TEL AVIV UNIVERSITY

Strong phases measurement at the Future Tau Charm Facilities

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WHY DO WE NEED TO MEASURE $\delta_{K^0 h}$?

Calculation of QCD contribution to charm decays is not a straightforward task. Long distance contribution (FSI) could mimic NP in charm. Pursuing the goal of the most precise measurements and searches for NP clear understanding of SM contribution is needed.

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-15.4 \pm 2.9) \times 10^{-4}$$

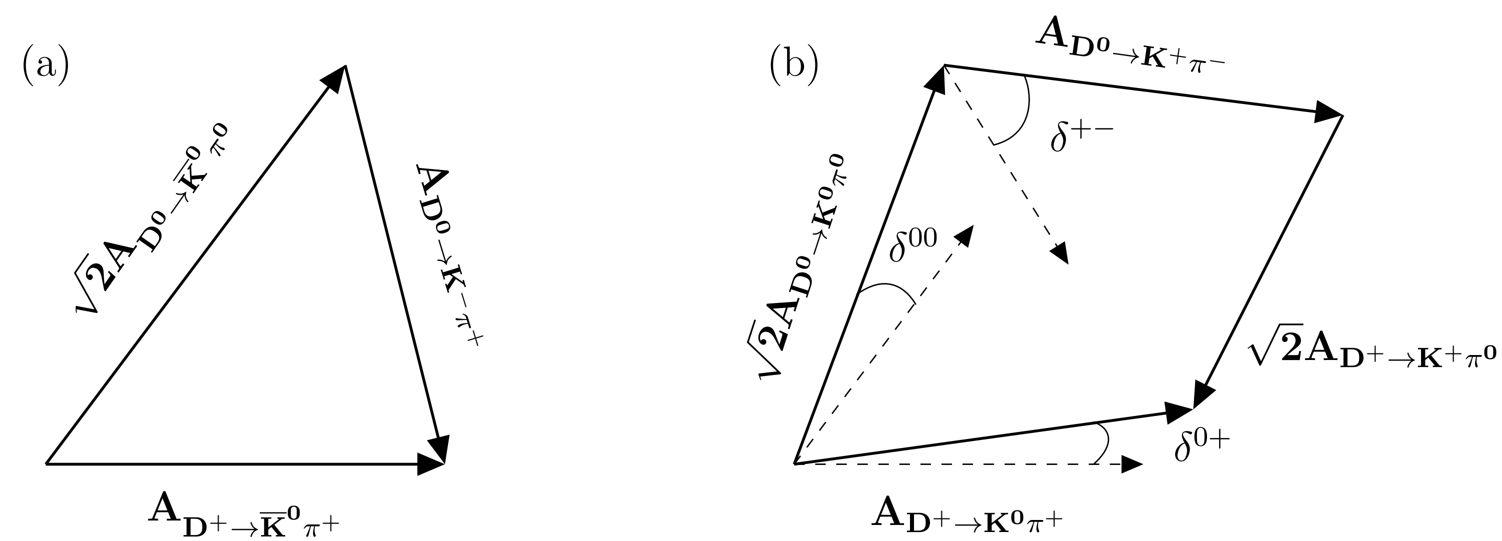
Phys . Rev . Lett . **122**, no.21,211803(2019)

SM or NP ?

Naive SM prediction: $\mathcal{O}(\alpha_s/\pi)\dfrac{\mathbf{V_{ub}V^*_{cb}}}{\mathbf{V_{us}V^*_{cs}}} \sim 10^{-4}$

Approach based on flavour symmetries allows us to get around QCD calculations.

- $SU(3)_f$ allows to obtain predictions for strong phase values;
- $SU(2)_f$ sum rules allow us to flavour symmetry approach



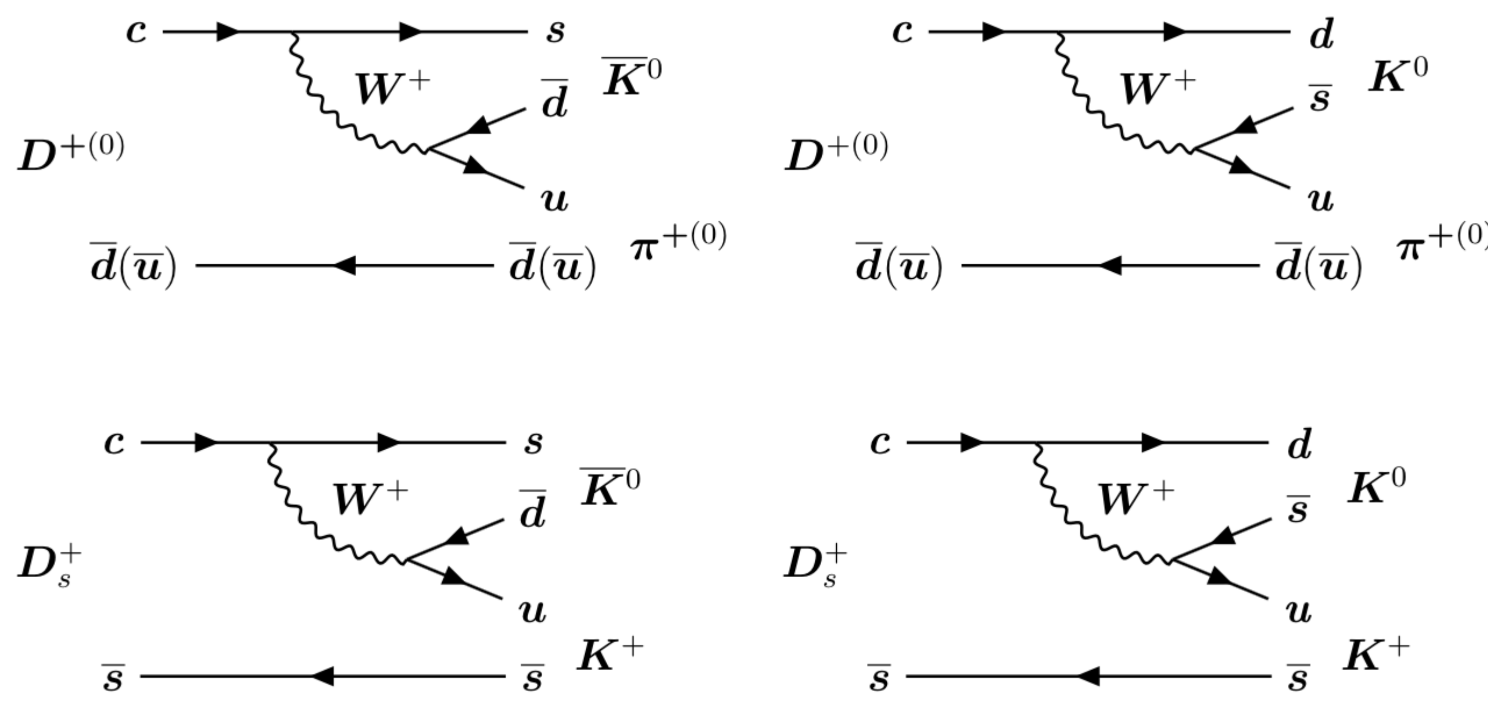
FRAMEWORK

$K^0 - \overline{K}^0$ evolution:

$$i\frac{\partial}{\partial t}\begin{pmatrix} K^0(t) \\ \overline{K}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} K^0(t) \\ \overline{K}^0(t) \end{pmatrix}$$

Initial state – $a|K^0\rangle + b|\overline{K}^0\rangle$:

- $D^+/D^-, \quad D^+ \to \overline{K}^0\pi^+,$
- $D^0/\overline{D}^0, \quad D^0 \to \overline{K}^0\pi^0,$
- $D_s^+/D_s^-, \quad D_s^+ \to \overline{K}^0K^+,$



Mass eigenstates evolution

$$|K^0(t)\rangle = \frac{1-\varepsilon}{\sqrt{2}}e^{-i\lambda_S t}|K_S\rangle + \frac{1-\varepsilon}{\sqrt{2}}e^{-i\lambda_L t}|K_L\rangle$$

$$|K^0(t)\rangle = \frac{1+\varepsilon}{\sqrt{2}}e^{-i\lambda_S t}|K_S\rangle - \frac{1+\varepsilon}{\sqrt{2}}e^{-i\lambda_L t}|K_L\rangle$$

Flavor states evolution

$$|K^0(t)\rangle = g_+(t)|K^0\rangle + \left(\frac{q}{p}\right)g_-(t)|\overline{K}^0\rangle$$

$$|\overline{K}^0(t)\rangle = g_+(t)|\overline{K}^0\rangle - \left(\frac{p}{q}\right)g_-(t)|K^0\rangle$$

MEASUREMENT WITH DECAY $K^0 \to \pi \ell \nu_\ell$

P. Pakhlov, VP
JHEP **02**,160(2020)

For the initial admixture $a\,|\,K^0\rangle + b\,|\,\overline{K}^0\rangle$ time-dependent decay rates:

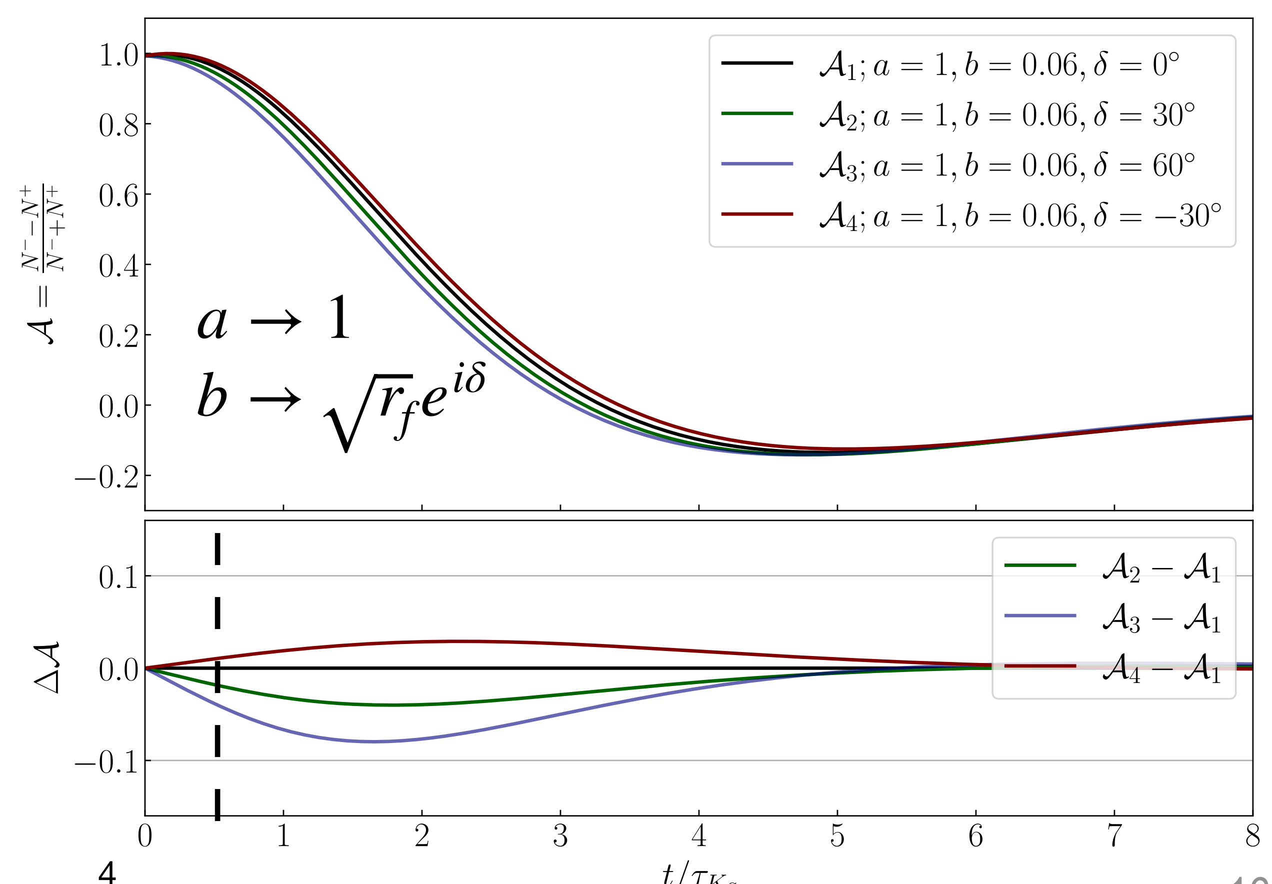
$$R(t) = \frac{1}{4}e^{-\Gamma t}|A_{l^+}|^2 \left[|a|^2 K_+ + \left| b\frac{p}{q} \right|^2 K_- + 2Re\{ab\frac{p}{q}(1 - e^{\Delta\Gamma t} + 2i\sin(\Delta m t)e^{\frac{1}{2}\Delta\Gamma t})\} \right]$$

