UNIVERSITÀ DEGLI STUDI DI TRIESTE

Study of the π^0 reconstruction efficiency for the $B^0 \to \pi^0\pi^0$ decay at the Belle II experiment

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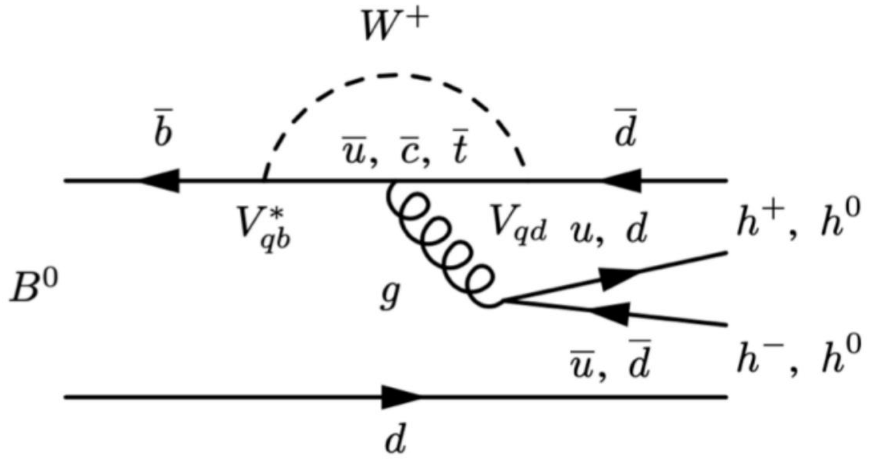
The «indirect» research of new physics

- The **Standard Model (SM)** is the best description of fundamental particles physics. However it **is incomplete** and nowadays a primary goal for particle physicists is finding an extension of the model.

- One way to look forward for **new physics** is the **«indirect» research**. **Quarks flavour physics** has several oppotunities to **test SM precise predictions** through **highly accurate measurements**.

- In quarks flavour physics, ***B*-mesons** have a crucial role, *i.e.* they offer the possibility to measure precisely the **parameters of the Cabibbo-Kobayashi-Maskawa (CKM) matrix**, that describes the weak interactions of quarks.



- The ***B*-mesons** are studied using special colliders called ***B*-Factories.**

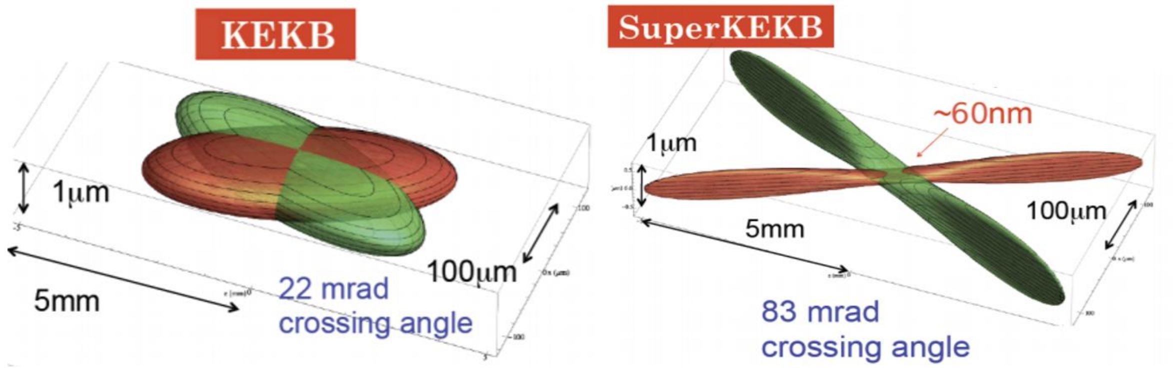
The SuperKEKB collider

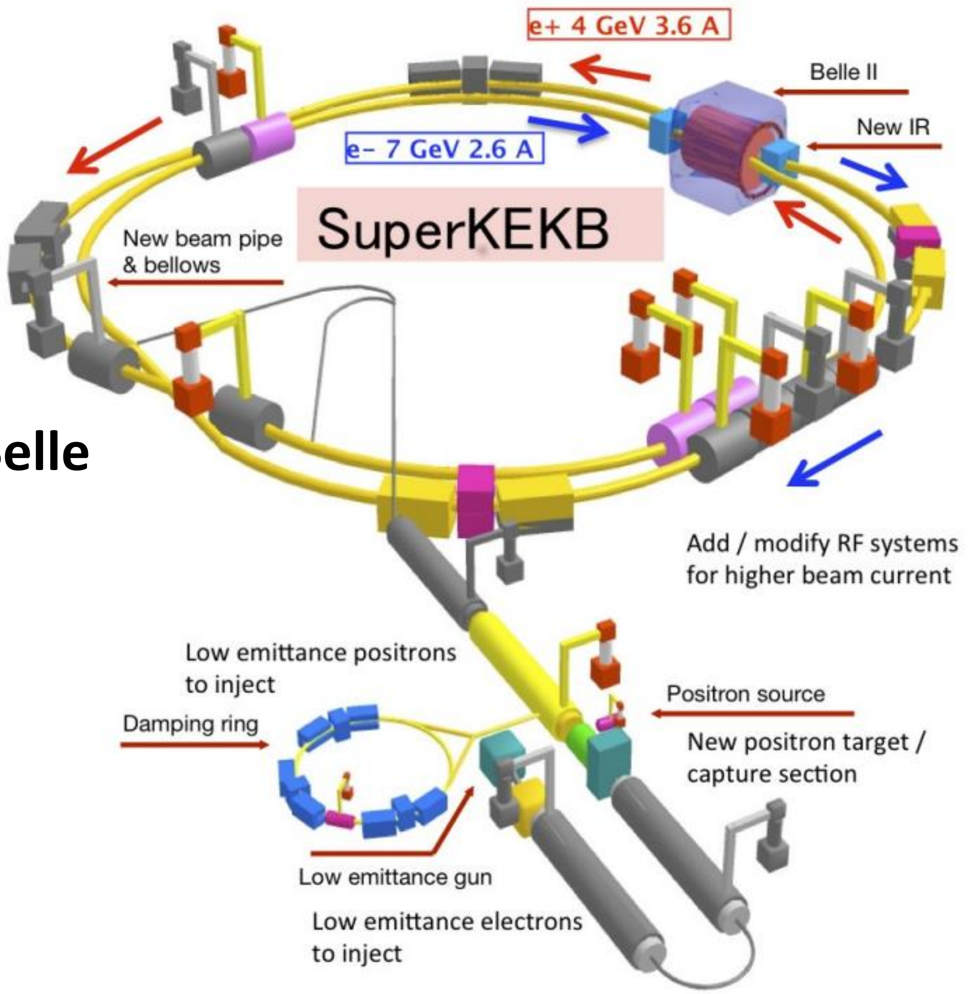
e^+e^- **energy asymmetric collider** with center-of-mass energy $\sqrt{s} = \mathbf{10.58\ GeV} = \ M_{\Upsilon(4S)}$.

Production of *B*-mesons ($1'000\ B\bar{B}$ pairs per second) and **tau leptons**.

The objective is to collect **a data sample ~50 larger than Belle**

World record luminosity: $4 \times 10^{34}\ cm^{-2}\ s^{-1}$
Design luminosity: $6.5 \times 10^{35}\ cm^{-2}\ s^{-1}$ (~30×KEKB)



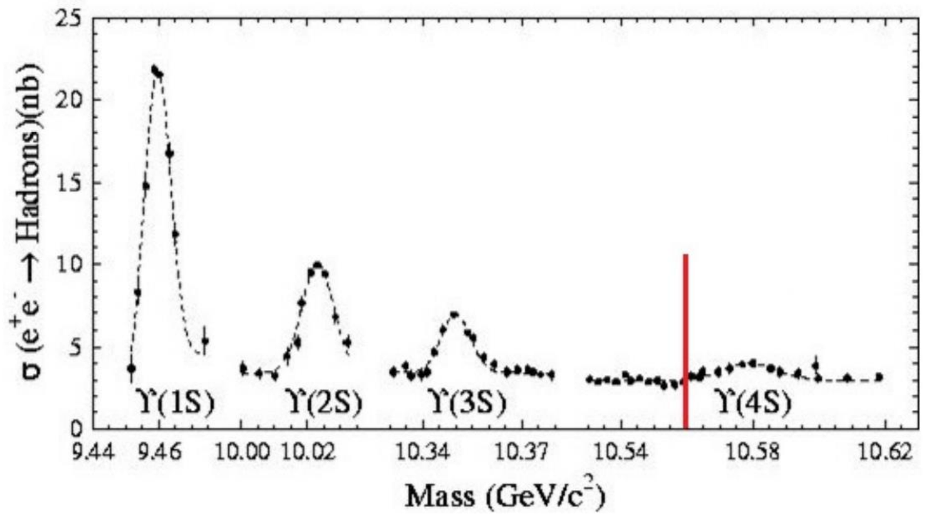


e^+e^- processes at $\sqrt{s} = 10.58$ GeV

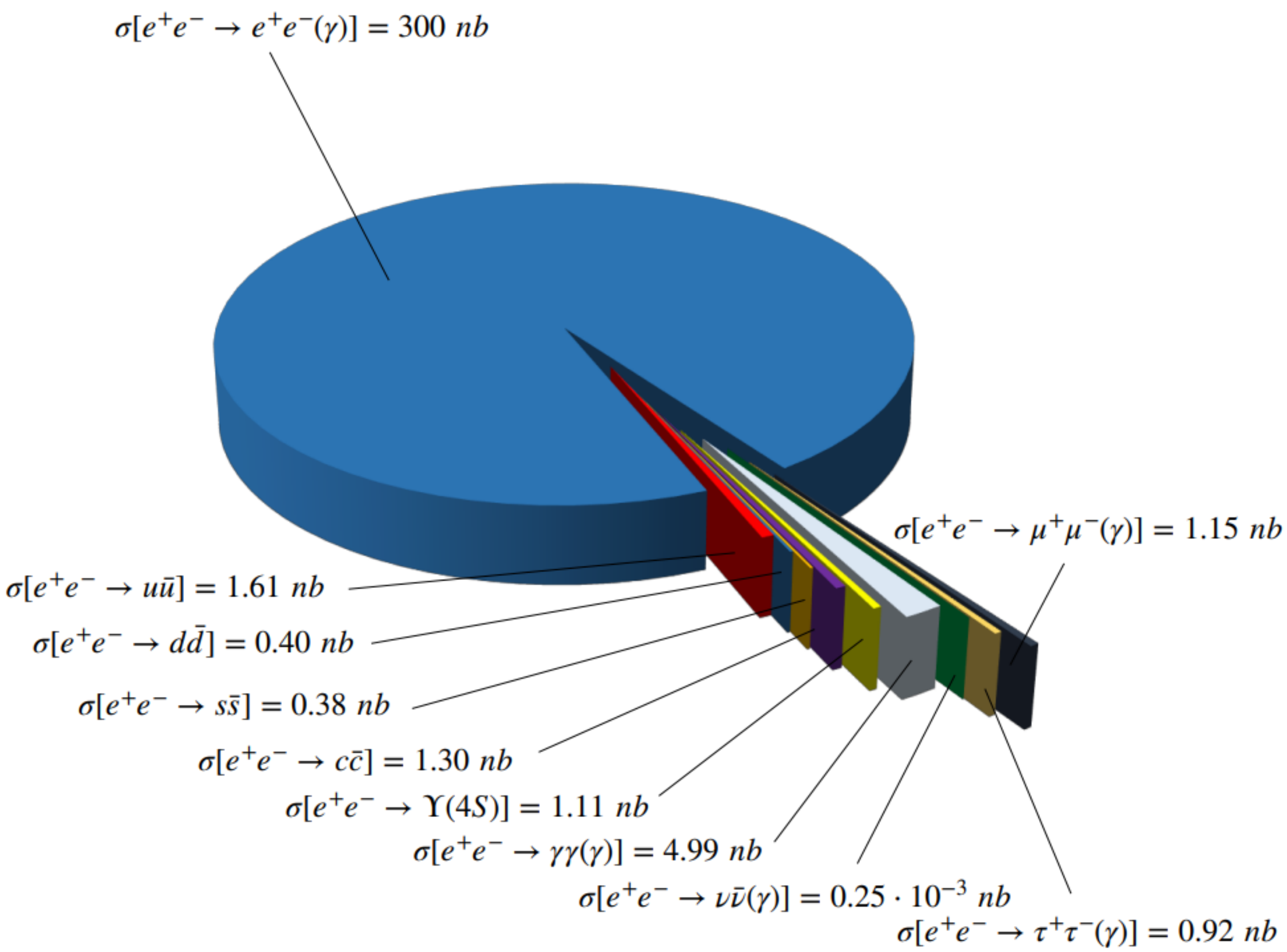
Electroweak processes as: $e^+e^- \to e^+e^-(\gamma)$, $e^+e^- \to e^+e^-$ and $e^+e^- \to \mu^+\mu^-(\gamma)$ are very frequent (**94% of the total cross section**).

Easy to be discriminated with an online trigger.

96% of the $\Upsilon(4S)$ decay in $B\bar{B}$ pairs.



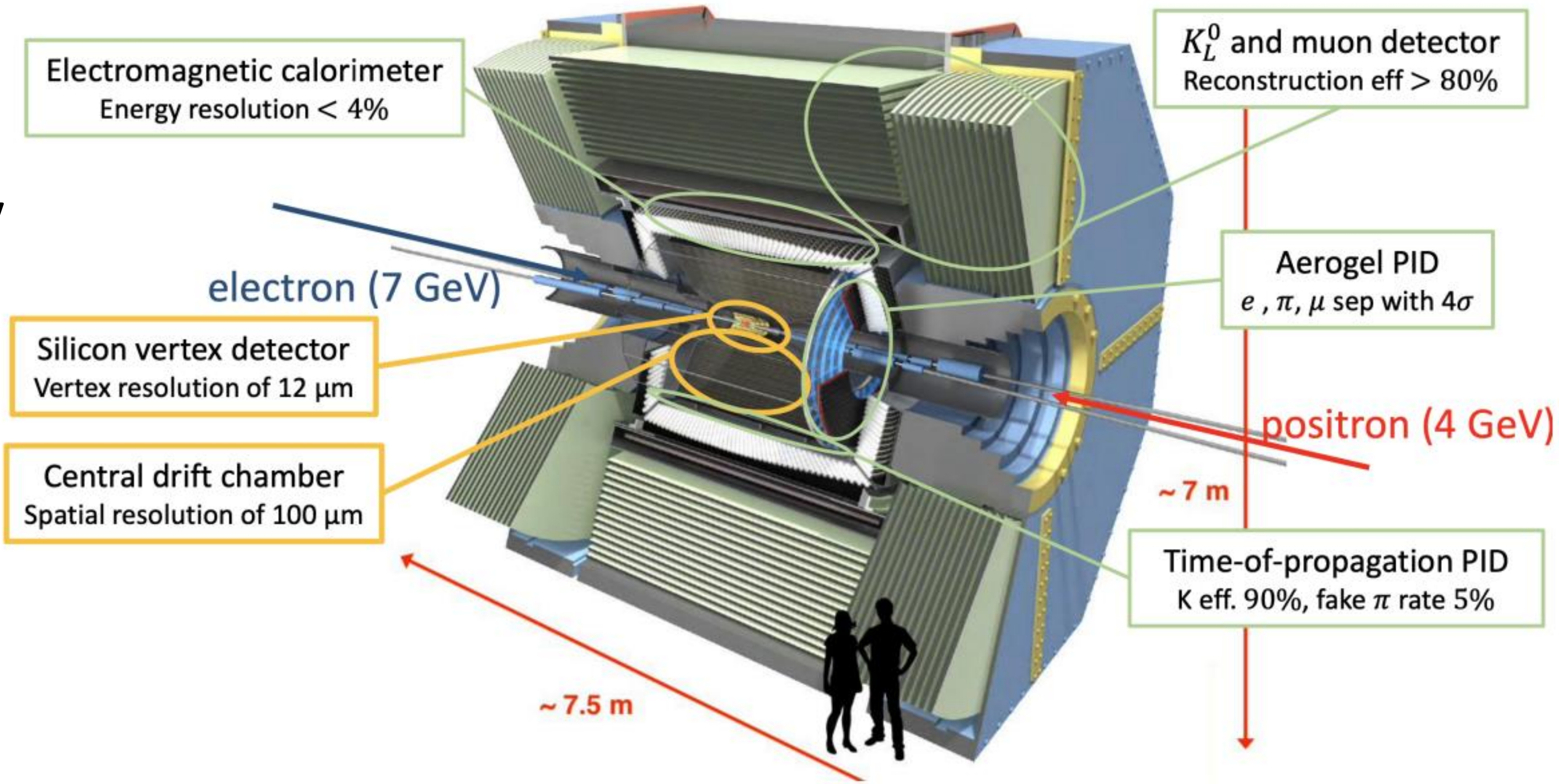
Cross section of $e^+e^- \to$ hadrons



Belle II experiment

Main features:

- *B*-mesons produced at threshold, with **exactly known energy**.
- **Low backgrounds** and unique conditions for **neutral particles reconstruction**.



