Feasibility study of the rare decay $D^0 \rightarrow \gamma\gamma$ & $D^0 \rightarrow \mu^+\mu^-\gamma$

Full & Fast MC simulation @ PANDA

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PANDA collaboration meeting, Forschungszentrum Jülich, 10 Dec. 2014

Motivation

- In Standard Model (SM), Flavor Changing Neutral Currents (FCNC) are forbidden at tree level and highly suppressed by GIM mechanism at loop level

- Search for the decay of $c \to u\gamma$ transition which has a sign of beyond SM
  If not seen, we can contribute to put constraints on new physics parameters

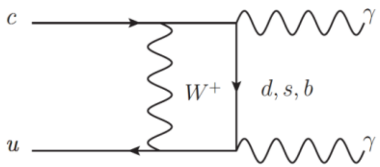
- FCNC rare decay $D^0 \to \gamma\gamma$ could be an opportunity to pursue with PANDA because electroweak channel involved photons allow a competition with LHCb

Sensitivity accessible @ PANDA?

Branching fraction

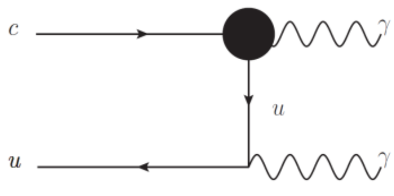
- Branching fraction of rare decay $D^0 \to \gamma\gamma$

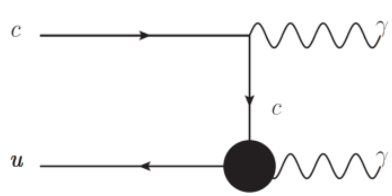
Short distance contribution



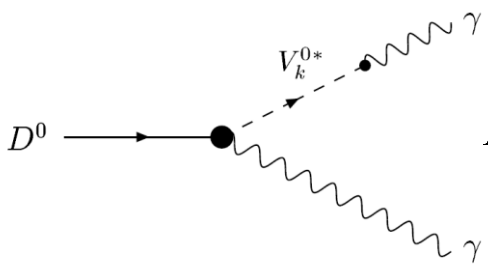
$$Br^{SD}_{D^0 \to \gamma\gamma} = 3 \times 10^{-11}$$

[PhysRev D66 014009 (2002)]





Long distance contribution

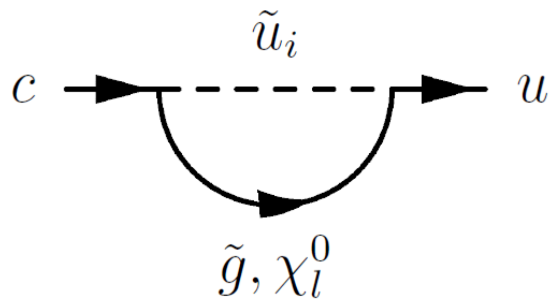


$$Br^{VMD}_{D^0 \to \gamma\gamma} = (3.5^{+4.0}_{-2.6}) \times 10^{-8}$$

[PhysRev D66 014009 (2002)]

New Physics

c→uγ transition can be enhanced by NP, e.g. some NP models can allow at sizeable levels



$$Br^{MSSM}_{D^0 \to \gamma\gamma} = 6 \times 10^{-6}$$

[Phys.Lett.B500 304-312 (2001)]

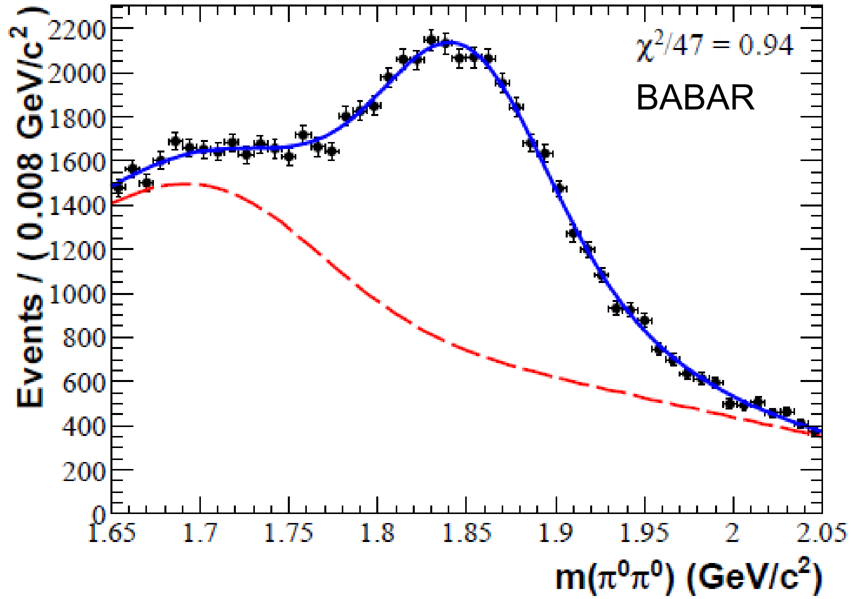
$$Br^{SM, HQ\chi PT}_{D^0 \to \gamma\gamma} = (1.0 \pm 0.5) \times 10^{-8}$$

[PhysRev D64 074008 (2001)]

Experimental result

Experimental results (upper limit @ CL=90%)

BABAR	:	$BR < 2.2 \times 10^{-6}$
BESIII	:	$BR < 4.6 \times 10^{-6}$
CLEOc	:	$BR < 8.63 \times 10^{-6}$



BABAR (Phys. Rev. D 85, 091107(R) (2012))

- Measured $D^0 \to \pi^0 \pi^0$ branching fraction :

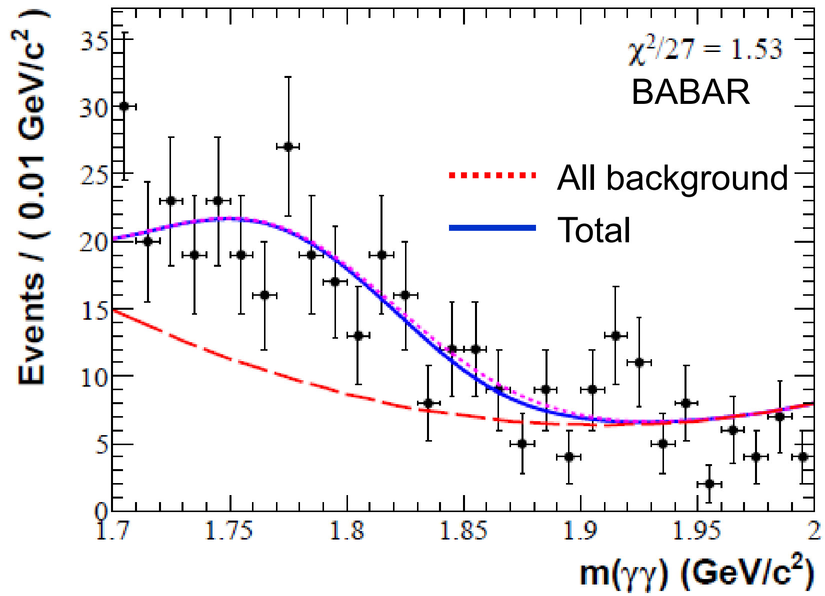
$$Br_{D^0 \to \pi^0\pi^0} = (8.4 \pm 0.1 \pm 0.3) \times 10^{-4}$$

- $D^0 \to \gamma\gamma$ found signal yield $N = -6 \pm 15$ events leading to an upper limit :

$$Br_{D^0 \to \gamma\gamma} < 2.2 \times 10^{-6}$$

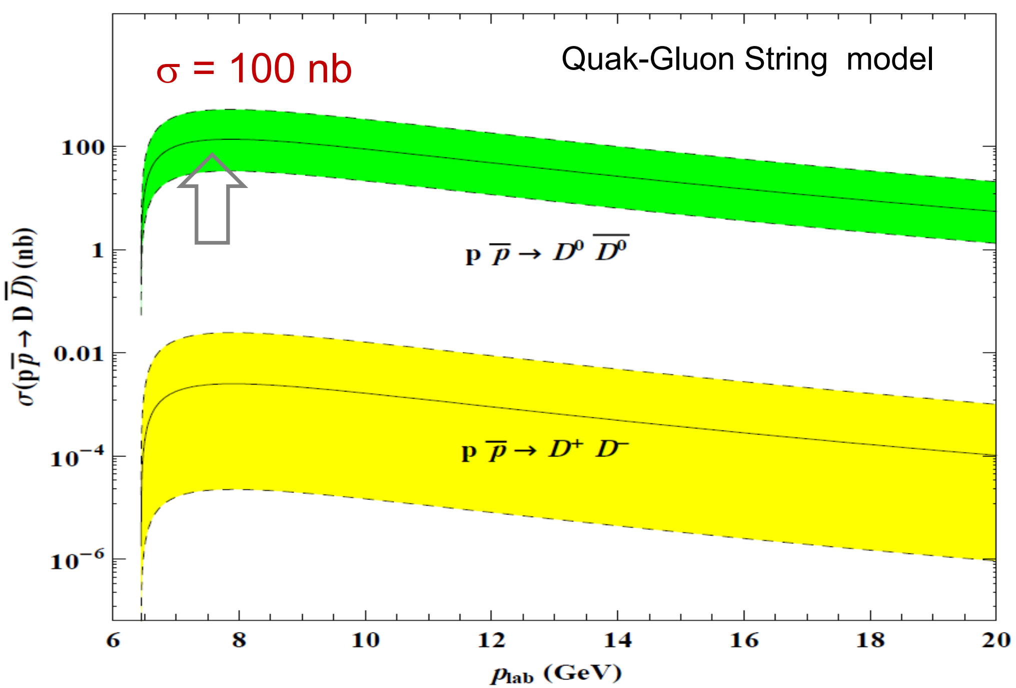
  with using the associated(reference) $D^0 \to K_s \pi^0$ decay

- Constraint NP to at most 70 times SM

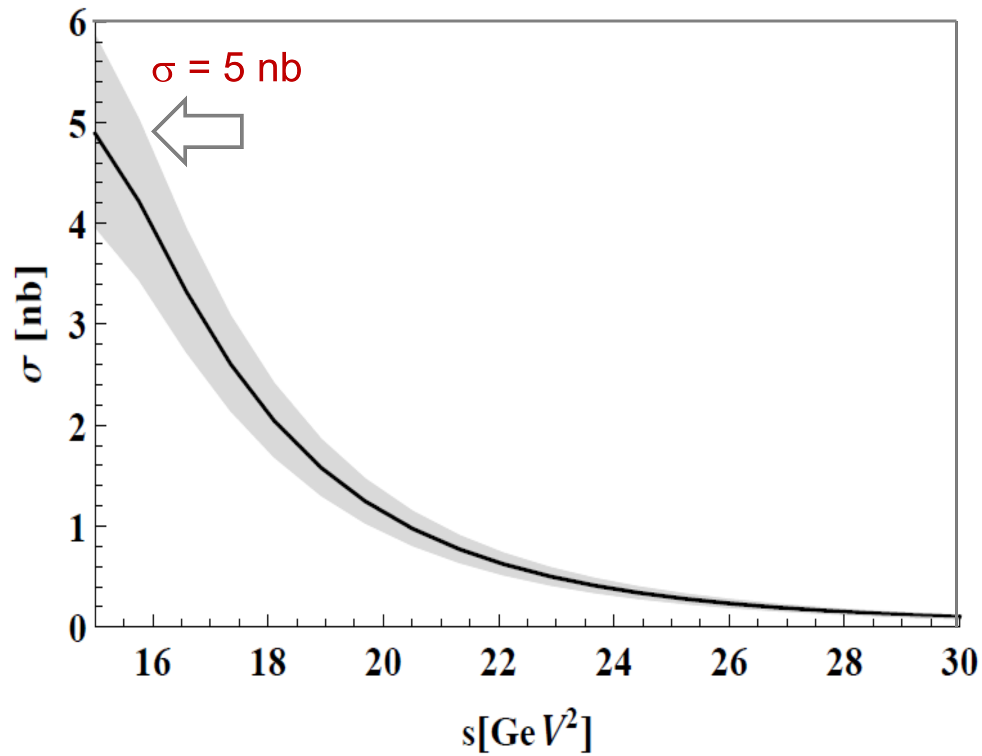


Open charm cross section

How much charm can PANDA produce?
A.Khodjamirian, Ch.Klein, Th.Mannel and Y.M. Wang
Eur.Phys.J.A 48 (2012) 31.



