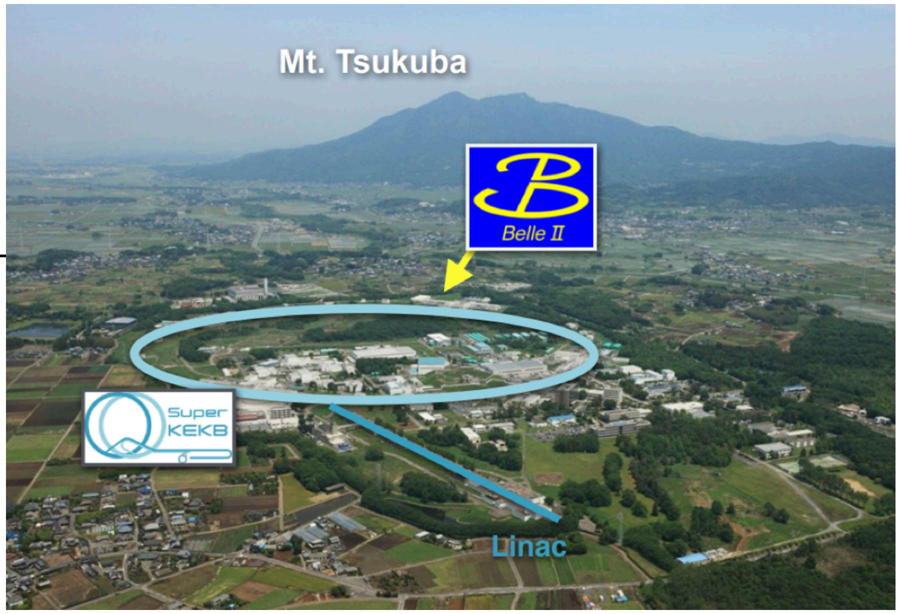
CPV measurements with *D* mesons at Belle (II)

Michel Bertemes on behalf of the Belle (II) collaboration

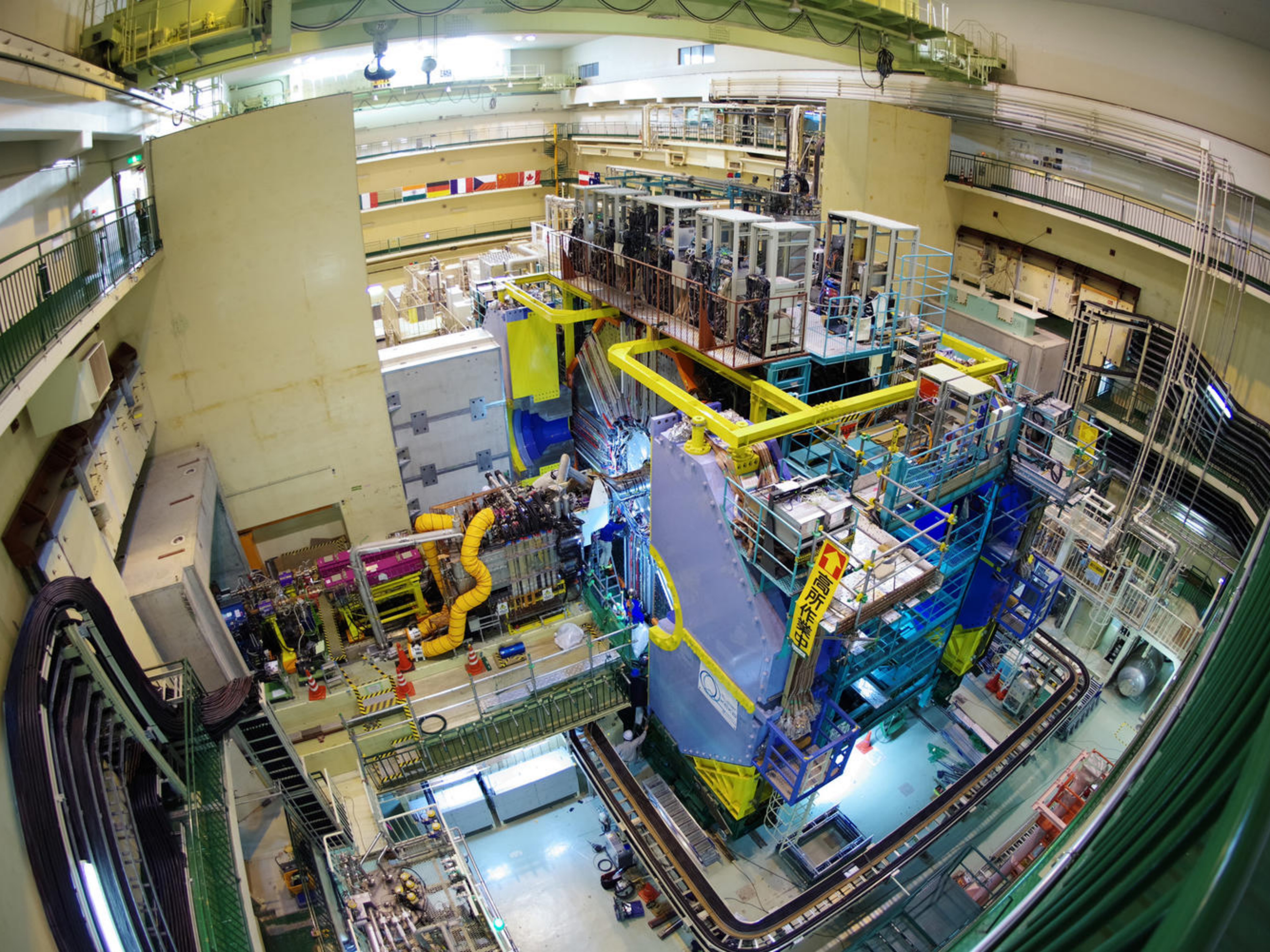
ICHEP Prague - 2024/07/20

Charm physics at Belle (II)



- *heavy-flavor collider experiment*
  - SuperKEKB: asymmetric e^+e^- collider in Tsukuba, Japan
  - Belle II: 4π spectrometer with **improved** vertexing, tracking, PID and calorimetry capabilities
- *"charm factory"*
  - **large** $e^+e^- \to c\bar{c}$ **cross-section** provides low-background event samples, 1.3M events per 1fb^{-1}
  - ~100% trigger efficiency uniform across decay time and kinematics
  - excellent reconstruction of **final states with neutrals** e.g. $D^+ \to \pi^+\pi^0, D^0 \to V\gamma, \pi^0\pi^0, K_S^0K_S^0, K\pi\pi^0, \pi\pi\pi^0 \ldots$

	Belle	Belle II
Years of operation	1999-2010	2019-
Beam energies	8 GeV (e^-) , 3.5 GeV (e^+)	7 GeV (e^-) , 4 GeV (e^+)
Data set (Y(nS))	980 fb^{-1}	531 fb^{-1}



