Open-charm inputs to B physics and CKM tests

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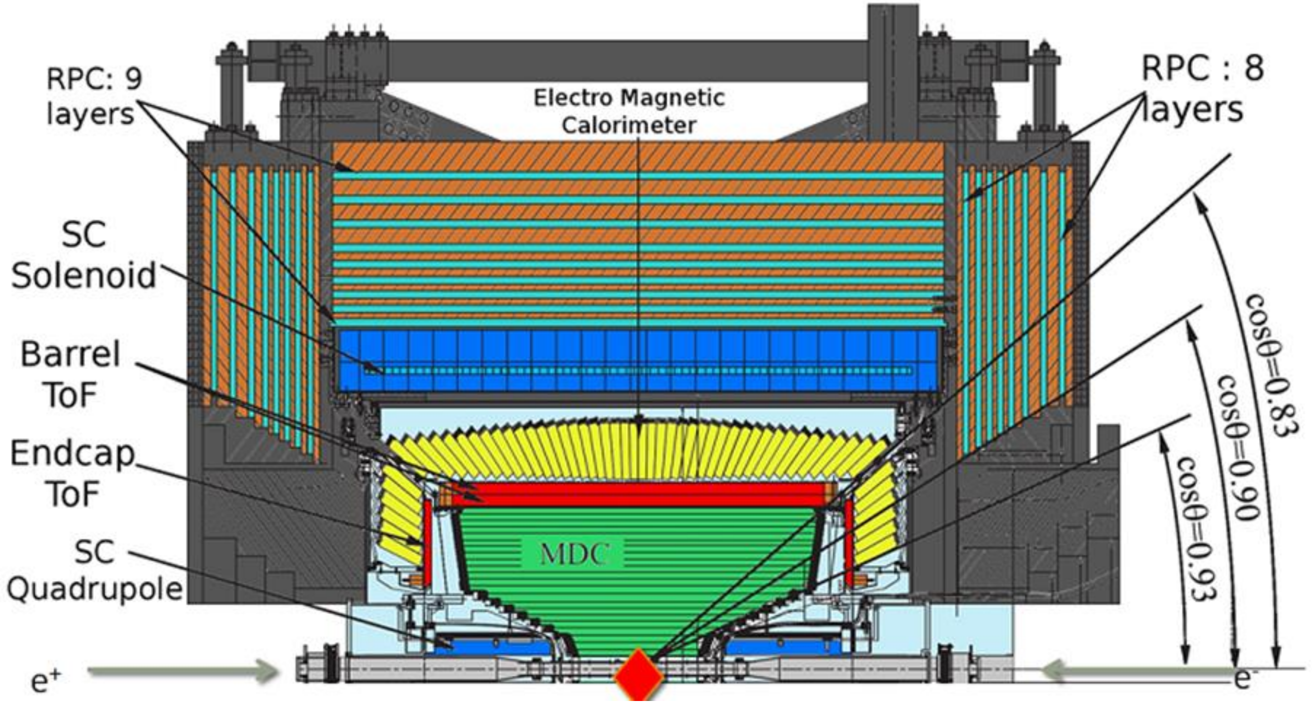
Outline

- Open charm and CKM
  - QCD
  - CKM and lepton universality
- Data sets and double tag
- Recent results
  - $D \to \tau\nu$
  - DCS decay
  - strong phases in $D \to Khh$
- Conclusions and outlook

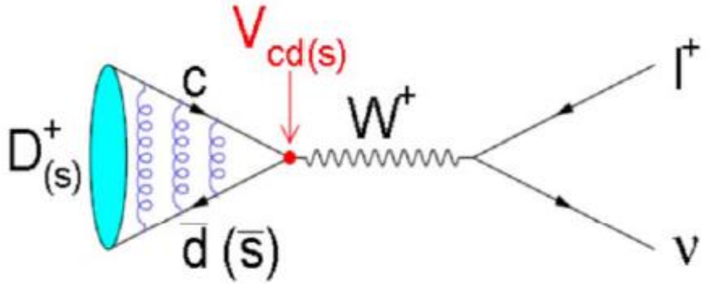
e^+e^- collisions at BEPCII between $\sqrt{s} = 2.0 - 4.7$ GeV

BESIII detector - NIM A **614**, 345 (2010)

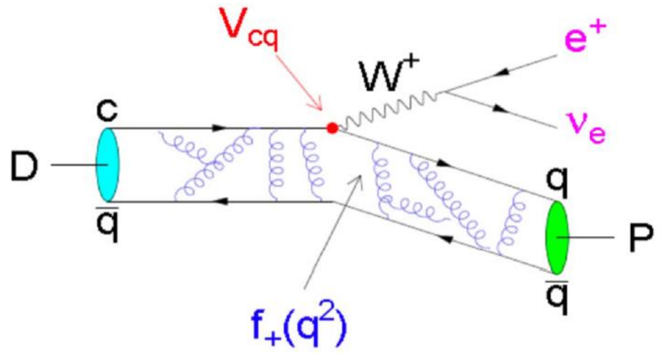


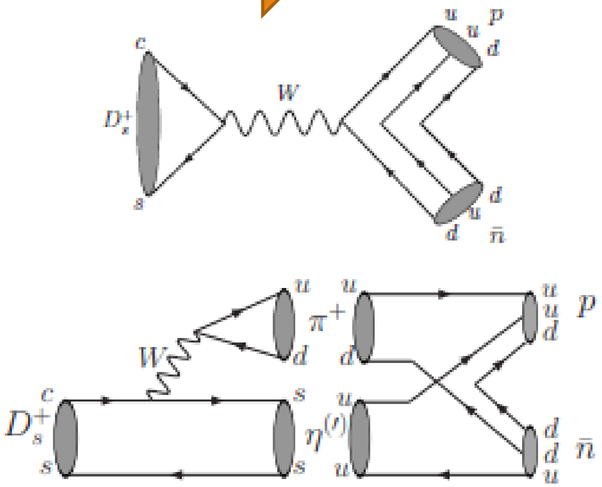
Why D meson decay? QCD

COMPLEXITY



$$\Gamma(D^+_{(s)} \to \ell^+ \nu_\ell) = \frac{G_F^2 f_{D^+_{(s)}}^2}{8\pi} |V_{cd(s)}|^2 m_\ell^2 m_{D^+_{(s)}} \left(1 - \frac{m_\ell^2}{m_{D^+_{(s)}}^2}\right)^2$$





Take V_{cx} from fits to CKM assuming unitarity and measure f

Precise test of lattice QCD in charm and extrapolate to beauty

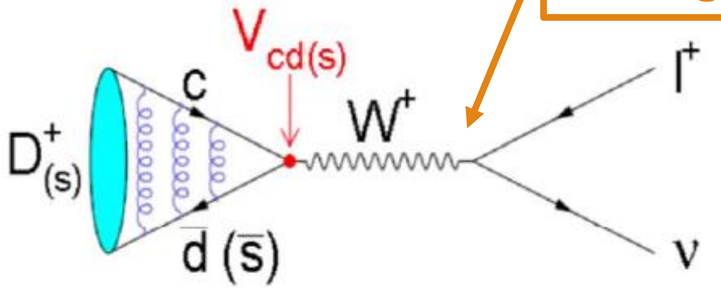
Similar to leptonic decay but now q (= four-momentum of W) dependent

Test QCD models of the form factor

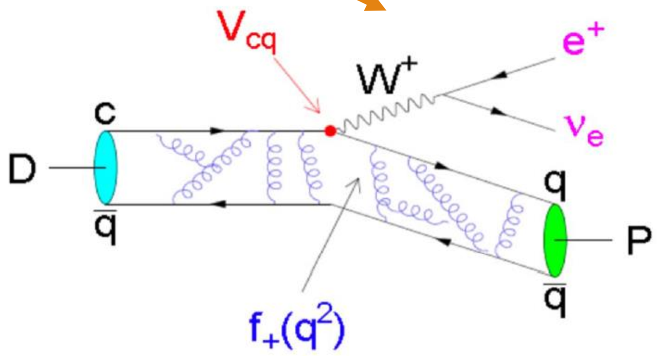
Models of hadronic decay
- Isospin
- SU(3) flavour
- Different amplitudes T, P, A, E
- Long and short distance effects

