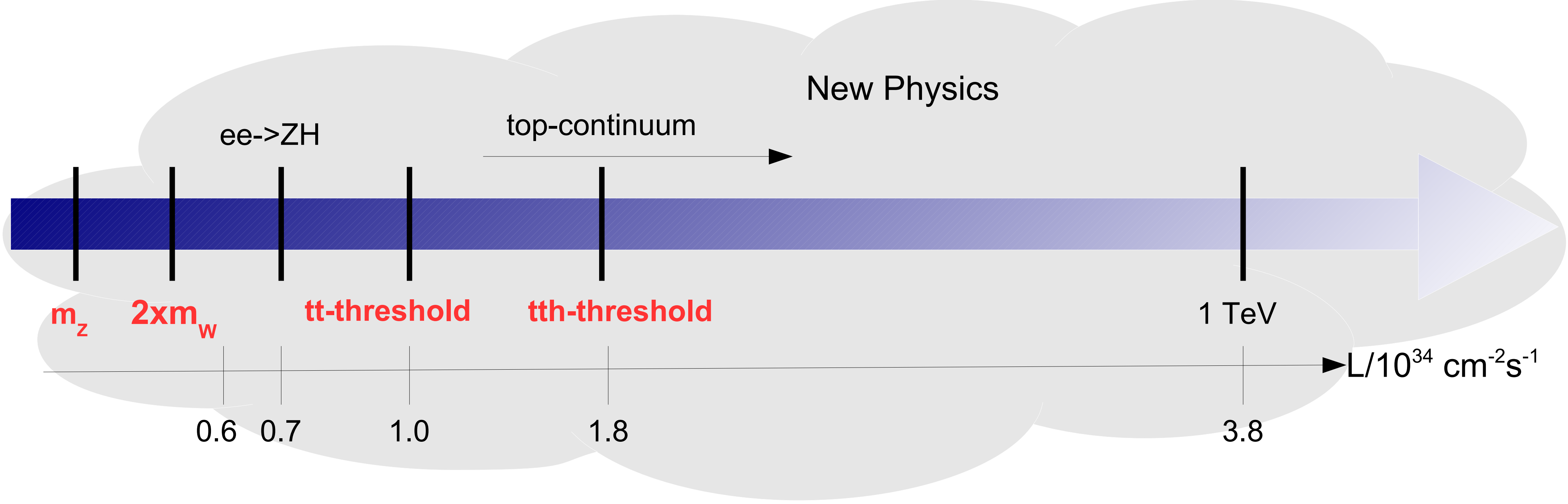
ILC at the Z-Pole - GigaZ

Roman Pöschl

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

ILD Main Meeting – 2/7/19

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

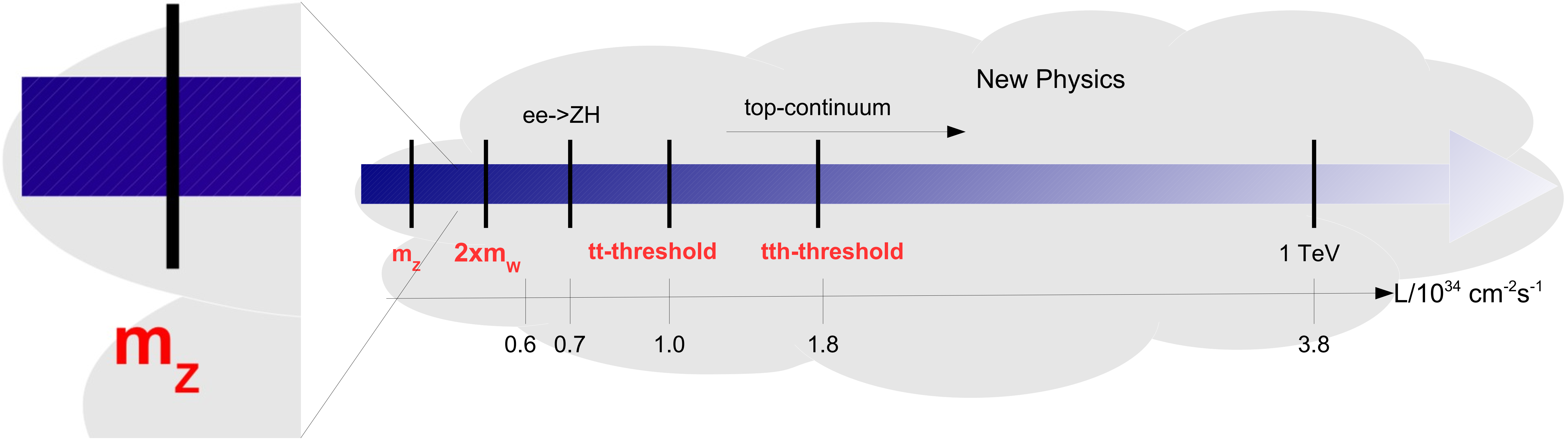
Machine settings can be “tailored” for specific processes

- 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

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)

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%)

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

$$M_W,\ \Gamma_W$$

0.02-O(1%)

