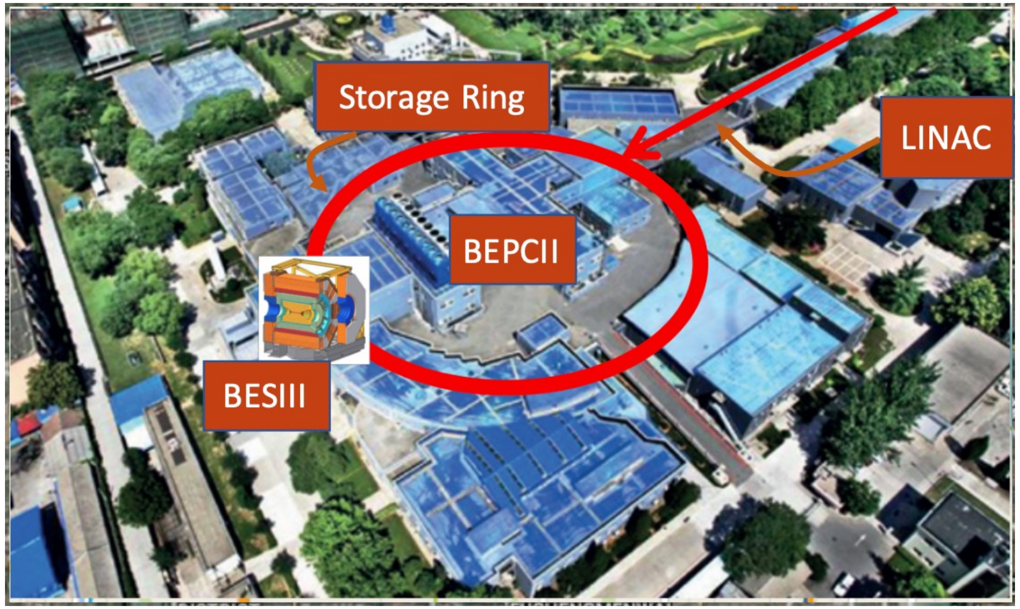
Recent charm meson results at BESIII

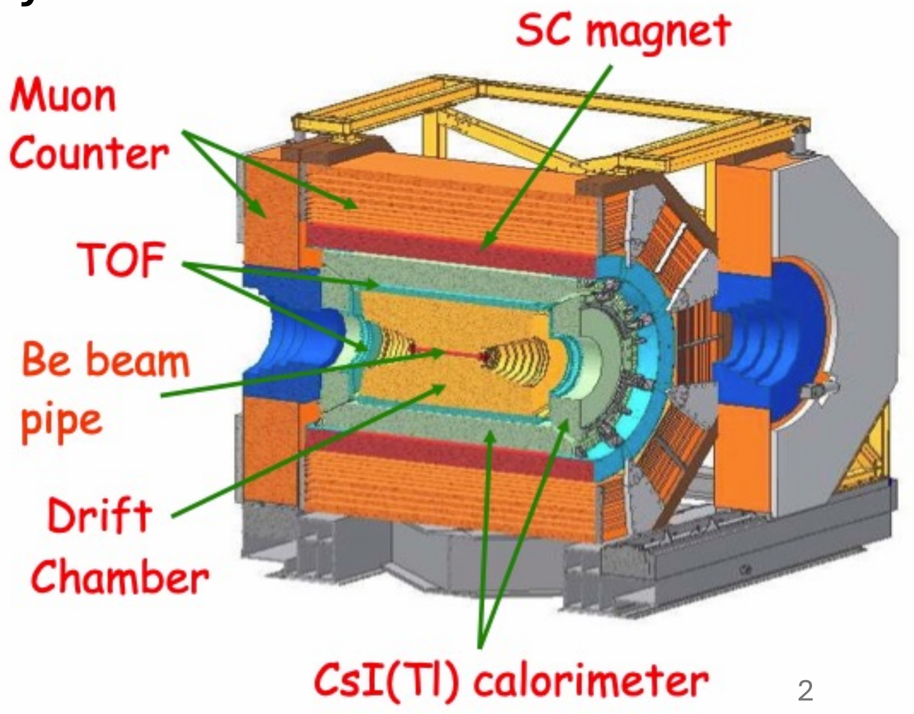
Innes Mackay on behalf of the BESIII collaboration

