Precision measurement of light-quark electroweak couplings at future e^+e^- colliders

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

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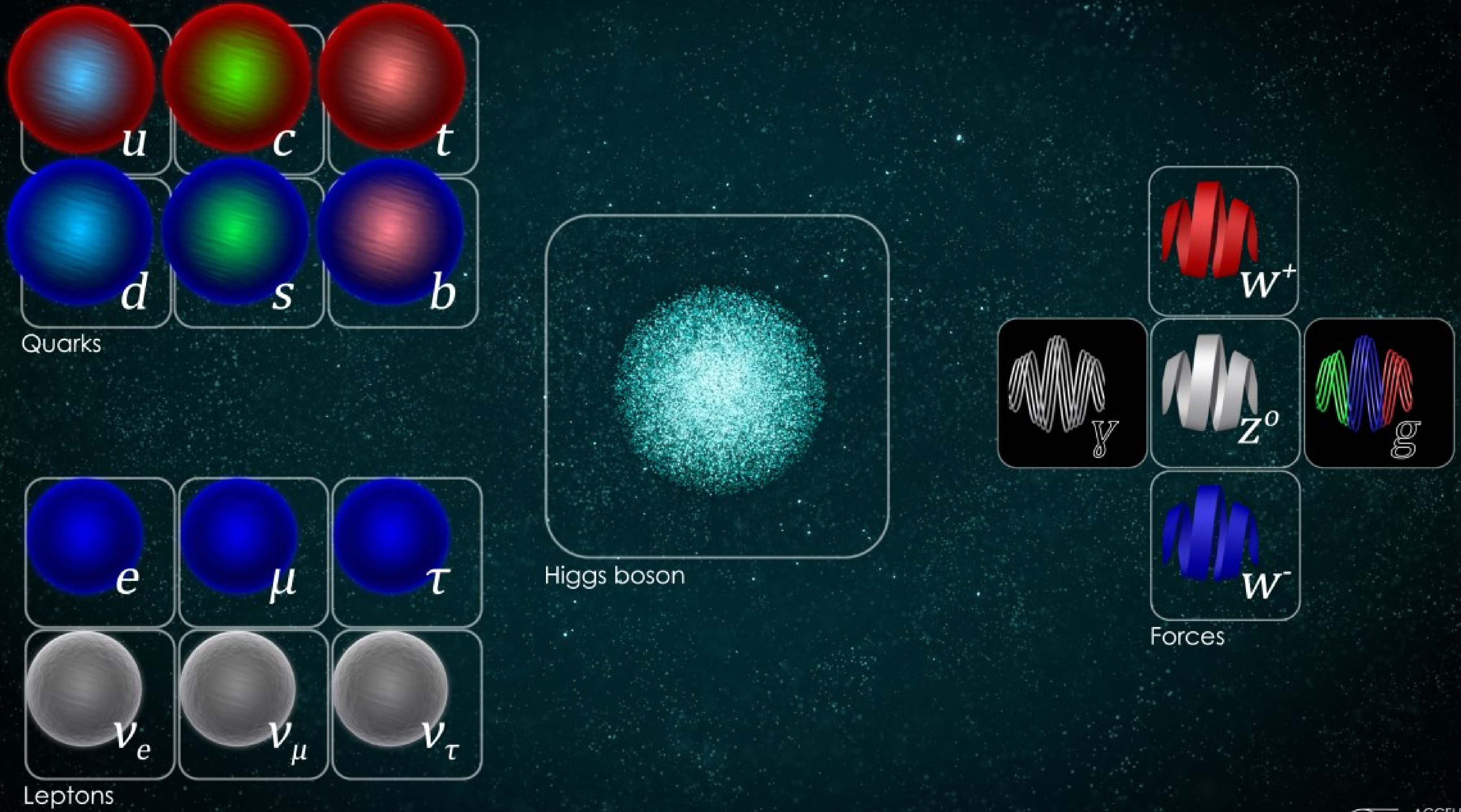

ACCELERATING SCIENCE

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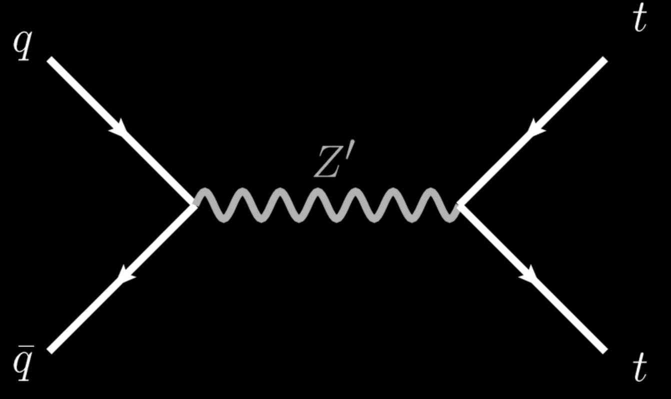
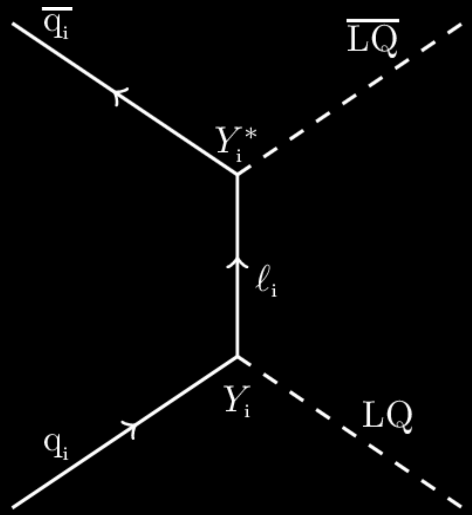
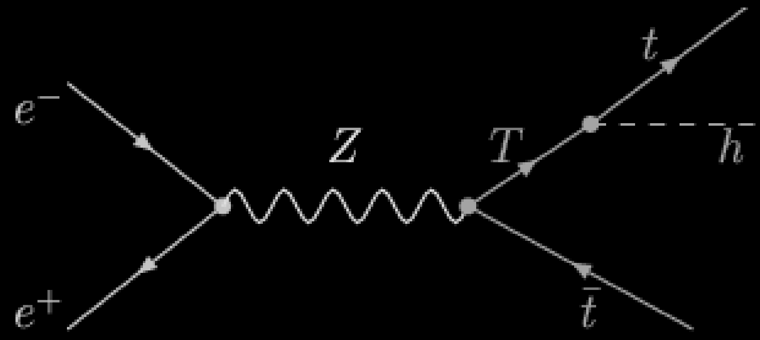
but it is not "**self-explanatory**":
it contains 19 free parameters.

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...

