Charm semileptonic decays at the B factories

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Review of results:

$D^0 \to K^- e^+ \nu$

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

$D_s^+ \to K^+ K^- e^+ \nu$

$D^+ \to K^- \pi^+ e^+ \nu$

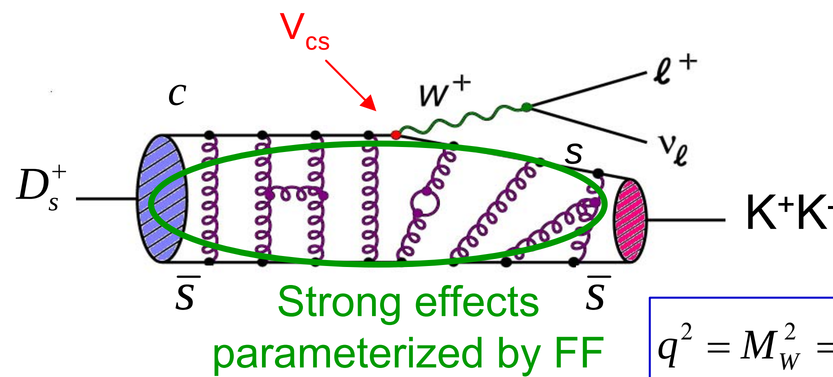
CKM2010

University of Warwick, september 7th

Importance of charm semileptonic decays

- Measurement of the decay rate

$$d\Gamma \propto |V_{cx}|^2 \times FF^2$$



$$q^2 = M_W^2 = (p_l + p_\nu)^2$$

Then 2 strategies:

- Use Lattice QCD input for the form factors to determine V_{cx}
- Use CKM unitarity to determine the form factors and validate LQCD results
  - ⇒ Once validated, they can be used in B sector to determine V_{ub} and V_{cb}

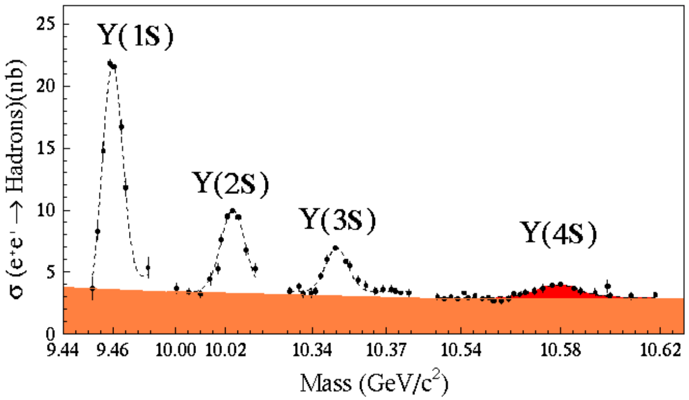
Golden mode: D → Pseudoscalar $\ell\nu$

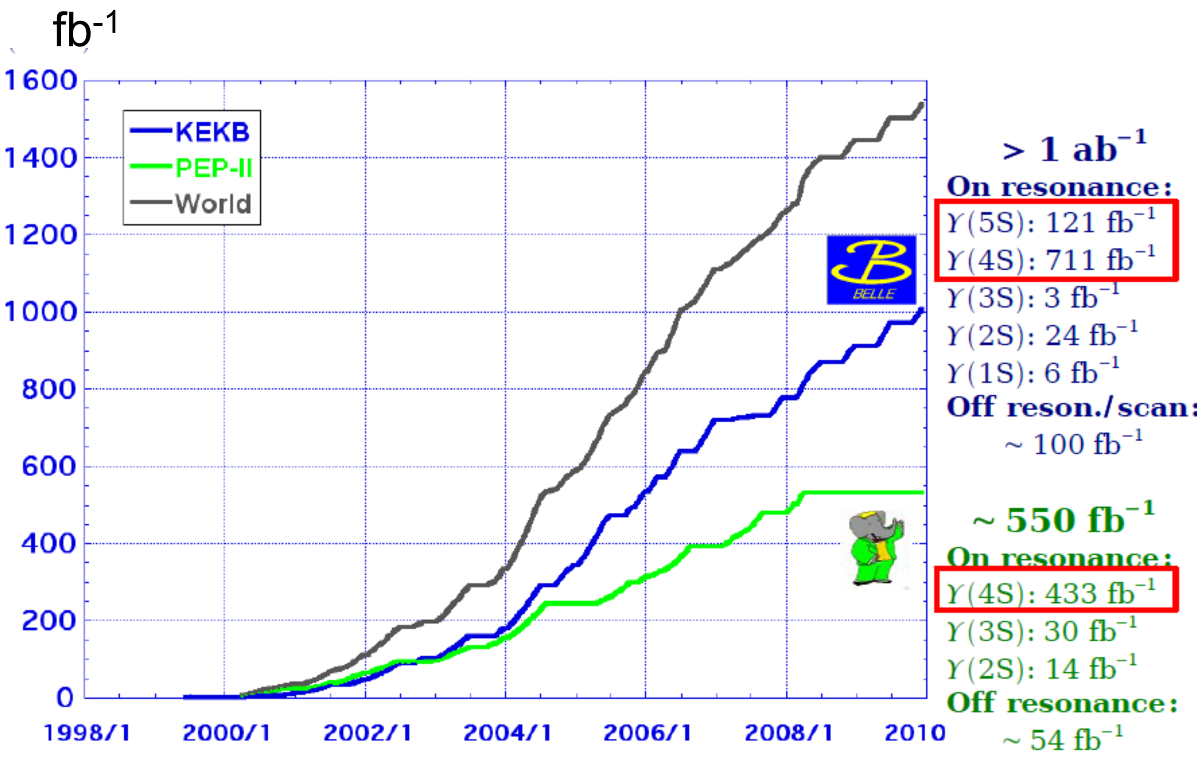
- Study other modes (D → Vector $\ell\nu$) to get a complete understanding of charm semileptonic decays

- Study of hadronic systems without additional hadrons in the final state using D → PP'$\ell\nu$

Charm SL decays at B factories

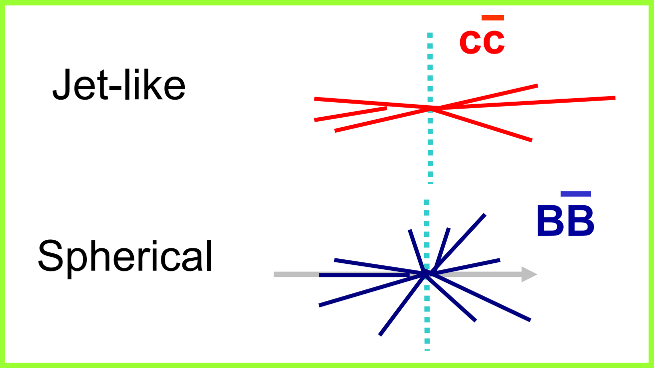
- Large statistics: at the Υ(4s) σ_{cc} **~1.3 nb**
- Fragmentation ⇒D, D_s, Λ_c,…
- Background to control





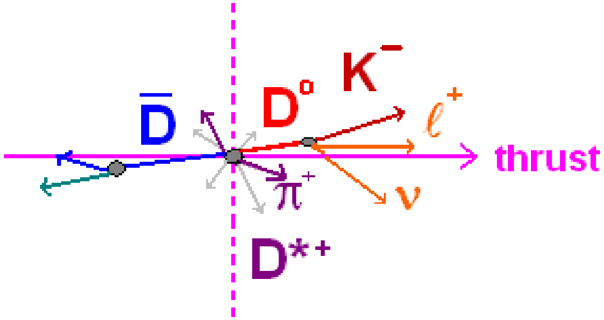
Analysis strategy @ BaBar

- Untagged analysis
- Use D from $c\bar{c}$ events $\Rightarrow$ jet like events



- Event reconstruction:
  - Define signal and recoil hemisphere

Ex: $D^0 \to K^- e^+ \nu$



- Compute D direction ($- p_{\text{all particles} \neq K,e}$)
- Compute the missing energy in the lepton hemisphere
- Mass constrained fit to obtain D momentum
- Compute the kinematic variables, $q^2=(p_D - p_K)^2$

→large statistics (ε~5%)