innes.mackay@physics.ox.ac.uk

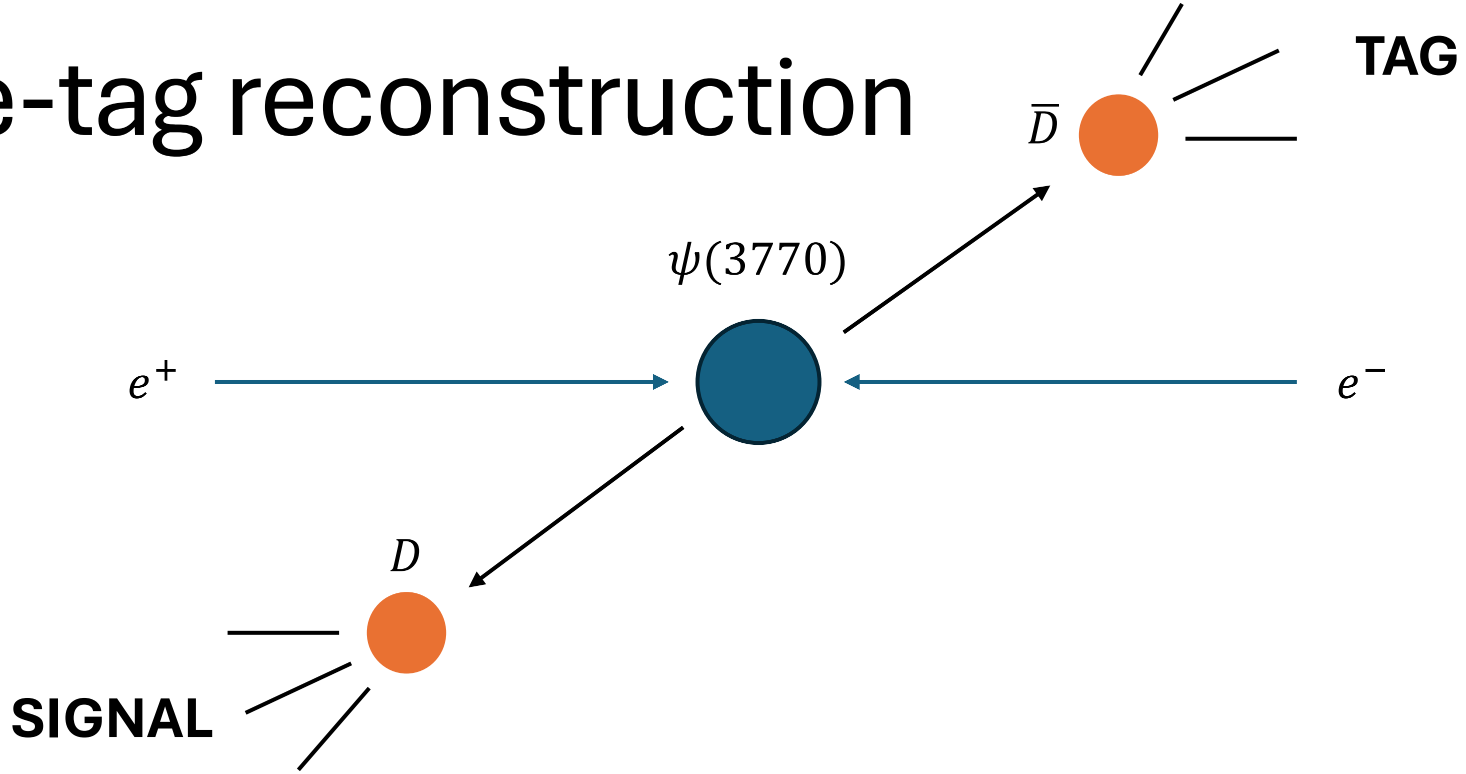
Introduction to the BESIII experiment

- Located in the symmetric e^+e^- BEPCII collider at IHEP, Beijing
- Operates in $E_{CM} = 2 - 5$ GeV with peak L~10^{33} $cm^{-2}s^{-1}$
- The detector has ~93% radial acceptance optimised for low momentum particles (~1 GeV)
- R-value, τ, **charm**, light hadron, charmonium physics + more





Double-tag reconstruction



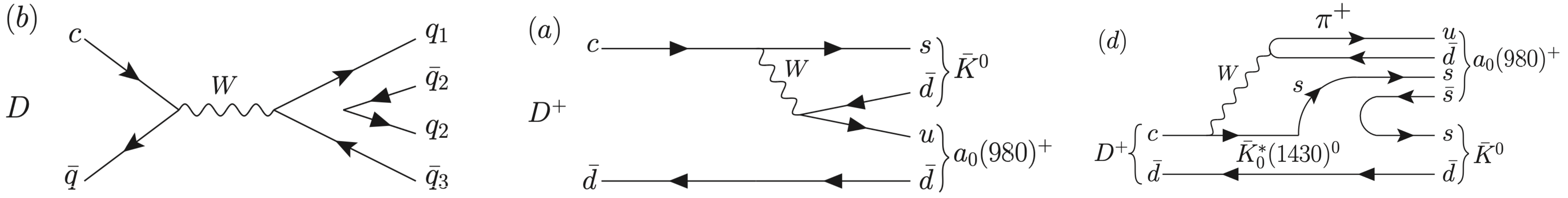
- Producing two D mesons on resonance allows for clean reconstruction
- Allows use of beam constrained and missing mass/energy variables
- Can determine branching fractions without knowledge of N_{DD}

$$B(D \rightarrow \text{signal}) = \frac{N_{sig}/\epsilon_{tag\,\&\,sig}}{N_{tag}/\epsilon_{tag}}$$

Observation of $\mathrm{D}^+ \rightarrow \mathrm{K}_S^0 \mathrm{a}_0(980)^+$

Phys. Rev. Lett. **132**, 131903

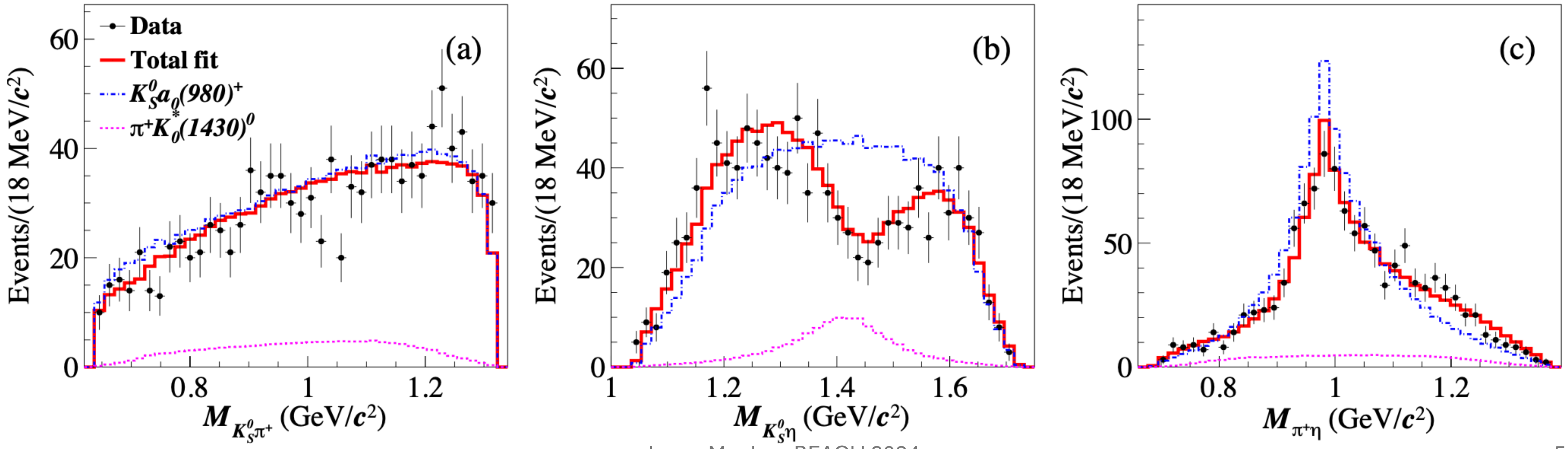
- Hadronic charm decays not yet accurately described by theory
- The diagrammatic approach[1] works for $D \rightarrow PP$ and $D \rightarrow VP$ decays but progress in $D \rightarrow SP$ is limited due to W-annihilation amplitudes
- $\mathrm{D}^+ \rightarrow \mathrm{K}_S^0 \mathrm{a}_0(980)^+$ contains no contributions from W-annihilation diagrams
- Discrepancies from predicted BF could tell us more about the a_0



