QED radiative corrections in semileptonic decays

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Based on work with Stefano Calì, Marcello Rotondo and Barbara Sciascia: Eur.Phys.J.C 79 (2019) 9, 744

LHCb Workshop on semileptonic exclusive $b \to c$ decays

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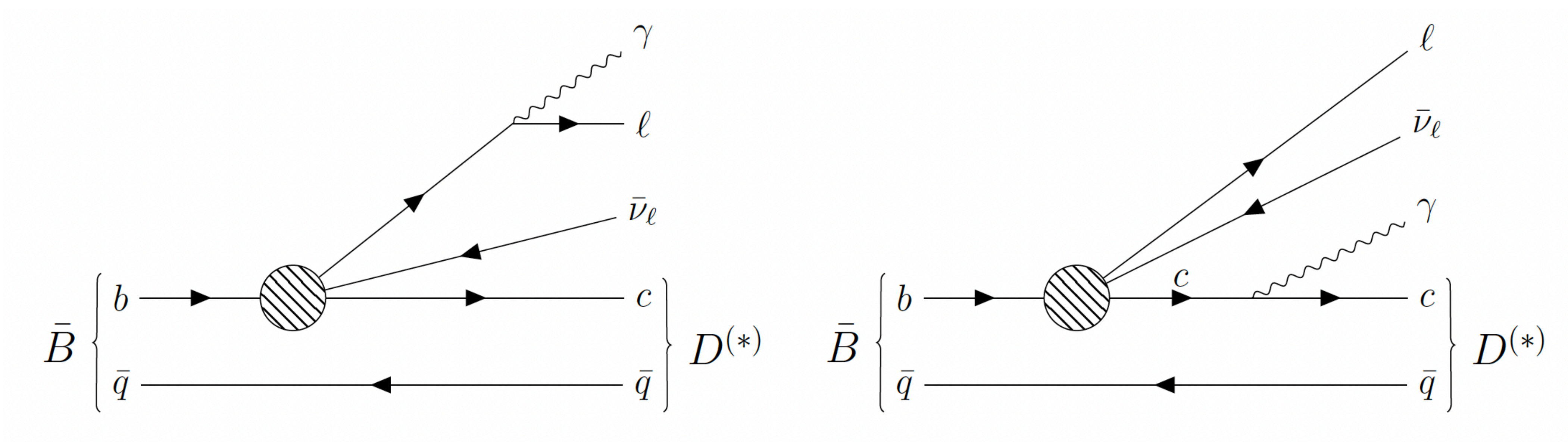
Introduction

- QED radiative corrections describe the exchange of virtual and real photons
  - alter values of physical quantities, *e.g.* mass, cross-section
  - impact predictions
  - also impacts measurements; especially MC shapes which we heavily rely on in semileptonic measurements
- Difficult to measure experimentally, how to make sure we understand the impact on our measurements?

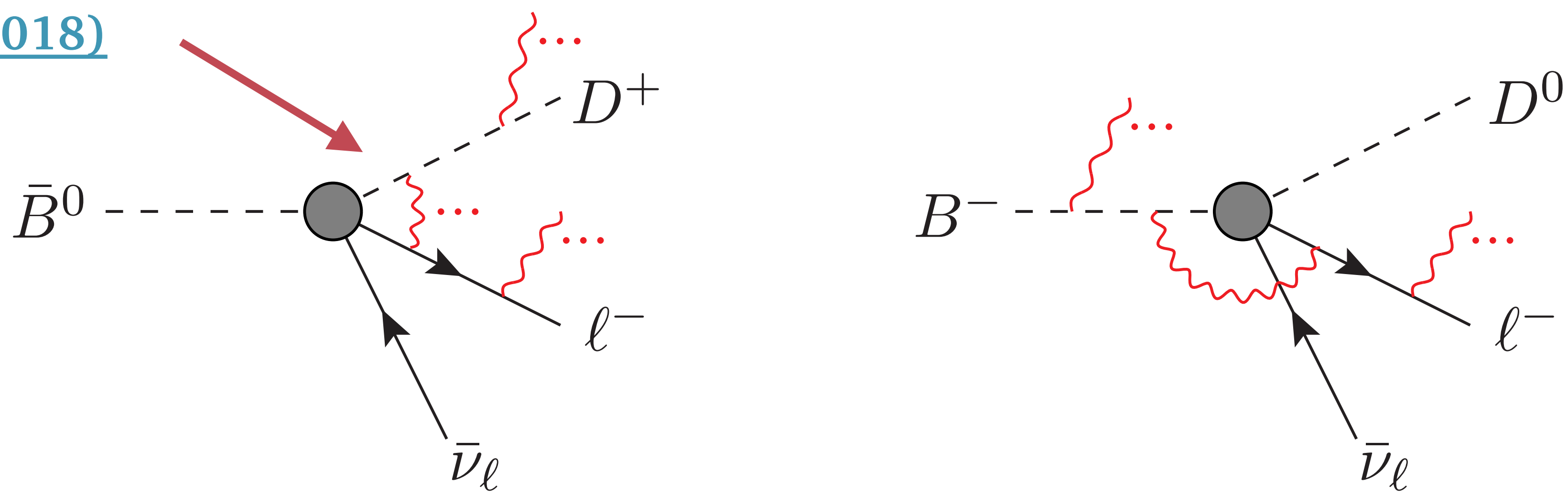


JHEP 43 (2022)

