3rd Generation Quark & EW Boson Couplings at the 250GeV stage of the ILC

This presentation is mainly based on arXiv:1710.07621 and https://pos.sissa.it/314/752/pdf.

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Topic 1: 3rd generation quarks —> BSM

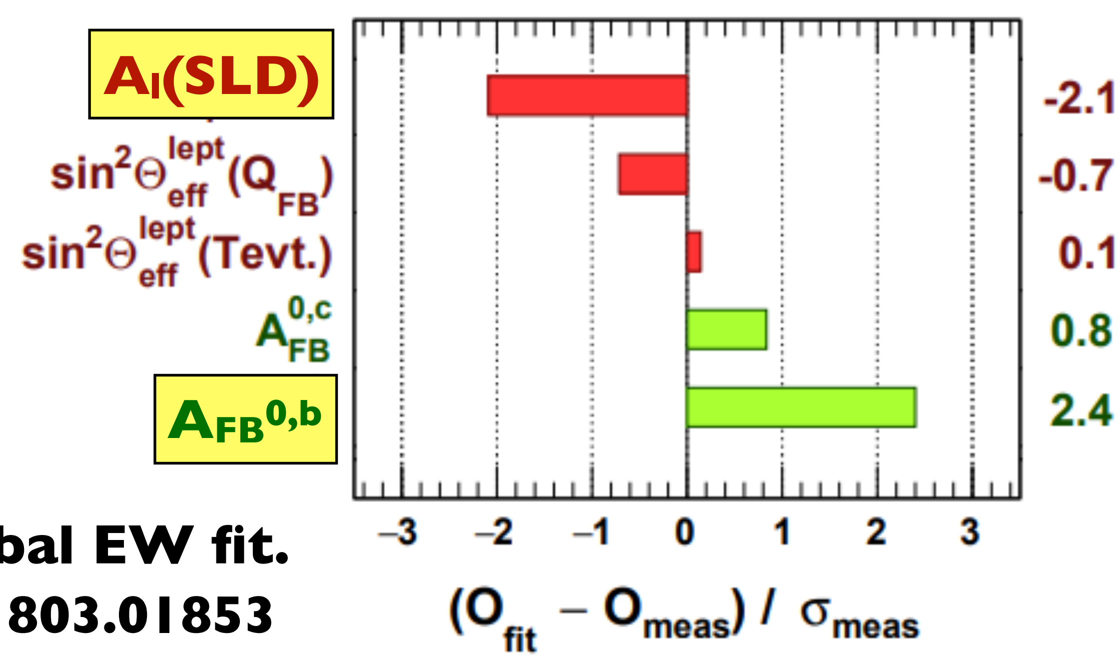
- **Top quark is the heaviest elementary particle in the SM.**
  - Expected to be strongly connected to EWSB mechanism.

- **Left bottom quark is heavy in the sense that the same SU(2)×U(1) multiplet as top quark. b-quark pair can be produced at 250GeV.**

- **Right bottom quark is not well constrained by earlier experiments compared to left-handed one and thus must be tested precisely if there is non-standard behaviour or not.**
  - Beam polarization is essential.

  - 3σ discrepancy between the value of $\sin^2\Theta_W$ from A^b_{FB} at LEP and the value from A_l at SLC.

$$g^Z := T_3 - Q\sin^2\theta_W$$

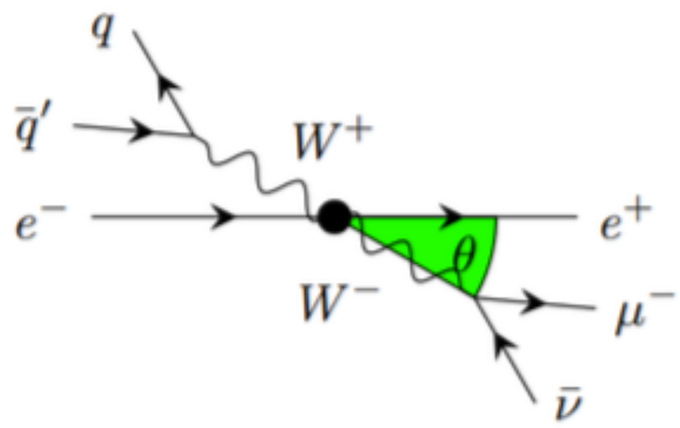


the global EW fit.
arXiv:1803.01853

Topic 2: EW Boson couplings —> BSM

- **Non-Abelian self-couplings of the W, Z and γ need more precise measurements.**
  - Only the triple gauge couplings (TGCs), namely WWZ, WWγ considered here.
  - Sufficient accurate measurements of TGCs can probe BSM.
  - 10^{-3} or better precision is necessary to constrain Brout-Englert-Higgs (BEH) models.

W pair production includes TGC.
Beam polarization disentangle WWZ and WWγ.



- **W pair production is also useful to measure average luminosity-weighted beam polarization by an angular fit technique.**
  - Strong dependence of the cross sections and angular distributions on the beam polarization. —> in situ beam polarization measurement.
  - I. Marchesini (http://www-library.desy.de/preparch/desy/thesis/desy-