→measure $B(D^0 \to K^- e^+ \nu)/B(D^0 \to K^- \pi^+)$

→non negligeable background

→poor resolution on kinematic variables

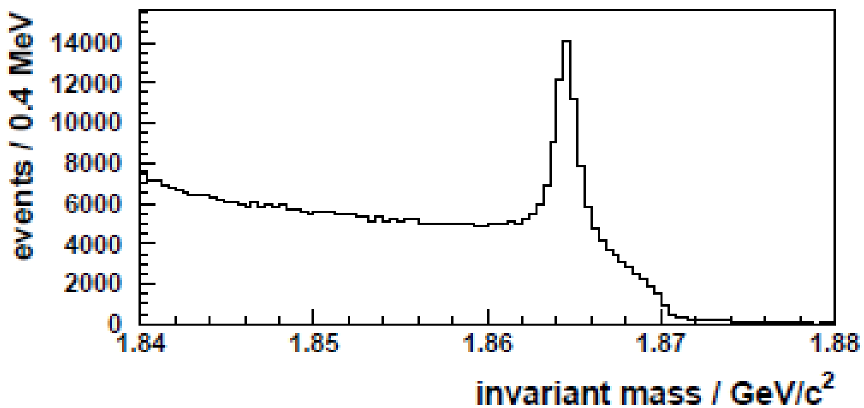
$\Delta(q^2) \sim 0.07\text{-}0.2\ \text{GeV}^2$

Use control samples to determine resolution and background

Analysis strategy @ Belle

- Full reconstruction of the event: tagged analysis
- Search for $e^+e^- \to D^{(*)}_{tag} D^*_{sig} X$
  - $D^{(*)}_{tag}$ reconstructed in $D^{*+} \to D^0 \pi$, $D^+\pi^0$ and $D^{*0} \to D^0 \pi^0$, $D^0\gamma$ with $D^{0/+} \to K(n\pi)$ n=1,2,3

Mass spectrum of D^0_{sig} candidates



56461 ± 309 ± 830
D^0 tagged in 282 fb^{-1}

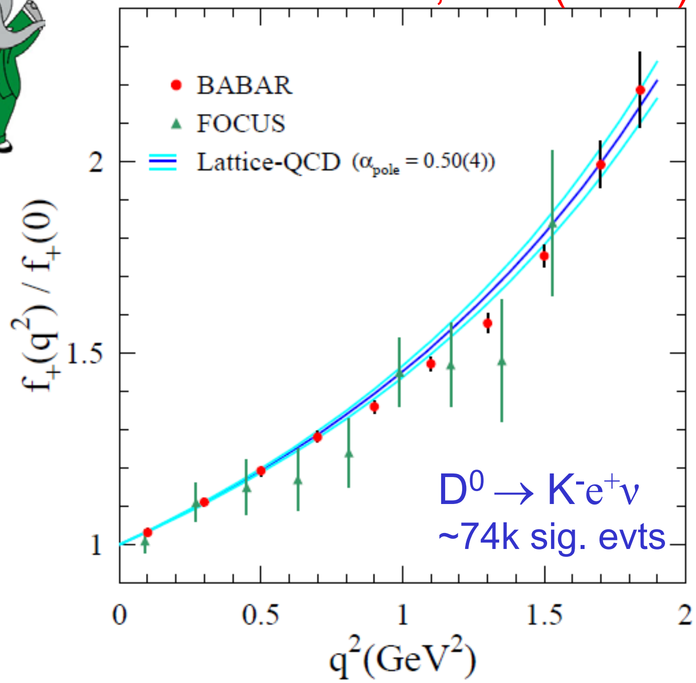
→ excellent resolution on kinematic variables $\Delta(q^2) \sim 0.015$ GeV^2
→ absolute BR measurement
→ low efficiency (ε~1‰)

$D^0 \to K^- e^+ \nu_e$, $D^0 \to \pi^- e^+ \nu_e$

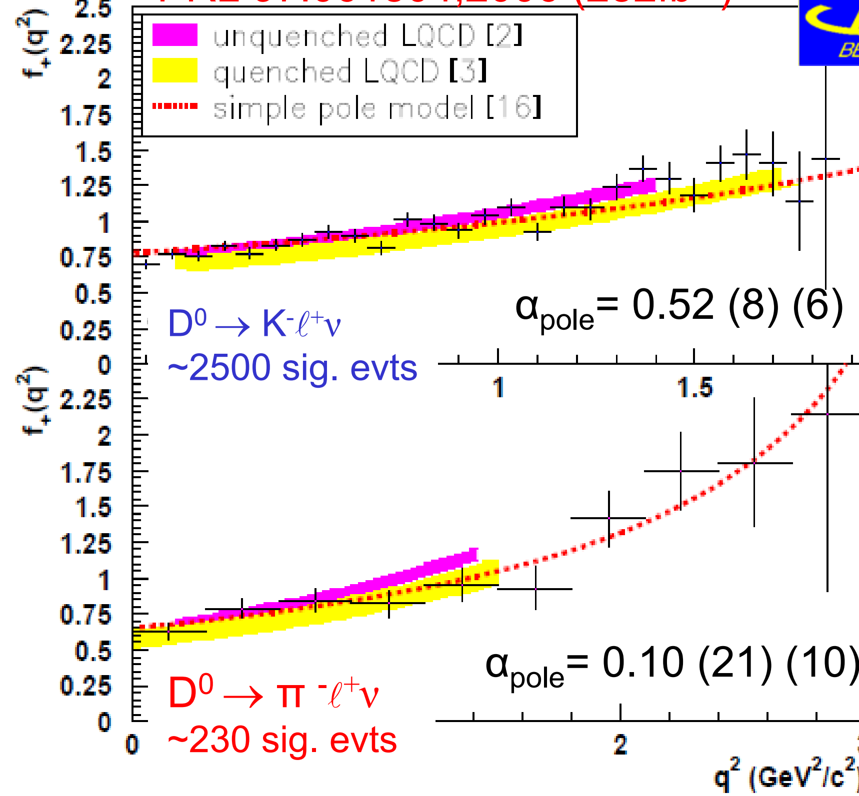
Form factor variation

$$\frac{d\Gamma}{dq^2} = \frac{G_f^2 |V_{q_1 q_2}|^2 p_{P'}^3}{24\pi^3} |f_+(q^2)|^2$$ (If $m_\ell \sim 0$)

PRD 76:052005,2007 (75fb[-1])



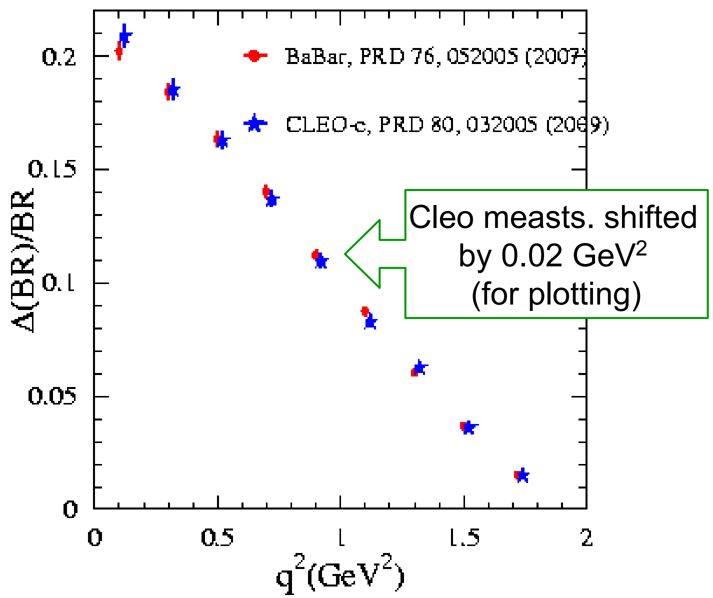
PRL 97:061804,2006 (282fb[-1])

