Prospects for Charm Physics at a Super τ-charm Factory

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Charm 2018 Satellite Workshop on a τ-charm Factory
Novosibirsk, Russia
May 26, 2018

with thanks to Hajime Muramatsu and Roy Briere

The Importance of Charm

new physics

(1) Of the flavored hadronic systems with mixing — K(s), D(c), B(b) — the D system is the only system involving heavy up-type quarks:

$\Rightarrow$ ***it provides sensitivity to different new physics phenomena***

(2) Mixing (found) and CP violation (not found) are small in the charm system:

$\Rightarrow$ ***deviations from SM expectations could be dramatic***

weak physics

(3) Flavor physics relies on global constraints derived from all systems *(e.g., the CKM matrix elements, and inputs from one system into another)*:

$\Rightarrow$ ***charm is an essential piece of a larger flavor physics program***

strong physics

(4) Weak physics and strong physics can be separated in charm leptonic and semi-leptonic decays:

$\Rightarrow$ ***charm decays offer opportunities for precision QCD***

(5) Many rare decays have backgrounds from "long-distance" hadronic processes:

$\Rightarrow$ ***a spotlight is placed on less-understood aspects of QCD***

Current Experimental Landscape

EXPERIMENTS	DATA	FEATURES
<u>High-energy pp collisions</u> LHCb	5 fb^{-1} (8×10^{12})	huge rates time-dependent decays large backgrounds difficult neutral reconstruction
<u>Asymmetric e^+e^- at $\Upsilon(4S)$</u> BaBar Belle	550 fb^{-1} (8×10^{8}) 1 ab^{-1} (13×10^{8})	large rates some time resolution mostly clean environment neutrals are no problem
<u>e^+e^- at $\psi(3770)$ (and $D_sD_s^{(*)}$)</u> CLEOc BESIII	0.8 fb^{-1} (5×10^{6}) 3 fb^{-1} (2×10^{7})	small rates no time resolution extremely clean quantum correlations best for neutrals/missing particles (also charmonium)

⇒ there is currently a delicate balance…

Future Experimental Landscape

EXPERIMENTS	DATA	FEATURES
High-energy pp collisions LHCb **Upgrades**	5 fb^{-1} (8×10^{12}) **50/300 fb^{-1} (run III/IV)**	huge rates time-dependent decays large backgrounds difficult neutral reconstruction
Asymmetric e^+e^- at $\Upsilon(4S)$ BaBar Belle **Belle II**	550 fb^{-1} (8×10^8) 1 ab^{-1} (13×10^8) **50 ab^{-1}**	large rates some time resolution mostly clean environment neutrals are no problem
e^+e^- at $\psi(3770)$ (and $D_sD_s^{(*)}$) CLEOc BESIII **τ-charm factory**	0.8 fb^{-1} (5×10^6) 3 fb^{-1} (2×10^7) **× ~100 luminosity**	small rates no time resolution extremely clean quantum correlations best for neutrals/missing particles (also charmonium)

⇒ with the τ-charm factory, maintain this important balance.

EXPERI

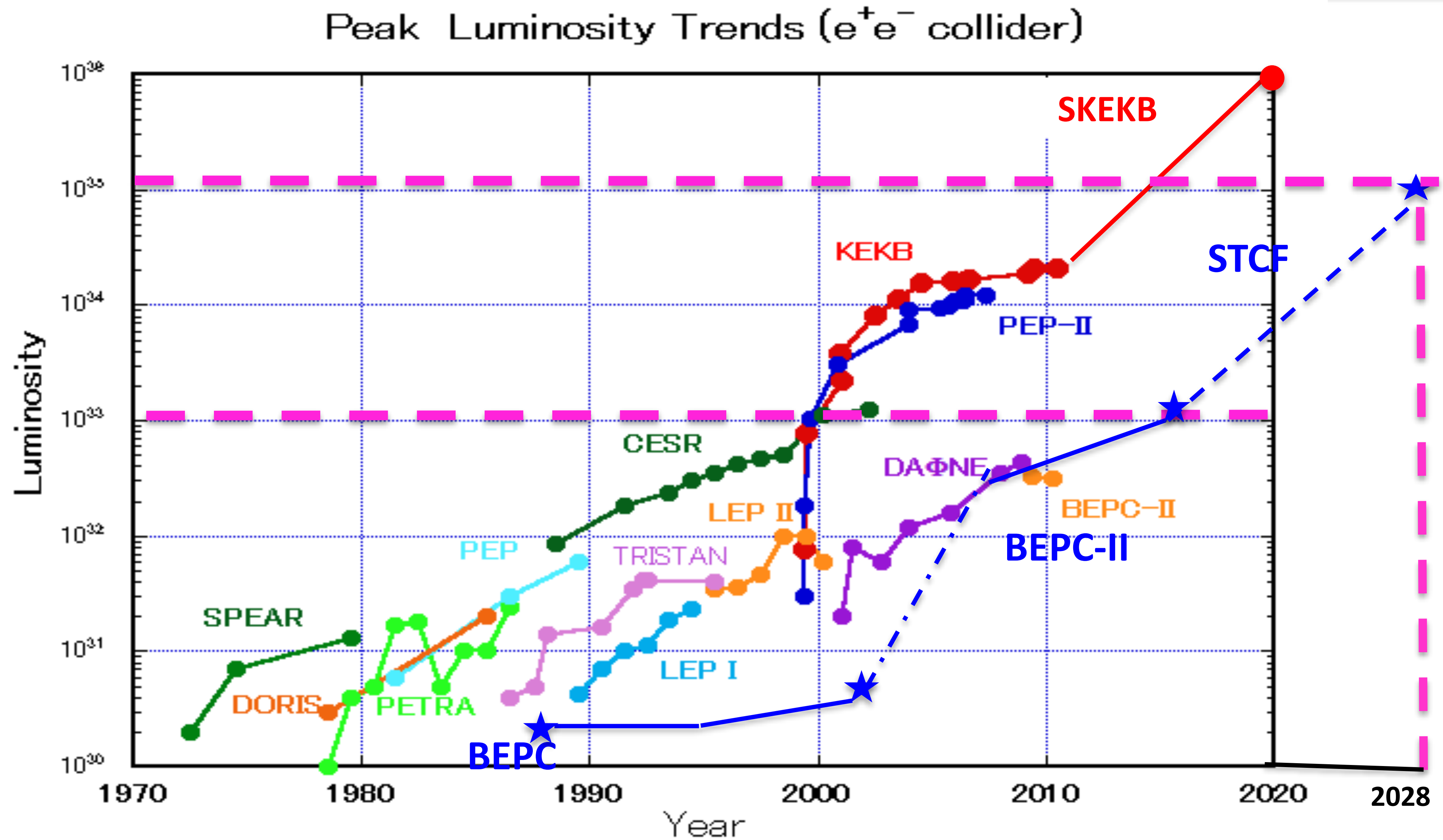
High-energ
LHCb
Upgrades

Asymmetr
BaBar
Belle
Belle II

e^+e^- at ψ(3
CLEOc
BESIII
τ-charm f

From Haiping Peng (last week CHARM 2018):

STCF in Perspective



A luminosity 1×10^{35} $cm^{-2}s^{-1}$ at 4 GeV at 2028 is reasonable !!

⇒ **with the τ-charm factory, maintain this important balance.**

Future Experimental Landscape

EXPERIMENTS	DATA	FEATURES
High-energy pp collisions LHCb **Upgrades**	$5\ fb^{-1}$ (8×10^{12}) **$50/300\ fb^{-1}$ (run III/IV)**	huge rates time-dependent decays large backgrounds difficult neutral reconstruction
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e^+e^- at $\psi(3770)$ (and $D_sD_s^{(*)}$) CLEOc BESIII **τ-charm factory**	$0.8\ fb^{-1}$ (5×10^6) $3\ fb^{-1}$ (2×10^7) **× ~100 luminosity**	small rates no time resolution extremely clean quantum correlations best for neutrals/missing particles (also charmonium)

⇒ with the τ-charm factory, maintain this important balance.

Strengths of LHCb: *mixing in $D^0 \to K^+\pi^-$*

Terminology/Formulae/Definitions:

Tagging the D^0: $D^{*+} \to D^0\pi_s^+$

Cabibbo-favored decay: $D^0 \to K^-\pi^+$

Cabibbo-suppressed decay: $D^0 \to K^+\pi^-$

Mixing then decay: $D^0 \to \bar{D}^0 \to K^+\pi^-$

Time-dependent ratio starting with D^0:

$$R^+(t) \equiv \frac{N(K^+\pi^-)(t)}{N(K^-\pi^+)(t)}$$

$$\approx \frac{|A(D^0 \to K^+\pi^-)(t) + A(D^0 \to \bar{D}^0 \to K^+\pi^-)(t)|^2}{|A(D^0 \to K^-\pi^+)(t)|^2}$$

$$\approx r^2 + ry'\frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

where

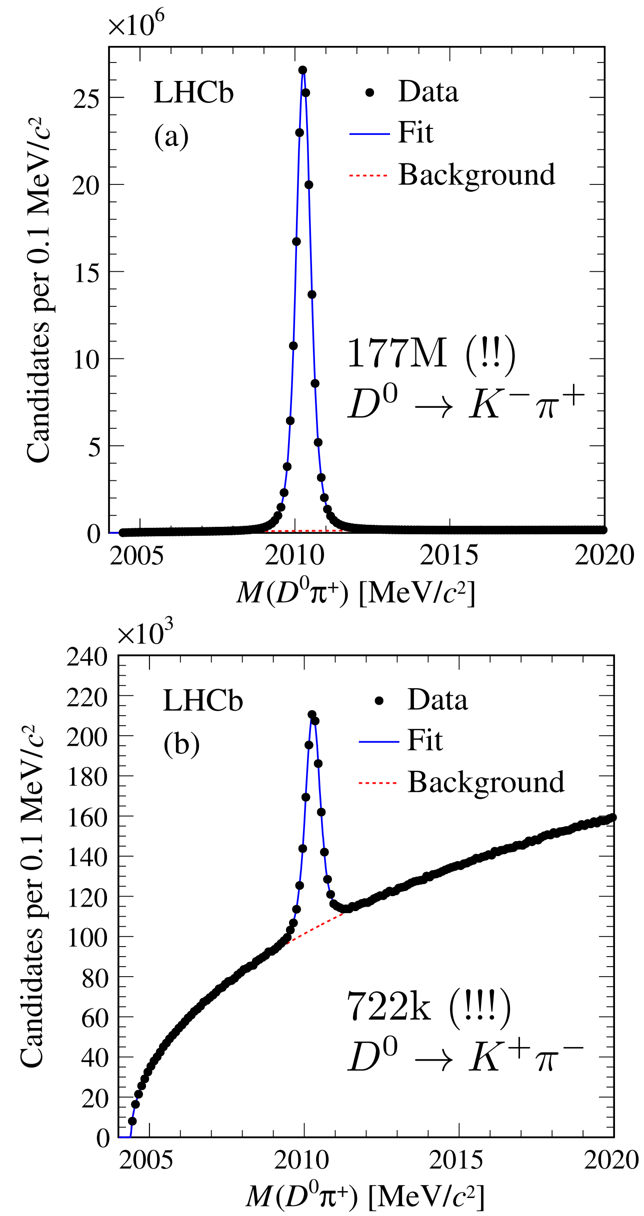
$$x' \equiv x\cos\delta + y\sin\delta$$

$$y' \equiv y\cos\delta - x\sin\delta$$

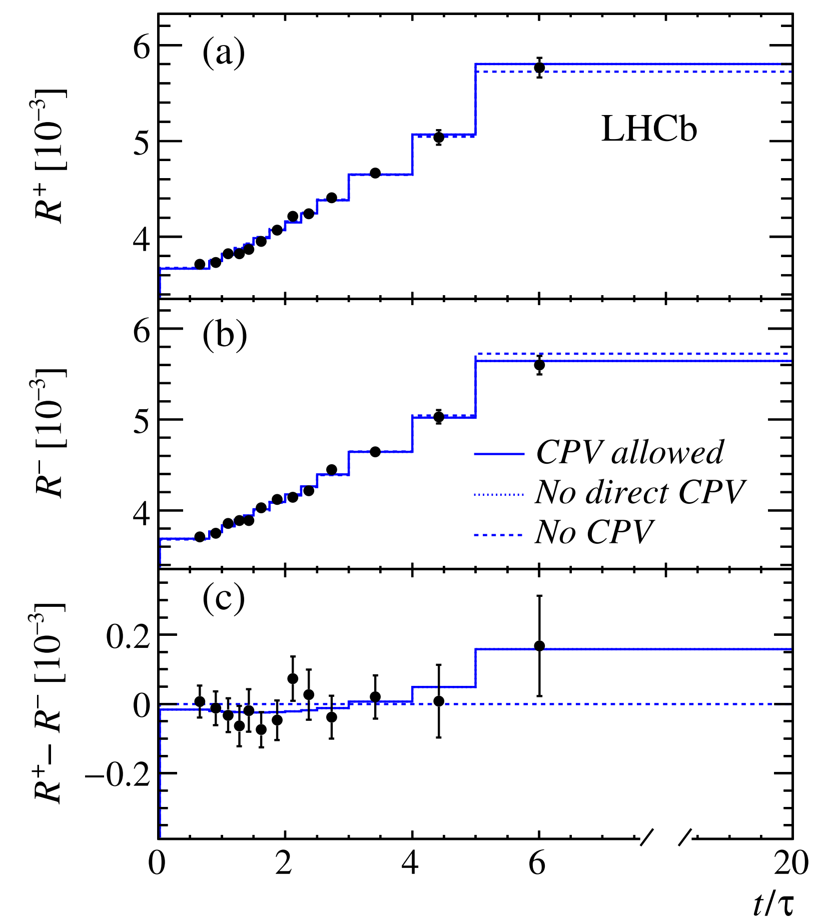
and x, y are mixing parameters

and δ is a strong phase

A. Massive statistics:



B. Time dependence:



C. Approaching precision in the mixing parameter y′.

LHCb, "Updated determination of D^0-$\bar{D}^0$ mixing and CP violation parameters with $D^0 \to K^+\pi^-$ decays," PRD 97, 031101(R) (2018)

***But D.** y′ depends on δ.*

Strengths of LHCb: *mixing in $D^0 \to K^+\pi^-\pi^+\pi^-$*

Terminology/Formulae/Definitions:

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Cabibbo-favored decay: $D^0 \to K^-\pi^+\pi^+\pi^-$

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Mixing then decay: $D^0 \to \bar{D}^0 \to K^+\pi^-\pi^+\pi^-$

Time-dependent ratio starting with D^0:

$$R^+(t) \equiv \frac{N(K^+\pi^-\pi^+\pi^-)(t)}{N(K^-\pi^+\pi^+\pi^-)(t)}$$

$$\approx \frac{|A(D^0 \to K^+3\pi)(t) + A(D^0 \to \bar{D}^0 \to K^+3\pi)(t)|^2}{|A(D^0 \to K^-3\pi)(t)|^2}$$

$$\approx r_{K3\pi}^2 + r_{K3\pi}R_{K3\pi}y'_{K3\pi}\frac{t}{\tau} + \frac{x^2+y^2}{4}(\frac{t}{\tau})^2$$

where

$$x'_{K3\pi} \equiv x\cos\delta_{K3\pi} + y\sin\delta_{K3\pi}$$

$$y'_{K3\pi} \equiv y\cos\delta_{K3\pi} - x\sin\delta_{K3\pi}$$

and x, y are mixing parameters

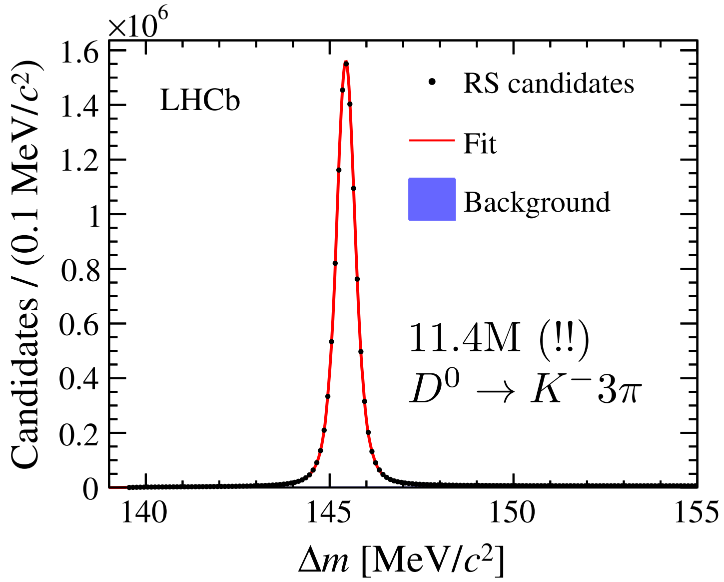
and $\delta_{K3\pi}$ is an average strong phase

