Studying the beauty mesons structure with radiative leptonic decays at the LHCb experiment

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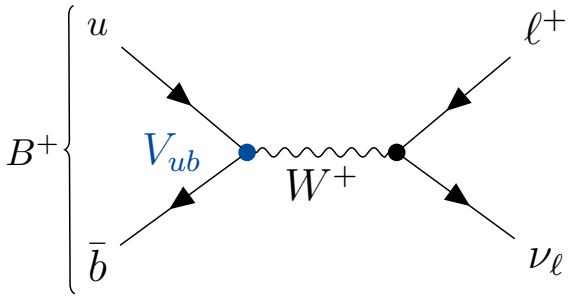
Motivation

- $B^+ \to \ell^+ \nu_\ell$ decay
  - suppressed by V_{ub} and helicity
  - very precise theory prediction, $BR = (3.8 \pm 0.4) \times 10^{-7}$
  - PDG $BR(\ell = \mu) < 8.6 \times 10^{-7}$ @ 90% CL

    $BR(\ell = e) < 9.8 \times 10^{-7}$ @ 90% CL



Test the SM

Measure V_{ub}

Search for H^+ and LQ

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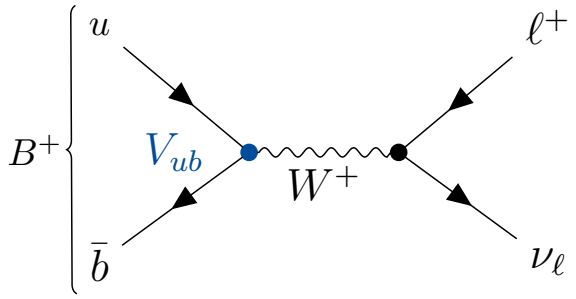
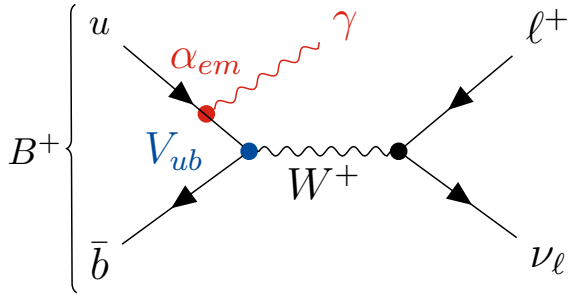


Test the SM

Measure V_{ub}

Search for H^+ and LQ

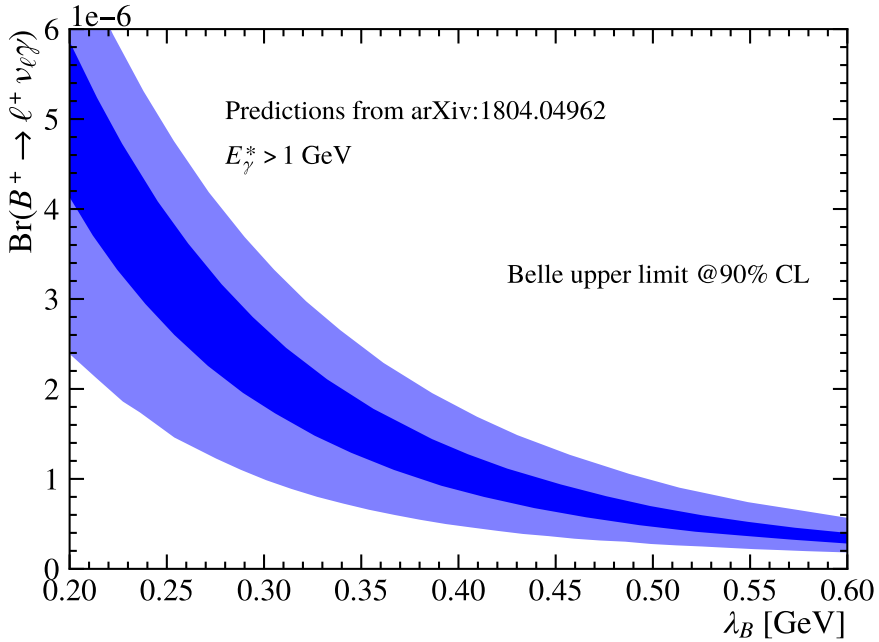
- $B^+ \to \ell^+ \nu_\ell \gamma$ decay
  - suppressed by V_{ub} and α_{em}
  - dependence on $B \to \gamma$ form factors, $BR \simeq 2 \times 10^{-6}$
  - PDG $BR(\ell = \mu) < 3.4 \times 10^{-6}$ @ 90% CL
    $BR(\ell = e) < 4.3 \times 10^{-6}$ @ 90% CL