QED corrections

- Coulomb corrections: interactions between charged particles:

PRL 120, 261804 (2018)



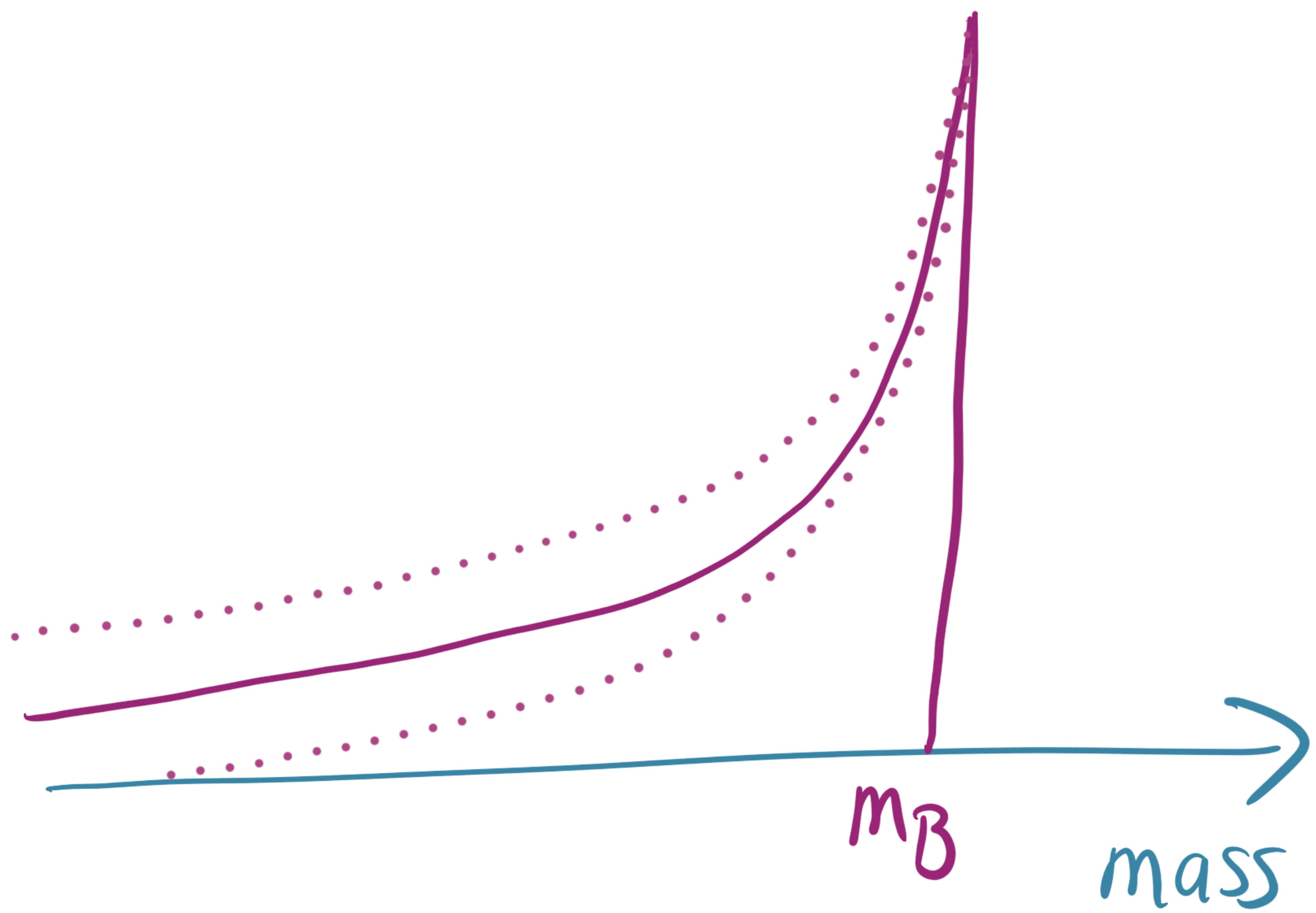
- Structure-dependent (SD) corrections: probe the quark process, parametrised by additional form factors. *E.g.* in the case of $B \to D^{(*)}\ell\nu_\ell$ this adds four new form factors: JHEP 43 (2022).
- Ideally use simulations that calculate structure-dependent matrix elements and QED corrections for every single decay.
- Instead we use PHOTOS which deals with bremsstrahlung in production and decay.

