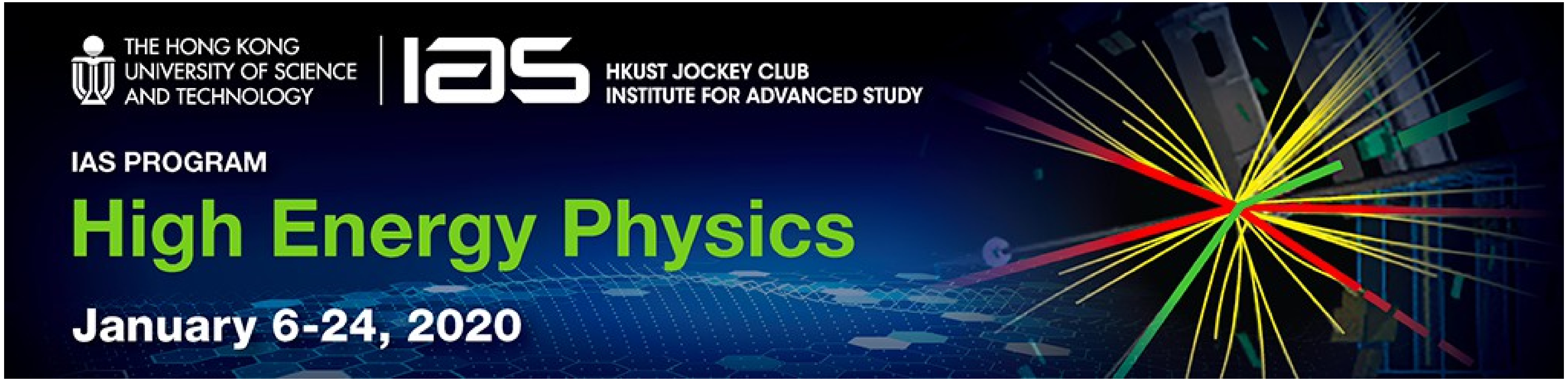


Polarisation in e+e- collisions

Roman Pöschl

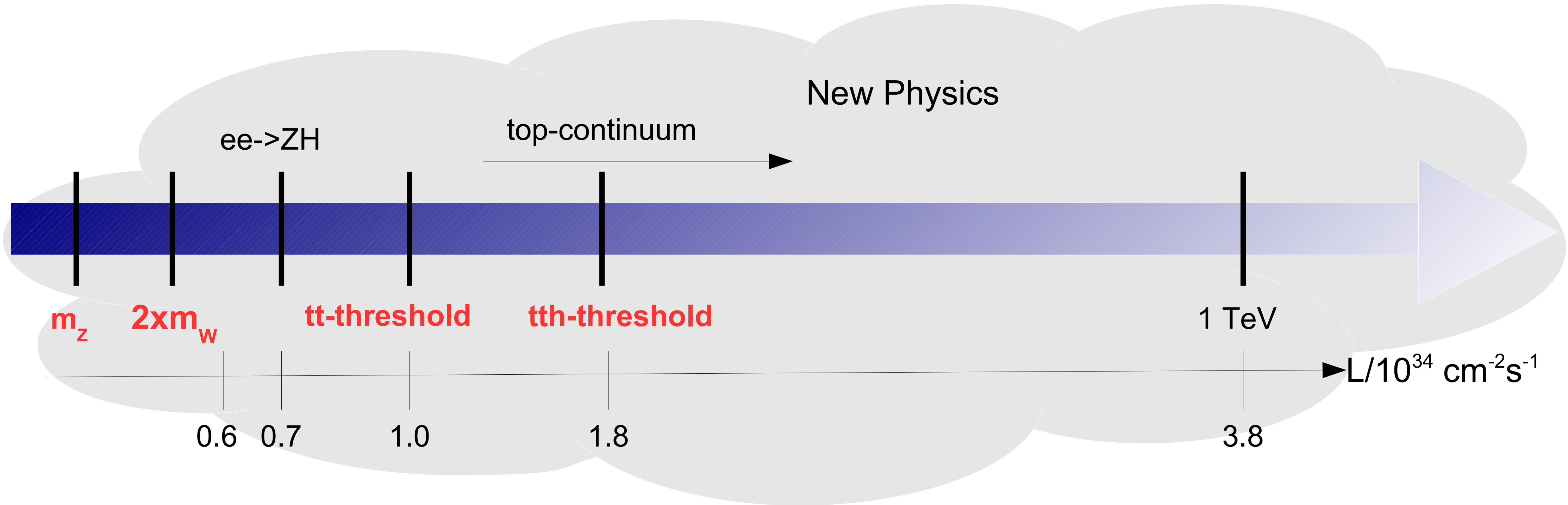
CNRS IN2P3 Les deux infinis

P2IO Physique des 2 Infinis et des Origines

~~LAL Laboratoire de l'Accélérateur Linéaire~~ → **IJCLab** IJC=Irène Joliot-Curie

~~Université Paris Sud Comprendre le monde, construire l'avenir~~ → université PARIS-SACLAY

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

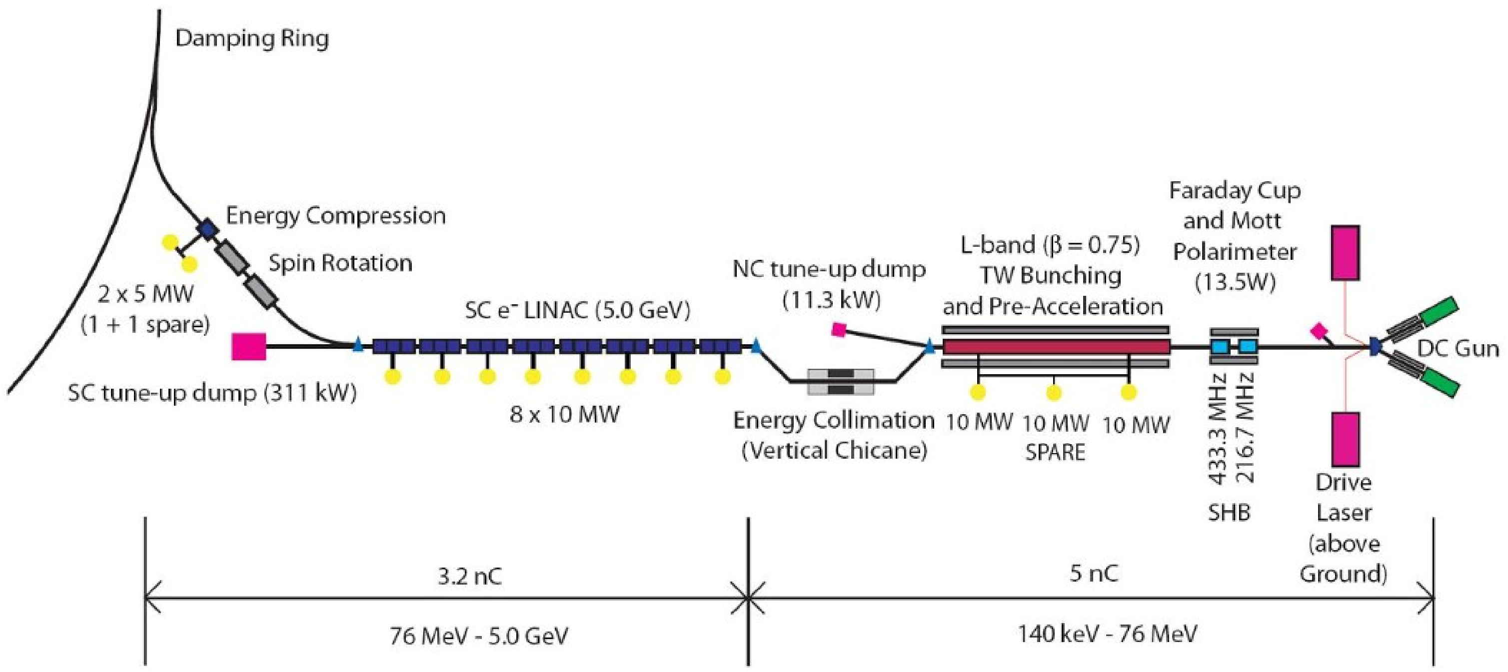
- Centre-of-Mass energy
- Beam polarisation (straightforward at linear colliders)

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

Background free searches for BSM through beam polarisation

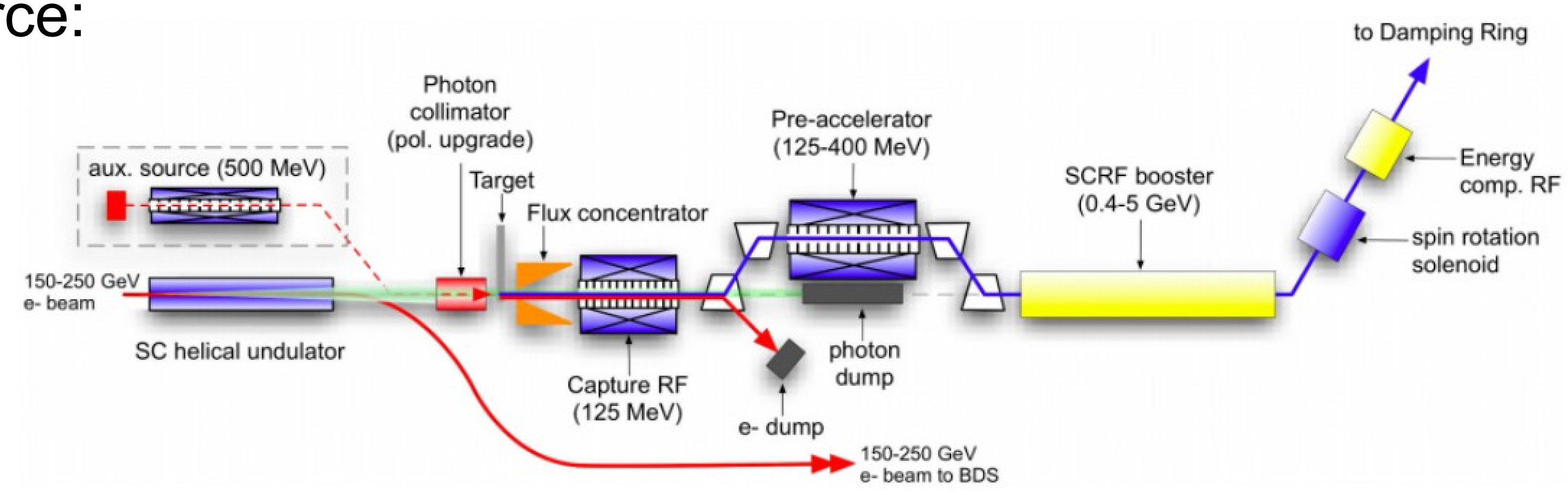
Polarised beams at Linear Colliders

e- - Source:



- Polarised photons incident on GaAs photocathode
- Method used for SLC
  - Beam polarisation of 80% achieved
  - Also target value for ILC and CLIC

e+ - Source:

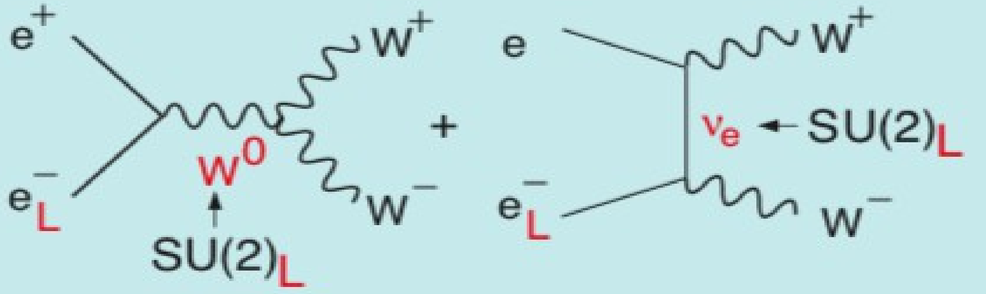


- Polarised positrons from polarised photons produced in helical undulator and reconversion in target
  - Proof of principle E166 in 2005
  - Polarisation of 80% in 1m undulator
- Target value for ILC 30% (20% at 1 TeV
  - No positron polarisation at CLIC

Power of beam polarisation – An overview

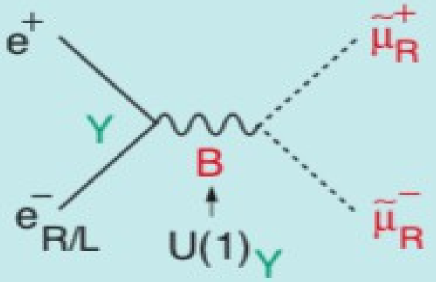
BG Suppression

***W^+W^-** (Largest SM BG in SUSY searches)*



In the symmetry limit, $\sigma_{WW} \to 0$ for e^-_R !

Slepton Pair

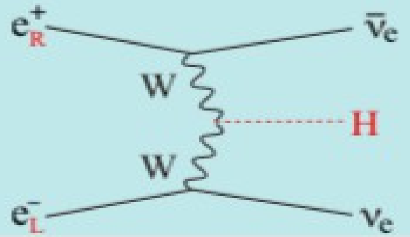


$Y_L = -1/2 : e^-_L$

$Y_R = -1 : e^-_R$

In the symmetry limit, $\sigma_R = 4\,\sigma_L$!

WW-fusion Higgs Prod.

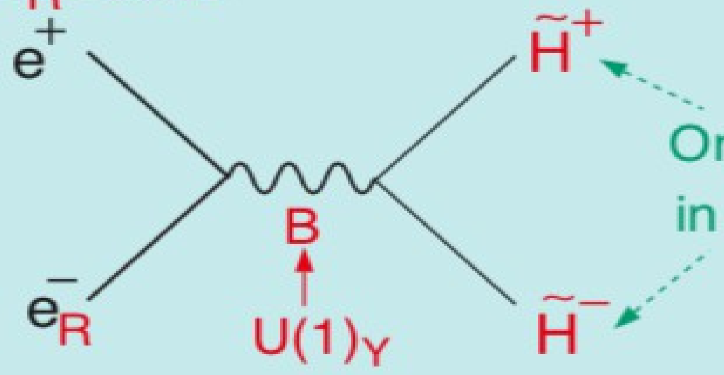


	ILC
Pol (e-)	-0.8
Pol (e+)	+0.3
$(\sigma/\sigma_0)_{\nu\nu H}$	1.8x1.3=2.34

Signal Enhancement

Chargino Pair

e^-_R Beam



Only $\tilde{H}^\pm$ components in $\tilde{\chi}^\pm_1$ contribute !

cf.) $e^+e^- \to W^+W^-$

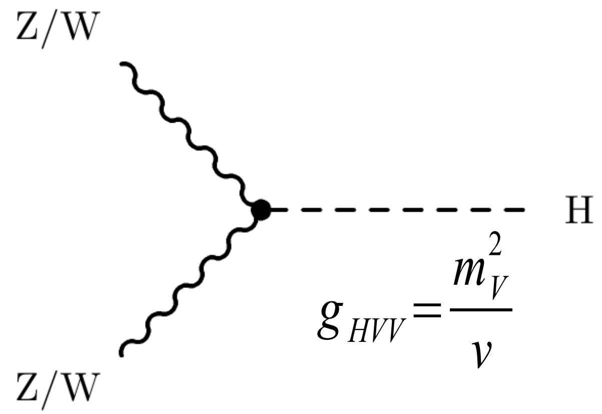
$$\tilde{\chi}^\pm_1 = \bigcirc \cdot \tilde{W}^\pm + \bullet \cdot \tilde{H}^\pm$$

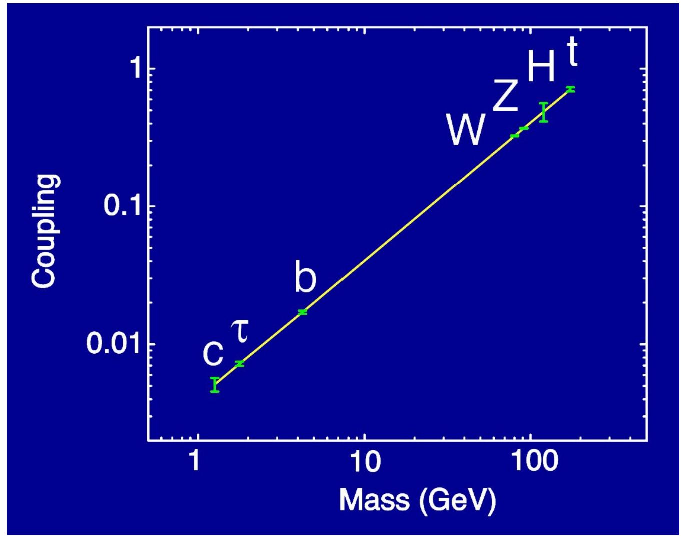
$$\bullet = \langle \tilde{H}^\pm | \tilde{\chi}^\pm_1 \rangle$$

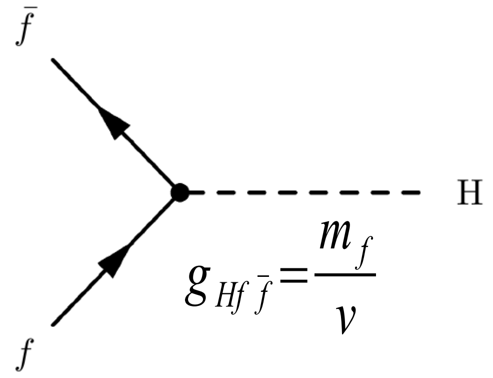
Decomposition

Fitting Higgs Couplings – Kappa and EFT

Couplings to Higgs Boson in Standard Model







Analysis using Kappa-fit:

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

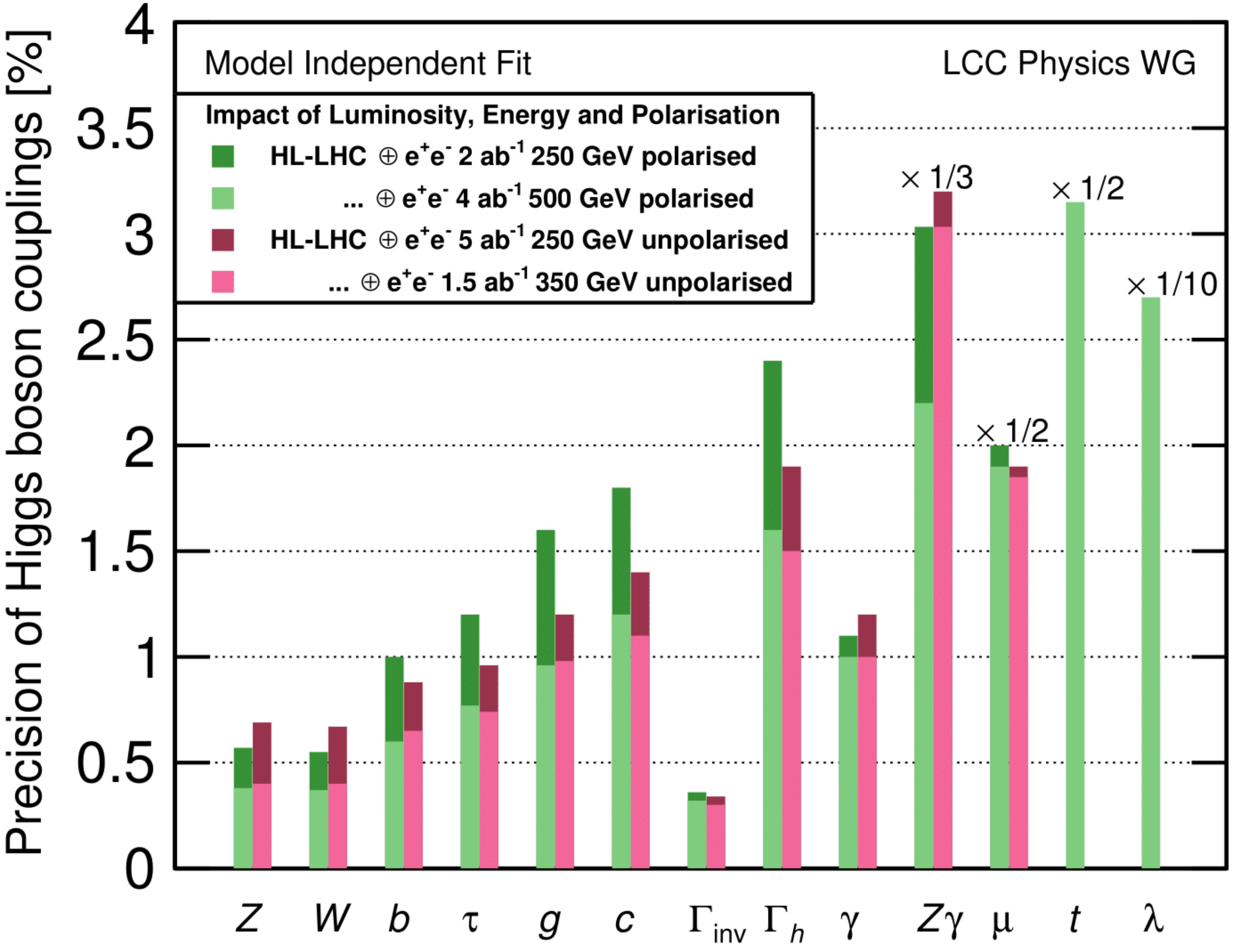
$$\frac{\Gamma(h \to ZZ^*)}{SM} = \kappa_Z^2 \ , \qquad \frac{\sigma(e^+e^- \to Zh)}{SM} = \kappa_Z^2$$