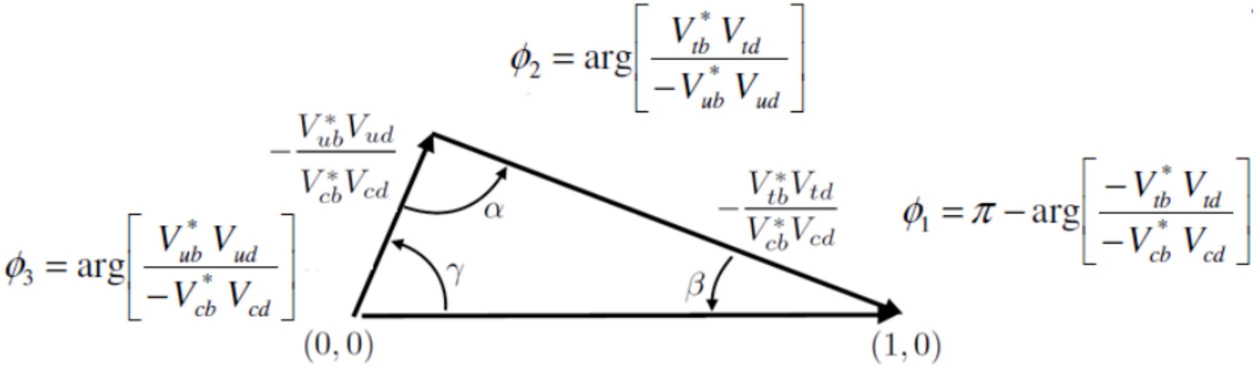
The CKM angle α

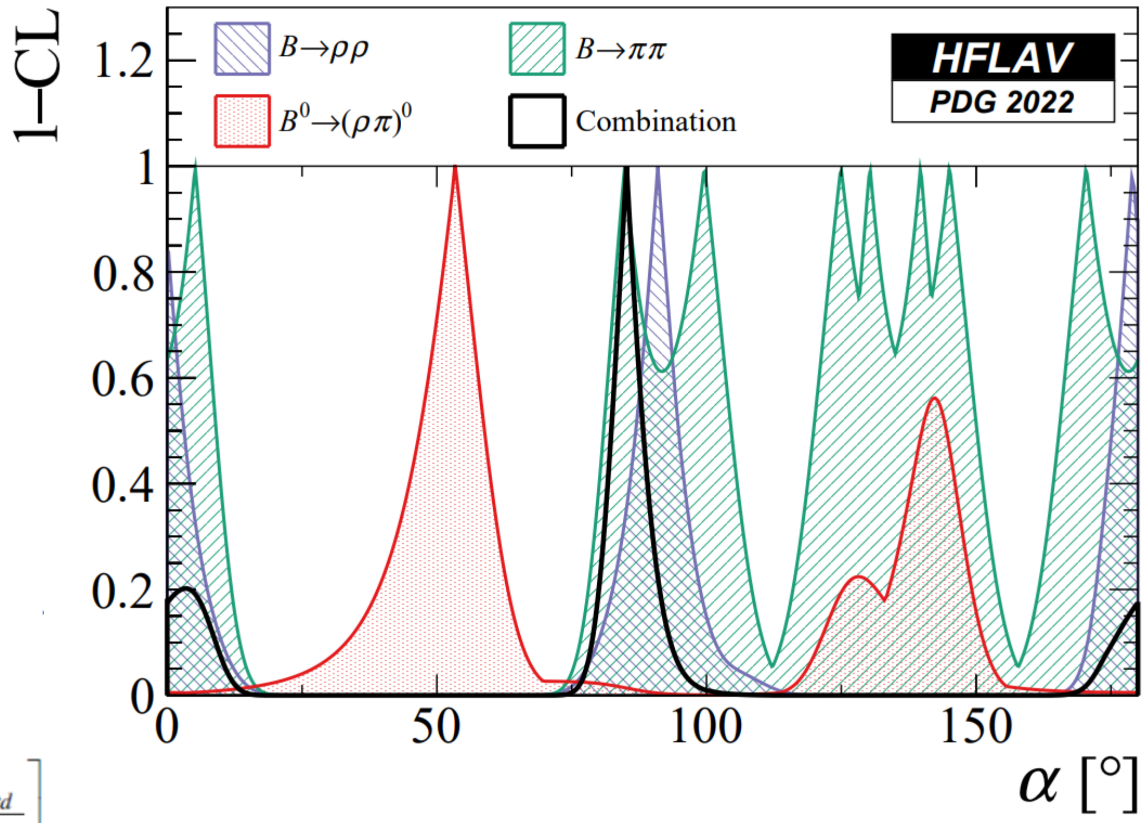
CKM $\alpha/\phi 2$ angle can be determined from **isospin analysis**.

Using:

- $B^0 \to \rho^+\rho^-, B^0 \to \rho^0\rho^0, B^+ \to \rho^+\rho^0,$
- $B^0 \to \pi^+\pi^-, B^0 \to \pi^0\pi^0 , B^+ \to \pi^+\pi^0,$
- $B^0 \to \rho^+\pi^-, B^0 \to \rho^0\pi^0$ and $B^+ \to \rho^+\pi^0$

All these decays can be studied coherently in Belle II





α from B $\rightarrow \pi\pi$ decays

$B^0 \rightarrow \pi^0\pi^0$ is the most challenging channel contributing the largest uncertanties.

Current experimental status:

Belle	BaBar	Belle II (preliminary)
$BF = (1.31 \pm 0.19 \pm 0.19)10^{-6}$	$BF = (1.83 \pm 0.21 \pm 0.13)10^{-6}$	$BF = (0.98^{+0.48}_{-0.44} \pm 0.22)10^{-6}$
$A_{CP} = -0.14 \pm 0.36 \pm 0.10$	$A_{CP} = -0.43 \pm 0.26 \pm 0.05$	

Belle II is the only current experiment capable of studying multi- π^0 final states.

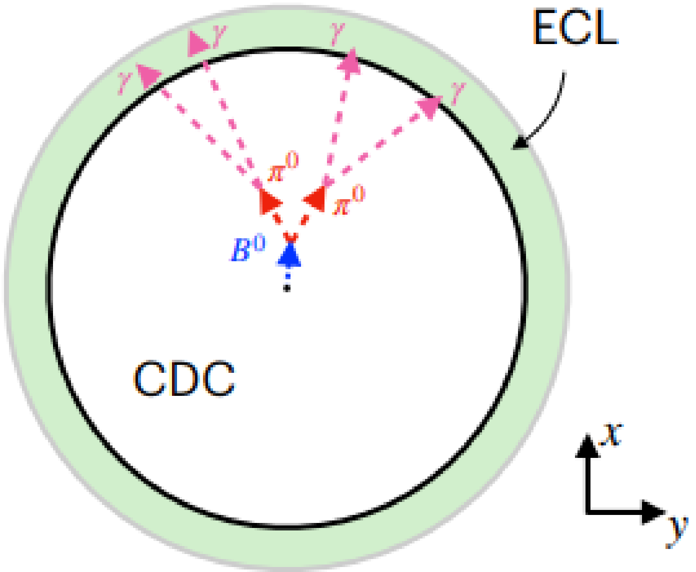
The **dominant systematic error** in the measurement of $\mathcal{B}(B^0 \rightarrow \pi^0\pi^0)$ is **the π^0 reconstruction efficiency** which contributes 10% per π^0.

This **work aims to reduce this contribution**, to improve the precision in the branching ratio of $B^0 \rightarrow \pi^0\pi^0$.

$B^0 \to \pi^0(\to \gamma\gamma)\pi^0(\to \gamma\gamma)$

Experimental challenges:

- $e^+e^- \to q\bar{q}$ background,
- ECL information less precise than tracking,
- Large background from real π^0's randomly combined.



$\boldsymbol{B^0 \to \pi^0(\to \gamma\gamma)\pi^0(\to \gamma\gamma)}$ is reconstructed from **four photons.**

1. Selection to obtain **true photons** candidate: energy, shape of the cluster and **photonMVA** (probability that the γ candidate comes from a $B^0 \to \pi^0\pi^0$ decay).

2. Combinations of photons candidates create $\boldsymbol{\pi^0}$ **candidates**. Selection on $m_{\gamma\gamma}$ and angles between the photons to retain true neutral pions.

3. Neutral pions candidate are combined to create $\boldsymbol{B^0}$ **candidates**.

Simulation pitfalls

The reconstruction efficiency accounts for: the efficiency of the selection, the geometrical acceptance and intrinsic efficiency of the detector.

Realistic simulation is used to measure the reconstruction efficiency.

In the $\pi^0 \rightarrow \gamma\gamma$ case possibile differences between data and simulation are:

- Imperfect modelling of the **material distribution** in the detector.
- **Secondary hadrons** due to the interaction of primary hadrons with the calorimeter (**split-offs**).
- Additional **background** (soft photons) **in data**.

π^0 reconstruction efficiency in data

It is important to compare the measurements of reconstruction efficiency in data and simulation.

How to evaluate the reconstruction efficiency using data?

Using two topologically similar "π^0 channel" and "track-only" control channels.

$\boldsymbol{D^{*+} \to D^0(\to K^-\pi^+\pi^0)\pi_s^+}$ and $\boldsymbol{D^{*+} \to D^0(\to K^-\pi^+)\pi_s^+}$

Large statistics and very clean channels

π^0 reconstruction efficiency

$$\boxed{\varepsilon(\pi^0) = \frac{Yield(K^-\pi^+\pi^0)}{Yield(K^-\pi^+)} \cancel{\left(\frac{\varepsilon_{D^0}\varepsilon_{D^{*+}}[\varepsilon(\pi_s^+)\varepsilon(K^-\pi^+)]_{K^-\pi^+\pi^0}}{\varepsilon_{D^0}\varepsilon_{D^{*+}}[\varepsilon(\pi_s^+)\varepsilon(K^-\pi^+)]_{K^-\pi^+}}\right)} \cdots \left(\frac{Br(D^0 \to K^-\pi^+)}{Br(D^0 \to K^-\pi^+\pi^0)Br(\pi^0 \to \gamma\gamma)}\right)}$$

Assumption: the joint efficiency for n particle factorizes and the single terms are eliminated in the ratio.

Efficiency uncertainty is due to yield uncertainties (from the fit) and BF uncertainties (from the PDG).

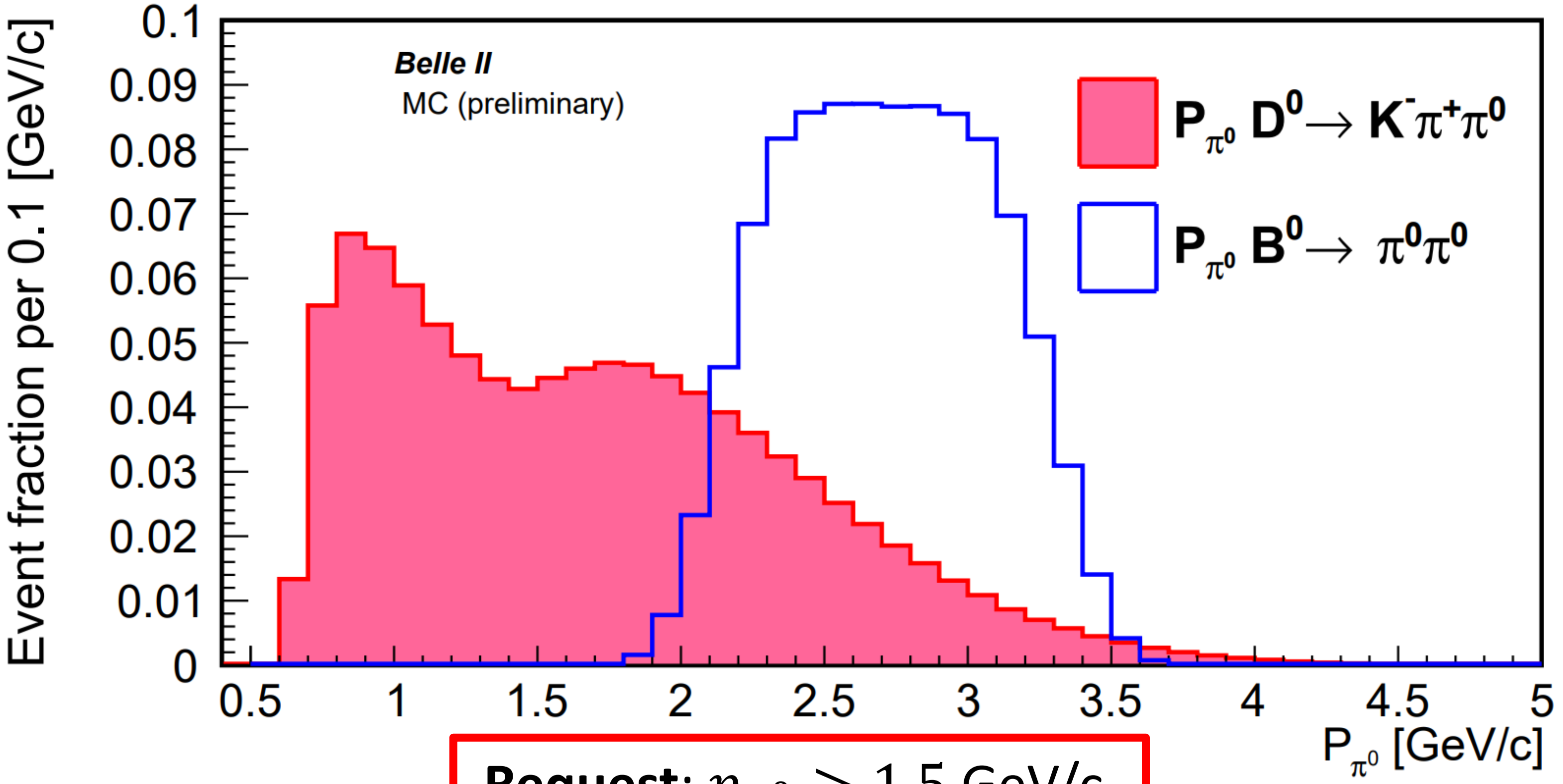
Ratio btw efficiencies $\varepsilon_{data}(\pi^0)/\varepsilon_{MC}(\pi^0)$ **determines an efficiency correction**; its uncertainty determines a systematic uncertainty:

$$\frac{\varepsilon_{data}(\pi^0)}{\varepsilon_{MC}(\pi^0)} = R \pm \sigma_R$$

$D^0 \to K^-\pi^+\pi^0$ photons and π^0 selection

$\boldsymbol{R}$ must be evaluated for the $\boldsymbol{B^0 \to \pi^0\pi^0}$ **decay**.

The $\boldsymbol{\pi^0}$ **sample** selected in $D^0 \to K^-\pi^+\pi^0$ decay **must mimic the properties of** those produced by the $\boldsymbol{B^0 \to \pi^0\pi^0}$ **decay**.

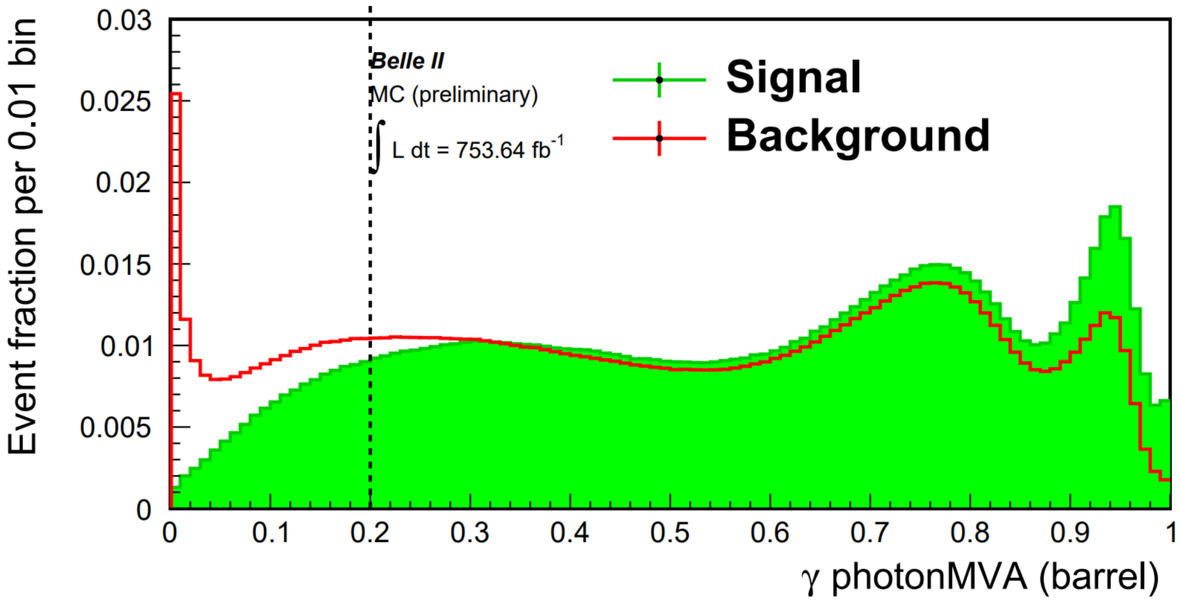


Request: $p_{\pi^0} > 1.5$ GeV/c.

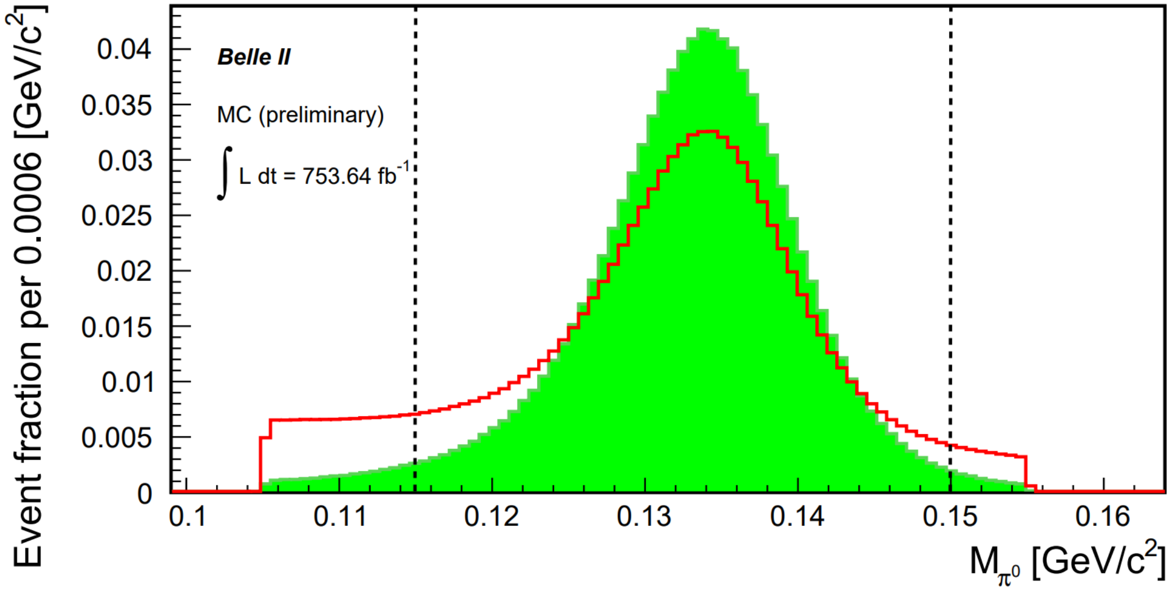
$D^0 \to K^-\pi^+\pi^0$ photons and π^0 selection

The **selection on $\boldsymbol{\pi^0}$** and photons **is the same used in the $\boldsymbol{B^0 \to \pi^0\pi^0}$ analysis**.

