# ILC at the Z-Pole - GigaZ

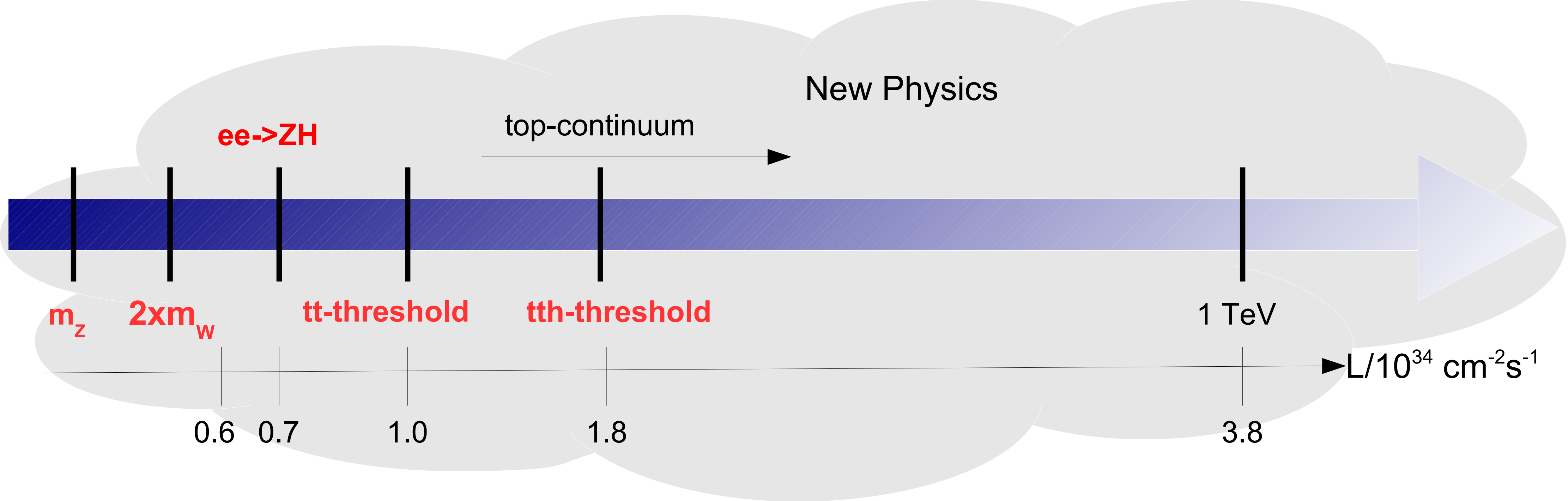
Roman Pöschl

CNRS IN2P3 Les deux infinis
Laboratoire de l'Accélérateur Linéaire
FLUO
Université Paris Sud — Comprendre le monde, construire l'avenir®
Université Paris-Saclay
P2IO Physique des 2 Infinis et des Origines
France-Japan Particle Physics — Toshiko Yuasa Lab.

R.P. Is indebted to François Richard for most of the results presented here
We reuse in part results of studies made by K. Moenig for TESLA report

CEPC 2019 Beijing China November 2019

# Physics program at Linear Electron Positron Colliders




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

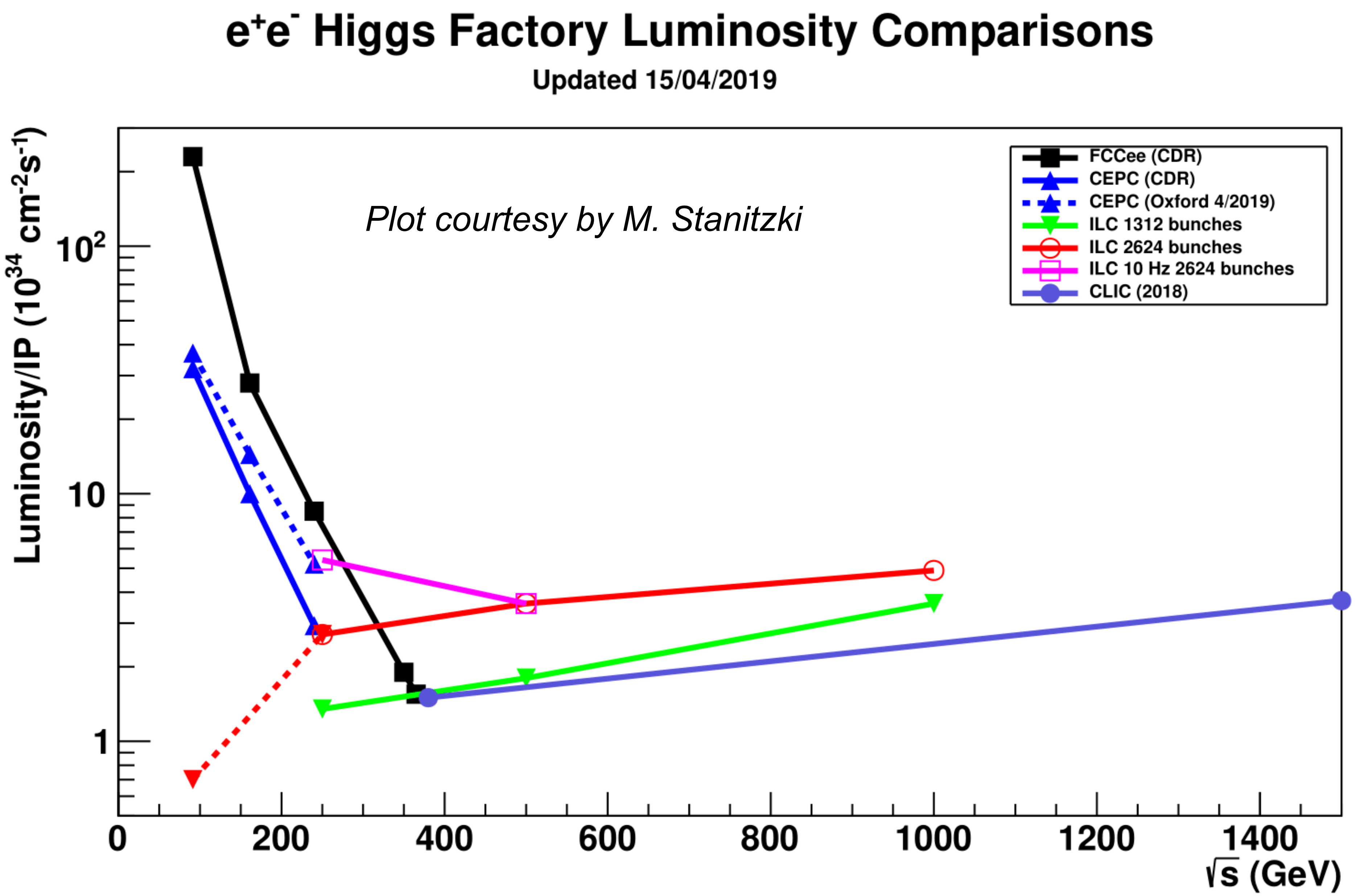
Machine settings can be “tailored” for specific processes

- 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

# Linear vs. circular e+e- machines – Instantaneous luminosity



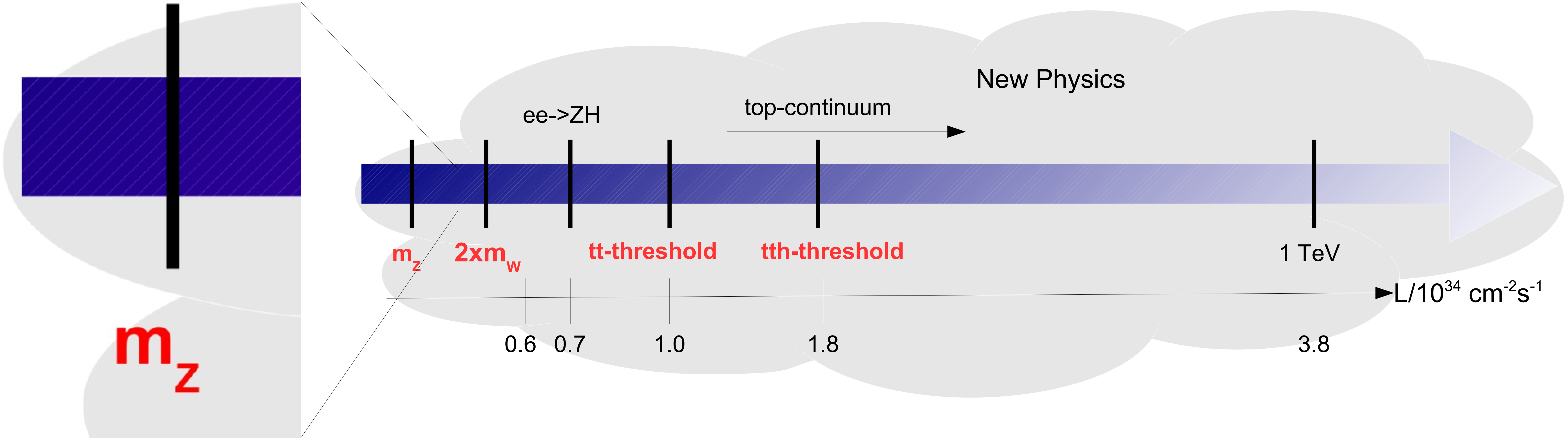

High energies ~above tt-threshold
Domain of linear colliders

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

# Why Z Pole Physics at the ILC?




- ILC is more than “just” a Higgs Factory
- Many new physics models have impact on electroweak processes e.g. 2f processes
- Z pole is “pure” Z => Therefore new physics (or not) due to Z has to be pinned down
- Many questions at Grenada to ILC capabilities on the pole
  - Some answers were at hand (arXiv: 1905.00220)

# GigaZ – Basic facts

| arXiv:1506.07830 | $\text{sgn}(P(e^-), P(e^+)) =$ (-,+) | (+,-) | (-,-) | (+,+) | sum |
|---|---|---|---|---|---|
| luminosity $[\text{fb}^{-1}]$ | 40 | 40 | 10 | 10 | |
| $\sigma(P_{e^-}, P_{e^+})$ [nb] | 83.5 | 63.7 | 50.0 | 40.6 | |
| $Z$ events $[10^9]$ | 2.4 | 1.8 | 0.36 | 0.29 | 4.9 |
| hadronic $Z$ events $[10^9]$ | 1.7 | 1.3 | 0.25 | 0.21 | 3.4 |

=230xLEP, 8500xSLC

- Accelerator scenario 3.7Hz@$M_Z$/2 + 3.7 Hz@125 GeV to produce positrons
- With 2625 bunches an instantaneous luminosity of $5\text{x}10^{33}$ $\text{cm}^{-2}$s-1 => 100 $\text{fb}^{-1}$ in 1.3 years after lumi upgrade
- More possible by improved damping rings and BDS system
- See arxiv: 1908.08212 for a recent revision

# Electroweak precision observables

*Copied from deBlas, Higgs-Hunting 2016*

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

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

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

$$M_W,\ \Gamma_W$$

W-observables
LEP2
0.02 - O(1%)

ILC (Wilson, Singer-Anguino@LCWS19):

$$\Delta m_W(MeV) = 2.4(stat.) \oplus 3.2(syst.) \oplus 0.8(\sqrt{s}) \oplus \text{theory}$$