Analysis using EFT-fit:

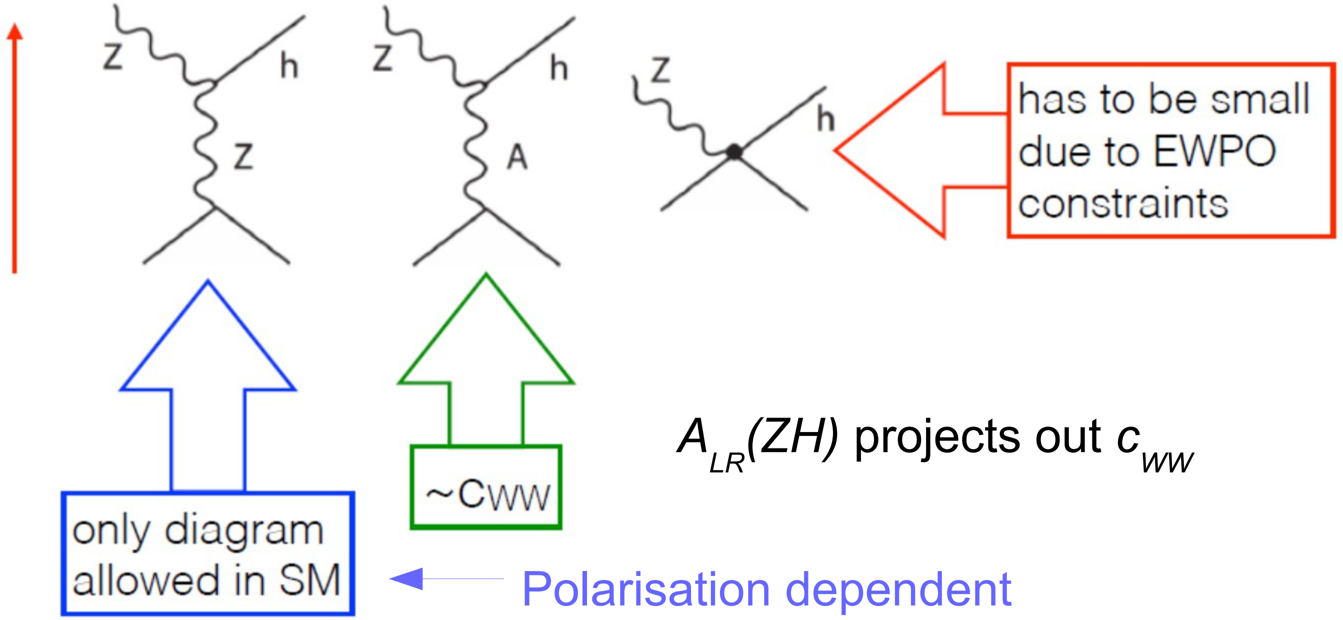
Introducing set of SU(2)xU(1) compatible operators
e.g. breaks simple relation between Higgs production and decay
Total width and Higgs to invisible as free parameters
Receives additional input from e.g. ee->WW and EWPO

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

EFT Framework and beam polarisation



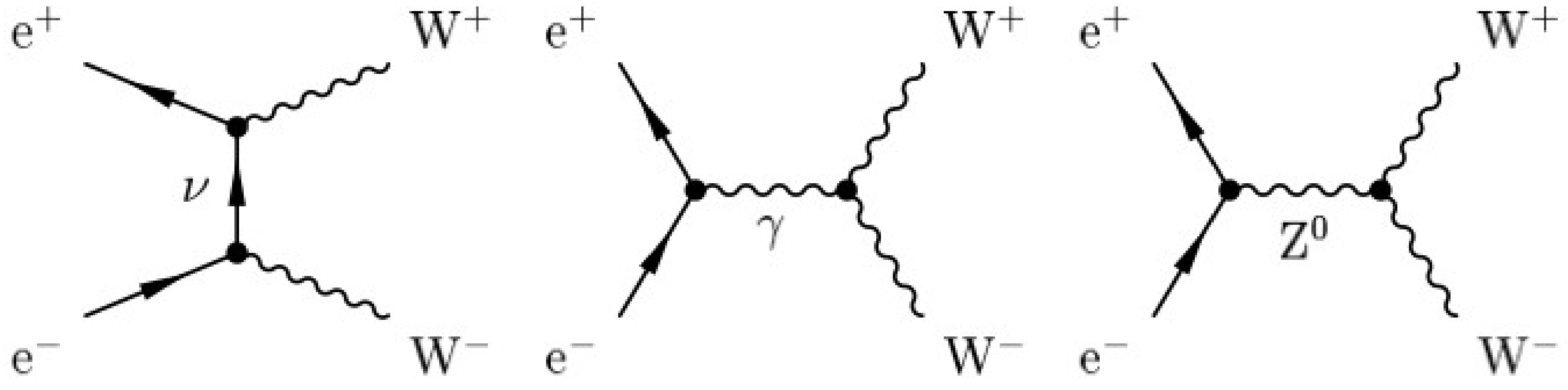
EFT adds additional spin structure to ZH production cross section



$A_{LR}(ZH)$ projects out c_{WW}

Precision for 2ab^{-1} polarised = 5ab^{-1} unpolarised

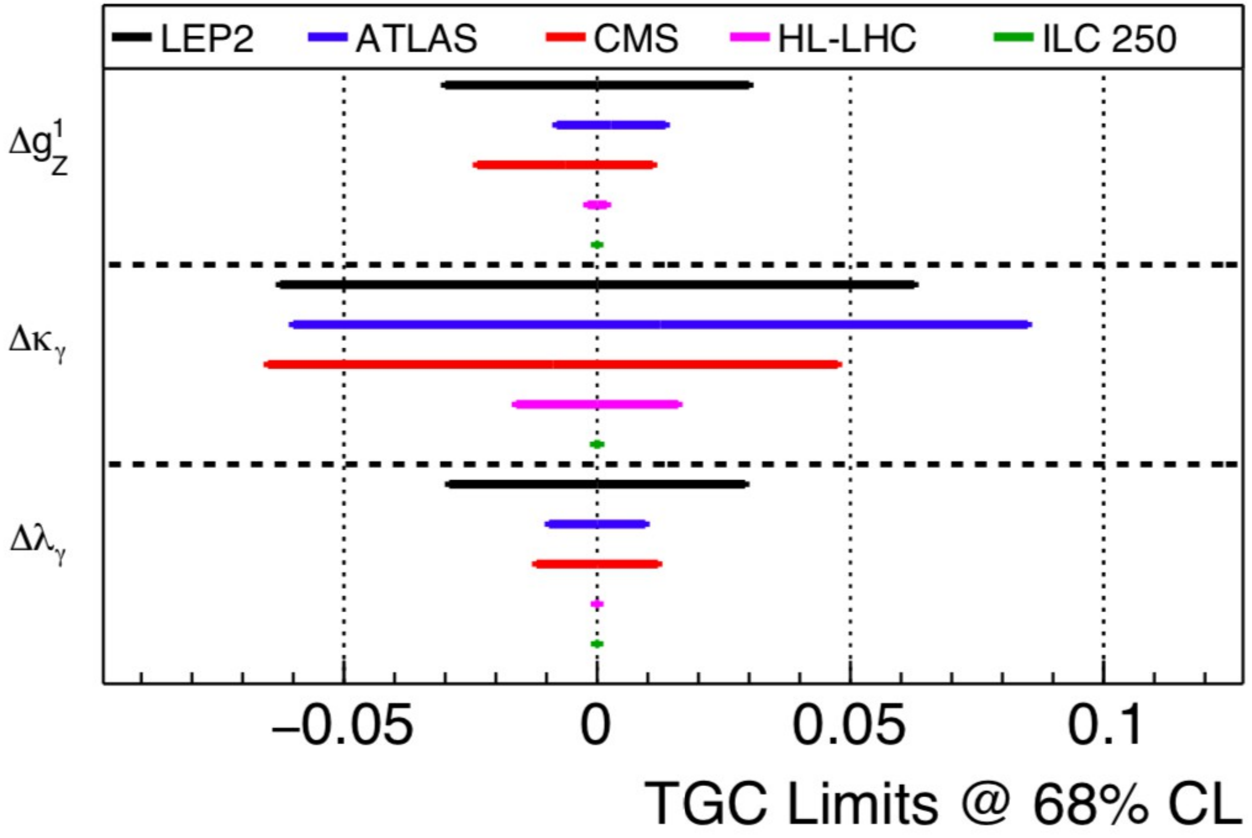
Double W Production

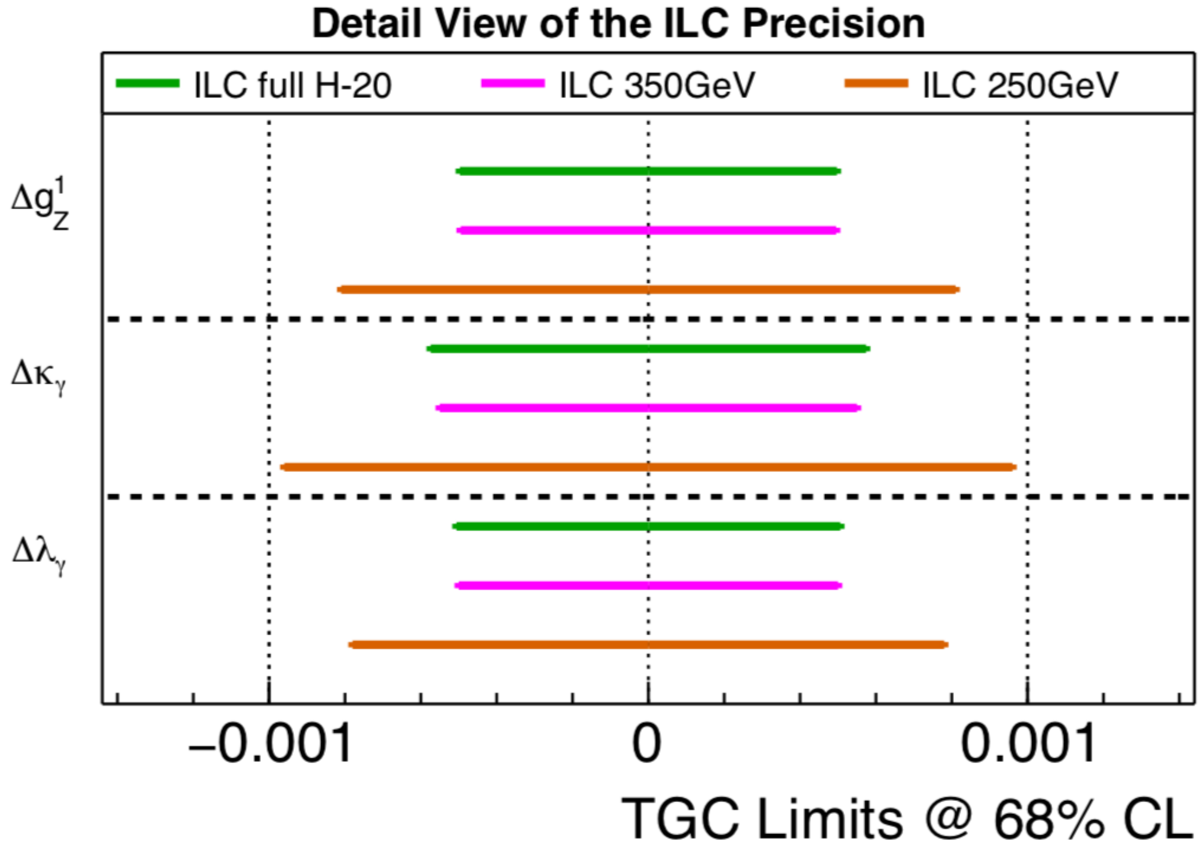


- Sensitivity to triple and quartic gauge Boson couplings (TGC and QGC)
- Observables depend strongly on beam polarisation

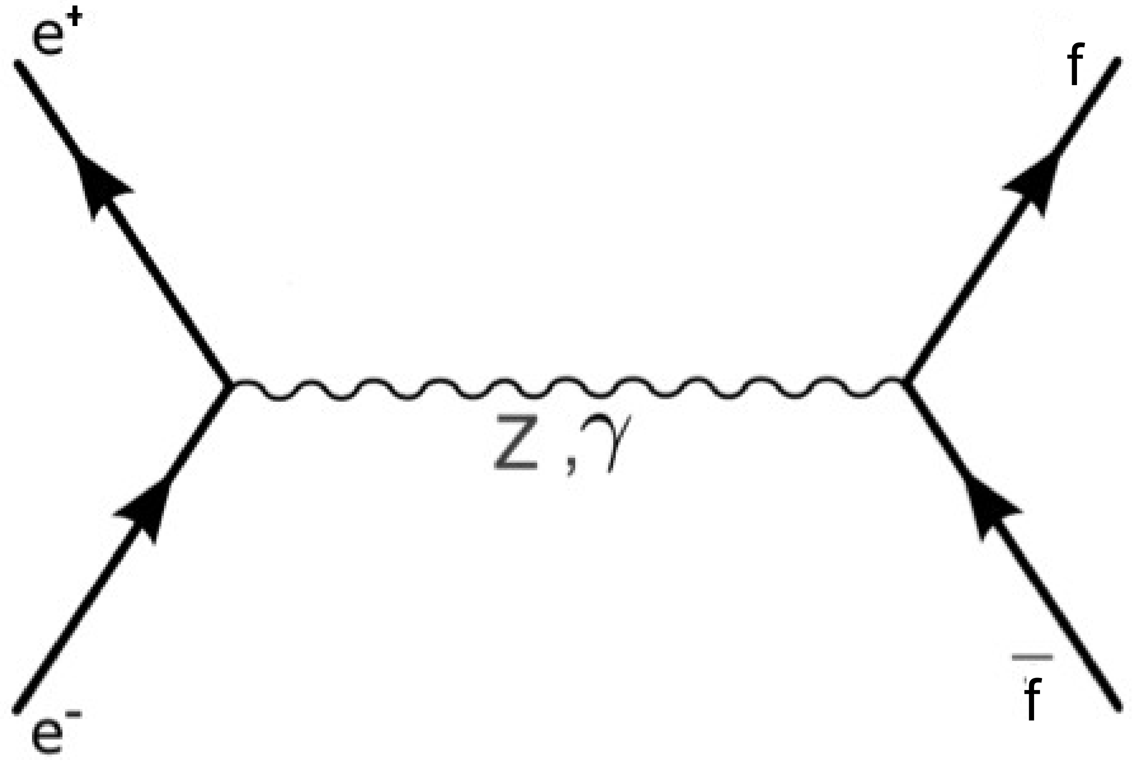
=> Enrich different helicity modes of W
=> Disentangling of couplings to Z and γ
=> in situ measurement of beam polarisation (and luminosity)

Limits on Triple Gauge Couplings@250 GeV





Two fermion processes



Differential cross sections for (relativistic) di-fermion production*:

$$\frac{d\sigma}{d\cos\theta}(e^-_L e^+_R \rightarrow f\bar{f}) = \Sigma_{LL}(1+\cos\theta)^2 + \Sigma_{LR}(1-\cos\theta)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^-_R e^+_L \rightarrow f\bar{f}) = \Sigma_{RL}(1+\cos\theta)^2 + \Sigma_{RR}(1-\cos\theta)^2$$

*add term ~$sin^2\theta$ in case of non-relativistic fermions e.g. top close to threshold

Σ_{IJ} are helicity amplitudes that contain couplings g_L, g_R (or g_V, g_A)

$\Sigma_{IJ} \neq \Sigma_{I'J}{}'$ => (characteristic) asymmetries for each fermion

Forward-backward in angle, general left-right in cross section

All four helicity amplitudes for all fermions **only available with polarised beams**

Helicity amplitudes and new physics

Helicity amplitudes can be analysed in several ways (not mutually exclusive):

Oblique Parameters W, Z:

$$Q_{e_i f_j} = Q_e^\gamma Q_f^\gamma + \frac{g_{e_i}^Z g_{f_j}^Z}{\sin^2\theta_W \cos^2\theta_W} \frac{s}{s - M_Z^2 + \mathrm{i}\Gamma_Z M_Z} + \frac{s}{m_W^2} f_{i,j}(W,Y)$$

Contact interactions with e.g. compositeness scale Λ:

$$Q_{e_i f_j} = Q_e^\gamma Q_f^\gamma + \frac{g_{e_i}^Z g_{f_j}^Z}{\sin^2\theta_W \cos^2\theta_W} \frac{s}{s - M_Z^2 + \mathrm{i}\Gamma_Z M_Z} + \frac{g_{contact}^2}{2\Lambda^2}\eta_{e_i f_j}$$

New propagators in concrete models of new physics:

$$Q_{e_i f_j} = Q_e^\gamma Q_f^\gamma + \frac{g_{e_i}^Z g_{f_j}^Z}{\sin^2\theta_W \cos^2\theta_W} \frac{s}{s - M_Z^2 + \mathrm{i}\Gamma_Z M_Z} + \sum \frac{g_{e_i}^{Z'} g_{f_j}^{Z'}}{\sin^2\theta_W \cos^2\theta_W} \frac{s}{s - M_{Z'}^2 + \mathrm{i}\Gamma_{Z'} M_{Z'}}$$

Always with I,j being the helicities of the initial state electron e and the final state fermion f

Rates and asymmetries (on the Z pole)

Partial fermion width:

$$R_f = \frac{N_f}{N_{had}} = \frac{(g_f^L)^2 + (g_f^R)^2}{\sum_{i=1}^{n_q}[(g_i^L)^2 + (g_i^R)^2]}$$

Sensitive to sum of coupling constants
Available at linear and circular colliders

Left-right asymmetry:

$$A_{LR} = \frac{1}{|\mathcal{P}_{eff.}|}\frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \mathcal{A}_e = \frac{(g_f^L)^2 - (g_f^R)^2}{(g_i^L)^2 + (g_i^R)^2} \sim 1 - 4\sin^2\theta^{\ell}_{eff.}$$

Direct sensitivity to Zee vertex
Only available at linear colliders due to beam polarisation
Circular colliders need auxiliary measurement

- e.g. $P_\tau \sim A_e$

Forward-backward asymmetry:

$$A_{FB}^f = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4}\frac{(\mathcal{A}_e - \mathcal{P}_e)\mathcal{A}_f}{(1 - \mathcal{P}_e\mathcal{A}_e)} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \;\; \text{for } \mathcal{P}_e = 0.$$

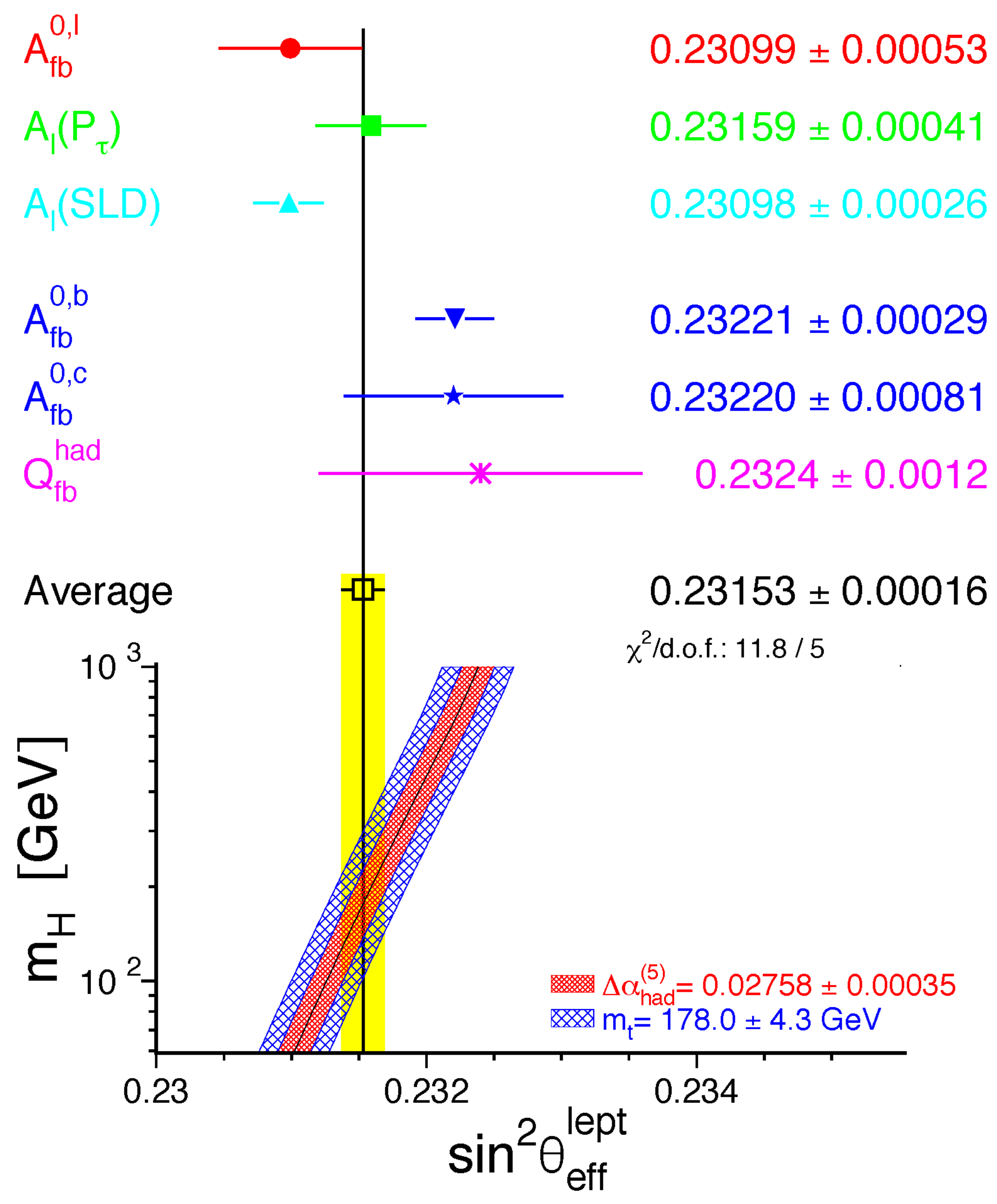
"Classical" observable to study P-violating effects in ee->ff
Available at circular and linear colliders
Asymmetry amplified by beam polarisation
Without beam polarisation interpretation is **always model dependent**