$R_b = \Gamma(b\bar{b})/\Gamma(\text{hadrons})$ **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

Review of Particle Physics,
PDG, 2022

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Review of Particle Physics, PDG, 2022

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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

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Review of Particle Physics,
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$\Gamma((u\bar{u}+c\bar{c})/2)/\Gamma(\text{hadrons})$ 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 $\Gamma(Z \to \gamma+$ 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.

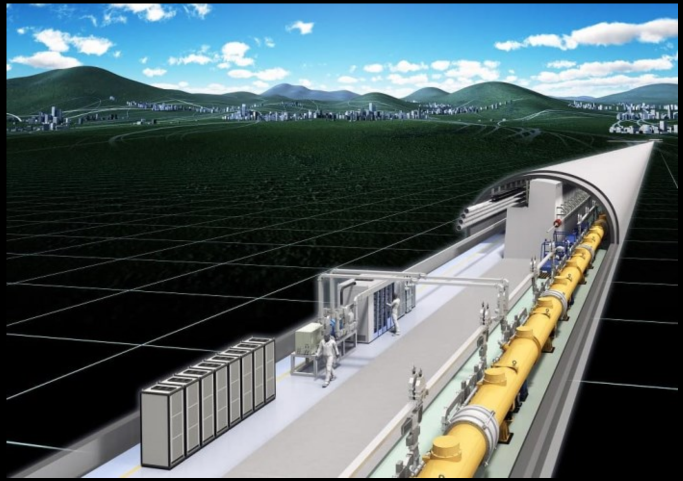
VALUE	DOCUMENT ID		TECN	COMMENT
0.166±0.009 OUR AVERAGE				
$0.172^{+0.011}_{-0.010}$	[1] ABBIENDI	04E	OPAL	E^{ee}_{cm} = 91.2 GeV
0.160±0.019±0.019	[2] ACKERSTAFF	97T	OPAL	E^{ee}_{cm}= 88–94 GeV
$0.137^{+0.038}_{-0.054}$	[3] ABREU	95X	DLPH	E^{ee}_{cm}= 88–94 GeV
0.137±0.033	[4] ADRIANI	93	L3	E^{ee}_{cm}=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

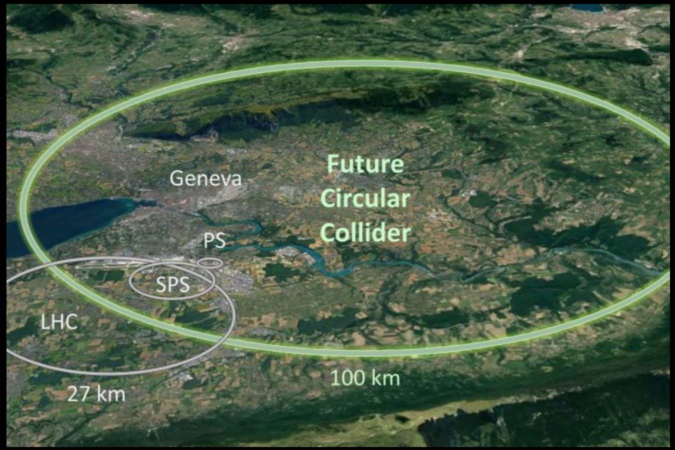
…but not all of them!

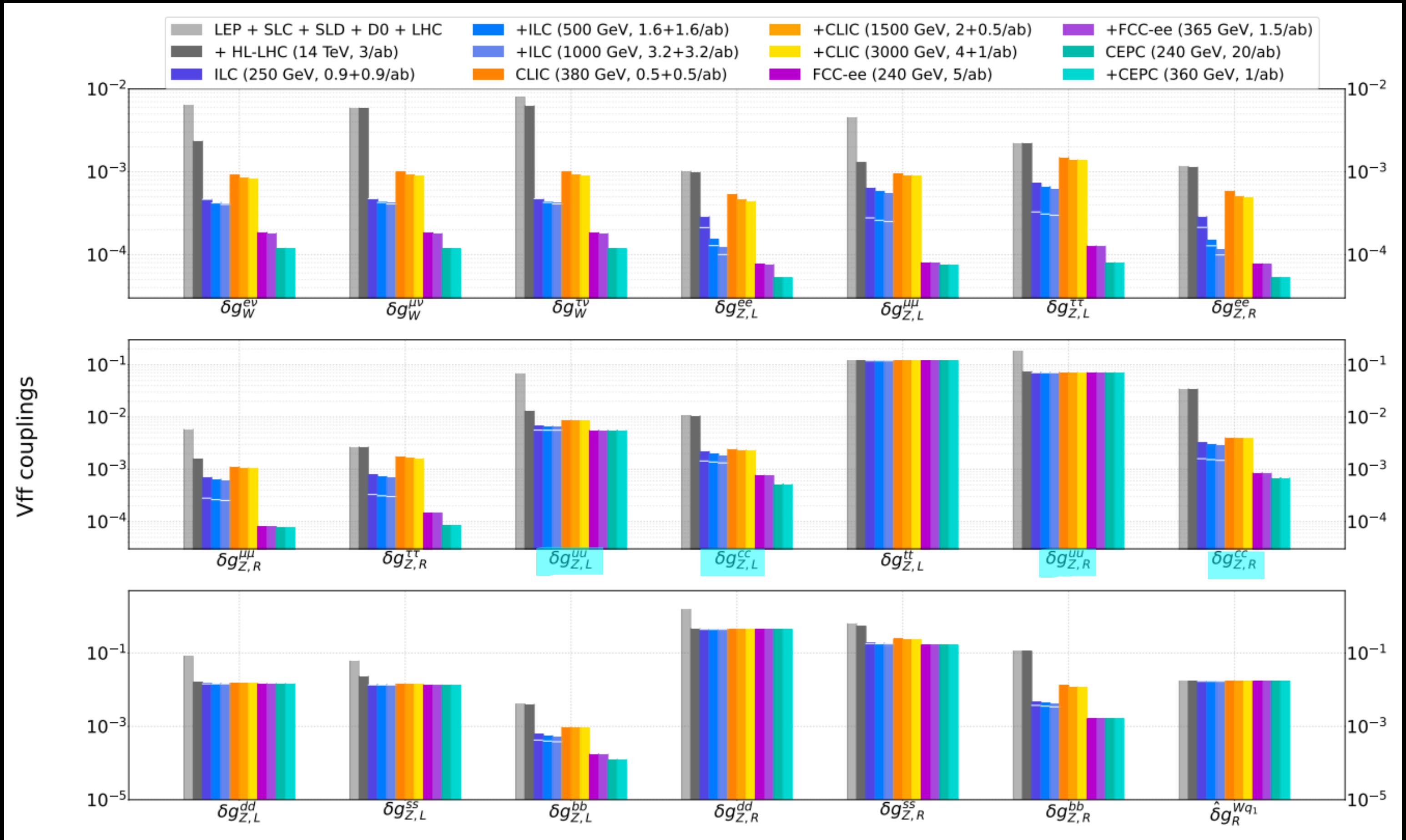
Quantity	Value	Value (universal)	Standard Model
$\Gamma_{e^+e^-}$	83.87 ± 0.12	83.942 ± 0.085	83.960 ± 0.009
$\Gamma_{\mu^+\mu^-}$	83.95 ± 0.18	83.941 ± 0.085	83.959 ± 0.009
$\Gamma_{\tau^+\tau^-}$	84.03 ± 0.21	83.759 ± 0.085	83.777 ± 0.009
Γ_{inv}	498.9 ± 2.5	500.5 ± 1.5	501.445 ± 0.047
$\Gamma_{u\bar{u}}$	—	—	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.