PHOTOS

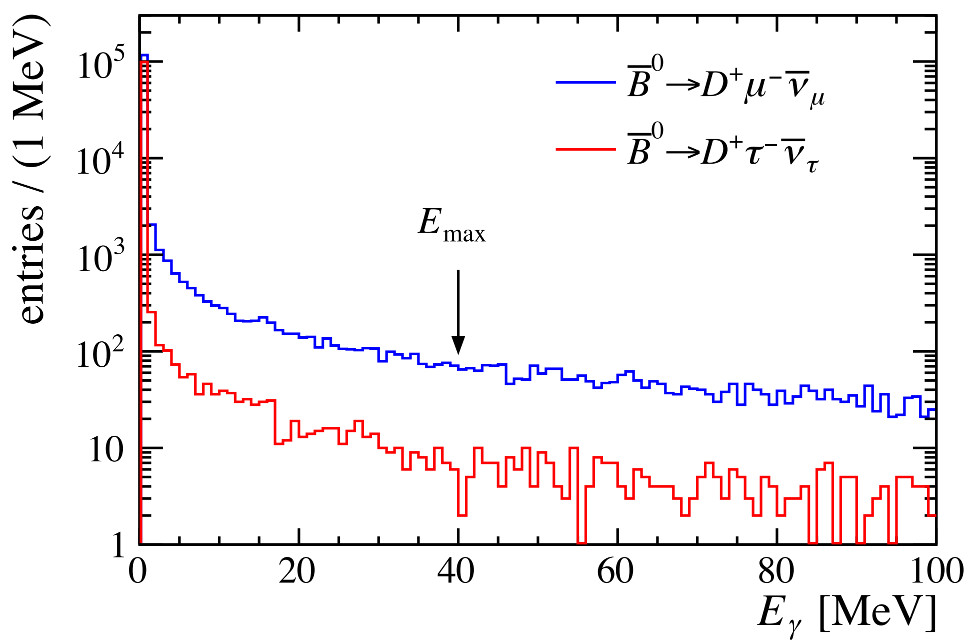
- PHOTOS is a universal MC algorithm that simulates QED corrections and is used by all HEP experiments.
- PHOTOS corrections depend only on four-momenta of particles and applied a Bremsstrahlung correction to cross-sections:
    - Soft-photon corrections and interferences are included
    - Structure-dependent photons are <u>not included</u>
    - Hard photons are generated, <u>but not validated</u>. Comp.Phys.Com. 79 (1994) 291-308
      "*Design of the program guarantees the correctness of the leading-log corrections and distributions in the soft-photon region only.* ***In many cases this would be very bad. In fact, not better than complete neglect of QED corrections.***"
    - Coulomb corrections are <u>not included</u>
- Successfully tested for W, Z and one B decay, should be tested for every type of measurements, especially when high precision is needed.
- Clearly incomplete, but the best we have so far. How can we deal with the uncertainties?

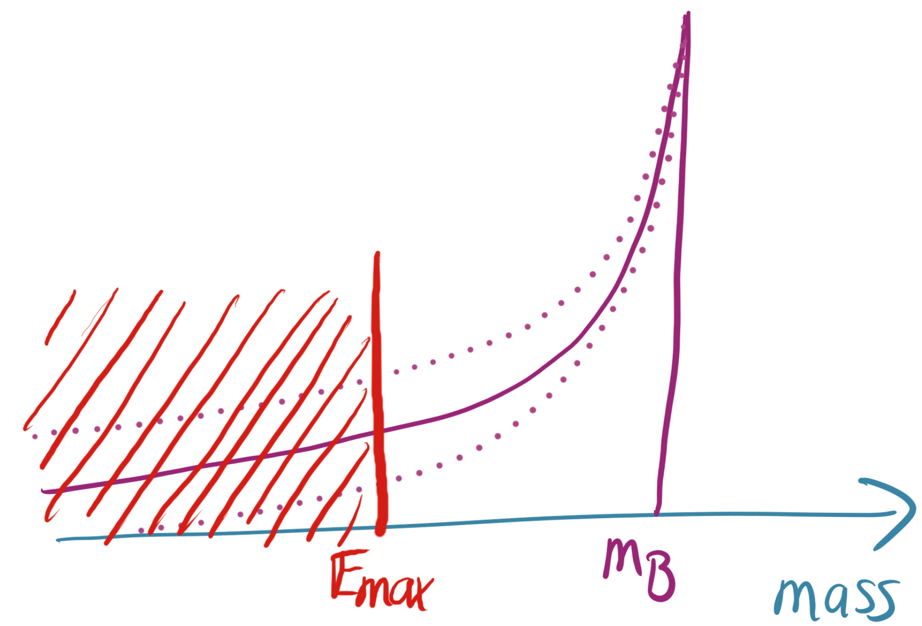
Impacts on measurements

- Since most QED corrections will come from soft photons, which are simulated well, can we assume the impact from the high-energy (structure-dependent) corrections are negligible?
    - ➤ How bad can it be?
      Perform a dummy analysis on MC to evaluate this



The E_{max} variable





- We know QED corrections work quite well for soft photons, and want to study the effect of mis-modelling high-energy photons.
- Let's cut on energy E_{max}, which is the maximum energy that radiative photon in an event is allowed to have for us to consider it signal rather than background.
  - ➤ effectively assuming that photons above that energy are completely wrong, following the suggestion of the PHOTOS authors: ***"In many cases this would be very bad. In fact, not better than complete neglect of QED corrections"***

