Feasibility study of the rare decay $D^0 \rightarrow \gamma\gamma$ at PANDA

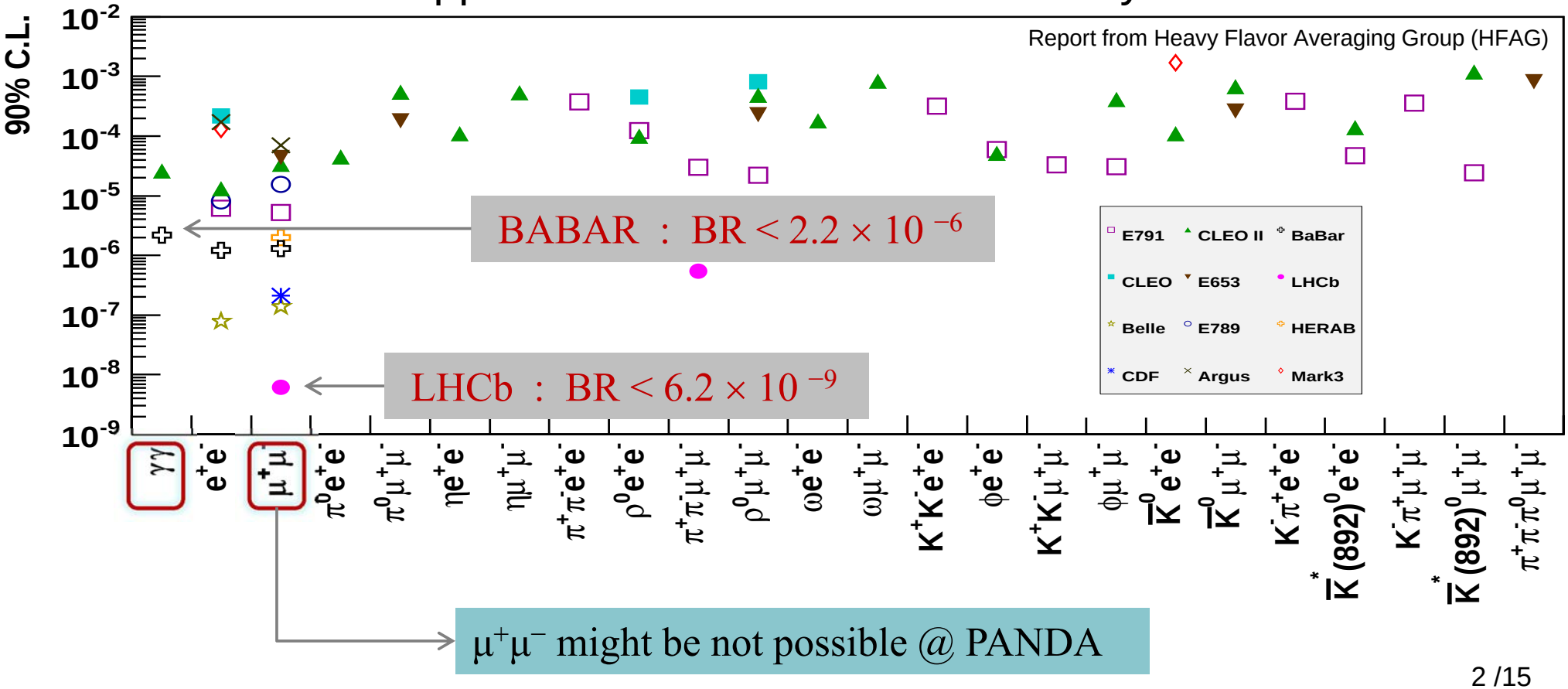
Donghee Kang

Helmholtz Institut Mainz, Universität Mainz

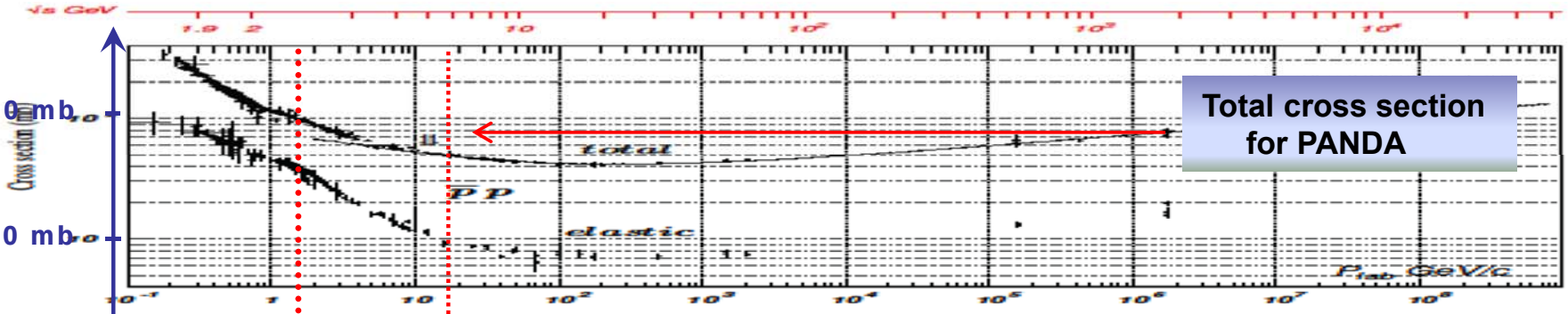
Motivation

- In Standard Model (SM), Flavor Changing Neutral Currents (FCNC) are forbidden at tree level and highly suppressed by GIM mechanism at loop level
- Enhancement of $c \to u\gamma$ transition has a sign of beyond SM
- Experimental observable is the branching ratio (BR)

Upper limit of BR for D^0 FCNC decay



$D^0\bar{D}^0$ Cross section

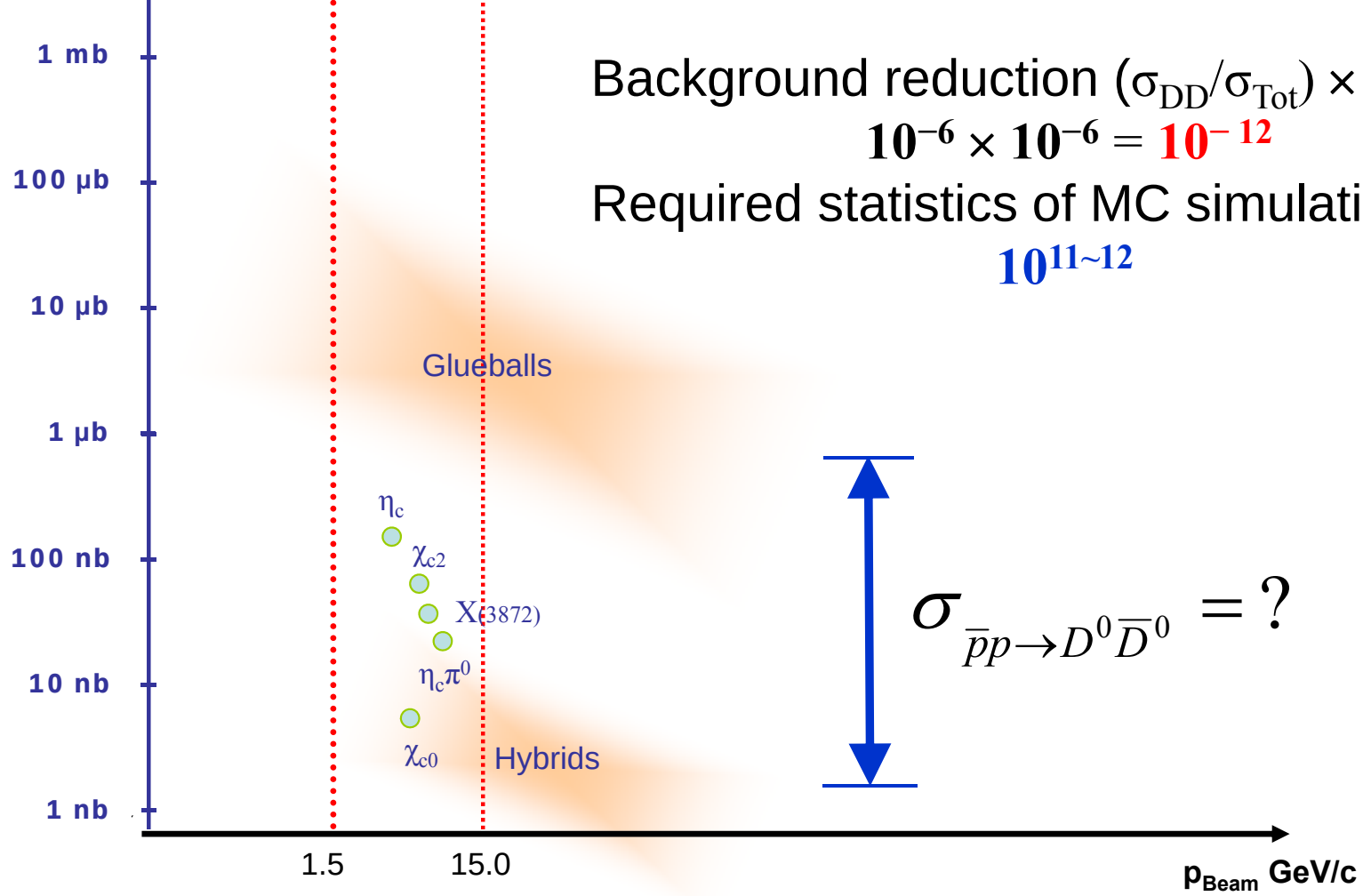


Background reduction $(\sigma_{DD}/\sigma_{Tot}) \times Br_{D\to\gamma\gamma}$

$10^{-6} \times 10^{-6} = 10^{-12}$

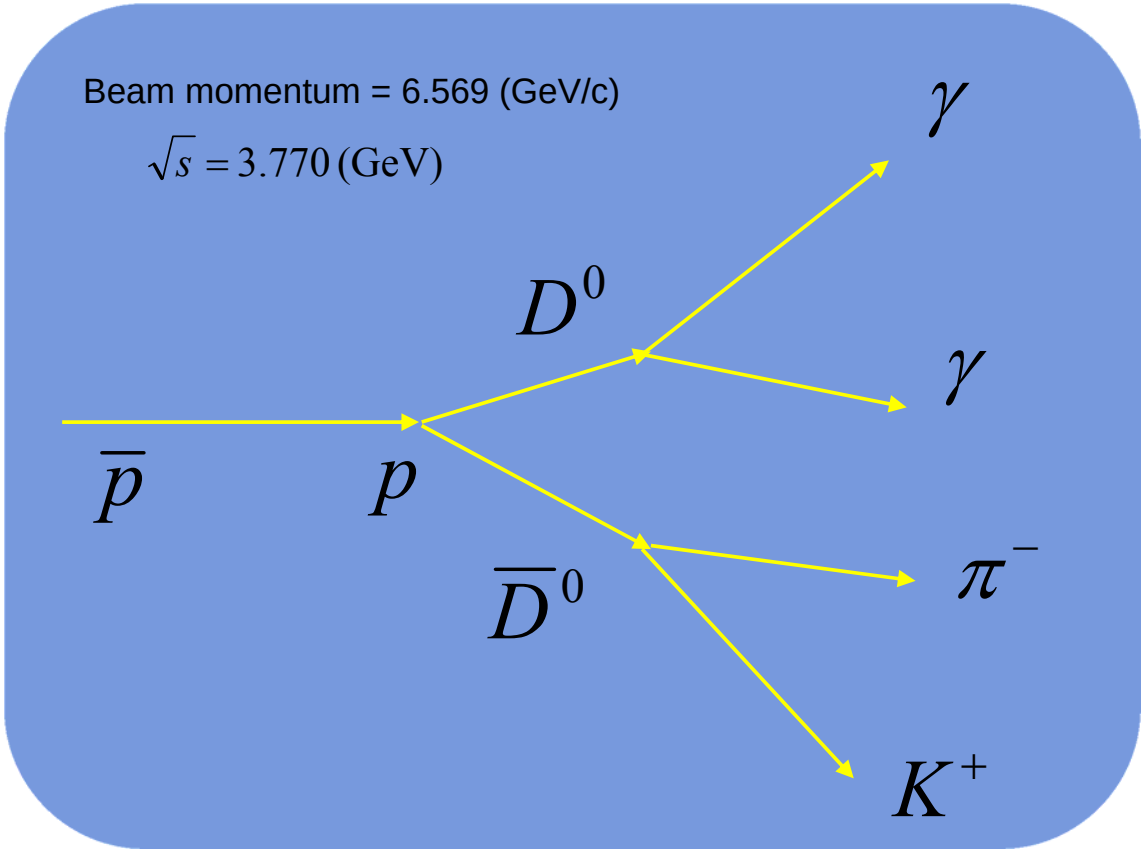
Required statistics of MC simulation

$10^{11\sim12}$



MC simulation

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



- PANDAroot : release oct14
- Signal MC :
  EvtGen
  Background MC :
  EvtGen, DPM, & FTF
- Double tag methods
- Pre-selection
  Neutral track : E > 50 MeV
  Charged track : p > 100 MeV/c

