Impacts of radiative corrections on measurements of LFU in $B \to D l \nu_l$ decays

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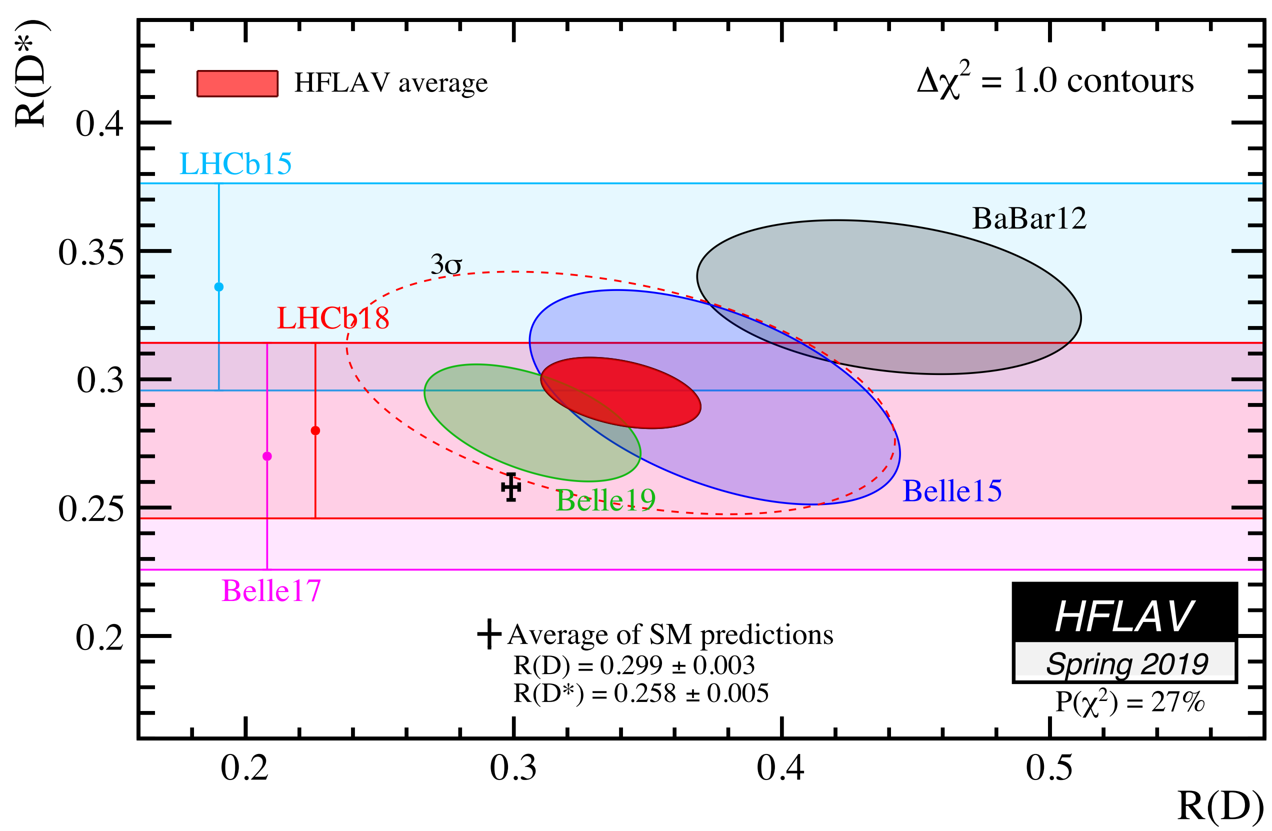
Introduction

- 3.1σ discrepancy between measurements and predictions of $R(D^{(*)})$.
- Usually, it's assumed QED radiative corrections cancel in the ratio.
- PRL 120, 261804 (2018) suggests they don't and SM predictions can be amplified by 3-4% for $R(D)$.
- What is the effect on measurements of $R(D)$? Can this reduce the tension?