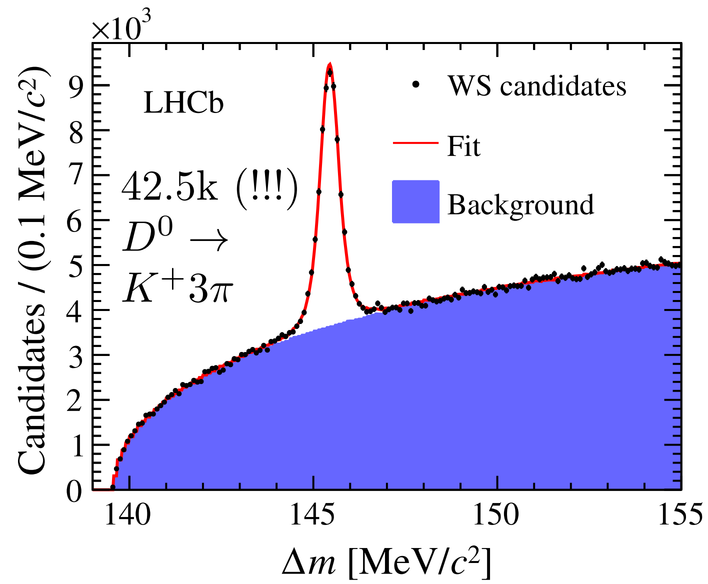
and $R_{K3\pi}$ is a coherence factor:

$$R_{K3\pi}e^{-i\delta_{K3\pi}} \equiv \; <\cos\delta> + \, i <\sin\delta>$$

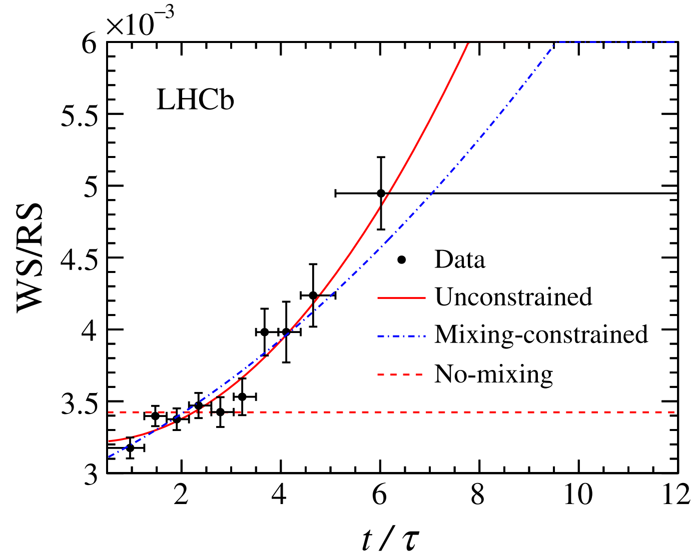
LHCb, "First observation of D^0-$\bar{D}^0$ oscillations in $D^0 \to K^+\pi^-\pi^+\pi^-$ decays and measurement of the associated coherence parameters," PRL 116, 241801 (2016)

A. Massive statistics:





B. Time dependence:



C. Another handle on mixing parameters.

But D. *Dependence on another strong phase and a coherence factor.*

Strengths of LHCb: *amplitude analysis of $D^0 \to K^+\pi^-\pi^+\pi^-$*

Terminology/Formulae/Definitions:

Tagging the D^0: $D^{*+} \to D^0\pi_s^+$

Cabibbo-favored decay: $D^0 \to K^-\pi^+\pi^+\pi^-$

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Mixing then decay: $D^0 \to \bar{D}^0 \to K^+\pi^-\pi^+\pi^-$

Time-dependent ratio starting with D^0:

$$R^+(t) \equiv \frac{N(K^+\pi^-\pi^+\pi^-)(t)}{N(K^-\pi^+\pi^+\pi^-)(t)}$$

$$\approx \frac{|A(D^0 \to K^+3\pi)(t) + A(D^0 \to \bar{D}^0 \to K^+3\pi)(t)|^2}{|A(D^0 \to K^-3\pi)(t)|^2}$$

$$\approx r_{K3\pi}^2 + r_{K3\pi}R_{K3\pi}y'_{K3\pi}\frac{t}{\tau} + \frac{x^2+y^2}{4}(\frac{t}{\tau})^2$$

where

$$x'_{K3\pi} \equiv x\cos\delta_{K3\pi} + y\sin\delta_{K3\pi}$$

$$y'_{K3\pi} \equiv y\cos\delta_{K3\pi} - x\sin\delta_{K3\pi}$$

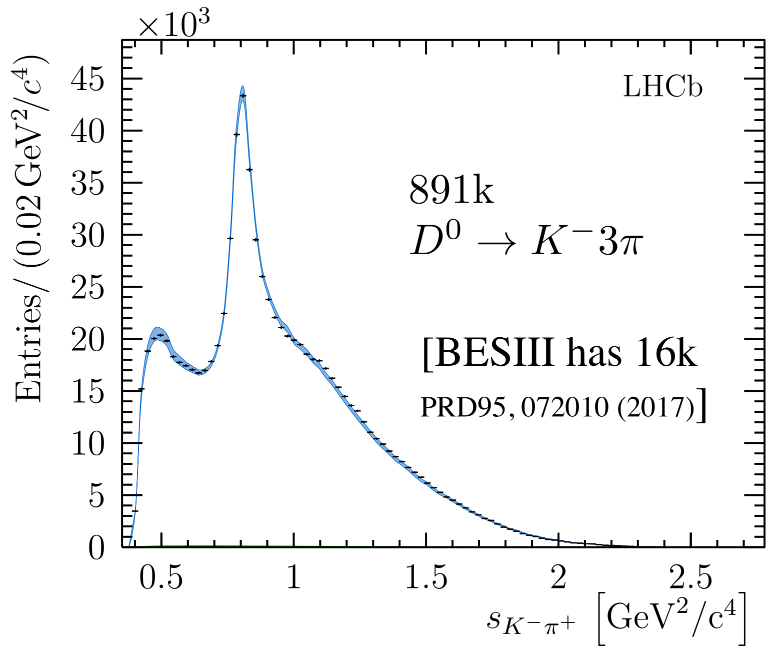
and x, y are mixing parameters

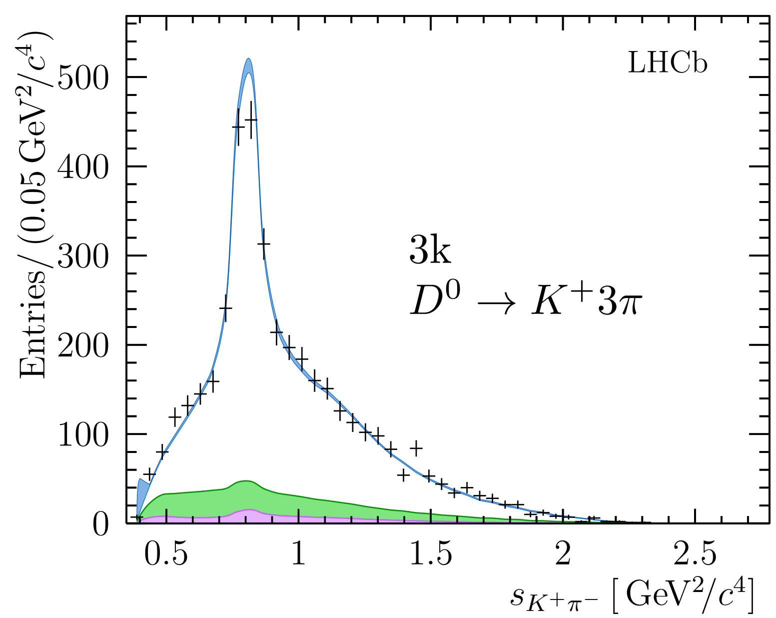
and $\delta_{K3\pi}$ is an average strong phase

and $R_{K3\pi}$ is a coherence factor:

$$R_{K3\pi}e^{-i\delta_{K3\pi}} \equiv \;<\cos\delta> + \, i <\sin\delta>$$

A. Massive statistics (tagging with π and μ):



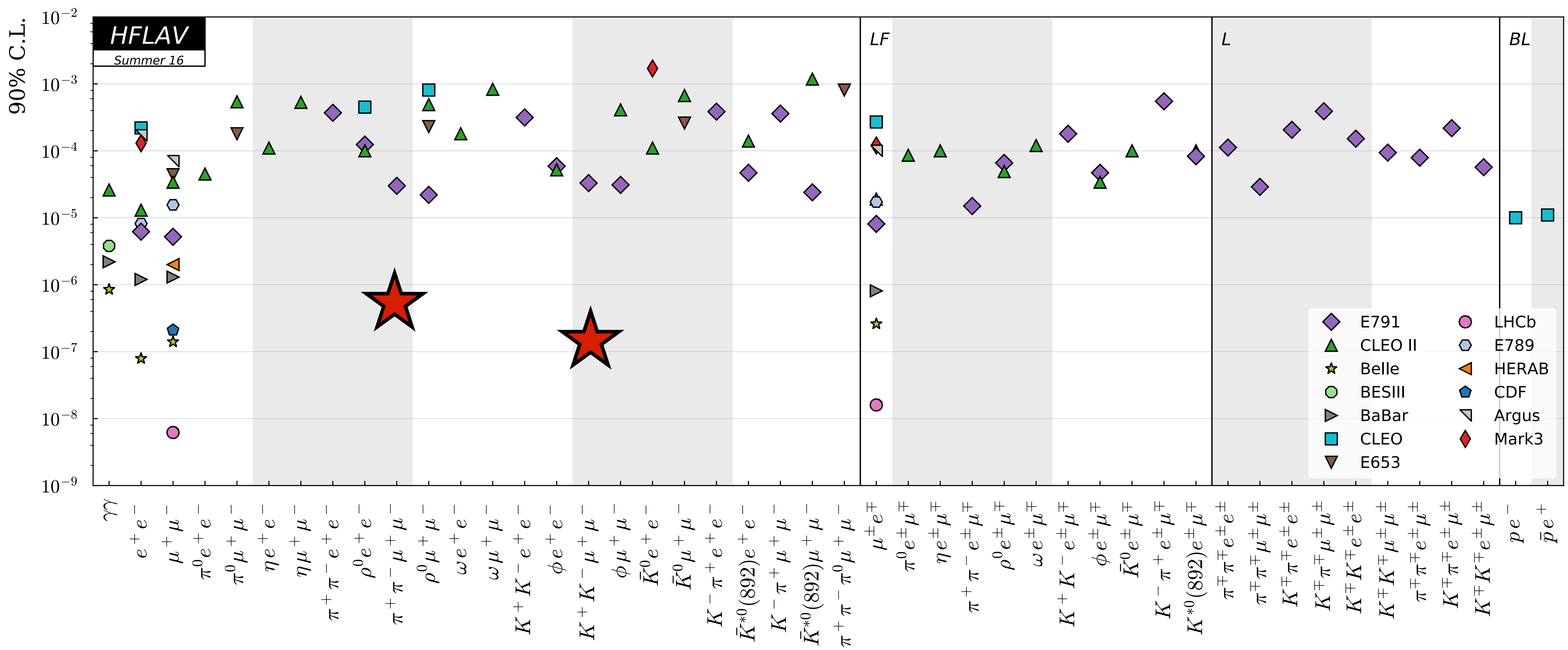


B. Amplitude analysis gives access to $R_{K3\pi}$

But C. *There is an arbitrary phase ⇒ insensitive to δ*

LHCb, "Studies of the resonance structure in $D^0 \to K^\mp\pi^\pm\pi^\pm\pi^\mp$ decays," arXiv:1712.08609 (2017)

Strengths of LHCb: *rare decay $D^0 \to h^+h^-\mu^+\mu^-$*



Observations of rare decays O(10^{-7}):

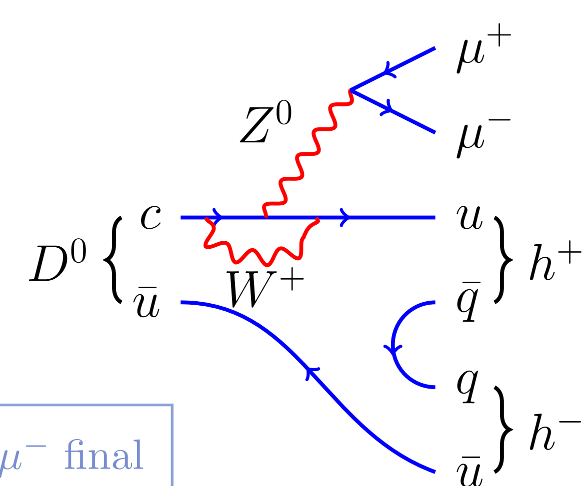
$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$

$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}$

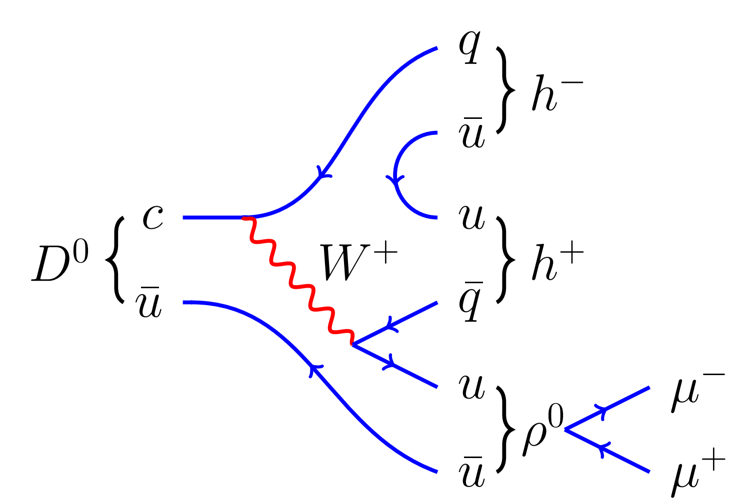
But note: *largest systematic errors are due to normalization branching fractions:*
relative to $K^-\pi^+\mu^+\mu^-$ (LHCb), relative to $K^-\pi^+\pi^+\pi^-$ (CLEO)

LHCb, "Observation of D^0 meson decays to $\pi^+\pi^-\mu^+\mu^-$ and $K^+K^-\mu^+\mu^-$ final states," PRL 119, 181805 (2017)

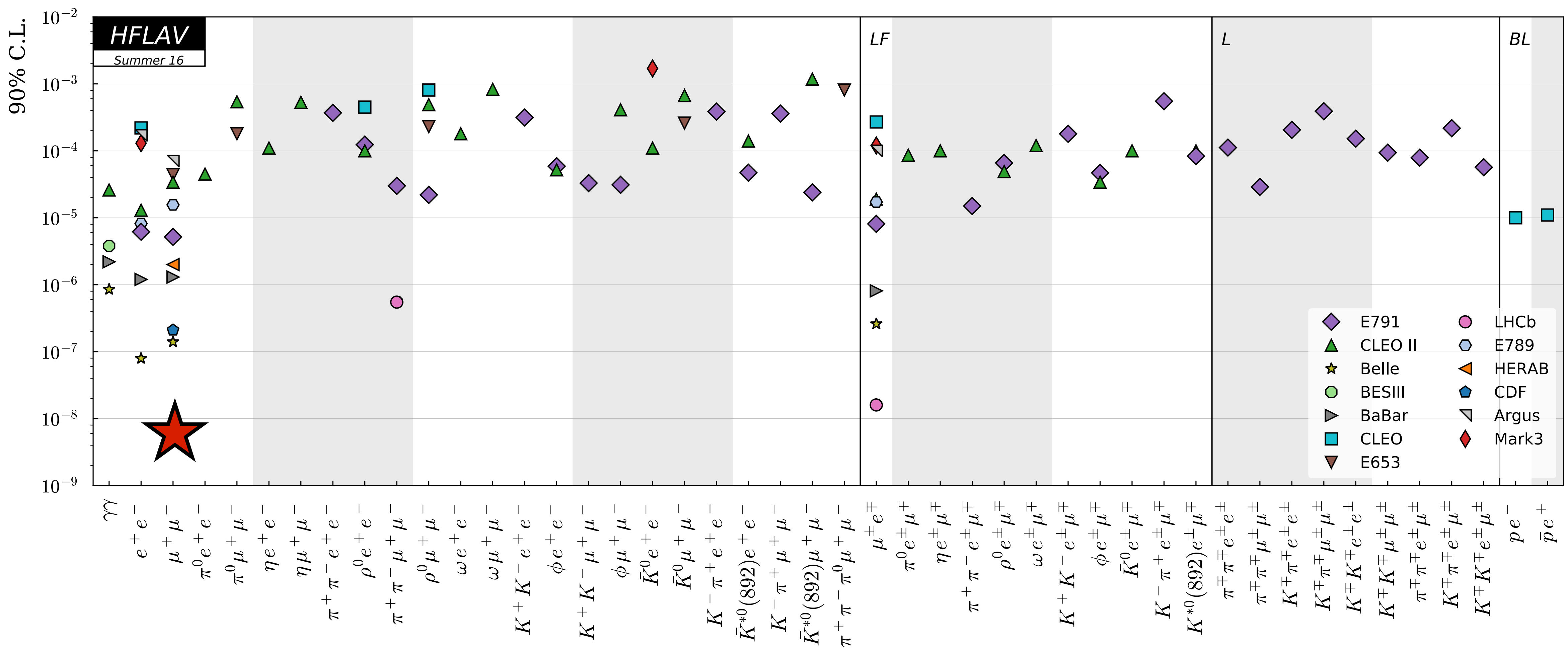
Short distance:



Long distance:



Strengths of LHCb: *rare decay $D^0 \to \mu^+\mu^-$*



Tightest upper limits O(10⁻⁹):

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$$

But note: standard model expectation depends on γγ:

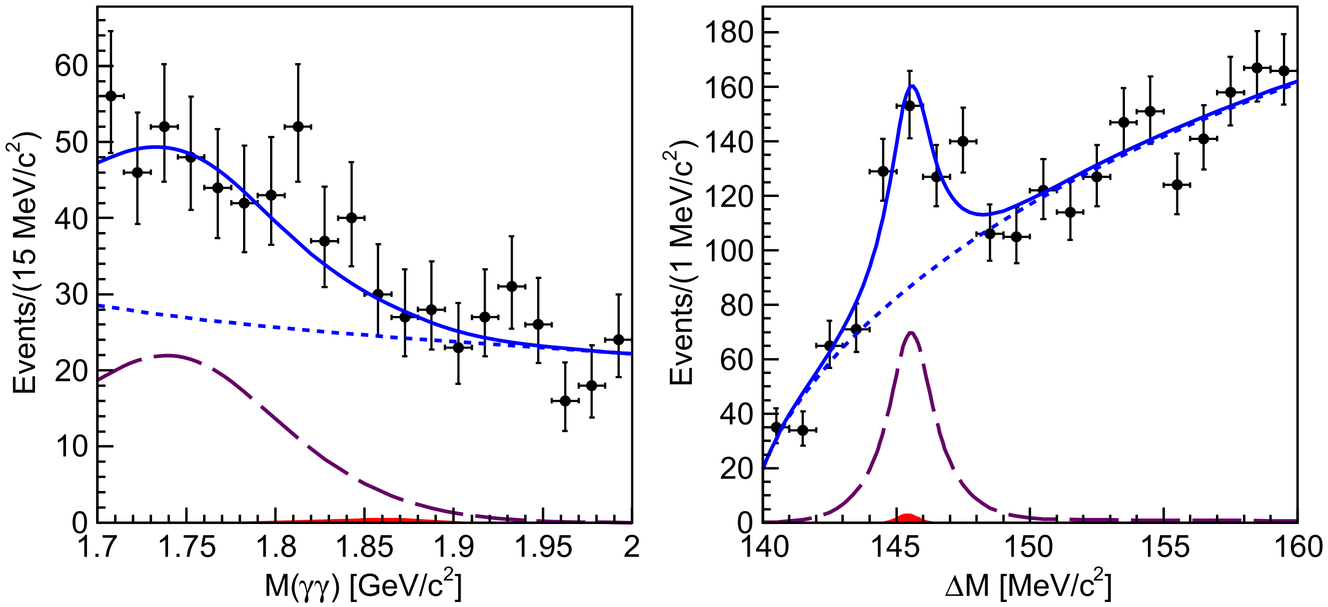
$$\mathcal{B}(D^0 \to \mu^+\mu^-) \approx (2.7 \times 10^{-5}) \times \mathcal{B}(D^0 \to \gamma\gamma)$$

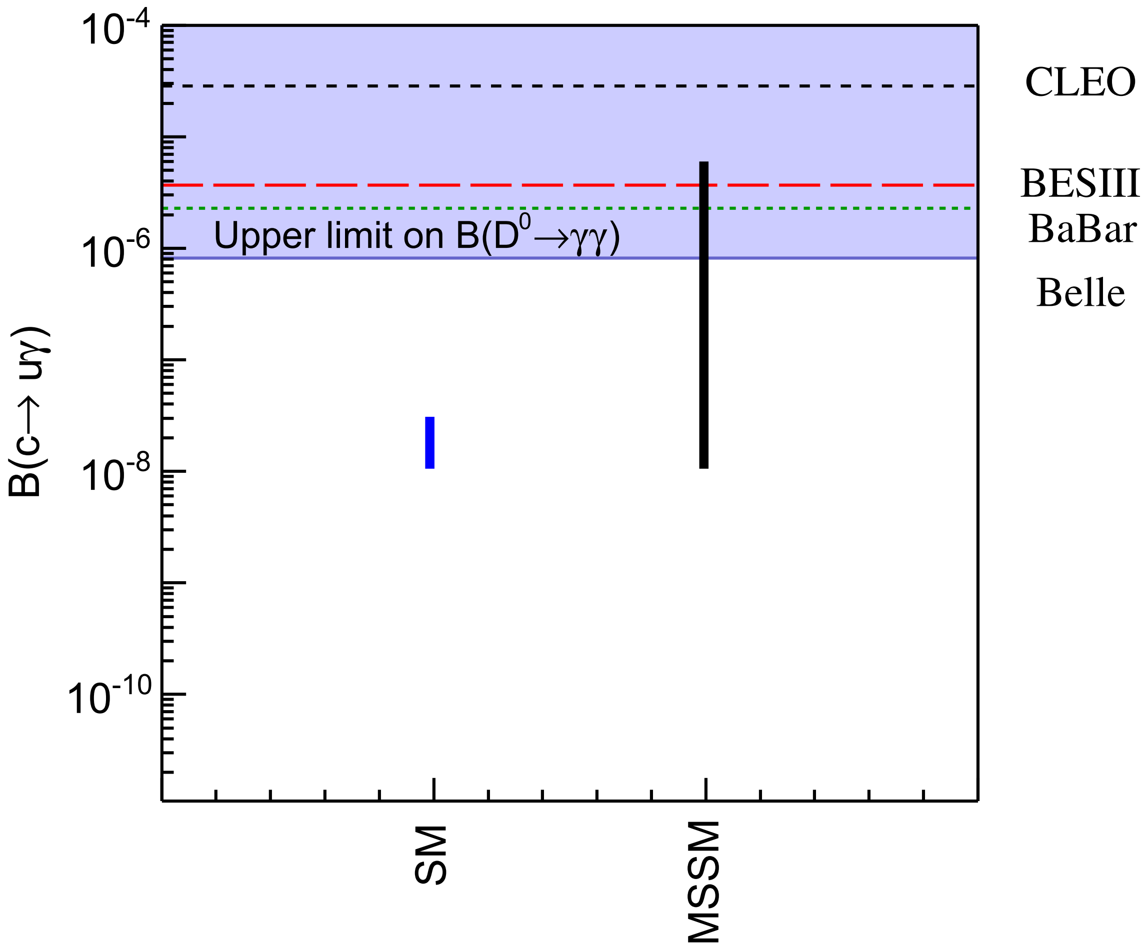
LHCb, "Search for the rare decay $D^0 \to \mu^+\mu^-$," PLB 725, 15 (2013)

Strengths of BaBar/Belle(II): *rare decay $D^0 \to \gamma\gamma$*

A. Big statistics; **B.** Sensitivity to neutral final states

Search for $D^0 \to \gamma\gamma$ to access FCNC $c \to u\gamma$:





* D^0 tagged using $D^{*+} \to D^0\pi^+$
* peaking background $D^0 \to \pi^0\pi^0$
* signal normalized using 343k $D^0 \to K_S\pi^0$ decays
* keep improving with more data

Belle, "Search for the rare decay $D^0 \to \gamma\gamma$ at Belle," PRD 93, 051102(R) (2016)

Strengths of BaBar/Belle(II): *CP violation in $D^+ \to \pi^+\pi^0$*

Terminology/Formulae/Definitions:

Tagging the D^+: $D^{*+} \to D^+\pi^0$

CP Asymmetry:

$$A^f_{CP} \equiv \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

Measure $D^+ \to \pi^+\pi^0$ relative to $K_S\pi^+$:

$$\Delta A_{CP} \equiv A^{\pi\pi}_{CP} - A^{K\pi}_{CP}$$

A. Big statistics

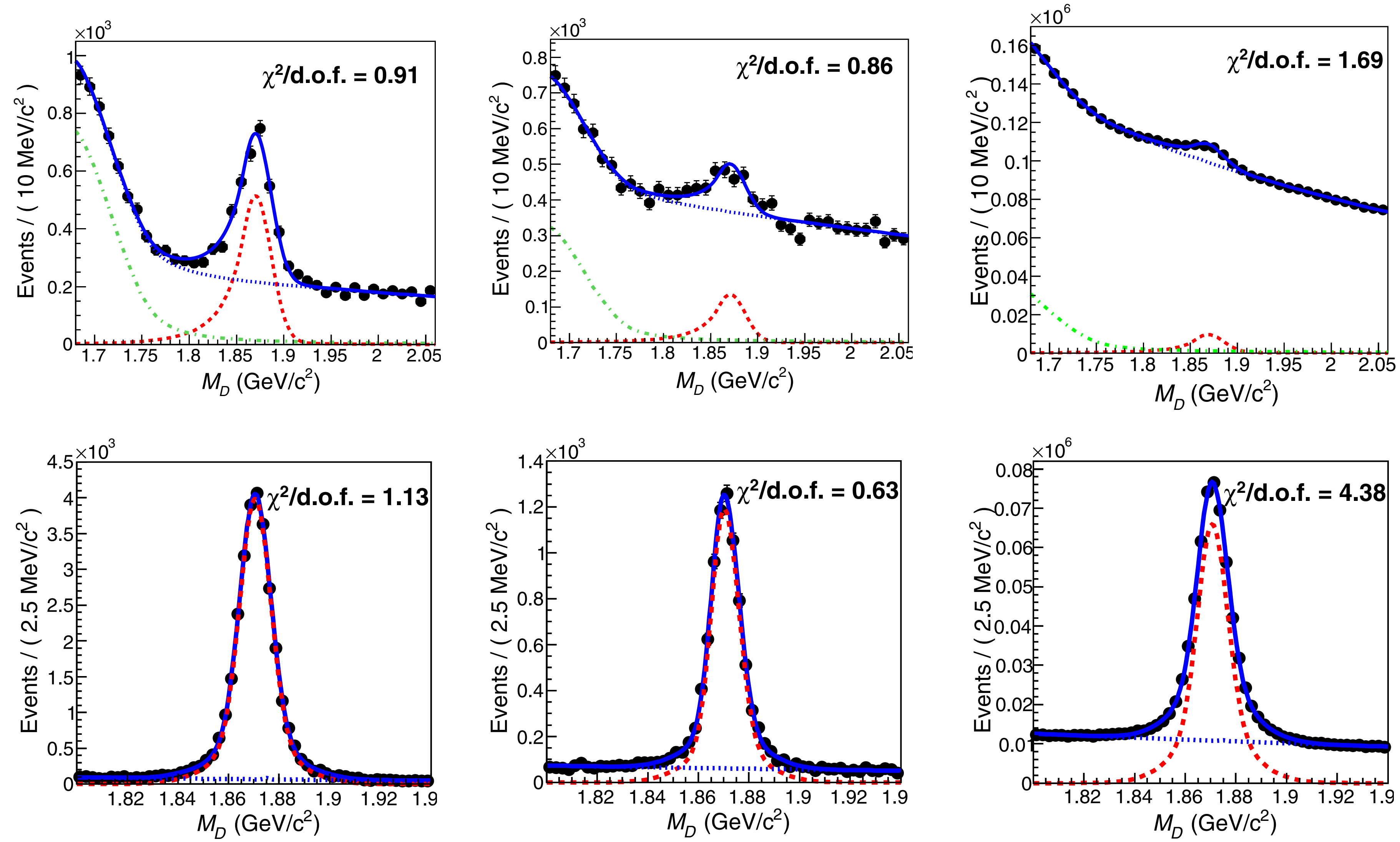
B. Sensitivity to final states with neutrals

C. Relatively clean environment

tagged, higher p(D*) | tagged, lower p(D*) | untagged

$D^+ \to \pi^+\pi^0$

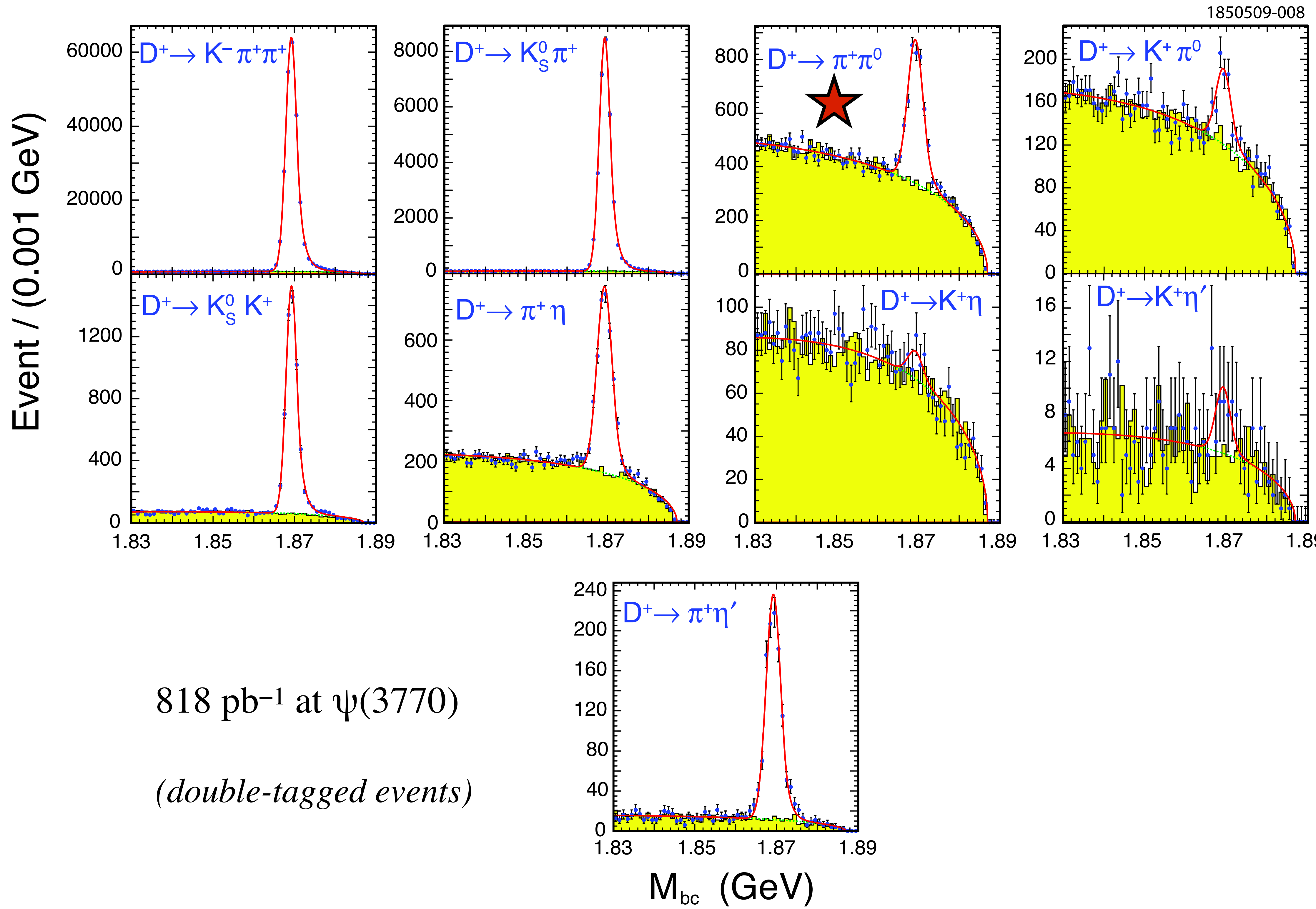
$D^+ \to K_S\pi^+$



Belle, "Search for CP violation in the $D^+ \to \pi^+\pi^0$ decay at Belle," PRD 97, 011101(R) (2018)

But D. Improvement over CLEO is only ×2…

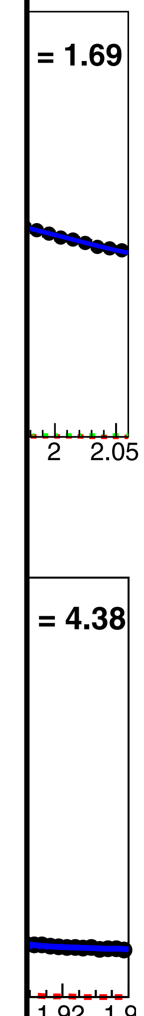
Termin
Tagging
CP Asy
A_{CP}^{f}
Measure
ΔA_{C}



818 pb^{-1} at $\psi(3770)$

(double-tagged events)

CLEO, "Measurements of D meson decays to two pseudoscalar mesons," PRD 81, 052014 (2010)



Belle, "Search for CP violation in the $D^+ \to \pi^+\pi^0$ decay at Belle," PRD 97, 011101(R) (2018)

But D. Improvement over CLEO is only ×2…

Termin

Taggin

CP As

A^{f}_{CP}

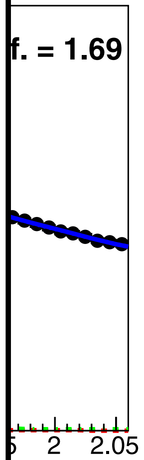
Measur

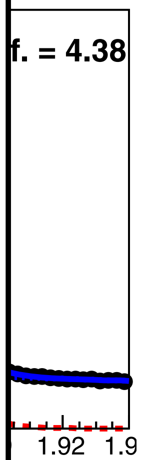
ΔA_{C}

Mode	$\mathcal{B}_{\text{mode}}/\mathcal{B}_{\text{Normalization}}$ (%)	This result $\mathcal{B}$ (%)	$\mathcal{A}_{CP}$ (%)
$D^0 \to K^+K^-$	$10.41 \pm 0.11 \pm 0.12$	$0.407 \pm 0.004 \pm 0.005 \pm 0.008$	
$D^0 \to K^0_S K^0_S$	$0.41 \pm 0.04 \pm 0.02$	$0.0160 \pm 0.0017 \pm 0.0008 \pm 0.0003$	
$D^0 \to \pi^+\pi^-$	$3.70 \pm 0.06 \pm 0.09$	$0.145 \pm 0.002 \pm 0.004 \pm 0.003$	
$D^0 \to \pi^0\pi^0$	$2.06 \pm 0.07 \pm 0.10$	$0.081 \pm 0.003 \pm 0.004 \pm 0.002$	
$D^0 \to K^-\pi^+$	100	3.9058 external input	$0.5 \pm 0.4 \pm 0.9$
$D^0 \to K^0_S\pi^0$	$30.4 \pm 0.3 \pm 0.9$	$1.19 \pm 0.01 \pm 0.04 \pm 0.02$	
$D^0 \to K^0_S\eta$	$12.3 \pm 0.3 \pm 0.7$	$0.481 \pm 0.011 \pm 0.026 \pm 0.010$	
$D^0 \to \pi^0\eta$	$1.74 \pm 0.15 \pm 0.11$	$0.068 \pm 0.006 \pm 0.004 \pm 0.001$	
$D^0 \to K^0_S\eta'$	$24.3 \pm 0.8 \pm 1.1$	$0.95 \pm 0.03 \pm 0.04 \pm 0.02$	
$D^0 \to \pi^0\eta'$	$2.3 \pm 0.3 \pm 0.2$	$0.091 \pm 0.011 \pm 0.006 \pm 0.002$	
$D^0 \to \eta\eta$	$4.3 \pm 0.3 \pm 0.4$	$0.167 \pm 0.011 \pm 0.014 \pm 0.003$	
$D^0 \to \eta\eta'$	$2.7 \pm 0.6 \pm 0.3$	$0.105 \pm 0.024 \pm 0.010 \pm 0.002$	
$D^+ \to K^-\pi^+\pi^+$	100	9.1400 external input	$-0.1 \pm 0.4 \pm 0.9$
$D^+ \to K^0_S K^+$	$3.35 \pm 0.06 \pm 0.07$	$0.306 \pm 0.005 \pm 0.007 \pm 0.007$	$-0.2 \pm 1.5 \pm 0.9$
$D^+ \to \pi^+\pi^0$	$1.29 \pm 0.04 \pm 0.05$	$0.118 \pm 0.003 \pm 0.005 \pm 0.003$	$2.9 \pm 2.9 \pm 0.3$
$D^+ \to K^0_S\pi^+$	$16.82 \pm 0.12 \pm 0.37$	$1.537 \pm 0.011 \pm 0.034 \pm 0.033$	$-1.3 \pm 0.7 \pm 0.3$
$D^+ \to K^+\pi^0$	$0.19 \pm 0.02 \pm 0.01$	$0.0172 \pm 0.0018 \pm 0.0007 \pm 0.0004$	$-3.5 \pm 10.7 \pm 0.9$
$D^+ \to K^+\eta$	<0.15 (90% C.L.)	<0.013 (90% C.L.)	
$D^+ \to \pi^+\eta$	$3.87 \pm 0.09 \pm 0.19$	$0.354 \pm 0.008 \pm 0.018 \pm 0.008$	$-2.0 \pm 2.3 \pm 0.3$
$D^+ \to K^+\eta'$	<0.20 (90% C.L.)	<0.019 (90% C.L.)	
$D^+ \to \pi^+\eta'$	$5.12 \pm 0.17 \pm 0.25$	$0.468 \pm 0.016 \pm 0.023 \pm 0.010$	$-4.0 \pm 3.4 \pm 0.3$

