Asymmetries in rare three-body charm decays with electrons at LHCb

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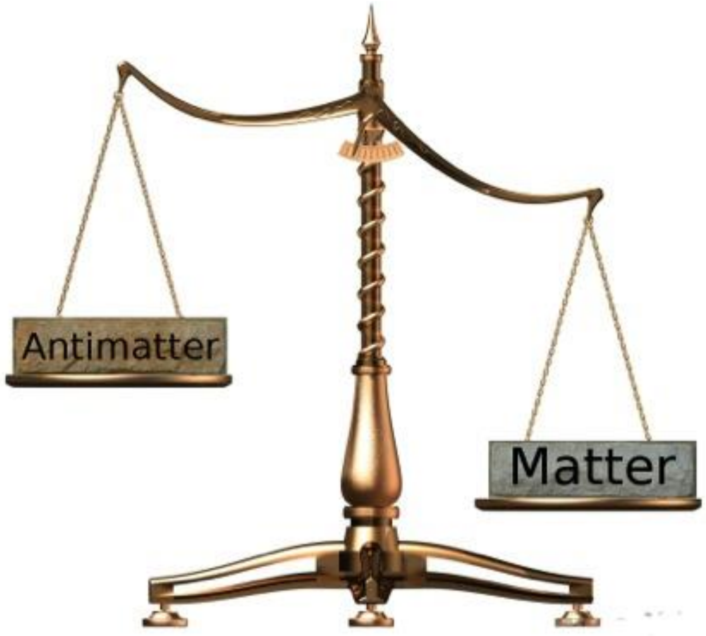
Matter-antimatter asymmetry

The huge **imbalance** between matter and antimatter in the universe (**CP asymmetry**) is not explained by the standard model for particle interactions (**SM**)

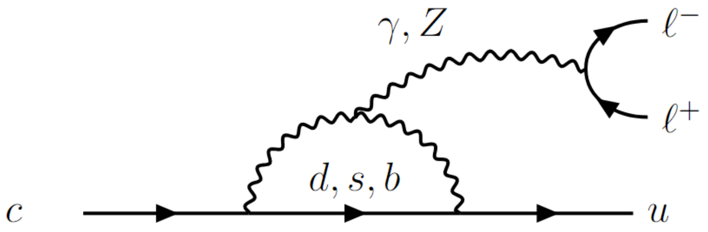
New Physics (**NP**) may be related to **new sources of CP violation**.

CP and forward-backward (**FB**) **asymmetries** for many decay processes can be used as **null tests** for the SM .



$c \to u$ transitions and D decays

Flavor-changing neutral currents only happen via **loop diagrams** in SM.

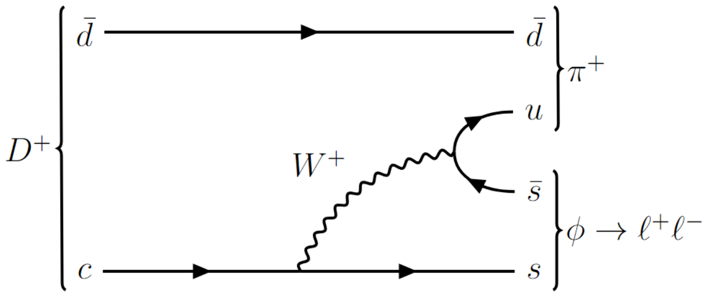


$c \to u$ transitions **extremely suppressed** due to:

- **CKM** elements ($\lambda_i = V_{ci}^* V_{ui}$, $\xi_b = \lambda_b / \lambda_s$)
- **GIM** mechanism ($f_i \sim (m_i / 4\pi m_W)$, $f_s - f_d \sim 0$)

$$A_{c \to u} \propto \lambda_s \left[(f_s - f_d) + \xi_b (f_b - f_s) \right]$$

Branching fraction of $D^+ \to \pi^+ e^+ e^-$ is **dominated by intermediate resonances** such as $D^+ \to \pi^+(\phi \to e^+ e^-)$.



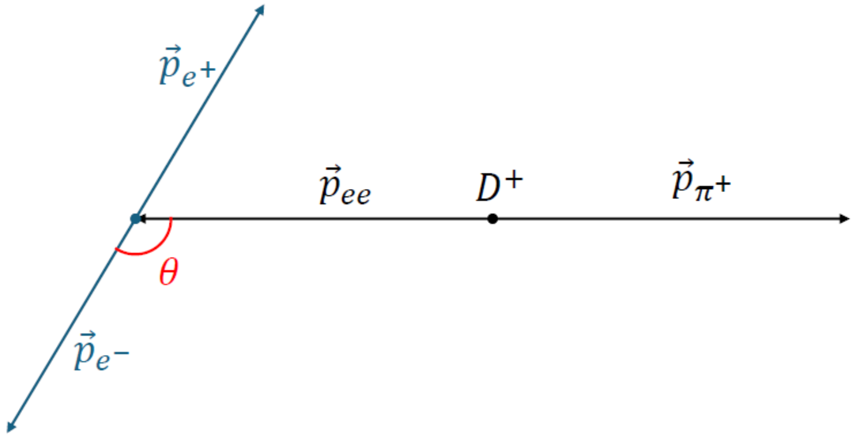
What is A_{FB}?

A_{FB} is a **parity** asymmetry.

Acceptance corrections needed.

A_{FB} is measured separately for **both D^+** and **D^-** .

The two measurements can then be **combined**.



