Prospects for the search of $B_{(c)}^{+} \to \mu^{+}\nu_{\mu}\gamma$ decays at LHCb

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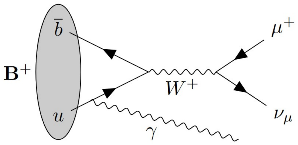
Why $B^+ \to \ell^+ \nu_\ell \gamma$ is interesting

- Standard Model tree level process
- Strong helicity suppression is lifted by emission of additional photon
- Decay $B^+ \to \ell^+ \nu_\ell \gamma$ has never been observed
- Current best upper limit from Belle using $\ell = e, \mu$ [PRD 98 (2018) 11, 112016]

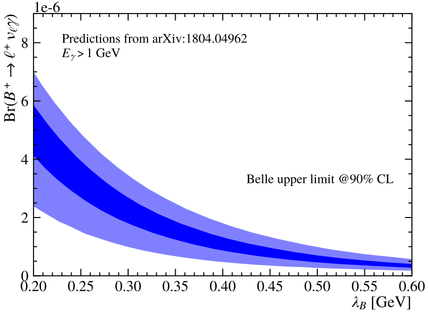
$$\mathcal{B}(B^+ \to \ell^+ \nu_\ell \gamma) < 3.0 \times 10^{-6} \text{ @90\%CL}$$

- Considered the golden mode to probe B^+ meson substructure



Leading order Feynman diagram for the decay $B^+ \to \mu^+ \nu_\mu \gamma$.

- Emission of γ probes first inverse moment λ_B of B meson light-cone distribution amplitude
  [Eur.Phys.J.C 71 (2011) 1818]
- Value of λ_B not well known but vital theory input
  [PRD 69 (2004) 034014] [Nucl.Phys.B 832 (2010) 109-151] [PLB 848 (2024) 138345]
- Strong dependence of predicted BR for $B^+ \to \ell^+\nu_\ell\gamma$ on λ_B
- Theory predictions only valid for $E^*_\gamma > 1.5\,\mathrm{GeV}$ with extrapolation to $E^*_\gamma > 1.0\,\mathrm{GeV}$ [JHEP 07 (2018) 154]



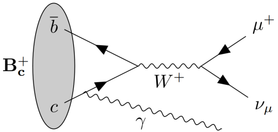
Predicted BR for $B^+ \to \ell^+\nu_\ell\gamma$ from [JHEP 07 (2018) 154] with the upper limit from Belle. The colored bands correspond to different theory models.

On the decay $B_c^+ \to \mu^+ \nu_\mu \gamma$

- Should be very similar to decay of B^+
- Never been searched for
- Potential background for the analysis of $B^+ \to \mu^+ \nu_\mu \gamma$
- Expect roughly similar rate [Phys.Rev.D 100 (2019) 11, 112006][PTEP 2022 (2022) 083C01]

$$\frac{N_{sig}(B_c^+ \to \mu^+ \nu_\mu \gamma)}{N_{sig}(B^+ \to \mu^+ \nu_\mu \gamma)} \approx \frac{|V_{cb}|^2}{|V_{ub}|^2} \frac{f_c}{f_u} \approx 1$$

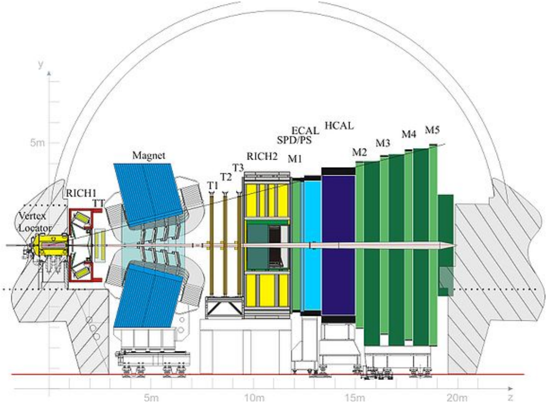
- In general limited knowledge of the B_c^+ meson
- What can we learn from $B_c^+ \to \mu^+ \nu_\mu \gamma$?



Feynman diagram for the decay $B_c^+ \to \mu^+ \nu_\mu \gamma$.