Why D meson decay? CKM and LUV

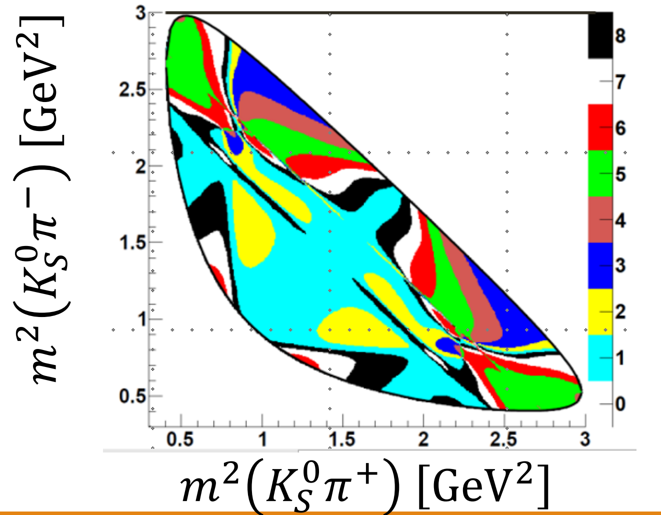
LUV tests in 2^{nd} generation



$$\Gamma(D^+_{(s)} \to \ell^+\nu_\ell) = \frac{G_F^2 f^2_{D^+_{(s)}}}{8\pi}|V_{cd(s)}|^2 m_\ell^2 m_{D^+_{(s)}}\left(1-\frac{m_\ell^2}{m^2_{D^+_{(s)}}}\right)^2$$



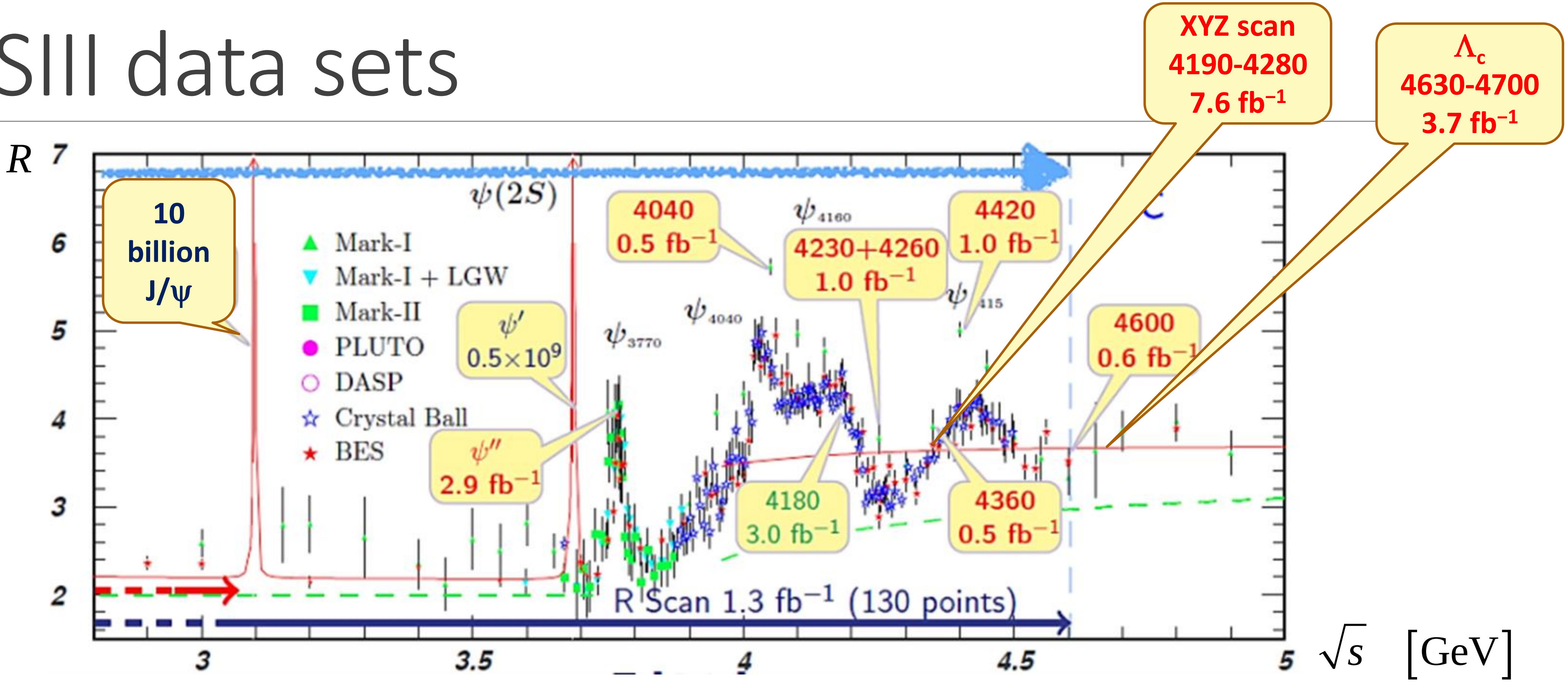
$D^0 \to K_S^0\pi^+\pi^-$ Dalitz binning



FLIP IT!
Take decay constant and form-factor predictions from QCD
Measurements of V_{cx} to test the unitarity of the CKM picture

Model-independent determinations of γ and charm mixing/direct CPV requires strong phase measured with quantum correlated $\psi(3770) \to D^0\bar{D}^0$

BESIII data sets



$\sqrt{s}$ (GeV)	Dominant processes of interest	Integrated luminosity (fb^{-1})	× CLEO-c
3.773	$e^+e^- \to \psi(3770) \to D^0\bar{D}^0/D^+D^-$	2.93	3.6
4.178	$e^+e^- \to D_s^+D_s^{*-}, D_s^{*-} \to D_s^-\gamma$	3.19	5.3

The "single vs. double-tag" techniques

- Threshold production means that **no other** particles are produced along with the *DD* or *DD** pair
- Full event reconstruction "double tag" possible

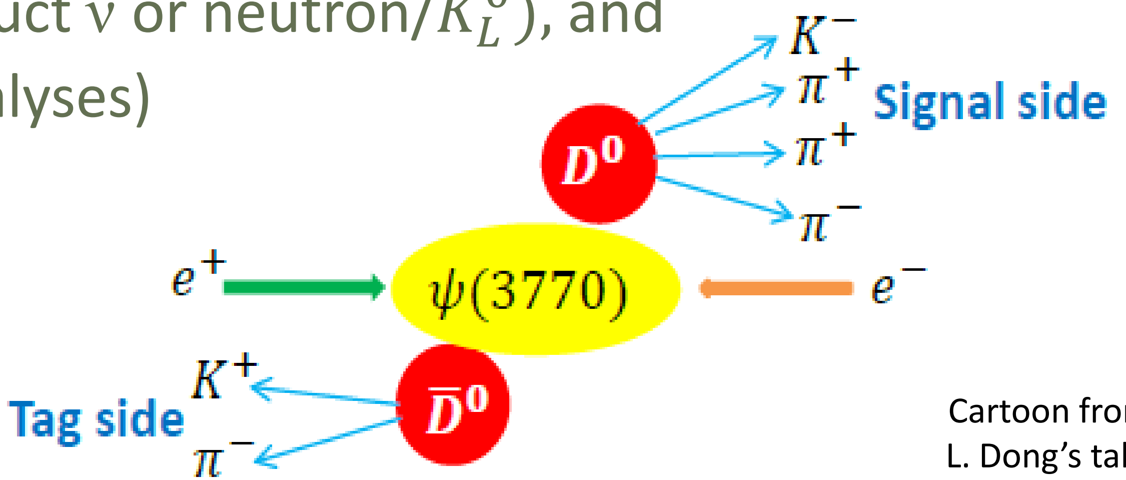
✓ Advantages

1. absolute branching fractions
2. full kinematic constraint to reconstruct ν or neutron/K_L^0), and
3. low backgrounds (i.e. amplitude analyses)