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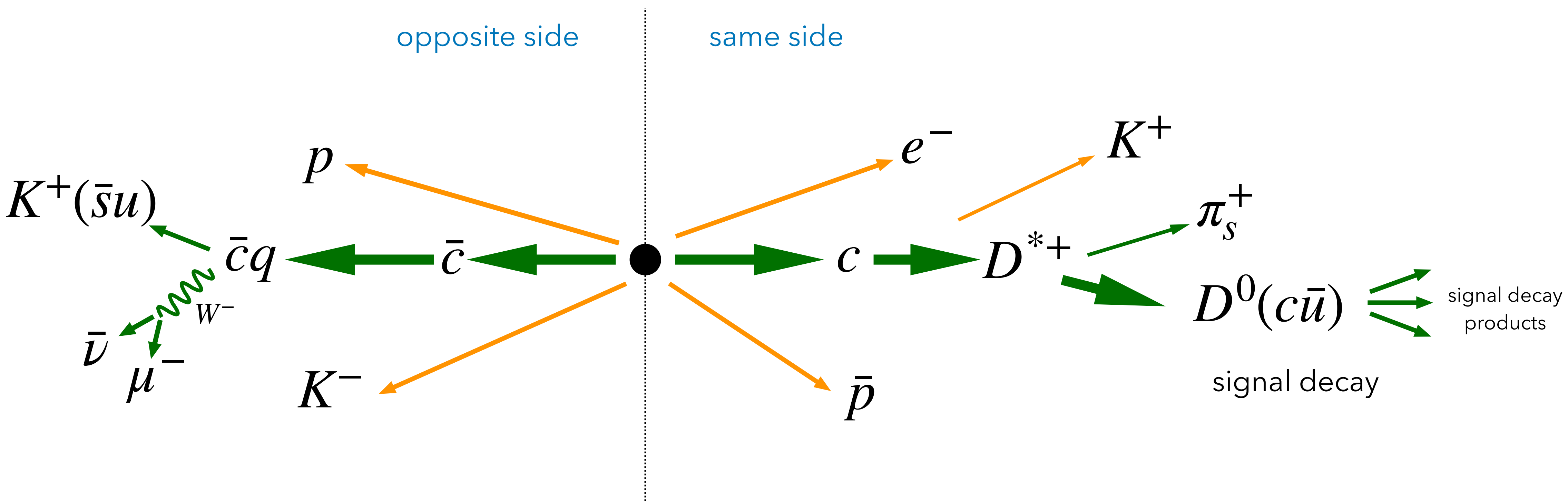
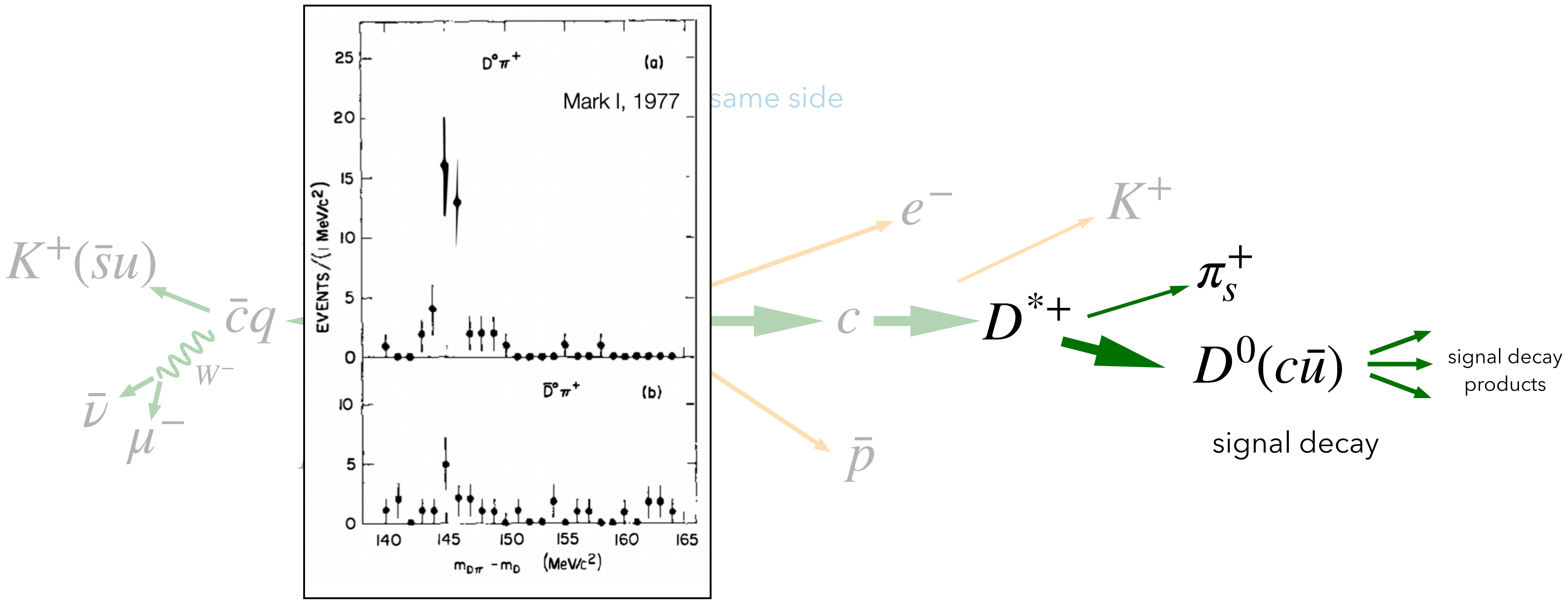
A beautiful charm event



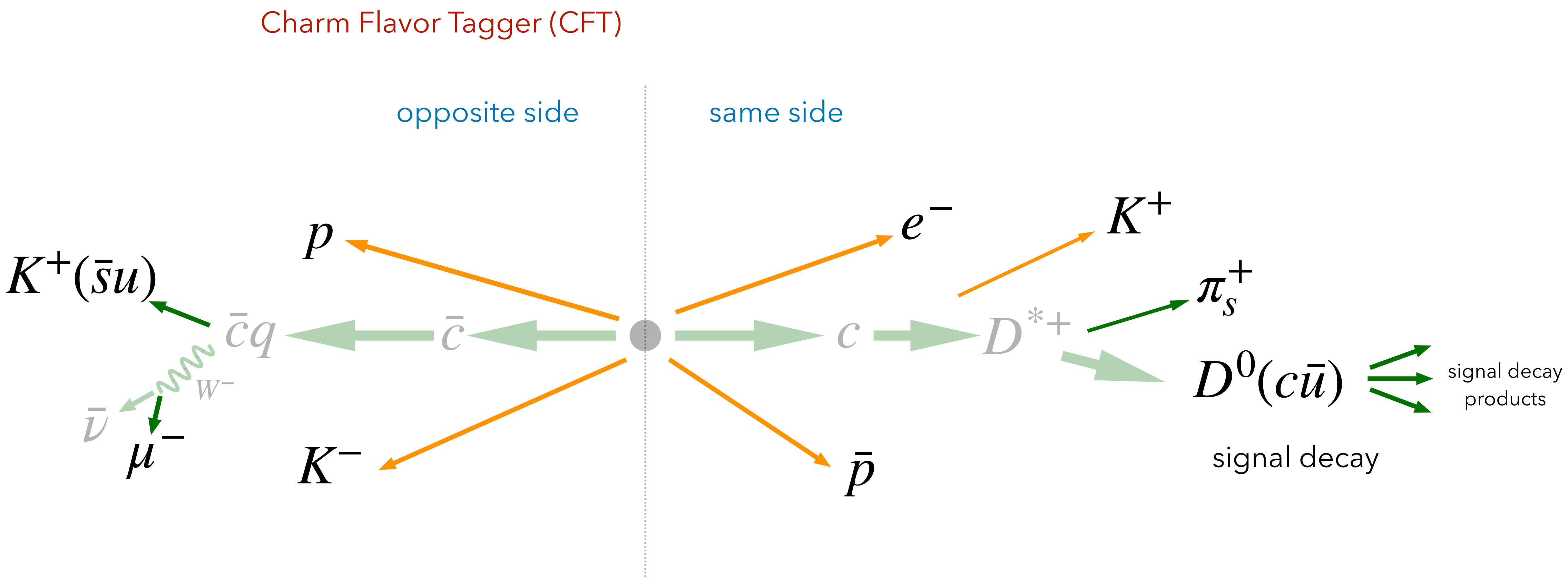
- $e^+e^- \to$ two charm hadrons + fragmentation
  - no entanglement, inaccessible strong phase

