Charm physics with D and D_s at BESIII

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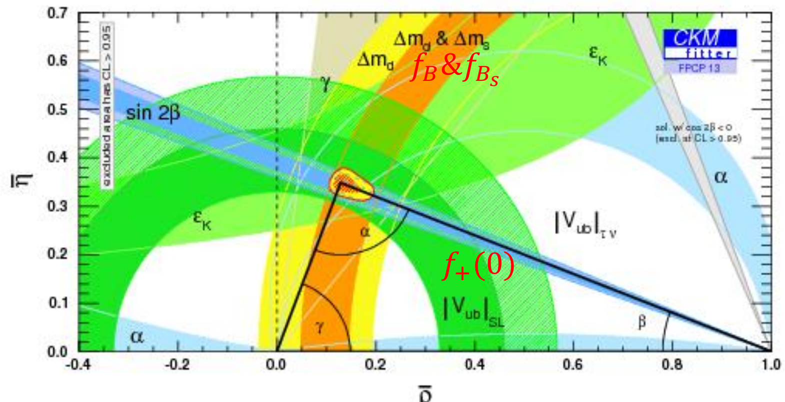
International Workshop on e+e- collisions from Phi to Psi 2013
Sep 9th 2013, Universita' de Roma La Sapienza, Italy

Outline

- **Introduction**
- **Preliminary results from BESIII**
  - Quantum correlation analysis on $D^0\overline{D}^0$ mixing
  - Leptonic *D* decays
  - Semi-leptonic *D* decays
  - Hadronic *D* decays
  - Rare *D* decays
  - D_s decays
- **Summary**

Major charm physics

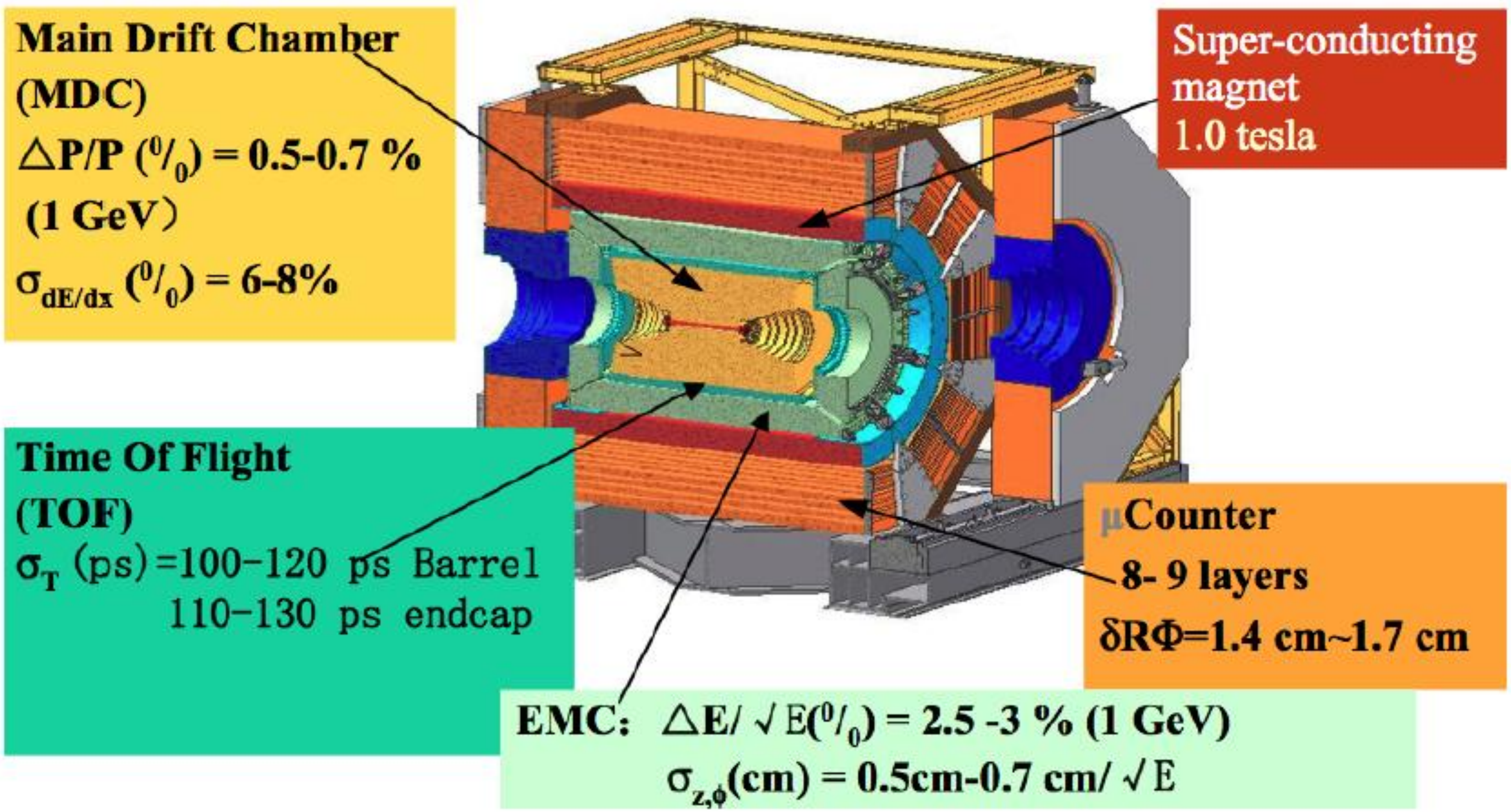
- **Precision quark flavor physics**
  - Decay constants
  - Form factors
  - V_{CKM} extraction
  - Validate QCD



Theoretical errors dominate width of bands

- **Probe for New Physics (NP)**
  - $D^0\overline{D}^0$ mixing
  - Searching for CP violation decays of D mesons
  - Searching for rare decays of D mesons

BESIII detector



Charm meson production near threshold

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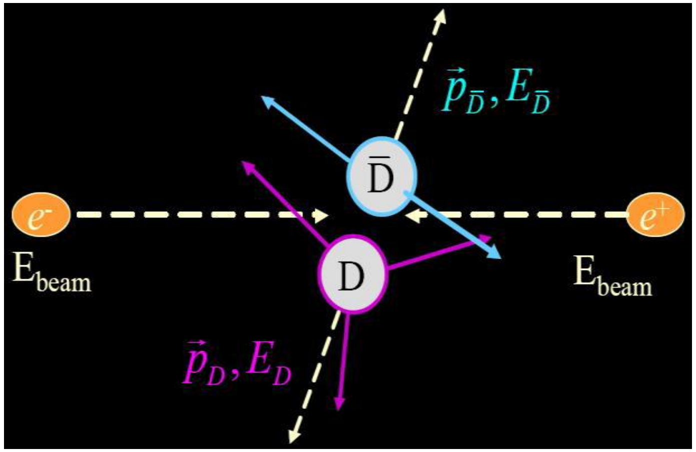
- **Near the peak of $\psi(3770)$ resonance, only $D\bar{D}$ pairs are produced**

Pros

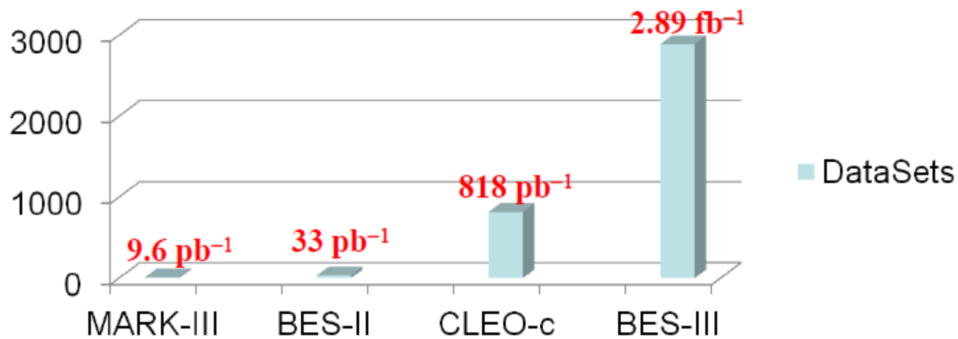
- ✓ Clean environment
- ✓ Known initial energy and quantum numbers (quantum correlated for $D^0\bar{D}^0$ pair)
- ✓ Both D and $\bar{D}$ can fully reconstructed
- ✓ Absolute measurement