+ D_s modes

CLEO, "Measurements of D meson decays to two pseudoscalar mesons," PRD 81, 052014 (2010)





Belle, "Search for CP violation in the $D^+ \to \pi^+\pi^0$ decay at Belle," PRD 97, 011101(R) (2018)

But D. Improvement over CLEO is only ×2…

Strengths of CLEO/BES/τc-Factory

(1) **Quantum-correlated pairs of D-mesons**

⇒ complementary to other mixing and CP studies (*and input for $B \to DK$*)

(2) **Leptonic decays**

⇒ precision QCD and tests of lepton-flavor universality

(3) **Special hadronic decays (*e.g.* $D^+ \to \pi^+\pi^0$)**

⇒ CP asymmetries and absolute branching fractions

(4) **Charmed baryons**

⇒ absolute branching fractions and features of production

(5) **Rare decays (*also from charmonium*)**

⇒ complementary searches

Strengths of CLEO/BES/τcF: (1) *Quantum Correlations — a global fit*

Terminology/Formulae/Definitions:

Amplitudes to a final state i:

$$A_i \equiv A(D^0 \to i)$$
$$\bar{A}_i \equiv A(\bar{D}^0 \to i)$$

Ratio of amplitudes:

$$r_i \equiv \frac{|\bar{A}_i|}{|A_i|}$$

Strong phase between A_i and $\bar{A}_i$:

$$R_i e^{-i\delta_i} \equiv \frac{\int \bar{A}_i A_i^* dx_i}{|A_i||\bar{A}_i|}$$

For the 2-body case:

$$R_i = 1; \quad r_i e^{-i\delta_i} = \frac{\bar{A}_i}{A_i}$$

For $e^+e^- \to \psi(3770) \to D^0\bar{D}^0 \to (i,j)$:

$$\begin{aligned}\Gamma(i,j) &= \frac{1}{\sqrt{2}}\int |A_i\bar{A}_j - \bar{A}_i A_j|^2 dx_i dx_j \\ &= |A_i|^2|A_j|^2\left[r_i^2 + r_j^2 - 2\mathrm{Re}(r_i R_i e^{i\delta_i} r_j R_j e^{-i\delta_j})\right] \\ B_i \equiv B(D^0 \to i) &= |A_i + \bar{A}_i A(D^0 \to \bar{D}^0)|^2 \\ &= |A_i|^2\left[1 + r_i R_i(y\cos\delta_i + x\sin\delta_i)\right]\end{aligned}$$

Exploit quantum correlations in ψ(3770) decays:

$$|\psi> \to \frac{1}{\sqrt{2}}(|D^0>_1|\bar{D}^0>_2 - |\bar{D}^0>_1|D^0>_2)$$

Measure many different pairs of final states (i,j):

$$\frac{\Gamma(i,j)}{B_iB_j} = f_{ij}(B_i, B_j, r_i, r_j, R_i, R_j, \delta_i, \delta_j, x, y) \propto \frac{N(i,j)}{B_iB_j}$$

Different (i,j) produce different parameter dependences:

	Final State	r_i	δ_i	$R_i\cos\delta_i$	$R_i\sin\delta_i$	$\mathcal{B}_{\bar{i}}/\mathcal{B}_i$
	$K^\mp\pi^\pm$	r	δ	$\cos\delta$	$\sin\delta$	R_{WS}
($K_S\pi^+\pi^-$)	$Y_k/\bar{Y}_k$	ρ_k	·	c_k	s_k	Q_k
(CP+)	S_+	1	π	-1	0	1
(CP−)	S_-	1	0	$+1$	0	1
(semilep.)	$\ell^\pm$	0	—	—	—	0

Create an overconstrained system and fit.

CLEO (legacy), "Updated measurement of the strong phase in $D^0 \to K^+\pi^-$ decay using quantum correlations in $e^+e^- \to D^0\bar{D}^0$ at CLEO," PRD 86, 112001 (2012)

CLEO: 261 measurements;
51 free parameters;
no external dependencies

Strengths of CLEO/BES/τcF: (1) *Quantum Correlations — a global fit*

Mode	Correlated
$K^-\pi^+$	$1+R_{\mathrm{WS}}$
S_+	2
S_-	2
Y_k	$1+Q_k$
$K^-\pi^+,\ K^-\pi^+$	$R_{\mathrm{M}}[(1+R_{\mathrm{WS}})^2-4r\cos\delta(r\cos\delta+y)]$
$K^-\pi^+,\ K^+\pi^-$	$(1+R_{\mathrm{WS}})^2-4r\cos\delta(r\cos\delta+y)$
$K^-\pi^+,\ S_+$	$1+R_{\mathrm{WS}}+2r\cos\delta+y$
$K^-\pi^+,\ S_-$	$1+R_{\mathrm{WS}}-2r\cos\delta-y$
$K^-\pi^+,\ \ell^-$	$1-ry\cos\delta-rx\sin\delta$
$K^-\pi^+,\ \ell^+$	$r^2(1-ry\cos\delta-rx\sin\delta)$
$K^-\pi^+,\ \bar{Y}_i$	$(1+R_{\mathrm{WS}})(1+Q_i)-r^2-\rho_i^2$ $-2(r\cos\delta+y)(\rho_i c_i+y)+2r\sin\delta\rho_i s_i$
$K^-\pi^+,\ Y_i$	$(1+R_{\mathrm{WS}})(1+Q_i)-1-r^2\rho_i^2$ $-2(r\cos\delta+y)(\rho_i c_i+y)-2r\sin\delta\rho_i s_i$
$S_+,\ S_+$	0
$S_-,\ S_-$	0
$S_+,\ S_-$	4
$S_+,\ \ell^-$	$1+y$
$S_-,\ \ell^-$	$1-y$
$S_+,\ Y_i$	$1+Q_i+2\rho_i c_i+y$
$S_-,\ Y_i$	$1+Q_i-2\rho_i c_i-y$
$Y_i,\ \ell^-$	$1-\rho_i y c_i-\rho_i x s_i$
$Y_i,\ \ell^+$	$\rho_i^2(1-\rho_i y c_i-\rho_i x s_i)$
$Y_i,\ \bar{Y}_j$	$(1+Q_i)(1+Q_j)-\rho_i^2-\rho_j^2$ $-2(\rho_i c_i+y)(\rho_j c_j+y)+2\rho_i s_i\rho_j s_j$
$Y_i,\ Y_j$	$(1+Q_i)(1+Q_j)-1-\rho_i^2\rho_j^2$ $-2(\rho_i c_i+y)(\rho_j c_j+y)-2\rho_i s_i\rho_j s_j$

Exploit quantum correlations in ψ(3770) decays:

$$|\psi> \to \frac{1}{\sqrt{2}}(|D^0>_1|\bar{D}^0>_2 - |\bar{D}^0>_1|D^0>_2)$$

Measure many different pairs of final states (i,j):

$$\frac{\Gamma(i,j)}{B_iB_j} = f_{ij}(B_i,B_j,r_i,r_j,R_i,R_j,\delta_i,\delta_j,x,y) \propto \frac{N(i,j)}{B_iB_j}$$

Different (i,j) produce different parameter dependences:

	Final State	r_i	δ_i	$R_i\cos\delta_i$	$R_i\sin\delta_i$	$\mathcal{B}_{\bar{i}}/\mathcal{B}_i$
	$K^\mp\pi^\pm$	r	δ	$\cos\delta$	$\sin\delta$	R_{WS}
($K_S\pi^+\pi^-$)	$Y_k/\bar{Y}_k$	ρ_k	$\cdot$	c_k	s_k	Q_k
(CP+)	S_+	1	π	-1	0	1
(CP−)	S_-	1	0	$+1$	0	1
(semilep.)	$\ell^\pm$	0	—	—	—	0

Create an overconstrained system and fit.

n $D^0 \to K^+\pi^-$
PRD 86, 112001

CLEO: 261 measurements;
51 free parameters;
no external dependencies

Strengths of CLEO/BES/τcF: (1) *Quantum Correlations — a global fit*

Terminology/

Amplitudes t

$A_i \equiv A(D^0$

$\bar{A}_i \equiv A(\bar{D}^0$

Ratio of ampl

$r_i \equiv \frac{|\bar{A}_i|}{|A_i|}$

Strong phase

$R_i e^{-i\delta_i} \equiv$

For the 2-bod

$R_i = 1; \quad r_i$

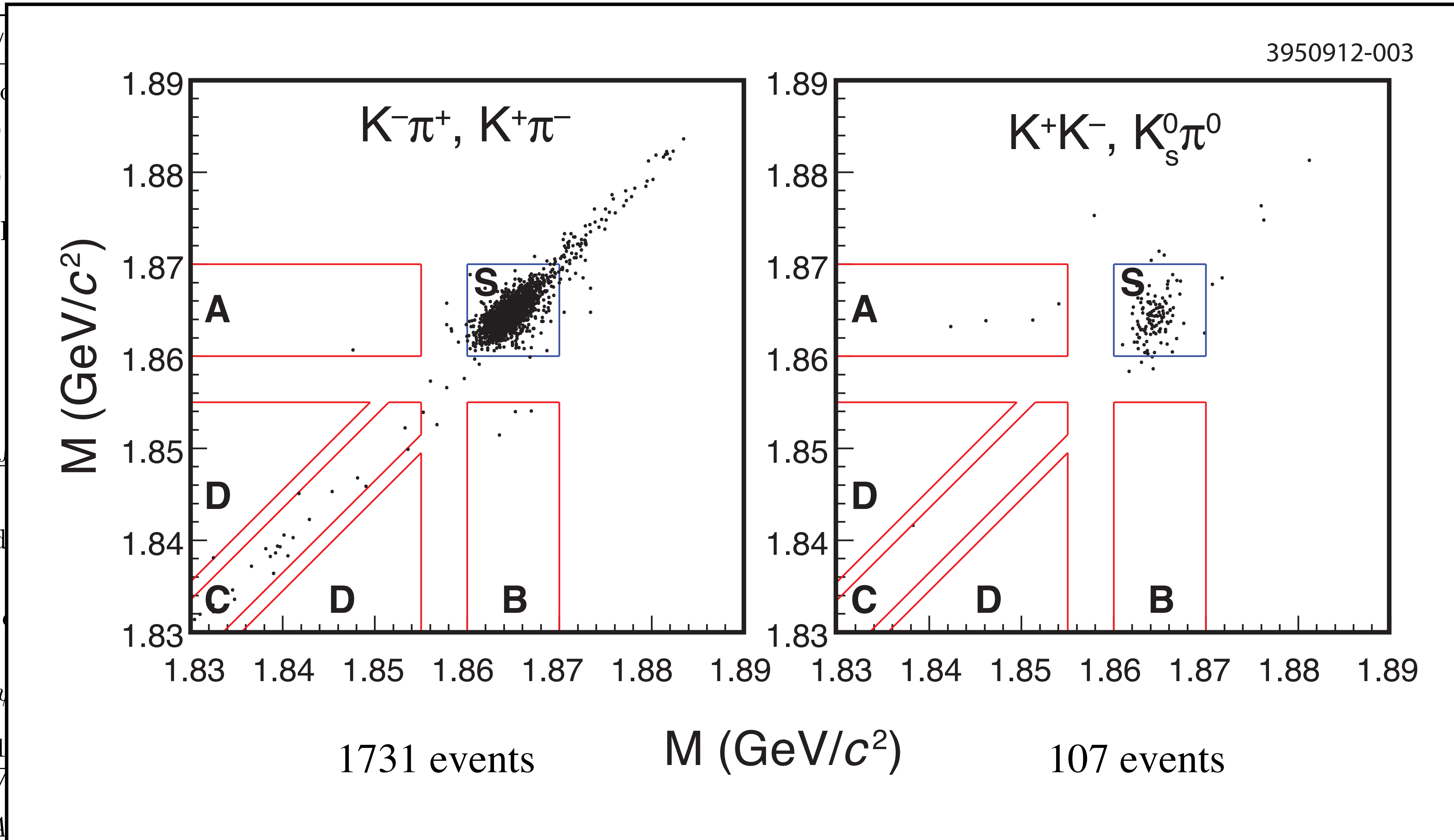
For $e^+e^- \to \psi$

$\Gamma(i,j) = \frac{1}{\sqrt{\ }}$

$= |A$

$B_i \equiv B(D^0 \to i) = |A_i + \bar{A}_i A(D^0 \to \bar{D}^0)|^2$

$= |A_i|^2 \left[1 + r_i R_i (y \cos\delta_i + x \sin\delta_i)\right]$



1731 events

107 events

$i, j)$

B_j

nces:

Create an overconstrained system and fit.

CLEO: 261 measurements;
51 free parameters;
no external dependencies

CLEO (legacy), "Updated measurement of the strong phase in $D^0 \to K^+\pi^-$ decay using quantum correlations in $e^+e^- \to D^0\bar{D}^0$ at CLEO," PRD 86, 112001 (2012)

Strengths of CLEO/BES/τcF: (1) *Quantum Correlations — a global fit*

Terminology/Formulae/Definiti

Amplitudes to a final state i:

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Ratio of amplitudes:

$$r_i \equiv \frac{|\bar{A}_i|}{|A_i|}$$

Strong phase between A_i and $\bar{A}$

$$R_i e^{-i\delta_i} \equiv \frac{\int \bar{A}_i A_i^* dx_i}{|A_i||\bar{A}_i|}$$

For the 2-body case:

$$R_i = 1; \quad r_i e^{-i\delta_i} = \frac{\bar{A}_i}{A_i}$$

For $e^+e^- \to \psi(3770) \to D^0\bar{D}^0$ -

$$\Gamma(i,j) = \frac{1}{\sqrt{2}} \int |A_i\bar{A}_j - \bar{A}_i A_j$$
$$= |A_i|^2|A_j|^2 \left[r_i^2 + r_j^2 -\right.$$
$$B_i \equiv B(D^0 \to i) = |A_i +$$
$$= |A_i|^2 \left[1 + r_i R_i (y \cos\right.$$

CLEO (legacy), "Updated meas
decay using quantum correlations
(2012)

Parameter	Standard Fit
$\mathcal{N}$ (10^6)	$3.092 \pm 0.050 \pm 0.040$
y (%)	$4.2 \pm 2.0 \pm 1.0$
r^2 (%)	$0.533 \pm 0.107 \pm 0.045$
$\cos\delta$	$0.81^{+0.22+0.07}_{-0.18-0.05}$
$\sin\delta$	$-0.01 \pm 0.41 \pm 0.04$
x^2 (%)	$0.06 \pm 0.23 \pm 0.11$
ρ_0^2	$0.337 \pm 0.030 \pm 0.006$
ρ_1^2	$0.270 \pm 0.044 \pm 0.005$
ρ_2^2	$0.235 \pm 0.028 \pm 0.003$
ρ_3^2	$0.399 \pm 0.066 \pm 0.005$
ρ_4^2	$0.592 \pm 0.067 \pm 0.010$
ρ_5^2	$0.343 \pm 0.044 \pm 0.000$
ρ_6^2	$0.146 \pm 0.023 \pm 0.000$
ρ_7^2	$0.445 \pm 0.039 \pm 0.002$
c_0	$-0.76 \pm 0.06 \pm 0.01$
c_1	$-0.75 \pm 0.11 \pm 0.00$
c_2	$0.00 \pm 0.10 \pm 0.01$
c_3	$0.45 \pm 0.15 \pm 0.01$
c_4	$0.95 \pm 0.07 \pm 0.01$
c_5	$0.79 \pm 0.09 \pm 0.01$
c_6	$-0.20 \pm 0.13 \pm 0.02$
c_7	$-0.41 \pm 0.07 \pm 0.01$
s_0	$0.55 \pm 0.16 \pm 0.00$
s_1	$0.53 \pm 0.28 \pm 0.00$
s_2	$0.93 \pm 0.15 \pm 0.00$
s_3	$0.47 \pm 0.30 \pm 0.00$
s_4	$0.55 \pm 0.24 \pm 0.00$
s_5	$-0.71 \pm 0.24 \pm 0.00$
s_6	$-0.42 \pm 0.27 \pm 0.06$
s_7	$-0.30 \pm 0.18 \pm 0.04$
χ^2_{fit}/ndof	193.2/210