Strategy

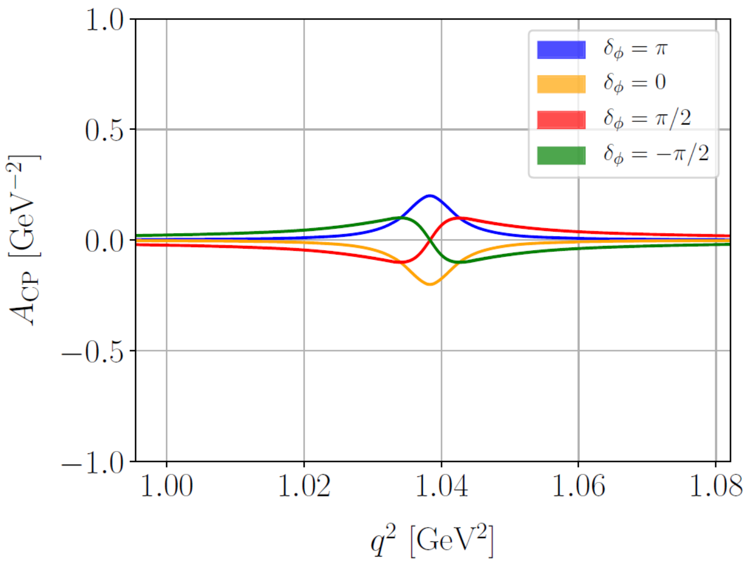
NP could induce **non-zero asymmetries**:

- $A_{CP}^{raw} = \frac{N(D^+)-N(D^-)}{N(D^+)+N(D^-)})$
- $A_{FB} = \frac{N(cos\theta>0)-N(cos\theta<0)}{N(cos\theta>0)+N(cos\theta<0)}$

A_{CP} depends on the **strong phase** difference between NP and resonance.

The **integrated** A_{CP} may **cancel**.

Measurement is performed in **two bins** of dilepton mass in order to be **sensible to this effect**.



[https://link.springer.com/article/10.1140/epjc/s10052-020-7621-7]

CP asymmetry

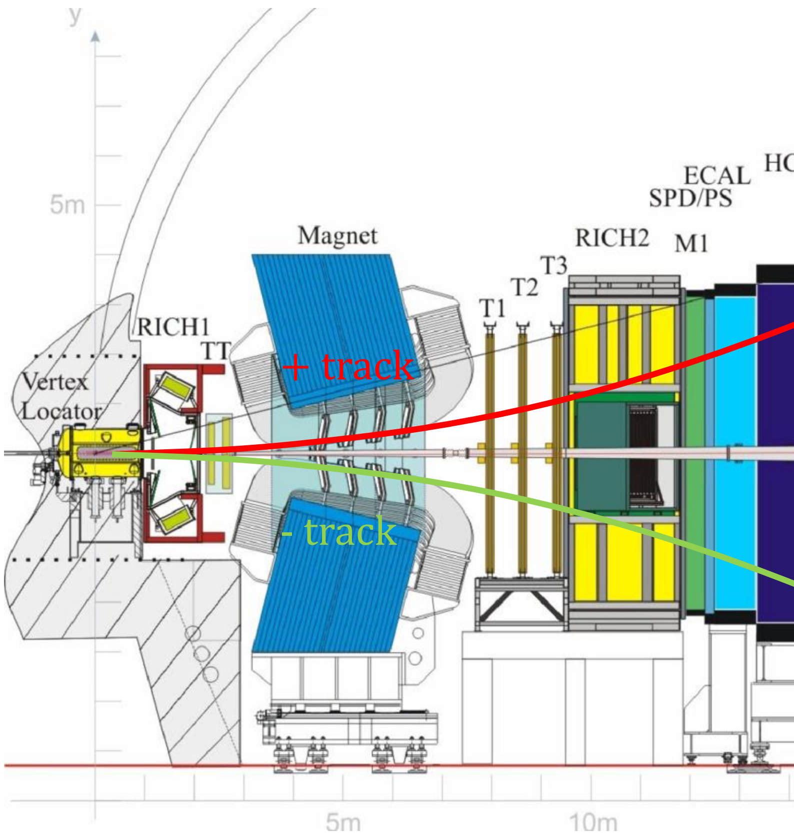
It is possible to extract A_{CP}^{raw} from data, but there are **nuisance asymmetries**.

$$A_{CP}^{raw} = A_{CP} + \boldsymbol{A_{det}(\pi)} + \boldsymbol{A_{prod}(D)}$$

Nuisance asymmetries are extracted with a **control channel** ($D^+ \to \pi^+ K_s$) with **negligible A_{CP}**.

$$A_{CP}^{raw}(D^+ \to \pi^+ K_s) = A_{det}(\pi) + A_{prod}(D)$$

$$A_{CP}(D^+ \to \pi^+ e^+ e^-) =$$
$$A_{CP}^{raw}(D^+ \to \pi^+ e^+ e^-) - A_{CP}^{raw}(D^+ \to \pi^+ K_s)$$

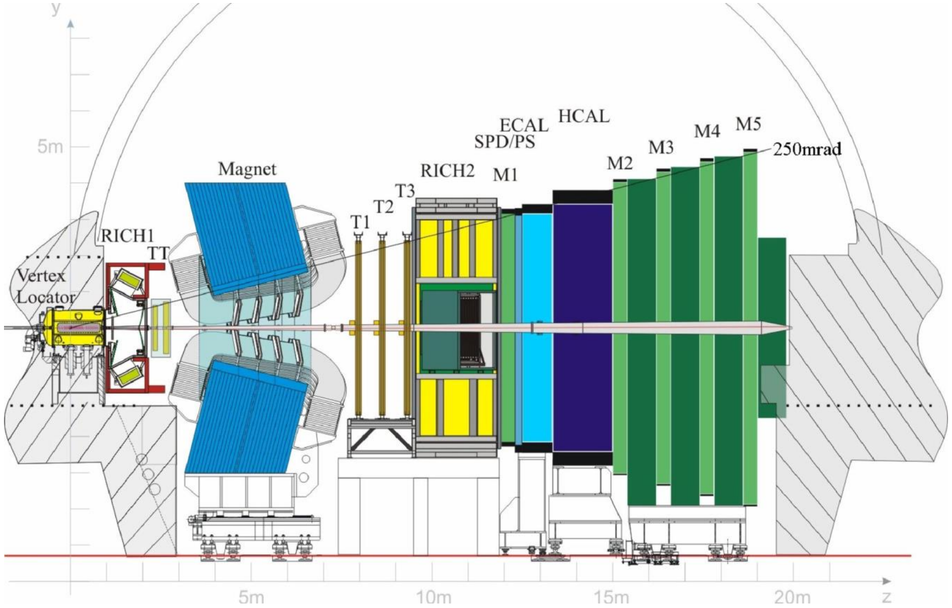


Data

Data used for the analysis has been collected during **Run 2** from 2015 to 2018 at **LHCb**.

