Measurement of $B^0 \to \rho^0\gamma$ branching fraction at LHCb

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Outline

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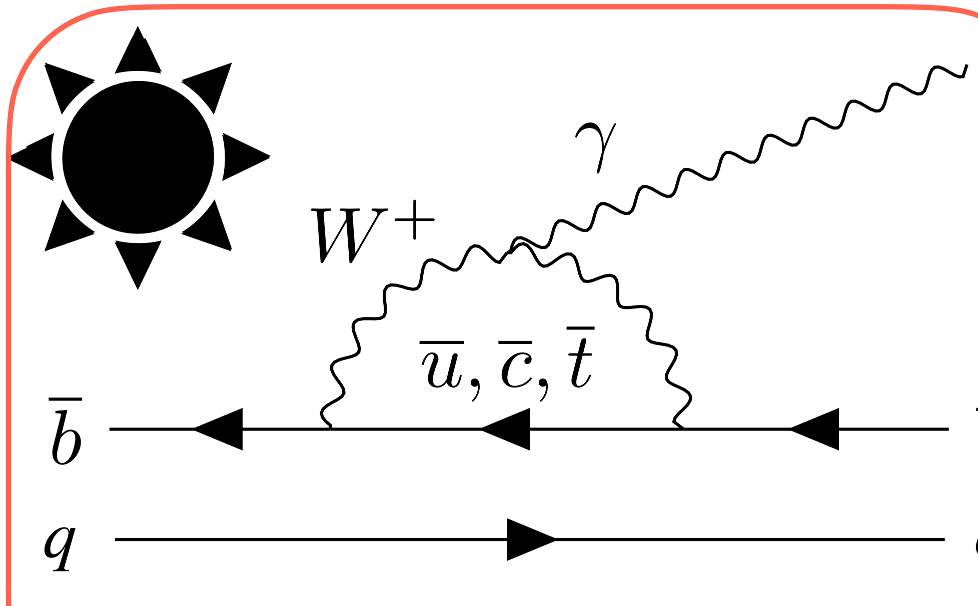
- Previous measurements
- Analysis overview
- Charge and neutral PID
- MC reweighting
- Multivariate analysis
- Background estimations
- Fit validation
- Conclusions

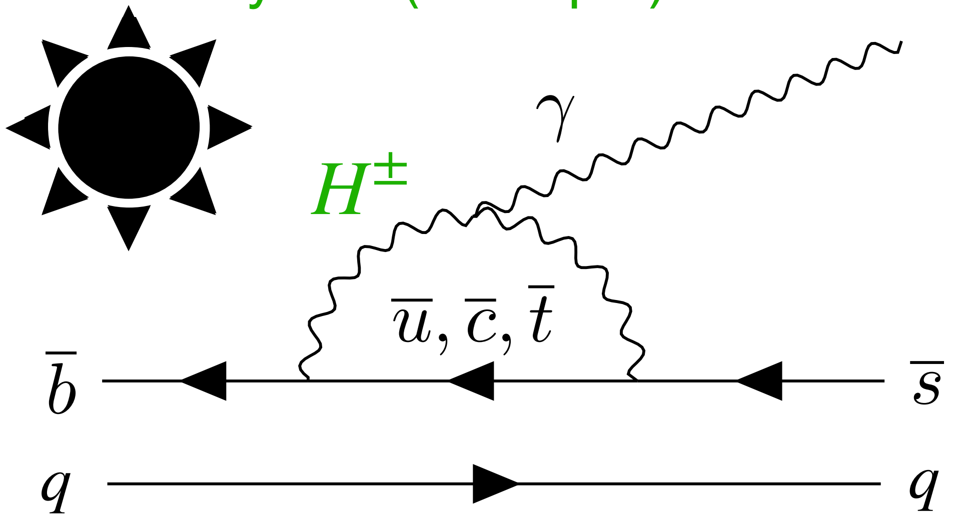
Motivation

- Rare B-decays:
  - Flavour Changing Neutral Currents (FCNC): $b \rightarrow s(d)\gamma$
    - Proceed at the loop-level → very suppressed in the SM
    - Low BF's due to CKM and GIM suppression decays
  - Very sensitive to NP since SM contribution is small!



radiative electroweak penguin decays

New Physics (example)



Motivation

- Search for NP using $b \to d\gamma$ transition
- Measure branching fraction of $B^0 \to \rho^0\gamma$ using $B^0 \to K^{*0}\gamma$ as reference channel
  - Well observed channel with large statistics
  - Most of the systematics cancels out in the ratio
  - Allow to test the SM consistency

$$\frac{\mathcal{B}(B^0 \to \rho^0\gamma)}{\mathcal{B}(B^0 \to K^{*0}\gamma)} \propto \left|\frac{V_{td}}{V_{ts}}\right|^2$$