- **Analysis technique**
  - Single tag, Double tag, Flavor tag, CP tag

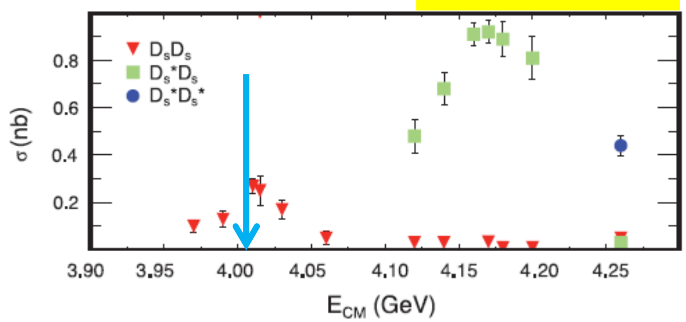
Data samples

- **We have the largest $\psi(3770)$ dataset**



- **We have also collected 482 pb^{-1} $\psi(4040)$ data @ 4.009 GeV**
  - Primary to search XYZ particles
  - Enhanced D_sD_s production
  - Below $D_sD_s^*$ threshold, low bkg

PRD 80, 072001



Quantum correlation analysis

- **$D^0\overline{D}^0$ mixing**
  - Flavor eigenstate $\neq$ mass eigenstate
  - Expected to be very small in SM, sensitive to New Physics

- **Mixing parameters**
  - Mixing parameters: $x = \frac{\Delta M}{\Gamma}, y = \frac{\Delta\Gamma}{2\Gamma}$
  - Mixing rate: $R_M = \frac{x^2+y^2}{2}$
  - $D^0/\overline{D}^0$ relative strong phase: δ
  - Effective parameters: $y' = ycos\delta - xsin\delta; x' = ysin\delta + xcos\delta$

QCA primarily sensitive to y, $cos\delta$

Quantum correlation @ $\psi(3770)$

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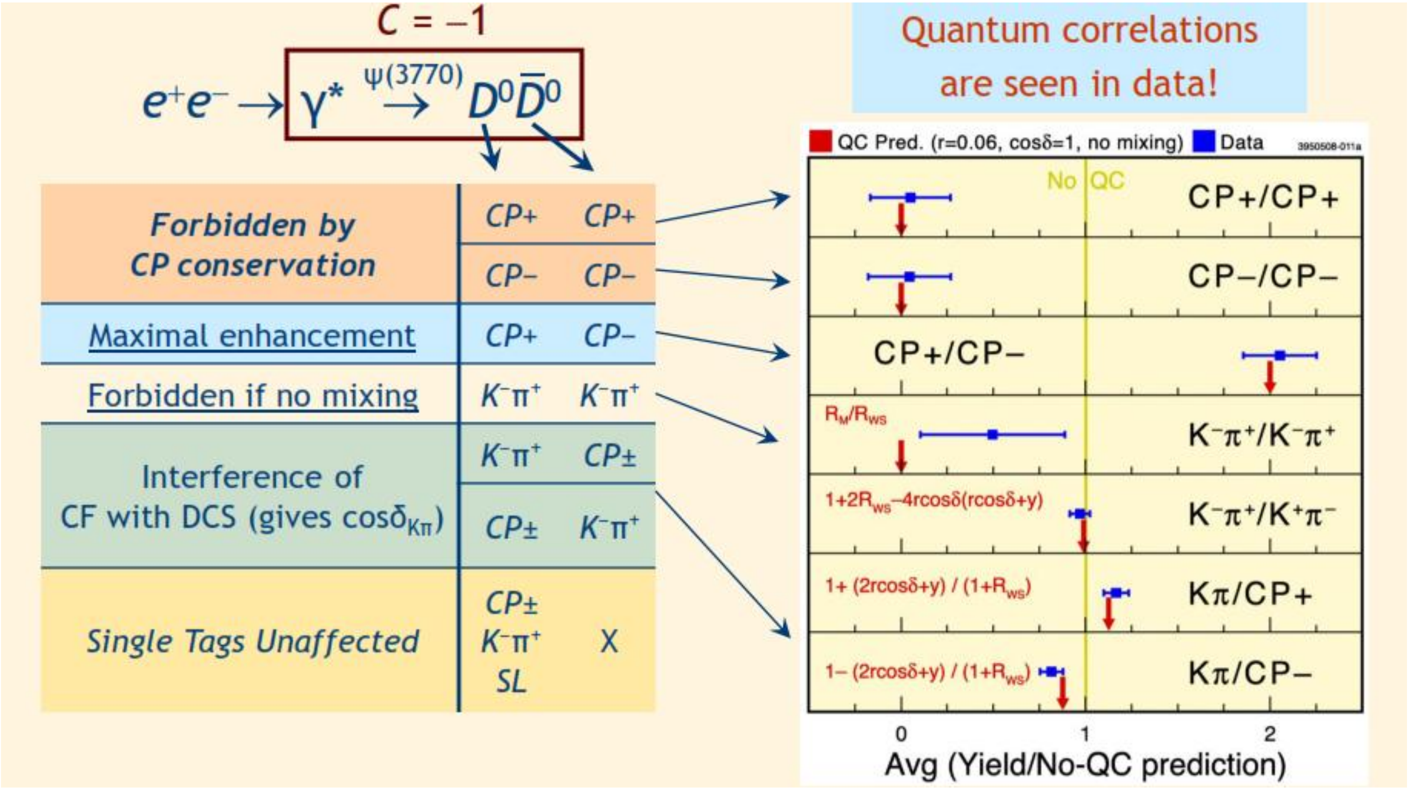
Running near $c\bar{c}$ threshold produces quantum correlated D^0 and $\bar{D}^0$

- ✓ $e^+e^- \to \psi(3770) \to D^0\bar{D}^0$ $[C = -1]$
- ✓ CP+ CP- decays are enhanced



From David Asner Charm 2010

Time-integrated decay rates

Correlated amplitudes

- $\Gamma_{i,j} = |\langle i|D^0\rangle\langle j|\bar{D}^0\rangle \mp \langle j|D^0\rangle\langle i|\bar{D}^0\rangle|^2$
- where $\frac{\langle i|\bar{D}^0\rangle^{DCS}}{\langle i|D^0\rangle^{CF}} = -re^{-i\delta}$

Selected references:

- Goldhaber and Rosner, PRD 15, 1254 (1977)
- Bigi and Sanda, PLB 171, 320 (1986)
- Xing, PRD 55, 196 (1997)
- Gronau, Grossman, Rosner, PLB 508, 37 (2001)
- Atwood and Petrov, PRD 71, 054032 (2005)
- Asner and Sun, PRD 73, 034024 (2006); PRD 77, 019901(E) (2008)

Final States			Time-Integrated Rate (x $A_i^2A_j^2$)
Exclusive	i	$\bar{j}$	$1 + r_i^2 r_j^2 - 2 r_i r_j \cos(\delta_i + \delta_j)$
	i	j	$r_i^2 + r_j^2 - 2 r_i r_j \cos(\delta_i - \delta_j)$
Inclusive	i	X	$1 + r_i^2 + 2 y r_i \cos\delta_i$

No y dependence (exclusive rates)

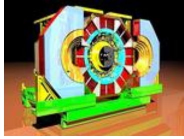
Same as incoherent decay (inclusive rate)

For some special states:

- CP eigenstates: r = 1, δ = 0 or π
- Semileptonic: r = 0

Parameters can be extracted by ratios of yields of carefully constructed exclusive modes and inclusive modes

- $\cos\delta_{K\pi}$: CP mode + flavor mode / CP mode
- y: CP mode + semileptonic mode / CP mode



