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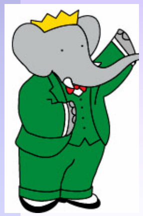
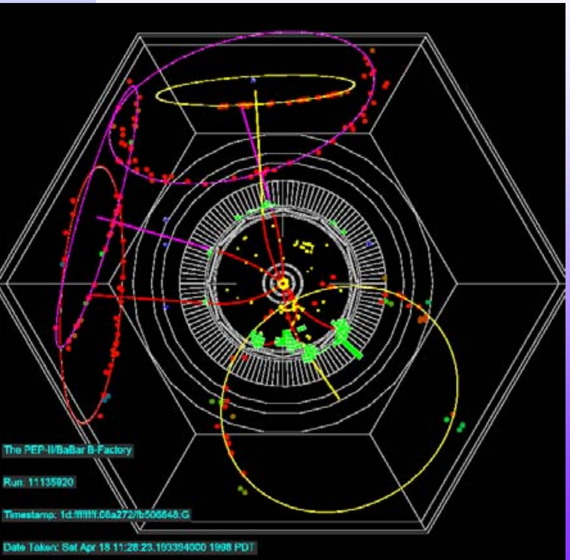
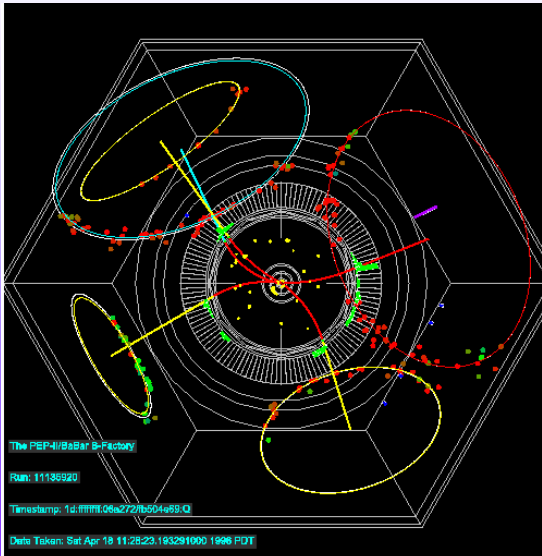


Charm semileptonic decays at Babar

Justine Serrano





LPNHE, 12 juin 2008

Overview

Introduction

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

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

Perspectives and summary

Why ?

➢ 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.

Weak eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Mass eigenstates

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$\lambda = |V_{us}| \sim 0.22$

η responsible for CP violation

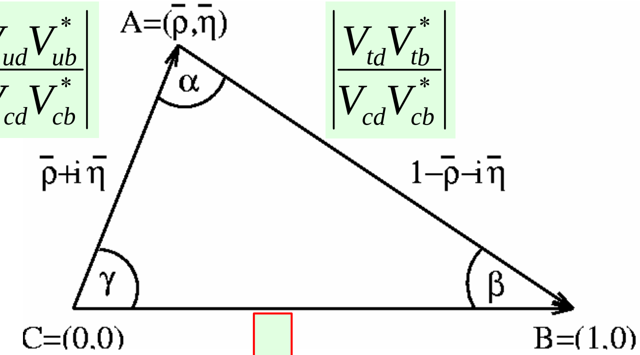
$$\bar{\rho}(\bar{\eta}) = (1-\lambda^2/2)\rho(\eta)$$

$$VV^\dagger = V^\dagger V = 1$$

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

$\Rightarrow$ *Unitarity triangle*

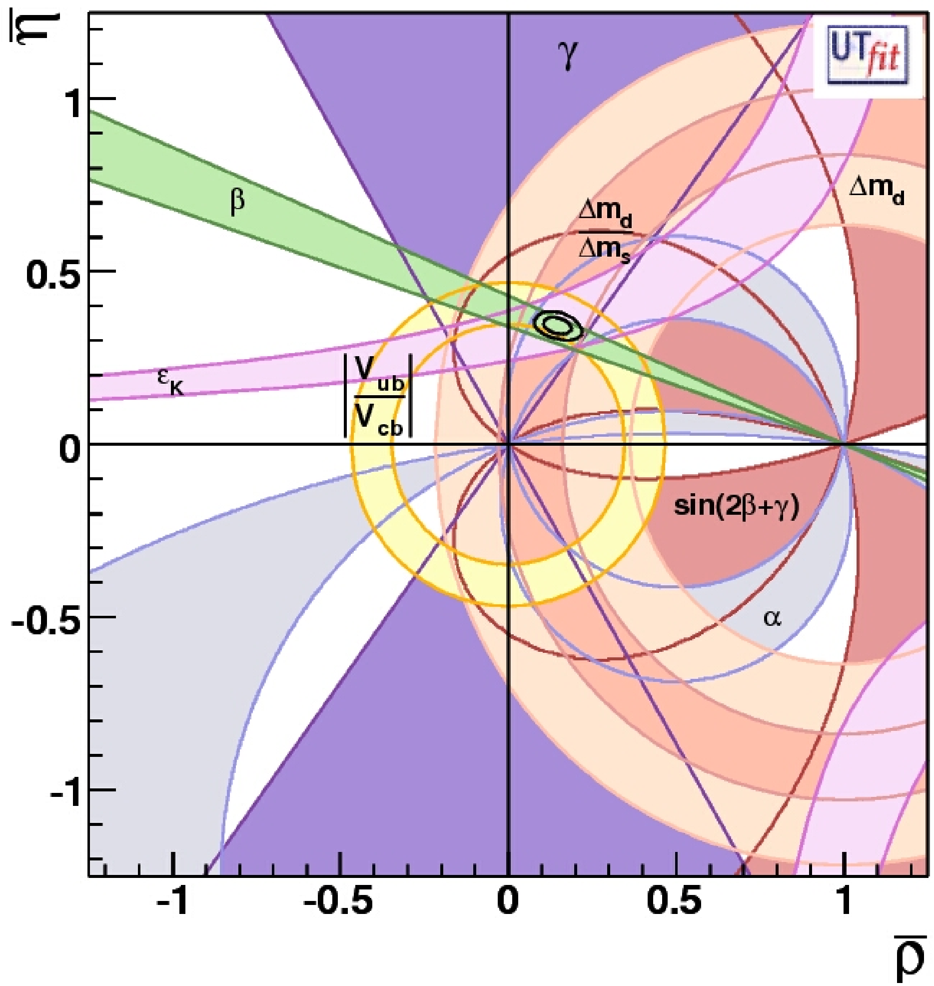
$$\left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right| \qquad \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right|$$



Test of the SM: measurements allow to overconstrain the apex

Status of the unitarity triangle

Global fit



No deviation from the SM observed until now

To constrain (ρ, η), some measurements need theoretical inputs

(ρ, η) { Δm_d ⇐ $f_{B_d}\sqrt{\hat{B}_{B_d}}$

$\frac{\Delta m_d}{\Delta m_s}$ ⇐ ξ

ε_K ⇐ $\hat{B}_K$

$\frac{V_{ub}}{V_{cb}}$ ⇐ Form factors

Lattice QCD calculations

Measured in B semileptonic decays

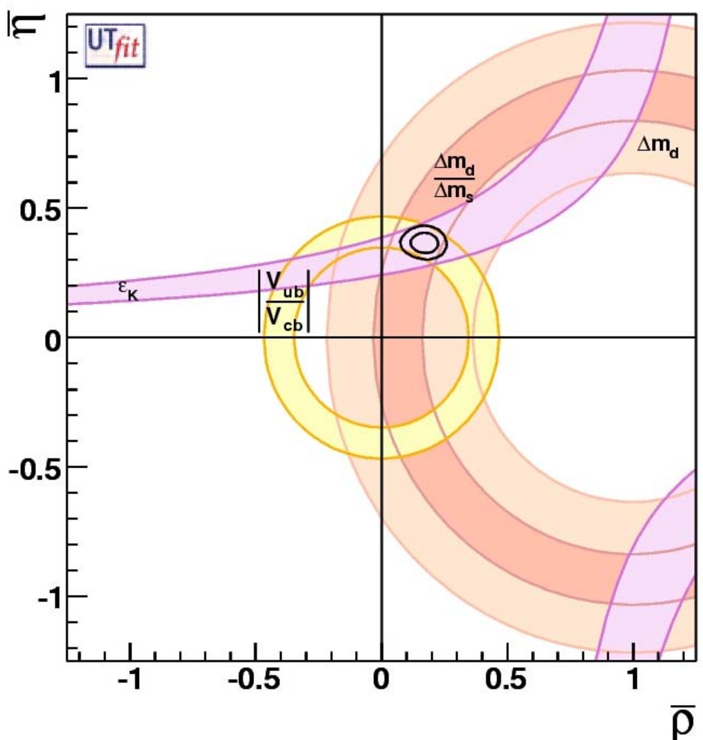
Errors (exclusive):

$|V_{ub}| \approx 14\%$, $|V_{cb}| \approx 2.5\%$

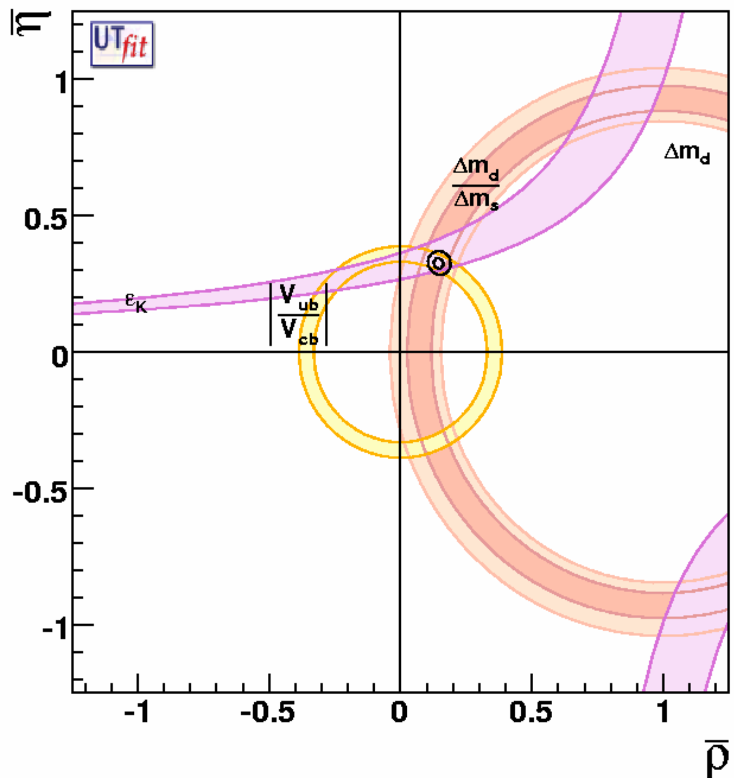
Importance of lattice QCD

The accuracy of SM test can be improved with:

- more precise measurements
- more precise lattice computations



Dividing theoretical errors by 3



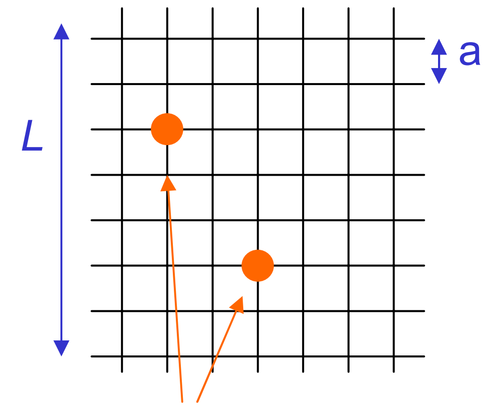
Lattice results have to be validated!

Lattice QCD

purpose: understand hadron structure and interactions from QCD Lagrangian

- Understand how QCD « works »
- Compute observables

Path integral: $\langle O \rangle = \frac{1}{Z} \int DA_\mu O e^{-s}$



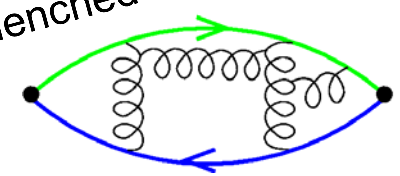
Method: discretize space-time

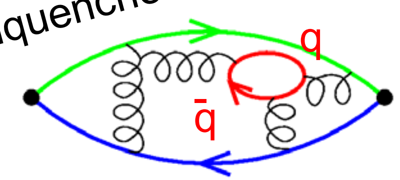
- Lattice spacing a ~ 0.1 fm
- Lattice size L~ 2 fm

"Real" QCD, but observables computed with statistical errors (due to the finite number of configurations)

Approximations:

- quark masses: u,d need a large volume, b needs a small spacing
- extrapolation a→0, infinite volume
- "quenched": (less used)





Validation:

comparison with the observables measured in experiments

- leptonic decays: decay constant (f_D, f_{Ds})
- semileptonic decays: form factors (q^2 dependent)

Charm semileptonic decays

Decay rate:

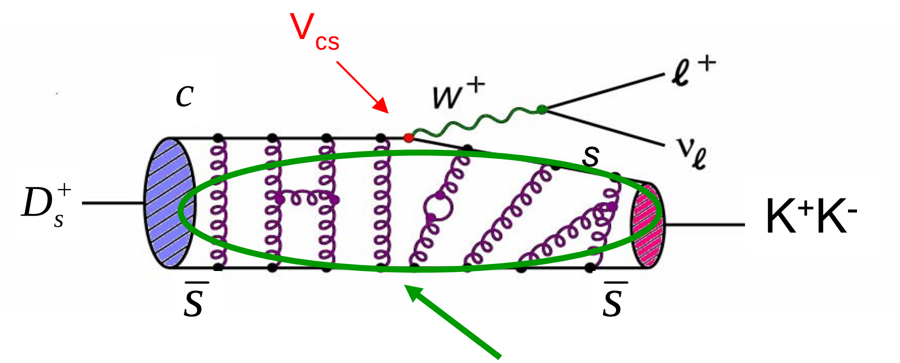
$$d\Gamma \propto |V_{ij}|^2 \times FF^2$$

- Charm: V_{cs} well known thanks to CKM unitarity $\Rightarrow$ we can measure precisely FF
- validate lattice QCD computation
- Apply this method to the B sector to improve the determination of V_{ub}

Example: $D_s^+ \to \phi e^+ \nu$

$\phi \to K^+K^-$

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



Strong interaction effects parameterized by FF

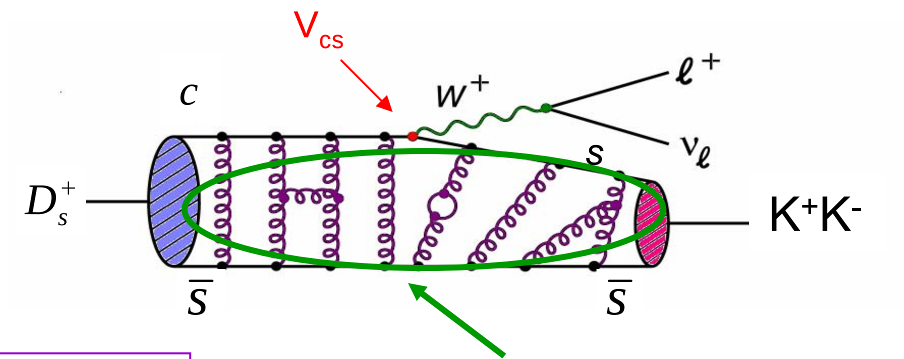
- **Pseudoscalar $\ell\ \nu$ decay** : one form factor, angular distribution known
- **Vector $\ell\ \nu$ decay** : 3 helicity states, 5 kinematic variables

$D^0 \to K^- e^+ \nu$	← Babar results →	$D_s^+ \to \varphi e^+ \nu$
$D^0 \to \pi^- e^+ \nu$	← Coming soon →	$D^+ \to \bar{K}^{*0} e^+ \nu$
…		…

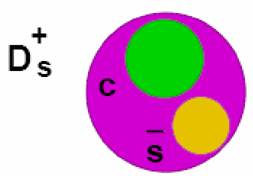
Dynamic of semileptonic decays

- q^2 dependence:

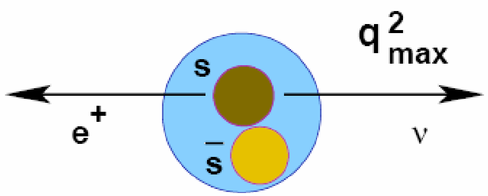
$$q^2 = M_W^2 = \left(p_l + p_\nu\right)^2$$



