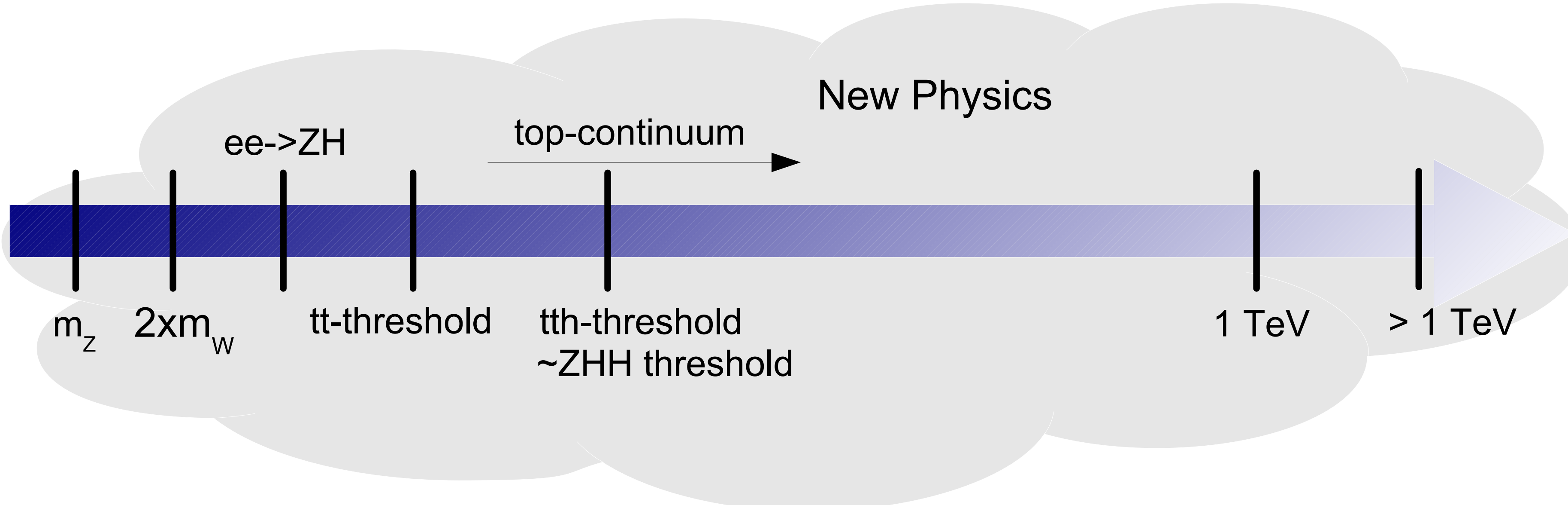
Higgs physics and electroweak couplings at the ILC

Roman Pöschl

On behalf of

IRN Terascale Meeting
European Strategy Session
May 2018

LC Physics program



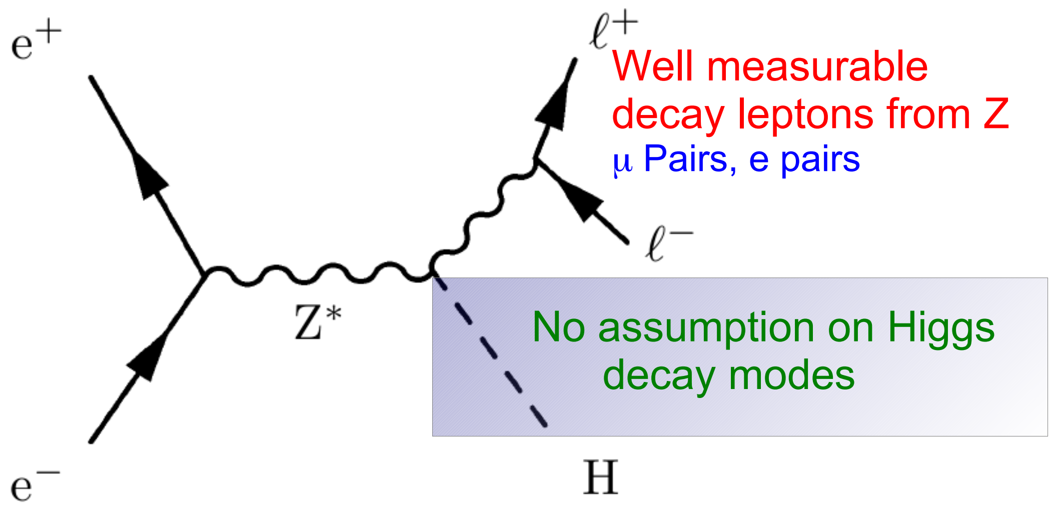
- All Standard Model particles within reach of e+e- linear colliders
  - High precision tests of Standard Model over wide range to detect onset of new physics
- Machine settings can be “tailored” for specific processes
  - Centre-of-Mass energy
  - Beam polarisation

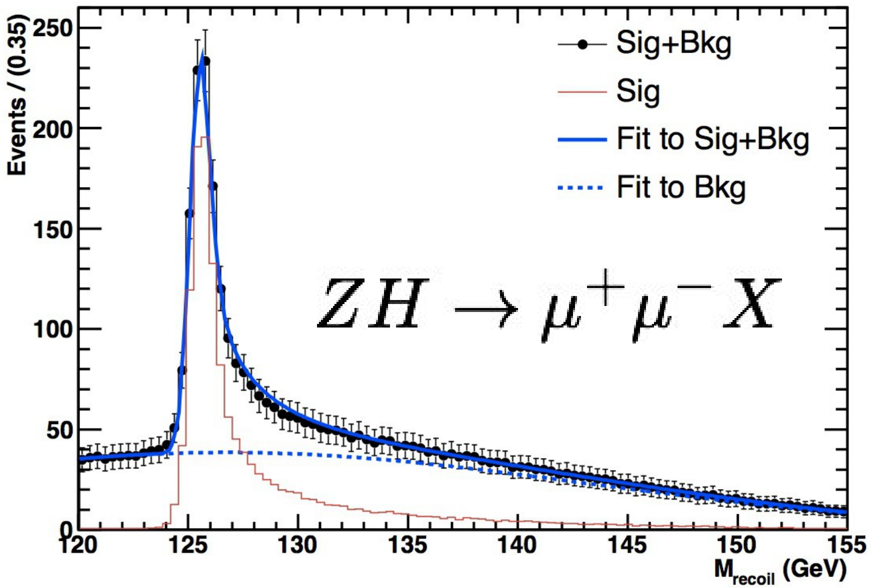
$$\sigma_{P,P'} = \frac{1}{4}[(1 - PP')(\sigma_{LR} + \sigma_{RL}) + (P - P')(\sigma_{RL} - \sigma_{LR})]$$

- “Background free” searches for BSM through beam polarisation

Higgs-strahlung at Lepton Colliders

“Golden Channel” for access to
absolute Higgs-couplings





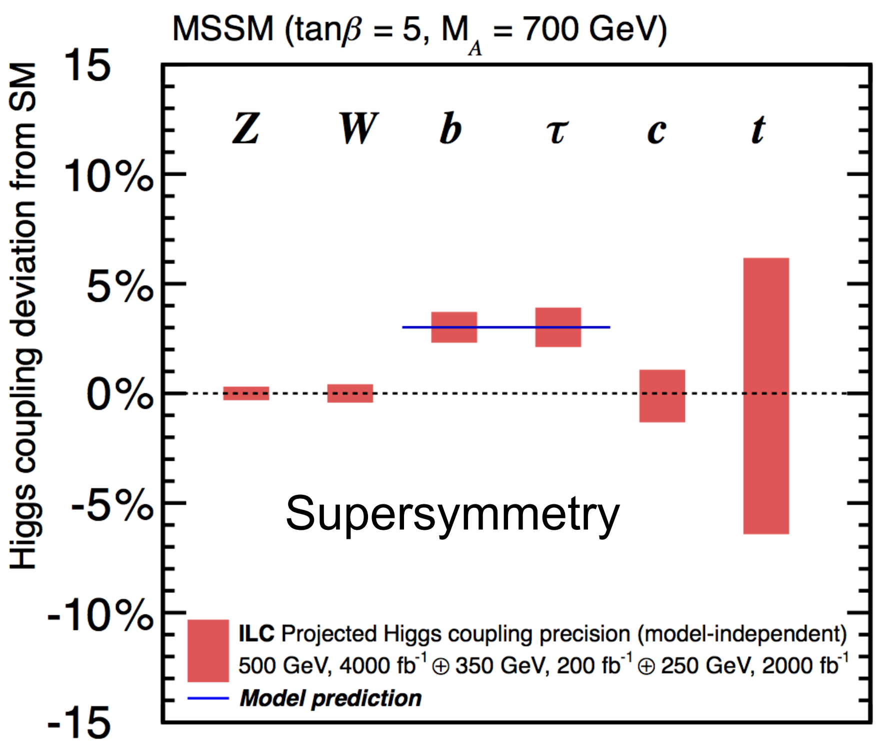
PhD Thesis, Hengne Li LAL -> Reference for machine design

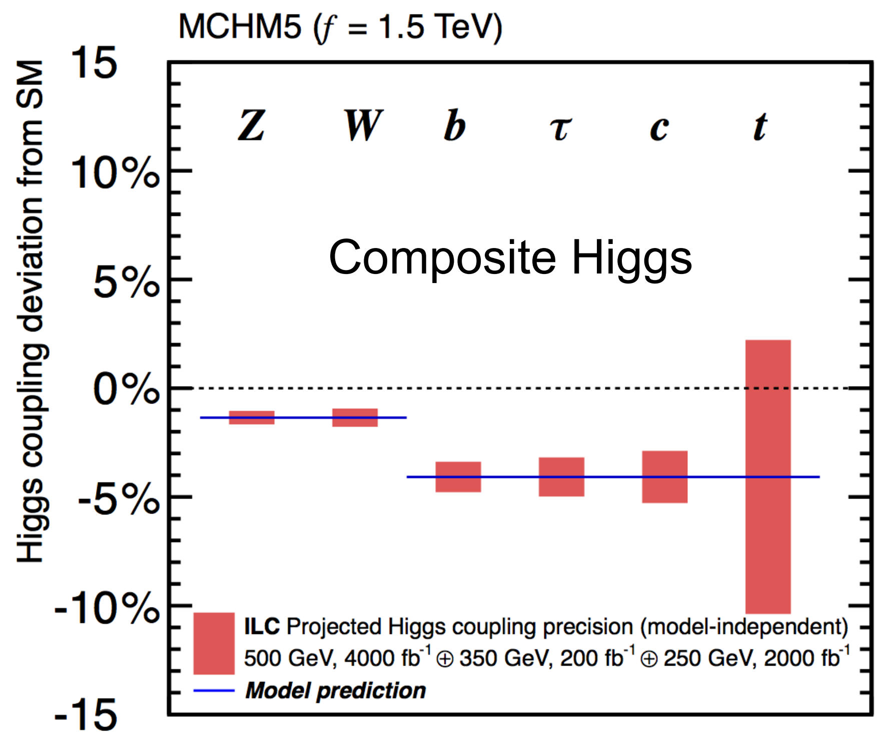
Higgs Recoil Mass: $M_h^2 = M_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$

Ideal channel to search for new (light) scalars as the radion
Arxiv: 1702.03984 – Collaboration LAL/LPT

Precision matters ...

Coupling precision after full ILC programme



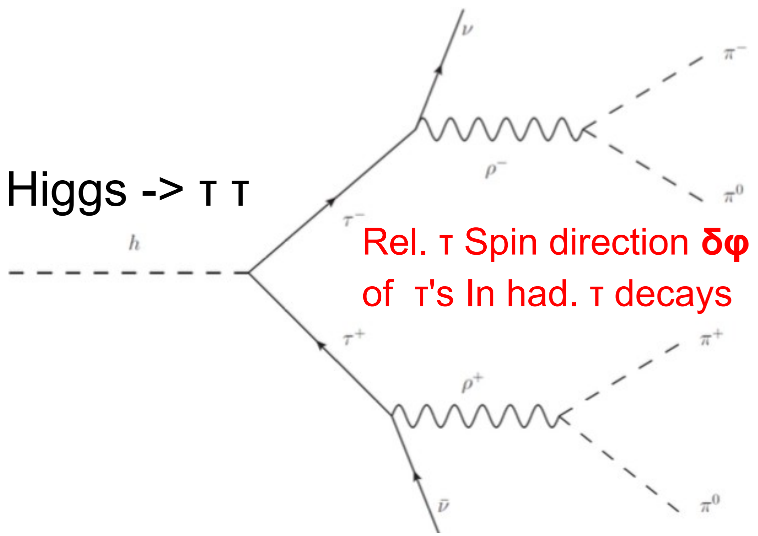


- Different new physics models lead to different patterns
- Full pattern can **only** be measured at Linear Collider

- ILC250 already powerful tool (see e.g. 1706.02146 and backup)

CP Violation in Higgs studies

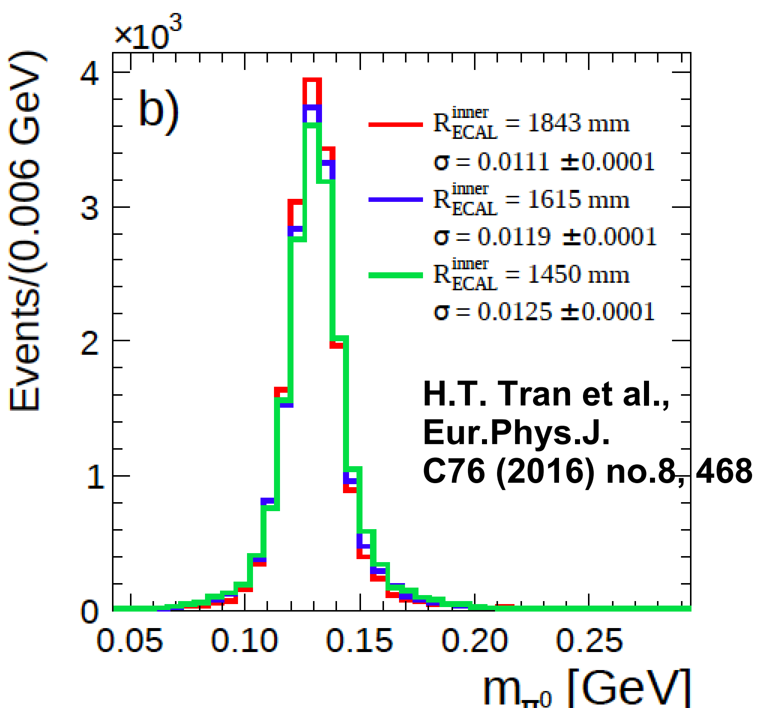
Higgs -> τ τ



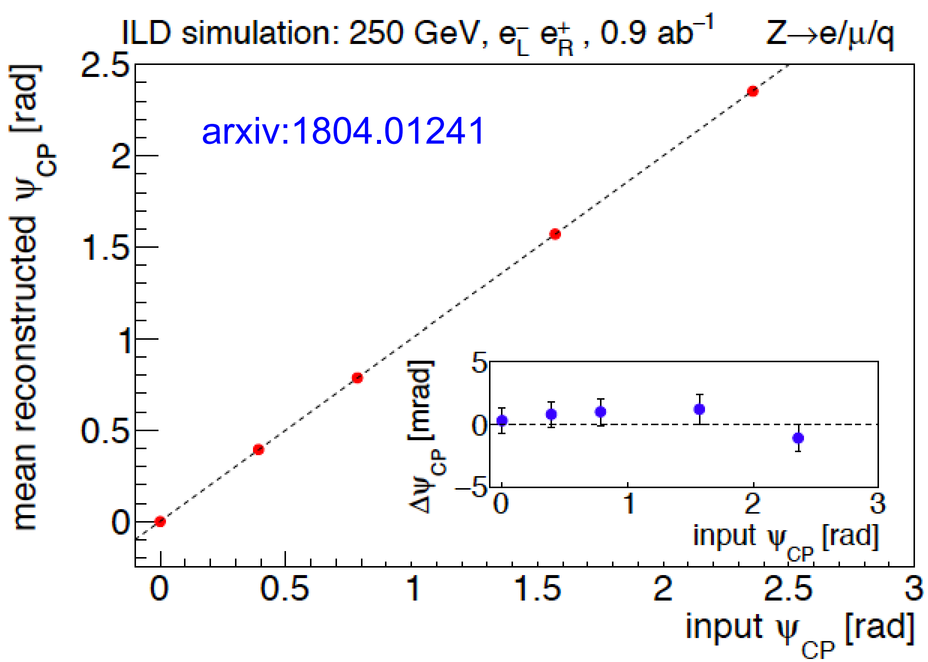
- π^0 in final state require excellent photon reconstruction

  => highly granular calorimeters (Ecal) and GARLIC algorithm

- Hadronic Z-decays dominate sensitivity

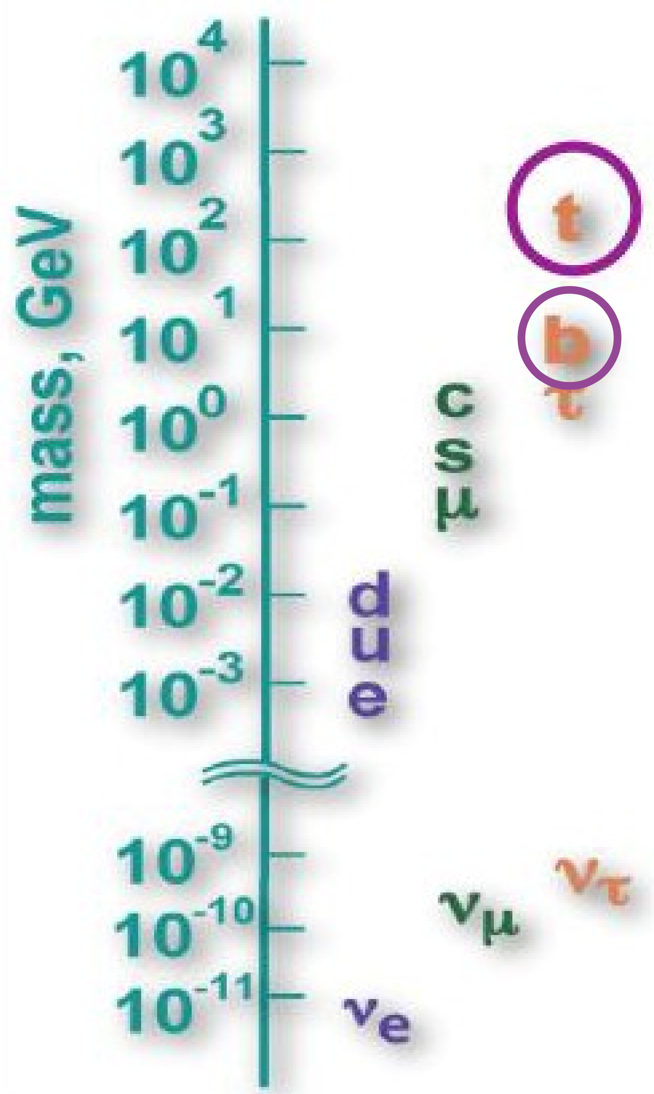


π^0-mass spectrum
for different detector models



Precise reconstruction of CP-Phase ψ

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

$$\begin{pmatrix} t \\ b \end{pmatrix}_L$$

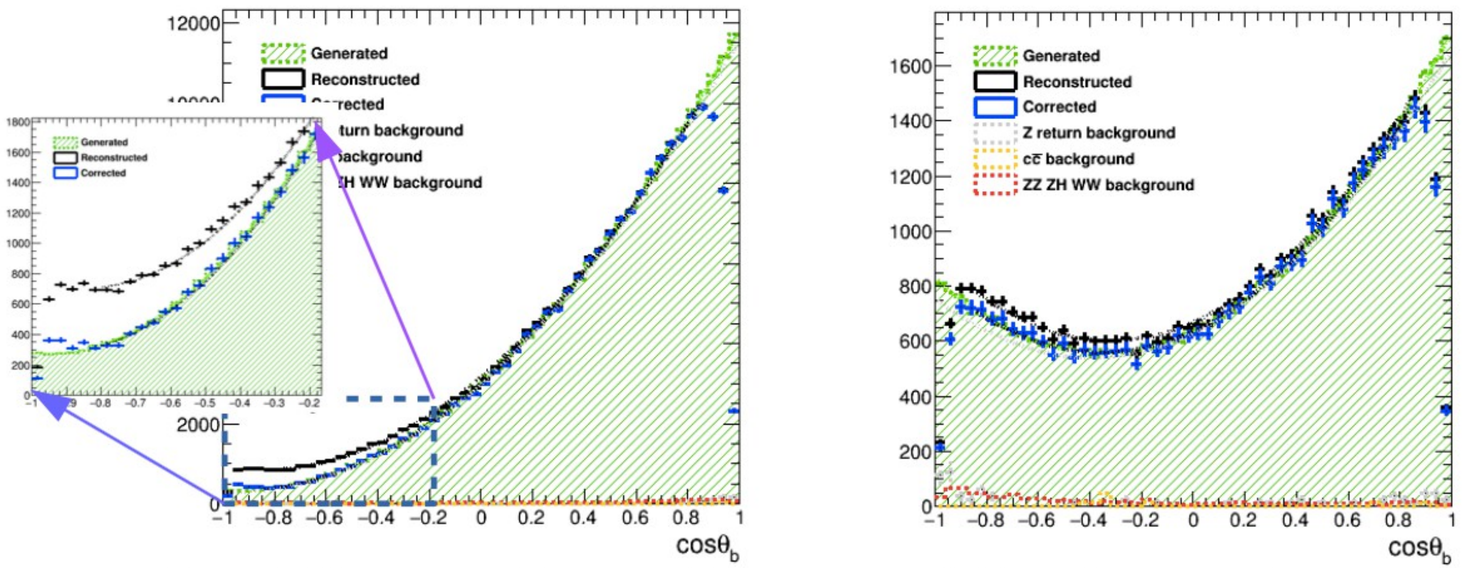
- LEP anomaly and recent LHCb anomalies!!!