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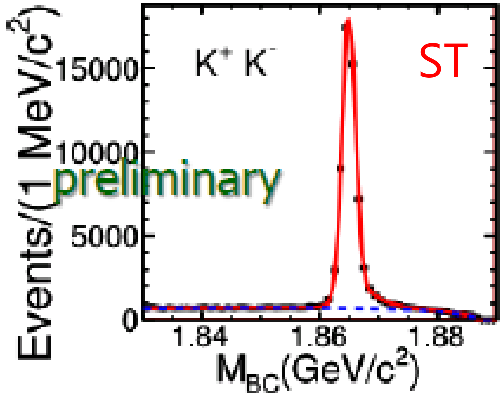
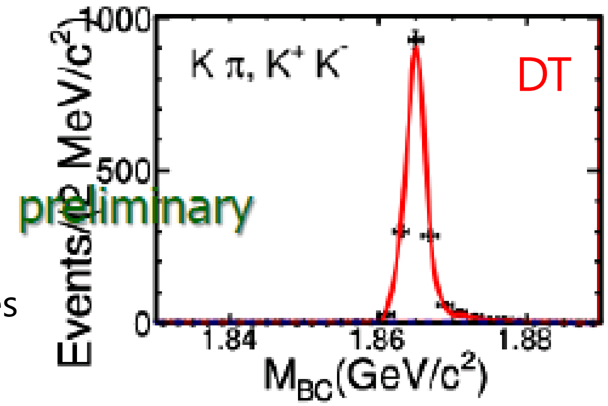
Strong phase in $D^0 \to K\pi$ decay

- **Omitting higher order mixing parameters and assuming CP conservation, we have**
  - $2r_{K\pi}cos\delta_{K\pi} + y = (1 + R_{WS})A_{CP\to K\pi}$
  - $A_{CP\to K\pi} = \frac{B_{D_2\to K^-\pi^+} - B_{D_1\to K^-\pi^+}}{B_{D_2\to K^-\pi^+} + B_{D_1\to K^-\pi^+}}$
  - $|D_1\rangle = \frac{|D^0\rangle + |\bar{D}^0\rangle}{\sqrt{2}}$, $|D_2\rangle = \frac{|D^0\rangle - |\bar{D}^0\rangle}{\sqrt{2}}$



- **Single Tag (ST): CP tags**
  - Flavor tags: $K^-\pi^+$, $K^+\pi^-$
  - CP+ tags: K^+K^-, $\pi^+\pi^-$, $K_S^0\pi^0\pi^0$, $\pi^0\pi^0$, $\rho^0\pi^0$
  - CP- tags: $K_S^0\pi^0$, $K_S^0\eta$, $K_S^0\omega$

- **Double Tag (DT): $K\pi$ + CP tags**



- $\boldsymbol{Br(D_{CP\pm} \to K\pi) = \frac{n_{K\pi,CP\pm}}{n_{CP\pm}}\frac{\epsilon_{CP\pm}}{\epsilon_{K\pi,CP\pm}}}$
  - Most systematics cancelled within $D \to CP\pm$ modes

Preliminary results of $\delta_{K\pi}$

- **With measured $Br(D_{CP\pm} \to K\pi)$, we get**
  - $A_{CP\to K\pi} = \frac{B_{D_2\to K^-\pi^+} - B_{D_1\to K^-\pi^+}}{B_{D_2\to K^-\pi^+} + B_{D_1\to K^-\pi^+}} = (12.77 \pm 1.31^{+0.33}_{-0.31})\%$

- **With external inputs of the parameters in HFAG2013 and PDG2012, we get**
  - $cos\delta_{K\pi} = 1.03 \pm 0.12 \pm 0.04 \pm 0.01$

- **Compare to CLEO's result**
  - 0.8 fb^{-1} $\psi(3770)$ data
  - Without external inputs: $cos\delta = 0.81^{+0.22+0.07}_{-0.18-0.05}$
  - With external inputs: $cos\delta = 1.15^{+0.19+0.00}_{-0.17-0.08}$

Our results have the best precision and compatible with the world average

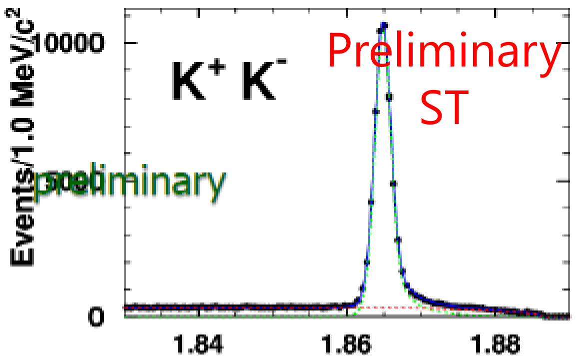
y_{CP} measurement

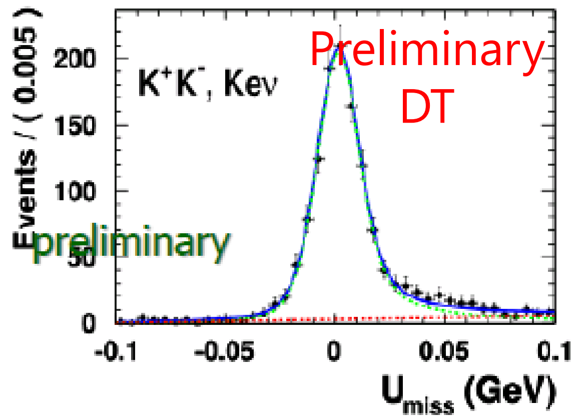
- **Neglect term y^2 or higher order**
  - $y_{CP} \approx \frac{1}{4}\left(\frac{\Gamma_{\ell,CP+}\Gamma_{CP-}}{\Gamma_{\ell,CP-}\Gamma_{CP+}} - \frac{\Gamma_{\ell,CP-}\Gamma_{CP+}}{\Gamma_{\ell,CP+}\Gamma_{CP-}}\right)$

- **Tag modes**

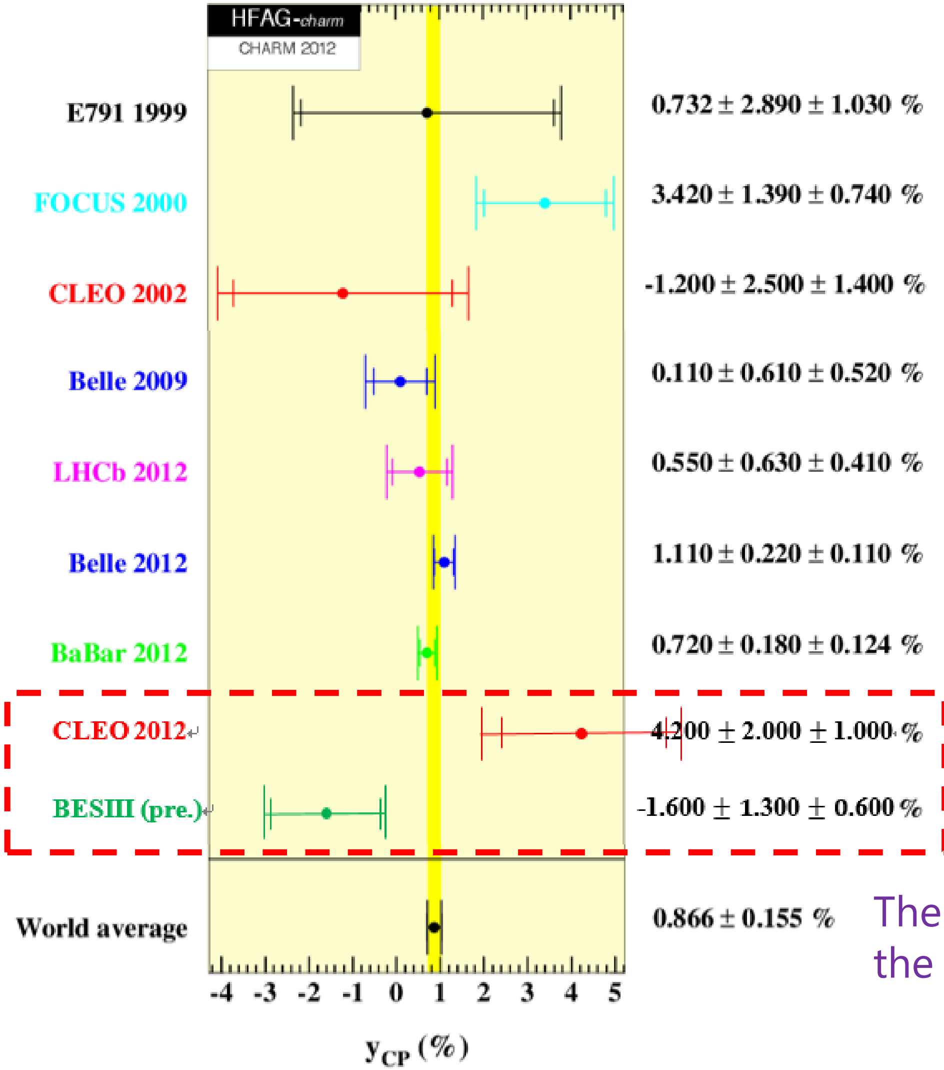
Type	Modes
CP^+	K^+K^-, $\pi^+\pi^-$, $K_S\pi^0\pi^0$
CP^-	$K^0_S\pi^0$, $K^0_S\omega$, $K^0_S\eta$
$l^\pm$	$Ke\nu$, $K\mu\nu$