Left-right-forward-backward asymmetry:

$$A_{FB,LR}^f = \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_L + \sigma_l)_R} = -\frac{3}{4}\mathcal{A}_f$$

Combination of asymmetries above
Only available linear colliders due to beam polarisation
Direct and model independent measurement of A_f

Reminder: LEP and SLD



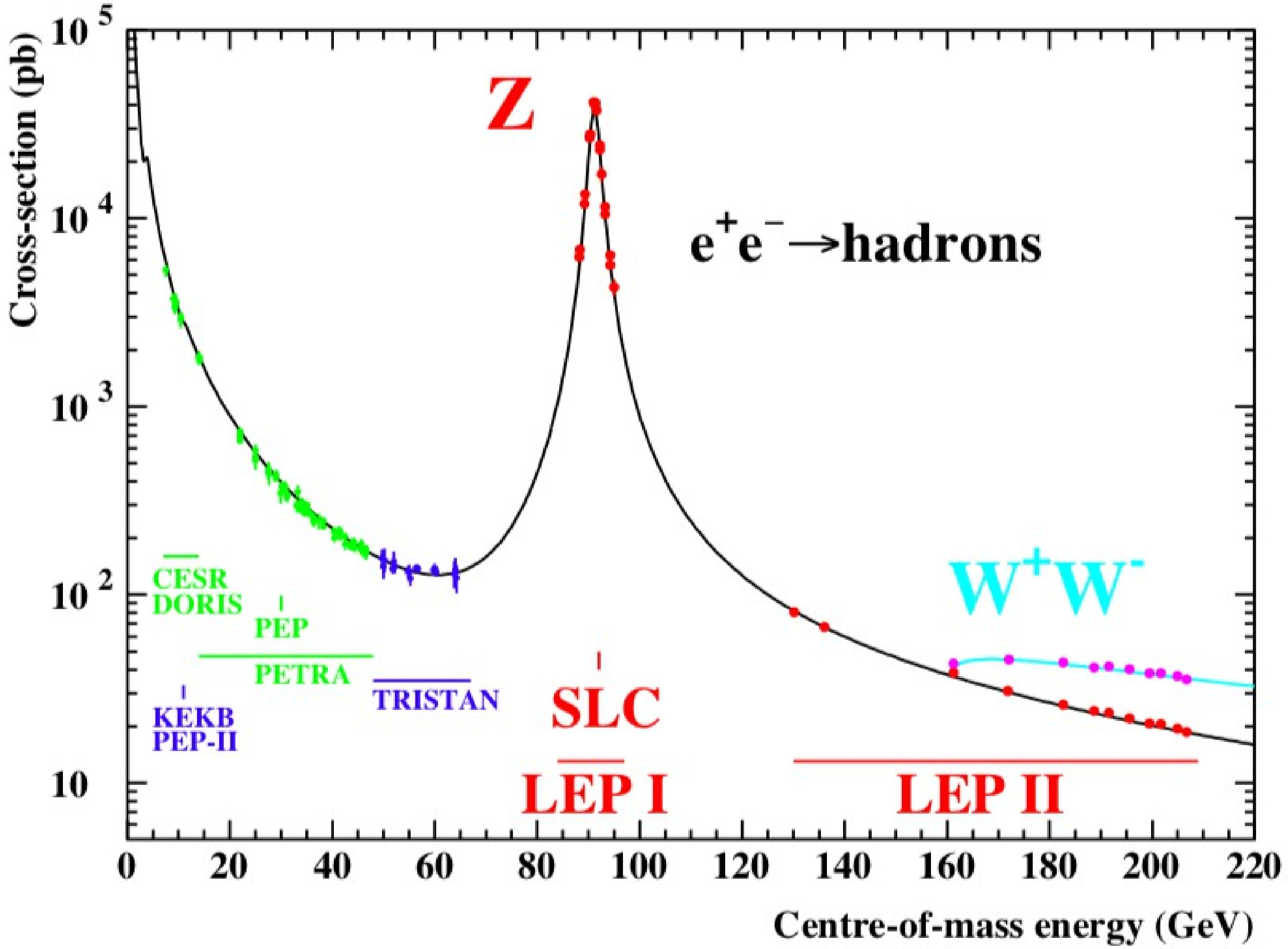
- Most precise single Individual determination of $\sin^2\theta^{\ell}_{\mathrm{eff.}}$ from SLC
  - Left-right asymmetry of leptons
- Most precise measurement of $\sin^2\theta^{\ell}_{\mathrm{eff.}}$ from forward backward asymmetry A^b_{FB} in ee->bb at LEP

Two lessons:

- Most precise determinations of $\sin^2\theta^{\ell}_{\mathrm{eff.}}$ differ significantly
  - Cries for verification
  - **Beam polarisation matches up for luminosity Factor 30 in case of LEP/SLC**

Coupling to on-shell Z-Bosons

Running on Z pole "GigaZ"

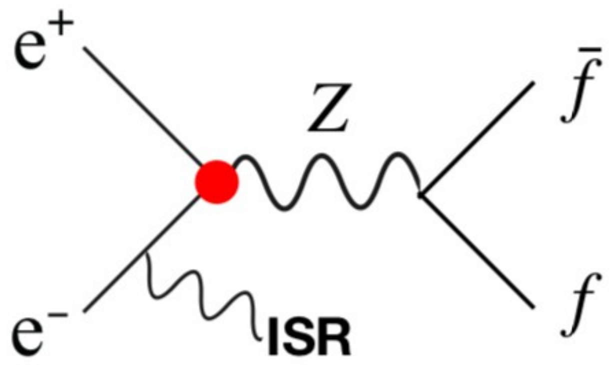


Around 5×10^9 Z events (250xLEP)

With beam polarisation

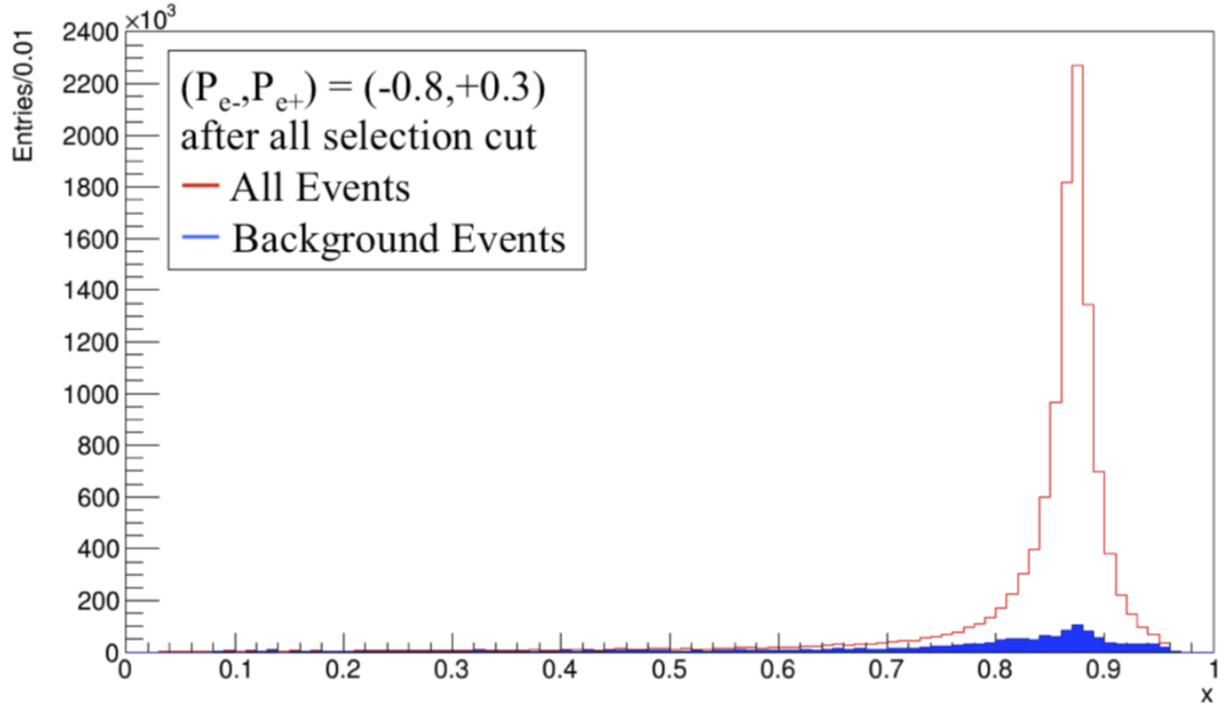
~30x250 = 7500 LEP!

Radiative return at higher energies



$$m_Z^2 = \frac{1-|\beta|}{1+|\beta|} \cdot s$$

$$\beta = \frac{|\sin(\theta_1 + \sin\theta_2)|}{\sin\theta_1 + \sin\theta_2}$$

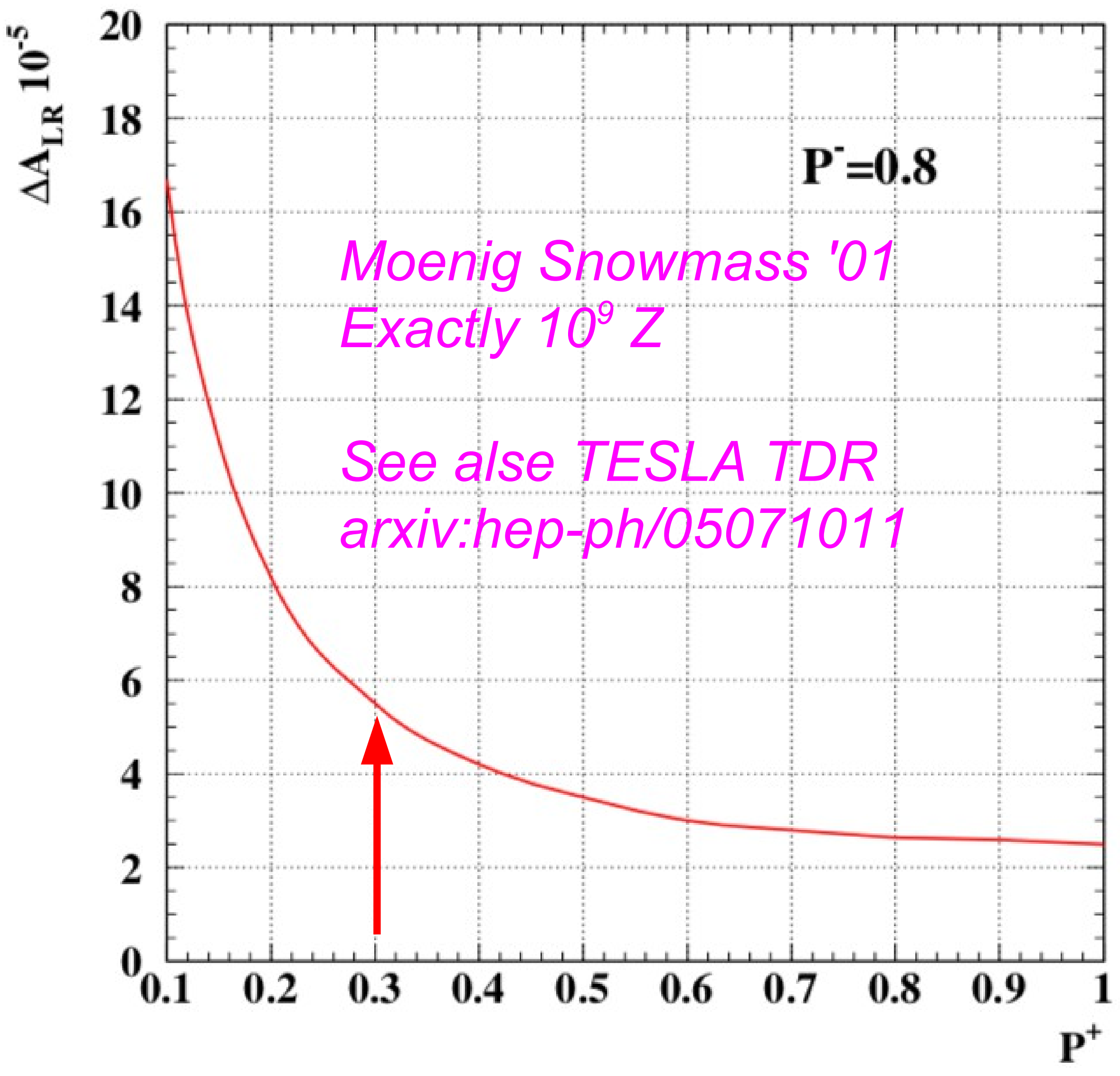


~10^8 events at 250 GeV with $2ab^{-1}$

Beam polarisation

A_{LR} at GigaZ?

Blondel scheme: $$A_{\rm LR} = \sqrt{\frac{(\sigma_{++}+\sigma_{-+}-\sigma_{+-}-\sigma_{--})(-\sigma_{++}+\sigma_{-+}-\sigma_{+-}+\sigma_{--})}{(\sigma_{++}+\sigma_{-+}+\sigma_{+-}+\sigma_{--})(-\sigma_{++}+\sigma_{-+}+\sigma_{+-}-\sigma_{--})}}$$



Blondel scheme independent of polarimeter precision

- Assumes perfect spin flip for polarised beams
- Residuals must be monitored by polarimeter
- Residual uncertainty of $\Delta A_{LR} = 0.5\text{x}10^{-4}$ seems possible
- The more positron polarisation the better (see backup)
- Don't forget energy dependency ($dALR/d\sqrt{s} \sim 2\text{x}10^{-5}/MeV$)

Precision **$\Delta A_{LR} = 1\text{x}10^{-4}$** is a realistic assumption for GigaZ

=> $\boxed{\delta \sin^2\theta^{\ell}_{\rm eff.} \sim 1.3 \cdot 10^{-5}}$

A_{LR} at GigaZ?

ALR is "simple counting" measurement

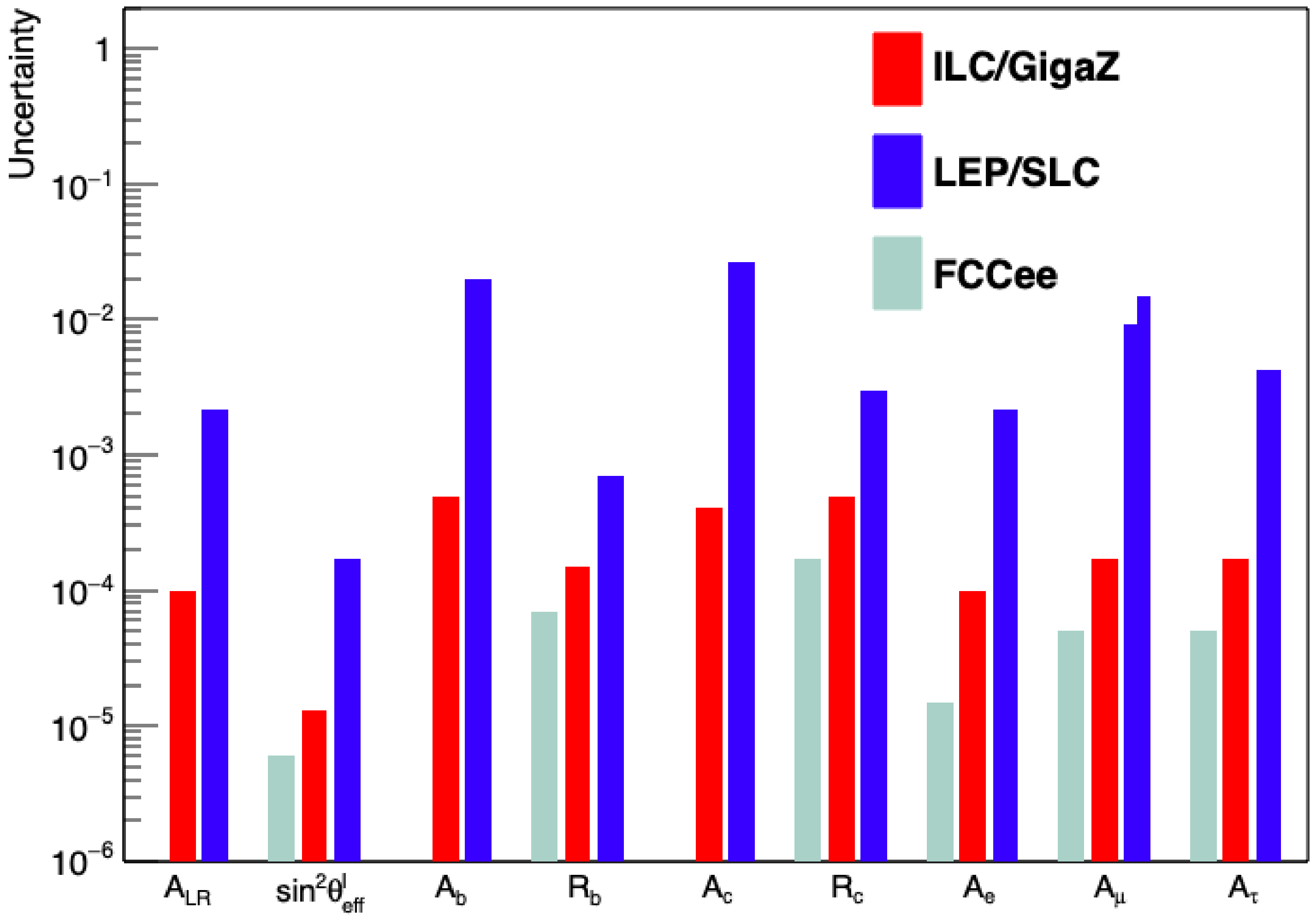
Errors?

- On Z-Pole
  - Energy dependency ($dA_{LR}/d\sqrt{s} \sim 2x10^{-5}/MeV$) due to γ/Z interference
    - Need excellent calibration of $\sqrt{s}$, *1 MeV seems possible*
  - Beam polarisation (Blondel scheme and polarimeters):
    - Residual uncertainty of $\Delta A_{LR} = 0.5x10^{-4}$ seems possible
  - Precision $\Delta A_{LR} = 1x10^{-4}$ is a realistic assumption for GigaZ

$$\boxed{\delta \sin^2\theta^{\ell}_{\mathrm{eff.}} \sim 1.3 \cdot 10^{-5}}$$

- Radiative return
  - Mainly limited by statistics $\Delta A_{LR} = 1.4x10^{-4}$
  - Beam polarisation $\Delta A_{LR} = 0.5x10^{-4}$ (More processes available)
  - Energy dependence 1000 x weaker than on Z-pole

Precision on relevant observables



Precise measurement of $\sin^2\theta^\ell_{\text{eff}}$.

