Model independent measurement of the CKM angle γ with $B^\pm \to [K^+K^-\pi^+\pi^-]_D h^\pm$ at LHCb and BESIII

Martin Tat

University of Oxford

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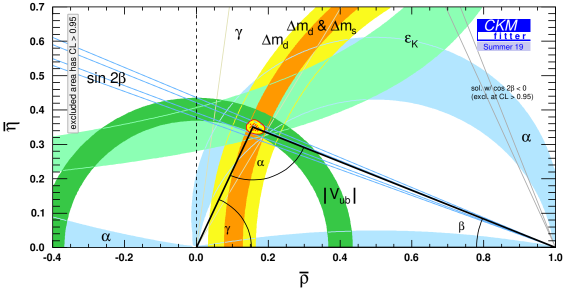
Introduction to γ and CP violation

Introduction to γ and CP violation

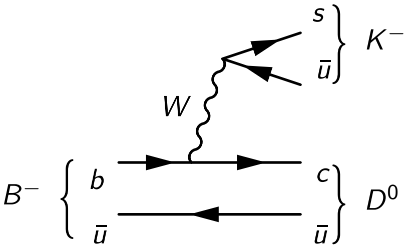
- CPV in SM is described by the Unitary Triangle, with angles α, β, γ
- The angle $\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$ is very important:
  1. Negligible theoretical uncertainties: Ideal SM benchmark
  2. Accessible at tree level: Indirectly probe New Physics that enter loops
  3. Compare with α, β measurements: Is the Unitary Triangle a triangle?



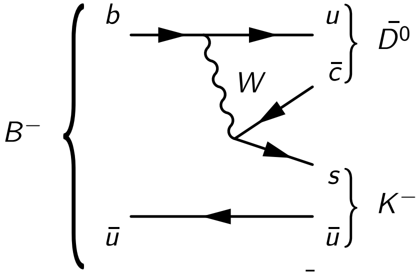
CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005)

Sensitivity through interference

Measure γ through interference effects in $B^{\pm} \to DK^{\pm}$



Favoured $B^- \to D^0 K^-$



Suppressed $B^- \to \bar{D}^0 K^-$

- Superposition of D^0 and $\bar{D}^0$
- $b \to u\bar{c}s$ and $b \to c\bar{u}s$ interference $\to$ Sensitivity to γ

$$\mathcal{A}(B^-) = \mathcal{A}_B\left(\mathcal{A}_{D^0} + r_B e^{i(\delta_B - \gamma)}\mathcal{A}_{\bar{D}^0}\right)$$
$$\mathcal{A}(B^+) = \mathcal{A}_B\left(\mathcal{A}_{\bar{D}^0} + r_B e^{i(\delta_B + \gamma)}\mathcal{A}_{D^0}\right)$$

- The magnitude of interference effects governed by $r_B \approx 0.1$

Sensitivity through interference

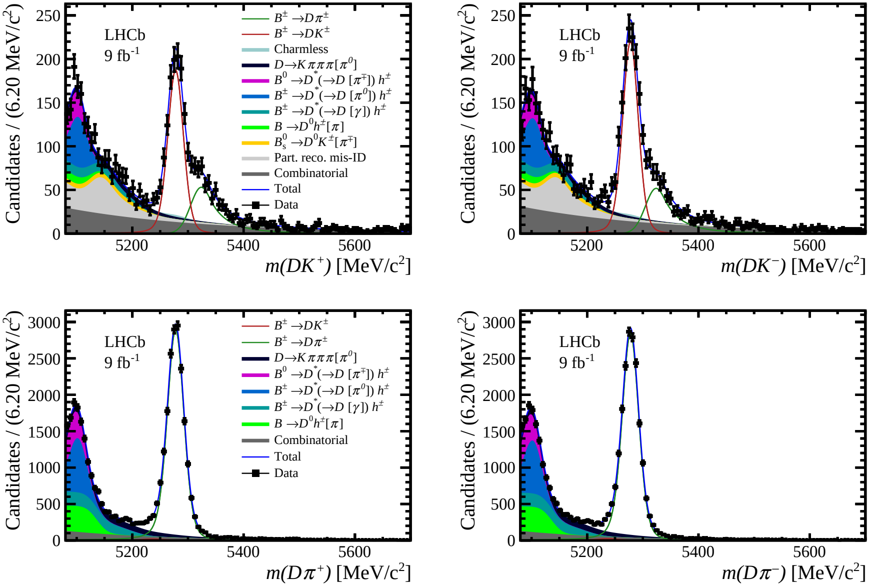
Phase space integrated analysis: Compare yields of B^+ and B^-