✘ Disadvantage

reduced reconstruction efficiency

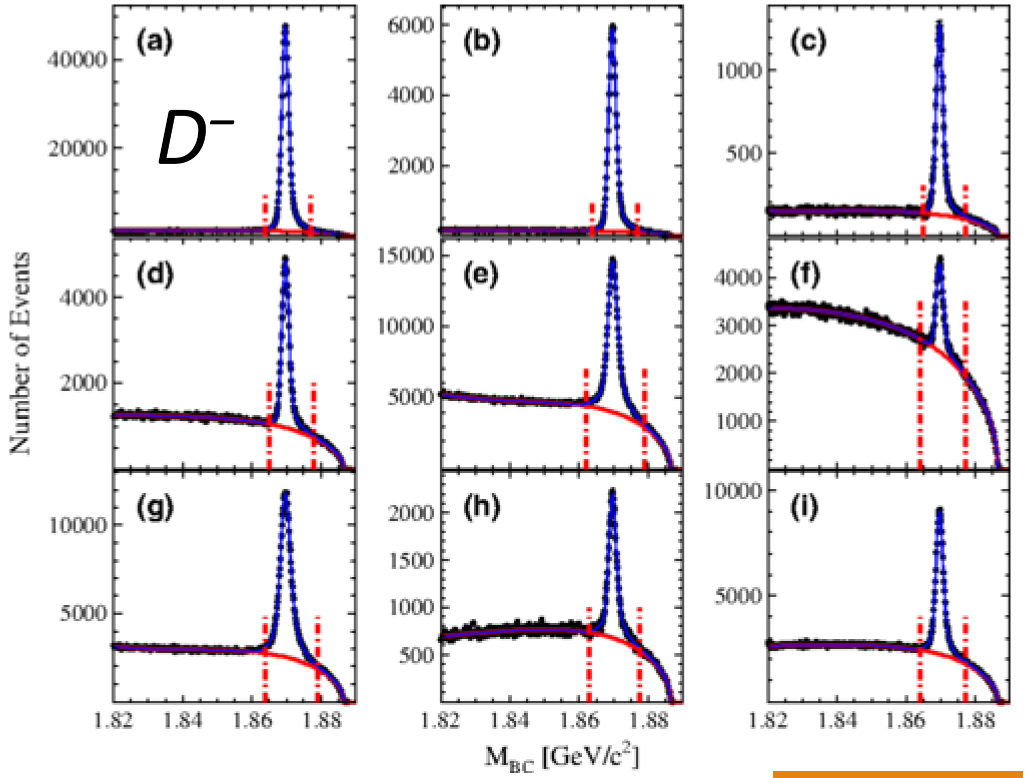
but still O(10%) c.f. FEI at Belle II



Cartoon from L. Dong's talk at ICHEP

Single tag samples

$$M_{\mathrm{BC}} = \sqrt{E_{\mathrm{beam}}^{2} - \left|\vec{\mathbf{p}}_{D}\right|^{2}}$$



$(a)\ K^+\pi^-\pi^-$

$(b)\ K_S^0\pi^-$

$(c)\ K_S^0K^-$

$(d)\ K^+K^-\pi^-$

$(e)\ K^+\pi^-\pi^-\pi^0$

$(f)\ \pi^+\pi^-\pi^-$

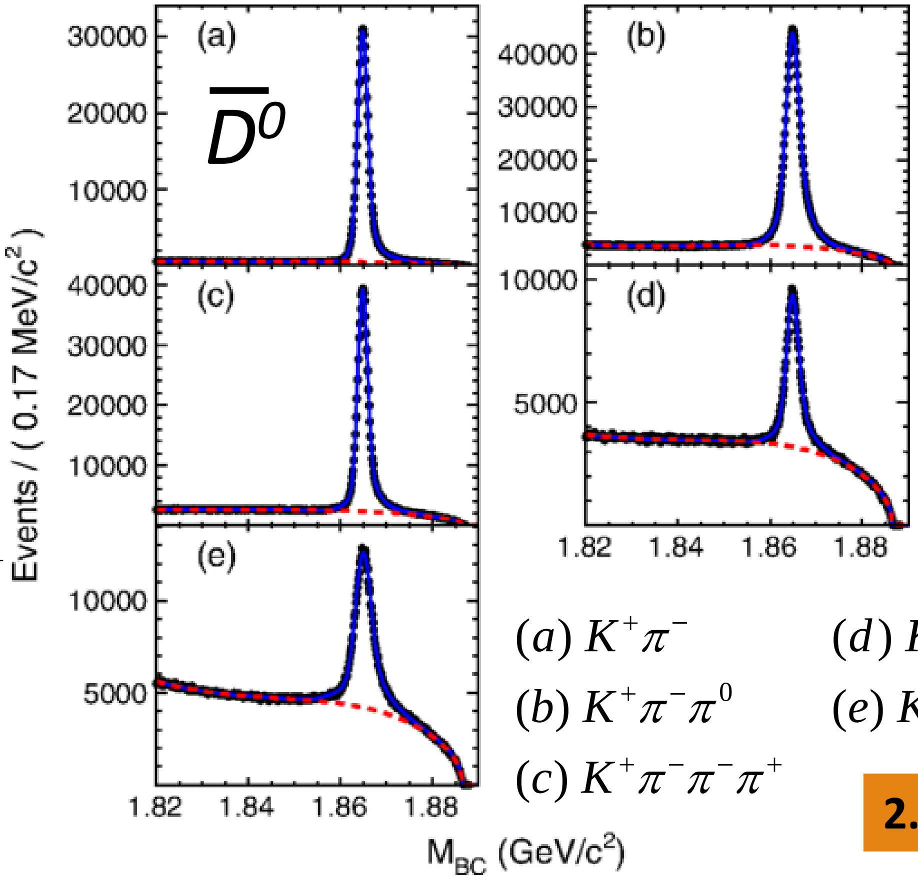
$(g)\ K_S^0\pi^-\pi^0$

$(h)\ K^+\pi^-\pi^-\pi^+$

$(i)\ K_S^0\pi^-\pi^+\pi^-$

1.7 million

Phys. Rev. D **89**, 051104(R) (2014)



$(a)\ K^+\pi^-$

$(b)\ K^+\pi^-\pi^0$

$(c)\ K^+\pi^-\pi^-\pi^+$

$(d)\ K^+\pi^-\pi^-\pi^+\pi^0$

$(e)\ K^+\pi^-\pi^0\pi^0$

2.8 million

Phys. Rev. D **92**, 072012 (2015)

$D^+ \to \tau^+ \nu$

PRL **123**, 211802 (2019)

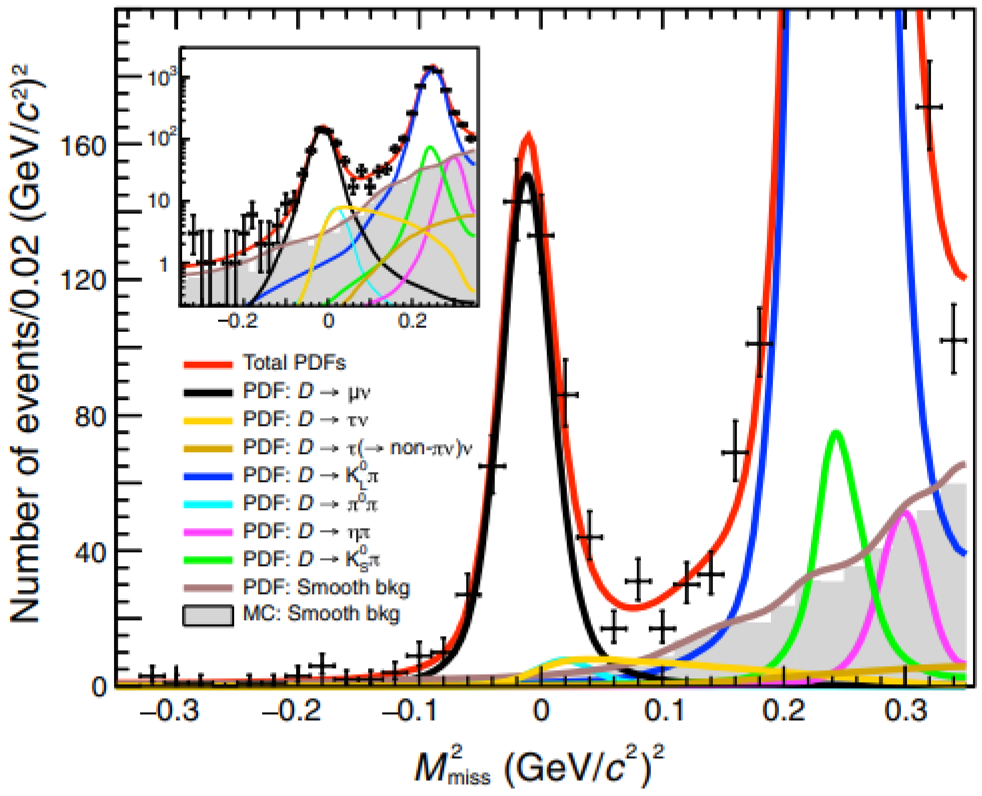
Leptonic measurements: $D^+ \to \tau^+(\to \pi^+\bar{\nu})\nu$

- 6 tag-modes and single track on signal side
- Use missing mass

$$M^2_{\mathrm{miss}} = (E_{\mathrm{beam}} - E_{\mu^+})^2 - (-\vec{p}_{D^-_{\mathrm{tag}}} - \vec{p}_\mu)^2$$