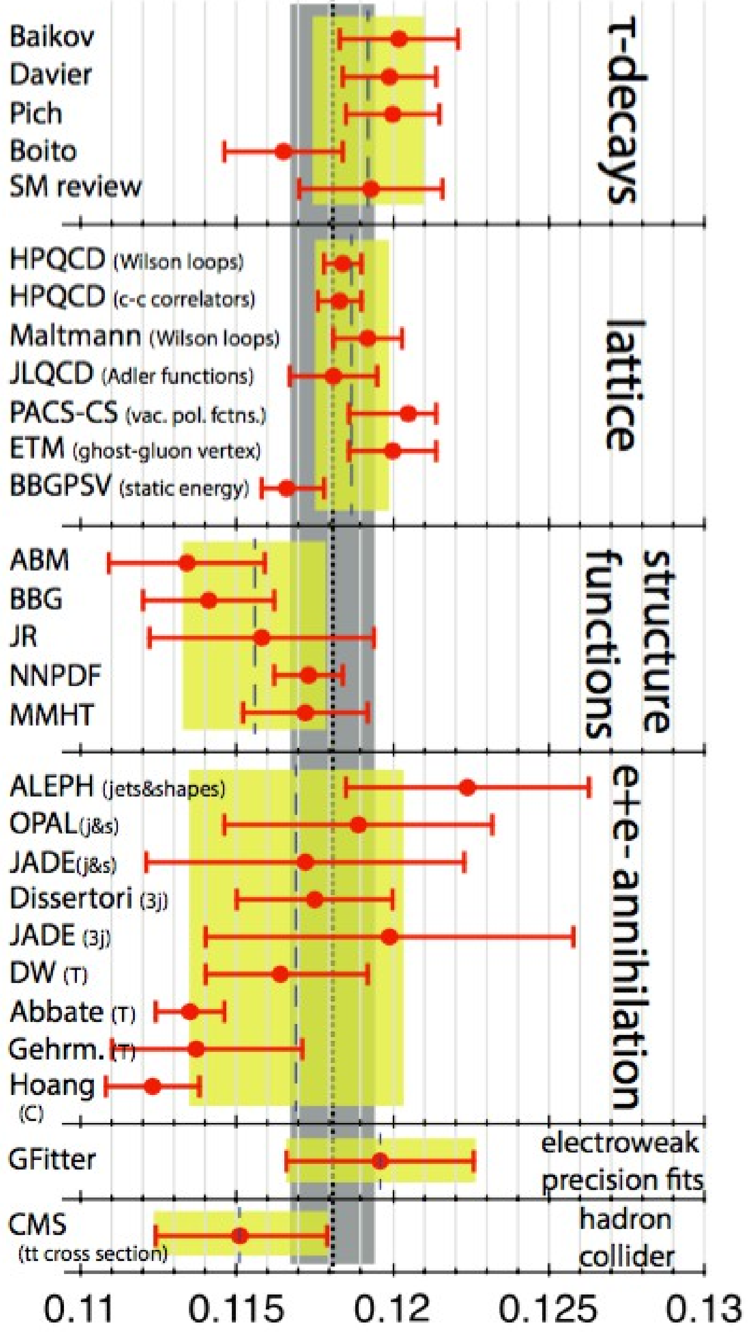
width: $\Delta\Gamma_w = 3.2$ MeV

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

| $M_W,\ \Gamma_W$ | $m_t$ | $M_H$ |
|---|---|---|
| 0.02-O(1%) | 0.4% | 0.2% |

# (A little bit) off topic - Uncertainty driver $\alpha_s$

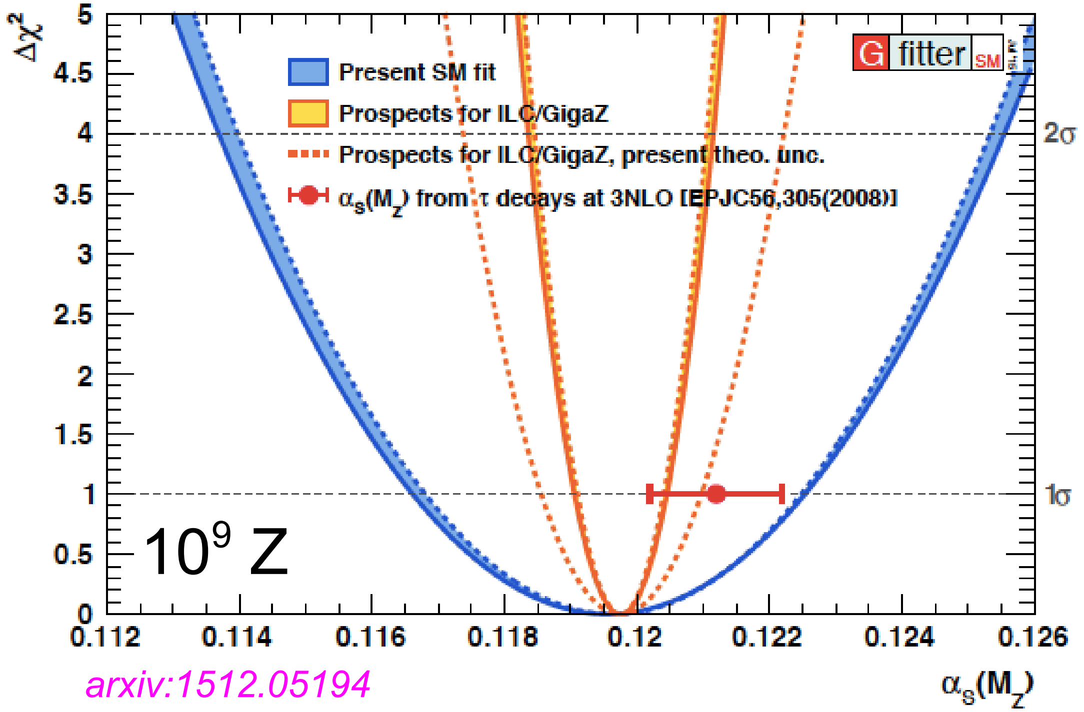
## Current status




Dominated by lattice QCD

## Prospects Z-running

*Slide made in 2016!*




arxiv:1512.05194

Electroweak fit with updated EWPO and theory uncertainties

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

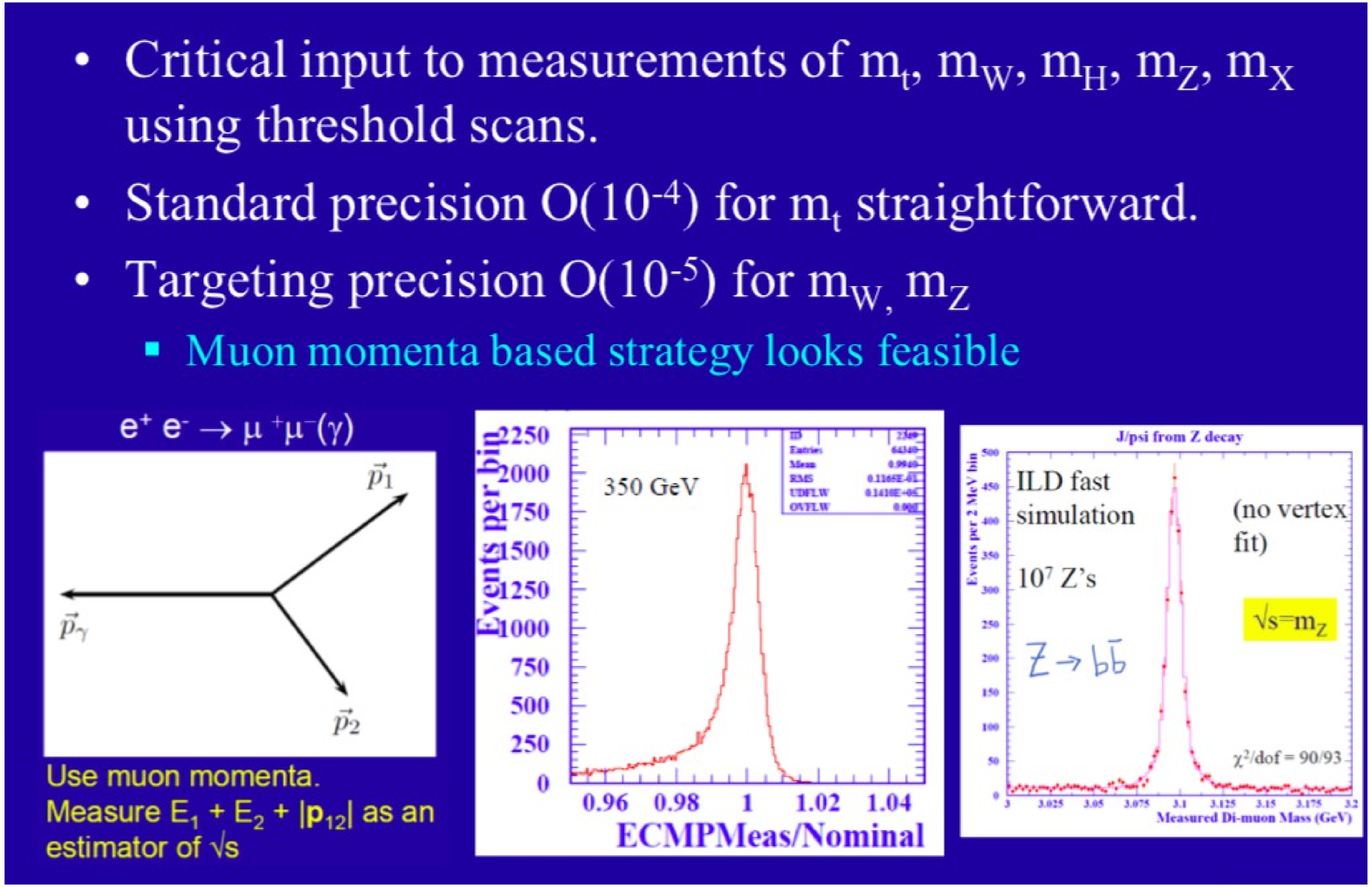
$\delta\ \alpha_s(M_Z) \sim 0.0003(16)$ for $10^{12}$Z

## Prospects Lattice

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

# GigaZ and Z Mass – Beam energy measurement

1) Scans around Z pole and measurement in upstream and downstream beam-spectrometers
2) In situ measurement using superb momentum resolution of ILC Detectors (G. Wilson)




=> $\Delta M_Z$ = 0.5 MeV

*2.1 MeV currently*

$\Delta\Gamma_Z$ = 0.33 MeV

2.3 MeV currently

- The Z-mass and width is (as far as I can see) the among the few parameters on which a LC cannot compete with a CC

- Is this casted in stone?

# Measurement of $\sin^2\theta^{\ell}_{\rm eff}$.

$$\mathcal{A}_e = \frac{(g^Z_{e_L})^2 - (g^Z_{e_R})^2}{(g^Z_{e_L})^2 + (g^Z_{e_R})^2} = \frac{2 g_{e_V}/g_{e_A}}{1 + (g_{e_V}/g_{e_A})^2} \quad \text{with} \quad g_{e_V}/g_{e_A} = 1 - 4\sin^2\theta^{\ell}_{\rm eff}.$$

## How to determine $A_e$?

Left Right Asymmetry
Requires polarised beams

$$A_{LR} = \frac{1}{|\mathcal{P}_{eff.}|}\frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \mathcal{A}_e$$

Available at LC

Using all hadronic decays of Z!!!

