Prospects for constraining light-quark electroweak couplings at e^+e^- colliders

Krzysztof Mękała

DESY, Hamburg, Germany

Faculty of Physics, University of Warsaw, Poland

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

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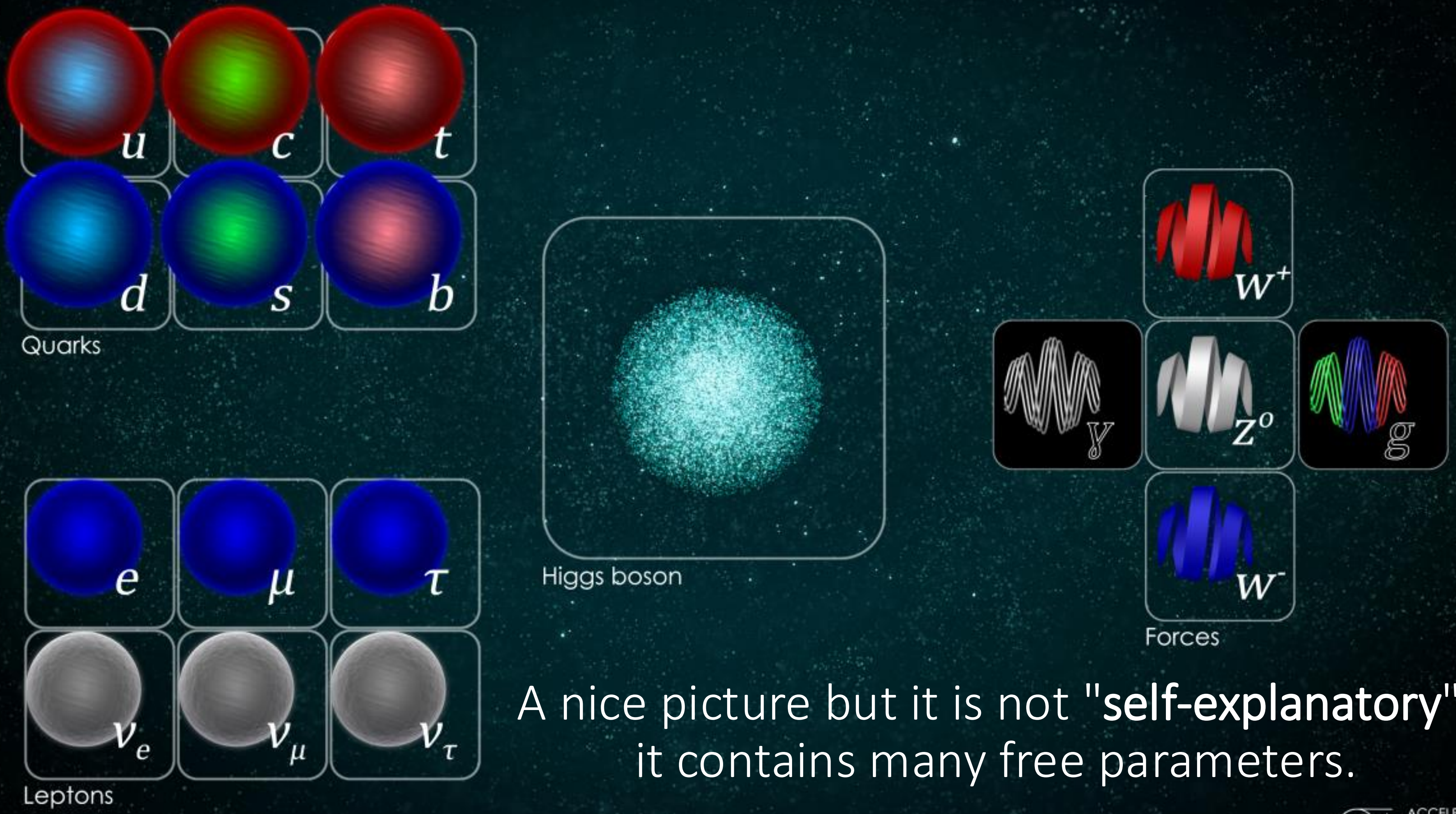
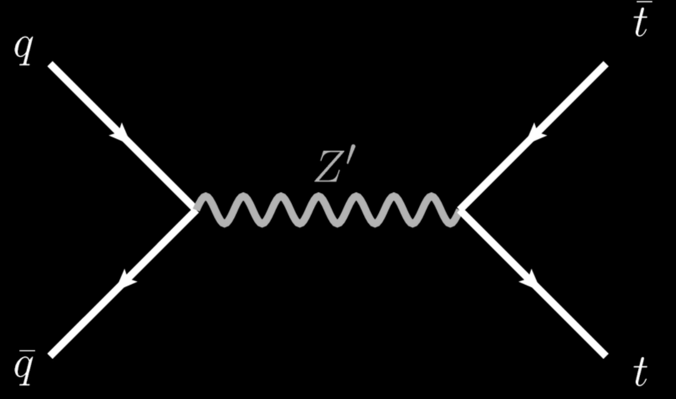
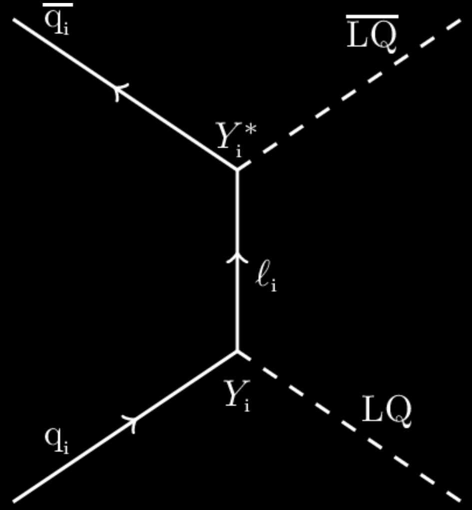
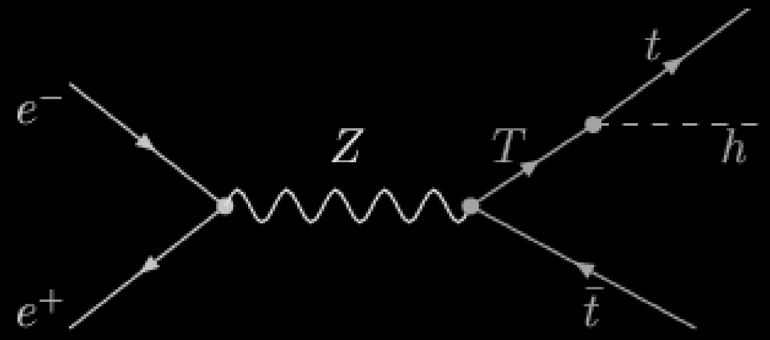


A nice picture but it is not "**self-explanatory**":
it contains many free parameters.

