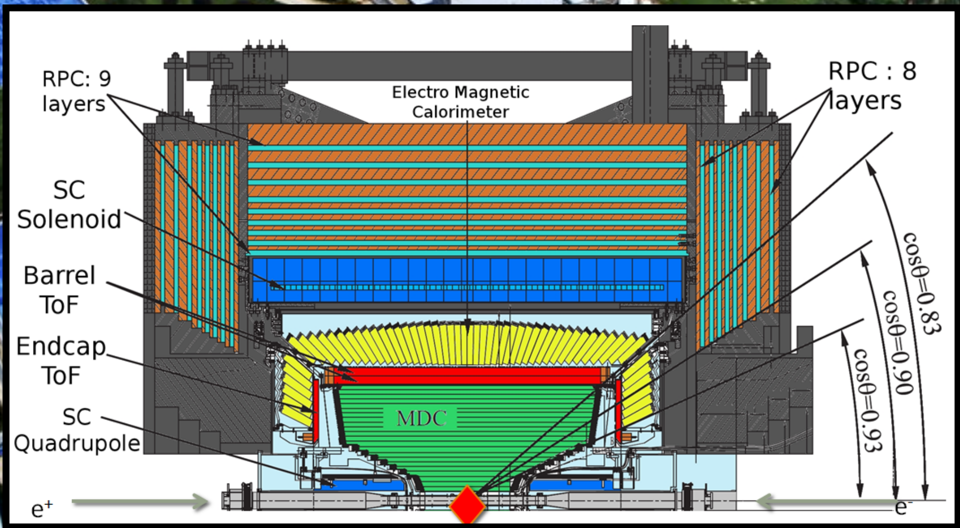
HADRONIC CHARM DECAYS @ BESIII

On behalf of the BESIII Collaboration, Sneha Malde, University of Oxford

FPCP, 7-11th June 2021



BESIII

Collision energy between
$\sqrt{S}$ = 2.0 → 4.9 GeV

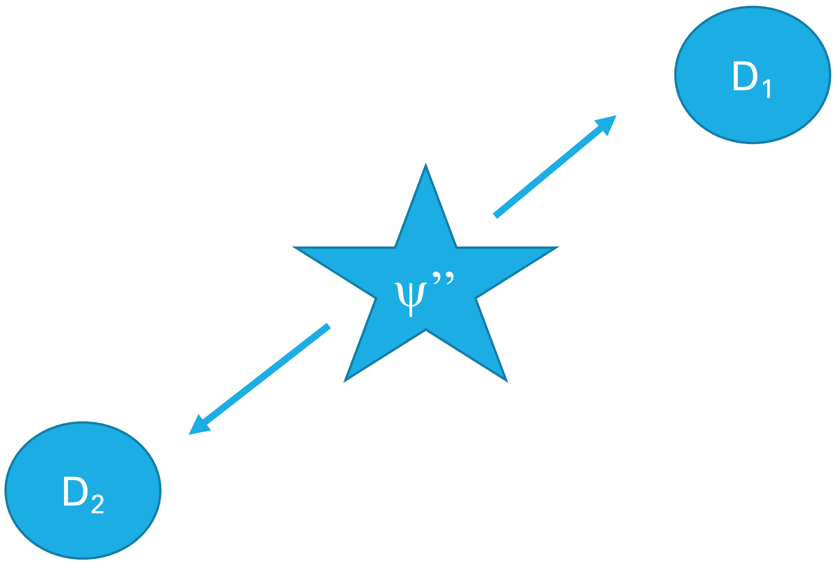
Varied physics programme

International collaboration

>500 members from 72 institutions
In 15 countries

- Charm strong-phase parameters
- Branching fractions
- Amplitude analyses

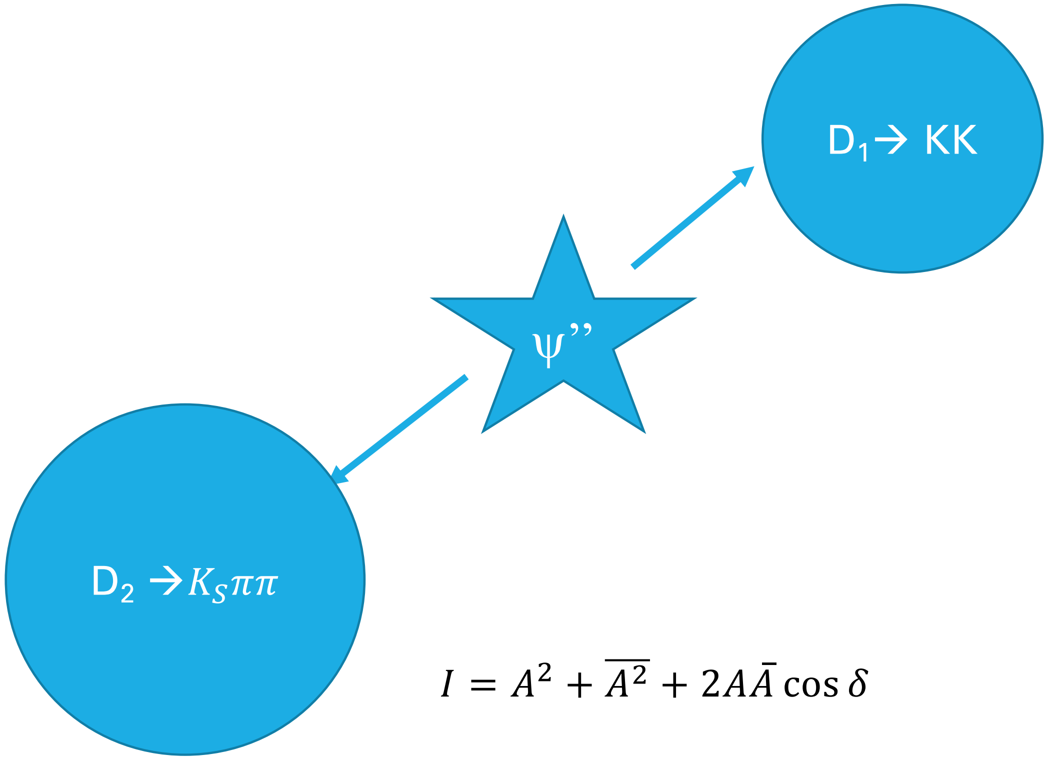
Neutral charm meson pair production



- $\psi''(3770)$ has mass just above charm meson pair production
- It has C=-1, which is conserved in its strong decay
- This means that the two resultant D mesons are quantum-correlated
- They are superpositions of D^0 and $\overline{D^0}$
- Their decays are not independent of each other
- Production mechanism allows for many unique results
- Largest dataset taken at ψ'' is at BESIII 3fb^{-1}

How does the quantum-correlation manifest? Why is it useful? How can it be exploited at BESIII ?

How does this manifest?



$$I = A^2 + \overline{A^2} + 2A\bar{A}\cos\delta$$

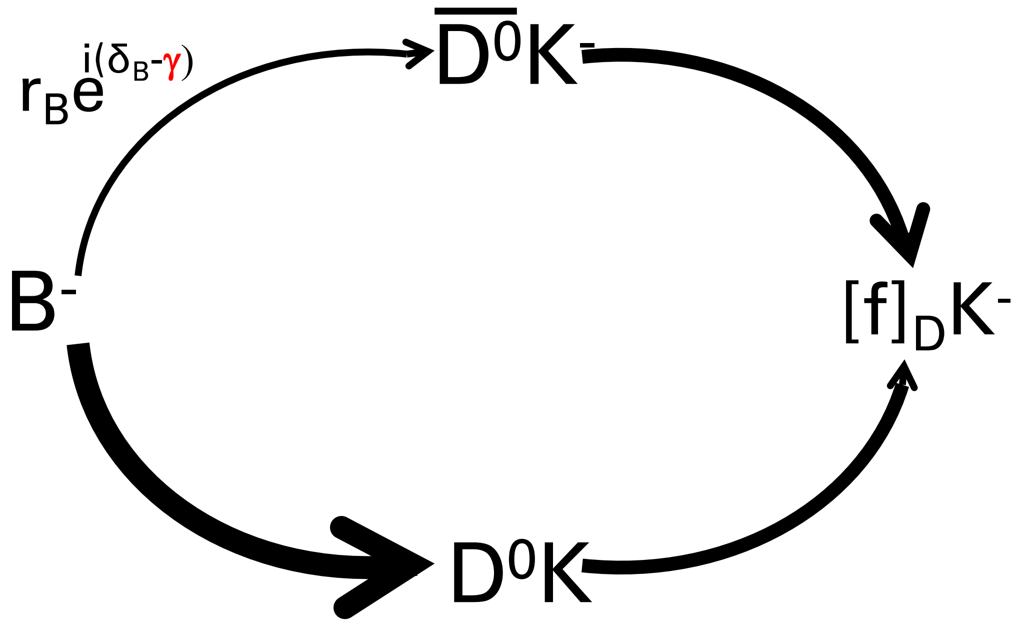
D_1 decays to a CP-even eigenstate.

In order to maintain overall C=-1, the D_2 decay is CP-odd.

