Prospects for constraining light-quark electroweak couplings at Higgs factories

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based on work in collaboration with D. Jeans, J. Reuter, J. Tian, A.F. Żarnecki

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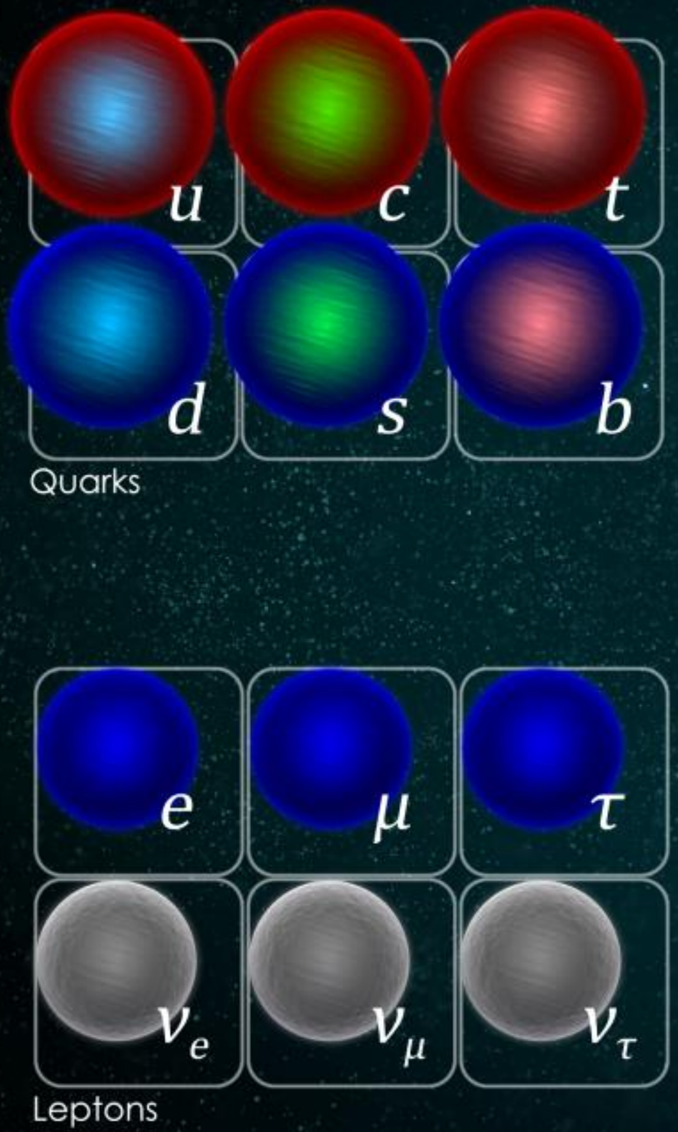
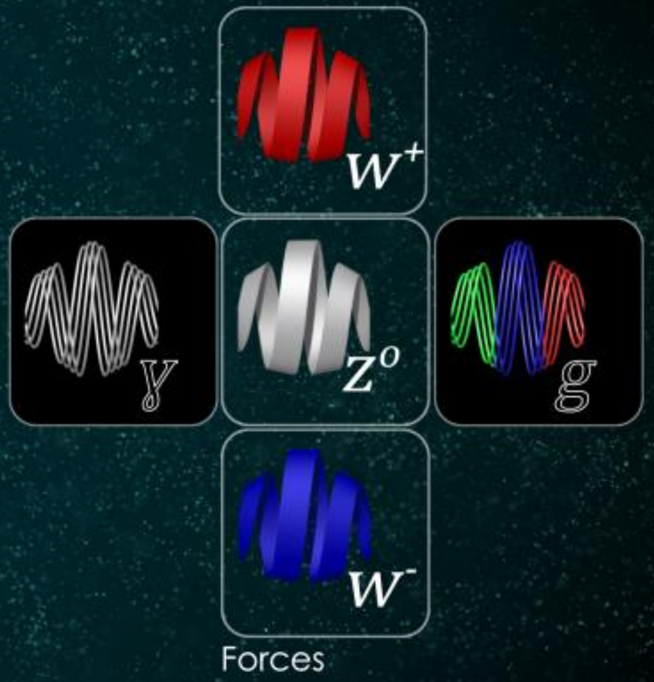
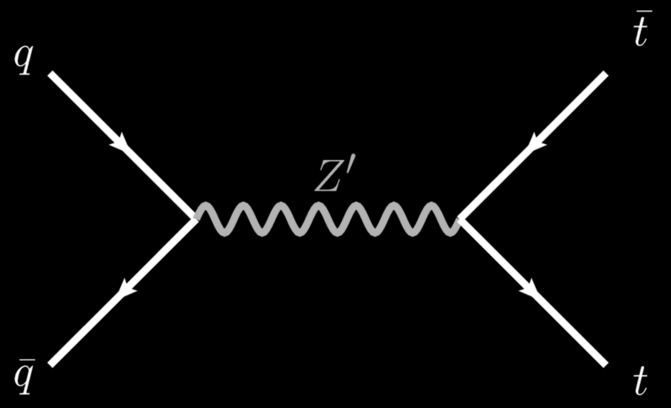
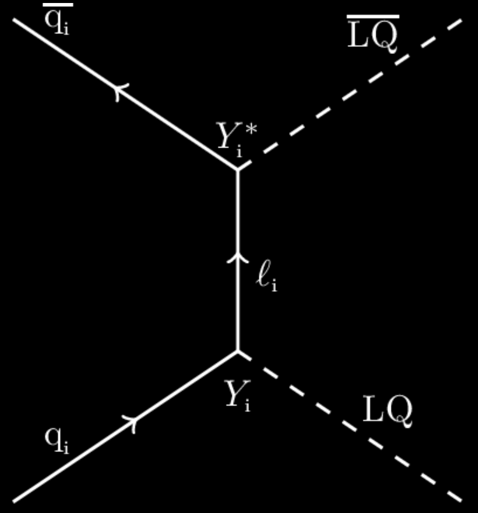


