Heavy quark studies at linear collider other than top – Quick review and outlook

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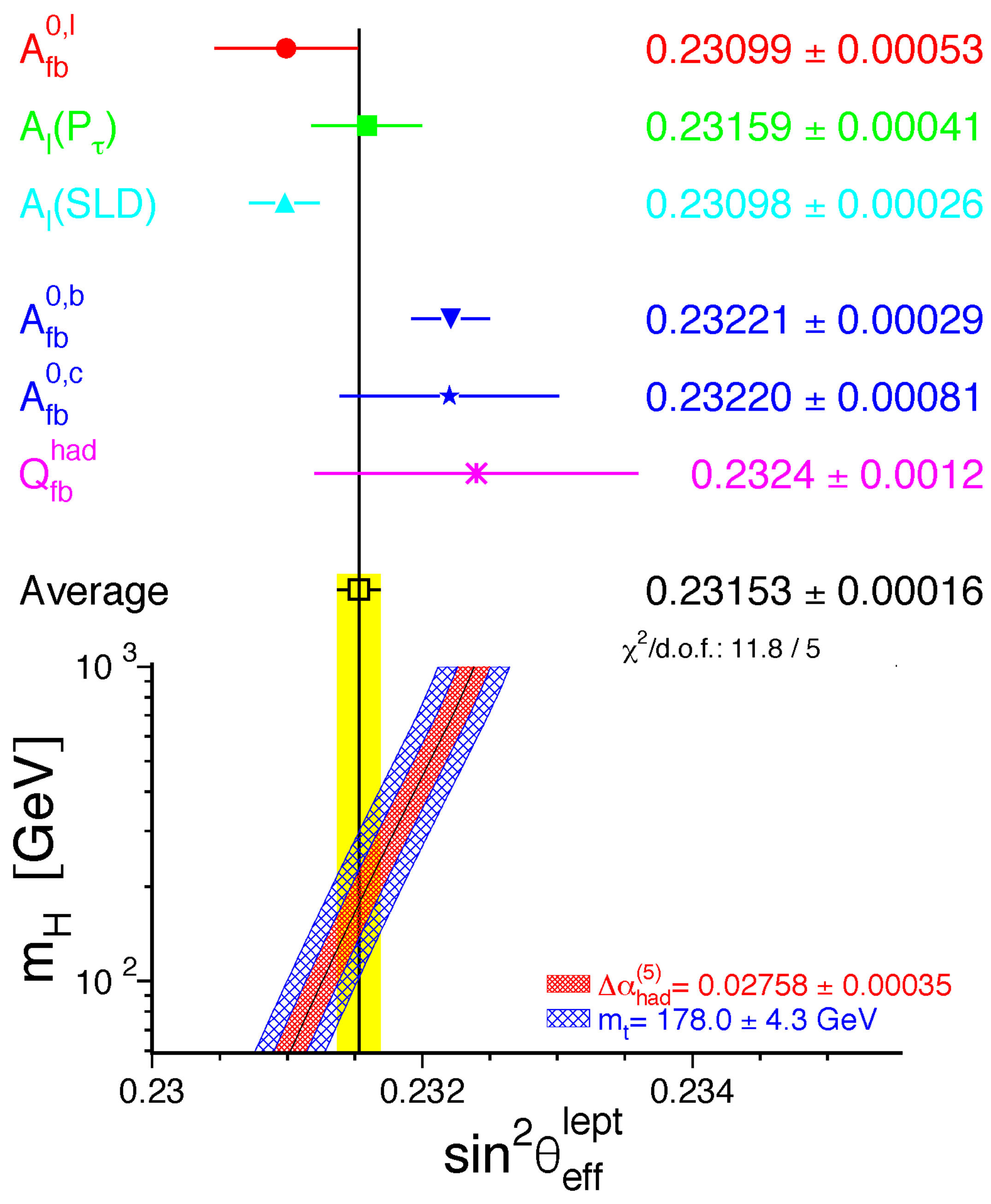
Snowmass Process EF03 Kickoff-Meeting 28/5/20

Anomalies in LEP/SLD data



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

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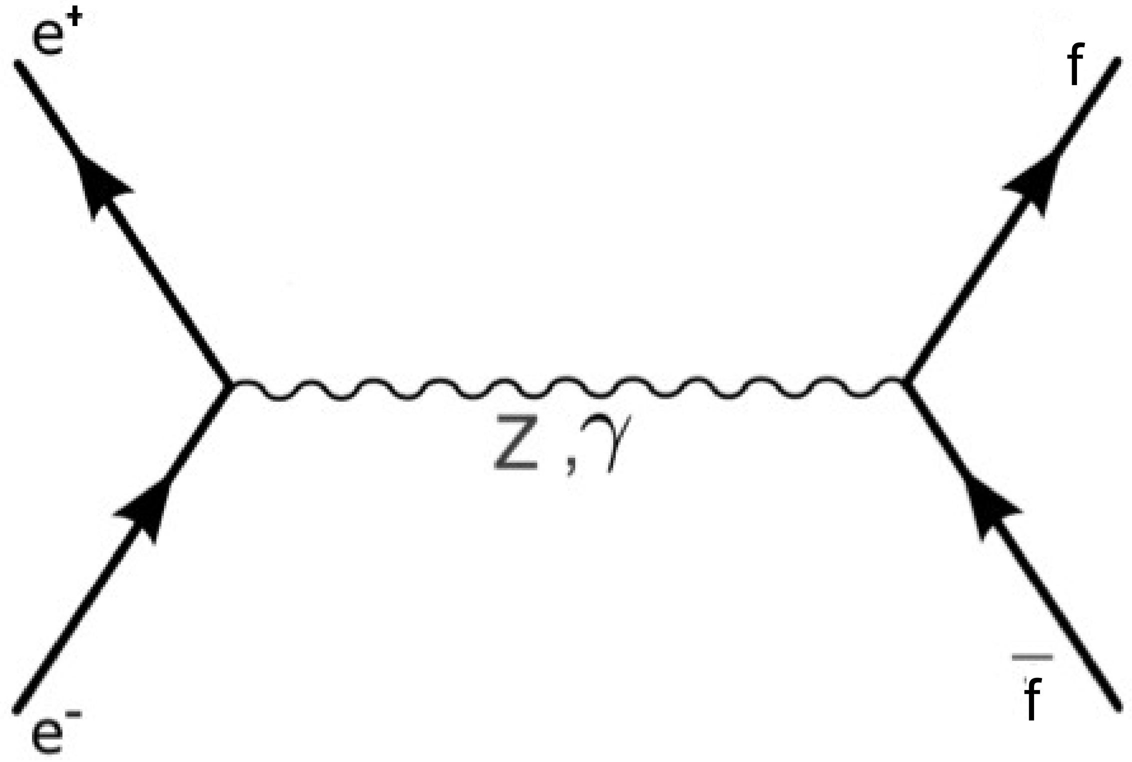
- Most precise determinations of $\sin^2\theta^\ell_{\mathrm{eff.}}$ differ significantly
  - Requires verification
  - **Heavy quark effect, effect on all quarks/fermions, no effect at all?**

Two fermion processes



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

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

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

*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)