$$m_t$$

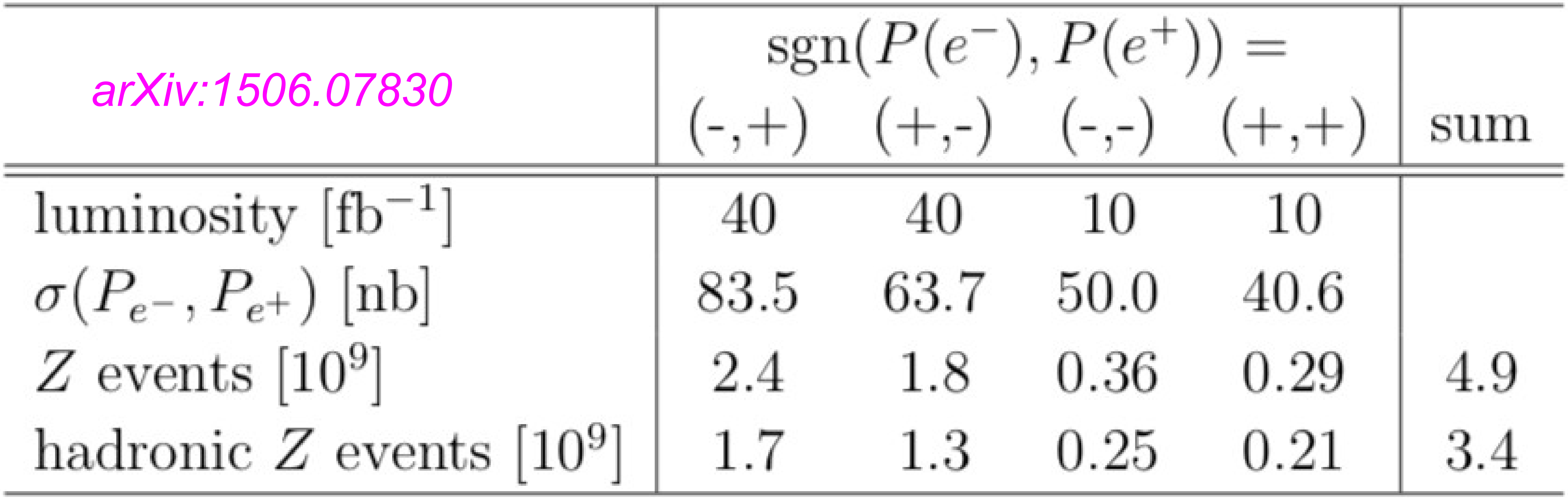
0.4%

$$M_H$$

0.2%

GigaZ – Basic facts

arXiv:1506.07830



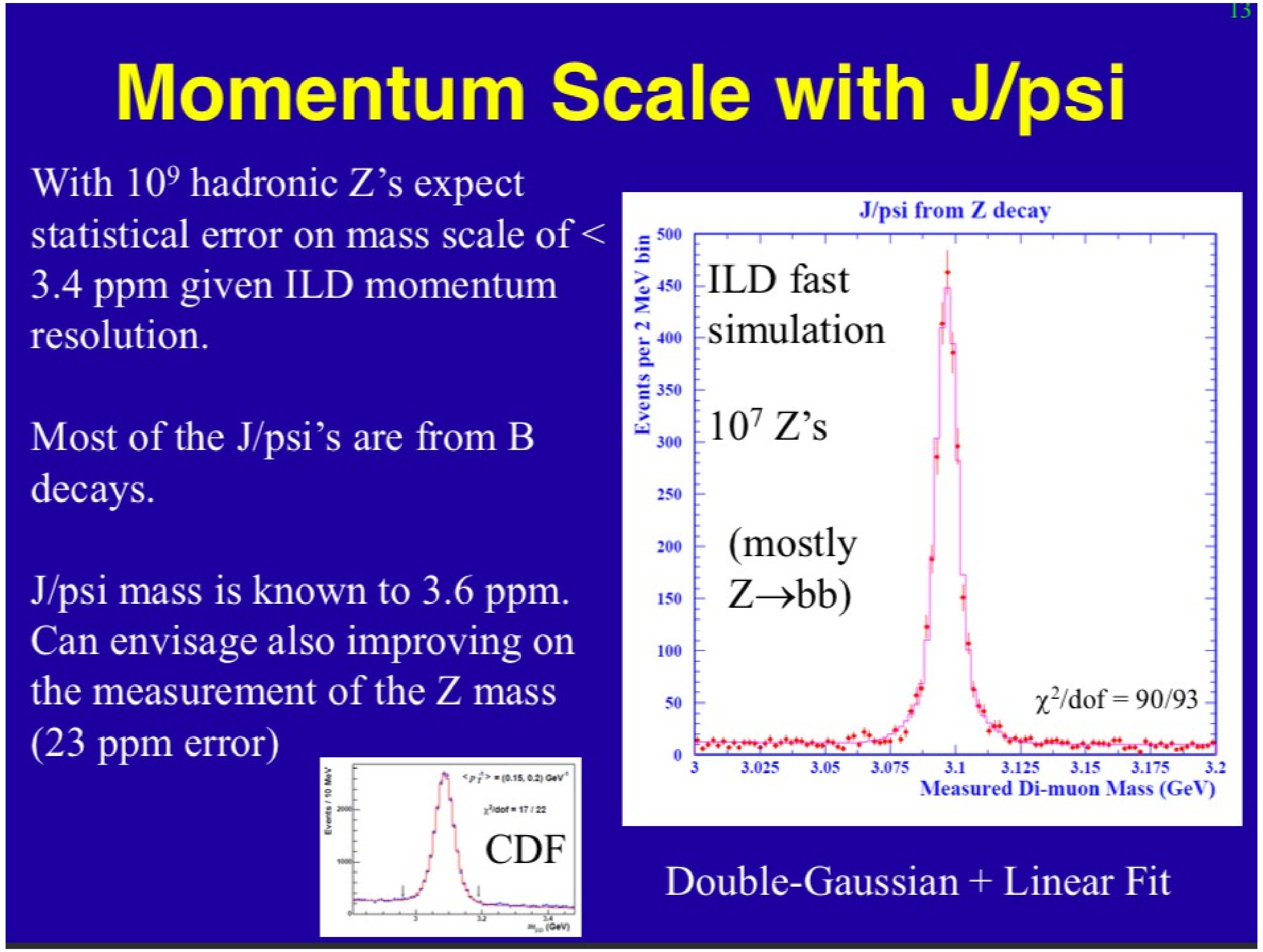
	$\text{sgn}(P(e^-), P(e^+)) =$				
	(-,+)	(+,-)	(-,-)	(+,+)	sum
luminosity $[\text{fb}^{-1}]$	40	40	10	10	
$\sigma(P_{e^-}, P_{e^+})$ [nb]	83.5	63.7	50.0	40.6	
Z events $[10^9]$	2.4	1.8	0.36	0.29	4.9
hadronic Z events $[10^9]$	1.7	1.3	0.25	0.21	3.4

=230xLEP, 8500xSLC

- Accelerator scenario 3.7Hz@M_Z/2 + 3.7 Hz@125 GeV to produce positrons
- With 2625 bunches an instantaneous luminosity of $5x10^{33}$ cm^{-2}s-1 => 100 fb^{-1} in 1.3 years after lumi upgrade
- More possible by improved damping rings and BDS system

GigaZ and Z Mass

- Main error on Z mass from unknown beam momentum
- Don't expect improvement on Z mass from ILC Beam spectrometers
- Reminder “Wilson method”



Momentum Scale with J/psi

With 10^9 hadronic Z’s expect statistical error on mass scale of < 3.4 ppm given ILD momentum resolution.

Most of the J/psi’s are from B decays.

J/psi mass is known to 3.6 ppm. Can envisage also improving on the measurement of the Z mass (23 ppm error)

Double-Gaussian + Linear Fit

=> ΔM_Z = 0.5 MeV

2.1 MeV currently

$\Delta\Gamma_Z$ = 0.33 MeV

2.3 MeV currently

Graham, Jenny please comment

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 *τ*

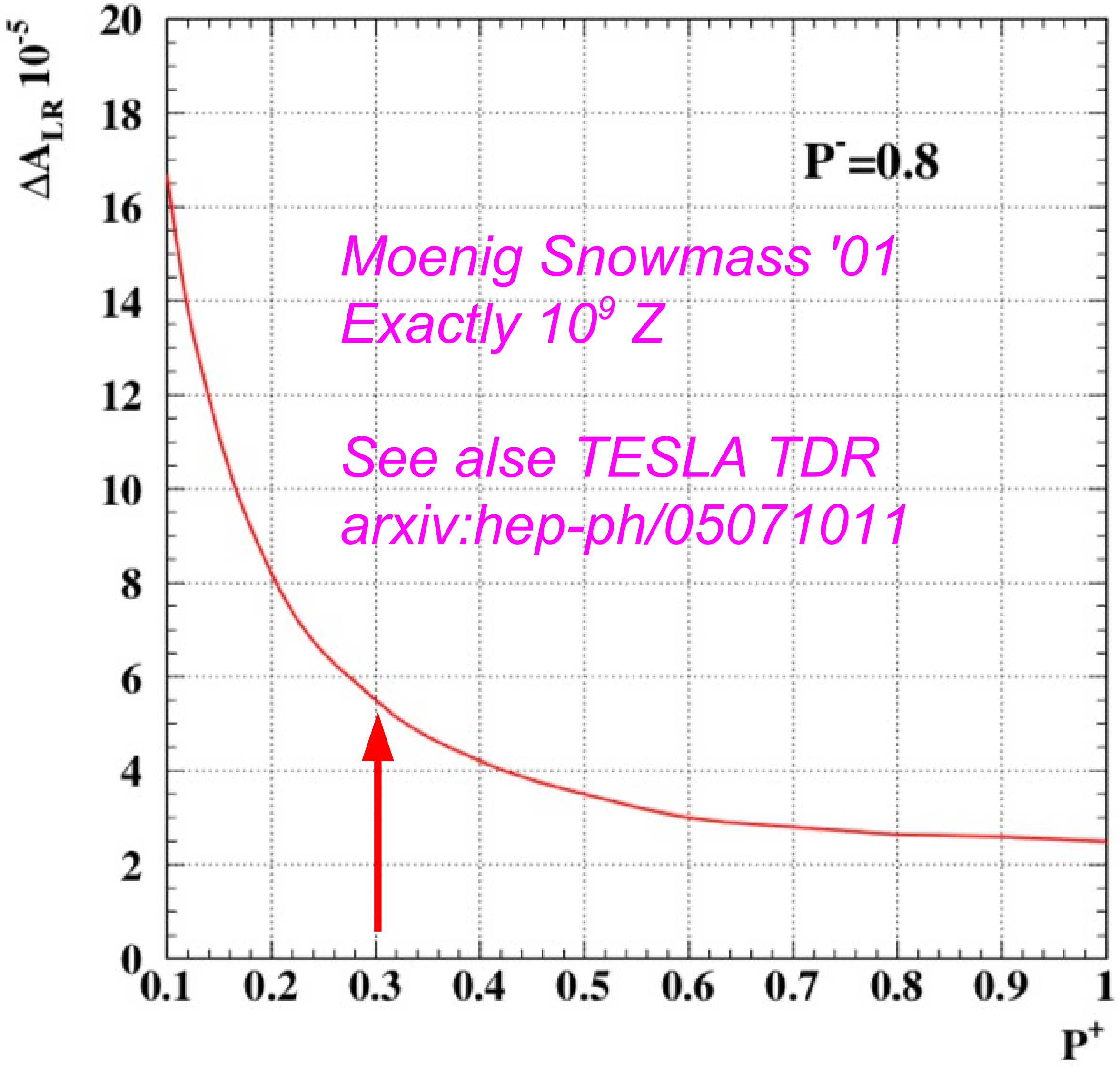
$$A^{pol}_{FB} = \frac{(\sigma_r - \sigma_l)_F - (\sigma_r - \sigma_l)_B}{(\sigma_r + \sigma_l)_F + (\sigma_r + \sigma_l)_B} = -\frac{3}{4}\mathcal{A}_e$$

