Acp in $D^+ \to \eta\pi^+$, $D^0 \to \eta\eta$

Status report

Yonsei Univ.

Jaeyoung Kim (jaeyoung_kim@yonsei.ac.kr)

2024.10.16.

(reminder)Analysis procedure

$D^+ \to \eta\pi^+$: D^{*+} tag & non- D^{*+} tag

- $\eta \to \gamma\gamma$ & $\eta \to \pi^+\pi^-\pi^0$
- Separate samples according to D^{*+} tag & non-D^{*+} tag
  - To use high background suppression with D^{*+} tag

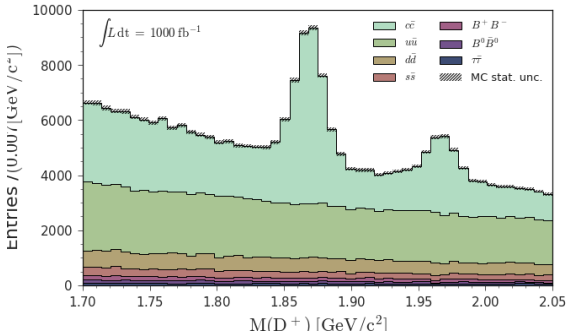
- Sample: MC15ri generic

$D^0 \to \eta\eta$: D^{*+} tag

- $\eta_{\gamma\gamma}\,\eta_{3\pi}$ & $\eta_{\gamma\gamma}\,\eta_{3\pi}$ (& $\eta_{3\pi}\eta_{3\pi}$: low statistics)
- non-D^{*+} tag
  - Not yet any planned.
  - If we don't have enough statistics, consider using CFT

Cut optimization(step2, tagged)

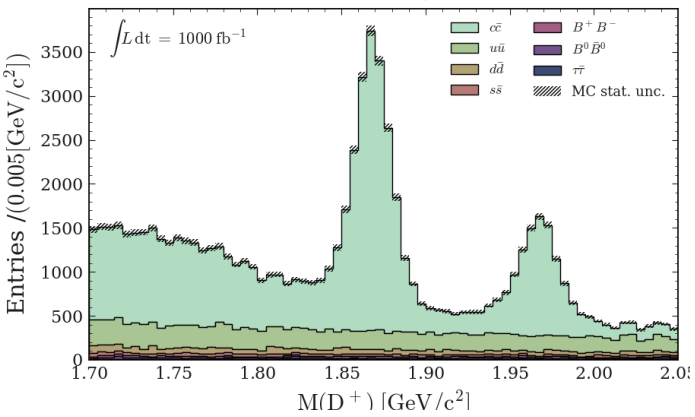
$D^+ \to \eta_{\gamma\gamma}\pi^+$

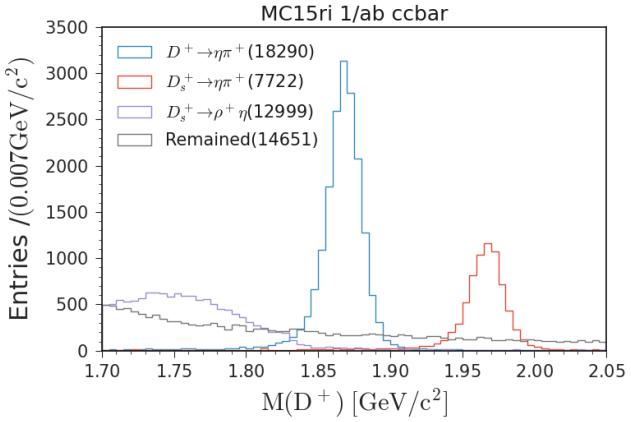


- ϵ decreased by 31%

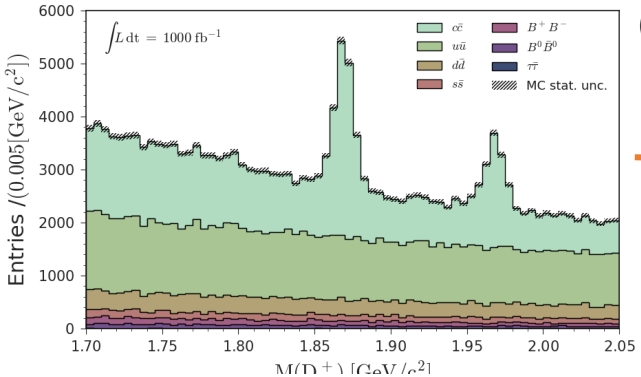
❑ Optimized cuts in $1.78 < \mathrm{M}(D^+) < 1.95$

- $\cos\theta_{xy} > 0.99964 (\theta_{xy} < 1.5°)$
- $p(\eta) > 1.14$GeV
- $p(\pi^+) > 0.48$GeV





$D^+ \to \eta_{3\pi}\pi^+$

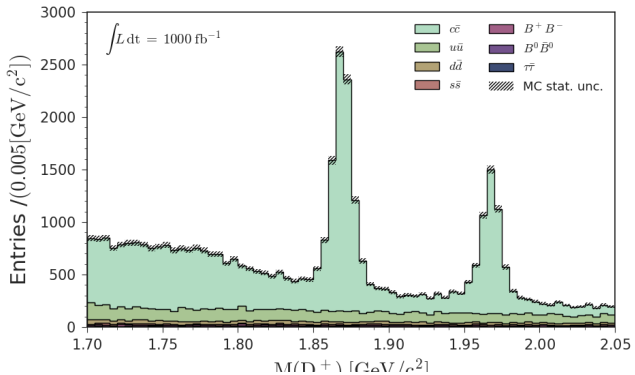


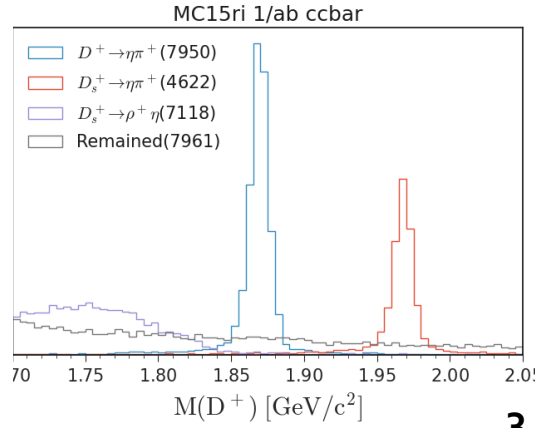
- $\cos\theta_{xy}$
  Cosine of angle between p and vertex vector
  (vector connecting IP and fitted vertex)

- ϵ decreased by 34%

❑ Optimized cuts in $1.80 < \mathrm{M}(D^+) < 1.94$

- $\cos\theta_{xy} > 0.9995 (\theta_{xy} < 1.8°)$
- $p(\eta) > 0.98$GeV
- $p(\pi^+) > 0.49$GeV

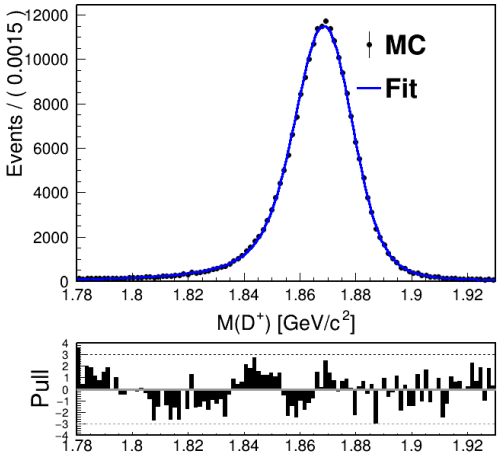


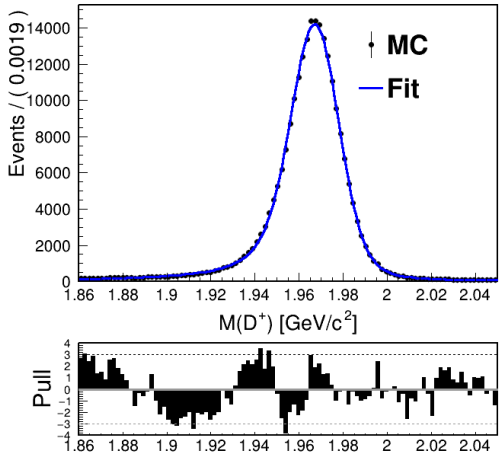


Signal pdf(arbitrary tight cuts)