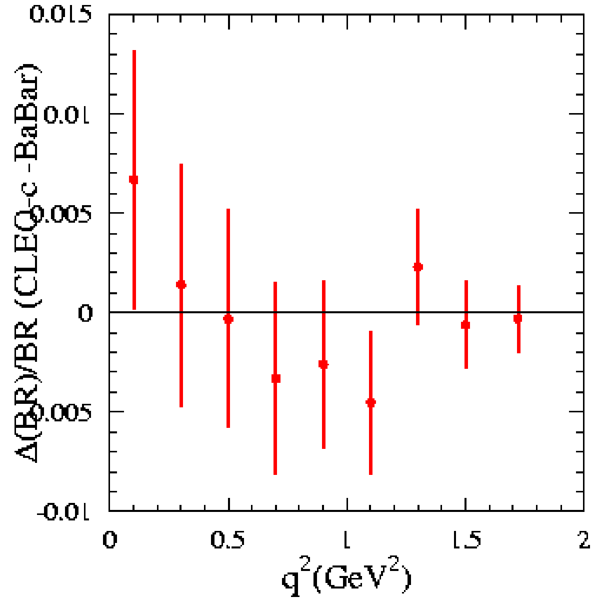


Theoretical ansatz	Unit	Parameters	χ^2/NDF	Expectations [χ^2/NDF]
z expansion		$r_1 = -2.5 \pm 0.2 \pm 0.2$	5.9/7	
		$r_2 = 0.6 \pm 6. \pm 5.$		
Modified pole		$\alpha_{pole} = 0.377 \pm 0.023 \pm 0.029$	6.0/8	
Simple pole	GeV/c^2	$m_{pole} = 1.884 \pm 0.012 \pm 0.015$	7.4/8	2.112 [243/9]
ISGW2	GeV^{-2}	$\alpha_I = 0.226 \pm 0.005 \pm 0.006$	6.4/8	0.104 [800/9]

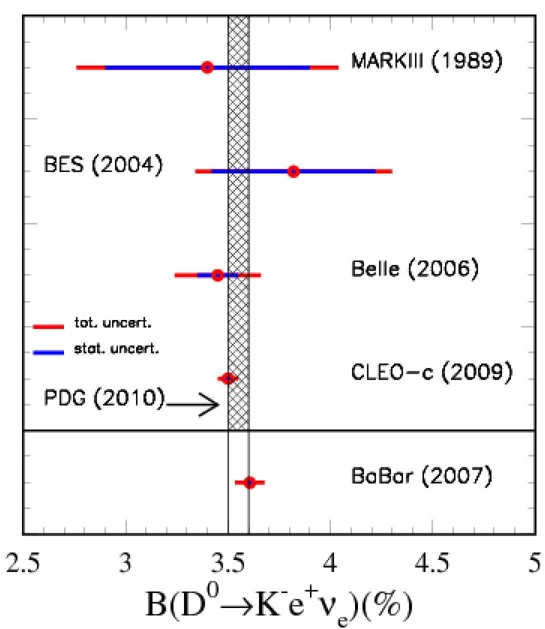
M_{pole}, ISGW, default values excluded

$D^0 \to K^- e^+ \nu$: comparison with other experiments





CLEO-c and BaBar measurements agree, Babar uncert. is similar to final CLEO-c (818 pb^{-1})



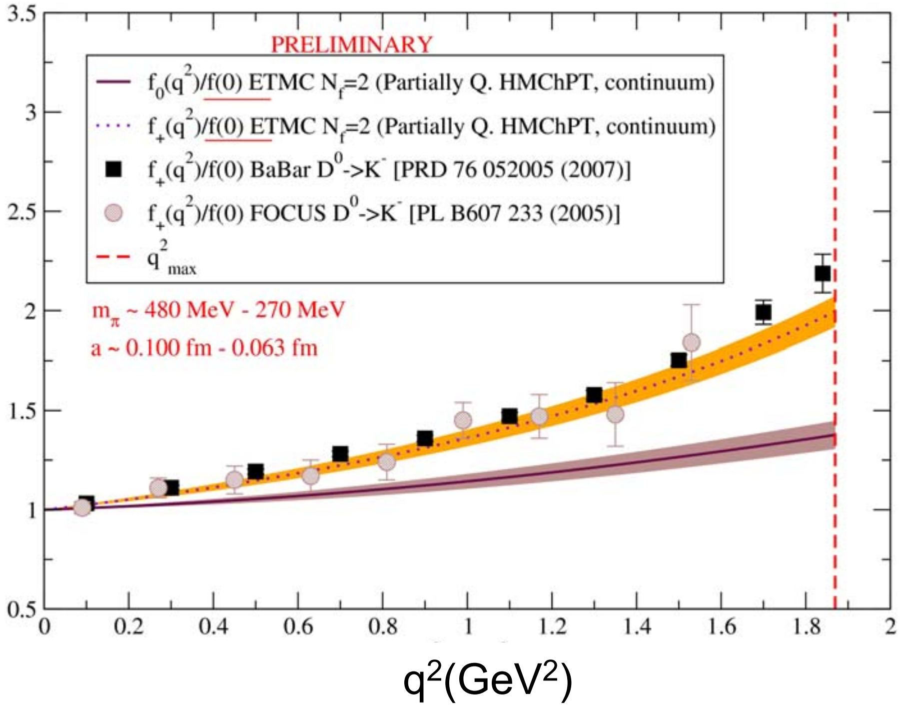
Modified pole parametrization:

$$f_+(q^2) = \frac{f_+(0)}{\left(1 - \frac{q^2}{m^2_{D_s^*}}\right)\left(1 - \alpha_{pole}\frac{q^2}{m^2_{D_s^*}}\right)}$$

α_{pole}= 0.38 (2) (3) BaBar
α_{pole}= 0.30 (3) (1) CLEO-c
[α_{pole}= 0.21 (4) (3) CLEO-c 281pb^{-1}]
α_{pole}= 0.52 (8) (6) Belle

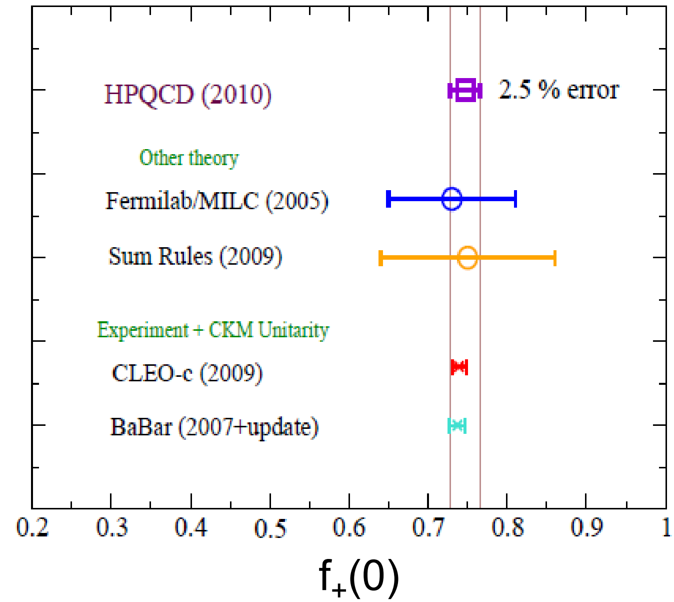
$D^0 \to K^- e^+ \nu$: comparison with LQCD

Lattice 2010, Di Vita



Good agreement in the full q^2 range

arXiv:1008.4562

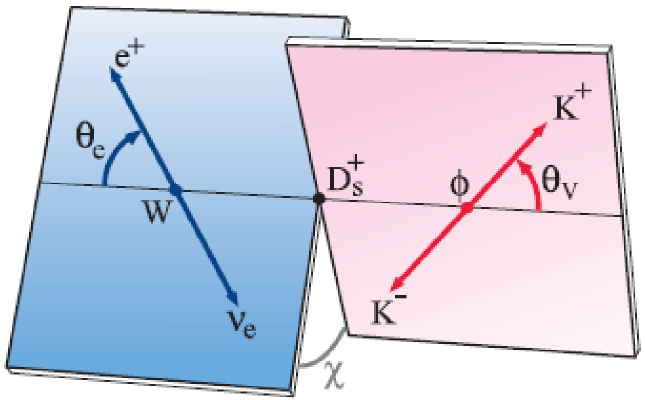


ETMC:	$f_+(0)$ = 0.76 (4) (?)
HPQCD:	$f_+(0)$ = 0.747 (11) (15)
Babar:	$f_+(0)$ = 0.735 (7) (5) (5)
Cleo-c:	$f_+(0)$ = 0.739 (7) (5)
Belle:	$f_+(0)$ = 0.695 (7) (22)

$D_s^+ \rightarrow K^+ K^- e^+ \nu_e$, $D^+ \rightarrow K^- \pi^+ e^+ \nu_e$

$D_s^+ \to K^+ K^- e^+ \nu$, $D^+ \to K^- \pi^+ e^+ \nu$

- Decay dominated by vector state (P-wave)
  - $D_s^+ \to \phi\, e^+ \nu_e$
  - $D^+ \to \overline{K}^* e^+ \nu_e$