Measuring precision observables allows to constrain the SM parameters but also 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.

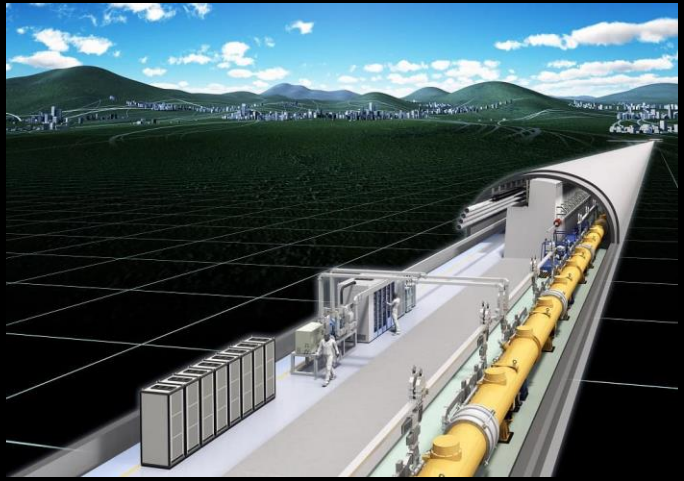
VALUE	DOCUMENT ID		TECN	COMMENT
0.1721±0.0030 OUR FIT				
0.1744±0.0031±0.0021	1 ABE	05F	SLD	E^{ee}_{cm}=91.28 GeV
0.1665±0.0051±0.0081	2 ABREU	00	DLPH	E^{ee}_{cm}= 88–94 GeV
0.1698±0.0069	3 BARATE	00B	ALEP	E^{ee}_{cm}= 88–94 GeV
0.180 ±0.011 ±0.013	4 ACKERSTAFF	98E	OPAL	E^{ee}_{cm}= 88–94 GeV
0.167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

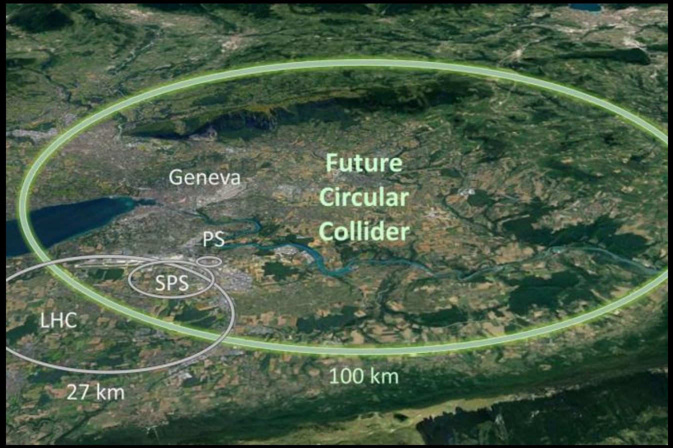
VALUE	DOCUMENT ID		TECN	COMMENT
0.166±0.009 OUR AVERAGE				
$0.172^{+0.011}_{-0.010}$	1 ABBIENDI	04E	OPAL	E^{ee}_{cm} = 91.2 GeV
0.160±0.019±0.019	2 ACKERSTAFF	97T	OPAL	E^{ee}_{cm}= 88–94 GeV
$0.137^{+0.038}_{-0.054}$	3 ABREU	95X	DLPH	E^{ee}_{cm}= 88–94 GeV
0.137±0.033	4 ADRIANI	93	L3	E^{ee}_{cm}= 91.2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

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



ILC

CEPC



FCC-ee

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 cross sections to heavy quarks could be well constrained at ILC250 thanks to the excellent flavour-tagging.

But how to take the measurement if...

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

Outline

1. How to measure *Z* couplings to light quarks?
2. How to generate Monte Carlo events?
3. How to select events?

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

Measurement at the *Z*-pole

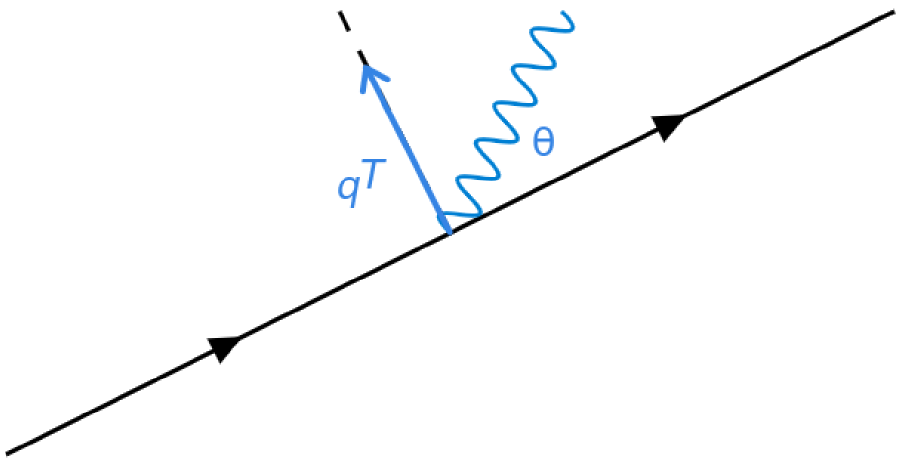
We can measure radiative and non-radiative cross sections separately and disentangle the couplings c_d and c_u:

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

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

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

Form factor $F(y_{cut})$



The cross sections are in fact related:

$$\sigma_{Z\to had+\gamma} = \sigma_{Z\to had} \cdot \frac{3c_d + 8c_u}{3c_d + 2c_u} \cdot \frac{\alpha}{\pi} \cdot F(y_{cut})$$

where $F(y_{cut})$ is a form factor depending on an arbitrarily chosen isolation parameter. For example, it might be defined as the photon transverse momentum w.r.t. the jet direction, q^T.

$$q^T = E_\gamma \sin(\theta_{j\gamma})$$

How to generate Monte Carlo events?