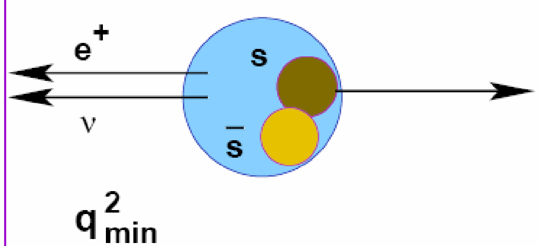
Strong interaction effects parameterized by FF



Initial meson



The daughter quark receives a small momentum kick, formation of daughter meson is favoured

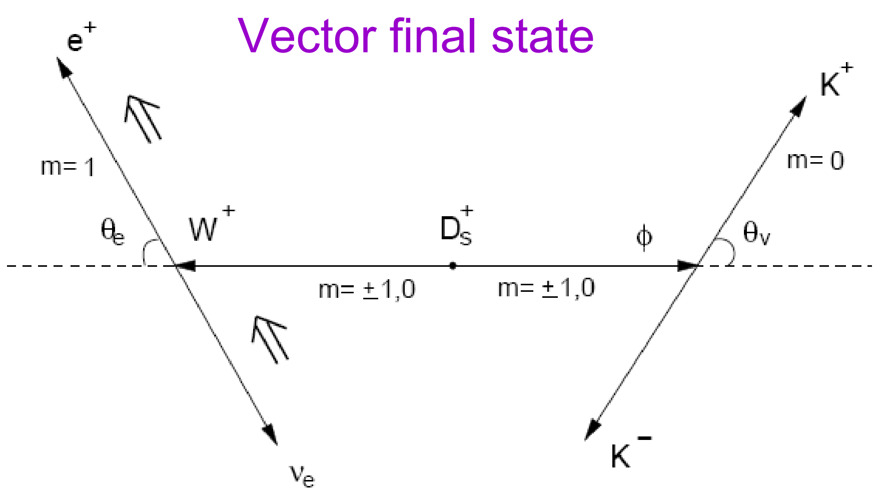


The daughter quark receives a large momentum kick, formation of bound state more difficult

- Form factors are expected to ↗ with q^2
- The relative variation of form factors depends on the q^2 range

Dynamic of semileptonic decays

- angular dependence, helicity considerations:



- Initial meson J=0,
- e is right-handed⇒ **m=1** in the W rest frame
- Φ decays into 2 pseudo-scalars⇒ **m=0** in the Φ rest frame
- Combining projections along the W direction in the D_s rest frame, we have to combine the helicity amplitudes:

helicity	$W+$	ϕ
$H_+(q^2)$	$\frac{1}{2}(1+\cos\theta_e)$	$\frac{1}{\sqrt{2}}\sin\theta_V e^{-i\chi}$
$H_-(q^2)$	$\frac{1}{2}(1-\cos\theta_e)$	$-\frac{1}{\sqrt{2}}\sin\theta_V e^{i\chi}$
$H_0(q^2)$	$\frac{1}{\sqrt{2}}\sin\theta_e$	$\cos\theta_V$

For a pseudoscalar final state, just the H_0 component contributes

⇒ Angular distribution ~ $\sin^2(\theta_e)$

Branching fractions

- Inclusive branching fractions

	D^0	D^+
Inclusive s.l. BR (%)[77]	$6.46 \pm 0.17 \pm 0.13$	$16.13 \pm 0.20 \pm 0.33$
Lifetime (ps)[4]	0.4101 ± 0.0015	1.040 ± 0.007
Inclusive s.l. width ($\times 10^{-2} ps^{-1}$)	$15.75 \pm 0.41 \pm 0.32$	$15.51 \pm 0.20 \pm 0.31$

← CLEO-c

For D_s no recent result, PDG gives BR=8 $^{+6}_{-5}$ %

- Exclusive branching fractions

D^0 decay channel	BR (%)	$\Gamma^{sl.}_{D^0}$ ($\times 10^{-2} ps^{-1}$)	D^+ decay channel	BR (%)	$\Gamma^{sl.}_{D^+}$ ($\times 10^{-2} ps^{-1}$)
$K^- e^+ \nu_e$	3.53 ± 0.05	8.61 ± 0.12	$\overline{K}^0 e^+ \nu_e$	8.55 ± 0.23	8.22 ± 0.22
$K^{*-} e^+ \nu_e$	2.17 ± 0.16	5.29 ± 0.39	$\overline{K}^{*0} e^+ \nu_e$	5.61 ± 0.31	5.39 ± 0.30
$(K\pi)^-_S e^+ \nu_e$			$(K\pi)^0_S e^+ \nu_e$	0.3 ± 0.1	0.3 ± 0.1
$K_1^-(1270) e^+ \nu_e$	$0.08^{+0.04}_{-0.03}$	0.2 ± 0.1	$\overline{K}_1^0(1270) e^+ \nu_e$		
$K_1^{*-}(1400) e^+ \nu_e$			$\overline{K}_1^{*0}(1400) e^+ \nu_e$		
$K_2^{*-}(1430) e^+ \nu_e$			$\overline{K}_2^{*0}(1430) e^+ \nu_e$		
$\pi^- e^+ \nu_e$	0.293 ± 0.011	0.71 ± 0.03	$\pi^0 e^+ \nu_e$	0.380 ± 0.024	0.37 ± 0.02
$\rho^- e^+ \nu_e$	0.19 ± 0.04	0.46 ± 0.10	$\rho^0 e^+ \nu_e$	0.22 ± 0.04	0.21 ± 0.04
			$\omega^0 e^+ \nu_e$	$0.16^{+0.07}_{-0.06}$	0.15 ± 0.07
Total measured	6.26 ± 0.18	15.26 ± 0.44		15.22 ± 0.41	14.63 ± 0.39

} dominant

Compatible with inclusive BF

D_s^+ decay channel	$\Gamma^{sl.}_{D}$ ($\times 10^{-2} ps^{-1}$)	D_s^+ BR expected SU(3)(%)	BR (PDG06) (%)
$(\eta + \eta') e^+ \nu_e$	8.52 ± 0.11	4.3 ± 0.1	4.2 ± 0.8
$\phi e^+ \nu_e$	5.35 ± 0.24	2.68 ± 0.13	2.4 ± 0.4
$f_0 e^+ \nu_e$	0.3 ± 0.1	0.15 ± 0.05	
$K^0 e^+ \nu_e$	0.71 ± 0.03	0.36 ± 0.02	
$K^{*0} e^+ \nu_e$	0.46 ± 0.10	0.23 ± 0.05	

Assuming

$\Gamma_{sl}(D) = \Gamma_{sl}(D_s)$

Not so much known about D_s

Charm SL decays at CLEO-c

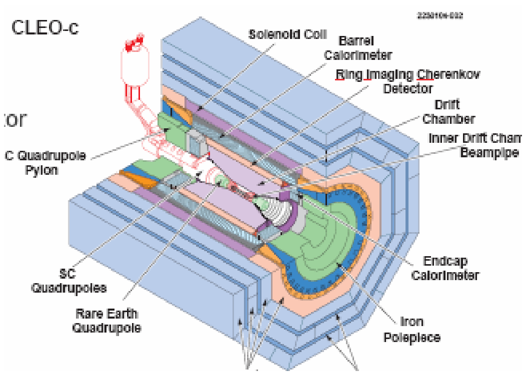
From Moriond EW 2008:

- $D\bar{D}$ @ 3770 : 800 pb^{-1} (56 & 281 pb^{-1} in this talk); 281 pb^{-1} $\sim 1.8 \times 10^6 D\bar{D}$
- $D_s^* \bar{D}_s$ @ 4170 : 314 pb^{-1} (will double the sample) 314 pb^{-1} $\sim 0.3 \times 10^6 D_s^* \bar{D}_s$

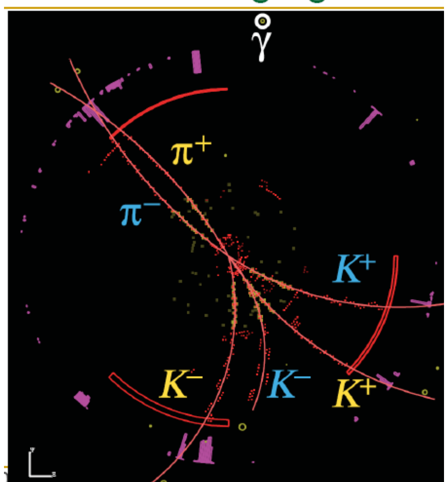
Favored Methods at CLEO-c

- Two-body production $e^+e^- \to D\bar{D}$
- Double tags at 3770 MeV: fully reconstruct one D^o or D^+, then can either fully reconstruct the other D (absolute branching ratios, quantum correlations) or look for events with one missing particle (leptonic decays, semileptonic decays, K_L)
- Similarly, double tags at 4170 MeV: here look for a D_S or a D_S^*
- Some measurements also done using single tags

FPCP May, 2008 2



$e^+e^- \to D_S D_S^*$



⊕ Clean environment

⊖ statistics

⊖ tagging (D_s), low efficiency

Charm SL decays at Babar

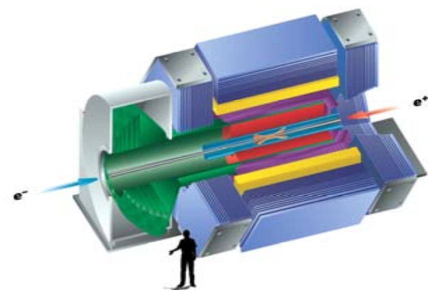
The PEP-II B factory:

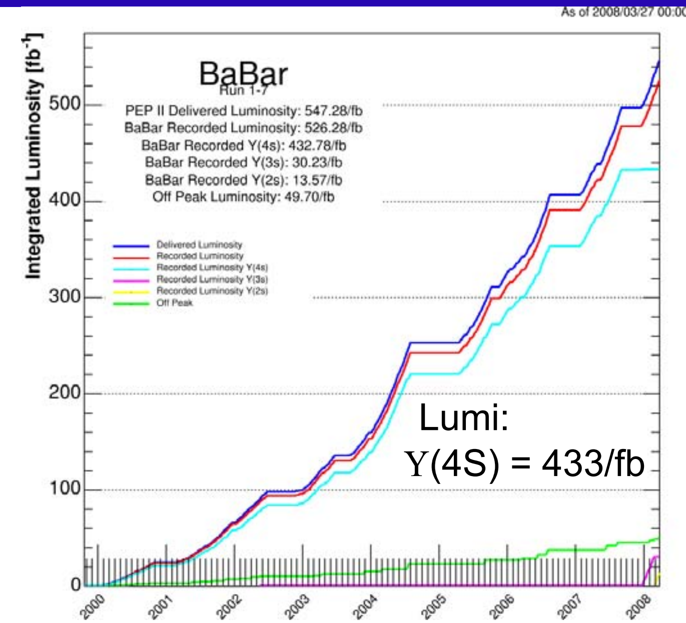
$B\bar{B}$ threshold: $\Upsilon(4S)$= 10.58 GeV

Asymetric beams

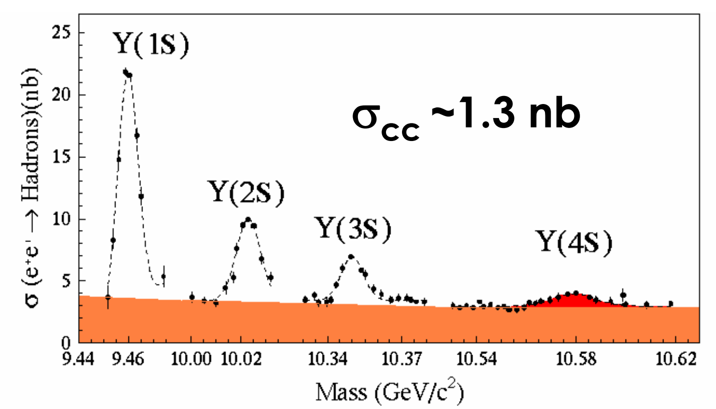
e^-: 9 GeV

e^+: 3.1 GeV





The PEP-II charm factory:



- (+) Large statistics: ~ 1×10^9 charm hadrons
- (+) fragmentation $\Rightarrow D, D_s, \Lambda_c, \ldots$
- (+) no tagging, better efficiency
- (−) background to control

Belle: similar environment, more statistics

One analysis ($D^0 \to K^- e^+ \nu$), done using complete reconstruction of the event

Introduction

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

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

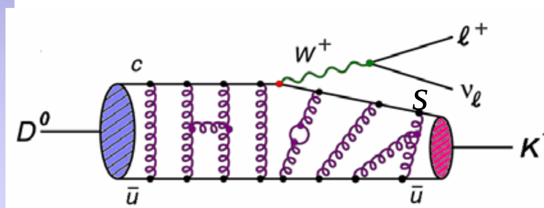
Perspectives and summary

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

★ Simplest channel

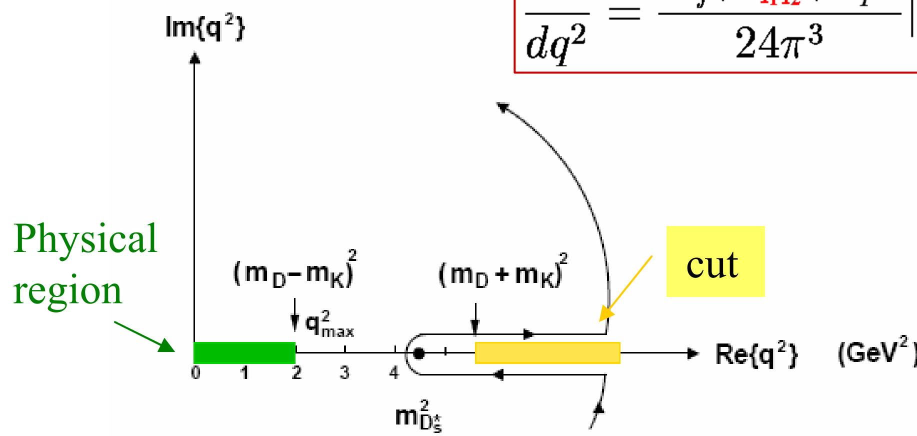
- ➜ Cabibbo-favoured
- ➜ One form factor: $f_+(q^2)$
- ➜ Angular distribution known → $\sin^2(\theta_l)$

In the hypothesis that m_e is negligible



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

Several theoretical models can be used to parameterized FF:



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

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

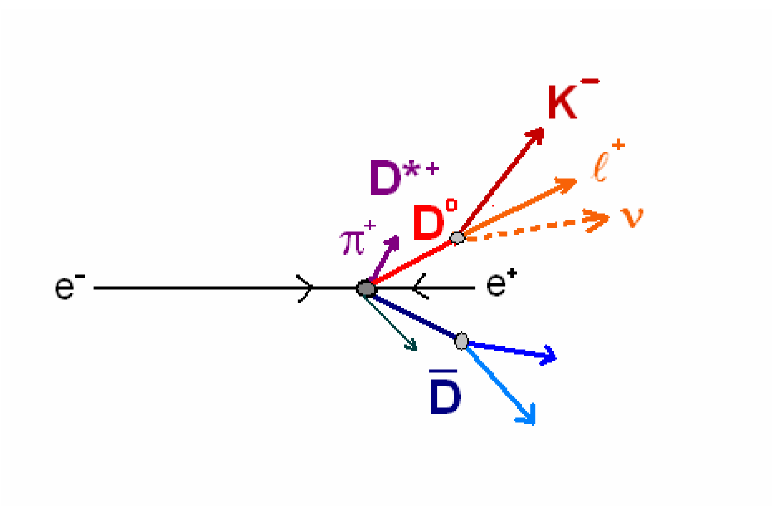
• **Modified pole mass** (B&K): add an effective pole to take into account higher resonances. Measure α_{pole}.