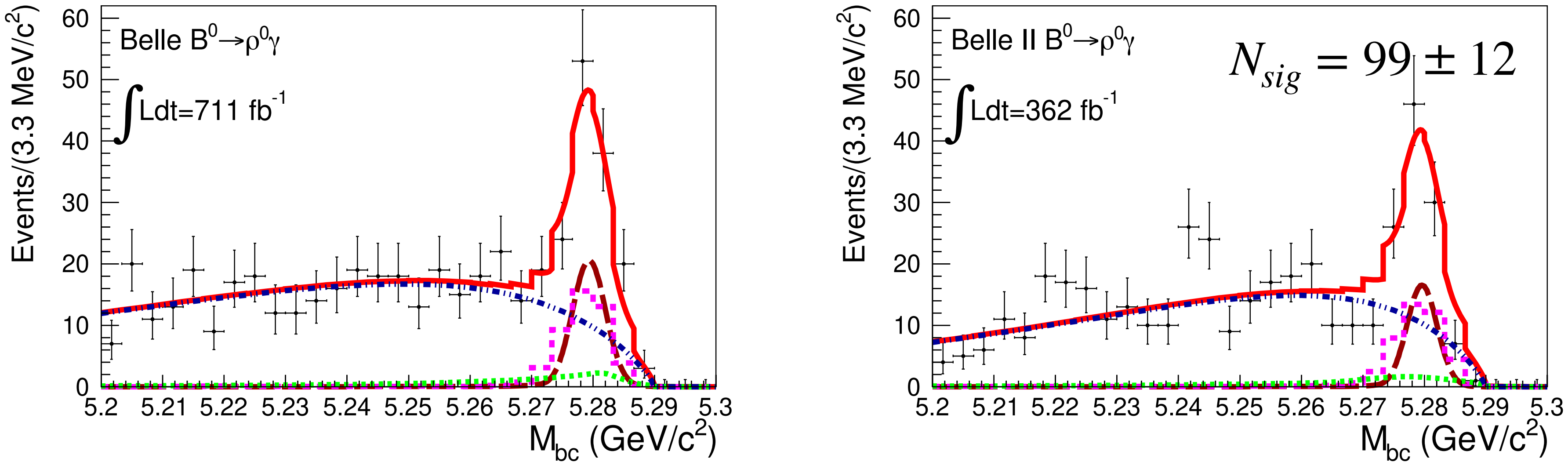
- Experimentally

$$\frac{\mathcal{B}(B^0 \to \rho^0\gamma)}{\mathcal{B}(B^0 \to K^{*0}\gamma)} = \mathcal{B}(K^{*0} \to K^+\pi^-) \underbrace{\frac{N_{\rho^0\gamma}}{N_{K^{*0}\gamma}}}_{\text{Unbinned maximum likelihood fit to data}} \overbrace{\frac{\epsilon^{K^{*0}\gamma}}{\epsilon^{\rho^0\gamma}}}^{\text{Simulation sample}}$$

  - In the ρ^0 region defined as $m_{\pi\pi} \in (630,\ 920)$ MeV/c^2 (similar to Babar and Belle)
  - First measurement by LHCb using Run 1 + 2 data (9 fb^{-1})

Previous measurements

- First studied in Belle [PRL 101, 111801] and Babar [PRD 78, 112001]
- Recent analysis based on Belle (711 fb^{-1}) + Belle II (362 fb^{-1}) data
- Measured branching fraction of $B^0 \to \rho^0\gamma$ and it's isospin companion $B^+ \to \rho^+\gamma$
- In addition to that, isospin asymmetry $A_I(B \to \rho\gamma)$ and CP asymmetry $A_{CP}(B^+ \to \rho^+\gamma)$



ArXiv: 2407.08984
Submitted to PRD

$$\begin{aligned}
\mathcal{B}\left(B^+ \to \rho^+\gamma\right) &= \left(13.1^{+2.0+1.3}_{-1.9-1.2}\right) \times 10^{-7} \\
\mathcal{B}\left(B^0 \to \rho^0\gamma\right) &= \left(7.5 \pm 1.3^{+1.0}_{-0.8}\right) \times 10^{-7} \\
A_{CP}\left(B^+ \to \rho^+\gamma\right) &= \left(-8.2 \pm 15.2^{+1.6}_{-1.2}\right) \% \\
A_{\mathrm{I}}\left(B \to \rho\gamma\right) &= \left(10.9^{+11.2+6.8+3.8}_{-11.7-6.2-3.9}\right) \%,
\end{aligned}$$

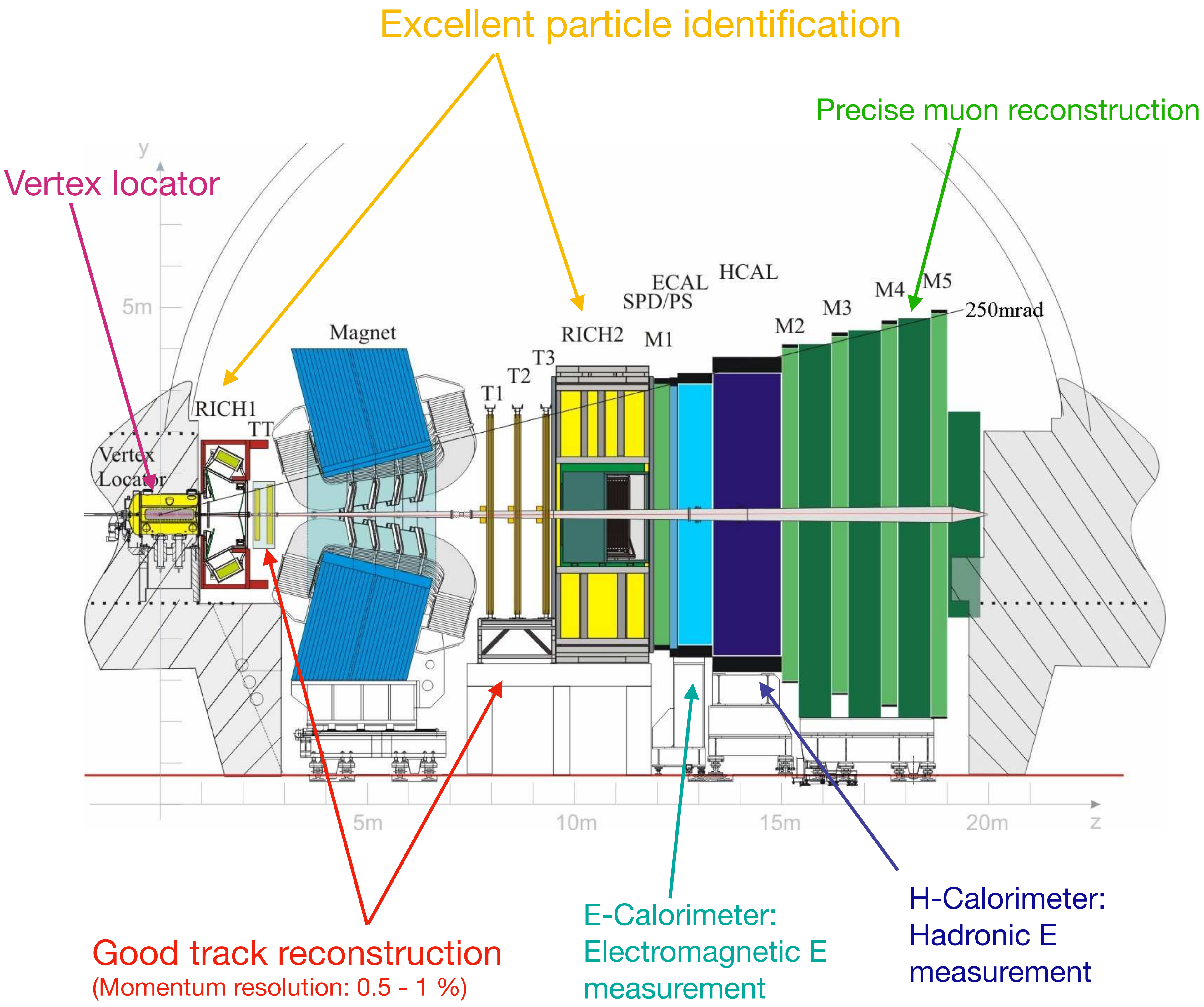
$$\mathscr{B}(B^0 \to \rho^0\gamma)_{PDG} = (8.6 \pm 1.5) \times 10^{-7}$$