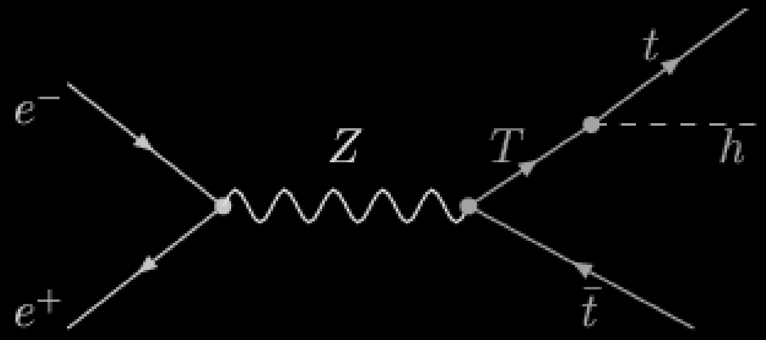


A nice picture but it is not "**self-explanatory**":
it contains many free parameters.

Measuring precision observables allows to constrain the SM parameters and to search for New Physics.







Z decays to hadrons are constrained from LEP and SLC...

Review of Particle Physics, PDG, 2022

$R_b = \Gamma(b\bar{b})/\Gamma(\text{hadrons})$ Γ_{12}/Γ_8

OUR FIT is obtained by a simultaneous fit to several c- and b-quark measurements as explained in the note "The Z boson" and ref. LEP-SLC 06.

The Standard Model predicts R_b=0.21581 for m_t=174.3 GeV and M_H=150 GeV.