Parameter	Standard Fit
$\mathcal{B}(K^-\pi^+)$ (%)	$3.77 \pm 0.06 \pm 0.05$
$\mathcal{B}(K^-K^+)$ (10^{-3})	$3.99 \pm 0.07 \pm 0.08$
$\mathcal{B}(\pi^-\pi^+)$ (10^{-3})	$1.36 \pm 0.03 \pm 0.04$
$\mathcal{B}(K_S^0\pi^0\pi^0)$ (%)	$0.99 \pm 0.02 \pm 0.06$
$\mathcal{B}(K_L^0\pi^0)$ (%)	$0.94 \pm 0.03 \pm 0.03$
$\mathcal{B}(K_L^0\eta)$ (10^{-3})	$3.36 \pm 0.30 \pm 0.17$
$\mathcal{B}(K_L^0\omega)$ (%)	$0.90 \pm 0.05 \pm 0.03$
$\mathcal{B}(K_S^0\pi^0)$ (%)	$1.17 \pm 0.02 \pm 0.03$
$\mathcal{B}(K_S^0\eta)$ (10^{-3})	$4.95 \pm 0.14 \pm 0.36$
$\mathcal{B}(K_S^0\omega)$ (%)	$1.15 \pm 0.02 \pm 0.04$
$\mathcal{B}(K_L^0\pi^0\pi^0)$ (%)	$0.95 \pm 0.06 \pm 0.05$
$\mathcal{B}(K^-e^+\nu_e)$ (%)	$3.54 \pm 0.05 \pm 0.08$
$\mathcal{B}(K^-\mu^+\nu_\mu)$ (%)	$3.38 \pm 0.05 \pm 0.08$
$\mathcal{B}(Y_0)$ (10^{-3})	$4.38 \pm 0.18 \pm 0.12$
$\mathcal{B}(Y_1)$ (10^{-3})	$1.65 \pm 0.10 \pm 0.04$
$\mathcal{B}(Y_2)$ (10^{-3})	$3.43 \pm 0.16 \pm 0.10$
$\mathcal{B}(Y_3)$ (10^{-3})	$0.99 \pm 0.08 \pm 0.03$
$\mathcal{B}(Y_4)$ (10^{-3})	$1.70 \pm 0.11 \pm 0.05$
$\mathcal{B}(Y_5)$ (10^{-3})	$2.11 \pm 0.13 \pm 0.07$
$\mathcal{B}(Y_6)$ (10^{-3})	$3.15 \pm 0.15 \pm 0.08$
$\mathcal{B}(Y_7)$ (10^{-3})	$3.68 \pm 0.16 \pm 0.09$

ecays:

$^0 >_2)$

s (i,j):

$, y) \propto \dfrac{N(i,j)}{B_i B_j}$

dependences:

$\mathcal{B}_{\bar{i}}/\mathcal{B}_i$
R_{WS}
Q_k
1
1
0

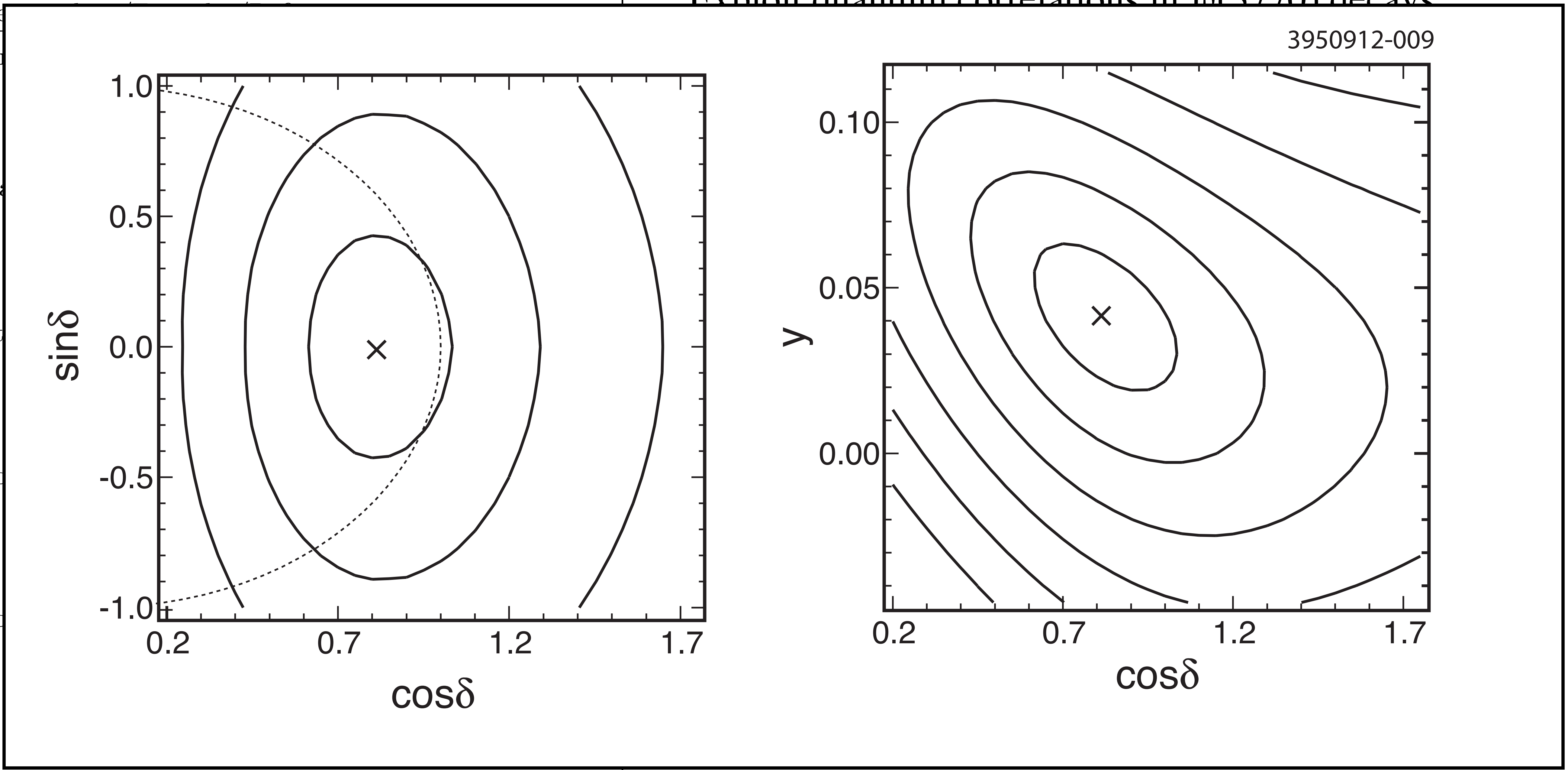
s;

rs;

no external dependencies

Strengths of CLEO/BES/τcF: (1) *Quantum Correlations — a global fit*

Exploit quantum correlations in ψ(3770) decays:



$$B_i \equiv B(D^0 \to i) = |A_i + \bar{A}_i A(D^0 \to \bar{D}^0)|^2$$
$$= |A_i|^2 \left[1 + r_i R_i (y \cos\delta_i + x \sin\delta_i)\right]$$

Create an overconstrained system and fit.

CLEO (legacy), "Updated measurement of the strong phase in $D^0 \to K^+\pi^-$ decay using quantum correlations in $e^+e^- \to D^0\bar{D}^0$ at CLEO," PRD 86, 112001 (2012)

CLEO: 261 measurements;
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Ratio of amplitudes:

$$r_i \equiv \frac{|\bar{A}_i|}{|A_i|}$$

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For the 2-body case:

$$R_i = 1; \quad r_i e^{-i\delta_i} = \frac{\bar{A}_i}{A_i}$$

For $e^+e^- \to \psi(3770) \to D^0\bar{D}^0 \to (i,j)$:

$$\Gamma(i,j) = \frac{1}{\sqrt{2}} \int |A_i\bar{A}_j - \bar{A}_i A_j|^2 dx_i dx_j$$
$$= |A_i|^2|A_j|^2 \left[r_i^2 + r_j^2 - 2\mathrm{Re}(r_i R_i e^{i\delta_i} r_j R_j e^{-i\delta_j})\right]$$
$$B_i \equiv B(D^0 \to i) = |A_i + \bar{A}_i A(D^0 \to \bar{D}^0)|^2$$
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Measure many different pairs of final states (i,j):

$$\frac{\Gamma(i,j)}{B_i B_j} = f_{ij}(B_i, B_j, r_i, r_j, R_i, R_j, \delta_i, \delta_j, x, y) \propto \frac{N(i,j)}{B_i B_j}$$

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	Final State	r_i	δ_i	$R_i \cos\delta_i$	$R_i \sin\delta_i$	$\mathcal{B}_{\bar{i}}/\mathcal{B}_i$
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($K_S\pi^+\pi^-$)	$Y_k/\bar{Y}_k$	ρ_k	$\cdot$	c_k	s_k	Q_k
(CP+)	S_+	1	π	-1	0	1
(CP−)	S_-	1	0	$+1$	0	1
(semilep.)	$\ell^\pm$	0	—	—	—	0

Create an overconstrained system and fit.

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CLEO: 261 measurements;
51 free parameters;
no external dependencies

Strengths of CLEO/BES/τcF: (1) *Quantum Correlations — the (S,Kπ) piece*

Terminology/Formulae/Definitions:

Amplitudes to a final state i:

$$A_i \equiv A(D^0 \to i)$$
$$\bar{A}_i \equiv A(\bar{D}^0 \to i)$$

Ratio of amplitudes:

$$r_i \equiv \frac{|\bar{A}_i|}{|A_i|}$$

Strong phase between A_i and $\bar{A}_i$:

$$R_i e^{-i\delta_i} \equiv \frac{\int \bar{A}_i A_i^* dx_i}{|A_i||\bar{A}_i|}$$

For the 2-body case:

$$R_i = 1; \quad r_i e^{-i\delta_i} = \frac{\bar{A}_i}{A_i}$$

For $e^+e^- \to \psi(3770) \to D^0\bar{D}^0 \to (i,j)$:

$$\begin{aligned}\Gamma(i,j) &= \frac{1}{\sqrt{2}}\int |A_i\bar{A}_j - \bar{A}_i A_j|^2 dx_i dx_j \\ &= |A_i|^2|A_j|^2\left[r_i^2 + r_j^2 - 2\mathrm{Re}(r_i R_i e^{i\delta_i} r_j R_j e^{-i\delta_j})\right] \\ B_i \equiv B(D^0 \to i) &= |A_i + \bar{A}_i A(D^0 \to \bar{D}^0)|^2 \\ &= |A_i|^2\left[1 + r_i R_i(y\cos\delta_i + x\sin\delta_i)\right]\end{aligned}$$

BESIII looked specifically at final states ($K^-\pi^+$, $S^\pm$) to determine $\delta_{K\pi}$:

$$\begin{aligned}A^{CP}_{K\pi} &\equiv \frac{B(D^{S-} \to K^-\pi^+) - B(D^{S+} \to K^-\pi^+)}{B(D^{S-} \to K^-\pi^+) + B(D^{S+} \to K^-\pi^+)} \\ &= \frac{2r\cos\delta_{K\pi} + y}{1 + R_{WS}}\end{aligned}$$

Final states included:

Type	Mode
Flavored	$K^-\pi^+$, $K^+\pi^-$
$S+$	K^+K^-, $\pi^+\pi^-$, $K^0_S\pi^0\pi^0$, $\pi^0\pi^0$, $\rho^0\pi^0$
$S-$	$K^0_S\pi^0$, $K^0_S\eta$, $K^0_S\omega$

Use external r, y, R_{WS} as input to extract $\delta_{K\pi}$:

$$\cos\delta_{K\pi} = 1.02 \pm 0.11 \pm 0.06 \pm 0.01$$

BESIII, "Measurement of the $D \to K^-\pi^+$ strong phase difference in $\psi(3770) \to D^0\bar{D}^0$," PLB 734, 227 (2014)

Strengths of CLEO/BES/τcF: (1) *Quantum Correlations — the (S,Kπ) piece*

Terminology/Formulae/Definitions:

Amplitudes to a final state i:

$A_i \equiv A(D^0 \to i)$

$\bar{A}_i \equiv$

Ratio

$r_i \equiv$

Strong

$R_i e$

For th

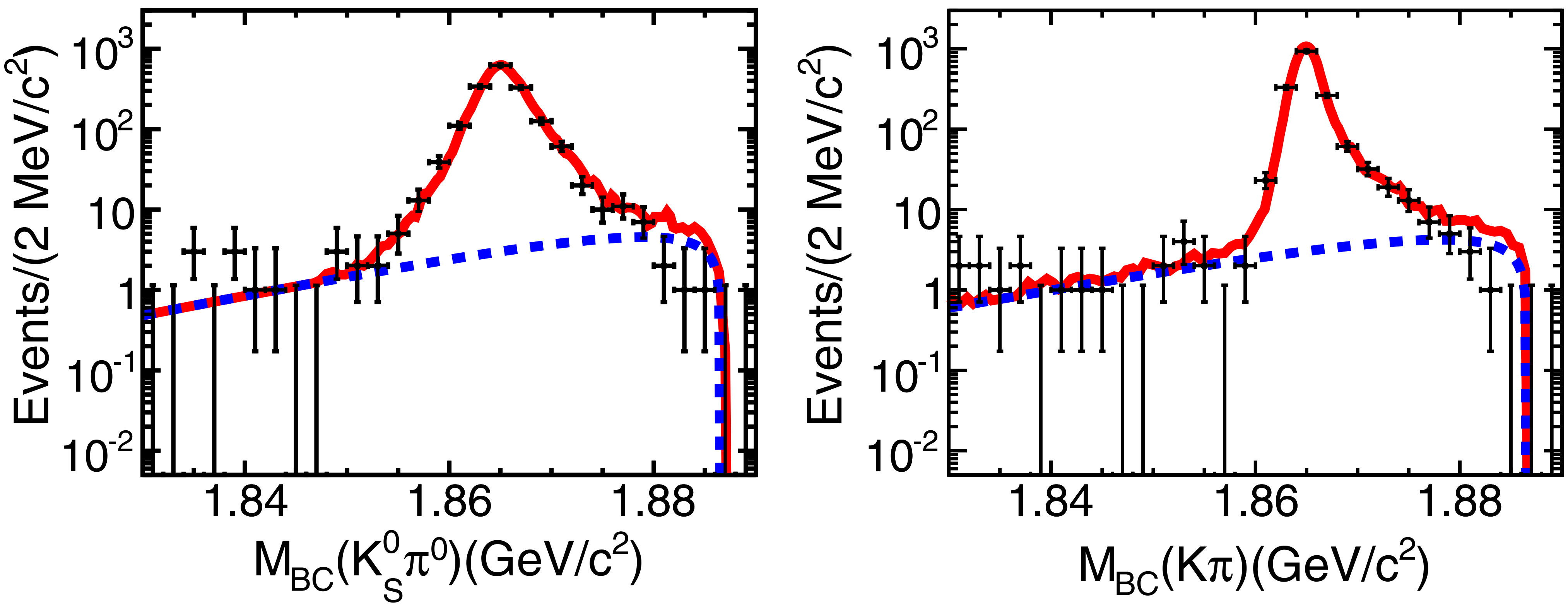
$R_i =$

For e^+

$\Gamma(i,$

BESIII looked specifically at final states ($K^-\pi^+$, $S^\pm$) to determine $\delta_{K\pi}$:

Largest double-tag combination ($K^-\pi^+$, $K_S\pi^0$):



1689 events

$$\cos\delta_{K\pi} = 1.02 \pm 0.11 \pm 0.06 \pm 0.01$$

BESIII, "Measurement of the $D \to K^-\pi^+$ strong phase difference in $\psi(3770) \to D^0\bar{D}^0$," PLB 734, 227 (2014)

Strengths of CLEO/BES/τcF: (1) *Quantum Correlations — the (S,l) piece*

Terminology/Formulae/Definitions:

Amplitudes to a final state i:

$$A_i \equiv A(D^0 \to i)$$
$$\bar{A}_i \equiv A(\bar{D}^0 \to i)$$

Ratio of amplitudes:

$$r_i \equiv \frac{|\bar{A}_i|}{|A_i|}$$

Strong phase between A_i and $\bar{A}_i$:

$$R_i e^{-i\delta_i} \equiv \frac{\int \bar{A}_i A_i^* dx_i}{|A_i||\bar{A}_i|}$$

For the 2-body case:

$$R_i = 1; \quad r_i e^{-i\delta_i} = \frac{\bar{A}_i}{A_i}$$

For $e^+e^- \to \psi(3770) \to D^0\bar{D}^0 \to (i,j)$:

$$\Gamma(i,j) = \frac{1}{\sqrt{2}} \int |A_i\bar{A}_j - \bar{A}_i A_j|^2 dx_i dx_j$$
$$= |A_i|^2|A_j|^2 \left[r_i^2 + r_j^2 - 2\mathrm{Re}(r_i R_i e^{i\delta_i} r_j R_j e^{-i\delta_j})\right]$$
$$B_i \equiv B(D^0 \to i) = |A_i + \bar{A}_i A(D^0 \to \bar{D}^0)|^2$$
$$= |A_i|^2 \left[1 + r_i R_i (y\cos\delta_i + x\sin\delta_i)\right]$$