The LHCb detector is **designed** for **indirect searches** for NP in decays of **heavy flavored** hadrons (*c*, *b*).

The analysis requires good **vertex reconstruction**, **momentum resolution** and particle identification (**PID**).



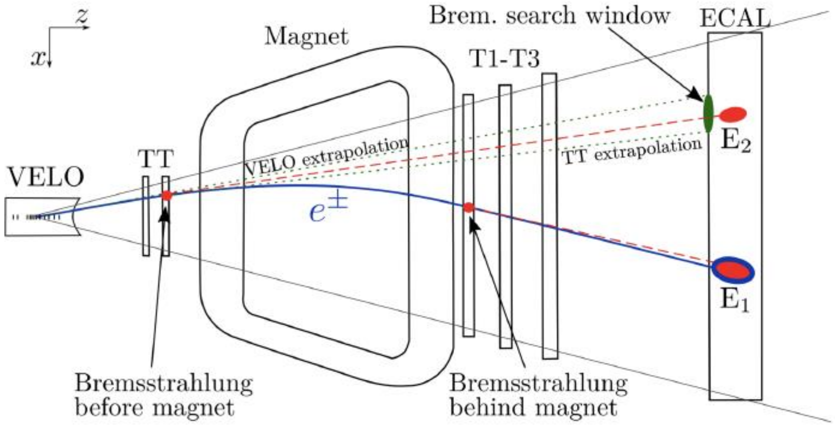
Electrons at LHCb

Electrons emits **bremsstrahlung** photons.

This leads to **complications** during **energy reconstruction**.

Bremsstrahlung reconstruction in the **calorimeter** is flawed:

1. **Resolution effects**
2. **Non-reconstructed photons**
3. **Random photons**

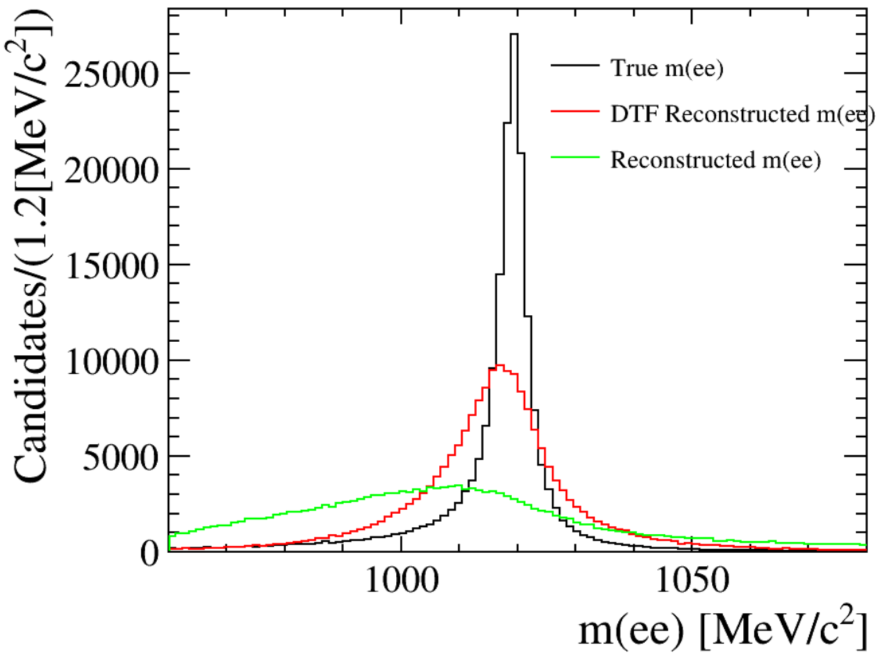


Dilepton-mass reconstruction

Reconstructed dilepton mass distribution **doesn't** represent correctly the one of the **true** $m(ee)$.

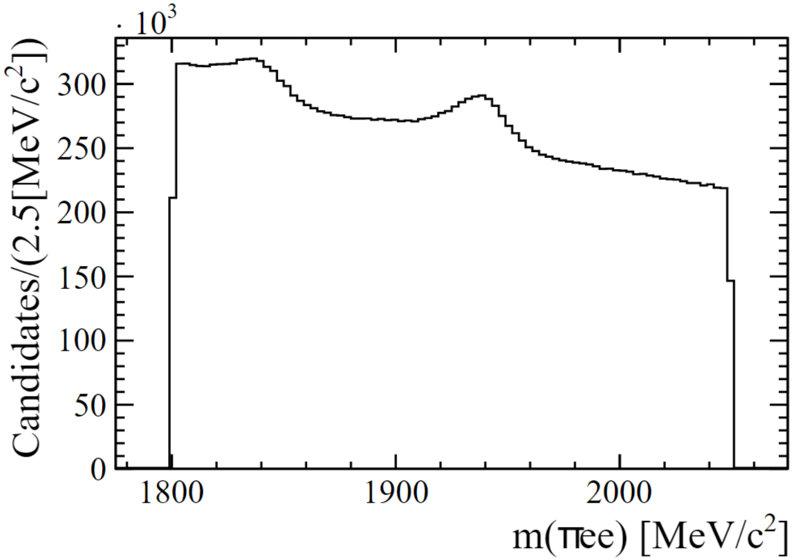
Decay Tree Fitter variables use additional constraints and are in **better agreement** with the true distribution.