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



Moenig Snowmass '01
Exactly 10^9 Z

See alse TESLA TDR
arxiv:hep-ph/05071011

Blondel scheme independent of polarimeter precision

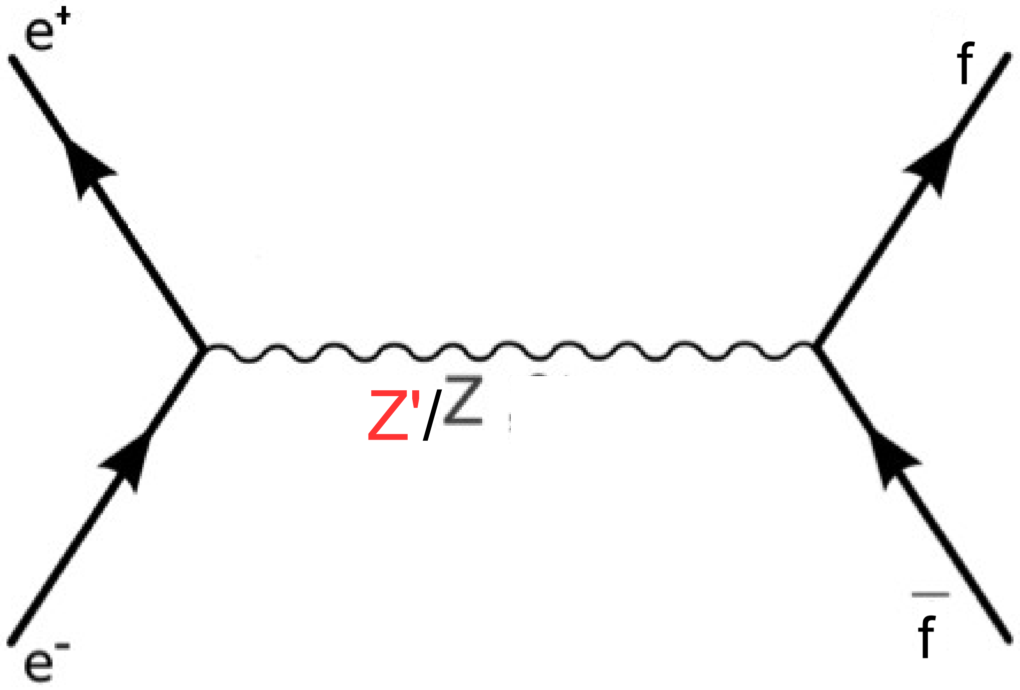
- Assumes perfect spin flip for polarised beams
- Residuals must be monitored by polarimeter
- Residual uncertainty of $\Delta A_{LR} = 0.5 \text{x} 10^{-4}$ seems possible
- The more positron polarisation the better (see backup)
- Don't forget energy dependency ($dALR/d\sqrt{s} \sim 2\text{x}10^{-5}/MeV$)

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

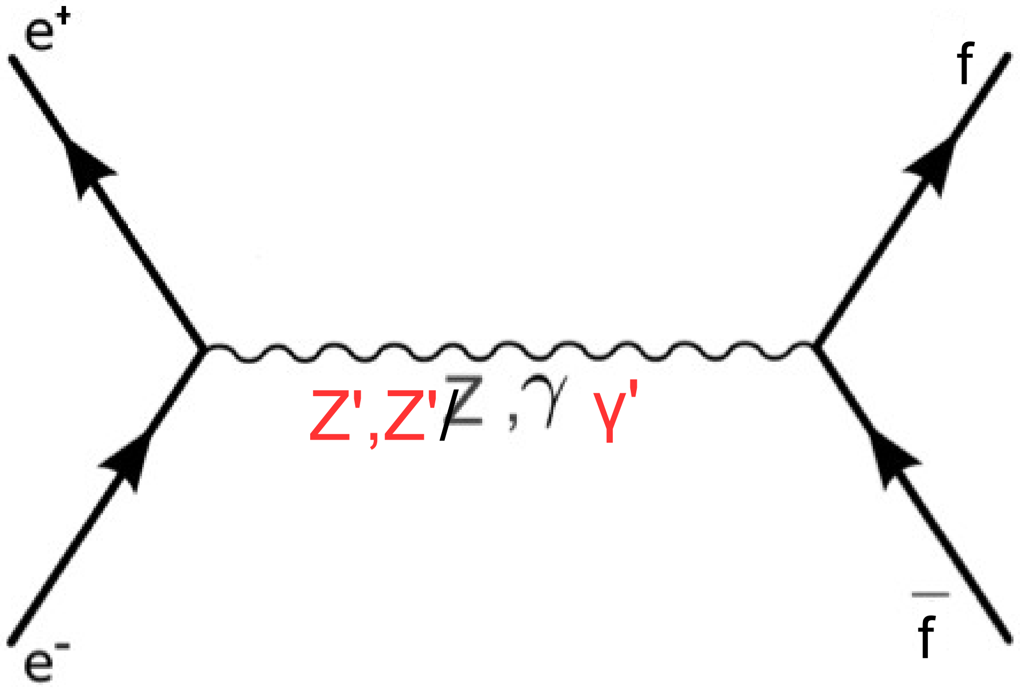
=> $$\boxed{\delta \sin^2\theta^{\ell}_{\text{eff.}} \sim 1.3 \cdot 10^{-5}}$$