A beautiful charm event



- $e^+e^-\rightarrow$ two charm hadrons + fragmentation
  - no entanglement, inaccessible strong phase
- **exclusive reconstruction** of strong decay $D^{*+} \rightarrow D^0\pi_s^+$
  - inefficient reconstruction of slow=low momentum pion
  - loss in statistics (only ~25% of all charm quarks hadronize into D^*)

A beautiful charm event



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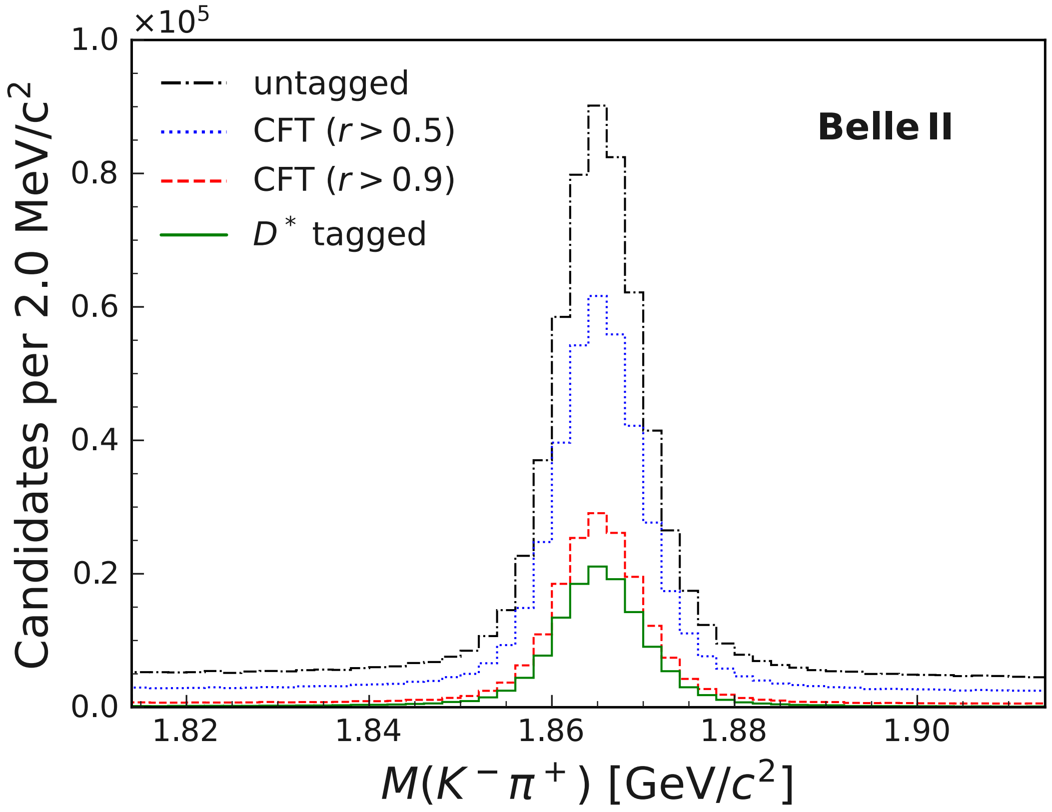
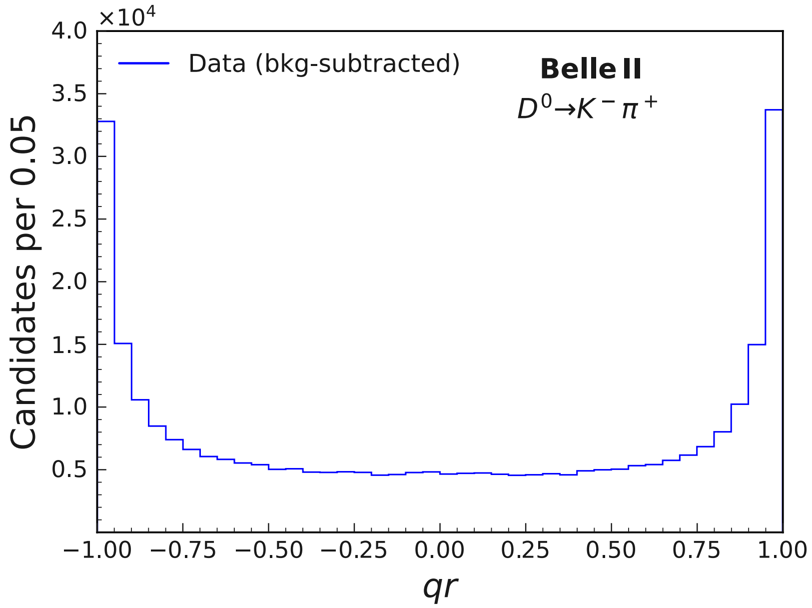
  - based on BDTs, uses kinematic features and PID as input
  - double the sample size w.r.t D^{*+}-tagged events

A beautiful charm event

Charm Flavor Tagger (CFT) PRD 107, 112010 (2023)





$$\epsilon_{\mathrm{tag}}^{\mathrm{eff}} = (47.91 \pm 0.07(\mathrm{stat}) \pm 0.51(\mathrm{syst}))\ \%$$

tagging power: $\epsilon_{\mathrm{tag}}^{\mathrm{eff}} = \epsilon_{\mathrm{tag}} \langle r^2 \rangle$, $\epsilon_{\mathrm{tag}}^{\mathrm{eff}}(D*) \sim 24\ \%$

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Search for CPV in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$ decays

New for ICHEP!

Search for CPV in $D^+_{(s)} \to K^+ K^0_S h^+ h^-$ decays and observation of $D^+_s \to K^+ K^- K^0_S \pi^+$

PRD 108, L111102 (2023)

Search for CPV using T-odd correlations in $D^+_{(s)} \to K^+ K^- \pi^+ \pi^0, K^+ \pi^- \pi^+ \pi^0$ and $D^+ \to K^- \pi^+ \pi^+ \pi^0$ decays

arXiv:2305.12806

Two approaches

$$A_{\rm raw} = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

$$A_{\rm raw} = A_{CP} + A_{\rm FB} + A_{\epsilon}$$

- obtain asymmetry from difference in partial widths
- $A_{\rm raw}$ includes asymmetries in production and reconstruction
  - $A_{\rm FB}$: arising from $\gamma - Z^0$ interference
  - A_{ϵ}: reconstruction of final-state particles
  - need control channel to correct
- in charm: singly-Cabibbo suppressed two-body decays