- Ten times better than LEP/SLD and often competetive with FCCee
- Polarisation compensates for ~30 times luminosity
- ... and A_{LR} at LC can benefit from hadronic Z decays
- **No assumption on lepton universality at LC**

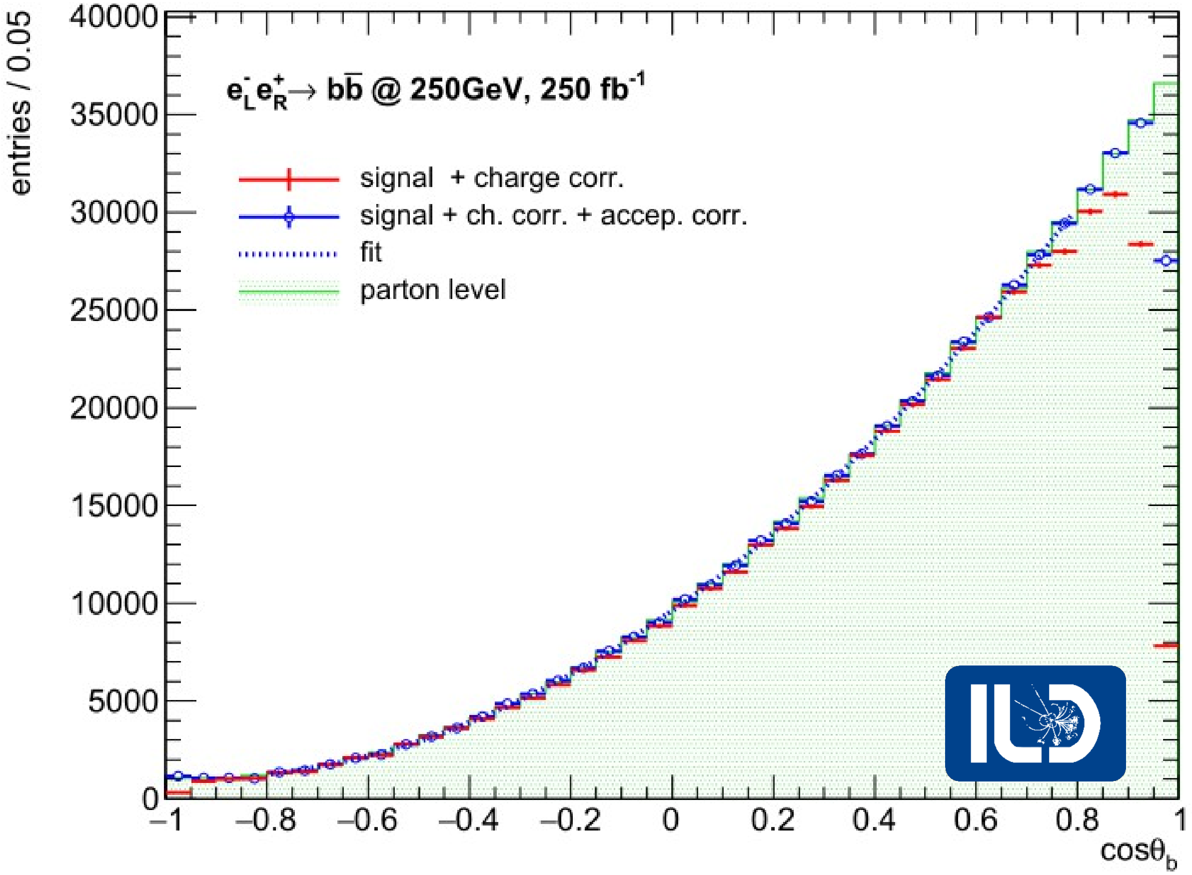
Complete test of lepton universality

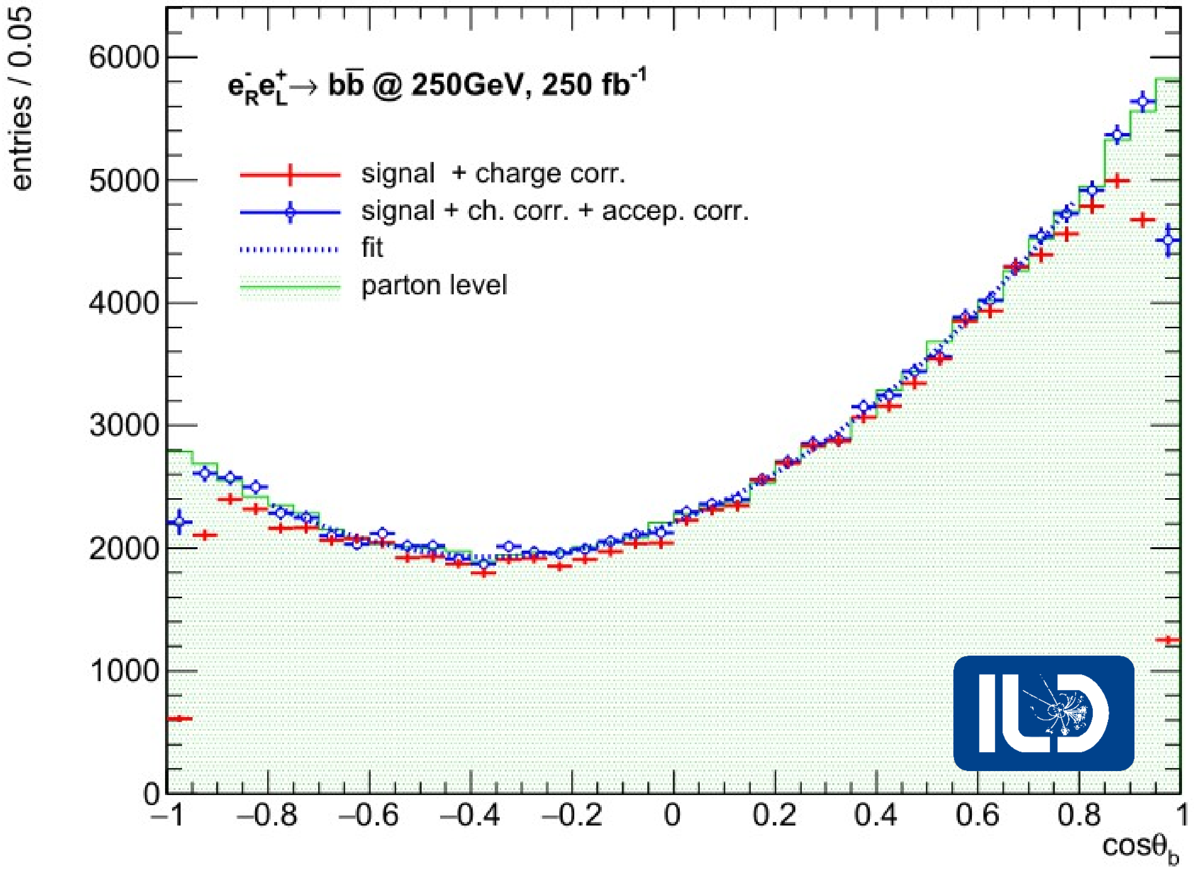
- Precisions of order 0.05%

Note excellent measurement of quark asymmetries

- Backed up by detailed simulation studies at higher energies
- *Important input for higher energies*

Decomposing ee->bb – Differential cross section





Full simulation study (with ILD concept), Benchmark reaction

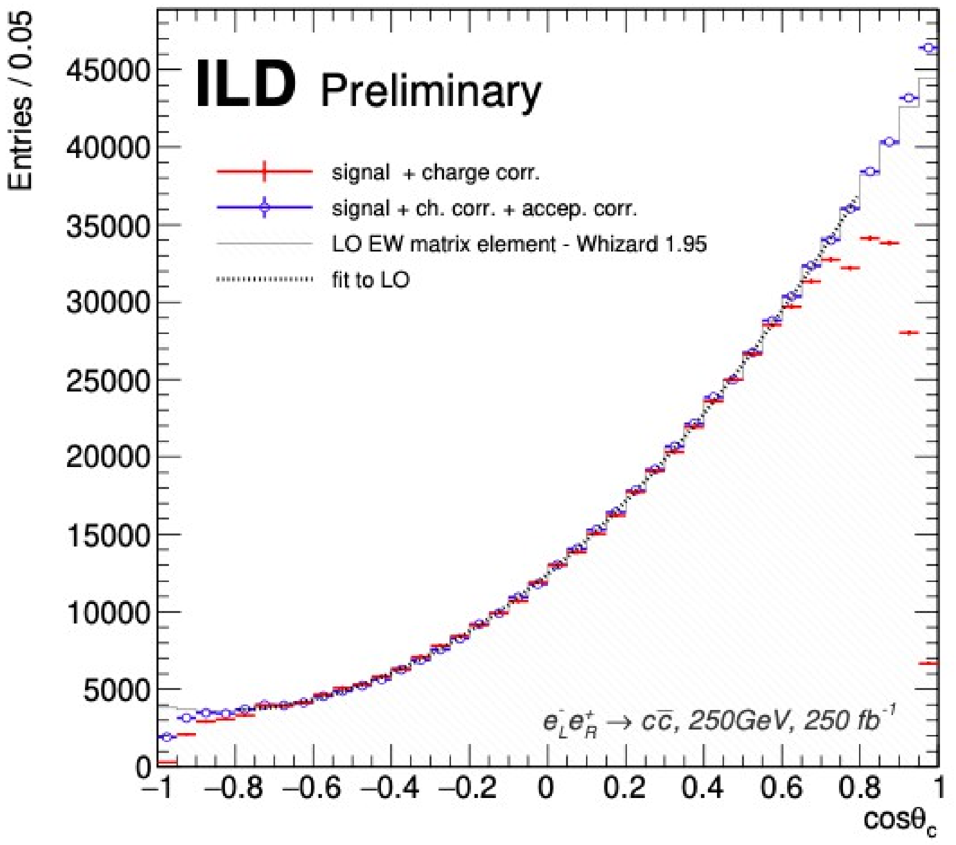
- Experimental challenge: Measurement of b-quark charge on event-by-event basis

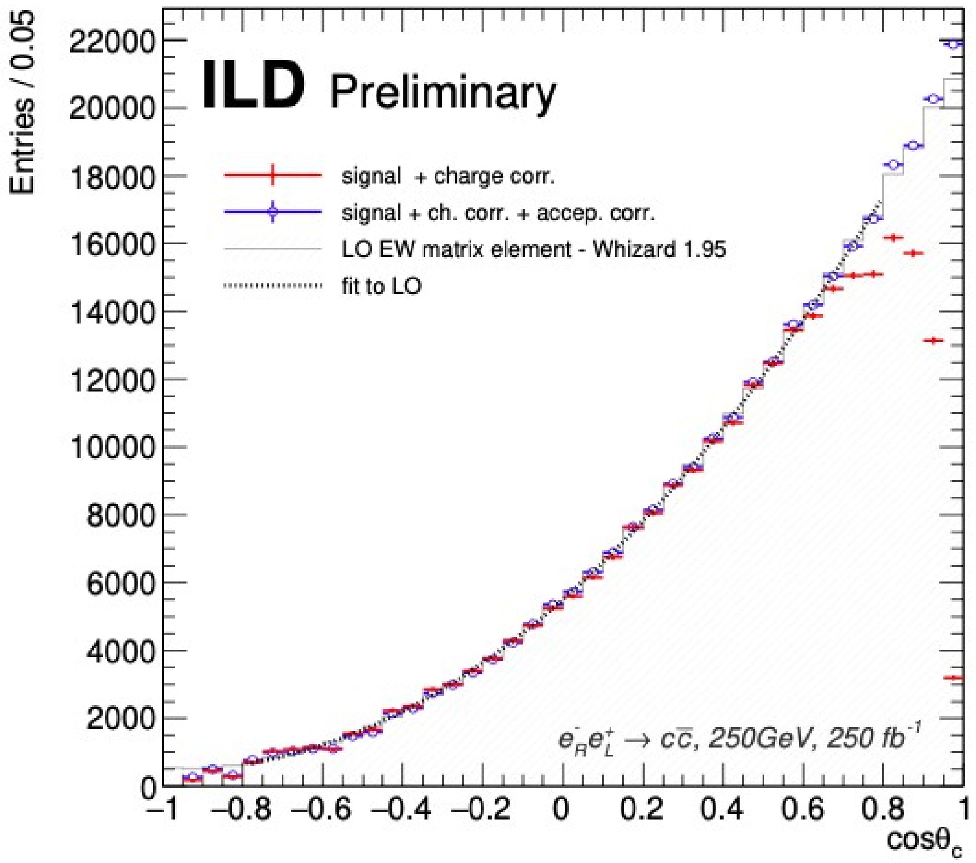
Long lever arm in cos θ_b to extract from factors or couplings

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

Form factors/couplings from S and A

New: Decomposing ee->cc – Differential cross section





Full simulation study (with ILD concept)

- Experimental challenge: Measurement of c-quark charge on event-by-event basis

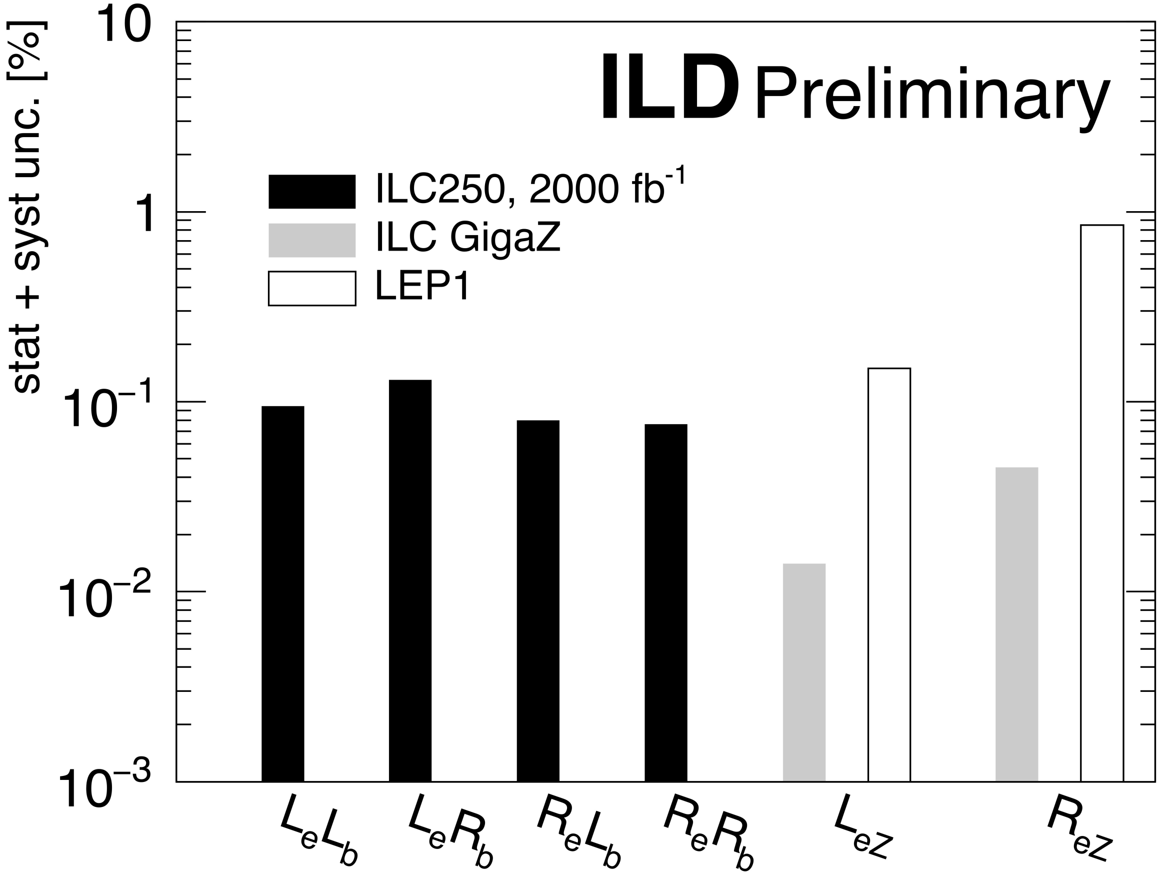
Long lever arm in cos θ_c to extract from factors or couplings

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

Form factors/couplings from S and A

Precision on couplings and helicity amplitudes and physics reach

Example b-couplings (same observation for c-couplings)



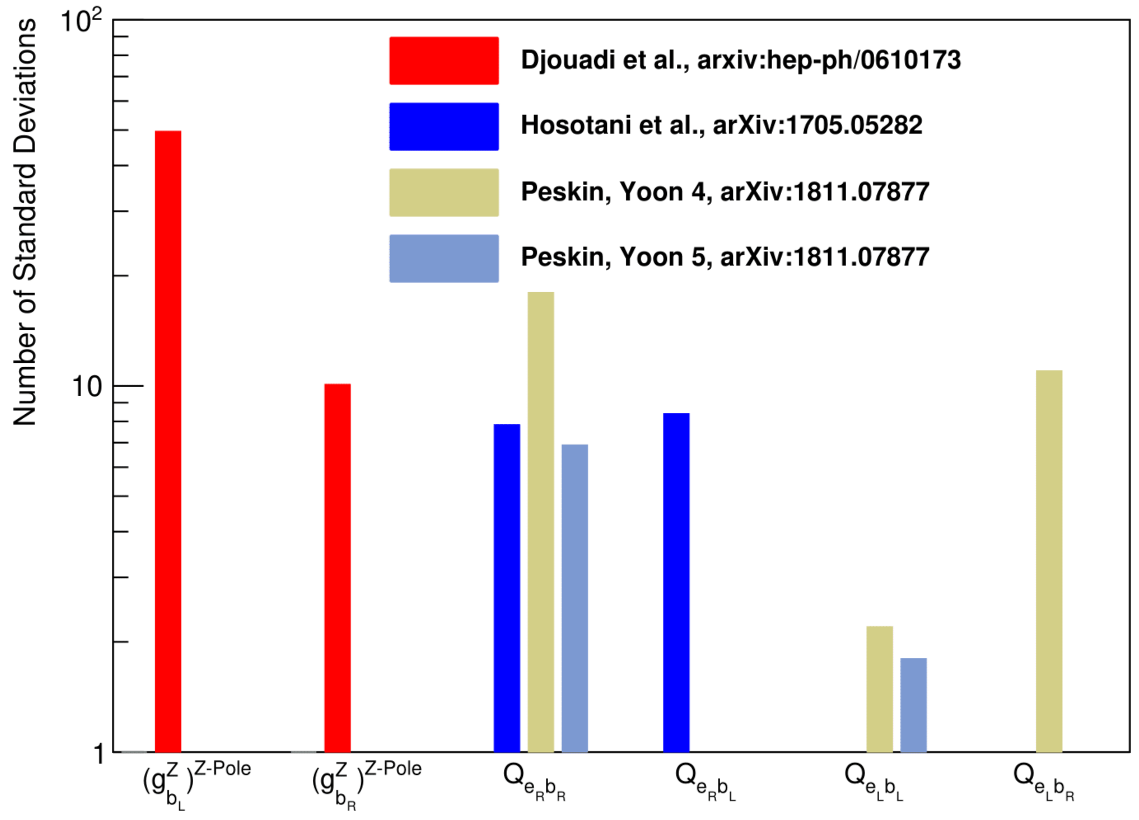
Couplings are order of magnitude better than at LEP

- In particular right handed couplings are much better constrained

New physics can also influence the Zee vertex

- in 'non top-philic' models

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



Impressive sensitivity to new physics in Randall Sundrum Models with warped extra dimensions