The LHCb experiment

- Single arm forward spectrometer covering $2 < \eta < 5$
- Tracking and vertexing: Vertex Locator (VELO), TT, Magnet, T1-T3
- Particle identification (PID): RICH, Calorimeters, Muon stations M1-M5



Schematic side view of the LHCb detector in Run 2 [JINST 3 (2008) S08005]

Reconstructing $B_{(c)}^{+} \to \mu^{+}\nu_{\mu}\gamma$ at LHCb

- Very challenging to reconstruct at hadron colliders, deemed impossible
- Two major challenges: Vertex reconstruction and Neutrino momentum recovery

Vertex reconstruction

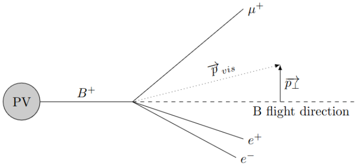
- B mesons produced in pp collisions
- Select B candidates from displaced secondary decay vertex
- Single charged track in $\mu^{+}\nu_{\mu}\gamma$
  $\Rightarrow$ no vertex reconstruction possible
- Crucial to require $\gamma \to e^{+}e^{-}$ conversions
  $\Rightarrow$ multiple charged tracks allow for vertex reconstruction
- Conversions in LHCb's vertex locator (VELO) provide excellent vertex resolution

Neutrino momentum recovery

- At LHCb cannot infer neutrino momentum from initial decay kinematics
- Correct for momentum imbalance $p_\perp$ perpendicular to B flight direction

$$m_{corr} = \sqrt{m^2(\mu^+\gamma_{ee}) + |p_\perp|^2} + |p_\perp|$$

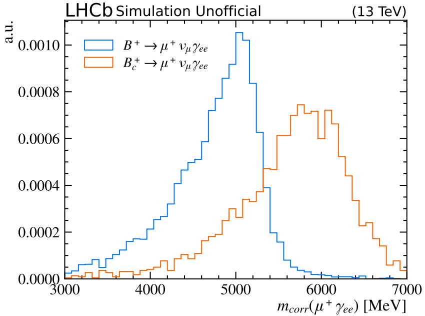
- Requires precise reconstruction of B decay vertex



- Using data recorded with LHCb experiment from 2016-2018 corresponding to $\mathcal{L}_{int} = 5.4\text{fb}^{-1}$
- Reconstruct the photon using $\gamma \to e^+e^-$ conversions in LHCb's VELO
- Search for signal peak in m_{corr} using binned template fit
- Background modelling from data-driven templates

Blinding strategy

- Signal region $4500\,\text{MeV} < \text{m}_{\text{corr}}(\mu^+\gamma_{\text{ee}}) < 6500\,\text{MeV}$ remains blinded



Corrected mass distribution for $B^+_{(c)} \to \mu^+\nu_\mu\gamma$ simulation. The grey area is the blinded signal region.

Signal selection

- Trigger selection (hardware + software)
- Cut based selection: kinematics, decay topology, reconstruction quality
- Boosted Decision Trees (BDT) to suppress:
  - Random combination of μ^+ and γ_{ee}
  - Decays with additional charged tracks e.g. $B^+ \to D^0(\to K^- \pi^+ \gamma_{ee})\mu^+\nu$
  - Decays with additional neutral clusters e.g. $\pi^0 \to \gamma_{ee}\gamma$
- Currently optimising the signal selection

Trigger	Requirement
L0 trigger	L0Electron or L0Muon
HLT1	B_TrackMVA or B_TwoTrackMVA
HLT2	B_Topo[2,3]Body or B_TopoMu[2,3]Body

Trigger requirements to select $B^+_{(c)} \to \mu^+\nu_\mu\gamma$ candidates.

Background modelling $\pi^0/\eta \to \gamma_{ee}\gamma$

Partially reconstructed $\pi^0/\eta \to \gamma_{ee}\gamma$

- By far the dominant source of background
- Expect much higher level of background compared to Belle
- Many sources including
  $b \to u\ell\nu$:
  - $B^+ \to \pi^0\mu^+\nu_\mu$
  - $B^+ \to \eta\mu^+\nu_\mu$
  - $B^0 \to \rho(770)^-(\to \pi^-\pi^0)\mu^+\nu_\mu$

  $b \to c\ell\nu$:
  - $B^+ \to \overline{D}^{(*)0}(\to h^+h^-\pi^0\ldots)\mu^+\nu_\mu$
  - $B^0 \to D^{(*)-}(\to h^-\pi^0\ldots)\mu^+\nu_\mu$

  Decays of B_s, B_c, Λ_b:
  - $B_s \to D_s^-(\to h^-\pi^0\ldots)\mu^+\nu_\mu$

  Random combinations of $\pi^0/\eta + \mu^+$
- Modeling all backgrounds from $\pi^0/\eta \to \gamma_{ee}\gamma$ not feasible using simulation