- $\pi\!-\!\mu$ separation with EMC

Muon-like in EMC



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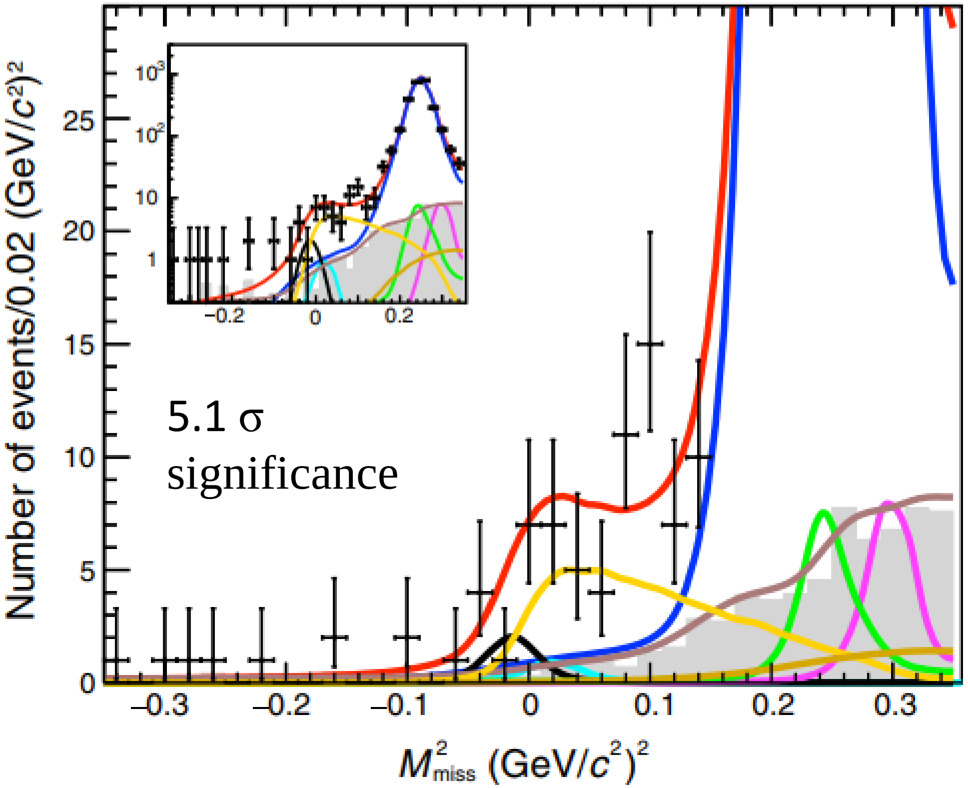
- π−μ separation with EMC

$$\mathcal{B}(D^+ \to \tau^+\nu_\tau) = \frac{N_{\rm DT}}{\mathcal{B}(\tau^+ \to \pi^+\bar{\nu}_\tau)\cdot \sum_i N^i_{\rm tag}\cdot(\epsilon^i_{\rm DT}/\epsilon^i_{\rm tag})}$$

$$= (1.20 \pm 0.24[\text{stat.}] \pm 0.12[\text{syst.}]) \times 10^{-3}$$

dominated by D→μν BF and bkg. parametrization

Pion-like in EMC



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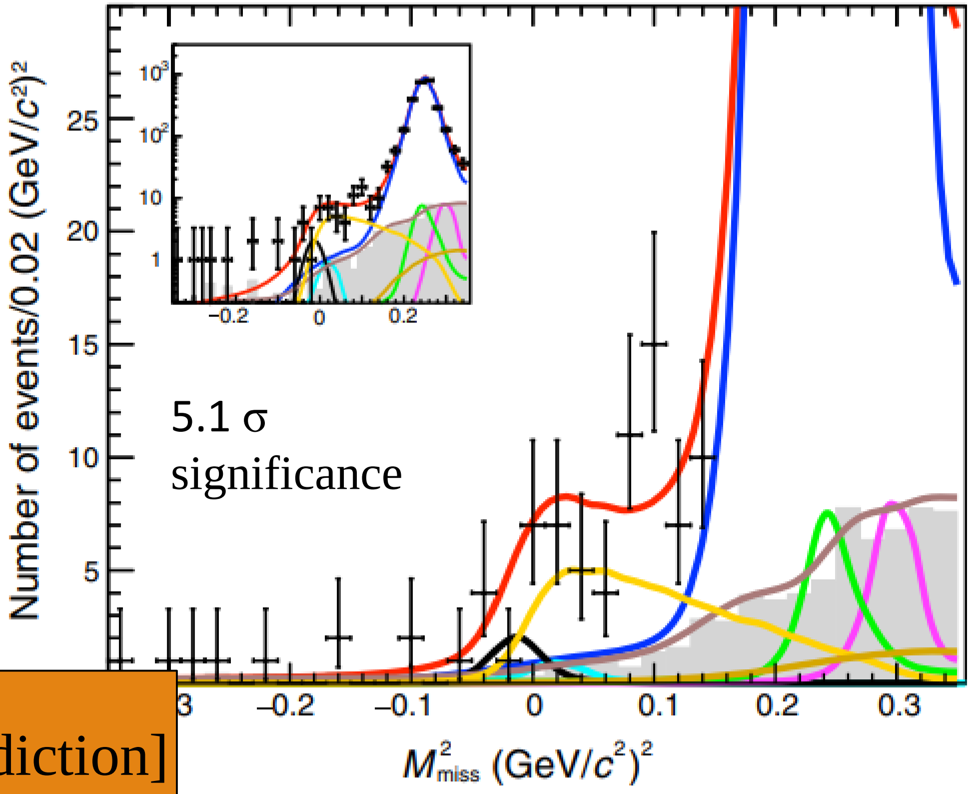
$$R = \frac{\Gamma(D^+ \to \tau^+\nu)}{\Gamma(D^+ \to \mu^+\nu)} = 3.21 \pm 0.64 \pm 0.43 \quad [2.67 \text{ SM prediction}]$$

Pion-like in EMC



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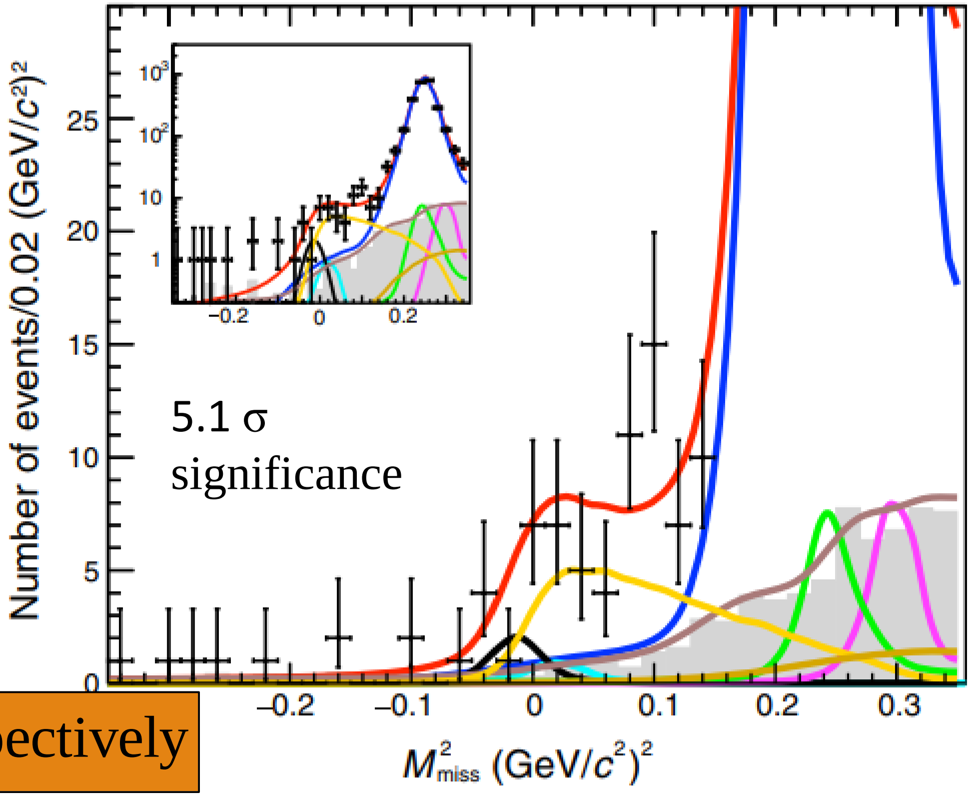
Pion-like in EMC



f_{D^+} and $|V_{cd}|$ reported - agree with LQCD and WA, respectively

Aside: DCS decay $D^+ \to K^+\pi^+\pi^-\pi^0$

Motivation and strategy

Test the naïve prediction that DCS decay should be suppressed by a factor $\tan^4\theta_C \sim 2.9\times10^{-3}$ with respect to CF decay

