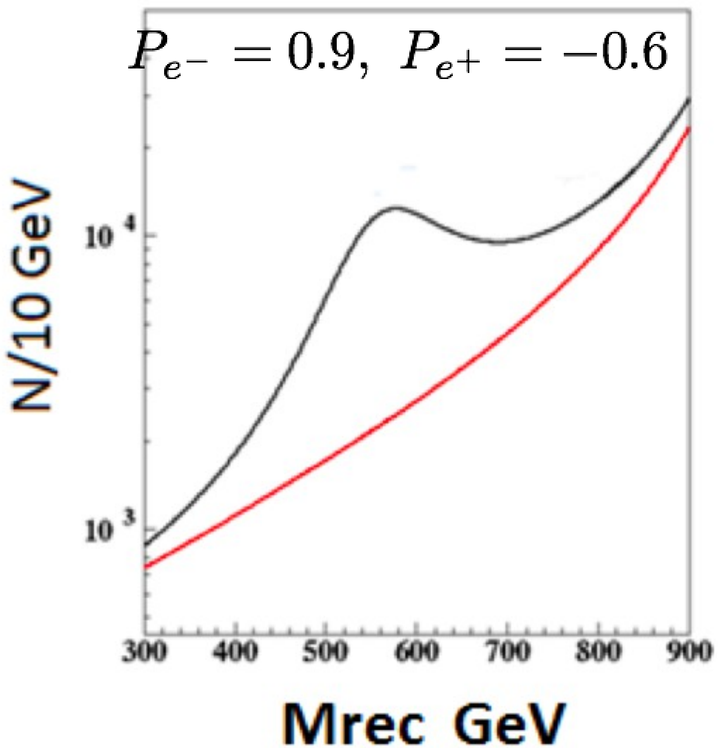
Z' with vector couplings to Dirac type Dark Matter X and axial couplings to ordinary matter

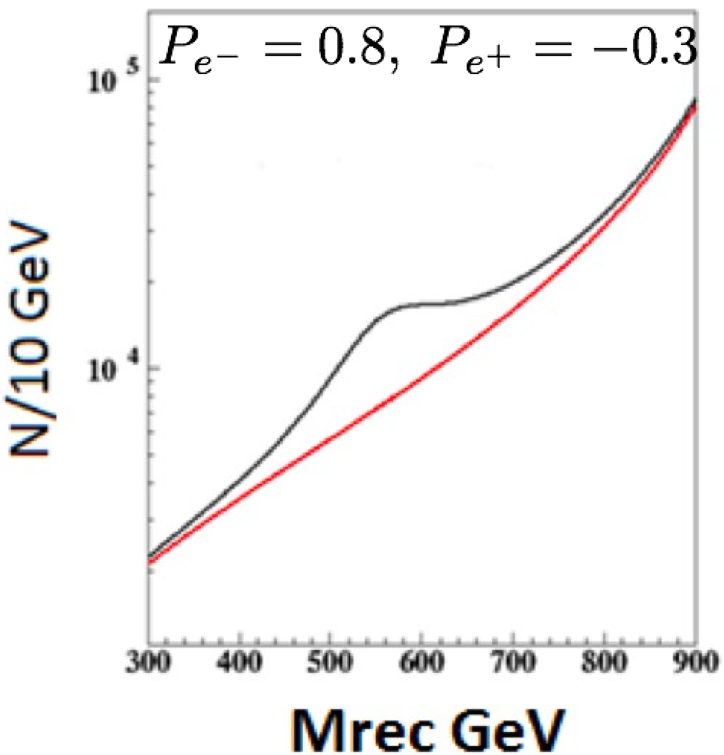


$$\sigma v = |g_V^X|^2 K^2 \sum_f n_{cf} |g_A^f|^2 \frac{2m_X^2 + s}{12\pi\left[(s - m_{Z'}^2) + (m_{Z'}\Gamma_{Z'})^2\right]}$$

-> Monophoton search
-> Background suppression through polarised beams

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

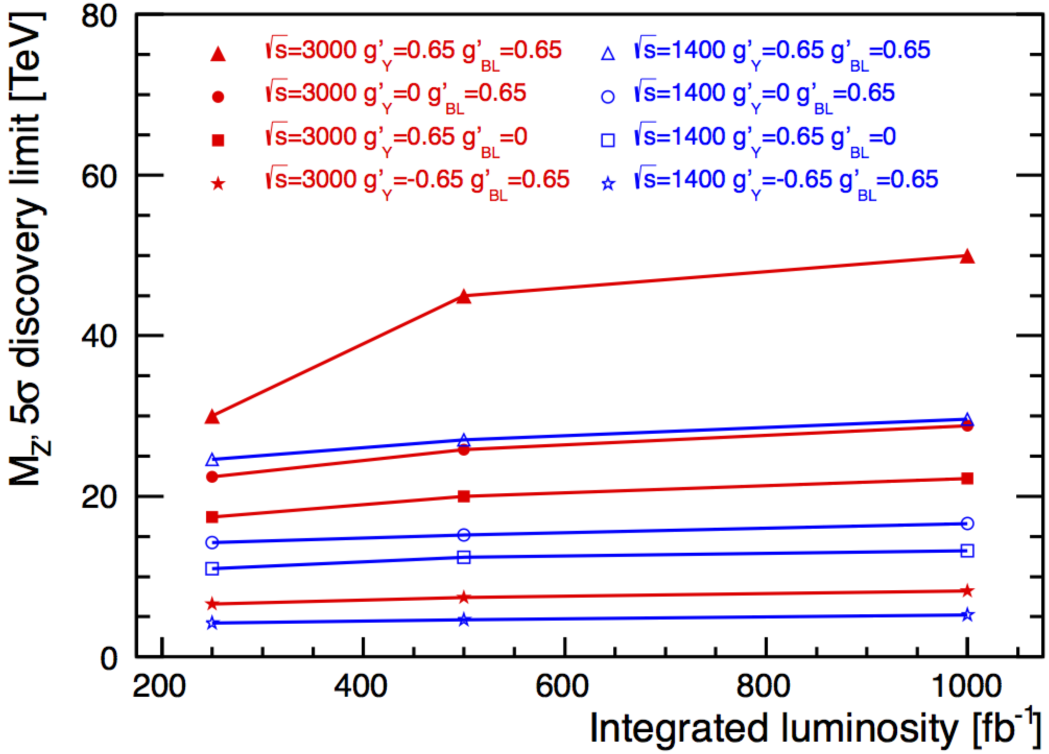




BSM Search at highest energies

arXiv:1608.07357

Z' discovery limit in $e^+e^- \to \mu^+\mu^-$



- Remarkable discovery potential
- Different sensitivities for different scenarios
- Sensitivities to $M_{Z'}$ of up to 50 TeV @ √s = 3 TeV

Summary

- Versatile machines for precision physics in the range m_Z – 3 TeV under study
  - Linear and circular machines would/could be complementary
- LEP/SLC programme can be repeated with much higher precision
- Which precision is reasonable precision?
- (Higgs and) Top quark are physics guaranteed
  - (My conviction) both are messengers to New Physics
  - Electroweak top quark pair production
  - tth coupling in clean environment
- Discovery potential up to $\sqrt{s}/2$
  - Sensitivity complementary to LHC and Dark Matter Experiments
  - Benefits from large lever arm in energy
  - Polarisation to suppress SM background
- The hardest part is to keep all the promises
  - Requires large effort on experimental and theory side and excellent communication

Summary

- Versatile machines for precision physics in the range m_Z – 3 TeV under study
  - Linear and circular machines would/could be complementary
- LEP/SLC programme can be repeated with much higher precision
- Which precision is reasonable precision?
- (Higgs and) Top quark are physics guaranteed
  - (My conviction) both are messengers to New Physics
  - Electroweak top quark pair production
  - tth coupling in clean environment
- Discovery potential up to $\sqrt{s}/2$
  - Sensitivity complementary to LHC and Dark Matter Experiments
  - Benefits from large lever arm in energy
  - Polarisation to suppress SM background
- The hardest part is to keep all the promises
  - Requires large effort on experimental and theory side and excellent communication

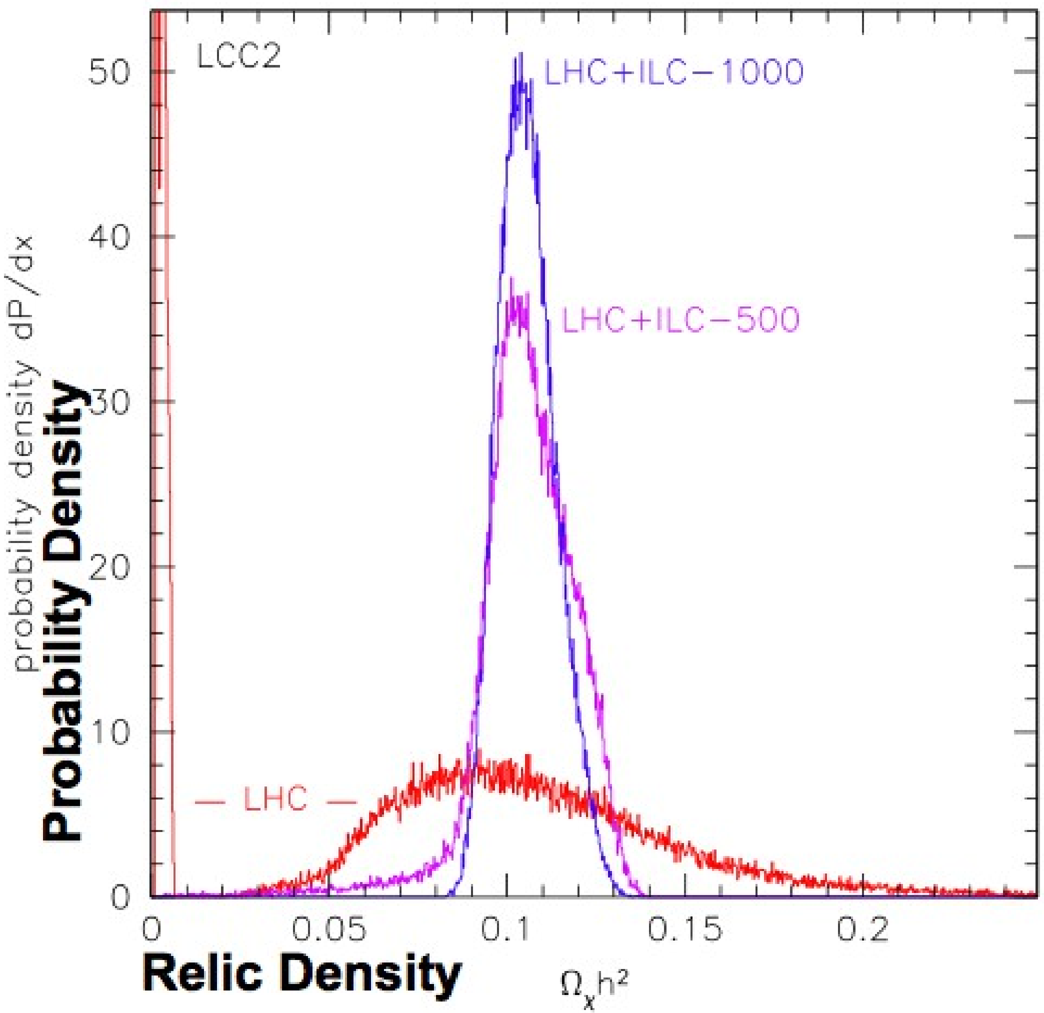
Rencontres de Vietnam on e+e- precision measurements?

Backup ....

Connection to relic dark matter density

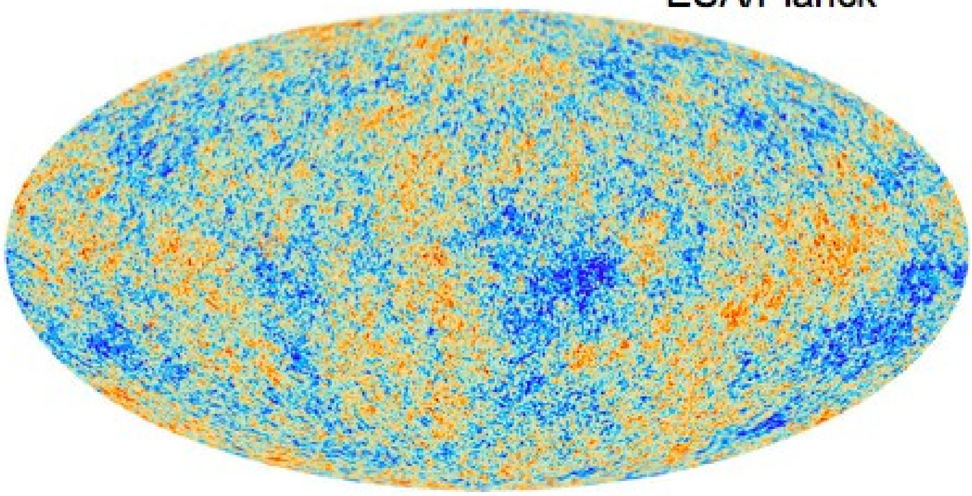
WMAP/Planck (68% CL)

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



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

Details on EWPO I

Current uncertainties for EWPOs

	Experiment	Theory error	Main source
$M_{\rm W}$	80.385 ± 0.015 MeV	4 MeV	α^3, $\alpha^2\alpha_{\rm s}$
Γ_Z	2495.2 ± 2.3 MeV	0.5 MeV	$\alpha^2_{\rm bos}$, α^3, $\alpha^2\alpha_{\rm s}$, $\alpha\alpha_{\rm s}^2$
$\sigma^0_{\rm had}$	41540 ± 37 pb	6 pb	$\alpha^2_{\rm bos}$, α^3, $\alpha^2\alpha_{\rm s}$
$R_b \equiv \Gamma^b_{\rm Z}/\Gamma^{\rm had}_{\rm Z}$	0.21629 ± 0.00066	0.00015	$\alpha^2_{\rm bos}$, α^3, $\alpha^2\alpha_{\rm s}$
$\sin^2\theta^\ell_{\rm eff}$	0.23153 ± 0.00016	4.5×10^{-5}	α^3, $\alpha^2\alpha_{\rm s}$

Methods for theory error estimates:

- Parametric factors, $i.e.$ factors of α, N_c, N_f, ...
- Geometric progression, $e.g.$ $\frac{\mathcal{O}(\alpha^3)}{\mathcal{O}(\alpha^2)} \sim \frac{\mathcal{O}(\alpha^2)}{\mathcal{O}(\alpha)}$
- Renormalization scale dependence (often underestimates error)
- Renormalization scheme dependence (may underestimate error)