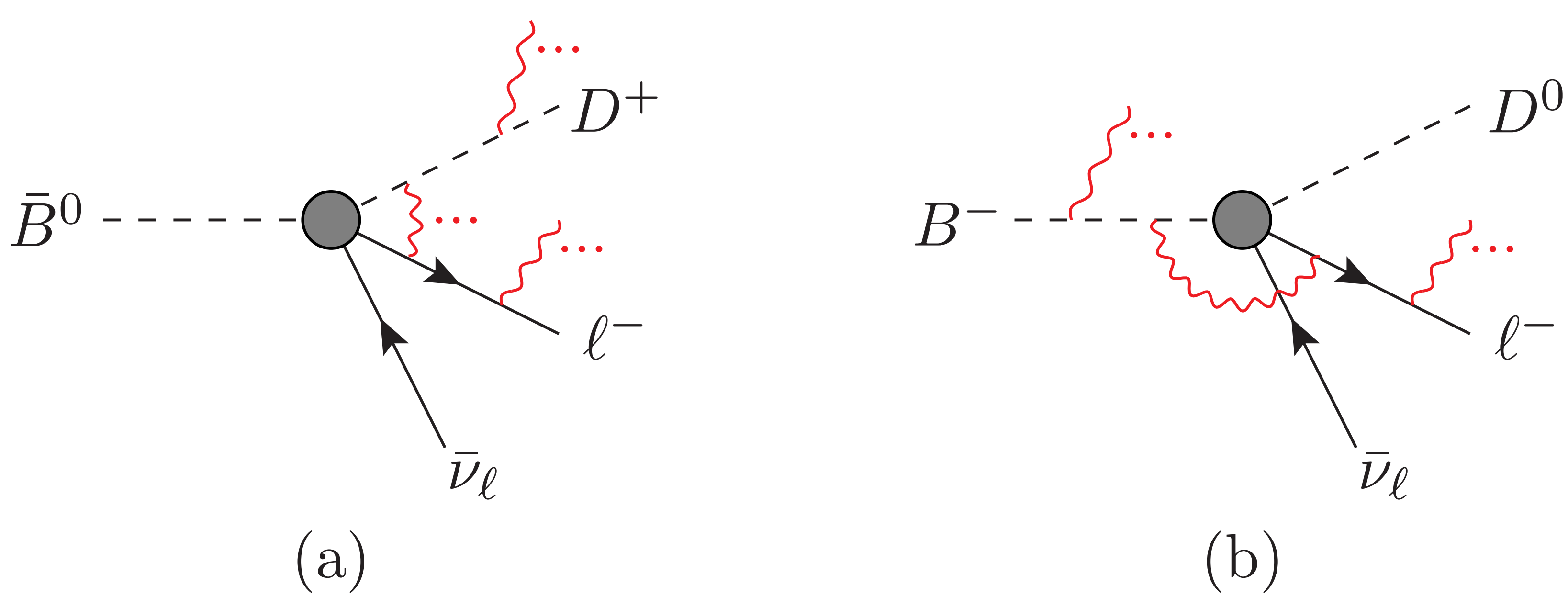
https://hflav-eos.web.cern.ch/hflav-eos/semi/spring19/html/RDsDsstar/RDRDs.html

Introduction

- All experiments (LHCb, Belle and BaBar) rely on PHOTOS package to simulate radiative corrections.
- According to authors of PRL 120, 261804 (2018):
  - “To our knowledge, our results are not fully covered by PHOTOS for $B \to D l \nu_l$, *e.g.*, we include interferences between different soft emission amplitudes, and virtual corrections including the Coulomb terms.”
- Our study comprises two parts:
  1. Compare the results from PRL 120, 261804 (2018) to PHOTOS.
  2. Determine effects of neglecting QED corrections in LHCb-like analysis.
- Caveat: it does not contain any corrections on published or ongoing LHCb analyses; talk is not on behalf of LHCb.