Study B mesons

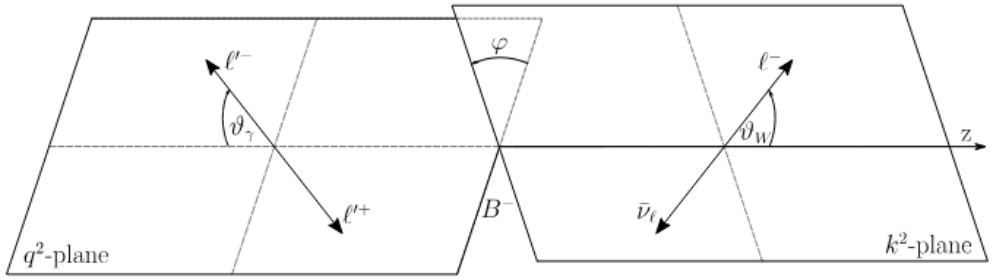
Motivation

- $B^+ \to \ell^+ \nu_\ell \gamma$ golden mode to probe B sub-structure
- Never been observed, Upper Limit by Belle
  - $BR(B^+ \to \ell^+ \nu_\ell \gamma) < 3.0 \times 10^{-6}$ @ 90% CL [PRD 98 (2018) 11, 112016]
- At 1st order $BR(B^+ \to \ell^+ \nu_\ell \gamma) \propto \lambda_B^{-1}$,
  with λ_B first inverse moment of B-meson
  Light-Cone Distribution Amplitude (LCDA) [Eur.Phys.J.C 71 (2011) 1818]
  - crucial theory input [PRD 69 (2004) 034014] [Nucl.Phys.B 832 (2010) 109-151] [PLB 848 (2024) 138345]
  - calculations of non-leptonic and non-perturbative B decays (QCD factorisation)

