Determination of the first-generation quark couplings at the Z-pole

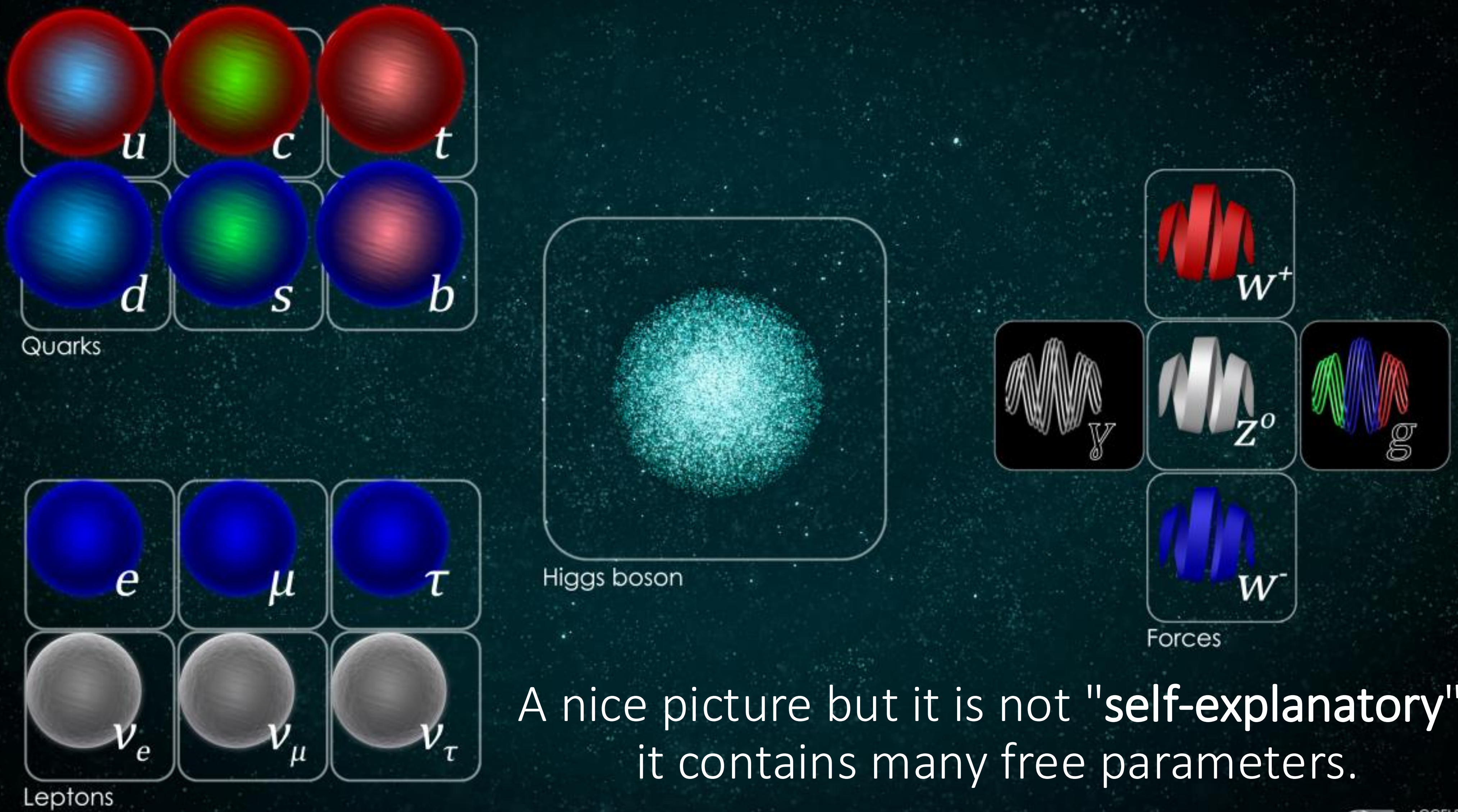
Krzysztof Mękała

DESY, Hamburg, Germany

Faculty of Physics, University of Warsaw, Poland

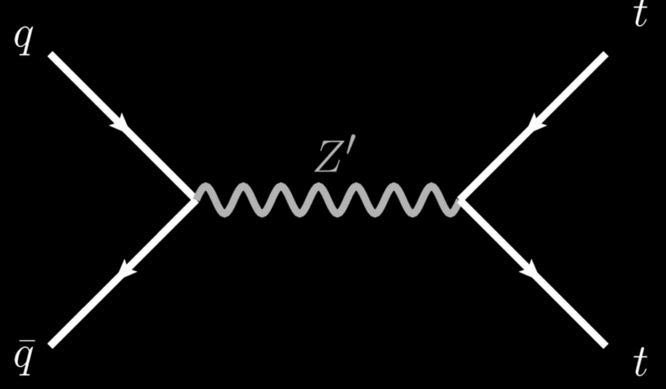
based on [2504.11365]

