New methods to boost sensitivity in the search for $B^0 \to \phi\phi$

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Rencontres du Vietnam

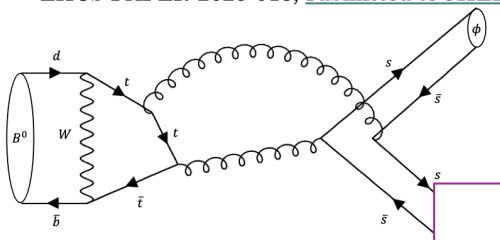
Modern Methods in Experiment and Analysis

The search for $B^0 \to \phi\phi$: recap from Monday

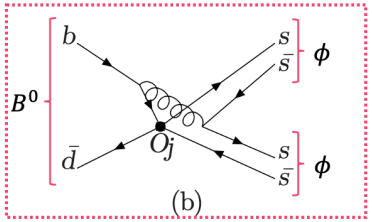
LHCb-PAPER-2025-018, submitted to JHEP

Search for $B^0 \to \phi\phi$

- **Complementary study**
- $\bar{b}d \to s\bar{s}$ annihilation: loop, Cabibbo and OZI suppressed
- Branching fraction may be enhanced in many scenarios: new physics, $\omega - \phi$ mixing…
- Predictions at ~ 10^{-8} level - vary by order of magnitude
- Leading-order non-factorizable contributions to $B^0 \to \phi\phi$ are higher-order corrections to $B_s^0 \to \phi\phi$



non-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

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- Charmless $P \to VV$
- relates to golden mode $B_s^0 \to \phi\phi$
- theory predictions very varied

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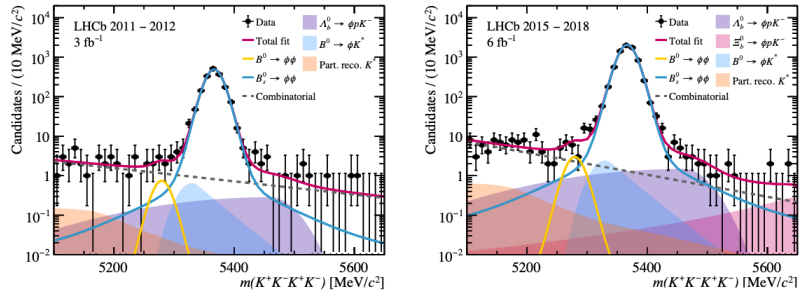
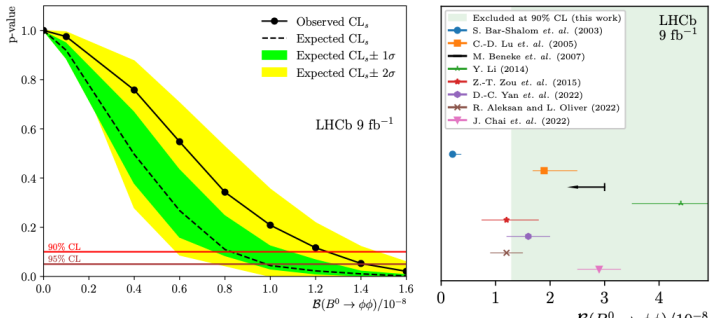
New limit set on branching fraction

- BF from fit to invariant mass, relative to $B_s^0 \to \phi\phi$
- Set a new limit on the branching fraction at 90% confidence level

