Branching fractions and CP asymmetries of $D_s^+ \to h^+ h^0$ at Belle

$$
\begin{aligned}
D_s^+ &\to K^+\pi^0, \\
&\to \pi^+\pi^0, \\
&\to K^+\eta, \\
&\to \pi^+\eta
\end{aligned}
$$

Based on *Phys.Rev.D* 103 (2021) 112005

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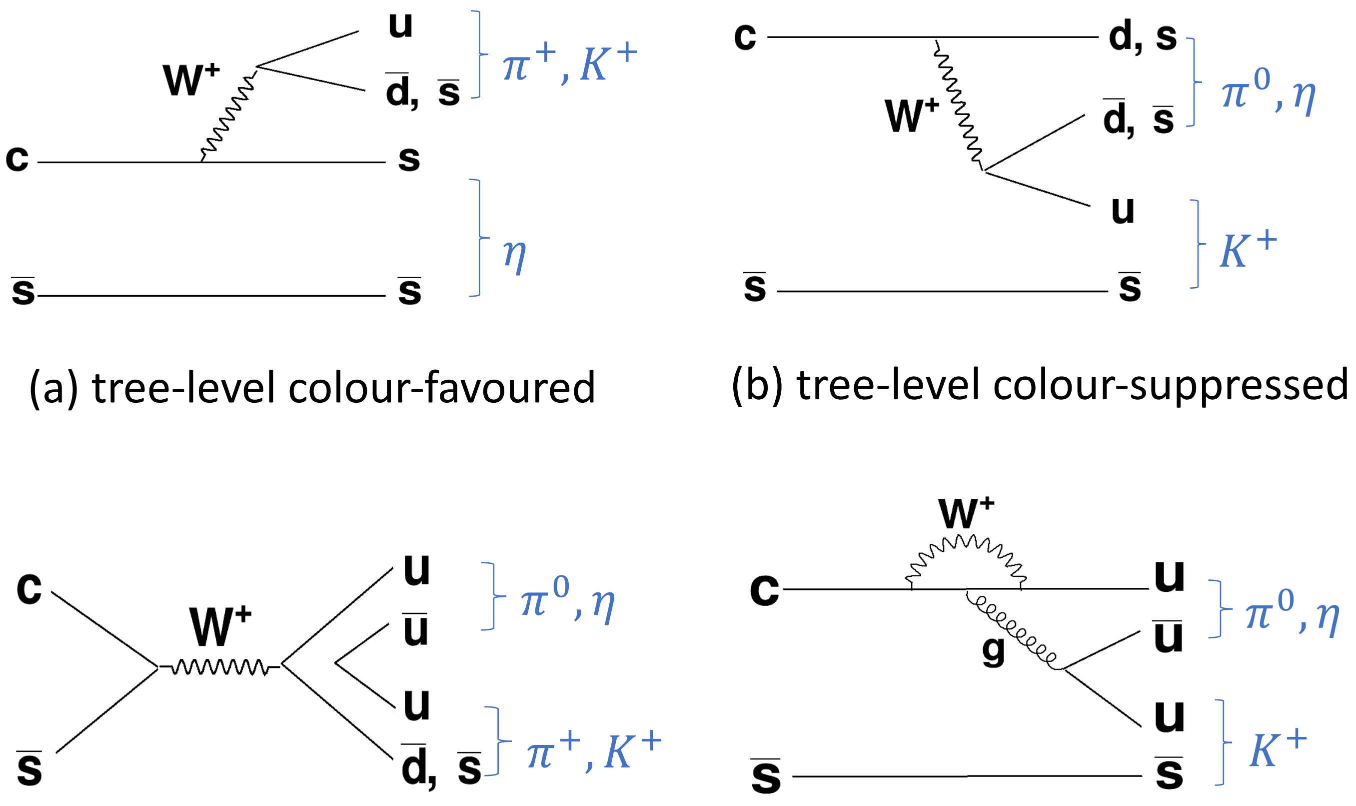
SCS: $D_s^+ \to K^+\pi^0/\eta$, CF: $D_s^+ \to \pi^+\eta$

Introduction

- Standard Model CP violation (CPV) in charm is expected to be $\sim 10^{-4} \sim 10^{-3}$.
- Largest effect in singly Cabibbo-suppressed (SCS) decays, contribution from penguin diagrams.
- Cabibbo-favored (CF) decays proceed via tree-level diagrams, nonzero CPV would be a clear sign of new physics.
- We measure direct CPV in D_s^+ decays:

$$A_{CP} = \frac{\Gamma(D_s^+ \to f) - \Gamma(D_s^- \to \bar{f})}{\Gamma(D_s^+ \to f) + \Gamma(D_s^- \to \bar{f})},$$



(a) tree-level colour-favoured

(b) tree-level colour-suppressed

(c) annihilation

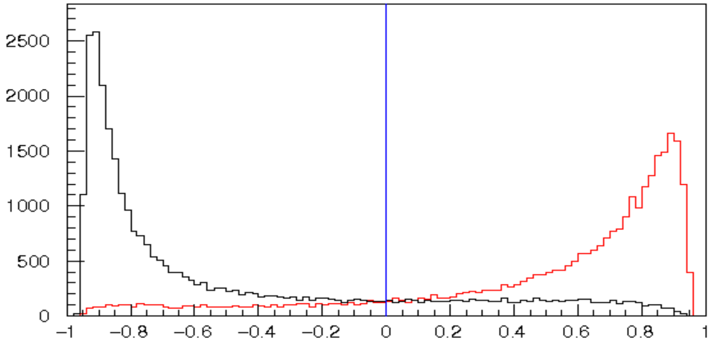
(d) penguin

- The $D_s^+ \to \pi^+\pi^0$ proceeds via annihilation, thus is highly suppressed.
- Improvements on the Branching fractions (BF) plays a key role for theoretical predictions on CPV. PRL 115, 251802.

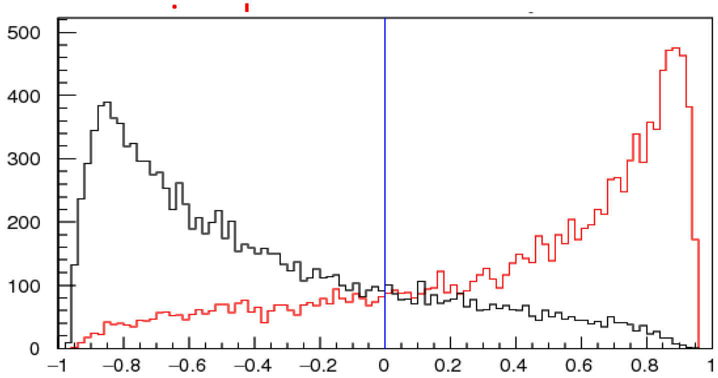
Analysis strategy

- Data set: $E_{CM}\sim$ 10.5 -10.9 GeV ($\Upsilon(4S)$, $\Upsilon(5S)$, off-resonance), 921 fb^{-1} , ~10^8 $D_s^\pm$ mesons.
- Branching fraction normalization mode: $D_s^+ \rightarrow \phi(\rightarrow K^+K^-)\pi^+$.
- Reconstruct D_s^+ from $D_s^{*+} \rightarrow D_s^+\gamma$: "tagged" D_s^+ sample.
- D_s^+ candidates that can not form D_s^{*+} : "untagged" D_s^+ sample.
- Reconstruct $\eta \rightarrow \gamma\gamma(\eta_{\gamma\gamma})$ and $\eta \rightarrow \pi^+\pi^-\pi^0(\eta_{3\pi})$
- Neural Network (NN) is utilized to suppress backgrounds as much as possible.

$D_s^+ \rightarrow K^+\pi^0$ (one charged track)



$D_s^+ \rightarrow K^+\eta\_3\pi$ (three charged tracks)

