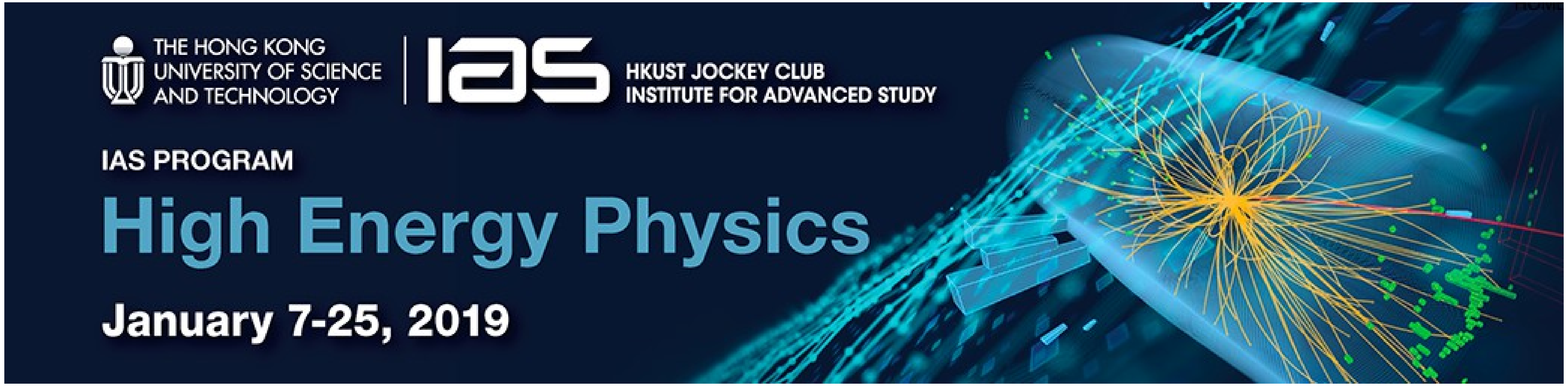

Precision physics with polarised beams

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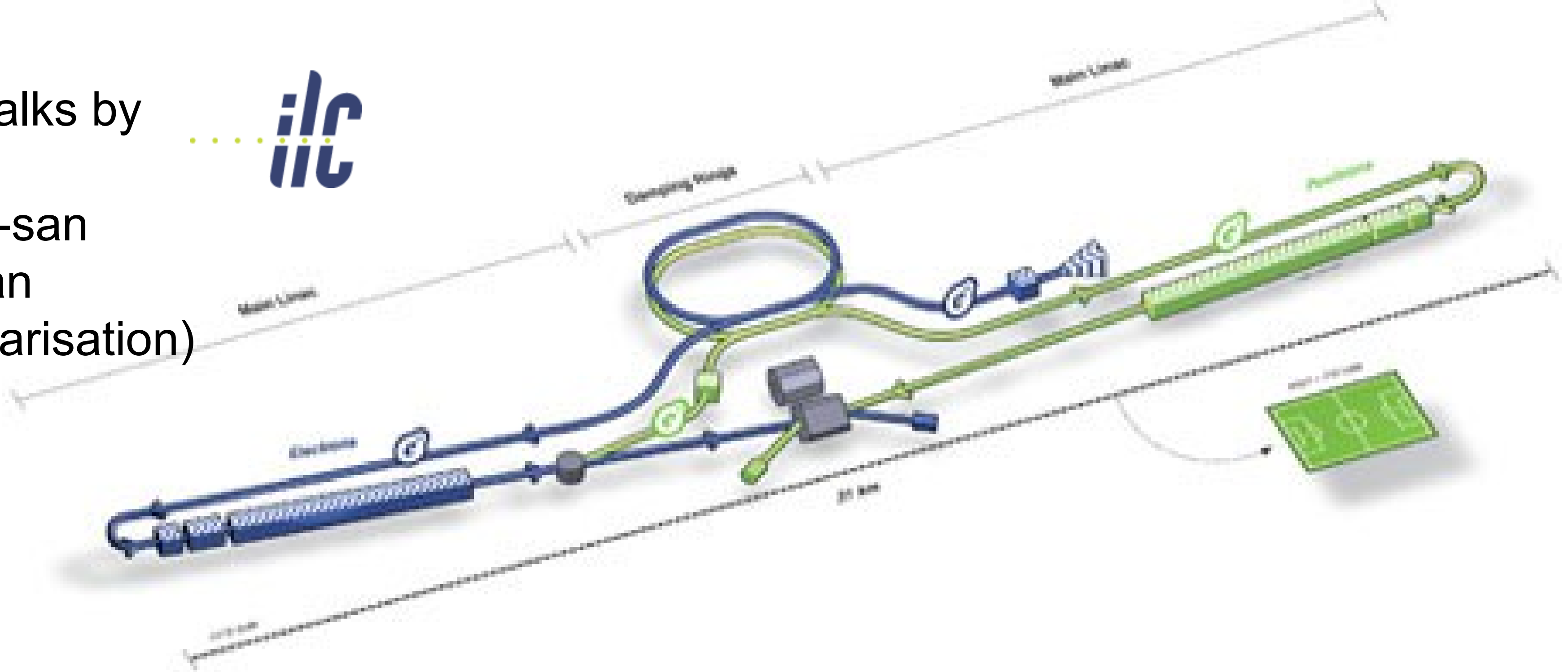
UNIVERSITÉ PARIS SUD Comprendre le monde, construire l'avenir®

HKUST Jockey Club Hong Kong – January 2019

Linear Electron Positron Colliders

See also talks by

Michizono-san
Yokoya-san
(Beam polarisation)



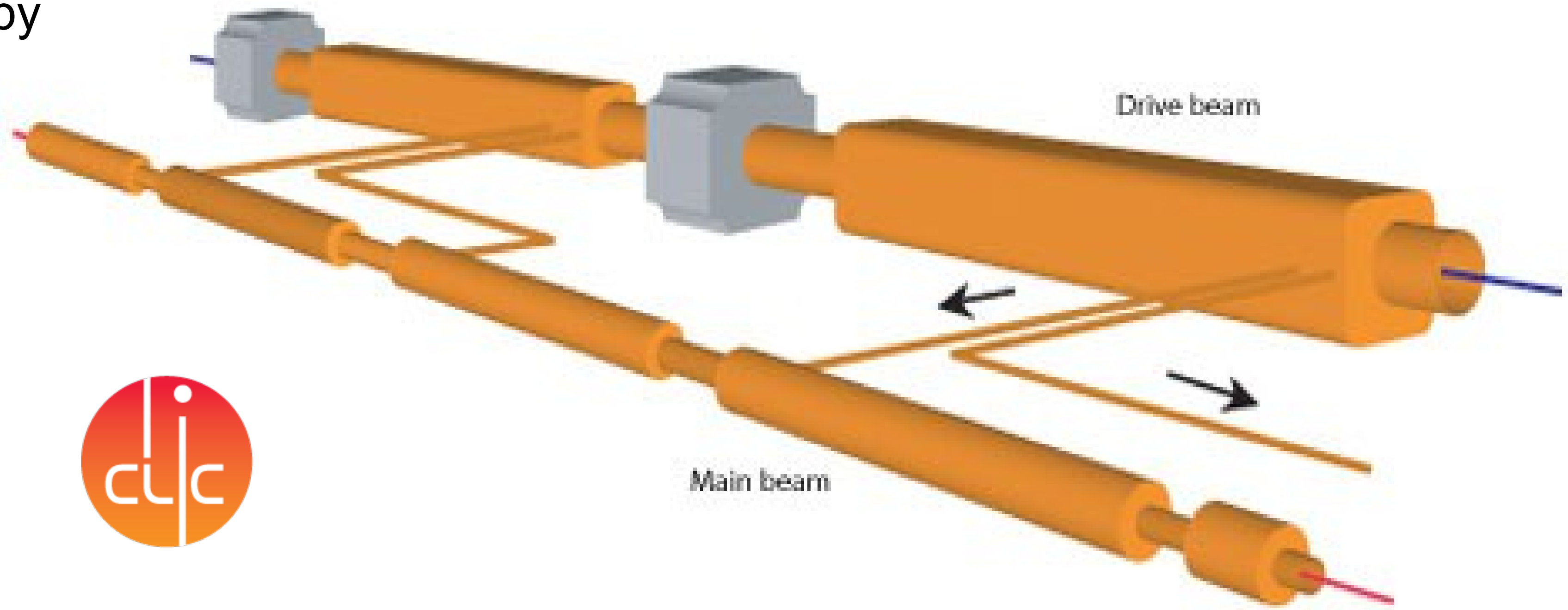
Energy: 0.1 - 1 TeV
Electron (and positron) polarisation
TDR in 2013
+ DBD for detectors
Footprint 31 km

Initial Energy 250 GeV – Footprint ~20km

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

See also talk by

Andrea Latina



Energy: 0.4 - 3 TeV

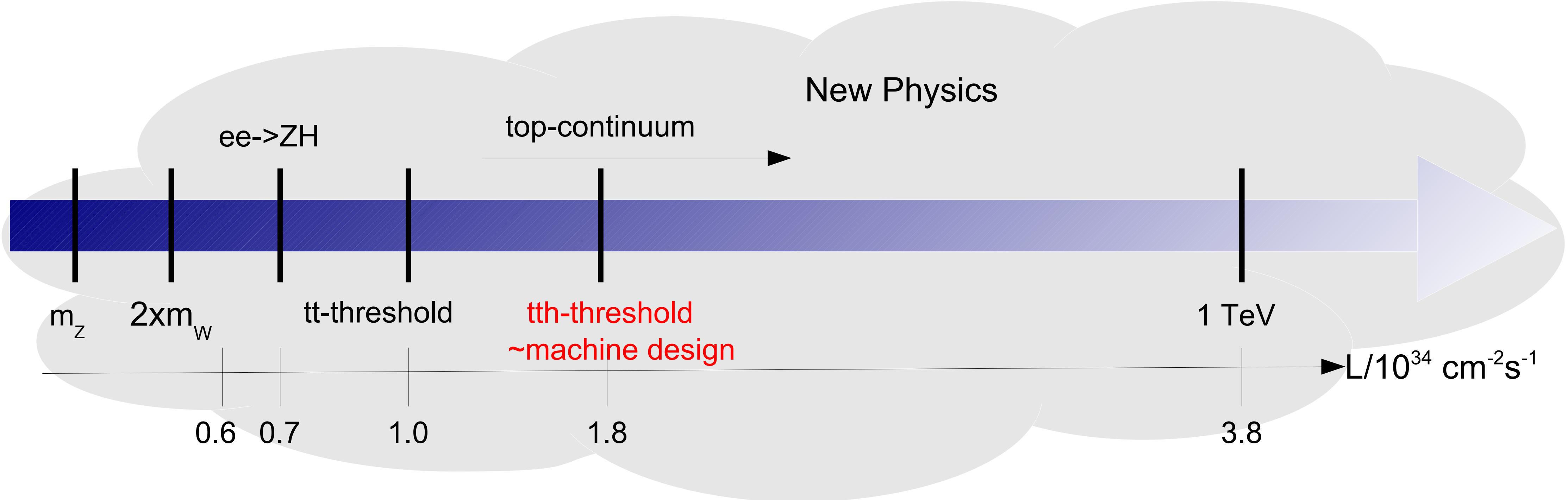
CDR in 2012

Footprint 48km

Initial Energy 380 GeV

Possible future project at CERN

Physics program at Linear Electron Positron Colliders



All Standard Model particles within reach of LC

- High precision tests of Standard Model over wide range to detect onset of New Physics

Machine settings can be “tailored” for specific processes

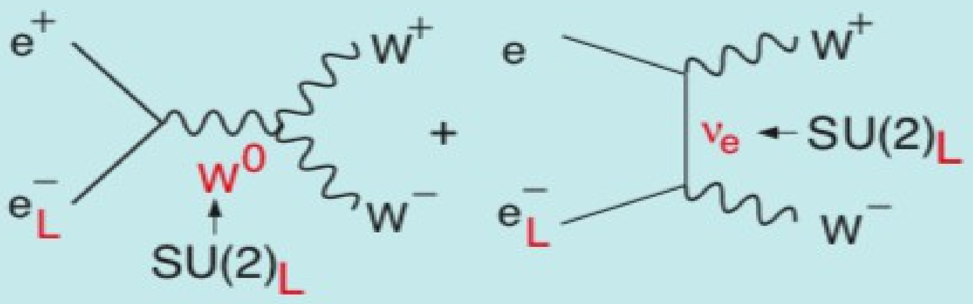
- Centre-of-Mass energy
- Beam polarisation

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

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

Power of beam polarisation – An overview

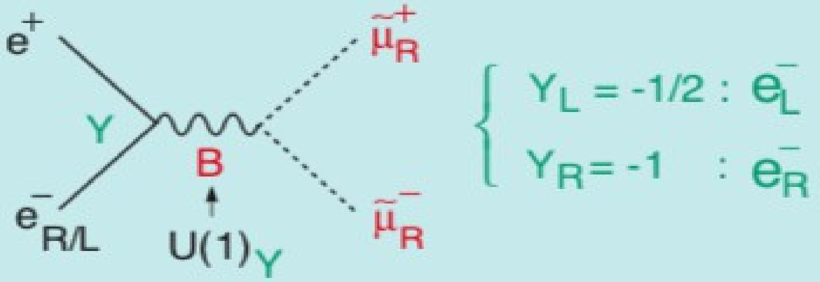
W^+W^- *(Largest SM BG in SUSY searches)*