Forward backward asymmetry
Has to assume lepton universality!!!

$$A^f_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \quad \text{for} \quad \mathcal{P}_e = 0.$$

Available at LC, CC

*Used e.g. In EPJC (2019) 79:474*

***with f = μ***

Final state polarisation (r,l)
e.g. with $\tau$

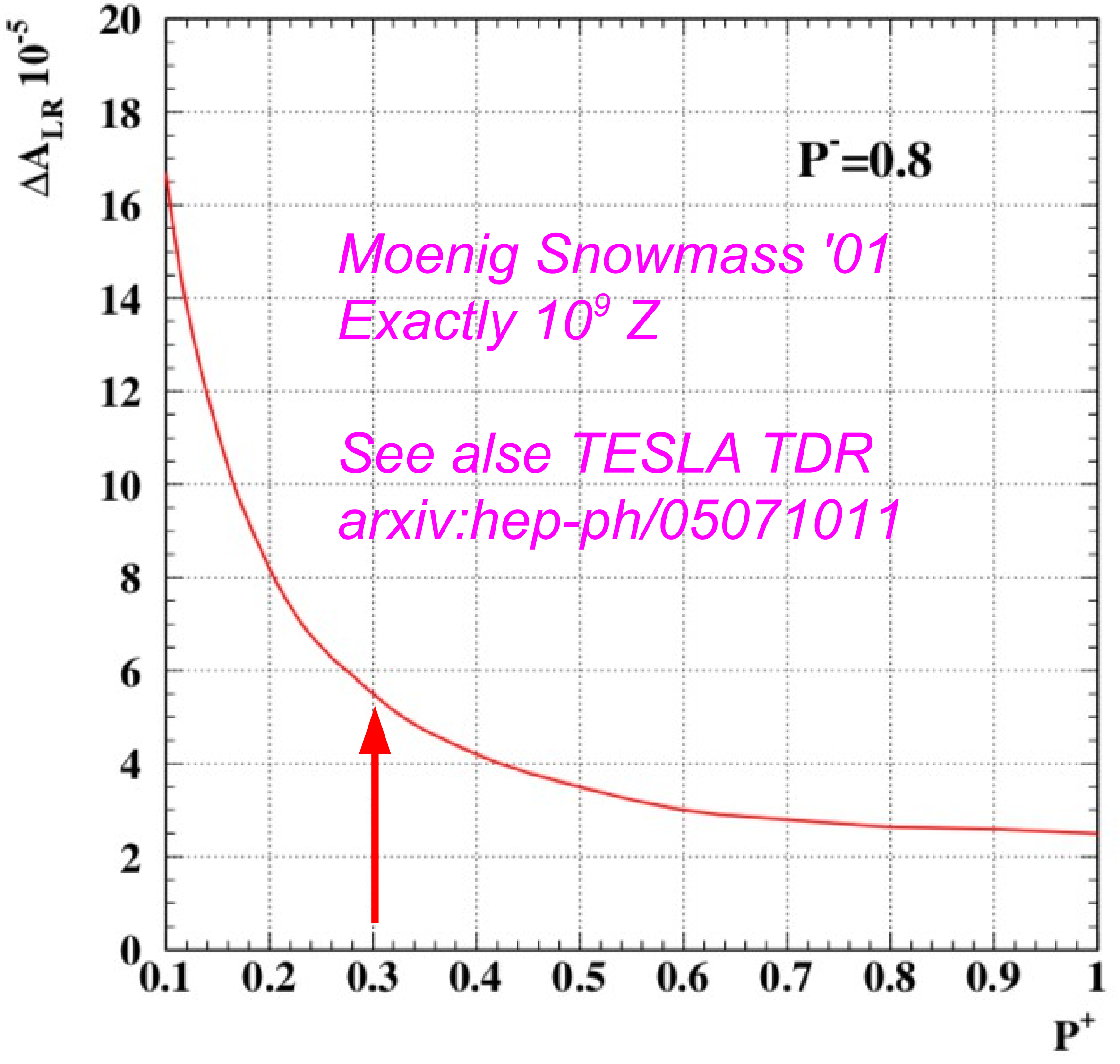
$$A^{pol}_{FB} = \frac{(\sigma_r - \sigma_l)_F - (\sigma_r - \sigma_l)_B}{(\sigma_r + \sigma_l)_F + (\sigma_r + \sigma_l)_B} = -\frac{3}{4}\mathcal{A}_e$$

Available at LC, CC

Beam polarisation is key: Remember SLC delivered most precise value of $\sin^2\theta^{\ell}_{\rm eff}$.
despite of 30 times less lumi

# $A_{LR}$ 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

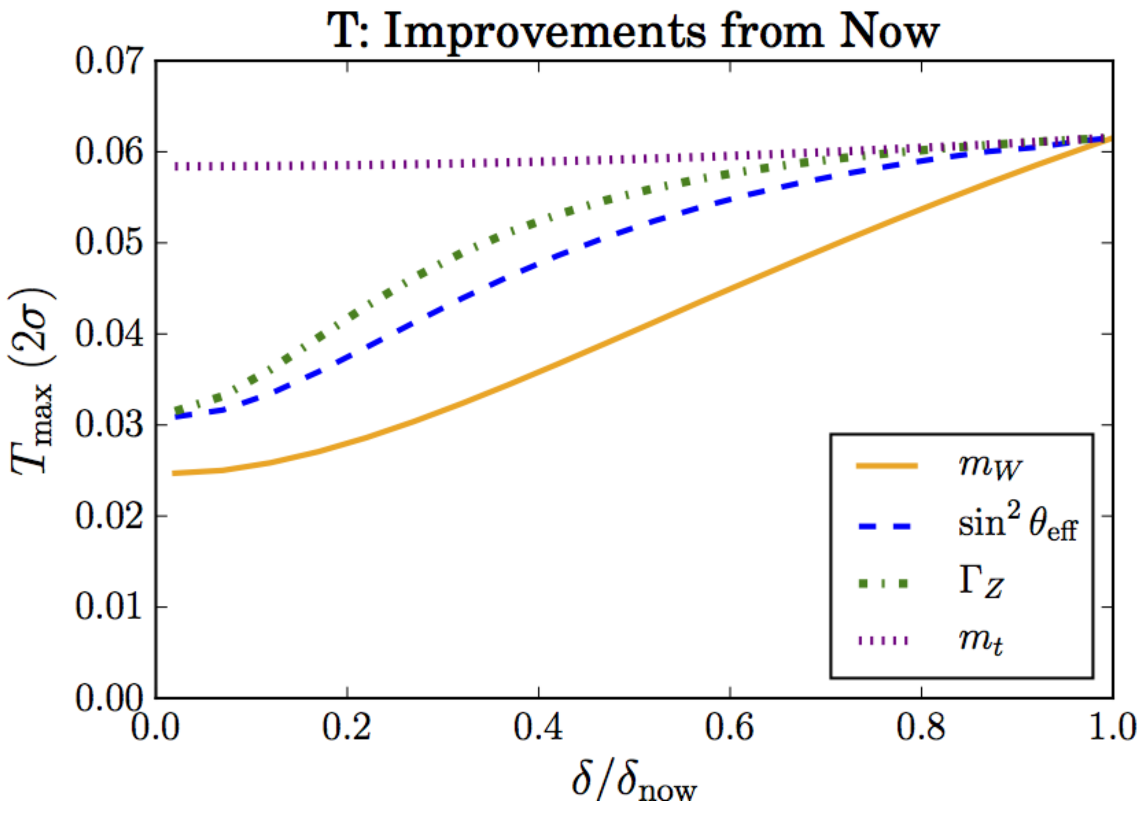
- Assumes perfect spin flip for polarised beams
- Residuals must be monitored by polarimeter
- Residual uncertainty of $\Delta A_{LR} = 0.5 \times 10^{-4}$ seems possible
- The more positron polarisation the better (see backup)
- Don't forget energy dependency ($dALR/d\sqrt{s} \sim 2 \times 10^{-5}/MeV$)

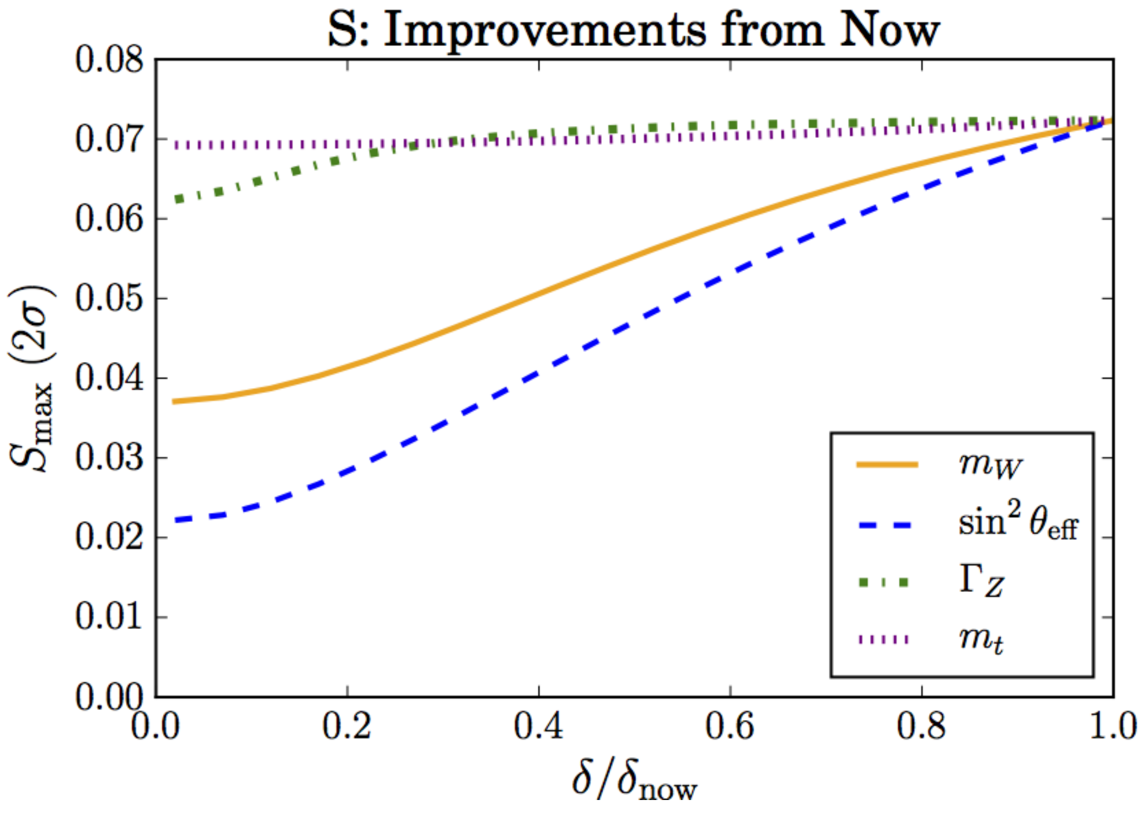
Precision $\Delta A_{LR} = 1 \times 10^{-4}$ is a realistic assumption for GigaZ

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

# Impact on oblique parameters?

*à la M. Reece 1609.03018*



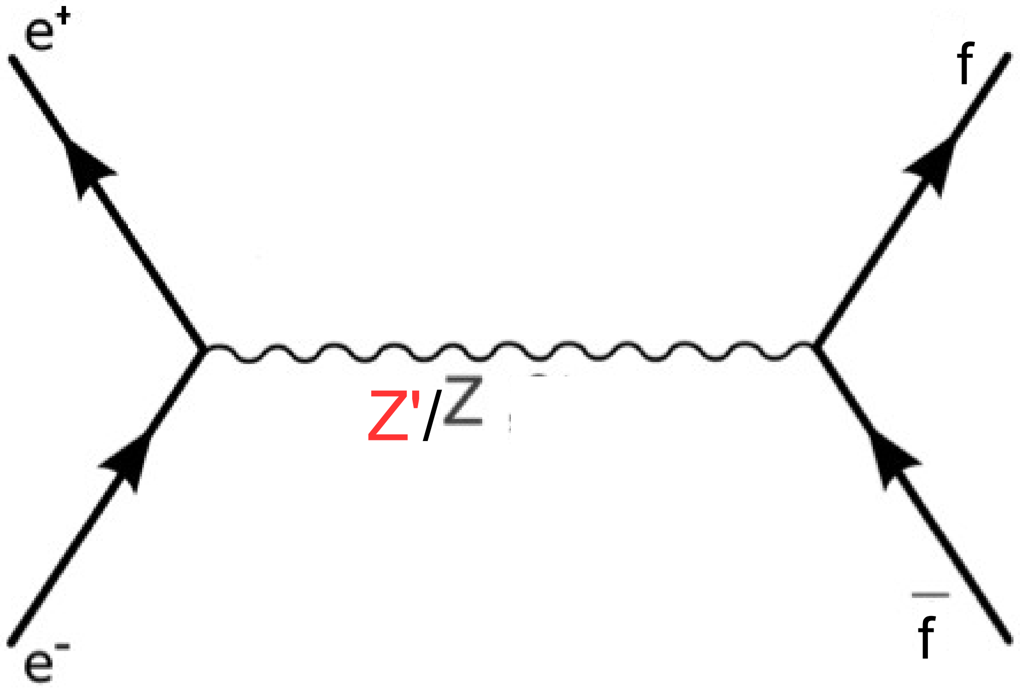

*Slide made in 2016!*

- T depends mainly on $M_W$
  - Threshold scan around $2M_W$ (with polarised beams), see above
- S depends mainly on $\sin^2\theta^2_{\rm eff}$.
  - Ultra-high statistics sample ee-> ff at Z-mass or smaller sample exploiting beam polarisation (Remember LEP and SLC times)