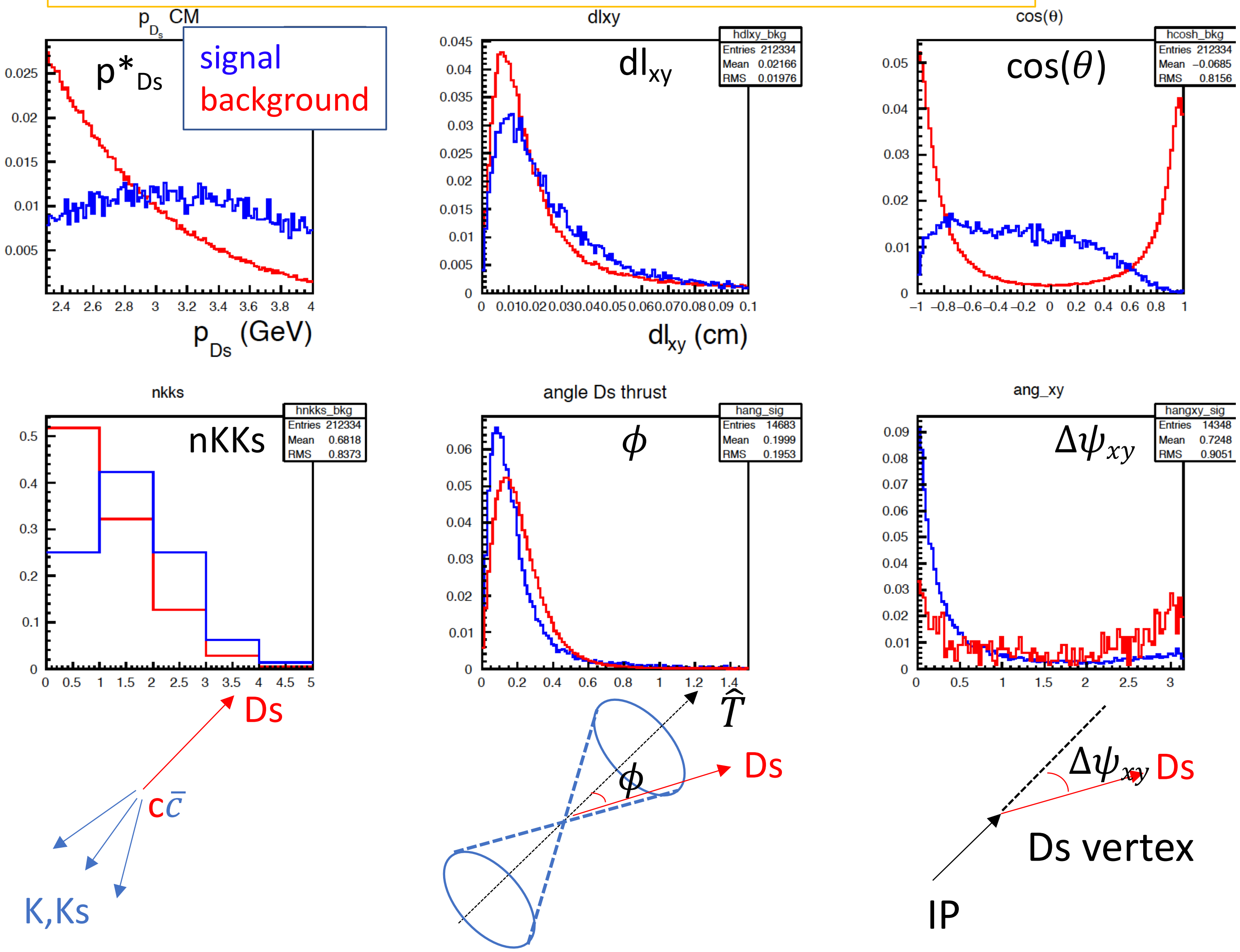


- NN is trained using one stream generic MC; expertise is then applied to the rest of generic MC samples and data. NN outputs a single variable O_{NN} in ranges [-1, 1].

Neural Network (NN)

$D_s^+ \to K^+ \pi^0, K^+ \eta\_\gamma\gamma, \pi^+ \pi^0, \pi^+ \eta\_\gamma\gamma$ (one charged track)

$D_s^+ \to K^+ \eta\_3\pi, \pi^+ \eta\_3\pi$, $D_s \to \phi\pi^+$ (three charged tracks)



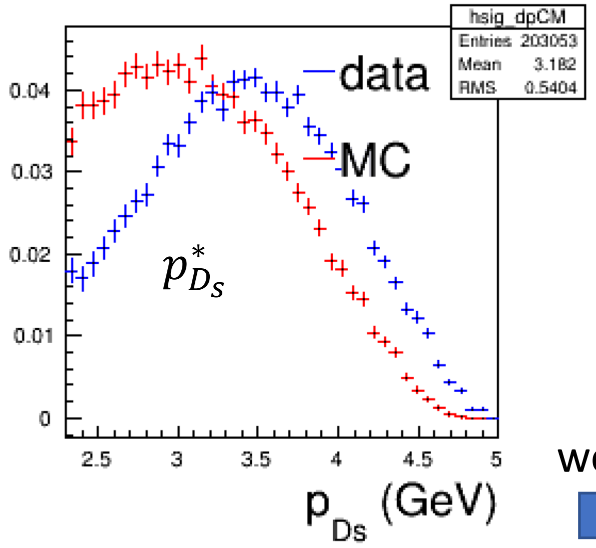
Input variables:

- 1) $p^*_{D_s}$: momentum of D_s^+ in the e^+e^- center-of-mass frame.
- 2) |dr|: impact parameter in x-y plane of the charged track. Or $|dl_{xy}|$: Distance between the decay and production vertex of D_s^+ in x-y plane.
- 3) $\cos(\theta)$: θ is the angle between momentum of the charged track (direct daughter of D_s^+) in the D_s^+ rest frame and momentum of D_s^+ in the lab frame.
- 4) nKKs: number of K/K_S in the opposite side against the D_s^+ candiate.
- 5) ϕ: angle between the momentum of D_s^+ and Thrust axis direction in the center-of-mass frame.
- 6) $\Delta\psi_{xy}$: “collinearity angle”, angle between the D_s^+ momentum vector and vector joining its decay and production vertices in x-y plane.

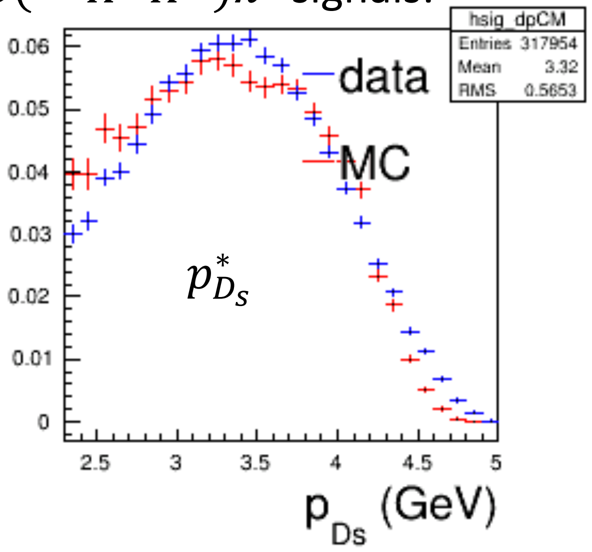
sPlot technique

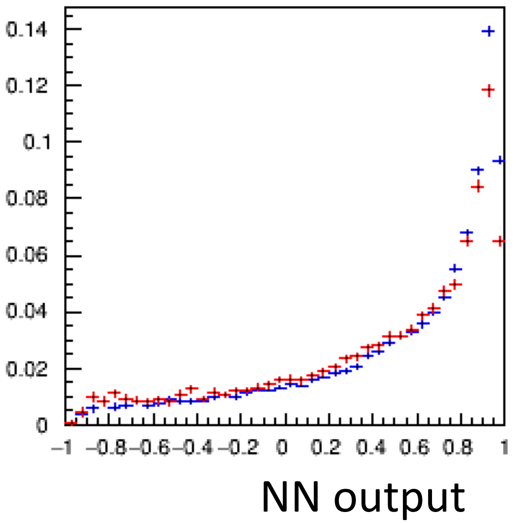
sPlot technique: [NIM A555, 356 (2005)]
ROOT Class "RooStats::SPlot"

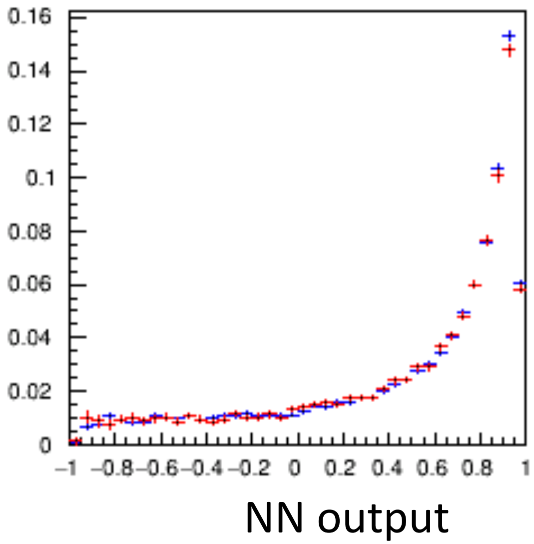
Distributions of reference mode $D_s^+ \to \phi(\to K^+K^-)\pi^+$signals:



weight MC

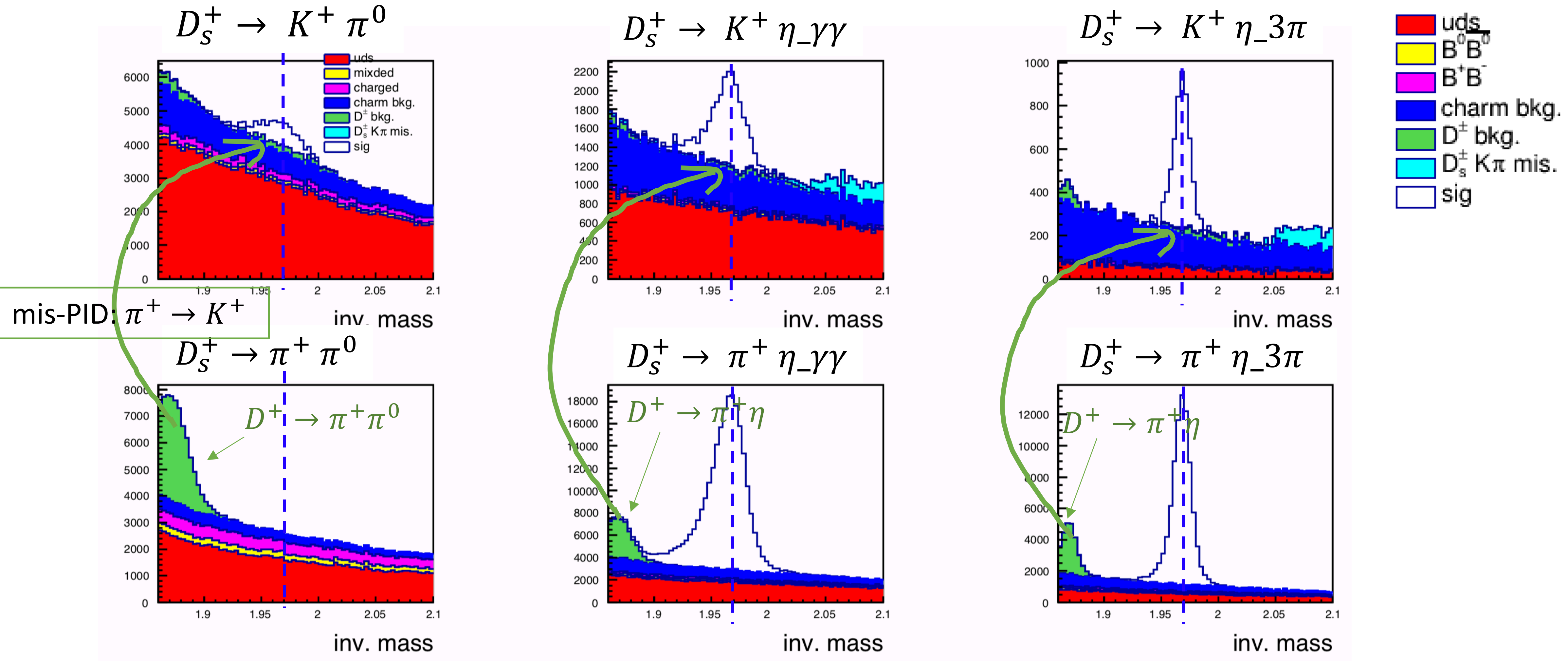






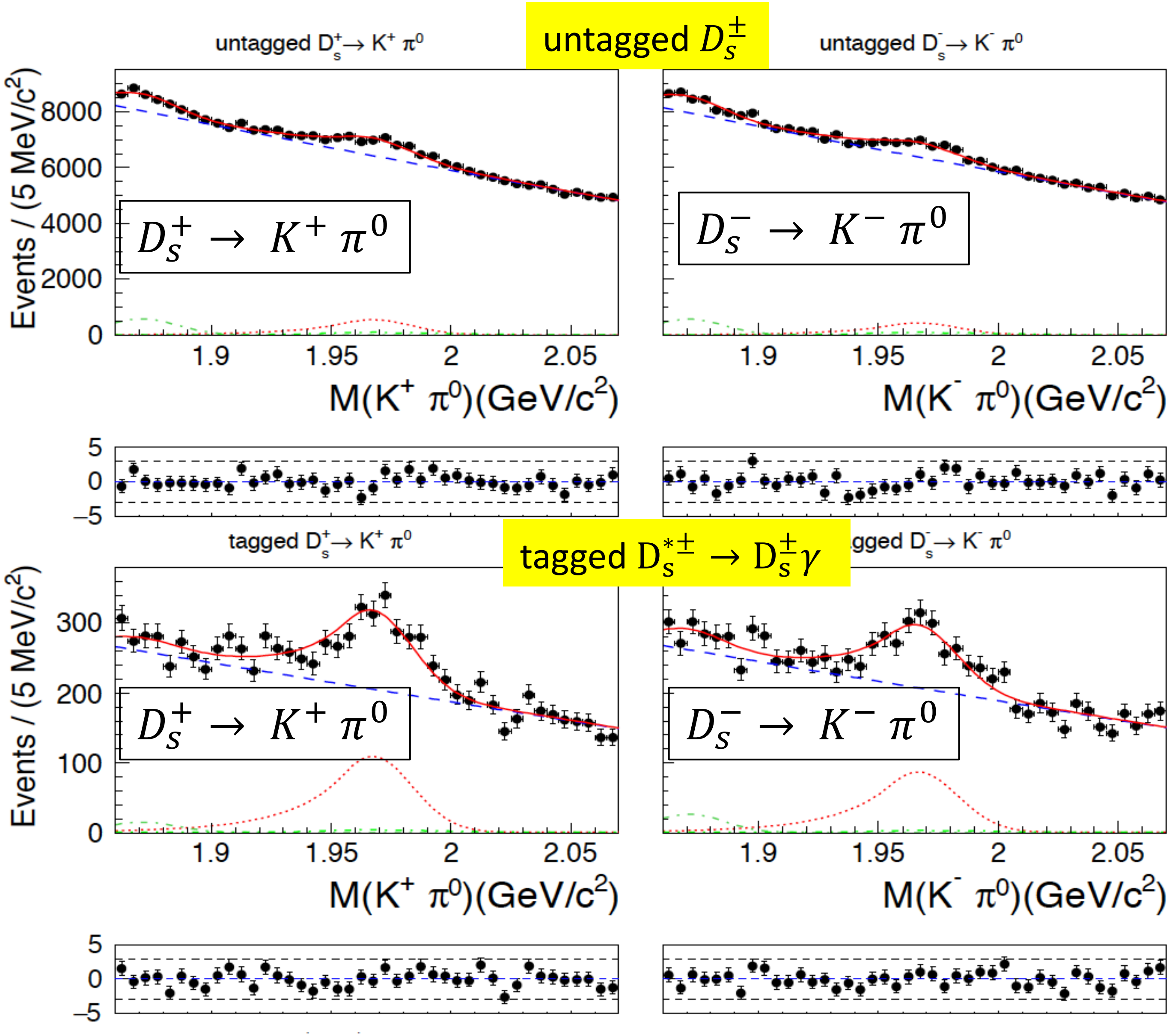
- MC/data consistency is important for detection efficiency estimation.
- sPlot: a statistical tool to unfold data distributions. Discriminating variable used in sPlot: D_s^+ invariant mass.
- Data/MC deviations are seen on the momentum of D_s^+ ($p^*_{D_s}$) distributions.
- Solution: weight MC sample to match data distributions.
- NN is trained with the weighted MC. NN output of data and weighted MC agree well.

Background study



- Check background using MC sample after final event selection. Main backgrounds are uds continuum process. Charged D^+ peak backgrounds are seen.
- $D^+ \to \pi^+\pi^0(\eta)$ produce backgrounds in D_s^+ signal region if π^+ is mis-identified as K^+. Need to be considered carefully in the fits.

Data fits (signal yield extraction)



Signal: a Crystal Ball function and a Gaussian function, sharing same mean value.

combinatorial background: a second-order Chebyshev polynomial, parameters are floated

D^+ peak: a Gaussian function

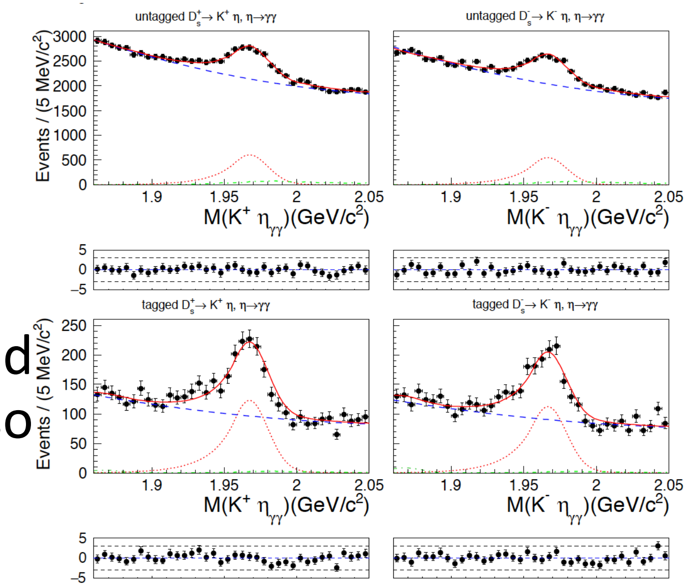
D^+ under D_s^+ peak ($\pi^\pm$ is mis-identified as $K^\pm$): MC shape, the amount is calibrated and fixed.

The plots beneath the distributions show the residuals.

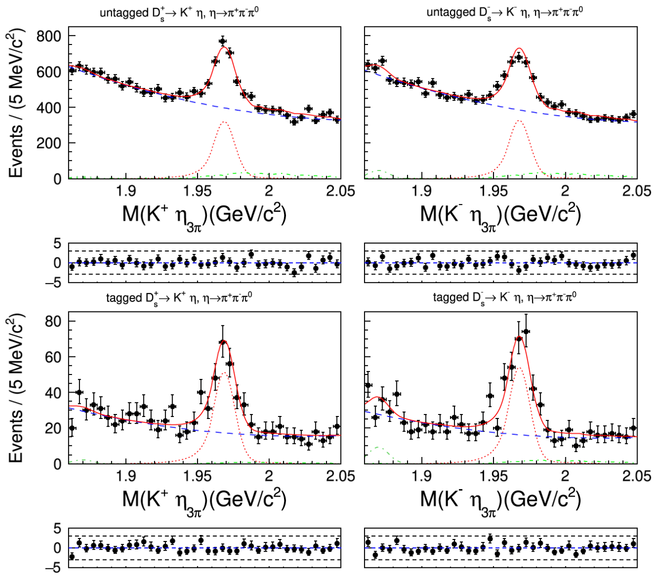
Data fits

- Unbinned maximum likelihood simultaneous fit to tagged and untagged samples.
- D_s^+ and D_s^- samples are separated for CPV measurement but are also fitted simultaneously.

