Physics at e+e- colliders

TYL/FJPPL, FKPPL Annual Meeting 2019

Roman Pöschl

Based on material of a number of distinguished colleagues

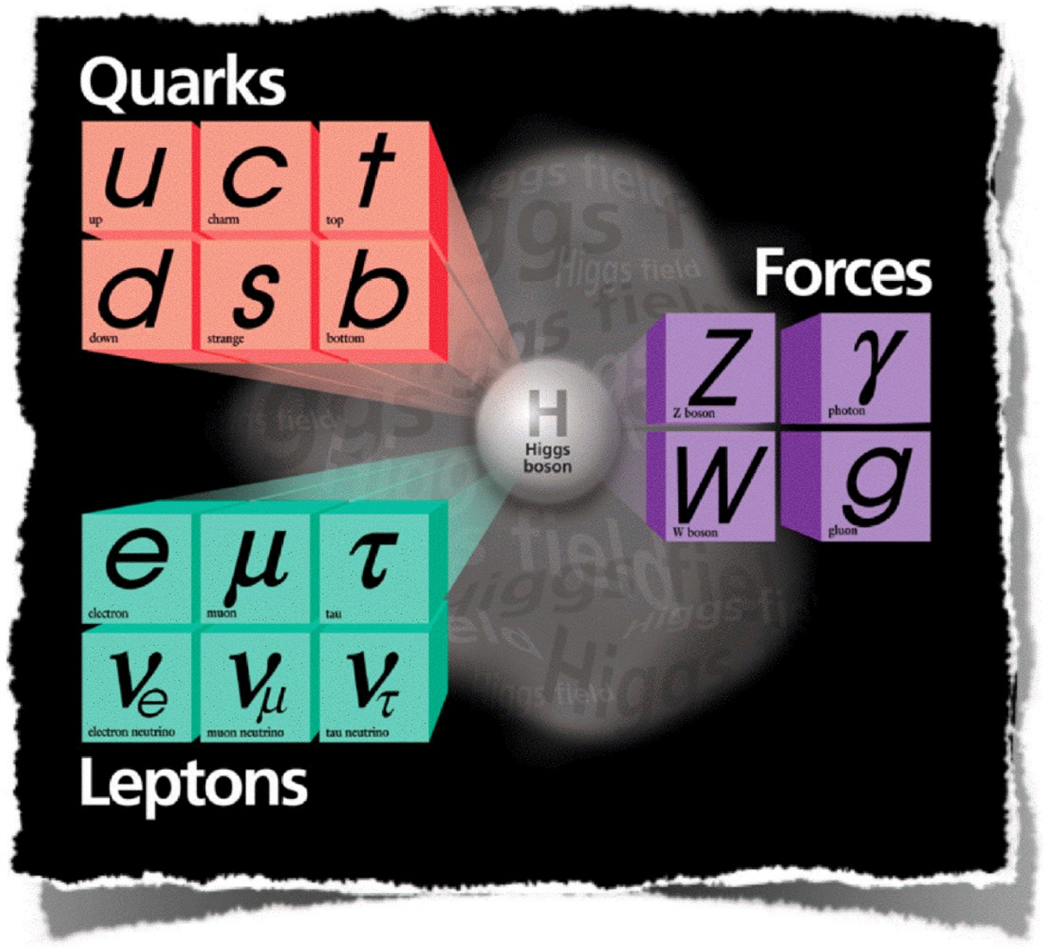
Partially you'll get a sneak preview on what will be shown at Grenada next week

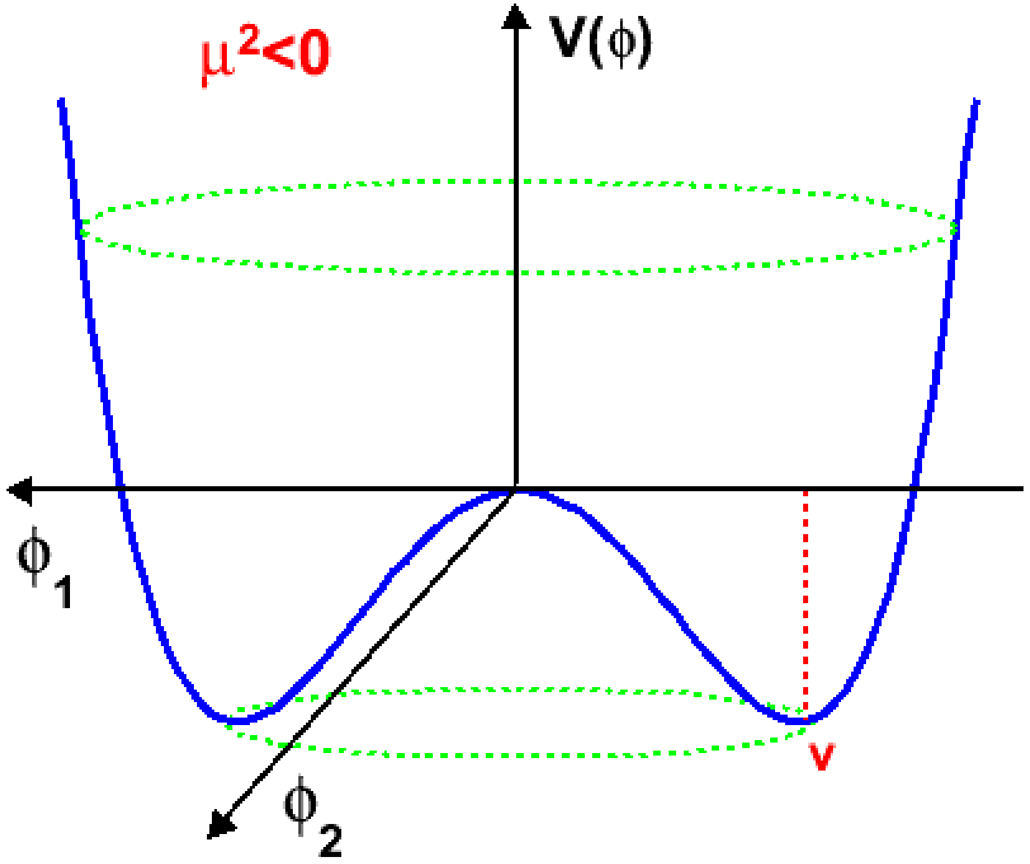
Jeju Island/South Korea – May 2019

Content of the talk

- Introduction
- Higgs physics at e+e- colliders
- 2 fermion processes
- Summary and conclusion

The Standard Model is complete





- We know that there exists at least one fundamental scalar with a non-vanishing expectation value
- We don't know what shapes the potential and whether the potential is the footprint of a larger mass scale

Open questions

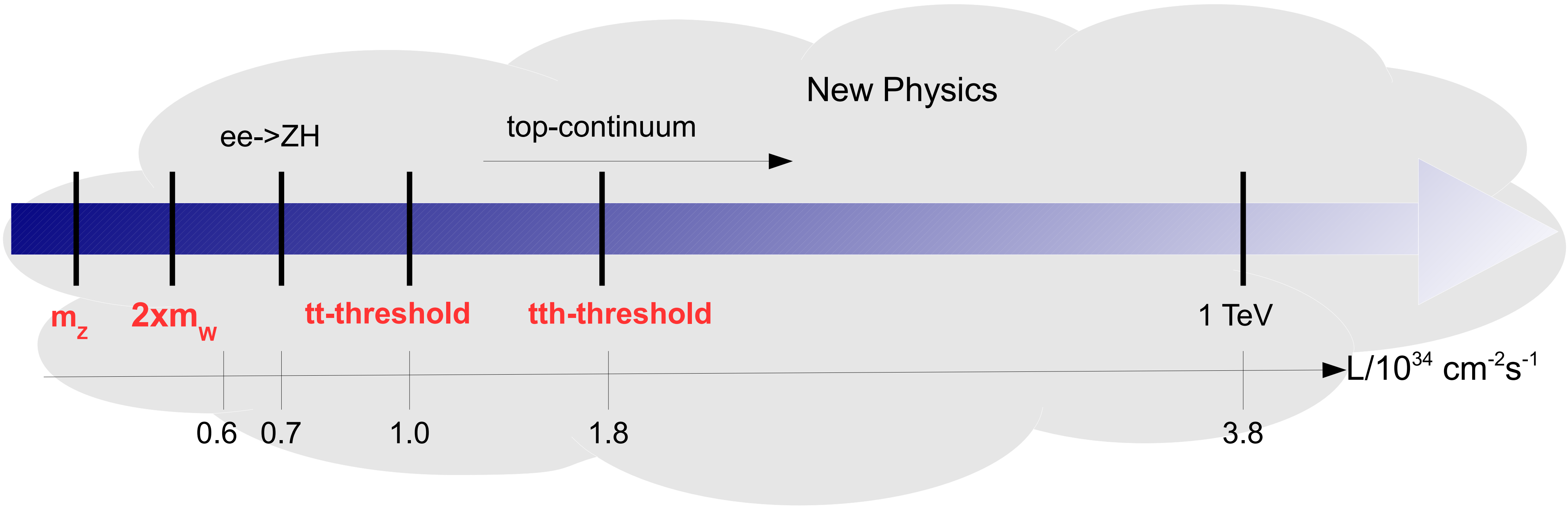
How to make progress?

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

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 (straightforward at linear colliders)

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

- **Background free** searches for BSM through beam polarisation

Energy Frontier Electron-Positron Collider Projects

	√s	beam polarisation	∫Ldt for Higgs	R&D phase
ILC	0.1 - 1 TeV	e-: 80% e+: 30%	2000 fb-1 @ 250 GeV 200 fb-1 @ 350 GeV 4000 fb-1 @ 500 GeV	TDR completed in 2013
CLIC	0.35 - 3 TeV	e-: (80%) e+: 0%	1000 fb-1 @ 380 GeV 2500 fb-1 @ 1.5 TeV 5000 fb-1 @ 3 TeV	CDR completed in 2012
CEPC	90 - 240 GeV	e-: 0% e+: 0%	5600 fb-1 @ 240 GeV	CDR completed in 2018
FCC-ee	90 - 350 GeV	e-: 0% e+: 0%	5000 fb-1 @ 250 GeV 1700 fb-1 @ 350 GeV	CDR completed in Jan 2019

Details see talk by Y. Okada

Details see talk by M. Ruan

Table courtesy of J. Brau

Linear vs. circular e+e- machines – Instantaneous luminosities

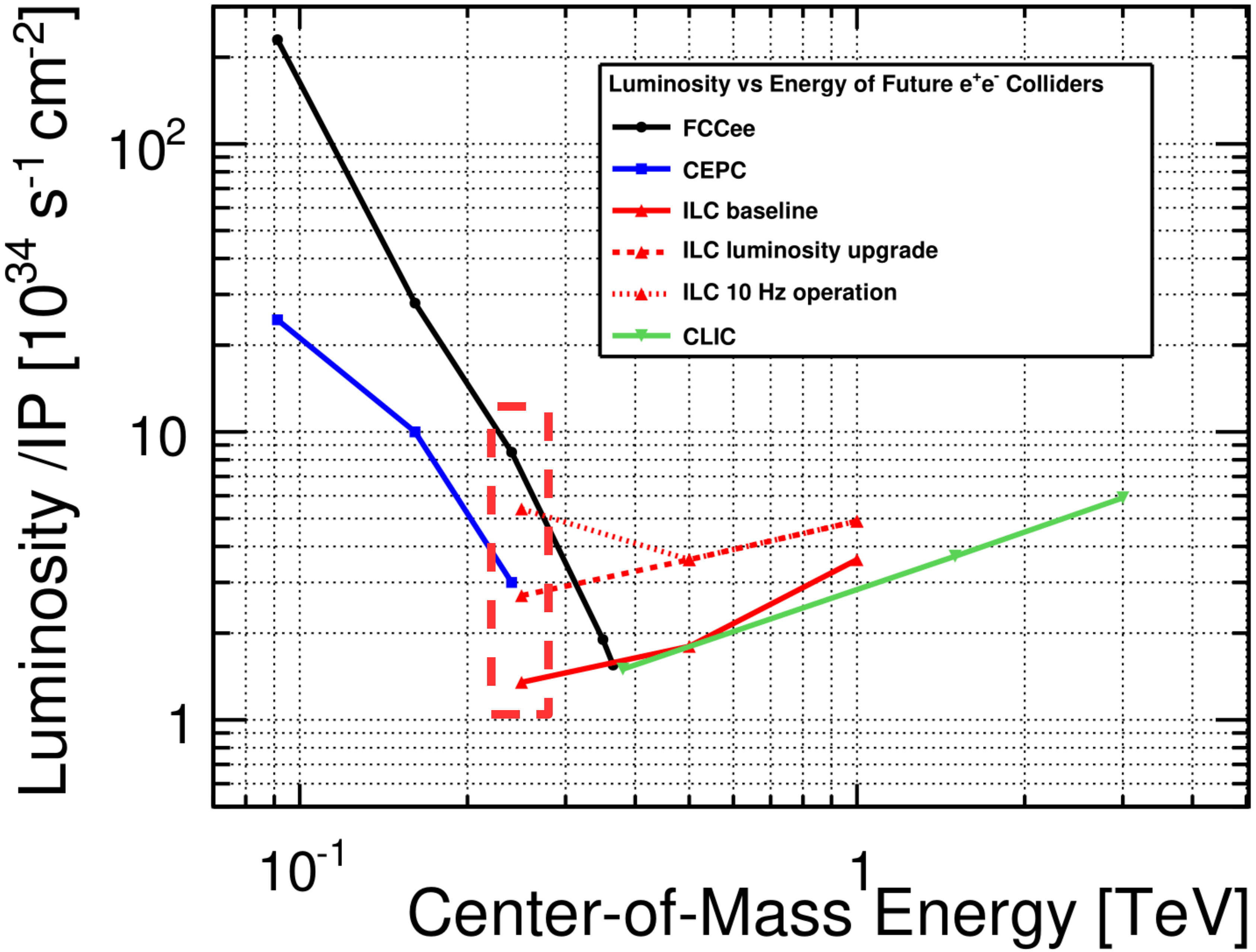
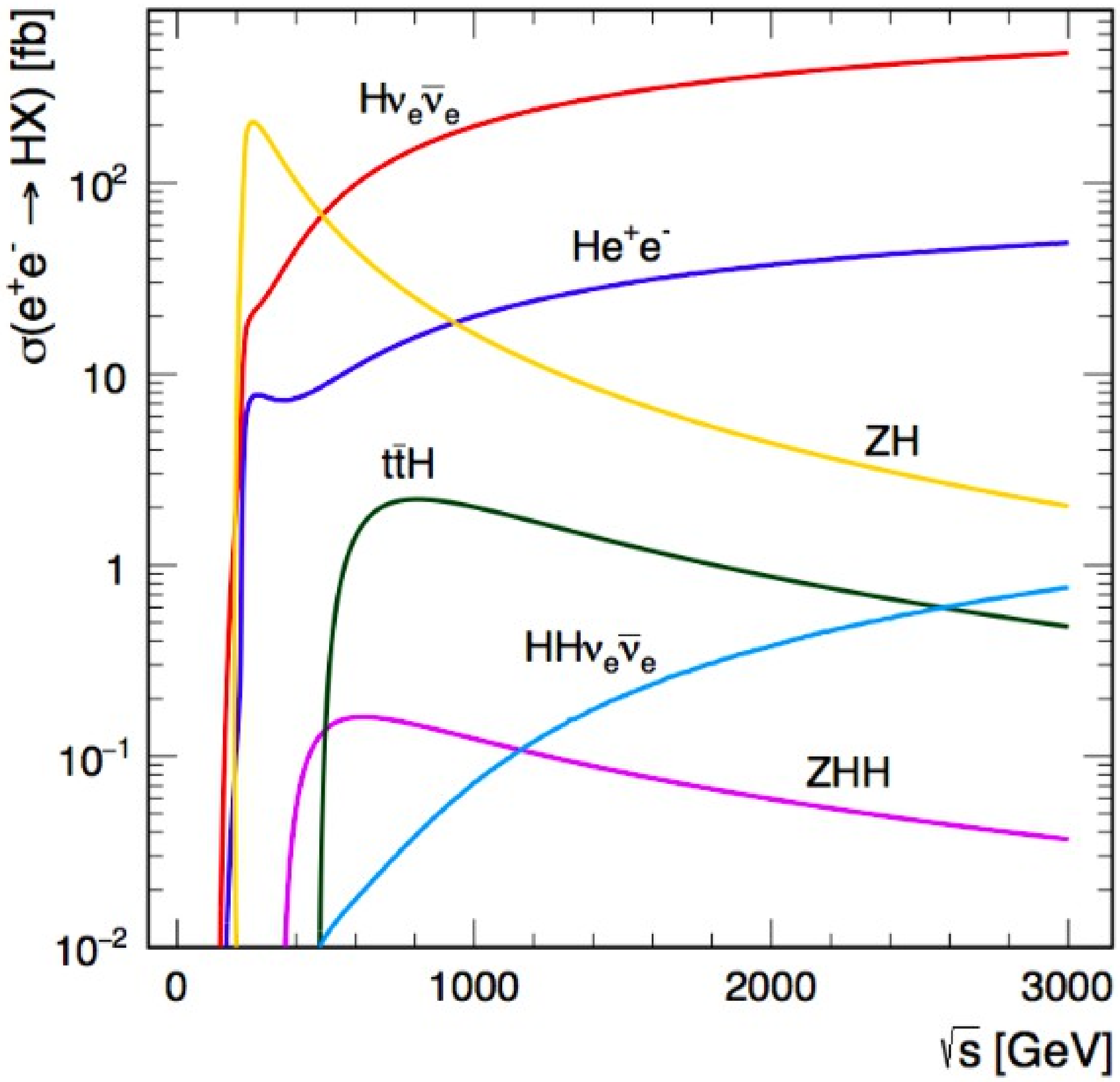
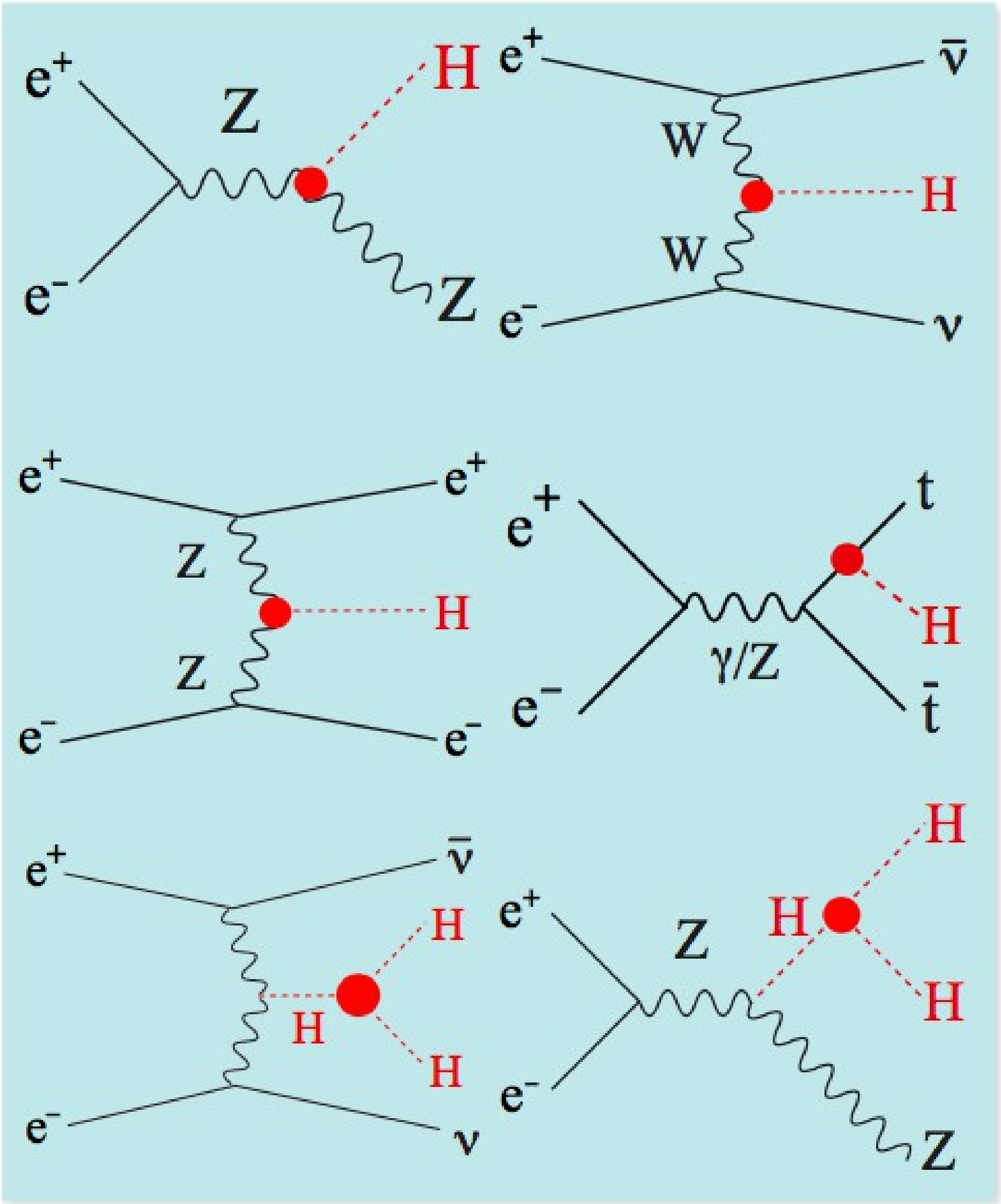


Figure J. List

- High energies ~above tt-threshold
  Domain of linear colliders
- Low energies e.g. Z-pole
  Domain of circular machines
  However, see later ...
- Transition region, i.e. HZ threshold
  … not so clear
  Comparable numbers for all proposals
- Linear colliders are more versatile to test chiral theory due to polarised beams
- Detailed design parameters see backup

Higgs production at e+e- colliders

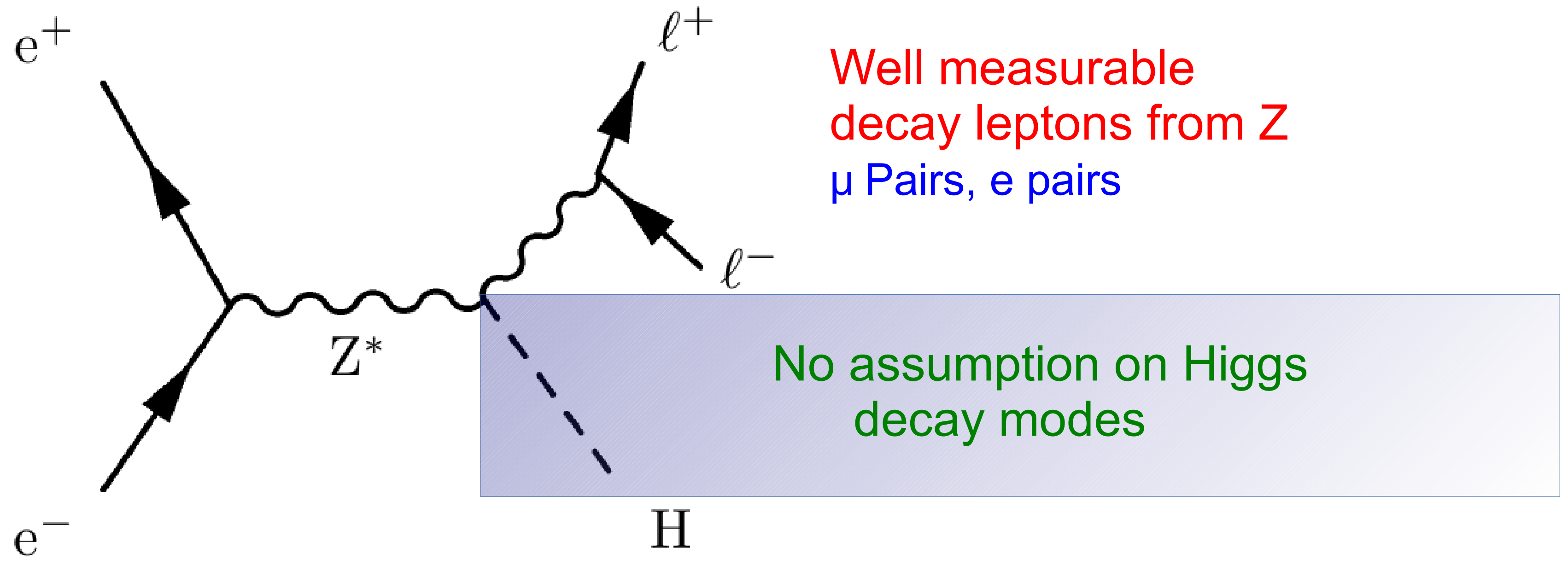


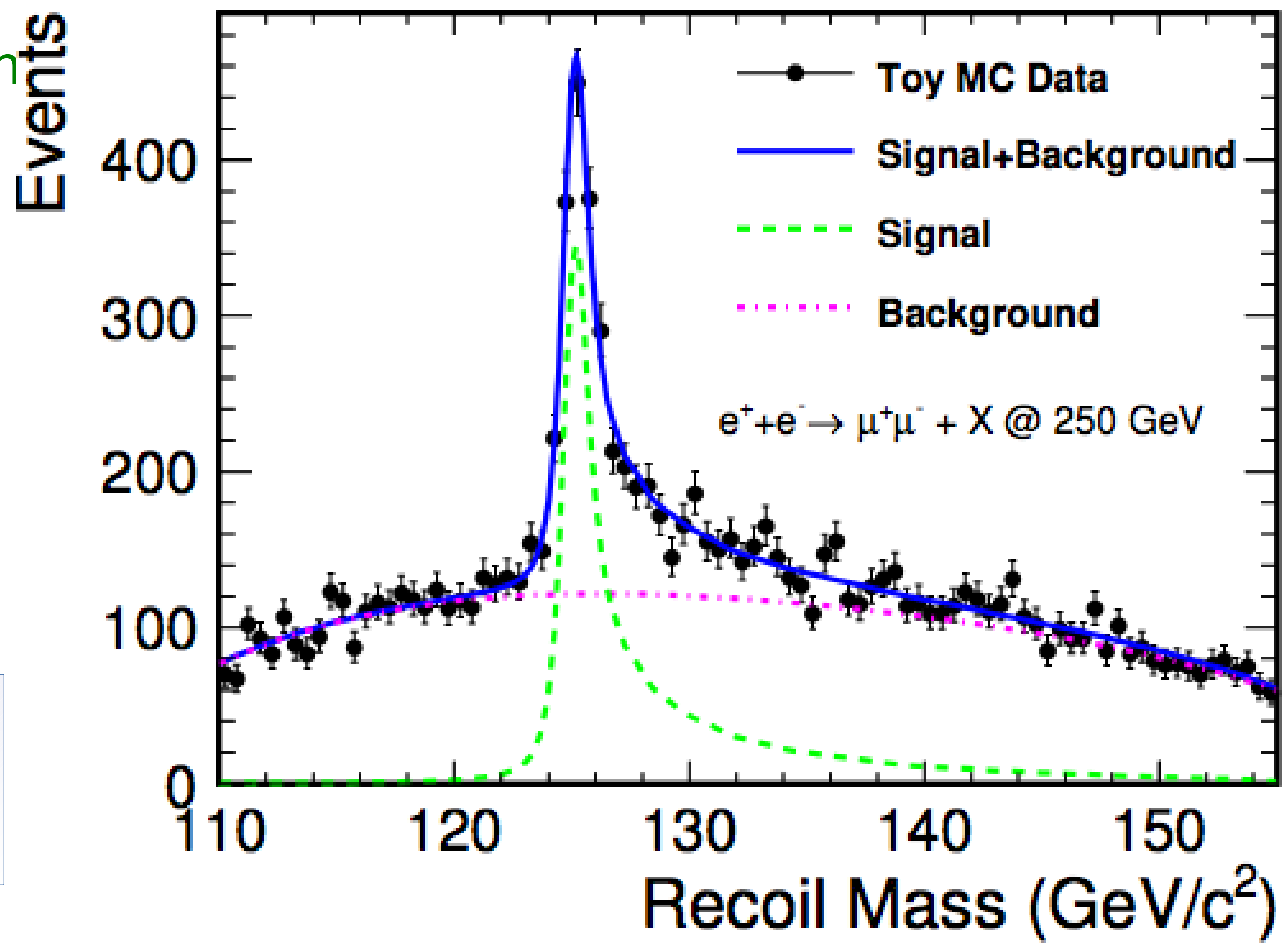


two important thresholds:
√s ~ 250 GeV for ZH, ~500 GeV for ZHH and ttH

Higgs-strahlung at lepton colliders

- Powerful channel for unbiased tagging of Higgs Events
- Absolute normalisation of Higgs couplings
- Sensitivity to invisible Higgs decays



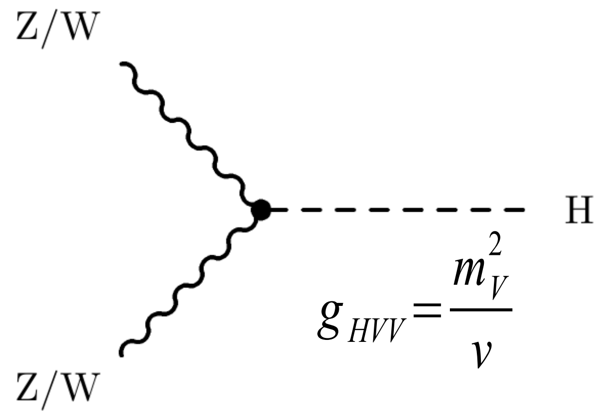


Higgs Recoil Mass: $M_h^2 = M_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$

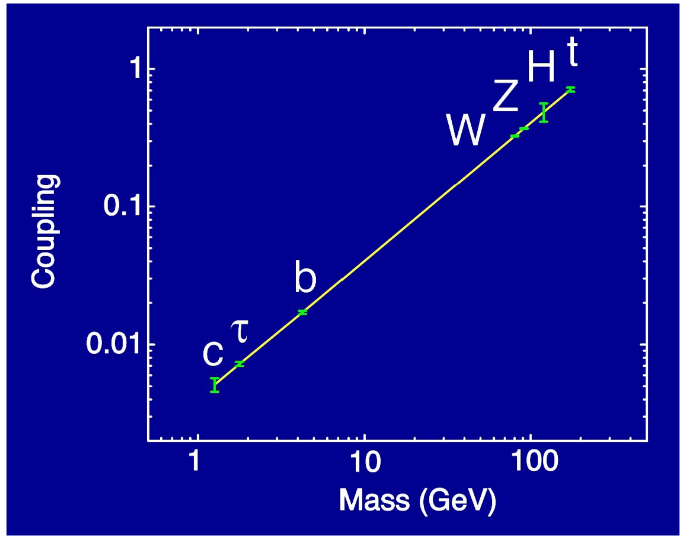
- Clean and sharp peak in Z recoil spectrum
- Illustrates precision that can be expected from e+e- colliders