Impacts on measurements

- Generated 3M events in 4 samples
  - ➤ $\overline{B}^0 \to D^+\ell^-\overline{\nu}_\ell$ and $B^- \to D^0\ell^-\overline{\nu}_\ell$, with $\ell^- = \mu^-, \tau^-$
  - ➤ generator level only, no detector reconstruction
  - ➤ PHOTOS version 3.56, *“Option with interference is active”*
- Calculate the four-momentum carried away by the radiative photons as:

$$p_\gamma = p_B - (p_D + p_{\ell^-} + p_{\bar{\nu}_\ell})$$

  - ➤ We only consider radiation from the *D* and not of its daughters.
- QED corrections are defined as relative variation of the branching ratio due to events lost because $E_\gamma > E_{\rm max}$:

$$\delta_{\rm QED} = \frac{\int_0^{E_{\rm max}} N(E_\gamma) dE_\gamma}{\int_0^\infty N(E_\gamma) dE_\gamma} - 1$$

MC analysis

- What is the effect of mis-modelling QED corrections in our MC on measurements of LHCb?
- Applied LHCb-like selection on generated samples (see next slide).
- Using this, we make a dummy analysis:
  - ➤ very simplified: just signal and normalisation samples
  - ➤ generate 10.000 toy samples per decay mode with no cuts on E_{max}
  - ➤ generate templates with different cuts on E_{max}
  - ➤ fit for $R(D)$ using 3D templates (q^2, m^2_{miss}, E_ℓ) (same as in muonic $R(D^*)$) and study the effect

PRL 115 (2015) 111803

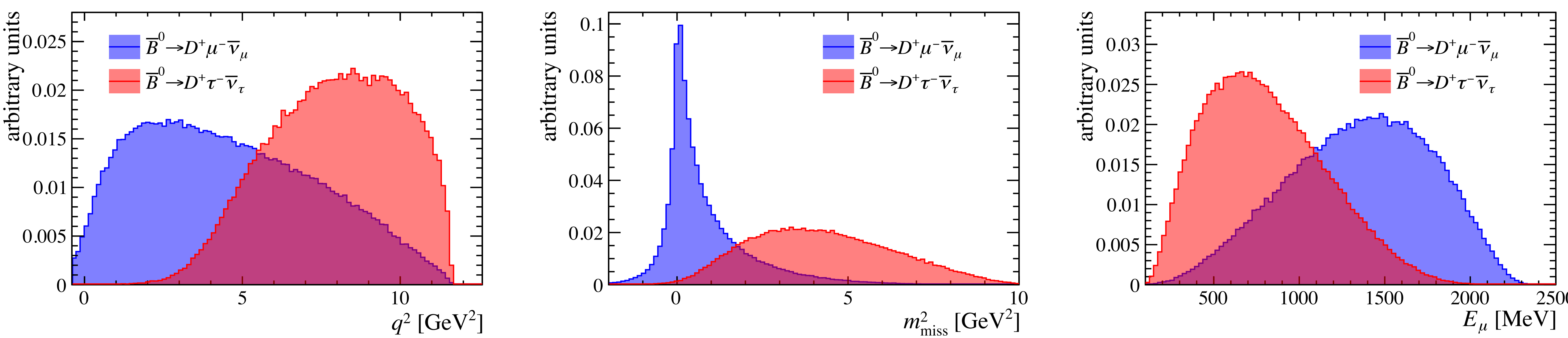
- This simulates worst-case scenario.
- Done to develop a method to determine the effect on measurements, does <u>not give corrections</u> to existing/future measurements.

LHCb-like selection

- Simulate vertex resolution by smearing the *pp* vertex by (±13, ±13, ±70) μm and the *B* decay vertex by (±20, ±20, ±200) μm   JHEP 02 (2017)021

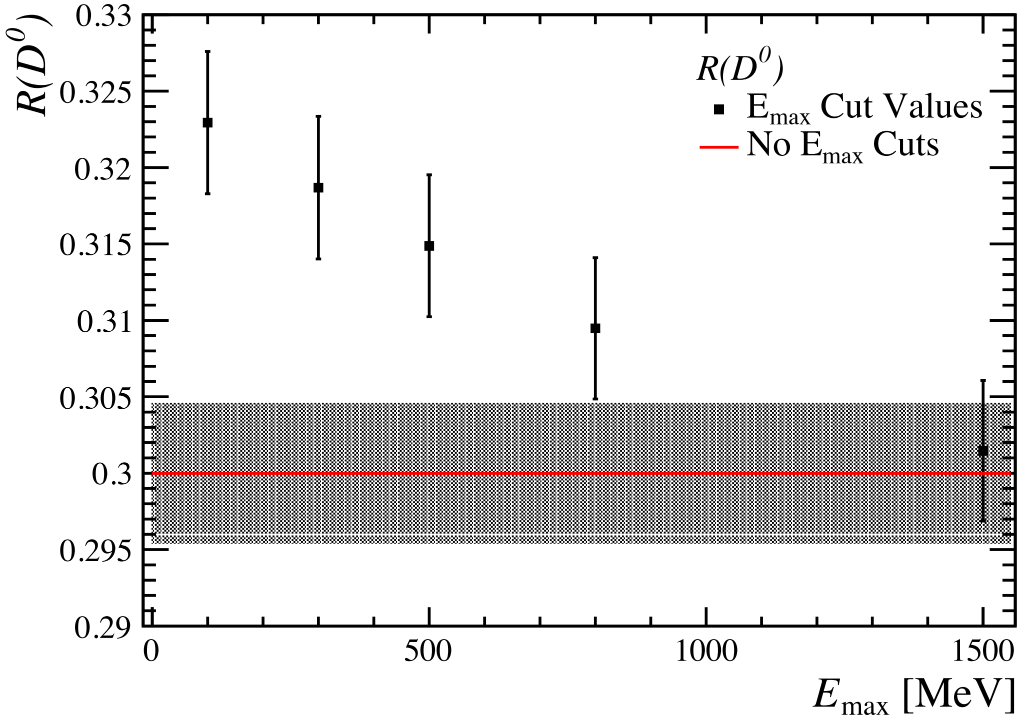
- Simulate LHCb acceptance using the cuts: $1.9 < \eta < 4.9$, $p > 5$ GeV, $p_T > 250$ MeV on kaons, pions and muons and a distance between *pp* and *B* vertex > 3 mm.

