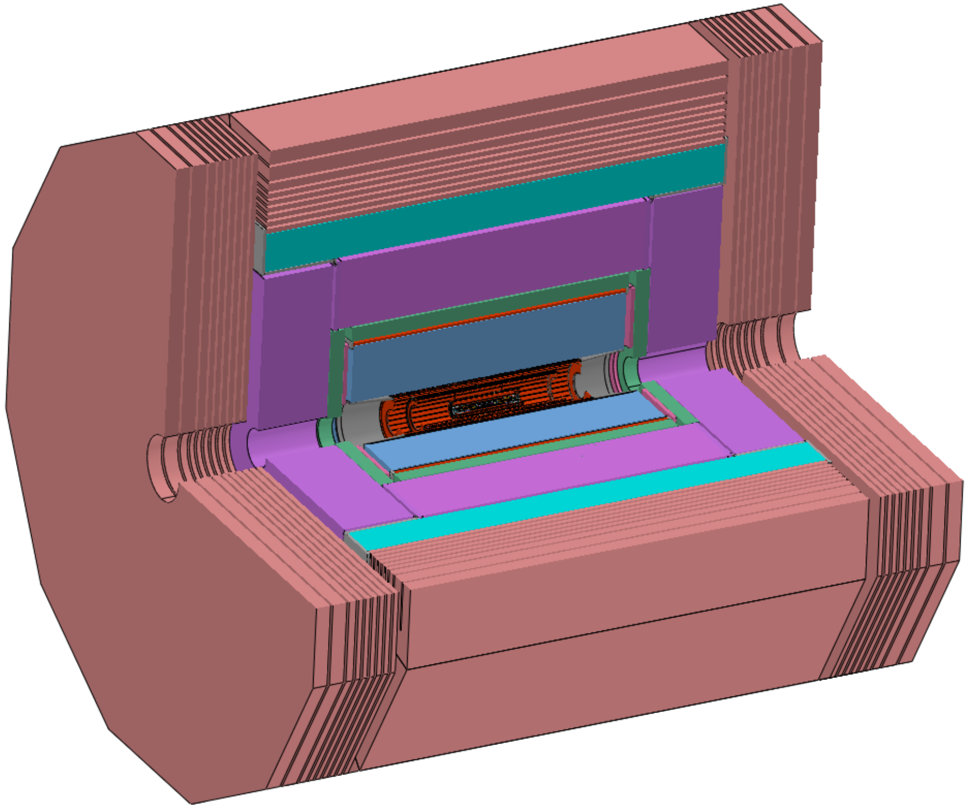
Flavor benchmark @ CEPC: CP violation searches in $D \rightarrow hh\pi^0$ decays



Shanzhen Chen
Jinfei Wu, Shi Wang

18 July 2025

CEPC Tera-Z mode

- CEPC operation modes
  - 50 MW scenario
  - Z decay modes:

$c\bar{c}$ (12.03 ± 0.21) %
$b\bar{b}$ (15.12 ± 0.05) %

Operation mode	Z factory	WW threshold	Higgs factory	$t\bar{t}$
$\sqrt{s}$ (GeV)	91.2	160	240	360
Run time (year)	2	1	10	5
Instantaneous luminosity (10^{34}cm^{-2}s^{-1}, per IP)	191.7	26.7	8.3	0.83
Integrated luminosity (ab^{-1}, 2 IPs)	100	6.9	21.6	1
Event yields	4.1×10^{12}	2.1×10^{8}	4.3×10^{6}	0.6×10^{6}

- Heavy flavor particle yields
  - The largest heavy flavor samples from e^+e^- collider

Particle	BESIII	Belle II (50 ab^{-1} on $\Upsilon(4S)$)	LHCb (300 fb^{-1})	CEPC (4×Tera-Z)
B^0, $\bar{B}^0$	-	5.4×10^{10}	3×10^{13}	4.8×10^{11}
$B^\pm$	-	5.7×10^{10}	3×10^{13}	4.8×10^{11}
B_s^0, $\bar{B}_s^0$	-	6.0×10^{8} (5 ab^{-1} on $\Upsilon(5S)$)	1×10^{13}	1.2×10^{11}
$B_c^\pm$	-	-	1×10^{11}	7.2×10^{8}
Λ_b^0, $\bar{\Lambda}_b^0$	-	-	2×10^{13}	1×10^{11}
D^0, $\bar{D}^0$	1.2×10^{8}	4.8×10^{10}	1.4×10^{15}	8.3×10^{11}
$D^\pm$	1.2×10^{8}	4.8×10^{10}	6×10^{14}	4.9×10^{11}
$D_s^\pm$	1×10^{7}	1.6×10^{10}	2×10^{14}	1.8×10^{11}
$\Lambda_c^\pm$	0.3×10^{7}	1.6×10^{10}	2×10^{14}	6.2×10^{10}
$\tau^+\tau^-$	3.6×10^{8}	4.5×10^{10}		1.2×10^{11}