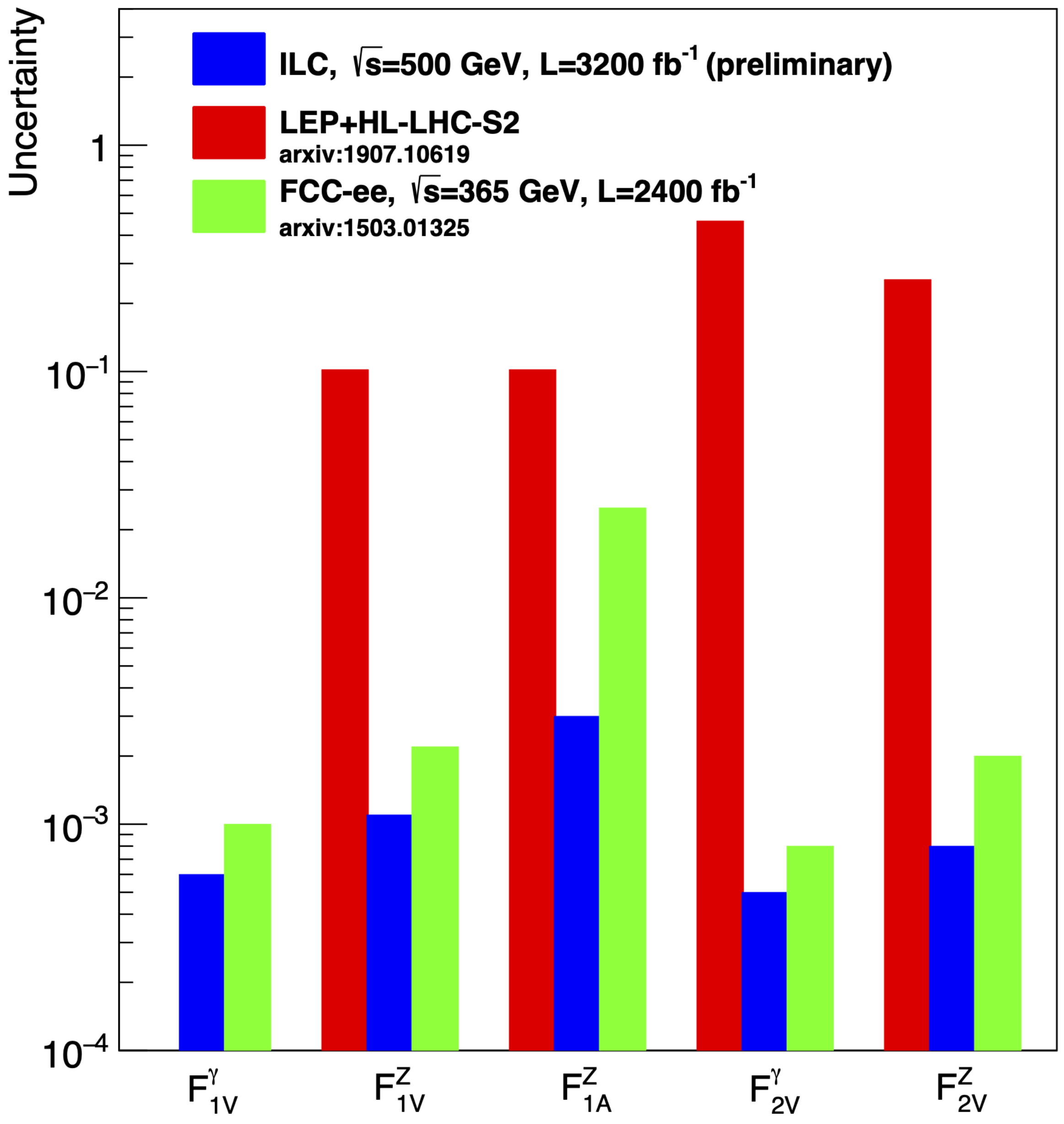
- **Complete tests only possible at LC**
- **Discovery reach O(10 TeV)@250 GeV and O(20 TeV)@500 GeV**

Pole measurements critical input

- Only poorly constrained by LEP

Top quark couplings at √s = 500 GeV and 365 GeV

Accuracy on CP conserving couplings

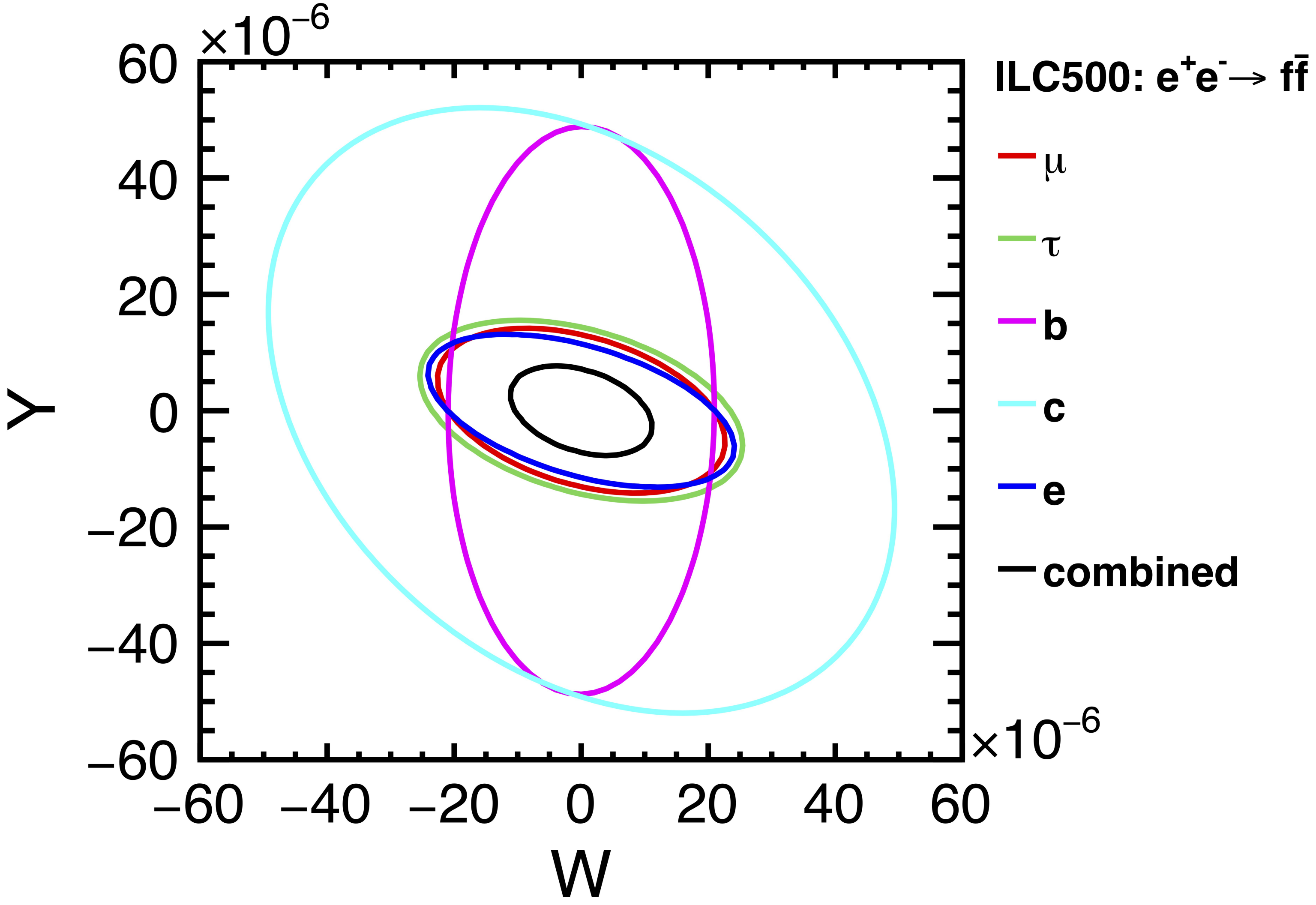


- e+e- collider might be up to two orders of magnitude more precise than LHC (√s = 14 TeV)
- Large disentangling of couplings for ILC thanks to polarised beams
- Final state analysis at FCCee
  - Also possible at LC => Redundancy

LC promises to be high precision machine for electroweak top couplings

Top quark couplings at √s = 500 GeV and 365 GeV

Contributions for different fermion species



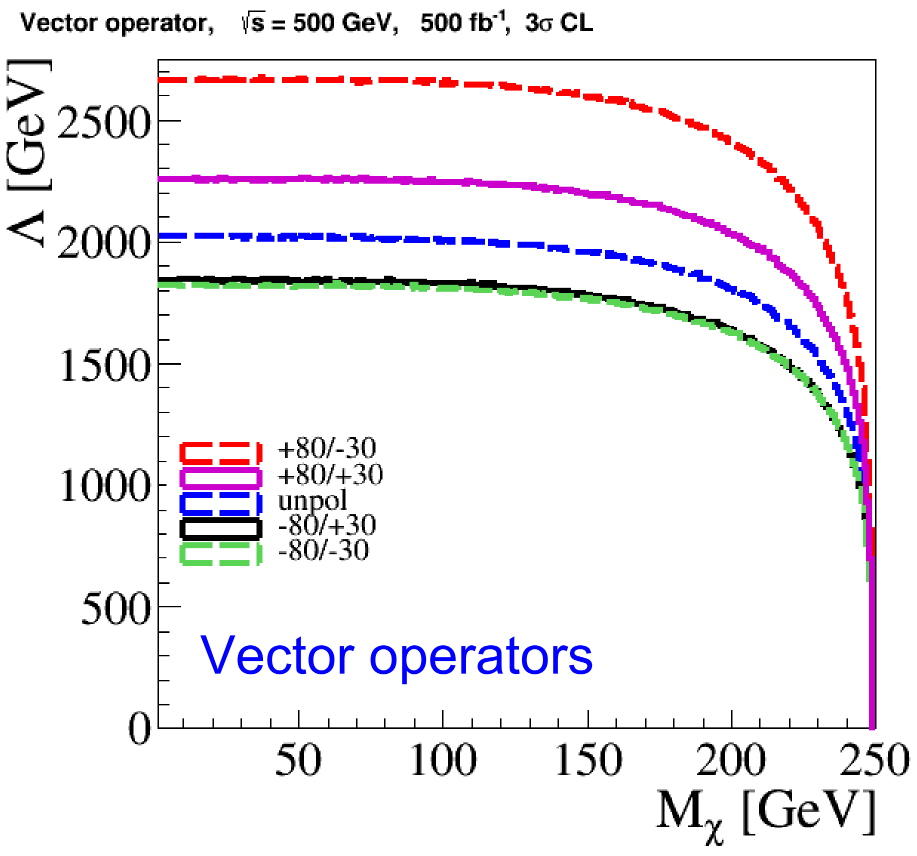
$\sqrt{s}$	ΔW	ΔY	ρ
HL-LHC	15×10^{-5}	20×10^{-5}	-0.97
ILC250	3.4×10^{-5}	2.4×10^{-5}	-0.34
ILC500	1.1×10^{-5}	0.78×10^{-5}	-0.35
ILC1000	0.39×10^{-5}	0.27×10^{-5}	-0.38
500 GeV, no beam pol.	2.0×10^{-5}	1.2×10^{-5}	-0.78

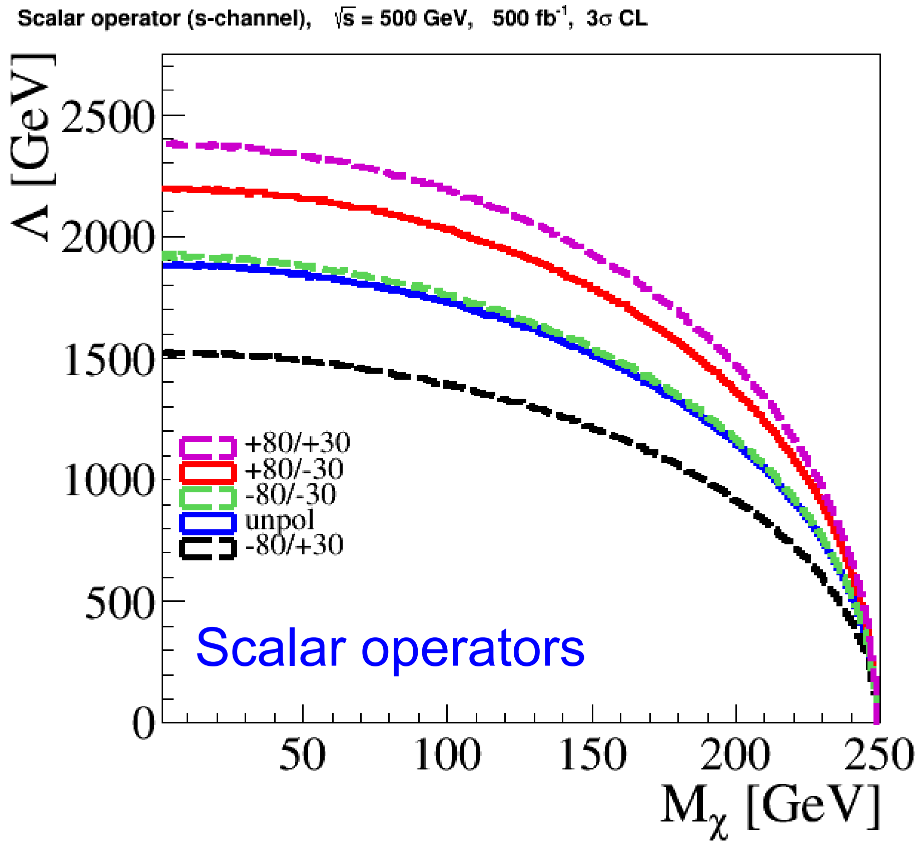
Beam polarisation essential to disentangle effects from W and Y

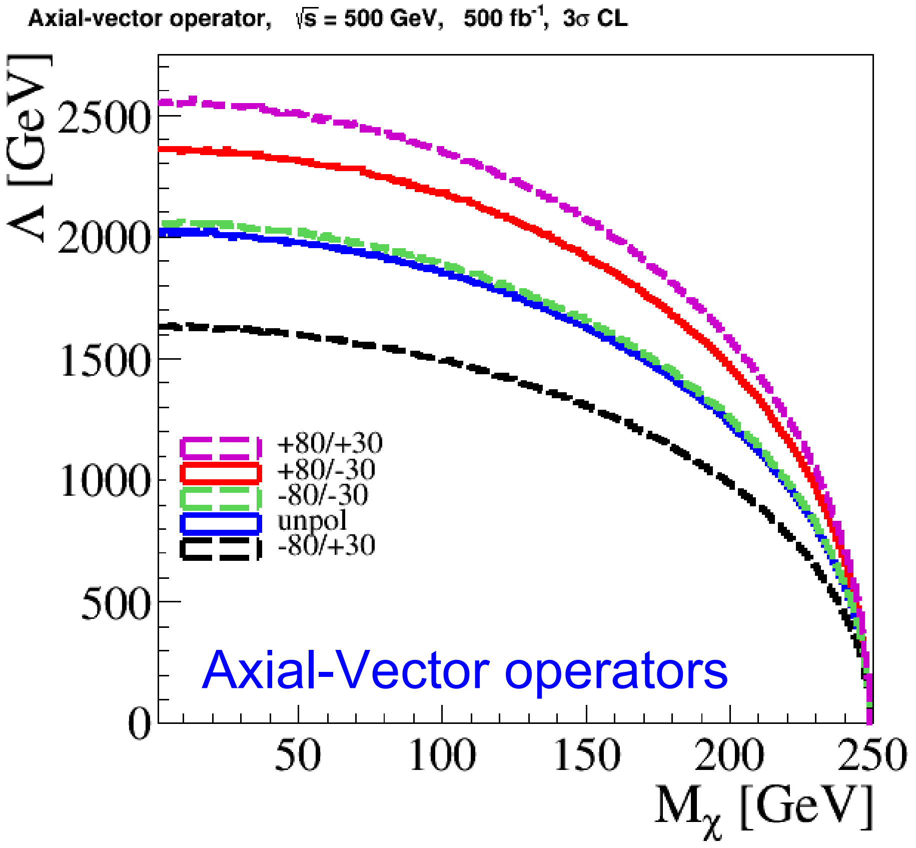
ILC250 outperforms LHC

ILC500 and above outperforms e+e- machines
w/o polarisation (at 4ab^{-1})

Monophoton searches

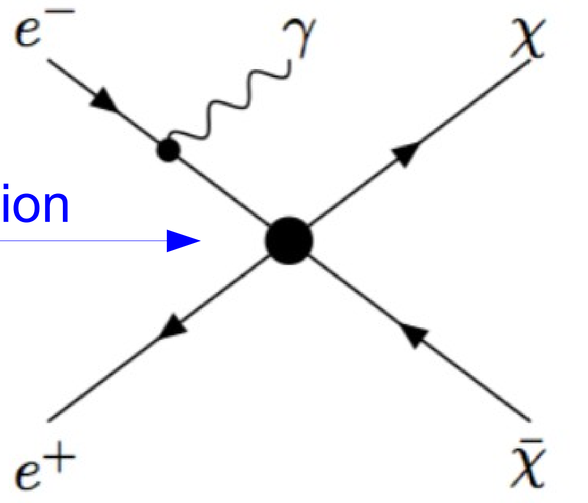






M. Habermehl

Four fermion vertex



- Search (or set limits) for dark matter production
- Scale reach depends on beam polarisation
  - Largest scale reach for positive electron beam polarisation
  - Positron polarisation makes a difference

Summary

- Beam polarisation is an essential asset for a successful e+e- precision program
  - Remember that the SM is a chiral theory!!!
  - For comprehensive overviews see also hep-ph/0507011 and 1801.02840

- Beam polarisation allows for large disentangling of various effects of new physics (or for constraining them further)
  - Helps a great deal to simplify analyses and interpretation of results due to adequate experimental setup for the theory under test

- Linear Collider concept allows for sweeping over large energy for precision tests and **direct and indirect discoveries**
  - Measurements from Z pole to > 1 TeV within one facility
  - Colliders w/o strong beam polarisation will provide important complementary information

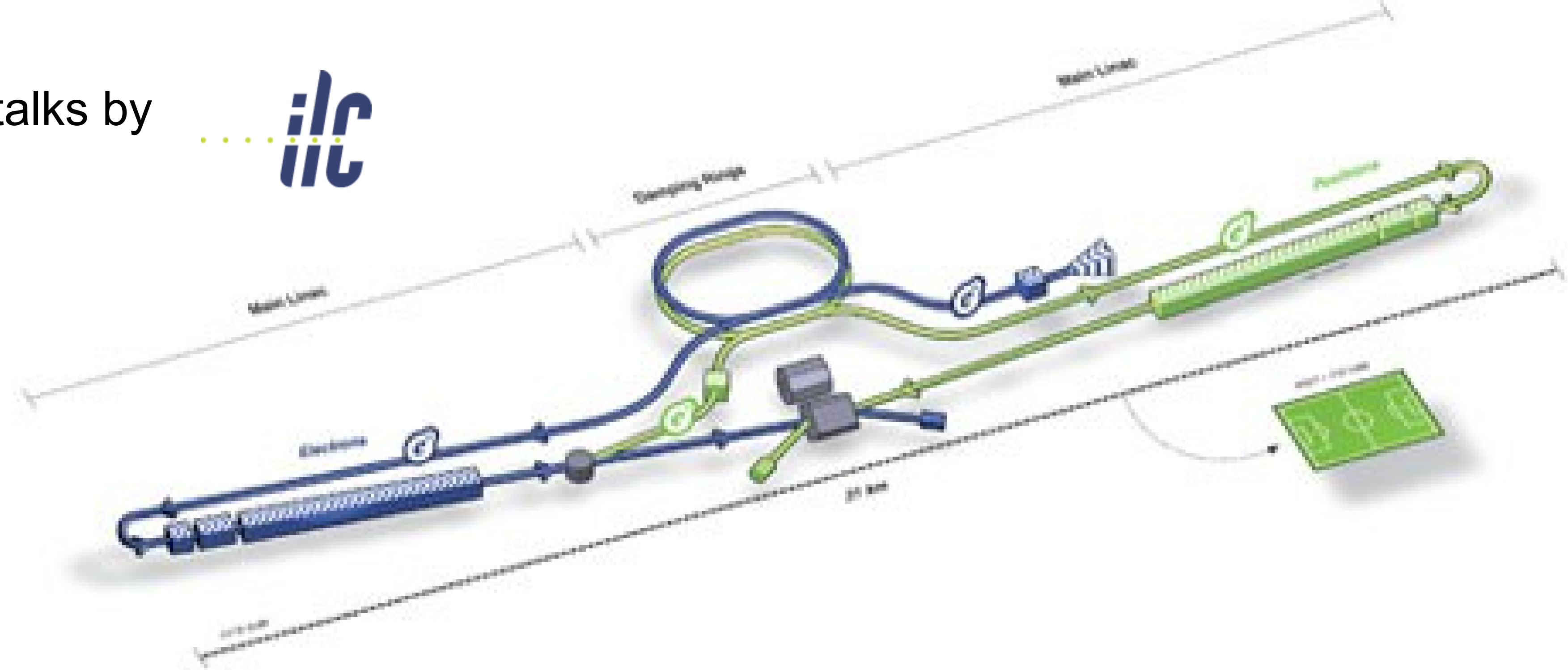
- A clear pattern of anomalies would be an excellent (and maybe the only) motivation for a large hadron machine

