Experimental challenges (*) at future e⁺e⁻ colliders

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ECFA kick-off meeting, Physics at a future electron-positron
Higgs/top/electroweak factory
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(*) Guideline from the conveners: focus on systematic uncertainties and their control

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The proposed Electroweak / Higgs / Top factories [1]

Energies (1st col.) in GeV, luminosities (2nd col.) in ab^{-1} . Yellow = in baseline plan

ILC		

FCC		

CLIC		

Numbers for two IPs

GigaZ	0.1	5 10^9 Z
WW	0.5	3.5 10^6 WW

TeraZ	150	5 10^{12} Z
WW	12	5 10^7 WW

GigaZ	0.1	5 10^9 Z

125	10/y	ee → H

250	2	750k H
tt	0.2	150k tt

240	5	1M H
tt	1.5	1M tt

tt	1	160k H 700k tt

500	4	1.5 M H 3 M tt

CEPC: same luminosity as FCC at ZH ; lower at lower √s ; no plan yet to run at the top threshold.

1500	2.5	1M H 400k tt
3000	5	3.3M H 300k tt

O(1 M) of Higgs, O(1 M) of tt
Trillions / Billions of Z

6/18/2

E.Perez

Introduction

Future ee colliders offer a broad programme of precision measurements in the electroweak, Higgs and top sectors.
- well established and documented

Statistical uncertainties: in general easy to assess
- they set the desired level for the systematic uncertainties (exp. and theo.)
- very large statistics: challenging goals on the understanding of syst. effects
- may also define challenging goals for detector and analysis design

Various studies already, different level of maturity
- work pays off: some sources of systematic looked initially challenging but ideas have been proposed and developed to control them to the desired level.

Outline:
- Key uncertainties that affect many measurements
- Go through a few examples

Luminosity measurement

- σ(ZH) for Higgs couplings with 1M Higgs: need Lumi at the per-mil level
- Precision EW measurements : call for $\Delta L/L$ of $O(10^{-4})$

Determine the luminosity from the rate of Bhabha events, measured in two forward calorimeters centered around the outgoing beam-pipes.

$d\sigma/d\theta \sim 1 / \theta^3$: excellent control of the acceptance is the key

Method of "asymmetric acceptance" :
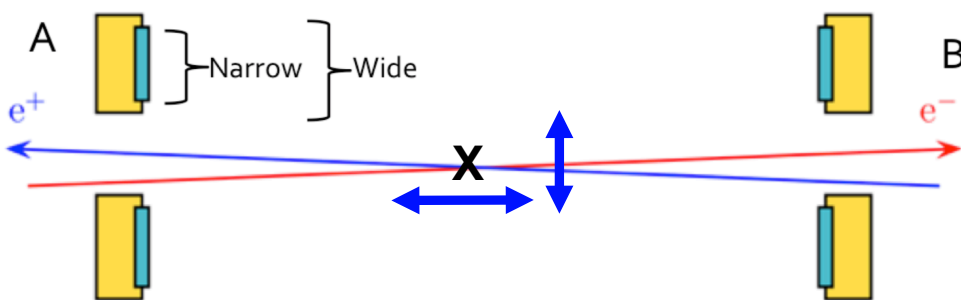
Events are selected if :
e- in Narrow and e+ in Wide
or
e+ in narrow and e- in Wide

Largely reduces the dependence of A on:
- radial or longitudinal displacements of the IP wrt lumi system.
- Any displacement of the vertex (e.g. ISR)

- **Inner radius of the detector must be known very precisely !** down to 1.6 μm for FCC

- Beam-induced effects must be corrected [2]
    - Depend on machine and bunch parameters
    - Method proposed recently [3] for a correction that doesnot rely fully on simulation

Determination of the beam polarisation

Longitudinal beam polarisation measured from inverse Compton scattering both upstream and downstream of the IP.
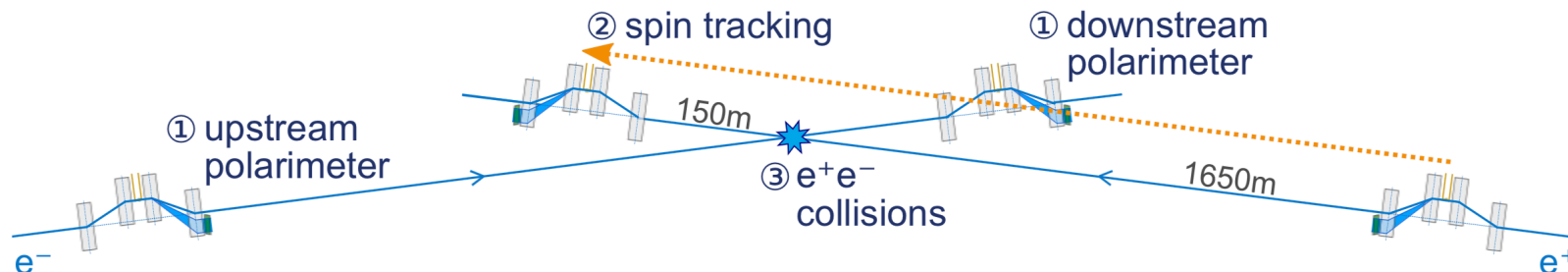

Complementarity of
- Dedicated, fast, measurements in the polarimeters, at the level of 0.25%
- In-situ measurements of cross-sections of processes with a strong P dependence
  - With both P(e-) and P(e+), as at ILC, can provide very high precision, at the per-mille level or better [4]
  - But requires a large statistics

In-situ measurements provide the overall scale to calibrate the polarimeters, which monitor the variations.

Note: also important to measure very precisely the non-polarisation (longitudinal) of beams at FCC !

Center-of-mass energy

- Need to know < √s > precisely
  - Key systematics for all mass measurements, and all EW observables.