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

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

Analysis overview

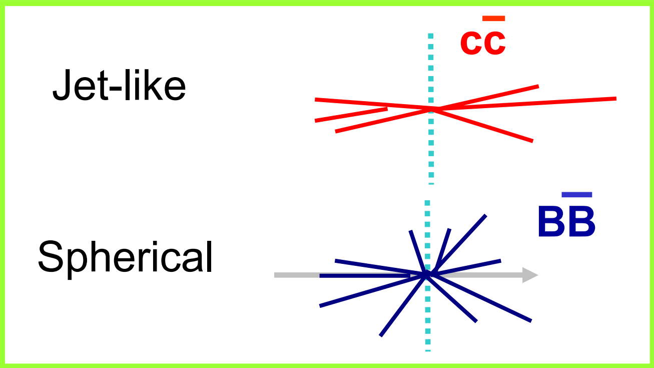
- **Untagged analysis**



- **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



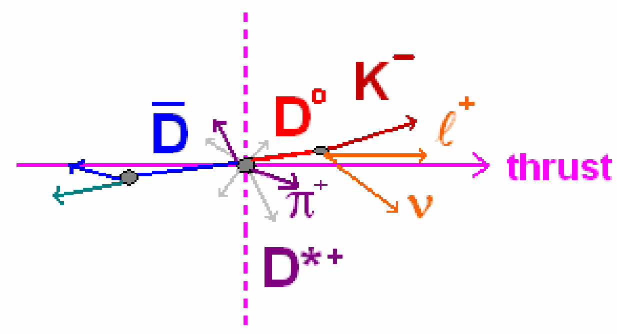
- **Determine** $q^2 = (p_D - p_K)^2 = (p_\ell + p_\nu)^2$ ← **two constrained fits** (m_{D0}, m_{D*})
- **Reduce the background** ← **Fisher discriminants ($b\bar{b}$ and $c\bar{c}$ events)**
- **Extract the form factor** ← **Unfolding: SVD method**
- **method validation** ← **Control samples**
- **FF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

Event reconstruction

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

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

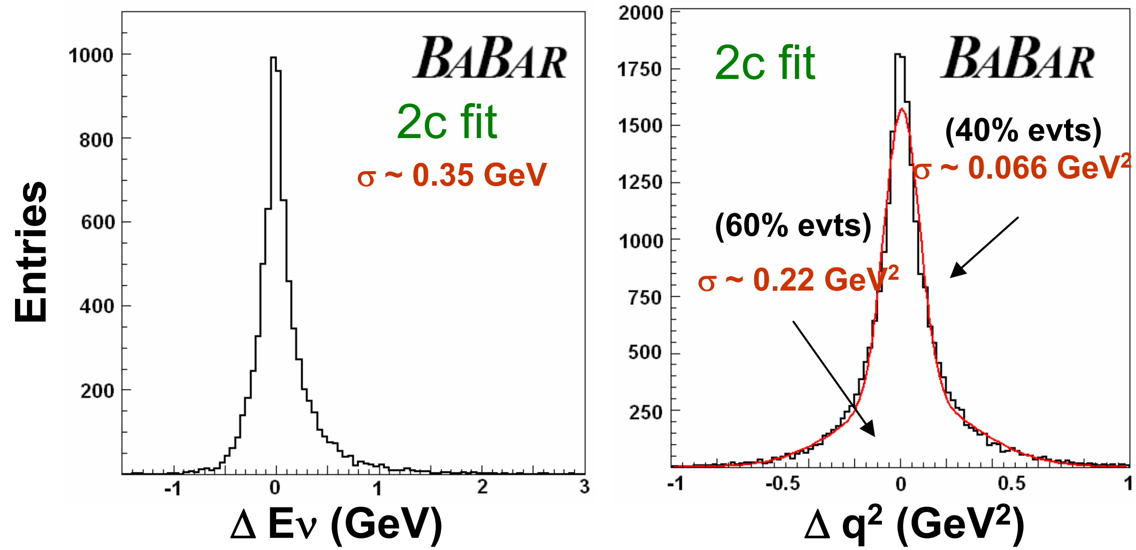
Υ(4S) rest frame : *jet-like* events



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

Event reconstruction

- Resolution:

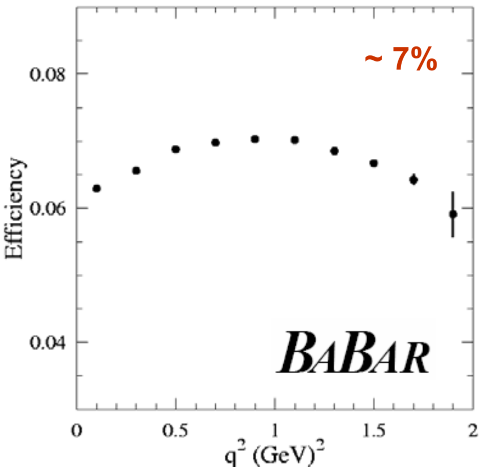


Δq^2

CLEO III: 0.4 GeV²
FOCUS: 0.22 GeV²
CLEO-c : 0.015 GeV²
BELLE: 0.015 GeV²

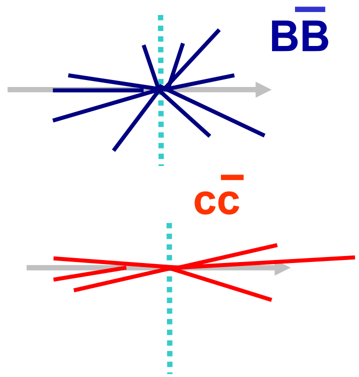
- Efficiency:

(Including all cuts in the analysis)



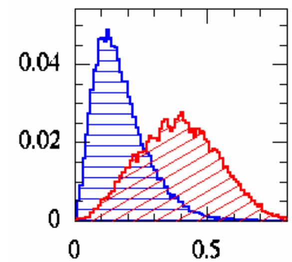
Background rejection

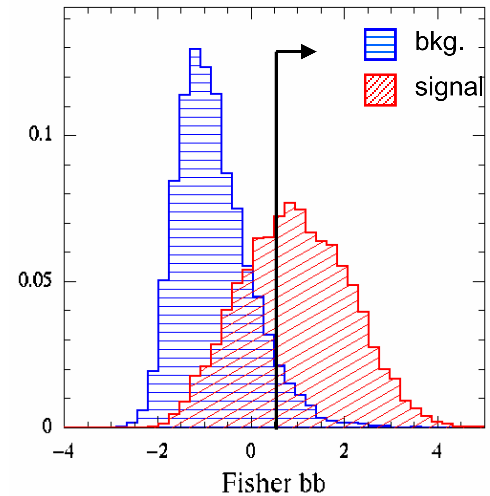
- $B\bar{B}$ events:



Event shape variables:

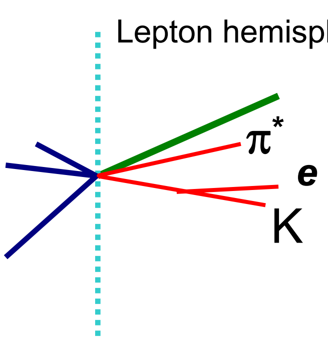
- H_2/H_0
- Track multiplicity
- p_{π^*}





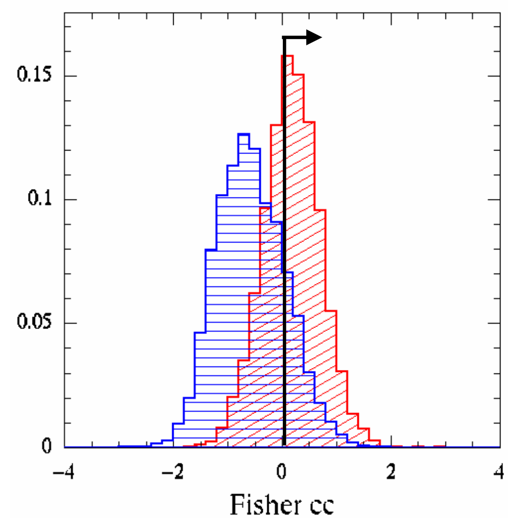
Efficiency: signal=65% BKG=6%

- $c\bar{c}$ events:



Spectator system

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



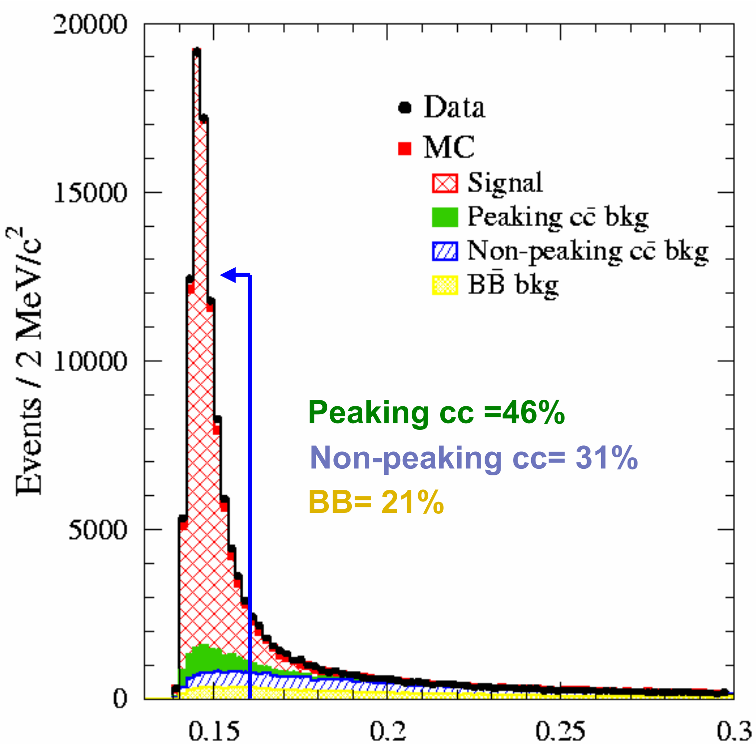
Efficiency: signal=77% BKG=34%

Signal yield

75 fb^{-1}

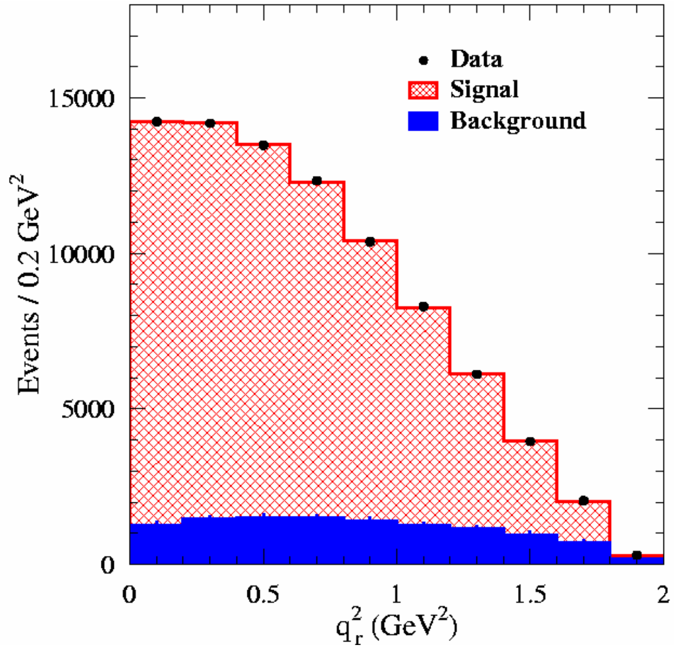
$\delta m < 0.16$ GeV

85000 events (13% bkg)



δm (GeV/c²)

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



$q^2 = (p_D - p_K)^2$
after the fit with 2 constraints: m_{D^*} and m_D

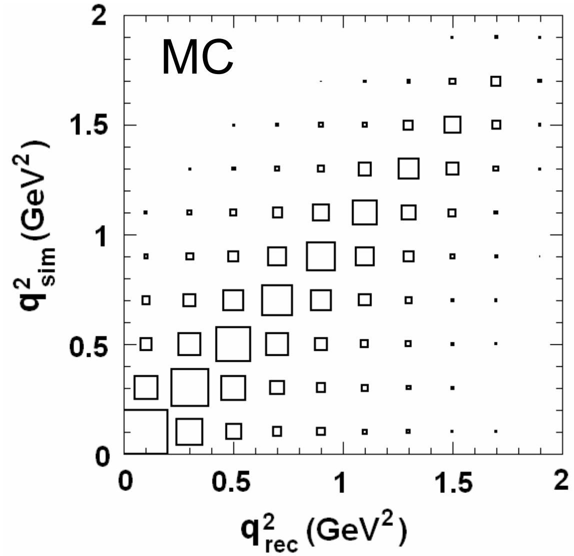
Form factor measurement

➢ Extraction of the q^2 dependence of the form factor:

To obtain the true q^2 distribution, we need to correct from efficiency and resolution effects

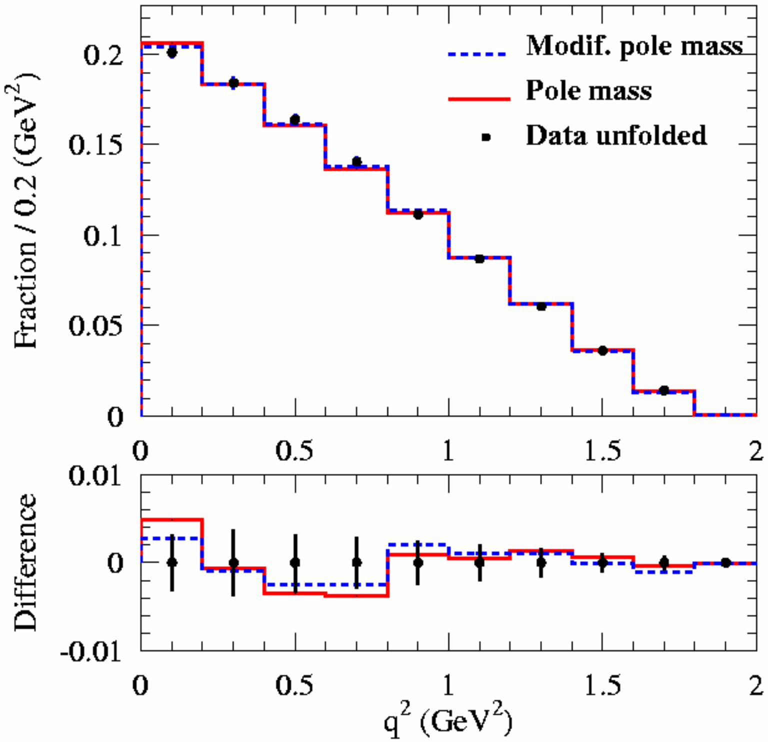
$$\frac{d\Gamma}{dq^2} = \frac{G_f^2 |V_{q_1 q_2}|^2 p_{P'}^3}{24\pi^3} |f_+(q^2)|^2$$ → Unfolding the measured q^2 distribution

- SVD * of the reconstruction matrix $S[q^2_{rec}, q^2_{sim}]$



(MC stat: 8 M signal evts (~7xdata) , mod. pole ff)

q^2 distribution after bkg subtraction and unfolding:



* Singular Value Decomposition; A. Höcker, V. Kartvelishvili [hep-ph/9509307]

Systematic uncertainties

- Main components:
  - Signal selection: data/MC differences in charm fragmentation, PID…
    (~ 0.4 σ_{syst})
  - q^2 reconstruction: data/MC differences entering in the algorithm, q^2 resolution
    (~ 0.5 σ_{syst})
  - Control of the background: data/MC differences in the composition (shape and normalization)
    (~ 0.5 σ_{syst})
  - Fitting procedure: remaining effects (MC stat., radiative events…)
    (~ 0.6 σ_{syst})

➡ Need to control the simulation!
Control samples from data:

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

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

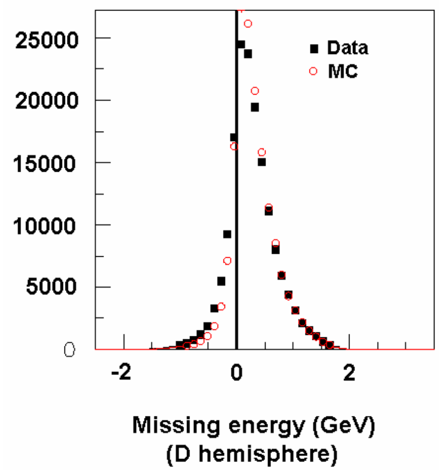
Systematic uncertainties

- Example: q^2 reconstruction

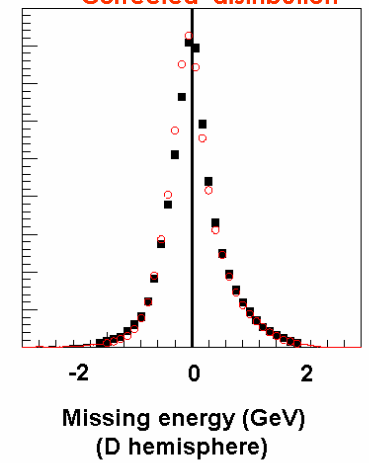
- data/MC differences in the reconstruction algorithm ($D^0 \rightarrow K^- \pi^+$)