J. de Blas *et al.*, [2206.08326]

These measurements are important to probe quark-coupling universality in the EW sector, e.g. in the EFT framework.

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 e.g. 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)?

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:

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

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Γ_{had} reads (exact at fixed order):

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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

Let us assume we can tag b and c quarks with 100% efficiency. Then, we can measure radiative and non-radiative cross sections separately for $q = u,d,s$ and disentangle the couplings c_d and c_u:

$$\sigma_{Z\to q\bar{q}} = (\text{some const.}) \cdot (2c_d + c_u)$$

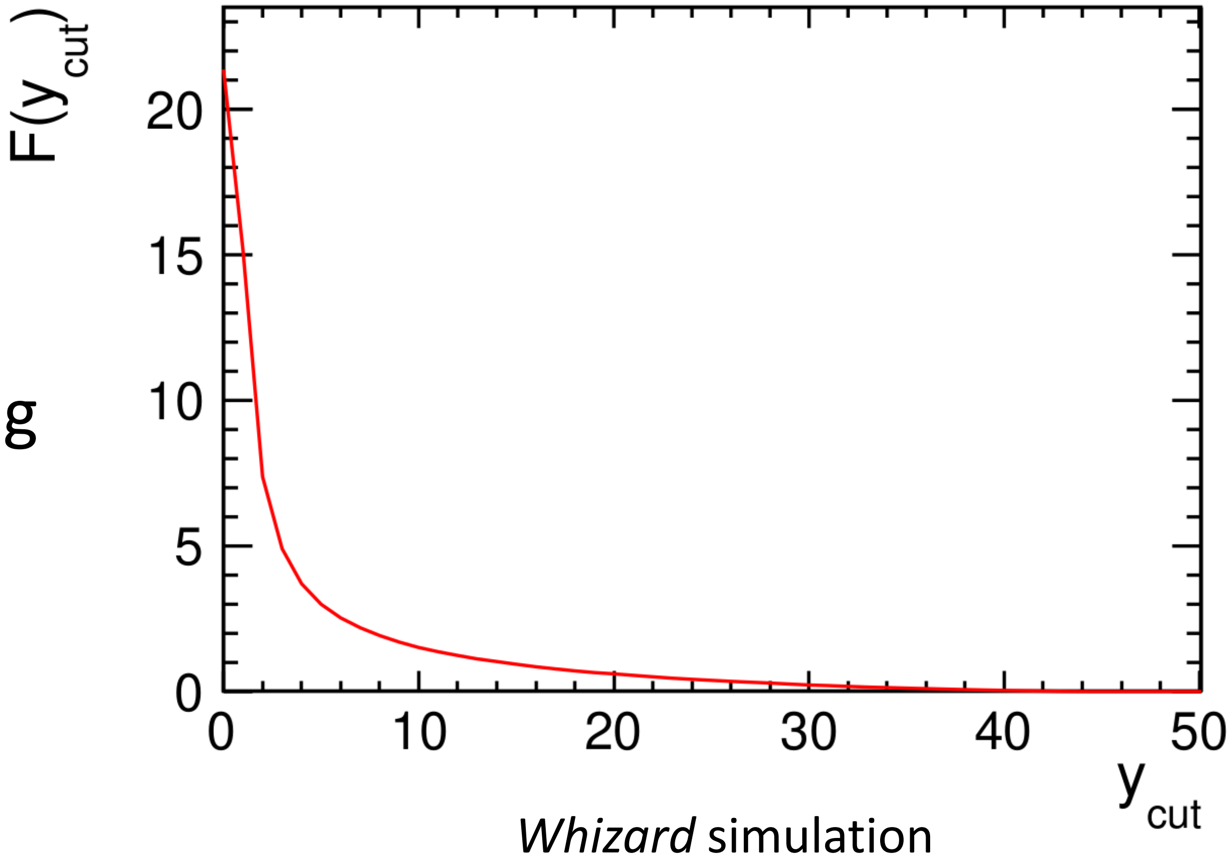
$$\begin{aligned}\sigma_{Z\to q\bar{q}\gamma} &= (\text{another const.}) \cdot (2q_d^2 c_d + q_u^2 c_u)\\ &= (\text{yet another const.}) \cdot (c_d + 2c_u)\end{aligned}$$

Form factor $F(y_{cut})$

The cross sections are in fact related:

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

where $F(y_{cut})$ is a form factor depending on an arbitrarily chosen isolation parameter, y_{cut} (e.g. transverse momentum w.r.t. the jet direction).



Whizard simulation

How to generate Monte Carlo events?

Analysis setup

We want to consider:

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

$$q = d, u, s$$

taking into account the experimental conditions at ILC (e.g. beam polarisation) which can be done in *Whizard*.

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

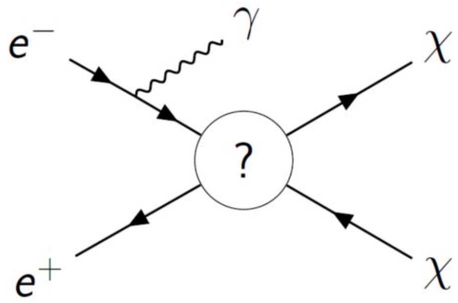
Monte Carlo generation of radiative events

In fact, the picture is even more complicated:

- **Matrix Element** calculations may be either divergent or very slow for small photon-emission angles,
- **ISR structure function** 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.