Interference depends on γ, but it is diluted by κ when integrated over phase space

$$\begin{tikzcd}
 & D^0 K^- \arrow[dr, bend left, "\mathcal{A}_{D^0}"] & \\
B^- \arrow[ur, bend left, "\mathcal{A}_B"] \arrow[dr, bend right, "\mathcal{A}_B r_B e^{i(\delta_B - \gamma)}"'] & & DK^- \\
 & \bar{D}^0 K^- \arrow[ur, bend right, "\mathcal{A}_{\bar{D}^0}"'] &
\end{tikzcd}$$

$$|\mathcal{A}(B^-)|^2 \propto 1 + r_B^2 + 2 r_B \kappa \cos(\delta_B - \gamma)$$

First look at $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D K^{\pm}$



First look at $B^\pm \to [K^+K^-\pi^+\pi^-]_D K^\pm$

$$\mathcal{A} = \frac{2r_B\kappa\sin(\delta_B)\sin(\gamma)}{1 + r_B^2 + 2r_B\kappa\cos(\delta_B)\cos(\gamma)} \tag{1}$$

Measuring the $B^\pm \to DK^\pm$ asymmetry $\mathcal{A}$ provide useful constraints on γ, but with some caveats:

1. Interference effects are diluted by a factor $\kappa = 0.46 \pm 0.08$
   - Phys. Rev. D **107**, 032009
2. Second order sensitivity to $\cos(\gamma)$
3. Four-fold symmetry:
   - $(\gamma, \delta_B) \to (\delta_B, \gamma)$
   - $(\gamma, \delta_B) \to (\pi - \gamma, \pi - \delta_B)$

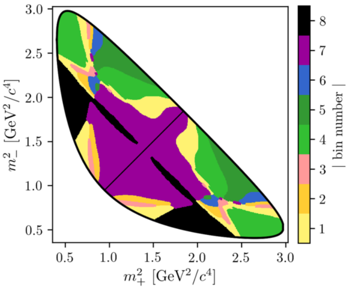
Solution: Perform analysis in local regions of phase space!

Phase space binned analysis of $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D K^{\pm}$

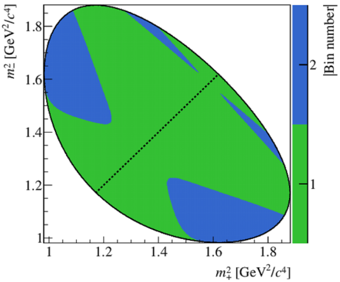
First study of *CP* violation in $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D K^{\pm}$

- Proposed by J. Rademacker and G. Wilkinson
  - Phys. Lett. **B647** (2007) 400
  - FOCUS amplitude model predicts a 14° precision with 1000 candidates
- State of the art amplitude analysis by LHCb:
  - JHEP **02** (2019) 126
  - Exploits the huge dataset of charm decays collected by LHCb
- Large interference effects in local regions of the 5D phase space
  - Identify regions with similar asymmetries and split into bins

- Analogous to the decays $D^0 \to K_S^0\pi^+\pi^-$ and $K_S^0K^+K^-$, where the binning scheme may be visualised on a Dalitz plot