Inputs of mass constrained fit: D direction estimate, missing energy (from all particles in the event)

→ bias and errors corrected (as function of the missing E in the opposite hemisphere)



Corrected distribution



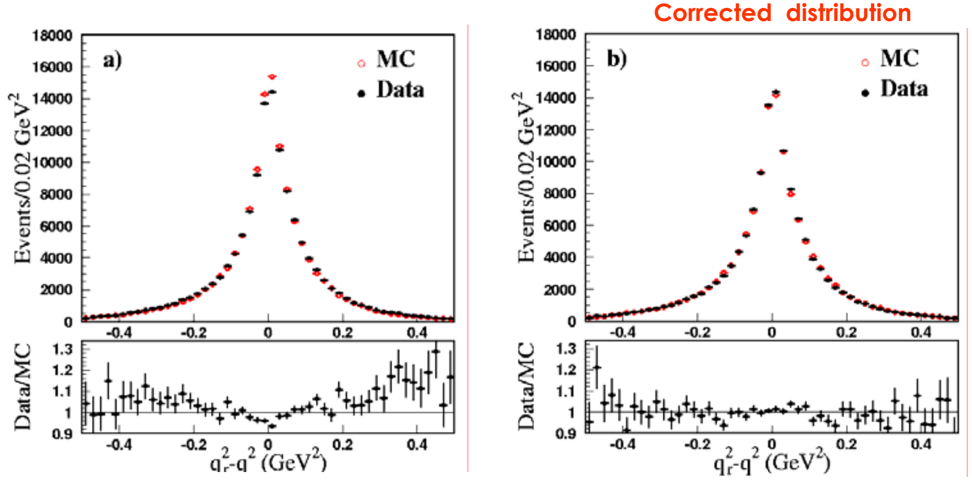
- data/MC differences in the resolution ($D^0 \rightarrow K^- \pi^+ \pi^0$)

The π^+ and π^0 play the roles of the e^+ and ν in the kinematic fit.

$$\tilde{q}^2_r=(p_{D^0}-p_{K^-})^2$$

$$\tilde{q}^2=(p_{\pi^+}+p_{\pi^0})^2$$

Corrected distribution



Form factor determination for $D^0 \to K^- e^+ \nu$

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

m_{pole} = 1.893 ± 0.012 ± 0.015 GeV/c²

Model prediction: m_{D^*s} = 2.112 GeV/c²

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

α_{pole} = 0.359 ± 0.023 ± 0.029

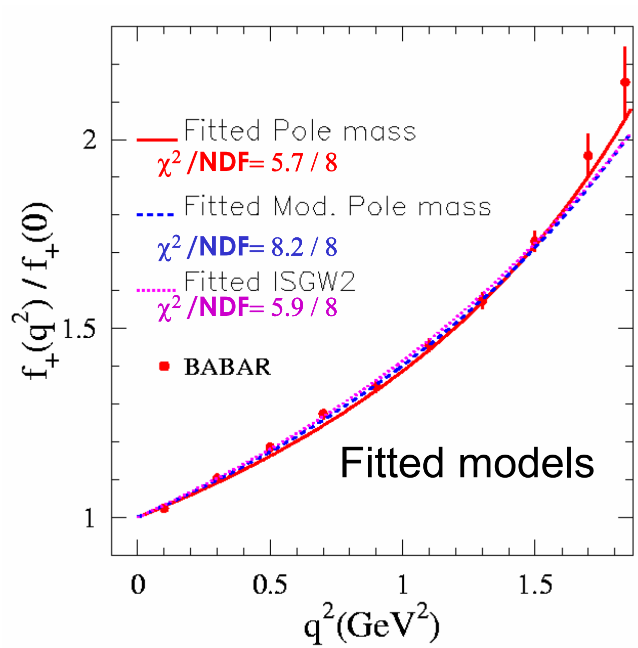
Lattice computation (HPQCD) :
α_{pole} = 0.50(4)

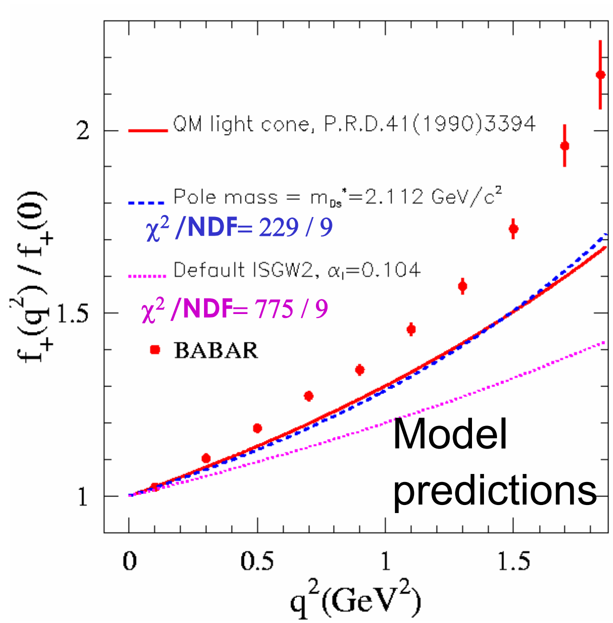
ISGW2 $f_+^{\text{ISGW2}}(q^2) = \frac{f_+(q^2_{max})}{(1 + \alpha_I(q^2_{max} - q^2))^2}$

α_I = 0.222 ± 0.005 ± 0.006 GeV⁻²

Model prediction: α_I = 0.104 GeV⁻²

popular model, used in the Babar MC





data

$m_{pole} = m_{D^*s}$

ISGW2

Simple pole and ISGW2 form factors with default parameters excluded

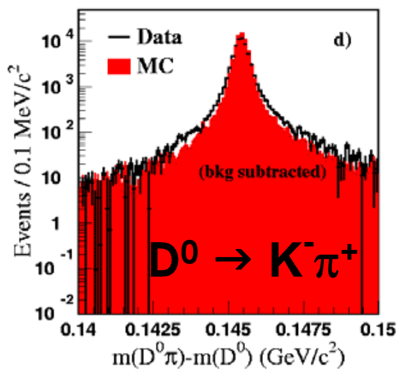
normalization measurement

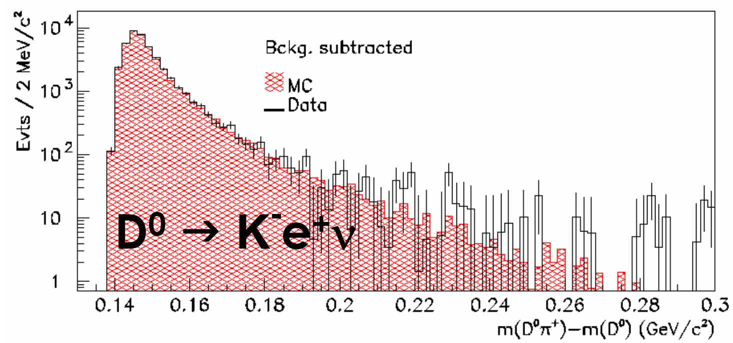
- Branching fraction measured relatively to **$D^0 \to K^-\pi^+$:**

$$R_D = \frac{BR(D^0 \to K^- e^+ \nu_e)_{data}}{BR(D^0 \to K^- \pi^+)_{data}}$$

Same reconstruction method and selection criteria as for SL channel, apart from :

$D^0 \to K^-\pi^+$	**$D^0 \to K^- e^+ \nu$**
m(Kπ) cut (1.83,1.89 GeV)	1C and 2C kinematical fits δm cut (δm <0.160 Gev)





We obtain:

$$R_D = 0.9269 \pm 0.0072 \pm 0.0119$$

$$BR(D^0 \to K^- e^+ \nu) = (3.522 \pm 0.027 \pm 0.045 \pm 0.065)\%$$

(using the world average for $Br(D^0 \to K^-\pi^+) = 3.80 \pm 0.07$ %)

$$f_+(0) = 0.727 \pm 0.007 \pm 0.005 \pm 0.007$$

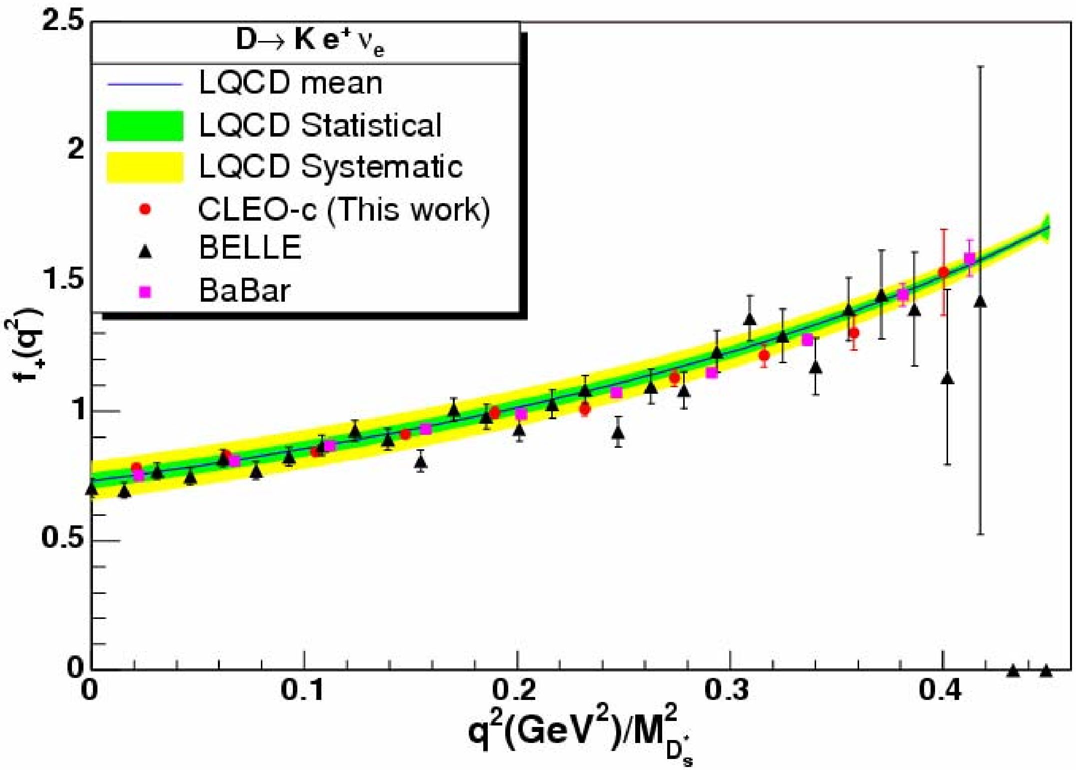
statistics *systematics* *External inputs*

Belle: $f_+(0) = 0.695 \pm 0.007 \pm 0.022$

Lattice: $f_+(0) = 0.73 \pm 0.03 \pm 0.07$

Babar results for $D^0 \rightarrow K^- e^+ \nu$

experiment	stat	$m_{pole}(GeV/c^2)$	α_{pole}	
CLEO-c	281 pb^{-1}	$1.97 \pm 0.03 \pm 0.01$	$0.21 \pm 0.05 \pm 0.03$	arXiv:0712.0998
FOCUS	13k evts	$1.93 \pm 0.05 \pm 0.03$	$0.28 \pm 0.08 \pm 0.07$	Phys.Lett.B607:233-242,2005.
Belle	282 fb^{-1}	$1.82 \pm 0.04 \pm 0.03$	$0.52 \pm 0.08 \pm 0.06$	hep-ex/0604049
BaBar	75 fb^{-1}	$1.884 \pm 0.012 \pm 0.015$	$0.38 \pm 0.02 \pm 0.03$	Phys.Rev.D76:052005,2007



- same accuracy as CLEO-c !
- Pole mass below $m_{D^*_s}$ (=**2.112 GeV**), we exclude the simple pole mass model
- α measurement lower than lattice QCD value: **α =0.50 ± 0.04** hep-ph/0408306
- Disagreement between values from BaBar and CLEO-c ⇒ has to be clarified !

Introduction

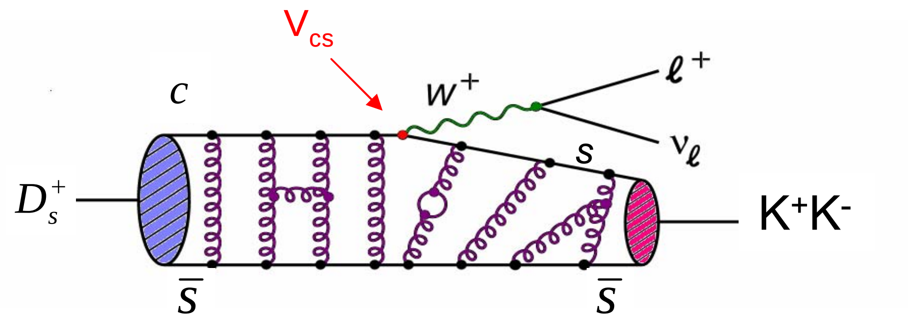
$D^0 \rightarrow K^- e^+ \nu$

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

Perspectives and summary

$D_s^+ \to \phi e^+ \nu_e$, $\phi \to K^+ K^-$

- More complicated channel
  - vector final state
  - 5 kinematic variables
  - 3 form factors



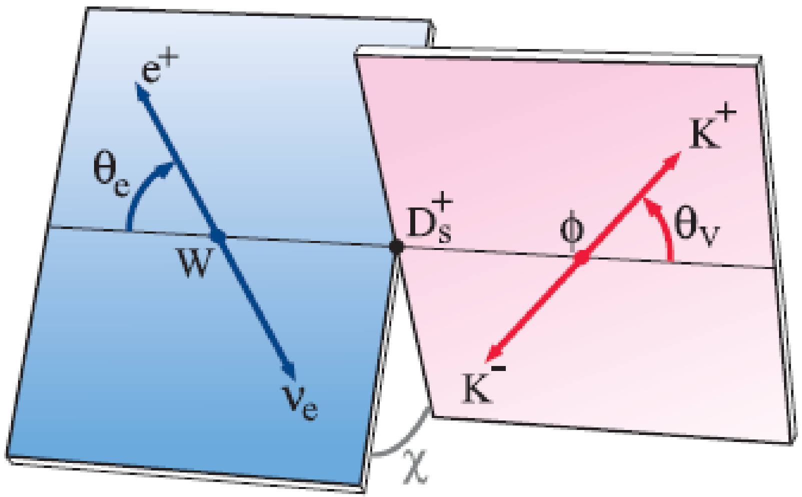
- Still Cabibbo-favoured

- Interesting because:
  - Lattice results should be more precise (quarks c and s involved)
  - Possibility to study the S wave component in the K^+K^- system (very clean environment with respect to hadronic decays)

In the following I will consider the channel $D_s^+ \to K^+K^-e^+\nu_e$

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

Main component: P wave ($J^p=1^-$) $\Rightarrow \phi$ M=1020 MeV/c² Γ= 4.3 MeV/c²



5 kinematic variables:

~~m_{KK}~~ q^2 $\cos\theta_e$ $\cos\theta_V$ χ

⇩

$$q^2 = \left(p_l + p_\nu\right)^2 \in [0, q^2_{max}]$$

$$q^2_{max} = (m_{Ds} - m_\phi)^2 = 0.9\ \mathrm{GeV}^2$$

Possibility to observe the S wave ($J^p=0^+$) in the K^+K^- system:

- visible through the interference with the ϕ
- only sensitive to the $s\bar{s}$ component of the S wave
- candidate : $f_0(980)$

S wave observed in the $D^+ \to K^- \pi^+ \ell^+ \nu$ channel (FOCUS) but never seen in $D_s^+ \to K^+K^-e^+\nu_e$

Decay rate

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

$$I = I_1 + I_2 \cos 2\theta_e + I_3 \sin^2\theta_e \cos 2\chi + I_4 \sin 2\theta_e \cos\chi + I_5 \sin\theta_e \cos\chi + I_6 \cos\theta_e + I_7 \sin\theta_e \sin\chi + I_8 \sin 2\theta_e \sin\chi + I_9 \sin^2\theta_e \sin 2\chi$$

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

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 $\cos\theta_V$

we consider a narrow range around the ϕ peak $\Rightarrow$ no mass dependence

We only consider electrons $\Rightarrow$ neglect terms in m_e^2

P wave parameterization

- P wave: ϕ

F_{11}, F_{21}, F_{31} related to the helicity form factors (H_0, H_+, H_-)