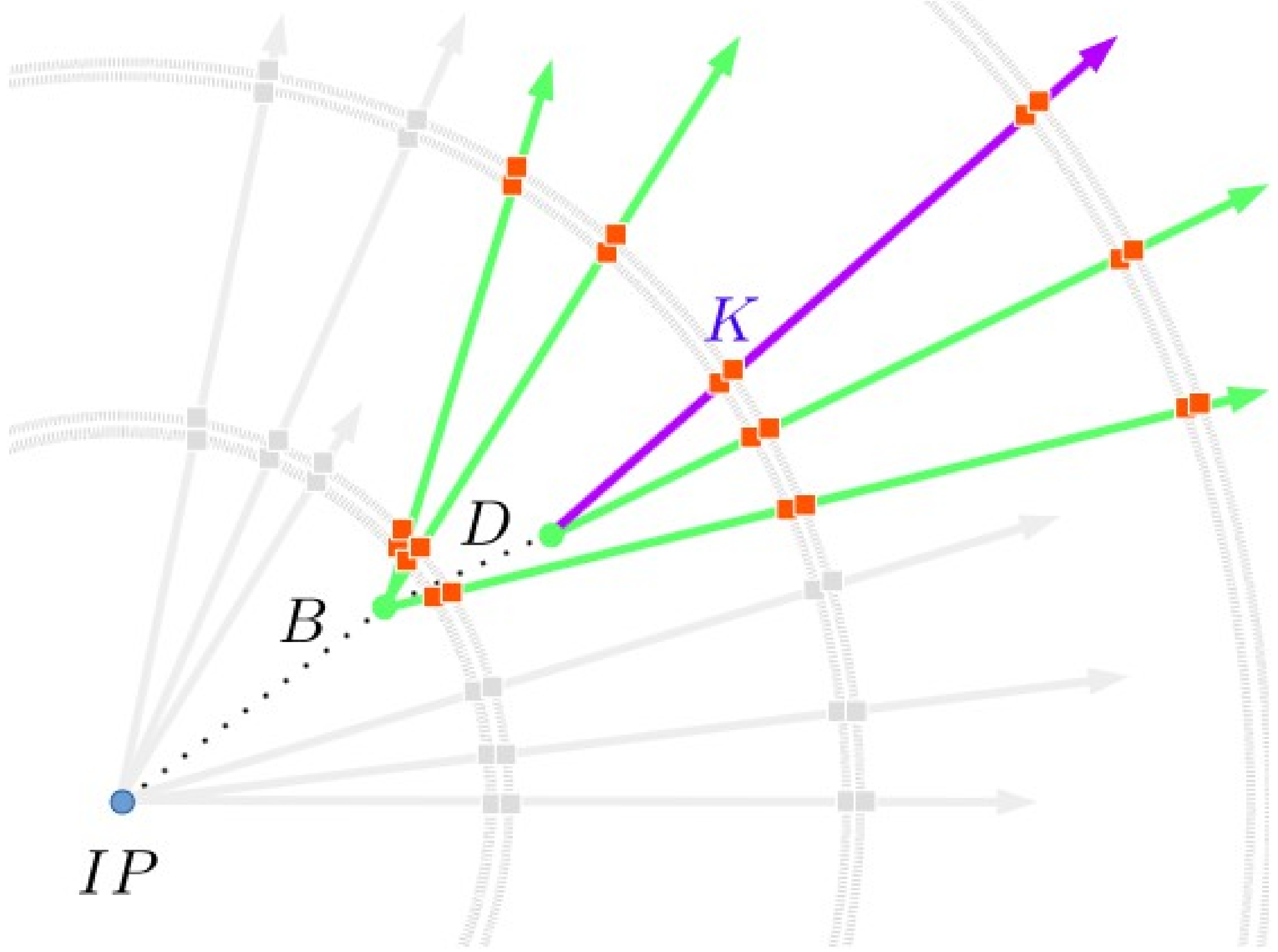
$\Sigma_{IJ} \neq \Sigma_{I'J}'$ => (characteristic) asymmetries for each fermion