- And the distribution of √s, i.e. :
  - basically the (gaussian) beam-energy spread (BES) for a circular machine
  - the luminosity spectrum for a linear collider
    - Large tail because of beamstrahlung
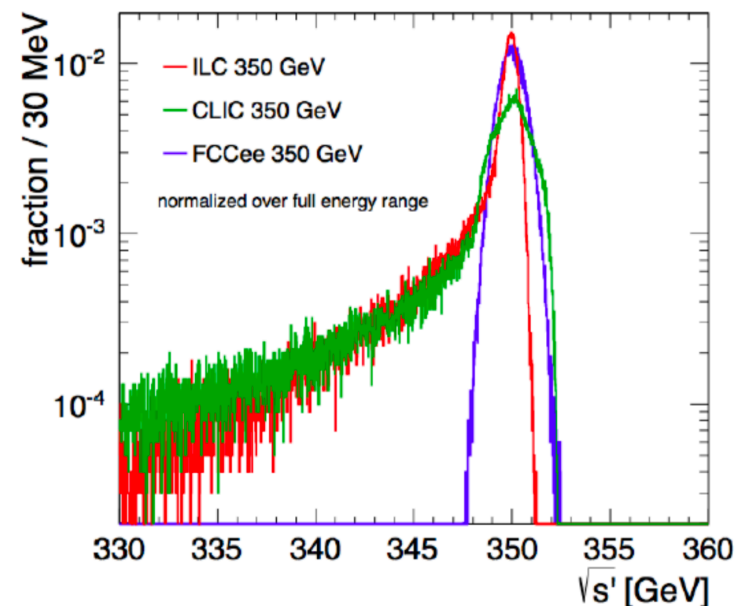
- FCC-ee, Z peak and WW threshold: exquisite precision on < √s > (100 keV at the Z, 300 keV at WW) thanks to quasi-continuous resonant depolarisation (RDP) measurements [5]
  - very powerful, unique to circular machines
  - allows a measurement of M_Z to 100 keV

- Circular at higher √s, and linear : exploit kinematic constraints of ee → ff (γ)
  - also used at circular machines to determine the BES

Constrained kinematics: $\langle \sqrt{s} \rangle$ from $ee \rightarrow ff$ (γ) events

- Above the Z peak: radiative return events, cf LEP2 : $$s = m_Z^2 \times \frac{\sin \vartheta_1 + \sin \vartheta_2 + |\sin(\vartheta_1 + \vartheta_2)|}{\sin \vartheta_1 + \sin \vartheta_2 - |\sin(\vartheta_1 + \vartheta_2)|}$$

  - Depends only on angles
  - Can use $Z \rightarrow qq$ in addition to $Z \rightarrow ll$
  - At FCC, can be used to determine $\langle \sqrt{s} \rangle$ (~ 2 MeV) at 240 GeV
    - method can be calibrated at 160 GeV against the RDP meas.
  - At 350-365 : complement with ZZ and WW events, expect O(5 MeV)

- Or, using muon momenta in (all) $\mu\mu(\gamma)$ events : [6]

  $$\sqrt{s} = E(\mu^+) + E(\mu^-) + E(\gamma) \text{ with } E(\gamma) = p(\gamma) = |\, \mathbf{p}(\mu^-) + \mathbf{p}(\mu^+) \,|$$
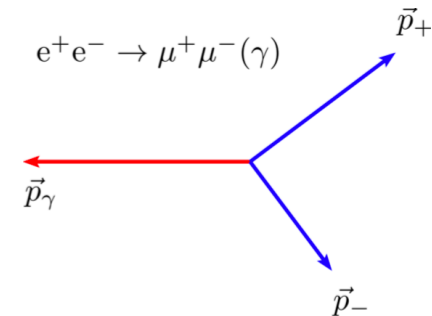
  "s_p" method, developed at ILC
  Much better statistical power with a good muon
  momentum resolution (not limited by the width of the Z).
  Stat potential with ILC/FCC tracker momentum resolution:
  $\Delta\sqrt{s}$ ~ 230 MeV per diµ event when p(µ) ~ 50 GeV
      - i.e. negligible stat error at 240 - 250 GeV for LC / CC
      - syst uncertainty given by the absolute p scale

$e^+e^- \rightarrow \mu^+\mu^- (\gamma)$

$\vec{p}_+$

$\vec{p}_\gamma$

$\vec{p}_-$

Measure $\sqrt{s_p}$ using,
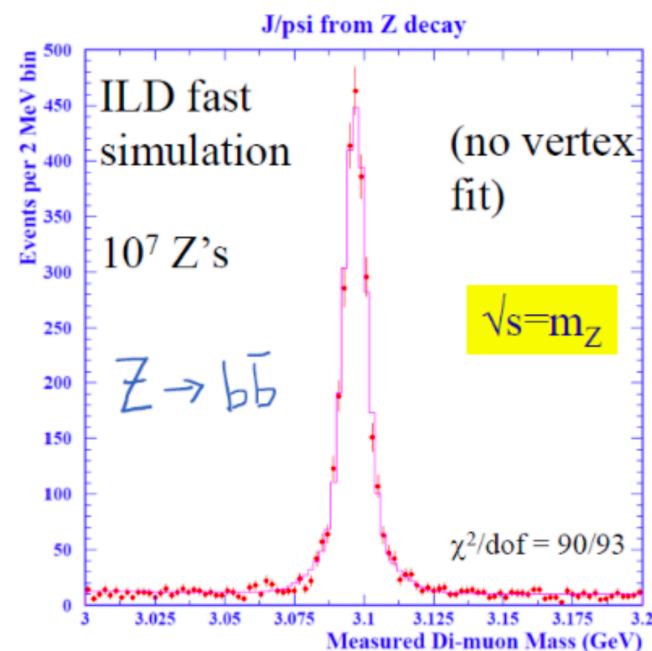$(|\vec{p}_+|, |\vec{p}_-|, |\vec{p}_+ + \vec{p}_-|)$

Key = tracker momentum calibration.