[1] Phys. Rev. Lett. **56**, 1655

Observation of $D^+ \to K_S^0 a_0(980)^+$

- Observed in an amplitude analysis of $D^+ \to K_S^0 \pi^+ \eta$ decays using 2.93 fb^{-1} data collected at E_{CM}=3.773 GeV
- Highly pure sample of ~1100 signal candidates obtained using the 6 hadronic DT final states method
- $B\left(D^+ \to K_S^0 a_0(980)^+, a_0^+ \to \pi^+\eta\right) = (1.33 \pm 0.05_{stat} \pm 0.04_{syst})\%$



Search for purely leptonic $D_s^{*+} \to e^+\nu_e$ decays

Phys. Rev. Lett. **131**, 141802

- The decay has never been observed but can be excellent probes of c→s transitions, CKM unitarity and LFU
- QCD effects absorbed into $f_{D_s^{*+}}$ which provides test of LQCD

$$\Gamma(D_s^{*+} \to \ell^+\nu_\ell) = \frac{G_F^2}{12\pi}|V_{cs}|^2 f_{D_s^{*+}}^2 m_{D_s^{*+}}^3 \left(1 - \frac{m_{\ell^+}^2}{m_{D_s^{*+}}^2}\right)^2 \times \left(1 + \frac{m_{\ell^+}^2}{2m_{D_s^{*+}}^2}\right),$$

- Measurement uses 7.33 fb^{-1} data collected between E_{CM}=4.128-4.226 GeV where $e^+e^- \to D_s^- D_s^{*+}$ production is possible
- Double-tag method used with 16 hadronic D_s^- decays

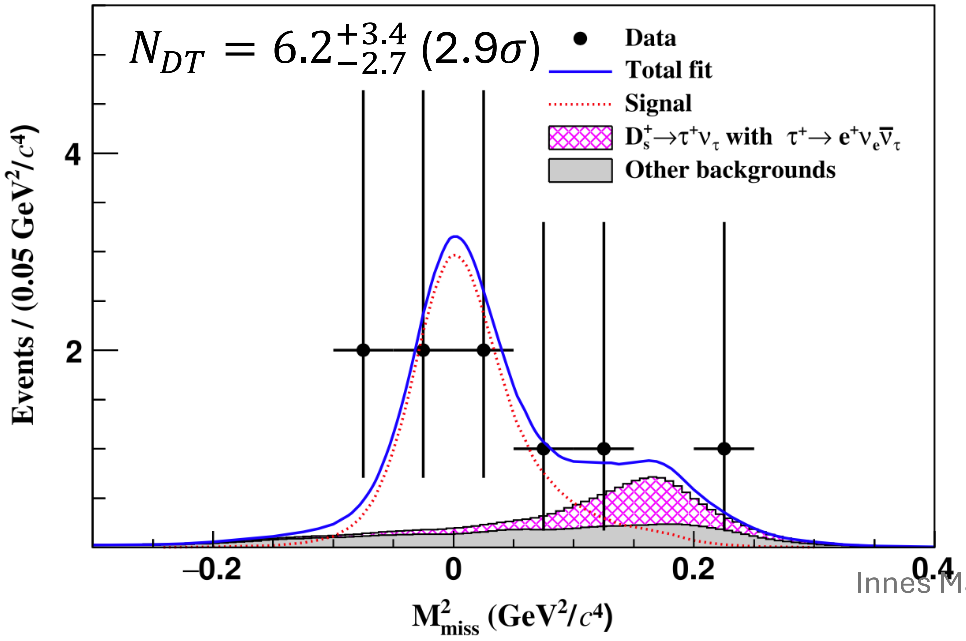
Search for purely leptonic $D_s^{*+} \to e^+\nu_e$ decays

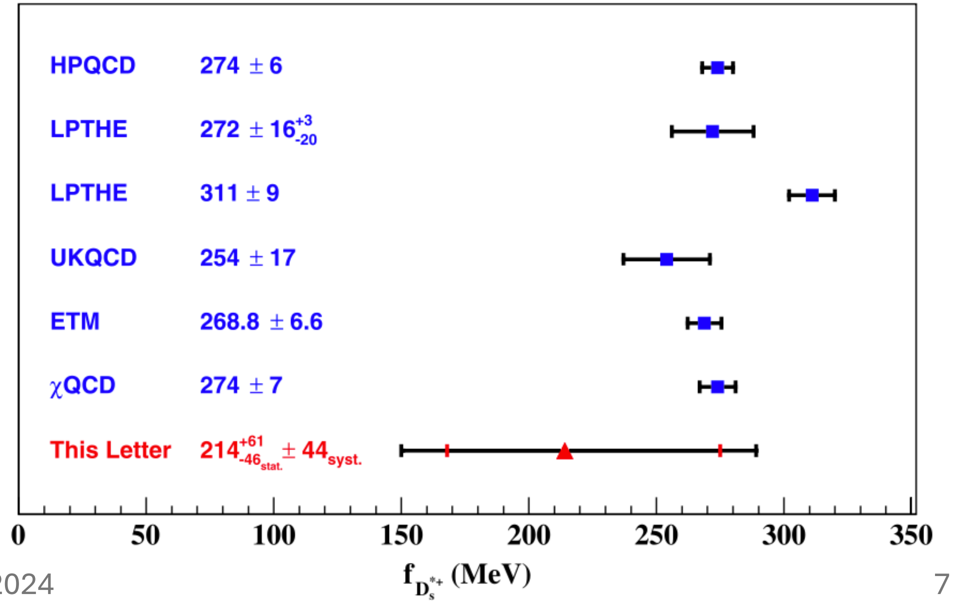
- Signal yield extracted from a fit to the squared missing mass

$$M^2_{\mathrm{miss}} \equiv \left|E_{\mathrm{cm}} - \sum_k E_k\right|^2/c^4 - \left|\sum_k \vec{p}_k\right|^2/c^2$$

where k loops over all particles used in reconstruction

- **First evidence for this decay and measurement of decay constant**
- $BF(D_s^{*+} \to e^+\nu_e) = (2.1^{+1.2}_{-0.9}{}_{stat} \pm 0.2_{syst})\times10^{-5}$ (<4×10^{-5} at 90%CL)