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

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

Here we focus first on (tt), bb and cc pair production

Experimental challenges - Flavor tagging and charge measurment

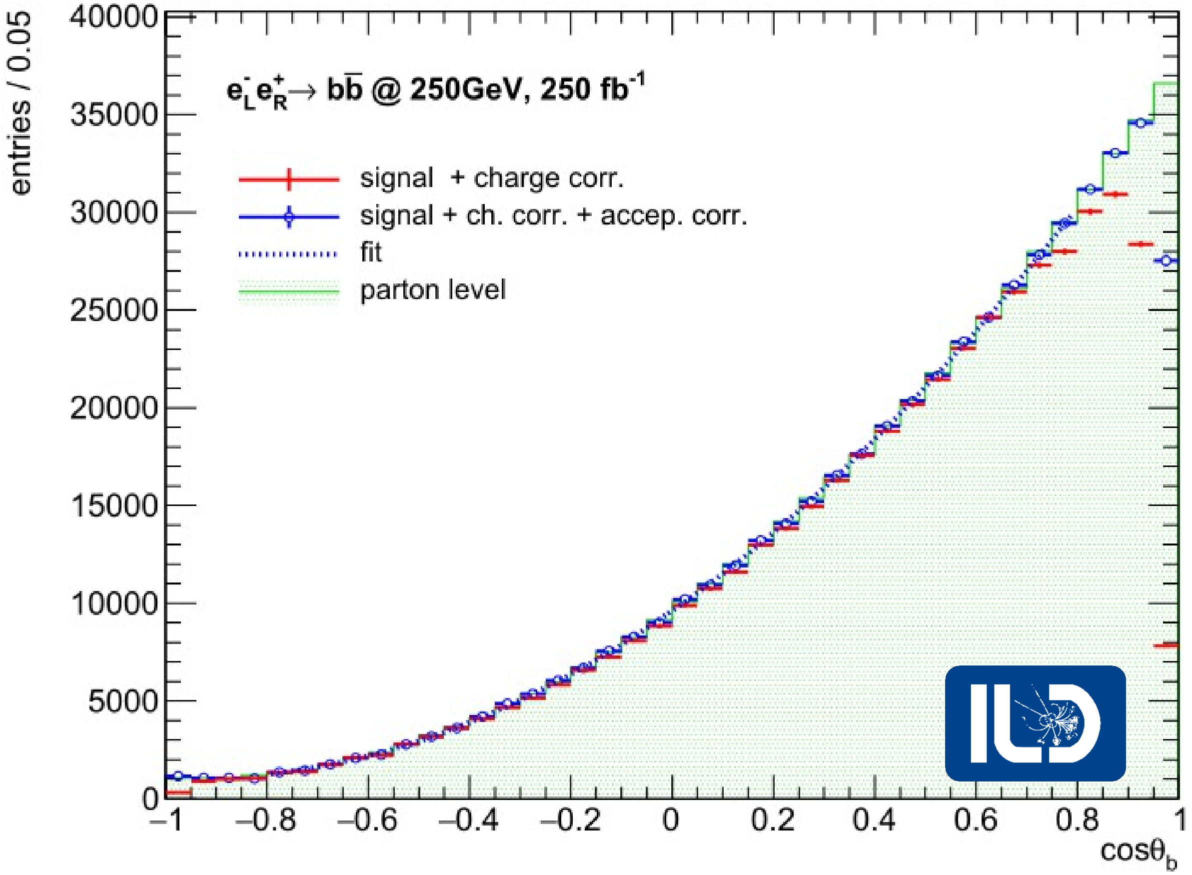


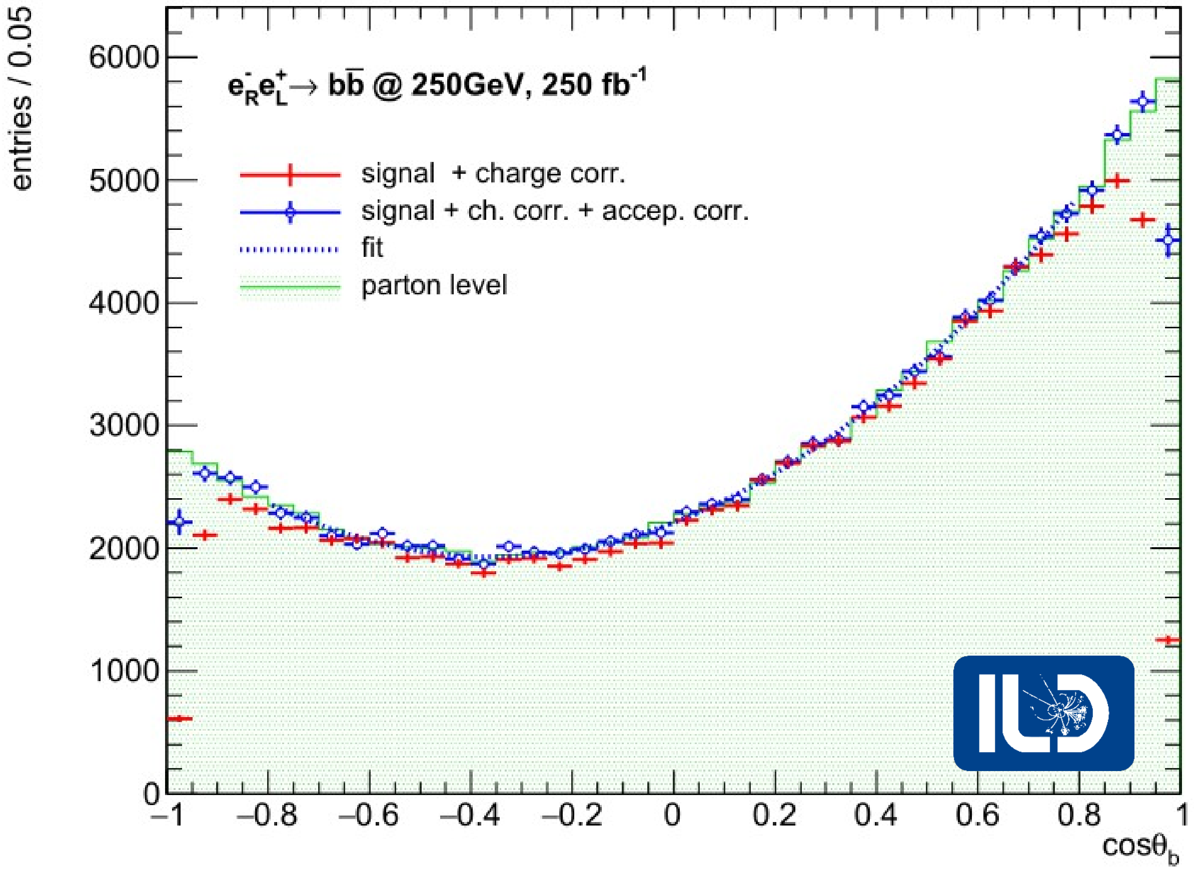
- Flavor tagging
  - Indispensable for analyses with final state quarks
- Quark charge measurement
  - Important for top quark studies,
  - indispensable for ee->bb, cc, ss, ...
- Control of migrations:
  - Correct measurement of vertex charge
  - Kaon identification by dE/dx (and more)
- Future detectors 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

Decomposing ee→bb – Differential cross section

Arxiv:1709.04289, ILD Paper in progress





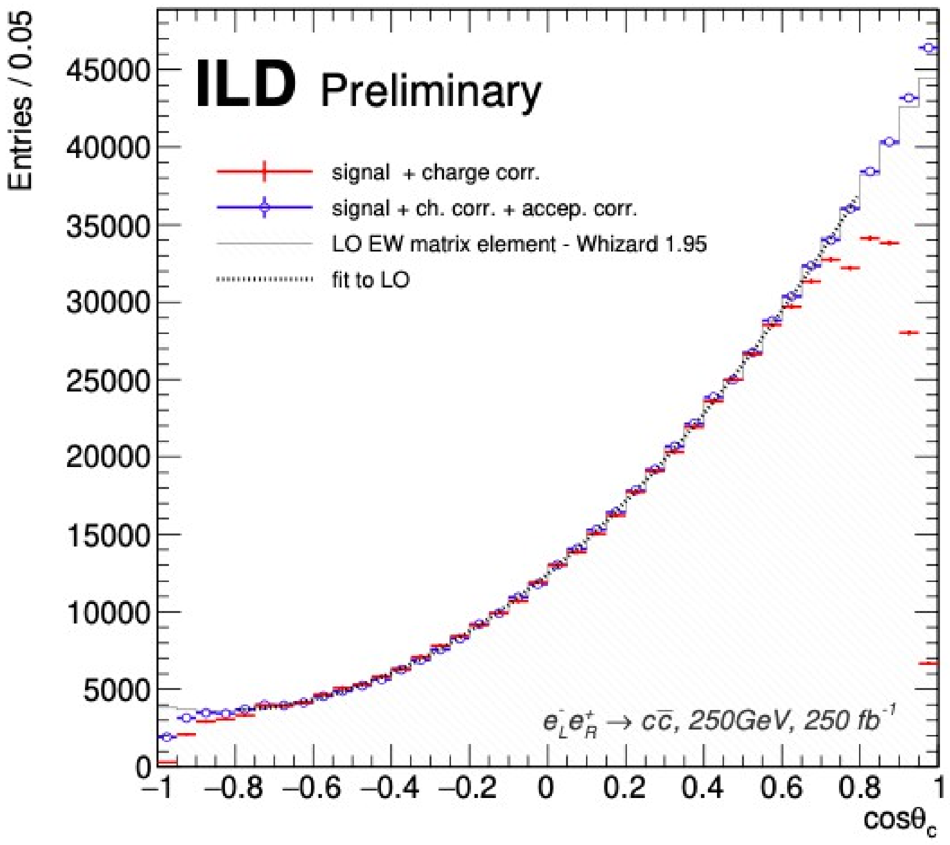
- Full simulation study (with ILD concept), Benchmark reaction
- Long lever arm in cos θ_b to extract from factors or couplings

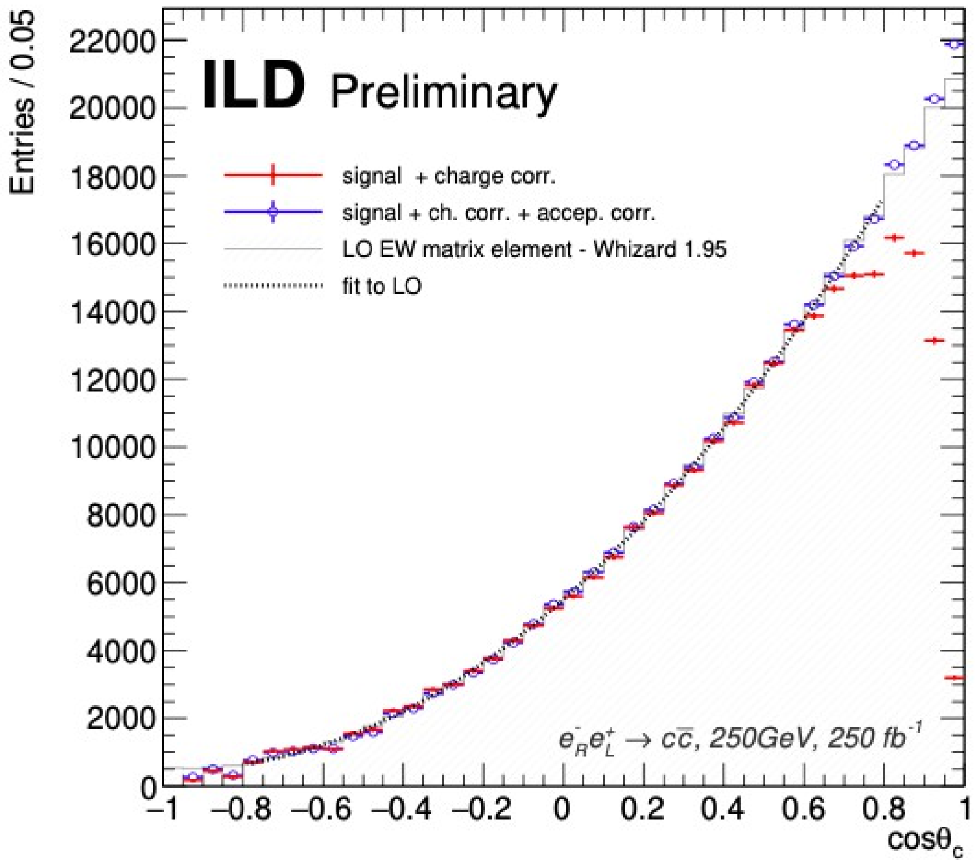
Status and plans in coming year:

- Preliminary results exist
- Plan to publish a paper still in 2020 with full assessment of potential systematic errors
- Note that the precision will reach the per-mill level -> requires full control over detector performance

New: Decomposing ee->cc – Differential cross section

arxiv:2002.05805



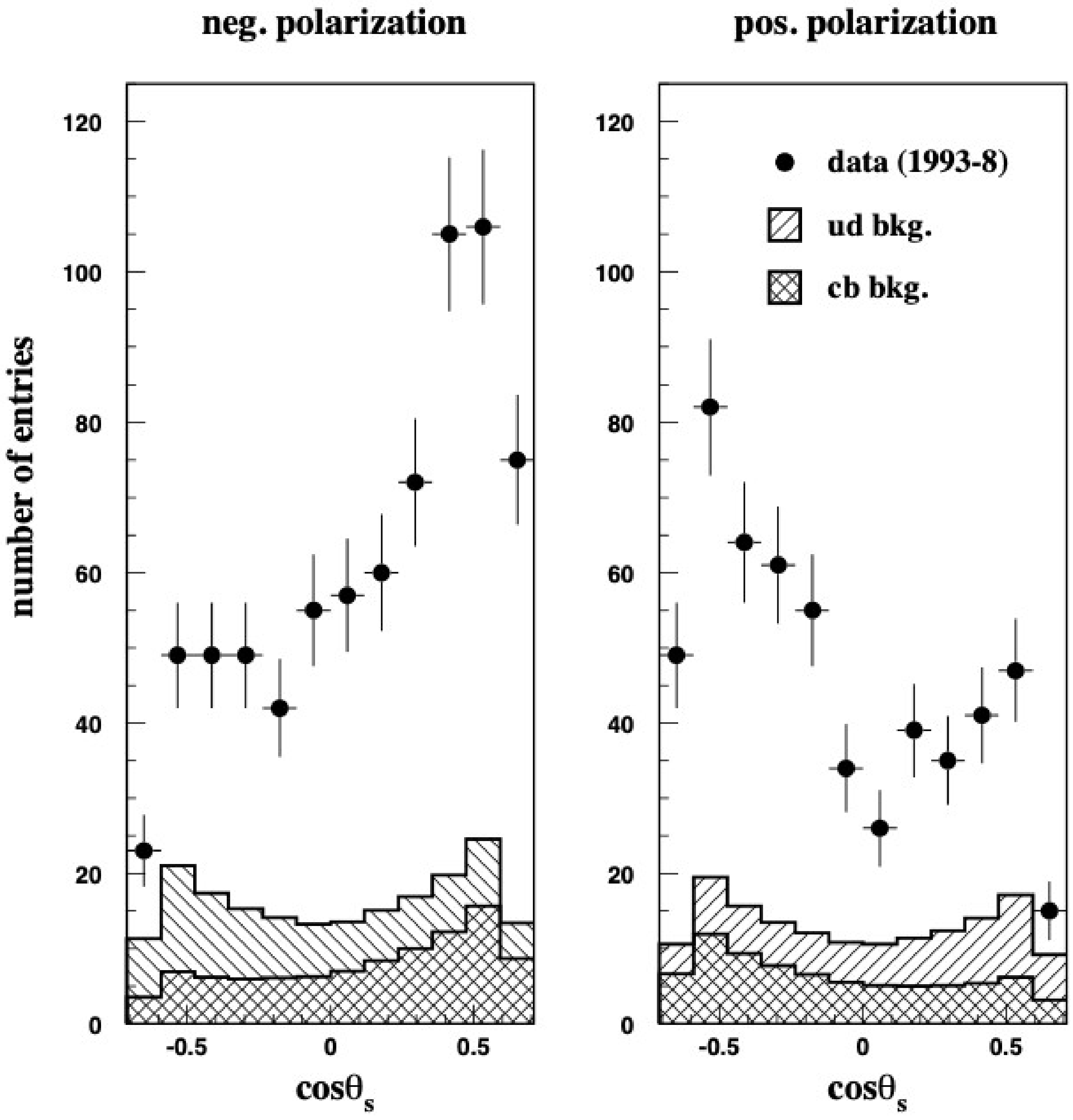


Full simulation study (with ILD concept)
Long lever arm in cos θ_c to extract from factors or couplings

Status and plans in coming year:
- Preliminary results exist
- Plan to publish a paper in early 2021 with full assessment of potential systematic errors
- Note that the precision will reach the per-mill level -> requires full control over detector performance

And tomorrow ?