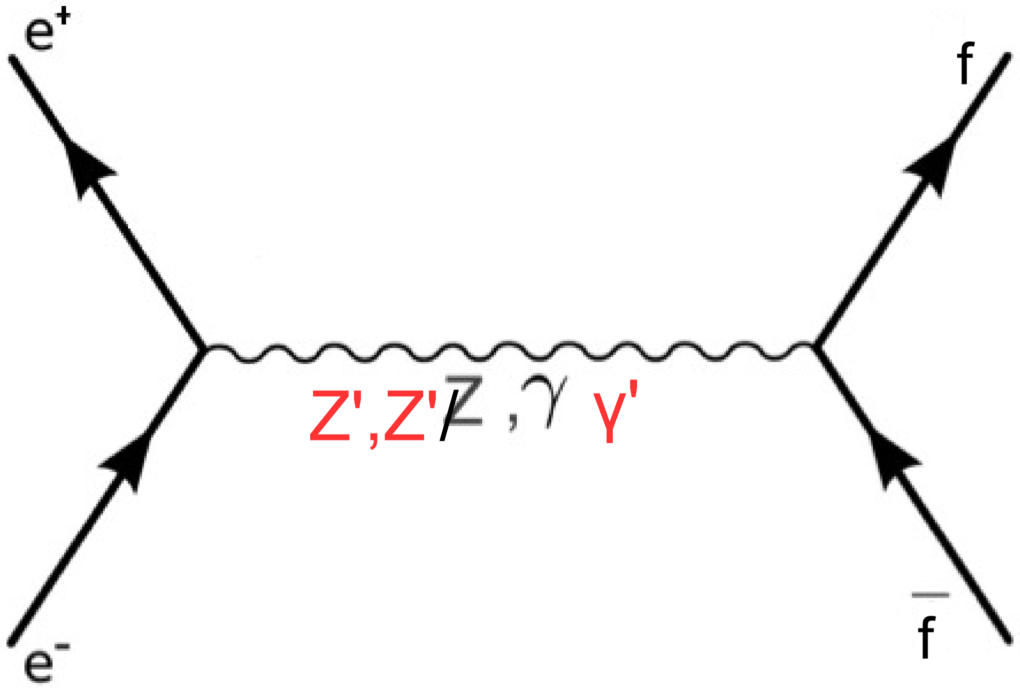
Precision on S and T seems to saturate at $\delta/\delta_{now} \approx 0.1 - 0.2$

# How can the Z pole help in 2f processes?

On the Z-pole




Above 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"

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

# Precision on couplings and helicity amplitudes in ee->bb at 250 GeV

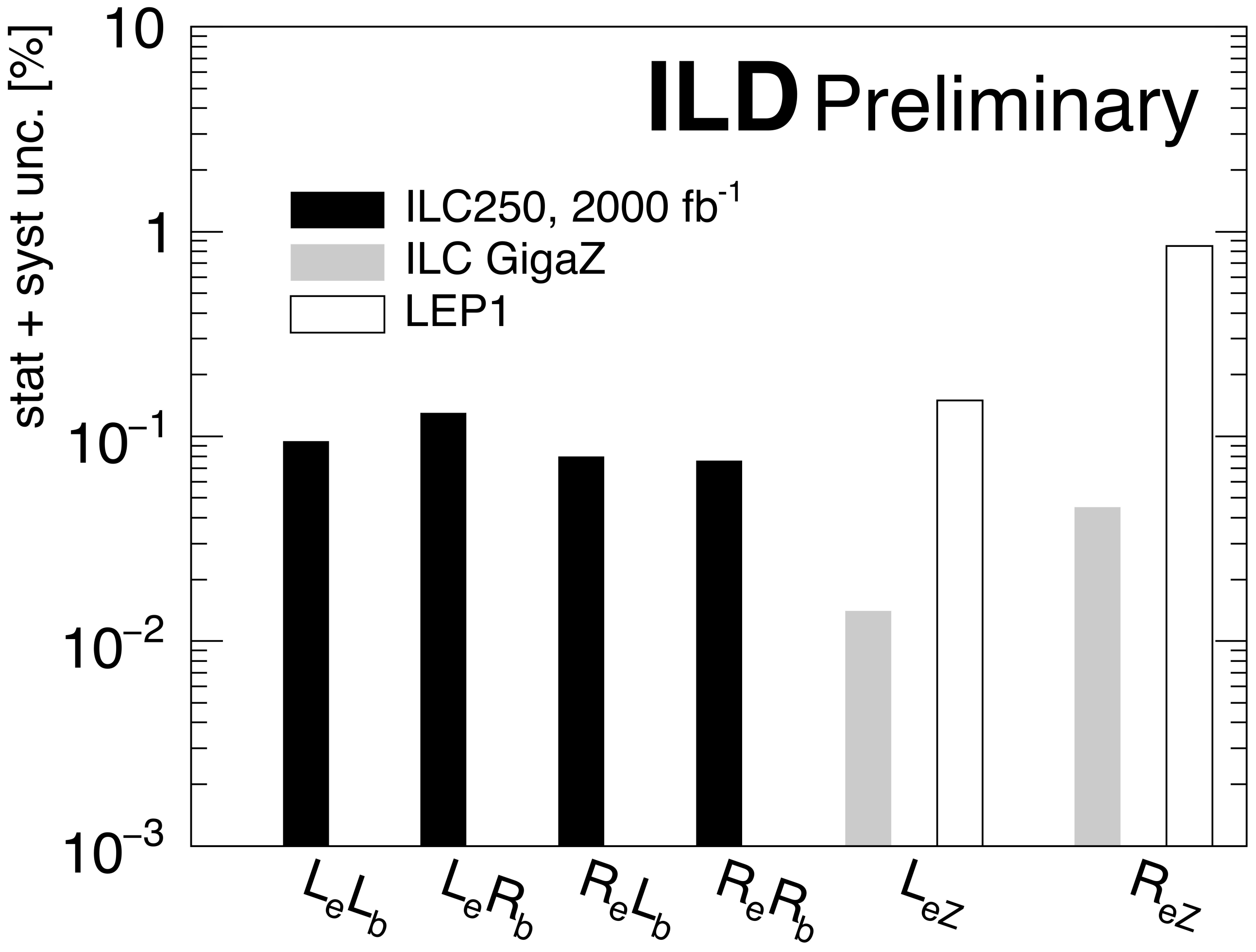



*Figure: A. Irles*

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

ILC250 SM GigaZ New resonances

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!!

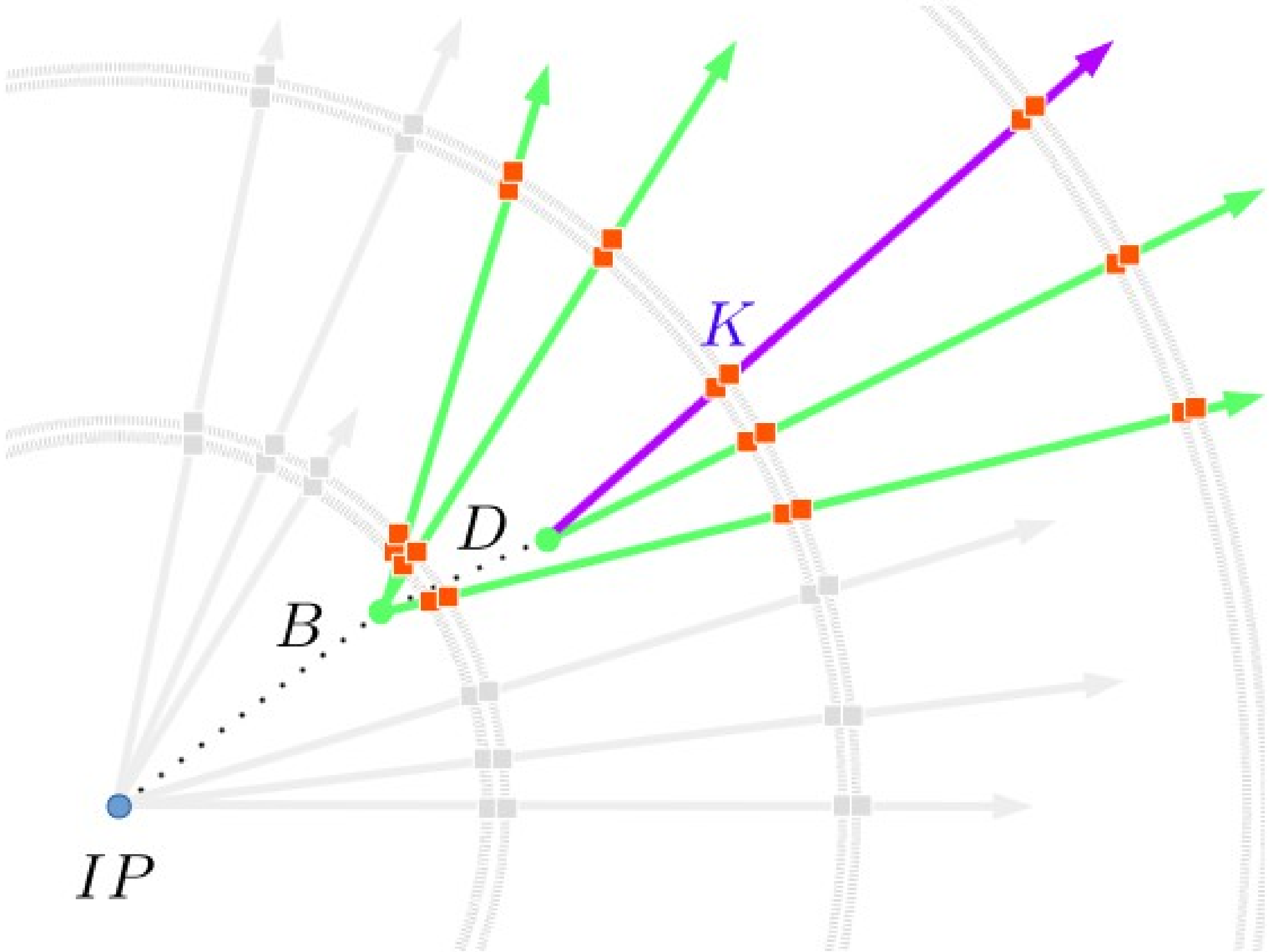
# Heavy quark measurements @ GigaZ

- There is a strong motivation to measure electroweak heavy quark couplings at the ILC
- New physics models predict deviations and b and c quarks are at the cross roads between 'top-philic' and 'non-top-philic' models
- Remember also LEP anomaly on $A^b_{FB}$
- ILC with GigaZ is a unique opportunity for a complete set of measurements and an unambiguous interpretation of the results
- Relevant observables at GigaZ are $A_b$ (see above) and

$$R_q = \frac{N_q}{N_{had}} = \frac{\Gamma_q}{\Gamma_{had}} = \frac{(g_q^L)^2 + (g_q^R)^2}{\sum_{i=1}^{n_q}[(g_i^L)^2 + (g_i^R)^2]}$$