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

BG Suppression

Slepton Pair

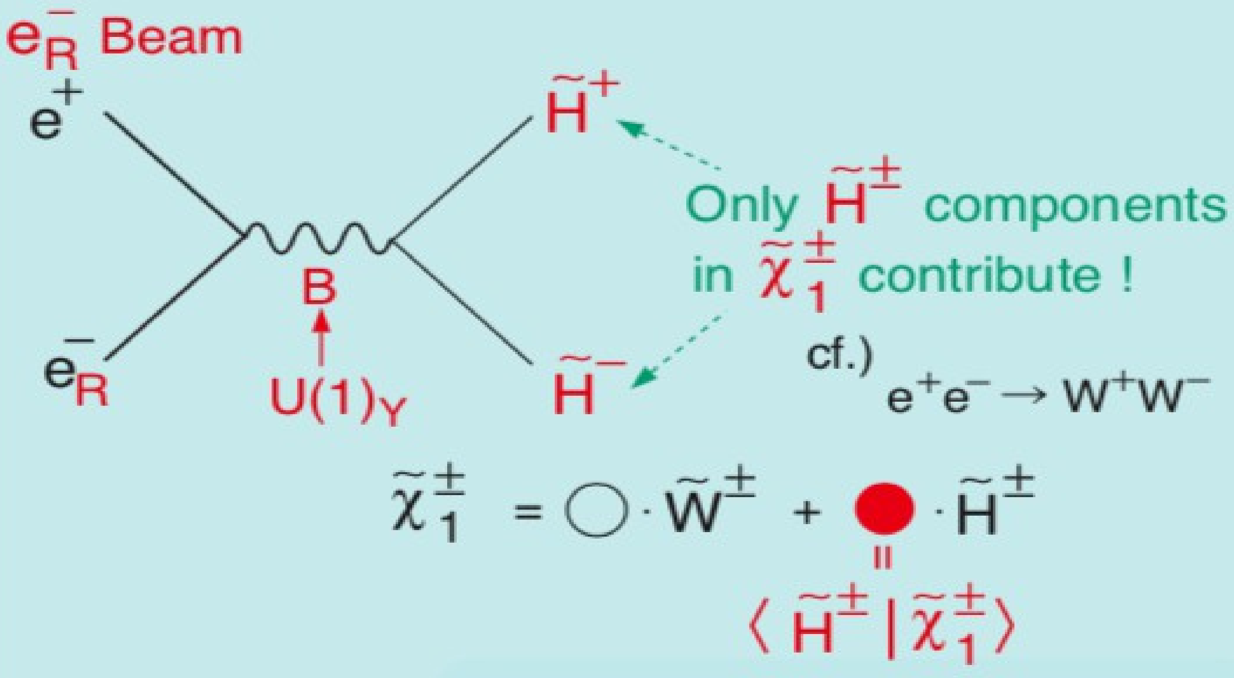


$Y_L = -1/2 : e^-_L$

$Y_R = -1 : e^-_R$

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

Chargino Pair

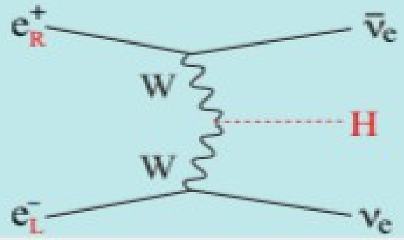


$\tilde{\chi}^\pm_1 = \bigcirc \cdot \tilde{W}^\pm + \bullet \cdot \tilde{H}^\pm$

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

Decomposition

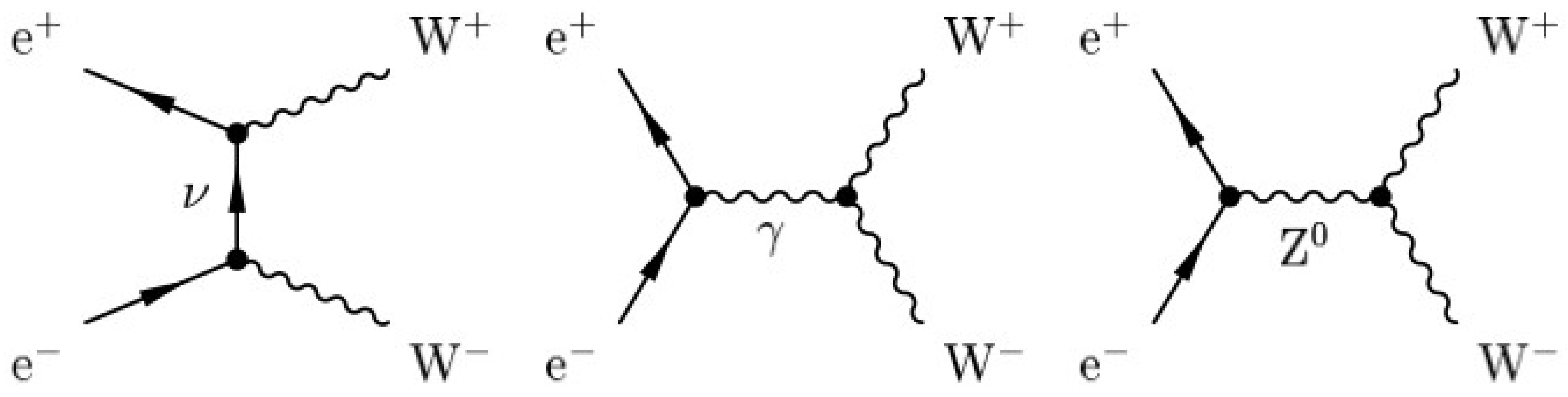
WW-fusion Higgs Prod.



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

Signal Enhancement

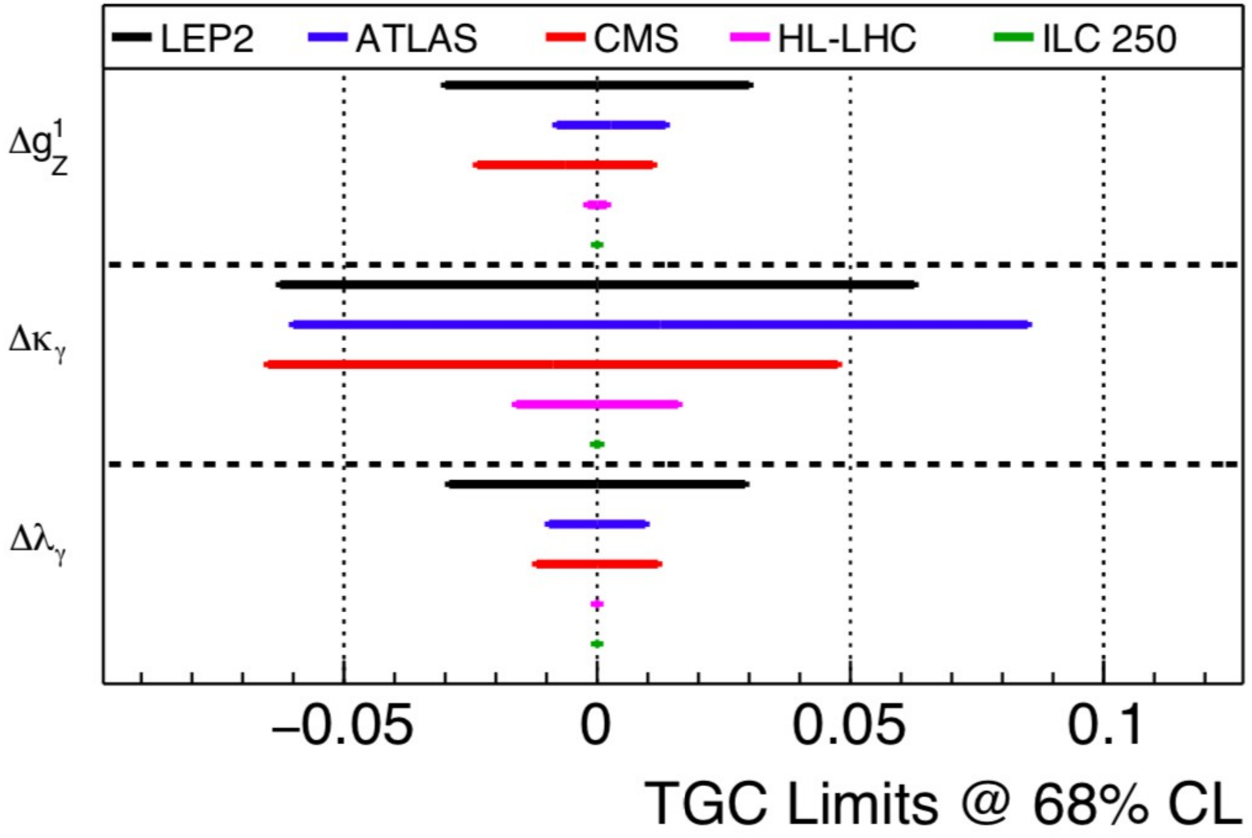
Double W Production

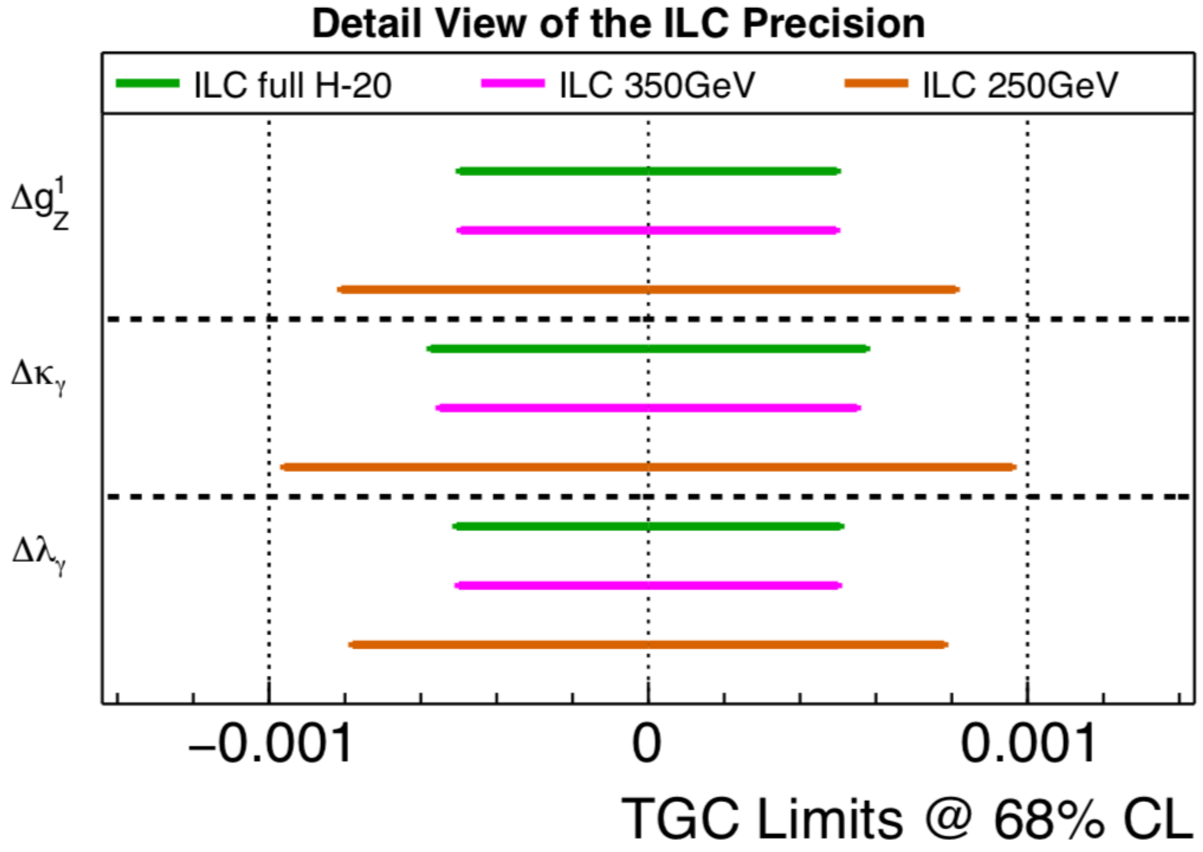


- Sensitivity to triple and quartic gauge Boson couplings (TGC and QGC)
- Observables depend strongly on beam polarisation

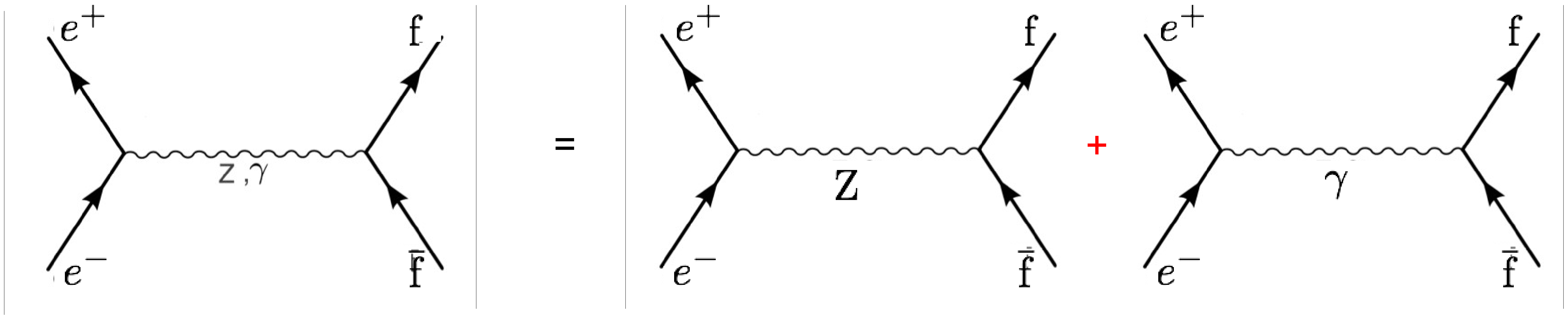
=> Enrich different helicity modes of W
=> Disentangling of couplings to Z and γ
=> in situ measurement of beam polarisation (and luminosity)