$\Rightarrow$ **Data-driven template including all sources of π^0 and η**

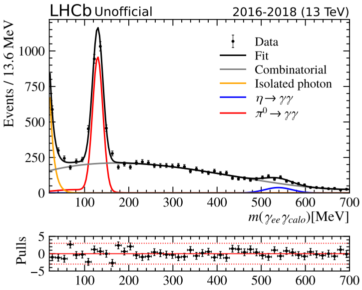
Background modelling $\pi^0/\eta \to \gamma_{ee}\gamma$

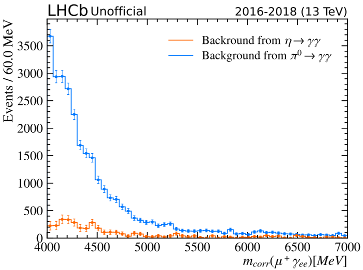
Get $\pi^0/\eta \to \gamma_{ee}\gamma$ background shape from data

- Search region in the calorimeter for missing photon from $\pi^0/\eta \to \gamma_{ee}\gamma$ decays
- Fit resulting distribution in $m(\gamma_{ee}\gamma_{calo})$
- Subtract background to get shape in $m_{corr}(\mu^+\gamma_{ee})$
- Correct for efficiency of finding additional photon and resolving π^0/η

$\Rightarrow$ Representative of all $\pi^0/\eta \to \gamma_{ee}\gamma$ backgrounds scaled to expected yield

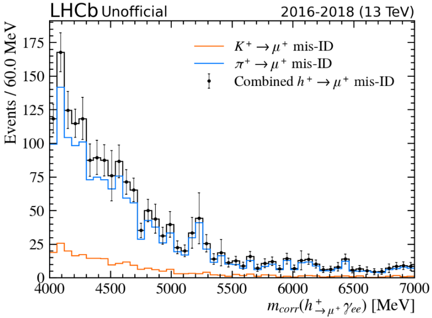
$\Rightarrow$ Crucial to get the background modelling correct
$\Rightarrow$ Requires further cross-checks





Background modelling muon mis-identification

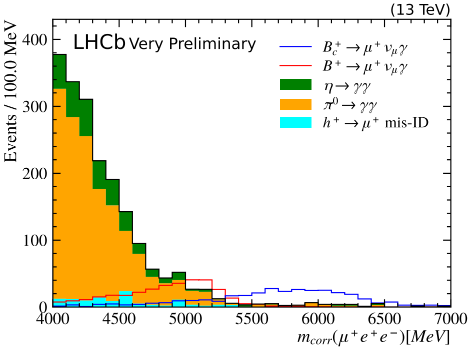
- Studied using control sample without PID requirement on muon track
- Select representative samples of $\pi^+/K^+ \rightarrow \mu^+$
- Get $m_{corr}(h^+_{\rightarrow\mu^+}\gamma_{ee})$ shape with muon-mass hypothesis on the hadron
- Correct for the PID efficiency



Template for background from $h^+ \rightarrow \mu^+$ mis-identification.

Optimise signal selection

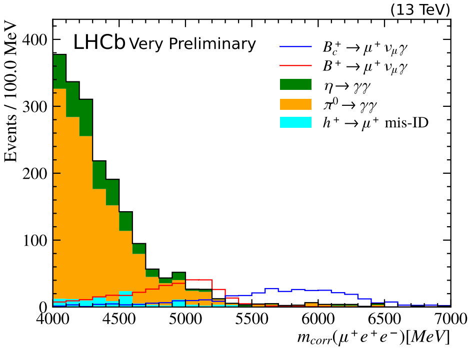
- Optimisation performed of pseudo-experiments
- Generate background only pseudo-data from derived templates
- Fit including signal shapes for $B^+_{(c)} \to \mu^+ \nu_\mu \gamma$
- Binned template fit using method from Conway [arXiv:1103.0354] to account for template uncertainties
- Signal selection not yet finalised



Background-only pseudo-data and signal shapes with arbitrary normalisation.

Optimise signal selection

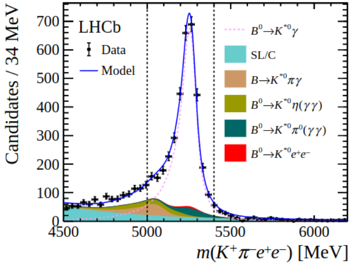
- Idea: Maximise sensitivity on $\mathcal{B}(B^+ \to \mu^+\nu_\mu\gamma)$
- For optimisation: Bayesian method with flat prior
- Computationally less demanding
- In the case of no significant signal after unblinding: $\mathrm{CL_S}$ method [J.Phys.G 28 (2002) 2693-2704]



Background-only pseudo-data and signal shapes with arbitrary normalisation.