$$\overline{R}(t) = \frac{1}{4}e^{-\Gamma t}|A_{l^-}|^2 \left[|a|^2 K_- + \left| b\frac{q}{p} \right|^2 K_+ + 2Re\{ab\frac{q}{p}(1 - e^{\Delta\Gamma t} + 2i\sin(\Delta m t)e^{\frac{1}{2}\Delta\Gamma t})\} \right]$$

$$K_\pm = 1 \pm 2\cos(\Delta m t)e^{\frac{1}{2}\Delta\Gamma t} + e^{\Delta\Gamma t}$$

The third term represents an interference of CF and DCS decay amplitudes and allows us to extract the strong phase difference — δ.

Both $\cos\delta$ and $\sin\delta$ could be measured, so there is no trigonometrical ambiguity in such measurement.



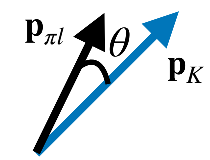
$K^0 \to \pi \ell \nu_\ell$ RECONSTRUCTION

P. Pakhlov, VP
JHEP **02**,160(2020)

Missing neutrino in the final state does not allow direct kaon momentum reconstruction, however momentum could be retrieved using 4-momenta conservation.

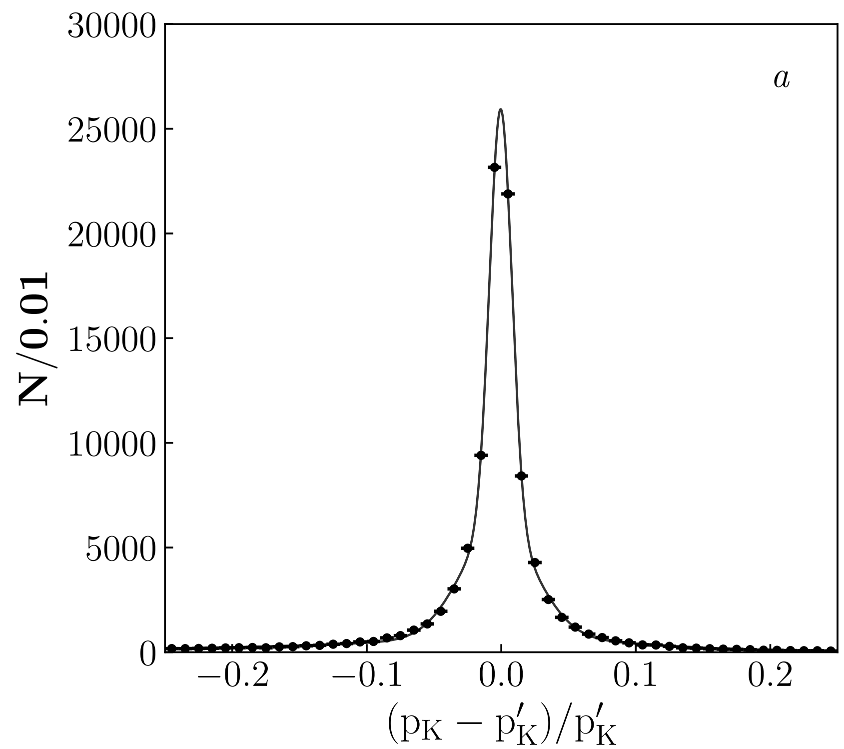
$$(P_{K^0} - P_{\pi l})^2 = P_\nu^2$$

$$|\mathbf{p}_K|_{(1,2)} = -\frac{p_{\pi l}\cos\theta(m_K^2 + m_{\pi l}^2) \pm \sqrt{t}}{2(p_{\pi l}^2\cos^2\theta - E_{\pi l}^2)},$$

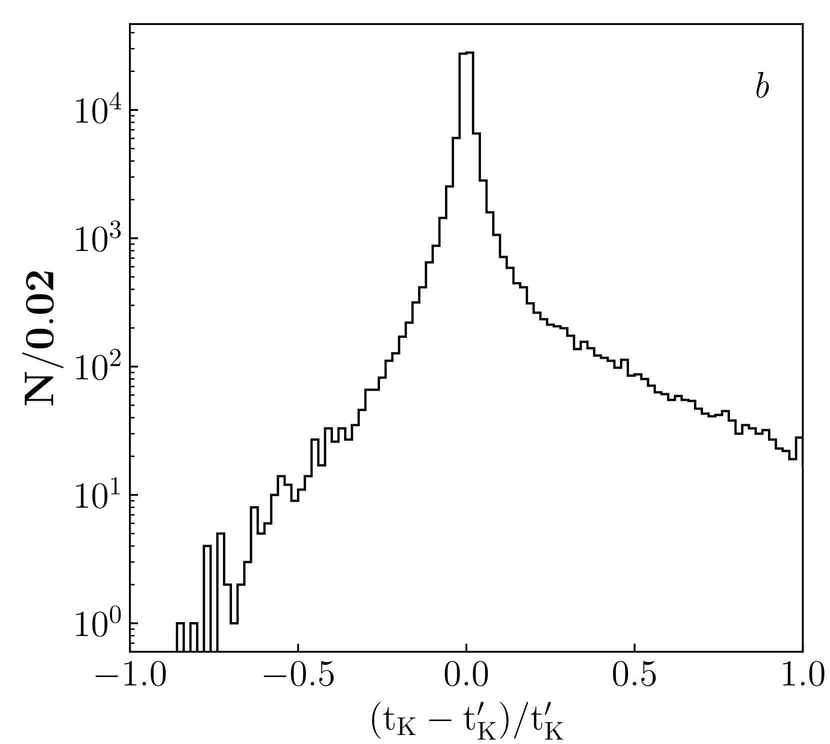


The question of choosing could be resolved through vertex and kinematic constrains and based on the simulation required resolution could be achieved. (For the FTCF picture even better since D-meson momentum is known.)

K^0 momentum resolution



K^0 lifetime resolution



CPV IN $K_S^0 \to \pi^+\pi^-$

Amplitudes:

$$|K^0(t)\rangle = \frac{1-\varepsilon}{\sqrt{2}} e^{-i\lambda_S t}|K_S\rangle + \frac{1-\varepsilon}{\sqrt{2}} e^{-i\lambda_L t}|K_L\rangle$$

$$|\overline{K}^0(t)\rangle = \frac{1+\varepsilon}{\sqrt{2}} e^{-i\lambda_S t}|K_S\rangle - \frac{1+\varepsilon}{\sqrt{2}} e^{-i\lambda_L t}|K_L\rangle$$

Time-dependent decay rates:

$$\overline{\mathcal{R}}(\mathcal{R}) \equiv \frac{1 \pm 2\mathrm{Re}(\varepsilon)}{2} |A_{fS}|^2 \Big[e^{-\Gamma_S t} + |\eta_{+-}|^2 e^{-\Gamma_L t} - \mp\; 2|\eta_{+-}| e^{-\frac{1}{2}(\Gamma_L+\Gamma_S)t} \cos\left(\Delta m t - \varphi_{+-}\right) \Big]$$

CPLEAR results:

Phys.Lett.B 456 (1999)

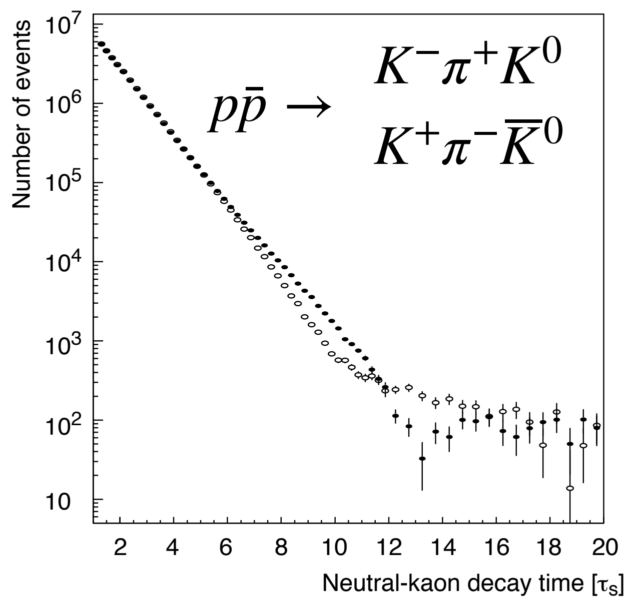
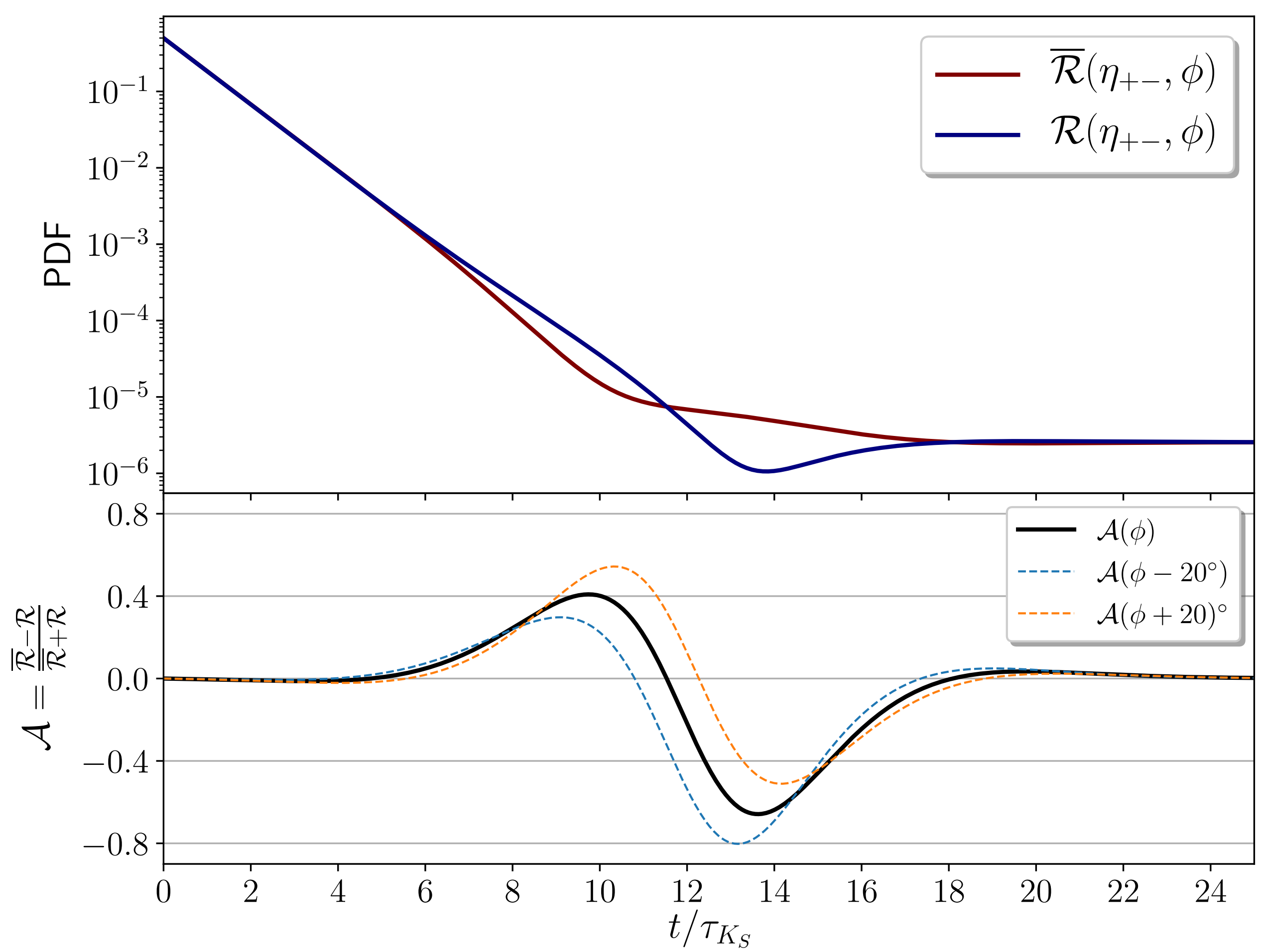