Flavor programs @ CEPC

- Precise measurements of Standard model
  - CKM matrix elements, Unitary triangles measurements, CPV searches
  - Lepton universality violation tests
  - ……
- Searches for rare and forbidden decays
  - Flavor changing neutral current decays
  - Lepton flavor violating decays / baryon number violating decays
  - ……
- Spectroscopy studies
  - Conventional hadron states searches
  - Exotics hadron states (pentaquarks, tetraquarks) searches
  - ……

Flavor benchmark @ CEPC

- Initial benchmark: CP-violating phase measurements with $B_s \to D_s K$ decays
  - Method established but with old detector design
  - Replaced after first IDRC meeting

> It looks important to clarify whether the strategy is to optimize detector performance or study the physics reach. Given the limited amount of time it is better to focus on demonstrating that the reference detector reaches adequate performance for physics. With this aim the list of complex channels should be reduced (e.g. the b-physics part) and some basic channels (e.g. Z→ mumu) added in. The performance on basic objects (leptons, photons, jets) as a function of energy and polar angle is an essential part of the TDR. Full analyses and physics reach can be limited to a restricted list of channels, encompassing Higgs, Z, W and top physics.
>
> 1st IDRC report

- Current benchmark: CP violation searches with $D \to hh\pi^0$ (h = Kaon or pion)
  - Simple, large branching fraction
  - Selection and reconstruction of the decay sensitive to: PID, p, E, … of final state particles, Decay vertices, π^0 reconstruction

JHEP

Published for SISSA by Springer

Received: February 19, 2025
Revised: April 15, 2025
Accepted: May 18, 2025
Published: June 20, 2025

Prospect for measurement of CP-violating observables in $B_s^0 \to D_s^{\mp} K^{\pm}$ decays at a future Z factory

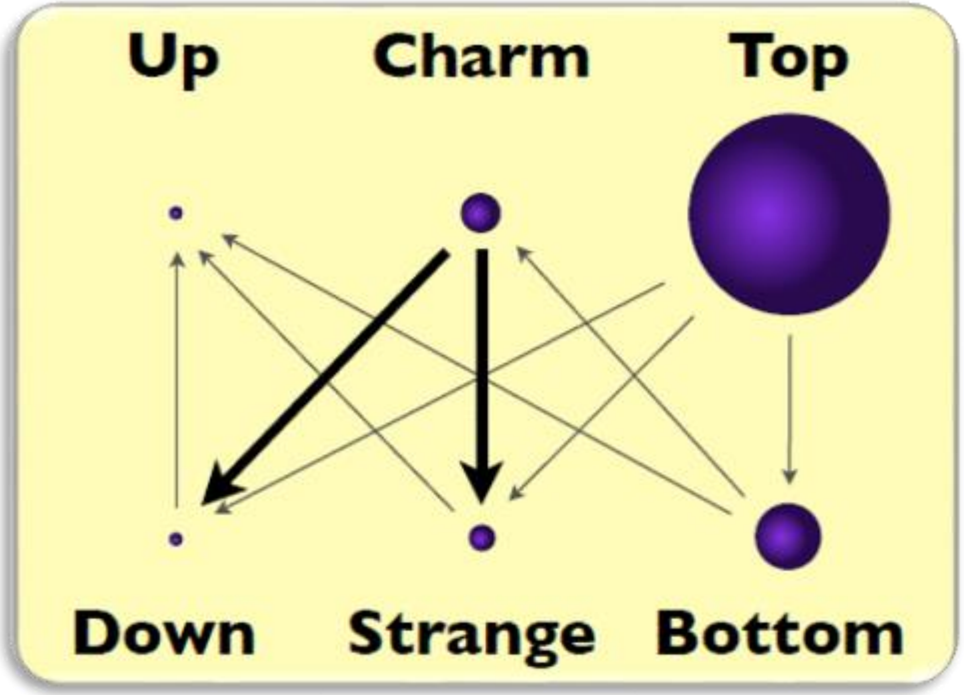
Ji Peng[a,b,*] Mingrui Zhao[c] Xiaolin Wang[d] Manqi Ruan[a] Hengne Li[d] and Shanzhen Chen[a,*]