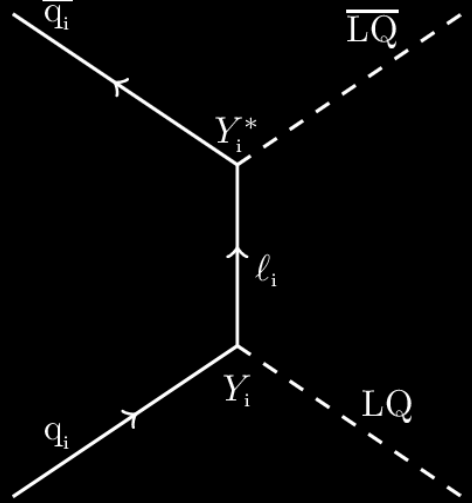
EPS-HEP, 10.07.2025

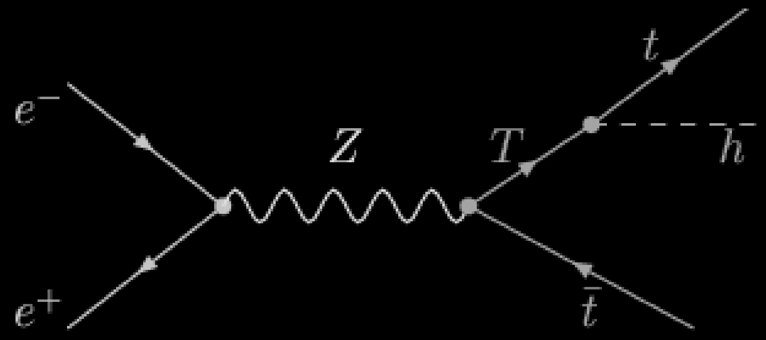


A nice picture but it is not "**self-explanatory**":
it contains many free parameters.

Precise measurements allow to constrain SM parameters and 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

$R_c = \Gamma(c\bar{c})/\Gamma(\text{hadrons})$ — 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.

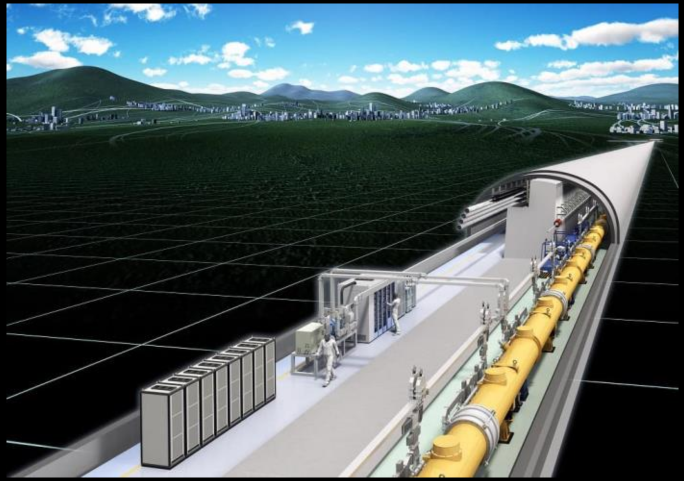
VALUE	DOCUMENT ID		TECN	COMMENT
0.1721±0.0030 OUR FIT				
0.1744±0.0031±0.0021	[1] ABE	05F	SLD	E^{ee}_{cm}=91.28 GeV
0.1665±0.0051±0.0081	[2] ABREU	00	DLPH	E^{ee}_{cm}= 88–94 GeV
0.1698±0.0069	[3] BARATE	00B	ALEP	E^{ee}_{cm}= 88–94 GeV
0.180 ±0.011 ±0.013	[4] ACKERSTAFF	98E	OPAL	E^{ee}_{cm}= 88–94 GeV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

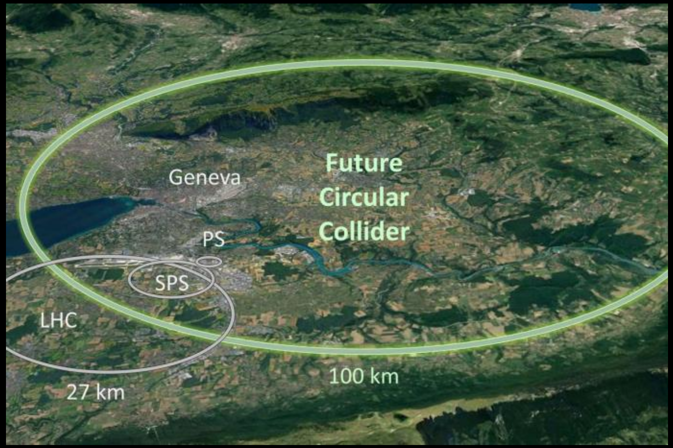
VALUE	DOCUMENT ID		TECN	COMMENT
0.166±0.009 OUR AVERAGE				
$0.172^{+0.011}_{-0.010}$	[1] ABBIENDI	04E	OPAL	E^{ee}_{cm} = 91.2 GeV
0.160±0.019±0.019	[2] ACKERSTAFF	97T	OPAL	E^{ee}_{cm}= 88–94 GeV
$0.137^{+0.038}_{-0.054}$	[3] ABREU	95X	DLPH	E^{ee}_{cm}= 88–94 GeV
0.137±0.033	[4] ADRIANI	93	L3	E^{ee}_{cm}=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

Future e^+e^- colliders operating at the Z-pole would be a perfect place to measure 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 LC250 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 analyse 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:

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

Γ_{had} scales as:

$$\Gamma_{had} \sim \sum_q c_q$$

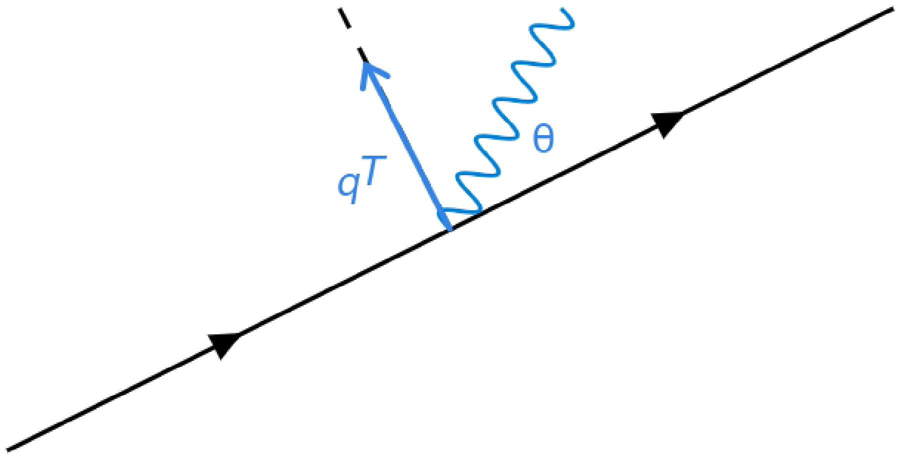
and $\Gamma_{had+\gamma}$ *as*:

$$\Gamma_{had+\gamma} \sim \sum_q c_q Q_q^2$$

Resolution parameter q^T

- By measuring the radiative and non-radiative decays, one can disentangle c_q. The definition of a *radiative* event is crucial.
- The photon resolution criterion may depend on an arbitrarily chosen isolation parameter, e.g. the photon transverse momentum w.r.t. the jet direction, q^T:

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



Measurement at the Z-pole – recipe

1. Count 2-jet events (n_j) and 2-jet events with a tagged photon ($n_{\gamma j}$). We consider 4 tags: "light", s, c and b.

$$j = (ud)(ud), (ud)s, (ud)c, ..., ss, sc, sb, ...$$

Measurement at the Z-pole – recipe

1. Count 2-jet events (n_j) and 2-jet events with a tagged photon ($n_{\gamma j}$). We consider 4 tags: "light", s, c and b.

$j = (ud)(ud), (ud)s, (ud)c, \ldots, ss, sc, sb, \ldots$

2. Compare to the expected numbers of events:

$$N_j = (\text{exp. acceptance}) \cdot (\text{class. prob.}) \cdot (\text{lumi.}) \cdot \sigma_q \equiv A_{jq} \cdot \sigma_q$$

$$N_{\gamma j} = B^{\gamma}_{jq}(y_{cut}) \cdot \sigma_{\gamma q} + B^{0}_{jq}(y_{cut}) \cdot \sigma_{0q} \equiv B_{jq} \cdot \sigma_q$$

[2310.03440]

Measurement at the Z-pole – recipe

1. Count 2-jet events (n_j) and 2-jet events with a tagged photon ($n_{\gamma j}$). We consider 4 tags: "light", s, c and b.

$$j = (ud)(ud), (ud)s, (ud)c, \ldots, ss, sc, sb, \ldots$$

2. Compare to the expected numbers of events:

$$N_j = (\text{exp. acceptance}) \cdot (\text{class. prob.}) \cdot (\text{lumi.}) \cdot \sigma_q \equiv A_{jq} \cdot \sigma_q$$

$$N_{\gamma j} = B^{\gamma}_{jq}(y_{cut}) \cdot \sigma_{\gamma q} + B^{0}_{jq}(y_{cut}) \cdot \sigma_{0q} \equiv B_{jq} \cdot \sigma_q$$

[2310.03440]

3. Minimise the χ^2 distribution to extract the cross sections:

$$\chi^2 = \sum_j \frac{(n_j - N_j)^2}{N_j} + \sum_j \frac{(n_{\gamma j} - N_{\gamma j})^2}{N_{\gamma j}}$$

Measurement at the Z-pole – recipe

1. Count 2-jet events (n_j) and 2-jet events with a tagged photon ($n_{\gamma j}$). We consider 4 tags: "light", s, c and b.

   $j = (ud)(ud), (ud)s, (ud)c, \ldots, ss, sc, sb, \ldots$

2. Compare to the expected numbers of events:

$$N_j = (\text{exp. acceptance}) \cdot (\text{class. prob.}) \cdot (\text{lumi.}) \cdot \sigma_q \equiv A_{jq} \cdot \sigma_q$$

$$N_{\gamma j} = B^{\gamma}_{jq}(y_{cut}) \cdot \sigma_{\gamma q} + B^{0}_{jq}(y_{cut}) \cdot \sigma_{0q} \equiv B_{jq} \cdot \sigma_q$$

[2310.03440]

3. Minimise the χ^2 distribution to extract the cross sections:

$$\chi^2 = \sum_j \frac{(n_j - N_j)^2}{N_j} + \sum_j \frac{(n_{\gamma j} - N_{\gamma j})^2}{N_{\gamma j}}$$

Systematic uncertainties can also be included:

$$\chi^2(\vec{\delta}) = \sum_j \frac{(n_j - N_j(\vec{\delta}))^2}{n_j} + \sum_j \frac{(n_{\gamma j} - N_{\gamma j}(\vec{\delta}))^2}{n_{\gamma j}} + \sum_k \delta_k^2 + \sum_q 2\lambda_q\, w_q(\vec{\delta})$$

How to generate Monte Carlo events?