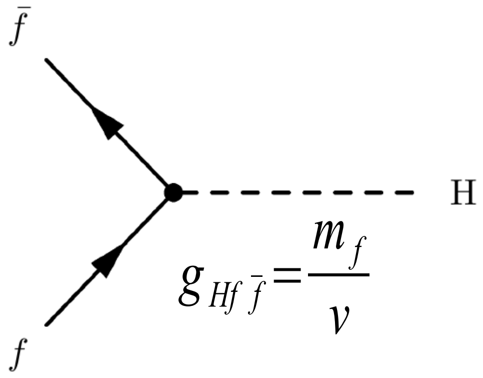
Fitting Higgs Couplings – Kappa and EFT

Couplings to Higgs Boson in Standard Model



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





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

Analysis using Kappa-fit:

- Simple scaling of SM-couplings
- Implies that Higgs coupling to Z in production and decay are identical
- No new operators

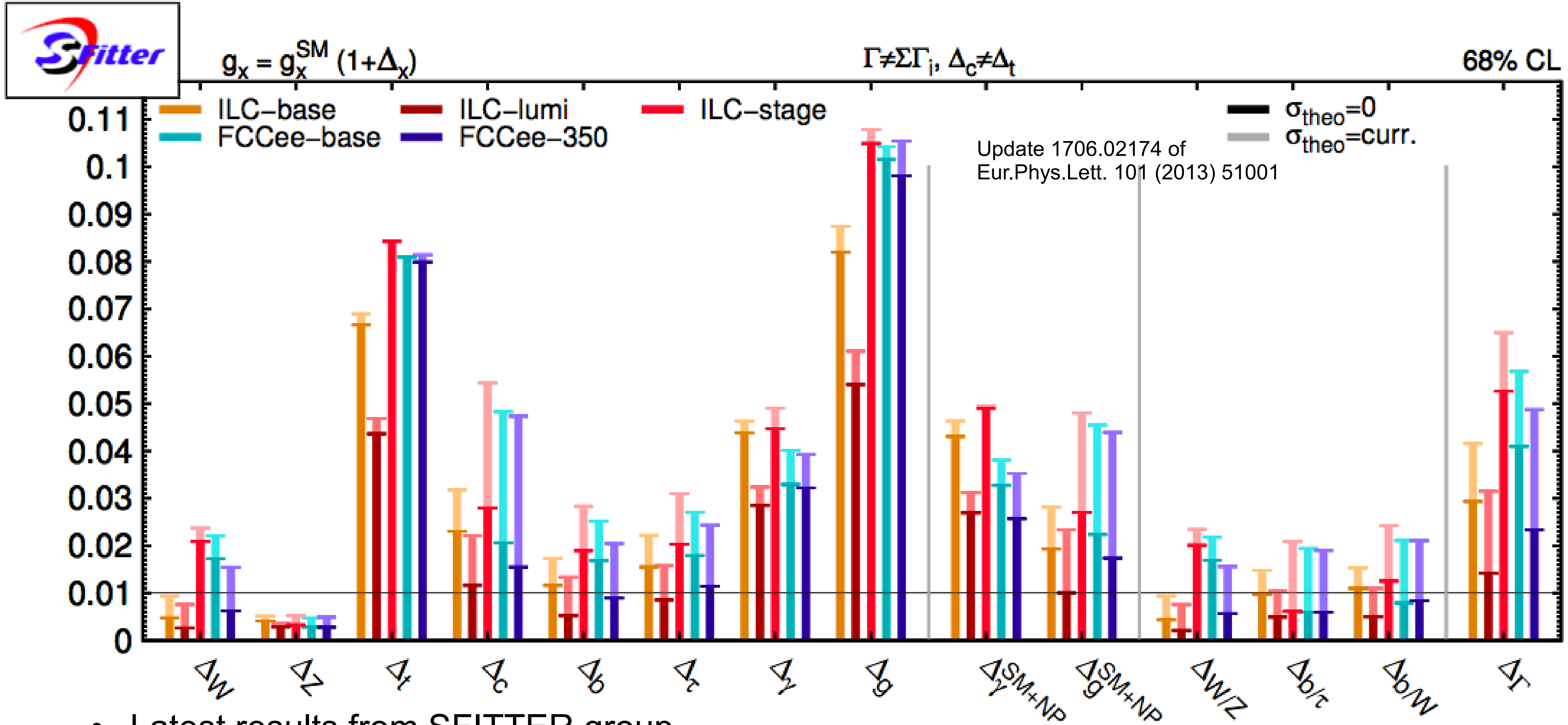
$$\frac{\Gamma(h \to ZZ^*)}{SM} = \kappa_Z^2 \,, \qquad \frac{\sigma(e^+e^- \to Zh)}{SM} = \kappa_Z^2$$

Analysis using EFT-fit:

- Introducing set of SU(2)xU(1) compatible operators
- e.g. breaks simple relation between Higgs production and decay
- Total width and Higgs to invisible as free parameters
- Receives additional input from e.g. ee->WW and EWPO

$$\Gamma(h \to ZZ^*)/SM = (1 + 2\eta_Z - 0.50\zeta_Z)$$
$$\sigma(e^+e^- \to Zh)/SM = (1 + 2\eta_Z + 5.7\zeta_Z)$$

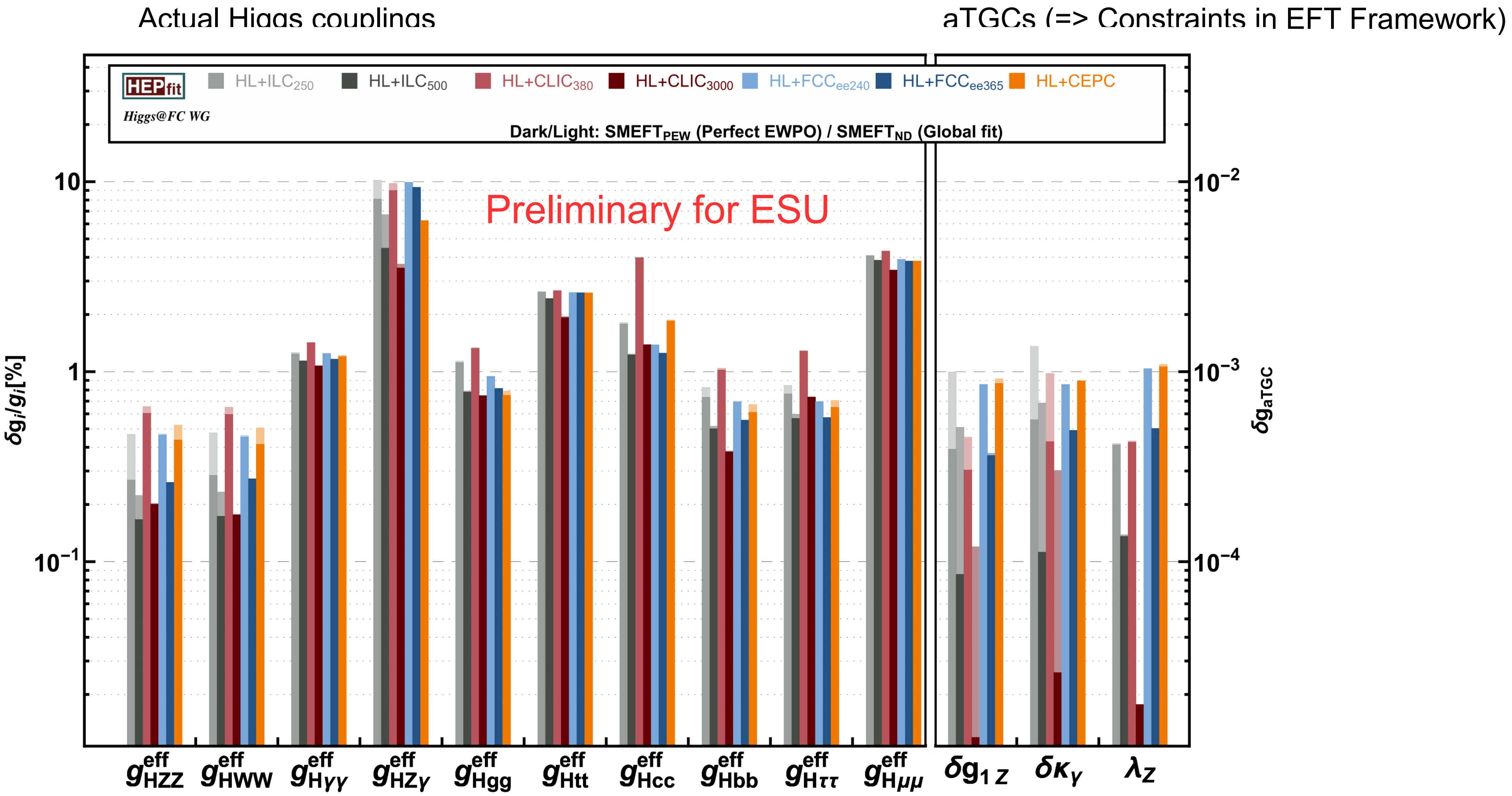
Precision on Higgs Physics – Kappa framework



- 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
  and top-Yukawa couplings (fit constraints and H->γγ)

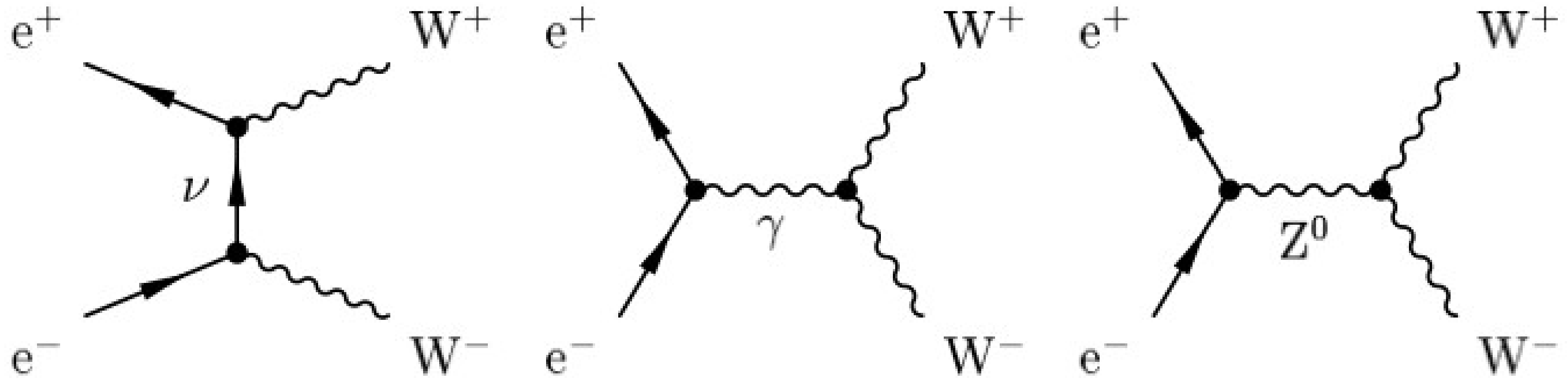
Precision on Higgs Couplings – EFT Framework

Courtesy of
Higgs ECFA Study group
For ESU



- Analysis in EFT Framework
- No clear winner among lepton colliders
- Polarisation at Linear Colliders compensate for higher integrated luminosity at Circular Marchines

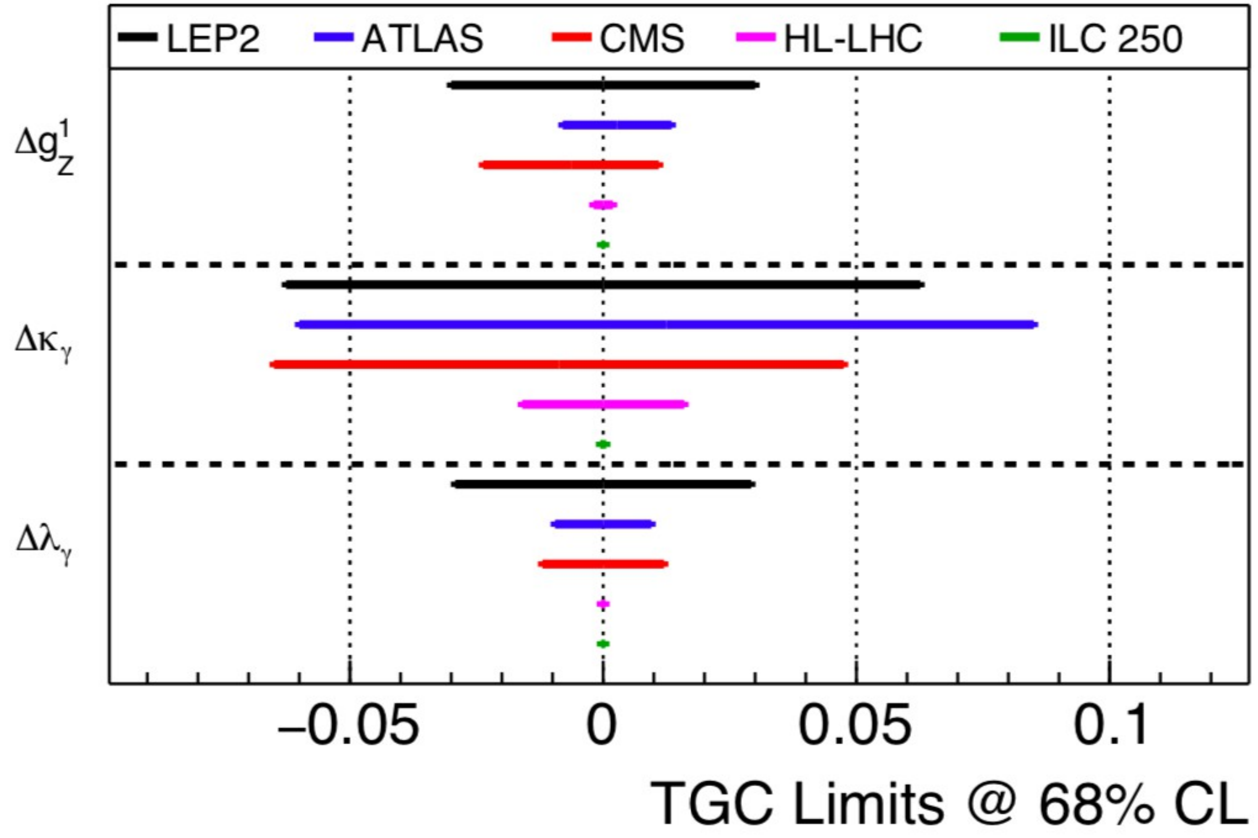
Anomalous Triple Gauge Couplings

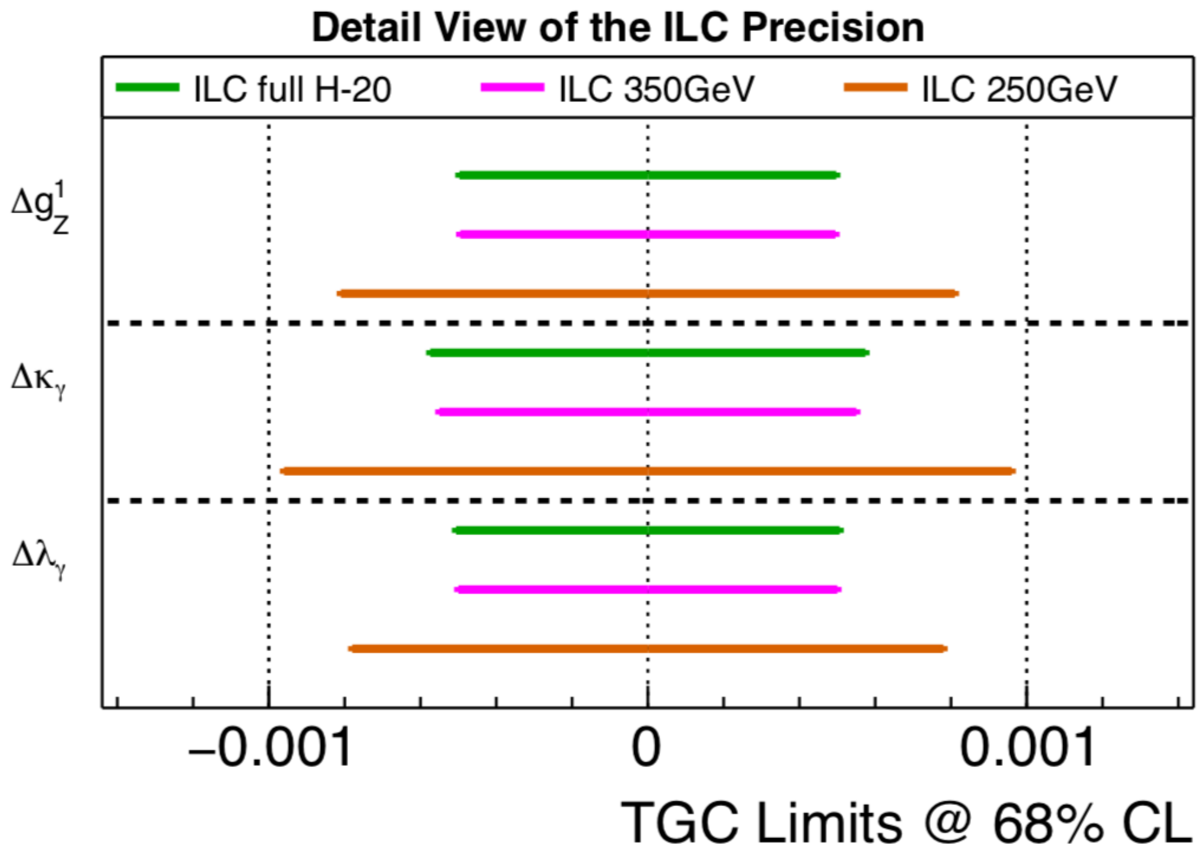


- Sensitivity to triple and quartic gauge Boson couplings (TGC and QGC)
- Observables depend strongly on beam polarisation

=> Enrich different helicity modes of W
=> Disentangling of couplings to Z and γ
=> in situ measurement of beam polarisation (and luminosity)

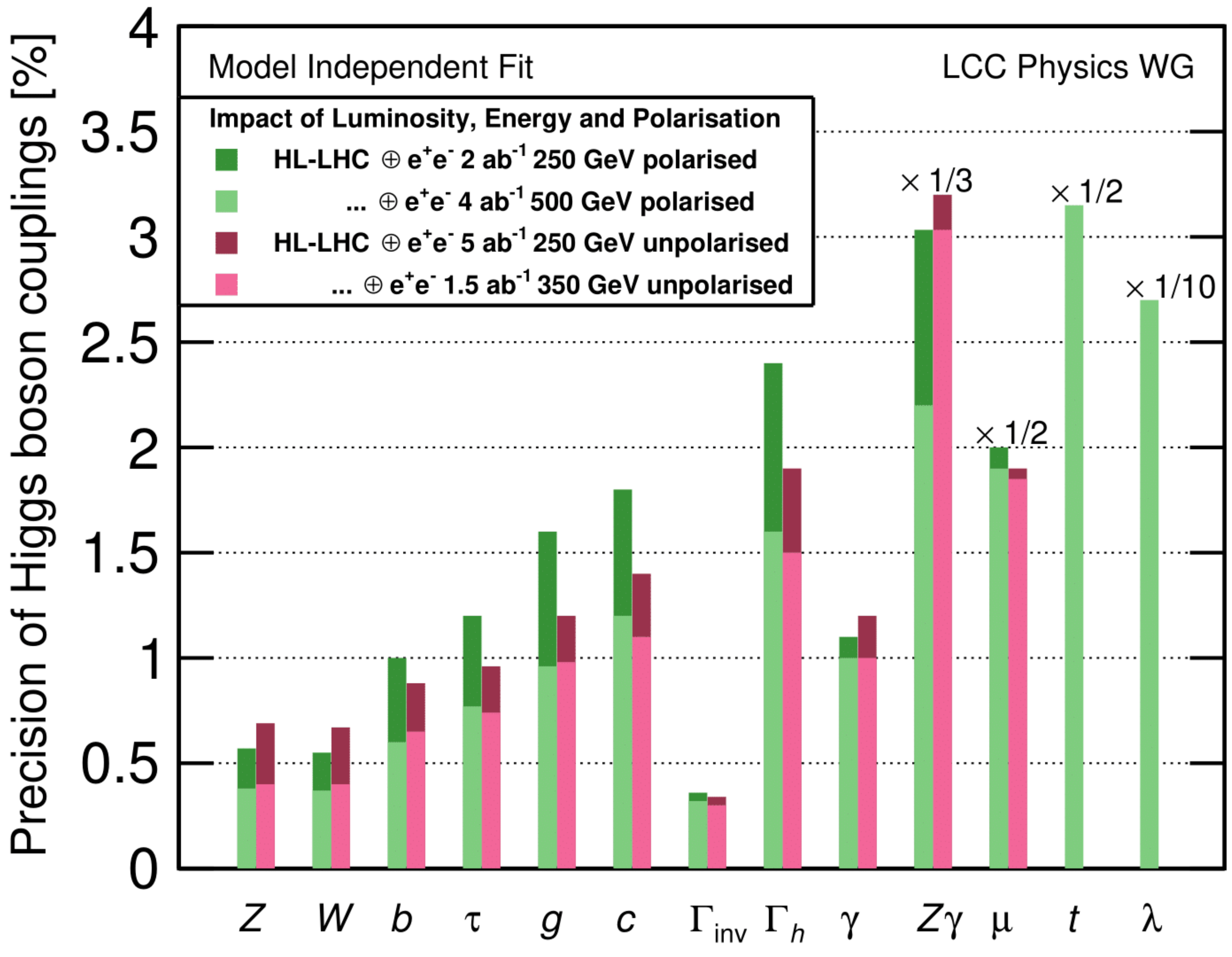
Limits on Triple Gauge Couplings@250 GeV



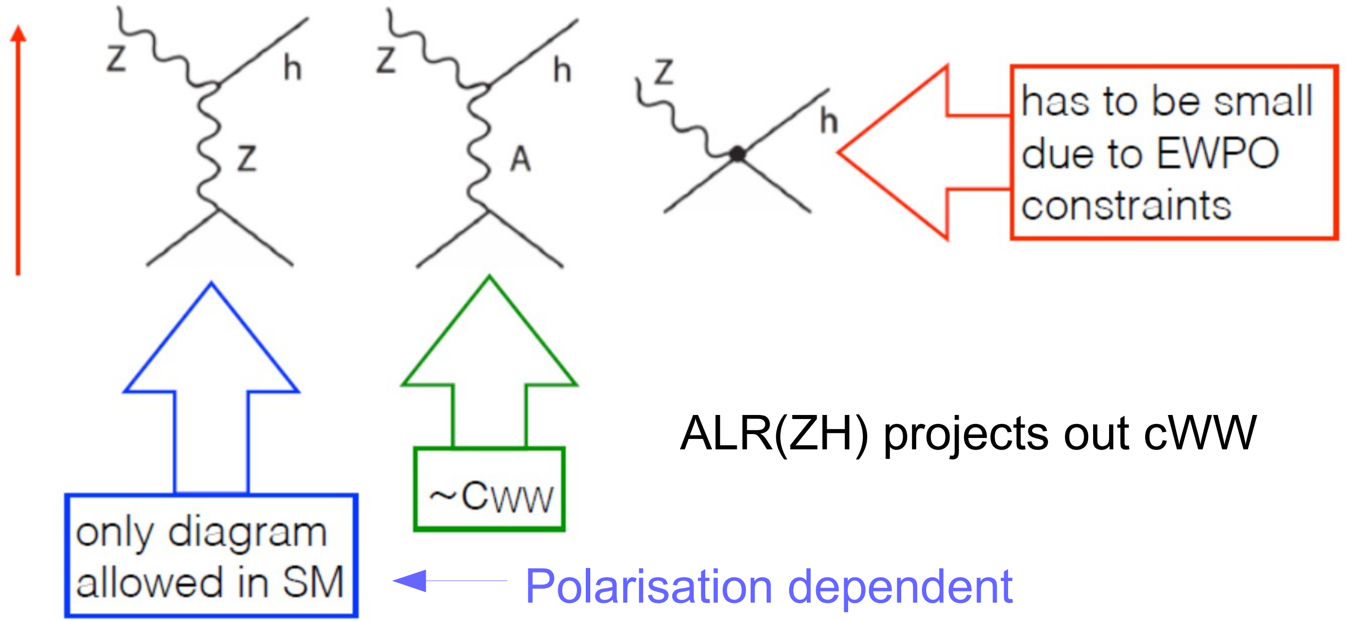


Rom

EFT Framework and beam polarisation

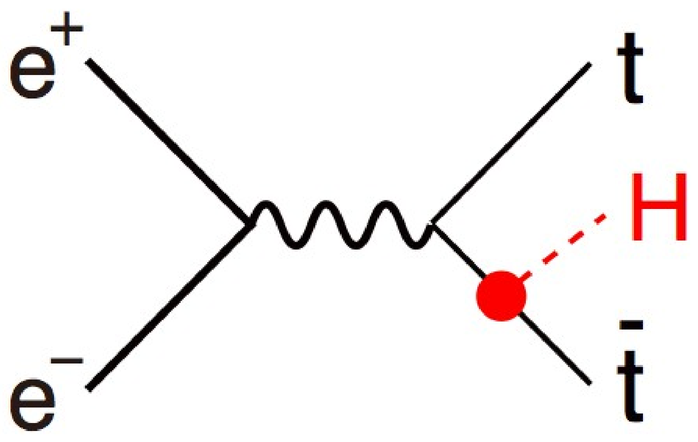


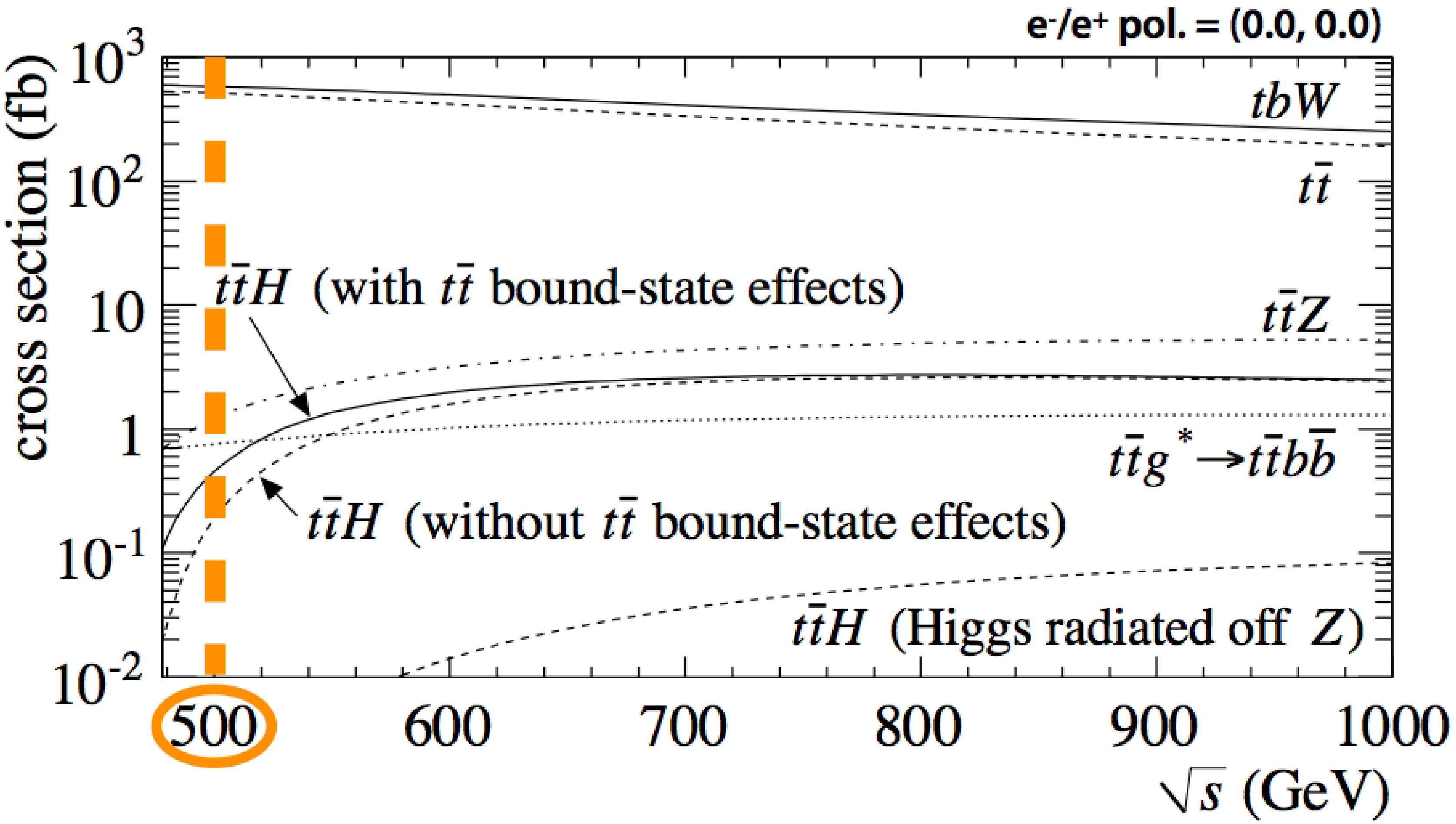
- EFT adds additional spin strucuture to ZH production cross section (see backup)



- Precision for 2ab-1 polarised = 5ab-1 unpolarised

Top Yukawa Coupling



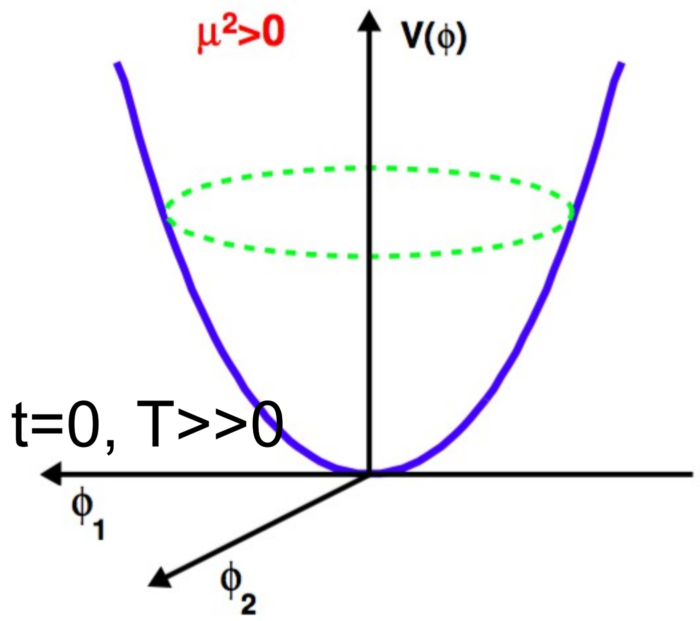


- Coupling of Higgs to heaviest particle known today

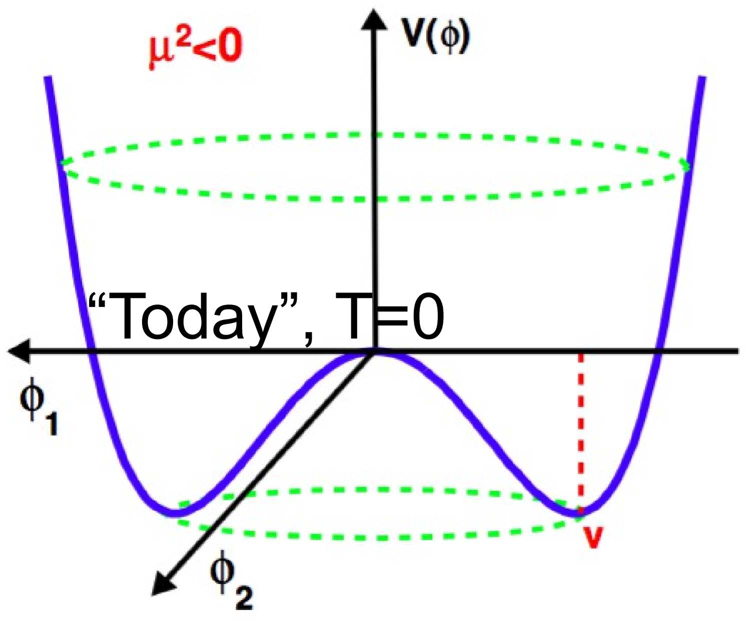
- Up to eight final state jets

√s[GeV]	550	1000	1400
L[ab-1]	4	8	2
δyt/yt[%]	2.8	2.0	2.7

The Higgs Potential



Perfect (electroweak) symmetry
and massless particles

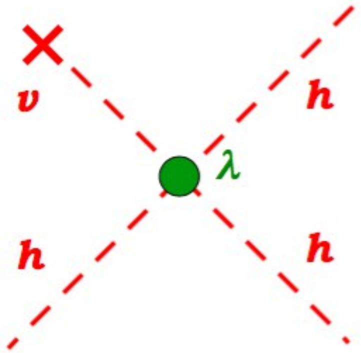


Broken (electroweak) symmetry
and massive particles

Two questions:

- Shape of “today's” Higgs Potential?

