Leptonic and semileptonic D decays at BaBar

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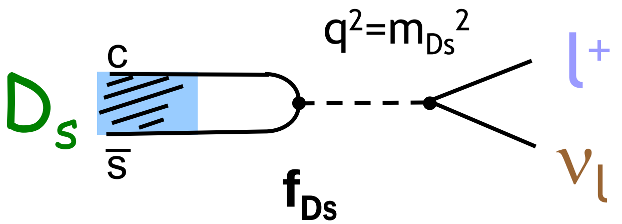
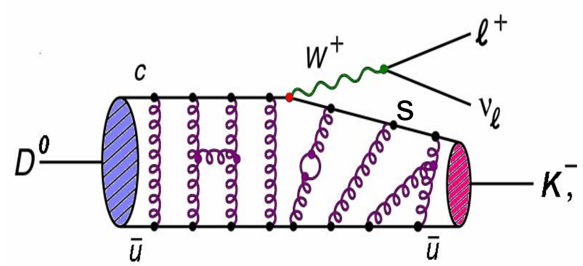
Introduction

➢ Charm leptonic and semileptonic decays provide an important way to test lattice QCD predictions. Techniques validated in the charm sector can then be used in the B sector to improve the accuracy on CKM parameters determination.

➢ QCD parametrization :





Leptonic : decay constant f_{Ds}

Semileptonic : form factors $F(q^2)$

In this talk :

$D_s^+ \to \mu^+\nu$

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

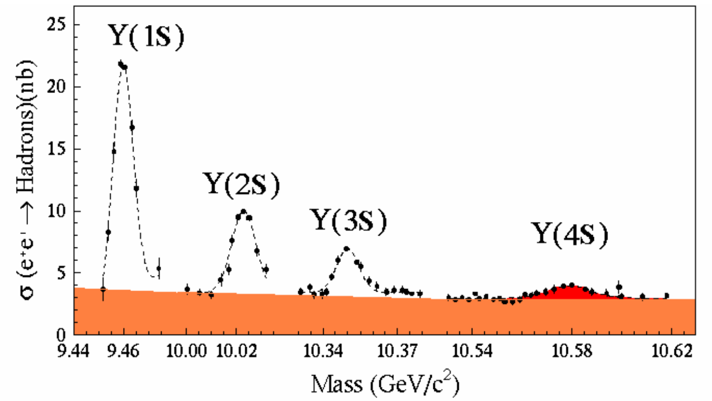
$D_s^+ \to \varphi e^+\nu$

Charm study at Babar

- Large cross section σ_{cc} ~1.3 nb
- Large integrated luminosity **400 fb^{-1}**

Large data sample available at Babar
(typically 0.5M evts with BR=1%, ε =10%)

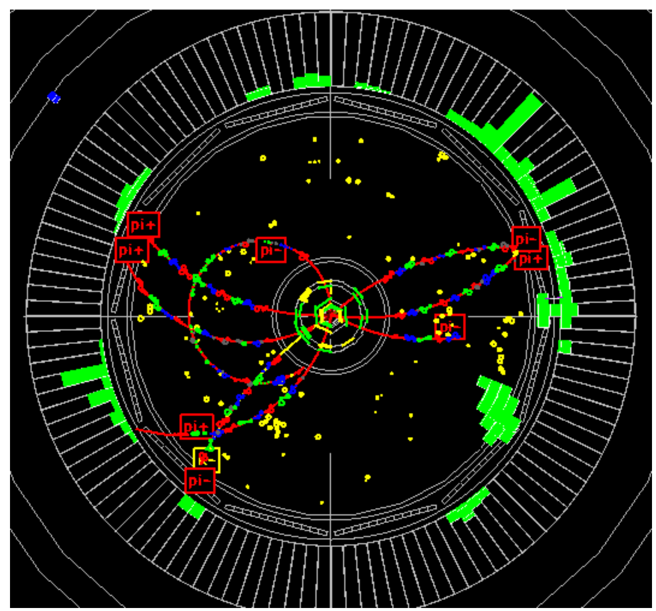
The analysis reported here are using just a fraction of the sample : 230 fb^{-1} and 75 fb^{-1}



- fragmentation (D, D_s,Λ_c,…)

- main challenge : background control

$c\bar{c}$

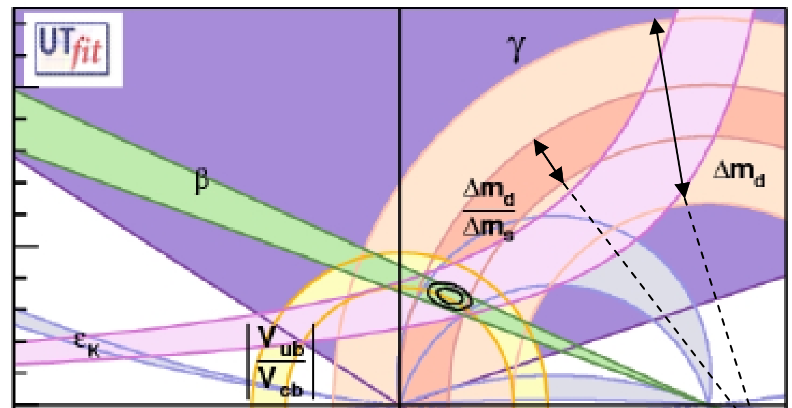


$D_s \to \mu\nu$

☆ Precise knowledge of f_{Bd} and f_{Bs} needed to improve constraints from ΔM_d and $\Delta M_d / \Delta M_s$

$$\Delta M_d = \frac{0.5}{ps}\left(\frac{f_{B_d}\sqrt{B_{B_d}}}{200MeV}\right)^2\left(\frac{V_{td}}{8.8\times10^{-3}}\right)^2$$

In LQCD similar techniques are used to measure b and c decay constant ⇒ experimental measurements of f_{Ds} and f_D can be used as a test of lattice QCD



theoretical uncertainties

☆ Partial width of $M^+ \to l^+\nu$:

$$\Gamma = \frac{G_F^2}{8\pi}\left|V_{Qq}\right|^2 f_M^2 M_M m_l^2 \left(1-\frac{m_l^2}{M_M^2}\right)^2$$

CKM Mixing

Phase space

Helicity Suppression

$D_s^+ \to \mu^+\nu$ is most accessible experimentally :

$$\Gamma(D_s^+ \to \tau^+\nu_\tau) : \Gamma(D_s^+ \to \mu^+\nu_\mu) : \Gamma(D_s^+ \to e^+\nu_e) = 10 : 1 : 10^{-5}$$

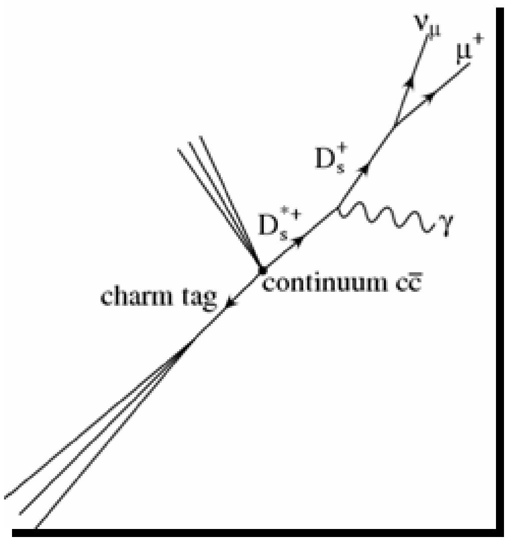
$D_s^+ \to \mu^+\nu$

Analysis overview

- Goal: Identify $D_s^* \to D_s\gamma$, $D_s \to \mu\nu_\mu$ decays in cc events

230.2 fb^{-1}

- Identify cc events: Charm -Tagging
  - Reconstruct charm mesons D^0, D^+, D_s^+, and D^{*+} using hadronic decay modes – the 'tag'
  - High tag momentum above the kinematic limit from B decays
- Search for $D_s^{*+} \to \gamma D_s^+ \to \gamma\mu^+\nu$ in recoil
- Advantages:
  - tag momentum reduces uds, BB, $\tau\tau$ backgrounds
  - tag direction improves fit to missing neutrino and the ΔM resolution
  - knowledge of tag's charm reduces pion→muon misidentification by 50%
- Disadvantage
  - Loss in efficiency due to tagging



Tagging strategy

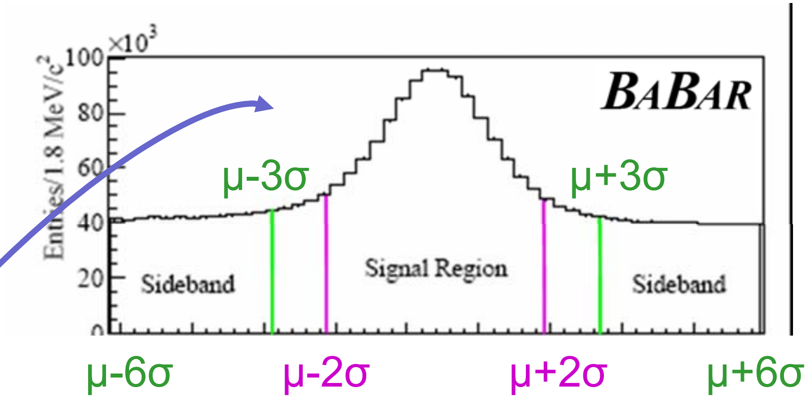
- Fully reconstructed D in 13 hadronic decay modes

- $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$
- $D^+ \to K^-\pi^+\pi^+(\pi^0)$, $K_S^0\pi^+(\pi^0)$, $K_S^0\pi^+\pi^+\pi^-$, $K^+K^-\pi^+$, $K_S^0K^+$
- $D_S^+ \to K_S^0K^+$, $\varphi\rho^+$
- $D^{*+} \to D^0\pi^+$, $D^0 \to K_S^0\pi^+\pi^-(\pi^0)$, $K_S^0K^+K^-$, $K_S^0\pi^0$