  - ST: CP tag
  - DT: CP tag + semileptonic tag





Preliminary results



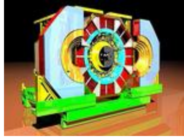
BESIII preliminary results

$$y_{CP} = (-1.6 \pm 1.3 \pm 0.6)\%$$

compatible with world average results

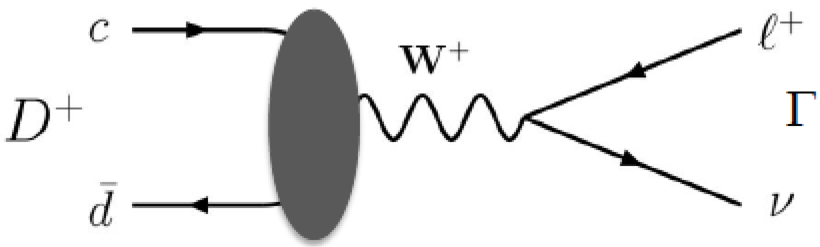
Best precision in Charm factory

The average value do not include the last two measurements



D^{+} leptonic decays

- In the SM, the leptonic decays of the $D^{+}_{(s)}$ provide a clean way to measure the decay constant $f^{+}_{D_{(s)}}$



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

- Test the LQCD calculation of the decay constant. The verified LQCD can help extract V_{td}, V_{ts} from $B_{(s)}$ mixing

- Search for possible new physics (charged Higgs contribution, R-parity violating SUSY …)

Event reconstruction

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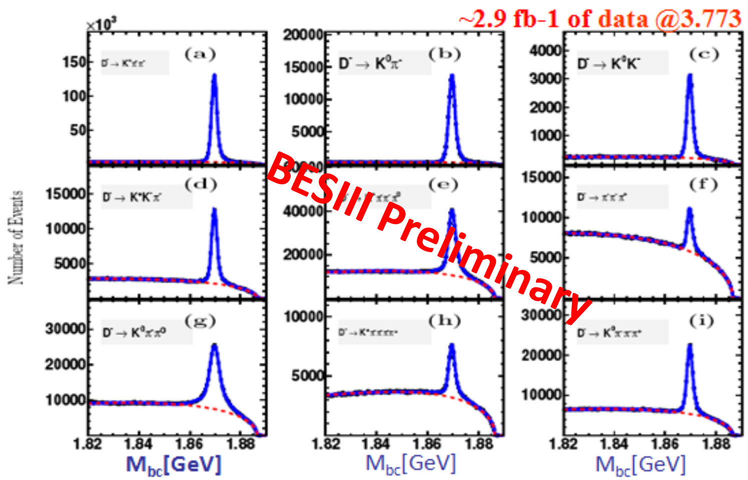


$N_{D^-}^{tag} = (1.566 \pm 0.002) \times 10^6$ in 2.9 fb^{-1}

Single tag channels

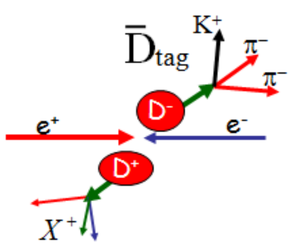
$D^- \to K^+\pi^-\pi^-$ $\quad$ $D^- \to K^-\pi^+\pi^+\pi^0$

$D^- \to K^0\pi^-$ $\quad$ $D^- \to \pi^-\pi^-\pi^+$

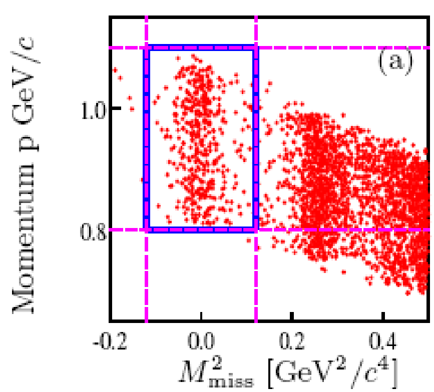
$D^- \to K^0K^-$ $\quad$ $D^- \to K^0\pi^-\pi^0$

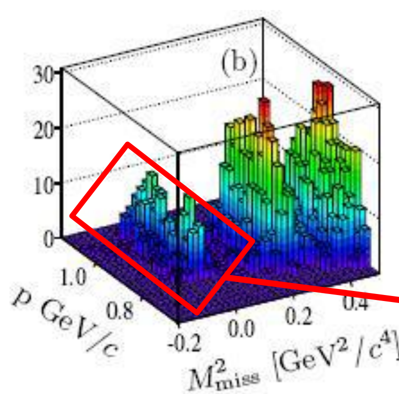
$D^- \to K^+K^-\pi^-$ $\quad$ $D^- \to K^+\pi^-\pi^-\pi^-\pi^+$

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



Using 9 singly tagged D⁻ modes to accumulate the D⁺D⁻ events.





- One charged tracks only
- Positive identified muon
- No isolate photon

BESIII Preliminary

425 signal candidates

After bkg subtraction, $N_{\mu\nu} = 377.3 \pm 20.6 \pm 2.6$

Preliminary results

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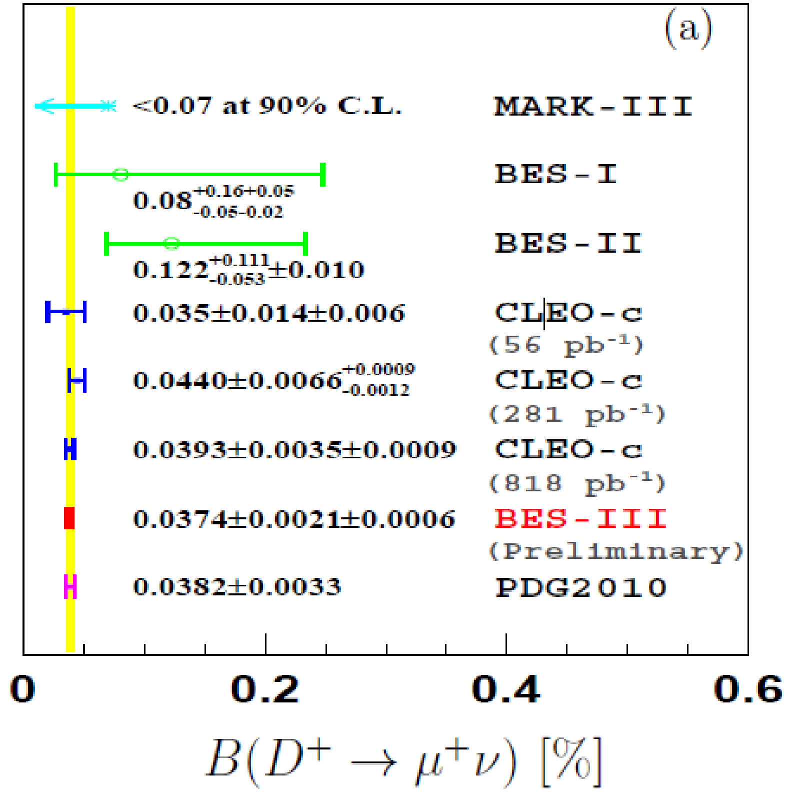

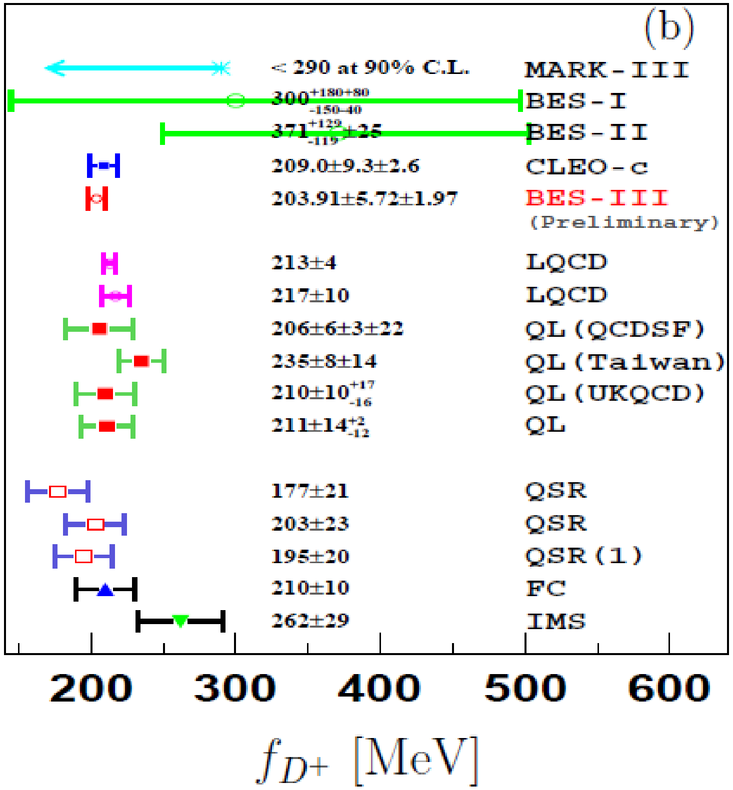

(3.74±0.21±0.06)

(203.91±5.72±1.97)

Best experimental precision to date!