$$A_{CP} \propto \sin(\phi)\sin(\delta)$$

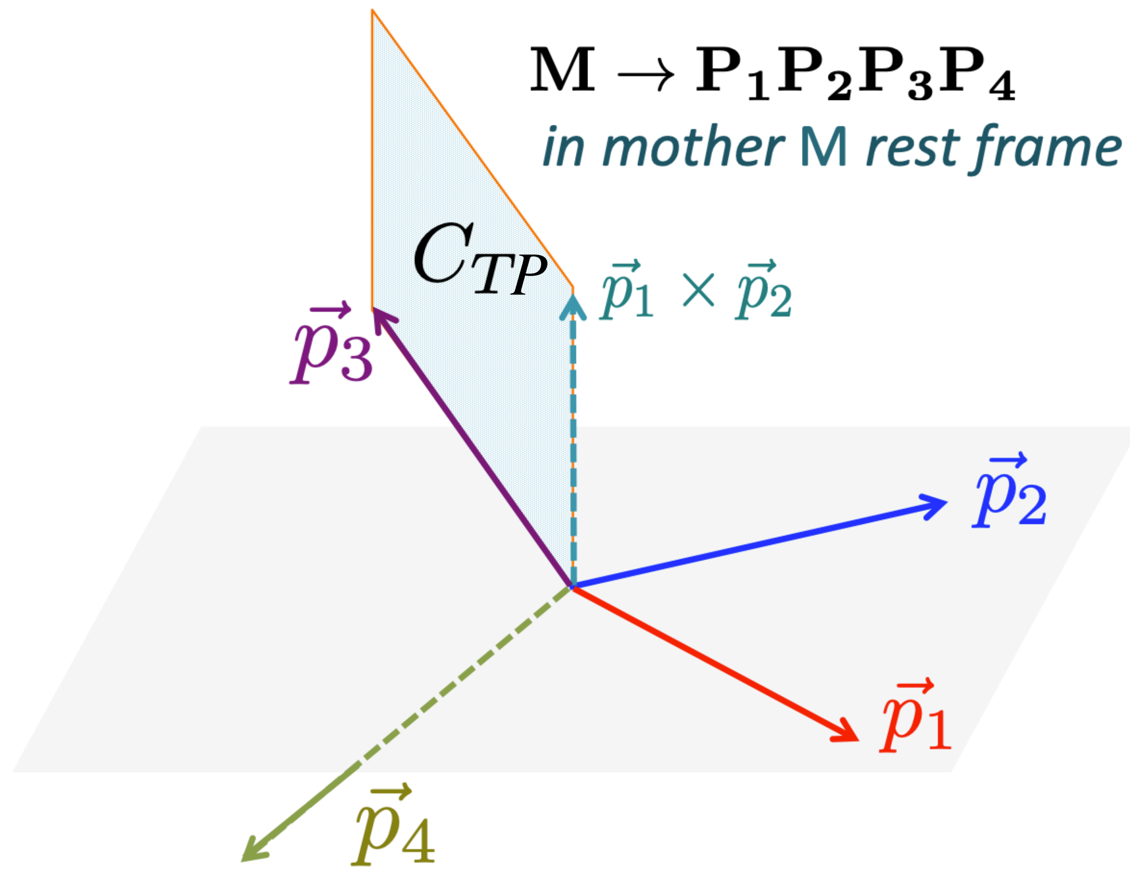
$$A_T = \frac{\Gamma(C_{TP} > 0) - \Gamma(C_{TP} < 0)}{\Gamma(C_{TP} > 0) + \Gamma(C_{TP} < 0)} \quad \bar{A}_T = \frac{\Gamma(-\bar{C}_{TP} > 0) - \Gamma(-\bar{C}_{TP} < 0)}{\Gamma(-\bar{C}_{TP} > 0) + \Gamma(-\bar{C}_{TP} < 0)}$$

$$a_{CP} = \frac{1}{2}(A_T - \bar{A}_T)$$

- measure asymmetry in kinematic observable (e.g. triple-product C_{TP})
- $A_T \neq 0$ can also arise from final-state interaction
  - isolate CP violation with a_{CP}
  - a_{CP} is unaffected by production and reconstruction asymmetries
- in charm: four-body decays

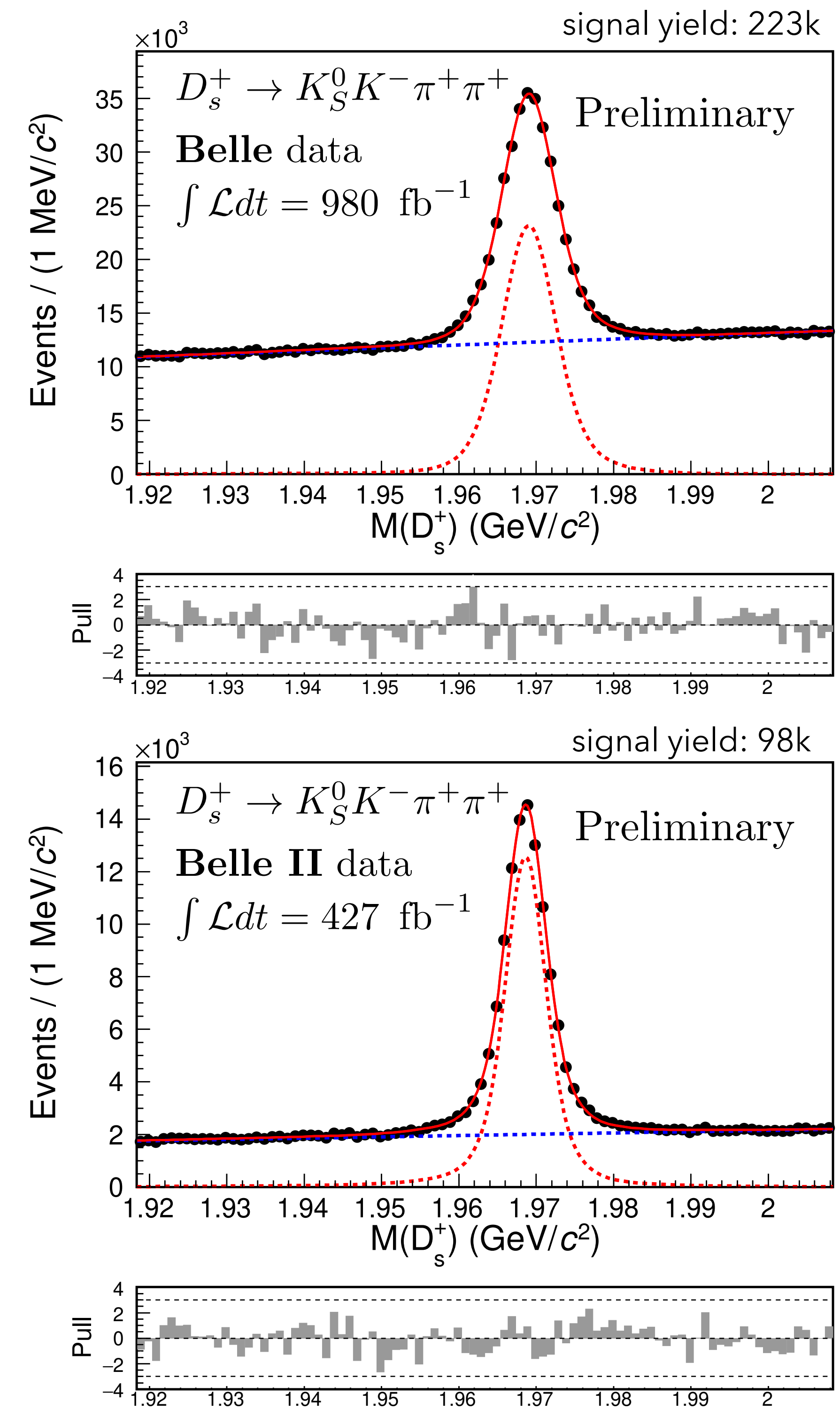
$$a_{CP} \propto \sin(\phi)\cos(\delta)$$

CPV in $D_{(s)}^{+} \to K_S^0 K^- \pi^+ \pi^+$



$$C_{TP} = (\vec{p}_{K^-} \times \vec{p}_{\pi_h^+}) \cdot \vec{p}_{K_S^0}$$

- better mass resolution and background suppression at Belle II
  - thanks to improved detector design/performance and additional pixel vertex detector