Intermezzo: PHOTOS

- PHOTOS is a universal MC algorithm that simulates QED corrections.
- PHOTOS includes both soft and hard photon corrections. The latter are not included in the study in PRL 120, 261804 (2018), so we cannot compare this.
- Has successfully been tested for W, Z and B decays, should be tested for every type of measurements, especially when high precision is needed.
- It does not include Coulomb interactions, which PRL 120, 261804 (2018) does. These are relevant for the D^+ (and D^{*+}) mode, but not for the D^0 mode:



Our samples

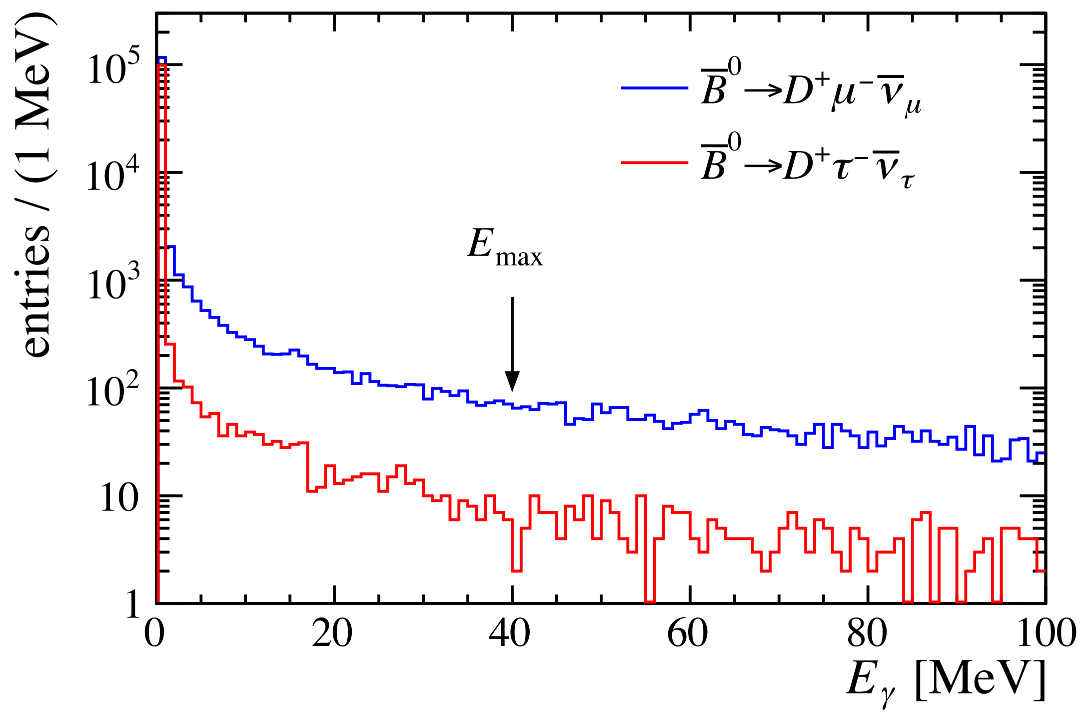
- Generated 3M events in 4 samples
  - ➤ $\overline{B}^0 \rightarrow D^+\ell^-\overline{\nu}_\ell$ and $B^- \rightarrow D^0\ell^-\overline{\nu}_\ell$, with $\ell^- = \mu^-, \tau^-$
  - ➤ generator level only, no detector reconstruction
  - ➤ PHOTOS version 3.56, “Option with interference is active”
-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

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

  - ➤ Like in the paper, 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 $E_\gamma > E_{\max}$:

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

The E_{max} variable

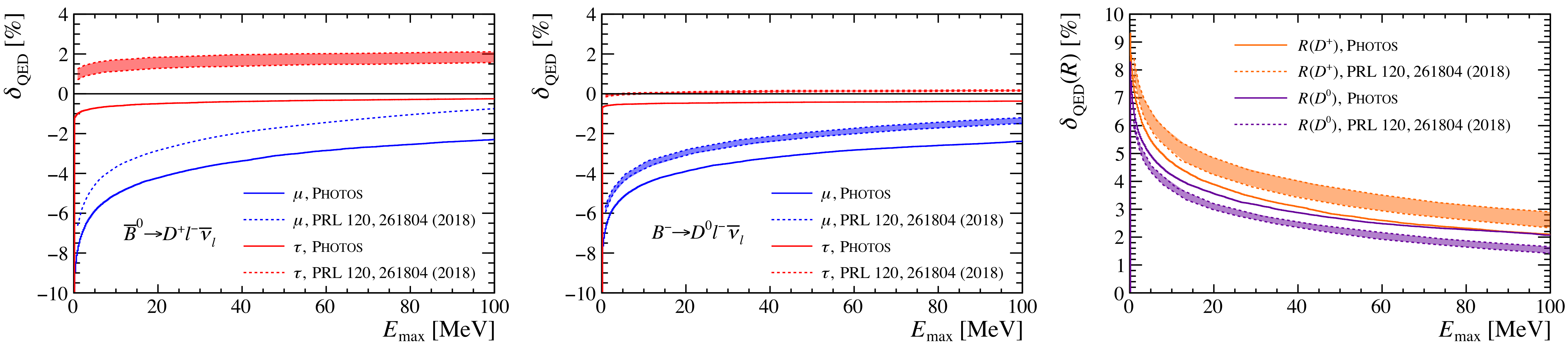


- Results are shown as a function of E_{max}, this is the maximum energy that radiative photons in the event are allowed to have for us to consider it signal rather than background.
- In LHCb there are no cuts this variable directly, but we do indirectly through the calorimeter, reconstruction algorithms, isolation etc.
- Moreover, the effects of the QED corrections are global, so they are still there when not applying a cut on E_{max}.

Comparing results

arXiv:1905.02702

- Results are shown as a function of E_{max}, to be able to compare with the results from PRL 120, 261804 (2018):

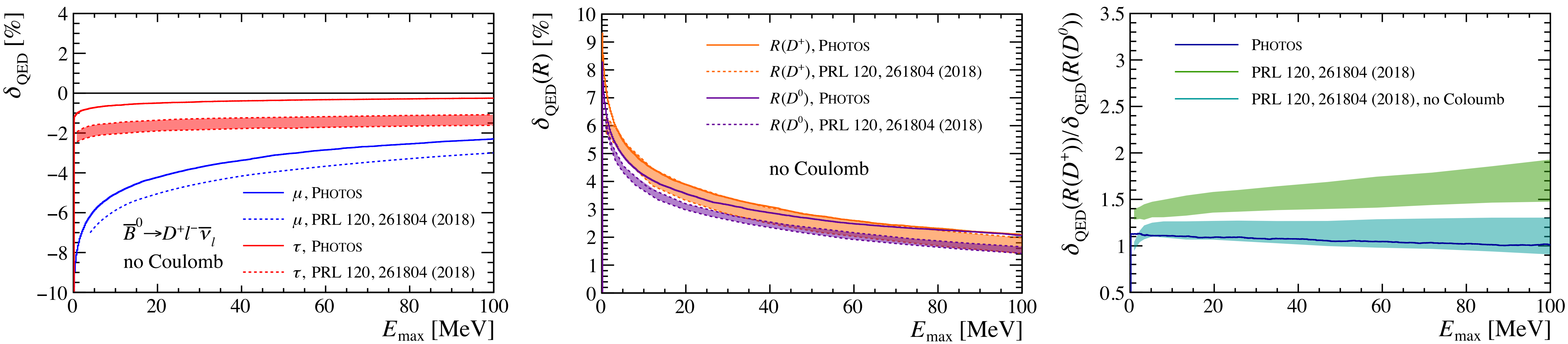


- Differences of 0.5-1% for B^- decays, even up to 2% for B^0.
- Discrepancies cancel largely, but not completely in the ratios $R(D^0)$ and $R(D^+)$, discrepant by 0.5%.

Comparing results II

arXiv:1905.02702

- When discarding the Coulomb corrections from PRL 120, 261804 (2018), results for B^0 decay get in closer agreement and corrections on $R(D^+)$ are very consistent.



- PRL 120, 261804 (2018) gives different results for $R(D^0)$ and $R(D^+)$, breaking isospin symmetry, while those are not there in PHOTOS. This difference disappears when ignoring the Coulomb corrections that are used for $R(D^+)$.