ILC and ILD

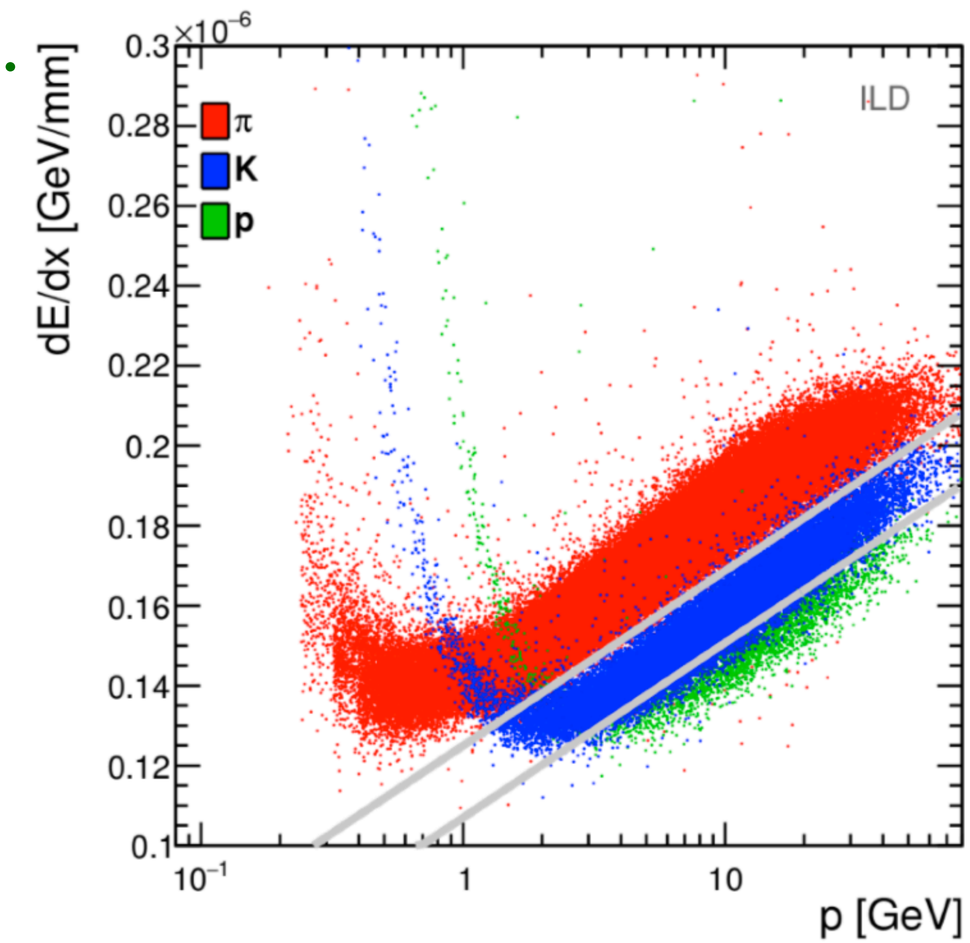
❖ ILC : e+ e- collider

- Controllable initial state (initial particle energy, **beam polarization**)
- $\sqrt{s}$=250GeV, L=2000fb^{-1}, fraction $e^-_L e^+_R$45%, $e^-_R e^+_L$45%, $e^-_L e^+_L$5%, $e^-_R e^+_R$5%)
- Precision measurements of BEH boson couplings and SM parameters.
- Extendable to 350GeV, 500 GeV, 1TeV.

❖ ILD : One of detector concepts for ILC

- Design philosophy : Reconstruct individual particle with **Particle Flow approach** to achieve ideal jet energy resolution.
- Example sub-detectors (relevant to this report)
  - TPC : Continuous tracking (V0, kink tracks)
    dEdx measurement > PID > Flavour tagging
  - Vertex detector :

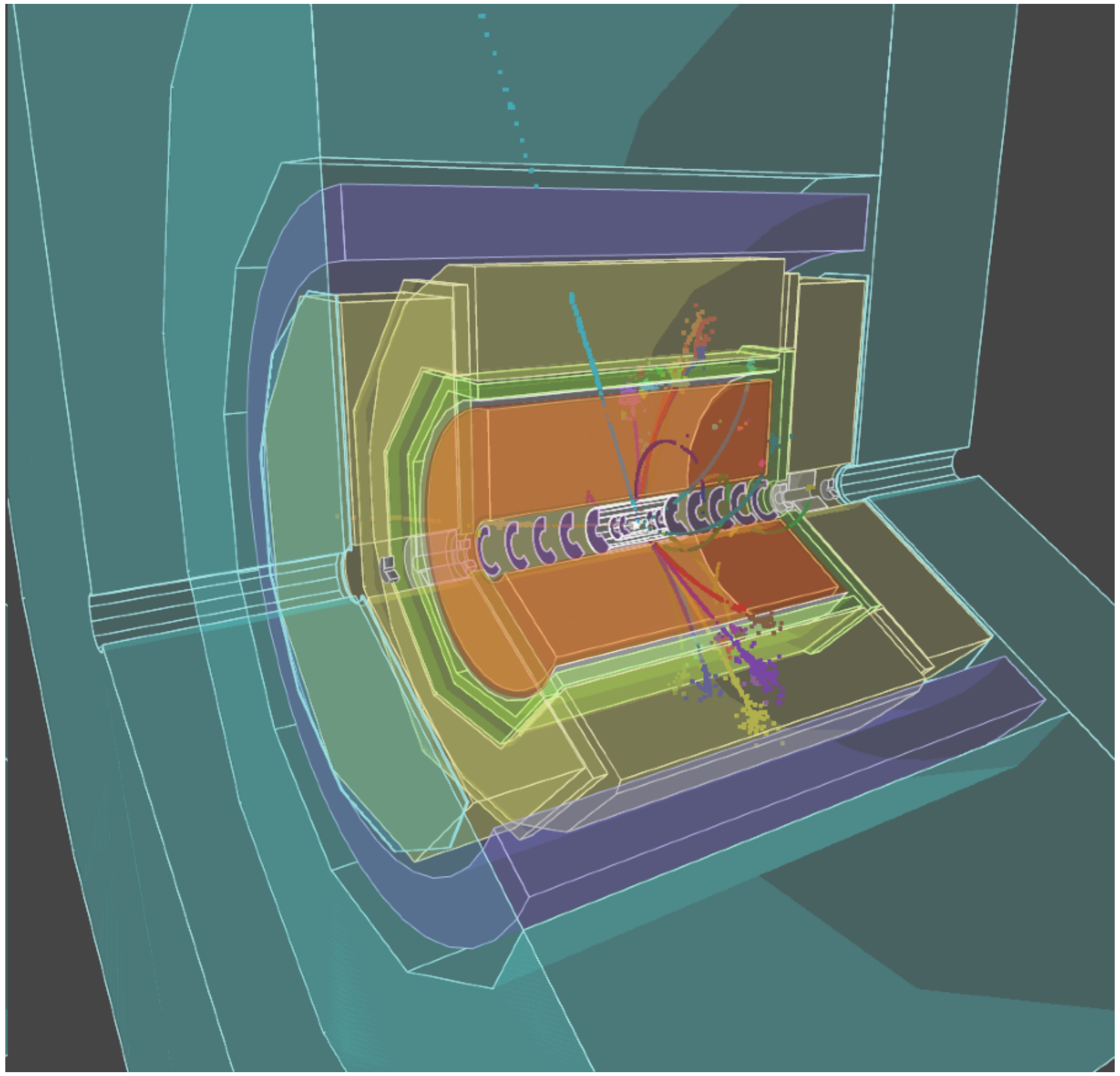
    Precise position measurement around IP.
    Essential for b-jet, c-jet identification by secondary vertex finding.



Simulation & Reconstruction

- **Realistic simulation**
  - Beam energy spectrum, ISR, beam-beam background.
  - Full detector simulation with detailed detector descriptions.

- **Most essential to this report in the reconstruction are heavy flavour tagging and vertex charge assignment.**
  - Flavour tagging
    - b-jet, c-jet
  - Vertex charge assignment
    - required by forward backward asymmetry measurement



Topic 1: 3rd generation quarks
(e+e- —> bbar)

Right-handed b-quark coupling to Z

- **BSM models can explain the LEP anomaly on $\sin\Theta_W$. It predicts a large correction for g_R^Z while Δg_L^Z remains small.**
  - e.g. A. Djouadi et. al., https://arxiv.org/pdf/hep-ph/0610173.pdf
  - ~25±10% shift from SM expected on g_R^Z.

- **Measurement : b-quark polar angular spectrum**
  - Key1 : b quark (charge) identification. PID and flavour tag are essential.
    - sum of all charges associated to the B-hadron
    - charge of the kaons found in a b-jet.

