The first angular analysis of the $B^+ \to \pi^+\mu^-\mu^+$ decay using Run I and Run II data at the LHCb experiment

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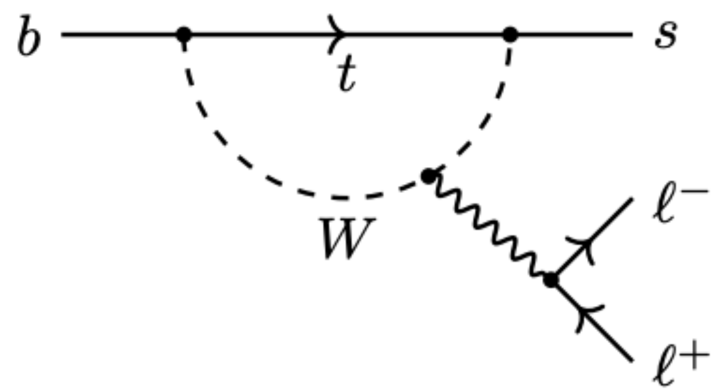
On behalf of the LHCb Collaboration

IOP Joint APP, HEPP and NP Conference April 2021

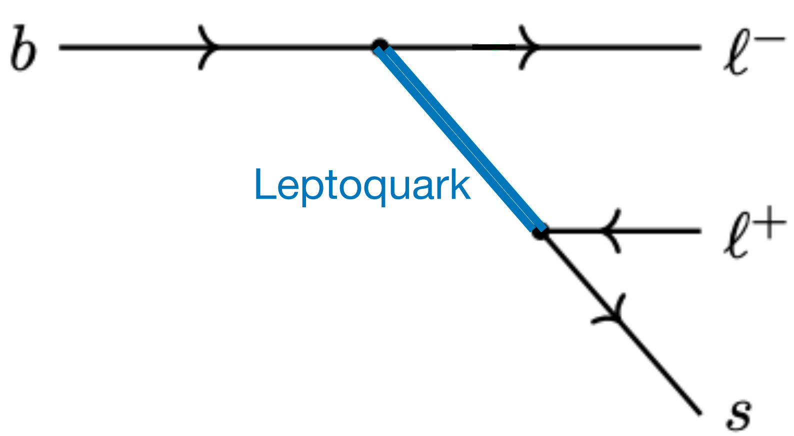
Rare B decays

- Flavour-Changing Neutral Current B decays are suppressed in the SM as they can only occur at loop level



- Because of their suppression in the SM, rare B decays are a good probe for New Physics

- A deviation from SM predictions in rare B decays could be evidence of New Physics



Rare B decays

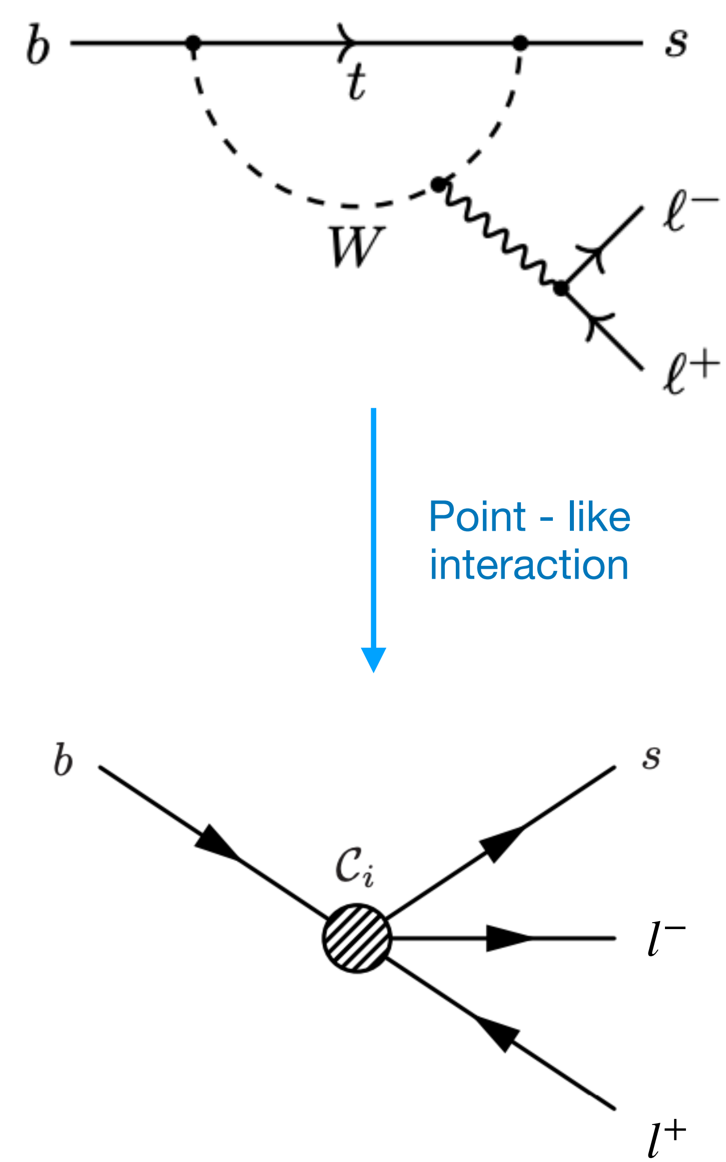
- Processes are described using an Effective field theory $(M_b \ll M_W)$:

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i \mathcal{O}_i$$

C_i = Wilson coefficients

related to

$\mathcal{O}_i$ = Local operators



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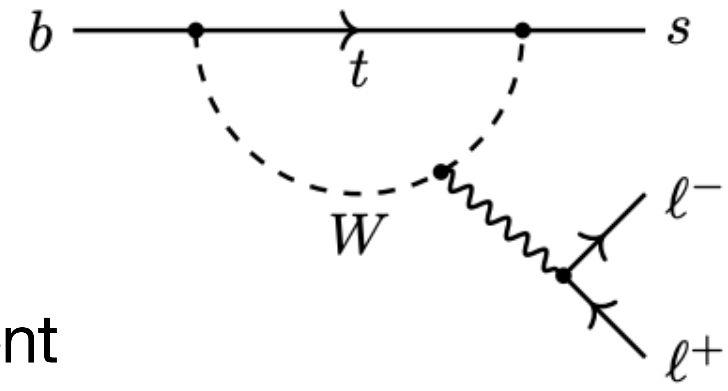

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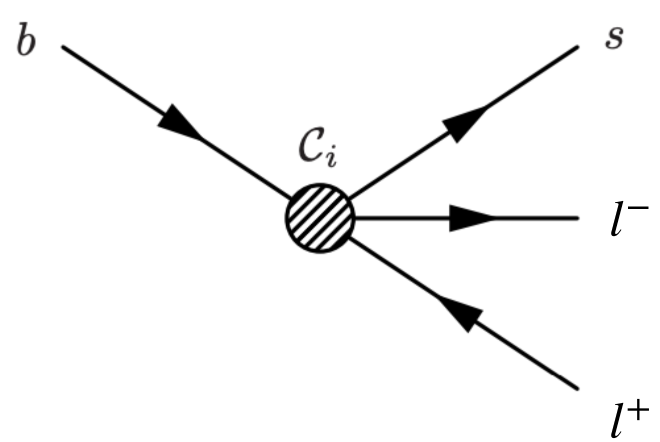
C_9 → vector current

C_{10} → axial vector current

Point - like interaction



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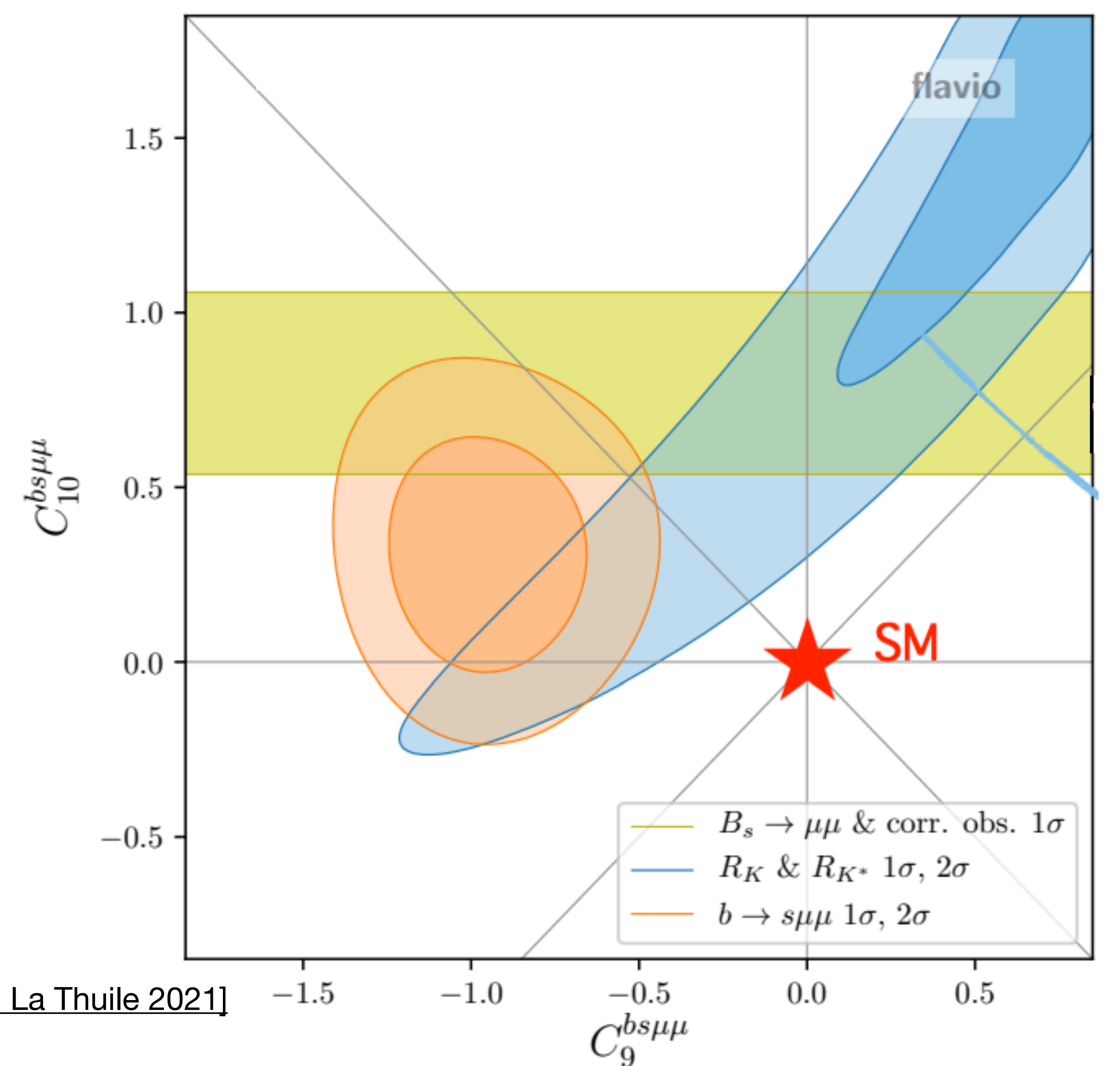
$$\begin{cases} C_9 \longrightarrow \text{vector current} \\ C_{10} \longrightarrow \text{axial vector current} \end{cases}$$

- Tension between measurements and SM predictions in the latest global fit.

