PHOTOS with the LHCb/Belle2 simulation

GDR-InF workshop: QED corrections to (semi-) leptonic B decays

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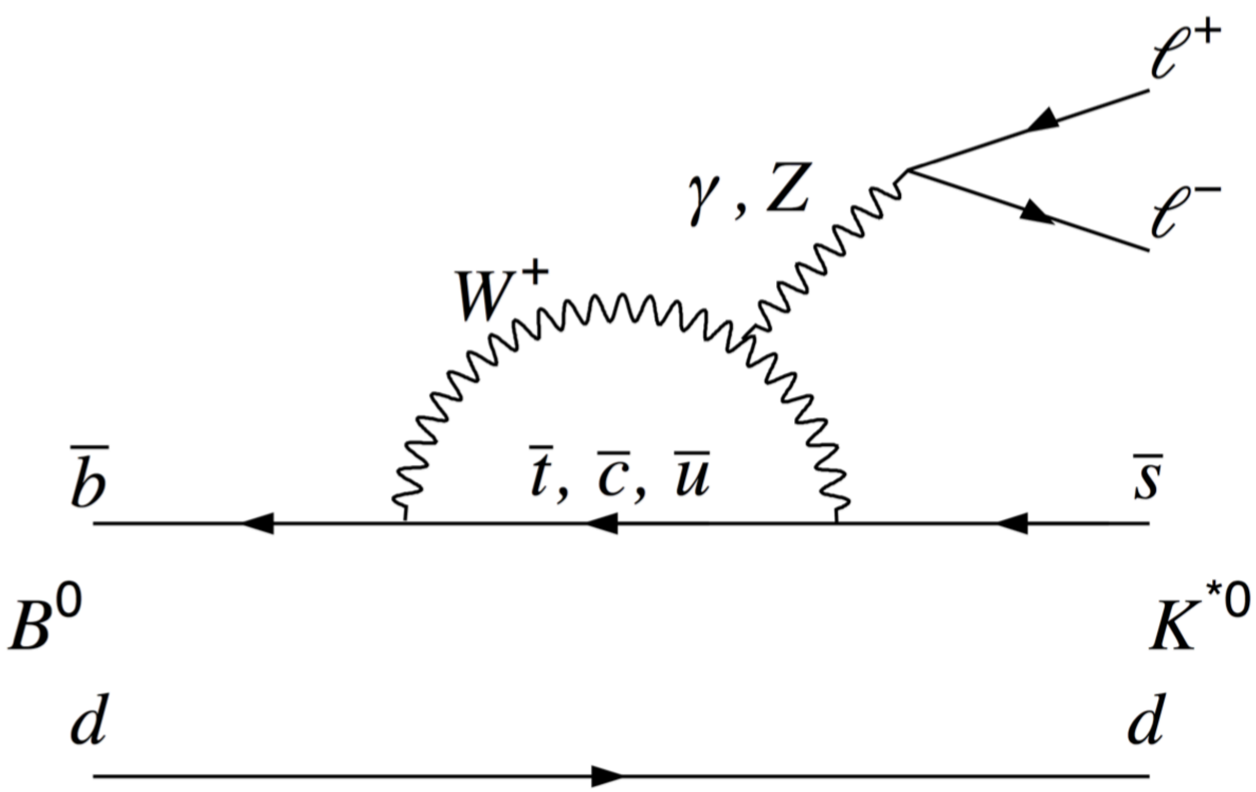
LHCb

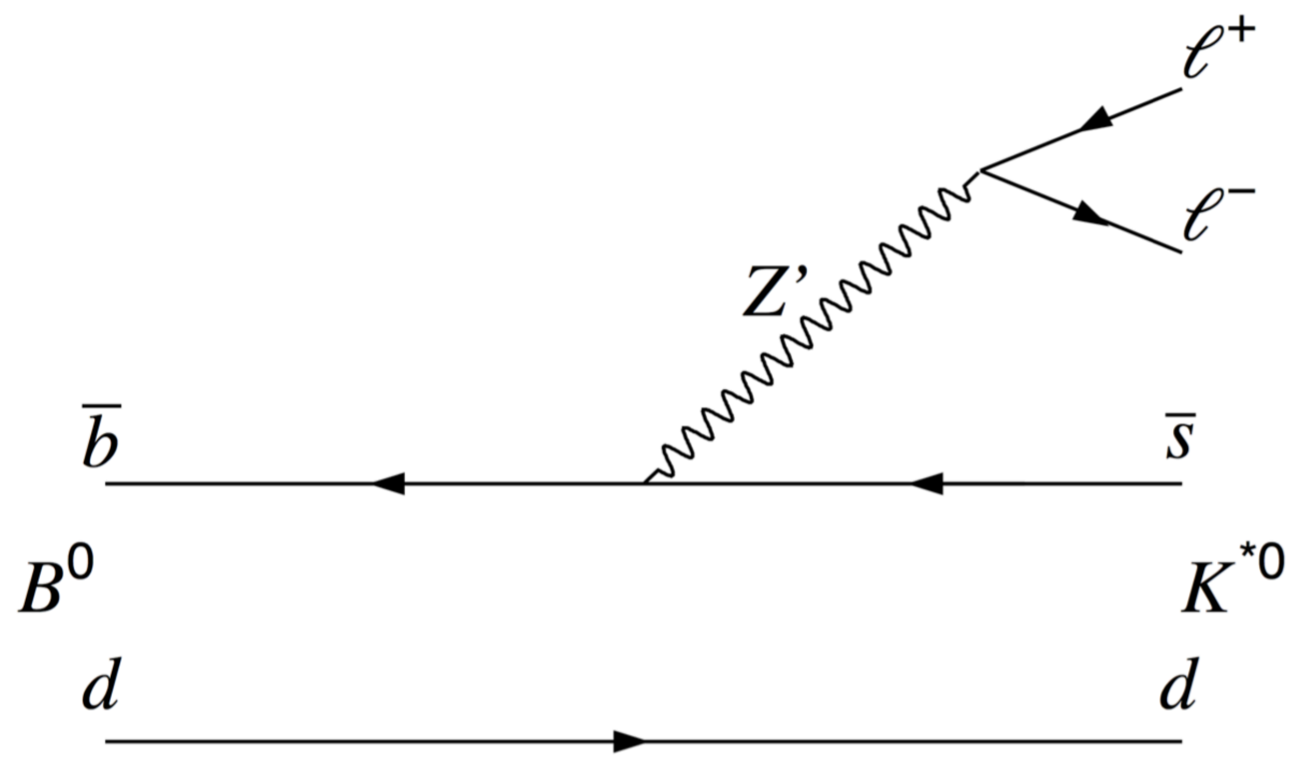
09/07/19

Rare B decays at LHCb and Belle 2

- The physics program at both LHCb and Belle 2 is focused on the precision measurement of heavy flavour processes
- Such precision measurements are potentially sensitive to new physics (NP) effects

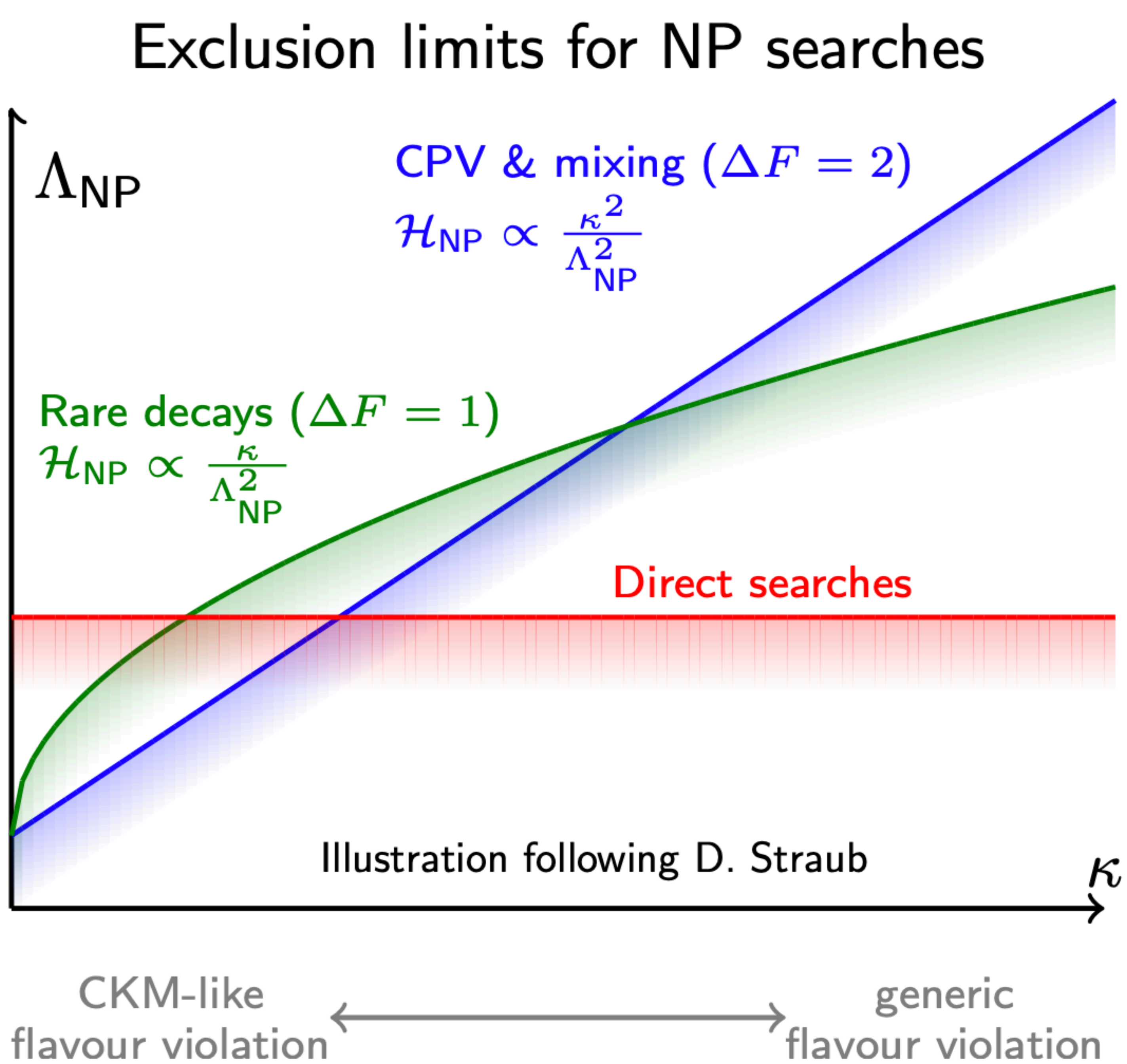


Example B decay



Example NP contribution

Rare B decays and new physics



- If NP flavour is SM like - reduced sensitivity from rare decays
- If NP flavour structure generic (i.e. $\mathcal{O}(1)$ couplings), rare decays very sensitive ~$\mathcal{O}(100)$TeV

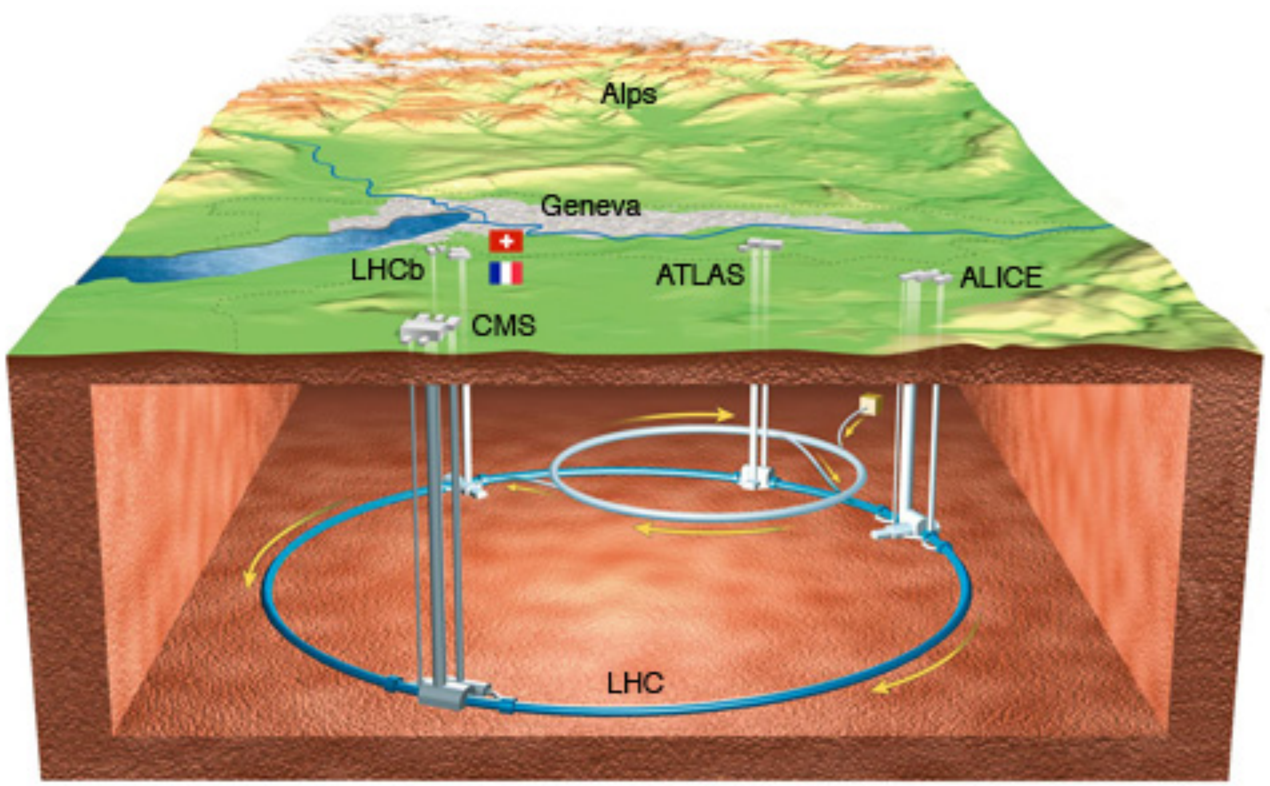
[A. Buras, arxiv:1505.00618]