This is regardless on whether it is a CP eigenstate or not

This interference then gives access to strong-phase differences.

Why are strong phases important?



A precision measurement of the CKM angle γ is a key goal in flavour physics

Typically measured in B→DK decays

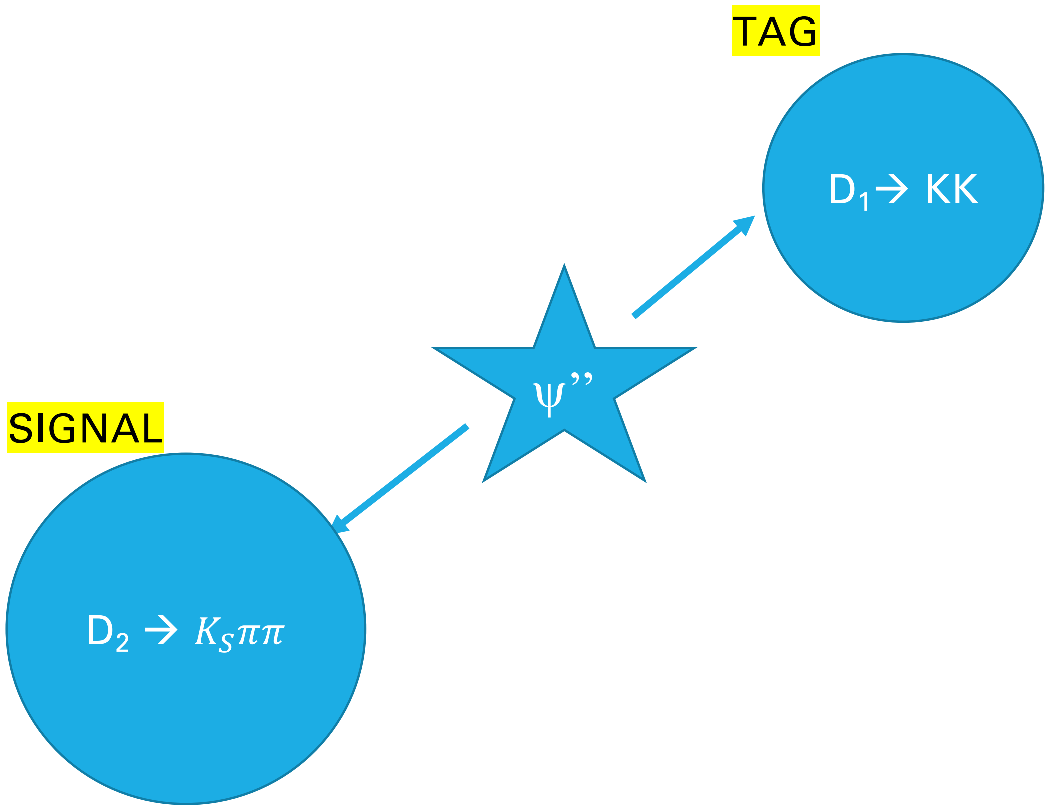
The physics associated with the D decay need to be known

For model-independent measurements of γ require information on strong-phases, often in regions of phasespace

BESIII can measure the required inputs

Great example of how BESIII measurements are critical to the goals of LHCb and Belle II

How do we make the measurements?



Double tag method:

The tag decay is a state of known CP, flavour or where the strong-phases are known from other measurement

The signal decay is the one of interest.

Double tag yields are dependent on the strong-phase parameters

Signal decay: S= $D \to K^-\pi^+\pi^+\pi^-$ & $D \to K^-\pi^+\pi^0$

$$R_S e^{-i\delta_D^S} = \frac{\int \mathcal{A}_S^\star(\mathbf{x})\mathcal{A}_{\bar{S}}(\mathbf{x})\mathrm{d}\mathbf{x}}{A_S A_{\bar{S}}} \quad \text{and} \quad r_D^S = A_{\bar{S}}/A_S$$

Definition of measured parameters

$$\rho_{CP\pm}^S \equiv \frac{N(S|CP) + N(\bar{S}|CP)}{2N_{D\bar{D}}\,\mathcal{B}\left(D^0 \to CP\right)\left[\mathcal{B}\left(D^0 \to S\right) + \mathcal{B}\left(D^0 \to \bar{S}\right)\right]}.$$

Incoherent expectation =1

$$\rho_{CP\pm}^S = \frac{\left(1 + (r_D^S)^2 \mp 2r_D^S R_S \cos\delta_D^S\right)}{\left(1 \mp y + (r_D^S)^2 - 2r_D^S R_S y \cos\delta_D^S\right)}.$$

Demonstrates how the observed fraction is dependent on the parameters of interest

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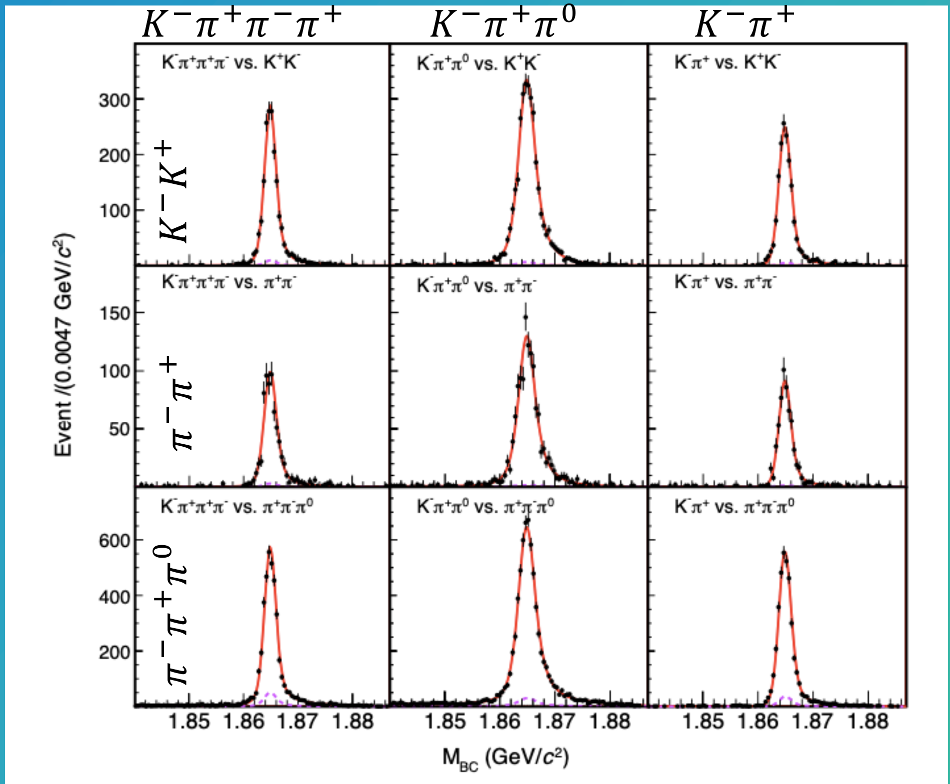
CP tags



- Very pure signals extracted
- Only 3 tags shown
- $K\pi$ vs CP used as a normalization
- Essentially removes uncertainties based on the BF and reconstruction efficiency of the CP tag

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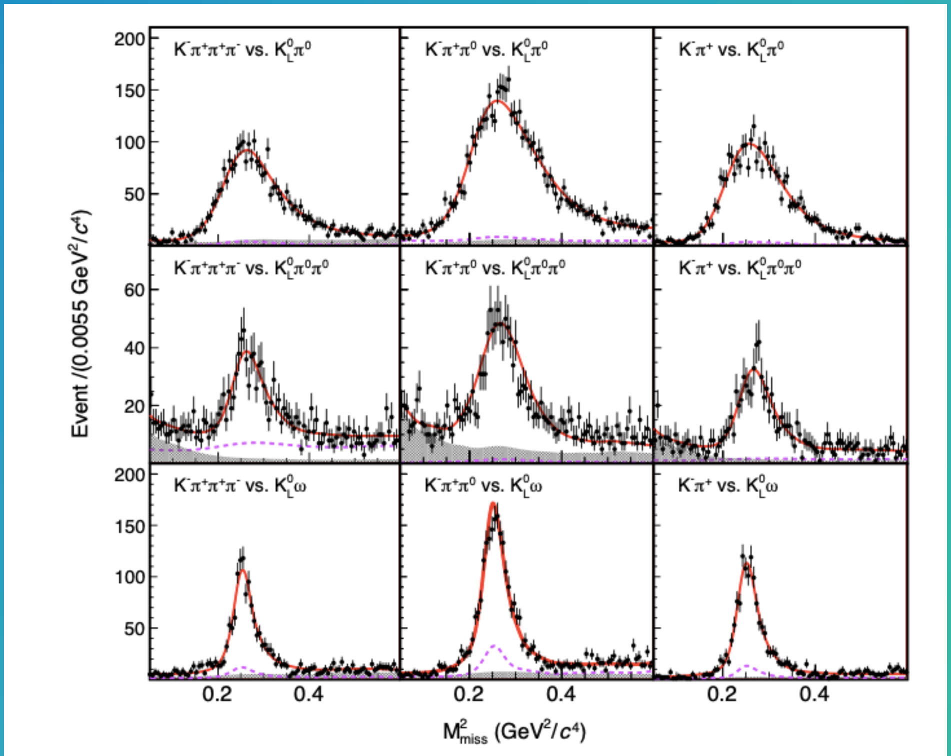
CP tags with K_L