- Measurements prefer NP contributions to the C_9 and C_{10} coefficients



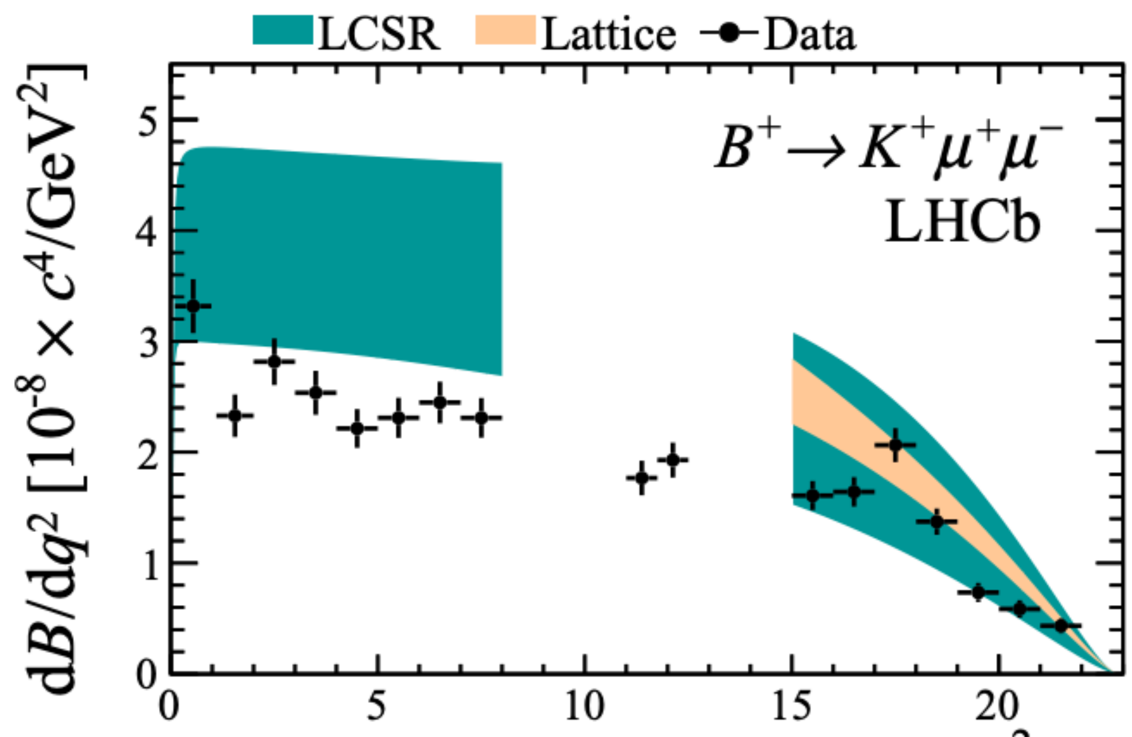
[Stangl @ La Thuile 2021]

Flavour anomalies in $b \to sl^+l^-$ processes

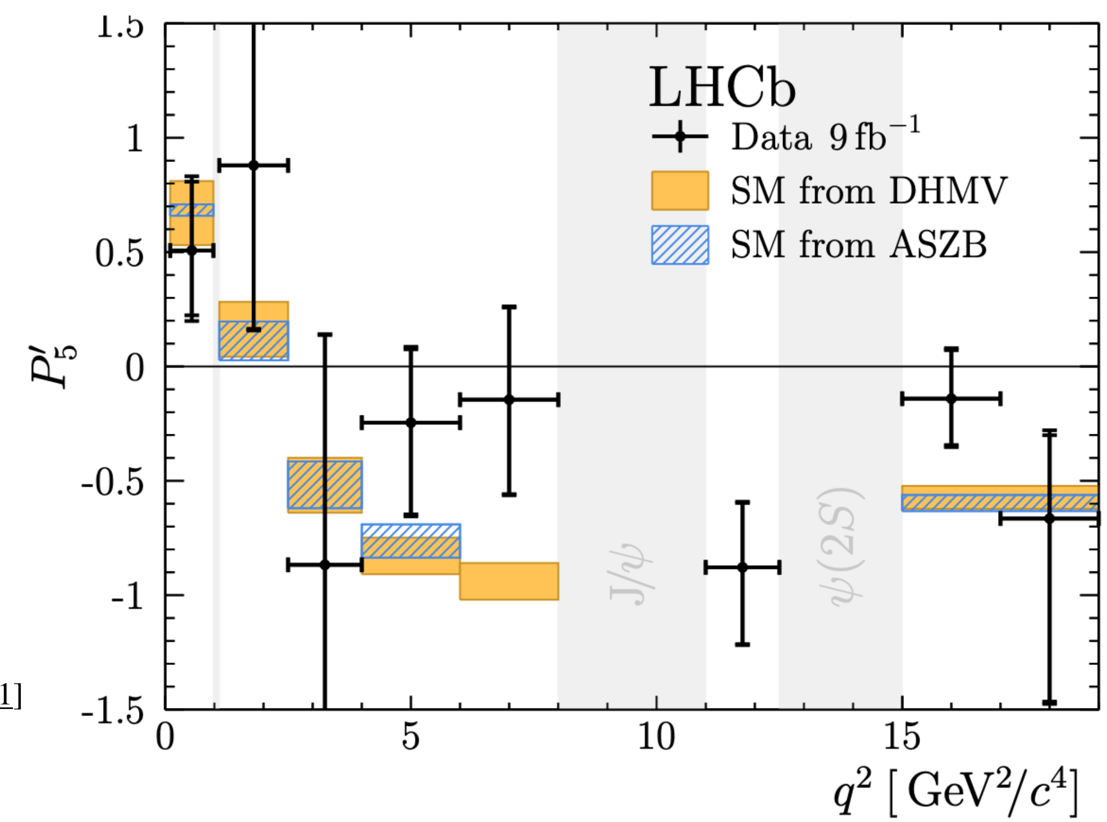
- Flavour anomalies observed consistently in $b \to sl^+l^-$ transitions

- Decay rate measurements lower than theory predictions at low $q^2 (= m_{ll}^2)$.

- Angular analyses of $B^0 \to K^{*0}\mu^+\mu^-$ and $B^+ \to K^{*+}\mu^+\mu^-$ measured a combination of angular observables finding a $\sim 3\sigma$ tension with SM predictions.



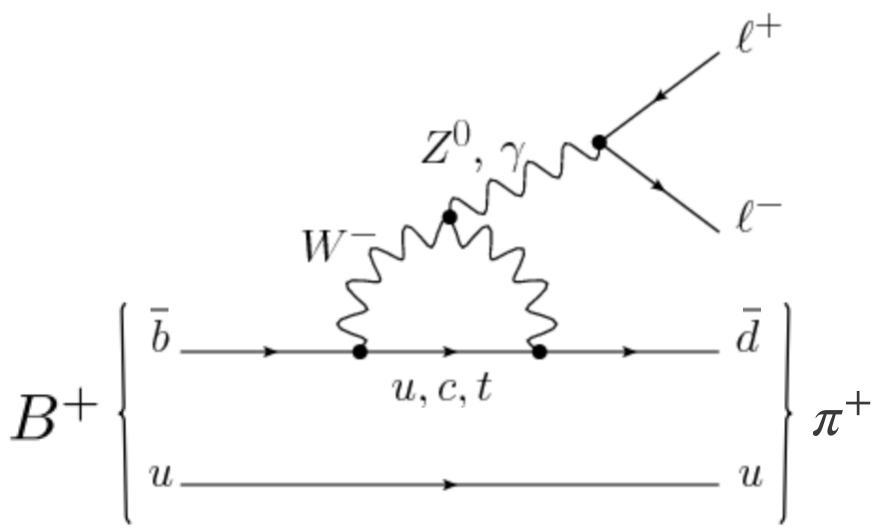
[JHEP06(2014)133]



[arXiv:2012.13241]

$B^+ \to \pi^+\mu^-\mu^+$ decay

$B^+ \to \pi^+\mu^-\mu^+$ is a FCNC process not allowed at tree-level in SM

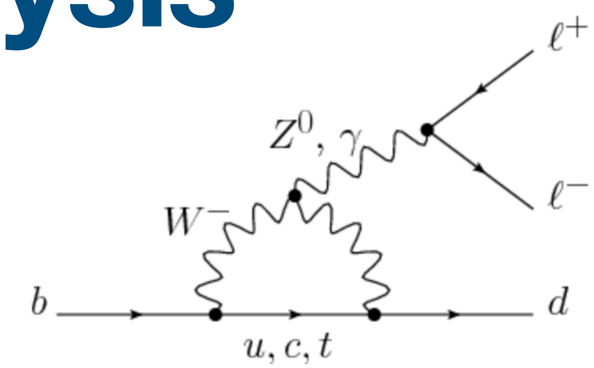


$b \to dl^+l^-$ transitions are further CKM-suppressed by $|V_{tb}/V_{td}|^2$ in the SM

$$\frac{\Gamma(b \to dl^+l^-)}{\Gamma(b \to sl^+l^-)} \sim \frac{1}{25}$$

[JHEP10(2015)034]

$B^+ \to \pi^+\mu^-\mu^+$ angular analysis



Angular distribution of $B^+ \to \pi^+\mu^-\mu^+$ is:

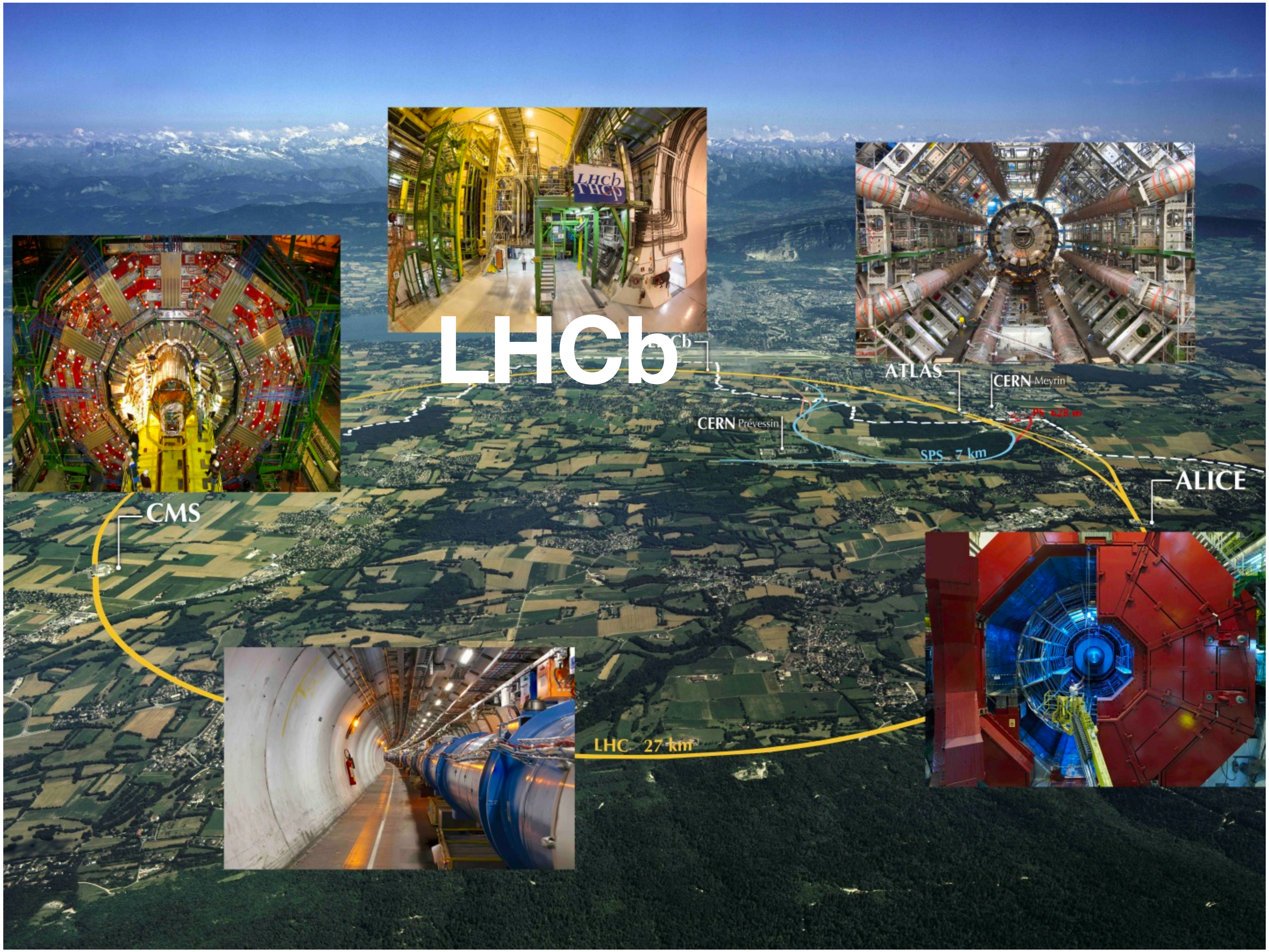
$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma(B \to Kl^+l^-)}{\mathrm{d}\cos\theta_l} = \frac{3}{4}(1 - F_H)(1 - \cos^2\theta_l) + \frac{1}{2}F_H + A_{FB}\cos\theta_l$$

- θ_l = angle between the direction of l^+ and that of π in the l^+l^- rest-frame
- F_{H} = the fractional contribution of scalar, pseudo-scalar and tensor amplitudes
- A_{FB} = the forward-backward asymmetry of the dilepton system.

