Search for $B^0 \to \phi\phi$ decays at the LHCb experiment

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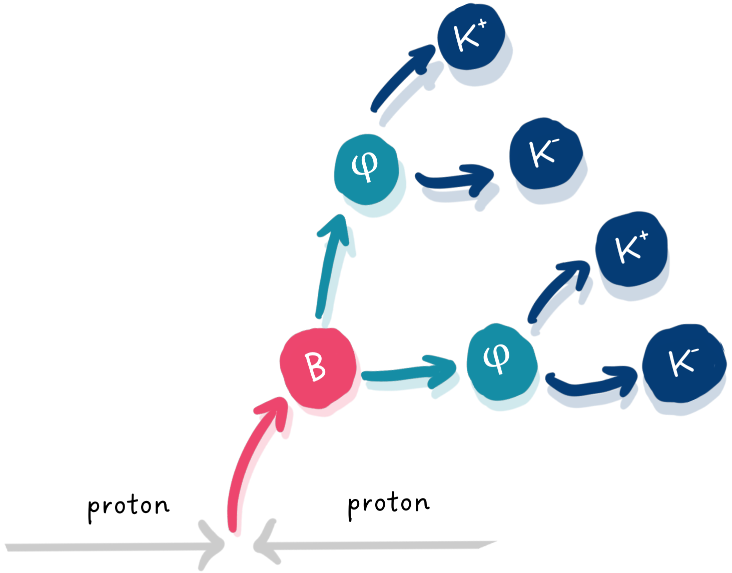
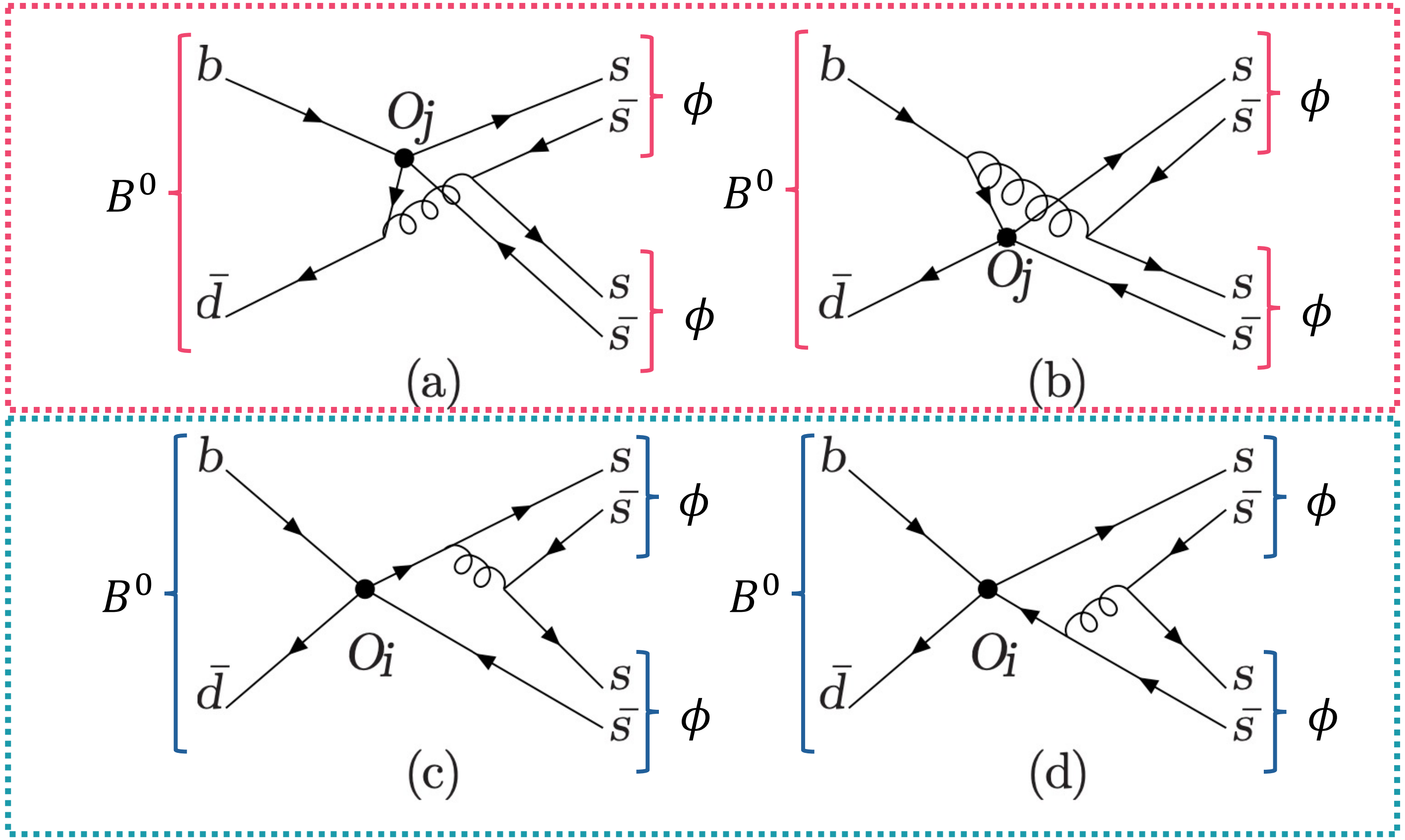
The $B^0 \to \phi\phi$ decay

- Decay of B^0 hadrons into two ϕ mesons via $\bar{b}d \to \bar{s}s$ annihilation
- Heavily suppressed and yet to be observed!



non-factorizable

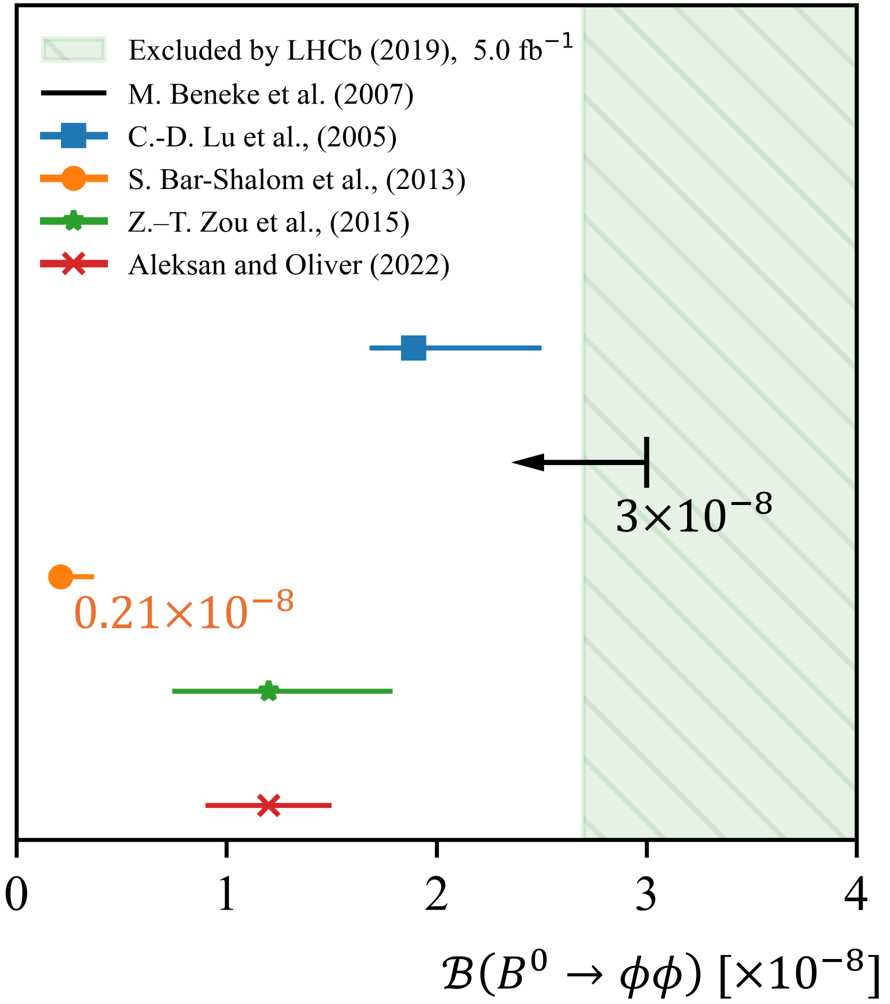


factorizable

Bar-Shalom, S., Eilam, G., & Yang, Y.-D. (2003). $B \to \phi\pi$ and $B^0 \to \phi\phi$ the standard model and new bounds on R-parity violation. Physical Review D, 67(1). https://doi.org/10.1103/physrevd.67.014007

Theory predictions for $\mathcal{B}(B^0 \to \phi\phi)$

- Branching fraction predictions vary by more than an order of magnitude
- **Branching fraction may be enhanced**
  - $\omega - \phi$ mixing
  - rescattering processes
  - R-parity-violating SUSY
- Important for understanding non-factorizable contributions to $B_s^0 \to \phi\phi$
  - $B_s^0 \to \phi\phi$ mode used for CP violation studies
- Probe for new physics!

