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First conservative assessment of the sensitivity of direct *CP*-Violation for the decay $D^0 \to \pi^0\pi^0$ at FCC-ee

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Department of Physics

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Overview

Physics motivations

- LHCb has measured *CP*-Violation in D^0 decays [$D^0 \to \pi^+\pi^-$, $D^0 \to K^+K^-$]

D^0 *CP*-Violating asymmetry difference measured by LHCb

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = -0.00154 \pm 0.00029$$

- Value is in agreement with the predictions of the Standard Model, but is situated in the upper limit of the predicted range of 10^{-4} to 10^{-3}
- Our comprehension of this *CP*-Violation can be enhanced through new perceptions for the decay mode $D^0 \to \pi^0\pi^0$

$D^0 \to \pi^0\pi^0$ *CP*-Violating decay-rate asymmetry measured by Belle

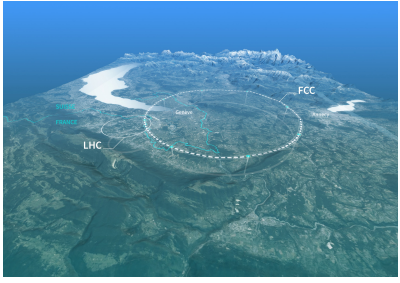
$$A_{CP}(D^0 \to \pi^0\pi^0) = 0.000 \pm 0.006$$

Detector motivations

- The electromagnetic calorimeter is essential for some of the precision measurements of electroweak physics at FCC-ee, especially in the flavour sector
- Neutral pions π^0 decay rapidly into two photons assessing requirements about energy and angular resolution
- The decay $D^0 \to \pi^0\pi^0 \to 4\gamma$ can set constraints on these resolutions

Questions to answer:

- Is FCC-ee able to improve on the $D^0 \to \pi^0\pi^0$ precision anticipated at the end of Belle II?
- Which influence has the energy resolution of the electromagnetic calorimeter (EMC)?



Presented studies

The branching fraction of $D^0 \to \pi^0\pi^0$ is small [$8.26 \cdot 10^{-4}$]

Step 1: D^0 reconstruction at FCC-ee

- Produce $D^0 \to \pi^0\pi^0$ signal samples using the IDEA detector card with different energy resolutions for the EMC
- Reconstruct the D^0 from the photons in the final state

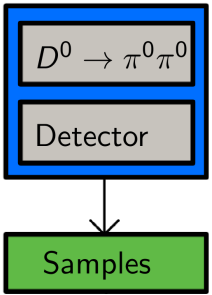
Step 2: Assessment of A_{CP}

- Use the inclusive $Z \to c\bar{c}$ samples produced for the IDEA detector system with $\frac{3\%}{\sqrt{E}}$ EMC resolution
- Reconstruct $D^0 \to \pi^0\pi^0$ decays that have been produced by pythia in some events

Name		Number of events	Sum of weights
p8_ee_Zcc_ecm91		499 786 495	4.99786e+8
Cross-section	**K-factor**	**Matching efficiency**	
5215.46 pb	1	1	

Analysis concept for D^0 reconstruction

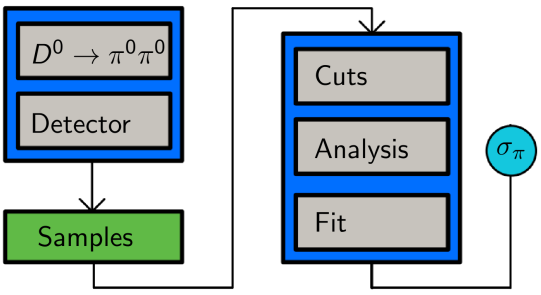
Simulation:



- Use FCCAnalyses framework to simulate collision events and detector response
  - Pythia8: ISR, FSR and hadronization process
  - EvtGen: hadronic decays (forced channel)
  - IDEA detector system (different EMC resolutions)
- Analysis starts with the collection of all detected photons

Analysis concept for D^0 reconstruction

Simulation: Analysis:



- Collection of all detected photons
- Calculate invariant mass of each pair of γ
  - Signal events: $\pi^0 \to \gamma\gamma$
  - Combinatorical background
- Use cuts to reduce combinatorical background in π^0 collection
- Fit resulting peak to determine $\sigma_{(m_{\pi^0})}$