In the SM: $F_{\text{H}} = 0$ and $A_{\text{FB}} \sim 0$. [JHEP05(2014)082]

LHCb Detector

- The detector is a single - arm forward spectrometer at CERN

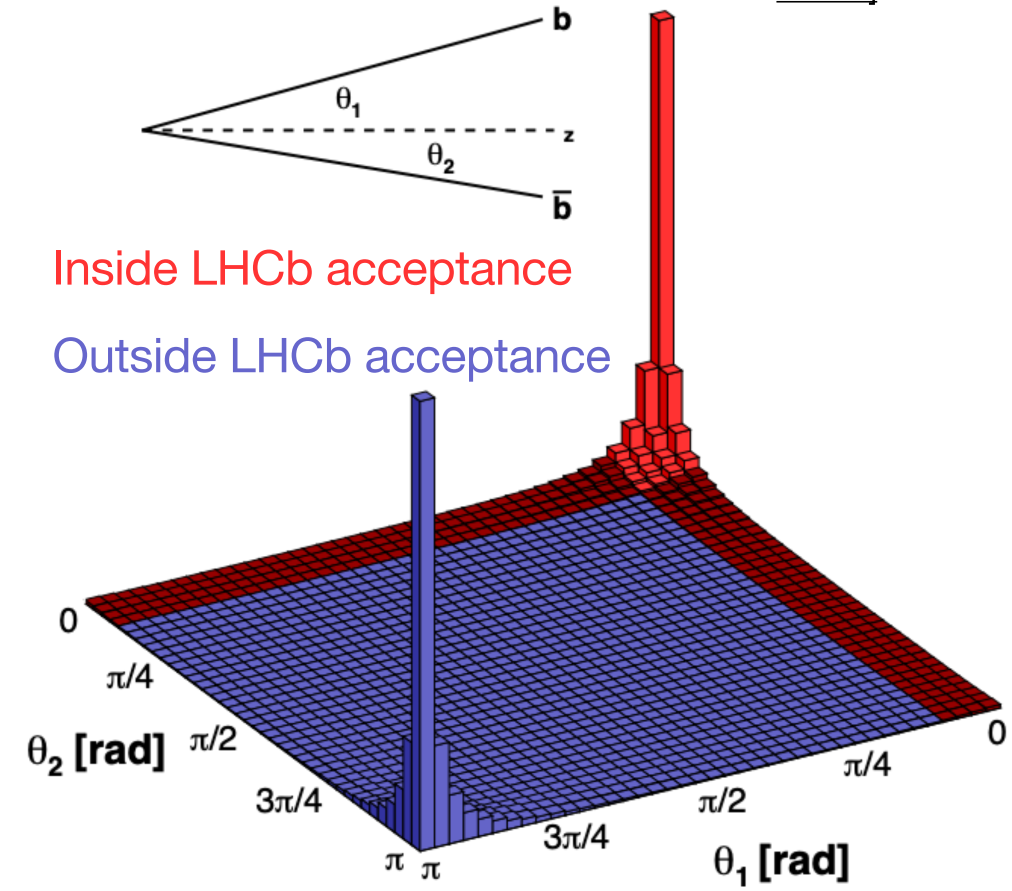


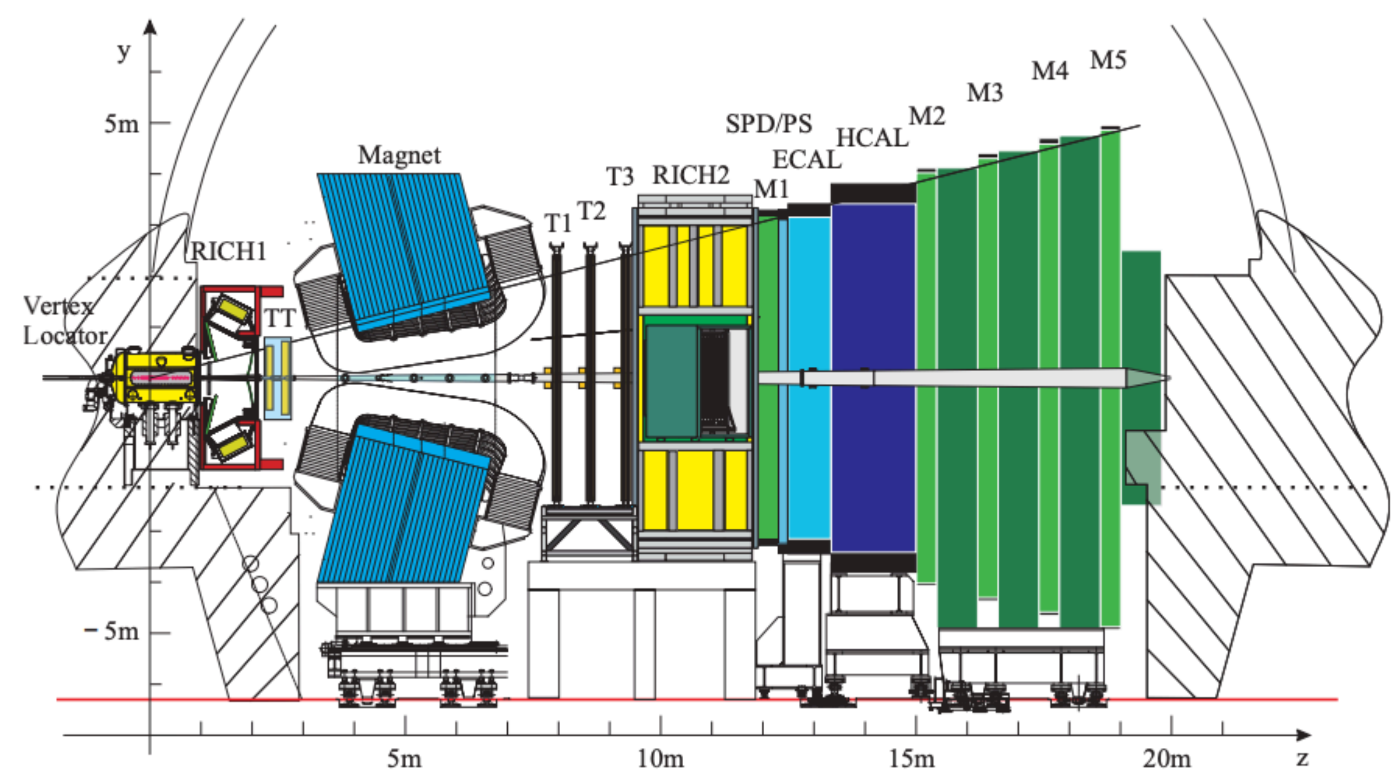
[Image provided by CERN]

LHCb Detector

- The detector is a single - arm forward spectrometer at CERN
- CoM energy at the LHC of 7, 8 and 13 TeV
- At 13 TeV LHCb provides a $b\bar{b}$ cross-section production of $500\ \mu$b, $24\ \%$ of pairs inside the detector acceptance

[$b\bar{b}$ production plots, Elsasser, LHCb Collaboration, 1/4/21]





[JINST 3 (2008) S08005]

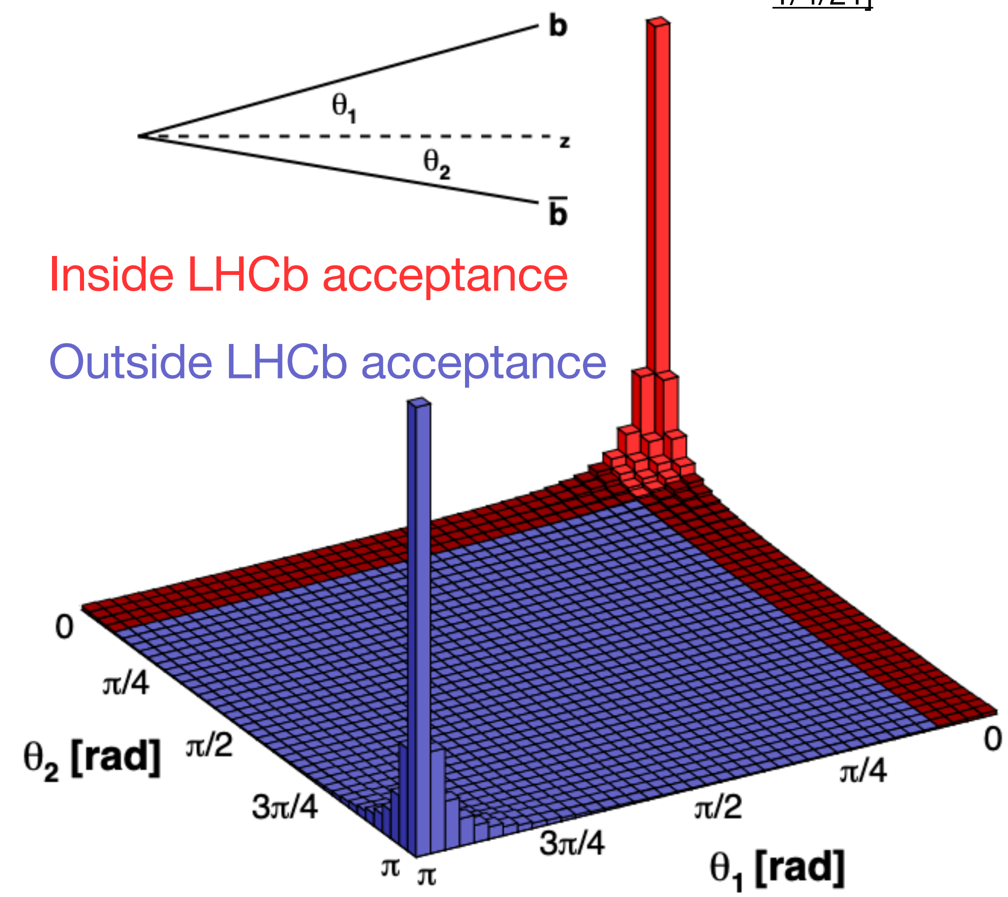
LHCb Detector

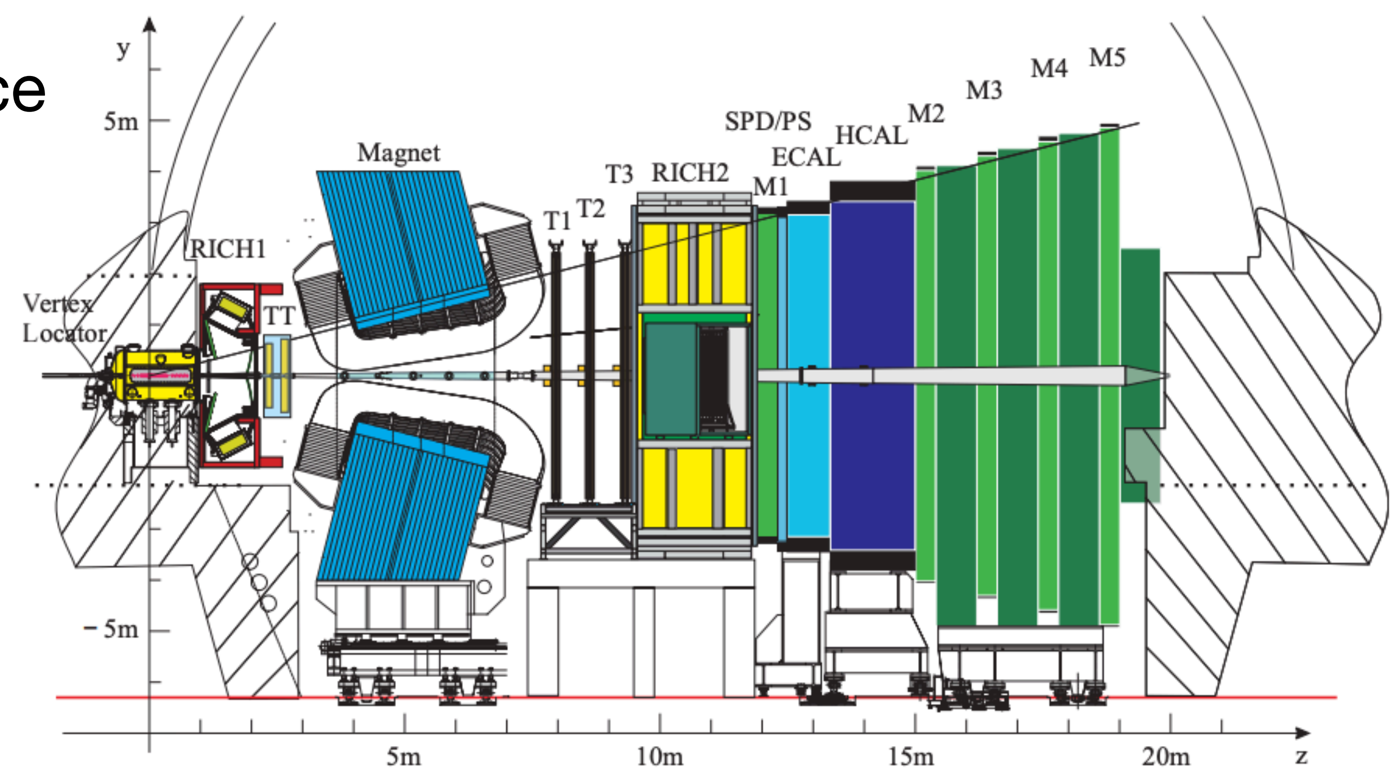
- The detector is a single - arm forward spectrometer at CERN
- CoM energy at the LHC of 7, 8 and 13 TeV
- At 13 TeV LHCb provides a $b\bar{b}$ cross-section production of $500\ \mu$b, $24\ \%$ of pairs inside the detector acceptance
- Excellent invariant mass ~22 MeV/c² for 2body B decays and vertex (15 +29/pT[GeV]) μm resolution
- RICH system PID typical performance between 2 and 100 GeV/c:

$$\epsilon(\mathrm{K} \rightarrow \mathrm{K}) \sim 95\ \%$$

$$\epsilon(\pi \rightarrow \mathrm{K}) \sim 5\ \%$$

[$b\bar{b}$ production plots, Elsasser, LHCb Collaboration, 1/4/21]