D^0bar D^0 production at pbar p collisions within a double handbag approach, A.T.Goritschnig, B.Pire and W.Schwieger, Phys.Rev.D87 (2013) 014017



BESIII suggested [arXiv:1403.6011v1 24 Mar 2014]

two different solution for D^0D^0 cross section using the $\psi(3770) \to pbarp$

either $\sigma = (9.8 \pm 5.7)$ nb or $\sigma = (425.6 \pm 42.9)$ nb

Expected S/B @ PANDA

Luminosity : $L = 2\times10^{32}\,\text{cm}^{-2}\text{s}^{-1},\quad t = 120\ \text{days (year)}$

Expected N : $N = L_{\text{int}} \times \sigma \times \varepsilon \ @ \sqrt{s} = 3.770(\text{GeV/c}^2)$

Number of signal

$$N_{D\to\gamma\gamma} = 2\ \text{fb}^{-1} \times 100\ \text{nb} \times \varepsilon_S \times Br$$
$$\leq 440 \times \varepsilon_S$$

Number of background

$$N_B = 2\text{fb}^{-1} \times 60\text{mb} \times \varepsilon_B$$
$$= 1.2\times10^{14} \times \varepsilon_B$$

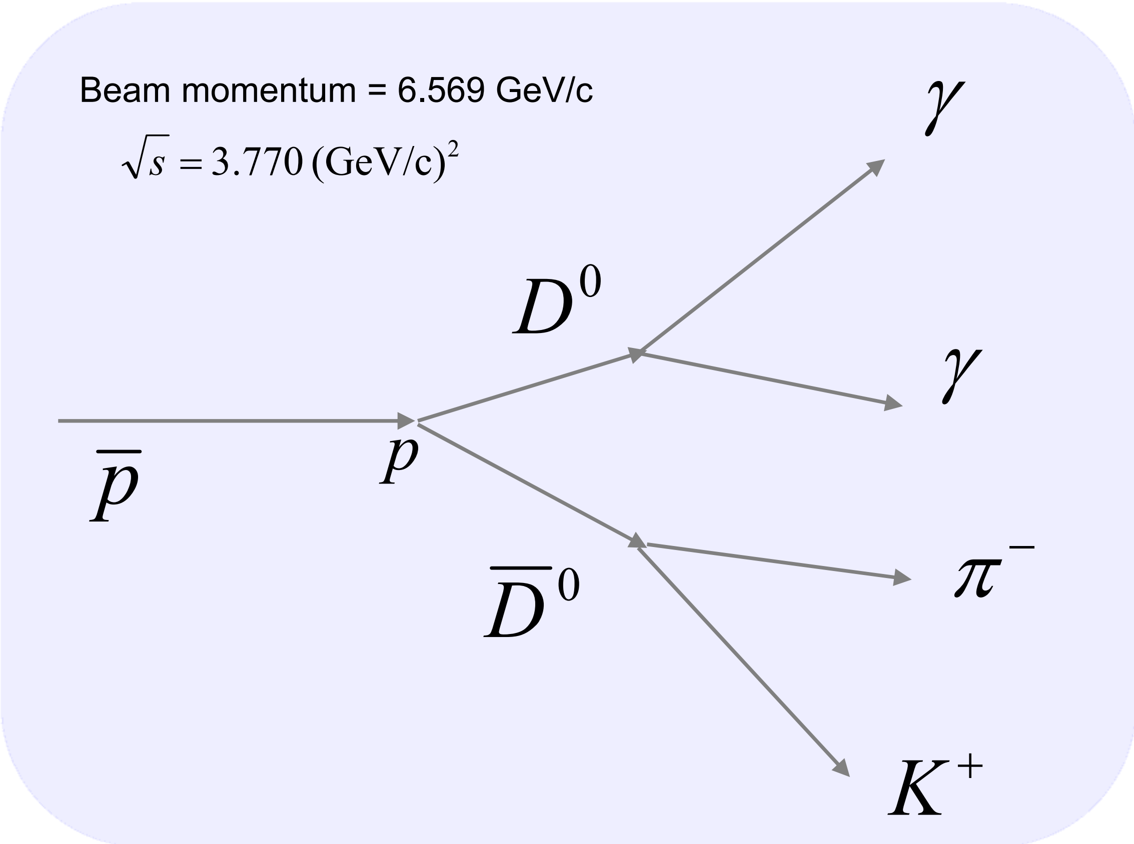
with $Br(D^0 \to \gamma\gamma) < 2.2\times10^{-6}$

$\&\ \sigma = 100\ \text{nb}$

$\frac{N_s}{N_B} = 0.01 \sim 1$ ➡ Background reduction $= \mathbf{10^{-10} \sim 10^{-12}}$

MC simulation

$$\bar{p}p \rightarrow D^0\overline{D}^0 \rightarrow \gamma\gamma\, K^+\pi^- (\mathrm{Br} = 3.89\%)$$



- PANDAroot release rev. scrut14
- Signal MC : EvtGen
  Background MC : DPM
  Background MC : $D^0 \rightarrow \pi^0\pi^0$ EvtGen
- Pre-selection of track candidates
  Neutral track : $E > 50$ MeV
  Charged track : $p > 100$ MeV/c
- Exclusive measurement

In addition, two other tag modes are used

$$\bar{p}p \rightarrow D^0\overline{D}^0 \rightarrow \gamma\gamma\, K^+\pi^-\pi^0 (\mathrm{Br} = 13.9\%)$$

$$\bar{p}p \rightarrow D^0\overline{D}^0 \rightarrow \gamma\gamma\, K^+\pi^-\pi^-\pi^+ (\mathrm{Br} = 8.09\%)$$

Event selection

$$\bar{p}p \rightarrow D^0 \bar{D}^0 \rightarrow \gamma\gamma\, K^+ \pi^-$$

- Efficiency by event based (not candidate based)
- No DPM background up to 10^7 in the full simulation
- **1.479×10^{11}** inelastic DPM event in the fast simulation

$D^0 \rightarrow \gamma\gamma$	Signal ε [%]	Bkg ε [%]	$D^0 \rightarrow K^+\pi^-$	Signal ε [%]	Bkg ε [%]
$P_t(\gamma) > 0.1 GeV/c^2$ $P_t(D) < P_{t,max} + 0.2 GeV/c^2$	81.72	2.649	$P_t(K,\pi) > 0.1 GeV/c^2$ $P_t(D) < P_{t,max} + 0.2 GeV/c^2$	69.13	23.119
$100° < \Delta\phi_{\gamma\gamma} < 260°$ $0.15 < P_{CM} < 0.4 GeV/c^2$	77.15	0.708	$100° < \Delta\phi_{K\pi} < 260°$ $0.15 < P_{CM} < 0.4 GeV/c^2$	66.65	5.133
π^0 veto	58.34	0.018	PID Prob$(\pi,K) > 0.25$	45.26	0.064
size of ECAL crystal < 36	58.33	0.018	Mass constrain : $0 < \chi^2 < 10$	43.32	0.008
Mass constrain : $0 < \chi^2 < 10$	53.84	0.002			

$pp \rightarrow D^0 D^0$	Signal ε [%]	Bkg ε
Combine $\gamma\gamma K^-\pi^+$	26.30	2.25×10^{-9}
$130° < \Delta\phi_{DD} < 230°$	25.96	1.78×10^{-9}
$-0.99 < \cos\theta_{CM} < 0.99$	25.78	1.76×10^{-9}
4-Constrain kinematic fit : $0 < \chi^2 < 20$ Only 1 best candidate by minimum χ^2	24.11	6.28×10^{-10}

Event selection

$$\bar{p}p \to D^0\bar{D}^0 \to \gamma\gamma\, K^+\pi^-\pi^0$$

- Efficiency by event based (not candidate based)
- No DPM background up to 10^7 in the full simulation
- **1.479×10^{11}** inelastic DPM event in the fast simulation

$D^0 \to \gamma\gamma$	Signal ε [%]	Bkg ε [%]	$D^0 \to K^+\pi^-\pi^0$	Signal ε [%]	Bkg ε [%]
$P_t(\gamma) > 0.1\mathrm{GeV/c^2}$ $P_t(D) < P_{t,max} + 0.2\mathrm{GeV/c^2}$	81.38	2.649	$P_t(\gamma \text{ of } \pi^0) < 1.0\ \mathrm{GeV/c^2}$ $P_t(D) < P_{t,max} + 0.2\ \mathrm{GeV/c^2}$	43.41	42.184
$100° < \Delta\phi_{\gamma\gamma} < 260°$ $0.15 < P_{CM} < 0.4\ \mathrm{GeV/c^2}$	76.53	0.708	$0.15 < P_{CM} < 0.45\ \mathrm{GeV/c^2}$	39.84	22.910
$\theta_{open} > 50°$	76.53	0.706	PID Prob(π,K) > 0.25	25.50	0.450
size of ECAL crystal < 36	76.53	0.706	Mass constrain : $0 < \chi^2 < 10$	22.16	0.066
Mass constrain : $0 < \chi^2 < 10$	69.06	0.078			

$pp \to D^0D^0$	Signal ε [%]	Bkg ε
Combine $\gamma\gamma K^+\pi^-\pi^0$	15.35	5.60×10^{-8}
$130° < \Delta\phi_{DD} < 230°$	15.08	3.53×10^{-8}
$-0.99 < \cos\theta_{CM} < 0.99$	14.98	3.50×10^{-8}
4-Constrain kinematic fit : $0 < \chi^2 < 20$ Only 1 best candidate by minimum χ^2	13.20	4.15×10^{-9}

Event selection

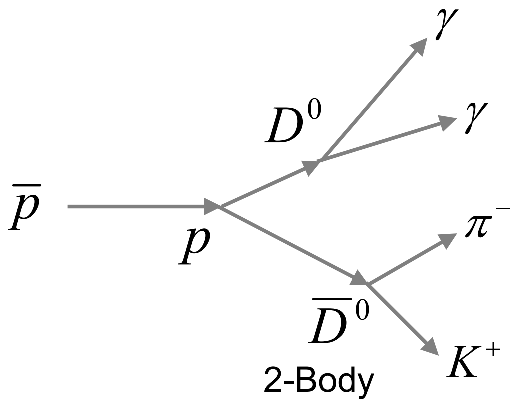
$$\bar{p}p \rightarrow D^0\overline{D}^0 \rightarrow \gamma\gamma\, K^+\pi^-\pi^-\pi^+$$

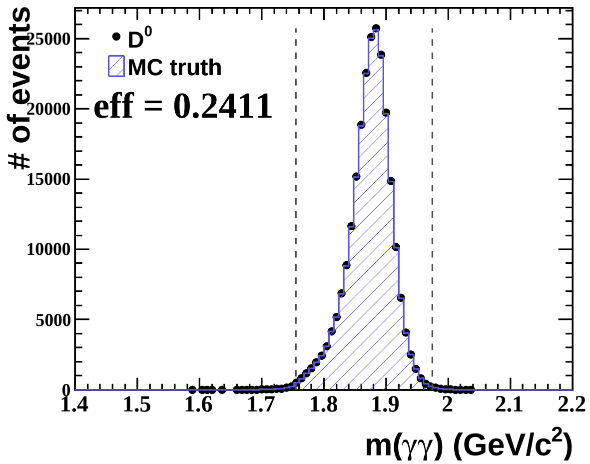
- Efficiency by event based (not candidate based)
- No DPM background up to 10^7 in the full simulation
- **1.479×10^{11}** inelastic DPM event in the fast simulation

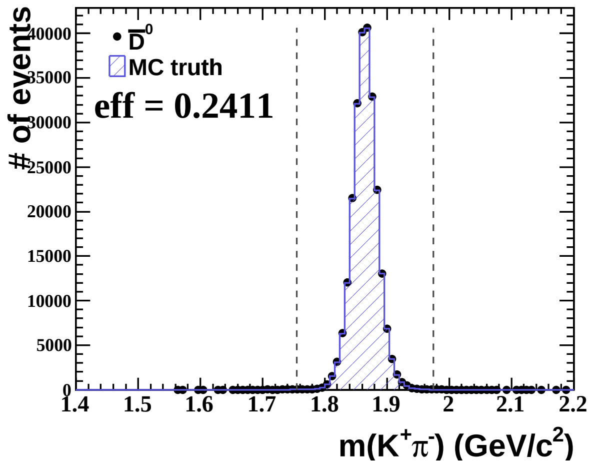
$D^0 \rightarrow \gamma\gamma$	Signal ε [%]	Bkg ε [%]	$D^0 \rightarrow K^+\pi^-\pi^-\pi^+$	Signal ε [%]	Bkg ε [%]
$P_t(\gamma) > 0.1 GeV/c^2$ $P_t(D) < P_{t,max} + 0.2 GeV/c^2$	78.30	2.649	$P_t(D) < P_{t,max} + 0.2$ GeV/c^2	30.03	14.014
$100° < \Delta\phi_{\gamma\gamma} < 260°$ $0.15 < P_{CM} < 0.4$ GeV/c^2	73.79	0.708	$0.15 < P_{CM} < 0.5$ GeV/c^2	27.72	7.733
π^0 veto	40.90	0.018	PID Prob(π,K) > 0.25	10.23	0.181
size of ECAL crystal < 36	40.90	0.018	Mass constrain : $0 < \chi^2 < 10$	8.17	0.029
Mass constrain : $0 < \chi^2 < 10$	37.92	0.002			

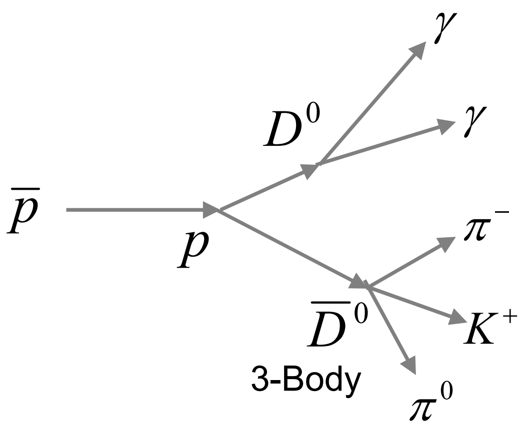
$pp \rightarrow D^0D^0$	Signal ε [%]	Bkg ε
Combine $\gamma\gamma K^+\pi^-\pi^-\pi^+$	4.06	2.61×10^{-9}
$130° < \Delta\phi_{DD} < 230°$	3.98	1.71×10^{-9}
$-0.99 < \cos\theta_{CM} < 0.99$	3.95	1.68×10^{-9}
4-Constrain kinematic fit : $0 < \chi^2 < 20$ Only 1 best candidate by minimum χ^2	3.38	2.02×10^{-10}