Good background rejection from the request on photonMVA and the reconstructed π^0 invariant mass:



photonMVA: probability that a reconstructed photon is a true photon

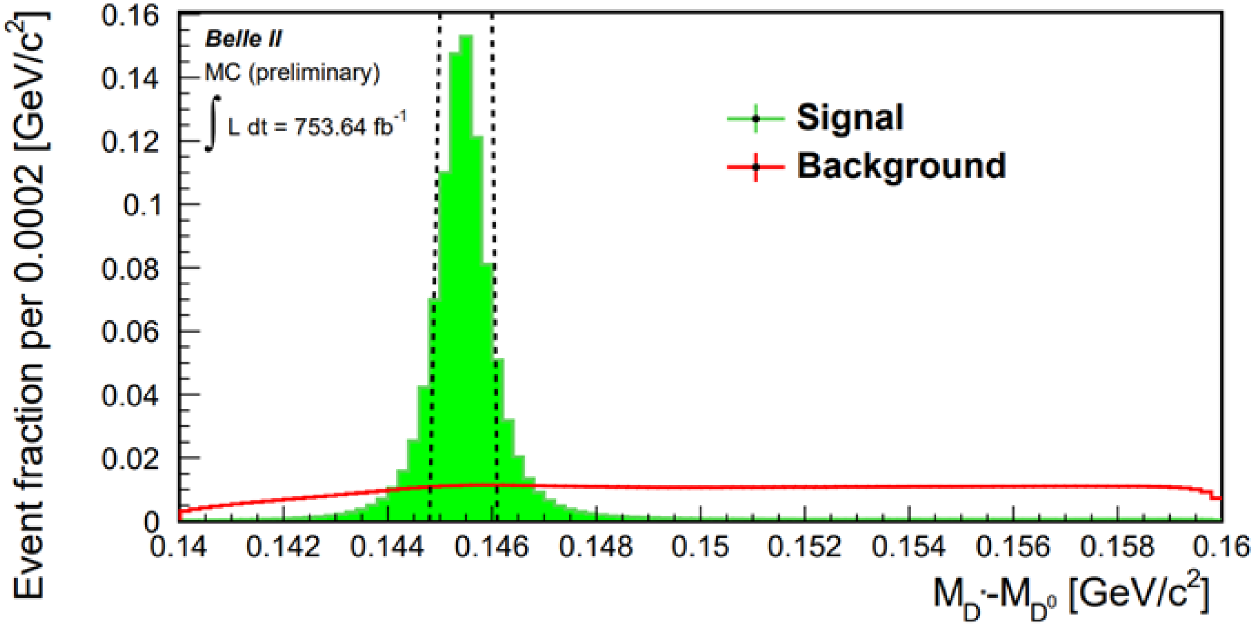


Reconstructed π^0 invariant mass

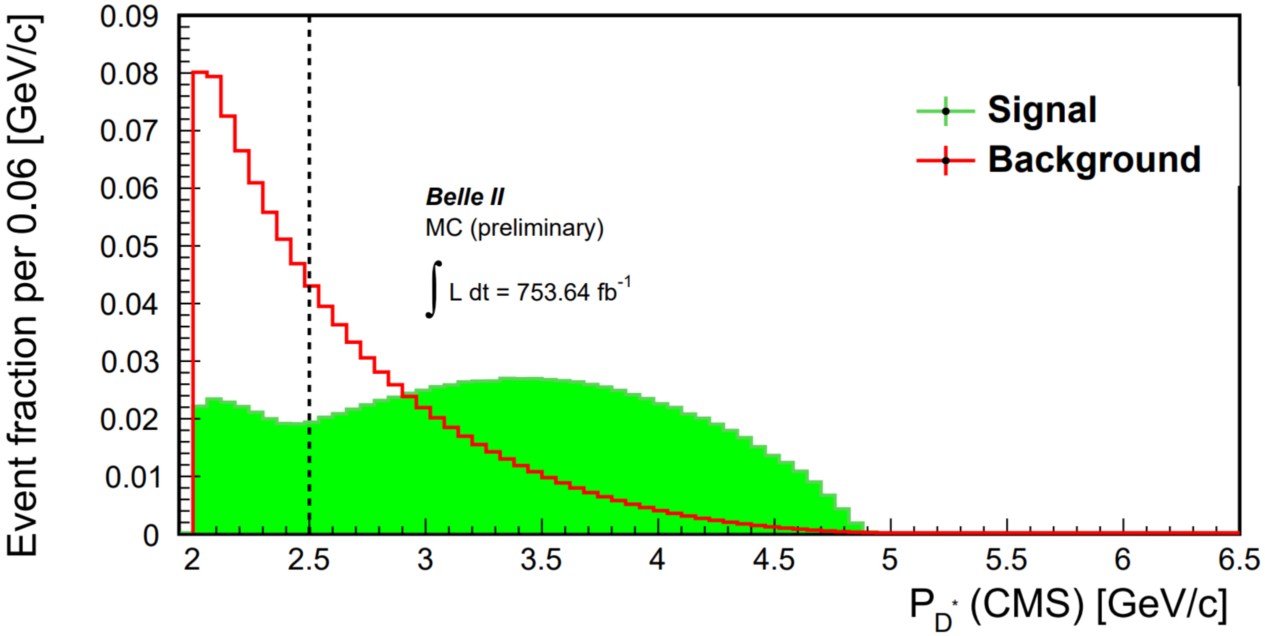
$D^0 \to K^-\pi^+\pi^0$ charmed mesons selection

High rejection power provided by: $\Delta \boldsymbol{m} = \boldsymbol{m}_{D^{*+}} - \boldsymbol{m}_{D^0}$ and $\boldsymbol{p}_{CMS}(\boldsymbol{D}^*)$.

Request on $p_{CMS}(D^*)$ selects only **prompt D^{*+}**.



$\Delta \boldsymbol{m}$



$\boldsymbol{p}_{CMS}(\boldsymbol{D}^*)$

$D^0 \to K^-\pi^+$selection

To eliminate the contribution of selection efficiency in the following formula:

$$\boxed{\varepsilon(\pi^0) = \frac{Yield(K^-\pi^+\pi^0)}{Yield(K^-\pi^+)}\cancel{\left(\frac{[\varepsilon(selection)]_{K^-\pi^+\pi^0}}{[\varepsilon(selection)]_{K^-\pi^+}}\right)}\left(\frac{Br(D^0 \to K^-\pi^+)}{Br(D^0 \to K^-\pi^+\pi^0)Br(\pi^0 \to \gamma\gamma)}\right)}$$

the selection applied on the $D^0 \to K^-\pi^+$ decay is **completely constrained** by the requests on $D^0 \to K^-\pi^+\pi^0$ decay:

- Same variables.
- Cut values choseen to have the **same signal efficiency**.

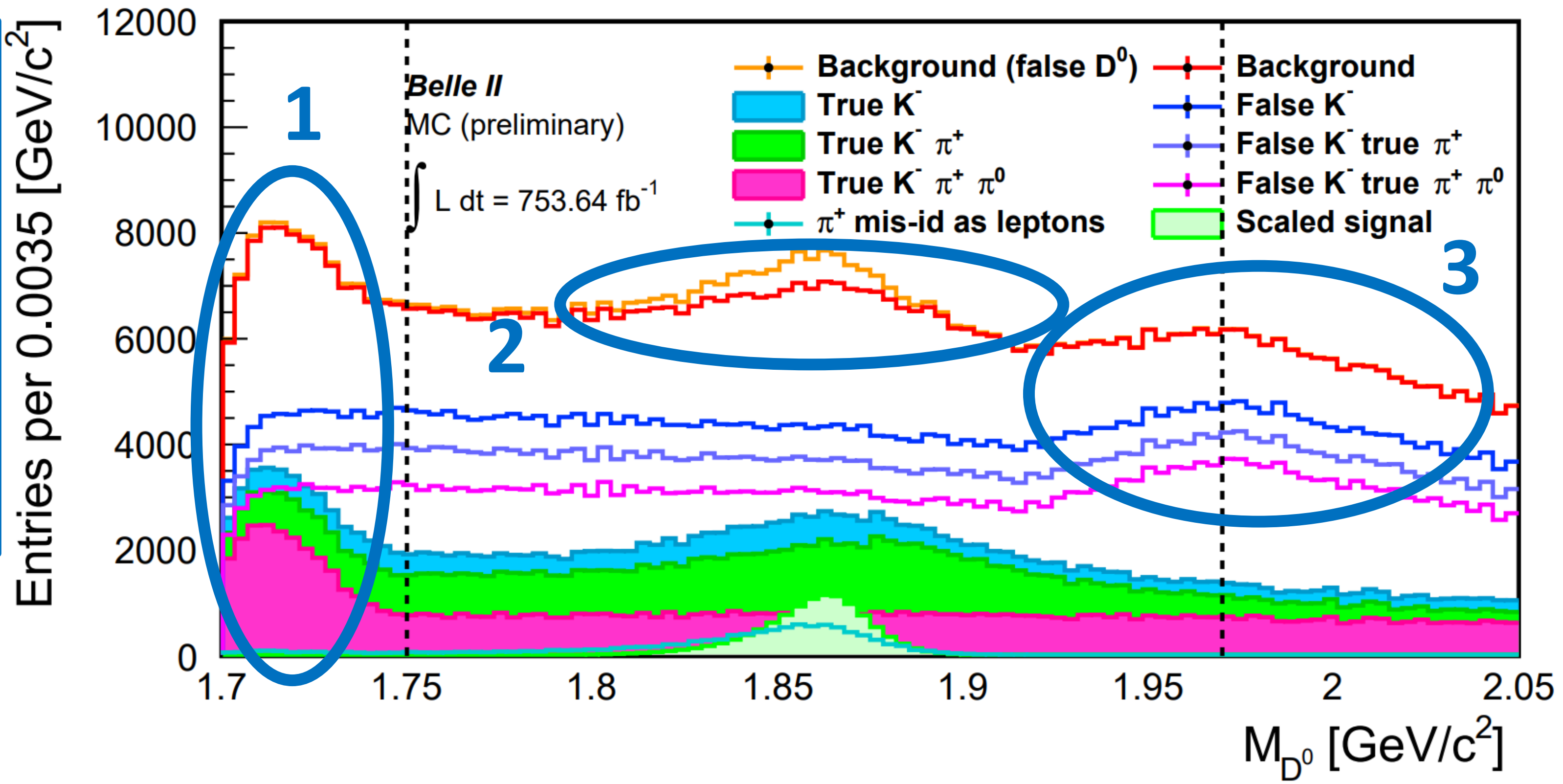
$D^0 \to K^-\pi^+\pi^0$ background composition

1. **D^0 four body decay** with one missing product.

2. **False neutral pions**.

3. **False kaons** (pions mis-identified as kaons).

No requests on p_{π^0}, and photonMVA are applied



Selected D^0 mass region: $[1.75, 1.97]$ GeV/c^2

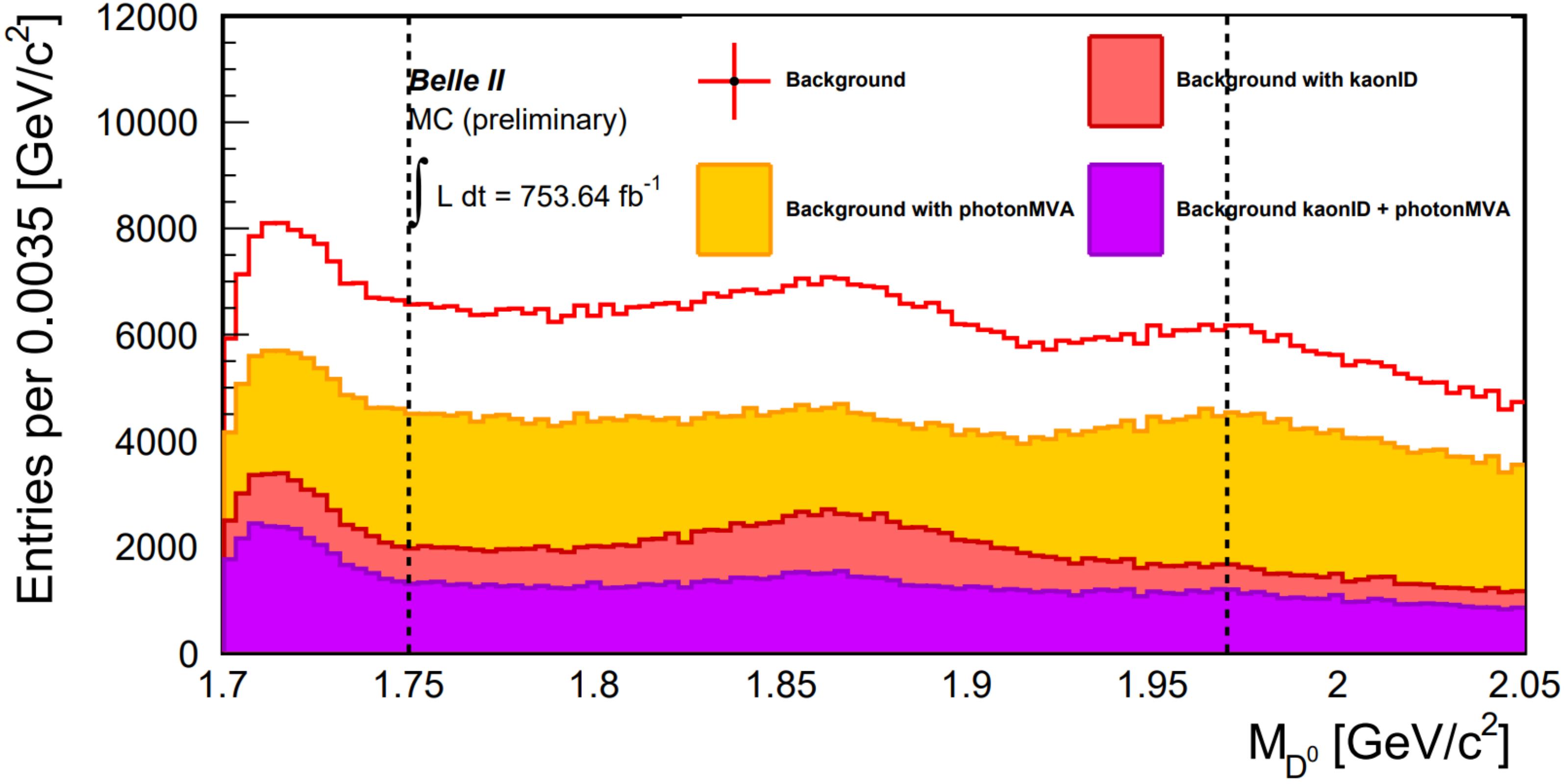
$D^0 \to K^-\pi^+\pi^0$ background composition

photonMVA: reduction of peaking background

kaonID: PID variabile to recognise true kaons and reduce particles mis-id as kaons

photonMVA combined with kaonID

No requests on p_{π^0} is applied



Selected D^0 mass region: $[1.75, 1.97]$ GeV/c^2

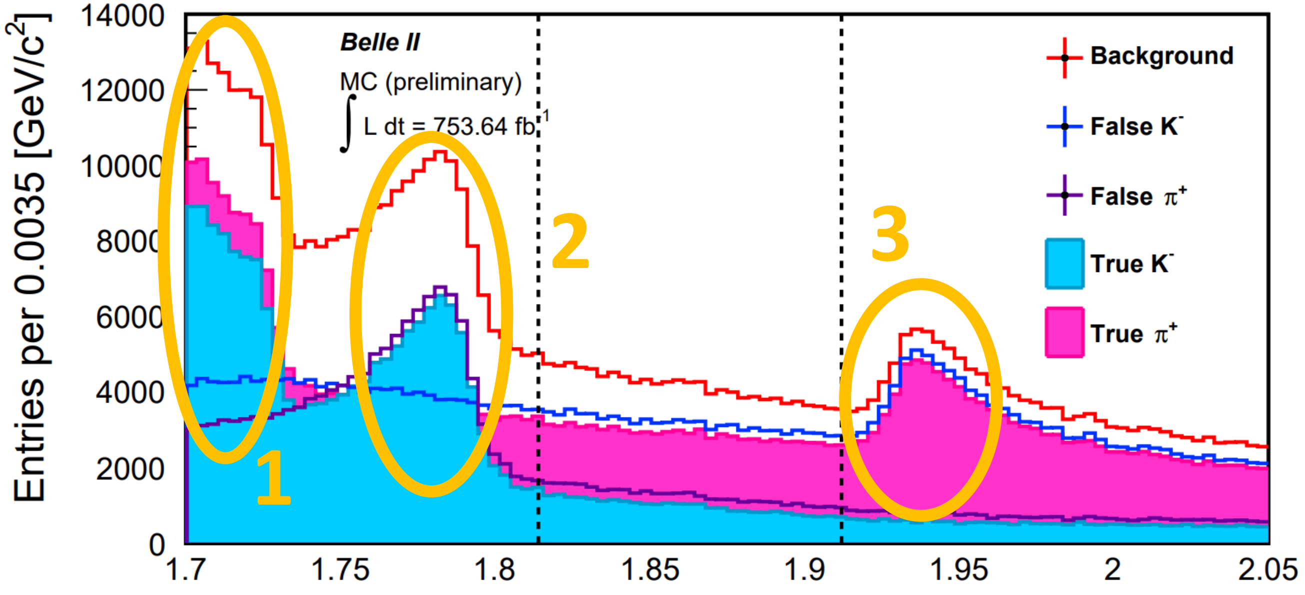
$D^0 \to K^-\pi^+$ background composition

No request on kaonID is applied

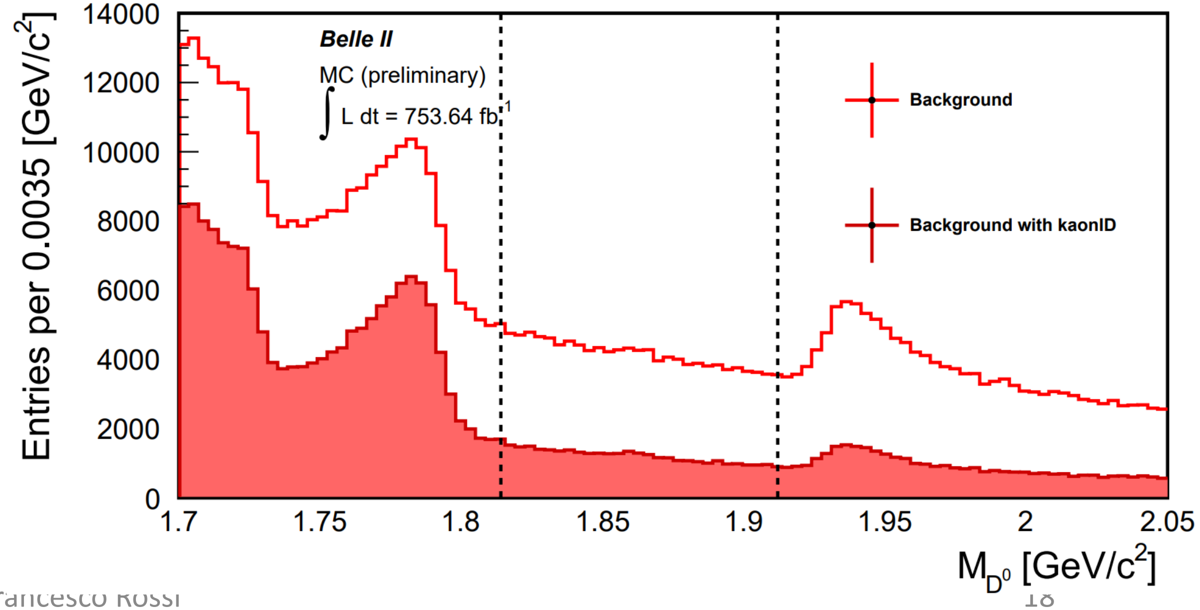
1. $\boldsymbol{D^0}$ **three body decay**, where one product is missing.