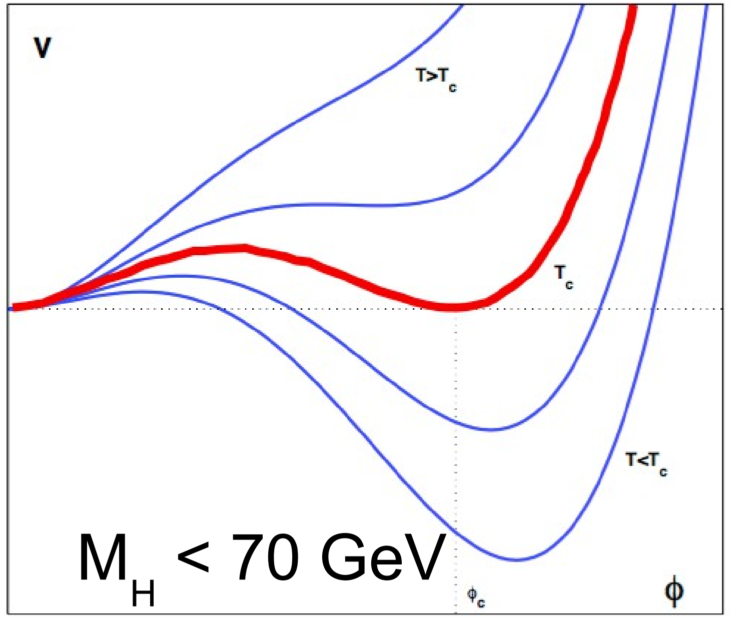
$$V(\eta) = \frac{1}{2}m^2\eta^2 + \lambda v\eta^3 + \frac{1}{4}\lambda\eta^4$$ => Triple Higgs-self coupling



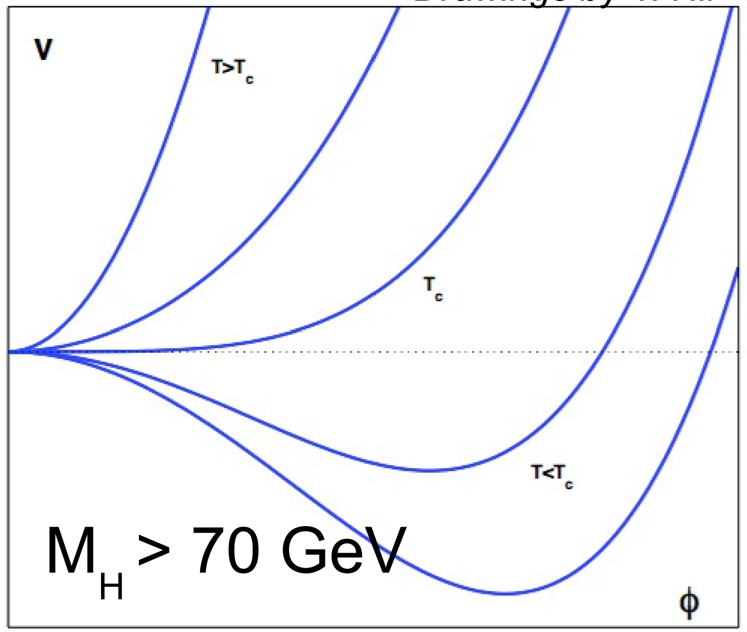
- Transition from symmetric, unbroken to broken phase?

Phase Transition in Standard Model

Electroweak Baryogenesis requires 1st Order PT



Drawings by Y. Nir



- Coexistence Two minima at **0 and v_c at T_c**

=> 1st order phase transition
and development into "today's" shape at T=0

- No coexistence of two minima at **0 and v_c**

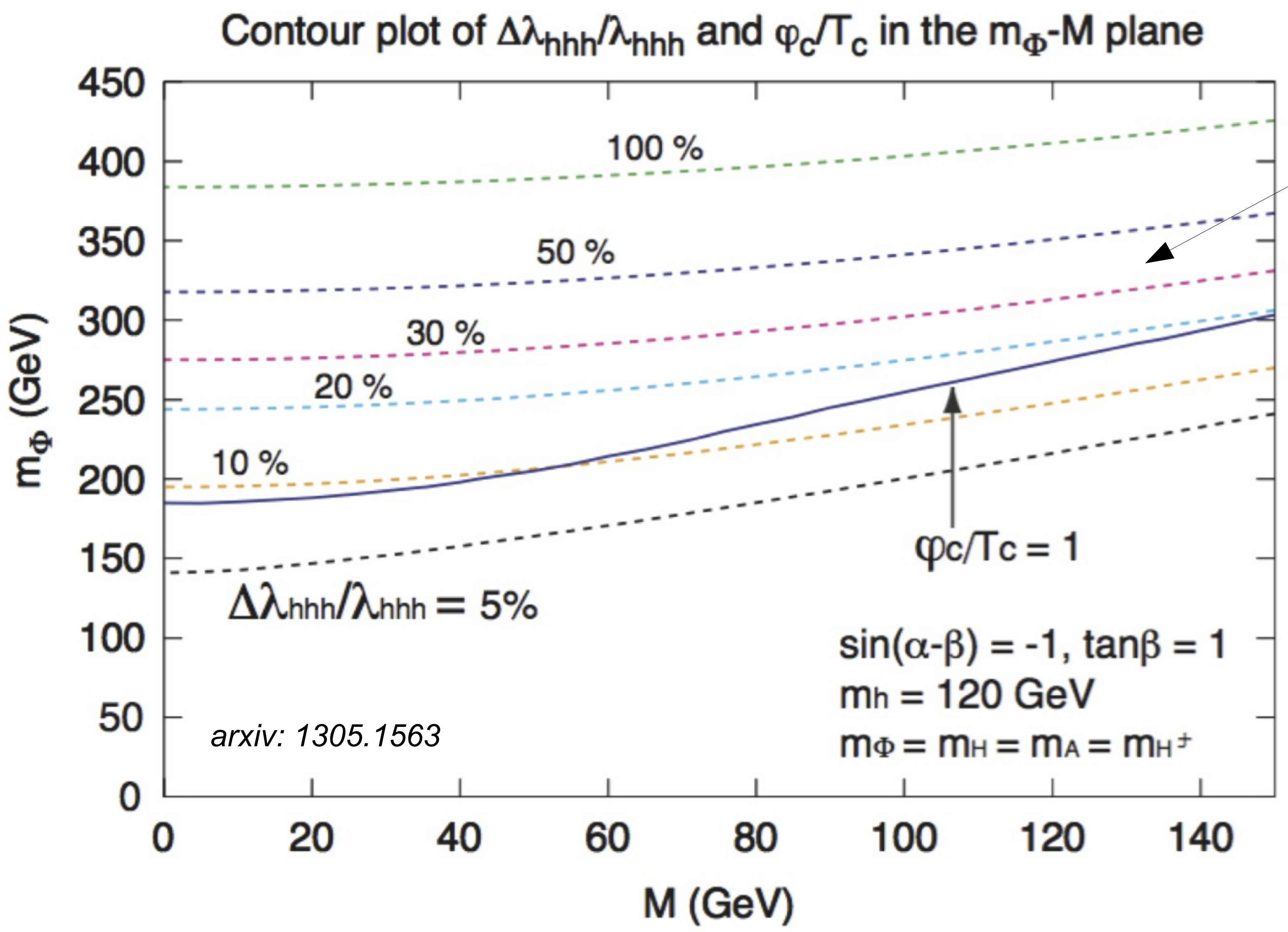
=> Cross over into "today's" shape at T=0

The discovered Higgs is too heavy to provoke a 1st order phase transition

=> New physics needed

New particles – Extended Higgs Sector

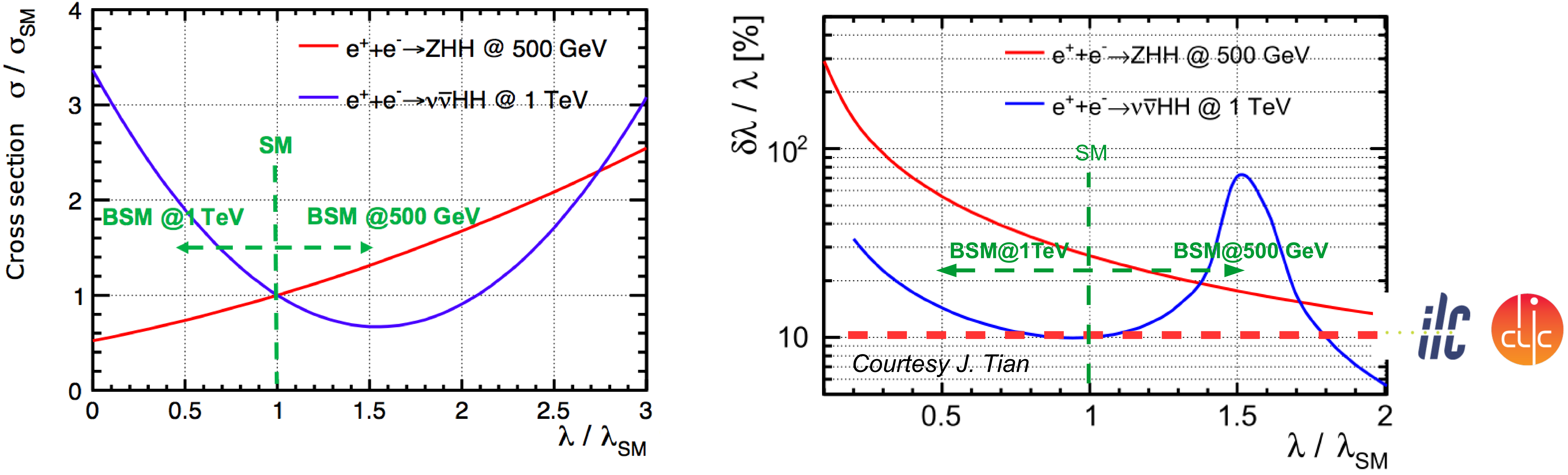
Heavy Higgs Mass



Deviations of λ from SM Value

- New (bosonic) particle may modify λ and enable 1st order phase transition
- Impact on measurements and achievable precisions of λ ?

Manifestation of new physics in observables and extracted results?

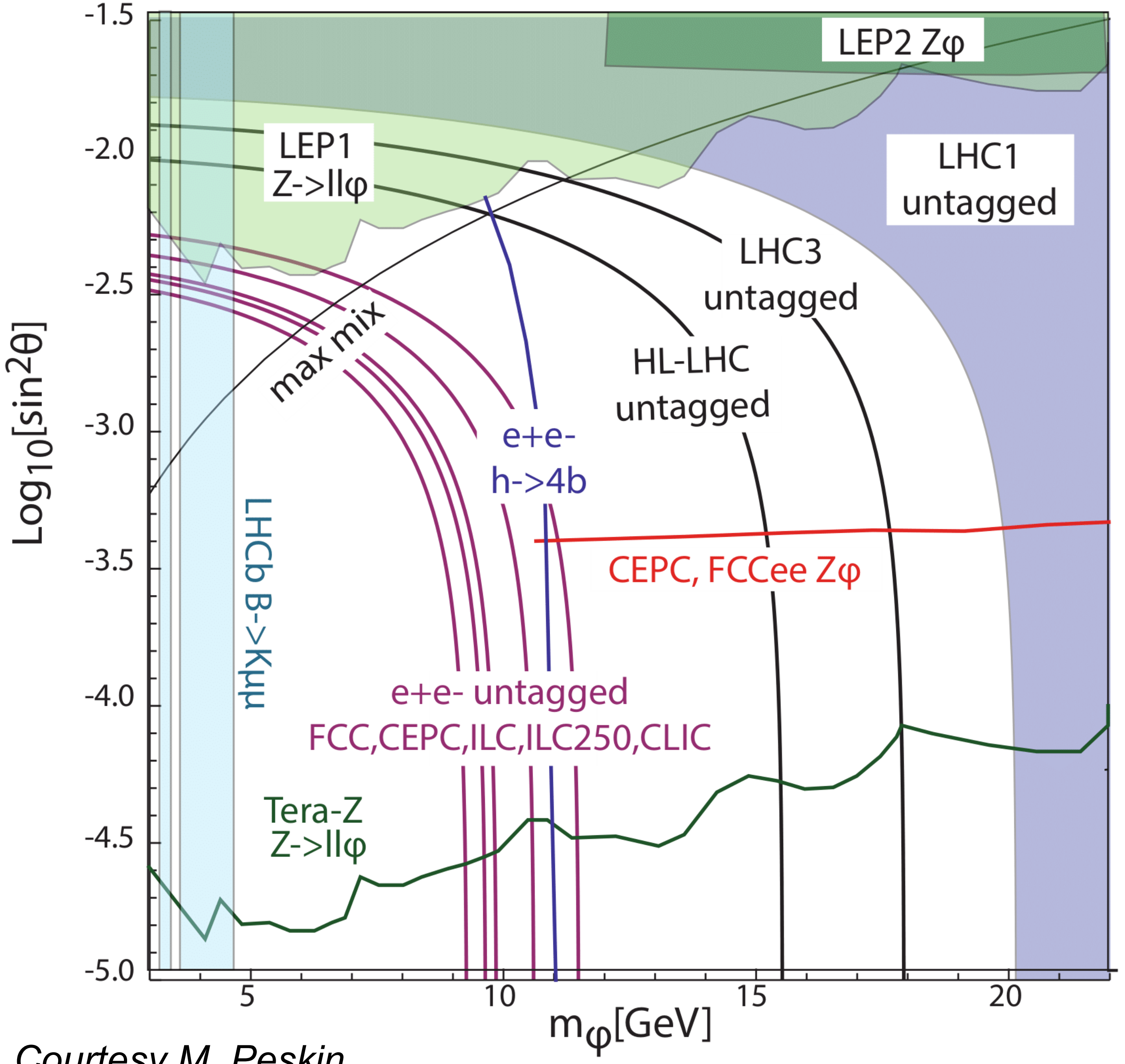


- Remarkable sensitivity of 500 GeV machine in case of large upward deviation
- 1 TeV machine superior for large upward and downward deviations

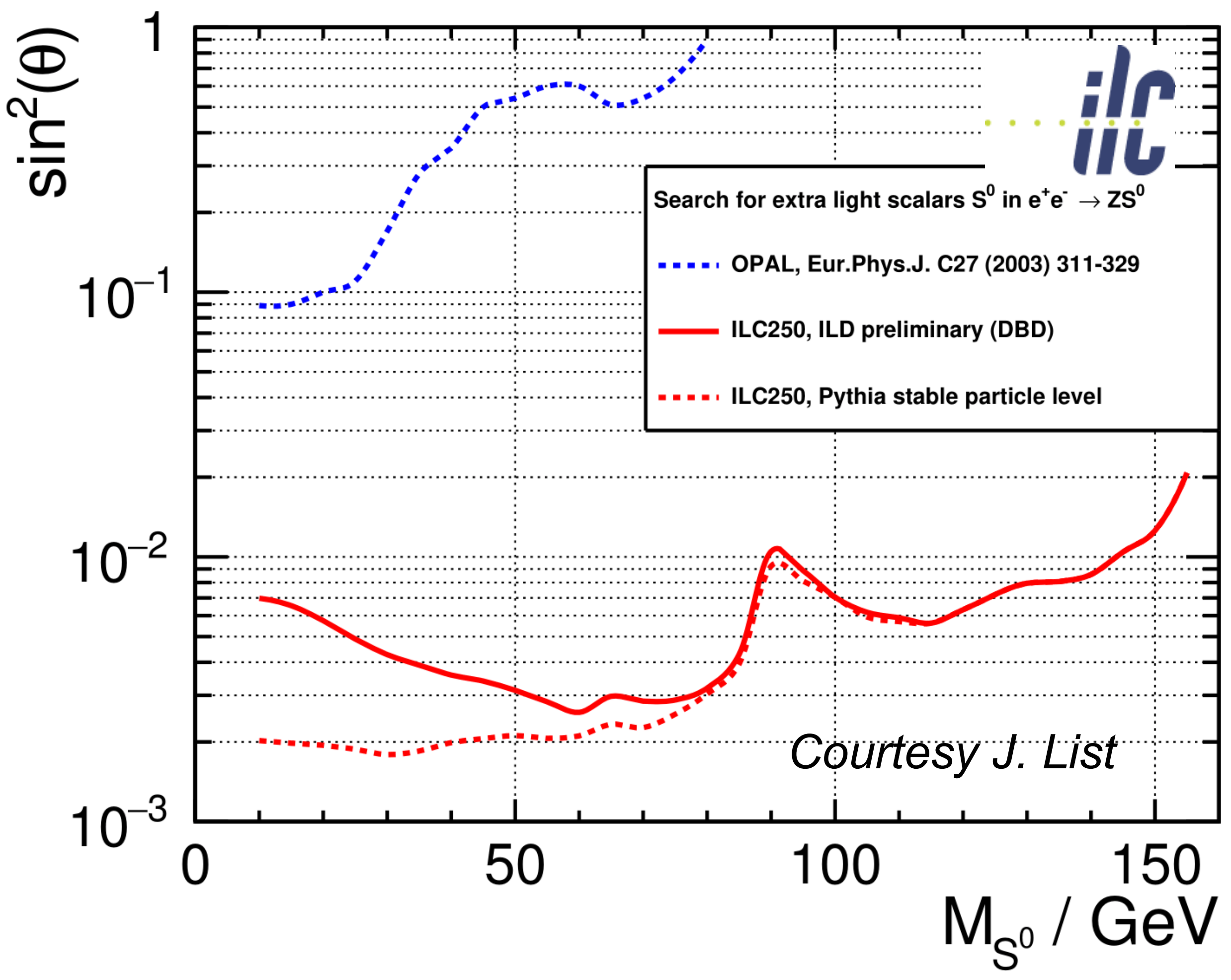
T. Tanabe, Higgs Coupling 2016

Feebly interacting particles – A summary

Light scalar may be missing piece to trigger first order 1st phase transition and/or being the radion in extra dimension theories

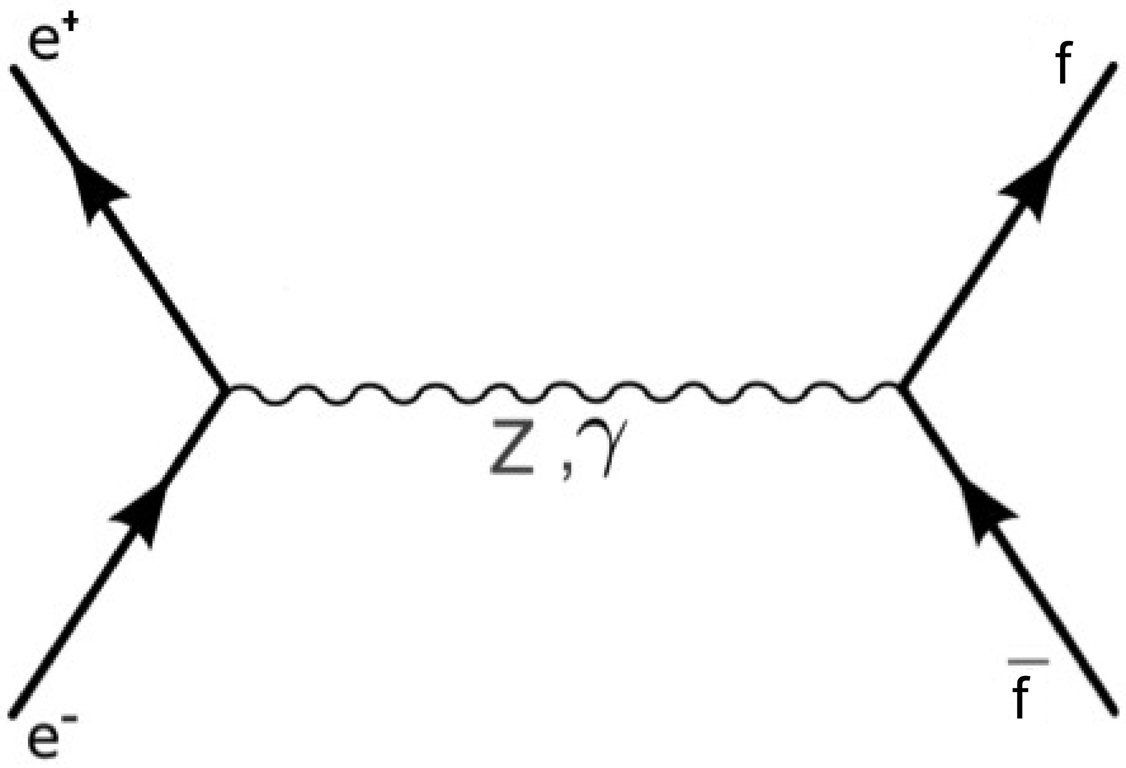


Courtesy M. Peskin



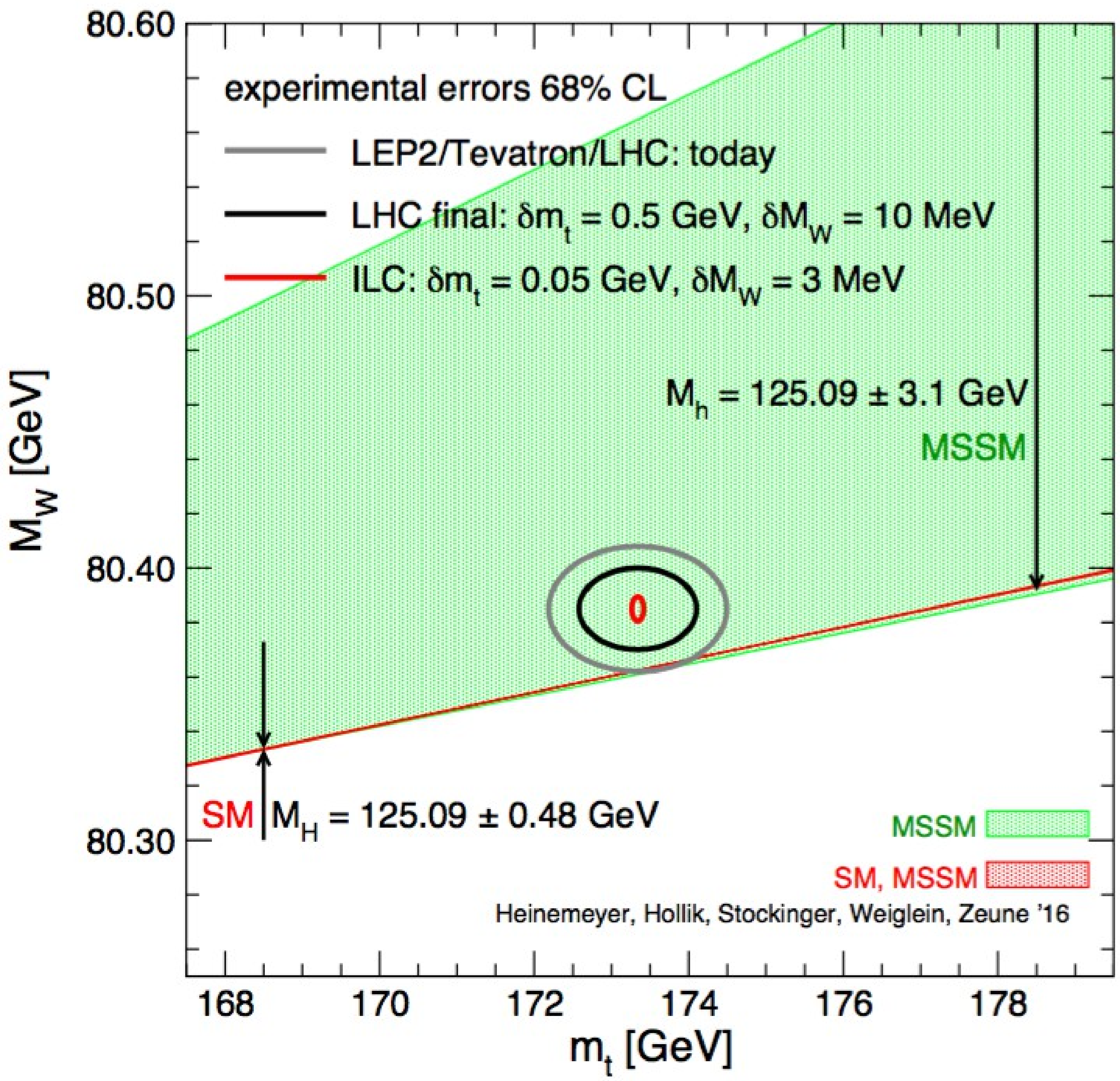
- e+e- colliders extend limits considerably w.r.t. LHC
  - Statistics helps at lowest masses
- CEPC, FCCee (>Z pole) limits order of magnitude better than ILC
  - Backgrounds taken correctly into account?
  - Similar at stable particle level

Two fermion processes



- Important threshold tt => top mass
- Sensivity to new physics at all cms energies

Top mass Higgs mass and BSM

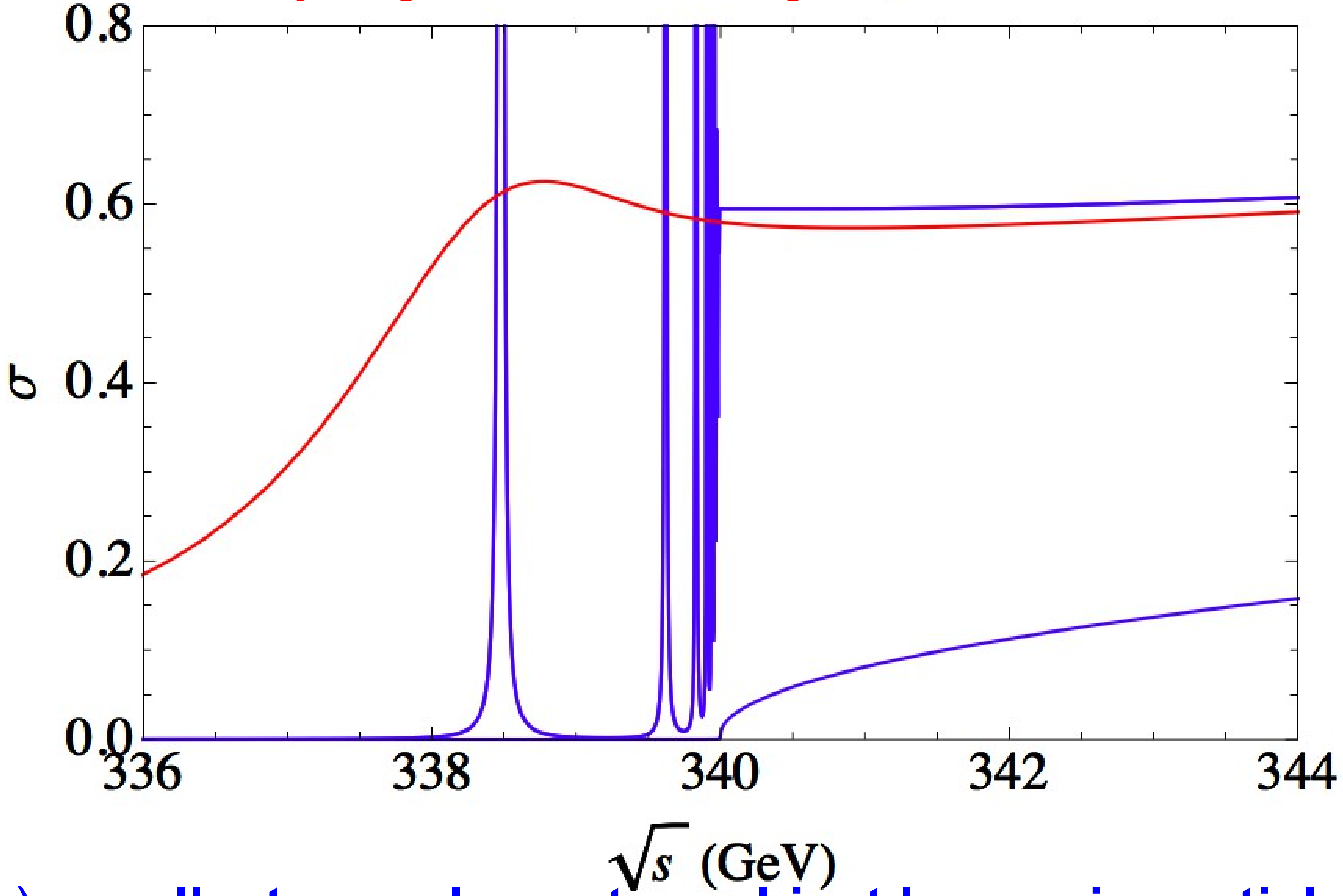


- Precise Top (and W) mass crucial to test compatibility of measured Higgs mass
- SM might not be sufficient to explain Higgs mass
- LHC may not reach sufficient discriminative power
- A lepton collider will for sure