Tracker momentum scale

- At $\sqrt{s} > M_Z$, can be determined from the Z(µµ) peak in Z(+X) events
  - Would be limited to > 2.3 MeV / M_Z = 25 10^{-6} with the current unc. on M_Z
  - At FCC: Improved M_Z to 100 keV, and regular runs at the Z peak: scale calibrated to 1 ppm for the post-TeraZ runs.

- Alternative: Use J/$\psi \to$ µµ [6], taking advantage from :
  - Statistics not so poor : 0.15 J/$\psi \to$ µµ events in 1000 Z $\to$ had decays
  - Excellent knowledge from the J/ψ mass (to 1.9 ppm)
  - Excellent σ(M) offered by the detector (2-3 MeV)

Statistical potential:
  - GigaZ: 100 fb^{-1} at Z peak : abs scale to < 5 ppm
  - ILC 250: abs. scale to < 10 ppm

Further improvements could come from using other resonances (D0, Ks) which are produced much more copiously [7].

J/psi from Z decay

ILD fast simulation

10^7 Z's

$Z \to b\bar{b}$

(no vertex fit)

$\sqrt{s}=m_Z$

χ^2/dof = 90/93

Muon momentum scale: challenges

This high statistical potential can be spoiled by whatever affects the tracking…
Need to know how to correct for non-uniformities of the momentum scale in time
or across the detector, in particular :
- Tracker alignment
- Material distribution, etc
- Knowledge of the (complicated) magnetic field: stability, magnetic field map
    - Precise mapping of the field + NMR probes (~ 10 ppm ?)

Need to be controlled:
- At the level of a few ppm to ensure a $\sqrt{s}$ uncertainty of a few ppm at ILC, opening up a programme of precision EW measurements at ILC [6, 8]
- At FCC at the Z peak: 1 ppm on $\sqrt{s}$ provided by RDP but 2x better precision is desirable for the point-to-point uncertainty, i.e. relative uncertainty on $\sqrt{s}$ across the $\sqrt{s}$ points in the lineshape scan [5].
    - measurement of Γ_Z to 25 keV, also for $A_{FB}(\mu\mu)$
    - Very large statistics of low mass resonances likely provides a sub-ppm monitoring of scale variations $\rightarrow$ pt-to-pt $\Delta\sqrt{s}$ can be obtained my comparing the position of the $M\mu\mu$ peak, across the scan.
- To be studied in detail !

Constrained kinematics: also brings the energy distribution

ee → f f (γ) : the relative longitudinal momentum imbalance can be reconstructed from the angles of the fermions only. Imbalance can be due to :
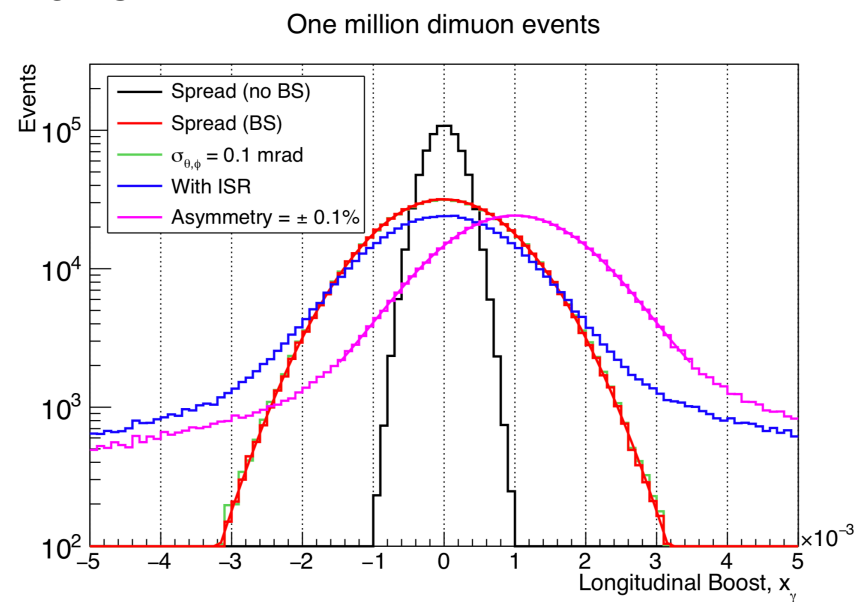- intrinsic energy spread of the beam
- intrinsic e^+ and e^- beam energy difference
- photon ISR or beamstrahlung along the z axis

- FCC: use dimuon events to reconstruct the distribution [5]

  The width of $x_\gamma = p_Z (\gamma) / \sqrt{s}$ gives the BES, precision of 0.1% with 1M events
    - 0.1% per 5 min at the Z peak
    - 1% per day at 240 GeV

- LC: use Bhabha events instead (stat), with e- detected in the tracker [9] (or dimuons too at a GigaZ run)

One million dimuon events

Events
- Spread (no BS)
- Spread (BS)
- $\sigma_{\theta,\phi}$ = 0.1 mrad
- With ISR
- Asymmetry = ± 0.1%

Longitudinal Boost, x_γ

The distribution of the acollinearity gives the luminosity spectrum.
Mostly relevant for CLIC at highest $\sqrt{s}$, e.g. leads to 0.15% on σ($\nu\nu$H).   [10]

Alignment

Tracker alignment needs to be in line with the exquisite intrinsic resolution – e.g. single hit resolution of a few mum.

- some measurements may set very challenging requirements – e.g. measure the tau lifetime at FCC-ee with a precision commensurate with what the statistic offers !

Surveys and laser-based systems usually provide a good starting point.

Precise alignment achieved with real tracks – from cosmics, collisions, with and without magnetic field. [11, 12]

LC specifics {
- power-pulsing, triggerless readout: not good for cosmics
- ILC: Need to re-establish alignment after each push-pull

- FCC: considers regular alignment / calibration runs at the Z peak. Provides very large rate of high p tracks. Was done at LEP, deemed good use of beam time !
  - E.g. every month (12 hours setup)
  - 100 10^6 Z in 12 hours: x20 LEP/exp ! each Z $\rightarrow$ had evt: about 15 tracks.