$$\Delta\mathcal{H}_{NP} = \frac{\boxed{k}}{\Lambda_{NP}^2}\mathcal{O}_i$$

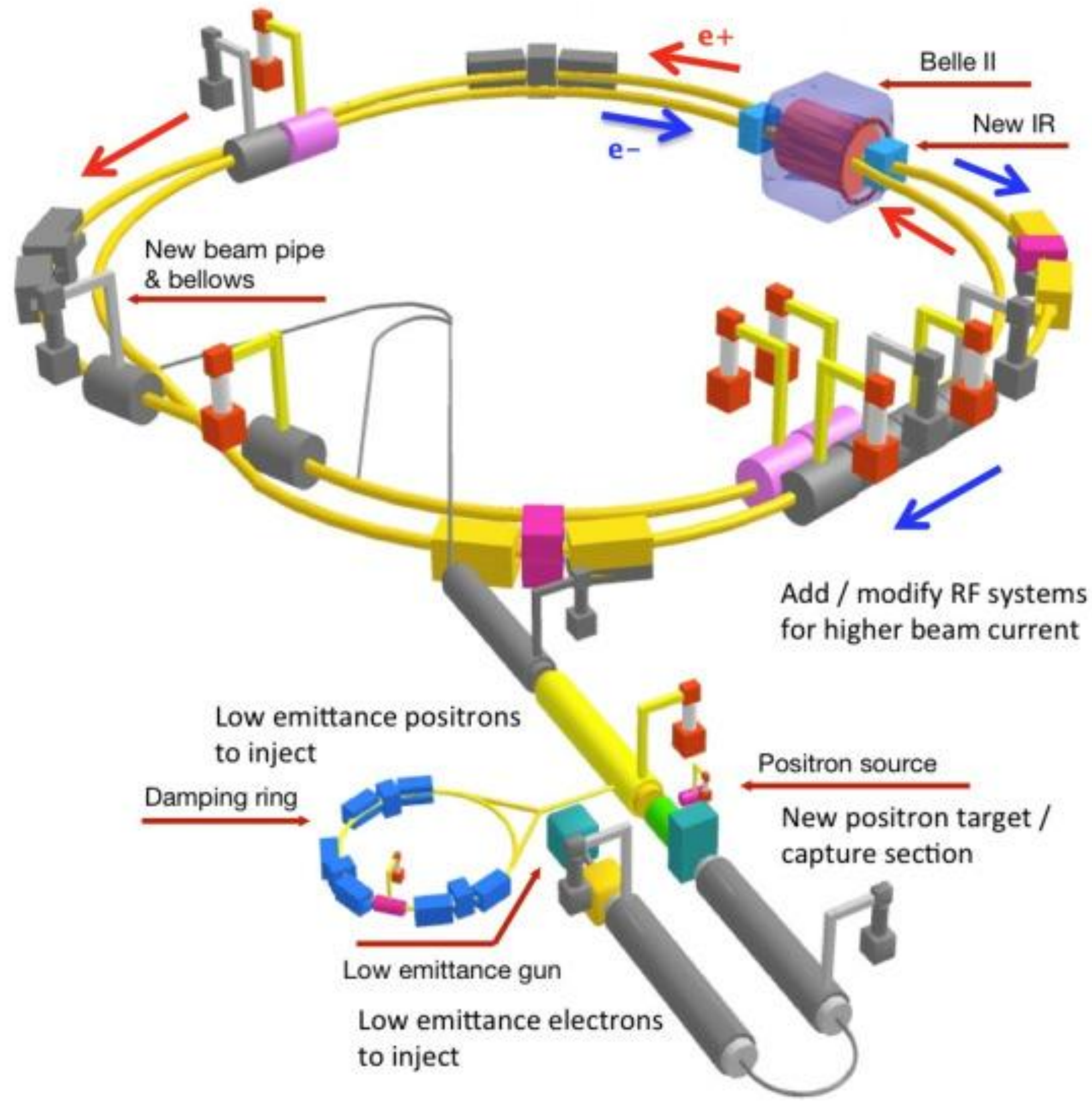
Flavour violating coupling

LHCb and Belle 2

LHCb: proton-proton

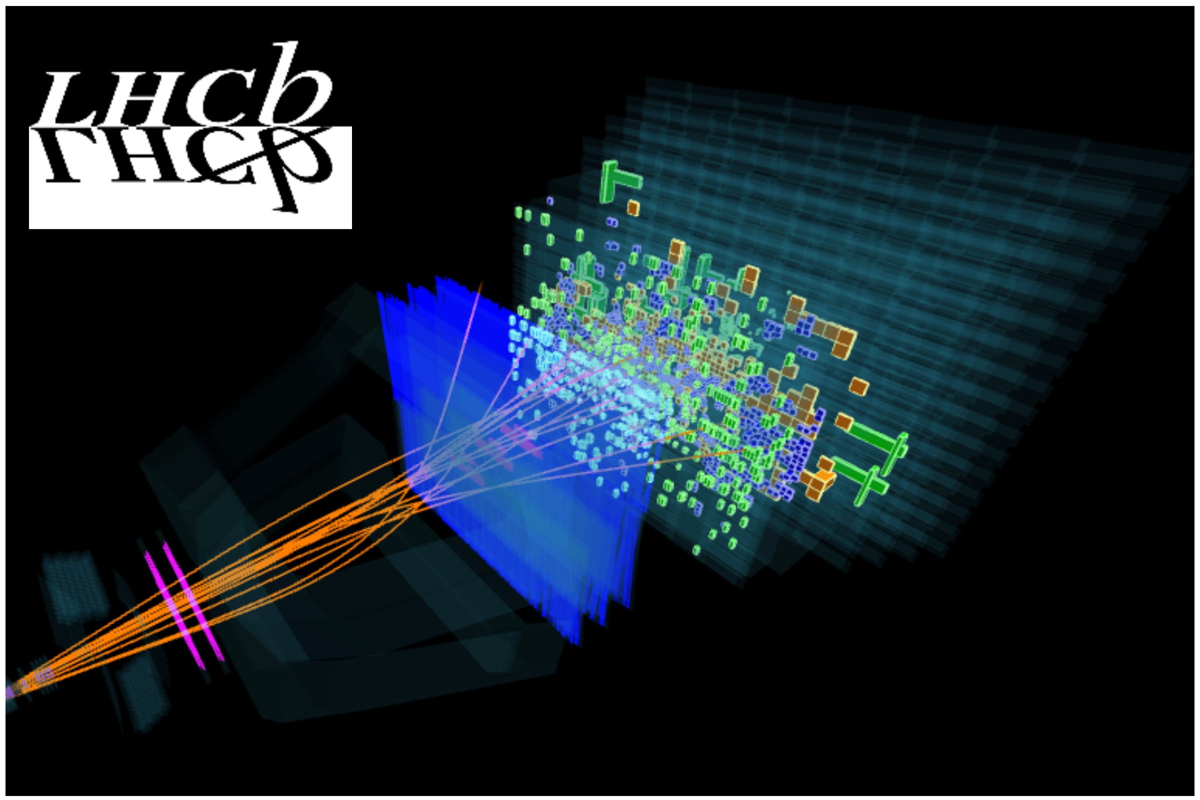


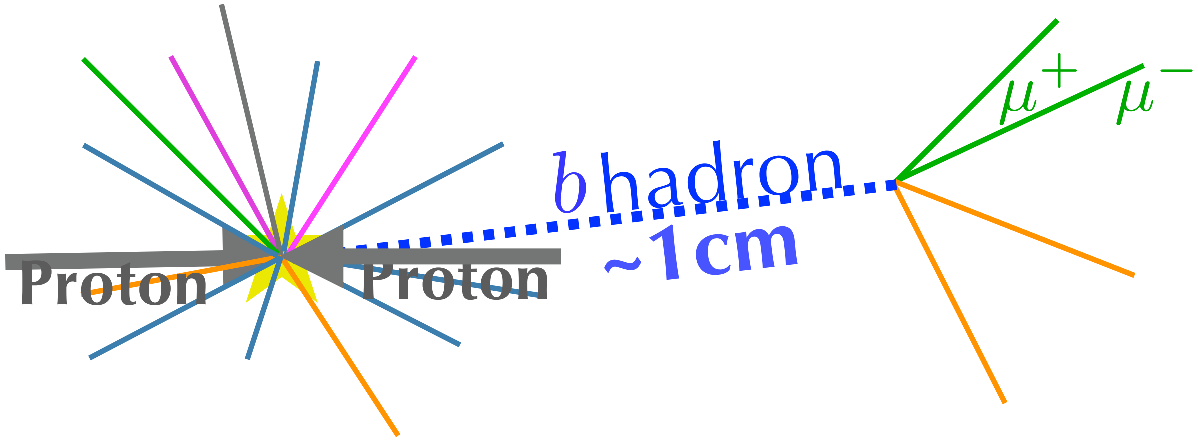
Belle 2: electron-positron



LHCb and Belle 2

LHCb: proton-proton





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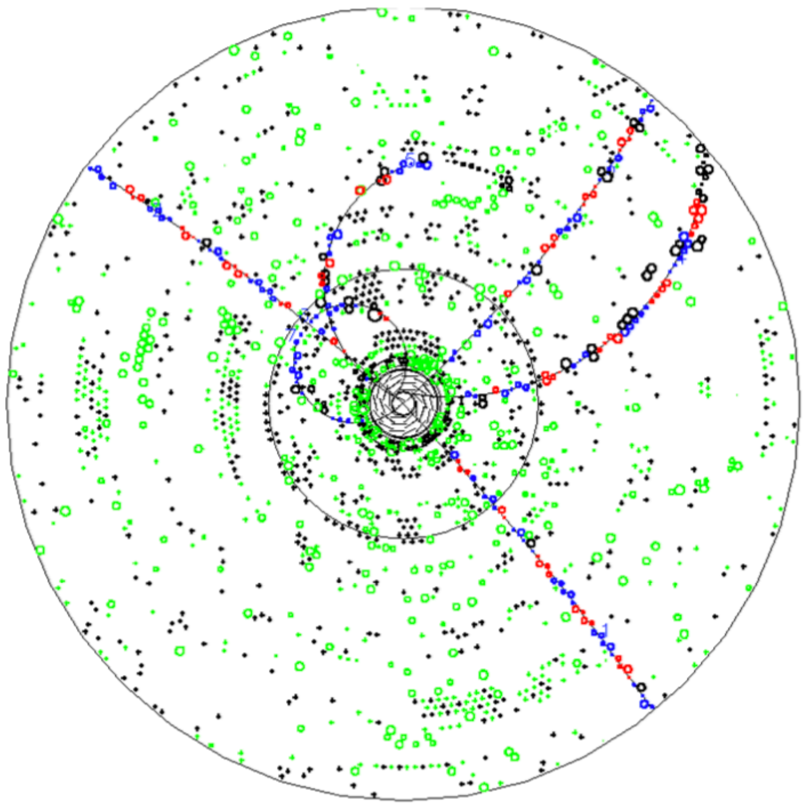
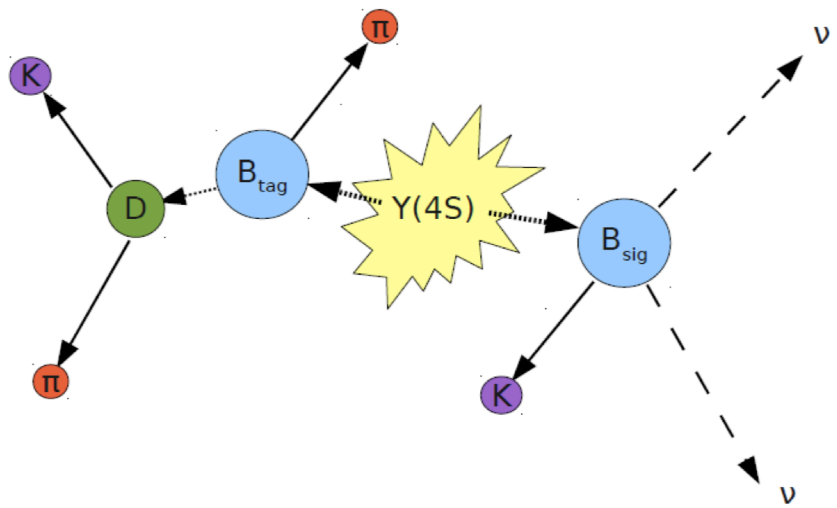
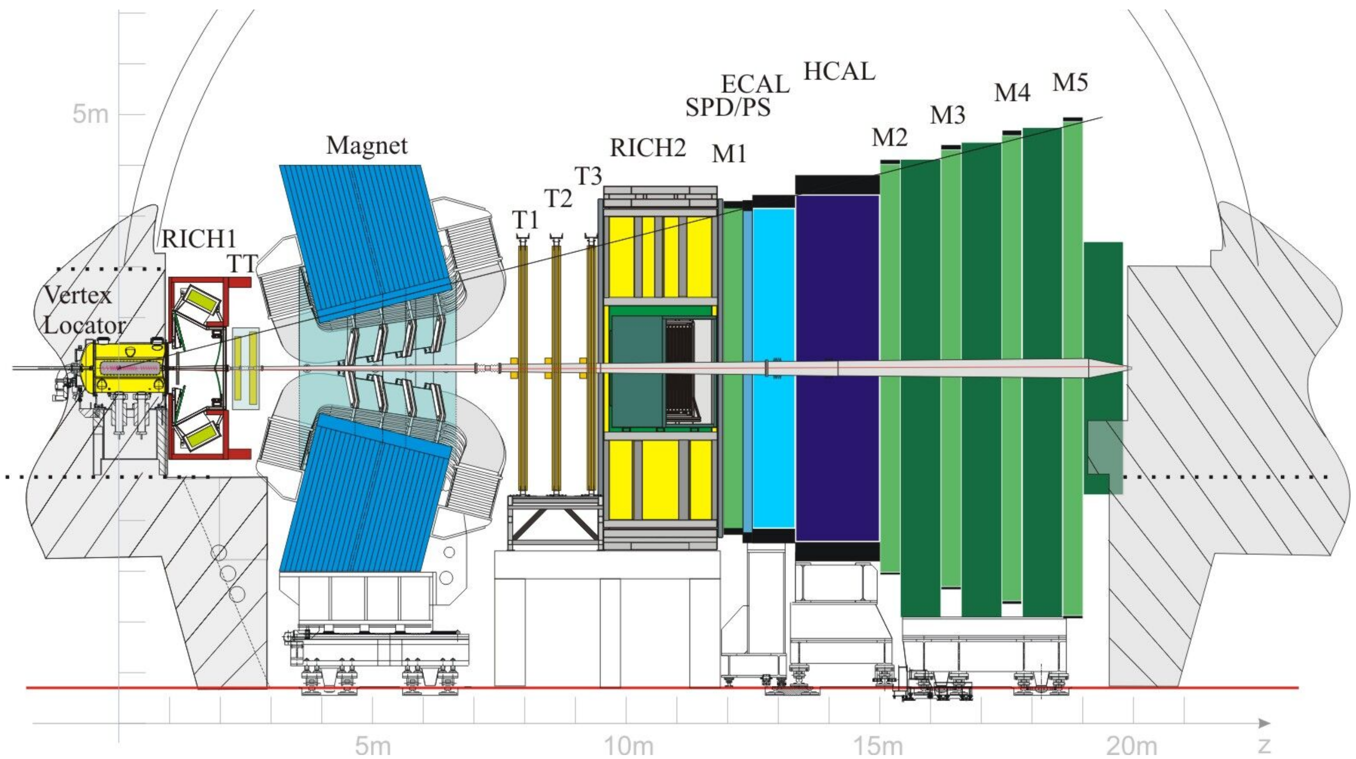