Backup

Linear Electron Positron Colliders

See also talks by

Jim Brau



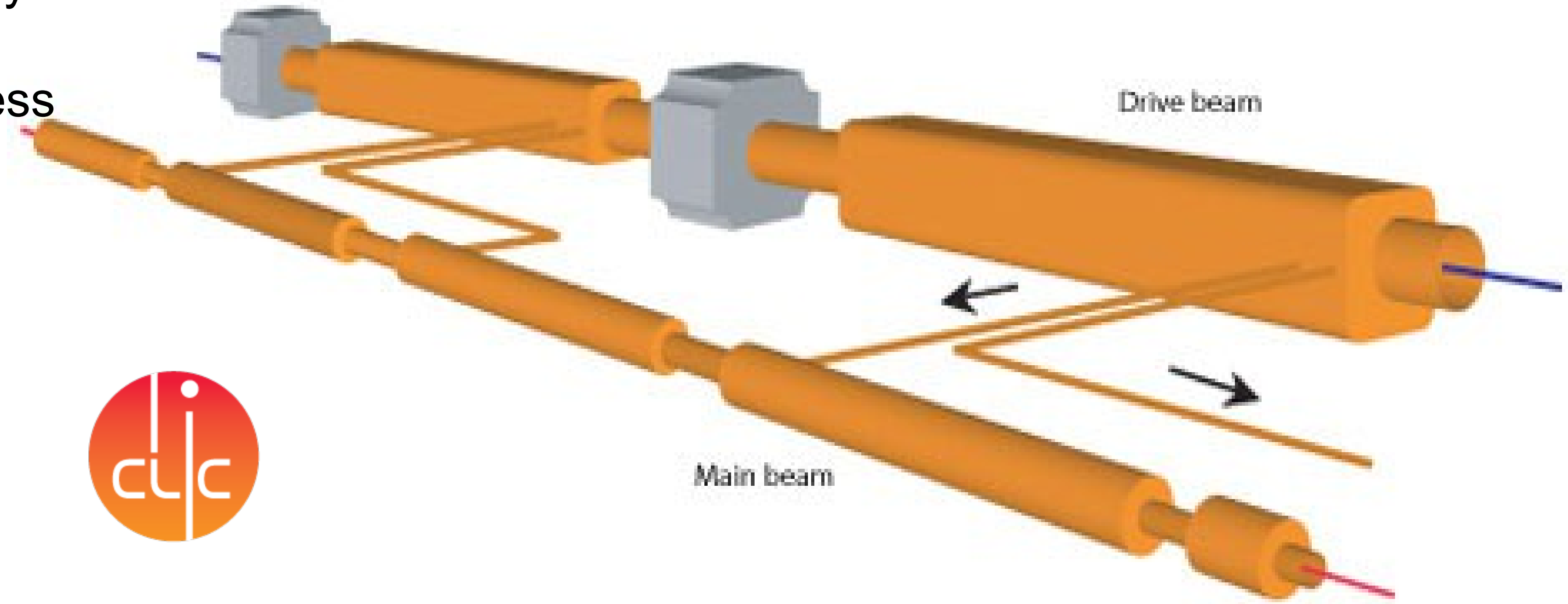
Energy: 0.1 - 1 TeV
Electron (and positron) polarisation
TDR in 2013
+ DBD for detectors
Footprint 31 km

Initial Energy 250 GeV – Footprint ~20km

Strong effort by Japanese Community to host ILC – Political decisions expected ... soon

See also talk by

Steinar Stapness



Energy: 0.4 - 3 TeV

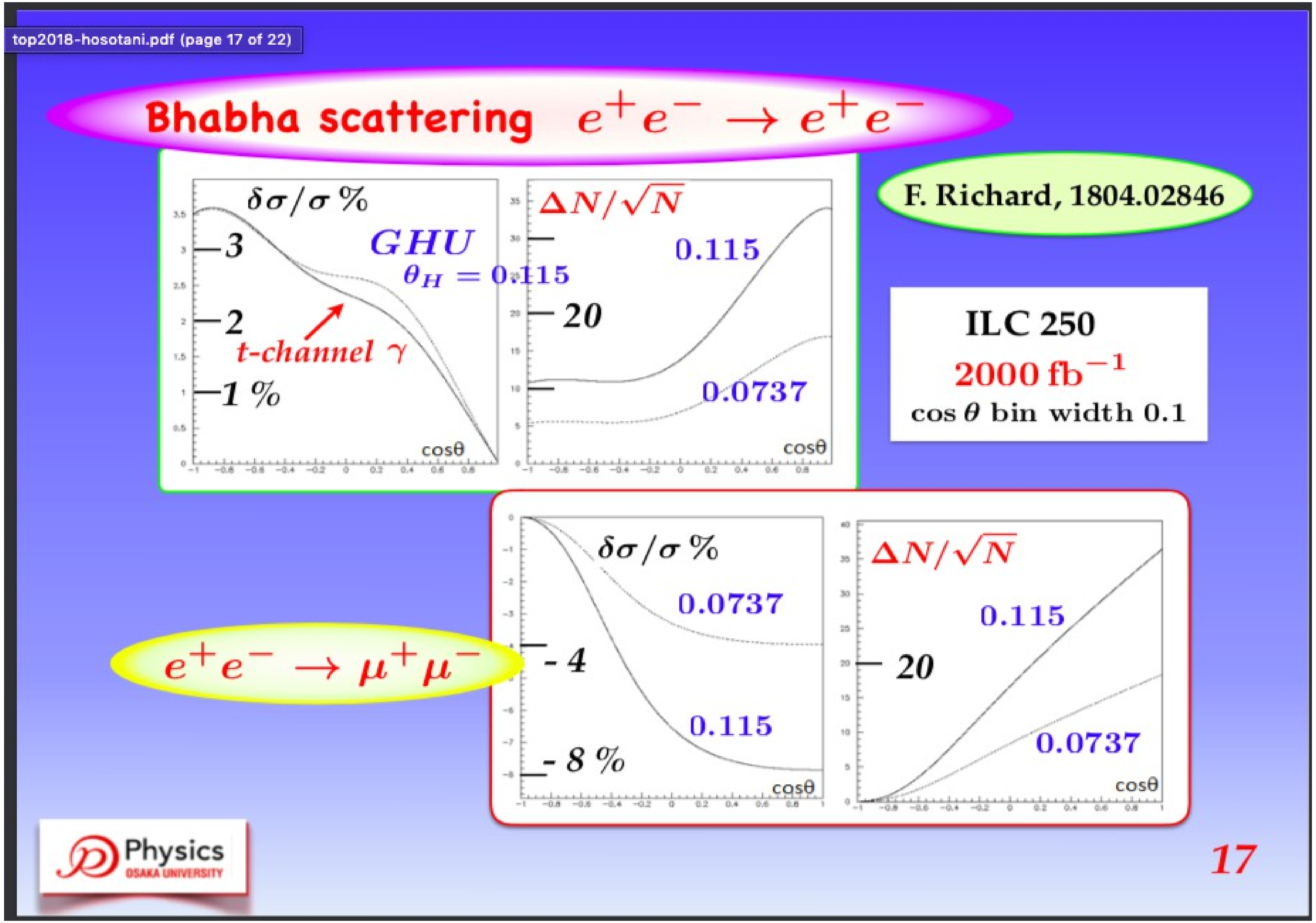
CDR in 2012

Footprint 48km

Initial Energy 380 GeV

Possible future project at CERN

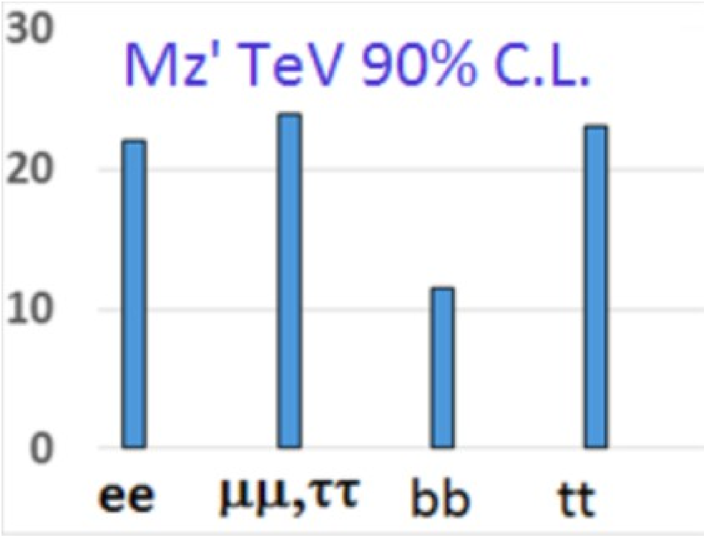
GHU and light fermions



GHU is example for model that implies

modifications of

"well known" couplings



Impressive mass reach already at ILC 250 GeV

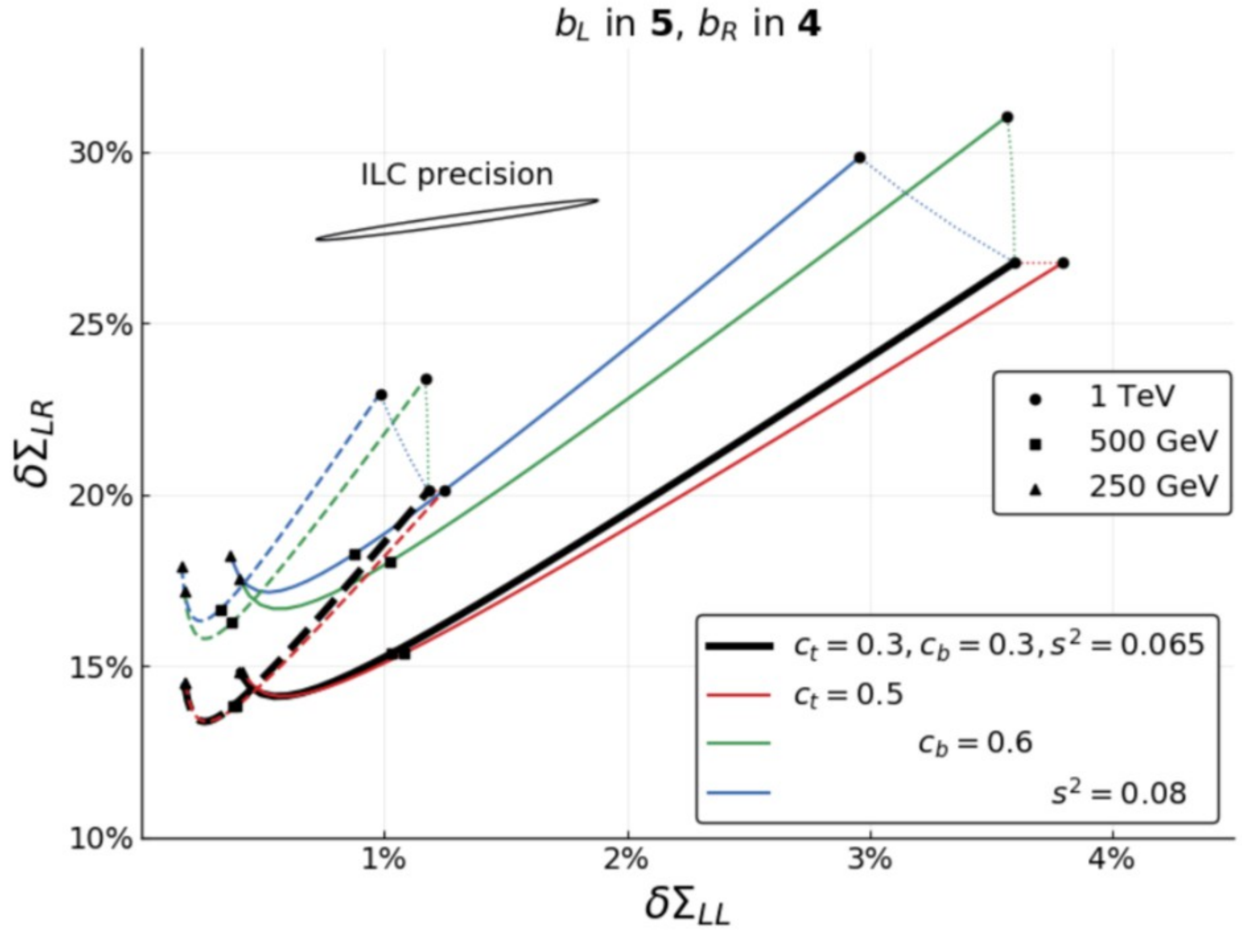
Randall-Sundrum Model and flavor mixing à la Peskin/Yoon

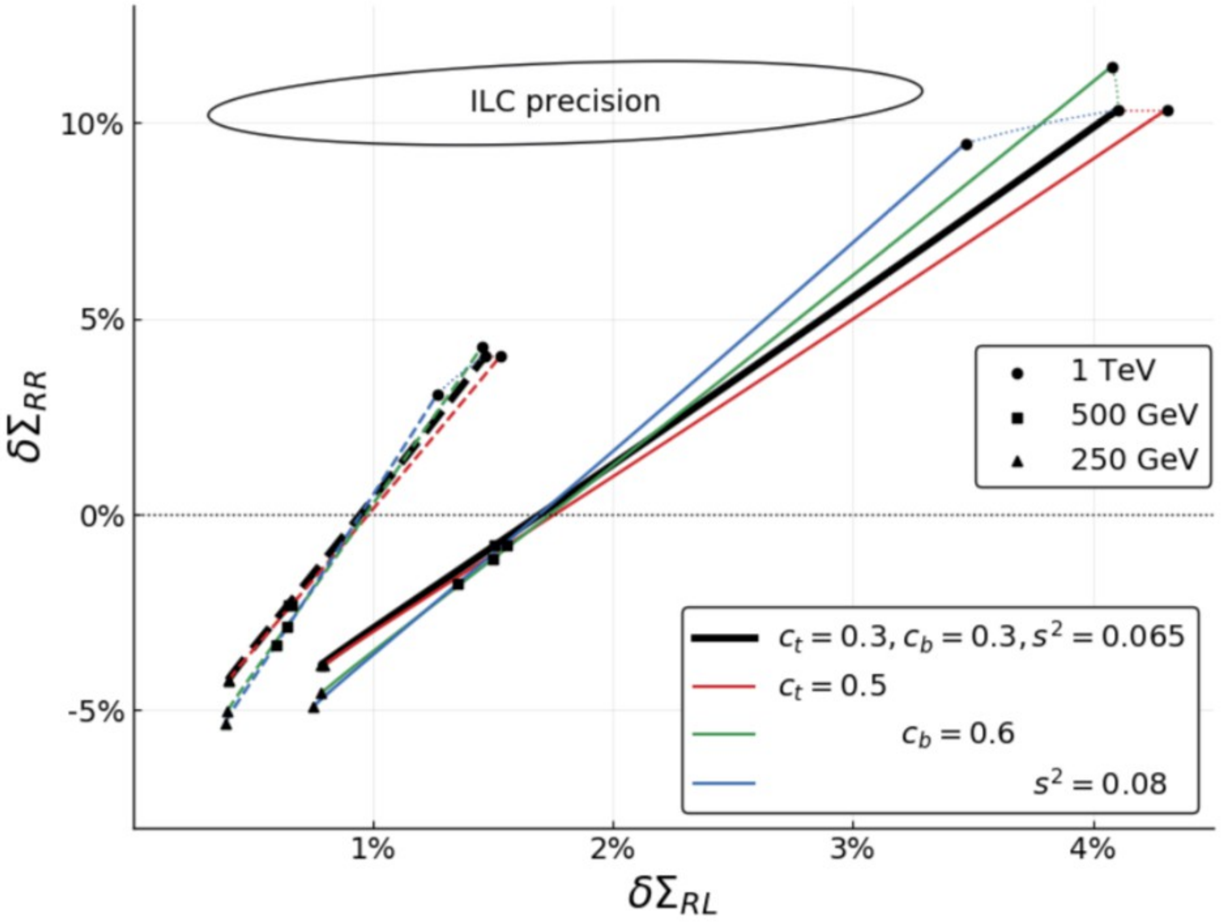
1811.07877

e.g. $$\frac{m_b^2}{m_t^2} = \frac{1}{2}\tan^2\theta_b \left(\frac{1+2c_b}{1+2c_t}\right)\left(\frac{z_0}{z_R}\right)^{2c_b-2c_t}$$

In short, mixing is consequence of arrangement of **heavy quarks** in 5D multiplets

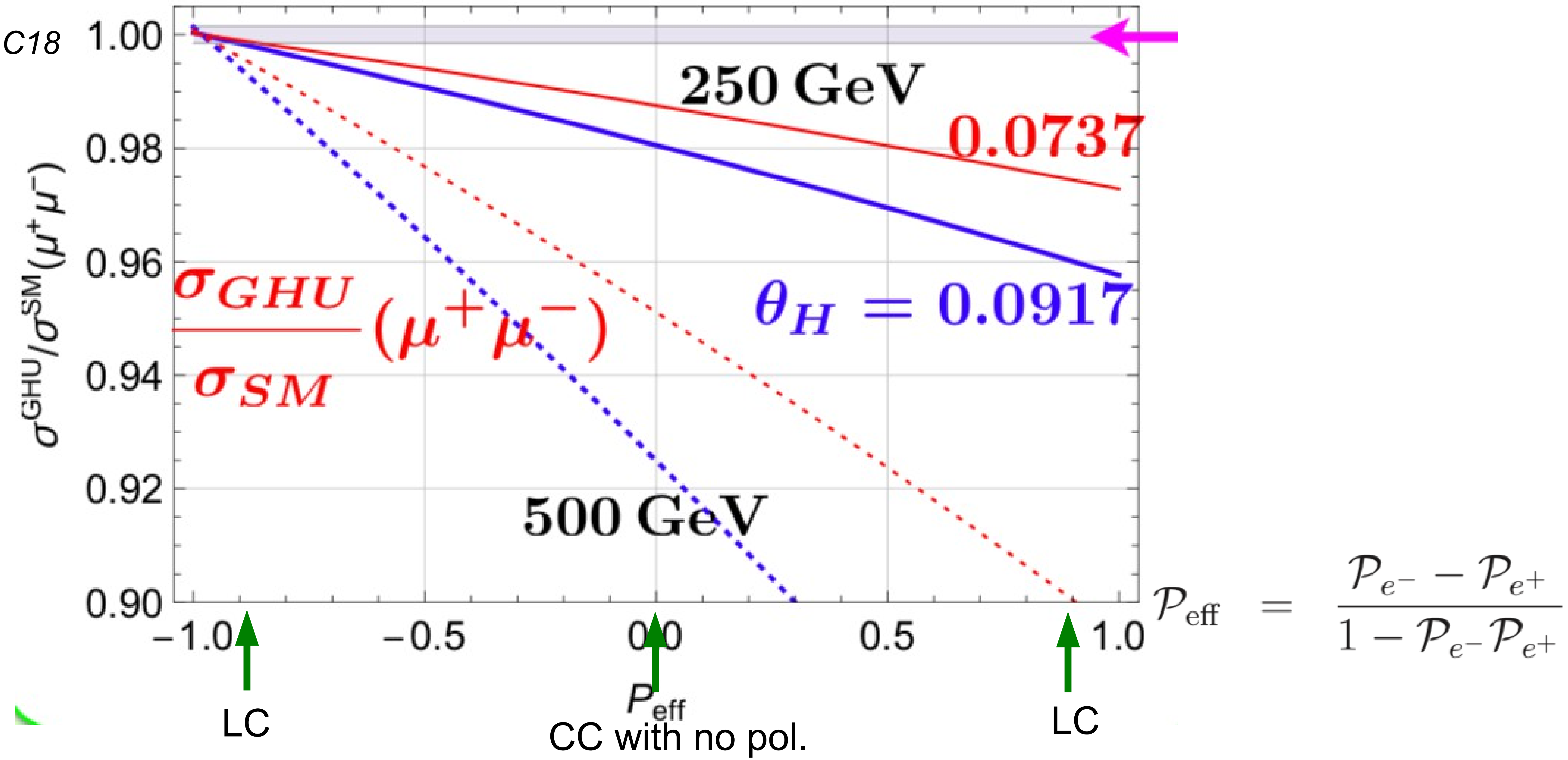
$$\frac{d\sigma}{d\cos\theta}(e_L^- e_R^+ \to b\bar{b}) = \Sigma_{LL}(s)\ (1+\cos\theta)^2 + \Sigma_{LR}(s)(1-\cos\theta)^2$$
$$\frac{d\sigma}{d\cos\theta}(e_R^- e_L^+ \to b\bar{b}) = \Sigma_{RL}(s)\ (1-\cos\theta)^2 + \Sigma_{RR}(s)(1+\cos\theta)^2$$