Analysis setup

We want to consider:

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

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 – divergent or very slow for low photon-emission angles;
- **ISR structure functions** – good for low angles, a proper matching procedure needed;
- **FSR showers** – important for QCD emissions, may cause double-counting;
- **hadron decays** – photons 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

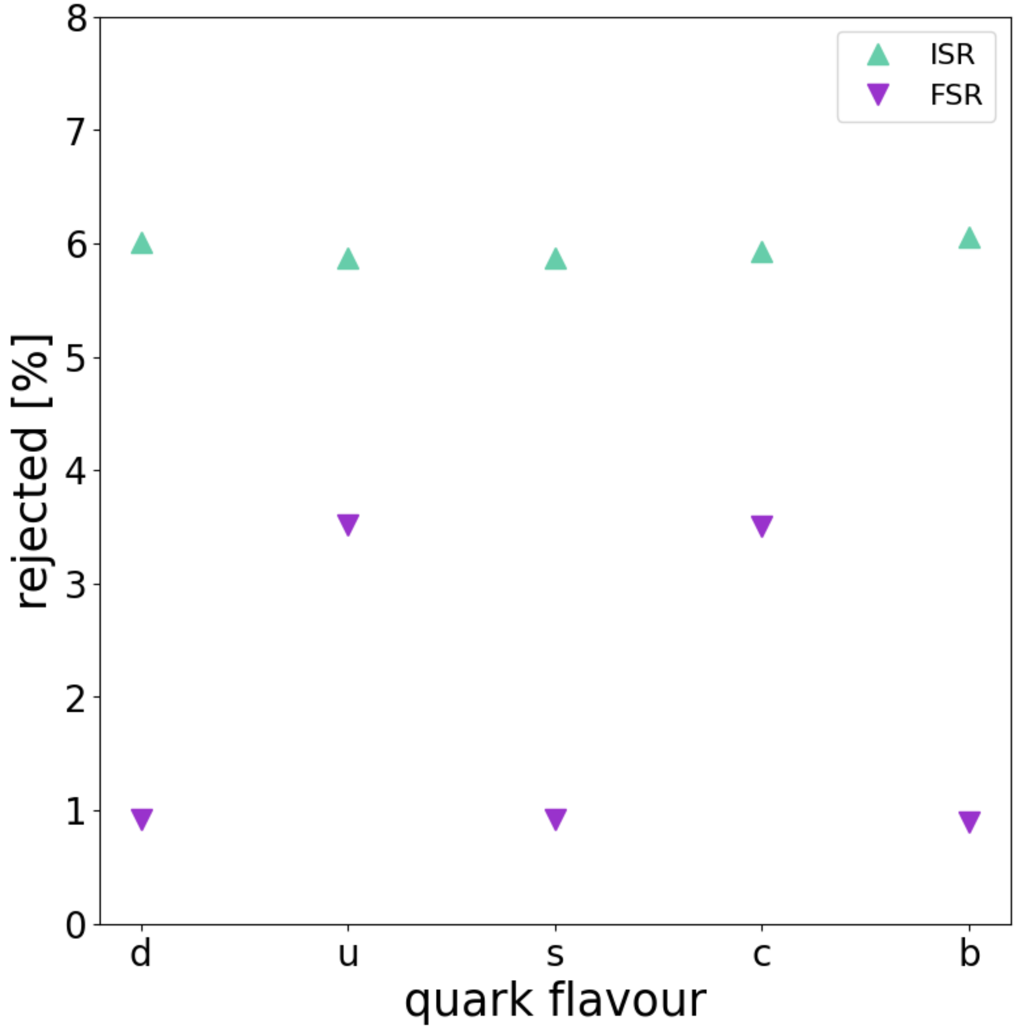
- soft FSR photons simulated using parton showers

- 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

About 7-8% of Whizard events are rejected to avoid double-counting.



How to analyse events?

Event reconstruction

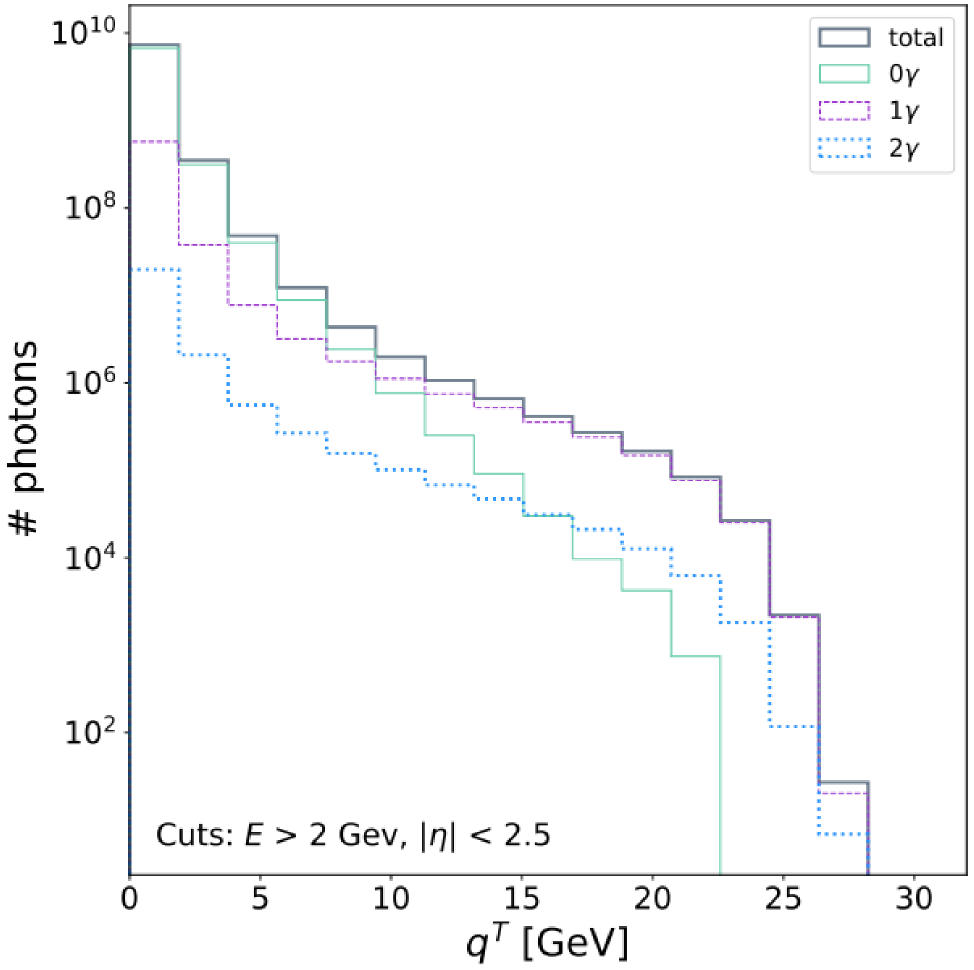
Measurable photons can originate from:

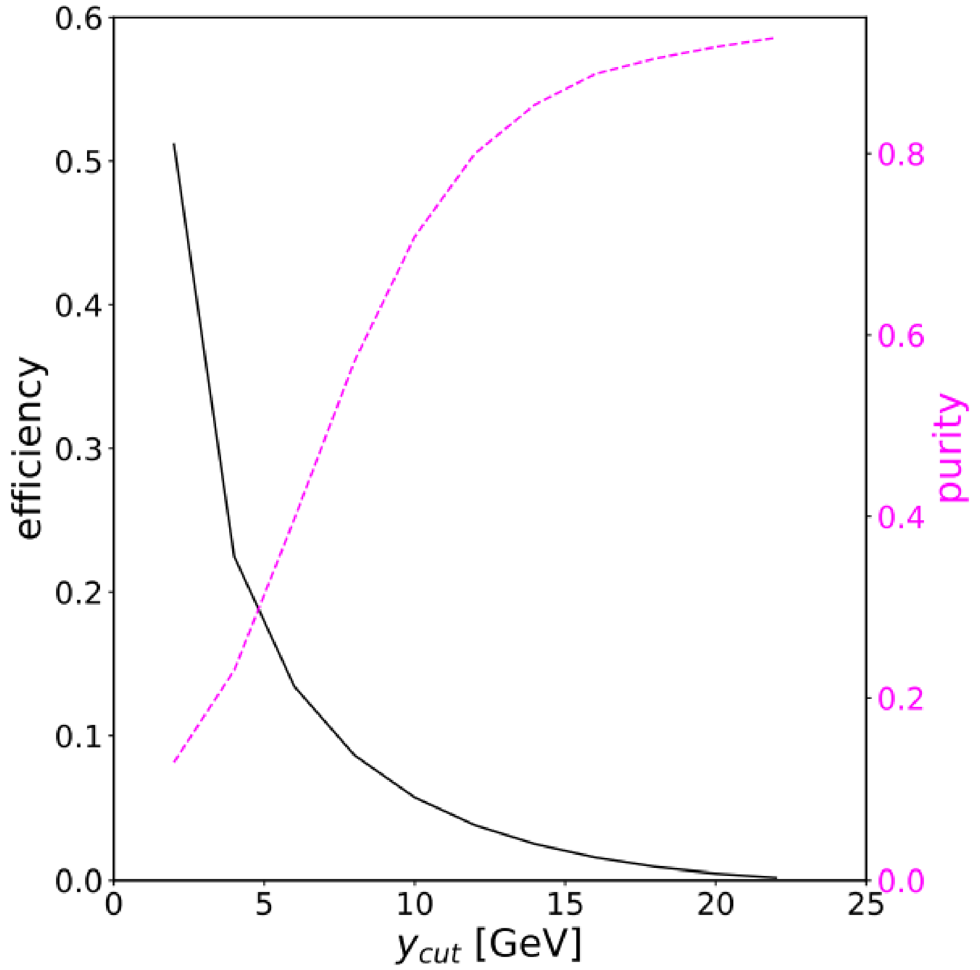
- Initial State Radiation,
- Final State Radiation,
- hadronisation and decays.

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

A dedicated approach is crucial. To detach from the standard convention, we cluster all photons into jets and then consider EFLow photon objects (Delphes-level study).