The **resolution** of the DTF $m(ee)$ is ~ 18 MeV/c^2.



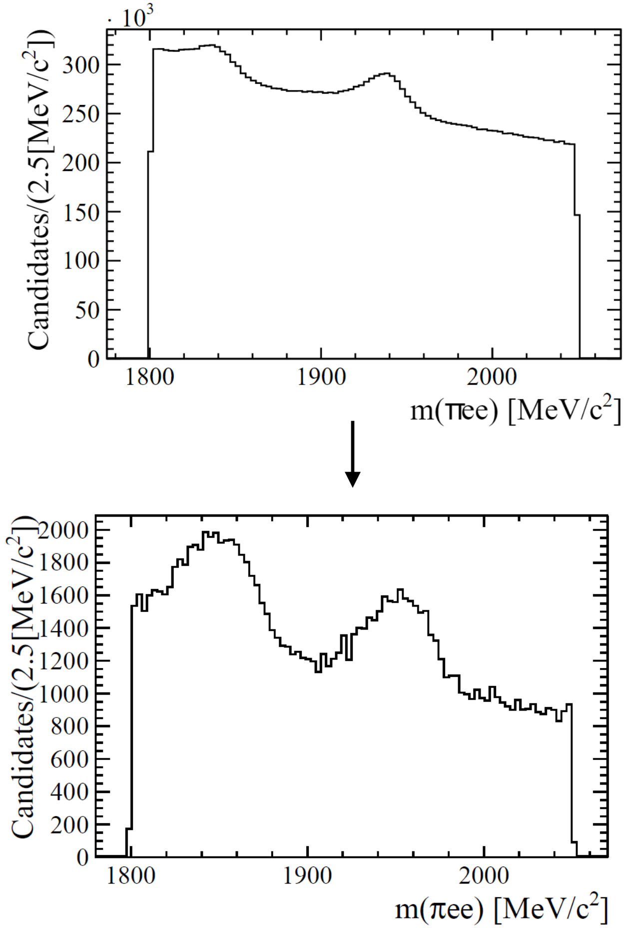
Analysis overview

1. Preselection
2. Multivariate analysis
3. Dataset components and cut optimization
4. Efficiency correction
5. Fit and results
6. Nuisance asymmetries



Preselection

- Impact Parameter for **secondaries rejection:** IP_PV < 0.06 mm
- Particle Identification (**PID**) for pion and electrons: ProbNNpi > 0.2, ProbNNe > 0.1 (**ProbNNe to be optimised**)
- **Ghost tracks rejection**: TRACK_GhostProb < 0.2
- **Combinatorial background rejection:** LTIME>0 (for bkg can be negative, not for signal).



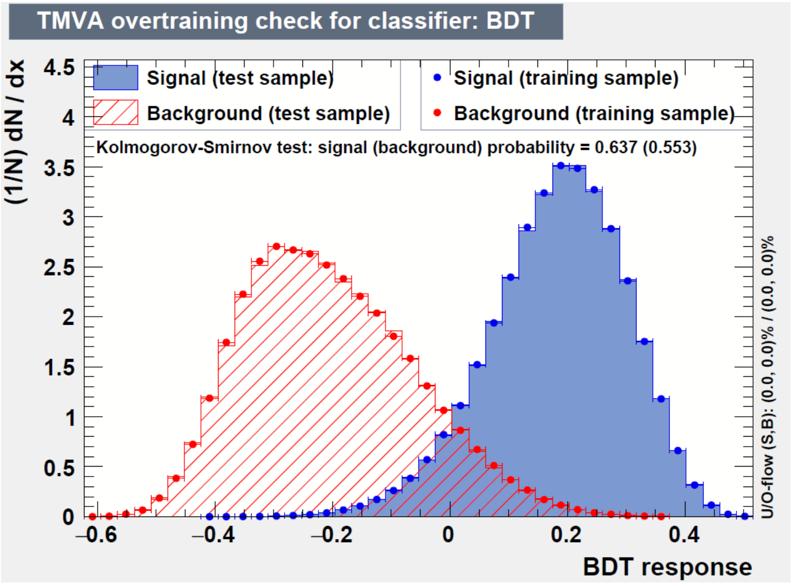
Multivariate analysis

Wrong Sign data used as **combinatorial background** sample. All final state particles have **same charge** so it can't be signal.

MC used as **signal sample** (both D and D_s).

The chosen MVA algorithm is a **Boosted Decision tree.**

Kinematical, **topological** and **isolation variables** with **different distributions** for the two samples are chosen for the BDT.

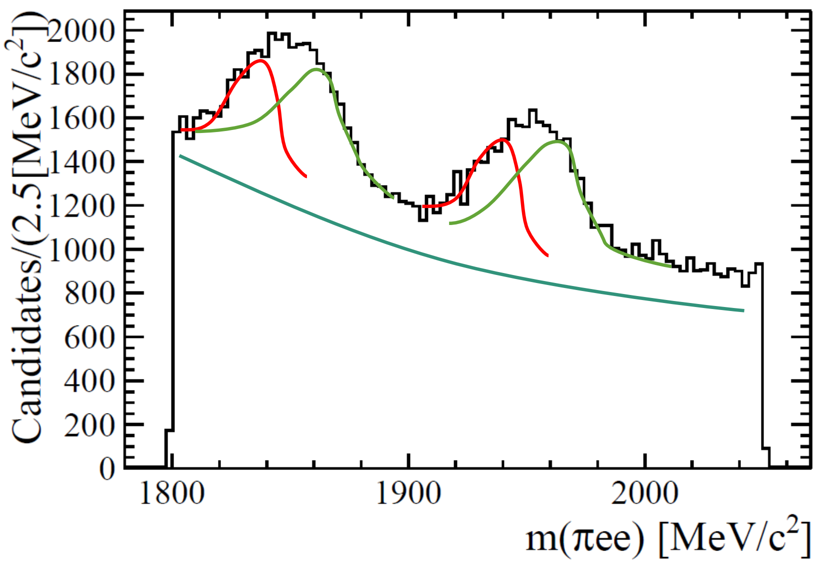


Components of the dataset

Data can be described by 5 components:

- The **signal** components of the D and the D_s
- The **misID** components of the D and the D_s $(D^+ \to \pi^+\pi^+\pi^-)$
- The **combinatorial background** component

The signal and misID components **distributions** are obtained **from MC**. Combinatorial background distribution is obtained **from WS data sample**.

