Search for CP violation and measurement of branching fraction for SCS decay $D^0 \rightarrow K_s^0 K_s^0 \pi^+ \pi^-$ at Belle experiment

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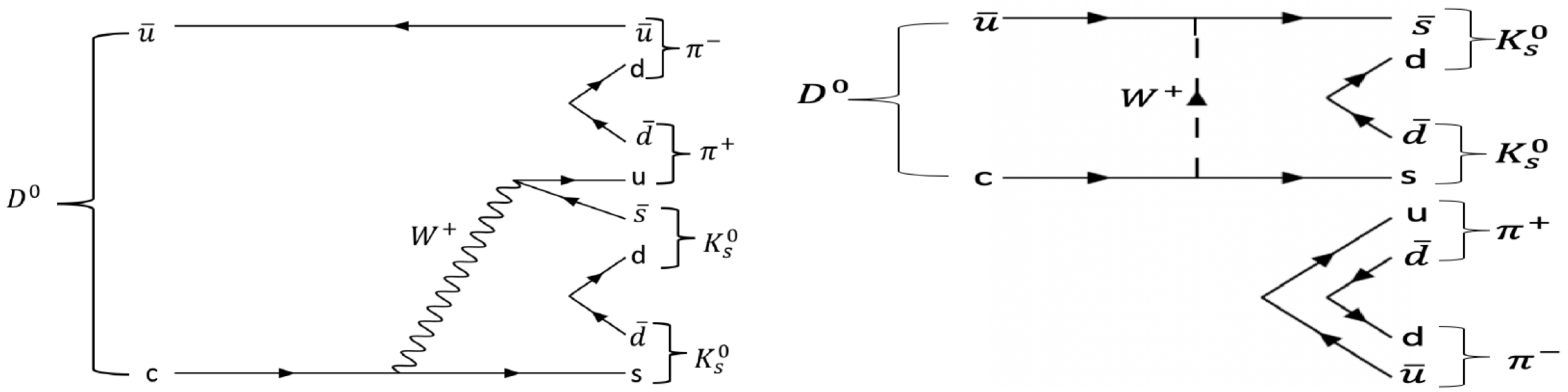
Motivation:

- In Standard Model framework, charm meson decays are expected to have very small CP violation, $\mathcal{O}(10^{-3})$ or smaller [1]
- CP violation measurement significantly deviating from SM expectation will probe new physics.

- Singly Cabibbo suppressed (SCS) charm decays are expected to be uniquely sensitive to new physics effects. [1]

- First experimental observation of CP violation in SCS charm mesons was made recently by LHCb. [2]

- In this analysis, we will search for CP violation in the SCS charm meson decay $D^0 \rightarrow K_S^0 K_S^0 \pi^+ \pi^-$
- We will also measure the branching fraction for this decay mode. *(previously measured by BESIII)*

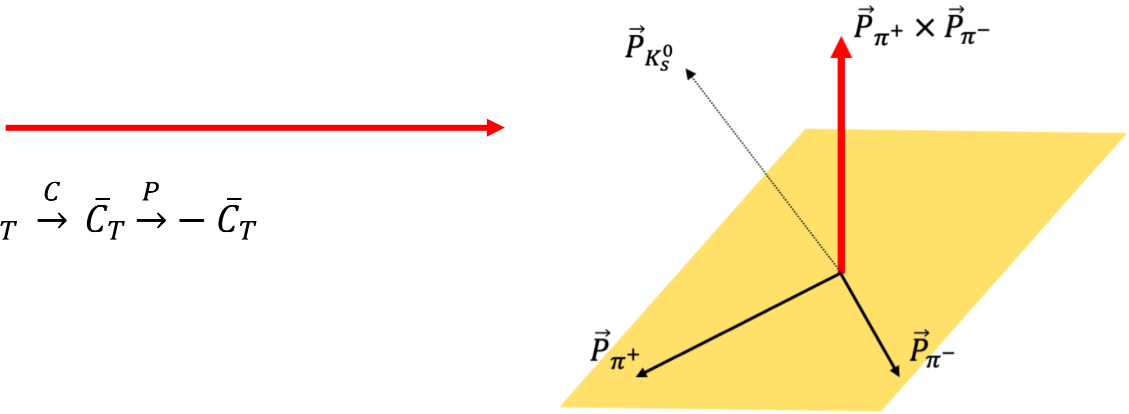


[1] (yuval grossman, et al. Phys.Rev.D 75 (2007), 036008)
[2] LHCb Collaboration Phys.Rev.Lett. 122 (2019) 21, 211803

CP violating observable:

- We measure the CP violation using T-odd triple product (TP) asymmetries:
  - $C_T = \vec{p}_{K_S^0} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$ (K_S^0 with higher momentum is used)
  - For D^0 decays, T-odd triple product asymmetry A_T is defined as :
    - $A_T = \frac{N_1\,(C_T>0) - N_2\,(C_T<0)}{N_1\,(C_T>0) + N_2\,(C_T<0)}$
  - For $\bar{D}^0$ decays, CP conjugate observables: $A_T \xrightarrow{CP} \bar{A}_T$, $C_T \xrightarrow{C} \bar{C}_T \xrightarrow{P} -\bar{C}_T$
    - $\bar{A}_T = \frac{N_3\,(-\bar{C}_T>0) - N_4(-\bar{C}_T<0)}{N_3\,(-\bar{C}_T>0) + N_4(-\bar{C}_T<0)}$

- *I. I. Y. Bigi. Charm physics: Like Botticelli in the Sistine Chapel.*
- *Michael Gronau et.al PRD,495 84(9), Nov 2011.*