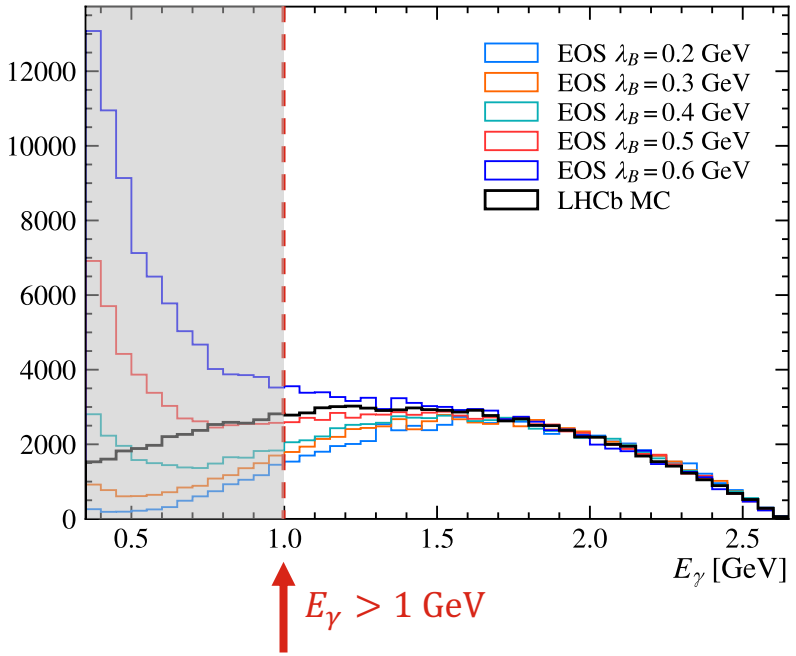


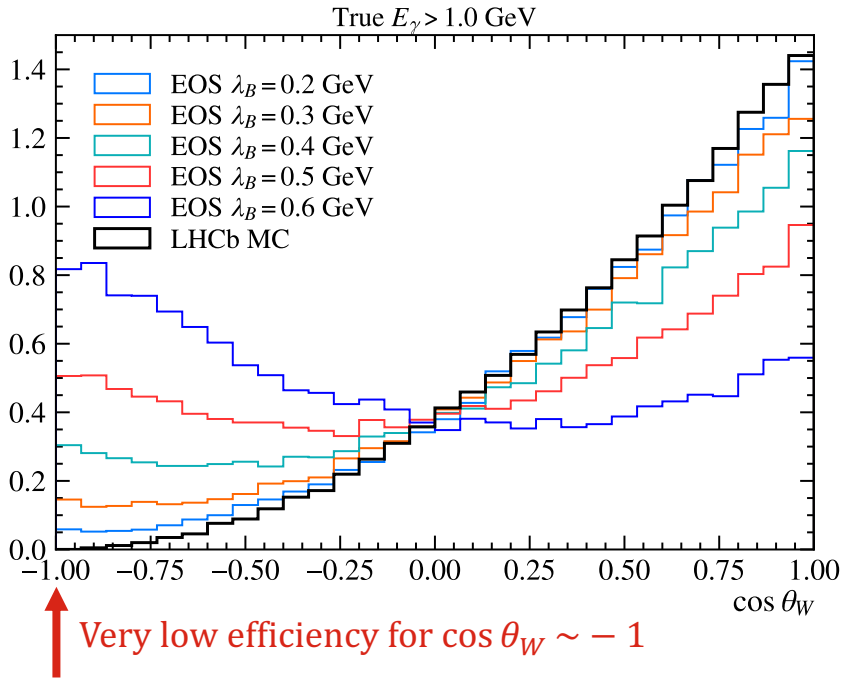
Model dependence

- Three-body decay described by E_γ and $\cos\theta_W$
  - θ_W angle between ℓ^+ and B^+ flight direction
- Strong dependence of E_γ and $\cos\theta_W$ on λ_B



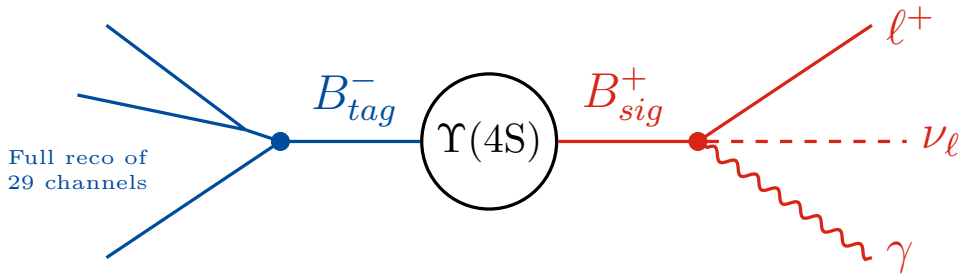
[PRD 107 (2023) 5, 053006]