VALUE	DOCUMENT ID		TECN	COMMENT
0.21629±0.00066 OUR FIT				
0.21594±0.00094±0.00075	[1] ABE	05F	SLD	E^{ee}_{cm}=91.28 GeV
0.2174 ±0.0015 ±0.0028	[2] ACCIARRI	00	L3	E^{ee}_{cm}= 89–93 GeV
0.2178 ±0.0011 ±0.0013	[3] ABBIENDI	99B	OPAL	E^{ee}_{cm}= 88–94 GeV
0.21634±0.00067±0.00060	[4] ABREU	99B	DLPH	E^{ee}_{cm}= 88–94 GeV
0.2159 ±0.0009 ±0.0011	[5] BARATE	97F	ALEP	E^{ee}_{cm}= 88–94 GeV

$R_c = \Gamma(c\bar{c})/\Gamma(\text{hadrons})$ Γ_{11}/Γ_8

OUR FIT is obtained by a simultaneous fit to several c- and b-quark measurements as explained in the note "The Z boson" and ref. LEP-SLC 06.

The Standard Model predicts R_c = 0.1723 for m_t = 174.3 GeV and M_H = 150 GeV.

VALUE	DOCUMENT ID		TECN	COMMENT
0.1721±0.0030 OUR FIT				
0.1744±0.0031±0.0021	[1] ABE	05F	SLD	E^{ee}_{cm}=91.28 GeV
0.1665±0.0051±0.0081	[2] ABREU	00	DLPH	E^{ee}_{cm}= 88–94 GeV
0.1698±0.0069	[3] BARATE	00B	ALEP	E^{ee}_{cm}= 88–94 GeV
0.180 ±0.011 ±0.013	[4] ACKERSTAFF	98E	OPAL	E^{ee}_{cm}= 88–94 GeV
0.167 ±0.011 ±0.012	[5] ALEXANDER	96R	OPAL	E^{ee}_{cm}= 88–94 GeV

$\Gamma((u\bar{u}+c\bar{c})/2)/\Gamma(\text{hadrons})$ Γ_9/Γ_8

This quantity is the branching ratio of $Z \to$ "up-type" quarks to $Z \to$ hadrons. Except ACKERSTAFF 97T the values of $Z \to$ "up-type" and $Z \to$ "down-type" branchings are extracted from measurements of Γ(hadrons), and $\Gamma(Z \to \gamma+\text{jets})$ where γ is a high-energy (>5 or 7 GeV) isolated photon. As the experiments use different procedures and slightly different values of M_Z, Γ(hadrons) and α_s in their extraction procedures, our average has to be taken with caution.

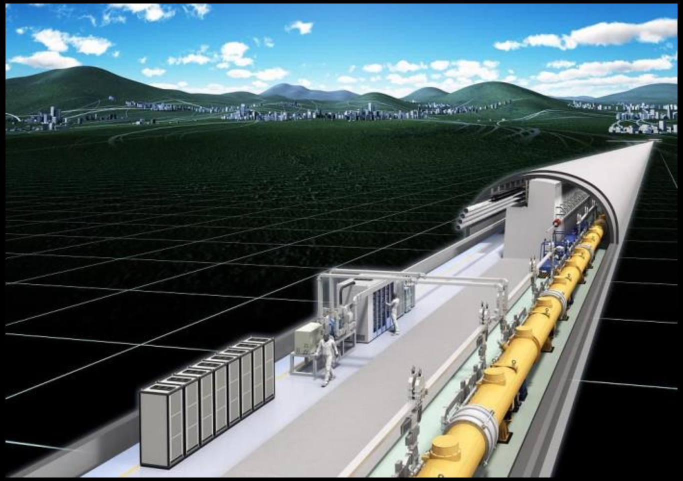
VALUE	DOCUMENT ID		TECN	COMMENT
0.166±0.009 OUR AVERAGE				
$0.172^{+0.011}_{-0.010}$	[1] ABBIENDI	04E	OPAL	E^{ee}_{cm} = 91.2 GeV
0.160±0.019±0.019	[2] ACKERSTAFF	97T	OPAL	E^{ee}_{cm}= 88–94 GeV
$0.137^{+0.038}_{-0.054}$	[3] ABREU	95X	DLPH	E^{ee}_{cm}= 88–94 GeV
0.137±0.033	[4] ADRIANI	93	L3	E^{ee}_{cm}= 91.2 GeV