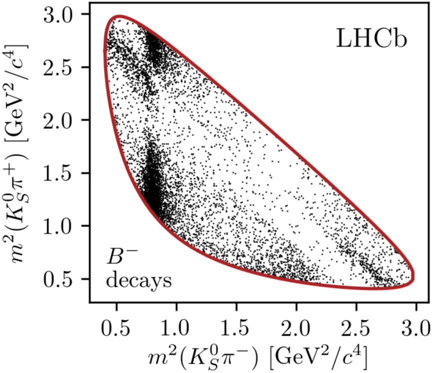


$K_S^0\pi^+\pi^-$

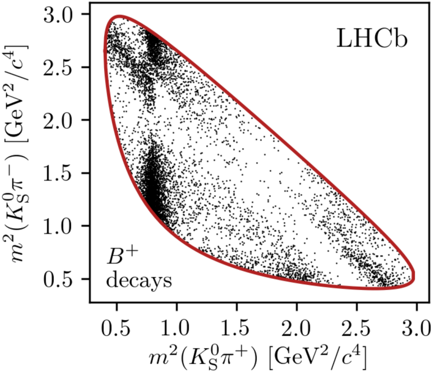


$K_S^0K^+K^-$

Binned analysis of the $D \to K^+K^-\pi^+\pi^-$ mode



$B^- \to [K_S^0\pi^+\pi^-]_D K^-$



$B^+ \to [K_S^0\pi^+\pi^-]_D K^+$

Can you find the asymmetries?

Binning scheme

Binning scheme

A binning scheme must satisfy the following:

- Minimal dilution of strong phases when integrating over bins
- Enhance interference between $B^{\pm} \to D^0 K^{\pm}$ and $B^{\pm} \to \bar{D}^0 K^{\pm}$

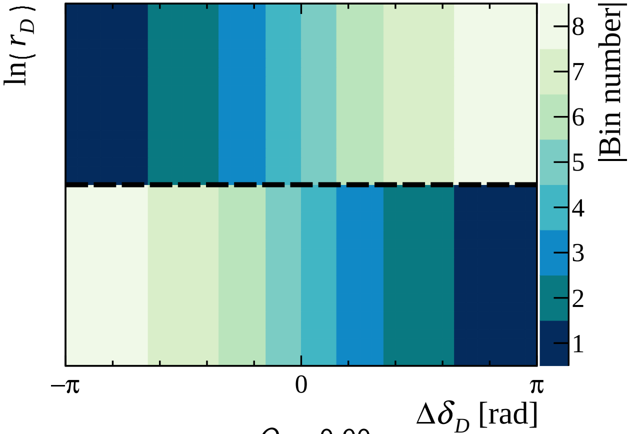
How to bin a 5-dimensional phase space?

1. For each $B^{\pm}$ candidate, use the amplitude model to calculate

$$\frac{\mathcal{A}(D^0)}{\mathcal{A}(\bar{D}^0)} = r_D e^{i\delta_D}$$

2. Split δ_D into uniformly spaced bins
3. Use the symmetry line $r_D = 1$ to separate bin $+i$ from $-i$
4. Optimise the binning scheme by adjusting the bin boundaries in δ_D

Binning scheme



$Q = 0.90$

Bins $i < 0$ on top, $i > 0$ below

Mass fits, *CP* fit and γ

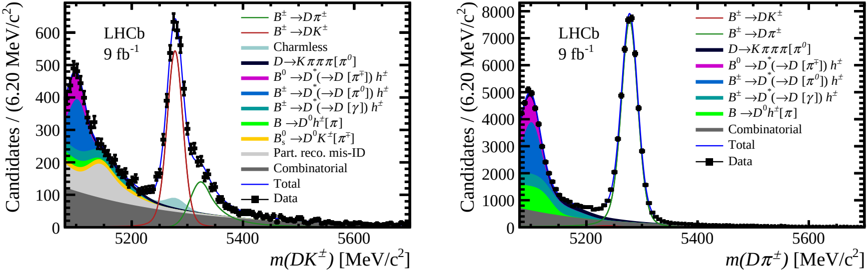
Mass fits, *CP* fit and γ

In the end, this analysis is a counting experiment

Counting strategy:

1. Perform a "global fit" of all $B^\pm$ candidates
2. Fix all shape parameters
3. Sort $B^\pm$ candidates by charge and bins
4. Perform a "*CP* fit" simultaneously, but only let bin yields float
5. From the 64 bin yields, determine γ using model-predicted values of c_i and s_i
   - In the future, model-independent measurements of c_i and s_i will become available

Mass fits, *CP* fit and γ



Signal yield:

$$B^\pm \to DK^\pm : \quad 3026 \pm 38$$

$$B^\pm \to D\pi^\pm : \quad 44\,349 \pm 218$$

Interpretation of γ

We can interpret our *CP* observables in terms of the physics parameters γ, r_B^{DK}, δ_B^{DK}, $r_B^{D\pi}$, $\delta_B^{D\pi}$

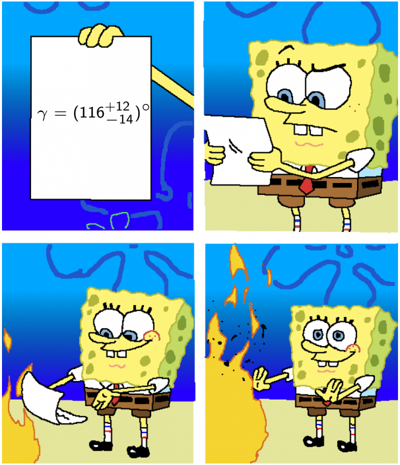
$$\begin{aligned}
\gamma &= (116^{+12}_{-14})^\circ, \\
\delta_B^{DK} &= (81^{+14}_{-13})^\circ, \\
r_B^{DK} &= 0.110^{+0.020}_{-0.020}, \\
\delta_B^{D\pi} &= (298^{+62}_{-118})^\circ, \\
r_B^{D\pi} &= 0.0041^{+0.0054}_{-0.0041},
\end{aligned}$$

However, the latest γ and charm combination result is:

$$\gamma = (63.8^{+3.5}_{-3.7})^\circ$$

What went wrong?!

Interpretation of γ



Do we trust the model predicted c_i and s_i, or their uncertainties?

The $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D K^{\pm}$ decay mode

There are several reasons why amplitude models cannot be trusted

1. Amplitude models are just models, which may not reflect reality
2. In fact, the model is fitted to data that knows nothing about $\delta_D(\Phi)$
3. It is impossible to assign an objective error to a model!

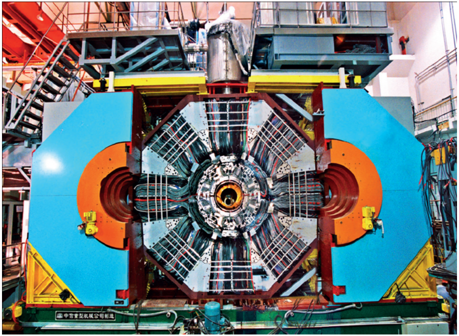
We wish to do a model independent measurement

Let's go and measure c_i and s_i at BESIII!

Strong phase analysis of $D^0 \to K^+K^-\pi^+\pi^-$ at BESIII

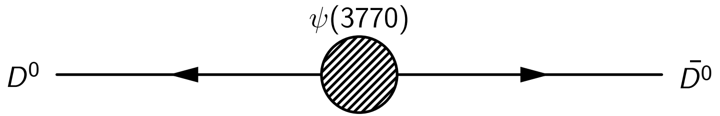
Strong phase analysis of $D^0 \to K^+K^-\pi^+\pi^-$ at BESIII

- BESIII: Beijing Spectrometer III, a detector at the Beijing Electron-Positron Collider II, located at IHEP
- e^+e^- collider at the $\psi(3770) \to D^0\bar{D}^0$ threshold
  - 2010-2011: $3\,\mathrm{fb}^{-1}$
  - 2022: $5\,\mathrm{fb}^{-1}$
  - Expect $20\,\mathrm{fb}^{-1}$ in total by end of 2024