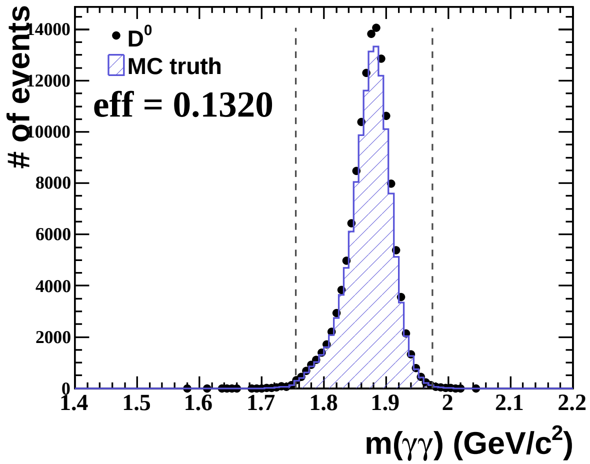
Signal efficiency

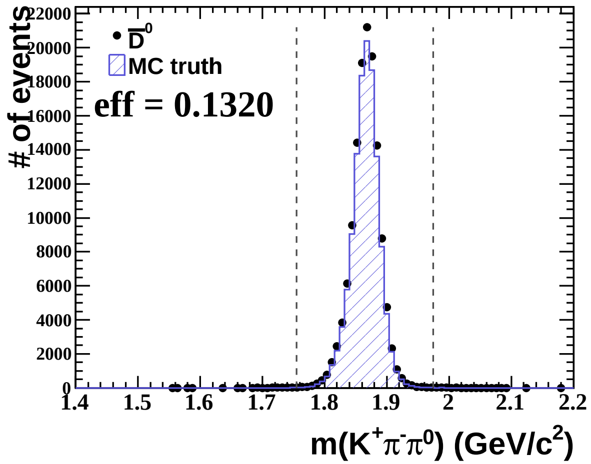


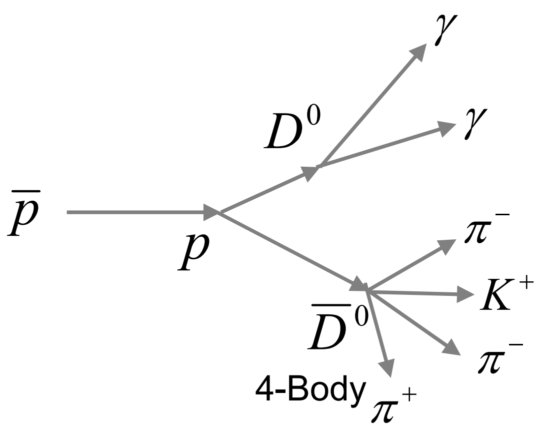


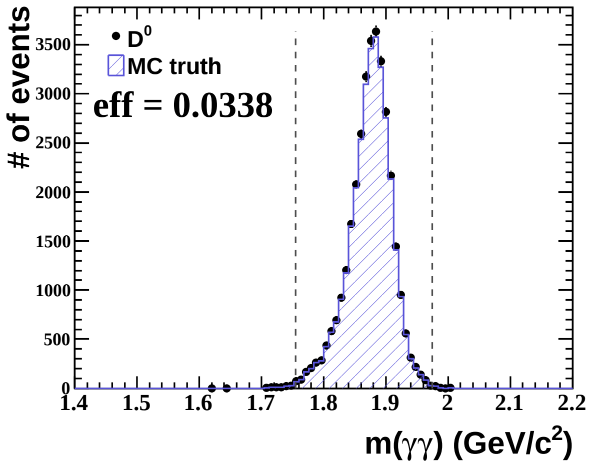


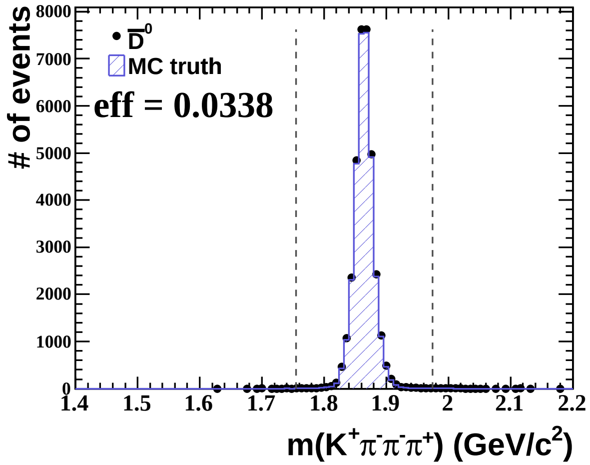




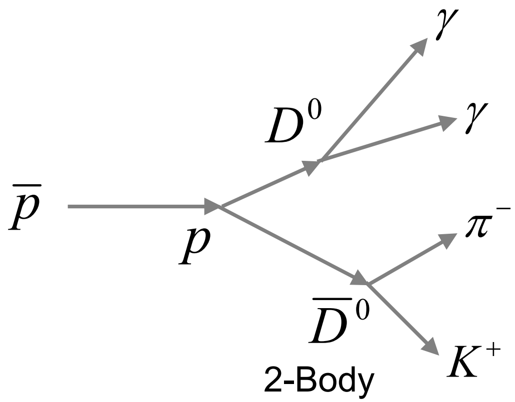


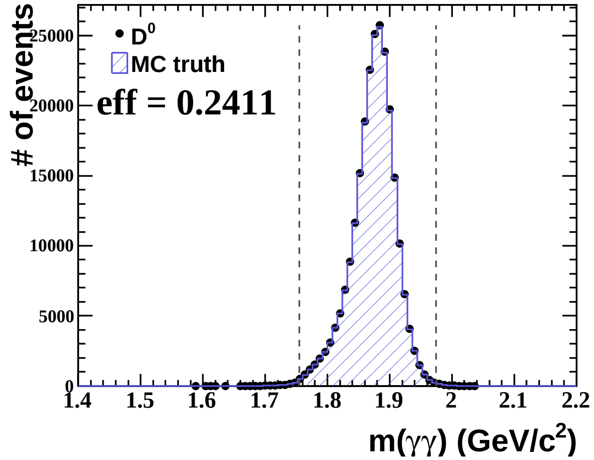






Expected statistics

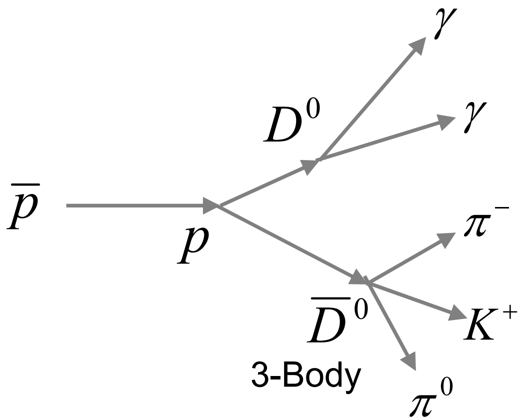


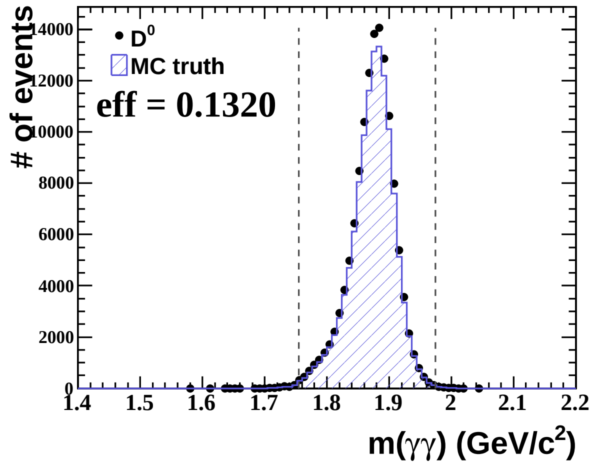


$$N_{D\to\gamma\gamma} = 2\ \mathrm{fb}^{-1} \times 100\ \mathrm{nb} \times \Sigma(Br_i) \times \varepsilon_{tag} \times 2$$

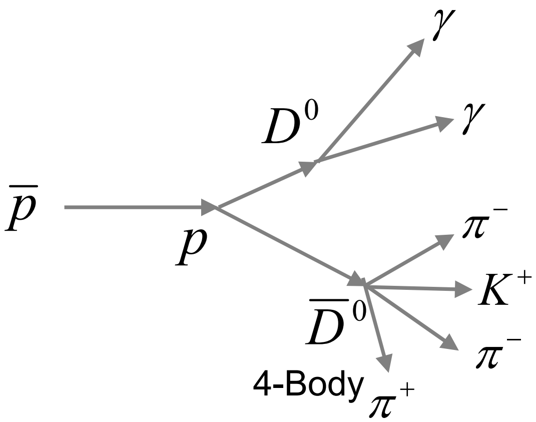
$$\text{with } Br_{D^0\to\gamma\gamma} < 2.2\times10^{-6}$$

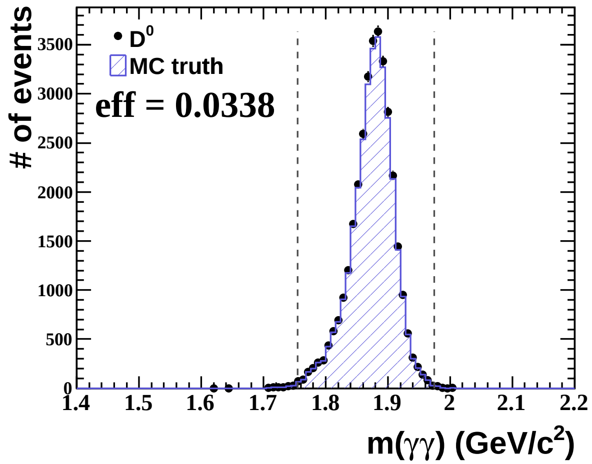
$$N_{D\to\gamma\gamma} = 8.3 \text{ events}$$





$$N_{D\to\gamma\gamma} = 16.1 \text{ events}$$





$$N_{D\to\gamma\gamma} = 2.4 \text{ events}$$

Background reduction

- PID loose to tight for all charged particle

Tag	All cuts	Signal efficiency	Background reduction	N_{Sig} / year	N_{Bkg} / year
$D^0 \to K^+\pi^-$	+ PID prob > 0.25	0.241	6.28×10^{-10}	**8.3**	55012
$D^0 \to K^+\pi^-\pi^0$		0.132	4.15×10^{-9}	**16.1**	363540
$D^0 \to K^+\pi^-\pi^-\pi^+$		0.034	2.02×10^{-10}	**2.4**	17695
$D^0 \to K^+\pi^-$	+ PID prob > 0.90	0.135	6.76×10^{-11}	**4.6**	5913
$D^0 \to K^+\pi^-\pi^0$		0.071	2.90×10^{-10}	**8.7**	25404
$D^0 \to K^+\pi^-\pi^-\pi^+$		0.005	$<1.47 \times 10^{-11}$	**0.3**	0

$$N_{D\to\gamma\gamma} = 2\ \mathrm{fb}^{-1} \times 100\ \mathrm{nb} \times \Sigma(Br_i) \times \varepsilon_{tag} \times 2$$

$$N_{D\to\gamma\gamma} = 2\mathrm{fb}^{-1} \times 43.8\mathrm{mb} \times \varepsilon_B$$

Background shape

- Main background EvtGen 1×10^{7} events :

$$N_{D\to\gamma\gamma} = 2\ \text{fb}^{-1}\times 100\ \text{nb}\times\Sigma(Br_i)\times\varepsilon_{tag}\times 2$$

$$D^0\to\pi^0\pi^0 (Br = 8.4\times10^{-4})$$

$$\bar{p}p\to D^0\overline{D}^0\to\pi^0\pi^0\ K^+\pi^-$$

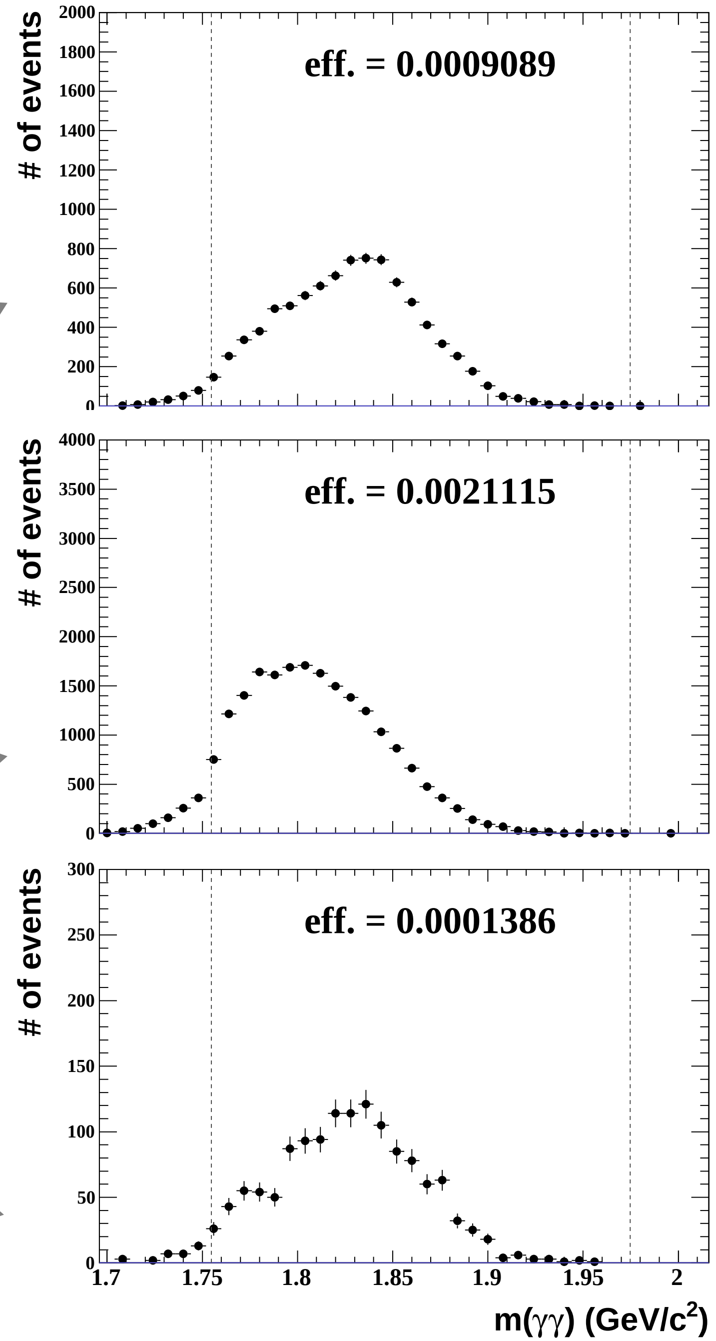
$$N_{D\to\gamma\gamma} = 11.8\ \text{events}$$