A. Freitas, FCC-ee Workshop, Feb. 2016

Details on EWPO II

Future projections

7/19

	ILC	FCC-ee	perturb. error with 3-loop†	Param. error ILC*	Param. error FCC-ee**
M_W [MeV]	3–5	~ 1	1	2.6	1
Γ_Z [MeV]	~ 1	~ 0.1	$\lesssim 0.2$	0.5	0.06
R_b $[10^{-5}]$	15	$\lesssim 5$	5–10	< 1	< 1
$\sin^2\theta^{\ell}_{\rm eff}$ $[10^{-5}]$	1.3	0.6	1.5	2	2

† **Theory scenario:** $\mathcal{O}(\alpha\alpha_s^2)$, $\mathcal{O}(N_f\alpha^2\alpha_s)$, $\mathcal{O}(N_f^2\alpha^2\alpha_s)$

(N_f^n = at least n closed fermion loops)

Parametric inputs:

* **ILC:** $\delta m_t = 100$ MeV, $\delta\alpha_s = 0.001$, $\delta M_Z = 2.1$ MeV

****FCC-ee:** $\delta m_t = 50$ MeV, $\delta\alpha_s = 0.0001$, $\delta M_Z = 0.1$ MeV

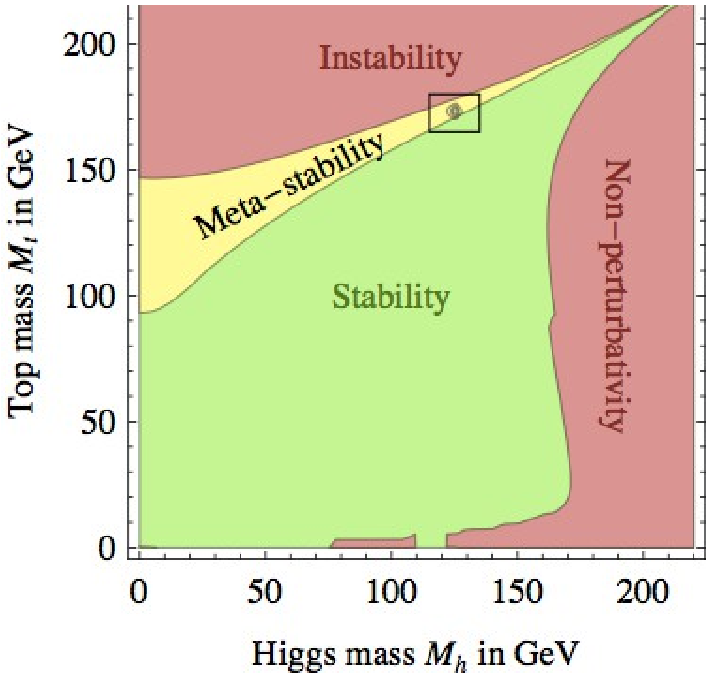
also: $\delta(\Delta\alpha) \sim 5 \times 10^{-5}$

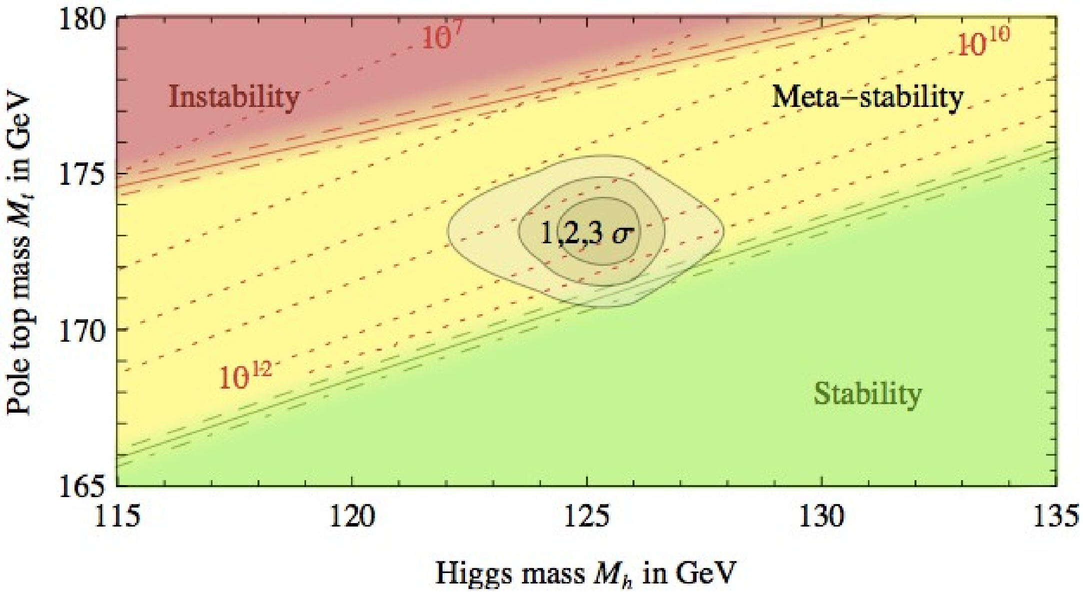
A. Freitas, FCC-ee Workshop, Feb. 2016

Vacuum stability and Top Quark Mass

Degrassi et al. arXiv:1205.6497

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

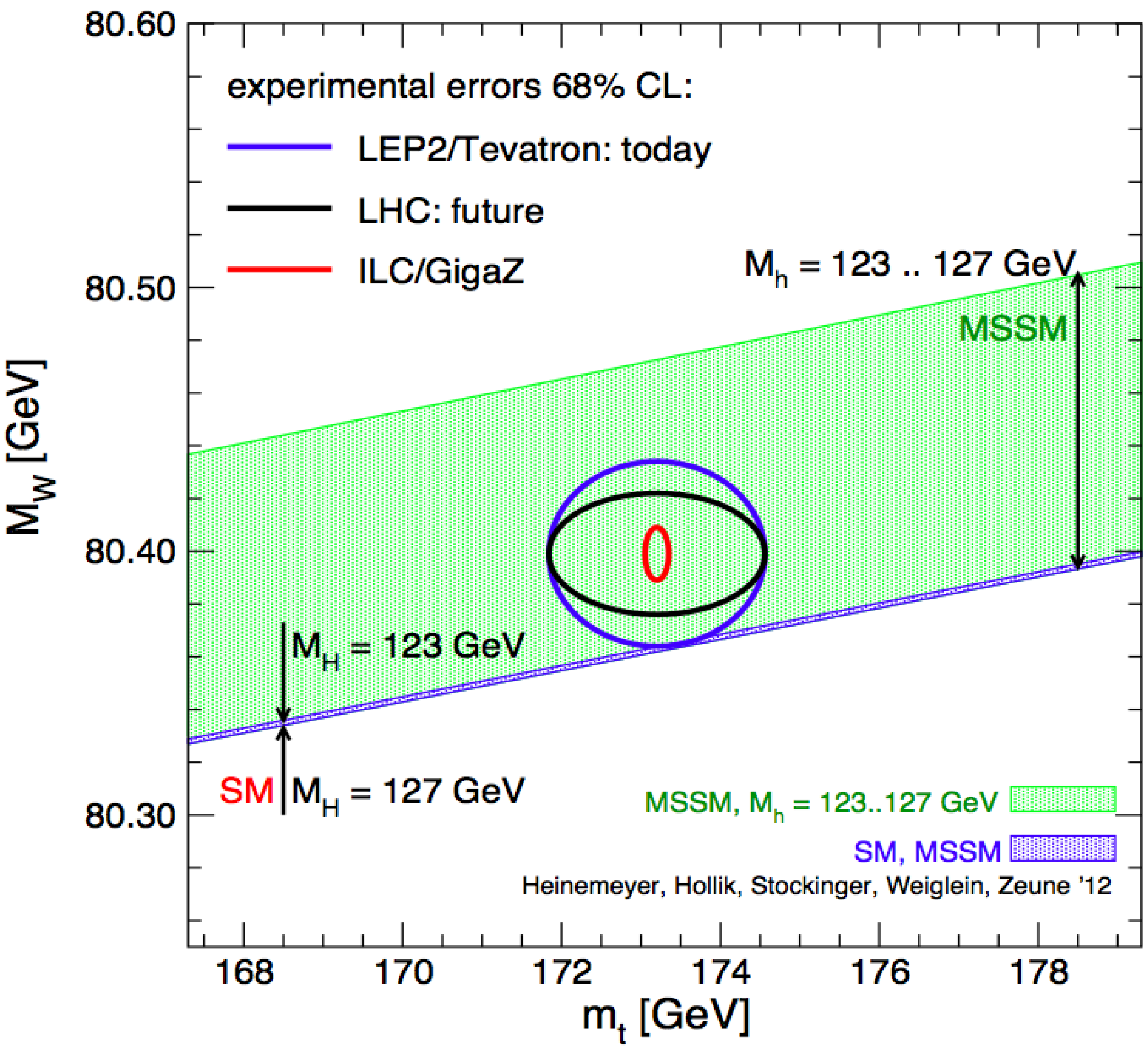




Type of error	Estimate of the error	Impact on M_h
M_t	experimental uncertainty in M_t	±1.4 GeV
α_s	experimental uncertainty in α_s	±0.5 GeV
Experiment	**Total combined in quadrature**	±1.5 GeV
λ	scale variation in λ	±0.7 GeV
y_t	$\mathcal{O}(\Lambda_{\mathrm{QCD}})$ correction to M_t	±0.6 GeV
y_t	QCD 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

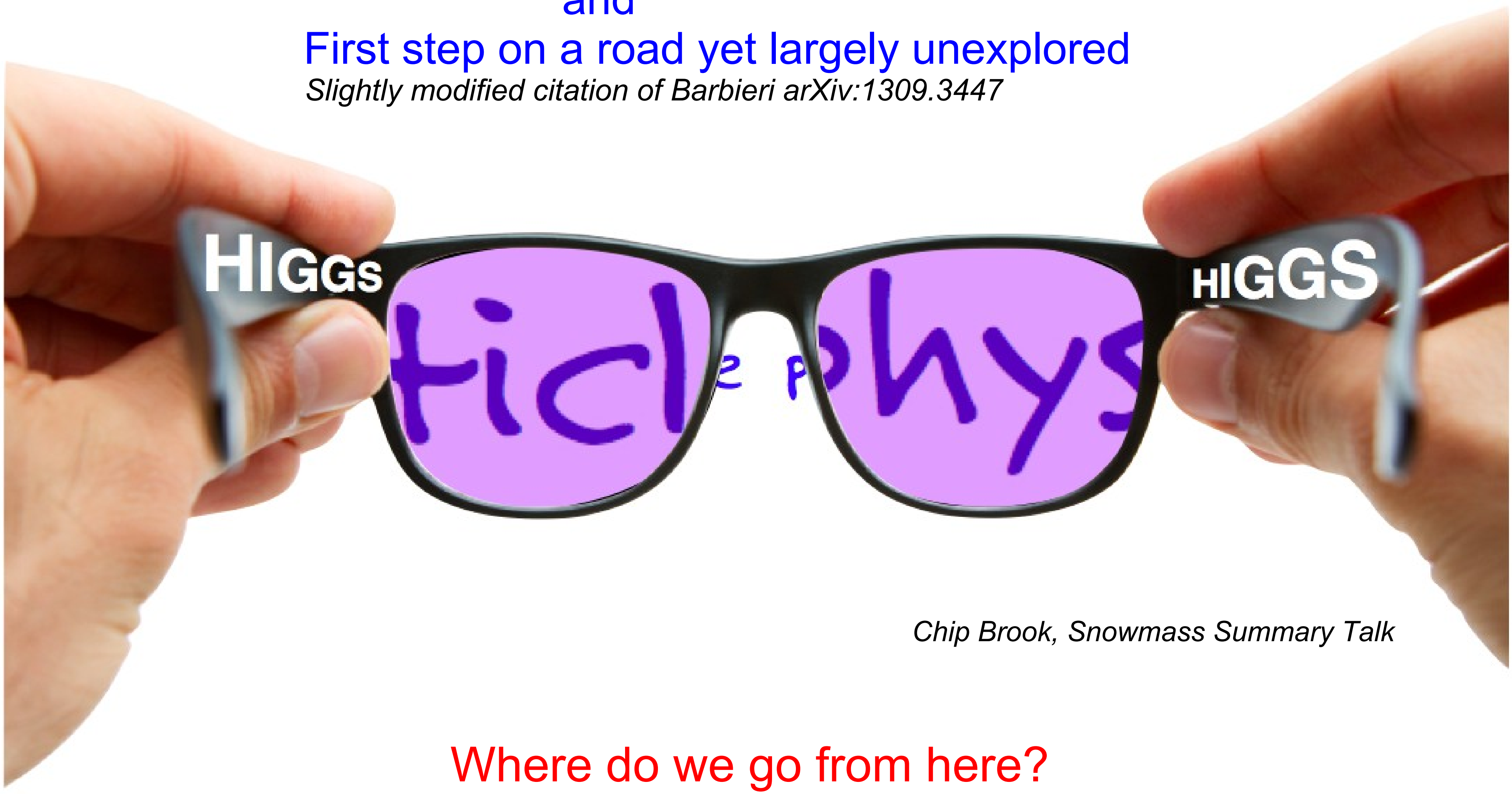
MS might not be sufficient to explain Higgs mass

LHC may not reach sufficient discriminative power

A lepton collider will

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?