$\mathcal{B}(B^0 \to \phi\phi) < 1.3 \times 10^{-8}$

- **factor of two better than previous limit**





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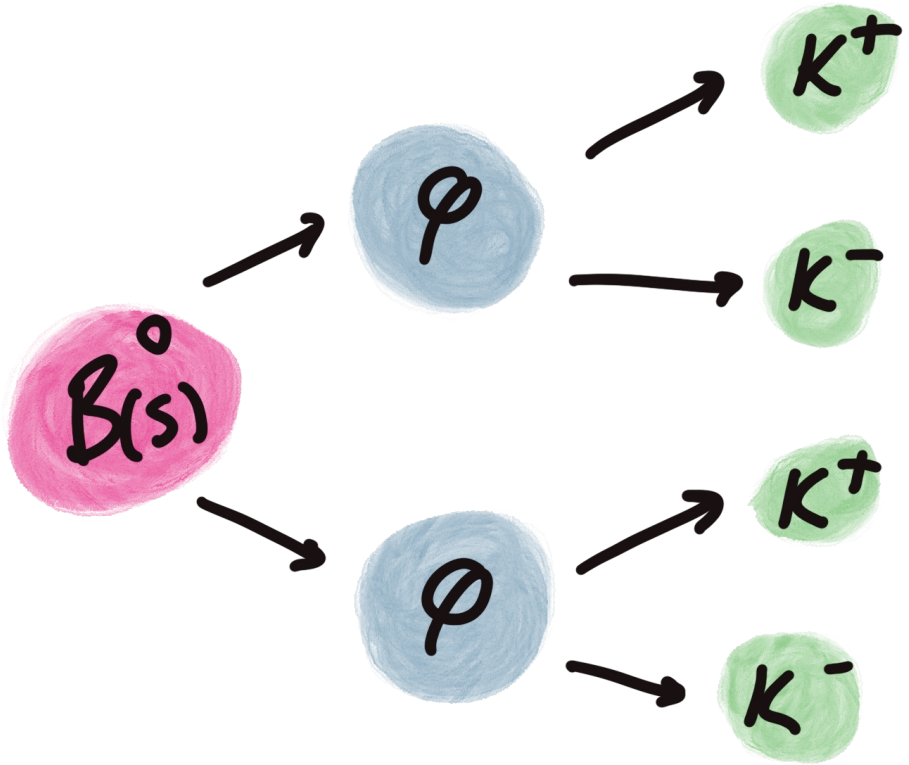
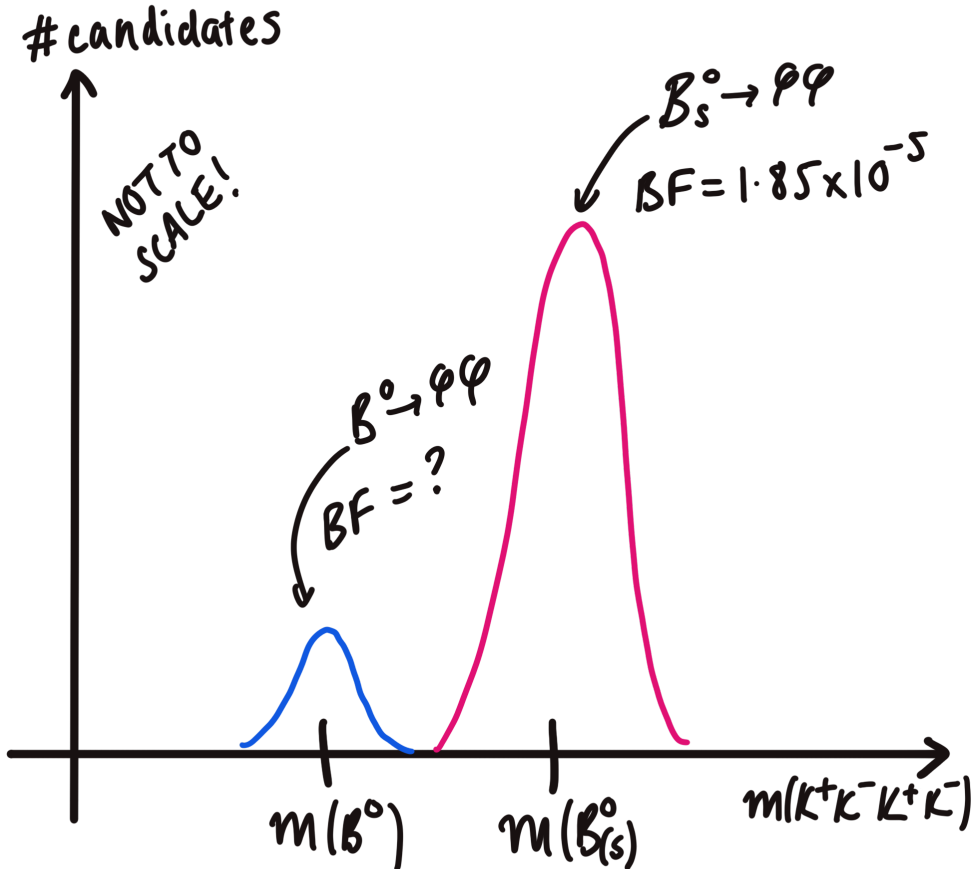
New limit set on the branching fraction at $\mathcal{B}(B^0 \to \phi\phi) < 1.3 \times 10^{-8}$ 90% C.L.

Analysis procedure



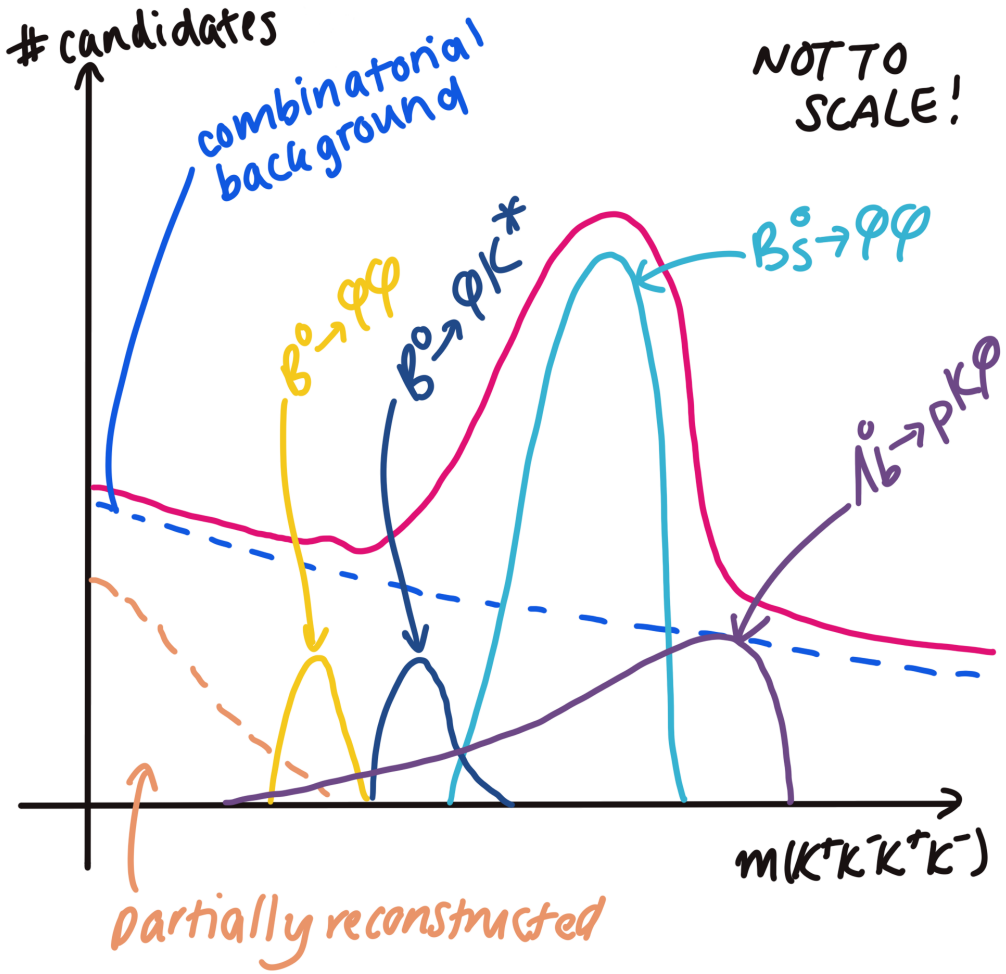
Select candidates:

- Pair charged kaons to form ϕ mesons
- Pair ϕ mesons consistent from $B^0_{(s)}$



Fit the $K^+K^-K^+K^-$ invariant mass distribution and look for significant peak at B^0 mass, using $B^0_s \to \phi\phi$ as control mode

Sounds simple?