Modes allow identification of the charm quark flavour

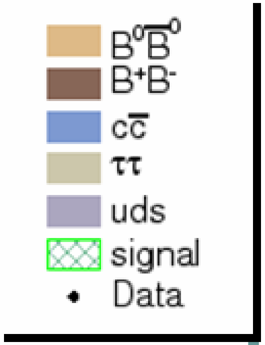
- Tag momentum above 2.35 GeV/c to remove D from B decays
- Fit tag mass peak: estimate μ, σ
- Define tag signal region μ±2σ, and sidebands between 3 and 6σ

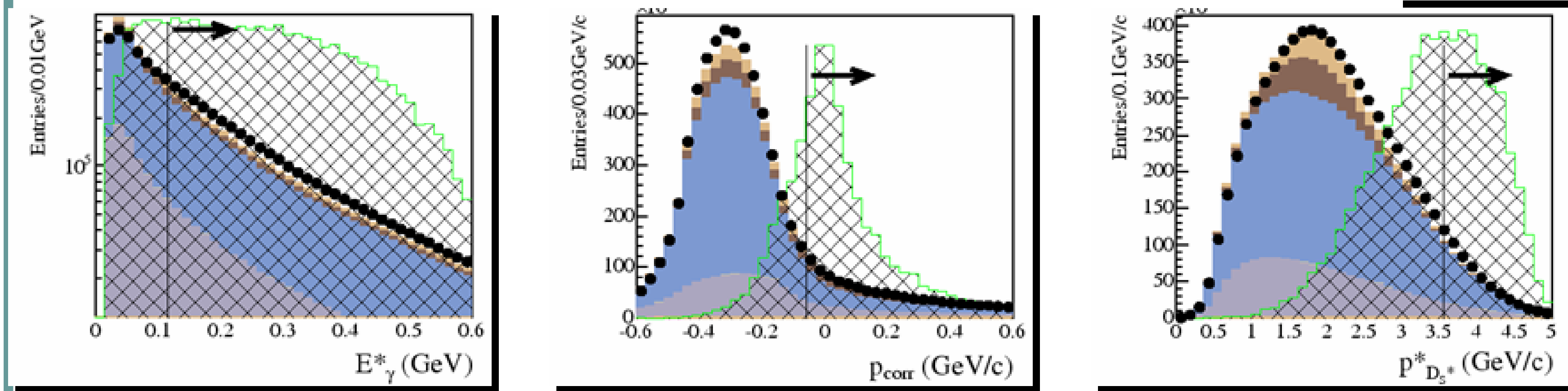
5.10^5 events with a muon in the recoil after bkg subtraction



Signal selection

- Signal is a peak in $\Delta M = M_{Ds*} - M_{Ds}$
- Tagging removes bb, uds, and $\tau\tau$ background, left with signal and cc background
- Identify kinematic quantities which distinguish signal





Photon energy | $p_{corr} = |p_{miss}| - |p_\nu|$ | D_s^{*+} momentum

More cuts with E_{miss}, angle (μ, D_s^+), θ_ν

- Cut optimization maximising the significance

Background

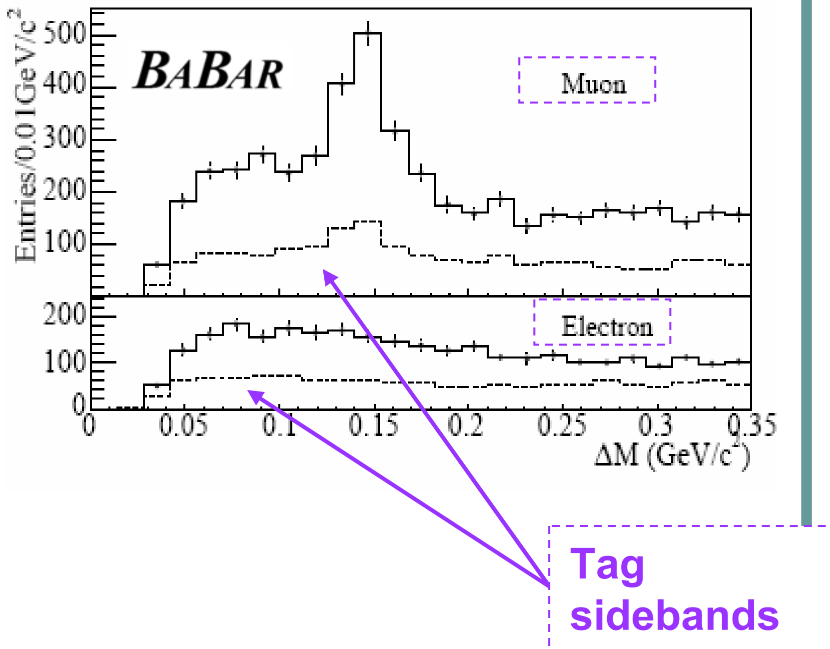
- Fake charm tag from uds, bb, $\tau\tau$, cc $\to$ 42 %

  $\Rightarrow$ Subtracted using the tag sidebands

- Correct tag but μ from charm semi leptonic decay or τ ($\tau \to \mu\nu_\mu\nu_\tau$) $\to$ 26 %

  $\Rightarrow$ Use electron : same decays appear with an e while there is no $D_s^+ \to e^+\nu$

  $\Rightarrow$ Take into account differences between μ and e (phase space, Bremsstrahlung, e from conversion)



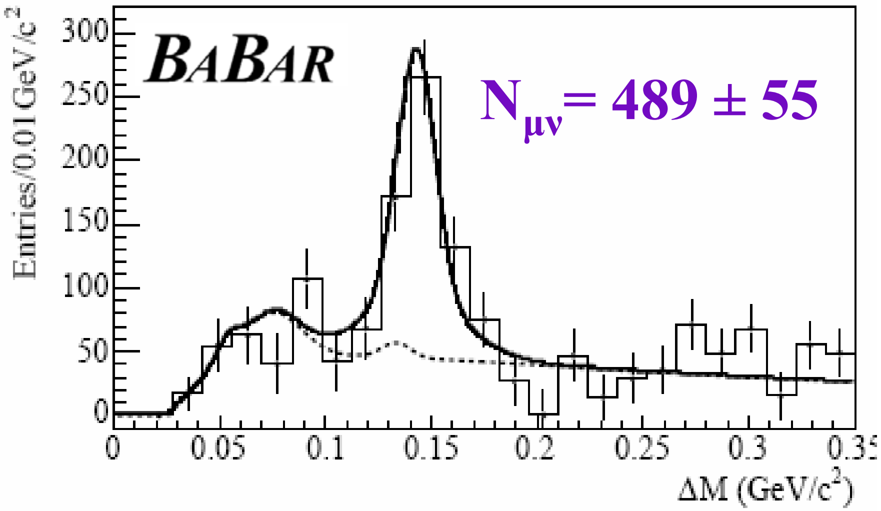
- Leptonic background
  $cc \to D_{(s)}^* \to D_{(s)}\pi^0,\ D_{(s)} \to \mu\nu_\mu$
  $cc \to D_{(s)} \to \mu\nu_\mu$
- Combinatoric

Estimated from simulated events

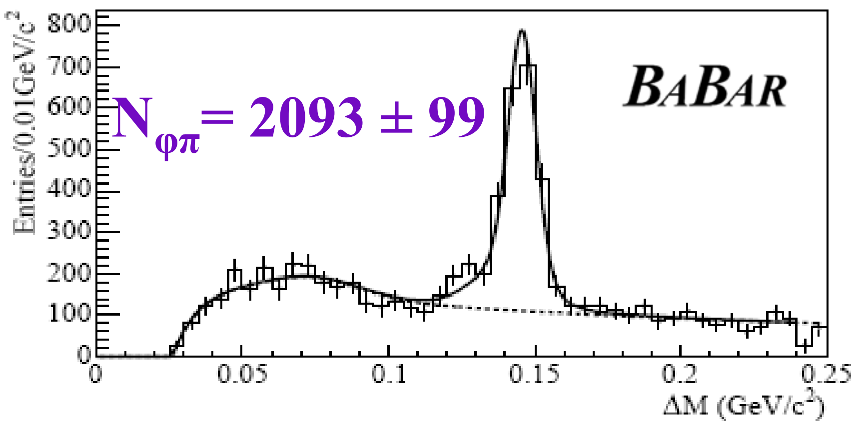
Signal yield

230.2 fb^{-1}

- Yield extraction :
  - bin-by-bin subtraction μ tag sideband from μ tag signal region
  - same for electrons
  - subtract electron from muon
  - Binned χ^2 fit



- Normalize to $D_s^+ \to \varphi\pi$:



We obtain :

$$\frac{\Gamma\left(D_s^+ \to \mu^+\nu_\mu\right)}{\Gamma\left(D_s^+ \to \phi\pi\right)} = 0.143 \pm 0.018 \pm 0.006$$

Independent measurement in BaBar :

$$B\left(D_s^+ \to \phi\pi\right) = (4.71 \pm 0.46)\%$$

PRD 71, 091104 (2005)

Results

230.2 fb^{-1}

We obtain $B(D_s^+ \to \mu^+\nu_\mu) = (6.74 \pm 0.83 \pm 0.26 \pm 0.66) \times 10^{-3}$

and $f_{D_s} = 283 \pm 17_{\text{stat}} \pm 7_{\text{syst}} \pm 14_{D_s \to \phi\pi}\ \text{MeV}$

Submitted to PRL hep-ex/0607094

Improvement possible (Babar: 1ab^{-1})

Small syst. uncertainty

Improvement possible

☆ Using CLEO-c value : $f_D = 222.6 \pm 16.7_{stat}{}^{+2.8}_{-3.4}{}_{syst}\text{MeV}$