- The latest combination by HFLAV results

$$\mathscr{B}(B^0 \to \rho^0\gamma) = (8.2 \pm 1.3) \times 10^{-7}$$

LHCb detector

JINST 3(2008) S08005



Excellent particle identification

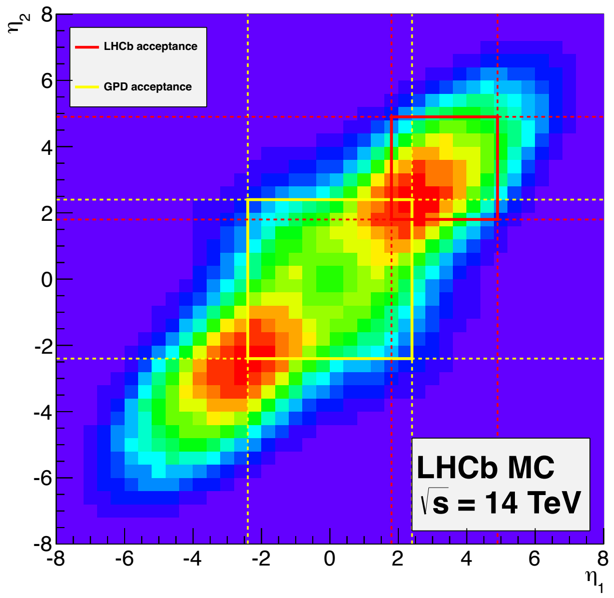
Precise muon reconstruction

Vertex locator

Good track reconstruction
(Momentum resolution: 0.5 - 1 %)

E-Calorimeter:
Electromagnetic E
measurement

H-Calorimeter:
Hadronic E
measurement



- Accelerator: LHC
- Forward-looking spectrometer for b and c meson studies
- Periods: 2011-12 and 2015-18
- Acceptance: $2 < \eta < 5$
- All species of B hadrons
- $\sigma(b\bar{b})_{7\ TeV} = 252\ \mu b$
- $\sigma(b\bar{b})_{13\ TeV} = 590\ \mu b$

Analysis overview

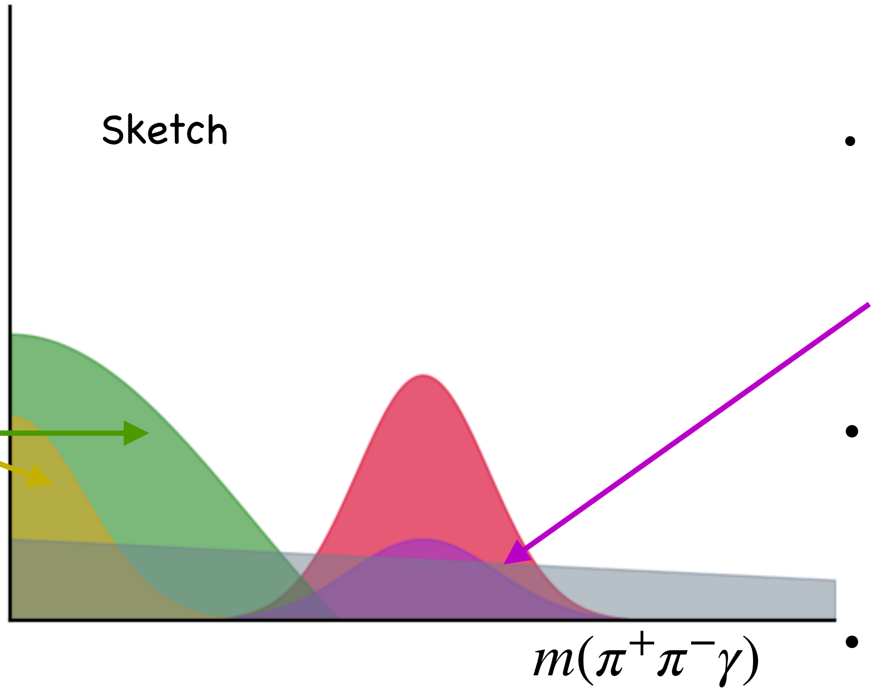
Signal

- Two displaced tracks along with one neutral photon

Partially reconstructed bkg.

- Missing one and two pions

$$B^0 \to hh\pi^{0(+)}\gamma,$$
$$B^0 \to hh\pi^{0(+)}\pi^{0(+)}\gamma$$



Combinatorial background

- Random combination of pions and photon

Peaking backgrounds

- $B \to hh'\gamma$ cross-feed ($K\pi, KK, pK$): single or double mis-identification of hadrons as pion
- $B \to hh'\pi^0$: if both γ's end up in the same cluster

- Combinatorial backgrounds are suppressed using multivariate classifier
- Peaking backgrounds are controlled by charged and neutral PID criteria

- Blind analysis: to keep the analysis unbiased, the data on the signal mass region is not seen until the full strategy is defined
- All the validations are performed using $B^0 \to K^{*0}\gamma$ control channel