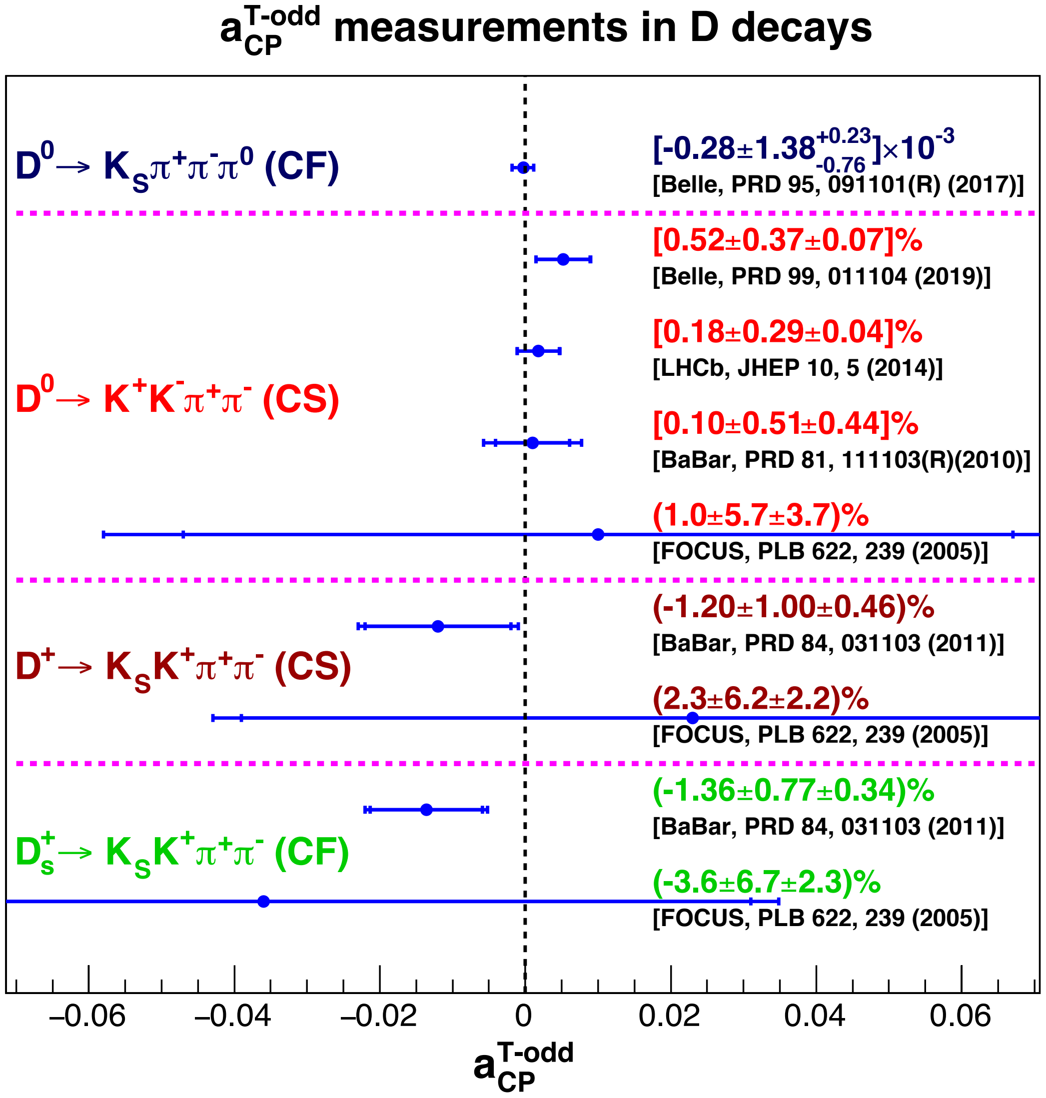
- The difference $a_{\mathrm{CP}}^{\mathrm{T-odd}} = \frac{1}{2}(A_T - \bar{A}_T)$ is a true CP violating observable.

- The observable $a_{\mathrm{CP}}^{\mathrm{T-odd}}$ is independent of effects from strong phases.
- *Michael Gronau et.al PRD,495 84(9), Nov 2011.*

- T-odd searches for CP violation differ from direct CP violation searches as they do not require a non-vanishing CP conserving strong phase difference between the contributing amplitudes.
- By construction, $a_{\mathrm{CP}}^{\mathrm{T-odd}}$ is mostly unaffected by production and detection related asymmetries.

- *A. Datta et.al, Int.J.Mod.Phys.A 19 (2004), 2505-2544*

Search for CP violation using a_{CP}^{T-odd} in D decays :