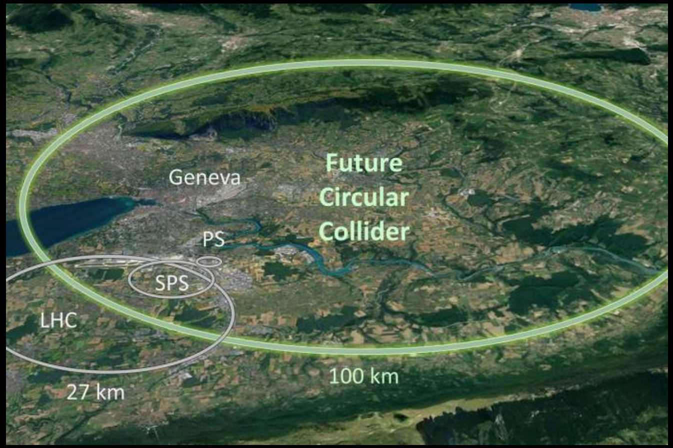
...but not all of them!

Quantity	Value	Value (universal)	Standard Model
$\Gamma_{e^+e^-}$	83.87 ± 0.12	83.942 ± 0.085	83.960 ± 0.009
$\Gamma_{\mu^+\mu^-}$	83.95 ± 0.18	83.941 ± 0.085	83.959 ± 0.009
$\Gamma_{\tau^+\tau^-}$	84.03 ± 0.21	83.759 ± 0.085	83.777 ± 0.009
Γ_{inv}	498.9 ± 2.5	500.5 ± 1.5	501.445 ± 0.047
$\Gamma_{u\bar{u}}$	—	—	299.89 ± 0.20
$\Gamma_{c\bar{c}}$	300.3 ± 5.3	300.0 ± 5.2	299.81 ± 0.20
$\Gamma_{d\bar{d}}, \Gamma_{s\bar{s}}$	—	—	382.77 ± 0.14
$\Gamma_{b\bar{b}}$	377.4 ± 1.3	377.0 ± 1.2	375.73 ∓ 0.18
Γ_{had}	1744.8 ± 2.6	1743.2 ± 1.9	1740.97 ± 0.85
Γ_Z	2495.5 ± 2.3	2495.5 ± 2.3	2494.11 ± 0.86

Review of Particle Physics,
PDG, 2022

Future e^+e^- colliders operating at the Z-pole would be a perfect place to study the couplings.





Source	$e^-e^+ \to c\bar{c}$				$e^-e^+ \to b\bar{b}$			
	$P_{e^-e^+}(-0.8,+0.3)$		$P_{e^-e^+}(+0.8,-0.3)$		$P_{e^-e^+}(-0.8,+0.3)$		$P_{e^-e^+}(+0.8,-0.3)$	
	R_c	$A_{FB}^{c\bar{c}}$	R_c	$A_{FB}^{c\bar{c}}$	R_b	$A_{FB}^{b\bar{b}}$	R_b	$A_{FB}^{b\bar{b}}$
Statistics	**0.18%**	**0.38%**	**0.27%**	**0.52%**	**0.12%**	**0.24%**	**0.23%**	**0.70%**
Preselection eff.	<0.01%	0.12%	0.02%	0.16%	<0.01%	0.08%	0.06%	0.12%
Background	0.01%	0.01%	0.02%	0.02%	0.01%	0.01%	0.06%	<0.01%
heavy quark mistag	0.11%	<0.01%	0.06%	<0.01%	0.12%	<0.01%	0.22%	<0.01%
uds mistag	0.03%	<0.01%	0.02%	<0.01%	0.08%	<0.01%	0.14%	<0.01%
Angular correlations	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%
Beam Polarisation	<0.01%	<0.01%	0.02%	0.01%	<0.01%	0.01%	0.03%	0.15%
Systematics	**0.15%**	**0.16%**	**0.12%**	**0.19%**	**0.18%**	**0.13%**	**0.29%**	**0.22%**
Total	**0.24%**	**0.41%**	**0.30%**	**0.55%**	**0.21%**	**0.27%**	**0.37%**	**0.73%**