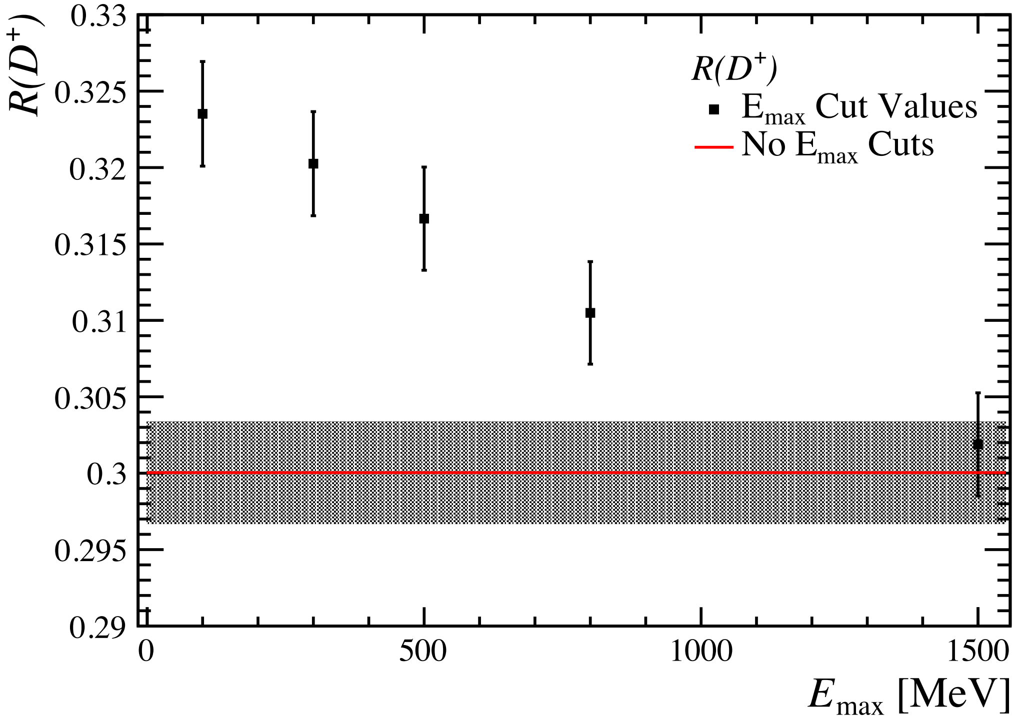
- Reconstruct B mesons momentum and related quantities using the LHCb rest frame approximation.



- Distributions look very similar to those from full detector simulation!

Outcome dummy analysis





- By including cuts on $E_{\max}$ in the templates, but not toys (or vice versa), study the effect of over- or underestimating radiative corrections in MC.
- Done for cuts on $E_{\max}$, at 100, 300, 500, 800, and 1500 MeV.
- Change on $R(D)$ is very similar for $R(D^+)$ and $R(D^0)$
- Largest when applying a cut on $E_{\max}$ around 100 MeV, shifting $R(D)$ by 0.02, or 7%.