Top pair production at threshold

"Bound states" at tt threshold

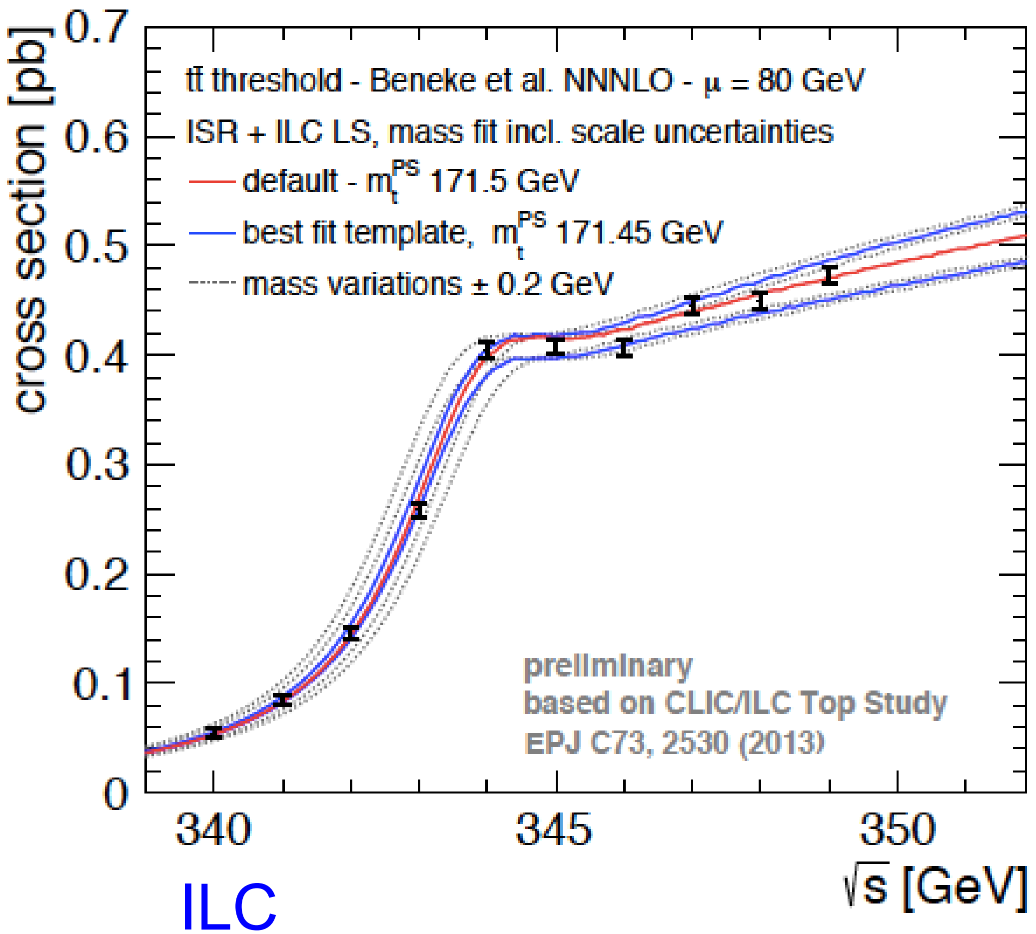
Hydrogen atom of strong interaction



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

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

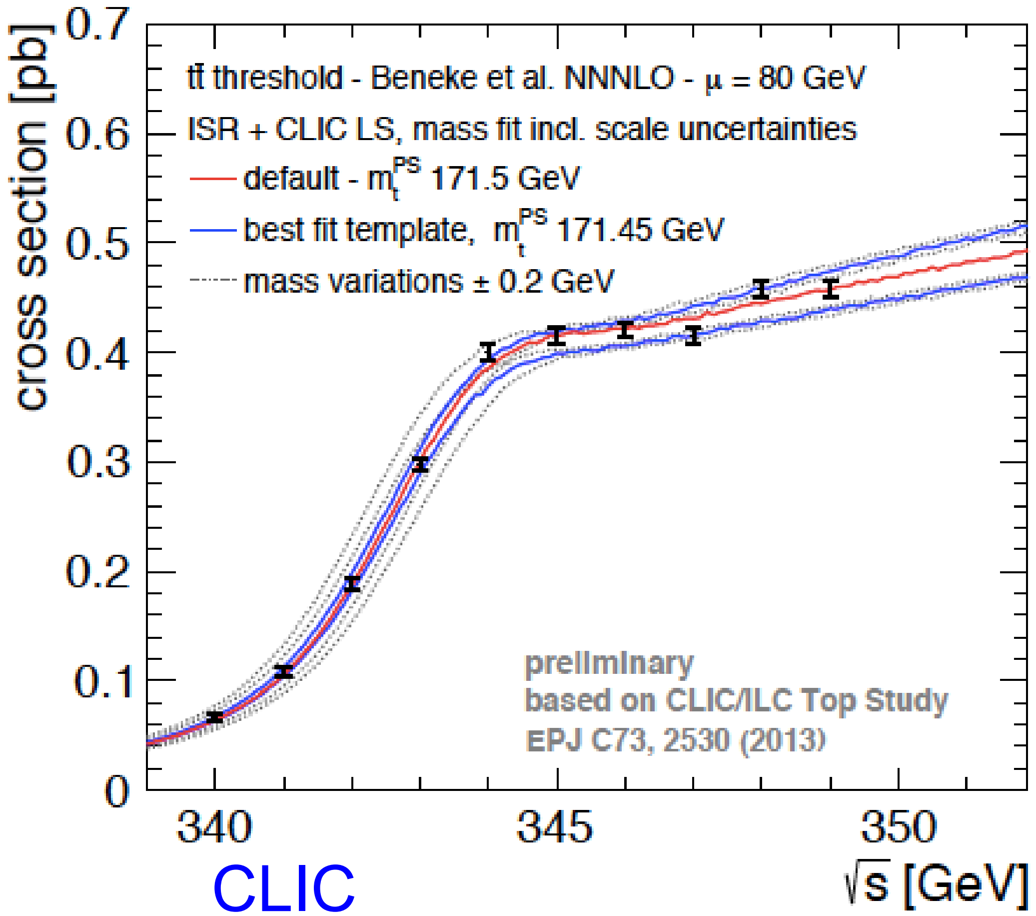
Top threshold scans at different e+e- colliders



ILC

Fit uncertainty:
28.5 MeV (18 MeV stat)

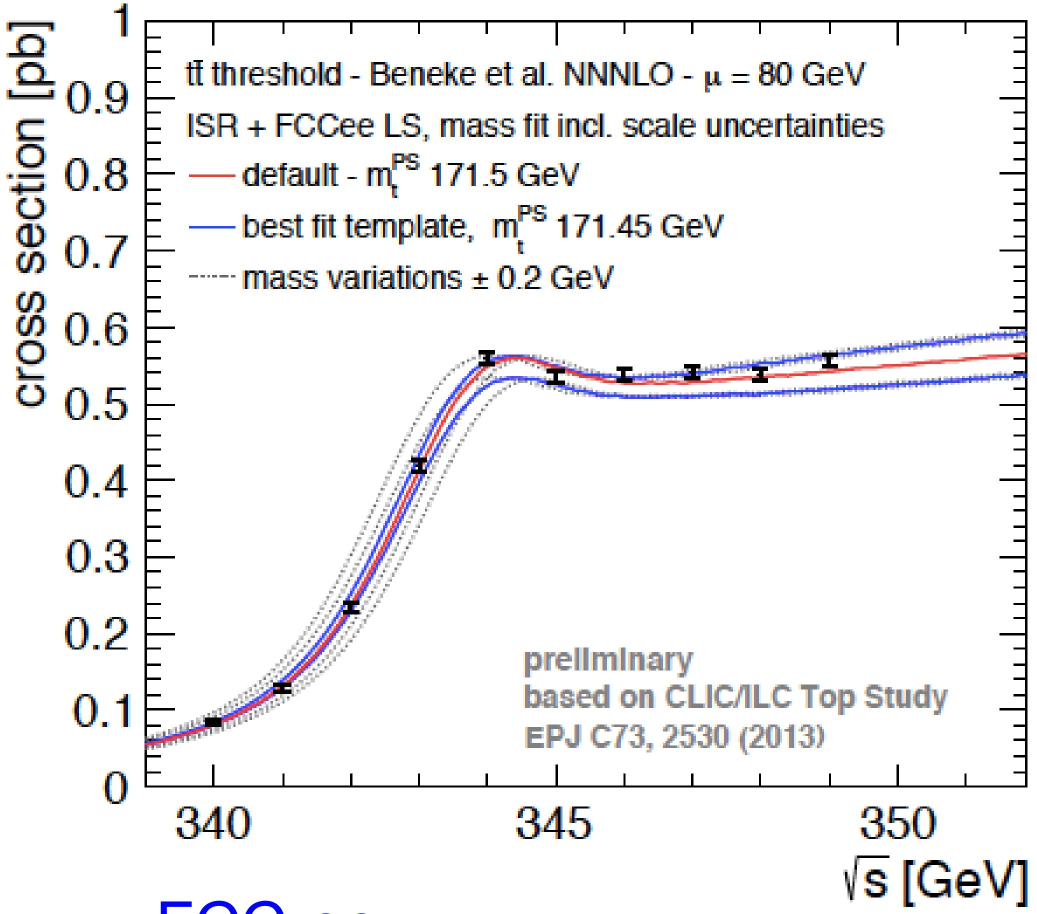
Scale uncertainty:
40 MeV



CLIC

Fit uncertainty:
31 MeV (21 MeV stat)

Scale uncertainty:
42 MeV



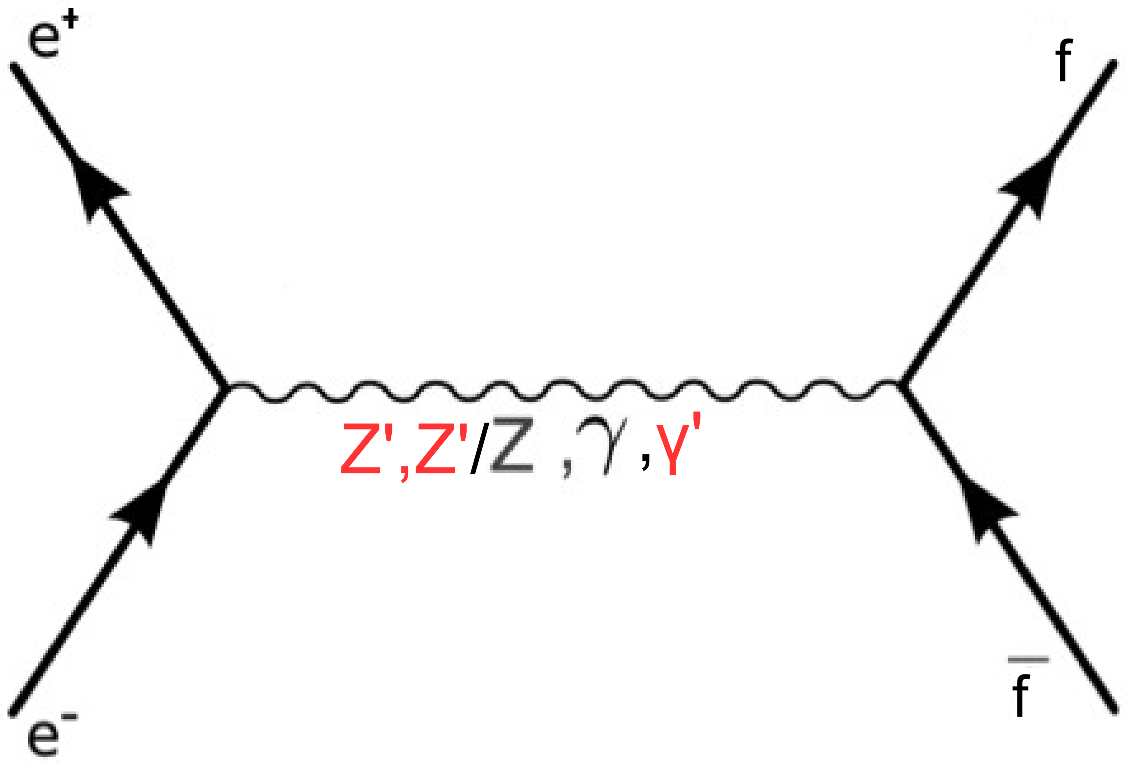
FCC-ee

Fit uncertainty:
27 MeV (15 MeV stat)

Scale uncertainty:
40 MeV

F. Simon Top@LC16

Two fermion production and asymmetries

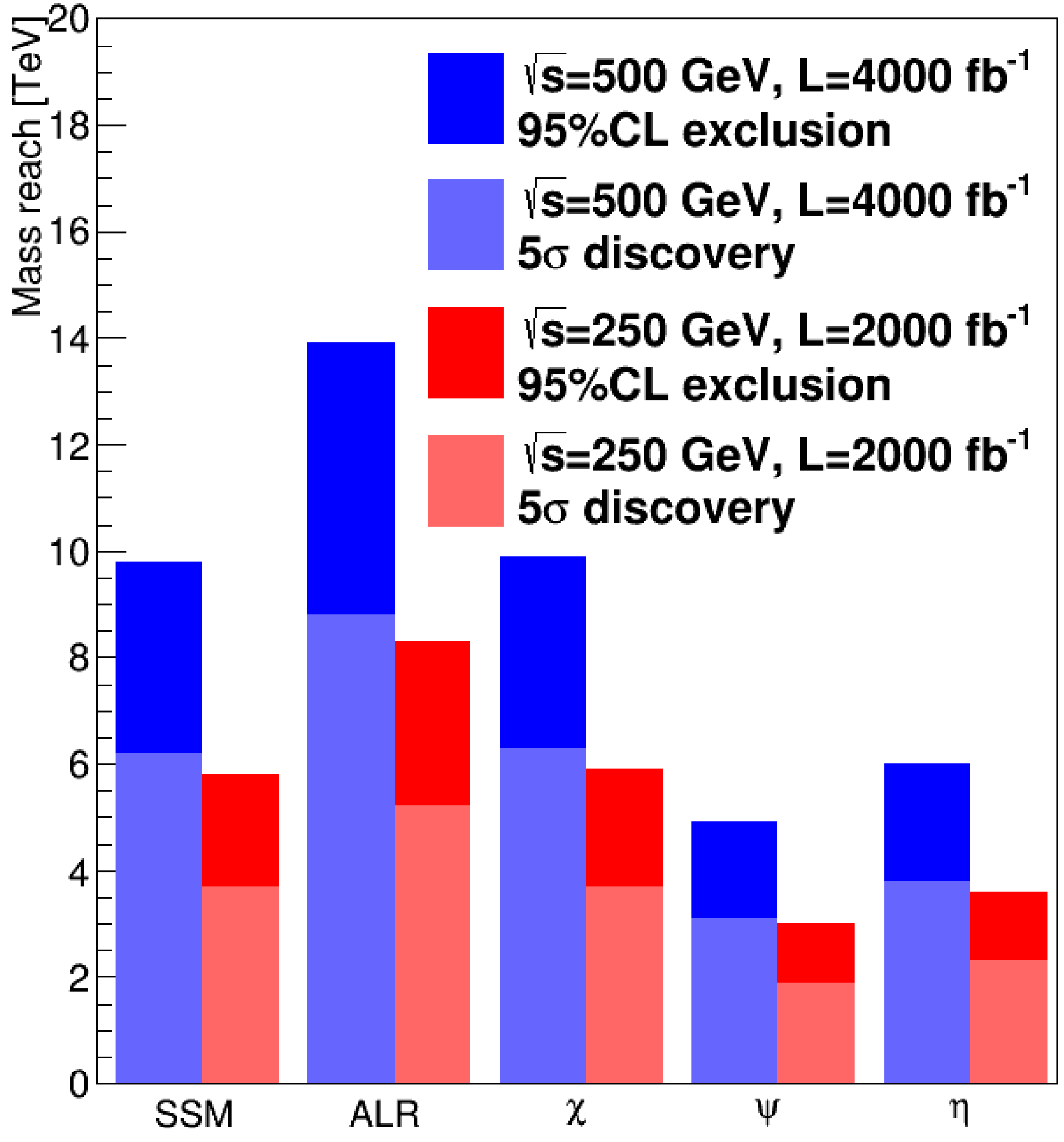


Differential cross section:

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

- $SU(2)_L xU(1)_Y$ symmetry of Standard Model introduces forward backward asymmetry and Left-Right asymmetry, i.e. $A_{i,L} \neq A_{i,R}$ => Observables highly dependent on beam polarisation
- New physics implying **new vector bosons** will modify coefficients and asymmetries
- Discovery potential in e+e- is supported best by **polarised beams**

Mass reach for vector new bosons (Z') in 2-fermion production



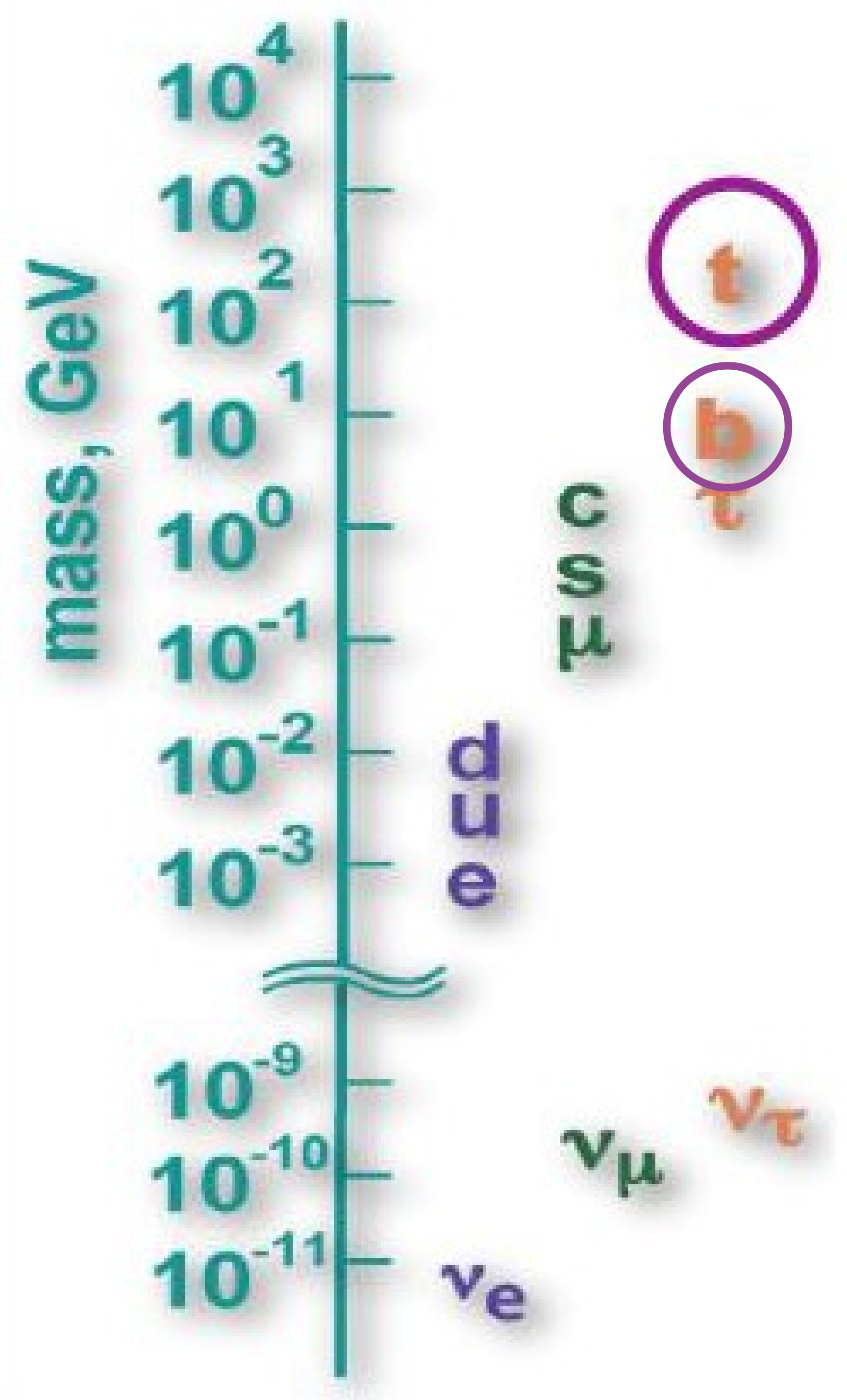
Study by Kyushu group and KEK group within TYL/FJPPL HEP01 Project

- SSM is "carbon" copy of SM Z and used as common metric in generic Z' searches
- ALR introduces an "ad hoc" $SU(2)_R$ and a Z' with orthogonal couplngs to the fermions
- X, ψ, η are linear combinations of bosons appearing in Grand Unified Theories with couplings orthogonal to the SM Z

Typical mass reach 5-10 TeV

- **Reach shown for e, μ, τ**
- **Adding quarks would improve limits**

Electroweak couplings of heavy quarks



- 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

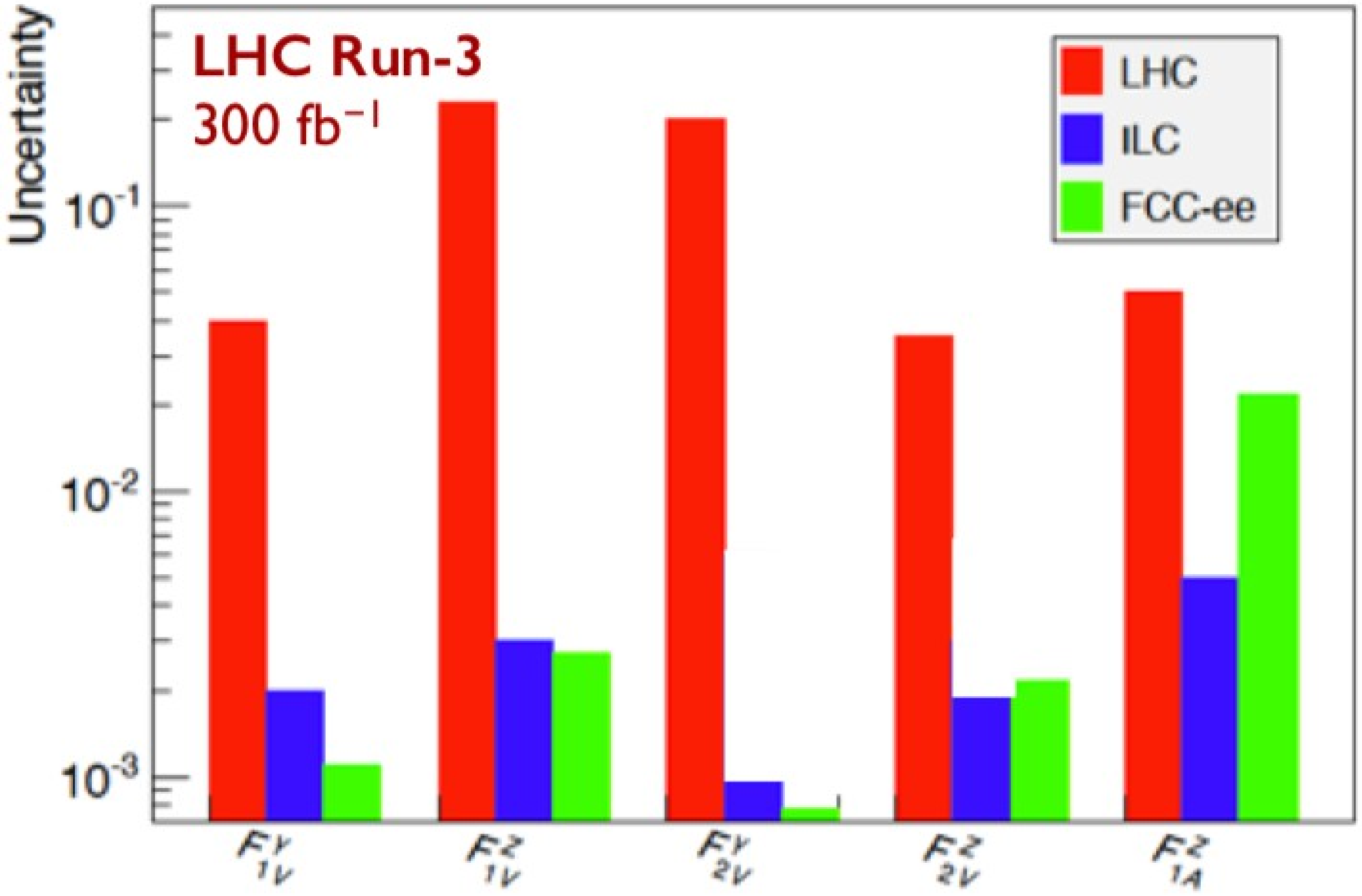
- Expect residual effects for particles with masses closest to symmetry breaking scale

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

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

Electroweak top couplings

Accuracy on CP conserving couplings



Arxiv:1503.01325
corrected for ILC values published in 1505.06020

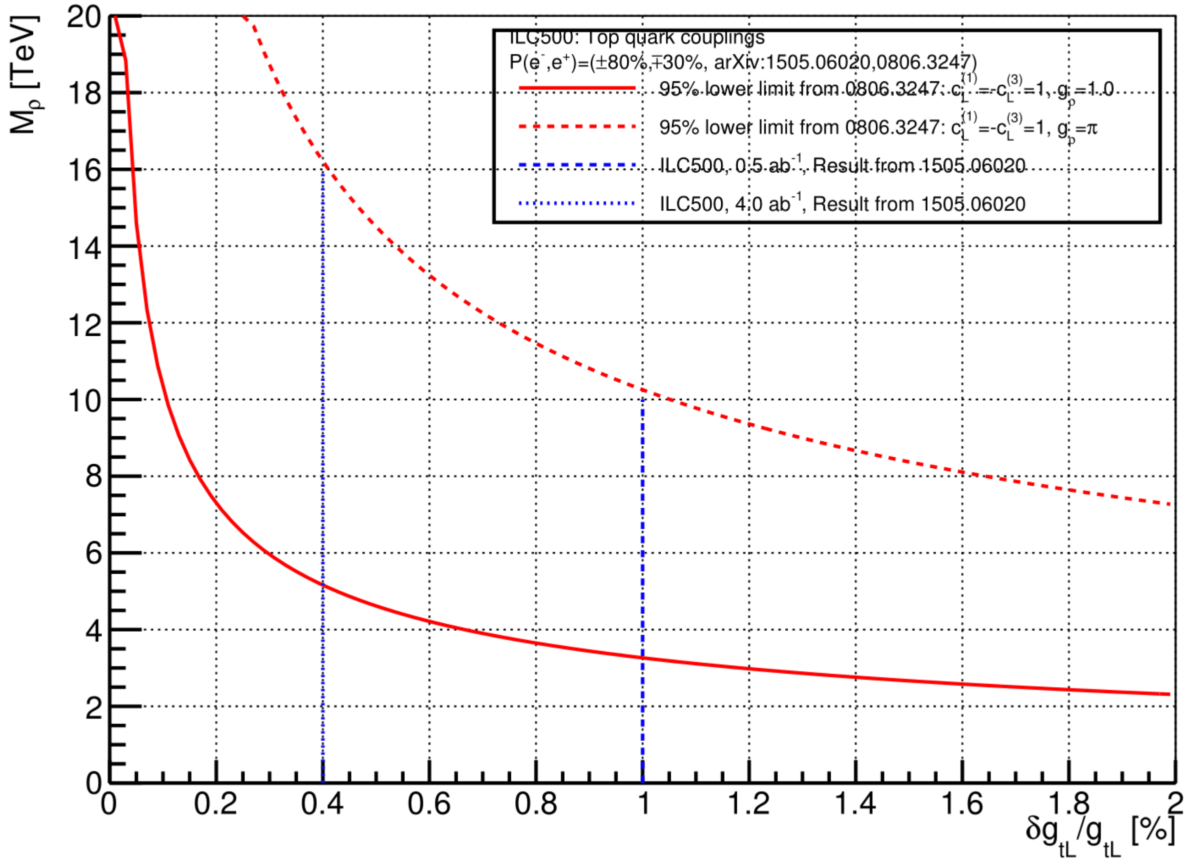
- e+e- collider might be up to two orders of magnitude more precise than LHC ($\sqrt{s}$ = 14 TeV)
- Large disentangling of couplings for ILC thanks to polarised beams
- Final state analysis at FCCee
  - Also possible at LC => Redundancy
- Note
  - Maximal Lumi scenario for FCCee
  - Minimal Lumi scenario for ILC (~factor 4 possible with increased lumi and improved selection)

LC promises to be high precision machine for electroweak top couplings
EFT Analysis for CLIC predicts mass reaches well above 10 TeV