Photon kinematics – transverse momentum





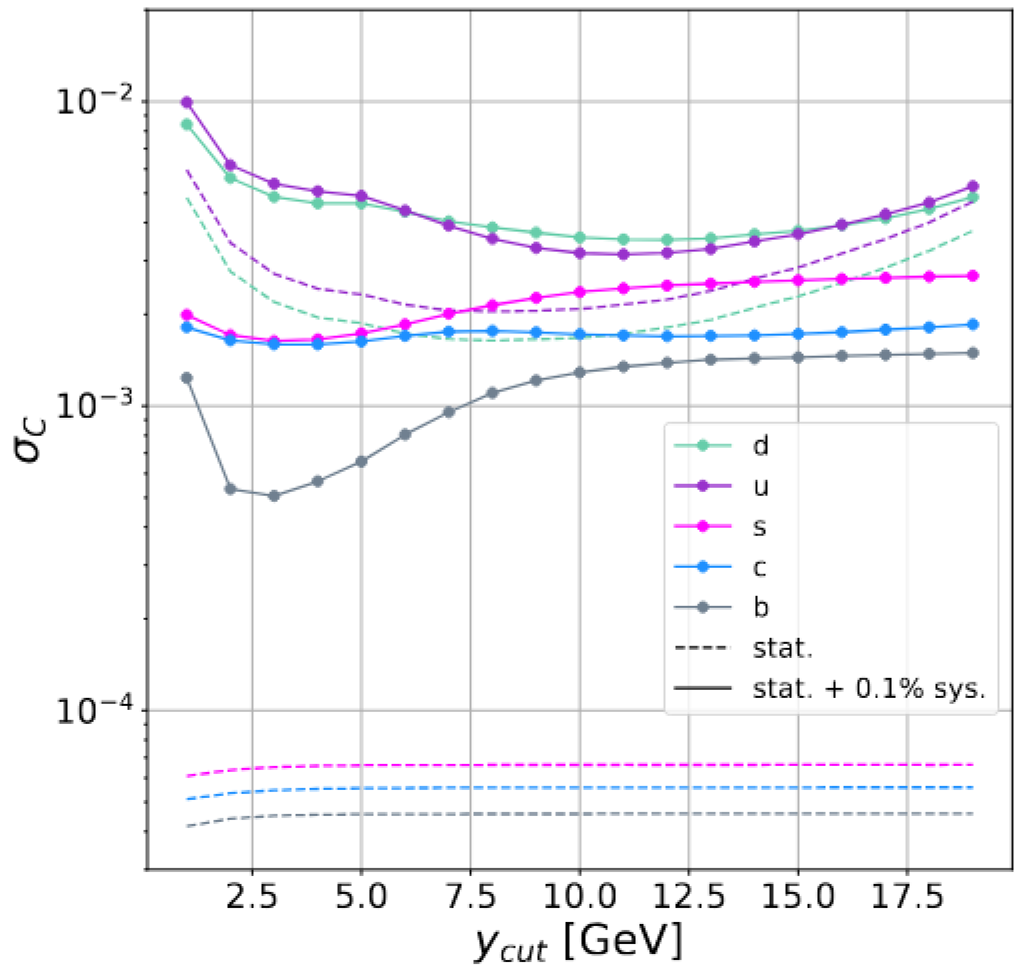
ILD as reference detector design

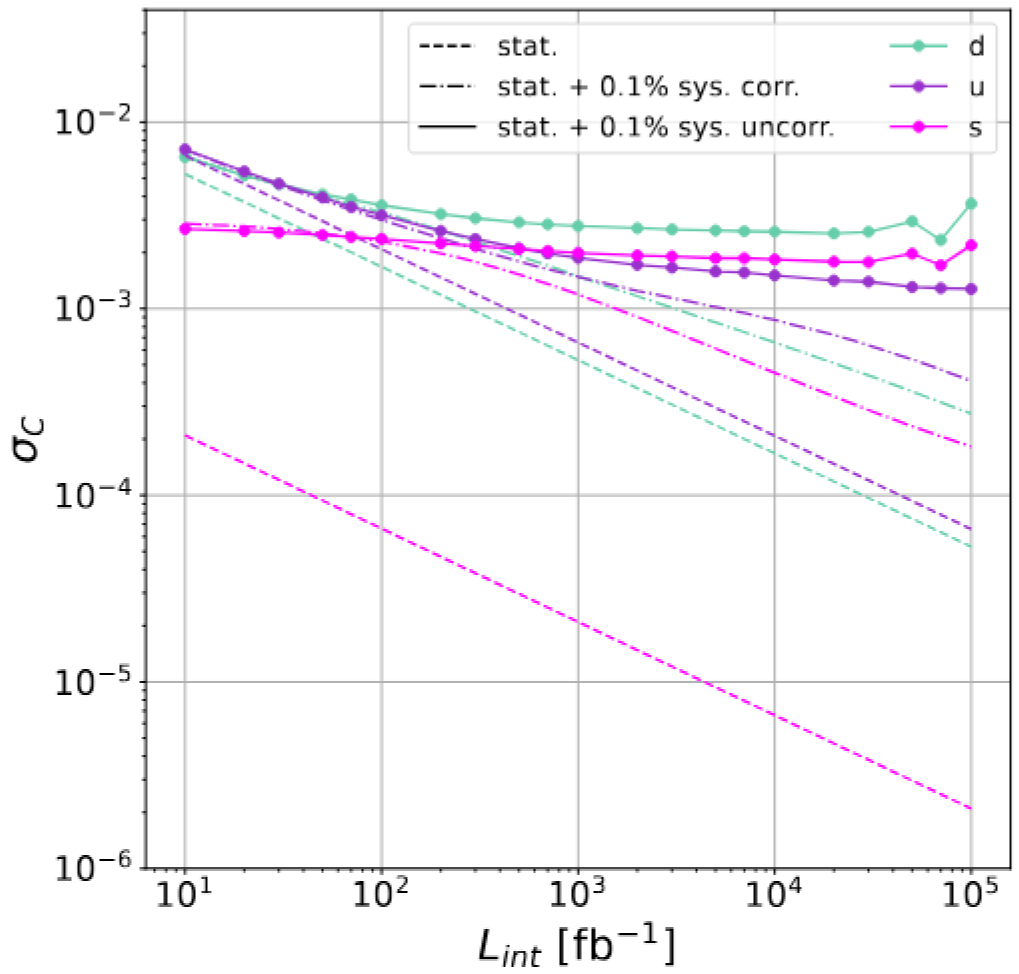
Systematic uncertainties

The optimal isolation parameter can only be found if systematic uncertainties are included.