  - Here $\Gamma_{had}$ is constrained by the fact that all hadrons are produced from the known quark species i.e. $R_b+R_c+R_{uds} = 1$ and has therefore no error, but the $g_i$ are correlated to fulfill this constraint
  - The <u>measured</u> $\Gamma_{had}$, which is sensitive to the experimental Z mass resolution has to be considered as a consistency check

# Our tool – Flavor tagging and charge measurment




- flavor tagging
- b-quark charge measurement
  - Important for top quark studies, indispensable for ee->bb
- Control of migrations:
  - Correct measurement of vertex charge
  - Kaon identification by dE/dx (and more)
- ILC/ILD can base the entire measurements on double Tagging and vertex charge
  - LEP/SLC had to include single tags and Semi-leptonic events

*PhD thesis: S. Bilokin*
*A. Irles*

# Why this luxury?

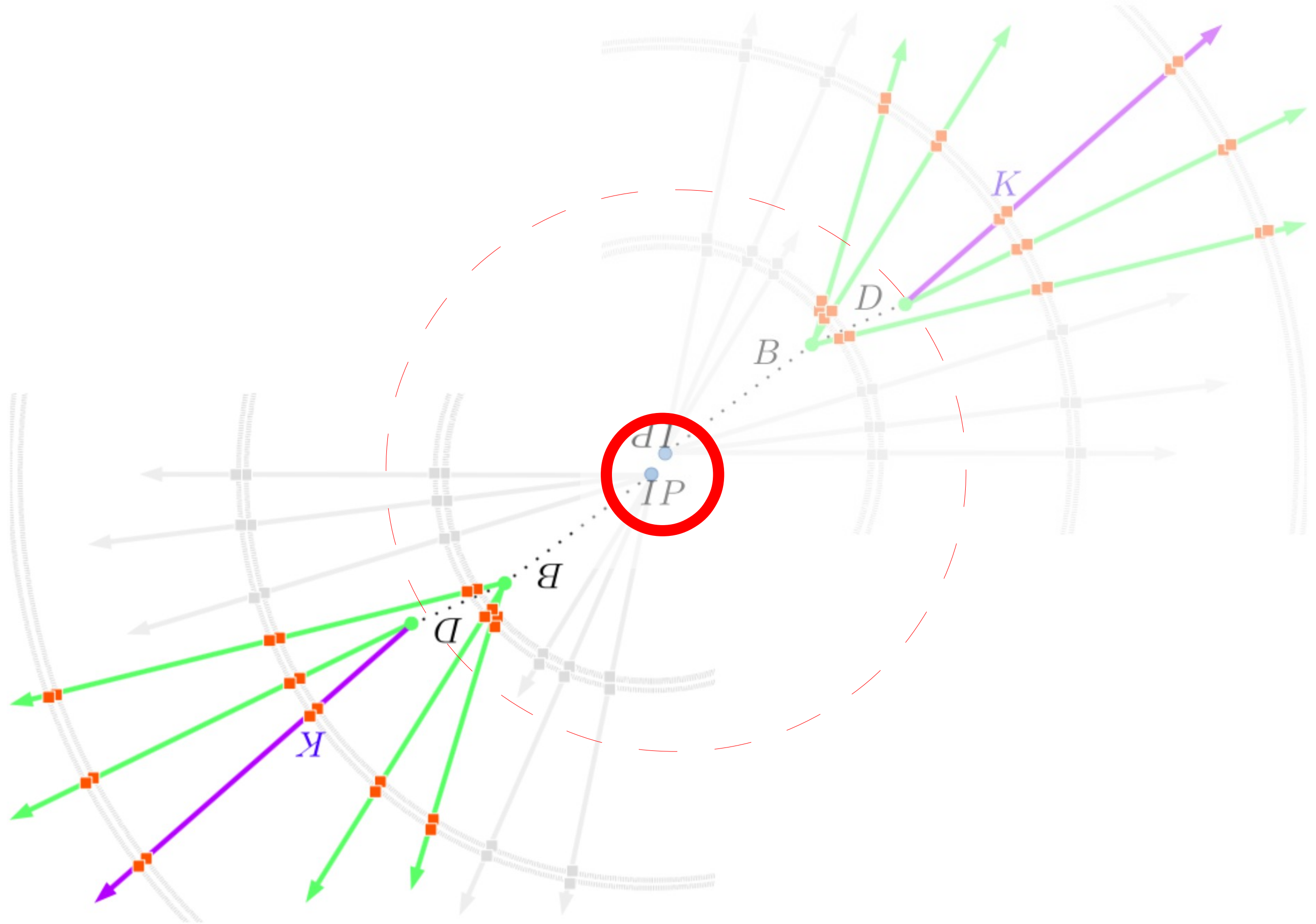
Beam spot size

| | FCCee | ILC | SLC | LEP |
|---|---|---|---|---|
| $\sigma_x$[nm] | 13700 | 516 | 1500 | 200000 |
| $\sigma_y$[nm] | 36 | 7.7 | 500 | 2500 |

*Source SLC, LEP, PDG*

**LEP >> SLC >> ILC**

# Double tagging




Important systematic error is knowledge of tagging efficiency $\varepsilon_q$

Can be derived from data if tagging is independent in two hemispheres, i.e. if

$$C_q = \frac{\epsilon_{double}}{\epsilon_q^2} \approx 1$$

If $C_q \neq 1$ => Hemisphere correlations => systematic error

For example:

LEP (large beam spot): $C_q$-1 ≈ 3% => $\Delta R_b$ ≈ 0.2%

SLC (smaller beam spot): $C_q$ -1 < 1% => $\Delta R_b$ ≈ 0.07%

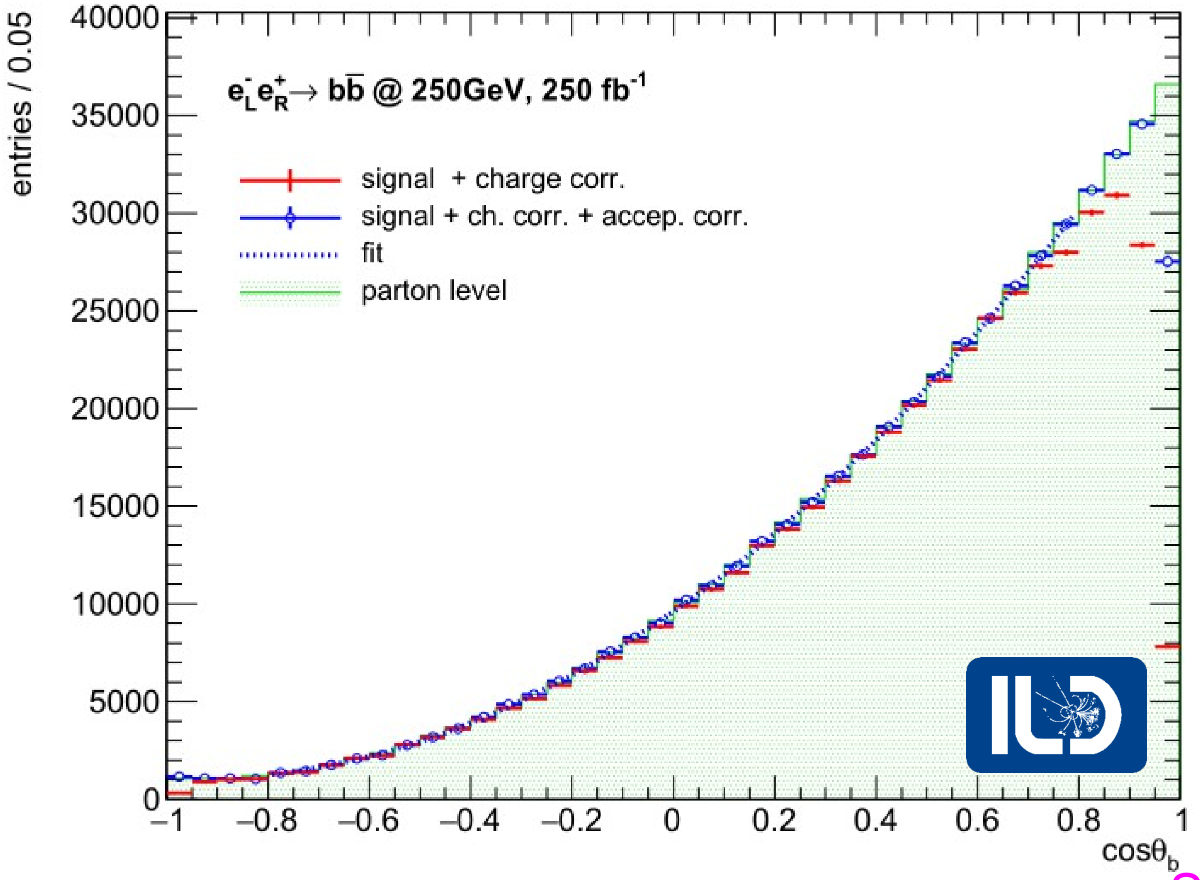
ILC (tiny beam spot): Expect $C_q$ -1 = 0 => $\Delta R_b$ ≈ 0

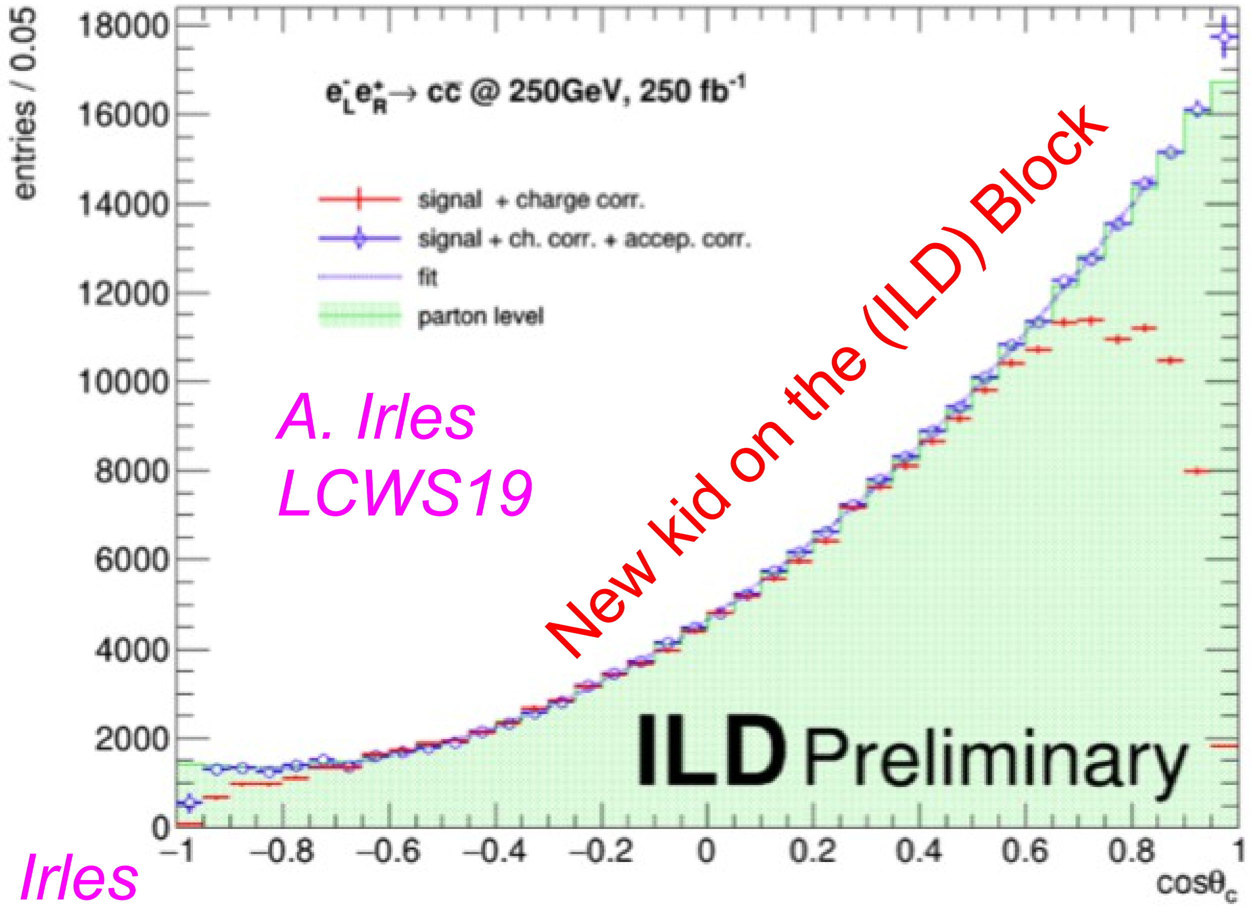
Full simulation studies for ILD confirm $C_q$ -1 = 0