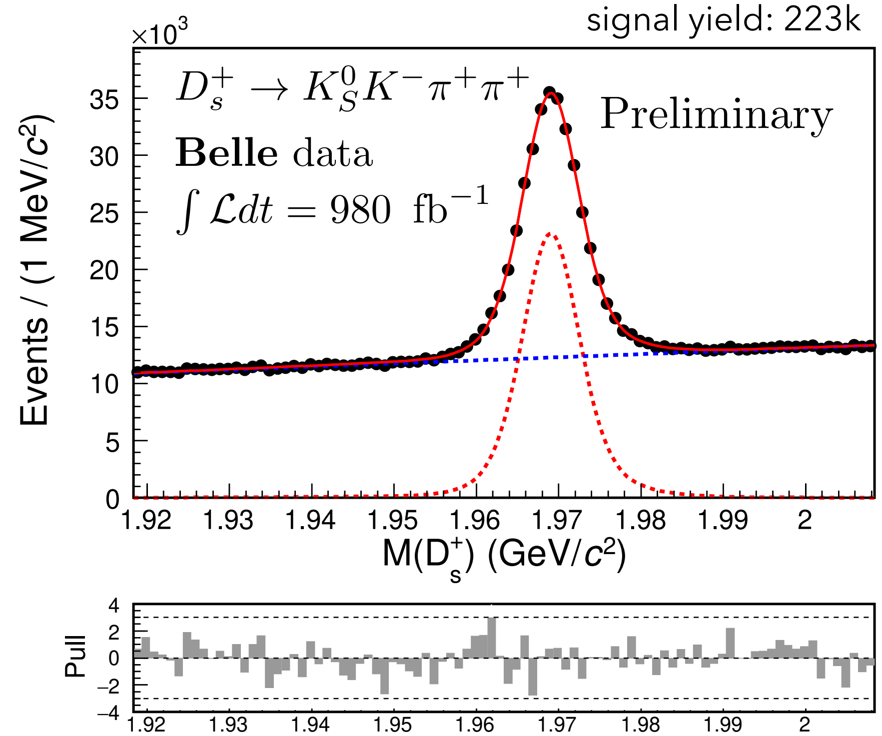


CPV in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$

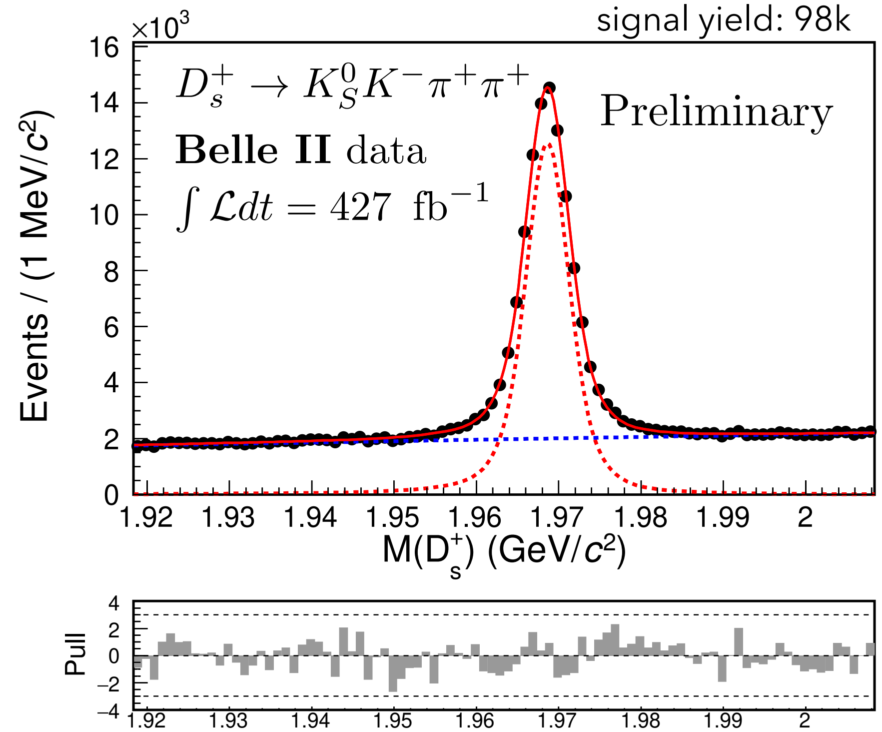
- divide D candidates into four subsamples based on charge and sign of C_{TP}
- obtain N_+, N_-, A_T and a_{CP} from simultaneous fit to subsamples

$$N(D^+_{(s)}, C_{TP} > 0) = \frac{N_+}{2}(1 + A_T)$$
$$N(D^+_{(s)}, C_{TP} < 0) = \frac{N_+}{2}(1 - A_T)$$
$$N(D^-_{(s)}, \bar{C}_{TP} > 0) = \frac{N_-}{2}(1 + A_T - 2a_{CP})$$
$$N(D^-_{(s)}, \bar{C}_{TP} < 0) = \frac{N_-}{2}(1 - A_T + 2a_{CP})$$