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

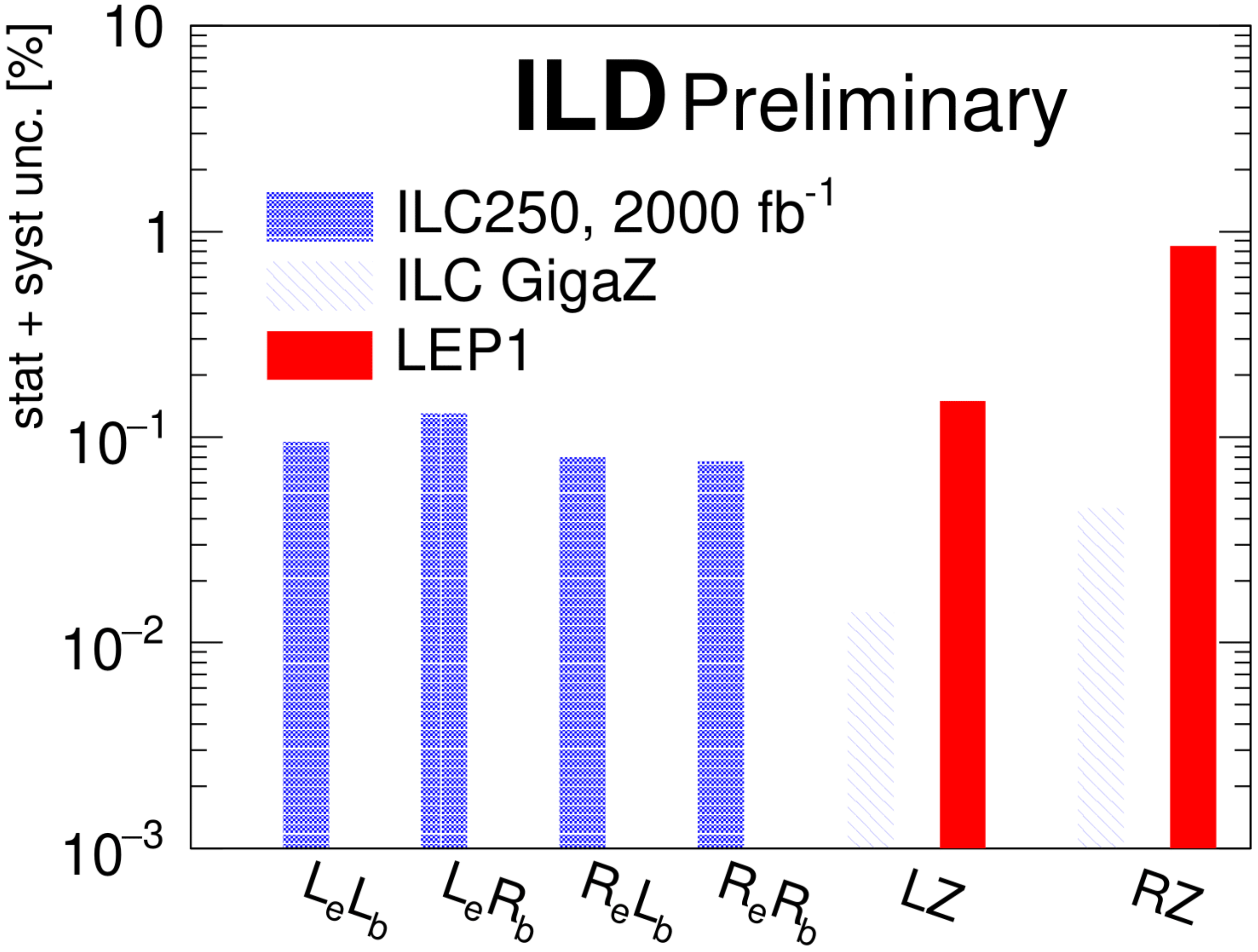
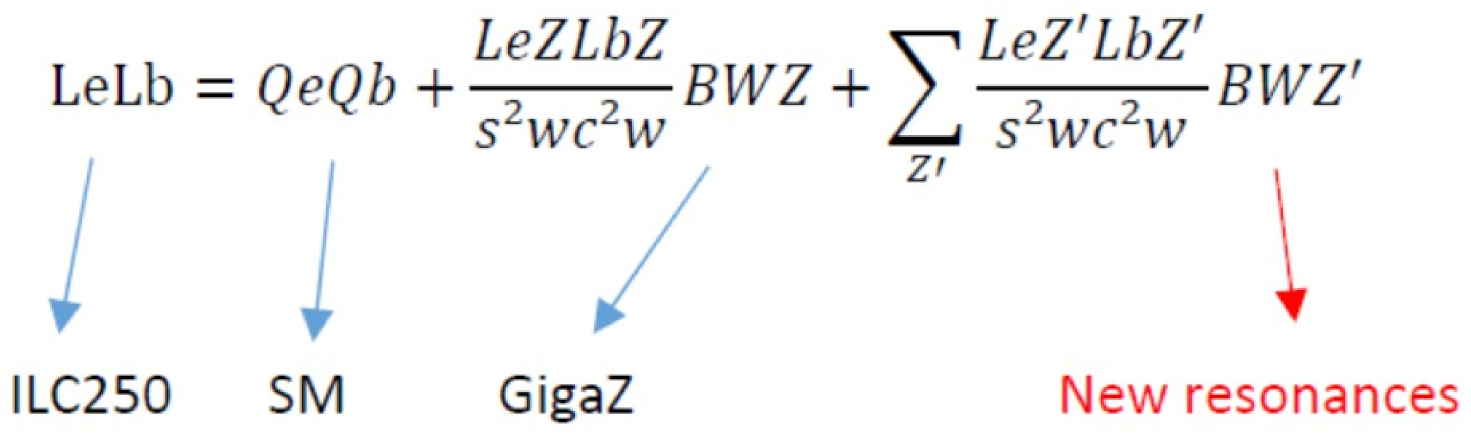


Figure: A. Irles



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

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

With about 11% on g_R LEP result would provide insufficient input tto precision measurements at higher energies

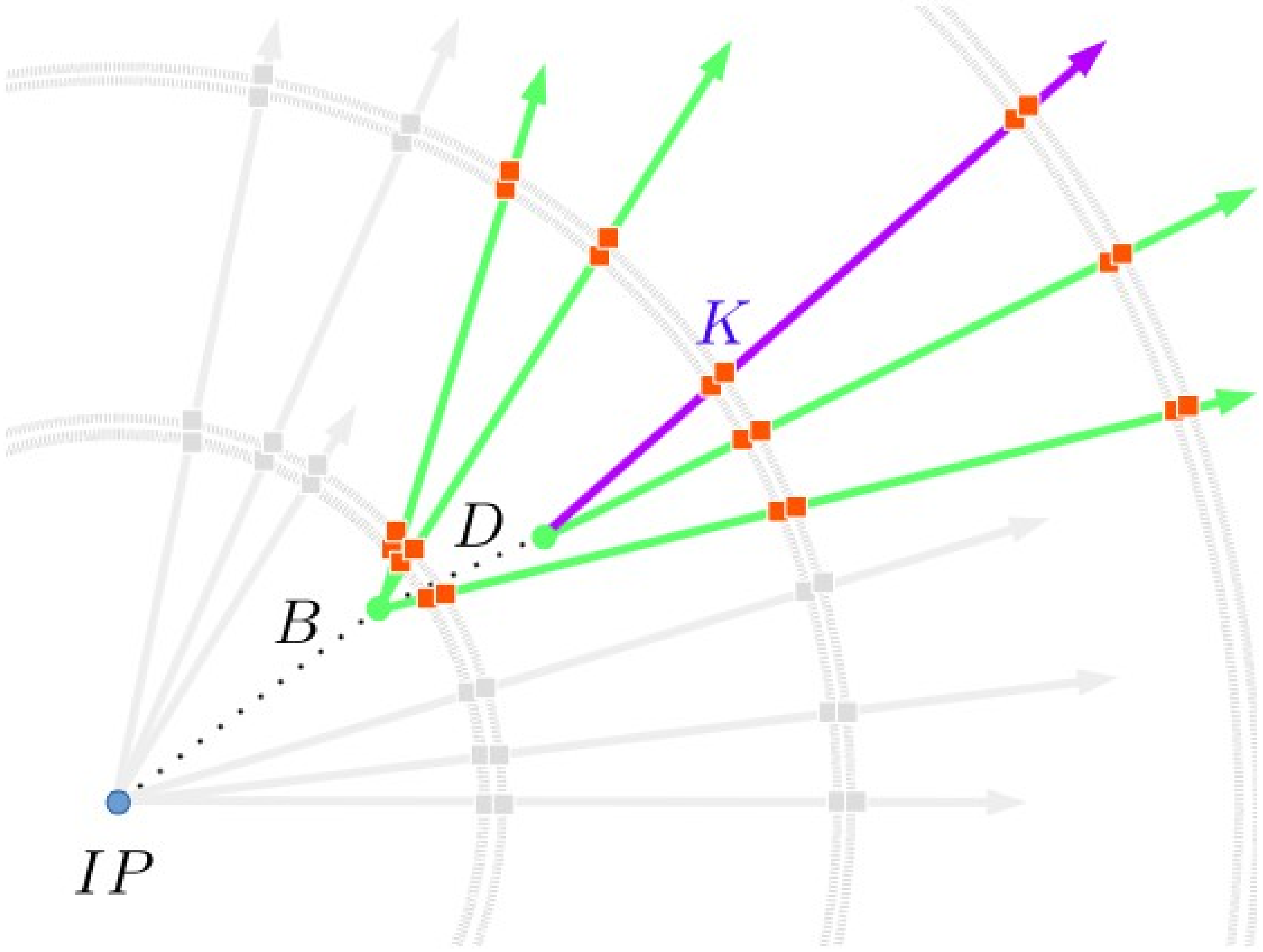
Heavy quark measurements @ GigaZ

- 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 Γ_{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> Γ_{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