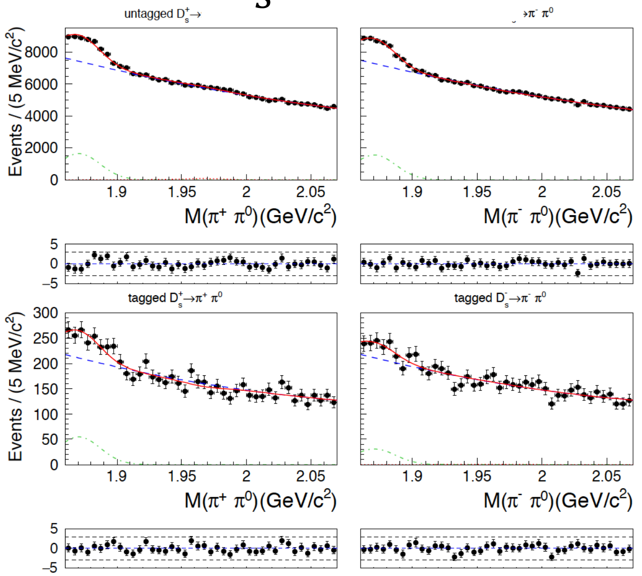
$D_s^+ \rightarrow K^+ \eta\_\gamma\gamma$



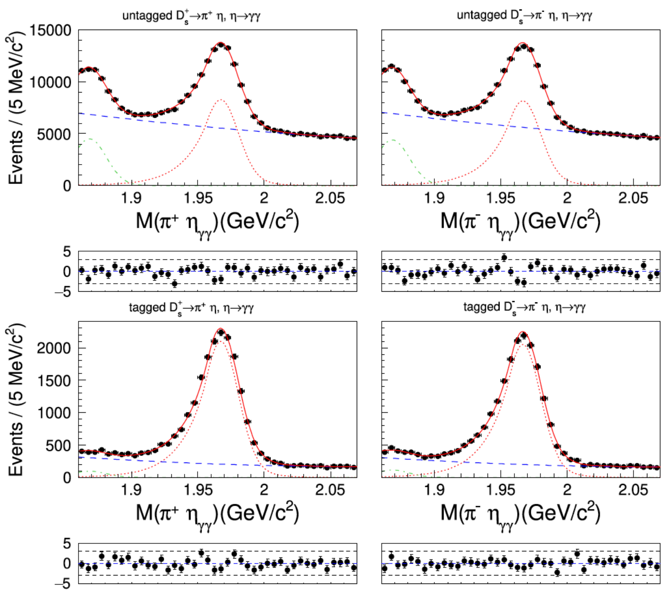
$D_s^+ \rightarrow K^+ \eta\_3\pi$



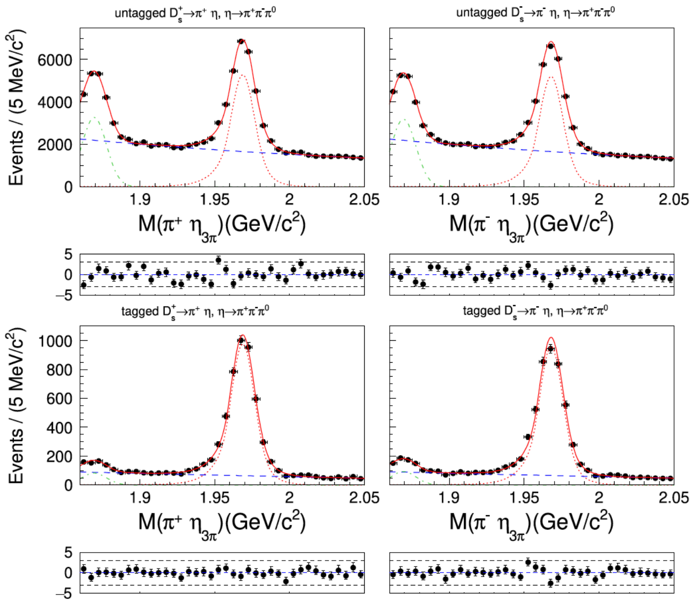
$D_s^+ \rightarrow \pi^+ \pi^0$



$D_s^+ \rightarrow \pi^+ \eta\_\gamma\gamma$

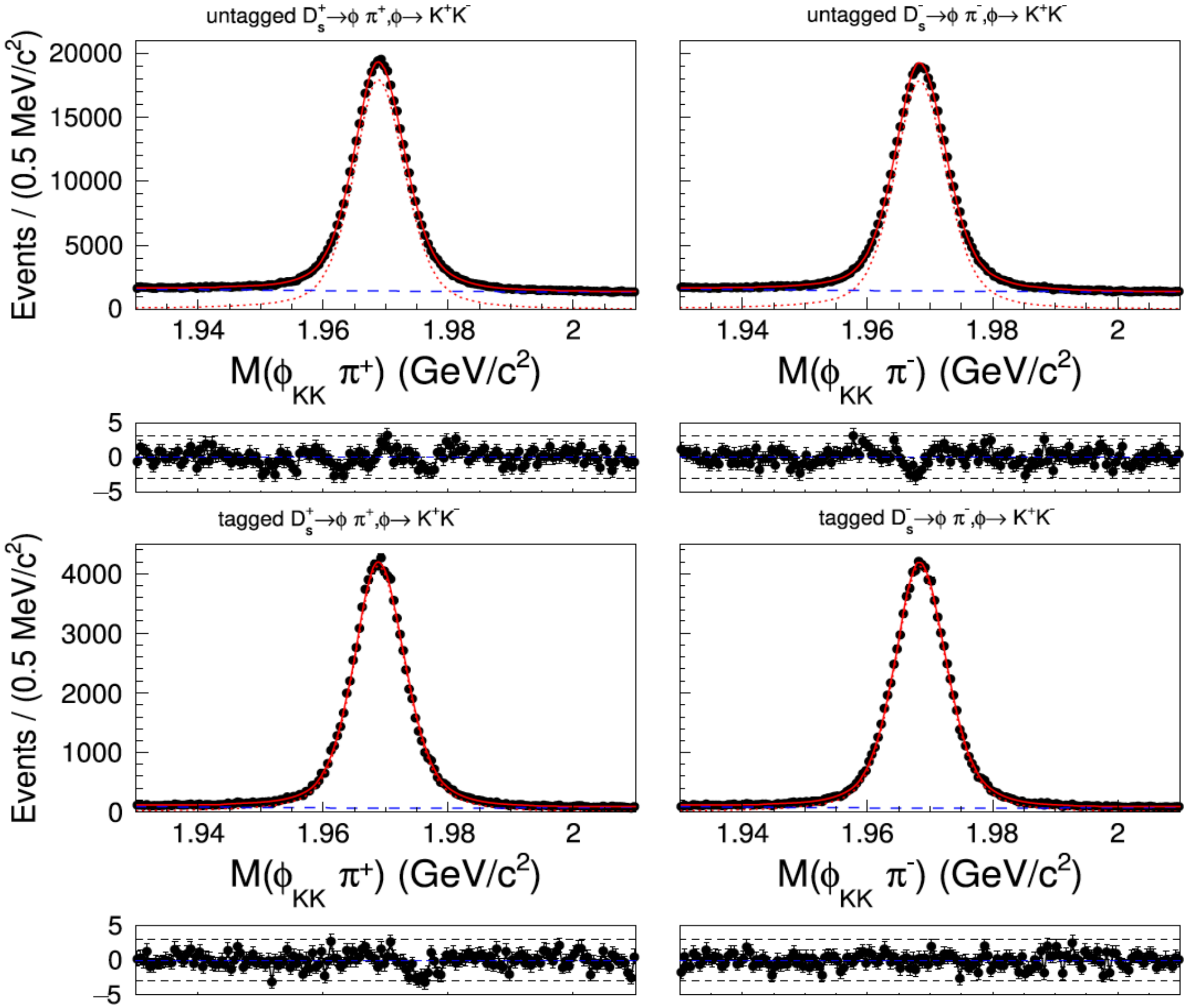


$D_s^+ \rightarrow \pi^+ \eta\_3\pi$



- No signal observed in $D_s^+ \rightarrow \pi^+\pi^0$

Data fits ($D_s^+ \to \phi\pi^+; \phi \to K^+K^-$)



Signal: a bifurcated Student's t-distribution and a Gaussian function.

combinatoral background: a second-order Chebyshev polynomial, parameters are floated.

There is a small peaking background $D_s^+ \to K^+K^-\pi^+$, can not separated in the fitting, the amount ($1.73 \pm 0.03\%$) will be corrected for to get final signal yield.