LHCb and Belle 2

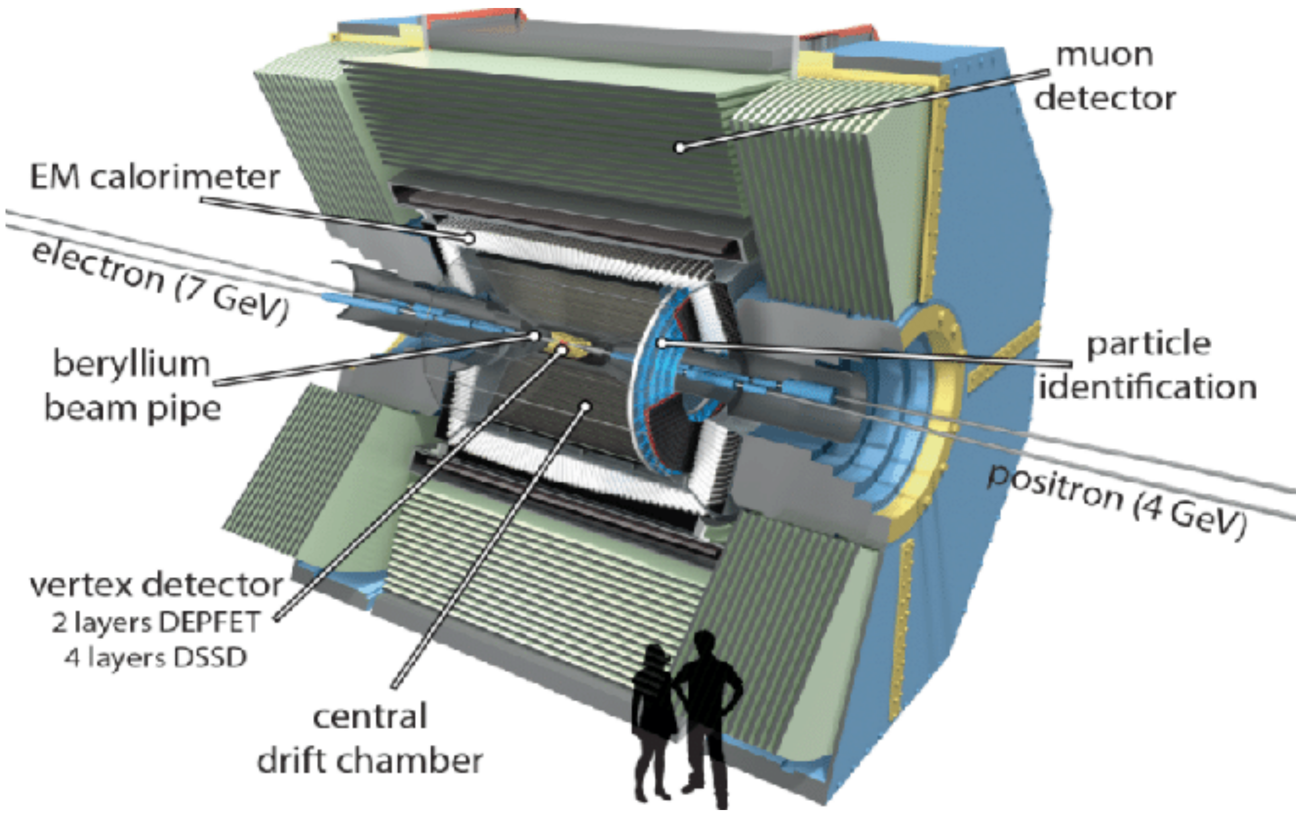
LHCb: proton-proton



Int. J. Mod. Phys. A 30 (2015) 1530022

$$\sigma_{IP} = (15 + 29/p_T[\mathrm{GeV}])\mu\mathrm{m}$$

Belle 2: electron-positron



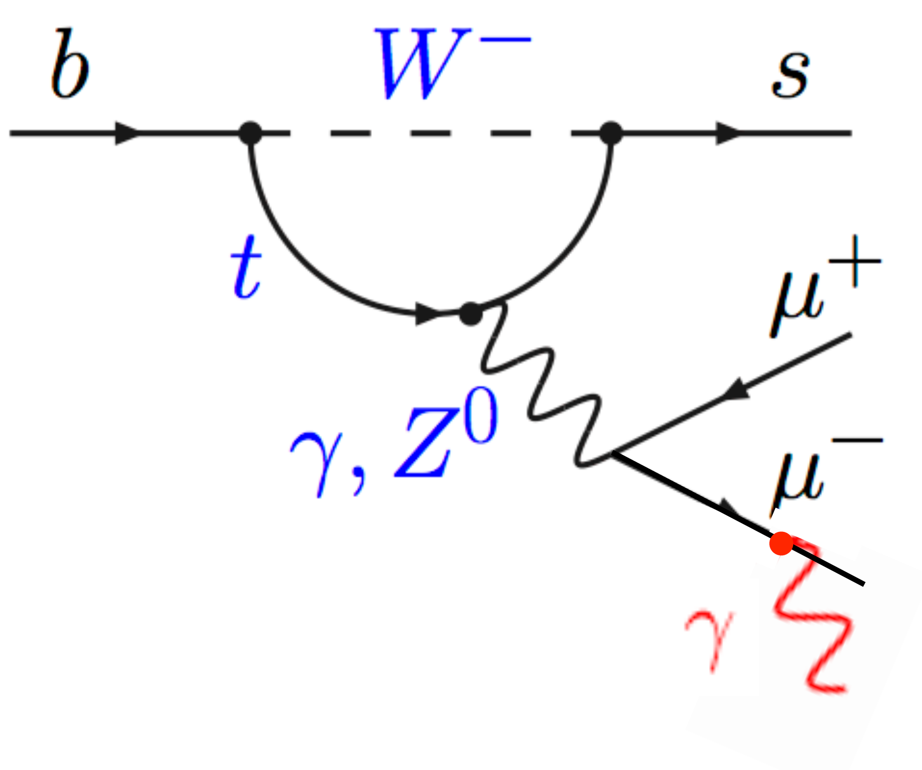
arXiv:1011.0352

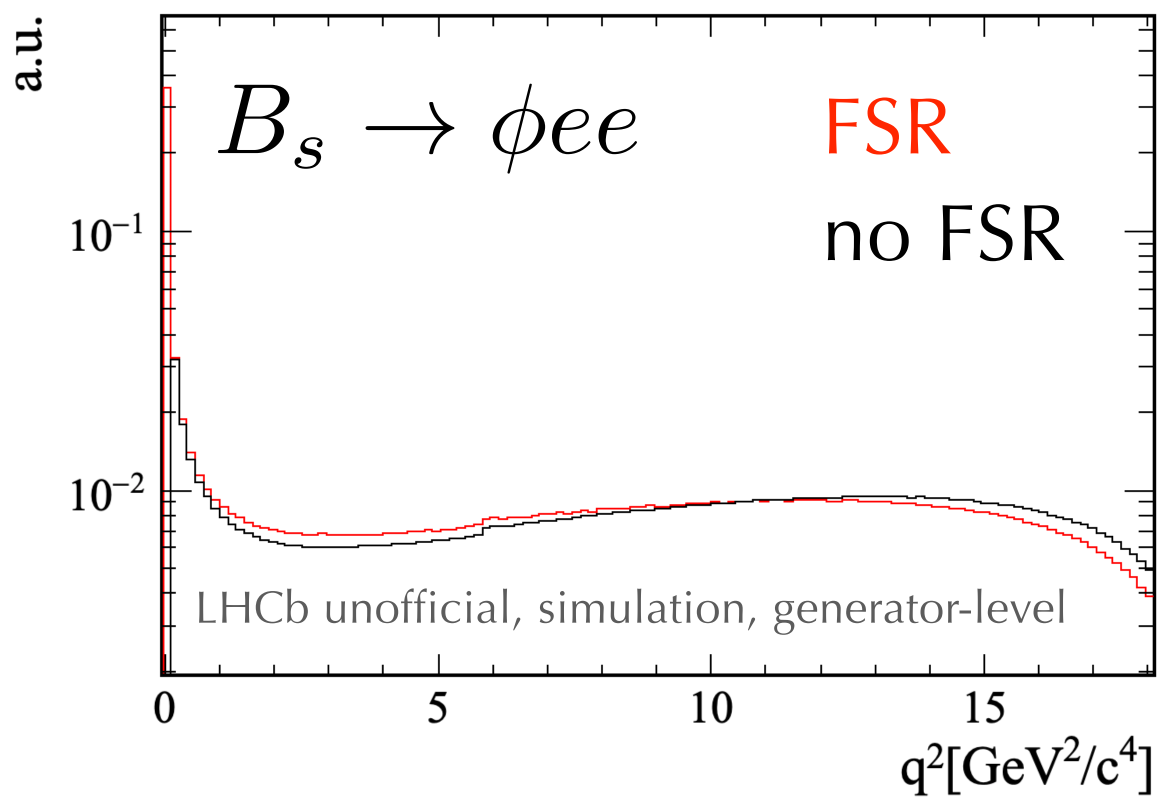
$$\sigma_{IP} \sim 20\mu\mathrm{m}$$

Final state radiation and PHOTOS in B physics

Final State Radiation (FSR)

- Creation of charged particles during the decay of B mesons can cause some energy to be radiated through photons
- FSR must be well accounted for in simulation, in order to correctly model distributions on which e.g. efficiencies may be dependent





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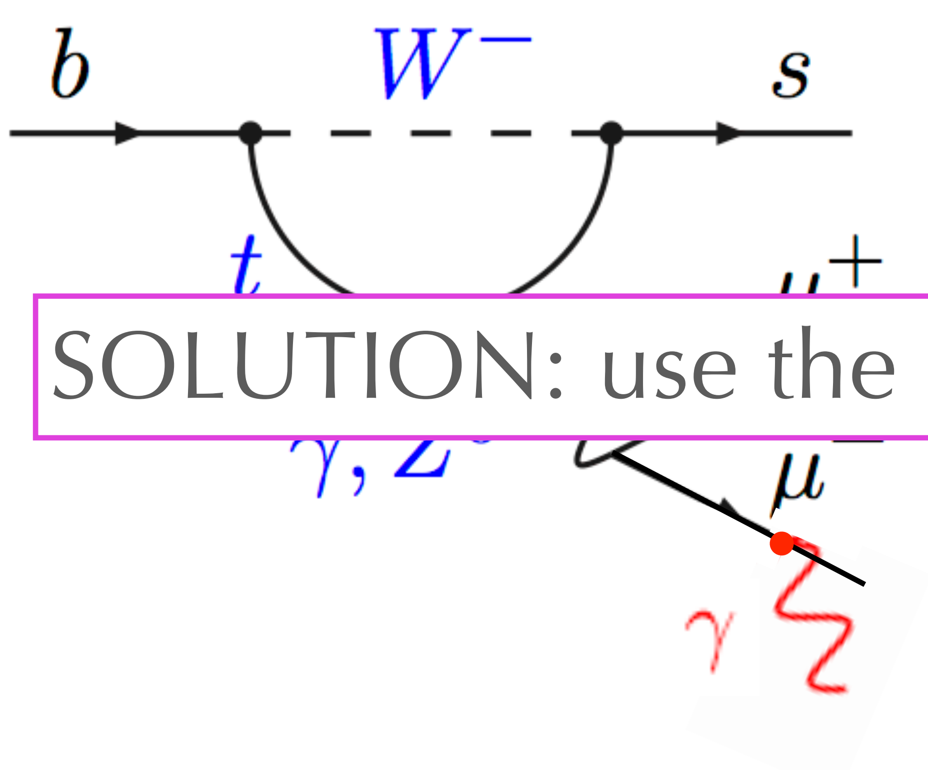
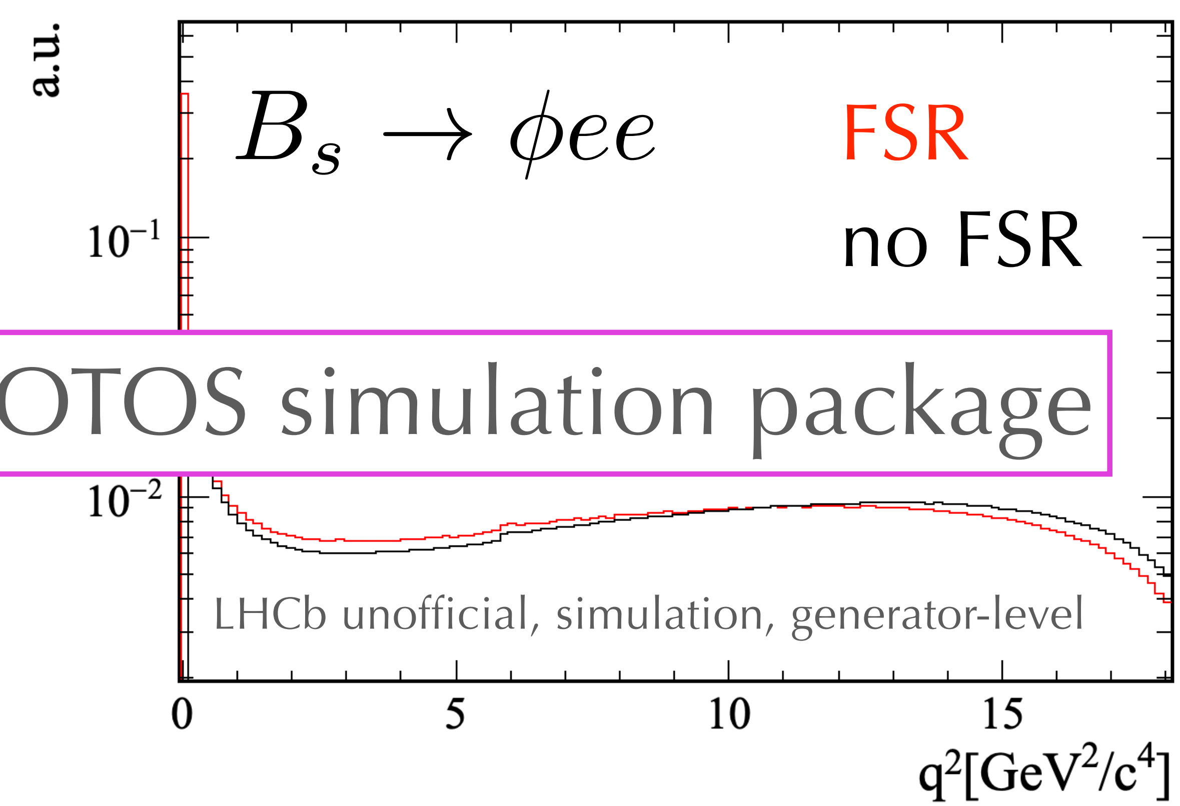


SOLUTION: use the PHOTOS simulation package

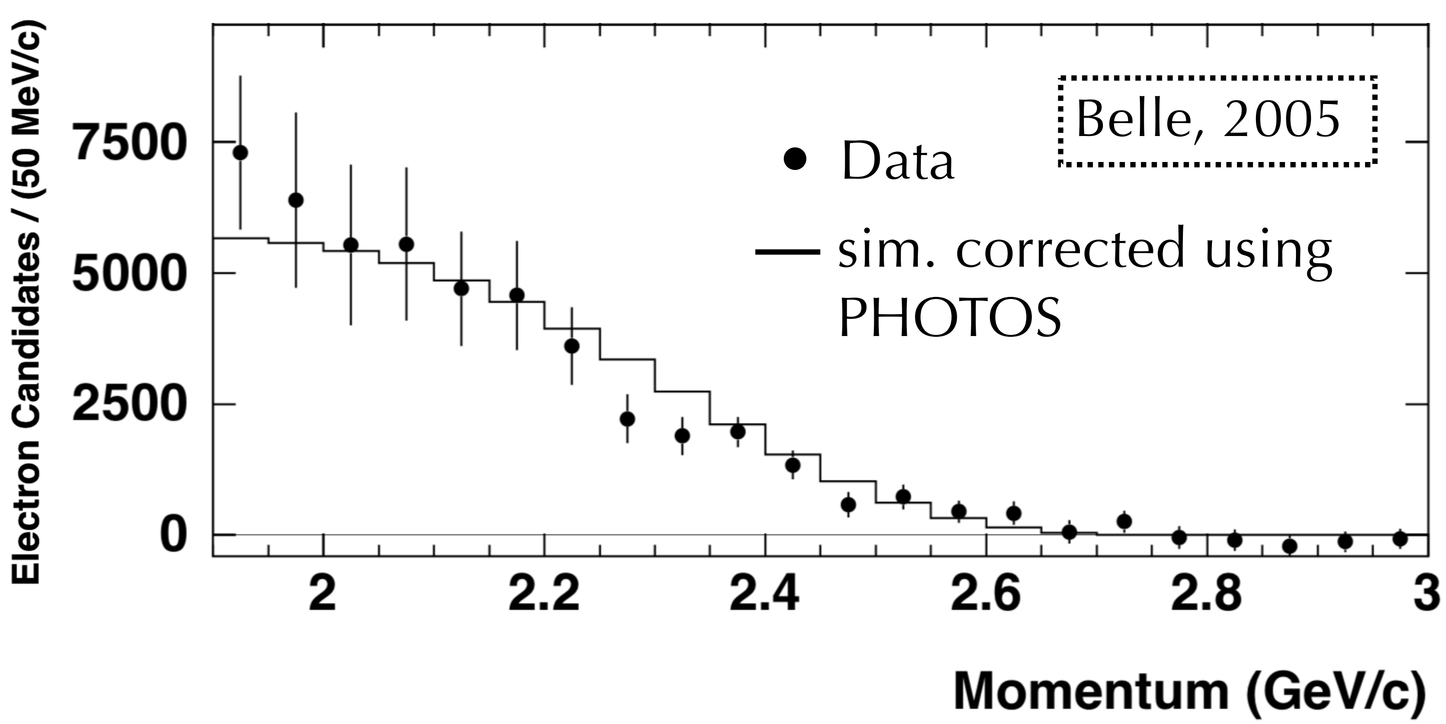


What is PHOTOS?