Fig. 16. The measured decay rates for K^0 (○) and $\overline{K}^0$ (●) after acceptance correction and background subtraction



World average:	$\lvert\eta_{+-}\rvert = (2.232 \pm 0.011) \times 10^{-3}$ $\varphi_{+-} = 43.51 \pm 0.05$

MEASUREMENT WITH DECAY $K_S^0 \to \pi^+\pi^-$

P. Pakhlov, VP
JHEP **09**,092(2021)

Amplitudes for the process $D \to K_S X$:

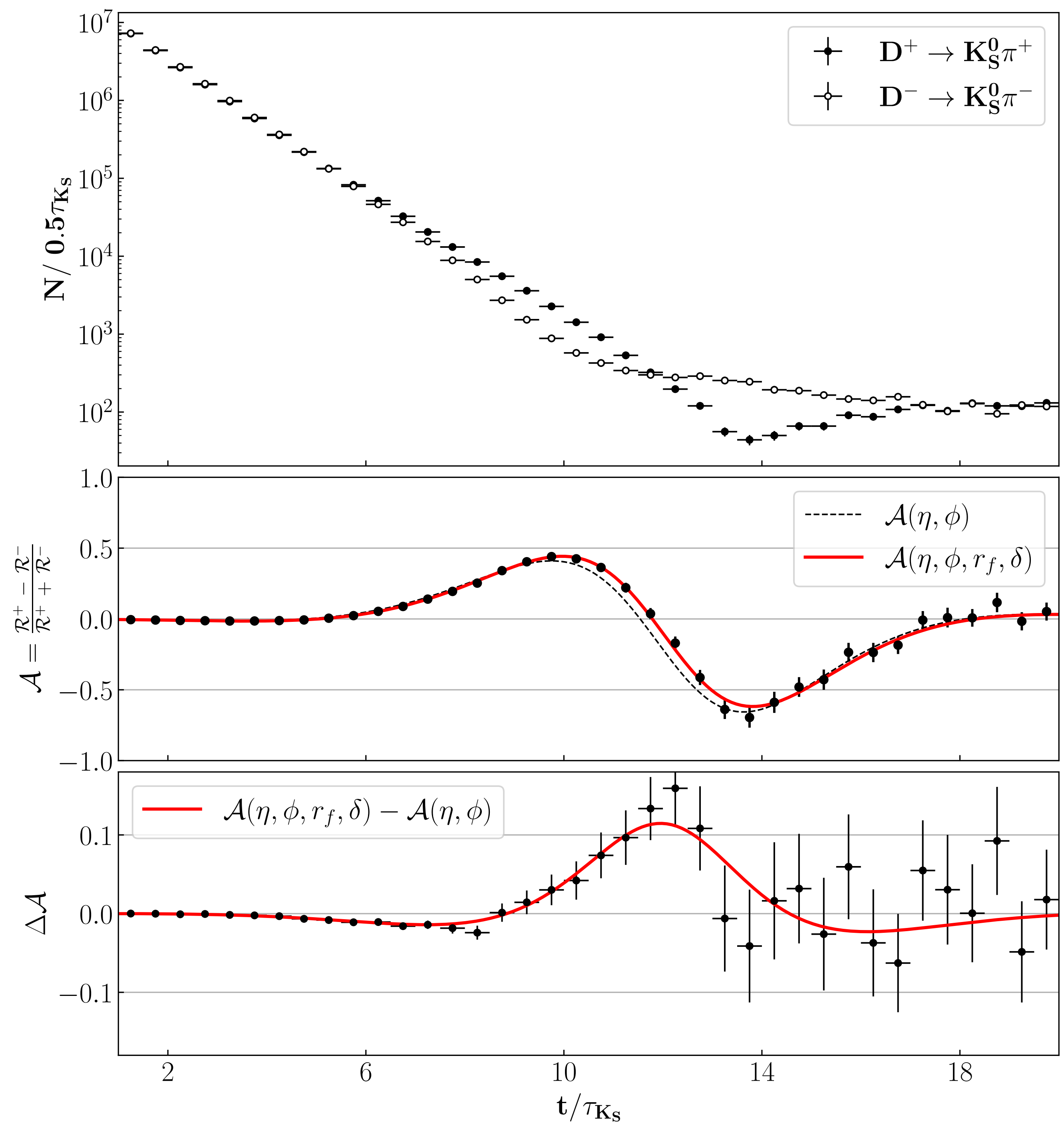
$$\langle f|H_{wk}|D^0\rangle = \langle f|H_{wk}|\overline{K}^0\rangle + \sqrt{r_D}e^{i\delta}\langle f|H_{wk}|K^0\rangle$$

$$\langle f|H_{wk}|\overline{D}^0\rangle = \sqrt{r_D}e^{i\delta}\langle f|H_{wk}|\overline{K}^0\rangle + \langle f|H_{wk}|K^0\rangle$$

Time dependent decay rates $K_S \to \pi^+\pi^-$:

$$\begin{aligned}\mathcal{R}^+(t) \equiv\ & |\Psi^+(t)|^2 = \overline{\mathcal{R}}(t) + r_f\mathcal{R}(t)\\ +\ & \sqrt{r_f}\,(\cos\delta + 2|\eta_{+-}|\sin\delta\sin\phi_{+-}) \times \left(e^{-\Gamma_S t} - |\eta_{+-}|^2 e^{-\Gamma_L t}\right)\\ +\ & 2\sqrt{r_f}|\eta_{+-}|\left(\sin\delta + 2|\eta_{+-}|\cos\delta\sin\phi_{+-}\right)e^{-\frac{1}{2}(\Gamma_L+\Gamma_S)t}\sin(\Delta m t - \phi_{+-}),\end{aligned}$$

$$\begin{aligned}\mathcal{R}^-(t) \equiv\ & |\Psi^-(t)|^2 = \mathcal{R}(t) + r_f\overline{\mathcal{R}}(t)\\ +\ & \sqrt{r_f}\,(\cos\delta - 2|\eta_{+-}|\sin\delta\sin\phi_{+-}) \times \left(e^{-\Gamma_S t} - |\eta_{+-}|^2 e^{-\Gamma_L t}\right)\\ -\ & 2\sqrt{r_f}|\eta_{+-}|\left(\sin\delta - 2|\eta_{+-}|\cos\delta\sin\phi_{+-}\right)e^{-\frac{1}{2}(\Gamma_L+\Gamma_S)t}\sin(\Delta m t - \phi_{+-}).\end{aligned}$$



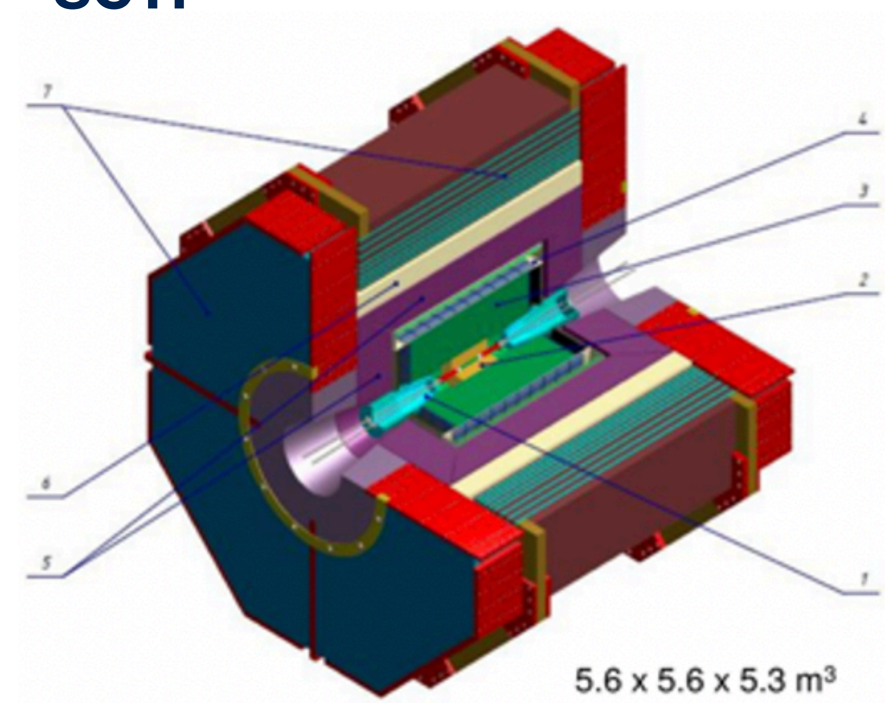
Strong phase enters both equations. No trigonometrical uncertainty in the measurement.

FUTURE SUPER TAU CHARM FACTORY

Proposed methods are universal however there are some requirements to achieve the best precision:

Requirement	SCTF
Good spatial resolution $\sim 100\mu m$	✓
Large tracking detector/slow kaons	✓
Good momentum resolution $\sigma_p/p < 0.01$	✓
Hadron identification	✓

SCTF



Luminosity per 1 year

	J/ψ	$\psi(2S)$	$\psi(3770)$	$\psi(4040)$	$\psi(4160)$	$\psi(4415)$
M, GeV	3.097	3.686	3.773	4.039	4.191	4.421
Γ, MeV	0.093	0.286	27.2	80	70	62
σ, nb	$\sim$3400	$\sim$640	$\sim$6	$\sim$10	$\sim$6	$\sim$4
L, fb^{-1}	300	150	300	10	100	25
N	10^{12}	10^{11}	2×10^9	10^8	6×10^8	10^8

FEASIBILITY STUDY: $K^0 \to \pi \ell \nu_\ell$

Feasibility study preformed with Monte-Carlo.