BESIII also looked specifically at final states ($l^{\pm}$, $S^{\pm}$) to determine y_{CP}:

$$y_{CP} \approx \frac{1}{4}\left(\frac{B(D^{S-} \to l)}{B(D^{S+} \to l)} - \frac{B(D^{S+} \to l)}{B(D^{S-} \to l)}\right)$$

Final states included:

Type	Mode
CP+	K^+K^-, $\pi^+\pi^-$, $K_S^0\pi^0\pi^0$
CP−	$K_S^0\pi^0$, $K_S^0\omega$, $K_S^0\eta$
Semileptonic	$K^{\mp}e^{\pm}\nu$, $K^{\mp}\mu^{\pm}\nu$

Directly extract y_{CP} (no external parameters):

$$y_{CP} = (-2.0 \pm 1.3 \pm 0.7)\%$$

(clean, but less precise than other methods: HFLAV 2016: (0.835 ± 0.155)%)

BESIII, "Measurement of y_{CP} in D^0-$\bar{D}^0$ oscillation using quantum correlations in $e^+e^- \to D^0\bar{D}^0$ at $\sqrt{s} = 3.773$ GeV," PLB 744, 339 (2015)

Strengths of CLEO/BES/τcF: (1) *Quantum Correlations — the (S,l) piece*

Terminology/Formulae/Definitions:

Amplitude

$A_i \equiv A($

$\bar{A}_i \equiv A($

Ratio of ar

$r_i \equiv \frac{|\bar{A}_i}{|A_i}$

Strong pha

$R_i e^{-i\delta_i}$

For the 2-b

$R_i = 1;$

For e^+e^-

$\Gamma(i,j) =$

$=$

$B_i \equiv$

$=$

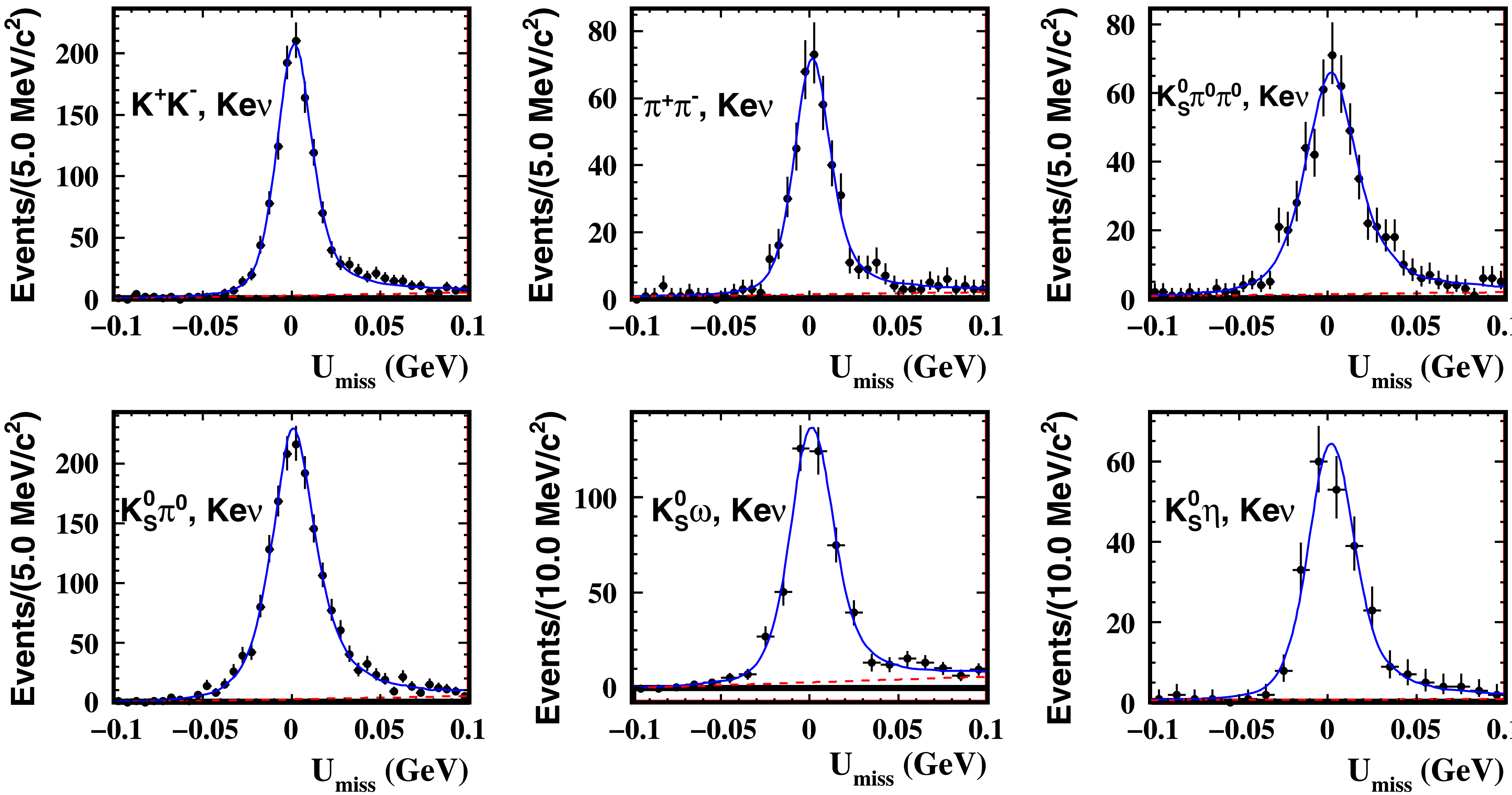
±)

$l)$

$l)$

$\pi^0\pi^0$

The double-tag combinations with Keν:



largest ($K_S\pi^0$, Keν) has 1699 events

$$U_{\text{miss}} \equiv E_{\text{miss}} - cp_{\text{miss}}$$

BESIII, "Measurement of y_{CP} in D^0-$\bar{D}^0$ oscillation using quantum correlations in $e^+e^- \to D^0\bar{D}^0$ at $\sqrt{s} = 3.773$ GeV," PLB 744, 339 (2015)

ods:

HFLAV 2016: (0.835 ± 155)%)

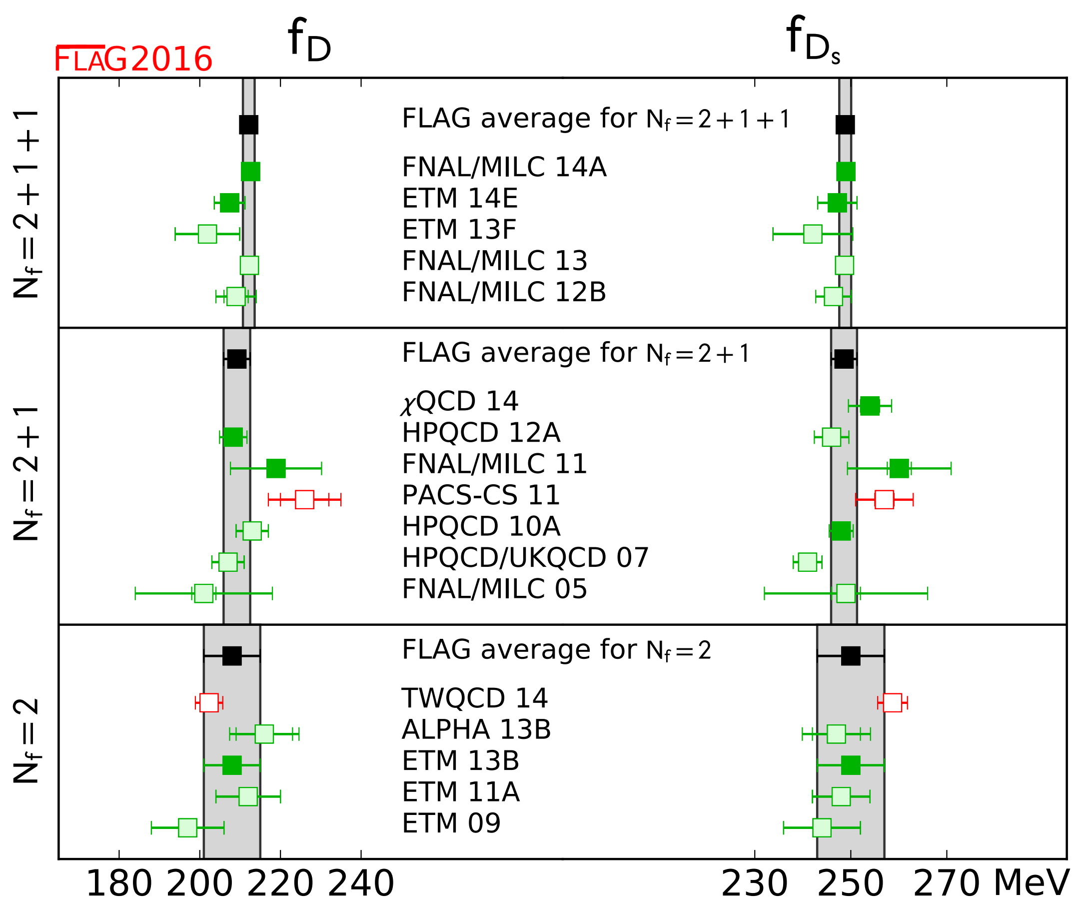
Strengths of CLEO/BES/τcF: (2) *Leptonic decays — $D^+ \to \mu^+\nu_\mu$*

Terminology/Formulae/Definitions:

Leptonic decays of the D and D_s:

$$B(D_{(s)} \to l\nu) = G_F^2 |V_{cq}|^2 f_{D_{(s)}}^2 \times \frac{\tau_{D_{(s)}} m_l^2 m_{D_{(s)}}}{8\pi} \left(1 - \frac{m_l^2}{m_{D_{(s)}}^2}\right)^2$$

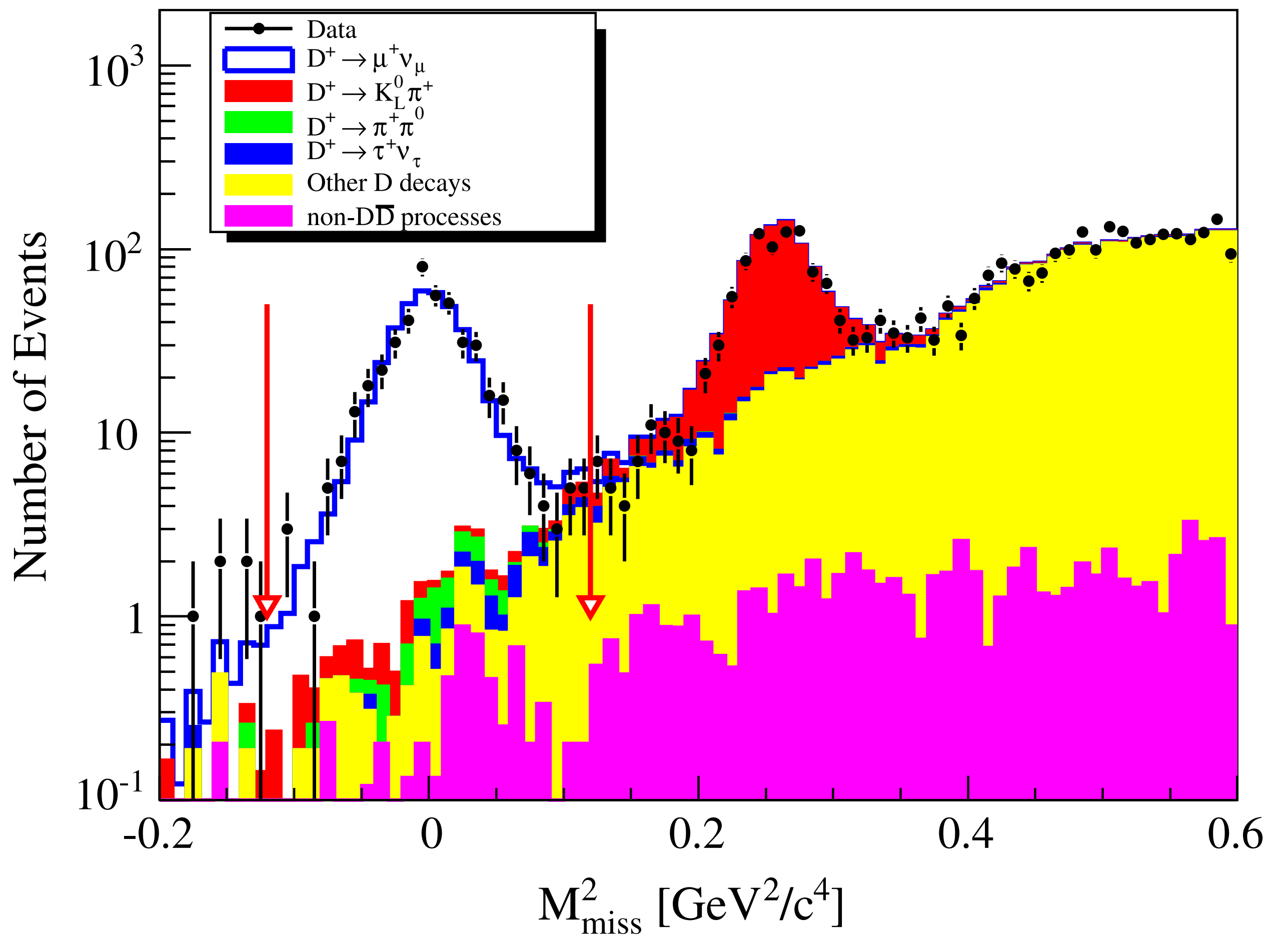
Lattice QCD results:



212.15(1.45) MeV **248.83(1.27) MeV**

BESIII has the most precise measurement of $D^+ \to \mu^+\nu_\mu$:

(3fb^{-1} at ψ(3770))



$$f_{D^+} = (203.2 \pm 5.3 \pm 1.8)\ \mathrm{MeV}$$

(still statistics limited)

BESIII, "Precision measurements of $B(D^+ \to \mu^+\nu_\mu)$, the pseudoscalar decay constant f_{D^+}, and the quark mixing matrix element $|V_{cd}|$," PRD 89, 051104(R) (2014)

Strengths of CLEO/BES/τcF: (2) *Leptonic decays — $D^+ \to \tau^+\nu_\tau$*

Terminology/Formulae/Definitions:

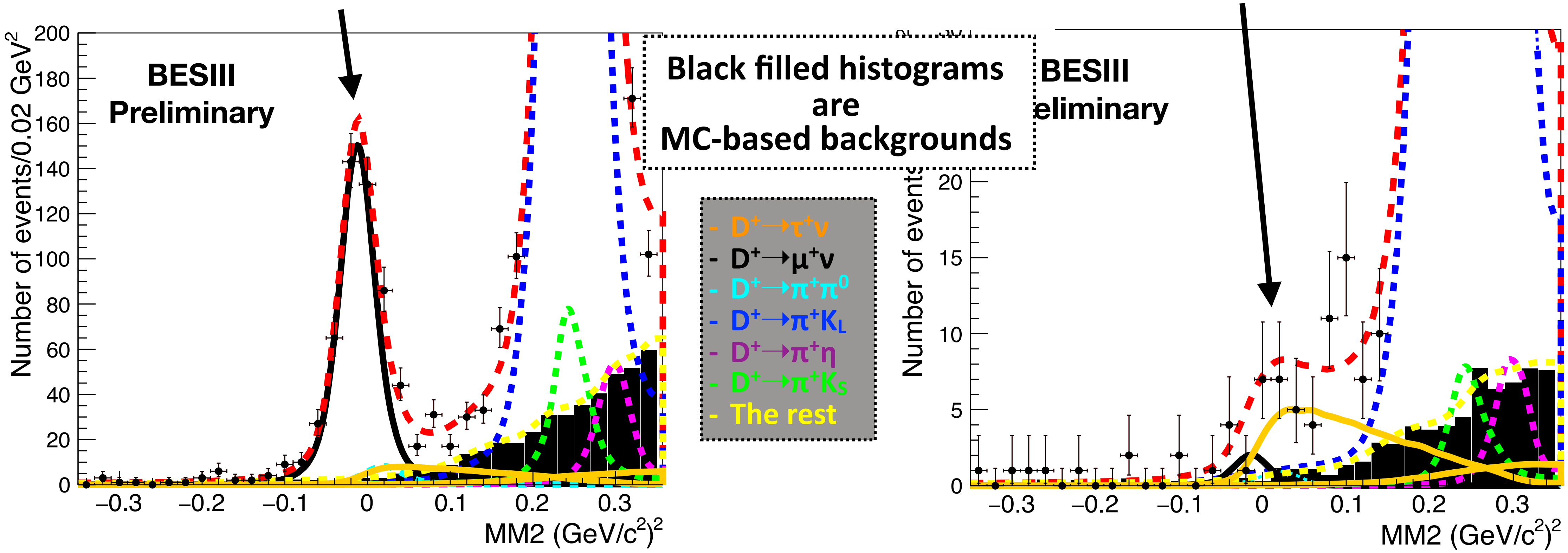
Leptonic decays of the D and D_s:

$$B(D_{(s)} \to l\nu) = G_F^2 |V_{cq}|^2 f_{D_{(s)}}^2 \times \frac{\tau_{D_{(s)}} m_l^2 m_{D_{(s)}}}{8\pi} \left(1 - \frac{m_l^2}{m_{D_{(s)}}^2}\right)^2$$

BESIII has first evidence for $D^+ \to \tau^+\nu_\tau$:
(137 ± 27 events)

Select $D^+ \to \mu^+\nu_\mu$
(Ecal < 300 MeV)