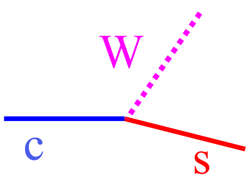
$$F_{11} \propto q H_0 A_\phi(m)$$
$$F_{21} \propto q (H_+ + H_-) A_\phi(m)$$
$$F_{31} \propto q (H_+ - H_-) A_\phi(m)$$

ϕ Breit - Wigner

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

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

Form factors axial-vector (A_1, A_2) and vector (V): pole dominance



Pole: $c\bar{s}$ bound state

Spectroscopic mass

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

1^+ $(D_{sJ}(2460), D_{s1}(2536))$

$\rightarrow$ $m_A = 2.5\ \mathrm{GeV}/c^2$

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

1^- (D_s^*)

$\rightarrow$ $m_V = 2.1\ \mathrm{GeV}/c^2$

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

No sensitivity m_V

S wave parameterization

- S wave: f_0

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

Normalisation:

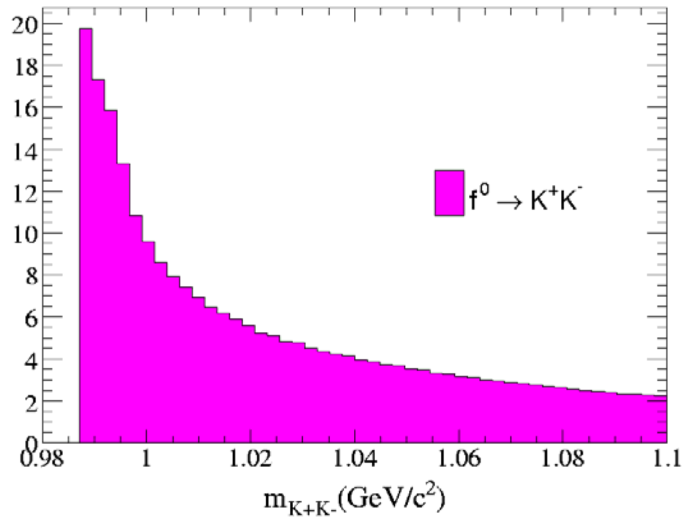
Fit parameter

Form factor

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

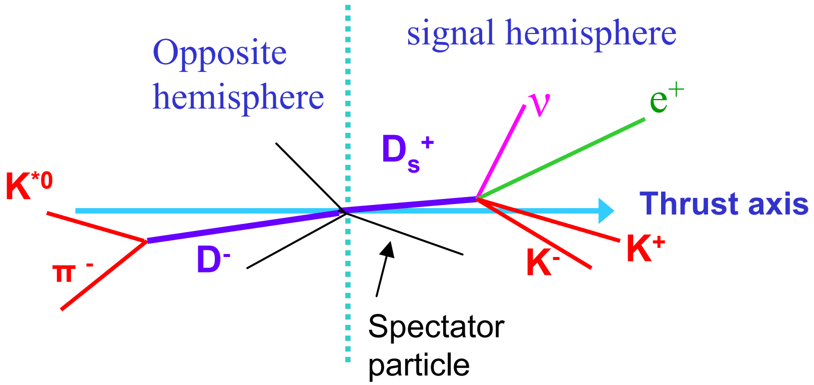
$$A_{f0}(m) = \frac{m_{fo} g_{\pi}}{m_{f0}^2 - m^2 - i m_{f0} \Gamma_{f0}}$$

f_0 amplitude: Flatté (parameters from BES)



Analysis overview

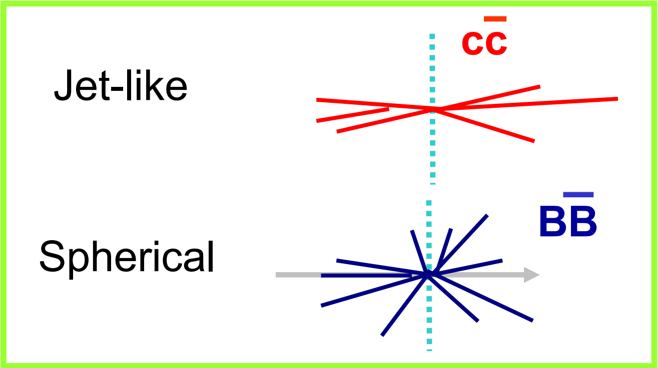
➢ Very similar to $D^0 \to K^- e^+ \nu$:



- **Untagged analysis**
- **Reconstruct the decay channel**

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

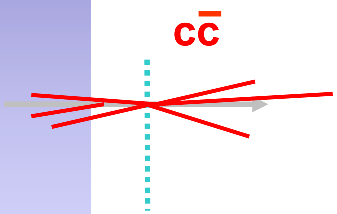
in $e^+e^- \to c\bar{c}$ continuum events



- **Determine** q^2, $\cos\theta_e$, $\cos\theta_V$, χ ← one constrained fit (m_{Ds})
- **Reduce the background** ← Fisher discriminants ($b\bar{b}$ and $c\bar{c}$ events)
- **Extract the form factor** ← 4-dim likelihood fit, using MC
- **methods validation** ← Control sample ($D_s \to \phi\pi$)
- **FF normalization** ← measurement of the branching fraction

Data/MC agreement is crucial !!

Fisher discriminants



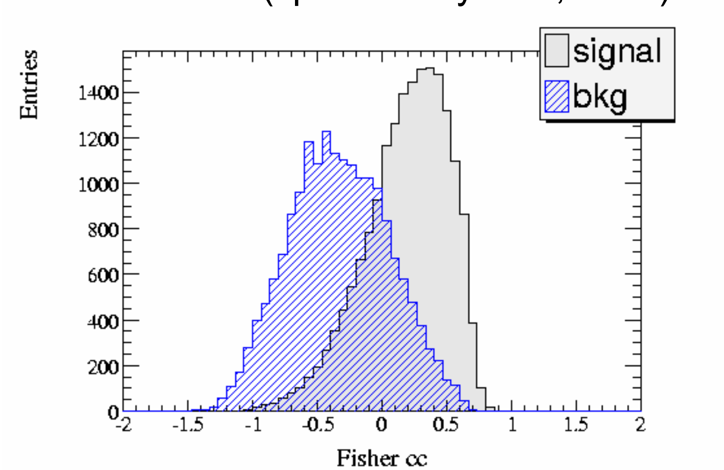
$c\bar{c}$ events

P(D_s),

Spectator system momentum and mass,

P(leading) ,

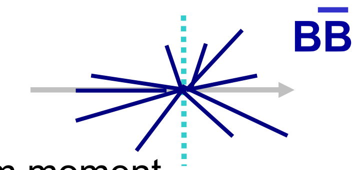
cos(spectator system,thrust)



Efficiency on signal : 71 %

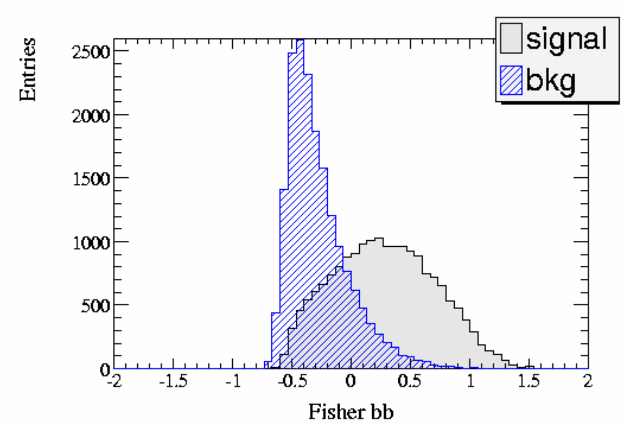
Background rejection : 72 %

$B\bar{B}$ events



2nd Fox wolfram moment

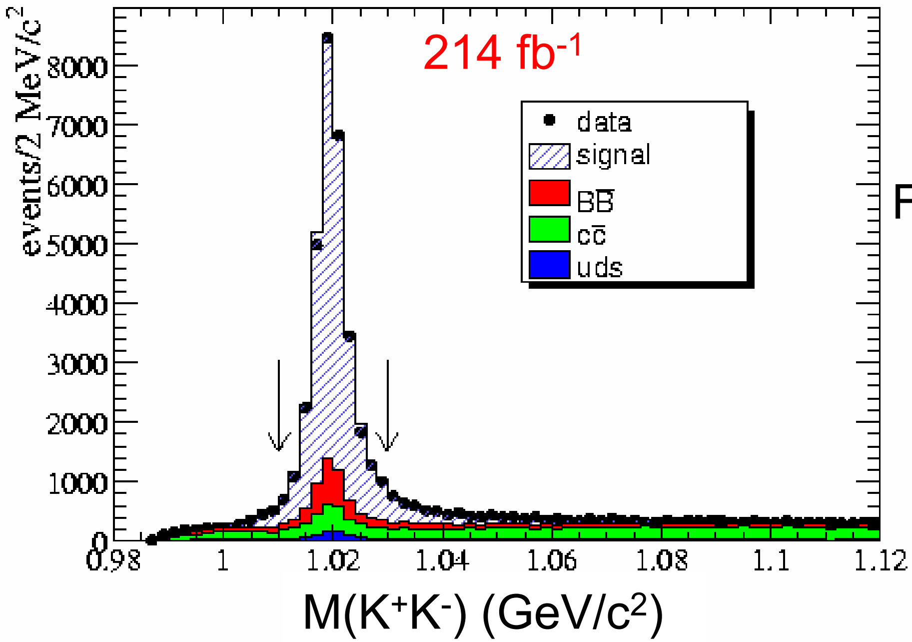
multiplicity



Efficiency on signal : 71 %

Background rejection : 86 %

K^+K^- mass distribution



$1.01 < m_{KK} < 1.03$ GeV/c^2:

31839 events

From simulation, 18 % of background

~ 26000 signal events

"Peaking bkg": events with a ϕ
(70% of background)

"continuum bkg": no ϕ
(30% of background)

Peaking bkg composition:

ϕ and lepton origin	fake lepton	conversion or π^0	lepton from charm	lepton from B
ϕ from fragmentation	6.5	6.4	16	0
ϕ from D_s^+	4.1	8.3	0.4	0
ϕ from D	1.7	4.9	0.5	0
ϕ from B	0.1	0.1	0	50.8

Continuum (for $K^+K^-e^+$ candidate):

- K^- fragmentation, K^+ from D_s : ~20%
- K^+ fragmentation, K^- from D^0 : ~44%
- K^+ fragmentation, K^- from D^+ : ~13%
- K^+ fragmentation, K^- from D_s : ~1%
- two K from fragmentation: ~13%
- one fake K, K from charm: ~7%

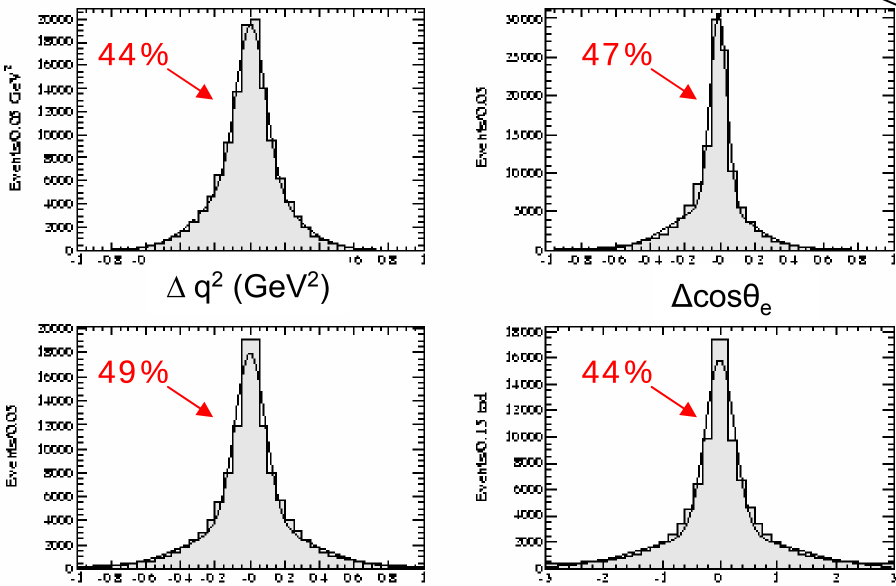
Kinematic variables

Typical resolutions :

$\sigma_1 \sim 0.08$ GeV²
$\sigma_2 \sim 0.23$ GeV²

$\sigma_1 \sim 0.05$
$\sigma_2 \sim 0.23$

MC

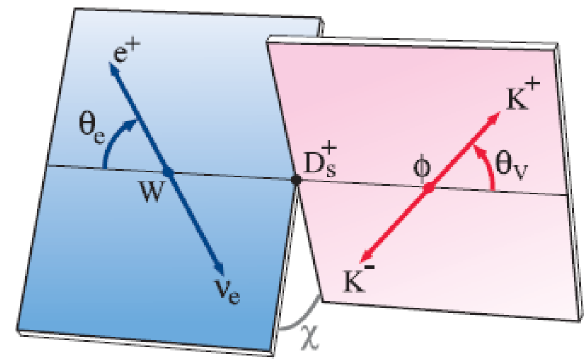


Δq^2 (GeV²) — $\Delta\cos\theta_e$

$\Delta\cos\theta_V$ — $\Delta\chi$

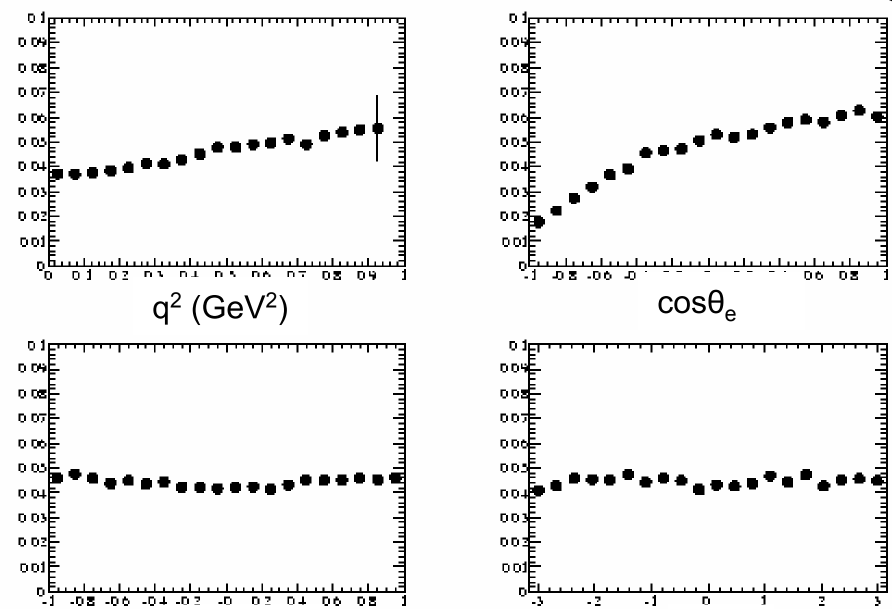
$\sigma_1 \sim 0.09$
$\sigma_2 \sim 0.33$

$\sigma_1 \sim 0.25$
$\sigma_2 \sim 1.22$



Global efficiency: ~4.5%

MC



q^2 (GeV²) — $\cos\theta_e$

$\cos\theta_V$ — χ

Control samples

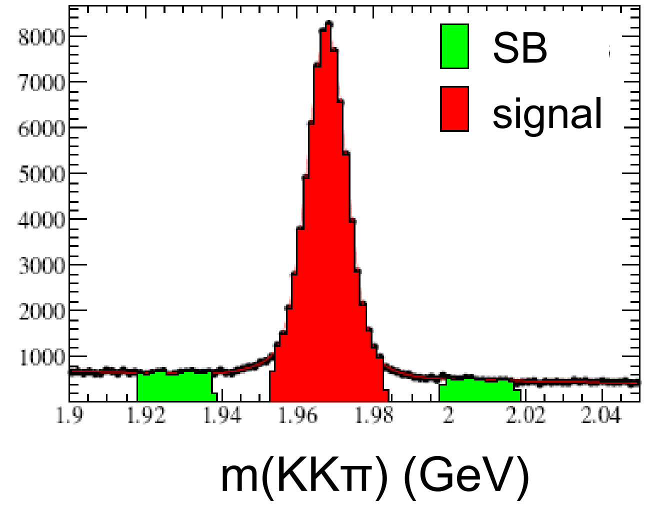
Control samples are used to:

- control agreement between data and MC for the variables used in the selection (Fisher discriminants)
  - signal ⟶ $D_s^+ \to \phi\pi^+$
  - background ⟶ $D_s^+ \to \phi\pi^+$, $D^0 \to K^-\pi^+$, off-peak ($B\bar{B}$), ϕ sidebands (continuum bkg)
- control of the D_s direction and missing energy determination (used as input of the kinematic fit) ⟶ $D_s^+ \to \phi\pi^+$

$D_s^+ \to \phi\pi^+$ reconstruction:

- Similar to $D_s^+ \to \phi e^+ \nu_e$
- to reject D_s from B decays, cut on the D_s momentum : $p(D_s)/p_{max} > 0.44$
- background subtraction using the sidebands

~ 70000 events



Control sample $D_s^+ \to \phi\pi^+$

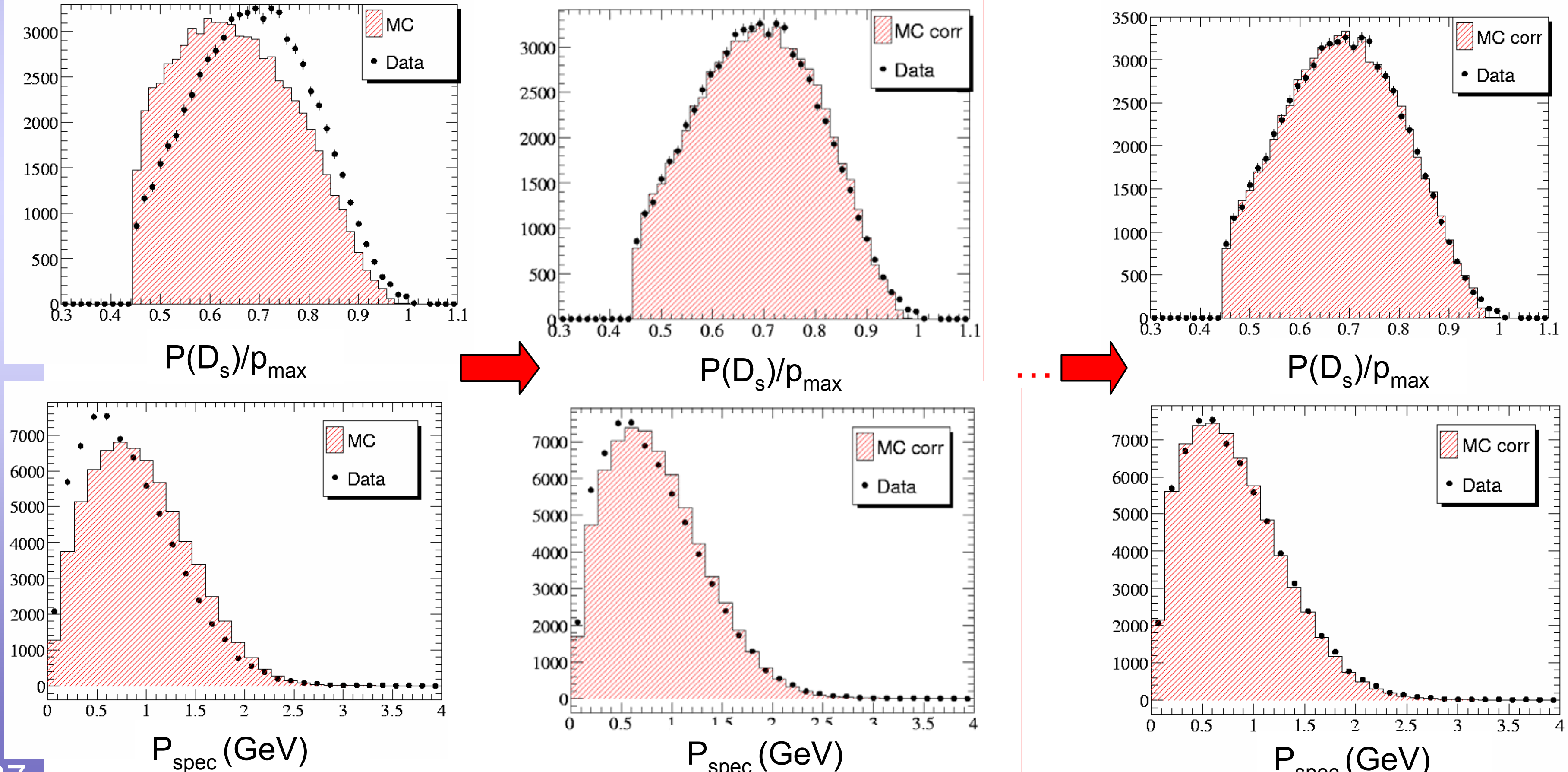
Test data/MC agreement for Fisher variables:

Define a correction (weight) as function of the different variables in an iterative way

Example:

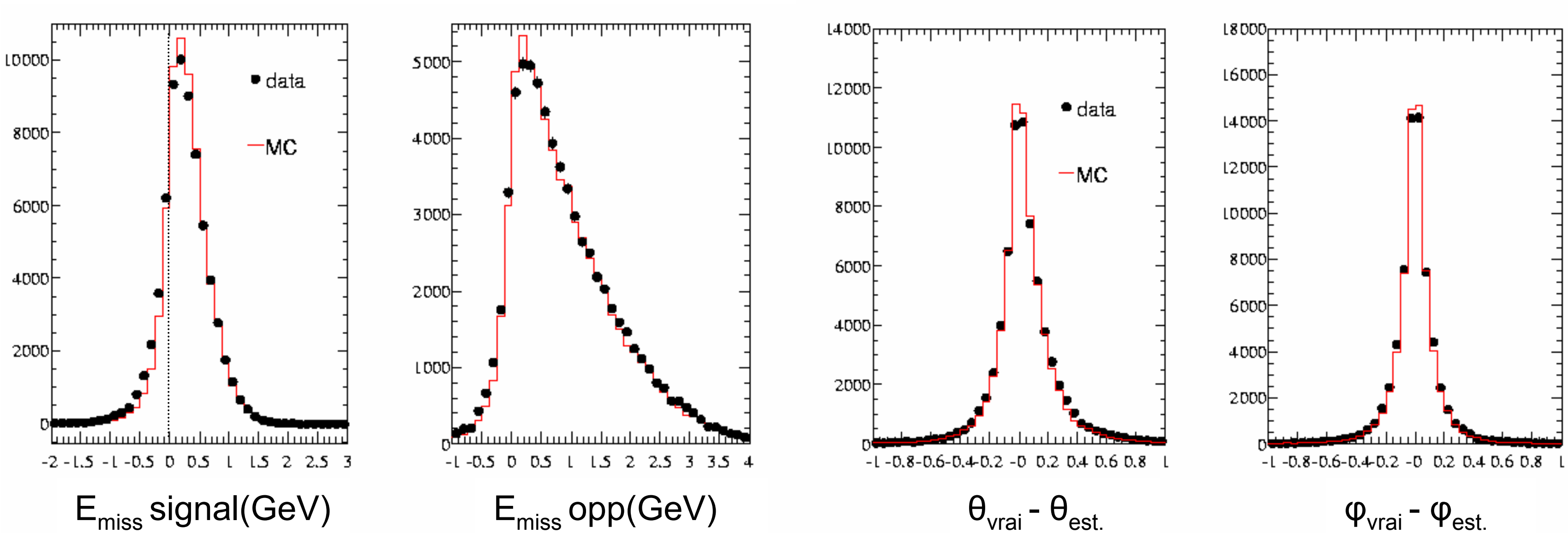
Iteration 1

Iteration n



Control sample $D_s^+ \rightarrow \phi\pi^+$

Control of missing energy in both hemispheres and D_s direction:



Should be 0 because $D_s \rightarrow \phi\pi$

Product of D_s : $\phi\pi$

Estimated from the rest of the event

- Control of data/MC agreement for these variables
- Biasis and uncertainty parameterization of as function of the **missing energy in the opposite hemisphere** (characteristic of the energy reconstruction in the event)

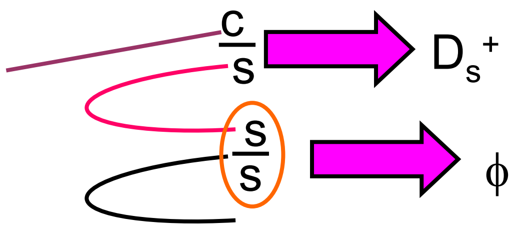
Background control

- $c\bar{c}$ peaking bkg: study the ϕ production rate in events with a D^{*+} and D_s

  $D^{*+} \rightarrow D^0 \pi^+$, $D^0 \rightarrow K^- \pi^+$ $\qquad D_s^+ \rightarrow \phi \pi^+$

Example of data/MC agreement and ϕ origin in D_s events:

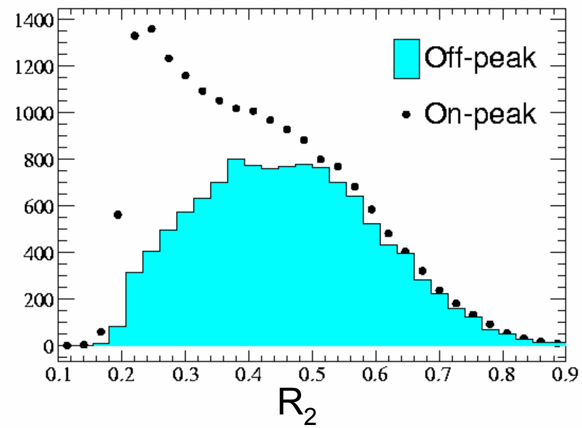
	Opposite hemisphere	D_s hemisphere
Data/MC	0.91±0.05	0.94±0.07
ϕ from D_s ϕ from D ϕ from fragmentation	37 % 29 % 34 %	1.5 % 0.1 % 98.4 %



- $c\bar{c}$ continuum bkg: study the K production rate in events with a D^{*+} and D_s

- $B\bar{B}$ background: use “off peak” (data recorded 40 MeV below l’Υ(4S))

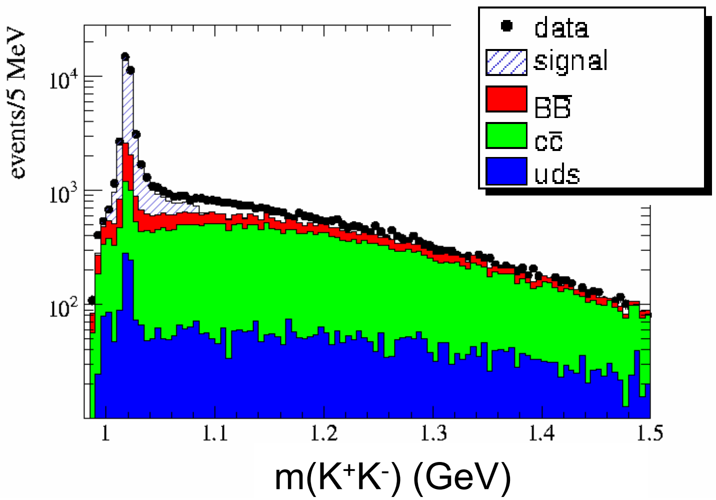
  Subtraction (“on peak” – “off peak”)
  $\Rightarrow$ BB contribution, to be compared with simulation

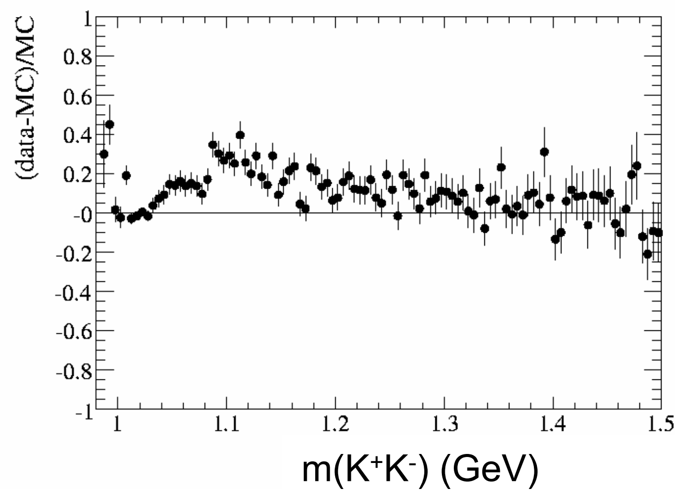


➡ *MC corrections defined for each type of bkg*

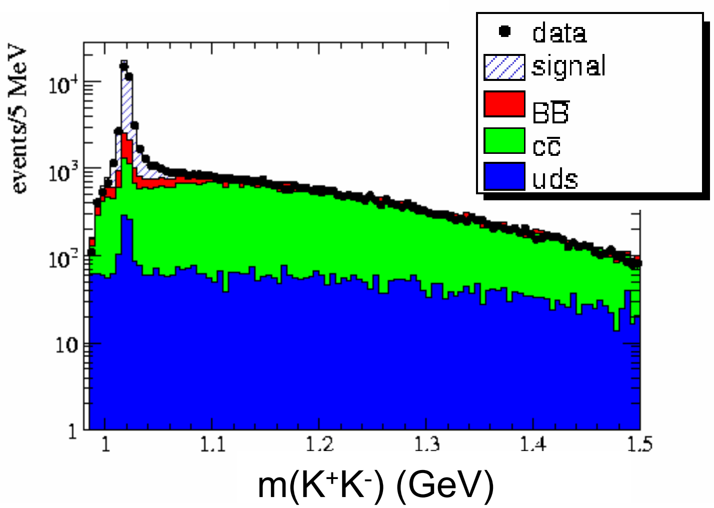
Continuum background

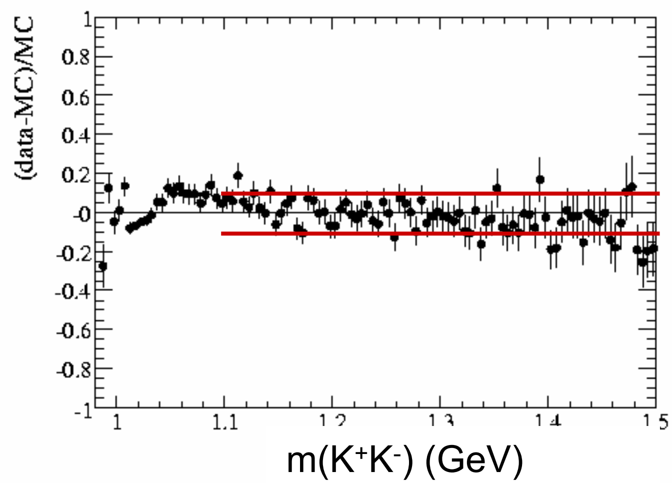
Before corrections





After corrections



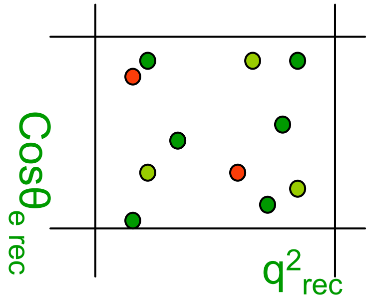


Agreement better than10%

Fit procedure

Use 5 bins for each *reconstructed* variables and perform a 4 D log-likelihood calculation :

MC signal sample = 7x data statistics



Poisson law

$$L = -\sum_{i=1}^{nbins} \ln P\left(n_i^{data} \mid n_i^{MC}\right)$$

Number of data events in bin i

Number of expected events from MC in bin i

n_i^{MC} results from :

-the number of signal events expected, that is deduced by applying a weight **w** to MC signal events ● generated according to SL pole model, using the *simulated values* of the variables.

So resolution effects are directly included in the fit

- the number of bkg events ● estimated from generic MC (normalized to data lumi).