A. Irles *et al.*, [2306.11413]

The branching ratios to heavy quarks could be well constrained at ILC thanks to excellent flavour-tagging.

But how to take the measurement if...

- tagging is imperfect (*s* quark)?
- tagging is unavailable (*u*, *d* quarks)?

How to measure Z couplings to light quarks?

General idea

We want to measure quark couplings:

$$c_f = v_f^2 + a_f^2$$

They are given in the SM by:

$$v_f = 2I_{3,f} - 4Q_f \sin^2\theta_W \qquad a_f = 2I_{3,f}$$

Γ_{had} reads (exact at fixed order):

$$\Gamma_{had} = N_c \frac{G_\mu M_Z^3}{24\pi\sqrt{2}} \left(1 + \frac{\alpha_s}{\pi} + \ldots\right) (3c_d + 2c_u)$$

and $\Gamma_{had+\gamma}$:

$$\Gamma_{had+\gamma} = N_c \frac{G_\mu M_Z^3}{24\pi\sqrt{2}} f(y_{cut}) \frac{\alpha}{2\pi} \left(3q_d^2 c_d + 2q_u^2 c_u\right)$$

The correction factor $f(y_{cut})$ to be determined for a given value of the resolution parameter y_{cut}.

Measurement at the Z-pole

We can measure radiative and non-radiative cross sections separately and disentangle the couplings c_d and c_u:

$$\sigma_{Z\to had} = \mathcal{C}_1 \cdot (3c_d + 2c_u)$$

$$\sigma_{Z\to had+\gamma} = \mathcal{C}_2 \cdot (3c_d + 8c_u)$$

Note: in this picture, the couplings are universal among quarks of the same type. This assumption can be lifted by employing heavy-flavour tagging.

How to generate Monte Carlo events?

Analysis setup

We want to consider:

$$e^+e^- \rightarrow q\bar{q}(\gamma)$$

Experimentally measured photons can originate not only from the Final State Radiation but also from the Initial State Radiation, hadronisation and decays...

One may encounter the following issues:

- **Matrix Element** calculations may be either divergent or very slow for small photon-emission angles,
- **ISR structure functions** can be used for small angles but a proper matching procedure is needed,
- **FSR showers** are important to account for QCD emissions but they may cause double-counting,
- photons coming from **hadronisation** and **hadron decays** have to be included properly.