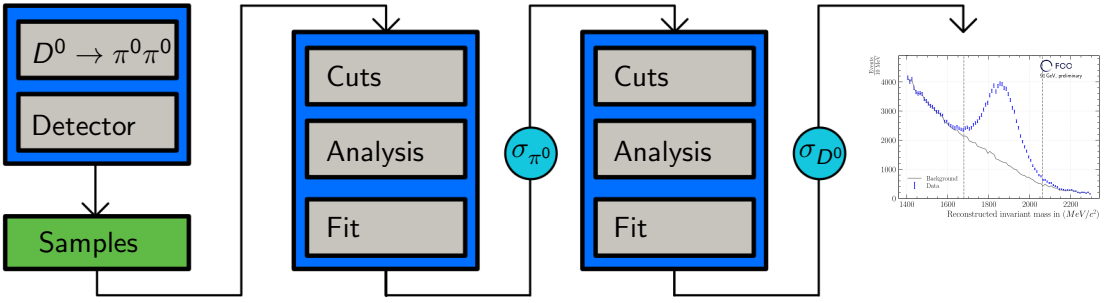
- Reconstruction of the D^0 works in a similiar way

Analysis concept for D^0 reconstruction

Simulation:

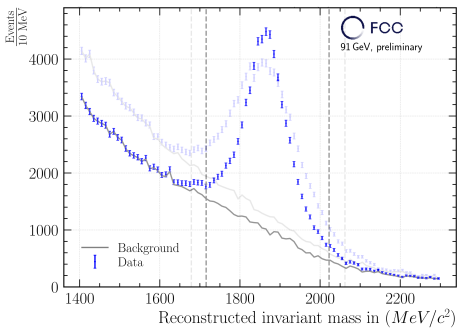
Analysis:

Result:



Results of the $D^0 \to \pi^0\pi^0$ reconstruction in signal samples

D^0 reconstruction with $\frac{3\%}{\sqrt{E}}$ and $\frac{10\%}{\sqrt{E}}$



- Reconstruction of $D^0 \to \pi^0\pi^0$ is possible with different energy resolutions
- The signal/background ratio improved with enhanced resolution
- Reconstruction effeciences with $\frac{3\%}{\sqrt{E}}$ (IDEA):
  - $\approx 96\%$ for neutral pions
  - $\approx 74\%$ for D^0-mesons
- The high momentum π^0 from boosted D^0 decays would deserve a dedicated reconstruction algorithm

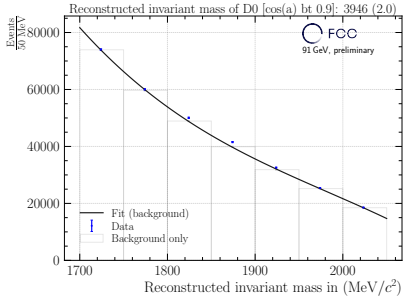
Overview

Reconstruction of $D^{*+} \to D^0(\to \pi^0\pi^0)\pi^+$ for inclusive $Z \to c\bar{c}$ samples

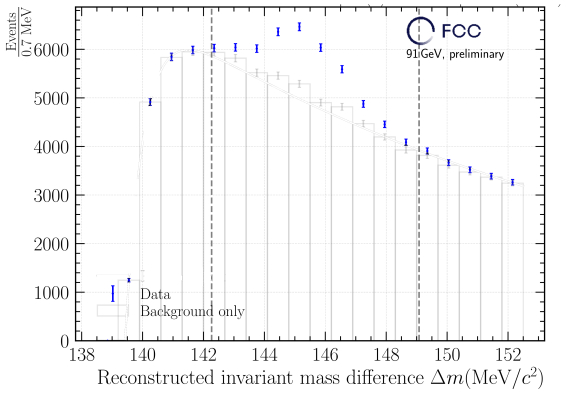
How to see *CP*-Violation in D^0 decays:

- **Goal**: Consideration of *CP* violation
- **Problem**: Need to know if reconstructed D^0 was particle or anti-particle
- **Solution**: Focusing on the D^0 produced from $D^{*+} \to D^0\pi^+$
  - In an inclusive $e^+e^- \to c\bar{c}$ sample: $\approx 24\%$

- Higher level of combinatorics for the inclusive $Z \to c\bar{c}$ sample
- Use selection rules per event to reduce combinatorical background for D^{*+} reconstruction
  - Select the D^0 candidate with highest momentum
  - Select the $\pi^{+/-}$ candidate with the closest angle to this D^0