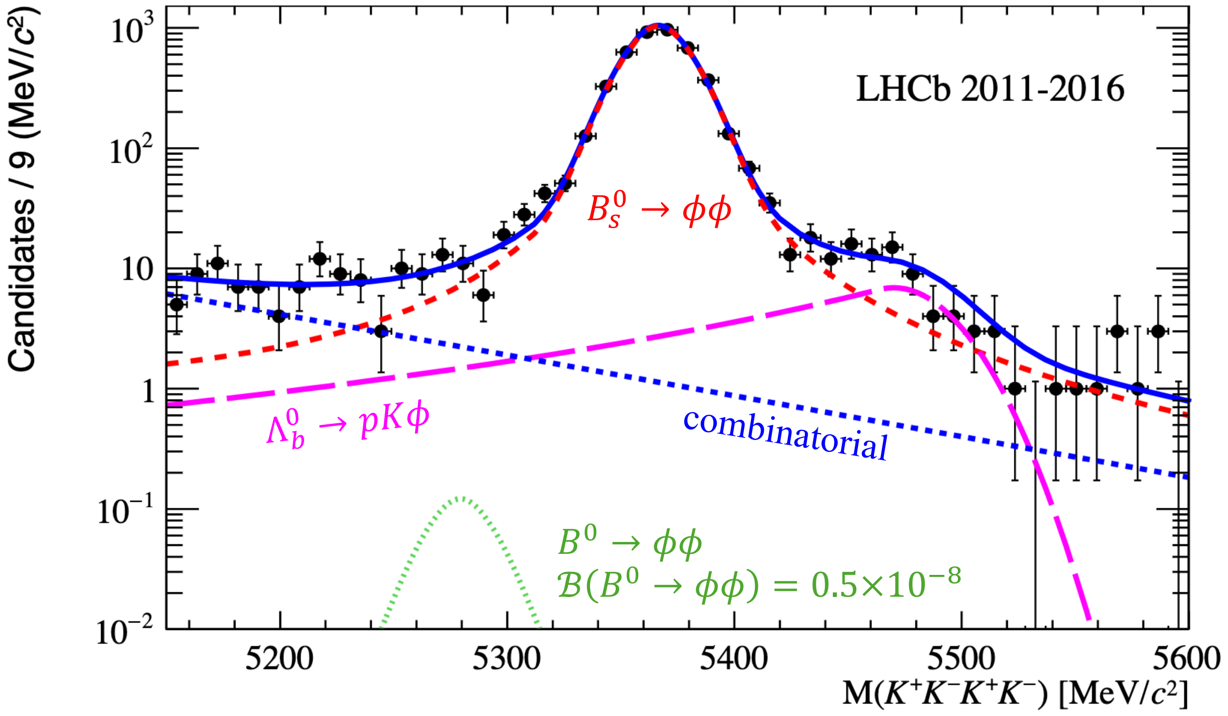


Previous analysis

The LHCb collaboration., Aaij, R., Abellán Beteta, C. *et al.* Measurement of CP violation in the decay $B_s^0 \to \phi\phi$ and search for the $B^0 \to \phi\phi$ decay. *J. High Energ. Phys.* **2019**, 155 (2019). https://doi.org/10.1007/JHEP12(2019)155

- Search done using data up to 2016 alongside $B_s^0 \to \phi\phi$ CP violation analysis - not dedicated search

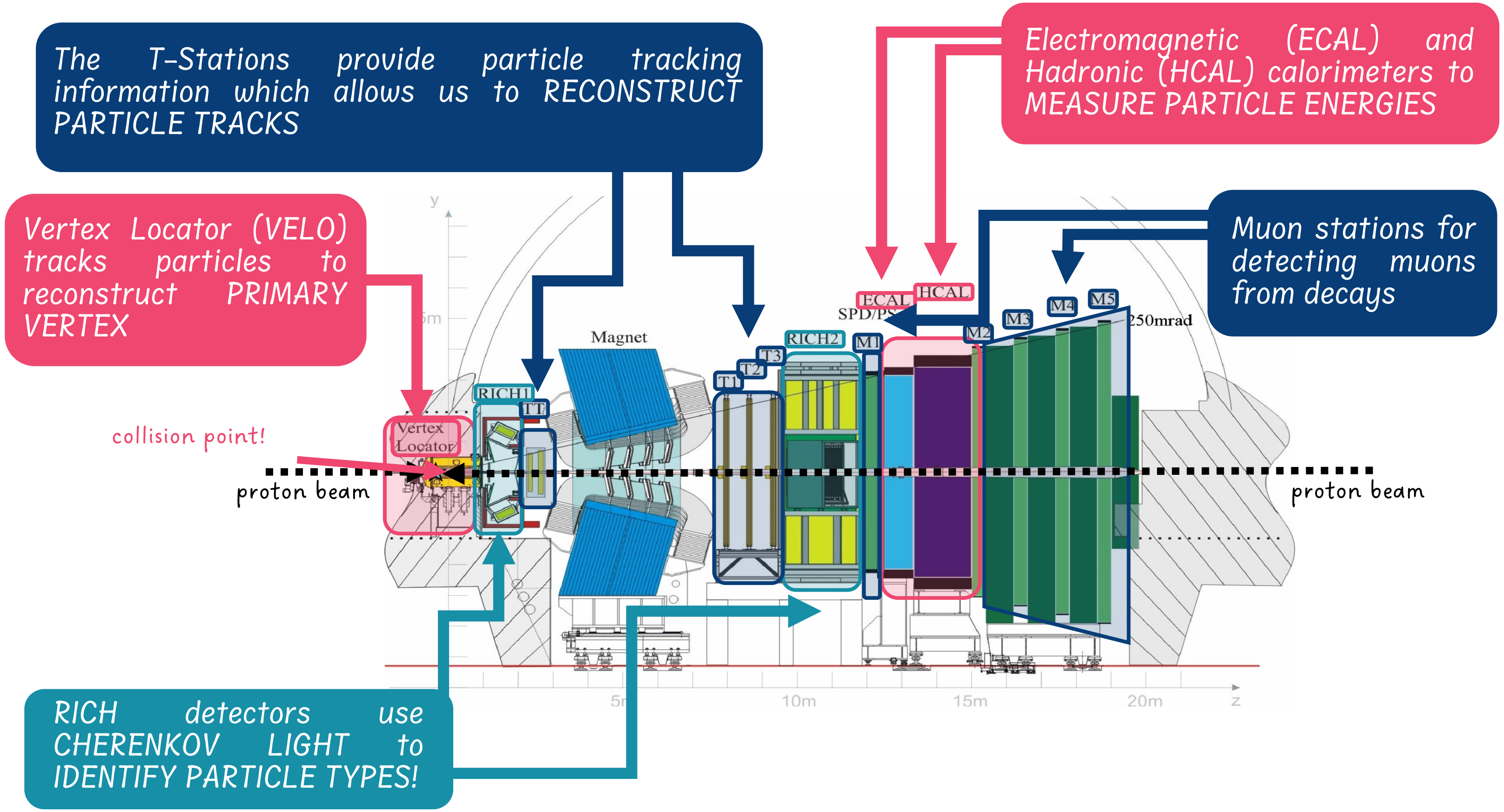
- Set the most competitive limit at 90% CL: $\mathcal{B}(B^0 \to \phi\phi) < 2.7 \times 10^{-8}$



We are now doing the first dedicated search at LHCb!
Using full Run 1 + Run 2 data

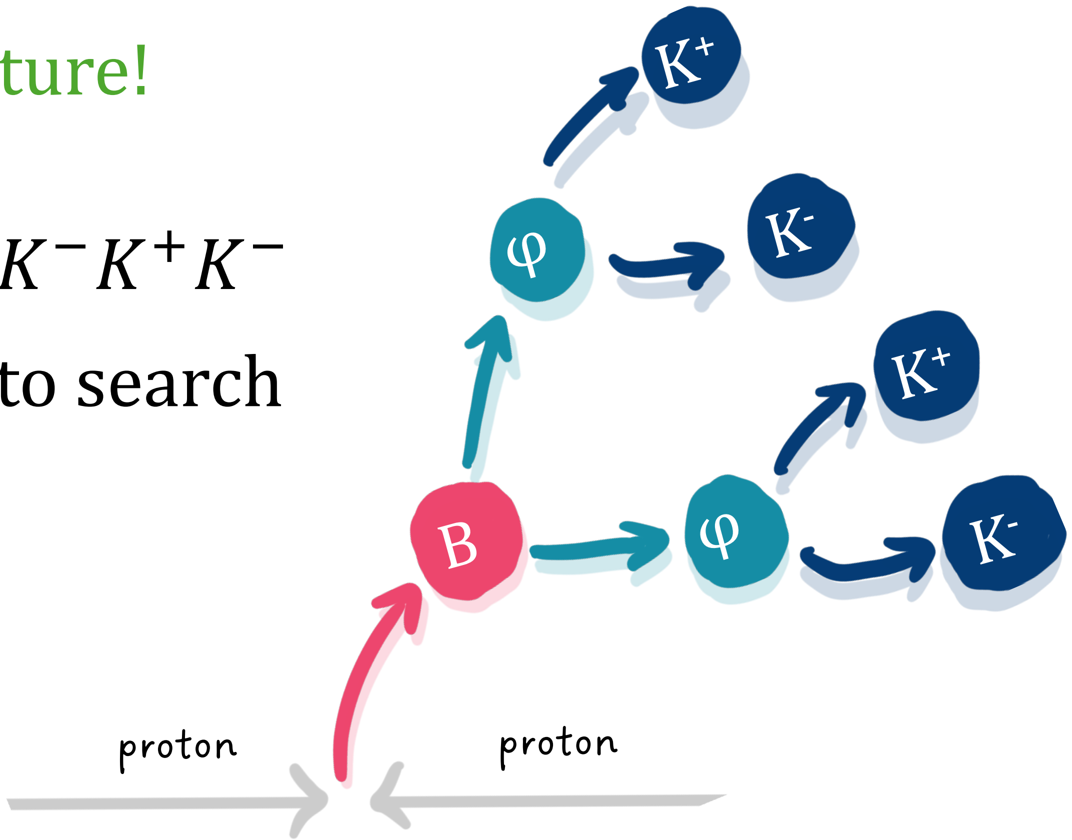
The LHCb detector

- Based at Interaction Point 8 on the LHC ring
- Forward-arm spectrometer designed for the study of b-hadrons
- This study uses data from Run 1 and Run 2 (2011 – 2018) corresponding to 9 fb^{-1} of data



