Flavor tagging of neutral D mesons

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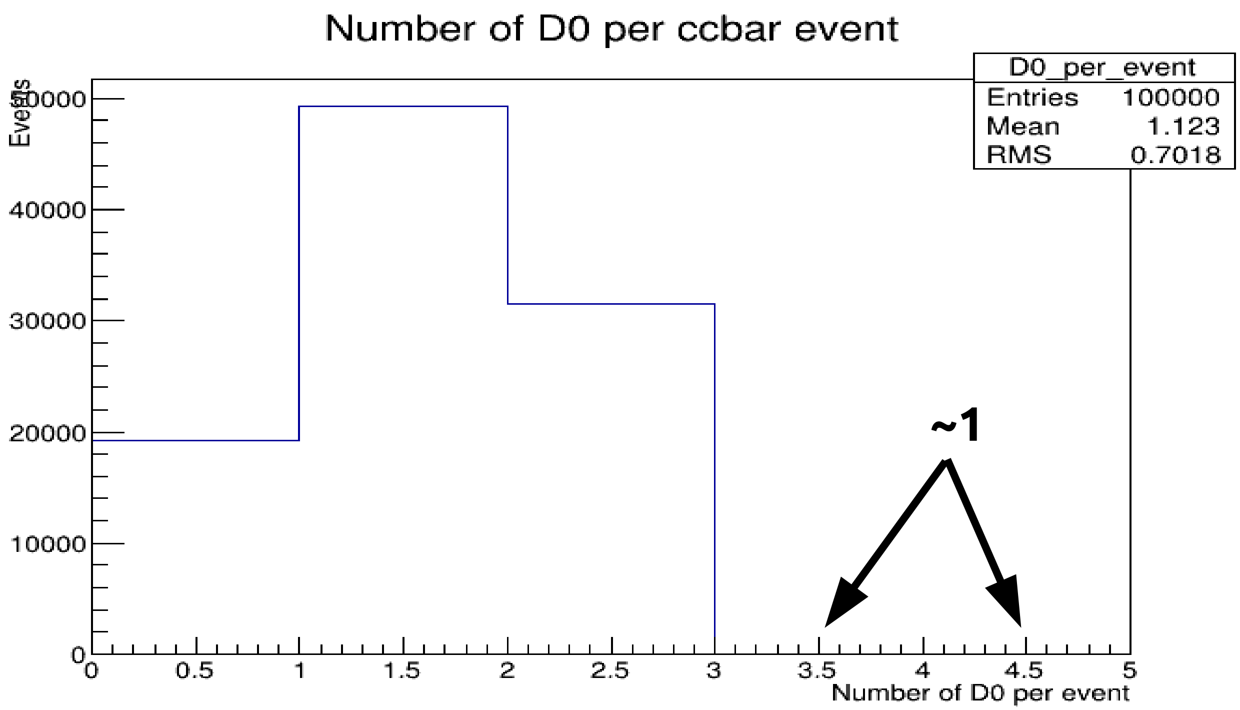
D^0 production in a $c\bar{c}$ event



In 100k $c\bar{c}$ events there are 112k generated D^0 (at the generator level, no reconstruction).

These D^0 come from:

- 41% directly from virtual photons ($e^+ e^- \rightarrow \gamma^* \rightarrow D^0 X$)
- 35% from D^{*0} ($D^{*0} \rightarrow D^0 \pi^0$)
- 24% from D^{*+} ($D^{*+} \rightarrow D^0 \pi^+$) ← **only these used for CP violation analysis:**
  - **π charge tags the D^0 flavour**
  - **improves the combinatorial background rejection**

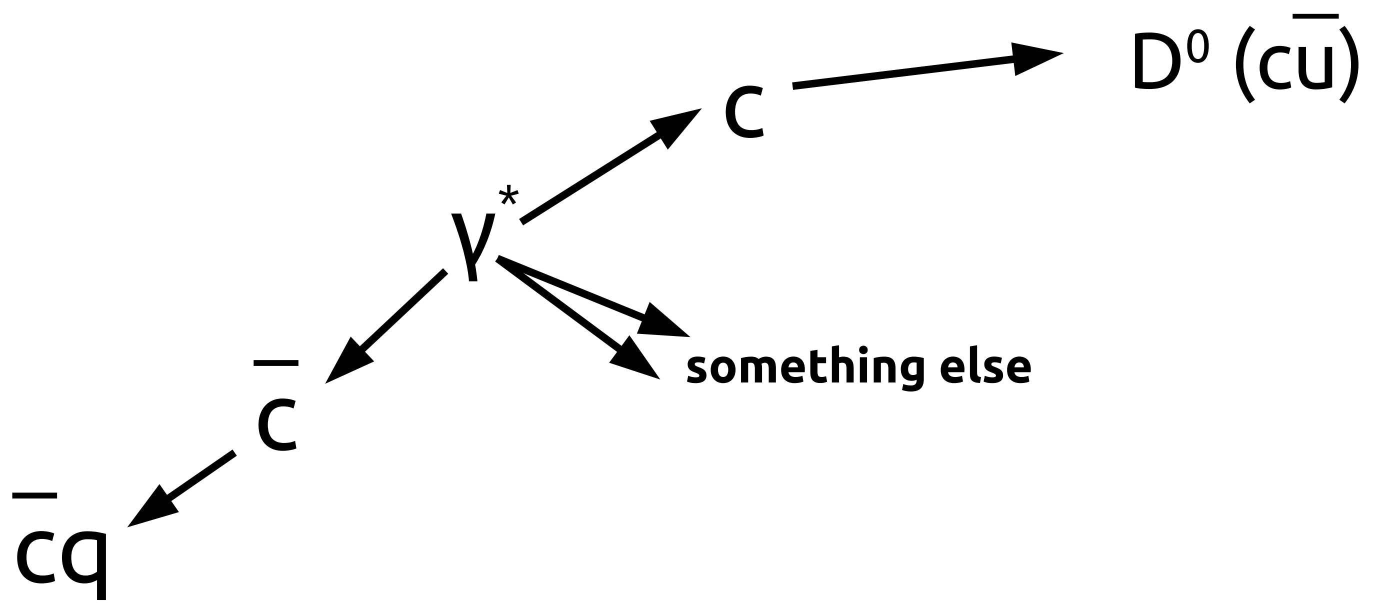
Can we recover at least a fraction of the ¾ of D^0 produced for CP violation analysis?

The idea

The purpose of my work is to study an alternative method to tag the flavor of a D^0, without the strong request that it is generated by a D^{*+}:

- **increasing the statistics**
- **providing control samples for other analysis**
  - **→ time-dependent CPV measurement thanks to the 2x improved resolution on the proper time**

The idea is to tag the D^0 flavor by looking at the **Rest of the Event** (= **ROE**, i.e. particles not coming from the decay of signal D^0).