Limits on Triple Gauge Couplings@250 GeV





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



Interference between individual amplitudes of γ and Z exchange

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

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

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

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

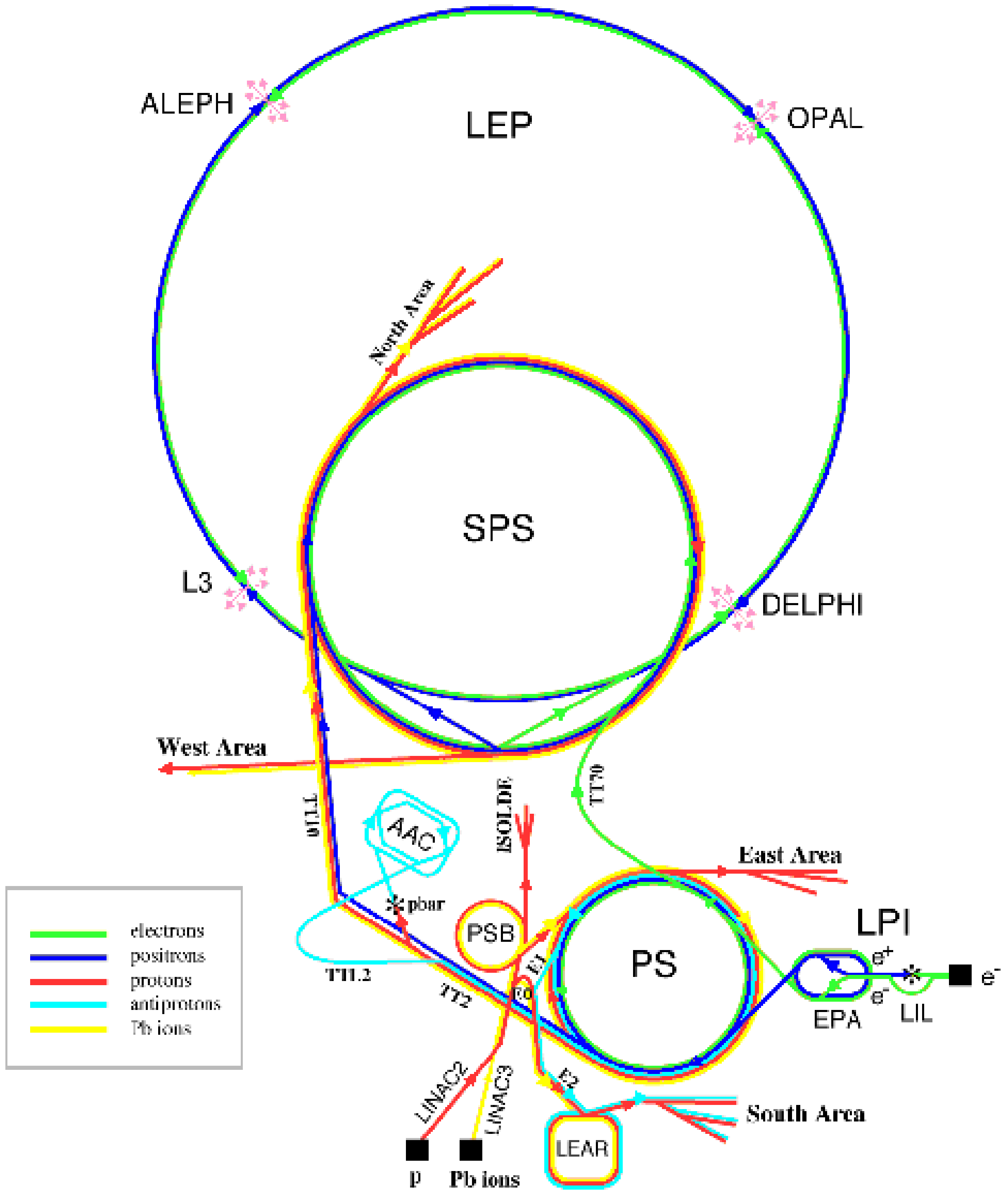
Differential cross section:

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

Weak interaction introduces forward backward asymmetry

=> Asymmetry is intrinsic to electroweak processes!!!

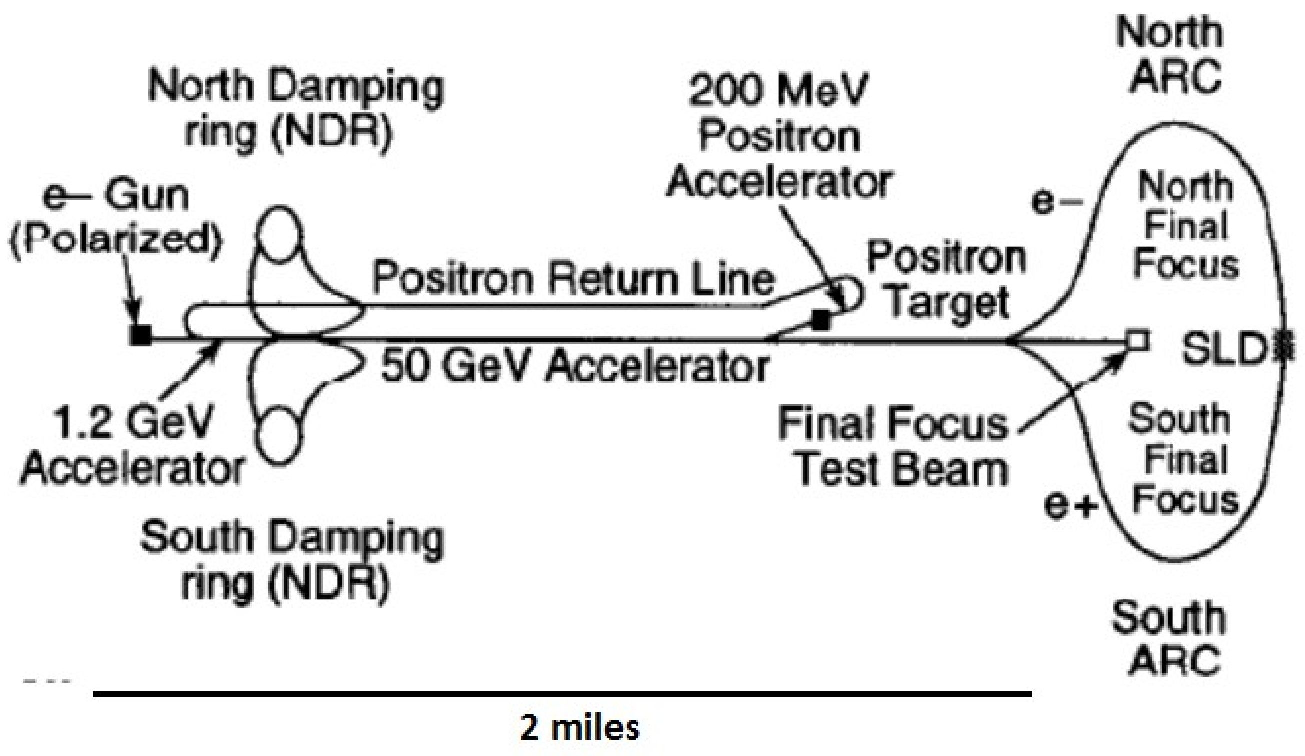
Review: LEP and SLD I



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

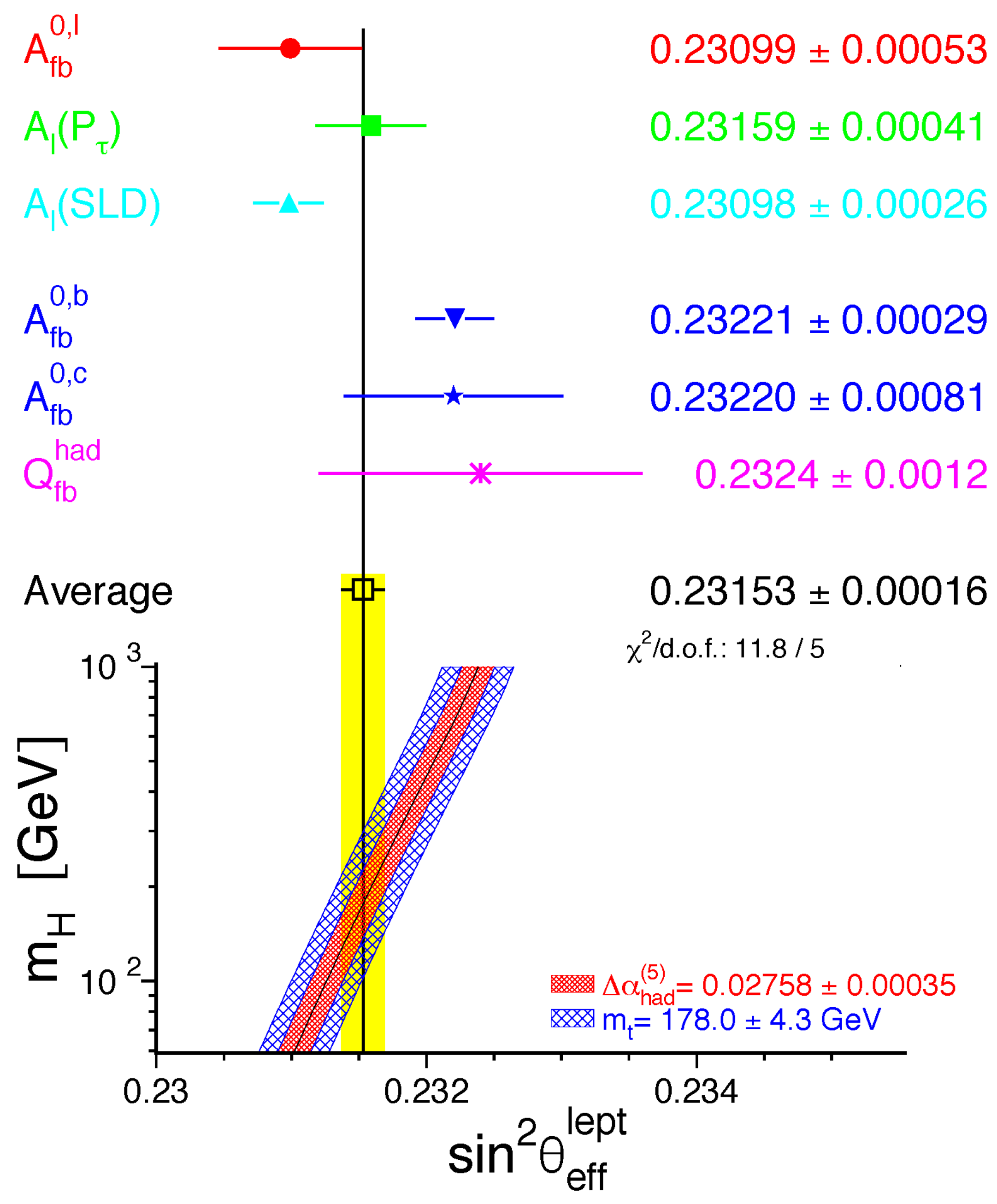
Review: LEP and SLD II



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 III



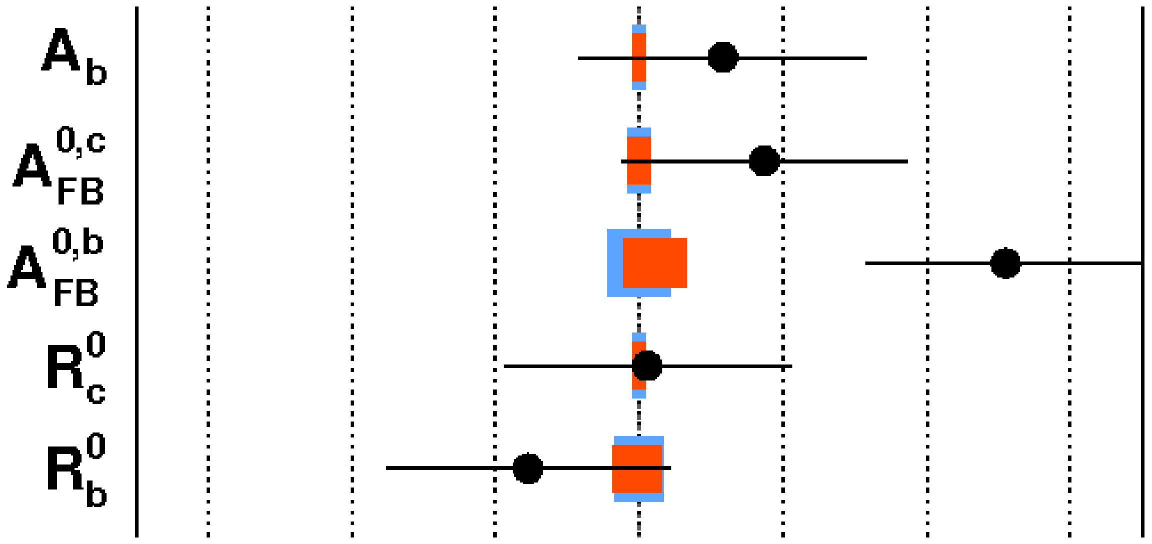
- Most precise single Individual determination of $\sin^2\theta^\ell_{\text{eff.}}$ from SLC
  - Left-right asymmetry of leptons
- Most precise measurement of $\sin^2\theta^\ell_{\text{eff.}}$ from forward backward asymmetry A^b_{FB} in ee->bb at LEP

Two lessons:

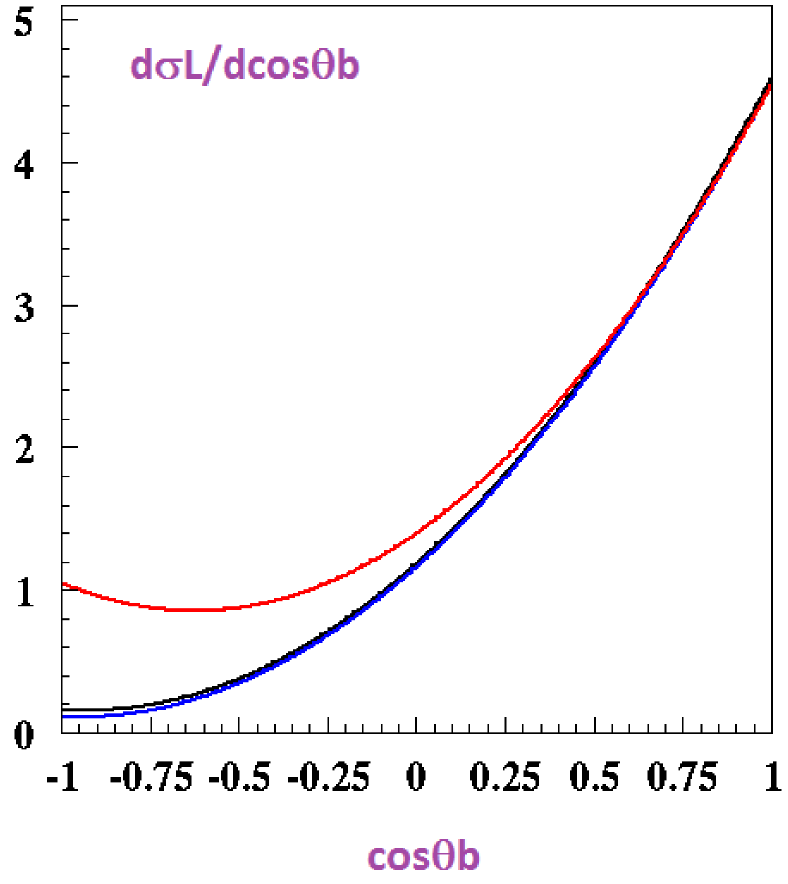
- Most precise determininations of $\sin^2\theta^\ell_{\text{eff.}}$ differ significantly
  - Cries for verification
  - Beam polarisation can match up for luminosity