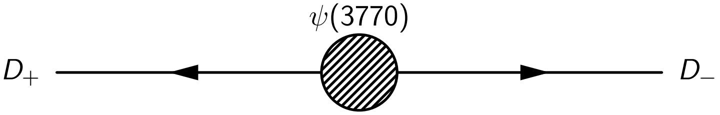


Strong phase analysis of $D^0 \to K^+K^-\pi^+\pi^-$ at BESIII

- Double-tag analysis: Reconstruct signal ($KK\pi\pi$) and tag mode
- $D^0\bar{D}^0$ pair is quantum correlated



- Equivalently, we can consider D_+D_-
  - $D_\pm = \frac{1}{\sqrt{2}}(D^0 \pm \bar{D}^0)$ are CP eigenstates

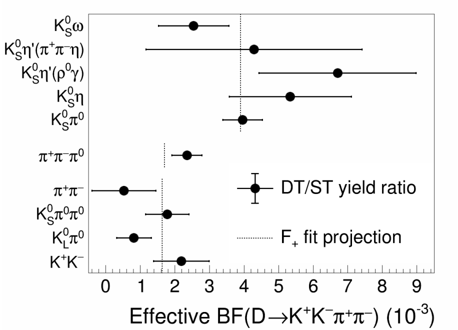


The DD pair is quantum correlated, spooky action at a distance!

Strong phase analysis of $D^0 \to K^+K^-\pi^+\pi^-$ at BESIII

Quantum correlation: The *CP* content of the tag can modify the effective branching fraction:

$$\frac{N^{\mathrm{DT}}}{N^{\mathrm{ST}}} = \mathcal{B}(D^0 \to KK\pi\pi)(1 \pm c_1)$$



Phys. Rev. D **107**, 032009

c_1 is the cosine of the strong phase, averaged over the <u>whole</u> phase space

Strong phase analysis of $D^0 \to K^+K^-\pi^+\pi^-$ at BESIII

Our next task is to change the phase space inclusive analysis,

$$\frac{N^{\mathrm{DT}}}{N^{\mathrm{ST}}} = \mathcal{B}(D^0 \to KK\pi\pi) \quad \text{(flavour tag)}$$
$$\frac{N^{\mathrm{DT}}}{N^{\mathrm{ST}}} = \mathcal{B}(D^0 \to KK\pi\pi)(1 \pm c_1) \quad \text{(CP tag)}$$

into a binned phase space analysis:

$$\frac{N_i^{\mathrm{DT}}}{N^{\mathrm{ST}}} = \mathcal{B}(D^0 \to KK\pi\pi)F_i \quad \text{(flavour tag)}$$
$$\frac{N_i^{\mathrm{DT}}}{N^{\mathrm{ST}}} = \mathcal{B}(D^0 \to KK\pi\pi)\left(F_i + \bar{F}_i \pm 2\sqrt{F_i\bar{F}_i}c_i\right) \quad \text{(CP tag)}$$

1. F_i: Measure using flavour tags
2. c_i: Determine from asymmetry of CP even and odd tags
3. s_i: Analogous to c_i, but requires binning of tag mode

Our next task is to change the phase space inclusive analysis,

$$\frac{N^{\rm DT}}{N^{\rm ST}} = \mathcal{B}(D^0 \to KK\pi\pi) \quad \text{(f[illegible])}$$

$$\frac{N^{\rm DT}}{N^{\rm ST}} = \mathcal{B}(D^0 \to KK\pi \text{[illegible]}) \quad \text{(CP tag)}$$

into a binned [illegible] ce analysis:

$$\frac{N_i^{\rm DT}}{N^{\rm ST}} = \mathcal{B}(D^0 \to KK \text{[illegible]}) \quad \text{([illegible] lavour tag)}$$

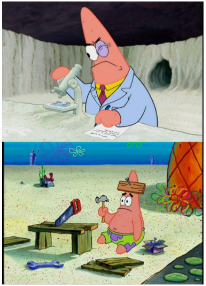
$$\frac{N_i^{\rm DT}}{N^{\rm ST}} = \mathcal{B}(D^0 \text{[illegible]})\left(F_i + \bar{F}_i \pm 2\sqrt{F_i\bar{F}_i}c_i\right) \quad \text{(CP tag)}$$

Work in progress!