Select $D^+ \to \tau^+\nu_\mu$ ($\tau^+ \to \pi^+\bar{\nu}_\tau$)
(Ecal > 300 MeV)



$$\frac{B(D^+ \to \tau^+\nu_\tau)}{B(D^+ \to \mu^+\nu_\mu)} = 3.21 \pm 0.64_{\text{stat}}$$

(SM expectation = 2.66 ± 0.01)

BESIII, "First evidence for $D^+ \to \tau^+\nu_\tau$," preliminary (2016)

Strengths of CLEO/BES/τcF: (2) *Leptonic decays* — $D_s^+ \to \mu^+\nu_\mu$

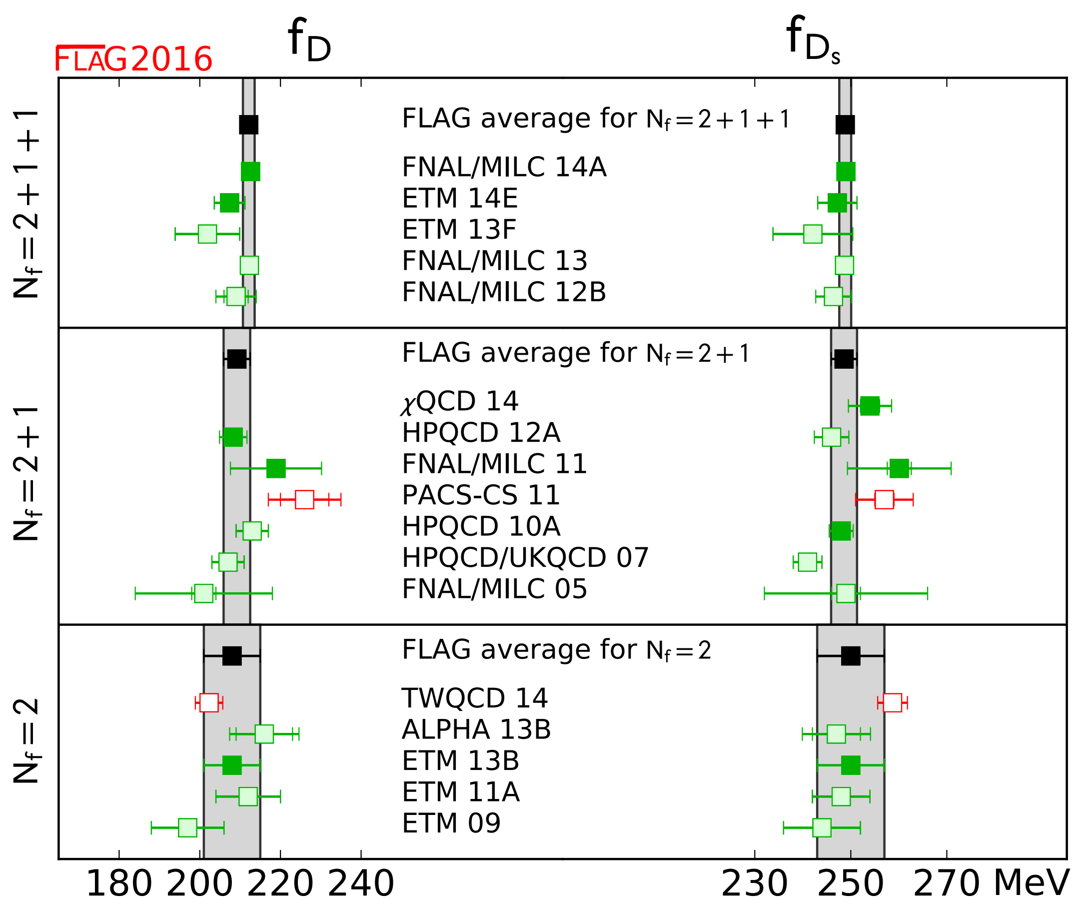
Terminology/Formulae/Definitions:

Leptonic decays of the D and D_s:

$$B(D_{(s)} \to l\nu) = G_F^2 |V_{cq}|^2 f_{D_{(s)}}^2 \times \frac{\tau_{D_{(s)}} m_l^2 m_{D_{(s)}}}{8\pi} \left(1 - \frac{m_l^2}{m_{D_{(s)}}^2}\right)^2$$

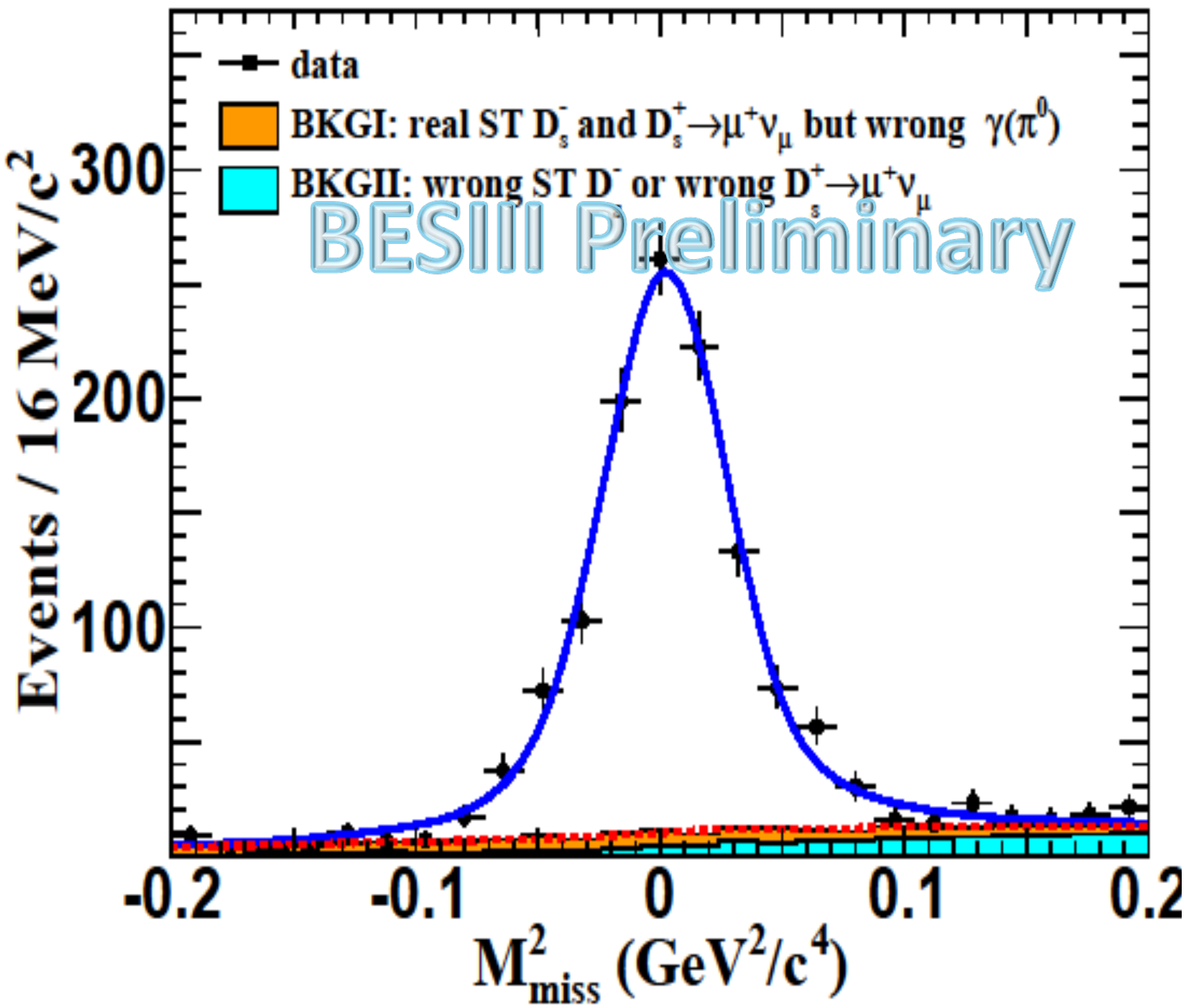
BESIII has the most precise measurement of $D_s^+ \to \mu^+\nu_\mu$:

Lattice QCD results:



212.15(1.45) MeV **248.83(1.27) MeV**

(3fb⁻¹ at 4180 MeV — DₛDₛ)*



$$f_{D_s} = (249.1 \pm 3.6 \pm 3.8)\ \mathrm{MeV}$$

BESIII, "Measurement of $D_s^+ \to \mu^+\nu_\mu$," preliminary (2017)

Strengths of CLEO/BES/τcF: (2) *Leptonic decays* — $D_s^+ \to \mu^+\nu_\mu$

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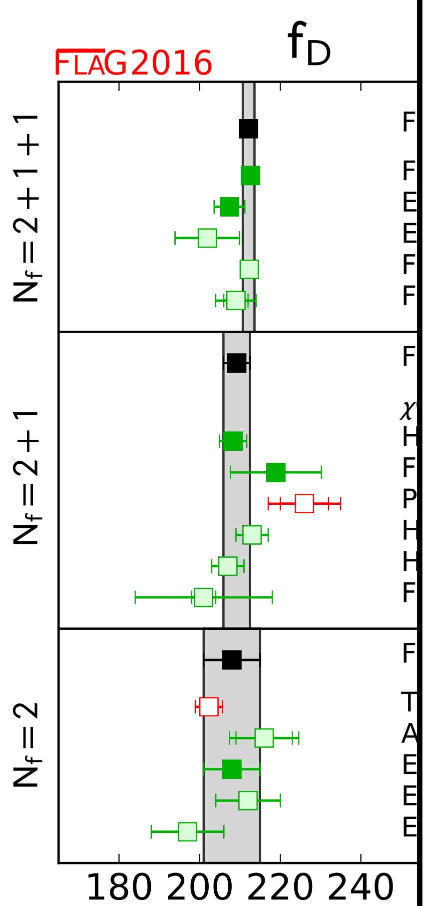
Leptonic decays of the D and D_s:

$$B(D_{(s)} \to l\nu) = G_F^2 \ldots$$

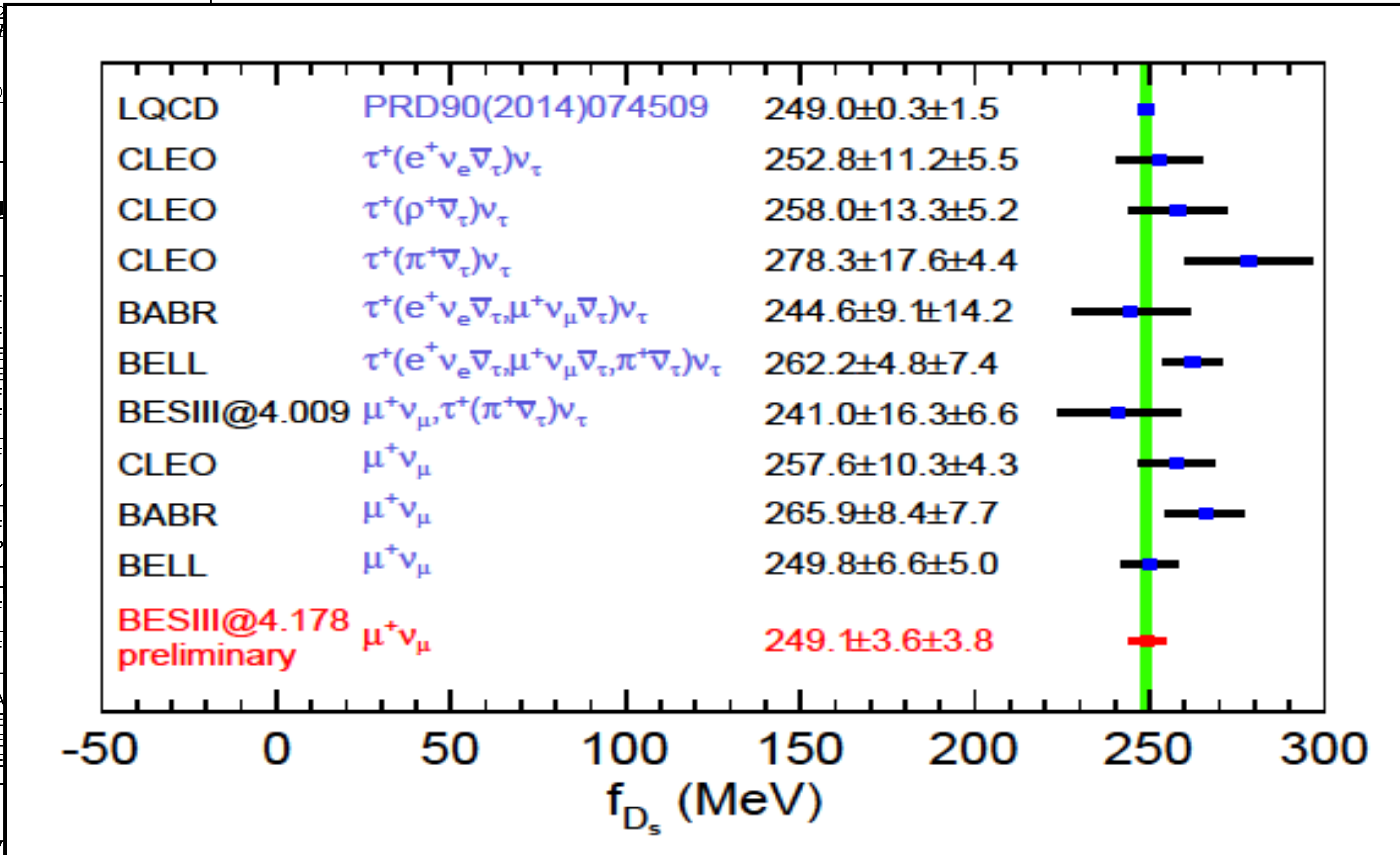
$$\times \frac{\tau_{D_{(s)}} m_l^2 m_{D_{(s)}}}{8\pi} \ldots$$

Lattice QCD resu...



212.15(1.45) MeV

BESIII has the most precise measurement of $D_s^+ \to \mu^+\nu_\mu$:

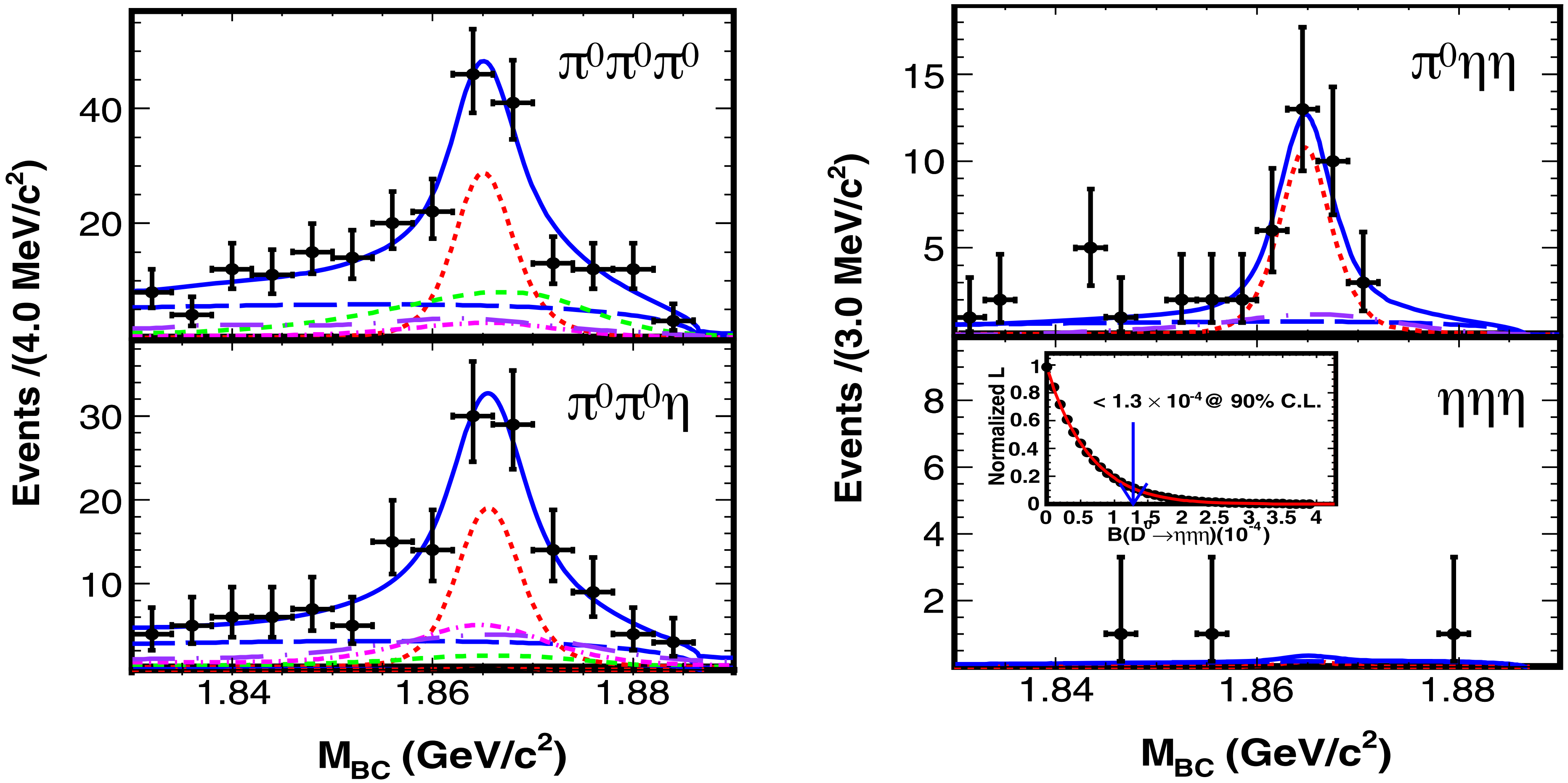


$$f_{D_s} = (249.1 \pm 3.6 \pm 3.8)\ \mathrm{MeV}$$

BESIII, "Measurement of $D_s^+ \to \mu^+\nu_\mu$," preliminary (2017)