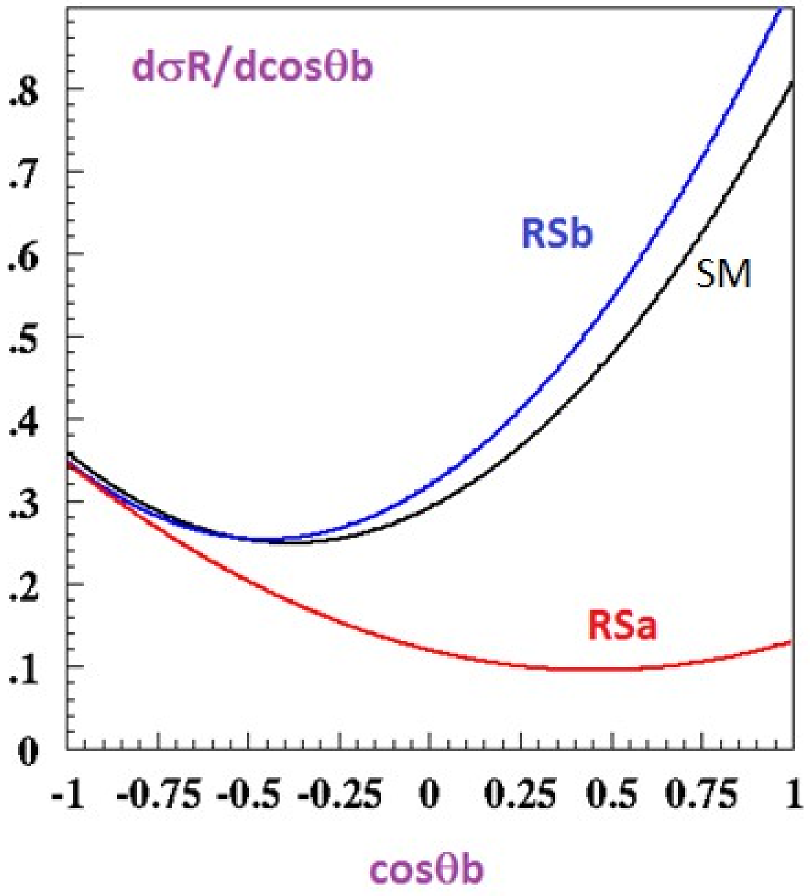
LEP Anomaly on A_{FB}^b

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



ee->bb@250 GeV



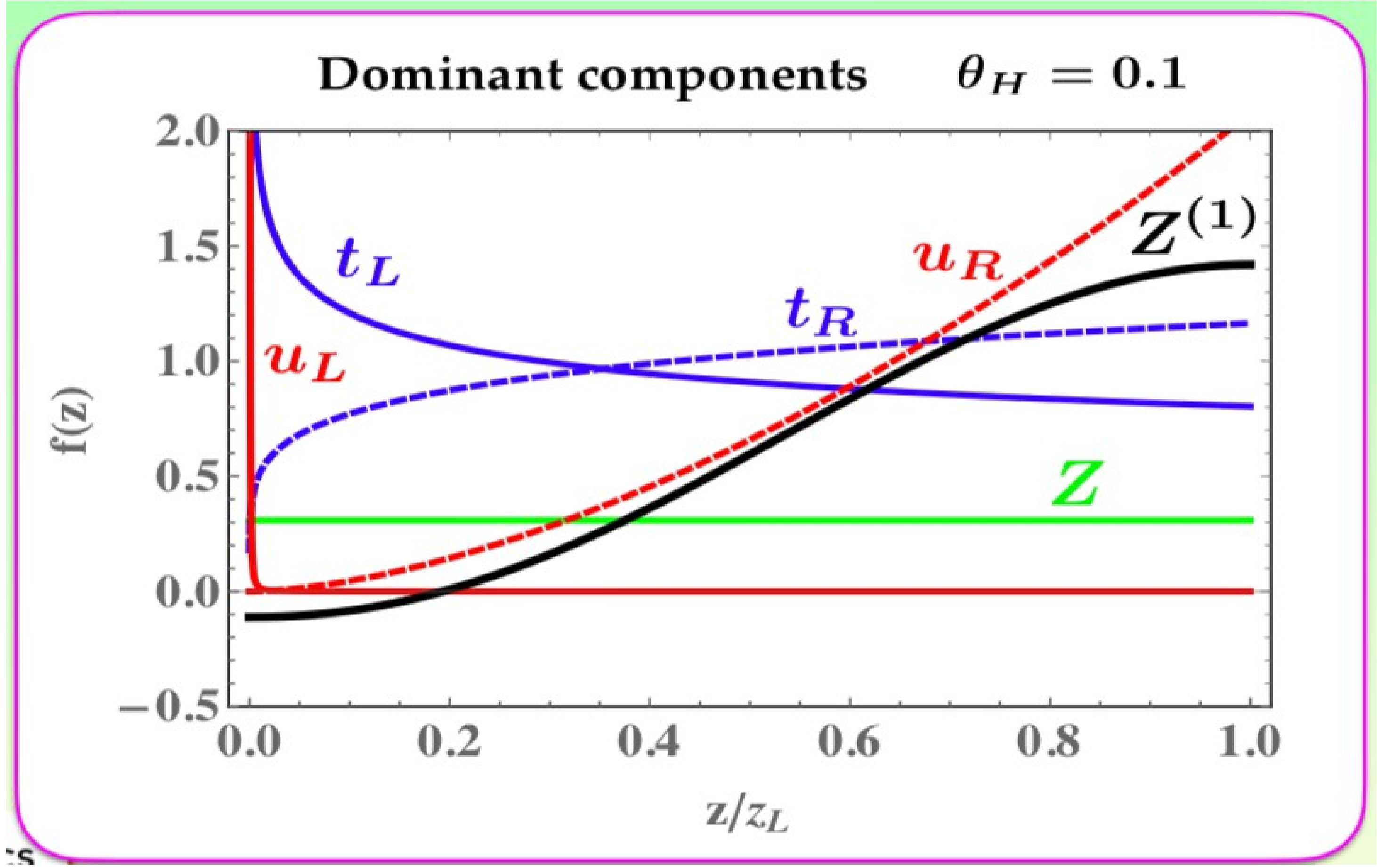


Randall Sundrum Models Djouadi/Richard '06

- 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

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

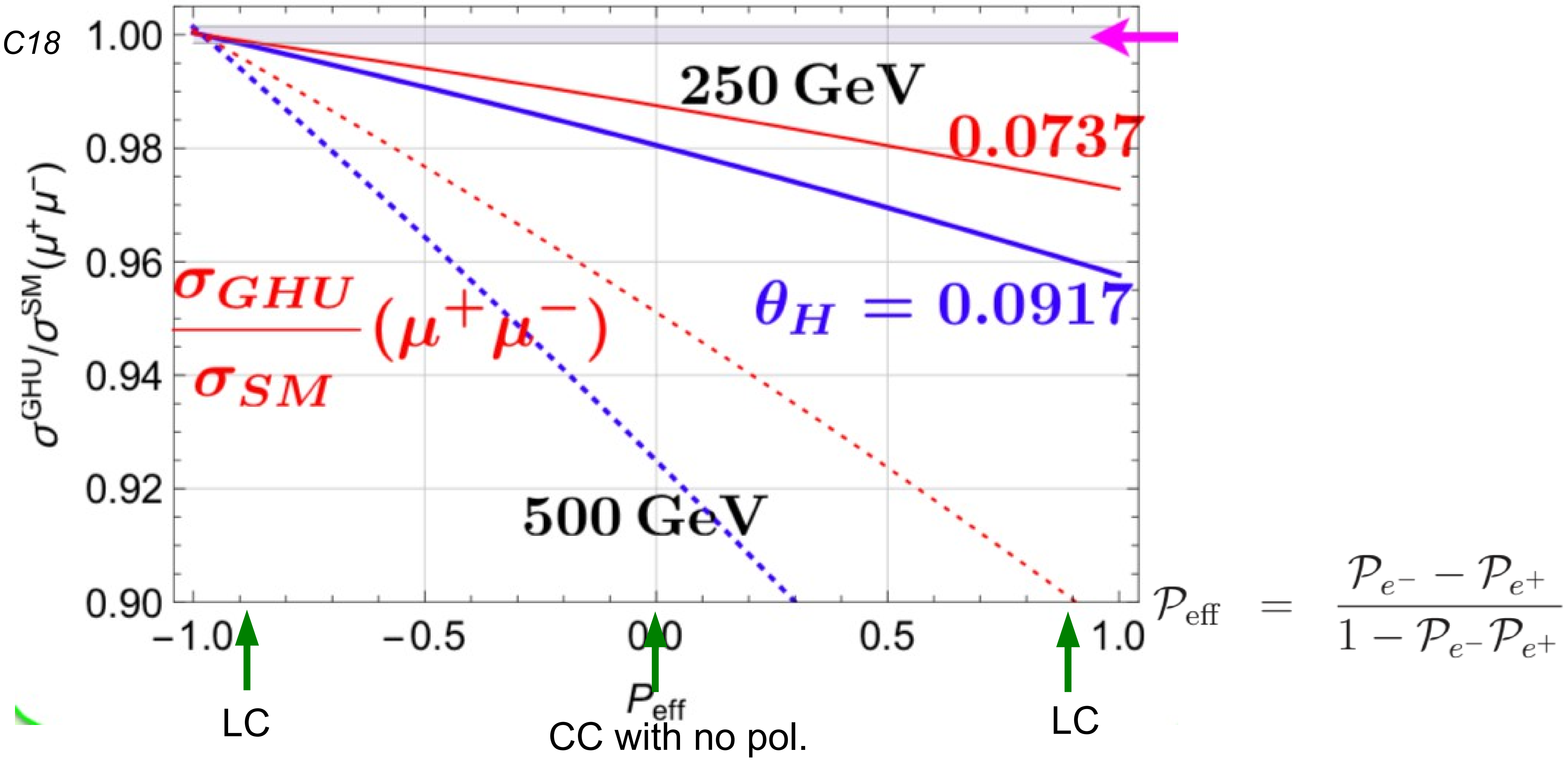


	SM: Z Left	SM: Z Right	$Z^{(1)}$ Left	$Z^{(1)}$ Right	$Z_R^{(1)}$ Left	$Z_R^{(1)}$ Right	$\gamma^{(1)}$ Left	$\gamma^{(1)}$ Right
ν_e			−0.183	0	0	0	0	0
ν_μ	0.5	0	−0.183	0	0	0	0	0
ν_τ			−0.183	0	0	0	0	0
e			0.099	0.916	0	−1.261	0.155	−1.665
μ	−0.2688	0.2312	0.099	0.860	0	−1.193	0.155	−1.563
τ			0.099	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**

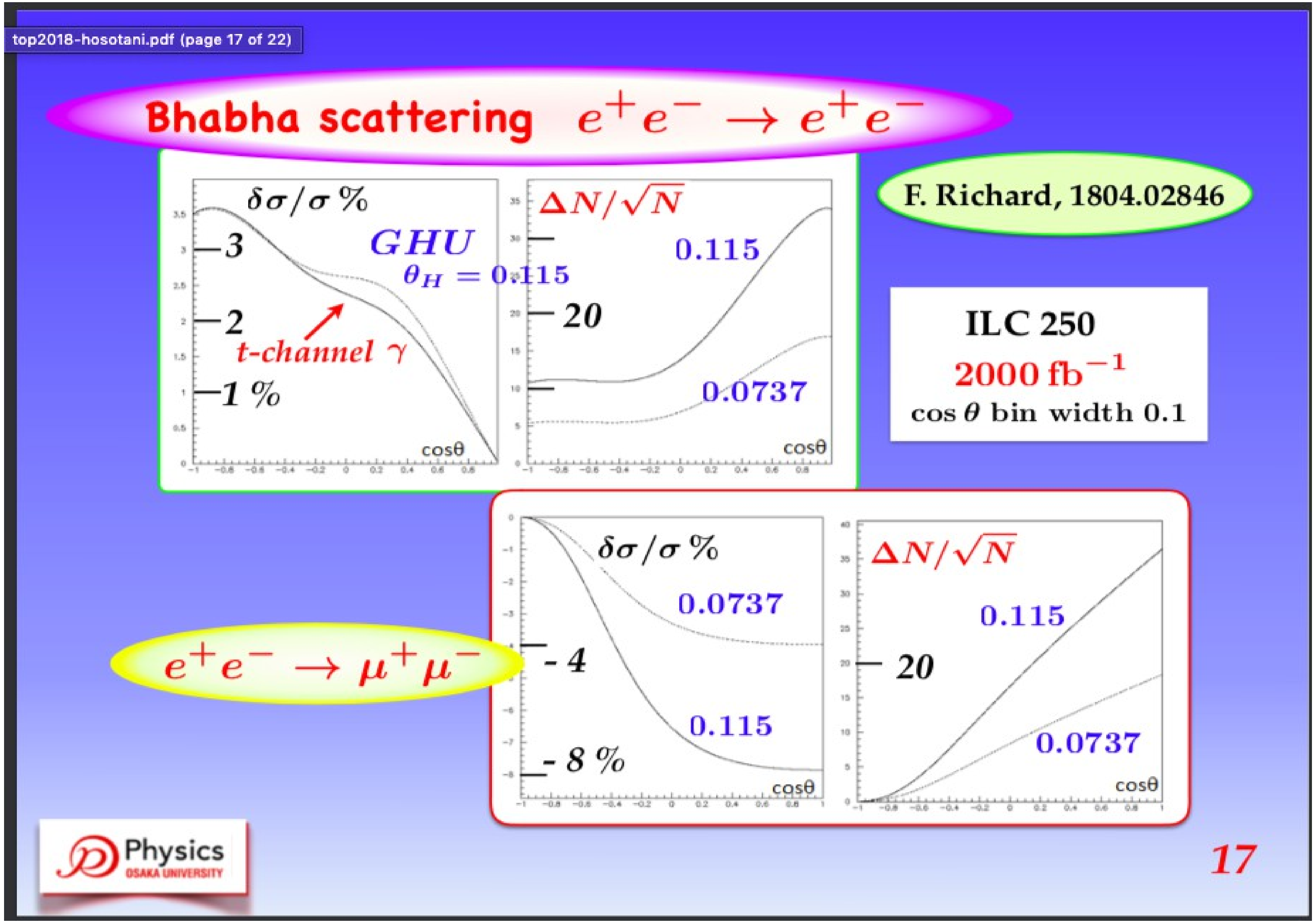
Grand Higgs Unification à la Hosotani – Dimuon production