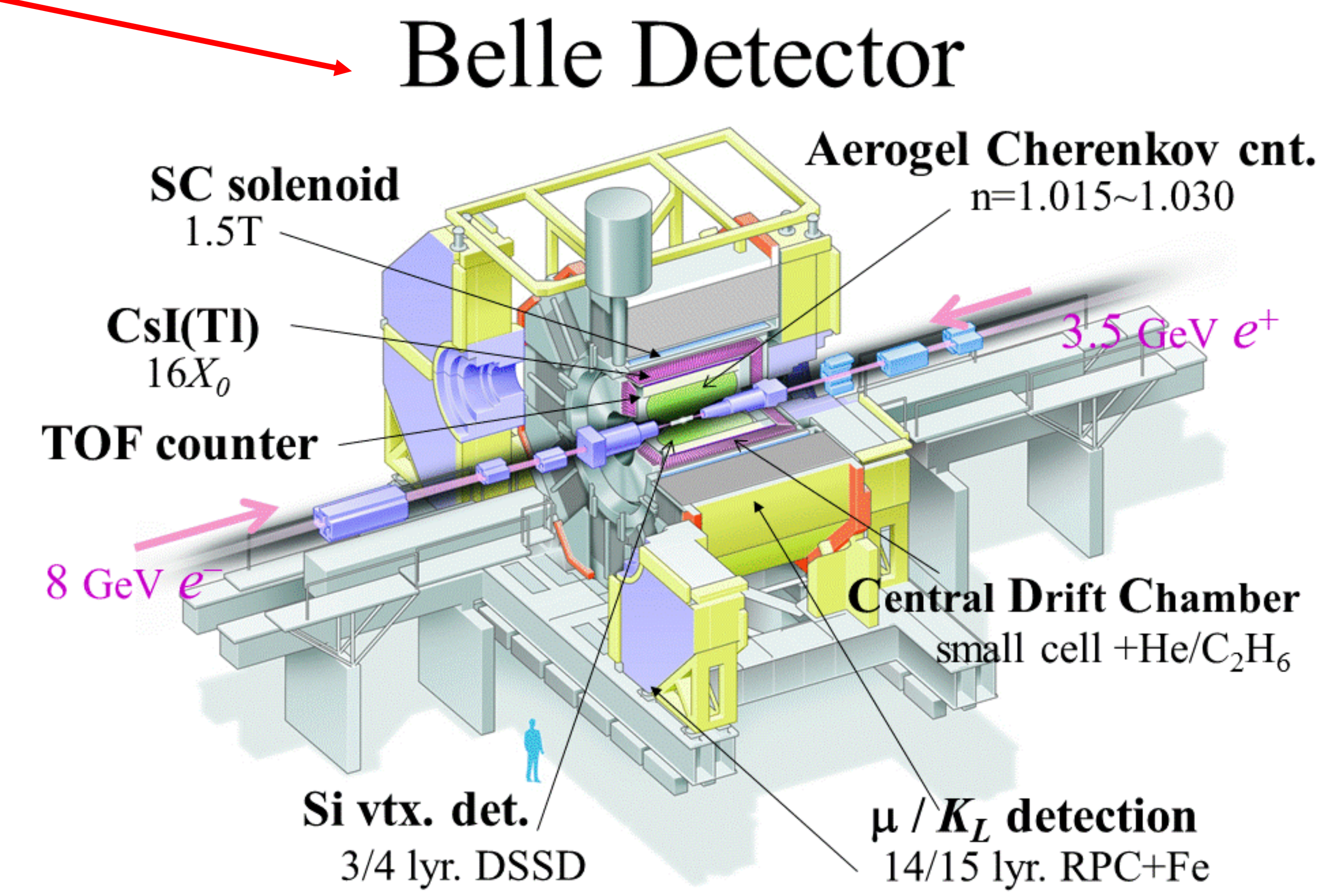
Belle detector and data sample:

- KEKB accelerator: collides 8 GeV e^- with 3.5 GeV e^+ . *(https://lib506extopc.kek.jp/preprints/PDF/1995/9524/ 9524007.pdf)*
- Belle detector is situated at collision point of KEKB accelerator. *(Nucl.Instrum.Meth.A 479 (2002), 117-232)*
- Belle detector had:
    - good PID
    (96.6 % π identification efficiency for this study)
    - good vertexing capability
    (important for reconstructed mass resolution)

- For this analysis we will use data sample corresponding to 922 fb^{-1} integrated luminosity.

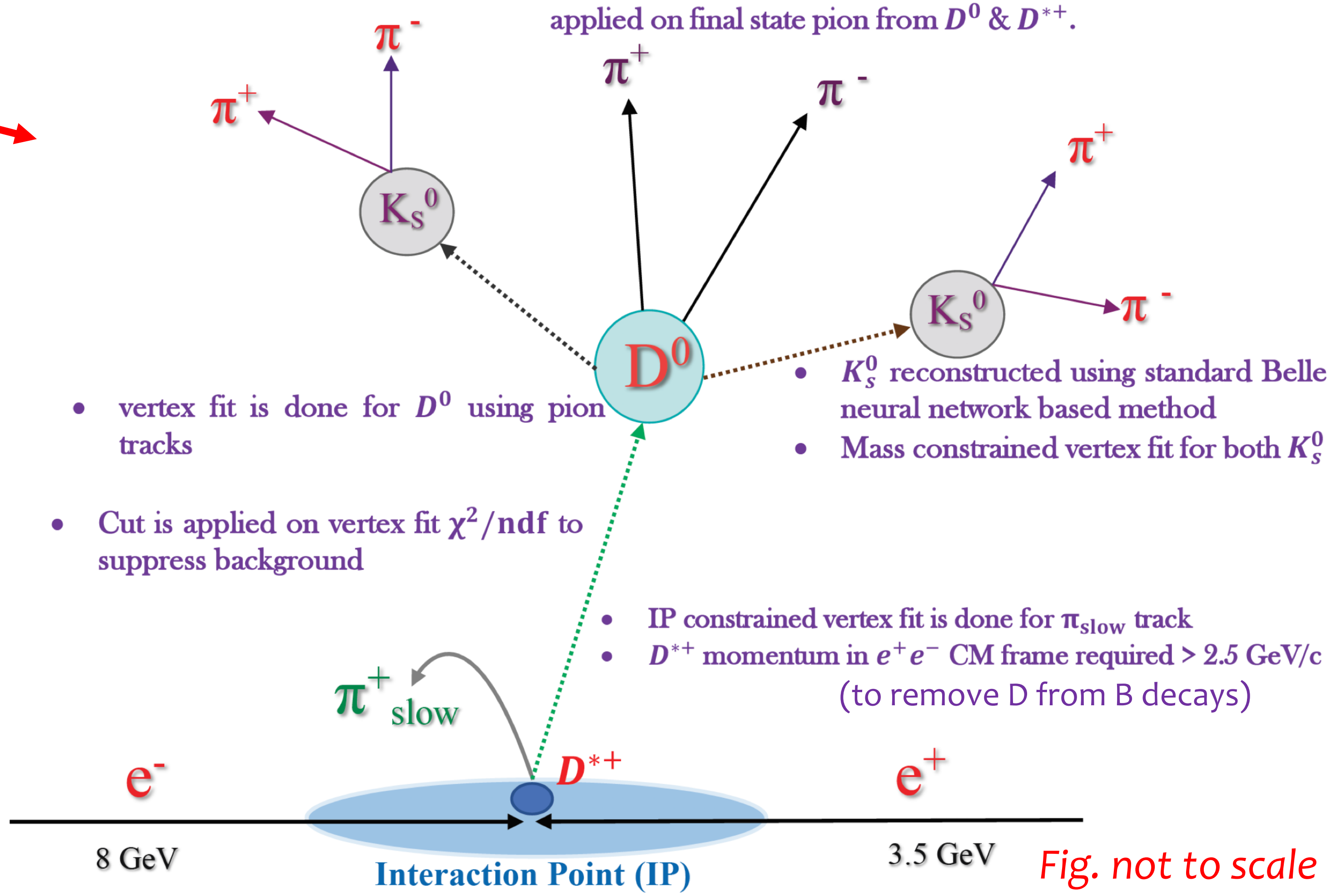
- Data is collected at e^+e^- COM energy equal to Υ(4S), 60 MeV below Υ(4S) and Υ(5S) resonances.