signal yield: 223k

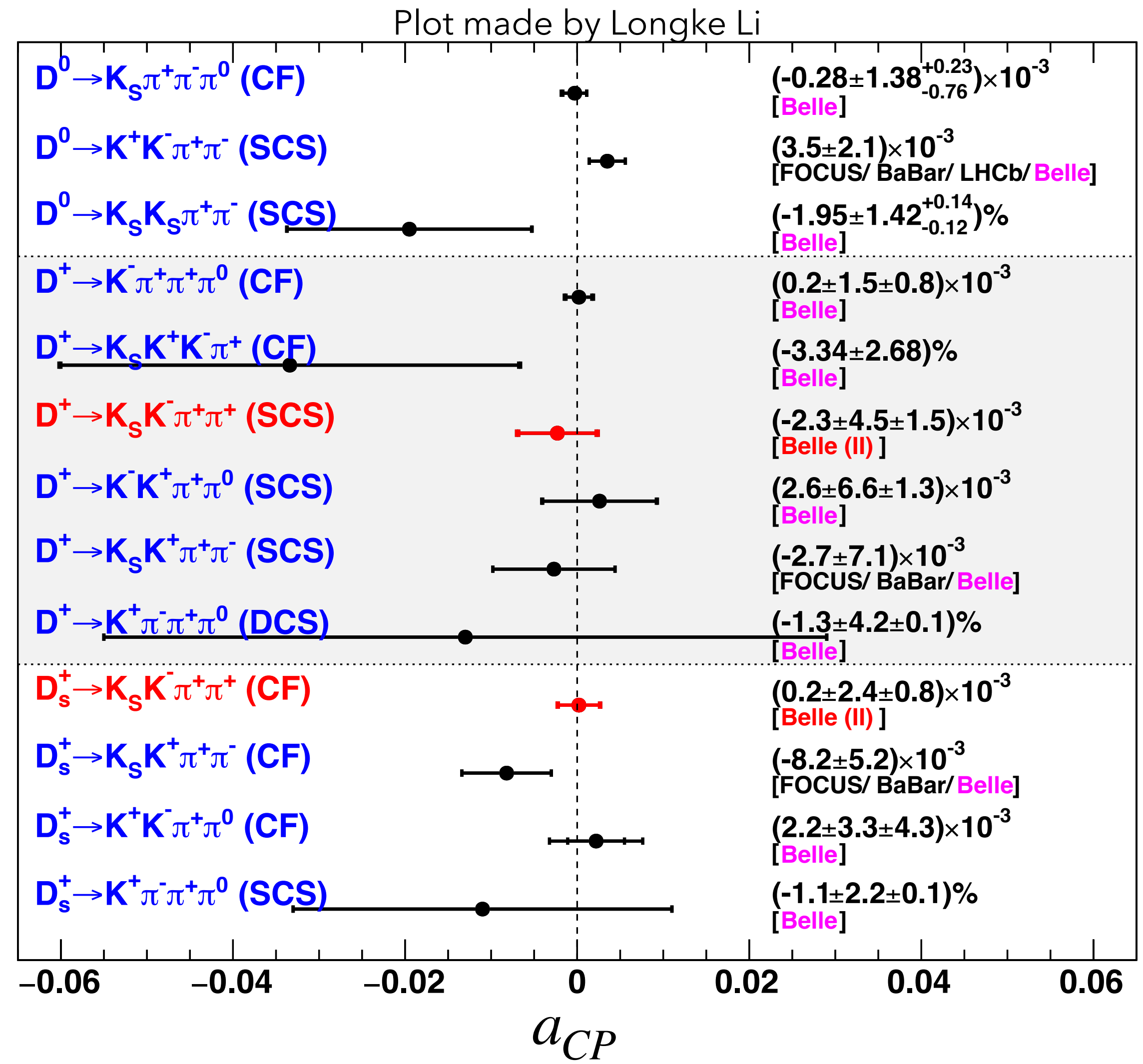


signal yield: 98k



CPV in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$

- divide D candidates into four subsamples based on charge and sign of C_{TP}
- obtain N_+, N_-, A_T and a_{CP} from simultaneous fit to subsamples
- systematic effects related to efficiency variation of C_{TP}
- results are among world's most precise measurements, no evidence of CPV



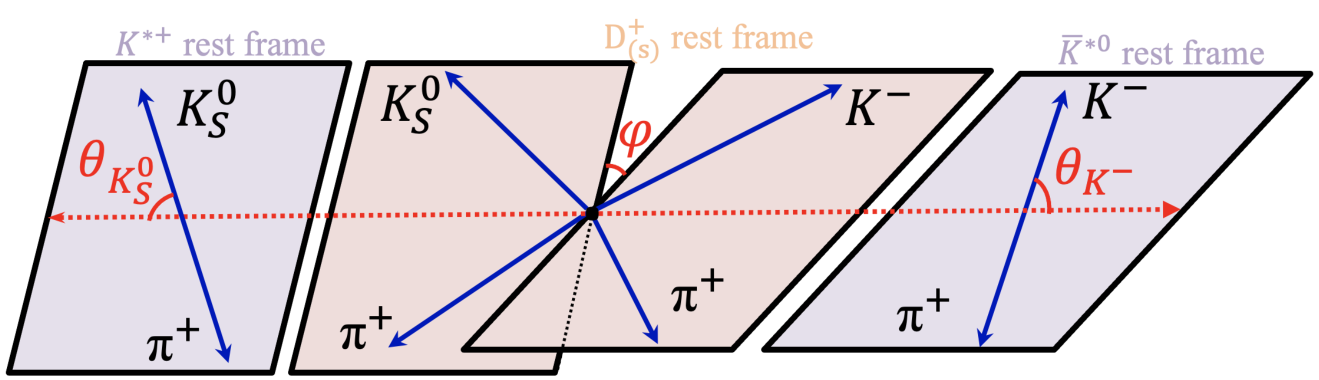
Belle I+II combined

$$D^+ : a_{CP} = (-0.23 \pm 0.45(\text{stat}) \pm 0.15(\text{syst}))\ \%$$

$$D^+_s : a_{CP} = (-0.02 \pm 0.24(\text{stat}) \pm 0.08(\text{syst}))\ \%$$

Noteworthy

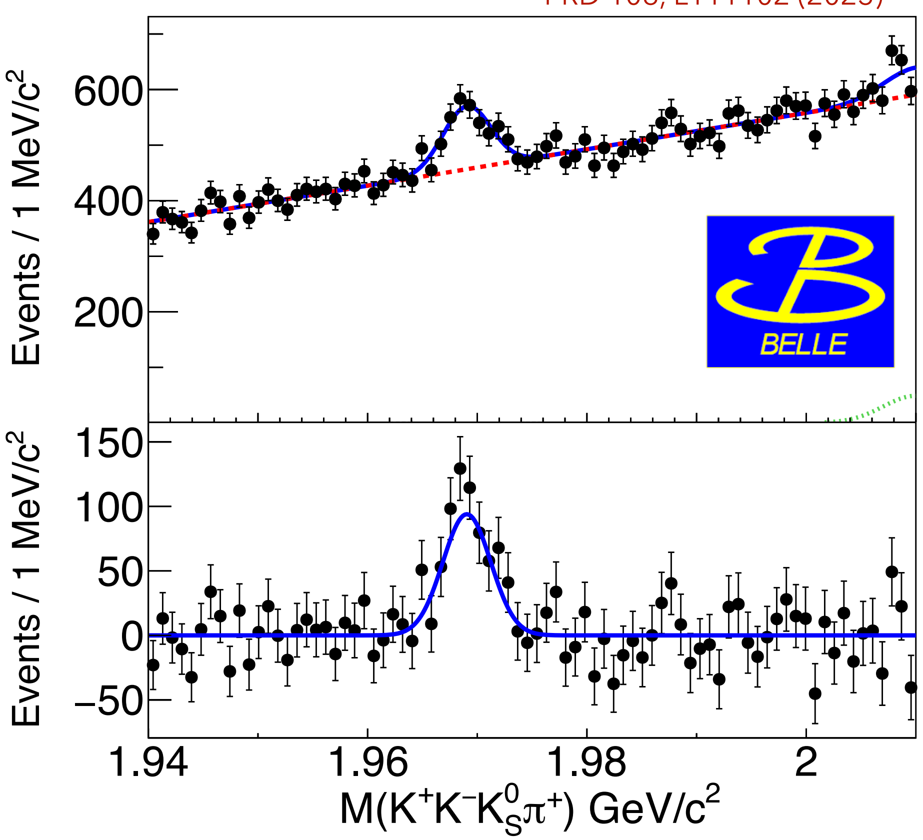
- asymmetries also measured in additional kinematic observables
  - quadruple products, helicity angle distributions
  - 12 results reported in total
  - all compatible with no CPV, first-time measurements
- first observation of $D_s^+ \to K^+K^-K_S^0\pi^+$:
  - $B(D_s^+ \to K^+K^-K_S^0\pi^+) = (1.29 \pm 0.14(\text{stat}) \pm 0.04(\text{syst}) \pm 0.11(\text{norm})) \times 10^{-4}$
  - norm. channel: $D_s^+ \to K^+K_S^0\pi^+\pi^-$
- measurement of a_{CP} in subregions of phase space:
  - largest asymmetry found in $D_s^+ \to K^{*0}\rho^+$
  - $a_{CP} = (6.2 \pm 3.0(\text{stat}) \pm 0.4(\text{syst}))\,\%$



$$C_{QP} = (\vec{p}_{K^-} \times \vec{p}_{\pi_h^+}) \cdot (\vec{p}_{K_S^0} \times \vec{p}_{\pi_l^+})$$

arXiv:2211.07332 PRD 92, 076013 (2015)

PRD 108, L111102 (2023)



Conclusion

- Charm Flavor Tagger
  - new inclusive algorithm that exploits correlation between signal flavor and charge of tagging particles
  - significantly enlarge the available sample size
  - more results on the way
- a_{CP} measurements
  - CPV probed in triple/quadruple products, helicity angles
  - complementary approach to asymmetries in partial width
  - use four-body charm decays, efficient reconstruction at Belle (II)
  - world's most precise results

Backup

CPV in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$

Table 2: Results for $\mathcal{A}^X_{CP}$ in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$ decays, where $X = C_{\rm TP}$ (1), $C_{\rm QP}$ (2), $C_{\rm TP}C_{\rm QP}$ (3), $\cos\theta_{K^0_S}\cos\theta_{K^-}$ (4), $C_{\rm TP}\cos\theta_{K^0_S}\cos\theta_{K^-}$ (5), and $C_{\rm QP}\cos\theta_{K^0_S}\cos\theta_{K^-}$ (6). The significance of the combined $\mathcal{A}^X_{CP}$ result from $\mathcal{A}^X_{CP} = 0$ is listed in the last column.