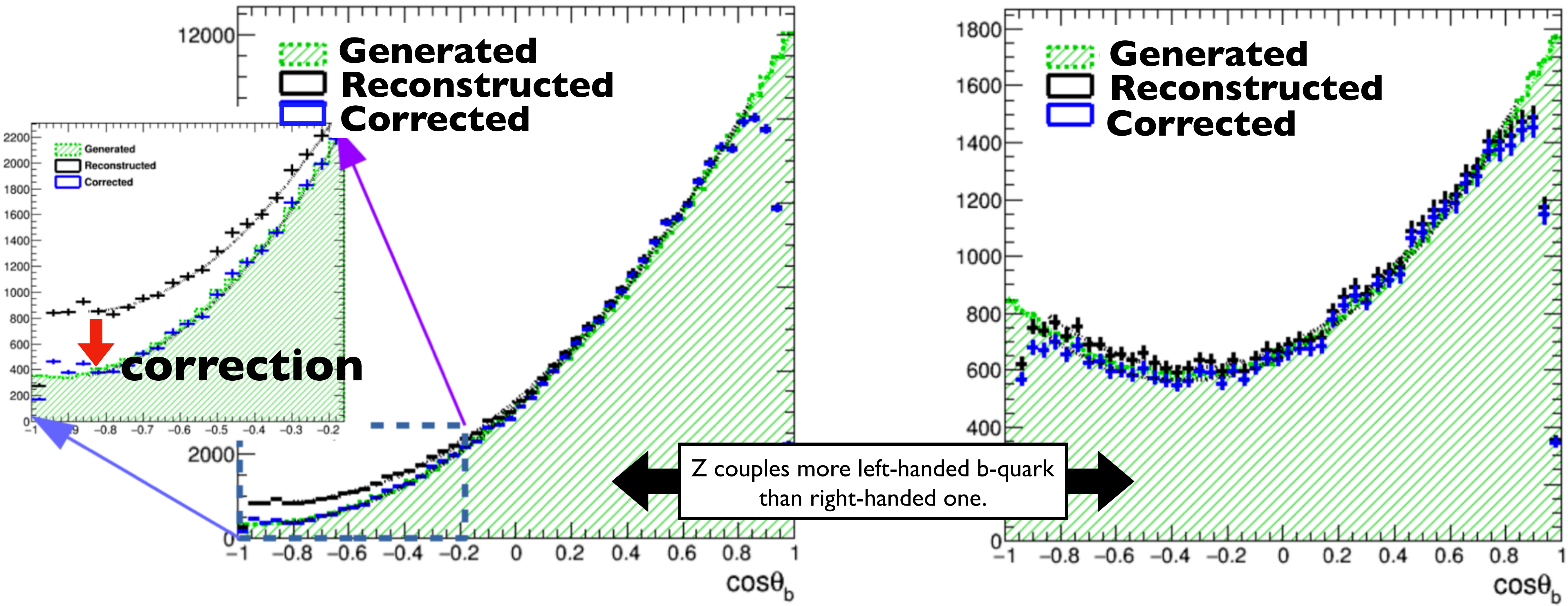
  - Key2 : b-quark charge assignment correction technique.
    - Implemented a method to correct for the b-quark charge mis-assignments, which requires no external inputs, but uses # of events in which only one b-quark charge is correctly assigned.
      See more details : S. Bilokin *et al.* arXiv:1709.04289

b-quark angular spectrum

S. Bilokin, https://pos.sissa.it/314/752/pdf

$\sqrt{s}$ = 250GeV, L = 250fb^{-1} for each polarization

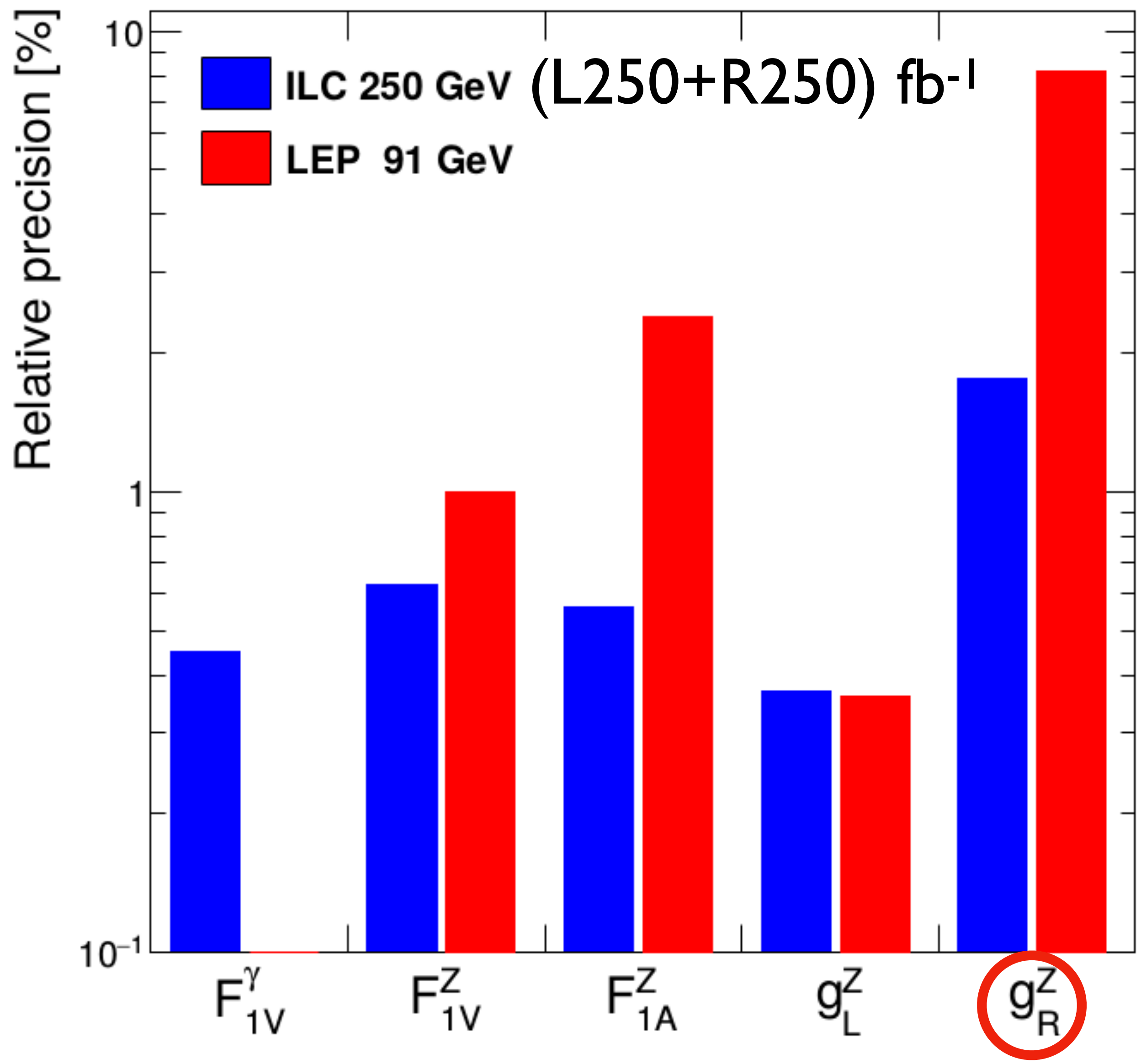
Left handed beam ($e^-_L e^+_R$) **Right handed beam ($e^-_R e^+_L$)**



- Long lever arm in cosΘ_b (-0.8,+0.8) enables to extract couplings or form factors.

g_L^Z, g_R^Z, g_L^γ, g_R^γ (F^L_{1V}, F^L_{1A}, F^R_{1V}, F^R_{1A}) **are extracted by fitting bin by bin using its dσ/dcosΘ formula.**

Fitting result compared to LEP



~5 times better precision for g_R^Z at ILC than the one at LEP is expected.