- One of the beauties of a hermetic detector
- Use missing momentum and energy to infer the presence of K_L
- Increases the number of CP tags available for analysis

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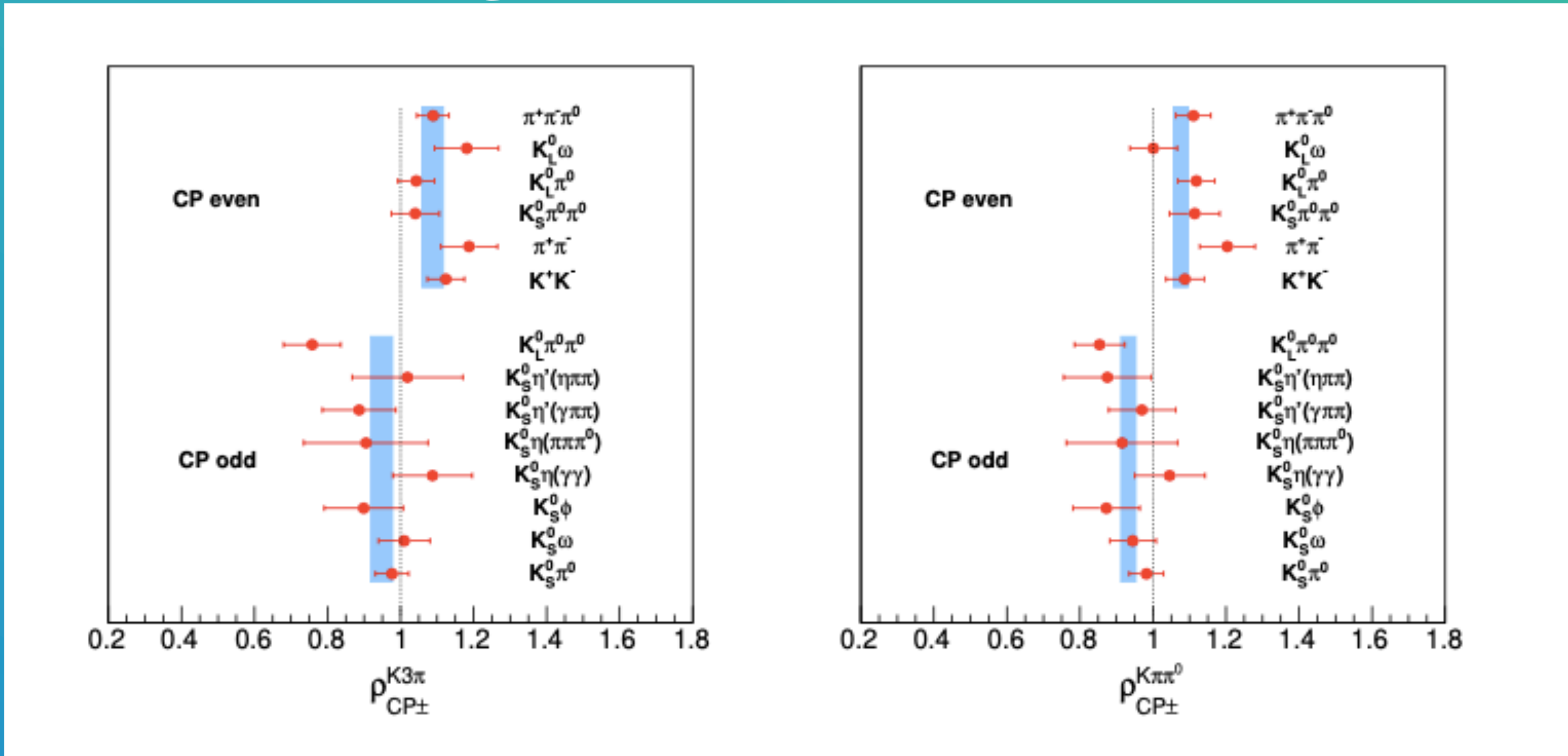
Measured ρ_{CP}



Clear difference for CP even and CP odd tags : Demonstration of QC effects
14 CP tags used in total. Many contain multiple neutral particles – demonstrates the capabilities of the BESIII detector

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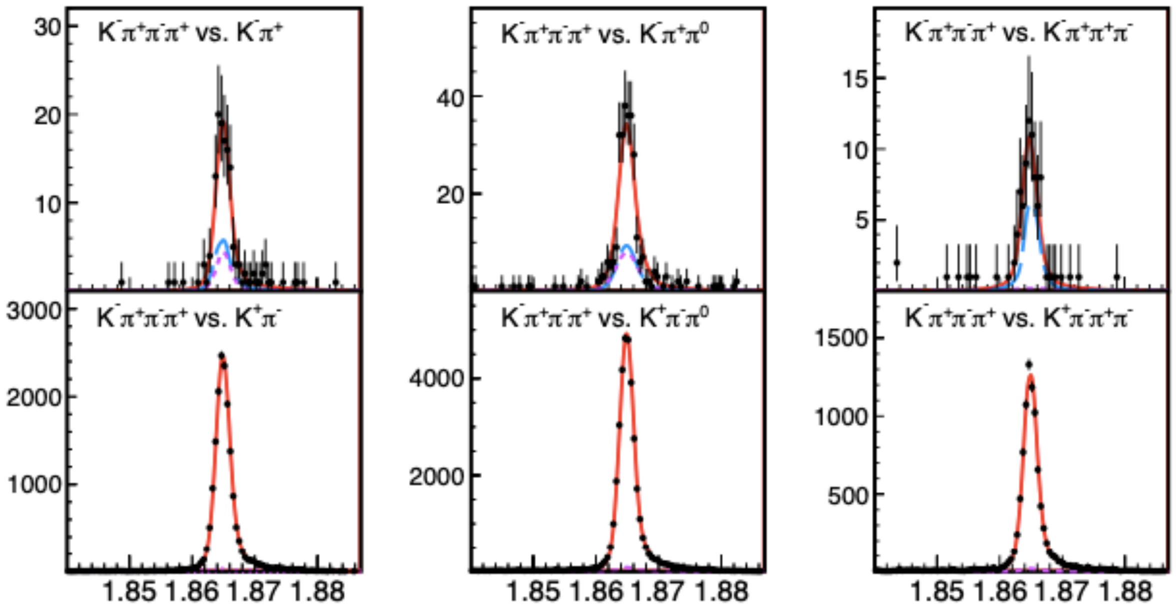
Like sign tags



$$\rho^S_{LS} = \frac{(1-R_S)^2}{1 - R_S\left((y/r^S_D)\cos\delta^S_D - (x/r^S_D)\sin\delta^S_D\right) + (x^2+y^2)/(2[r^S_D]^2)}$$

Like sign tags very sensitive to The coherence factor R_S

Higher backgrounds from D→$K_SK\pi$ and double mis-ID from the opposite signed tags

D→$K_SK\pi$ gives rise to leading systematic uncertainty

Full analysis is statistically dominated.

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Measured observables

Observable	Value	Observable	Value
$\Delta_{CP}^{K3\pi}$	$0.070 \pm 0.011 \pm 0.012$	$\Delta_{CP}^{K\pi\pi^0}$	$0.078 \pm 0.007 \pm 0.012$
$\rho_{LS}^{K3\pi}$	$0.740 \pm 0.157 \pm 0.161$	$\rho_{LS}^{K\pi\pi^0}$	$0.440 \pm 0.095 \pm 0.014$
$\rho_{K\pi,LS}^{K3\pi}$	$0.570 \pm 0.109 \pm 0.069$	$\rho_{K\pi,LS}^{K\pi\pi^0}$	$0.213 \pm 0.062 \pm 0.004$
$\rho_{K\pi\pi^0,LS}^{K3\pi}$	$0.715 \pm 0.094 \pm 0.089$		

Like-sign observables not consistent with 1, again indicating sensitivity to the strong-phase parameters.