D semileptonic decays to K and π

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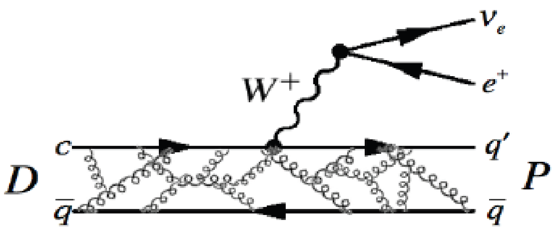
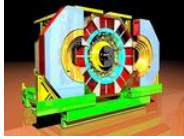
- **Charm mesons can decay into other hadrons by emitting a $\ell^+\nu$ lepton pair via the weak interactions**



$$\frac{d\Gamma\left(D \to K(\pi)e\nu\right)}{dq^2} = \frac{G_F^2 \left|V_{cs(d)}\right|^2 P_{K(\pi)}^3}{24\pi^3}\left|f_+\left(q^2\right)\right|^2$$

- **Use theory for form factors, extract CKM parameters**
- **Use unitarily for CKM parameters, test QCD**
- **Verified QCD can help extract V_{ub} from $B \to \pi\ell\nu$**



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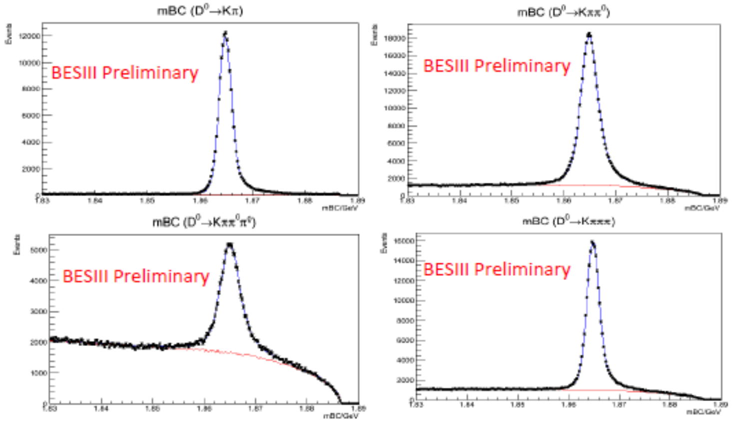
Event recon. & BR meas.

Tag side:

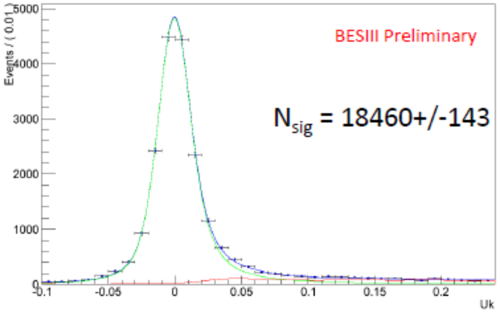
4 tag modes

Mode	Data Yield
$D^0 \to K^-\pi^+$	159,929 ± 413
$D^0 \to K^-\pi^+\pi^0$	323,348 ± 667
$D^0 \to K^-\pi^+\pi^0\pi^0$	78,467 ± 480
$D^0 \to K^-\pi^+\pi^-\pi^+$	211,910 ± 550

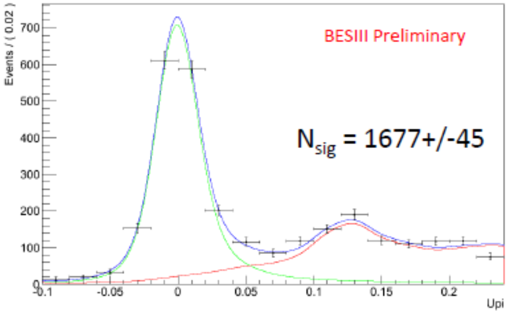


Signal side:

$$U = E_{\text{miss}} - c\left|\vec{P}_{\text{miss}}\right| \approx 0$$



D^0 -> K e ν



D^0 -> π e ν

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Mode	measured branching fraction(%)	PDG	CLEOc
$\bar{D}^0 \to K^+e^-\bar{\nu}$	3.542 ±0.030±0.067	3.55 ±0.04	3.50 ±0.03 ±0.04
$\bar{D}^0 \to \pi^+e^-\bar{\nu}$	0.288 ±0.008±0.005	0.289 ±0.008	0.288 ±0.008±0.003

BR results:

1/3 data, consistent with CLEOc's

PHIPSI13

Partial decay rates and $f(q^2)$

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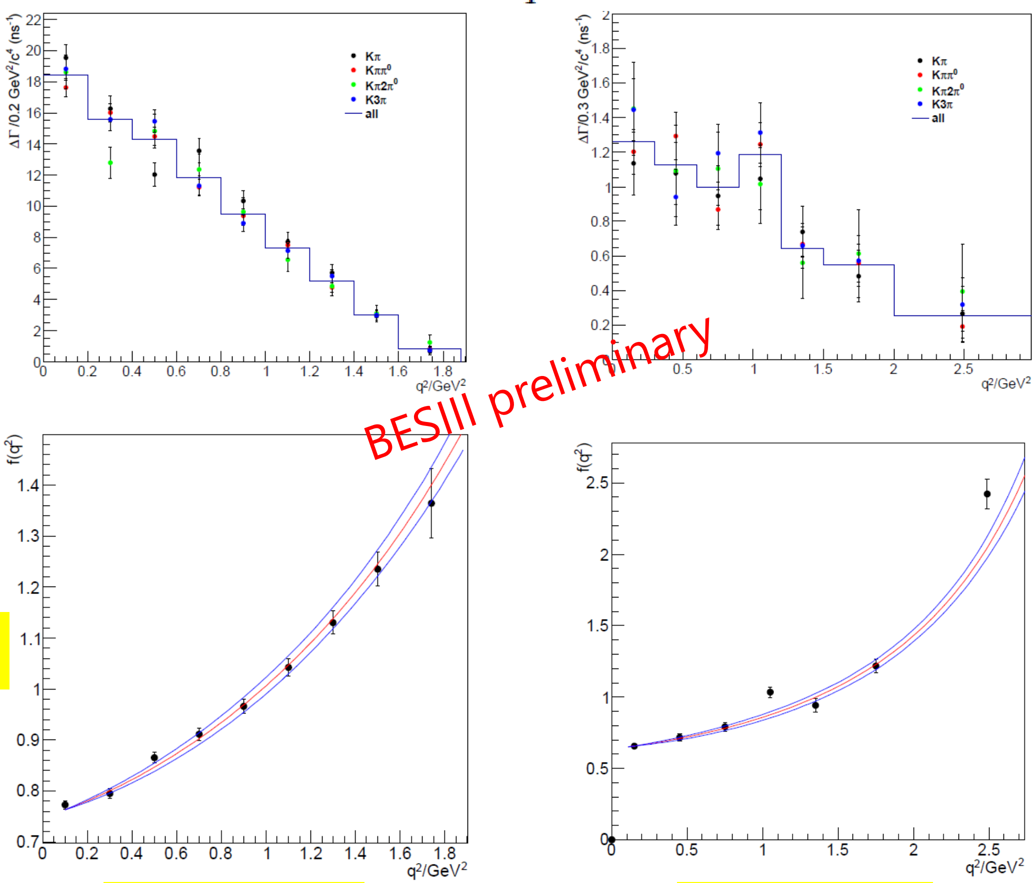
$$\frac{\Delta\Gamma(D \to \pi(K)e\nu)}{dq^2} = \frac{G_F^2\,|V_{cd(s)}|^2}{24\pi^3}\,p^3\,|f_+(q^2)|^2$$