Two additional tag modes

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

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

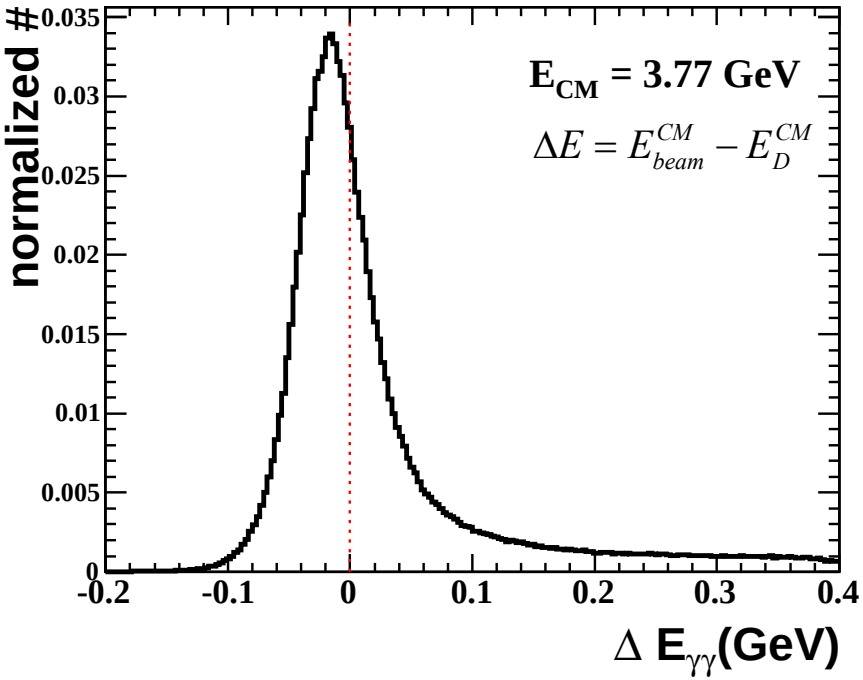
Event selection

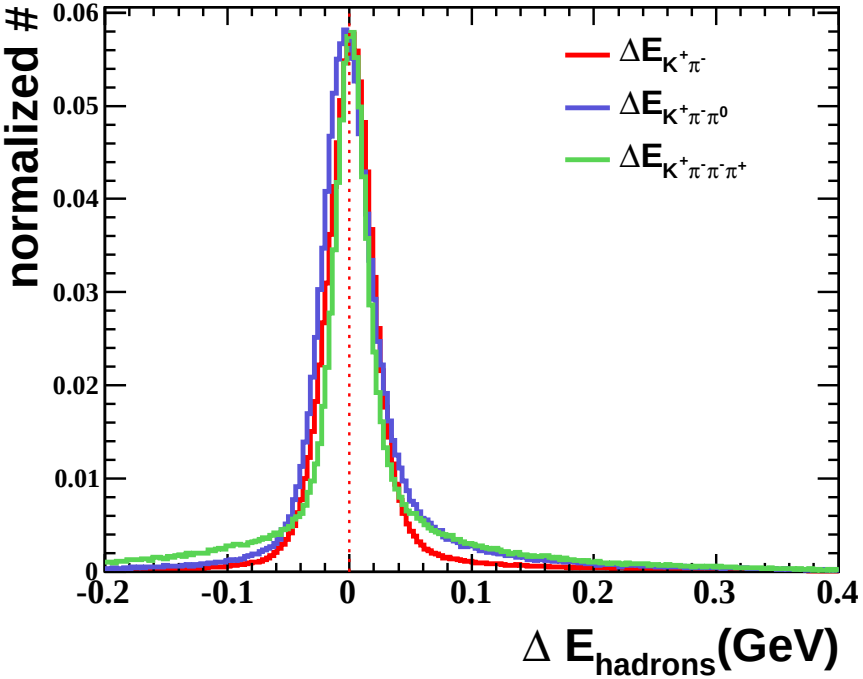
Signal	Tag
$D^0 \to \gamma\gamma$	$\overline{D}^0 \to K^+\pi^-$
$P_t(D) < P_{t,max} + 0.2$ GeV/c	$P_t(D) < P_{t,max} + 0.2$ GeV/c
$M_{BC} > 1.84$ GeV/c^2	$M_{BC} > 1.85$ GeV/c^2
$-0.14 < \Delta E < 0.4$ GeV	$-0.12 < \Delta E < 0.2$ GeV
π^0 veto	PID Prob(π,K) > 0.25(upto 0.9)

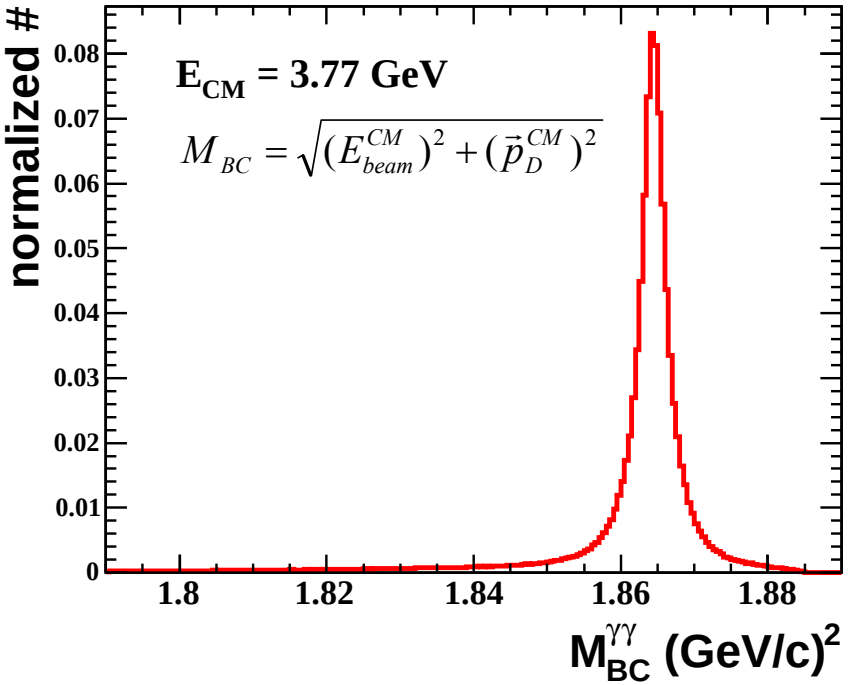
$$\bar{p}p \to D^0\overline{D}^0 \to \gamma\gamma\, K^+\pi^-$$

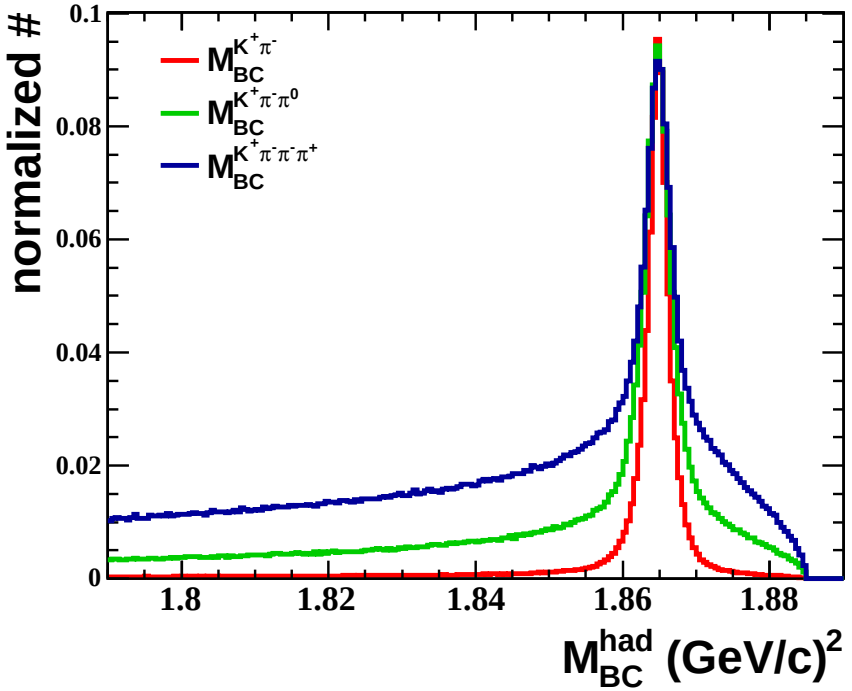
$130° < \Delta\phi_{DD} < 230°$
$-0.99 < \cos\theta_{CM} < 0.99$
4Constrain kinematic fit : $0 < \chi^2 < 20$
Only 1 best candidate by minimum χ^2
3.715 GeV/c$^2 < \Sigma m_{4C\text{-fitted}} < 3.725$ GeV/c^2

Beam constraint E and M









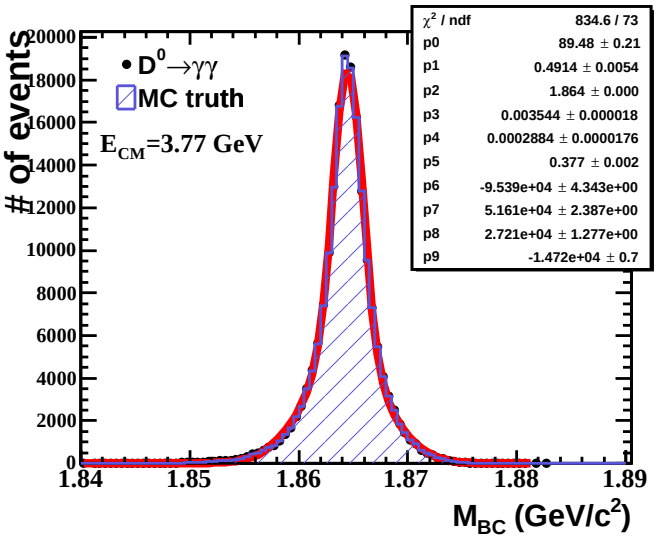
Main background source

Tag 1	Tag 2	Tag 3
$D^0\overline{D}^0 \to \gamma\gamma\, K^+\pi^-$	$D^0\overline{D}^0 \to \gamma\gamma\, K^+\pi^-\pi^0$	$D^0\overline{D}^0 \to \gamma\gamma\, K^+\pi^-\pi^-\pi^+$
DPM pion background $\bar{p}p \to \mathrm{X} \to \pi^+\pi^-\pi^0\pi^0$ σ = 374.7 μb Open charm background $\bar{p}p \to D^0\overline{D}^0 \to K^+\pi^-\pi^0\pi^0$	DPM pion background $\bar{p}p \to \mathrm{X} \to \pi^+\pi^-\pi^0\pi^0\pi^0$ σ = 658.8 μb Open charm background $\bar{p}p \to D^0\overline{D}^0 \to K^+\pi^-\pi^0\pi^0\pi^0$	DPM pion background $\bar{p}p \to \mathrm{X} \to 2\pi^+2\pi^-\pi^0\pi^0$ σ = 2255.4 μb Open charm background $\bar{p}p \to D^0\overline{D}^0 \to K^+\pi^-\pi^-\pi^+\pi^0\pi^0$