See talk at LCWS

# Our "basis"

Excellent measurement of quark polar angle spectrum by double tagging track assignment




S. Bilokin, A. Irles

- Knowledge obtained at 250 GeV can be extrapolated to the Z-pole
  - Relatively safe for b-quark case
    - To be verified for c-case (study for ILC in infancy state)
    - No show stopper observed by studying relevant SLC papers

# Migration and Dilution?

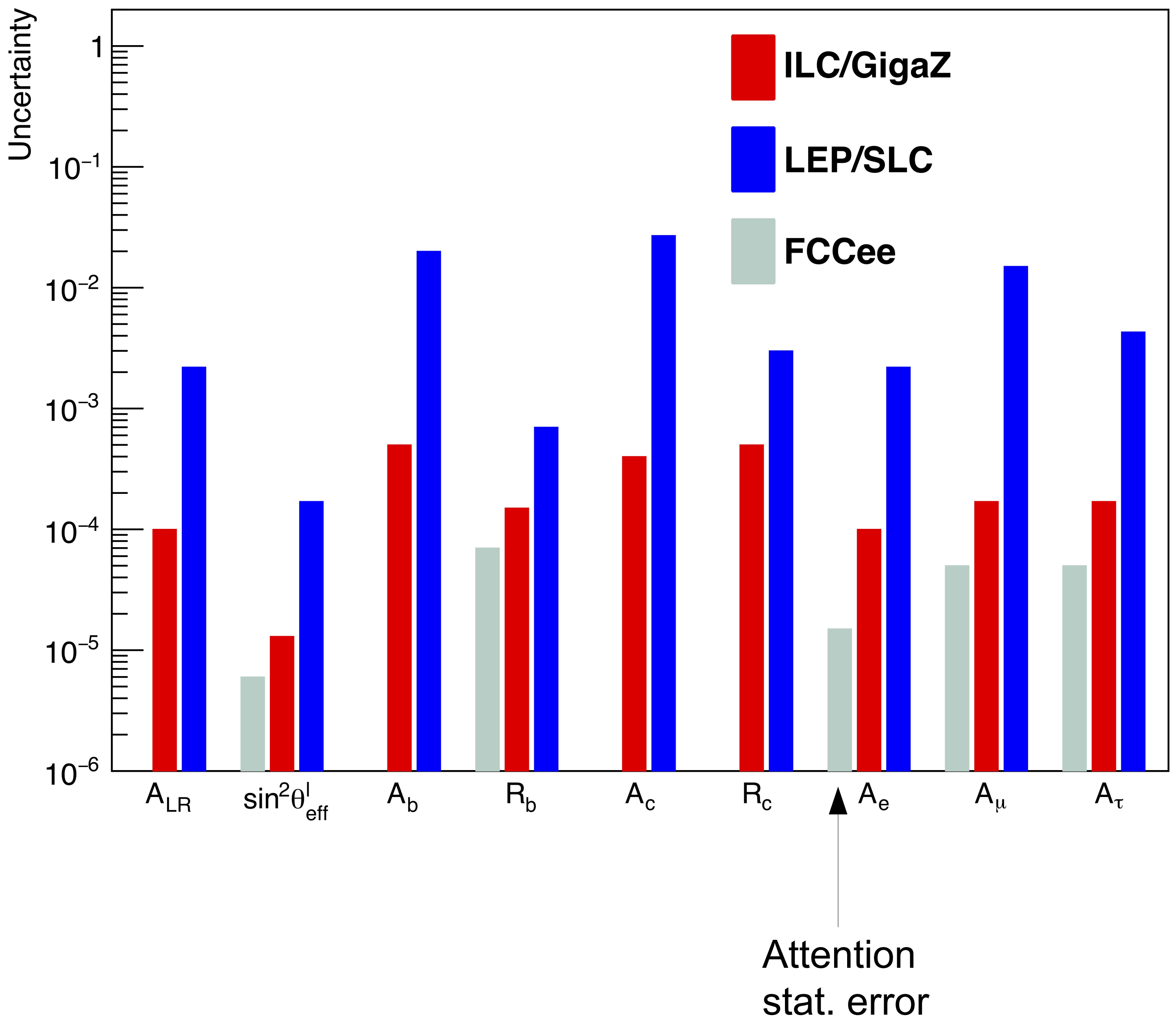
- Create two samples
  - One with consistent charge measurement in both jets (-,+) => $N_{acc.}$
  - One with inconsistent charge measurement (--, ++) => $N_{rej..}$

$$N_{acc} = Np^2 + Nq^2$$
$$N_{rej} = 2Npq$$
$$1 = p + q$$

*p:* probability of a correct charge assignment
*q=1-p:* probability of an incorrect charge assignment

- Two equations for two unknowns
  *pq*-formula allows for correcting for migrations and in particular for the last and ultimate migration (dilution) due to B0 oscillations
- Only possible since we always analyse quark and anti-quark
  - i.e. exclusive use of double tag events (was very limited at LEP and SLC)
  - All papers praise the usefulness of double tag and vertex charge measurements, well here it is!

# Precision on relevant observables




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

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

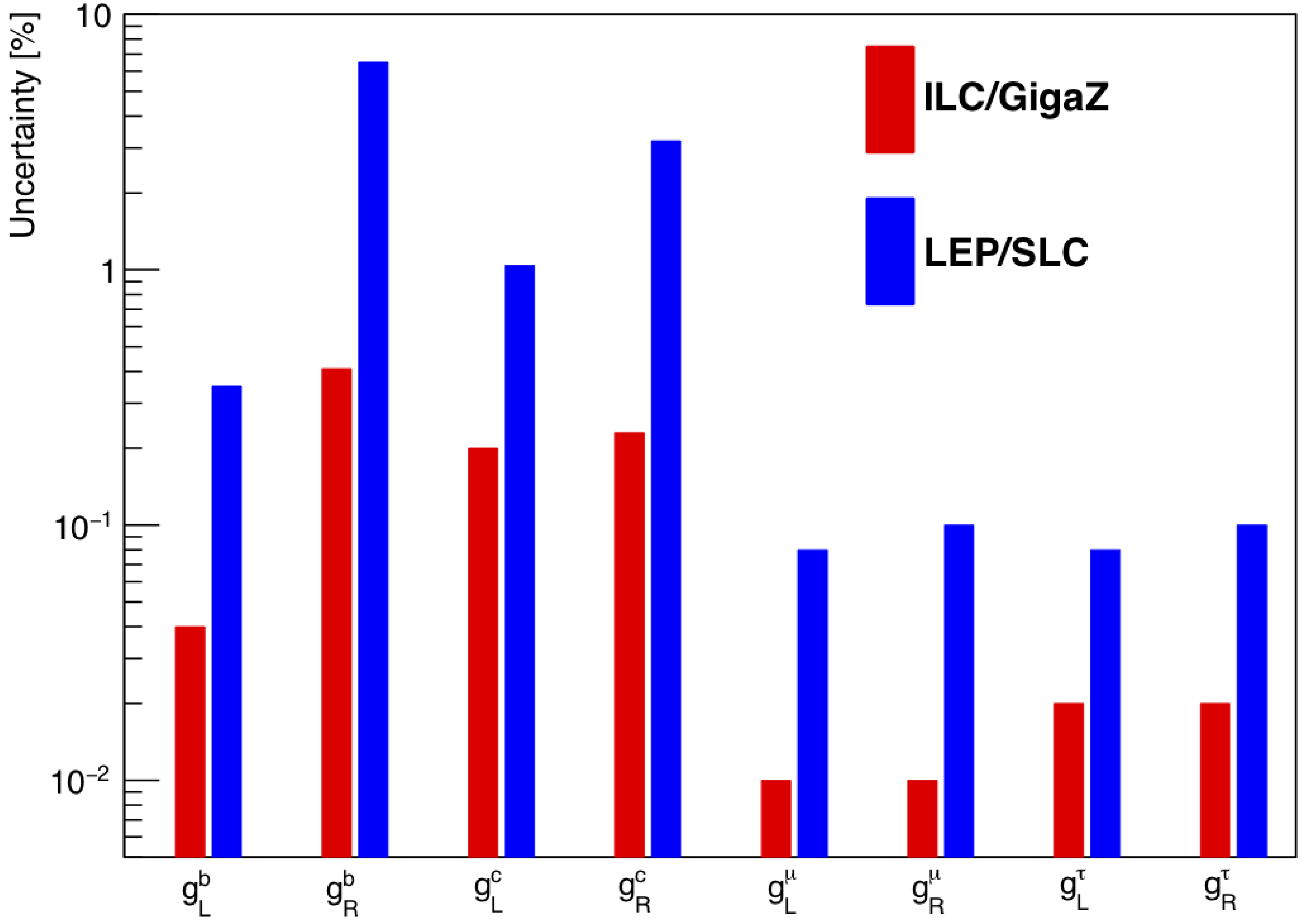
Complete test of lepton universality

- Precisions of order 0.05%

Note excellent measurement of quark asymmetries

- See above for ee->bb at 250 GeV
- *More details in talks by A. Irles and R.P. in parallel sessions*

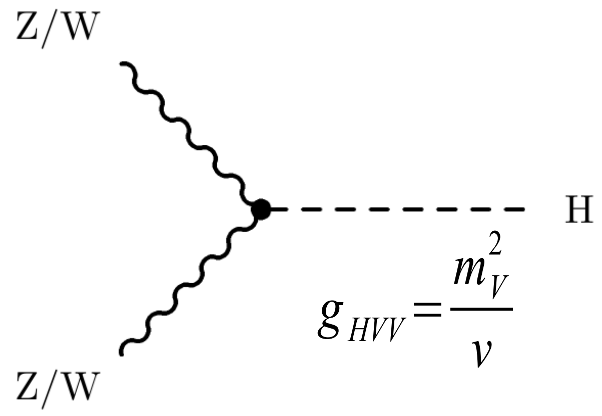
# Precision on electroweak couplings

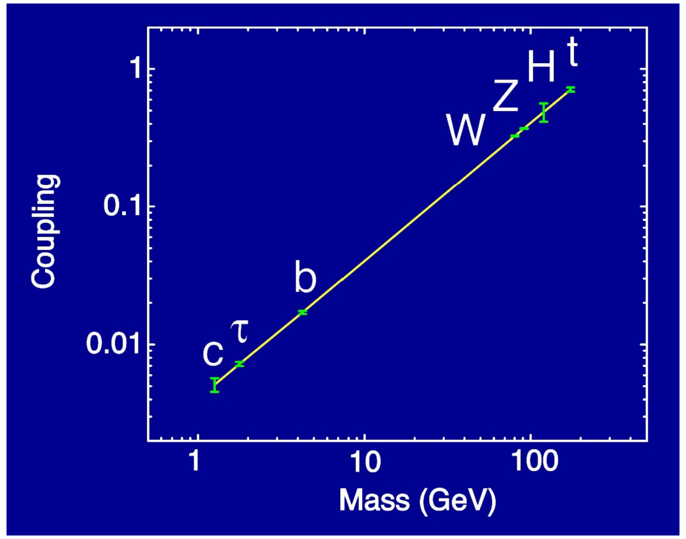


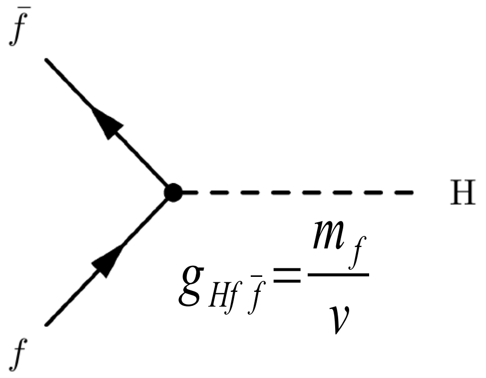
# What about the Higgs?