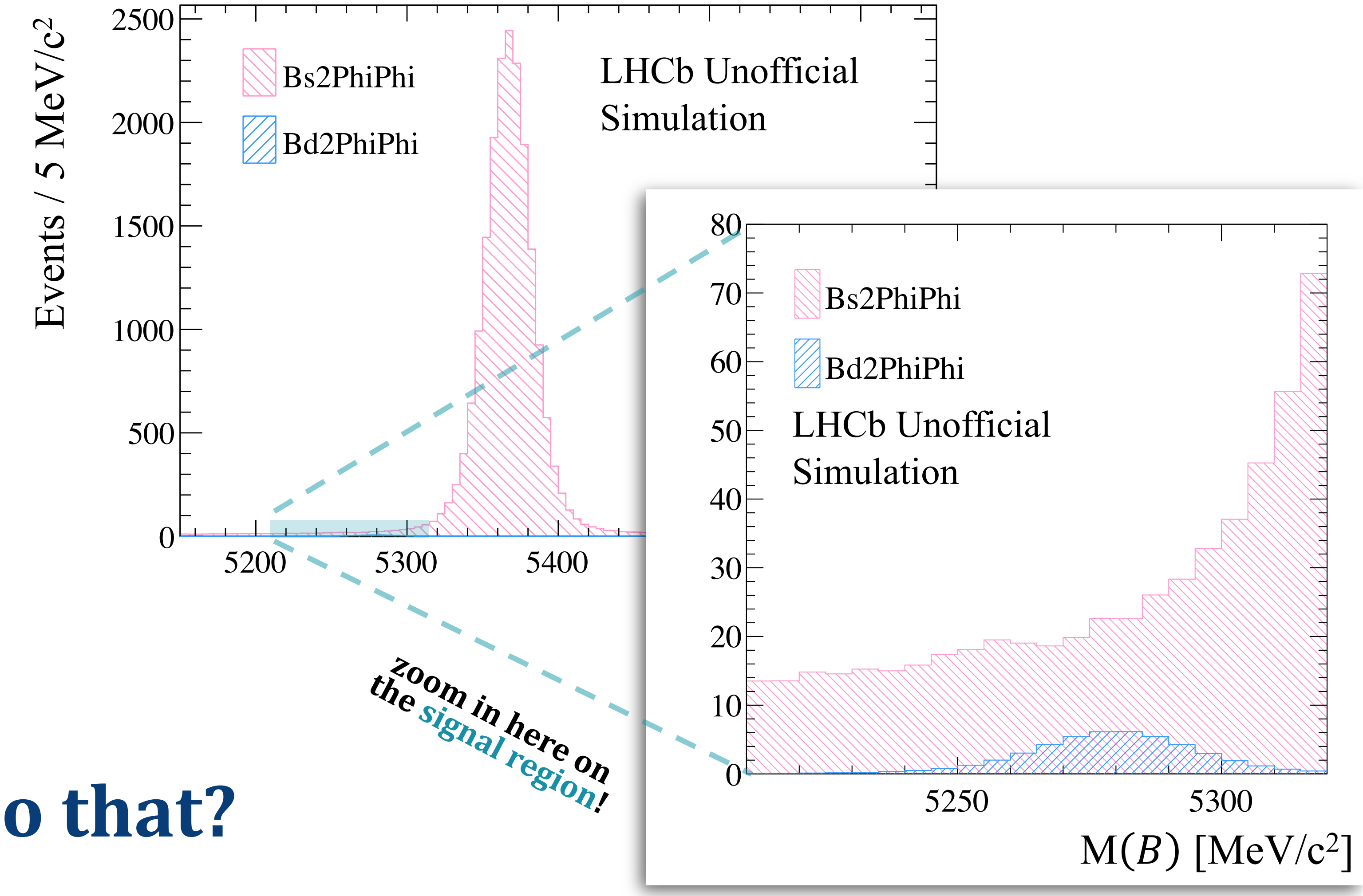
How do we search for $B^0 \to \phi\phi$?

- Four-kaon final state – clean signature!
- Use LHCb triggers to select events reconstructed as $B^0_{(s)} \to \phi\phi \to K^+K^-K^+K^-$
- Plot the four-kaon invariant mass to search for a peak at the B^0 mass



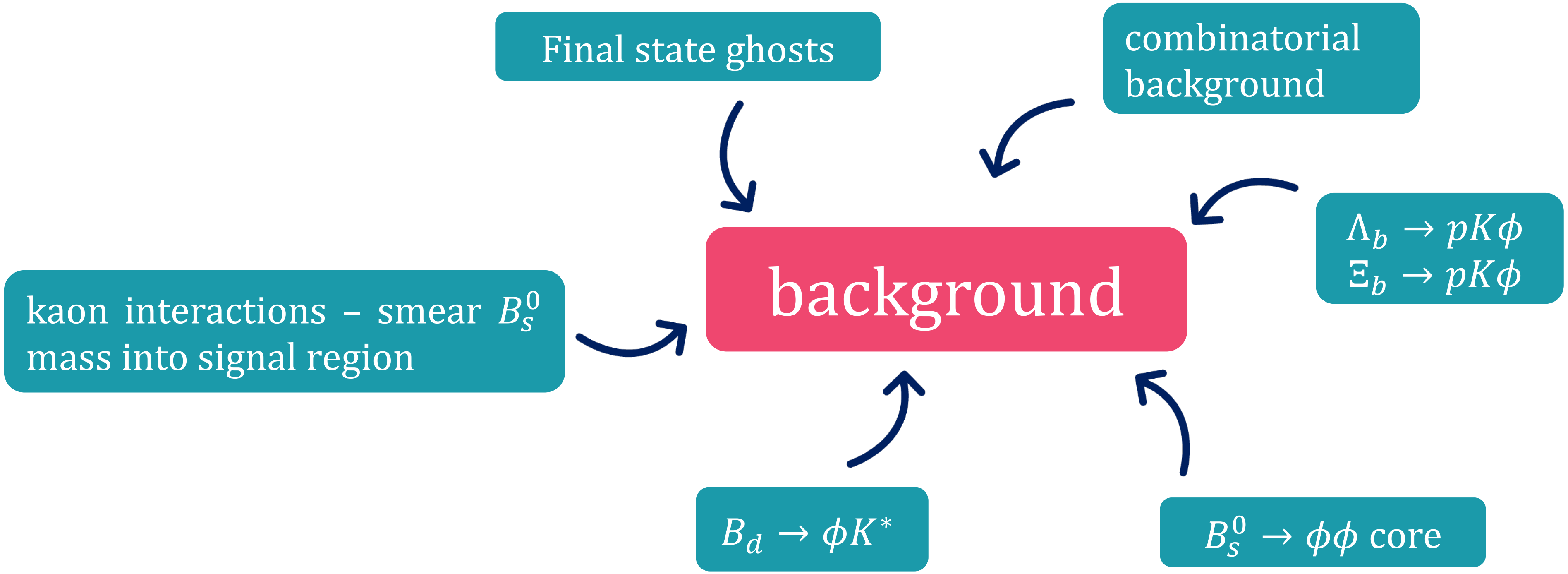
Not as simple as it seems…

- Branching fraction of $B_s^0 \to \phi\phi$ is 1.85×10^{-5}
- $B^0 \to \phi\phi$ has on the order of 1500 times smaller rate!
- Want to keep the BLUE events and remove the PINK events to improve our sensitivity to the signal



How do we do that?