Measurement of $D_s^+ \to \mu^+ \nu_\mu$

Phys. Rev. D **108**, 112001

- Measure $|V_{cs}|$, LFU tests and LQCD checks

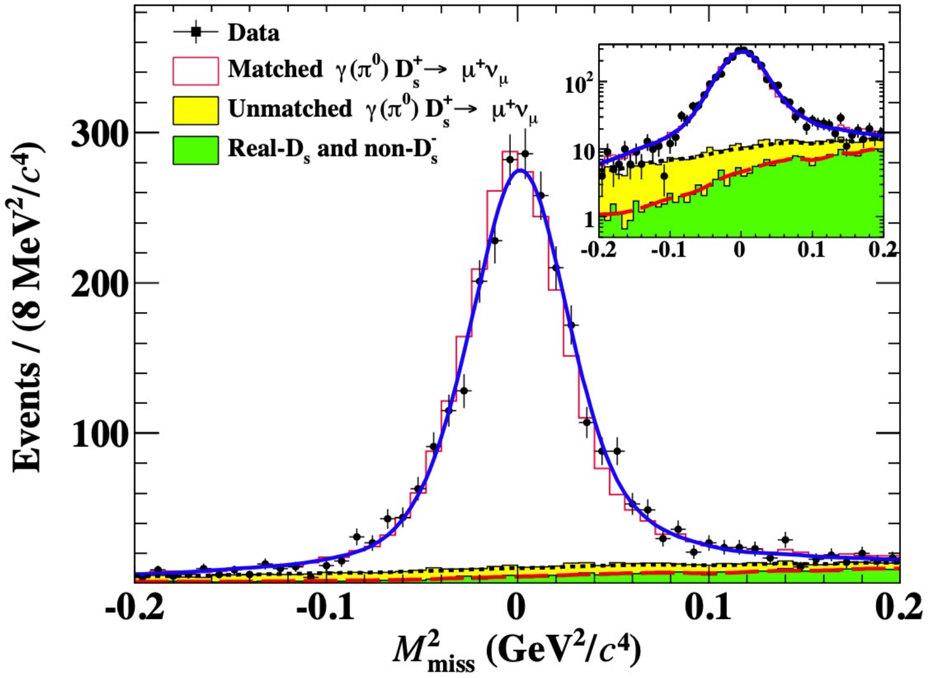
$$\Gamma_{D_s^+ \to \ell^+ \nu_\ell} = \frac{G_F^2}{8\pi} |V_{cs}|^2 f_{D_s^+}^2 m_\ell^2 m_{D_s^+} \left(1 - \frac{m_\ell^2}{m_{D_s^+}^2}\right)^2$$

- Measurement uses 7.33 fb^{-1} data collected between E_{CM}=4.128-4.226 GeV where $e^+e^- \to D_s^+ D_s^{*-}$ production is possible
- Double-tag method used with 16 hadronic D_s^- decays with fully reconstructed $D_s^{*-} \to D_s^- \gamma$ or $D_s^- \pi^0$

Measurement of $D_s^+ \to \mu^+\nu_\mu$

- Branching fraction determined using yields from fit to $\mathrm{M}^2_{\mathrm{miss}}$
- Determine $B\left(D_s^+ \to \mu^+\nu_\mu\right) = (0.5294 \pm 0.0108)\%$

$$\mathcal{B}_{D_s^+ \to \mu^+\nu_\mu} = \frac{N_{\mathrm{DT}}}{N_{\mathrm{ST}} \cdot \epsilon_{\gamma(\pi^0)\mu^+\nu_\mu}}$$



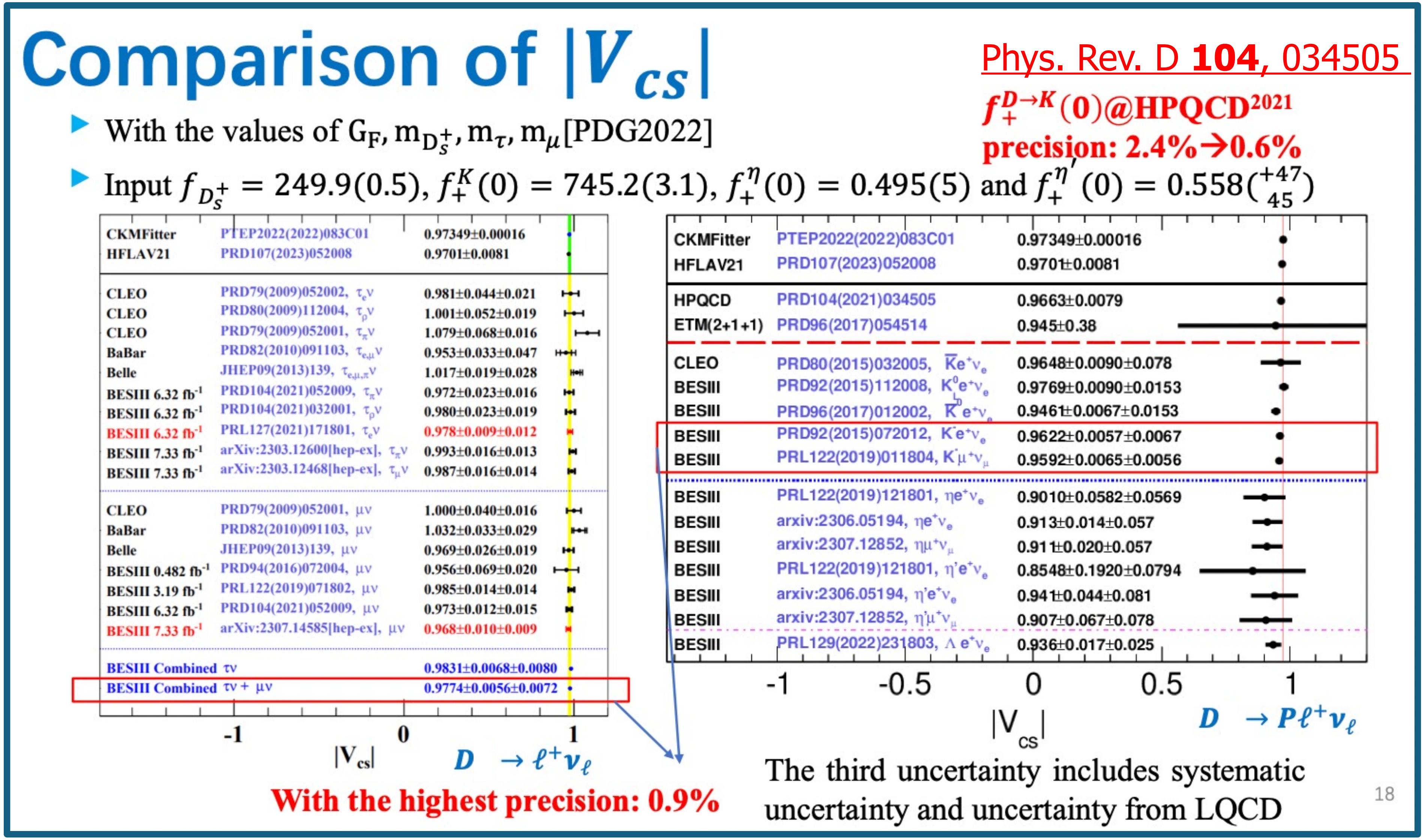
With input for $f_{D_s^+}$: $|\boldsymbol{V_{cs}}| = \mathbf{0.968 \pm 0.010}_{\boldsymbol{stat}} \pm \mathbf{0.009}_{\boldsymbol{syst}}$