# 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:

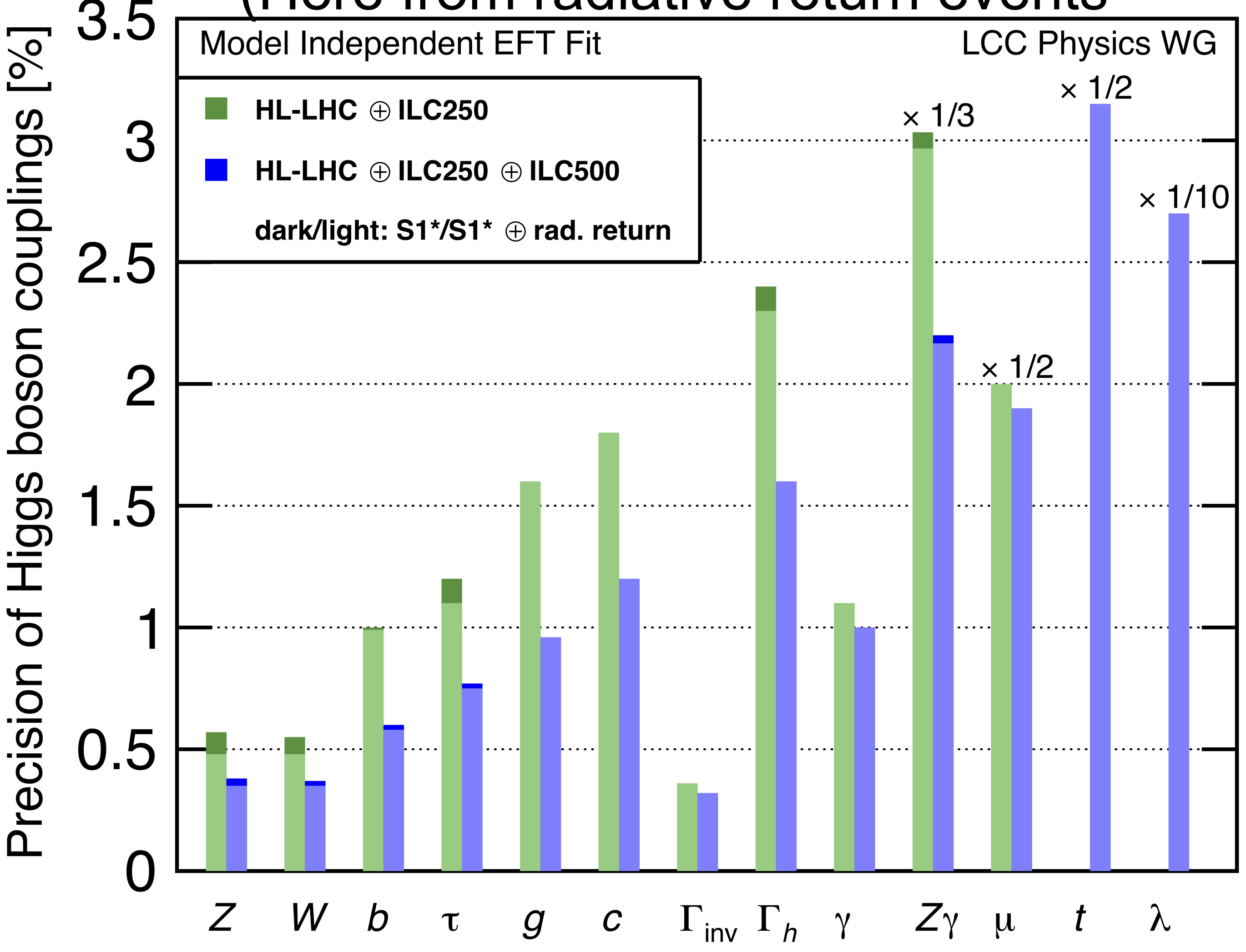
Introducing set of SU(2)xU(1) compatible operators
e.g. breaks simple relation between Higgs production and decay
Total width and Higgs to invisible as free parameters
**Receives additional input from e.g. ee->WW and EWPO**

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

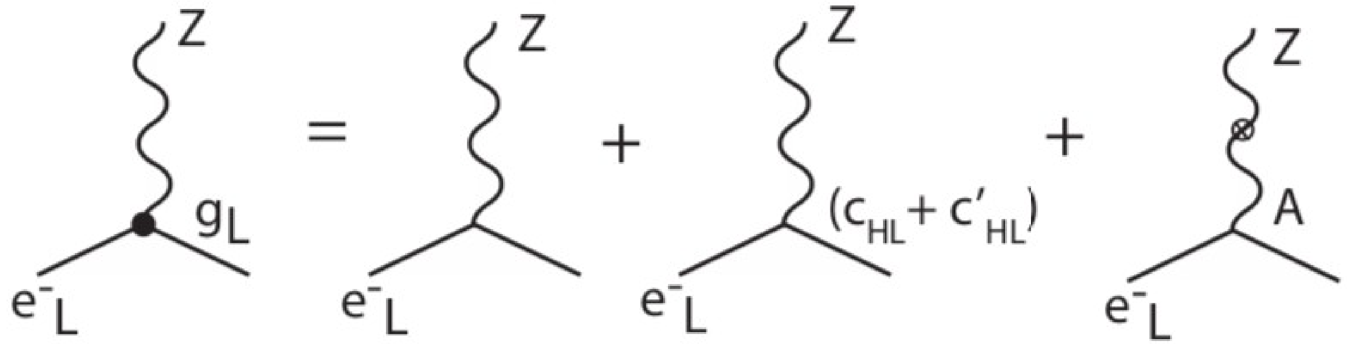
# EFT Framework and EWPO

Higgs couplings in EFT using $A_{LR}$

(Here from radiative return events

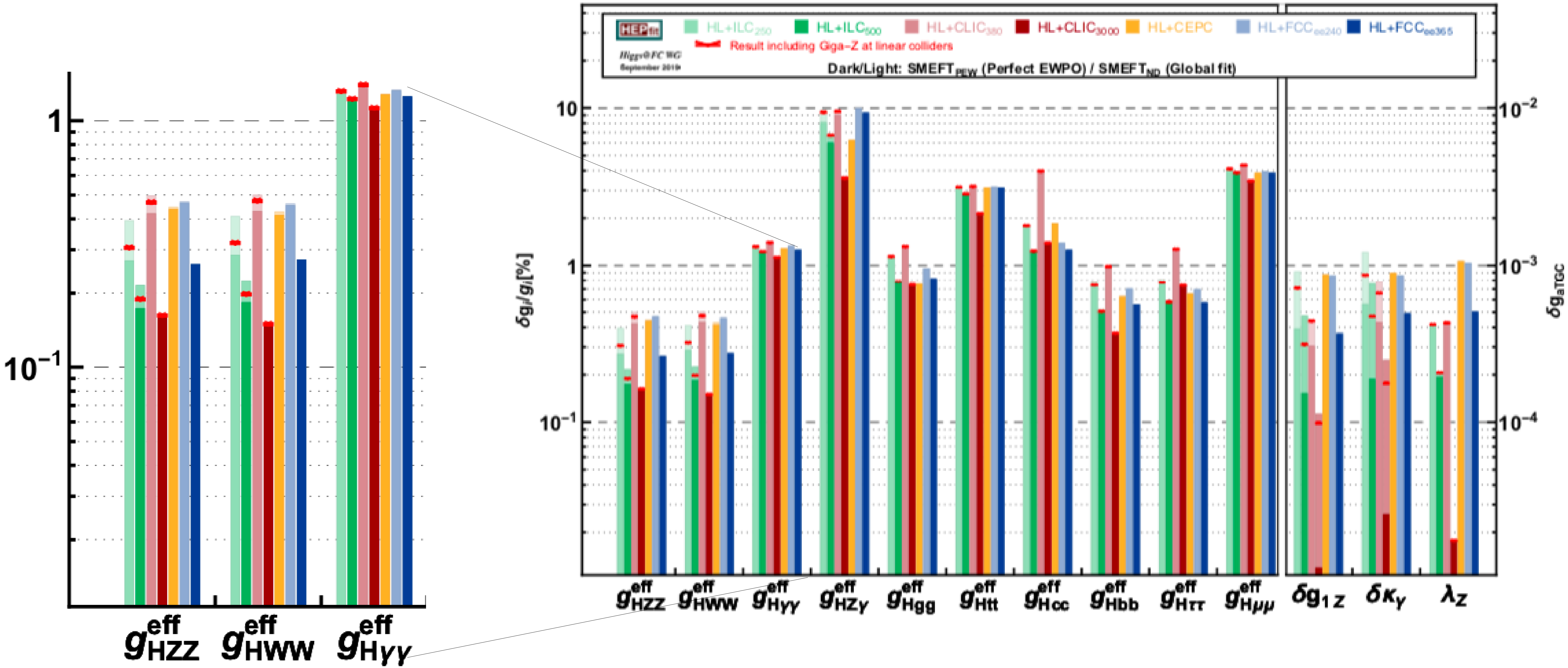



*Corrections to Zee-vertex due to additional terms in EFT*




- Model independent, clean $A_e$ from $A_{LR}$ and $\Gamma_e$ from $R_e$ to constrain EFT fit
  - (again) No assumption of Lepton Universality
- Mild but visible improvement on some Higgs couplings at 250 GeV
  - Effect stronger in fit presented in 1905.03764 (see next slide)

# Higgs couplings and EWPO in ESU fit – 1905.03764



# Summary

- GigaZ with polarised beams allows for including EWPO into ILC program
  - Polarisation compensates a great deal the lower luminosity
  - For comprehensive overviews see also hep-ph/0507011 and TESLA TDR
- “GigaZ Comeback” after Grenada
- Higher precision on relevant quantitates (e.g. elw. b couplings) needed for correct interpretation of ILC results at all energies
- Machine can be set up to run on the Z-pole
  - May put additional challenges to detectors
- Heavy quark observables show nicely the progress that can be expected compared with LEP/SLC
- LCC Physics Group input for Physics Briefing Book of European Strategy arxiv:1908.1299