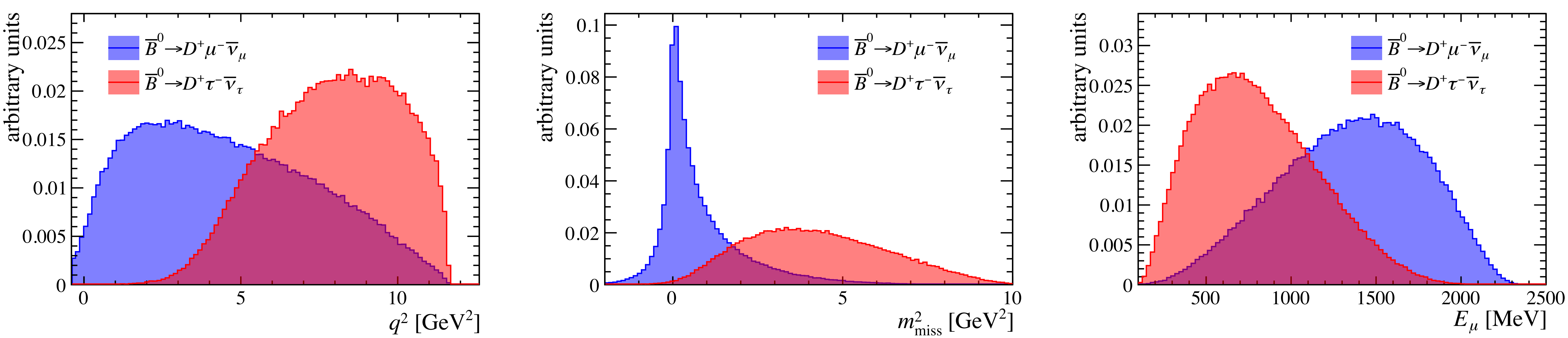
Second part of our study

- What is the effect of mismodelling 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_{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 not give corrections to existing/future measurements.

LHCb-like selection

arXiv:1905.02702
based on JHEP 02 (2017) 021

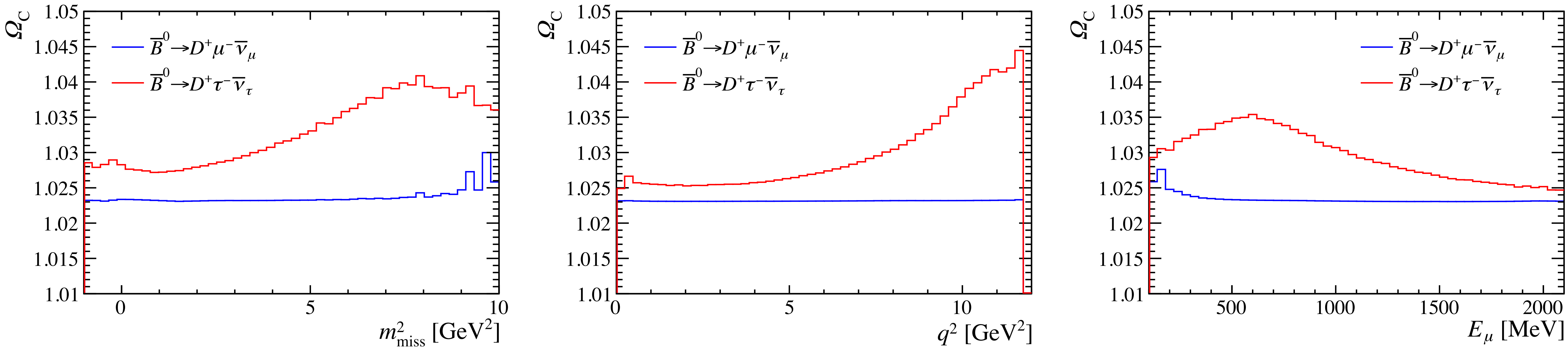
- Simulate vertex resolution by smearing the *pp* vertex by (±13, ±13, ±70) μm and the *B* decay vertex by (±20, ±20, ±200) μm
- Simulate LHCb acceptance using the cuts: $1.9 < \eta < 4.9$, $p > 5$ GeV, $p_{\mathrm{T}} > 250$ MeV on kaons, pions and muons and a distance between *pp* and *B* vertex > 3 mm.
- Reconstruct *B* meson momentum and related quantities using the LHCb rest frame approximation.