- Possibility to study S-wave through interference with the P-wave

- Complicated channels:
  - 5 kinematic variables: m_{KK}, q^2, $\cos\theta_e$, $\cos\theta_V$, χ
  - 3 form factors for each resonance (apart the S-wave): axial-vector (A_1,A_2) and vector V parameterized by pole dominance

$$A_i(q^2) = \frac{A_i(0)}{1 - q^2/m_A^2} \qquad V(q^2) = \frac{V(0)}{1 - q^2/m_V^2}$$

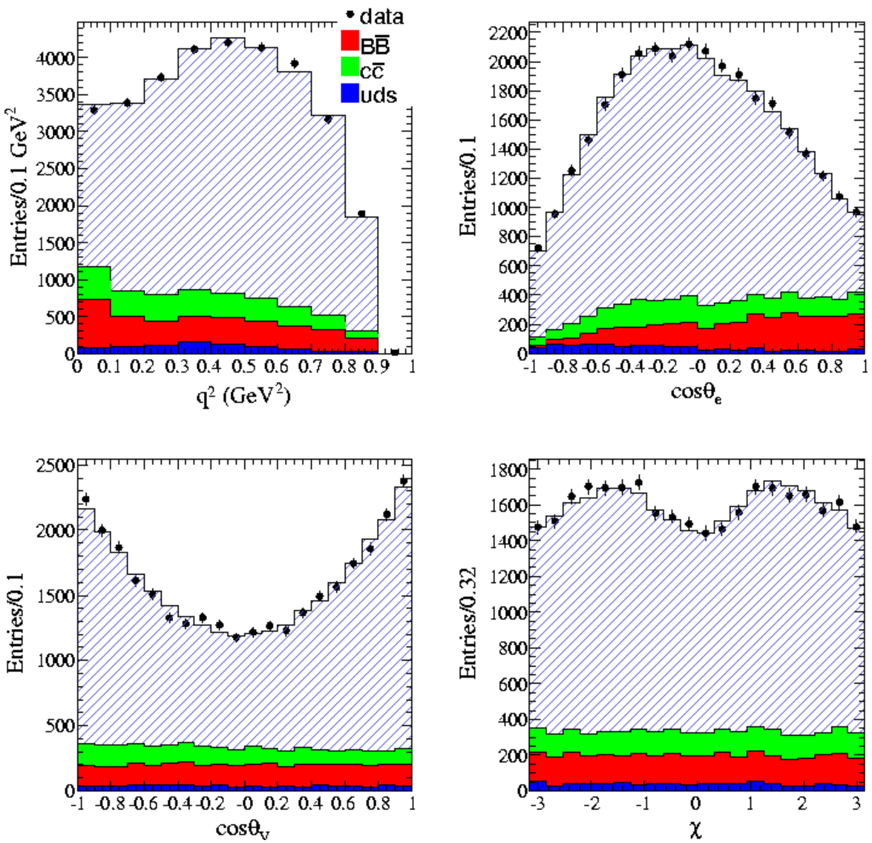
we measure : $r_V = V(0)/A_1(0)$ $r_2 = A_2(0)/A_1(0)$ $A_1(0)$ m_A

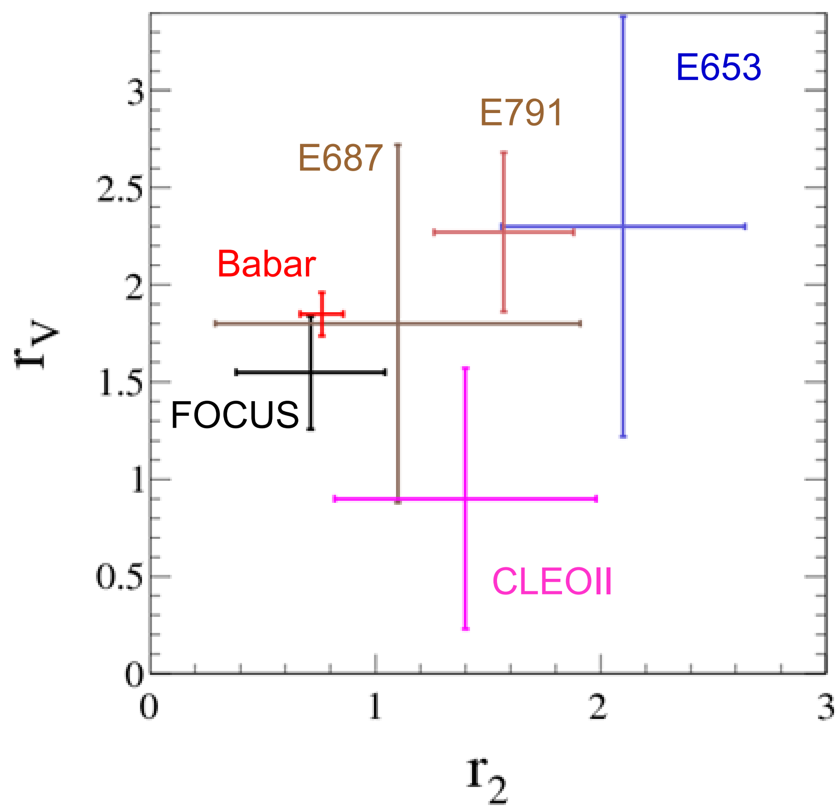
$D_s^+ \to K^+ K^- e^+ \nu$

- 25000 signal events anaylised (50 times FOCUS, ~250 times CLEO-c)
- 4D fit in the ϕ region

- Accurate determination of $D_s \to \phi e \nu$ FF (first measurement of q^2 variation for the axial vector FF, m_A=2.3±0.2±0.2 GeV/c^2)
- BR normalized to $D_s^+ \to K^+K^-\pi^+$: $A_1(0)$=0.607±0.011±0.019±0.018

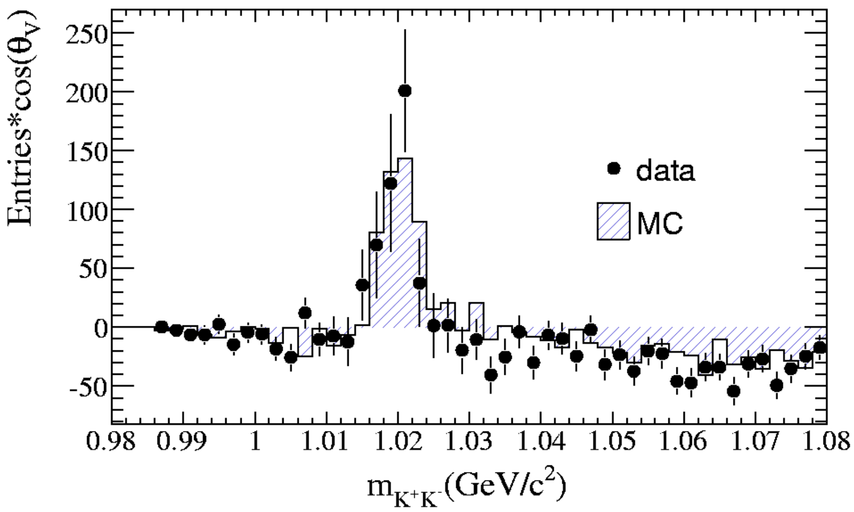
PRD 78:051101,2008 (214fb^{-1})





K^+K^- S wave

Asymmetry can be seen on the mass distribution weighted by $\cos\theta_V$:



First measurement of S wave in this decay!

$r_0 = 15.1 \pm 2.6 \pm 1\ GeV^{-1}$ (S-wave relative amplitude)

Babar approach complementary to CLEO-c, very large statistics needed to observe the S-wave in the KK system

Between $1.01 < m_{KK} < 1.03$ GeV/c² :

$$\frac{BR(D_s^+ \to f_0 e^+ \nu) \times BR(f_0 \to K^+K^-)}{BR(D_s^+ \to K^+K^- e^+ \nu)} = (0.22^{+0.12}_{-0.08} \pm 0.03)\%$$

Extrapolation to the total mass range using BES parameters for the f_0
Phys Lett B607, 243 (2005)

$$\frac{BR(D_s \to f_0 e^+ \nu)}{BR(D_s \to \varphi\, e^+ \nu)} = (4.5^{+2.5}_{-1.6} \pm 0.6)\%$$

Cleo-c: $(17 \pm 4)\%$

PRD80, 052009 (2009)

Fraction similar to the Kπ system

$$\frac{BR(D^+ \to K^-\pi^+ e^+ \nu)_S}{BR(D^+ \to K^-\pi^+ e^+ \nu)_{total}} = (5.79 \pm 0.16 \pm 0.15)\%$$