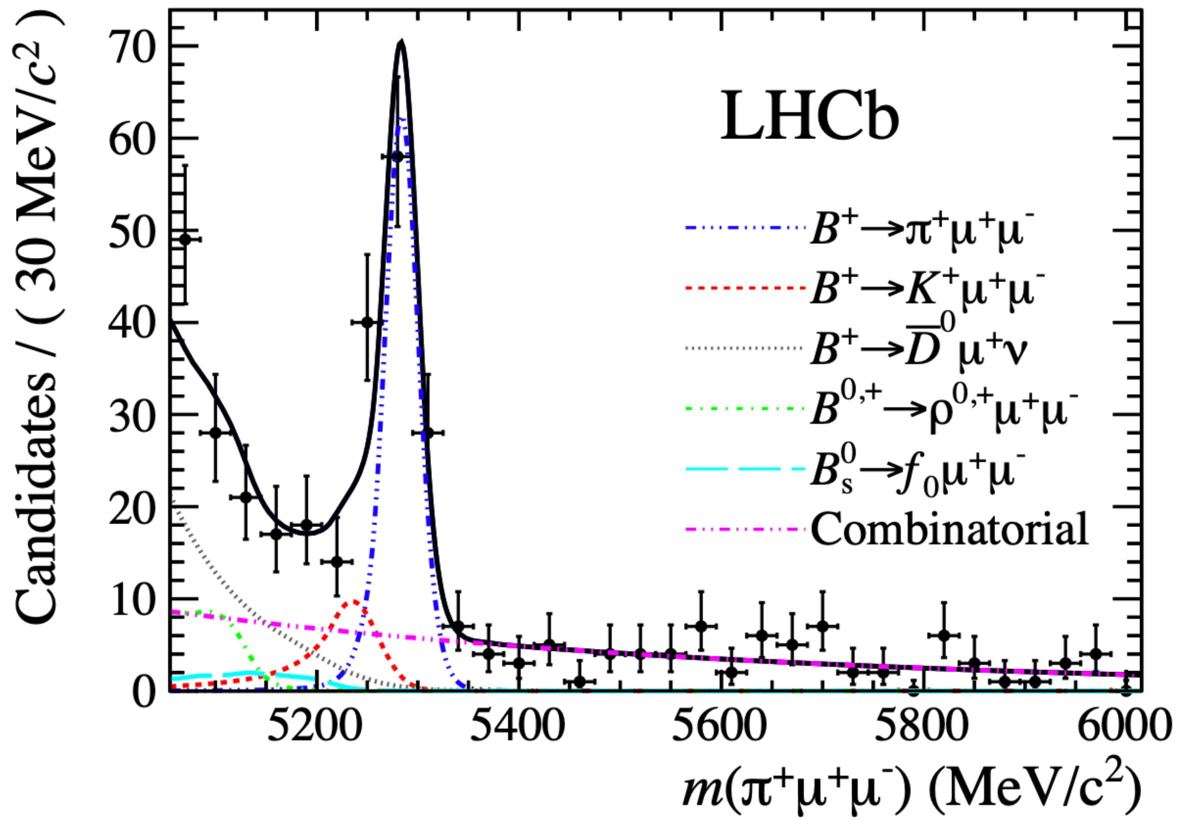


[JINST 3 (2008) S08005]

$B^+ \to \pi^+\mu^-\mu^+$ at LHCb

- First measurement: differential branching fraction and CP asymmetry, using LHCb Run I data

- Found 28.8 and 24.1 signal decays for the $(1.1, 6.0)$ GeV/c^4 and $(15.0, 22.0)$ GeV/c^4 q^2 regions



[JHEP10(2015)034]

- Differential BF analysis using Run I+II datasets is on the way
  - Expecting 95 and 80 signal decays for the low and high q^2 regions from Run I+II datasets

Backgrounds

- Combinatorial

Backgrounds

- Combinatorial → Modelled using an exponential function

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- Partially reconstructed:
  - $B^0 \to K^{*0}\mu^-\mu^+$
  - $B^0 \to \rho\mu^-\mu^+$
  - $B_s^0 \to f_0\mu^-\mu^+$
  - $B^+ \to \rho^+\mu^-\mu^+$

where:

$K^{*0} \to K\pi$

$\rho \to \pi\pi$

$f_0 \to \pi\pi$

$\rho^+ \to \pi\pi$

and a hadron is not reconstructed

Backgrounds

- Combinatorial → Modelled using an exponential function
- Partially reconstructed: → Modelled using ARGUS functions
  - $B^0 \to K^{*0}\mu^-\mu^+$
  - $B^0 \to \rho\mu^-\mu^+$
  - $B_s^0 \to f_0\mu^-\mu^+$
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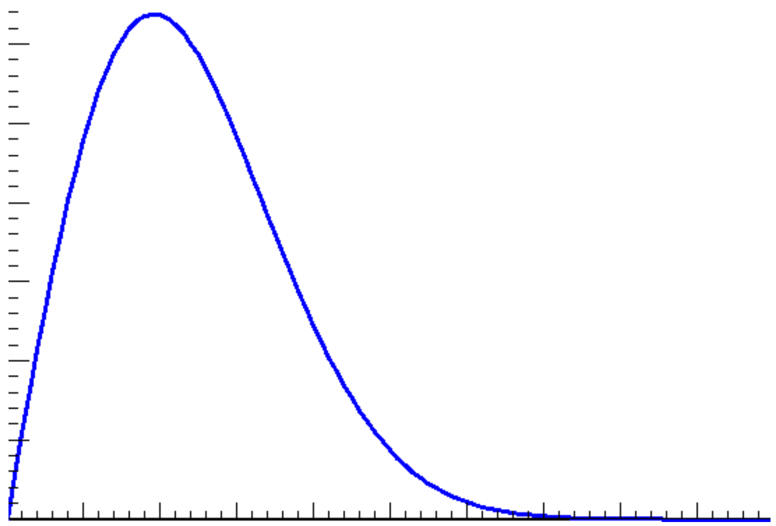

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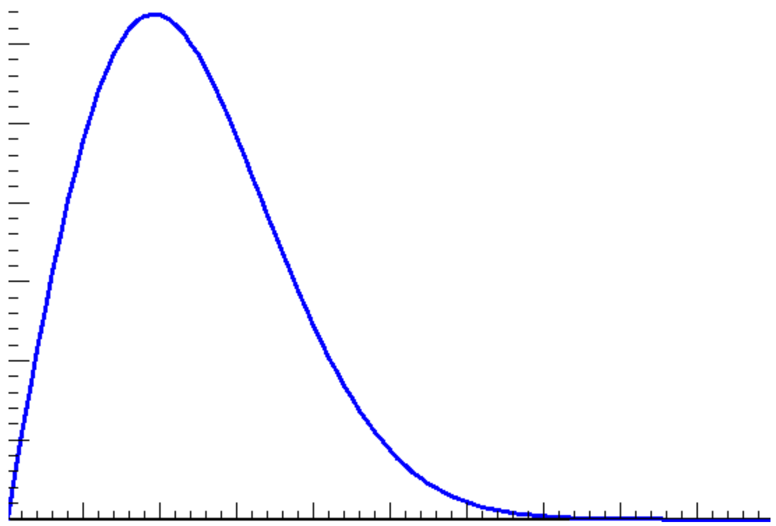

- Mis-reconstructed:
    - $B^+ \to K^+\mu^-\mu^+$ where $K^+ \to \pi^+$ mis-ID takes place

Backgrounds

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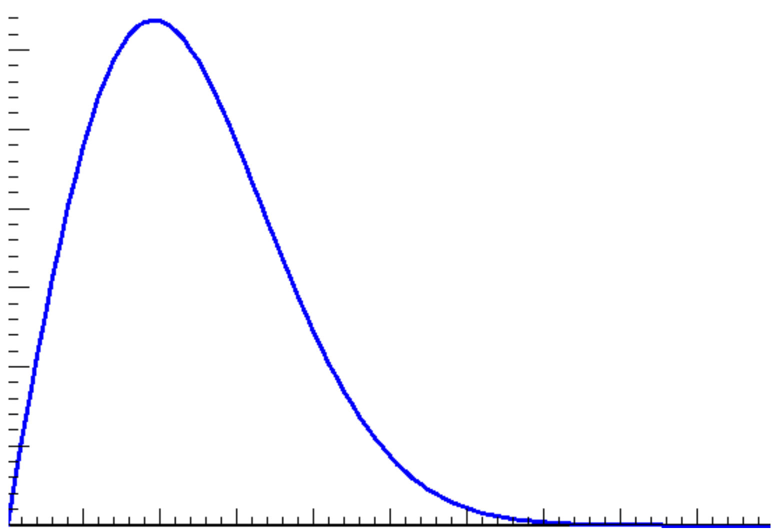
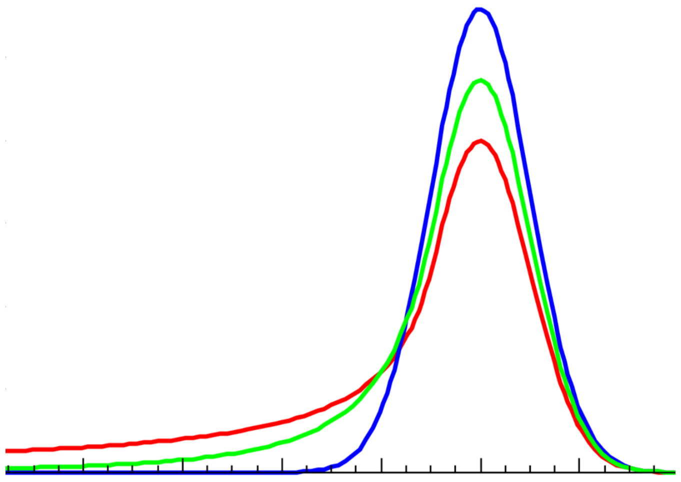
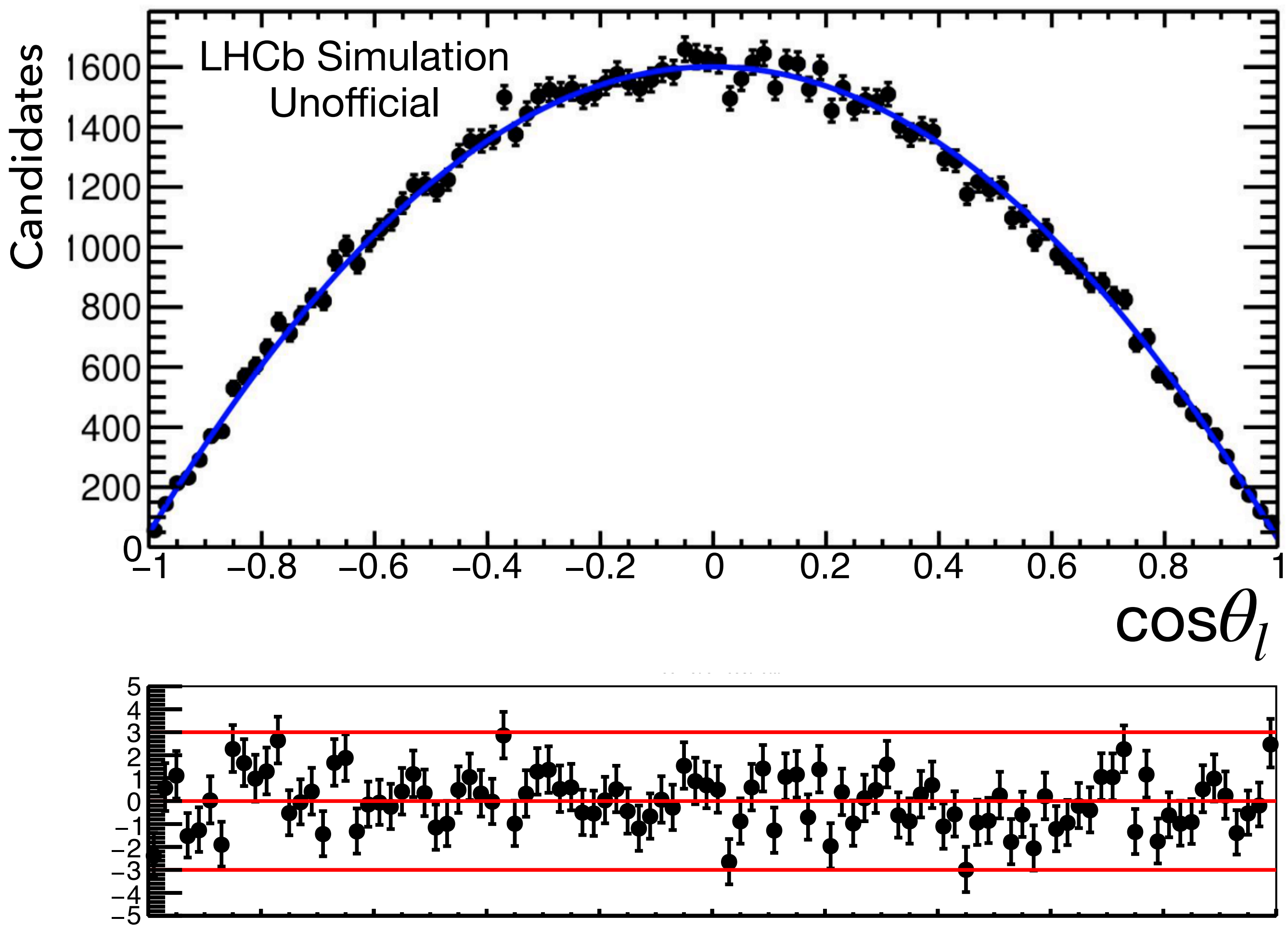