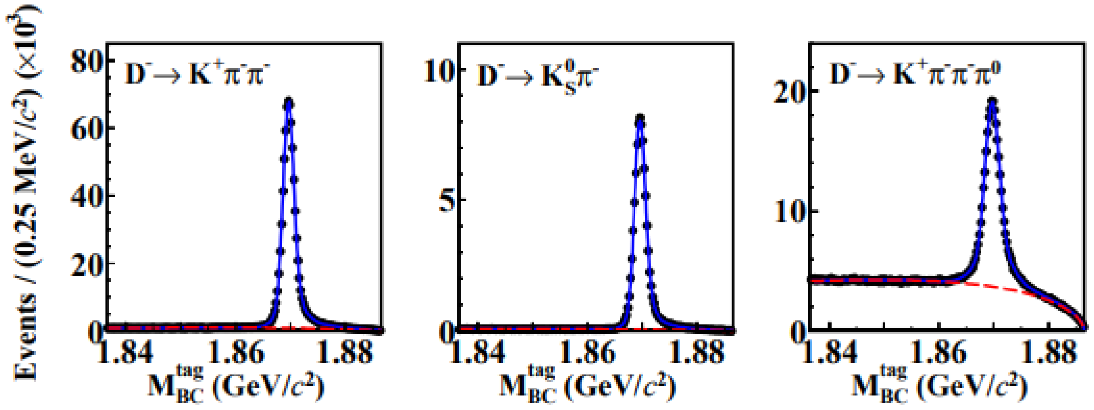
Not so many measured – clean double-tag sample at BESIII allows previously unobserved decays to be searched for particularly multi-body decay including $D^+ \to K^+\pi^+\pi^-\pi^0$ and $K^+\omega$

In addition *D→PV SU(3)* test

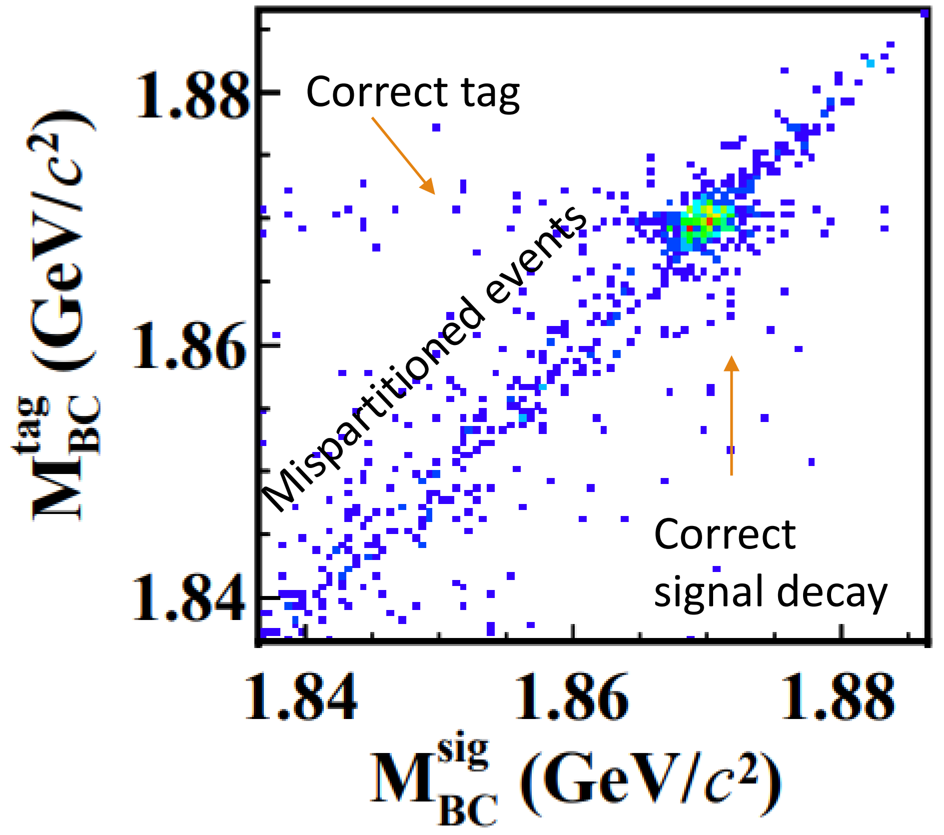
Three high purity D^- tags inc. CF partner

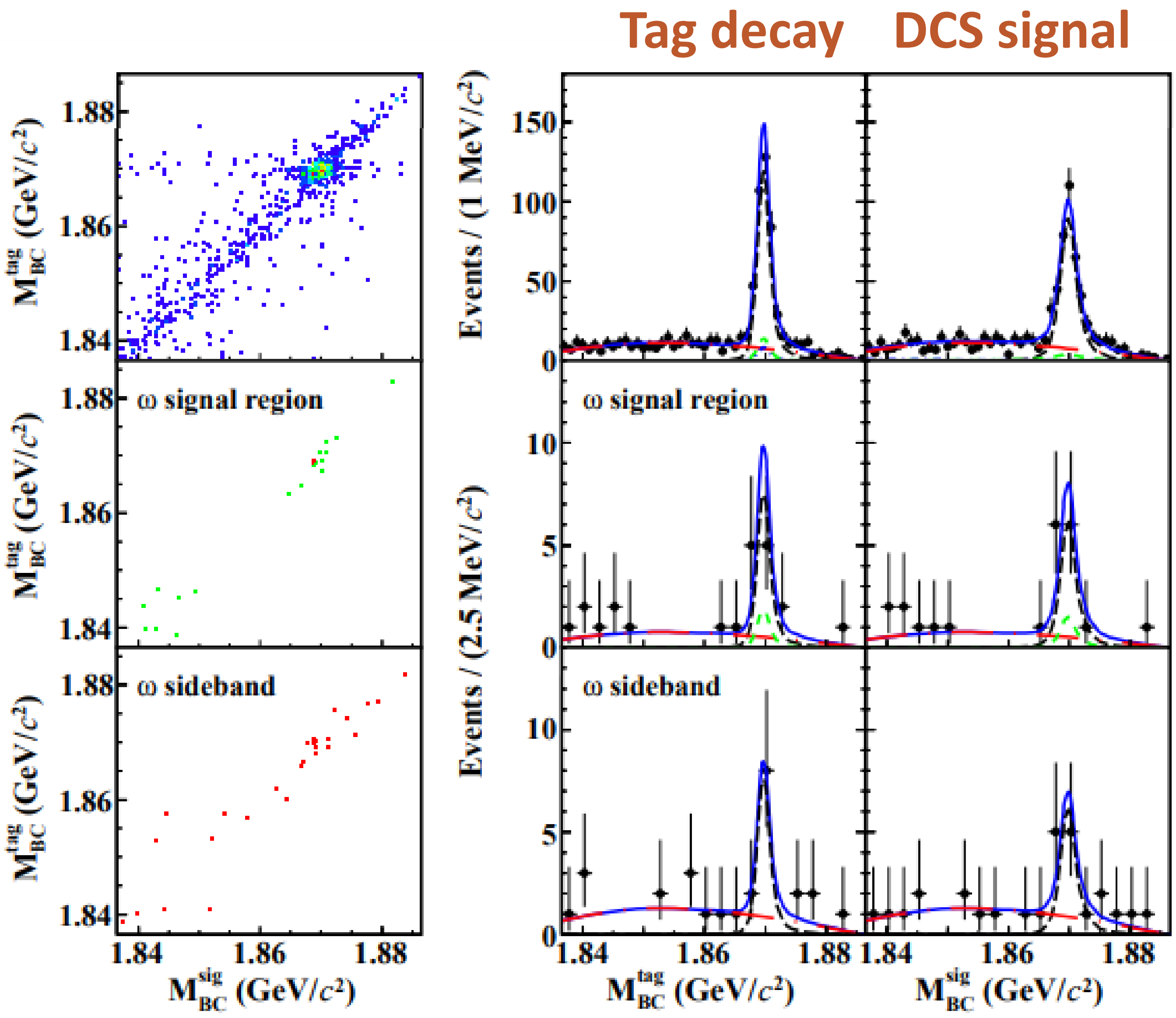
1.15 million single tags

Then 2D fit to M_{BC} – signal vs. tag D



Signal extraction





Results

arXiv: 2007.07674 [hep-ex] accepted by PRL

$$B\left(D^{+} \to K^{+}\omega\right) = \left(5.7^{+2.5}_{-2.1} \pm 0.2\right) \times 10^{-5}$$