Grand Higgs Unification à la Hosotani – Dimuon production

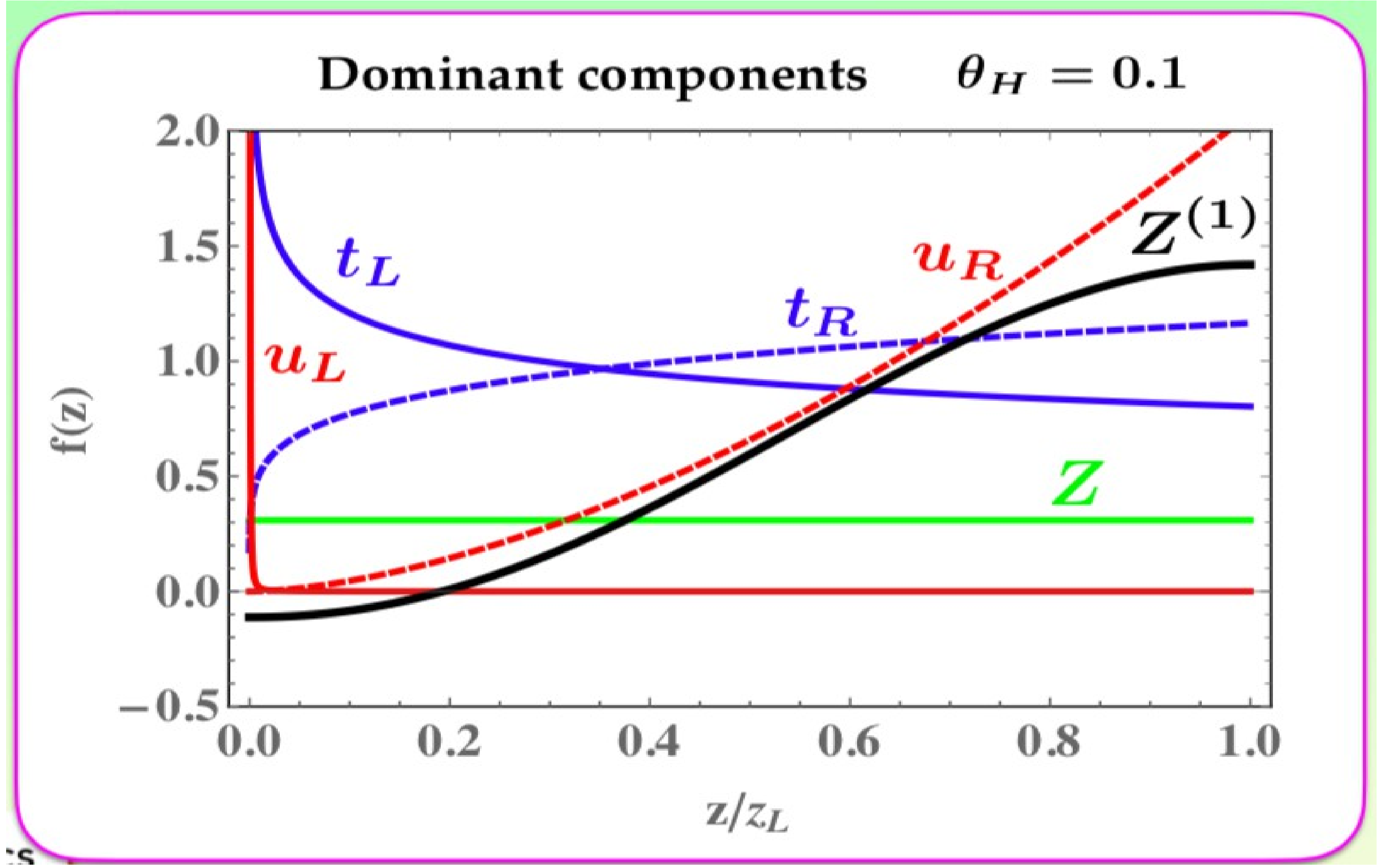
Y. Hosotani, Top@LC18



- Visible effects for Peff ≥ -0.5
- LC would add two points that ideally are complemented by a point from Circular Collider
- Huge amplification of effect at higher centre-of-mass energies

Example – Grand Higgs Unification à la Hosotani

Randall Sundrum Models imply arrangement of fermion wave functions in (warped) extra dimension
The more overlap on IR-Brane the larger the interaction

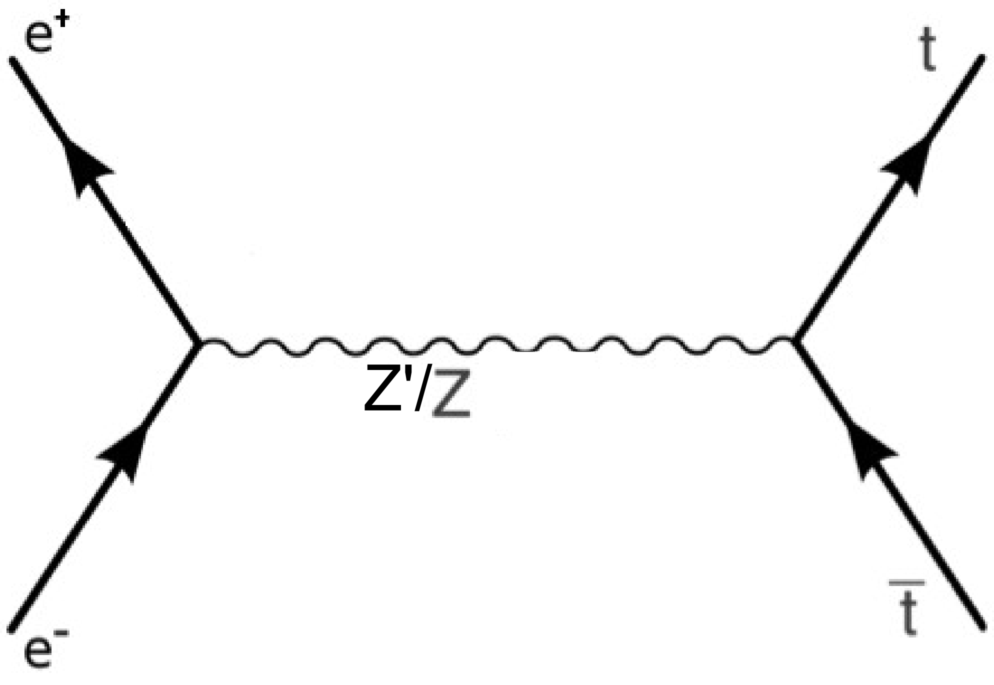


	SM: Z Left	SM: Z Right	$Z^{(1)}$ Left	$Z^{(1)}$ Right	$Z_R^{(1)}$ Left	$Z_R^{(1)}$ Right	$\gamma^{(1)}$ Left	$\gamma^{(1)}$ Right
ν_e			−0.183	0	0	0	0	0
ν_μ	0.5	0	−0.183	0	0	0	0	0
ν_τ			−0.183	0	0	0	0	0
e			0.099	0.916	0	−1.261	0.155	−1.665
μ	−0.2688	0.2312	0.099	0.860	0	−1.193	0.155	−1.563
τ			0.099	0.814	0	−1.136	0.155	−1.479
u			−0.127	−0.600	0	0.828	−0.103	1.090
c	0.3458	−0.1541	−0.130	−0.555	0	0.773	−0.103	1.009
t			0.494	−0.372	0.985	0.549	0.404	0.678
d			0.155	0.300	0	−0.414	0.052	−0.545
s	−0.4229	0.0771	0.155	0.277	0	−0.387	0.052	−0.504
b			−0.610	0.186	0.984	−0.274	−0.202	−0.339

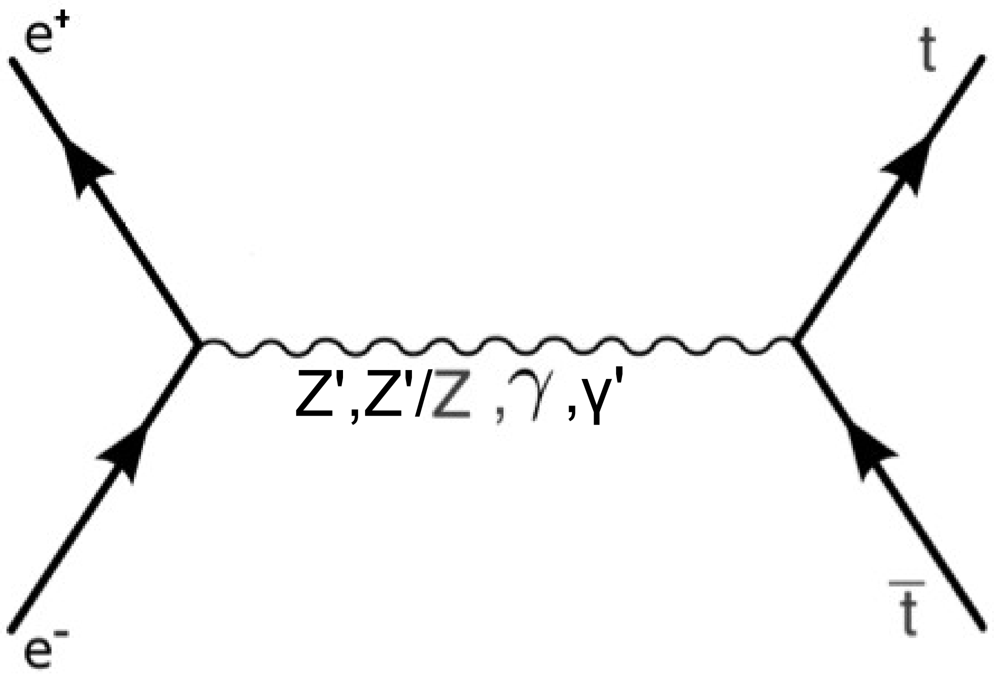
GHU Model:
- Interaction of right handed (light) fermions -> **Heavy and light fermion effect**
- Interaction of left and right handed heavy quarks
- Note also asymmetry in couplings to $\gamma^{(1)}$ => **F1Aγ ≠ 0**

Testing the chiral structure in 2-fermion processes

On the Z-pole



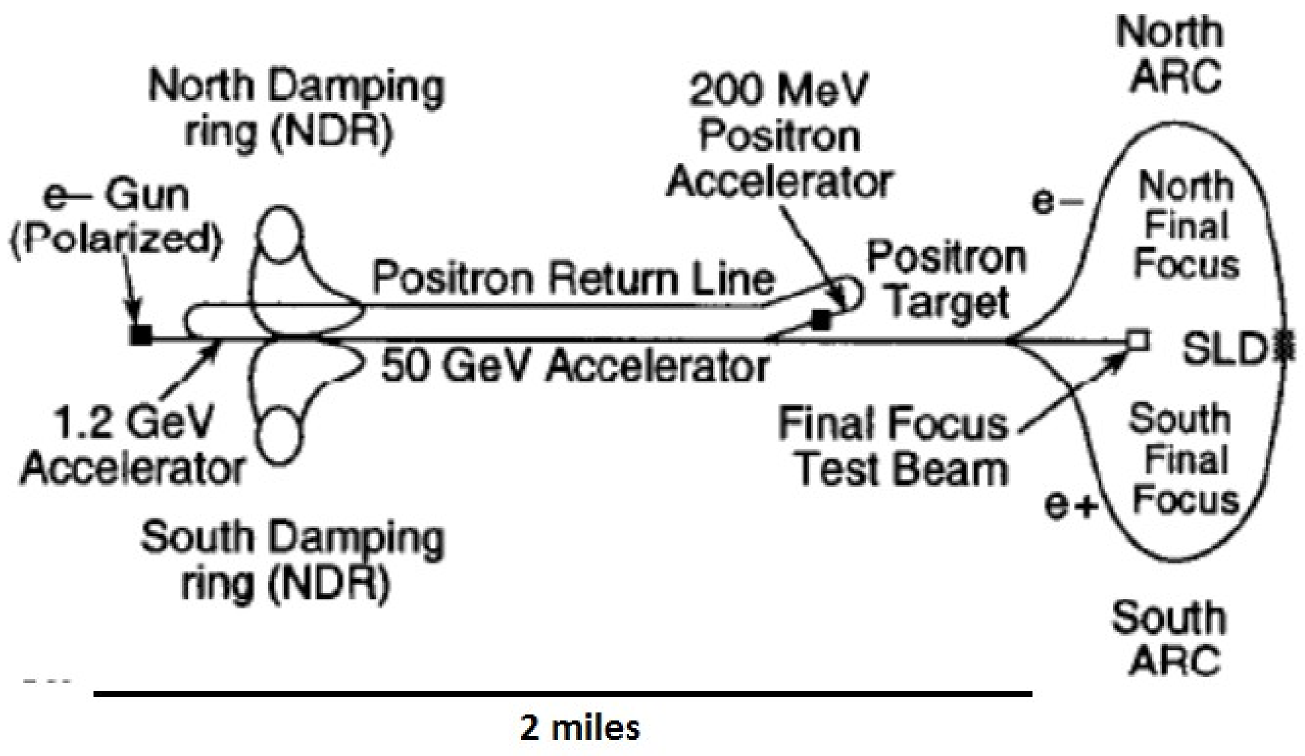
Above the Z-pole



- Sensitivity to Z/Z' mixing
- Sensitivity to vector and tensor couplings of the Z
  - (the photon does not “disturb”)

- Sensitivity to interference effects of Z and photon!!
  - There is no reason to assume that the photon is standard model like, which is a model dependent assumption in EFT fits!!!

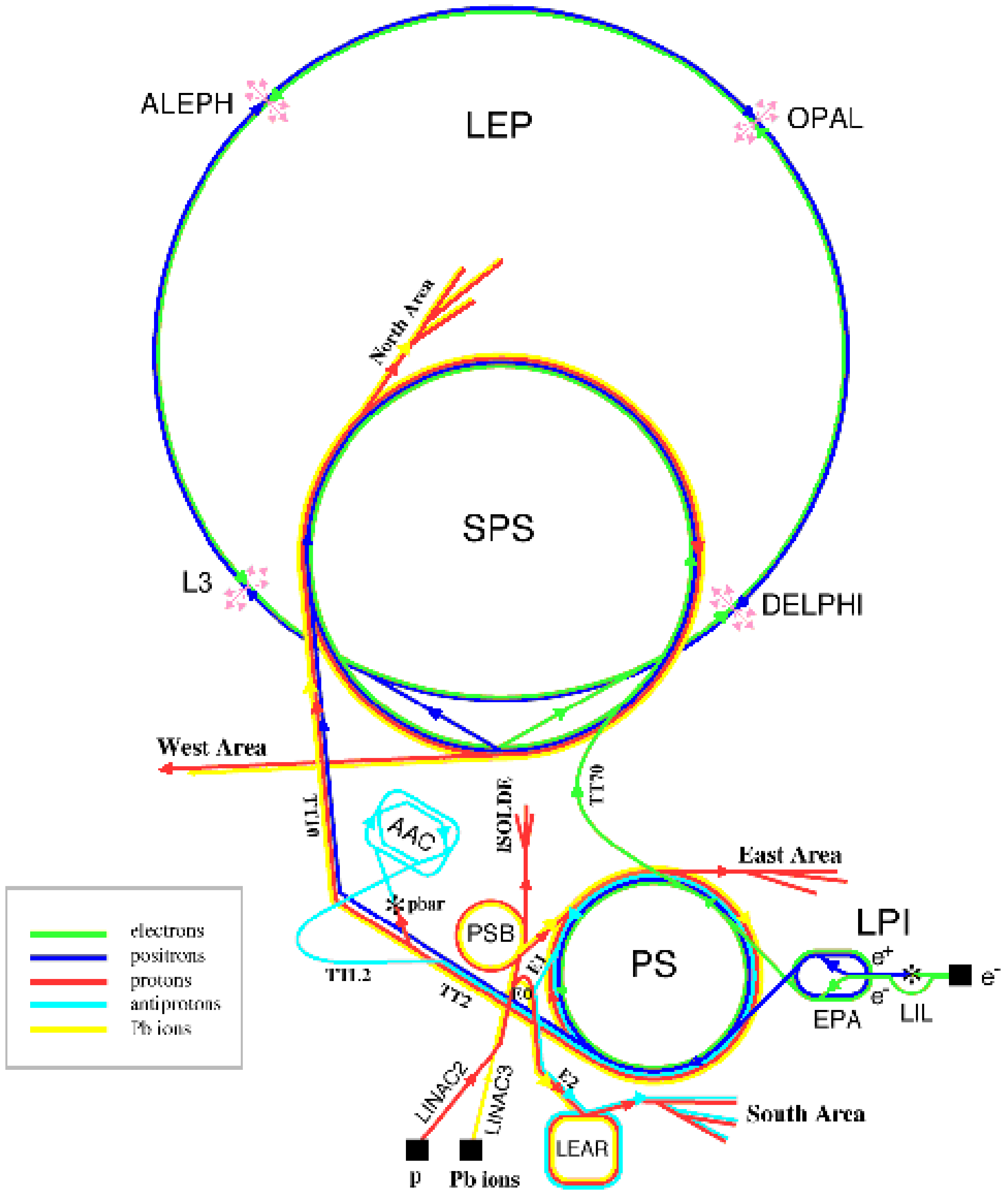
Review: LEP and SLD II



SLAC Linear Collider – SLC:

- Linear electron positron collider
- Centre of mass energy m_Z
- Operated at SLAC between 1992 and 1998
- Electron beam polarisation 90%
- One single interaction point
  - Around 400k Z events collected

Review: LEP and SLD I



Large Electron Positron Collider – LEP:

- Circular electron positron collider
- Centre of mass energes m_Z – 209 GeV
- Operated at CERN between 1989 and 2000
- No beam polarisation but high luminosity at
- four interaction points
  - Around 10M Z events collected
- No beam polarisation

Beam polarisation and disentangling

With two beam polarisation configurations

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

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

Beam polarisation – Uncertainty and positron polarisation II

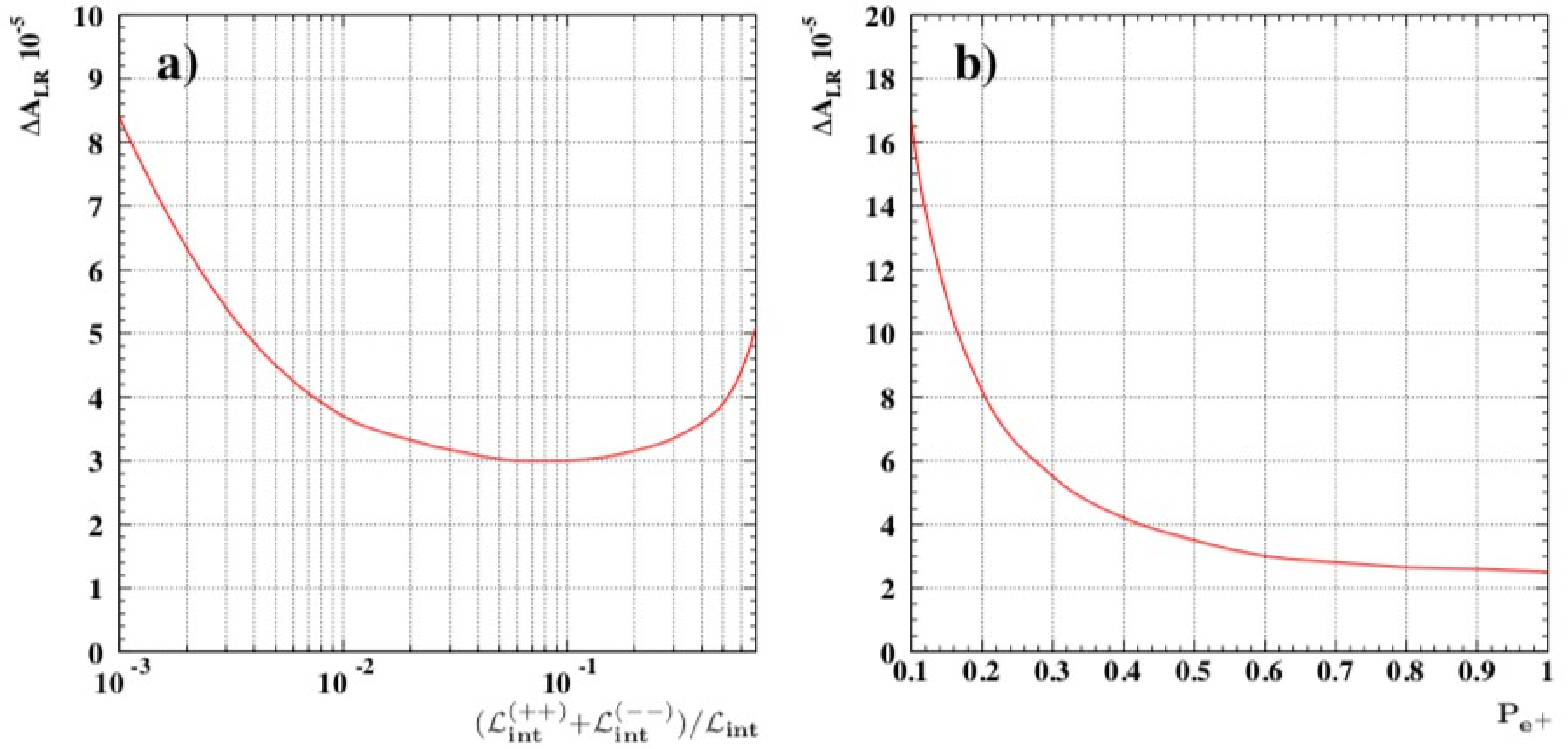
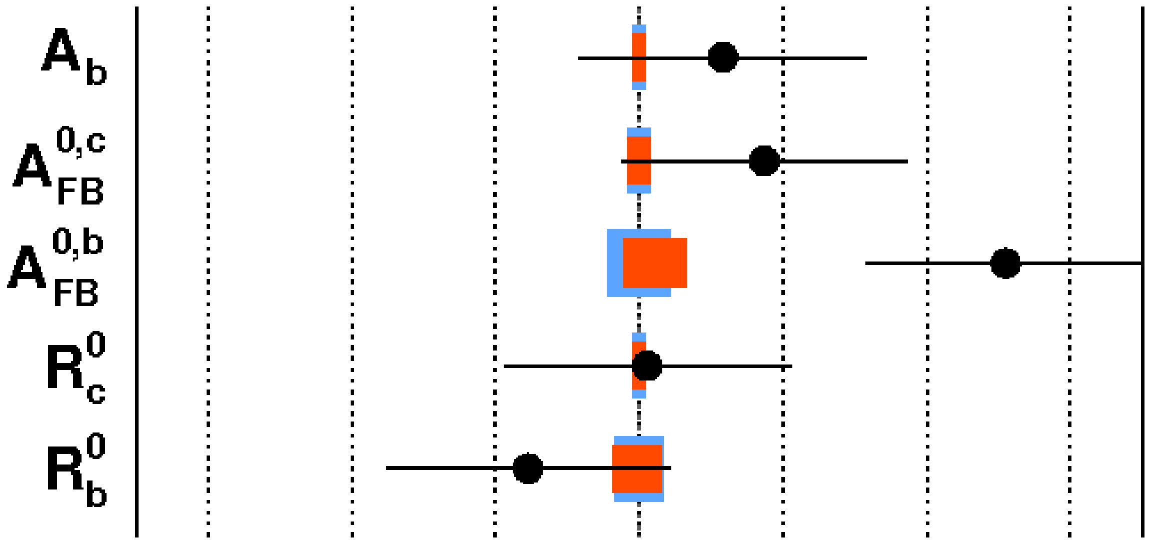


Figure 2.7: Test of the electroweak theory: the statistical error on A_{LR} of $e^+e^- \to Z \to \ell\bar{\ell}$ at GigaZ, (a) as a function of the fraction of luminosity spent on the less favoured polarization combinations σ_{++} and σ_{--} and (b) its dependence on P_{e^+} for fixed $P_{e^-} = \pm 80\%$ [51].