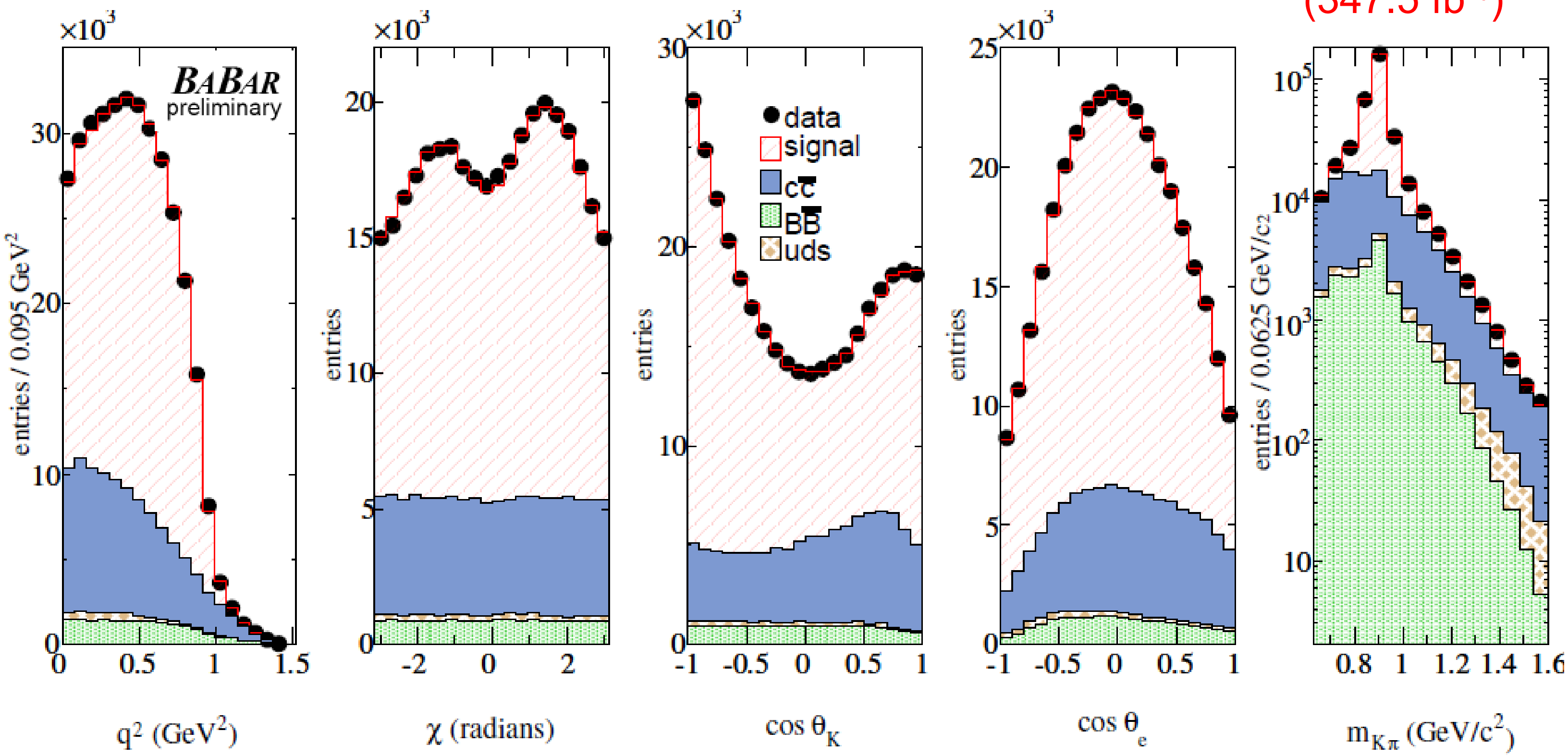
$D^+ \rightarrow K^- \pi^+ e^+ \nu$

Preliminary result

- 245K events analysed (CLEO-c (e+μ): 11800 events)
- Fit in 5D in all phase space including S-wave (phase parameterization from LASS, parameters fitted), K*(892) and K*(1410)
  - Accurate measurement of the K*(892) form factor parameters
  - Determination of the K*(892) resonance parameters
  - Search for possible higher mass state contribution

Fit result:

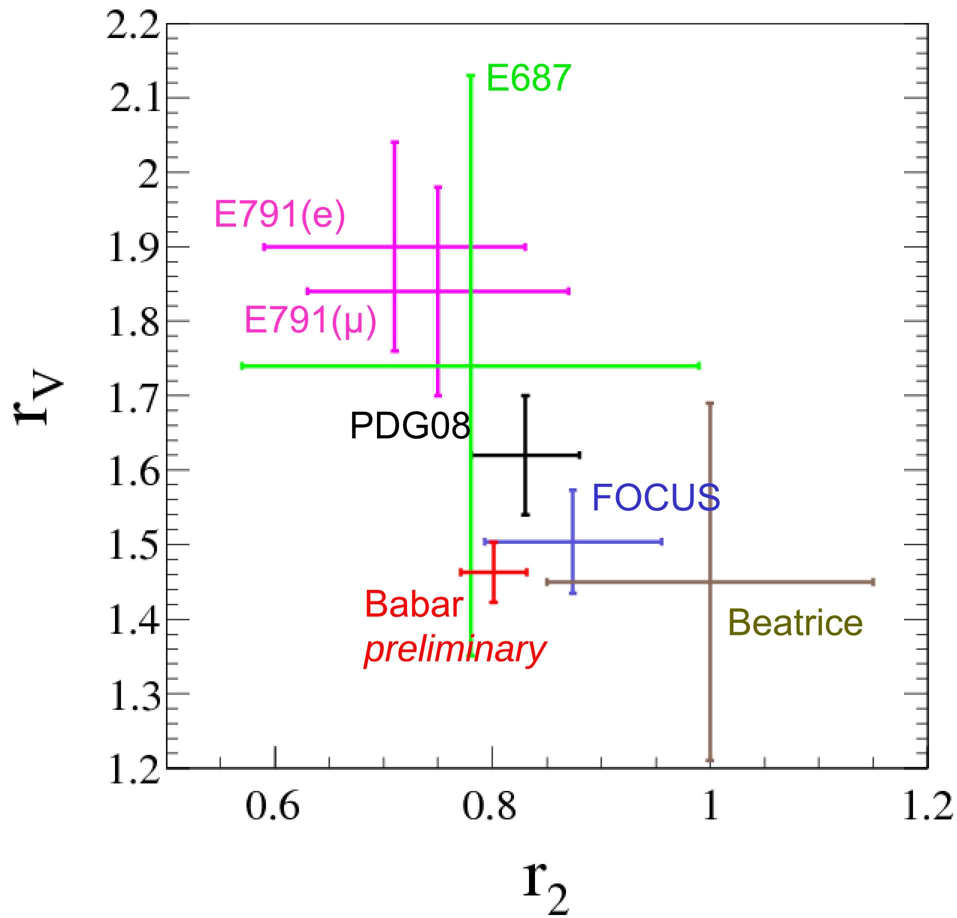
(347.5 fb^{-1})



$D^+ \to \bar{K}^* e^+ \nu_e$ form factors

- Accurate determination of $D^+ \to \bar{K}^* e^+ \nu_e$ decay characteristics (first measurement of q^2 variation for the axial vector form factor, $m_A = 2.63 \pm 0.10 \pm 0.13$ GeV/c^2)

- BR normalized to $D \to K^+ \pi^- \pi^+$: $A_1(0) = 0.6226 \pm 0.0056 \pm 0.0065 \pm 0.0074$



Flavour independence of $D \to V e \nu$

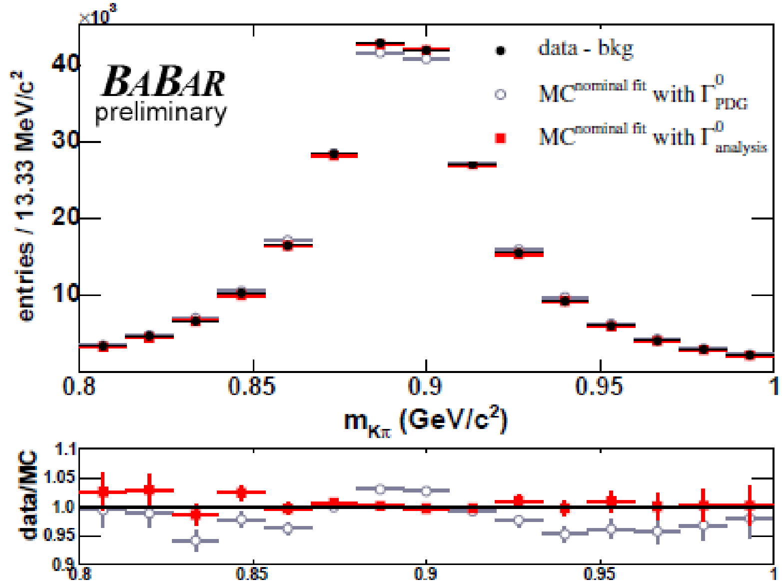
	$D^+_s \to \phi e^+ \nu$	$D^+ \to K^{*0} e^+ \nu$
$A_1(0)$	0.61±0.03	0.62±0.01
r_2	0.76±0.10	0.80±0.03
r_V	1.85±0.11	1.46±0.04
m_A (GeV/c^2)	2.3±0.3	2.63±0.16