ILC Basic Parameters and Comments

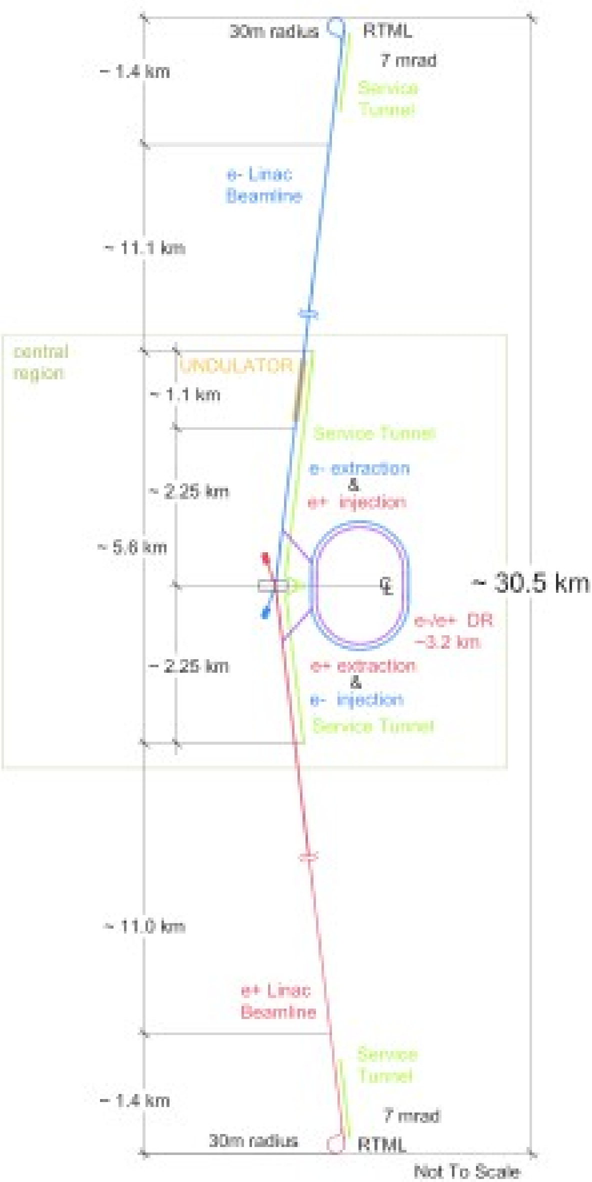
ILC design parameters		Comment
$\sqrt{s}$	91-500 GeV	500 GeV is baseline Option to upgrade to 1 TeV
$\mathcal{L}$	2×10^{34} cm^{-2}s^{-1}	~Factor 4 technically possible
P_{e^-}	>80%	Proven by SLC
P_{e^+}	upto 30%	~Conservative estimate
Length	~31 km	Current site allows for 50km

- 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

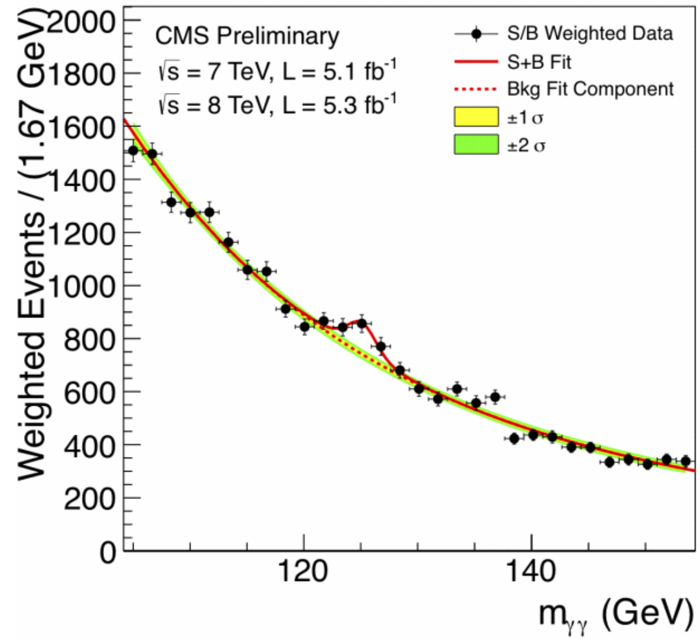
Luminosity

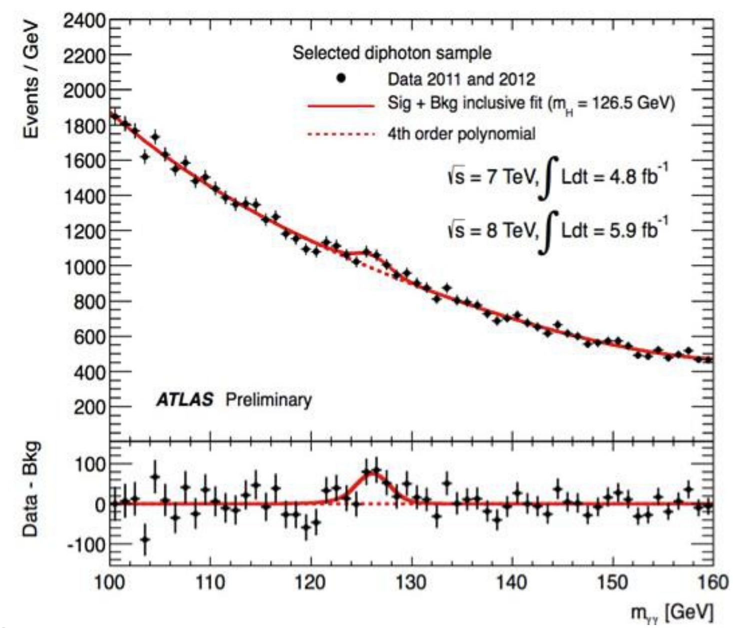
$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}} \sqrt{\frac{\delta_{BS}}{\varepsilon_{n,y}}} H_D$$

η_{RF} ~ 40% for SCRF technology

-> efficient technology

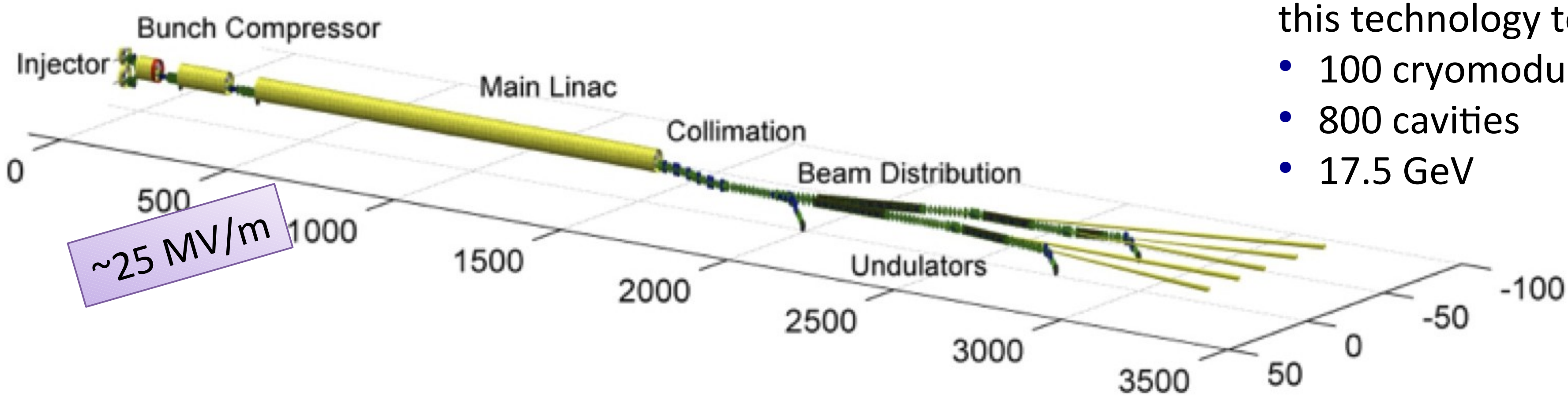
4th of July 2012





Accelerator - Test and reality

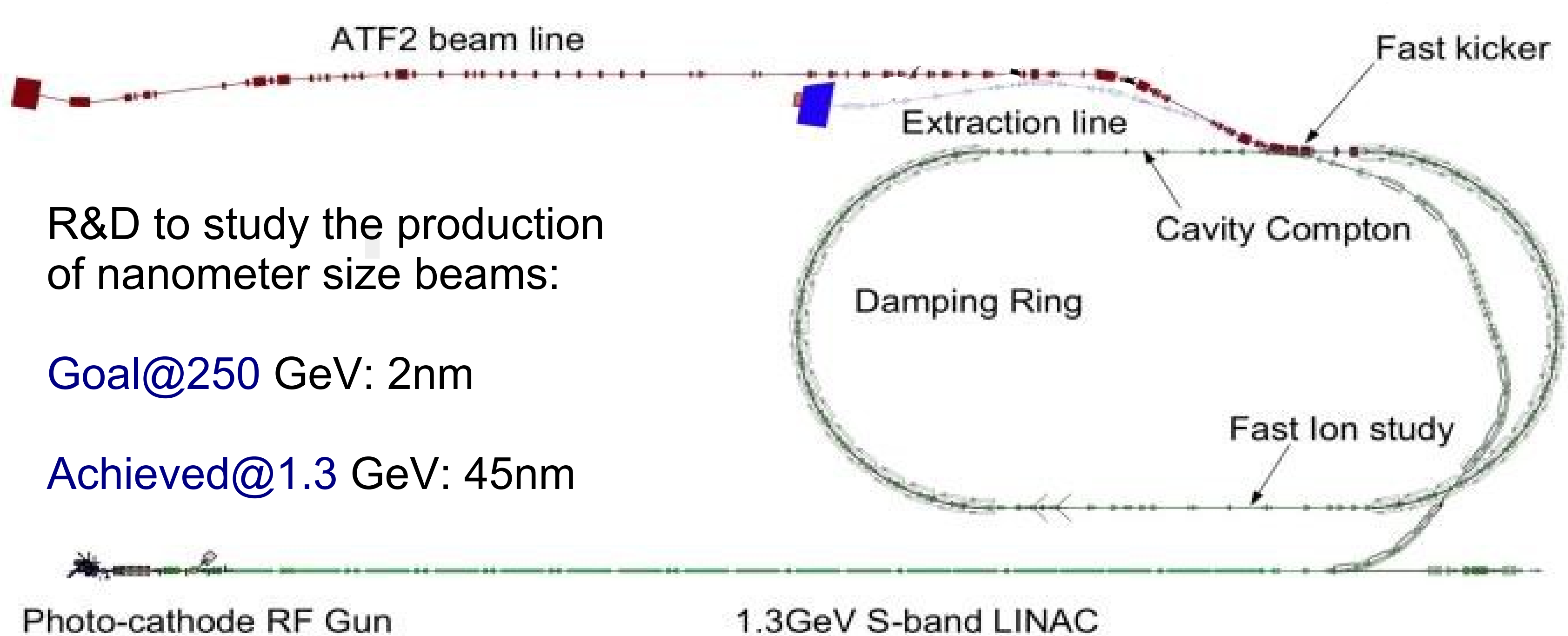
European XFEL Project: Location DESY Hamburg, Start 2015



Largest deployment of this technology to date

- 100 cryomodules
- 800 cavities
- 17.5 GeV

ATF at KEK Japan:



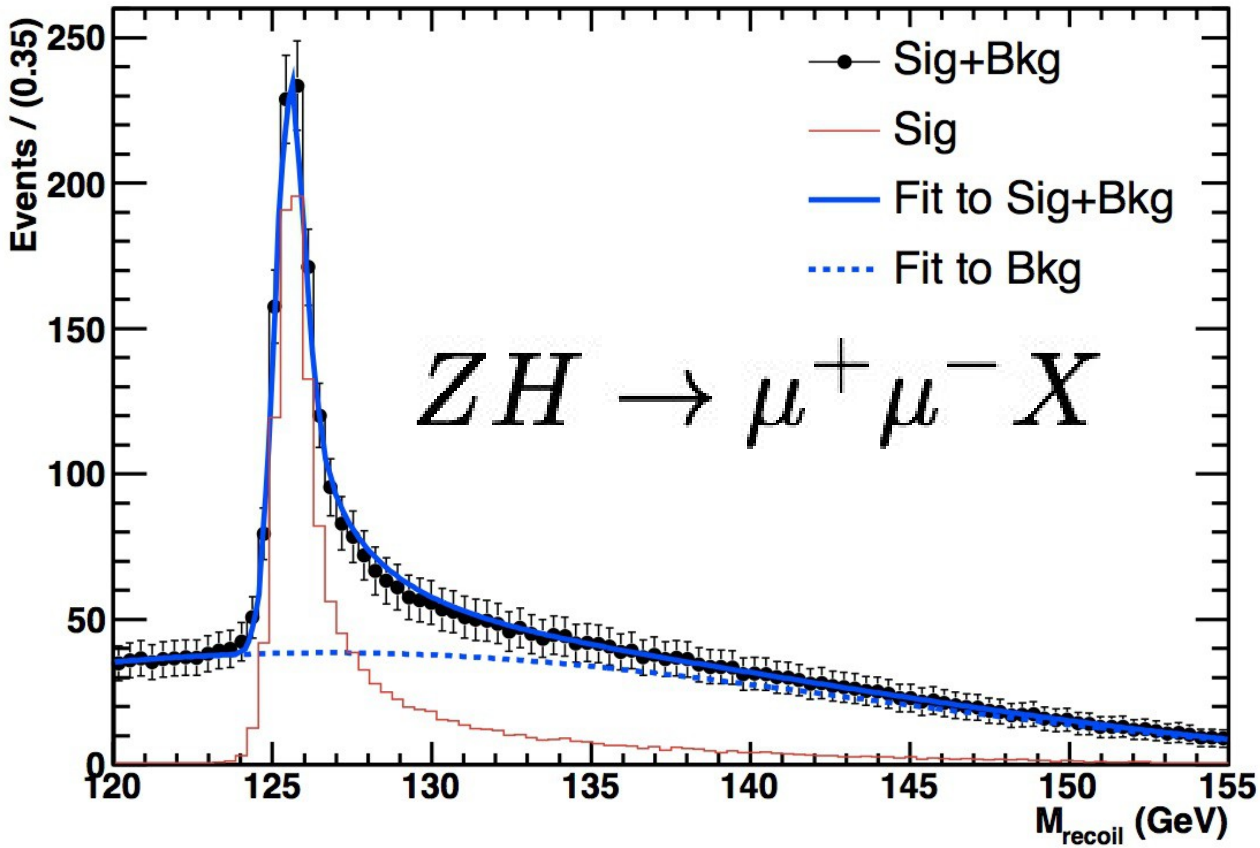
R&D to study the production of nanometer size beams:

Goal@250 GeV: 2nm

Achieved@1.3 GeV: 45nm

2. Higgs Physics at the ILC

Full simulation study at 250 GeV

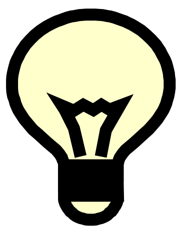


$$M_h = 125.3 \pm 0.03\,\mathrm{GeV}$$

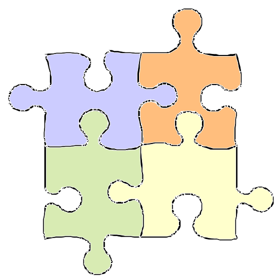
$$\sigma_{ZH} = 10.32 \pm 0.37\,\mathrm{fb},\ 3.6\%$$

More on Higgs Physics, see talk of Junping

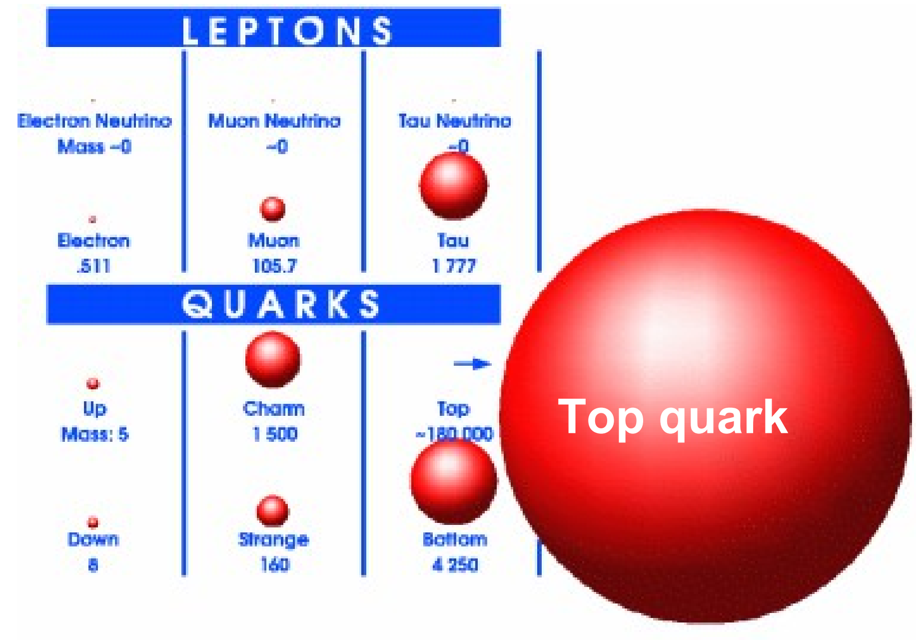
An enigmatic couple



Elementary Scalar?