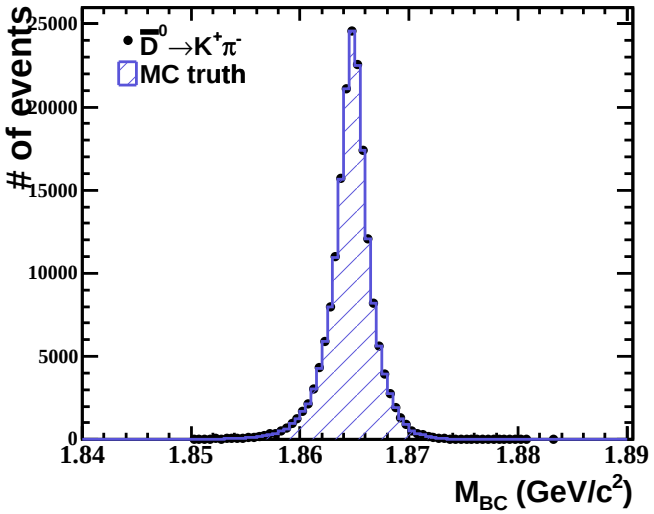
- define main background from the study on the filtered DPM and EvtGen
- reduce statistics of background simulation by
  σ=0.37 / 0.65 / 2.2 mb instead of σ=60 mb → **N_{sim}~10^9** instead of N_{sim}~10^{11}

Efficiency & bkg. reduction

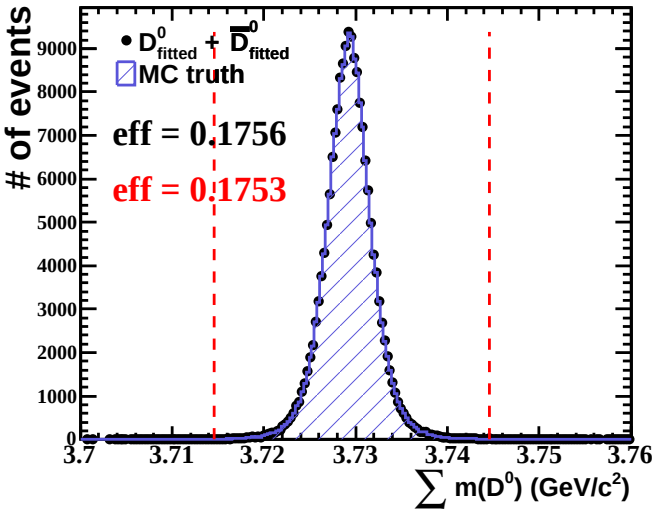
D^0 signal



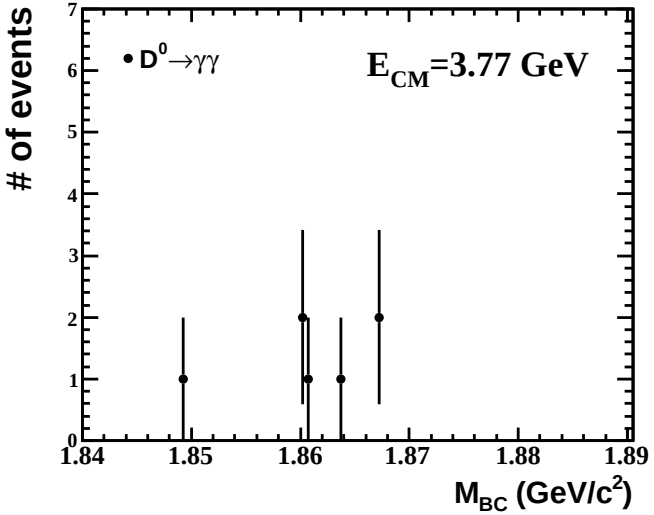
$\overline{D}^0$ tag

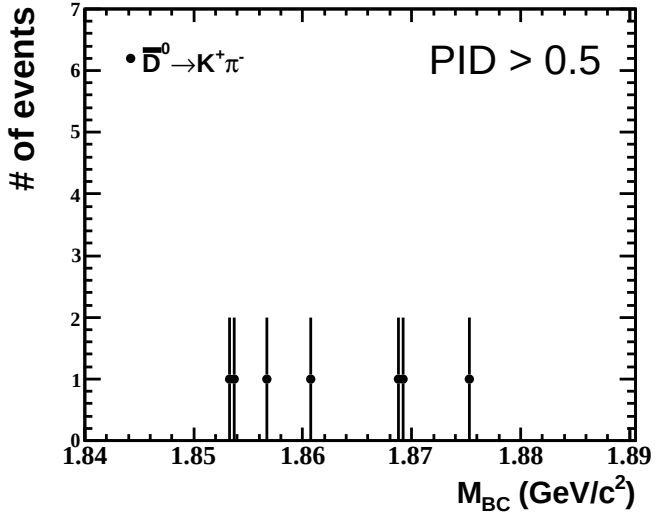


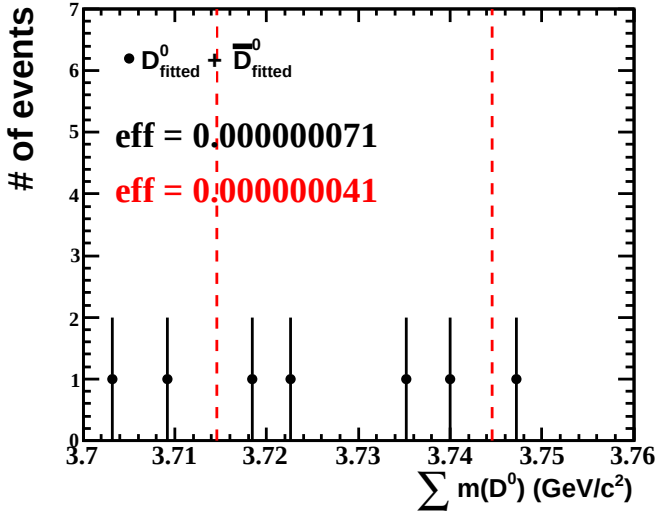
Signal MC data



DPM multi pion background $\bar{p}p \to \pi^+\pi^-\pi^0\pi^0$: $N_{sim}=1.0\times10^8$ events







Efficiency & bkg. reduction

Apply global PID cut to the tag side and find best background reduction

Tag mode	PID > 0.25	PID > 0.5	PID > 0.6	PID > 0.7	PID > 0.8	PID > 0.9
		Tag3 ↓		Tag1 ↓		Tag2 ↓
$E_{CM} = 3.77$ (GeV)						
Sig. Efficiency (%)						
$\bar{D}^0 \to K^+\pi^-$	21.58	17.56	16.23	14.87	13.32	11.18
$\bar{D}^0 \to K^+\pi^-\pi^0$	11.70	8.63	7.80	7.13	6.43	5.51
$\bar{D}^0 \to K^+\pi^-\pi^-\pi^+$	3.32	1.33	0.99	0.76	0.56	0.36
Bkg. reduction (%)						
$\bar{D}^0 \to K^+\pi^-$	4.17×10^{-7}	7.13×10^{-8}	4.07×10^{-8}	2.03×10^{-8}	2.03×10^{-8}	0
$\bar{D}^0 \to K^+\pi^-\pi^0$	6.30×10^{-6}	1.26×10^{-6}	6.20×10^{-7}	4.47×10^{-7}	3.05×10^{-7}	1.62×10^{-7}
$\bar{D}^0 \to K^+\pi^-\pi^-\pi^+$	1.21×10^{-7}	2.03×10^{-8}	0	0	0	0

– before cut on the Σm_{Fitted}

- can be achievable to the level of $\varepsilon_{Bkg}<10^{-8}$, but this is a upper limit before performing full statistics
- leads to $N_{Bkg}<10^{5}$ as a pessimistic estimation with common experimental parameters

Expected number of events

Experimental parameters :
Luminosity, Branching fraction, and Cross section

$$N_{sig} = L_{\rm int} \times \sigma_{DD} \times \Sigma Br_D \times \varepsilon_{sig} \qquad L_{\rm int} = 2\ {\rm fb}^{-1}\ (t = 120\ {\rm days})$$
$$N_{Bkg}^{DPM} = L_{\rm int} \times \sigma_{\pi^0} \times \varepsilon_{Bkg}^{DPM} \qquad Br(D^0 \to \gamma\gamma) = 1.0 \times 10^{-6}$$
$$N_{Bkg}^{D\to 2\pi^0} = L_{\rm int} \times \sigma_{DD} \times \Sigma Br_D \times \varepsilon_{Bkg}^{D\to 2\pi^0} \qquad \sigma_{DD} = 100\ {\rm nb}$$

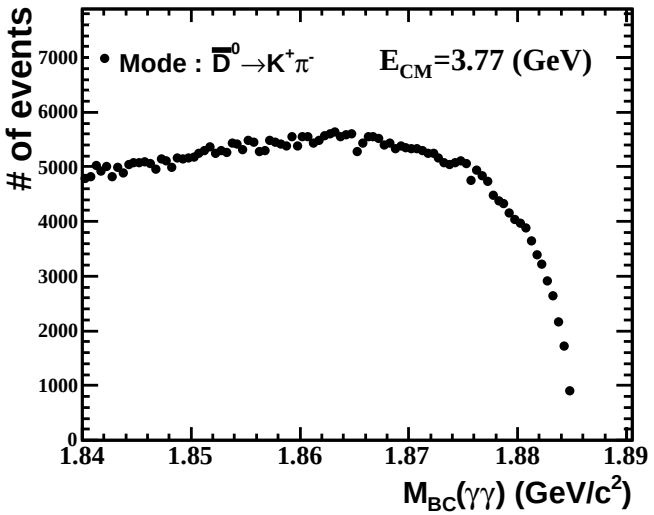
Mode : $E_{CM} = 3.77$ GeV	Efficiency	$N_{expected}$	comments
Signal			
$D^0\bar{D}^0 \to \gamma\gamma K^+\pi^-$	14.85%	61.5	
$D^0\bar{D}^0 \to \gamma\gamma K^+\pi^-\pi^0$	5.48%	22.7	
$D^0\bar{D}^0 \to \gamma\gamma K^+\pi^-\pi^-\pi^+$	1.31%	5.5	
DPM background			
$p\bar{p} \to \pi^0\pi^0\pi^+\pi^-$	$< 2.03 \times 10^{-8}$ (2 events)	$< 3.1 \times 10^4$	100 M events simulated
$p\bar{p} \to \pi^0\pi^0\pi^+\pi^-\pi^0$	$< 4.06 \times 10^{-8}$ (4 events)	$< 1.1 \times 10^5$	(remaining event)
$p\bar{p} \to \pi^0\pi^0\pi^+\pi^-\pi^-\pi^+$	$< 1.00 \times 10^{-8}$ (0 events)	$< 9.3 \times 10^4$	
Open charm background			
$D^0\bar{D}^0 \to \pi^0\pi^0K^+\pi^-$	5.1×10^{-4}	179.4	
$D^0\bar{D}^0 \to \pi^0\pi^0K^+\pi^-\pi^0$	6.6×10^{-4}	230.6	
$D^0\bar{D}^0 \to \pi^0\pi^0K^+\pi^-\pi^-\pi^+$	5.2×10^{-5}	18.1	