With input for $|V_{cs}|$: $f_{D_s^+} = 248.4 \pm 2.5_{stat} \pm 2.2_{syst}$ MeV

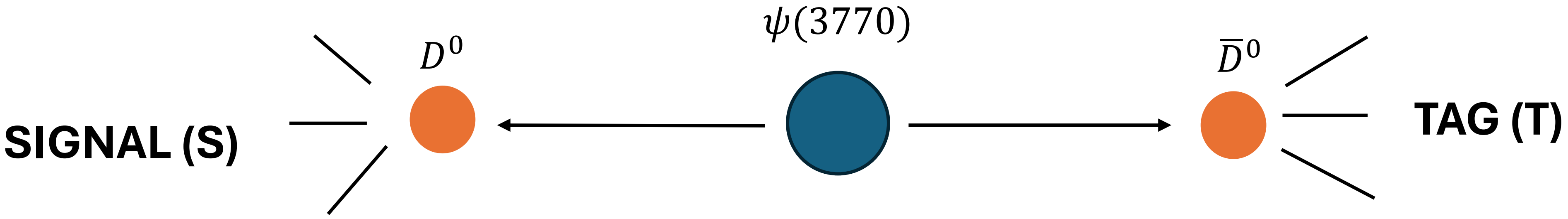
BESIII results: $\frac{B(D_s^+ \to \tau^+\nu_\tau)}{B(D_s^+ \to \mu^+\nu_\mu)} = 10.05 \pm 0.35$

Theoretical prediction = 9.75

Slide from Tengjiao Wang presented at CKM 2023



Quantum correlated $D^0\overline{D}^0$ pairs



$$\mathcal{A} = \langle S|D^0\rangle\langle T|\overline{D}^0\rangle - \langle T|D^0\rangle\langle S|\overline{D}^0\rangle$$

- $e^+e^- \to \psi(3770)$ proceeds through γ^* which is C-odd -- conserved in final state so decays of the D^0 and $\overline{D}^0$ are correlated
- Interference between the D^0 and $\overline{D}^0$ decays is sensitive to the strong-phase difference in the signal and tag final states
- Key inputs in measurements of the CKM angle γ and charm mixing and CPV parameters

Measurement of the CP even fraction of $D^0 \to K_S^0\pi^+\pi^-\pi^0$

- C-odd constraint places CP restrictions on the final states

Phys. Rev. D **108**, 032003

$$|D^0\overline{D}^0\rangle - |\overline{D}^0 D^0\rangle = |D_- D_+\rangle - |D_+ D_-\rangle$$

- Allows for measurement of the CP even fraction (F_+) in a decay, which is key input to measurements of the CKM angle γ
- Multiple different tag final states are used with different CP properties

Type	Tag modes
CP-even	$K^+K^-, \pi^+\pi^-, K_S^0\pi^0\pi^0, K_L^0\omega, K_L^0\pi^0$
CP-odd	$K_S^0\pi^0, K_S^0\eta(\gamma\gamma), K_S^0\eta'(\eta\pi^+\pi^-), K_S^0\eta'(\gamma\pi^+\pi^-)$
Quasi-CP	$\pi^+\pi^-\pi^0, \pi^+\pi^-\pi^+\pi^-$
Mixed CP	$K_{S,L}^0\pi^+\pi^-$
Self-tag	$K_S^0\pi^+\pi^-\pi^0$

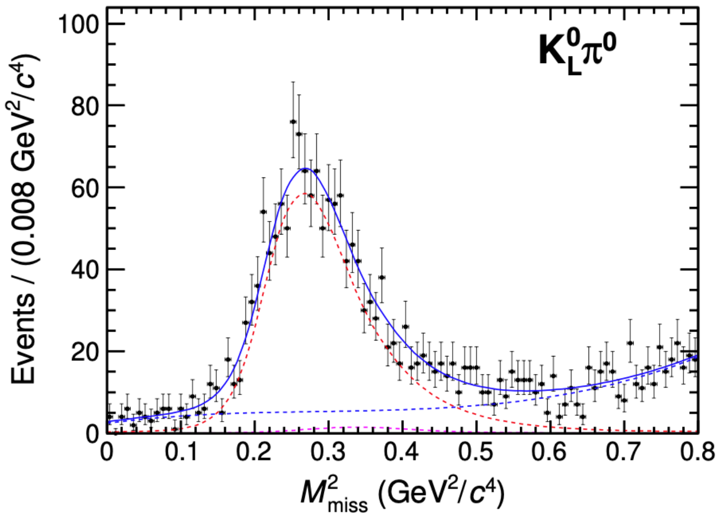
Measurement of the CP even fraction of $D^0 \to K_S^0\pi^+\pi^-\pi^0$

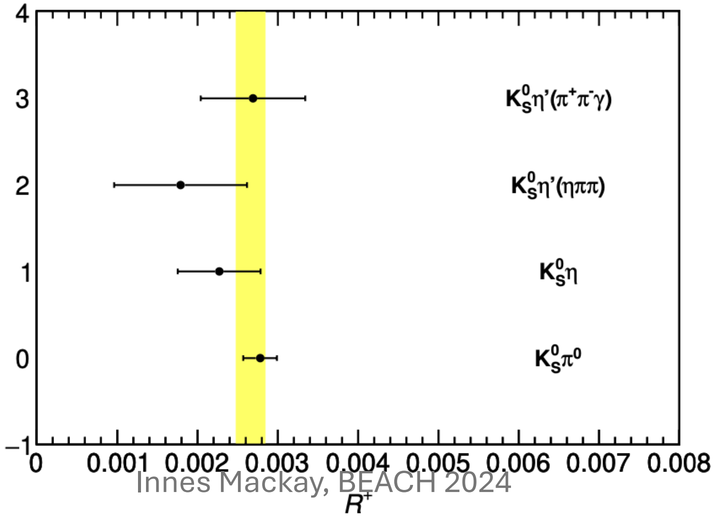
- F_+ is determined using 5 CP even and 4 CP odd tags
- Single tags used for cancellation of systematic uncertainties and $N_{D\bar{D}}$
- Fit to M_{BC} (M^2_{miss}) for tags without (with) K_L^0 particles
- Similar procedure for the quasi-CP tags e.g. $\pi^+\pi^-\pi^0$