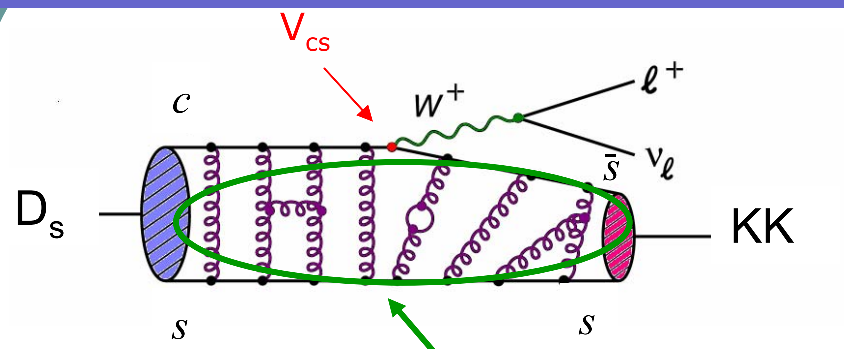
PRL 95, 251801 (2005)

We obtain $f_{Ds}/f_D = 1.27 \pm 0.14$ (11%)

Consistent with lattice QCD : $f_{Ds}/f_D = 1.24 \pm 0.07$ (5.6%)

PRL 95, 122002 (2005)

Charm semileptonic decays



hadronic effects : parameterized by form factors (ff)

$$q^2 = (P_l + P\nu)^2 = (P_P - P_{P'})^2$$

Motivation: Study QCD effects through the form factors and compare measurements to theoretical models

- Pseudoscalar ℓ ν decay : one form factor, angular distribution known

- Vector ℓ ν decay : 3 helicity states, 5 kinematic variables

Only the spectator quark differs

- $D^0 \to K^- e^+ \nu$
- $D_s \to \eta/\eta' e\nu$
- $D^0 \to \pi^- e^+ \nu$

Can help in V_{ub} determination

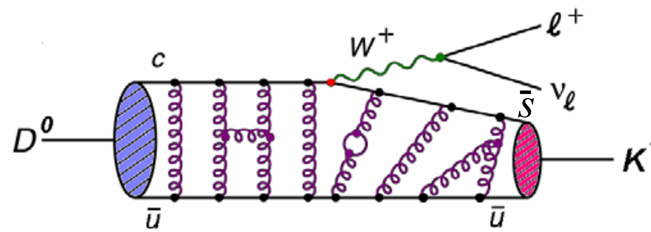
$$\frac{d\Gamma(B \to \pi \ell \nu)/dw}{d\Gamma(D \to \pi \ell \nu)/dw} = \left|\frac{V_{ub}}{V_{cd}}\right|^2 \left(\frac{M_B}{M_D}\right) \left|\frac{f_+^{B\to\pi}}{f_+^{D\to\pi}}\right|^2$$

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

Study Kπ system

D→Keν

☆ If the lepton is massless, the decay rate depends on one (vector) **ff** :



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

The measured ff can be compared with different theoretical models and test LQCD determination of the parameter involved :

- **Simple pole mass** : suppose that the decay is governed by the spectroscopic pole. The measured parameter is the "effective pole mass" m_{pole}.

$$\left|f_+(q^2)\right| = \frac{f_+(0)}{1 - \frac{q^2}{m_{pole}^2}}$$

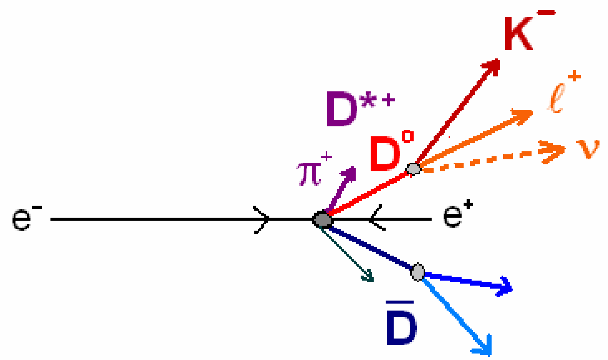
- **Modified pole mass** (B&K): add an effective pole to take into account higher resonances. Measure α_{pole}.

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

Spectroscopic mass pole, mD_s^* for Keν (1^- $c\bar{s}$ state)

Analysis overview

- Untagged analysis



- Reconstruct the decay channel

  $D^{*+} \to D^0 \pi^+, \quad D^0 \to K^- \ell^+ \nu$

  in $e^+e^- \to c\bar{c}$ continuum events

- Determine $q^2 = (p_D - p_K)^2 = (p_\ell + p_\nu)^2$ ← two constrained fits (m_{D0}, m_{D^*})
- Reduce the background ← Fisher analyses ($b\bar{b}$ and $c\bar{c}$ events)
- Extract the form factor ← Unfolding: SVD method
- methods validation ← Control samples

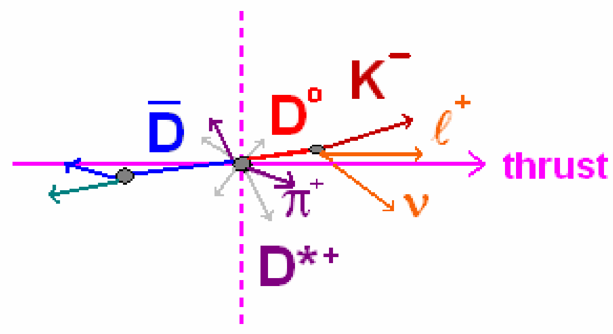
$D^0 \to K^- e^+ \nu$

Event reconstruction

- **Define two hemispheres:**
  - take soft π^+, K^- and ℓ^+ in the same hemisphere

Cuts
  - p^*_ℓ , p_ℓ > 0.5 GeV
  - $p^*_{\pi+}$ < 0.4 GeV
  - $\cos\theta_{thrust}$ < 0.6

$\Upsilon(4S)$ rest frame : *jet-like* events



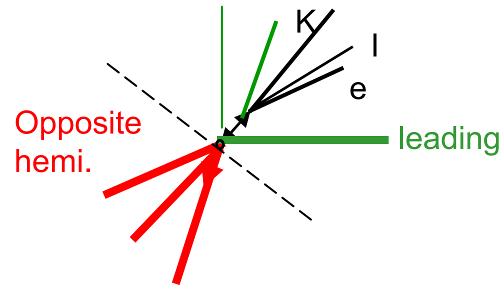
- **Compute D direction** ($-p_{\text{all particles} \neq K,\ell}$)
- **Compute the missing energy in the ℓ hemisphere**
- **Fit $p_D = p_K + p_\ell + p_\nu$**
  - From p_K, p_ℓ, computed E_{miss} and D^0 direction
  - Constraints using m_D and m_{D^*} (1c or 2c fit)