2. **Pions mis-identified as kaons.** Contribute from $D^0 \to K^-K^+$.

3. False **kaons, mis-identified as pions.** Contribute from $D^0 \to \pi^+\pi^-$



Effect of the cut on **kaonID** on background

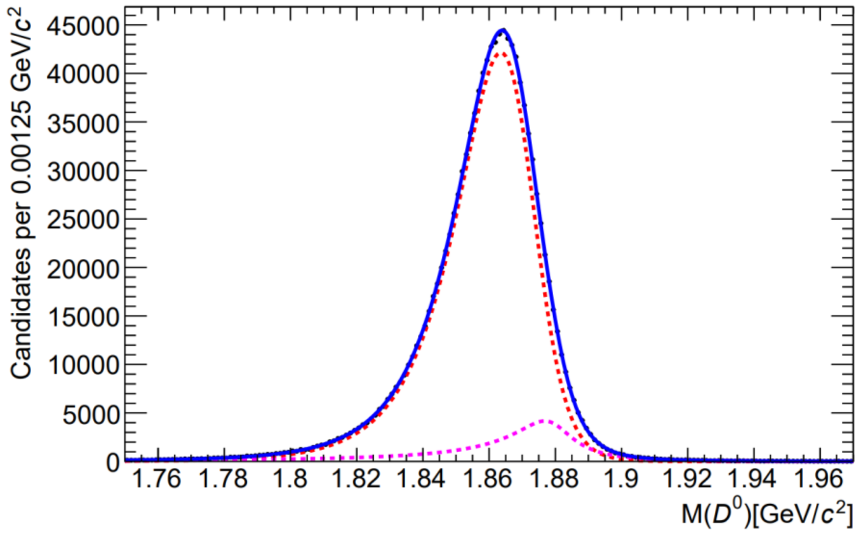


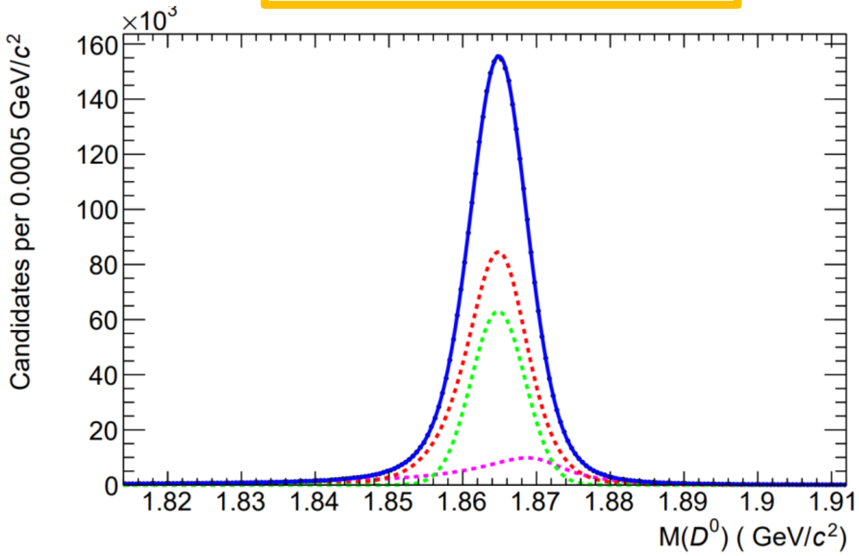
Signal and background models in MC

$D^0 \rightarrow K^-\pi^+\pi^0$

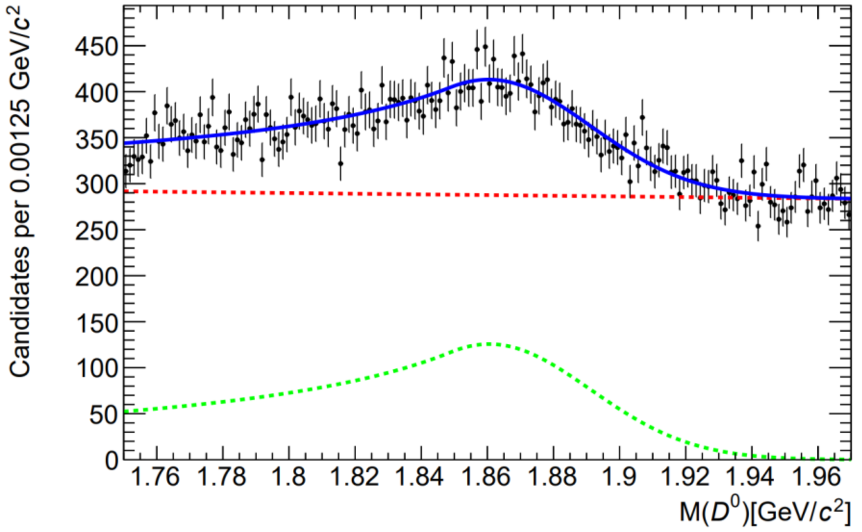
$D^0 \rightarrow K^-\pi^+$

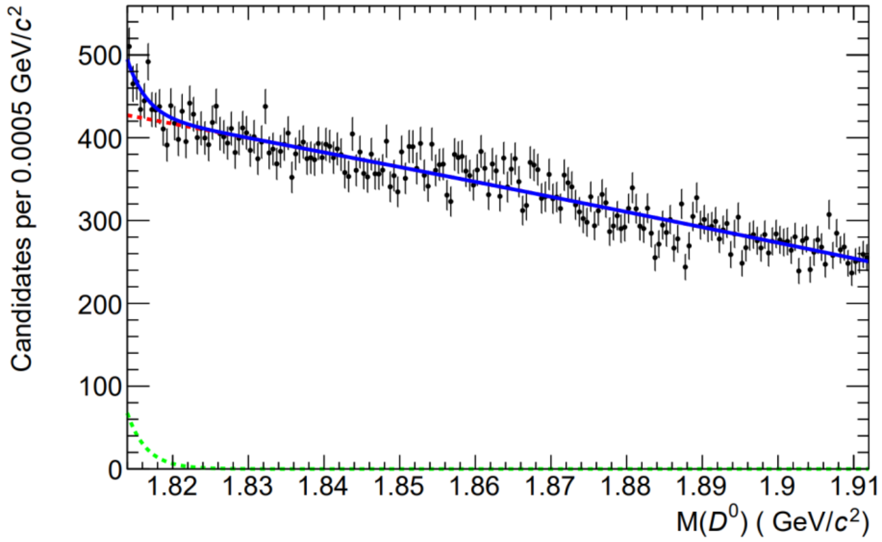
Signal





Background

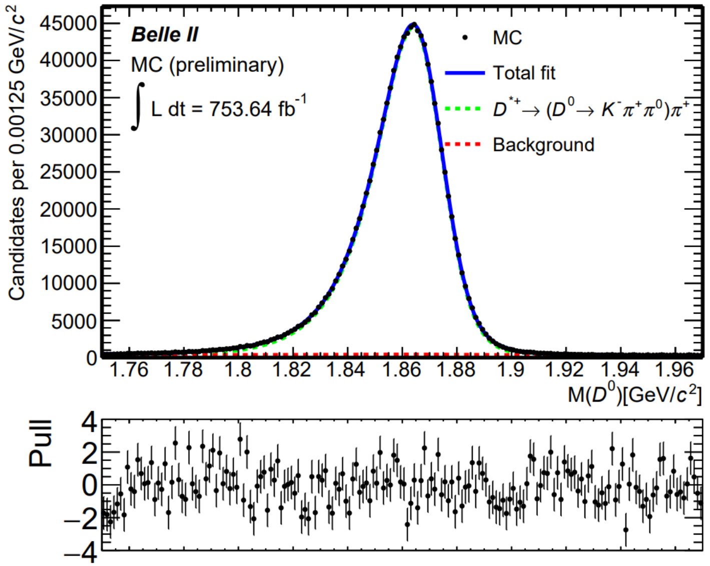


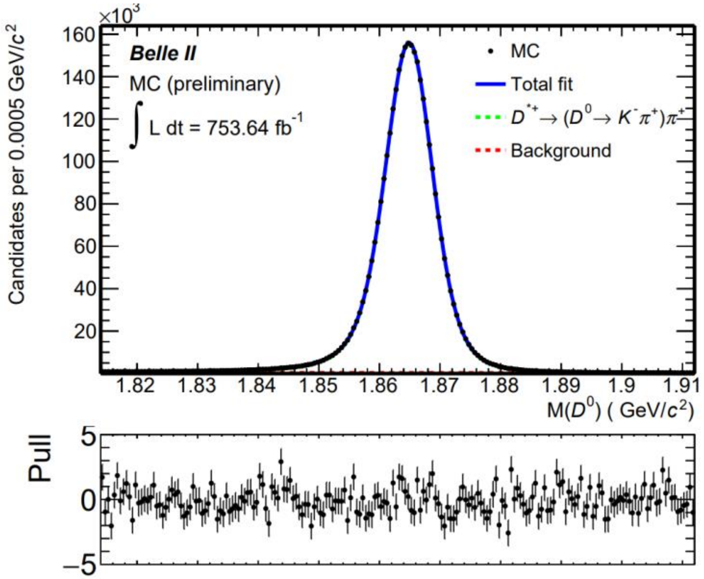


Data-Monte Carlo correction factor

$D^0 \rightarrow K^- \pi^+ \pi^0$

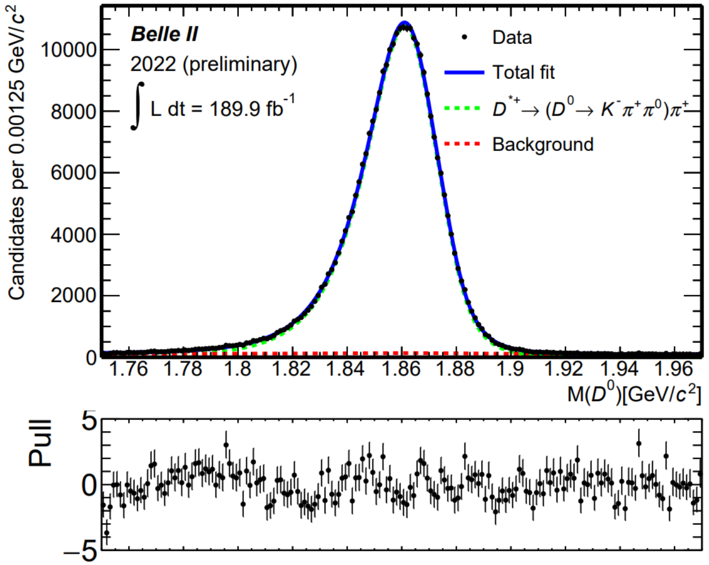
$D^0 \rightarrow K^- \pi^+$

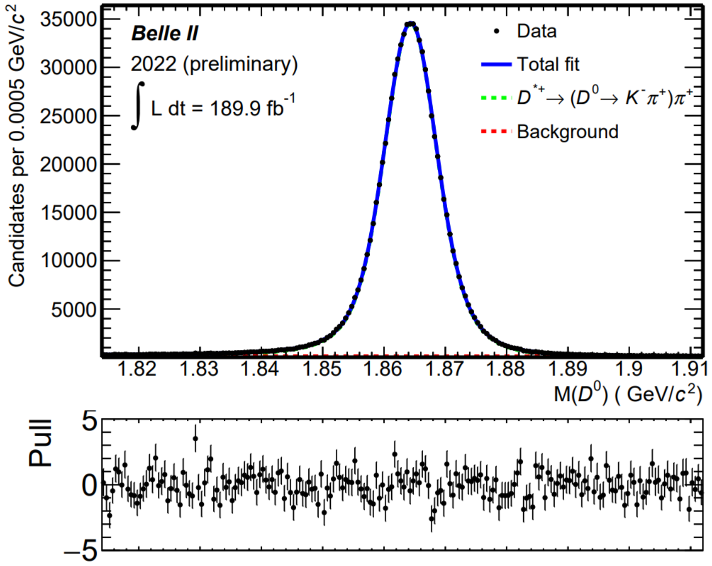




Monte Carlo

$$\varepsilon_{MC} = 0.0984 \pm 0.0001$$





Data

$$\varepsilon_{Data} = 0.1006 \pm 0.0003 \pm 0.0356\ (\text{BR})$$

$$\boldsymbol{\frac{\varepsilon_{Data}}{\varepsilon_{MC}} = 1.023 \pm 0.003\ (\text{stat.}) \pm 0.036\ (\text{BR})}$$

Motivation to study the sample dependence

A **sample dependence** must be introduced if the correction factor is a function of a certain variable.

The variables studied are:

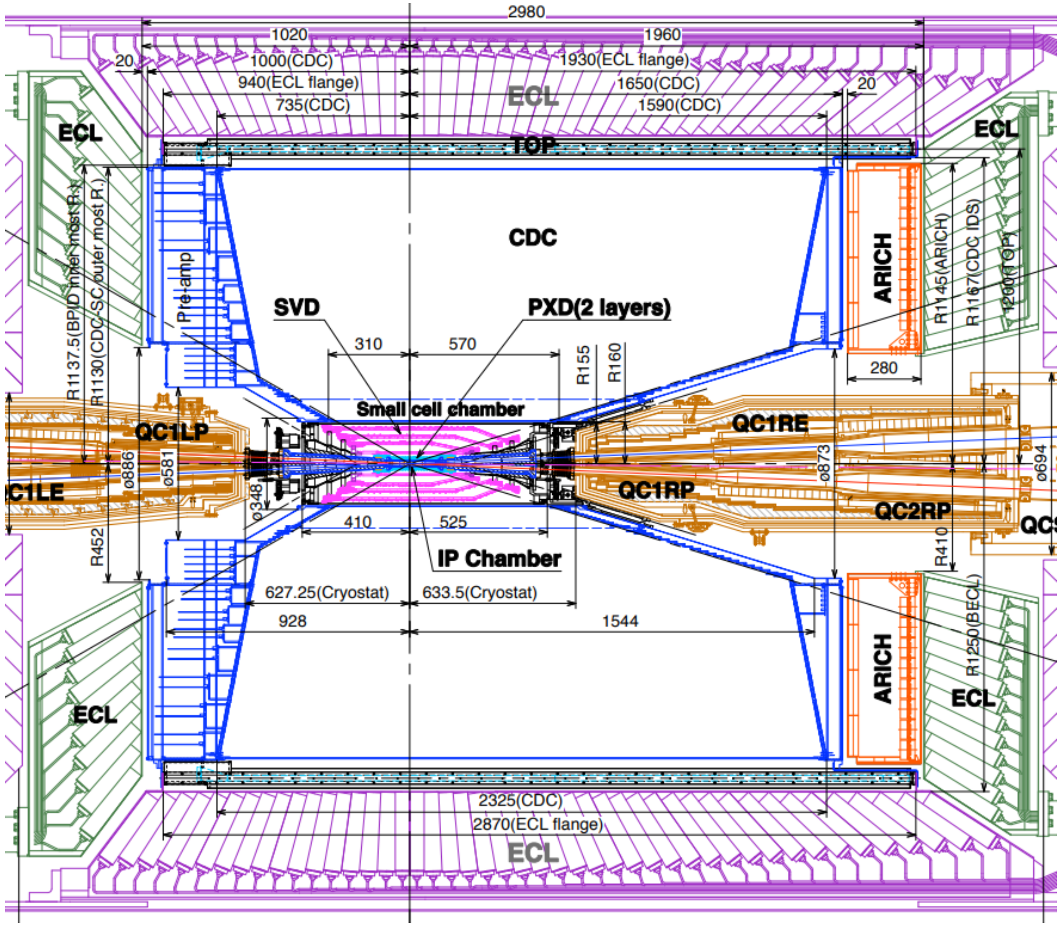
- **ECL regions**: different intrinsic efficiency, different material budget.
- $\boldsymbol{\pi^0}$ **momentum**: the intrinsic efficiency of the detector varies with energy.
- $\boldsymbol{\pi^0}$ $\boldsymbol{cos(\theta)}$: different cluster shape and material budget.