Effect on measurements: Coulomb

- As a start, we can evaluate the impact of Coulomb corrections missing in PHOTOS
- A correction term can be calculated for generator level MC following the assumptions and equations in PRL 120, 261804 (2018)

$$\Omega_C = -\frac{2\pi\alpha}{\beta_{D\ell}} \frac{1}{e^{-\frac{2\pi\alpha}{\beta_{D\ell}}} - 1}$$

$$\alpha = 1/137$$

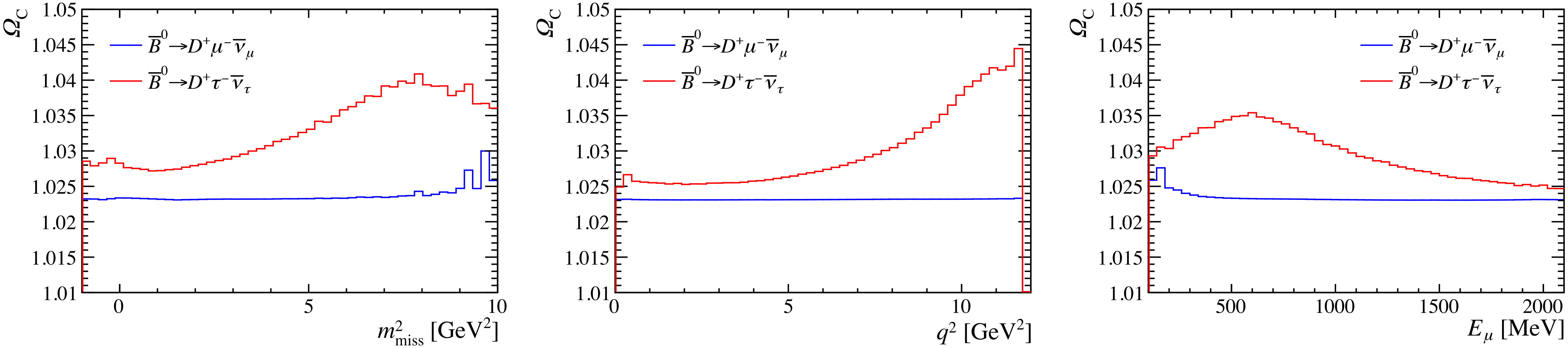
$$\beta_{D\ell} = \left[1 - \frac{4m_D^2 m_\ell^2}{(s_{D\ell} - m_D^2 - m_\ell^2)^2}\right]^{1/2}$$

$$s_{D\ell} = (p_D + p_\ell)^2$$

- Using these expressions, we can see the effect of the Coulomb corrections as a function of our usual fit variables, *e.g.* m^2_{miss}, q^2, E_μ

Coulomb corrections in toys

- Coulomb correction as a function of fit variables:

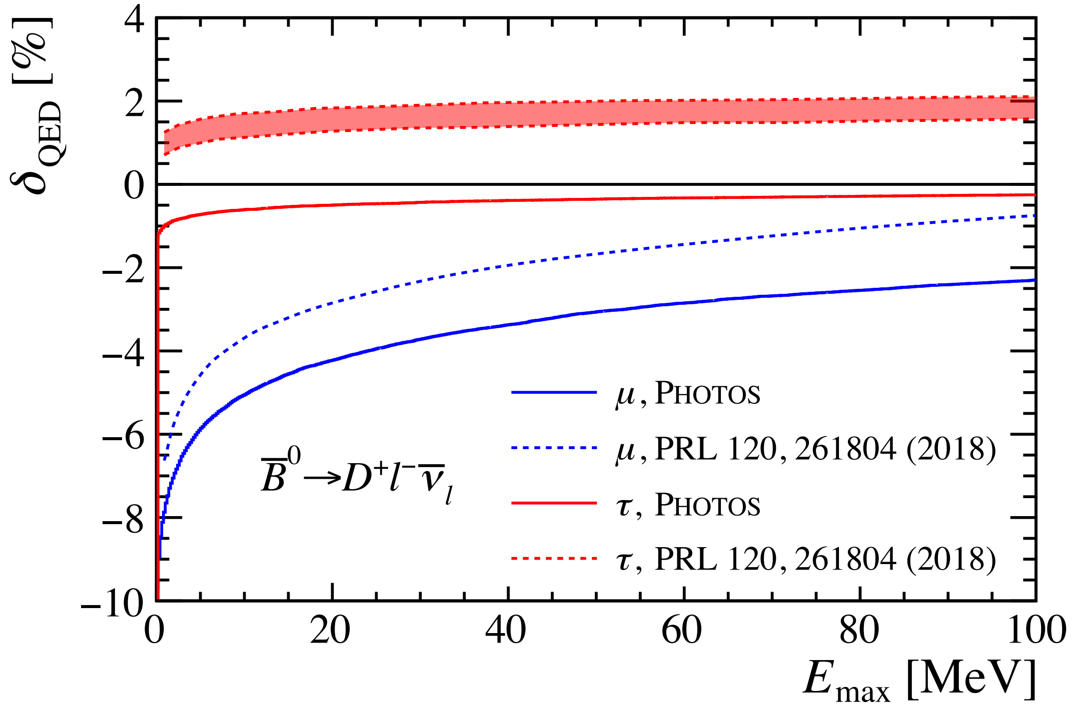


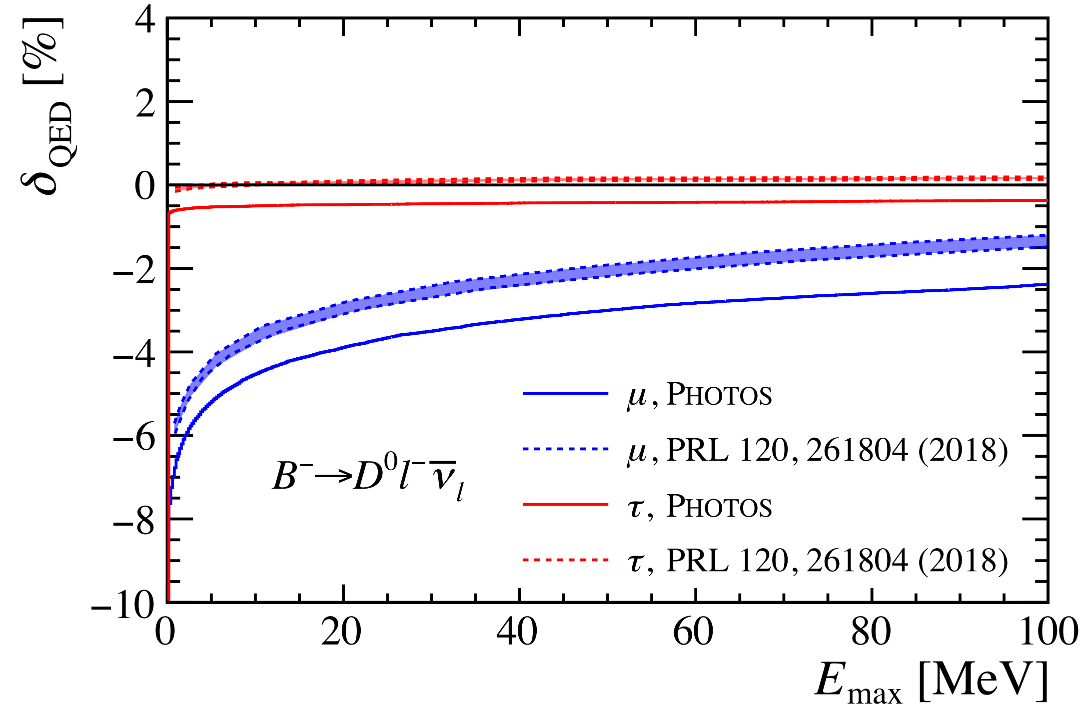
- This does not cancel in the ratios of $R(D)$.
- In our LHCb-like analysis, shift on $R(D^+)$ is -0.003 (-1%) when including Coulomb corrections on toys, but not templates.
- This can and should be studied for each analysis separately, because it depends on selection, reconstruction efficiency etc.

Comparing to theory

Eur.Phys.J.C 79 (2019) 9, 744

- Results are shown as a function of $E_{\max}$, and compared with the results from PRL 120, 261804 (2018):





- Differences of 0.5-1% for B^- decays, even up to 2% for B^0.
- Discrepancies cancel largely, but not completely in the ratios $R(D^0)$ and $R(D^+)$; they are discrepant by 0.5%.
- Only up to 100 MeV (lepton mass), no predictions for electrons

How do experiments treat QED corrections

- In the B-factories, systematic uncertainty on the PHOTOS QED corrections is typically assessed by producing an additional MC sample where PHOTOS is switched off.
  1/3 or 1/4 of the difference is assigned as a systematic.

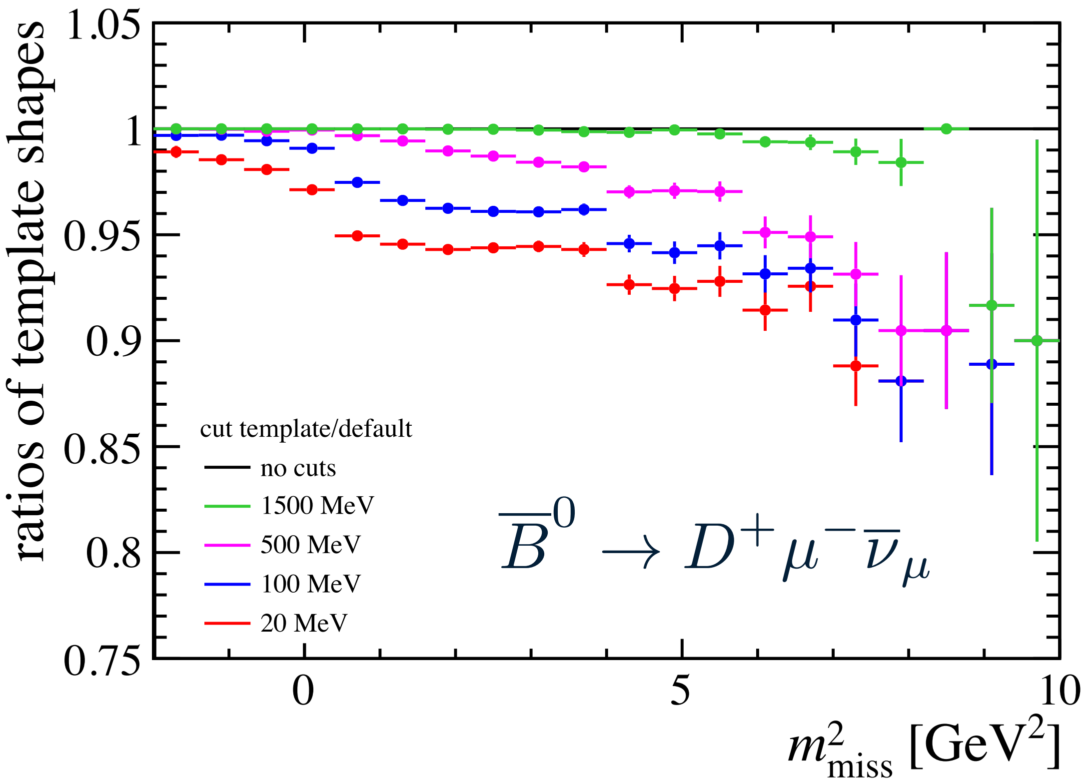
- In semileptonic analyses in LHCb, we usually do not assign a systematic to QED corrections, with two exceptions:
  - Form factor measurement of $B_s^0 \to D_s^* \mu \nu_\mu$ follows the recipe from B-factories of assigning a systematic uncertainty of 1/3 difference with MC generated with and without PHOTOS
    JHEP 12 (2020) 144
  - Latest $R(D)$-$R(D^*)$ result assigns a systematic for missing Coulomb corrections, but not for uncertainty on PHOTOS
    arXiv:2302.02886