- **Compute $q^2 = (p_D - p_K)^2$**

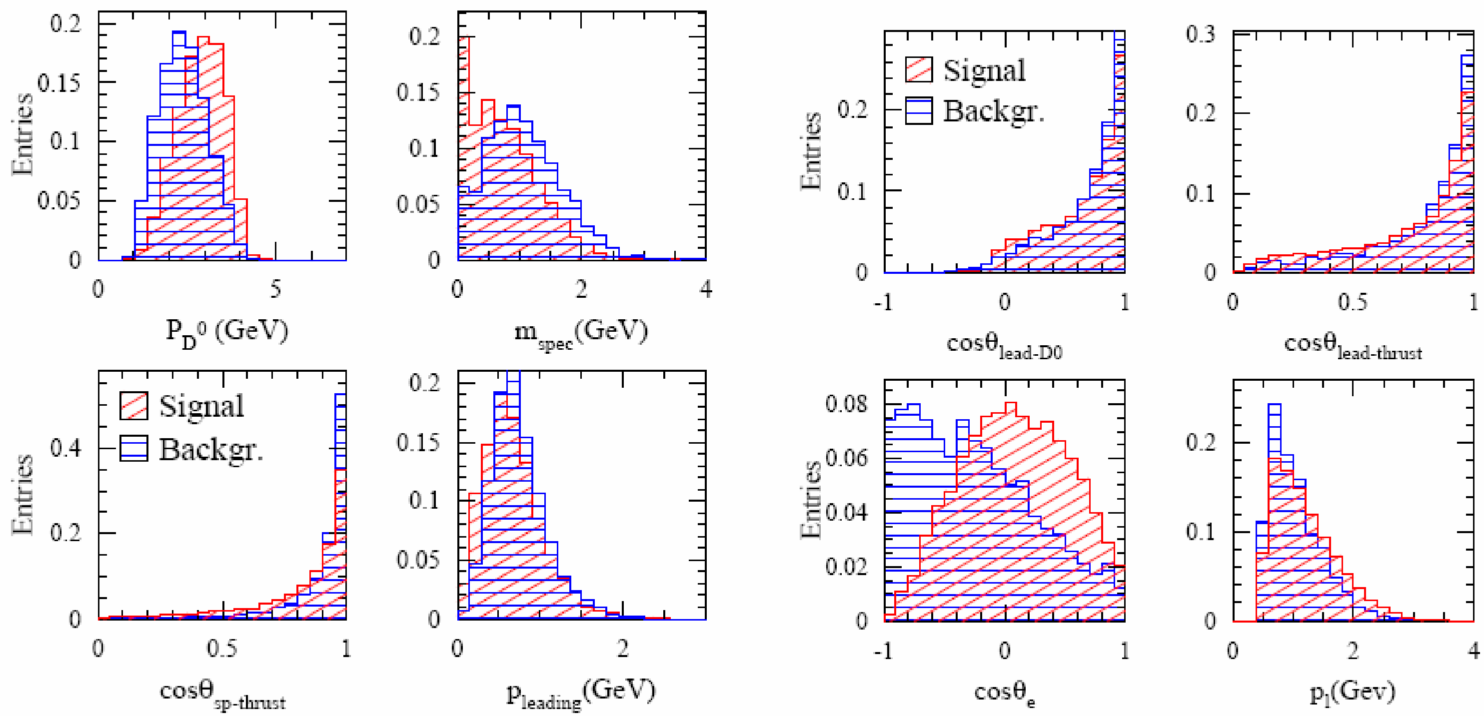
Background rejection

2 Fisher variables :

- **$c\bar{c}$ background:** Spectator system variables

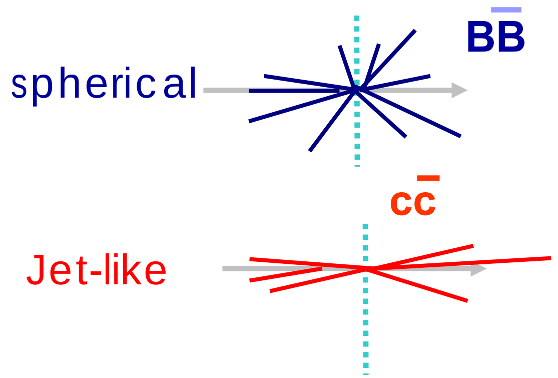


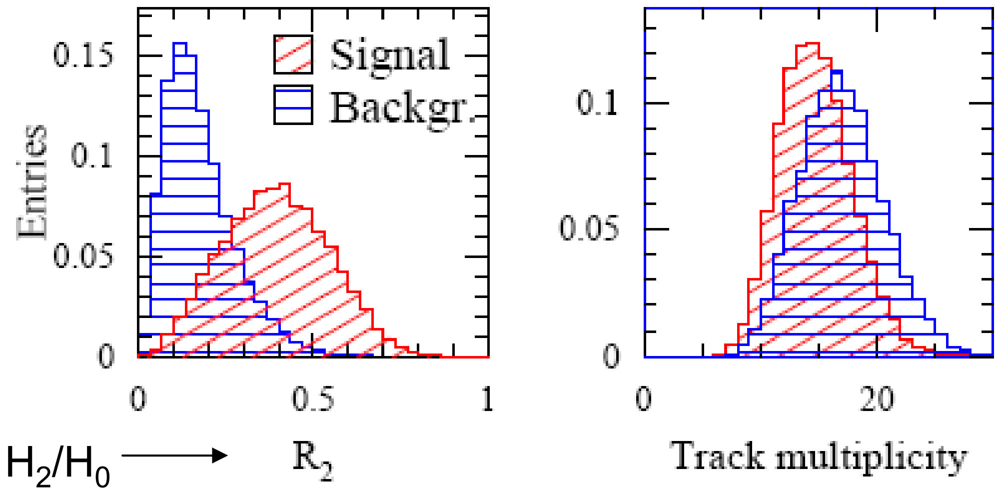
(mass, angular distribution, momentum and angular distribution of the leading particle + kinematic variables: p_D, p_ℓ, $\cos\vartheta_{W\ell}$)



Background rejection

- **$b\bar{b}$ events rejection:** Event shape variables





Fox-Wolfram moment H_2/H_0 ⟶

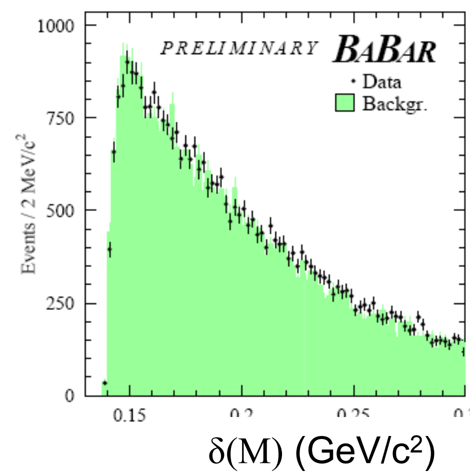
Remaining background composition :

B^0B^0 evts = 17% **B^+B^- evts = 7%** **uds evts = 3%**

Peaking cc = 48%
(real D*, with for ex : $D^0 \to K^-\pi^0 e\nu$ or $D^0 \to K^-\pi^0\pi^+$)

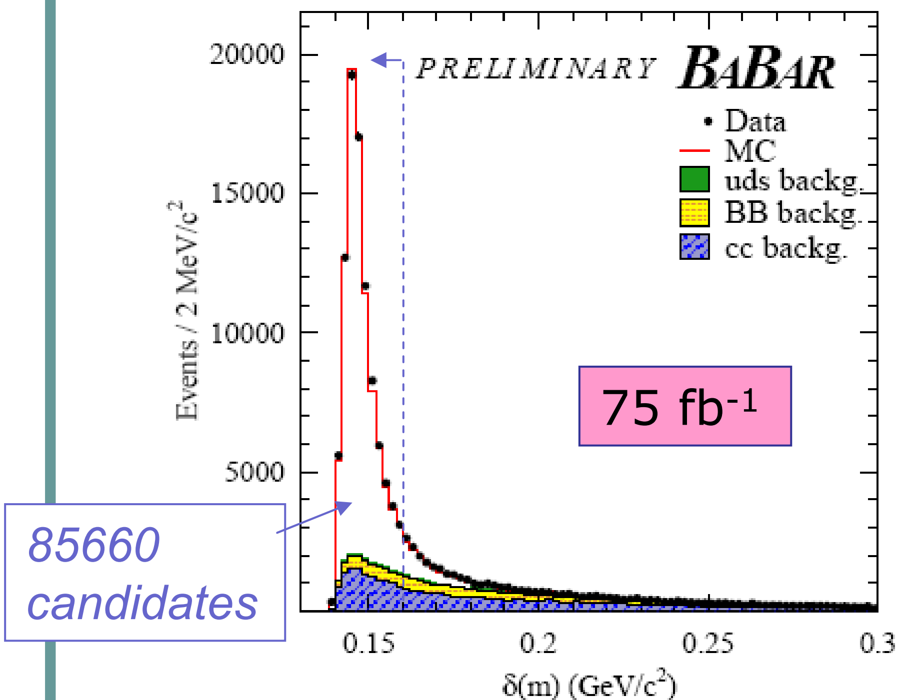
Non-peaking cc = 25%

check data/MC agreement with wrong sign events



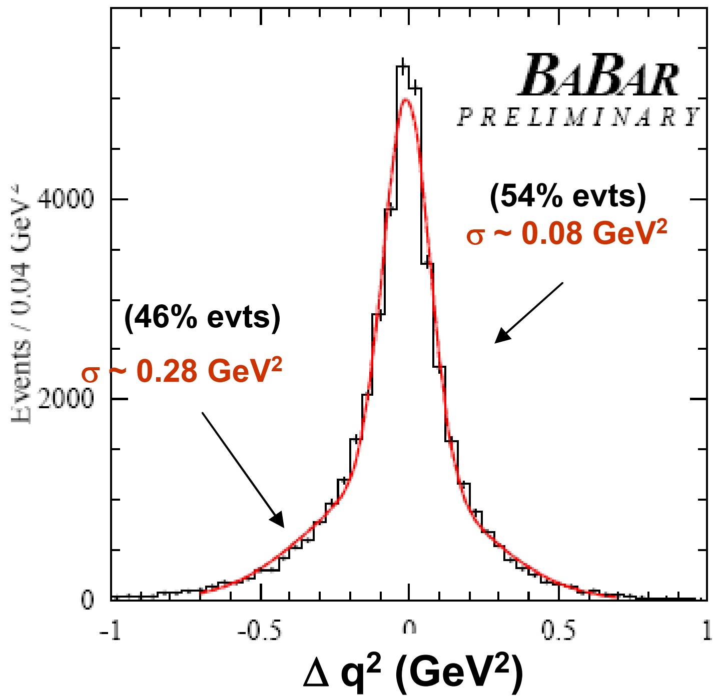
Decay characterisics

☆ Mass difference distribution



$\delta m = m(K^- \ell^+ \nu \pi^+) - m(K^- \ell^+ \nu)$ after the fit with 1 constraint on m_D