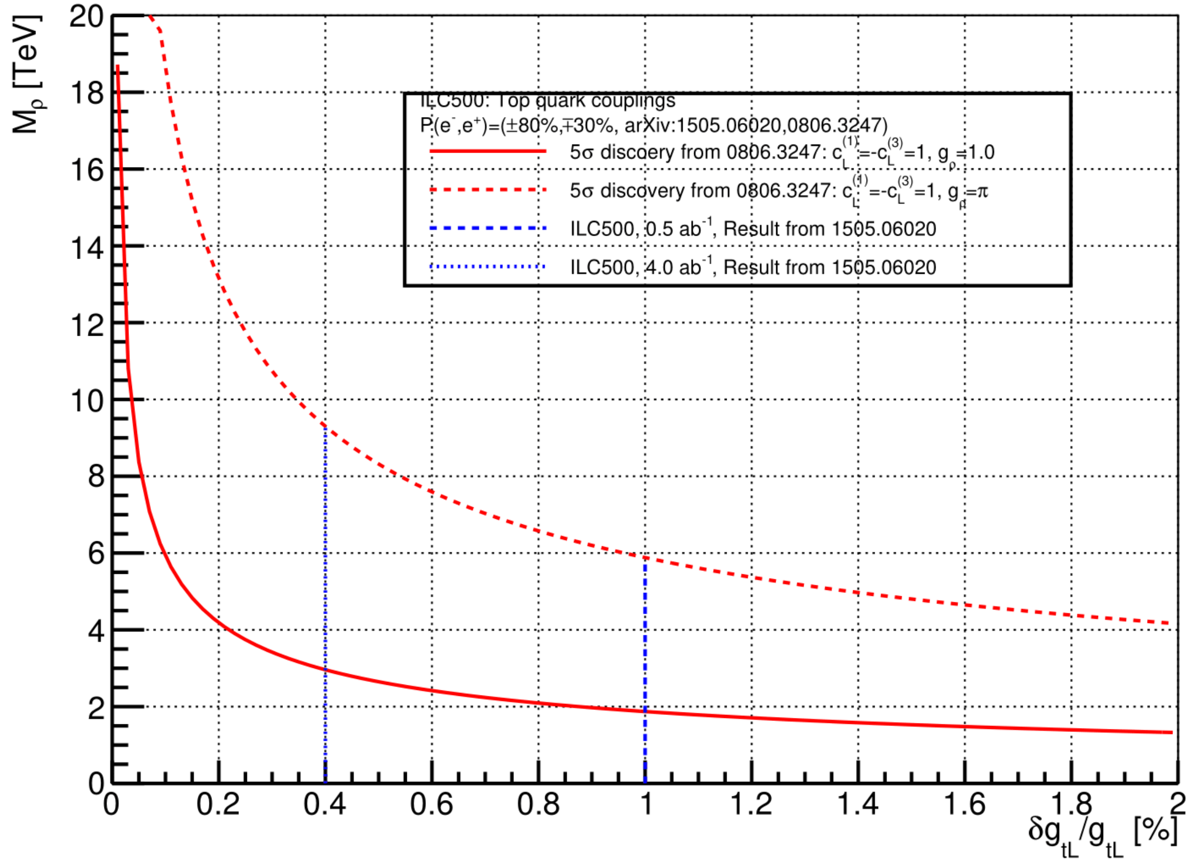
Electroweak top couplings and discovery reach

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

95% Exclusion Limit



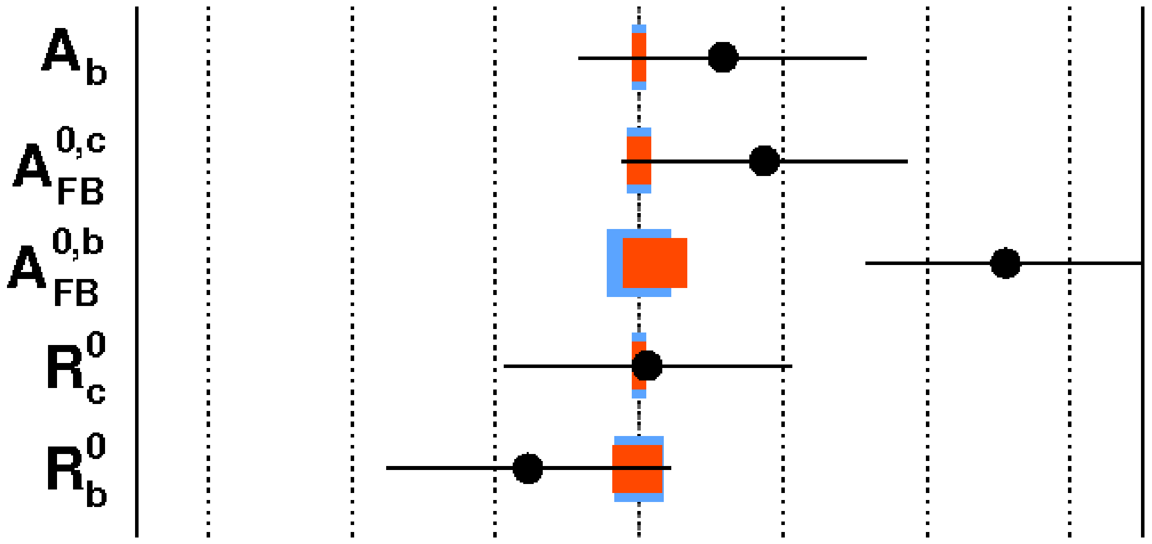
5σ discovery



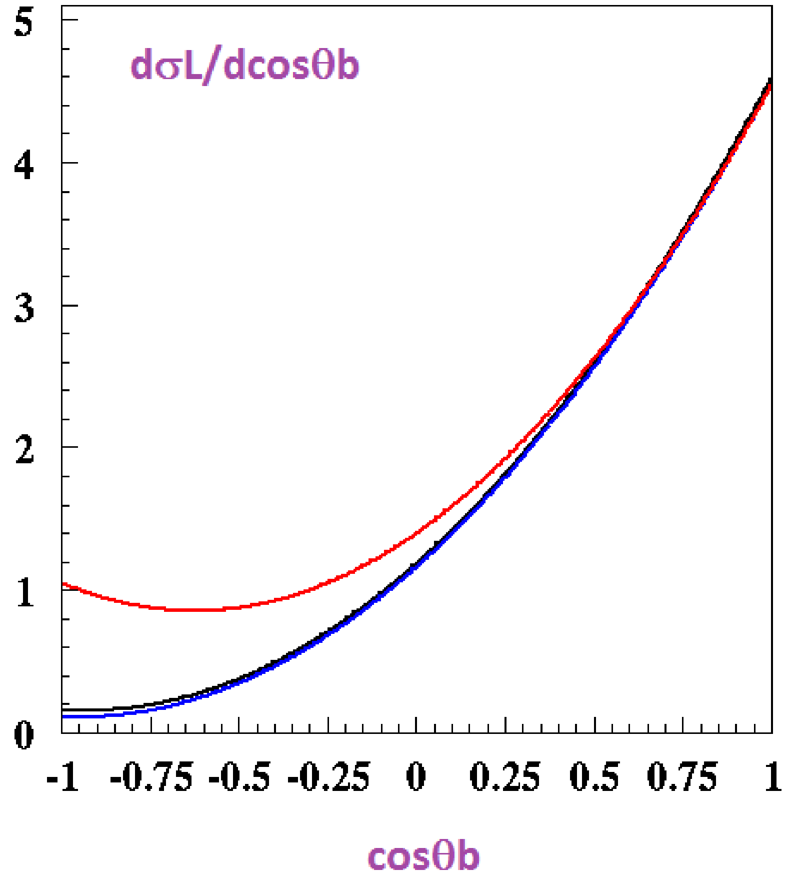
ILC@500 has discovery potential up to 10 TeV for typical BSM scenario
More cms e.g. at CLIC would of course help a great deal (also for disentangling effects)

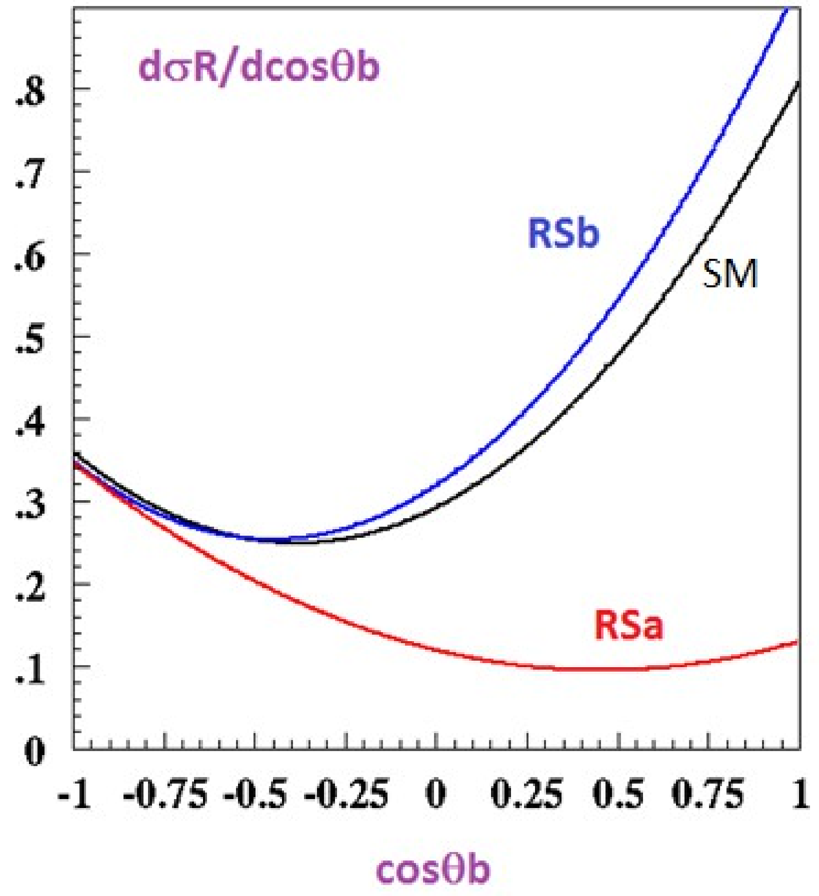
New physics below tt threshold? - Example b quark couplings

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



ee->bb@250 GeV

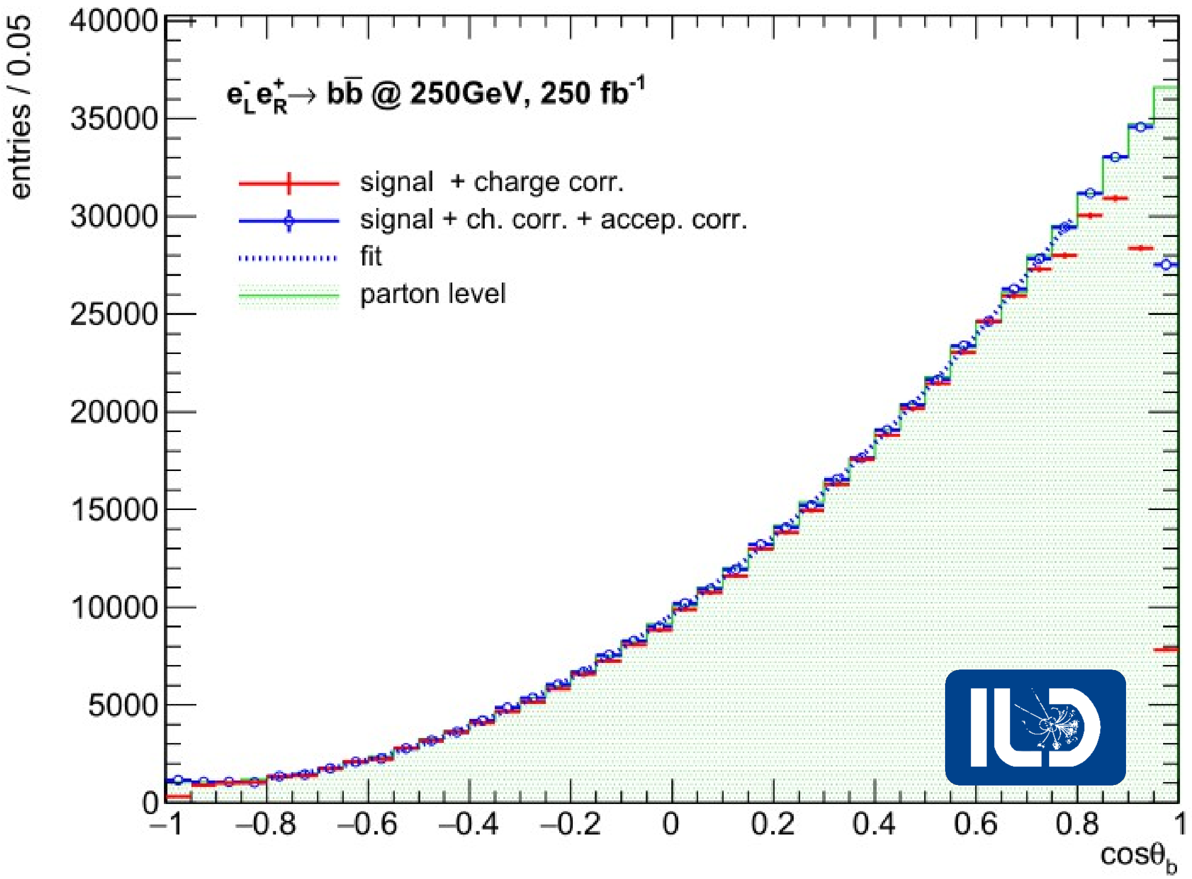


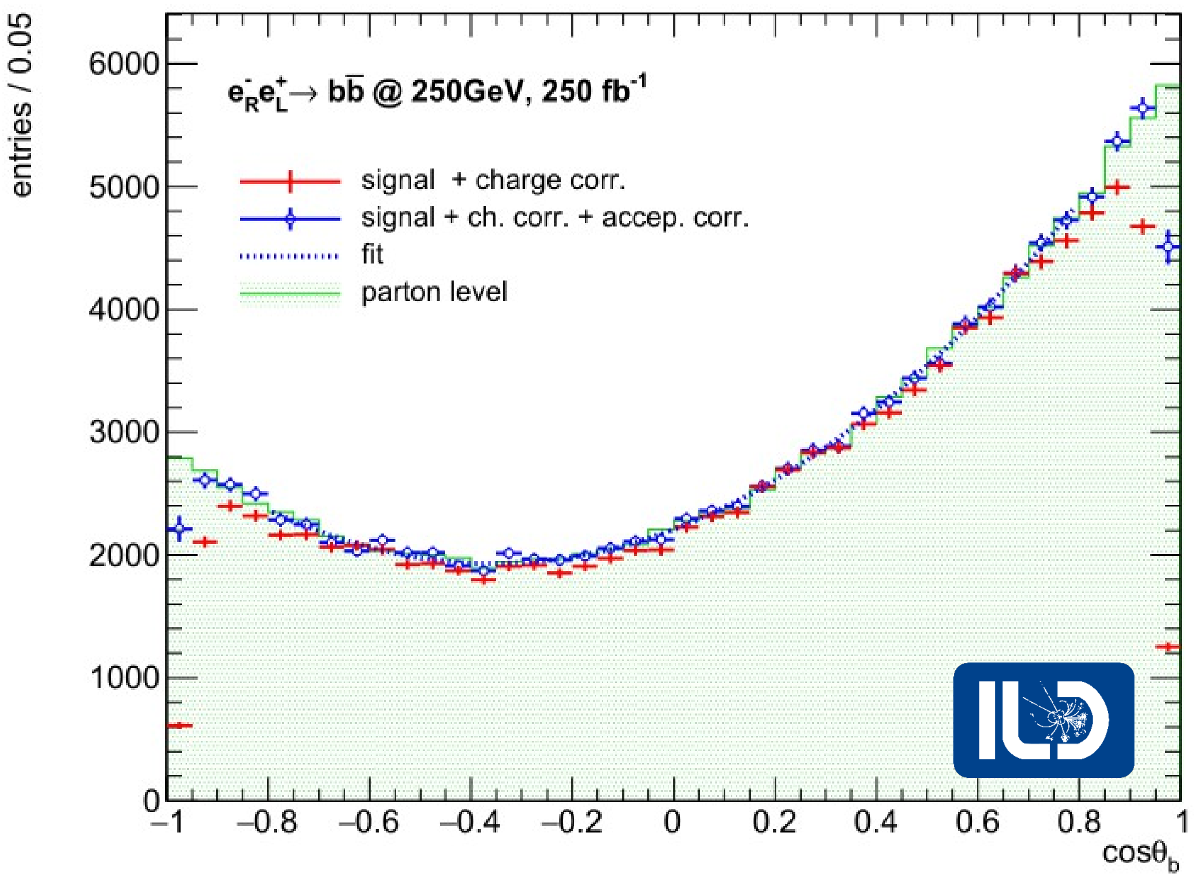


Randall Sundrum Models Djouadi/Richard '06

- 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
- Randall Sundrum Models generate basically automatically a symmetry group of type $SU(2)_R$

Decomposing ee->bb – Differential cross section





Study by S. Bilokin (TYL/FJPPL Laureate) and A. Irles (LAL) within TYL/FJPPL HEP01 Project

- 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 from factors or couplings

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

Form factors/couplings from S and A

-

Precision on couplings and helicity amplitudes in ee->bb

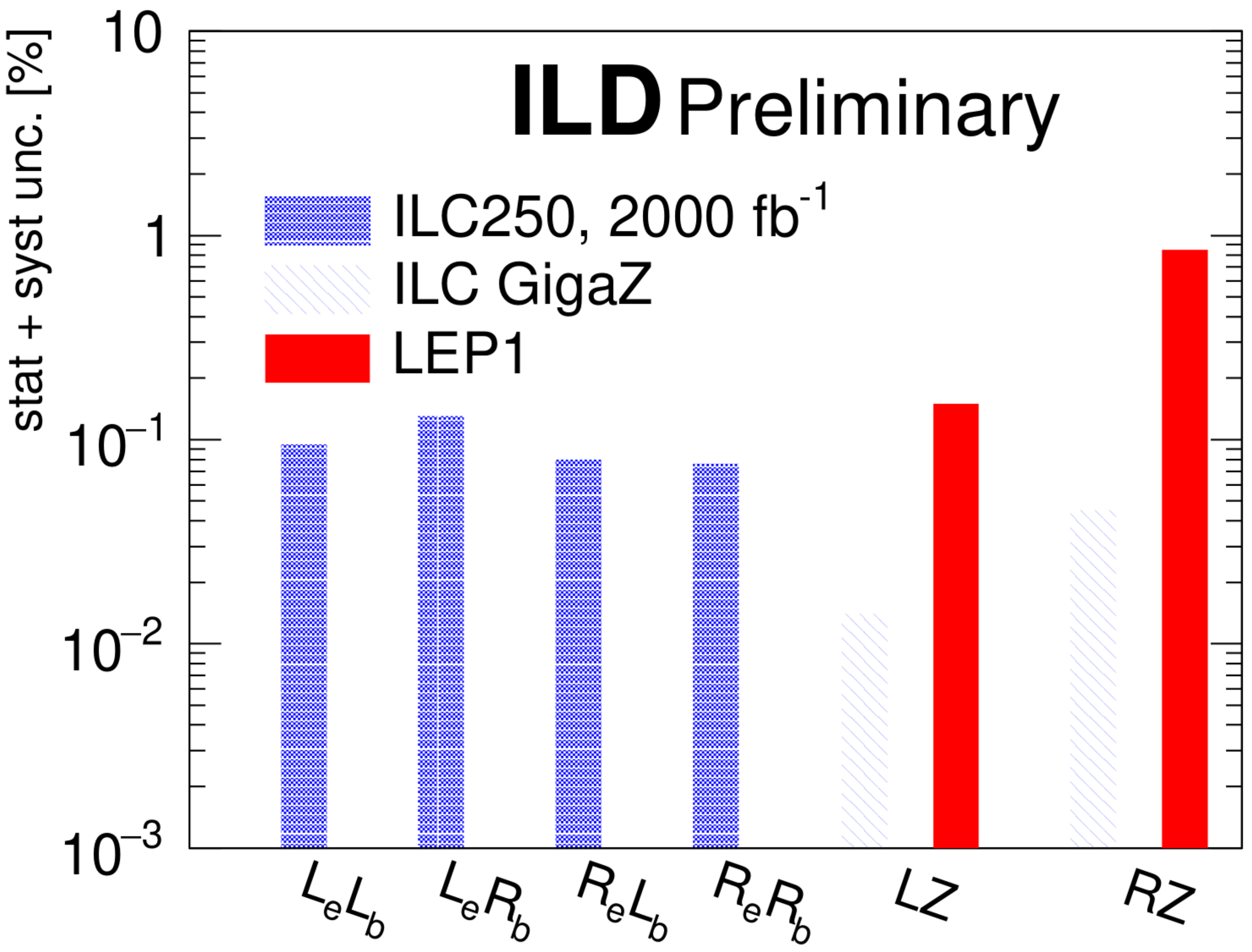


Figure: A. Irles

$$\mathrm{LeLb} = QeQb + \frac{LeZLbZ}{s^2wc^2w}BWZ + \sum_{Z'} \frac{LeZ'LbZ'}{s^2wc^2w}BWZ'$$

- Couplings are order of magnitude better than at LEP

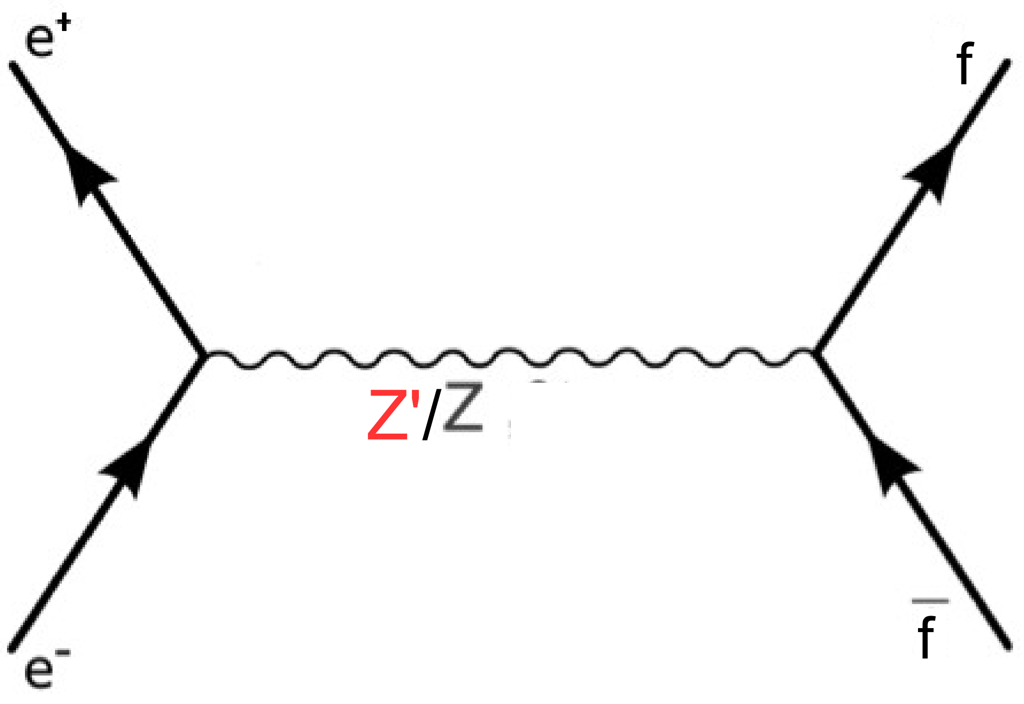
- In particular right handed couplings are much better constrained
- => Sensitivity to 'right handed' Z' (see above)

- Presentation of helicity amplitudes preferrable since new physics can also infliuence the Zee vertex
  - in 'non top-philic' models

- Full disentangling of helicity structiure for all fermions only possible with polarised beams!!

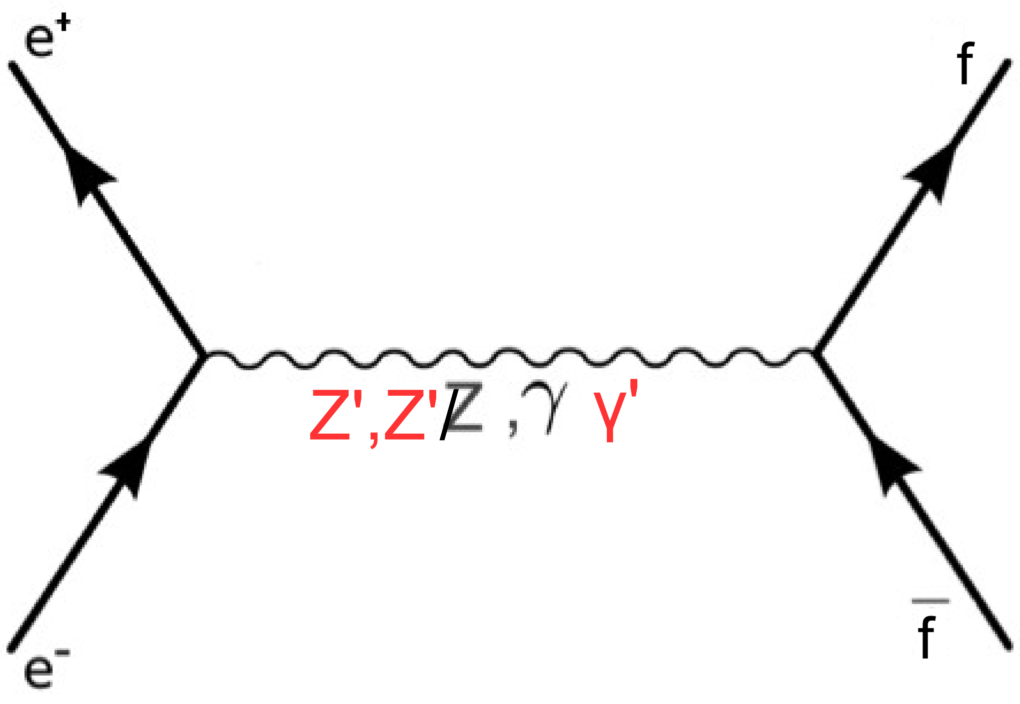
How can the Z-pole help?

On the Z-pole



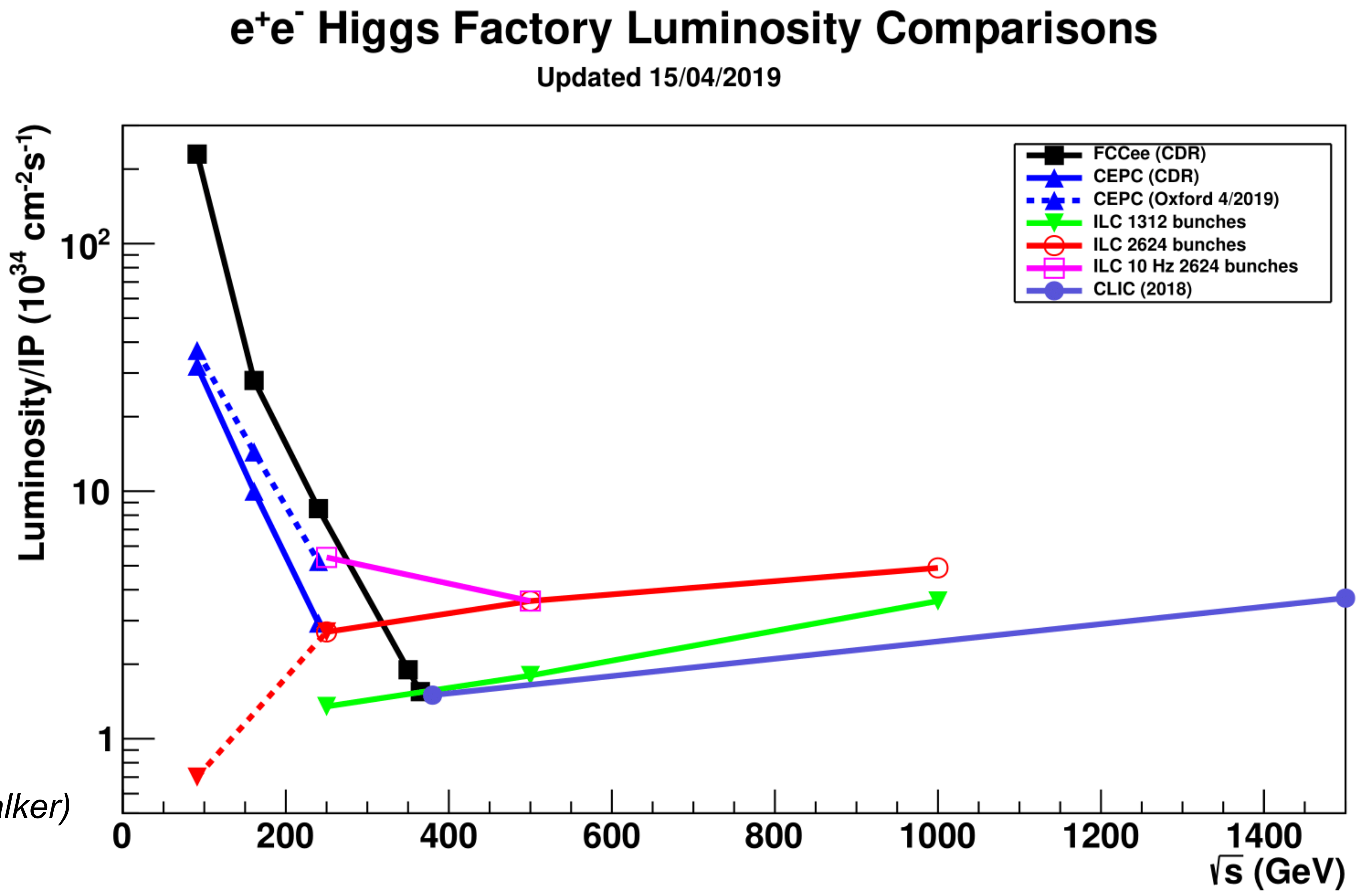
- ILC/GigaZ with ~10^9 Z
- Sensitivity to Z/Z' mixing
- Sensitivity to vector (and tensor) couplings of the Z
  - the photon does not "disturb"

Above the Z-pole



- Sensitivity to interference effects of Z and photon!!
- Measured couplings of photon and Z can be influenced by new physics effects
- Interpretation of result is greatly supported by precise input from Z pole

For the record – ILC with (inofficial) extension to the Z pole



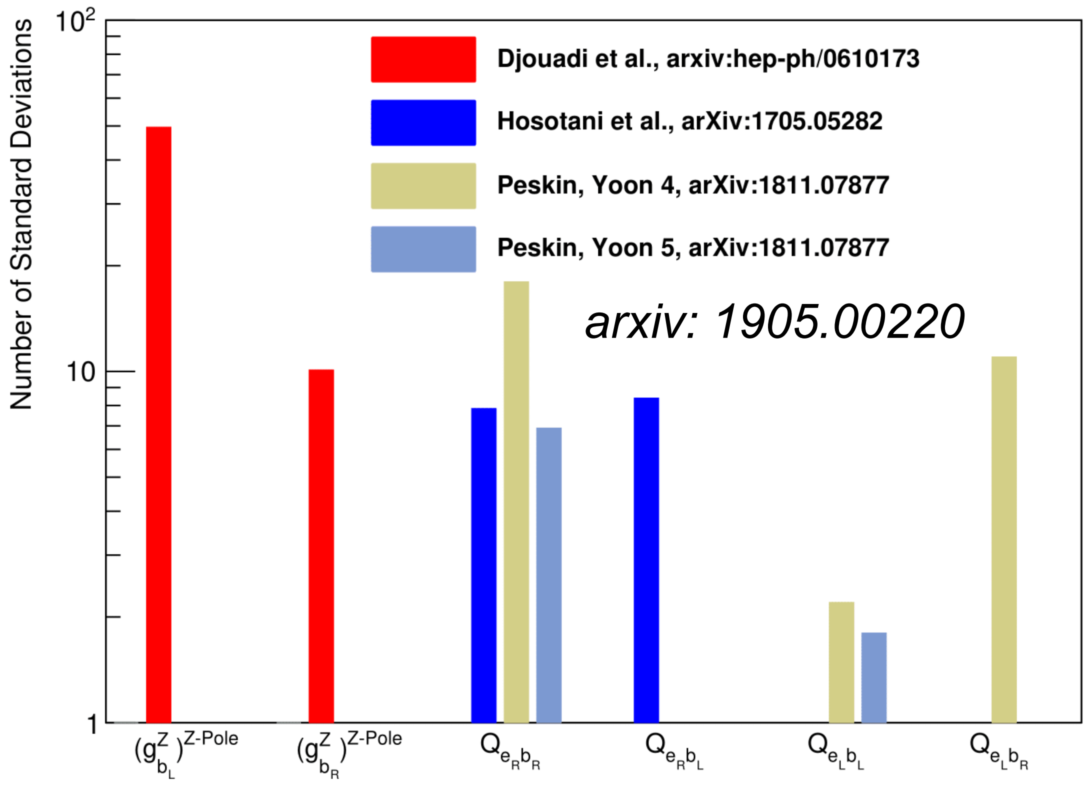
Plot by M. Stanitzki

Number follow discussion between H. Yamamoto, S. Michizono and F. Richard (see also LC-Note by Nick Walker)