3σ?

m_A fitted
m_V fixed

K* parameters and other contributions

Fitting Babar data keeping the K* width fixed to PDG 2008 value gives poor agreement with data



	BaBar	PDG 2008
$m_{K^*(892)}$ (MeV/c^2)	895.4±0.2±0.2	896.00±0.25
$\Gamma_{K^*(892)}$ (MeV/c^2)	46.5±0.3±0.2	50.3±0.6

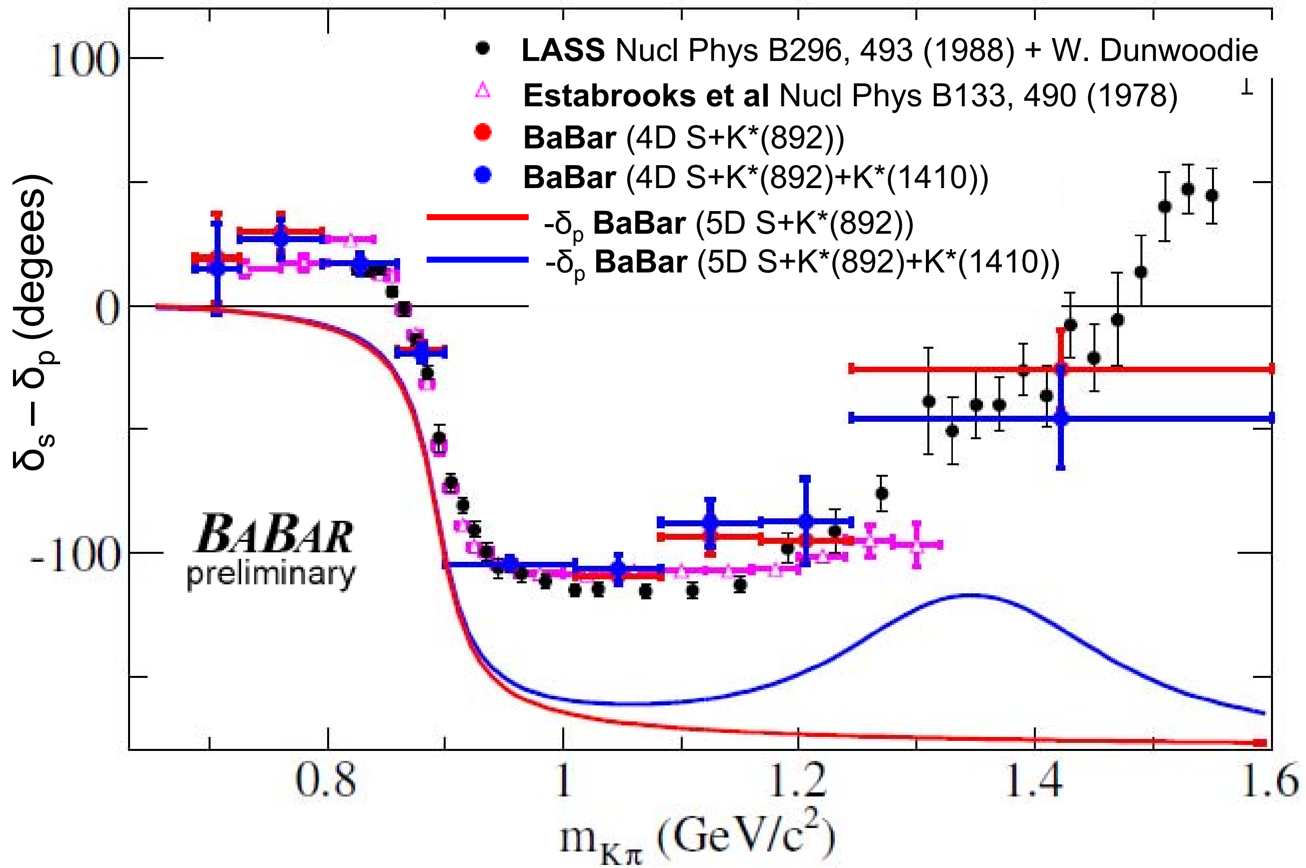
Measured branching fractions :

	BaBar	PDG
$\mathcal{B}(D^+ \to K^-\pi^+e^+\nu_e)(\%)$	$4.04 \pm 0.03 \pm 0.04 \pm 0.09$	4.1 ± 0.6
$\mathcal{B}(D^+ \to K^-\pi^+e^+\nu_e)_{\overline{K}^{*0}}(\%)$	$3.80 \pm 0.04 \pm 0.05 \pm 0.09$	3.66 ± 0.21
$\mathcal{B}(D^+ \to K^-\pi^+e^+\nu_e)_{S-wave}(\%)$	$0.234 \pm 0.007 \pm 0.007 \pm 0.005$	0.21 ± 0.05
$\mathcal{B}(D^+ \to \overline{K}^*(1410)^0e^+\nu_e)(\%)$	$0.30 \pm 0.12 \pm 0.18 \pm 0.06$ $(< 0.6$ at 90% C.L.$)$	
$\mathcal{B}(D^+ \to \overline{K}_2^*(1430)^0e^+\nu_e)(\%)$	$0.023 \pm 0.011 \pm 0.011 \pm 0.001$ $(< 0.05$ at 90% C.L.$)$	

- S wave and K*(1410) components correspond to ~5% of total rate (large uncertainty for the K*(1410) because of small coupling to Kπ)
- low limit placed on K_2^*(1430)

Kπ S wave phase

- Fixing the K*(892) parameters, signal and background numbers fitted previously, the S wave phase is measured in bins of $m_{K\pi}$



Watson's theorem: same phase variation (modulo π) with regards to Kπ scattering in the elastic regime

- Babar in agreement with LASS (Kπ scattering experiment) with a difference of π
- This may help understanding the effect of the spectator π in $D^+ \to K^-\pi^+\pi^+$ analyses

Summary

- B factories have demonstrated their capability to do precision measurements of charm semileptonic decays

- $D^0 \to K^- e^+ \nu$:
  - Babar and CLEO-c agree on the rate and FF q^2 variation
  - New lattice QCD results compatible with experiments ☺

- $D_s^+ \to \phi e^+ \nu_e$. $D^+ \to K^* e^+ \nu_e$:
  - Accurate measurement of decay rate and FF q^2 variation (first measurement of the axial-vector FF q^2 variation)
  - No LQCD unquenched results ☹

- $D_s \to K^+ K^- e^+ \nu$:
  - First measurement of S-wave component in a D_s sl decay channel
  - Using BES parameters for the f_0, Babar obtains a $BR(D_s^+ \to f_0 e^+ \nu_e)$ smaller than CLEO-c

- $D^+ \to K^- \pi^+ e^+ \nu$:
  - Measurement of the $K\pi$ S-wave phase in agreement with LASS
  - Detailed measurement of the K^{*0} mass distribution
  - Low limit placed on $K_2^*(1430)$ contribution in the $K^-\pi^+$ final state

Future

- Present accuracy on hadronic FF is already much higher than LQCD evaluations

- Other sl D decay channels can be measured at B-factories using present data: $D^0 \to \pi e\nu$, $D_s \to \eta/\eta' e\nu$, $\Lambda_c \to \Lambda e\nu$, … (manpower?)