Strengths of CLEO/BES/τcF: (3) *Hadronic decays — $D^0 \to 3(\pi^0/\eta)$*

BESIII is still finding new D^0 hadronic decays:

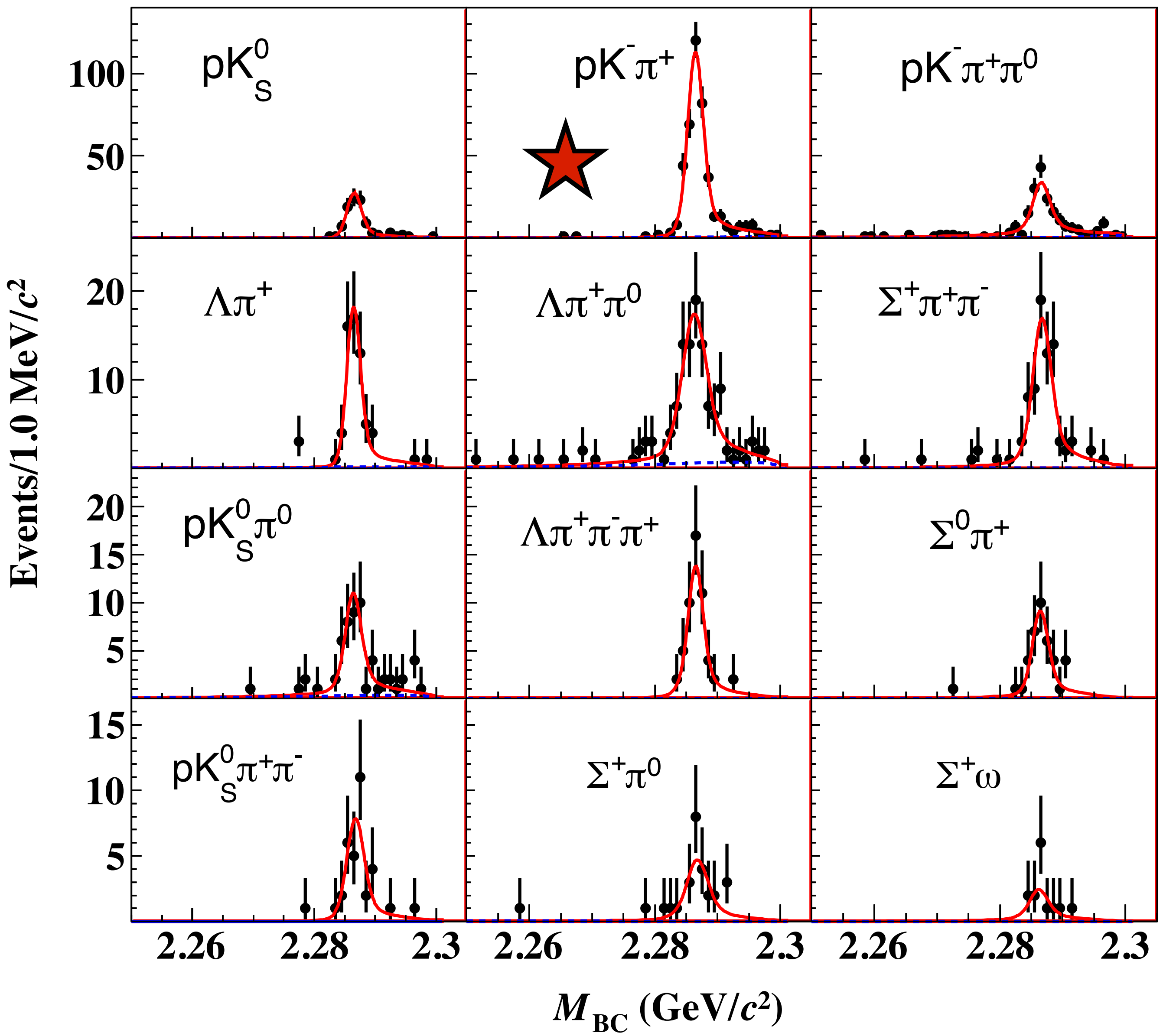


$$B(D^0 \to \pi^0\pi^0\pi^0) = (2.0 \pm 0.4 \pm 0.3) \times 10^{-4} \quad (4.8\sigma)$$
$$B(D^0 \to \pi^0\pi^0\eta) = (3.8 \pm 1.1 \pm 0.7) \times 10^{-4} \quad (3.8\sigma)$$
$$B(D^0 \to \pi^0\eta\eta) = (7.3 \pm 1.6 \pm 1.5) \times 10^{-4} \quad (5.5\sigma)$$
$$B(D^0 \to \eta\eta\eta) < 1.3 \times 10^{-4} \quad (90\% \text{ C.L.})$$

BESIII, "Measurement of singly Cabibbo-suppressed decays $D^0 \to \pi^0\pi^0\pi^0$, $\pi^0\pi^0\eta$, $\pi^0\eta\eta$, and $\eta\eta\eta$," PLB 781, 368 (2018)

Strengths of CLEO/BES/τcF: (4) *Charmed baryons — absolute BF's*

With 567 pb^{-1} of data at 4.6 GeV (200k Λ_c), measure absolute BF's with double-tags:



$$B(\Lambda_c^+ \to pK^-\pi^+) = (5.84 \pm 0.27 \pm 0.23)\%$$

But compare to the Belle measurement:

$$B(\Lambda_c^+ \to pK^-\pi^+) = (6.84 \pm 0.24^{+0.21}_{-0.27})\%$$

[Belle, PRL 113, 042002 (2014)]

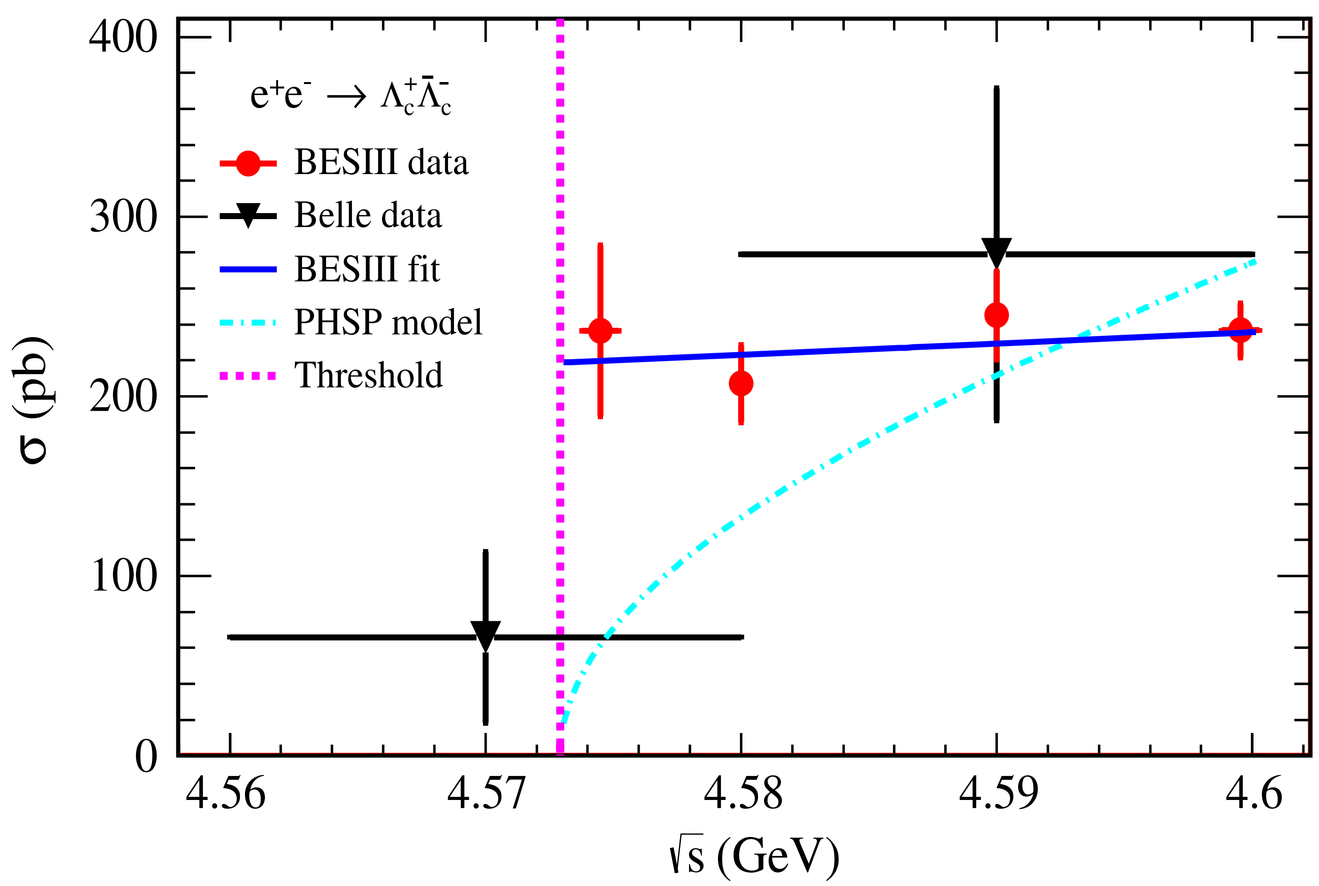
(A reminder that it is important to measure the same quantities with different techniques.)

With higher energies, access absolute BF's for other charmed baryons.

BESIII, "Measurements of absolute hadronic branching fractions of the Λ_c^+ baryon," PRL 116, 052001 (2016)

Strengths of CLEO/BES/τcF: (4) *Charmed baryons — $\sigma(e^+e^- \to \Lambda_c^+\Lambda_c^-)$*

Also study the production of charmed baryons…



$\sqrt{s}$ (MeV)	$\mathcal{L}_{\rm int}$ (pb^{-1})	$f_{\rm ISR}$	σ (pb)
4574.5	47.67	0.45	$236 \pm 11 \pm 46$
4580.0	8.54	0.66	$207 \pm 17 \pm 13$
4590.0	8.16	0.71	$245 \pm 19 \pm 16$
4599.5	566.93	0.74	$237 \pm 3 \pm 15$

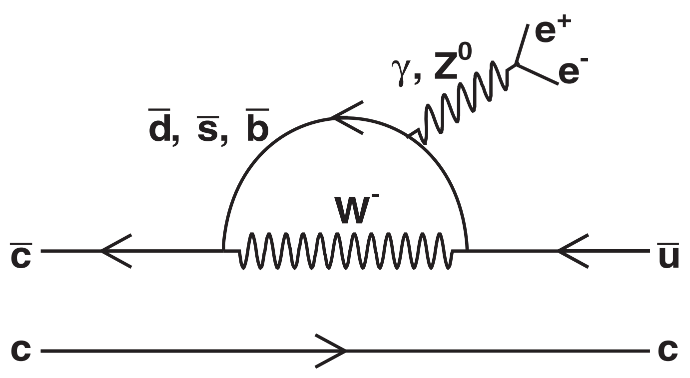
(interesting results even with small data sets)

Scanning in E_{CM} would be an important tool at a τ-charm factory.

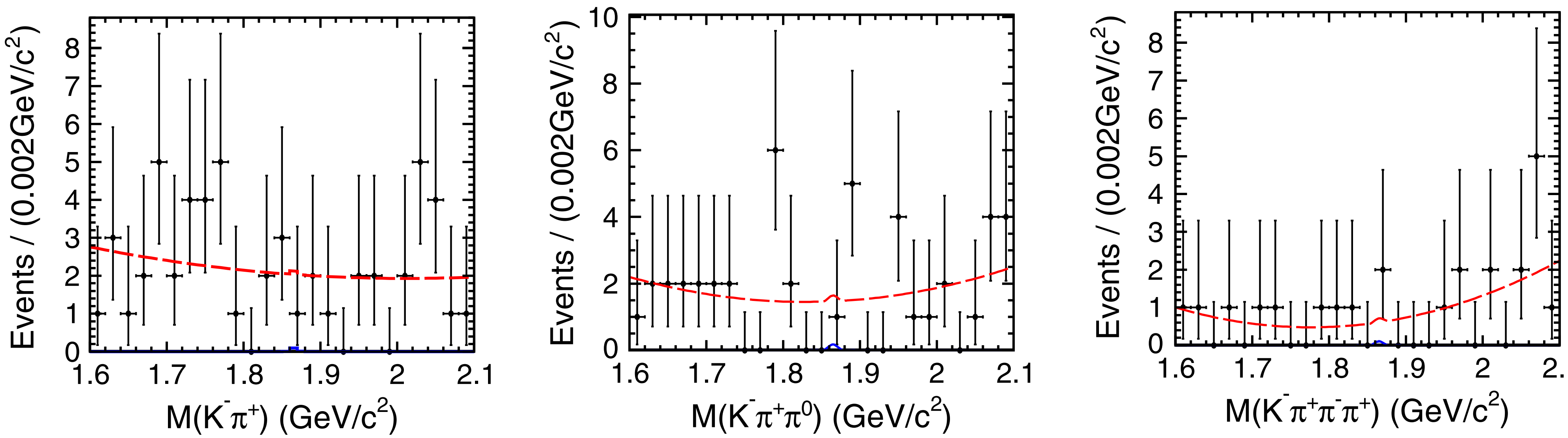
BESIII, "Precision measurement of the $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ cross section near threshold," PRL 120, 132001 (2018)

Strengths of CLEO/BES/τcF: (5) *Rare decays — $J/\psi \to D^0 e^+ e^-$*

Besides the usual open charm decays, J/ψ decays might provide a complementary approach…



1.3 billion J/ψ — O(months) at BESIII



$$B(J/\psi \to D^0 e^+ e^-) < 8.5 \times 10^{-8} \quad (90\%\ \text{C.L.})$$

UL is factor of $10^2 - 10^4$ above SM expectations

(but c.f. $B(D^0 \to \gamma\gamma)$, $10^1 - 10^2$ above SM)

⇒ ***might* be competitive**

BESIII, "Search for the rare decays $J/\psi \to D^0 e^+ e^-$ + c.c. and $\psi(3686) \to D^0 e^+ e^-$ + c.c.," PRD 96, 111101(R) (2017)

Strengths of CLEO/BES/τcF: (5) *Rare decays — LFV*

Other ideas to probe new physics with quarkonia decays…

Studies of lepton flavor violation with charm

★ Multitude of NP operators: single operator dominance hypothesis (SODH)

- but it is not often that only a single operator contributes, e.g. for quarkonia

$$\begin{aligned}\mathcal{L}_{lq} = -\frac{1}{\Lambda^2}\sum_q \Big[& \left(C^q_{VR}\bar{\ell}_1\gamma^\mu P_R \ell_2 + C^q_{VL}\bar{\ell}_1\gamma^\mu P_L \ell_2\right)\bar{q}\gamma_\mu q \\ & + \left(C^q_{AR}\bar{\ell}_1\gamma^\mu P_R \ell_2 + C^q_{AL}\bar{\ell}_1\gamma^\mu P_L \ell_2\right)\bar{q}\gamma_\mu\gamma_5 q \\ & + m_2 m_q G_F\left(C^q_{SR}\bar{\ell}_1 P_R \ell_2 + C^q_{SL}\bar{\ell}_1 P_L \ell_2\right)\bar{q}q \\ & + m_2 m_q G_F\left(C^q_{PR}\bar{\ell}_1 P_R \ell_2 + C^q_{PL}\bar{\ell}_1 P_L \ell_2\right)\bar{q}\gamma_5 q + h.c.\Big]\end{aligned}$$

- Can (partially) do away with SODH if designer initial states are used

Vector:

$$\begin{aligned}\mathcal{A}(V \to \ell_1\bar{\ell}_2) = \bar{u}(p_1, s_1) & \left[A_V^{\ell_1\ell_2}\gamma_\mu + B_V^{\ell_1\ell_2}\gamma_\mu\gamma_5 + \frac{C_V^{\ell_1\ell_2}}{m_V}(p_2-p_1)_\mu \right. \\ & \left. + \frac{iD_V^{\ell_1\ell_2}}{m_V}(p_2-p_1)_\mu\gamma_5\right] v(p_2, s_2)\ \epsilon^\mu(p).\end{aligned}$$

Scalar:

$$\mathcal{A}(S \to \ell_1\bar{\ell}_2) = \bar{u}(p_1, s_1)\left[E_S^{\ell_1\ell_2} + iF_S^{\ell_1\ell_2}\gamma_5\right] v(p_2, s_2)$$

$\psi(2S) \to \gamma\chi_{c0}$

- No data (other than J/psi) exist!!!

D. Hazard and A.A.P., PRD94 (2016), 074023

Alexey A Petrov (WSU & MCTP) 8 CHARM 2018, Novosibirsk, Russia

… a τ-charm factory would be ideally suited for this.

Strengths of CLEO/BES/τc-Factory

(1) **Quantum-correlated pairs of D-mesons**

⇒ complementary to other mixing and CP studies (*and input for* $B \to DK$)

(2) **Leptonic decays**

⇒ precision QCD and tests of lepton-flavor universality

(3) **Special hadronic decays (*e.g.* $D^+ \to \pi^+\pi^0$)**

⇒ CP asymmetries and absolute branching fractions

(4) **Charmed baryons**

⇒ absolute branching fractions and features of production

(5) **Rare decays (*also from charmonium*)**

⇒ complementary searches

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⇒ complementary searches

The statistics of LHCb and Belle II will be formidable…
… a super τ-charm factory would be formidable in a complementary way!