- We perform a blind analysis:
    - Optimize all selection criteria using simulation before looking at signal region in real data.



Reconstruction of decay at Belle detector

- Reconstructed decay chain and the corresponding selection criteria are summarized in the figure on right.
- In case of multiple candidate events, we choose a single candidate corresponding to the highest value for $\sum\chi^2/\mathrm{ndf}$ of D^*, D^0 and K_S^0 vertex fit.
- We get a reconstruction efficiency of 6.87% for $D^0 \to K_S^0 K_S^0 \pi^+\pi^-$
- We apply same set of selection cuts for normalization channel $D^0 \to K_S^0\pi^+\pi^-$ and obtain a reconstruction efficiency of 14.97 %



- Impact parameter and PID cuts are applied on final state pion from D^0 & D^{*+}.

- vertex fit is done for D^0 using pion tracks

- K_S^0 reconstructed using standard Belle neural network based method
- Mass constrained vertex fit for both K_S^0

- Cut is applied on vertex fit χ^2/ndf to suppress background

- IP constrained vertex fit is done for π_{slow} track
- D^{*+} momentum in e^+e^- CM frame required > 2.5 GeV/c (to remove D from B decays)

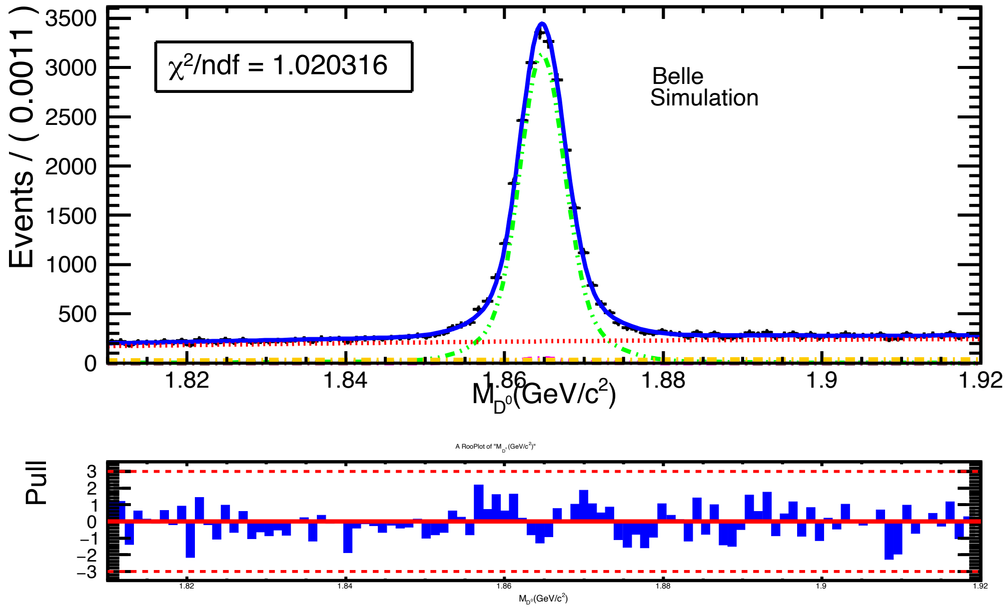
Fig. not to scale

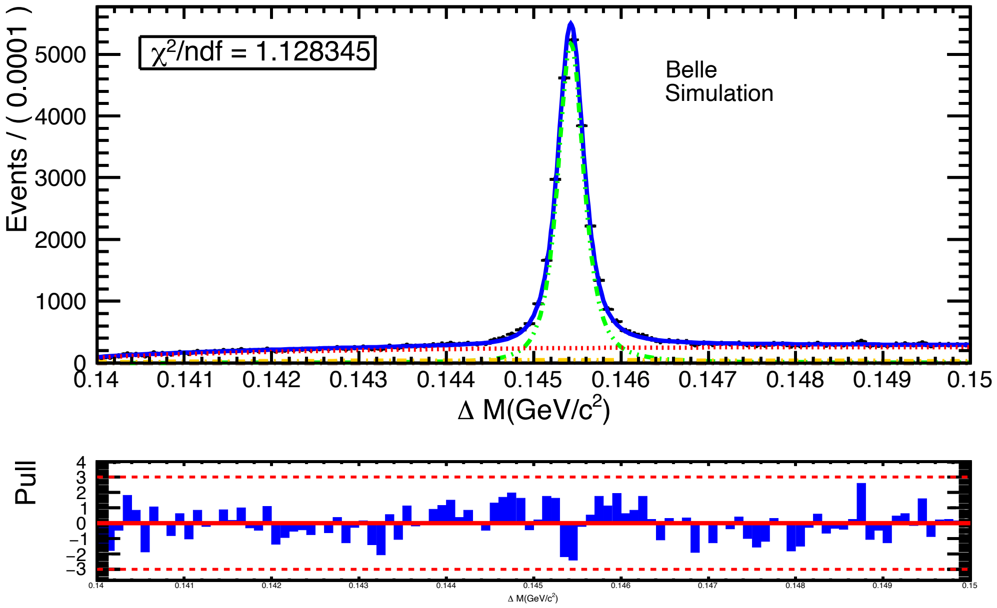
Branching fraction measurement

Signal extraction for BF measurement:

- $D^0 \to K_s^0 K_s^0 \pi^+ \pi^-$:
    - To extract the signal events from data sample we have used a 2d unbinned extended maximum likelihood fit in variables: $M_{D^0}[M(K_s^0 K_s^0 \pi^+ \pi^-)]$ and $\Delta M\ [M(K_s^0 K_s^0 \pi^+ \pi^- \pi_{slow}^+) - M(K_s^0 K_s^0 \pi^+ \pi^-)]$
    - Fit results from **Belle Simulation:**

Details on signal and background pdf in backup slide #17



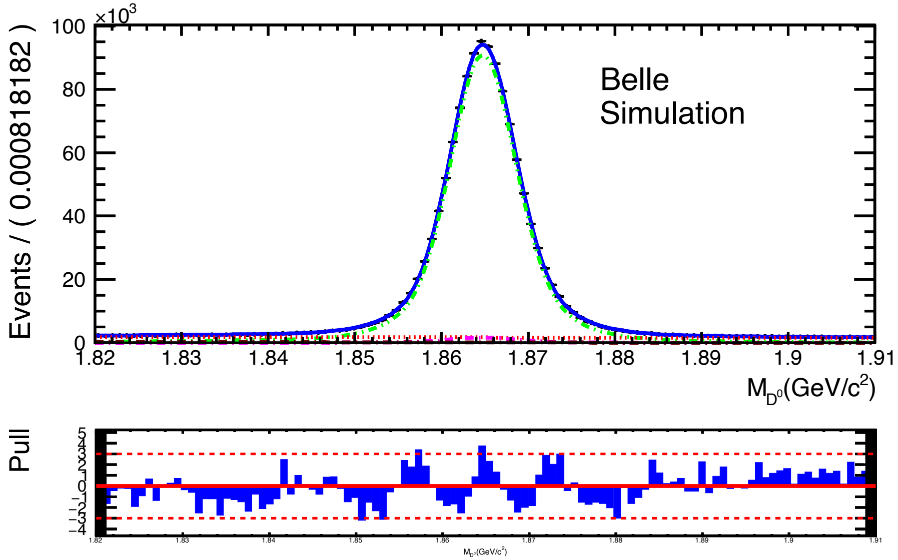


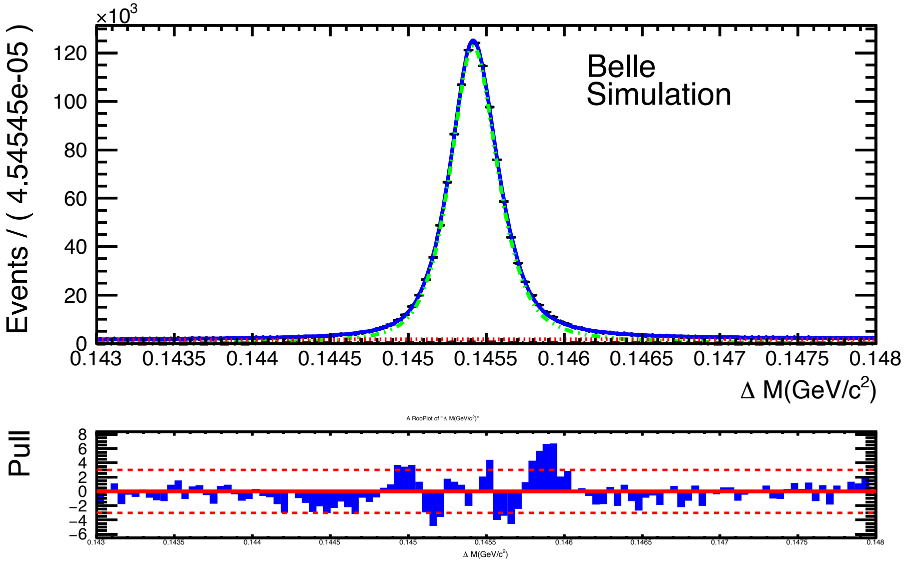
- We expect ~6.9 k signal events from 922 fb^{-1} of data.
- We perform the branching fraction measurement relative to normalization channel $D^0 \to K_s^0 \pi^+ \pi^-$

Signal extraction for BF measurement:

- $D^0 \rightarrow K_s^0\pi^+\pi^-$:
  - To extract the signal events from data sample we have used a 2d *binned* extended maximum likelihood fit in variables M_{D^0} and ΔM
  - Fit results from **Belle Simulation:**

Details on signal and background pdf in backup slide #17



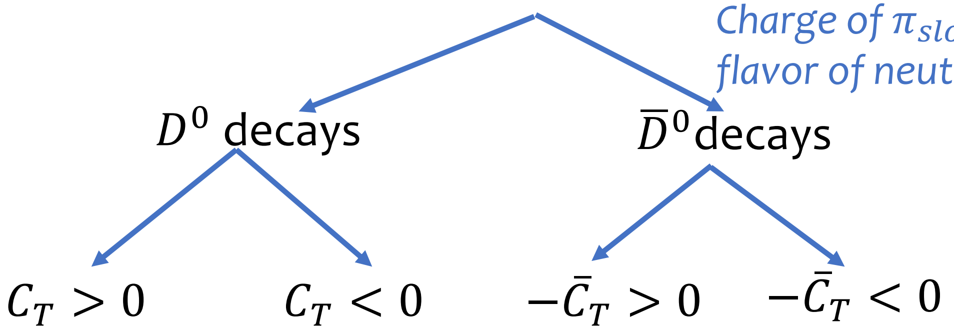


- We expect ~1.1M $D^0 \rightarrow K_s^0\pi^+\pi^-$ events from 922 fb^{-1} of data.
- For branching fraction measurement, we expect a precision of order $\Delta BF/BF$ ~ 2 %