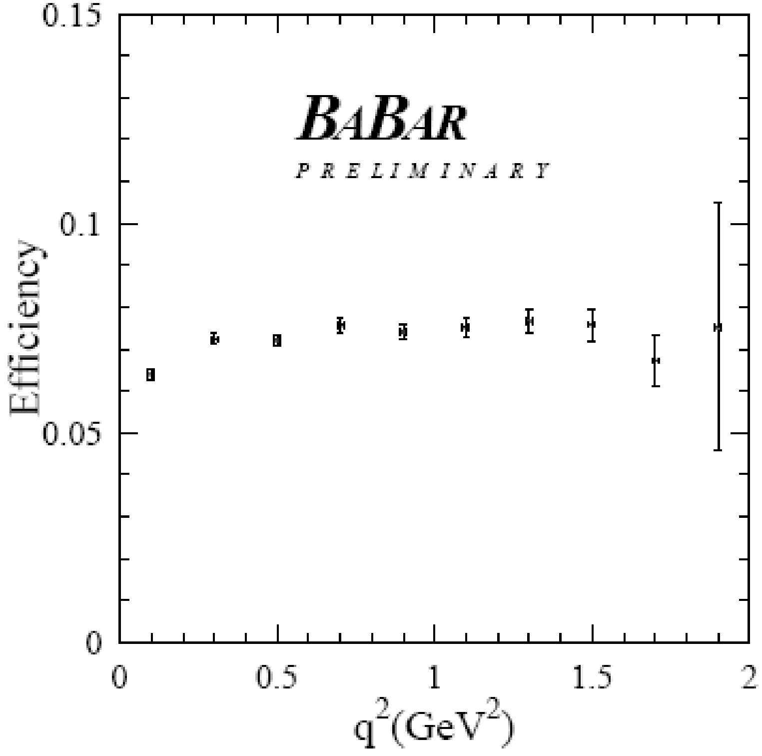
☆ q^2 resolution



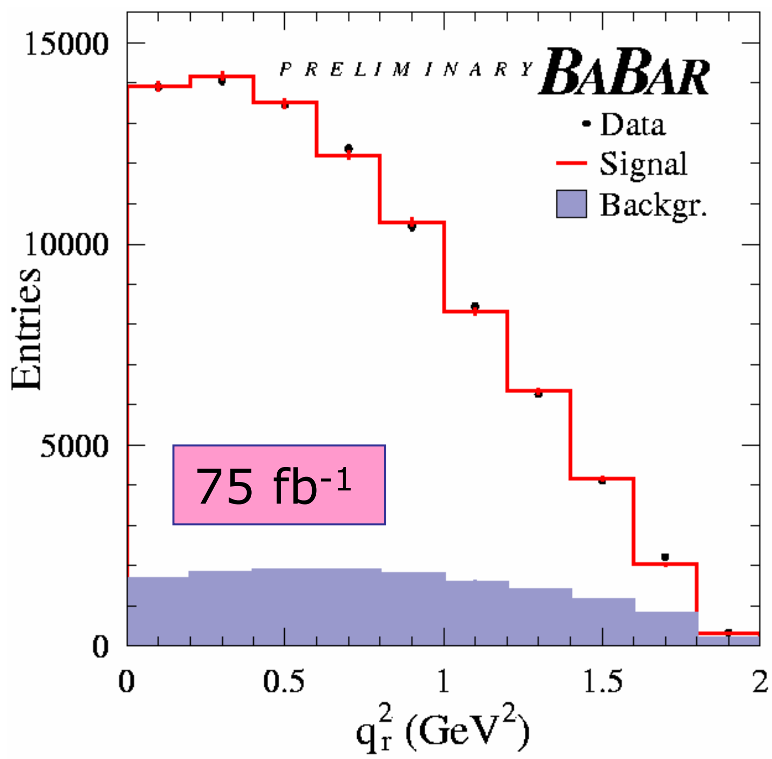
$D^0 \to K^- e^+ \nu$

Decay characteristics

☆ Efficiency vs q^2



☆ Reconstructed q^2 distribution



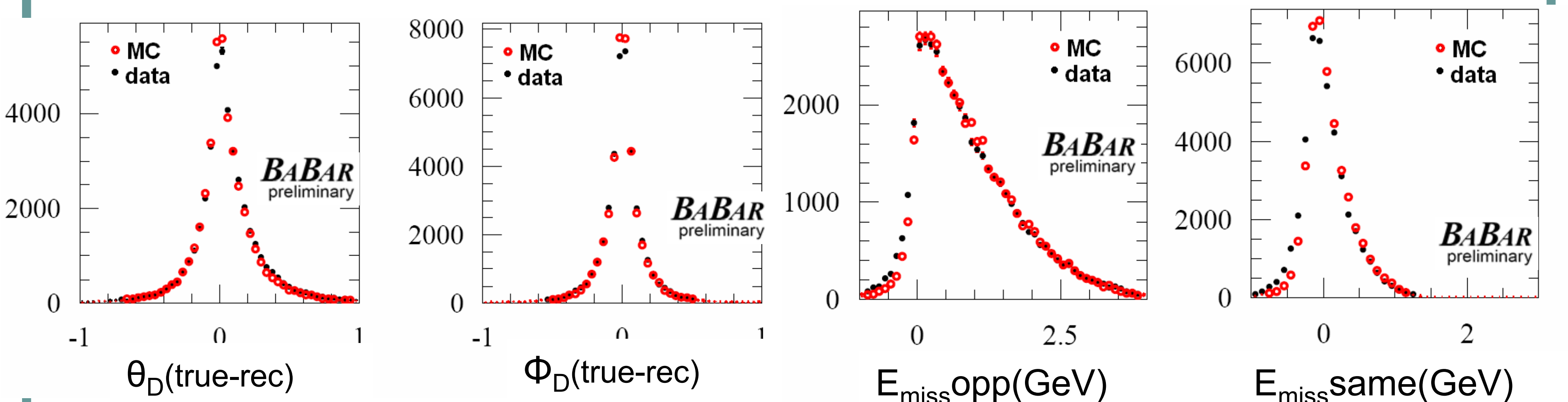
Control samples

We use two control samples:

- **$D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$**

Same criteria and selection cuts as for the semileptonic channel (apart for the lepton)

- **control of the Fisher bb and cc variables against background**
- **control of missing energy and p_D resolution used in the constrained fit**



Define a parametrization of the differences to take into account possible biases.

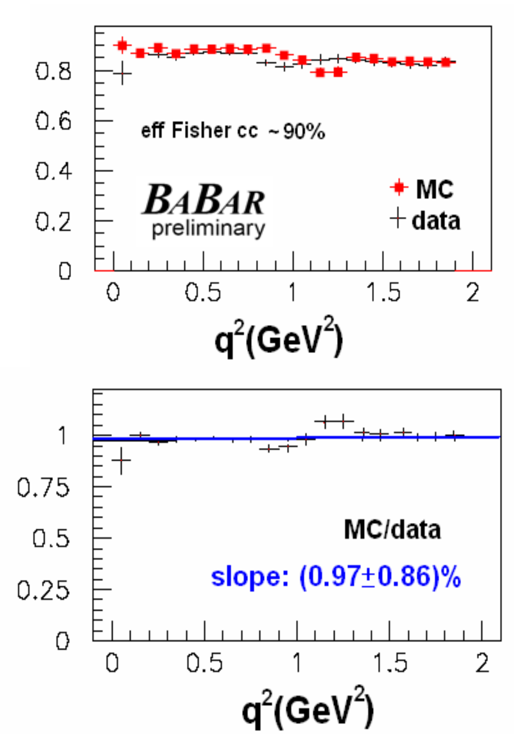
Control samples

- **$D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+\pi^0$ ($\pi^0 \to \gamma\gamma$)**

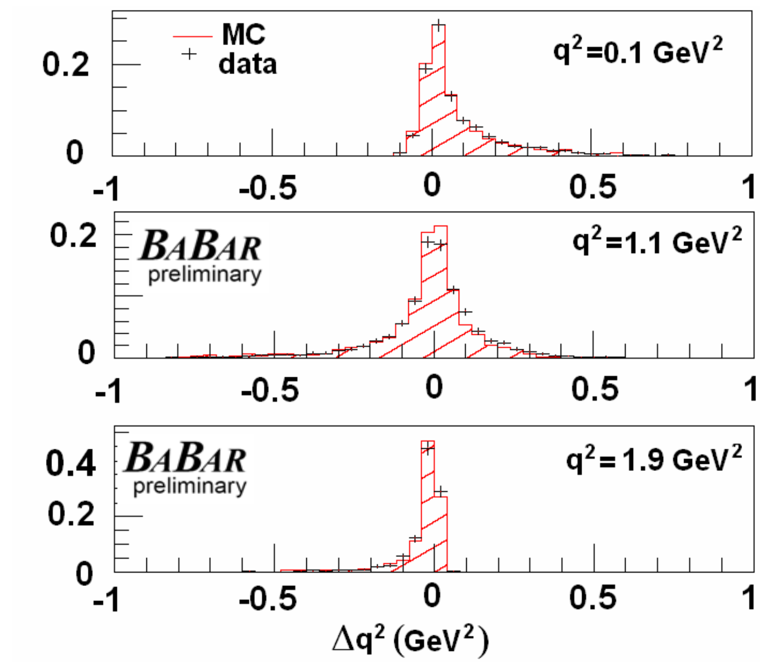
Same criteria and selection cuts as for the semileptonic channel + cut around the D^0 mass.

Treat the π^+ as the e^+ ($m_e \to m_\pi$) and the π^0 as the ν ($m_\nu \to m_\pi$) to control :

☆ **Reconstruction efficiency**



☆ **q^2 and angular resolution from data**

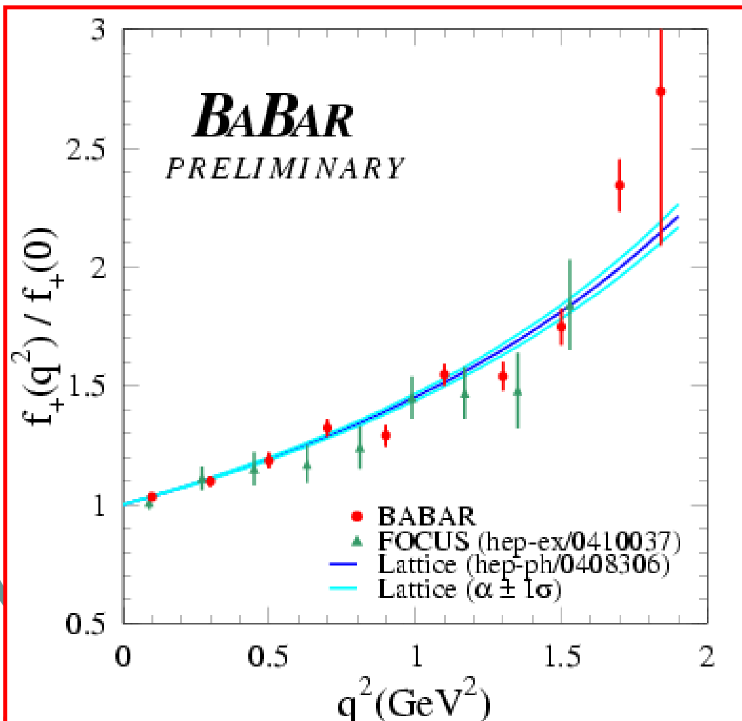


⇒Small differences included as systematics

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

Results

experiment	stat	m_{pole}(GeV/c²)	α_{pole}	
CLEO-c	281 pb^{-1}	1.98±0.03±0.02	0.19±0.05±0.03	*preliminary*
FOCUS	13k evts	1.93±0.05±0.03	0.28±0.08±0.07	hep-ex/0410037
Belle	282 fb^{-1}	1.82±0.04±0.03	0.52±0.08±0.06	hep-ex/0604049
BaBar	75 fb^{-1}	1.854±0.016±0.020	0.43±0.03±0.04	*preliminary*

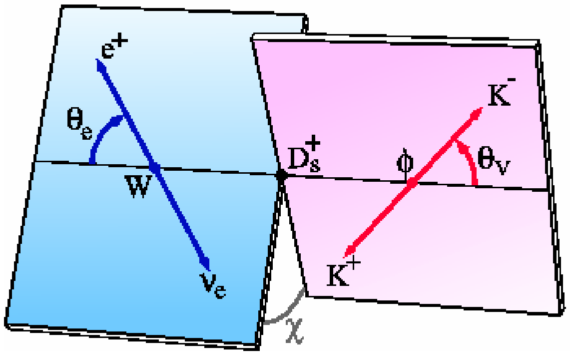


- Pole mass below $m_{D^*_s}$ (=2.112 GeV)
- α measurement in agreement with lattice QCD: α =0.50 ± 0.04 hep-ph/0408306
- Disagreement between values from BaBar and CLEO-c ⇒ has to be clarified !