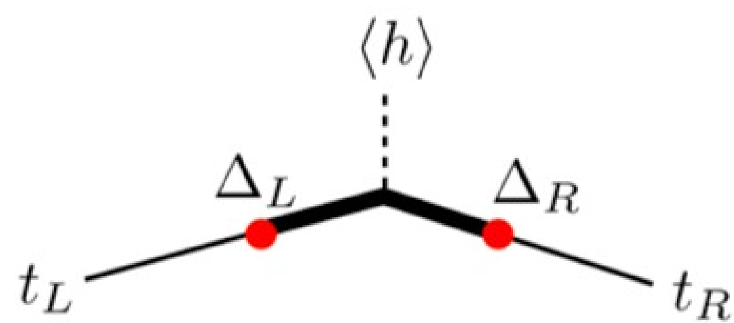


Composite object?



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

- New physics by compositeness?
  Higgs and top composite objects?



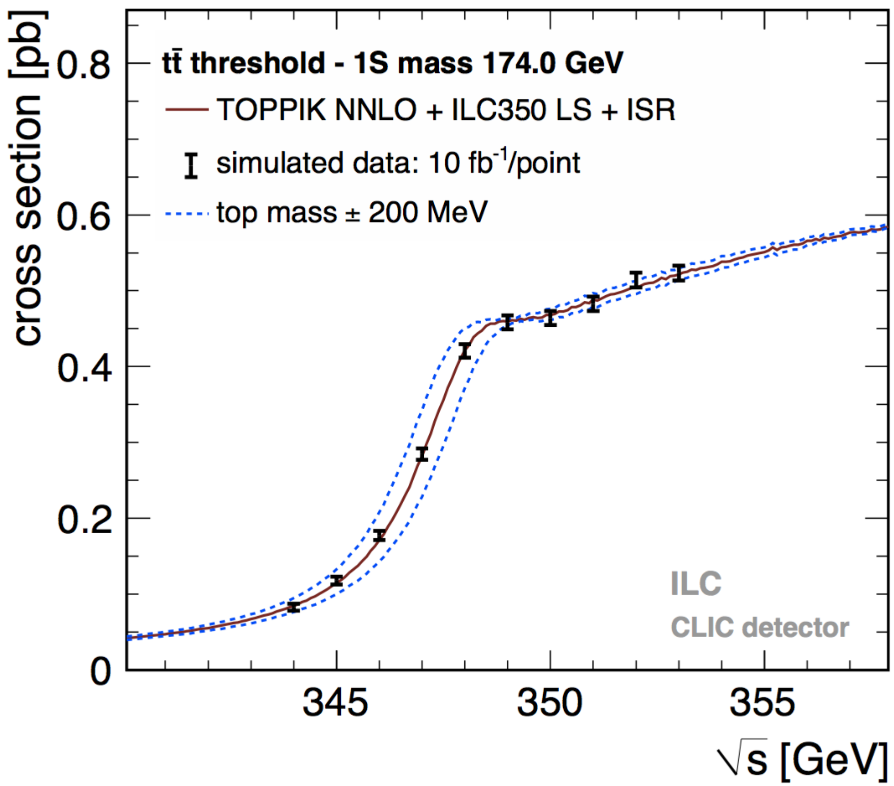
Courtesy of S. Rychkov

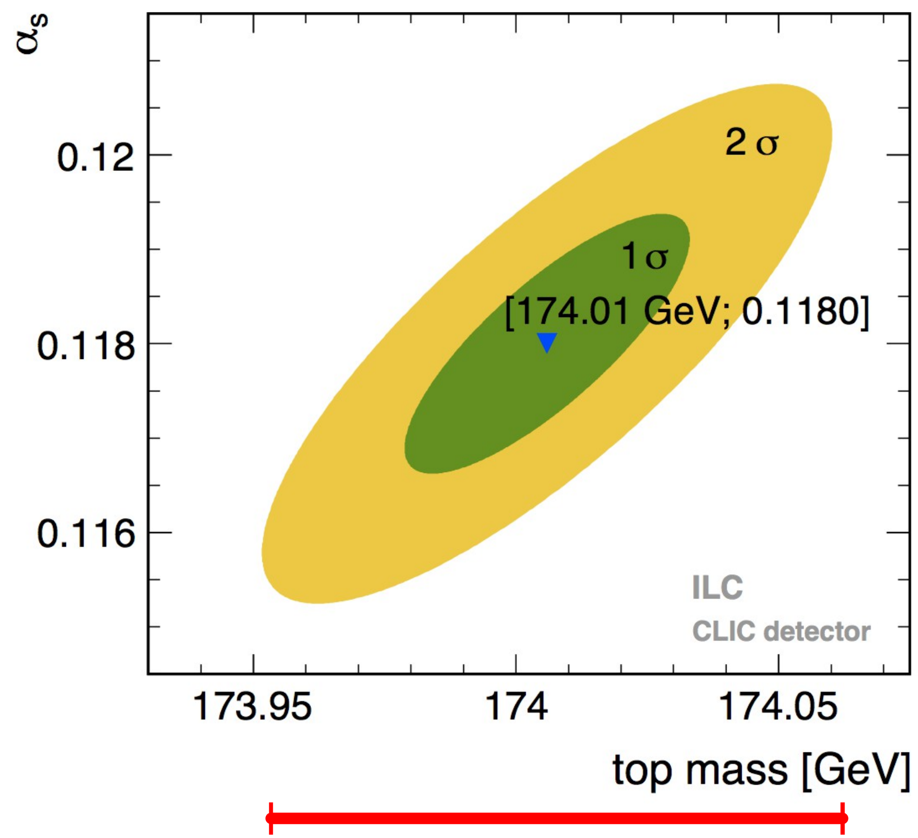
- e+e- collider perfectly suited to decipher both particles
  The higher the energy the better!!!

Top Quark Mass – Results of Full Simulation Studies

Mass and α_s

EPJC C73 (2013) 2530

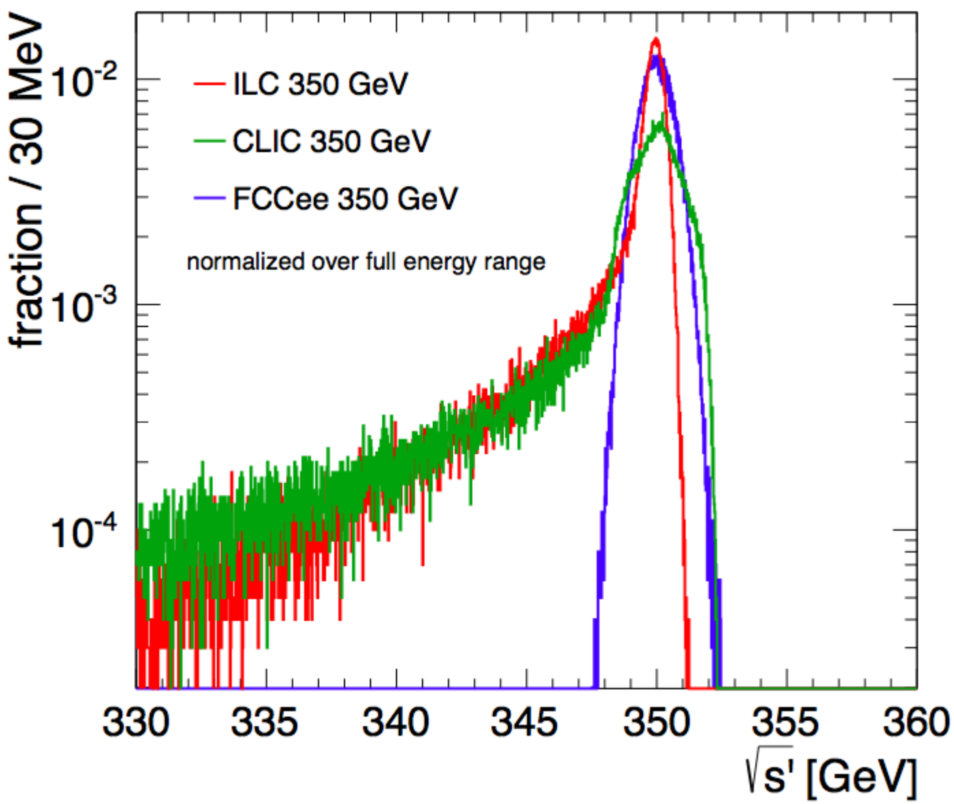




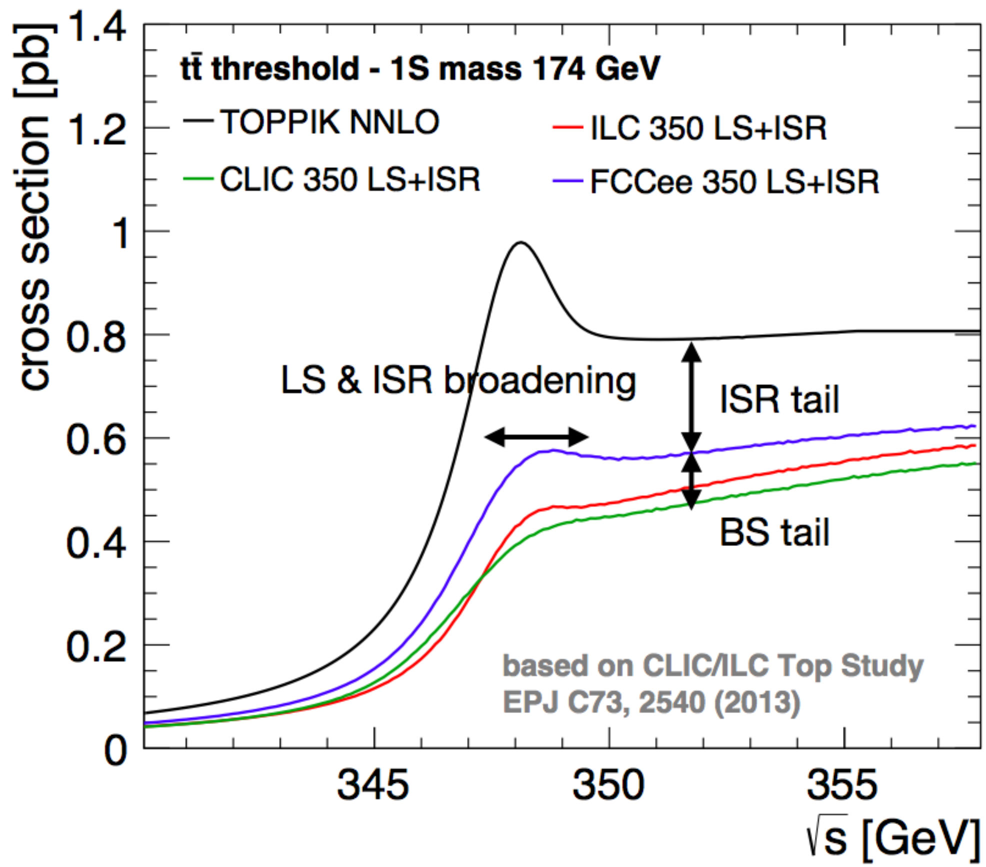
~100 MeV

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 – Influence of beam parameters



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

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

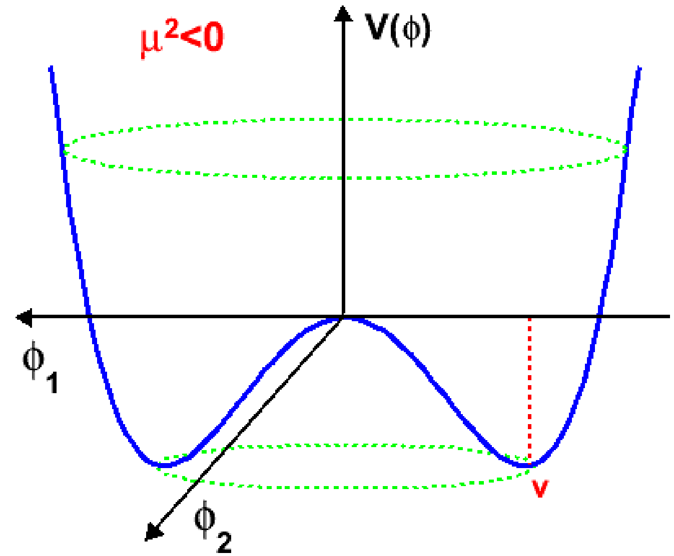
F. Simon, Top@LC15 Valencia

Higgs Mechanism

Scalar field which doesn't vanish in the vacuum

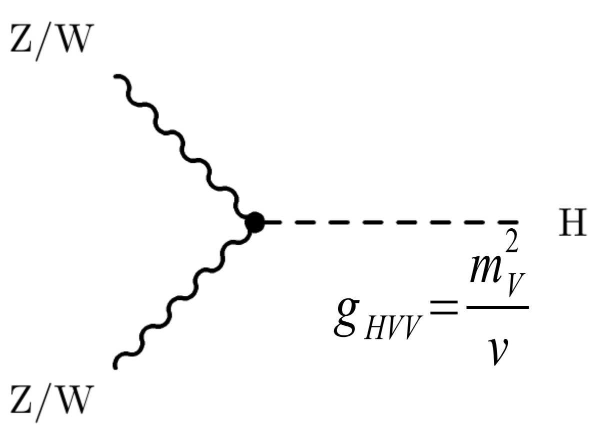
Choice in SM: Doublet Field $\Phi = \begin{pmatrix} \phi^{+} \\ \phi^{0} \end{pmatrix}$ 4 degrees of freedom