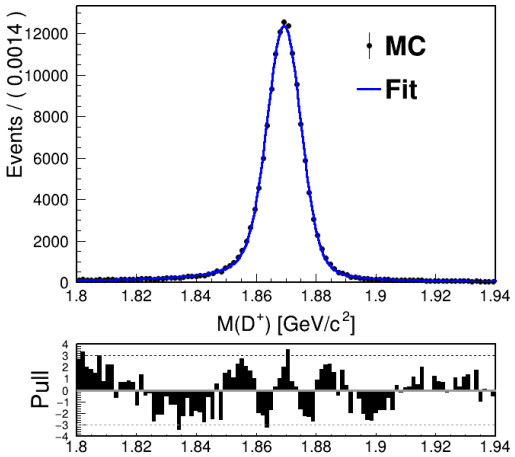
$D^+ \to \eta_{\gamma\gamma}\pi^+$

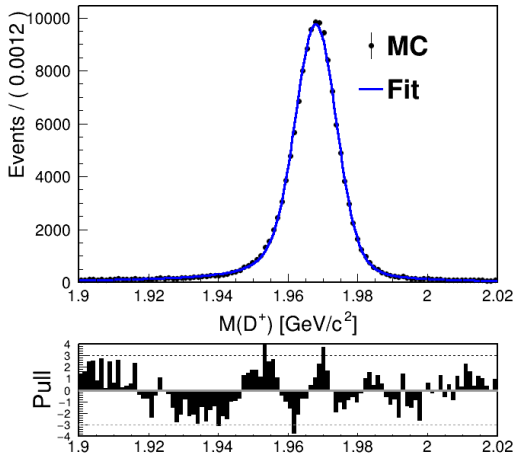
- Johnson with gaussian convolution(parameters of johnson are fixed by signal MC)





$D^+ \to \eta_{3\pi}\pi^+$





$D^+ \to \eta_{\gamma\gamma}\pi^+$(arbitrary tight cuts)

First fit

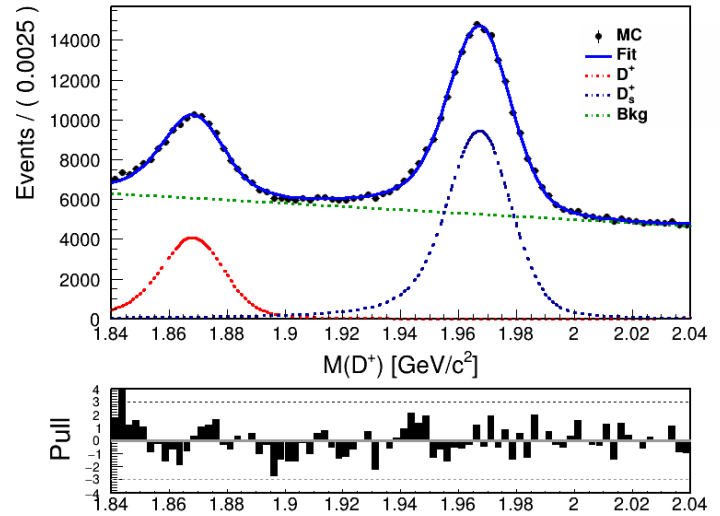
- Learned how to do simultaneous fit(D+ and D-)
- Implemented using RooFit(pyROOT)

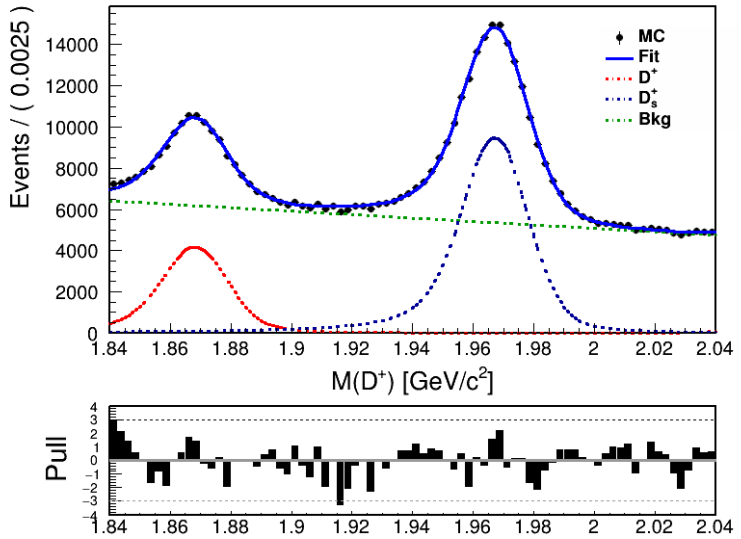
```
Nsig_D_plus = RooFormulaVar("Nsig_D_plus",
    "0.5 * N_total * (1 + Acp)",
    RooArgList(N_total, Acp))

Nsig_D_minus = RooFormulaVar("Nsig_D_minus",
    "0.5 * N_total * (1 - Acp)",
    RooArgList(N_total, Acp))
```

```
RooFitResult: minimized FCN value: -1.62215e+07, e
              covariance matrix quality: Full, acc
              Status : MINIMIZE=0 HESSE=0 HESSE=0

  Floating Parameter    FinalValue +/-  Error
--------------------  --------------------------
                 Acp   -1.0376e-02 +/-  6.93e-03
              Acp_Ds   -3.3211e-04 +/-  3.36e-03
   Ds_mean_gaussian   -2.4300e-02 +/-  4.54e-05
  Ds_sigma_gaussian    9.4382e-03 +/-  5.19e-05
             N_total    9.5634e+04 +/-  1.10e+03
          N_total_Ds    2.4012e+05 +/-  9.43e+02
         Nbkg_D_minus    4.4632e+05 +/-  1.15e+03
          Nbkg_D_plus    4.3841e+05 +/-  1.12e+03
        mean_gaussian   -1.0648e-02 +/-  9.30e-05
       sigma_gaussian    8.8648e-03 +/-  1.33e-04
      x_bkg1_Cheby_c0   -3.8889e-01 +/-  2.61e-03
      x_bkg1_Cheby_c1    2.1969e-03 +/-  1.07e-03
```