- **This result shows potential capability of 250 GeV ILC to constrain models by measuring right-handed coupling to Z thanks to**
  - beam polarization
  - high luminosity
- **This can be extended to the other two fermion pairs.**

Topic 2: EW Boson couplings

TGC parameters to be measured

General form of the effective Lagrangian (up to 6 dim.) requiring CP conservation and SU(2)×U(1) symmetry :

(V = γ, Z)

$$
\begin{aligned}
\mathscr{L}_{\mathrm{WWV}}/g_{\mathrm{WWV}} = \quad & i g_1^V \quad V^{\mu}(W^{-}_{\mu\nu}W^{+\nu} - W^{+}_{\mu\nu}W^{-\nu}) \\
+ \quad & i\kappa_V \quad W^{+}_{\mu}W^{-}_{\nu}V^{\mu\nu} \\
+ \quad & i\frac{\lambda_V}{m_W^2} \quad W^{-\ \rho}_{\ \mu}W^{+}_{\ \nu\rho}V^{\mu\nu}
\end{aligned}
$$

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$$

$$g_1^\gamma = 1$$
$$\kappa_Z = -(\kappa_\gamma - 1)\tan^2\theta_W + g_1^Z$$
$$\lambda_Z = \lambda_\gamma$$

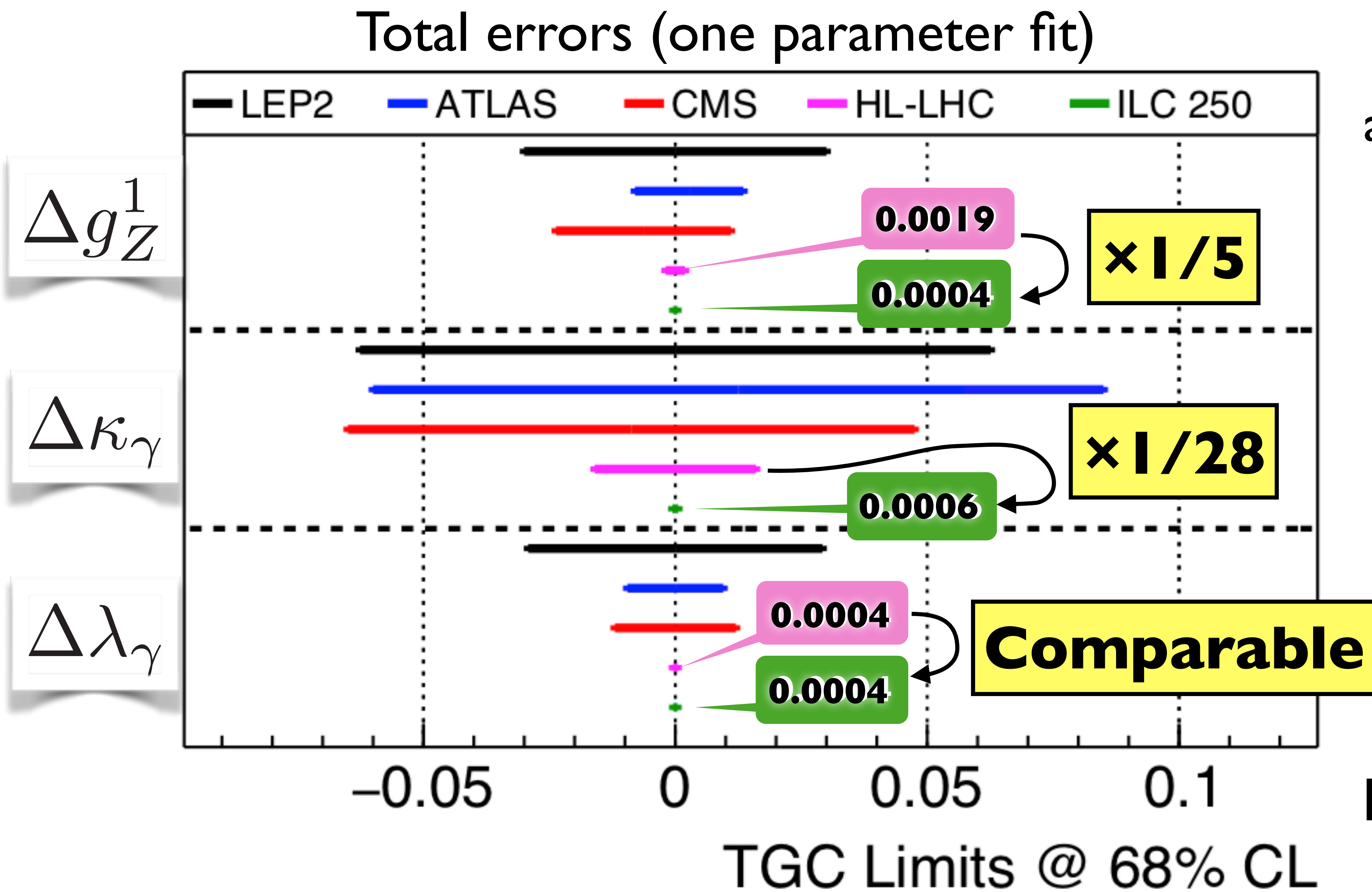
→ $g_1^Z, \kappa_\gamma, \lambda_\gamma$

ILC 250 GeV result (ILD) expectation

- **Full ILD study is work in progress.**
  - No results available yet.

- **500GeV (ILD) full simulation study has been done. The results is extrapolated to 250GeV.**
  - ILD 500 GeV result referred here :
    I. Marchesini, http://www-library.desy.de/preparch/desy/thesis/desy-thesis-11-044.pdf
  - Scaling factors :
    (1) Statistics : $1/\sqrt{(\sigma L)}$
    (2) Energy dependence of $SU(2)\times U(1)$ diagram cancellation : $1/s$

Precision estimation



arXive:1710.07621

Better than 10^{-3} !

LEP2: √s=200GeV, 0.68fb^{-1}, Phys. Lett. B614, 7 (2005)
ATLAS: √s=7TeV, 4.6 fb^{-1}, arXiv:1410.7238
HL-LHC (CMS):14TeV, 3000 fb^{-1}, https://cds.cern.ch/record/1510150/files/ATL-PHYS-SLIDE-2013-042.pdf
ILC: √s=250GeV, 2000 fb^{-1}

※ 3-parameter fit estimation by using LEP2 data can be found in arXive:1710.07621.