CP asymmetry extraction ($D_s^+ \to \pi^+\eta$)

$$A_{\rm raw} = \frac{N_{D_s^+} - N_{D_s^-}}{N_{D_s^+} + N_{D_s^-}} . \qquad A_{\rm raw} = A_{CP} + A_{FB} + A_\epsilon$$

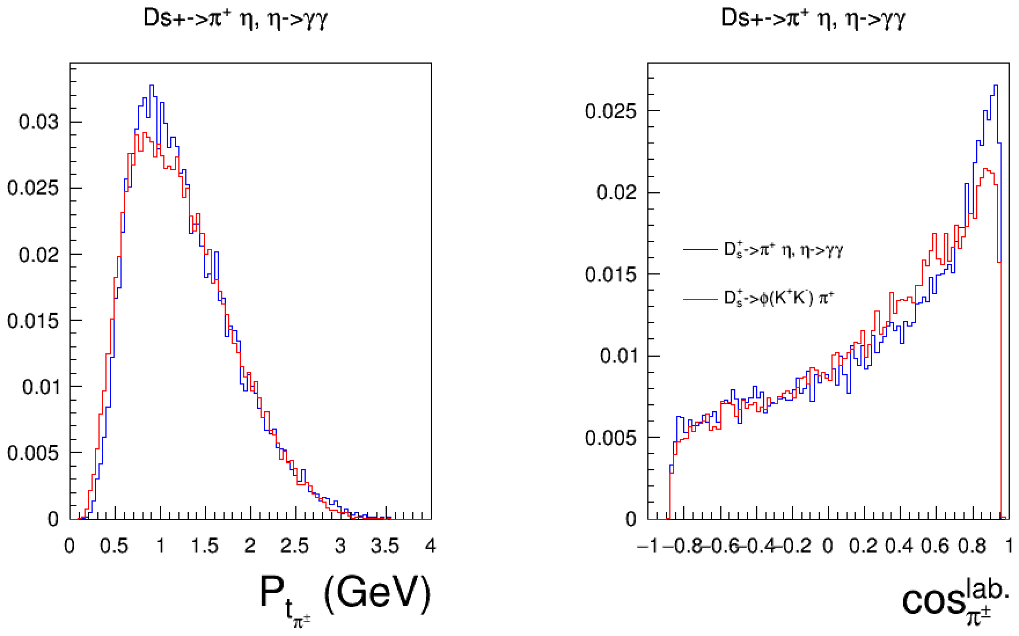
- A_{FB}, forward-backward asymmetry. It is an odd function of the cosine of the D_s^+ polar angle in the CM frame ($cos\theta_{D_s}^{CM}$), same for signal mode and reference mode.

- A_ε, detection efficiency asymmetry, is a function of the momentum and polar angle of the charged tracks.

$$\Delta A_{\rm raw} \equiv A_{\rm raw}^{\pi\eta} - A_{\rm raw}^{\phi\pi} = A_{CP}^{\pi\eta} - A_{CP}^{\phi\pi}.$$

$$\boxed{A_{CP}^{\pi\eta} = \Delta A_{\rm raw} + A_{CP}^{\phi\pi}}$$

signal $D_s^+ \to \pi^+\eta$ vs. reference mode $D_s^+ \to \phi\pi^+$

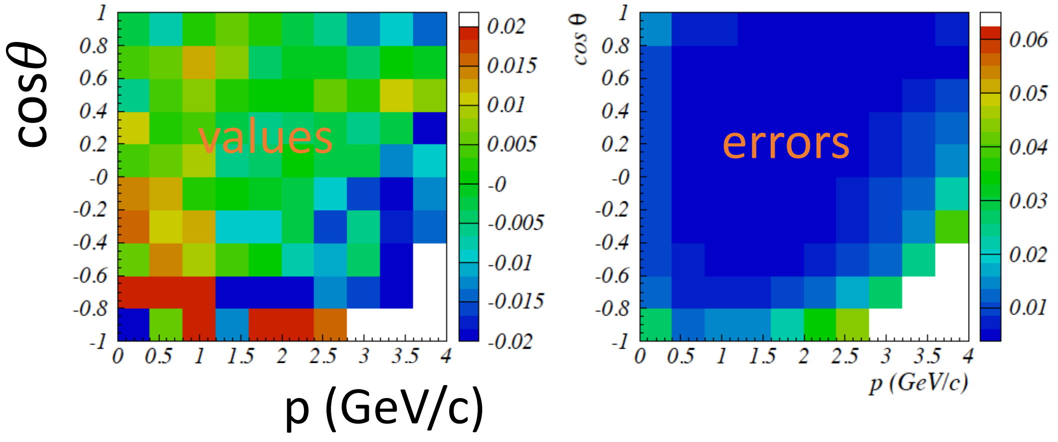


- Charged Pion detection charge asymmetry can be canceled by the reference mode ($D_s^+ \to \phi\pi^+$).

CP asymmetry extraction ($D_s^+ \to K^+\pi^0, K^+\eta$)

- Charged Kaon detection asymmetry can not be canceled by the reference mode, its detection asymmetries is measured at Belle and corrected for, then we obtain A_{corr}.

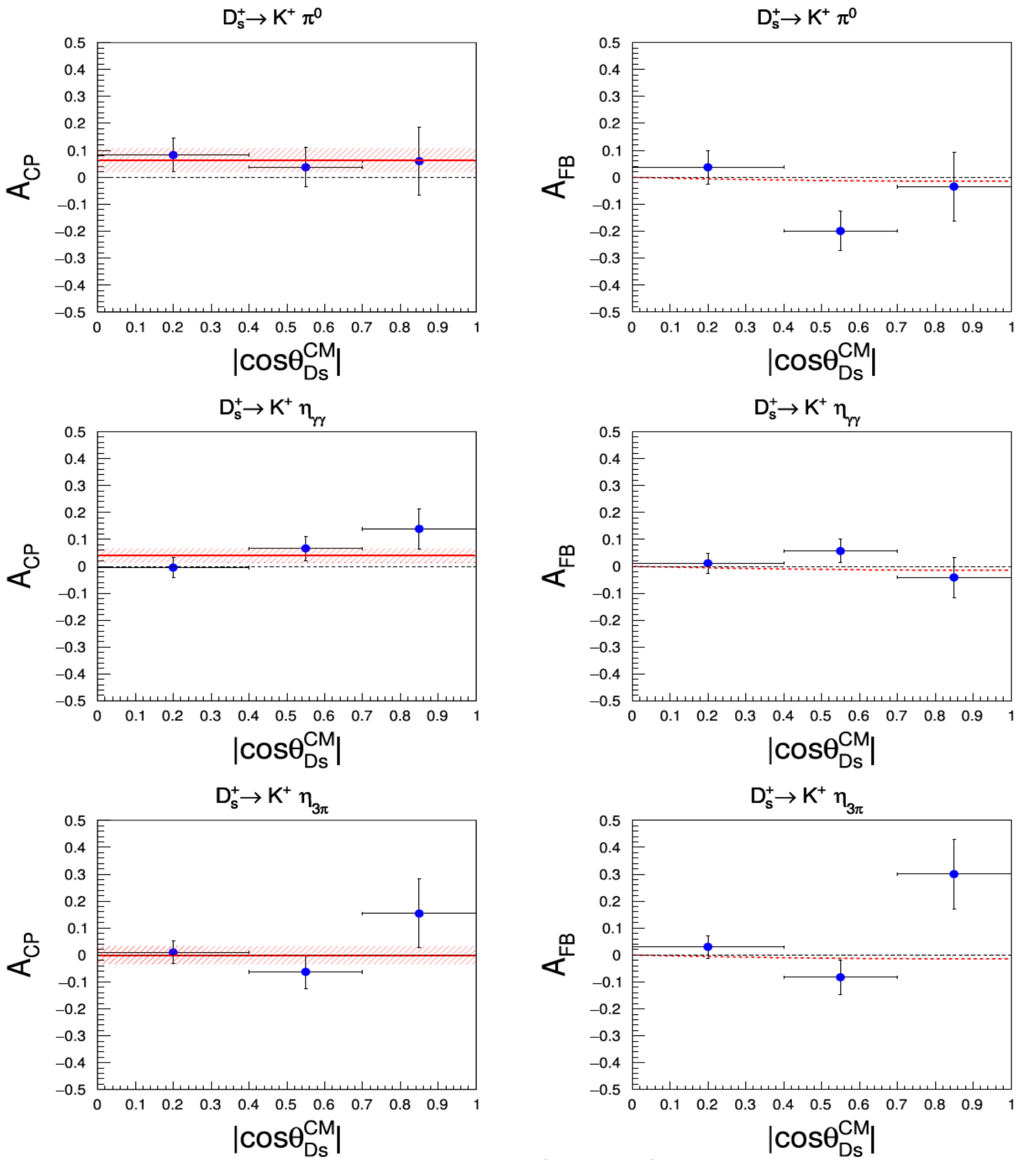
Kaon detection asymmetry $A_\epsilon^K = \frac{\epsilon_{K+} - \epsilon_{K-}}{\epsilon_{K+} + \epsilon_{K-}}$: map of values (left) and errors (right).



- Since A_{FB} is an odd function of $cos\theta_{D_s}^{CM}$, we can extract A_{CP} and A_{FB} by calculating:

$$A_{CP}(\cos\theta_{D_s}^{\mathrm{CM}}) = \frac{A_{\mathrm{corr}}(\cos\theta_{D_s}^{\mathrm{CM}}) + A_{\mathrm{corr}}(-\cos\theta_{D_s}^{\mathrm{CM}})}{2}$$

$$A_{\mathrm{FB}}(\cos\theta_{D_s}^{\mathrm{CM}}) = \frac{A_{\mathrm{corr}}(\cos\theta_{D_s}^{\mathrm{CM}}) - A_{\mathrm{corr}}(-\cos\theta_{D_s}^{\mathrm{CM}})}{2}.$$



Phys.Rev.D 103 (2021) 112005

Results

Belle: Phys.Rev.D 103 (2021) 112005
BESIII BF: JHEP 08 (2020) 146
LHCb CPV: JHEP 06 (2021) 019

BF:

Decay mode	ε (%)	Fitted yield	$\mathcal{B}$ (10^{-3})	$\mathcal{B}$ (10^{-3}) BESIII
$D_s^+ \to K^+\pi^0$	8.10 ± 0.04	11978 ± 846	$0.735 \pm 0.052 \pm 0.030 \pm 0.026$	$0.748 \pm 0.049 \pm 0.018 \pm 0.023$
$D_s^+ \to K^+\eta_{\gamma\gamma}$	7.42 ± 0.05	10716 ± 429	$1.80 \pm 0.07 \pm 0.08 \pm 0.06$	
$D_s^+ \to K^+\eta_{3\pi}$	4.04 ± 0.02	3175 ± 121	$1.71 \pm 0.07 \pm 0.08 \pm 0.06$	
$D_s^+ \to K^+\eta$	–	–	$1.75 \pm 0.05 \pm 0.05 \pm 0.06$	$1.62 \pm 0.10 \pm 0.03 \pm 0.05$
$D_s^+ \to \pi^+\pi^0$	6.63 ± 0.04	491 ± 734	$0.037 \pm 0.055 \pm 0.021 \pm 0.001$	–
$D_s^+ \to \pi^+\eta_{\gamma\gamma}$	10.84 ± 0.02	166696 ± 1173	$19.16 \pm 0.14 \pm 0.74 \pm 0.68$	
$D_s^+ \to \pi^+\eta_{3\pi}$	6.50 ± 0.03	56132 ± 407	$18.72 \pm 0.14 \pm 0.98 \pm 0.67$	
$D_s^+ \to \pi^+\eta$	–	–	$19.00 \pm 0.10 \pm 0.59 \pm 0.68$	$17.46 \pm 0.18 \pm 0.27 \pm 0.54$
$D_s^+ \to \phi\pi^+$	22.05 ± 0.13	1005688 ± 2527	–	–

- BF: Belle results for $D_s^+ \to K^+\eta$ and $D_s^+ \to \pi^+\pi^0$ are the most precise to date. For $D_s^+ \to K^+\pi^0$ we have slightly worse precision than BESIII. For the $D_s^+ \to \pi^+\eta$, which is systematic uncertainties dominated, BESIII result is better.

A_{CP}:

Decay mode	$A_{\rm raw}$	A_{CP}	A_{CP}(LHCb)
$D_s^+ \to K^+\pi^0$	0.115 ± 0.045	$0.064 \pm 0.044 \pm 0.011$	$-0.008 \pm 0.039 \pm 0.012$
$D_s^+ \to K^+\eta_{\gamma\gamma}$	0.046 ± 0.027	$0.040 \pm 0.027 \pm 0.005$	
$D_s^+ \to K^+\eta_{3\pi}$	-0.011 ± 0.033	$-0.008 \pm 0.034 \pm 0.008$	
$D_s^+ \to K^+\eta$	–	$0.021 \pm 0.021 \pm 0.004$	$0.009 \pm 0.037 \pm 0.011$
$D_s^+ \to \pi^+\eta_{\gamma\gamma}$	0.007 ± 0.004	$0.002 \pm 0.004 \pm 0.003$	
$D_s^+ \to \pi^+\eta_{3\pi}$	0.008 ± 0.006	$0.002 \pm 0.006 \pm 0.003$	
$D_s^+ \to \pi^+\eta$	–	$0.002 \pm 0.003 \pm 0.003$	$0.008 \pm 0.007 \pm 0.005$
$D_s^+ \to \phi\pi^+$	0.002 ± 0.001	–	–

- A_{CP}: showing no hint for *CP* violation. Belle achieved better precisions in $D_s^+ \to K^+/\pi^+\eta$ and similar precision in $D_s^+ \to K^+\pi^0$ comparing to LHCb.

Summary

- Using full Belle data sample, measurement of branching fractions and CP asymmetries is performed for:

$$D_s^+ \to K^+ \pi^0,$$
$$\to \pi^+ \pi^0,$$
$$\to K^+\eta,$$
$$\to \pi^+\eta$$

- These branching fractions and A_{CP} values can be used in sum rules to provide constraints on the predictions for CPV in charm. PRL 115, 251802
- In charm analyses, we face competitions from BESIII and LHCb.
  - For BF measurements, systematics uncertainties at BESIII is much smaller, Belle(II) has advantages in statistical uncertainties dominated (charged) CS modes.
  - For CPV measurements, Belle(II) has advantages in modes with neutral particles (π^0/η), especially multiple neutral particles in the final state.

backup

$D_{(s)}^{+} \rightarrow K^{+}\pi^{0}(\eta), \pi^{+}\pi^{0}(\eta)$ at belle and LHCb

- LHCb is using $h^0 \rightarrow e^+e^-\gamma$ or $h^0 \rightarrow \gamma\gamma$ followed by a photon conversion.

Employ Dalitz $h^0 \rightarrow e^+e^-\gamma$ decays and converted photons;

- lower BR balanced by larger $D_{(s)}^{+}$ production w.r.t. e^+e^- colliders.

Decay	BF
$\pi^0 \rightarrow \gamma\gamma$	98.8%
$\pi^0 \rightarrow e^+ e^- \gamma$	1.2%
$\eta \rightarrow \gamma\gamma$	39.41%
$\eta \rightarrow e^+ e^- \gamma$	0.69%

Belle results: *Phys.Rev.D* 103 (2021) 112005
Phys.Rev.D 97 (2018) 1, 011101
Phys.Rev.Lett. 107 (2011) 221801

LHCb results: *JHEP* 06 (2021) 019

	CPV Belle (%)	CPV LHCb (%)
Ds+ -> K+ pi0	6.4 +- 4.4 +- 1.1	-0.8 +- 3.9 +- 1.2
Ds+ -> K+ eta	2.1 +- 2.1 +- 0.4	0.9 +- 3.7 +- 1.1
Ds+ -> pi+ eta	0.2 +- 0.3 +- 0.3	0.8 +- 0.7 +- 0.5
D+ -> K+ pi0	-	-3.2 +- 4.7 +- 2.1
D+ -> K+ eta	-	-6 +- 10 +- 4
D+ -> pi+ pi0	2.31 +- 1.24 +- 0.23	-1.3 +- 0.9 +- 0.6
D+ -> pi+ eta	1.74 +- 1.13 +- 0.19 (791 fb^{-1})	-0.2 +- 0.8 +- 0.4

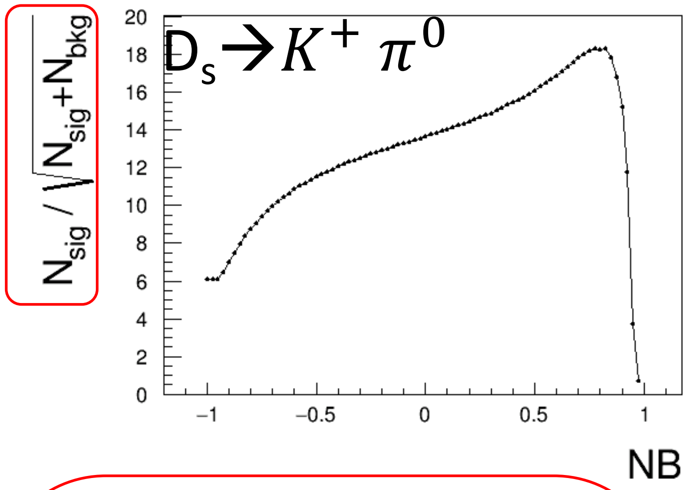
Event selection

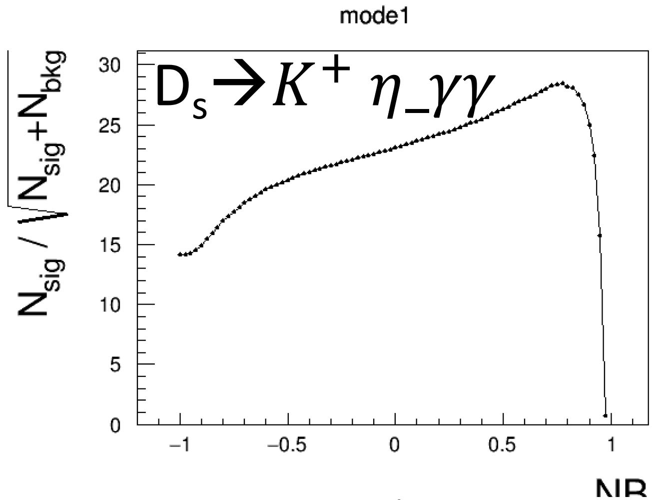
- Reconstruct D_s^+ from $D_s^{*+} \to D_s^+\gamma$: "tagged" signal. D_s^+ candidates that can not form D_s^{*+} : "untagged" D_s^+.
- η is reconstructed from $\eta \to \gamma\gamma(\eta_{\gamma\gamma})$ and $\eta \to \pi^+\pi^-\pi^0(\eta_{3\pi})$
- Neural Network (NN) is utilized to suppress backgrounds as much as possible.