Correction factor in different ECL regions

Event fraction in each region of the electromagnetic calorimeter.

ECL region	MC event fraction	Data event fraction
Forward	4.5%	4.5%
Forward-Barrel	3.6%	3.4%
Barrel	89.3%	90.2%
Barrel-Backward	1.0%	0.8%
Backward	1.6%	1.2%

ECL **barrel** and **endcaps.**



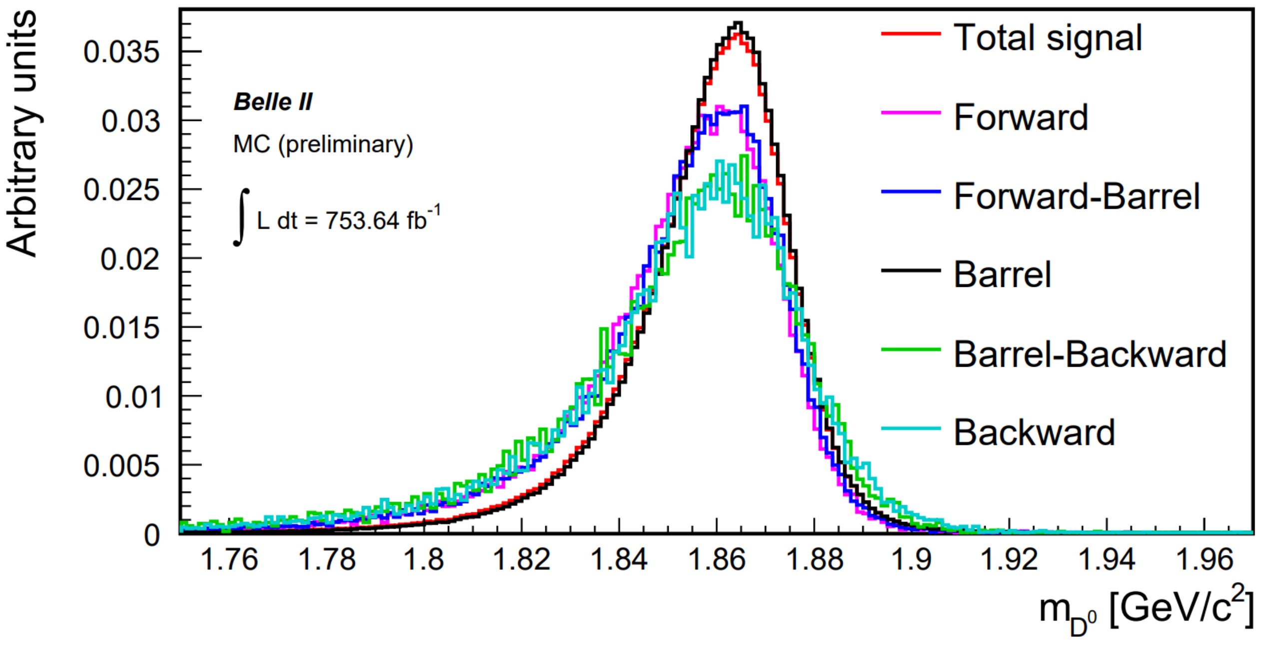
Correction factor in different ECL regions

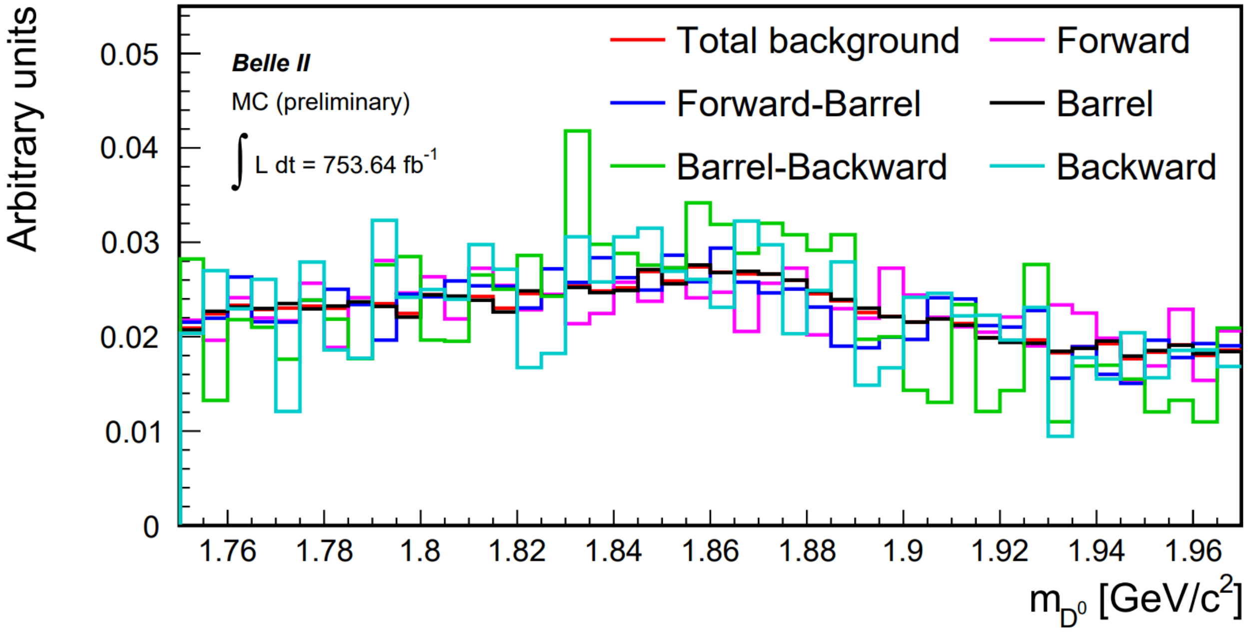
Comparison of the **signal and background shape** in each region.

Three different signal shapes due to **different energy resolution**.

One single background shape.

Determination of **the signal yields from the fit.**

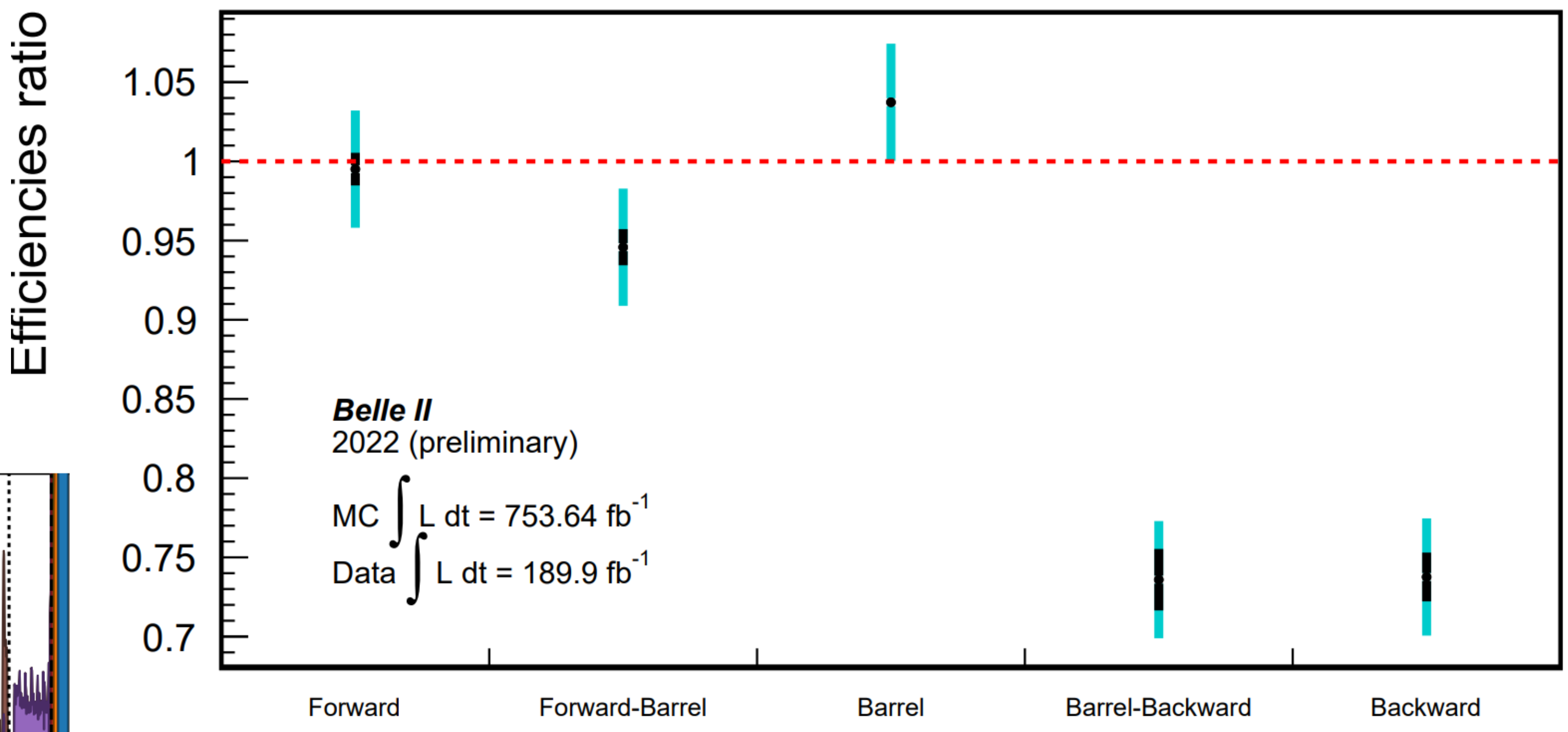


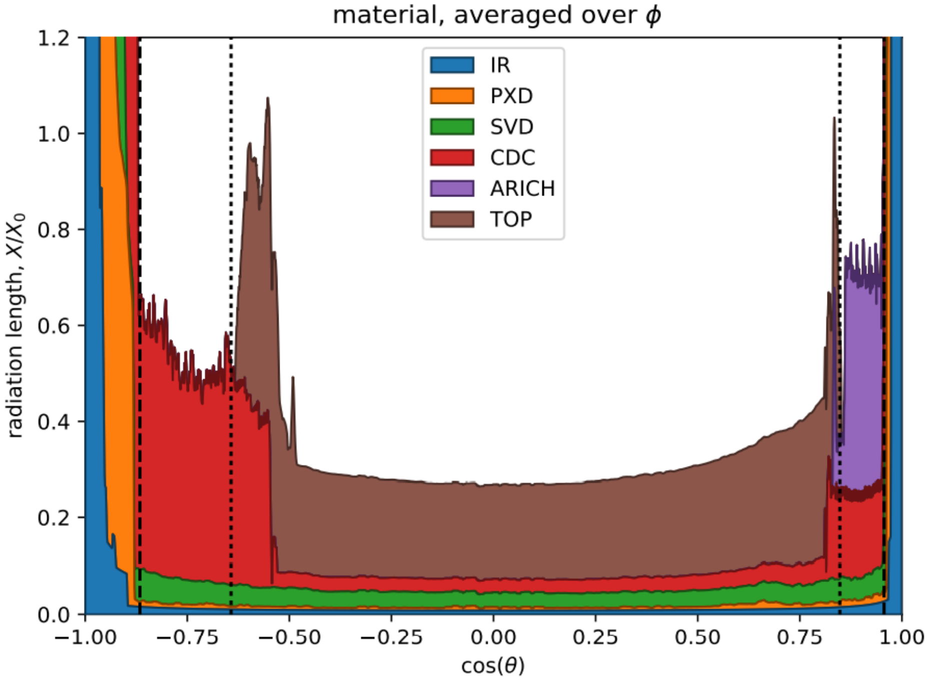


Correction factor in different ECL regions

Statistical uncertainty (black line) due to the $K^{-}\pi^{+}\pi^{0}$ sample.

Total uncertainty (blue line), $K^{-}\pi^{+}$ sample and systematic uncertanties.





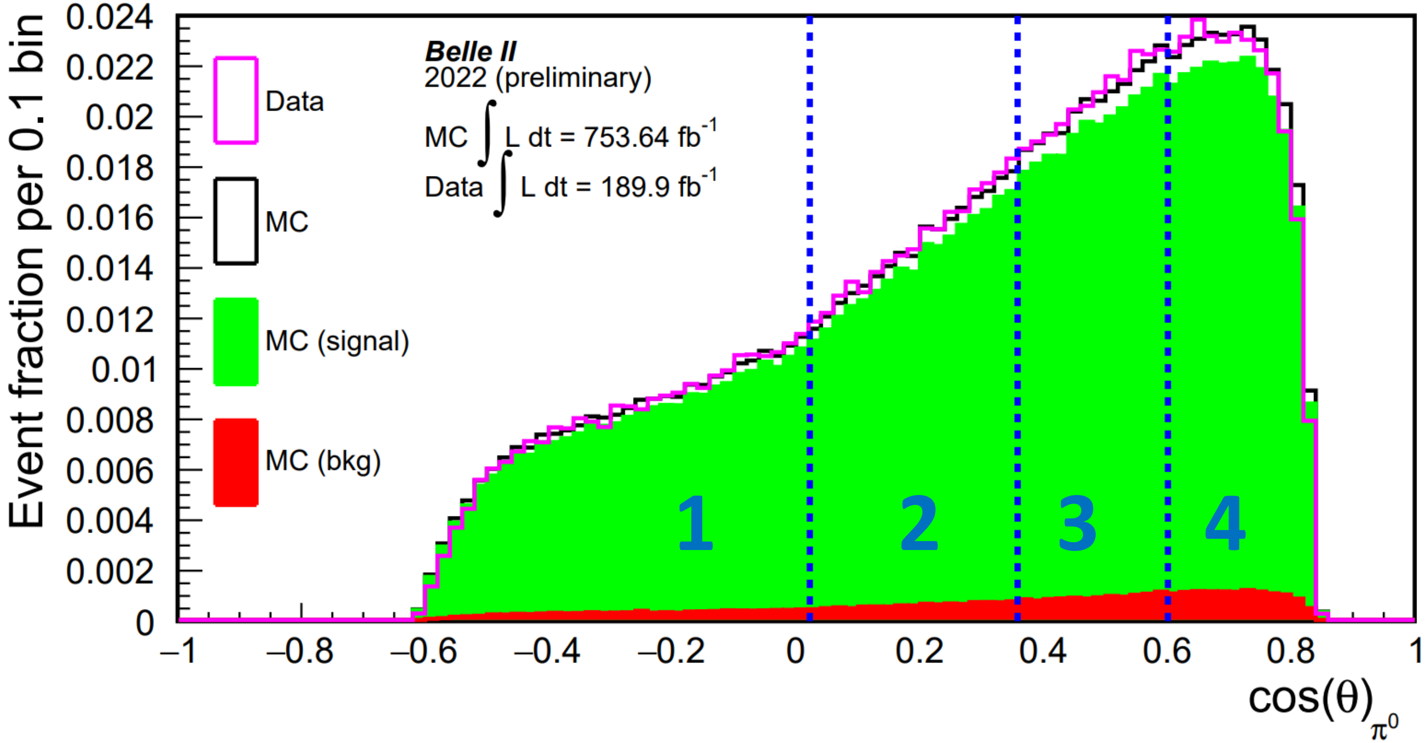
Simplified description of the **material budget before the calorimeter**.

Dependence on π^0 direction

Four $\cos(\theta)$ bin with the same signal events from MC.

Only photons detected from the barrel are considered.

Comparison of the **signal and background** shape in each bin.

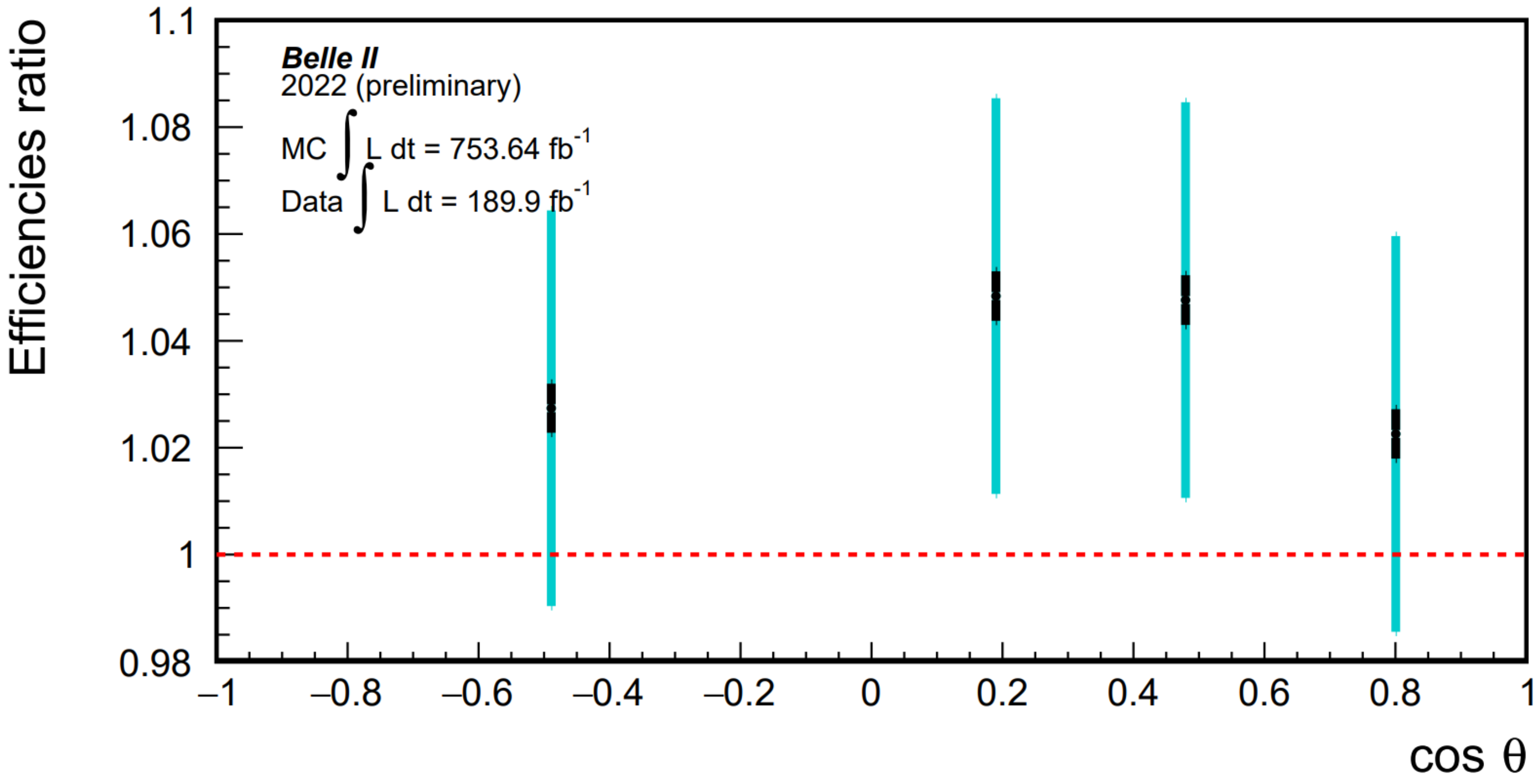


Dependence on π^0 direction

Statistical uncertainty (black line) due to the $K^-\pi^+\pi^0$ sample.