Analysis setup

At the *Z*-pole, we can consider:

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

Hadronic decays of the *Z* boson are easy to be measured inclusively.

The photon multiplicity is affected not only by the Final State Radiation but also the Initial State Radiation, hadronisation and decays...

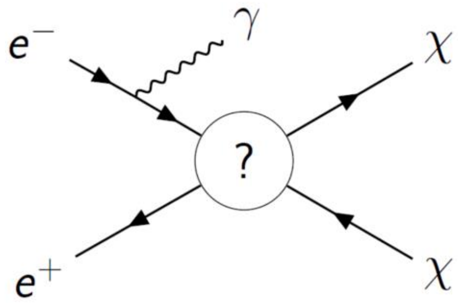
Monte Carlo generation of radiative events

One may encounter the following issues:

- **Matrix Element** calculations – divergent or very slow for low photon-emission angles;
- **ISR structure functions** – good for small angles, a proper matching procedure needed;
- **FSR showers** – important for QCD emissions, may cause double-counting;
- **hadron decays** – photons to be included properly.

Starting point

Some part of the work has already been done...



Simulating hard photon production with WHIZARD

J. Kalinowski *et al.*, [2004.14486]

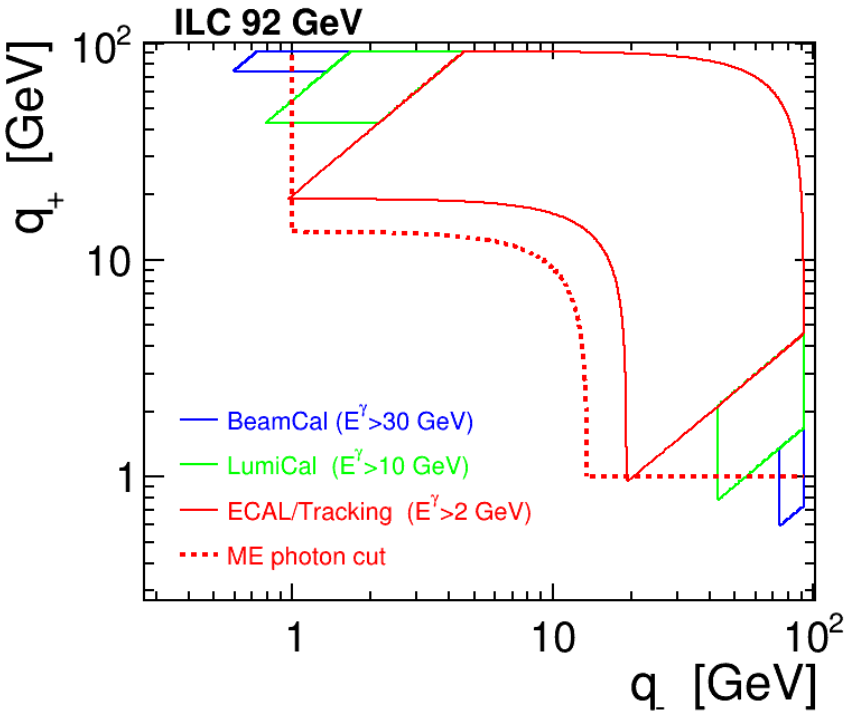
General idea:

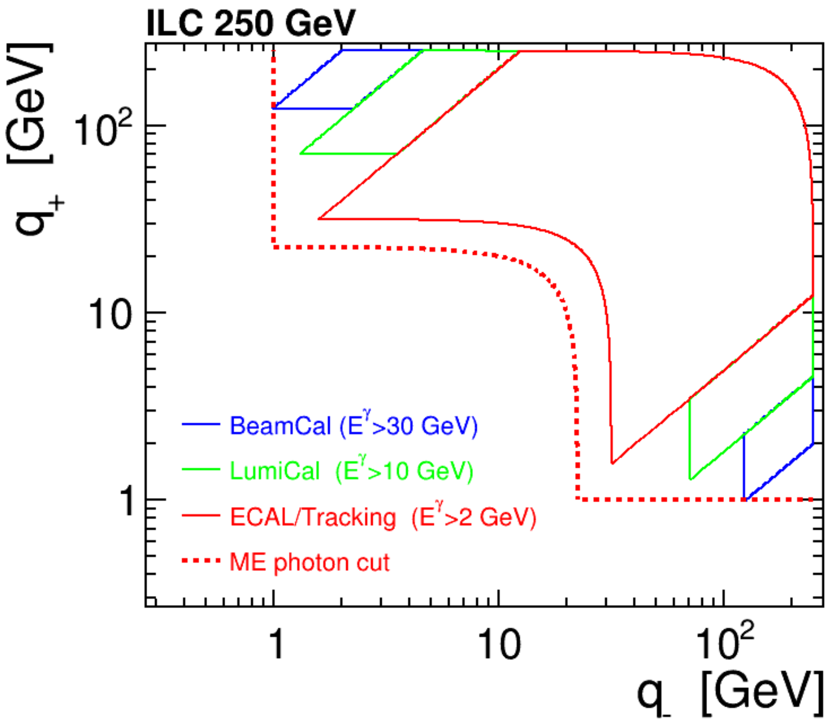
- soft ISR photons simulated using the built-in structure function
- hard ISR photons simulated at the ME level
- matching in $q_{\pm}$:

$$q_- = \sqrt{4E_0 E_\gamma} \sin\frac{\theta_\gamma}{2}$$
$$q_+ = \sqrt{4E_0 E_\gamma} \cos\frac{\theta_\gamma}{2}$$