Conclusions

- **250GeV ILC will be powerful tool for searching BSM.**
  - Beam polarization is essential.
  - Not only Higgs precision measurements but also the other SM paramters' precise measurements for BSM are expected.

- **Topic1: 3rd generation quark**
  - 250GeV ILC can investigate b quark (L, R) and shows its good potential capability to measure right-handed couplings, which are keys in many BSM scenarios.

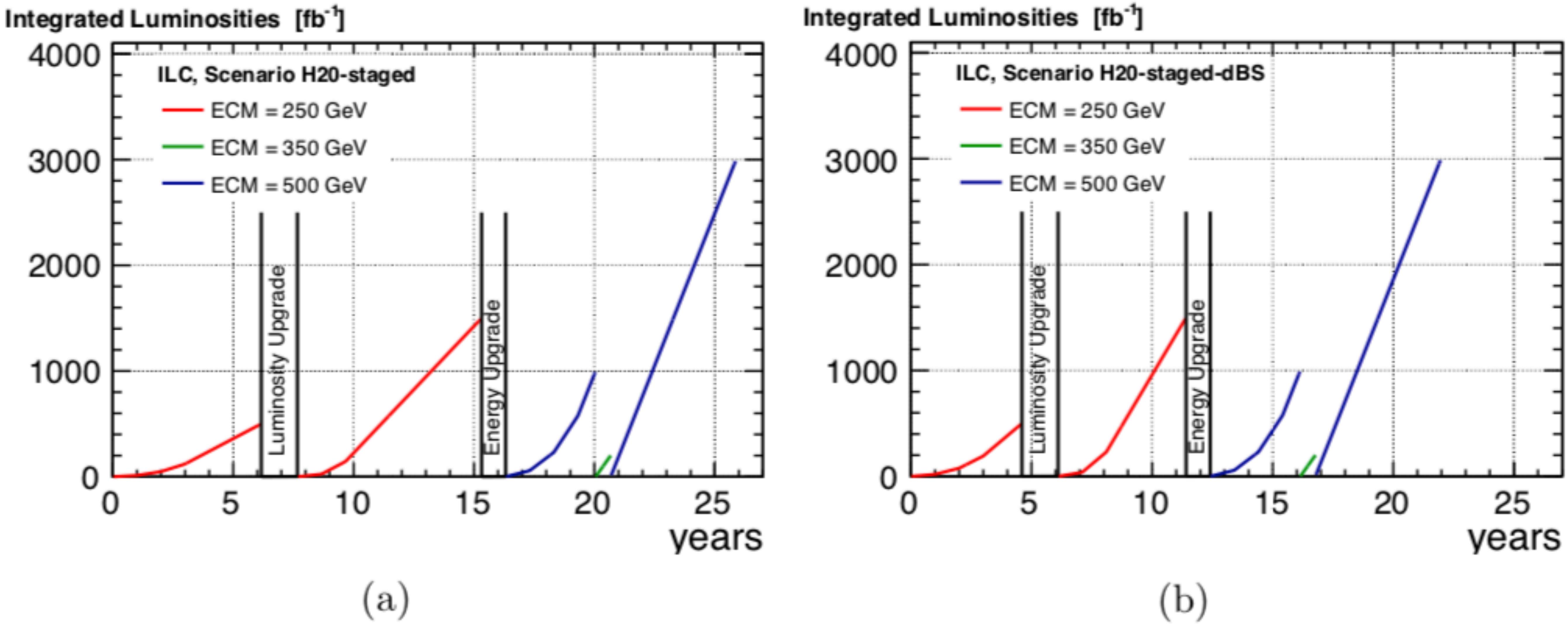
  - ILC can shed light on the long-standing 3σ discrepancy between value of $\sin^2\Theta_W$ derived from the b forward backward asymmetry at LEP and the value obtained at the SLC.

- **Topic2: EW boson coupling**
  - 10^{-3} level or better TGC measurements are feasible. Full simulation study is work in progress. Stay tuned.

Backup

Run scenarios

arXiv:1710.07621



(a) (b)

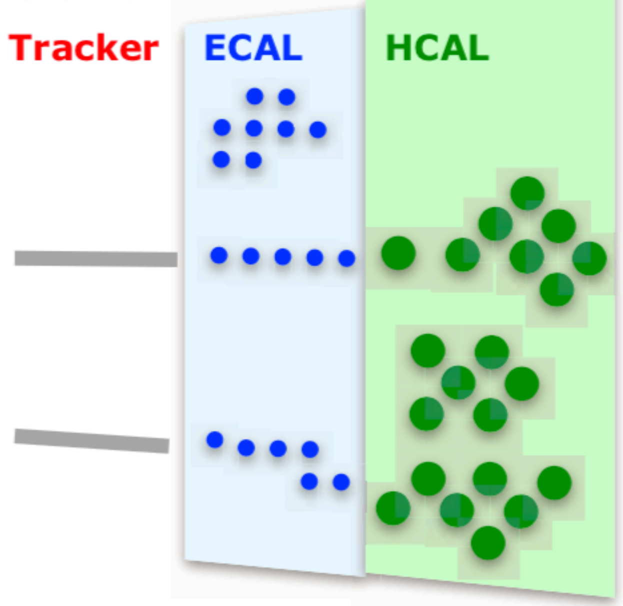
Figure 2: Run plan for the staged ILC starting with a 250-GeV machine under two different assumptions on the achievable instantaneous luminosity at 250 GeV. Both cases reach the same final integrated luminosities as in Fig. 1.

Particle Flow

	σ_E / E	@5 GeV	@50 GeV	@500 GeV
Tracker	0.00002 × E	0.01%	0.1%	1%
ECAL	0.2 / √E	9%	3%	1%
HCAL	0.6 / √E	30%	8%	3%

for single particles

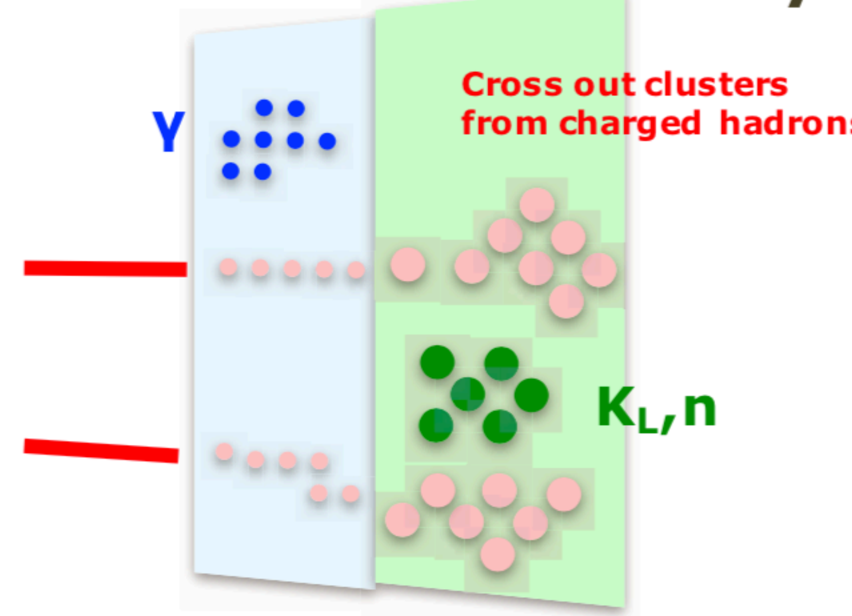
Traditional Calorimetry



E_{jet} = E(ECAL) + E(HCAL)