Total uncertainty (blue line) $K^-\pi^+$ sample and systematic unceratinties.

Only photons detected by the barrel are considered.

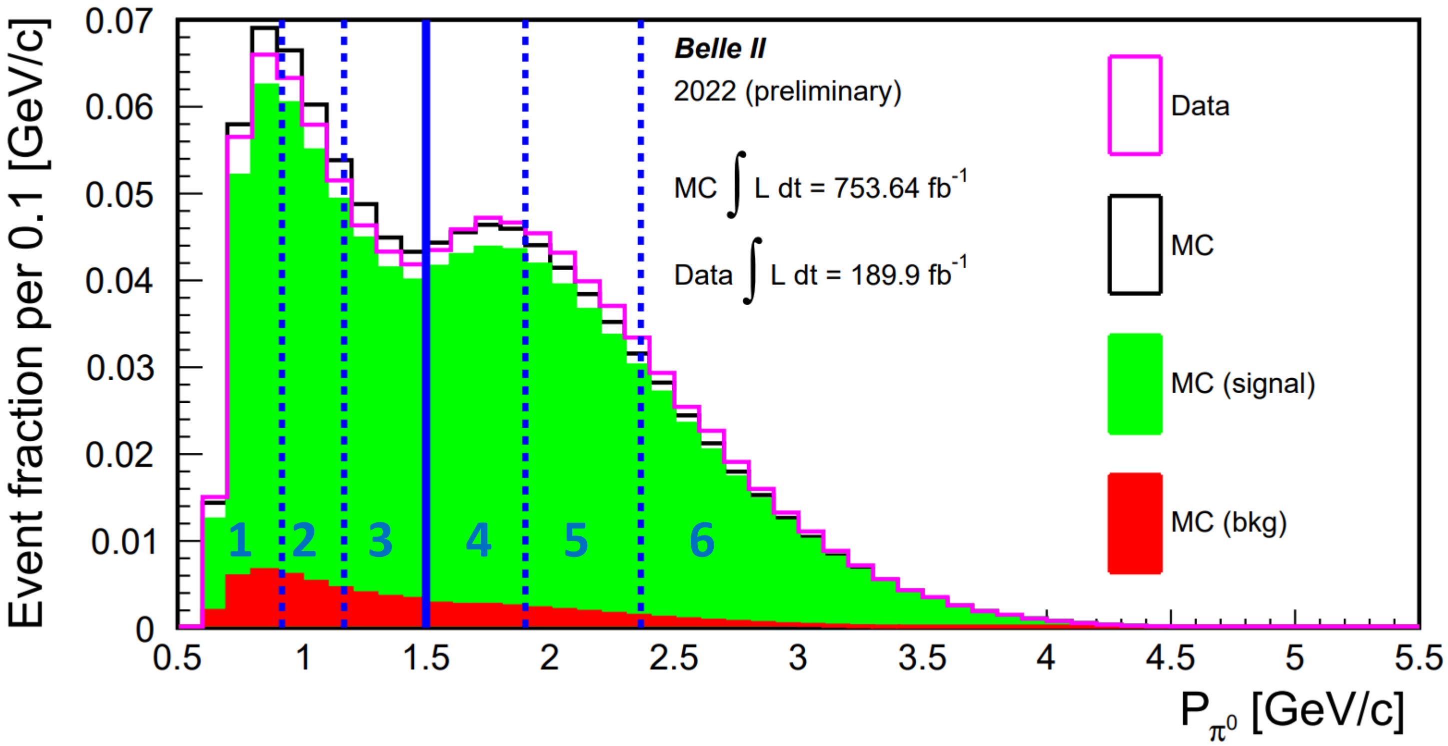


Dependence on π^0 momentum

Six π^0 momentum bin with the same signal events from MC.

No cut on p_{π^0} to **study the correction factor in low momentum region**.

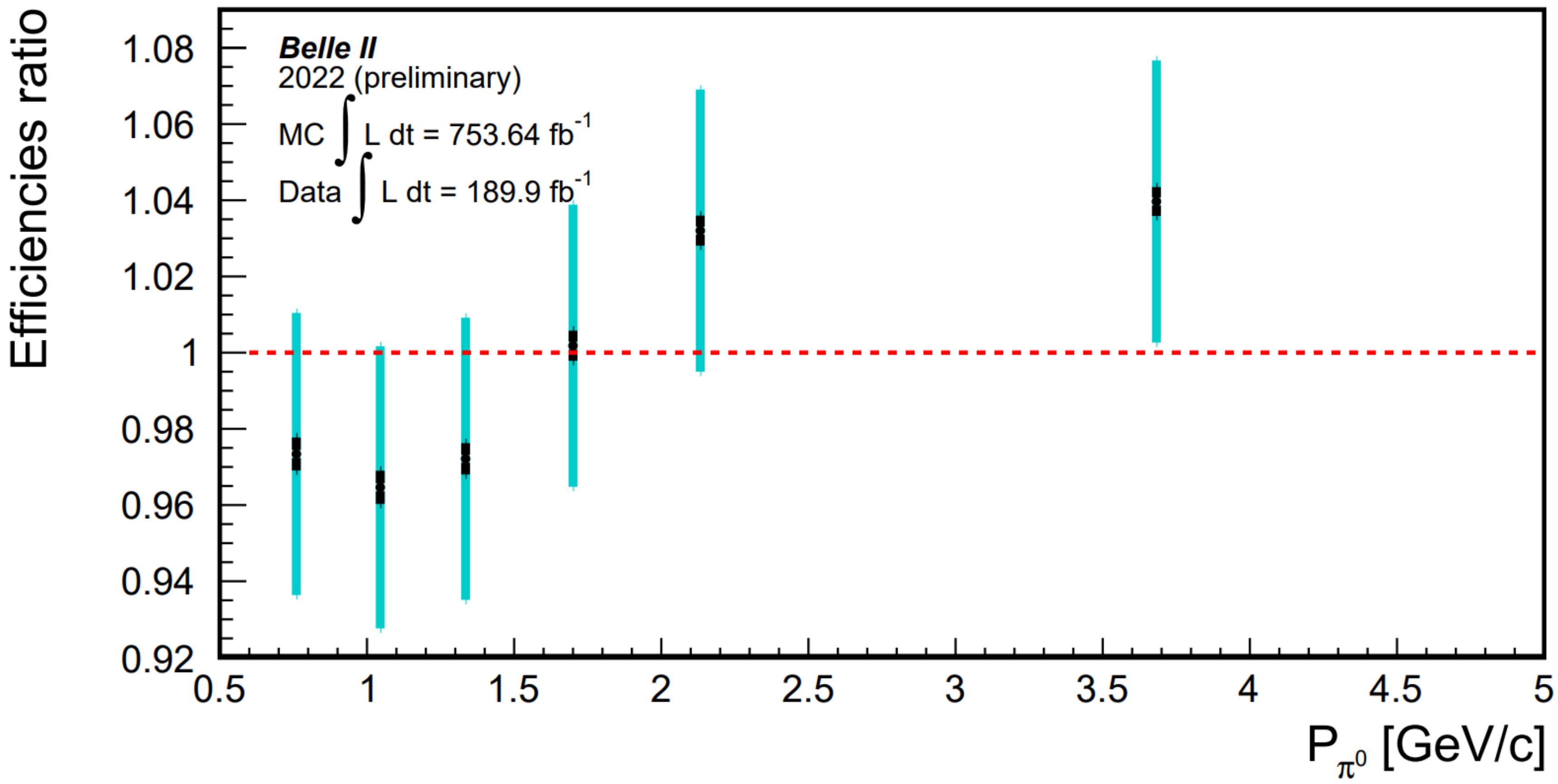
Three bin below and three bin above the requirement $p_{\pi^0} > 1.5$ GeV/c .



Dependence on π^0 momentum

Statistical uncertainty (black line) due to the $K^-\pi^+\pi^0$ sample.

Total uncertainty (blue line) $K^-\pi^+$ sample and systematic unceratintíes).



Systematic uncertainties

$$\boldsymbol{\varepsilon(\pi^0) = \frac{Yield(K^-\pi^+\pi^0)}{Yield(K^-\pi^+)}\left(\frac{\varepsilon_{D^0}\varepsilon_{D^{*+}}[\varepsilon(\pi_s^+)\varepsilon(K^-\pi^+)]_{K^-\pi^+\pi^0}}{\varepsilon_{D^0}\varepsilon_{D^{*+}}[\varepsilon(\pi_s^+)\varepsilon(K^-\pi^+)]_{K^-\pi^+}}\right)\dots\left(\frac{Br(D^0 \to K^-\pi^+)}{Br(D^0 \to K^-\ \pi^+\pi^0)Br(\pi^0 \to \gamma\gamma)}\right)}$$

The terms $\boldsymbol{\varepsilon(K)}$, $\boldsymbol{\varepsilon(\pi^+)}$, $\boldsymbol{\varepsilon(\pi^+_{slow})}$, $\boldsymbol{\varepsilon(D^0)}$ and $\boldsymbol{\varepsilon(D^{*+})}$ **should factorize and cancel in the ratio**. This assumption introduces three sytematic uncertanties:

1. **Tracking efficiencies**; inspection of $\cos(\theta)$ and momentum distributions of K^-, π^+ and π^+_{slow}.

2. **Particle identification (PID) for kaons.**

3. $\boldsymbol{\Delta m}$ **and** $\boldsymbol{D^{*+}}$ **selections**; checks on the $\Delta m, m_{D^0}$ and $p_{D^{*+}}(CMS)$ distributions.

Other systematic uncertainties come from:

1. **Fit models**; considerations of alternative models.

2. **Branching ratios** uncertainty.

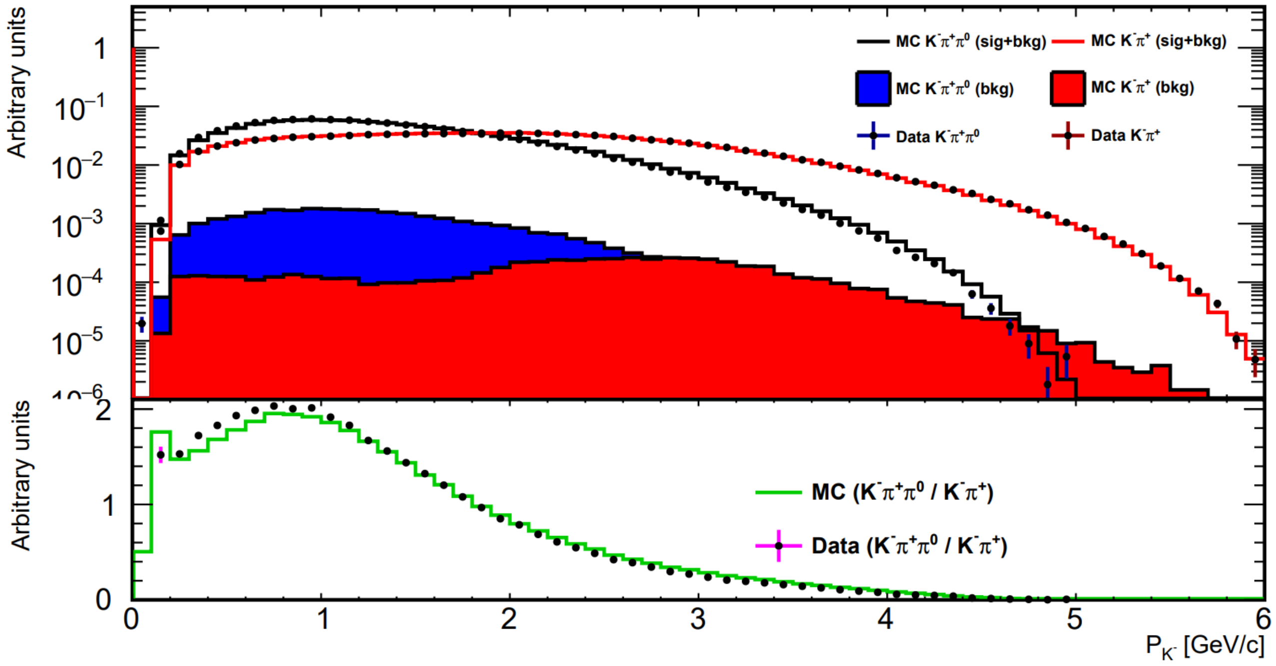
The systematic uncertainties have been evaluated without a cut on $\boldsymbol{p_{\pi^0}}$

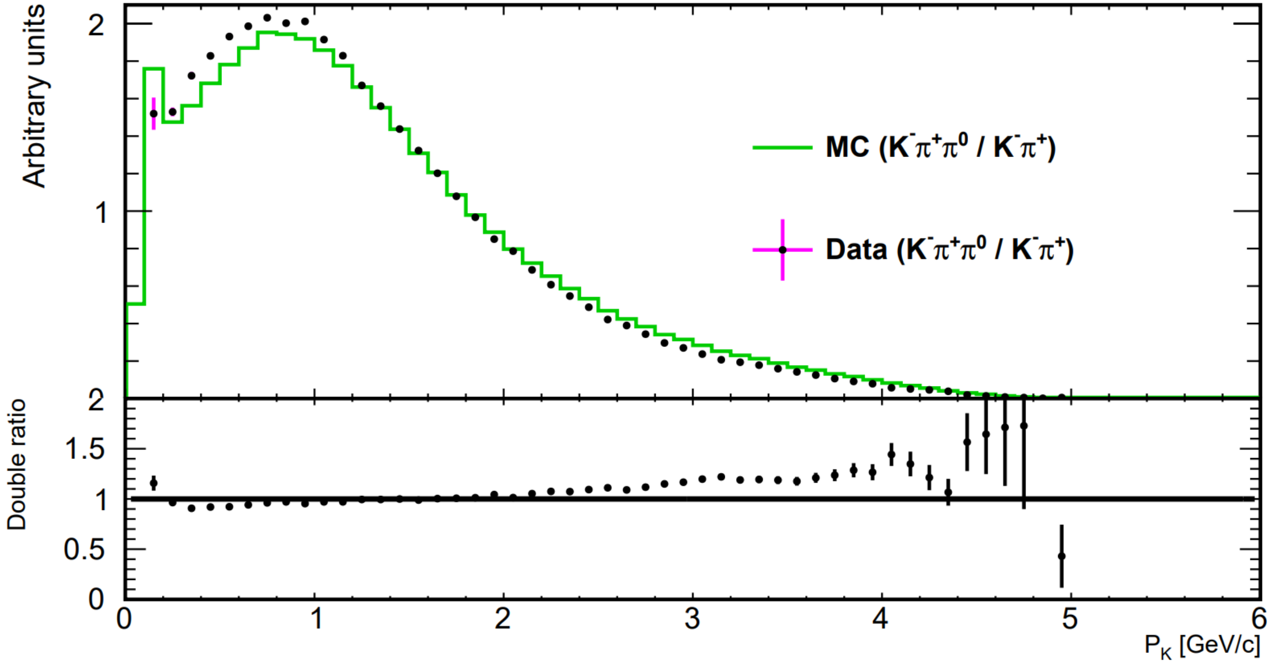
Tracking efficiencies

Tracking efficiency depends on **momentum** and $\boldsymbol{\cos(\theta)}$ of the charged particle.

Differences between simulation and data on the momentum and $\cos(\theta)$ distributions will also affect the tracking efficiency.

Ratio between the $K^-\pi^+\pi^0$ and $K^-\pi^+$ distributions in data and simulation; afterwords, the ratio between MC and data is considered. This procedure is called: **double ratio**.