Results - Mass Diff



- Using 100 Mil. $Z \to c\bar{c}$ events
- Our target variable is the mass difference $\Delta m = m(D^{*+}) - m(D^0)$ of the reconstructed decay $D^{*+} \to D^0\pi^+$
- Lead to improved signal/background ratio
- Still a lot of background after using the selection rules

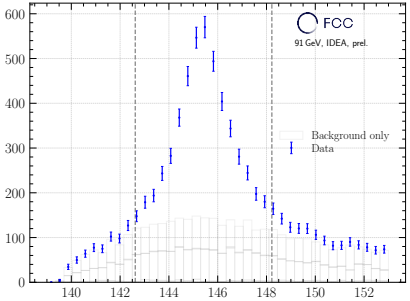
MVA approach

Train a DNN to do a signal-background-classification for the D^0 candidates

Utilized features:

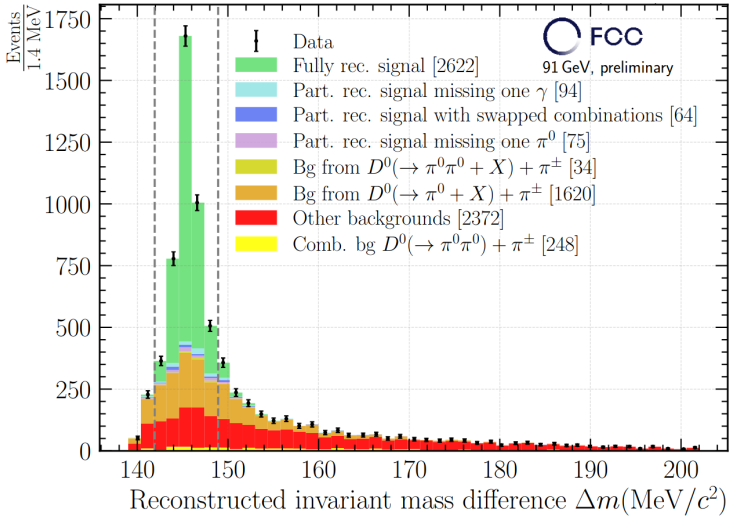
- Energy of γ_1
- Energy of γ_2
- Angle between γ_1,γ_2
- Energy of π_1
- Energy of γ_3
- Energy of γ_4
- Angle between γ_3,γ_4
- Energy of π_2
- Angle between π_1,π_2
- Momentum of D^0

- Use only kinematic variables of the decay chain $D^0 \to \pi^0\pi^0 \to 4\gamma$
- Photons and pions are ordered by their energy
- There is space for future improvements



$D^{*+} \to D^0(\to \pi^0\pi^0)\pi^+$ reconstruction result

Our goal is to target A_{CP} for the decay chain $D^{*+/-} \to D^0(\to \pi^0\pi^0(\to 4\gamma))\pi^{+/-}$



A_{CP} precision prediction

$$A_{CP} = \frac{N_{D^+,\,\text{(data-bg)}} - N_{D^-,\,\text{(data-bg)}}}{N_{D^+,\,\text{(data-bg)}} + N_{D^-,\,\text{(data-bg)}}}$$

$D^0 \to \pi^0\pi^0$ *CP*-Violating decay-rate asymmetry (Belle)

$A_{CP}(D^0 \to \pi^0\pi^0) = 0.000 \pm 0.006 = 0.0 \pm 0.6\%$

- Already with 1700 Mil. $Z \to c\bar{c}$ events one achieves a higher sensitivity than the one of Belle ($\approx$ 2 days of operation)

Upscaled to $7.24 \cdot 10^{11}$ $Z \to c\bar{c}$ events expected at FCC-ee

$\sigma_{A_{CP}}(D^0 \to \pi^0\pi^0) = 0.028\%$

- This analysis (which is still to be optimised) improves by a factor 3-4 the anticipated precision at the end of Belle II

Conclusion and Outlook

Conclusion

At FCC-ee, we are sensitive to direct CP violation in $D^0 \to \pi^0\pi^0$ with $\frac{3\%}{\sqrt{E}}$ EMC resolution

Next steps:

- Consider the effect of the calorimeter resolution on the assessment of A_{CP}

Suggested improvements for a less conservative analysis:

- Merged π^0 are disregarded - reconstruction can lead to statistical improvement
- Background rejection can be improved by the use of global hemisphere variables
  - Signal should contain 0 leptons, 0 displaced tracks and 0 missing energy
  - Use of c-tagger in opposite hemisphere

Thanks for listening!

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