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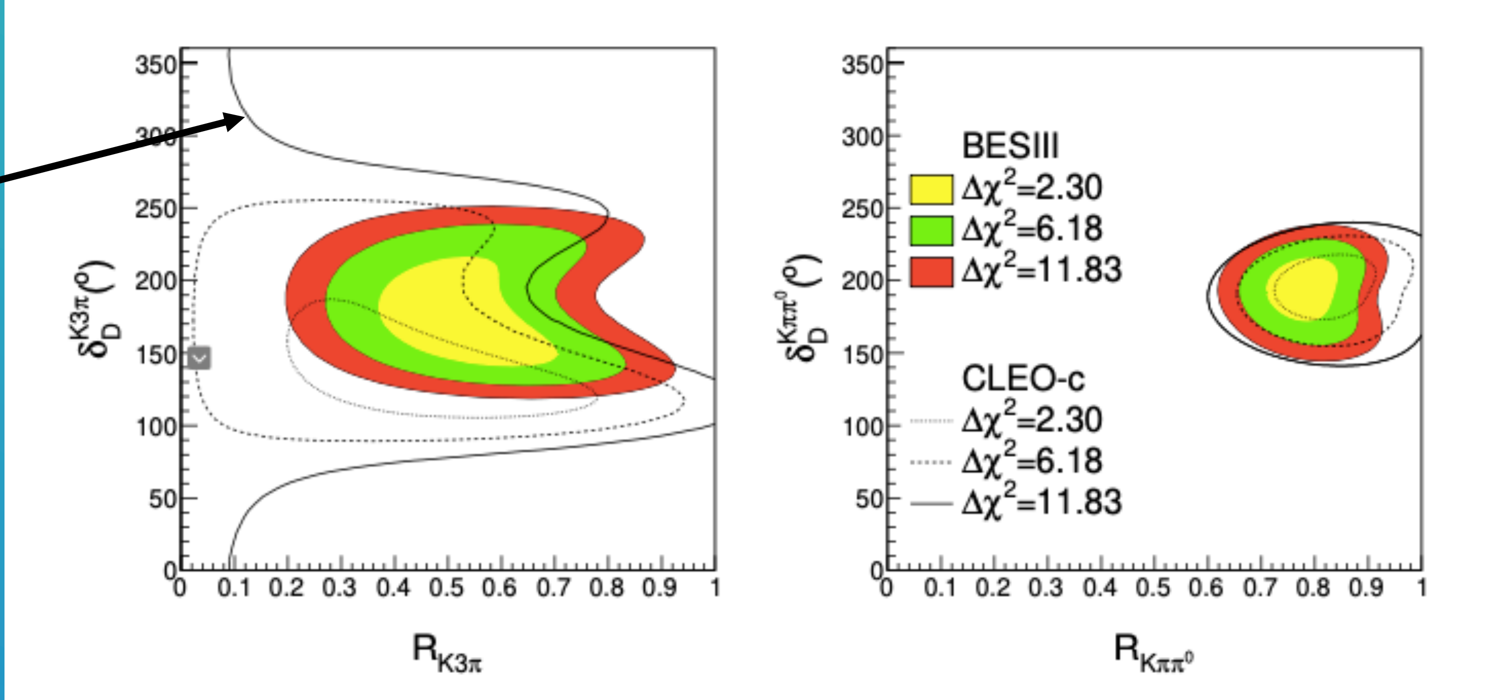
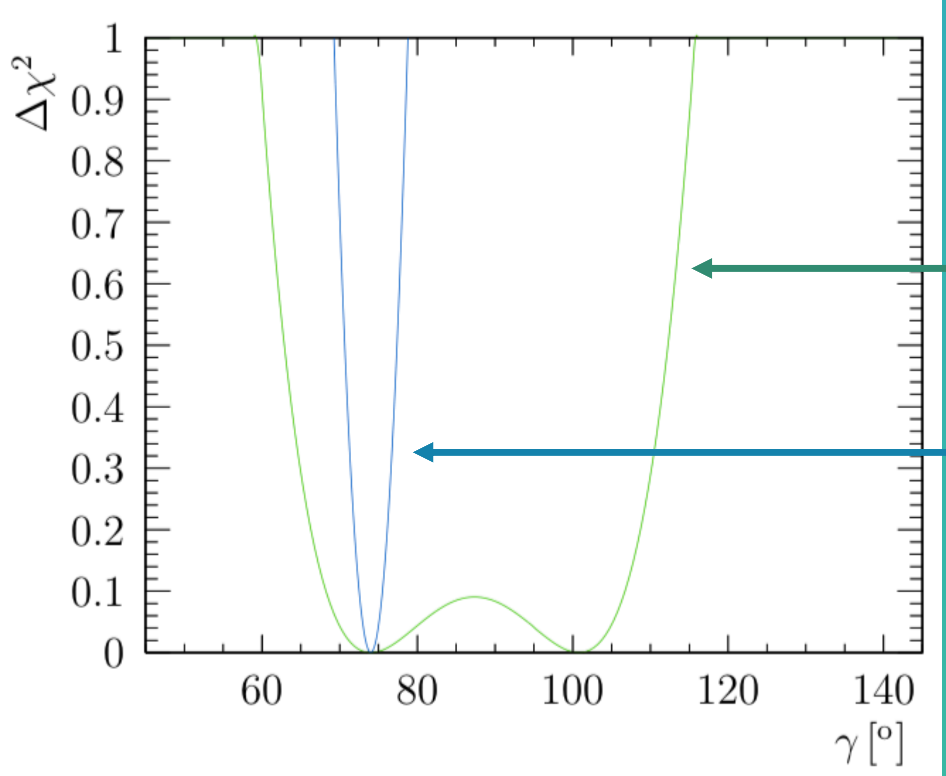
FITTED STRONG-PHASE PARAMETERS

Precision from CLEO





PLB, 802, 2020,135188

Exploiting $K^-\pi^+\pi^+\pi^-$ further

- Analysis of B→DK with inclusive D→ $K^-\pi^+\pi^+\pi^-$ provides limited sensitivity
- By targeting sensitive regions of phasespace it is possible to make a much more accurate measurement of γ using the same B data.
- Re-perform analysis in 4 regions of phase space
- Remove the region of D→$K_S K\pi$

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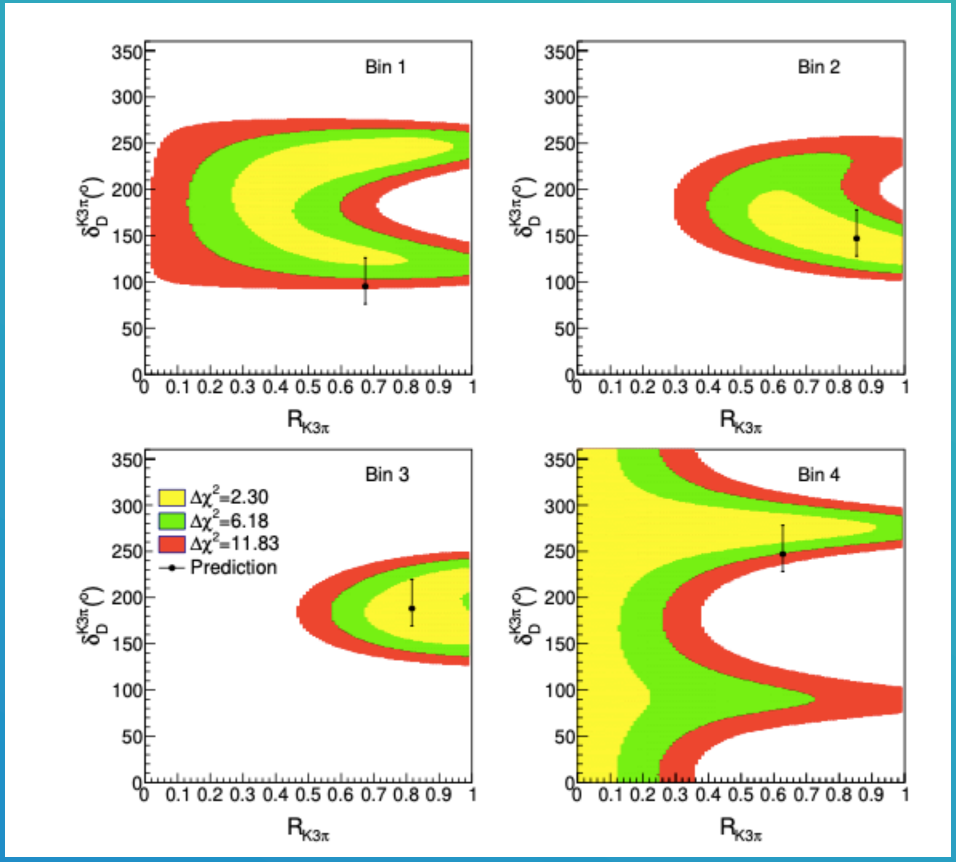
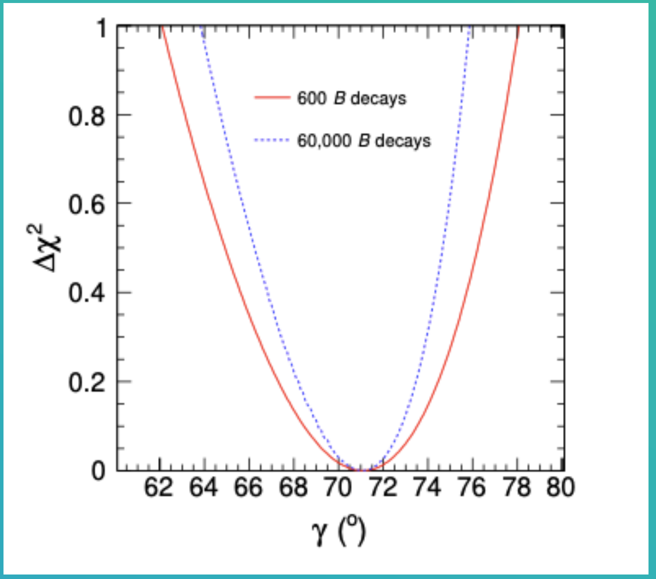
Binned results