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

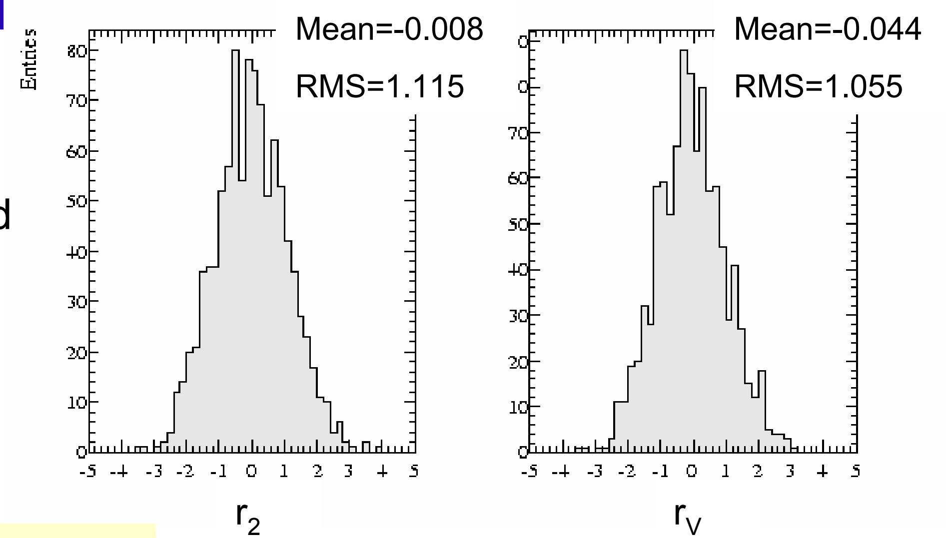
Floatted

$$\lambda_k = r_2, r_V, m_A, r_0$$

Parameters to be fitted

$$W_{tot}(\lambda_k) = \sum_{i=1}^{i=nbins} \sum_{j=1}^{j=n_i^{signal}} w_j(\lambda_k)$$

Validation



Toy Monte Carlo

- 1000 independent experiments generated with statistics and ratio S/B similar to data
- resolution effects not included

Pull distributions allow the evaluation of 2 sources of statistical fluctuations not included in the fit :

- the # of MC signal used in the fit
- the estimate of average number of bkg in each bin

σ_{pull} ~1.06-1.1

error: $\sqrt{1.1^2 - 1} \times \sigma_{fit} = 0.46 \times \sigma_{fit}$

Analysis on fully simulated events :

parameter	Exact value	Fitted value
N_S	68674	68640 ± 262
r_V	1.5	1.519 ± 0.023
r_2	0.7	0.667 ± 0.021

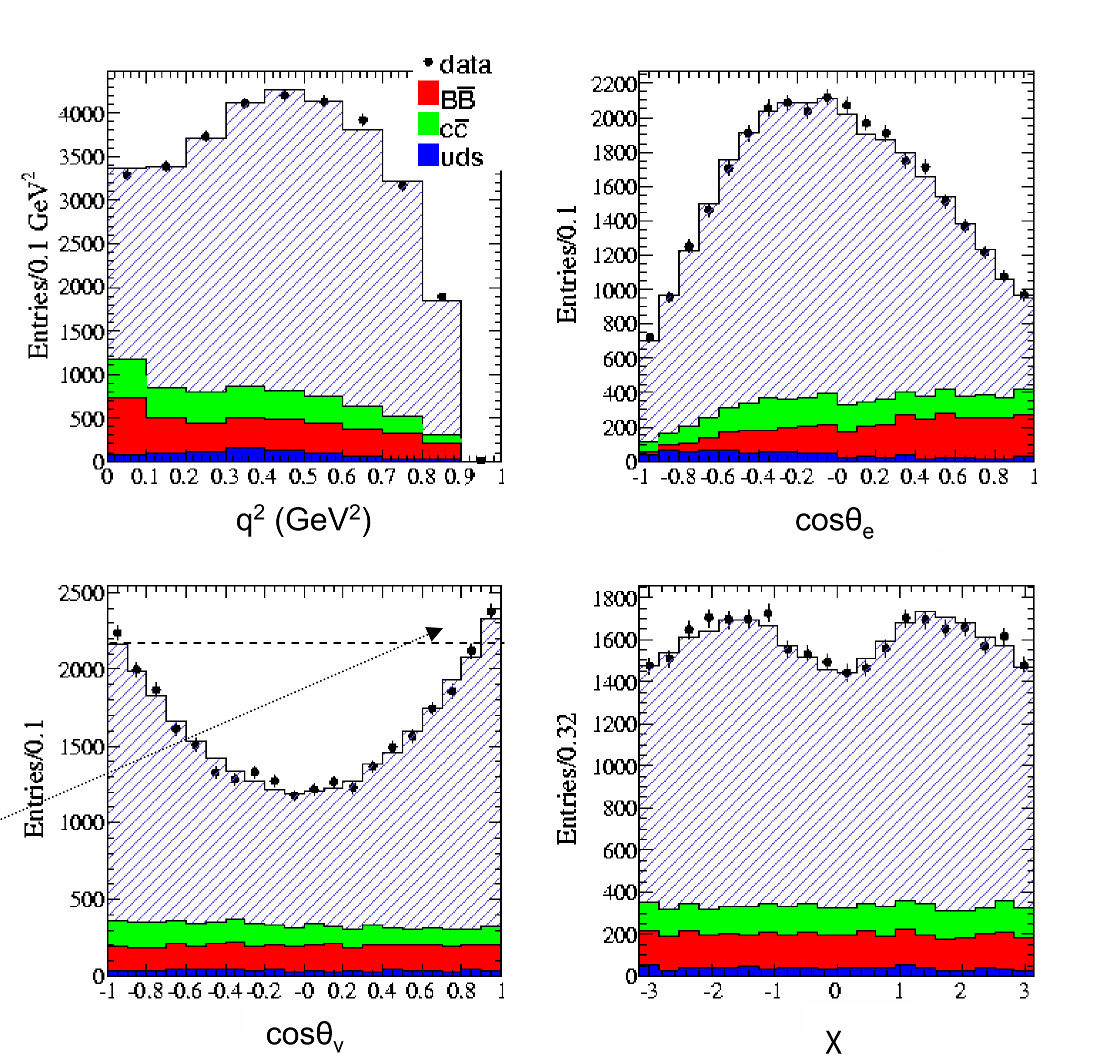
parameter	Exact value	Fitted value
N_S	68674	68640 ± 262
r_V	1.5	1.516 ± 0.027
r_2	0.7	0.675 ± 0.039
m_A	2.5 GeV/c^2	$(2.54^{+0.18}_{-0.15})$GeV/c^2

Fitted values compatible with input

Results

$$r_V = 1.849 \pm 0.060$$
$$r_2 = 0.763 \pm 0.071$$
$$m_A = 2.28^{+0.23}_{-0.18} \ GeV / c^2$$
$$r_0 = 15.1 \pm 2.6 \ GeV^{-1}$$

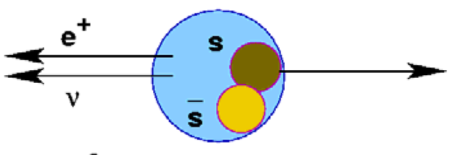
- model prediction: m_A= 2.5 GeV/c^2
- S wave contribution observed!



Results in q^2 bins

$0<q^2<0.18$ GeV^2

(ℓ and ν parallel in the D_s center of mass)



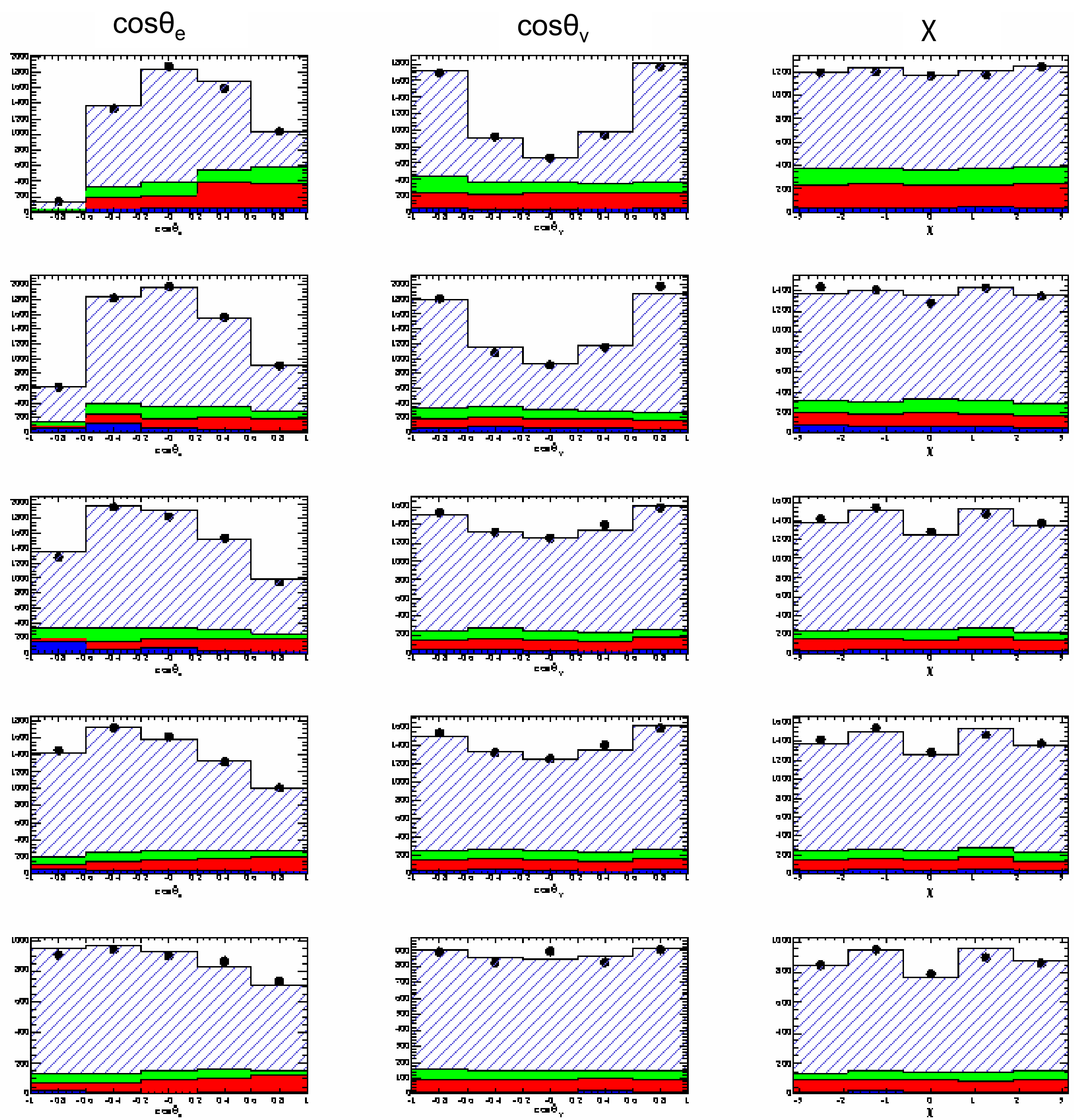
$0.18<q^2<0.36$ GeV^2

$0.36<q^2<0.54$ GeV^2

$0.54<q^2<0.72$ GeV^2

$0.72<q^2<0.9$ GeV^2

(W and ϕ at rest, no helicity defined)



Systematic uncertainties

Corrections to the simulation

Source	error on N_s	error on r_0	error on r_V	error on r_2	error on λ_A
Fisher variables for signal MC	1	0.1	0.013	0.009	0
smearing D_s^+ angles	10	0	0.001	0.005	0
smearing missing energy	5	0.1	0.009	0.013	0.02
total signal MC corrections	11	0.1	0.016	0.017	0.02
Fragmentation corr. on $c\bar{c}$ events	38	0.1	0.007	0.004	0.01
Fisher variables for $B\overline{B}$ events	472	0.1	0.094	0.042	0.05
continuum bkg.	202	0.6	0.032	0.023	0.03
ϕ from fragmentation	120	0.1	0.019	0.013	0.03
ϕ from c-hadrons	80	0.1	0.002	0.013	0.02
ϕ from uds	100	0.1	0.007	0.024	0.03
total bckg MC corrections	550	0.6	0.102	0.057	0.08
Monte-Carlo statistics	81	-	0.029	0.034	0.04
PID efficiencies	1	0.6	0.006	0.011	0.01
neutral correction	5	0.2	0.018	0.012	0.02
radiative events	5	0.3	0.028	0.011	0.03
$S-$wave parameterization	-	0.3	-	-	-
Total	550	1	0.112	0.071	0.10

$m_A = \lambda_A^2 + 1$

Generally, uncertainties coming from corrections applied to the MC are evaluated doing variation of the corrections and measuring the corresponding variation on fitted values

Dominant systematic: $B\overline{B}$ background

Normalization measurement

Branching fraction measured relatively to $D_s^+ \to \phi\pi^+$:

$$R_{Ds} = \frac{BR(D_s^+ \to K^+K^-e^+\nu)_{data}^{\Delta m1}}{BR(D_s^+ \to K^+K^-\pi^+)_{data}^{\Delta m2}}$$

with

$$\begin{cases} \Delta m1 = [1.01,\ 1.03]\ \mathrm{GeV/c^2} \\ \Delta m2 = [1.0095,\ 1.0295]\ \mathrm{GeV/c^2} \end{cases}$$

to use CLEO-c measurement

$$BR(D_s^+ \to K^+K^-\pi^+)_{data}^{\Delta m2} = (1.99 \pm 0.10 \pm 0.05)\%$$

We obtain: $R_{Ds} = 0.5577 \pm 0.0065 \pm 0.0168$

➡ $BR(D_s^+ \to K^+K^-e^+\nu)^{\Delta m1} = (1.110 \pm 0.013 \pm 0.033 \pm 0.062)\%$

➡ Correcting for the mass range and S wave contribution : $BR(D_s^+ \to \phi e^+\nu) = (2.606 \pm 0.031 \pm 0.086 \pm 0.150)\%$

$$\Gamma = \frac{\hbar BR(D_s^+ \to \phi e^+\nu_e)}{\tau_{D_s}} = \frac{2G_F^2|V_{cs}|^2}{3(4\pi)^3 m_{D_s}^2}|A_1(0)|^2 I$$

➡ $A_1(0) = 0.607 \pm 0.011 \pm 0.020 \pm 0.018$

statistics — systematics — External inputs

Comparison with previous experiments

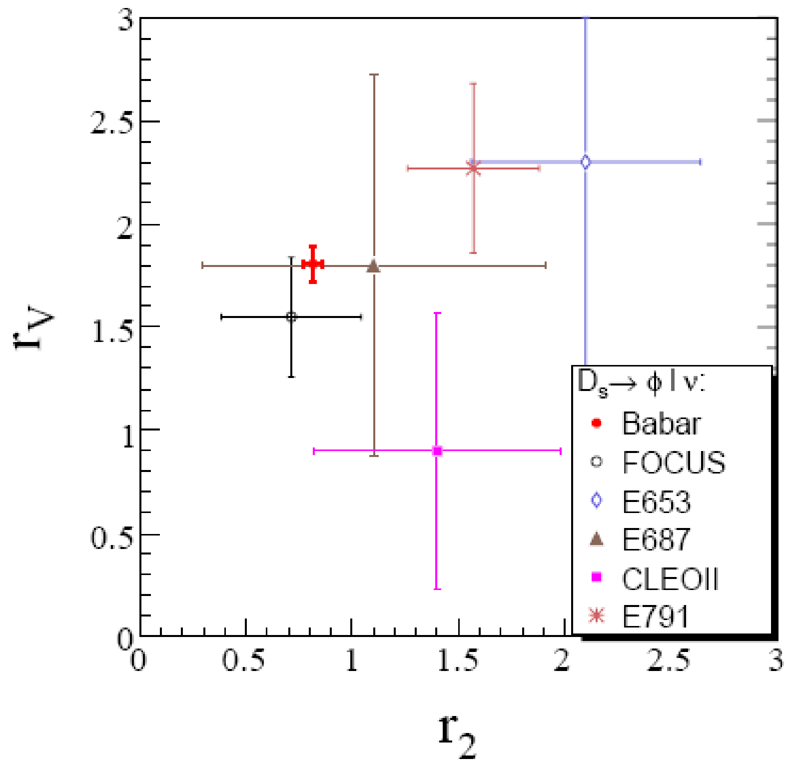
No previous determination of the q^2 dependence and absolute normalization

Expérience	Stat. (S/B)	r_v	r_2
E653	19/5	$2.3^{+1.1}_{-0.9}\pm0.4$	$2.1^{+0.6}_{-0.5}\pm0.2$
E687	90/33	1.8±0.9±0.2	1.1±0.8±0.1
CLEOII	308/166	0.9±0.6±0.3	1.4±0.5±0.3
E791	~300/60	2.27±0.35±0.22	1.57±0.25±0.19
FOCUS	~560/250	1.549±0.250 ±0.145	0.713±0.202±0.266