- PHOTOS (E. Barberio, B. van Eijk, Z. Was, P .Golonka) [Comput. Phys. Commun. 66 (1991) 115] has been around since ~1990
- PHOTOS is a MC package which corrects a MC event *after it has been fully generated* to account for FSR
- Already has long history of use in previous B factories

Example of PHOTOS applied in B physics: energy spectrum of electrons used in V_{ub} measurement at Belle

Phys. Lett. B621, 28-40, 2005



How PHOTOS corrects simulation

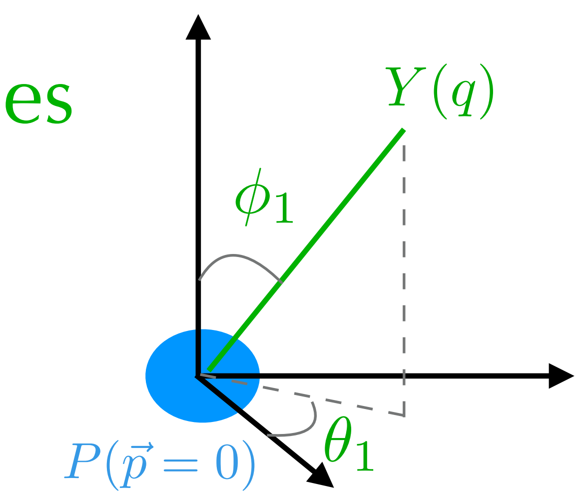
WARNING - experimentalists very superficial interpretation!

What happens before PHOTOS QED correction is applied:

Assuming only one charged particle and **no FSR**

$$\mathrm{P}(\vec{p}) \rightarrow ch(\vec{q})Y_i(\vec{q}_i)$$

Mother — Leading charged particle — Other particles



$$\mathrm{d}\sigma^{\mathrm{Born}}(\mathrm{P} \rightarrow \mathrm{ch\ Y}) = |M_{\mathrm{B}}|^2 \frac{1}{m_{\mathrm{P}} 16(2\pi)^2} \frac{\lambda^{1/2}(m_{\mathrm{P}}^2, m_{\mathrm{ch}}^2, M_{\mathrm{Y}}^2)}{m_{\mathrm{P}}^2} \mathrm{d}\cos\theta_1\, \mathrm{d}\phi_1 .$$

$$d\sigma^{\mathrm{Born}}(P \rightarrow chY) = |M_{Born}|^2 \times \mathrm{PHSP}(m_P, m_{ch}, M_Y) dcos\theta_1 d\phi_1$$

Matrix element — *Phasespace terms*

How PHOTOS corrects simulation

⚠ WARNING - experimentalists very superficial interpretation!

Including FSR radiation in the process:

$$d\sigma(P \to ch\ Y\ \gamma) = |M|^2 \frac{1}{m_P 32(2\pi)^5} \frac{\lambda^{1/2}(m_P^2(1-2k/m_P),\ m_{ch}^2,\ M_Y^2)}{m_P^2(1-2k/m_P)} \times k\ dk\ d\cos\theta_1\ d\phi_1,\ d\cos\theta_2\ d\phi_2,$$

Different matrix element

Photon momentum

$$d\sigma^{FSR}(P \to chY\gamma) = |M_{chY\gamma}|^2 \times \mathrm{PHSP}(m_P, m_{ch}, M_Y, k) \times kdkdcos\theta_1 d\phi_1 dcos\theta_2 d\phi_2$$

Photon angles wrt ch

Phasespace term now includes photon kinematics

Photon momentum restricted by phase space

$$0 < k < k_{max}(m_P, m_{ch}, m_Y)$$

How PHOTOS corrects simulation

From no FSR to FSR: assume <u>factorisation</u> of bremsstrahlung kernels in leading log approximation

$$\Rightarrow \quad |M_{chY\gamma}|^2 = |M_{Born}|^2 \times \text{bremsstrahlung factor}$$

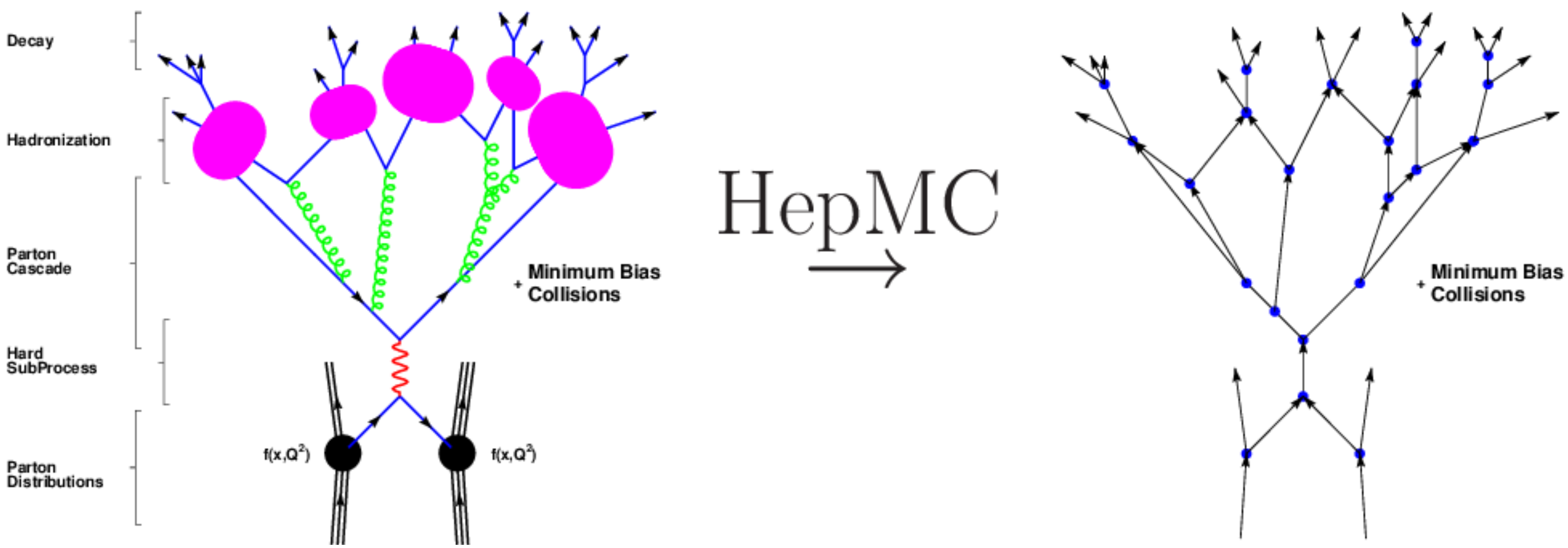
$$d\sigma^{FSR}(P \to chY\gamma) = d\sigma^{Born}(P \to chY) f(k, cos\theta_2, \phi_2) k dk dcos\theta_2 d\phi_2$$

Functional form of brem. factor f dependent on properties of ch

- $f(k, cos\theta_2, \phi_2)$ is calculated, according to the properties of the charged particle (ch)
- A brem. photon is then generated according to $f(k, cos\theta_2, \phi_2)$
- Once the photon has been generated, the event is modified accordingly

How PHOTOS interfaces with simulation

- PHOTOS needs access to the information of the mother and daughters of a process to calculate $f(k, cos\theta_2, \phi_2)$
- An MC generator must allow for e.g reading, adding, modification and list making of particles in event trees -> HepMC event record
- PHOTOS interface with C++ HepMC well-developed



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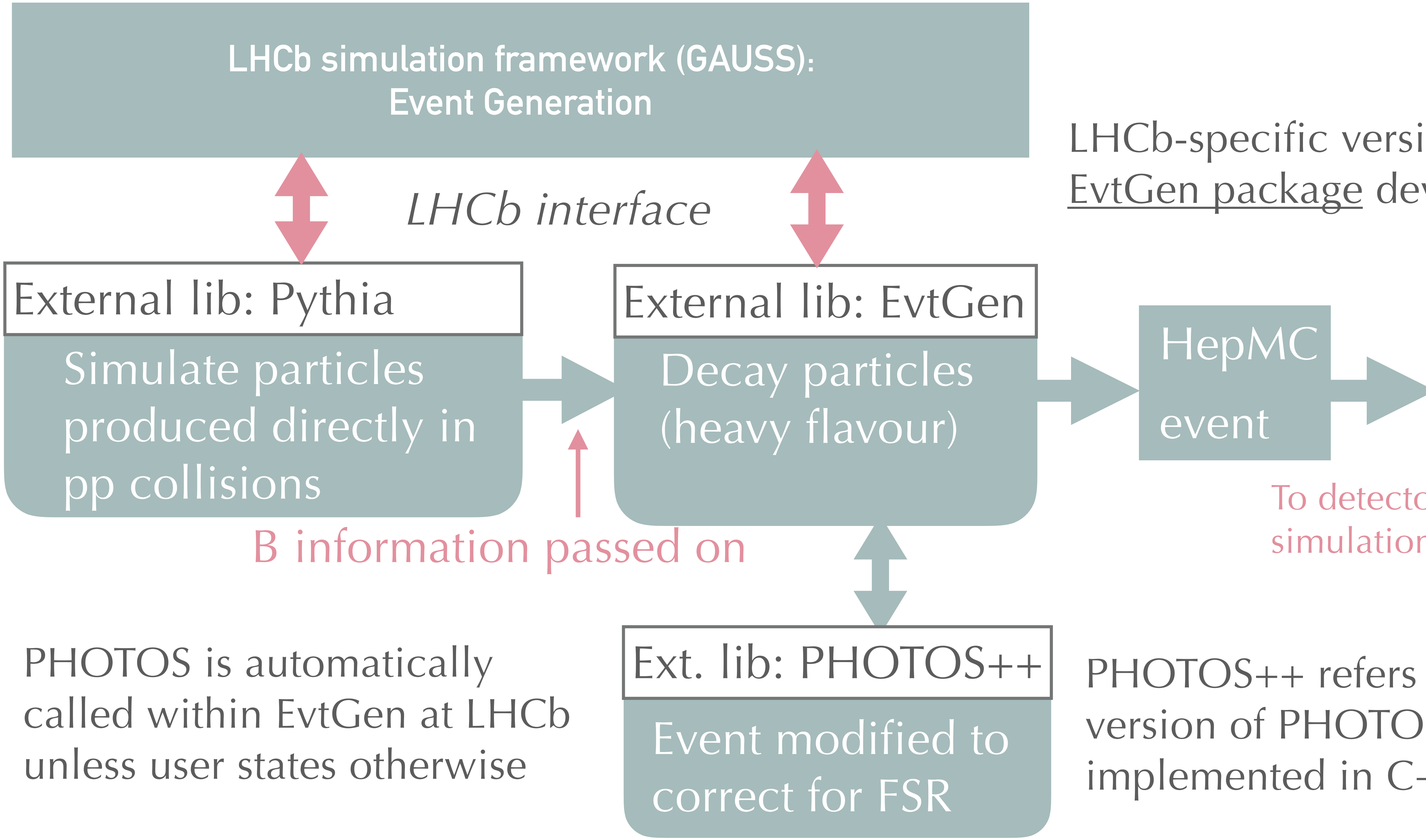
How PHOTOS interfaces with LHCb



LHCb-specific version of EvtGen package developed

PHOTOS is automatically called within EvtGen at LHCb unless user states otherwise

PHOTOS++ refers to the version of PHOTOS implemented in C++

How PHOTOS interfaces with LHCb

LHCb simulation framework (GAUSS):
Event Generation

LHCb interface

LHCb-specific version of EvtGen package developed

External lib: Pythia
Simulate particles produced directly in pp collisions

External lib: EvtGen
Decay particles

HepMC
nt

To detector simulation

B informatio

Interface with PHOTOS in both Belle 2 and LHCb simulation is via the EvtGen package

Ext. lib: PHOTOS++
Event modified to correct for FSR

PHOTOS is automatically called within EvtGen at LHCb unless user states otherwise

PHOTOS++ refers to the version of PHOTOS implemented in C++

The EvtGen library

- EvtGen is a Monte Carlo event generator that simulates the decays of heavy flavour particles, primarily B and D mesons.