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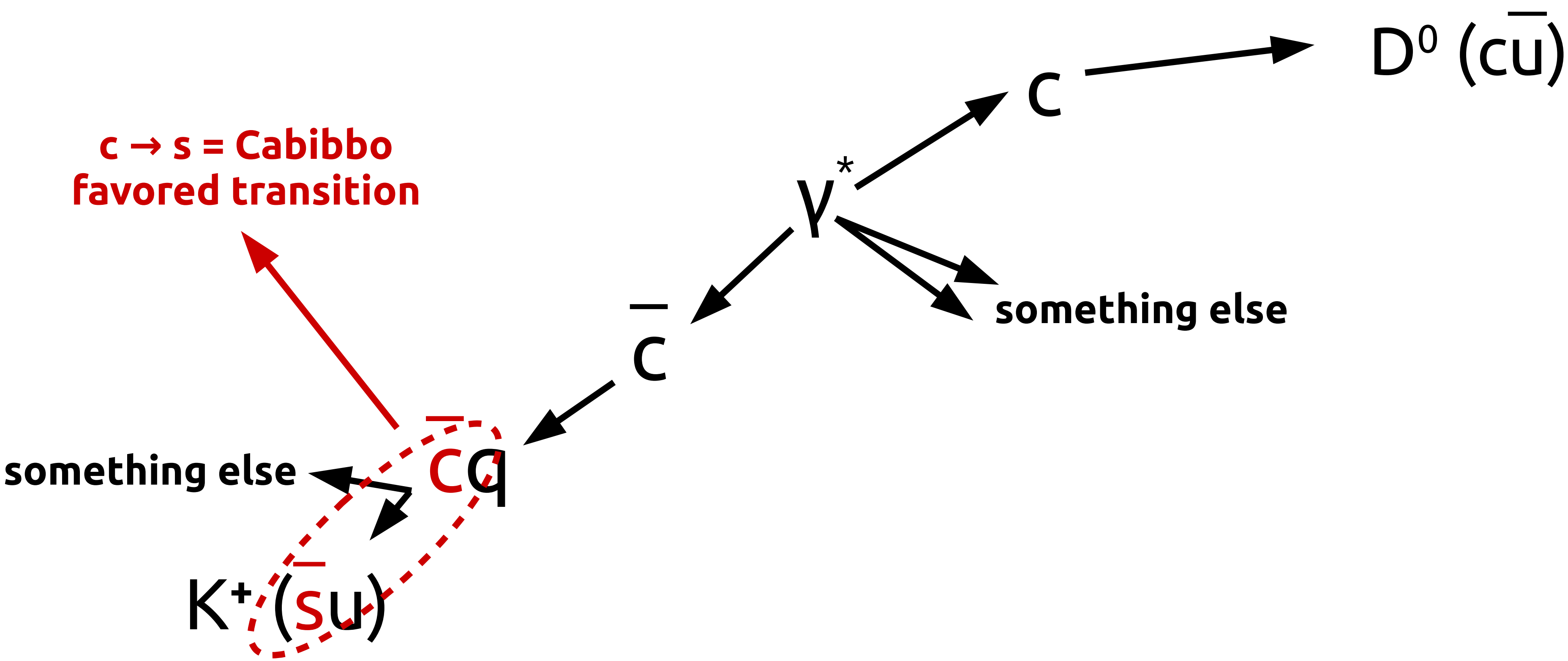

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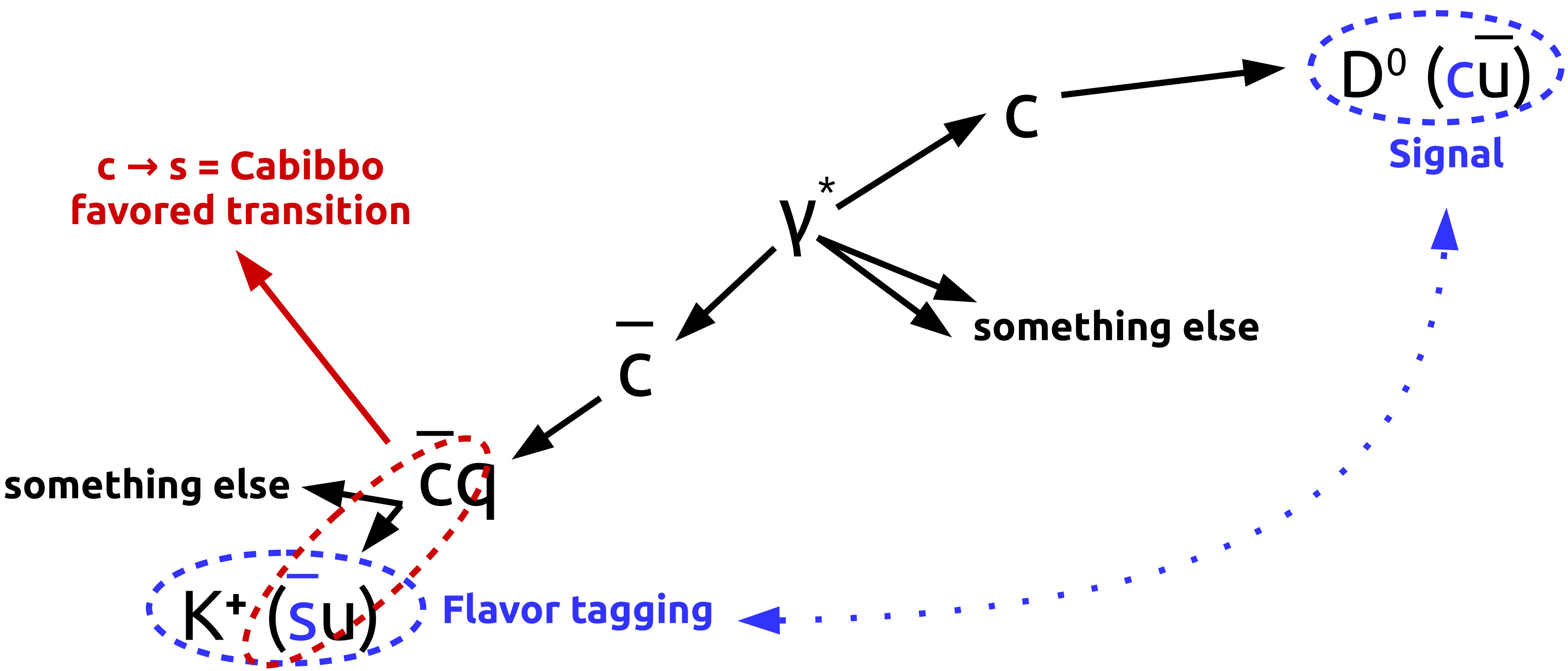


Requirements on the events

This tagging technique can be applied to events with the following charateristics:

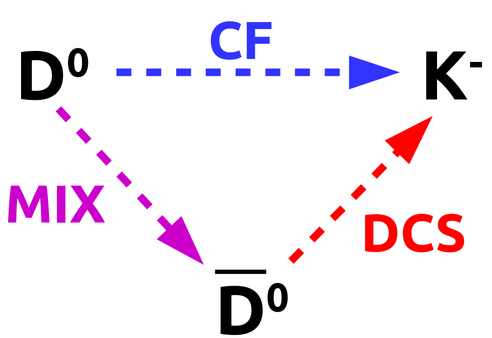
1) only **1 K^+ candidate in the ROE**

2) only **1 D^0 in the event** to avoid mistagging from D^0-$\overline{D}^0$ mixing

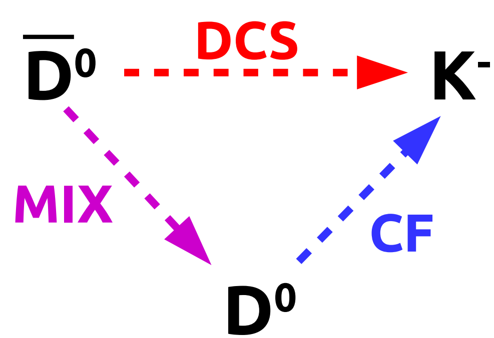
} **~ 21% of events (generator level)**

The second requirement is more philosophical than pratical:

Correct tagging



Wrong tagging



CF ~ $O(1)$

DCS ~ $O(10^{-2})$

MIX ~ $O(10^{-2})$

As first approach, I have discarded events with one or more D^0 in the ROE.

Signal and background events

A correctly tagging K^+ comes from a D^- or a Λ_c^-.

Examples of signal events (**~ 54%** of $c\bar{c}$ events with 1 D^0 & 1 K^+ in **ROE**) are:

$c\bar{c} \rightarrow D^0 D^- X$; $\mathbf{D^0} \rightarrow X$; $D^- \rightarrow \mathbf{K^+} \pi^- e^- \bar{\nu}_e$

$D^- \rightarrow K^{*0} e^- \bar{\nu}_e$; $K^{*0} \rightarrow \mathbf{K^+} \pi^-$

$c\bar{c} \rightarrow D^0 \Lambda_c^- X$; $\mathbf{D^0} \rightarrow X$; $\Lambda_c^- \rightarrow \Delta^{--} K^{*+}$; $K^{*+} \rightarrow \mathbf{K^+} \pi^0$

Background events (**~ 46%**) are the following ones:

1) Doubly Cabibbo Suppres. decay of D^- (eg. $D^- \rightarrow K^- \pi^0$): **~ 9.5%**

2) DCS decay of charmed baryons (eg. $\Lambda_c^- \rightarrow \Xi^+ K^- \pi^+$): **~ 6%**

3) $c\bar{c}s\bar{s}$ events: **~ 84.5%**

  3a) K^-/K^+ directly from hadronization of s quark (K^-/K^+ from γ^*) **~ 76.2%**

  3b) K^-/K^+ from the decay of D_s^+/D_s^- : **~ 8.3%**

Data referred to $c\bar{c}$ events at generator level!