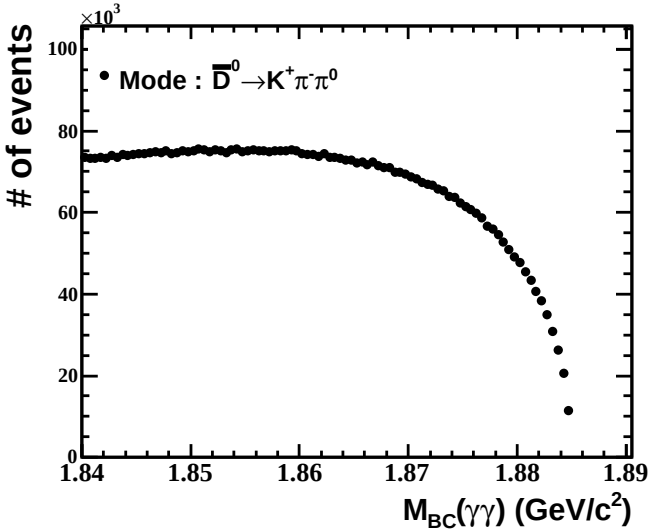
- found ratio for two different background sources
  $S/B_{\text{multi pion}} < 1/10^3$ and $S/B_{\text{open charm}} \sim 1/5$

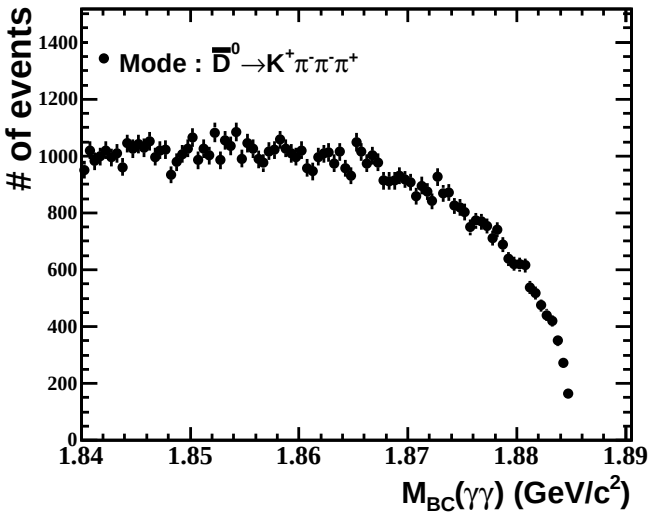
- 4 weeks @ GSI computing farm, but still missing one order of magnitude

Background shape

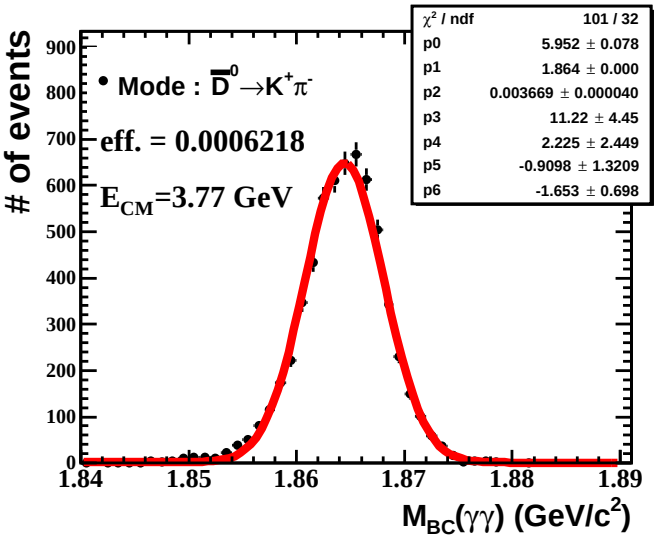
Argus distribution from multi pion background (DPM)

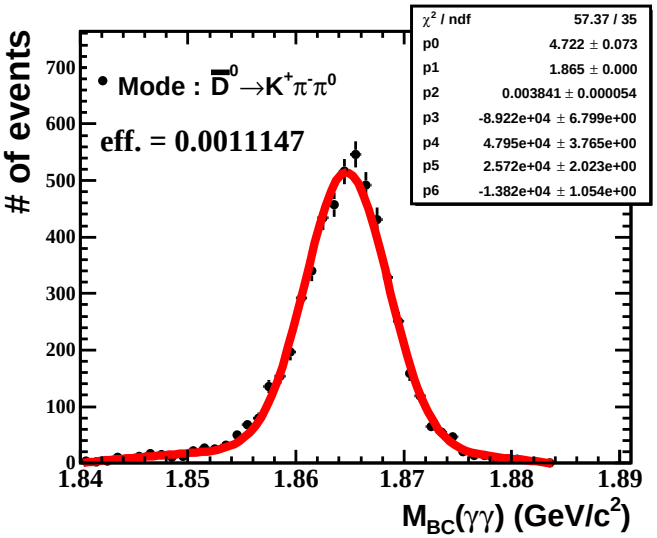


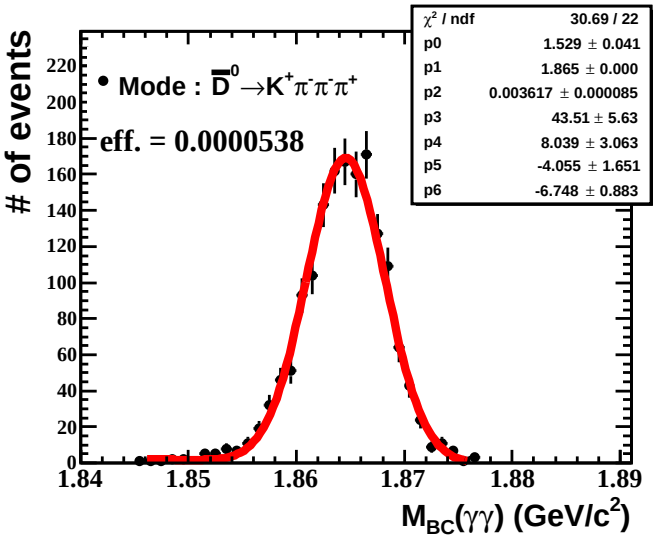




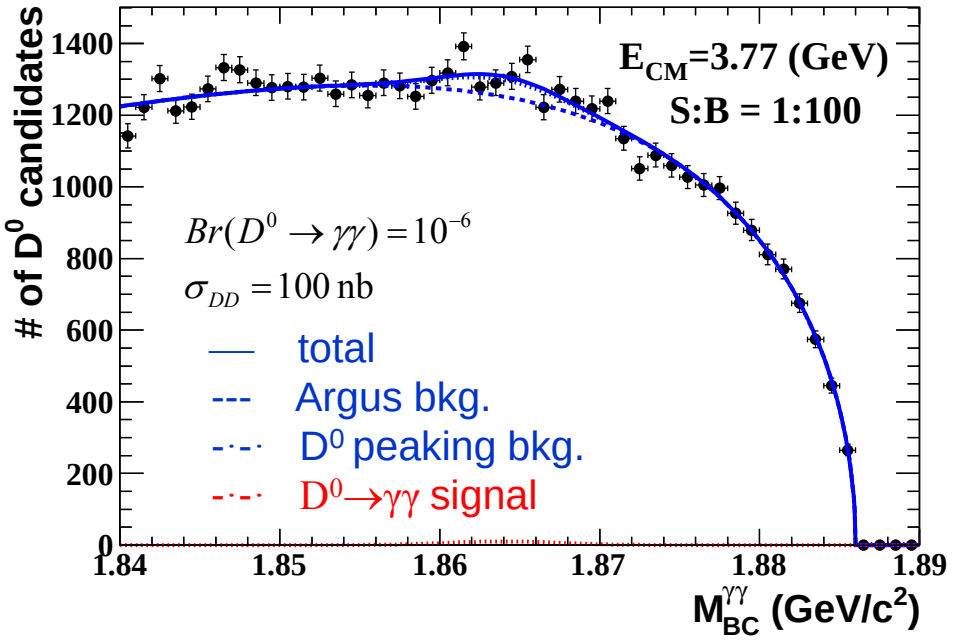
D^0 peaking background via other open charm decay mode $D^0 \to \pi^0\pi^0$