The challenge – controlling backgrounds



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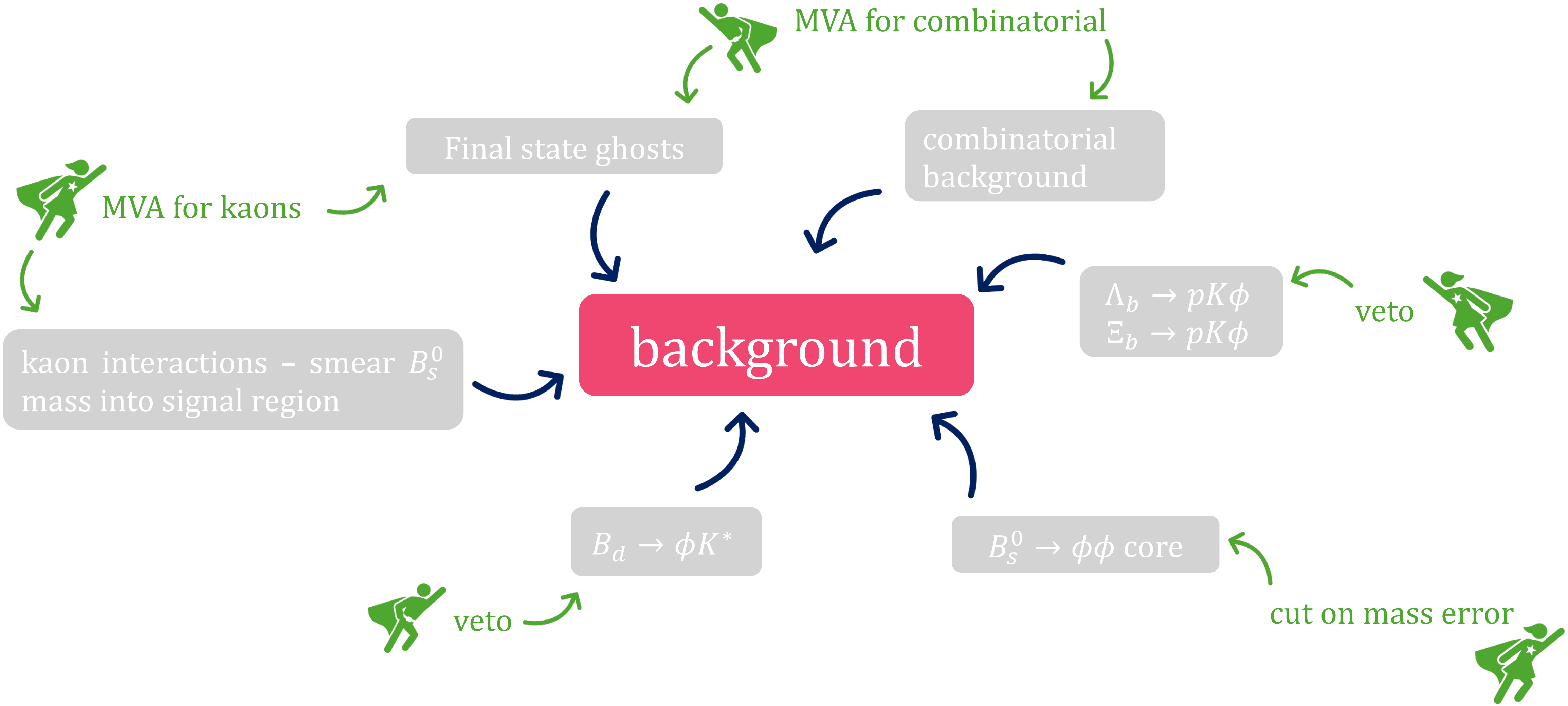
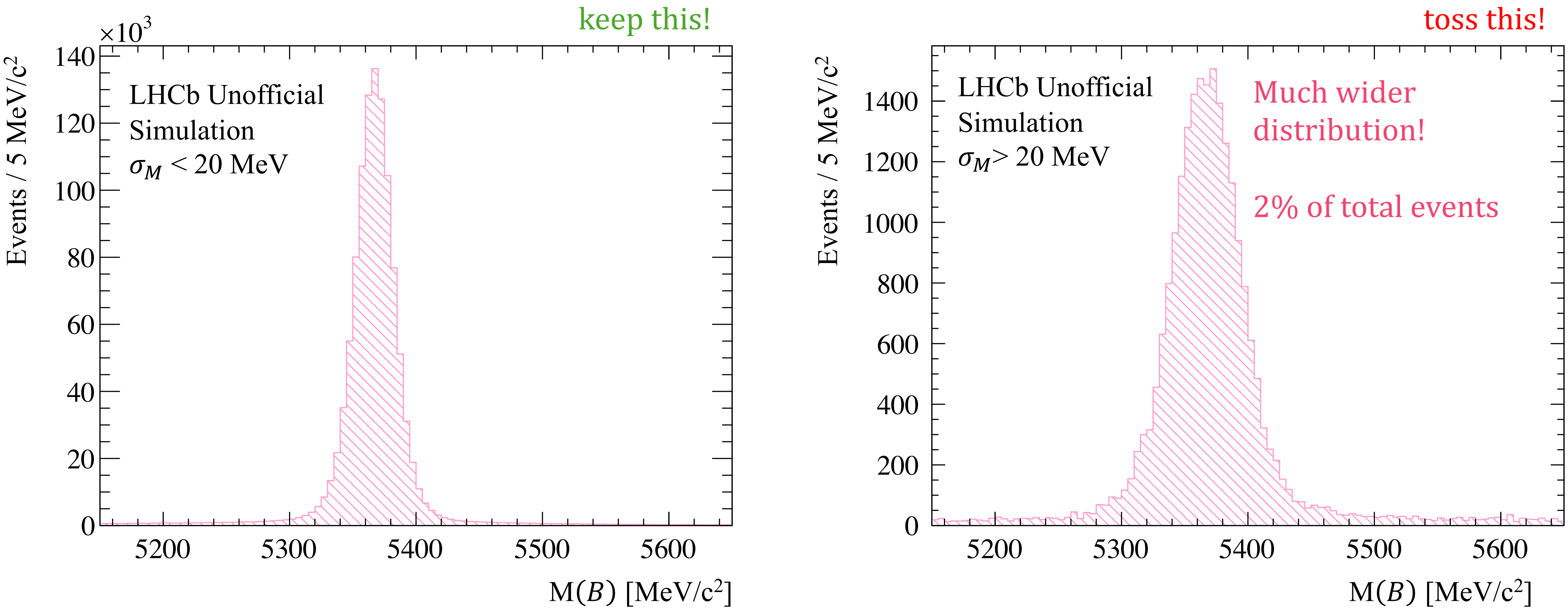
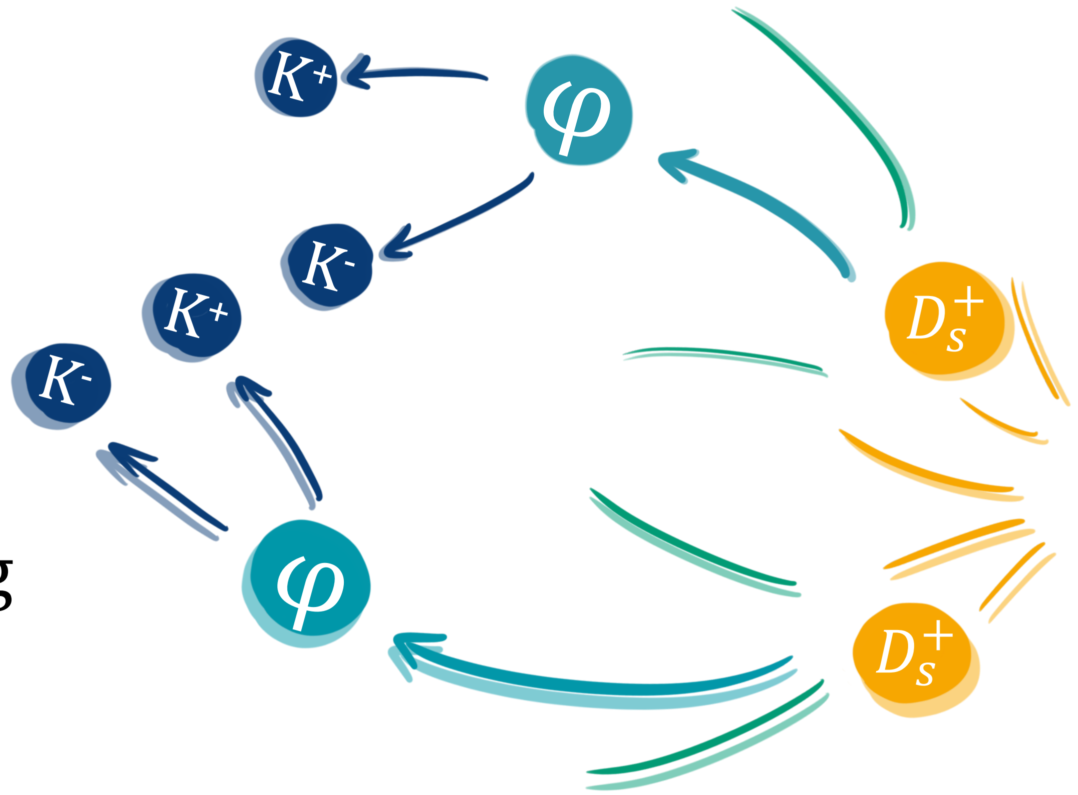


Why do we cut on the mass error?



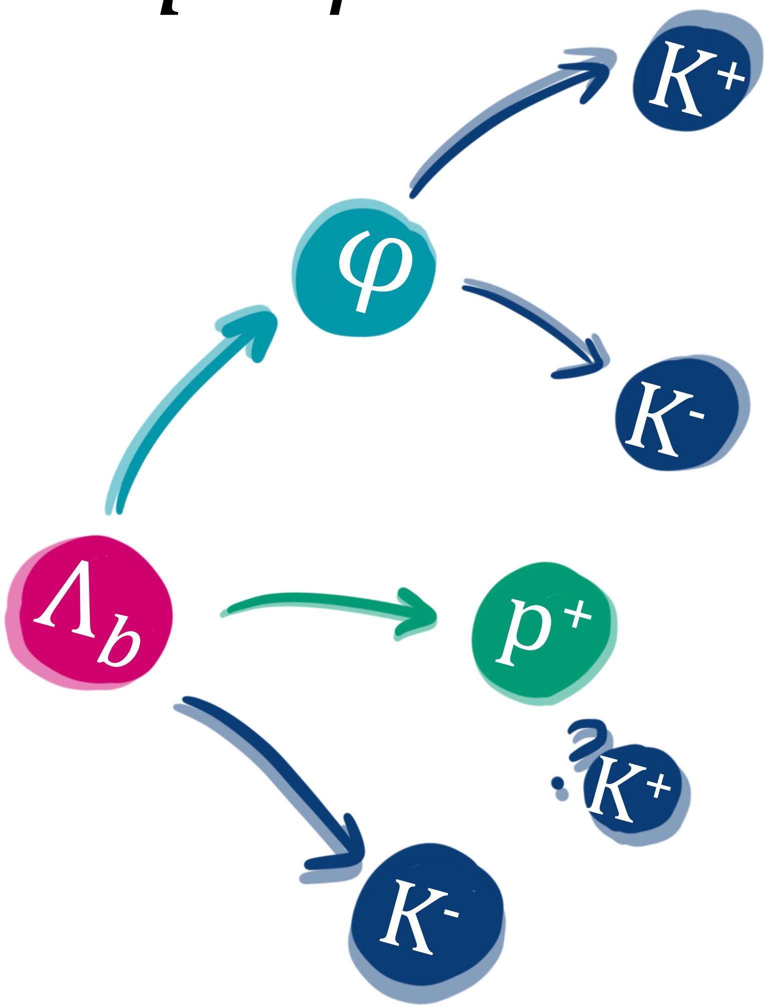
What is combinatorial background?