Lots of background can mimic the $B^0_{(s)} \to \phi\phi$ – how can we search for a tiny signal on top of the backgrounds?

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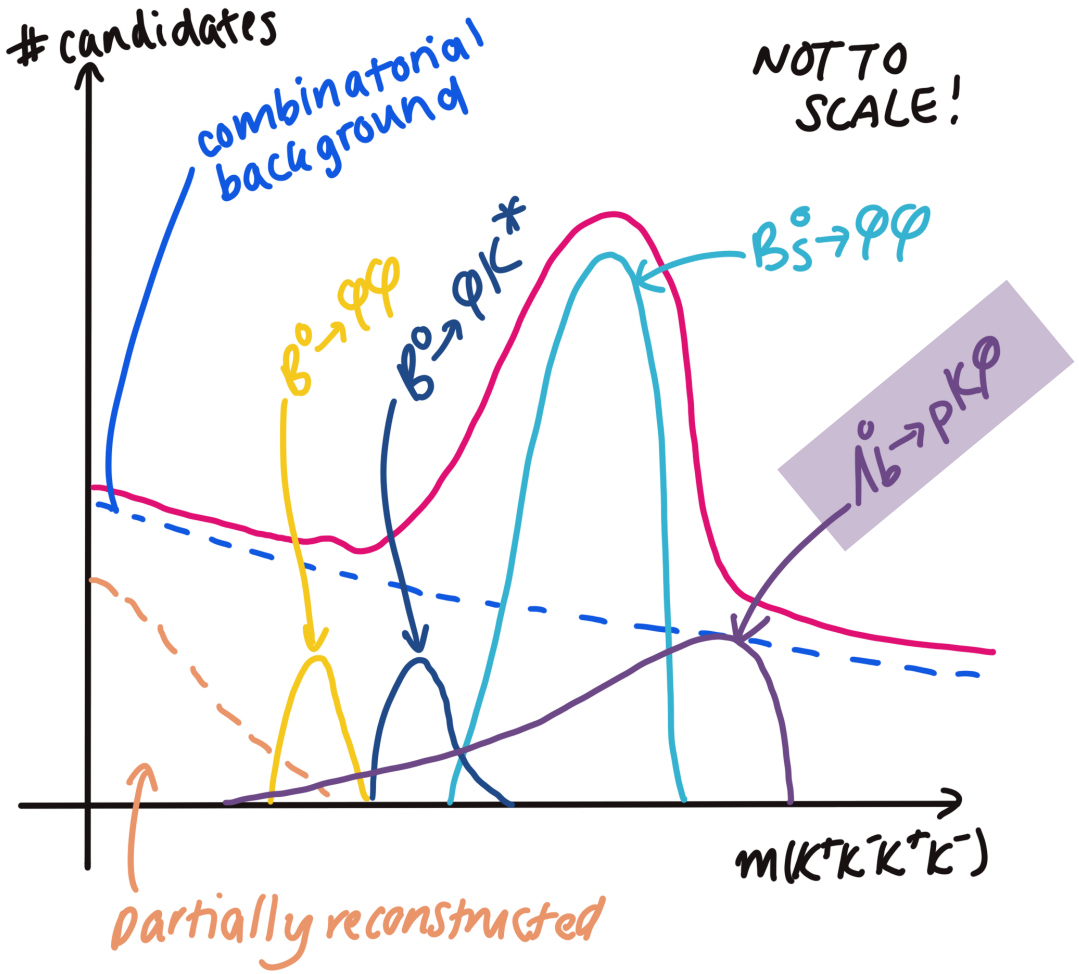