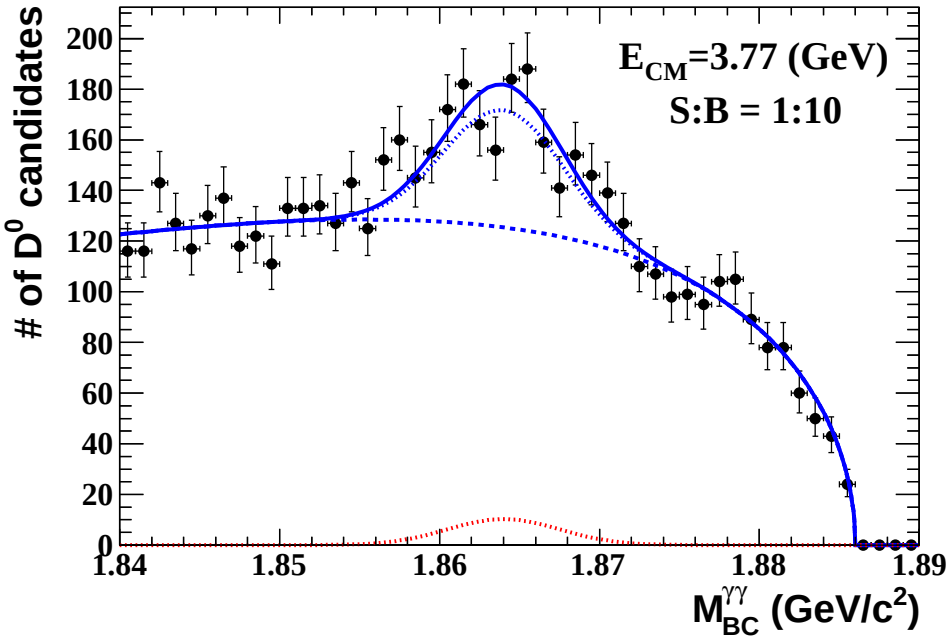




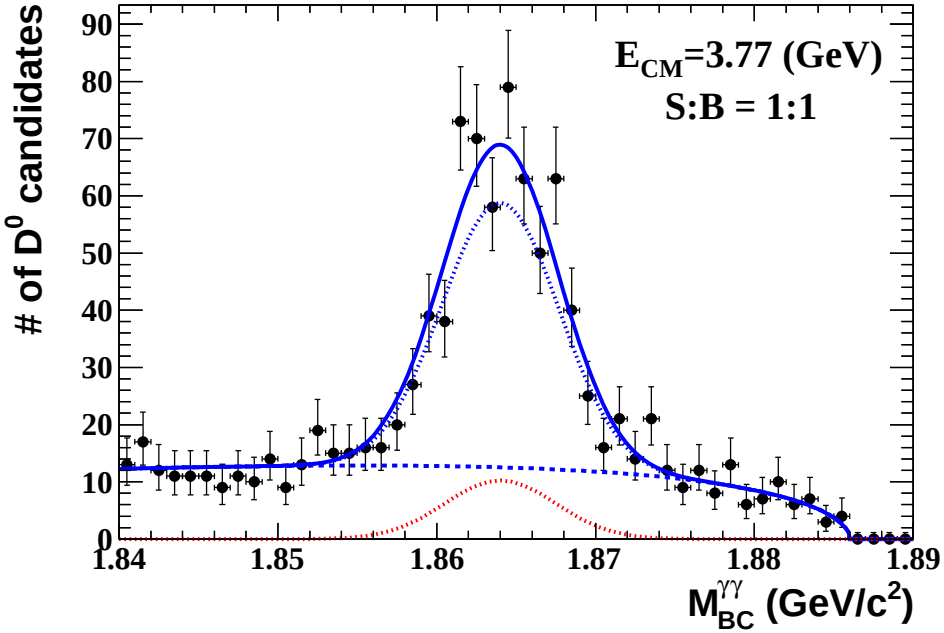


Expected distribution

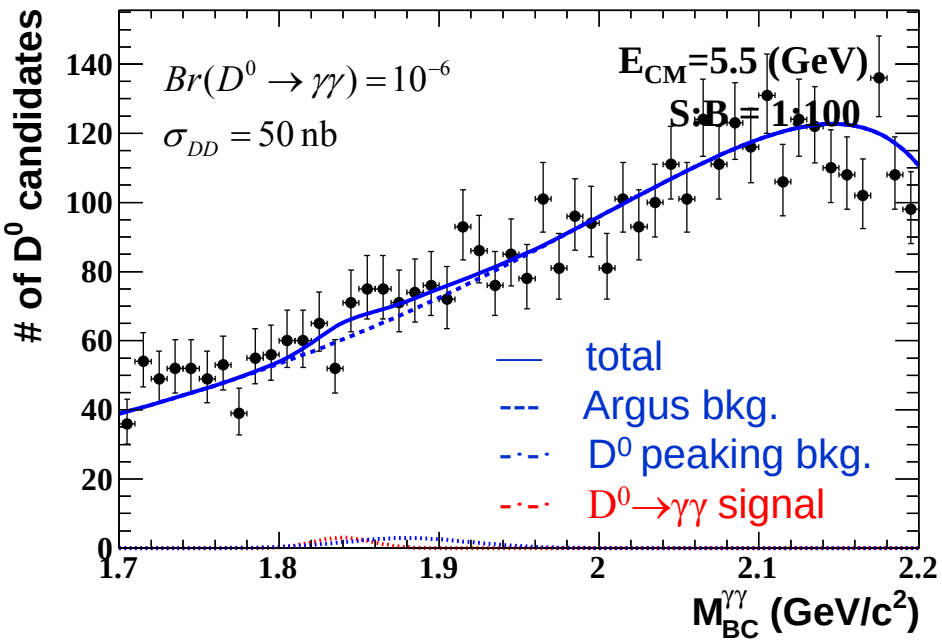


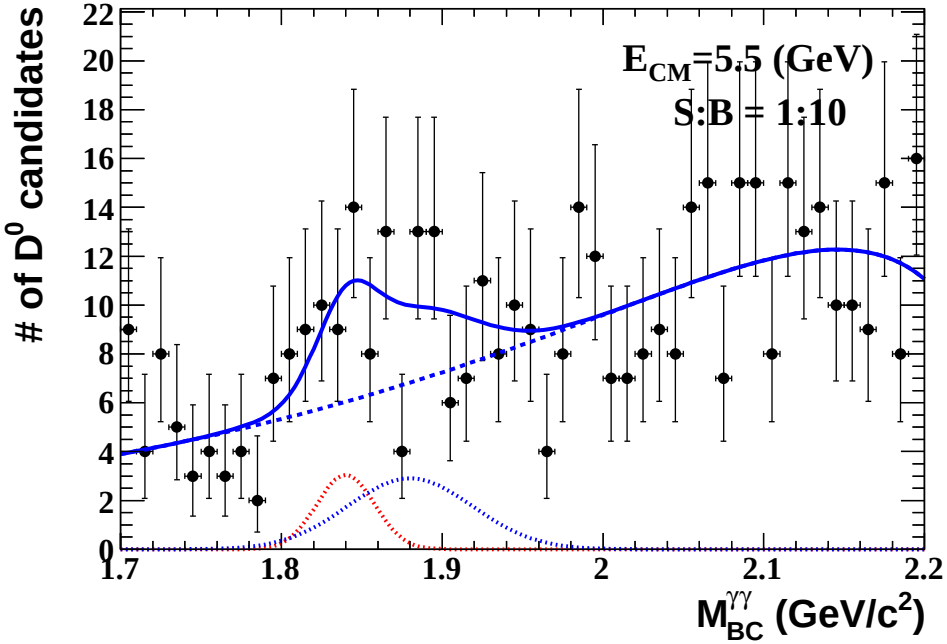


- Dependence on S:B ratio
- Demanding S/B is below 1/100
- Open charm peaking bkg. from π^0 is still dominated

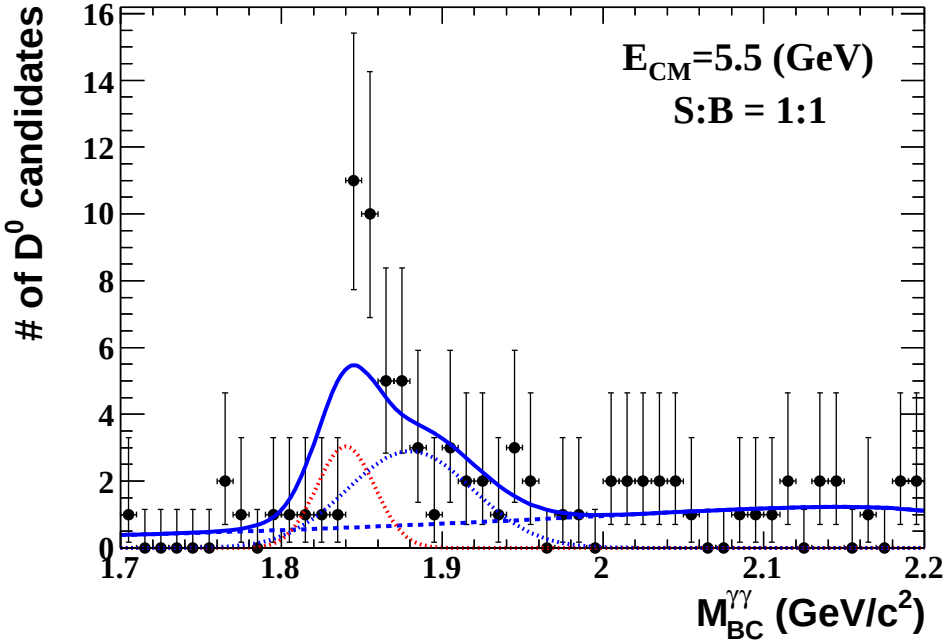


Expected distribution

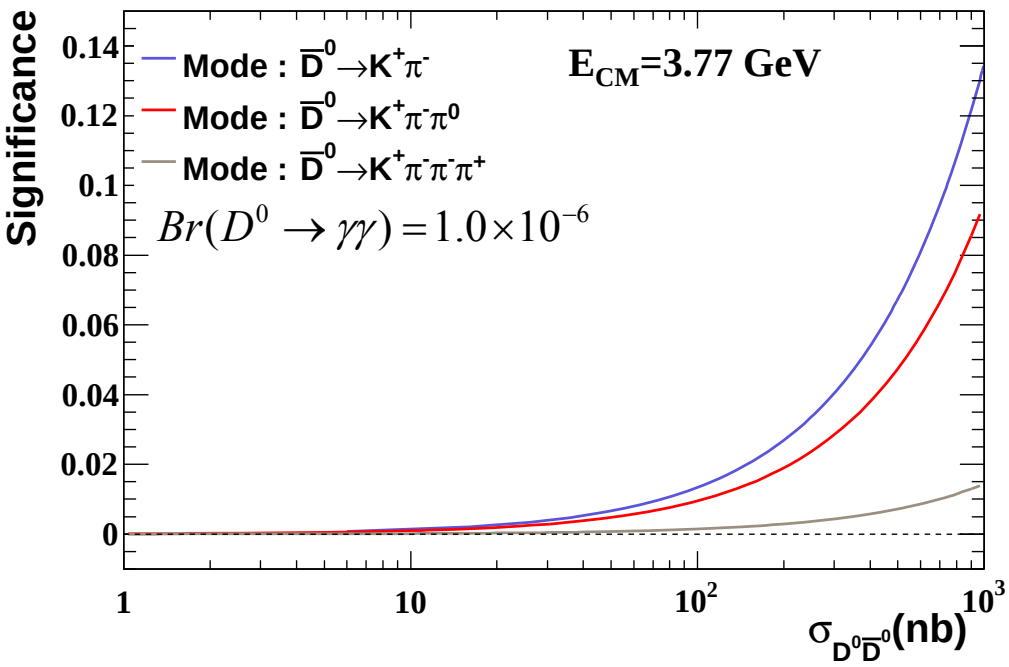


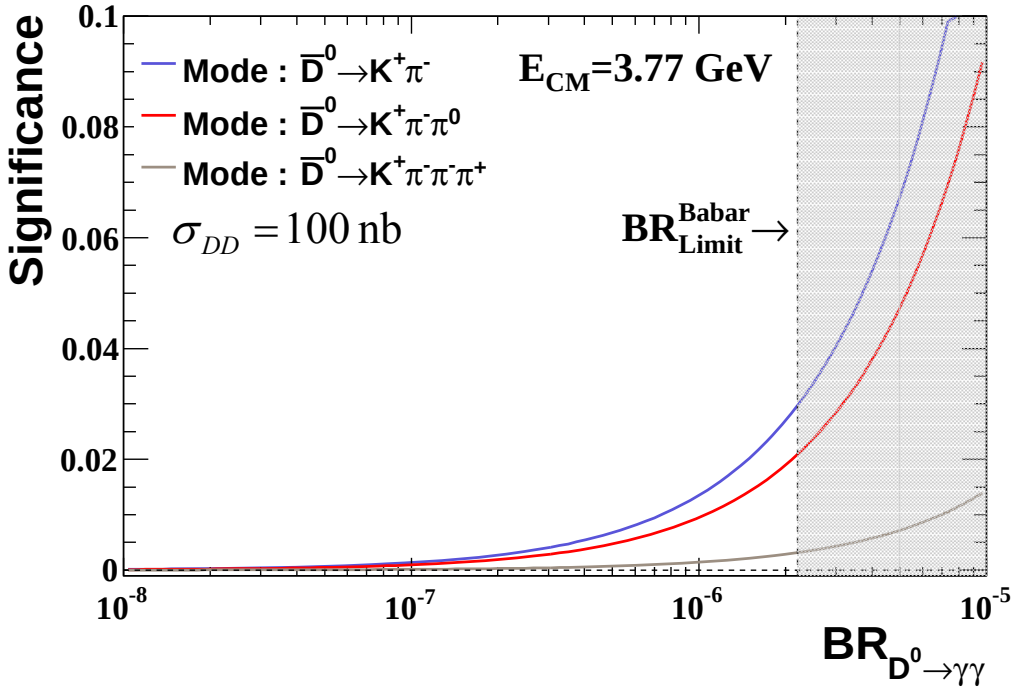


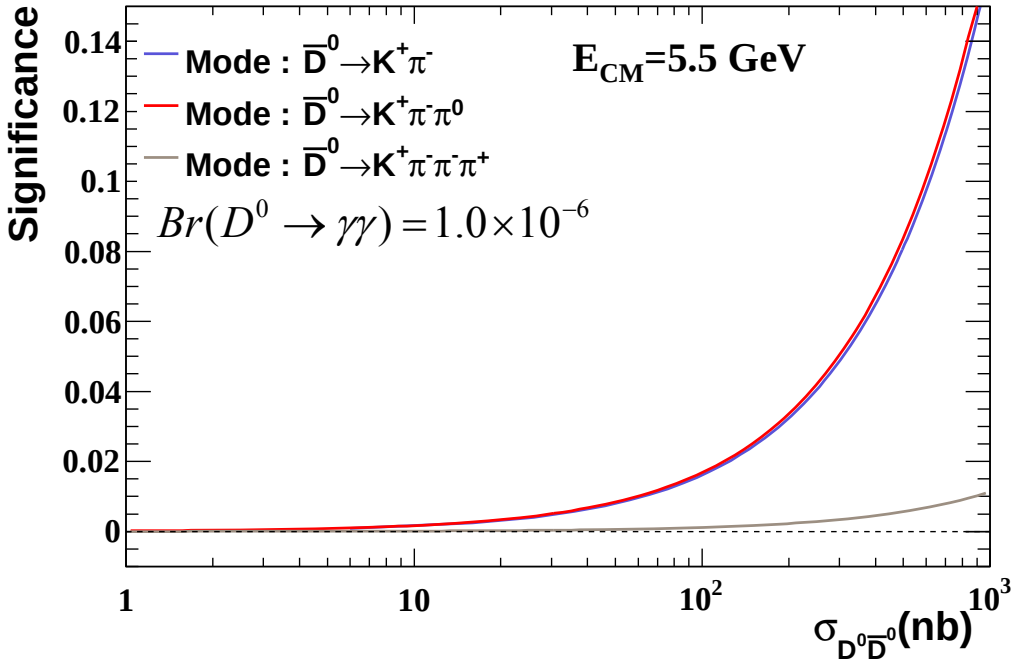
- Extend to maximum energy E_{CM}=5.5 GeV
- open charm peaking bkg. is shifted to higher M_{BC}
- number of signal event is expected to be small ~ 10