$\Delta\Gamma$

$f(q^2)$

$D^0 \to Ke\nu$

$D^0 \to \pi e\nu$

Measured in each q^2 bin, by fitting U distribution

Points: data with stat. err. only
Curves: from Fermilab-MILC within one stat. err. (**arXiv: 1111.5471**)

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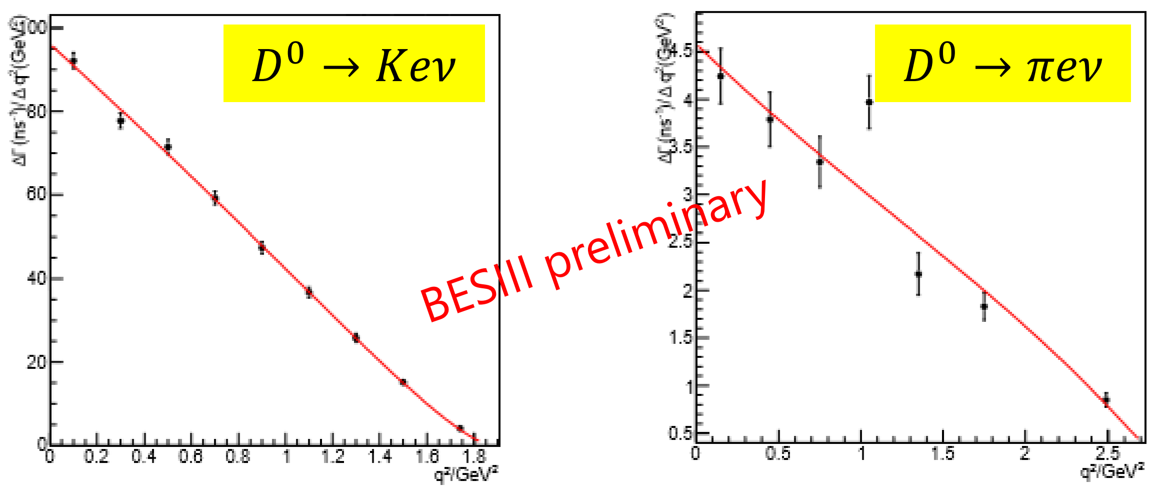
Form factor fits

$$f_+(q^2) = \frac{1}{P(q^2)\,\phi(q^2,t_0)} \sum_{k=0}^{\infty} a_k(t_0)\, \left[z(q^2,t_0)\right]^k$$

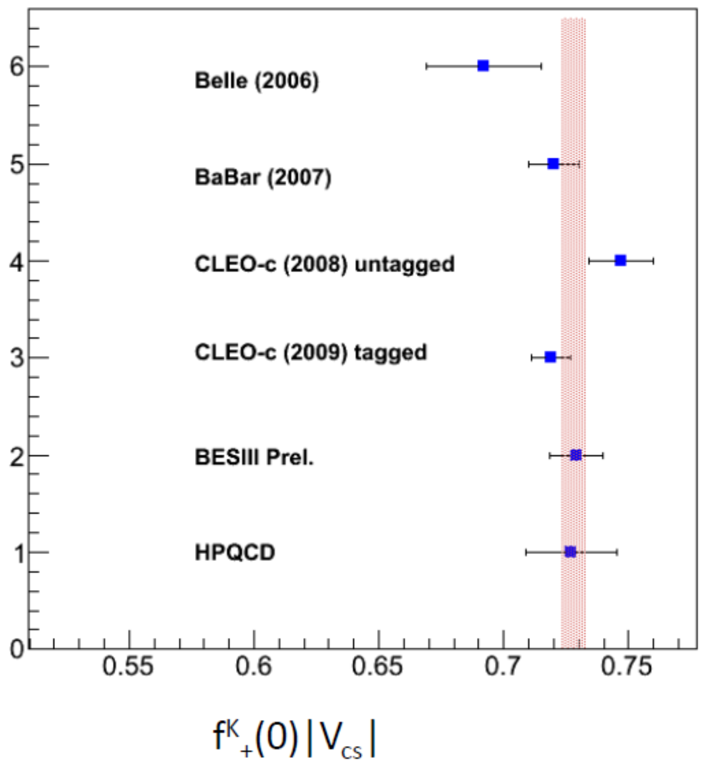
Series expansion: Becher and Hill PLB 633, 61 (2006)

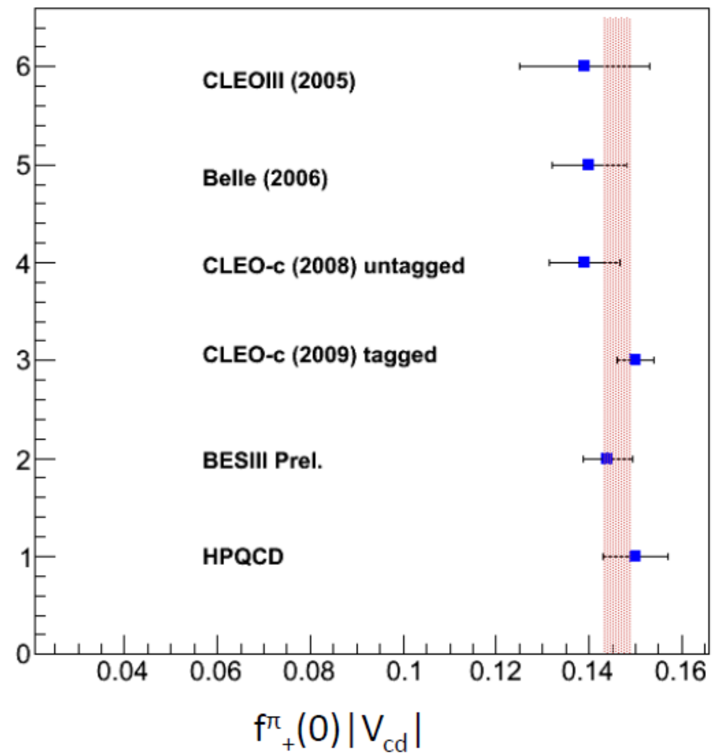
Could fit: $f_+(0)$, $r_1 = a_2/a_1$, $r_2 = a_3/a_1$



3 par. series	$f_+(0)\lvert V_{cd(s)}\rvert$	r_1	r_2
$D^0 \rightarrow Ke\nu$	0.729±0.008±0.007	−2.179±0.355±0.053	4.539±8.927±1.103
$D^0 \rightarrow \pi e\nu$	0.144±0.005±0.002	−2.728±0.482±0.076	4.194±3.122±0.448

Comparisons of form factor normalization results





- Numbers are from HFAG 2012 report (**arXiv:1207.1158**)
- Error bar of BESIII prel. will shrink with full data

Dalitz plot analysis of $D^+ \to K_S^0\pi^+\pi^0$

- **There are many three bodies final states with large BR and including $K\pi$ and $\pi\pi$ two body resonances**

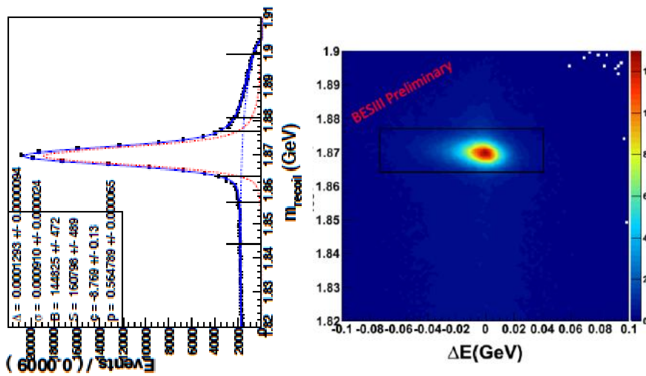
- **$K\pi$ S wave and low-mass $K\pi$ scalar resonance κ have been observed significantly in earlier experiments (E691-791, CLEO) through MIPWA in $K^-\pi^+\pi^+$**