Starting point

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



Simulating hard photon production with WHIZARD

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

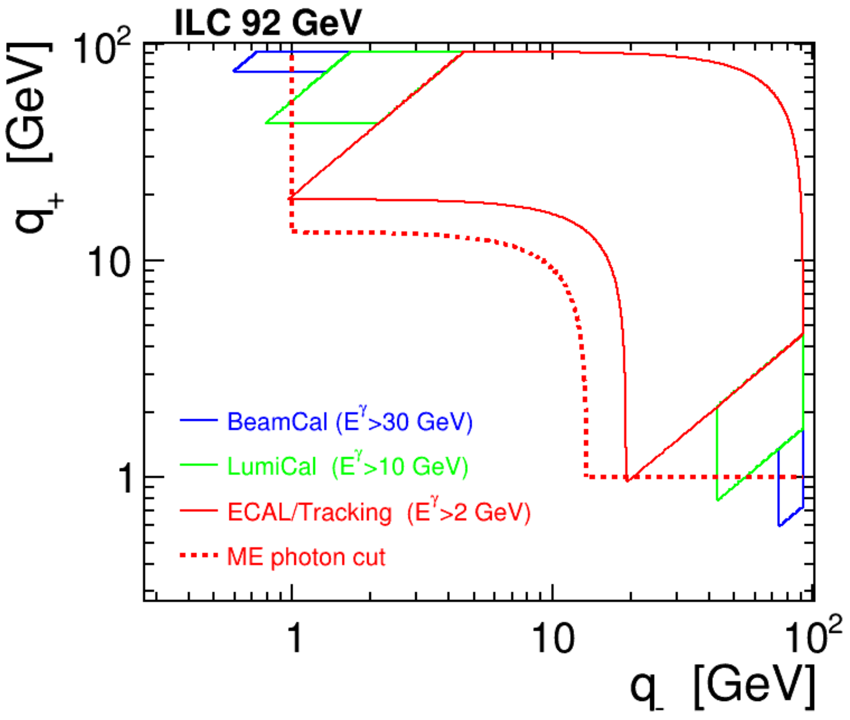
General idea:

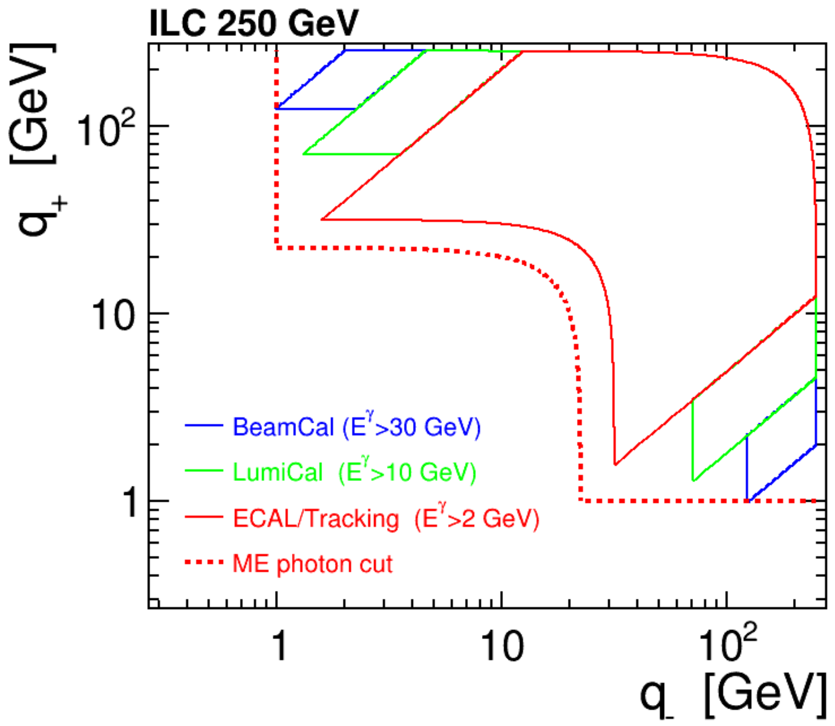
- soft ISR photons simulated using the built-in structure function
- hard ISR photons simulated at the ME level
- matching in $q_{\pm}$:

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

(q_+, q_-) plane

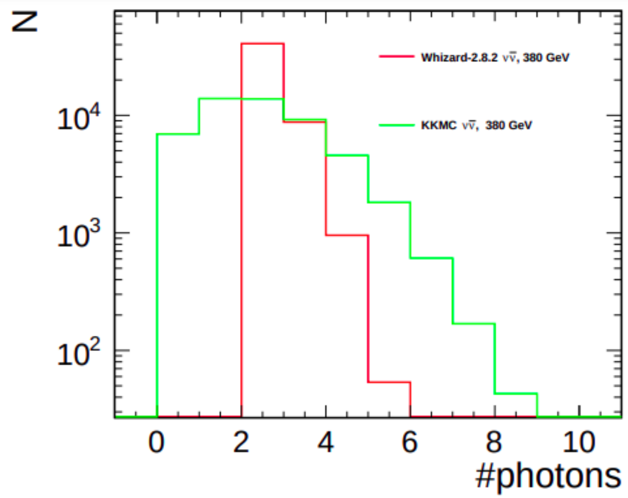
"ME photon cut" divides the photon phase space into two non-overlaping regions, corresponding to soft+collinear (ISR and FSR) and hard (ME) radiation.



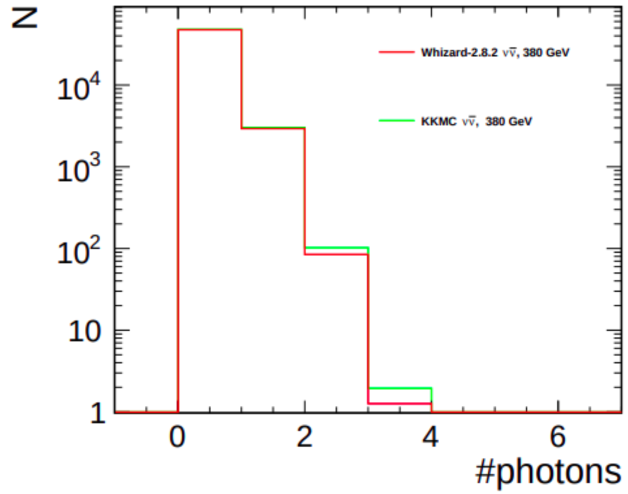


[2004.14486]