Tracking efficiencies

Ratio between the $K^-\pi^+\pi^0$ and $K^-\pi^+$ distributions in data and simulation; afterwords, the ratio between MC and data is considered.
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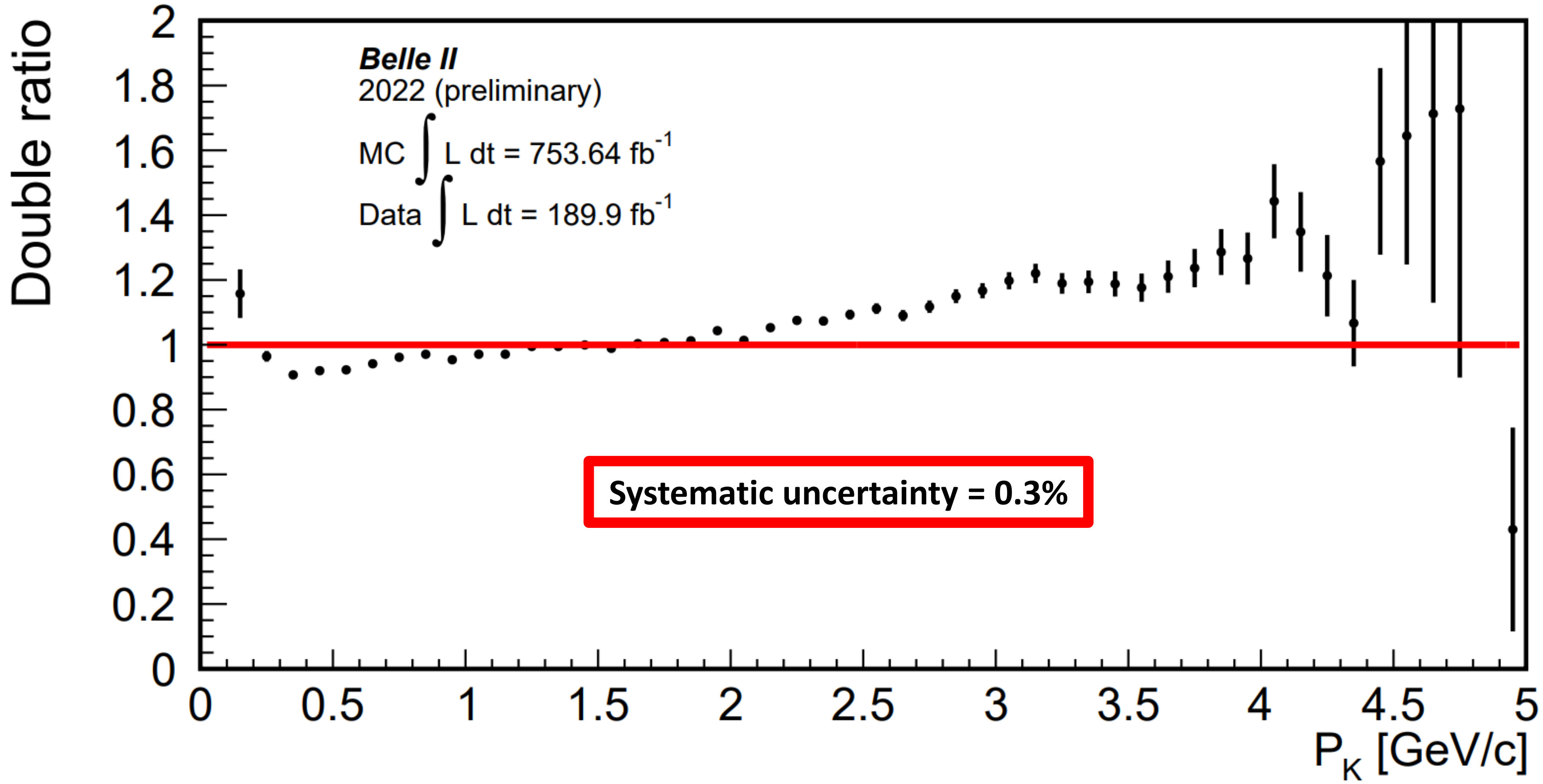
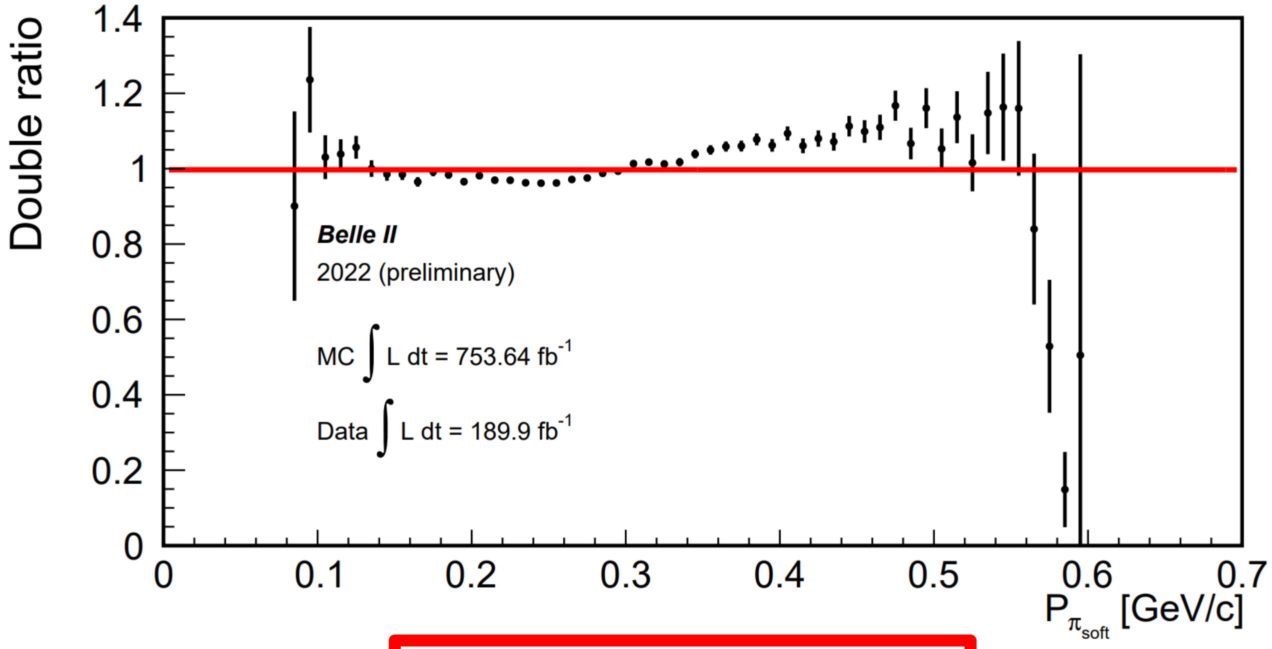


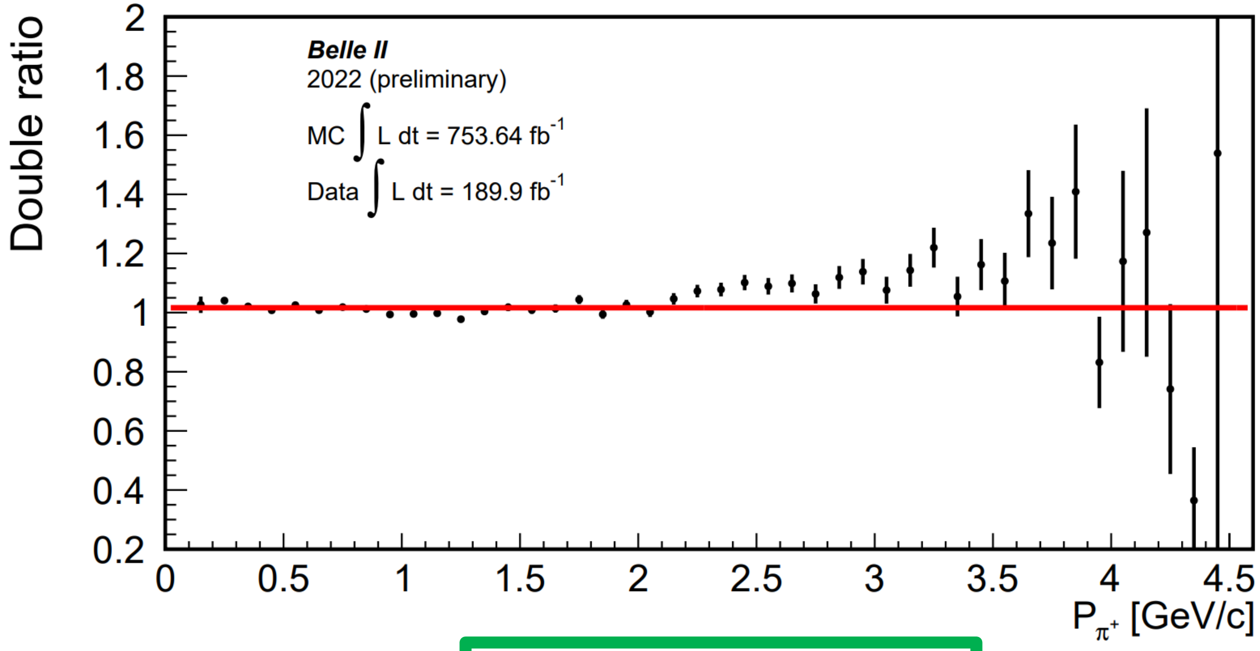
Tracking efficiencies

Tracking efficiencies contribution:

$$\sqrt{(2\cdot 0.3\%)^2{}_{K^-} + (2\cdot 0.3\%)^2{}_{\pi^+_{slow}}} = \mathbf{0.85\%}$$



Systematic uncertainty = 0.3%



No systematic uncertainty

PID for kaons, Δm and D^{*+} selections

Corrections have been used as weights to scale MC histograms.

Synchronous variation of $\pm 1\boldsymbol{\sigma}$ respect to the mean on $D^0 \to K^-\pi^+\pi^0$ and $D^0 \to K^-\pi^+$ decays.

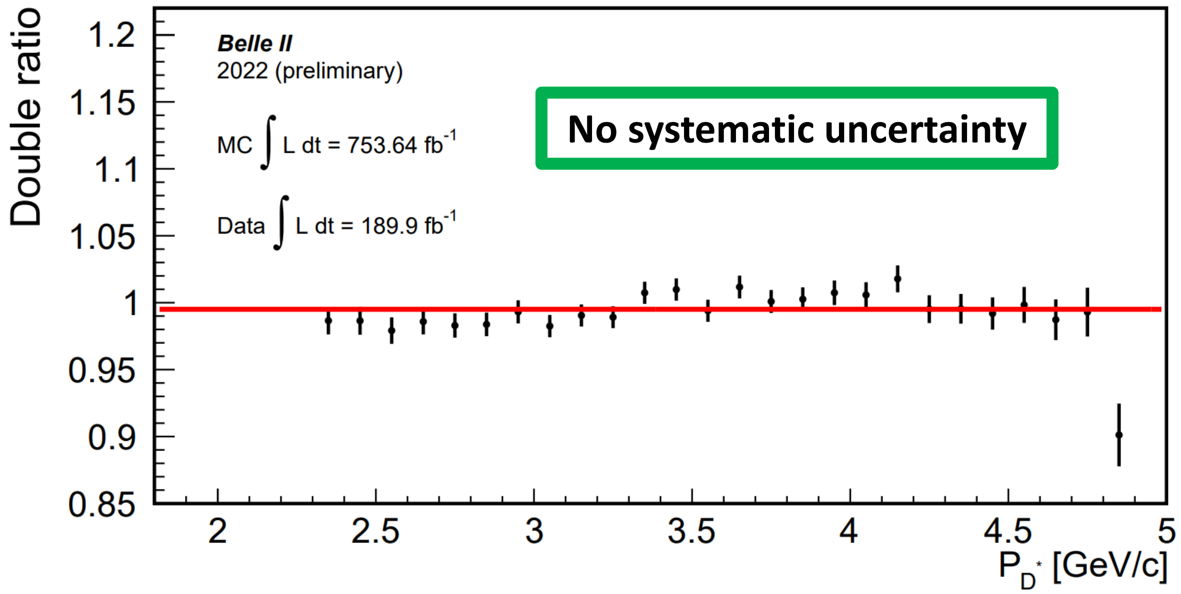
$$\left(\frac{\varepsilon_{Data}}{\varepsilon_{MC}}\right)_{+1\sigma} = 1.003 \pm 0.003\ (\text{stat.}); \left(\frac{\varepsilon_{Data}}{\varepsilon_{MC}}\right)_{mean} = 1.007 \pm 0.003(\text{stat.}); \left(\frac{\varepsilon_{Data}}{\varepsilon_{MC}}\right)_{-1\sigma} = 1.011 \pm 0.003(\text{stat.})$$

PID contribution : $1.011 - 1.007 = \mathbf{0.40\%}$

The **distributions of $\boldsymbol{\Delta}$m and $\boldsymbol{m_{D^0}}$ in data and simulation are very similar**: same peak position and distribution width within $\mathcal{O}(1\%)$.

No systematic uncertainty

Double ratio of the $p_{D^{*+}}(CMS)$ distribution.



No systematic uncertainty

Fit models

The systematic uncertainty is evaluated without a cut on $\boldsymbol{p_{\pi^0}}$, thus the **case with highest statistic** has been considered.

Definition of **alternative models for signal and background** of both the decays.

Extraction of the **signal yields from the fit, no significance varations have been observed**.

Considering all the four possible combinations of the models, four correction factors are obtained.

The RMS of these values corresponds to the systematic uncertainty

Fit models contribution: $\mathbf{0.58\%}$

Total systematic uncertainties

Summary of all the single contributions:

Source	Contribution (%)
K^- tracking efficiency	0.60
π^+_{slow} tracking efficiency	0.60
PID efficiency	0.40
Fit model	0.58
Ratio of branching fractions	3.56
Total	3.70

$$\boxed{\sqrt{(0.85\%)^2 + (0.58\%)^2 + (0.40\%)^2 + (3.56\%)^2} = \mathbf{3.70\%}}$$

This total systematic uncertainty is considered common to all the analysis presented.

Conclusions

- The $\boldsymbol{\pi^0}$**-reconstruction efficiency correction factor** is found to be:

$$\frac{\varepsilon_{Data}}{\varepsilon_{MC}} = \mathbf{1.023 \pm 0.003(stat.) \pm 0.037\ (syst.)}$$

The **systematic for the $\boldsymbol{B^0 \to \pi^0\pi^0}$analysis** is set to $\mathbf{3.7\%}$ **per $\boldsymbol{\pi^0}$**. The previous result feautured a systematic uncertainty of 10.0% per π^0.

This result has been used in the Belle II analysis of the $B^0 \to \pi^0\pi^0$ decay presented at **ICHEP 2022 in Bologna**.

The D^0-meson method has an **irreducible systematic** of $\mathbf{3.6\%}$ due to the **branching ratios fraction**, corresponding to the maximum precision available**.**

- **Three different dependencies of the correction factor** have been identified: region of the electromagnetic calorimeter, direction and momentum of the π^0.

The study could be extended considering a two-dimensional map as function of momentum and $\cos(\theta)$.

Thank you for your attention!

BACKUP

Background fraction discrepancies in ECL regions

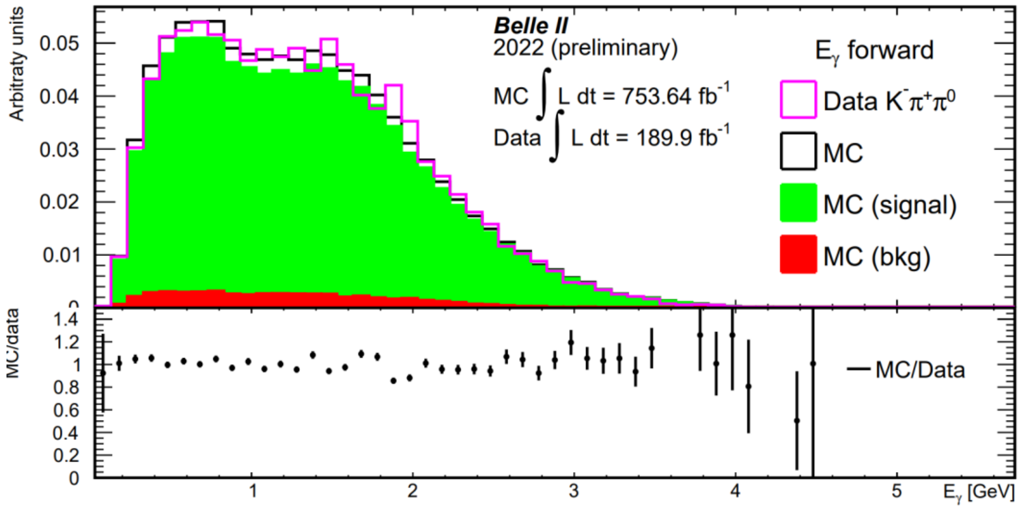
Large **background fraction** discrepancies in the endcaps.

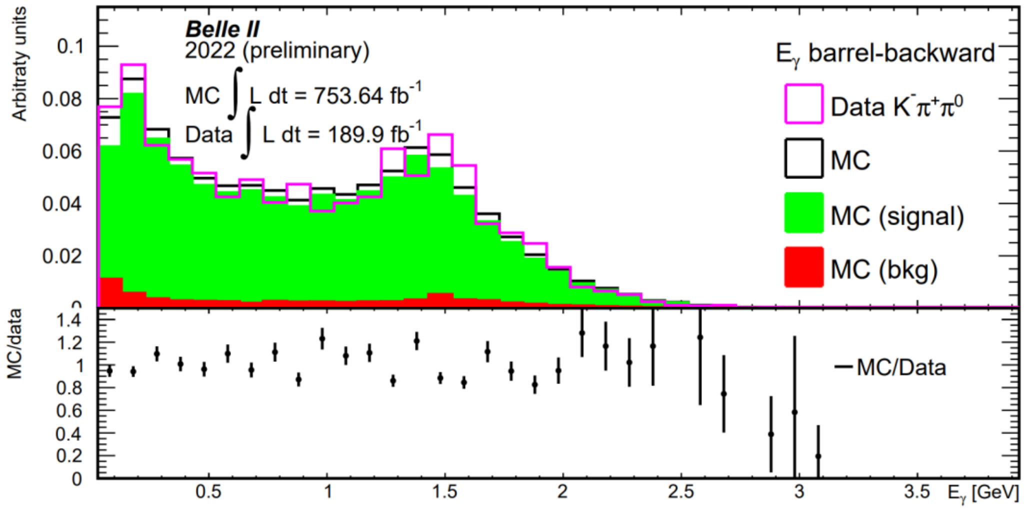
Comparison of the **photon energy spectra** between MC and data in each region.

Checks on **MC/data** distribution **ratio**.

Simulation reproduce the **shape** of the spectra but fails to model the overall **normalization**.