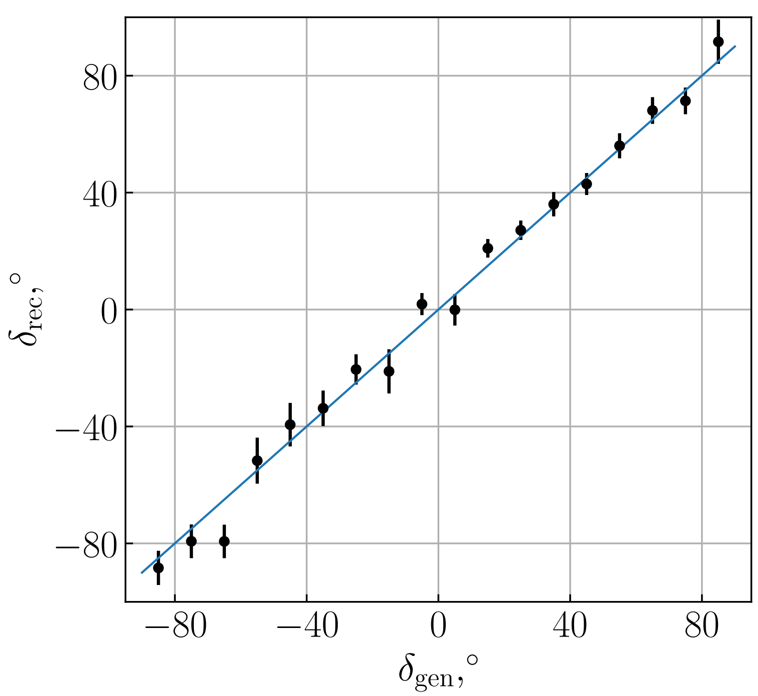
Both RS and WS distributions fitted (χ^2) simultaneously.

Studies showed no bias in such measurement.

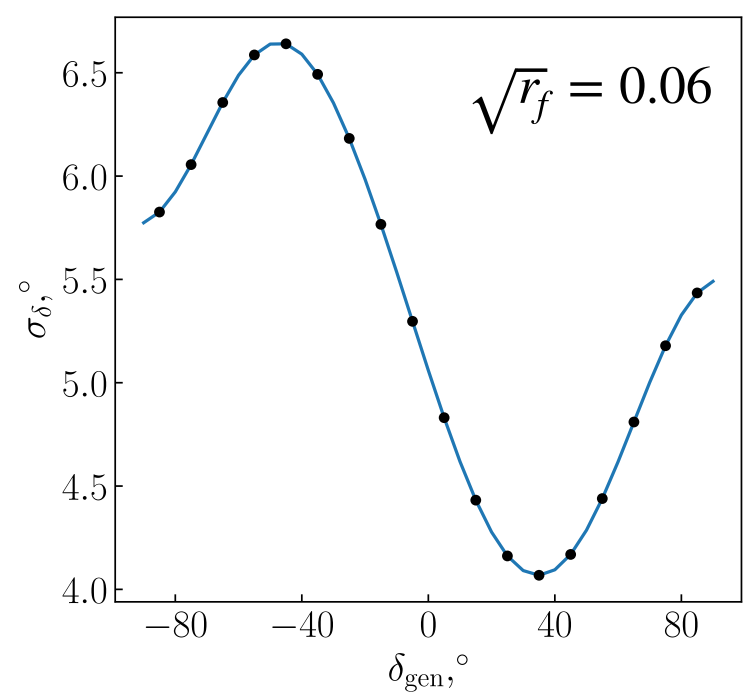
Expected number of events:

Decay channel	FTCF, $\times 10^4$
$D^0 \to \overline{K}^0 \pi^0$	6
$D^+ \to \overline{K}^0 \pi^+$	15
$D_s^+ \to \overline{K}^0 K^+$	12

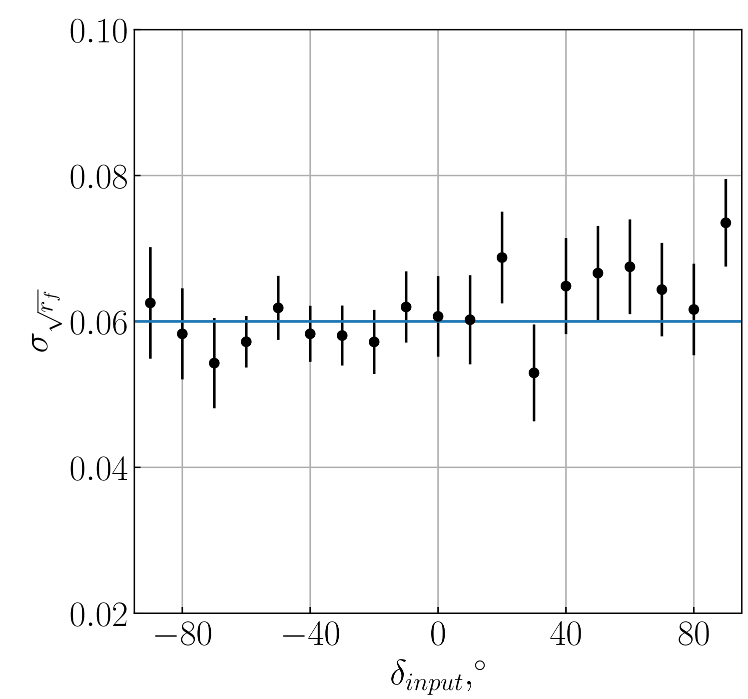
Strong phase difference



Uncertainty in δ

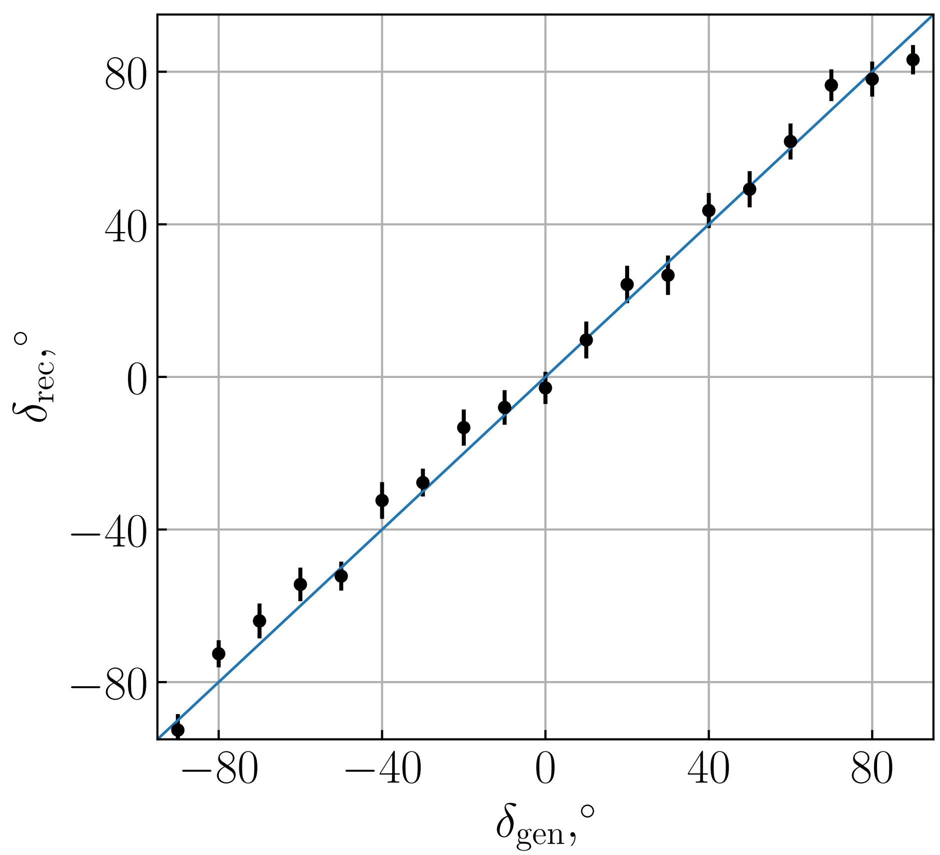


DCS/CF amplitude ratio



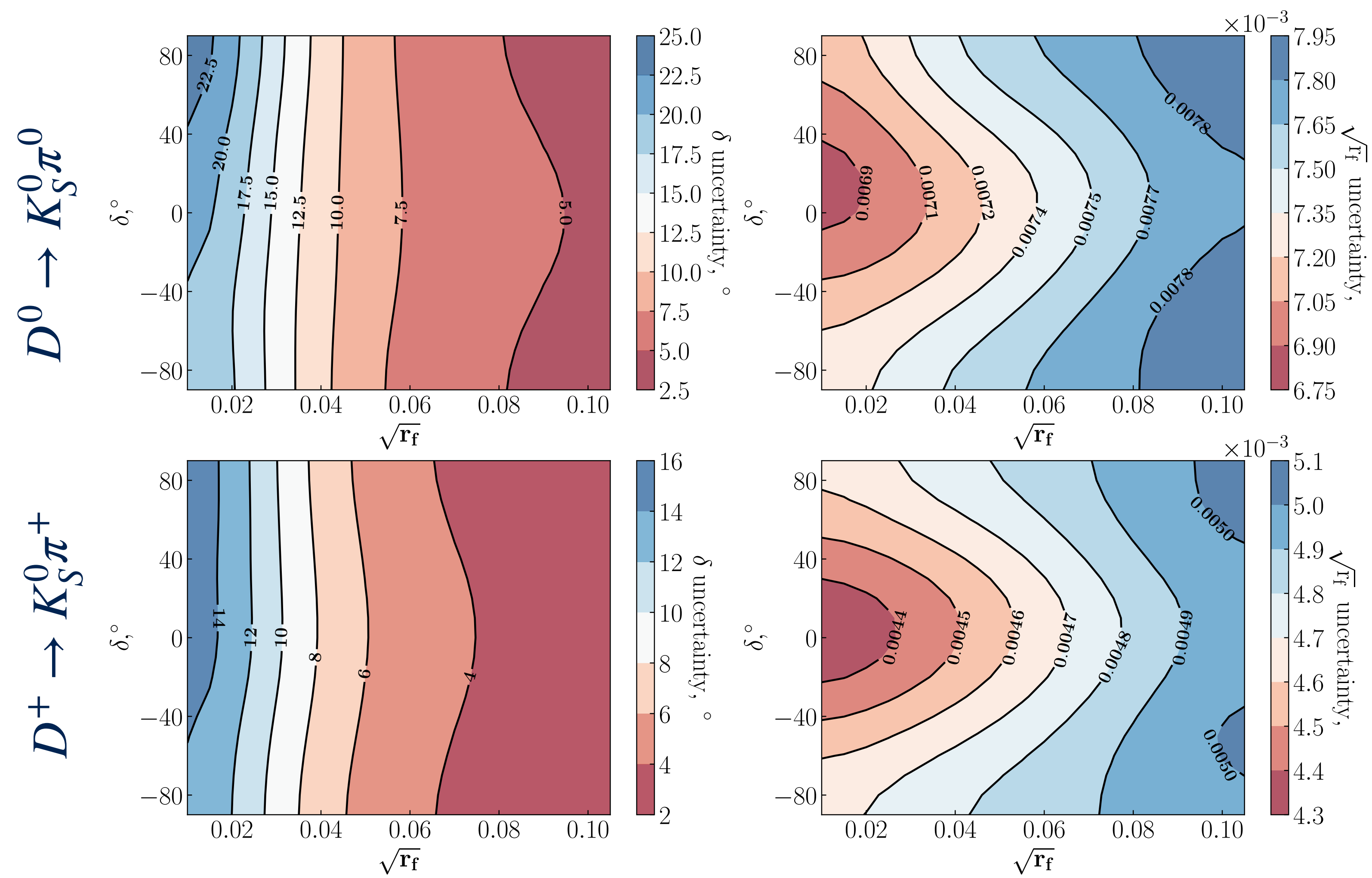
FEASIBILITY STUDY: $K_S^0 \to \pi^+\pi^-$

Obtained with Monte-Carlo simulation samples fitted (ML) and no bias observed in proposed measurement.