- ILC : feasibility now established for interesting luminosity (L of 2-4 10^{33} cm^{-2} s^{-1}) at the Z peak.
  - 14 10^6 Z in one day : x3 LEP/exp
  - To be compared with ~ 100 10^6 Z at 250 GeV, full sample.

Calibrations: energy scales, efficiencies, etc

- Running at the Z peak offers a standard candle for calibration of energy scales, reconstruction efficiencies, particle ID efficiencies, etc.
  - LEP expts typically achieved uncertainties of 0.1% - 1% on tracking reco, lepton id, flavour tagging etc, jet energy calibration at 1-2%.
  - At FCC, should be controlled to 10^{-4} with regular calib. runs at the Z peak

- Calibrations should anyway be controlled in-situ too

  Example full simulation studies, at ILC 250 and CLIC [12], using Z + γ events and the constrained kinematics:

  - Photon energy scale from Z($\mu\mu$) + γ [13]
    - Reconstruct E(γ) from the momenta of the muons and the angles of the muons and γ
    - Calibration: a few 10^{-5} to a few 10^{-4}
  - Jet energy scale from Z(jj) + γ [14]
    - Reconstruct the jet energies from the angles only (of both jets and the γ)
    - Calibration to O(10^{-4})
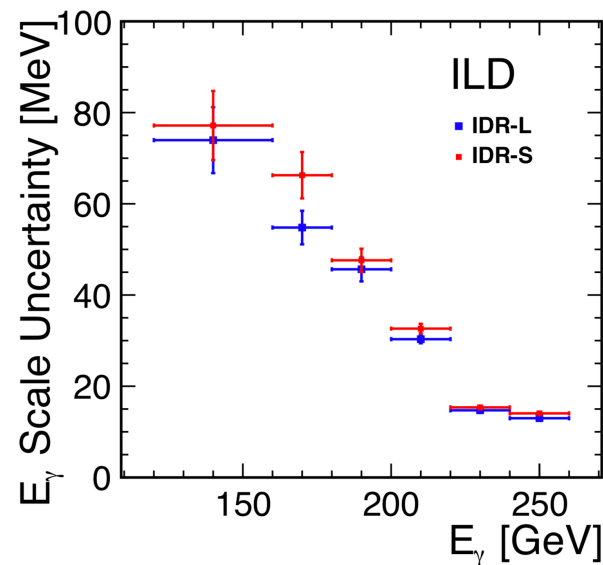
Now a few examples of measurements…

[illustrating some areas where further work is needed]

Measurement of the W mass (and width) from a threshold scan

Sensitivity to mass and width is different at different √s: can optimize mass and width by choosing carefully the √s points [15].

Lumi	Collider	ΔM_W (stat.)
12 ab^{-1}	FCC-ee	400 keV
0.5 ab^{-1} w P = (90%, 60%)	ILC (not in baseline)	1100 keV [16]

Key exp. systematics :

- √s : near threshold: $\Delta M_W \approx \Delta(\sqrt{s}) / 2$
- Point-to-point normalisation uncertainties
    - lumi, signal efficiencies : a few 10^{-4}
- Background: $\Delta M_W \approx 500$ keV x ($\Delta\sigma$ / 1 fb)
    - E.g. 4 jet channel: σ(bckgd) is ~ 200-300 fb
    - Polarised : constrained from 4 (P-, P+) configurations.
    - Unpolarised : constrained from data below the WW threshold

σ indep. of the W width for √s ~ 162 GeV
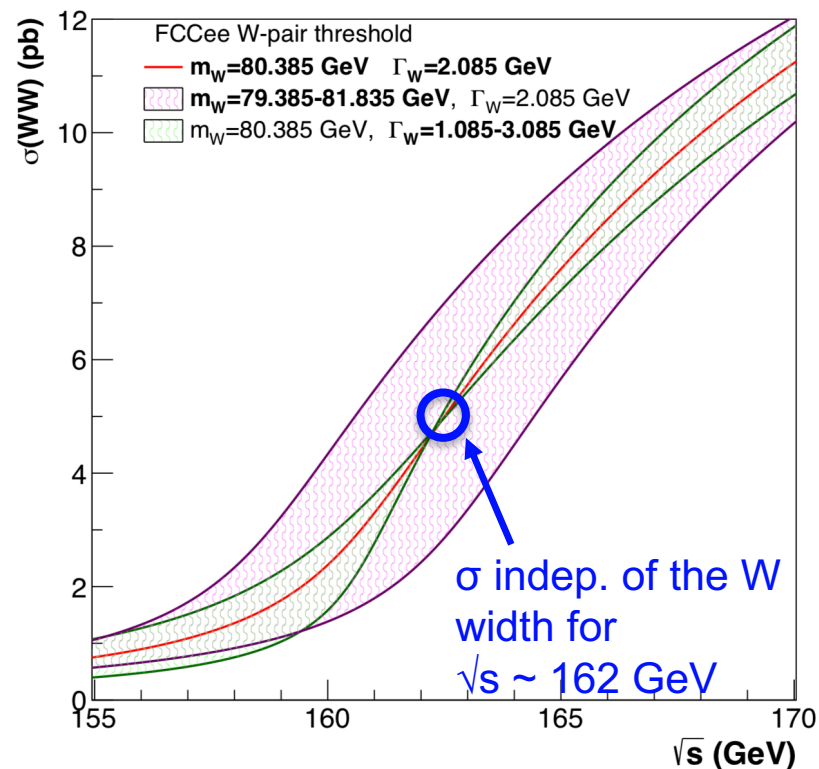
Syst < stat demanding. Need to find an optimal scan scenario which minimizes the background uncertainties thanks to correlations.