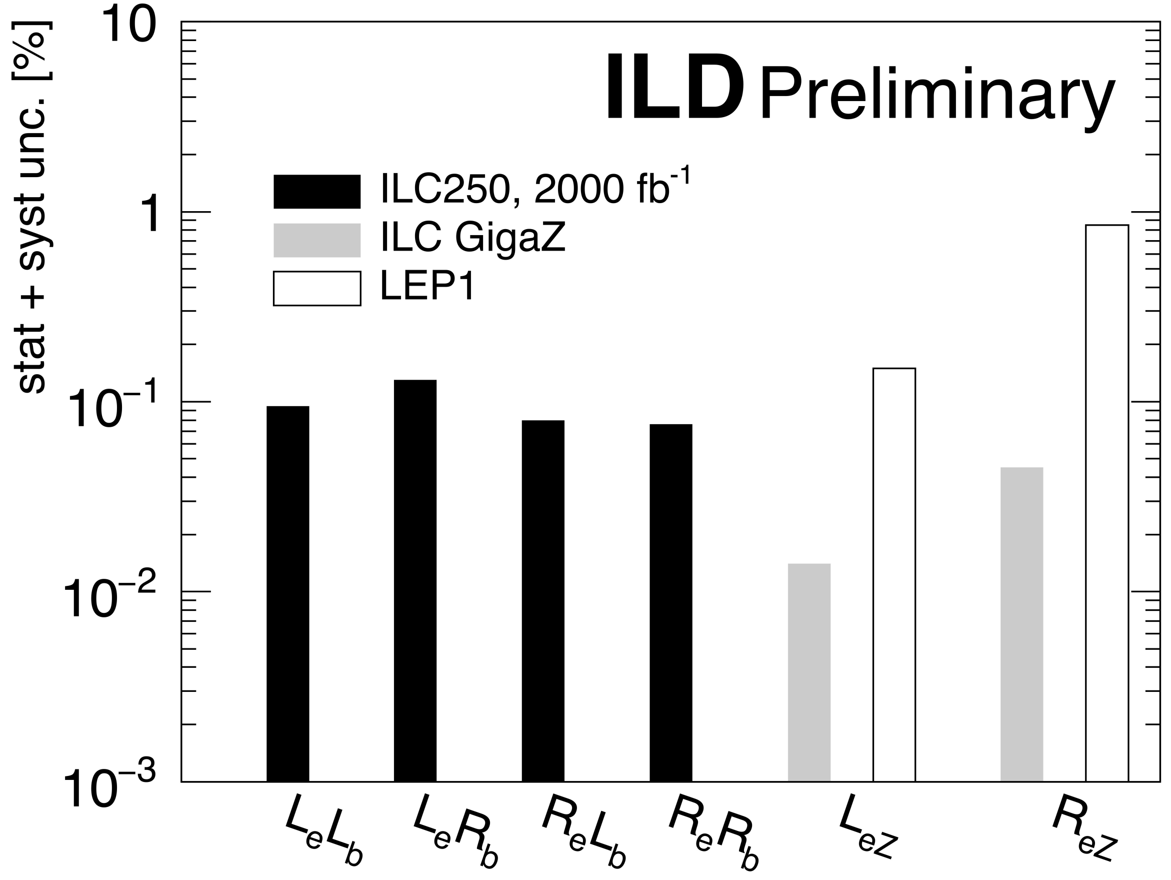
ee -->ss: SLD Analysis at Z Pole



- Extend the heavy quark analyses to light quarks to get full picture
- Optimise vertexing and particle ID (i.e .Kaon ID with full simulation studies

Precision on couplings and helicity amplitudes and physics reach

Example b-couplings (same observation for c-couplings, arxiv:2002.05805)



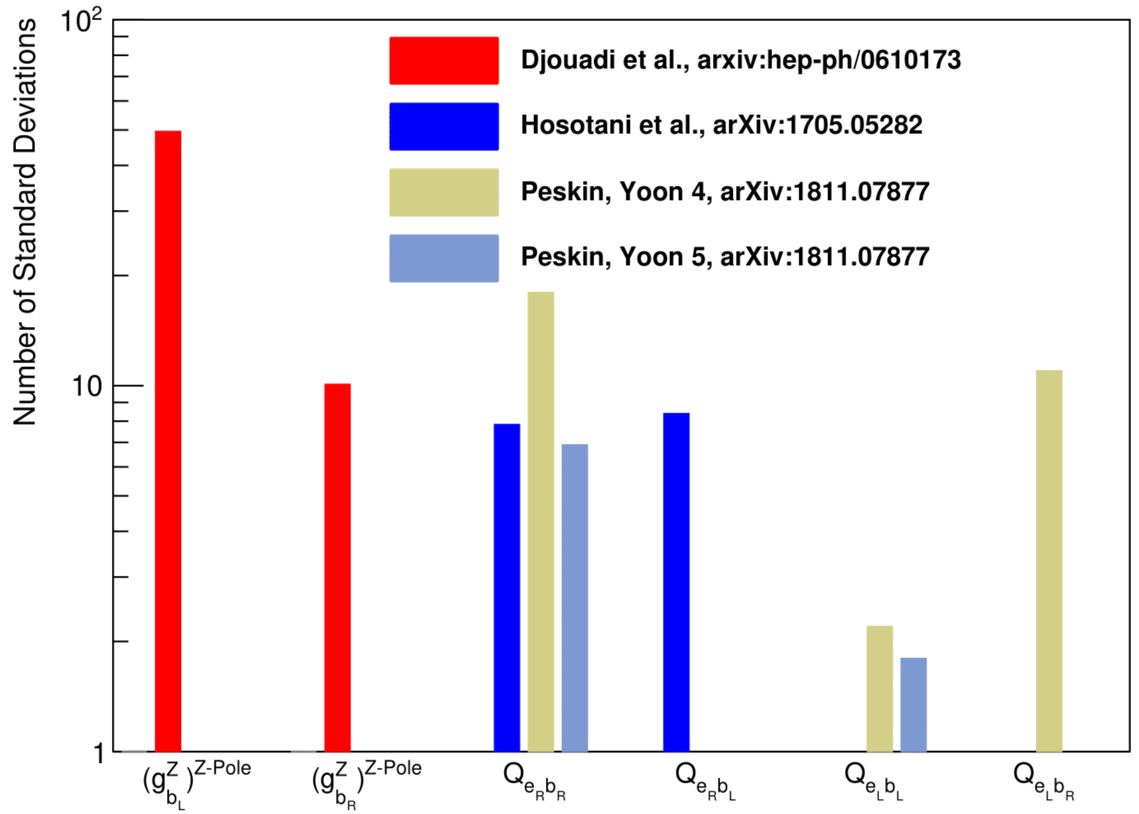
Couplings are order of magnitude better than at LEP

- 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

Summary and outlook

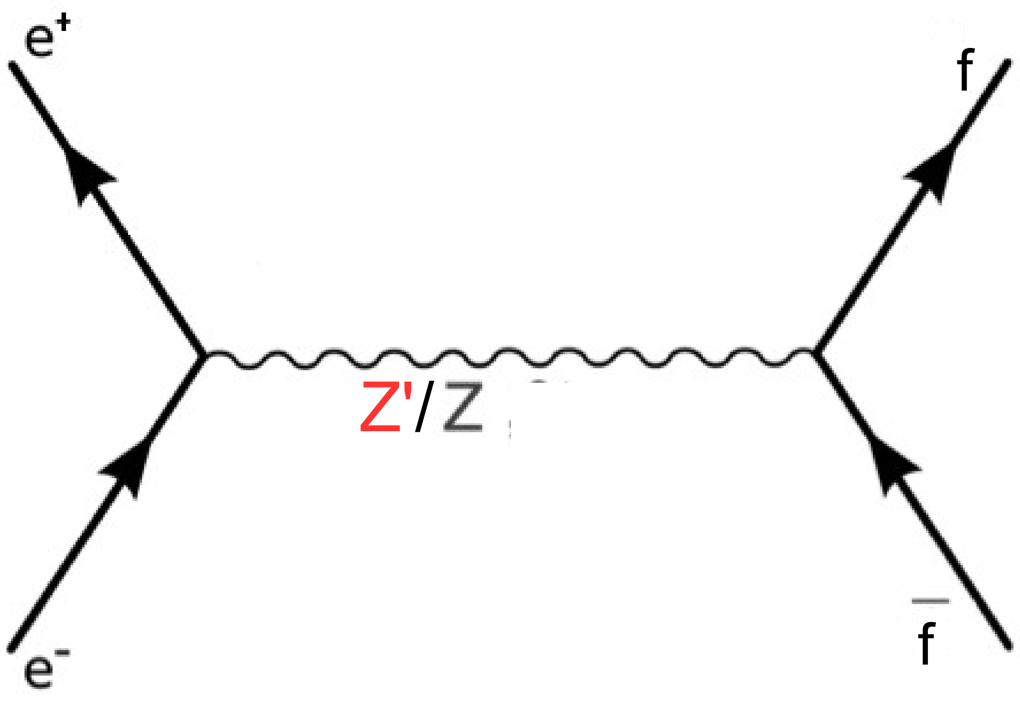
- Future e+e- machines are more than Higgs factories
  - ee->qq (here b and c) processes will reach the per-mill precision
  - These processes are important to establish full patterns of electroweak couplongs that may lead to discoveries
    - Note also that in some current models Higgs couplings will be agnostic to new physics
    - Marcel and Gauthier will also address issues like contact terms
  - Precision on Z-Pole as input to search for new physics at higher energies (see backup)
    - This may imply complementarity between linear and circular colliders if one can afford two machines
    - Detector optimisation to be studied (and to be brought in phase with the detector optimisation at higher energies)
      - One may exchange several times a vertex detector but not a calorimeter