- Mis-reconstructed: → Modelled using a Crystal Ball function
  - $B^+ \to K^+\mu^-\mu^+$



Mis - reconstructed background

- $B^+ \to K^+\mu^-\mu^+$ decay where the K is reconstructed as a π^+
- Used LHCb simulation data to plot: $\cos\theta_l$ in bins of q^2 → Fit → Chebychev Polynomial



Mis - reconstructed background

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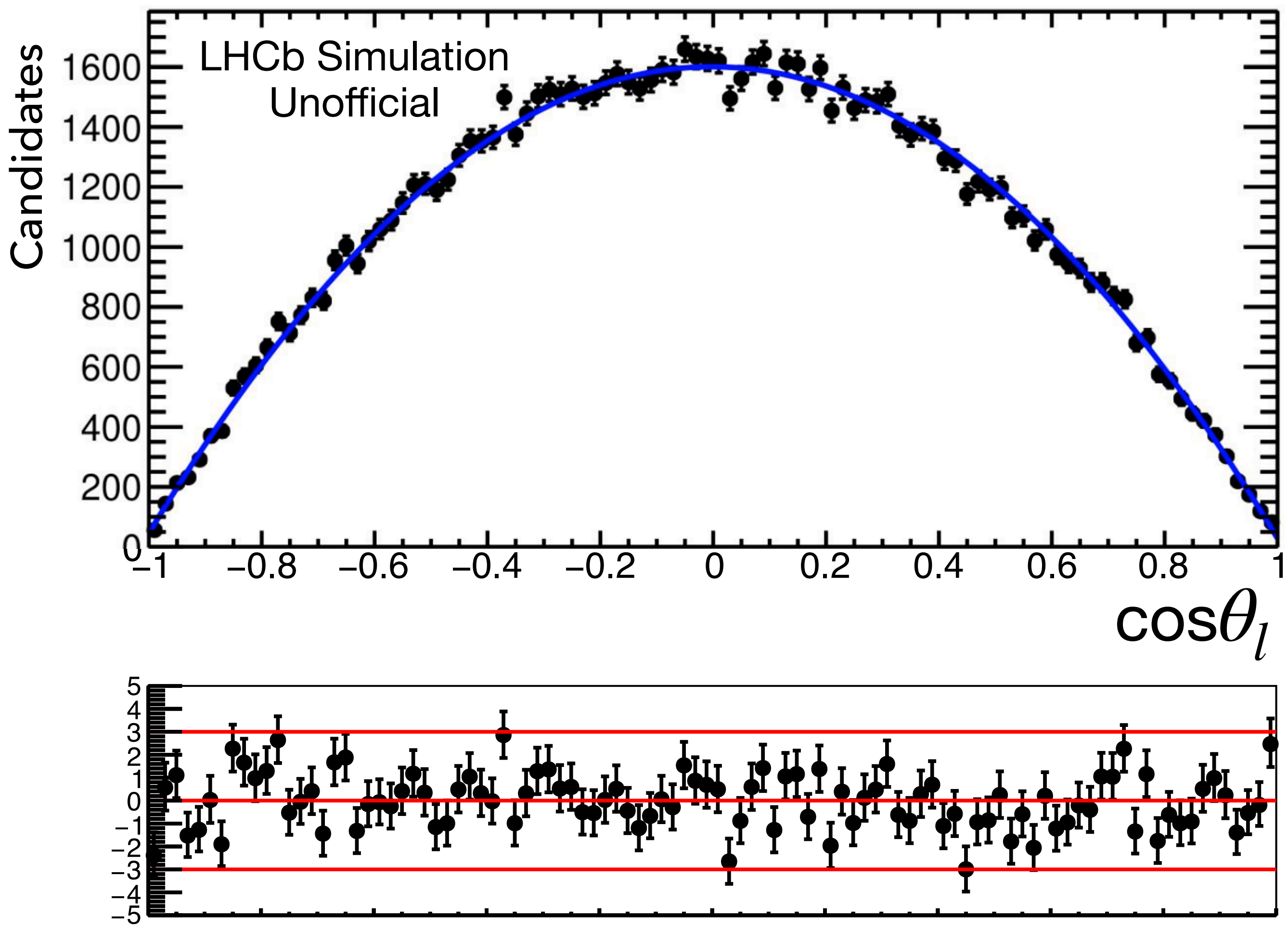
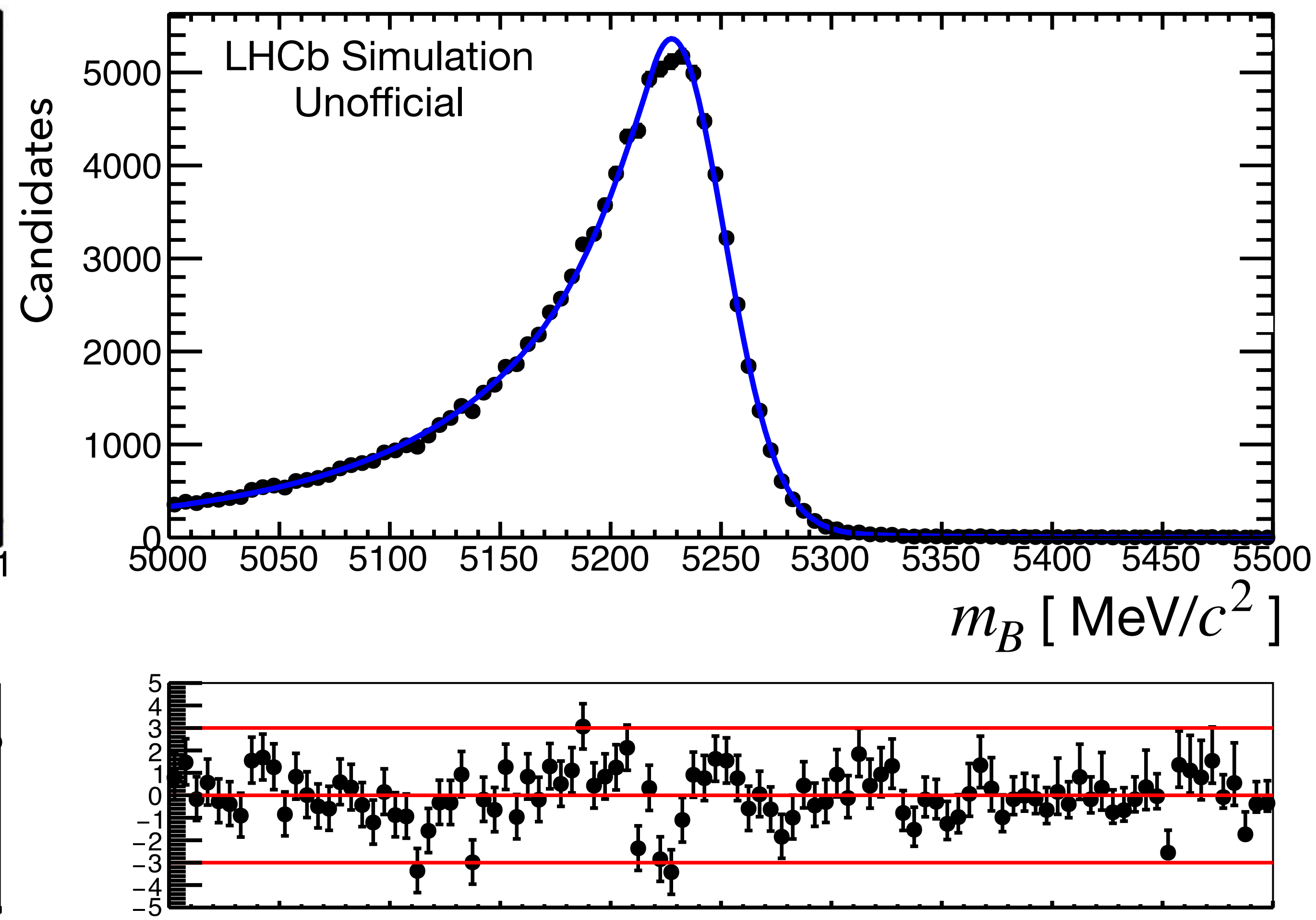
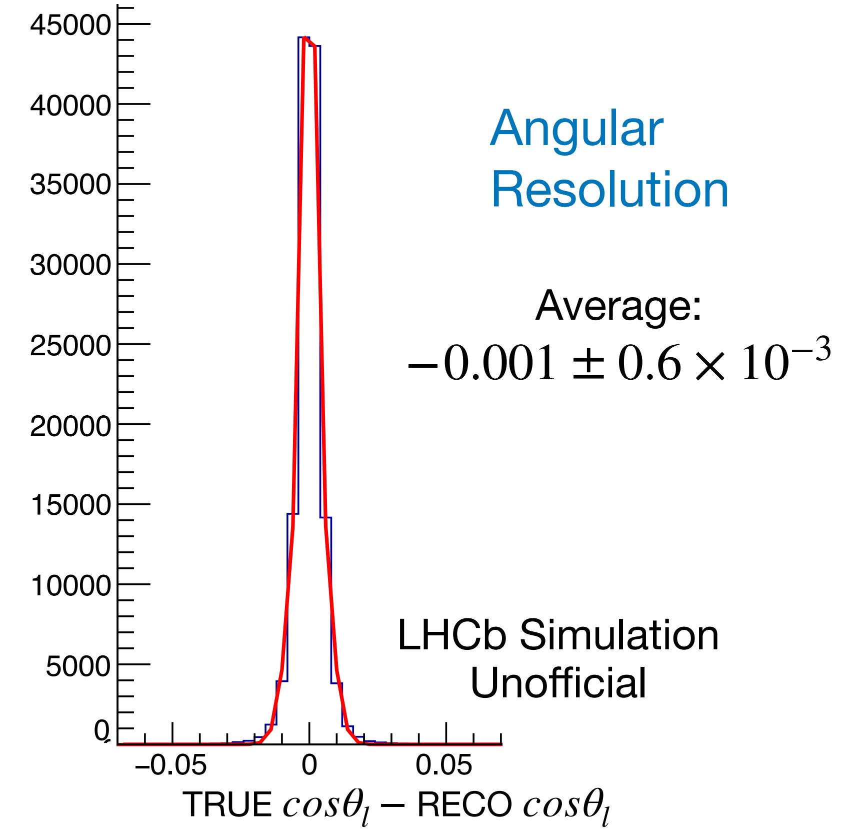
- Used LHCb simulation data to plot:
  - $\cos\theta_l$ in bins of q^2 → Fit → Chebychev Polynomial
  - B_{mass} → Fit → Double Crystal Ball