- To obtain higher accuracy, operating at threshold is better: low background, high resolution on kinematic variables, possibility to measure radiated photons, access rare decay modes, control of detector performances using J/ψ decays, …

- BES III, from FPCP 2010 (Hai-Bo Li):

Proposed Running Plan at BESIII

In the next two years` running, BES-III will collect 3.2 fb^{-1} @$\psi(3770)$ which is more than 4 times larger than that at CLEO-c

- Much more statistics would be available with a Super-flavour factory running at charm threshold (1.5 ab^{-1} per year: 2 months of data taking= 300xCLEO-c)

Backup

Decay rate

$$d^5\Gamma = \frac{G_F^2|V_{cs}|^2}{(4\pi)^6 m_D^3} p_{KK} m_D \frac{2p^*}{m} I(m^2, q^2, \theta_V, \theta_e, \chi) dm^2 dq^2 d\cos\theta_e d\cos\theta_V d\chi$$

$$\begin{aligned} I = {} & I_1 + I_2 \cos 2\theta_e + I_3 \sin^2\theta_e \cos 2\chi \\ & + I_4 \sin 2\theta_e \cos\chi + I_5 \sin\theta_e \cos\chi \\ & + I_6 \cos\theta_e + I_7 \sin\theta_e \sin\chi \\ & + I_8 \sin 2\theta_e \sin\chi + I_9 \sin^2\theta_e \sin 2\chi \end{aligned}$$

$$I_1 = \frac{1}{4}\left\{|F_1|^2 + \frac{3}{2}\sin^2\theta_V\left(|F_2|^2 + |F_3|^2\right)\right\} \quad ,....$$

Partial wave decomposition (S and P)

$$F_1 = F_{10} + F_{11}\cos\theta_V$$

$$F_2 = \frac{1}{\sqrt{2}} F_{21}$$

$$F_3 = \frac{1}{\sqrt{2}} F_{31}$$

F_{10}: S wave

F_{11}, F_{21}, F_{31}: P wave

Interference term α $\cos\theta_V$

S wave parameterization

- S wave: f_0

$$F_{10} = r_0 f_{10}(q^2) A_{f0}(m)$$

Normalisation:

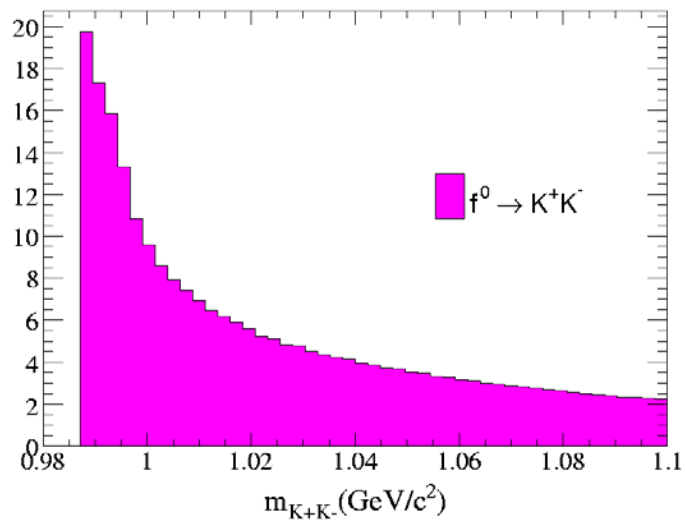
Fit parameter

Form factor

$$f_{10}(q^2) = \frac{p_{KK} m_D}{1 - q^2 / M_A^2}$$

$$A_{f0}(m) = \frac{m_{fo} g_\pi}{m_{f0}^2 - m^2 - i m_{f0} \Gamma_{f0}}$$

f_0 amplitude: Flatté (parameters from BES)



$D^+ \rightarrow K^- \pi^+ e^+ \nu$

resonance	J^P	branching fraction to $K\pi$ (%)	mass MeV/c^2
$K_0^*(800)$ (?)	0^+	100(?)	672 ± 40
$K^*(892)$	1^-	100	896.00 ± 0.25
$K_1(1270)$	1^+	0	1272 ± 7
$K_1(1400)$	1^+	0	1403 ± 7
$K^*(1410)$	1^-	6.6 ± 1.3	1414 ± 15
$K_0^*(1430)$	0^+	93 ± 10	1425 ± 50
$K_2^*(1430)$	2^+	49.9 ± 1.2	1432.4 ± 1.3
$K^*(1680)$	1^-	38.7 ± 2.5	1717 ± 27

LASS parametrization of the S wave phase

$$\delta^{1/2}_{LASS} = \delta^{1/2}_{BG} + \delta_{K_0^*(1430)}$$

$$\cot\left(\delta^{1/2}_{BG}\right) = \frac{1}{a^{1/2}_{S,BG}\, p^*} + \frac{b^{1/2}_{S,BG}\, p^*}{2}$$

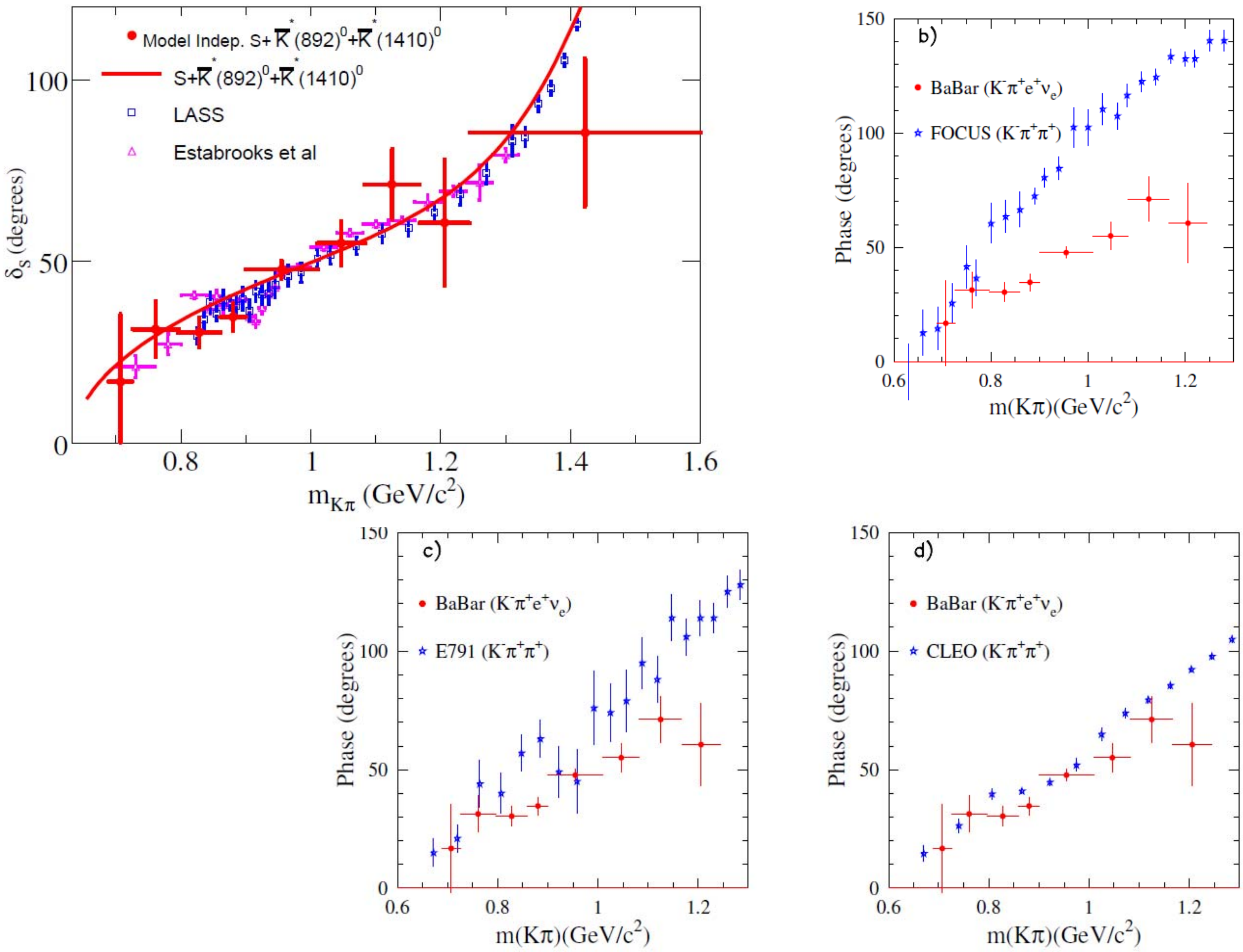
$$\cot\left(\delta_{K_0^*(1430)}\right) = \frac{m^2_{K_0^*(1430)} - m^2_{K\pi}}{m_{K_0^*(1430)}\Gamma_{K_0^*(1430)}(m_{K\pi})}$$