(q_+, q_-) plane

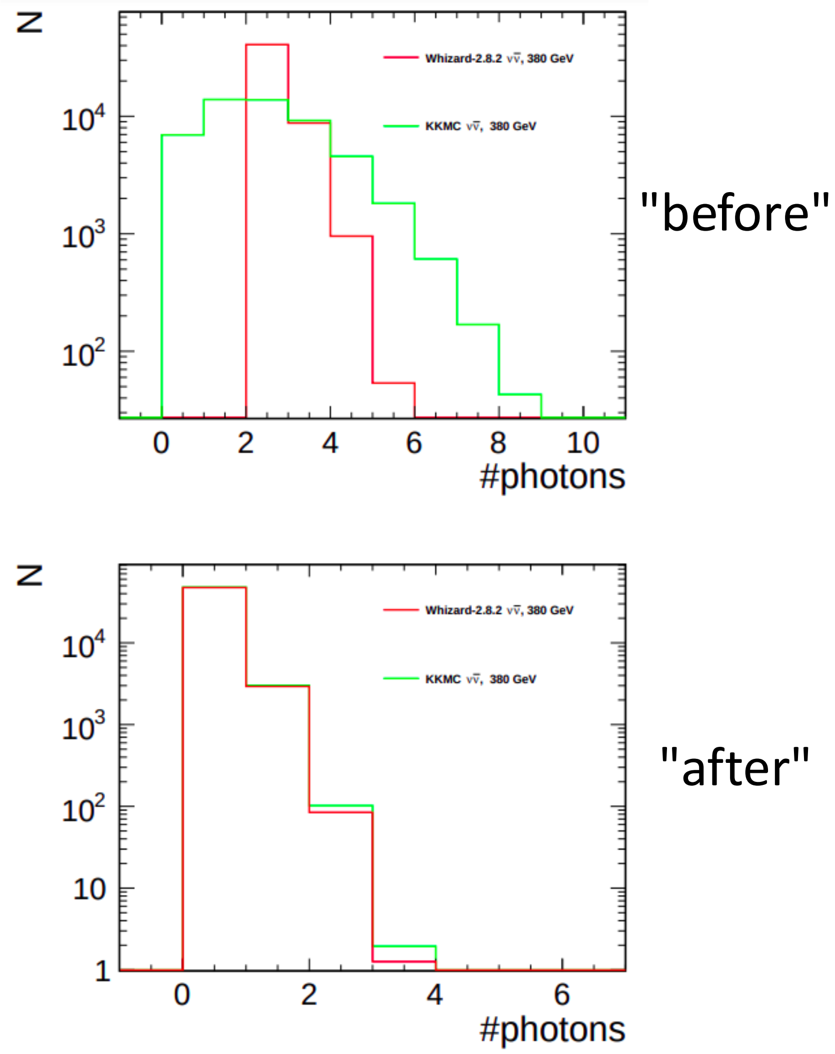
"ME photon cut" divides the photon phase space into two non-overlaping regions, corresponding to soft+collinear (ISR and FSR) and hard (ME) radiation.

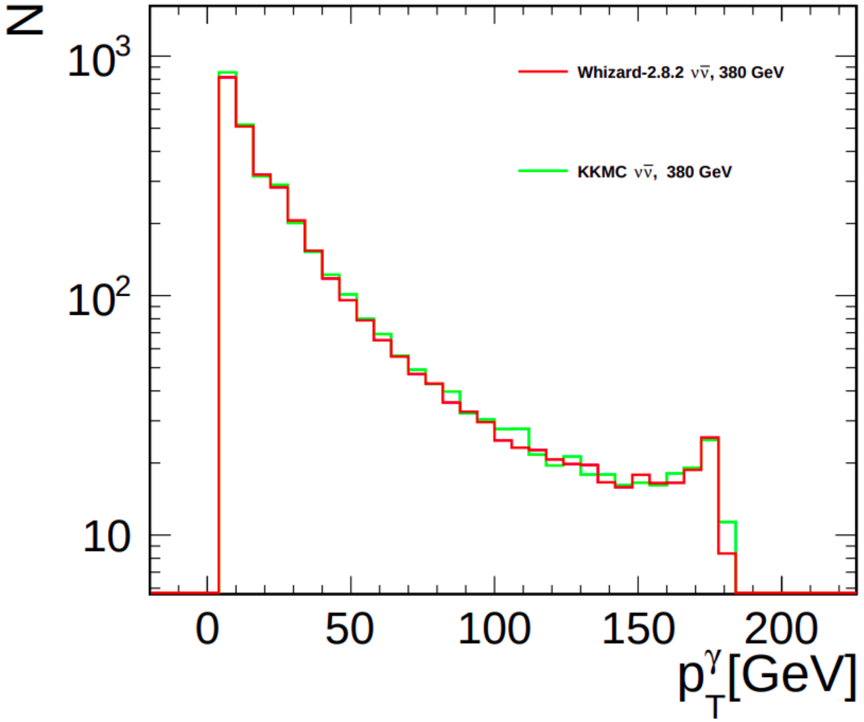




[2004.14486]

How does the procedure work?





CLIC 380 GeV, [2004.14486]

Extension of the procedure

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

- ME cuts:
  - **all** γ's:

    $$q_{\pm} > 0.5 \text{ GeV } \underline{\text{and}}\ E > 0.5 \text{ GeV } \underline{\text{and}}\ M(\gamma, q_i) > 1 \text{ GeV}$$

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

    $$q_{\pm} < 0.5 \text{ GeV } \underline{\text{or}}\ E < 0.5 \text{ GeV } \underline{\text{or}}\ M(\gamma, q_i) < 1 \text{ GeV}$$