Decay	X	$\mathcal{A}^X_{CP}$ (10^{-3}) at Belle	$\mathcal{A}^X_{CP}$ (10^{-3}) at Belle II	Combined $\mathcal{A}^X_{CP}$ (10^{-3})	Significance
D^+	(1)	$-4.0 \pm 5.9 \pm 3.0$	$-0.2 \pm 7.0 \pm 1.8$	$-2.3 \pm 4.5 \pm 1.5$	0.5σ
	(2)	$-1.0 \pm 5.9 \pm 2.5$	$-0.4 \pm 7.0 \pm 2.4$	$-0.7 \pm 4.5 \pm 1.7$	0.2σ
	(3)	$+6.4 \pm 5.9 \pm 2.2$	$+0.6 \pm 7.0 \pm 1.3$	$+3.9 \pm 4.5 \pm 1.1$	0.8σ
	(4)	$-4.7 \pm 5.9 \pm 3.0$	$-0.6 \pm 6.9 \pm 3.0$	$-2.9 \pm 4.5 \pm 2.1$	0.6σ
	(5)	$+1.9 \pm 5.9 \pm 2.0$	$-0.2 \pm 7.0 \pm 1.9$	$+1.0 \pm 4.5 \pm 1.4$	0.2σ
	(6)	$+14.9 \pm 5.9 \pm 1.4$	$+7.0 \pm 7.0 \pm 1.6$	$+11.6 \pm 4.5 \pm 1.1$	2.5σ
D^+_s	(1)	$-0.3 \pm 3.1 \pm 1.3$	$+1.0 \pm 3.9 \pm 1.1$	$+0.2 \pm 2.4 \pm 0.8$	0.1σ
	(2)	$+0.6 \pm 3.1 \pm 1.2$	$+2.0 \pm 3.9 \pm 1.4$	$+1.1 \pm 2.4 \pm 0.9$	0.4σ
	(3)	$+1.5 \pm 3.2 \pm 1.4$	$-2.7 \pm 3.9 \pm 1.7$	$-0.2 \pm 2.5 \pm 1.1$	0.1σ
	(4)	$-3.7 \pm 3.1 \pm 1.1$	$-6.3 \pm 3.9 \pm 1.2$	$-4.7 \pm 2.4 \pm 0.8$	1.8σ
	(5)	$-4.4 \pm 3.2 \pm 1.4$	$+0.8 \pm 3.9 \pm 1.4$	$-2.2 \pm 2.5 \pm 1.0$	0.8σ
	(6)	$-1.6 \pm 3.1 \pm 1.3$	$-0.0 \pm 3.9 \pm 1.7$	$-1.0 \pm 2.4 \pm 1.0$	0.4σ

Table 3: Systematic uncertainties (absolute) for $\mathcal{A}^X_{CP}$ in units of 10^{-3} in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$ decays, where $X = C_{\rm TP}$ (1), $C_{\rm QP}$ (2), $C_{\rm TP}C_{\rm QP}$ (3), $\cos\theta_{K^0_S}\cos\theta_{K^-}$ (4), $C_{\rm TP}\cos\theta_{K^0_S}\cos\theta_{K^-}$ (5), and $C_{\rm QP}\cos\theta_{K^0_S}\cos\theta_{K^-}$ (6).

Source	$D^+ \to K^0_S K^- \pi^+ \pi^+$ at Belle						$D^+ \to K^0_S K^- \pi^+ \pi^+$ at Belle II					
	(1)	(2)	(3)	(4)	(5)	(6)	(1)	(2)	(3)	(4)	(5)	(6)
X-dependent efficiency	3.0	2.4	1.9	2.8	1.8	1.4	1.2	2.4	1.1	2.6	1.5	1.3
X-resolution asymmetry	0.2	0.7	0.4	0.7	0.6	0.3	0.7	0.1	0.1	0.9	0.2	0.7
Signal/background PDF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Simultaneous fit bias	0.2	0.2	0.1	0.2	0.1	0.2	0.2	0.2	0.2	0.1	0.2	0.2
D^+_s feeddown background	0.4	0.3	1.0	0.7	0.1	0.2	1.1	0.4	0.6	1.1	1.2	0.6
Total $\sigma_{\rm syst}$	3.0	2.5	2.2	3.0	2.0	1.4	1.8	2.4	1.3	3.0	1.9	1.6

Source	$D^+_s \to K^0_S K^- \pi^+ \pi^+$ at Belle						$D^+_s \to K^0_S K^- \pi^+ \pi^+$ at Belle II					
	(1)	(2)	(3)	(4)	(5)	(6)	(1)	(2)	(3)	(4)	(5)	(6)
X-dependent efficiency	1.2	1.1	1.4	1.1	1.2	1.3	1.1	1.4	1.7	1.2	1.4	1.6
X-resolution asymmetry	0.6	0.5	0.1	0.2	0.8	0.3	0.2	0.1	0.2	0.0	0.2	0.4
Signal/background PDF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Simultaneous fit bias	0.1	0.0	0.0	0.1	0.1	0.0	0.1	0.2	0.2	0.3	0.2	0.2
Total $\sigma_{\rm syst}$	1.3	1.2	1.4	1.1	1.4	1.3	1.1	1.4	1.7	1.2	1.4	1.7

Search for CPV in $D^+_{(s)} \to K^+ K^0_S h^+ h^-$ decays and observation of $D^+_s \to K^+ K^- K^0_S \pi^+$

TABLE I. Results of A_T and $a^{T\text{-odd}}_{CP}$ measurements. The uncertainties listed are statistical.