# Backup

# Beam polarisation and disentangling

**With two beam polarisation configurations**

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

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

$\sigma_I$

x-section

$$A^t_{FB,I} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$

Forward backward asymmetry

$$(F_R)_I = \frac{(\sigma_{t_R})_I}{\sigma_I}$$

Fraction of right handed top quarks

⇩

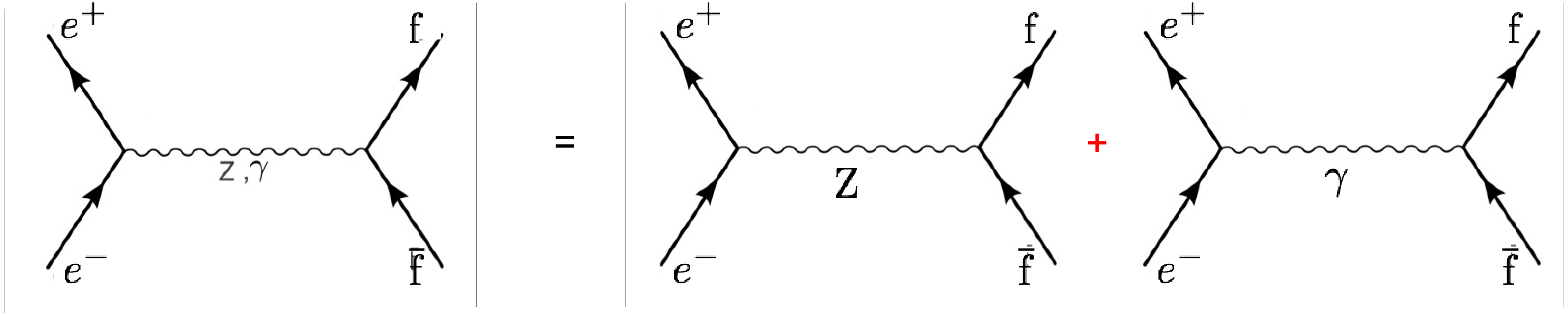
Extraction of relevant unknowns

$F^{\gamma}_{1V},\ F^{Z}_{1V},\ F^{\gamma}_{1A} = 0,\ F^{Z}_{1A}$
$F^{\gamma}_{2V},\ F^{Z}_{2V}$

or equivalently

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

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




Interference between individual amplitudes of γ and Z exchange

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

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

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

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

Differential cross section:

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

Weak interaction introduces forward backward asymmetry

=> Asymmetry is intrinsic to electroweak processes!!!

# Beam polarisation – Uncertainty and (positron) polarisation

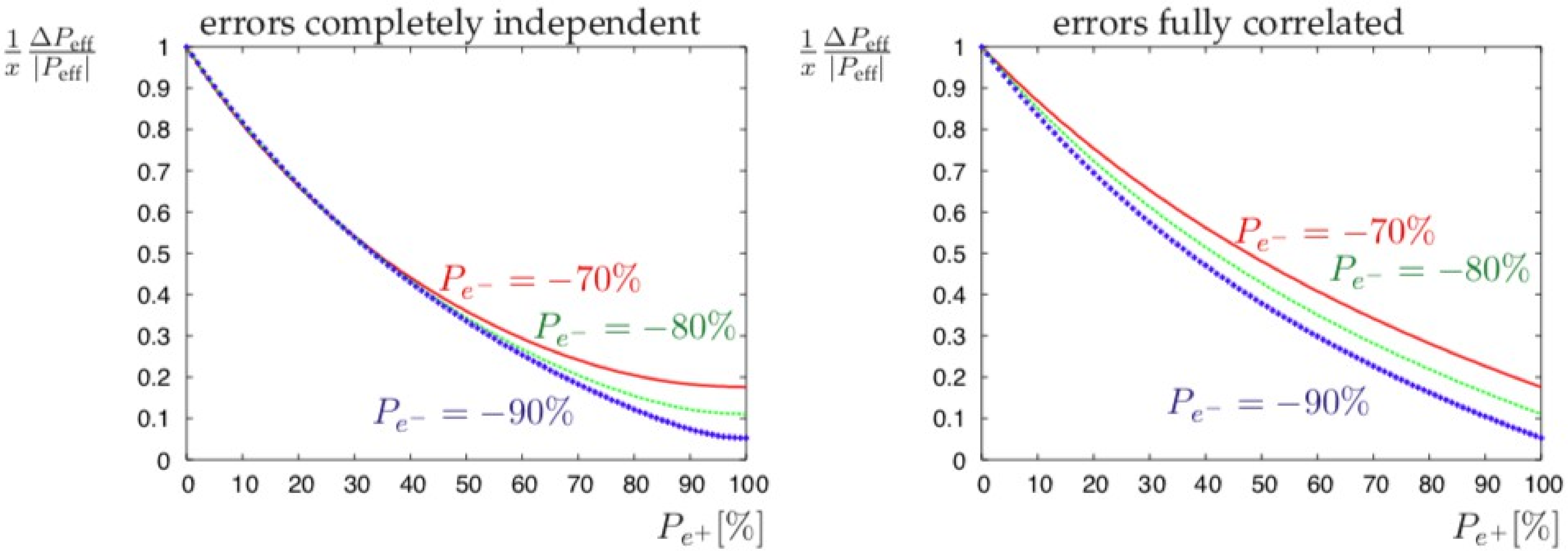


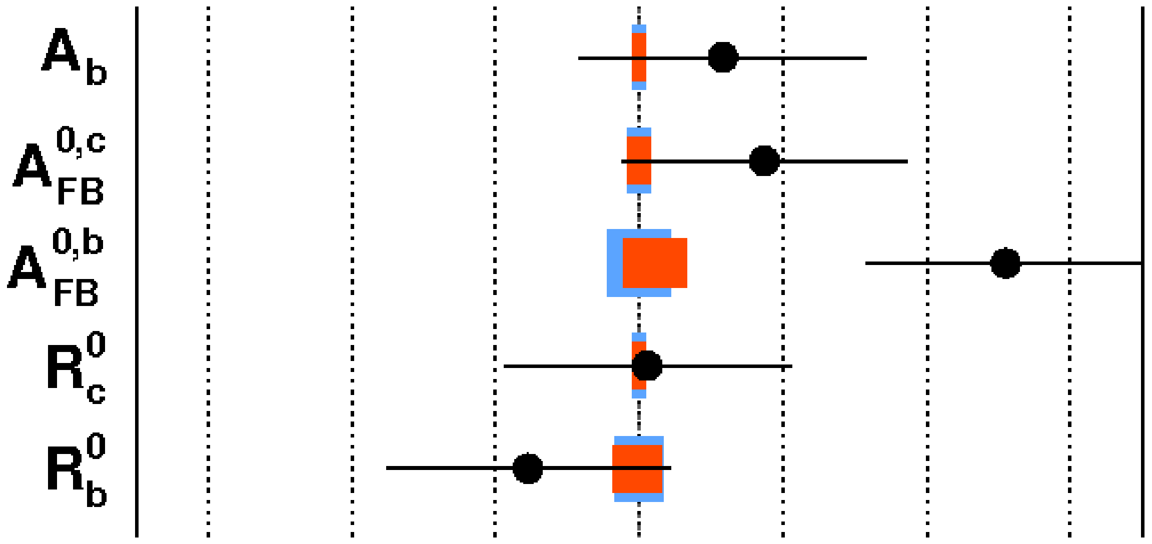

Figure 1.6: Relative uncertainty on the effective polarization, $\Delta P_{\rm eff}/|P_{\rm eff}| \sim \Delta A_{\rm LR}/A_{\rm LR}$, normalized to the relative polarimeter precision $x = \Delta P_{e^-}/P_{e^-} = \Delta P_{e^+}/P_{e^+}$ for independent and correlated errors on $P_{e^-}$ and $P_{e^+}$,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

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

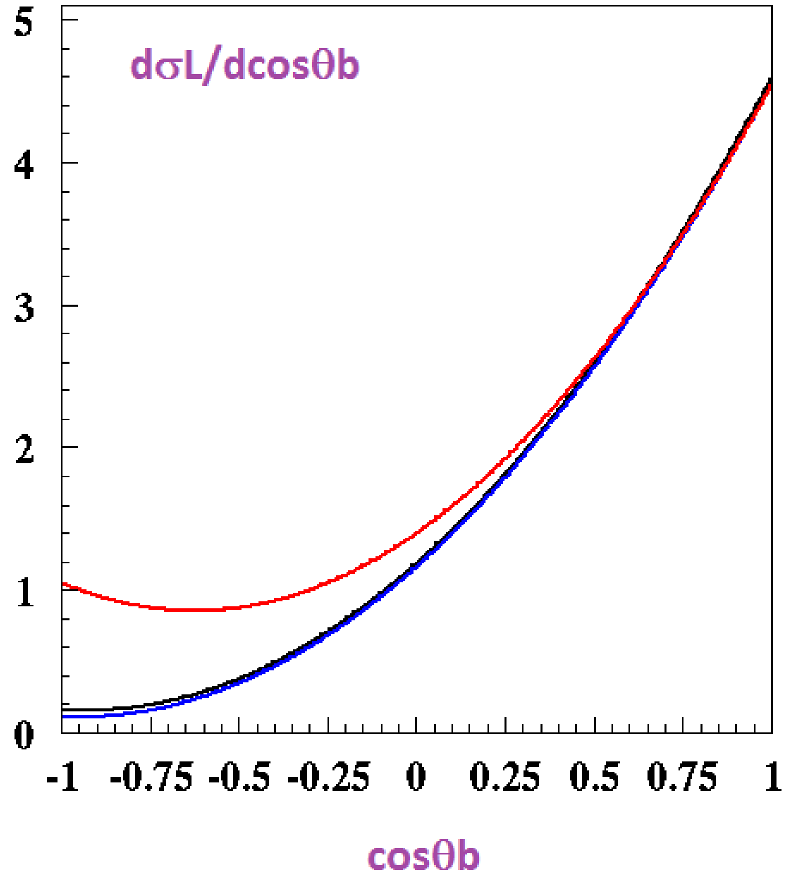
*From hep-ph/0507011*

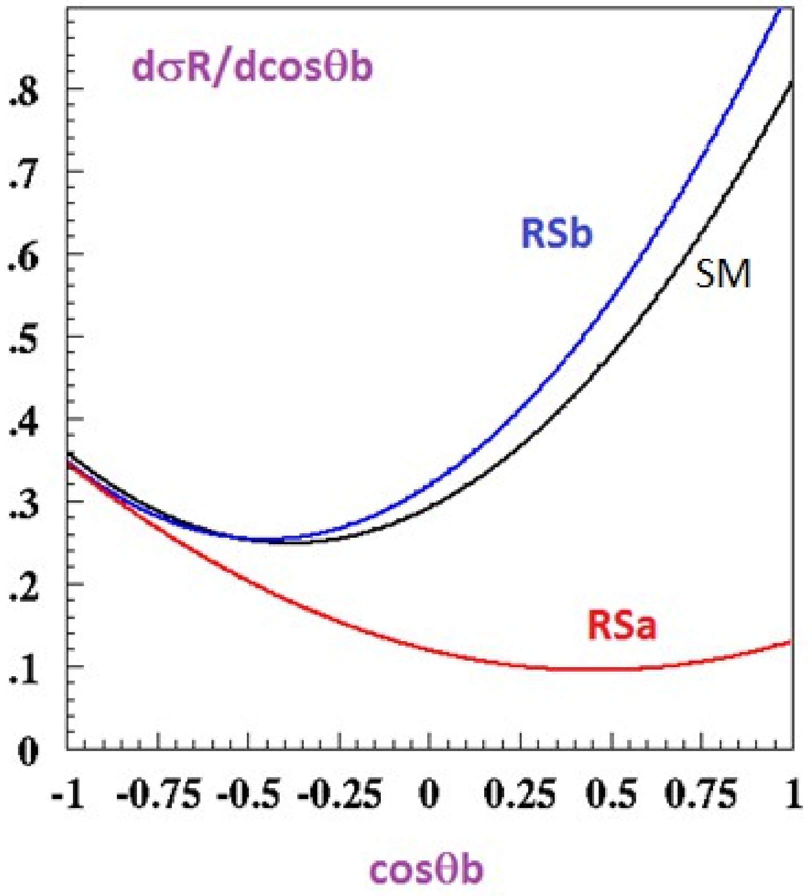
# LEP Anomaly on $A_{FB}^b$

~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