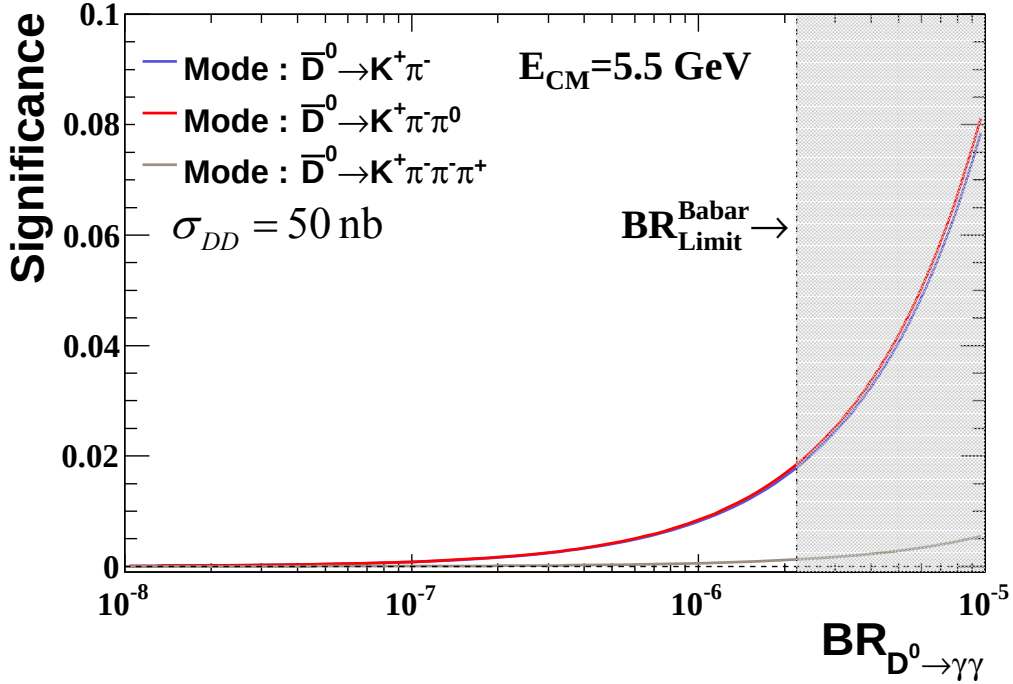


Statistical significance









Summary

- Open charm rare decay for $\mathrm{BR}_{(D\to\gamma\gamma)} < 2.2\times10^{-6}$ can be feasible with assuming of $\sigma_{DD} > 100$ nb

- Evaluate the size and shape of background and provide the significance map in sensitivity of cross section and $\mathrm{BR}_{(D\to\gamma\gamma)}$

- Necessary further background reduction : one order of magnitude

- Above E_{CM}=3.77 GeV, there are other considerable channels

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

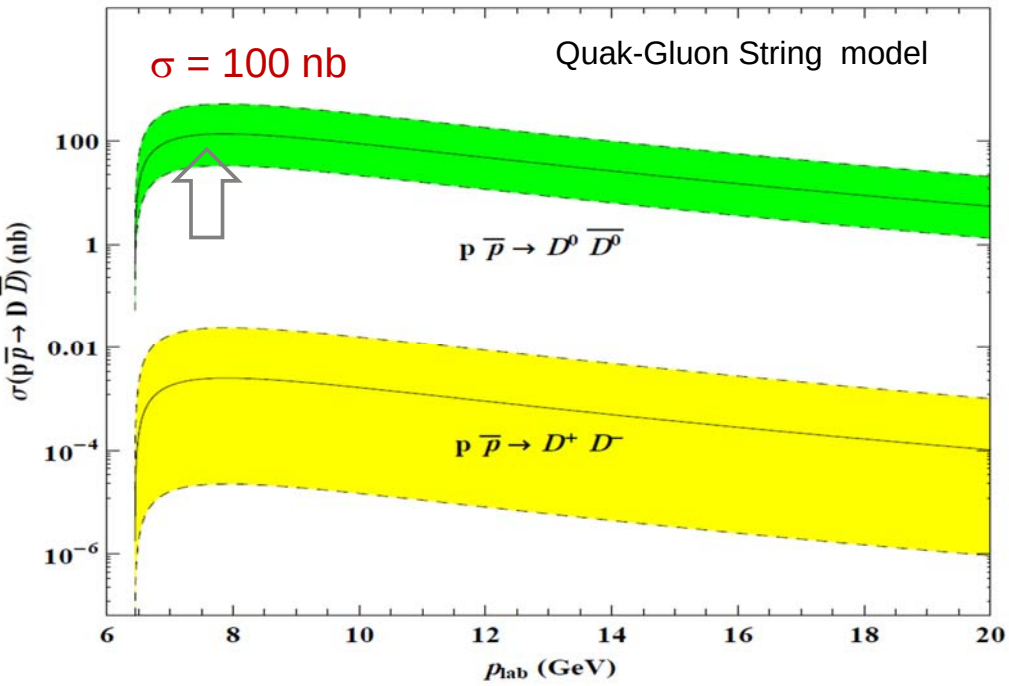
$$\bar{p}p \to D^{0*}\overline{D}^0, D^0\overline{D}^{0*}, D^{0*}\overline{D}^{0*}$$

- Technical note: https://panda.gsi.de/publication/in-rep-2015-007.pdf

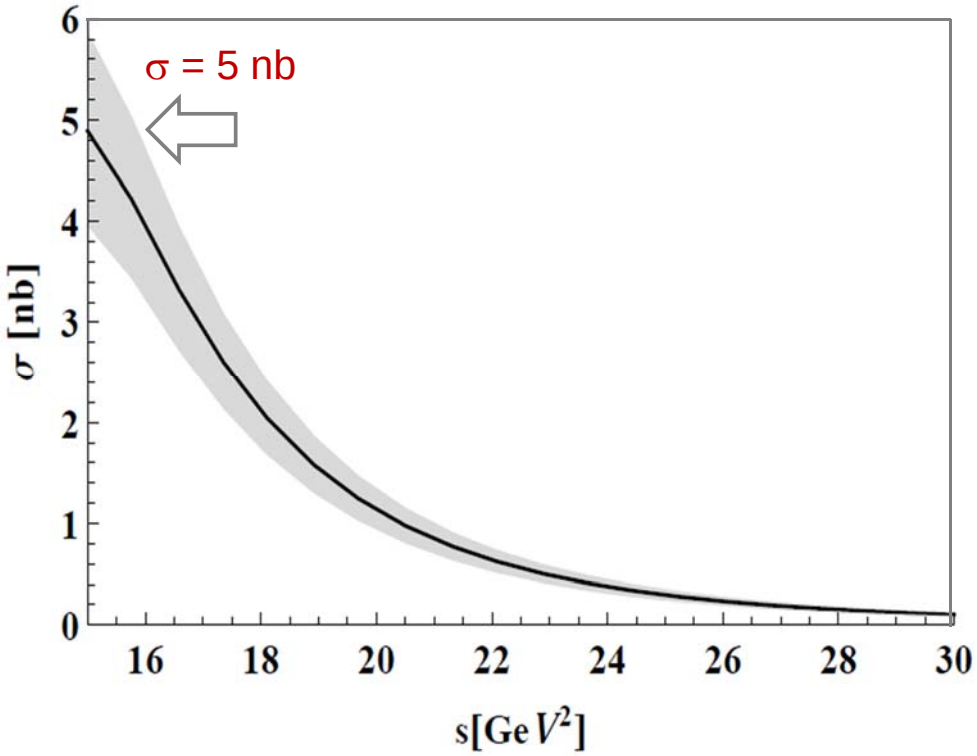
Backup

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



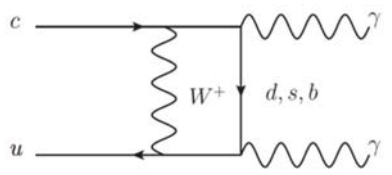
BESIII suggested [arXiv:1403.6011v1 24 Mar 2014]
two different solution for D^0D^0 cross section using the $\psi(3770) \to pbarp$

either $\sigma=(9.8\pm5.7)$ nb or $\sigma=(425.6\pm42.9)$ nb

Branching ratio of $D^0 \to \gamma\gamma$

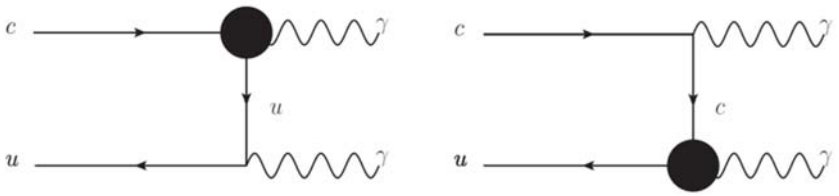
Standard Model

- Short distance contribution

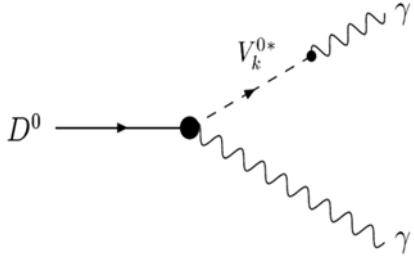


$$Br^{SD}_{D^0\to\gamma\gamma} = 3\times10^{-11}$$

[Phys.Rev D66 014009 (2002)]



- Long distance contribution
  - Vector Meson Dominance



$$Br^{VMD}_{D^0\to\gamma\gamma} = (3.5^{+4.0}_{-2.6})\times10^{-8}$$

[Phys.Rev D66 014009 (2002)]

  - Heavy Quark Chiral Pertubation Theory

$$Br^{HQ\chi PT}_{D^0\to\gamma\gamma} = (1.0\pm0.5)\times10^{-8}$$

[Phys.Rev D64 074008 (2001)]

New Physics

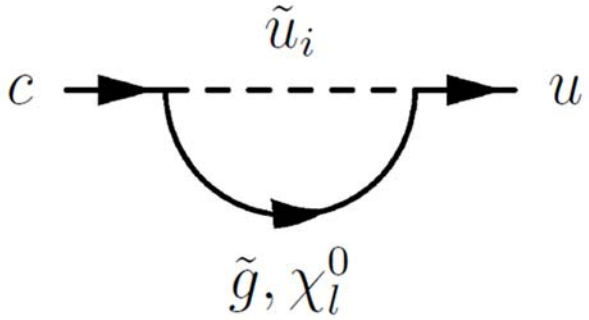
$c\to u\gamma$ transition can be enhanced by NP, e.g. some NP models can allow FCNC decay at sizeable level