Let's have a look to reconstructed events

New backgrounds from reconstruction:

→ K^- from D^0 not reconstructed

→ Events with not reconstructed K^- (they seem events with only 1 K^- in ROE)

→ Events with fake K^-

Limits from kinematics:

→ K^- from γ^* has low p_T and therefore the resolution on the impact parameters is deteriored by multiple scattering

Reconstruction software:

→ The reconstrucion of K_L has a very poor purity

→ Improvements on selection of Final State Particles and reconstruction of composite states is expected

Veto events with D^0 in the Rest of Event

I have processed 1M $c\bar{c}$ event and searched D^0s in these channels:

- $D^0 \rightarrow K^- \pi^+ \pi^0$ (BR = 14.3%)
- $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ (BR = 8.07%)
- $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+ \pi^0$ (BR = 4.2%)
- $D^0 \rightarrow K^- \pi^+$ (BR = 3.93%)
- $D^0 \rightarrow K^- K^+$ (BR = 0.4%)

→ **Sum(BR) ~ 30% < 1**

The **average** efficiency of D^0 reconstruction is **~ 20%**.

As a consequence, **only ~ 6% of events with more than 1 D^0 are reconstructed**.

Background (?) from D^0 not reconstructed

At present, a veto can be applied only on ~ 6% of events with 2 D^0s.

The expected background from not reconstructed D^0 in the ROE is:

$$(1 - 6\%) \cdot 40\% \sim 38\%.$$

A dedicated effort is needed to improve:

- **the efficiency of reconstruction** **(hard to go significantly beyond 20%)**
- **the number of D^0 channels** **(many channels with small BR)**

As shown before, mixing in the charm sector is small: **a D^0 decays before starting to mix with $\overline{D}^0$**.

So, the mistagging caused by DCS decays of D0 is comparable with the one caused by mixing.

Reconstruction of K^+ in the Rest of Event

My aim is to recognise events with only 1 K^+ in ROE.

The reconstruction of K^+ introduces new types of background events:

1) an event with a misidentified K^+ (mainly real p or $\pi^\pm$)
   → **no correlation between the charge of K^+ and flavor of D^0**

2) an event with a not reconstructed K^+
   → **this modifies the number of K^+ in the rest of event**

3) an event with a tagging K^+ reconstructed with the wrong charge
   → **negligible contribute**

So, the reconstruction of K^+ is a **non-trivial** part of my analysis:

→ I don't want **too much tight** requirements to avoid to **lose some K^+** and miscalculate the number of K^+;

→ I don't want **too much loose** requirements to avoid to introduce a **large number of fake K^+**.

Reconstruction of K^+: several approaches

To reconstruct the K^+s I tried several approaches:

- PID(K) > 0.5
  → Purity of reconstructed K^+: **~ 64.0%**
  → "Purity" of events with 1 K^+: **~62.3%**

- PID(K) > 0.5 & PID(p) < 0.995 & PID(π) < 0.2
  → Purity of reconstructed K^+: **~ 81.1%**
  → "Purity" of events with 1 K^+: **~69.8%**

- PID(K) > 0.5 & PID(p) < 0.995 & PID(π) < 0.2
  + Selection of events with 1 K in ROE
  + BDT on K candidates
  → Purity of reconstructed K^+: **~ 99.1%**
  → "Purity" of events with 1 K^+: **~80.6%**

$$\text{“Purity” of events with 1 } K^+ = \frac{\text{evts with 1 MC } K^+ \text{ ROE}}{\text{evts with 1 } K^+ \text{ ROE reconstructed}}$$

Reconstruction of K^+: the best strategy

The best strategy I found to reconstruct the K^+ in the ROE is the following one:

→ Preliminary selection of K^+ (tracks with PID(K) > 0.1 and Prob(χ^2) > 10^{-3} of fitted track);

→ Check if the selected track is part of the ROE;

→ First “loose” selection BDT-based to cut away most of the background (**ε_{sig} = 87.3%**; **1 - ε_{bkg} = 92.4%**);

→ Check if the list of K^+ contains only 1 candidate;

→ Final “tight” selection BDT-based (the same training as before, but a different point of work: **ε_{sig} = 62.8%, 1 - ε_{bkg} = 99.4%)**.

Performances for events with 1 K^+ in ROE → $\#evts^{GEN}$ / $\#evts^{RECO}$ = **83.9%**

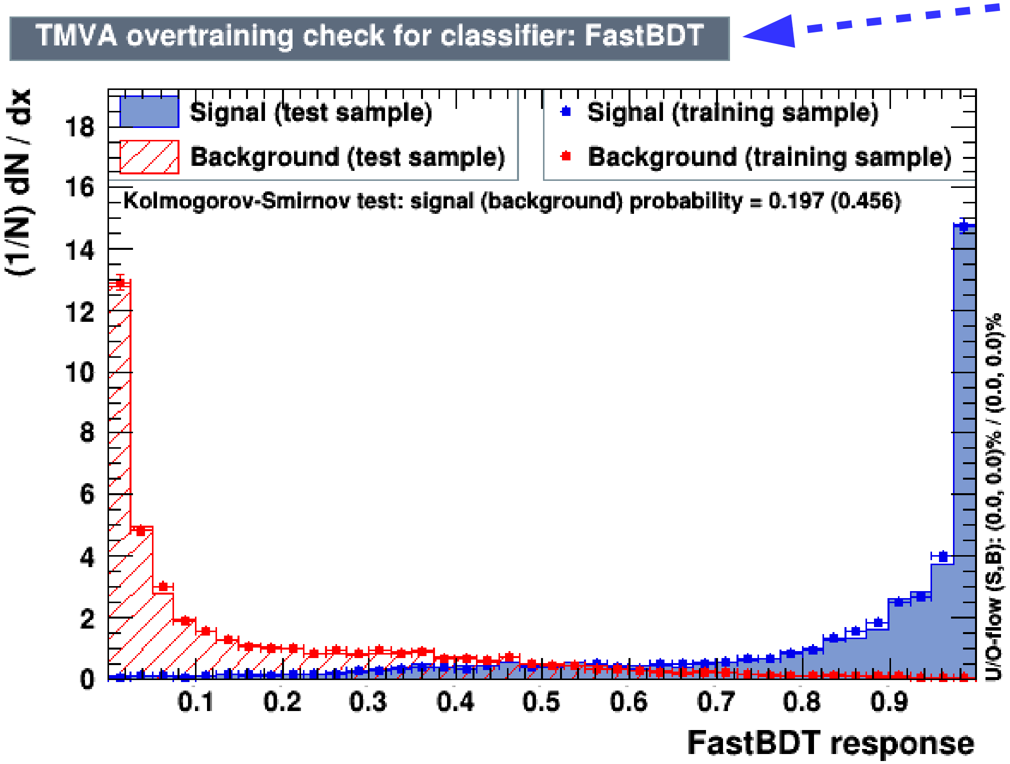
$evts^{RECO}$ = evts with 1 MC K^+ ROE **$evts^{GEN}$ = evts with 1 K^+ ROE reconstructed**