- Comes from combining real ϕ mesons that have not come from the same process
- An example D_s^+ decays, which have a large branching fraction to ϕ mesons
- This background is controlled using multivariate classifiers trained on B-hadron kinematics and decay cone isolation parameters



Why are $\Lambda_b \to pK\phi$ and $\Xi_b \to pK\phi$ background?

- These decays can mimic $B^0_{(s)} \to \phi\phi$ if the proton is misidentified as a kaon
- Normally high momentum protons beyond the threshold of RICH detectors – worse particle identification
- Veto applied to high momentum tracks on particle identification variables



Why are kaon interactions background?

1. Kaon without interaction has nice continuous track

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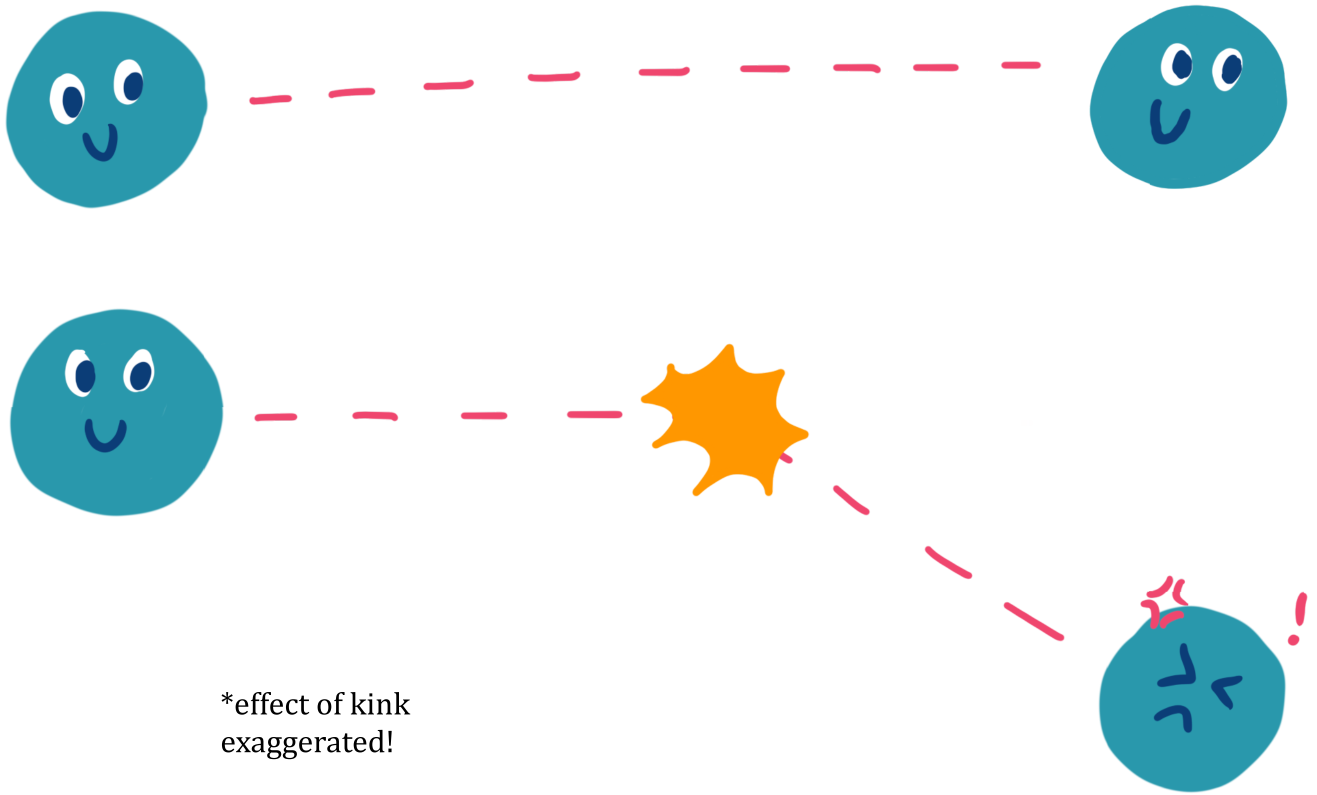

*effect of kink exaggerated!

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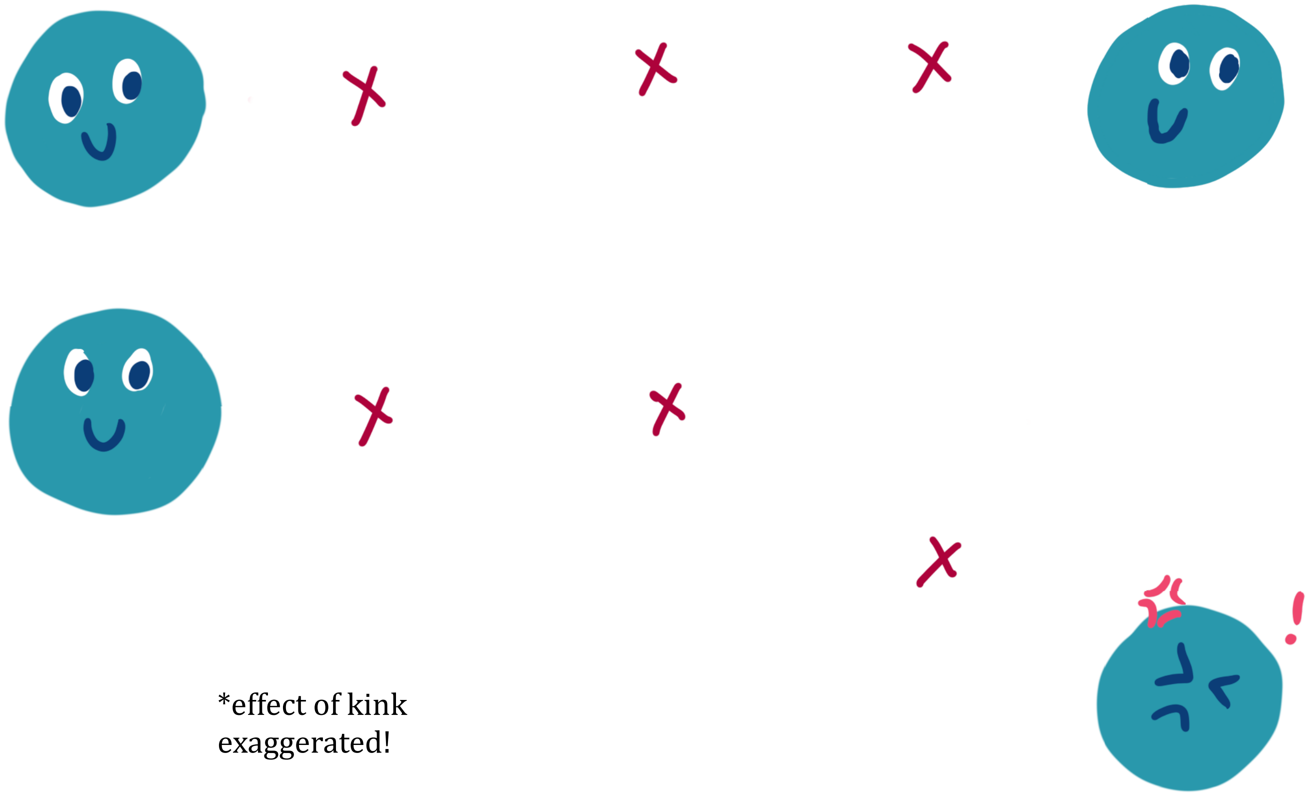