Charged PID

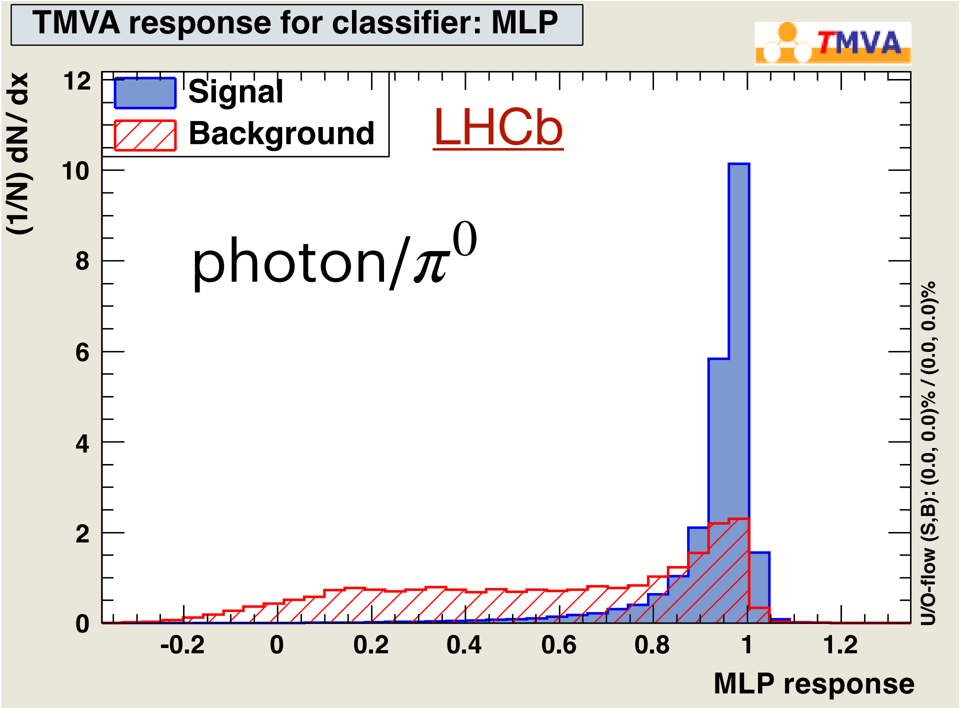
- Charged particle identification is important to control the mis-identified backgrounds in the signal region
- For particle identification, LHCb uses two RICH systems, calorimeters and muon chambers
- PID informations are combined in a multivariate classifier based on neural network
- PID performance are checked using high statistics samples in data: $K^0_S \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow \mathrm{p}\pi^-$, $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+$
- In this analysis, PID optimisation is performed by maximising the signal significance
  - In this optimisation, the backgrounds are estimated from different possible misidentified backgrounds like $B^0 \rightarrow K^+\pi^-\gamma$, $\Lambda^0_b \rightarrow pK^-\gamma$ and $B^0_s \rightarrow K^+K^-\gamma$

$B^0 \rightarrow K^{*0}\gamma$	
$\epsilon^{PID}(K\pi \rightarrow K\pi)$	$\sim 90~\%$
$\epsilon^{PID}(KK \rightarrow K\pi(\pi K))$	$\sim 4~\%$
$\epsilon^{PID}(pK \rightarrow K\pi)$	$< 0.5~\%$

$B^0 \rightarrow \rho^0\gamma$	
$\epsilon^{PID}(\pi\pi \rightarrow \pi\pi)$	$\sim 75~\%$
$\epsilon^{PID}(K\pi(\pi K) \rightarrow \pi\pi)$	$\sim 0.5~\%$
$\epsilon^{PID}(Kp(pK) \rightarrow \pi\pi)$	$< 0.01~\%$
$\epsilon^{PID}(KK \rightarrow \pi\pi)$	$< 0.01~\%$

Neutral PID

- Neutral PID algorithm are based on multivariate classifiers using sub-detector information from calorimeter system
  - Three different Neural Network are trained to separate between photon/hadron, photon/electron and photon/π^0 separation



- Calibration samples: $B^0 \to K^*(K^+\pi^-)\gamma$, $D^{*+} \to D^0(K^-\pi^+\pi^0)\pi^+$

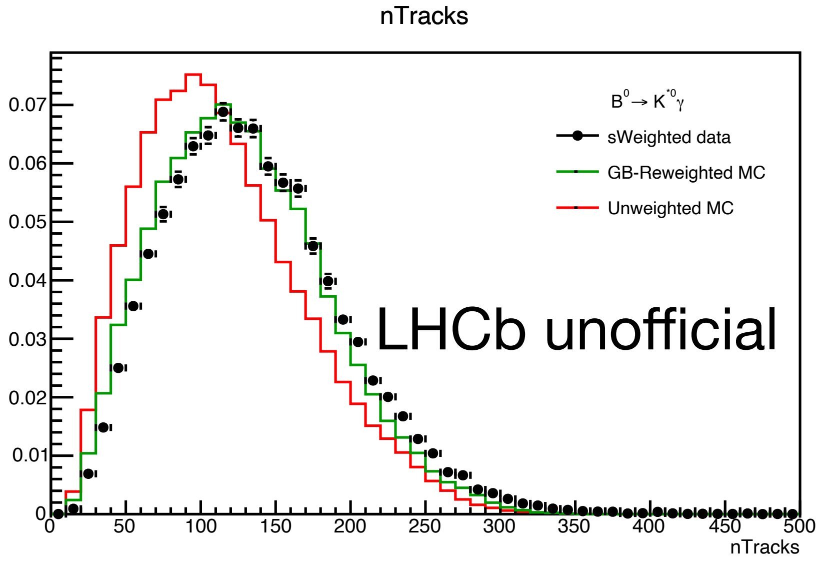
- For what concerns the photon/π^0 separation, a cut at 0.6 gives 95 % efficiency for $B^0 \to K^*\gamma$ and 50 % for $D^0 \to K^-\pi^+\pi^0$

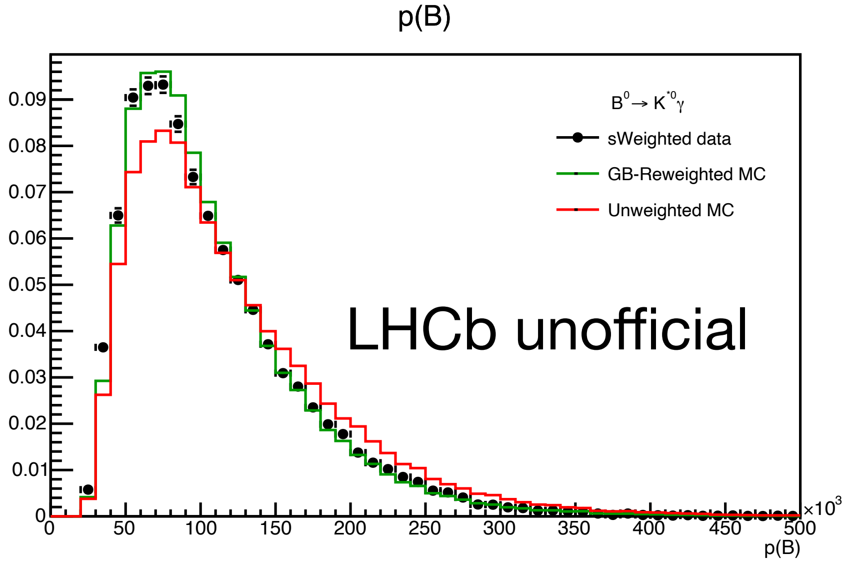
- Charmless $B^0 \to \pi^+\pi^-\pi^0$ decay is the most dangerous background
  - Dominant intermediate states $B^0 \to \rho^\pm(\to \pi^\pm\pi^0)\pi^\mp$ are removed by the anti-charm veto ($m_{h^\pm(\gamma\to\pi^0)} > 2000$ MeV/c^2)
  - Left with $B^0 \to \rho^0\pi^0$ which has a poorly measured branching fraction: $(2.0 \pm 0.5) \times 10^{-6}$