Uncertainty	[%]
integrated luminosity (relative)	0.01
radiative event selection efficiency F (relative)	0.01-1
background to the radiative sample due to photons coming from hadronisation G (relative)	
tagging uncertainties	

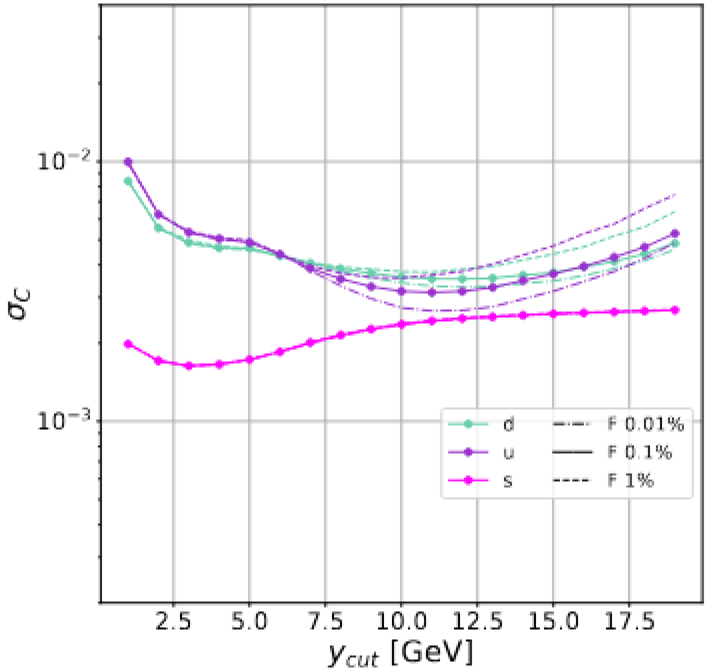
Results – 5-flavour decomposition

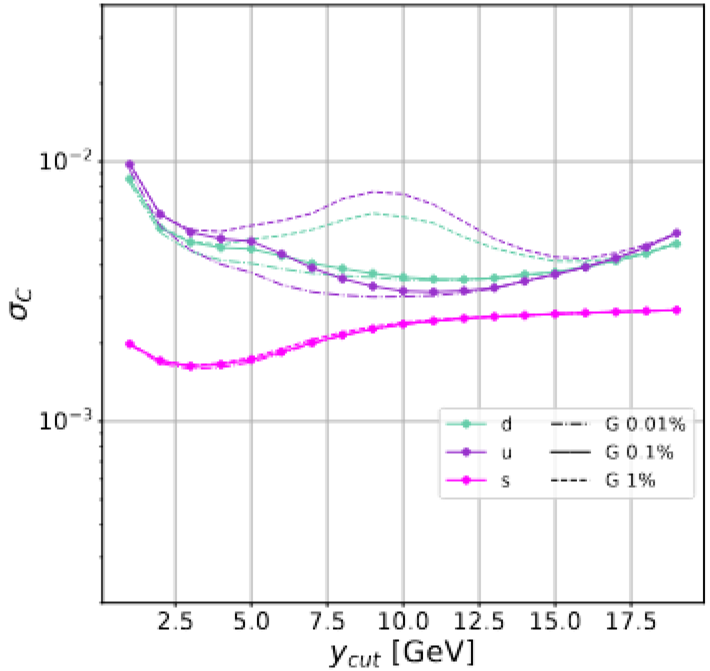


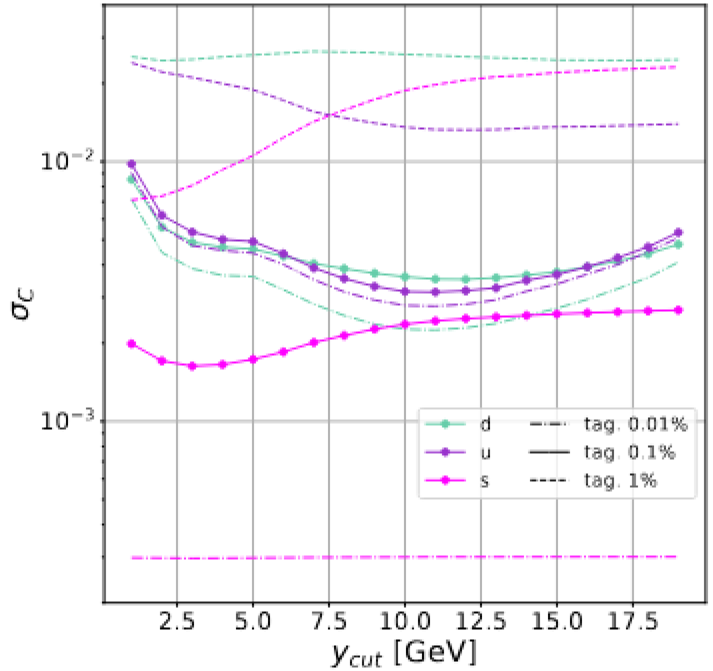


assuming int. lumi of 100 fb^{-1}

Results – syst. uncertainties







assuming int. lumi of 100 fb^{-1}

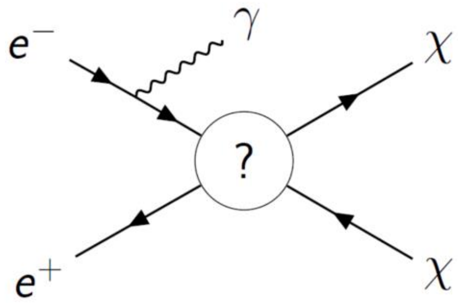
Conclusions

- The couplings of the Z boson to light quarks are weakly constrained but a significant improvement could be achieved at future colliders.
- Proper assessment of the uncertainties requires deep understanding of theoretical calculations, event simulation and reconstruction.