[a] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
[b] University of Chinese Academy of Sciences (UCAS), Beijing 100049, China
[c] Science and Technology on Nuclear Data Laboratory, China Institute of Atomic Energy, Beijing 102413, China
[d] South China Normal University (SCNU), Guangzhou 510631, China

E-mail: pengji@ihep.ac.cn, mingrui.zhao@cern.ch, xiaolin.wang@cern.ch, ruanmq@ihep.ac.cn, hengne.li@cern.ch, shanzhen.chen@ihep.ac.cn

CP violation in charm sector

- Charm is the only weak up-type quark decay from a bound system
  - The only up-type sector that could search for CP violation
- CP violation expected to be small in charm sector within SM
  - Imaginary part of V_{cd} very small (10^{-2} to 10^{-3})
  - May enhance through new process and new particles – clean probe to NP
- CP violation in charm observed in two-body ΔA_{CP} by LHCb
  - $\Delta A_{CP} = (-1.54 \pm 0.29) \times 10^{-3}$



$$V_{CKM} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda - iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\hat{\rho}-i\hat{\eta}) & -A\lambda^2 - iA\lambda^4\eta & 1 \end{pmatrix}$$

CP violation in Multibody decays

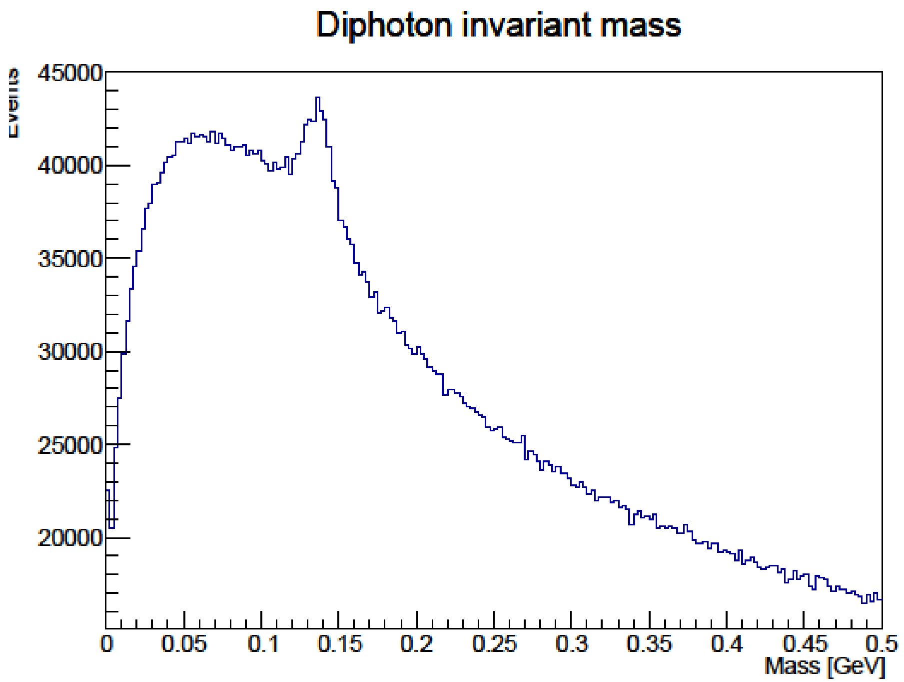
- Multi-body decays can help to understand the source of CP violation
  - CP violation originates from interferences of at least two decay amplitudes, decay phase space can identify the interfering resonances
  - CP violation may be canceled in two-body processes [See the new result in *Nature*]
    - Example: $A_{CP}^{\Lambda_b^0 \to pK^-} = (-1.1 \pm 0.7 \pm 0.4)\%$, $A_{CP}^{\Lambda_b^0 \to pk\pi\pi} = (2.45 \pm 0.46 \pm 0.10)\%$
  - Some multi-body decays, *i.e.* $D \to hh\pi^0$ has larger branching fraction than two-body decays
    - Br($D \to \pi\pi\pi^0$) $\sim$10 times larger than Br($D \to \pi\pi$)
    - Br($D \to K\pi\pi^0$) $\sim$100 times larger than Br($D \to \pi\pi$)
    - In the searches for CP violation, STATISTICS MATTERS!
- The only experiment that has charm yields larger than CEPC is LHCb
  - As a hadron collider, efficiency of reconstructing π^0 is extremely low