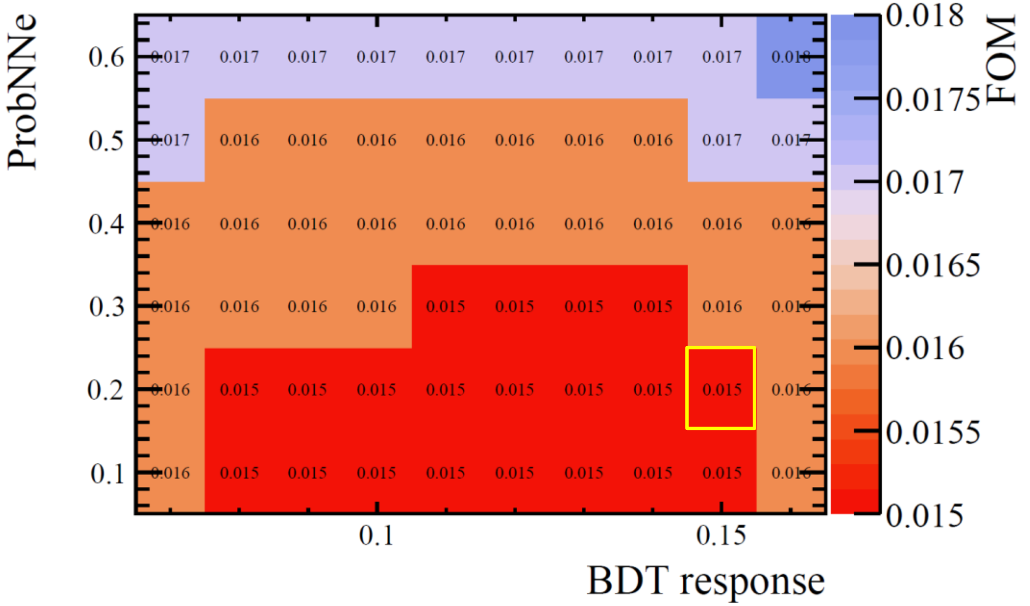


Data-driven 2D cut optimization

Fake asymmetry implemented to choose **best cuts** for **BDT response** and **probNNe**.

The **asymmetry uncertainty** is chosen to be the **figure of merit**.

Best cuts are BDT response > 0.15 and ProbNNe > 0.2.



Efficiency correction

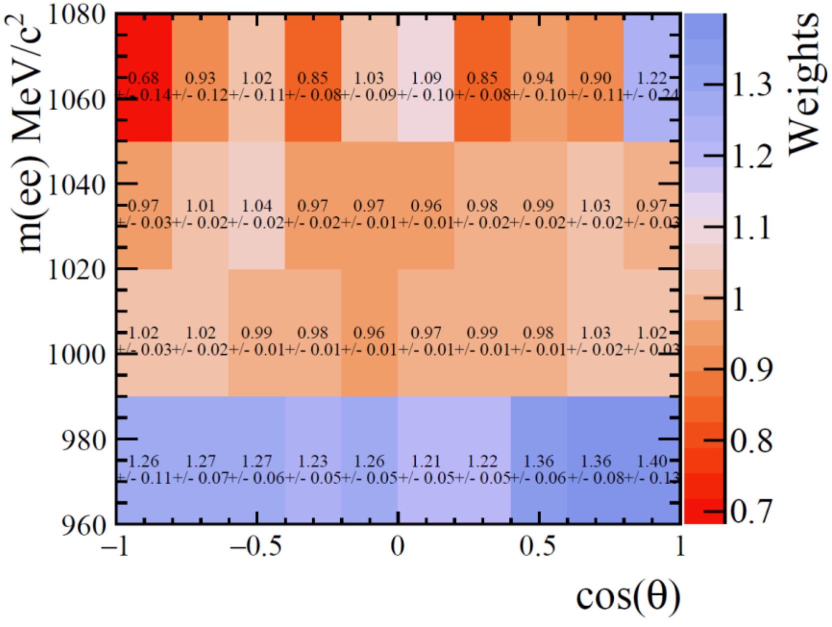
Reconstruction **efficiency not uniform over** ($\boldsymbol{m(ee)}$, $\boldsymbol{\cos\theta}$) phase space.

Efficiency correction weights calculated using a **generated sample** with no **detector reconstruction** applied.

$$w(m(ee), \cos\theta) = \frac{f_{generated}(m(ee), \cos\theta)}{f_{selected}(m(ee), \cos\theta)}$$

Weights are mapped in a **binned phase space**.