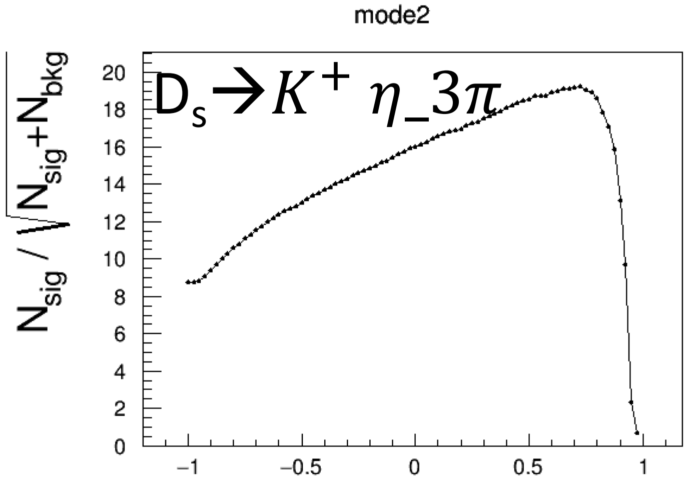
Charged tracks	$r < 1\,cm$, $\lvert z\rvert < 4\,cm$, $p_t > 0.1$ GeV
Kaon PID	$\mathcal{L}(K)/(\mathcal{L}(K)+\mathcal{L}(\pi)) > 0.6$
pion PID	$\mathcal{L}(K)/(\mathcal{L}(K)+\mathcal{L}(\pi)) < 0.6$
γ	$E_\gamma > 50$ MeV (barrel), $E_\gamma > 100$ MeV (endcaps)
π^0	0.12 GeV/c$^2 < M_{\gamma\gamma} < 0.15$ GeV/c^2, mass-vertex constraint fit
$\eta \to \gamma\gamma$	0.5GeV/c$^2 < M_{\gamma\gamma} < 0.58$ GeV/c^2, mass-vertex constraint fit, π^0 veto
$\eta \to \pi^+\pi^-\pi^0$	0.53GeV/c$^2 < M_{\gamma\gamma} < 0.56$ GeV/c^2, mass-vertex constraint fit
$\phi \to K^+K^-$	1.01 GeV/c$^2 < M_{K^+K^-} < 1.03$ GeV/c^2
D_S^+	$p^*_{D_S} > 2.3$ GeV (CMS), vertex constraint fit
γ from $D_S^{*+} \to D_S^+\gamma$	$E_\gamma > 150$ MeV, π^0 veto
ΔM	0.10GeV/c$^2 < \Delta M < 0.18$ GeV/c^2

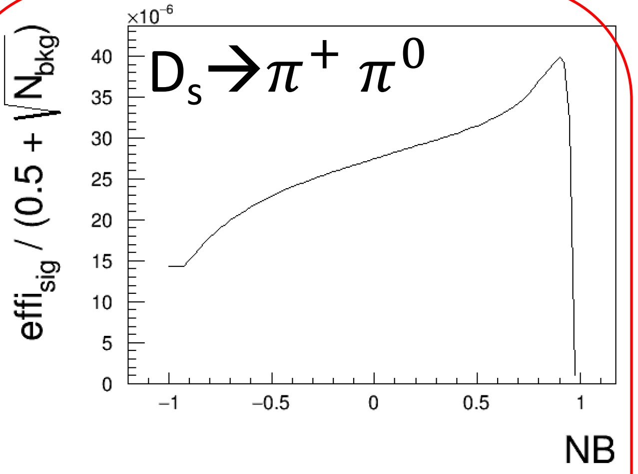
- $p^*_{D_s}$: momentum of D_s^+ in the e^+e^-center-of-mass frame, to exclude D_s^+ from B decays and supress backgrounds.
- π^0 veto: if γ can form a good π^0 candidate with any other γ, it will not be used to form η or D_S^{*+}.

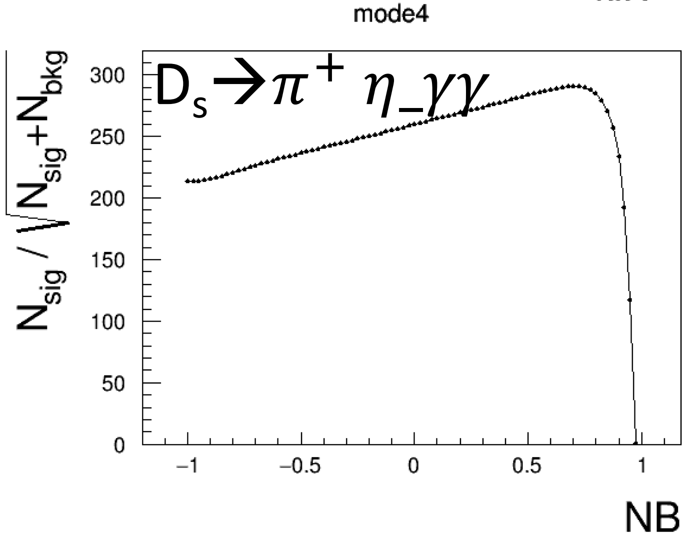
NN output requirement (Figure Of Merit)

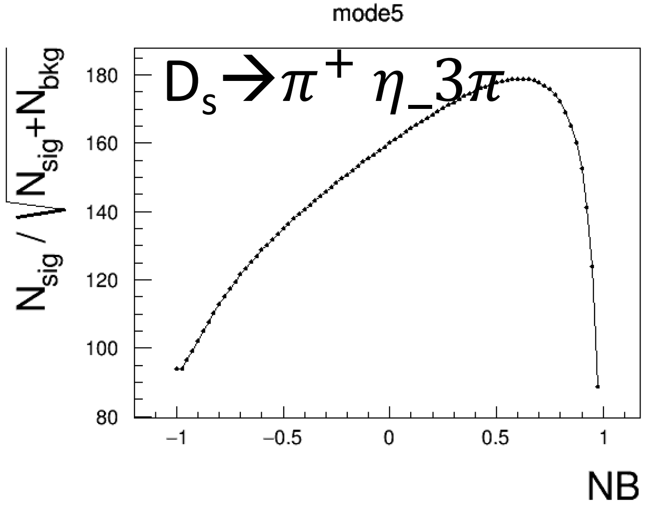












$$\mathrm{FOM} = \frac{\varepsilon(t)}{a/2 + \sqrt{B(t)}}$$

arXiv:physics/0308063v2

- The requirement on NN output is determined by optimizing a figure-of-merit (FOM): $N_{\rm sig}/\sqrt{N_{\rm sig}+N_{\rm bkg}}$
- While for rare signal search, FOM is defined as $\varepsilon_{\rm sig}/\sqrt{N_{\rm bkg}}$,

Best candidate selection (BCS)

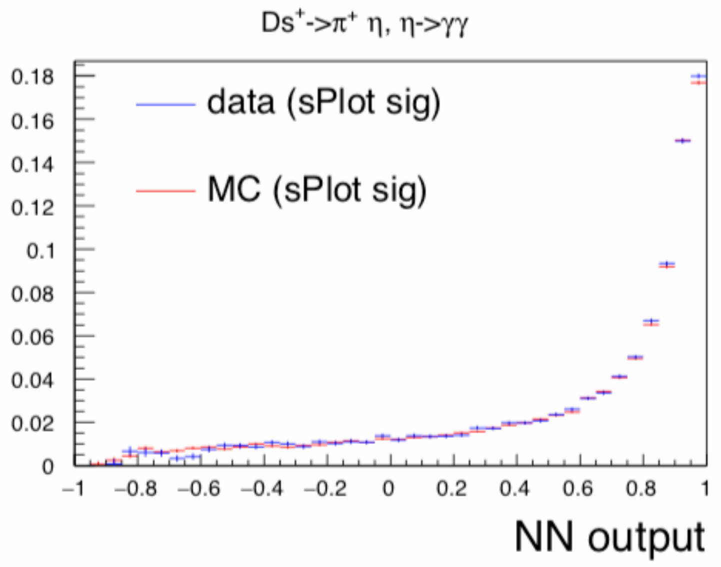
- For D_s^+, step(1): choose the best π^0/η candidate which has the smallest χ^2 from the mass constraint fit.
- step(2): if there are still multiple Ds^+ candidates, choose the one with the best NN output.
- For Ds^{*+} → $D_s^+\gamma$, if there are multiple γ, choose the one with the maximum energy.

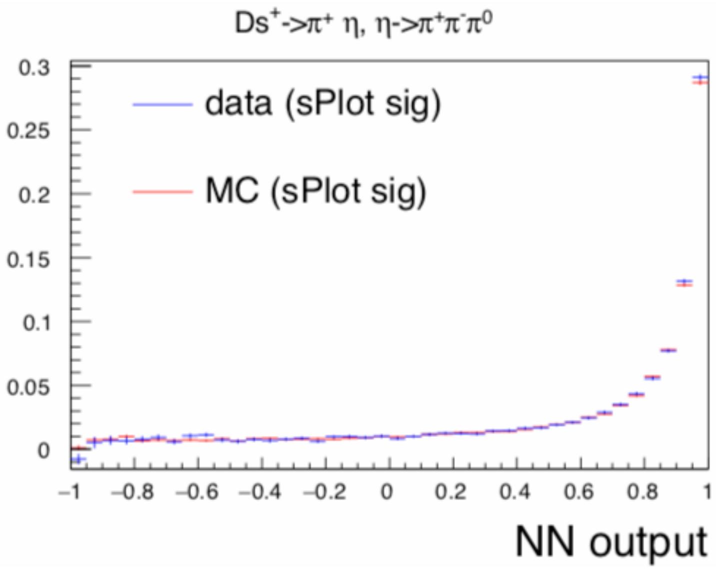
Table 3: Efficiency of Best Candidate Selection (BCS).

mode	Fraction of Ncan>1	Nsig	Nsig (select best $\chi^2_{\pi^0/\eta}$)	Nsig (Ncan>1)	Nsig (select best NB)	BCS efficiency
$D_s^+ \to K^+\pi^0$	9.2%	238	172 (72.3%)	20	14 (70.0%)	69.7%
$D_s^+ \to K^+\eta_{\gamma\gamma}$	3.1%	954	756 (79.2%)	238	151 (63.4%)	70.1%
$D_s^+ \to K^+\eta_{3\pi}$	5.0%	647	482 (74.5%)	25	17 (68.0%)	73.3%
$D_s^+ \to \pi^+\pi^0$	1.0%	161	110 (68.3%)	7	4 (57.1%)	66.5%
$D_s^+ \to \pi^+\eta_{\gamma\gamma}$	3.1%	1531	1167 (76.2%)	193	146 (75.6%)	73.2%
$D_s^+ \to \pi^+\eta_{3\pi}$	5.5%	1539	1161 (75.4%)	60	43 (71.7%)	74.1%
reference modes:						
$D_s^+ \to \phi(K^+K^-)\pi^+$	2.2%	1361	-	-	877 (64.4%)	64.4%