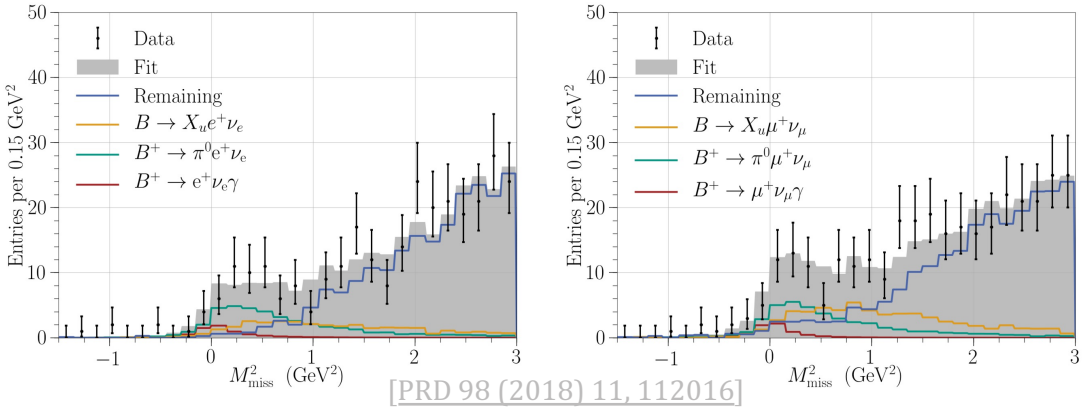
Reconstruction strategies

Belle



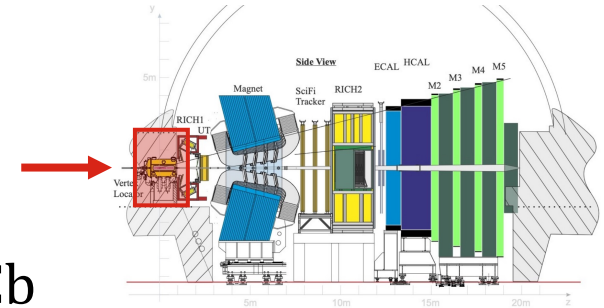
Full reconstruction of B^-_{tag} with $\varepsilon \simeq 0.8\ \%$

$$p_{B^+_{sig}} = \left(\frac{\sqrt{s}}{2}, -\vec{p}_{B^-_{tag}}\right) \qquad M^2_{miss} = p^2_\nu = \left(p_{B^+_{sig}} - p_\ell - p_\gamma\right)^2$$



[PRD 98 (2018) 11, 112016]

Reconstruction strategies



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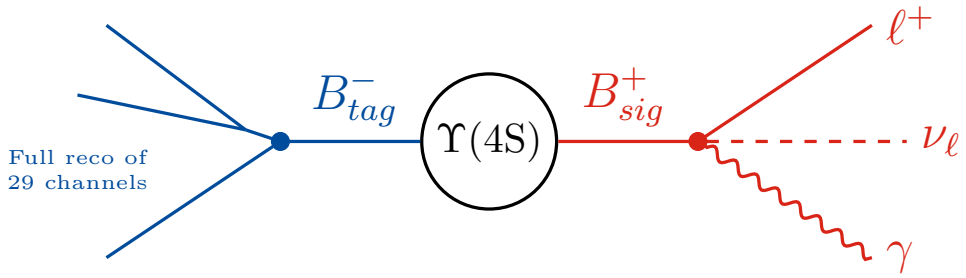

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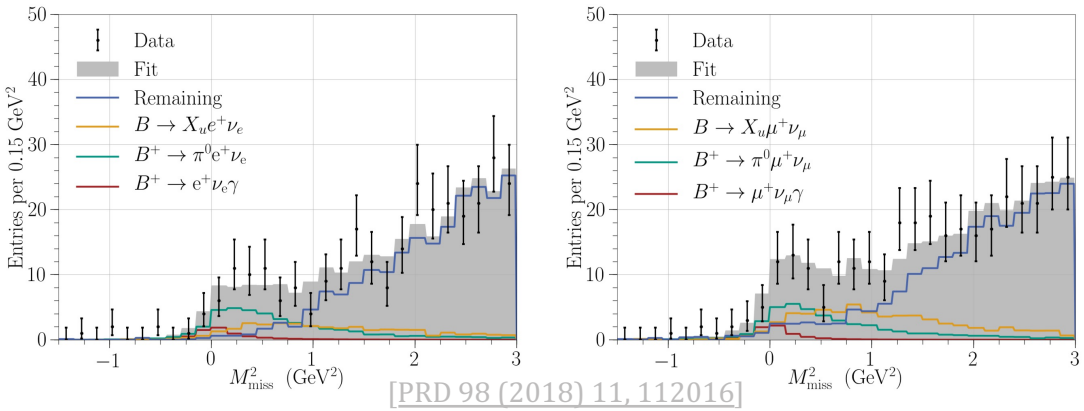
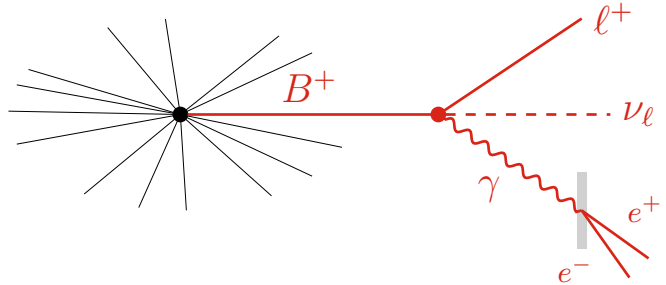