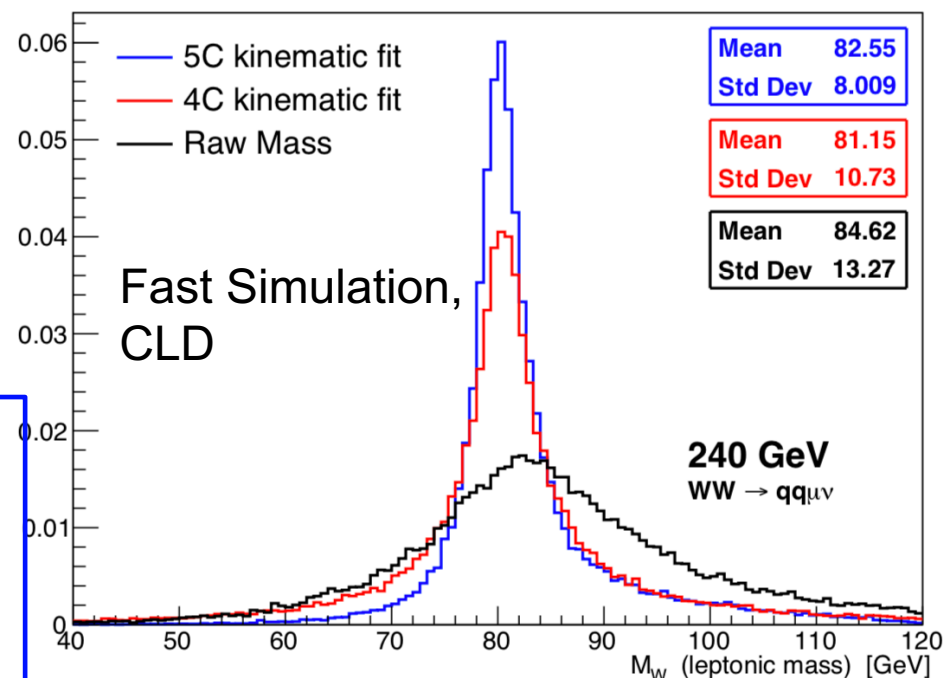# Measurement of the W mass from final state reconstruction

Both at threshold and at higher $\sqrt{s}$:

M_W can be obtained from final state reconstruction.

Several methods can be contemplated.

- esp. with precise knowledge of $\sqrt{s}$, does not have to rely only on hadronic masses (JES syst.)

FCC: at threshold, precision may compete with scan – i.e. O(500 keV) - if systematic uncertainties are controlled [17].
ILC baseline : could allow a < 3 MeV measurement with 250 GeV dataset [8].

	Mean	Std Dev
5C kinematic fit	82.55	8.009
4C kinematic fit	81.15	10.73
Raw Mass	84.62	13.27

Fast Simulation, CLD

240 GeV
WW → qqμν

Example: Kinematic fit
- Exploit 4-momentum conservation: thanks to precise knowledge of $\sqrt{s}$
  - $\Delta\sqrt{s}$ at FCC 240 GeV: yet to be improved to compete with the scan !
  - Requires very good understanding of full error matrices of objects
  - Effect of ISR and beamstrahlung ?
- Hadronic channel : uncertainties from WW → had modeling ?
  - Controlled from precise measurements of frag. properties of Z → qq

Precision meas. of EW couplings: $\sin^2\theta_{eff}$ from A_e $\qquad A_f = \dfrac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2}$.

- **Polarized collider:** $A_e = A_{LR} = (\sigma_L - \sigma_R)/(\sigma_L + \sigma_R)$. Robust. Dominant syst. from the polarisation measurement, measured in-situ thanks **to both P+ and P- :**

  - **ILC 250**, 2 ab^{-1}: 80 M hadronic Z's from radiative return: **stat dominated:**
    - Stat error (rel) = 10^{-3}, i.e. $\Delta(\sin^2\theta_{eff}) \sim 2\ 10^{-5}$ ($\sim$ current / 10)
  - **Giga-Z** : $3\ 10^9$ hadronic Z's, **dominated by systematics** [8]
    - Precise meas. of $\sqrt{s}$ is crucial: rel error = $1.3\ 10^{-4}$ x $\Delta\sqrt{s}$ / MeV
    - Pol: $5\ 10^{-4}$ (rel) expected from $\sigma(2f)$, i.e. $\Delta(\sin^2\theta_{eff}) \sim 10^{-5}$

  NB: Such precisions on $\sin^2\theta eff$ call for improved M_Z, $\alpha_{QED}(M^2_Z)$!!

At the Z pole: less in-situ constraints on pol (no WW) absent, i.e. larger impact of the polarimeter measurement ? Independent meas. useful - via $P(\tau)$ for example.

- **FCC: get A_e from the angular distrib. of the tau polarisation**

Fit of $P(\tau)$ vs $\cos\theta\tau$: A_e much less affected by syst. than A_τ.

- Main uncertainty: Bhabha bckgd, measured in-situ.
- Should provide $\Delta(\sin^2\theta_{eff}) = 2\text{-}3\ 10^{-6}$

A_τ more demanding: e.g. systematics on ECAL scale and γ misid to be studied. Focus on $\rho\nu$ or $\tau \to h\nu$: avoid modelling uncertainties affecting the a1 channel.
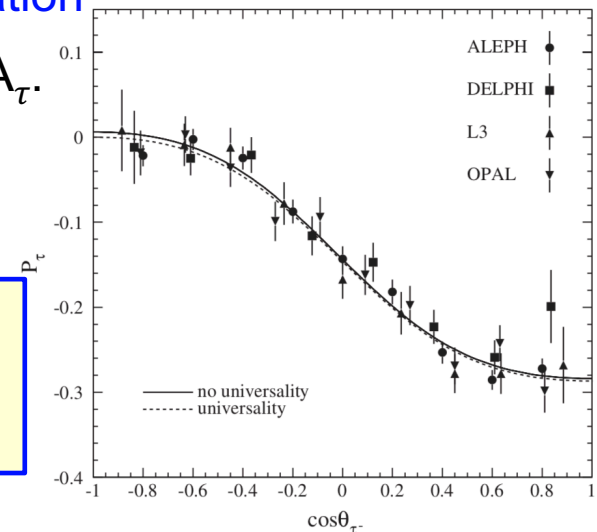
Precision meas. of Z couplings: R_l, R_b and R_c

$$1 / R_l = \Gamma_l / \Gamma_{had},$$
$$R_{b,c} = \Gamma_{b,c} / \Gamma_{had}$$

- Dominant systematic on R_l expected to come :
    - from identification efficiencies with a few times the LEP statistics (ILC 250)
    - from the determination of the acceptance at GigaZ / FCC