- Option for Z-Pole extension exists for ILC (may need to be further scrutinized)
- It is useful to remind on the potential of a linear collider running on the pole

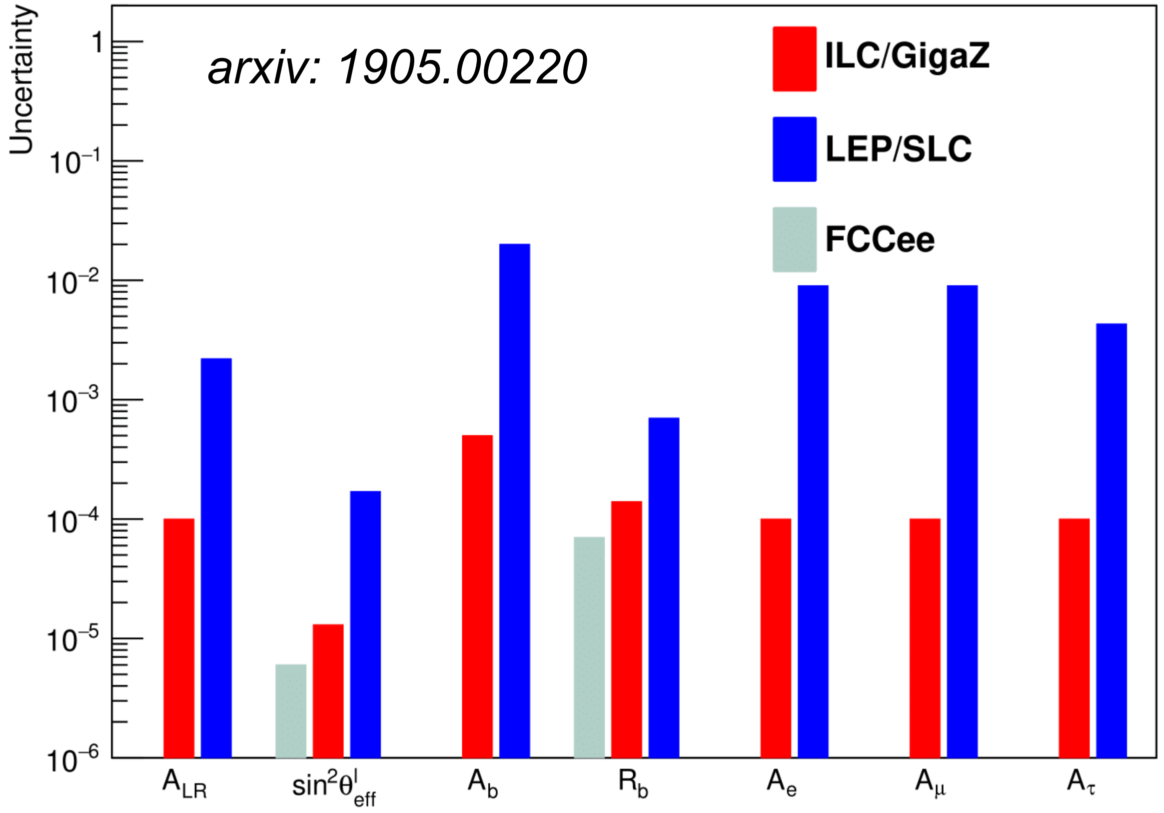
Precision on Z-pole and interplay with measurements above pole

Example: b couplings and helicity amplitudes



- Spectacular sensitivity to new physics in RS Models
  - **Complete tests only possible at LC**
  - **Discovery reach O(10 TeV)@250 GeV and O(20 TeV)@500 GeV**
- Pole measurements critical input
  - Only poorly constrained by LEP
- Pole measurements will (most likely) influence also top electroweak precision program
  - (t,b) doublet

Don't forget: Electroweak observables



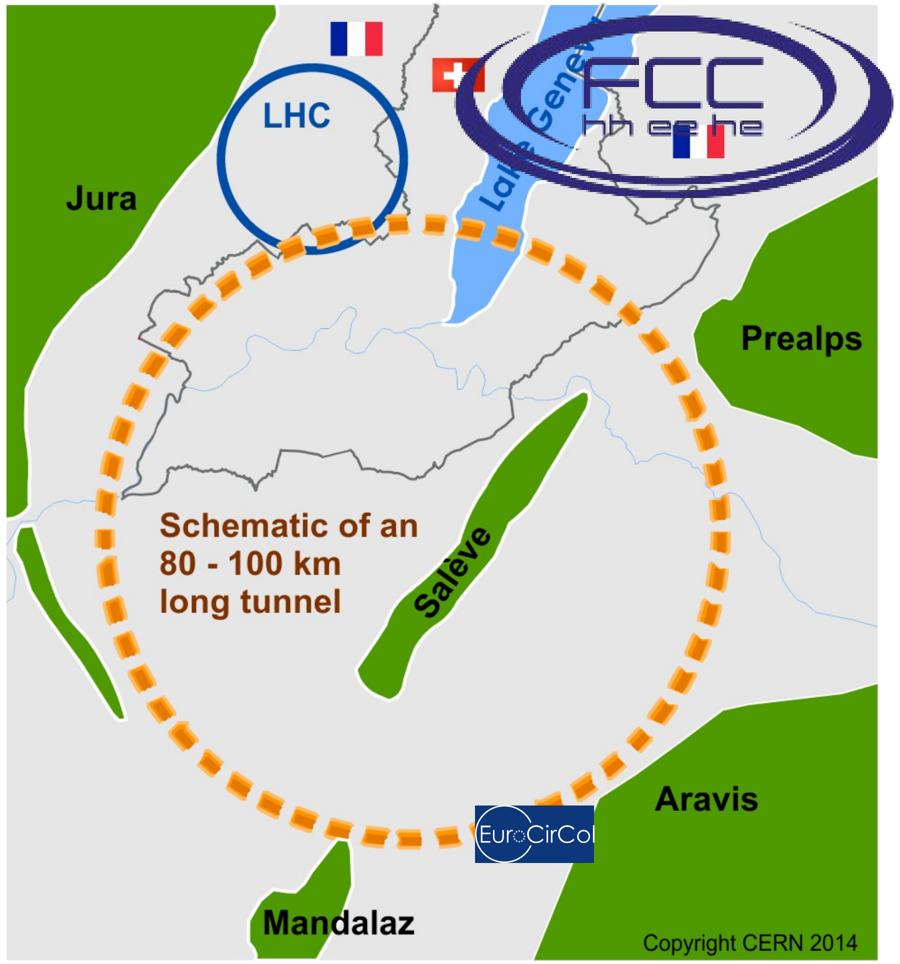
- Precise measurement of $\sin^2\theta^\ell_{\rm eff}$.
  - Ten times better than LEP/SLD
  - Polarisation compensates for ~30 times luminosity
  - ... and ALR at LC can benefit from hadronic Z decays
  - **No assumption on lepton universality at LC**
- Complete test of lepton universality
  - Precisions of order 0.05%
- Excellent control of beam polarisation(dP/P ~ 5x10^{-4}) and beam energy (~MeV or better) required

Summary and conclusion

- As of today e+e- colliders are the most promising tools to detect the onset of new physics
  - Precision on Higgs couplings at or below 1% level
  - Indrect and direct discovery potential at all centre-of-mass energies
  - Light scalars or vector bosons with different gauge symmetry
- e+e- colliders ranked high in international strategies for particle physics (by scientists)
  - Clear priority in inputs to European Strategy:
    - long term contributions to ILC
    - CLIC project @CERN
    - FCC-ee CDR
  - Asia:
    - ILC discussed at gouvernmental level in Japan for implementation
    - CEPC CDR
  - US: ILC is integral part of P5 strategy
- Full exploitation of physics potential requires large energy coverage and polarised beams
  - Effects at HZ threshold and below are expected to become more prominent at higher energies
  - New physics signals and relevant operators depend on chiral state of initial and final state fermions
  - Both premises are fulfiled only by linear e+e- colliders (=> preferred choice!?)
- ILC is shovel ready. Why don't we build it?
- A clear pattern of anomalies would be an excellent (and maybe the only) motivation for a large hadron machine

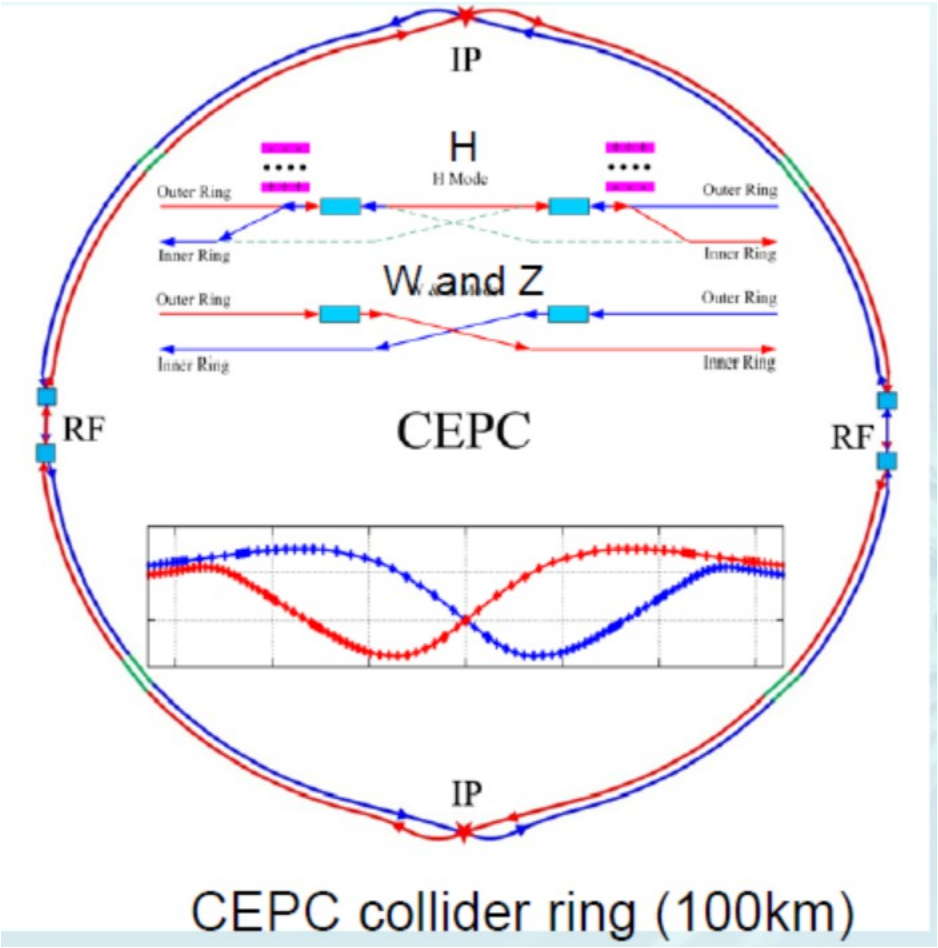
Backup

Circular Electron-Positron Colliders



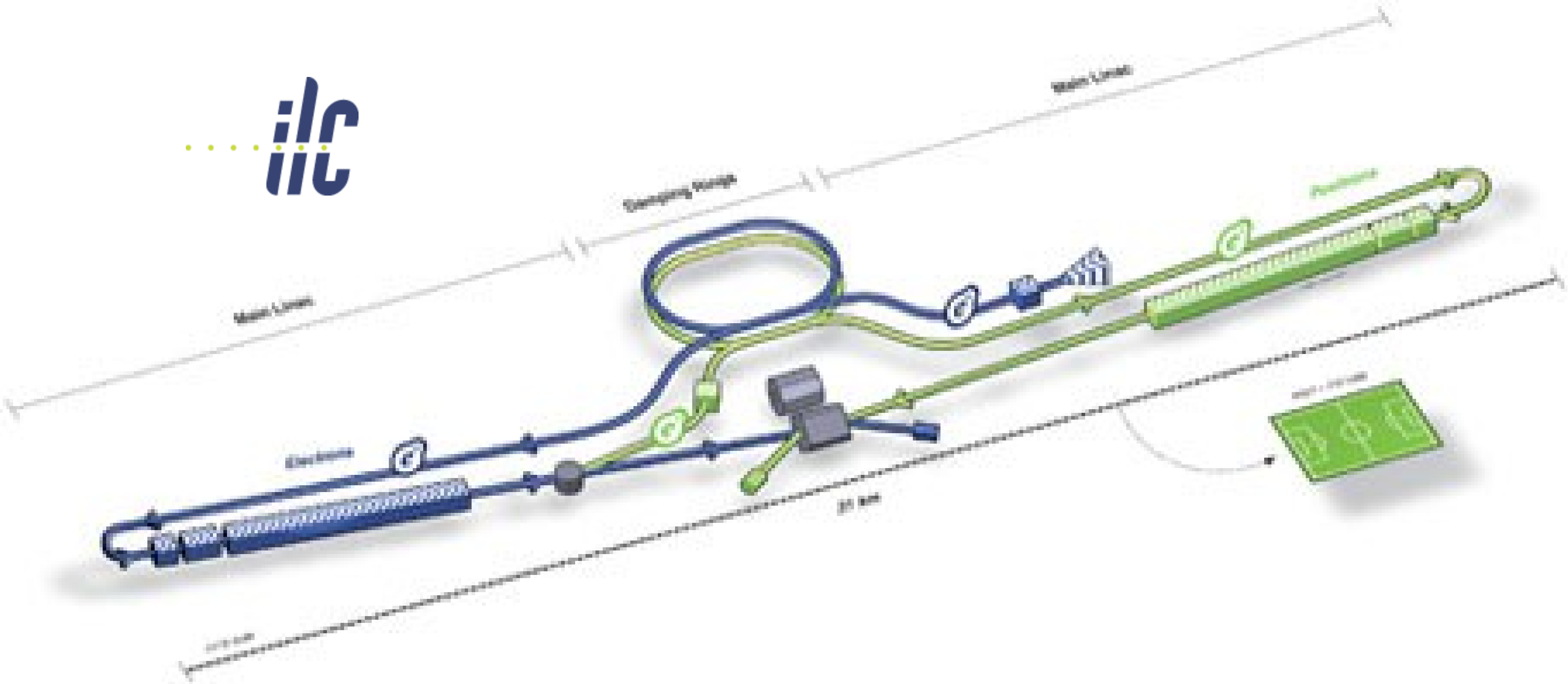
- ~100 km storage rings
- Coupled to hadron collider proposal
- 90 – 350 GeV cms energy
- No long. beam polarisation
- CDR completed January 2019
  http://fcc-cdr.web.cern.ch

CEPC



- ~100 km storage rings
- Coupled to hadron collider proposal
- 90 – 240 GeV cms energy
- No long. beam polarisation
- CDR completed September 2018
- Arxiv:1809.00285

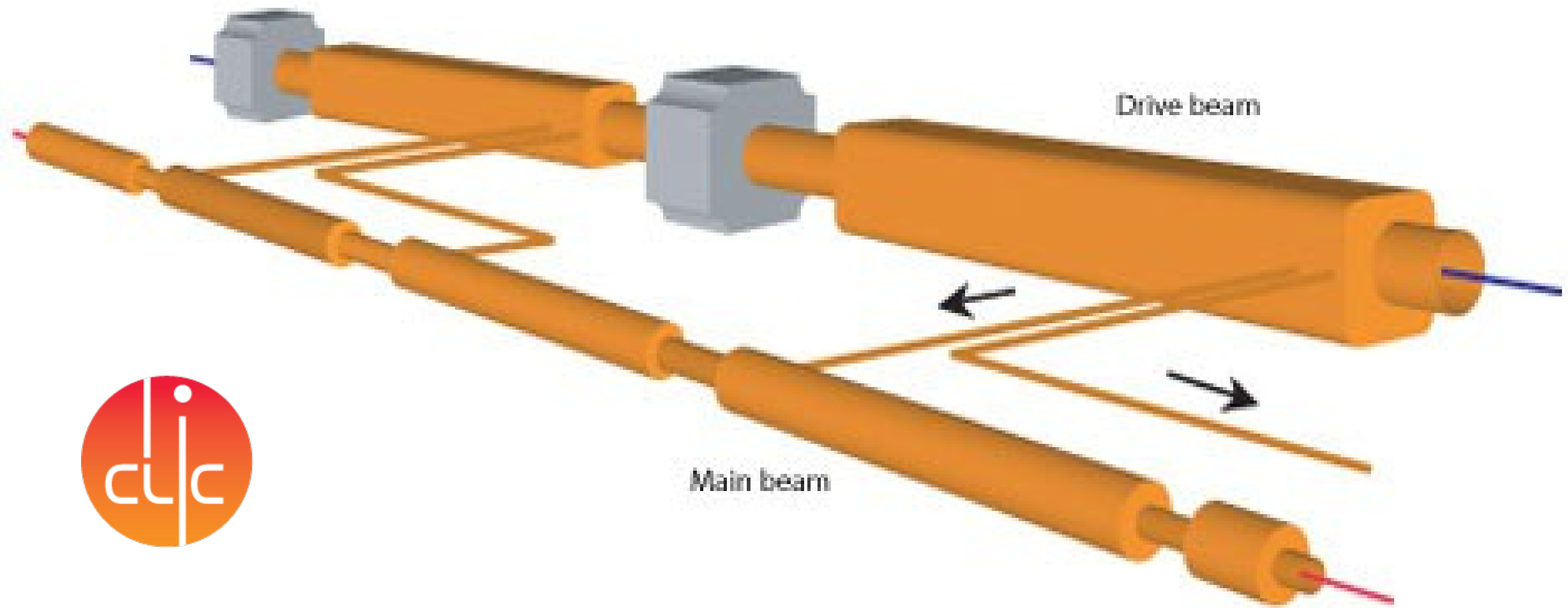
Linear Electron-Positron Colliders



Japanese Gouvernment expressed its interest in project in March 2019

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

Initial Energy 250 GeV – Footprint ~20km



Possible future project at CERN

Energy: 0.4 - 3 TeV

CDR in 2012

Footprint 48km

Initial Energy 380 GeV

New physics?

EFT: Two distinct observations

Observables at fixed mass m
(e.g. Z pole of Higgs decays)

$$\frac{\sigma}{\sigma_{SM}} \approx |1 + \frac{c_6 m^2}{\Lambda^2}|^2$$

Increasing UV scales probed in EFT achieved solely by increasing the measurement precision

$c_6 \sim (g^*)^2$

Typical experimental precision 0.1-1%

High energy tails of distributions
(e.g. Drell-Yan Productions

$$\frac{\sigma}{\sigma_{SM}} \approx |1 + \frac{c_6 E^2}{\Lambda^2}|^2$$

Increasing UV scales probed in EFT achieved solely by increasing the energy scale of measurement precision

Typical experimental precision 10%

A. Falkowski, Journée Grands Accél., LAL

New physics?

- Polarized beams play a crucial role in disentangling the two spin structures

$$\sigma = \frac{2}{3}\frac{\pi\alpha_w^2}{c_w^4}\frac{m_Z^2}{(s-m_Z^2)}\frac{2k_Z}{\sqrt{s}}(2+\frac{E_Z^2}{m_Z^2})\cdot Q_Z^2\cdot\left[1+2a+2\,\frac{3\sqrt{s}E_Z/m_Z^2}{(2+E_Z^2/m_Z^2)}\,b\right]$$

The a and b coefficients depend on beam polarization:

$e^-_L e^+_R$

$$Q_{ZL} = (\frac{1}{2} - s_w^2)\ , \qquad a_L = -c_H$$

$$b_L = c_w^2(1 + \frac{s_w^2}{1/2 - s_w^2}\frac{s - m_Z^2}{s})(8c_{WW})$$

$e^-_R e^+_L$

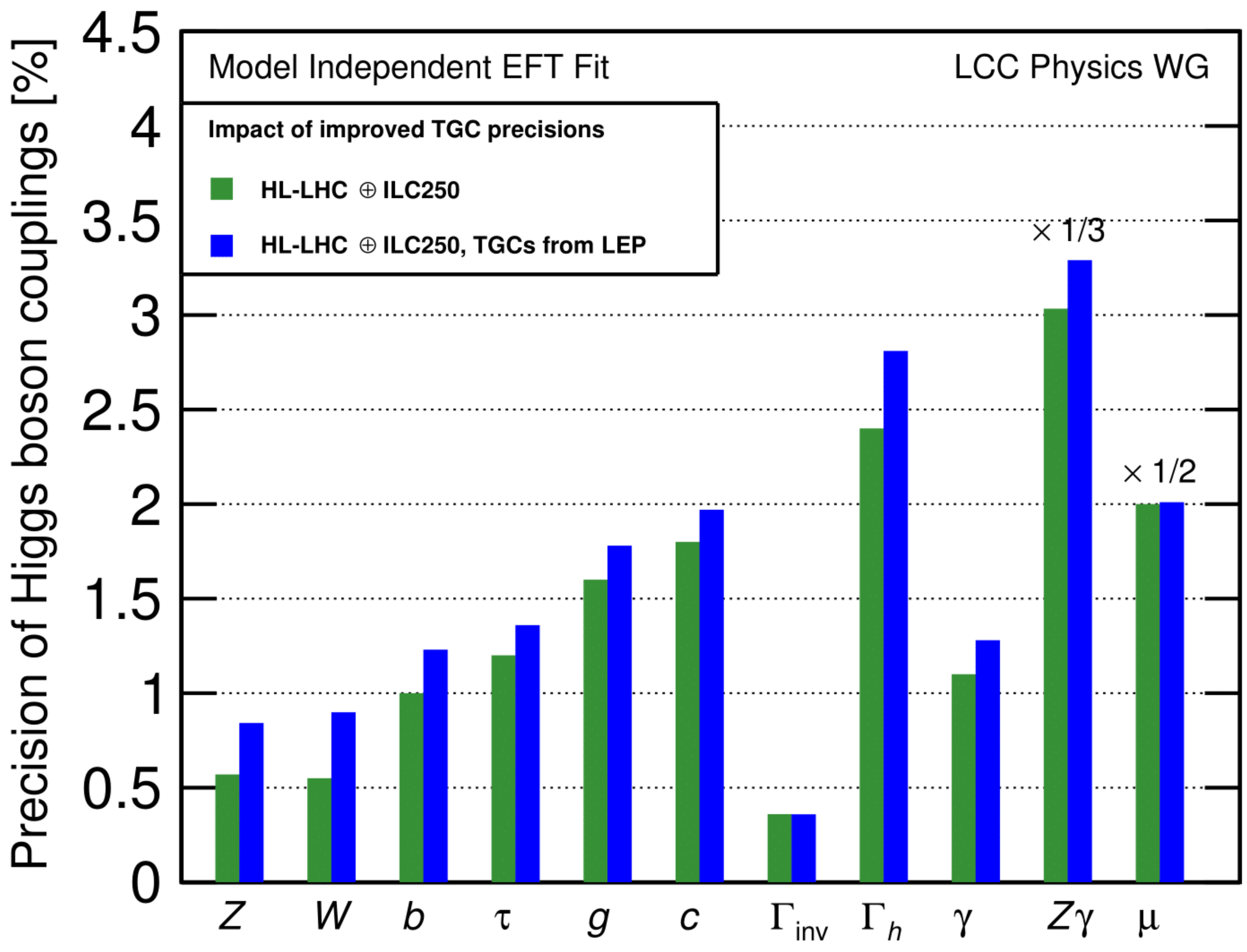
$$Q_{ZR} = (-s_w^2)\ , \qquad a_R = -c_H$$

$$b_R = c_w^2(1 - \frac{s - m_Z^2}{s})(8c_{WW})$$

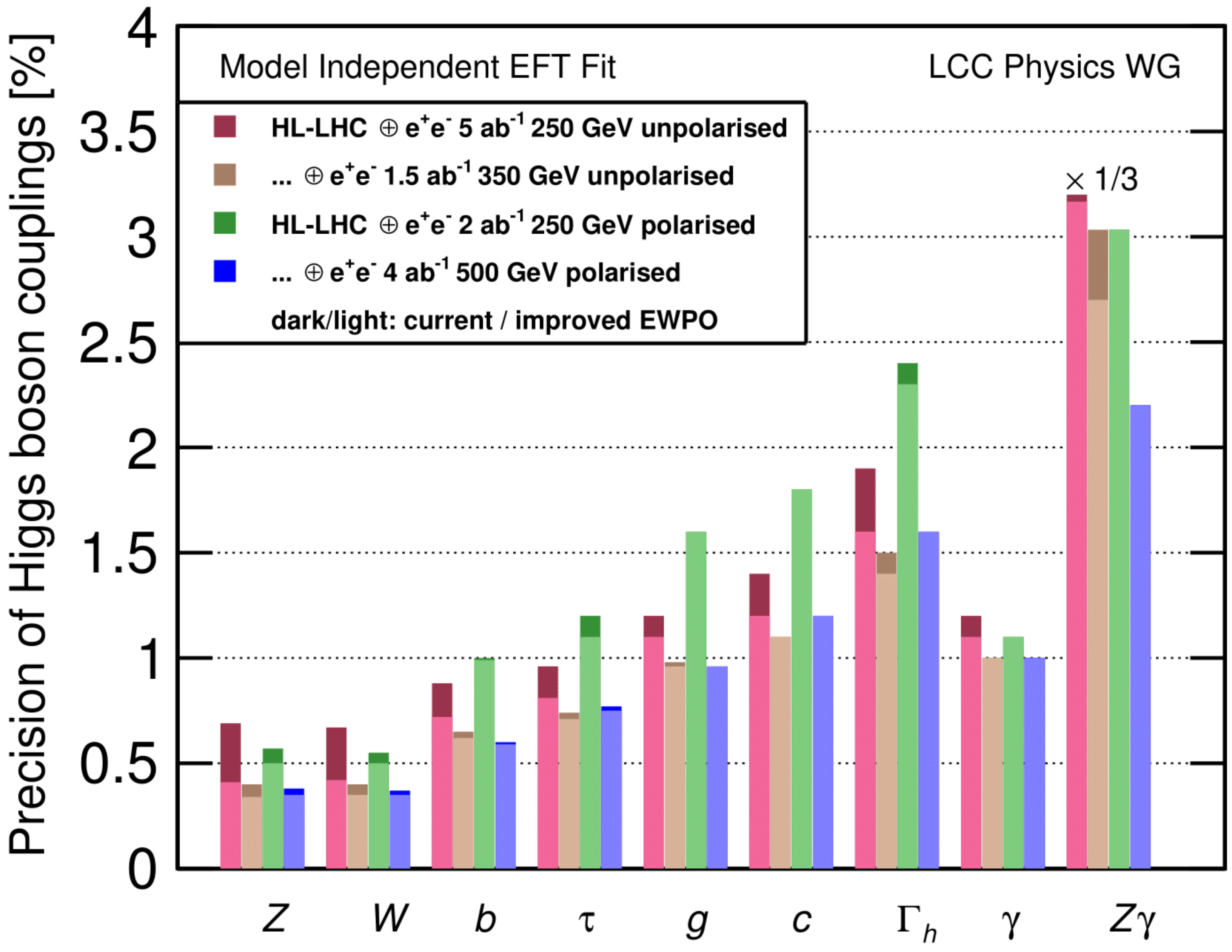
- Angular distributions in $e^+e^- \to hZ$ can also be used, but have weaker analyzing power and require more luminosity to achieve the same result

M. Perelstein: AWLC2017

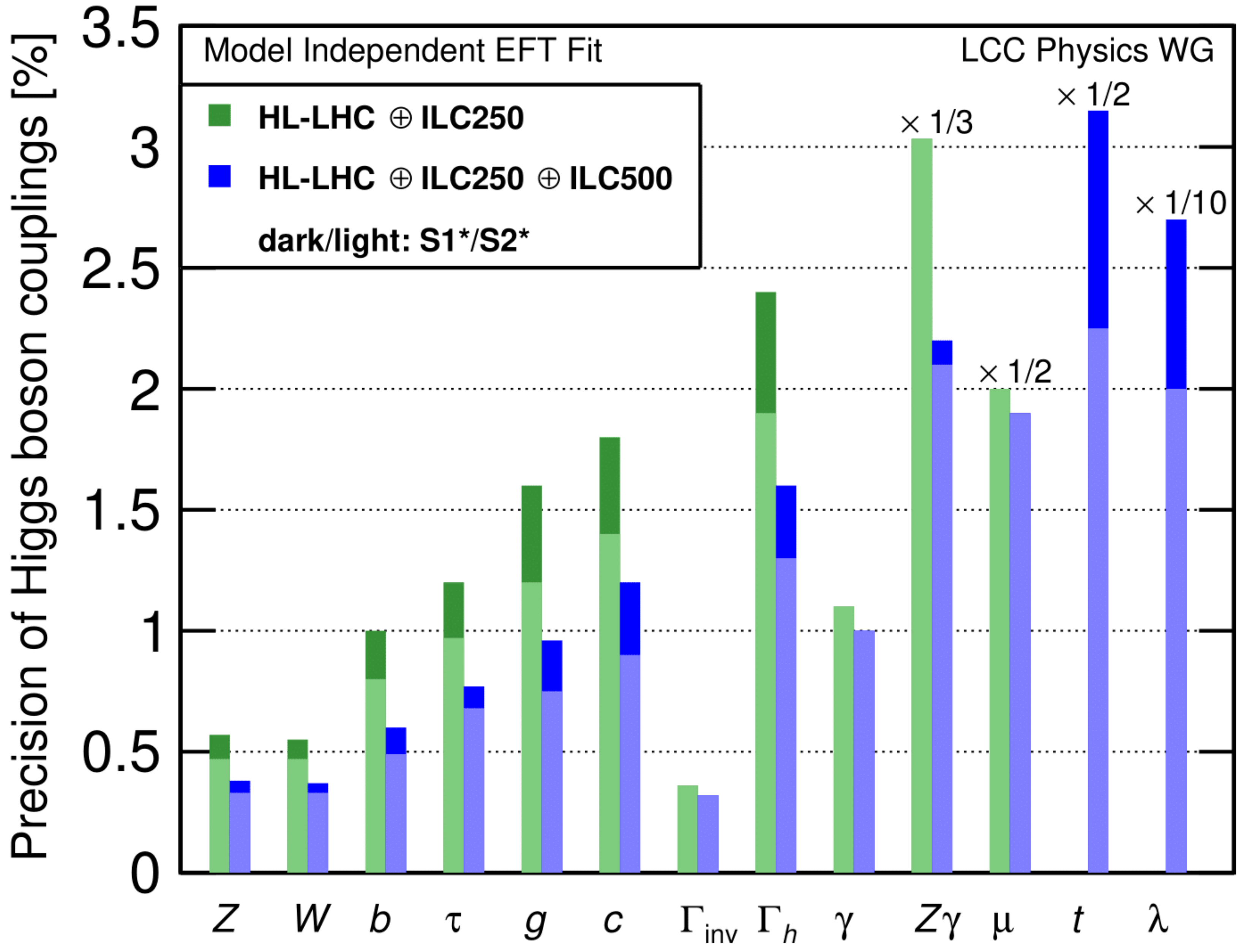
Higgs couplings – Impact of TGC



Higgs couplings – Polarisation + EWPO

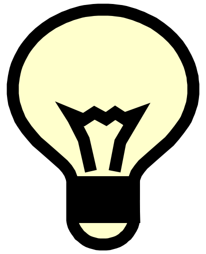


Higgs couplings – Polarisation + EWPO

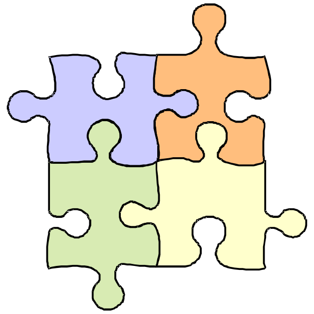


Science drivers

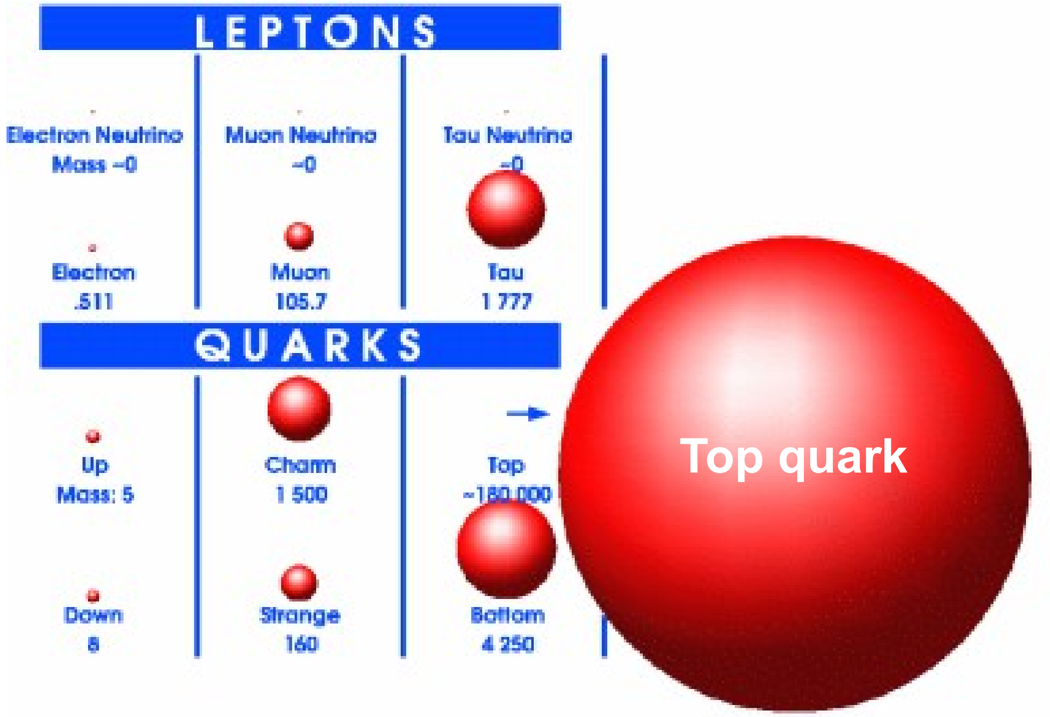
Higgs Boson



Elementary Scalar?