Reconstruct $D \to hh\pi^0$ decays at CEPC detector

- MC sample produced from $e^+e^- \to Z \to b\bar{b}$ at $\sqrt{s} = 91.2$ GeV
  - /cefs/higgs/zhangkl/Production/25036/E91.2_eebb/Reco/rec_E91.2_eebb_*.root
  - The version of CEPCSW is tdr.25.3.2
- Test with 160k collisions
  - Number of truth D^0: 211,231
  - Number of truth $D^0 \to K^-\pi^+\pi^0$: 23,842
  - Number of truth $D^0 \to \pi^-\pi^+\pi^0$: 3,215

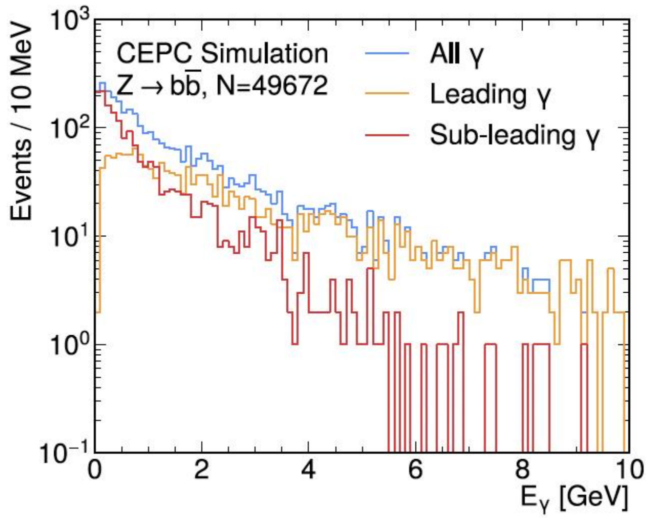
Step 1: reconstruct π^0 from two γ's

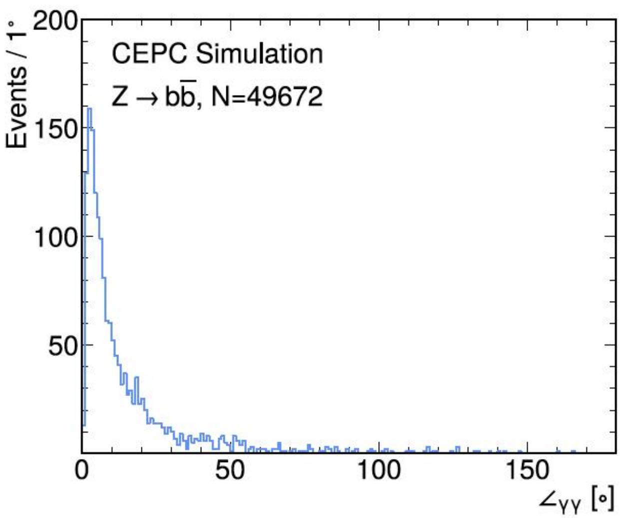
- CEPCSW now could provide PID information in PFO
  - Possible to identify γ, charged π, charged K,
- Combining two γ's, could see π^0 peak in the spectrum