Fixing the pole masses, we obtain:

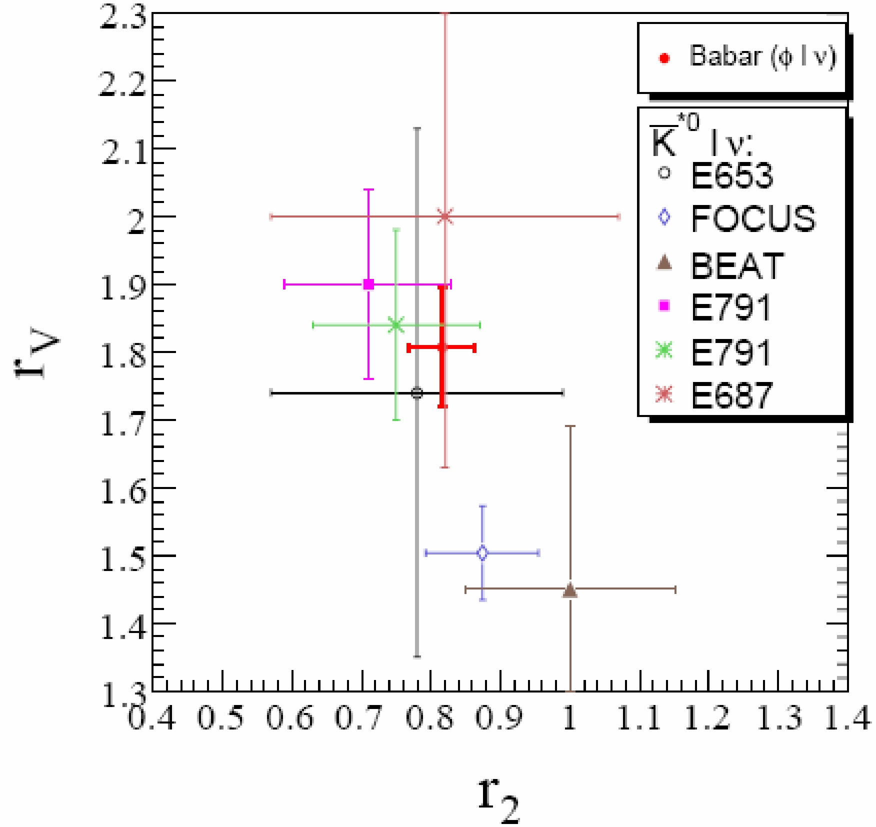
$$r_V = 1.807 \pm 0.046 \pm 0.075$$
$$r_2 = 0.816 \pm 0.036 \pm 0.030$$

- results are compatible with FOCUS
- No result from Belle and CLEO-c until now



Comparison with $D^+ \to \bar{K}^{*0}\ell^+\nu$ channel

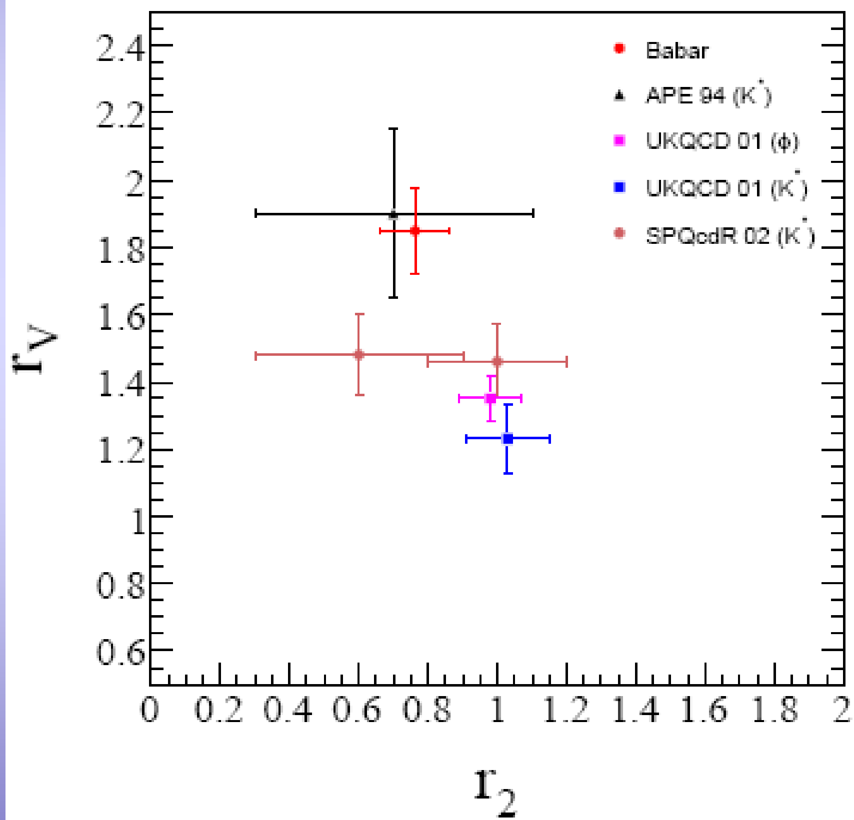
- the 2 channels are expected to have similar form factors
- Babar measurement has same order of precision as world average for $D^+ \to \bar{K}^{*0}\ell^+\nu$ channel



	$D_s^+ \to \phi e^+\nu$	average $D^+ \to \bar{K}^{*0}\ell^+\nu$
r_V	1.807±0.046±0.075	1.62±0.08
r_2	0.816±0.036±0.030	0.83±0.05

Comparison with lattice QCD

Lattice computation for $D^+ \to \overline{K}^{*0} \ell^+ \nu$ and $D_s^+ \to \phi \ell^+ \nu$:



- r_2 compatible with lattice results
- our value of r_V is higher than the more recent determinations
- One can note that the lattice computation for D_s are more precise than for D decays
- UKQCD (2001) give $A_1(0)=0.63\pm0.02$, compatible with our result

$$A_1(0) = 0.607 \pm 0.011 \pm 0.020 \pm 0.018$$

All these measurements use the "quenched" approximation

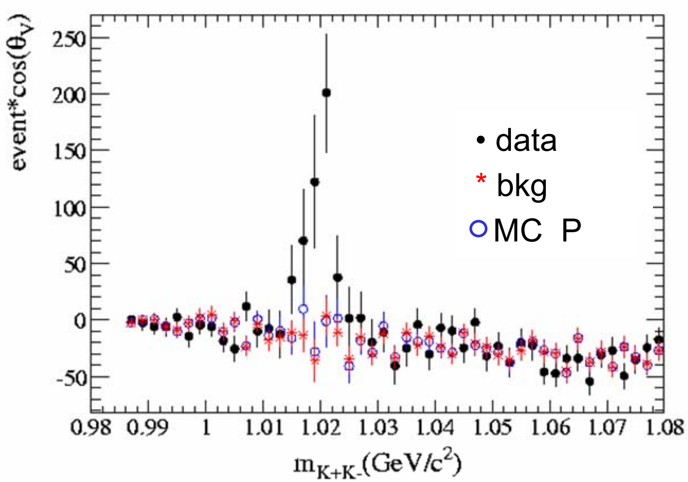
It would be very interesting to have *unquenched* results!!

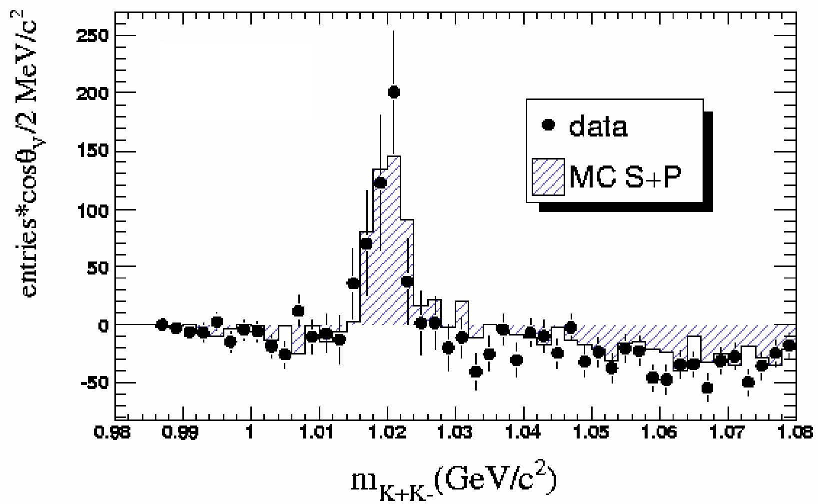
S wave

$r_0 = 15.1 \pm 2.6 \pm 1\ GeV^{-1}$

First evidence!

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





Clear signal in data, not visible in the MC (P wave only)

Using the fitted value of r_0 to reweight the MC

Between $1.01<m_{KK}<1.03$ GeV/c^2 :

$$\frac{BR(D_s^+ \to f_0 e^+ \nu_e)^{\Delta m1} \times BR(f_0 \to K^+K^-)}{BR(D_s^+ \to K^+K^- e\nu_e)^{\Delta m1}} = 0.22^{+0.12}_{-0.08} \pm 0.03\%$$

Only sensitive to the $s\bar{s}$ component of the f_0

Introduction

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

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

Perspectives and summary

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

☆ As for $D^0 \to K^- e^+ \nu$ channel ➜ One form factor: $f_+(q^2)$
➜ Angular distribution known → $\sin^2(q_l)$

BUT ➜ Cabibbo-suppressed

Challenge: background control

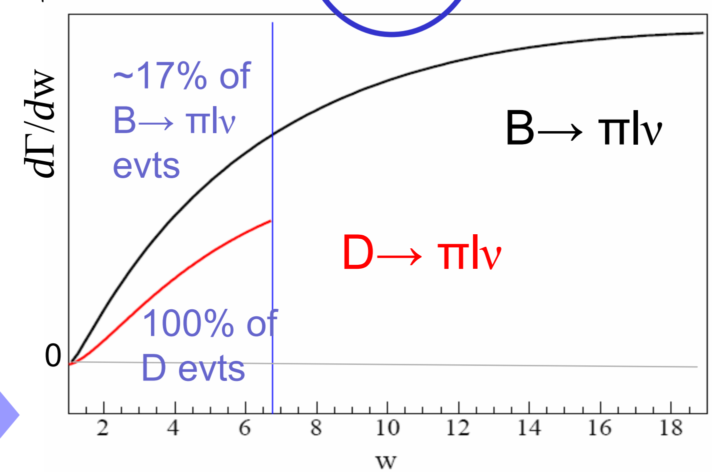
☆ Motivation: V_{ub} determination

From Lattice QCD

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

Experimentally, we need a common range in w for the two channels.

Possible with $w \in [1,6.7]$ which corresponds to $q^2_D \in [0; 2.975]$ and $q^2_B \in [18; 26.4]$ GeV^2

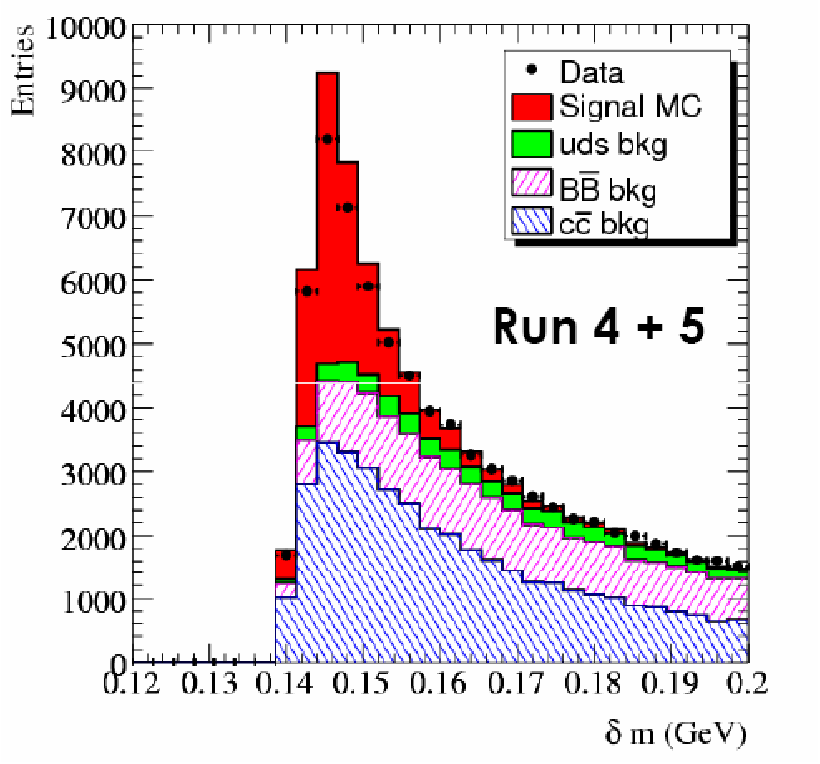


ff shape from B&K parametrization

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

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

233 fb^{-1} $\to$ ~ 11000 signal events (signal/bkg~0.6)



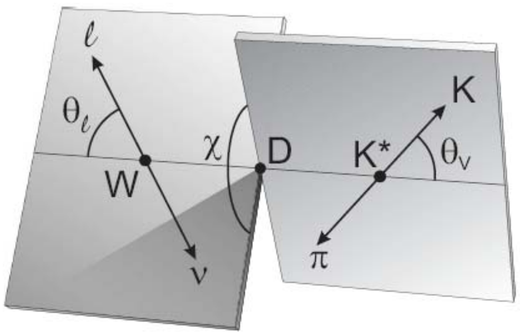
CLEO-c preliminary (280 pb^{-1}):

~1200 signal events

Ongoing analysis…

$D \to K\pi e\nu$

- ☆ As for $D_s^+ \to K^+K^-e^+\nu_e$ channel
  - ➔ vector final state
  - ➔ 5 kinematic variables
  - ➔ 3 form factors
  - ➔ Cabibbo-favoured



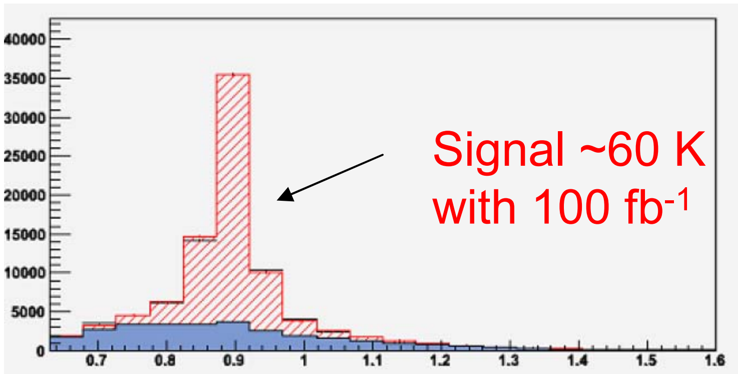
- ☆ Motivation: in addition to the FF measurement, study the S wave component of the hadronic system in a clean environment

Main component: P wave ($J^P=1^-$) $\Rightarrow$ K*(892) $\Gamma \sim 50$ MeV/c^2

5 kinematic variables:

$m_{K\pi}$ q^2 $\cos\theta_e$ $\cos\theta_V$ χ

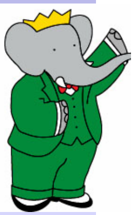
Activity in two channels:
- $D^0 \to K_s \pi^- e\nu$
- $D^+ \to K^-\pi^+ e\nu$



Signal ~60 K with 100 fb^{-1}

m(Kπ)

Summary



- Charm semileptonic decays are of great interest to validate lattice QCD calculations through form factors measurements. This requires accurate experimental measurements implying large statistics and a good control of systematics.
- Thanks to an original method for the reconstruction of SL decays, Babar is competitive with charm factory
- $D^0 \rightarrow K^- e^+ \nu$ form factor :
  - first study of Babar potential in charm SL decays
  - very successful, measurement much more precise than lattice
- $D_s^+ \rightarrow K^+ K^- e^+ \nu$:
  - Very precise determination of (r_2, r_V), first determination of the q^2 dependence (m_A) and absolute normalization ($A_1(0)$)
  - first evidence of an S wave component in this SL decay
  - disagreement with “quenched” lattice results (r_V), it would be nice to have new computations
- Charm semileptonic decays also a provide a clean environment to study S wave components
- Other charm SL decays are under study, results will come soon!