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

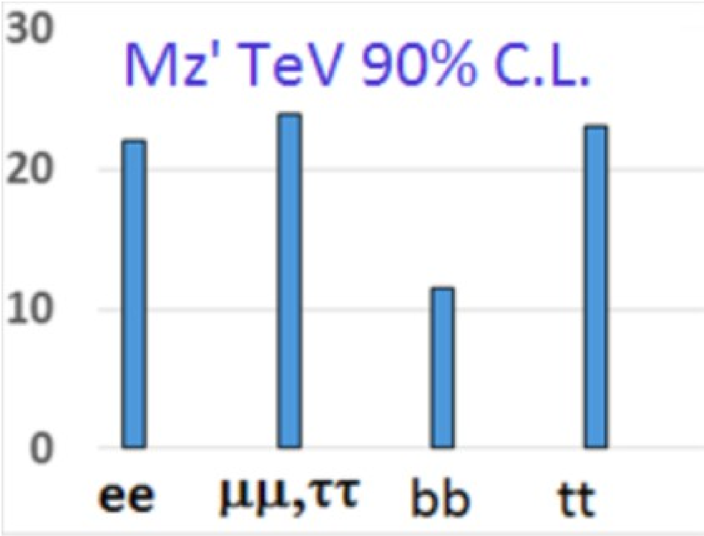
GHU and light fermions



GHU is example for model that implies

modifications of

“well known” couplings



Impressive mass reach already at ILC 250 GeV

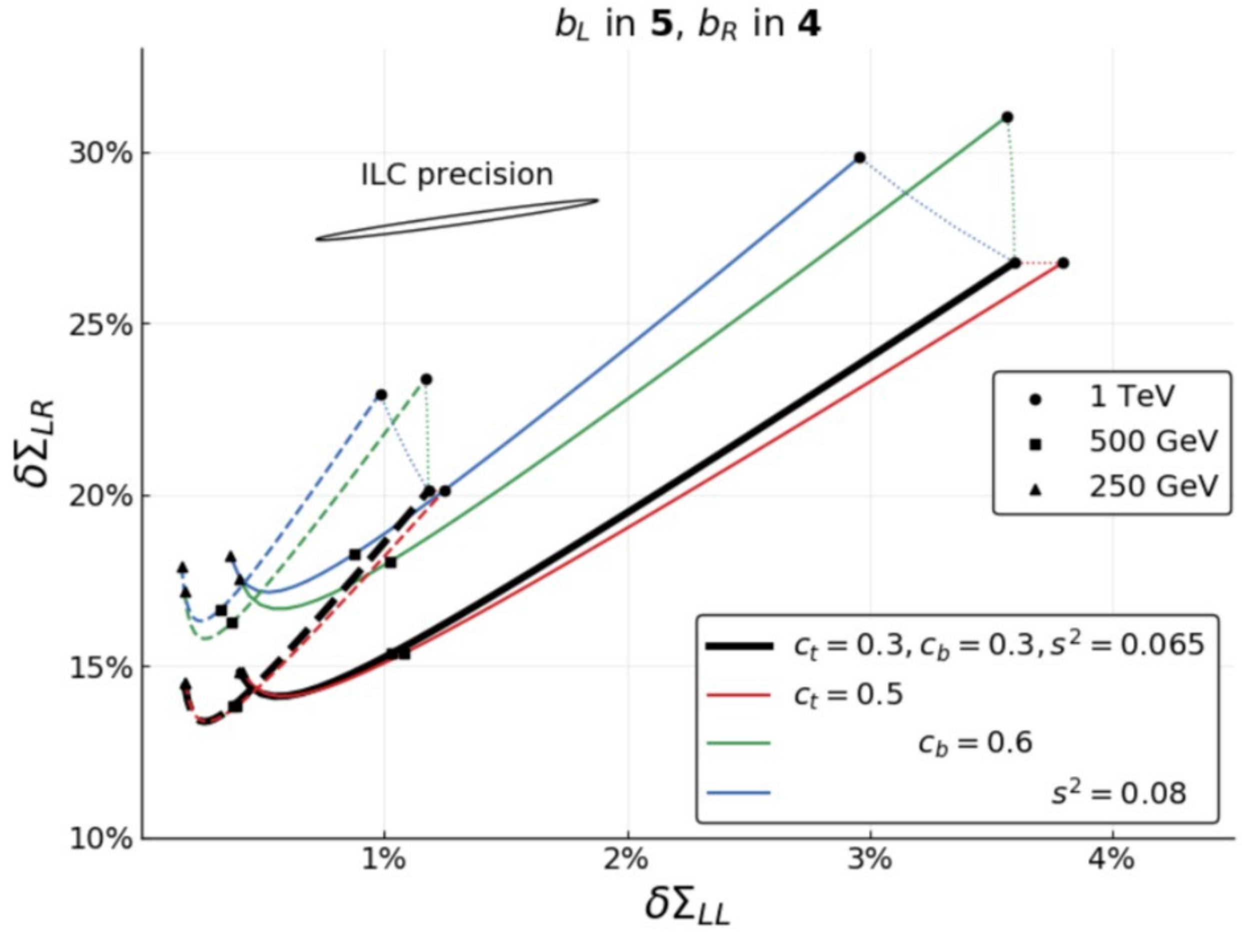
Randall-Sundrum Model and flavor mixing à la Peskin/Yoon

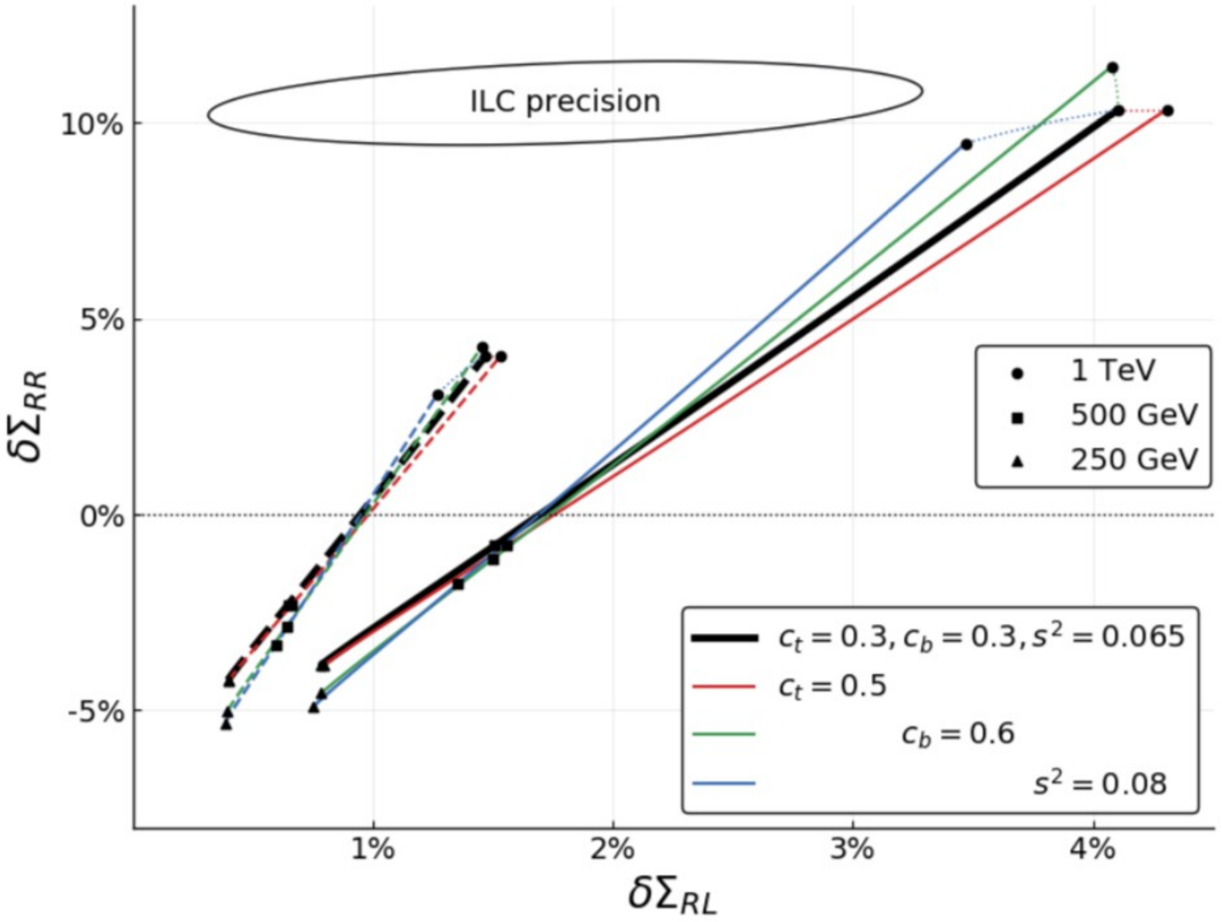
1811.07877

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

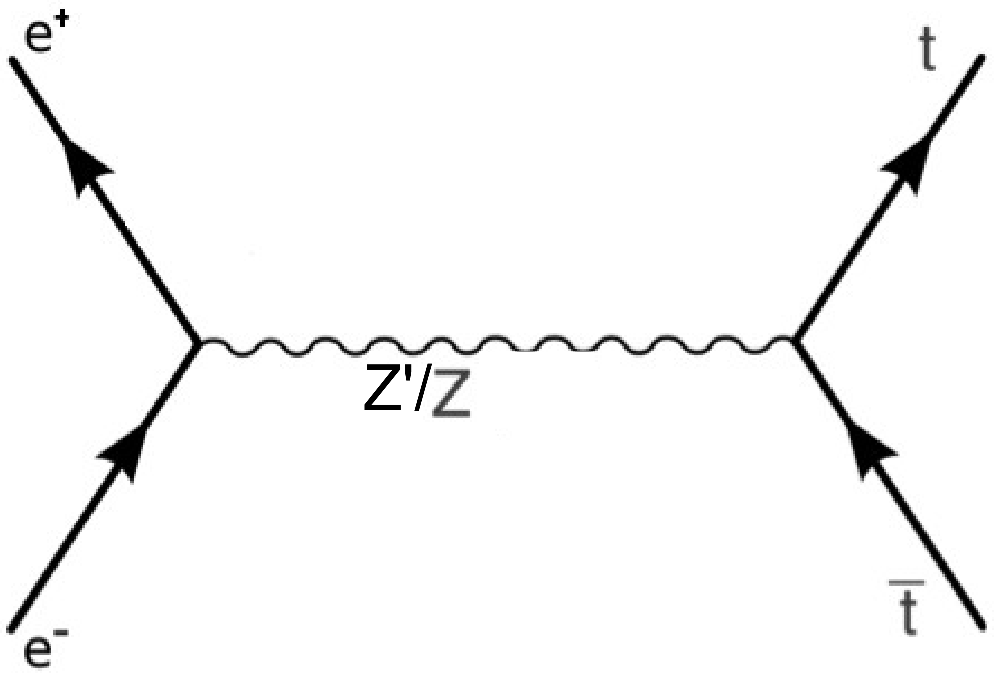
$$\frac{d\sigma}{d\cos\theta}(e^-_L e^+_R \to b\bar{b}) = \Sigma_{LL}(s)\ (1+\cos\theta)^2 + \Sigma_{LR}(s)(1-\cos\theta)^2$$
$$\frac{d\sigma}{d\cos\theta}(e^-_R e^+_L \to b\bar{b}) = \Sigma_{RL}(s)\ (1-\cos\theta)^2 + \Sigma_{RR}(s)(1+\cos\theta)^2$$