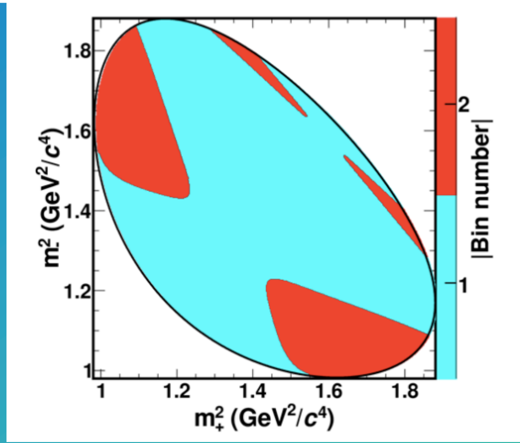


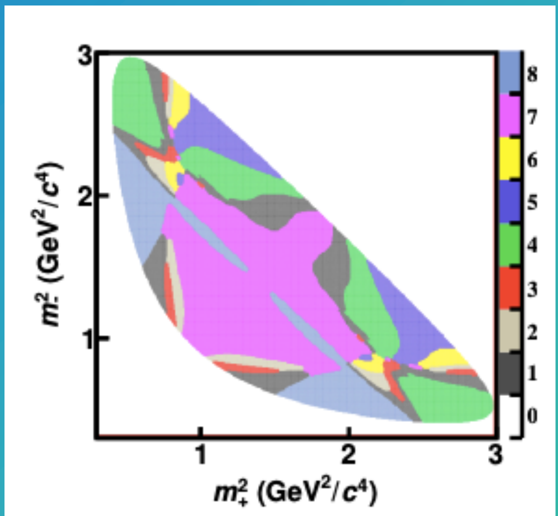


Expected sensitivity ~ $+7° \;\; -9°$

Look forward to their use at the B factories

BESIII related uncertainties dominant





Other strong-phase measurements

- For $D \to K_S\pi\pi$, and $D \to K_SKK$ binned measurements are appropriate
- Amplitude-averaged cosine (c_i) and sine (s_i) of the strong-phase difference in each region are measured
- One scheme is shown for each decay

RESULTS

PRL 124 241802 (2020)
PRD 101 112002 (2020)

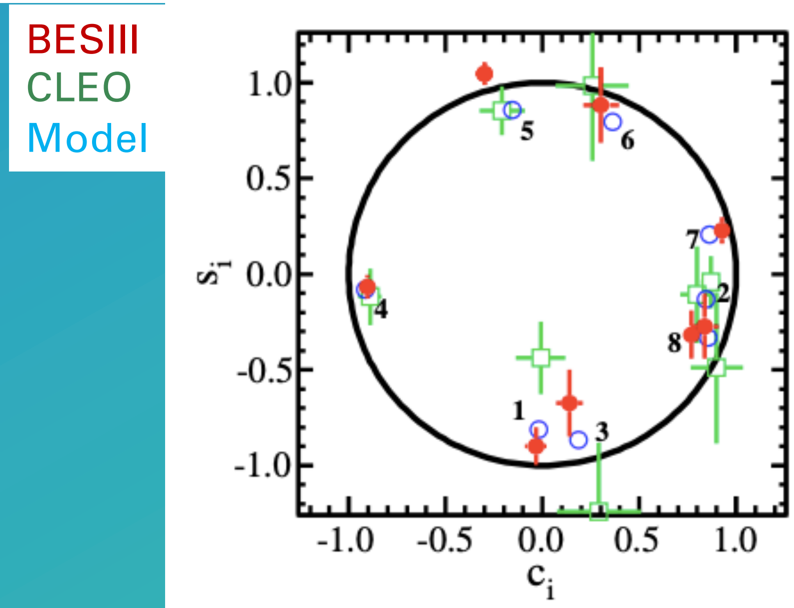
PRD 102 052008 (2020)

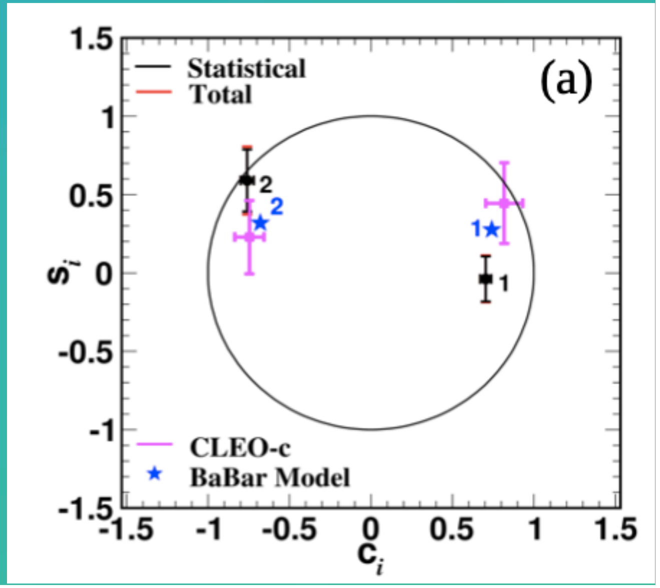
Large improvement over CLEO

- x3.5 more data
- Wider range of tags
- Pursuit of partial reconstruction e.g in $D \to K_S\pi\pi$ use $K_S \to \pi^0\pi^0$, where a π^0 is missed

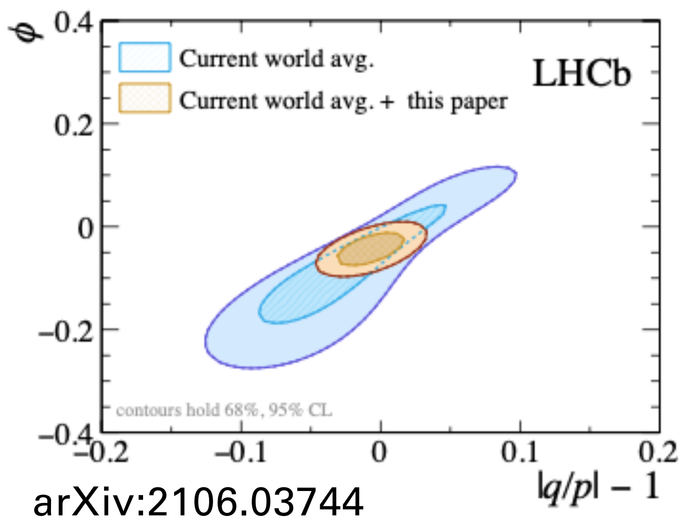
Models look consistent with the data

- With increased data these measurements are good ways to test amplitude models
- These measurements have already been used by LHCb to measure $\gamma = 68.7 \pm 5.2°$
- **Contribution of the BESIII uncertainty was less than 1°**





CPV in charm mixing



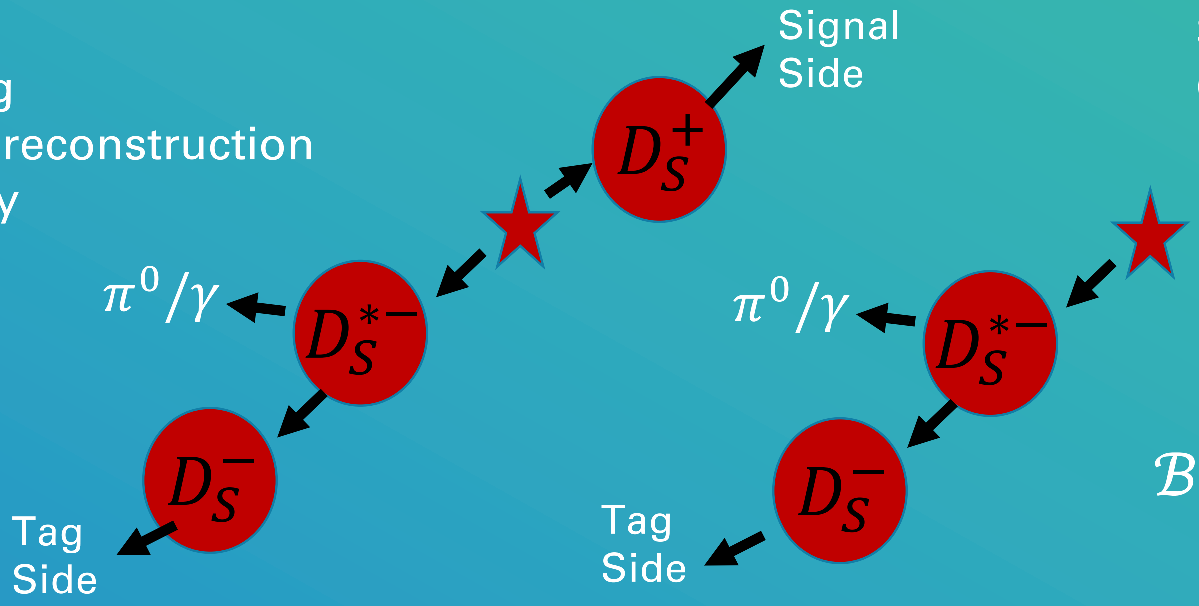
arXiv:2106.03744

- Yet to observe indirect CPV in the charm sector
- All the strong-phase measurements can be used as inputs to measurements of mixing and CPV in neutral D mesons.
- This week's result from LHCb another use $D \to K_S\pi\pi$ strong-phases from BESIII
- Places significant constraints on CPV
- BESIII input vital, but not a negligible systematic uncertainty contribution: Improved precision going forward is key