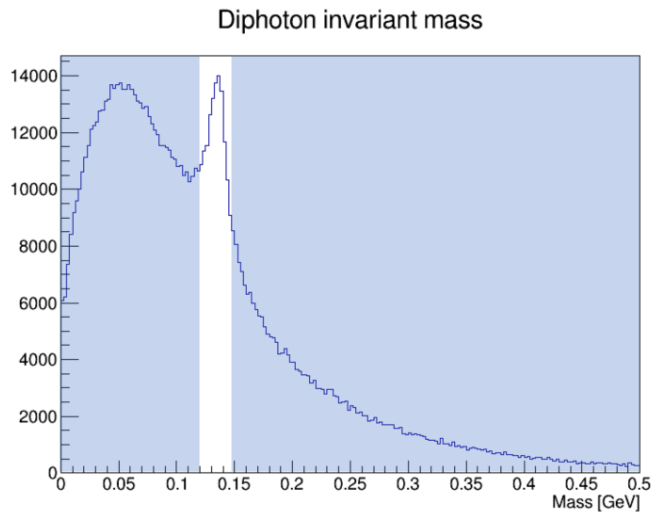
Step 1: reconstruct π^0 from two γ's

- Truth distribution of γ energy and open angle between 2 γ's



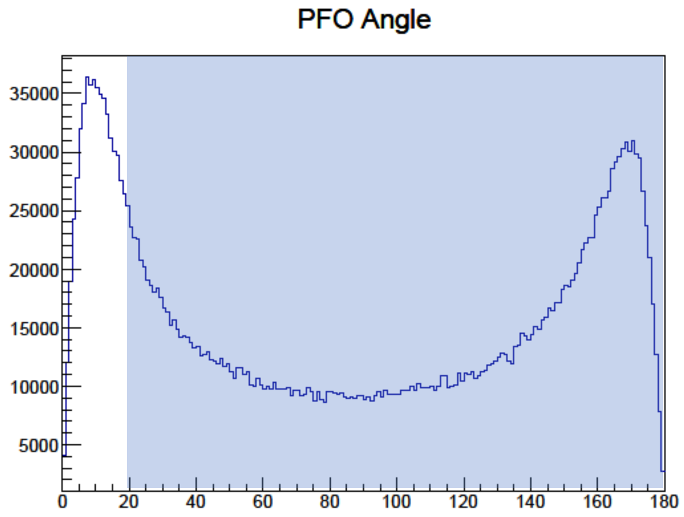


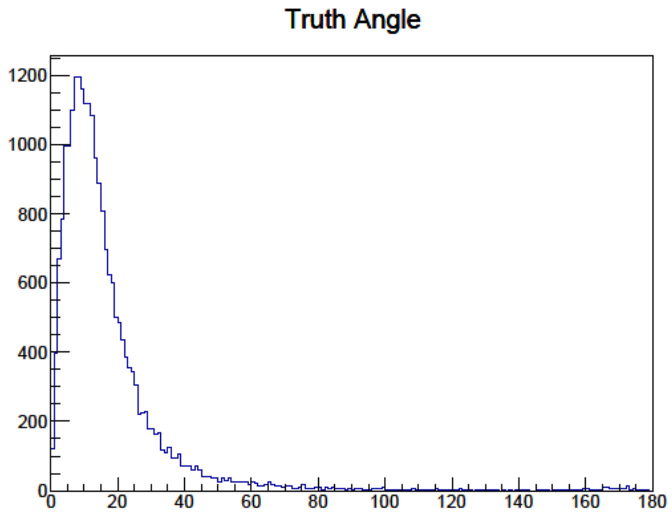
- Select one γ in PFOs with E > 0.5 GeV, then combine a second γ within 10 degrees of open angle
  - Select diphoton between 0.12 and 0.15 GeV as π^0 candidates



Step 2: combining π^0 with two other tracks

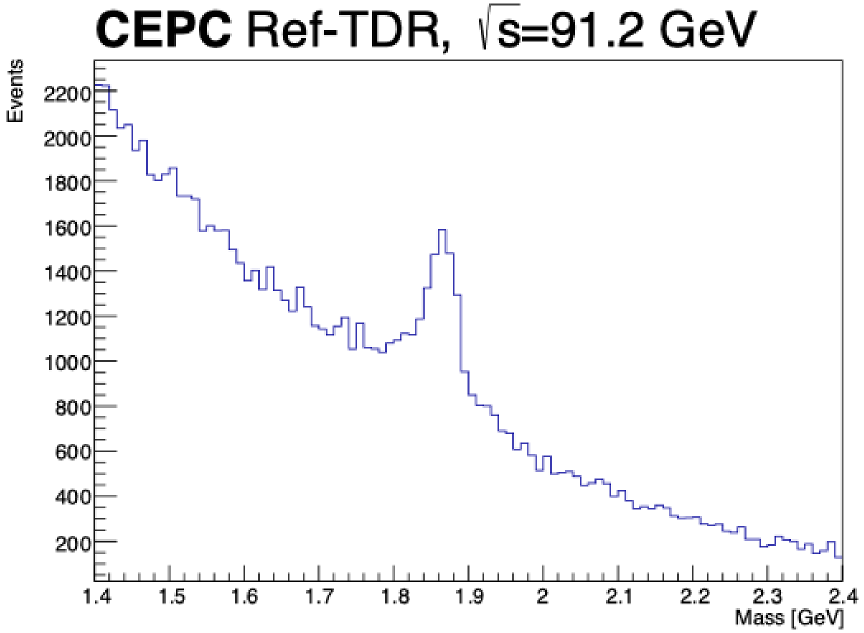
- Two tracks:
  - Select one K(π) track and one π track from PFOs using PID information
  - Combine them with π^0 candidates
- Constrain PFO objects with
  - Momentum of charged tracks
  - Angle between charged K(π) and the other π tracks