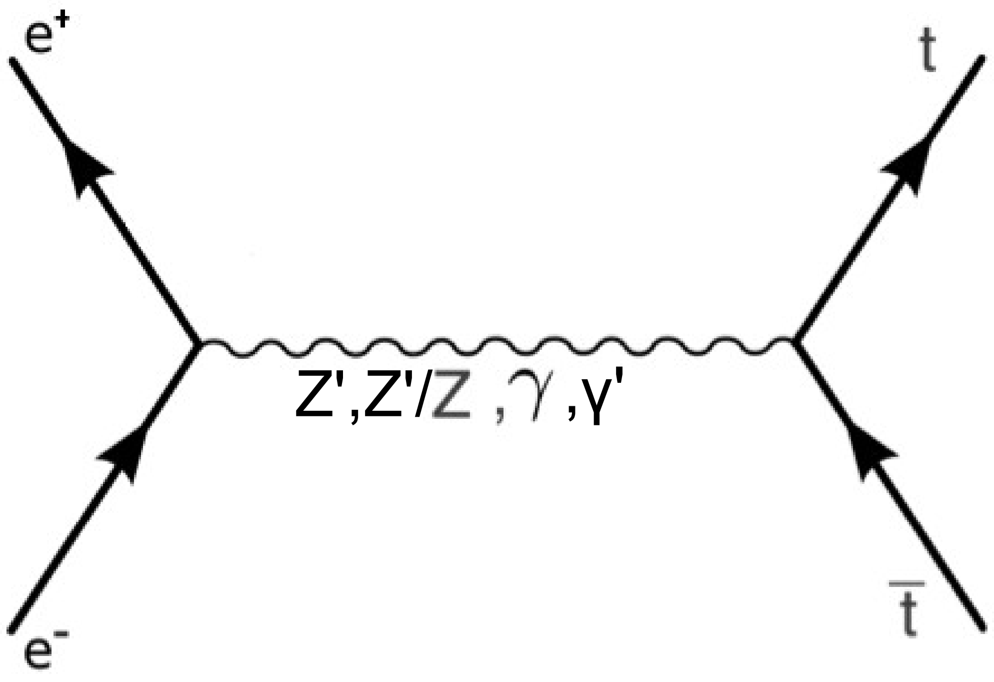


Testing the chiral structure in 2-fermion processes

On the Z-pole



Above the Z-pole

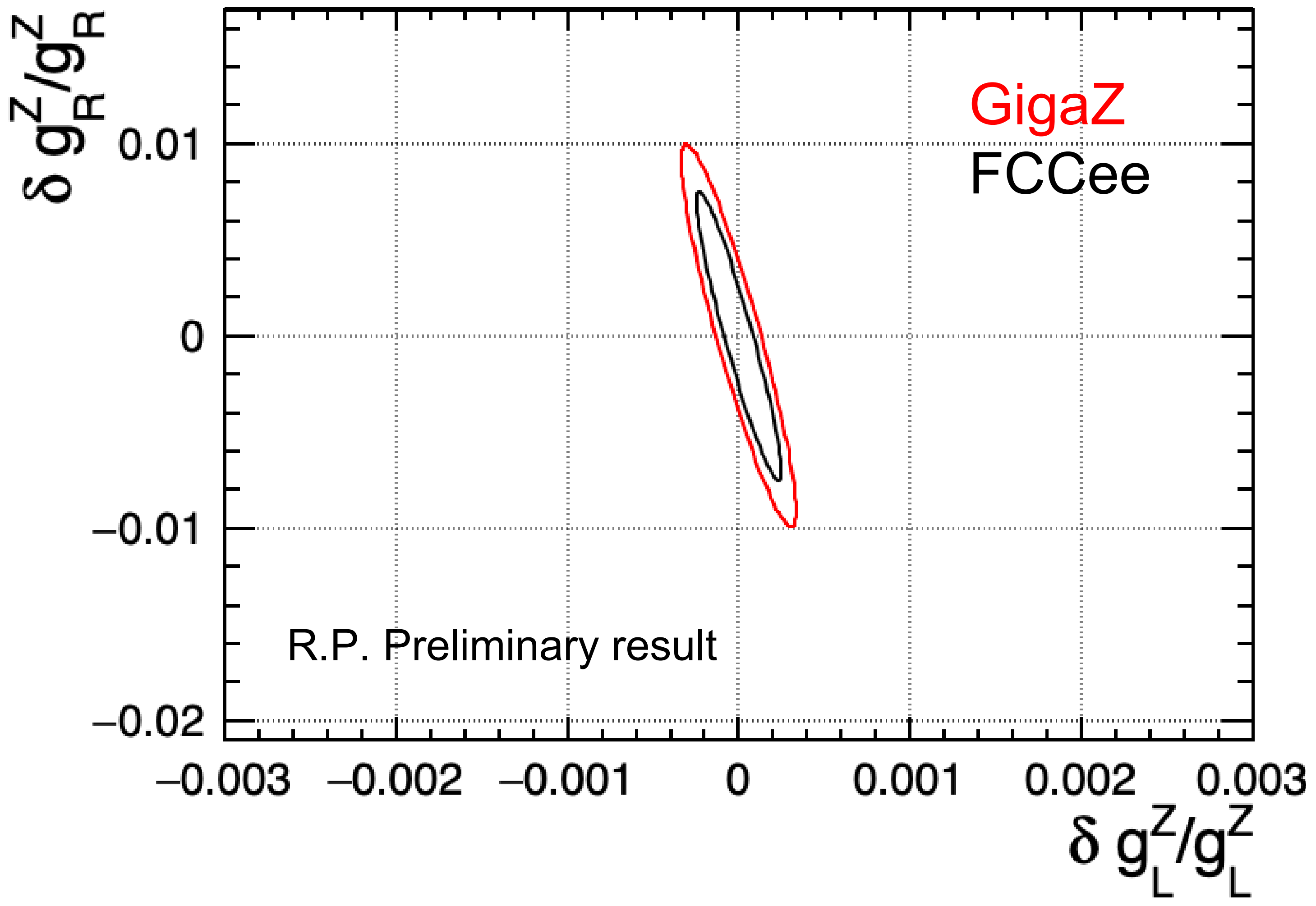


- Sensitivity to Z/Z' mixing
- Sensitivity to vector and tensor
- Couplings of the Z
  - (the photon does not “disturb”

- 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!!!

Decomposing ee->bb

b-quark couplings on the Z pole

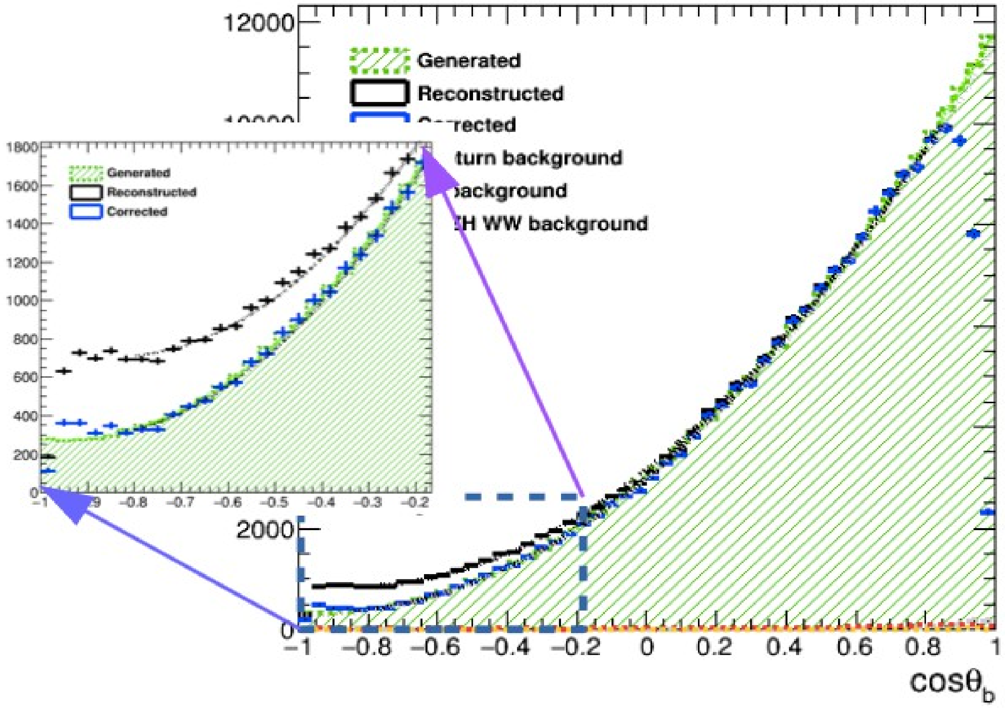


- GigaZ results extrapolated from LEP1
  - Taking into account excellent b-tagging at e+e- detectors but also split of lumi due to polarisation
  - Resulting statistical error multiplied by two to account for systematics
- FCCee using optimistic estimation of systematic error
  - See recent CDR
- Upshot:
  - Precise tests for Z/Z' mixing on Z pole
  - Dominant effect through statistics
  - Polarisation (100% e- only) improves result by ~30%
    - Better control of systematic errors (see backup)
  - GigaZ competitive

Decomposing ee->bb – Differential cross section

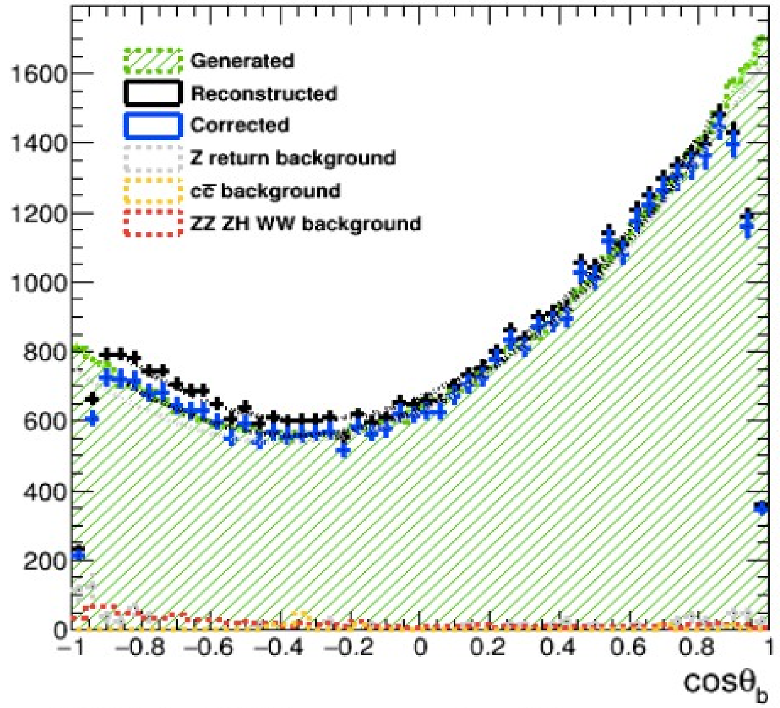
$$\sqrt{s} = 250\,\mathrm{GeV} \quad L = 250\,\mathrm{fb}^{-1}$$

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



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

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



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

Full simulation study (with ILD concept), Benchmark reaction for 250 GeV running

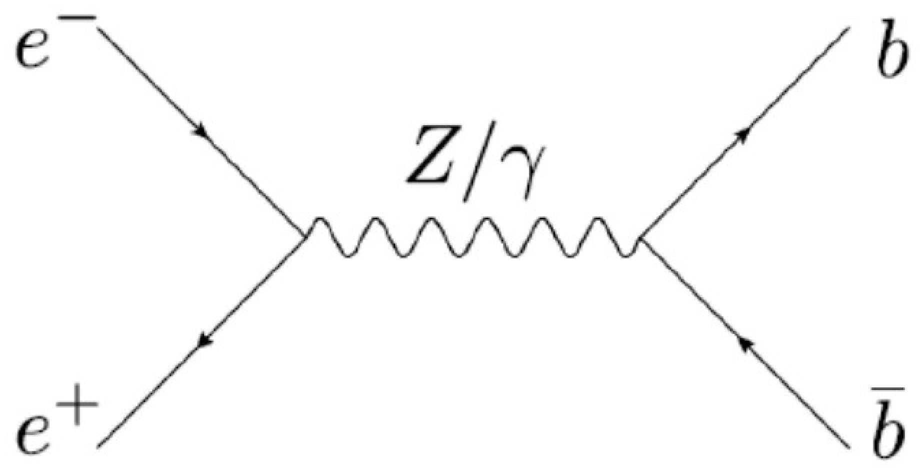
- Experimental challenge: Measurement of b-quark charge on event-by-event basis

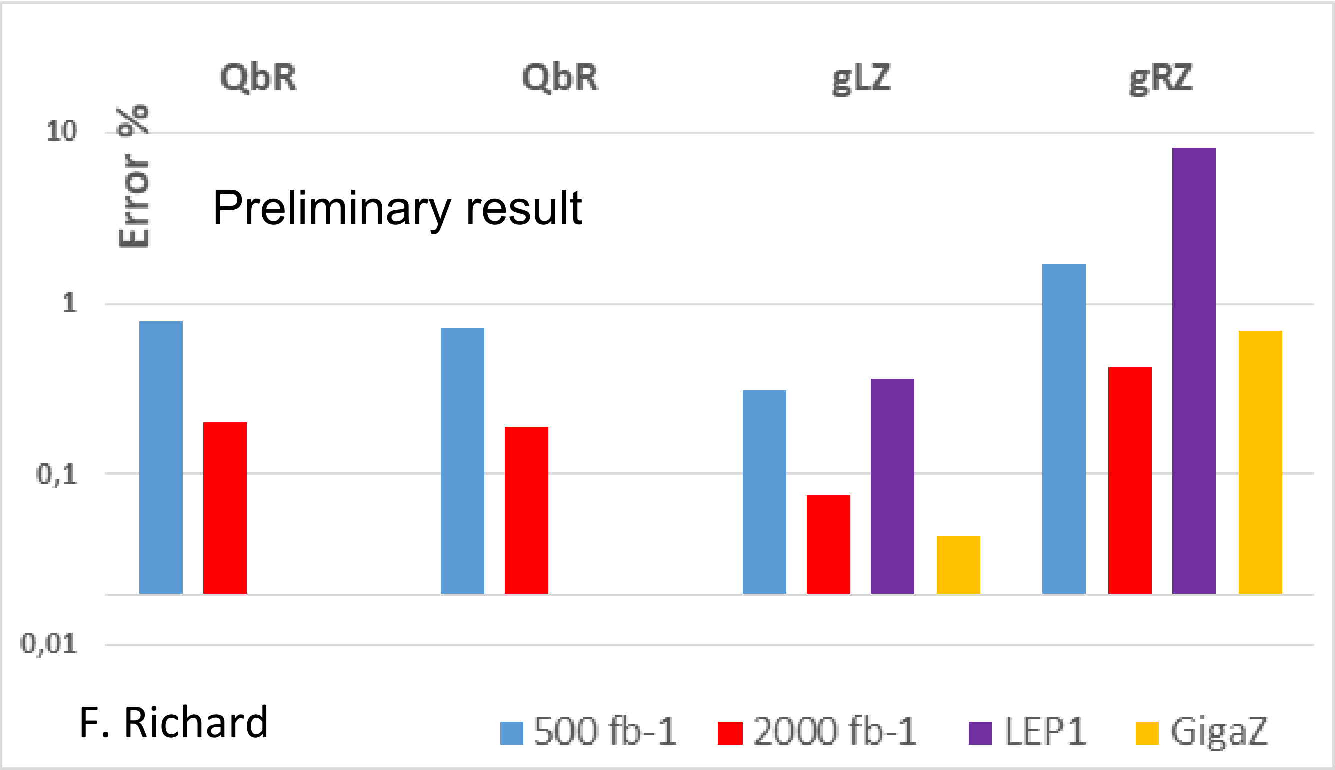
Long lever arm in cos θ_b to extract from factors or couplings