1. F_i: Measure using [illegible] our tags
2. c_i: Determine from asymmetry of CP even and odd tags
3. s_i: Analogous to c_i, but requires binning of tag mode

Summary and conclusion

1. I have presented the first model-independent measurement of γ using $B^\pm \to [K^+K^-\pi^+\pi^-]_D h^\pm$
2. The optimised binning scheme, developed with an amplitude model, successfully identified regions with large, local CP asymmetries
3. However, amplitude model predictions of δ_D <u>should not be trusted</u>
4. 3σ tension with world average



Making binning scheme with amplitude model

Predicting strong phases with amplitude model

5. External inputs from charm factories, such as BESIII, are crucial to constrain charm strong phases

Thanks for your attention!

Backup slides

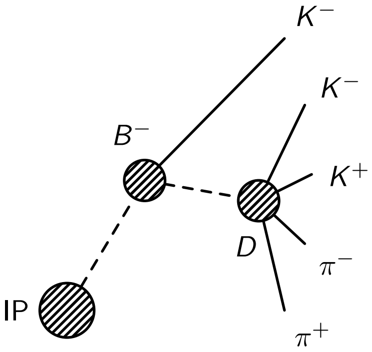
Event selection

Event selection

Decay topology

Look for:

1. 5 charged tracks
2. Displaced B vertex
3. 1 bachelor track with good PID information
4. Displaced D vertex with invariant mass within 25 MeV of the D^0 mass



Event selection

Offline selection has 3 stages

Initial cuts:

1. Invariant D and B mass cuts
2. Momentum and RICH requirements

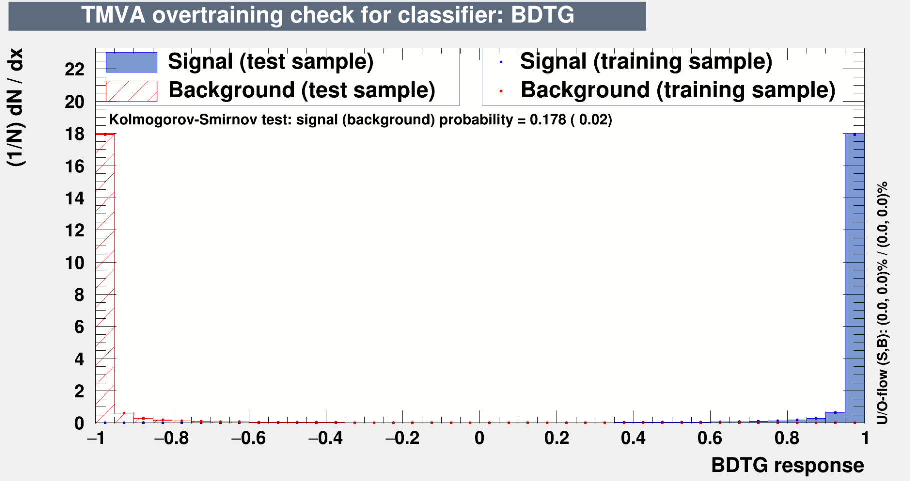
Boosted Decision Tree (BDT)

- Signal sample: Simulation samples
- Background sample: Upper B mass sideband
- 28 variables describing kinematics, impact parameters, vertex quality