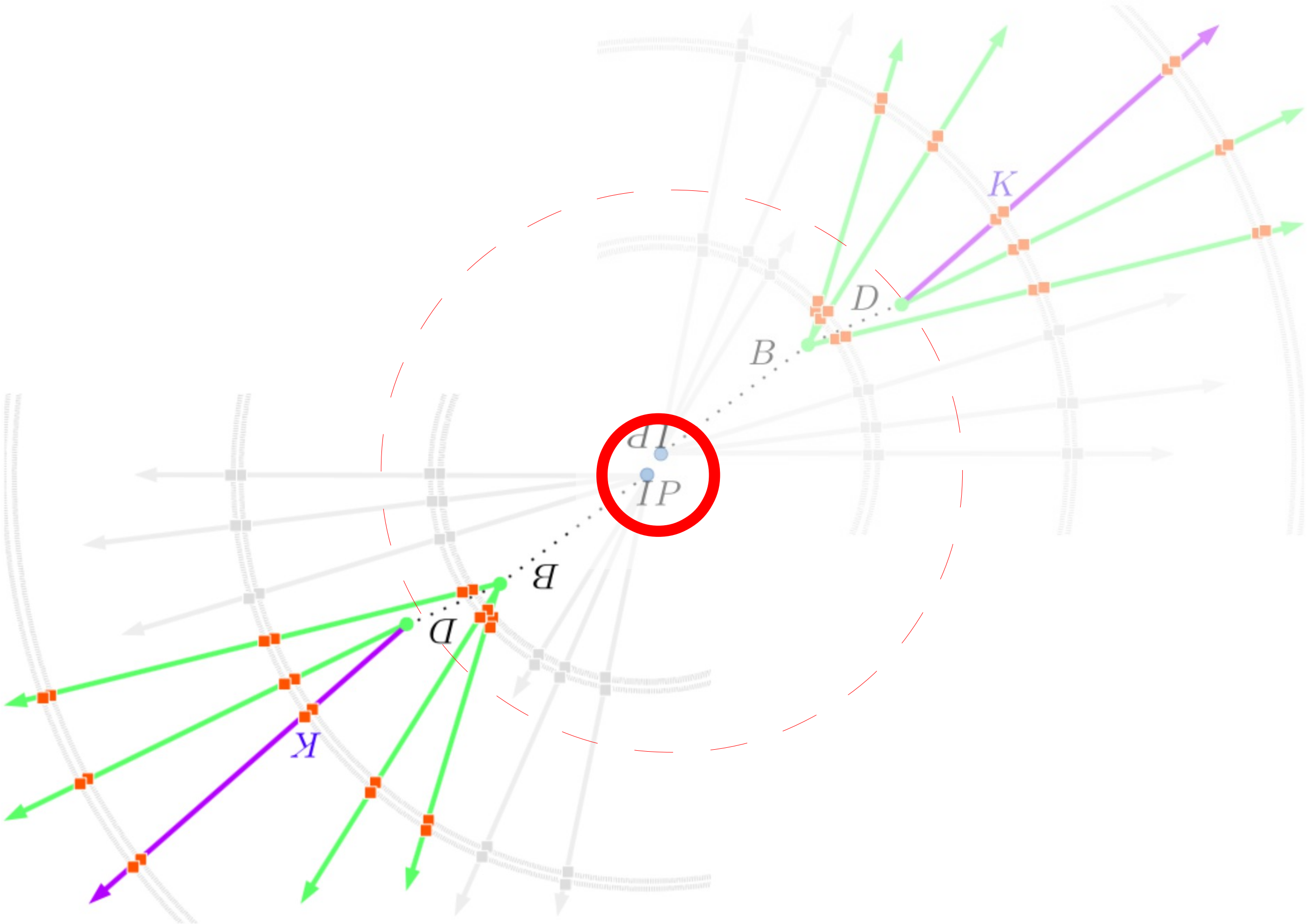
PhD thesis: S. Bilokin
A. Irles

Why this luxury?

Beam spot size

LEP >> **SLC** >> **ILC**

Double tagging



Important systematic error is knowledge of tagging efficiency ε_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:

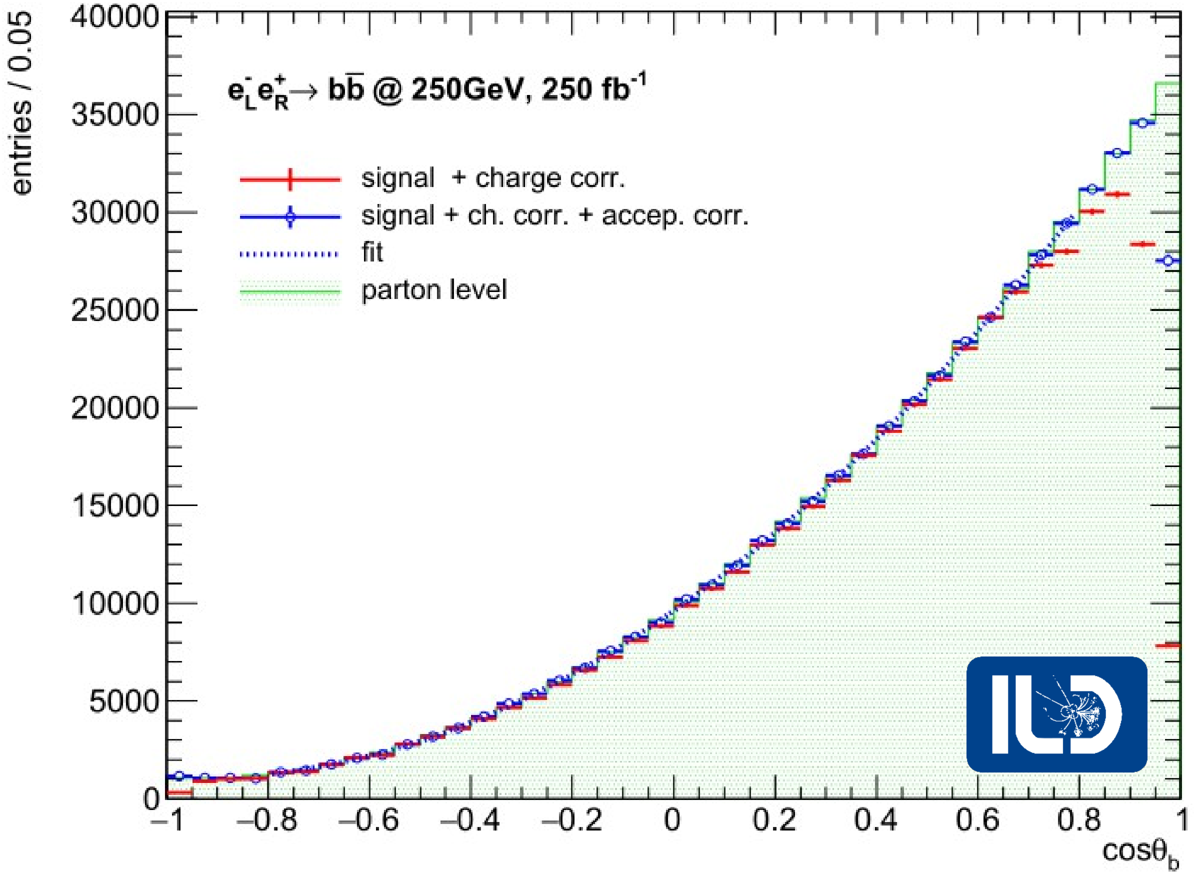
LEP (large beam spot): C_q-1 ≈ 3% => $\Delta R_b \approx 0.2\%$