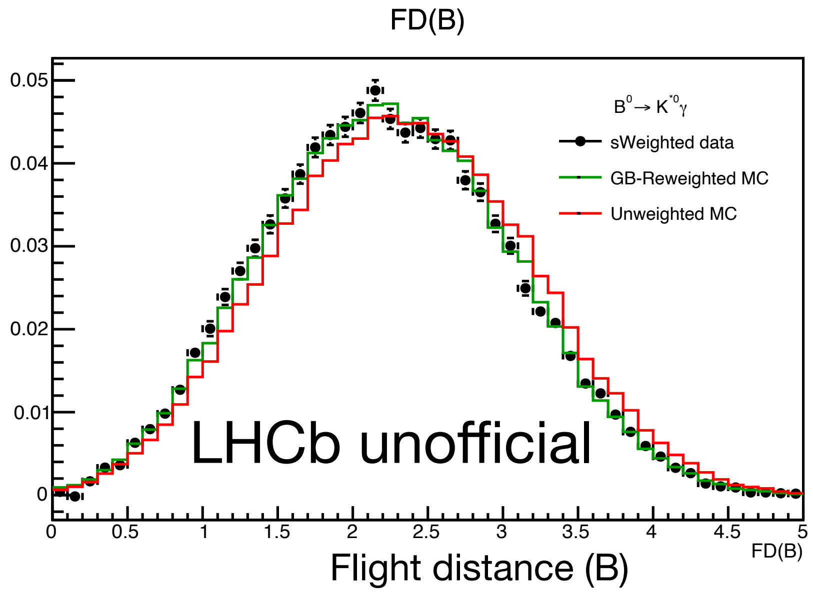
- In the analysis, the photon/π^0 neutral PID cut is optimised - after BDT - by minimising the signal relative uncertainty (taking into account BF unc.)

MC reweighting

- Comparison between sWeighted $B^0 \to K^{*0}\gamma$ and MC shows disagreement in different decay kinematics (after preselection and PID cuts) which will affect the MVA training
- A separate multivariate classifier is trained to correct the simulated sample: Gradient Boosted (GB) Reweighter
- List of input variables used in the GB Reweighter: nTracks, kinematics of B, Isolation of B
- After correction the agreement in the different variables is satisfactory
- The same weights are applied on the $B^0 \to \rho^0\gamma$ MC sample