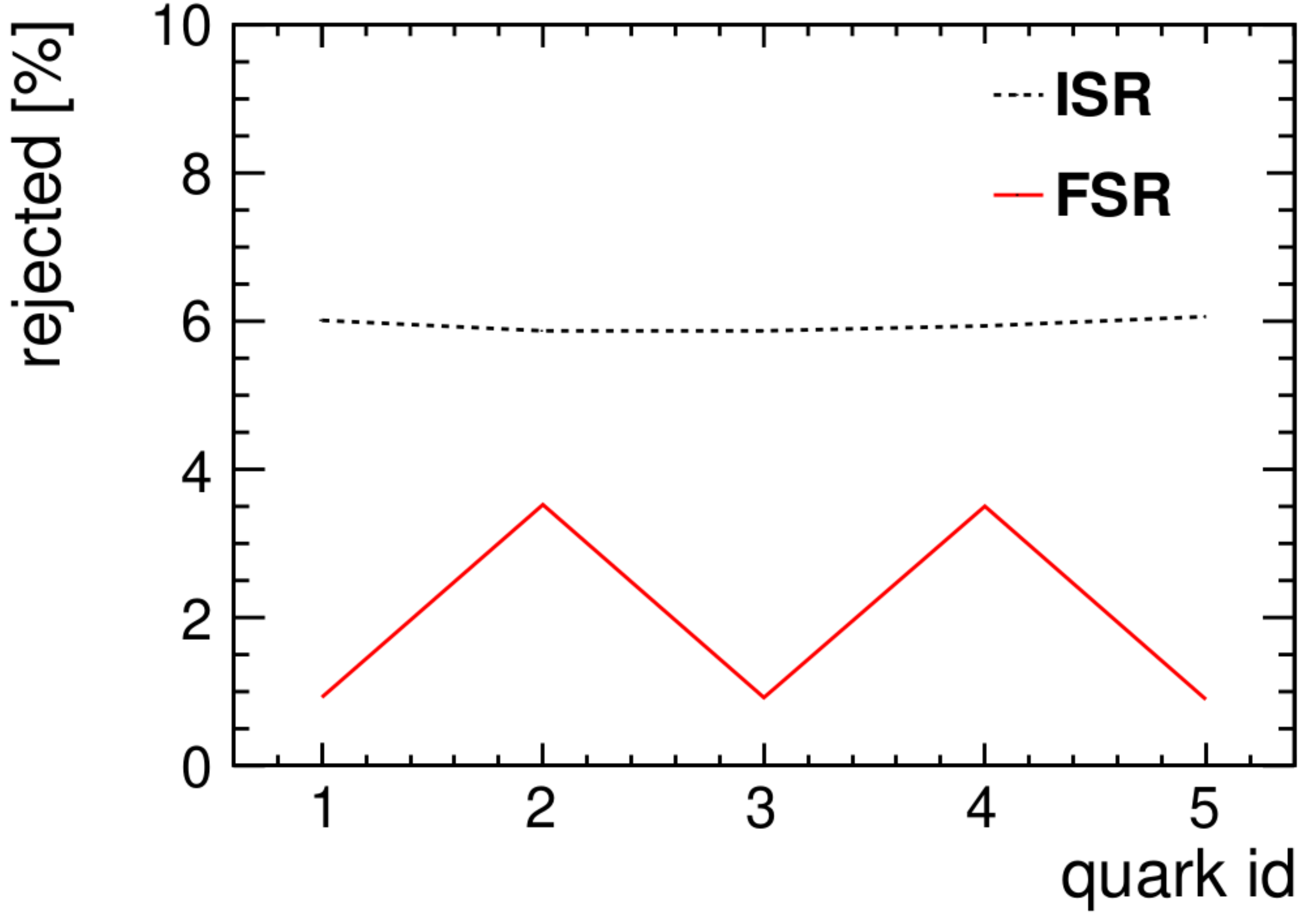
  - **all** FSR shower γ's whose parents are initial quarks:

    $$q_{\pm} < 0.5 \text{ GeV } \underline{\text{or}}\ E < 0.5 \text{ GeV } \underline{\text{or}}\ M(\gamma, q_i) < 1 \text{ GeV}$$

Note: a single quark can emit multiple photons.

Efficiency of the matching procedure

About 7-8% 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.

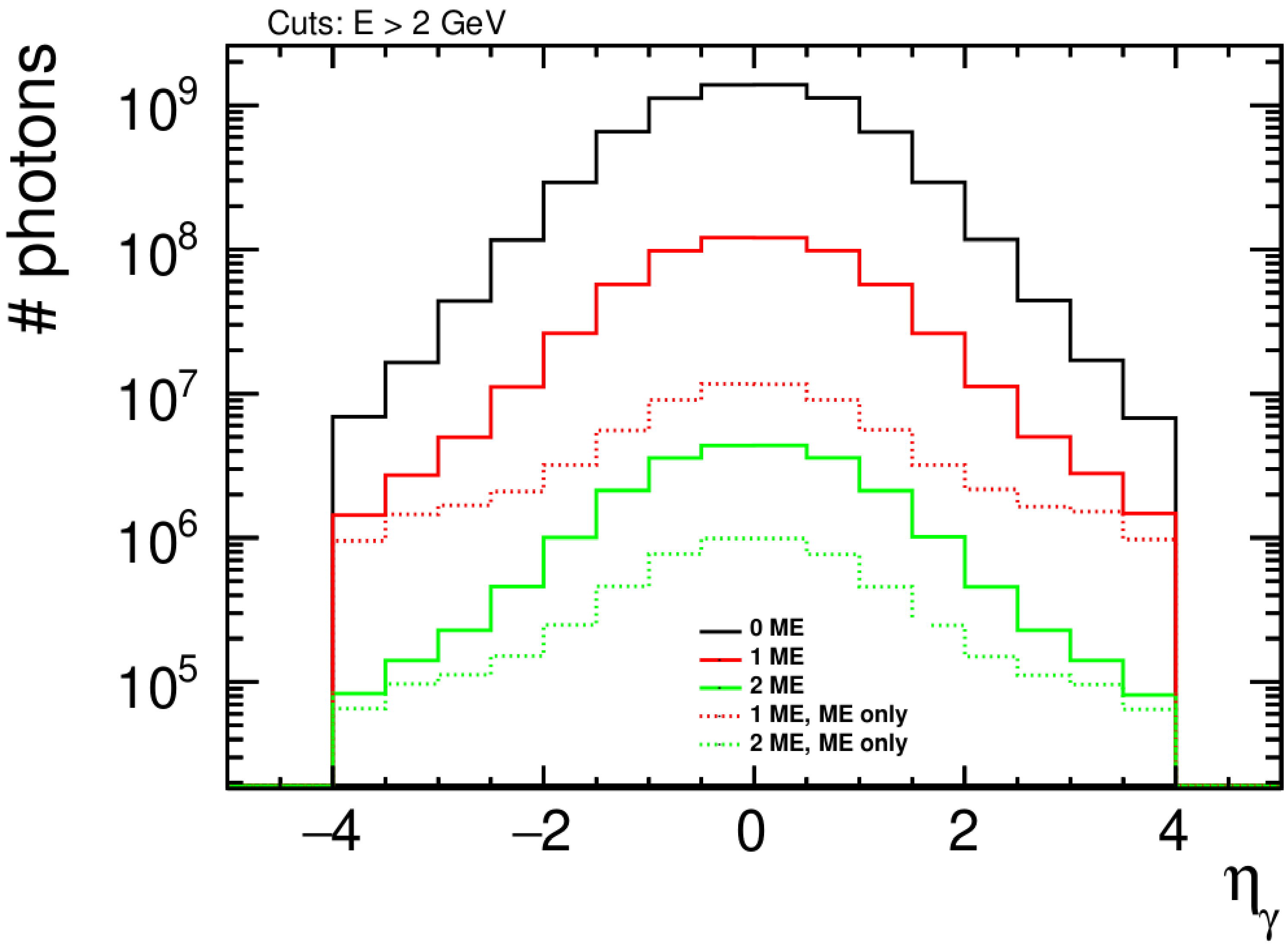
The interesting information comes only from FSR so the reconstruction criteria should reduce the other contributions.