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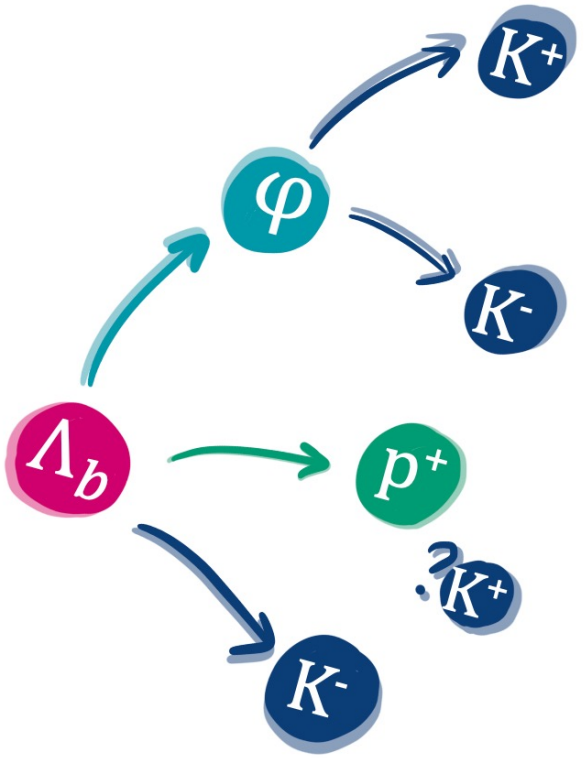
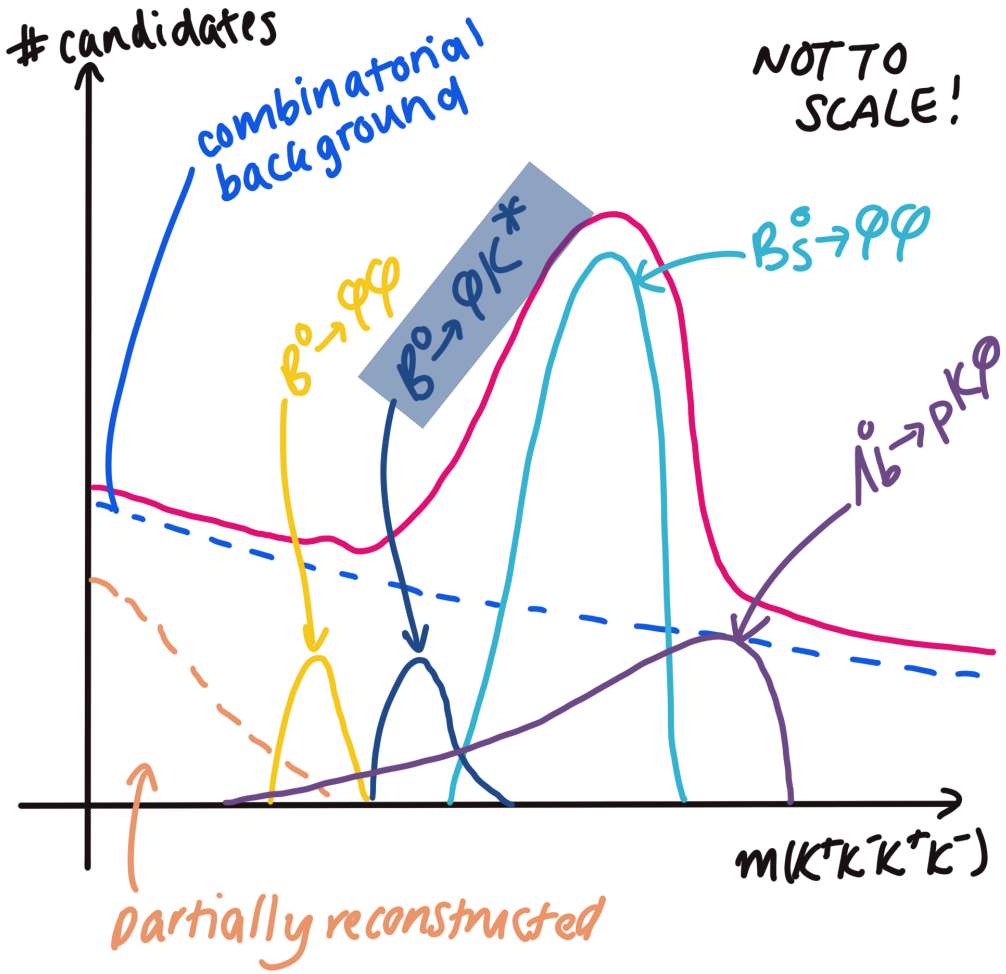


If proton looks like a kaon – looks like the same final state

Sounds simple?



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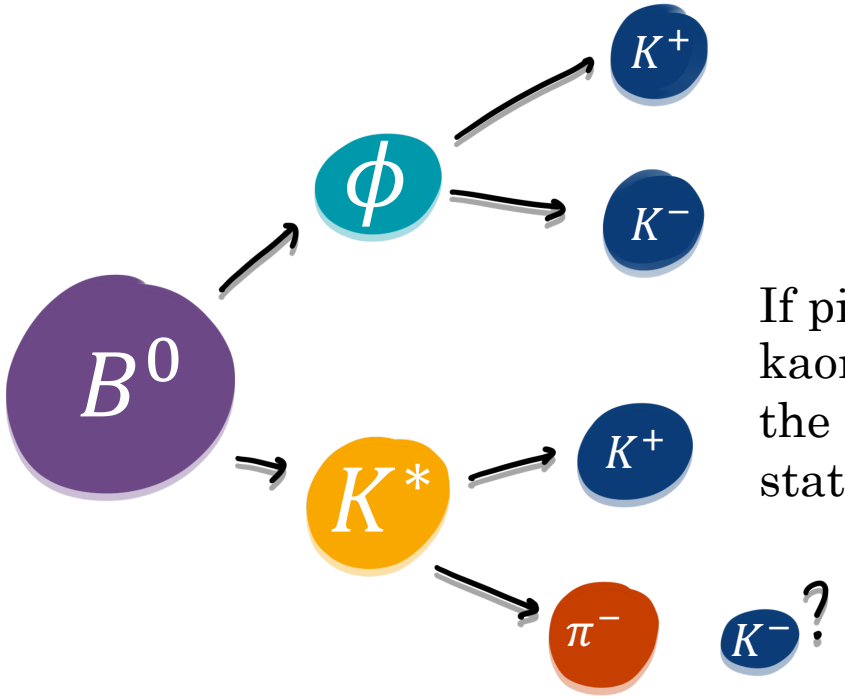