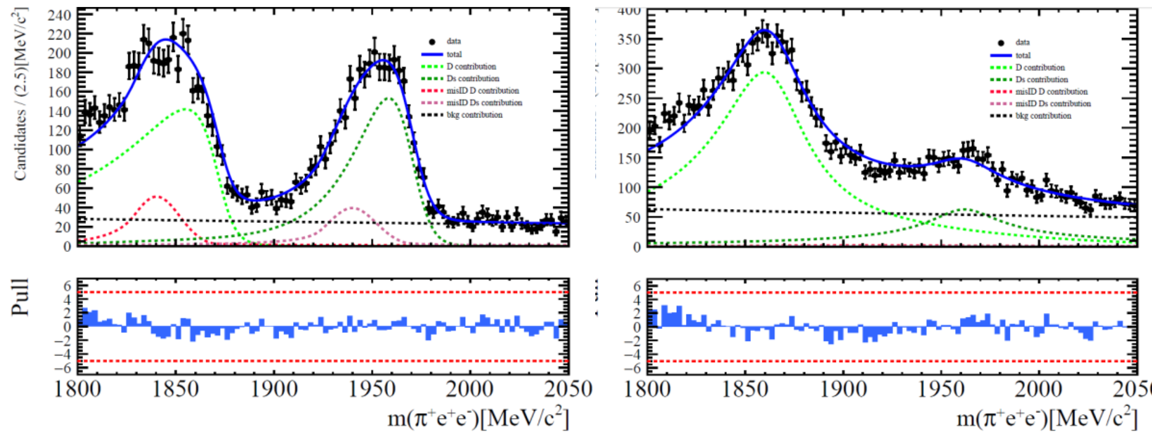
The **binning** on the map is chosen **accordingly to the DTF resolution**.



Fit results

Data can be also divided into **brem categories** (mis-ID events are negligible in brem1).

Asymmetries are extracted by **simultaneously fitting the dataset** split by charge sign and sign of cosθ.



The values are **blinded** according to **LHCb regulations**.

low-$m(ee) \in$ [960-1020] MeV/c^2

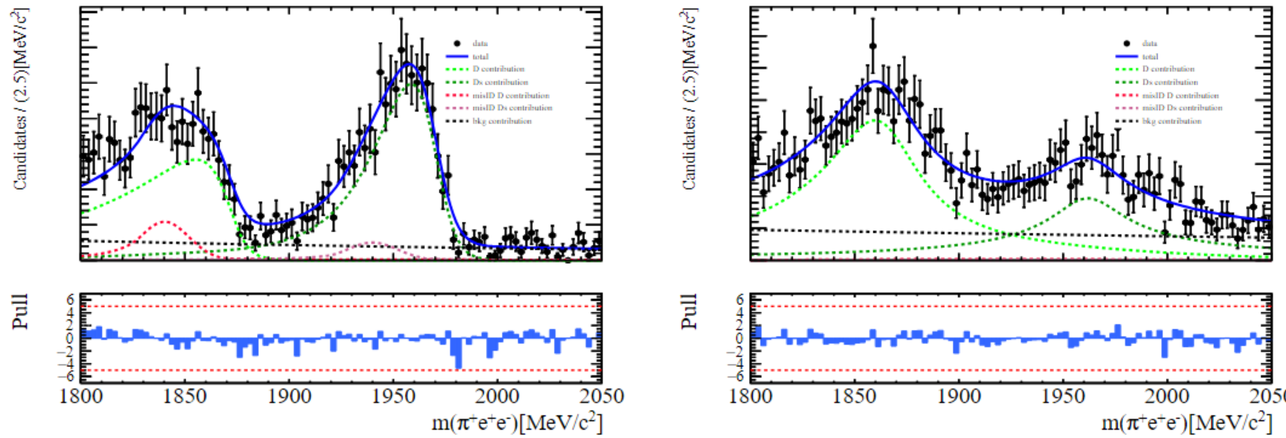
high-$m(ee) \in$ [1020-1080] MeV/c^2

	low-$m(ee)$	high-$m(ee)$
A_{CP}^{raw}	x±0.021	x±0.025
$A_{FB}^{D^+}$	x±0.026	x±0.036
$A_{FB}^{D^-}$	x±0.029	x±0.034

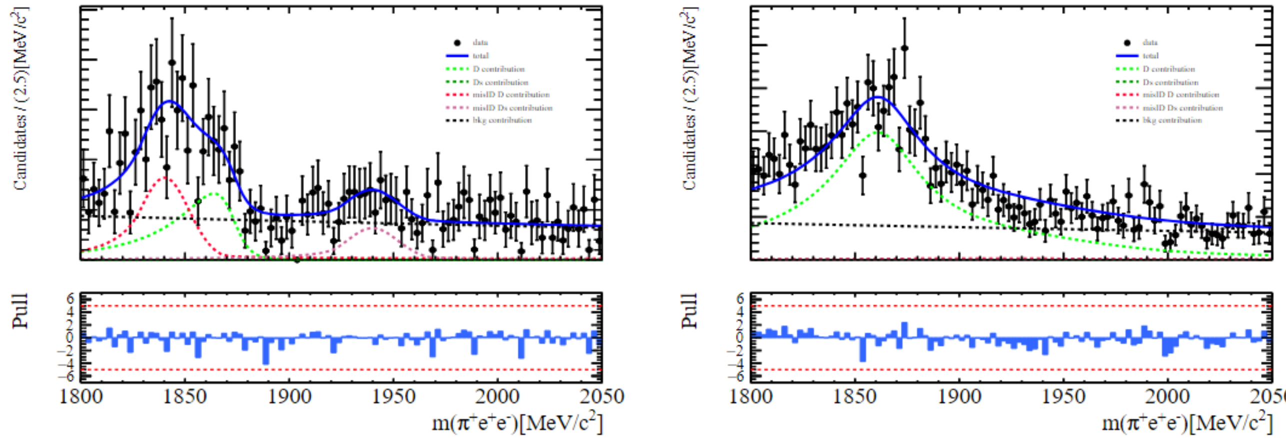
Preselection → MVA → Cut opt. → Eff. correction → Fit → Nuisance asym.