Composition ~30% : ~70%

Particle Flow Calorimetry

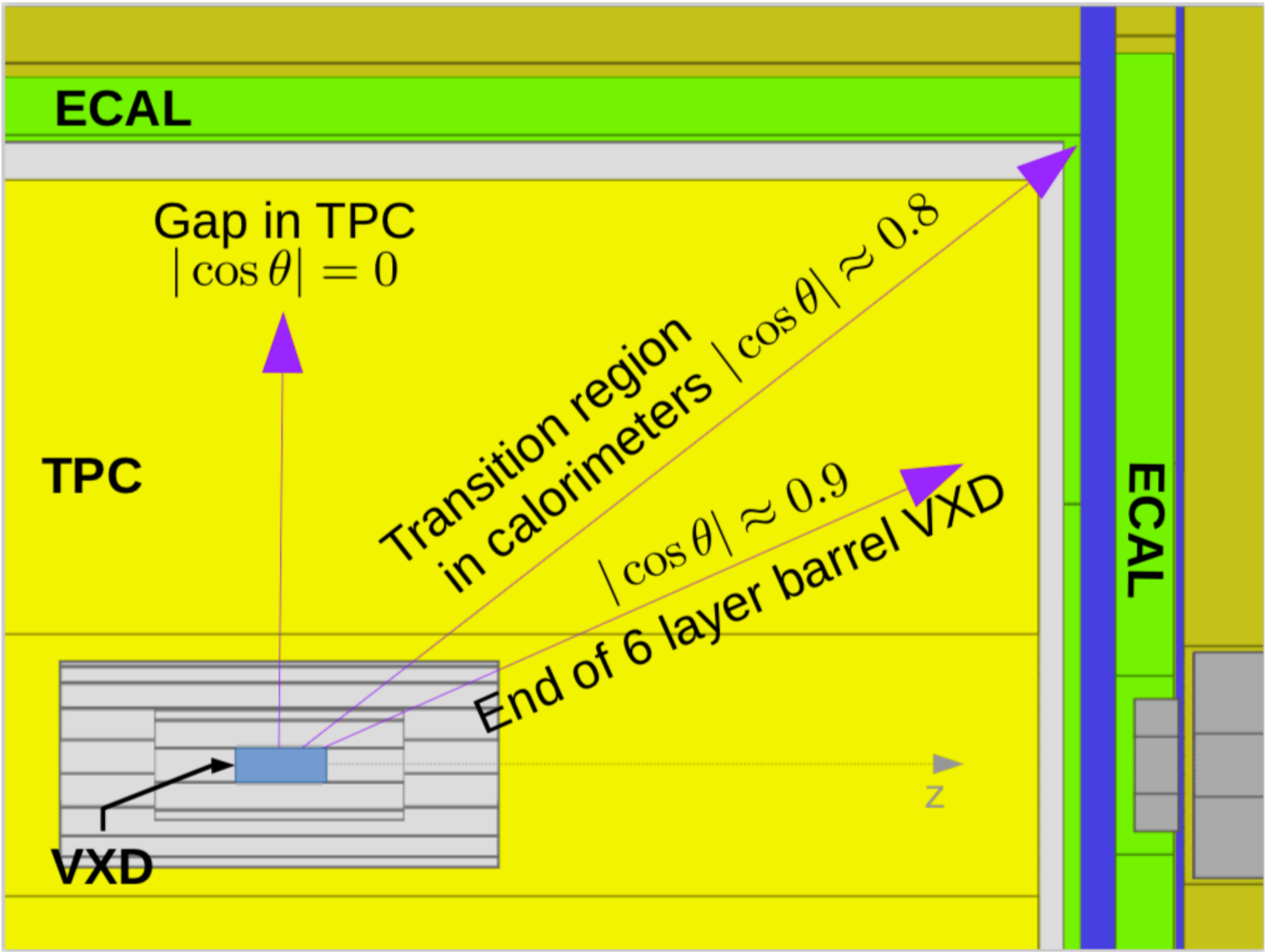


E_{jet} = E(Tracker) + E(γ) + E(K_L,n)

Composition ~60% : ~30% : ~10%

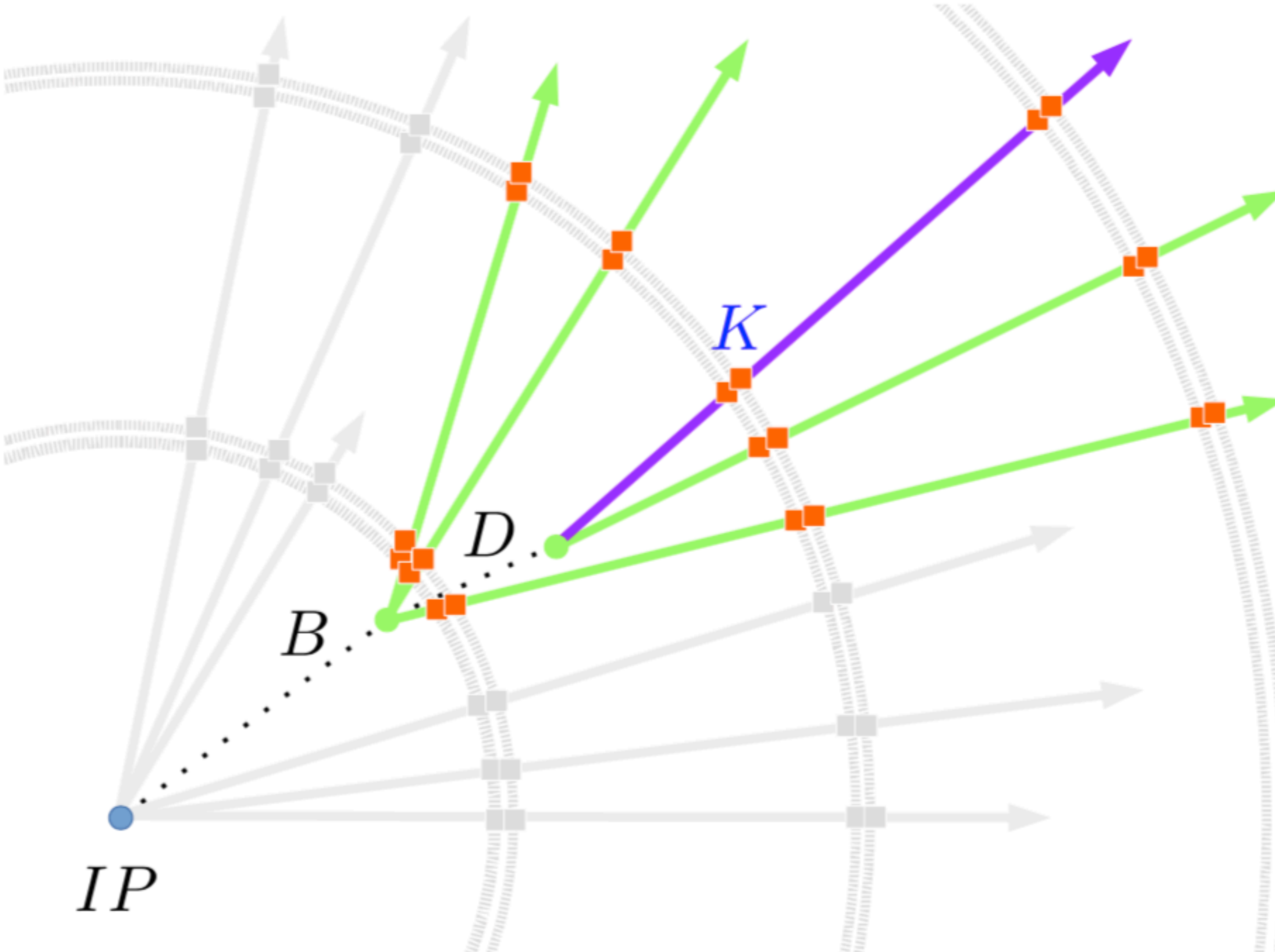
Reducing HCAL dependence improves E_{jet} resolution
→ Require highly granular ECAL & HCAL