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

Form factors/couplings from S and A

Decomposing ee->bb – Complete picture on couplings



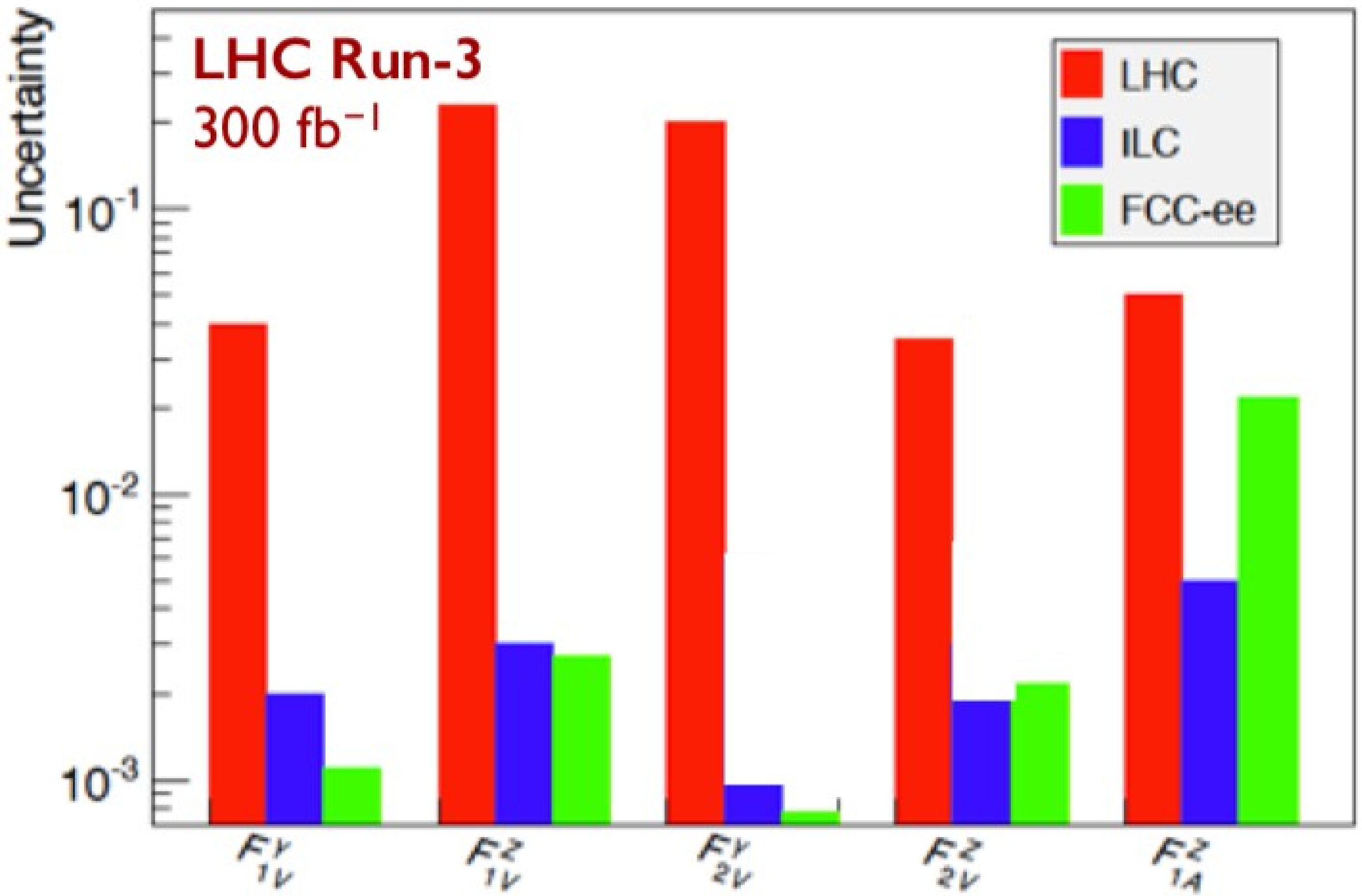


See also 1709.04289

- ILC measurements with beam polarisation provide model independent access to photon and Z couplings (or vector and tensor couplings)
- $\delta g_{RZ}/g_{RZ}$~2% sufficient to confirm at >5σ or to discard the LEP1 effect which is at the 25% level
  - Already by measuring 250 GeV
- Recall the sign uncertainty on LEP1 solutions $\delta g_{RZ}/g_{RZ}$ =25% or $\delta g_{RZ}/g_{RZ}$ =-225%
  - Not a problem at 250 GeV to make the right choice for the sign due to interference photon/Z

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

Accuracy on CP conserving couplings

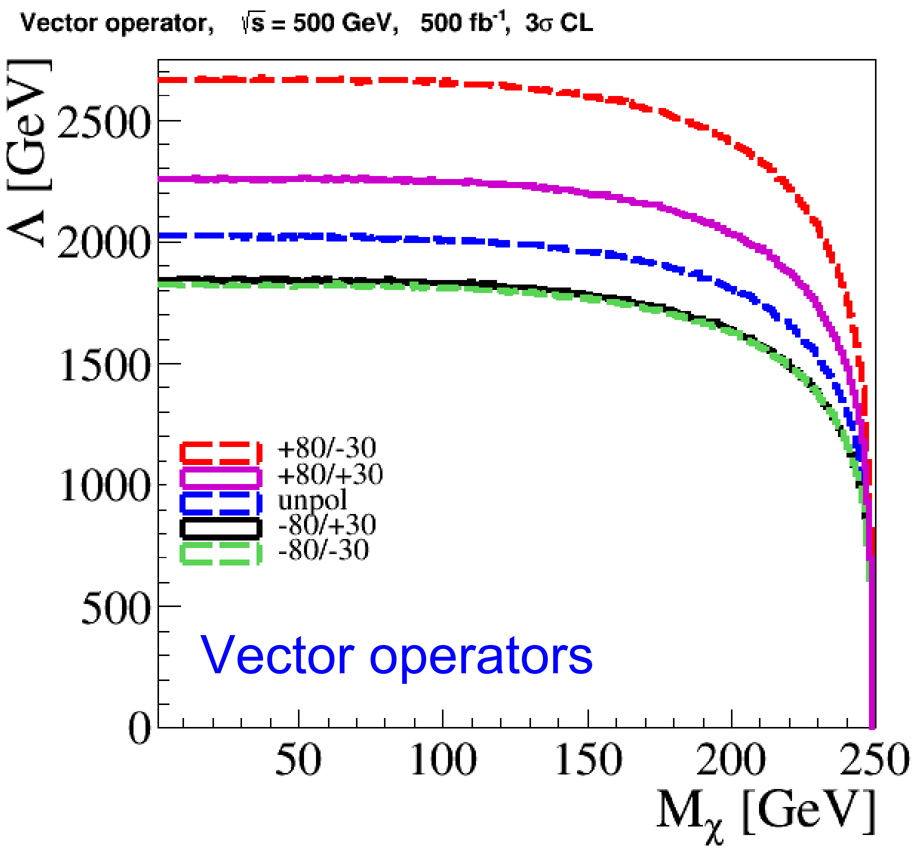


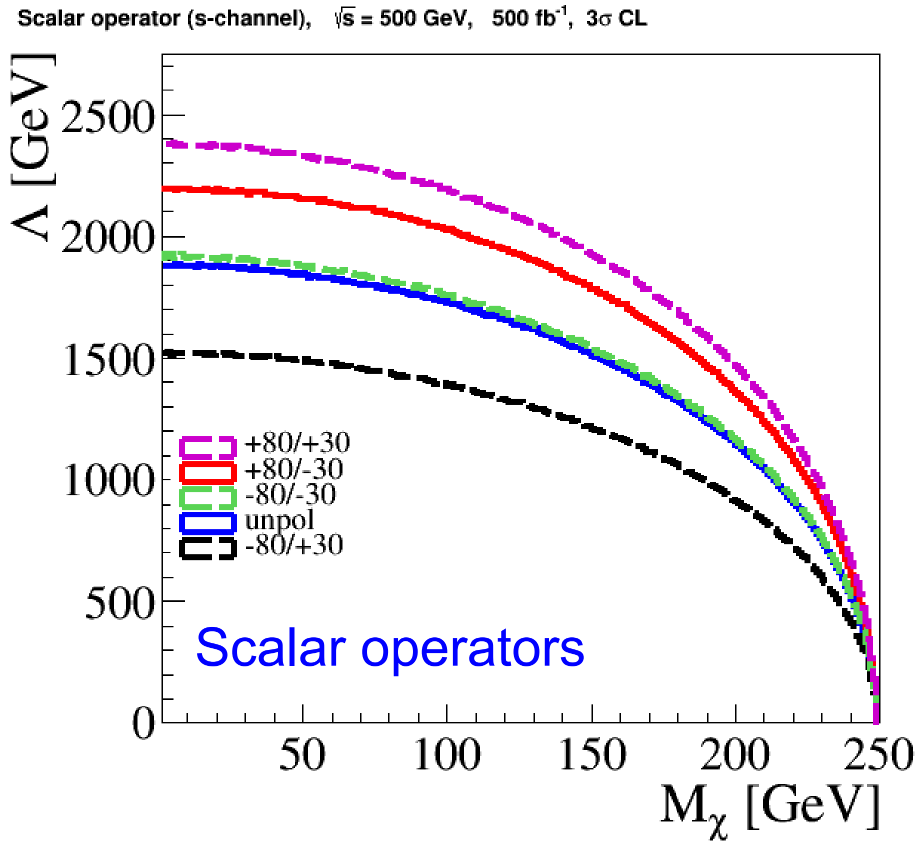
Arxiv:1503.01325
corrected for ILC values published in 1505.06020

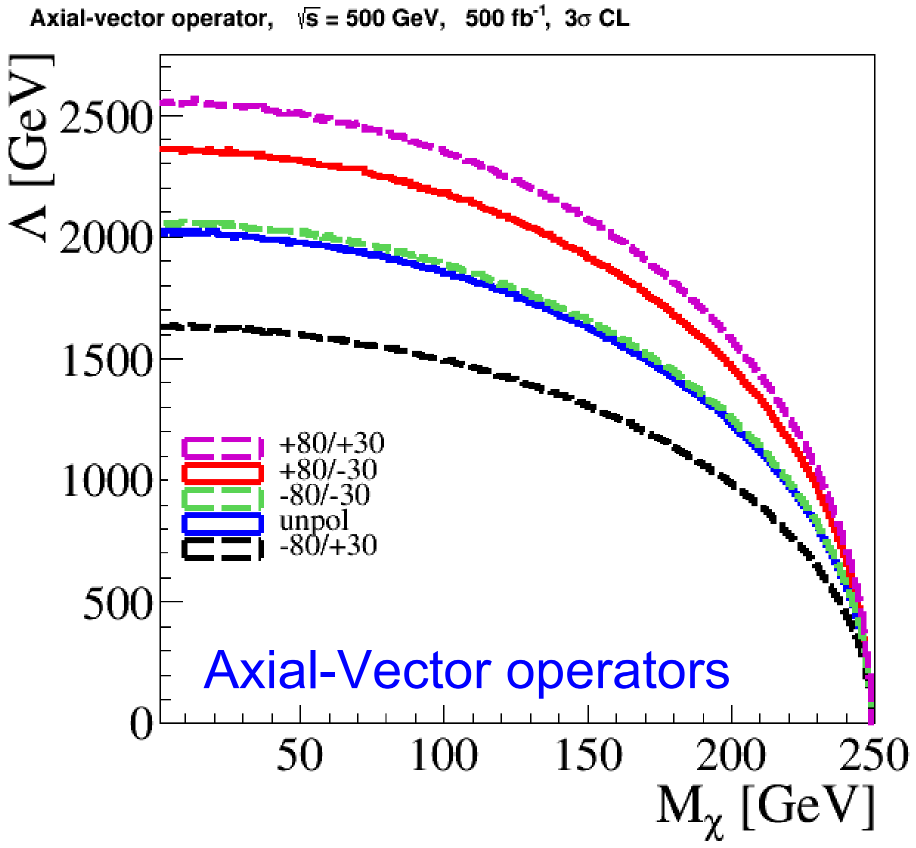
- e+e- collider might be up to two orders of magnitude more precise than LHC (√s = 14 TeV)
- Large disentangling of couplings for ILC thanks to polarised beams
- Final state analysis at FCCee
  - Also possible at LC => Redundancy
- Note
  - Maximal Lumi scenario for FCCee
  - Minimal Lumi scenario for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

LC promises to be high precision machine for electroweak top couplings

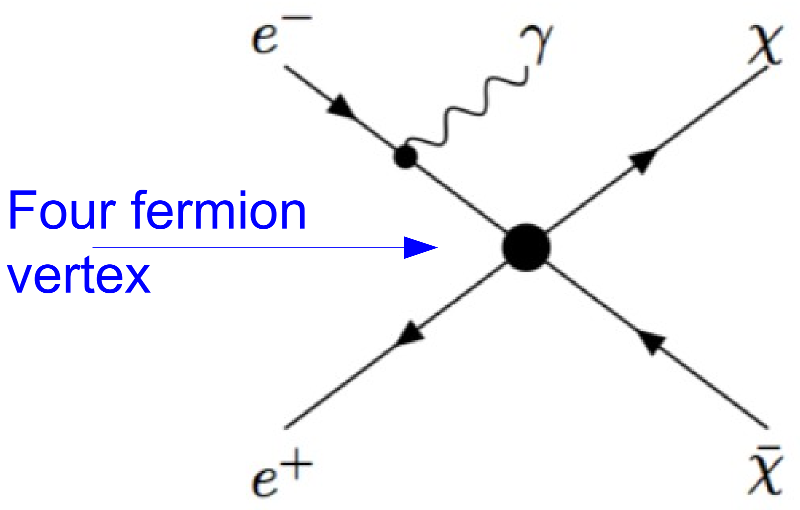
Monophoton searches







M. Habermehl



- 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)
  - Examples are electroweak fermion couplings and TGC
  - 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

Beam polarisation and disentangling

With two beam polarisation configurations

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

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

Beam polarisation – Uncertainty and positron polarisation II

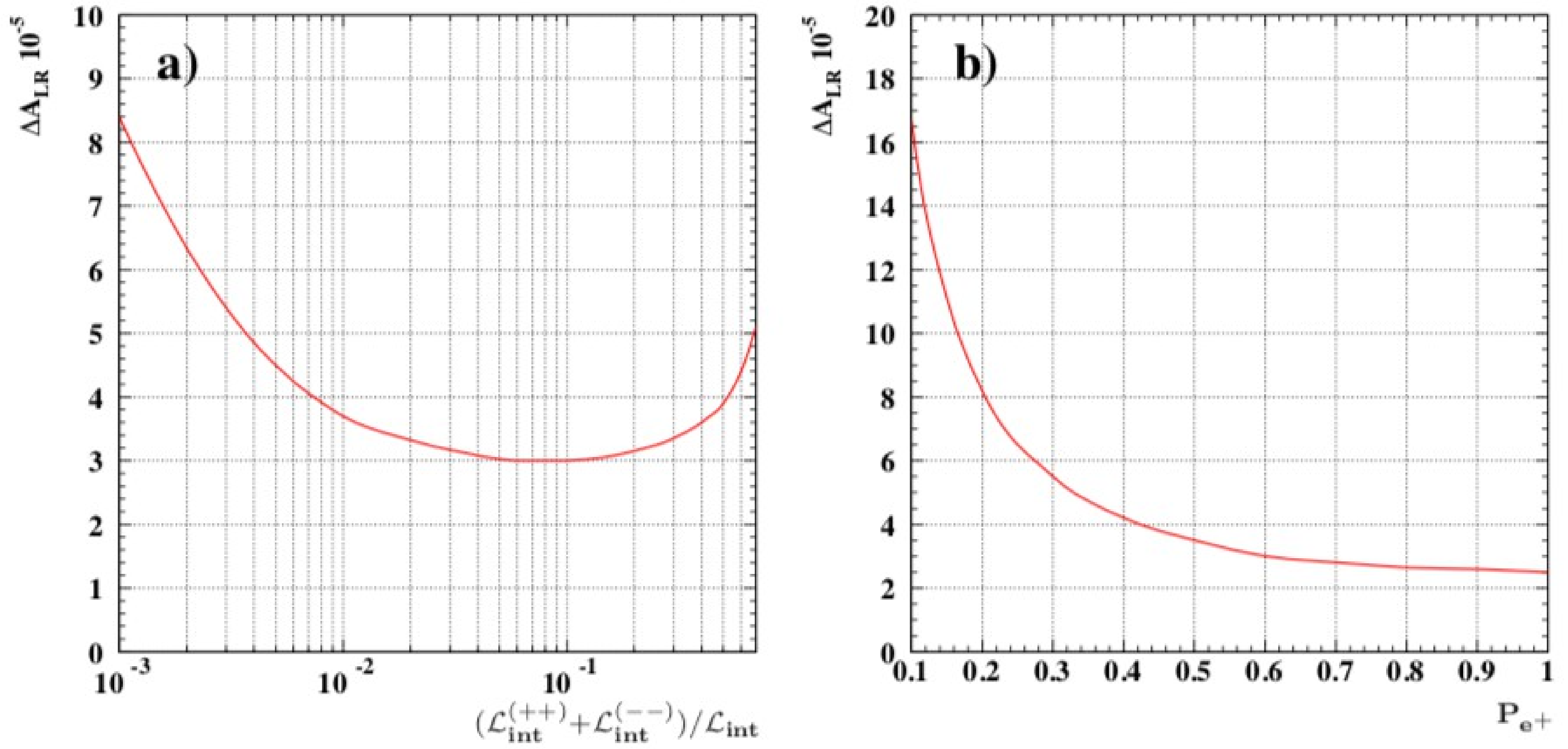


Figure 2.7: Test of the electroweak theory: the statistical error on A_{LR} of $e^+e^- \to Z \to \ell\bar{\ell}$ at GigaZ, (a) as a function of the fraction of luminosity spent on the less favoured polarization combinations σ_{++} and σ_{--} and (b) its dependence on P_{e^+} for fixed $P_{e^-} = \pm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