DCS/CF amplitude ratio was never measured in decay modes with K_S^0, so scan in $\delta/\sqrt{r_f}$ performed.

$$r_f \equiv \left| \frac{\langle K\pi | H | D \rangle}{\langle \overline{K}\pi | H | D \rangle} \right|^2 \simeq \left| \frac{V_{cd}V_{us}^*}{V_{cs}V_{ud}^*} \right|^2 \sim \mathcal{O}(\tan^4 \theta_c) \,.$$



K^0 REGENERATION

Strangeness conservation in strong interactions lead to inequality of rescattering amplitudes for K^0 and $\overline{K}^0$ on matter — $\Delta f \neq 0$. Regeneration of neutral kaons can imitate CPV and introduce a bias in strong phase measurement.

Equations for evolution should be modified as:

$$i\partial_t \begin{pmatrix} K^0(t) \\ \bar{K}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right) \begin{pmatrix} K^0(t) \\ \bar{K}^0(t) \end{pmatrix} - \begin{pmatrix} \chi & 0 \\ 0 & \overline{\chi} \end{pmatrix} \begin{pmatrix} K^0(t) \\ \bar{K}^0(t) \end{pmatrix}$$

, где $\chi(\overline{\chi}) = \dfrac{2\pi N}{m} f(\bar{f})$

Introducing regeneration parameter — r:

$$\alpha_{S,L} = e^{-i\Sigma t}\left[\alpha^0_{S,L} \cos\left(\frac{\Delta\lambda}{2}\sqrt{1+4r^2}t\right) \pm i\frac{\alpha^0_{S,L} \mp 2r\alpha^0_{L,S}}{\sqrt{1+4r^2}} \sin\left(\frac{\Delta\lambda}{2}\sqrt{1+4r^2}t\right)\right]$$

, где $r = \dfrac{1}{2}\dfrac{\Delta\chi}{\Delta\lambda}$

With expansion for r:

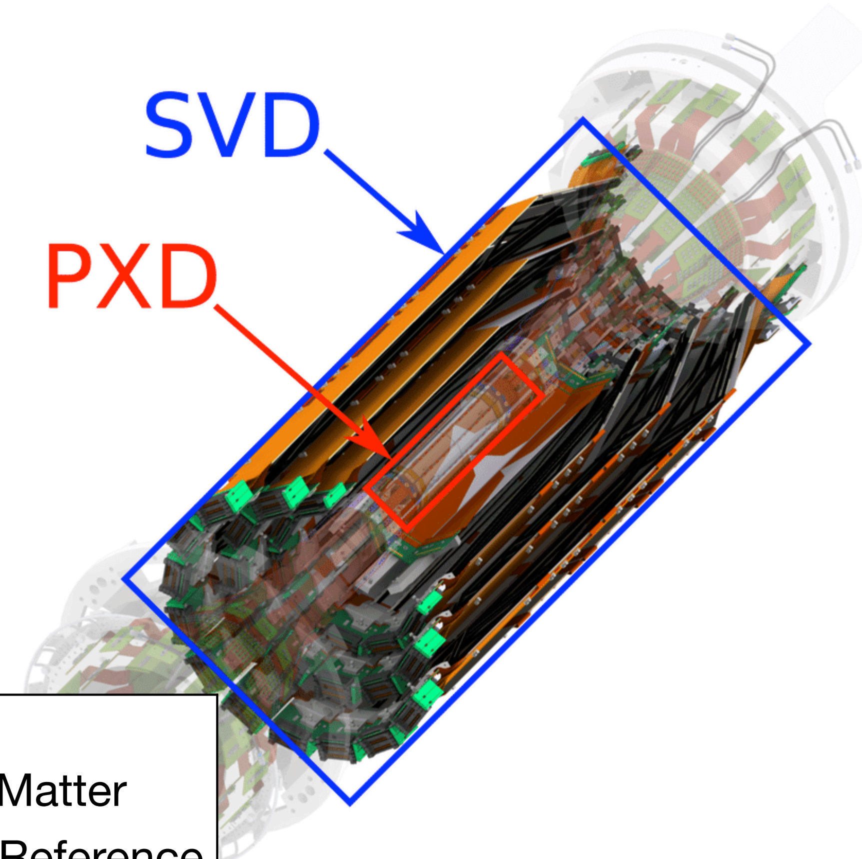
$$\alpha_S(t) = e^{\frac{1}{2}(\chi+\overline{\chi})t} e^{-i\lambda_S t}(\alpha^0_S + \zeta\alpha^0_L e^{-i\Delta\lambda t})$$
$$\alpha_L(t) = e^{\frac{1}{2}(\chi+\overline{\chi})t} e^{-i\lambda_L t}(\alpha^0_L + \zeta\alpha^0_S).$$

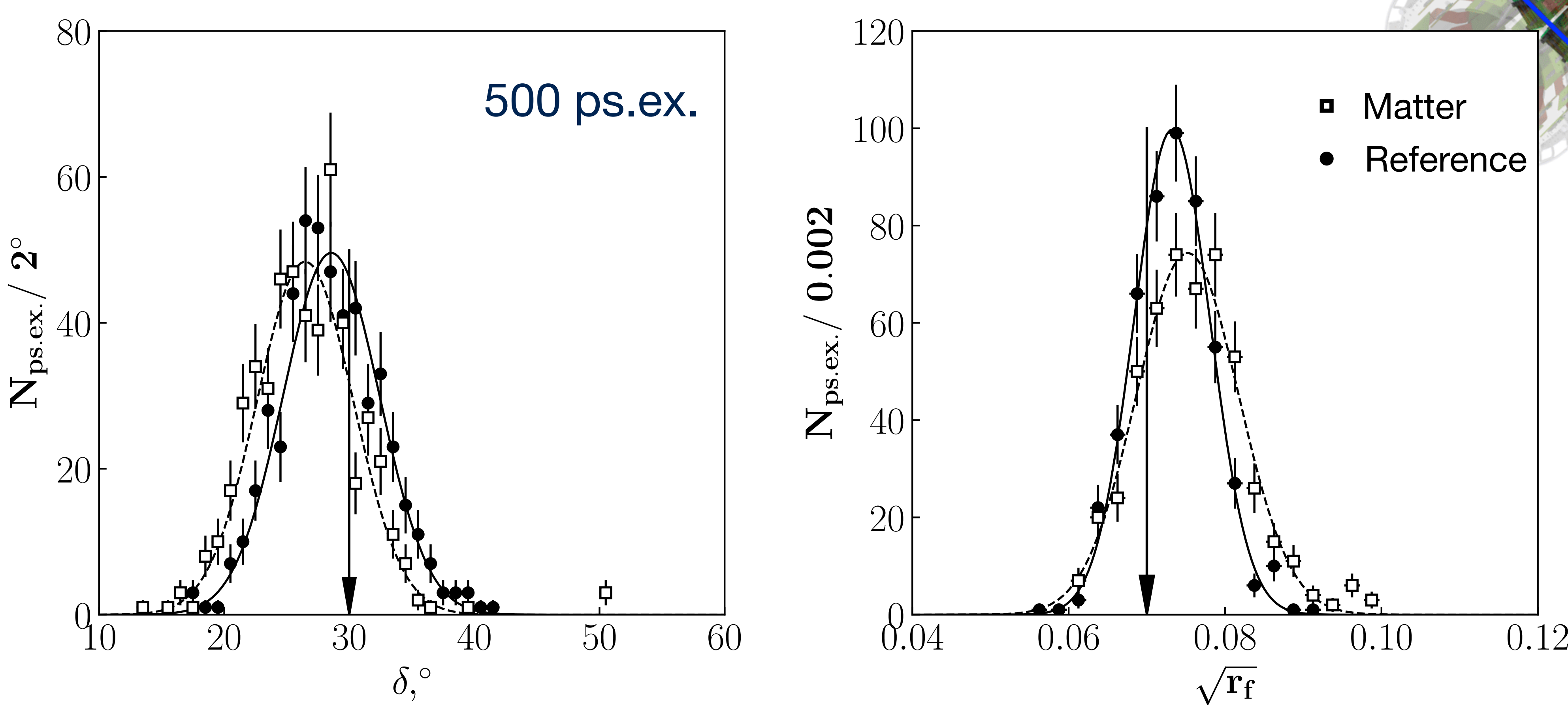
, where $\zeta = r\left(1 - e^{i\Delta\lambda\frac{Lm}{p}}\right)$

K^0 REGENERATION

Estimations for Belle II experiment.
Be — 1 mm, Si — $L_{1,2} = 50\ \mu m$, $L_{3-6} = 300\ \mu m$

Материал	σ_{tot}, (mb)	ReΔf, fm	ImΔf, fm
Si	553.0	-7.5	-12.9
Be	219.1	-3.9	-6.2





UNCERTAINTY DUE TO D-MIXING

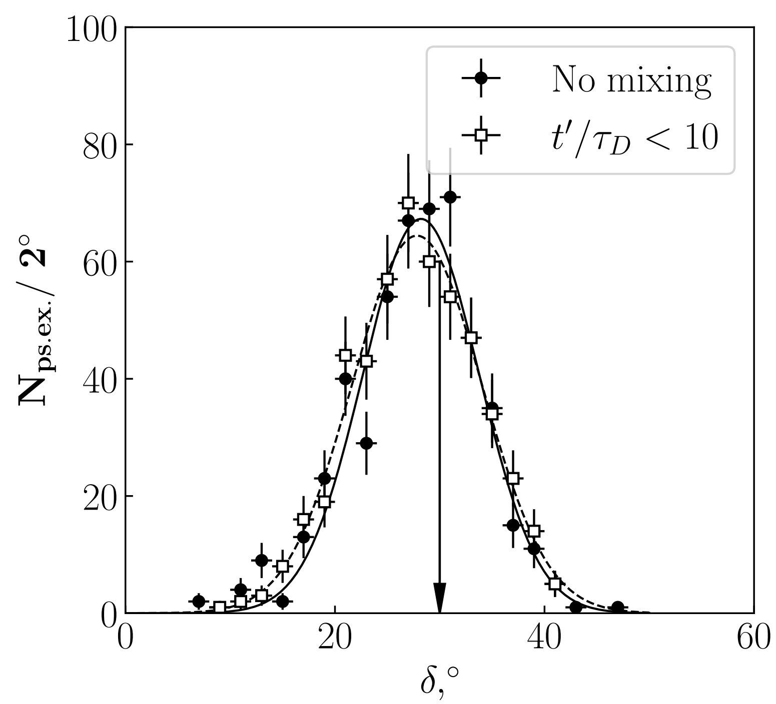
In the decay channel $D^0 \to K_S^0\pi^0$ there is potential bias due to charm mixing. Parameters a, b become dependent on D^0 decay time. Both evolution of K_S^0 and D^0 should be taken into consideration.