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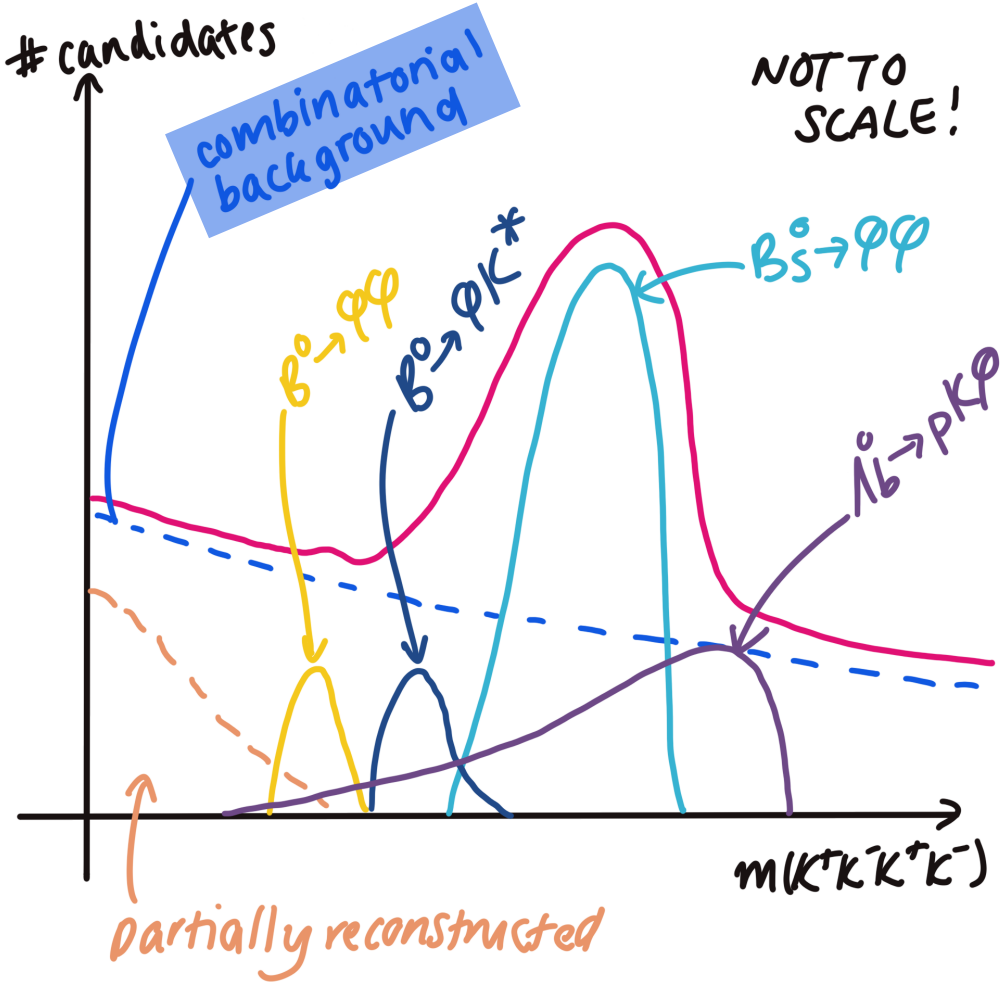
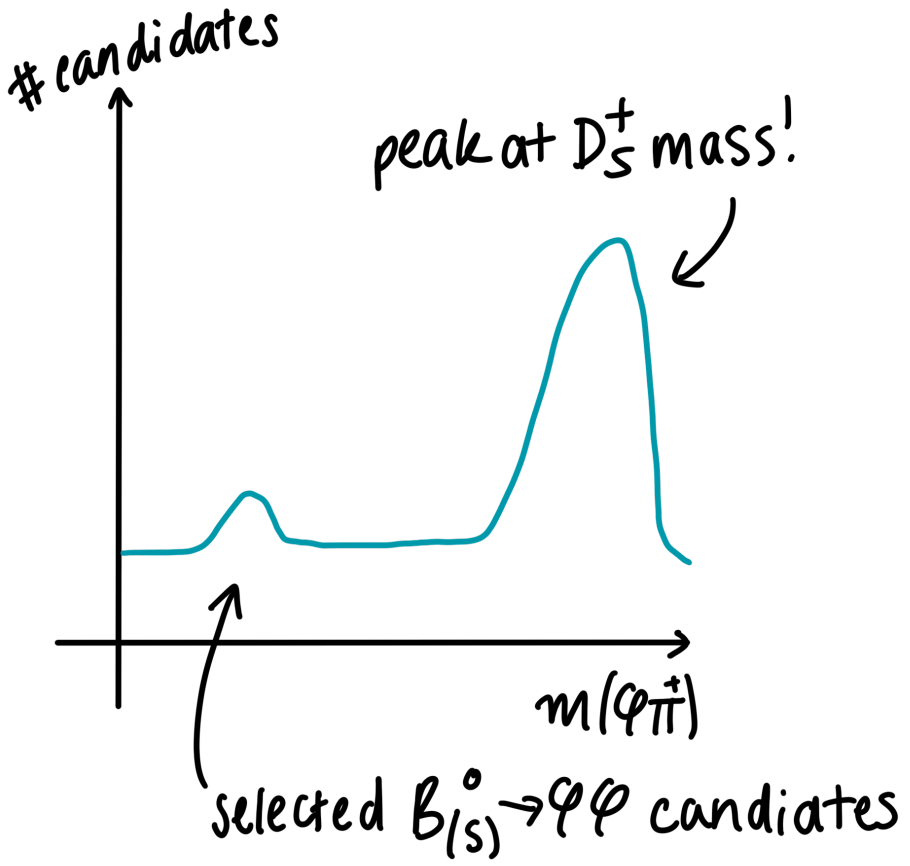


Lots of background can mimic the $B^0_{(s)} \to \phi\phi$ – how can we search for a tiny signal on top of the backgrounds?

Can get pairs of ϕ mesons from different $D_s^\pm$ decays!

How can we use the fact we get lots of ϕ mesons from D_s^+ decays?