$a_{\mathrm{CP}}^{\mathrm{T-odd}}$ measurement

Simultaneous fit for $a_{\mathrm{CP}}^{\mathrm{T-odd}}$ measurement:

- To measure $a_{\mathrm{CP}}^{\mathrm{T-odd}}$, data sample is divided into four categories:



Charge of π_{slow} is used to tag the flavor of neutral D meson

D^0 decays

$\bar{D}^0$decays

$C_T > 0$ $C_T < 0$ $-\bar{C}_T > 0$ $-\bar{C}_T < 0$

- To obtain $a_{\mathrm{CP}}^{\mathrm{T-odd}}$, we perform a 2d unbinned extended maximum likelihood fit simultaneously to these four datasets.
- Instead of yields N_1, N_2, N_3 and N_4 , we float N_1 , A_T , N_3 and $a_{\mathrm{CP}}^{\mathrm{T-odd}}$. This choice is made to get correct uncertainty in $a_{\mathrm{CP}}^{\mathrm{T-odd}}$ from fit results instead of calculating them using the uncertainty in yields.
- The expression for N_2 and N_4 in terms of N_1 , A_T , N_3 and $a_{\mathrm{CP}}^{\mathrm{T-odd}}$ are obtained as shown below:
- $A_T = \dfrac{N_1\,(C_T{>}0) - N_2\,(C_T{<}0)}{N_1\,(C_T{>}0) + N_2\,(C_T{<}0)}, \longrightarrow N_2 = \dfrac{N_1\,(1-A_T)}{(1+A_T)}$
- $\bar{A}_T = \dfrac{N_3\,(-\bar{C}_T{>}0) - N_4(-\bar{C}_T{<}0)}{N_3\,(-\bar{C}_T{>}0) + N_4(-\bar{C}_T{<}0)}$ and $a_{\mathrm{CP}}^{\mathrm{T-odd}} = \frac{1}{2}(A_T - \bar{A}_T) \longrightarrow N_4 = \dfrac{N_3\,(1-(A_T - 2 * a_{\mathrm{CP}}^{\mathrm{T-odd}}))}{1+(A_T - 2 * a_{\mathrm{CP}}^{\mathrm{T-odd}})}$

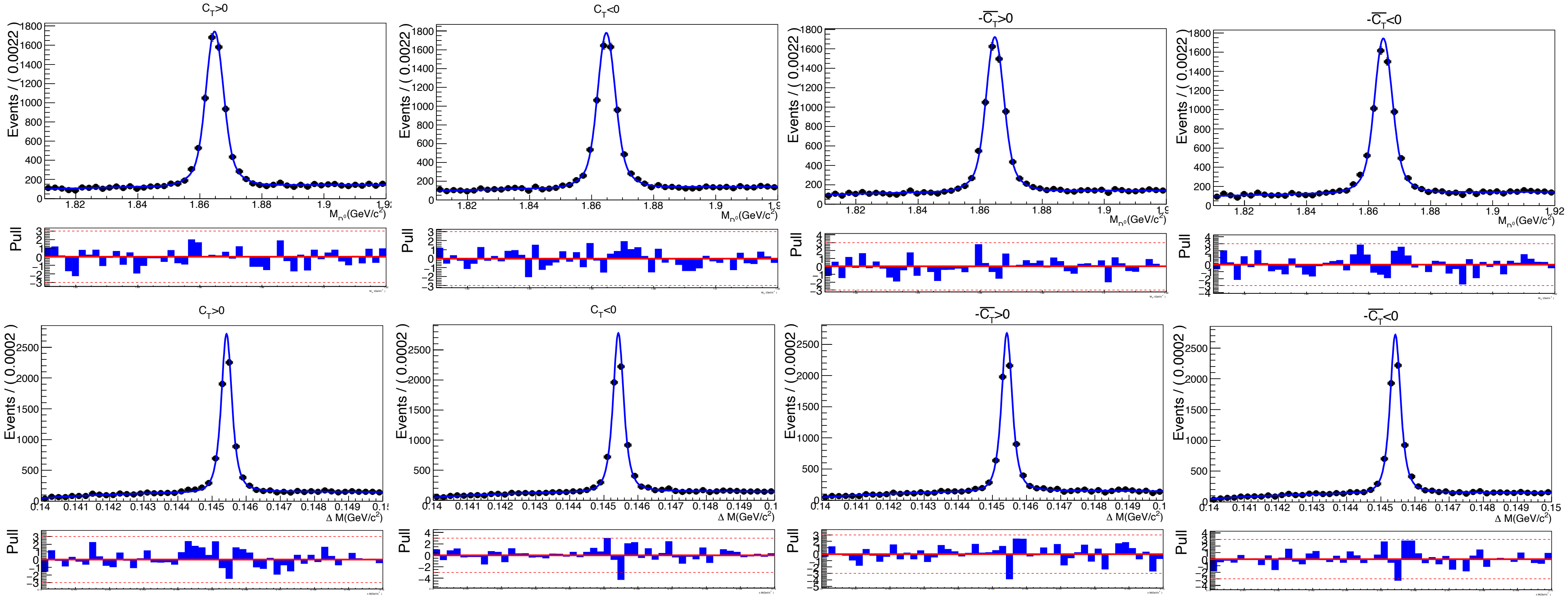
Simultaneous fit for $a_{\mathrm{CP}}^{\mathrm{T-odd}}$ measurement:

- Simultaneous fit projections on M_{D^0} and ΔM for four data samples obtained using Belle simulation are shown below:

$C_T > 0$ $C_T < 0$ $-\overline{C}_T > 0$ $-\overline{C}_T < 0$

M_{D^0} projections

ΔM projections



- For CP violation measurement, based on MC studies expected precision is: ~1.4 %

Summary:

- We are in the final stage of performing CP violation measurement using T-odd triple product asymmetries for SCS charm meson decay $D^0 \rightarrow K_S^0 K_S^0 \pi^+\pi^-$ at the Belle experiment.