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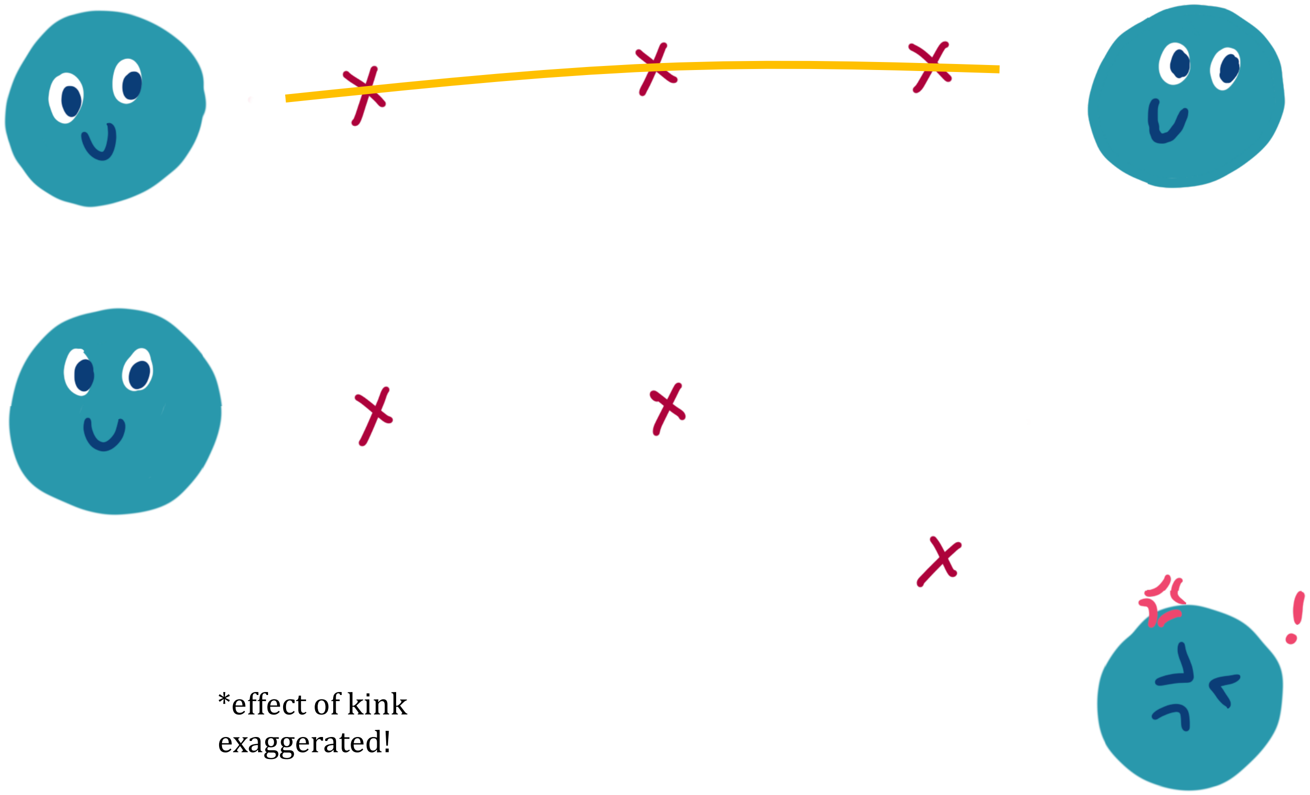

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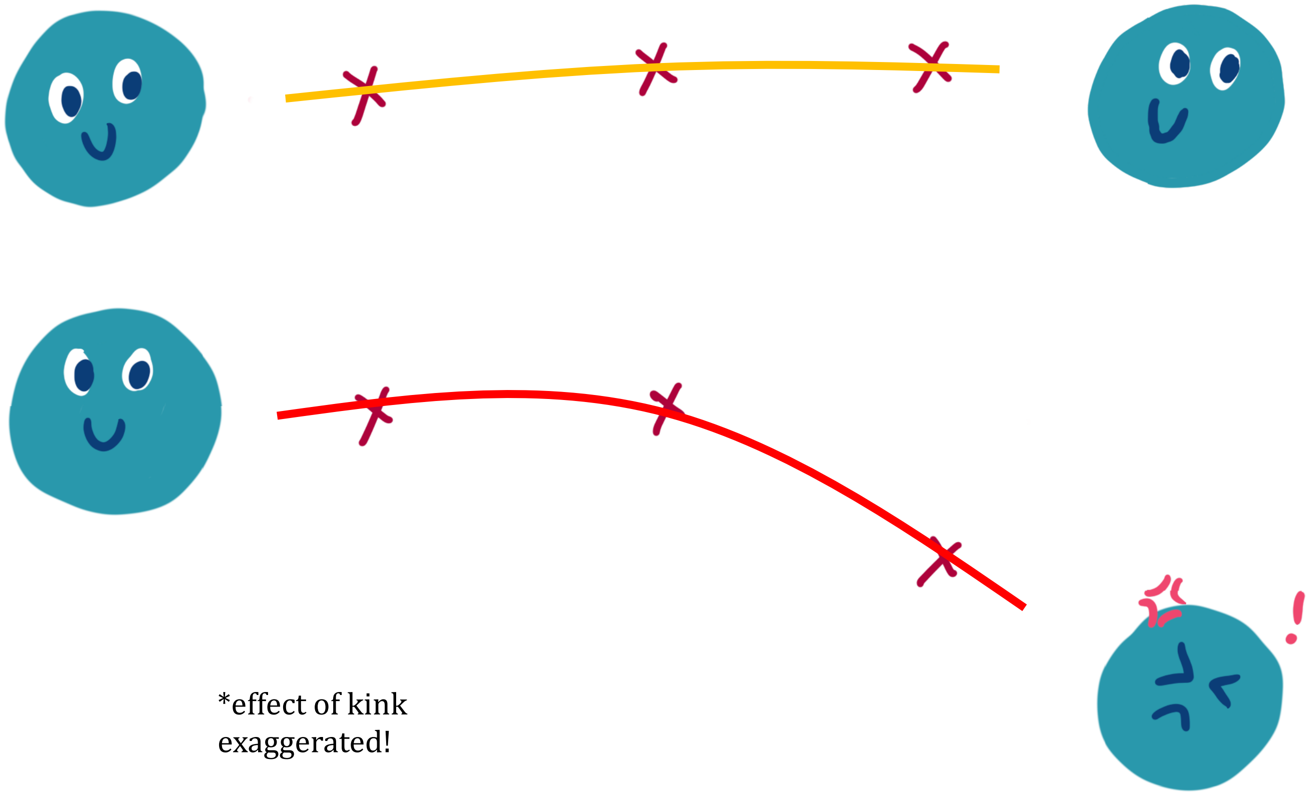

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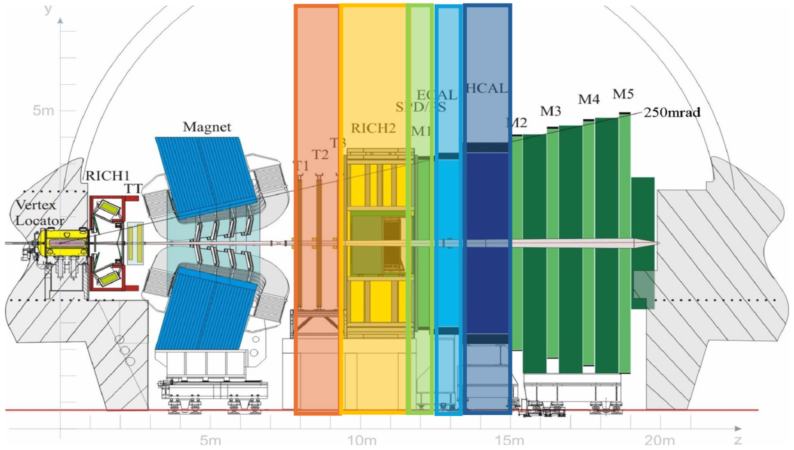
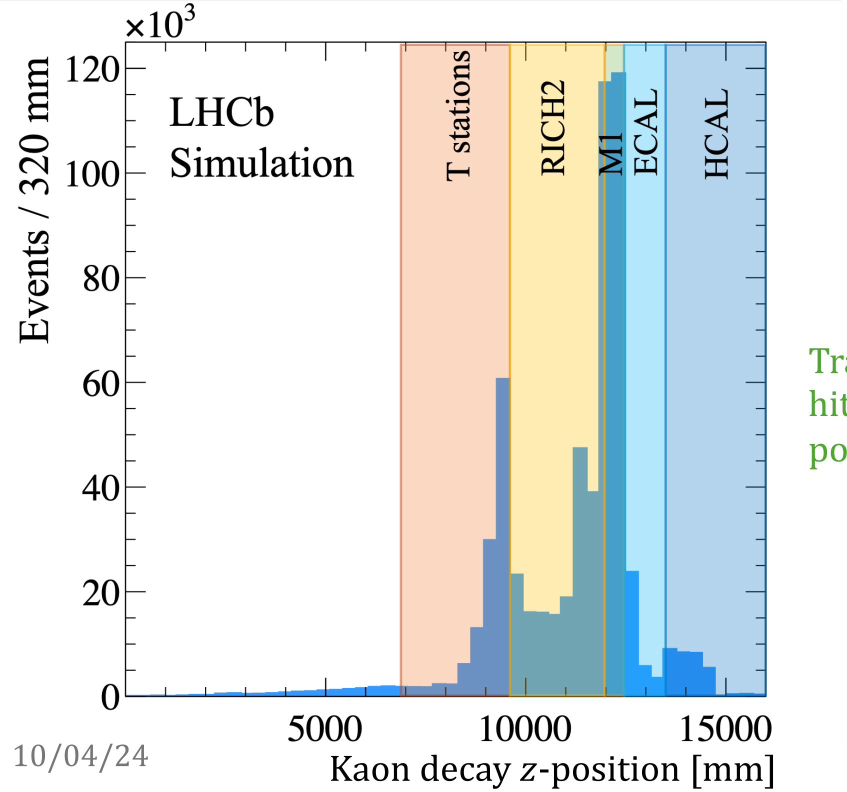
1. Kaon without interaction has nice continuous track
2. Kaon that decays in flight or has hadronic interaction will have a kinked track
3. In the detector we see hits in individual tracking stations
4. Hits used to reconstruct track and measure particle momentum
5. Kinked track will be poorly reconstructed
6. **Incorrectly reconstructed momentum and therefore incorrect reconstruction of *B*-hadron mass**