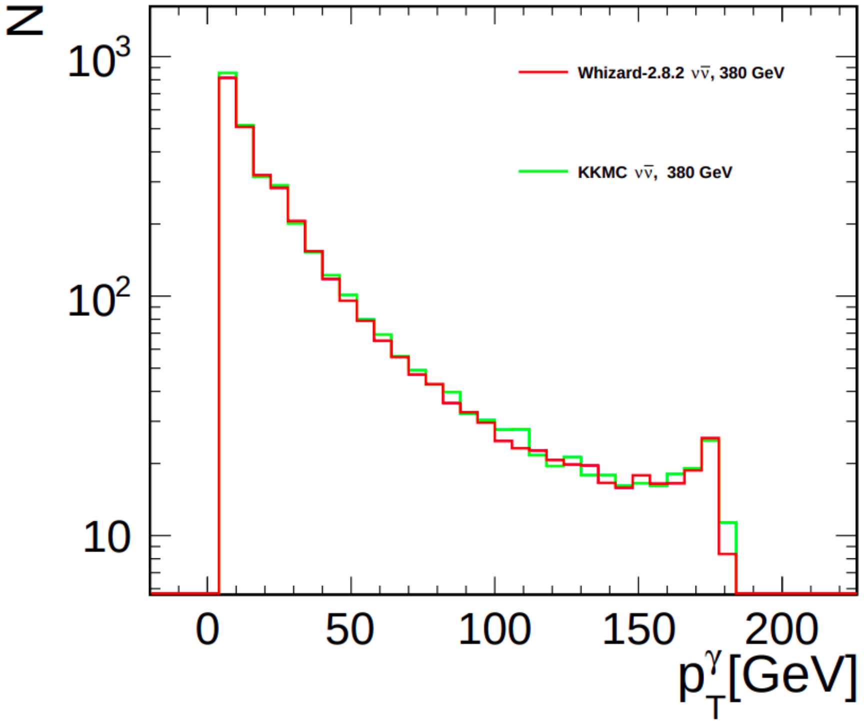
How does the procedure work?



"before"



"after"



CLIC 380 GeV, [2004.14486]

Extension of the procedure

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

- ME cuts:
  - **all** γ's:

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

  - **any** γ:

    $$p^{T} > 2\ \text{GeV}\ \underline{\text{and}}\ 5° < \theta < 175°\ \text{[useful for efficiency]}$$

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

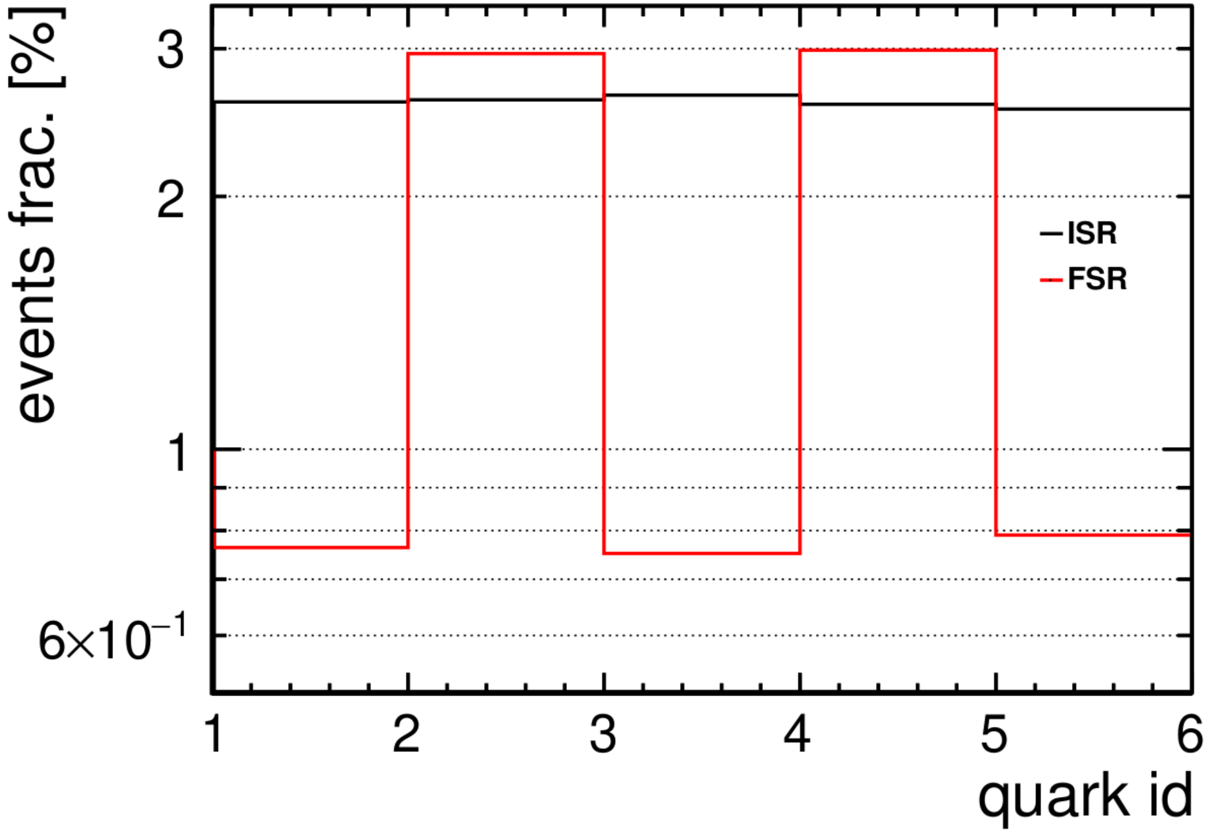
    $$q_{\pm} < 1\ \text{GeV}\ \underline{\text{or}}\ E < 1\ \text{GeV}\ \underline{\text{or}}\ M(\gamma, q_{i}) < 1\ \text{GeV}$$

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

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

Efficiency of the matching procedure

- At the *Z*-pole, the ISR is reduced so the FSR contribution should be dominant.
- Only 4% of Whizard events are rejected to avoid double-counting.