A dedicated approach is crucial!

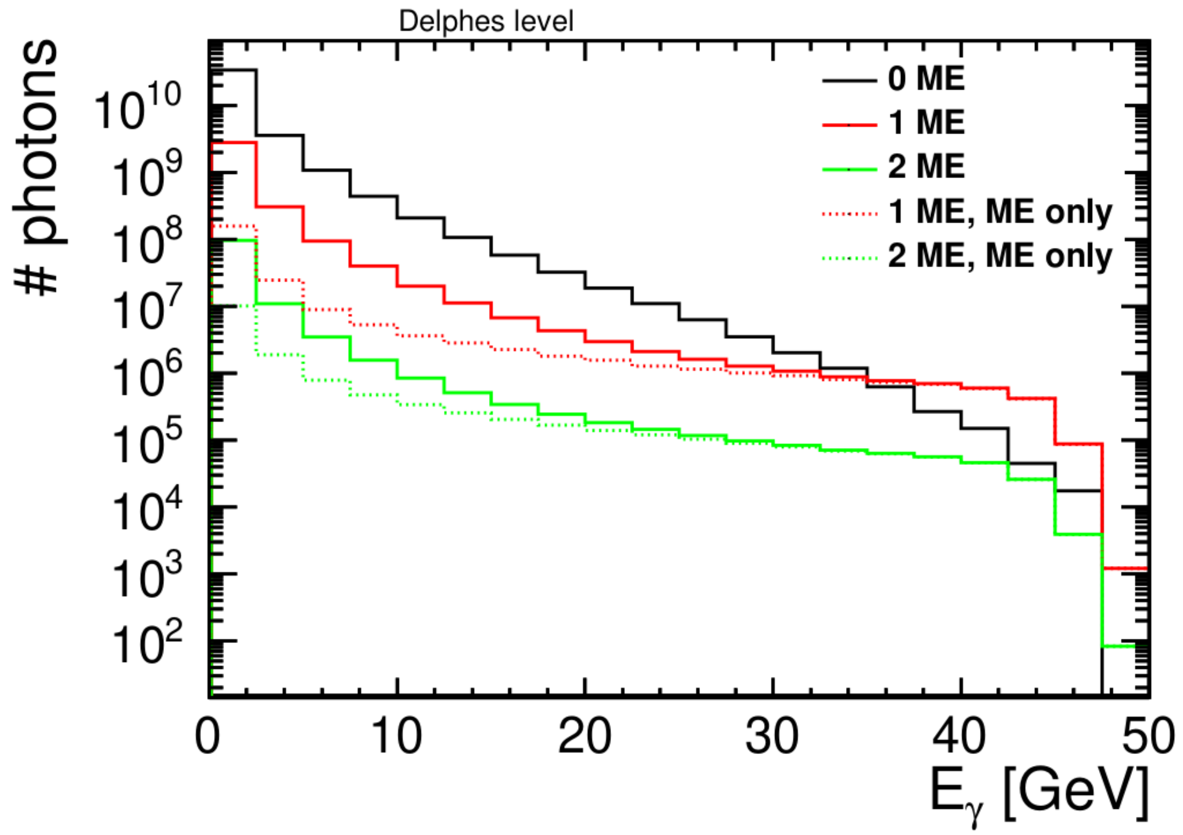
Analysis strategy

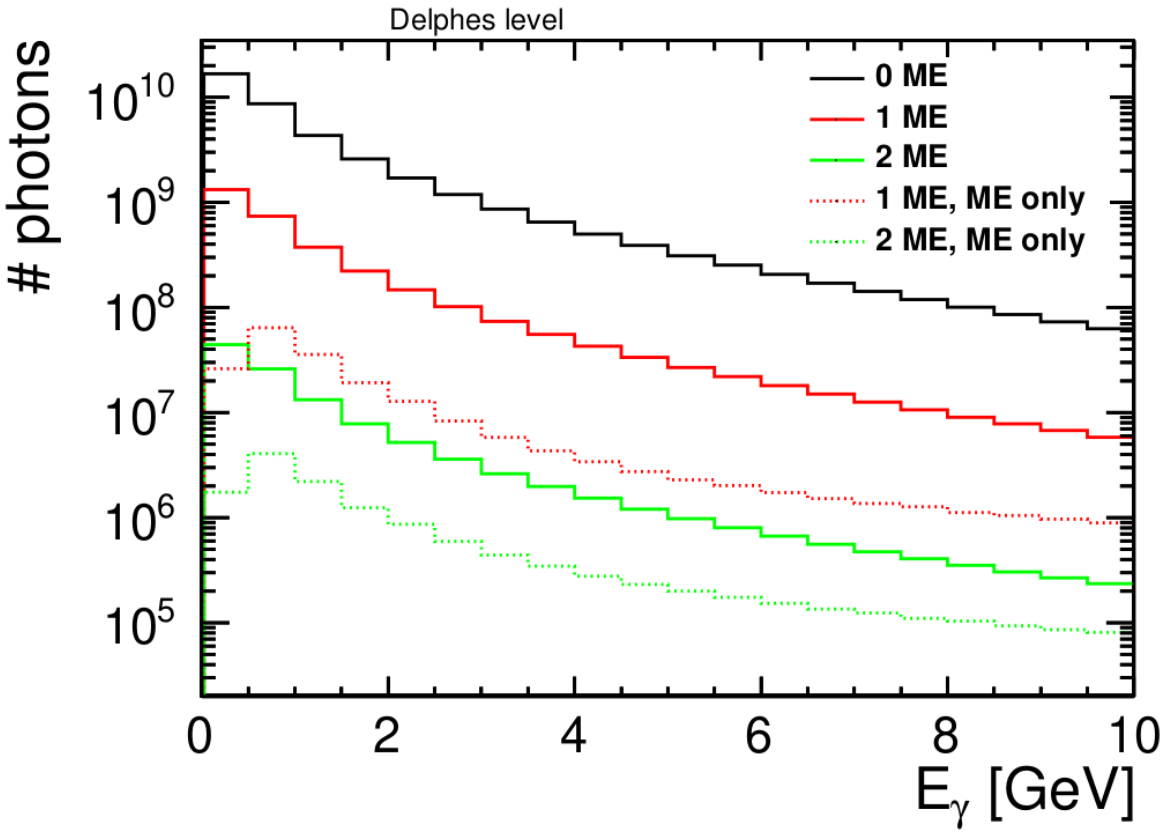
1. events with 0-2 ME photons generated in Whizard
2. samples matched according to the procedure
3. detector response in *Delphes* using default ILD cards modified to cluster **all** photons into jets
4. cuts optimised to enhance the 1-photon contribution