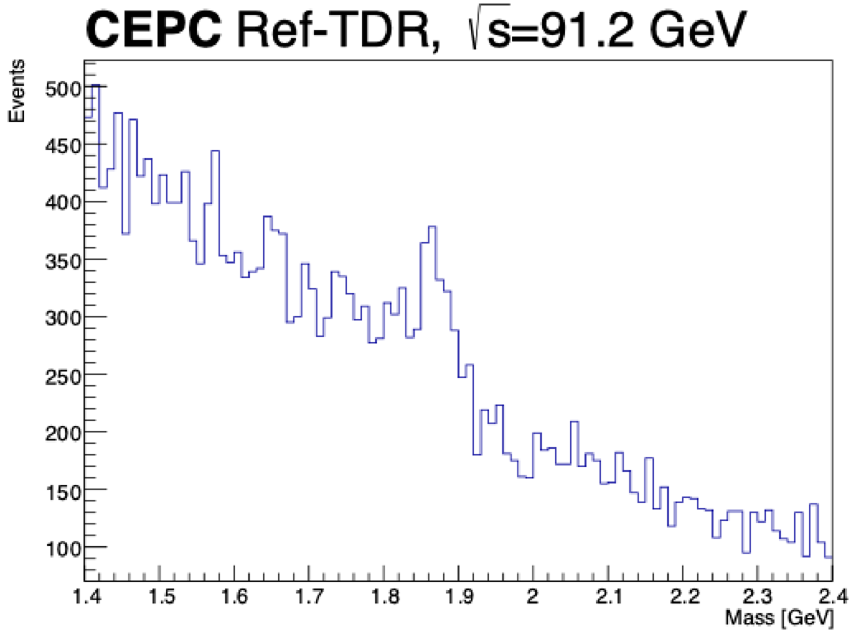


Step 2: combining π^0 with two other tracks

- Other selection criteria that should be used in the selection
  - Vertices, impact parameters, flight distances, …
- Current such parameters in CEPCSW did not link properly, thus did not improve the purity