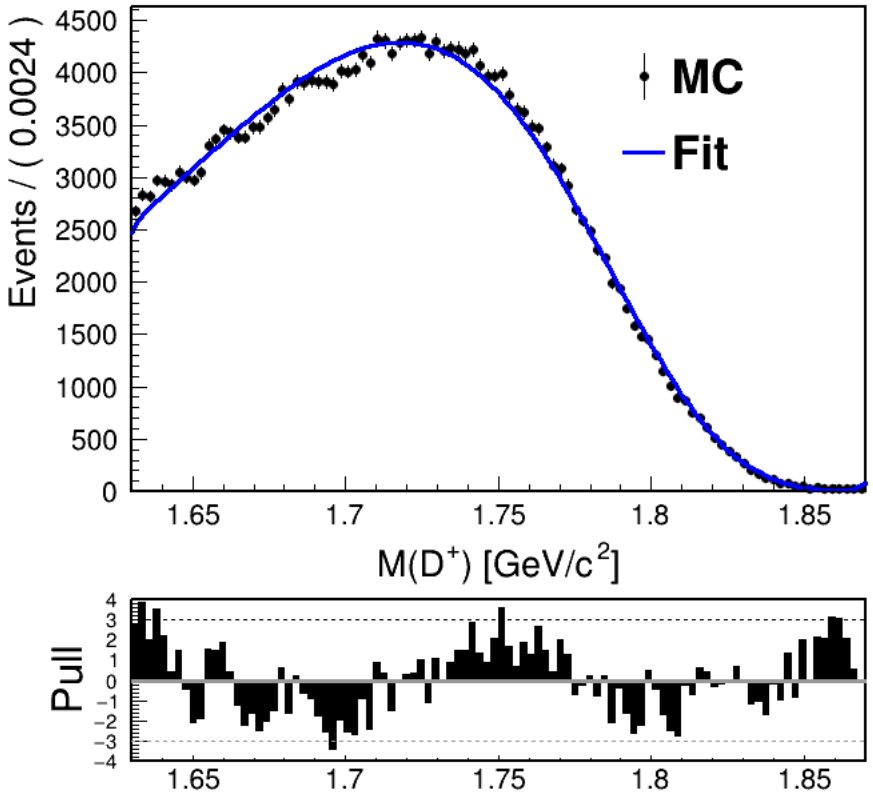




Lower region

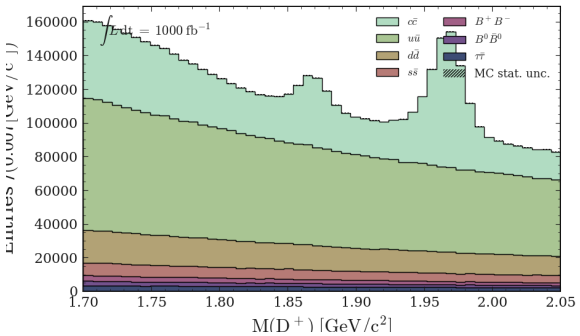
Source: $D_s^+ \to \eta_{\gamma\gamma}(\rho^+ \to \pi^+\pi^0)$

- Novo with gaussian convolution



Cut optimization(step2, non-tagged)

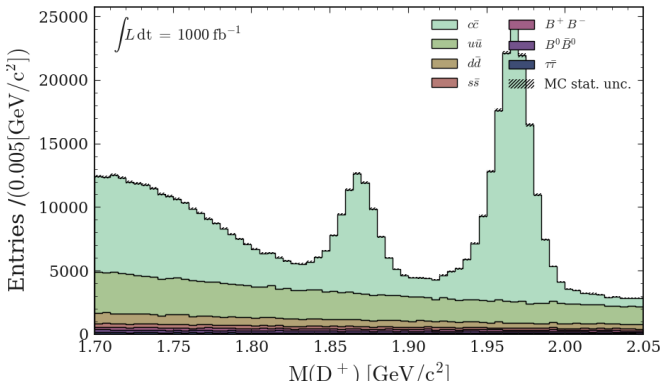
$D^+ \to \eta_{\gamma\gamma}\pi^+$

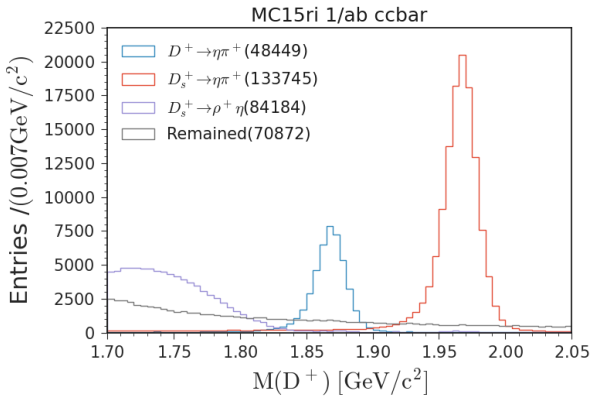


- ϵ decreased by 45%

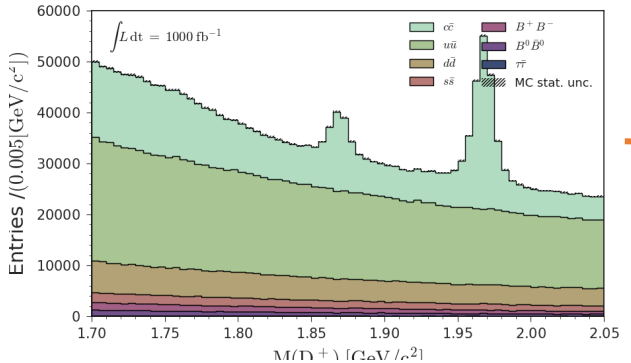
❑ Optimized cuts in $1.78 < \mathrm{M}(D^+) < 1.95$

- $\cos\theta_{xy} > 0.99930 (\theta_{xy} < 2.14°)$
- $p(\eta) > 1.24$GeV
- $p(\pi^+) > 0.63$GeV





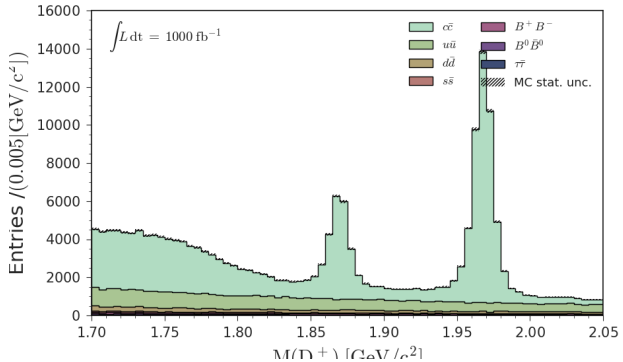
$D^+ \to \eta_{3\pi}\pi^+$

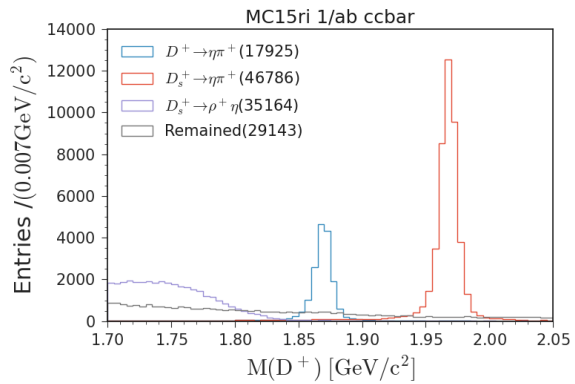


- ϵ decreased by 43%

❑ Optimized cuts in $1.80 < \mathrm{M}(D^+) < 1.94$

- $\cos\theta_{xy} > 0.99967 (\theta_{xy} < 1.47°)$
- $p(\eta) > 1.11$GeV
- $p(\pi^+) > 0.61$GeV





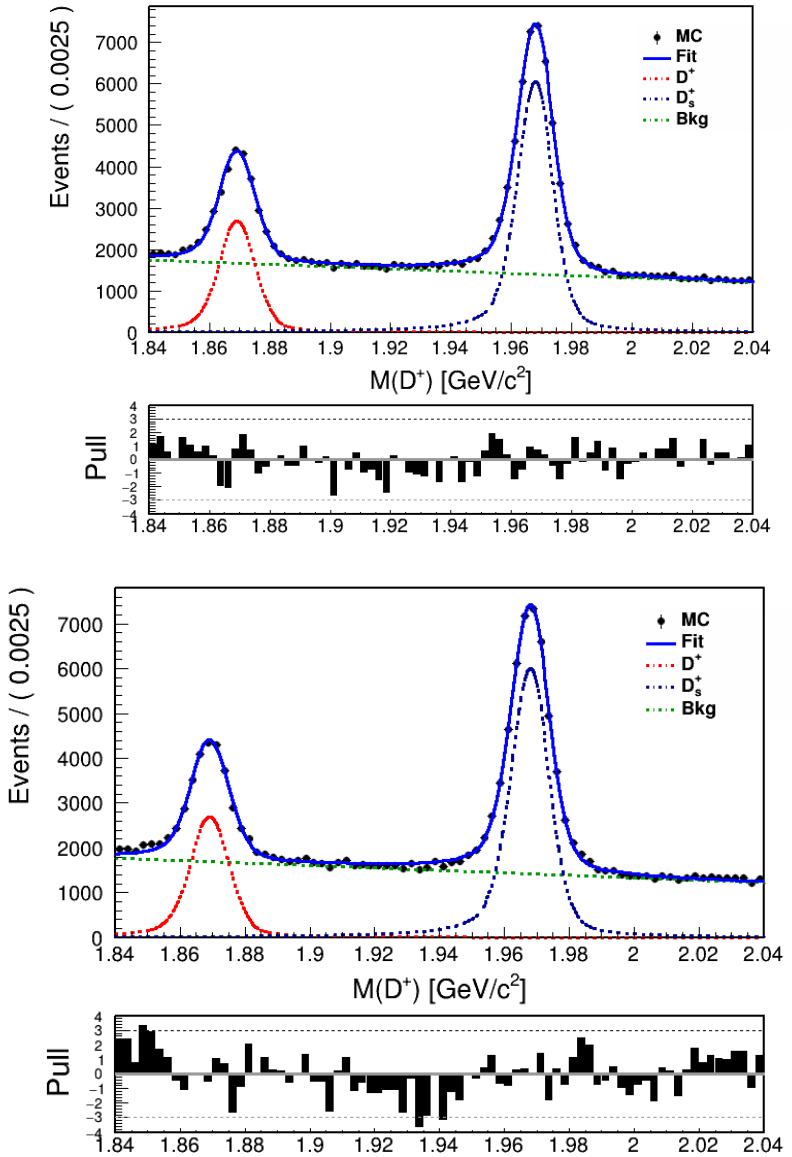
$D^+ \to \eta_{3\pi}\pi^+$(arbitrary tight cuts)