- Main challenge at future machines will be the control of systematic errors
  - Experimentally
    - Vertex charge and particle ID
    - PFO for final state jets
  - Theoretically (not discussed)
    - Need at least NLO electroweak predictions (and MC programs) for correct interpretation of results

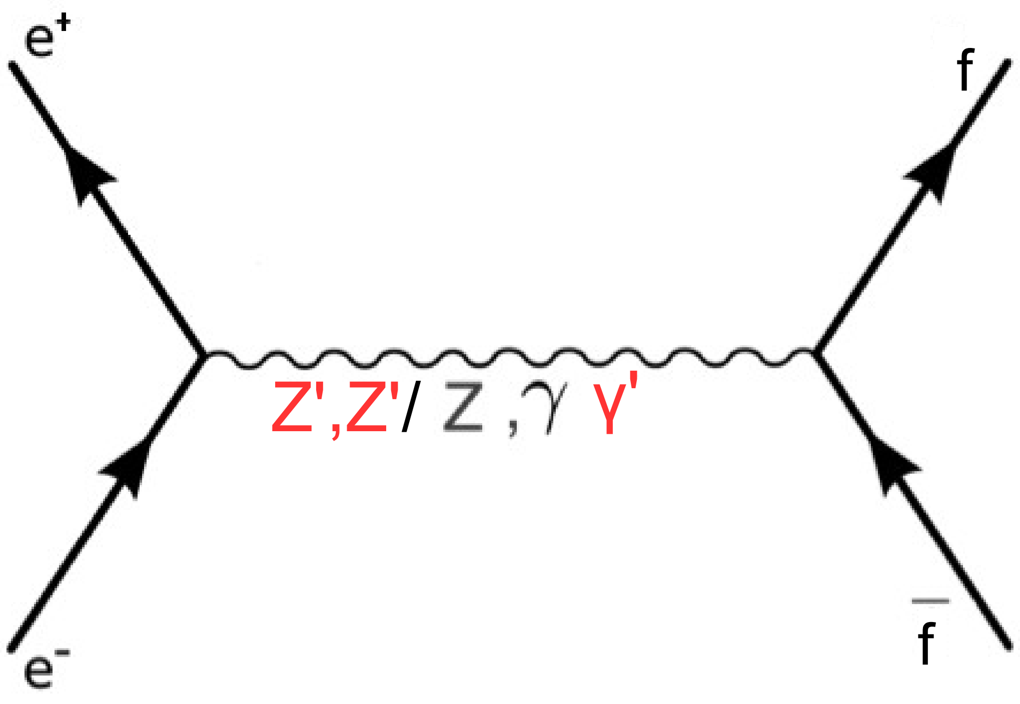
Backup

From the Z pole to higher energies?

On the Z-pole



Above the Z-pole

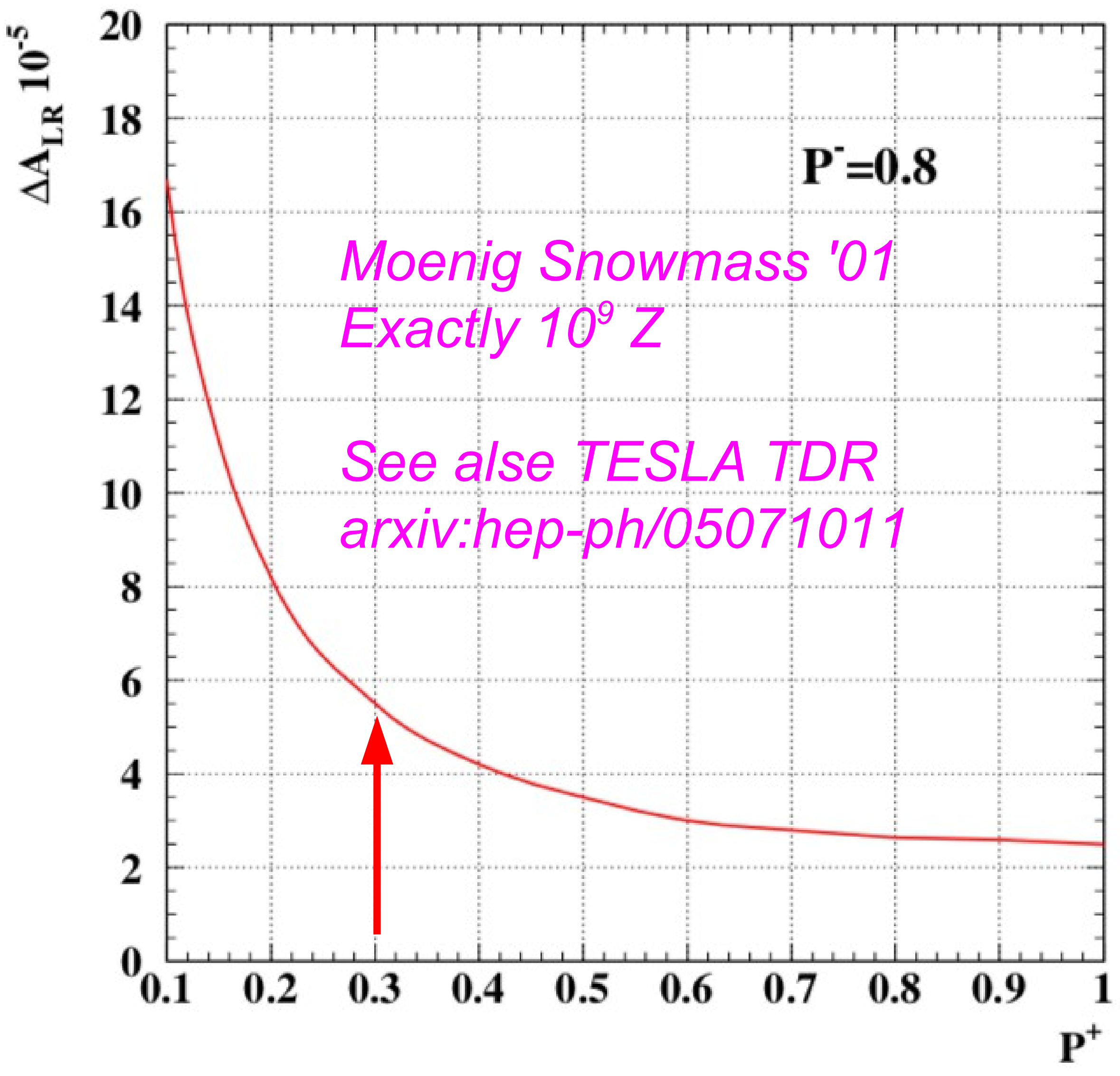


Sensitivity to Z/Z' mixing
Sensitivity to vector (and tensor) couplings of the Z
- the photon does not “disturb”

Sensitivity to interference effects of Z and photon!!
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

A_{LR} at GigaZ?