$$\bar{p}p\to D^0\overline{D}^0\to\pi^0\pi^0\ K^+\pi^-\pi^0$$

$$N_{D\to\gamma\gamma} = 98.6\ \text{events}$$

$$\bar{p}p\to D^0\overline{D}^0\to\pi^0\pi^0\ K^+\pi^-\pi^-\pi^+$$

$$N_{D\to\gamma\gamma} = 3.7\ \text{events}$$



Background event topology

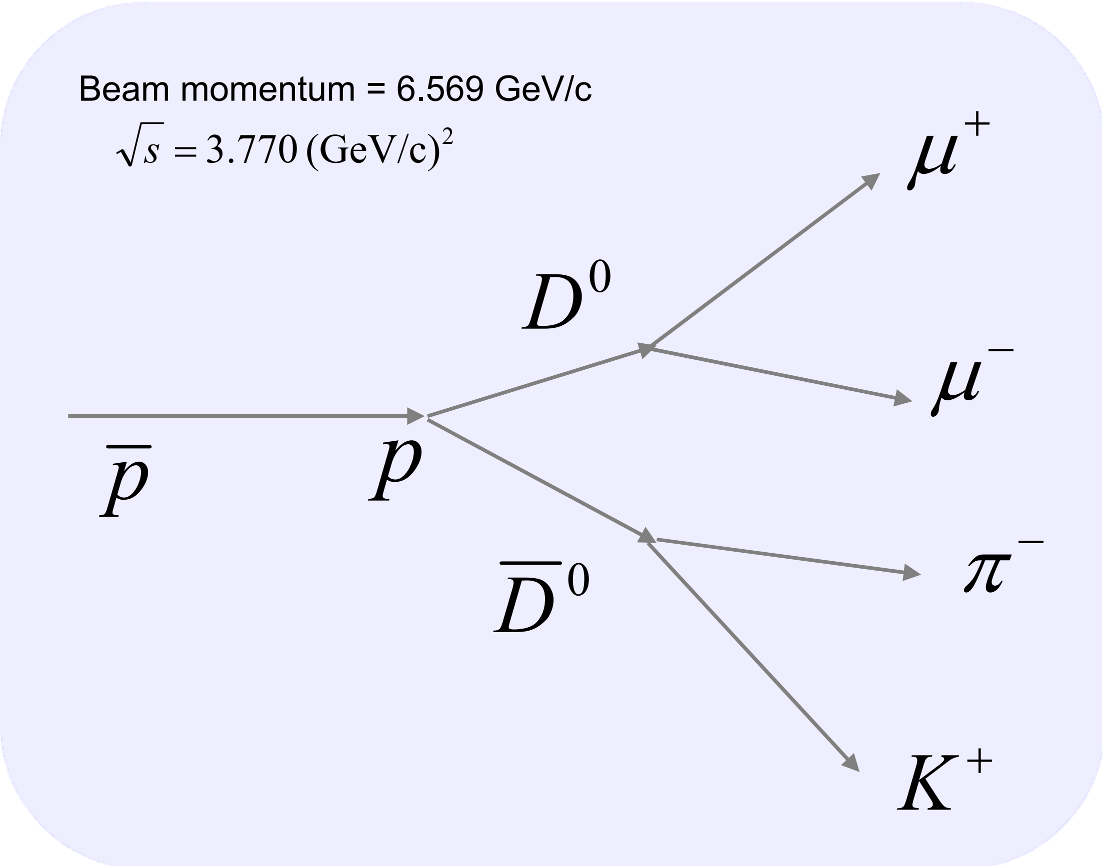
- Events pass through the selection (based on **1.0×10^{11}** DPM inelastic events)

	channel		channel		channel	
	$D^0\overline{D}^0 \to \gamma\gamma K^+\pi^-$		$D^0\overline{D}^0 \to \gamma\gamma K^+\pi^-\pi^0$		$D^0\overline{D}^0 \to \gamma\gamma K^+\pi^-\pi^-\pi^+$	
Mis-reconstructed events @ DPM	$\bar{p}p \to \pi^+\pi^-2\gamma$	2	$\bar{p}p \to \pi^+\pi^-4\gamma$	104	$\bar{p}p \to 2\pi^+2\pi^-3\gamma$	1
	$\bar{p}p \to \pi^+\pi^-4\gamma$	66	$\bar{p}p \to \pi^+\pi^-5\gamma$	12	$\bar{p}p \to 2\pi^+2\pi^-4\gamma$	19
			$\bar{p}p \to \pi^+\pi^-6\gamma$	329	$\bar{p}p \to 2\pi^+2\pi^-5\gamma$	1
			$\bar{p}p \to \pi^+\pi^-7\gamma$	2		
			$\bar{p}p \to \pi^+\pi^-8\gamma$	8		

- Mis-identification of $\pi^\pm$ as a $K^\pm$ and combination of high energetic γs can build same event signature
- Investigate most efficient way to reject those events

FCNC decay into 2 leptons

$$\bar{p}p \rightarrow D^0\bar{D}^0 \rightarrow \mu^+\mu^- \, K^+\pi^-$$



- Experimental results upper limit @ LHCb(2013) :

  $\mathrm{BR}(D^0 \rightarrow \mu^+\mu^-) < 6.2 \times 10^{-9}$

- Signal efficiency

  $$\varepsilon_{tag}^{sig} = 0.158$$

- Background rejection

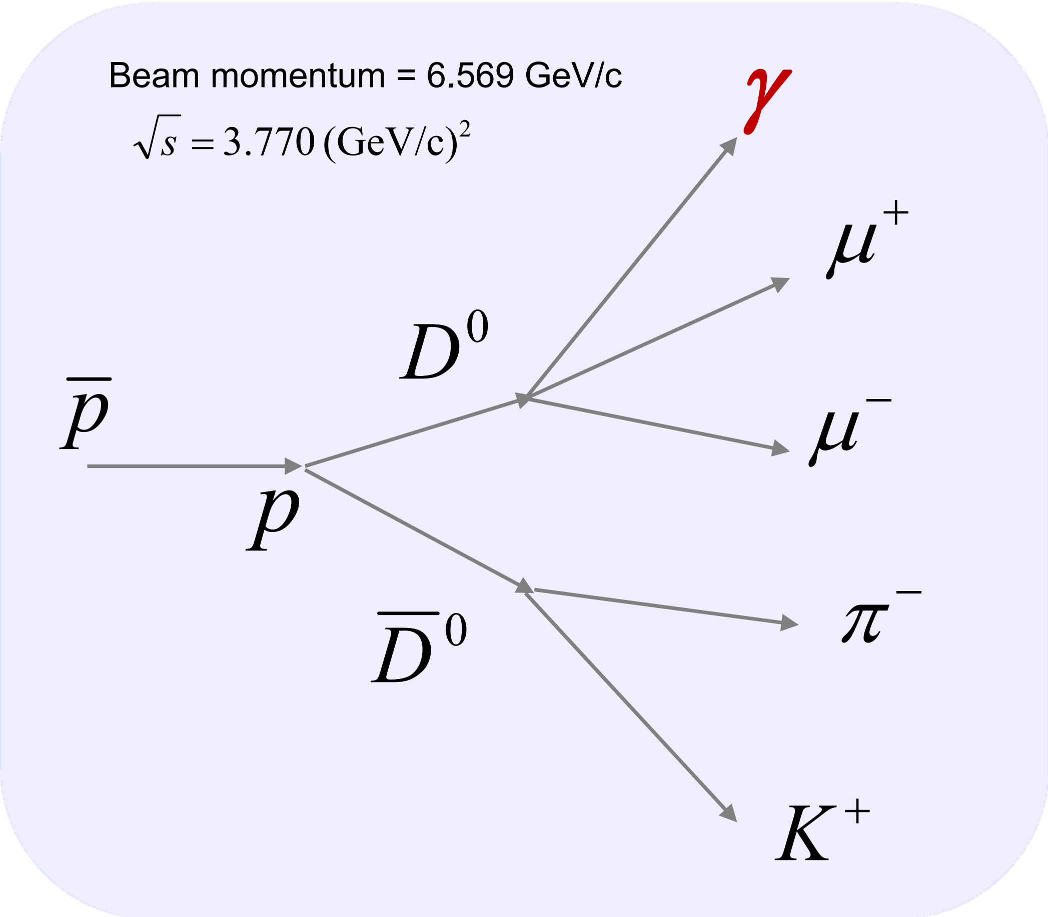
  $$\varepsilon_{tag}^{back} \sim 6.4 \times 10^{-12}$$

- Sensitivity may not be accessible due to very small branching fraction

$$N_{D \rightarrow \mu\mu} = 0.011\,\text{events} \quad \text{with} \;\; \sigma = 100\,\text{nb}$$

FCNC with radiative process

$$\bar{p}p \to D^0\bar{D}^0 \to \mu^+\mu^-\gamma\, K^+\pi^-$$



Radiative B_c meson decays $B_c \to \gamma \bar{u} d$
A.K. Likhoded, A.V. Luchinsky, S.V. Poslavsky
[Phys. Rev. D 90, 034017 (2014)]

- can remove the suppression, if one consider emission of additional γ
- possible to increases the branching fraction of B_c decay by factor **10^4**

Same effect could be observed also in the case of $D^0 \to \mu^+\mu^-$ process

$$\mathrm{BR} \le 6.2 \times 10^{-9} \quad \to \quad \mathrm{BR} \le 6.2 \times 10^{-5}$$

Event selection

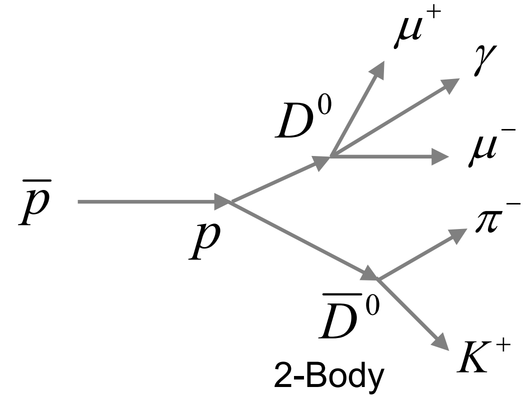
- phase space decay model for $D^0 \to \mu^+\mu^-\gamma$

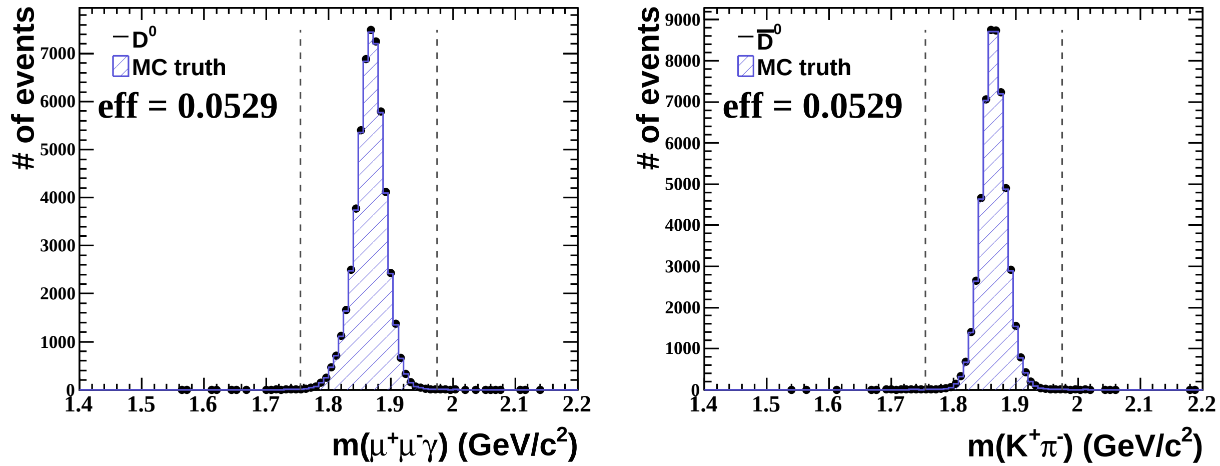
$D^0 \to \mu^+\mu^-\gamma$	$\overline{D}^0 \to hadrons$
$P_t(D) < P_{t,max} + 0.2GeV/c^2$	$P_t(\pi,K) > 0.1$ GeV/c² for 2 body-decay
$0.15 < P_{CM} < 0.4$ GeV/c²	$P_t(D) < P_{t,max} + 0.2$ GeV/c²
# of ECAL crystal < 36	$P_t(\gamma$ from $\pi^0) < 1.0$ GeV/c²
PID Prob(μ) > 0.25	$0.15 < P_{CM} < 0.4/0.45/0.5$ GeV/c²
Muon chamber iron length > 10cm	$100° < \Delta\phi_{\pi K} < 260°$ for 2 body-decay
Muon Layer ≥ 1	PID Prob(π,K) > 0.25
Mass constrain : $0 < \chi^2 < 10$	Mass constrain : $0 < \chi^2 < 10$

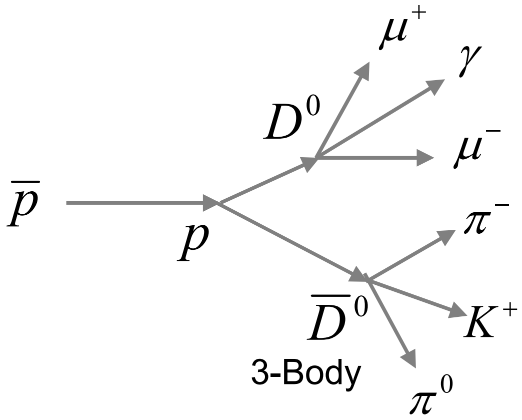
⇩

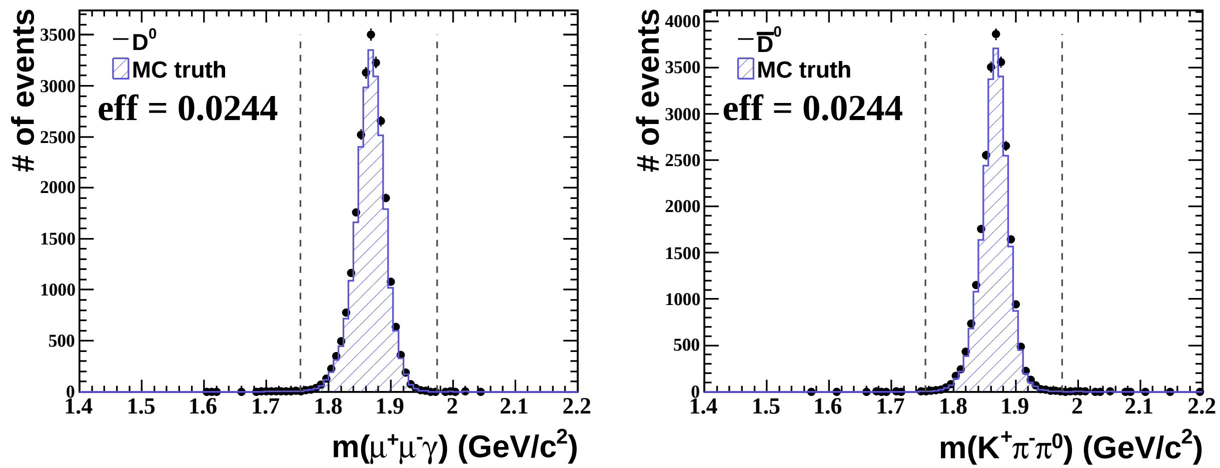
$\bar{p}p \to D^0\overline{D}^0$
$130° < \Delta\phi_{DD} < 230°$
$-0.99 < \cos\theta_{CM} < 0.99$
4-Constrain kinematic fit: $0 < \chi^2 < 20$, only 1 best candidate by minimum χ^2