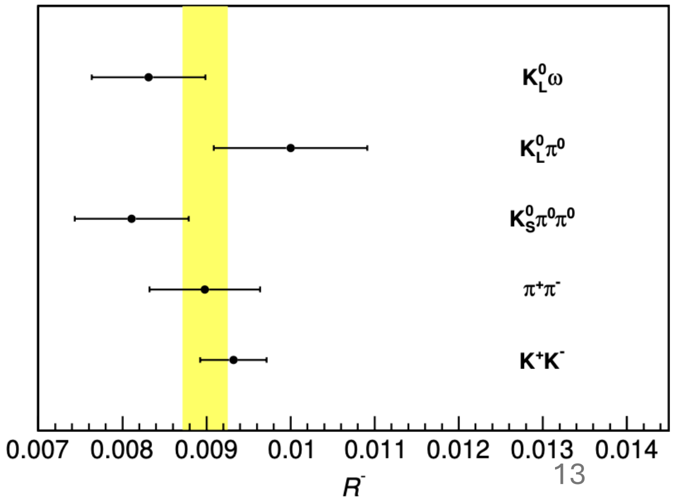
$$R^{\mp} = \frac{N(S|T)}{N(T)} = BF(S)\epsilon(S)[1 - \eta_T^{\pm}(2F_+ - 1)]$$

where $\eta_T^{\pm}$ is the CP eigenvalue of the tag

$$F_+ = \frac{R^+}{R^+ + R^-}$$





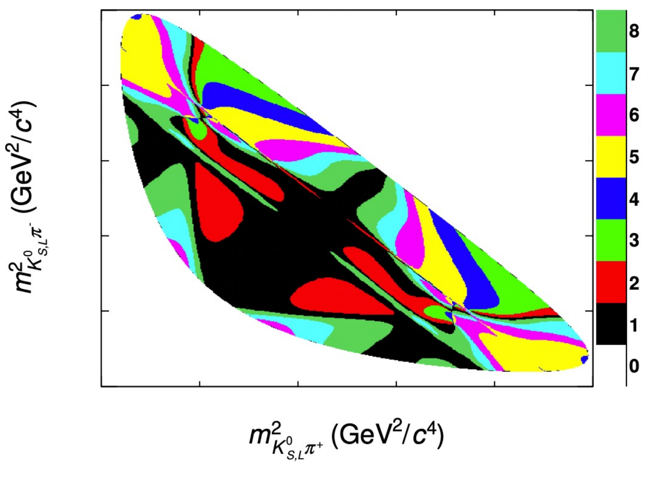


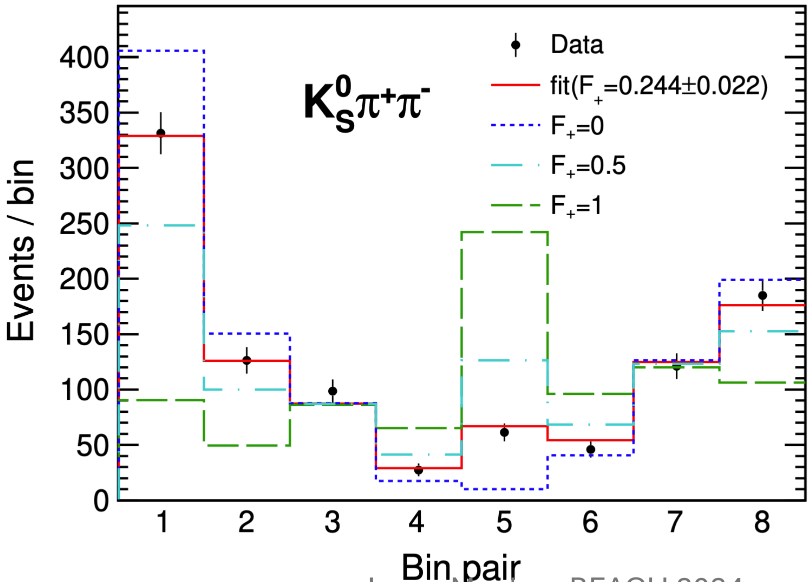
Measurement of the CP even fraction of $D^0 \to K_S^0\pi^+\pi^-\pi^0$

- Integrated $F_+^{K_{S,L}^0\pi^+\pi^-} \sim 0.5$ so measurement performed in PS regions
- Symmetric 16 bin scheme is used to describe the PS

$$M_i = h\left[K_i + K_{-i} - 2c_i\sqrt{K_iK_{-i}}(2F_+ - 1)\right]$$

- Likelihood fit to the double tag yields performed to determine F_+ with Gaussian constrained K_i, c_i