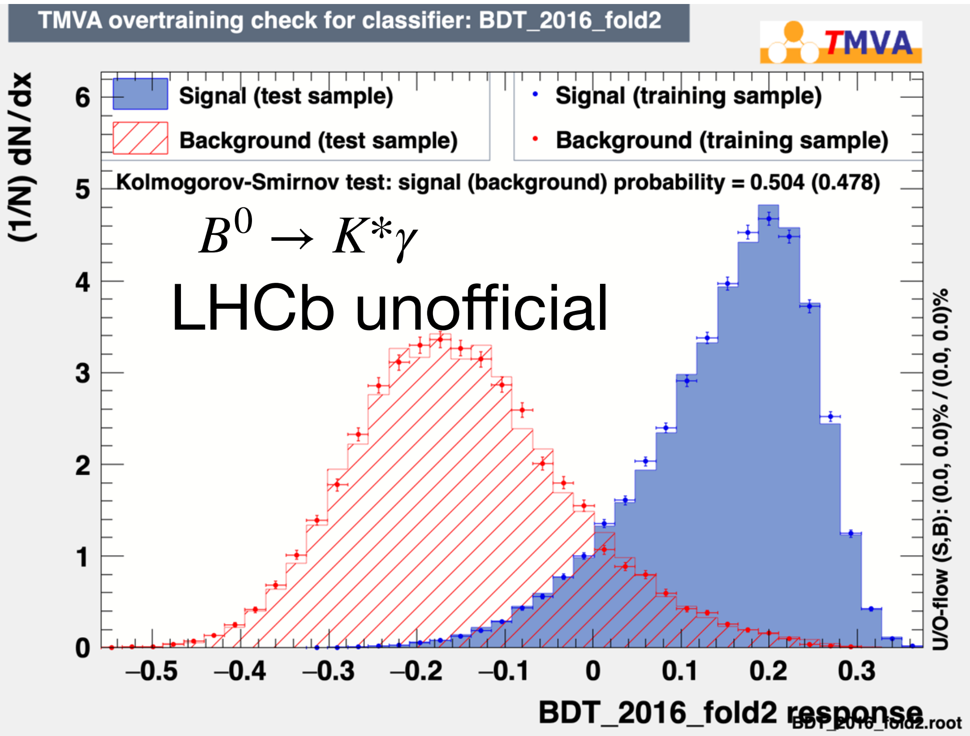


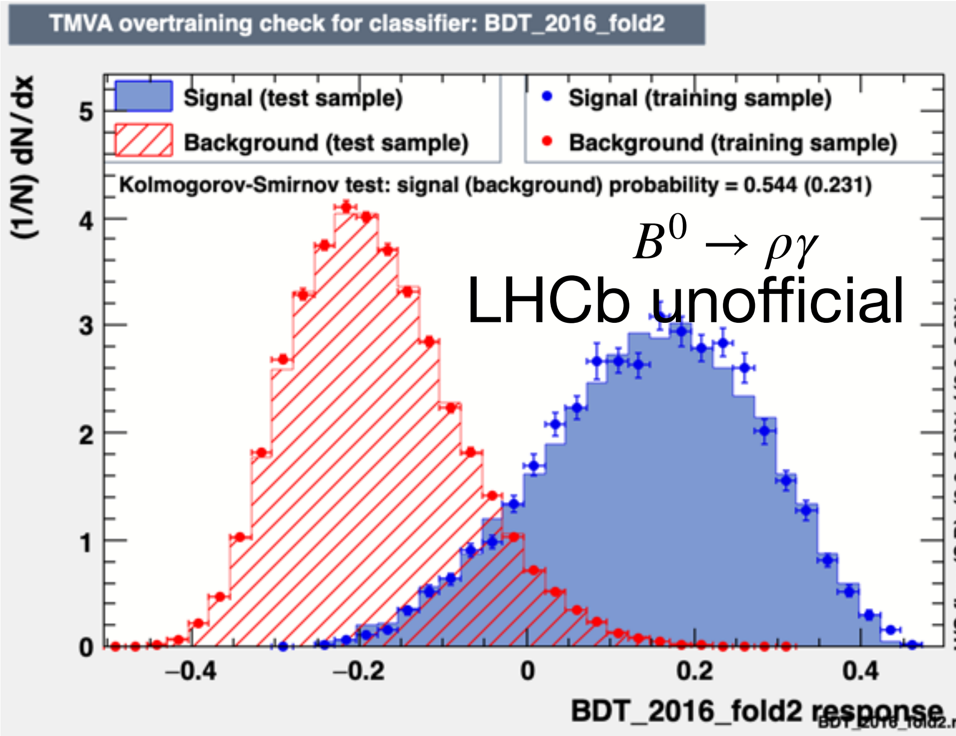
BDT training

- To reduce the combinatorial background, Boosted Decision Trees (BDT) are trained using signal/control MC samples and the corresponding high mass sideband data as background proxies
  - Two BDTs, one for $B^0 \to \rho^0\gamma$, another for $B^0 \to K^{*0}\gamma$
- Input variables: nTracks, kinematics of B mesons, isolation of daughters and intermediate resonances

- Optimisation

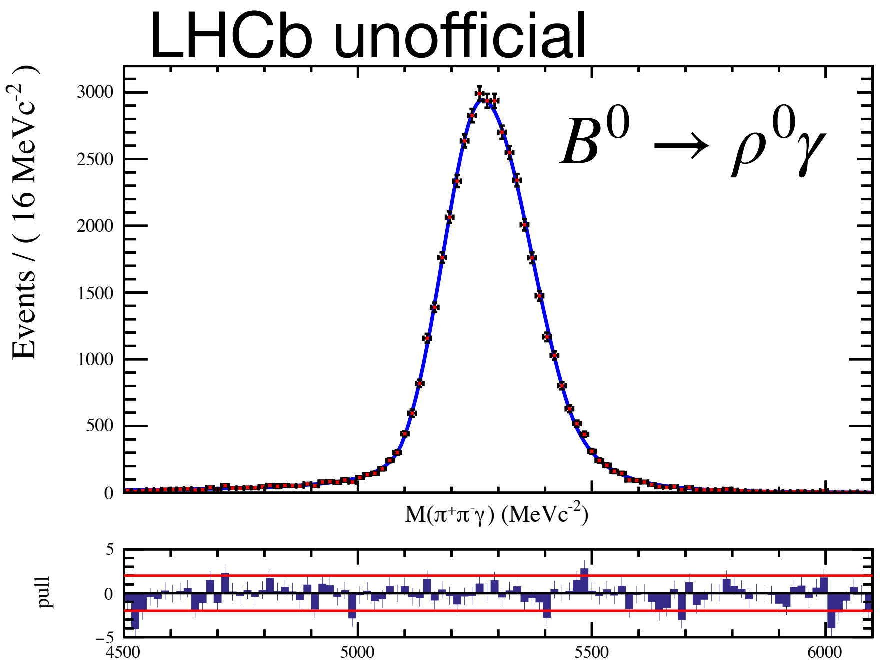
$$FoM(BDT) = \frac{S}{\sqrt{S+B}}$$



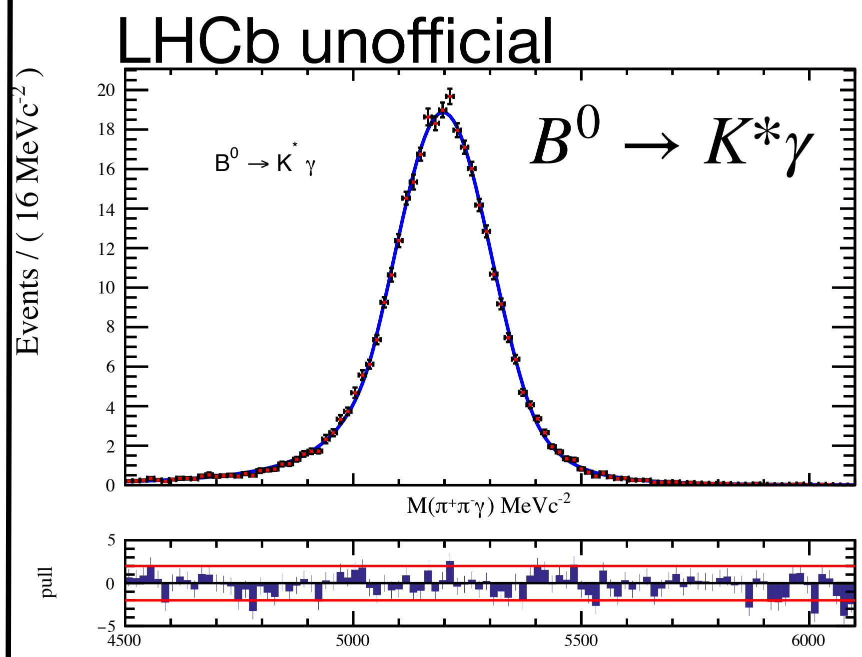


- B: expected combinatorial background in the signal region, scaled from high mass sideband