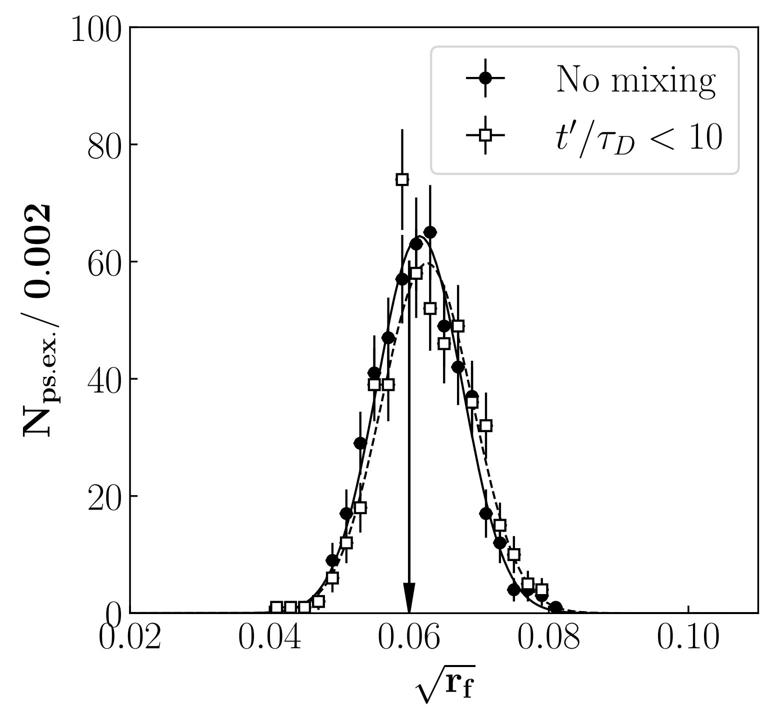
$$a^+(t') \equiv \langle \bar{K}^0\pi^0|H|D^0_{phys}(t')\rangle = A_{D^0}\left[f_+(t') - \sqrt{r_f}e^{i(\delta+\phi)}f_-(t')\right]$$
$$b^+(t') \equiv \langle K^0\pi^0|H|D^0_{phys}(t')\rangle = A_{D^0}\left[\sqrt{r_f}e^{i(\delta-\phi)}f_+(t') - f_-(t')\right]$$

World average:

$$x = (0.43^{+0.10}_{-0.11})\ \%$$
$$y = (0.60 \pm 0.06)\ \%$$
$$\phi = (0.08 \pm 0.31)^\circ$$

Smallness of mixing parameters and experimental factor (obtaining proper D^0 decay time resolution) brought us to consider integration over D^0 decay time. We found the bias from mixing to be negligible (compare to stat. uncertainty).





STUDY OF CORRELATED D^0-$\overline{D}^0$

	J/ψ	$\psi(2S)$	$\psi(3770)$	$\psi(4040)$	$\psi(4160)$	$\psi(4415)$
M, GeV	3.097	3.686	3.773	4.039	4.191	4.421
Γ, MeV	0.093	0.286	27.2	80	70	62
σ, nb	~3400	~640	~6	~10	~6	~4
L, fb^{-1}	300	150	300	10	100	25
N	10^{12}	10^{11}	2×10^{9}	10^{8}	6×10^{8}	10^{8}

$$\Psi_{D\overline{D}} = \frac{1}{\sqrt{2}}[|D^0_{phys}(t)\rangle|\bar{D}^0_{phys}(t)\rangle - |\bar{D}^0_{phys}(t)\rangle|D^0_{phys}(t)\rangle]$$

For correlated D^0 pair time dependent decay rate for final states f_1, f_2:

$$R(f_1,t_1,f_2,t_2) \propto |A_{f_1}|^2|A_{f_2}|^2 e^{-\Gamma(t_1+t_2)}\Big[\frac{1}{2}|\xi+\zeta|^2 e^{-\Delta\Gamma/2(t_2-t_1)} + $$
$$+\frac{1}{2}|\xi-\zeta|^2 e^{\Delta\Gamma/2(t_2-t_1)} - (|\xi|^2-|\zeta|^2)\cos\left(\Delta m(t_2-t_1)\right) + 2Im(\xi^*\zeta)\sin\left(\Delta m(t_2-t_1)\right)\Big]$$

where $\zeta = \frac{\overline{A}_{f_2}}{A_{f_2}} - \frac{\overline{A}_{f_1}}{A_{f_1}}$, $\xi = \left(\frac{p}{q}\right)_D - \left(\frac{q}{p}\right)_D \frac{\overline{A}_{f_1}}{A_{f_1}}\frac{\overline{A}_{f_2}}{A_{f_2}}$

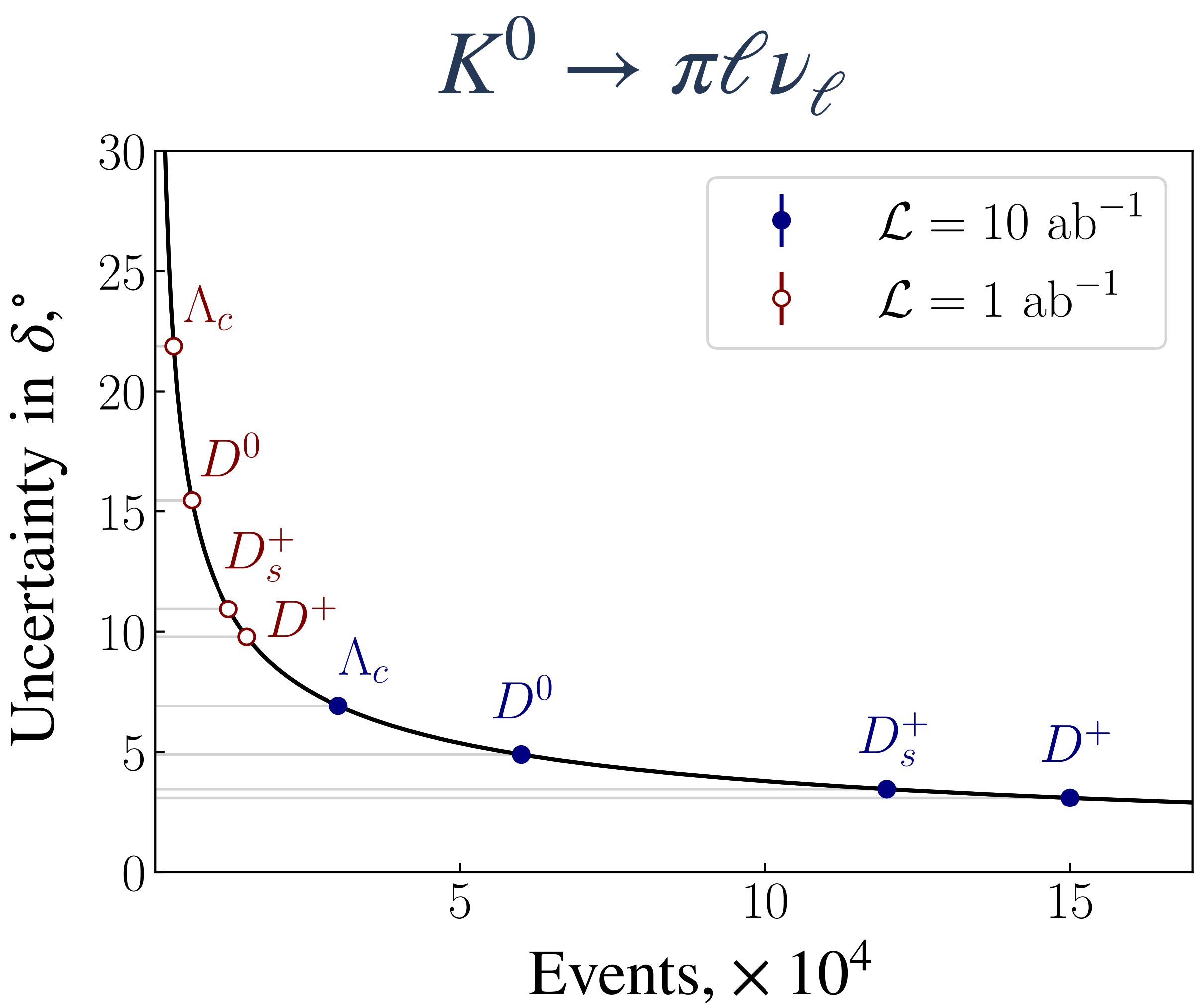
Than for combination of final states: $\left\{\mathbf{D \to K^-\pi^+; D \to \overline{K}^0\pi^0}\right\}$

$$R(t_1,t_2) \propto 2|A_{K^-\pi^+}|^2|A_{\overline{K}^0\pi^0}|^2 e^{-\Gamma(t_1+t_2)}\left[\left(r_f^0 + r_f^- - \Delta_-\right) + \Gamma\Delta t\Delta_{12} + \left(\left|\frac{p}{q}\right|_D^2 + \left|\frac{q}{p}\right|_D^2 r_f^0 r_f^- - \Delta_+\right)\frac{(\Gamma\Delta t)^2}{4}(x^2+y^2)\right],$$

$$\Delta_\pm = 2\sqrt{r_f^0 r_f^-}\cos(\delta_{00}\pm\delta_{-+}) \quad , \quad \Delta_{12} = \sqrt{r_f^-}\left(\frac{p}{q}x' + \frac{q}{p}r_f^0 y'\right) - \sqrt{r_f^0}\left(\frac{p}{q}x'' + \frac{q}{p}r_f^- y''\right)$$

CONCLUSION

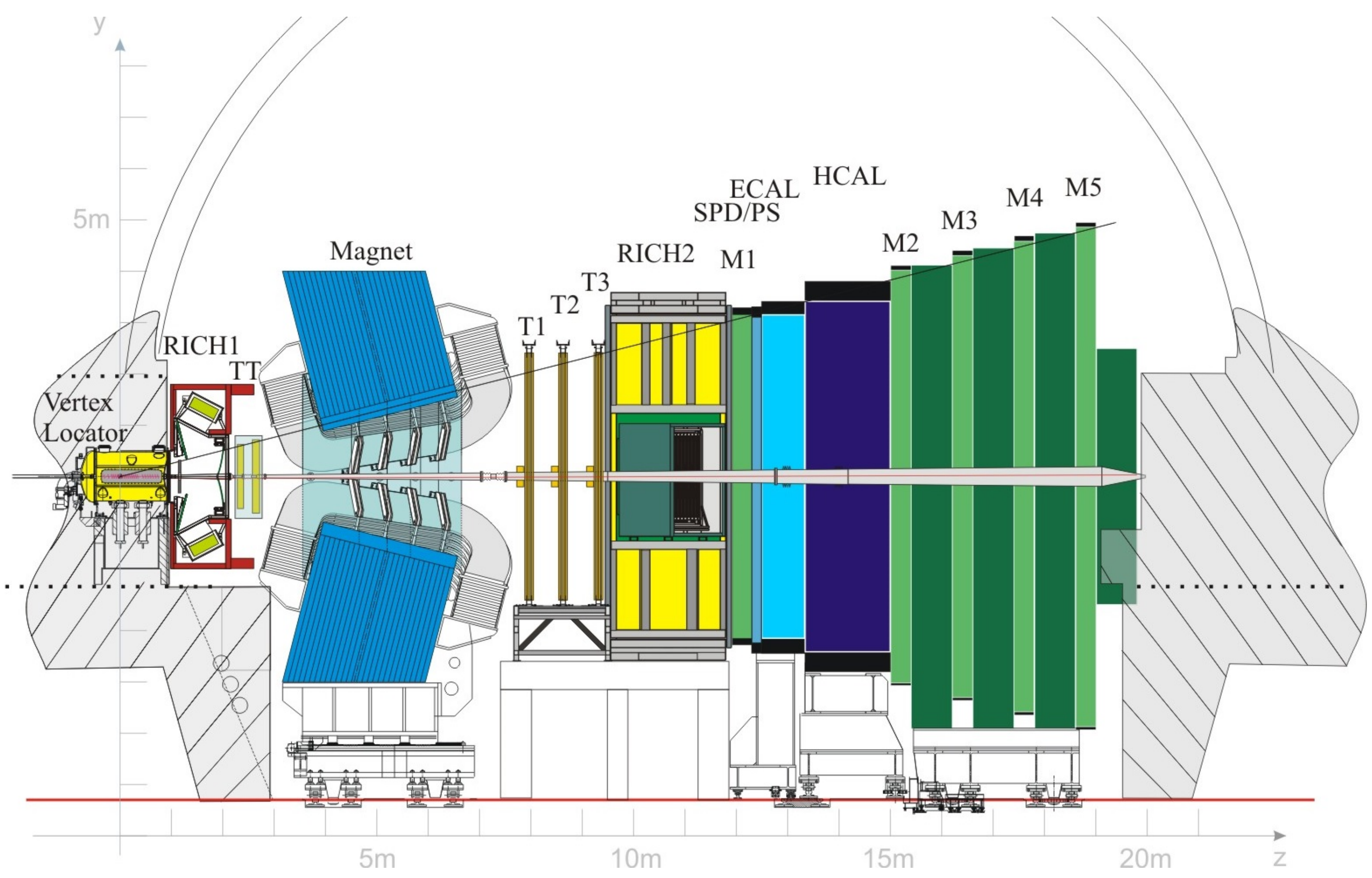
- Strong phase measurement could significantly improve our estimations for long distance QCD contribution in charm;
- The adequacy of flavour symmetry approach could be checked;
- **FTCF** is an **ideal candidate** for such measurements;
- Both presented methods give similar accuracy at the level of 5°;
- Secondary vertex reconstruction is crucial for such analysis.