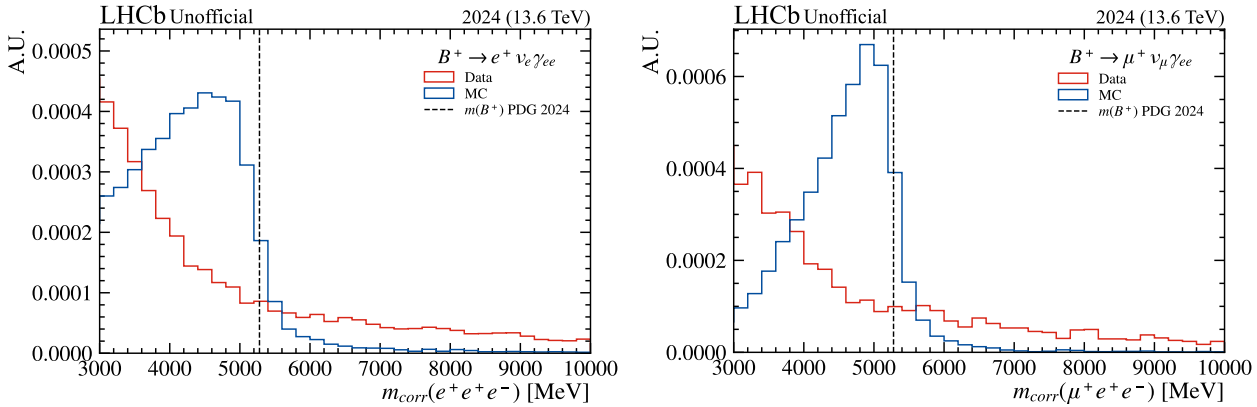
[PRD 98 (2018) 11, 112016]

LHCb



$\gamma \to e^+e^-$ conversions in material $\to B^+$ displaced vertex

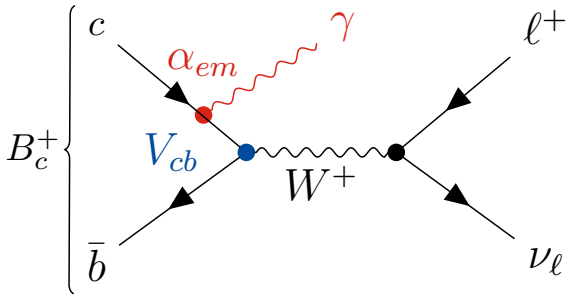
$$m_{corr}(\ell^+e^+e^-) = \sqrt{m^2_{visible}(\ell^+e^+e^-) + p^2_\perp} + p_\perp$$



Very preliminary! No offline selection applied → backgrounds dominate

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

- B_c^+ channel comes (almost) for free and
  - it is exclusively accessible at LHCb
  - it has never been searched for, μ^+-channel for first time with Run 2 data (stay tuned!)