Strong motivation to study chiral structure of heavy quark vertices in high energy e+e- collisions

ee->bb – Polar angle spectrum

$$\sqrt{s} = 250\,\mathrm{GeV} \;\; L = 250\,\mathrm{fb}^{-1}$$

$$e^-_L e^+_R \to b\bar{b} \qquad\qquad e^-_R e^+_L \to b\bar{b}$$



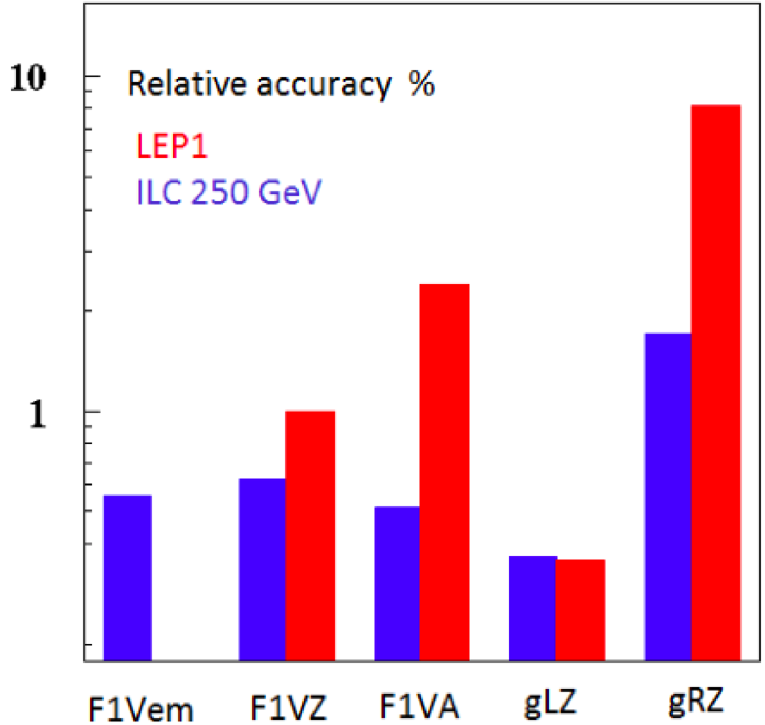
$$A^{rec}_{fb}/A^{gen}_{fb} = 100.7\% \pm 0.62\% \qquad\qquad A^{rec}_{fb}/A^{gen}_{fb} = 104.9\% \pm 2.25\%$$

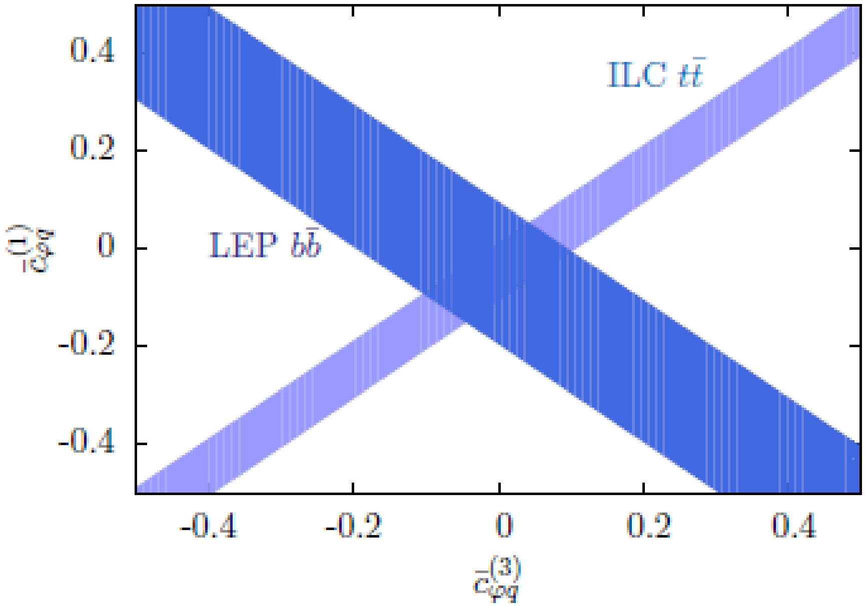
- Full simulation study (with ILD concept)
- Benchmark reaction for 250 GeV running
  - Experimental challenge: Measurement of b-quark charge on event-by-event basis

- Long lever arm in cos θ_b to extract form factors or couplings

Thesis S. Bilokin
and arxiv:1709.04289

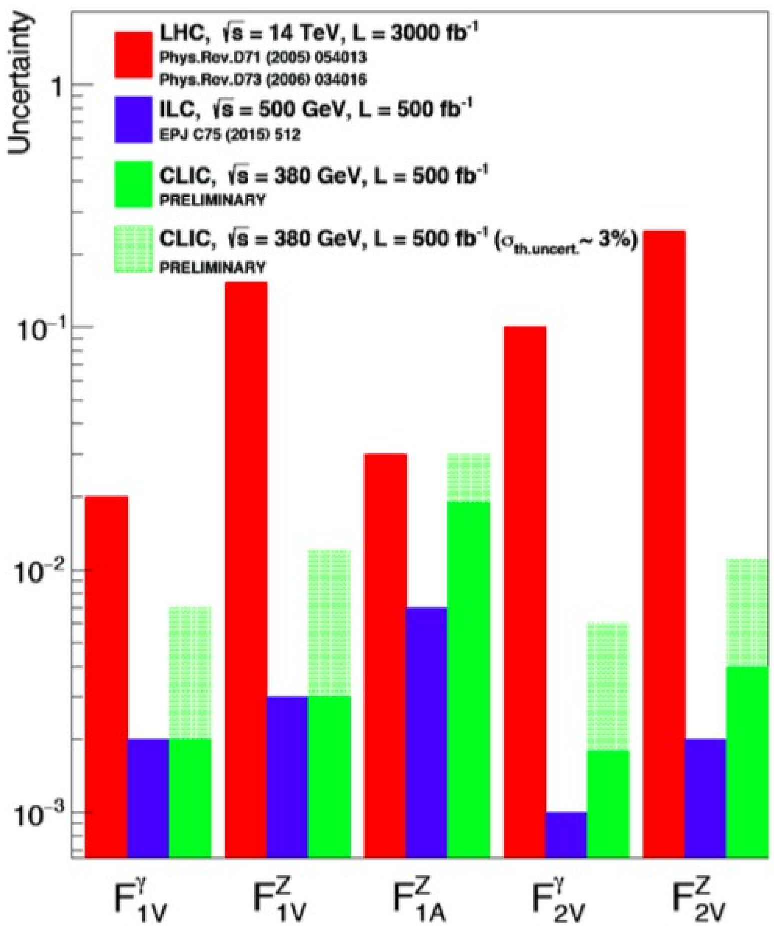
Xbb Form Factors and EFT





- ILC 'beats' LEP in particular on the right-handed coupling due to **beam polarisation**
- Final word on LEP/SLC anomaly
- Results on b and t couplings complementary for EFT interpretation
  Scales for new physics up to Λ=10 TeV are reachable

Accuracy on CP conserving couplings

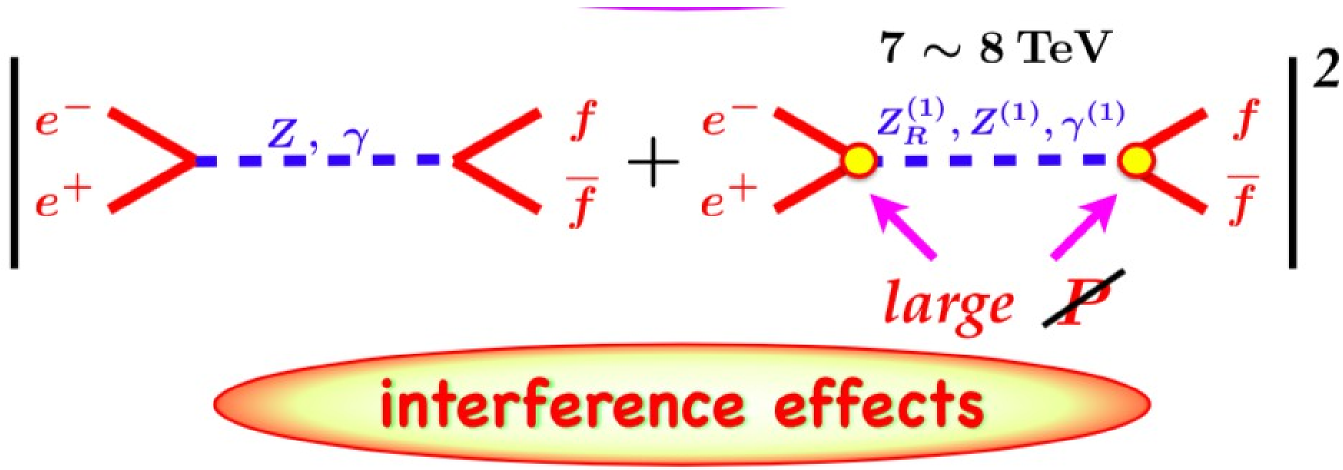


- LC might be up to two orders of magnitude more precise than LHC (√s = 14 TeV, 3000 fb-1)
- Large disentangling of couplings for ILC thanks to polarised beams
- One variable at a time for LHC
  LHC projections from 8 years old study
- Note
  Minimal Lumi scenario for ILC
  Maximal Lumi scenario for CLIC
  Maximal Lumi scenario for LHC
- Alternative by Matrix Element Method

LC promises to be high precision machine for electroweak top couplings
Clear distinction between models of new physics (see backup)

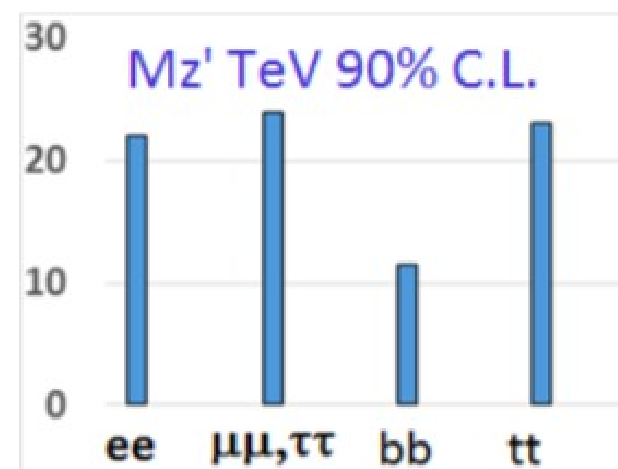
Breaking old habits – Light fermion couplings

Dynamical electroweak symmetry breaking in the Hosotani mechanism
Realisation of Randall-Sundrum Model



Funatsu, Hatanaka, YH, Orikasa, 1705.05282 (PLB 775, Nov 2017)

- Modulation of 2f cross section by interference with heavy Z'
- ... acts on light fermions -> Even revision of Bhabha is necessary
- ... to be distinguished from RS variants that act only on heavy fermions
- Anomalies at B-Factories?
- Mass reach for Z', 10-20 TeV
- Right handed beam polarisation is (always) essential



1804.02846
See talk by F. Richard

Summary and conclusion

- ILC would/will be powerful tool to trace the onset of new physics

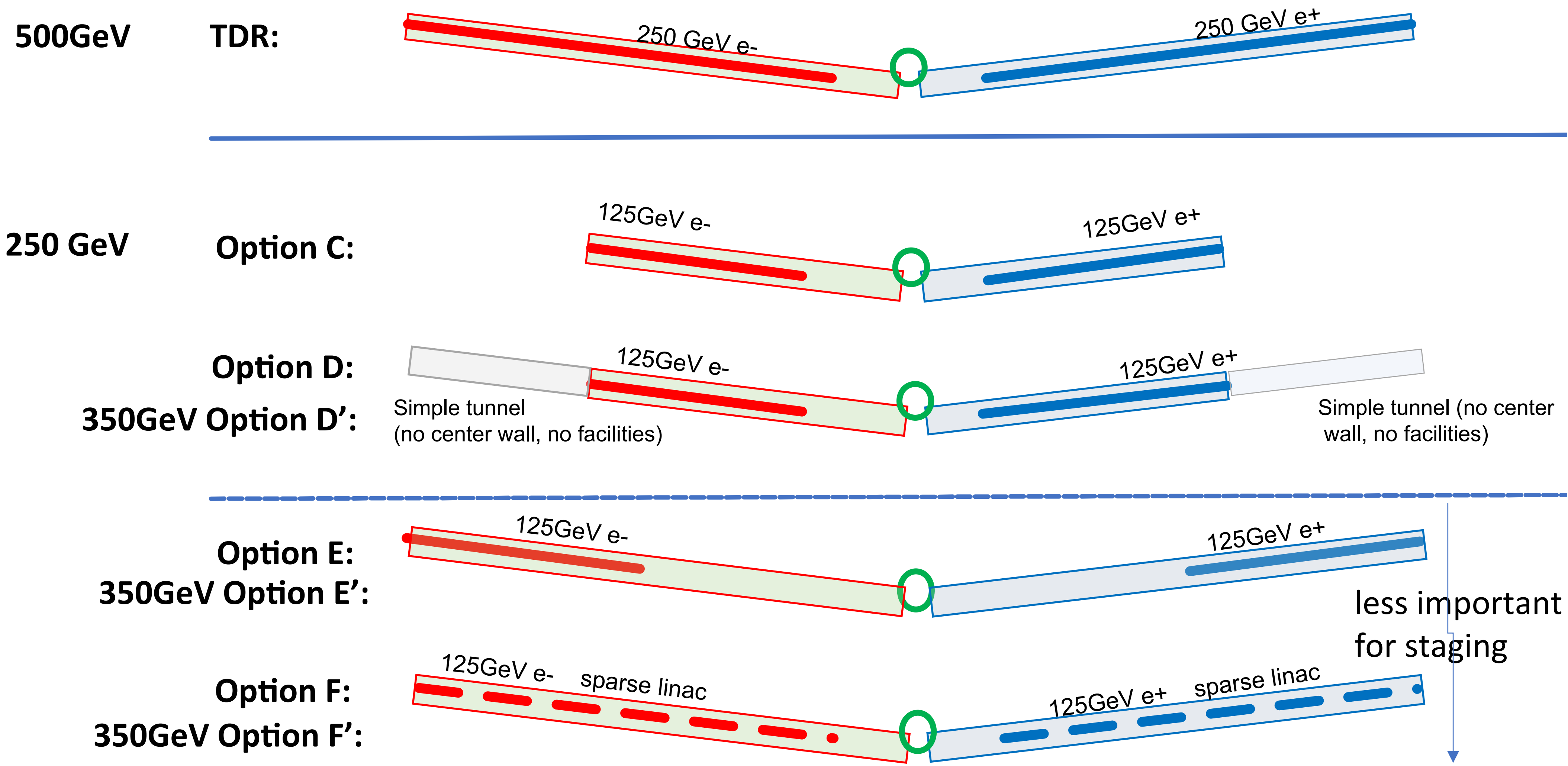
- Unique opportunities due to adjustable centre-of-mass energy and polarised beams
  - Exciting program starts at 250 GeV
  - Full development of physics potential above tt-threshold

- Full pattern of Higgs couplings and all electroweak fermion couplings
  - Discovery potential and necessary guidance for future high energy hadron machine

- Significant contributions of IN2P3 groups to the definition of the physics program

Backup ....

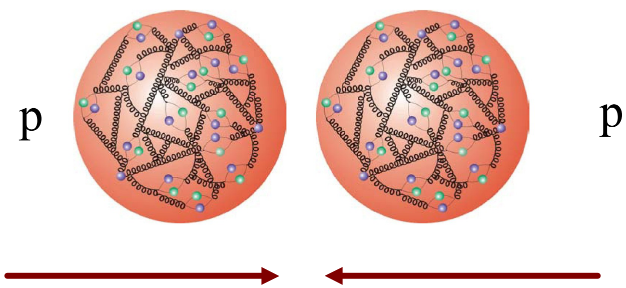
ILC – Staging options

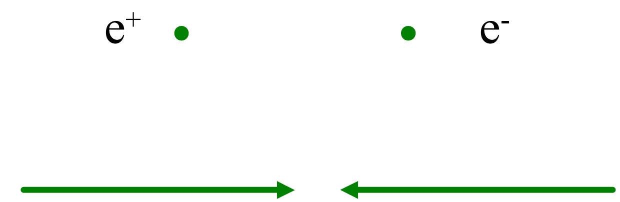


ILC could start at 250 GeV as Higgs (and elw.) precision machine

L. Evans and S. Michizono @ AWLC2017

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:

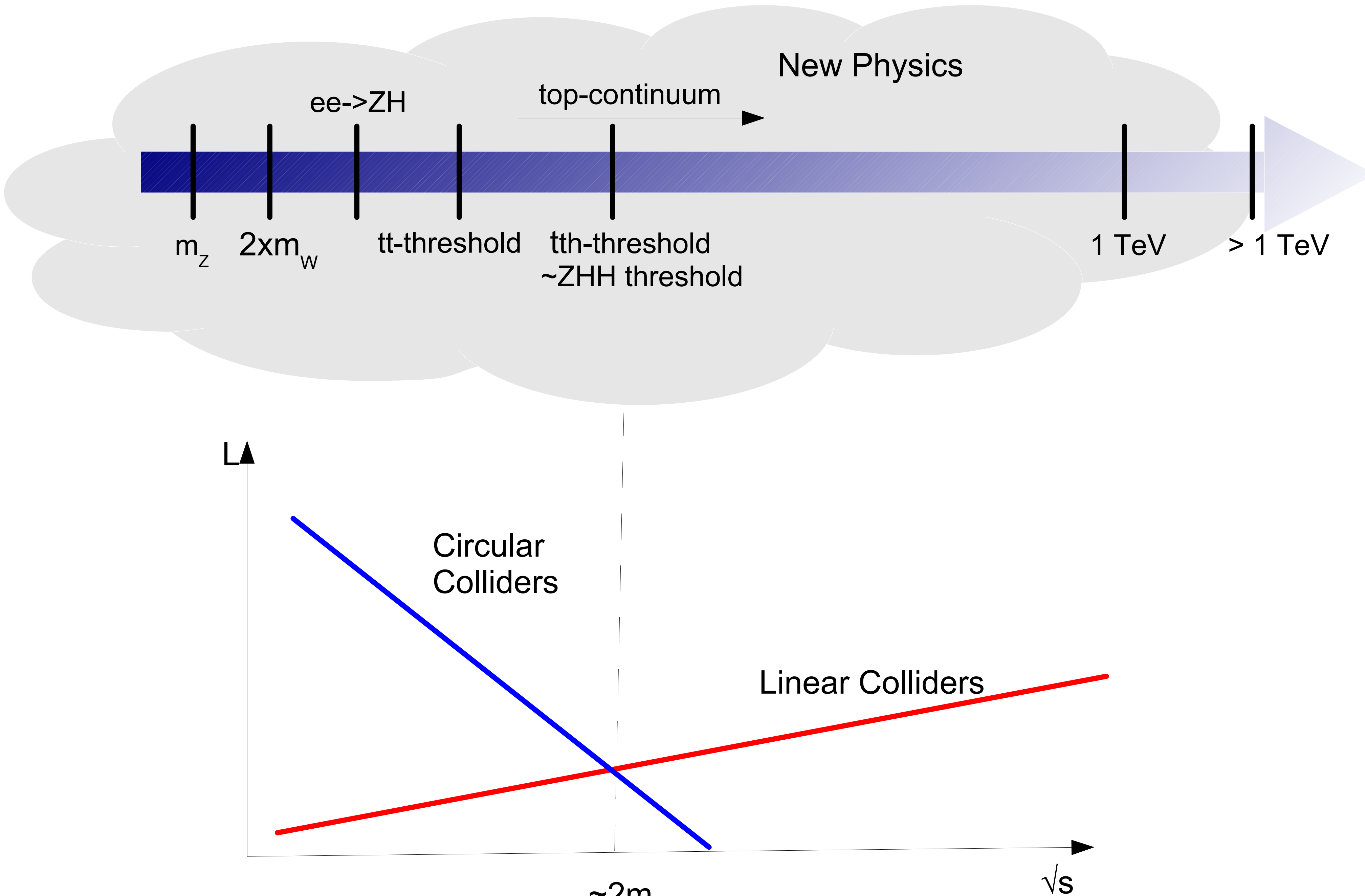
Elementary particle

Well known and adjustable
energy of collision partners

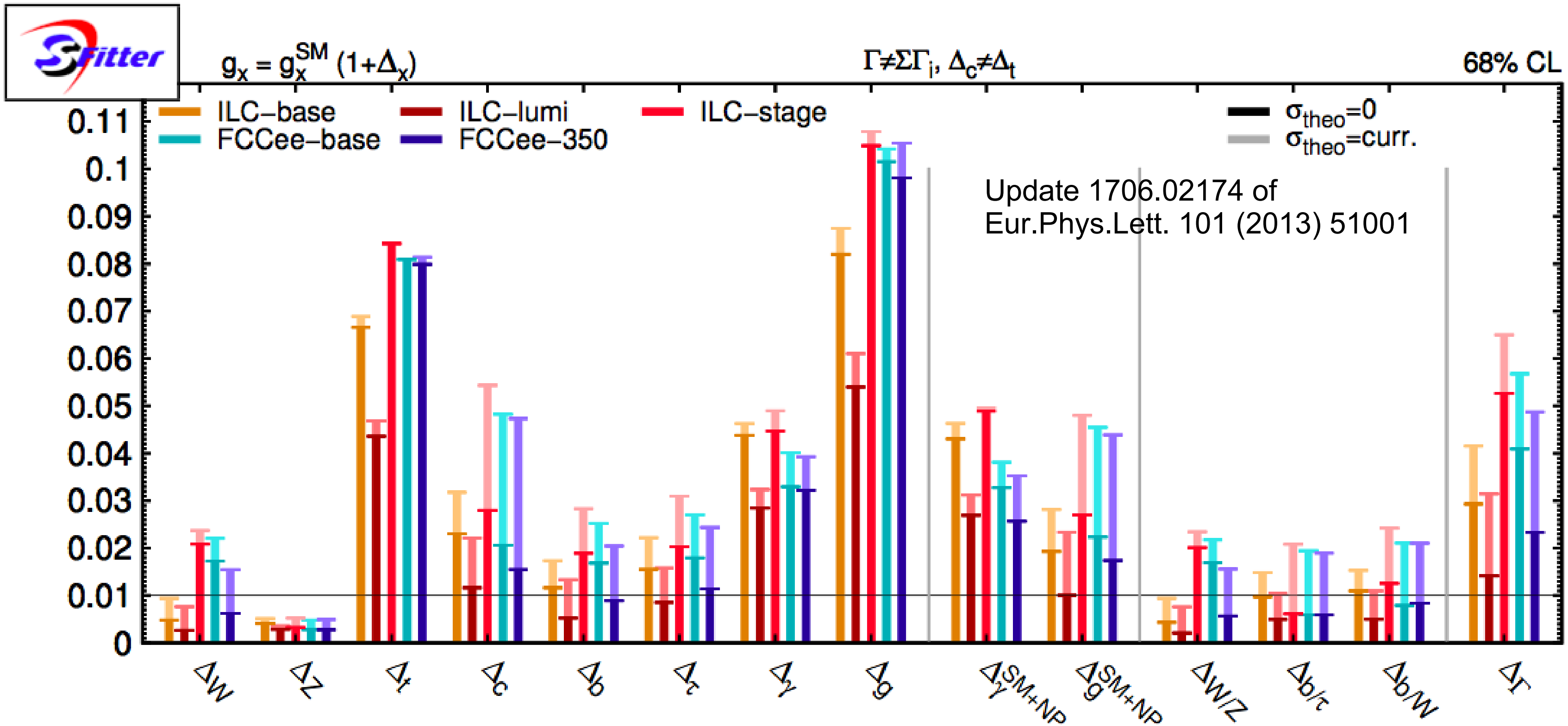
High precision measurements
in a model independent way
with small electroweak backgrounds

Each energy point needs a
new set of machine parameters

e+e- Physics program



Precision of Higgs couplings



- Latest results from SFITTER group
  Assumption: HL-LHC basically completed before e+e- machine starts
- ILC250 already powerful program (needs however e.g. top-Yukawa as input)
- Higher energies beneficial for total width (Holy grail)
  and top-Yukawa couplings (fit constraints and H->γγ)

Higgs as discovery tool

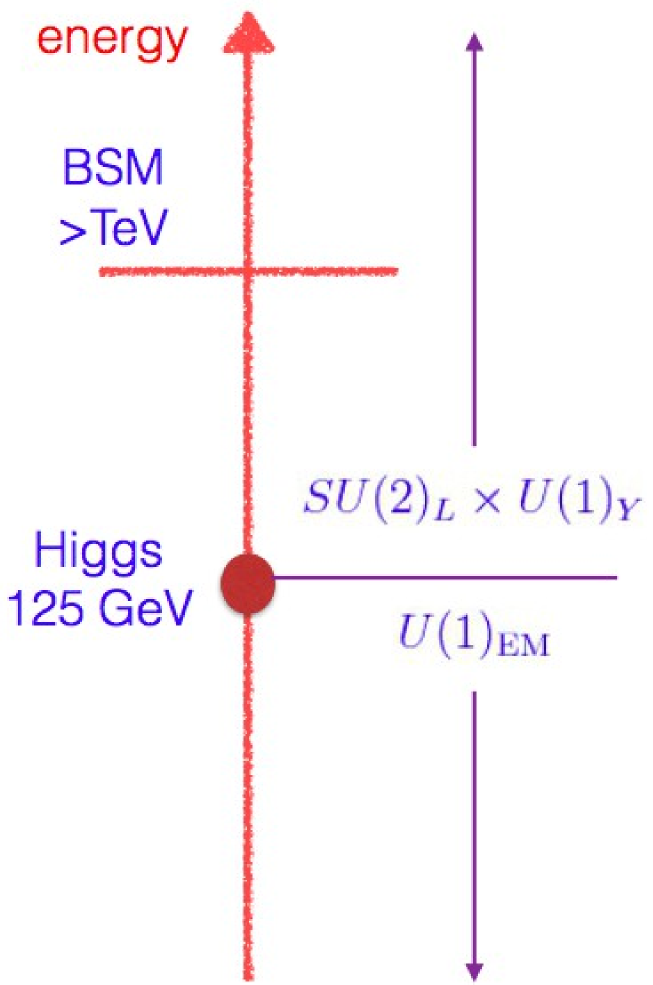
- LHC results strongly suggest that there is a significant mass gap between the Higgs and BSM particles

- In this situation, BSM corrections to Higgs properties are parametrically small:

$$\delta O \sim m_h^2 / M_{\mathrm{BSM}}^2$$

- Moreover, BSM physics must respect the full gauge symmetry of the SM

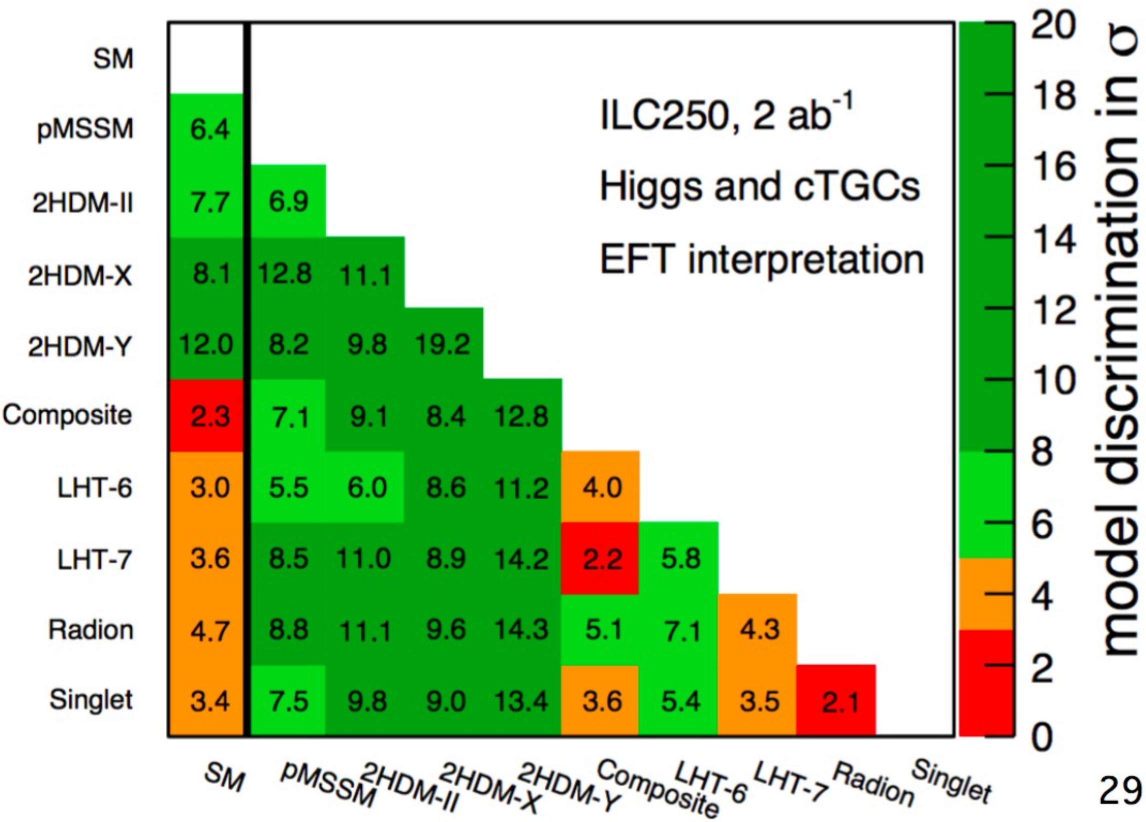
- Effective Field Theory (EFT) gives a systematic way to parametrize correction to Higgs properties under these conditions, by adding "effective operator" terms to the SM Lagrangian

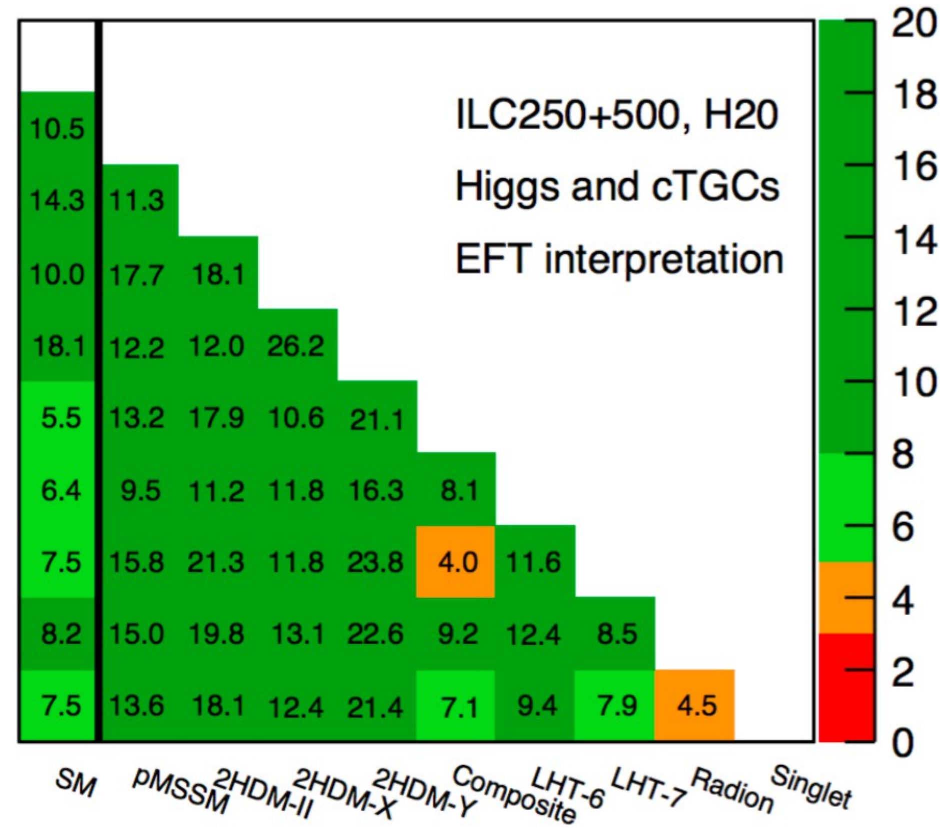


20

M. Perelstein AWLC17

Higgs – Discovery potential by precision





- Already large discriminative power at 250 GeV
- Full discovery potential developed at higher energies (e.g. 500 GeV)

M. Peskin et al., Work in progress

EFT Coupling Fit

- An interesting example is couplings to W/Z bosons

$$\mathcal{L} = (1+\eta_Z)\frac{2m_Z^2}{v}hZ_\mu Z^\mu + \zeta_Z Z_{\mu\nu}Z^{\mu\nu} +$$
$$(1+\eta_W)\frac{2m_W^2}{v}hW_\mu W^\mu + \zeta_W W_{\mu\nu}W^{\mu\nu}$$

<<1 from PEW

$$\eta_W = -\frac{1}{2}c_H \qquad \eta_Z = -\frac{1}{2}c_H \boxed{- c_T}$$

$$\zeta_W = (8c_{WW})$$
$$\zeta_Z = c_w^2(8c_{WW}) + 2s_w^2(8c_{WB}) + (s_w^4/c_w^2)(8c_{BB})$$

- Compare this to the usual "kappa framework":

$$\mathcal{L} = \kappa_Z\frac{2m_Z^2}{v}hZ_\mu Z^\mu + \kappa_W\frac{2m_W^2}{v}hW_\mu W^\mu$$

- HEFT relates W and Z couplings, but introduces additional spin structure

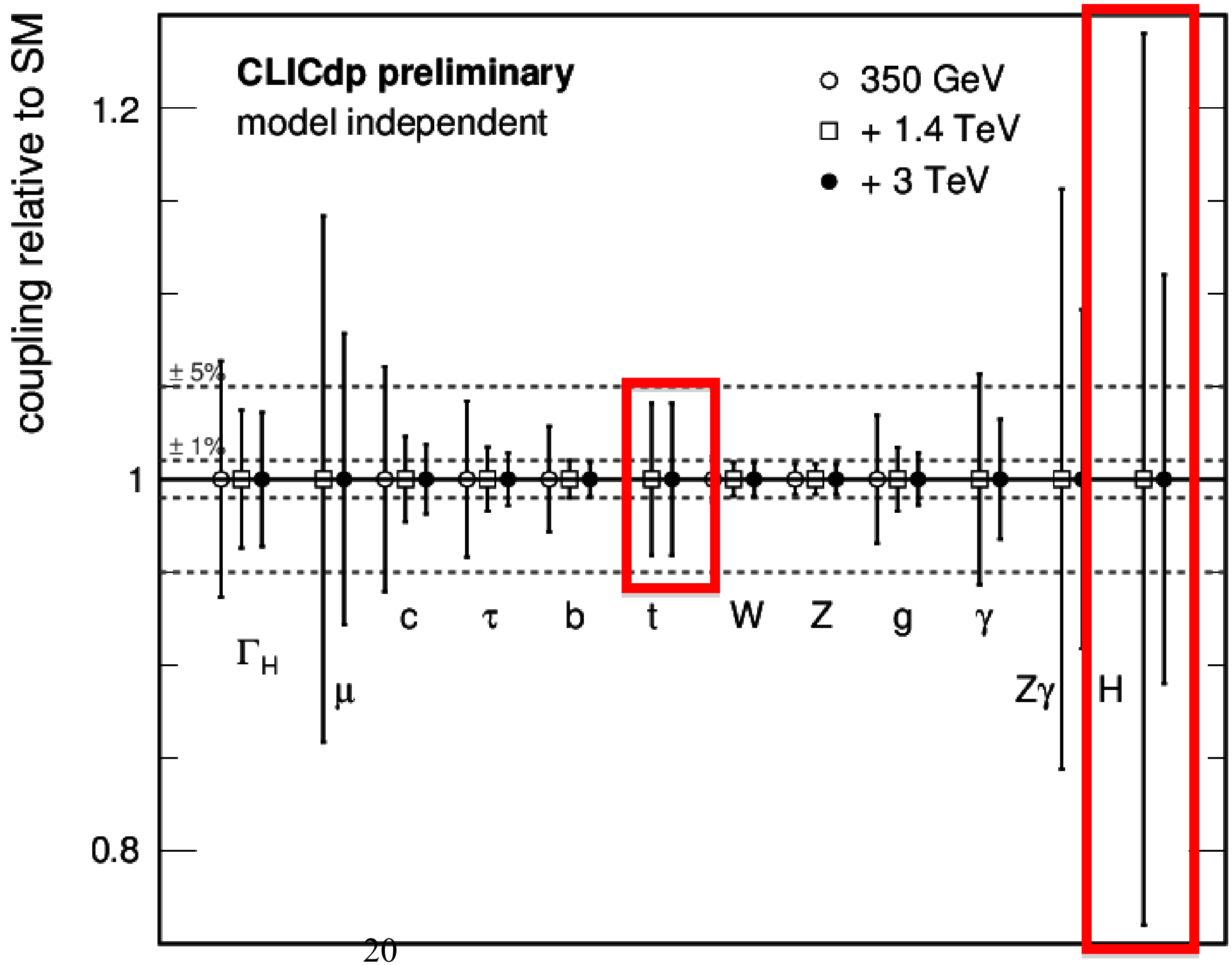
  ... that can be resolved in Higgs-strahlung with polarised beams

M. Perelstein AWLC17

Full Higgs program at LC

Higgs couplings to heavy particles benefit from higher c.m. energies:

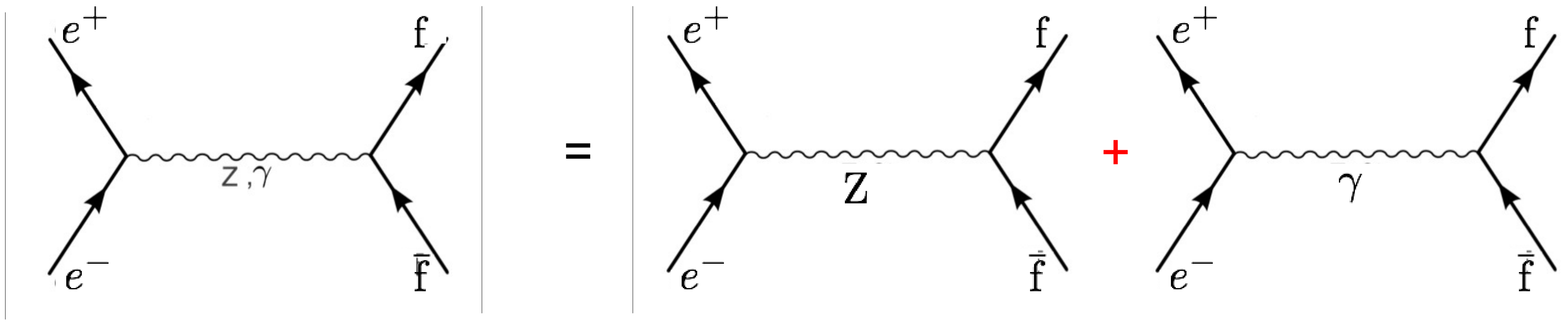
ttH ~ 4%
HH ~ 10%



20

P. Burrows/CLIC @ AWLC2017

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:

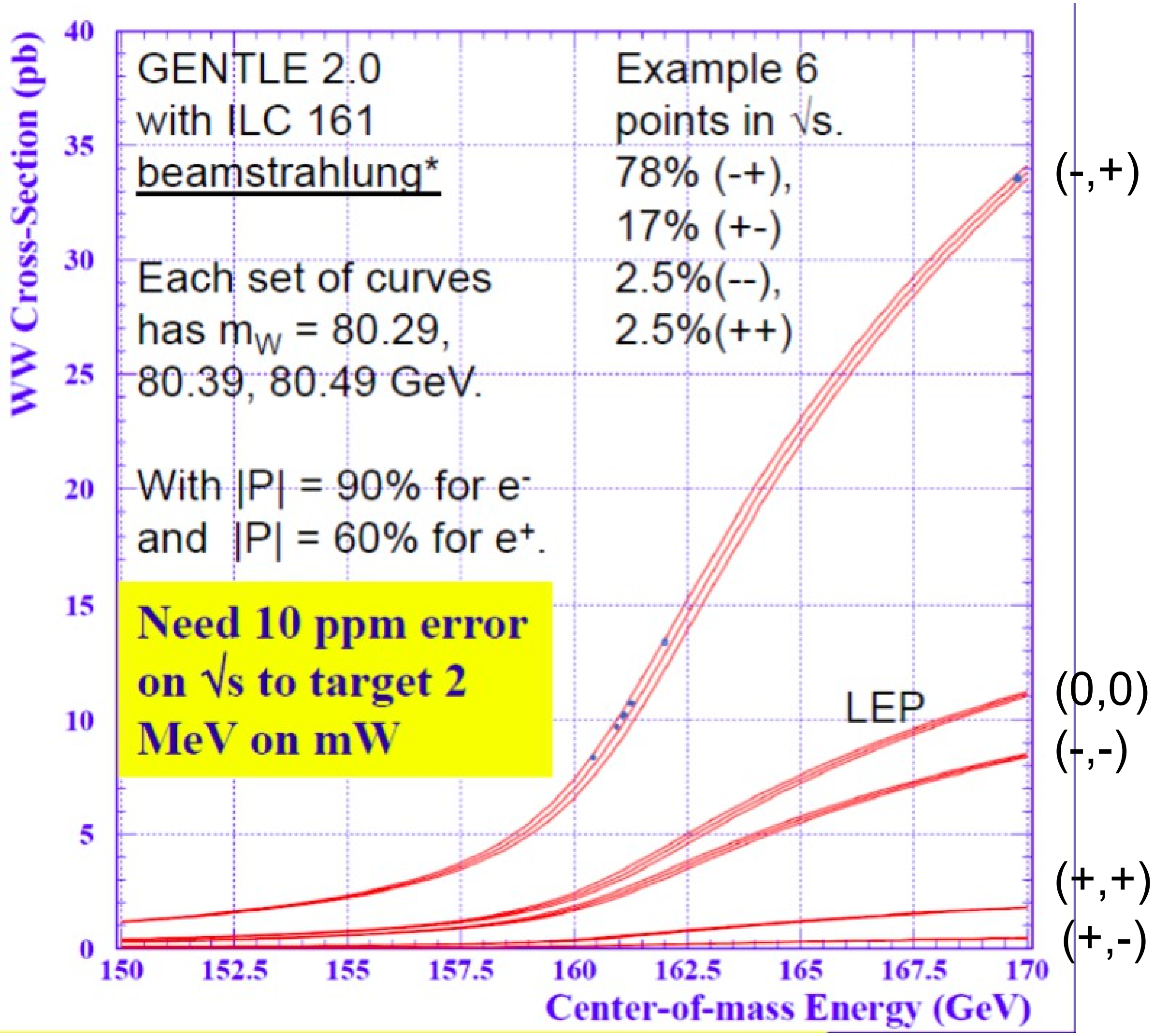
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\left[A_0(1+\cos^2\theta) + A_1\cos\theta\right]\begin{cases} \sim (1+\cos^2\theta) & \text{'Usual' Vector current, symmetric in } \cos\theta \\ \backsim \cos\theta & \text{Axial Vector current, asymmetric in } \cos\theta \end{cases}$$

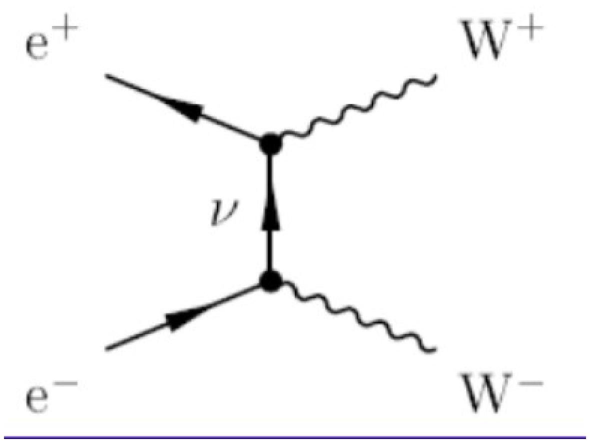
Weak interaction introduces forward backward asymmetry

=> Asymmetry is intrinsic to electroweak processes!!!

21

Example: Future W mass measurement



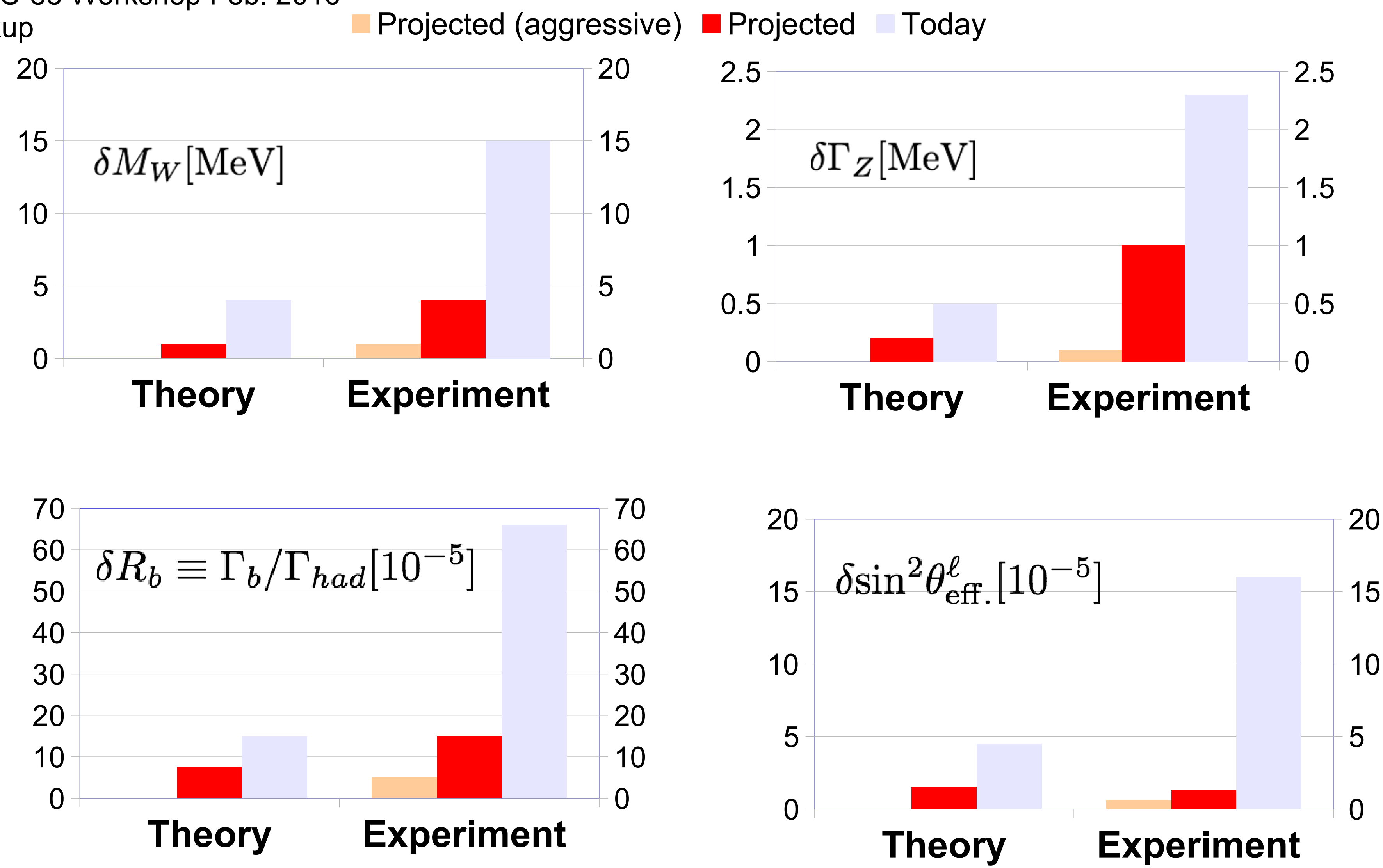


- Robust method
- Beam polarisation essential
- Need extreme good control of beam energy

G. Wilson

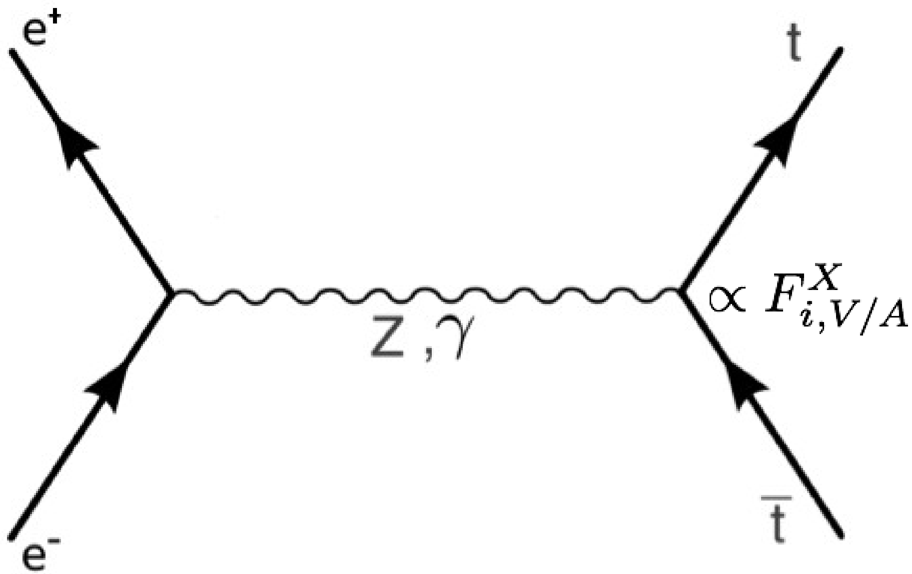
Projected development of precision

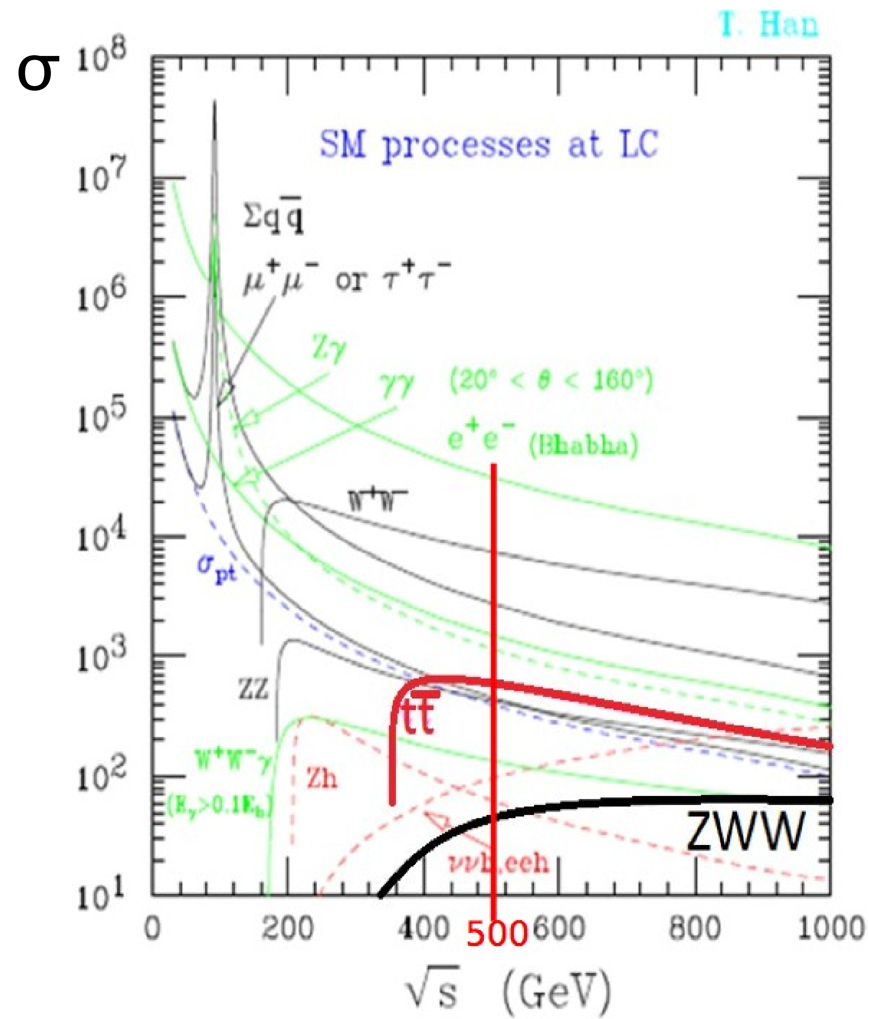
à la Freitas, FCC-ee Workshop Feb. 2016
Details -> backup



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

Top Quark Physics at Electron-Positron Colliders





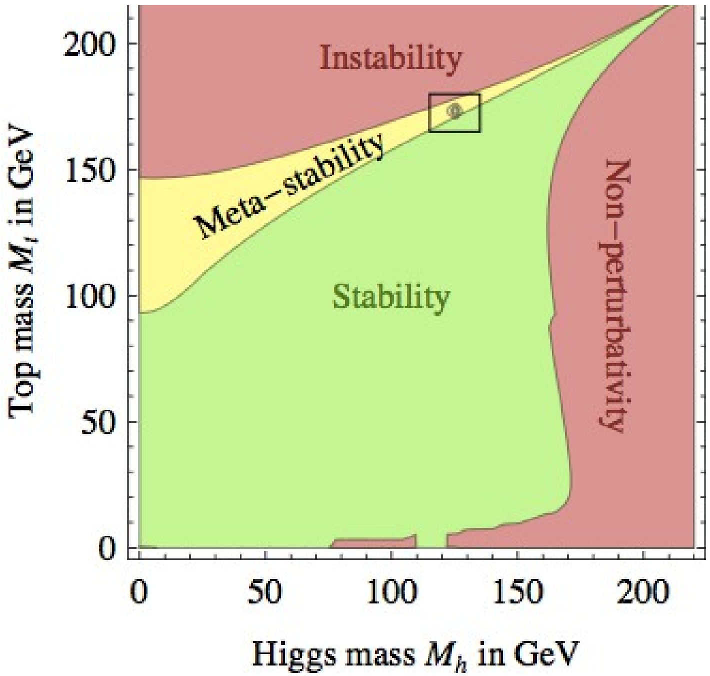
- Top quark production through electroweak processes
  no competing QCD production => Small theoretical errors!

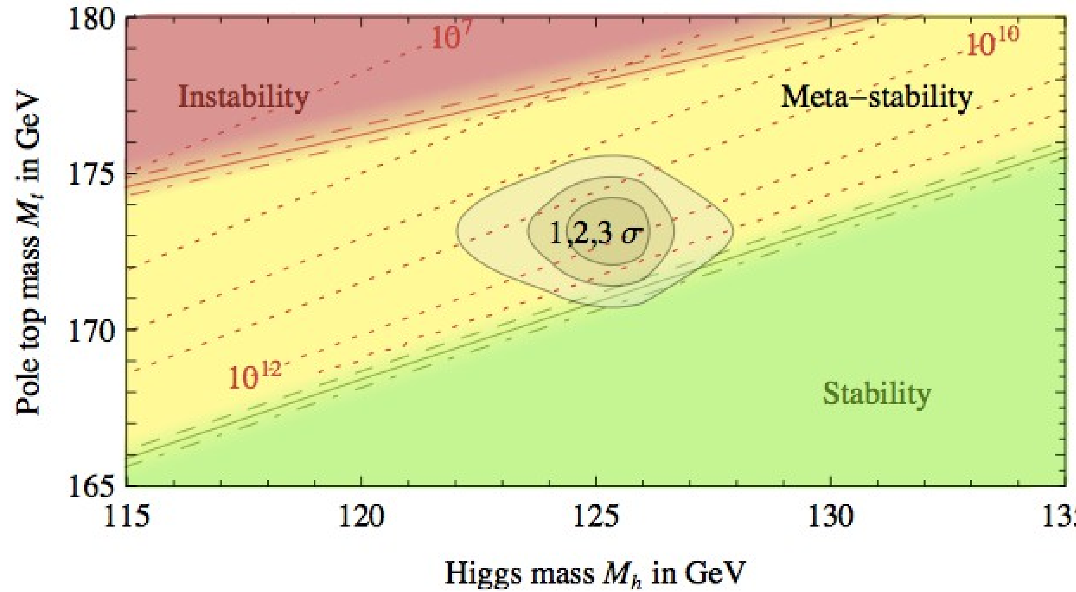
- High precision measurements
  - Top quark mass at ~ 350 GeV through threshold scan
  - Polarised beams allow testing chiral structure at ttX vertex
    => Precision on form factors F

Vacuum stability and Top Quark Mass

Degrassi et al. arXiv:1205.6497

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



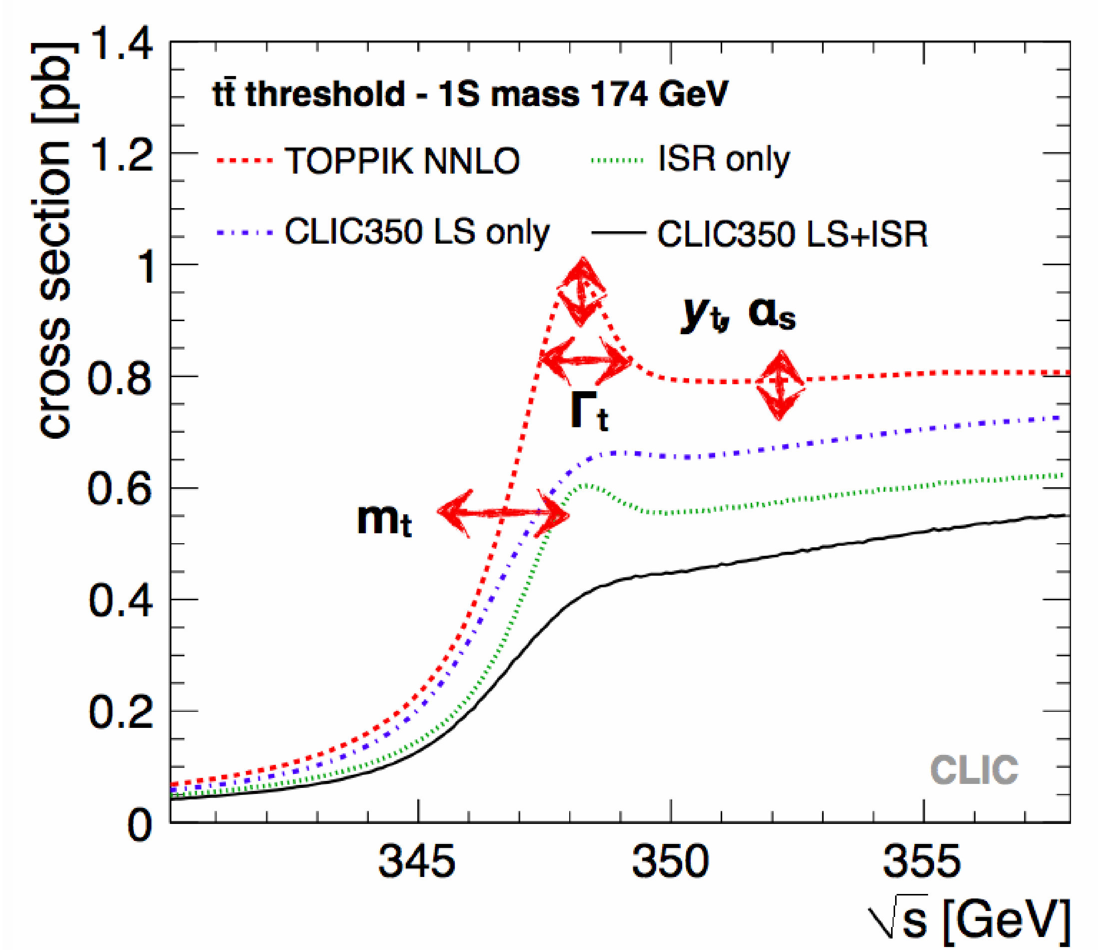


Type of error	Estimate of the error	Impact on M_h
M_t	experimental uncertainty in M_t	± 1.4 GeV
α_s	experimental uncertainty in α_s	± 0.5 GeV
Experiment	**Total combined in quadrature**	± 1.5 GeV
λ	scale variation in λ	± 0.7 GeV
y_t	$\mathcal{O}(\Lambda_{\mathrm{QCD}})$ correction to M_t	± 0.6 GeV
y_t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

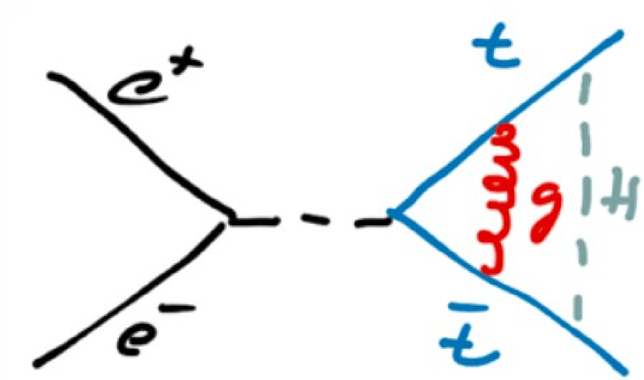
Small size of ttbar “bound state” at threshold ideal premise for precision physics