- Littlest Higgs model with T parity

$$Br^{LHT}_{D^0\to\gamma\gamma} = Br^{SM,SD}_{D^0\to\gamma\gamma} + O(10\%)$$

[Phys.Rev D82 094006 (2010)]

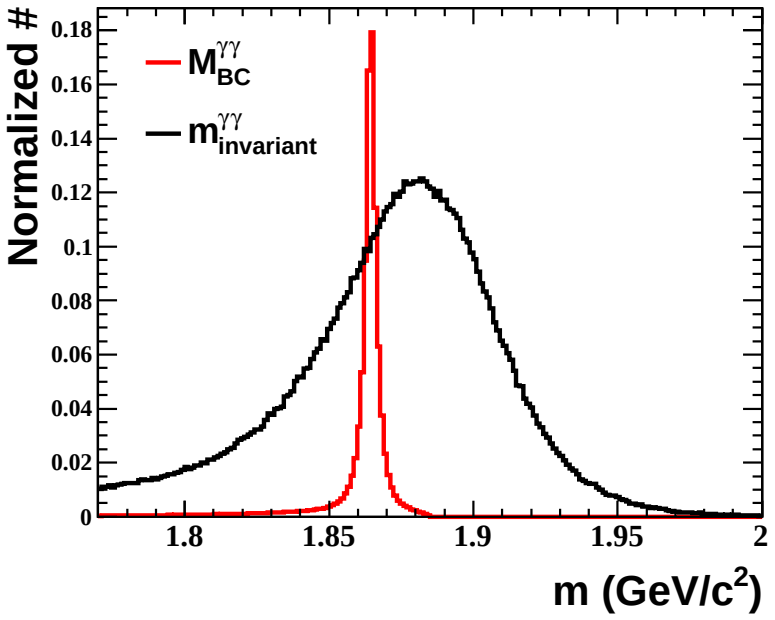
- Minimal Supersymmetry SM

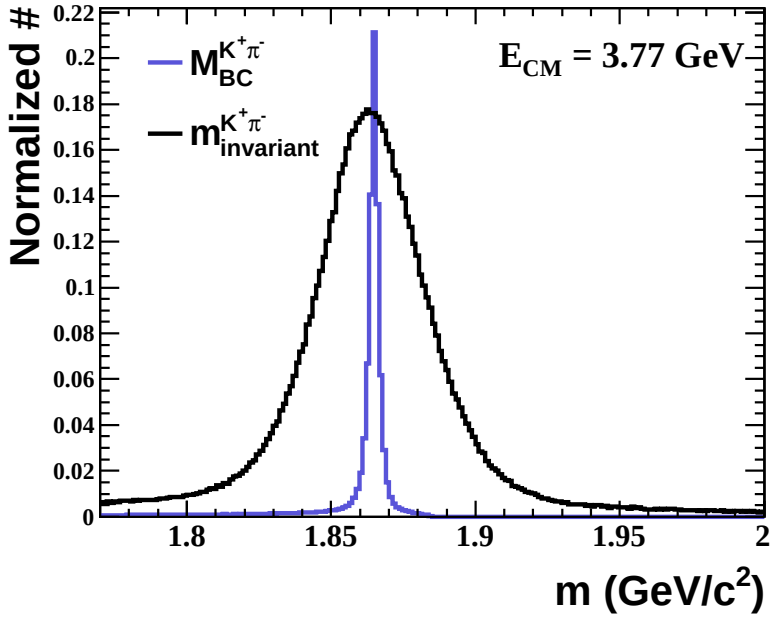


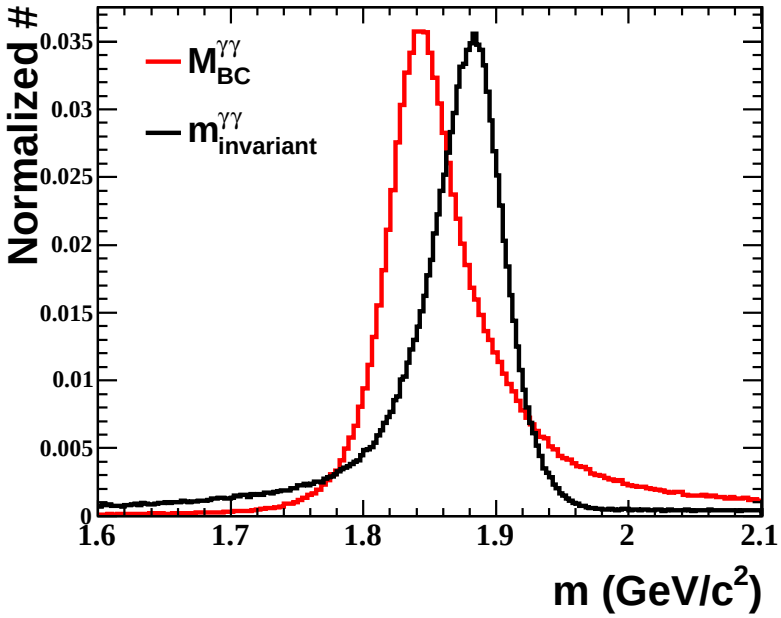
$$Br^{MSSM}_{D^0\to\gamma\gamma} = 6\times10^{-6}$$

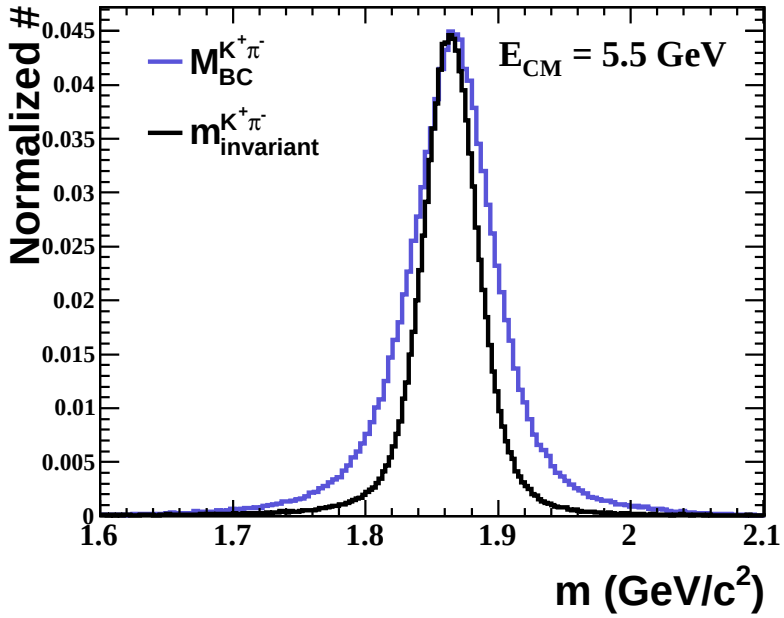
[Phys.Lett.B500 304-312 (2001)]

Beam constraint mass



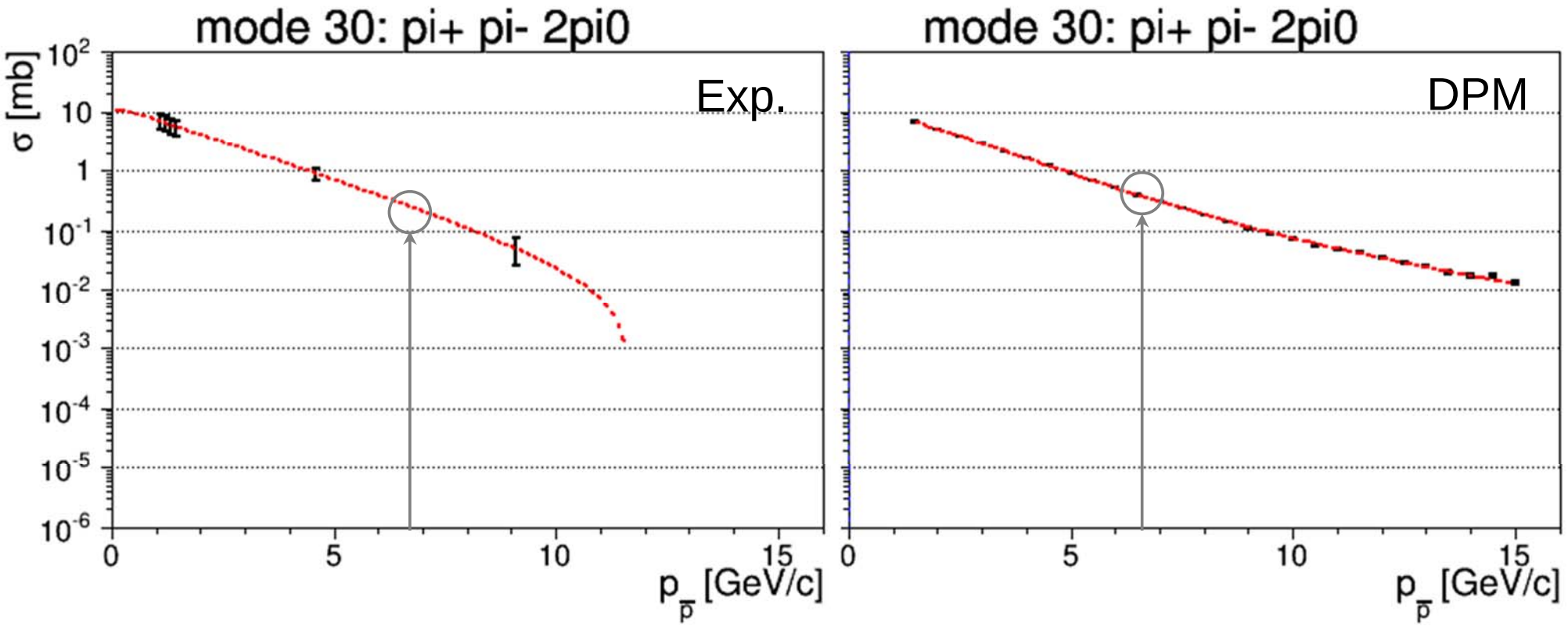






Study on pion background

DPM describe experimental data for relating $2\pi^0$ / $3\pi^0$ / $2\pi^0$ background channels well → no sizable systematic uncertainty due to incorrect fraction



Expected number of events

Extend to maximum energy E_{CM}=5.5 GeV: $S/B_{peaking}$ is assumed to be 0.5

Mode : $E_{CM} = 5.50$ GeV			
Signal			
$D^0\bar{D}^0 \to \gamma\gamma K^+\pi^-$	4.16%	8.6	
$D^0\bar{D}^0 \to \gamma\gamma K^+\pi^-\pi^0$	1.88%	3.9	
$D^0\bar{D}^0 \to \gamma\gamma K^+\pi^-\pi^-\pi^+$	0.51%	1.1	
DPM Background			
$p\bar{p} \to \pi^0\pi^0\pi^+\pi^-$	$< 3.48 \times 10^{-8}$ (1 events)	$< 1.7 \times 10^3$	30 M events simulated
$p\bar{p} \to \pi^0\pi^0\pi^+\pi^-\pi^0$	$< 3.42 \times 10^{-8}$ (1 events)	$< 4.1 \times 10^3$	(remaining event)
$p\bar{p} \to \pi^0\pi^0\pi^+\pi^-\pi^-\pi^+$	$< 3.0 \times 10^{-8}$ (0 events)	$< 2.2 \times 10^5$	
Open charm background			
$D^0\bar{D}^0 \to \pi^0\pi^0K^+\pi^-$	3.62×10^{-5}	6.3	
$D^0\bar{D}^0 \to \pi^0\pi^0K^+\pi^-\pi^0$	1.20×10^{-4}	20.9	
$D^0\bar{D}^0 \to \pi^0\pi^0K^+\pi^-\pi^-\pi^+$	5.13×10^{-6}	0.9	