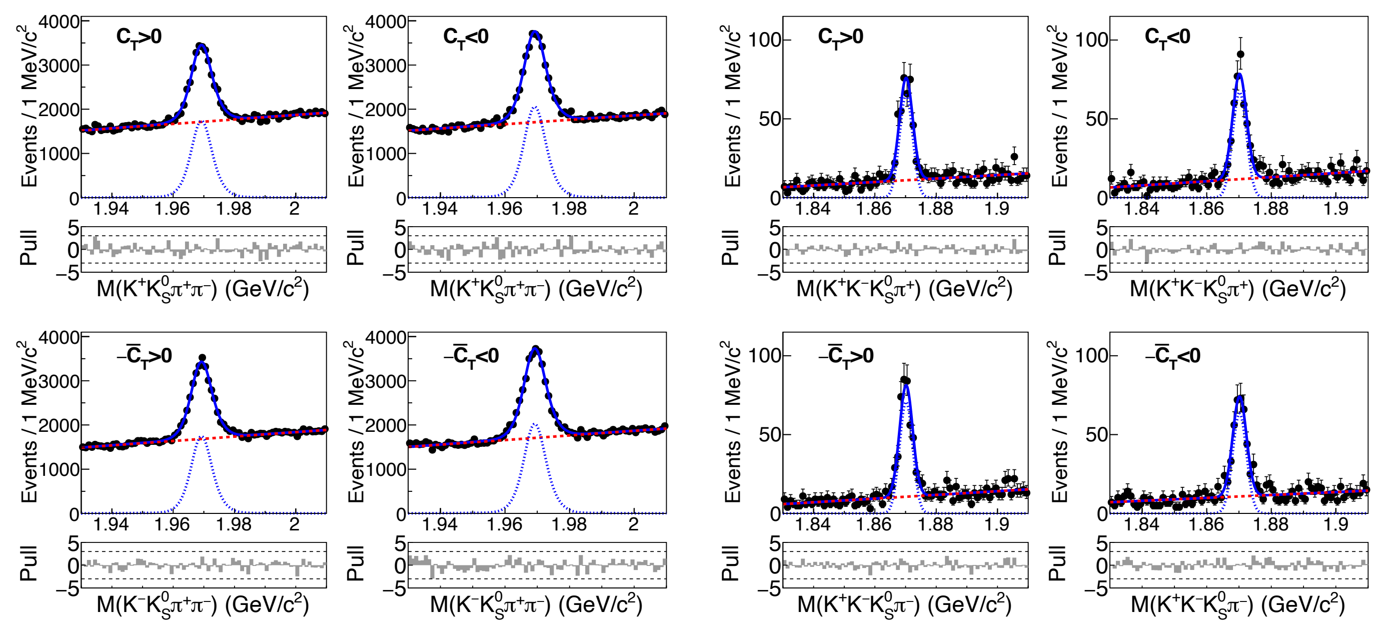
Mode	A_T (%)	$a^{T\text{-odd}}_{CP}$ (%)
$D^+ \to K^+ K^0_S \pi^+ \pi^-$	(3.67 ± 1.23)	(0.34 ± 0.87)
$D^+_s \to K^+ K^0_S \pi^+ \pi^-$	(-8.31 ± 8.89)	(-0.46 ± 0.63)
$D^+ \to K^+ K^- K^0_S \pi^+$	(-1.40 ± 4.23)	(-3.34 ± 2.66)

TABLE II. Contributions to the absolute systematic uncertainty for $a^{T\text{-odd}}_{CP}$ in units of % for each mode.

Sources	D^+(CS)	D^+_s(CF)	D^+(CF)
Fit model	0.01	0.02	0.12
Detector bias	0.32	0.32	0.32
Efficiency variation with C_T, $\overline{C}_T$	0.03	0.20	0.06
Total	0.32	0.38	0.35

TABLE III. Fitted signal yields and $a^{T\text{-odd}}_{CP}$ values. The first uncertainties are statistical and the second are systematic.

Mode	$N(D^+_{(s)})$	$a^{T\text{-odd}}_{CP}$ (%)
$D^+ \to K^+ K^0_S \pi^+ \pi^-$	18632 ± 214	$(0.34 \pm 0.87 \pm 0.32)$
$D^+_s \to K^+ K^0_S \pi^+ \pi^-$	70080 ± 676	$(-0.46 \pm 0.63 \pm 0.38)$
$D^+ \to K^+ K^- K^0_S \pi^+$	1425 ± 44	$(-3.34 \pm 2.66 \pm 0.35)$



Search for CPV using T-odd correlations in $D^+_{(s)} \to K^+K^-\pi^+\pi^0, K^+\pi^-\pi^+\pi^0$ and $D^+ \to K^-\pi^+\pi^+\pi^0$ decays

TABLE I. Fitted $D^+_{(s)}$ and $D^-_{(s)}$ signal yields (N_D and $N_{\overline{D}}$, respectively), T-odd asymmetry A_T, and T-odd CP-violating asymmetry $a_{CP}^{T\text{-odd}}$, obtained from a simultaneous fit to the four subsamples of each decay mode. The uncertainties listed are statistical only.

Decay	$D^+ \to f$			$D_s^+ \to f$	
Final state (f)	$K^+K^-\pi^+\pi^0$	$K^+\pi^-\pi^+\pi^0$	$K^-\pi^+\pi^+\pi^0$	$K^+\pi^-\pi^+\pi^0$	$K^+K^-\pi^+\pi^0$
N_D	27284 ± 254	2062 ± 127	438432 ± 947	15197 ± 484	167357 ± 786
$N_{\overline{D}}$	27177 ± 255	2044 ± 125	450667 ± 961	14945 ± 479	167064 ± 788
A_T (%)	$+3.63 \pm 0.93$	-0.4 ± 6.0	-0.76 ± 0.22	$+1.4 \pm 3.2$	$+2.96 \pm 0.47$
$a_{CP}^{T\text{-odd}}$ (%)	$+0.26 \pm 0.66$	-1.3 ± 4.2	$+0.02 \pm 0.15$	-1.1 ± 2.2	$+0.22 \pm 0.33$

TABLE II. T-odd CP-violating asymmetries ($a_{CP}^{T\text{-odd}}$) in seven subregions of phase space (see text) corresponding to the intermediate $D^+_{(s)} \to VV$ processes listed. The uncertainties listed are statistical and systematic, respectively.

Subregion	$D^+_{(s)} \to VV$	Signal region (SR)	$a_{CP}^{T\text{-odd}}$ ($\times 10^{-2}$)
(1) SCS	$D^+ \to \phi\rho^+$	ϕ-SR, ρ^+-SR	$0.85 \pm 0.95 \pm 0.25$
(2) SCS	$D^+ \to \overline{K}^{*0}K^{*+}$	$K^{*(0,+)}$-SR, veto ϕ-SR	$0.17 \pm 1.26 \pm 0.13$
(3) CF	$D^+ \to \overline{K}^{*0}\rho^+$	K^{*0}-SR, ρ^+-SR	$0.25 \pm 0.25 \pm 0.13$
(4) SCS	$D_s^+ \to K^{*0}\rho^+$	K^{*0}-SR, ρ^+-SR	$6.2 \pm 3.0 \pm 0.4$
(5) SCS	$D_s^+ \to K^{*+}\rho^0$	K^{*+}-SR, ρ^0-SR	$1.7 \pm 6.1 \pm 1.5$
(6) CF	$D_s^+ \to \phi\rho^+$	ϕ-SR, ρ^+-SR	$0.31 \pm 0.40 \pm 0.43$
(7) CF	$D_s^+ \to \overline{K}^{*0}K^{*+}$	$K^{*(0,+)}$-SR, veto ϕ-SR	$0.26 \pm 0.76 \pm 0.37$

TABLE III. Systematic uncertainties for $a_{CP}^{T\text{-odd}}$ in % for five $D^+_{(s)}$ decay channels: (a) $D^+ \to K^-K^+\pi^+\pi^0$; (b) $D^+ \to K^+\pi^-\pi^+\pi^0$; (c) $D^+ \to K^-\pi^+\pi^+\pi^0$; (d) $D_s^+ \to K^+\pi^-\pi^+\pi^0$; and (e) $D_s^+ \to K^-K^+\pi^+\pi^0$.

Decay channel	(a)	(b)	(c)	(d)	(e)
C_T-dependent efficiency	0.13	0.02	0.08	0.02	0.41
C_T resolution	0.01	0.06	0.01	0.07	0.02
PDF parameters	0.01	0.07	0.01	0.07	0.04
Mass resolution	0.03	0.01	...	0.02	0.11
Fit bias	0.01	0.07	0.00	0.06	0.02
Total syst.	0.13	0.12	0.08	0.12	0.43