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

- Top mass, width Yukawa coupling

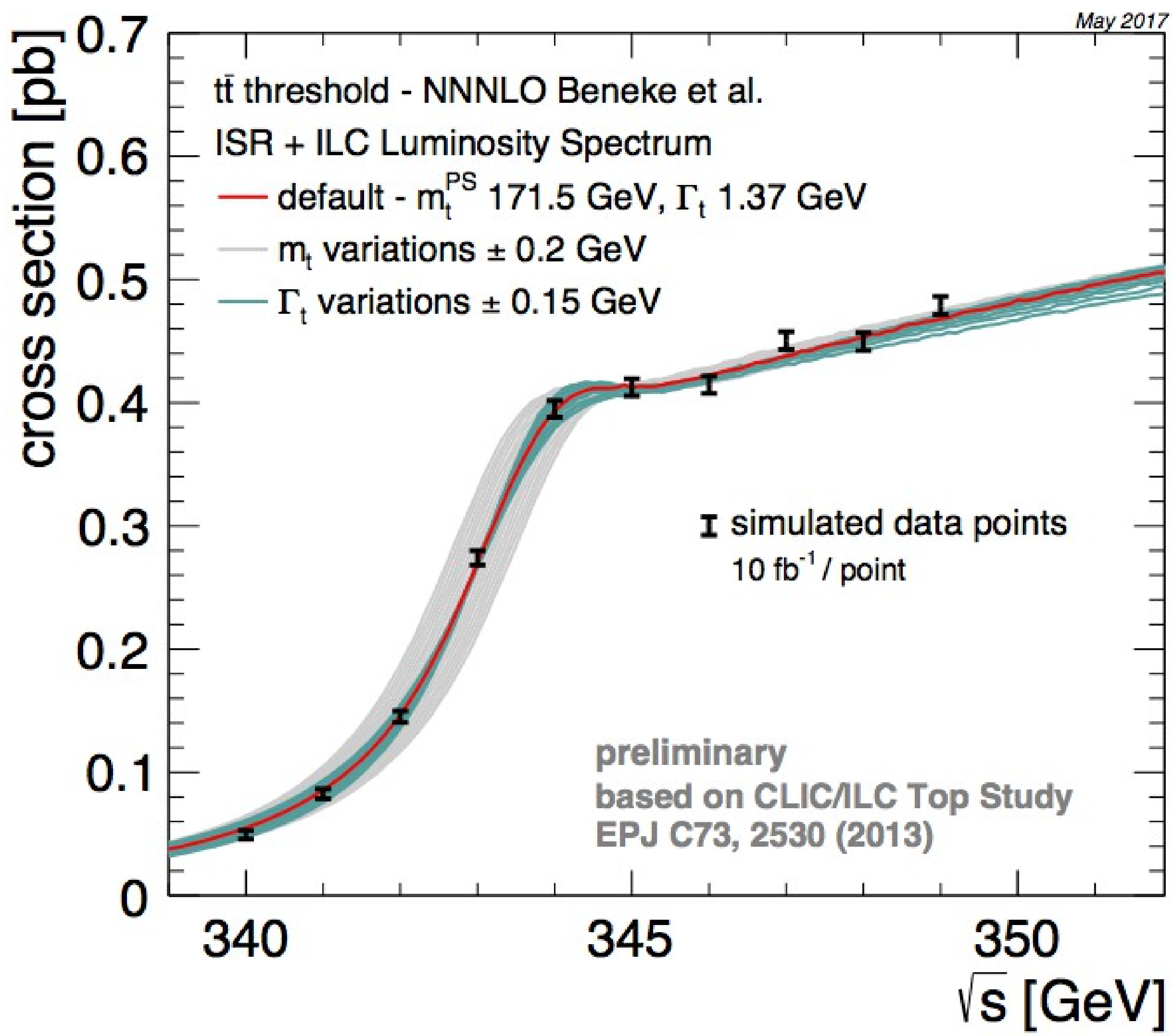
- Strong coupling constant



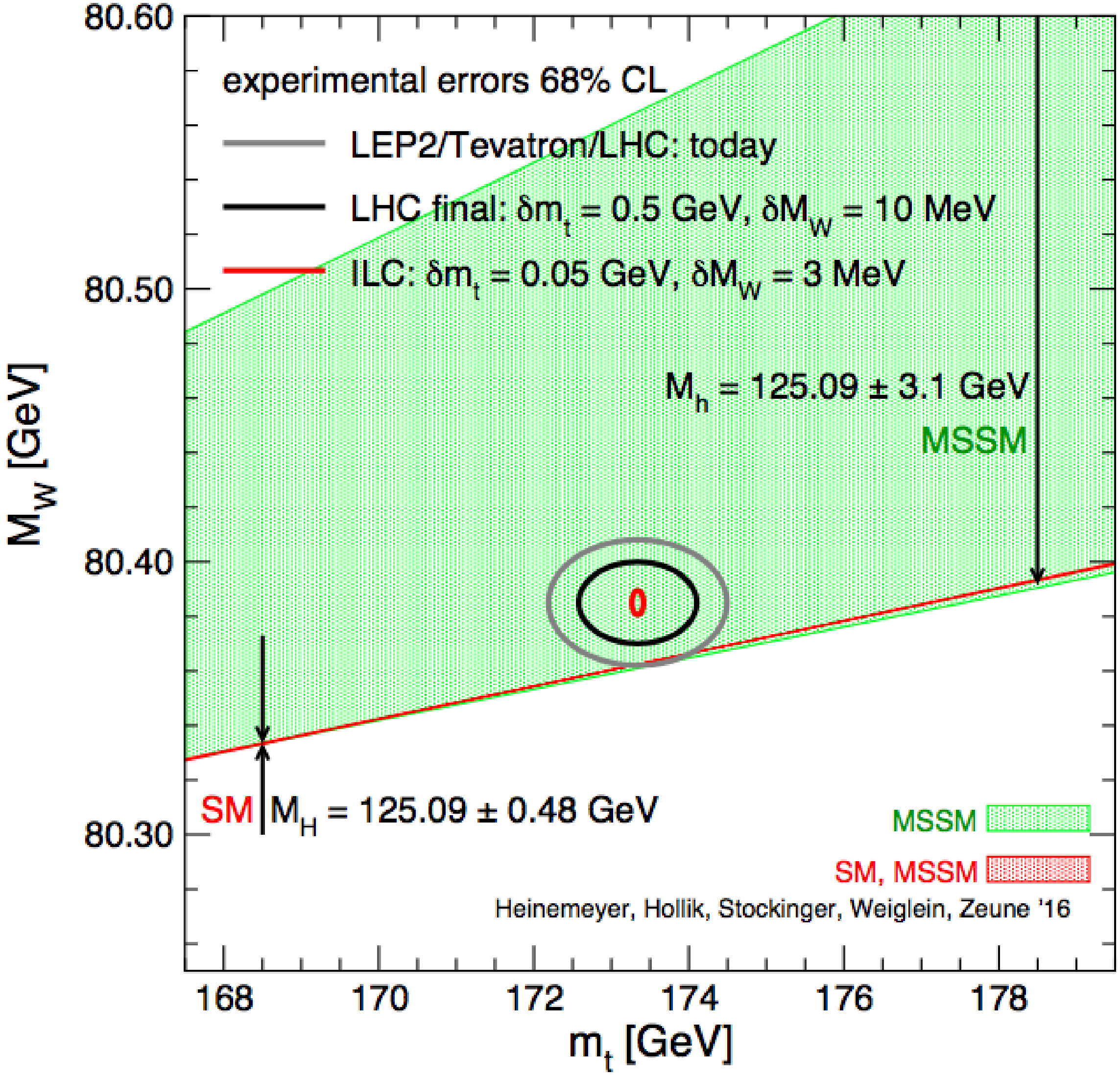
Effects of some parameters are correlated:
Dependence on Yukawa coupling rather weak,
Precise external α_s helps

F. Simon, Top@LC15 Valencia

Top Mass Threshold Scan



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

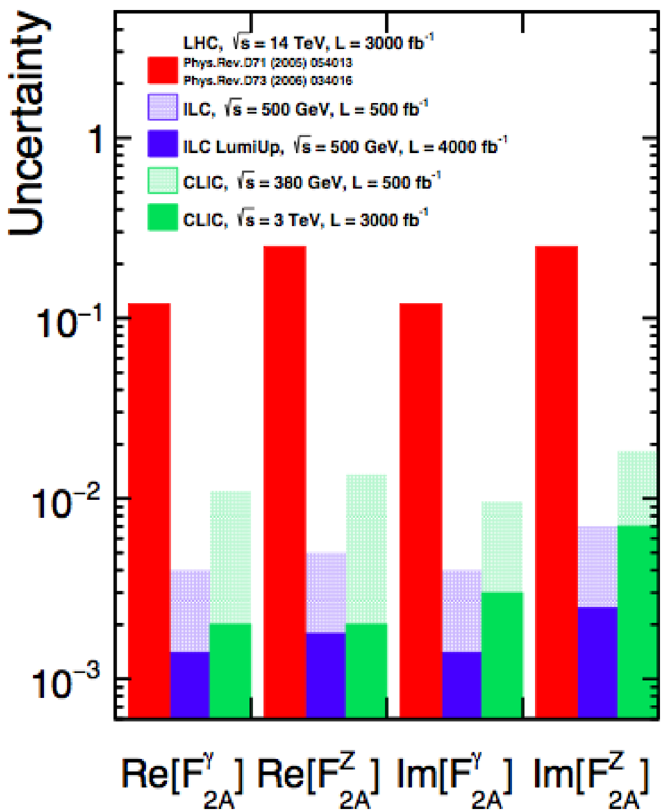
LHC may not reach sufficient discriminative power

A lepton collider will

Top quark – CP Violating Form Factors

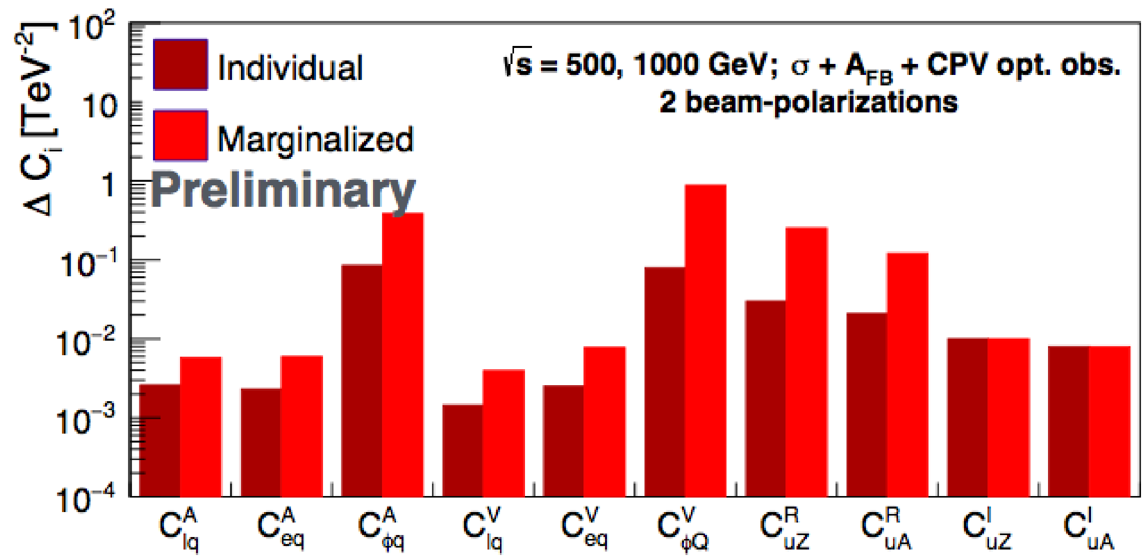
- Nominal **ILC** and the **CLIC low-energy stages** have a very similar sensitivity to these form factors, reaching **limits of $|F_{2A}^{\gamma}|$<0.01** for the EDF

- Assuming that systematic uncertainties can be controlled to the required level, a luminosity upgrade of both machines **may bring a further improvement**



Including CPV observables in the EFT global fit…

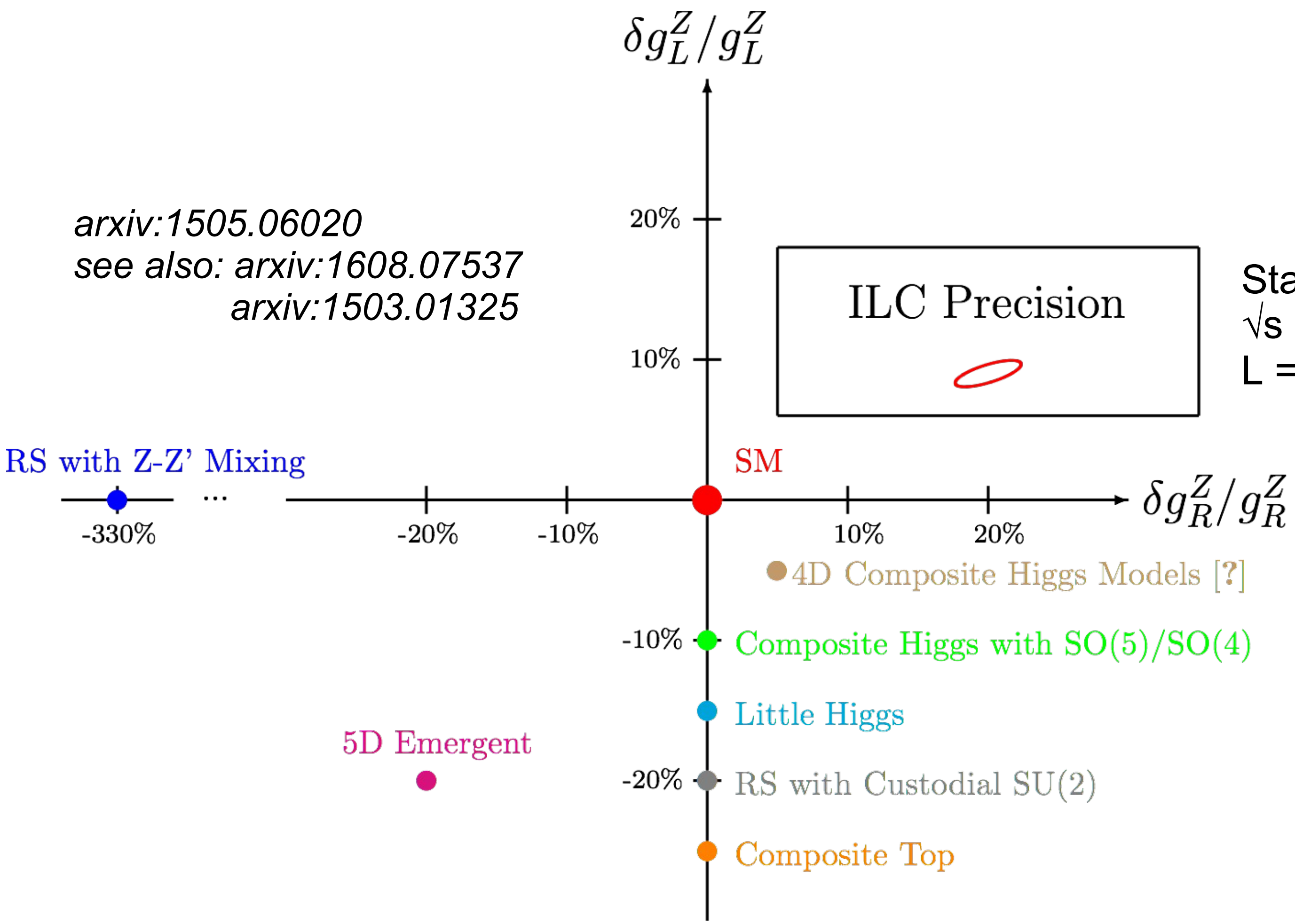
$$[F_{2,A}^{Z}, F_{2,A}^{\gamma}] \quad \propto \quad [\mathrm{Im}\{C_{uA}\}, \mathrm{Im}\{C_{uZ}\}]$$



Top quark 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

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



Statistical error:
√s ~ 500 GeV
L = 500 fb^{-1}

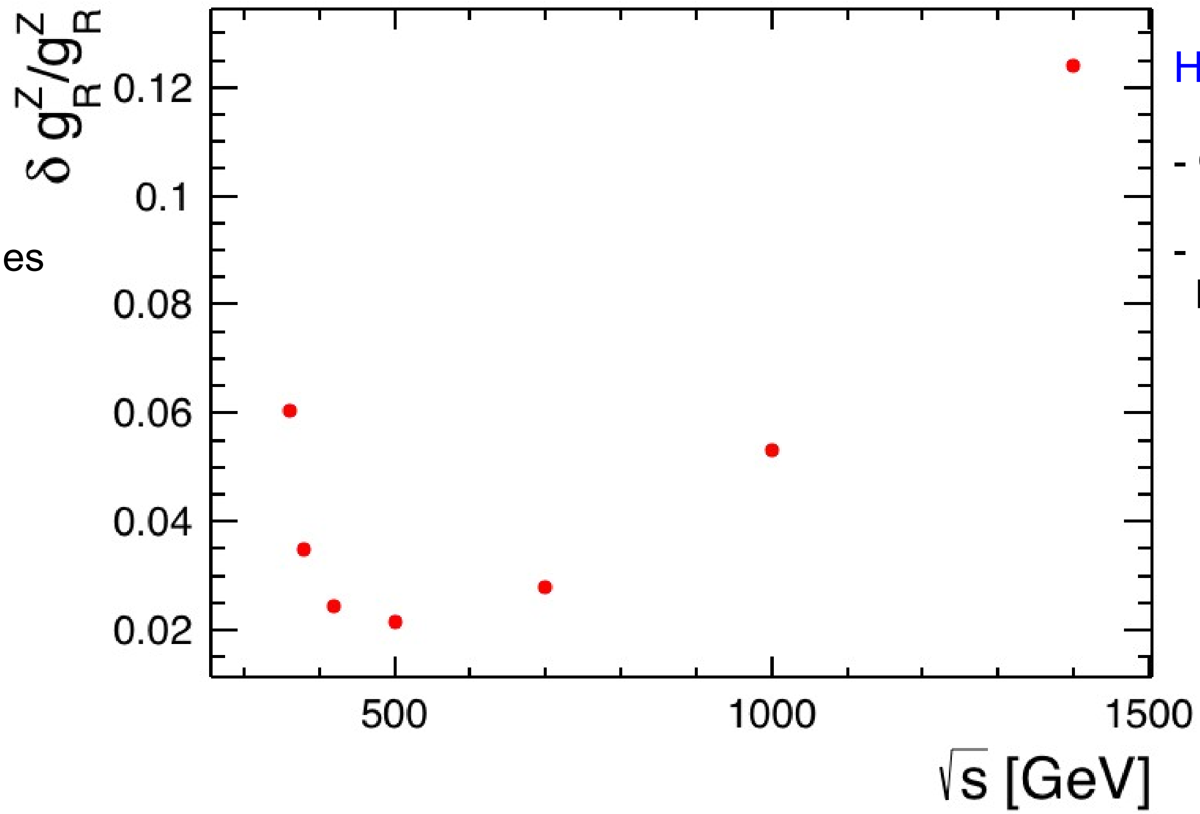
Precision expected for top quark couplings will allow to distinguish between models
Remark: All presented models are compatible with LEP elw. precision data

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

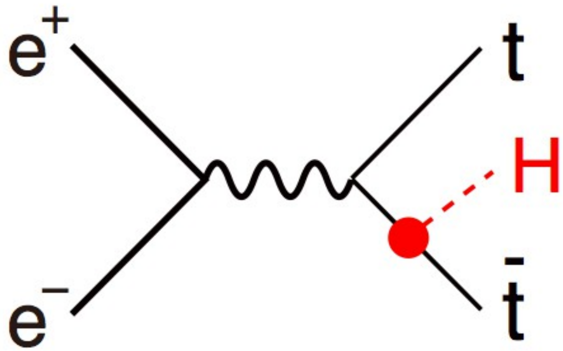
Broad minimum between 400 and 700 GeV

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

However:

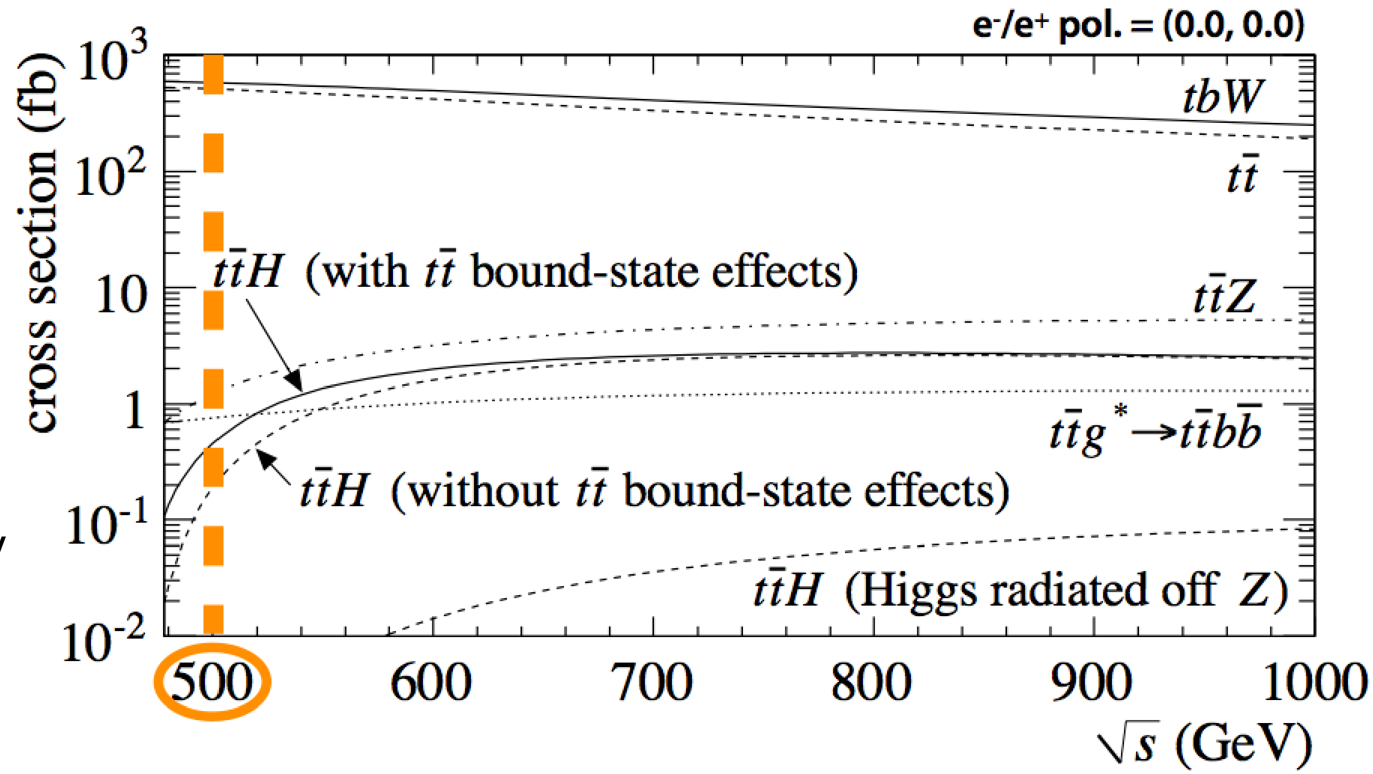
- Sensitivity to CP violating Higgs at smaller cms energies
- New physics at higher energies may increase cross section

Top Yukawa Coupling



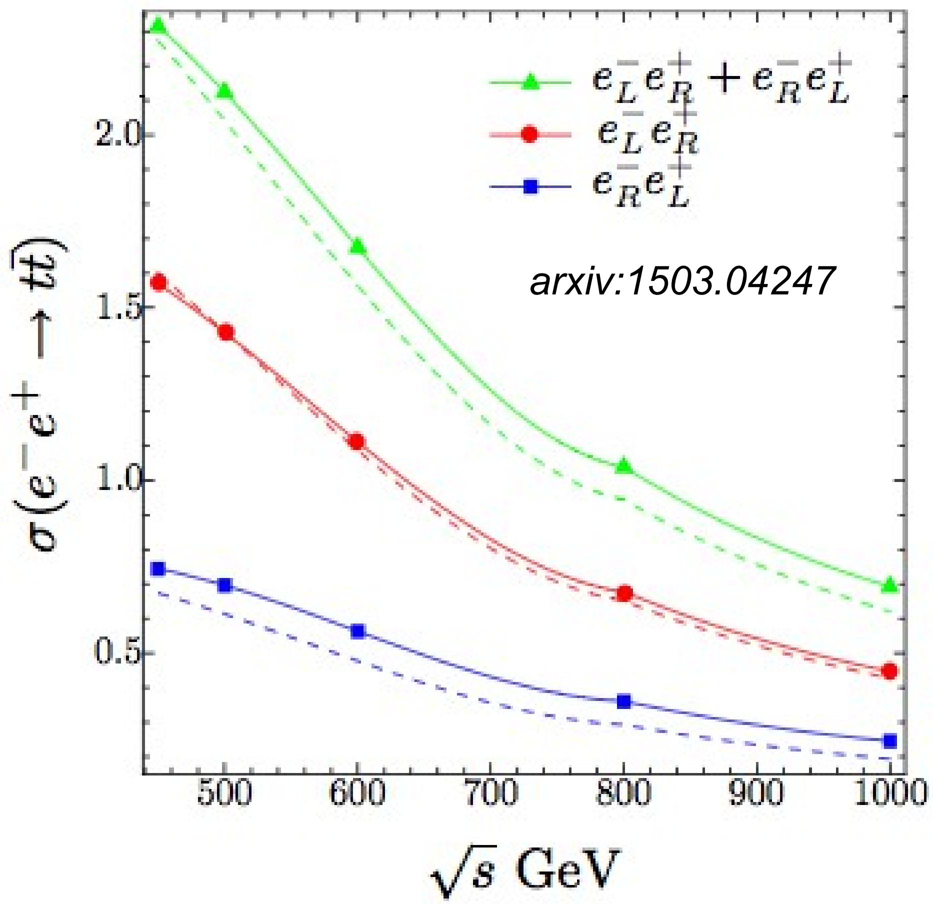
- Coupling of Higgs to heaviest particle known today

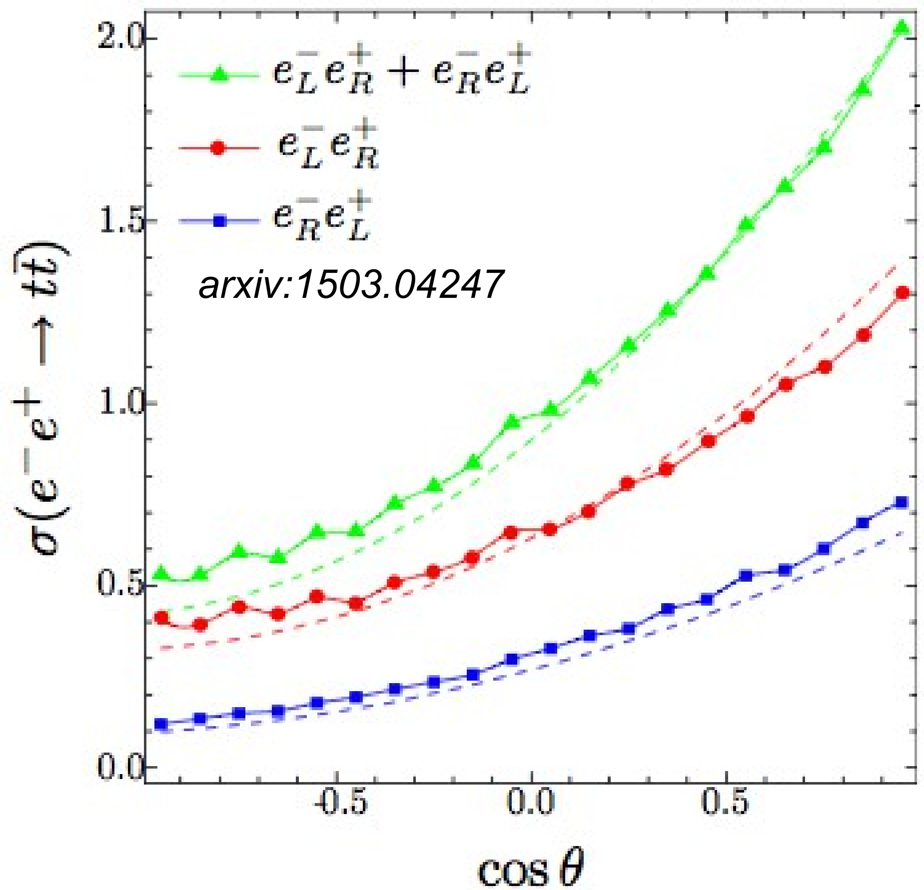
- Up to eight final state jets



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

Detailed look at higher order elw. corrections - GRACE



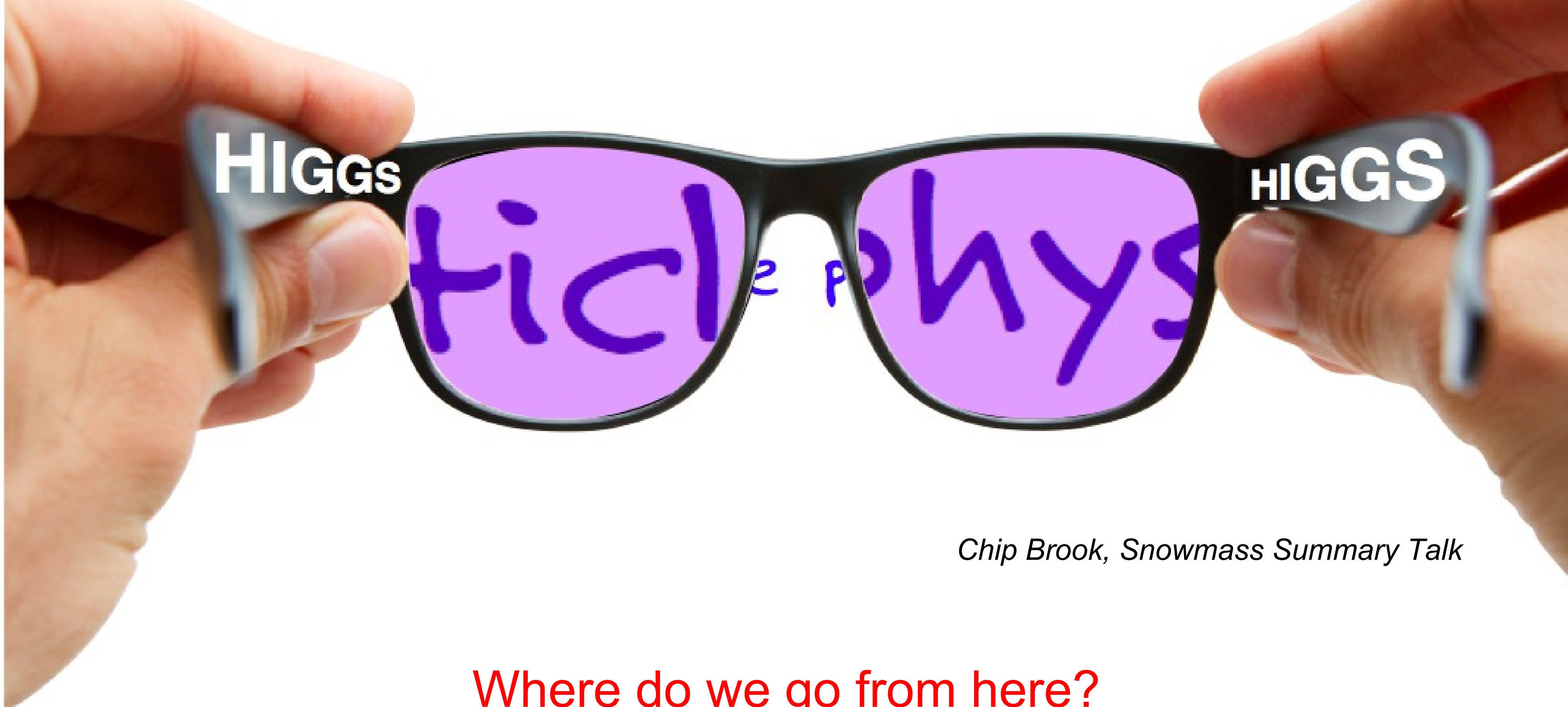


- Electroweak corrections manifest themselves differently for different beam polarisations

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

Coronation of the Standard Model
and
First step on a road yet largely unexplored

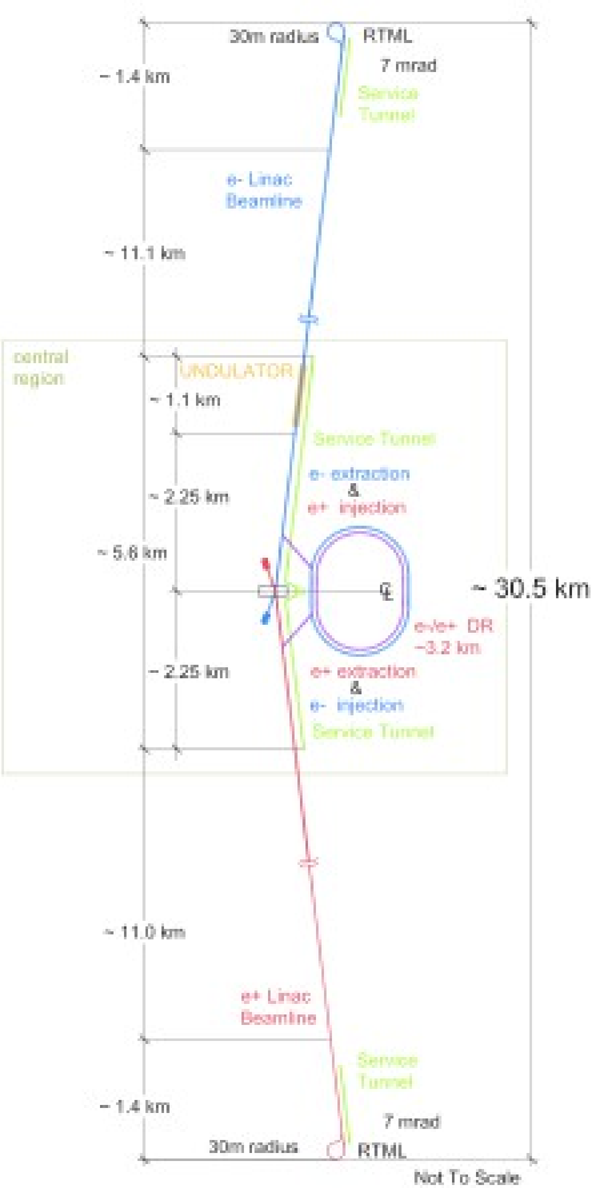
Slightly modified citation of Barbieri arXiv:1309.3447



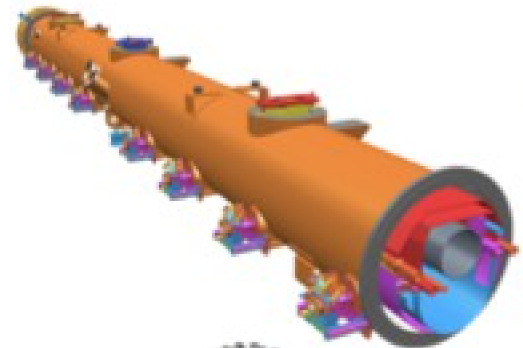
Chip Brook, Snowmass Summary Talk

Where do we go from here?

ILC 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

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

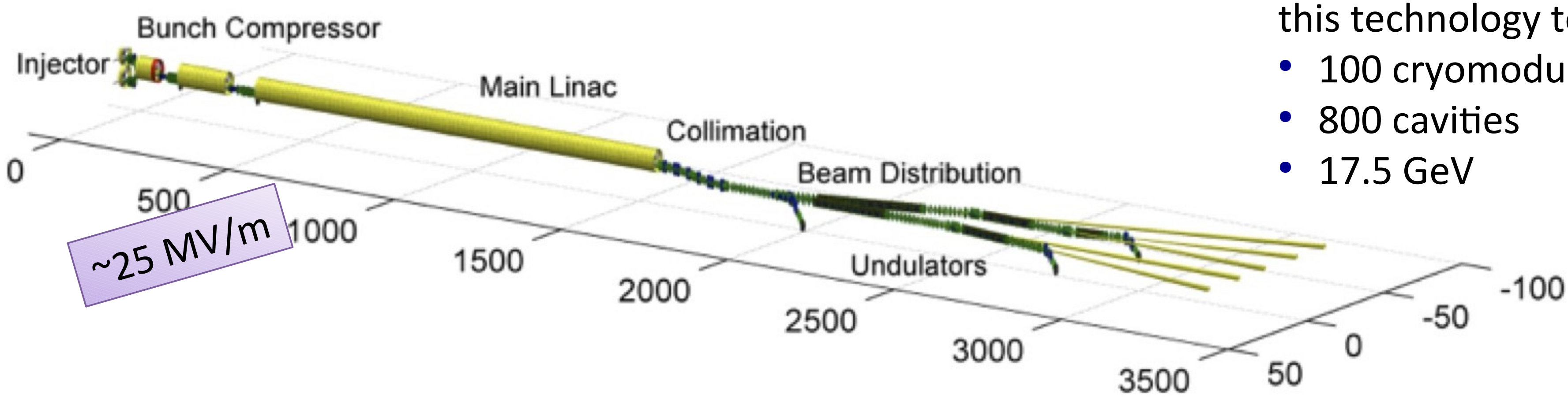
- Discussion on possible running scenarios has started

- 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

Accelerator - Test and reality

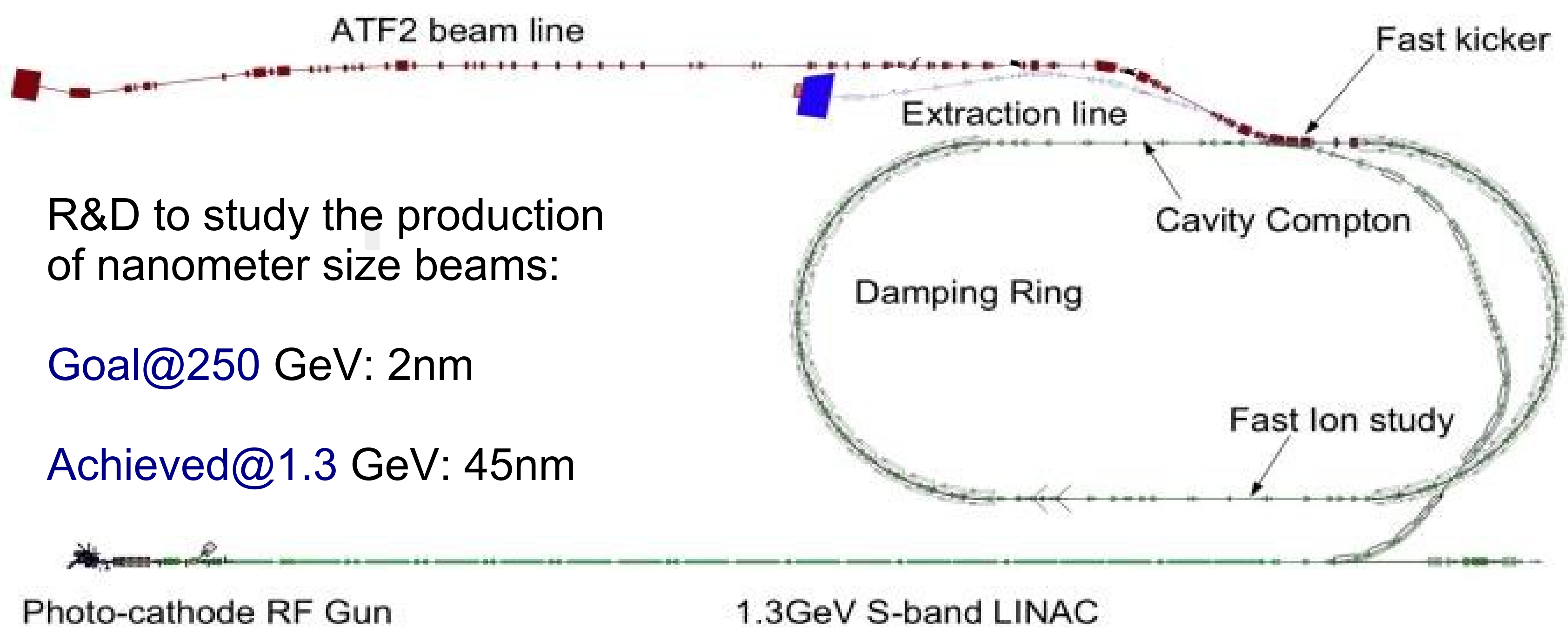
European XFEL Project: Location DESY Hamburg, Start 2015



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:

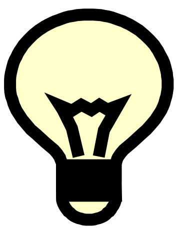
Goal@250 GeV: 2nm

Achieved@1.3 GeV: 45nm

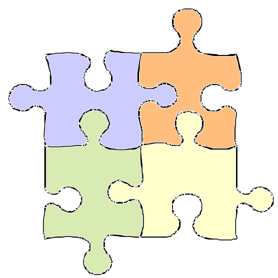
2. Higgs Physics at the ILC

Open questions

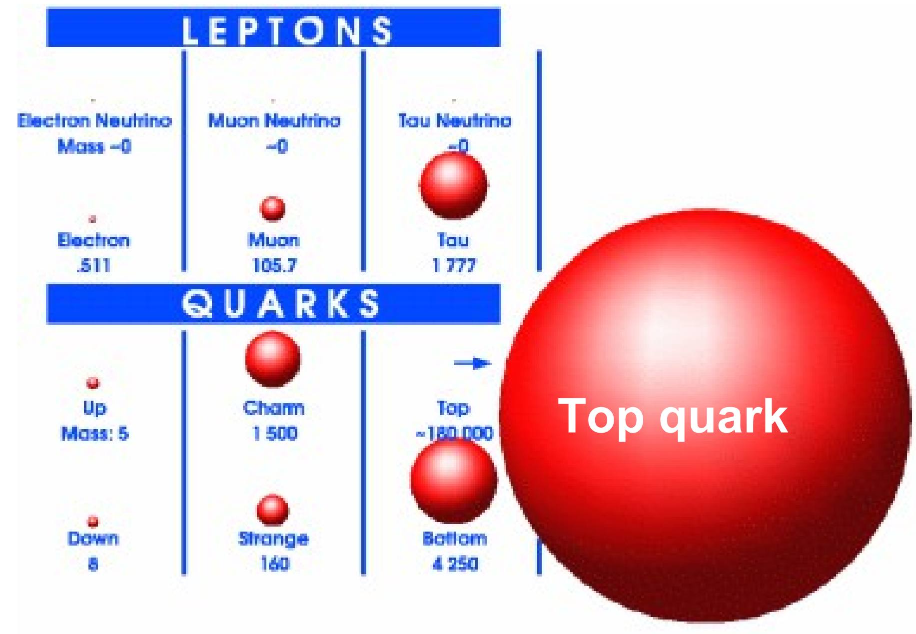
An enigmatic couple



Elementary Scalar?