Phys. Rev. D99 (2019) 012007
Phys. Rev. D91 (2015) 094032
Phys. Lett. B 710 353 (2011)

Amplitude Analysis & Branching fractions

Double tag
Full event reconstruction
High purity



Single tag
Only tag side reconstruction

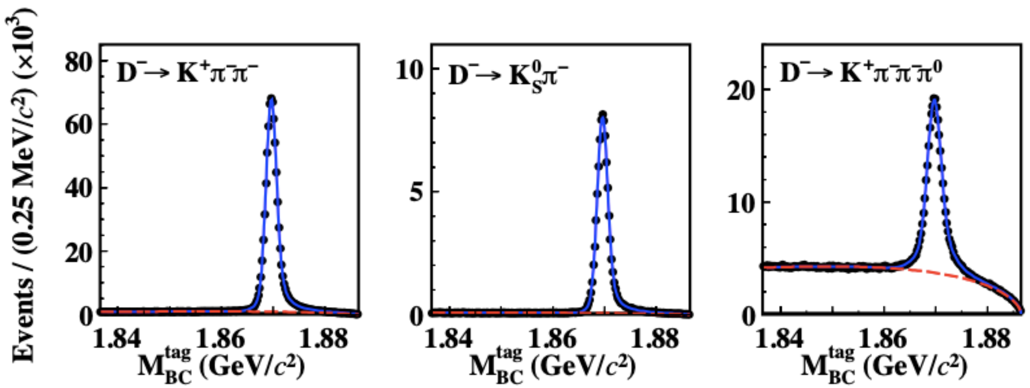
$$\mathcal{B}(D \to f) = \frac{N_{DT}\varepsilon_{ST}}{N_{ST}\varepsilon_{DT}}$$

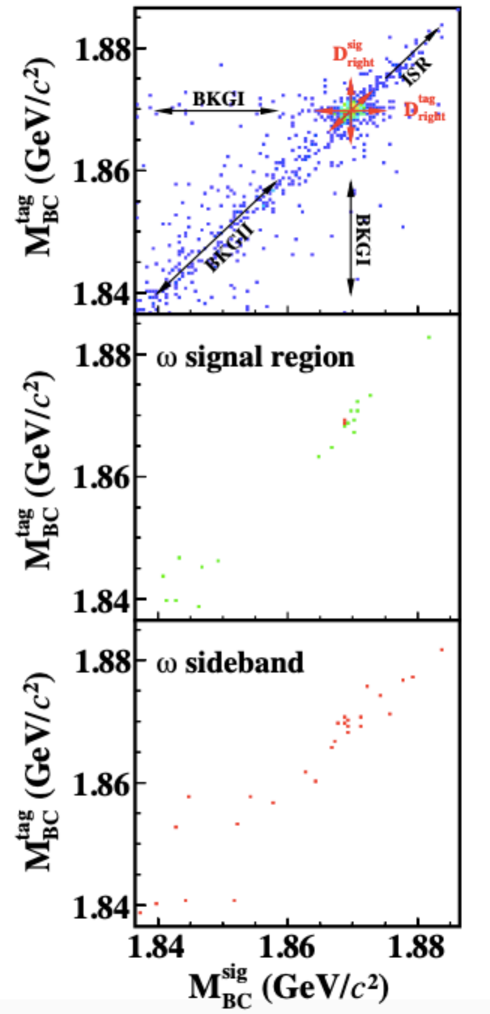
Meson Pair	$\sqrt{s}$ GeV	Int $\mathcal{L}$ fb^{-1}	CLEO-c
$D^0\overline{D^0}/D^+D^-$	3.773	2.93	x 3.5
$D_S D_S^*$	4.178	3.19	x 5.3
$D_S^* D_S^*$	4.189—4.226	3.13	-

Tag side reconstruction and branching fractions cancel.
Precision *absolute* BF measurement possible

PRL 125 141802 (2020)

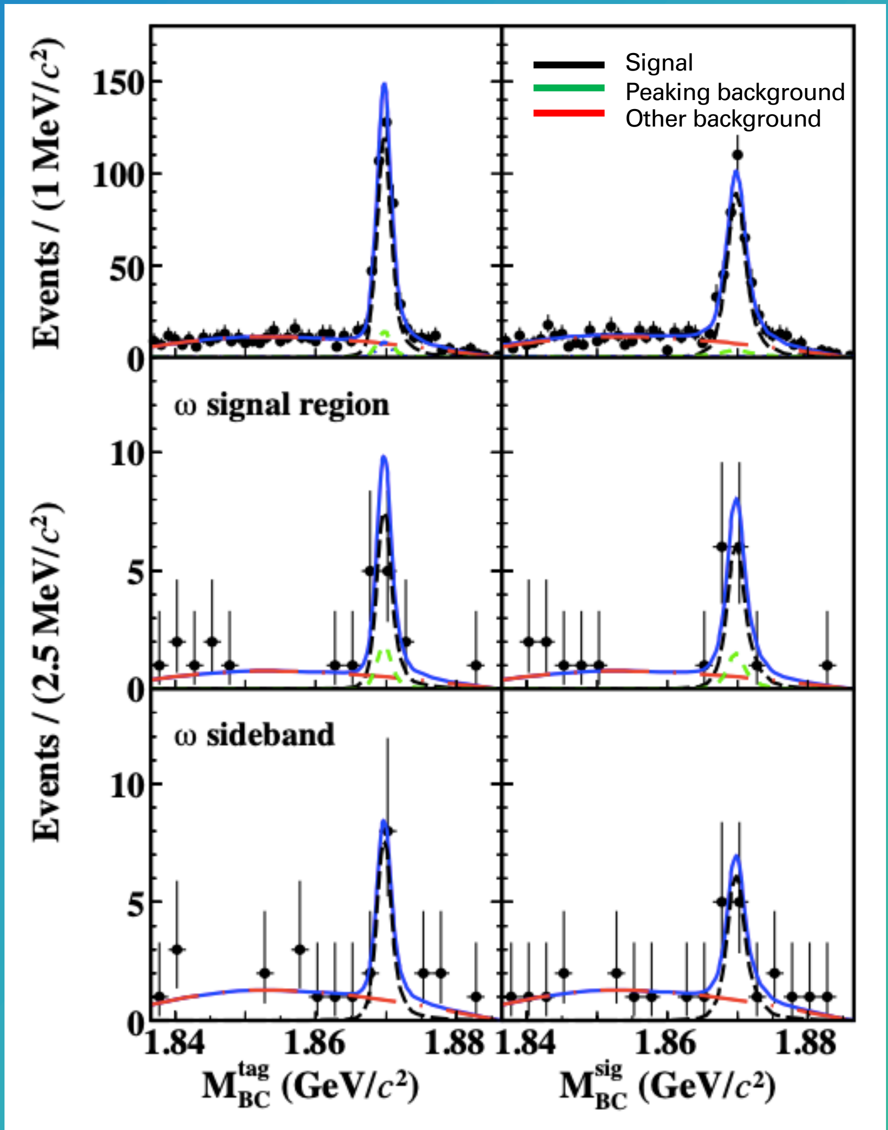
$D^+ \to K^+\pi^+\pi^-\pi^0$ (DCS decay) and evidence for $D^+ \to K^+\omega$