Higgs Boson — Longitudinally degrees of W,Z Bosons

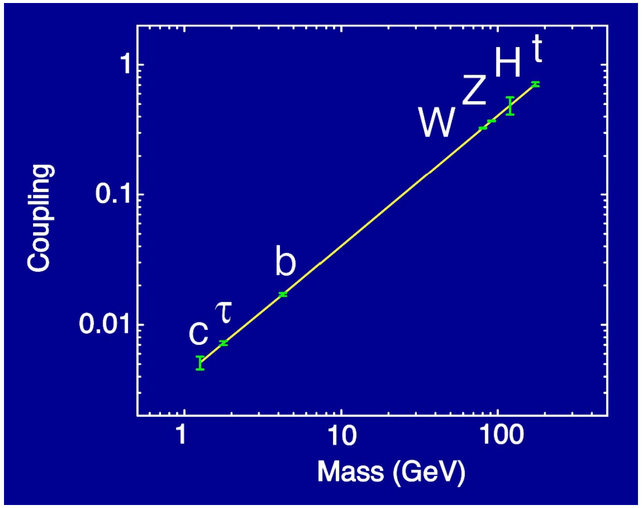


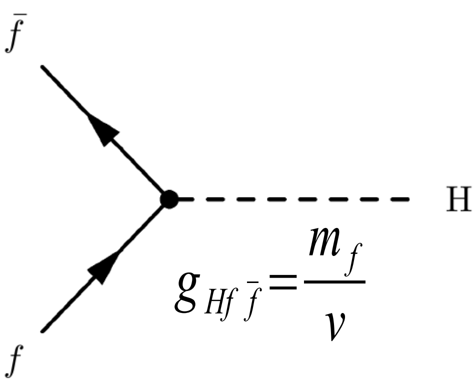
Couplings to Higgs Boson in Standard Model

Increase with particle mass



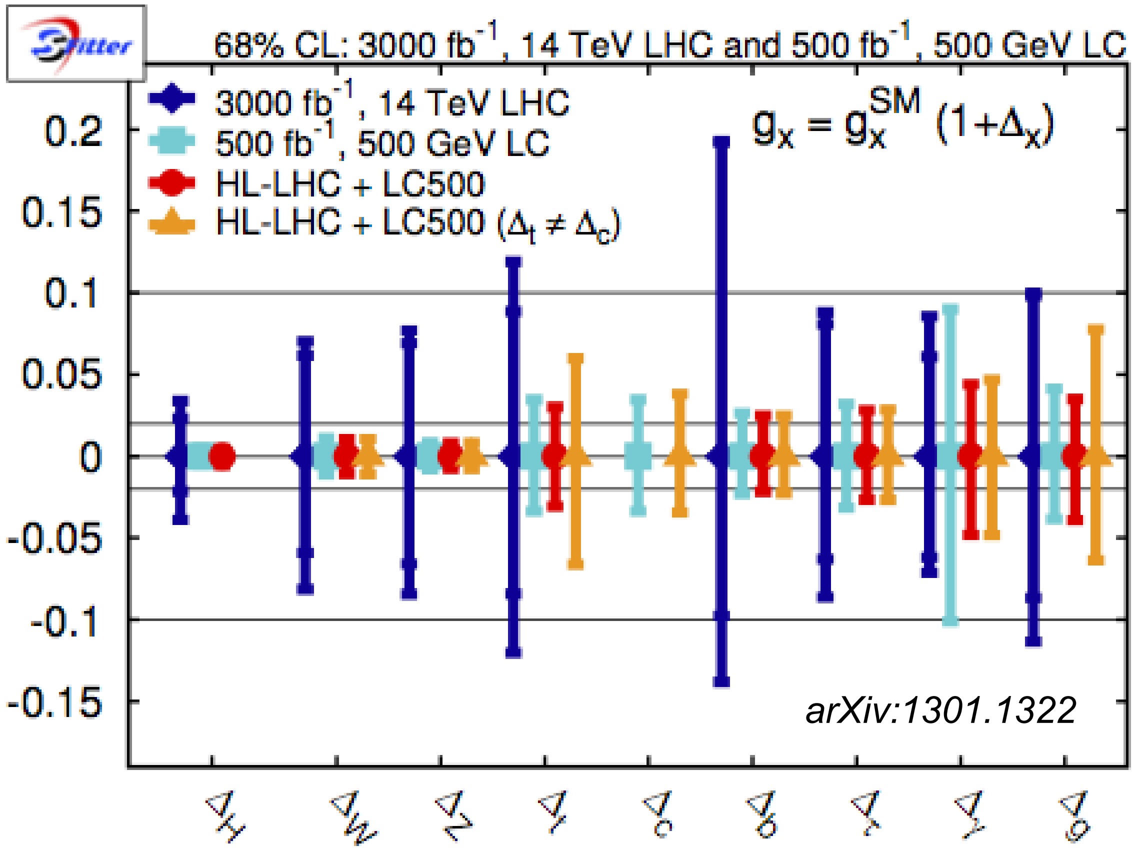
$$g_{HVV} = \frac{m_V^2}{v}$$





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

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

Systematic studies – Example top mass

- Expected statistical uncertainty **10 – 30 MeV**

- Experimental systematics

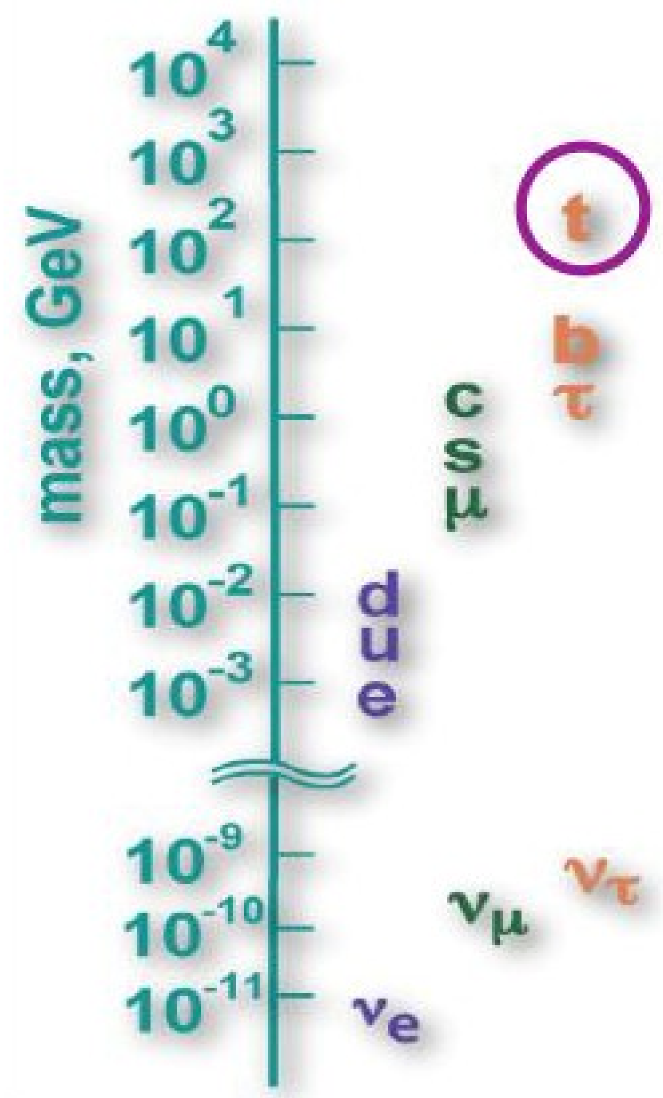
  - Beam energy: **~30 MeV** or lower
  - Non-ttbar background, selection efficiencies: **~ 15 MeV**
  - Luminosity spectrum: **10 MeV**
  - Single top contamination: **< 30 MeV**

- Theory uncertainties

  - **~40-45 MeV** due to scale uncertainties in NNNLO calculations
  - When not included in the fit: ~ 3 MeV per 10^{-4} uncertainty on α_s today → **~18 MeV**
  - Conversion from 1S/PS masses to MSbar mass Currently: **~50 MeV**
    However conversion now known to N^4LO (arxiv:1502.01030)
  - Now at point where results become sensitive to effects other than QCD

F. Simon, Top@LC15 Valencia and Top@LC16 KEK

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

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

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

x-section $\qquad$ Forward backward asymmetry $\qquad$ Fraction of right handed top quarks

⇩

Extraction of relevant unknowns

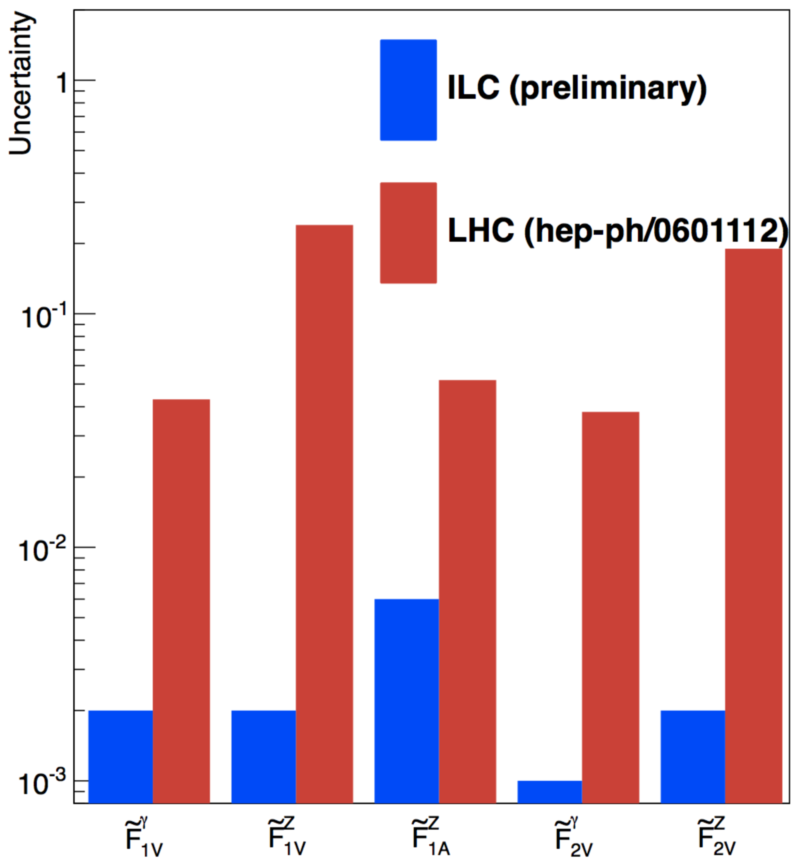
$$F^\gamma_{1V},\ F^Z_{1V},\ F^\gamma_{1A} = 0,\ F^Z_{1A}$$
$$F^\gamma_{2V},\ F^Z_{2V}$$

or equivalently $\quad g^\gamma_L,\ g^\gamma_R,\ g^Z_L,\ g^Z_R$

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

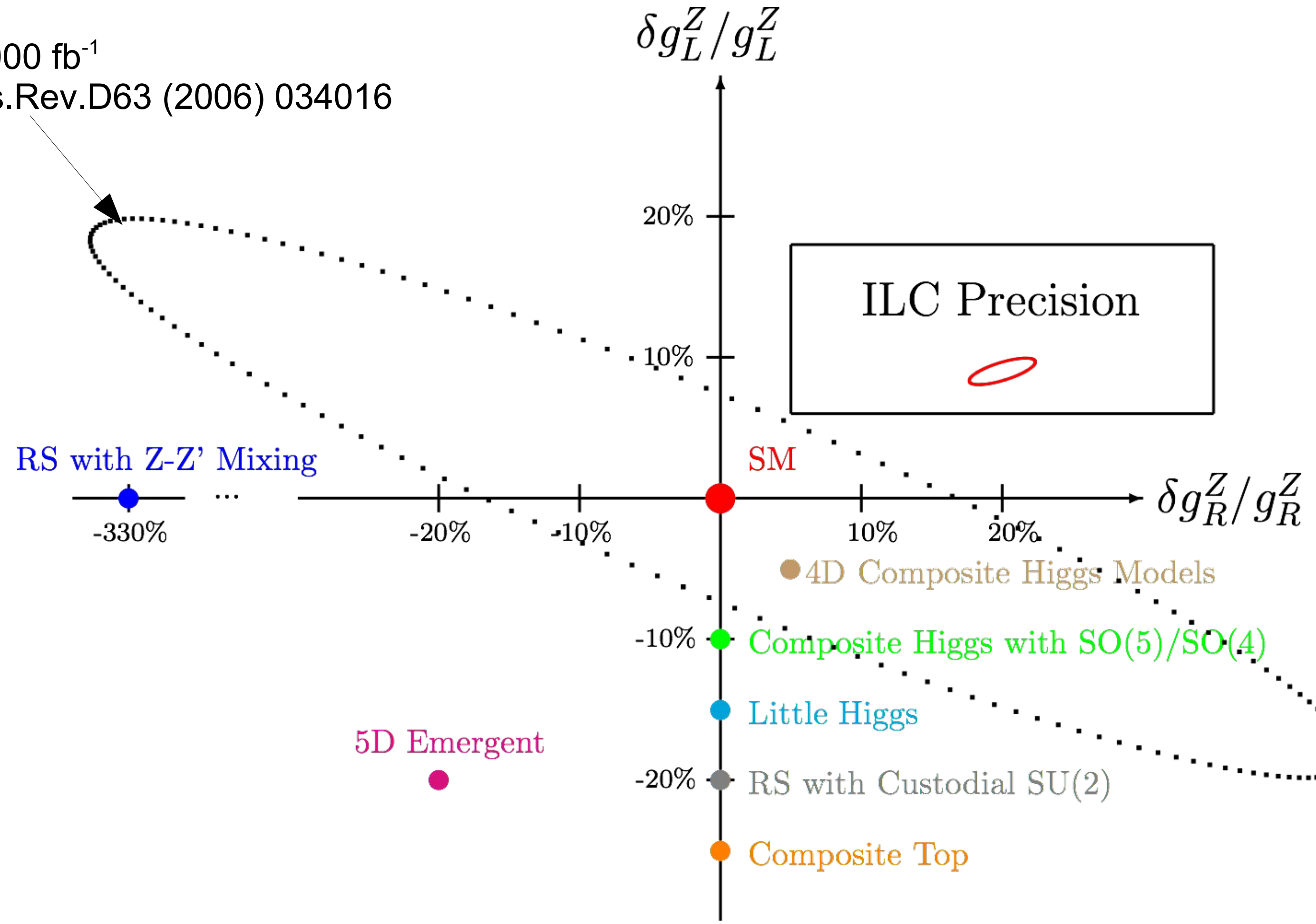
- Need to control experimental (e.g. Top angle) and theoretical uncertainties (e.g. Electroweak corrections)
  -> Dedicated work has started

- Potential for CP violating couplings at ILC under study

ILC promises to be high precision machine for electroweak top couplings

What about LHC perspectives?