ECL region	Signal yields		$\frac{B}{B+S}$		Fit χ^2	
	MC	Data	MC	Data	MC	Data
For.	$54'545 \pm 247$	$13'471 \pm 126$	0.0580 ± 0.0018	0.0892 ± 0.0043	1.10	1.24
For.-Bar.	$43'308 \pm 222$	$10'166 \pm 111$	0.0718 ± 0.0022	0.0981 ± 0.0053	1.43	1.35
Bar.	$1'098'600 \pm 1'220$	$282'840 \pm 620$	0.0447 ± 0.0006	0.0527 ± 0.0012	1.27	1.24
Bar.-Back.	$12'498 \pm 121$	$2'283 \pm 56$	0.0554 ± 0.0042	0.1175 ± 0.0138	1.39	0.95
Back.	$18'933 \pm 149$	$3'466 \pm 67$	0.0519 ± 0.0033	0.1014 ± 0.0103	1.20	0.87





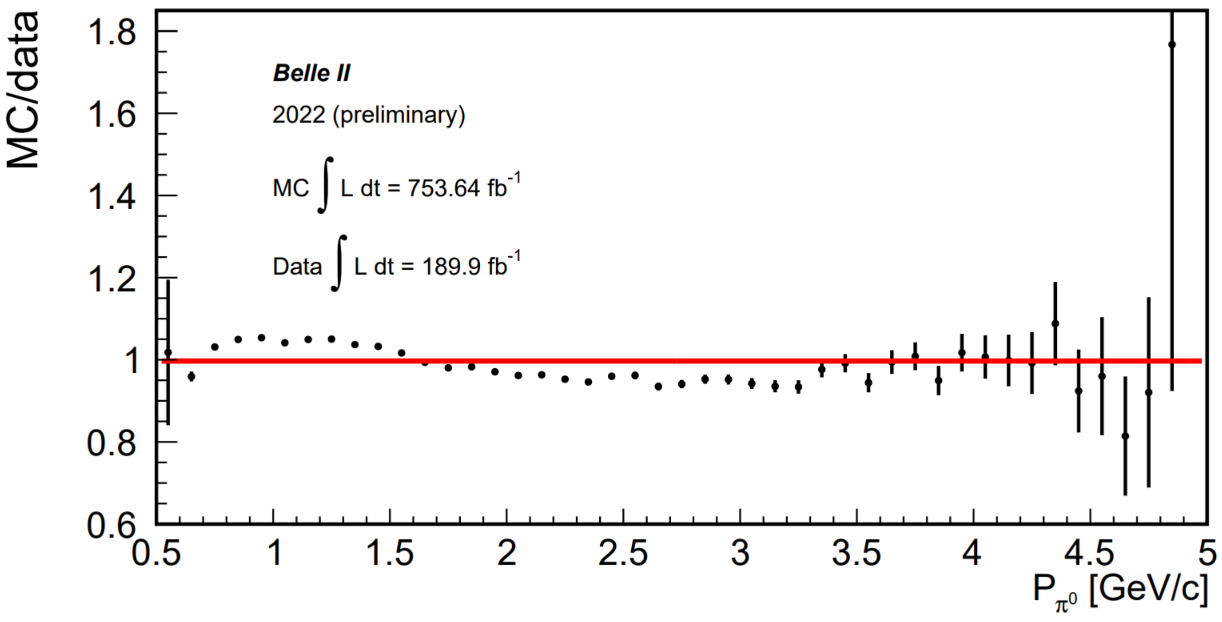
Additional checks

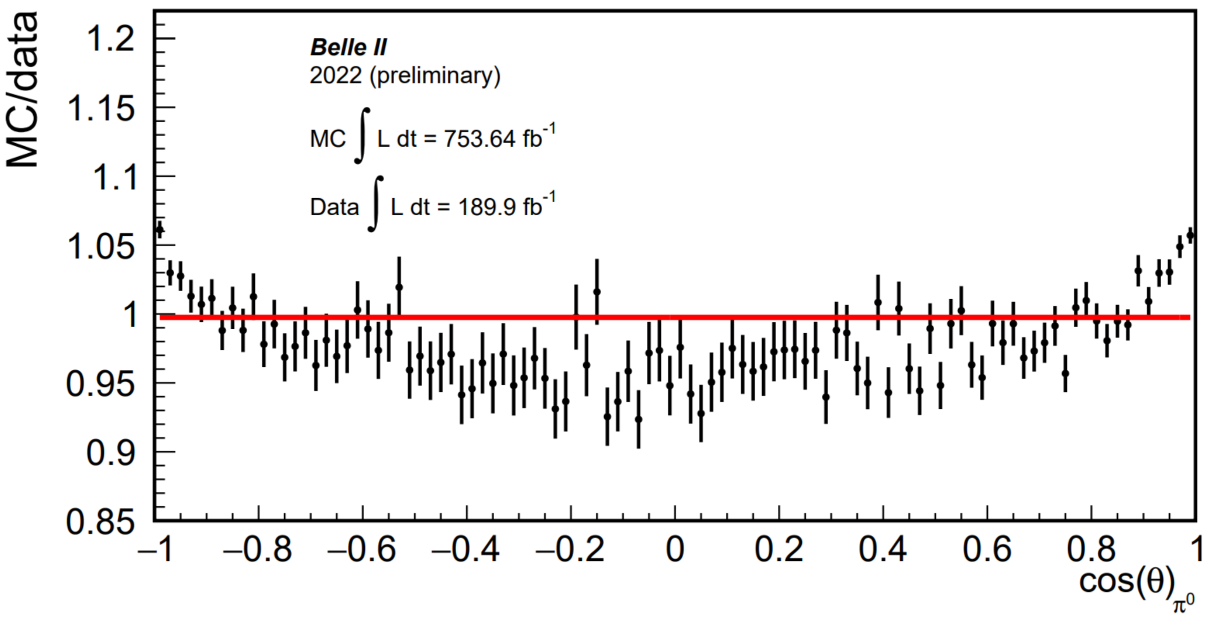
The $\mathbf{D^0} \rightarrow \boldsymbol{K^-\pi^+\pi^0}$ **has a rich Dalitz structure**.

Possible MC-data discrepancies, should appear in the **momentum distributions of the particles**.

The tracks have alredy been controlled.

Neutral pion MC over data ratio, for the momentum and $\boldsymbol{\cos(\theta)}$ distributions:





Fit models

The systematic unceratainty is evaluated without a cut on p_{π^0}.
The **worst case possible** has been considered.

Definition of **alternative models for signal and background** of both the decays.

	Model 1		Model 2	
Signal:	$K^-\pi^+\pi^0$	$K^-\pi^+$	$K^-\pi^+\pi^0$	$K^-\pi^+$
	3 johnson	3 johnson	3 crystal ball	2 crystal ball + johnson
Background:	exp. + crystal ball	exp. + 1st deg. pol.	johnson + 2nd deg. pol.	1st deg. pol.

Extraction of the **signal yields from the fit, no significance varations have been observed**.

Considering all the four possible combinations of the models, four correction factors are obtained.

The RMS of these values corresponds to the systematic uncertainty

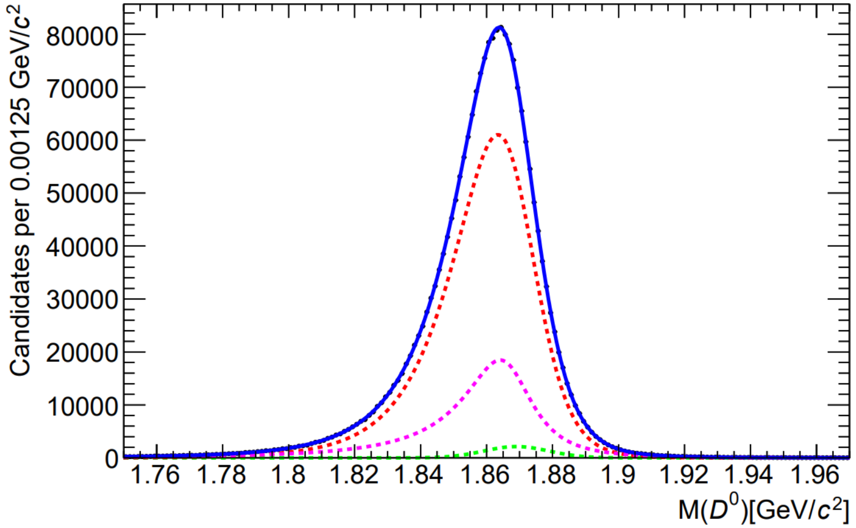
$\boxed{\textbf{Fit models contribution}: \mathbf{0.58\%}}$

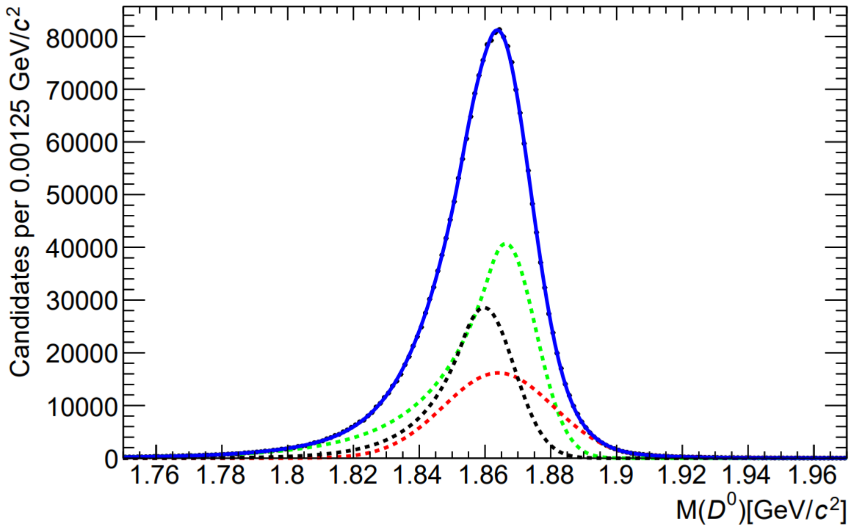
$D^0 \to K^-\pi^+\pi^0$ fit models

Model 1

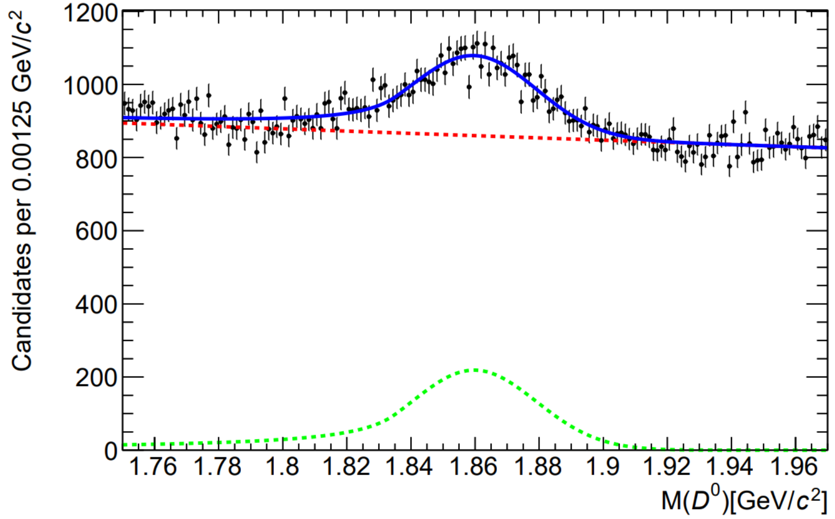
Model 2

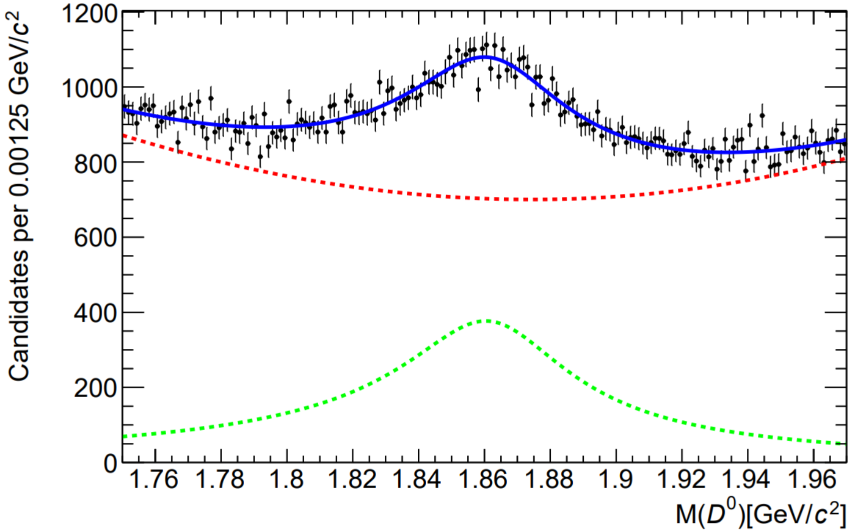
Signal





Background

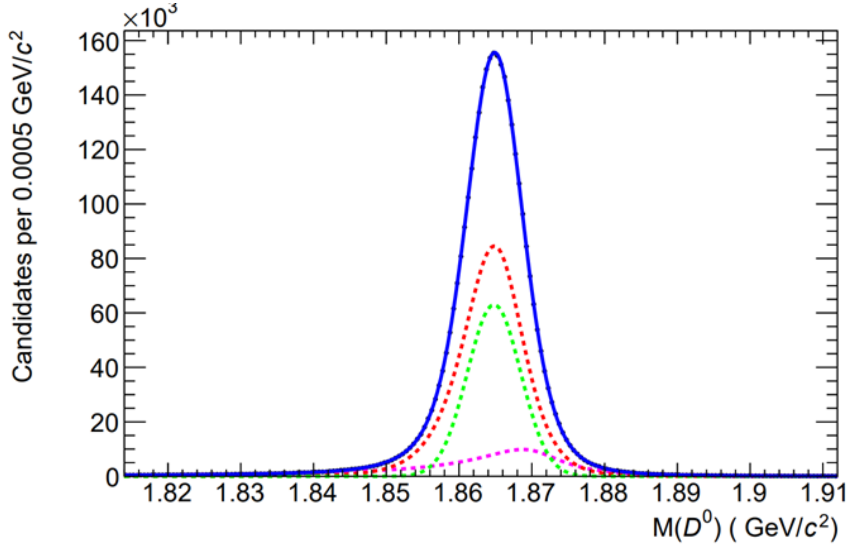


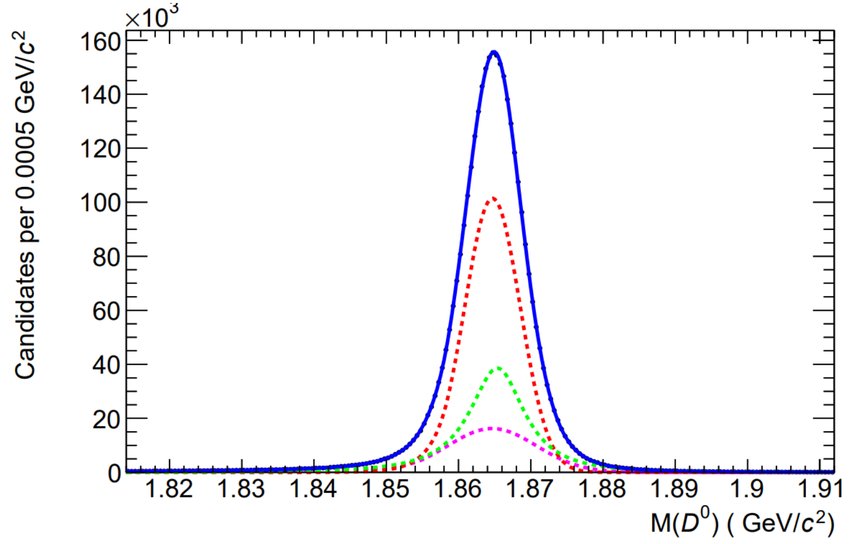


$D^0 \to K^- \pi^+$ fit models

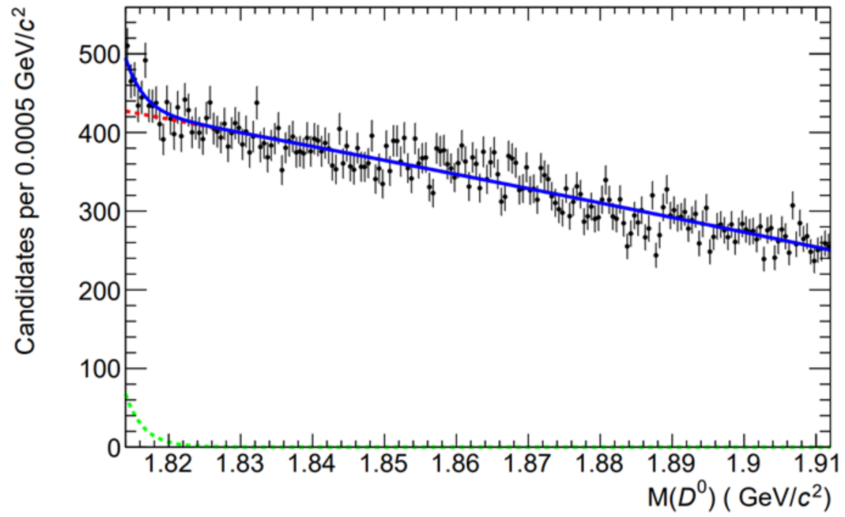
Model 1

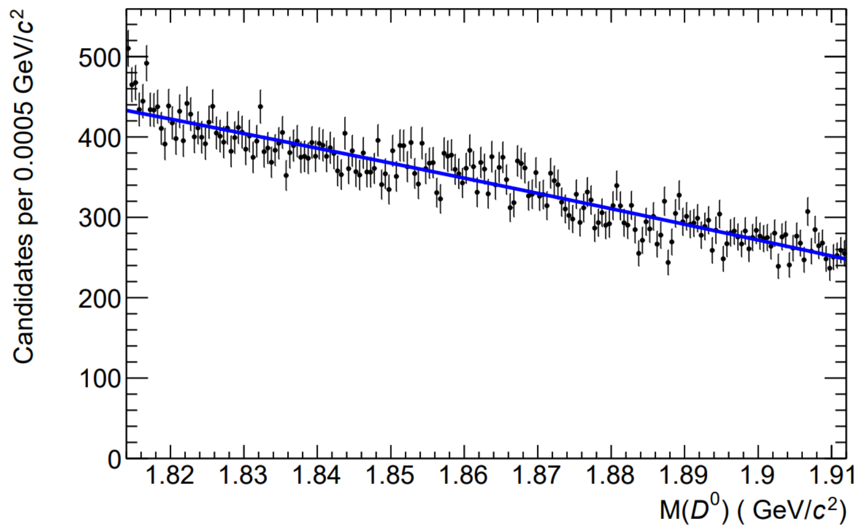
Model 2





Signal





Background