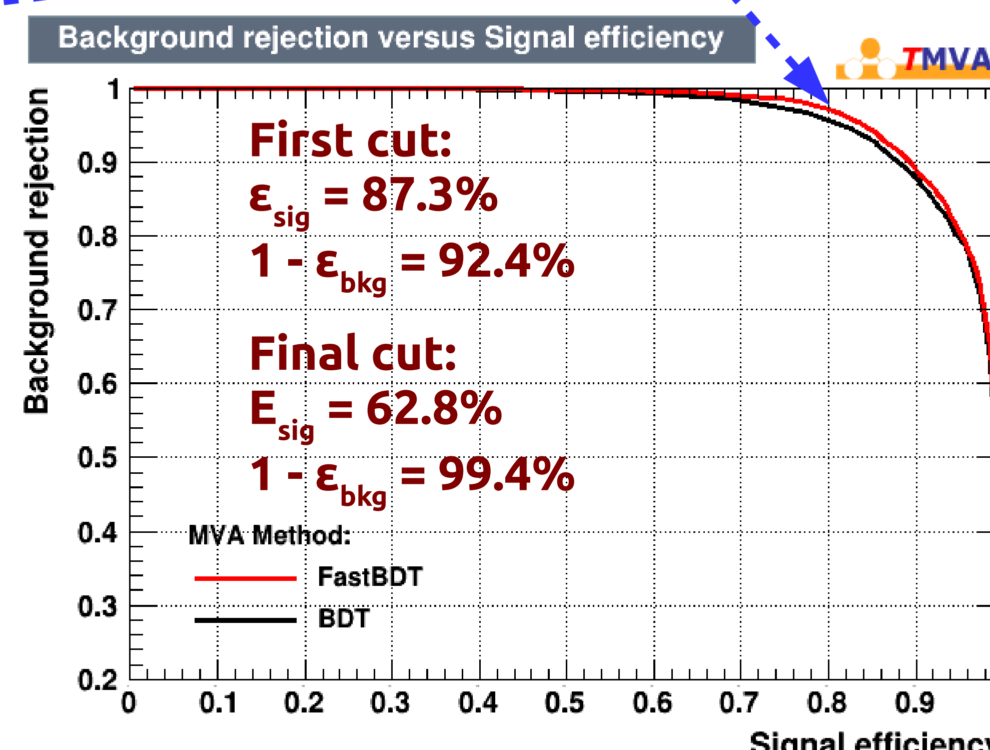
Reconstruction of K^+: BDT

Variables used during the training of the BDT:

→ p, cos(θ)
→ d_0, z_0, pValue
→ nHitsPXD, nHitsSVD, nHitsCDC
→ Kid_ARICH, Kid_TOP, Kid_dEdx
→ prid_TOP, prid_dEdx
→ muid_ARICH, muid_TOP, muid_dEdx
→ eid_ARICH, eid_TOP, eid_dEdx

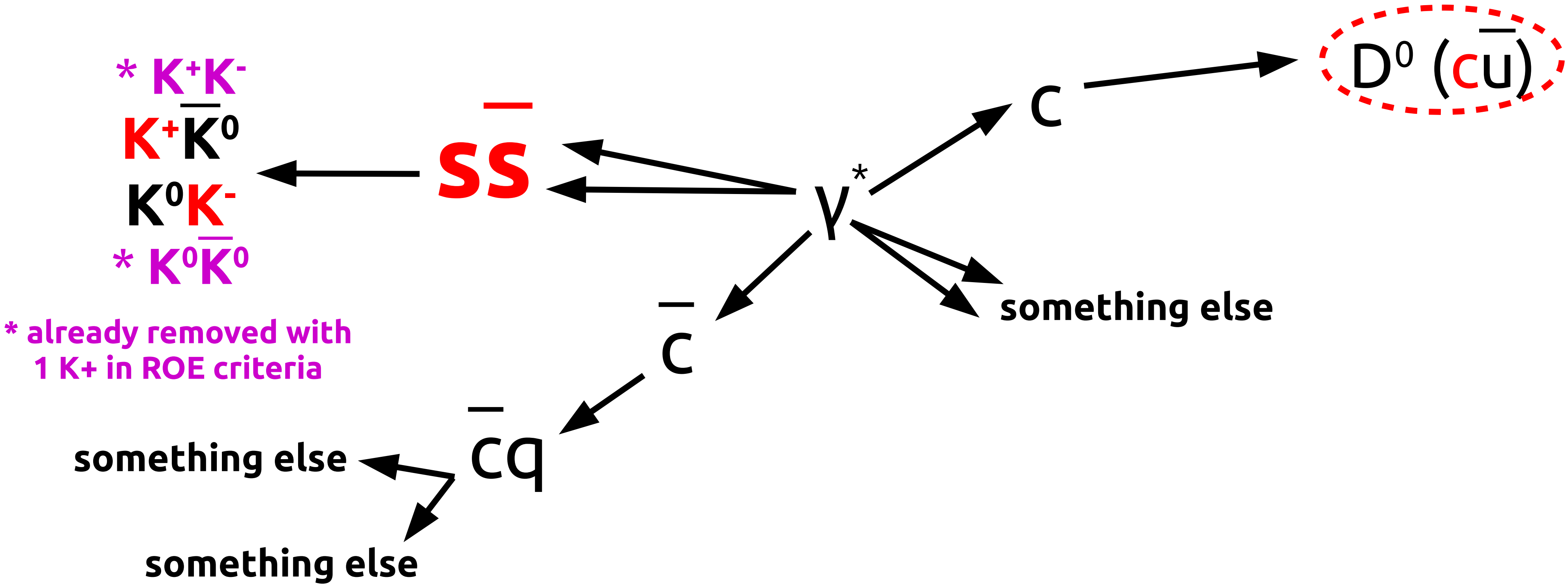
Chosen method: FastBDT (the plugin method implemented in basf2)





K^+/K^- from γ^* ($c\bar{c}s\bar{s}$ events) → Selection & cuts

To improve the reduction of background from $c\bar{c}s\bar{s}$ event, it's possible to apply a **veto on neutral K (K_S and K_L) in the ROE**.



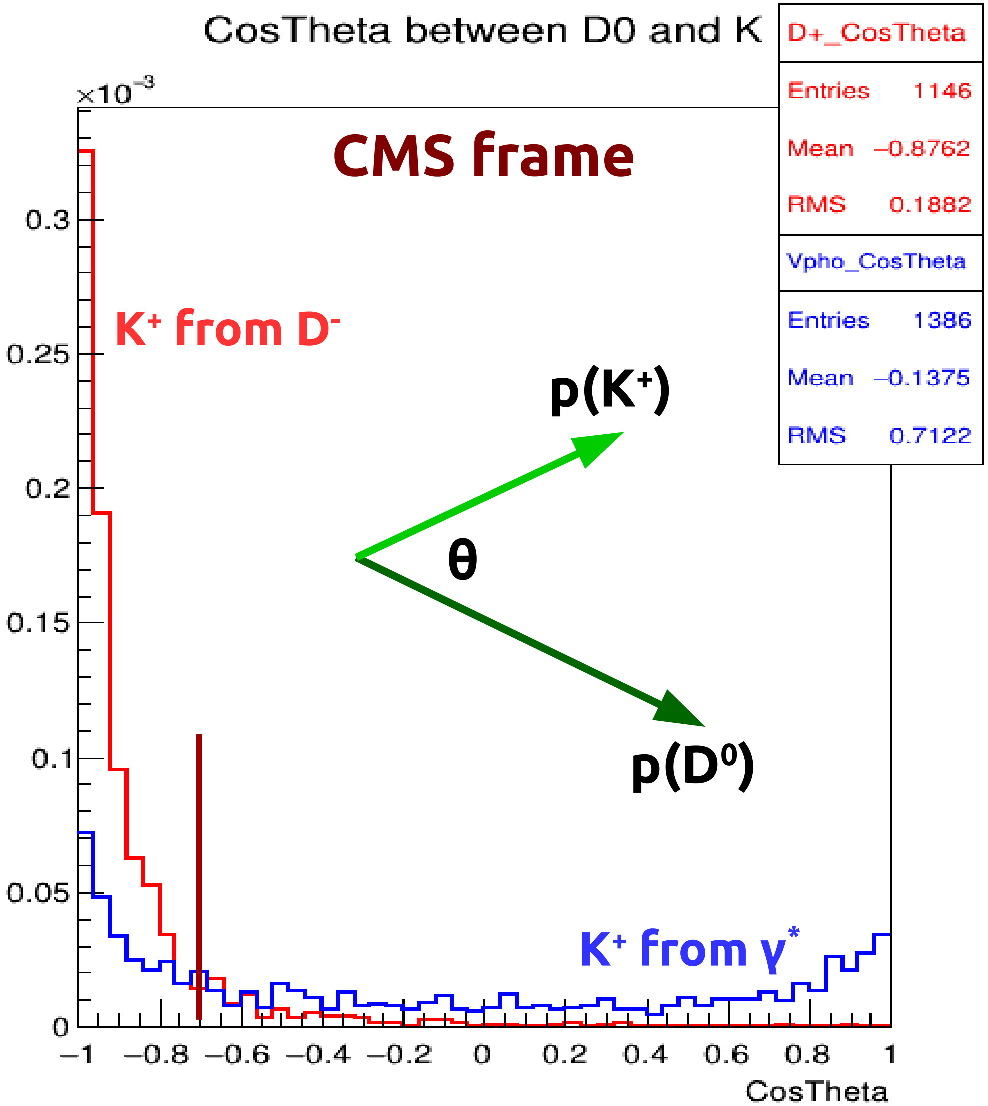
At present, the reconstruction of K_L is to be optimized (too large background), so it's not possible to apply any veto on K_L.