LHC14, 3000 fb⁻¹
From Phys.Rev.D63 (2006) 034016



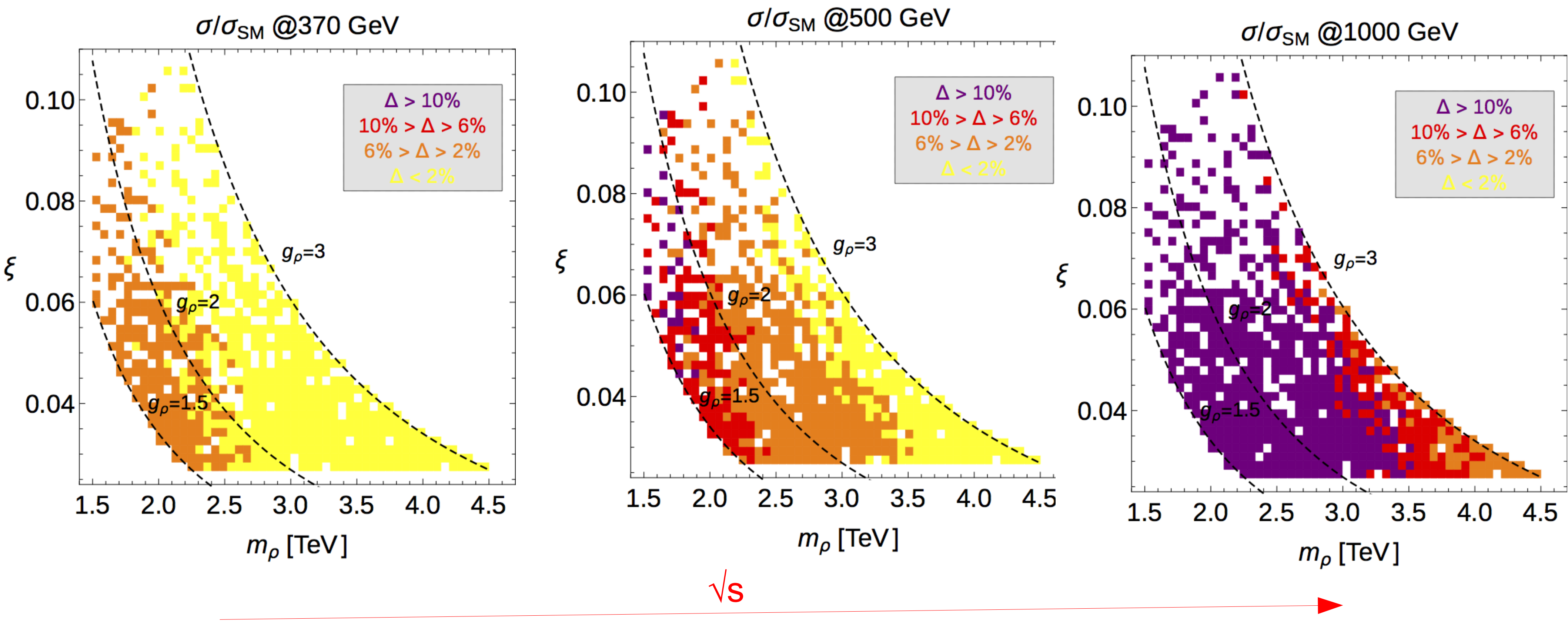
Linear Collider will outperform LHC results

- 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

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

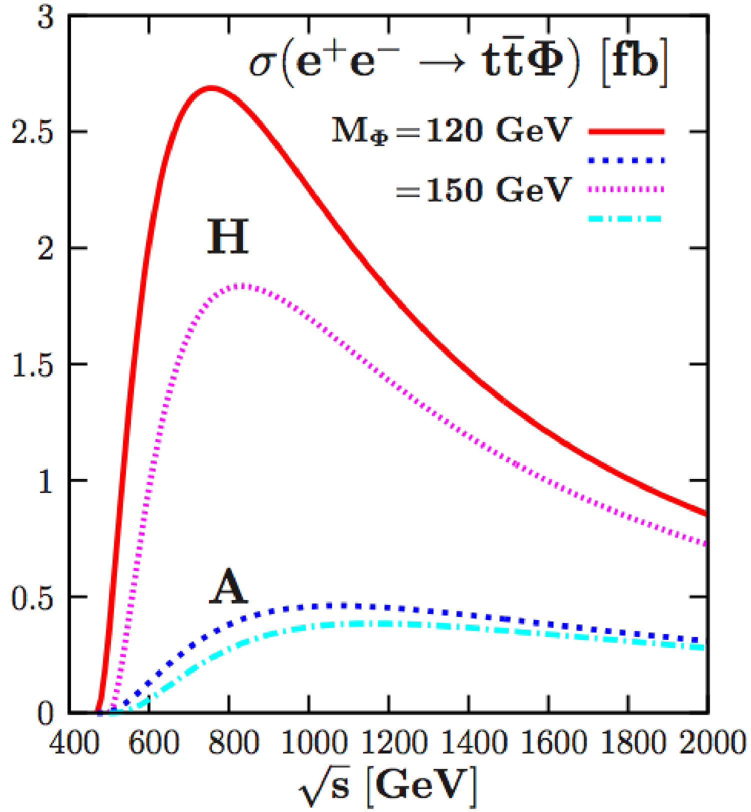


Effects observed at smaller energies may be amplified at higher energies

Higgs Quantum Numbers – CP via tth

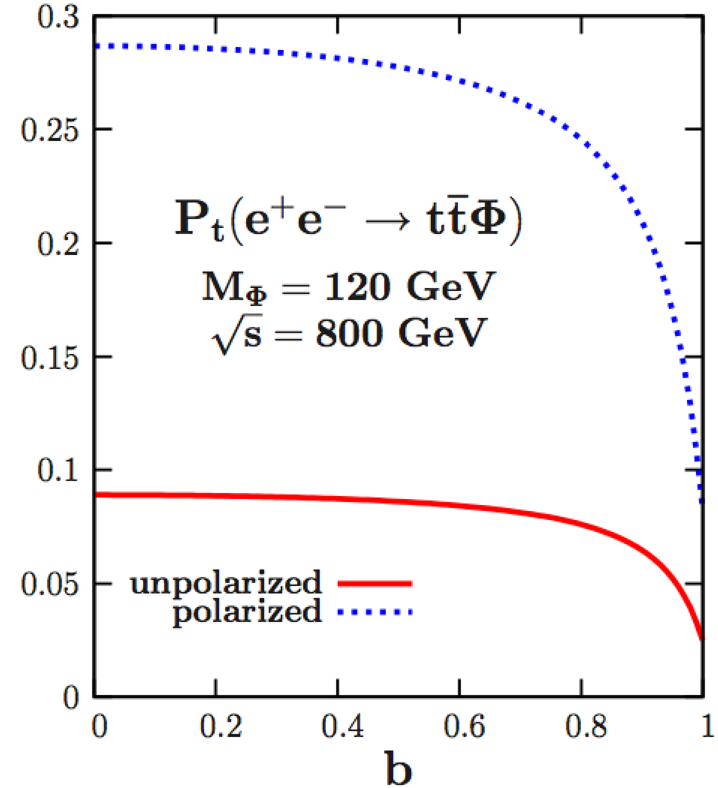
Direct coupling of top quark to CP odd and CP even scalar

Cross section



Dramatic differences for
CP odd and CP even scalar

Top quark polarisation

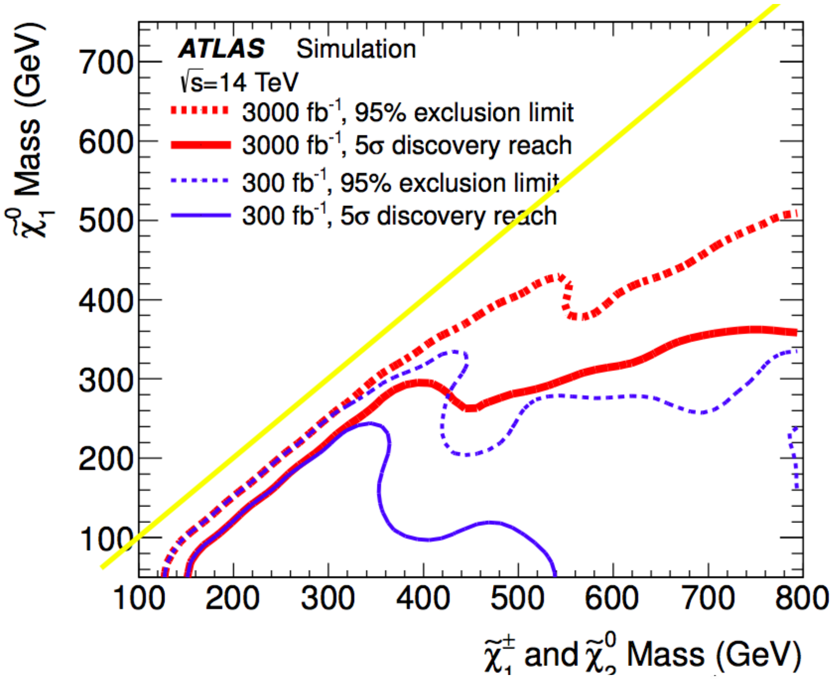


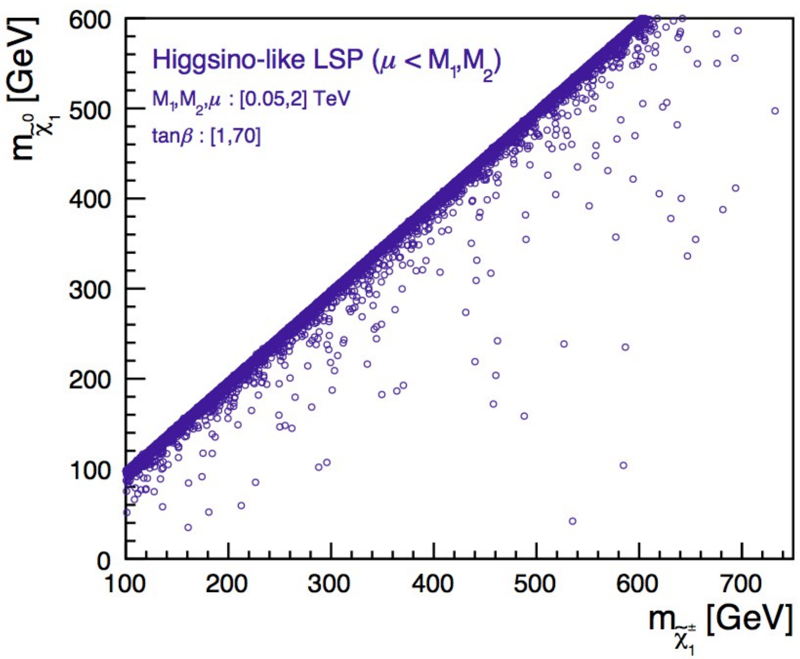
Sensitivity to CP odd admixture b
Merit of beam polarisation

Determination of CP nature of scalar boson in an unambiguous way

Godbole et al., LCWS07

Direct searches





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

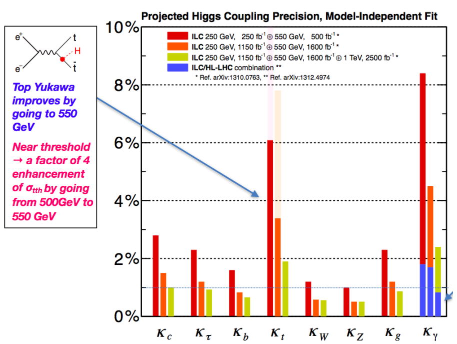
- Hadron colliders cannot exclude low mass SUSY with light neutralino and chargino(s) Degenerated in mass

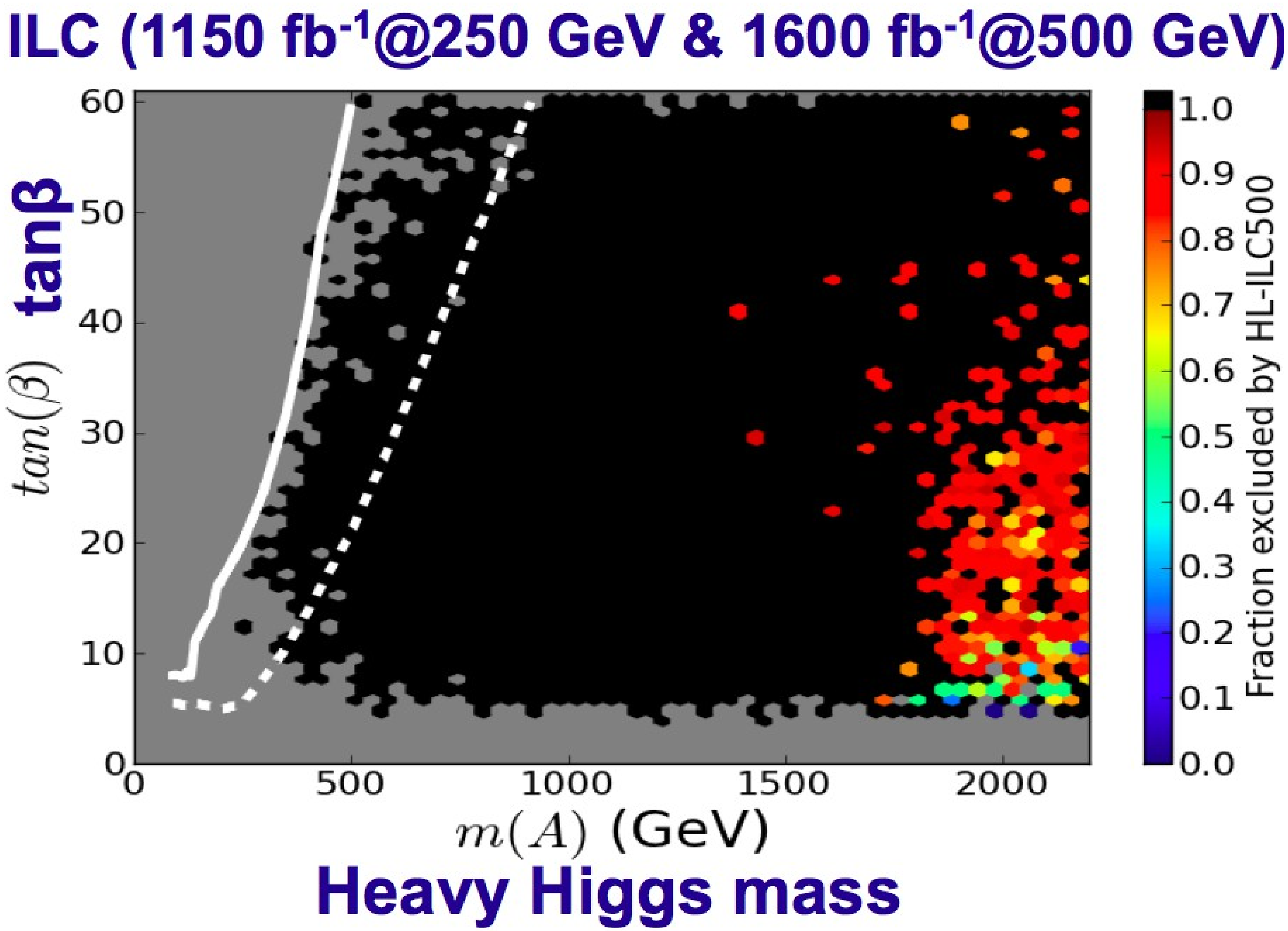
- Example: scenario with light higgsinos $\mu \sim O(v)$