Example, R_l at FCC: goal for $\Delta R_l / R_l$ = 1-5 10^{-5} . Position of edge of the forward calorimeter, edge of tracking acceptance: must be known to O(10 µm).
- the fwd detector must be carefully designed
    - e.g. hermetic calo, precise pre-shower in front
- will need "asymmetric" selection as done for the luminosity measurement

- Measurement of $R_{b,c}$: large statistics + improved VTX detectors w.r.t LEP / SLD allows to focus on double-tagged events. Expected systematics:
    - Hemisphere correlations: much less an issue than at LEP thanks to very small beam-spot. Further minimized with a tagger whose efficiency is independent on the b kinematics.
    - Large control samples to study effect of gluon splittings
    - Selections that minimize QCD effects

    Uncertainties O(10x – 100x) better than current ones within reach: [8, 18]
        $\Delta R_b / R_b$ ~ (0.5 – 1) . 10^{-4} at FCC, (7 – 10). 10^{-4} at GigaZ / LC

Conclusions

- Strategies are being developed to control luminosity, √s, polarisation, calibrations, alignment at a level such such that these should not limit the experimental accuracy of the majority of measurements. Still lots of work ahead, e.g. :
  - ○ Improving further on the precision on √s is worth the effort
  - ○ Reaching 10^{-4} on the Luminosity with Bhabha is a real challenge: alternative? Can we use ee $\rightarrow \gamma\gamma$ events ? (acceptance, ee background)

- Systematic uncertainties related to background subtraction: must be studied separately for each analysis
  - ○ In many cases, scale down with the increased statistics (control samples, in-situ bckgd determinations). How low can we go ?

- Kinematic fits can lead to reduced uncertainties. Full potential to be understood and quantified - can serve several analyses

- Systematic uncertainties vs detector design :
  - ○ Unprecedented requirements e.g. on :
    - • The determination of the acceptances at GigaZ / TeraZ
    - • The stability of the momentum reconstruction and magnetic field
  - ○ Importance of redundancy

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      et al, arXiv:1909.12245

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[8] Tests of the Standard Model at the International Linear Collider, K.Fujiii et al,
<u>arXiv:1908.11299</u>

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the ILC, A. Sailer,   <u>Diploma thesis</u>
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<u>Eur. Phys. J. C 77, 475 (2017)</u>

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<u>http://cds.cern.ch/record/2686663</u>

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[16] The uncertainty from [8] has been scaled to 500 fb-1. See also: Updated Study of a Precision Measurement of the W Mass from a Threshold Scan Using Polarized e−e− and e+e+ at ILC, G. Wilson, arXiv:1603.06016

[17] Calorimetry and W mass measurement for future experiments, M. Beguin, PhD thesis, Université de Paris-Saclay,

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[21] Determination of the electroweak couplings of the 3rd generation of quarks at the ILC , A. Irles et al, PoS EPS-HEP2019 (2020) 624

[22] Revisiting QCD corrections to the forward-backward charge asymmetry of heavy quarks in e+e- collisions at the Z pole, J. Alcaraz Maestre, arXiv:2010.08604

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Backup

Example of Higgs measurements: M_H

Extracted from an analysis of the distribution of the recoil mass

$\Delta M_H \sim 6$ MeV

CEPC [19]

$\Delta M_H \sim 14$ MeV

ILC [20]

$\Delta M_H \sim 100$ MeV

CLIC [10]
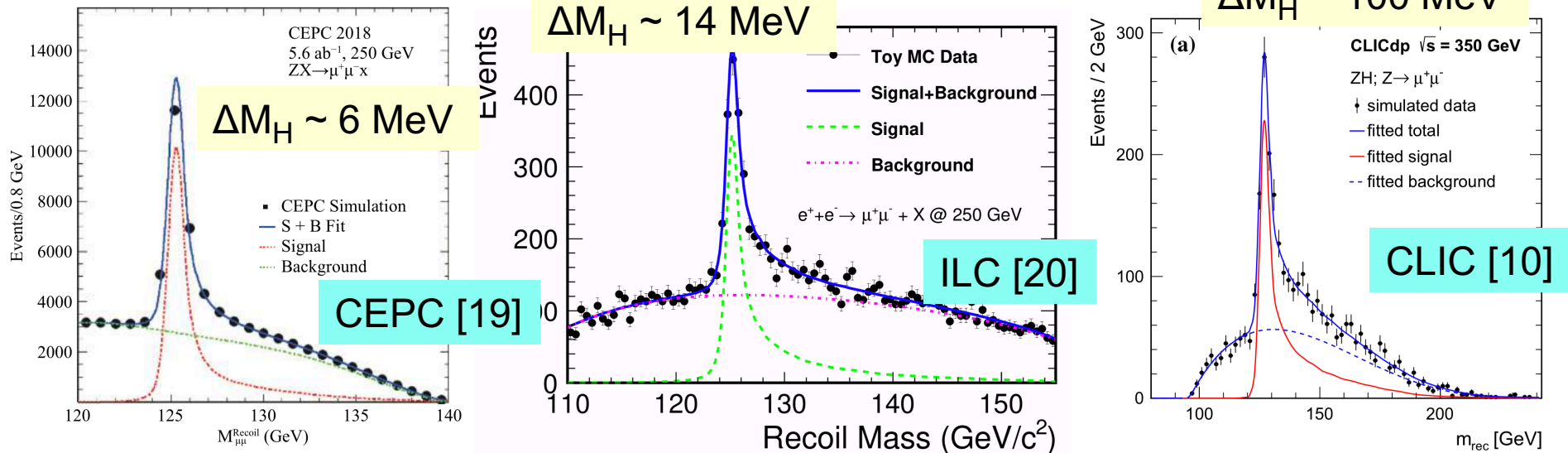
Better precision (Γ_H or even better !) desirable in view of a potential run at 125 GeV at FCC.
- $\Delta(\sqrt{s})$ of 1-2 MeV and uncertainty on BES adequate
- Optimize the resolution of $Z \rightarrow$ ee channel and use exclusive modes, including $Z \rightarrow$ had., exploiting kinem. constraints: many systematic studies to be carried out !