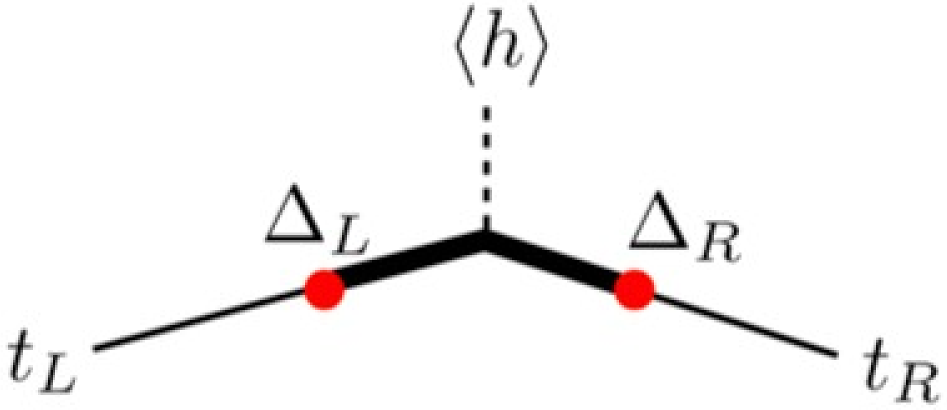
Composite object?



- 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?

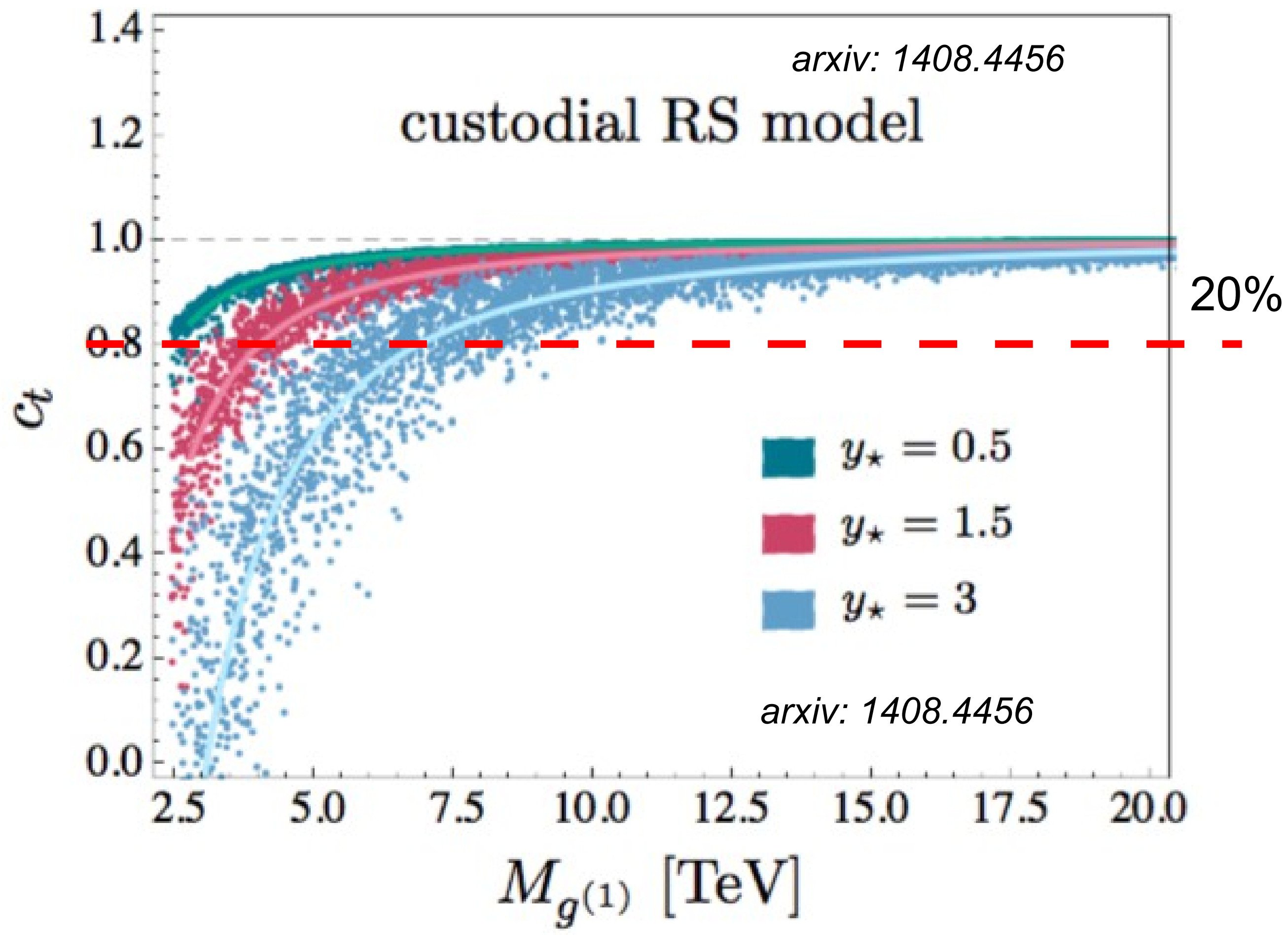
- e+e- collider perfectly suited to decipher both particles

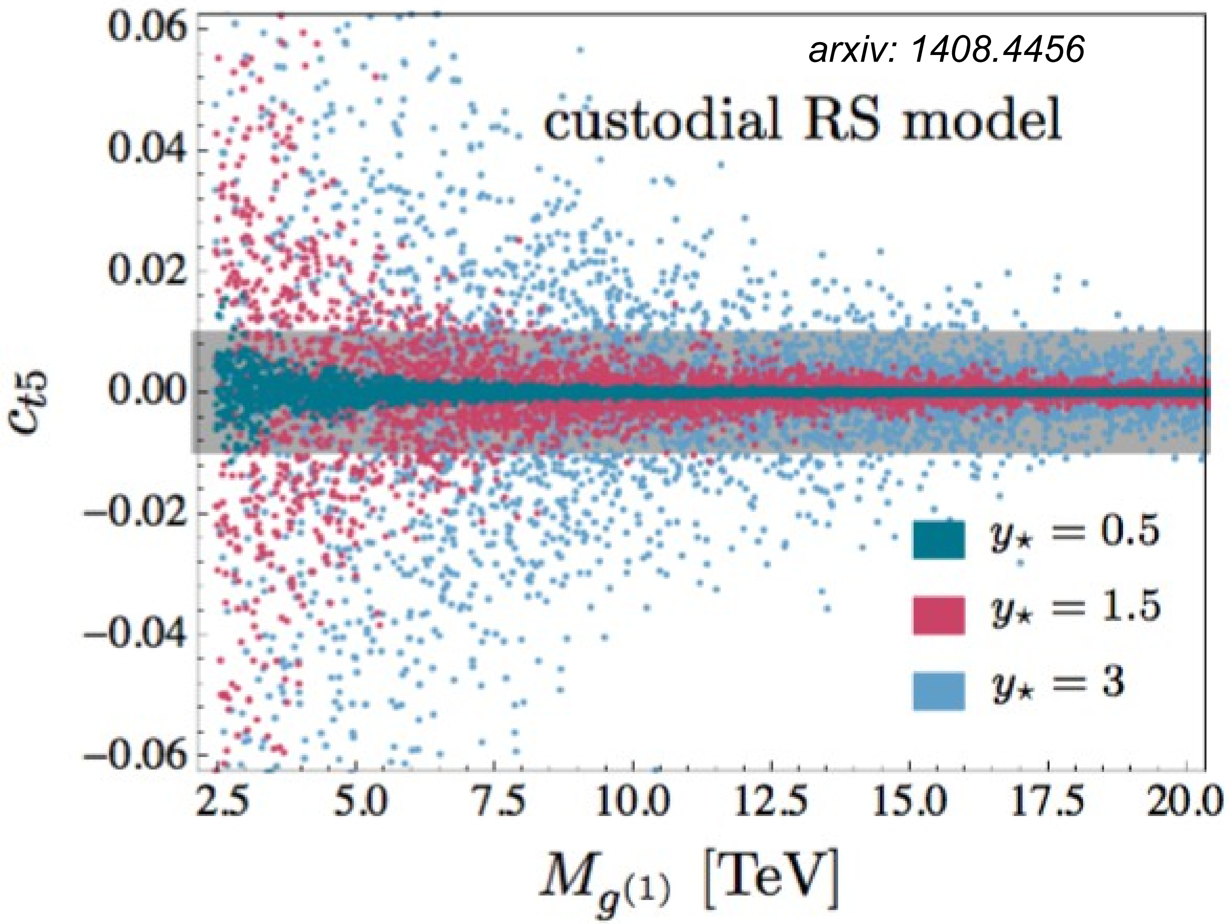


Courtesy of S. Rychkov

Top Yukawa Coupling and New Physics

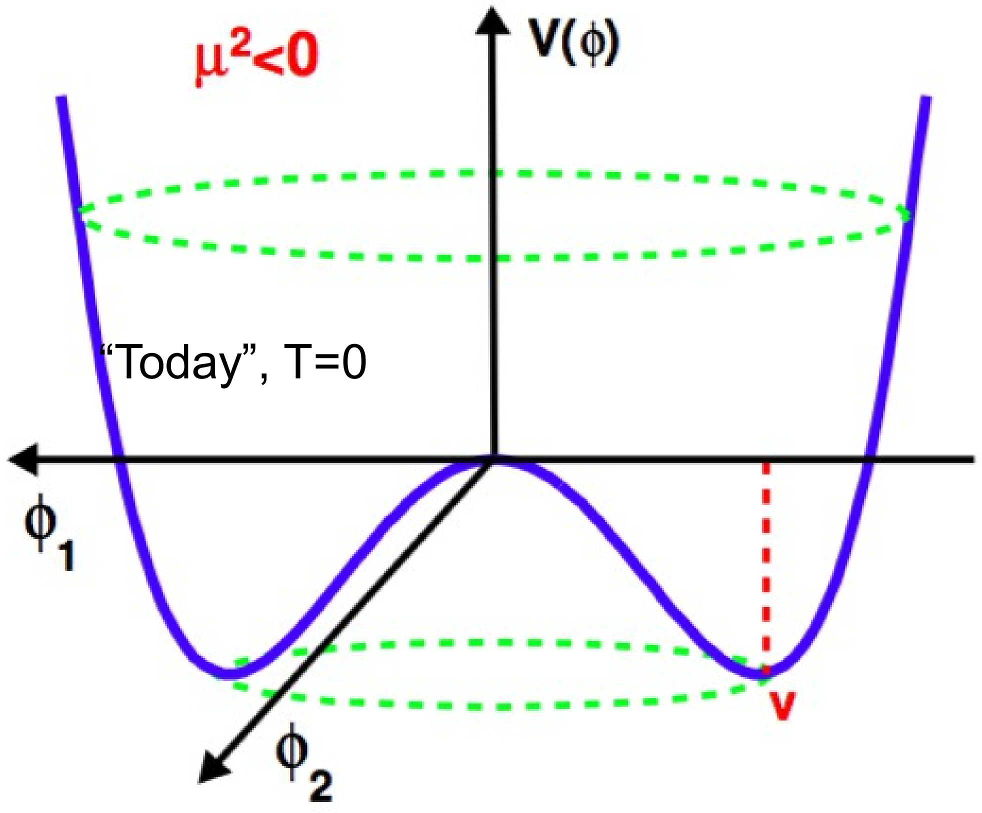
Top-Higgs couplings in “presence” of heavy particles

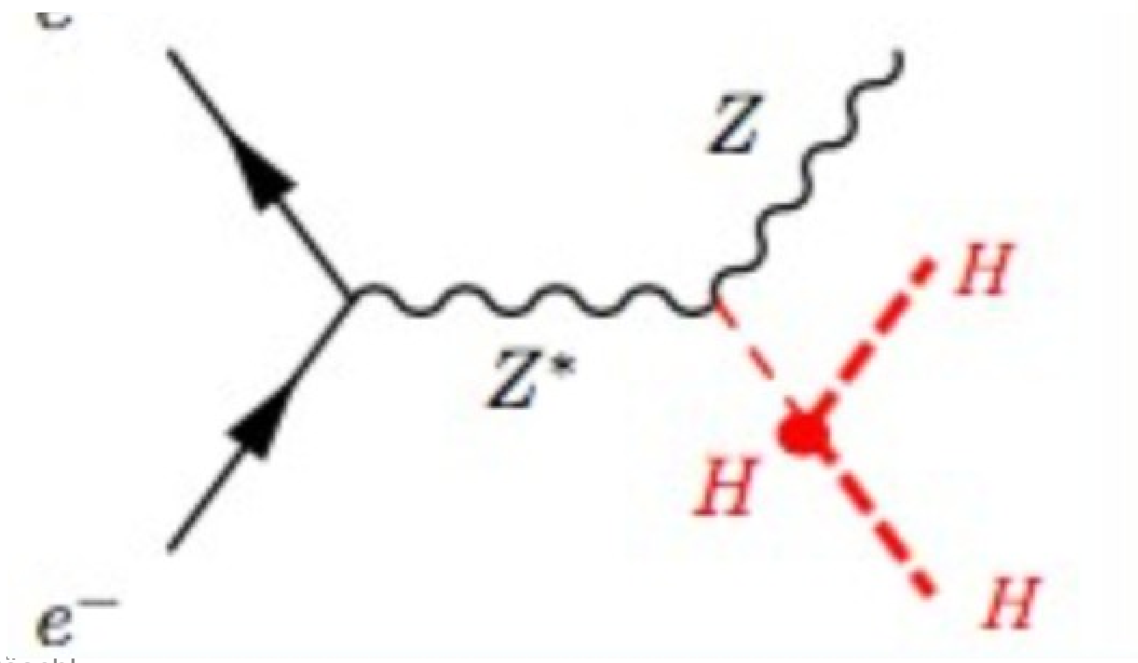


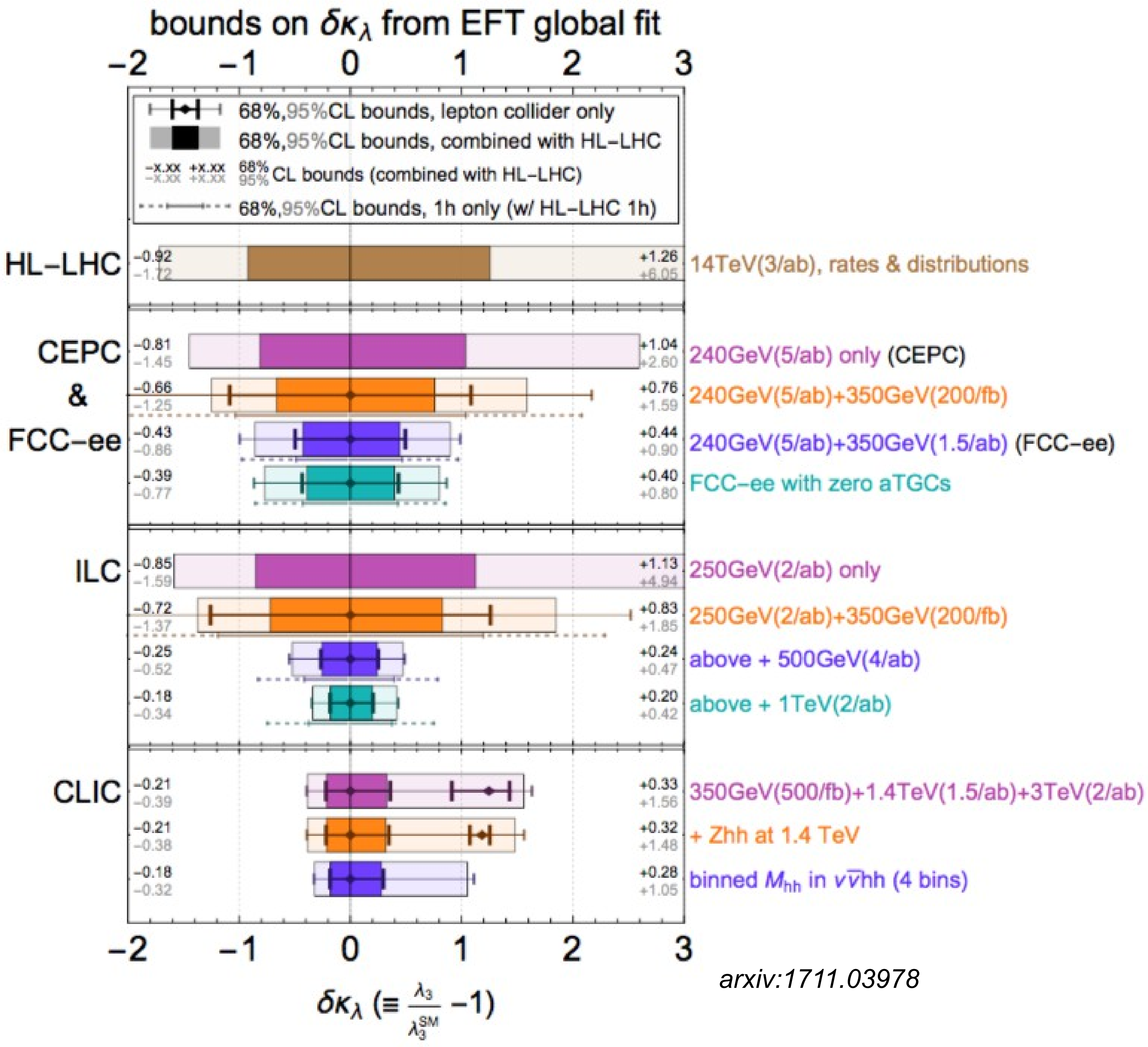


- Heavy particles, e.g. (Kaluza Klein) “duplicas” of SM particles provoke sizable effects
- Sensitivity to CP Violation !?

Higgs Self-couplings – An overview



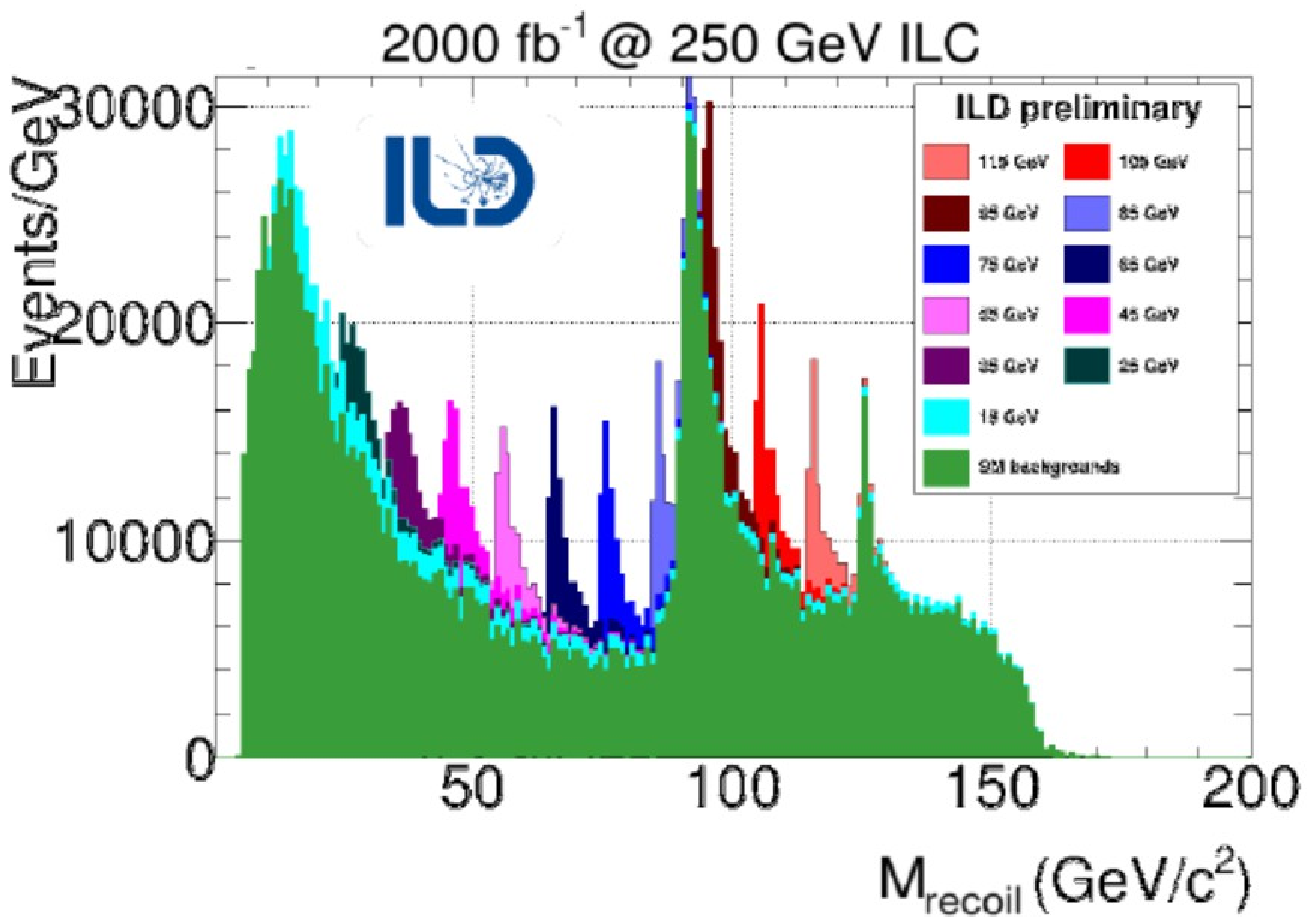


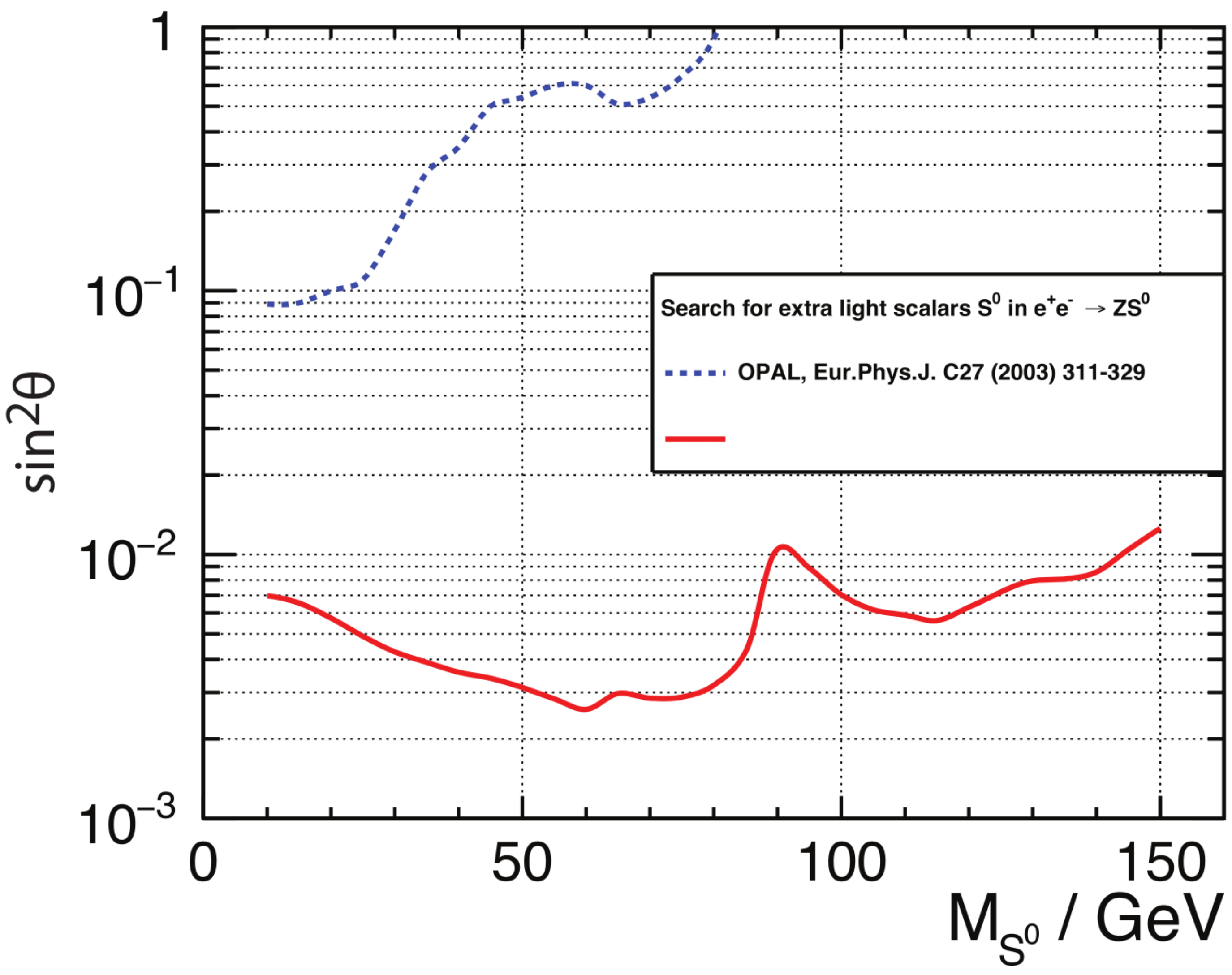


arxiv:1711.03978

Light scalar study in ILD

Light scalar may be missing piece to trigger first order 1st transition and/or the being the radion in extra dimension theories