- **The $D^+ \to K_S^0\pi^+\pi^0$ decay is also a golden mode. Previous dalitz plot analysis of $K_S^0\pi^+\pi^0$ from MARK III only include $K_S^0\rho^+$ and $\overline{K}^{*0}\pi^+$**

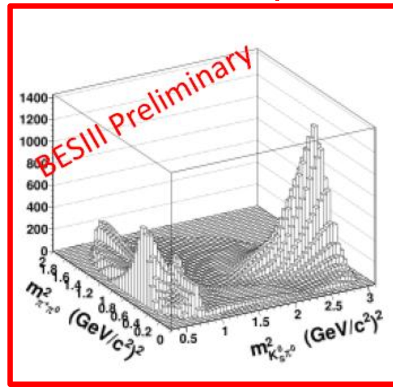
- **With much larger dataset, we can do much more precise measurement.**

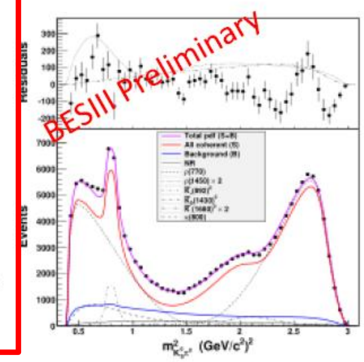
Data fitting

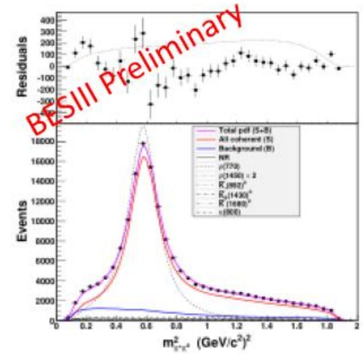
Fully reconstruct $D^+ \to K_S^0\pi^+\pi^0$ final states

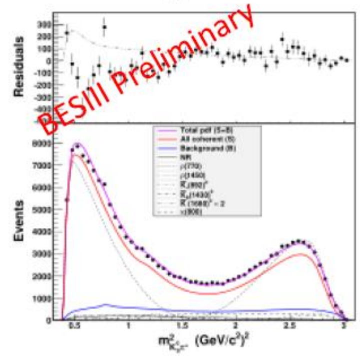


The dalitz plot









Using isobar model to fit data

Coherent sum of 6 intermediate resonances ($K_S^0\rho^+$, $K_S^0\rho(1450)^+$, $\overline{K}^{*0}\pi^+$, $\overline{K}_0(1430)^0\pi^+$, $\overline{K}(1680)^0\pi^+$, $\kappa^0\pi^+$)

+ a non-resonant component

Float $\overline{K}(1430)^0$ and $\kappa(800)^0$ parameters

Resonance parameters

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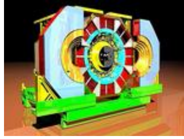
Resonance	Parameter (MeV)		BES-III	E791 Model C	CLEO-c Model C	CLEO-c Model I2
$\overline{K}^*_0(1430)$	BW	Mass	$1464 \pm 6 \pm 9^{+9}_{-28}$	1459 ± 14	$1463.0 \pm 0.7 \pm 2.4$	$1466.6 \pm 0.7 \pm 3.4$
		Width	$190 \pm 7 \pm 11^{+6}_{-26}$	175 ± 17	$163.8 \pm 2.7 \pm 3.1$	$174.2 \pm 1.9 \pm 3.2$
PDG	Flatt	Mass	1482 ± 10		1462.5 ± 3.9	1471.2 ± 0.8
1425 ± 50		$g_{K\pi}$	585 ± 14		532.9 ± 8.5	546.8 ± 4.2
270 ± 80		$g_{K\eta}$	0		0	0
		$g_{K\eta'}$	452 ± 85		197 ± 106	230 ± 32
κ	BW	Mass	860 ± 11	797 ± 47	809 ± 14	888 ± 2
		Width	446 ± 23	410 ± 97	470 ± 18	550 ± 12
	Pole	Re	$752 \pm 15 \pm 69^{+55}_{-73}$		769.9 ± 6.3	$706.0 \pm 1.8 \pm 22.8$
		Im	$-229 \pm 21 \pm 44^{+40}_{-55}$		-221.2 ± 8.4	$-319.4 \pm 2.2 \pm 20.2$

BESIII Preliminary

- **The mass and width of K*0(1430) are consistent with E791 and CLEO-c from D+→K-π+π+**
- **The pole of κ(800) is consistent with the model C of CLEO-c**



Fit fraction & BR results

Fit fraction & phase

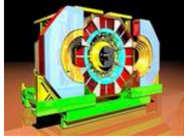
Parameters	Value	Stat	Experimental Errors				Modeling Errors		
			Bkg	Eff	Resol	Total	Shape	Add	Total
NR FF(%)	4.63	0.67	3.45	0.96	0.02	3.59	$^{+2.89}_{-1.50}$	$^{+2.65}_{-3.24}$	$^{+3.93}_{-3.57}$
NR Phase	278.62	5.36	4.32	14.27	0.06	14.91	$^{+5.96}_{-24.40}$	$^{+21.61}_{-11.54}$	$^{+22.42}_{-26.99}$
$\rho(770)^+$ FF(%)	83.41	2.19	2.66	0.62	0.01	2.74	$^{+1.02}_{-1.87}$	$^{+6.33}_{-1.05}$	$^{+6.42}_{-2.15}$
$\rho(1450)^+$ FF(%)	2.13	0.22	0.87	0.82	0.01	1.20	$^{+0.62}_{-0.02}$	$^{+0.73}_{-1.48}$	$^{+0.96}_{-1.48}$
$\rho(1450)^+$ Phase	187.02	2.56	3.03	3.69	[illegible]	4.78	$^{+8.66}_{-14.53}$	$^{+25.67}_{-4.63}$	$^{+27.09}_{-15.25}$
$\overline{K}^*(892)^0$ FF(%)	3.58	0.17	0.12	[illegible]	0.01	0.17	$^{+0.31}_{-0.18}$	$^{+0.16}_{-0.28}$	$^{+0.35}_{-0.34}$
$\overline{K}^*(892)^0$ Phase	293.22	1.25	0.73	1.45	0.01	1.63	$^{+1.12}_{-6.52}$	$^{+5.67}_{-1.17}$	$^{+5.78}_{-6.63}$
$\overline{K}^*_0(1430)^0$ FF(%)	3.66	0.57	0.57	0.42	0.01	0.71	$^{+0.34}_{-0.29}$	$^{+0.66}_{-0.74}$	$^{+0.75}_{-0.80}$
$\overline{K}^*_0(1430)^0$ Phase	334.36	[illegible]	7.38	3.63	0.04	8.23	$^{+0.33}_{-9.53}$	$^{+2.04}_{-27.43}$	$^{+2.07}_{-29.04}$
$\overline{K}^*(1680)^0$ FF(%)	1.27	0.11	0.60	0.16	0.01	0.63	$^{+0.51}_{-0.07}$	$^{+0.01}_{-1.07}$	$^{+0.52}_{-1.08}$
$\overline{K}^*(1680)^0$ Phase	251.81	1.90	8.45	5.60	0.08	10.14	$^{+5.70}_{-1.21}$	$^{+6.92}_{-27.87}$	$^{+8.97}_{-27.90}$
κ^0 FF(%)	7.73	1.19	2.43	3.09	0.01	3.94	$^{+1.93}_{-2.64}$	$^{+4.70}_{-0.10}$	$^{+5.09}_{-2.65}$
κ^0 Phase	92.89	6.23	24.24	13.55	0.16	27.77	$^{+13.17}_{-6.56}$	$^{+15.72}_{-21.52}$	$^{+20.51}_{-22.50}$
NR+κ^0 FF(%)	18.59	1.69	1.08	0.95	0.01	1.44	$^{+1.54}_{-3.70}$	$^{+0.50}_{-2.21}$	$^{+1.62}_{-4.31}$
$K^0_S\pi^0$ S wave	17.29	1.34	2.01	0.49	0.01	2.07	$^{+0.63}_{-3.75}$	$^{+2.58}_{-0.59}$	$^{+2.66}_{-3.80}$