Increasing tail of M_{rec} distribution with increasing beamstrahlung !

CLIC: best prospect from exclusive H $\rightarrow$ bb reco. Systematics from b-jet energy scale is comparable to the stat. uncertainty (40 MeV).
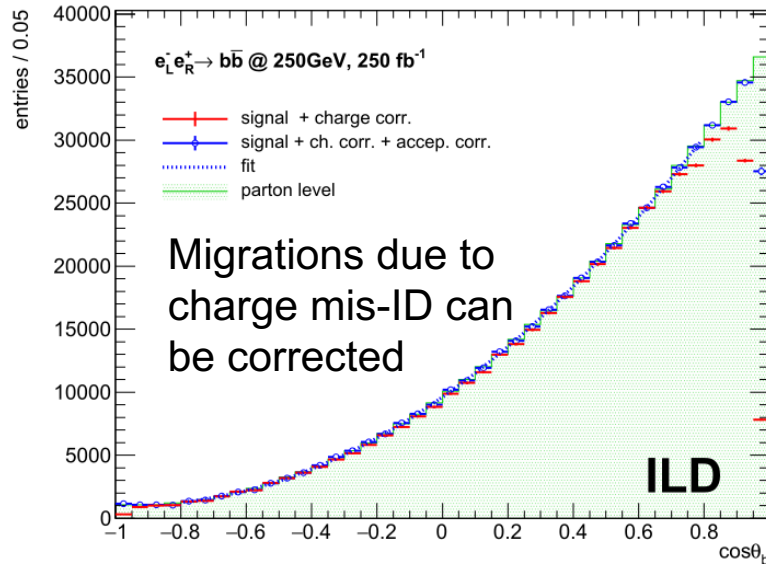
Precision meas. of the EW couplings: A_{FB}^b

$e_L^- e_R^+ \to b\bar{b}$ @ 250GeV, 250 fb^{-1}

- signal + charge corr.
- signal + ch. corr. + accep. corr.
- fit
- parton level

Migrations due to charge mis-ID can be corrected

ILD

[$\sin^2\theta_{eff}$]

A_l(SLD)	—▲—	0.23098 ± 0.00026
$A_{fb}^{0,b}$	—▼—	0.23221 ± 0.00029

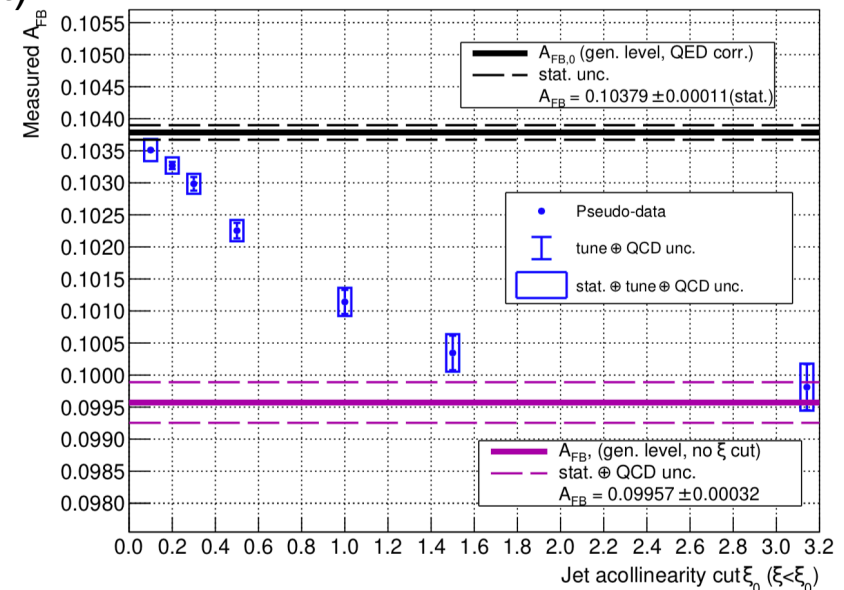Additional challenge w.r.t. R_b : need to determine the charge of the b

→ vertex charge, lepton charge, also Kaon charge very powerful ⇒ particle ID [21]