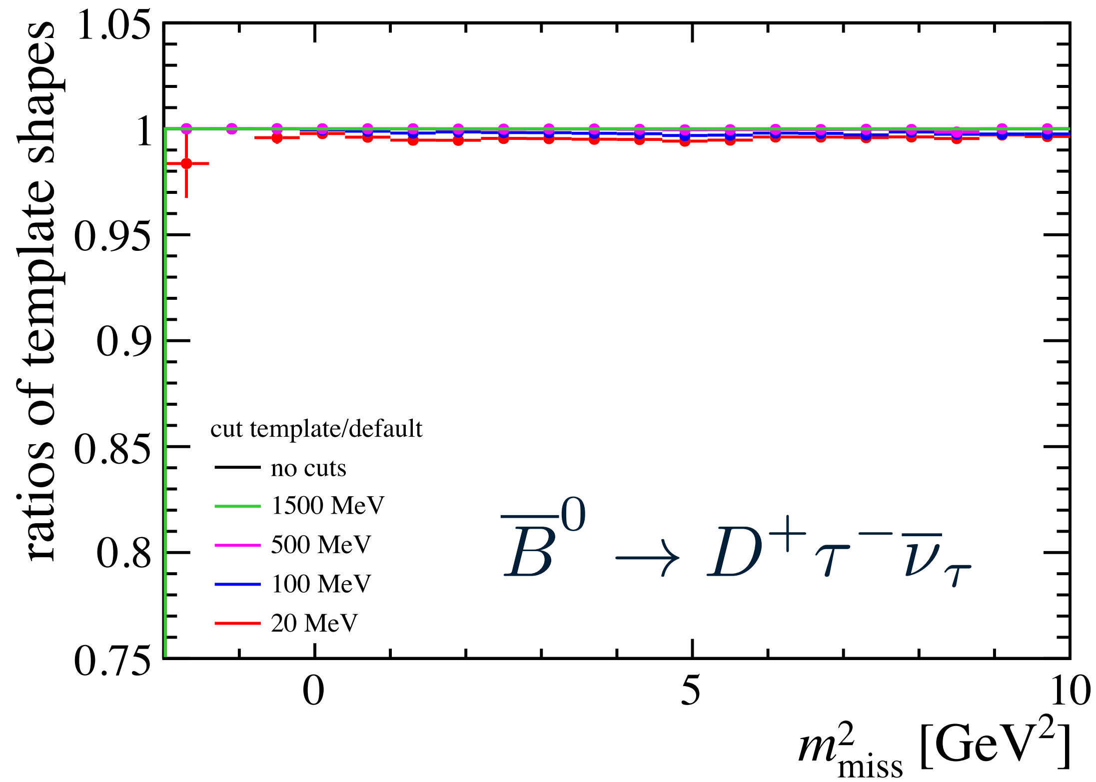
Conclusion

- PHOTOS does not include all types of radiative corrections; works well at low energies, but no structure-dependent corrections at higher energies
- For SL decays, we do not know how much exactly is missing, but it can have a serious impact on our measurements, especially when they become more precise
  - Even in ratios like $R(D^0)$ and $R(D^+)$ this effect does not cancel
  - Not yet assessed in other types of semileptonic LHCb analyses, like V_{ub}, V_{cb}
- What we need to make precision measurements:
  - LHCb: assess systematic uncertainty due to **uncertainty from PHOTOS** and **impact from Coulomb corrections** on every measurement
  - Theory: **numerical predictions** of high-energy and structure-dependent radiative corrections to compare to PHOTOS:
    - QED calculations from lattice?
    - such that we can at least assess how good/bad our MC is and **assign a systematic uncertainty**

Backup

Dummy analysis: effect on template





- Applying different cuts on E_{max}: at 20, 100, 500, and 1500 MeV changes shape of fit templates.
- Most clearly visible on missing mass variable, which is effected strongly in the μ decays, barely in the τ decay.