Angular resolution and efficiency

- Angular resolution and efficiency are measured using LHCb simulation data
- Difference in $cos\theta_l$ between true and reconstructed events is small enough for the resolution to be neglected



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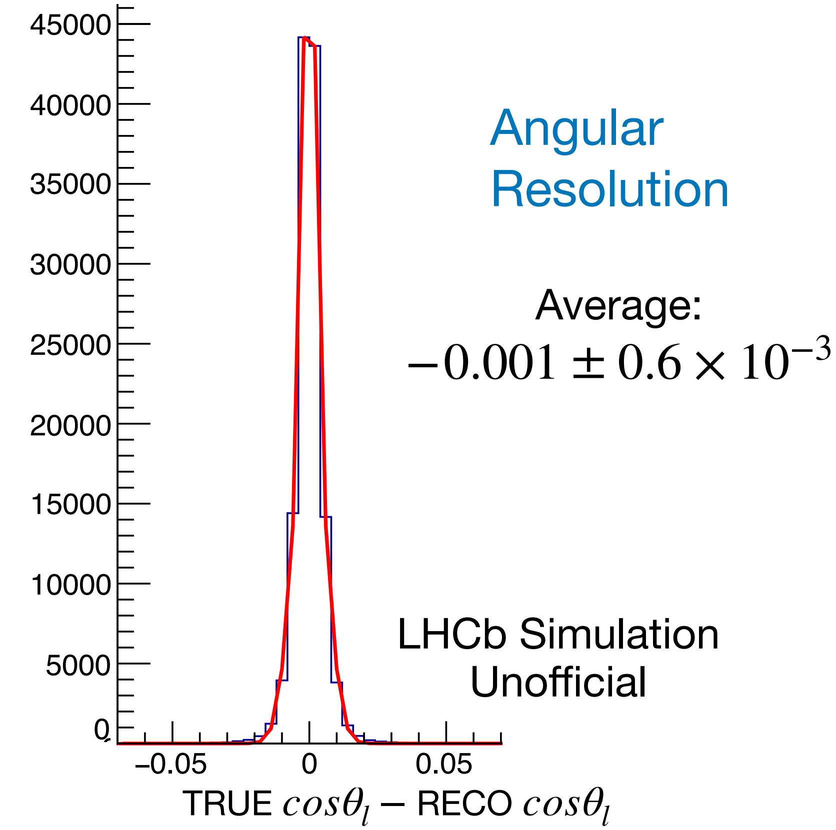

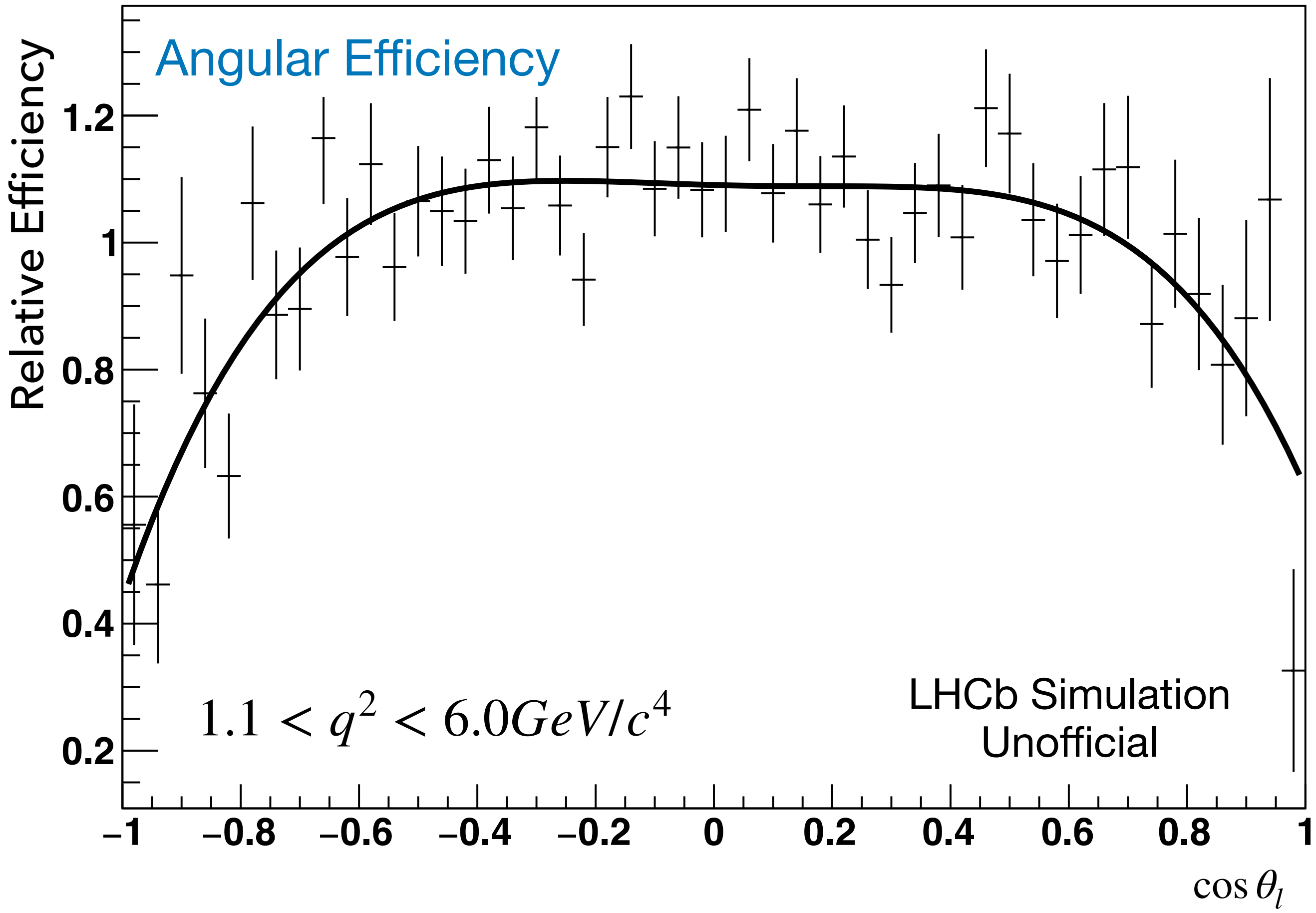

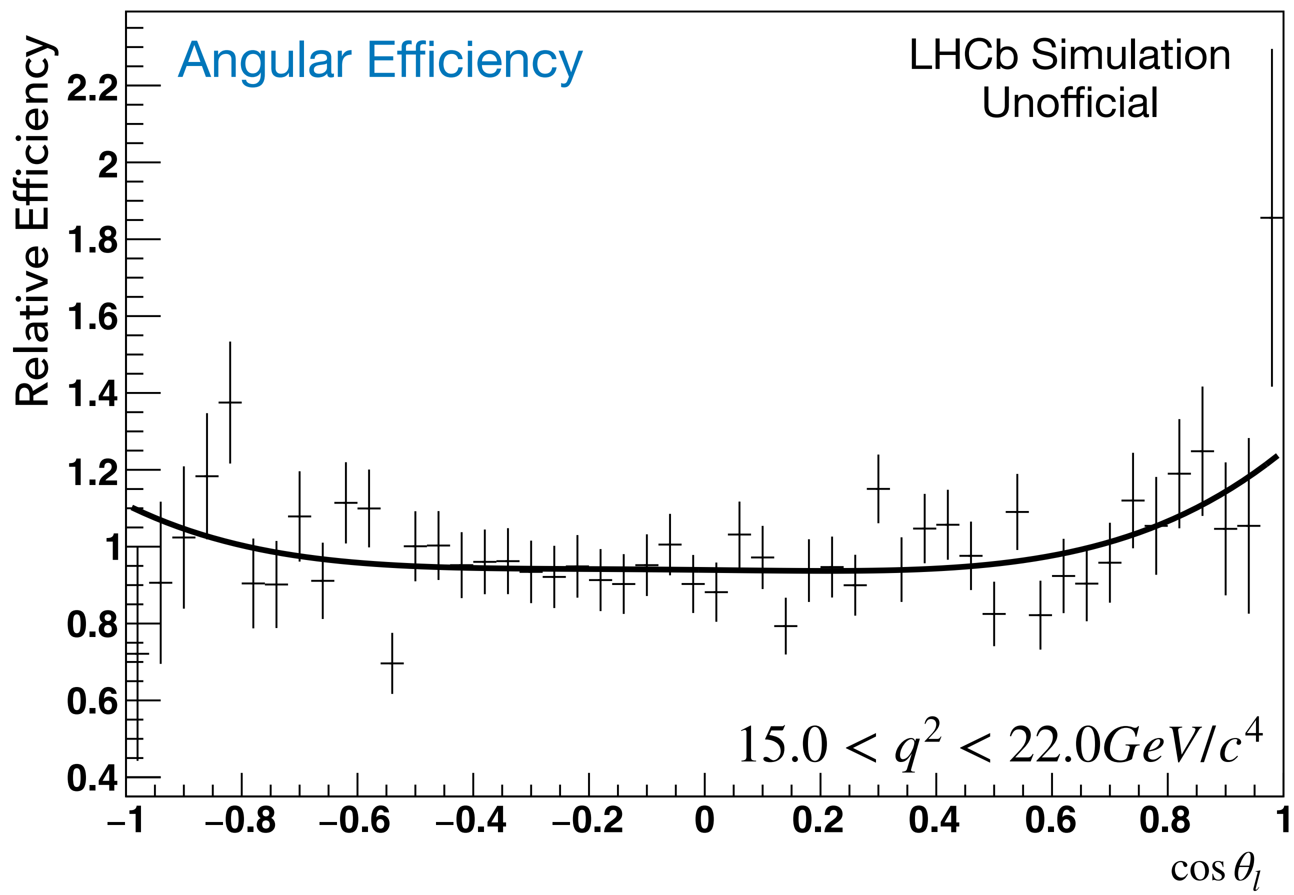

Toy experiments: Profiling log-likelihood

Goal:

Reliably determine A_{FB} and F_{H}

- Toy experiment simulating
  - $B^+ \to \pi^+\mu^-\mu^+$ decay signal
  - Angular efficiency
  - Background from mis-reconstructed $B^+ \to K^+\mu^-\mu^+$ decay
- Set the initial values: $A_{\text{FB}} = 0.0,\ F_{\text{H}} = 0.1$
- 2D Profile of the Negative LogLikelihood function