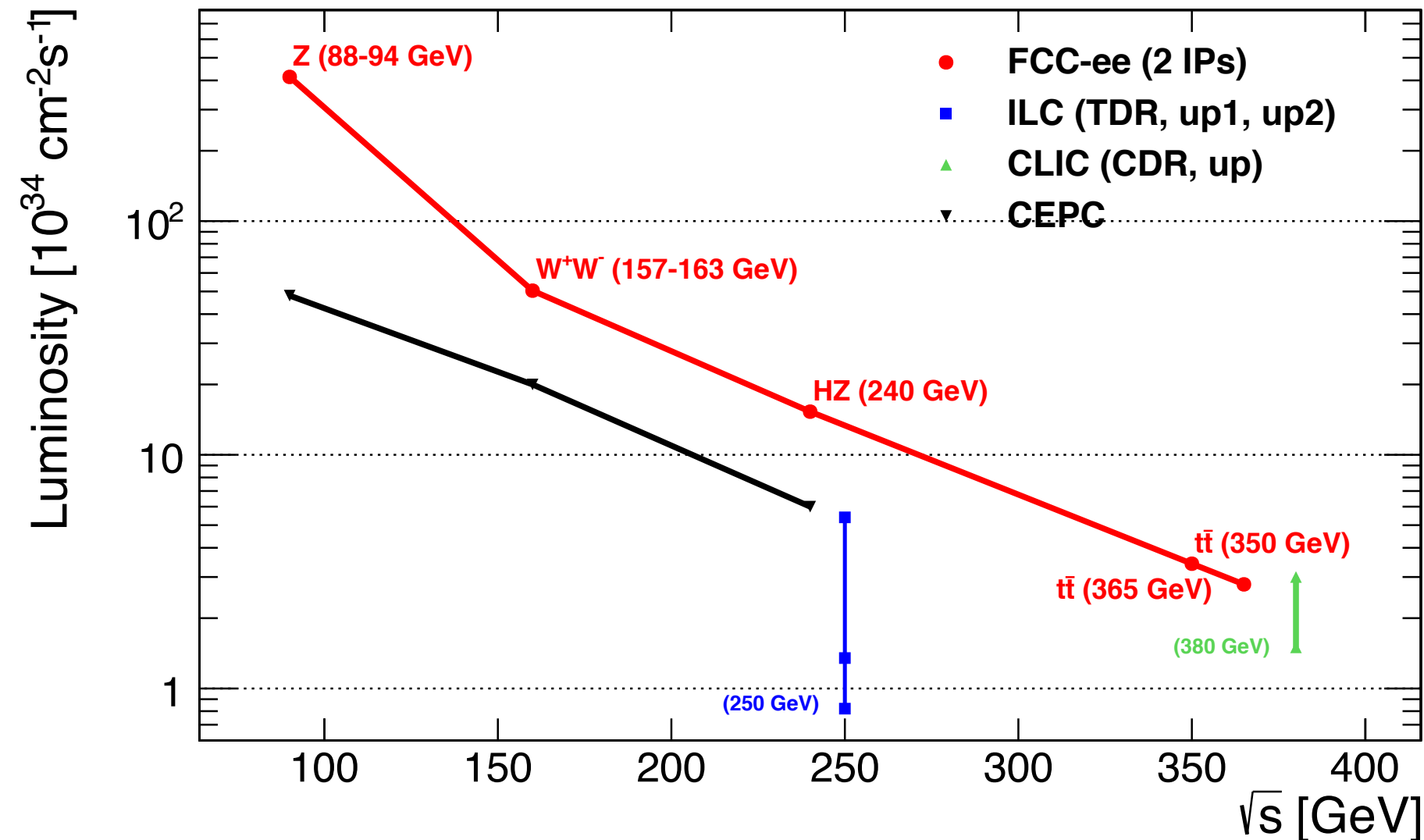At Z peak: ΔA_{FB}^b : 0.0016 (stat) ± 0.0007 (syst). Contributions to this systematics :

- **Charge confusion + Contamination from charm and light:** scale with the statistics, as can be reduced from large control samples.
  moreover, with huge stat: can use exclusive B+ modes to largely get rid of it.

- **QCD corrections:** 3 10^{-4}
 can be reduced by O(10) with acollinearity cuts [22]

FCC-ee simulation, 7×10^7 $e^+e^- \to b\bar{b}(g)$ events

$A_{FB,0}$ (gen. level, QED corr.)
stat. unc.
A_{FB} = 0.10379 ±0.00011(stat.)

- Pseudo-data
  tune ⊕ QCD unc.
  stat. ⊕ tune ⊕ QCD unc.

A_{FB}, (gen. level, no ξ cut)
stat. ⊕ QCD unc.
A_{FB} = 0.09957 ±0.00032

Jet acollinearity cut ξ_0 ($\xi < \xi_0$)

5

The proposed "low energies" Electroweak / Higgs / Top factories

Alternative measurement of the luminosity : $ee \rightarrow \gamma\gamma$ at large angles
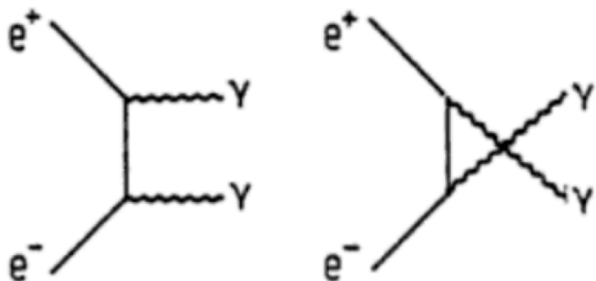
- Pure QED process (at LO)
- Well controlled theoretically

Much smaller σ than small angle Bhabhas, but statistics still adequate for a precision of 10^{-4}

Example: [23]
θ_{min} = 20 deg

Huge contamination from $e^+e^- \rightarrow e^+e^-$ before any id cut
(20 - 100x signal)

Energy	Process	Cross Section	Large angle $e^+e^- \rightarrow \gamma\gamma$	Large angle $e^+e^- \rightarrow e^+e^-$
90 GeV	$e^+e^- \rightarrow Z$	40 nb	0.039 nb	2.9 nb
160 GeV	$e^+e^- \rightarrow W^+W^-$	4 pb	15 pb	301 pb
240 GeV	$e^+e^- \rightarrow ZH$	0.2 pb	5.6 pb	134 pb
350 GeV	$e^+e^- \rightarrow tt$	0.5 pb	2.6 pb	60 pb

Need a good control of the e/γ separation (γ conversions, e $\rightarrow \gamma$ fake rate).

e.g. with ε (γ id) = 99% and fake(e $\rightarrow \gamma$) = 1%, would need to know the γ id inefficiency to the % level and the fake rate to a few per-mille.

Worth to take a closer look – systematics completely different from small angle Bhabhas (and no beam induced effect !)