First fit

- Learned how to do simultaneous fit(D+ and D-)
- Implemented using RooFit(pyROOT)

```
RooFitResult: minimized FCN value: -4.3625e+06, es
              covariance matrix quality: Full, acc
              Status : MINIMIZE=0 HESSE=0 HESSE=0

  Floating Parameter    FinalValue +/-  Error
--------------------  --------------------------
                 Acp   -9.7866e-04 +/-  8.31e-03
              Acp_Ds    4.0440e-03 +/-  4.56e-03
    Ds_mean_gaussian   -7.4788e-03 +/-  3.34e-05
   Ds_sigma_gaussian    5.2763e-03 +/-  3.43e-05
             N_total    3.6424e+04 +/-  3.85e+02
          N_total_Ds    8.4336e+04 +/-  4.07e+02
         Nbkg_D_minus    1.1995e+05 +/-  4.60e+02
          Nbkg_D_plus    1.1825e+05 +/-  4.56e+02
       mean_gaussian   -5.2831e-03 +/-  6.34e-05
      sigma_gaussian    5.3849e-03 +/-  7.30e-05
     x_bkg1_Cheby_c0   -4.1845e-01 +/-  3.75e-03
     x_bkg1_Cheby_c1    6.8695e-03 +/-  1.58e-03
```



Belle II ECL resolution

- $\sigma E/\sqrt{E}$, slightly changed from about 2.5% at 100 MeV to 1.7% at 5 GeV. - Link

Summary and plans

$D^+ \to \eta\pi^+$

- ❑ Do simultaneous fit
- ❑ Plans
  - MVA study(on-going)
  - Extract expected stats. uncertainty

$D^0 \to \eta\eta$

- ❑ Plans
  - Focus on $D^+ \to \eta\pi^+$ first
  - Try simultaneous fit

Backup

Cuts

Pre-selection(step0)

Particles	Selection Criteria
Hard $\pi^{\pm}$	In CDC acceptance $dr < 1$, $\lvert dz\rvert < 3$ $\mathcal{L}_{\pi} > 0.6$
Normal $\pi^{\pm}$ in $\eta_{3\pi}$	In CDC acceptance $dr < 1$, $\lvert dz\rvert < 3$ $\mathcal{L}_{\pi} > 0.1$
Slow π^{+}	In CDC acceptance $dr < 1$, $\lvert dz\rvert < 3$
γ of η	clusterNHits>1.5 0.2967< clusterTheta < 2.6180 $E > 0.1$[GeV]
γ of π^0	clusterNHits>1.5 0.2967< clusterTheta < 2.6180 $E_{\text{forward}} > 0.05$[GeV] or $E_{\text{barrel}} > 0.05$[GeV] or $E_{\text{backward}} > 0.075$[GeV]
π^0	$0.120 < M$[GeV] < 0.145 kFit(mass): reject if fit fails
$\eta_{\gamma\gamma}$	$0.52 < M$[GeV] < 0.57
$\eta_{3\pi}$	$0.535 < M$[GeV] < 0.57

Charm mesons

D^0	$1.6 < M(D^0)$[GeV] < 2.1 $p^* > 2$GeV
D^{*+}	$\Delta m < 0.160$GeV $p^* > 2.5$GeV Vertex TreeFit: Min(confidence level) $= 0.001$ IP constraint η, π^0 mass constraint

$\eta_{\gamma\gamma}$	$p > 0.4$[GeV]
$\eta_{3\pi}$	$p > 0.4$[GeV]
D^+	$1.6 < M(D^0)$[GeV] < 2.1 $p^* > 2.5$GeV Vertex TreeFit: Min(confidence level) $= 0.001$ IP constraint η, π^0 mass constraint

π^0 mass veto for $\eta_{\gamma\gamma}$

particles	selection criteria
γ_{ROE}	$\lvert$clusterTiming$\rvert < 200ns$ $\lvert\frac{\text{clusterTiming}}{\text{clusterErrorTiming}}\rvert < 2.0$ clusterNHits> 1.5 $E > 75$MeV

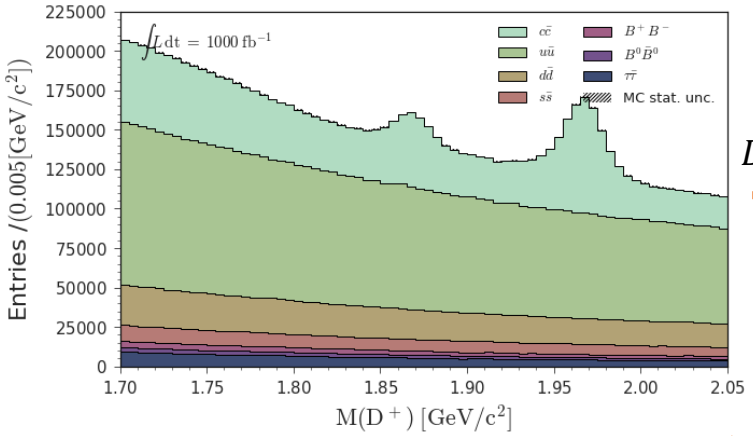
particles	selection criteria
$\lvert M(\gamma\gamma_{ROE}) - m_{\pi^0)}\rvert$	> 0.011GeV/c^2

D^{*+} tag for D^+

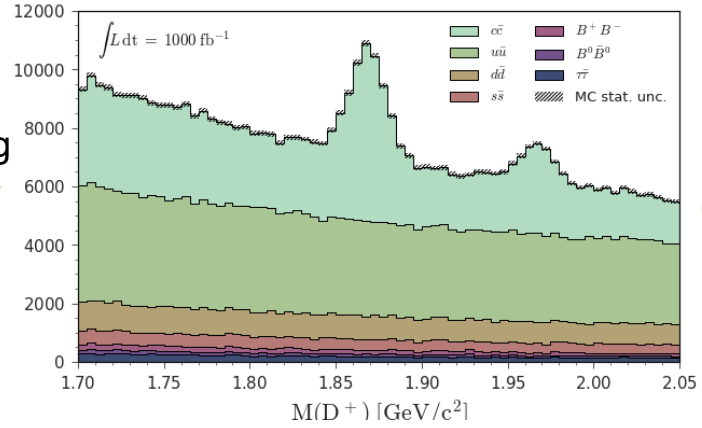
γ for slow π^0	$\lvert$clusterTiming$\rvert < 200ns$ $\lvert\frac{\text{clusterTiming}}{\text{clusterErrorTiming}}\rvert < 2.0$ clusterNHits> 1.5 $E_{\text{forward}} > 0.025$[GeV] or $E_{\text{barrel}} > 0.025$[GeV] or $E_{\text{backward}} > 0.040$[GeV]
slow π^0	$0.105 < M$[GeV] < 0.150 $p > 0.1$GeV
D^{*+}	$0.138 < \Delta m$[GeV] < 0.143 choose lowest $\lvert M(D^{*+}) - m(D^{*+})\rvert$