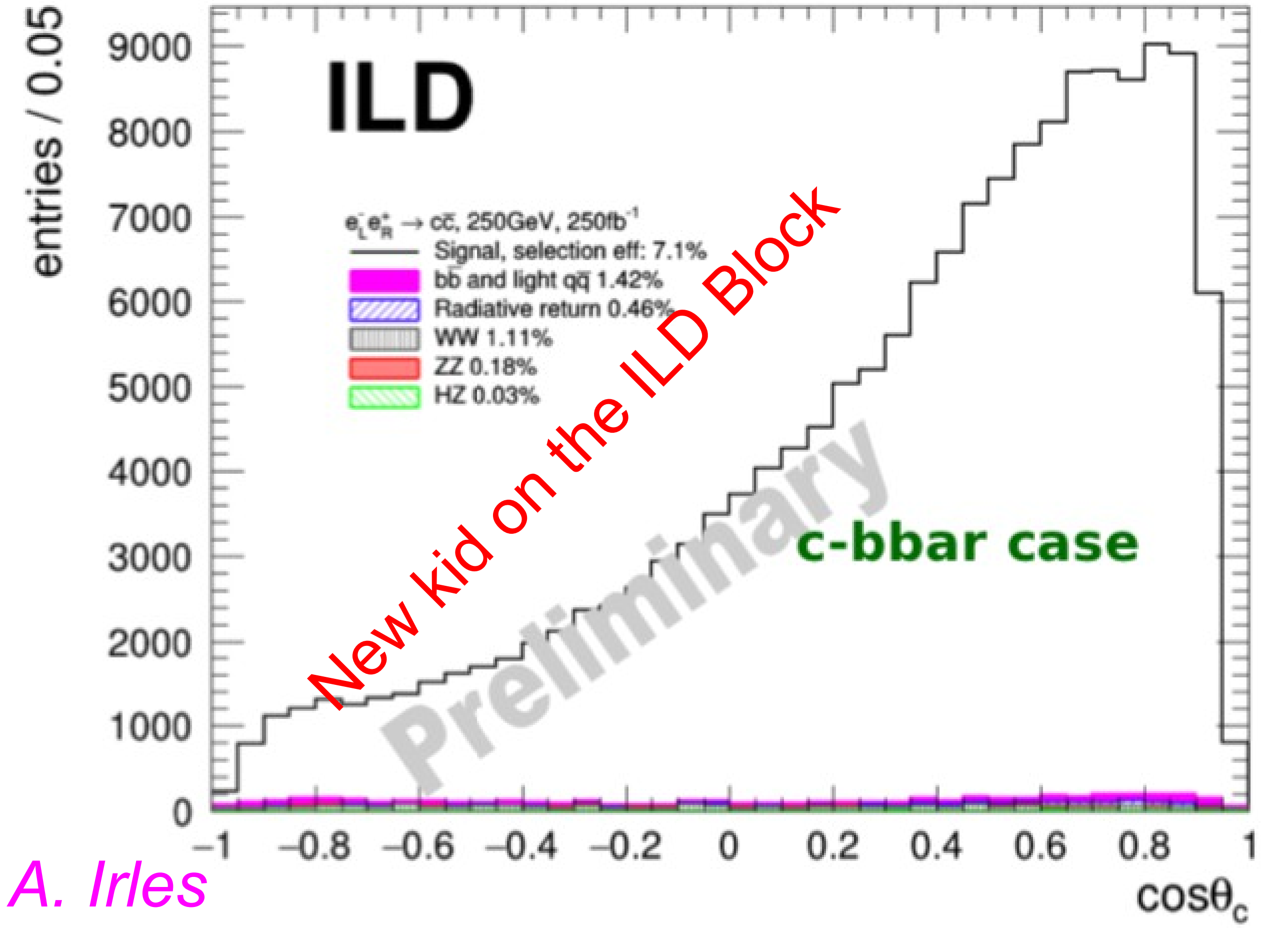
SLC (smaller beam spot): C_q -1 < 1% => $\Delta R_b \approx 0.07\%$

ILC (tiny beam spot): Expect C_q -1 = 0 => $\Delta R_b \approx 0$
to be verified however

Our “basis”

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





New kid on the ILD Block

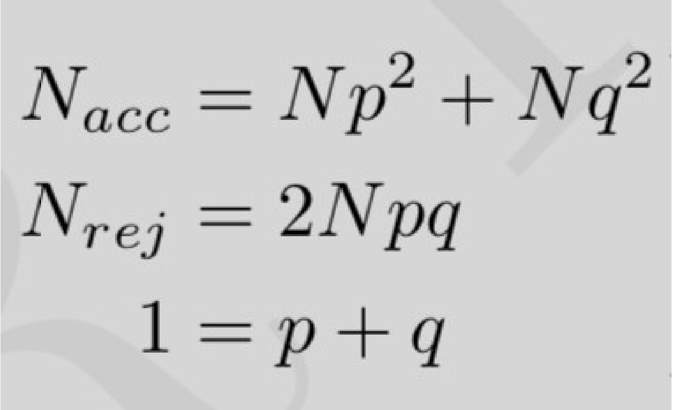
c-bbar case

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 (--, ++) => $N_{rej..}$

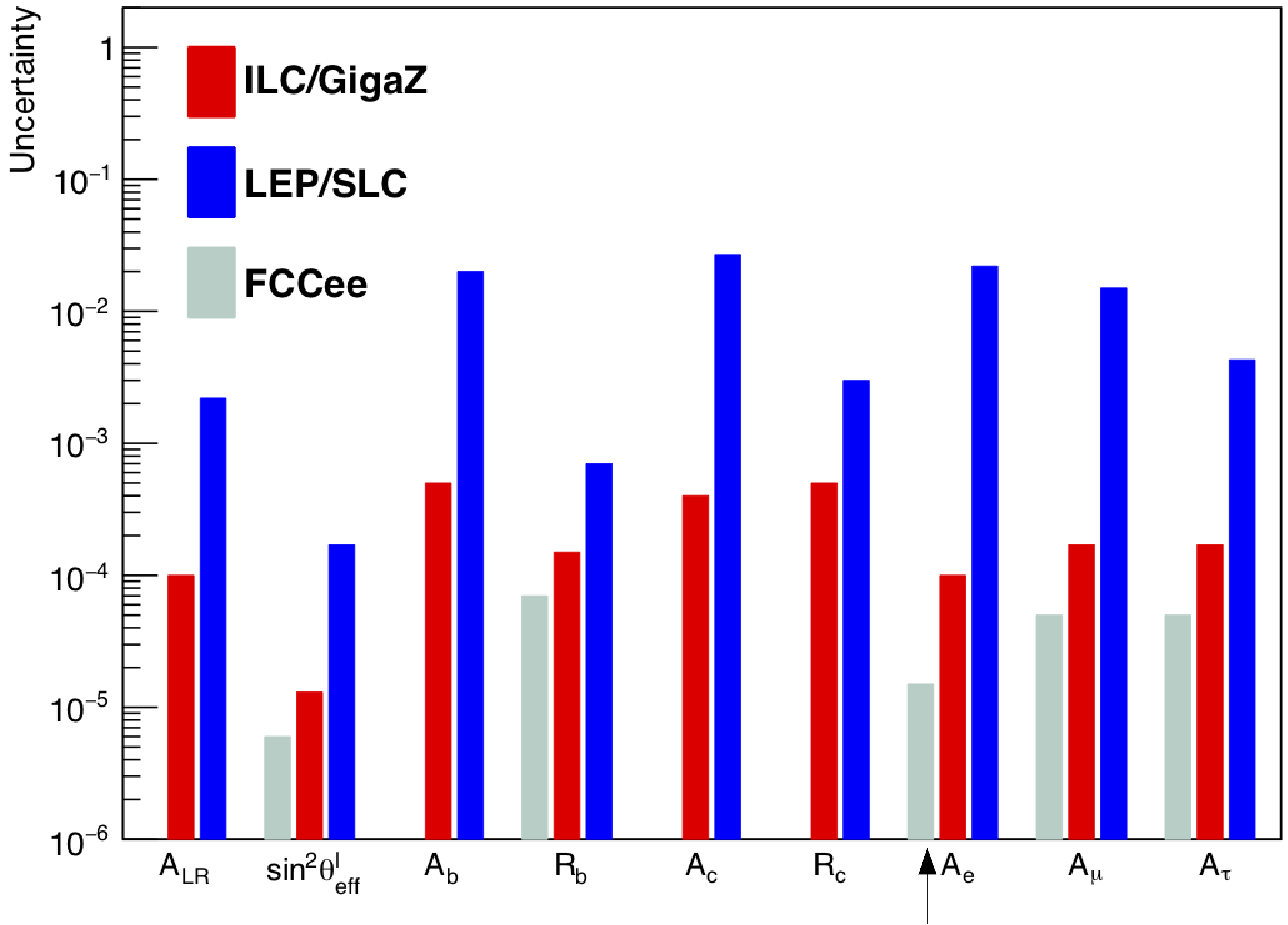


$$N_{acc} = Np^2 + Nq^2$$
$$N_{rej} = 2Npq$$
$$1 = p + q$$

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!