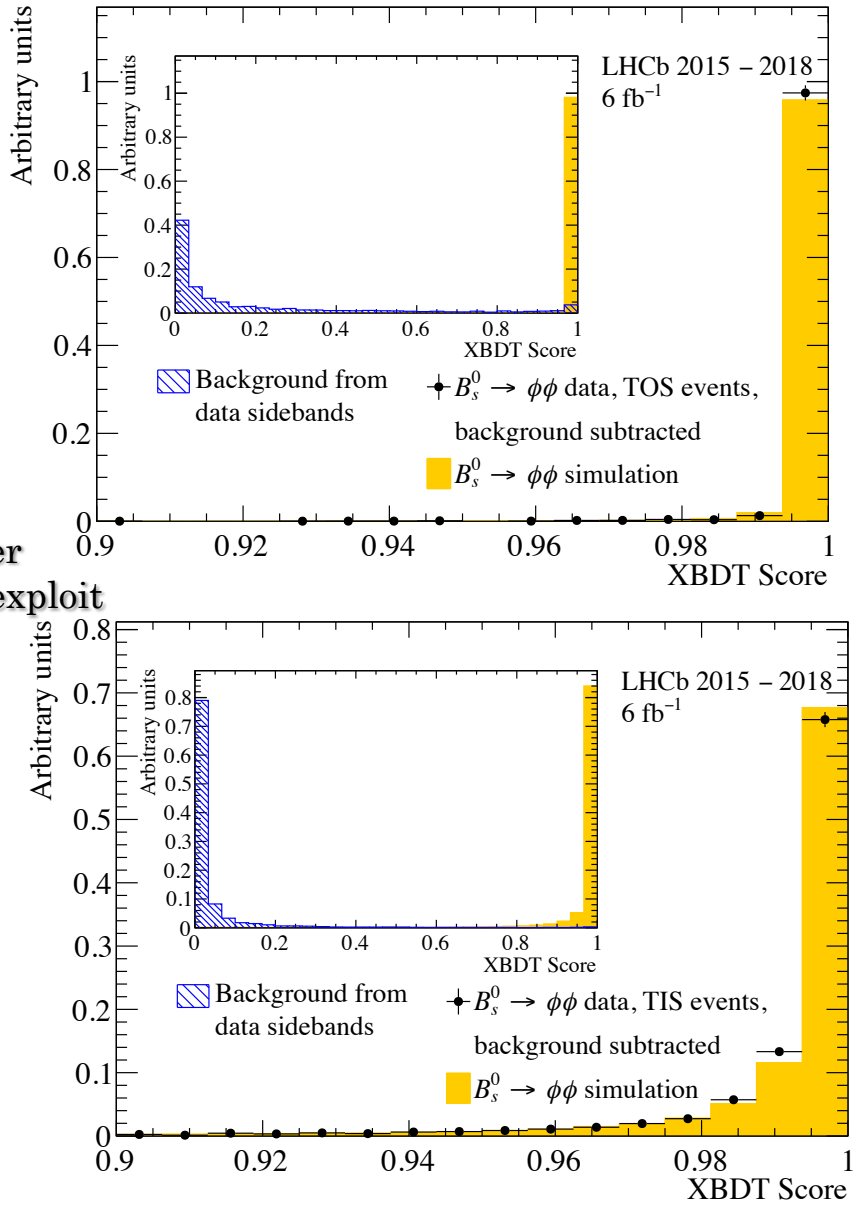
- High branching fraction of $D_s^+ \to \phi X$
- Easy to get lots of detached ϕ mesons that can be **incorrectly paired together** to form a B candidate
- Look at data sideband, look at ϕ mesons individually and see if it **forms a vertex with a pion**, as example
- Use this to train a classifier to target these – **discriminating variables are those relating to vertex quality**



Combinatorial background reduction

- Two types of classifiers
  - One targets D_s^+ decays specifically
  - **One targets combinatorial background in general**

Split by trigger categories to exploit differences in kinematics



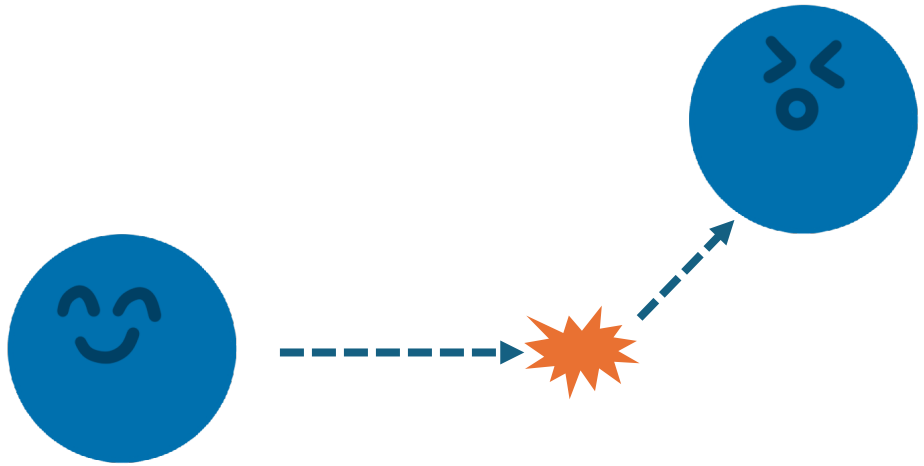
- Allows to target the specific properties of each category
- **Provides much better control of the combinatorial background**

Background from $B_s^0 \to \phi\phi$

- Wait, the control mode is a background? **Yes.**
- Due to momentum resolution, the $B_s^0 \to \phi\phi$ and $B^0 \to \phi\phi$ distributions **overlap**
- In particular – poorly reconstructed kaon tracks will create tails in the distributions
- Poorly reconstructed kaons are those that **decay in flight** or undergo **hadronic interactions**