First observation with 3.3 σ significance – no CF analogue – agrees with SU(3) predictions that incorporate symmetry breaking - Q. Qin et al. Phys. Rev. D **89**, 054006 (2014)

$$B\left(D^{+} \to K^{+}\pi^{+}\pi^{-}\pi^{0}\right) = \left(1.13 \pm 0.08 \pm 0.03\right) \times 10^{-3}$$

$$= (6.28 \pm 0.52) \times \tan^{4}\theta_{C} \times B\left(D^{+} \to K^{-}\pi^{+}\pi^{+}\pi^{0}\right)$$

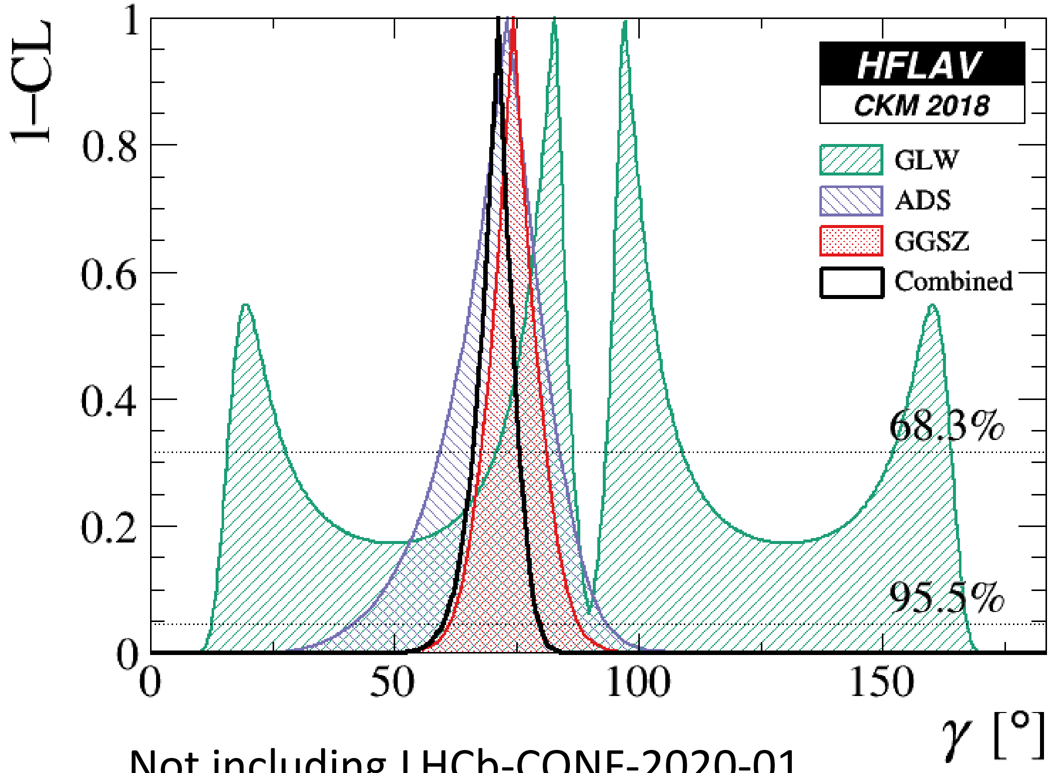
Big isospin violating effect i.e. not seen in $D^{0} \to K^{+}\pi^{+}\pi^{-}\pi^{-}$

Maybe FSI?

Only way to learn more is more data and amplitude analysis

Quantum correlated decays

Quantum correlated decay: Why γ?



Not including LHCb-CONF-2020-01

CKMfitter 2019

$$\gamma_{\text{measured}} = \left(72.1^{+5.4}_{-5.7}\right)^{\circ}$$

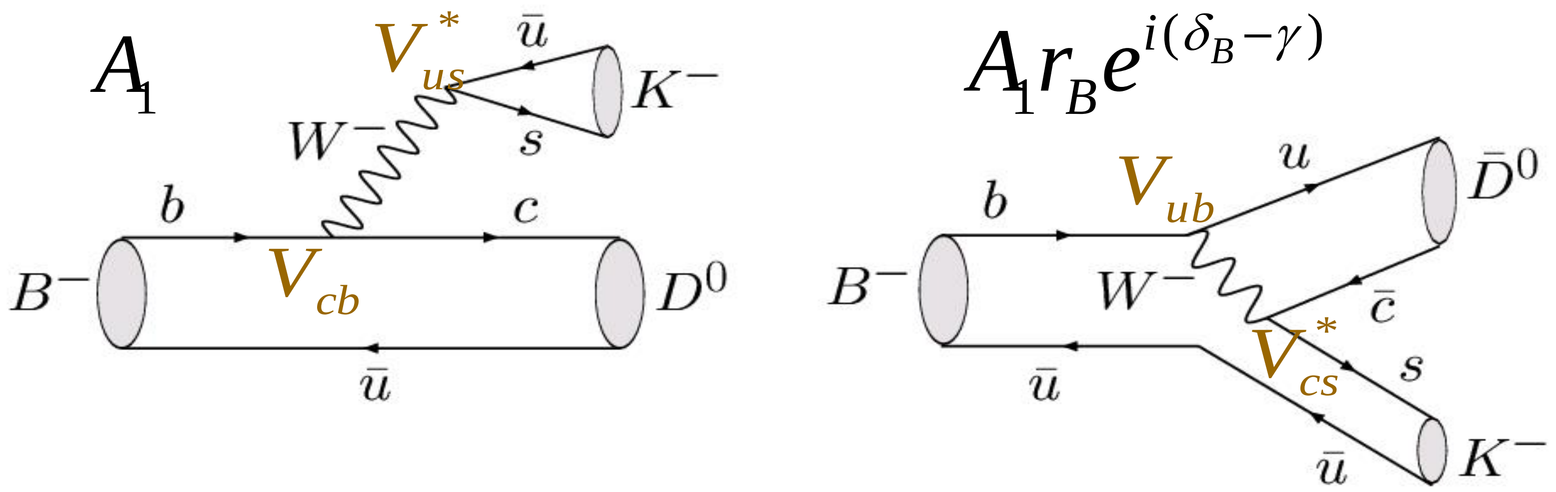
$$\gamma_{\text{predicted}} = \left(65.66^{+0.90}_{-2.65}\right)^{\circ}$$

$$\beta_{\text{measured}} = \left(22.14^{+0.69}_{-0.67}\right)^{\circ}$$

NP could lead to 4^{o} effects
e.g. PRD 92, 033002 (2015)

Principal experimental goal in CKM physics in the next decade is to reduce uncertainty to 1^{o}

Measuring γ: $B \to DK$



Same final state for D and $\overline{D} \Rightarrow$ interference $\Rightarrow$ **the possibility of DCPV**

Different types of D final states generally used

1. **Self-conjugate multibody states: $K_S h^+ h^-$ [Dalitz/BPGGSZ]**
   Giri, Grossman, Soffer and Zupan, PRD **68**, 054018 (2003); Bondar (unpublished)
2. **CP-eigenstates [GLW]**
   Gronau & London, PLB **253**, 483 (1991), Gronau, & Wyler, PLB **265**, 172 (1991)
3. **K^+X^- ($X^-=\pi^-$, $\pi^- \pi^0$, $\pi^-\pi^- \pi^+$) - CF and DCS [ADS]**
   Atwood, Dunietz & Soni, PRD **63**, 036005 (2001)

Many modes required to get good precision because of the small branching fractions involved but need to know the D dynamics too

Dalitz model-independent method

Binned fit proposed by Giri *et al.* [PRD 68 (2003) 054018] and developed by Bondar & Poluektov [EPJ C 55 (2008) 51; EPJ C47 (2006) 347] removes model dependence by relating events in bin i of Dalitz plot to *experimental observables.*