Systematics uncertainties

- Tracking, PID, π^0/η reconstruction
- Fitting (signal shape, fitting range, fitting bias)
- Ratio of untagged and tagged samples
- Neural Network
  - Remove the NN output requirement for the large statistics reference mode and CF signal mode $D_s^+ \rightarrow \pi^+ \eta$
  - Use sPlot to extract the distribution of NN output
  - Differences between data and MC efficiencies are assigned as systematic uncertainties.
  - Low statistics signal modes $D_s^+ \rightarrow K^+\pi^0, K^+\eta$ can reuse these NN output distributions.
- $cos\theta_{D_s}^{CM}$ binning
- uncertainties from the reference mode





Systematic uncertainties

- systematic uncertainties for BF measurements:

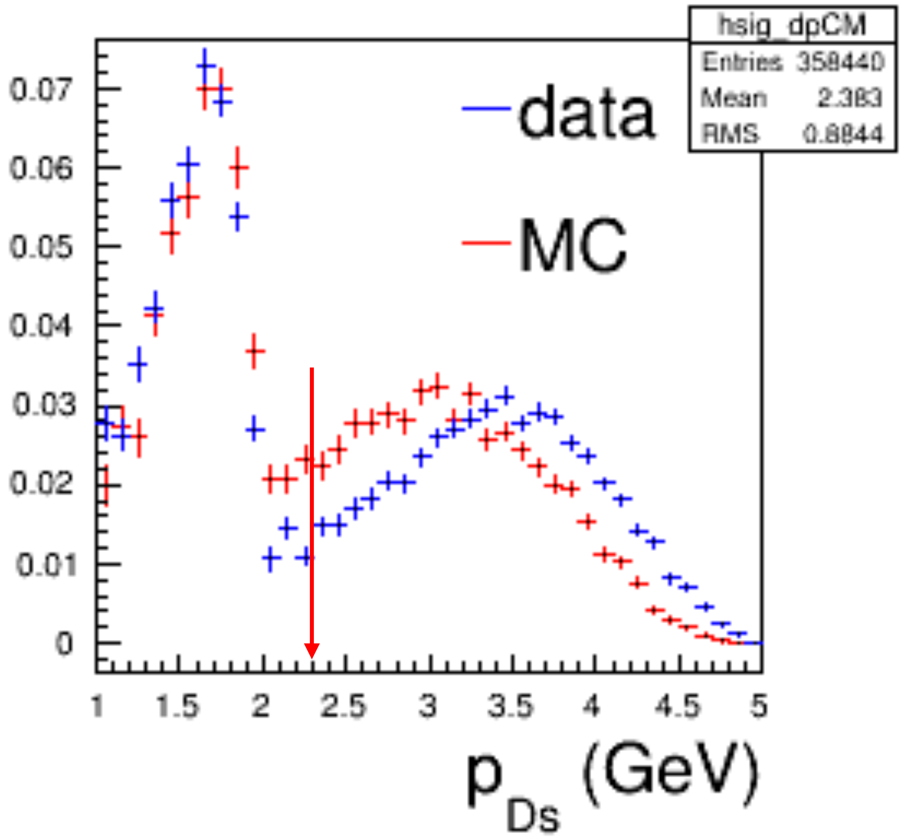
Source	$\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(\phi\pi^+)}$	$\frac{\mathcal{B}(K^+\eta_{\gamma\gamma})}{\mathcal{B}(\phi\pi^+)}$	$\frac{\mathcal{B}(K^+\eta_{3\pi})}{\mathcal{B}(\phi\pi^+)}$	$\frac{\mathcal{B}(\pi^+\pi^0)}{\mathcal{B}(\phi\pi^+)}$	$\frac{\mathcal{B}(\pi^+\eta_{\gamma\gamma})}{\mathcal{B}(\phi\pi^+)}$	$\frac{\mathcal{B}(\pi^+\eta_{3\pi})}{\mathcal{B}(\phi\pi^+)}$
Tracking	0.7	0.7	...	0.7	0.7	...
Particle identification	1.8	1.8	1.9	1.9	1.9	4.0
$\pi^0/\eta \to \gamma\gamma$	2.4	2.4	2.4	2.4	2.4	2.4
O_{NN} requirement	1.1	1.3	1.2	1.3	1.3	1.3
D_s^{*+} fraction in ε	0.7	0.7	0.7	0.7	0.7	0.7
MC statistics	0.8	0.8	0.8	0.8	0.7	0.7
Fitting	2.2	2.6	2.4	56.2	1.5	1.2
$\mathcal{B}(\eta \to \gamma\gamma)$	...	0.5	...	...	0.5	...
$\mathcal{B}(\eta \to \pi^+\pi^-\pi^0)$	...	...	1.2	...	...	1.2
Overall uncertainty	4.1	4.4	4.4	56.3	3.9	5.2

- systematic uncertainties for A_{CP} measurements:

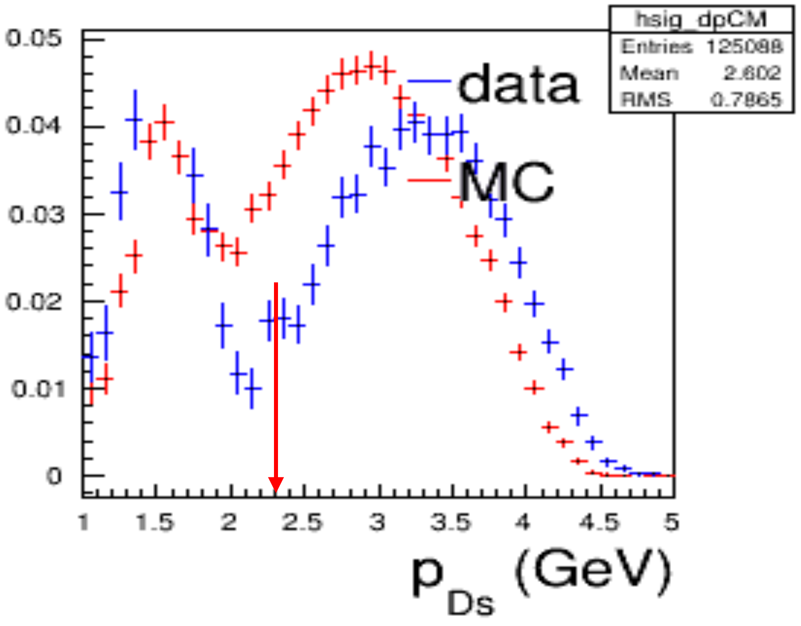
Source	$K^+\pi^0$	$K^+\eta_{\gamma\gamma}$	$K^+\eta_{3\pi}$	$\pi^+\eta_{\gamma\gamma}$	$\pi^+\eta_{3\pi}$	$\phi\pi^+$
Fitting	0.0056	0.0035	0.0020	0.0005	0.0005	0.0002
$D^+ \to \pi^+(\pi^0/\eta)$ background	0.0062	0.0022	0.0031	...	...	...
$\cos\theta_{D_s}^{\mathrm{CM}}$ binning	0.0068	0.0028	0.0068	...	...	...
A_{CP} in $D_s^+ \to \phi\pi^+$	...	...	...	0.0027	0.0027	...
Overall uncertainty	0.0108	0.0050	0.0077	0.0027	0.0027	0.0002

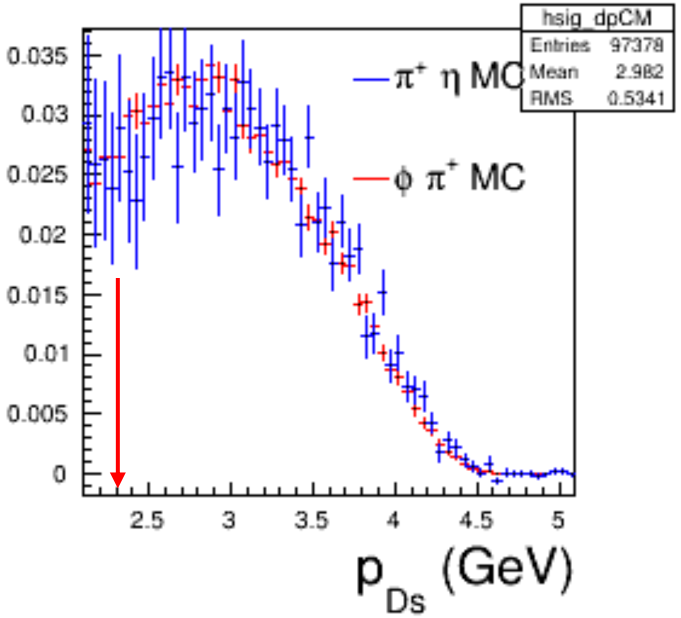
Splot $D^+_s \to \phi\pi^+$

untagged Ds



tagged Ds, and Egam > 0.15GeV





- data/MC differences are seen on the momentum of Ds distributions (CMS frame).
- Low momentum of Ds coming from B decays, excluded by P^*_{Ds}>2.3 GeV/c.