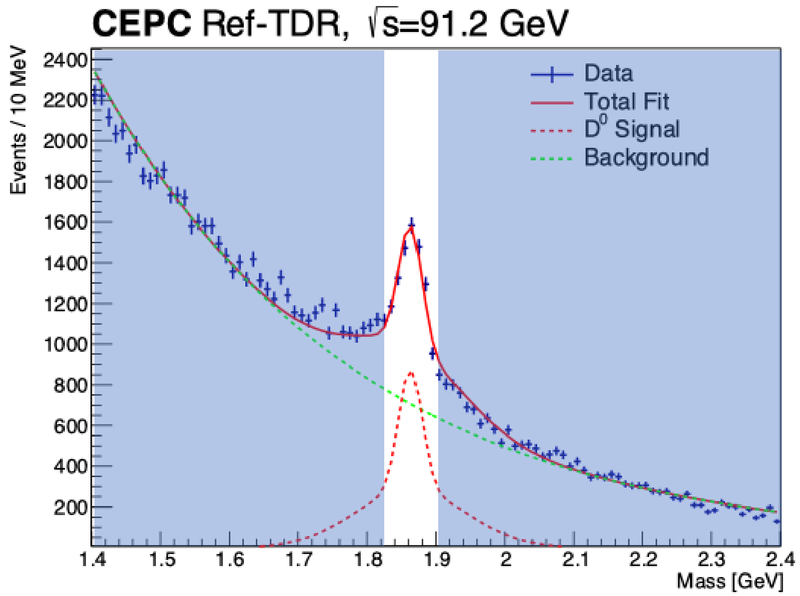
Kpipi0

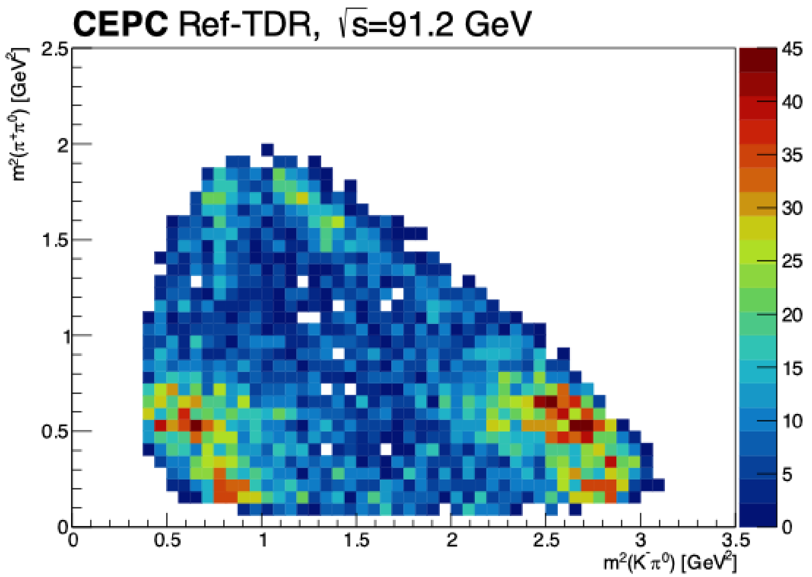


pipipi0

Step 3: fits and Dalitz plot

- Clear D^0 peak
  - Purity ~ 40%, eff ~20%
  - With other parameters included, purity could certainly improve
  - LHCb CPV study purity: 81% for π^0s reconstructed from two γ clusters
- Clear K* and ρ resonance structures on Dalitz plot





CP violation prospects at CEPC

- CEPC generally do not have advantages in statistics for charm hadrons compare to LHCb
- But π^0 may change the game
- Assumption: 10% selection efficiency, reconstructed $D \to hh\pi^0$ statistics may better than LHCb

Decays	LHCb (6 fb^{-1})	LHCb (300 fb^{-1})	CEPC (4 Tera Z)
D^{*+}	4.7×10^{12}	2.4×10^{14}	4.6×10^{11}
D^0 from D^{*+}	3.2×10^{12}	1.6×10^{14}	3.1×10^{11}
$D^{*+} \to (D^0 \to K^-K^+)\pi^+$	1.6×10^{10}	6.5×10^{11}	1.3×10^{9}
$D^{*+} \to (D^0 \to \pi^-\pi^+)\pi^+$	4.6×10^{9}	2.3×10^{11}	4.5×10^{8}
$D^{*+} \to (D^0 \to K^-\pi^+)\pi^+$	1.6×10^{11}	6.3×10^{12}	1.2×10^{10}
$D^{*+} \to (D^0 \to \pi^-\pi^+\pi^0)\pi^+$	4.8×10^{10}	2.4×10^{12}	4.6×10^{9}
$D^{*+} \to (D^0 \to K^-\pi^+\pi^0)\pi^+$	4.6×10^{11}	2.3×10^{13}	4.4×10^{10}
Reco. & Sel. $D^0 \to K^-K^+$	5.8×10^{7} [147]	2.9×10^{9}	1.3×10^{8}
Reco. & Sel. $D^0 \to \pi^-\pi^+$	1.8×10^{7} [147]	9×10^{8}	4.5×10^{7}
Reco. & Sel. $D^0 \to K^-\pi^+$	5.2×10^{8} [147]	2.6×10^{10}	1.2×10^{9}
Reco. & Sel. $D^0 \to \pi^-\pi^+\pi^0$	2.5×10^{6} [148]	1.2×10^{8}	4.6×10^{8}
Reco. & Sel. $D^0 \to K^-\pi^+\pi^0$	1.9×10^{7} [148]	9.6×10^{8}	4.4×10^{9}

Conclusions

- Current LHCb sensitivity to CP violation in $D^0 \rightarrow \rho(770)^+\pi^-$ process: 0.5° asymmetry in phase or 0.5% asymmetry in magnitude
- With statistics more than 100 times larger than current statistics, sensitivity expected to be improved by a factor of ~0.1
  - 0.05° asymmetry in phase or 0.05% asymmetry in magnitude
- Charm CP violation expected / found in permille level, CEPC sensitivity very likely to observe CP violation in multi-body charm decays