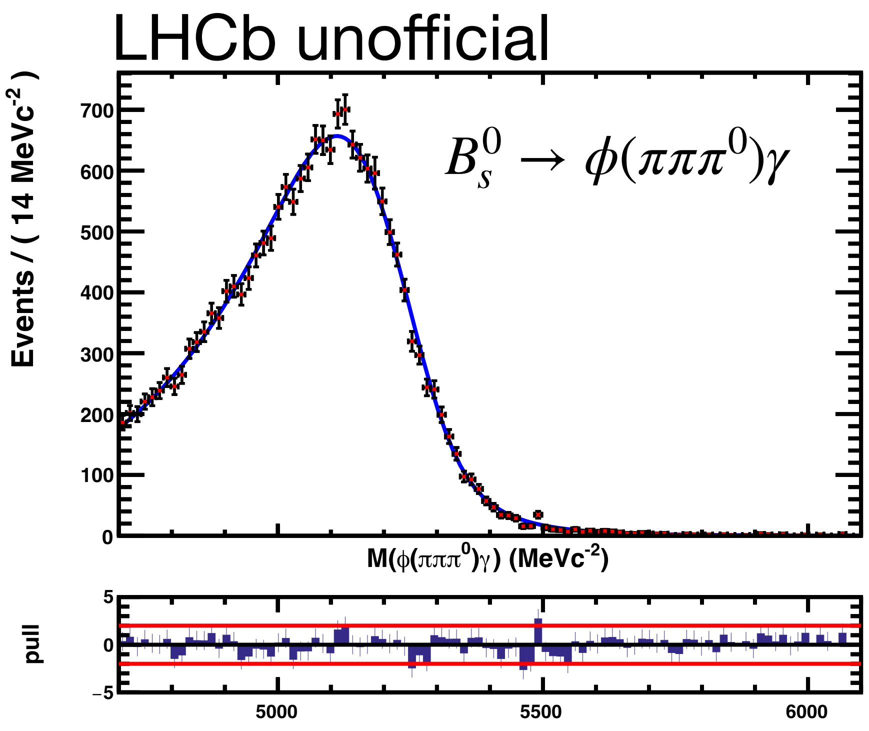
Fit to simulations



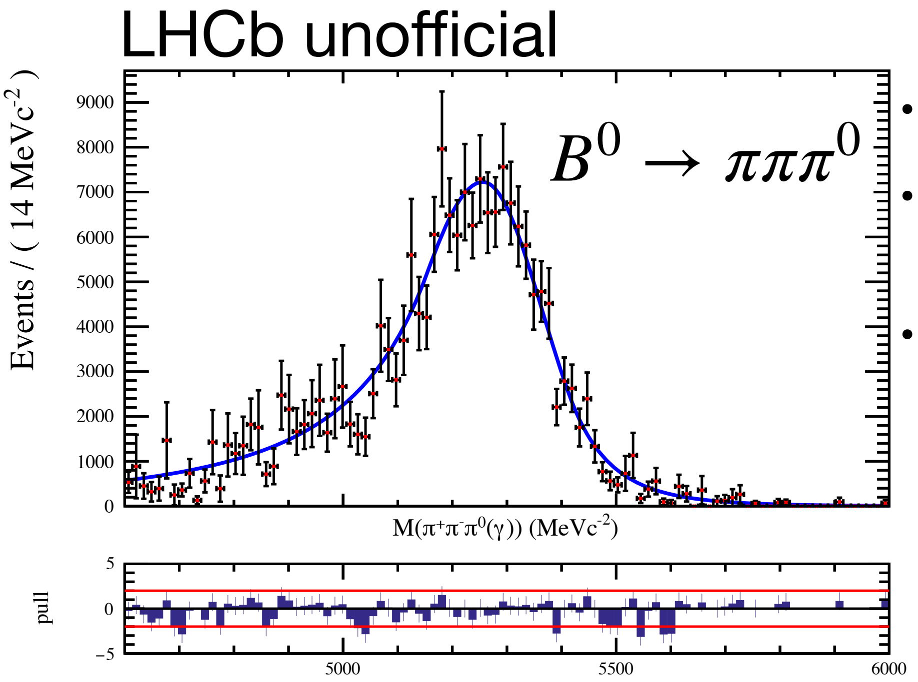
- Signal distribution
- Model with double sided Crystal-Ball function



- Mis-identified bkg. distribution
- Peaking close to signal
- Model with double sided Crystal-Ball function



- One π^0 missing background
- Wider distribution than peaking
- Model with Argus function



- Photon from π^0
- Peaking close to signal
- Model with double sided Crystal-Ball function

Background estimations

- The relative background contaminations are estimated using

$$C^{signal}_{H_b\to Z} = \frac{\mathcal{B}(H_b \to Z)}{\mathcal{B}(signal)} \frac{f_{H_b}}{f_d} \frac{\epsilon^{H_b\to Z}}{\epsilon^{signal}}$$

$$\epsilon = \epsilon^{Acc}\epsilon^{presel}\epsilon^{BDT}\epsilon^{PID(hh)}\epsilon^{PID(\gamma)}$$

PRD 104, 032005 (2021)

$$\frac{f_s}{f_d} = 0.254 \pm 0.0079 \text{ @ } 13 \text{ TeV}$$

$$= 0.239 \pm 0.0076 \text{ @ } 7 \text{ TeV}$$

$$= 0.2385 \pm 0.0075 \text{@ } 8 \text{ TeV}$$

$B^0 \to K^{*0}\gamma$

$H_b \to Z$	$\bar{\mathcal{C}}^{B^0\to K^{*0}\gamma}_{H_b\to Z}$
$B^0 \to K^*\eta$	~ 2 %
$B^0 \to K\pi\pi^0$	~ 2 %
$\Lambda_b \to \Lambda^*\gamma$	~ 1 %
$B^0_s \to \phi\gamma$	< 1 %
$B^0_s \to K^*\gamma$	~ 1 %