BESIII preliminary

Fit fractions * world average $Br\left(D^+ \to K^0_S\pi^+\pi^0\right)$

Mode	Partial Branching Fraction (%)
$B(D^+ \to K^0_S\pi^+\pi^0)$ Non Resonant	$0.32\pm0.05\pm0.25^{+0.21}_{-0.25}$
$B(D^+ \to \rho^+ K^0_S) \times B(\rho^+ \to \pi^+\pi^0)$	$5.83\pm0.16\pm0.30^{+0.08}_{-0.15}$
$B(D^+ \to \rho(1450)^+ K^0_S) \times B(\rho(1450)^+ \to \pi^+\pi^0)$	$0.15\pm0.02\pm0.09^{+0.05}_{-0.11}$
$B(D^+ \to \overline{K}^*(892)^0\pi^+) \times B(\overline{K}^*(892)^0 \to K^0_S\pi^0)$	$0.250 \pm 0.012 \pm 0.015^{+0.022}_{-0.024}$
$B(D^+ \to \overline{K}^*_0(1430)^0\pi^+) \times B(\overline{K}^*_0(1430)^0 \to K^0_S\pi^0)$	$0.26\pm0.04\pm0.05^{+0.03}_{-0.06}$
$B(D^+ \to \overline{K}^*(1680)^0\pi^+) \times B(\overline{K}^*(1680)^0 \to K^0_S\pi^0)$	$0.09\pm0.01\pm0.05^{+0.04}_{-0.08}$
$B(D^+ \to \overline{\kappa}^0\pi^+) \times B(\overline{\kappa}^0 \to K^0_S\pi^0)$	$0.54\pm0.09\pm0.28^{+0.14}_{-0.19}$
NR+$\overline{\kappa}^0\pi^+$	$1.30\pm0.12\pm0.12^{+0.11}_{-0.30}$
$K^0_S\pi^0$ S wave	$1.21\pm0.10\pm0.16^{+0.05}_{-0.27}$

BESIII Preliminary



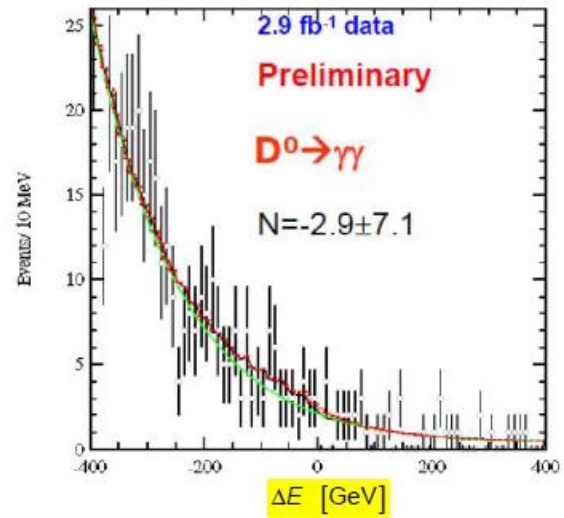
BESIII

Search for $D^0 \rightarrow \gamma\gamma$

- **Flavor Changing Neutral Current (FCNC) ($c \rightarrow u + \gamma$) is forbidden at tree level**
- **Dominated by long-distance effect**
- **In SM, $Br(D^0 \rightarrow \gamma\gamma) \sim 10^{-8}$ or less (see Fajfer et al. PRD 64, 074008 (2001))**
- **In minimal super-symmetric standard model, the predicted rate is $\sim 10^{-6}$ (see Prelovsek and Wyler, PLB500, 304 (2001))**

Preliminary results

Signal reconstruction
- ✓ Reconstruct two photons
- ✓ Extract signals from a ΔE distribution



Gives : -2.9 ± 7.1 events
No significant signals

- **Upper limit**

$$B(D^0 \to \gamma\gamma)/B(D^0 \to \pi^0\pi^0) < 5.8 \times 10^{-3} @ 90\% \text{C.L.}$$

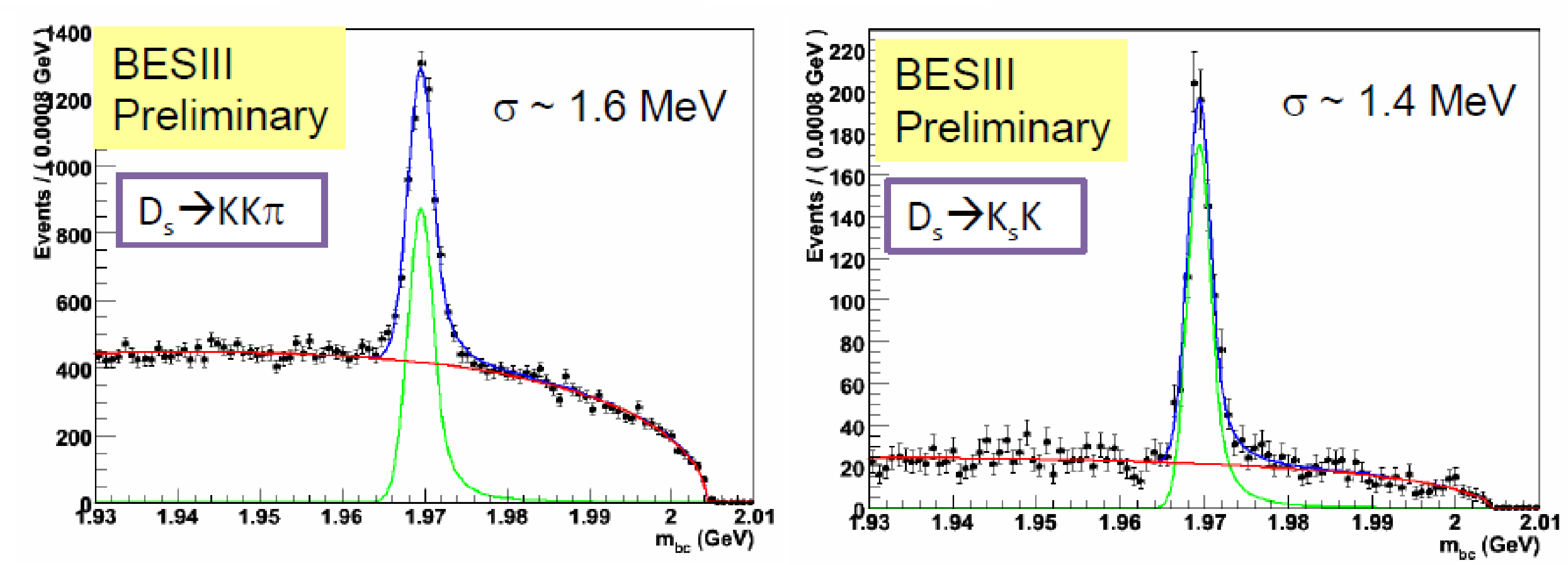
Experiments	BESIII	BABAR	CLEOc	PDG11
$B^{up}(D^0 \to \gamma\gamma)$ [$\times 10^{-6}$]	<4.6	<2.2	<8.63	<27

– Another double-tag technique is ongoing
– Intend to look for other radiative decays of D^+, D^0 and D_s^+ as well

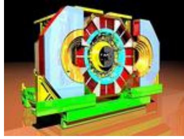
D_s decays

- **Taken data @ 4.009 GeV. Only $D_s^+ D_s^-$ pairs are produced (below $D_s D_s^*$ threshold)**
- **Many analysis can be studied by exploiting the "tagging" technique (MARK III's method)**
- **D_s^+ tagging is clean compared to CLEO-c's $D_s D_s^*$ data taken @ 4.17 GeV**
  - But statistics limited : Low Xsection compared to 4.17 GeV (See slide 5)

D_s tagging



Several ongoing analysis
Results will come out soon ....



Summary

- **Many new results come from BESIII**
  - Quantum correlation analysis
    - Strong phase $\delta_{K\pi}$: with the best accuracy
    - mixing parameter y_{CP}: compatible with the world average
  - D^+ leptonic: most precise $D^+ \to \mu^+ \nu$ measurement
  - D^0 semiletonic: 1/3 data analyzed $D^0 \to K/\pi e \nu$, comparable precision to CLEO-c, better precision expected
  - D^+ hadronic: dalitz analysis of $D^+ \to K_S^0 \pi^+ \pi^0$ is performed, the measured partial branching fraction are consistent with E791 & CLEO-c
  - D^0 Rare decay: have searched for $D^0 \to \gamma\gamma$, confirm the latest results from BaBar
  - D_S^+ decays: clean tags, results coming soon

Thanks for your attention!