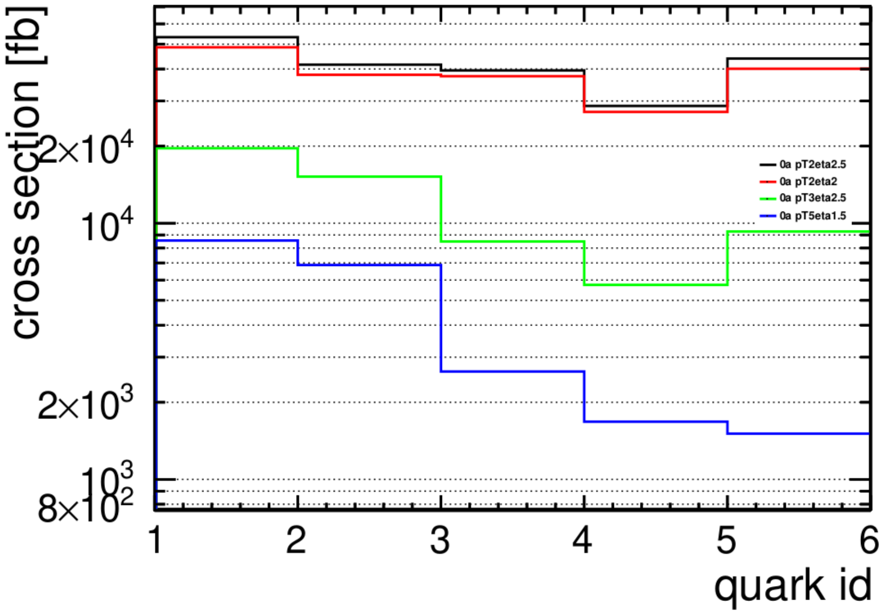


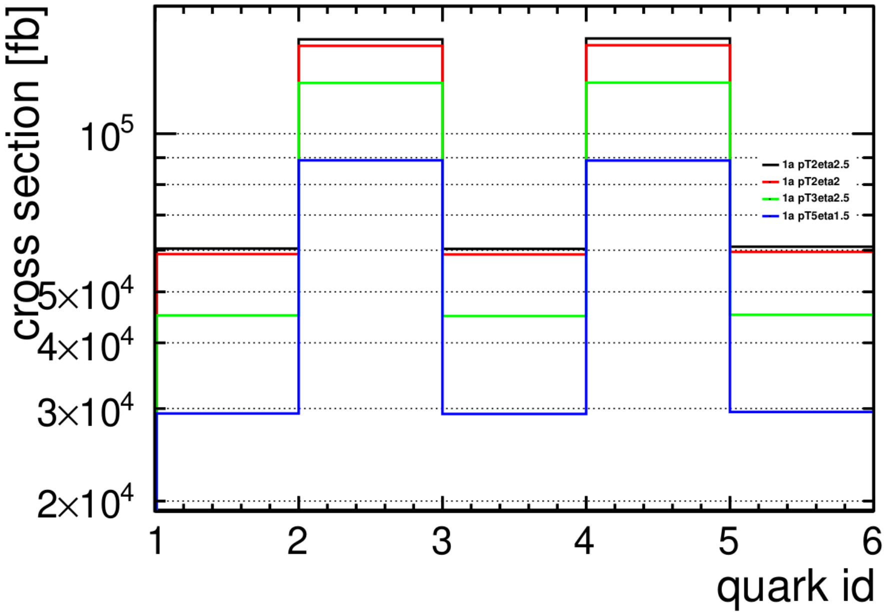
How to select events?

work in progress

Event reconstruction

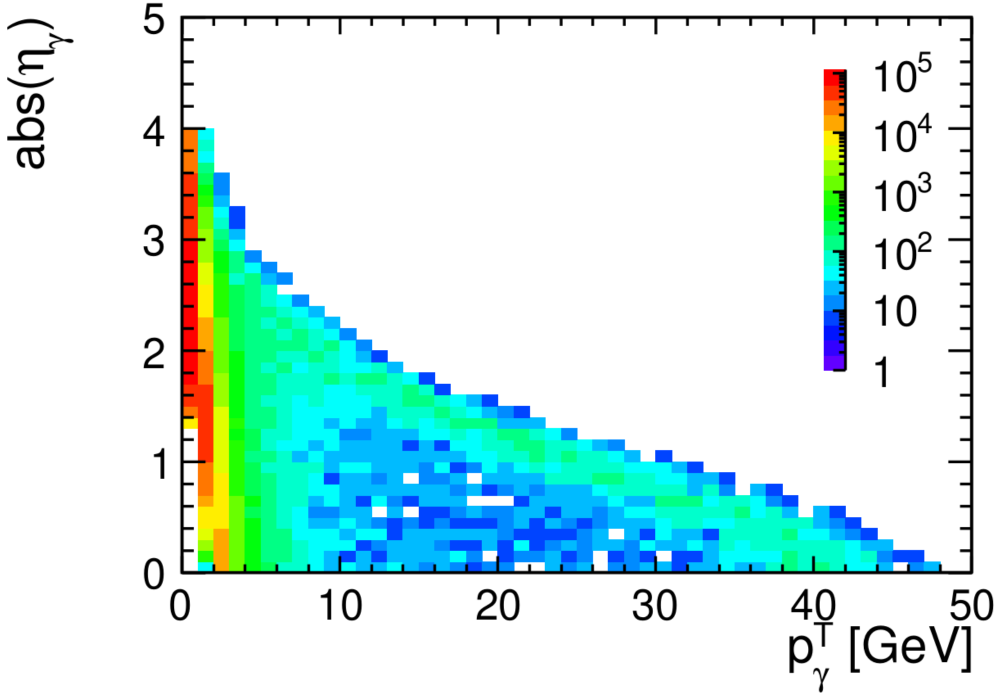
- events with 0 and 1 ME photons generated with *Whizard* (higher multiplicities neglected for now)
- detector simulation in *Delphes* with default *ILCgen* cards
- analysis cuts:
  - 2 jets
  - exactly 1 reconstructed photon with specific (p^T , η)



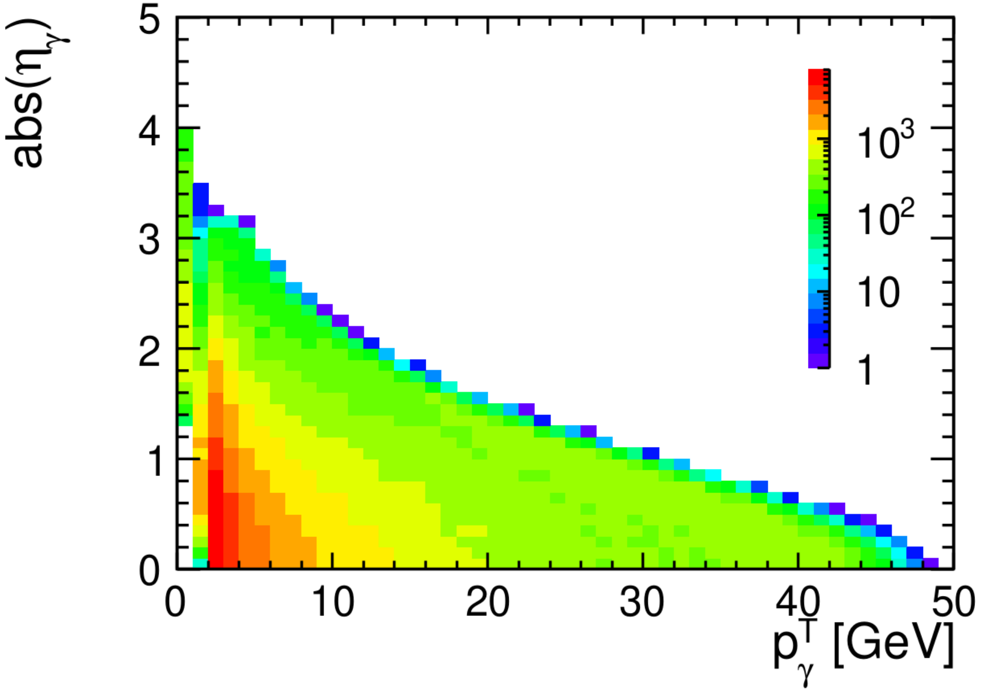


(p^T, η) distribution

By a wise choice of the cuts, one may obtain a ratio of accepted events $N_{1\gamma} / N_{0\gamma} > 20$, keeping the event statistics at a reasonable level.