- Contains a range of decay models for intermediate and final states containing scalar, vector and tensor mesons or resonances, as well as leptons, photons and baryons

- Takes into account angular and time-dependent correlations which allows for the simulation of CP-violating processes

```
Decay MyD0
  0.25 K+ K- mu+ mu- PHSP;
  0.75 MyPhi mu+ mu- PHSP;
Enddecay
CDecay MyantiD0

Decay MyPhi
  1.000 K+  K-    VSS;
Enddecay
```

EvtGen and PHOTOS: specifics

- Treatment of interference between between photon emission from multiple sources important for precision in B decays
- Interference modelled via universal weight

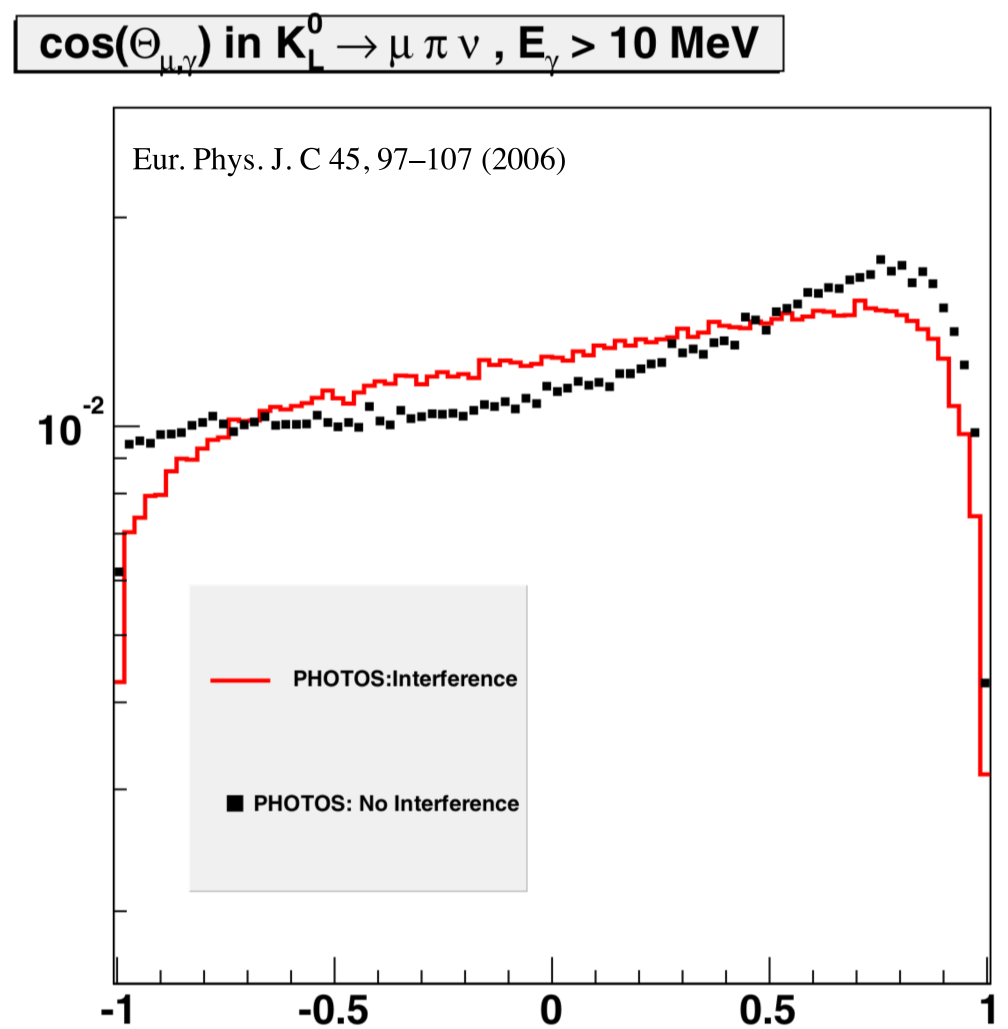
Decay products charge

Photon energy & polarisation

$$W_{multi} = \frac{\sum_{\varepsilon} \left| Q_1 \frac{q_1 \cdot \varepsilon}{q_1 \cdot k} + Q_2 \frac{q_2 \cdot \varepsilon}{q_2 \cdot k} + \ldots \right|^2}{\sum_{\varepsilon} Q_1^2 \left| \frac{q_1 \cdot \varepsilon}{q_1 \cdot k} \right|^2 + Q_2^2 \left| \frac{q_2 \cdot \varepsilon}{q_2 \cdot k} \right|^2 + \ldots},$$

Decay products momenta

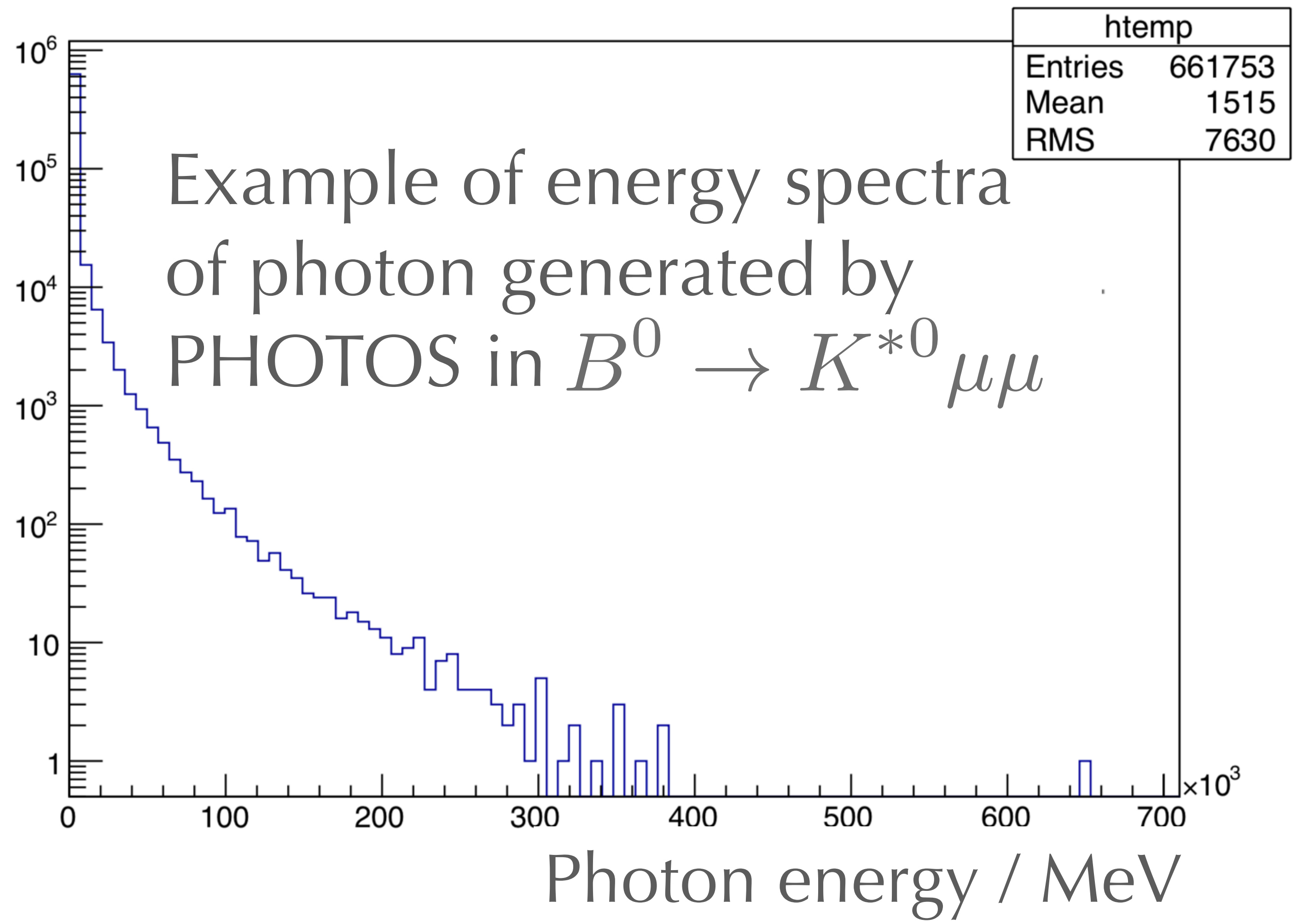
- $W_{multi}|_{\max} = 64$ -> upto *7 charged particles* in decay[*] (higher = increase in CPU time)



[*] max weight = 2^{n-1}

EvtGen and PHOTOS: specifics

- Minimum threshold for photons to be generated explicitly: ~0.1KeV [**] for the case of a B meson

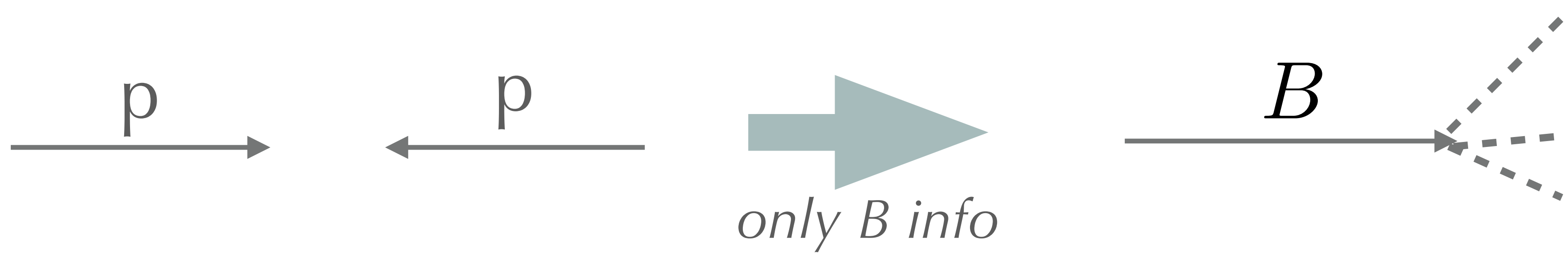


If any expert in the audience thinks these settings could be optimised, please let us know!

[**] 10^{-7} in units of half the decaying particles mass

EvtGen and PHOTOS: interfacing issues

- One distinction of EvtGen is that it does not store the initial 4-momenta of the colliding input beam particles, *just that of the already generated B meson*



- In version v3.60 of PHOTOS this caused issues as this beam information was required

✓ This has been since rectified (with much help from the PHOTOS developers) in v3.61

EvtGen and PHOTOS: more interfacing

- Although the PHOTOS interfacing runs smoothly, the running of PHOTOS within EvtGen takes a non-neglible amount of time (~45%)
- Much of this processing time is spent creating the HepMC event for Photos++, then extracting the information back
- *Could there be a more efficient way of doing this?*

Any other upcoming developments in PHOTOS that EvtGen developers should be aware of?

EvtGen code currently being modified to run in multi-threaded environments - any plans for something similar in PHOTOS?

PHOTOS in practice: a use case example

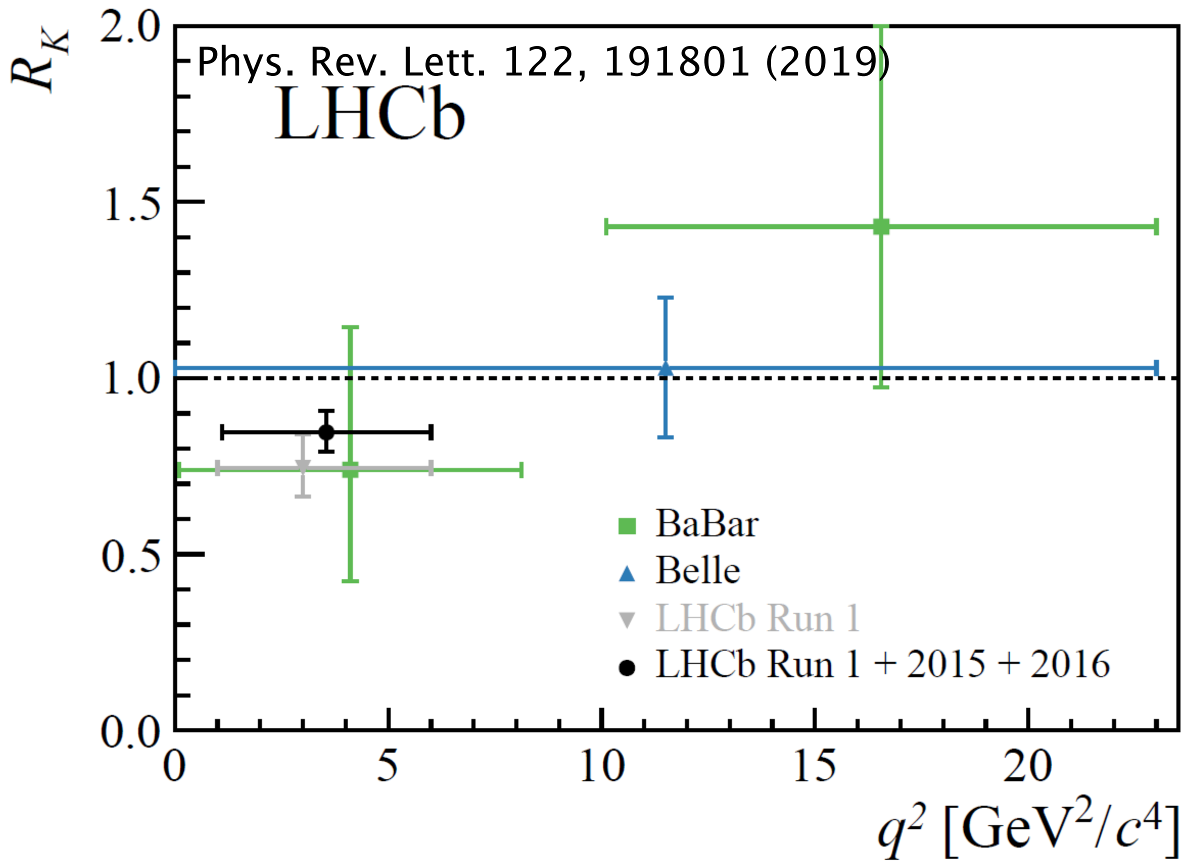
Example measurement: lepton flavour universality

$$R(X) = \frac{\mathcal{B}(B \to X\mu\mu)}{\mathcal{B}(B \to Xee)}$$

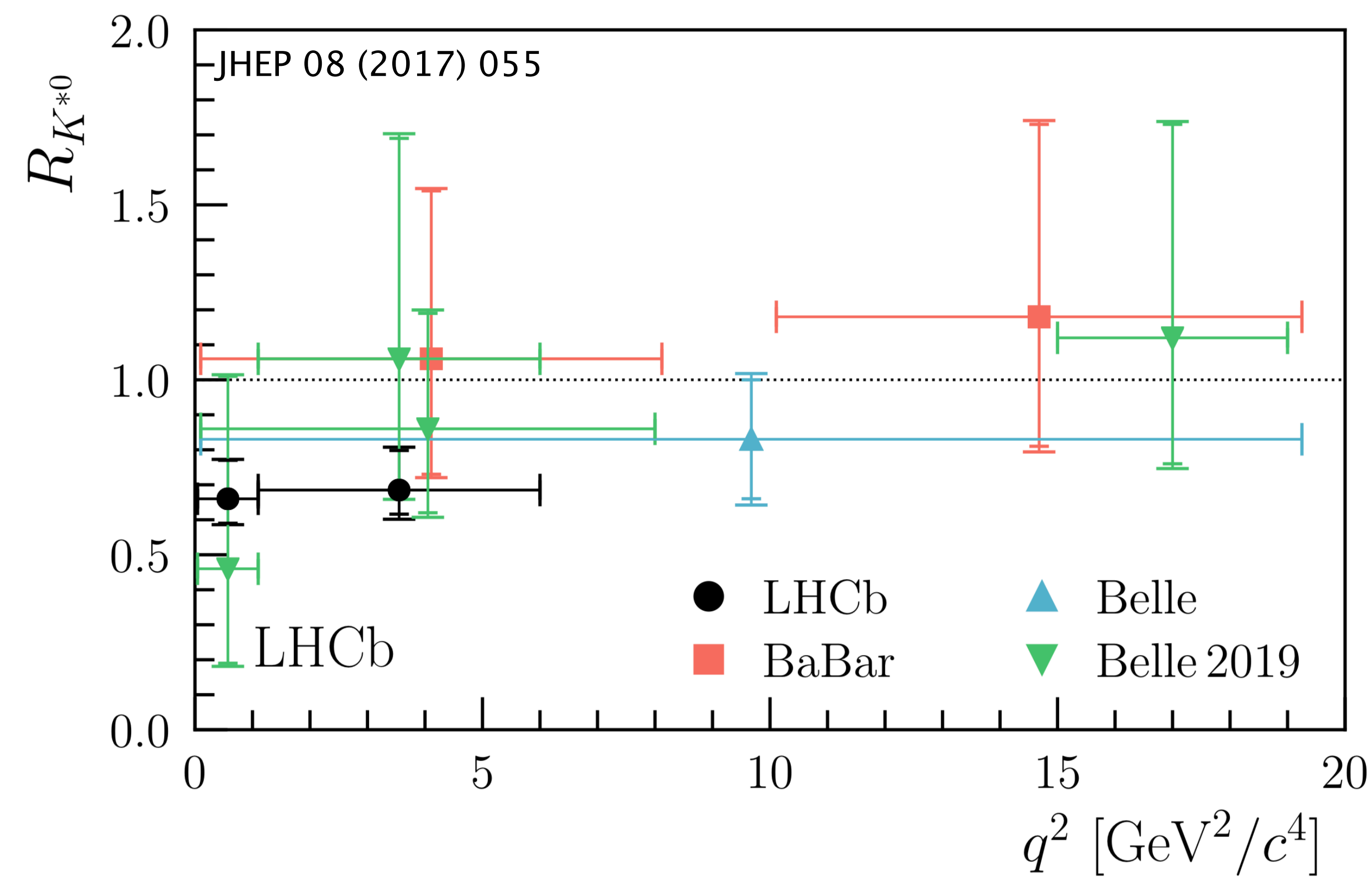
- **Very theoretically clean** as hadronic contributions cancel
- QED corrections however do not necessarily cancel and so must be well controlled
- *It is key that we model these QED corrections to a good level in our simulation*