3 tags used to search for the signal decays

Double tags show clear observation of the DCS decay



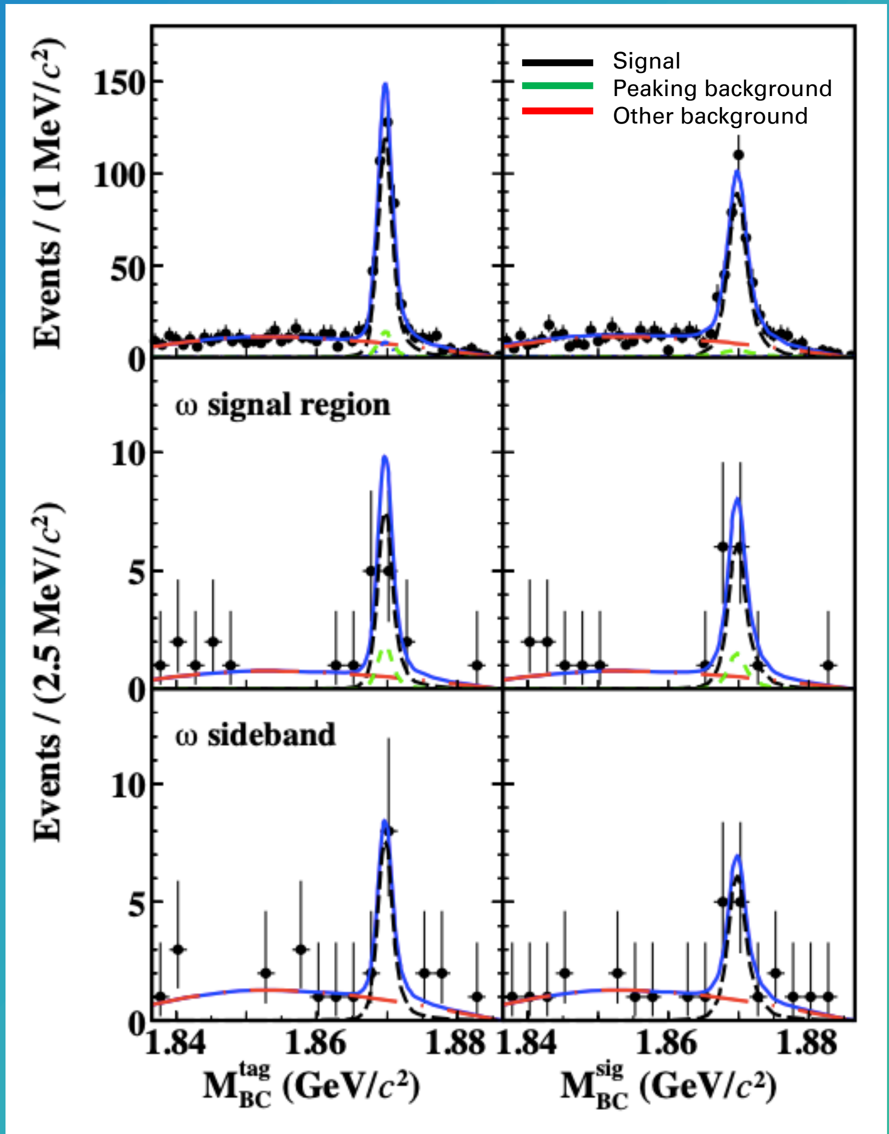
PRL 125 141802 (2020)

Results on DCS decay

- $\mathcal{B} = 1.21 \pm 0.08 \times 10^{-3}$
- Ratio of DCS/CF = 1.81 $\pm$ 0.15 %
- Significantly larger than other DCS/CF ratios (0.21-0.58)%
- Unexpected – suggests that perhaps there is large isopin symmetry violation in the DCS/CF decays caused by final state interactions or differing resonant structure
- Amplitude analysis of larger sample required to understand the origin of what is observed

PRL 125 141802 (2020)

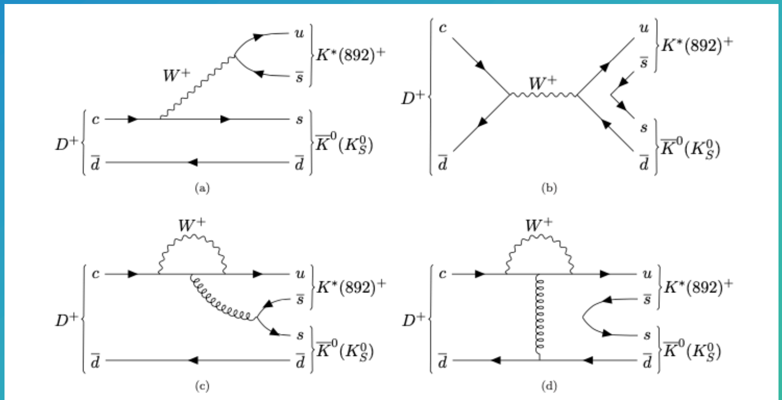
Results $D^+ \to K^+\omega$



- Evidence for $D^+ \to K^+\omega$ found.
- $\mathcal{B} = 5.7^{+2.5}_{-2.1} \pm 0.2 \times 10^{-5}$
- BF of D→VP decays can be calculated with the incorporation of quark SU(3)-flavour symmetry and symmetry breaking and CP violation.
- Results favours that of SU(3)-flavour symmetry and symmetry breaking

arXiv: 2104.09131

Study of $D^+ \to K^+ K_s \pi^0$



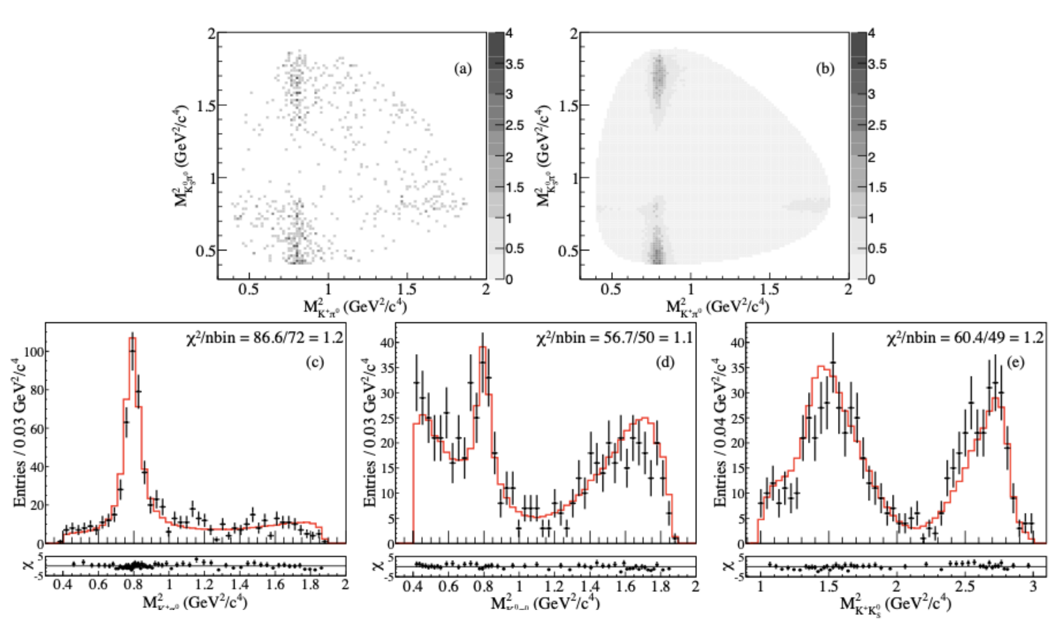
Model	$\mathcal{B}(D^+ \to K^*(892)^+ K_S^0)(\times 10^{-3})$
Pole	6.2 ± 1.2
FAT[mix]	5.5
TDA[tree]	5.02 ± 1.31
TDA[QCD-penguin]	4.90 ± 0.21
PDG	17 ± 8

- SCS decays are expected to exhibit larger CPV than CF, DCS decays
- Theoretical understanding of CPV in charm is limited by non-perturbative dynamics
- Understanding BF D→VP better will allow better tests of theoretical models
- $D^+ \to K^* K_S$ has a number of competing diagrams

arXiv: 2104.09131

Results from $D^+ \rightarrow K^+ K_s \pi^0$

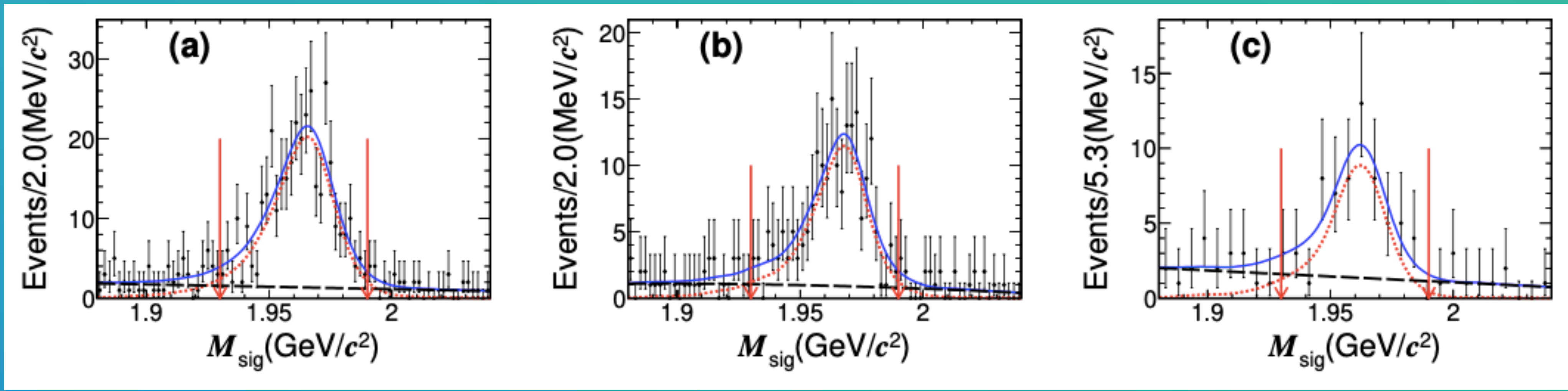
- 692 events selected >97% purity
- Substantial improvement on the BF of D→K*Ks
- These results can help constrain theoretical models and thus improve CP violation predictions