Fits projections

low-$m(ee)$



high-$m(ee)$



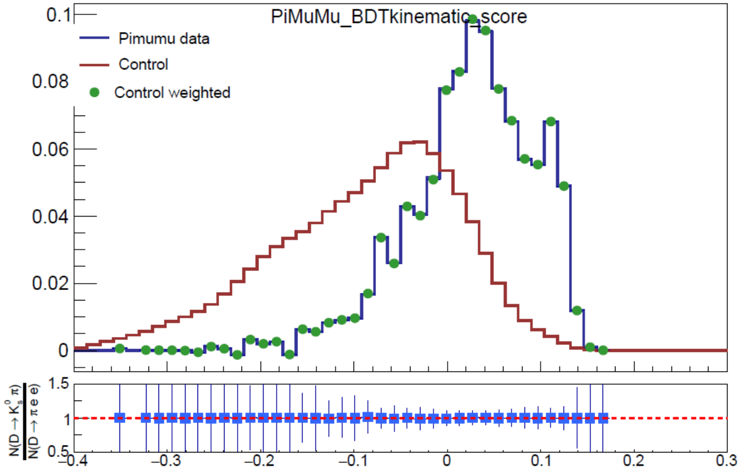
Nuisance asymmetry

Nuisance asymmetries are extracted from the **control channel** $D^+ \rightarrow \pi^+ K_s$.

The **kinematics** of the control channel **need to be reweighted** according to the kinematics of $\boldsymbol{D}$ and $\boldsymbol{\pi}$ from $D^+ \rightarrow \pi^+ e^+ e^-$.

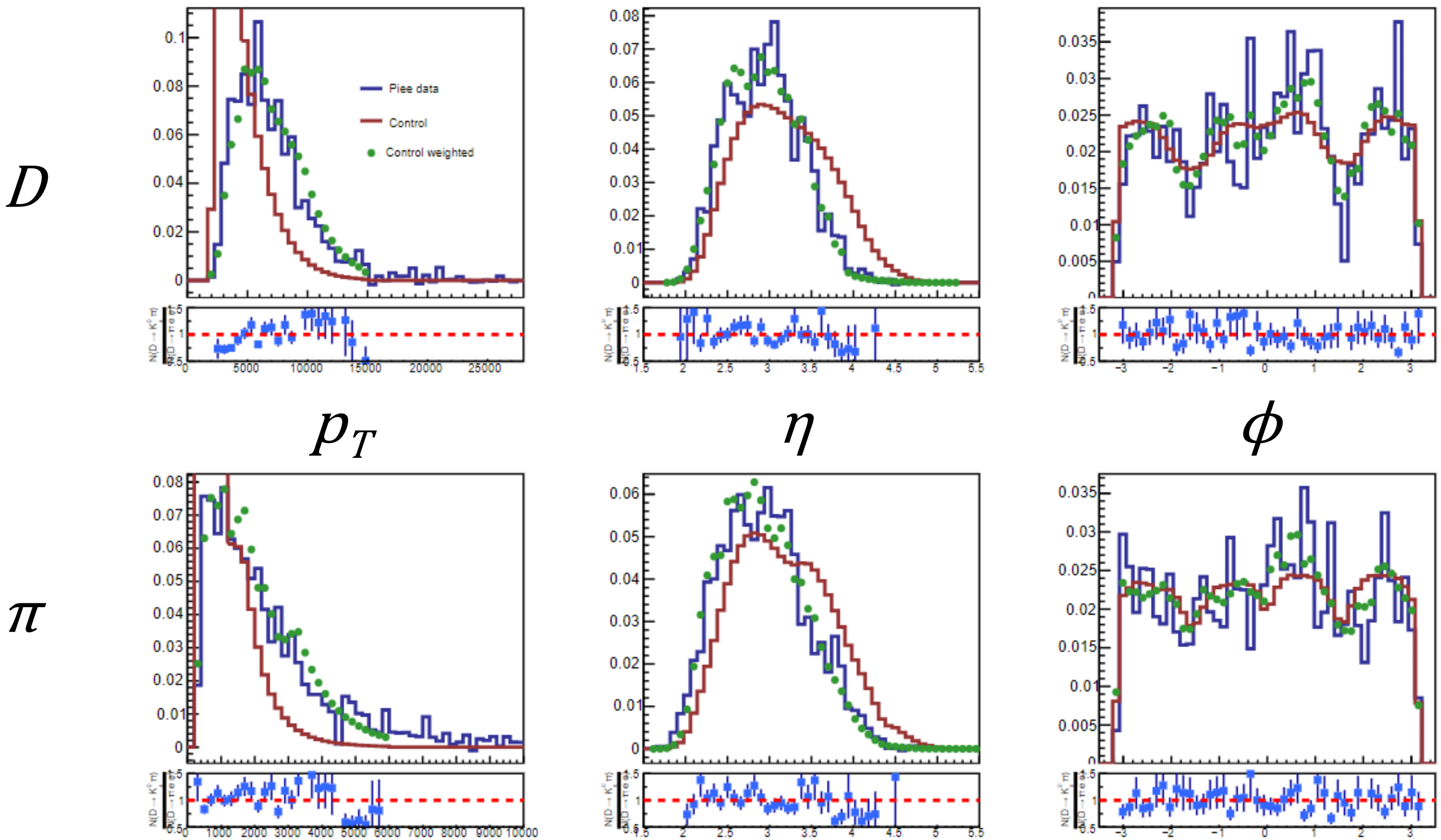
Control and signal datasets have to be **background subtracted.**

The **kinematical variables** are then used in a **BDT** that is used for the **reweighting.**



Preselection → MVA → Cut opt. → Eff. correction → Fit → Nuisance asym.