Example measurement: lepton flavour universality

BaBar :PRD 86 (2012) 032012
Belle :PRL 103 (2009) 171801



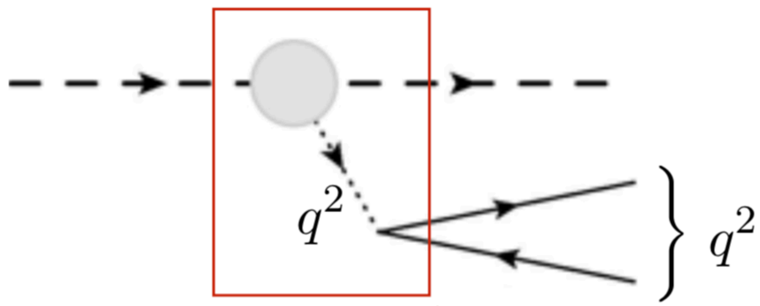
BaBar :PRD 86 (2012) 032012 Belle 2019 :arXiv:1904.02440
Belle :PRL 103 (2009) 171801

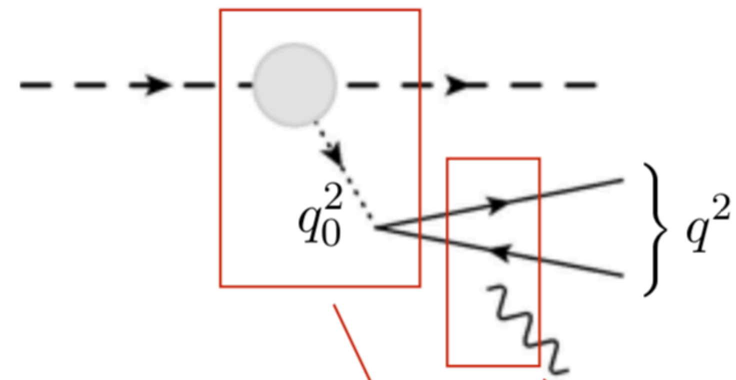


- *Accuracy of QED corrections of particular importance, given the tensions observed with the SM in these measurements*

Example measurement: lepton flavour universality

- ➤ Expected magnitude of QED corrections on $R(K^{(*)})$





$$\frac{\mathrm{d}\Gamma(B \to K^{(*)}\ell^+\ell^-)}{\mathrm{d}q^2} \equiv \mathcal{F}_K^\ell(q^2)$$

$$\frac{\mathrm{d}^2\Gamma(B \to K\ell^+\ell^-)}{\mathrm{d}q_0^2\,\mathrm{d}q^2} = \mathcal{F}_K^\ell(q_0^2)\,\omega\left(\frac{q^2}{q_0^2}, m_\ell^2\right)$$

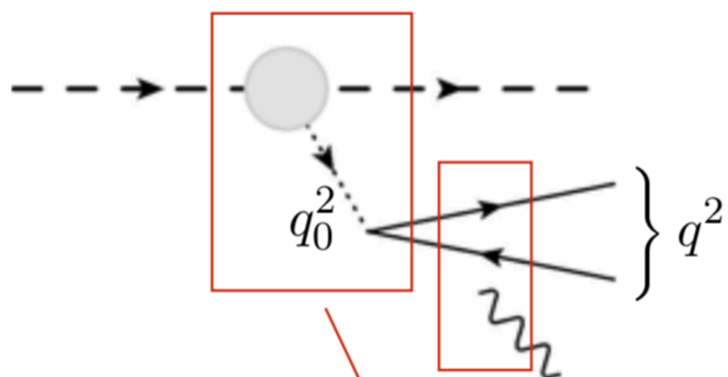
No FSR ⟶ FSR

Diagrams taken from proponents of Eur.Phys.J. C76 (2016) no.8, 440

Eur.Phys.J. C76 (2016) no.8, 440

Example measurement: lepton flavour universality

- Expected magnitude of QED corrections on $R(K^{(*)})$



$$\frac{\mathrm{d}^2\Gamma(B \to K\ell^+\ell^-)}{\mathrm{d}q_0^2\,\mathrm{d}q^2} = \mathcal{F}_K^{\ell}(q_0^2)\,\omega\left(\frac{q^2}{q_0^2}, m_\ell^2\right)$$

$$= \quad R_K = \frac{\int_{1\,\mathrm{GeV}^2}^{6\,\mathrm{GeV}^2}\left[\int_{q^2}^{f(q^2, m_B^{\mathrm{rec},\mu})} \mathcal{F}_K^{\mu}(q_0^2)\,\omega(q^2/q_0^2, m_\mu^2)\,\mathrm{d}q_0^2\right]\mathrm{d}q^2}{\int_{1\,\mathrm{GeV}^2}^{6\,\mathrm{GeV}^2}\left[\int_{q^2}^{f(q^2, m_B^{\mathrm{rec},e})} \mathcal{F}_K^{e}(q_0^2)\,\omega(q^2/q_0^2, m_e^2)\,\mathrm{d}q_0^2\right]\mathrm{d}q^2}$$

$$\frac{d\Gamma^{\mathrm{NLO}}}{dq^2}$$

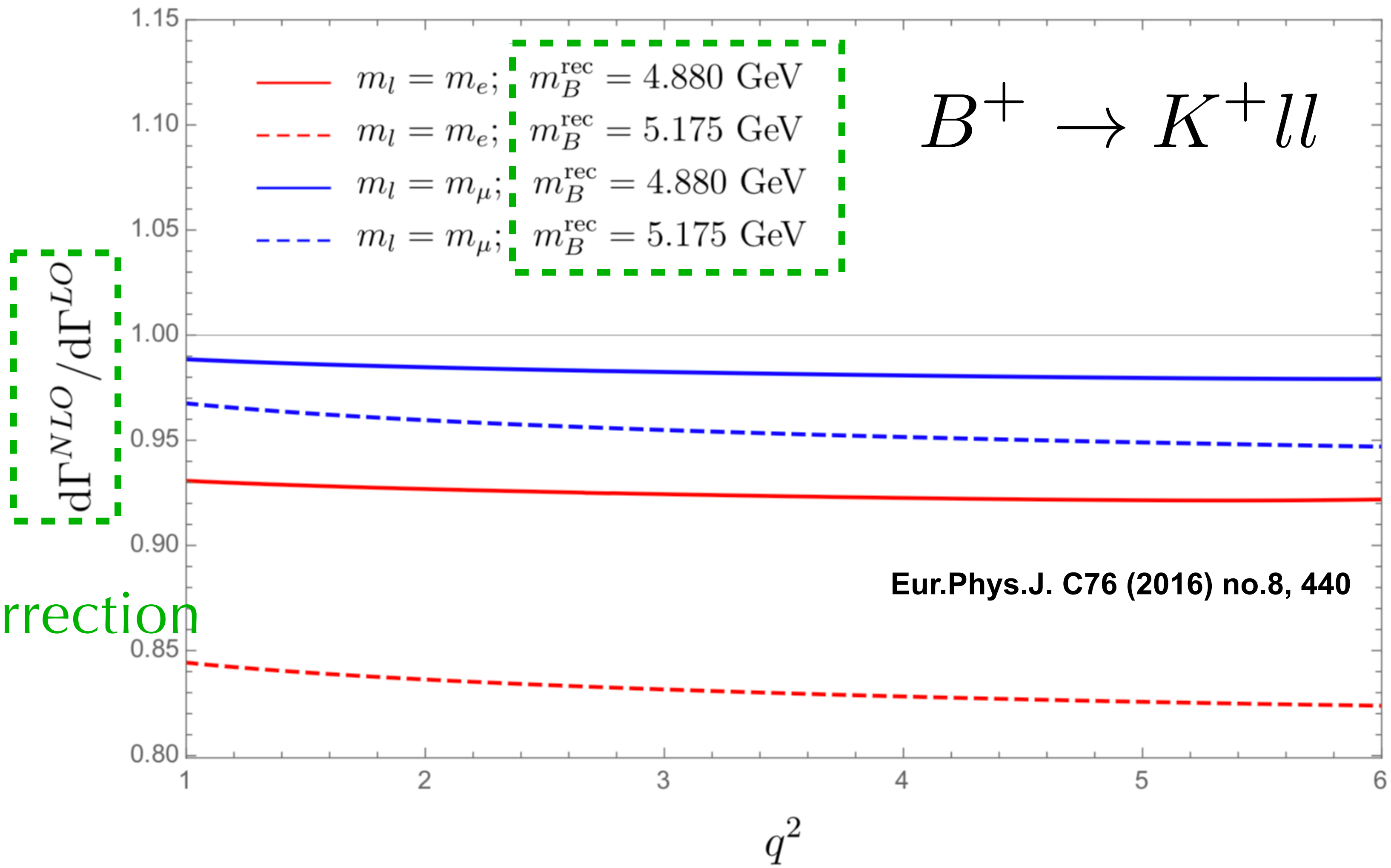
The size of the QED correction will depend on allowed range of reconstructed B mass, as well as the lepton mass

Diagrams taken from proponents of Eur.Phys.J. C76 (2016) no.8, 440

Eur.Phys.J. C76 (2016) no.8, 440

Example measurement: lepton flavour universality

Different minimum B masses correspond to those used in the Run 1 LHCb $R(K)$ analysis [Phys. Rev. Lett. 113 (2014) 151601]



Size of QED correction

[accounting for only log-enhanced QED corrections]

Example measurement: lepton flavour universality

Different minimum B masses correspond to those used in the Run 1 LHCb $R(K)$ analysis [Phys. Rev. Lett. 113 (2014) 151601]

$B \to K\ell^+\ell^-$ Eur.Phys.J. C76 (2016) no.8, 440	$\ell = e$	$\ell = \mu$
$m_B^{\text{rec}} = 4.880$ GeV	-7.6%	-1.8%
$m_B^{\text{rec}} = 5.175$ GeV	-16.9%	-4.6%
$m_B^{\text{rec}} = 4.500$ GeV	$\sim 3\%$	—

Larger QED effect in electrons partially compensated for by tighter mass cut in muons

$$\Delta R_K \approx -4.6\% - (-7.6\%) = +3.0\%$$

Expected QED correction

Eur.Phys.J. C76 (2016) no.8, 440

Example measurement: lepton flavour universality

Different minimum B masses correspond to those used in the Run 1 LHCb $R(K)$ analysis [Phys. Rev. Lett. 113 (2014) 151601]

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$m_B^{\text{rec}} = 5.175$ GeV	-16.7%	-4.5%

Larger QED effect in electrons partially compensated for by tighter mass cut in muons

$$\Delta R_{K^*} \approx -4.5\% - (-7.3\%) = +2.8\%$$

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Eur.Phys.J. C76 (2016) no.8, 440

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[illegible]	[illegible]	[illegible]
$m_B^{\mathrm{rec}} = 5.175$ GeV	-16.7%	-4.5%

Larger QED effect in … tighter mass cut in muons

As will be discussed in next slides, these corrections are well account for in LHCb analyses, via the use of PHOTOS

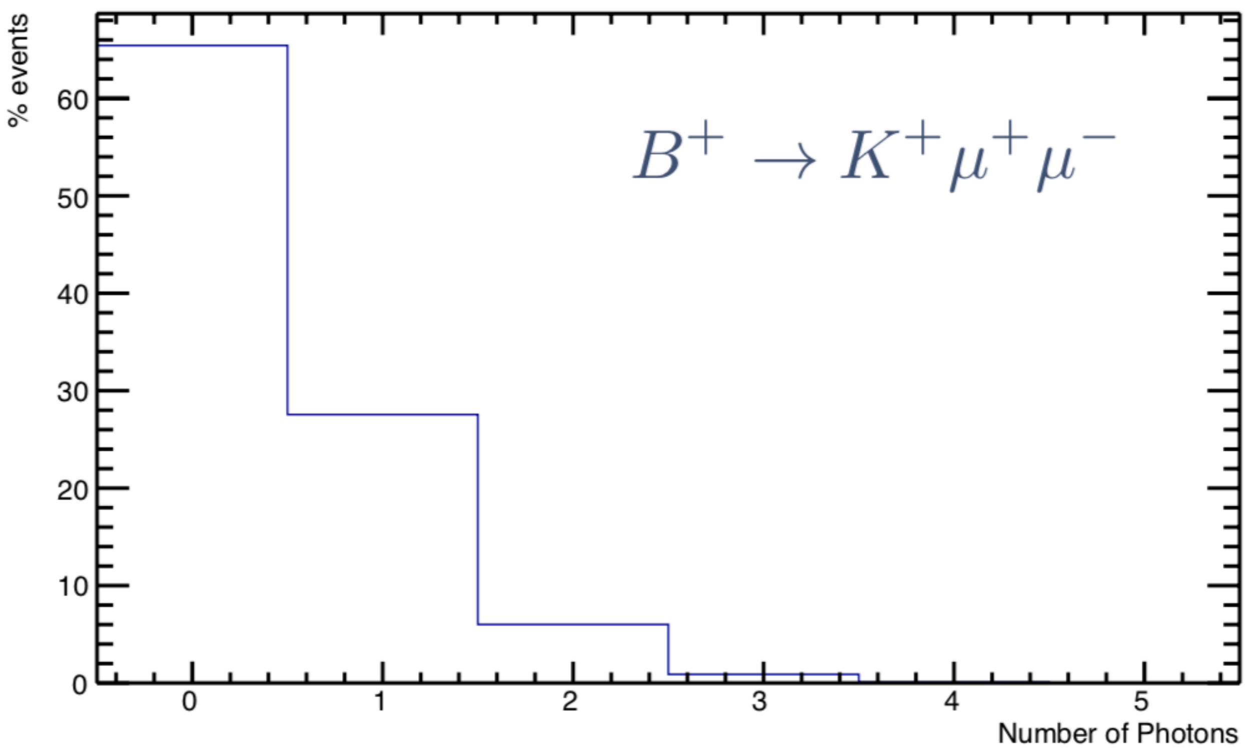
$$\Delta R_{K^*} \approx -4.5\% - (-7.3\%) = +2.8\%$$

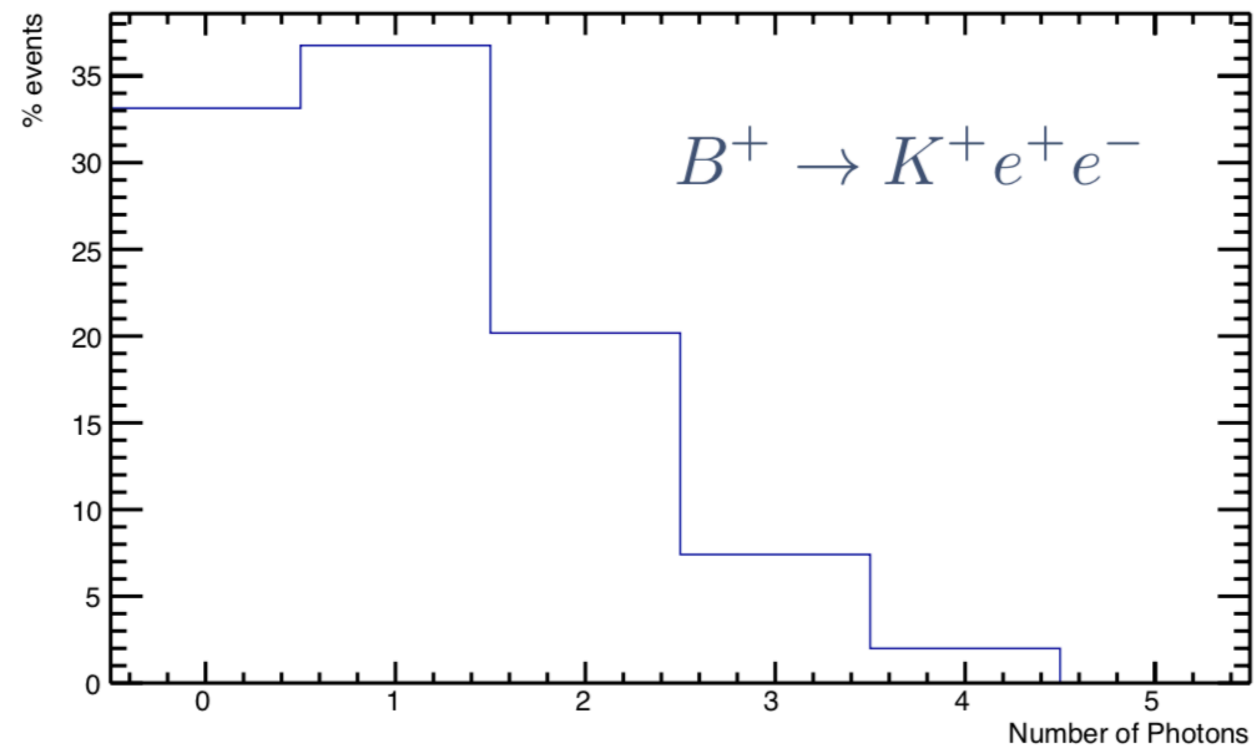
Expected QED correction

Eur.Phys.J. C76 (2016) no.8, 440

How well does PHOTOS model these effects?