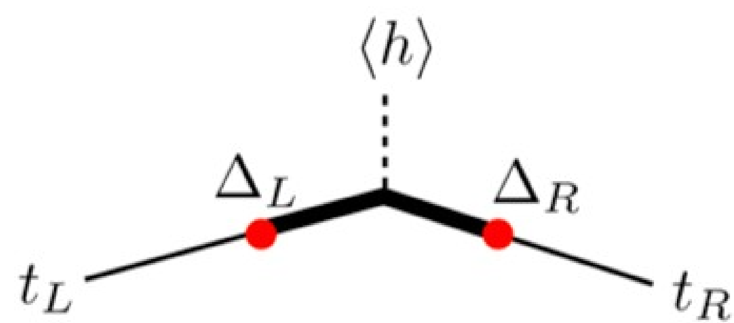


Composite object?



- 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?

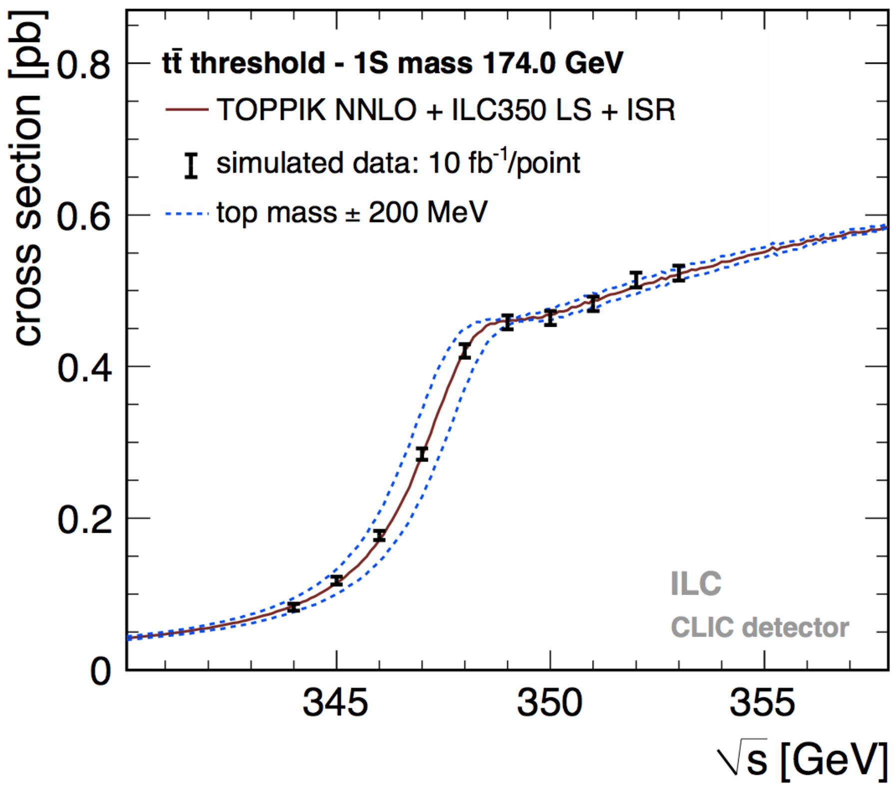


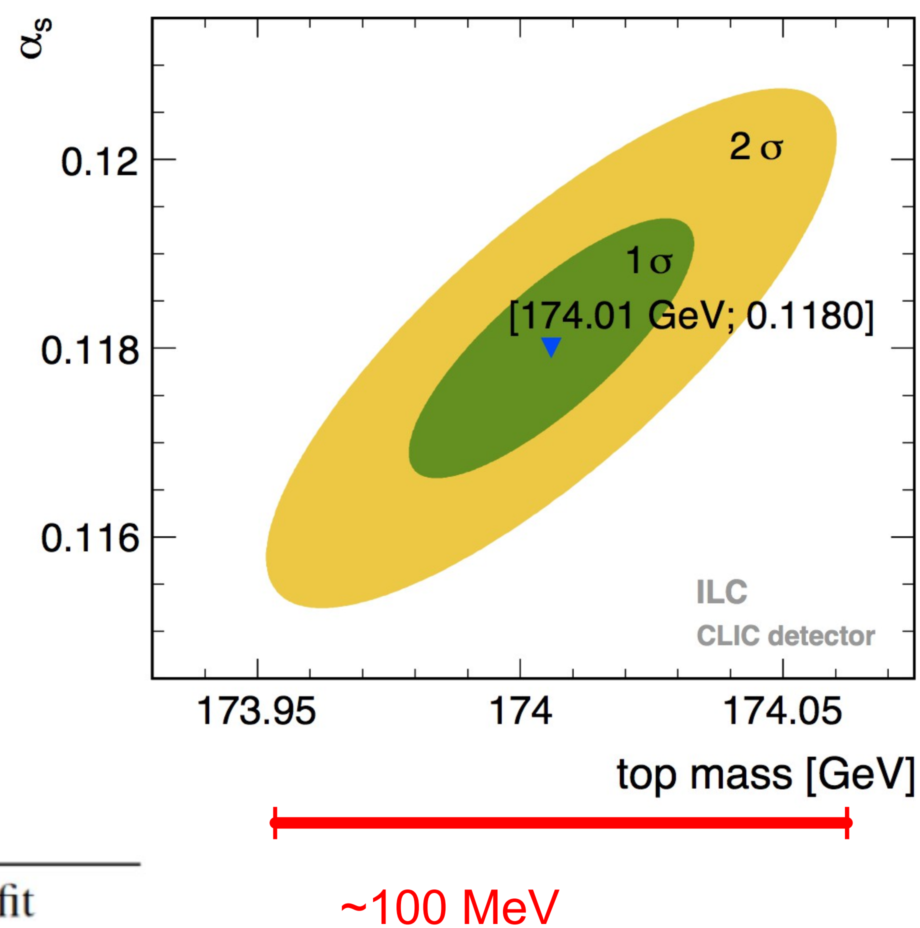
Courtesy of S. Rychkov

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

Mass and α_s

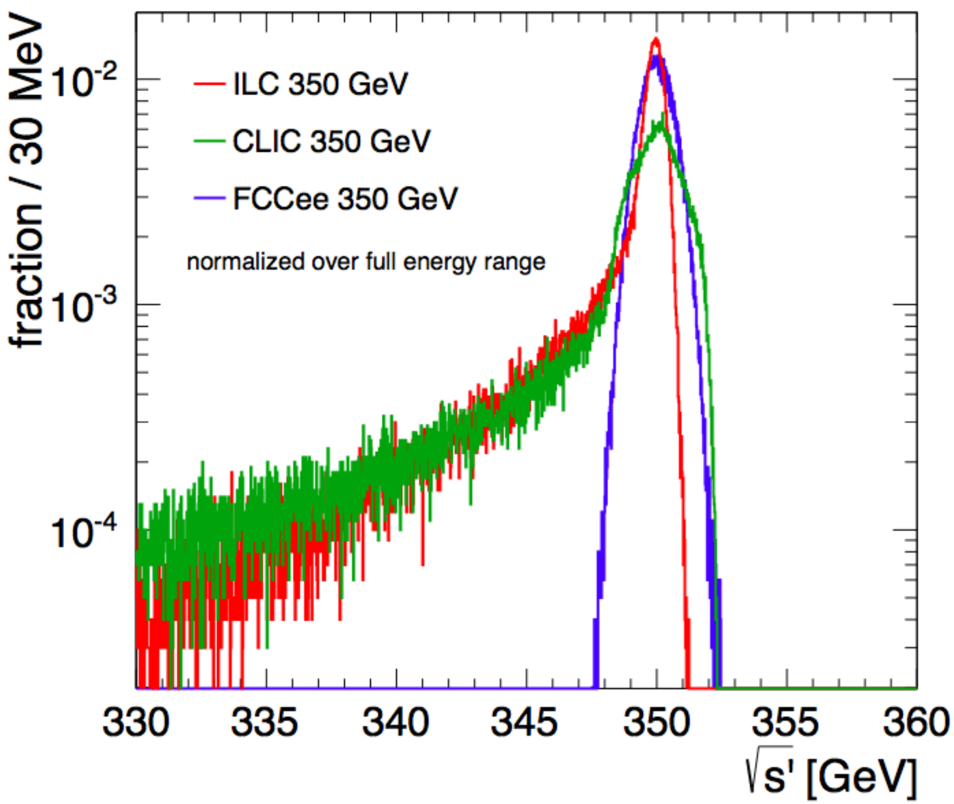
EPJC C73 (2013) 2530



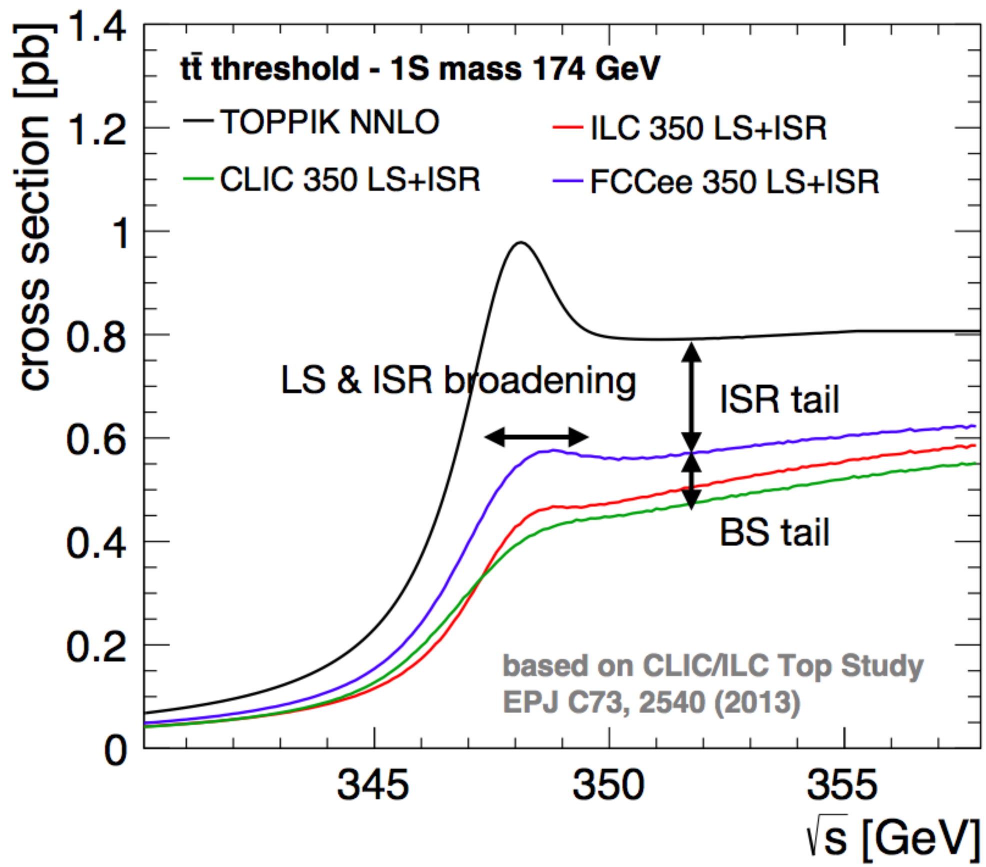


1S top mass and α_s combined 2D fit	
m_t stat. error	27 MeV
m_t theory syst. (1%/3%)	5 MeV / 9 MeV
α_s stat. error	0.0008
α_s theory syst. (1%/3%)	0.0007 / 0.0022

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

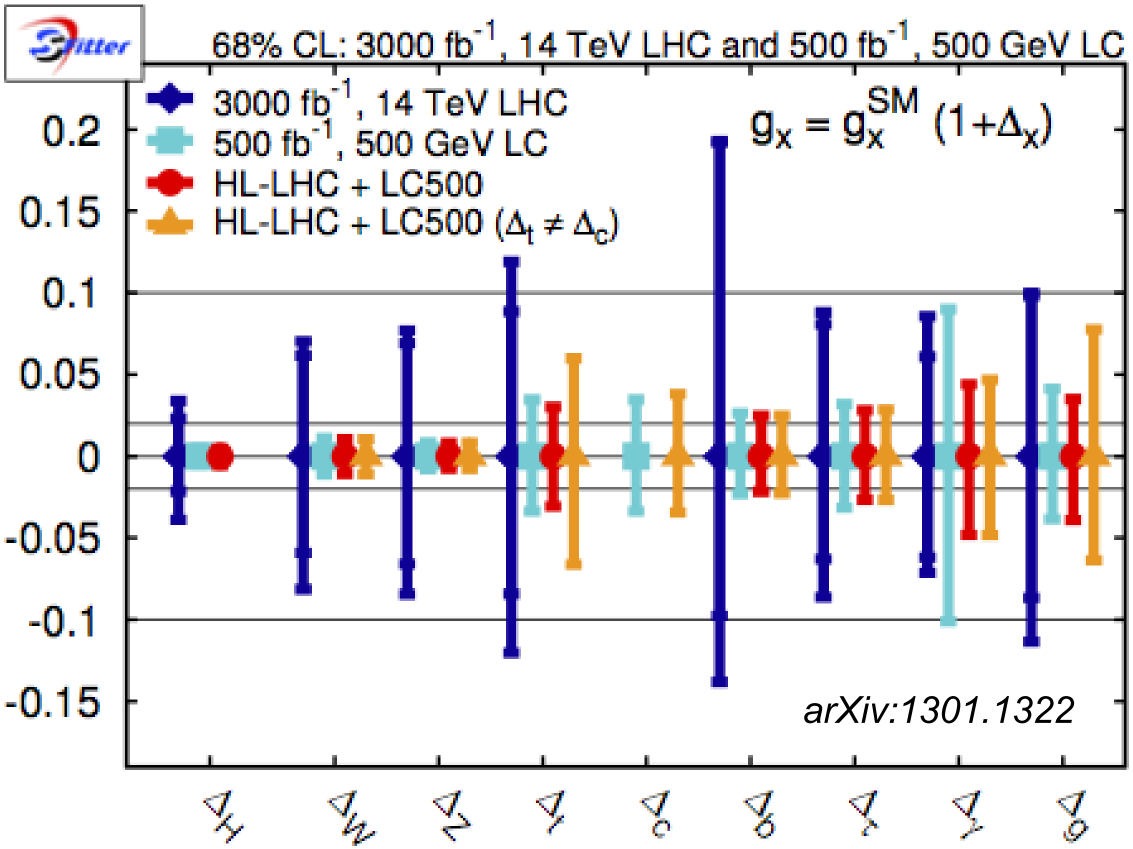


- Slight changes in statistics due to cross section, changes in sensitivity due to steepness of threshold turn on
- For 100 fb-1, no polarisation, 1D mass fit

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

F. Simon, Top@LC15 Valencia

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

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   Forward backward asymmetry   Fraction of right handed top quarks

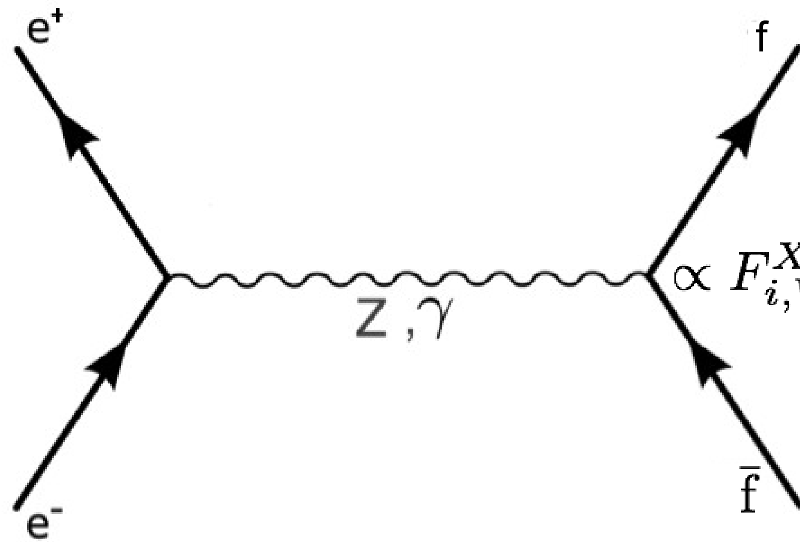
⇩

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 $g^{\gamma}_L,\ g^{\gamma}_R,\ g^{Z}_L,\ g^{Z}_R$

Testing the Chiral Structure of the Standard Model



$$\propto F^X_{i,V/A}$$

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

$$\frac{d\sigma^I}{d\cos\theta} = S^I(1+\cos^2\theta) + A^I\cos\theta \qquad I = L, R$$

Form factors/couplings from S and A

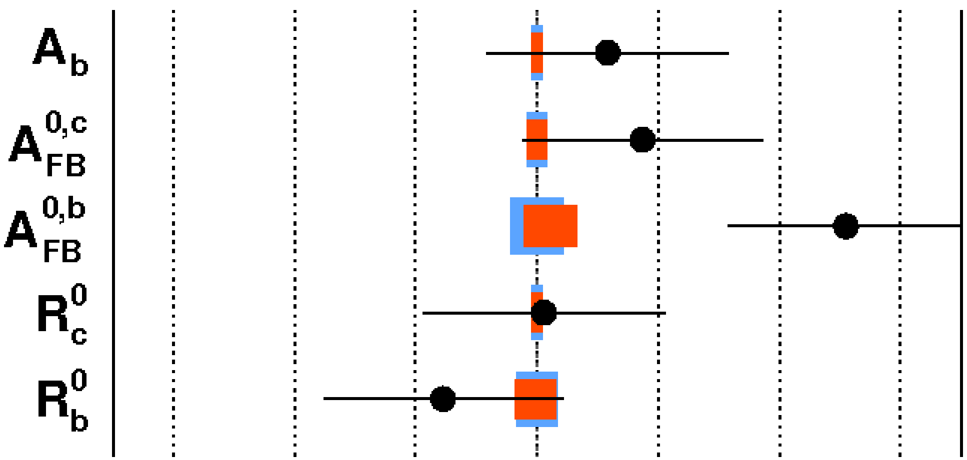
$$\text{Pure } \gamma \text{ or pure } Z^0 : \sigma \backsim (F_i)^2 \Rightarrow \text{ No sensitivity to sign of Form Factors}$$

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

Couplings and Form Factors: $g^Z_L = F^Z_{1V} - F^Z_{1A}, \qquad g^Z_R = F^Z_{1V} + F^Z_{1A}$

LEP Anomaly on A_{FB}^{b}

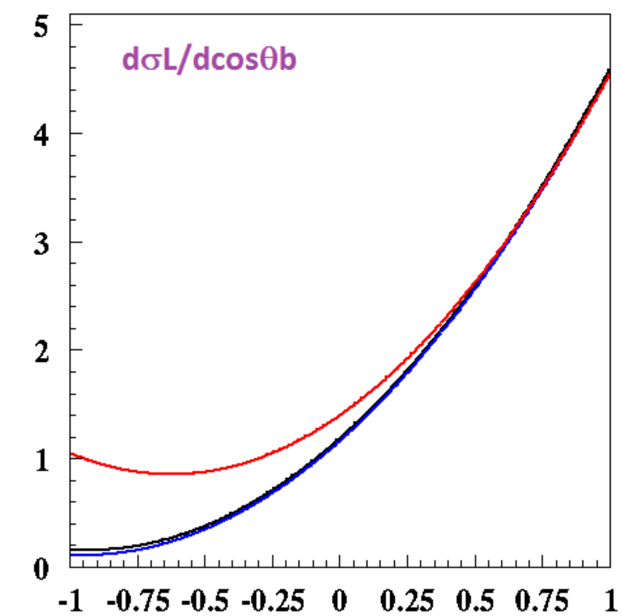
~3σ in heavy quark observable A_{FB}^{b}

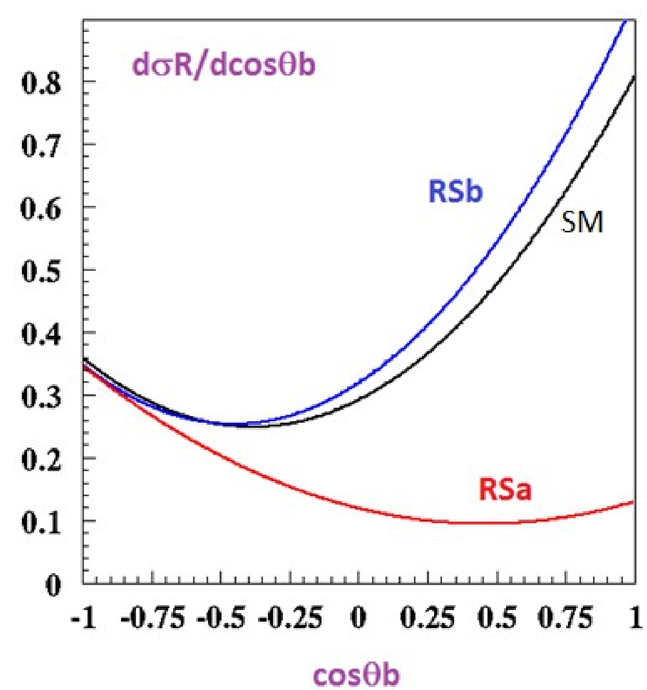


- Is tension due to underestimation of errors or due to new physics?