Final selection

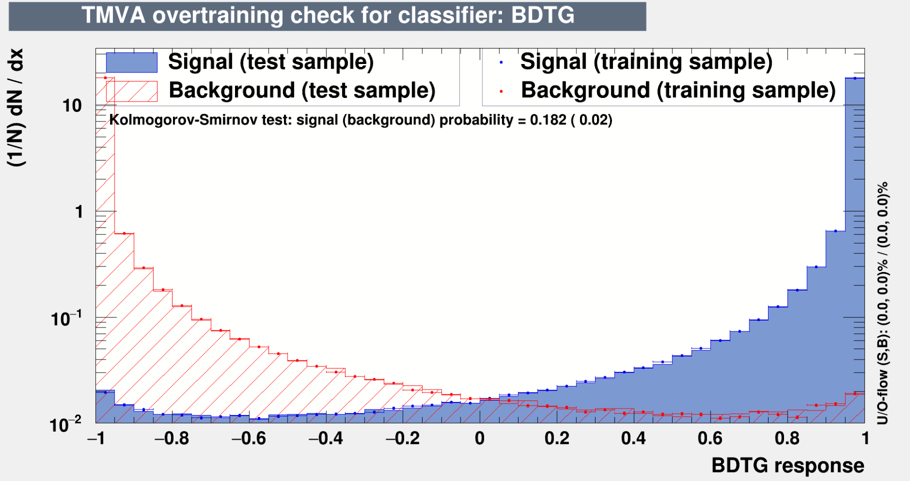
1. D Flight distance
2. Particle Identification of bachelor
3. K_S^0 veto

Event selection



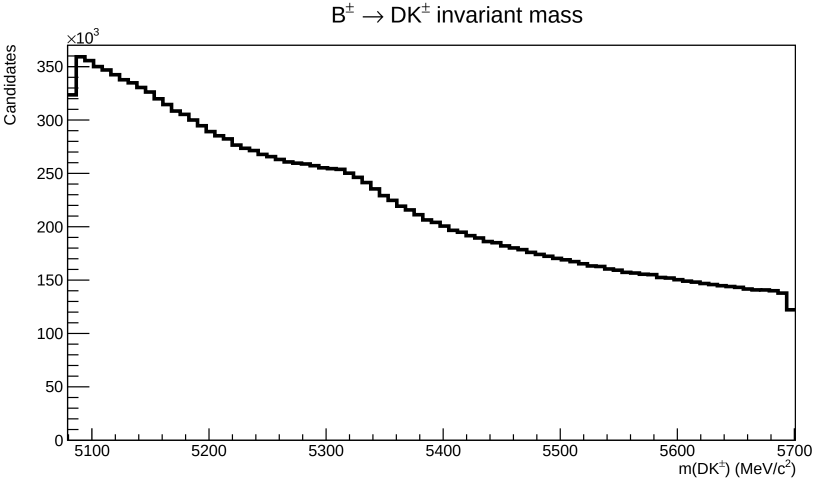
BDT is highly efficient at rejecting combinatorial background

Event selection



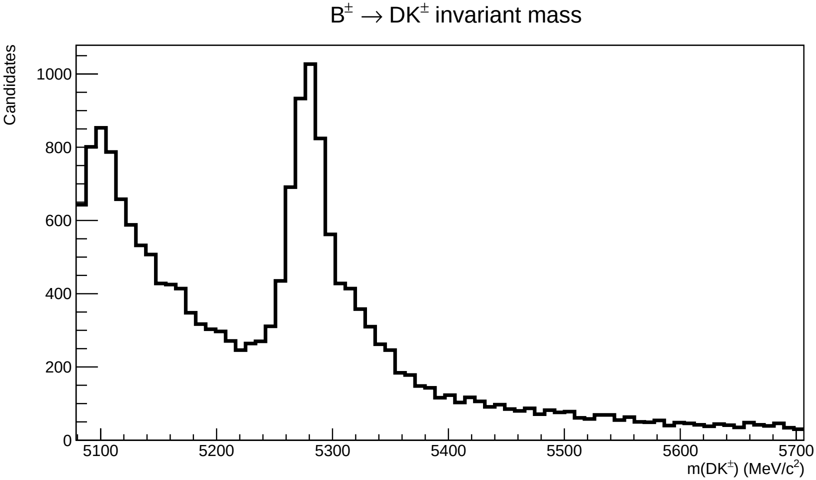
Very important, combinatorial background is large in multi-body decays

Event selection



The invariant B mass, after online selection, show no visible signal...

Event selection



... but the BDT does a great job cleaning this up!