$B^0 \to K^{*0}\gamma_{ee}$ with $K^{*0} \to K^+\pi^-$

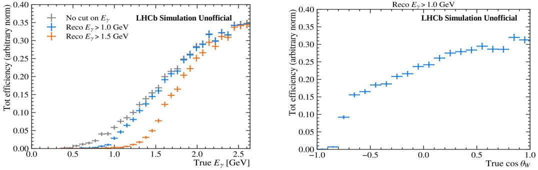
- No muon but very clean and can largely follow previous LHCb analysis [JHEP 12 (2020) 081]
- $\mathcal{B}(B^0 \to K^{*0}\gamma) = (4.18 \pm 0.25) \times 10^{-5}$ [PTEP 2022 (2022) 083C01]
- Align selection as much as possible with selection of $B^+_{(c)} \to \mu^+\nu_\mu\gamma$
- Expect about 1200 events for 2016-2018



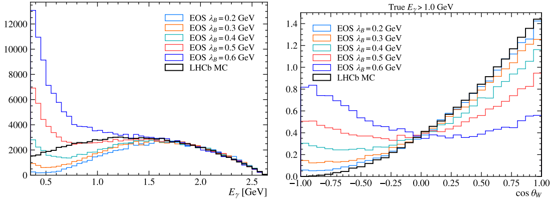
Massfit from the $B^0 \to K^{*0}e^+e^-$ analysis at very low q^2 using Run 1+2 [JHEP 12 (2020) 081] .

Model dependence

- BR prediction reliable for $E_\gamma^* > 1.5\,\mathrm{GeV}$
- Decided to cut at $E_\gamma^* > 1.0\,\mathrm{GeV}$ following Belle
- Distributions in E_γ^* and $cos\theta_W$ depend on B^+ meson LCDA
- Studied using EOS [Eur.Phys.J.C 82 (2022) 6, 569] with the model from [JHEP 10 (2022) 162]
- Non-uniform efficiency in $cos\theta_W$ introduces strong model dependence



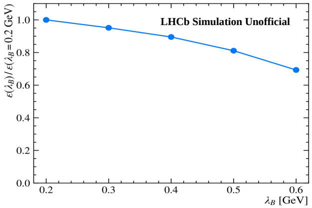
Reconstruction efficiency for E_γ^* and $cos\theta_W$

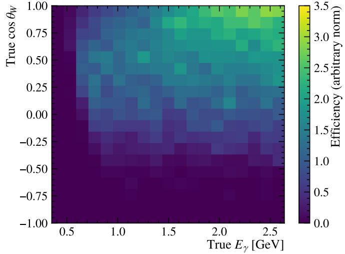


Model dependence of E_γ^* and $cos\theta_W$ on the parameter λ_B

Presentation of results

- Model dependence on λ_B of up to 30%
- Calculated using phase-space simulation reweighted in in $cos\theta_W$ and E^*_γ
- Interpreting BR in terms of λ_B also non-trivial, LCDA not only depends on λ_B
- Currently no LCDA model for $B_c^+ \to \mu^+\nu_\mu\gamma$
- Present main result for $E^*_\gamma > 1.0\,\mathrm{GeV}$ using simple well-defined LCDA model to allow easy comparison with Belle
- Provide full efficiency map in E^*_γ and $cos\theta_W$ to allow for re-interpretation and change of model parameters





Efficiency dependence on λ_B (top) and exemplary efficiency map in E^*_γ and $cos\theta_W$ (bottom).

Summary

- First search for $B^+ \to \mu^+ \nu_\mu \gamma$ at LHCb
- First search for $B_c^+ \to \mu^+ \nu_\mu \gamma$
    - Comes for free in LHCb analysis
    - Which information can we gain from $B_c^+ \to \mu^+ \nu_\mu \gamma$?
- Analysis possible using photon conversion in VELO for vertex reconstruction and peaking m_{corr}
- Analysis strategy is in place
    - Developed new data-driven method to model background from π^0 and η
    - First optimisation maximising sensitivity on $\mathcal{B}(B^+ \to \mu^+ \nu_\mu \gamma)$ in place
- Selection of candidates still being optimised
- Further cross-checks of the background modelling required
- Expected sensitivity towards $\mathcal{B}(B_{(c)}^+ \to \mu^+ \nu_\mu \gamma)$ soon to be evaluated

Future prospects

- Expect to collect three times more data during Run 3 of the LHC
- Commissioning almost completed and expect good quality data in 2024 and 2025
- Removed LHCb's hardware trigger
- Improved algorithms for reconstruction of $\gamma \rightarrow e^+e^-$
- Hopefully LHCb can contribute to the Belle2 studies of $B^+ \rightarrow \mu^+\nu_\mu\gamma$ and provide clean experimental constraints on B meson LCDA