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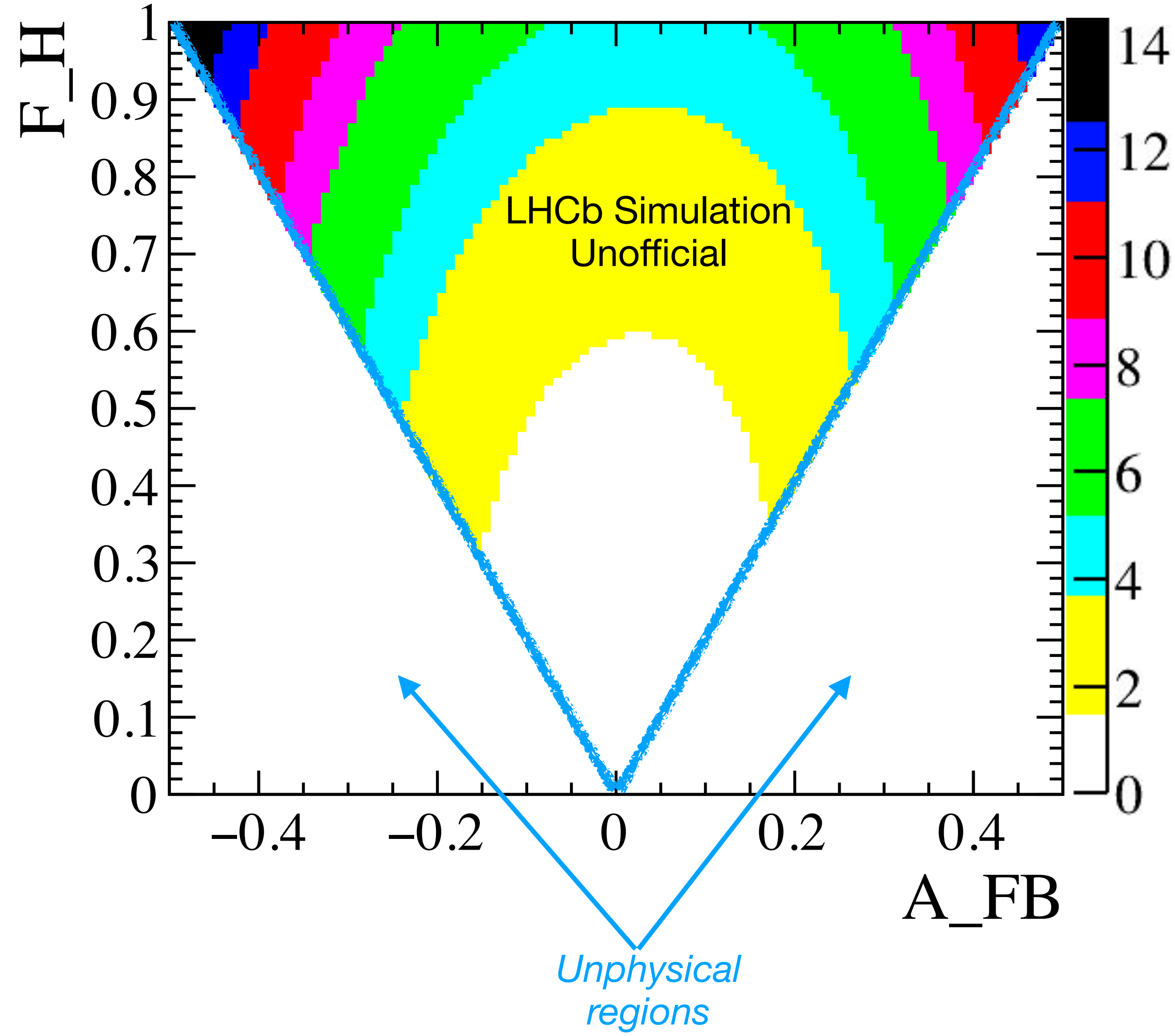

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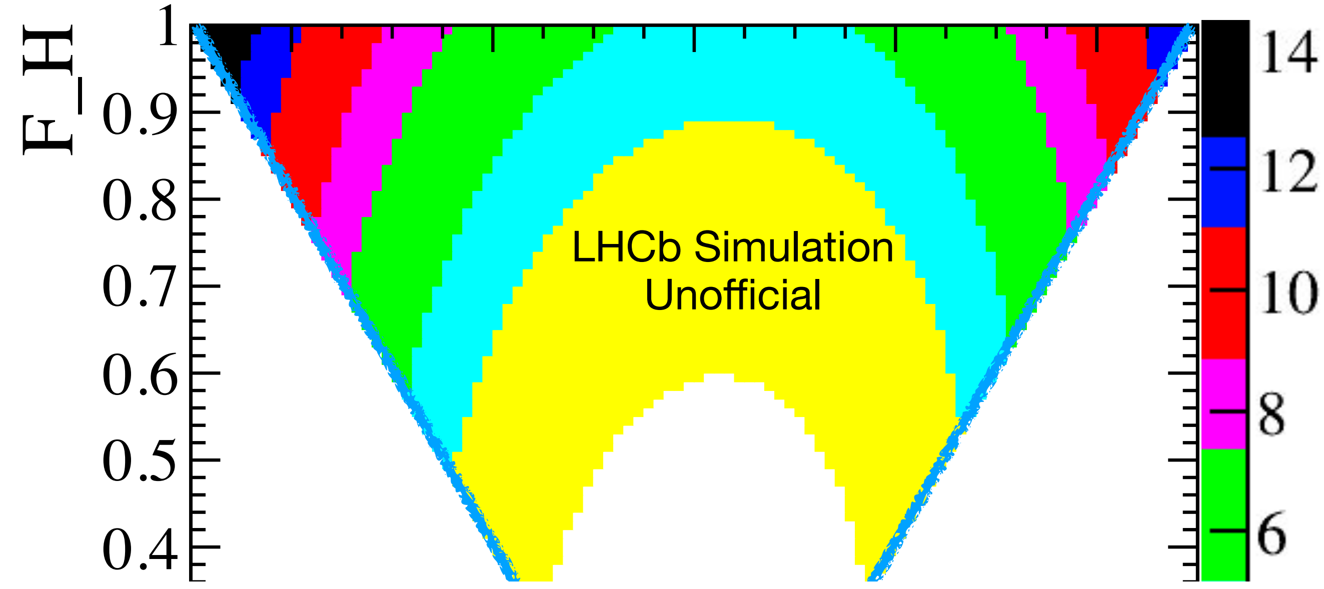
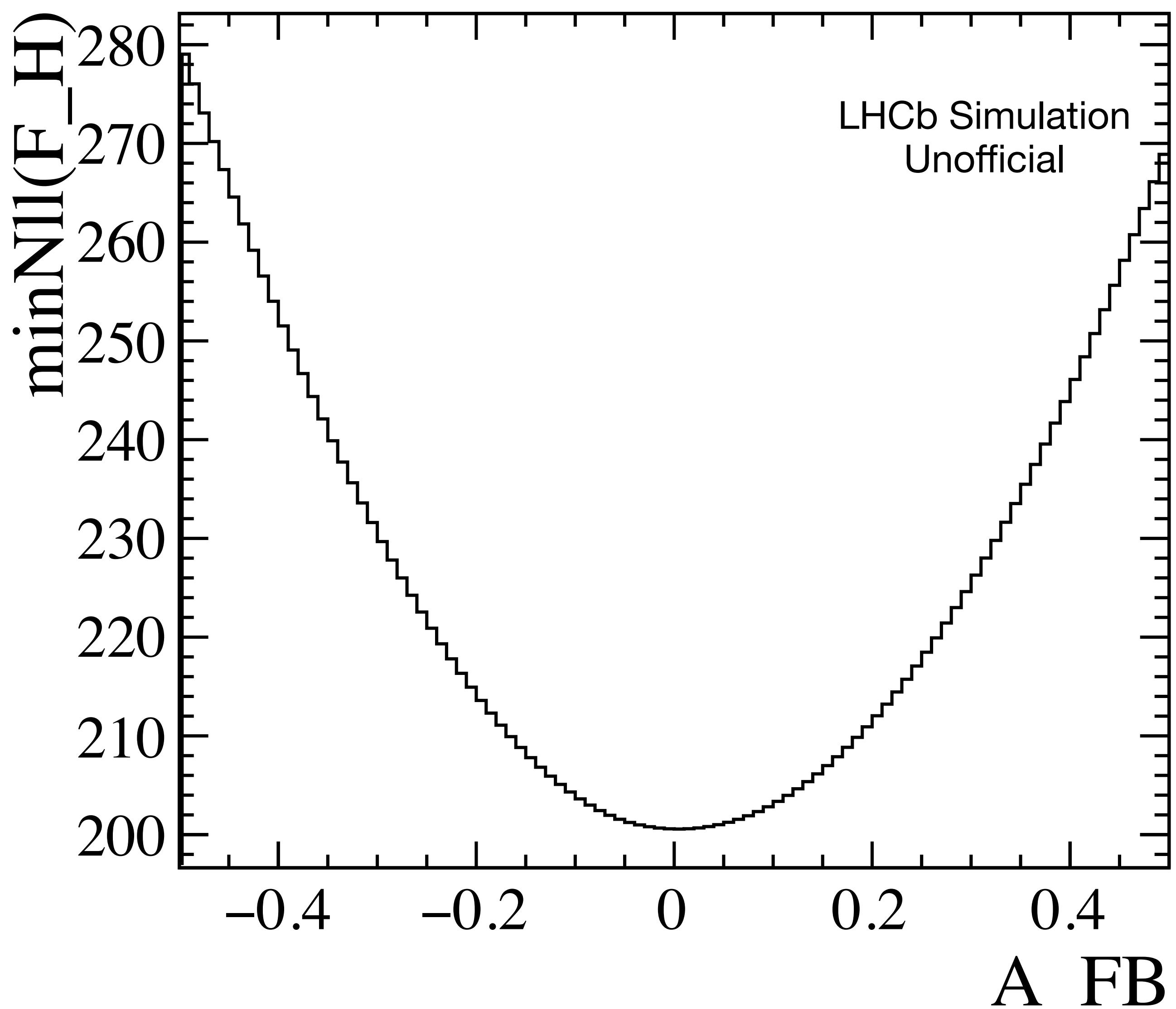




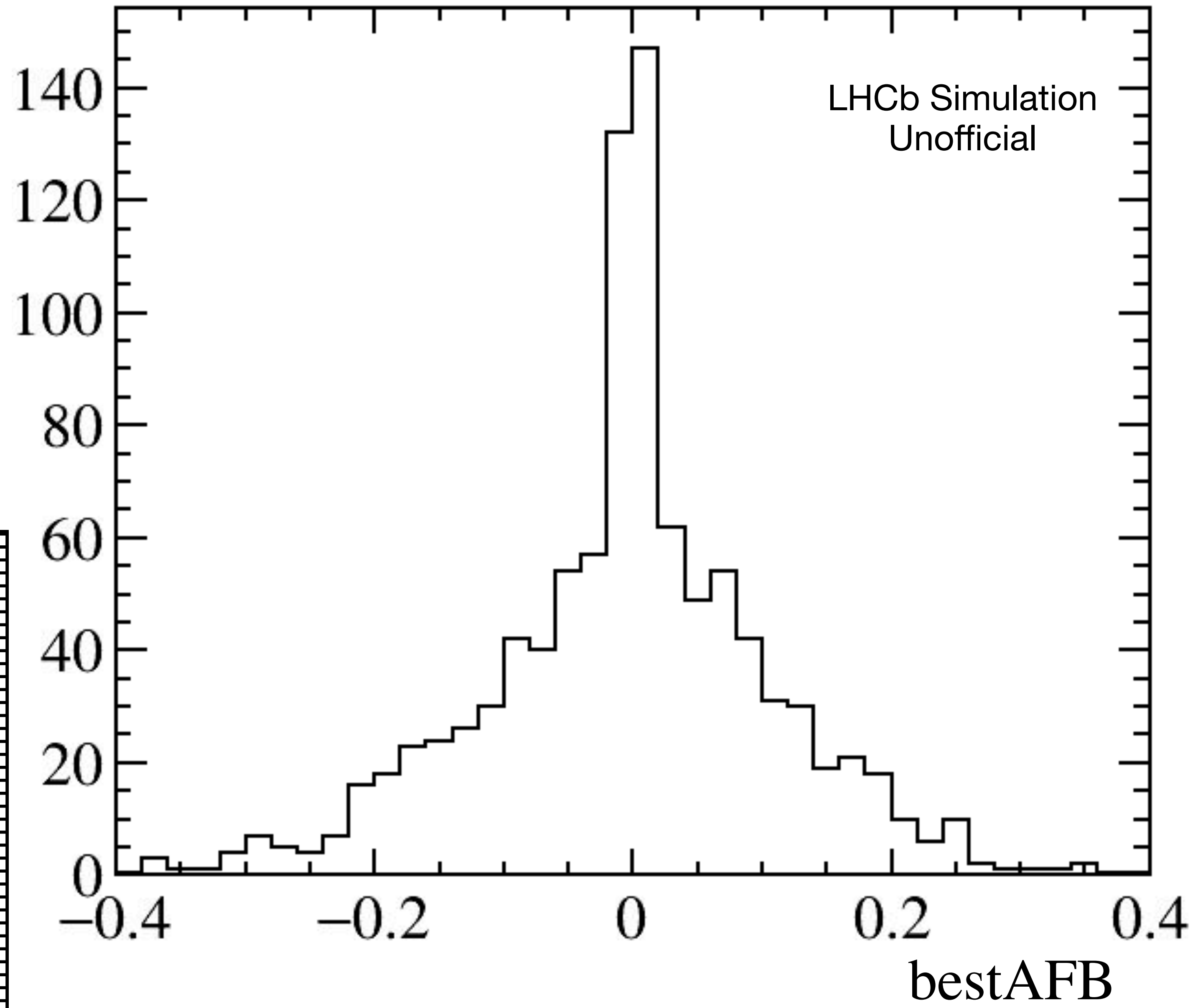
- Toy experiment simulating
  - $B^+ \to \pi^+\mu^-\mu^+$ decay signal
  - Angular efficiency
  - Background from mis-reconstructed $B^+ \to K^+\mu^-\mu^+$ decay
- Set the initial values: $A_{\text{FB}} = 0.0,\ F_{\text{H}} = 0.1$
- 2D Profile of the Negative LogLikelihood function
- Minimise the $NLL(F_{\text{H}})$ for every A_{FB}