$D_s \to \varphi e\nu$

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

4 kinematic variables :
q^2, θ_V, θ_l, χ



Decay rate : (assuming $m_\ell = 0$)

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_V d\cos\theta_e d\chi} \propto p_{KK} q^2 \left| (1+\cos\theta_e)\sin\theta_V e^{i\chi} H_+ - (1-\cos\theta_e)\sin\theta_V e^{-i\chi} H_- - 2\sin\theta_e \cos\theta_V H_0 \right|^2$$

Helicity ff :

$$H_\pm(q^2) = (M_D + m_{KK}) A_1(q^2) \mp 2 \frac{M_D p_{KK}}{M_D + m_{KK}} V(q^2)$$

$$H_0(q^2) = \frac{1}{2m_{KK}\sqrt{q^2}} \left[(M_D^2 - m_{KK}^2 - q^2)(M_D + m_{KK}) A_1(q^2) - 4 \frac{M_D^2 p_{KK}^2}{M_D + m_{KK}} A_2(q^2) \right]$$

pole dominance parametrization:

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

Two parameters are usually measured : ratios of the ff at $q^2 = 0$

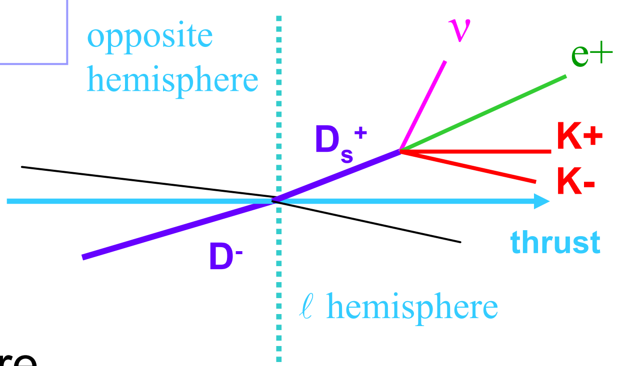
$$r_V = V(0)/A_1(0) \quad \text{and} \quad r_2 = A_2(0)/A_1(0)$$

$D_s^+ \to \varphi e^+ \nu$

Analysis overview

- **Event reconstruction :**

*same method as for $D \to K e \nu$ but without D**



- Define 2 hemispheres

take K^+, K^- , ℓ in the same hemisphere

- Compute D_s direction $(- p_{\text{all particles} \neq K+,K-,l})$
- Compute the missing energy in the ℓ hemisphere
- Fit $p_{Ds} = p_{K+} + p_{K-} + p_{\ell} + p_{\nu}$ → **one constrained fit m_{Ds}**
- Compute kinematic variables : q^2 , θ_ν, θ_l, χ

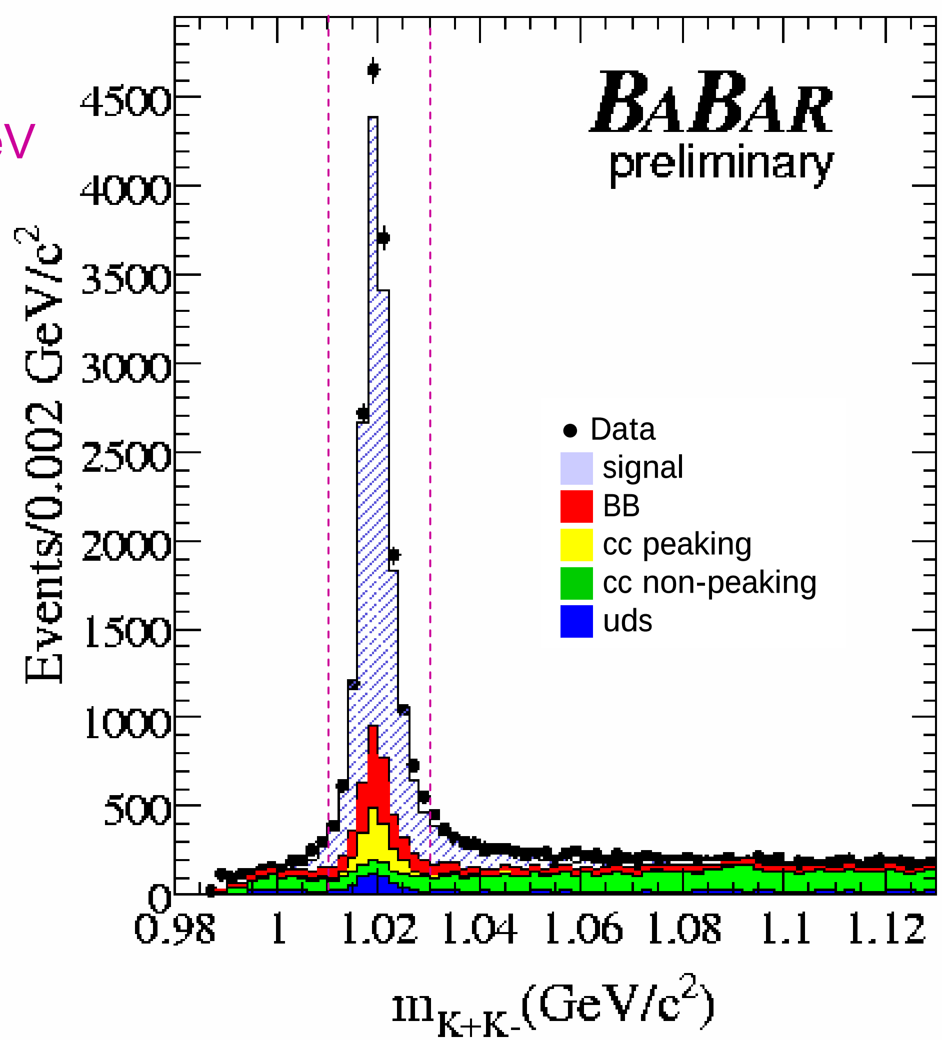
- **Reduce the background** → **Fisher analyses ($b\bar{b}$ and $c\bar{c}$ events)**
- **Extract the ff parameters** → **Maximum log likelihood fit**
- **control sample** → **$D_s \to \varphi\pi$**

$D_s^+ \to \varphi e^+ \nu$

Decay characteristics

signal region :

1.01 GeV <mφ<1.03GeV



78.5 fb^{-1}

Signal yield : 13000

Background composition :

B^0B^0 evts = 23%

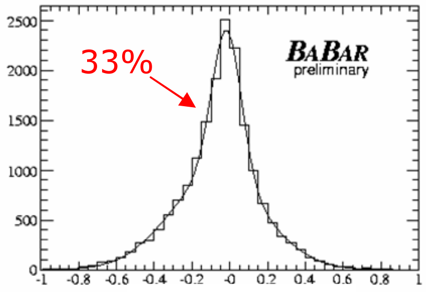
B^+B^- evts = 22%

uds evts = 14%

$c\bar{c}$ = 41%

Kinematic variables

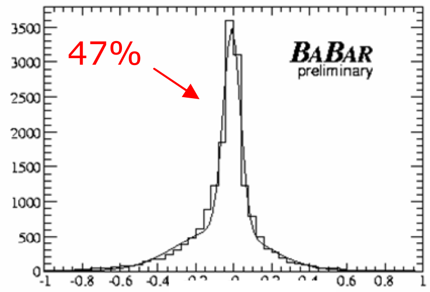
Typical resolutions :



$\Delta\, q^2$ (GeV^2)

$\sigma_1 \sim 0.08$ GeV^2

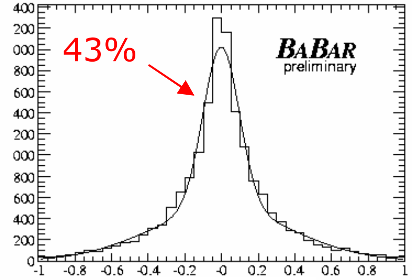
$\sigma_2 \sim 0.25$ GeV^2



$\Delta\cos\theta_l$

$\sigma_1 \sim 0.05$ GeV^2

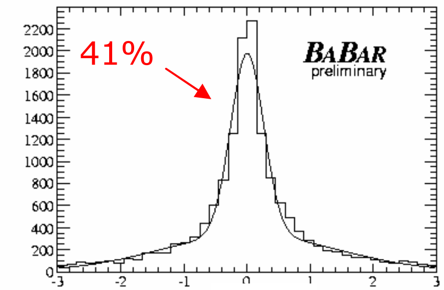
$\sigma_2 \sim 0.23$ GeV^2



$\Delta\cos\theta_v$

$\sigma_1 \sim 0.1$ GeV^2

$\sigma_2 \sim 0.39$ GeV^2

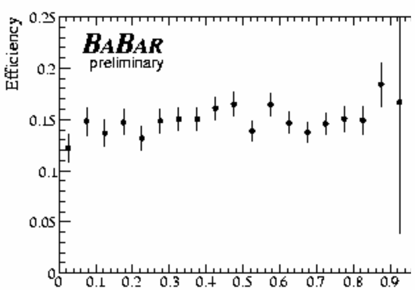


$\Delta\chi$

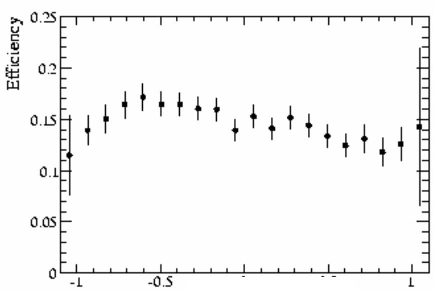
$\sigma_1 \sim 0.26$ rad

$\sigma_2 \sim 1.39$ rad

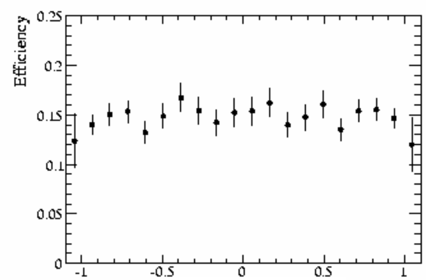
Efficiencies (including all cuts of the analysis but SL filter) : ~ 15%