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

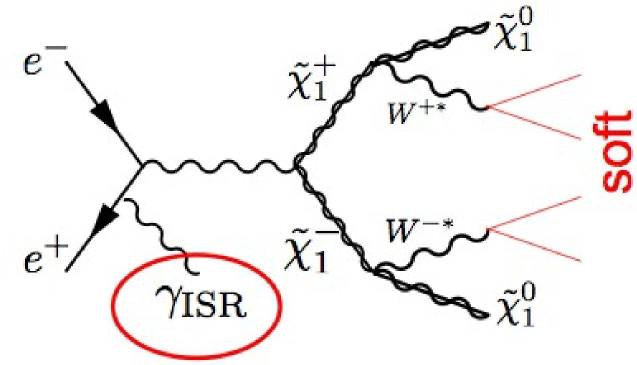
Study of Higgsino pair production, with ISR tag

Benchmark models with

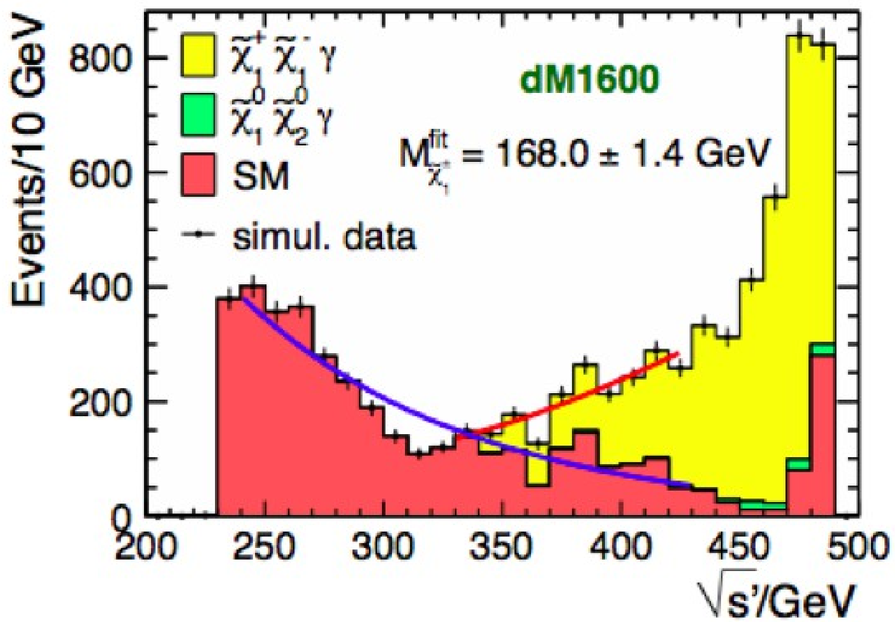
m(NLSP) – M(LSP) = 1.6 GeV and 0.8 GeV

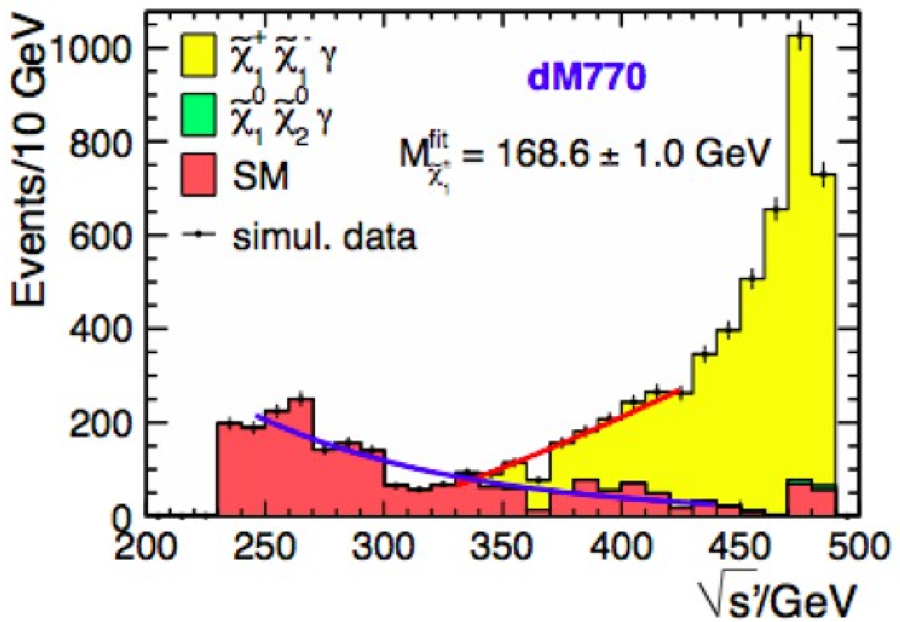
$$\sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-) = 78.7\ (77.0)\ \text{fb}$$

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



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

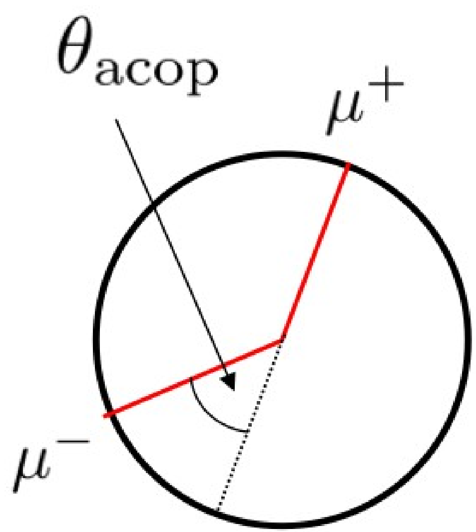


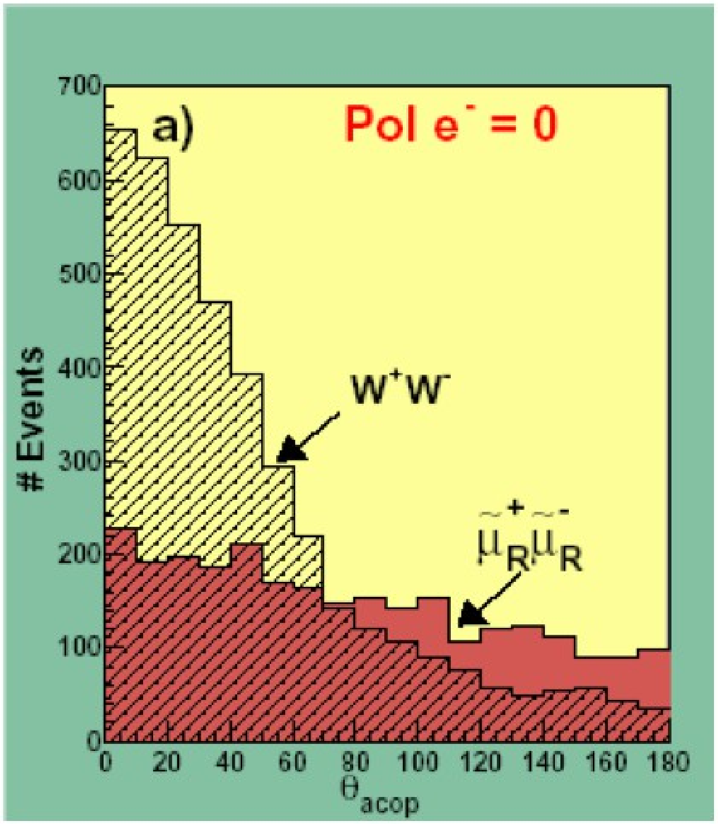


$\sqrt{s}$=500 GeV, Lumi=500 fb^{-1}, P(e-,e+)=(-0.8,+0.3) → LSP mass resolution ~1%

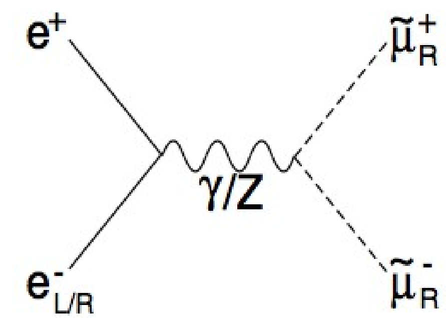
Clear signal => ILC covers important corner of phase space for SUSY Searches

Example: Smuon pair production

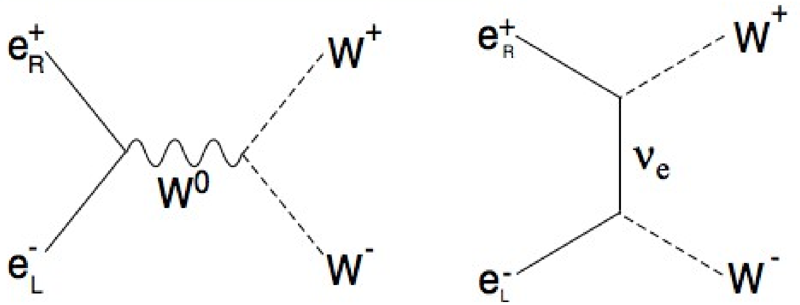




signal



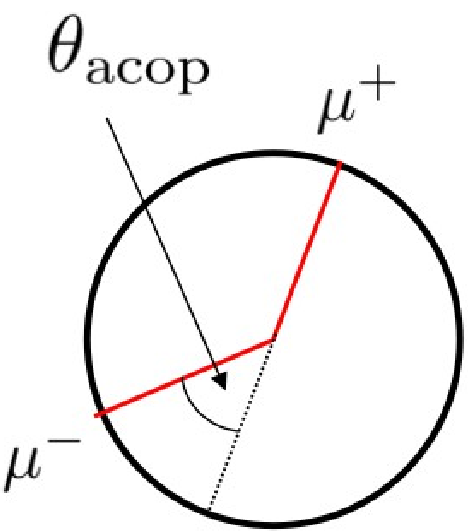
SM background

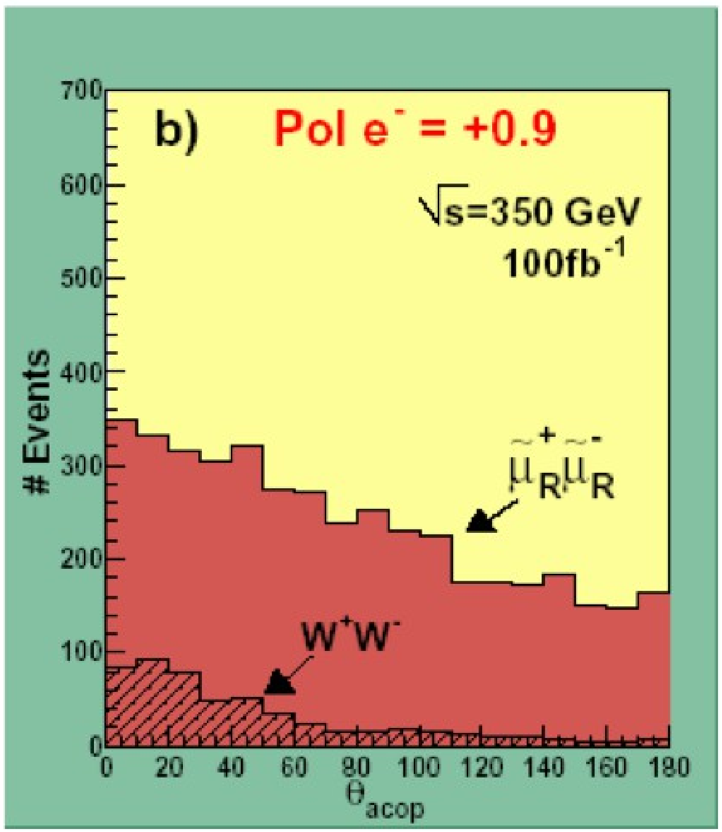


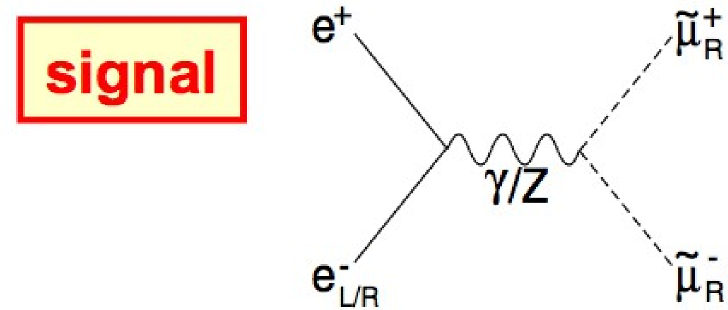
M. Thomson, IoP Meeting 2007

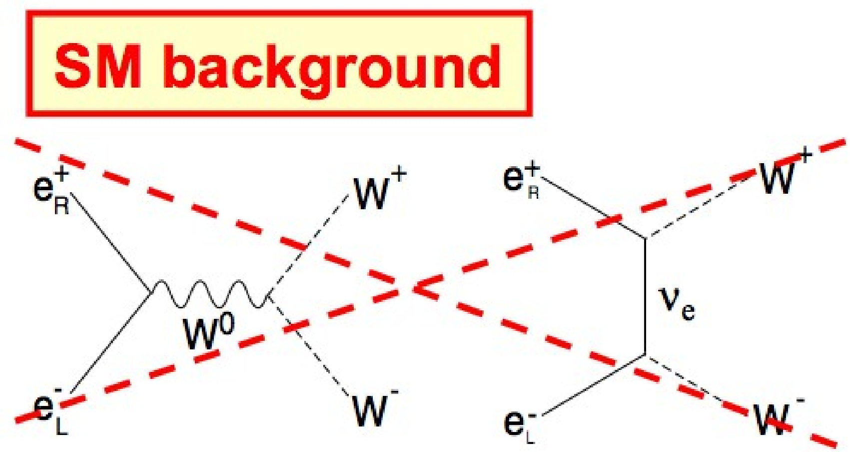
Strong SM Background

Example: Smuon pair production









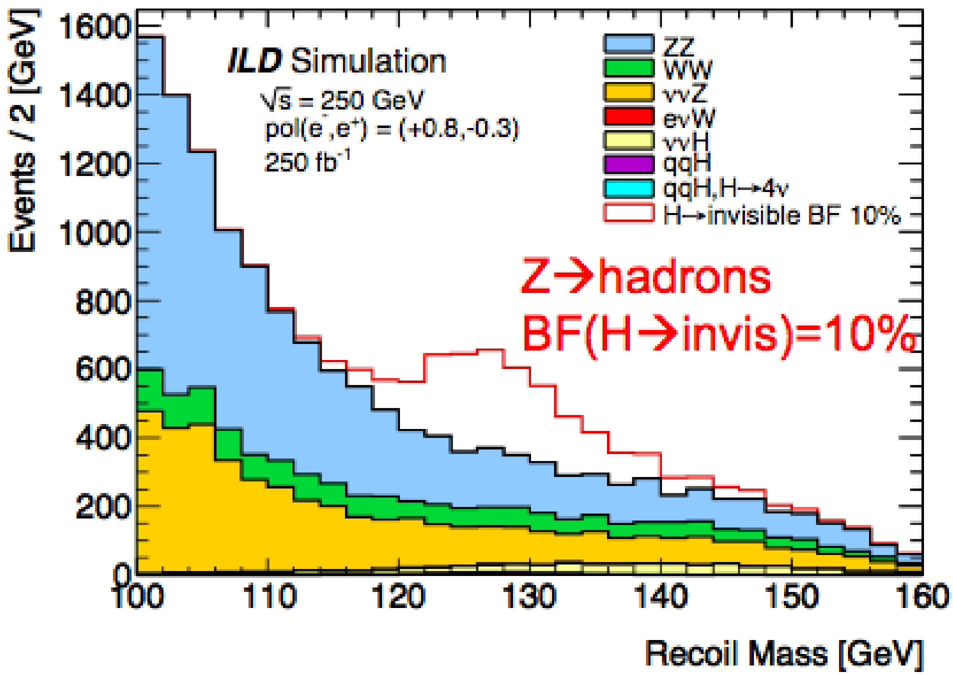
M. Thomson, IoP Meeting 2007

Strong background suppression through beam polarisation

WIMP searches at colliders are complementary to direct/indirect searches.