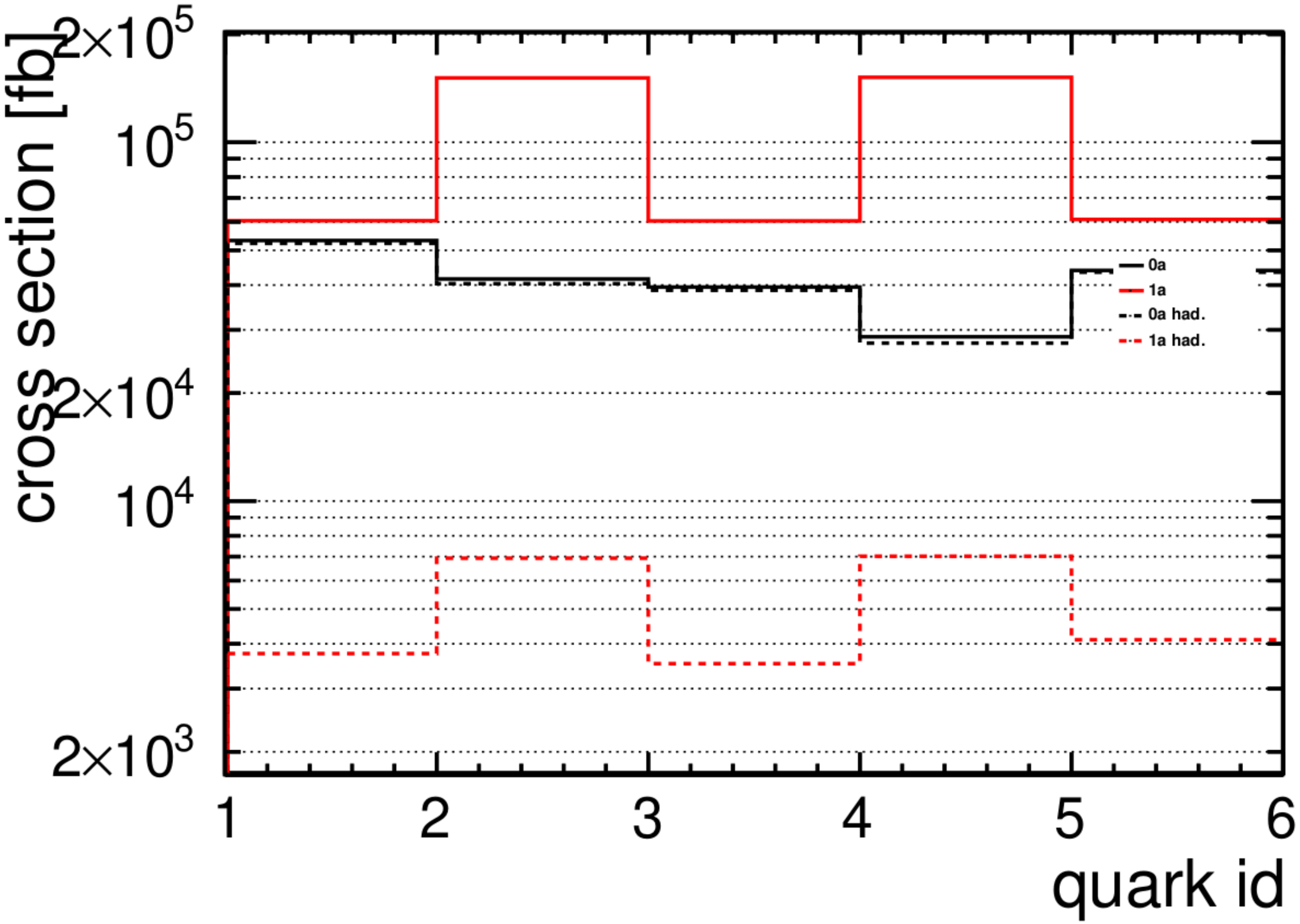
0 ME γ



1 ME γ

Hadronisation photons

Photons in the 0 ME γ sample come from hadronisation and decays.