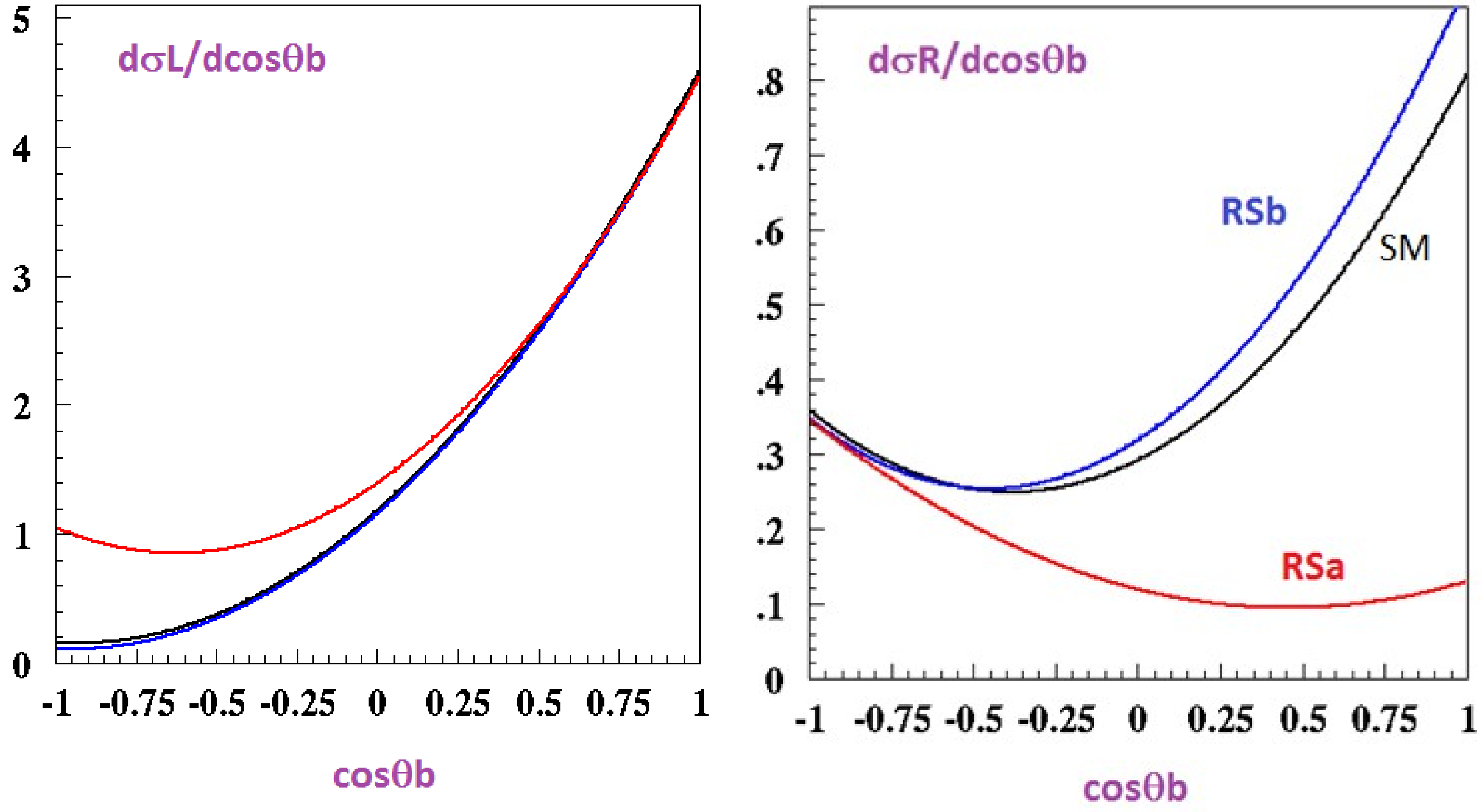
From hep-ph/0507011

LEP Anomaly on A_{FB}^b

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



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 (Remember Zb_lb_l is protected by cross section)
- Note that also B-Factories report on anomalies

Beam polarisation – Uncertainty and (positron) polarisation

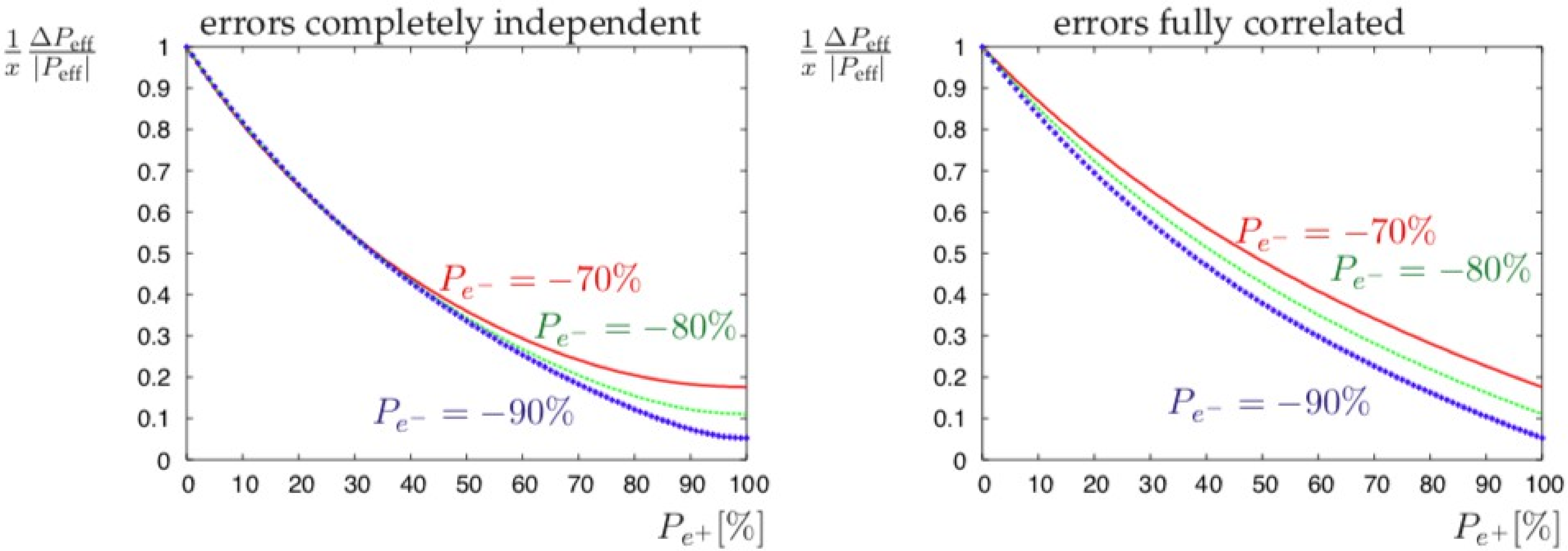


Figure 1.6: Relative uncertainty on the effective polarization, $\Delta P_{\rm eff}/|P_{\rm eff}| \sim \Delta A_{\rm LR}/A_{\rm LR}$, normalized to the relative polarimeter precision $x = \Delta P_{e^-}/P_{e^-} = \Delta P_{e^+}/P_{e^+}$ for independent and correlated errors on P_{e^-} and P_{e^+}, see eqs. (1.25), (1.27).

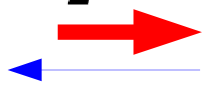
$$A_{\rm LR} = \frac{1}{P_{\rm eff}} A_{LR}^{\rm obs} = \frac{1}{P_{\rm eff}} \frac{\sigma_{-+} - \sigma_{+-}}{\sigma_{-+} + \sigma_{+-}}, \qquad (1.24)$$

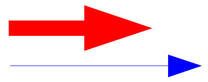
From hep-ph/0507011

Beam polarisation – Some words on the basics

Helicity is projection of Spin $\vec{\sigma}$ onto direction $\hat{\mathbf{p}}$ of motion of massive particle

Eigenvalues of $\frac{1}{2}\vec{\sigma}\hat{\mathbf{p}}$:

-1/2  Left handed helicity

1/2  Right handed helicity

Caveat:
Helicity is frame dependent!

=> Not Lorentz invariant

Helicity projection operator

$$\Pi^{\pm}(\mathbf{p}) = \frac{1}{2}(1 \pm \vec{\sigma}\hat{\mathbf{p}})$$

$\xrightarrow{m=0}$

Chirality projection operator

$$\Pi^{\pm}(\mathbf{p}) = \frac{1}{2}(1 \pm \gamma^5)$$

Chirality is projection of Spin $\vec{\sigma}$ onto direction $\hat{\mathbf{p}}$ of motion of massless particle

Chirality is frame independent! => Basis to define helicity states

$$u_L = \left(1 + \frac{|\vec{p}|}{E+m}\right) u_{LC} + \left(1 - \frac{|\vec{p}|}{E+m}\right) u_{RC}$$

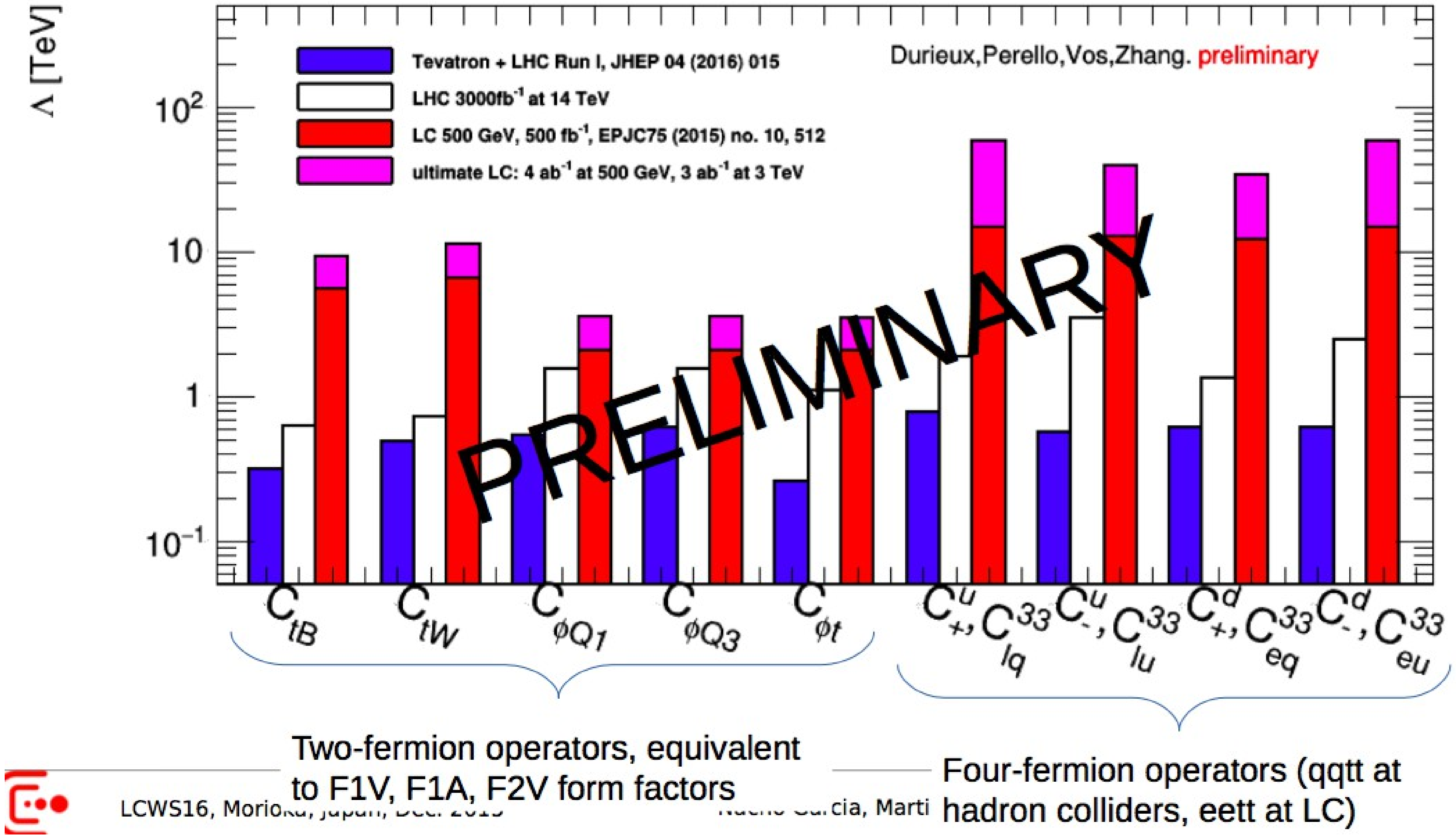
$$u_R = \left(1 - \frac{|\vec{p}|}{E+m}\right) u_{LC} + \left(1 + \frac{|\vec{p}|}{E+m}\right) u_{RC}$$

E >> m

Precisions of top quark form factors – EFT Fit

Tevatron + LHC from TopFitter (individual 95% limits)
Prospects for 3000/fb -> Schultz, Soreq, Vos, Perello ... + extrapolation

LC 500 prospects from arxiv: 1505.06020
Prospects somewhat speculative but may be covered by full ILC lumi

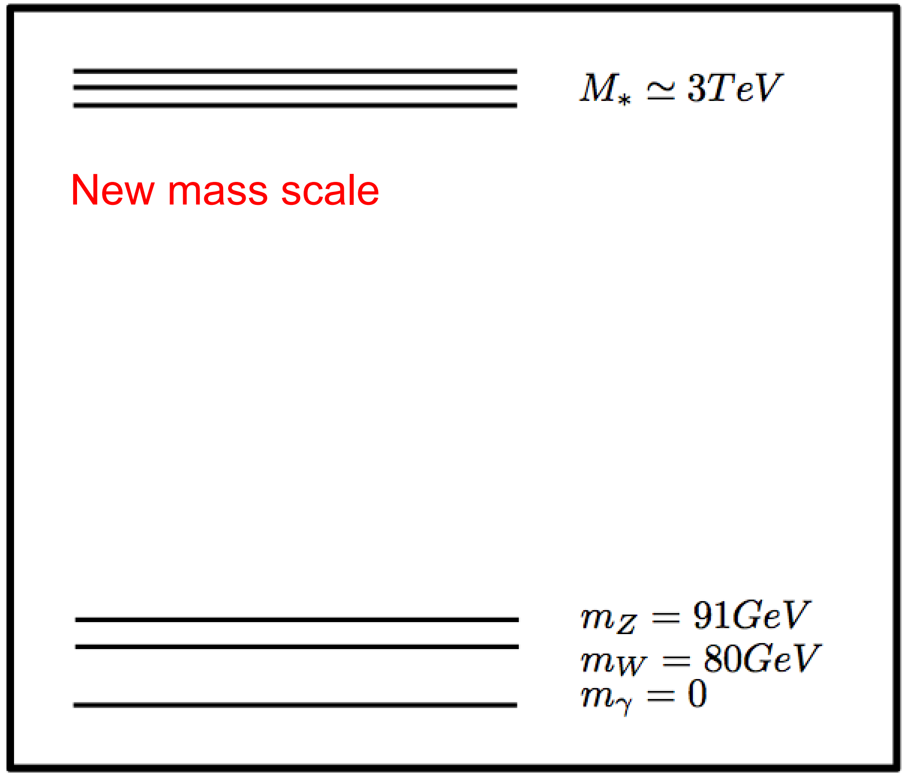


Example Compositeness

à la G.M. Pruna, LC 13, Trento

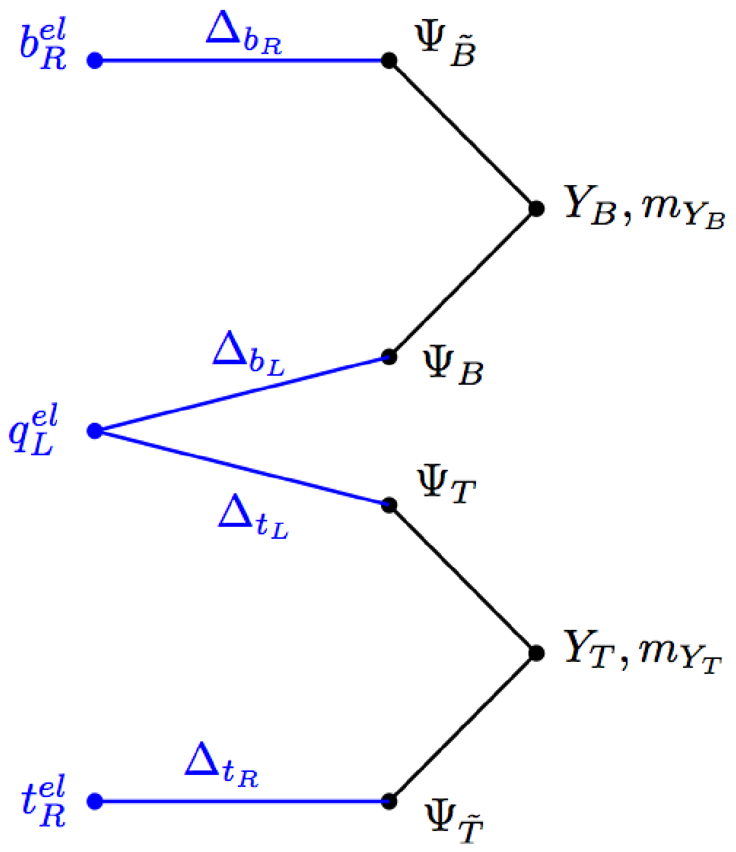
Compositeness:
- ... provides elegant solution for naturalness
- ... few tensions with SM predictions
- ... **all** scalar objects observed in nature turned out to be bound states of fermions
- ... Duality with Randall-Sundrum Models

Bosonic sector mass spectrum



Fermionic resonances

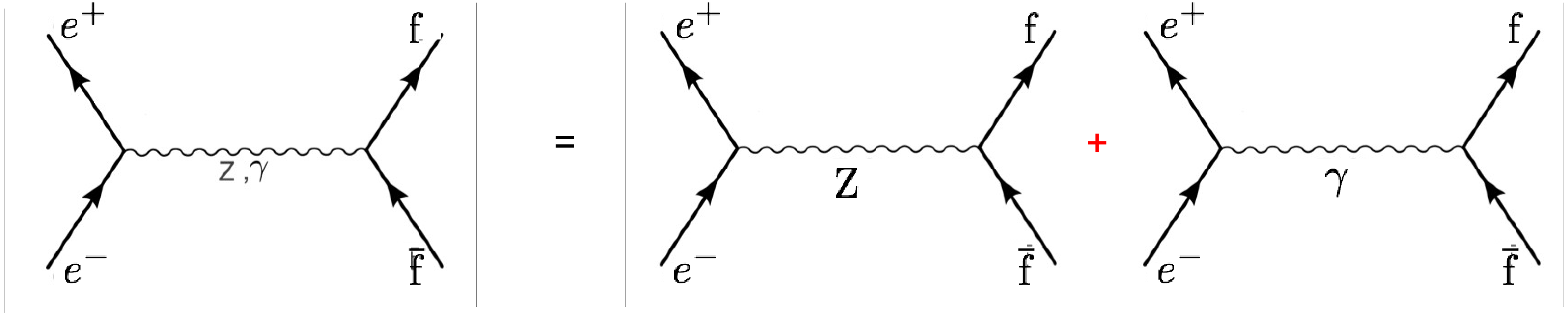
From heavy left handed SM doublet and heavy right handed SM singlet



Physics modify Yukawa couplings and Ztt, Zbb

Heavy fermion effect!

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



Interference between individual amplitudes of γ and Z exchange

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

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

$$g_L^f = c_V^f + c_A^f$$

$$g_R^f = c_V^f - c_A^f$$

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!!!