From hep-ph/0507011

Beam polarisation – Uncertainty and (positron) polarisation

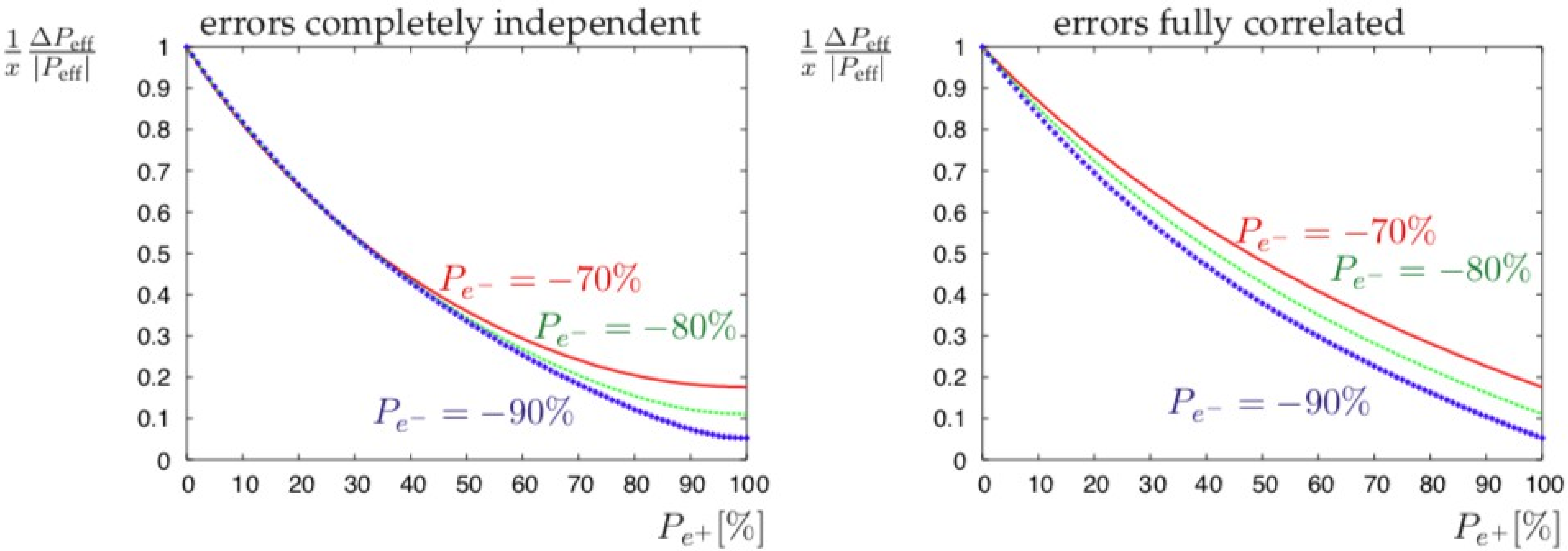


Figure 1.6: Relative uncertainty on the effective polarization, $\Delta P_{\rm eff}/|P_{\rm eff}| \sim \Delta A_{\rm LR}/A_{\rm LR}$, normalized to the relative polarimeter precision $x = \Delta P_{e^-}/P_{e^-} = \Delta P_{e^+}/P_{e^+}$ for independent and correlated errors on P_{e^-} and P_{e^+}, see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

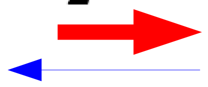
$$A_{\rm LR} = \frac{1}{P_{\rm eff}} A_{LR}^{\rm obs} = \frac{1}{P_{\rm eff}} \frac{\sigma_{-+} - \sigma_{+-}}{\sigma_{-+} + \sigma_{+-}}, \qquad (1.24)$$

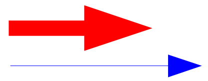
From hep-ph/0507011

Beam polarisation – Some words on the basics

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

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

-1/2  Left handed helicity

1/2  Right handed helicity

<u>Caveat:</u>
Helicity is frame dependent!

=> Not Lorentz invariant

Helicity projection operator

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

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 <u>massless</u> particle

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

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

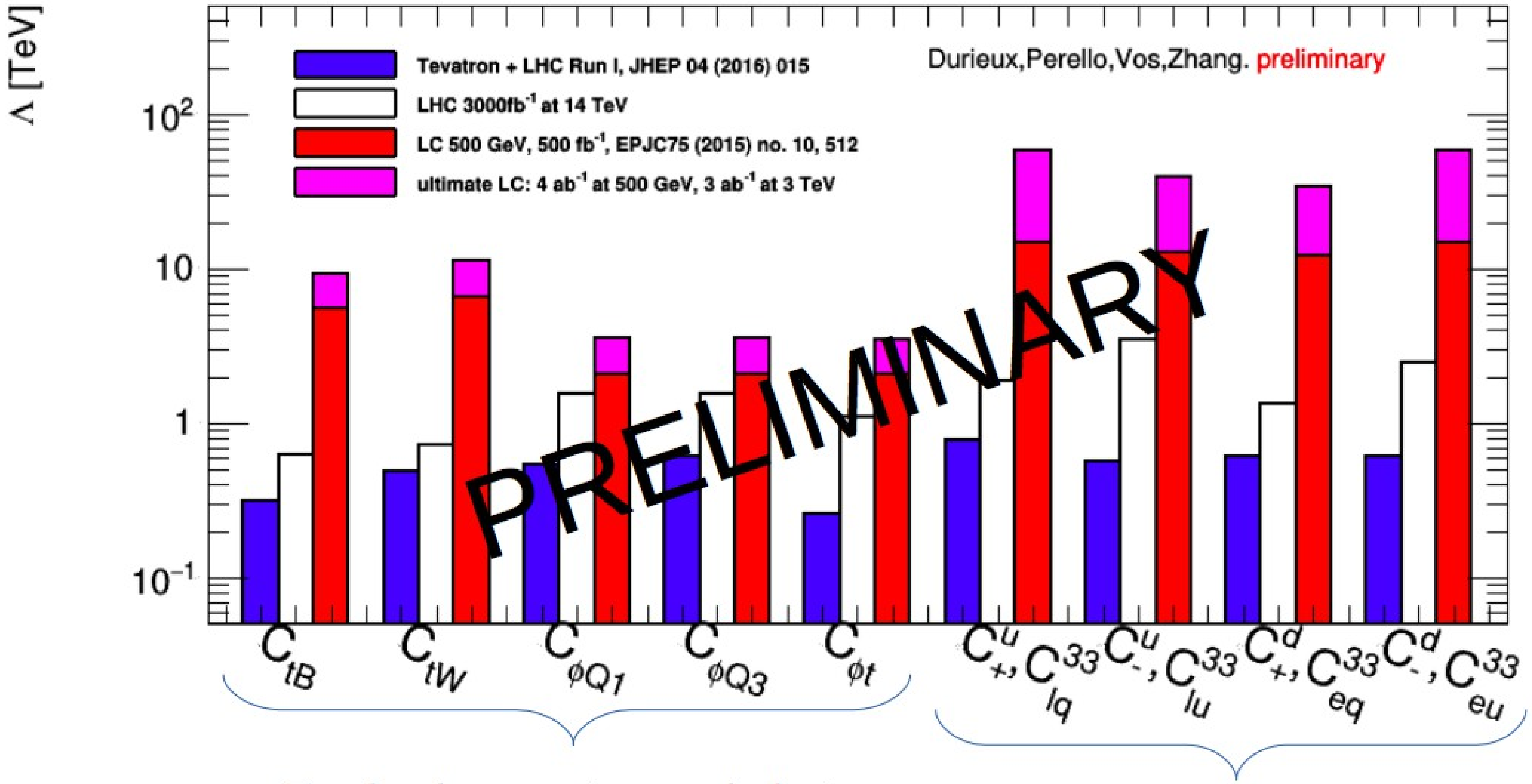
$$u_R = \left(1 - \frac{|\vec{p}|}{E+m}\right) u_{LC} + \left(1 + \frac{|\vec{p}|}{E+m}\right) u_{RC}$$

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



Two-fermion operators, equivalent to F1V, F1A, F2V form factors

Four-fermion operators (qqtt at hadron colliders, eett at LC)

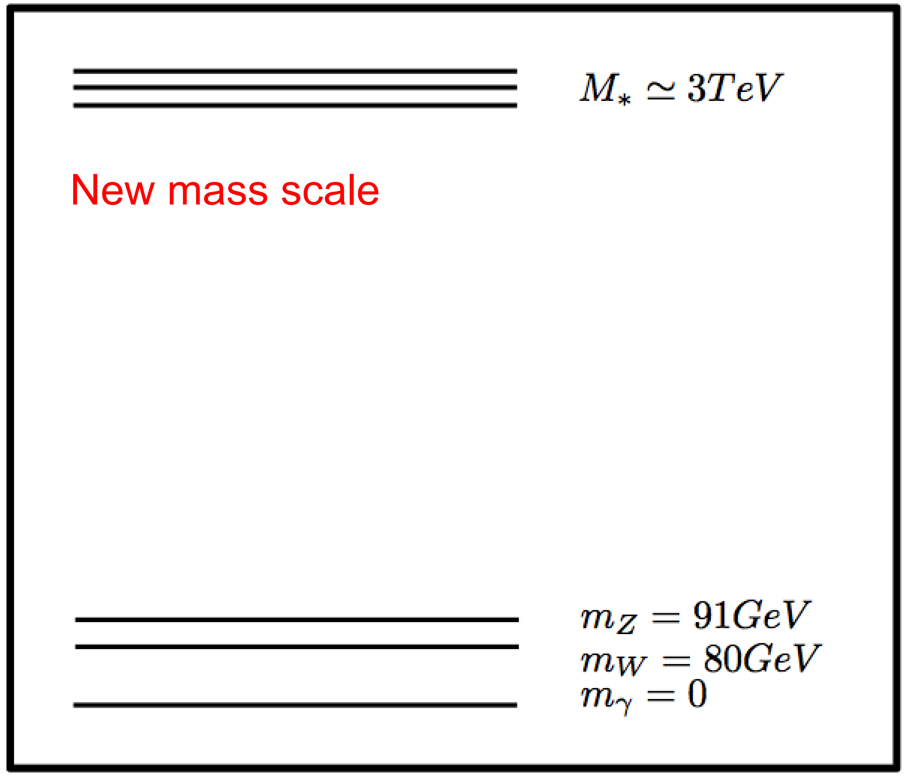
Example Compositeness

à la G.M. Pruna, LC 13, Trento

Compositeness:

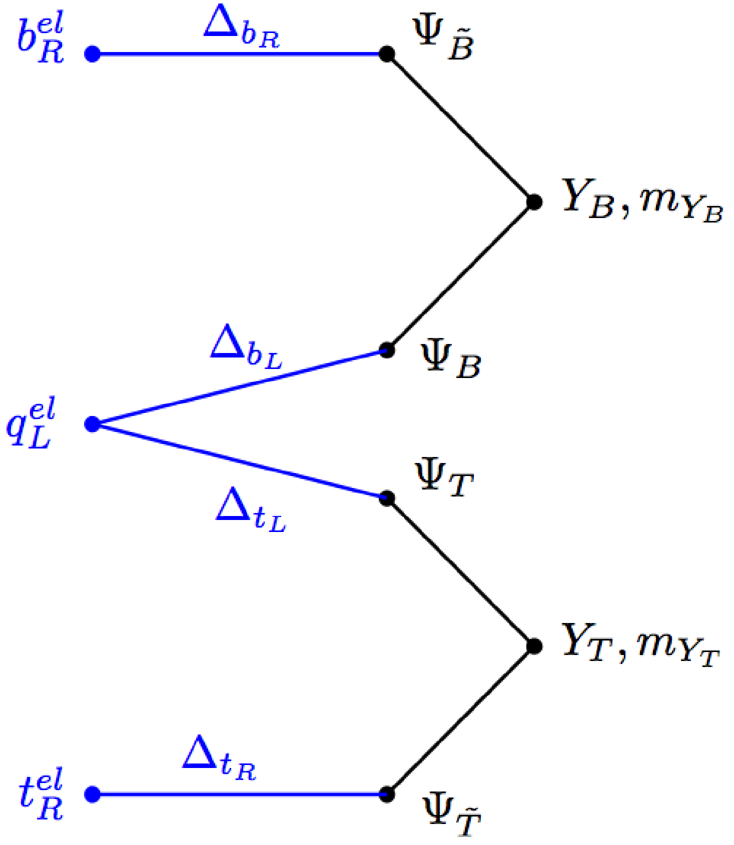
- ... provides elegant solution for naturalness
- ... few tensions with SM predictions
- ... **all** scalar objects observed in nature turned out to be bound states of fermions
- ... Duality with Randall-Sundrum Models

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!