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



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

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

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

⇩

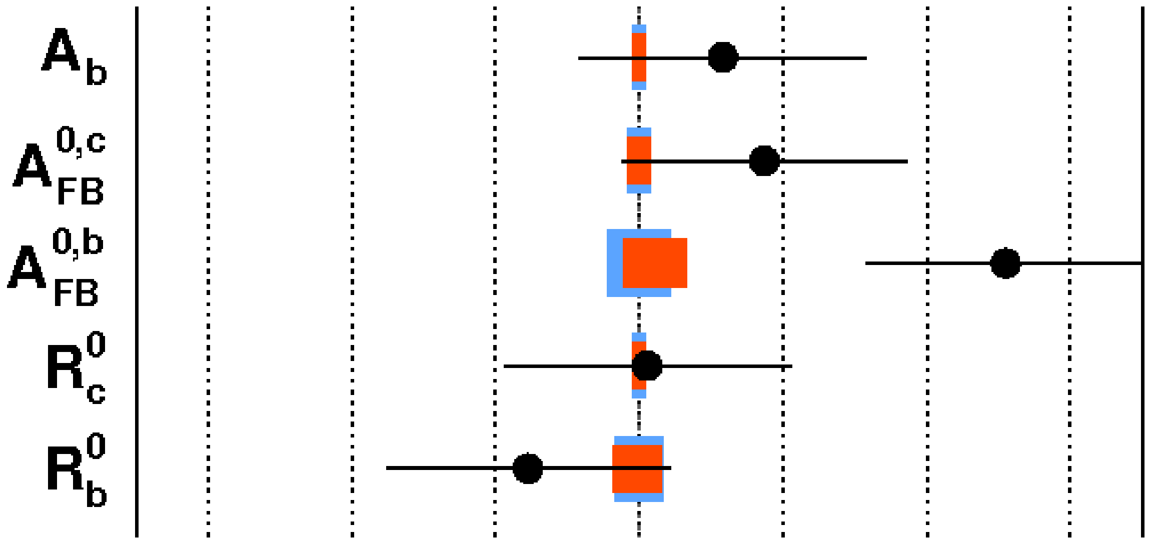
Extraction of relevant unknowns

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

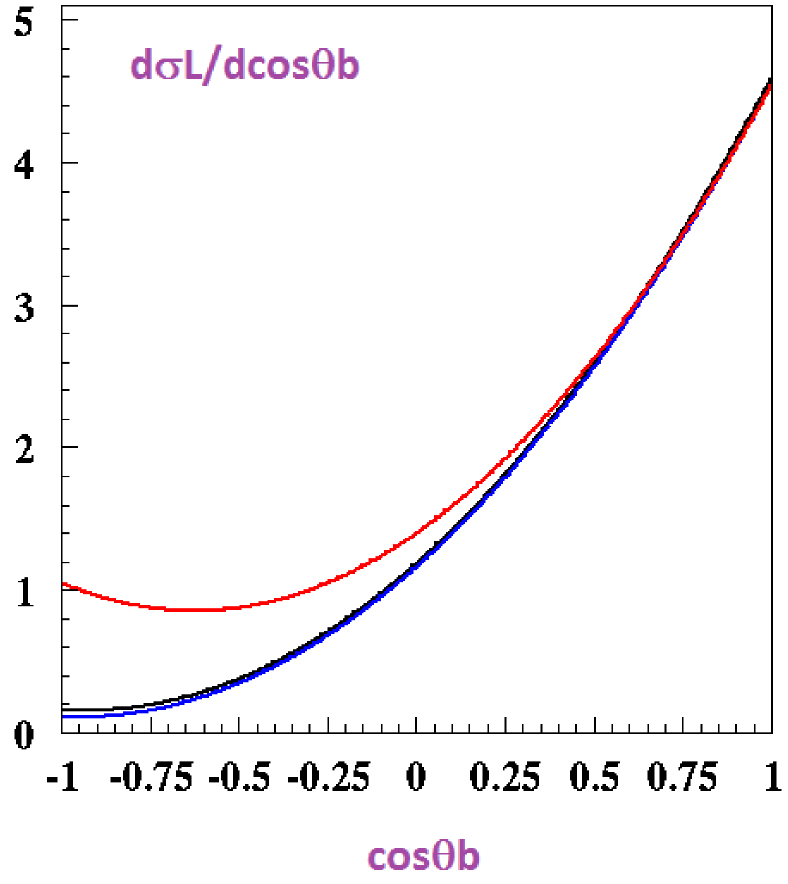
or equivalently $\quad g^{\gamma}_{L},\ g^{\gamma}_{R},\ g^{Z}_{L},\ g^{Z}_{R}$

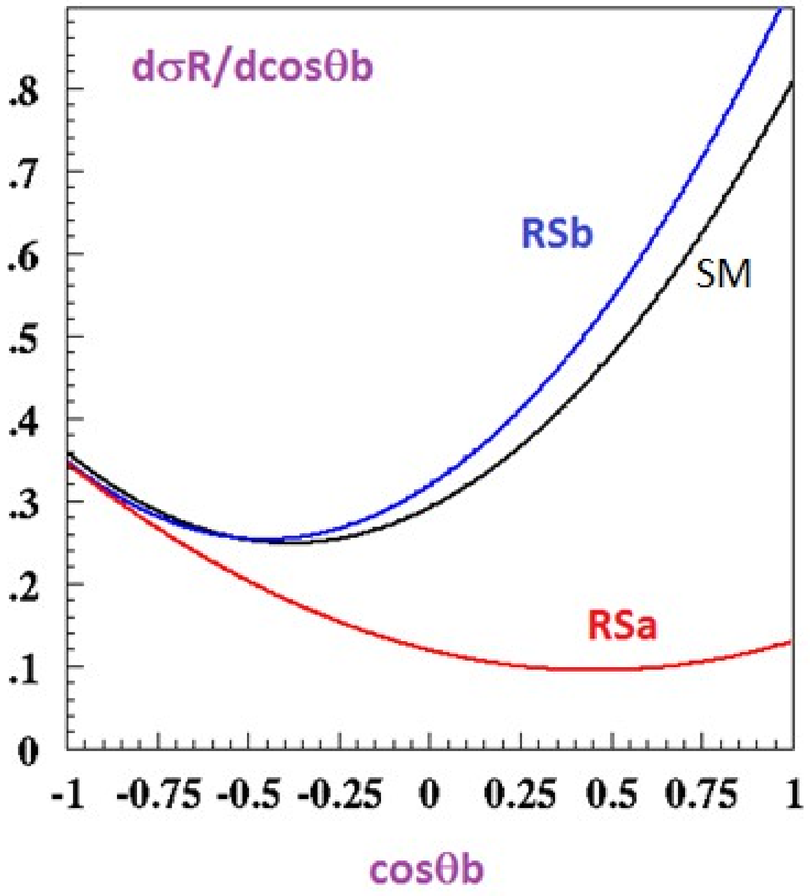
LEP Anomaly on A_{FB}^{b}

~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

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

Why this luxury?