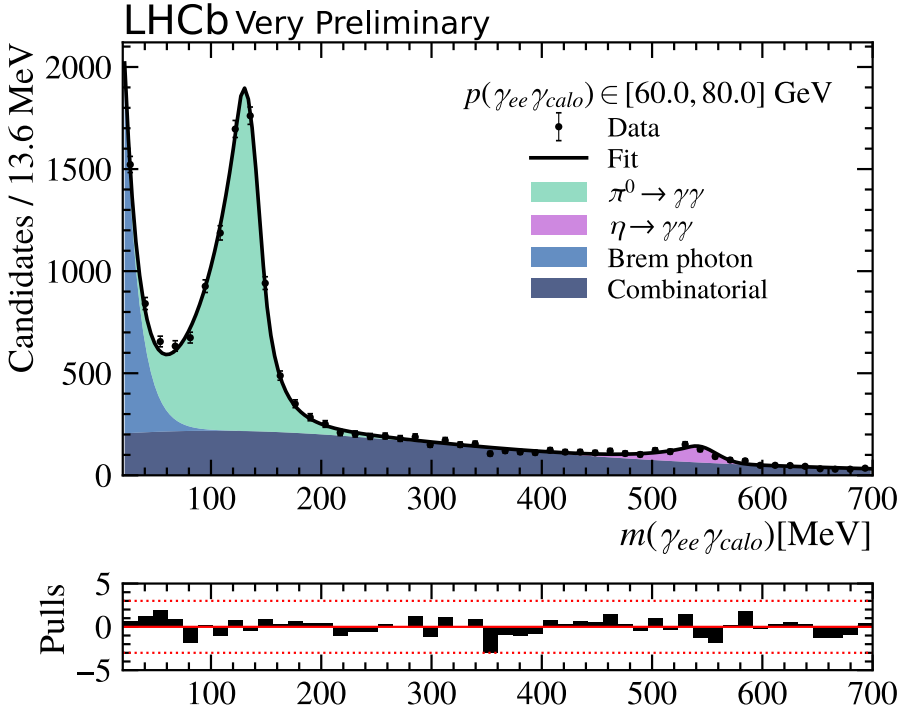


- Lower efficiency due to $\tau(B_c^+) \simeq 0.3 \times \tau(B^+)$
- Smaller cross section, but CKM favoured thanks to $\frac{f_c}{f_u} \simeq \frac{|V_{cb}|^2}{|V_{ub}|^2} \to$ similar rate as B^+
- Much lower background

Background modelling

- Boosted Decision Trees for background classification
  1. combinatorial → random ℓ^+-γ_{ee} combinations
  2. charged isolation → additional charged tracks
  3. neutral isolation → $\pi^0/\eta \to \gamma_{ee}\gamma_{calo}$

- Main contributions from $\pi^0/\eta \to \gamma_{ee}\gamma_{calo}$
  with γ_{calo} additional calorimetric photon
  → data-driven templates, also for μ^+/e^+ misID