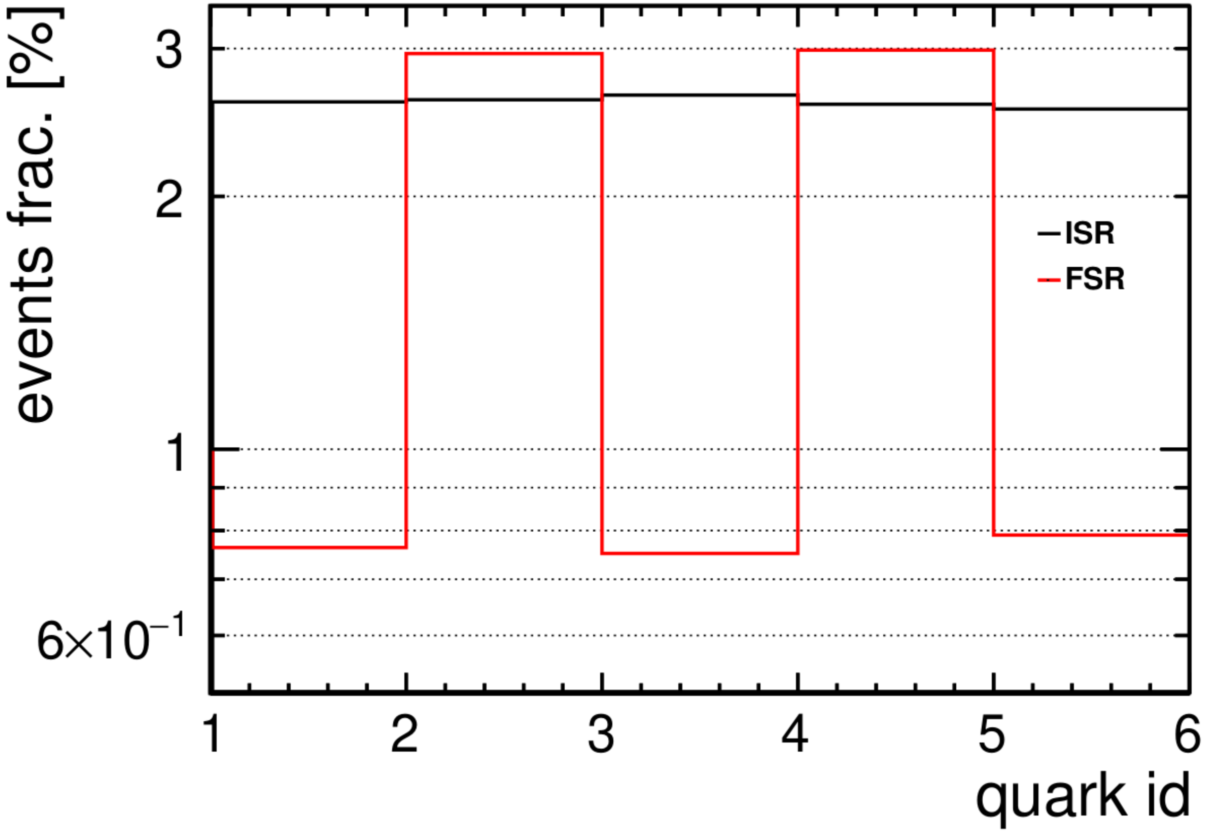
Matching procedure – *Whizard* perspective

- matching: *soft* physics invisible in the detector, *hard* physics properly reconstructed
- soft ISR photons simulated using built-in structure functions
- soft FSR photons simulated using parton showers
- hard photons simulated using full ME calculations (0, 1, 2... ME γ samples)

→ momentum transfer and energy to define the soft and hard regimes

Efficiency of the matching procedure

- ILC@Z-pole: about 4% of *Whizard* events are rejected to avoid double-counting.



How to select events?