$D^+ \to \eta_{\gamma\gamma}\pi^+$(step1)

From pre-selection(step0)

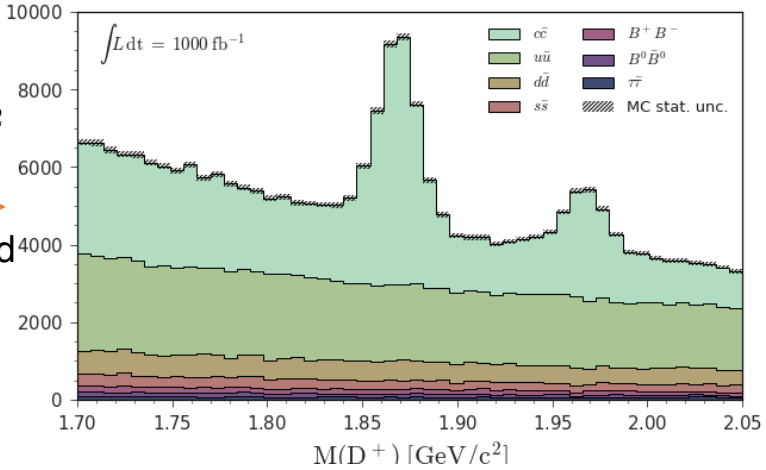


D^{*+} tag

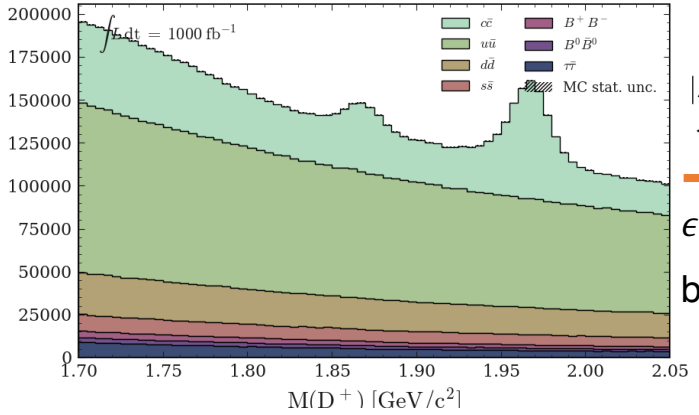


$\eta_{\gamma\gamma}$
$|\Delta\phi(\gamma_1,\gamma_2)| < 2$
$\sphericalangle(\gamma_1,\gamma_2) < 1.7$

ϵ decreased by 6%

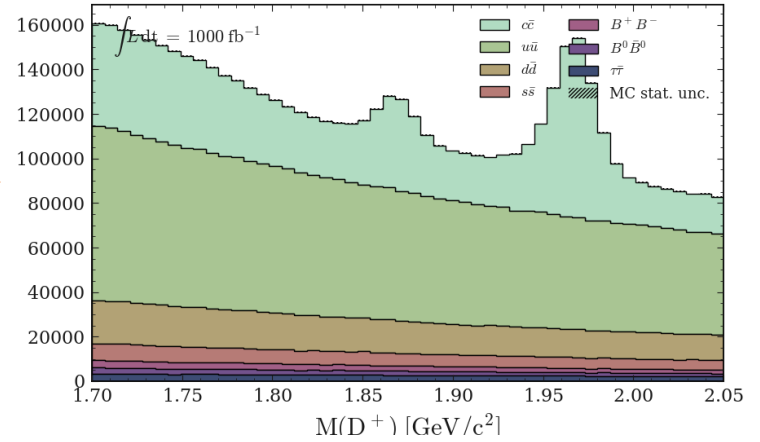


D^{*+} not tagged



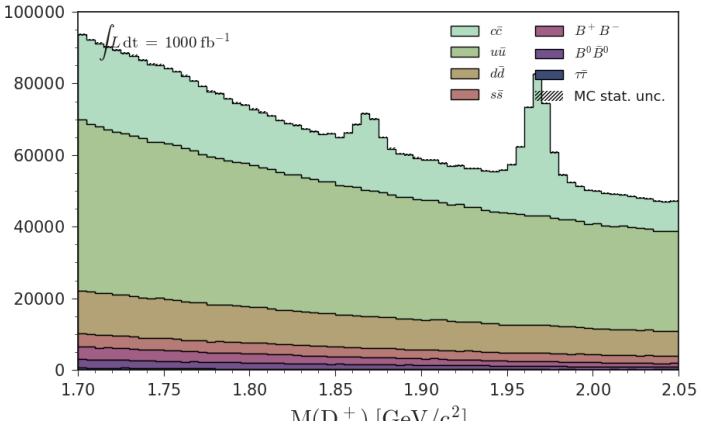
$\eta_{\gamma\gamma}$
$|\Delta\phi(\gamma_1,\gamma_2)| < 2$
$\sphericalangle(\gamma_1,\gamma_2) < 1.7$

ϵ decreased by 6%

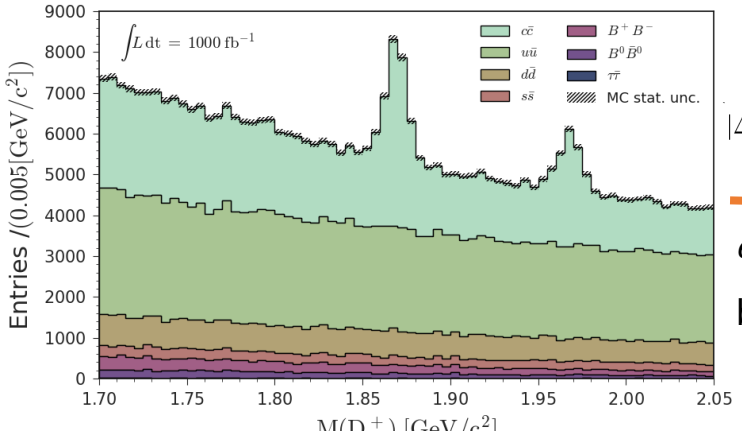


$D^+ \to \eta_{\pi^+\pi^-\pi^0}\pi^+$(step1)

From pre-selection(step0)