Background from $B_s^0 \to \phi\phi$

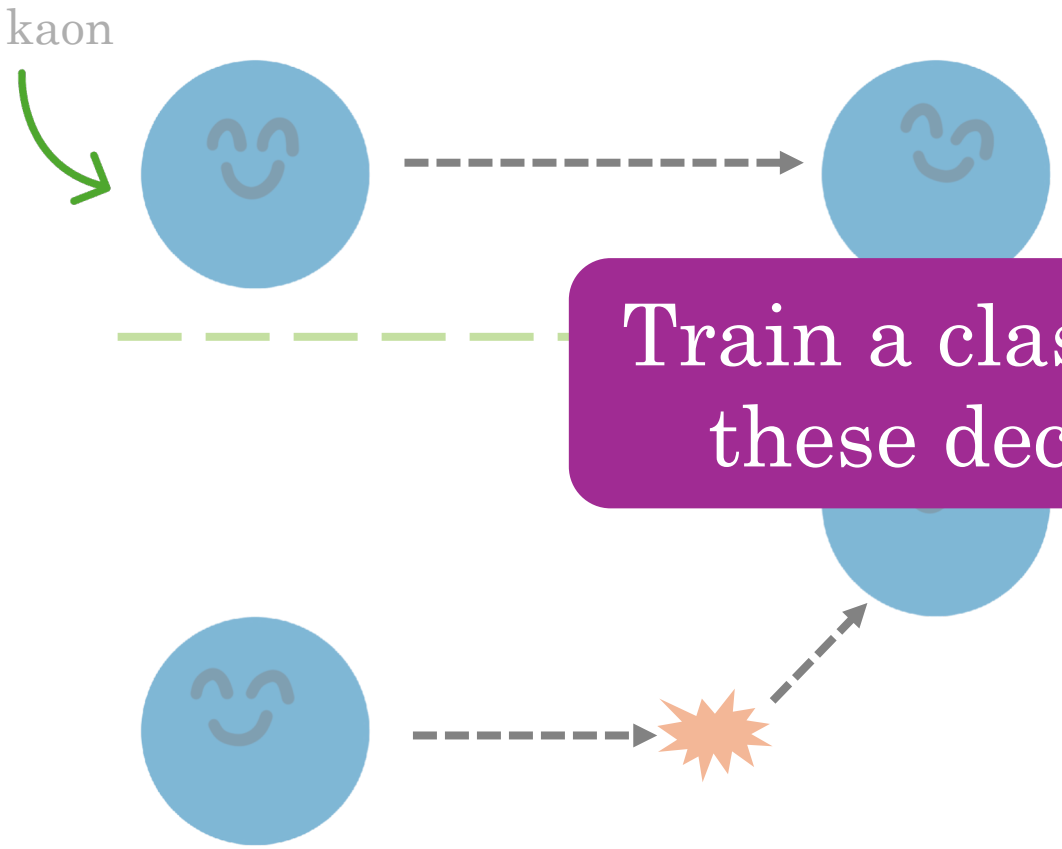
Hasn't interacted, nice track



Something happened – kinked track

If this happens before the tracking stations, **poorer track reconstruction** and **worse determination** of B mass as a result

Background from $B_s^0 \to \phi\phi$



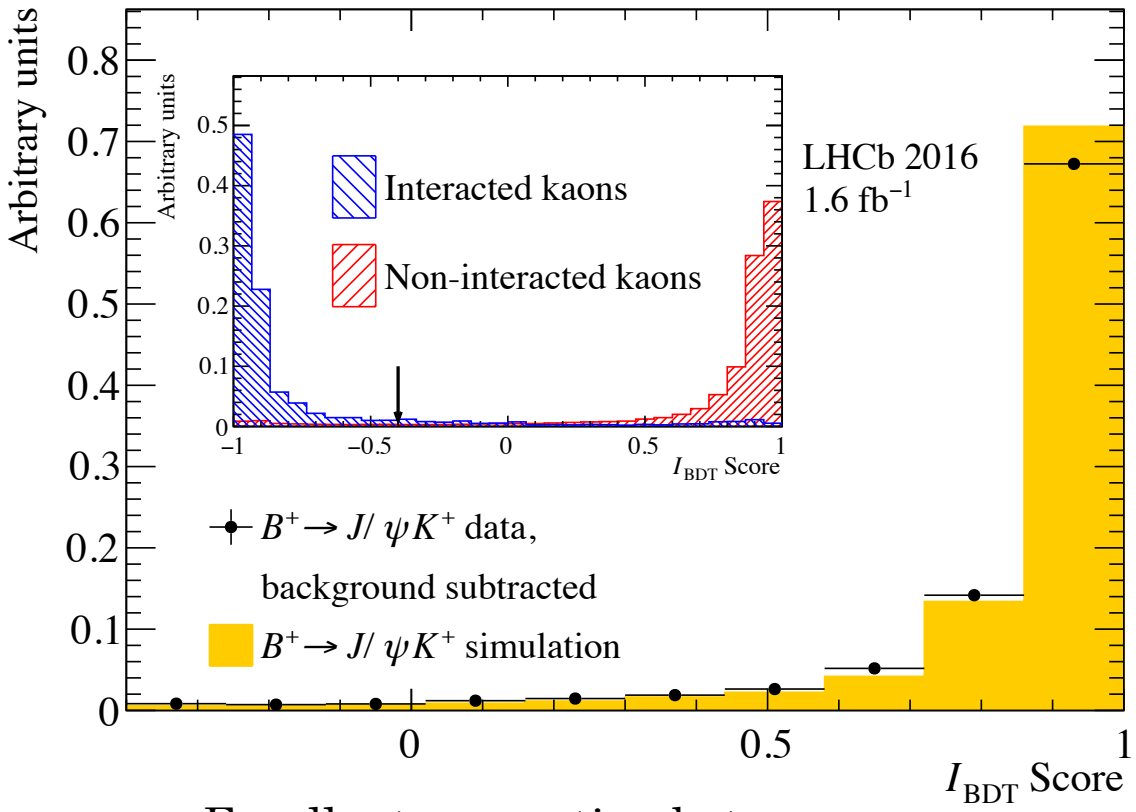
Hasn't interacted, nice track

Train a classifier to target these decays in flight!