With a veto on K_S:

K^+ from γ^*: - 25%
K^+ from D^-: - 10%

Kinematics of events: relative angle

Since $c\bar{c}$ are back to back, tagging K^+ tends to go to the opposite direction respect to D^0.



We can partially distinguish K^+ from D^- and K^+ from γ^*: selecting events with **$\cos(\theta) < -0.7$** we can cut away part of the physics background:

K^+ from γ^*: - 66%
K^+ from D^-: - 10%

Signal and background: results

1M $c\bar{c}$ events → (1 true reconstructed D^0; 1 K^+ in ROE from BDT) → **~ 16.6k events** → ($\cos(\theta) < -0.7$; veto K_S) → **~10.6k events**

At present, the background is very large if we consider K- from D0 as a source of background:

→ **signal events: ~ 25%**
- K^- from D^+: **~ 96%**
- K^- from γ^*: **~ 4%**

→ **bkg events: ~ 75%**
- K^- from $D^0/\bar{D}^0$: **~ 69.5%** → **Expected**
- Events with missing K^-: **~ 15.1%**
- K^- from γ^*: **~ 9.6%**
- K^- from D^+ DCS: **~ 2.2%**
- K^- from D_s^+/D_s^-: **~ 1.8%**
- Events with fake K^-: **~ 1.2%**
- K^- from baryons DCS: **~ 0.6%**

Only a veto on K_S has been applied (for K^- from γ^*, K^- from D^+ DCS, K^- from D_s^+/D_s^-, K^- from baryons DCS)

Including K^- from D^0 in the signal sample

1M $c\bar{c}$ events → (1 true reconstructed D^0; 1 K^+ in ROE from BDT) → **~ 16.6k events** → ($\cos(\theta) < -0.7$; veto K_S) → **~10.6k events**

Huge improvement if **K^-s from D^0** are moved to signal events:

→ **signal events: ~ 76.4%**
- K^- from D^0: **~ 67.1%** ← D⁰s from all the decay channels!
- K^- from D^+: **~ 30.9%**
- K^- from baryons: **~ 2.0%**

→ **bkg events: ~ 23.6%**
- Events with missing K^-: **~ 47.9%**
- K^- from γ^*: **~30.4%**
- K^- from D^- DCS: **~ 7.0%**
- K^- from D_s^+/D_s^-: **~ 5.7%**
- Events with fake K^-: **~ 3.9%**
- K^- from $\bar{D}^0$ DCS: **~ 3.2%** ← D^0s from all the decay channels!
- K^- from baryons DCS: **~ 1.9%**

Only a veto on K_S has been applied

Possible future performance improvements

In order to evaluate the expected performances with an improved reconstruction, I made some additional requirements from MC truth: **0 MC K_S** and **0 MC K_L** per event.

1M $c\bar{c}$ events → (**1 true reconstructed D^0**; **1 K^+ in ROE from BDT**; **$\cos(\theta) < -0.7$ + veto MC K_S + veto MC K_L**) → **~9.8k events**

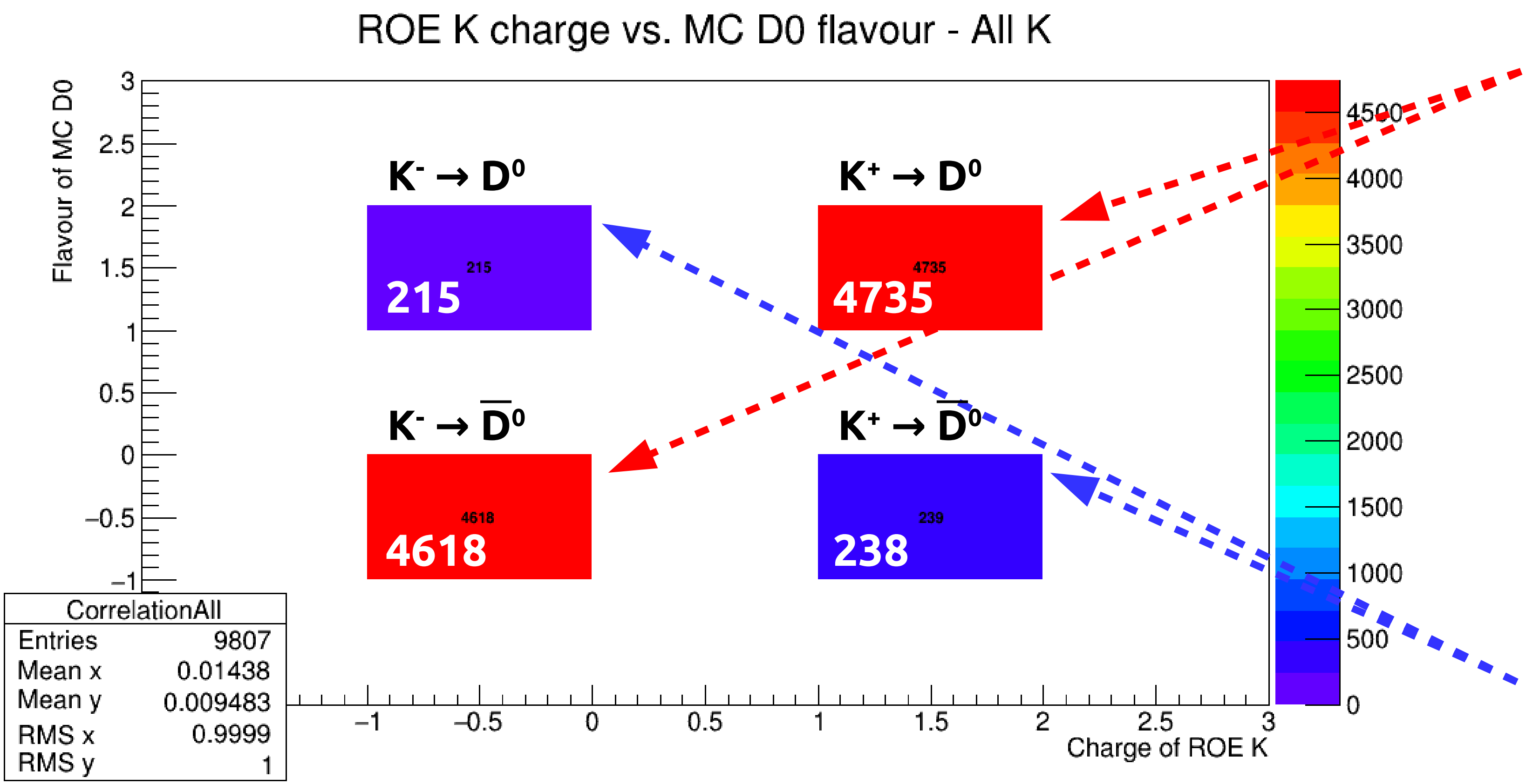
→ **signal events: ~ 86.8%**

- K^- from D^0: **~ 68.4%**
- K^- from D^+: **~ 29.7%**
- K^- from baryons: **~ 1.9%**

→ **bkg events: ~ 13.2%**

- Events with missing K^-: **~ 52.2%**
- K^- from γ^*: **~30.0%**
- K^- from $\bar{D}^0$ DCS: **~ 8.1%**
- Events with fake K^-: **~ 6.1%**
- K^- from baryons DCS: **~ 2.8%**
- K^- from D^- DCS: **~ 0.5%**
- K^- from D_s^+/D_s^-: **~ 0.3%**

Tagging efficiency with MC improvements



~95.3% of charged K give us a **correct** tagging.

Among them:
~ 9% of K gives a "random" tagging

~4.7% of charged K give us a **wrong** tagging.

Results shown for events with 1 D^0 and 1 K^+ in ROE
Cuts applied: cos(θ) < -0.7; veto on MC K_S; veto on MC K_L.

Comparison with D^{*+} method

In order to evaluate the tagging efficiency and mistagging level, I will perform in next days a comparison with the D^{*+} (standard) method.

I already generated and simulated 100k cc events with at least 1 D^{*+} per event.