D^{*+} tag

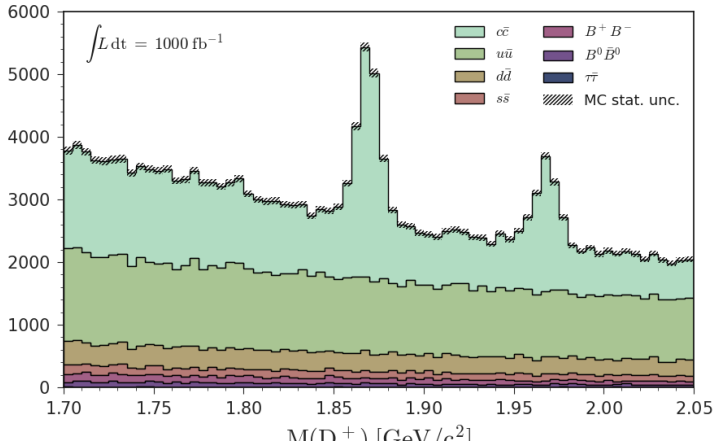


π^0

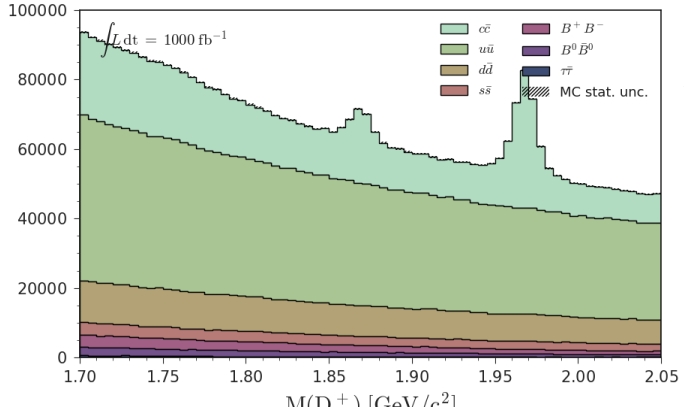
$|\Delta\phi(\gamma_1,\gamma_2)| < 1.5$

$\sphericalangle(\gamma_1,\gamma_2) < 1.4$

ϵ decreased by 5%



D^{*+} not tagged

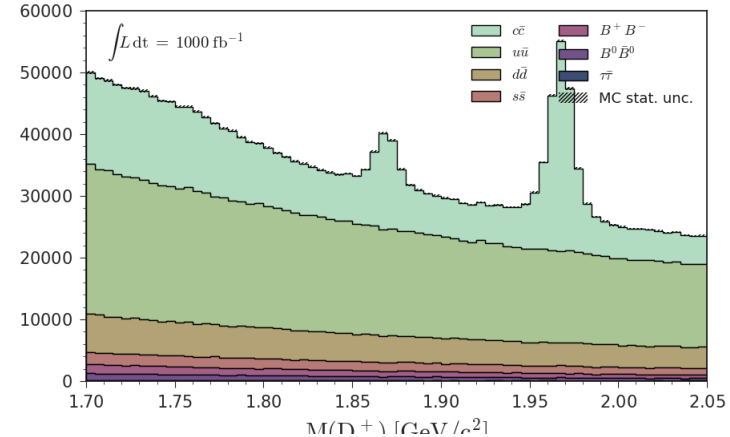


π^0

$|\Delta\phi(\gamma_1,\gamma_2)| < 1.5$

$\sphericalangle(\gamma_1,\gamma_2) < 1.4$

ϵ decreased by 5%



Estimation of signal yields

- Fitting is not done yet. Will do fit using simultaneous fit($D^+ + D^-$)
- Let's estimate signal yields by counting

Belle II: Nsig events(Topoana, counting)	$D^+ \to \eta_{\gamma\gamma}\pi^+$	$D^+ \to \eta_{3\pi}\pi^+$
Tagged, 1/ab	18290 ± 135.2	7950 ± 89.2
Non-tagged, 1/ab	48449 ± 220.1	17925 ± 133.9
Expected Nsig events in Run1(426/fb)	28430 ± 168.6	11023 ± 105.0

Previous results(fitted error)	$D^+ \to \eta_{e^+e^-\gamma}\pi^+$	$D^+ \to \eta_{\pi^+\pi^-\gamma}\pi^+$	$D^+ \to \eta_{3\pi}\pi^+$
LHCb(2021), 6/fb (ref.)	32760 ± 380		
LHCb(2023), 6/fb (ref.)		$(110.8 \pm 0.7) \cdot 10^3$	
Belle(2011), 791/fb (ref.)			6476 ± 110

Estimation of signal yields

- Still there would be room to improve yields. Trying to improve with MVA.

Belle II MC: pre-selection

Nsig true signal events after pre-selection (MC matched, counting)	$D^+ \to \eta_{\gamma\gamma}\pi^+$	$D^+ \to \eta_{3\pi}\pi^+$
Tagged, 1/ab	22922 ± 151	9681 ± 98
Non-tagged, 1/ab	93102 ± 305	31525 ± 178
Total: expected Nsig in Run1(426/fb)	116024 ± 341	41206 ± 203

Non tagged: signal efficiency decreased significantly

cut based study

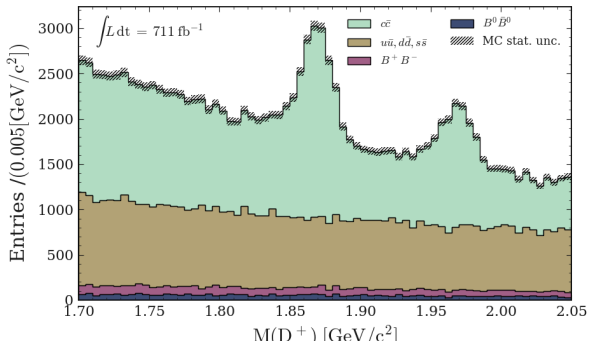
Belle + Belle II?

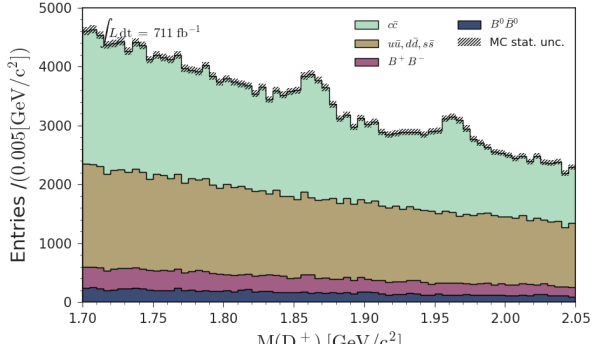
Estimation of signal yields

Belle MC: pre-selection(detail will be in later report)

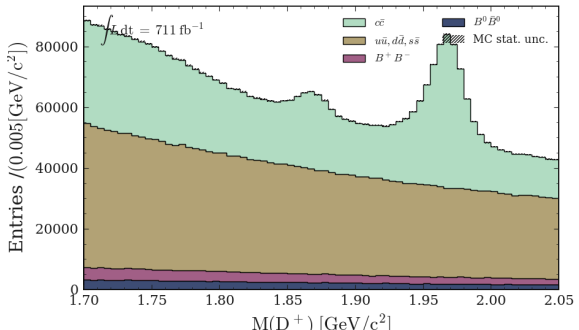
Belle: Nsig true events after pre-selection (MC matched, counting)	$D^+ \to \eta_{\gamma\gamma}\pi^+$	$D^+ \to \eta_{3\pi}\pi^+$
Tagged in $\Upsilon(4S)$ MC(711/fb)	7815±88	3668±61
Non-tagged in $\Upsilon(4S)$ MC(711/fb)	43214±208	17692±133
Total in $\Upsilon(4S)$ MC(711/fb)	51029±226	21360±146
Expected Nsig true events in full data (943/fb)	67680±260	28330±168

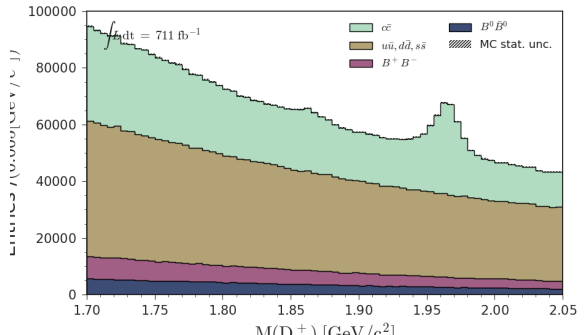
- Tag





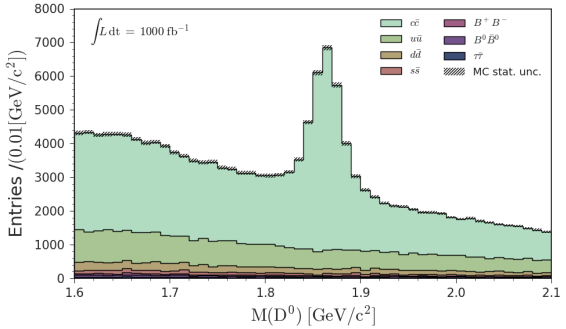
- Non-tagged

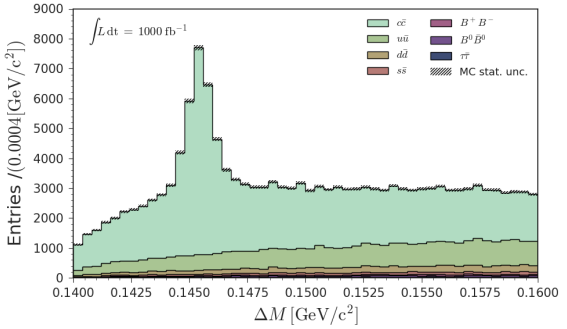




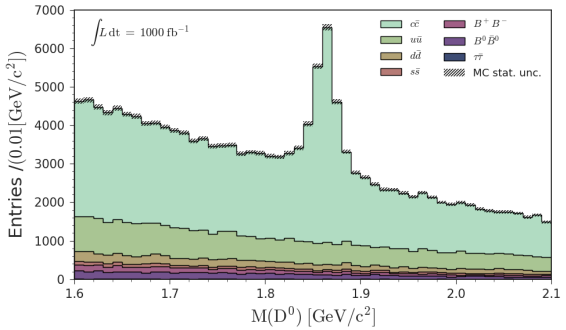
$D^0 \to \eta\eta$ distribution after pre-selection