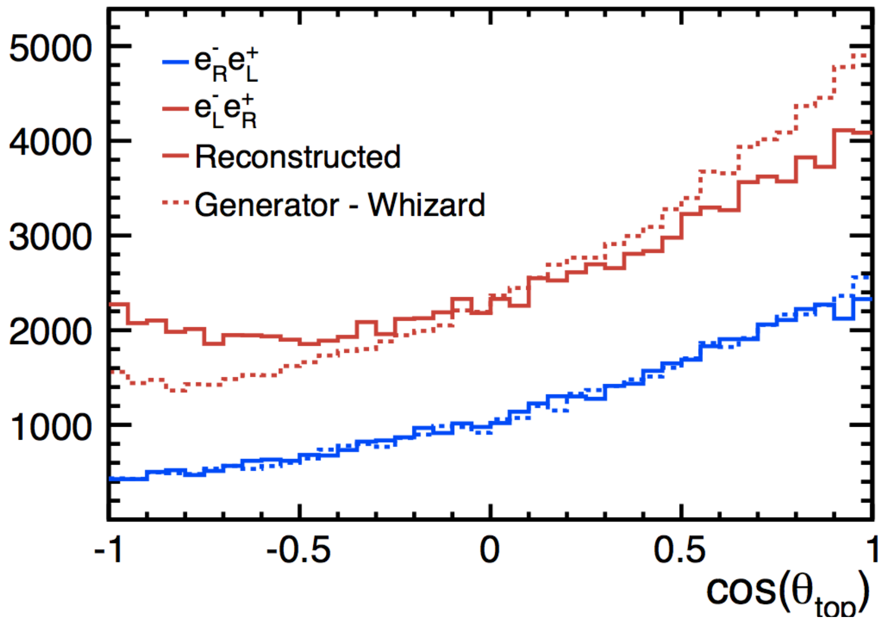
- ILC will give final word on anomaly

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



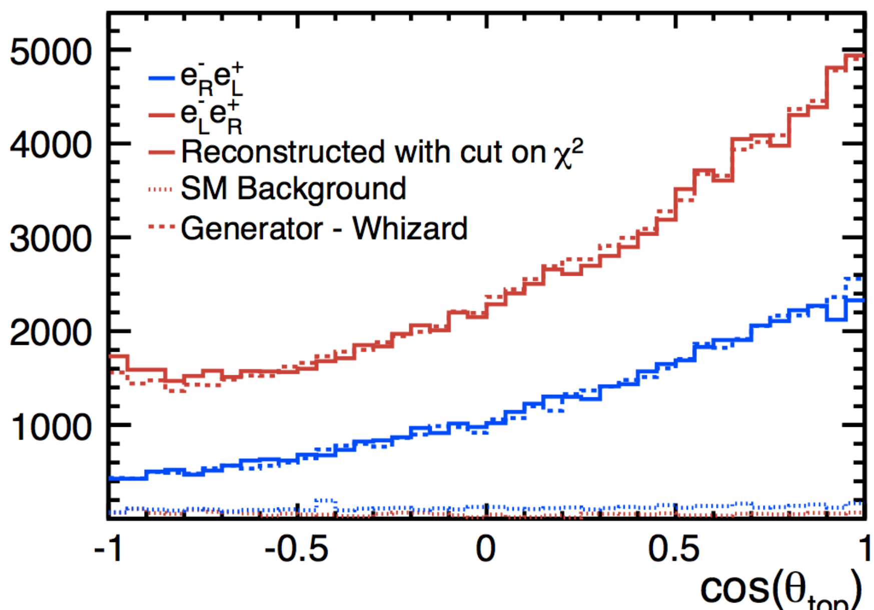


arxiv:1505.06020



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:
<u>Select cleanly reconstructed events by χ^2 analysis</u>
or
Reconstruction of b quark charge

Precise reconstruction for both beam polarisations

- Efficiency Penalty for e_L
- ε_{tot}: e_R ~ 50%, e_L ~ 30%

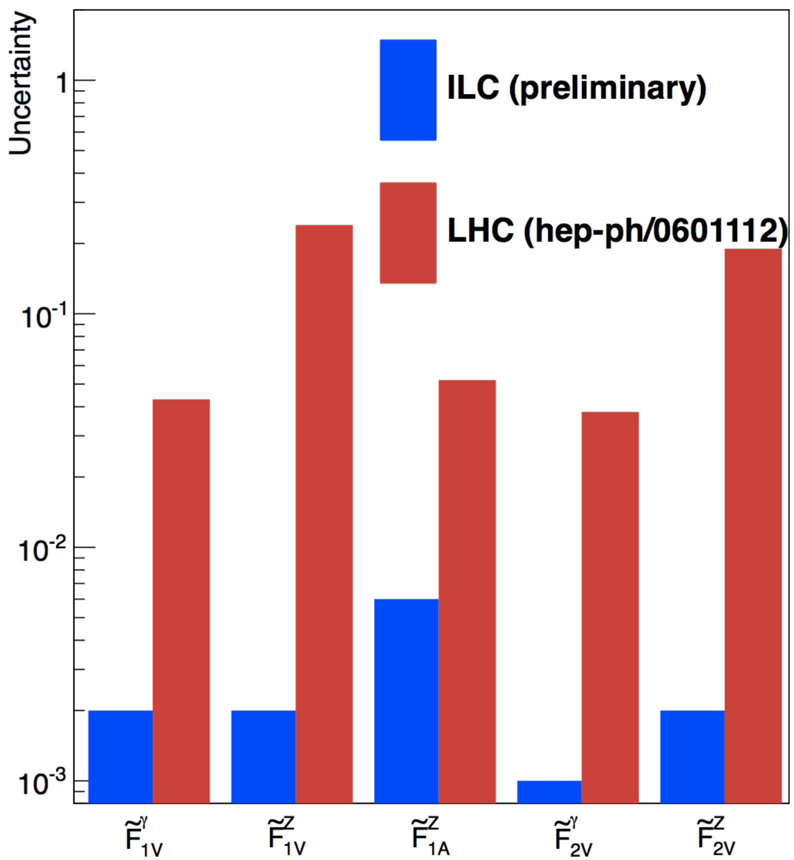
Results:

$\mathcal{P}_{e^-}, \mathcal{P}_{e^+}$	$(\delta\sigma/\sigma)_{stat.}$ [%]	$(\delta A^t_{FB}/A^t_{FB})_{stat.}$ [%]
$-0.8, +0.3$	0.47	1.8
$+0.8, -0.3$	0.63	1.3

ArXiv: 1307.8102

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

Accuracy on CP conserving couplings



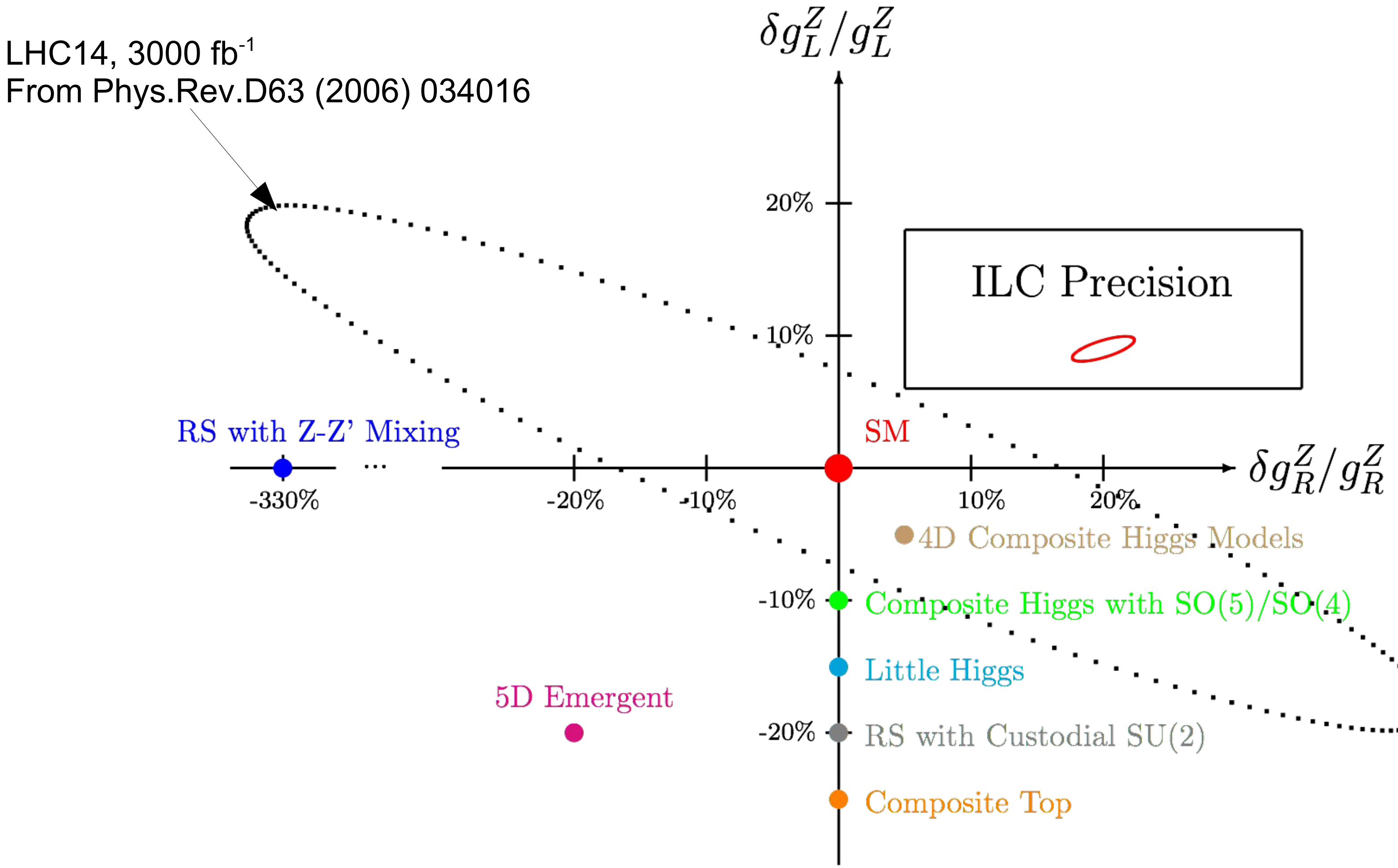
- ILC might be up to two orders of magnitude more precise than LHC ($\sqrt{s}$ = 14 TeV, 300 fb^{-1})
  Disentangling of couplings for ILC
  One variable at a time For LHC
  However LHC projections from 8 years old study

- 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?



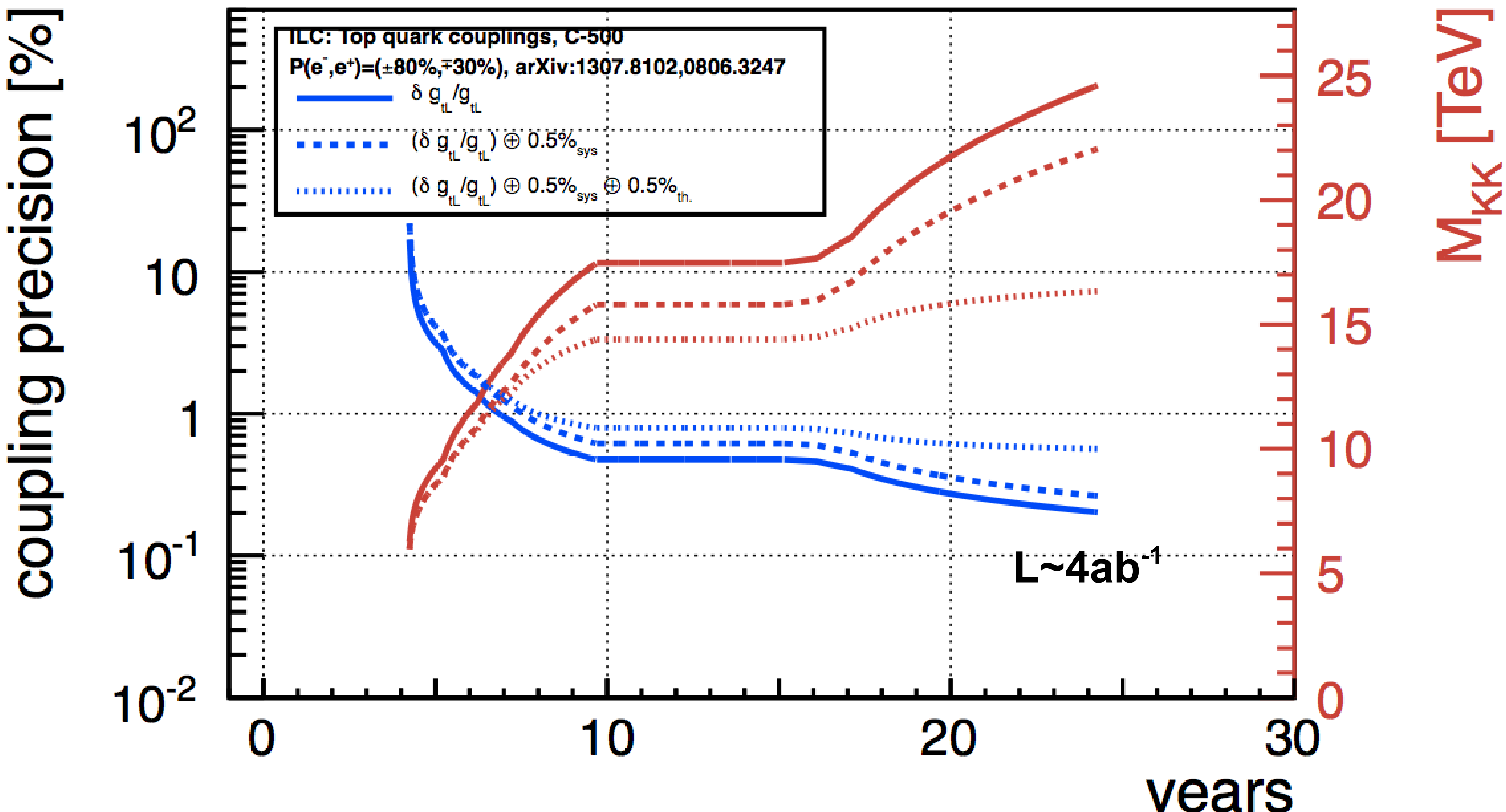
Linear Collider will outperform LHC results

- 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

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



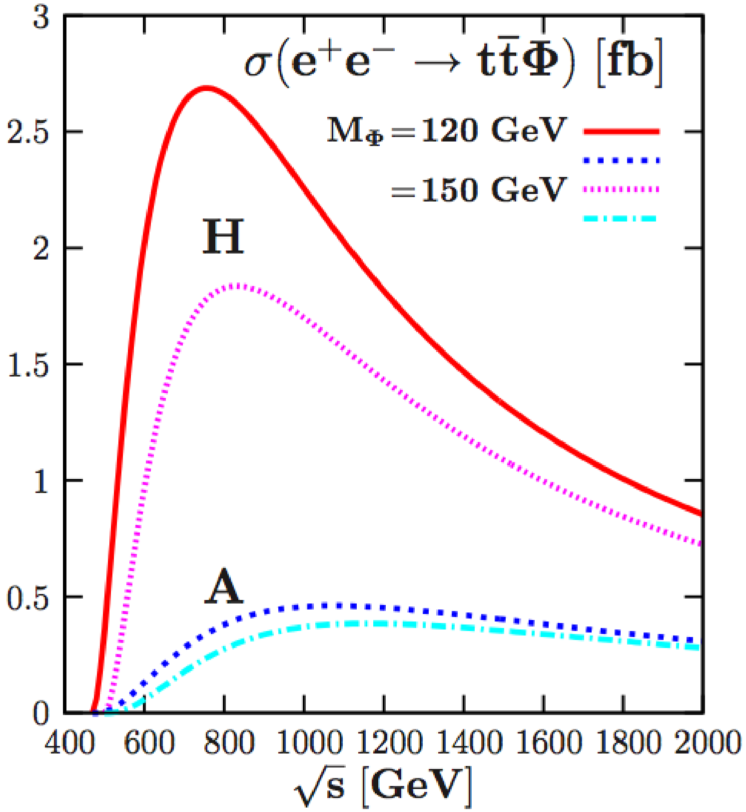
Can probe scales of ~25 TeV in typical scenarios

(… and up tp 80 TeV for extreme scenarios)

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

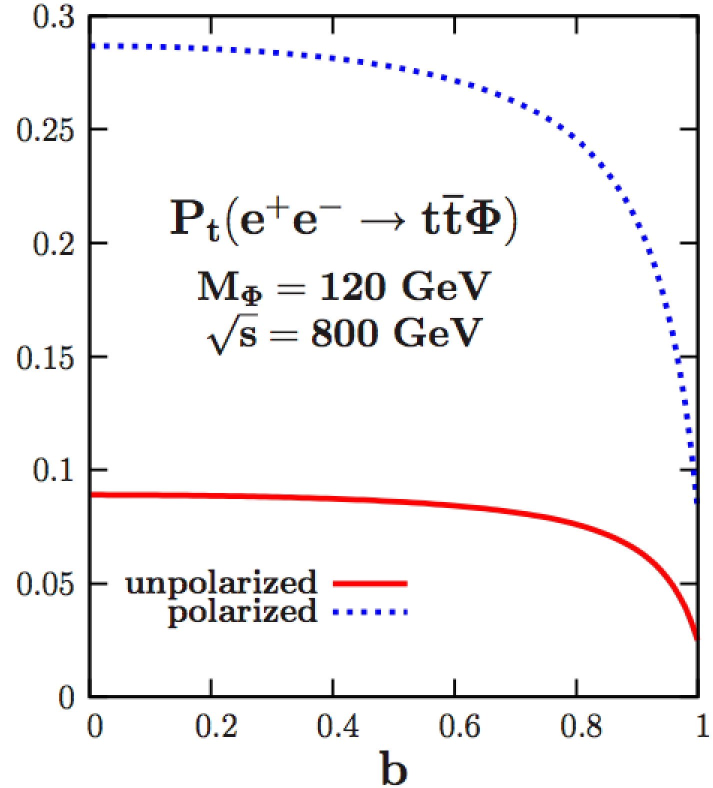
Direct coupling of top quark to CP odd and CP even scalar

Cross section



Dramatic differences for
CP odd and CP even scalar

Top quark polarisation



Sensitivity to CP odd admixture b
Merit of beam polarisation

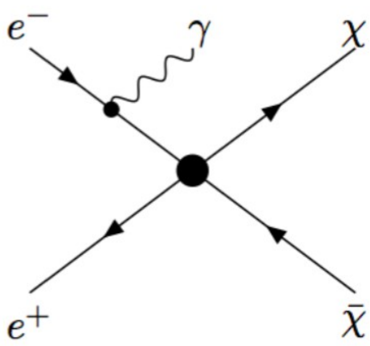
Determination of CP nature of scalar boson in an unambiguous way

Godbole et al., LCWS07

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



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

-> Monophoton search
-> Background suppression through polarised beams

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