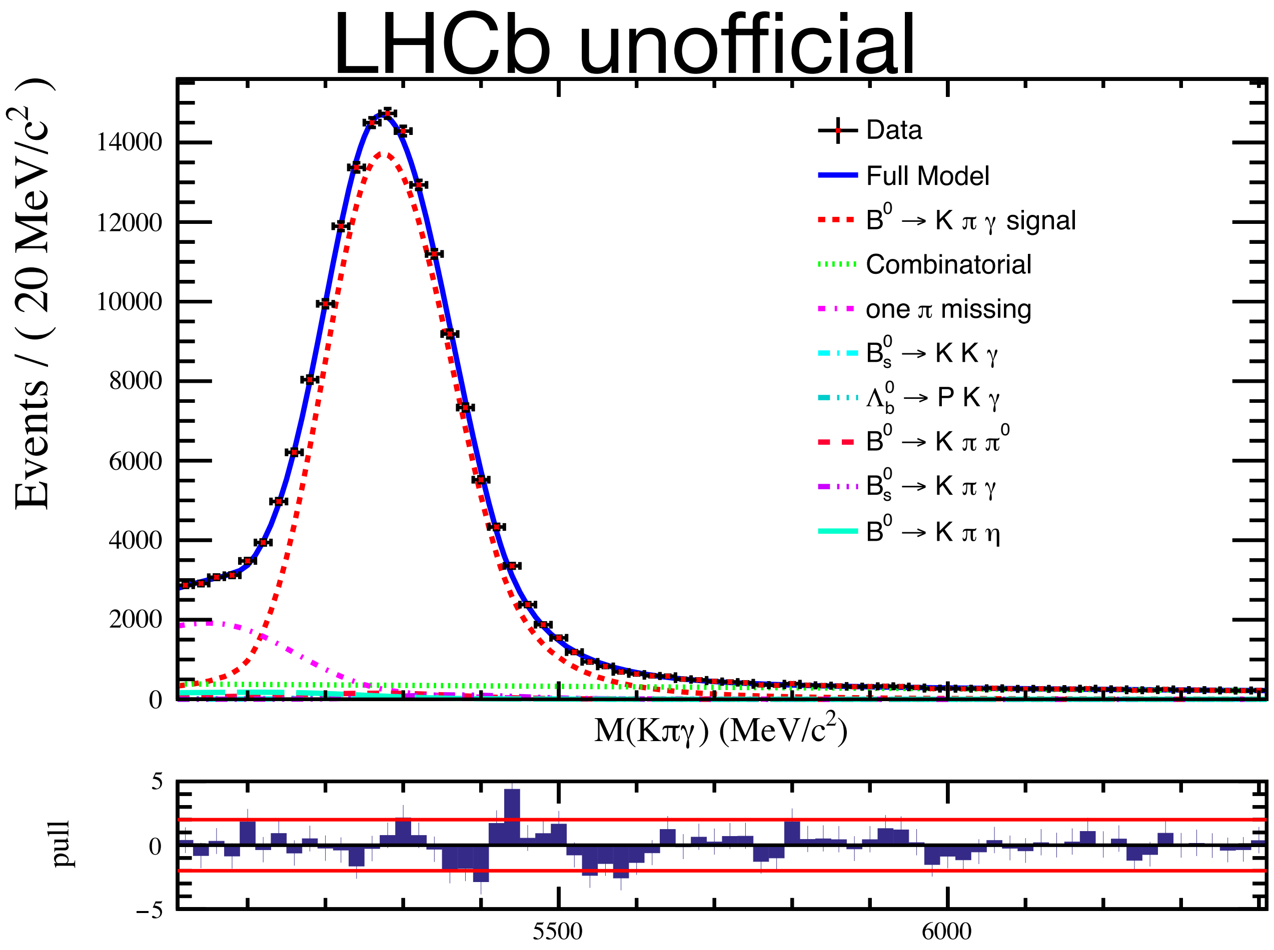
$B^0 \to \rho^0\gamma$

$H_b \to Z$	$\bar{\mathcal{C}}^{B^0\to \pi^+\pi^-\gamma}_{H_b\to Z}$
$B^0 \to K^*\gamma$	~ 10 %
$B^0 \to \pi\pi\pi^0$	~ 10 %
$B^0_s \to \phi(\pi\pi\pi^0)\gamma$	~ 15 %
$B^0 \to \rho\eta$	< 1 %

- Other backgrounds are studied and found to be negligible
- Dominant background for $B^0 \to \rho^0\gamma$ are misidentified $B^0 \to K^{*0}\gamma$, $B^0 \to \pi\pi\pi^0$ and $B^0_s \to \phi(\to \pi\pi\pi^0)\gamma$

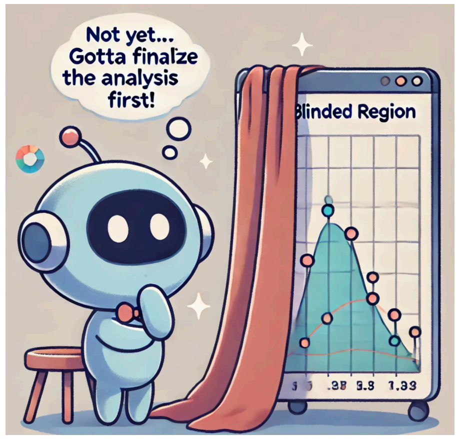
Data fit

- A simultaneous unbinned maximum likelihood fit to the invariant-mass distributions in $K\pi\gamma$ and $\pi\pi\gamma$ modes



- Few signal shape parameters are shared between $B^0 \to \pi\pi\gamma$ and $B^0 \to K\pi\gamma$ and others are fixed from simulation
- Partially reconstructed background: one missing-pion
  - Fixed slopes (from MC), floated curvatures, floated yields
- Combinatorial background: first order polynomial with floated slopes and yields
- Peaking backgrounds
  - Shapes from MC, yields fixed using $K^*\gamma$ yield as normalisation for both $\pi\pi\gamma$ and $K\pi\gamma$

- Projection for signal mode is blinded (few thousand $\rho^0\gamma$ events expected)



Status

- All the necessary pre-unblinding studies are performed

  - ✓ Selection strategy
  - ✓ PID optimisation
  - ✓ Analysis MVA training and optimisation
  - ✓ Background modelling and its estimations
  - ✓ Bias study due to model with huge toys
  - ✓ Systematic studies (being finalised) ☞

➡ Analysis currently in review process and waiting for unblinding

Conclusions

- FCNC's are attractive to probe SM and physics beyond
- Radiative b-hadron decays provides sensitive to new physics
- Thanks to high statistics, LHCb is competitive to study those decays
  - First LHCb measurements related to $b \to d\gamma$ are in the horizon

- Run 3 is providing more statistics (> 9 fb^{-1} in 2024), it will further reduce the uncertainty on different observables and also allow to study even further rare decays

Exciting results are coming soon…