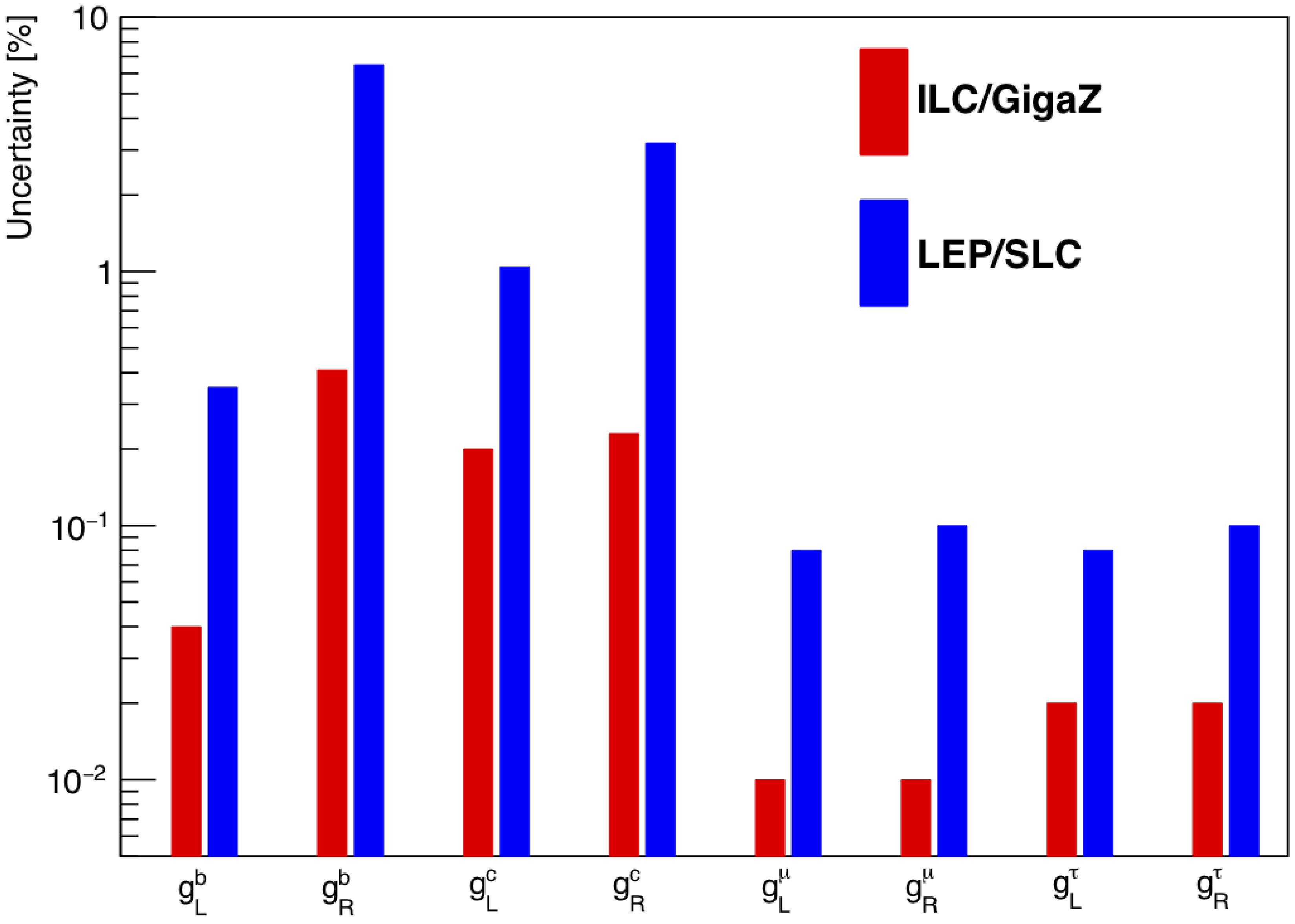
Precision on relevant observables



Attention stat. eror

- GigaZ improves LEP SLD program by an order of magnitude, sometimes more
- At least competitive to FCCee albeit ~1000 times less lumi
- Important input to program at higher ILC energies

Precision on electroweak couplings



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 prepares input for Physics Briefing Book of European Strategy

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 $\quad$ Forward backward asymmetry $\quad$ Fraction of right handed top quarks