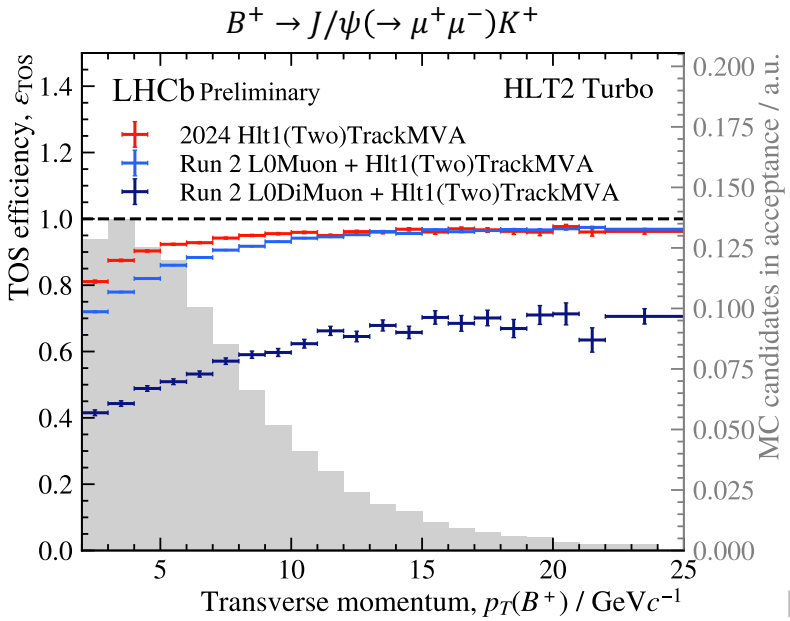


Run 3 news: electron channel

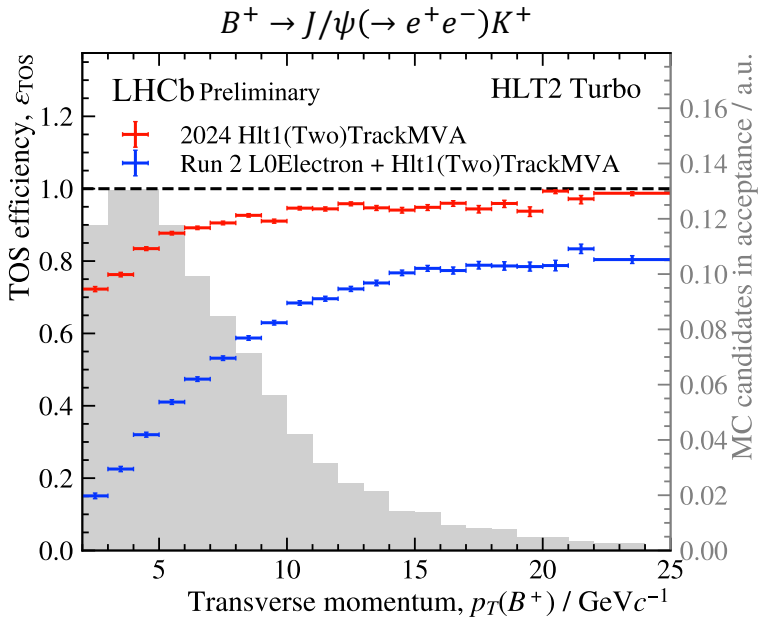
- $e^{\pm}$ reconstruction efficiency: in Run 2 the bottleneck was hardware trigger (L0)

  → removed in Run 3

  → increase in statistics with electron channel



[LHCb-FIGURE-2024-030]



Conclusions

- First search for $B^+_{(c)} \to \ell^+ \nu_\ell \gamma$ at LHCb
  - μ^+-channels with Run 2 data
  - e^+-channels added in Run 3 analysis
- Reconstruction strategy possible and competitive
  - $\gamma \to e^+e^-$ to get B^+ displaced vertex
  - data-driven technique to get backgrounds
- Run 2 sensitivity compatible with current world-best limit
- Prospects:
  - first observation possible with Run 3 → measurement of BR
  - combined results from LHCb+Belle2 expected to provide clean experimental constraints to λ_B
  - measurement of λ_B expected to improve QCD-factorisation predictions for several B-meson decay channels

Thank you!

Back-up slides

$BR(B^+ \to \ell^+ \nu_\ell \gamma)$ depends on λ_B

$$\frac{d\Gamma(B^+ \to \ell^+ \nu_\ell \gamma)}{E_\gamma^*} = \frac{\alpha_{em} G_F^2 |V_{ub}|^2}{6\pi^2} m_B E_\gamma^{*3} \left(1 - \frac{2E_\gamma^*}{m_B}\right)\left(|F_V|^2 + \left|F_A + \frac{e_\ell f_B}{E_\gamma^*}\right|^2\right)$$

$$E_\gamma^* > 1\ GeV \quad \to \quad \begin{aligned} F_V(E_\gamma^*) &= \frac{e_u f_B m_B}{2E_\gamma^* \lambda_B(\mu)} R(E_\gamma^*, \mu) + \xi(E_\gamma^*) + \Delta\xi(E_\gamma^*) \\ F_A(E_\gamma^*) &= \frac{e_u f_B m_B}{2E_\gamma^* \lambda_B(\mu)} R(E_\gamma^*, \mu) + \xi(E_\gamma^*) - \Delta\xi(E_\gamma^*) \end{aligned}$$