- Tagging uncertainty is a crucial factor in the study.
- Prospects for 100 fb^{-1}: **sub-percent** precision for *d* and *u*, **sub-permille** precision for *b if* tagging uncertainty ~ 0.1%.

Backup

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 $q_{\pm}$:

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

Matching 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:

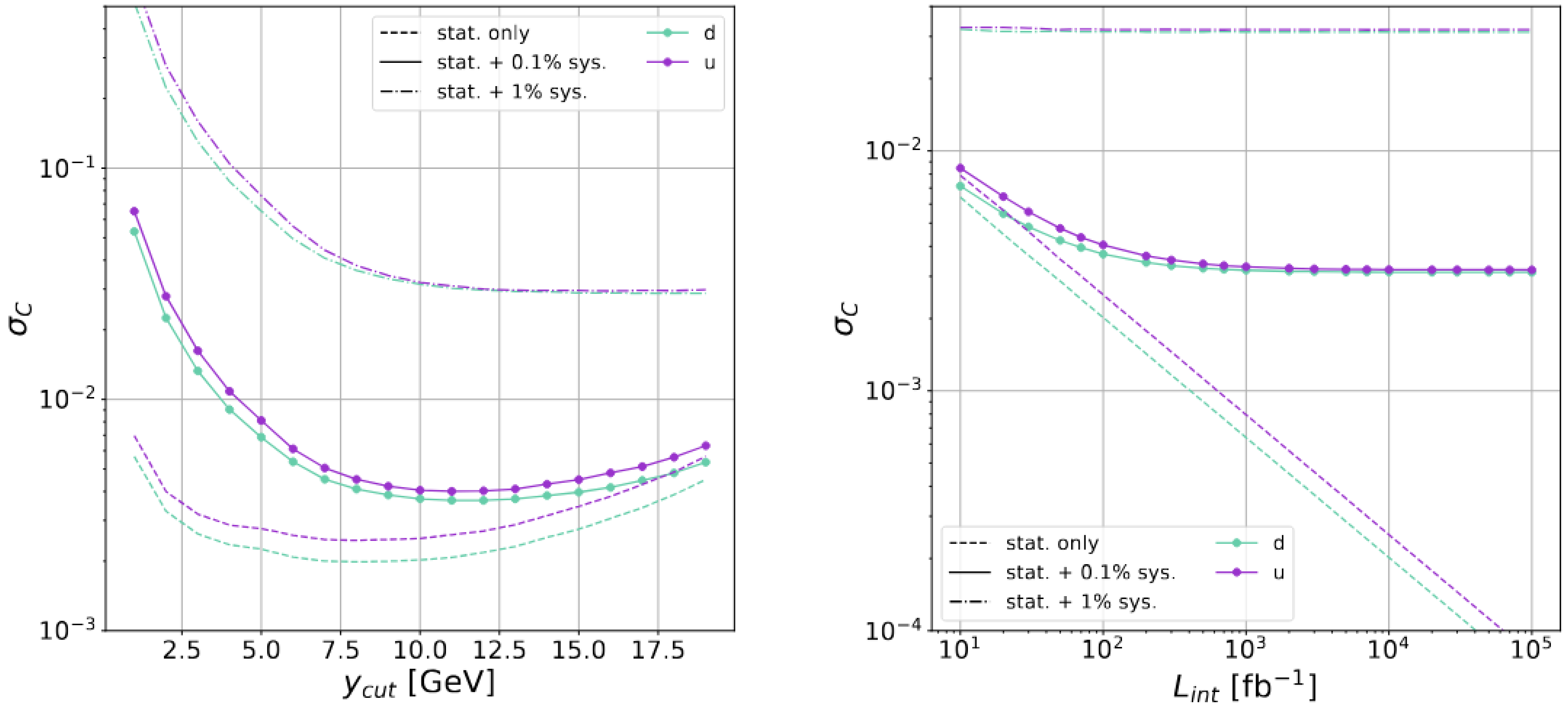
$$q_{\pm} < 0.5 \text{ GeV } \underline{\text{or}} \ E < 0.5 \text{ GeV } \underline{\text{or}} \ M(\gamma, q_i) < 1 \text{ GeV}$$

  - **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.

Results – 2 flavours only



assuming int. lumi of 100 fb^{-1}

Fit correlations

int. lumi of 100 fb^{-1}