Slide from S. Bilokin at ICHEP 2018



Flavour tagging

Kaon charge gives b charge information.



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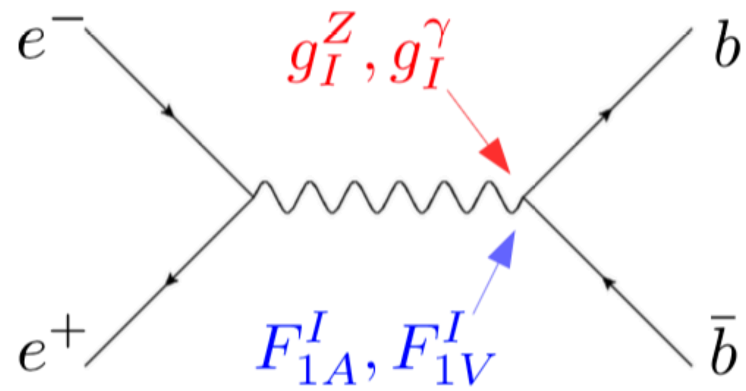
Determination of the Form Factors



- We are measuring the differential cross section

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

- where the S A are

S^I cross section magnitude $\propto F_{1V}^I, F_{1A}^I, g_I^Z, g_I^\gamma$

A^I asymmetry magnitude $\propto F_{1V}^I, F_{1A}^I, g_I^Z, g_I^\gamma$

- Independent estimation of 4 observables and 4 EW form factors using beam polarization

Relation between A^f_{FB} and A_f

$$A^f_{FB} = \frac{\sigma^f_F - \sigma^f_B}{\sigma^f_F + \sigma^f_B} = \frac{3}{4} A_f A_e$$

A^f_{FB} is used in LEP where polarized beams are unavailable.
A_f and A_e can be more accurately measured individually at SLC.

The left right asymmetry (beam polarization):

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = P A_e$$ (All Z decay modes can be used.)

$$A_f = \frac{T_3^2 - 2T_3 Q \sin^2\theta_W}{T_3^2 - 2T_3 Q \sin^2\theta_W + 2Q^2 \sin^4\theta_W}$$

A_{LR} —>$\sin\Theta_W$ or A_e

A_{FB} —> A_f

Slide from S. Bilokin at ICHEP 2018

Charge purity and polar angle correction

- We can use refused events with contradictory charges as a measure of our charge purity and calculate correction factors
- Let p be a probability of a correct charge measurement of a jet
- Then q = *1 – p* is an incorrect charge probability
- We can compute it from the following equations:

$$N = N_a + N_r$$

\# of refused events (N_r); # of accepted events (N_a)

$$N_a = N_a^+ + N_a^- = p^2 N + q^2 N \qquad N_r = 2pqN$$

- We define a number of original events:

$$\begin{cases} N_a^+ = p^2 N_{orig}^+ + q^2 N_{orig}^- \\ N_a^- = p^2 N_{orig}^- + q^2 N_{orig}^+ \end{cases}$$

$N_{orig}^{\pm}$ Original number of non-migrated events in the forward/backward bins

Migration terms: $q^2 N_{orig}^-$, $q^2 N_{orig}^+$

- Corrected values:

$$\begin{cases} N_a^{+\prime} = p^2 N_{orig}^+ \\ N_a^{-\prime} = p^2 N_{orig}^- \end{cases}$$

- We do not use generator information for correction

The accepted events include both b-quarks are assigned correct charges and both are assigned incorrect charges.

Given a probability to assign correct charge: p, we can compute the fraction of "both correct" case and "both incorrect" case.
p can be estimated from the number of events in which only one b-quark is assigned correct charge.