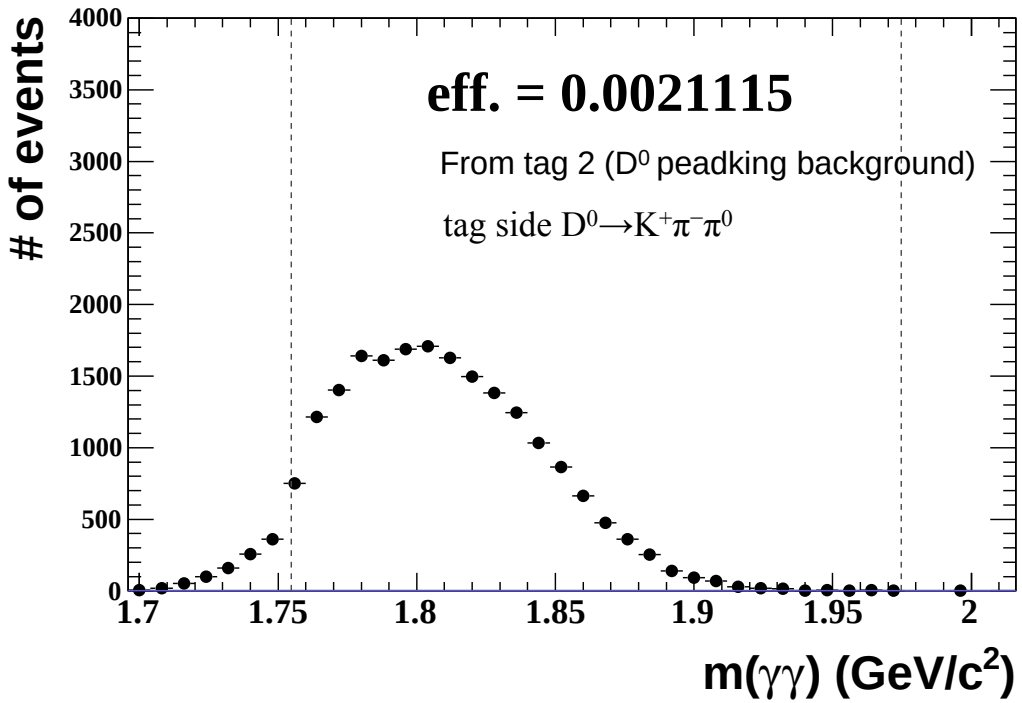
Background reduction

Main background source

1. $\bar{p}p \to X \to \pi^+\pi^-(\pi^0,\eta,\gamma) \to \pi^+\pi^- 3\gamma(\text{upto } 8\gamma)$

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

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



	Channel	σ (μb)
1	$\pi^+\pi^-3\pi^0$	658.867
2	$\pi^+\pi^-4\pi^0$	601.661
3	$\pi^+\pi^-2\pi^0$	374.696
4	$\pi^+\pi^-3\pi^0\eta$	289.990
5	$\pi^+\pi^-2\pi^0\eta$	249.004
6	$\pi^+\pi^-\pi^0$	126.814
7	$\pi^+\pi^-\pi^0\eta$	109.646
8	$\pi^+\pi^-2\pi^02\eta$	41.710
9	$\pi^+\pi^-3\pi^0\gamma$	31.438
10	$\pi^+\pi^-\pi^02\eta$	28.497
11	$\pi^+\pi^-4\pi^0\gamma$	28.068
12	$\pi^+\pi^-\eta$	14.801
13	$\pi^+\pi^-2\pi^0\gamma$	14.579
14	$\pi^+\pi^-2\pi^02\gamma$	13.374
15	$\pi^+\pi^-3\pi^02\gamma$	11.127
16	$\pi^+\pi^-3\pi^0\gamma\eta$	9.213
17	$\pi^+\pi^-2\eta$	8.122
18	$\pi^+\pi^-2\pi^0\gamma\eta$	8.084
19	$\pi^+\pi^-\pi^02\gamma$	7.531
20	$\pi^+\pi^-\pi^0\gamma$	4.683
... 24	$\pi^+\pi^-2\gamma\eta$	1.047
Σ		2455.320

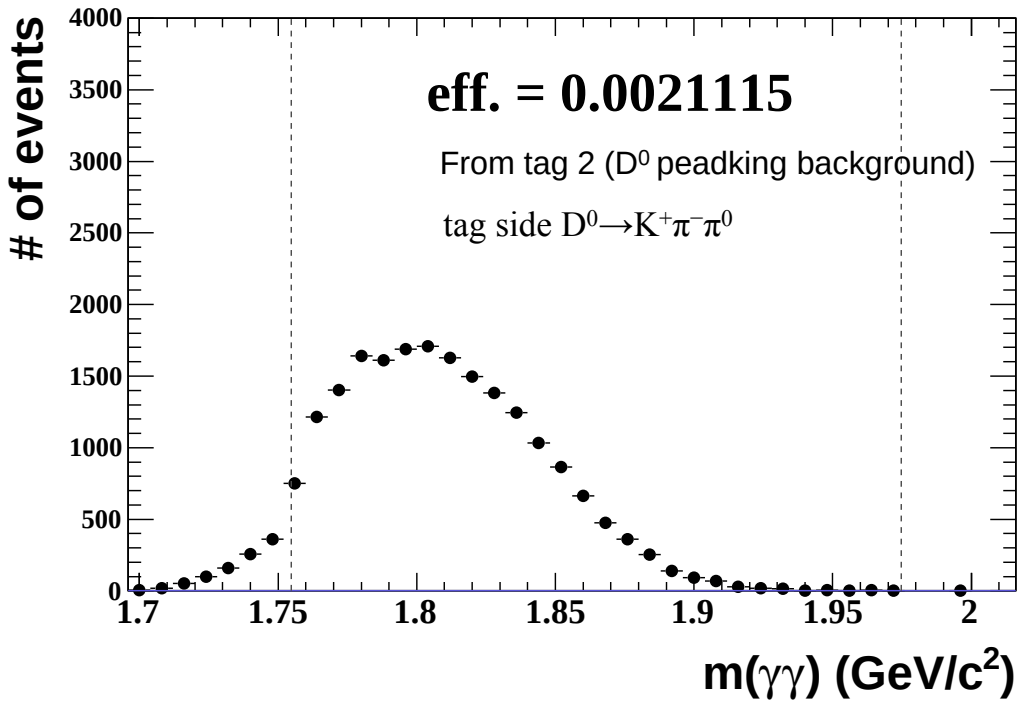
Background reduction

Main background source

1. $\bar{p}p \to X \to \pi^+\pi^-(\pi^0,\eta,\gamma) \to \pi^+\pi^- 3\gamma(\text{upto } 8\gamma)$

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

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



BR	Channel	decay mode
0.0006	K- pi0 e+ nu_e	PHOTOS PHSP;
0.0006	K- pi0 mu+ nu_mu	PHOTOS PHSP;
0.0212	anti-K0 pi0	PHSP;
0.1390	K- pi+ pi0	D_DALITZ;
0.0085	K*BR pi0	SVS;
0.0071	anti-K_10 pi0	SVS;
0.0078	anti-K0 pi0 pi0	PHSP;
0.0116	anti-K*0 pi0 pi0	PHSP;
0.0100	K*- pi+ pi0	PHSP;
0.0068	K- rho+ pi0	PHSP;
0.0085	anti-K0 pi+ pi- pi0	PHSP;
0.0258	K- pi+ pi0 pi0	PHSP;
0.0143	anti-K0 pi0 pi0 pi0	PHSP;
0.0038	K- pi+ pi+ pi- pi0	PHSP;
0.0038	K- pi+ pi0 pi0 pi0	PHSP;
0.0638	anti-K0 pi+ pi- pi0 pi0	PHSP;
0.0192	anti-K0 pi+ pi- pi0 pi0 pi0	PHSP;
0.0007	phi pi0	SVS;
0.0030	K+ K- pi0 pi0	PHSP;
0.0015	anti-K0 K0 pi0 pi0	PHSP;
0.0008	pi0 pi0	PHSP;
0.0010	eta pi0	PHSP;
0.0010	eta' pi0	PHSP;
0.0020	rho0 pi0	SVS;
0.0060	pi+ pi- pi0	PHSP;
0.0010	pi0 pi0 pi0	PHSP;
0.0050	pi+ pi- pi0 pi0	PHSP;
0.0177	pi+ pi- pi+ pi- pi0	PHSP;
0.0060	pi+ pi- pi0 pi0 pi0	PHSP;
0.0005	pi- K+ pi0	PHSP;

List of background subset

	$D^0\overline{D}^0 \to \gamma\gamma\, K^+\pi^-$		$D^0\overline{D}^0 \to \gamma\gamma\, K^+\pi^-\pi^0$		$D^0\overline{D}^0 \to \gamma\gamma\, K^+\pi^-\pi^-\pi^+$	
	Channel	σ (μb)	Channel	σ (μb)	Channel	σ (μb)
1	$\pi^+\pi^-2\pi^0$	374.696	$\pi^+\pi^-3\pi^0$	658.867	$2\pi^+2\pi^-2\pi^0$	2255.403
2	$\pi^+\pi^-\pi^0$	126.814	$\pi^+\pi^-4\pi^0$	601.661	$2\pi^+2\pi^-\pi^0$	1189.368
3	$\pi^+\pi^-\pi^0\eta$	109.646	$\pi^+\pi^-2\pi^0$	374.696	$2\pi^+2\pi^-\pi^0\eta$	515.681
4	$\pi^+\pi^-\eta$	14.801	$\pi^+\pi^-3\pi^0\eta$	289.990	$2\pi^+2\pi^-\eta$	155.669
5	$\pi^+\pi^-2\pi^0\gamma$	14.579	$\pi^+\pi^-2\pi^0\eta$	249.004	$2\pi^+2\pi^-2\pi^0\gamma$	113.998
6	$\pi^+\pi^-2\eta$	8.122	$\pi^+\pi^-\pi^0\eta$	109.646	$2\pi^+2\pi^-\pi^0\gamma$	54.200
7	$\pi^+\pi^-\pi^02\gamma$	7.531	$\pi^+\pi^-2\pi^02\eta$	41.710	$2\pi^+2\pi^-2^\eta$	29.245
8	$\pi^+\pi^-\pi^0\gamma$	4.683	$\pi^+\pi^-3\pi^0\gamma$	31.438	$2\pi^+2\pi^-\pi^0\gamma\eta$	20.193
9	$\pi^+\pi^-2\gamma$	1.397	$\pi^+\pi^-\pi^02\eta$	28.497	$2\pi^+2\pi^-\pi^02\gamma$	19.577
10	$\pi^+\pi^-2\gamma\eta$	1.047	$\pi^+\pi^-2\pi^0\gamma$	14.579	$2\pi^+2\pi^-2\gamma$	8.007
11			$\pi^+\pi^-2\pi^02\gamma$	13.374	$2\pi^+2\pi^-\gamma\eta$	5.639
12			$\pi^+\pi^-3\pi^02\gamma$	11.127	$2\pi^+2\pi^-2\gamma\eta$	2.294
13			$\pi^+\pi^-2\eta$	8.122		
14			$\pi^+\pi^-2\pi^0\gamma\eta$	8.084		
15			$\pi^+\pi^-\pi^02\gamma$	7.531		
16			$\pi^+\pi^-2\pi^02\gamma\eta$	3.195		
17			$\pi^+\pi^-\pi^02\gamma\eta$	2.757		
18			$\pi^+\pi^-2\gamma\eta$	1.047		