➤ Using PHOTOS in EvtGen

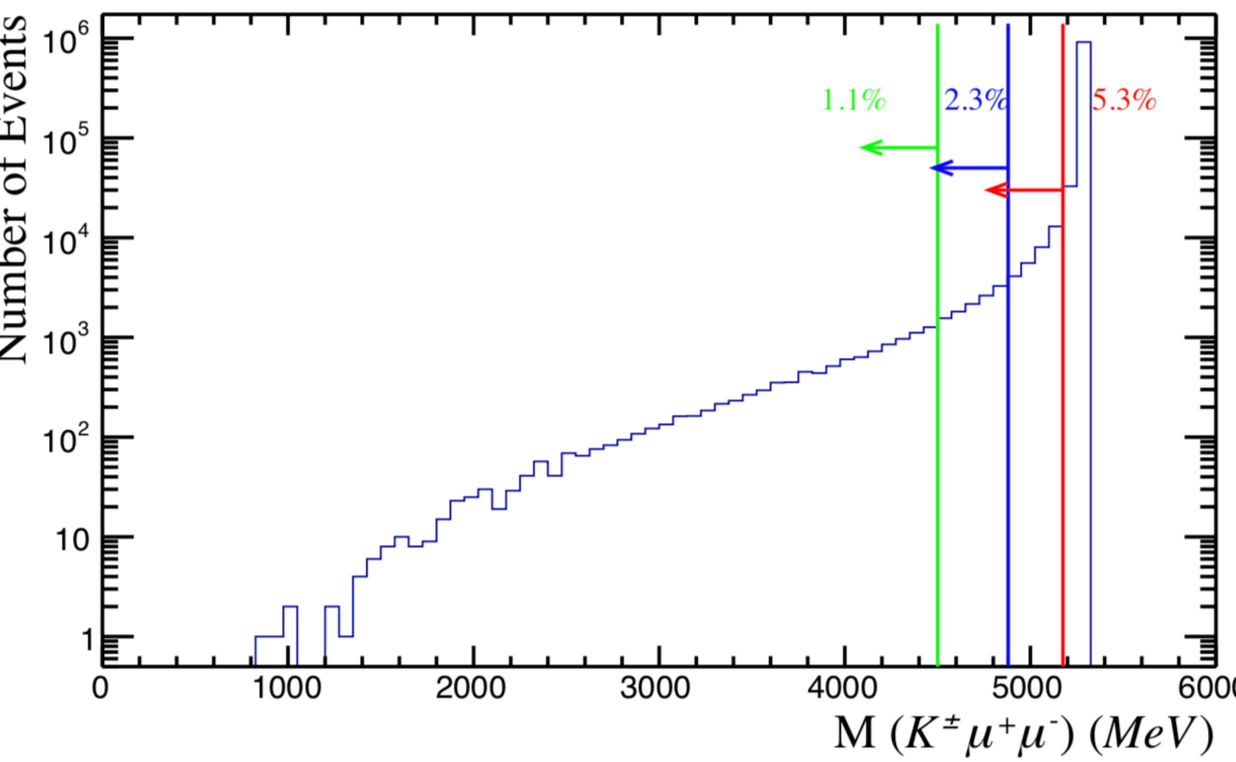


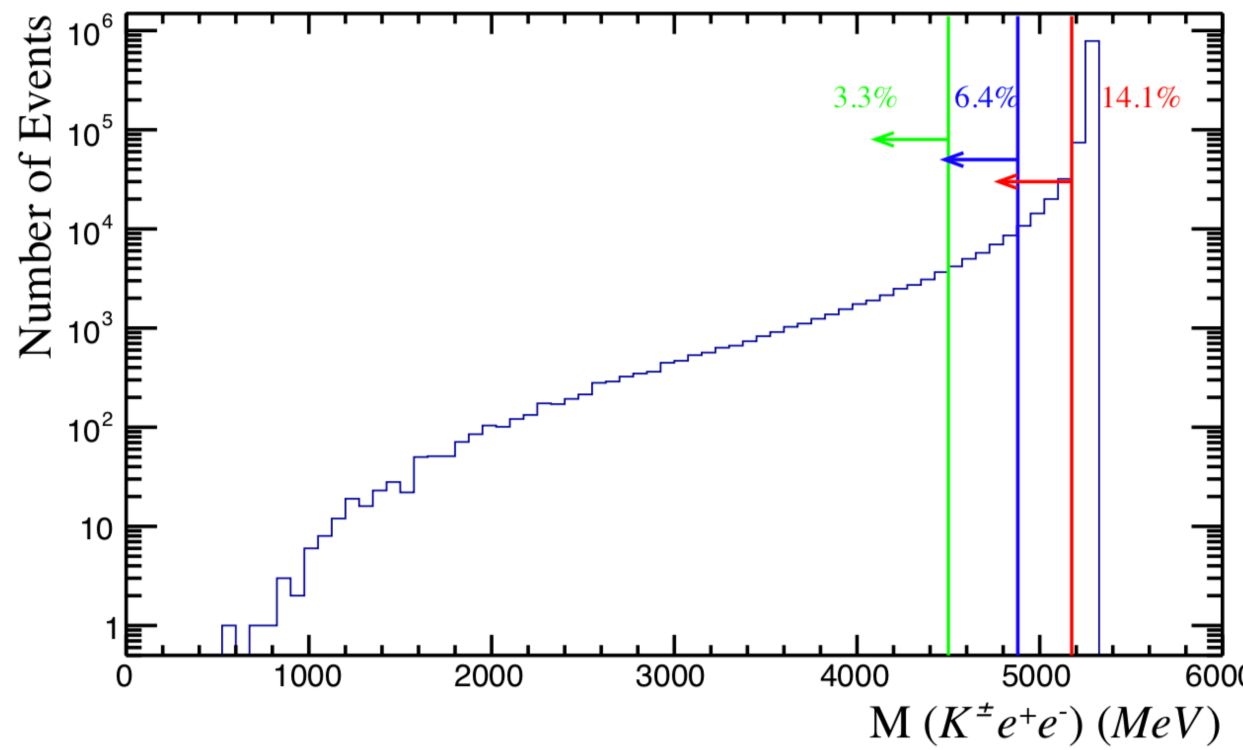


Plots generated by Rafael Silva Coutinho

How well does PHOTOS model these effects?

- Using PHOTOS in EvtGen





$5175 < m(Kll) < 5700\ \mathrm{MeV}/c^2$

$4880 < m(Kll) < 5700\ \mathrm{MeV}/c^2$

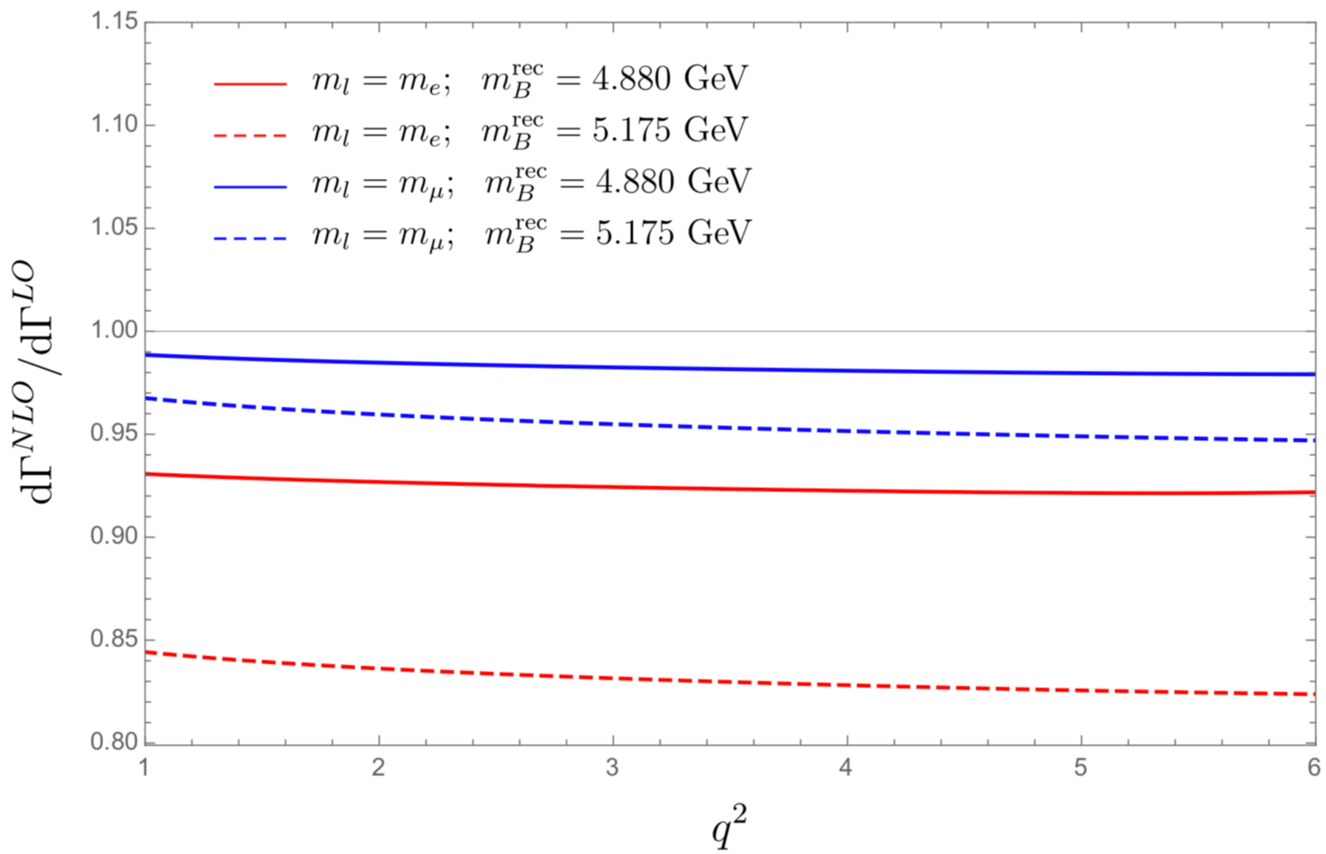
$4550 < m(Kll) < 5700\ \mathrm{MeV}/c^2$

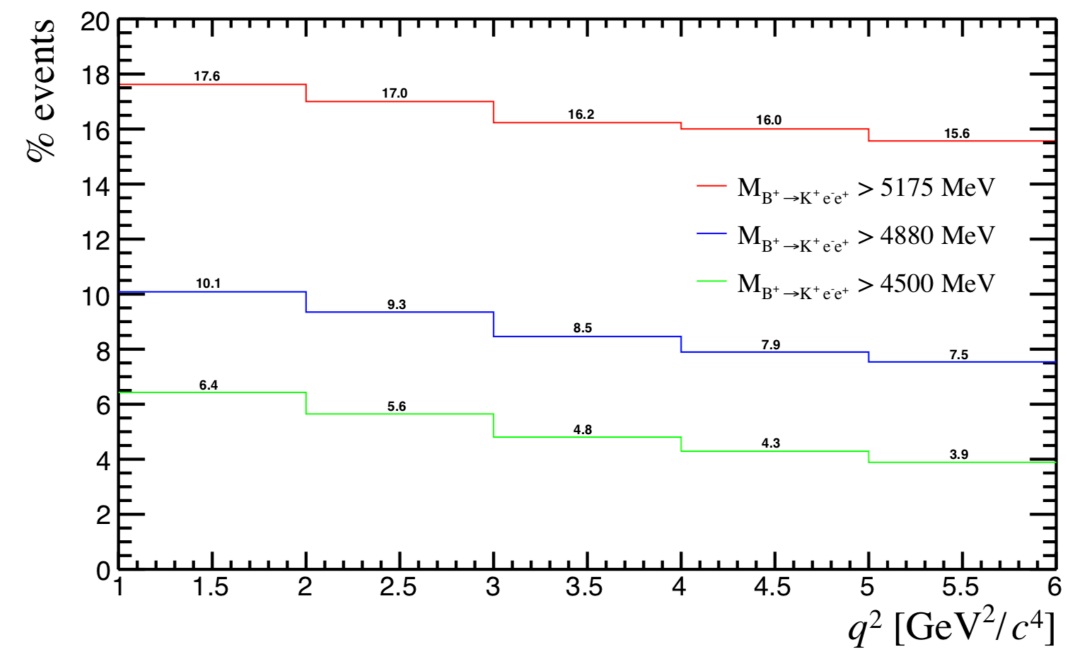
$5175 < m(K\mu\mu) < 5700\ \mathrm{MeV}/c^2$

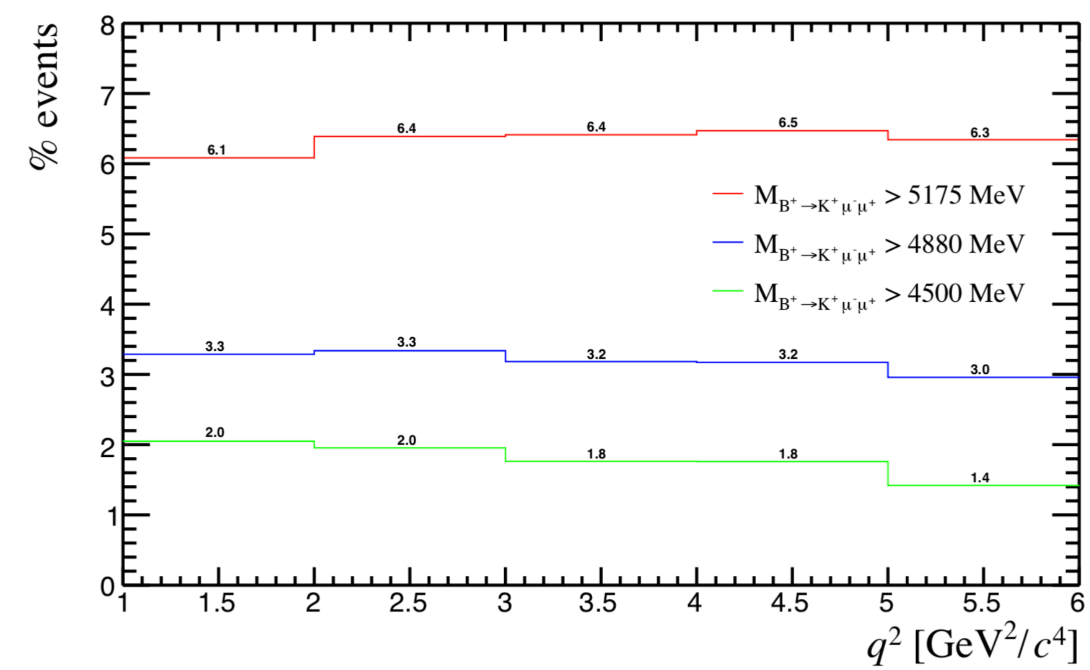
$4880 < m(Kee) < 5700\ \mathrm{MeV}/c^2$

Plots generated by Rafael Silva Coutinho

How well does PHOTOS model these effects?