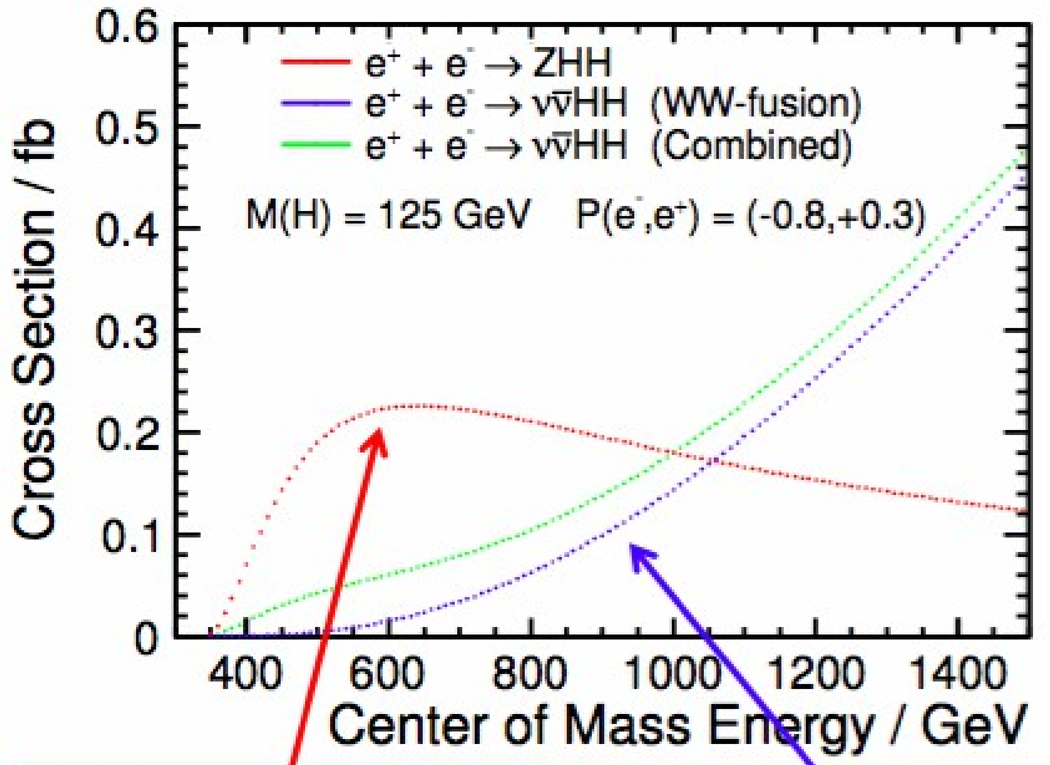


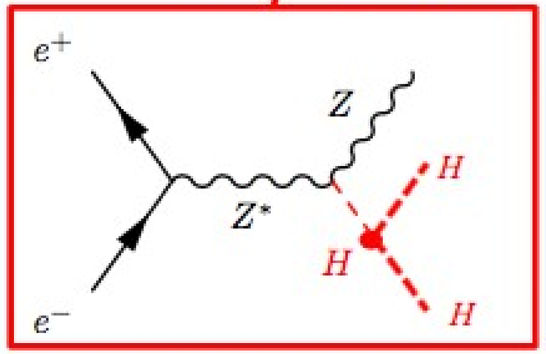


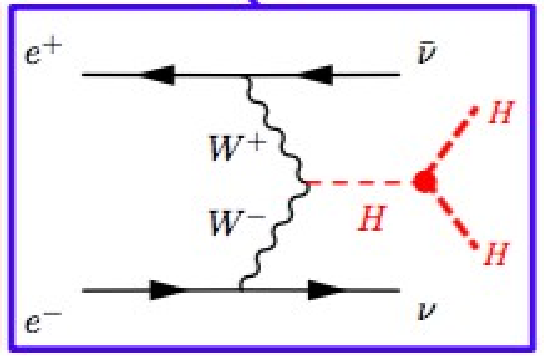
- New resonances cleanly dinstiguishable for large range of masses
- Sensitivity to mixing angle θh down to 10^{-2} (taking all relevant backgrounds into account)
- └new scalar would count as “Feebly interacting Particle” (FIPS)

Higgs self-coupling – Precisions at LC

Cross section vs CM energy (e+e-)







Diagrams with triple-Higgs coupling

Expected precision based on **full detector simulation** studies:

ILC	ILC
500 GeV, 4 ab-1 **δλ = 27%**	500 GeV, 4 ab-1 & 1 TeV, 8 ab-1 **δλ = 10%**

References:
J. Tian, LC-REP-2013-003
M. Kurata, LC-REP-2014-025
C. Duerig, Ph.D. thesis at DESY, 2016
HH→bbbb, bbWW* combination

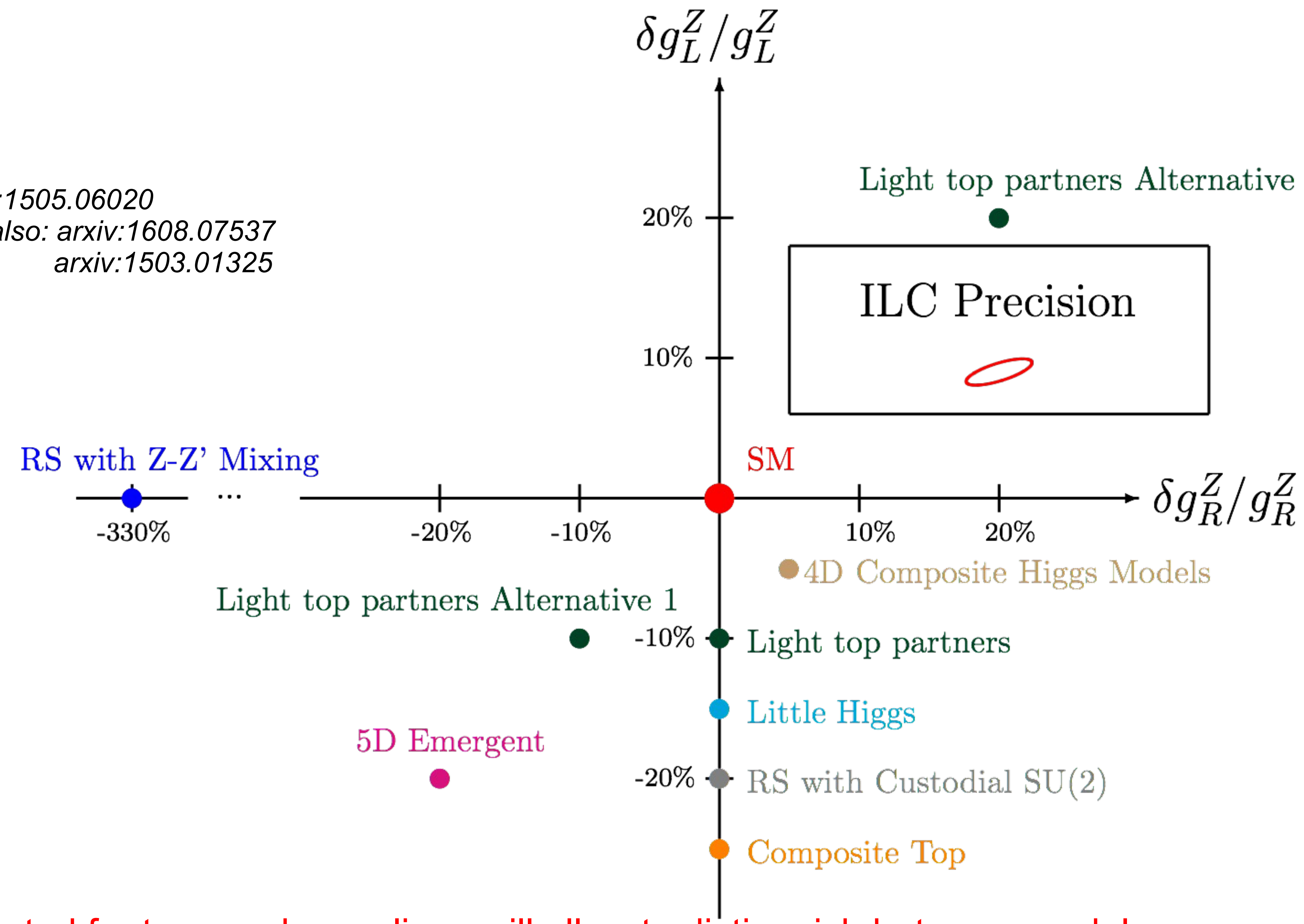
CLIC	CLIC
1.4 TeV, 1.5 ab-1 **δλ = 21%**	1.4 TeV, 1.5 ab-1 & 3 TeV, 2 ab-1 **δλ = 10%**

References:
arXiv: 1307.5288
HH→bbbb only, upgrade in progress including bbWW*

Electroweak top couplings

Top is primary candidate to be a messenger new physics in many BSM models

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

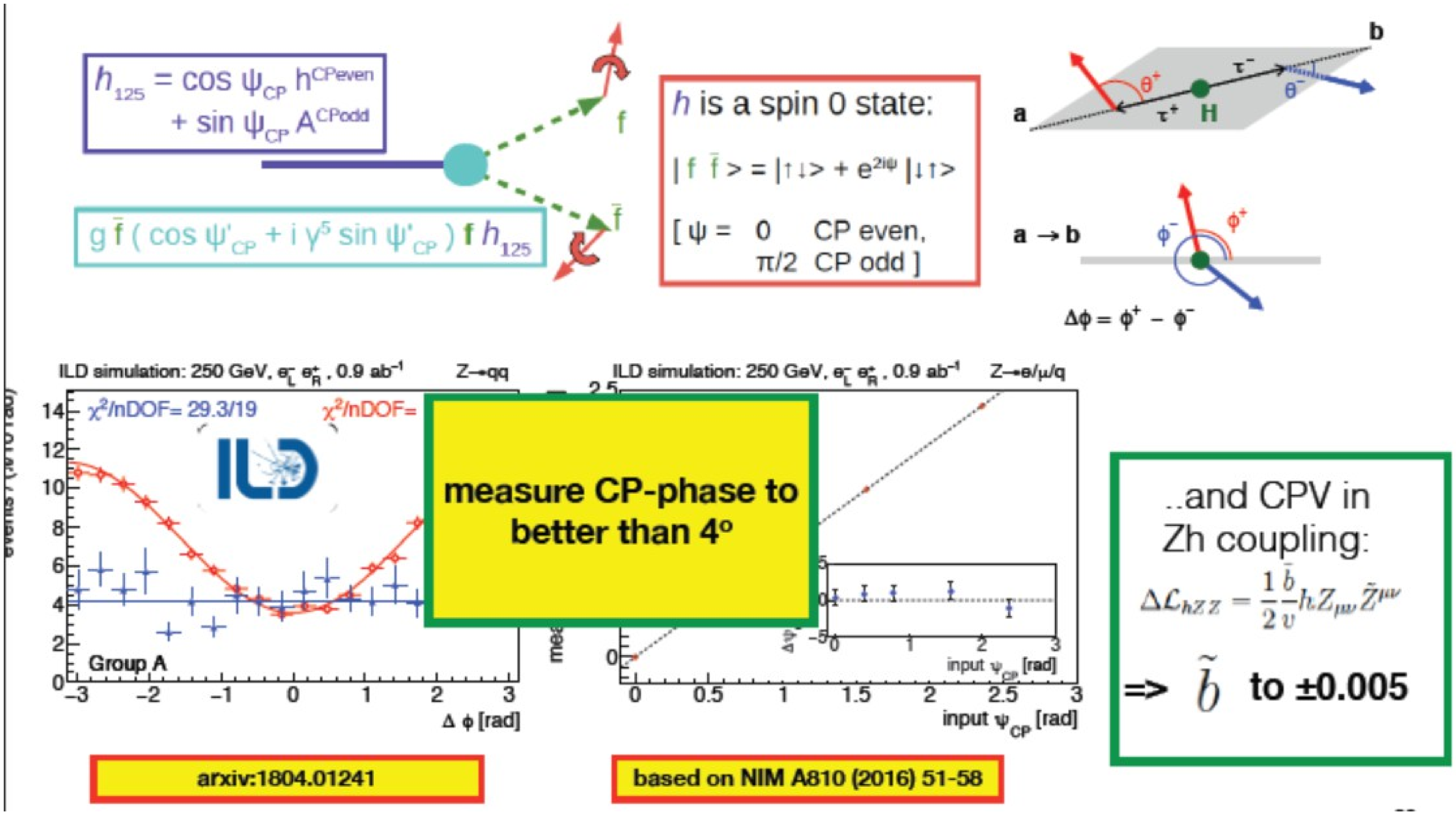


Statistical error:
√s ~ 500 GeV
L = 500 fb^{-1}

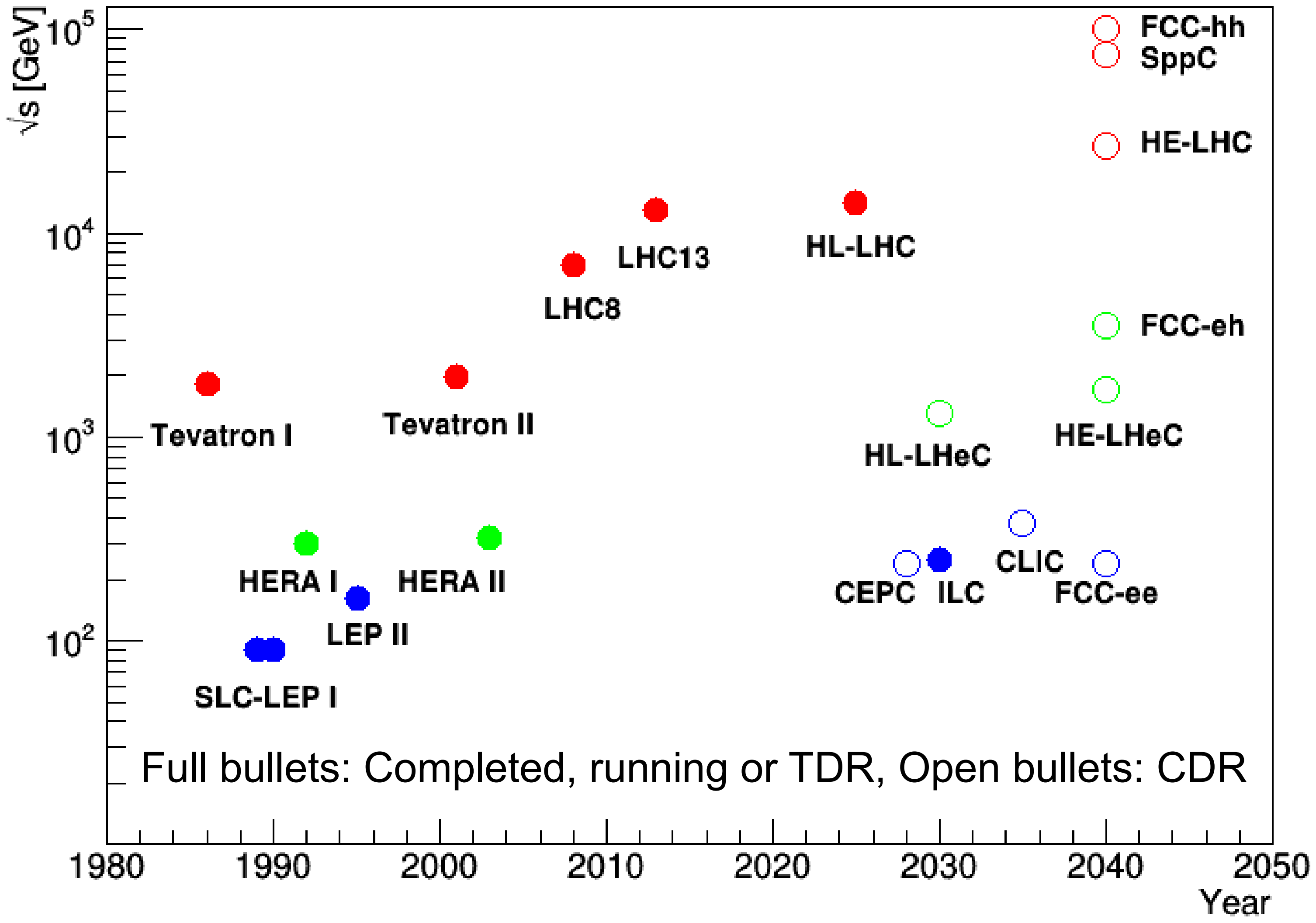
Precision expected for top quark couplings will allow to distinguish between models

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

htautau


$h_{125} = \cos\psi_{CP}\, h^{CPeven} + \sin\psi_{CP}\, A^{CPodd}$
$g\,\bar{f}\,(\cos\psi'_{CP} + i\gamma^5 \sin\psi'_{CP})\, f\, h_{125}$
f
$\bar{f}$
h is a spin 0 state:
$|f\,\bar{f}> = |\uparrow\downarrow> + e^{2i\psi}|\downarrow\uparrow>$
[ψ = 0 CP even, π/2 CP odd]
a
b
H
a → b
$\Delta\phi = \phi^+ - \phi^-$
ILD simulation: 250 GeV, $e^-_L e^+_R$, 0.9 ab^{-1} Z→qq
χ^2/nDOF= 29.3/19
Group A
Δ φ [rad]
ILD simulation: 250 GeV, $e^-_L e^+_R$, 0.9 ab^{-1} Z→e/μ/q
input ψ_{CP} [rad]
measure CP-phase to better than 4°
arxiv:1804.01241
based on NIM A810 (2016) 51-58
..and CPV in Zh coupling:
$\Delta\mathcal{L}_{hZZ} = \frac{1}{2}\frac{\tilde{b}}{v} h Z_{\mu\nu}\tilde{Z}^{\mu\nu}$
=> $\tilde{b}$ to ±0.005

e+e- machines (and others) - Readiness



- ILC is the only machine that can be built now
  - European XFEL gives credbility for construction

European Strategy - Reminder

High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

Points 1,2,4:

- Exploit LHC and implement HiLumi. Well underway.
- High field magnets and high gradient acceleration, project planning for CLIC and FCC/He-LHC. Studies being summarized for the European Strategy update in 2019-20.
- Develop a neutrino programme at CERN. Neutrino platform implementation.

Point 3:

- There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. ***Europe looks forward to a proposal from Japan to discuss a possible participation.***

Update of European Strategy of Particle Physics

European Strategy Update

Why European Particle Physics Strategy?

- Relation between ESFRI and CERN had to be clarified within the European Commission
  - ESFRI, the European Strategy Forum on Research Infrastructures, is a strategic instrument to develop the scientific integration of Europe and to strengthen its international outreach.
  - CERN's convention mandates coordination of infrastructure of particle physics for Member States

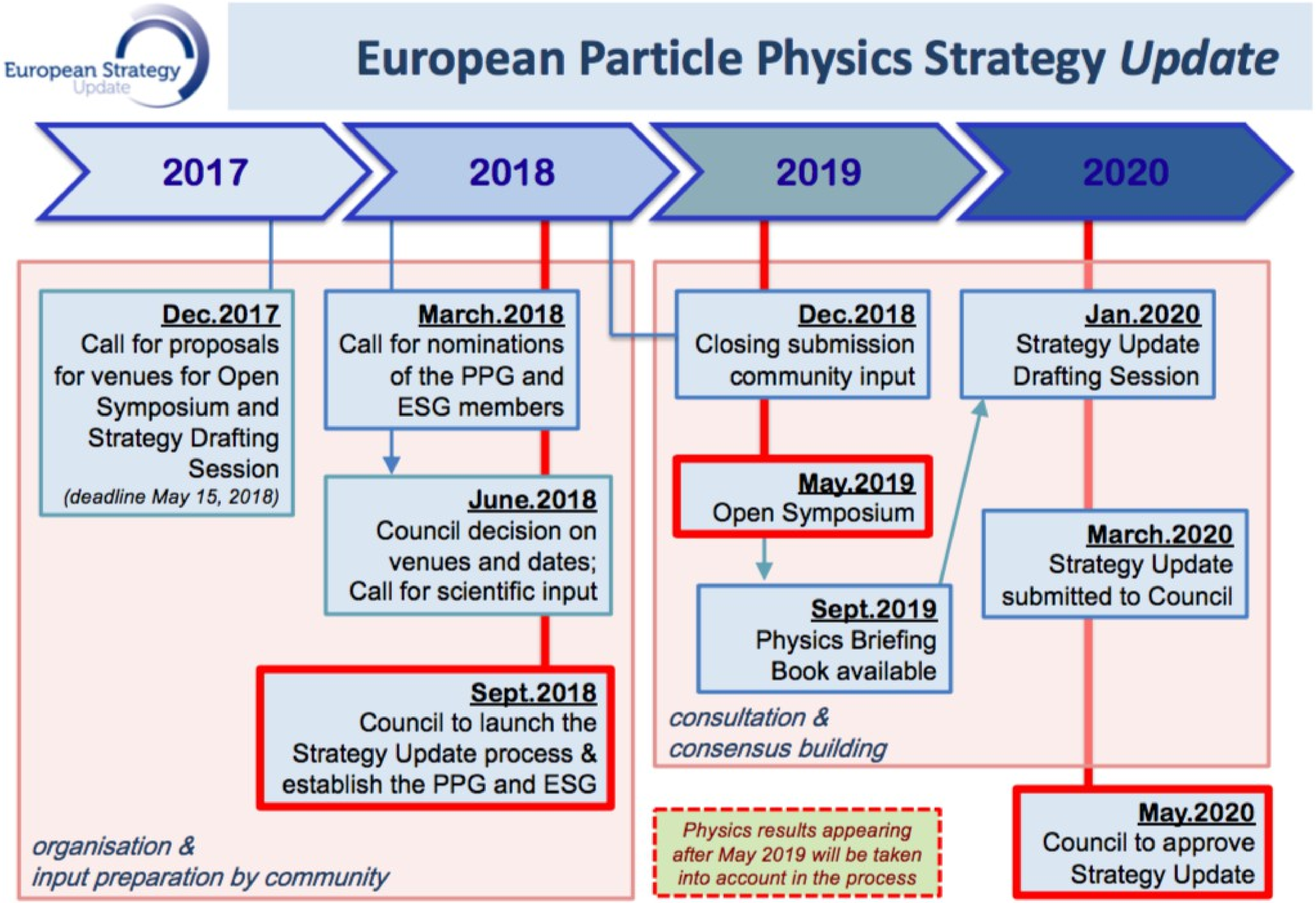
- First ESFRI roadmap published in 2006, with 35 projects, the Roadmap was updated in 2008 bringing the number of RIs of pan-European relevance to 44. Later updates 2008, 2010, 2016, 2018

- First European Particle Physics Strategy (EPPS) called by CERN Council in 2005 and endorsed in 2006, latest update in 2013… next in 2020.

Current period

EPPSU – The Schedule

EPPSU Secretary:
H. Abramowicz

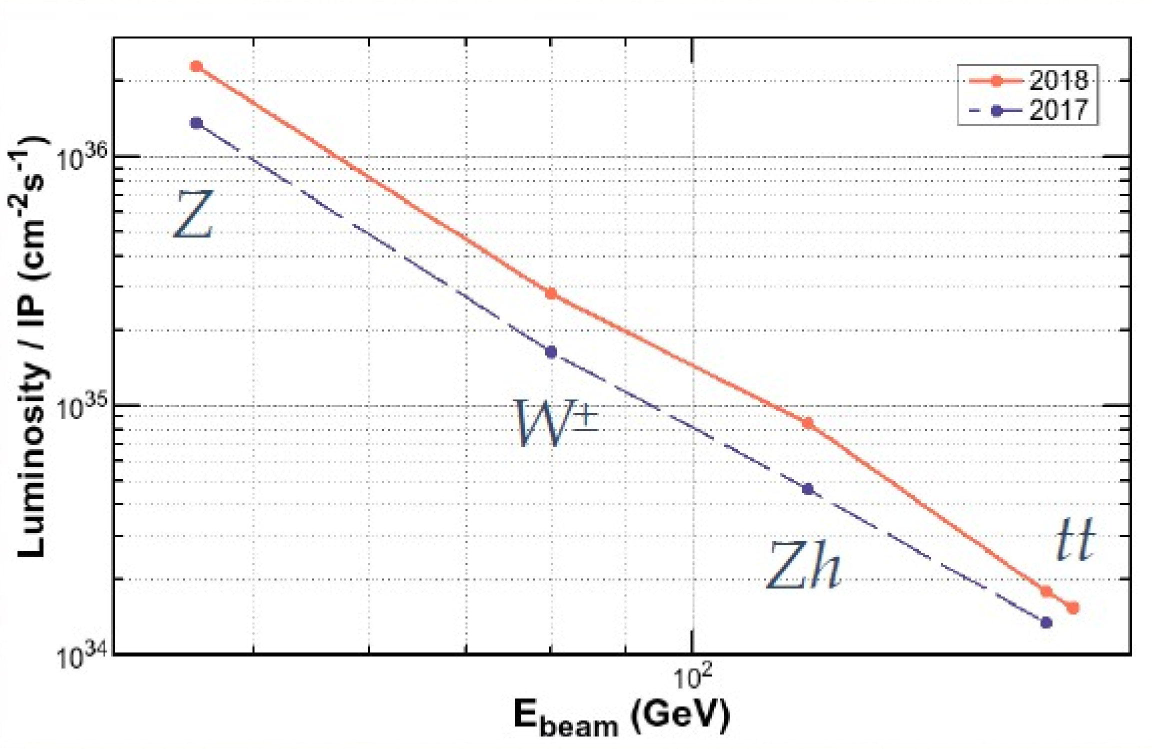


ILC Parameters

			TDR		New
Center-of-mass energy	E_{CM}	GeV	250	500	250
Bunch population	N	e10	2	2	2
Bunch separation		ns	554	554	554
Beam current		mA	5.78	5.78	5.78
Number of bunches per pulse	Nb		1312	1312	1312
Collision frequency		Hz	5	5	5
Electron linac rep rate		Hz	10	5	5
Beam power (2 beams)	P_B	MW	5.26	10.5	5.26
r.m.s. bunch length at IP	σ_z	mm	0.3	0.3	0.3
relative energy spread at IP (e−)	σ_E/E	%	0.188	0.124	0.188
relative energy spread at IP (e+)	σ_E/E	%	0.15	0.07	0.15
Normalized horizontal emittance at IP	ε_{nx}	μm	10	10	5
Normalized vertical emittance at IP	ε_{ny}	nm	35	35	35
Beam polarization (e−)		%	80	80	80
Beam polarization (e+)		%	30	30	30
Beta function at IP (x)	β_x	mm	13	11	13
Beta function at IP (y)	β_y	mm	0.41	0.48	0.41
r.m.s. beam size at IP (x)	σ_x	nm	729	474	516
r.m.s. beam size at IP (y)	σ_y	nm	7.66	5.86	7.66
r.m.s. beam angle spread at IP (x)	θ_x	μr	56.1	43.1	39.7
r.m.s. beam angle spread at IP (y)	θ_y	μr	18.7	12.2	18.7
Disruption parameter (x)	Dx		0.26	0.26	0.51
Disruption parameter (y)	Dy		24.5	24.6	34.5
Upsilon (average)	Υ		0.020	0.062	0.028
Number of beamstrahlung photons	n_γ		1.21	1.82	1.91
Energy loss by beamstrahlung	δ_{BS}	%	0.97	4.50	2.62
Geometric luminosity	Lgeo	e34/cm²s	0.374	0.751	0.529
Luminosity	L	e34/cm²s	0.82	1.79	1.35

FCC-ee Parameters

		Z	$W^{\pm}$	Zh	$t\bar{t}$	
Circumference	[km]	97.756				
Bending radius	[km]	10.760				
Free length to IP ℓ^*	[m]	2.2				
Solenoid field at IP	[T]	2.0				
Full crossing angle at IP	[mrad]	30				
SR power / beam	[MW]	50				
Beam energy	[GeV]	45.6	80	120	175	182.5
Beam current	[mA]	1390	147	29	6.4	5.4
Bunches / beam		16640	2000	328	59	48
Average bunch spacing	[ns]	19.6	163	994	2763[1]	3396??
Bunch population	[10^{11}]	1.7	1.5	1.8	2.2	2.3
Horizontal emittance ε_x	[nm]	0.27	0.84	0.63	1.34	1.46
Vertical emittance ε_y	[pm]	1.0	1.7	1.3	2.7	2.9
Arc cell phase advances	[deg]	60/60	60/60	90/90		
Momentum compaction	[10^{-6}]	14.8	14.8	7.3		
Arc sextupole families		208		292		
Horizontal β_x^*	[m]	0.15	0.2	0.3	1.0	
Vertical β_y^*	[mm]	0.8	1.0	1.0	1.6	
Horizontal size at IP σ_x^*	[μm]	6.4	13.0	13.7	36.7	38.2
Vertical size at IP σ_y^*	[nm]	28	41	36	66	68
Energy spread (SR/BS)	[%]	0.038/0.132	0.066/0.131	0.099/0.165	0.144/0.196	0.150/0.192
Bunch length (SR/BS)	[mm]	3.5/12.1	3.0/6.0	3.15/5.3	2.75/3.82	1.97/2.54
Crab sextupole ratio	[%]	97	87	80	50	50
Energy loss / turn	[GeV]	0.036	0.34	1.72	7.8	9.2
RF frequency	[MHz]	400			400 / 800	
RF voltage	[GV]	0.1	0.75	2.0	4.0 / 5.4	4.0 / 6.9
Long. damping time	[turns]	1273	236	70.3	23.1	20.4
RF acceptance	[%]	1.9	2.3	2.3	3.5	3.36
Energy acceptance (DA)	[%]	±1.3	±1.3	±1.7	-2.8 +2.4	
Synchrotron tune Q_z		-0.0250	-0.0506	-0.0358	-0.0818	-0.0872
Luminosity / IP	[10^{34}/cm^{2}s]	230	28	8.5	1.8	1.55
Horizontal tune Q_x		269.139	269.124	389.129	389.104	
Vertical tune Q_y		269.219	269.199	389.199	389.175	
Beam-beam ξ_x/ξ_y		0.004/0.133	0.010/0.115	0.016/0.118	0.088/0.148	0.099/0.126
Lifetime by rad. Bhabha	[min]	68	59	38	37	40
Actual lifetime by BS	[min]	> 200	> 200	18	24	18



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CEPC Parameters

	Higgs	*W*	*Z* (3T)	*Z* (2T)
Number of IPs	2			
Beam energy (GeV)	120	80	45.5	
Circumference (km)	100			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	16.5×2			
Piwinski angle	2.58	7.0	23.8	
Number of particles/bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number (bunch spacing)	242 (0.68μs)	1524 (0.21μs)	12000 (25ns+10%gap)	
Beam current (mA)	17.4	87.9	461.0	
Synchrotron radiation power /beam (MW)	30	30	16.5	
Bending radius (km)	10.7			
Momentum compact (10^{-5})	1.11			
β function at IP β_x^* / β_y^* (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015	0.2/0.001
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0031	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.068	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.031/0.109	0.013/0.106	0.0041/0.056	0.0041/0.072
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz) (harmonic)	650 (216816)			
Natural bunch length σ_z (mm)	2.72	2.98	2.42	
Bunch length σ_z (mm)	3.26	5.9	8.5	
Betatron tune ν_x/ν_y	363.10 / 365.22			
Synchrotron tune ν_s	0.065	0.0395	0.028	
HOM power/cavity (2 cell) (kw)	0.54	0.75	1.94	
Natural energy spread (%)	0.1	0.066	0.038	
Energy acceptance requirement (%)	1.35	0.4	0.23	
Energy acceptance by RF (%)	2.06	1.47	1.7	
Photon number due to beamstrahlung	0.29	0.35	0.55	
Lifetime simulation (min)	100			
Lifetime (hour)	0.67	1.4	4.0	2.1
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP *L* (10^{34}cm^{-2}s^{-1})	2.93	10.1	16.6	32.1

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