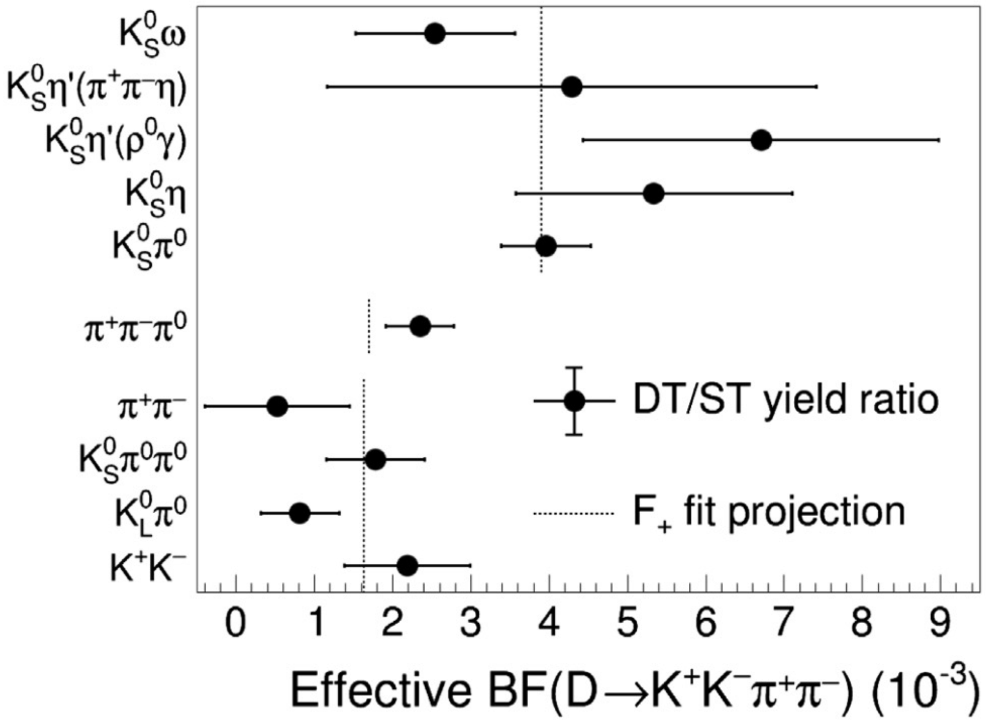


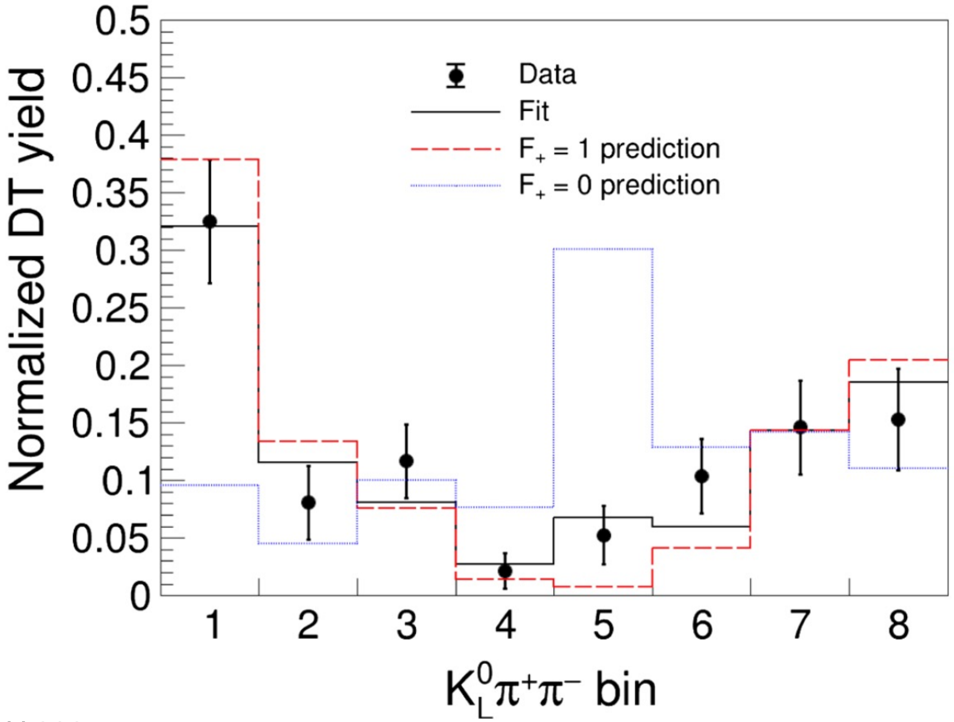
Method	F_+
CP-tag modes	$0.229 \pm 0.013 \pm 0.002$
$\pi^+\pi^-\pi^0$ tag mode	$0.227 \pm 0.014 \pm 0.003$
$\pi^+\pi^-\pi^+\pi^-$ tag mode	$0.227 \pm 0.016 \pm 0.003$
Self-tag modes	$0.244 \pm 0.019 \pm 0.002$
$K^0_{S,L}\pi^+\pi^-$	$0.244 \pm 0.021 \pm 0.006$
Combined	$0.235 \pm 0.010 \pm 0.002$

Measurement of the CP even fraction of $D^0 \to K^+K^-\pi^+\pi^-$

- Same procedure as in $D^0 \to K_S^0\pi^+\pi^-\pi^0$
- $F_+ = 0.730 \pm 0.037\ (stat.) \pm 0.021 (syst.)$

Category	Tag modes
CP even	K^+K^-, $\pi^+\pi^-$, $K_S^0\pi^0\pi^0$, $\pi^+\pi^-\pi^0$, $K_L^0\pi^0$
CP odd	$K_S^0\pi^0$, $K_S^0\eta_{\gamma\gamma}$, $K_S^0\eta'(\pi\pi\eta)$, $K_S^0\eta'(\rho^0\gamma)$, $K_S^0\omega$
Mixed CP	$K_S^0\pi^+\pi^-$, $K_L^0\pi^+\pi^-$



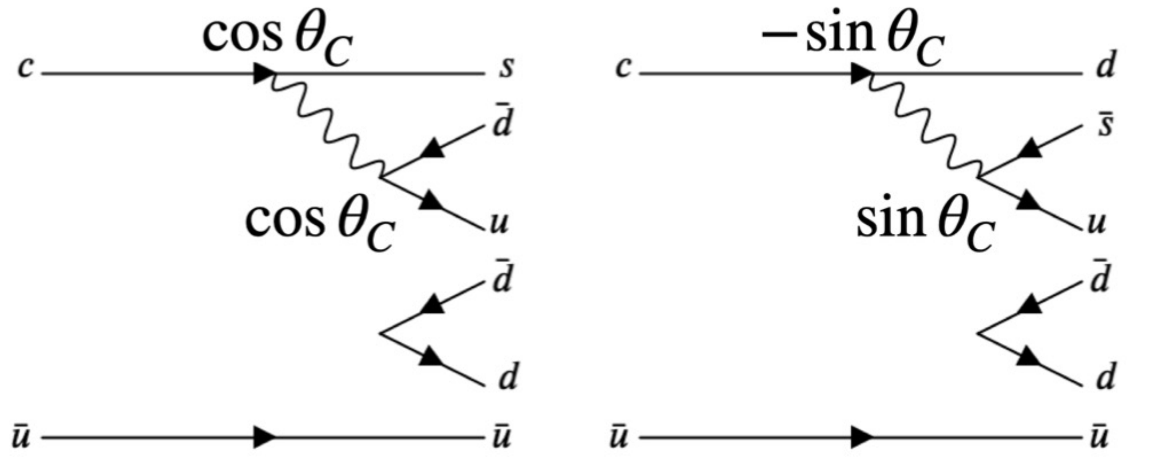


Phys. Rev. D **107**, 032009

Measurement of U-spin breaking parameters in $D^0 \to K_L^0\pi^+\pi^-$

- Interference between CF and DCS contributions to the $D^0 \to K_L^0(\pi^+\pi^-)_{k_{CP}}$ final state can break U-spin symmetry
- $D \to K_S^0\pi^+\pi^-$ strong-phases measured using $K_L^0\pi^+\pi^-$ tags at BESIII with assumptions about U-spin breaking parameters ($\hat{\rho}$)
- Measuring will reduce systematic uncertainties on measurements of the CKM angle γ