- This will be a first CP violation measurement for the SCS decay $D^0 \rightarrow K_S^0 K_S^0 \pi^+\pi^-$.

- SCS charm decays are recommended to search for CP violation due to expected enhanced sensitivity towards the new physics effects.

- We are also making a branching fraction measurement, expecting to improve upon the precision compared with existing measurement.
- Branching fraction measurement is done relative to the normalization channel $D^0 \rightarrow K_S^0 \pi^+\pi^-$.

- For CP violation measurement, based on MC studies expected precision is: ~1.4 %

- For branching fraction measurement, we expect a precision of order $\Delta BF/BF \sim 2\ \%$

Backup

Variables used for K_S^0 reconstruction by Belle neural network based method

- K_S^0 momentum in lab frame.
- Distance along the z axis between two track helices at their closest approach.
- Flight length in x-y plane.
- Angle between K_S^0 momentum and the vector joining IP to K_S^0 decay vertex.
- Angle between π momentum and laboratory frame direction in K_S^0 rest frame.
- Distance of closest approach in the x-y plane between the IP and the two pion helices.
- Total number of hits in SVD (silicon vertex detector) and CDC (central drift chamber) for two pion tracks.

Signal extraction for BF measurement:

- $\boldsymbol{D^0 \rightarrow K_s^0 K_s^0 \pi^+ \pi^-}$:
  - Using simulation, events are divided into following categories:
    - **Events with correctly reconstructed signal decays.**
    - **Random $\boldsymbol{\pi_{\text{slow}}}$ background.** *(correctly reconstructed D^0 combined with wrong π_{slow})*
    - **Broken charm peaking background.** *(reconstruction missed one or more final state particles from a real D^0 decay to a non signal final state)*
    - **$\boldsymbol{D^0 \rightarrow 3K_s^0}$ peaking background** *(96% vetoed by selection on $\pi^+\pi^-$ invariant mass).*
    - **Combinatorial background.** *(random combination of final state particles)*

- $\boldsymbol{D^0 \rightarrow K_s^0 \pi^+ \pi^-}$:
  - Using simulation, events are divided into following categories:
    - **Events with correctly reconstructed signal decays.**
    - **Random $\boldsymbol{\pi_{\text{slow}}}$ background.**
    - **Broken charm peaking background.**
    - **Combinatorial background.**

Details of pdfs used to extract signal:

1> $D^0 \to K_S^0 K_S^0 \pi^+ \pi^-$:

Component type	M_{D^0}	ΔM
Signal decays	3 Asymmetric Gaussian (AG)	2AG + 1 student-t
Mis-reconstructed signal	2nd order chebychev polynomial	4th order chebychev polynomial
Random π_{slow} background	Same as signal	$Q^{\frac{1}{2}} + \alpha Q^{\frac{3}{2}}$ (Q = $\Delta M - M_\pi$)
Broken charm background	2 gaussian	student-t
$D^0 \to 3K_S^0$ background	gaussian	student-t
Combinatoric background	2nd order chebychev polynomial	$Q^{\frac{1}{2}} + \alpha' Q^{\frac{3}{2}}$

2> $D^0 \to K_S^0 \pi^+ \pi^-$:

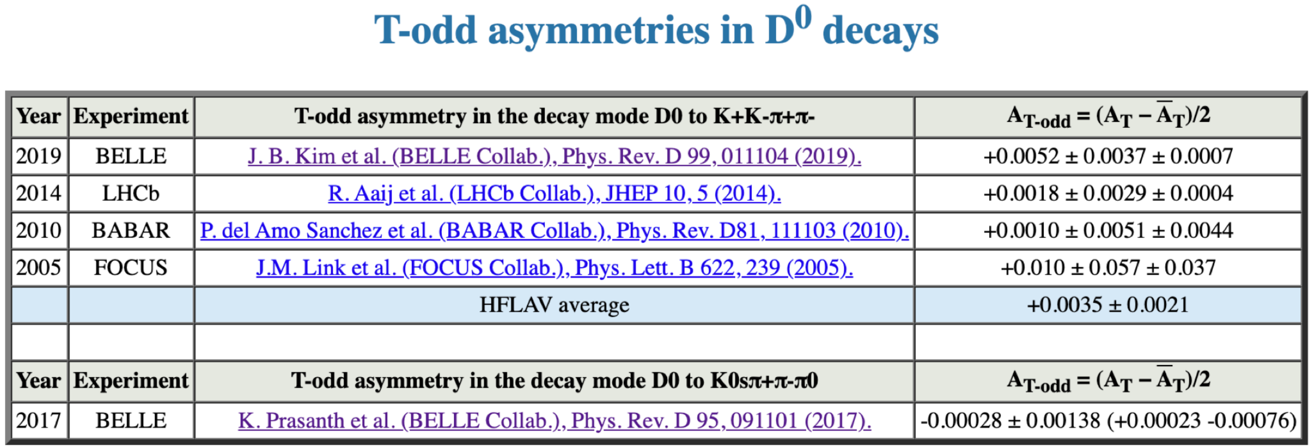
Component type	M_{D^0}	ΔM
Signal decays	3 Asymmetric Gaussian (AG)	1G + 1 Asymmetric student-t
Random π_{slow} background	Same as signal	$Q^{\frac{1}{2}} + \alpha Q^{\frac{3}{2}}$ (Q = $\Delta M - M_\pi$)
Broken charm background	gaussian + 2nd order polynomial	student-t
Combinatoric background	1st order chebychev polynomial	$Q^{\frac{1}{2}} + \alpha' Q^{\frac{3}{2}}$