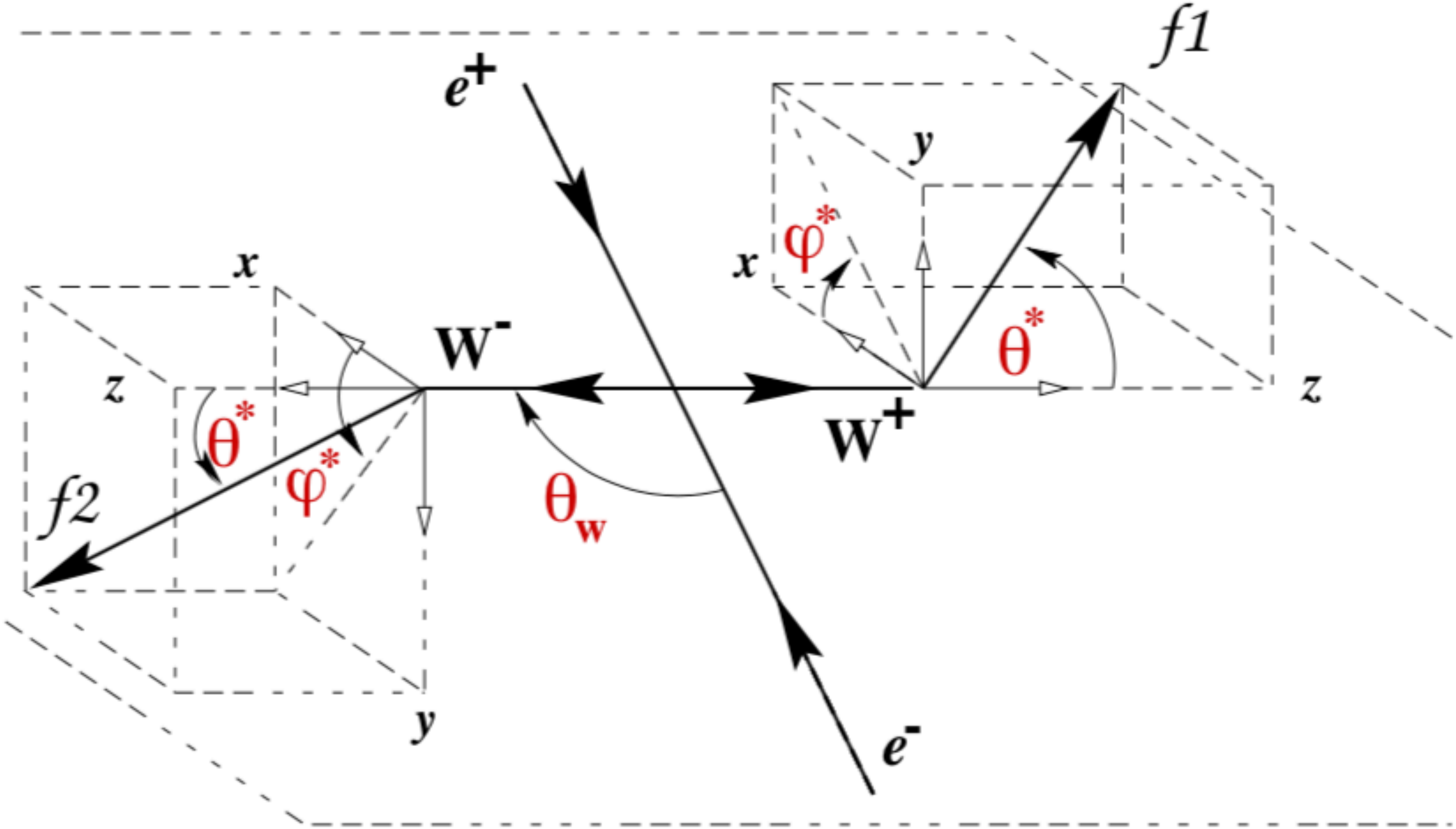


Figure 5.16: *Definition of the angles in an $e^+e^- \rightarrow W^+W^-$ event.*

f_1, f_2 are down type fermions.

Θ_w is defined as an angle between incoming e^- and outgoing W^-.

W direction can be measured by reconstruction W—>qq.

W charge can be measured by W—> lν.

Θ* and φ* are measured with W—> lν.

Θ* and φ* measurement can increase the sensitivity to the TGCs.

R. Karl, https://pos.sissa.it/314/763/pdf

ILD full simulation [8]		Extrapolations		
E_{CMS}	500 GeV	250 GeV	350 GeV	H-20 [10]
Δg_1^Z	$4.3 \cdot 10^{-4}$	$8.1 \cdot 10^{-4}$	$5.0 \cdot 10^{-4}$	$5.0 \cdot 10^{-4}$
$\Delta\kappa_\gamma$	$4.4 \cdot 10^{-4}$	$9.6 \cdot 10^{-4}$	$5.5 \cdot 10^{-4}$	$5.7 \cdot 10^{-4}$
$\Delta\lambda_\gamma$	$4.1 \cdot 10^{-4}$	$7.8 \cdot 10^{-4}$	$5.0 \cdot 10^{-4}$	$5.1 \cdot 10^{-4}$

Table 3: Achievable precision of the Triple Gauge Couplings measurement for $\mathscr{L}_\text{I} = 2\,\text{ab}^{-1}$ displayed for different center-of-mass energies and the full benchmark running scenario H-20 of the ILC.

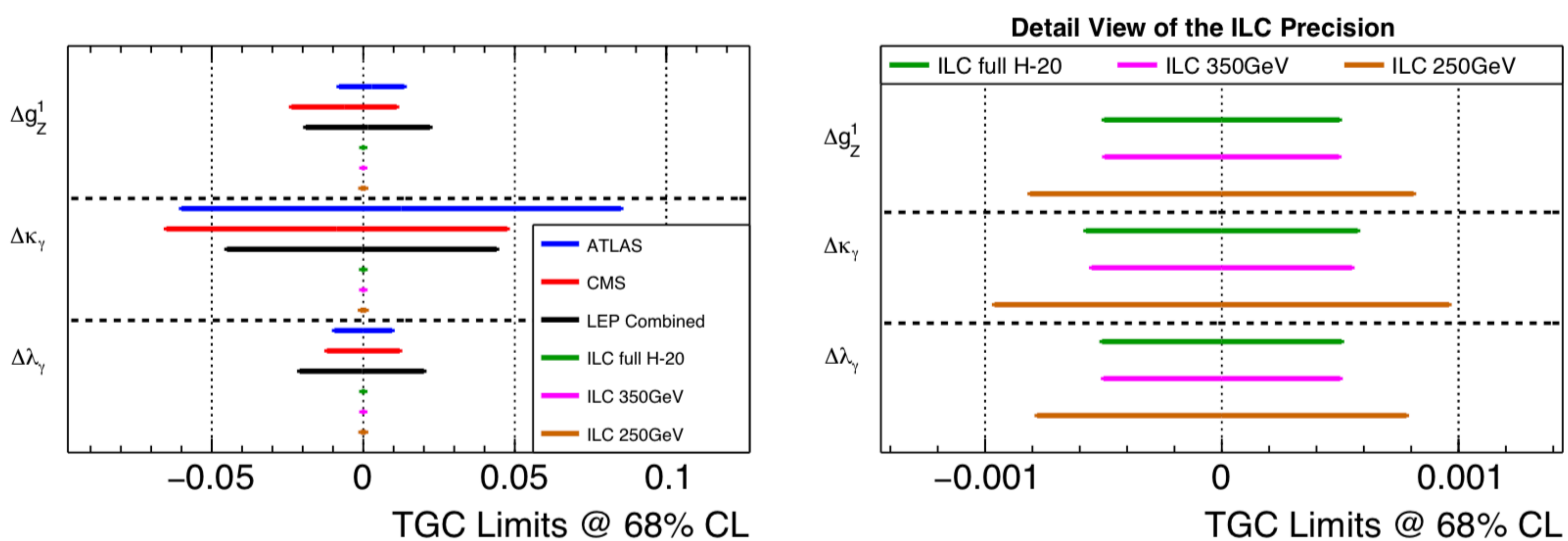


Figure 1: Comparison of the reachable TGC precision of the ILC, shown in Table 3, with the final results from LEP combined from ALEPH, L3 and OPAL results [11] and the LHC TGC limits for $\sqrt{s} = 8\,\text{TeV}$ data and an integrated luminosity of $\mathscr{L}_I = 20.3\,\text{fb}^{-1}$ and $\mathscr{L}_I = 19.4\,\text{fb}^{-1}$ for ATLAS and CMS, respectively [12].

Why we need Luminosity-Weighted Polarization?

Depolarization effects (spin precession and spin-flip) are expected to occur at the IP due to beam-beam interactions during beam bunch crossing, which increases at higher energies.
These beam-beam effects have been implemented both in Guinea Pig++ and CAIN.

It is important to cross-check the theoretical calculations (Guinea Pig++, CAIN) with measurements.
W pair production process is well known and thus can measure the luminosity-weighted polarization at IP, which can be used as an absolute scale calibration.

The total cross section is large and sensitive to the beam polarization.