$D^+ \to K^- \pi^+ e^+ \nu$

- Fit results

variable	$S+\overline{K}^*(892)^0$	$S+\overline{K}^*(892)^0$ $\overline{K}^*(1410)^0$	$S+\overline{K}^*(892)^0$ $\overline{K}^*(1410)^0+D$
$m_{K^*(892)}(\mathrm{MeV}/c^2)$	894.77 ± 0.08	895.43 ± 0.21	895.27 ± 0.15
$\Gamma^0_{K^*(892)}(\mathrm{MeV}/c^2)$	45.78 ± 0.23	46.48 ± 0.31	46.38 ± 0.26
$r_{BW}(\mathrm{GeV}/c)^{-1}$	3.71 ± 0.22	2.13 ± 0.48	2.31 ± 0.20
$m_A(\mathrm{GeV}/c^2)$	2.65 ± 0.10	2.63 ± 0.10	2.58 ± 0.09
r_V	1.458 ± 0.016	1.463 ± 0.017	1.471 ± 0.016
r_2	0.804 ± 0.020	0.801 ± 0.020	0.786 ± 0.020
r_S	-0.470 ± 0.032	-0.497 ± 0.029	-0.548 ± 0.027
$r_S^{(1)}$	0.17 ± 0.08	0.14 ± 0.06	0.03 ± 0.06
$a^{1/2}_{S,BG}(\mathrm{GeV}/c)^{-1}$	1.82 ± 0.14	2.18 ± 0.14	2.10 ± 0.10
$b^{1/2}_{S,BG}(\mathrm{GeV}/c)^{-1}$	-1.66 ± 0.65	1.76 fixed	1.76 fixed
$r_{K^*(1410)^0}$		0.074 ± 0.016	0.052 ± 0.013
$\delta_{K^*(1410)^0}(degree)$		8.3 ± 13.0	0 fixed
r_D			0.78 ± 0.18
$\delta_D(degree)$			0 fixed
N_{sig}	243850 ± 699	243219 ± 713	243521 ± 688
N_{bkg}	107370 ± 593	108001 ± 613	107699 ± 583
Fit probability	4.6%	6.4%	8.8%

$D^+ \to K^- \pi^+ e^+ \nu$: S-wave



Form factors parameterization

$$\frac{d\Gamma}{dq^2} = \frac{G_f^2 |V_{q_1 q_2}|^2 p_{P'}^3}{24\pi^3} |f_+(q^2)|^2$$ (If $m_\ell \sim 0$)

Parametrizations of $f_+(q^2)$:

- **Simple pole mass** :

$$f_+(q^2) = \frac{f_+(0)}{1 - \frac{q^2}{m^2_{\text{pole}}}}$$

- **Modified pole mass** (B&K):

$$f_+(q^2) = \frac{f_+(0)}{\left(1 - \frac{q^2}{m^2_{D_s^*}}\right)\left(1 - \alpha_{\text{pole}} \frac{q^2}{m^2_{D_s^*}}\right)}$$

- **Isgur-Wise:**

$$f_+^{\text{ISGW2}}(q^2) = \frac{f_+(q^2_{max})}{(1 + \alpha_I (q^2_{max} - q^2))^2}$$

- **Series expansion** (model independent):

$$f_+(t) = \frac{1}{P(t)\Phi(t, t_0)} \sum_{k=0}^{\infty} a_k(t_0)\ z^k(t, t_0),$$

$$z(t, t_0) = \frac{\sqrt{t_+ - t} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - t} + \sqrt{t_+ - t_0}}.$$

Measure $r_1 = a_1/a_0$ and $r_2 = a_2/a_0$

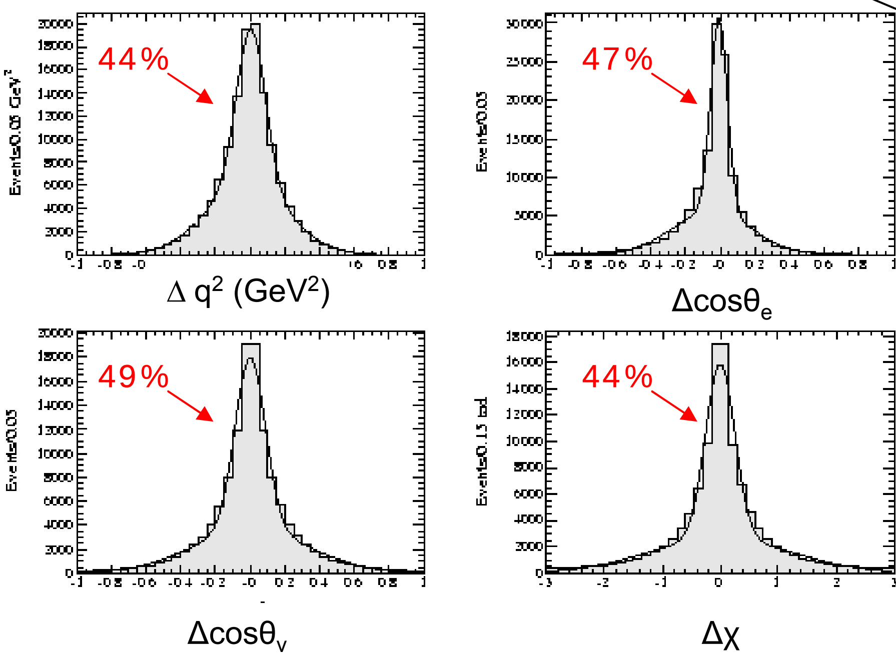
Kinematic variables

Typical resolutions :

σ_1 ~ **0.08 GeV²**
σ_2 ~ **0.23 GeV²**

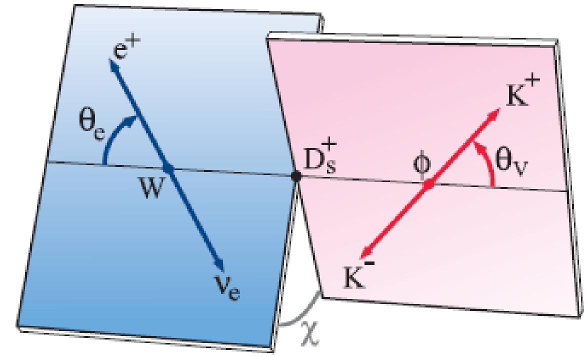
σ_1 ~ **0.05**
σ_2 ~ **0.23**

MC



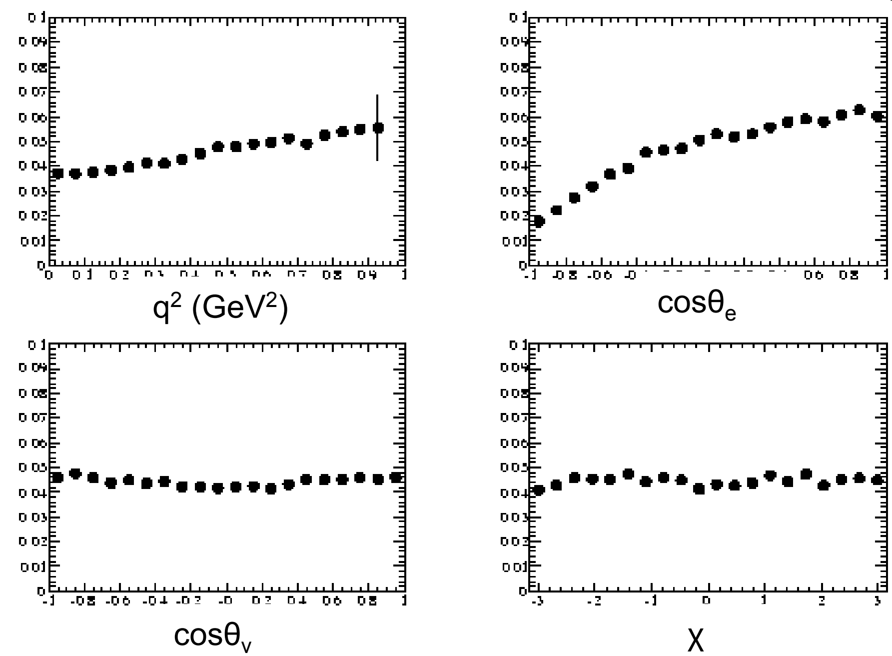
σ_1 ~ **0.09**
σ_2 ~ **0.33**

σ_1 ~ **0.25**
σ_2 ~ **1.22**



Global efficiency: ~4.5%

MC



Charm sl decays a