$B^{\pm}$ events in bin i of Dalitz plot

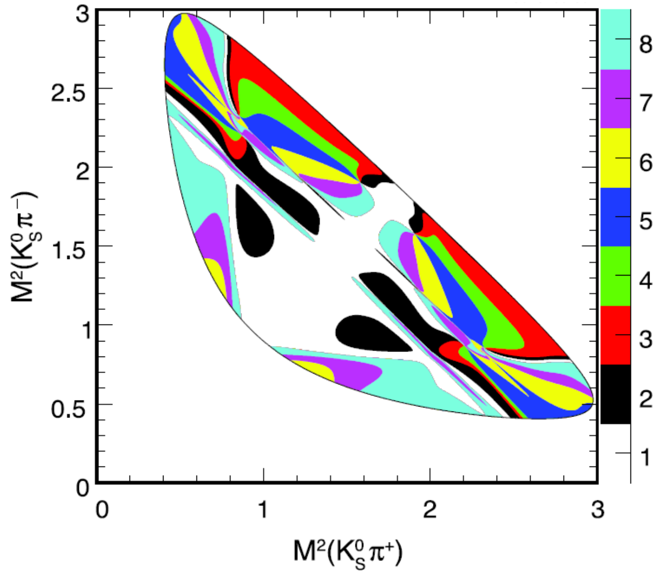
Number of events for flavour-tagged D sample

$x_{\pm} = r_B \cos(\delta_B \pm \gamma)$

$y_{\pm} = r_B \sin(\delta_B \pm \gamma)$

$$N_i^{\pm} = h(K_{\pm i} + r_B^2 K_{\mp i} + 2\sqrt{K_i K_{-i}}(x_{\pm} c_i \pm y_{\pm} s_i))$$

c_i, s_i : average in bin of cosine, sine of strong phase difference



Choosing bins of *expected* similar strong phase difference maximises statistical precision – currently 16 bins

Loss in statistical sensitivity w.r.t. unbinned result…(here ~20%) but no model error!

Quantum correlated measurements

At the ψ (3770) neutral *D* pairs produced in quantum entangled state:

$$e^+e^- \to \psi'' \to \tfrac{1}{\sqrt{2}}\left[D^0\bar{D}^0 - \bar{D}^0D^0\right]$$

$$e^+e^- \to \psi'' \to \tfrac{1}{\sqrt{2}}\left[D_{CP-}D_{CP+} - D_{CP+}D_{CP-}\right]$$

$$\text{where } D_{CP\pm} = \tfrac{1}{\sqrt{2}}\left[D^0 \pm \bar{D}^0\right]$$

Reconstruct one D in decay of interest (eg. $K_s\pi\pi$), & other in CP eigenstate (eg. KK, $K_s\pi^0$ …) then CP of the other is fixed.

CP tag
$$M_i^{\pm} = \frac{S_{\pm}}{2S_f}\left(K_i + K_{\bar{i}} \pm 2c_i\sqrt{K_iK_{\bar{i}}}\right),$$

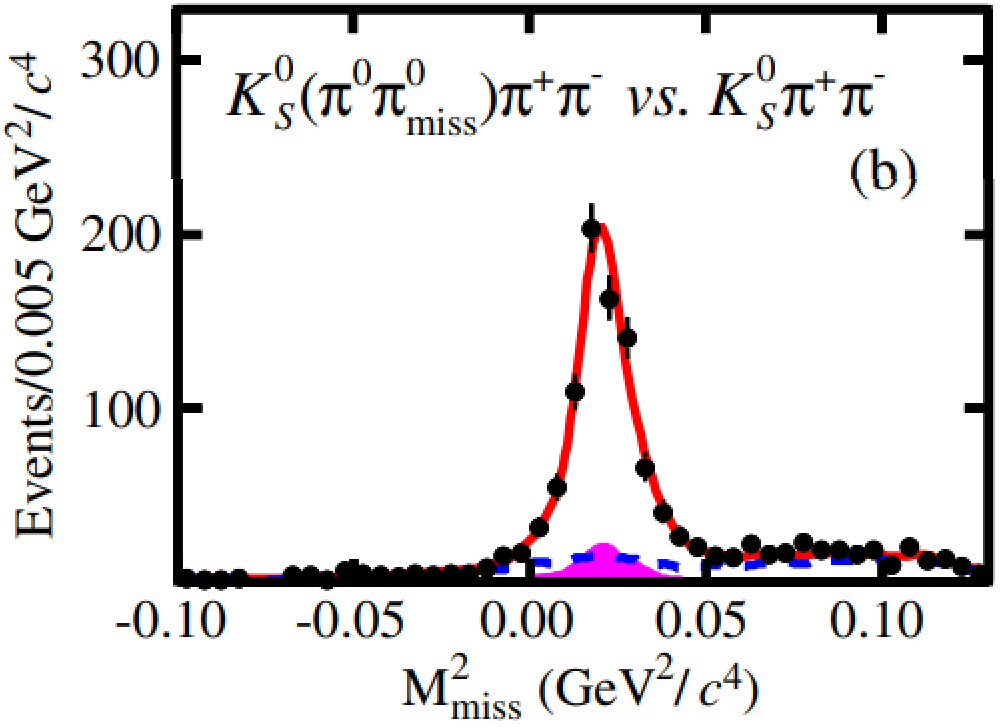
$K_s\pi\pi$ tag
$$M_{i,j} = \frac{N_{D^0,\bar{D}^0}}{2S_f^2}\left(K_iK_{\bar{j}} + K_{\bar{i}}K_j - 2\sqrt{K_iK_{\bar{j}}K_{\bar{i}}K_j}(c_ic_j + s_is_j)\right)$$

Yields

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

2.93 fb^{-1} of data compared with 0.82 fb^{-1} for the only previous measurement by CLEO - PRD **82**, 112006 (2010)

New final states: CP even $\pi^+\pi^-\pi^0$ and $K_S^0(\pi^0\pi^0)\pi^+\pi^-$ where one π^0 is not reconstructed



CP-even tags	$N_{DT}^{K_S^0\pi^+\pi^-}$	$N_{DT}^{K_L^0\pi^+\pi^-}$
K^+K^-	443 ± 22	1289 ± 41
$\pi^+\pi^-$	184 ± 14	531 ± 28
$K_S^0\pi^0\pi^0$	198 ± 16	612 ± 35
$\pi^+\pi^-\pi^0$	790 ± 31	2571 ± 74
$K_L^0\pi^0$	913 ± 41	
CP-odd tags		
$K_S^0\pi^0$	643 ± 26	861 ± 46
$K_S^0\eta_{\gamma\gamma}$	89 ± 10	105 ± 15
$K_S^0\eta_{\pi^+\pi^-\pi^0}$	23 ± 5	40 ± 9
$K_S^0\omega$	245 ± 17	321 ± 25
$K_S^0\eta'_{\pi^+\pi^-\eta}$	24 ± 6	38 ± 8
$K_S^0\eta'_{\gamma\pi^+\pi^-}$	81 ± 10	120 ± 14
$K_L^0\pi^0\pi^0$	620 ± 32	
Mixed-CP tags		
$K_S^0\pi^+\pi^-$	899 ± 31	3438 ± 72
$K_S^0\pi^+\pi^-_{miss}$	224 ± 17	
$K_S^0(\pi^0\pi^0_{miss})\pi^+\pi^-$	710 ± 34	

Results

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

Three different binning schemes

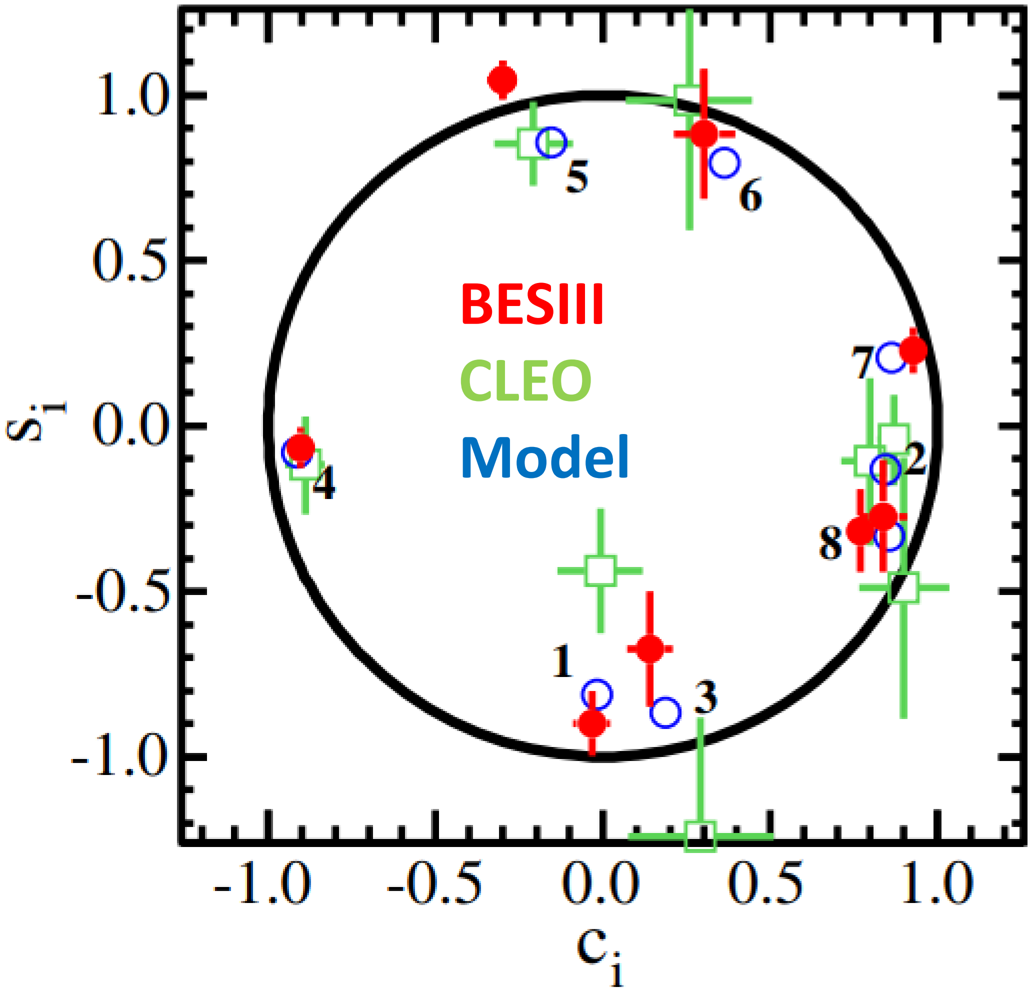
Fit binned quantum-correlated yields to extract c_i and s_i