black – 0 ME γ sample

red – 1 ME γ sample

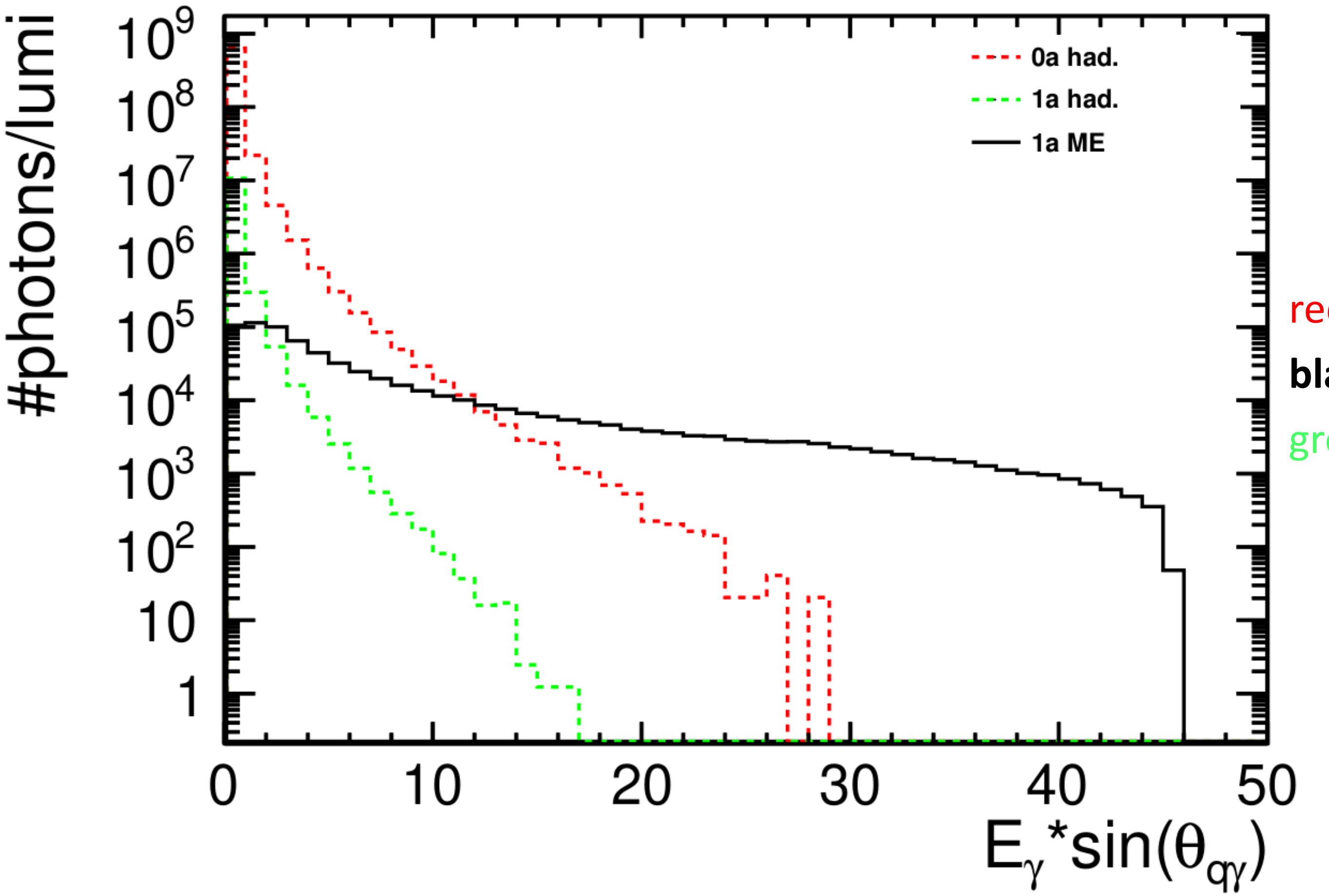
dashed – the reconstructed photon comes from hadronisation

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 done in *Pythia6*

Event reconstruction revisited



red – 0 ME γ, hadro. photons
black – 1 ME γ, ME photons
green – 1 ME γ, hadro. photons

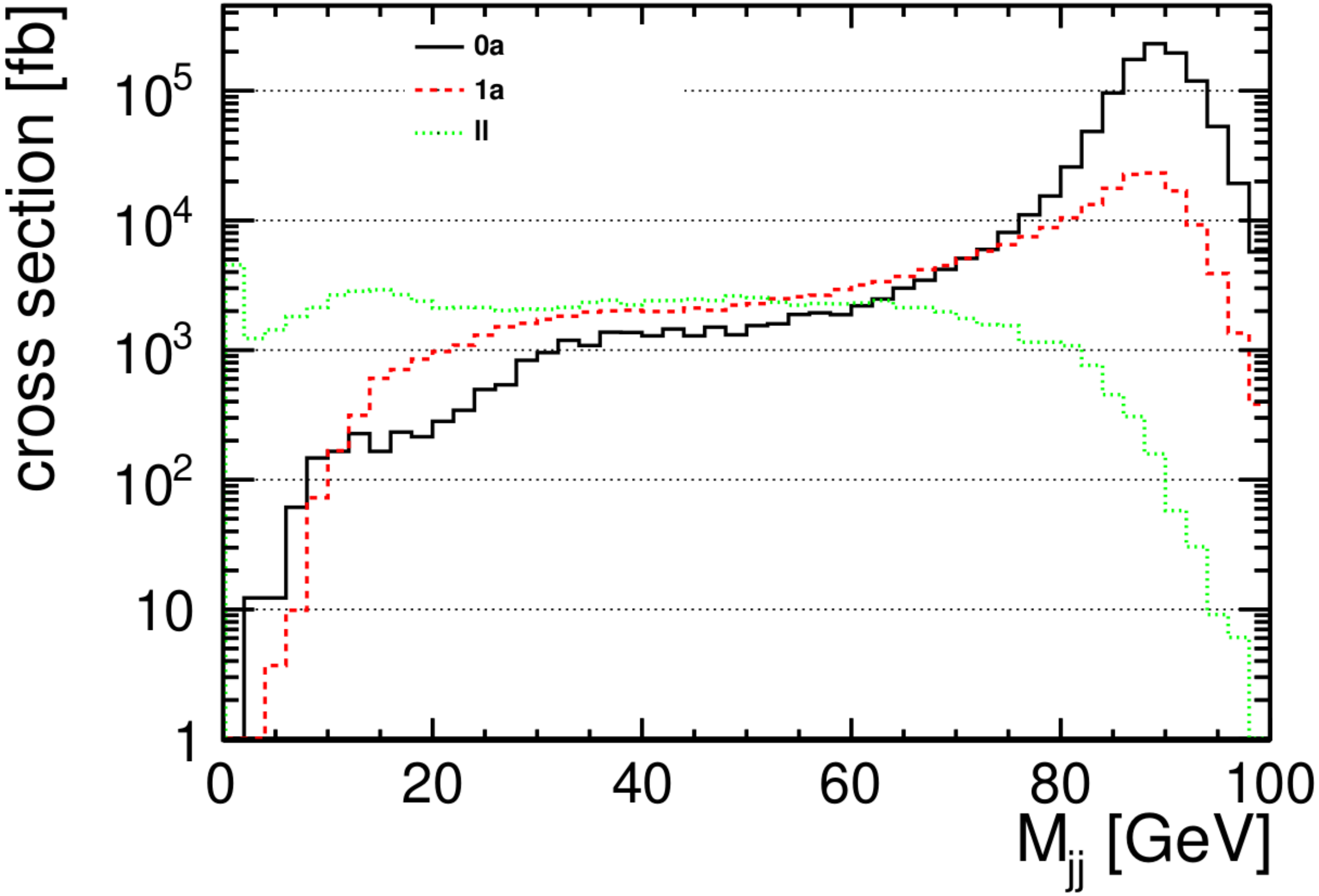
Photon isolation critieria to be tuned...

Conclusions

- Couplings of the Z boson to light quarks are poorly constrained but an improvement could be achieved at future lepton colliders.
- We have established a dedicated generation procedure accounting for photons coming from different sources.
- We have performed preliminary studies on the experimental cuts and their efficiency.
- The next step is to study photon isolation criteria which are crucial for reducing the contribution originating from hadronisation.
- Work in progress: the goal is to estimate the uncertainty of the measurement at future e^+e^- colliders depending on the reconstruction criteria and experimental cuts.

Backup

$Z \to \tau\tau$ background



The contribution can be easily suppressed by cuts.