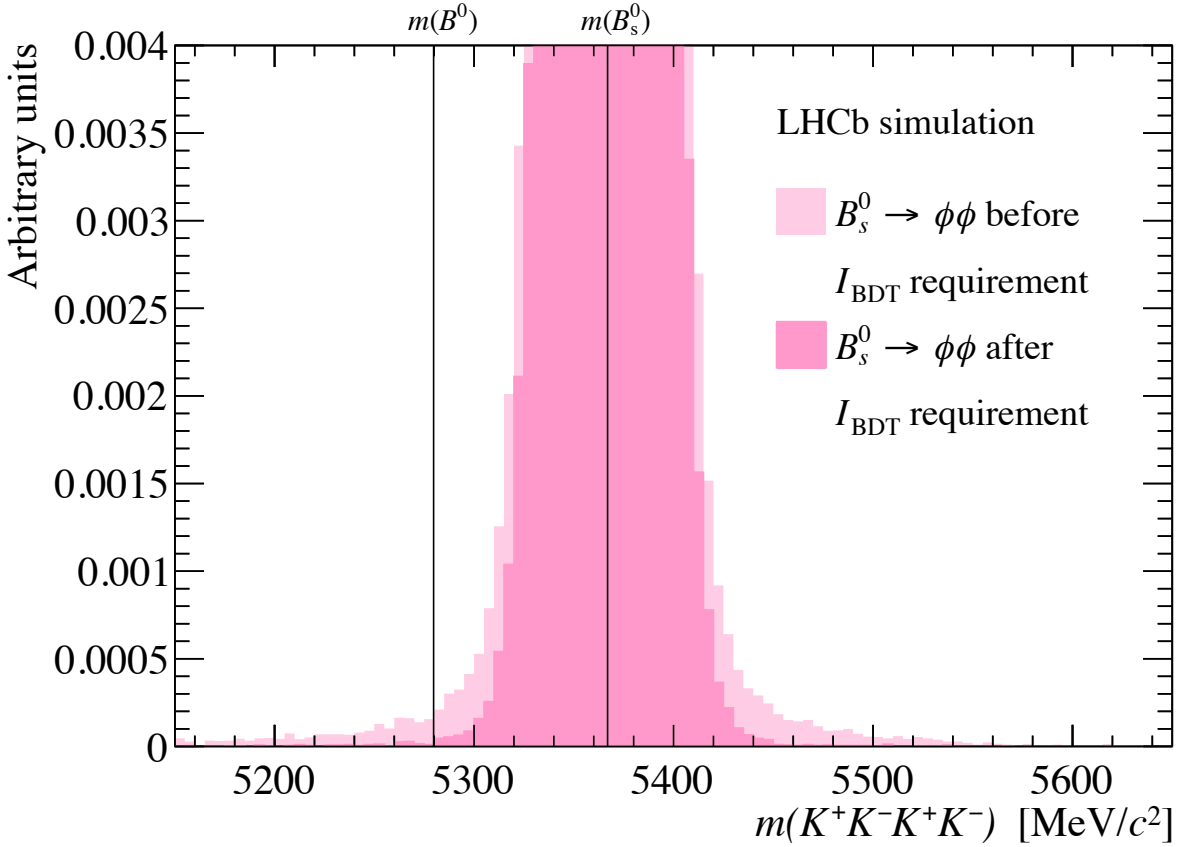
ed – kinked track

If this happens before the tracking stations, **poorer track reconstruction** and **worse determination** of B mass as a result

Tails of $B_s^0 \to \phi\phi$ much reduced using this technique



Excellent separation between interacted and non-interacted kaons

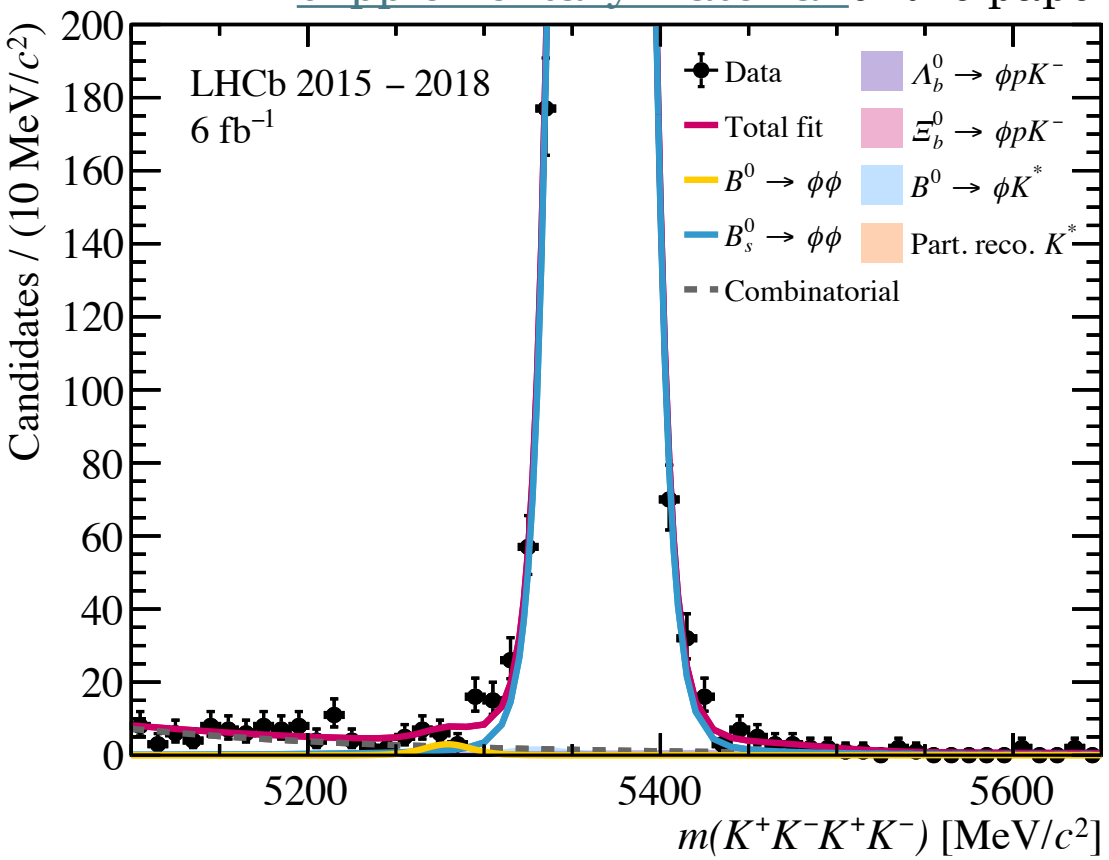


$B_s^0 \to \phi\phi$ events in region of B^0 mass much reduced

Results

- Don't see a signal ☹
- Set **new upper limit** on the branching fraction – factor of 2 better than the previous result from LHCb (Run 1 + 2016)
- This is a factor of **1.8 times** more than increase in statistics alone!

In supplementary material of the paper



Run 2 data on suppressed y-axis to show low levels of background

Summary

- We carefully studied the various background contributions that affect the sensitivity to potential $B^0 \to \phi\phi$ signal
- Use multivariate classifiers to target many specific contributions to the invariant mass distribution
- By using these techniques improve sensitivity by additional factor of 1.8
- We are always looking for ways of squeezing the best results from our data!
- Interest from LHCb community to use the kaon interaction technique to improve other analyses where this plays a part