Nuisance asymmetry

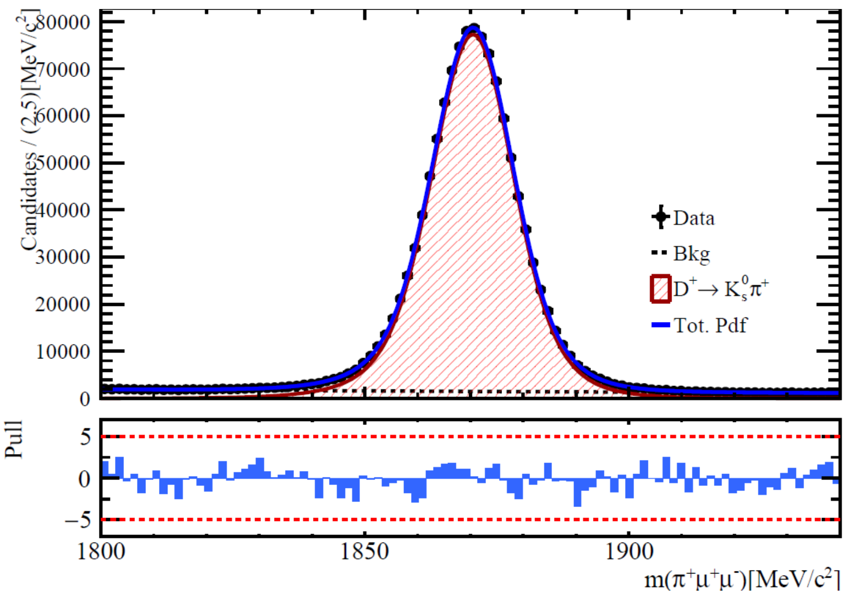


Nuisance asymmetry

Nuisance asymmetries are extracted by **fitting the control channel.**

The **uncertainties** are **neglible** if compared to the ones of the signal sample.

	low-$m(ee)$	high-$m(ee)$
A_{CP}^{raw}	$(-3.81 \pm 0.55) \cdot 10^{-3}$	$(-3.74 \pm 0.70) \cdot 10^{-3}$



Conclusions

The objective of this analysis is to measure for the **first time** $\boldsymbol{A_{CP}}$ and $\boldsymbol{A_{FB}}$ for $\boldsymbol{D^+ \to \pi^+ e^+ e^-}$ across the $\boldsymbol{\phi}$ resonance region. Those observables can be used as **null tests** for the SM as they could indicate to NP effects.

The **sensitivities** reached to this analysis amount to **~2%** for A_{CP} and **~3%** for A_{FB}.

The **results** are **blinded** and the evaluations of **systematic uncertainties** is yet to be performed. Source of systematics:

- Invariant mass shape description
- Efficiency correction uncertainties
- Imperfect kinematical reweighting
- Secondary contamination

The impact of those effects is expected to be **sub-leading** in respect to the statistical uncertainties.

Summary

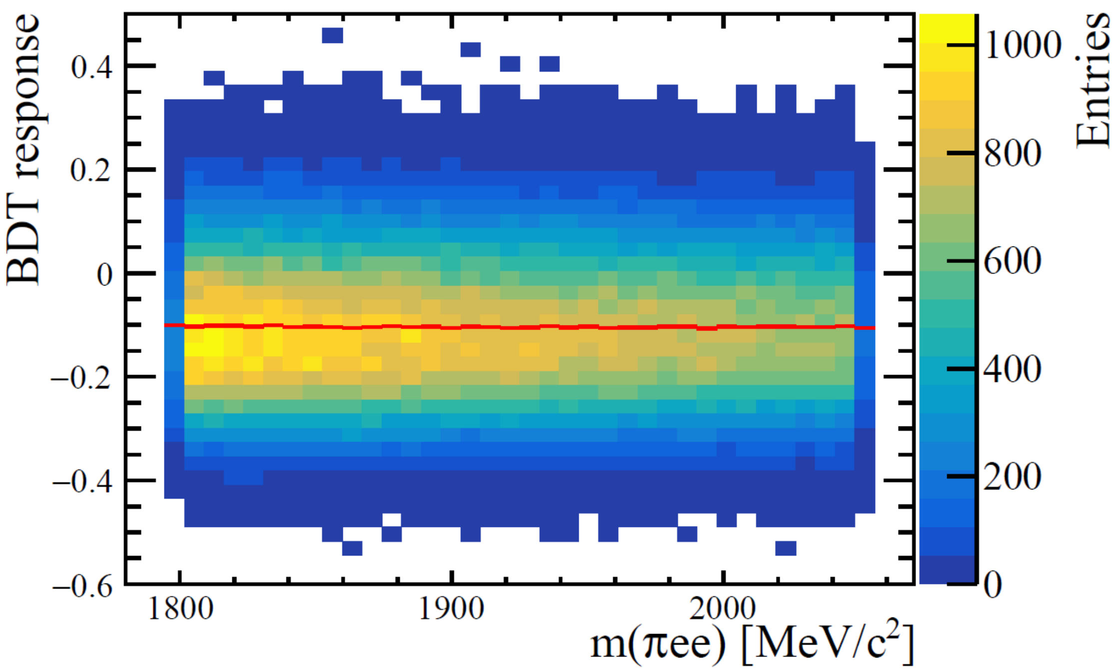
- Flavor physics introduction and charmed meson decays
- Asymmetries
- Data and electron reconstruction
- Preselection
- Multivariate analysis
- Cut optimization
- Efficiency correction
- Fit Results
- Nuisance asymmetry

Backup

BDT Variables

BDT variables
CONEPTASYM (l1 & l2)
TRKISOBDT (h & D)
VTXISOBDT
AMAXDOCA
ENDVERTEX_CHI2
ETA
BPVDIRA
BPVLTIME
VTXISONUMVTX
VTXISODCHI2MASSTWOTRACK

BDT vs mass



BDT response
0.4
0.2
0
−0.2
−0.4
−0.6
1800
1900
2000
m(πee) [MeV/c²]
1000
800
600
400
200
0
Entries

Signal mass-models