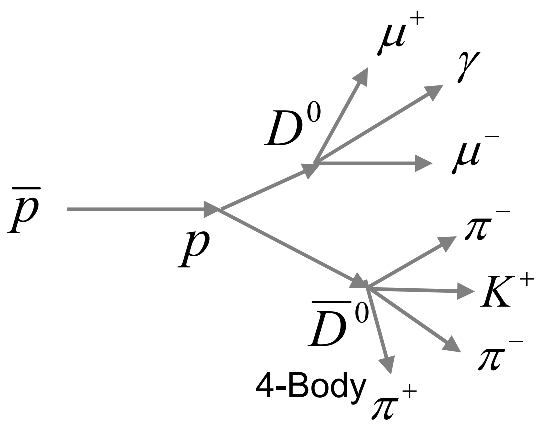
Signal efficiency

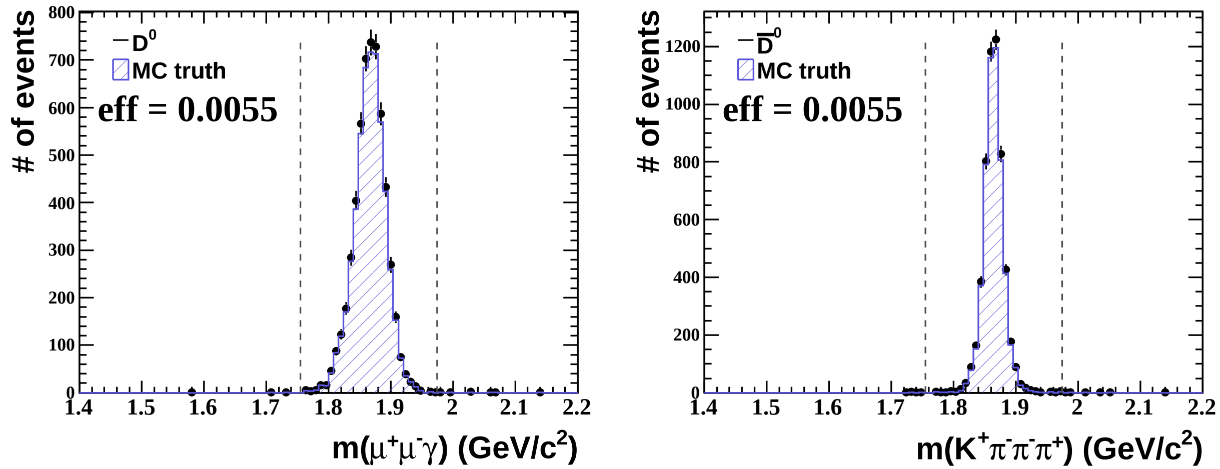








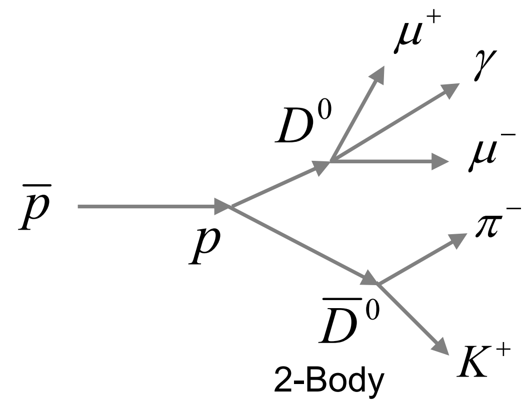


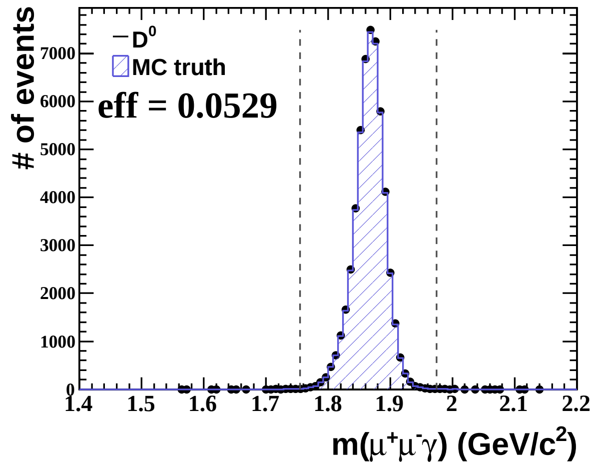


Expected statistics

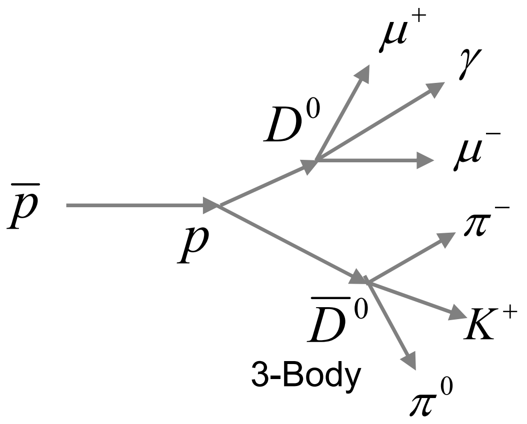
$$N_{D\to\mu\mu\gamma} = 2\ \text{fb}^{-1} \times 100\ \text{nb} \times \Sigma(Br_i) \times \varepsilon_{tag} \times 2$$

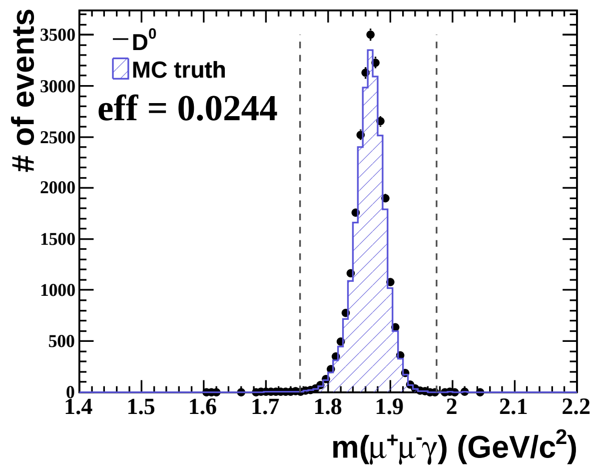
$$\text{with } Br_{D^0\to\mu\mu\gamma} = 1.0 \times 10^{-5}$$



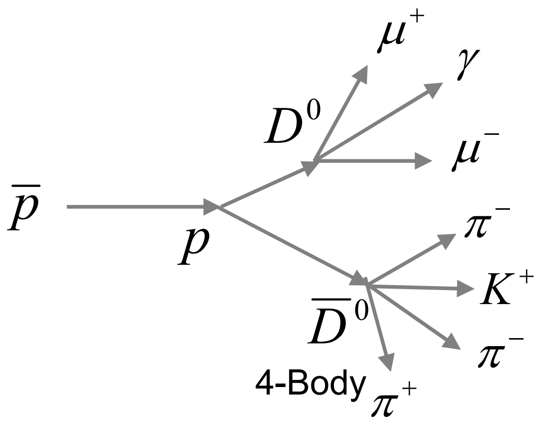


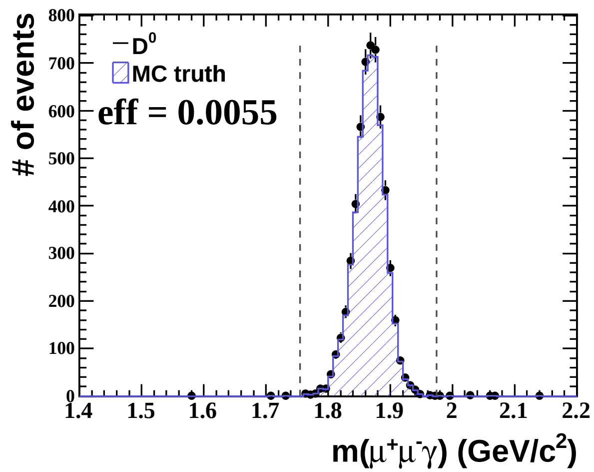
$$\Rightarrow N_{D\to\mu\mu\gamma} = 8.2 \text{ events}$$





$$\Rightarrow N_{D\to\mu\mu\gamma} = 13.6 \text{ events}$$





$$\Rightarrow N_{D\to\mu\mu\gamma} = 1.8 \text{ events}$$

Background reduction

- PID loose to tight for all charged particle

Tag	All cuts	Signal efficiency	Background reduction	N_{Sig} / year	N_{Bkg} / year
$D^0 \to K^+\pi^-$	+ PID prob > 0.25	0.0529	5.40×10^{-11}	**8.2**	4736
$D^0 \to K^+\pi^-\pi^0$		0.0244	1.14×10^{-10}	**13.6**	10065
$D^0 \to K^+\pi^-\pi^-\pi^+$		0.0055	1.35×10^{-11}	**1.8**	1184
$D^0 \to K^+\pi^-$	+ PID prob > 0.90	0.0269	$<1.47\times 10^{-11}$	**4.2**	0
$D^0 \to K^+\pi^-\pi^0$		0.0117	$<1.47\times 10^{-11}$	**6.5**	0
$D^0 \to K^+\pi^-\pi^-\pi^+$		0.0006	$<1.47\times 10^{-11}$	**0.2**	0

$$N_{D\to\gamma\gamma} = 2\ \text{fb}^{-1} \times 100\ \text{nb} \times \Sigma(Br_i) \times \varepsilon_{tag} \times 2$$

$$N_{D\to\gamma\gamma} = 2\text{fb}^{-1} \times 43.8\text{mb} \times \varepsilon_B$$

Background shape

- Main background EvtGen 3×10^{7} events :

$$N_{D\to\mu\mu\gamma} = 2\ \mathrm{fb}^{-1}\times 100\ \mathrm{nb}\times\Sigma(Br_i)\times\varepsilon_{tag}\times 2$$

$$D^0 \to \pi^+\pi^-\pi^0 (Br = 1.44 \pm 0.06\%)$$

$$\bar{p}p \to D^0\bar{D}^0 \to \pi^+\pi^-\pi^0\ K^+\pi^-$$

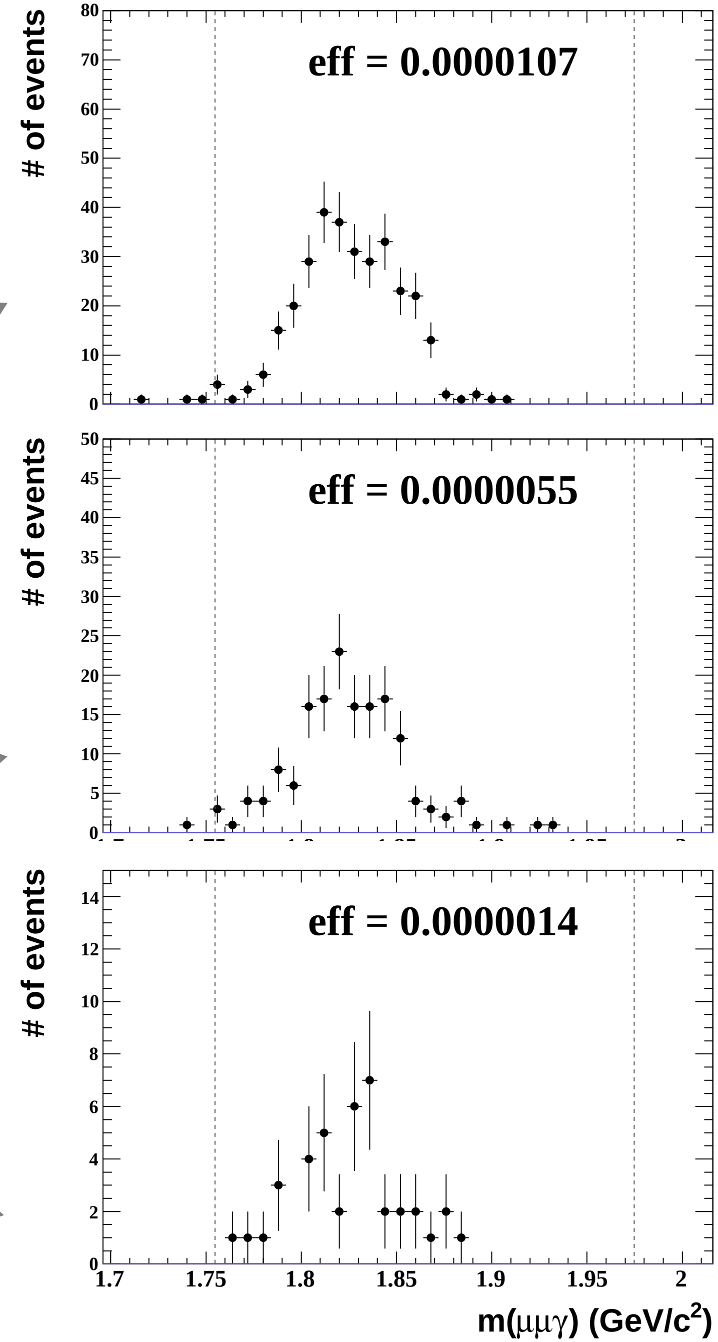
$$N_{D\to\mu\mu\gamma} = 2.4\ \text{events}$$

$$\bar{p}p \to D^0\bar{D}^0 \to \pi^+\pi^-\pi^0\ K^+\pi^-\pi^0$$

$$N_{D\to\mu\mu\gamma} = 4.4\ \text{events}$$

$$\bar{p}p \to D^0\bar{D}^0 \to \pi^+\pi^-\pi^0\ K^+\pi^-\pi^-\pi^+$$

$$N_{D\to\mu\mu\gamma} = 0.7\ \text{events}$$



Summary

An estimation for rare open charm decay has been made

- Other models for $D^0\overline{D}^0$ cross section could be larger than $\sigma_{DD} > 100$ nb
  e.g. BESIII second solution : $\sigma_{DD} = 486$ nb