$$A\left(D^0 \to K_L^0(\pi\pi)_{k_{CP}}\right) = \frac{1}{\sqrt{2}} A\left(D^0 \to \bar{K}^0(\pi\pi)\right)\left(1 - \hat{\rho}_{k_{CP}} \tan^2\theta_C\right)$$



CF $D^0 \to \bar{K}^0\pi^+\pi^-$ (*left*) and DCS $D^0 \to K^0\pi^+\pi^-$ (*right*) decay diagrams.

arXiv:2212.09048

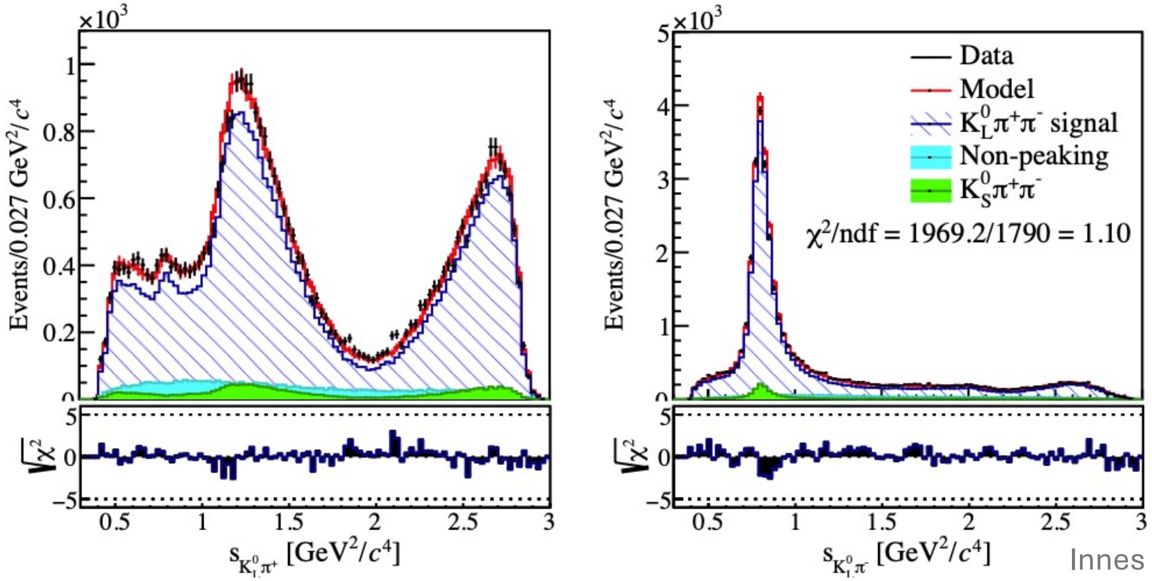
Measurement of U-spin breaking parameters in $D^0 \to K_L^0\pi^+\pi^-$

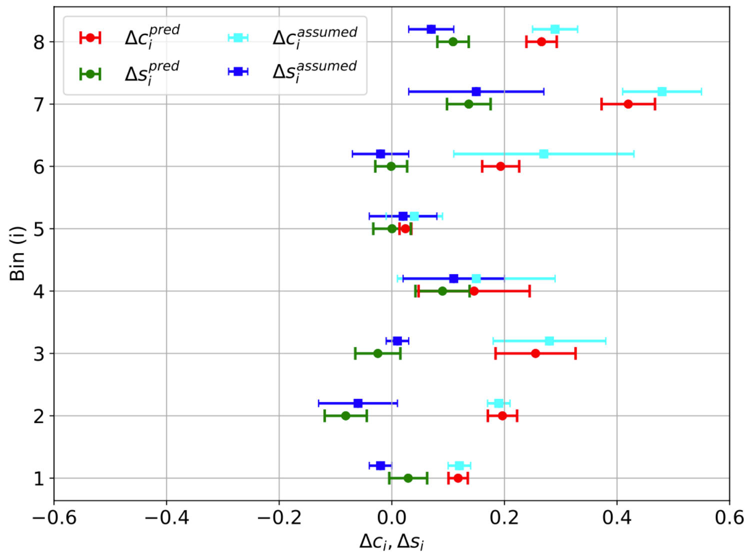
- $D^0 \to K_L^0\pi^+\pi^-$ amplitude analysis performed (first with a K_L^0) constraining to well-studied $D^0 \to K_S^0\pi^+\pi^-$ mode assuming

$$A\left(D^0 \to K_L^0(\pi\pi)_{k_{CP}}\right) = A\left(D^0 \to K_S^0(\pi\pi)_{k_{CP}}\right)\left(1 - 2\hat{\boldsymbol{\rho}}_{\boldsymbol{k_{CP}}} \tan^2\theta_C\right)$$

- Significant deviations from 1 show U-spin symmetry breaking

Resonance	$\lvert\hat{\rho}\rvert$
$\rho(770)$	$1.93 \pm 0.27 \pm 0.42$
$\omega(782)$	$6.13 \pm 0.75 \pm 0.53$
$f_2(1270)$	$3.75 \pm 0.90 \pm 0.81$
$\rho(1450)$	$12.12 \pm 2.92 \pm 1.88$
$\pi\pi$ S-wave	$0.37 \pm 0.21 \pm 0.37$





Measured strong-phase differences agree with assumptions in $K_S^0\pi^+\pi^-$ analysis - but now with justified errors

Summary

- BESIII is an excellent laboratory for charm physics – clean reconstruction and quantum correlations
- Exciting new measurements in amplitude analyses, leptonics, flavour physics
- Much more to come with the collaboration having recently finished collection of ~20fb^{-1} data at E_{CM}=3.773 GeV (~7x larger)

Questions?