Photon kinematics – pseudorapidity

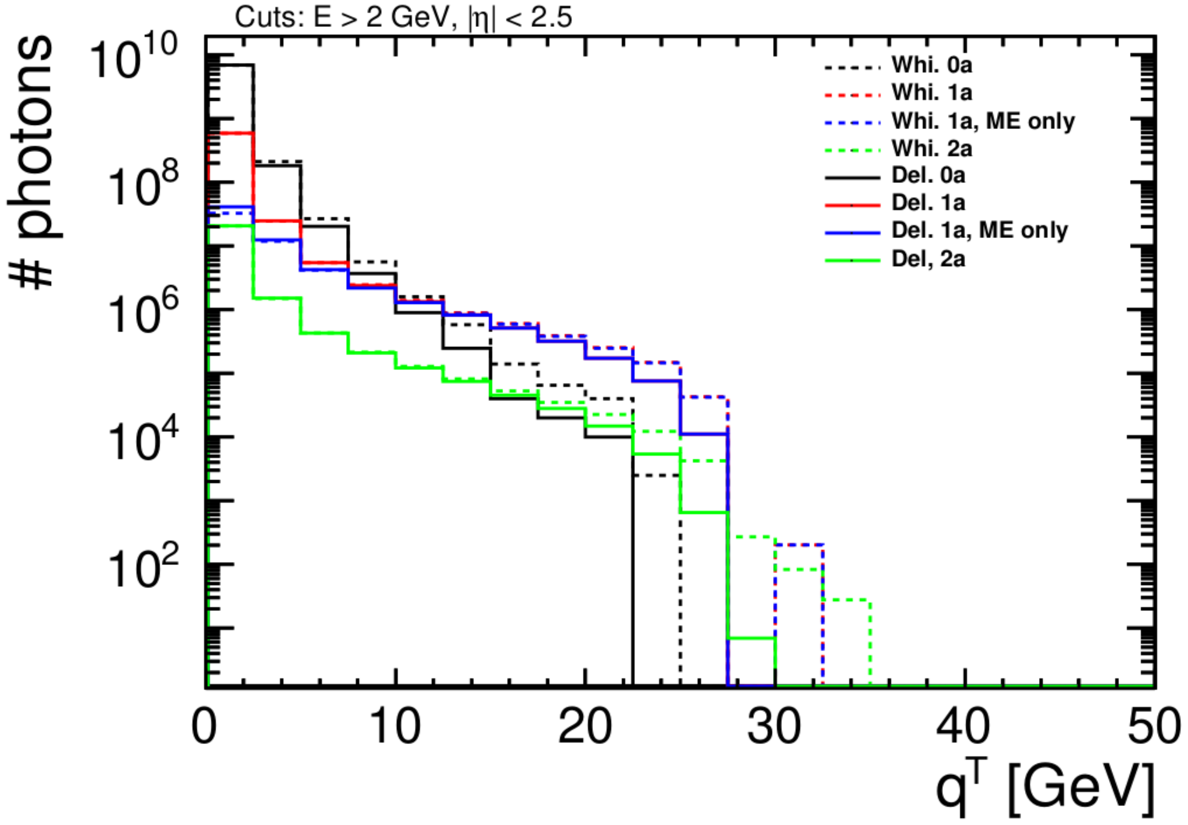


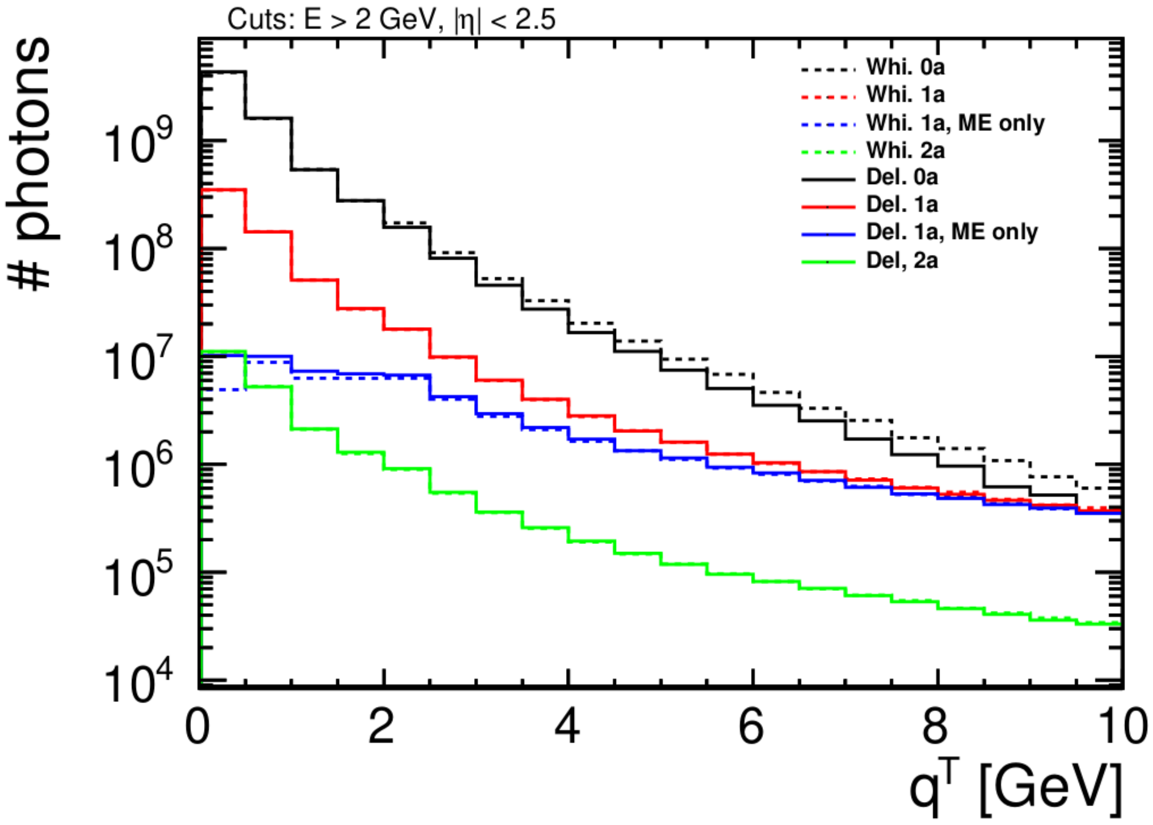
Photon kinematics – energy



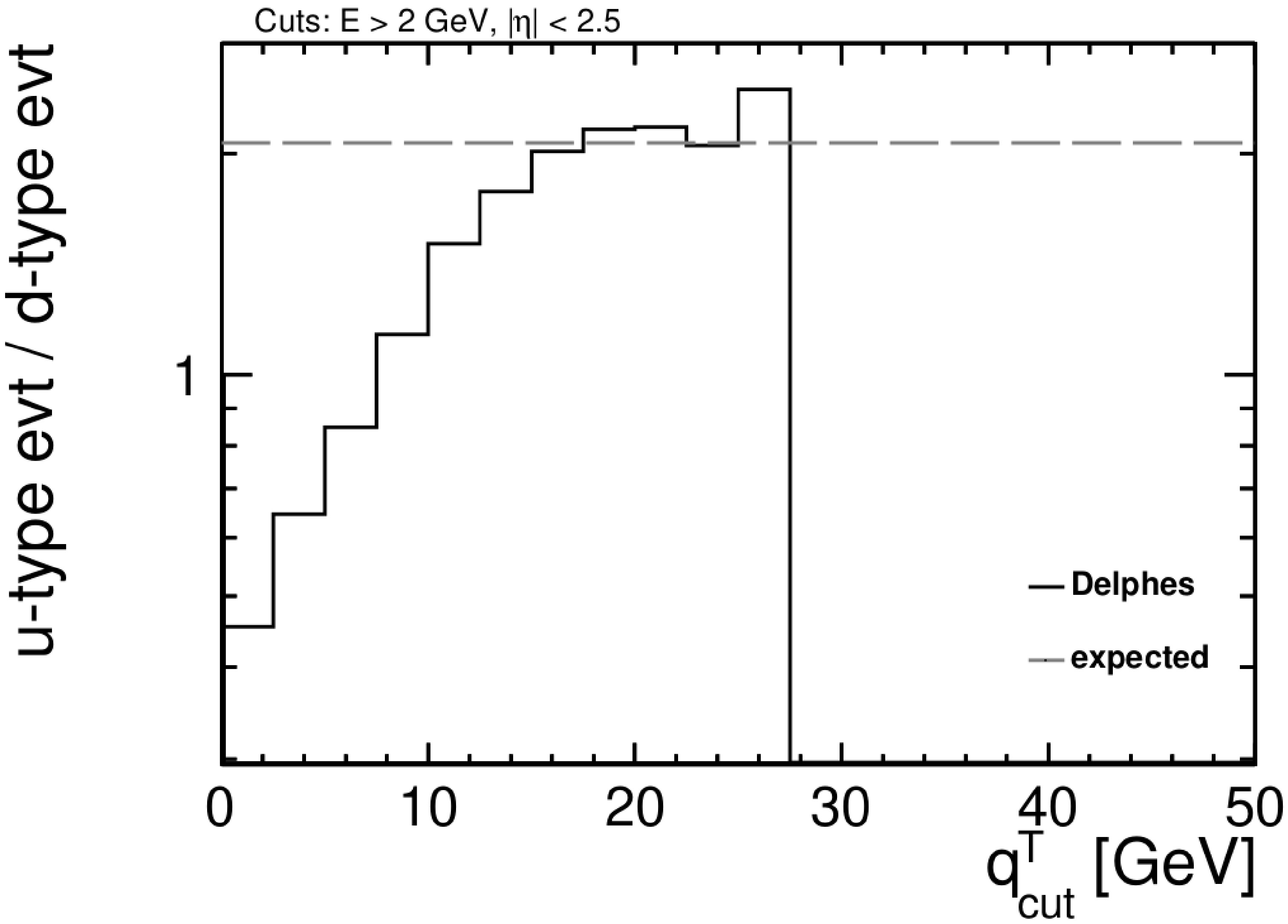


Photon kinematics – transverse momentum





Expected results



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

For the cut value of 10 GeV:

stat. error < 1‰

sys. error *tbd*

Conclusions

- The couplings of the Z boson to light quarks are poorly constrained but an excellent 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

What decays?

[%]	*d*	*u*	*s*	*c*	*b*
π^0	94	94	94	93	88
η	4.5	4.5	4.3	3.7	3.6
D mesons	-	-	-	1.9	2.0
B mesons	-	-	-	-	5.6

hadronisation by *Pythia6*