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

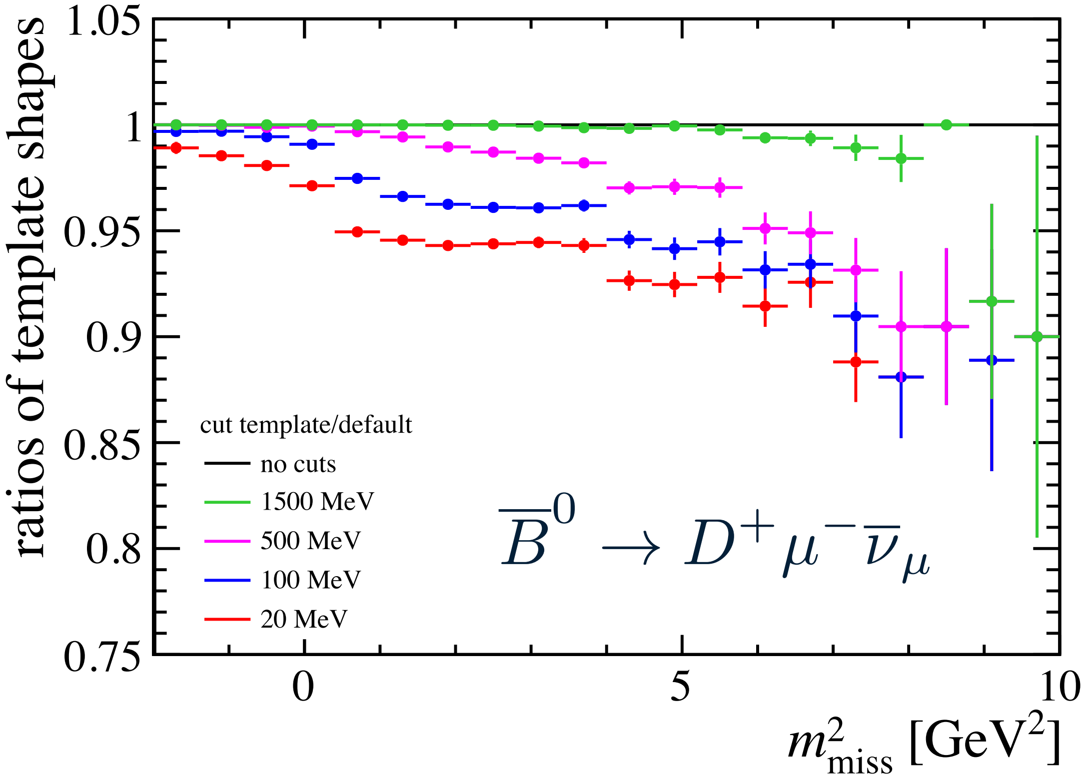
Coulomb corrections in toys

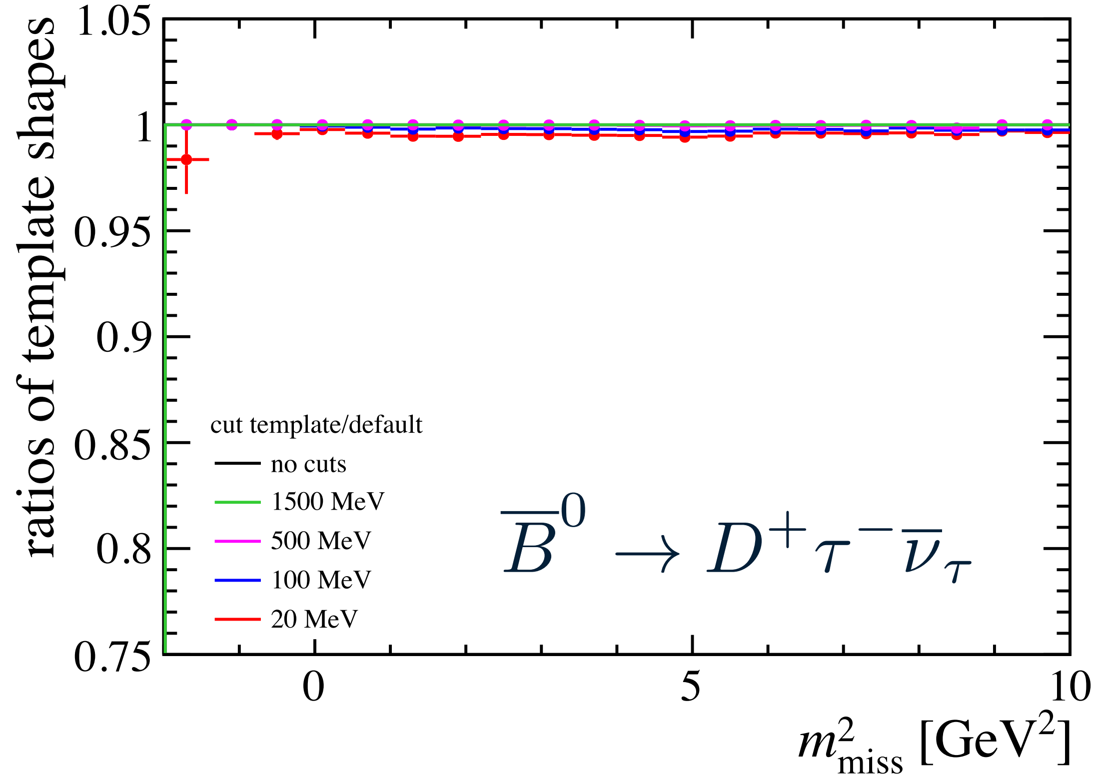
- Coulomb correction as a function of fit variables:



- 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.

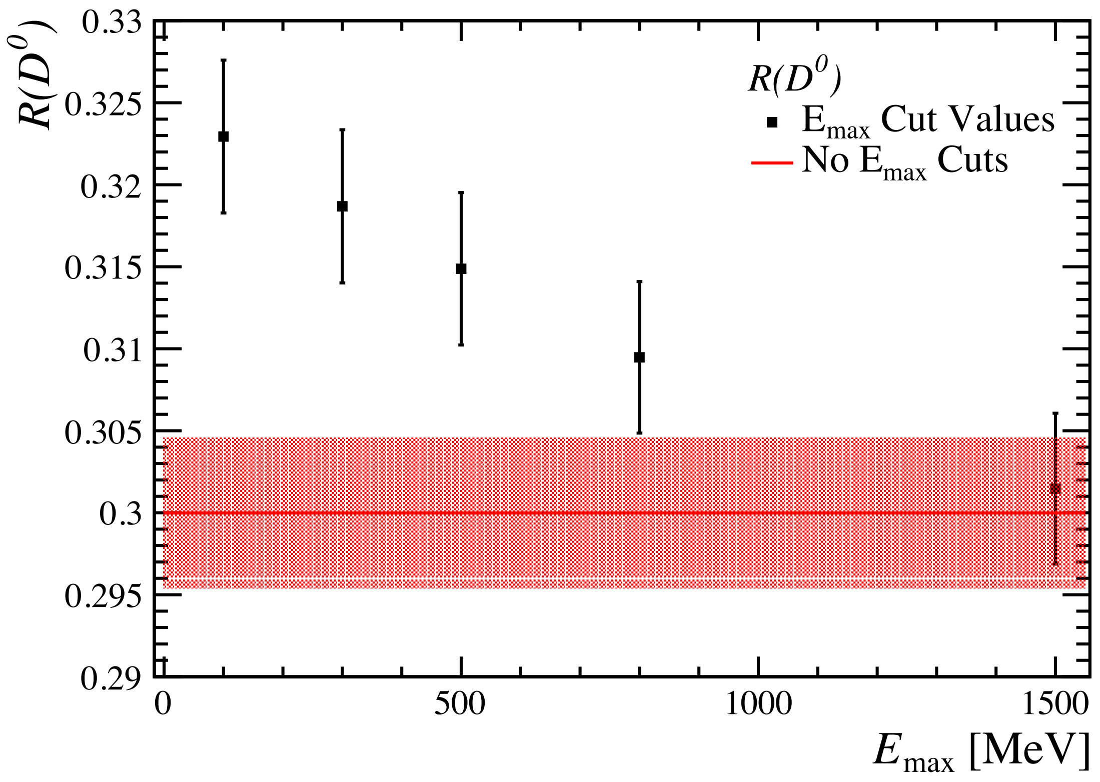
Dummy analysis: effect on template

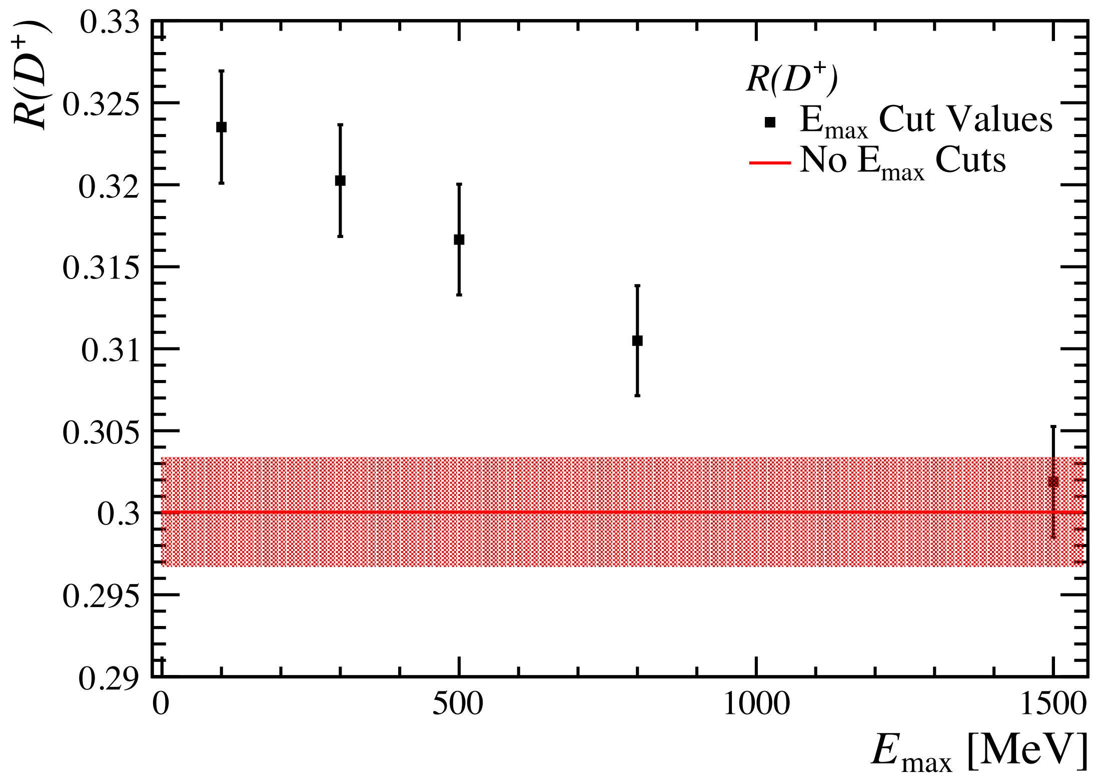




- Applying different cuts on E_{max}: at 20, 100, 500, and 1500 MeV changes shape of fit templates.
- Most clearly visible on missing mass variable, which is effected strongly in the μ decays, barely in the τ decay.

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%.

Conclusions and recommendations

- Corrections described in PRL 120, 261804 (2018) are not fully included in PHOTOS.
- Small corrections largely cancel out in the ratio $R(D)$, but a 1% difference between $R(D^0)$ and $R(D^+)$ is due to Coulomb corrections.
- Coulomb corrections affect kinematics of τ decays, which impacts shapes templates, yielding corrections of 1% on LHCb-like analysis.
    - ➤ Can and should be determined for each analysis separately.
- Mis-modelling QED corrections in a **worst-case scenario** can lead to a bias of $\sim$7% in LHCb-like analysis.
    - ➤ Cuts on photon energy should be studied by analysts.
- Input is needed from the theory community to make accurate comparisons of radiative corrections, especially for future measurements with higher precision. Current studies stop at energies of 100 MeV, while we need also hard photons.
- Paper is available on arXiv: arXiv:1905.02702. Comments are welcome!

Backup

More on Coulomb corrections

- A large discrepancy between our results and those in PRL 120, 261804 (2018) comes from the Coulomb interactions, which are not implemented in PHOTOS.
- This correction term can be calculated using:

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

$$\alpha = 1/137$$

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

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

- Asking Z.A. Was (PHOTOS author) if he plans to include Coulomb corrections to PHOTOS: "*No, because it forms to good approximation a separate class of corrections which can (and should) be integrated as correction to Born level matrix element.*"