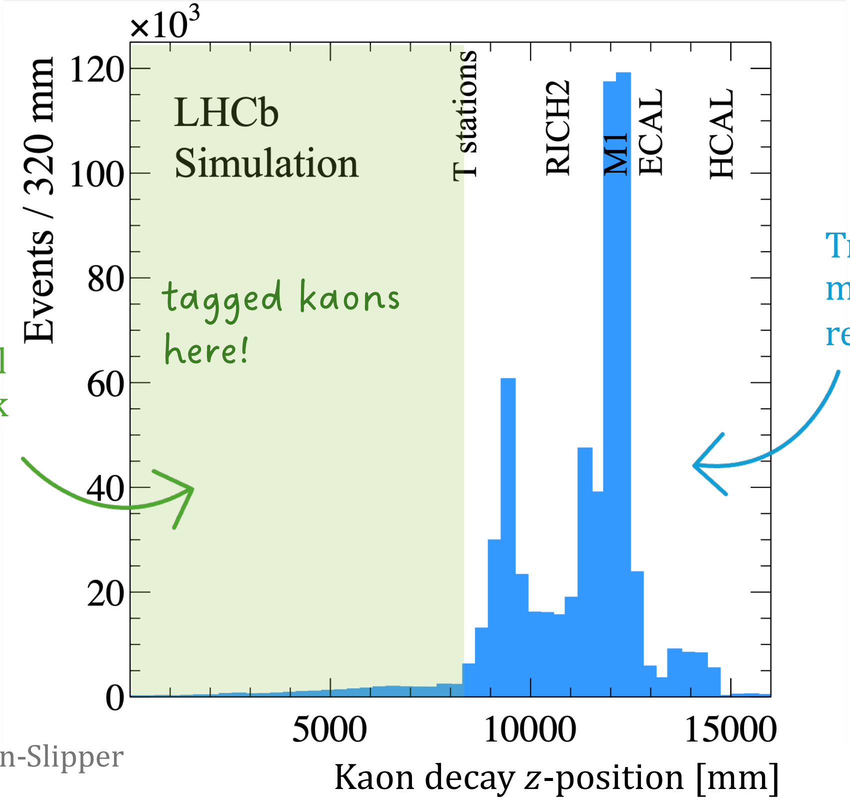
What does this look like?



- Using MC simulation, we can select events where at least one of the kaons has decayed before the tracking stations and therefore have a bad track
- Use the kaon decay vertex position to 'tag' a kaon as interacted



Track kinks before all hits measured – track poorly reconstructed

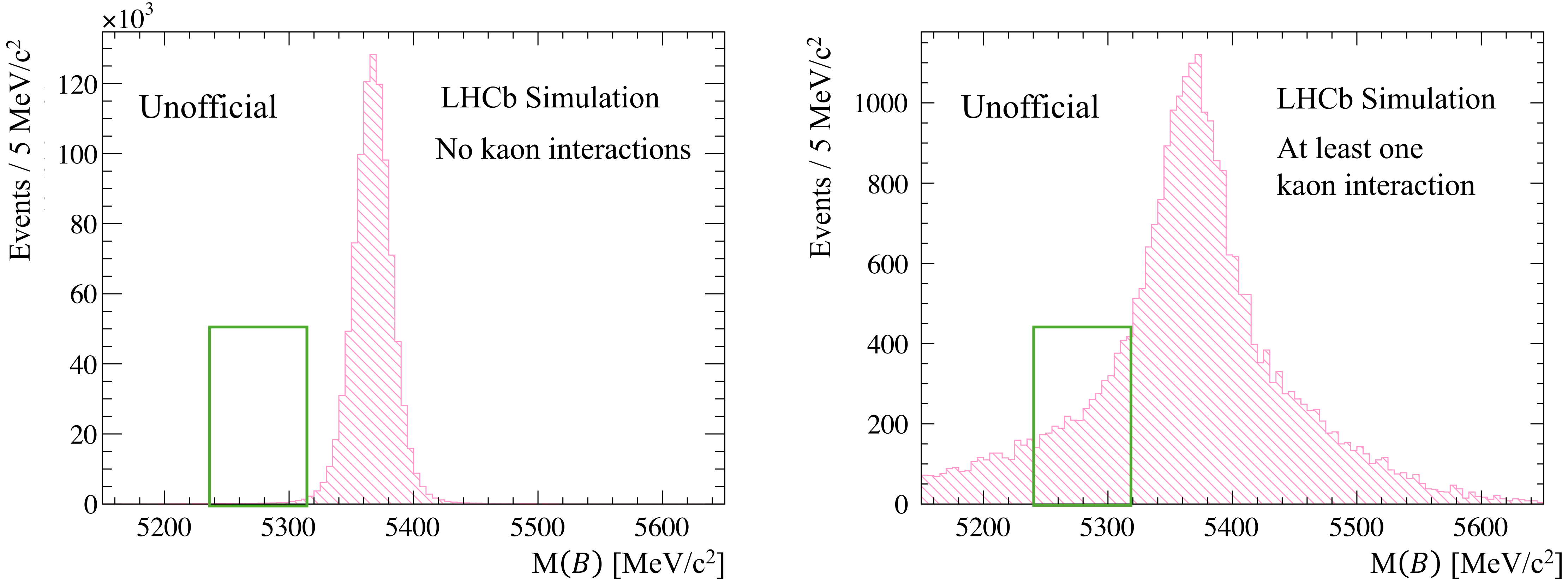


Track kinks but all hits measured – track well reconstructed

What does this look like?

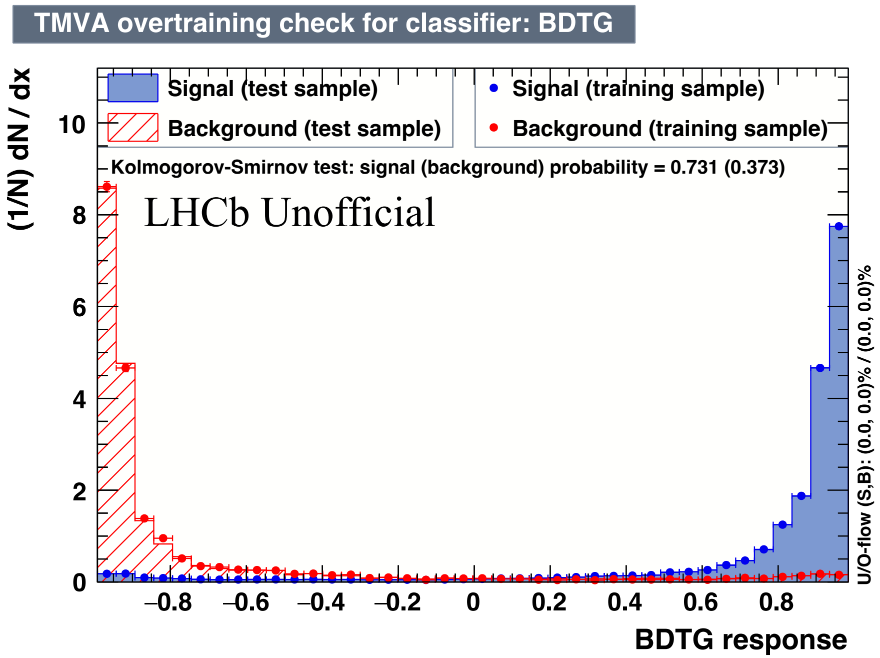
- Now we tagged the interacted kaons, we can look at how this affects the invariant mass distribution

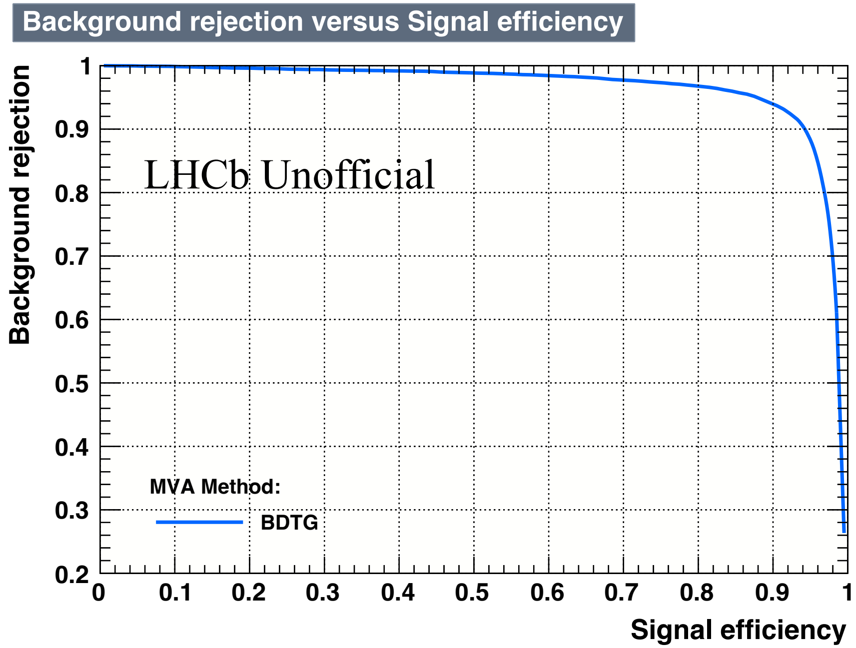
At least one interacted kaon in truth matched MC
- **3% of total sample**
- **34% of blinded region**



How do we remove this background?