Rearranging asymmetry equations on slide 5

- $A_T = \frac{N_1\,(C_T>0) - N_2\,(C_T<0)}{N_1\,(C_T>0) + N_2\,(C_T<0)}$, $\Rightarrow N_2 = \frac{N_1\,(1-A_T)}{(1+A_T)}$
- $\bar{A}_T = \frac{N_3\,(-\bar{C}_T>0) - N_4(-\bar{C}_T<0)}{N_3\,(-\bar{C}_T>0) + N_4(-\bar{C}_T<0)}$ and $a_{\mathrm{CP}}^{\mathrm{T-odd}} = \frac{1}{2}(A_T - \bar{A}_T) \Rightarrow N_4 = \frac{N_3\,(1-(A_T - 2*a_{\mathrm{CP}}^{\mathrm{T-odd}}))}{1+(A_T - 2*a_{\mathrm{CP}}^{\mathrm{T-odd}})}$

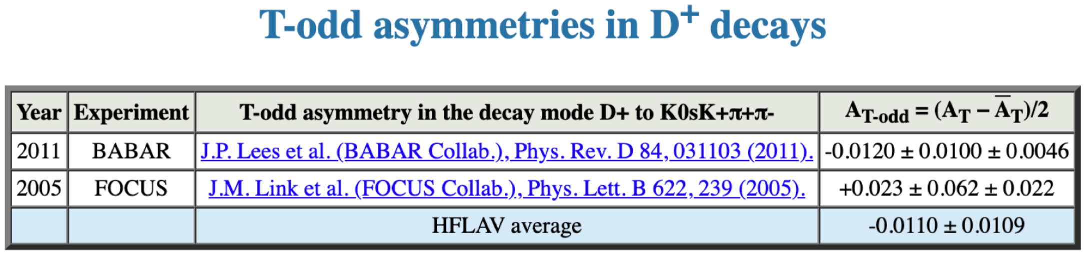
All measurements of CP violation in charm decays using $a_{\mathrm{CP}}^{\mathrm{T-odd}}$:

- *https://hflav-eos.web.cern.ch/hflav-eos/charm/cp_asym/charm_todd_19Sep19.html*



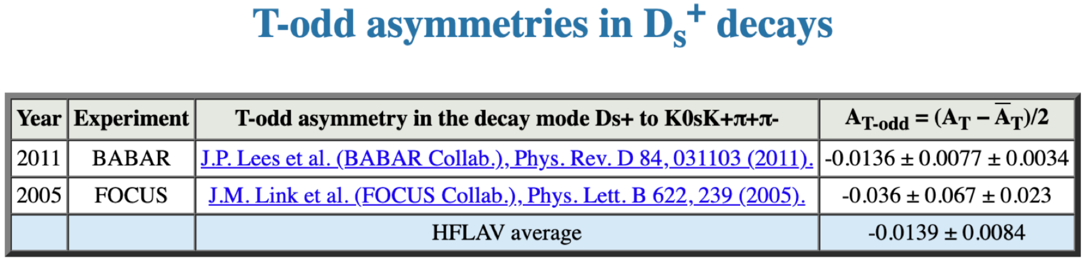
T-odd asymmetries in D^0 decays

Year	Experiment	T-odd asymmetry in the decay mode D0 to K+K-π+π-	$A_{T\text{-odd}} = (A_T - \bar{A}_T)/2$
2019	BELLE	J. B. Kim et al. (BELLE Collab.), Phys. Rev. D 99, 011104 (2019).	+0.0052 ± 0.0037 ± 0.0007
2014	LHCb	R. Aaij et al. (LHCb Collab.), JHEP 10, 5 (2014).	+0.0018 ± 0.0029 ± 0.0004
2010	BABAR	P. del Amo Sanchez et al. (BABAR Collab.), Phys. Rev. D81, 111103 (2010).	+0.0010 ± 0.0051 ± 0.0044
2005	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 622, 239 (2005).	+0.010 ± 0.057 ± 0.037
		HFLAV average	+0.0035 ± 0.0021
Year	**Experiment**	**T-odd asymmetry in the decay mode D0 to K0sπ+π-π0**	**$A_{T\text{-odd}} = (A_T - \bar{A}_T)/2$**
2017	BELLE	K. Prasanth et al. (BELLE Collab.), Phys. Rev. D 95, 091101 (2017).	-0.00028 ± 0.00138 (+0.00023 -0.00076)



T-odd asymmetries in D^+ decays

Year	Experiment	T-odd asymmetry in the decay mode D+ to K0sK+π+π-	$A_{T\text{-odd}} = (A_T - \bar{A}_T)/2$
2011	BABAR	J.P. Lees et al. (BABAR Collab.), Phys. Rev. D 84, 031103 (2011).	-0.0120 ± 0.0100 ± 0.0046
2005	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 622, 239 (2005).	+0.023 ± 0.062 ± 0.022
		HFLAV average	-0.0110 ± 0.0109



T-odd asymmetries in D_s^+ decays

Year	Experiment	T-odd asymmetry in the decay mode Ds+ to K0sK+π+π-	$A_{T\text{-odd}} = (A_T - \bar{A}_T)/2$
2011	BABAR	J.P. Lees et al. (BABAR Collab.), Phys. Rev. D 84, 031103 (2011).	-0.0136 ± 0.0077 ± 0.0034
2005	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 622, 239 (2005).	-0.036 ± 0.067 ± 0.023
		HFLAV average	-0.0139 ± 0.0084