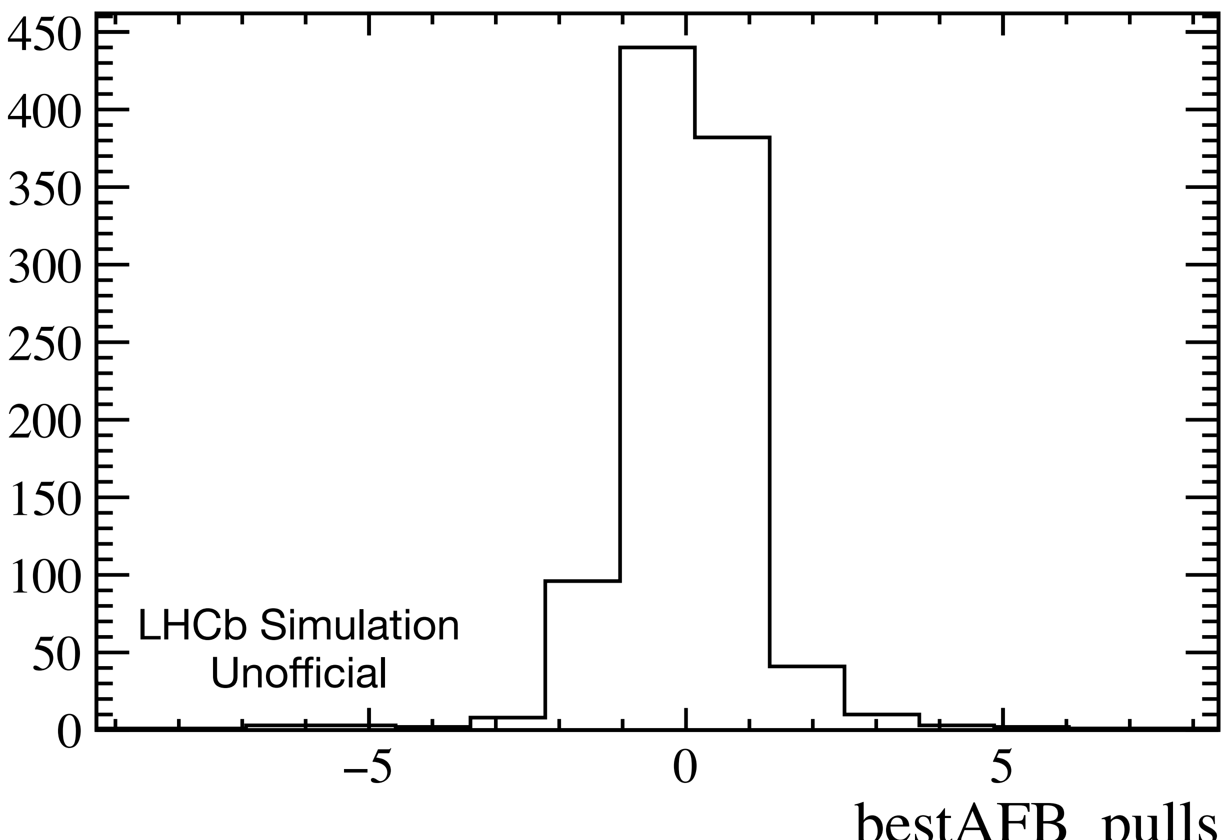
Toy experiments: Profiling log-likelihood

Goal:

Reliably determine A_{FB} and F_{H}

- Ensemble of 1000 toys, initial values: $A_{\mathrm{FB}} = 0.0, \ F_{\mathrm{H}} = 0.1$
- Results from the toys ensemble:





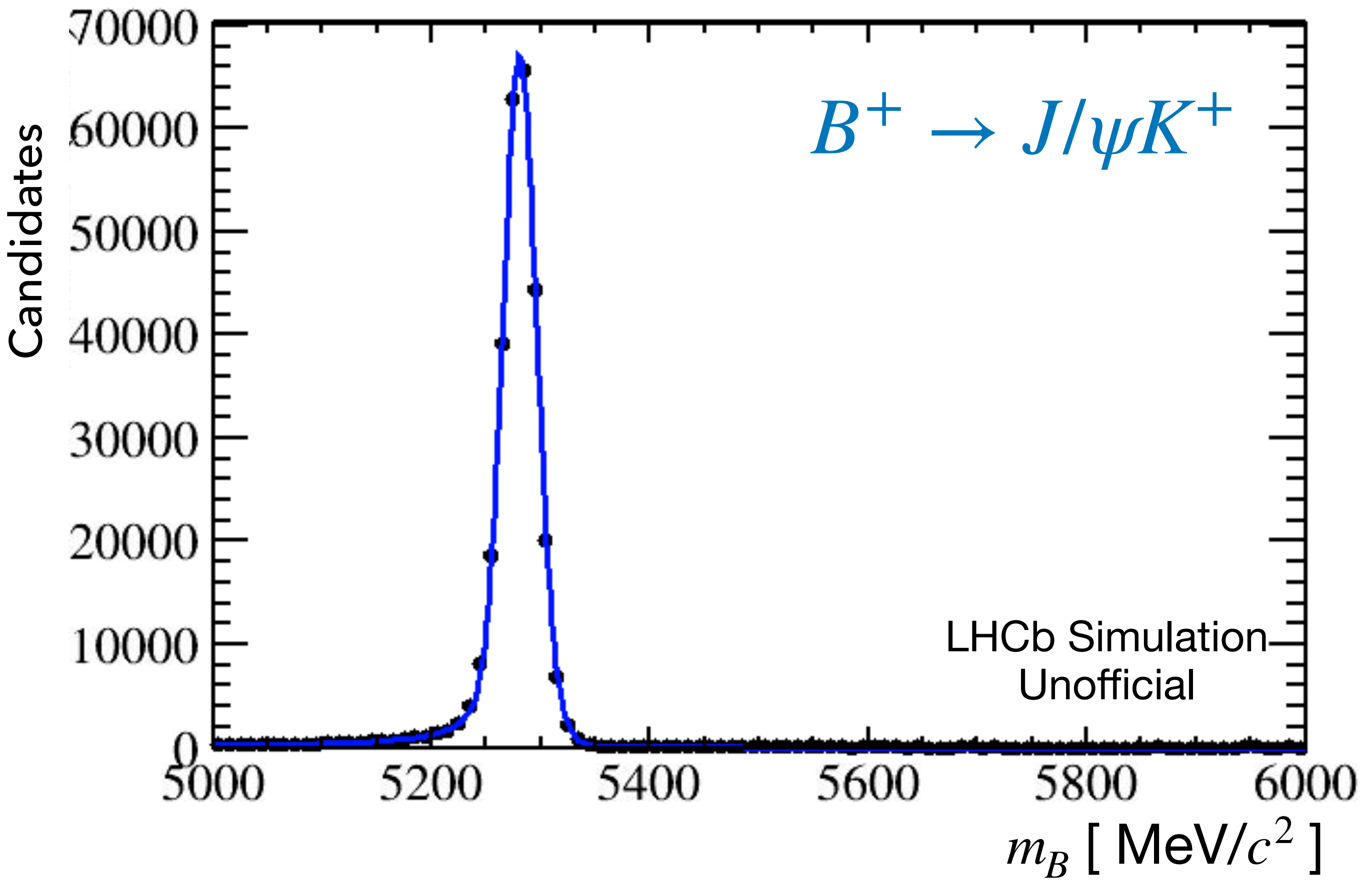
Control mode mass fits

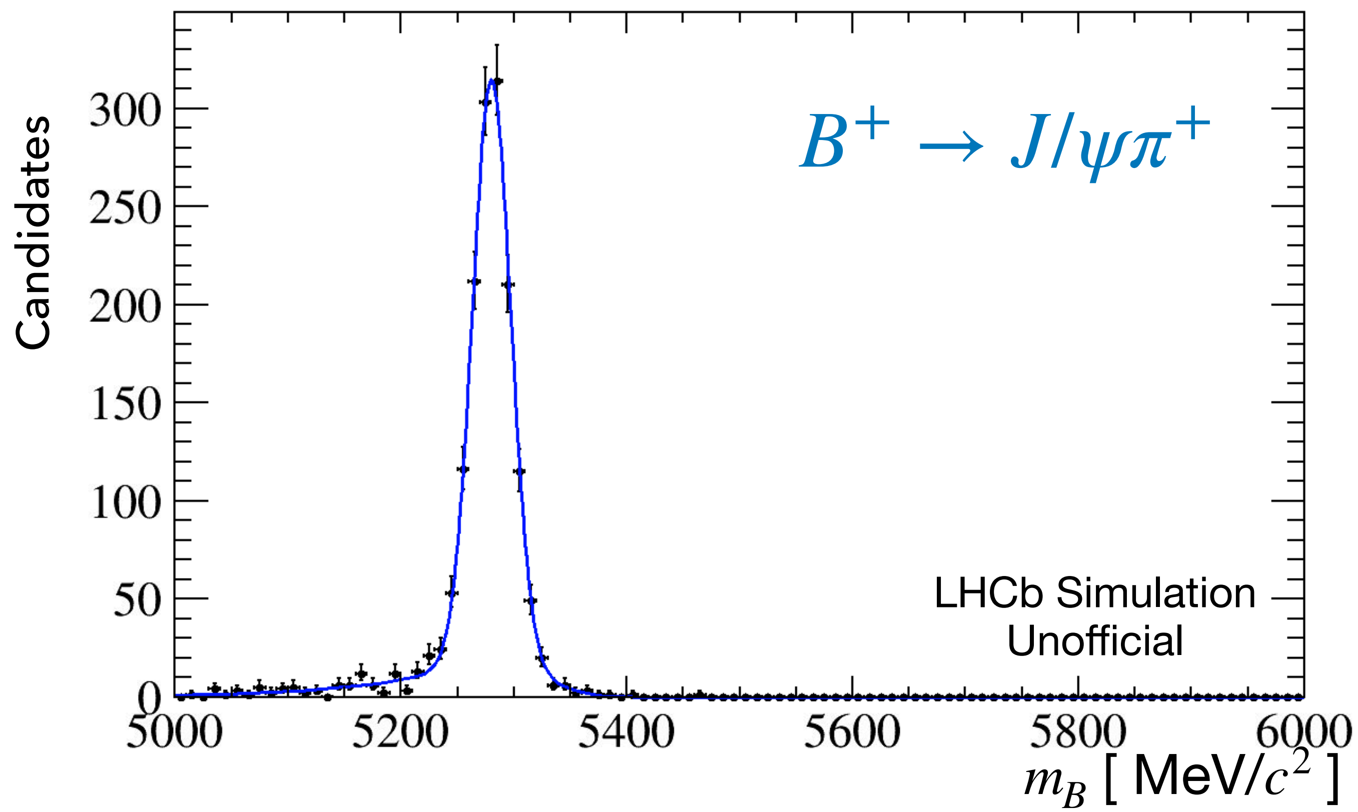
- Well measured control modes:

  $B^+ \to J/\psi K^+$

  $B^+ \to J/\psi \pi^+$

- Mass fit to LHCb simulation data,
  selecting control mode events,
  fitting with a Double Crystal Ball function





Next steps and Summary

- Conduct a 2D mass and angular fit on the control modes to validate the fit.

- Perform the angular analysis on the rare mode using the Feldman-Cousins method on data from Run I and Run II.

    ➡ This method is preferred for better statistical properties.

- Excellent sensitivity to the SM in $B^+ \to \pi^+\mu^-\mu^+$ decay.

- Aim to test the SM with $b \to dl^+l^-$ processes as has already been done with $b \to sl^+l^-$.

Backup slides

Control mode mass fits

- Well measured control modes are $B \to J/\psi K$ and $B \to J/\psi\pi$
- Performed a mass fit to LHCb simulation data, selecting $B \to J/\psi K$ events and fitting with a Double Crystal Ball function
  - Pass preselection cuts:
    - B_PT, hadron_PT, μ^- _PT, μ^+_PT > 300 GeV
    - hadron_isMuonLoose == 0
    - hadron_InAccMuon!=0
  - Pass trigger selection cut
  - Apply mva_mcweights from MVA conducted by the BF group
  - Apply PIDresampling cuts (ProbNNpi_resampled<0.25 && ProbNNK_resampled>0.2)
  - Apply BDT to >0.4 from BF analysis
- Simulation correction weights applied