The generated D^{*+} decays in:

- ~ 33% of times in $D^+ \pi^0$;
- ~ 67% of times in D^0 ($\rightarrow K^- \pi^+$) π^+.

I already performed the reconstruction (I reached purities of **~ 98.2%** on D^{*+} reconstrucion and **~ 99.6%** on D^0 reconstrucion).

On recostructed events, I will apply both methods to flavour tag the D^0s in order **to measure the efficiency of my method respect the efficiency of the D^{*+} techinque**.

This means that it will be possible to measure the efficiency of my method directly on the data!

Note that the two tagging technique are not correlated.

Conclusions

- The possibility to flavor tag the prompt D^0 with a new method has been studied.

- Since the basf2 software isn't at the final version, some improvements are expected in the future:
  → the selection of K^+ will improve;
  → the reconstruction of K_S will improve;
  → the reconstruction of K_L will improve.

- It's necessary to repeat the study with the final version of the software in order to evaluate correctly the performances of this method.

- It would be useful to apply this method for some analysis to evaluate the sistematic error introduced.

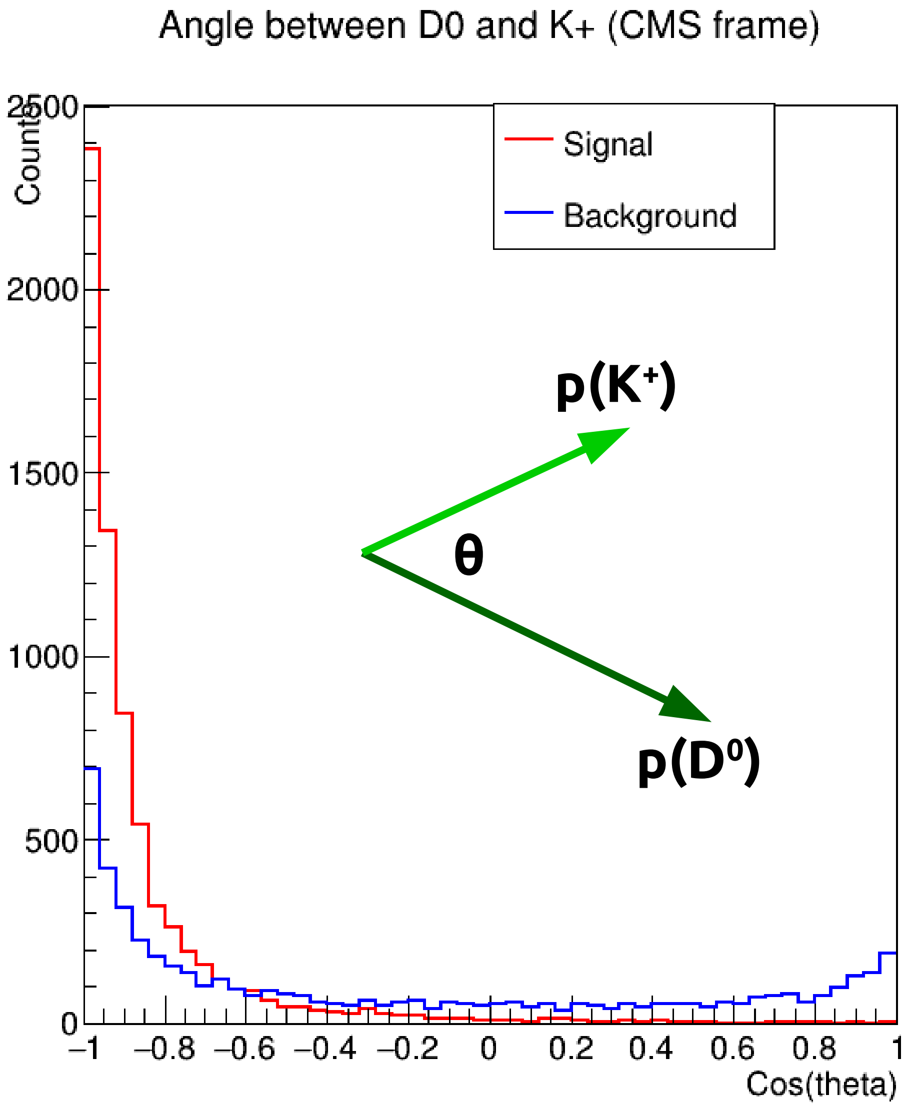
- Future plan: measure the mistag level of my method by a comparison with the D^{*+} method: possibility to make the measurement with real data!

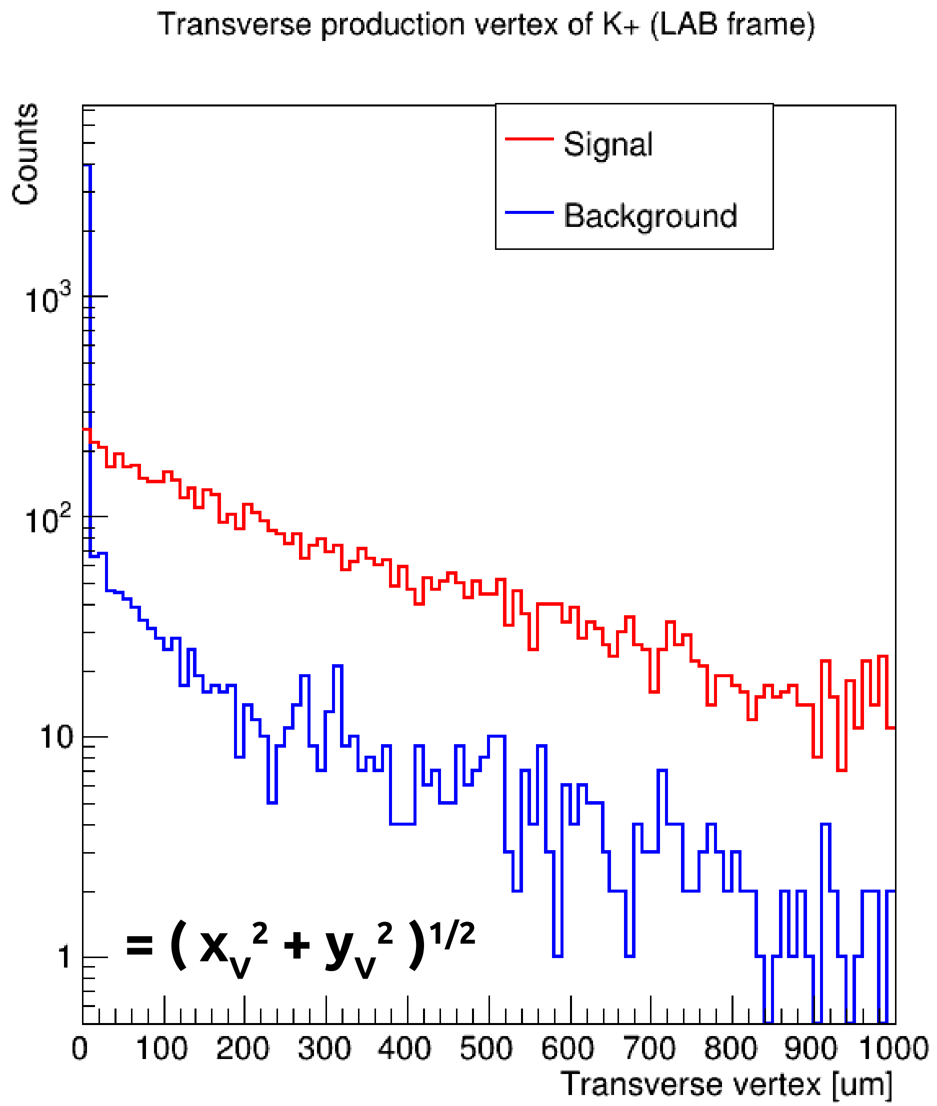
Thank you for the attention!