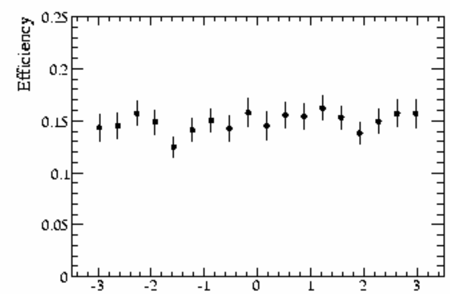
q^2 (GeV^2)



$\cos\theta_l$



$\cos\theta_v$



χ

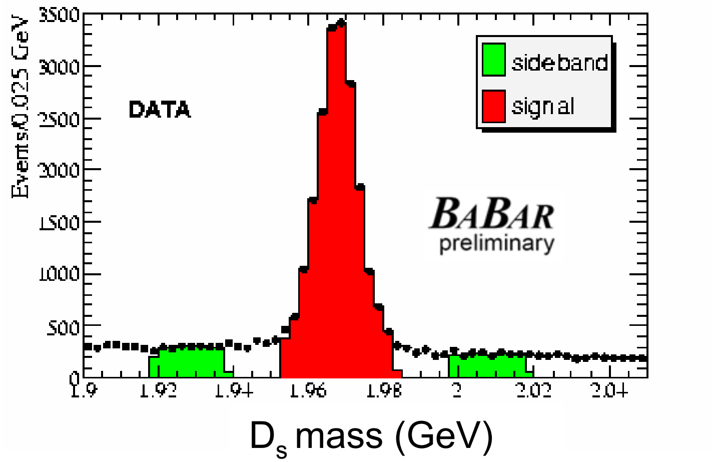
Efficiency uniform versus the 4 variables

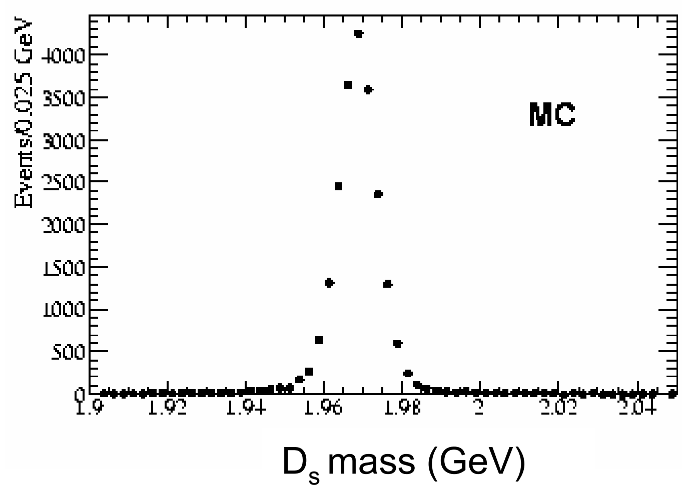
Control sample I

Use $D_s \to \varphi\pi$ to check :

- the agreement data/MC for the variables used in the Fisher analysis
- D_s direction and missing energy determination

Event selection :





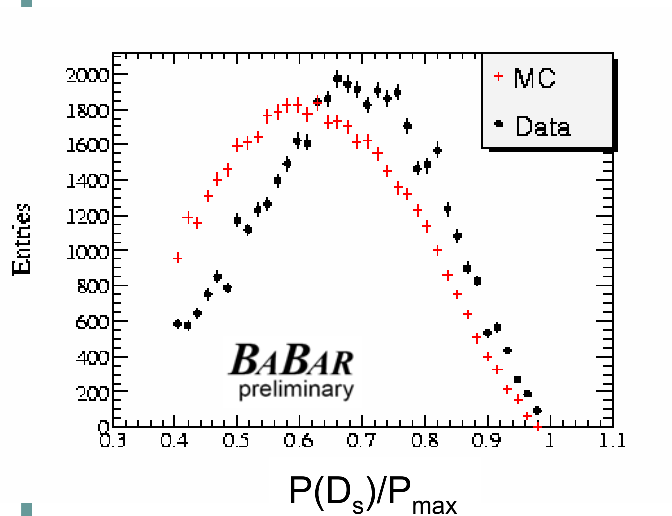
- Similar selection as $\varphi l \nu$ as possible
- Background subtraction using the sidebands

$D_s^+ \to \varphi e^+ \nu$

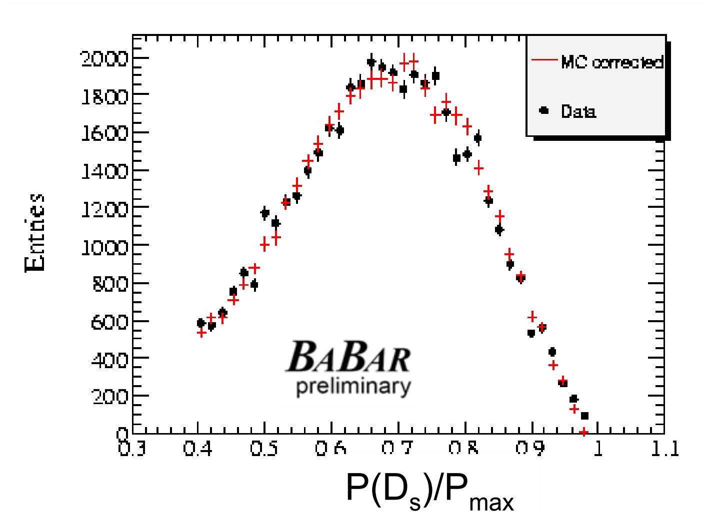
Control sample II

Fisher variables :

Large disagreement data/MC observed in the fragmentation distribution

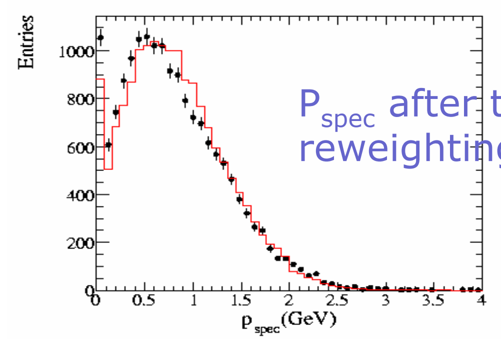


simulated events after reweighting



Check other Fisher variables after correction : small discrepancy remains, ex: spect. syst. momentum

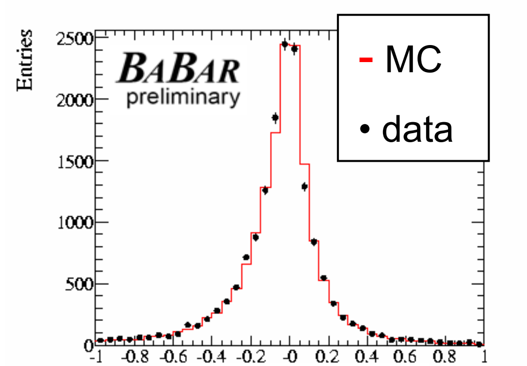
Taken into account in the systematic uncertainties by defining an additional weight on this variable.



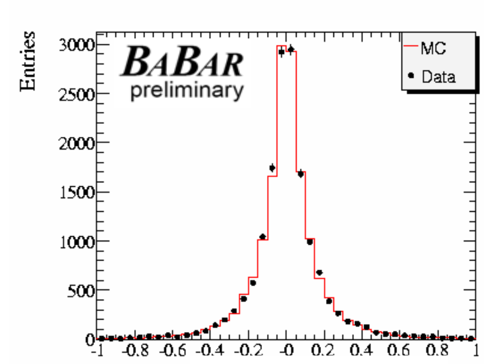
P_{spec} after the 1st reweighting

Control sample III

D_s direction determined using all the other tracks in the event is compared to its real value :

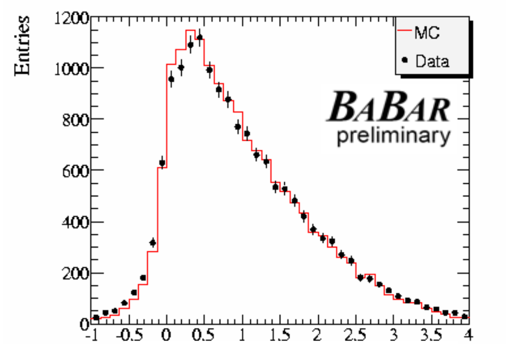


θ_{Ds}(true-rec)

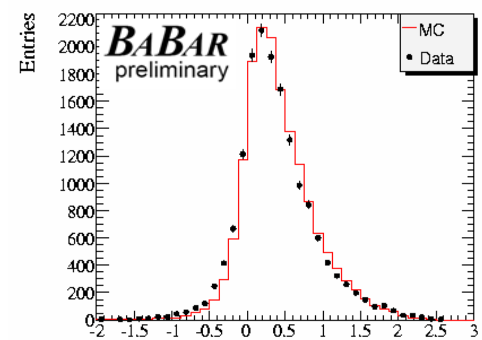


φ_{Ds}(true-rec)

Missing energy in the 2 hemispheres :



E_{miss}opp (GeV)



E_{miss}same (GeV)

Define a parametrization of the differences to take into account possible biases.

Fitting procedure

Use 5 equal bins for each reconstructed variable and perform a log-likelihood minimisation :

$$\mathcal{L} = -\sum_{i=1}^{nbins} \ln \mathcal{P}(n_i^{data} | n_i^{MC}).$$

Number of data events in bin i

Number of expected events from MC in bin i

n_i^{MC} results from :

• the number of bkg events estimated from generic MC (normalized to data lumi). We take the average over $\cos\theta_V$ and χ (flat distribution).