- Necessary further background reduction : remains one order of magnitude

- Above E=3.77 GeV, there are other considerable channels

$$\bar{p}p \to D^0\overline{D}^0 \to \gamma\gamma\, K_S^0\pi^+\pi^-(\mathrm{Br} = 2.94\%)$$

$$\bar{p}p \to D^{0*}\overline{D}^0 \to D^0\pi^0(\gamma) + \overline{D}^0$$

$$\bar{p}p \to D^0\overline{D}^{0*} \to D^0 + \overline{D}^0\pi^0(\gamma)$$

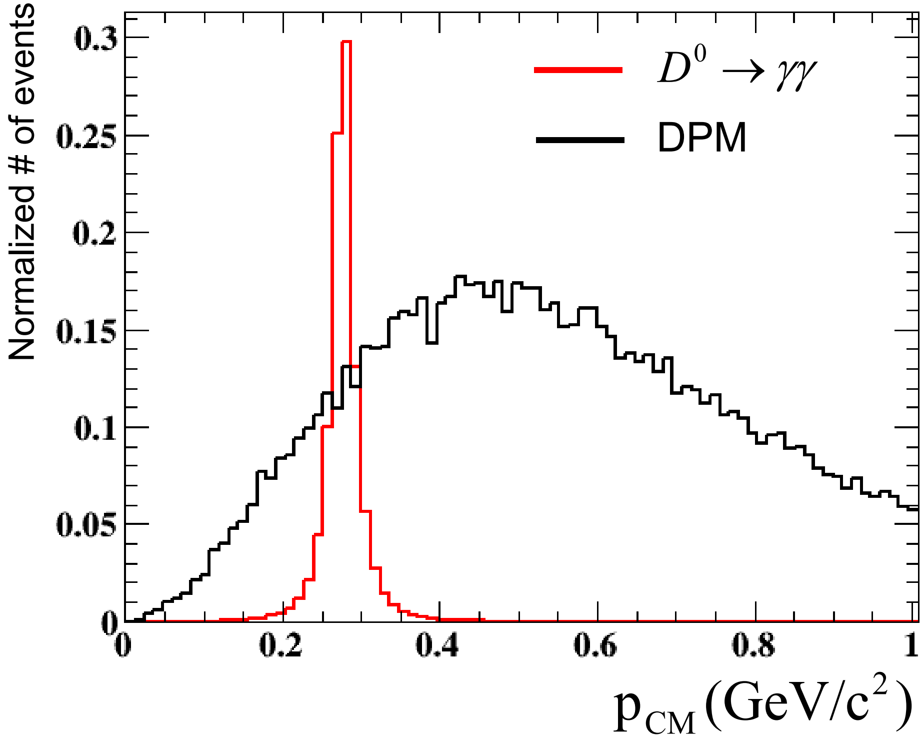
$$\bar{p}p \to D^{0*}\overline{D}^{0*} \to D^0\pi^0(\gamma) + \overline{D}^0\pi^0(\gamma)$$

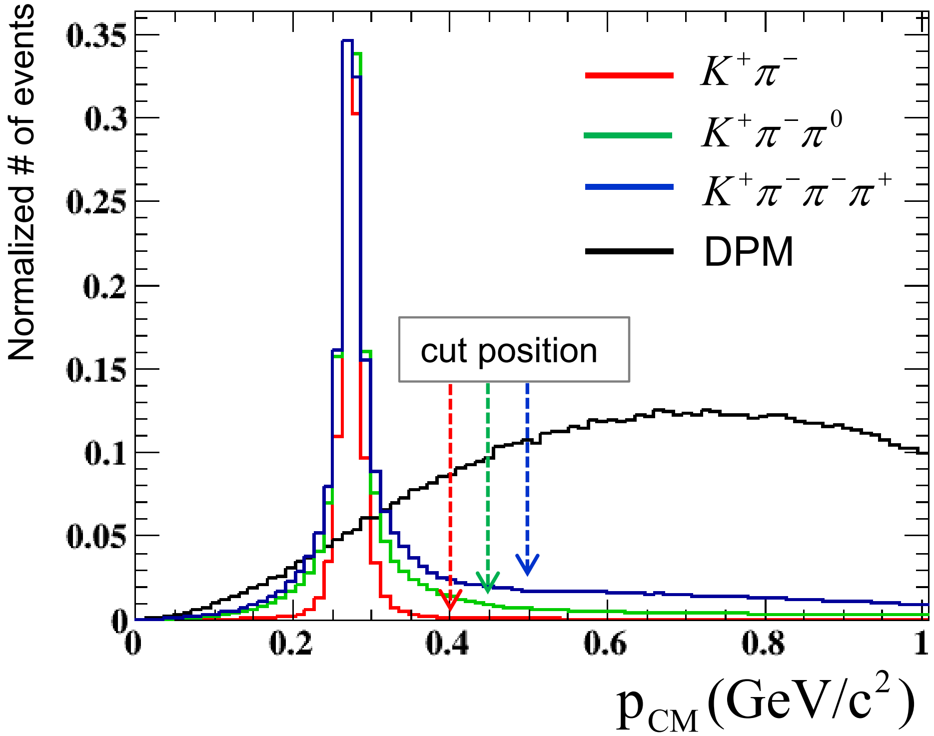
- Phase space models → physics models for gamma

Backup

Event selection

- Apply p_{CM} cut to D^0 candidates :
  introduced cut in the application of online software trigger





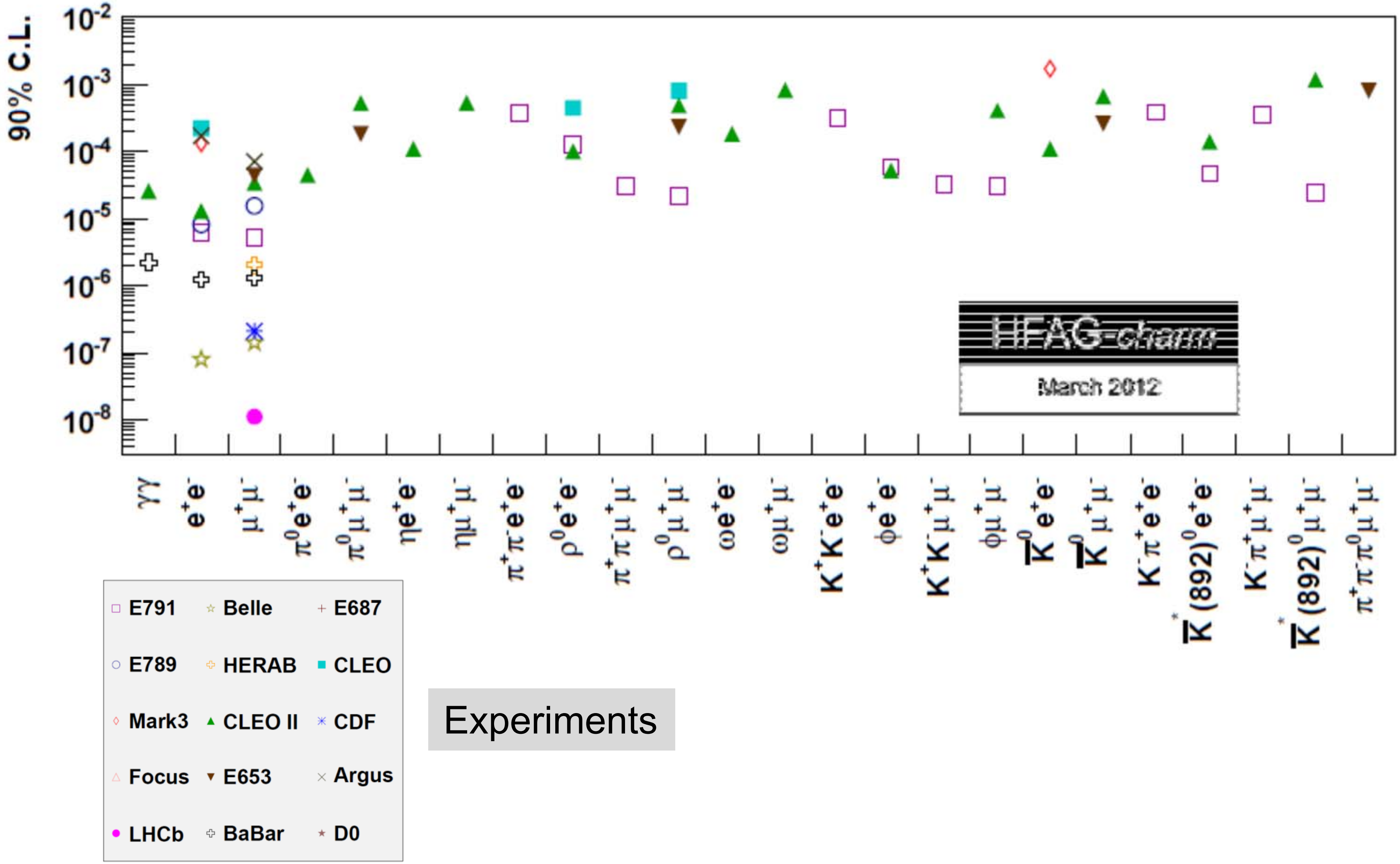
events only within the D^0 or $\overline{D}^0$ mass window $\pm 5\sigma$

- Mass constraint fit → 4 constraint fit for $\bar{p}p \to D^0\overline{D}^0$
  background reduction improve at least one order of magnitude

Experimental result

Upper limit for FCNC D^0 decays

Report from Heavy Flavor Averaging Group (HFAG) arXiv:2307.1158



Experiments

Event selection

$$\bar{p}p \rightarrow D^0 \bar{D}^0 \rightarrow \mu^+ \mu^- \gamma \, K^+ \pi^-$$

- Efficiency by event based (not candidate based)
- No DPM background up to 10^7 in the full simulation
- **1.479×10^{11}** inelastic DPM event in the fast simulation

$D^0 \rightarrow \mu^+\mu^-\gamma$	Signal ε [%]	Bkg ε [%]	$D^0 \rightarrow K^+\pi^-$	Signal ε [%]	Bkg ε [%]
$P_t(D) < P_{t,max} + 0.2 GeV/c^2$	89.25	40.3570	$P_t(K,\pi) > 0.1 GeV/c^2$ $P_t(D) < P_{t,max} + 0.2 GeV/c^2$	75.95	23.1191
$0.15 < P_{CM} < 0.4 GeV/c^2$	82.09	14.7828	$100° < \Delta\phi_{K\pi} < 260°$ $0.15 < P_{CM} < 0.4 GeV/c^2$	66.34	5.1334
MDT iron length > 10cm size of ECAL crystal < 36	26.16	0.1104	PID Prob(π,K) > 0.25	39.74	0.0646
# of muon layer > 0 PID Prob(π,K) > 0.25	19.34	0.0039	Mass constrain : $0 < \chi^2 < 10$	36.97	0.0082
Mass constrain : $0 < \chi^2 < 10$	16.57	0.0006			

$pp \rightarrow D^0 D^0$	Signal ε [%]	Bkg ε
Combine $\mu^+\mu^-\gamma K^+\pi^-$	6.01	1.21×10^{-10}
$130° < \Delta\phi_{DD} < 230°$	5.91	8.92×10^{-11}
$-0.99 < \cos\theta_{CM} < 0.99$	5.87	8.92×10^{-11}
4Constrain kinematic fit : $0 < \chi^2 < 20$ Only 1 best candidate by minimum χ^2	5.29	4.87×10^{-11}

Event selection

$$\bar{p}p \to D^0\bar{D}^0 \to \mu^+\mu^-\gamma\, K^+\pi^-\pi^0$$

- Efficiency by event based (not candidate based)
- No DPM background up to 10^7 in the full simulation
- **1.479×10^{11}** inelastic DPM event in the fast simulation

$D^0 \to \mu^+\mu^-\gamma$	Signal ε %	Bkg ε [%]	$D^0 \to K^+\pi^-\pi^0$	Signal ε [%]	Bkg ε [%]
$P_t(D) < P_{t,max} + 0.2 GeV/c^2$	85.91	40.3570	$P_t(\gamma$ of $\pi^0) < 1.0$ GeV/c^2 $P_t(D) < P_{t,max} + 0.2$ GeV/c^2	64.78	42.1840
$0.15 < P_{CM} < 0.4$ GeV/c^2	77.25	14.7828	$0.15 < P_{CM} < 0.45$ GeV/c^2	53.82	22.9107
MDT iron length > 10cm size of ECAL crystal < 36	25.50	0.1104	PID Prob(π,K) > 0.25	25.02	0.4501
# of muon layer > 0 PID Prob(π,K) > 0.25	19.13	0.0038	Mass constrain : $0 < \chi^2 < 10$	20.24	0.0662
Mass constrain : $0 < \chi^2 < 10$	16.09	0.0006			

$pp \to D^0D^0$	Signal ε [%]	Bkg ε
Combine $\mu^+\mu^-\gamma K^+\pi^-\pi^0$	15.35	8.27×10^{-10}
$130° < \Delta\phi_{DD} < 230°$	15.08	5.91×10^{-10}
$-0.99 < \cos\theta_{CM} < 0.99$	14.98	5.91×10^{-10}
4Constrain kinematic fit : $0 < \chi^2 < 20$ Only 1 best candidate by minimum χ^2	13.20	1.29×10^{-10}