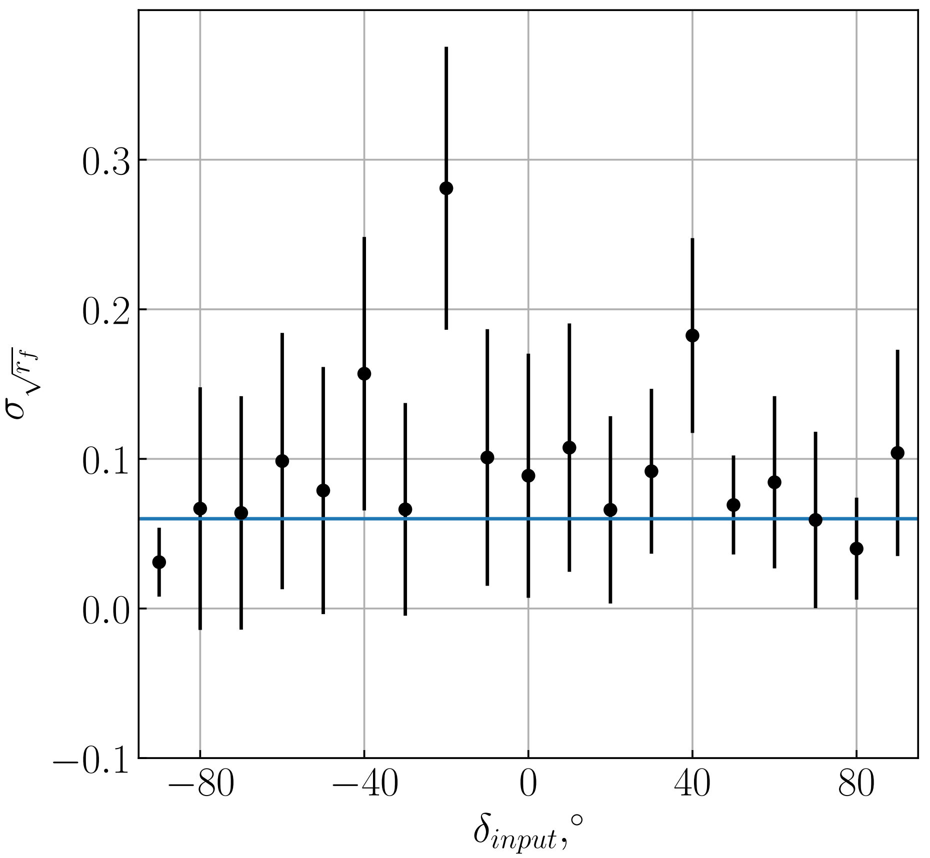


BACKUP SLIDES

MEASUREMENTS IN LHCb

LHCb experiment meet many requirements for the experiment to perform proposed measurement. However for typical momenta of kaons $\sim 5\ \mathrm{GeV}/c$ LHCb tracker is very "short", only few lifetimes could be analysed.



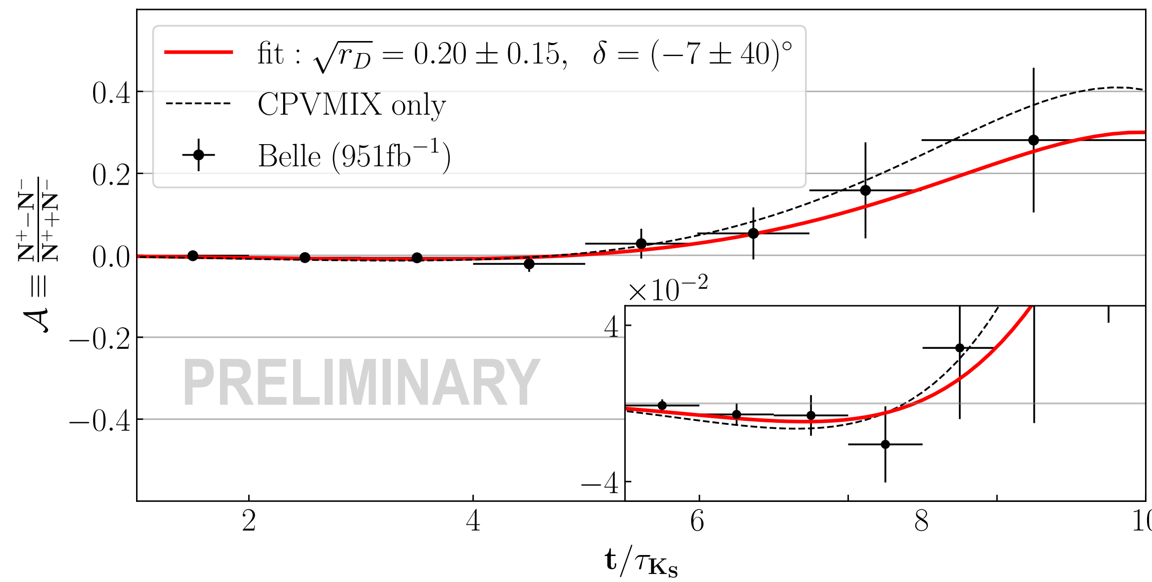


PRELIMINARY RESULTS FROM BELLE DATA

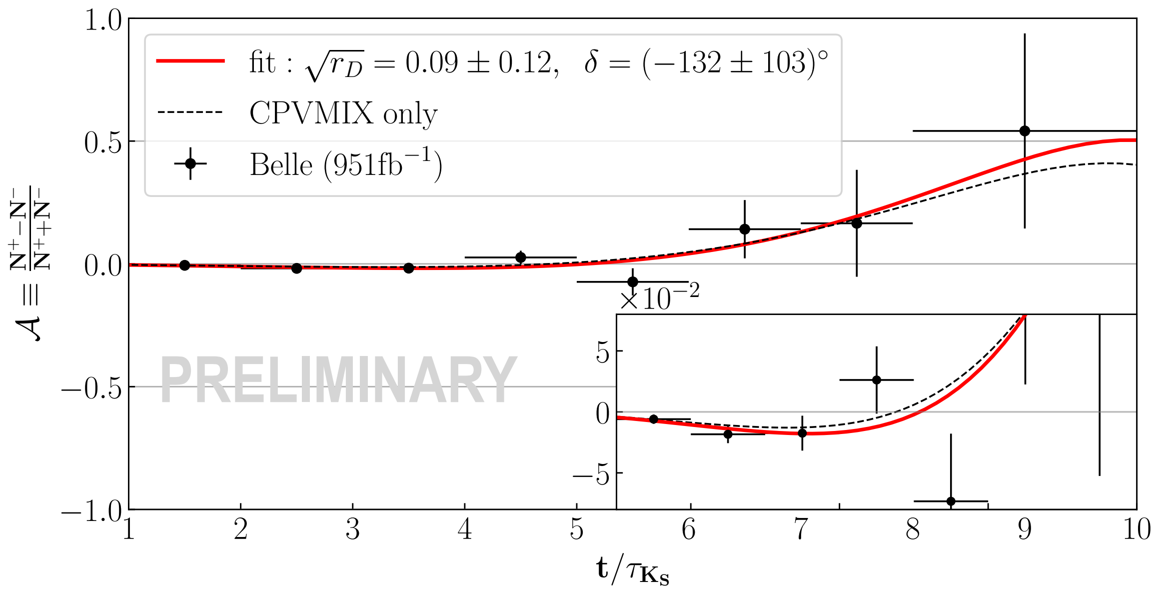
Using data sample collected by Belle experiment the following values for r_f and δ were obtained. While uncertainties are quite large (which is anticipated) the ability to perform such measurement could be seen.

Decay channel	$\sqrt{r_f}$	$\delta,\ ^\circ$
$D^+ \to K_S\pi^+$	0.07 ± 0.10	-56 ± 61
$D_s^+ \to K_S K^+$	0.09 ± 0.12	-132 ± 103
$D^0 \to K_S\pi^0$	0.20 ± 0.15	-7 ± 40