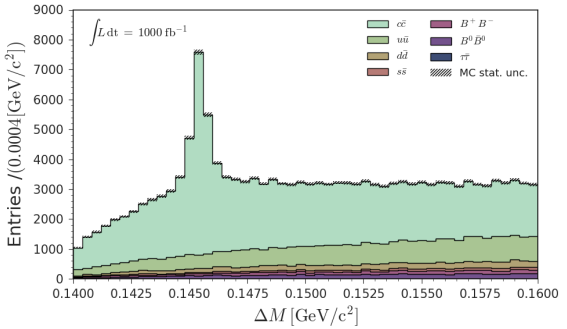
$D^0 \to \eta_{\gamma\gamma}\eta_{\gamma\gamma}$



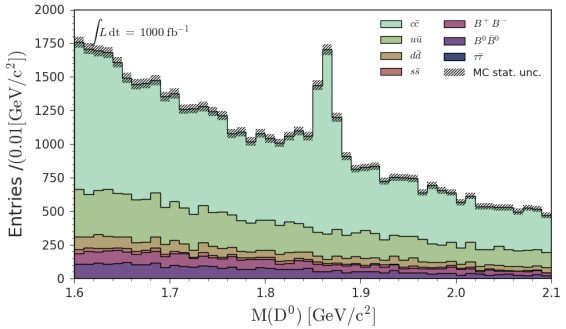


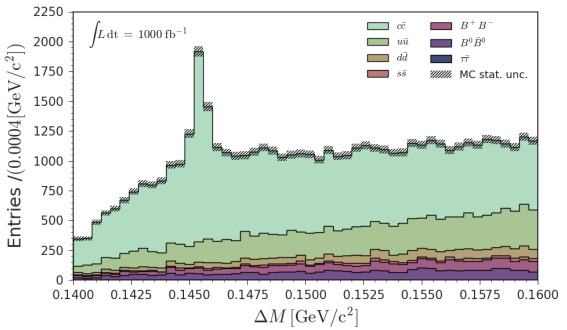
$D^0 \to \eta_{\gamma\gamma}\eta_{3\pi}$





$D^0 \to \eta_{3\pi}\eta_{3\pi}$



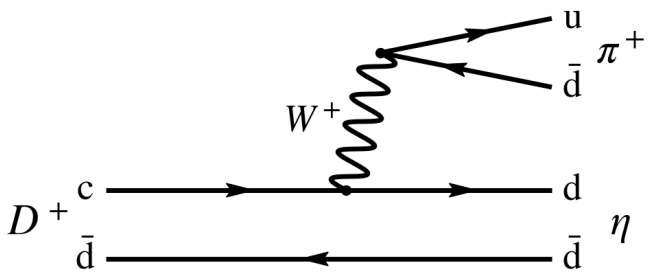


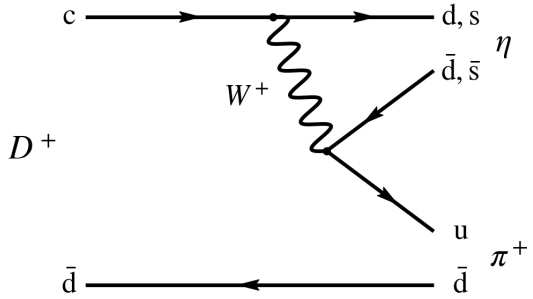
Particles	Selection Criteria
Hard $\pi^{\pm}$	In CDC acceptance $dr < 1$, $\lvert dz\rvert < 3$ $\mathcal{L}_{\pi} > 0.6$
Normal $\pi^{\pm}$ in $\eta_{3\pi}$	In CDC acceptance $dr < 1$, $\lvert dz\rvert < 3$ $\mathcal{L}_{\pi} > 0.1$
Slow π^{+}	In CDC acceptance $dr < 1$, $\lvert dz\rvert < 3$
γ of η	clusterNHits>1.5 0.2967< clusterTheta < 2.6180 $E > 0.1$[GeV]
γ of π^0	clusterNHits>1.5 0.2967< clusterTheta < 2.6180 $E_{\text{forward}} > 0.05$[GeV] or $E_{\text{barrel}} > 0.05$[GeV] or $E_{\text{backward}} > 0.075$[GeV]
π^0	$0.120 < M$[GeV] < 0.145 kFit(mass): reject if fit fails
$\eta_{\gamma\gamma}$	$0.52 < M$[GeV] < 0.57
$\eta_{3\pi}$	$0.535 < M$[GeV] < 0.57

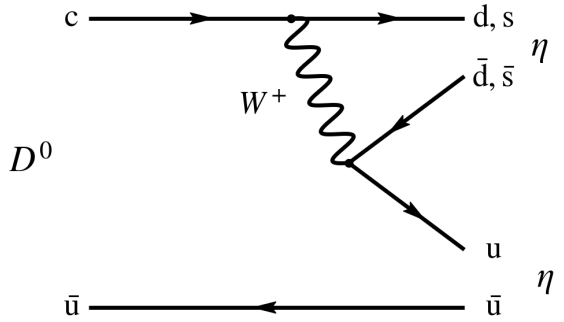
Motivation

Theoretical

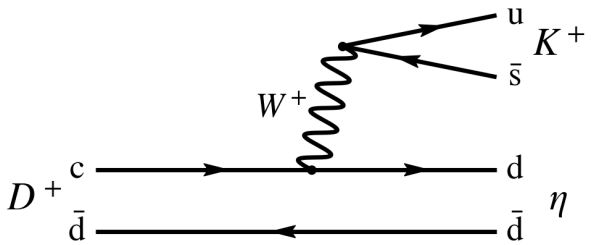
- $D^+ \to \eta\pi^+, D^0 \to \eta\eta$(SCS): possible CP violation through interference of two different CKM phases, $V_{cd}V_{ud}^*$ and $V_{cs}V_{us}^*$
  - Tree diagrams







- $D^+ \to \eta\pi^+, D^0 \to \eta\eta$: could be used to probe U-spin sum rule (slide #18 in ref.)
  - Studying $D^+ \to \eta K^+$(DCS) is included in the plan, currently.



Motivation

Experimental

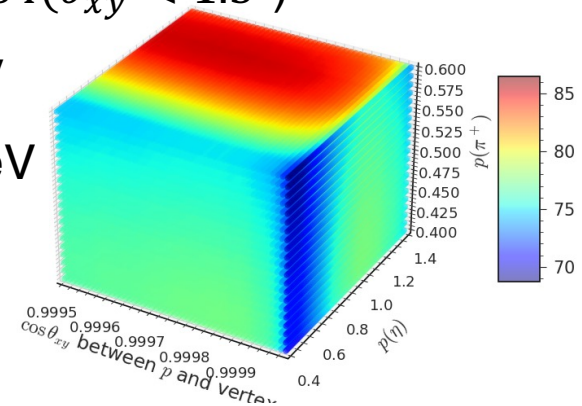
- $D^+ \to \eta_{3\pi}\pi^+$ studied at Belle with only 790/fb, not full data(2011, PRL.107.221801)
  - Belle + Belle II expects improvement in stats. uncertainty
  - Belle: signal yields($D^+ + D^-$): 6476 $\pm$ 110
- $D^+ \to \eta h^+ (h^+ = \pi^+, K^+)$ studied twice by LHCb at 2021, 2023
  - JHEP(2021) : $\eta_{e^+e^-\gamma}$, signal yields($D^+ + D^-$): 32760 $\pm$ 380
  - JHEP(2023) : $\eta_{\pi^+\pi^-\gamma}$, signal yields($D^+ + D^-$): (110.8 $\pm$ 0.7) $\cdot 10^3$
  - Totally, ~140k yields
- $D^0 \to \eta\eta$: never searched in terms of CP violation
  - Br measured by BESIII(2018, PRD.97.052005), CLEO(2010, PRD.81.052013), CLEO(2008, PhysRevD.77.092003)