Event selection

$$\bar{p}p \rightarrow D^0\bar{D}^0 \rightarrow \mu^+\mu^-\gamma K^+\pi^-\pi^-\pi^+$$

- Efficiency by event based (not candidate based)
- No DPM background up to 10^7 in the full simulation
- **1.479×10^{11}** inelastic DPM event in the fast simulation

$D^0 \rightarrow \mu^+\mu^-\gamma$	Signal ε [%]	Bkg ε [%]	$D^0 \rightarrow K^+\pi^-\pi^-\pi^+$	Signal ε [%]	Bkg ε [%]
$P_t(D) < P_{t,max} + 0.2GeV/c^2$	78.08	40.3570	$P_t(D) < P_{t,max} + 0.2$ GeV/c^2	48.49	14.0144
$0.15 < P_{CM} < 0.4$ GeV/c^2	63.69	14.7828	$0.15 < P_{CM} < 0.5$ GeV/c^2	38.48	7.7332
MDT iron length > 10cm size of ECAL crystal < 36	21.61	0.1104	PID Prob(π,K) > 0.25	9.19	0.1812
# of muon layer > 0 PID Prob(π,K) > 0.25	16.64	0.0038	Mass constrain : $0 < \chi^2 < 10$	6.28	0.0290
Mass constrain : $0 < \chi^2 < 10$	13.31	0.0006			

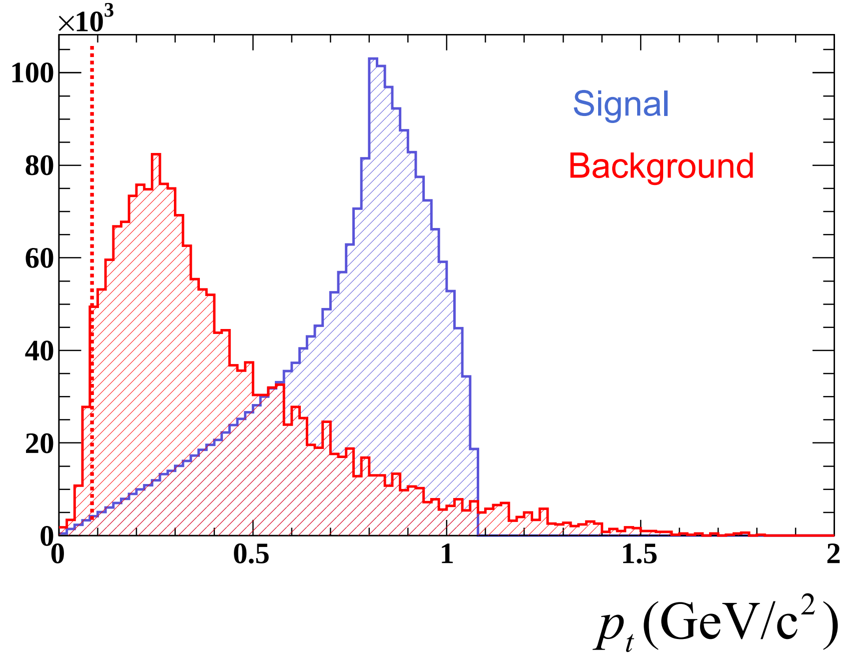
⇩

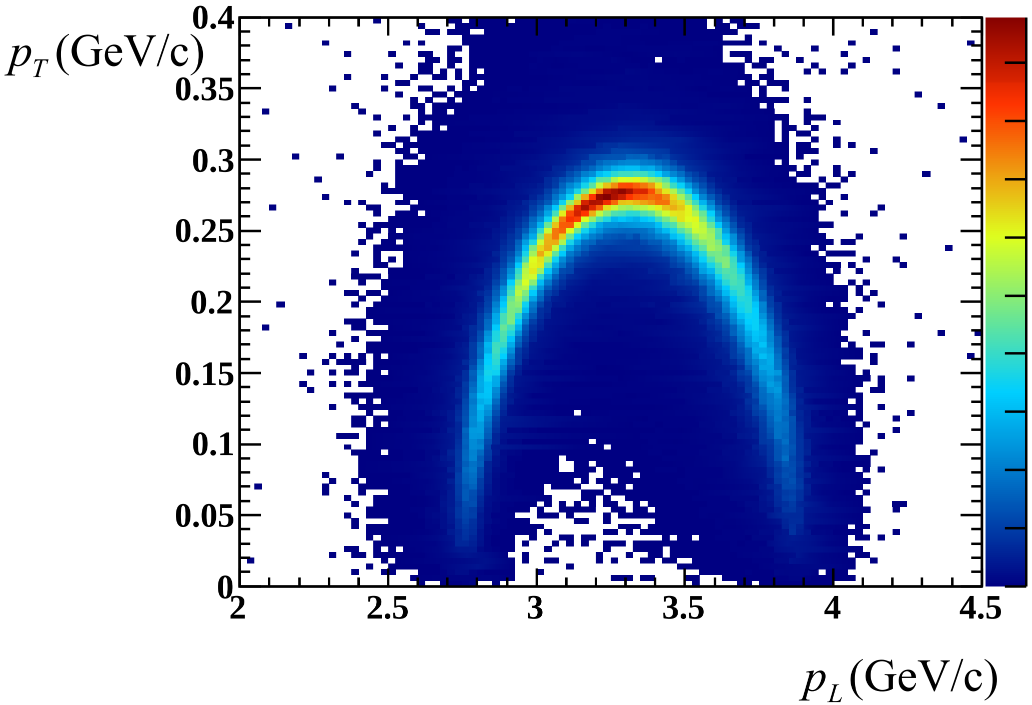
$pp \rightarrow D^0D^0$	Signal ε [%]	Bkg ε
Combine $\mu^+\mu^-\gamma K^+\pi^-\pi^-\pi^+$	4.06	3.81×10^{-10}
$130° < \Delta\phi_{DD} < 230°$	3.98	3.08×10^{-10}
$-0.99 < \cos\theta_{CM} < 0.99$	3.95	3.08×10^{-10}
4Constrain kinematic fit : $0 < \chi^2 < 20$ Only 1 best candidate by minimum χ^2	3.38	1.62×10^{-11}

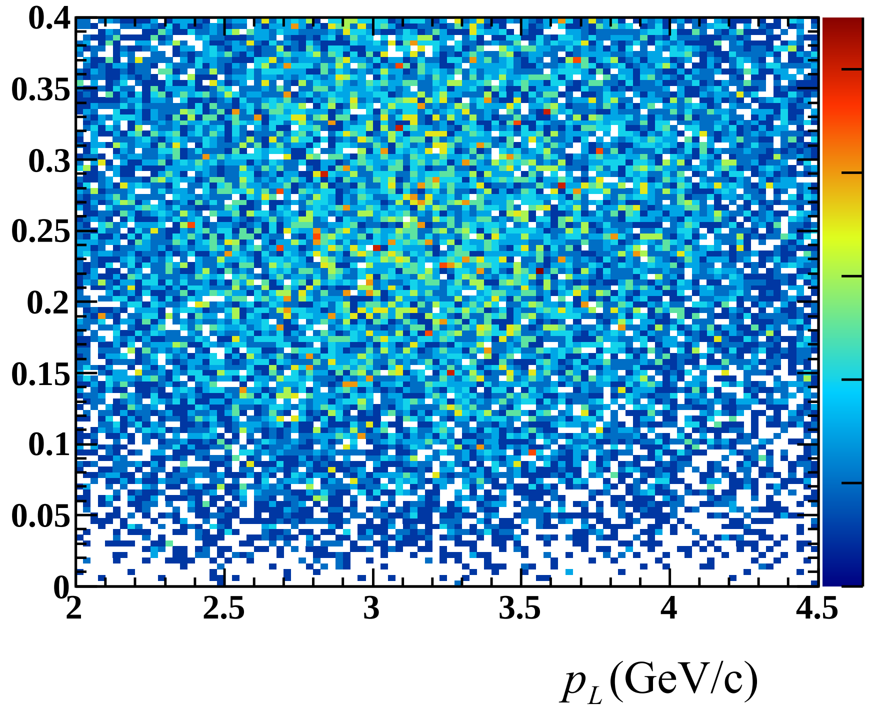
Background rejection

- $p_T > 0.1(\mathrm{GeV/c})$ for γ
- $p_T < p_T^{\max} + 0.2(\mathrm{GeV/c})$ for D^0