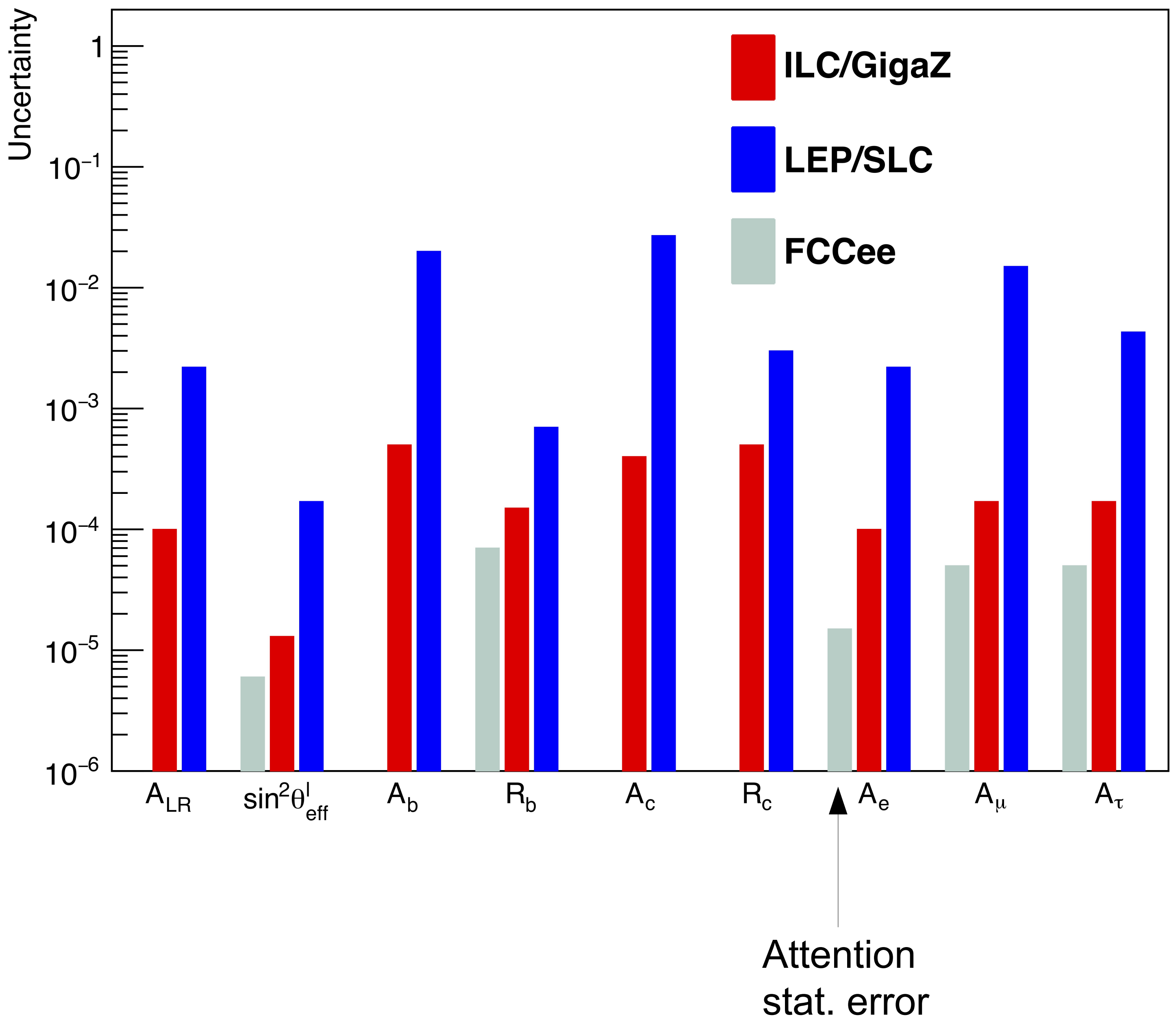
Beam spot size

	FCCee	ILC	SLC	LEP
σ_x[nm]	13700	516	1500	200000
σ_y[nm]	36	7.7	500	2500

Source SLC, LEP, PDG

LEP >> SLC >> ILC

Precision on relevant observables



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

- 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**

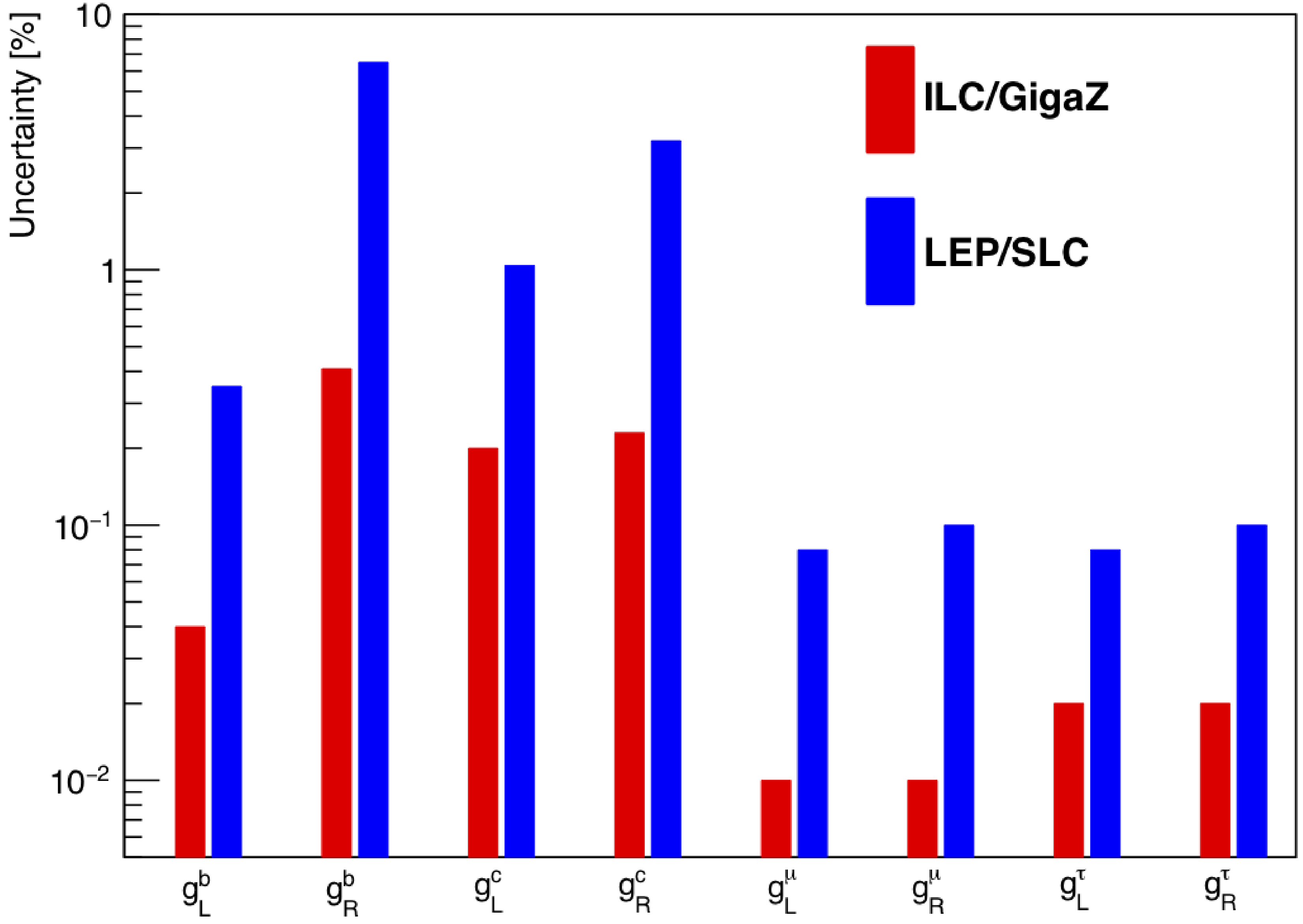
Complete test of lepton universality

- Precisions of order 0.05%

Note excellent measurement of quark asymmetries

- See above for ee->bb at 250 GeV

Precision on electroweak couplings



Rates and asymmetries

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:

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

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

Left-right-forward-backward asymmetry:

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

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

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