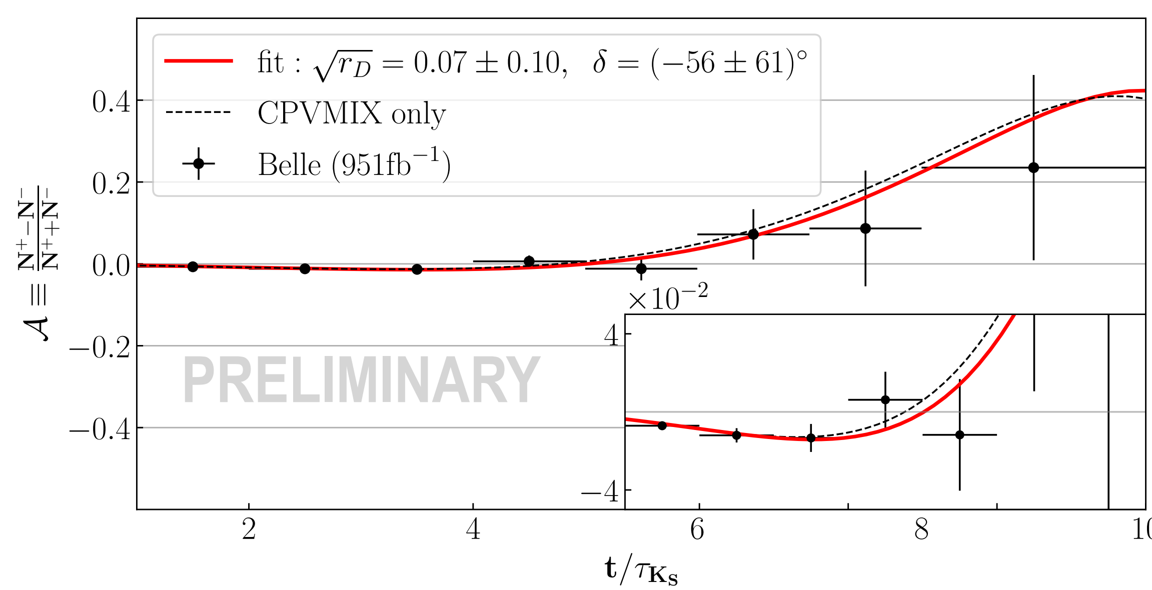
$D^{*+} \to (K_S\pi^0)_D\pi^+$



$D_s^\pm \to K_S K^\pm$

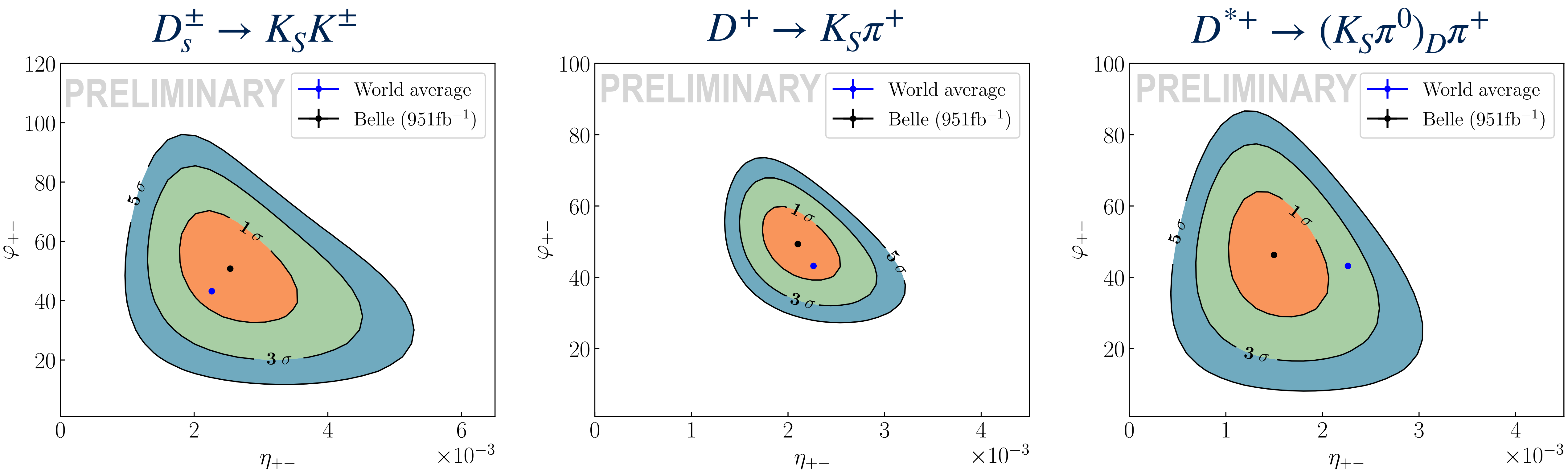


$D^+ \to K_S\pi^+$



PRELIMINARY RESULTS FROM BELLE DATA

Measurement (preliminary) of indirect CPV in neutral kaons on the Belle data sample — $951\ \mathrm{fb}^{-1}$. Obtained values are in good agreement with World average.

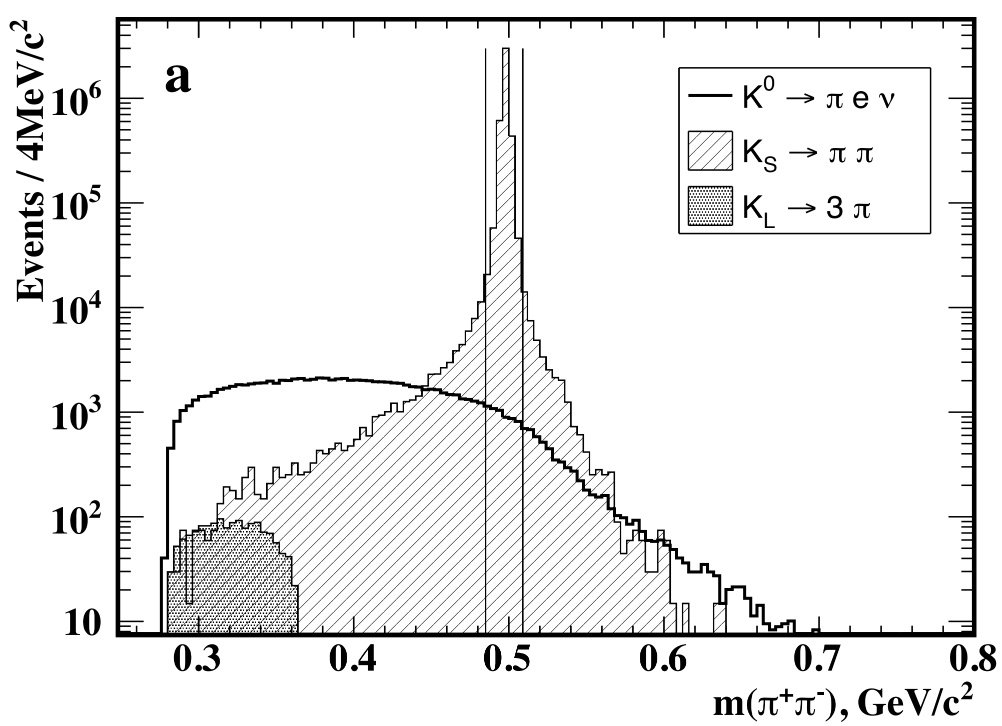


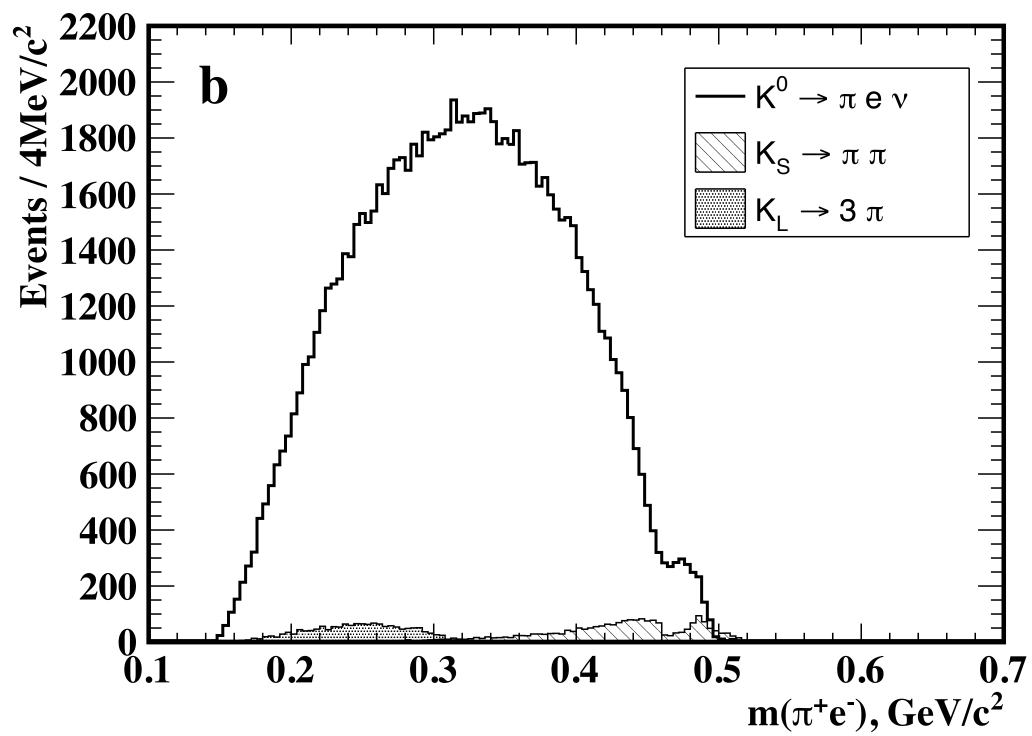
BACKGROUND SUPPRESSION FOR $K^0 \to \pi \ell \nu_\ell$

- Background from primary vertex;

  For the small lifetimes there is no sensitivity for the strong phase measurement. And this background could be "cut off" without loosing precision.

- True secondary vertices: $K_S \to \pi^+\pi^-$, $K_L \to \pi^+\pi^-\pi^0$.





Requirement of the identification and K_S-veto allow us effectively suppress the background secondary vertices.

OTHER POSSIBLE APPLICATIONS

- B-physics:

$$|B^0(t)\rangle = e^{-i\frac{M_1+M_2}{2}t}e^{-\frac{\Gamma}{2}t}\left[\cos\left(\frac{\Delta m t}{2}\right)|B^0\rangle + i\left(\frac{q}{p}\right)_B \sin\left(\frac{\Delta m t}{2}\right)|\bar{B}^0\rangle\right]$$

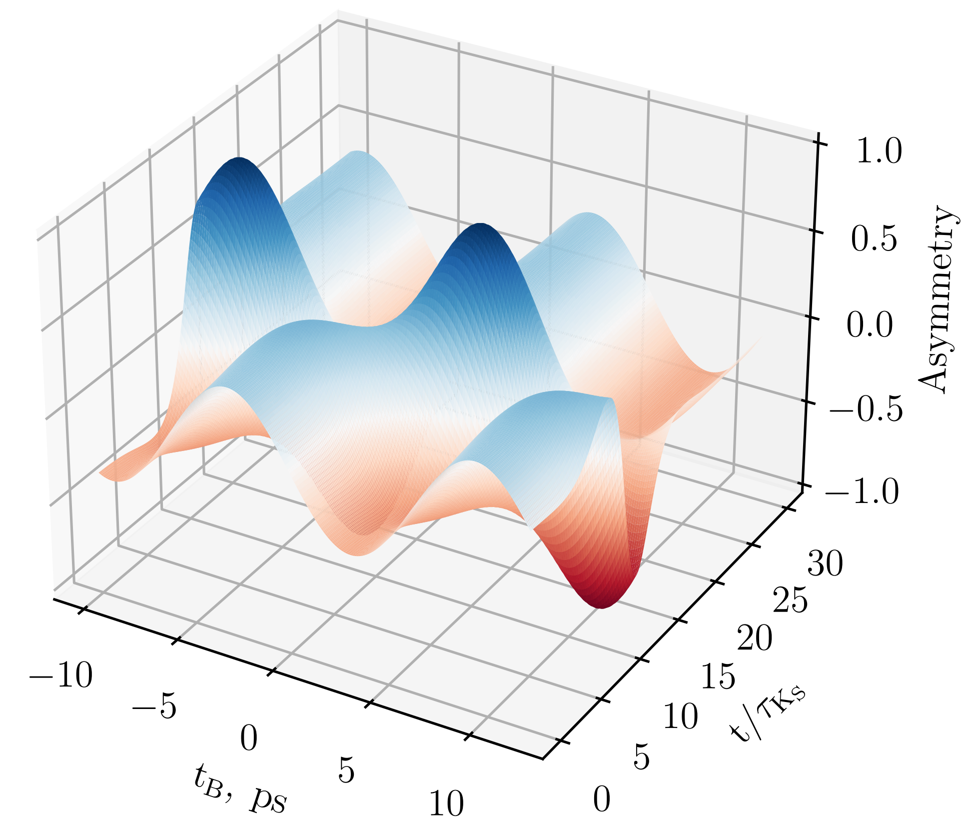
$$|\bar{B}^0(t)\rangle = e^{-i\frac{M_1+M_2}{2}t}e^{-\frac{\Gamma}{2}t}\left[i\left(\frac{p}{q}\right)_B \cos\left(\frac{\Delta m t}{2}\right)|B^0\rangle + \sin\left(\frac{\Delta m t}{2}\right)|\bar{B}^0\rangle\right]$$

$$a_{CP} = \frac{P(\bar{B}^0 \to f) - P(B^0 \to f)}{P(\bar{B}^0 \to f) + P(B^0 \to f)} = \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1}\cos(\Delta m t) + \frac{\mathrm{Im}\lambda}{|\lambda|^2+1}\sin(\Delta m t) \equiv$$
$$\equiv -C_f \cos(\Delta m t) + S_f \sin(\Delta m t),$$

$$A_{B\to\pi\pi} \sim s_{12}^3 T + s_{12}^3 P$$

$$A_{B\to K\pi} \sim s_{12}^4 T + s_{12}^2 P$$

$$\lambda = \left[e^{2i\alpha}\frac{1 + |P/T|e^{i(\delta+\gamma)}}{1+|P/T|e^{i(\delta-\gamma)}}\right]$$



- New Physics searches in the SCS D -decays.