$$p_T^{\max}(\sqrt{s};m) = \frac{\sqrt{s^2 - 4 \cdot s \cdot m^2}}{2\sqrt{s}}$$



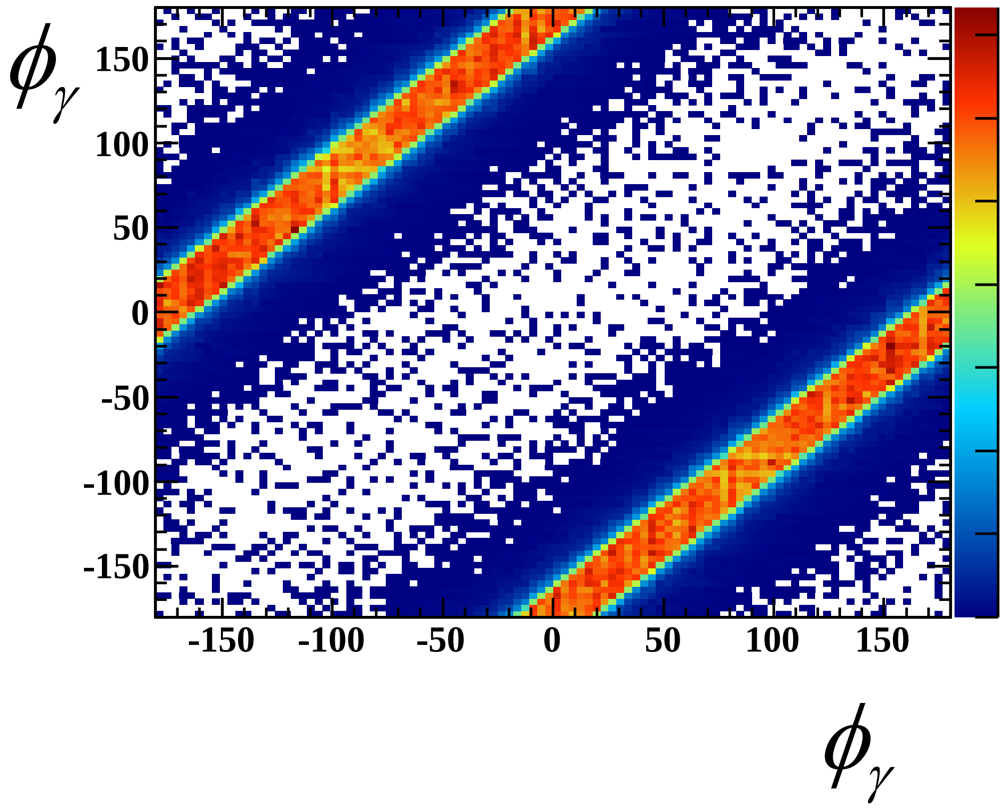




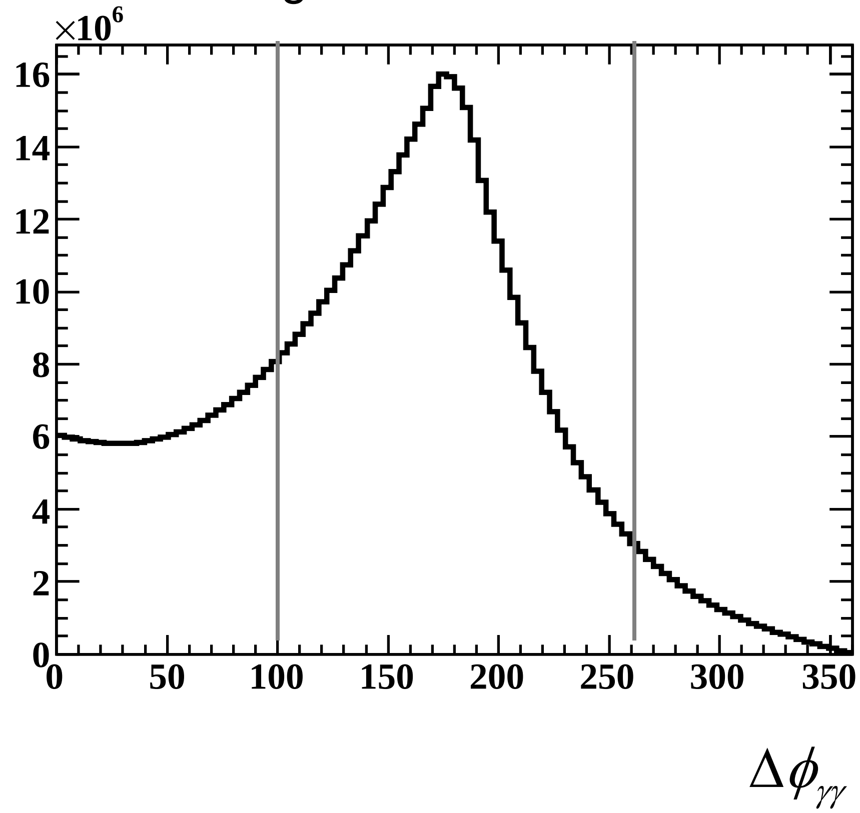
Background rejection

Angular correlation of $\gamma\gamma$

Signal MC generated



Background DPM reconstructed

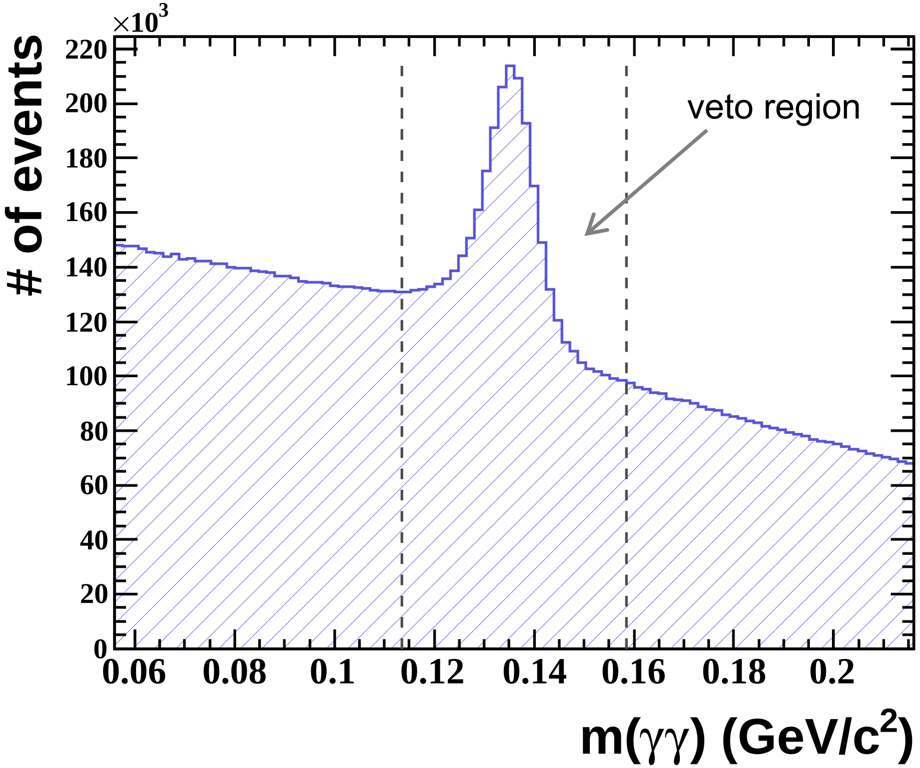


Background rejection

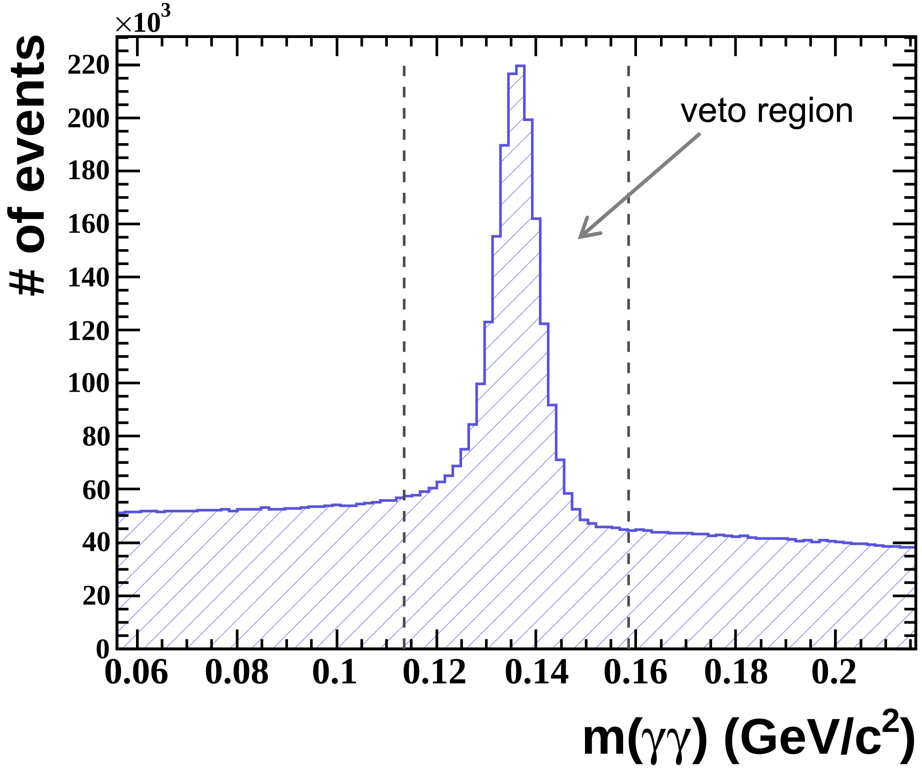
π^0 veto : reject events in which one of the photons can be combined with any other photon candidate in the event to form a π^0

Lower threshold (E= 50 MeV) is more efficient than higher value for π^0 veto

DPM background



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

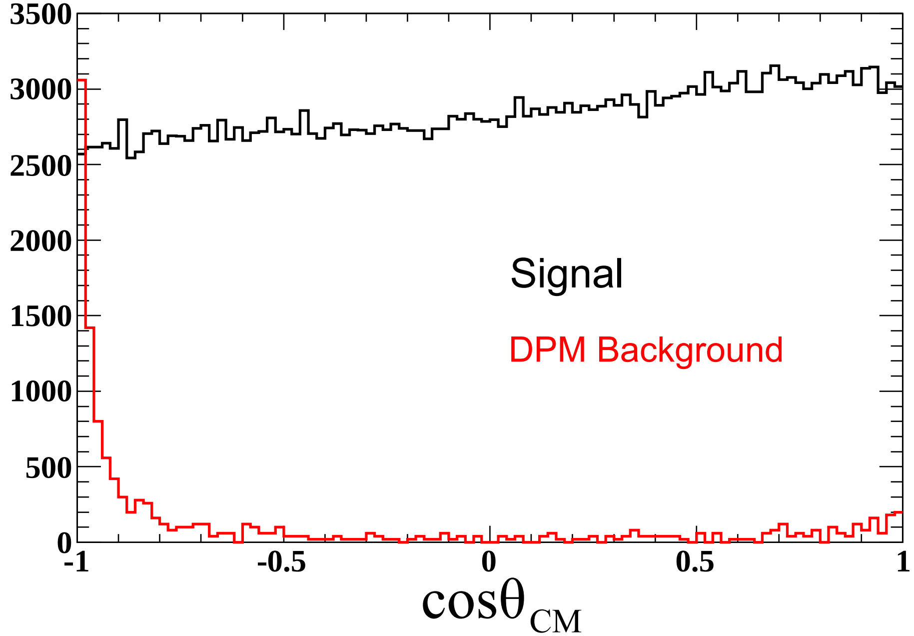


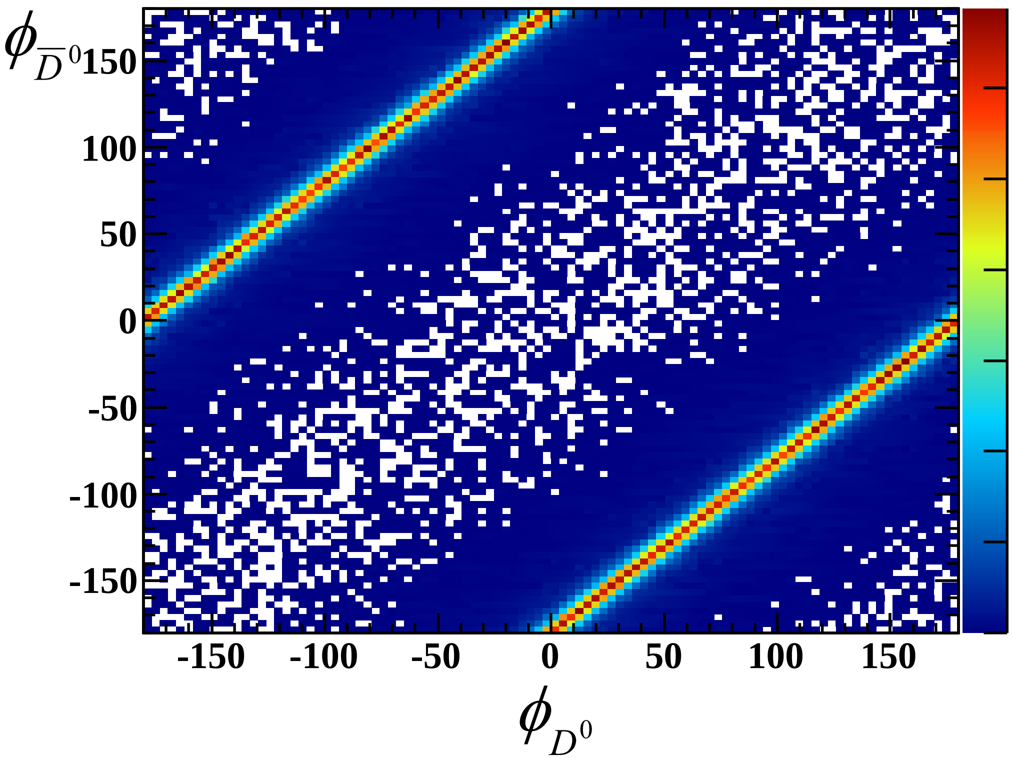
Background rejection

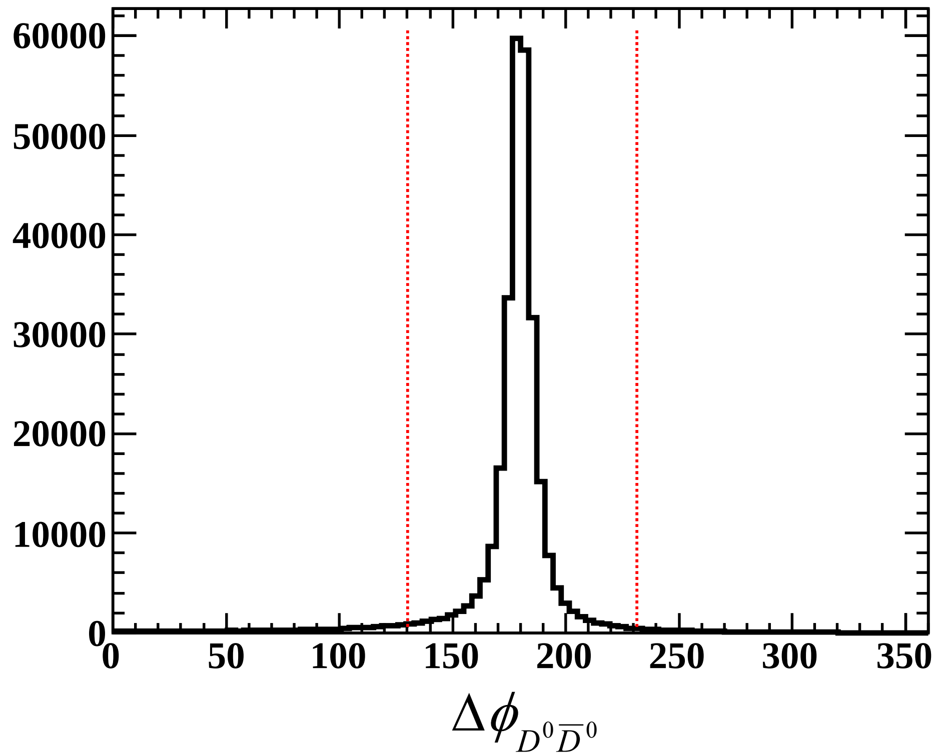
Angular correlation of $D^0\overline{D}^0$

$$-0.99 < \cos\theta_{\mathrm{CM},D^0} < 0.99$$

$$-130^\circ < \Delta\phi_{D^0\overline{D}^0} < 230^\circ$$

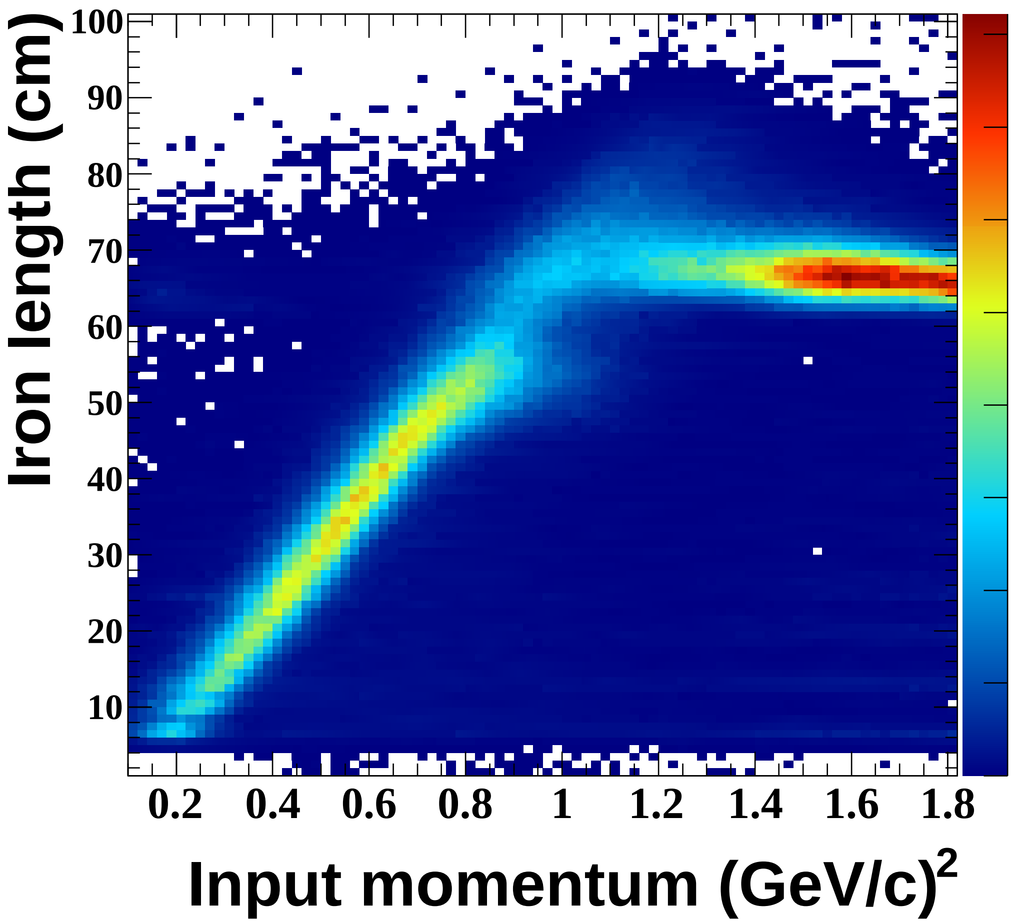






Background rejection

$D^0 \to \mu^+ \mu^-$



DPM background