• the number of signal events expected is deduced by applying a weight **W** to MC signal events generated according to phase space.

$$p_{KK} q^2 \left| \begin{array}{l} (1+\cos\theta_e)\sin\theta_V e^{i\chi} H_+ \\ -(1-\cos\theta_e)\sin\theta_V e^{-i\chi} H_- \\ -2\sin\theta_e \cos\theta_V H_0 \end{array} \right|^2$$

Phase space

$W(\lambda_k)$

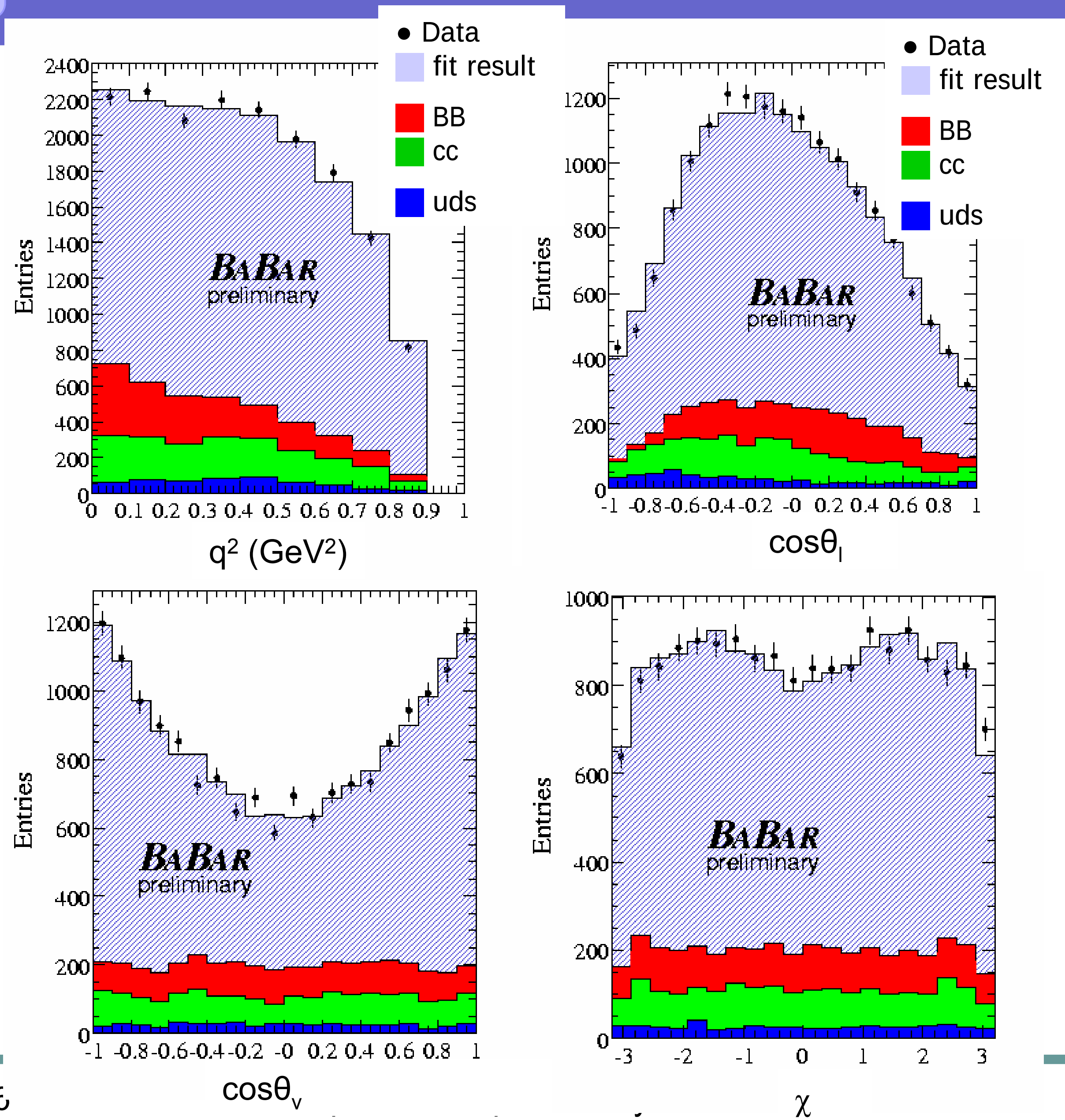
$$n_i^{MC} = N_S \frac{\sum_{j=1}^{n_i^{signal}} w_j(\lambda_k)}{W_{tot}(\lambda_k)} + n_i^{bckg.}$$

N_s is a parameter

The fitting procedure has been checked on toy simulations

$D_s^+ \to \varphi e^+ \nu$

Results



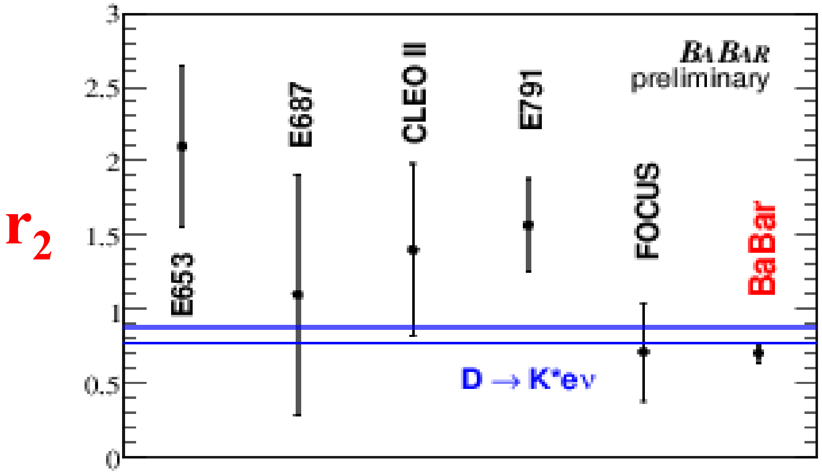
$D_s^+ \to \varphi e^+ \nu$

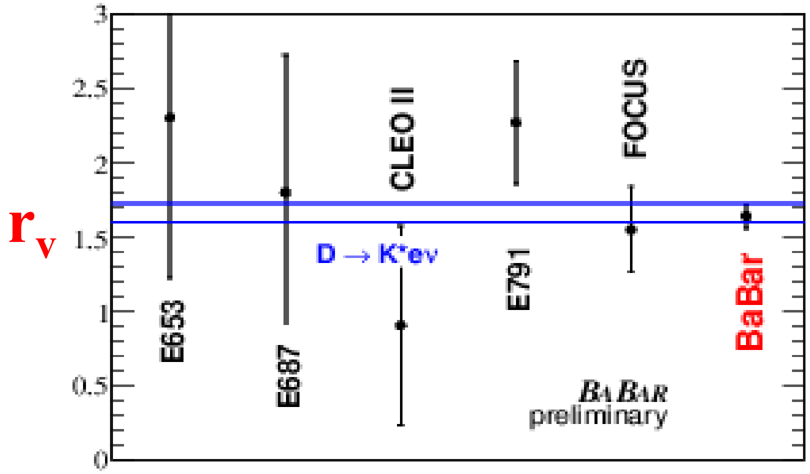
Results

★ Form factor ratios at $q^2=0$ (fixing m_A= 2.5GeV/c^2 and m_V = 2.1GeV/c^2) :

$r_2 = 0.705 \pm 0.056 \pm 0.029$

$r_v = 1.636 \pm 0.067 \pm 0.038$





➡ Same accuracy as $D \to K^* e \nu$ (FPCP 2006, J.Wiss)

★ Fixing only the vector pole mass :

$r_2 = 0.711 \pm 0.111 \pm 0.096$

$r_v = 1.633 \pm 0.081 \pm 0.068$

$m_A = 2.53^{+0.54}_{-0.35} \pm 0.054$ GeV/c^2

Conclusion and perspectives

BaBar has obtained a precise measurement of the charm leptonic decay $D_s^+ \to \mu^+\nu$

- D_s decay constant : $f_{D_s} = 283 \pm 17_{\text{stat}} \pm 7_{\text{syst}} \pm 14_{D_s \to \phi\pi}\ \text{MeV}$

we are still far from what can be achieved on lattice (% accuracy)

- determination of f_{Bs}/f_{Bd} using double ratio :

$$R = \frac{\Phi_s(m_b)/\Phi_d(m_b)}{\Phi_s(m_c)/\Phi_d(m_c)} \quad \text{with} \quad \frac{\Phi_s(m_b)}{\Phi_d(m_b)} = \frac{\sqrt{m_{Bs}}\, f_{Bs}}{\sqrt{m_{Bd}}\, f_{Bd}}$$

R can be determined very precisely on the lattice thanks to the cancellation of chiral logs : R = *1.01(3)* (from Becirevic et al, Phys. Rev. D 60 (1999) 074501)

So if f_{Ds}/f_D is measured very precisely → f_{Bs}/f_{Bd} could be known at % level

We can improve experimental results with more statistics and a better determination of $B(D_s^+ \to \phi\pi)$

Conclusion and perspectives

Semileptonic decays :

- $D \rightarrow Ke\nu$ form factor : First study of the Babar potential in charm sl decays

Very successful, same precision as lattice reached

$m_{pole} = 1.854 \pm 0.016 \pm 0.020$ GeV/c^2

$\alpha_{pole} = 0.43 \pm 0.03 \pm 0.04$

preliminary

Open a large perspective in ff measurements in BaBar …

- $D_s \rightarrow \varphi e\nu$ form factors :

$r_2 = 0.705 \pm 0.056 \pm 0.029$

$r_v = 1.636 \pm 0.067 \pm 0.038$

preliminary

Still a lot of interesting measurement that we can do :

- ff in $D \rightarrow \pi l\nu$ and $D \rightarrow K\pi l\nu$
- More detailed study of ff in $D_s \rightarrow Xe\nu$
- Comparison between different channels
- Charm baryons,....