work in progress

Event reconstruction

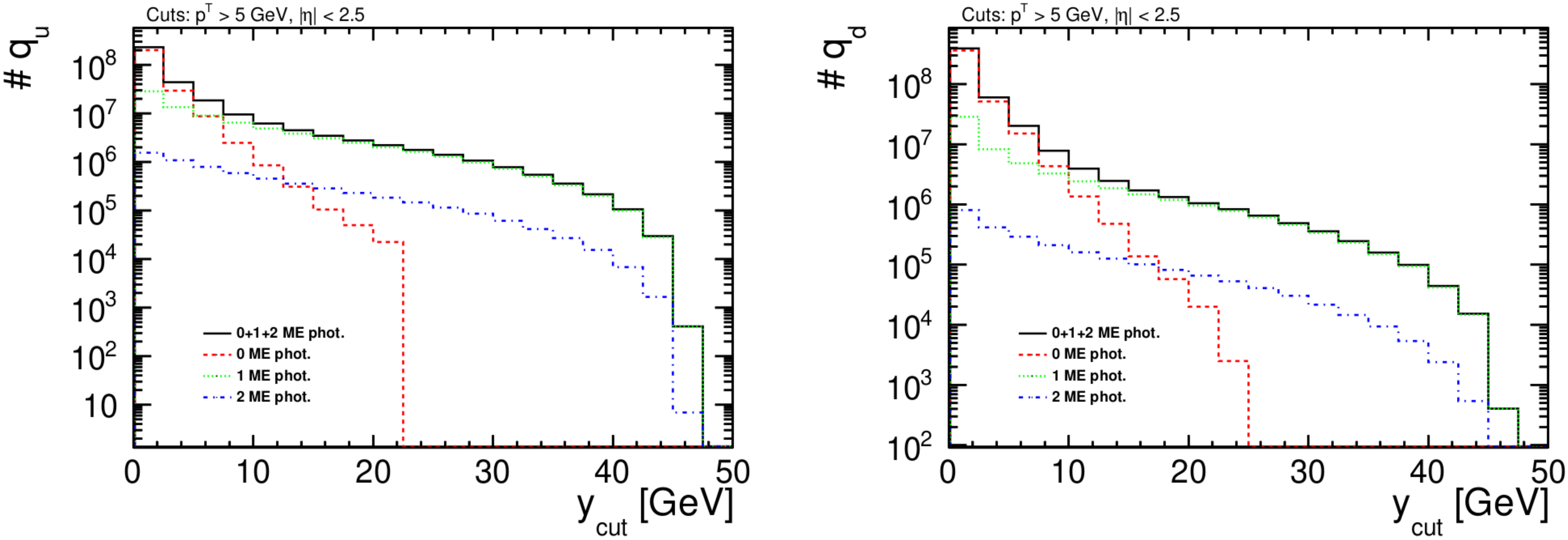
Measurable photons can originate from:

- Initial State Radiation,
- Final State Radiation,
- hadronisation and decays.

The interesting information comes only from FSR so reconstruction criteria should reduce other contributions.

Z-pole: ISR naturally reduced (but often not in the *baseline* scenario)