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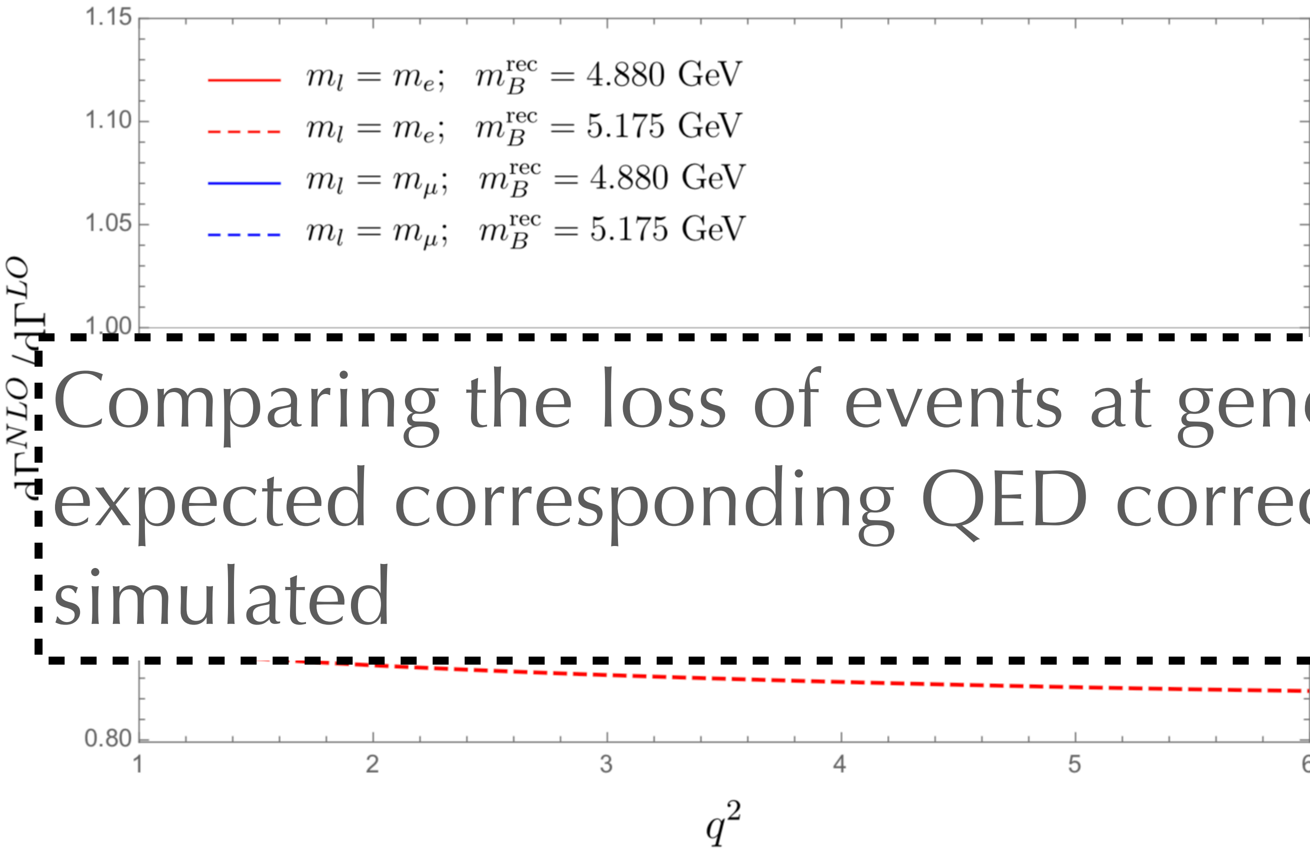
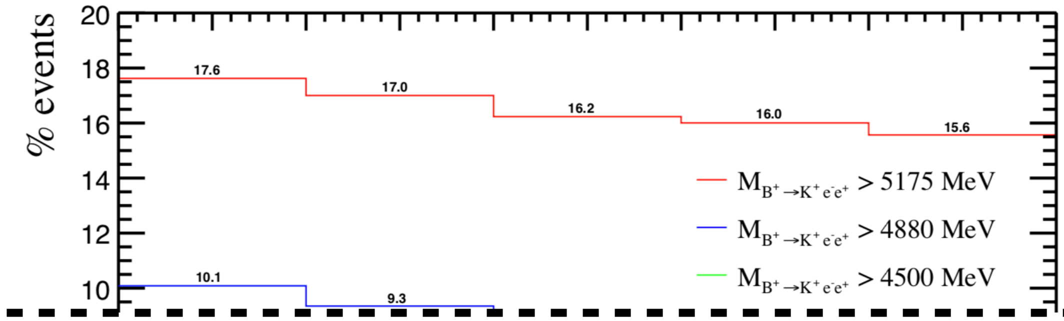
Plots generated by Rafael Silva Coutinho

How well does PHOTOS model these effects?



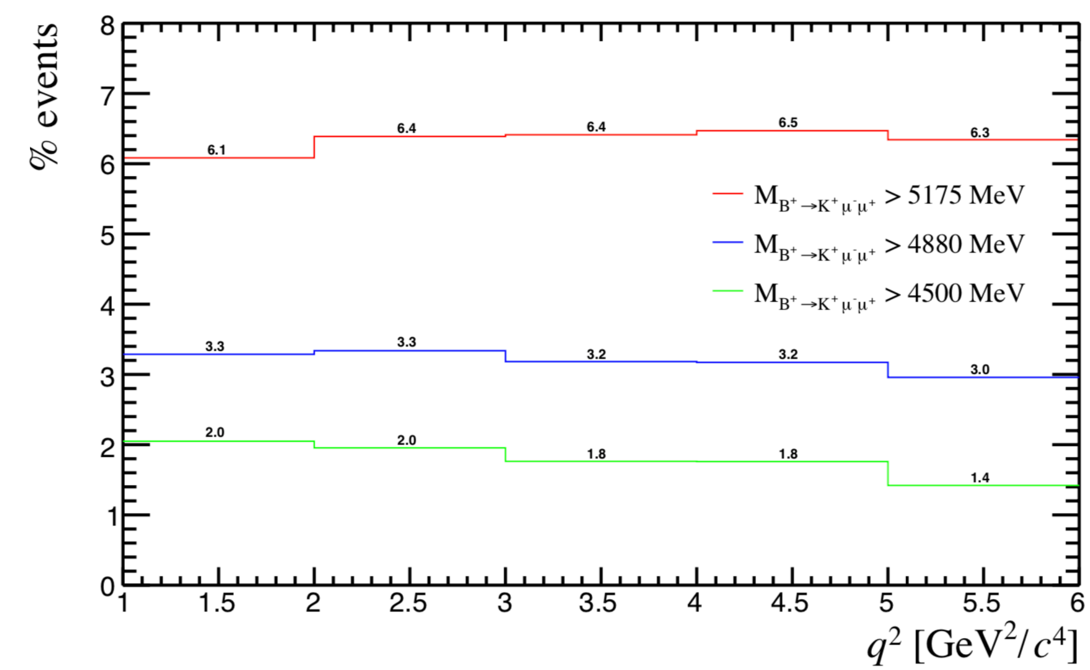


Comparing the loss of events at generator level in simulation with the expected corresponding QED correction, this effect seems to be well simulated

$5175 < m(Kll) < 5700\ \mathrm{MeV}/c^2$

$4880 < m(Kll) < 5700\ \mathrm{MeV}/c^2$

$4550 < m(Kll) < 5700\ \mathrm{MeV}/c^2$



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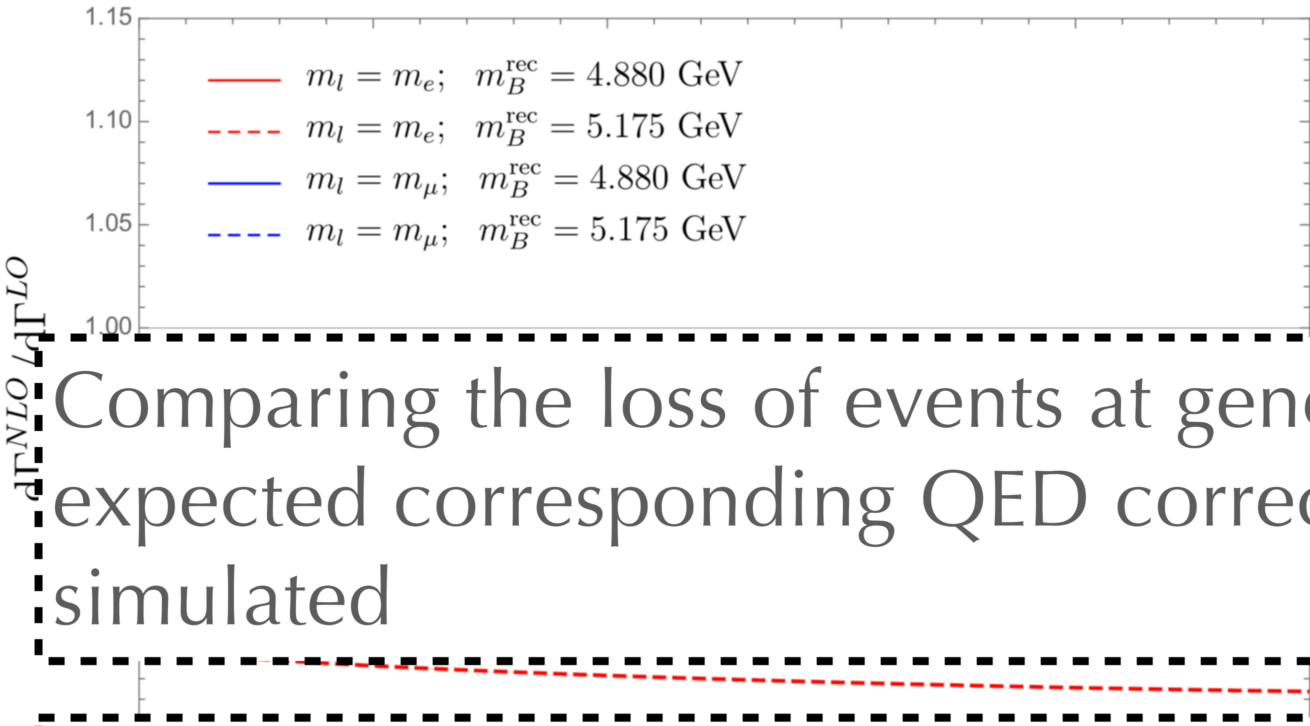
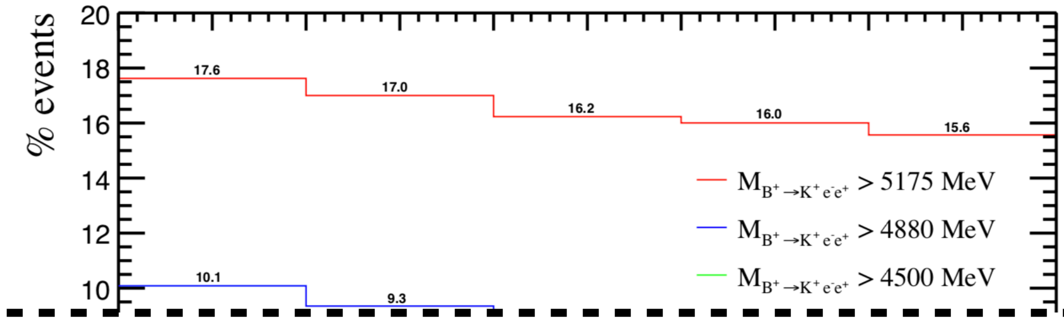
How well does PHOTOS model these effects?



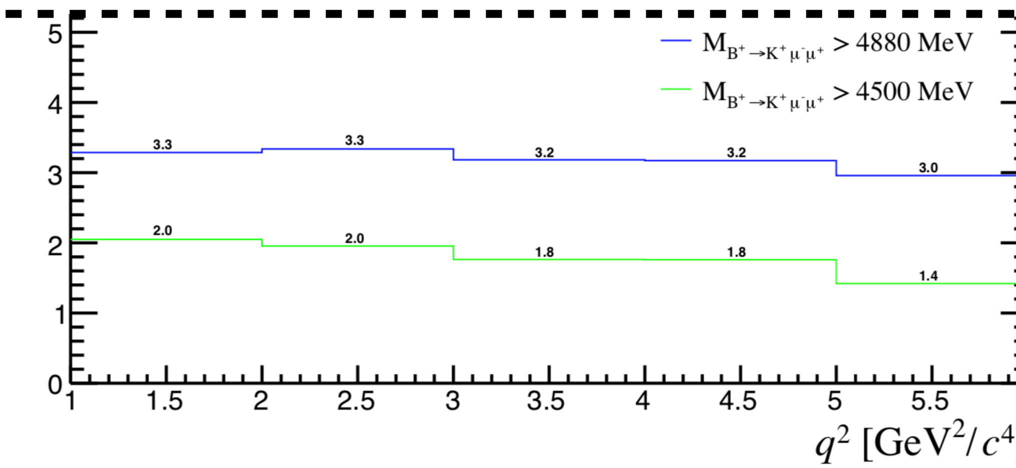


Comparing the loss of events at generator level in simulation with the expected corresponding QED correction, this effect seems to be well simulated

Conclusion of [Eur.Phys.J. C76 (2016) no.8, 440]:estimate of $\Delta R(K)$ agrees with results obtained by PHOTOS within $\pm 1\%$

$4880 < m(Kll) < 5700\ \text{MeV}/c^2$

$4550 < m(Kll) < 5700\ \text{MeV}/c^2$



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Summary

- The correct simulation of QED corrections in B physics is paramount to obtaining reliable results
- PHOTOS is used for final state QED corrections in both Belle 2 and LHCb
- For both the LHCb and Belle 2 simulation, the interface with the PHOTOS package is via the EvtGen library, which sets the relevant, B physics appropriate, parameters.
- PHOTOS currently appears to model QED corrections to a good level
- Further optimisation could be made with the interfacing of EvtGen with PHOTOS