Examples at the ILC:

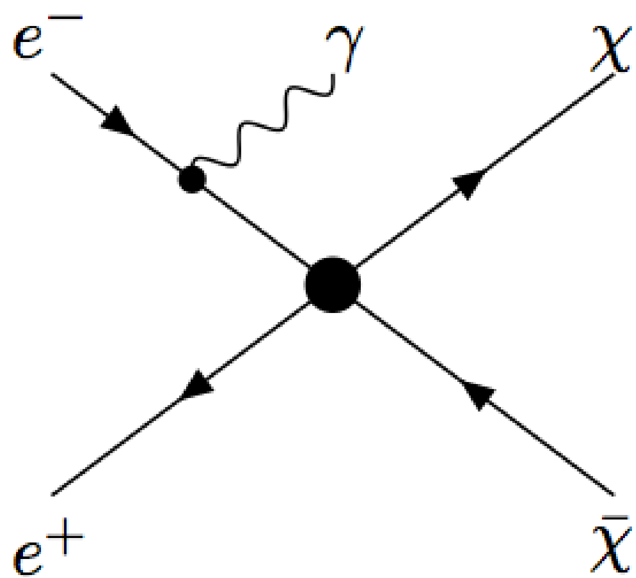
Higgs Invisible Decays



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

Impact of jet energy resolution

Monophoton Searches

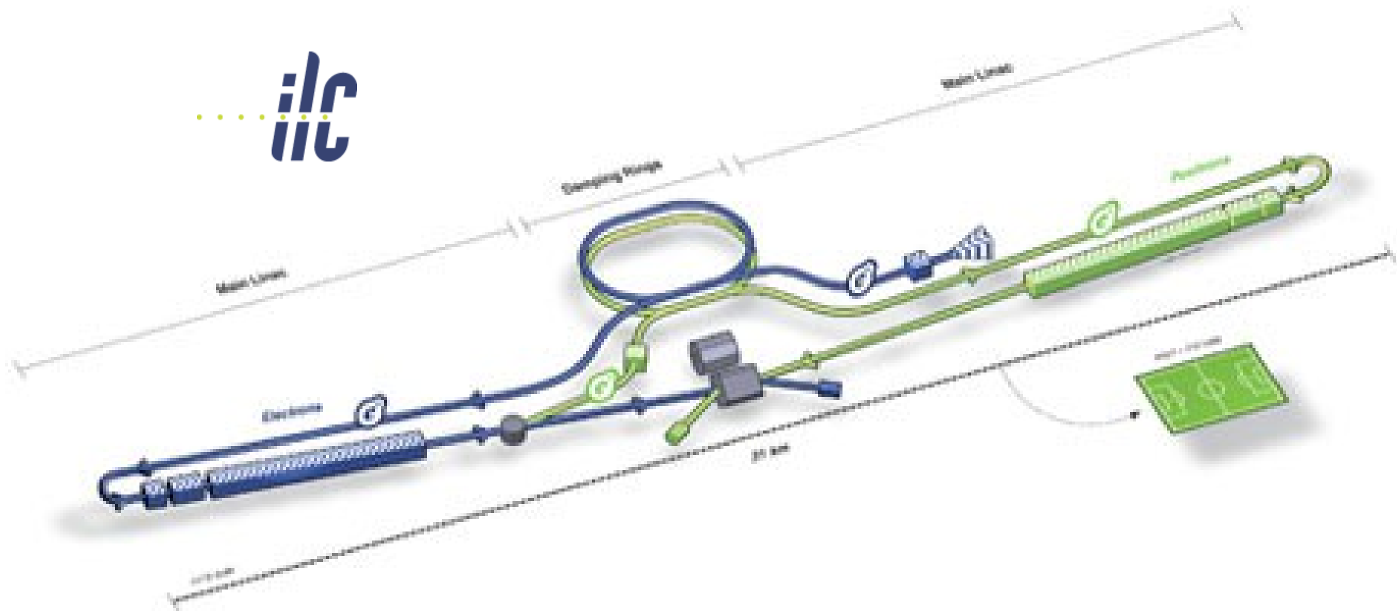


→ DM mass sensitivity nearly half √s

Soft photons, forward detectors

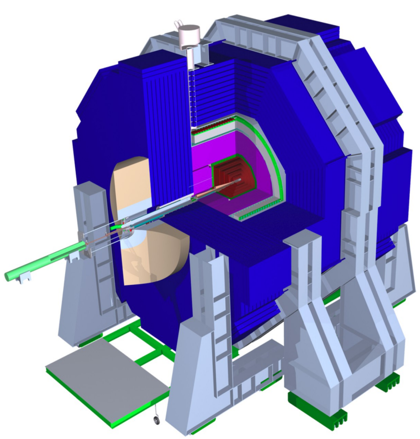
Tomohiko Tanabe
ILD Meeting 2014

ILC Project - Machine and detectors

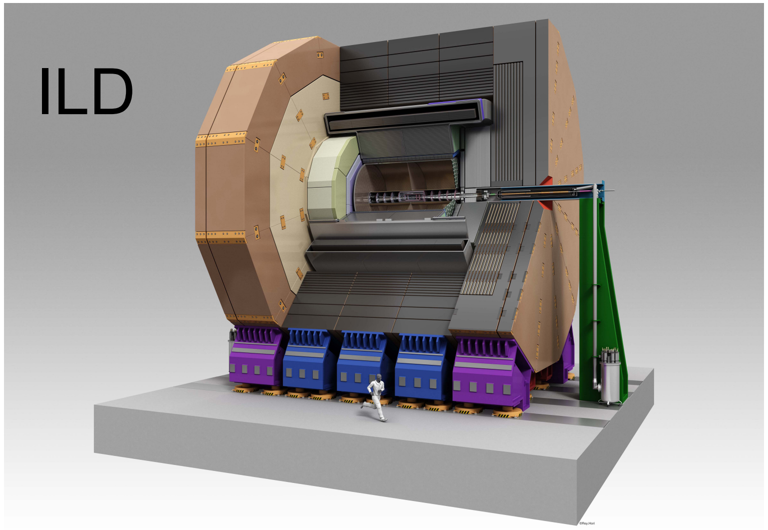


ILC design parameters	
$\sqrt{s}$	91-500 GeV
$\mathcal{L}$	2×10^{34} cm^{-2}s^{-1}
P_{e^-}	>80%
P_{e^+}	~30%
Length	~31 km

-> Talk by Steinar Stapnes



SiD

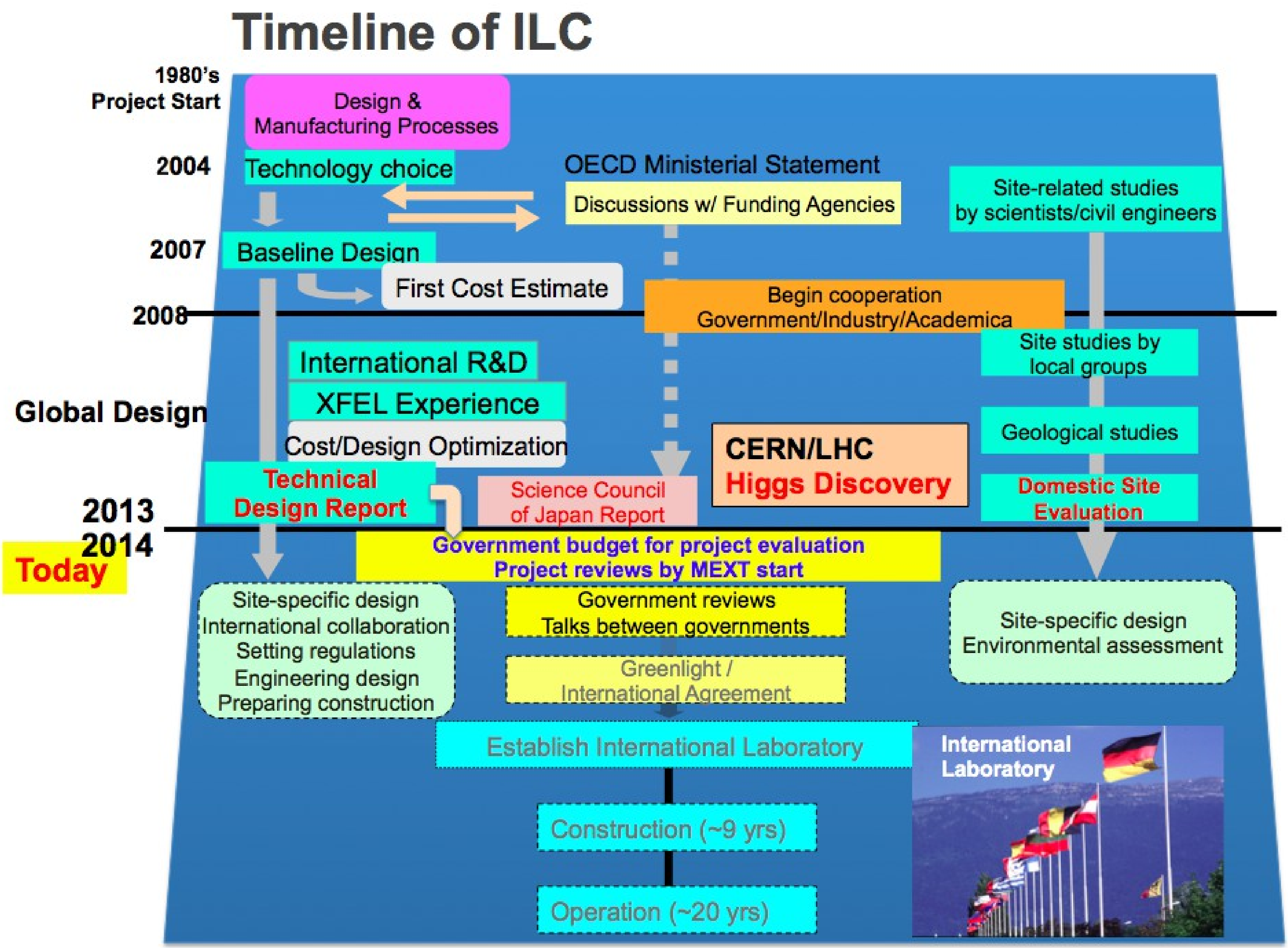


Talks by:

Imad Laktineh
Frank Simon
Marek Idzik
Lucie Linssen

Machine TDR in 2013 + DBD for detectors

ILC Roadmap

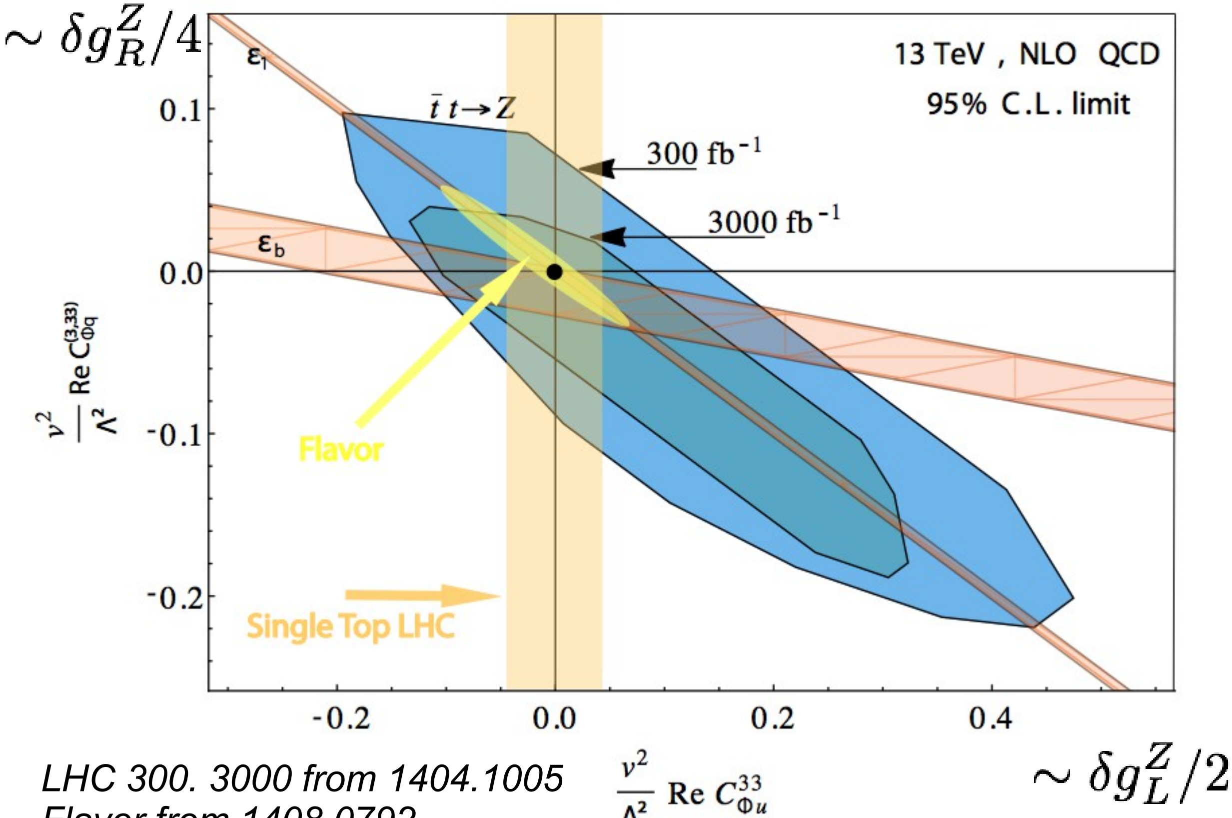


Remark R.P.: MEXT report in March 2016

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