D, or not D that is the question

Backup slides

Kinematics of the generated events



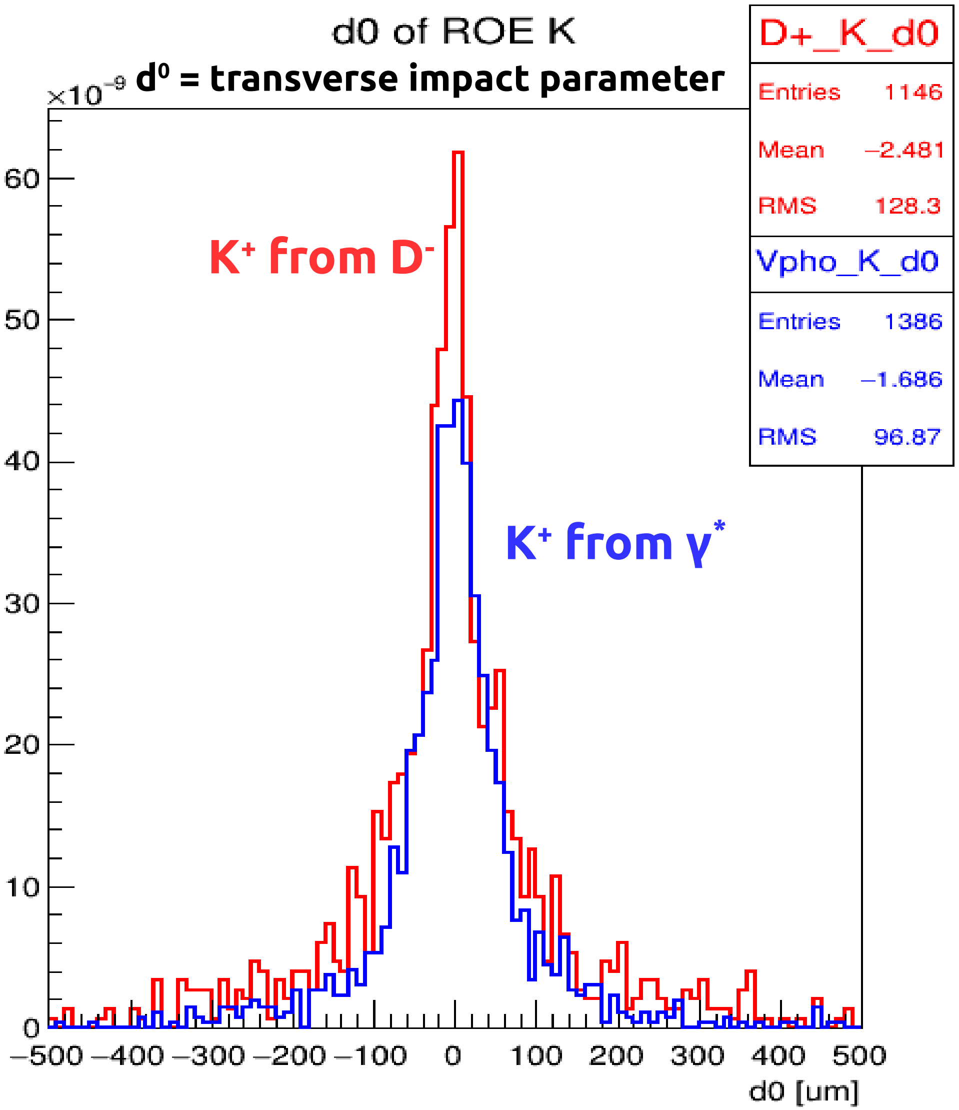


Since $c\bar{c}$ are back to back, tagging K^+ tends to go to the opposite direction respect to D^0

Transverse production vertex of K^+ coming from γ^* is within the beam spot (**correlated to d_0 of the track**)

Data referred to $c\bar{c}$ events at generator level!

Kinematics of the recons. events: impact parameter



d_0 of K$^+$ from γ* should be of the order of the dimension of the beam spot (**<10 μm, w.r.t. cτ(D^0) ~123 μm**).

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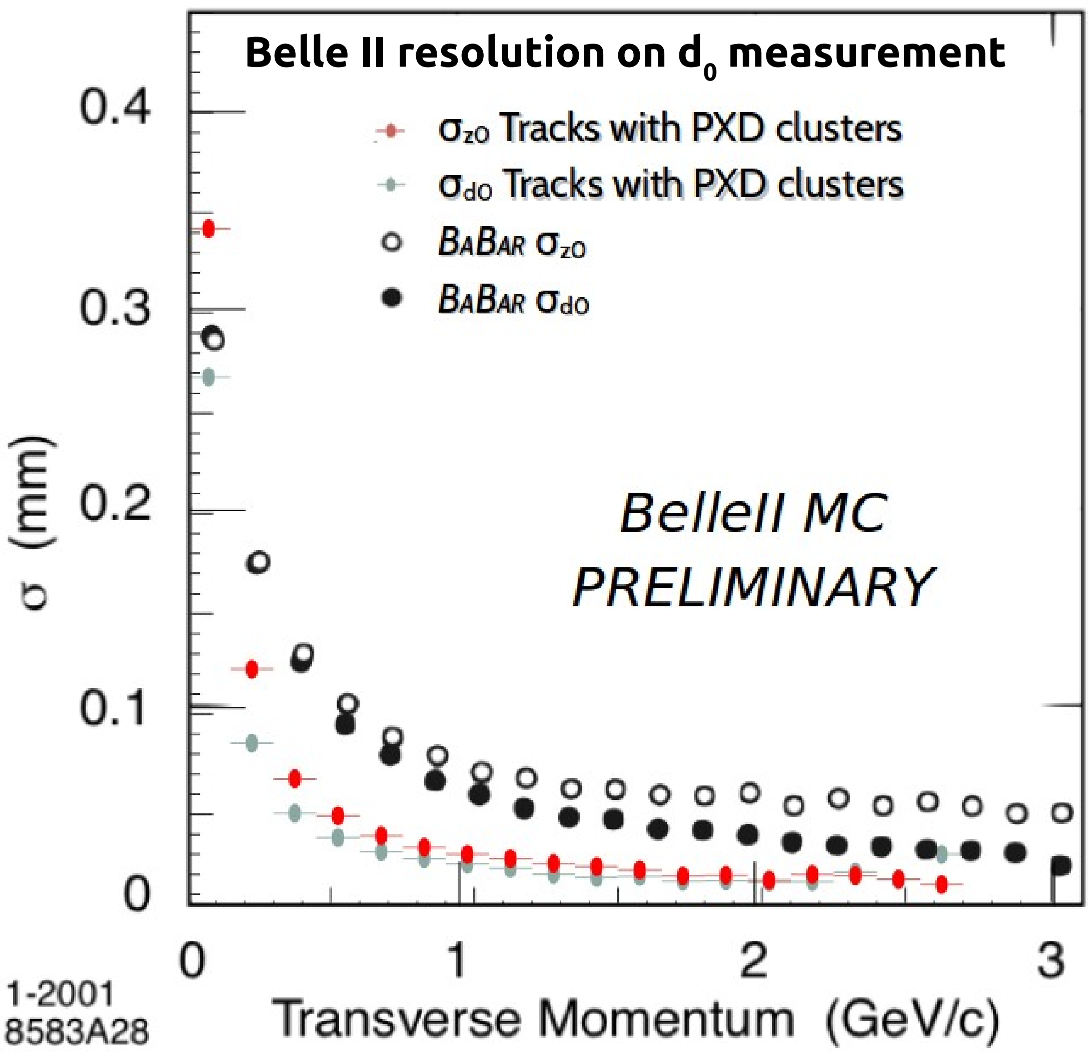
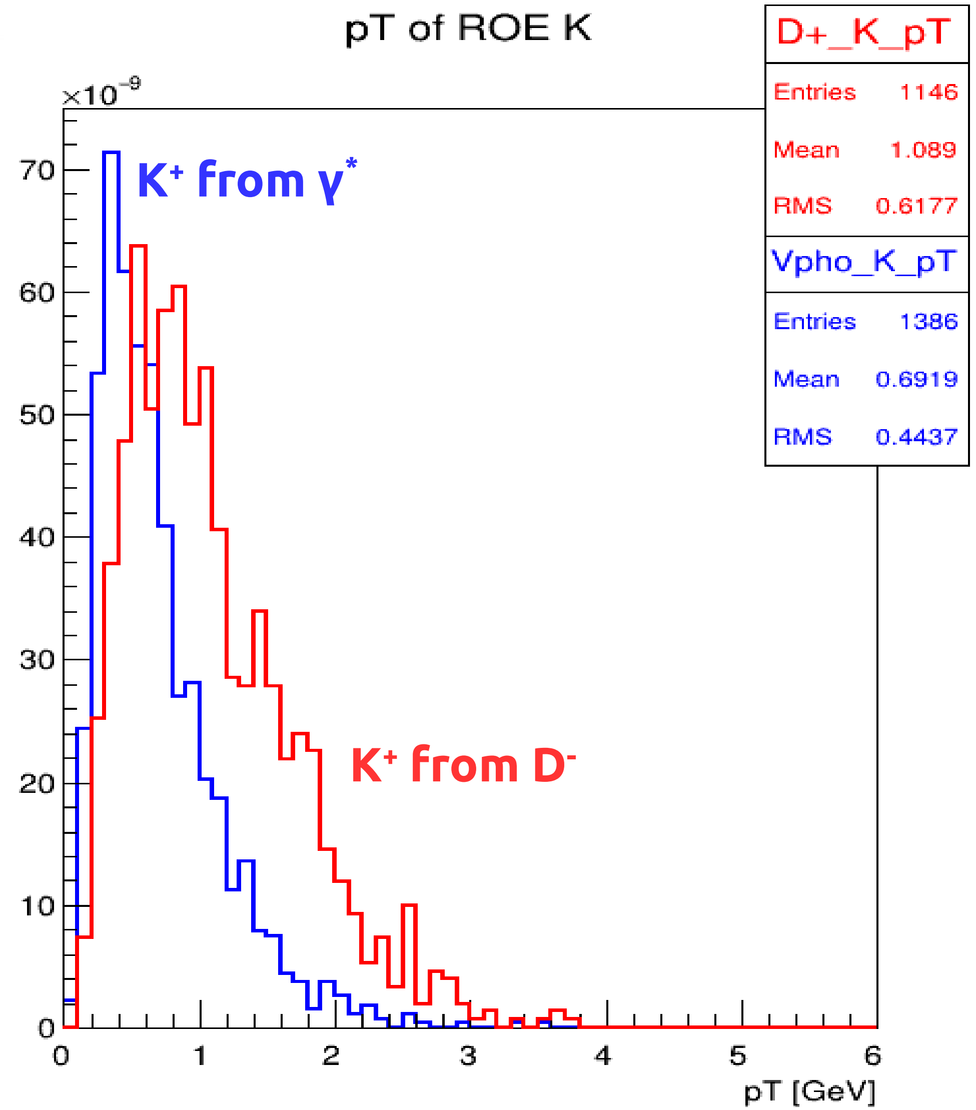