BF	This work	PDG
$\frac{\mathcal{B}(D^+\to K^*(892)^+(K^+\pi^0)K^0_S)}{\mathcal{B}(D^+\to K^+K^0_S\pi^0)}$	$(57.1 \pm 2.6_{\text{stat.}} \pm 4.2_{\text{syst.}})\%$	—
$\frac{\mathcal{B}(D^+\to \bar{K}^*(892)^0(K^0_S\pi^0)K^+)}{\mathcal{B}(D^+\to K^+K^0_S\pi^0)}$	$(10.2 \pm 1.5_{\text{stat.}} \pm 2.2_{\text{syst.}})\%$	—
$\mathcal{B}(D^+ \to K^*(892)^+ K^0_S)$	$(8.69 \pm 0.40_{\text{stat.}} \pm 0.64_{\text{syst.}} \pm 0.51_{\text{Br.}}) \times 10^{-3}$	$(17 \pm 8) \times 10^{-3}$
$\mathcal{B}(D^+ \to \bar{K}^*(892)^0 K^+)$	$(3.10 \pm 0.46_{\text{stat.}} \pm 0.68_{\text{syst.}} \pm 0.18_{\text{Br.}}) \times 10^{-3}$	$(3.74^{+0.12}_{-0.20}) \times 10^{-3}$

arXiv: 2103.15098

Analysis of $D_s \to K_s\pi^+\pi^0$



4.178 GeV

4.189—4.219 GeV

4.226 GeV

9 tag modes used and full use of available data

609 signal events in total

Another SCS decay with a relatively large BF often used as normalization

arXiv: 2103.15098

$D_s \to K_S\pi^+\pi^0$

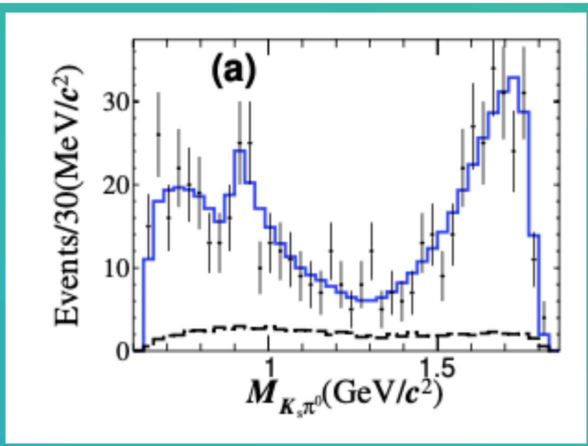
$\mathcal{B}(D_s \to K_S\pi^+\pi^0) = (5.43 \pm 0.30 \pm 0.15)\times 10^{-3}$

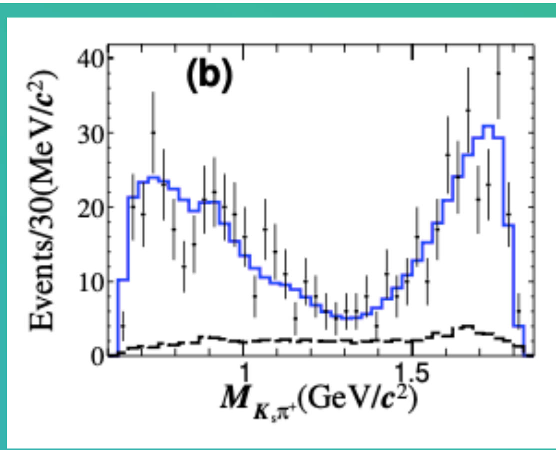
Precision improved by factor 3

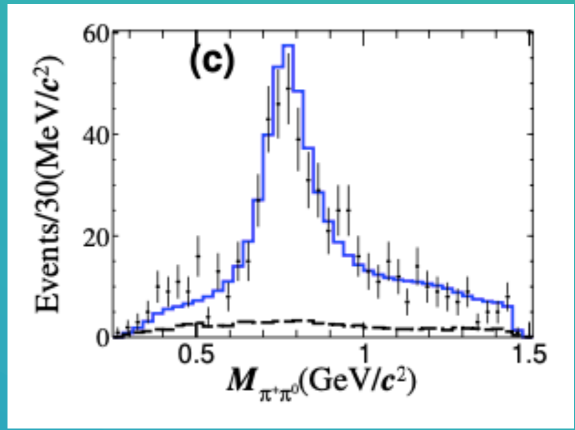
Further BF determined using the amplitude analysis

Valuable to understand the theoretical models behind these hadronic decays, further precision required

Intermediate process	BF (10^{-3})
$D_s^+ \to K_S^0\rho^+$	$2.73 \pm 0.42 \pm 0.22$
$D_s^+ \to K_S^0\rho(1450)^+$	$1.11 \pm 0.24 \pm 0.24$
$D_s^+ \to K^*(892)^0\pi^+$	$0.45 \pm 0.12 \pm 0.05$
$D_s^+ \to K^*(892)^+\pi^0$	$0.25 \pm 0.08 \pm 0.02$
$D_s^+ \to K^*(1410)^0\pi^+$	$0.18 \pm 0.09 \pm 0.03$







Measure CP asymmetry $A_{CP} = (2.7 \pm 5.5 \pm 0.9)\%$

No evidence.

See also Tuesday 12.15 Dai Xinchen

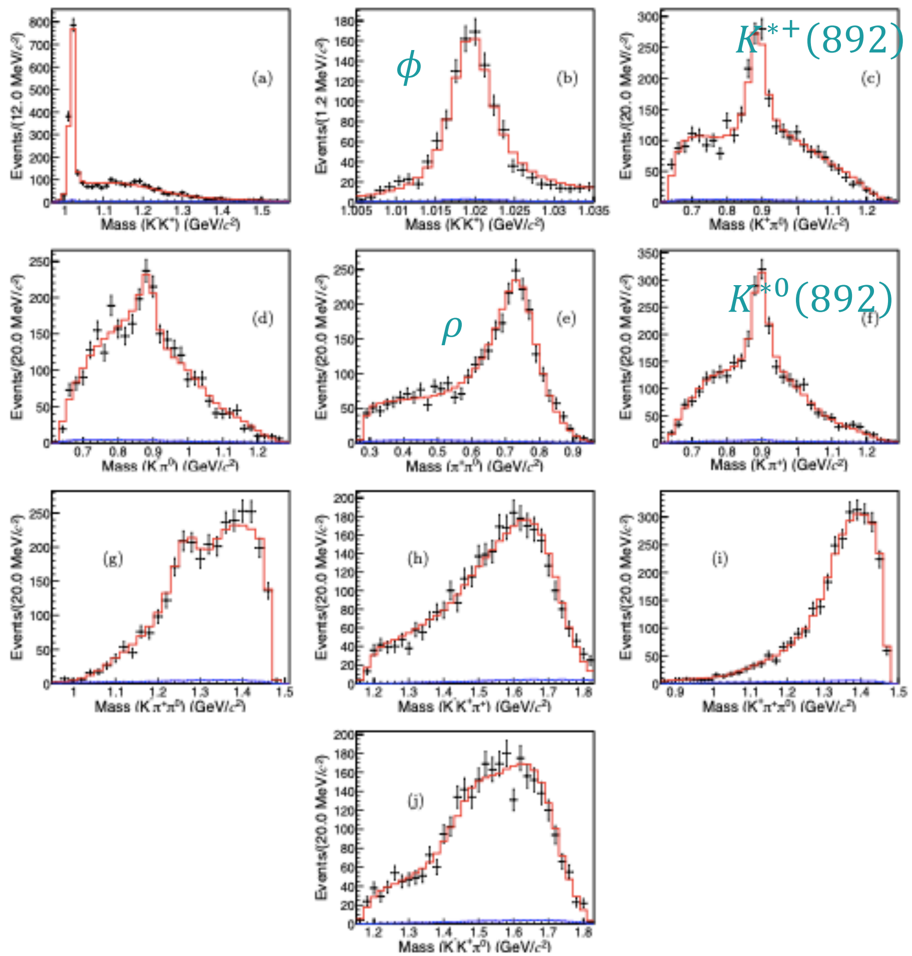
$D_S^+ \to K^-K^+\pi^+\pi^0$ amplitude analysis & BF

arXiv: 2103.02482

- CF decay, large BF (5.42± 0.10± 0.17)%
- Phasespace is 5-D
- Decay dominated by D→VV decay
  - $D_S^+ \to \phi\rho$ BF(3.06 ± 0.08 ± 0.12) %
  - $D_S^+ \to K^*K^*$BF (1.21 ± 0.05 ± 0.04)%
  - Significant improvements on the PDG
- Study D→AP decays

$$R_{K_1(1270)} \equiv \frac{Br(K_1(1270) \to K^*\pi)}{Br(K_1(1270) \to K\rho)} = 0.51 \pm 0.12_{stat.} \pm 0.09_{syst.}$$

- Across many experiments this ratio is observed to vary – limits of narrow width approximation?



See also Tuesday 12.15 Dai Xinchen

Summary

Comprehensive programme of strong-phase measurements underway at BESIII

Data expected to increase by x5 in the near future

Critical inputs for CPV measurements in the precision era

Plenty to explore in hadronic charm decays via amplitude analyses and BF measurements

Greater than 4 GeV dataset also set to increase

Very exciting prospects for the future