⇩

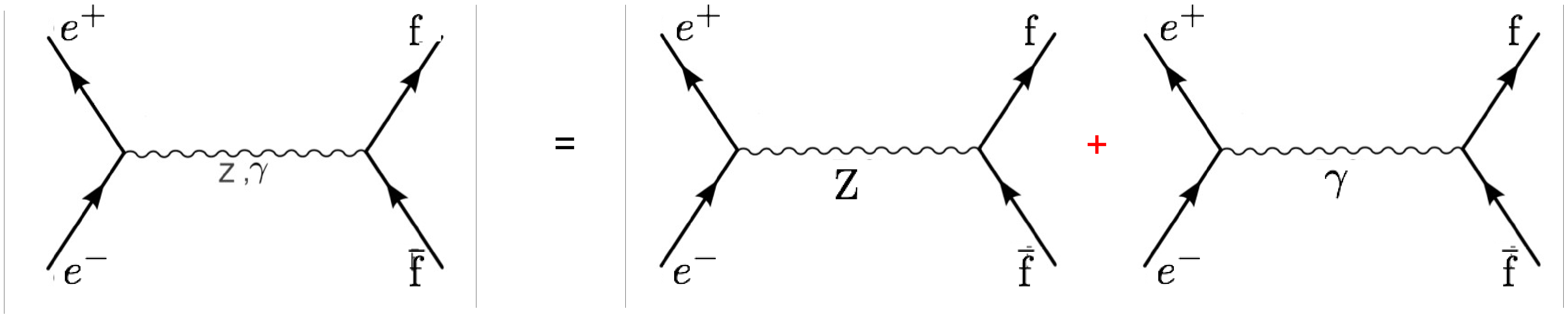
Extraction of relevant unknowns

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

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

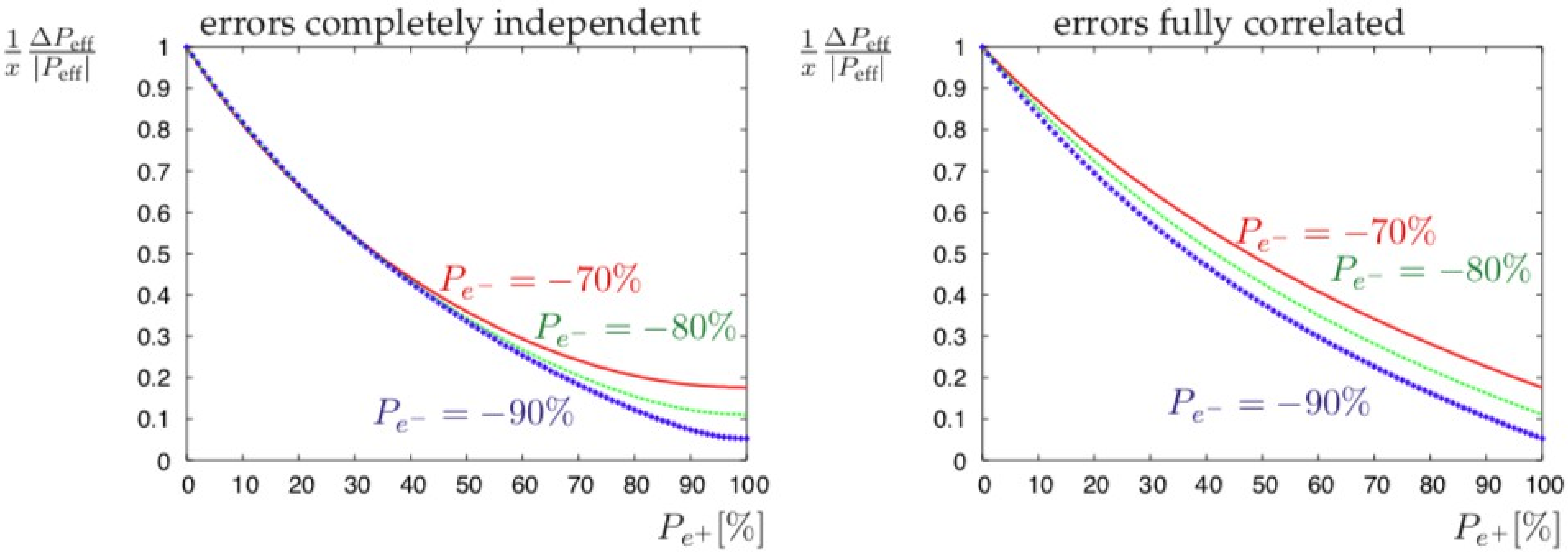


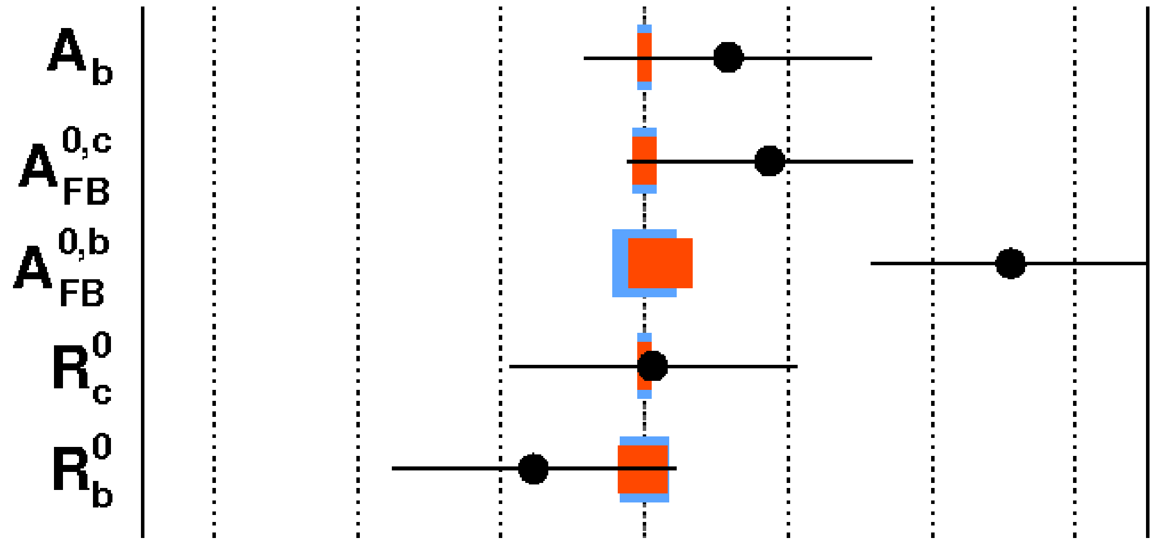
Figure 1.6: Relative uncertainty on the effective polarization, $\Delta P_{\text{eff}}/|P_{\text{eff}}| \sim \Delta A_{\text{LR}}/A_{\text{LR}}$, normalized to the relative polarimeter precision $x = \Delta P_{e^-}/P_{e^-} = \Delta P_{e^+}/P_{e^+}$ for independent and correlated errors on P_{e^-} and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

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

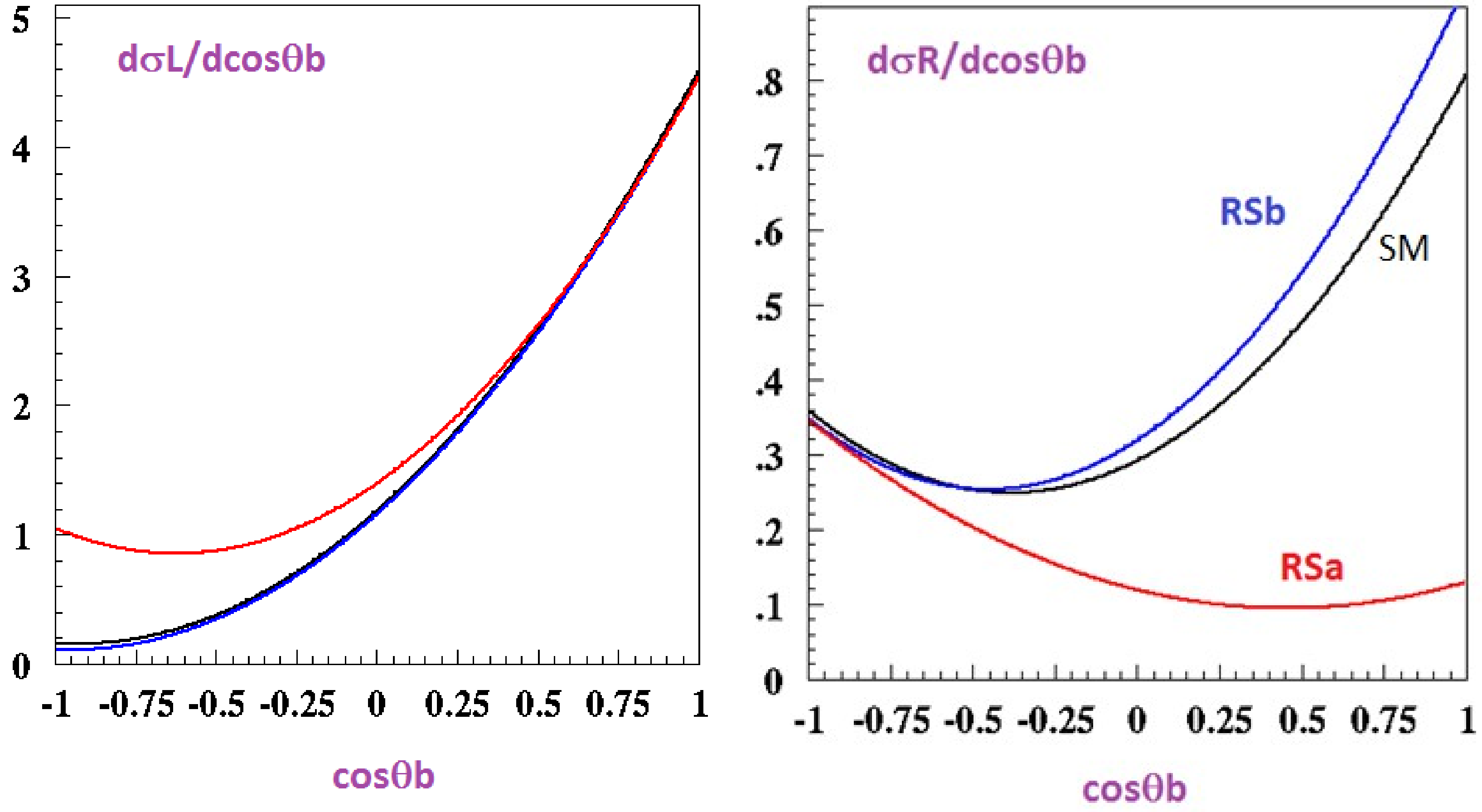
From hep-ph/0507011

LEP Anomaly on A^b_{FB}

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