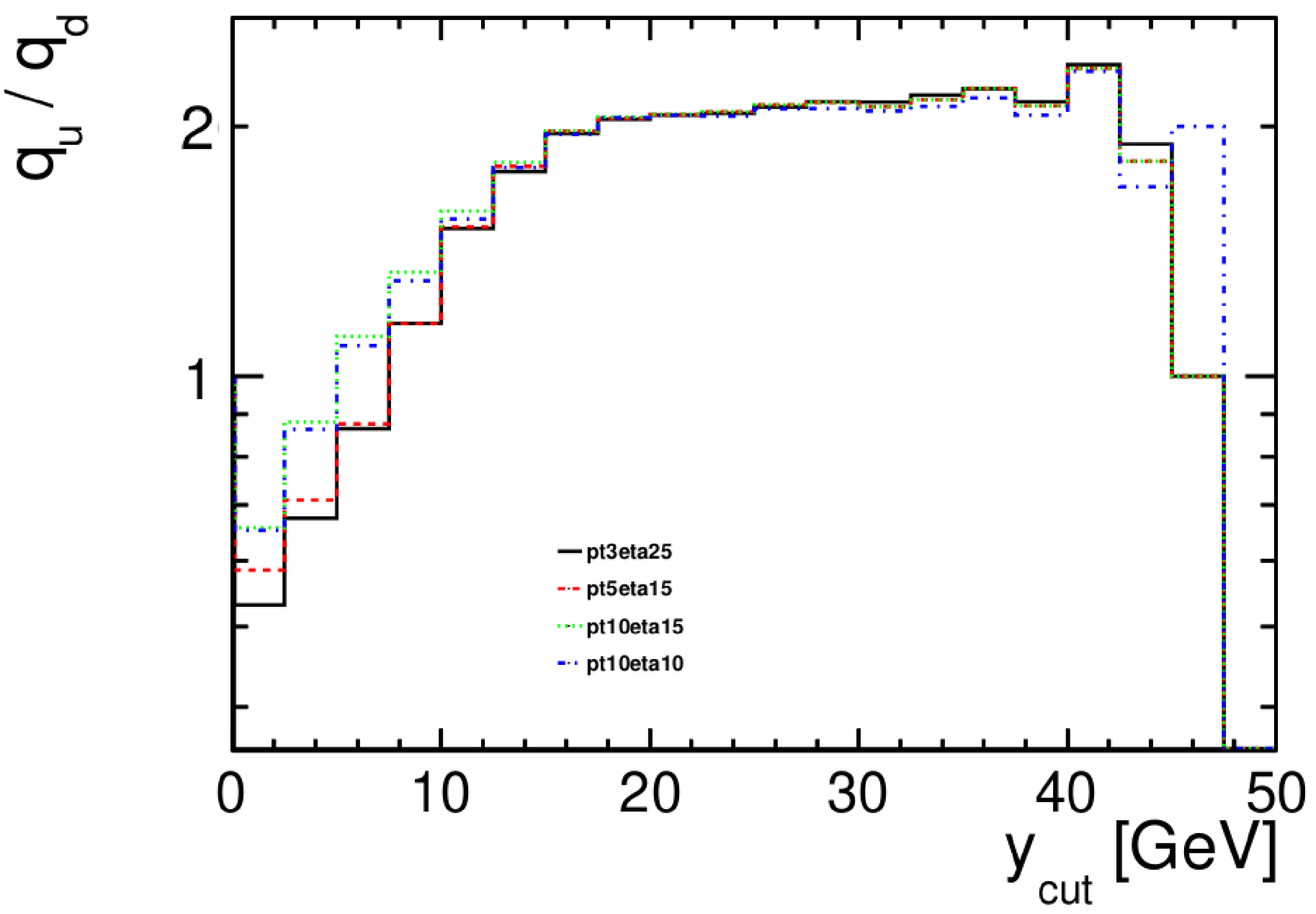
Isolation criterion y_{cut}



$$y_{\text{cut}} = E_\gamma \cdot \sin(\theta^{\text{min}}_{\gamma q_i})$$

preliminary, ILC@Z-pole

Isolation criterion y_{cut}



$$\frac{q_u}{q_d} = \left(\frac{Q_u}{Q_d}\right)^2 \cdot \frac{N_u}{N_d} \cdot \frac{c_u}{c_d} \approx 2.1$$

preliminary, ILC@Z-pole

Conclusions

- Couplings of the Z boson to light quarks are poorly constrained but an improvement could be achieved at future lepton colliders.
- Proper assessment of the uncertainties requires deep understanding of theoretical calculations, event simulation and reconstruction.
- *Work in progress...*

Backup

Backup: matching criteria

$$q_- = \sqrt{4E_0E_\gamma}\sin\frac{\theta_\gamma}{2}$$
$$q_+ = \sqrt{4E_0E_\gamma}\cos\frac{\theta_\gamma}{2}$$

Simulating events with *Whizard* and *Pythia6* (shower and hadronisation)

- ME cuts:
  - **all** γ's:

    $q_\pm > 1$ GeV and $E > 1$ GeV and $M(\gamma, q_i) > 1$ GeV

- event selection:
  - **all** ISR SF γ's:

    $q_\pm < 1$ GeV or $E < 1$ GeV or $M(\gamma, q_i) < 1$ GeV
  - **all** FSR shower γ's whose parents are initial quarks:

    $q_\pm < 1$ GeV or $E < 1$ GeV or $M(\gamma, q_i) < 1$ GeV