	c_i	s_i
1	$-0.034 \pm 0.052 \pm 0.017$	$-0.899 \pm 0.094 \pm 0.030$
2	$0.839 \pm 0.062 \pm 0.037$	$-0.272 \pm 0.166 \pm 0.031$
3	$0.140 \pm 0.064 \pm 0.028$	$-0.674 \pm 0.172 \pm 0.038$
4	$-0.904 \pm 0.021 \pm 0.009$	$-0.065 \pm 0.062 \pm 0.006$
5	$-0.300 \pm 0.042 \pm 0.013$	$1.047 \pm 0.055 \pm 0.019$
6	$0.303 \pm 0.088 \pm 0.027$	$0.884 \pm 0.191 \pm 0.043$
7	$0.927 \pm 0.016 \pm 0.008$	$0.228 \pm 0.066 \pm 0.015$
8	$0.771 \pm 0.032 \pm 0.015$	$-0.316 \pm 0.123 \pm 0.021$

Statistically dominated

Systematics from assumptions of including K0Lpipi and flavour tag

Optimal binning scheme used for γ

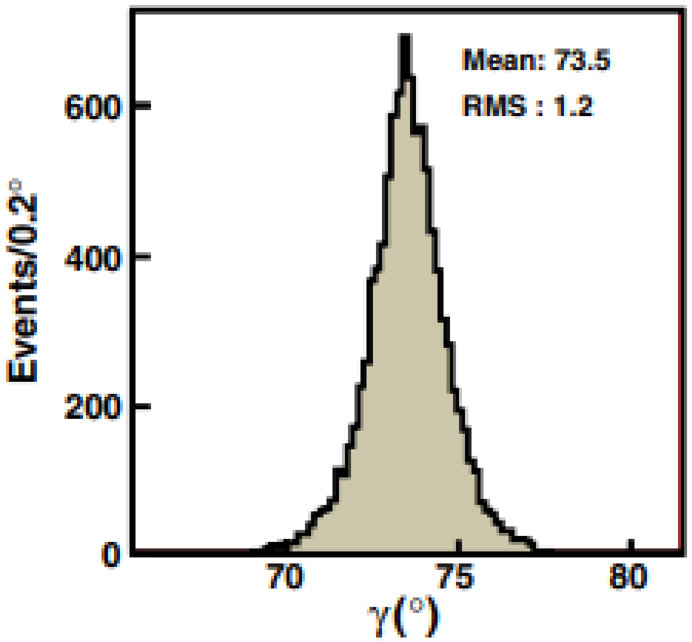


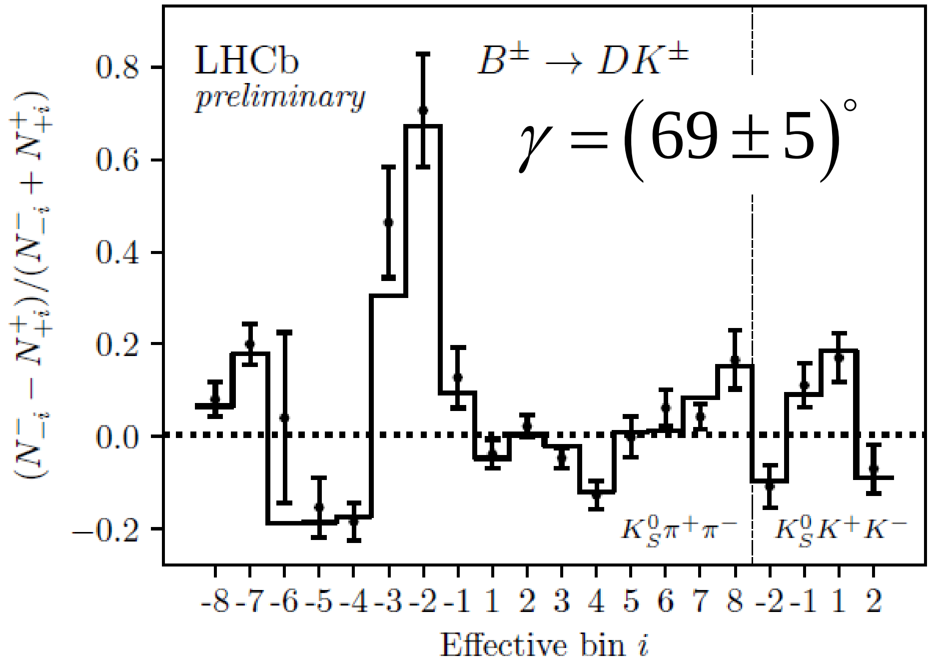
LHCb-CONF-2020-01 and
A. Poluektov talk tomorrow

Impact on γ

Used in the most precise single measurement of γ to date

Systematic from the c_i and s_i measurements approximately ~1°





-We have also measured $D^0 \to K_S^0 K^+ K^-$ strong phases:

- 12% more data in the γ measurement
- arXiv:2007.07959 [hep-ex] (acc. PRD)

Conclusion and outlook

Presented highlights from BESIII related to CKM in last year:

- Observation of $D \rightarrow \tau\nu$, surprisingly large rate for DCS decay $D^+ \rightarrow K^+\pi^+\pi^-\pi^0$ and new generation of c_i and s_i measurements that result in γ systematic of $\sim 1^\circ$

Many other results in open charm

- 12 other papers submitted since Beauty 2019 (see backup)
- also many results in spectroscopy see Zhentian Sun tomorrow

Future Physics Programme at BESIII - Chin. Phys. C 44, 040001 (2020)

- 20 fb^{-1} at $\psi(3770)$ – planned during 2021-2022 running
- more precise CKM, LQCD and LUV tests and strong phase measurements
- hadron branching fraction and amplitude analysis particularly multibody

Backup

List of other results – since Beauty 2019

1. Search for rare decay $D_s^+ \to p\bar{p}e^+\nu$ – PRD **100**, 112008 (2019)
2. Measurements of BFs for $D \to \eta\pi\pi$ – PRD **101**, 052009 (2020)
3. Measurements of Branching Fractions for $D^+ \to \omega\mu^+\nu$ Decays – PRD **101**, 072005(2020)
4. First measurement of $D^+ \to \eta\mu^+\nu$ - PRL **124**, 231801
5. Measurements of the absolute branching fractions of the exclusive $D^0 \to \eta X$ decays - PRL **124**, 241803(2020)
6. Study of $D_s^+ \to PP$ – JHEP **2020**, 146 (2020)
7. Analysis of the decay $D^0 \to K_S^0 K^+ K^-$ - submitted to PRD - arXiv:2006.02800
8. Measurements of the Cabibbo-suppressed $D^0 \to \eta/\omega\pi\pi$ decays - PRD **102** 052003 (2020)
9. Searches for $D \to b_1(1235)e^+\nu$ – submitted to PRD - arXiv:2008.05754
10. Measurements of Branching Fractions for $D^0 \to \pi\pi KK$ Decays – submitted to PRD - arXiv:2007.10563
11. Measurement of absolute branching fraction of the inclusive decay $\Lambda_c \to K_S^0 + X$ – accepted by EPJC - arXiv:2005.11211