d_0 of K^+ from γ^* should be of the order of the dimension of the beam spot (**<10 μm, w.r.t. cτ(D^0) ~123 μm**).

Since most of K^+ from γ^* have **pT < 1 GeV**, Belle II doesn't have the proper resolution to measure correctly the d^0 of these K^+.

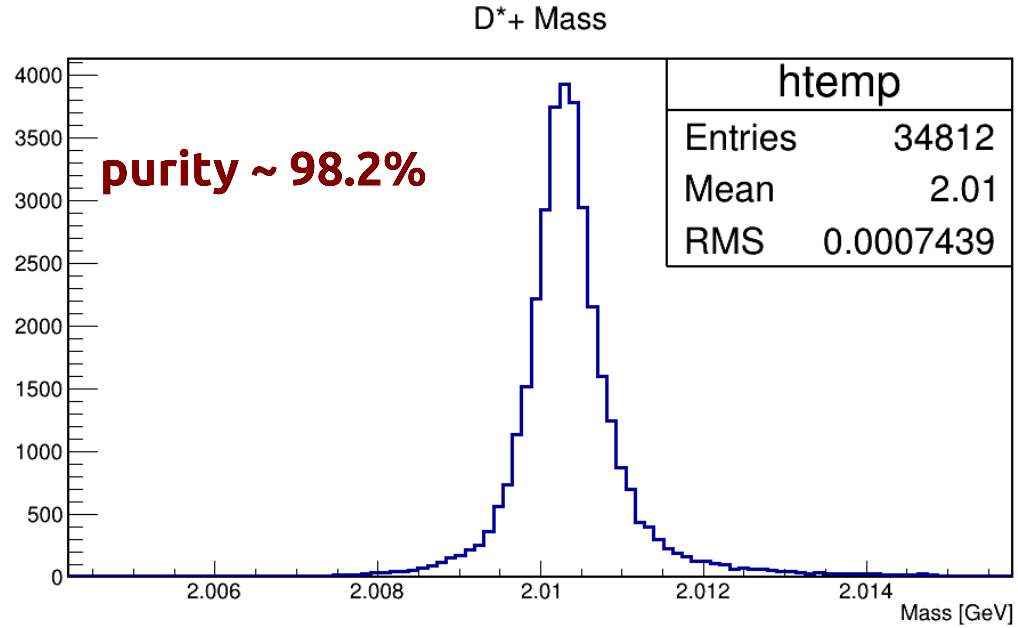
$D^{*+} \rightarrow D^0 \pi^+$ / $D^0 \rightarrow K^- \pi^+$

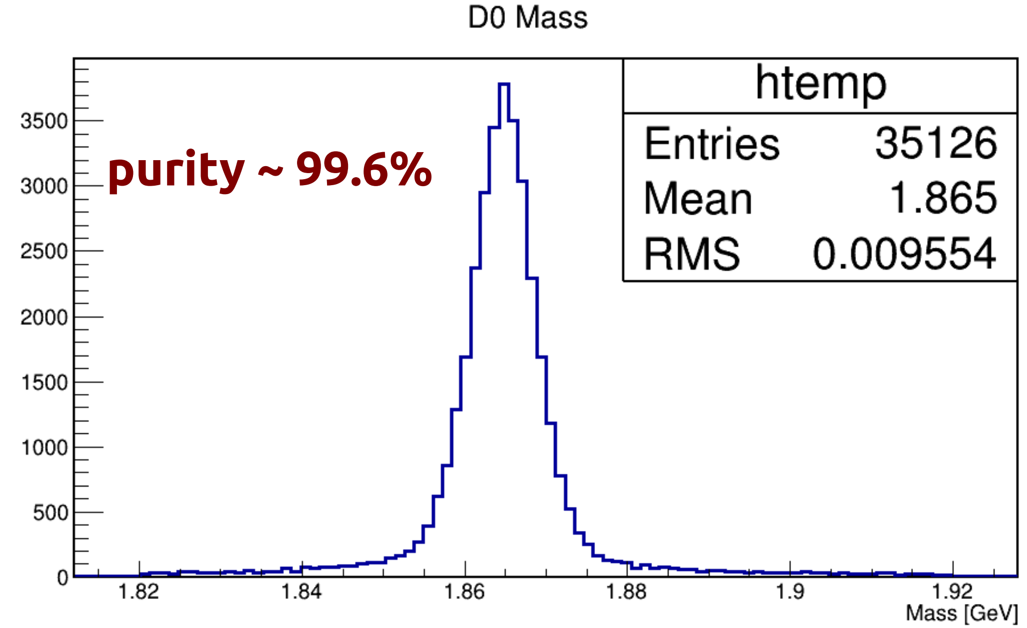
Reconstruction of $D^0 \rightarrow K^- \pi^+$:

→ PID(K) > 0.5 and Prob(χ^2) > 10^{-3} of fitted track
→ PID(π) > 0.5 and Prob(χ^2) > 10^{-3} of fitted track
→ 1.82 GeV < m($K^- \pi^+$) < 1.92 GeV
→ mass-vertex-fit (RAVE) with Prob(χ^2) > 10^{-3} of fit

Reconstruction of $D^{*+} \rightarrow D^0 \pi^+$:

→ PID(π) from dEdX > 0.5
→ 0 MeV <= Q-value < 20 MeV
→ mass-vertex-fit (RAVE) with Prob(χ^2) > 10^{-3} of fit





D^0 from $b\bar{b}$ events

The best cut to remove the background D^0 coming from bb events is p > 2.5 GeV in CMS frame:

$\varepsilon_{sig} \sim 71.5\%$ $\varepsilon_{bkg} \sim 6 \cdot 10^{\wedge -5}$

I tried a selection based on a BDT using:

- z coordinate of the D^0 vertex
- D^0 momentum
- R2 Fox-Wolfram moment
- cosine of the angle between thrust axis of D^0 and ROE

To keep low the background, a possible selection gives:

$\varepsilon_{sig} \sim 78.5\%$ $\varepsilon_{bkg} \sim 5 \cdot 10^{\wedge -3}$