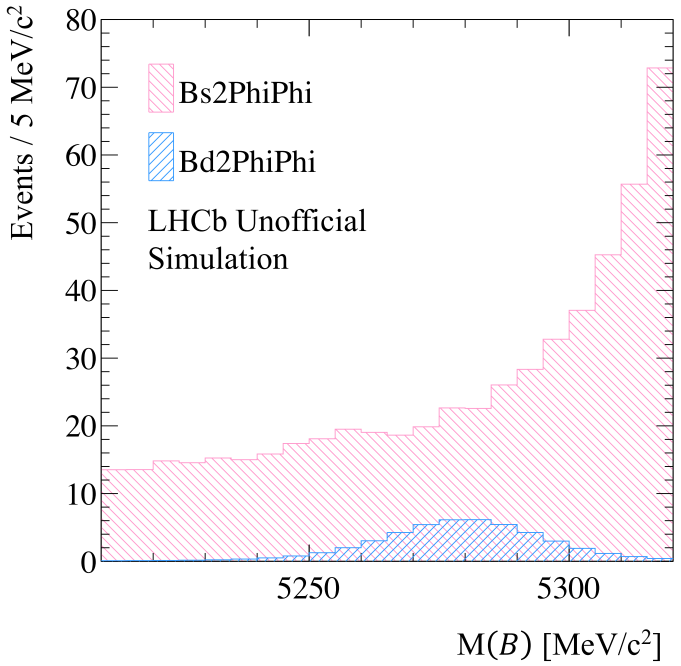
- Train a Boosted Decision Tree
- Use variables relating to the track quality, kinematics and number of hits to discriminate
- Per kaon track, achieve 95% signal retention for 88% background rejection



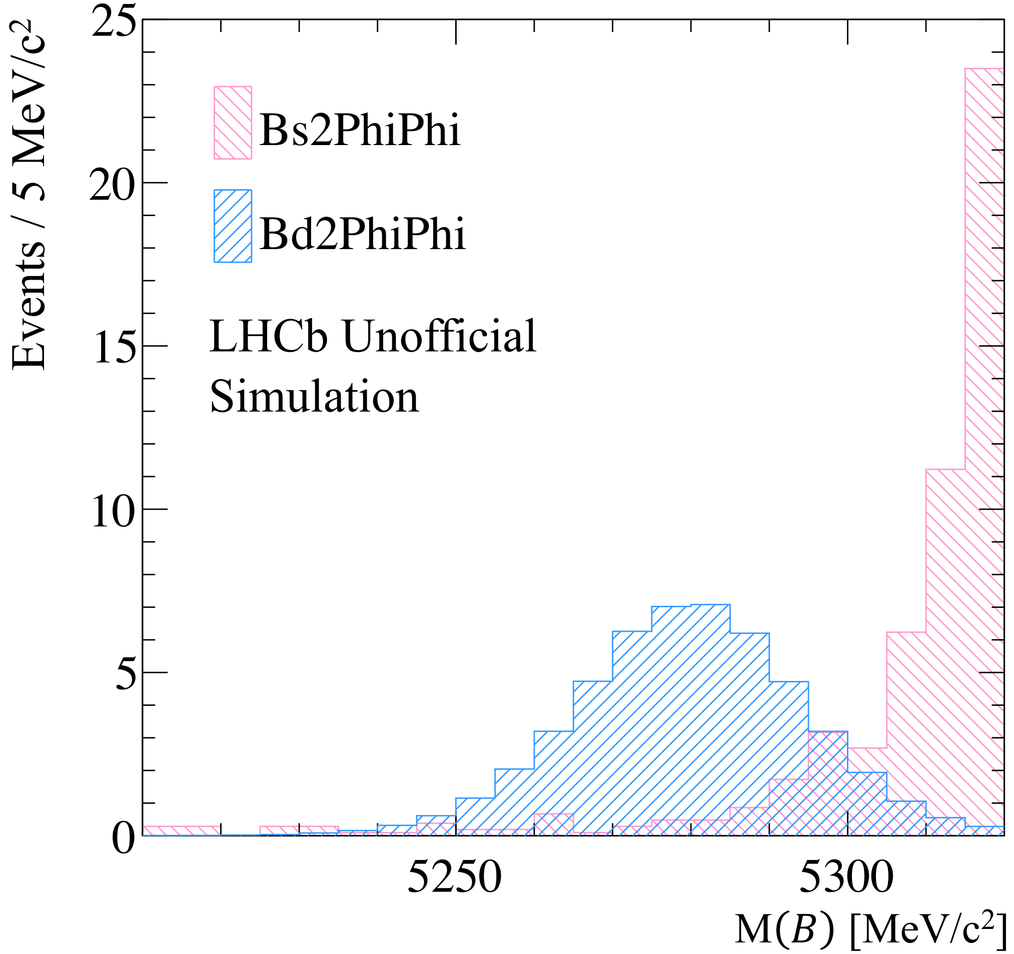


How do our selections improve things?

- Using signal MC – we see our signal region is much cleaner!



Applying all selection criteria – including trigger, MVAs, vetoes and other cuts



So how well do we do?

Fit to blinded Run 2 data returns yields of order:

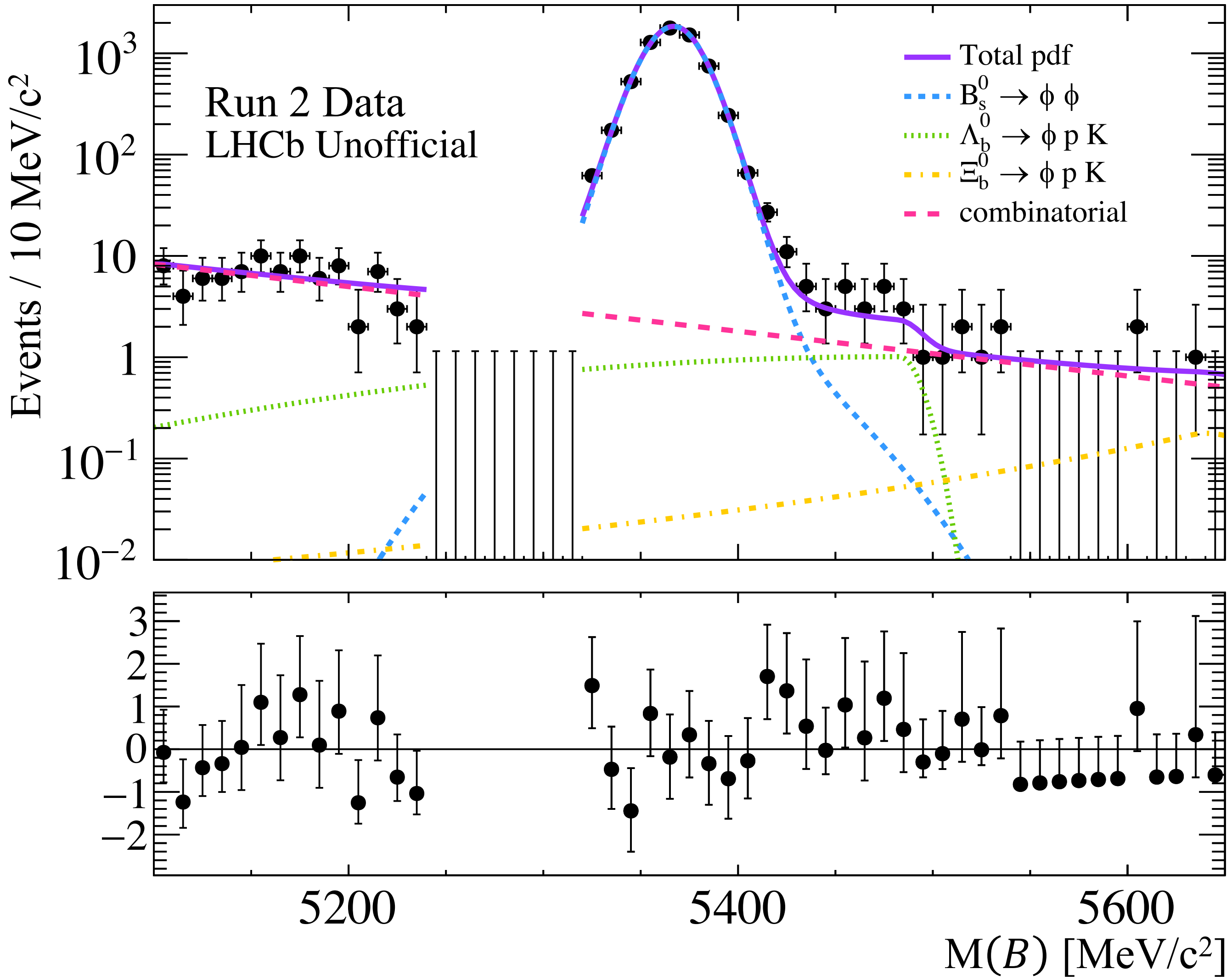
- B_s^0 ~6500
- $\Lambda_b^0 \sim 30$
- $\Xi_b \sim 2$
- Combinatorial ~ 100

Integrate shapes in blinded region:

- $B_s^0 \sim 16$
- $\Lambda_b \sim 6$
- $\Xi_b \sim 1$
- Combinatorial ~ 26

Total ~ 50

PRELIMINARY



How does this compare to the previous analysis?

Comparing previous analysis with current analysis of Run 2:

<u>Previous analysis – 2011 – 2016</u> (5fb^{-1})

- $N_{B_s^0} = 4453 \pm 69$
- Total number of background events in signal region: **141**

<u>Current analysis – 2015 – 2018</u>

- $N_{B_s^0} \sim 6500$
- Total number of background events in signal region: $\sim$**50**

1.4 times more signal, factor 2.8 times less background

Overall factor 4 improvement in purity!

Run 1 data still to be added!

Summary and outlook

- Now understand the backgrounds very well – a factor 4 improvement on last published work!
- Analysis ongoing – Run 1 data still to be added
- Expected sensitivity sufficient to challenge a range of branching fraction predictions

Will be interesting to see what we see – **not clear what we are expecting from BF predictions!**

PRELIMINARY