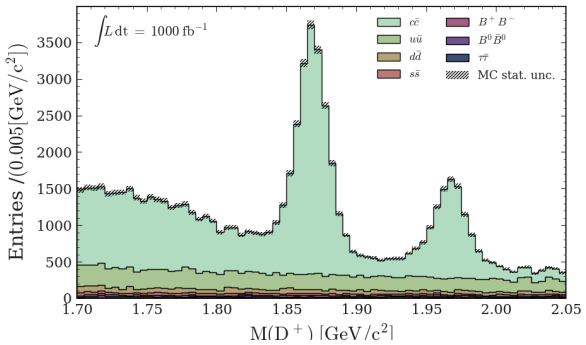
Cut optimization(tag)

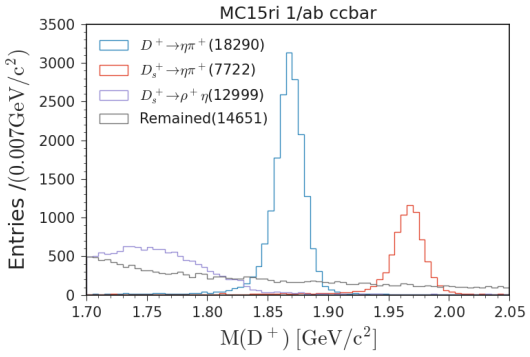
$D^+ \to \eta_{\gamma\gamma}\pi^+$

❑ Optimized cuts

- $\cos\theta_{xy} > 0.99964 (\theta_{xy} < 1.5°)$
- $p(\eta) > 1.14$GeV
- $p(\pi^+) > 0.48$GeV



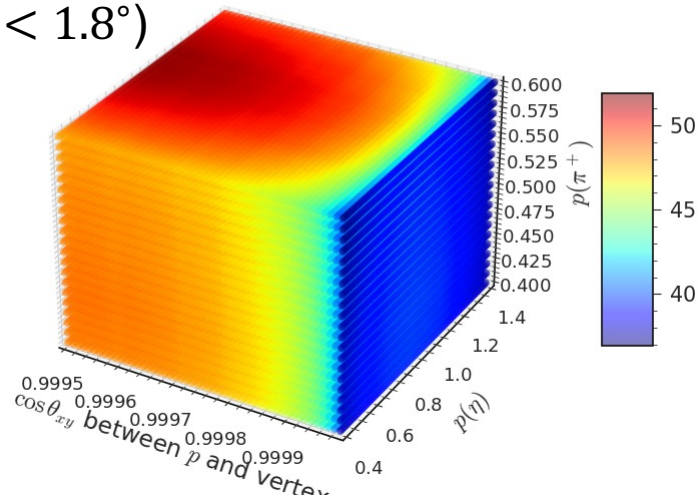


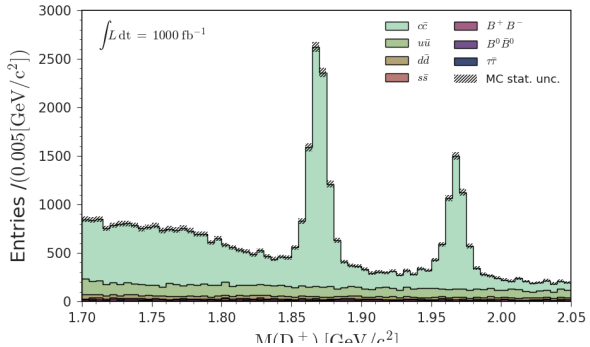


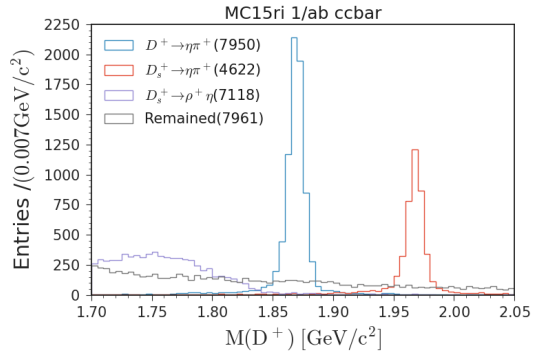
$D^+ \to \eta_{3\pi}\pi^+$

❑ Optimized cuts

- $\cos\theta_{xy} > 0.9995 (\theta_{xy} < 1.8°)$
- $p(\eta) > 0.98$GeV
- $p(\pi^+) > 0.49$GeV





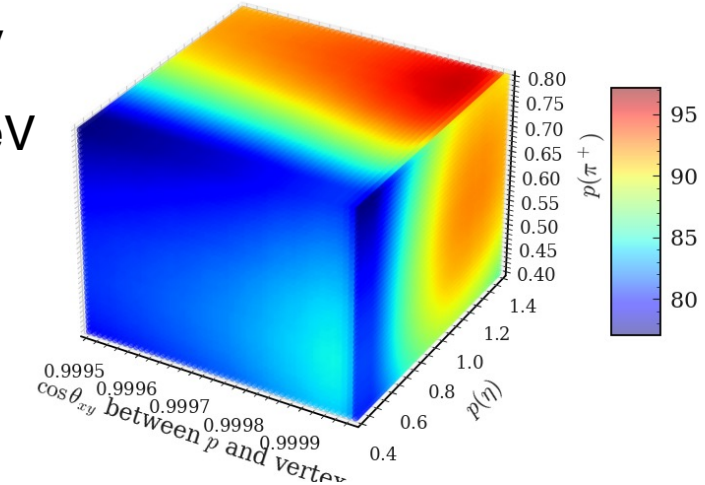


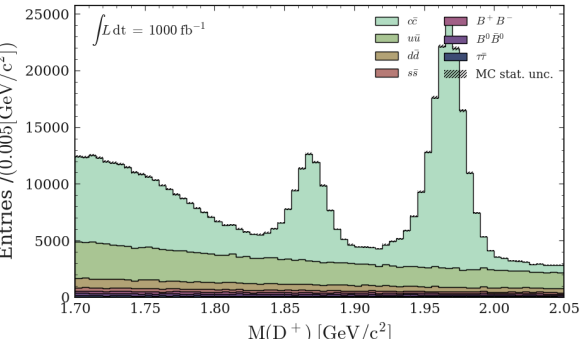
Cut optimization(non-tag)

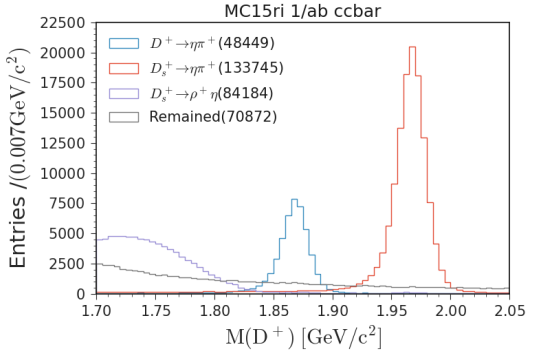
$D^+ \to \eta_{\gamma\gamma}\pi^+$

❑ Optimized cuts

- $\cos\theta_{xy} > 0.99930 (\theta_{xy} < 2.14°)$
- $p(\eta) > 1.24$GeV
- $p(\pi^+) > 0.63$GeV







$D^+ \to \eta_{3\pi}\pi^+$

❑ Optimized cuts

- $\cos\theta_{xy} > 0.99967 (\theta_{xy} < 1.47°)$
- $p(\eta) > 1.11$GeV
- $p(\pi^+) > 0.61$GeV